Combined Measurement of the *CP* Violating Angle β by the BaBar and Belle Experiments

Tomo Miyashita
Caltech
On Behalf of the BaBar Collaboration

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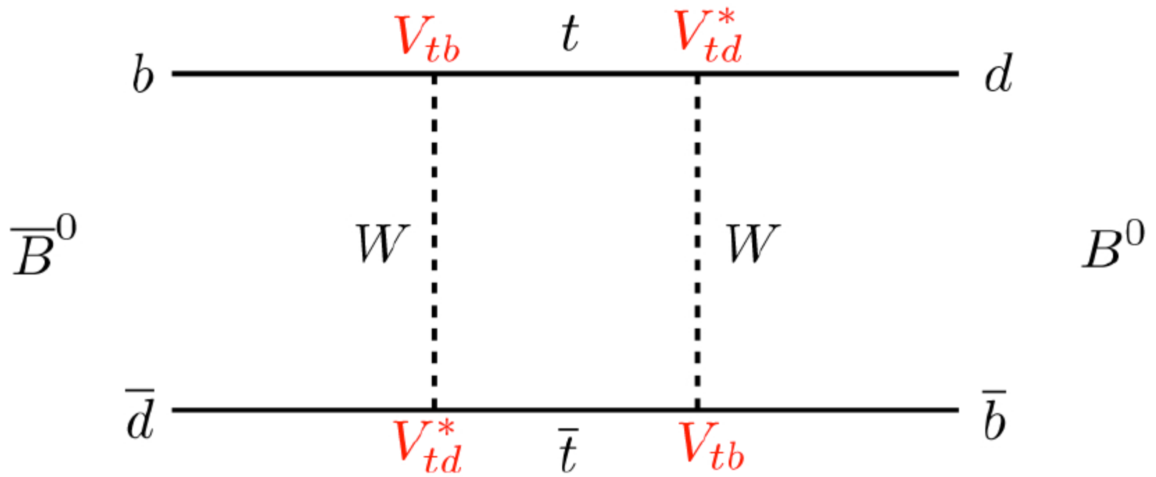
CP Violation in the Standard Model

- Within the Standard Model (SM), *CP* violation is accounted for by a single weak phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The CKM Matrix



Neutral *B* Meson Mixing Diagram

- CKM matrix describes weak coupling constants between quarks
- Under the Wolfenstein parameterization, we approximate the CKM matrix as:

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

where $\lambda \approx 0.22$ and $A \approx 0.83$

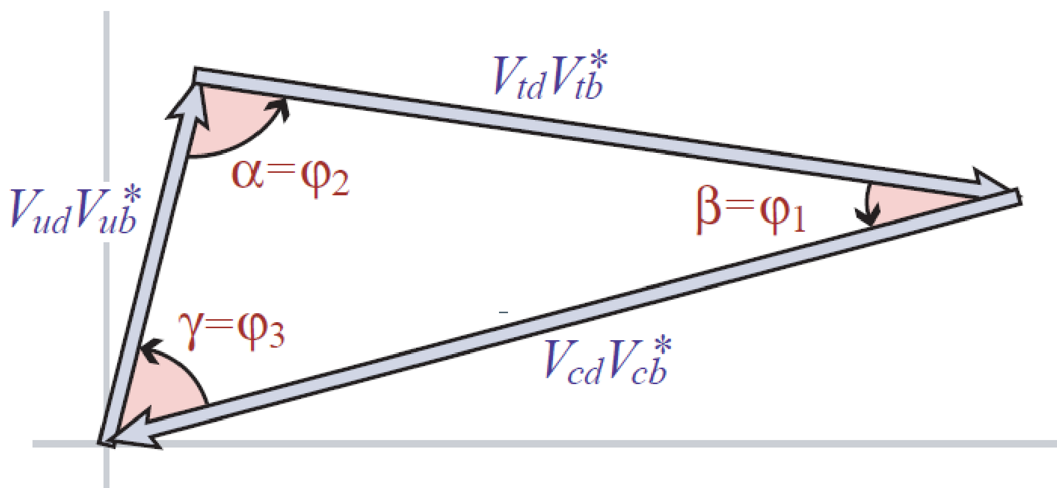
- We have *CP* violation if $\eta \neq 0$

CP Violation in the Standard Model

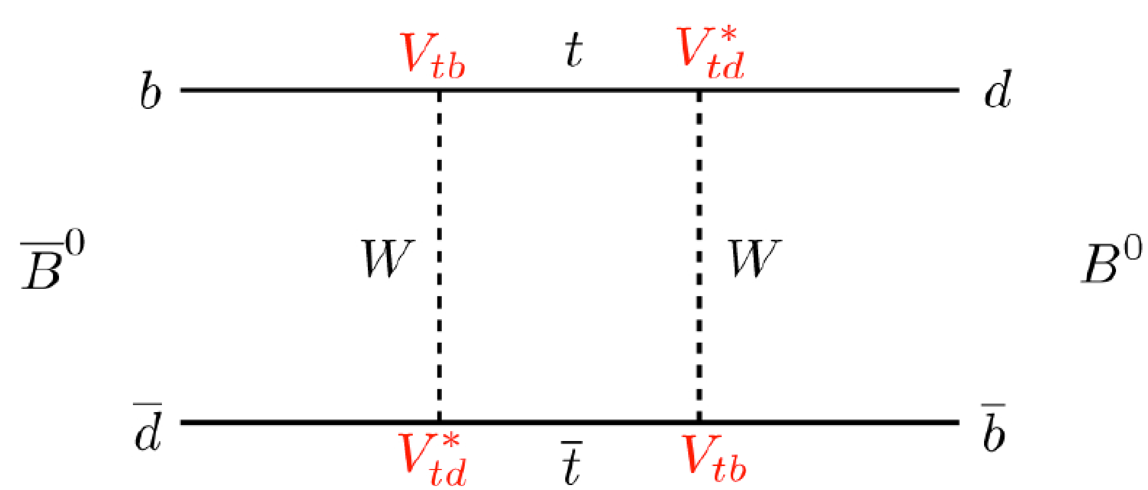
- Unitarity of the CKM matrix ($V^\dagger V = I$) leads to 6 independent constraints on sums of cross-terms ($V_{q_1 q_2} V^*_{q_3 q_4}$)
- These constraints can be represented as triangles in the complex plane
- All but two are severely elongated:

$$V_{td}V^*_{ud} + V_{ts}V^*_{us} + V_{tb}V^*_{ub} = 0$$
$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

- The second of these relates to quark transitions involved in B_d mixing



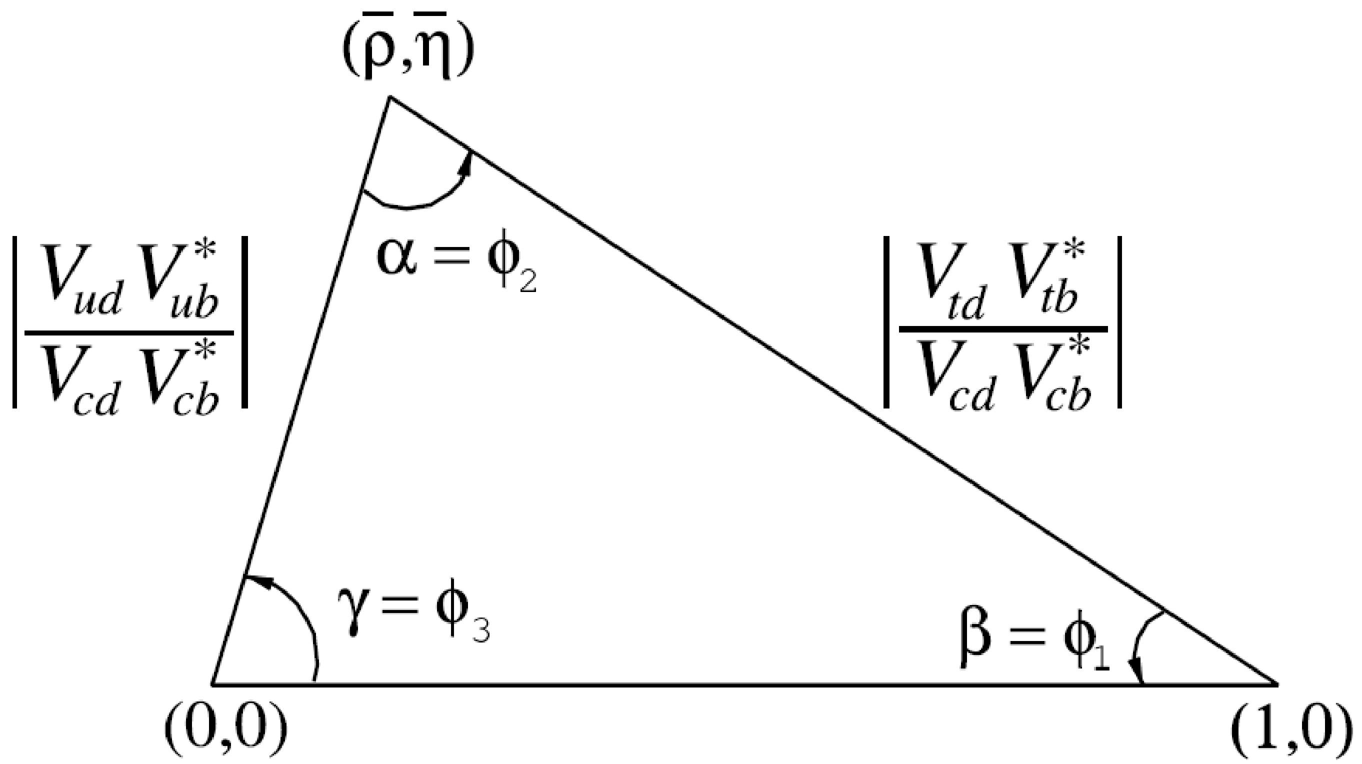
The Unitarity Triangle



Neutral B Meson Mixing Diagram

The Unitarity triangle

- Dividing each side of the triangle by the best-known one ($V_{cd}V_{cb}^*$), we get:

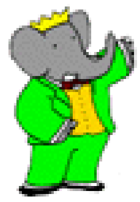


$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

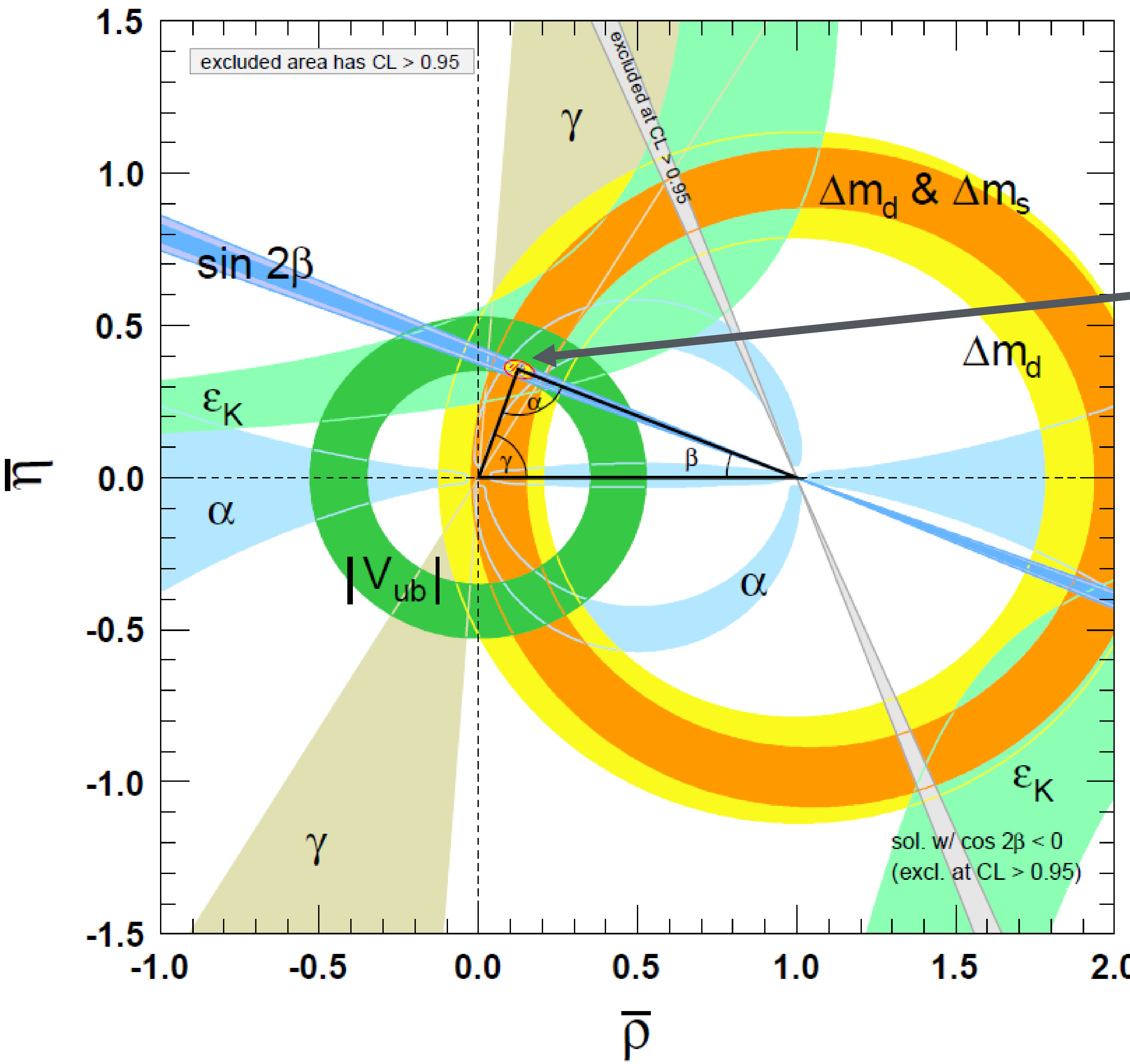
$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- By measuring 3 angles and 2 sides, one can overconstrain the apex of the unitarity triangle



Unitarity Triangle Constraints



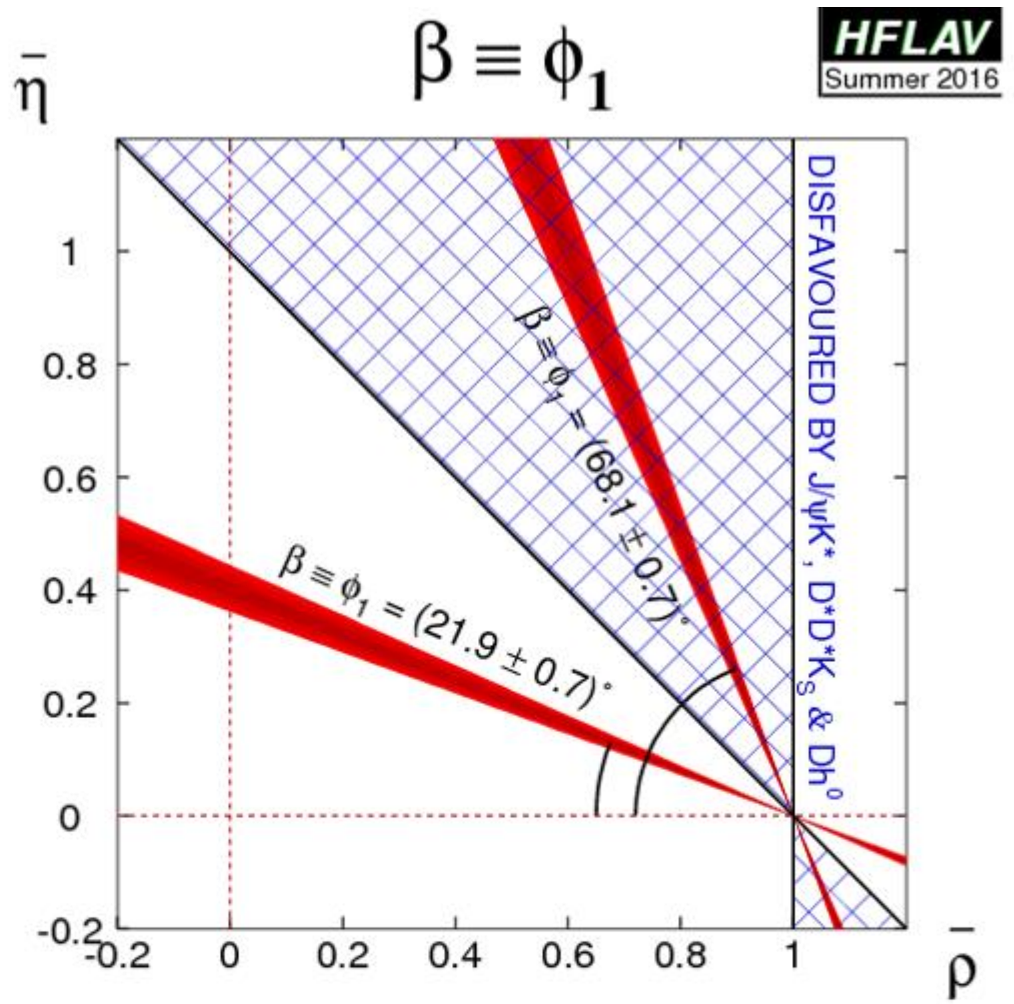
Global Fit Result

Constraints on the Unitarity Triangle

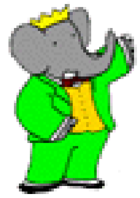
Measuring β

- Traditionally, time-dependent *CP* violation measurements in the “golden mode” $B^0 \to J/\psi K_S^0$ and other decays mediated by $b \to \bar{c}c\bar{s}$ transitions have been used to extract $\sin 2\beta$ and thus β

- However, measurements of $\sin 2\beta$ suffer from a trigonometric 2-fold ambiguity between 2β and $\pi - 2\beta$:



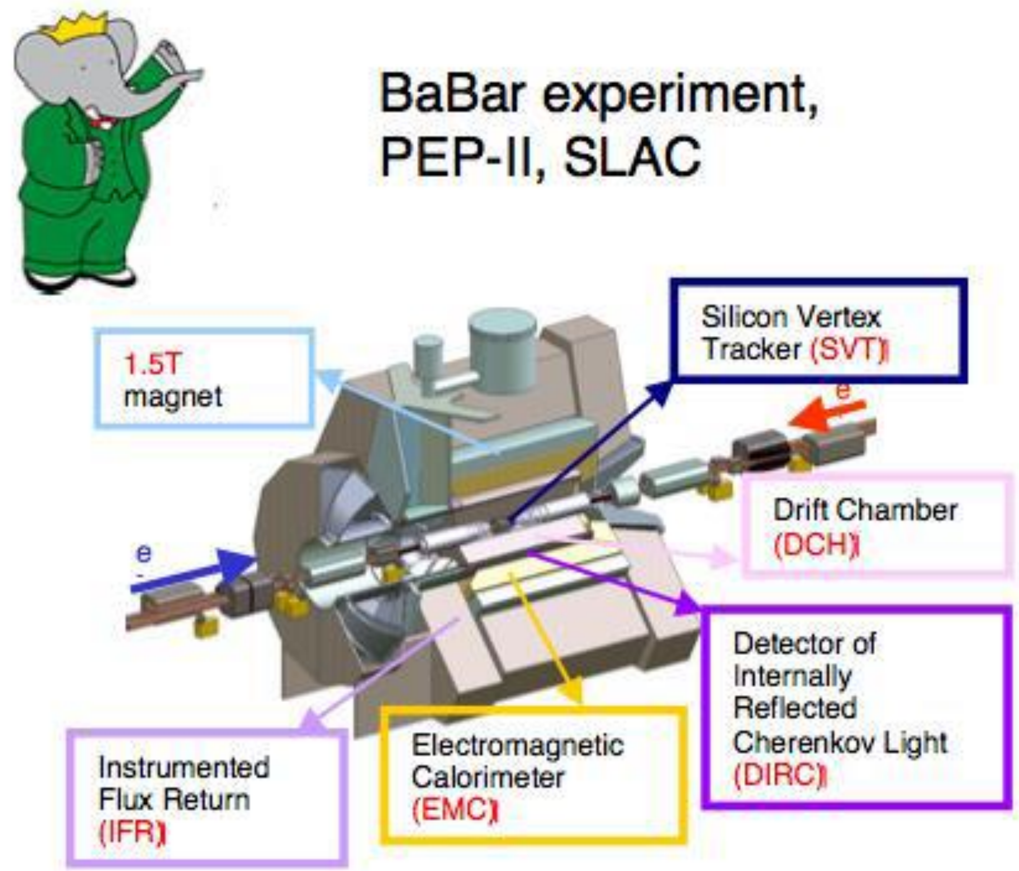
- This ambiguity can be resolved by measuring $\cos 2\beta$



- So far, there has been no conclusive determination of the sign of $\cos 2\beta$ (Previous measurements had large uncertainties)

The B Factories

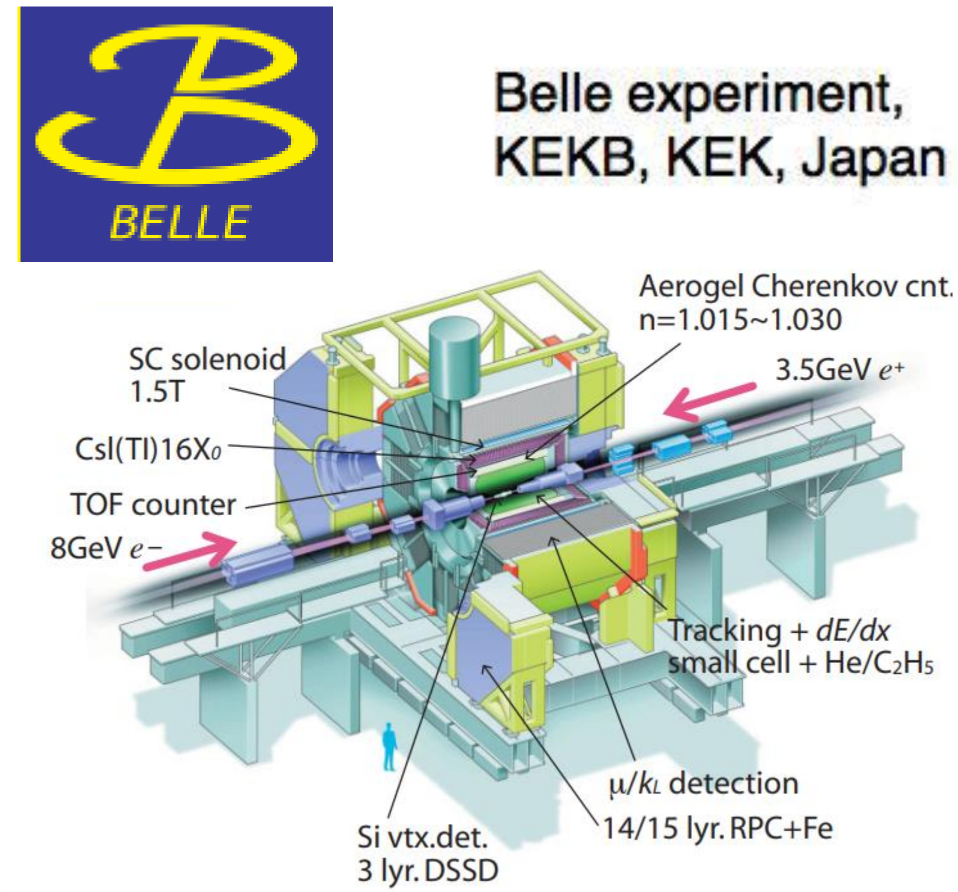
- This analysis was performed using data collected by both the BaBar and Belle experiments



3.1 GeV e^+ & 9 GeV e^- beams

L = 1.2 x10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$

$\int L\,dt$ = 530 fb^{-1} @ $\Upsilon(4S)$+off (~10%)



3.5 GeV e^+ & 8 GeV e^- beams

L = 2.11 x10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (world record)

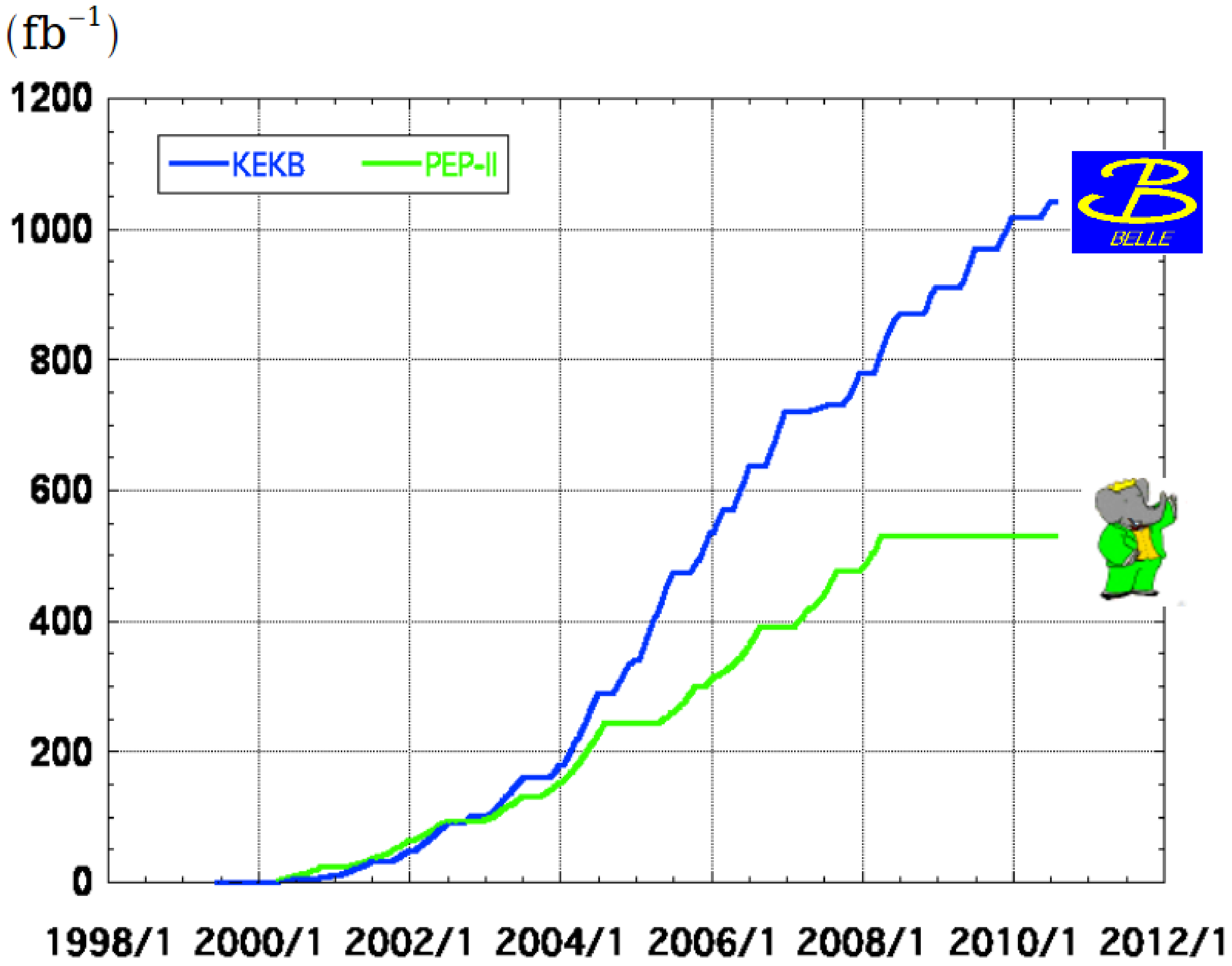
$\int L\,dt$ ~ 850 fb^{-1} @ $\Upsilon(4S)$+off(~10%)

- Designed as "B factories" operating primarily at the Υ(4S) resonance ($\sqrt{s}$ ≈10.58 GeV/c^2)

- 1.24 billion $B\bar{B}$ pairs recorded

The *B* Factories - Luminosity

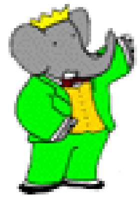
- Integrated Luminosity of the *B* Factories:



> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

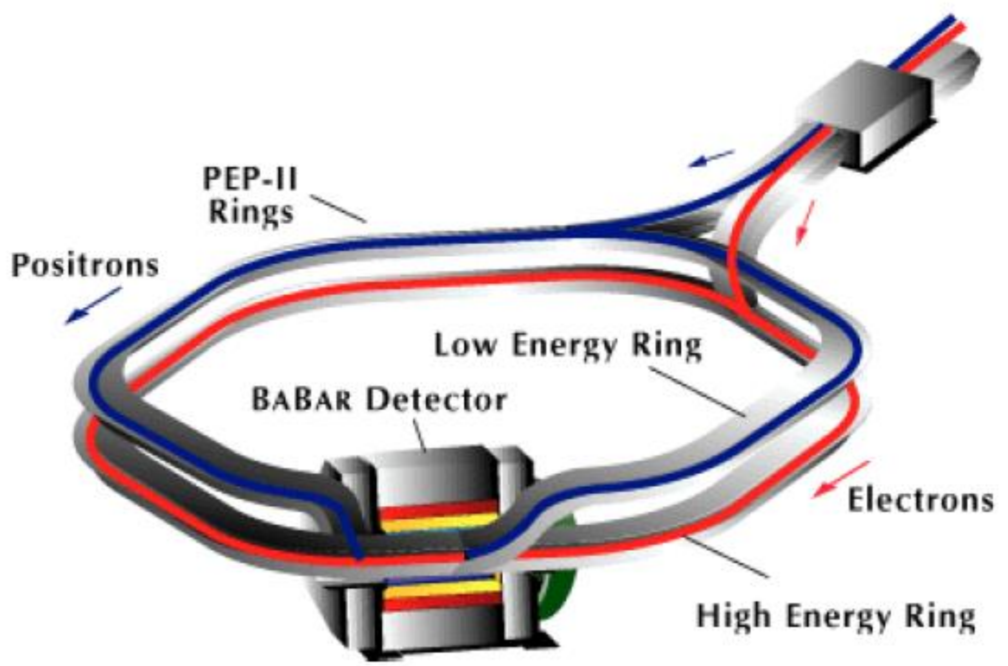
~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

- Also operated at other Υ resonances as well as "Off resonance" ($\approx$ 40 MeV/c^2 below the $\Upsilon(4S)$)



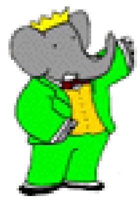
The *B* Factories - Boost

- A key feature of the *B* factories is that they used asymmetric energy electron and positron beams
  - 9 GeV electrons and 3.1 GeV positrons at BaBar
  - 8 GeV electrons and 3.5 GeV positrons at Belle



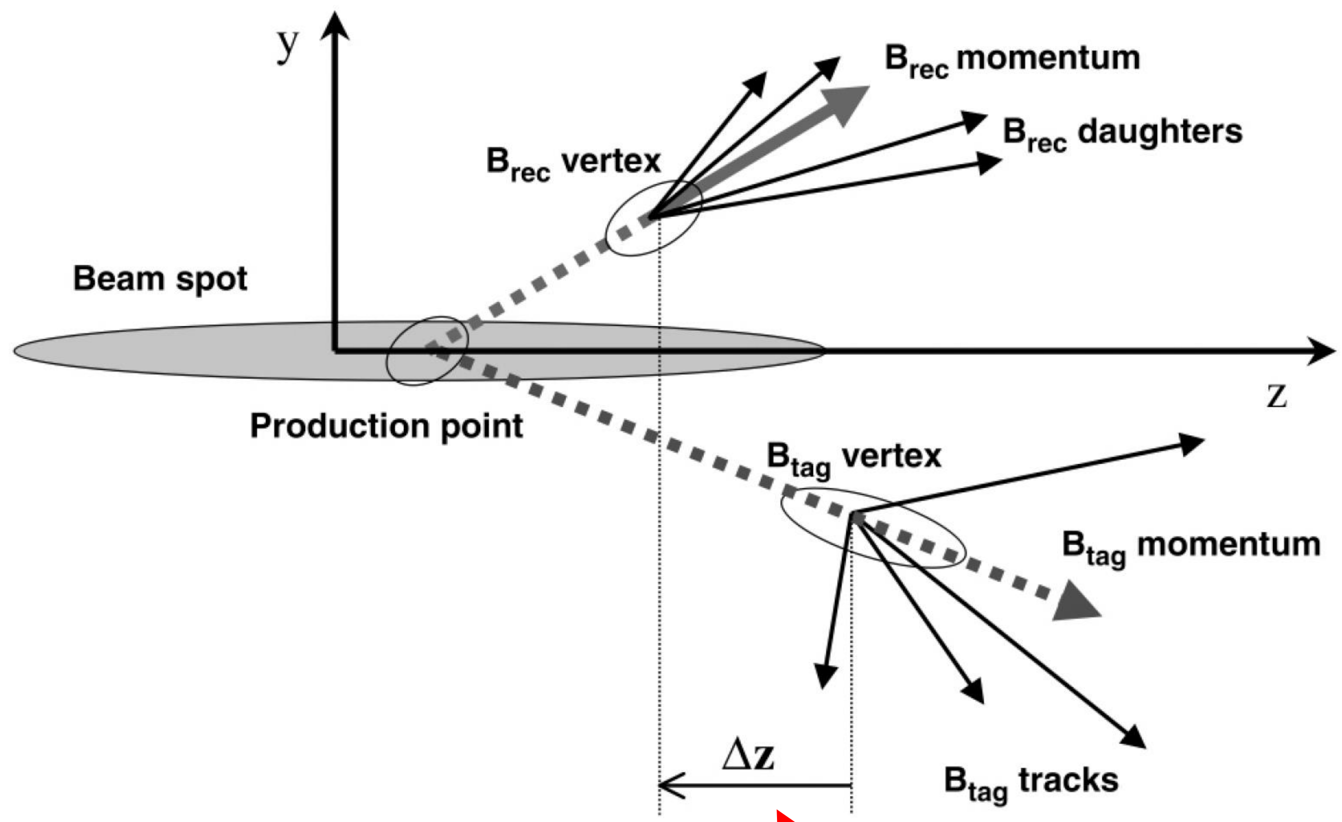
The PEP – II Storage Rings at SLAC

- The asymmetric energy beams caused the e^+e^- CM to be boosted in the lab frame
  - $\beta\gamma \approx 0.56$ at BaBar and $\beta\gamma \approx 0.43$ at Belle



The B Factories – Measuring Δt

- Due to the boost, the distance between the B decay vertices can be used to calculate the time between B and $\bar{B}$ decays
- Fully reconstruct the decay of one B meson (B^0_{rec}) and use the decay of the other B meson (B^0_{tag}) to determine its flavor
  - The B mesons are produced as entangled pairs and evolve coherently, so at the moment the first B decays, the other B is the opposite flavor
  - Define $\Delta t \equiv t_{\mathrm{rec}} - t_{\mathrm{tag}}$ as the time between the decays of the two mesons (based on their separation Δz along the boost direction)



$$\Delta z = \gamma\beta c\Delta t$$

Time-Dependent DP Analysis

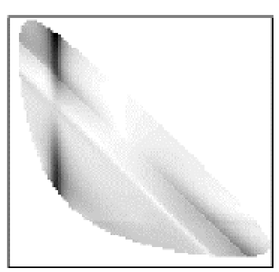
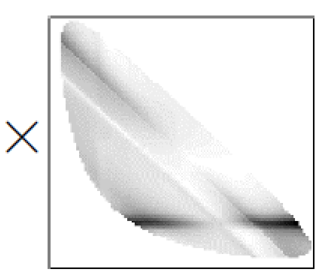
- We use a time-dependent Dalitz Plot analysis to extract both $\sin 2\beta$ and $\cos 2\beta$
  - Signal mode is $B^0 \to D^{(*)}h^0$ where $D^0 \to K_S^0\pi^+\pi^-$
- Our signal decay rate is proportional to:

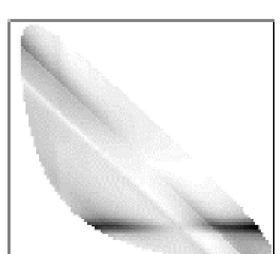
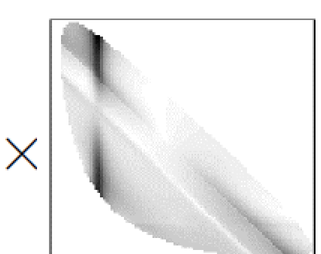
$$\frac{e^{\frac{-|\Delta t|}{\tau_{B^0}}}}{2}\Big\{\left[|\mathcal{A}_{\overline{D}^0}|^2 + |\mathcal{A}_{D^0}|^2\right] - q\left(|\mathcal{A}_{\overline{D}^0}|^2 - |\mathcal{A}_{D^0}|^2\right)\cos(\Delta m_d \Delta t) + 2q\eta_{h^0}(-1)^L \,\mathrm{Im}\left(e^{-2i\beta}\mathcal{A}_{D^0}\mathcal{A}^*_{\overline{D}^0}\right)\sin(\Delta m_d\Delta t)\Big\}$$

where the β-dependence in the last term can be rewritten as:

$$\mathrm{Im}\left(e^{-2i\beta}\mathcal{A}_{D^0}\mathcal{A}^*_{\overline{D}^0}\right) = \mathrm{Im}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\overline{D}^0}\right)\boxed{\cos(2\beta)} - \mathrm{Re}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\overline{D}^0}\right)\boxed{\sin(2\beta)}$$

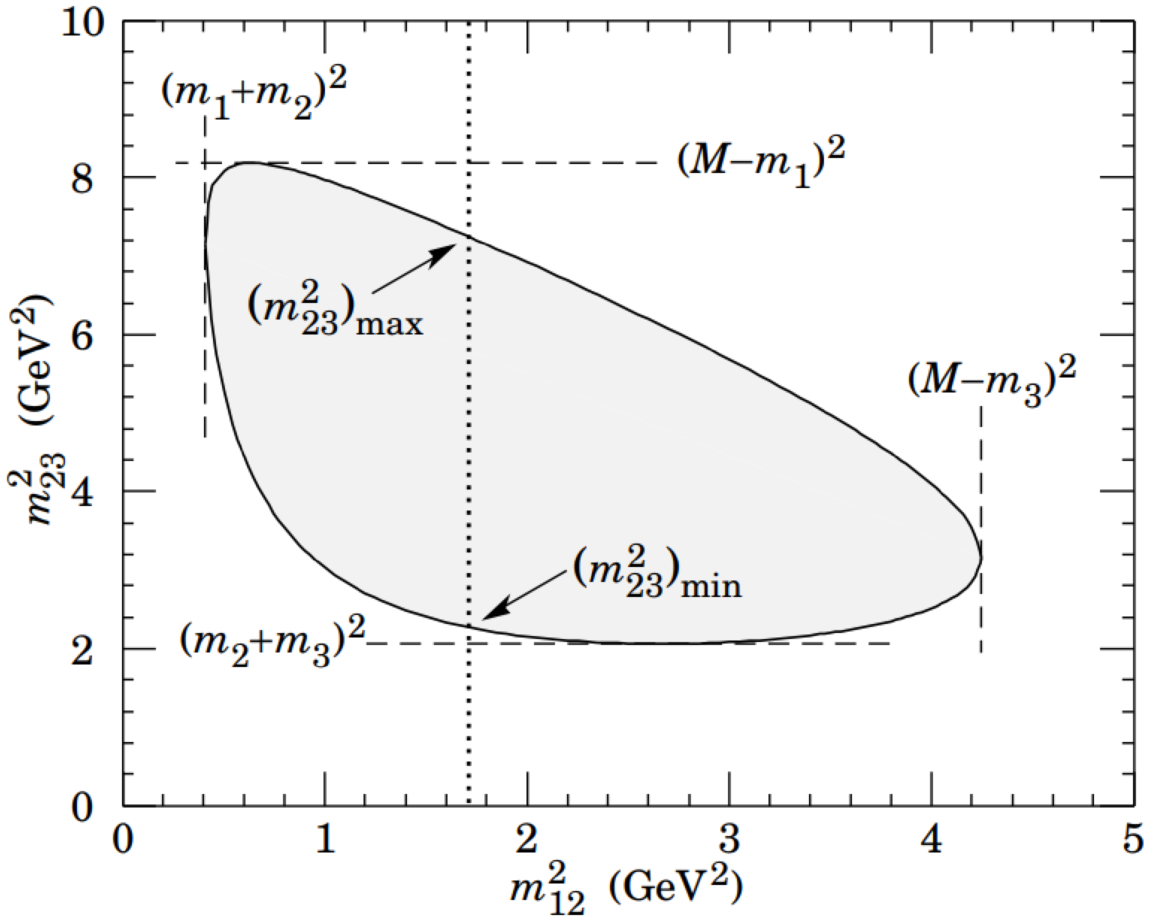
- The interference between D^0 and $\overline{D}^0$ and the variations across the DP allow the extraction of the CP-violating weak phase 2β

$$|M_{B^0}(\Delta t)|^2 = \Big|$$  $$\times\cos(\Delta m\Delta t/2) - ie^{+2i\beta}\times$$  $$\times\sin(\Delta m\Delta t/2)\Big|^2$$

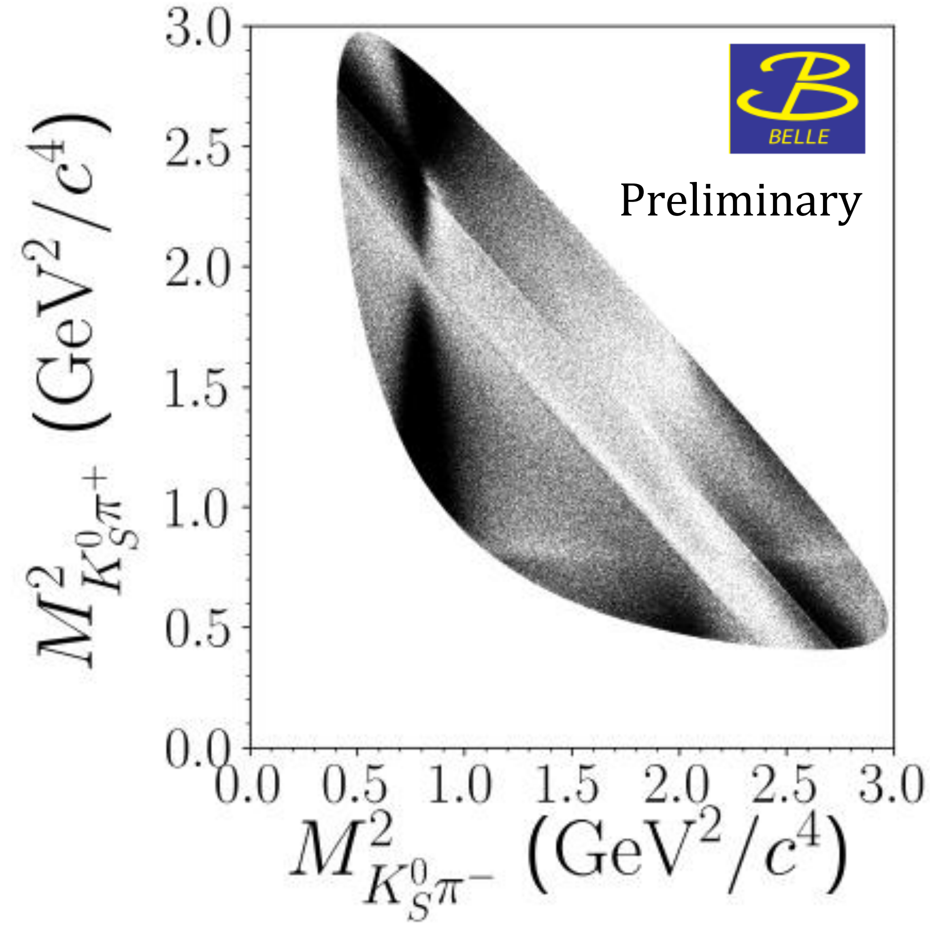
$$|M_{\bar{B}^0}(\Delta t)|^2 = \Big|$$  $$\times\cos(\Delta m\Delta t/2) - ie^{-2i\beta}\times$$  $$\times\sin(\Delta m\Delta t/2)\Big|^2$$

Dalitz Plot Parameterization

- The kinematics of a spin-0 particle decaying into three spin-0 particles are fully described by two parameters
  - Typically, we use the squared invariant masses of two pairs of final state particles
  - This allows easy determination of intermediate state masses, and phase space decays are uniform in these variables
  - Parameterization referred to as "Dalitz Plot" (DP)



Dalitz Plot (DP)



Example $D^0/\overline{D}^0 \to K_S^0\pi^+\pi^-$ DP

Analysis Steps

- (1) Perform a 2D fit to Belle $c\bar{c}$ data to obtain yields for the signal and background categories

- (2) Extract the $D^0 \to K_S^0\pi^+\pi^-$ Dalitz model from the high-statistics Belle $c\bar{c}$ data

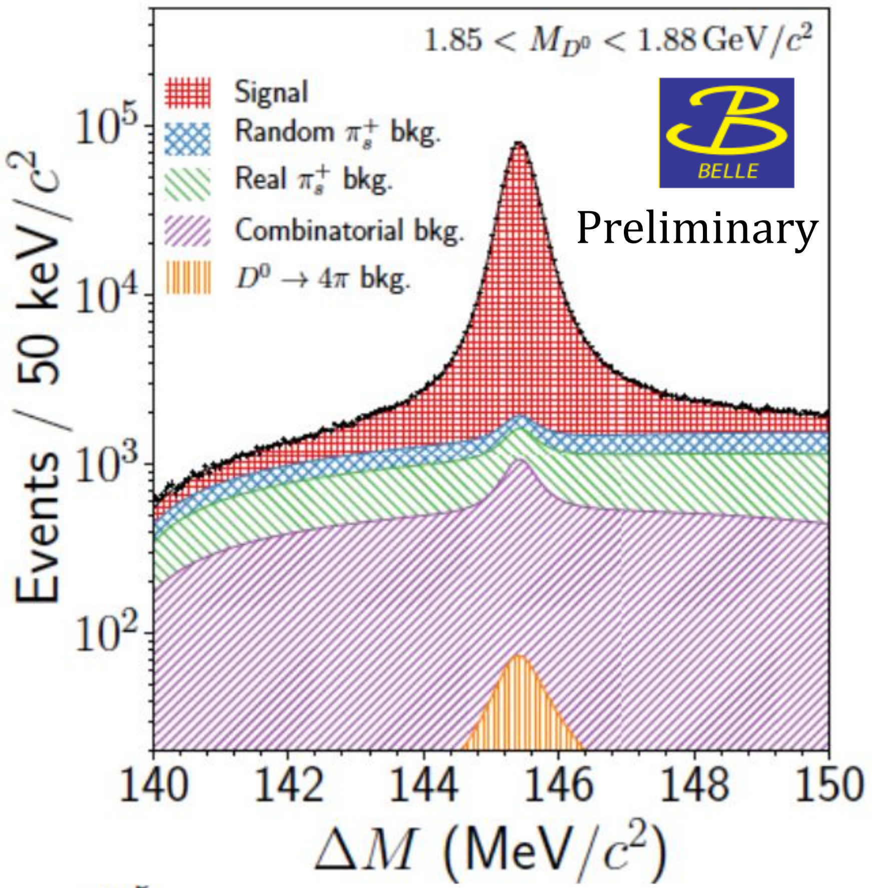
- (3) Perform a 3D fit to $B^0 \to D^{(*)}h^0$ events to extract yields for the signal and background categories

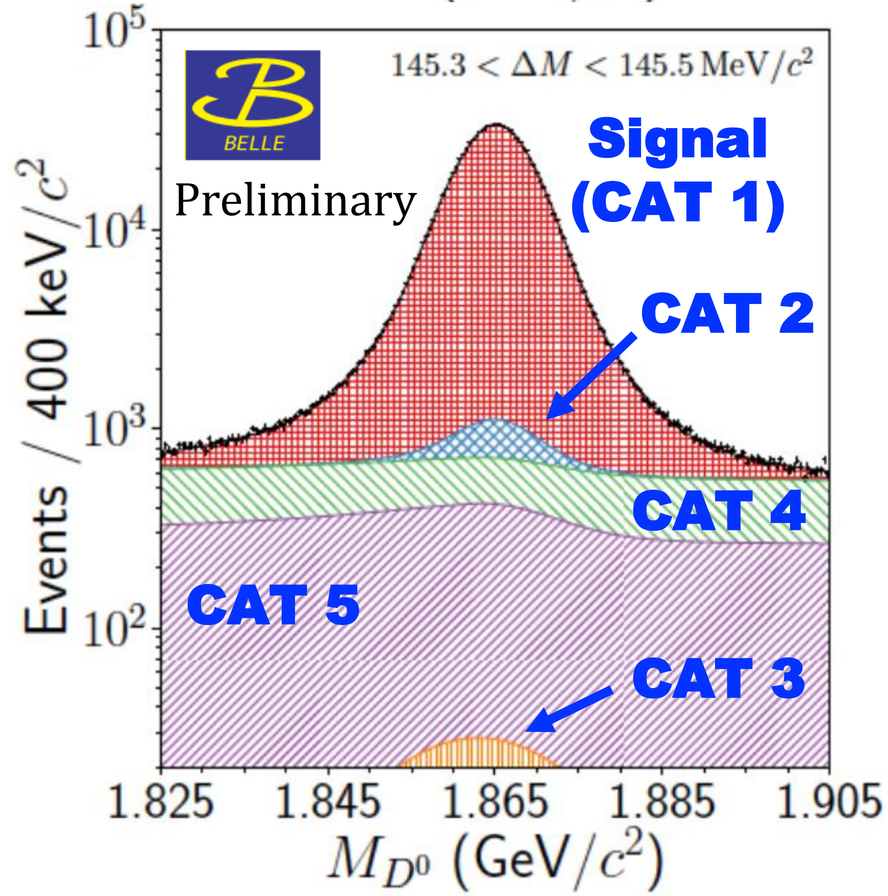
- (4) Perform the final time-dependent Dalitz plot fit to $B^0 \to D^{(*)}h^0$ events, using the $D^0 \to K_S^0\pi^+\pi^-$ Dalitz plot model obtained earlier

$D^{*+} \to D^0\pi_s^+$ Yield Extraction

- We perform time-integrated analysis of the Belle $c\bar{c}$ data to extract sig+bkg yields for the DP model fit
- Signal (CAT 1) is correctly reconstructed $D^{*+} \to D^0\pi_s^+$ with $D^0 \to K_S^0\pi^+\pi^-$ decays
- Background is divided into 4 categories:
  - CAT 2: True D, random soft pion
  - CAT 3: $D^0 \to K_S^0 K_S^0$ and 4π
  - CAT 4: True π_s^+ mesons, but incorrect D
  - CAT 5: Remaining combinatorial bkg.
- We extract the yields in a 2D unbinned maximum likelihood fit to the M_{D^0} vs. ΔM (the $D^{*+} - D^0$ mass difference)

Component	Yield
Category 1: Signal	1217329 ± 2015
Category 2: True D, random soft pion	61330 ± 1282
Category 3: $D^0 \to K_S^0 K_S^0$ and 4π	3438 (fixed to MC expectation)
Category 4: True π_s^+ mesons, but incorrect D	249701 ± 10017
Category 5: Remaining combinatorial bkg.	270990 ± 9077





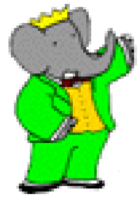
$D^0 \to K_S^0\pi^+\pi^-$ Dalitz Model Extraction

- In order to measure $\cos 2\beta$ using $B^0 \to D^{(*)}h^0$ decays, the Dalitz model of the D decay needs to be known
  - Extract the $D^0 \to K_S^0\pi^+\pi^-$ Dalitz model from Belle $c\bar{c}$ data
  - With 924 fb^{-1} of Belle data collected at or near the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances, we do not need to include BaBar data for this part of the analysis
- Decay Amplitude Parameterization:

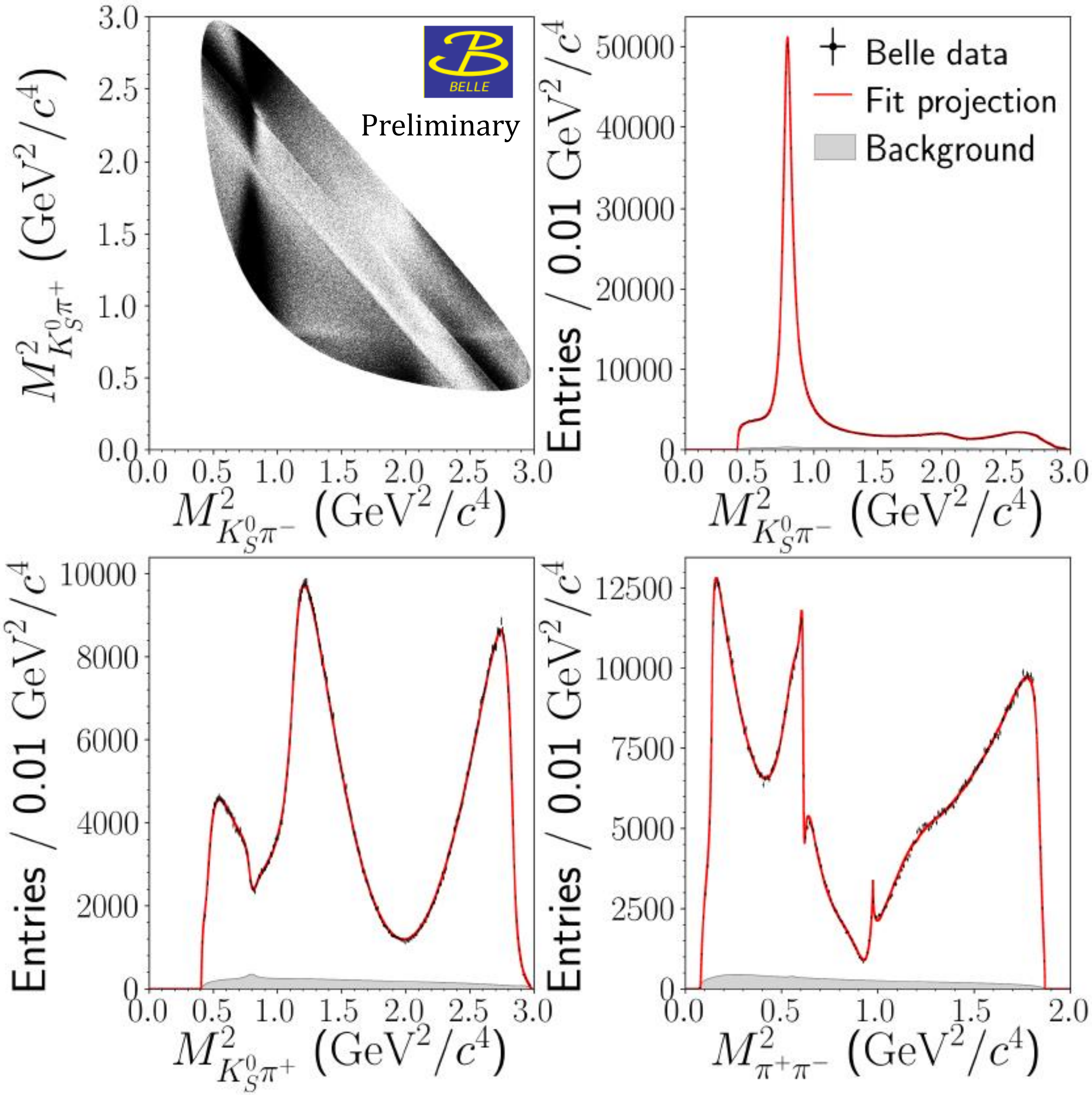
$$\mathcal{A}(M^2_{K_S^0\pi^-}, M^2_{K_S^0\pi^+}) = \sum_{r \neq (K\pi/\pi\pi)_{L=0}} a_r e^{i\phi_r} \mathcal{A}_r(M^2_{K_S^0\pi^-}, M^2_{K_S^0\pi^+}) + F_1(M^2_{\pi^+\pi^-}) + \mathcal{A}_{K\pi_{L=0}}(M^2_{K_S^0\pi^-}) + \mathcal{A}_{K\pi_{L=0}}(M^2_{K_S^0\pi^+})$$

Quasi 2 – Body Resonances (Relativistic Breit – Wigner) | $\pi\pi$ S – Wave (K Matrix) | $K\pi$ S – Wave + $K_0^*(1430)$ (LASS Parameterization)

- Intermediate resonances:
  - Cabibbo-favored: $K^*(892)^-$, $K_2^*(1430)^-$, $K^*(1680)^-$, $K^*(1410)^-$
  - Cabibbo-suppressed: $K^*(892)^+$, $K_2^*(1430)^+$, $K^*(1410)^+$
  - CP eigenstates: $\rho(770)^0$, $\omega(782)$, $f_2(1270)$, $\rho(1450)^0$



$D^0 \to K_S^0\pi^+\pi^-$ Dalitz Plot Fit Projections



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

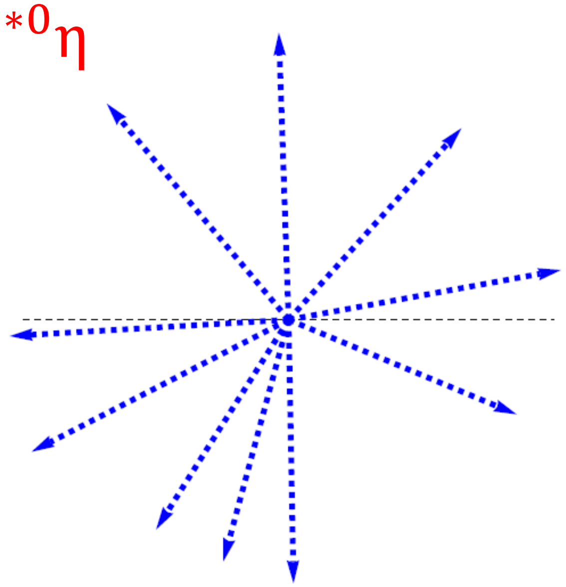
- Before performing the final time-dependent *CP* analysis using $B^0 \to D^{(*)0} h^0$ decays, we must also extract signal and background yields for these modes
  - The specific modes we reconstruct are: $D^0\pi^0$, $D^0\eta$, $D^0\omega$, $D^{*0}\pi^0$, $D^{*0}\eta$
  - Similar selection criteria are used for the BaBar and Belle data
- We use a neural network (NN) combining event-shape variables to reject continuum $e^+e^- \to q\bar{q}$
- Yields are extracted in 3-dimensional maximum likelihood fits to:
  - Modified beam-energy constrained mass (M'_{bc}):

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

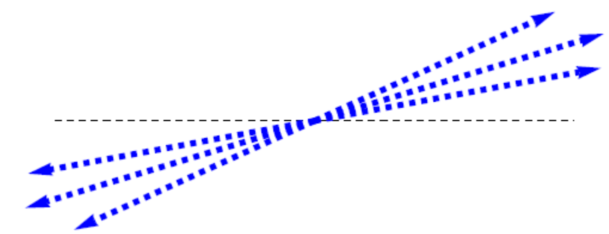
  - ΔE

$$\Delta E = E^*_B - E^*_{\rm beam}$$

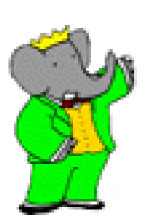
  - Neural Network Output ($\mathrm{NN_{out}}$)



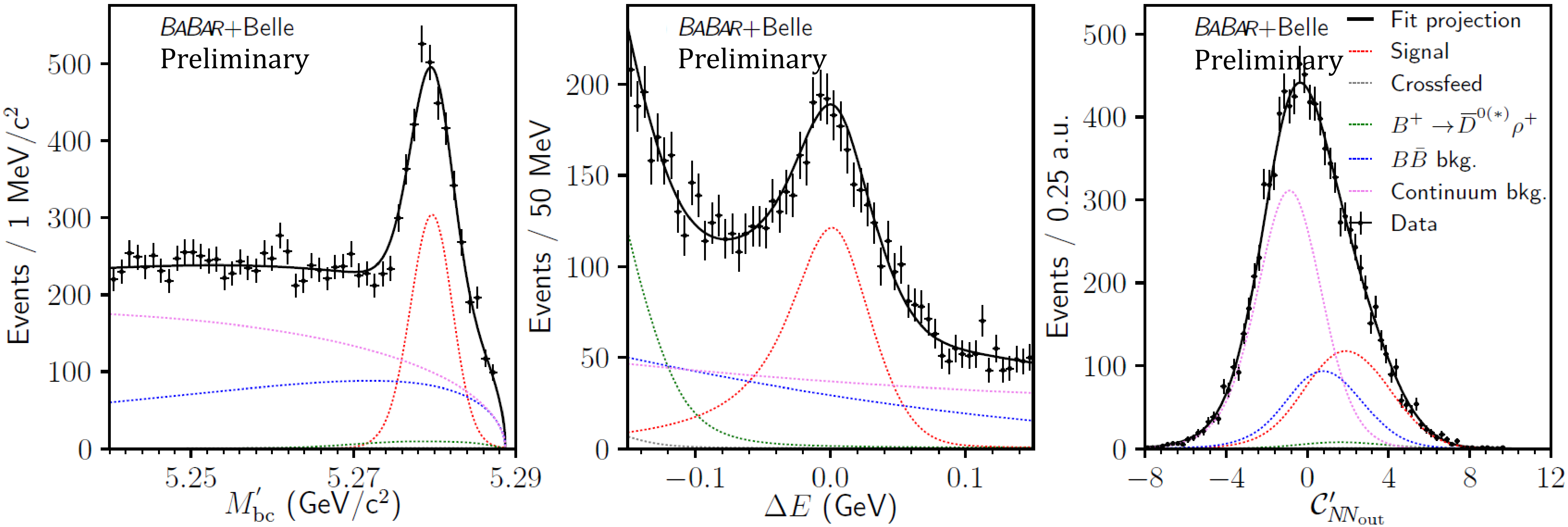
Signal-Like Event Shape



Continuum Event Shape



$B^0 \to D^{(*)0} h^0$ Yield Fit Results



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

BaBar and Belle Event Signal Yields

$B^0 \to D^{(*)0} h^0$ Time-Dependent Fit

- Finally, we perform a time-dependent fit to $B^0 \to D^{(*)0} h^0$ events where $D^0 \to K_S^0 \pi^+ \pi^-$ in order to simultaneously extract $\sin 2\beta$ and $\cos 2\beta$

- Our final likelihood is a combination of BaBar and Belle likelihoods:

$$\ln P = \sum_i \ln P_i^{\text{BaBar}} + \sum_j \ln P_j^{\text{Belle}}$$

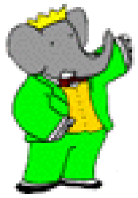
- We use a common Dalitz plot model for BaBar and Belle data and fit to the Δt distributions

  - The signal decay rate is proportional to:

$$\frac{e^{\frac{-|\Delta t|}{\tau_{B^0}}}}{2} \Big\{ \left[|\mathcal{A}_{\bar{D}^0}|^2 + |\mathcal{A}_{D^0}|^2 \right] - q \left(|\mathcal{A}_{\bar{D}^0}|^2 - |\mathcal{A}_{D^0}|^2 \right) \cos(\Delta m_d \Delta t) + 2q\eta_{h^0} \, (-1)^L \, \mathrm{Im} \left(e^{-2i\beta} \mathcal{A}_{D^0} \mathcal{A}^*_{\bar{D}^0} \right) \sin(\Delta m_d \Delta t) \Big\}$$

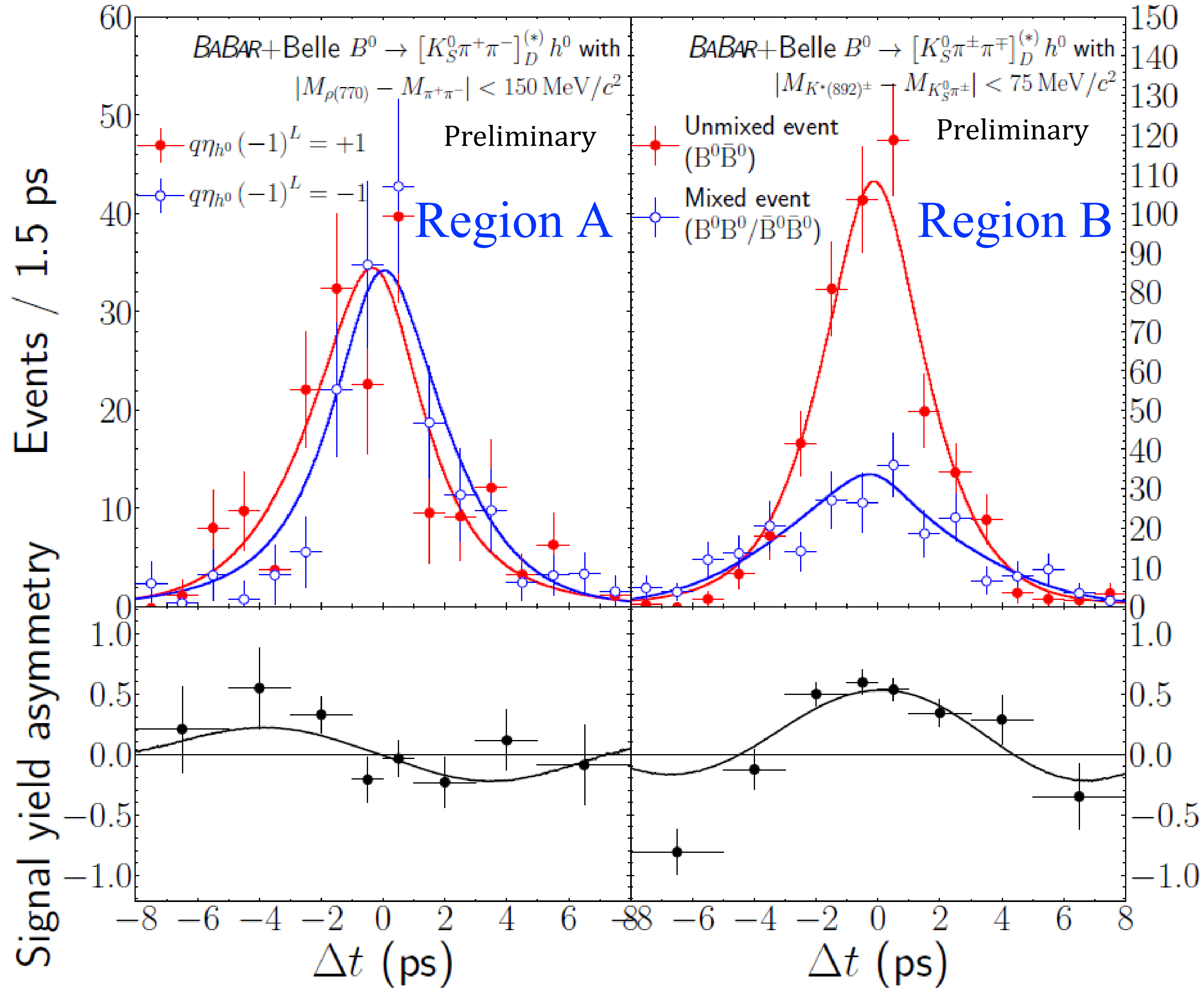
where $\mathrm{Im}\left(e^{-2i\beta}\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right) = \mathrm{Im}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right)\cos(2\beta) - \mathrm{Re}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right)\sin(2\beta)$

  - We use separate resolution models and flavor-tagging algorithms for BaBar and Belle

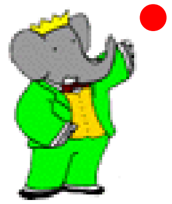


Final Fit Results I

- Region A:
  - Predominantly populated by *CP* eigenstates
  - Interference between direct decays of neutral *B* mesons, and mixing followed by decays
  - Sinusoidal oscillation in *CP* asymmetry reflects mixing-induced *CP* violation governed by weak phase β
- Region B:
  - Predominantly populated by quasi-flavor-specific decays
  - Time evolution exhibits $B^0 - \bar{B}^0$ oscillations governed by the oscillation frequency, Δm_d
  - The time-dependent asymmetry exhibits an oscillation pattern proportional to $\cos(\Delta m_d \Delta t)$



BaBar+Belle Δt fits in two regions of the $D^0 \to K_S^0\pi^+\pi^-$ phase space



Final Fit Results II

- Final Fit Results

World Average:
$\sin 2\beta = 0.69 \pm 0.02$

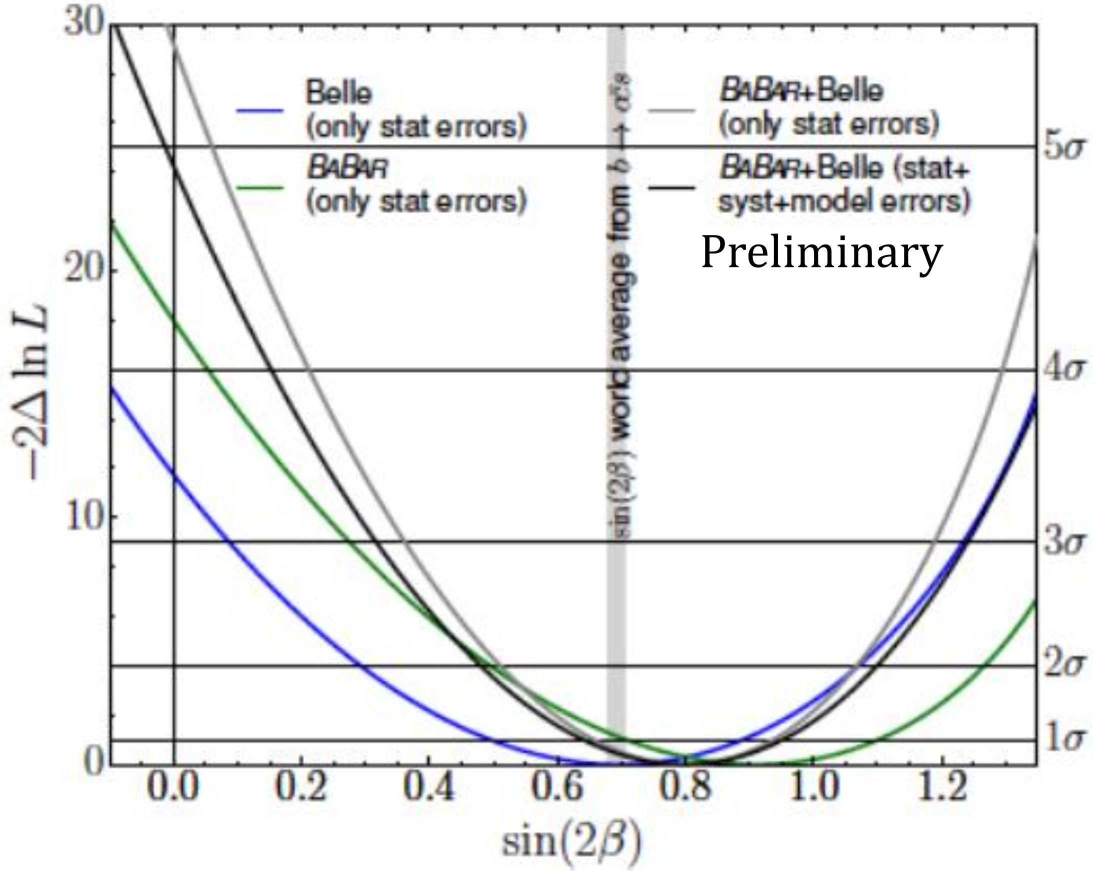
$$\sin 2\beta = 0.80 \pm 0.14\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.03\,(\text{model})$$

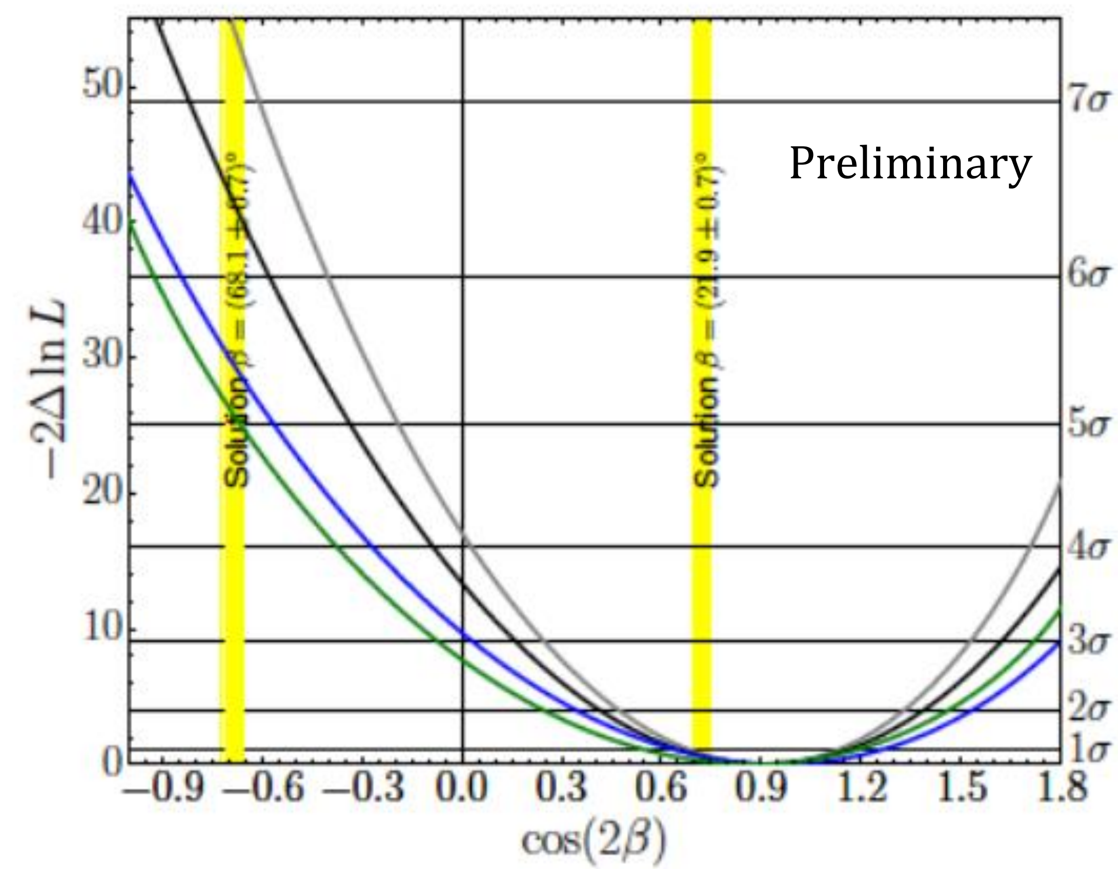
$$\cos 2\beta = 0.91 \pm 0.22\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model})$$

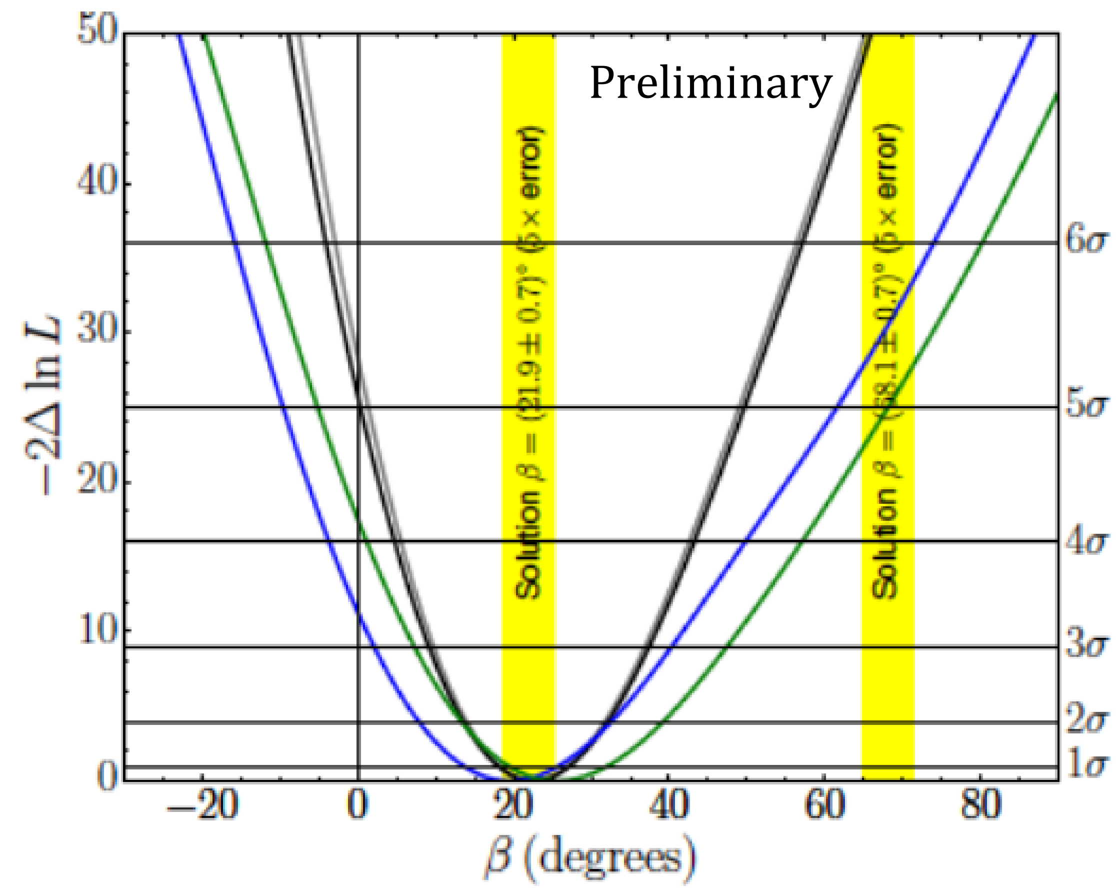
$$\boxed{\beta = (22.5 \pm 4.4\,(\text{stat.}) \pm 1.2\,(\text{syst.}) \pm 0.6\,(\text{model}))^\circ}$$

- Most precise measurement of $\cos 2\beta$
- First evidence for $\cos 2\beta > 0$ (3.7σ)
  - We exclude the second solution $(\pi/2 - \beta = (68.1 \pm 0.7)^\circ)$ at 7.3σ significance, resolving the ambiguity in the apex of the CKM Unitarity Triangle
  - We exclude $\beta = 0$ at 5.1σ, and thus observe *CP* violation in $B^0 \to D^{(*)}h^0$

Result Comparison







Summary

- We have combined the final BaBar and Belle data samples (an integrated luminosity of more than 1 ab^{-1} collected at the $\Upsilon(4S)$ resonance) and performed a time-dependent Dalitz plot analysis of $B^0 \to D^{(*)}h^0$ with $D \to K_S^0\pi^+\pi^-$ decays

- We report the world's most precise measurement of $\cos 2\beta$

- We obtain the first evidence for $\cos 2\beta > 0$ and exclude the trigonometric multifold solution at 7.3σ significance

- Papers have been submitted to PRL and PRD

[arXiv:1804.06152 [hep-ex]] [arXiv:1804.06153 [hep-ex]]