Exclusion of multifold solutions of the CKM Unitarity Triangle by a time-dependent Dalitz plot analysis of $\overline{B}^0 \to D^{(*)} h^0$ with $D^0 \to K^0_S \pi^+\pi^-$ decays combining BABAR and Belle data

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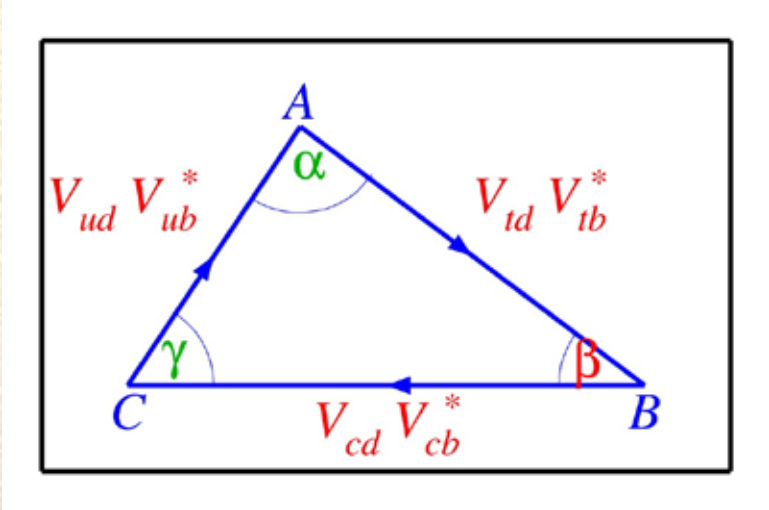
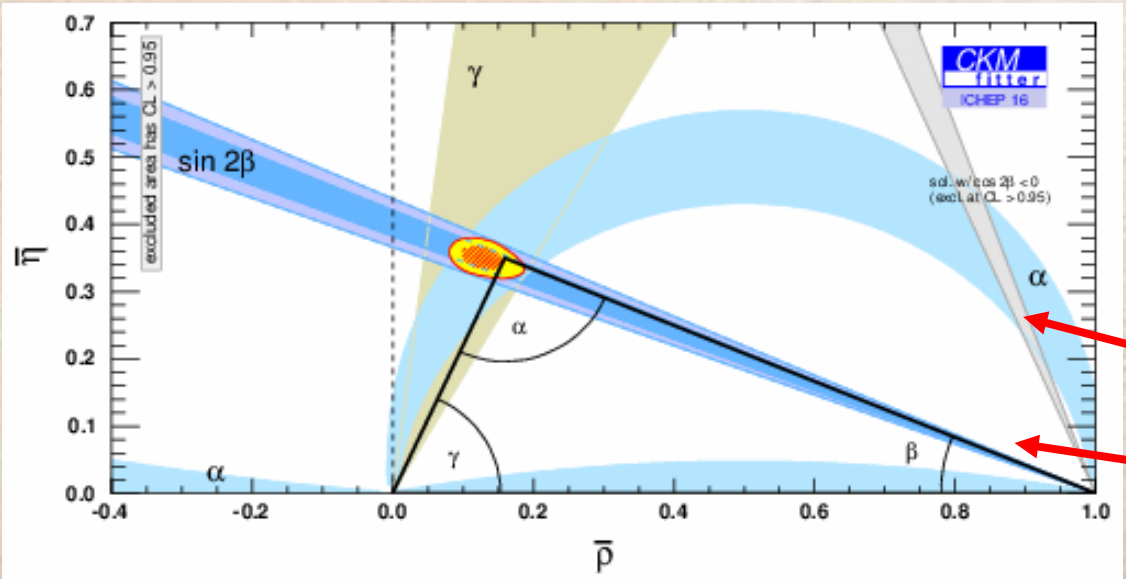
Introduction

- In the Standard Model, *CP* violation originates from the phase of the CKM matrix
- The unitarity relation $V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$

  represents the so-called Unitarity Triangle (UT)
  ➔ the sides $V^*_{ub}V_{ud}$, $V^*_{cb}V_{cd}$, $V^*_{tb}V_{td}$ and angles α, β, γ are extracted from many measurements in the B and K systems



- The determination of β from sin 2β measurements leads to a two-fold ambiguity on 2β



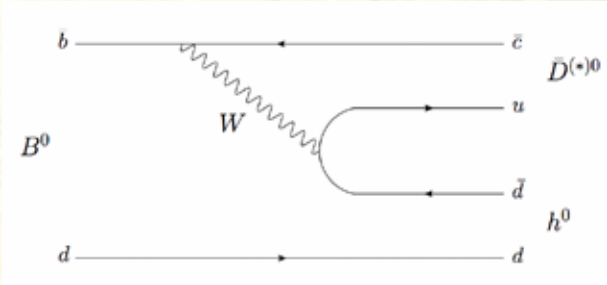
β=π/2-21.9°=68.1°

β=21.9°

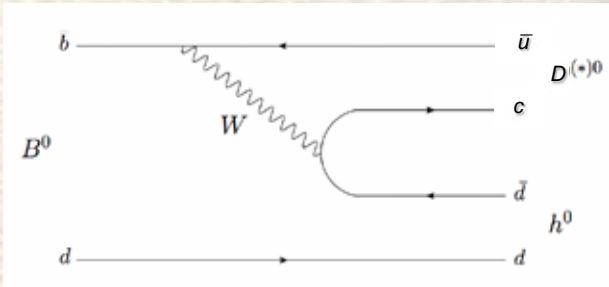
Analysis Methodology

- $\bar{B}^0 \to D^{0\,(*)} h^0$, with $D^0 \to K^0_S \pi^+ \pi^-$ decays, enables the extraction of both sin(2β) & cos(2β)
- The h^0 represents π^0, η and ω

Tree



Doubly-CKM-suppressed tree



$$\left|M_{B^0}(\Delta t)\right|^2 = \left| \underset{D^0}{\boxed{}} \times\cos\left(\tfrac{1}{2}\Delta m \Delta t\right) - i e^{+2i\beta} \times \underset{\bar{D}^0}{\boxed{}} \times\sin\left(\Delta m \tfrac{1}{2}\Delta t\right)\right|^2$$

$$\left|M_{\bar{B}^0}(\Delta t)\right|^2 = \left| \underset{\bar{D}^0}{\boxed{}} \times\cos\left(\tfrac{1}{2}\Delta m \Delta t\right) - i e^{-2i\beta} \times \underset{D^0}{\boxed{}} \times\sin\left(\Delta m \tfrac{1}{2}\Delta t\right)\right|^2$$

- Belle measured cos(2β)=$1.05 \pm 0.33^{+0.21}_{-0.15}$ in $\bar{B}^0 \to D^{(*)0} h^0$

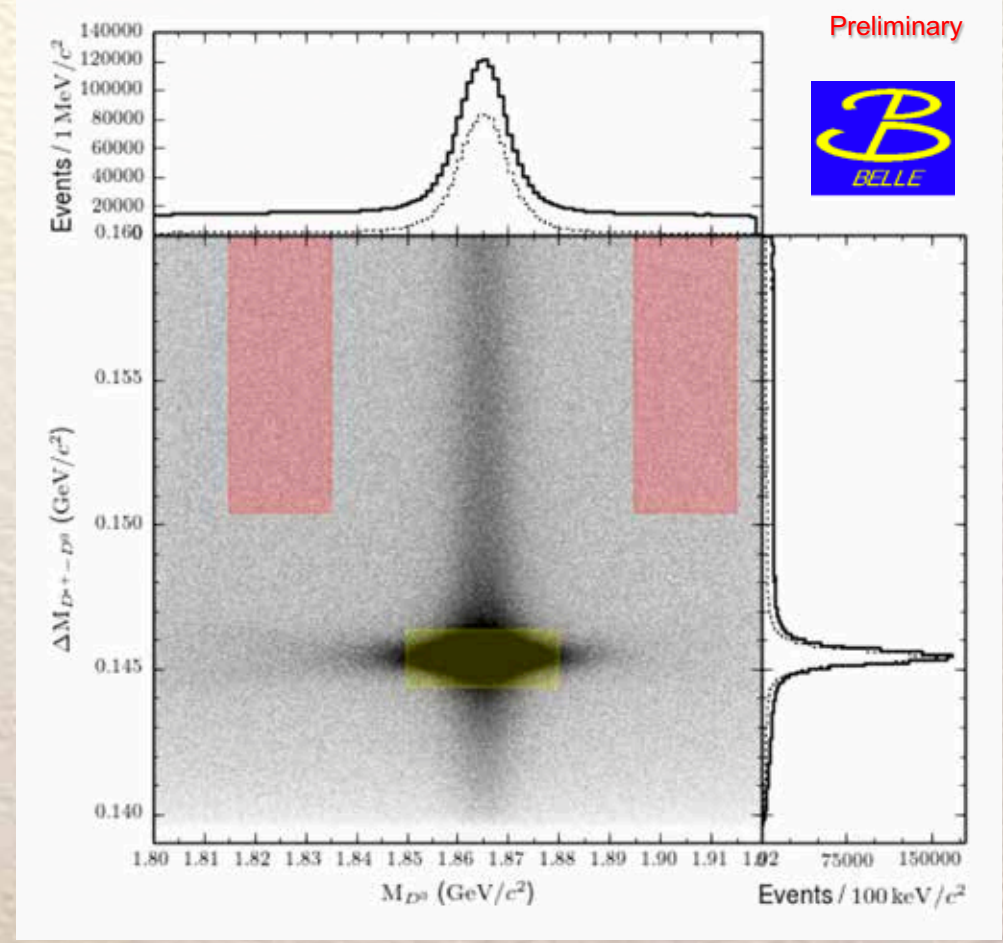
[PLB 624, 1 (2004)]

[PRD 94, 052004 (2016)]

- Perform time-dependent Dalitz plot analysis combining ***BABAR*** & **Belle** data (1.1 ab^{-1})
  ➔ improves sensitivity to cos(2β)

$D^0 \to K^0_S\pi^+\pi^-$ Dalitz Plot Amplitude Model

- $D^{*+} \to D^0 \pi^+_s$ with $D^0 \to K^0_s\pi^+\pi^-$ decays are reconstructed from **Belle** $e^+e^- \to c\bar{c}$ data
- The charge of the slow π^+_s determines the flavor of the D^0
- Require $p^*(D^{*+})$ >2.5 (3.1) GeV for candidates from $\Upsilon(4S)$ ($\Upsilon(5S)$) to reject background from B decays
- Determine D^* decay vertex by kinematic fit of the D^0 with constraint to originate from e^+e^- interaction region
- Require slow π^+_s to originate from D^{*+} decay vertex in the kinematic fit to improve resolution of the D^{*+}-D^0 mass difference
- Extract $D^{*+} \to D^0 \pi^+_s$ yield from 2-dimensional fit of D^0 mass & D^{*+}-D^0 mass difference
- Yield 1.22 million signal events
- Signal purity in signal region is **94%**
  $144.4 < M_{D^*-D} < 146.4$ MeV &
  $1850 < M_D < 1880$ MeV



$D^0 \to K^0_S \pi^+ \pi^-$ Dalitz Plot Amplitude Model

- Fit D^0 Dalitz plot with isobars and $\pi\pi$ and $K\pi$ S-waves used by ***BABAR*** **& Belle**

$$\mathcal{A}_{D^0}\left(m_+^2, m_-^2\right) = \sum_{r \neq (K\pi/\pi\pi)_{L=0}} a_r e^{i\phi_r} \mathcal{A}_r\left(m_+^2, m_-^2\right) + \mathcal{A}_{K\pi_{L=0}}(s) + F_1(s)$$

isobar model for L ≠ 0 LASS K - matrix

[PRD 78, 034023 (2008)]

[PRD 89, 091103 (2014)]

- The Dalitz plot isobar model accounts for 13 intermediate 2-body resonances
- $\pi\pi$ and $K\pi$ S-waves are modeled by the K-matrix and LASS parameterizations
- The a_r and ϕ_r are magnitude and phase of the rth resonance
- The amplitude can be factorized as
- where $$\mathcal{A}_r\left(m_+^2, m_-^2\right) = Z_L\left(m_+^2, m_-^2\right) \cdot F_D\left(m_+^2, m_-^2\right) \cdot F_r\left(m_+^2, m_-^2\right) \cdot T_r\left(m_+^2, m_-^2\right)$$

Z_L: Zemach tensor describing angular distribution of final state

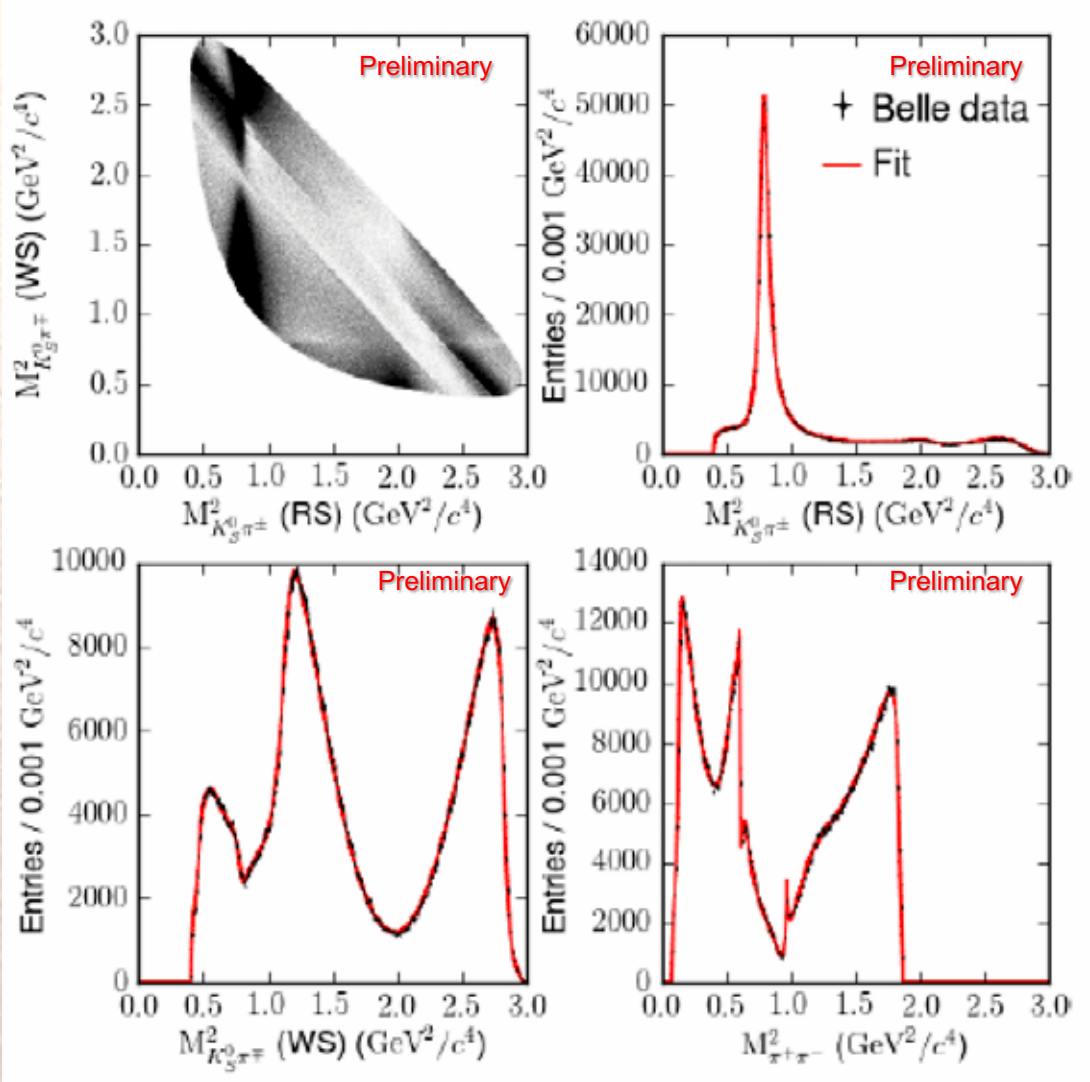
F_D, F_r: Blatt-Weisskopf barrier penetration factor for D meson, resonance

T_r: Propagator describing decay dynamics of resonances parameterized by Breit-Wigner

$D^0 \to K^0_S \pi^+ \pi^-$ Dalitz Plot Amplitude Model

- The 2-body resonances include
  - Cabibbo-allowed states:
    $K^*(890)^-$, $K^*_0(1430)^-$, $K^*_2(1430)^-$, $K^*(1680)^-$, $K^*(1410)^-$
  - Doubly-CKM-suppressed states:
    $K^*(890)^+$, $K^*_0(1430)^+$, $K^*_2(1430)^+$, $K^*(1410)^+$
  - *CP* eigenstates:
    $\rho(770)$, $\omega(782)$, $f_2(1270)$, $\rho(1450)$
- Perform Dalitz Plot fit for flavor-tagged events in signal region with correction for efficiency variations in DP phase space
- Take background from D^0 mass and D^{*+}-D^0 mass difference sidebands

Dalitz plot and fit projections



- Free parameters: a_r, ϕ_r relative to $\rho(770)$, LASS parameters, K-matrix parameters, $K^*(892)$ mass & width, $K^*_0(1430)$ mass & width

Methodology of the Combined Analysis

- In total reconstruct 5 $\bar{B}^0$ decay modes:
  $D^0\pi^0$, $D^0\eta$, $D^0\omega$, $D^{*0}\pi^0$, $D^{*0}\eta$, with $D^0 \to K^0_S\pi^+\pi^-$,
  $D^{*0} \to D\pi^0$, h^0 ($\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$ or $\pi^+\pi^-\pi^0$, $\omega \to \pi^+\pi^-\pi^0$)

- Introduce transformed M_{bc} to remove correlation between $\Delta E = E^*_B - E^*_{beam}$ and M_{bc}

$$M'_{bc} = \sqrt{E^{*2}_{beam} - \left(\vec{p}^{\,*}_{D^{(*)0}} + \frac{\vec{p}^{\,*}_{h^0}\sqrt{\left(E^*_{beam} - E^*_{D^{(*)0}}\right)^2 - M^2_{h^0}}}{\left|\vec{p}^{\,*}_{h^0}\right|} \right)^2}$$

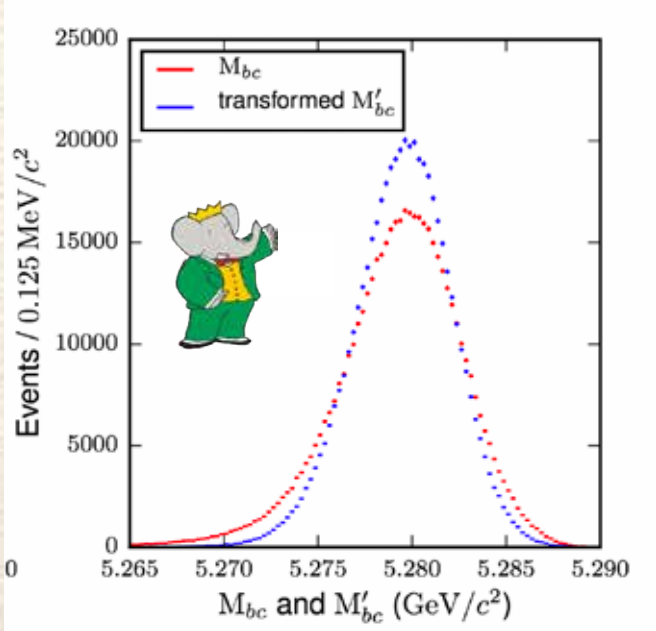
[PRD 69, 11201 (2004)]

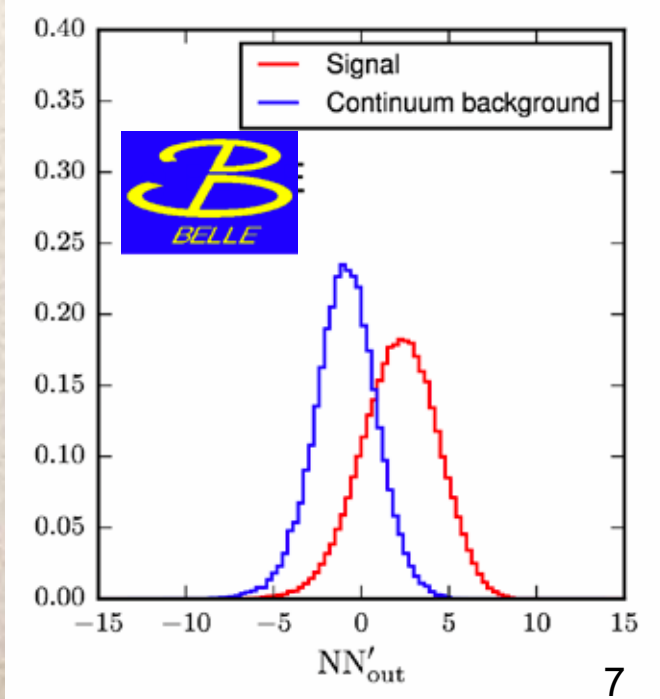
- Define transformed neural network output

$$NN'_{out} = \log \frac{NN_{out} - NN^{min}_{out}}{NN^{max}_{out} - NN_{out}}$$

- where NN combines event shape information from 16 modified Fox-Wolfram moments to separate signal from continuum background $e^+e^- \to q\bar{q}$ ($q \in \{u, d, s, c\}$)

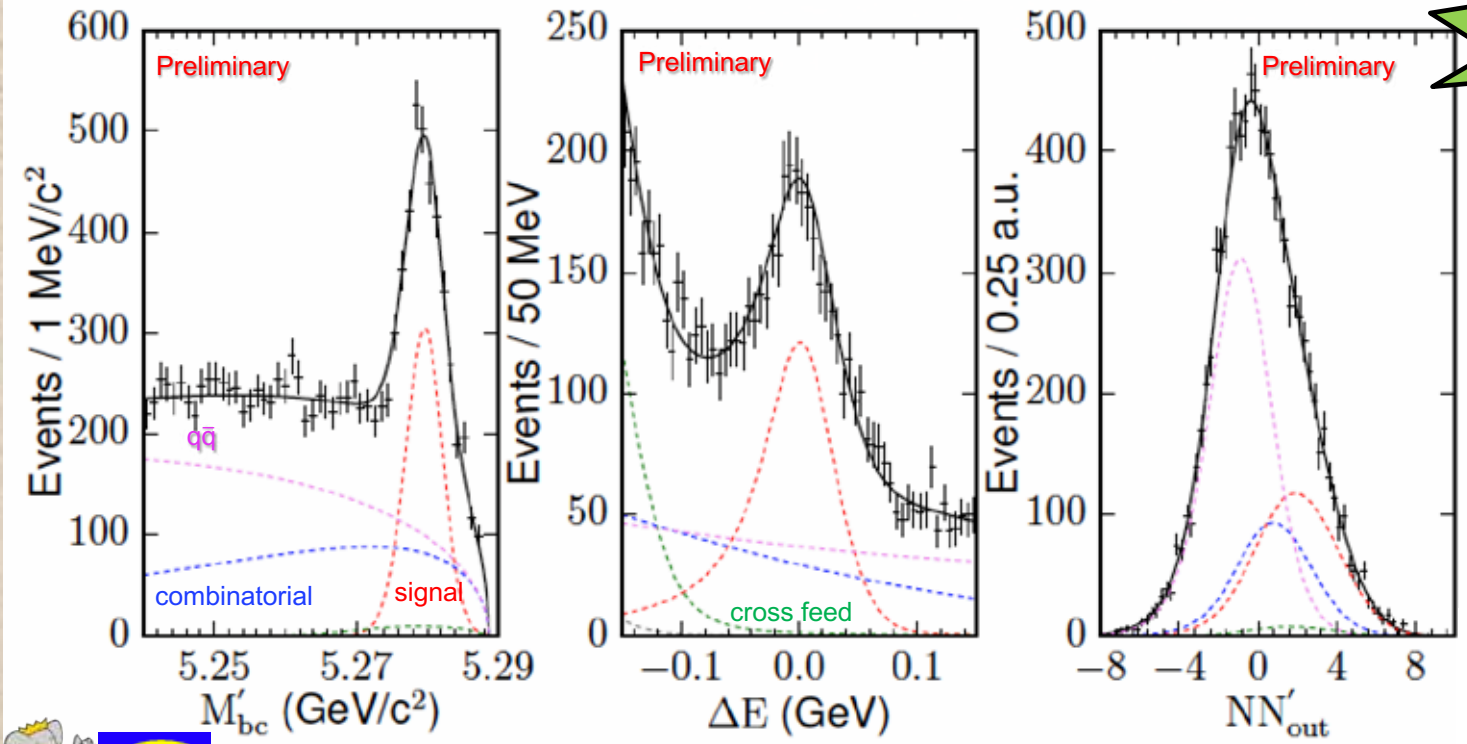
- Coherent analysis strategy, applying essentially same selection on *BABAR* & **Belle** data





Results of 3-dimensional Fit

- Extract signal via 3-D fits of **M'$_{bc}$**, ***ΔE*** and ***NN'$_{out}$***
- Fit are performed separately for individual modes and experiment with individual resolutions
- The fit projections describe the experimental distributions rather well



New

BABAR:
1129±48 signal events

Belle:
1567±56 signal events

Preliminary

Decay mode	*BABAR*	Belle
$\overline{B}^0 \to D\pi^0$	469 ± 31	768 ± 37
$\overline{B}^0 \to D\eta$	220 ± 22	238 ± 23
$\overline{B}^0 \to D\omega$	219 ± 21	285 ± 26
$\overline{B}^0 \to D^*\pi^0$	147 ± 18	182 ± 19
$\overline{B}^0 \to D^*\eta$	74 ± 11	94 ± 13
All above $\overline{B}^0$ -	1129 ± 48	1567 ± 56

Time-dependent *CP* Analysis

- Maximize the log-likelihood function that describes the Δt distribution

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

- The physics PDFs ($\mathcal{P}_i$, $\mathcal{P}_j$) are convolved with experiment-specific resolution functions

$$\mathcal{P}_{\text{exp}} = \sum_k f_k \int \left[\mathcal{P}_k\left(\Delta t'\right) R_k\left(\Delta t - \Delta t'\right) \right] \mathrm{d}\Delta t'$$

- Apply ***BABAR***- and **Belle**-specific flavor-tagging algorithms
- Apply a **common** signal model for both experiments

$$P_{sig}\left(\Delta t\right) \propto \left[\left|\mathcal{A}_{\bar{D}^0}\right|^2 + \left|\mathcal{A}_{D^0}\right|^2 \right] \mp \left(\left|\mathcal{A}_{\bar{D}^0}\right|^2 - \left|\mathcal{A}_{D^0}\right|^2 \right) \cos\left(\Delta m \Delta t\right)$$
$$\pm 2\eta_{h^0} \left(-1\right)^L \left[\Im\mathrm{m}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right)\cos\left(2\beta\right) - \Re\mathrm{e}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right)\sin\left(2\beta\right) \right] \sin\left(\Delta m \Delta t\right)$$

- Parameters τ_{B0}, τ_{B+} and Δm_d are fixed to PGD world averages
- Dalitz plot amplitude model parameters are fixed to fit result of $D^0 \to K^0_S \pi^+ \pi^-$
- Only free parameters are sin(2β) and cos (2β)

CP Violation Results

- With 1.1 ab^{-1} of ***BABAR*** & **Belle** data measure

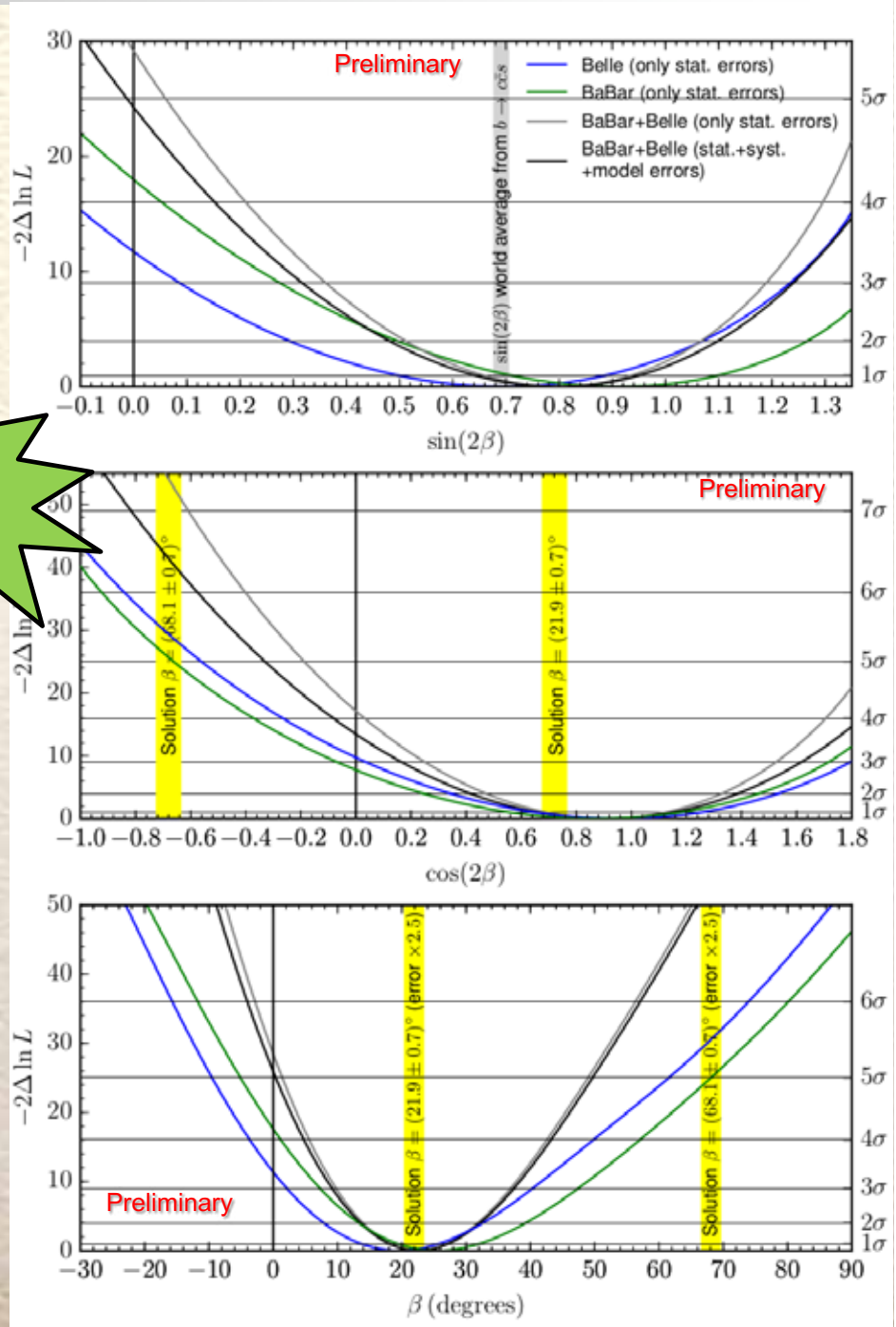
$$\sin(2\beta) = 0.80 \pm 0.14_{(\mathrm{stat})} \pm 0.06_{(\mathrm{sys})} \pm 0.03_{(\mathrm{model})}$$
$$\cos(2\beta) = 0.91 \pm 0.22_{(\mathrm{stat})} \pm 0.09_{(\mathrm{sys})} \pm 0.07_{(\mathrm{model})}$$
$$\beta = \left(22.5 \pm 4.4_{(\mathrm{stat})} \pm 1.2_{(\mathrm{sys})} \pm 0.6_{(\mathrm{model})}\right)^{\circ}$$

New result

- First evidence for cos(2β) >0 @ 3.7σ
- Direct exclusion of the 2nd solution of the Unitarity Triangle, $\pi/2-\beta=(68.1\pm0.7)^{\circ}$ @ 7.3σ
  ➔ ambiguity is removed
- Exclusion of $\beta=0^{\circ}$ @ 5.1σ
- Observe *CP* violation in the decay
  $\bar{B}^0 \to D^{(*)0}h^0$

$$\langle \sin 2\beta \rangle = 0.69 \pm 0.02$$
$$\langle \beta \rangle = \left(21.9 \pm 0.7\right)^{\circ}$$

- HFLAV:



Systematic Uncertainties

- Largest systematic uncertainties on cos(2β) result from Δt resolution functions (0.058), followed by the vertex reconstruction, possible fit bias and signal purity

- Systematic uncertainties from the background Δt pdfs are smaller while those from flavor tagging, physics parameters, Dalitz plot reconstruction efficiency corrections are negligible

Preliminary

TABLE III. Summary of the experimental systematic uncertainties on the CP violation parameters.

Source	$\sin(2\beta)$ $(\times 10^2)$	$\cos(2\beta)$ $(\times 10^2)$	β $(^\circ)$
Vertex reconstruction	3.16	4.79	0.53
Δt resolution functions	2.84	5.75	0.41
Background Δt p.d.f.s	1.24	1.76	0.16
Signal purity	2.13	3.39	0.53
Flavor-tagging	0.34	0.39	0.07
Physics parameters	0.07	0.14	0.02
Possible fit bias	3.67	3.90	0.79
Dalitz plot reconstruction efficiency correction	0.01	0.17	0.02
Total	6.14	9.27	1.18

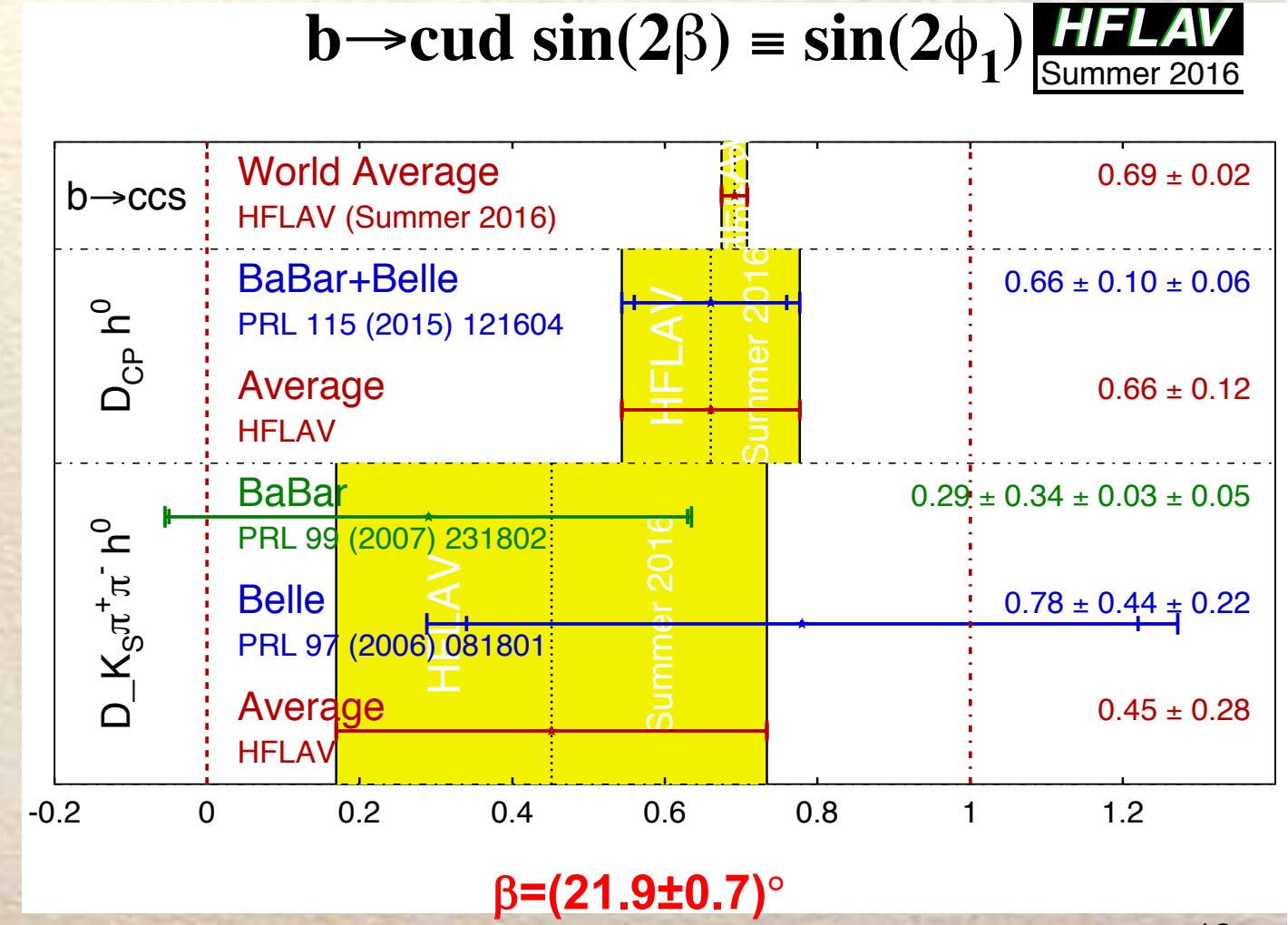
Conclusion

- The combined ***BABAR*** and **Belle**- time-dependent Dalitz plot analysis in $\bar{B}^0 \to D^{0\,(*)} h^0$ with $D \to K^0_S \pi^+ \pi^-$ measures $\cos(2\beta)$=**$0.91 \pm 0.22_{stat} \pm 0.09_{sys} \pm 0.07_{mod}$** from which the 2nd β solution is excluded @ **7.3** standard deviations

- This lifts the ambiguity in the determination of β in the Unitarity Triangle

- The most precise value is

$$\langle \beta \rangle = (21.9 \pm 0.7)^\circ$$



Backup Slides

Results of the Dalitz Plot Fit

TABLE I. Summary of the $D \to K_S^0\pi^+\pi^-$ Dalitz plot amplitude model parameters estimated using Belle $e^+e^- \to c\bar{c}$ data. The errors are statistical only.

Resonance	Amplitude	Phase (deg)	Fit fraction (%)
$\rho(770)$	1 (fixed)	0 (fixed)	20.4
$\omega(782)$	0.0388 ± 0.0005	120.7 ± 0.7	0.5
$f_2(1270)$	1.43 ± 0.03	-36.3 ± 1.1	0.8
$\rho(1450)$	2.85 ± 0.10	102.1 ± 1.9	0.6
$K^*(892)^-$	1.720 ± 0.006	136.8 ± 0.2	59.9
$K_0^*(1430)^-$	2.36 ± 0.06	99.4 ± 1.7	7.0
$K_2^*(1430)^-$	1.27 ± 0.02	-44.1 ± 0.8	1.3
$K^*(1680)^-$	3.31 ± 0.20	-118.2 ± 3.1	0.5
$K^*(1410)^-$	0.29 ± 0.03	99.4 ± 5.5	0.1
$K^*(892)^+$	0.164 ± 0.003	-42.2 ± 0.9	0.6
$K_0^*(1430)^+$	0.11 ± 0.01	162.3 ± 6.6	< 0.1
$K_2^*(1430)^+$	0.10 ± 0.01	-89.6 ± 7.6	< 0.1
$K^*(1410)^+$	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	
$f_{11}^{\rm prod}$	8.0 ± 0.4	-126.0 ± 2.5	
$f_{12}^{\rm prod}$	26.3 ± 1.6	-152.3 ± 3.0	
$f_{13}^{\rm prod}$	33.0 ± 1.8	-93.2 ± 3.1	
$f_{14}^{\rm prod}$	26.2 ± 1.3	-121.4 ± 2.7	
$s_0^{\rm prod}$	-0.07 (fixed)		
$K\pi$ S-wave Parameters			
$M_{K_0^*(1430)^\pm}$ (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		