Measurement of cos2β at *BABAR*

Resolving Ambiguity from sin2β

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on behalf of the

BABAR Collaboration

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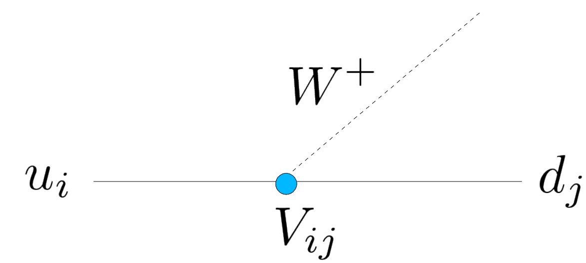
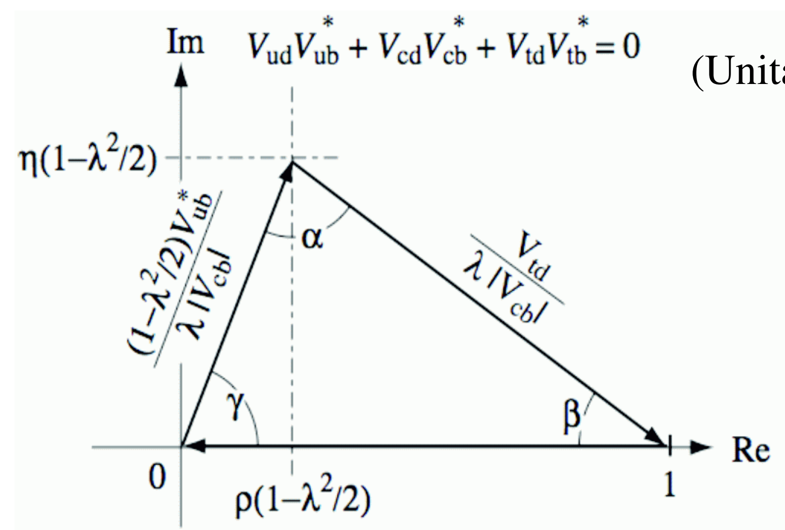
CKM Physics

- CKM matrix describes weak couplings in quarks

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



- Primary goal of the B-factories is to measure these parameters (magnitudes and phases) in as many ways as possible, over constraining the Standard Model parameter space.

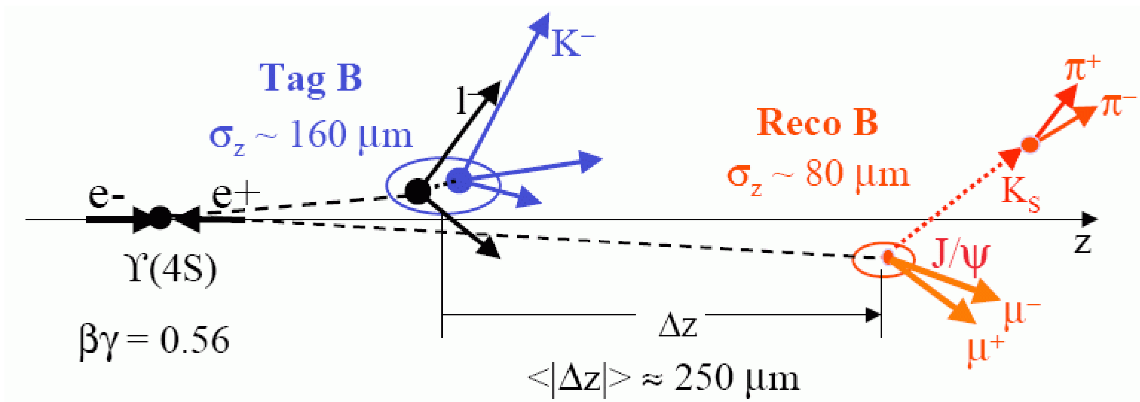


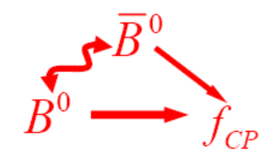
(Unitarity)

In this convention, only V_{ub} and V_{td} contain phases of order 1.

Time-Dependent Measurement

- Υ(4S) decays to $B^0\overline{B}^0$ coherently.
- Center-of-mass boosted βγ=0.56, separating two B vertices.





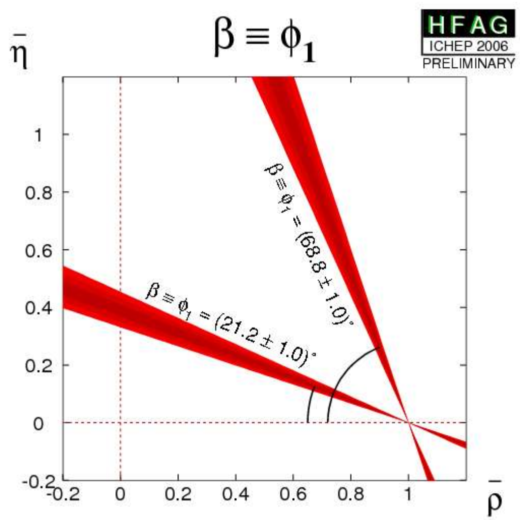
- Interference between decay and decay via mixing resulting in CP asymmetry.

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP}) - \Gamma(B^0_{\rm phys}(t) \to f_{CP})}{\Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP}) + \Gamma(B^0_{\rm phys}(t) \to f_{CP})} = \mathcal{S}\cdot\sin(\Delta m_d t) - \mathcal{C}\cdot\cos(\Delta m_d t)$$

$$\mathcal{S} = 2\eta_f \frac{\mathrm{Im}(\lambda)}{1+|\lambda|^2} \qquad \lambda = \frac{q}{p}\frac{\overline{A}_f}{A_f} \;; \qquad \mathcal{S} = \eta_f \sin 2\beta \quad \text{if} \quad \frac{\overline{A}_f}{A_f} \quad \text{has no non-trivial phase.}$$

Ambiguity in β

- $\sin 2\beta$ has been measured pretty precisely using charmonium-K^0 decays.

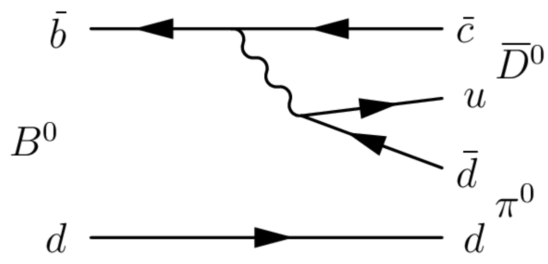


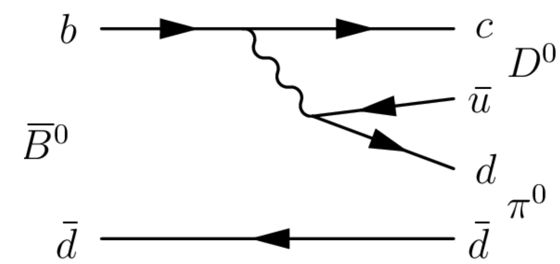
- Four-fold ambiguity in β.
- Solution β=21° (+180°) is consistent with other constraints in SM, but there is room for new phase in mixing so that it might not be the right solution.
- Measuring (the sign of) $\cos 2\beta$ can resolve the ambiguity.
- Idea: Use the decay modes that have more than one amplitude contributing with different strong phases and the strong phase difference can either be measured or calculated.

Resolving Ambiguity in 2β at BABAR

- First attempt: $B^0/\overline{B}^0 \to J/\psi K^{*0}$: use angular analysis to resolve $|A_0|e^{\delta_0}$ $|A_{\|}|e^{\delta_{\|}}$ $|A_{\perp}|e^{\delta_{\perp}}$ amplitudes and use P-wave/S-wave interference in Kπ to resolve strong phase ambiguity.
  - [PRD 71, 032005] (not in this talk)
- Time-dependent Dalitz analysis in $B^0/\overline{B}^0 \to D^{(*)0}/\overline{D}^{(*)0}h^0$ with $D^0 \to K_S^0\pi^+\pi^-$ (⇒ this talk).
- Time-dependent analysis in $B^0/\overline{B}^0 \to D^{*+}D^{*-}K_S^0$ in partial phase space (⇒ this talk) .
- Time-dependent Dalitz analysis in $B^0/\overline{B}^0 \to K^+K^-K^0$
  - See Denis Dujmic's talk later today.

Color-Suppressed B→D(*)0h0 Decays

- B0 decay 

; via mixing 

  $D^0/\overline{D}^0 \to K^0_S\pi^+\pi^-$ to reach a common final state.

- $$\mathcal{P}_\pm = \frac{1}{2}e^{-\Gamma t}|A|^2 \cdot \Big[(|A_{\overline{D}}|^2 + |A_D|^2) \mp (|A_{\overline{D}}|^2 - |A_D|^2)\cos(\Delta m t) \pm 2\eta_{h^0}(-1)^L \mathrm{Im}\Big(e^{-2i\beta}A_D A^*_{\overline{D}}\Big)\sin(\Delta m t)\Big]$$

  $$\mathrm{Im}\Big(e^{-2i\beta}A_D A^*_{\overline{D}}\Big) = \underline{\mathrm{Im}(A_D A^*_{\overline{D}})\cos 2\beta} - \mathrm{Re}(A_D A^*_{\overline{D}})\sin 2\beta$$

- Strong phases in D0 and D̄0 amplitudes are different at a given point on the Dalitz plot => $\mathrm{Im}(A_D A^*_{\overline{D}}) \neq 0$

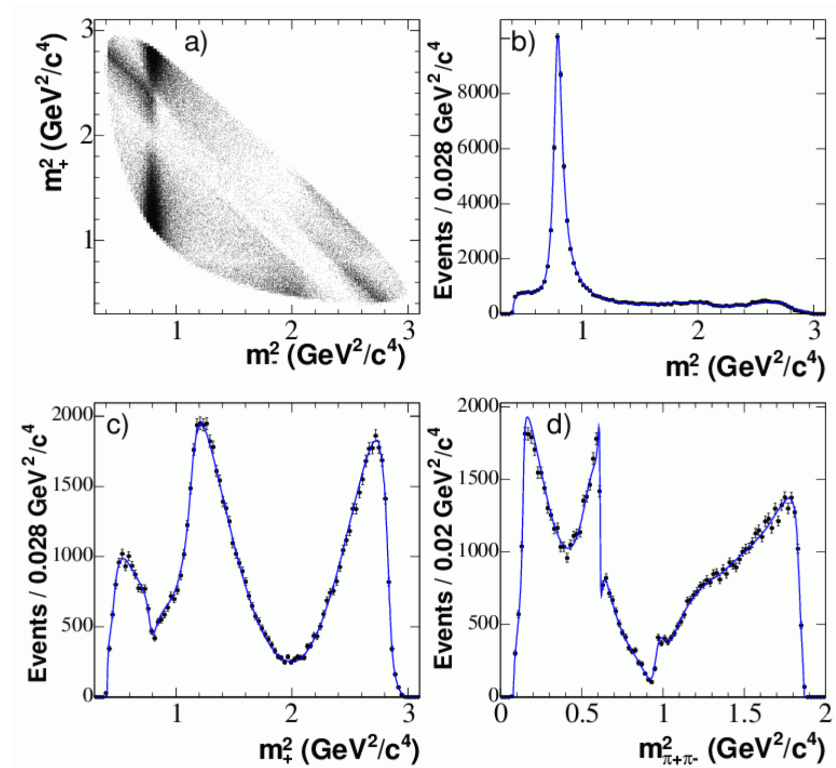
- Need to model $D^0/\overline{D}^0 \to K^0_S\pi^+\pi^-$ amplitudes.

Dalitz Plot Model

- Isobar model

$$A_D(m_+^2, m_-^2) = \sum_r a_r e^{i\phi_r} A_r(m_+^2, m_-^2) + a_{\rm NR} e^{i\phi_{\rm NR}}$$

- Parameters determined from a large $D^* \to D^0\pi$ sample.



Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.781 ± 0.018	131.0 ± 0.8	0.586
$K_0^*(1430)^-$	2.45 ± 0.08	-8.3 ± 2.5	0.083
$K_2^*(1430)^-$	1.05 ± 0.06	-54.3 ± 2.6	0.027
$K^*(1410)^-$	0.52 ± 0.09	154 ± 20	0.004
$K^*(1680)^-$	0.89 ± 0.30	-139 ± 14	0.003
$K^*(892)^+$	0.180 ± 0.008	-44.1 ± 2.5	0.006
$K_0^*(1430)^+$	0.37 ± 0.07	18 ± 9	0.002
$K_2^*(1430)^+$	0.075 ± 0.038	-104 ± 23	0.000
$\rho(770)$	1 (fixed)	0 (fixed)	0.224
$\omega(782)$	0.0391 ± 0.0016	115.3 ± 2.5	0.006
$f_0(980)$	0.482 ± 0.012	-141.8 ± 2.2	0.061
$f_0(1370)$	2.25 ± 0.30	113.2 ± 3.7	0.032
$f_2(1270)$	0.922 ± 0.041	-21.3 ± 3.1	0.030
$\rho(1450)$	0.52 ± 0.09	38 ± 13	0.002
σ	1.36 ± 0.05	-177.9 ± 2.7	0.093
σ'	0.340 ± 0.026	153.0 ± 3.8	0.013
Non Resonant	3.53 ± 0.44	128 ± 6	0.073

[PRL 95, 121802 (2005)]

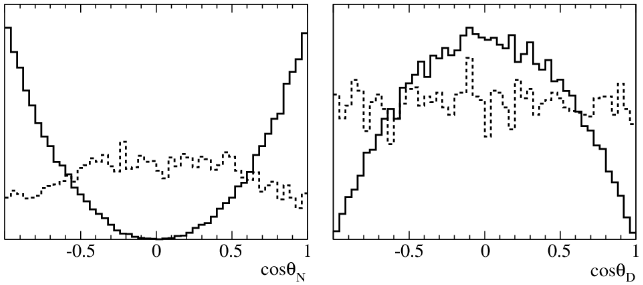
$B \to D^{(*)0} h^0$ Modes

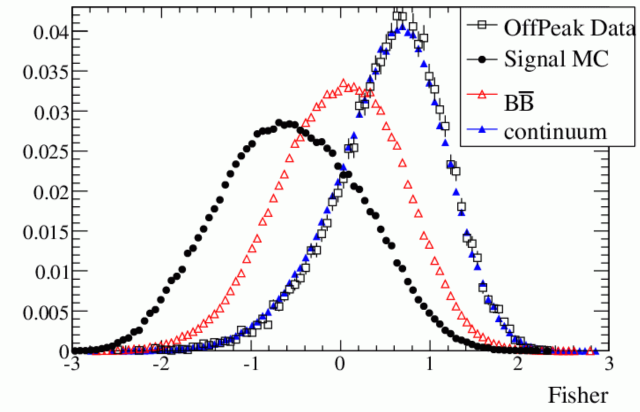
- Used modes: $D^0\pi^0$, $D^0\eta$, $D^0\eta'$, $D^0\omega$, $D^{*0}\pi^0$, $D^{*0}\eta$

  $\eta \to \gamma\gamma$ $\eta \to \gamma\gamma,\ \pi^+\pi^-\pi^0$ $\eta' \to \pi^+\pi^-\eta$ $\omega \to \pi^+\pi^-\pi^0$

  $D^{*0} \to D^0\pi^0$

- Use a Fisher discriminate to reduce the major background, continuum event (thrust angle, Legendre polynomial, B flight angle, event thrust, sphericity. Also exploit ω decay angles)





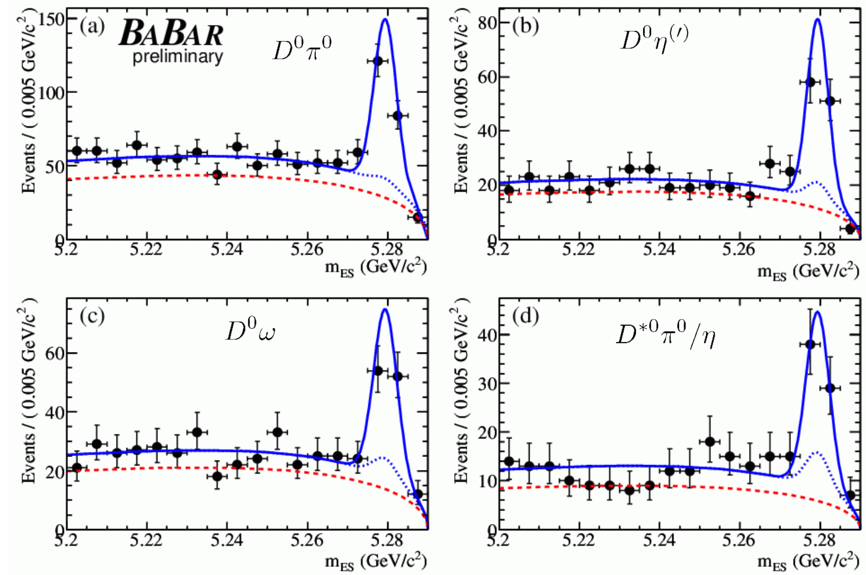
- Cut $|\Delta E|<80$ MeV for $h^0 \to \gamma\gamma$ modes,

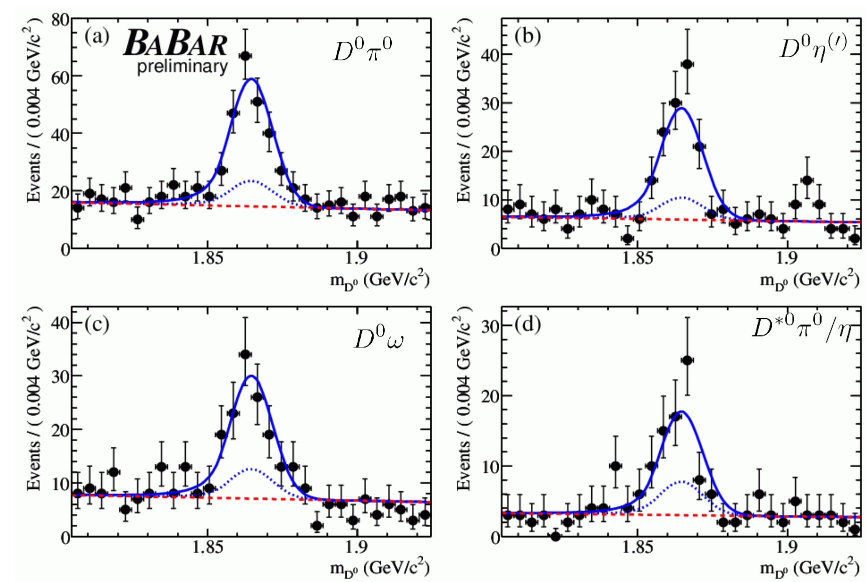
  $|\Delta E|<40$ MeV for $h^0 \to \pi\pi\pi^0$ modes.

Event Yield

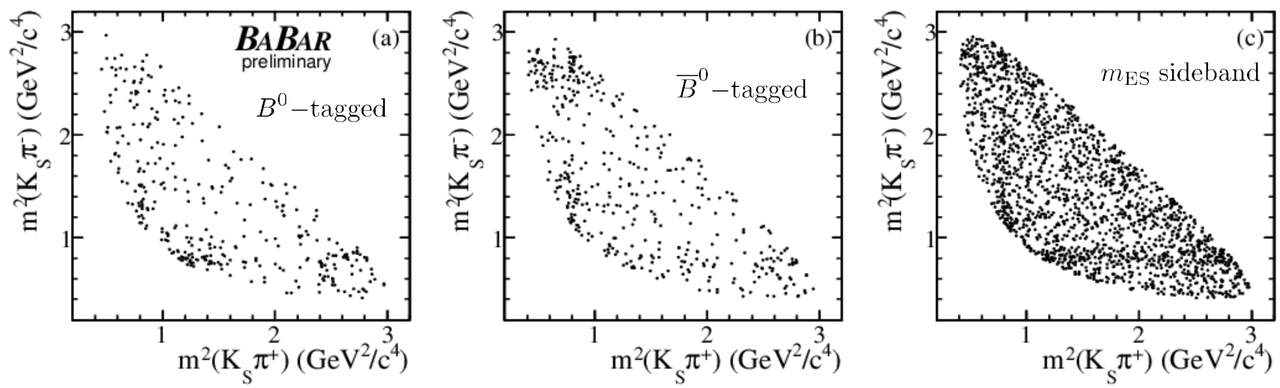
- Fit to m_{ES}, m_{D0}, Δt and Dalitz variables simultaneously.
- (m_{ES}, m_{D0}) discriminate peak and background with/without a real D^0.
- Fake D^0 Dalitz distribution modeled empirically from sideband.
- Peaking background determined from simulation.
- Data= 311 M $B\overline{B}$ pairs.

signal= 384±28 events



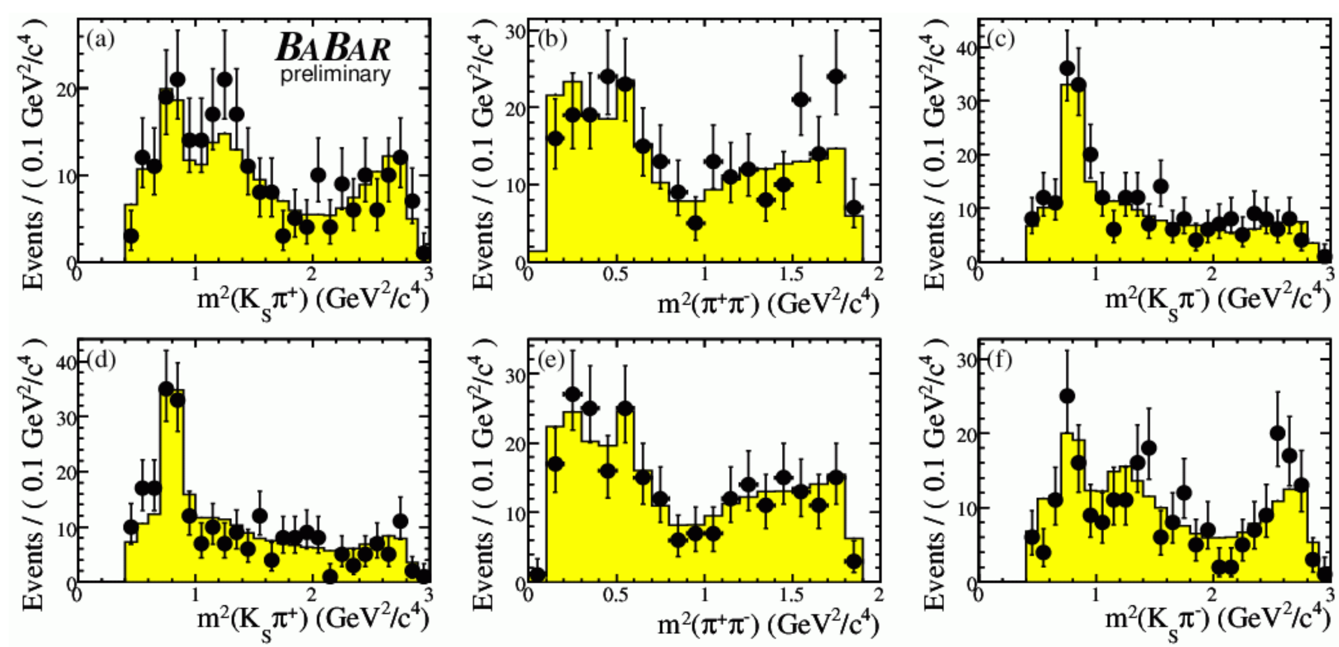


Dalitz Distribution



B^0−tagged

$\overline{B}^0$−tagged



Preliminary Results

- Fit for cos2β, sin2β and |λ|:

$$\cos 2\beta = 0.54 \pm 0.54 \pm 0.08 \pm 0.18$$
$$\sin 2\beta = 0.45 \pm 0.35 \pm 0.05 \pm 0.07$$
$$|\lambda| = 0.975^{+0.093}_{-0.085} \pm 0.012 \pm 0.002$$

- Fix sin2β at world average and |λ|=1:

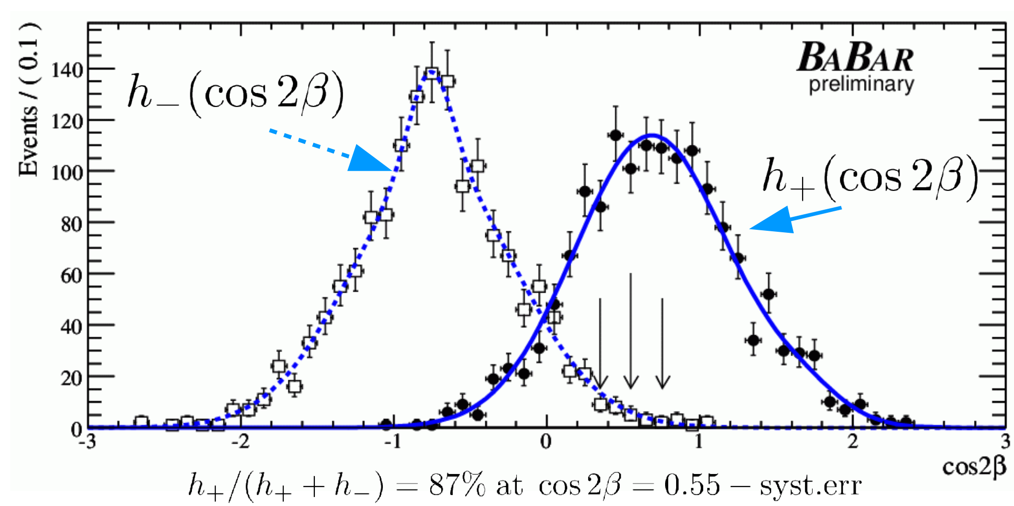
$$\cos 2\beta = 0.55 \pm 0.52 \pm 0.08 \pm \underline{0.18}$$

Dalitz model uncertainty

- Largest systematic error from Dalitz model.

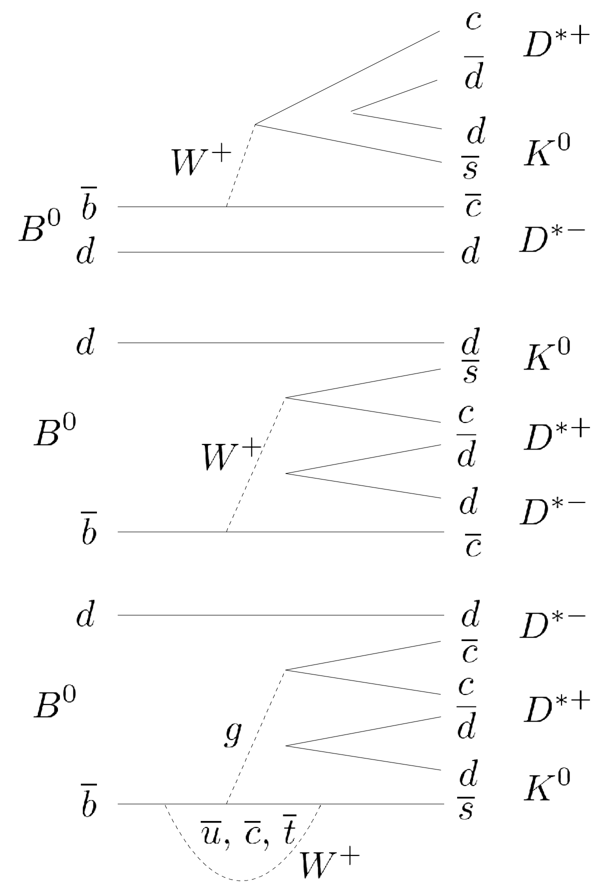
- Generate toys with $\sin 2\beta = \sin 2\beta_{WA}$, and $\cos 2\beta = \pm(1-\sin^2 2\beta)^{1/2}$; compare fit distributions and data fit result:

  $\cos 2\beta = +(1-\sin^2 2\beta)^{1/2}$ is favored at 87% C.L.



B→D*+D*−K0 Decays

- Tree-dominated process. If ignoring penguin, asymmetry amplitude = $\mathcal{D}$ sin2β.
  - $\mathcal{D}$ is dilution due to possible resonances of different J^P and non-resonance.
- Again, there is a varying strong phase over the DDK Dalitz plot. Integrate half of the Dalitz plot: (we don't know the detail of Dalitz model)



$$A(t) \equiv \frac{\Gamma_{\overline{B}^0} - \Gamma_{B^0}}{\Gamma_{\overline{B}^0} + \Gamma_{B^0}} = \eta_y \frac{J_c}{J_0} \cos(\Delta m_d t) - \left(\frac{2J_{s1}}{J_0} \sin 2\beta + \eta_y \frac{2J_{s2}}{J_0} \cos 2\beta \right) \sin(\Delta m_d t)$$

$\eta_y = -1(+1)$ for $m^2(D^{*+}K^0) < (>) m^2(D^{*-}K^0)$

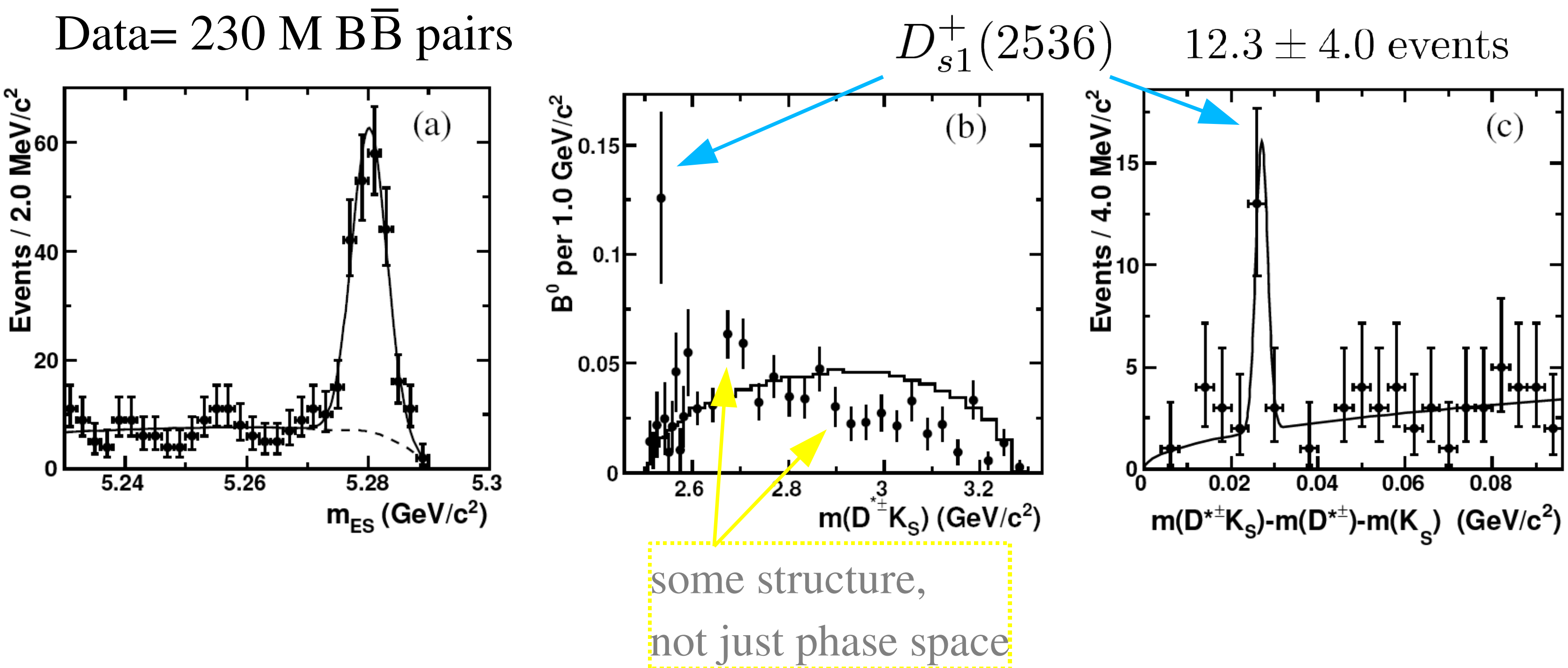
$$J_0 = \int |A|^2 + |\overline{A}|^2 \qquad J_c = \int |A|^2 - |\overline{A}|^2 \qquad J_{s1} = \int \mathrm{Re}(\overline{A}A^*) \qquad J_{s2} = \int \mathrm{Im}(\overline{A}A^*)$$

over the region where $m^2(D^{*+}K^0) < m^2(D^{*-}K^0)$

Branching Fraction Results

- Modes: $D^{*+} \to D^0\pi^+$, $D^+\pi^0$; $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$; $D^+ \to K^-\pi^+\pi^+$.

Data= 230 M $B\overline{B}$ pairs



$$\mathcal{B}(B^0 \to D^{*+}D^{*-}K^0_S) = (4.4 \pm 0.4 \pm 0.7) \times 10^{-3}$$

$$\mathcal{B}(B^0 \to D^{*-}D^+_{s1}(2536)) \times \mathcal{B}(D^+_{s1}(2536) \to D^{*+}K^0_S) = (4.1 \pm 1.3 \pm 0.6) \times 10^{-4}$$

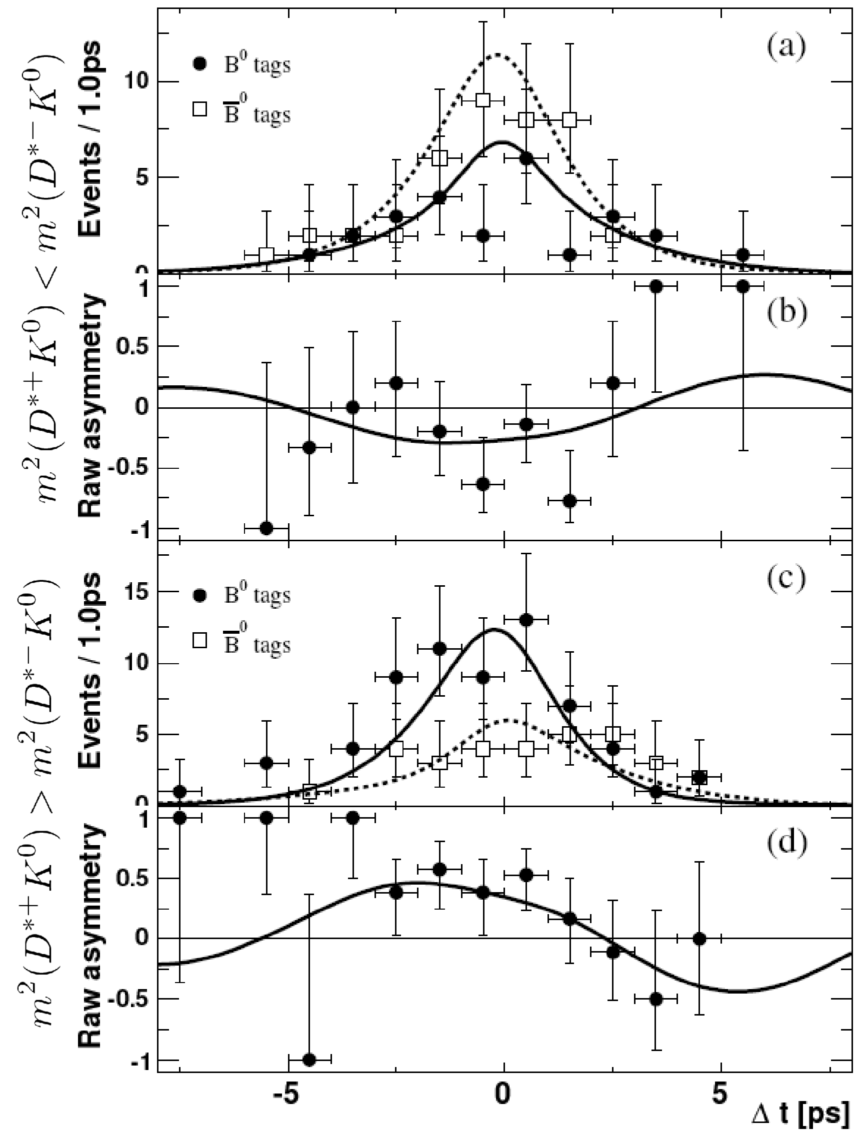
4.6σ significance

Time-Dependent Results

$$\frac{J_c}{J_0} = 0.76 \pm 0.18(\text{stat}) \pm 0.07(\text{syst})$$

$$\frac{2J_{s1}}{J_0}\sin 2\beta = 0.10 \pm 0.24(\text{stat}) \pm 0.06(\text{syst})$$

$$\frac{2J_{s2}}{J_0}\cos 2\beta = 0.38 \pm 0.24(\text{stat}) \pm 0.05(\text{syst})$$



- Large J_c/J_0 => sizable broad D_{s1}^{+}
- [PRD 61, 054009 (2000)] predicts $J_{s2}>0$ (factorization+heavy hadron chiral perturbation theory)
- Our data show $J_{s2}\cos 2\beta > 0$ at 94% confidence level.

Conclusions

- B*A*B*AR* has measured (the sign of) cos2β using $D^{(*)0}h^0$ ($D^0 \to K_S \pi^+ \pi^-$) and $D^{*+}D^{*-}K_S$ decays. The sign is determined to be positive at 87% and 94% confidence level.
- See another cos2β measurement using $B^0 \to K^+K^-K^0$ decays in D. Dujmic's talk later today.
- Combining these results and Belle's result, β=69° (+180°) is excluded at a very high confidence level. Standard Model is still intact.