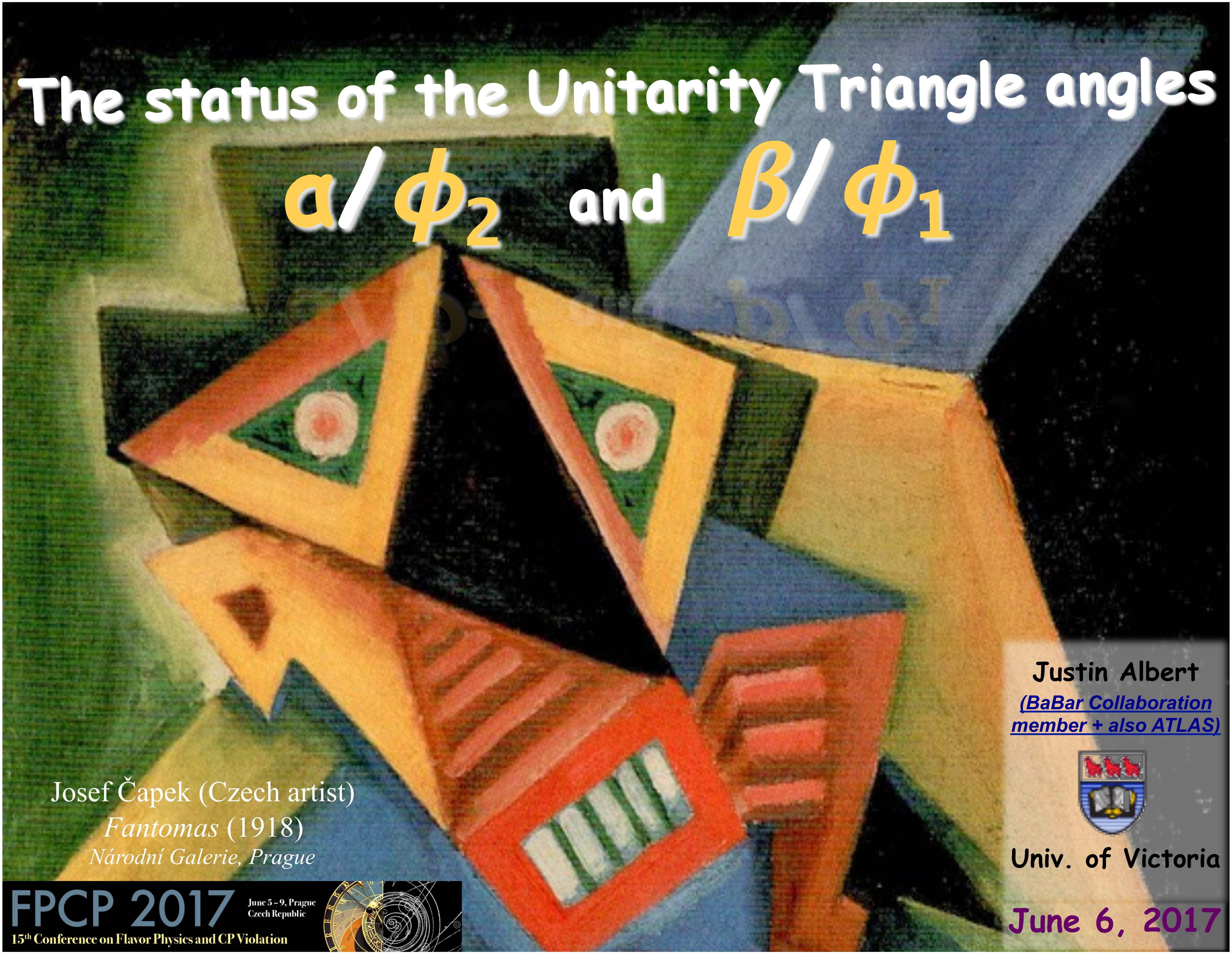
The status of the Unitarity Triangle angles α/ϕ_2 and β/ϕ_1



Josef Čapek (Czech artist)
Fantomas (1918)
Národní Galerie, Prague

Justin Albert
[(BaBar Collaboration member + also ATLAS)]
Univ. of Victoria

June 6, 2017

FPCP 2017
June 5 – 9, Prague
Czech Republic
15th Conference on Flavor Physics and CP Violation

"*FPCP 101*": The Unitarity Triangle(s)

- The constraint that the CKM matrix is unitary results in ***six*** equations (in the $\mathbb{C}$ plane) that sum to zero, and each must be satisfied:

$$V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0 \quad \text{(a)}$$

$$V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0 \quad \text{(b)}$$

$$V_{cd}^* V_{td} + V_{cs}^* V_{ts} + V_{cb}^* V_{tb} = 0 \quad \text{(c)}$$

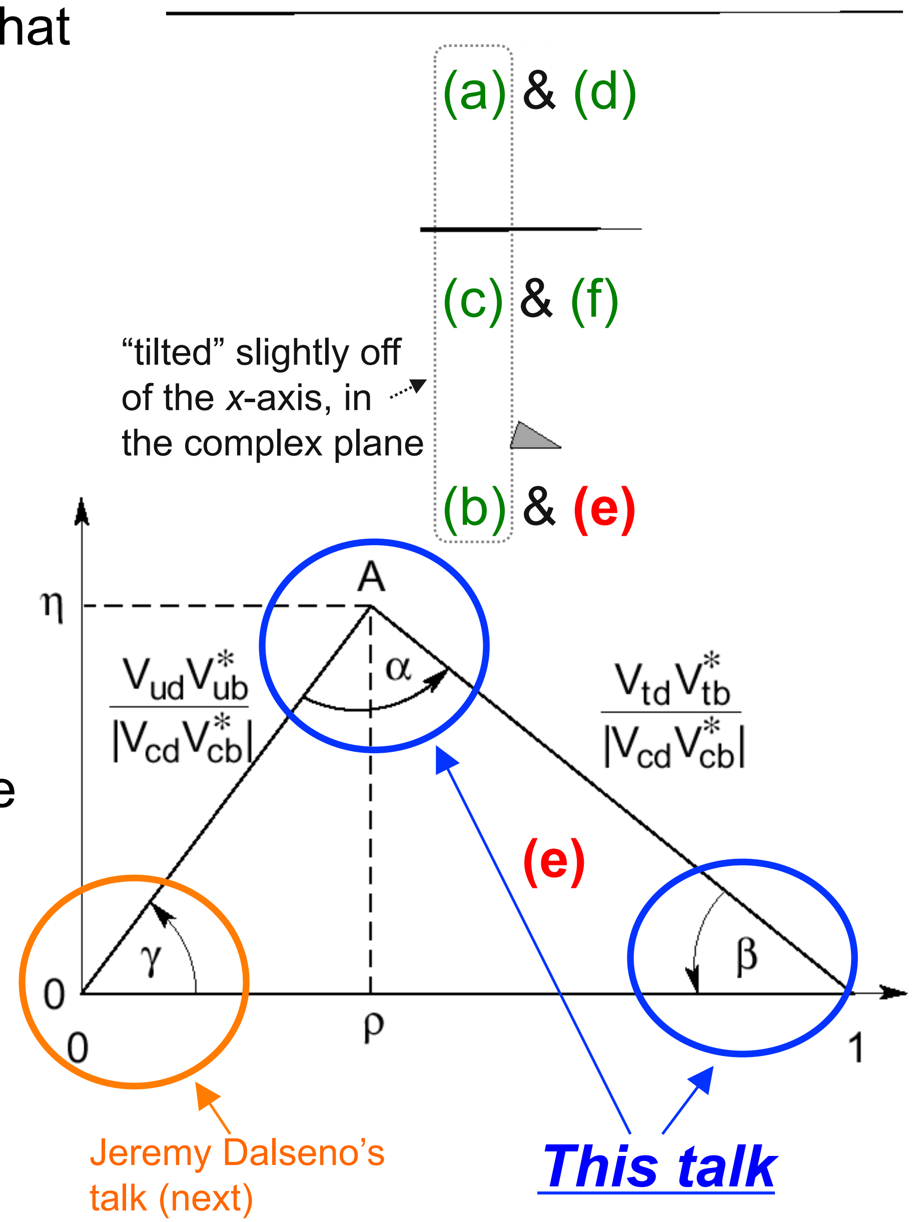
$$V_{ud} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* = 0 \quad \text{(d)}$$

$$\boxed{V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0} \quad \text{(e)}$$

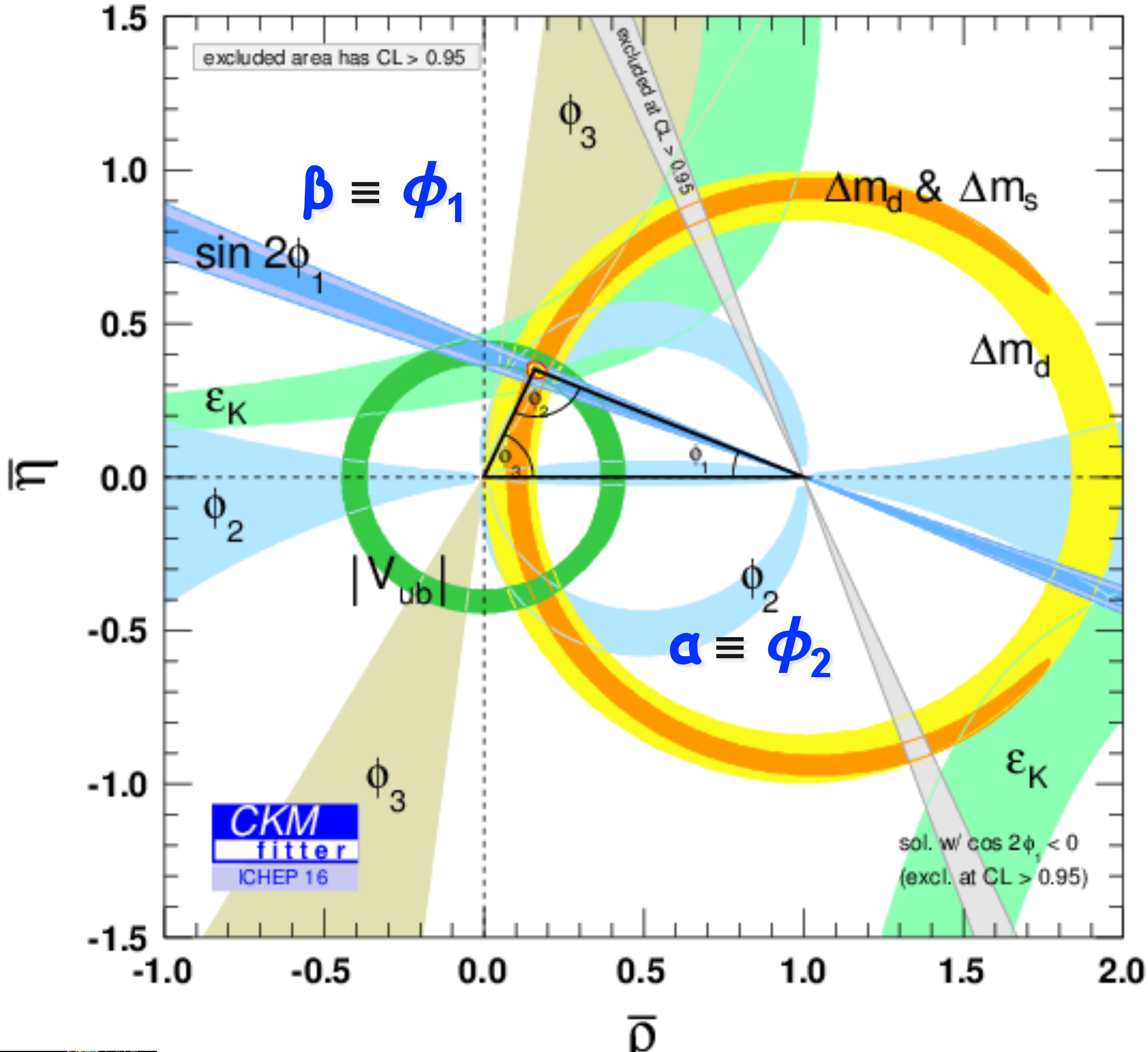
$$V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0 \quad \text{(f)}$$

- Triangles (a) & (d), and (c) & (f) (sensitive to CPV in the kaon and the B_s systems, respectively) are *nearly degenerate*.

- Only triangles (b) & **(e)** (which correspond to *CP* asymmetries in the ***B* system**) have large *CP* violating effects.

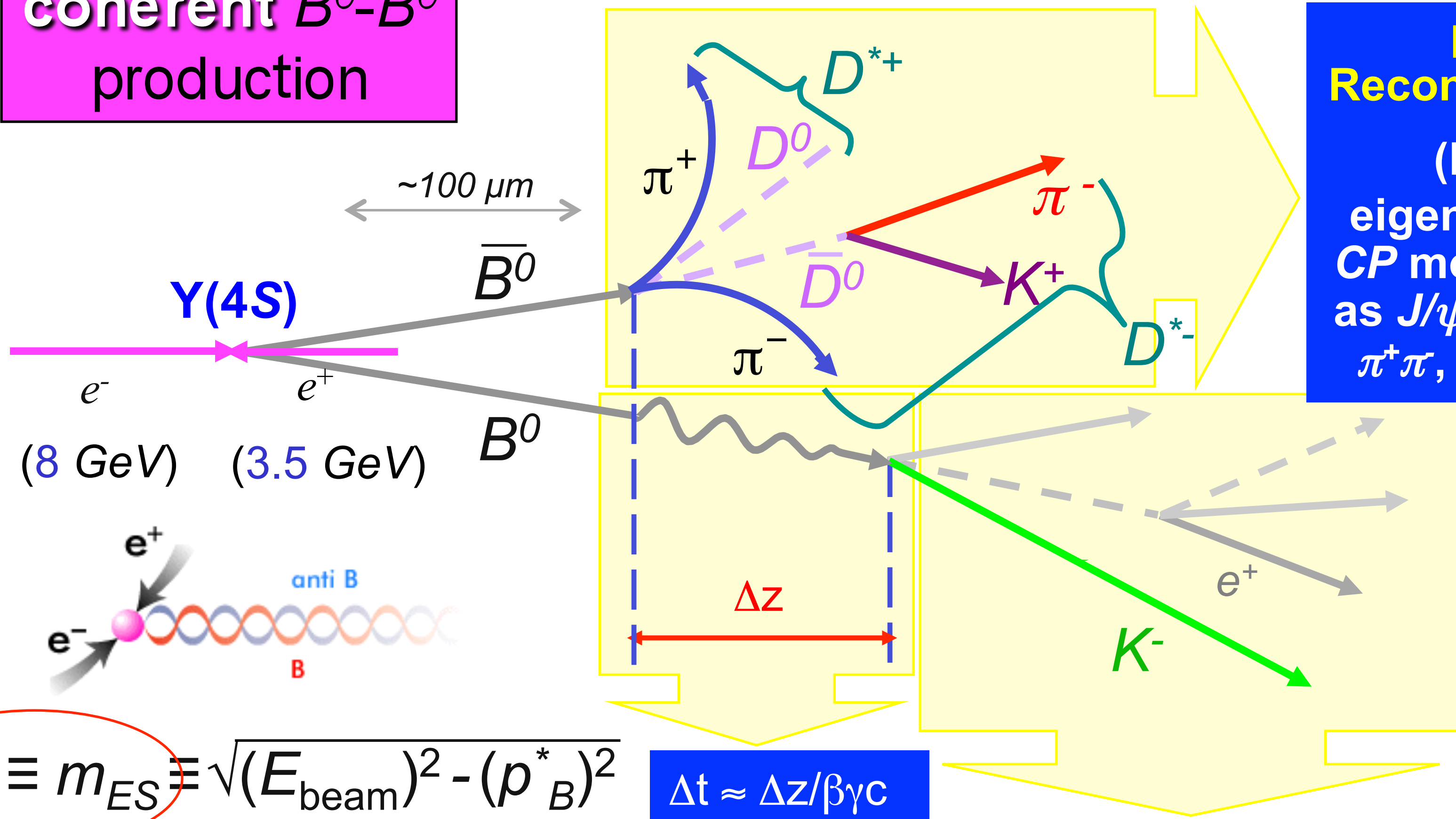


Precision Measurements in a Precision World



How it's measured at e^+e^- B-Factories:

coherent B^0-$\overline{B}^0$ production



Fully Reconstructed B

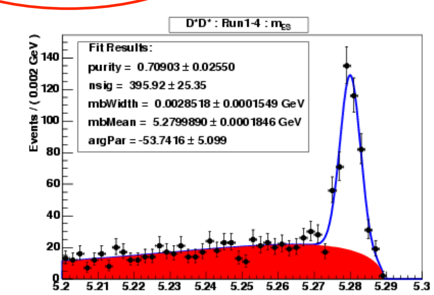
(Flavor eigenstates or CP modes such as $J/\psi K_s$, $J/\psi K_L$, $\pi^+\pi^-$, $D^{(*)}D^{(*)}$,…)

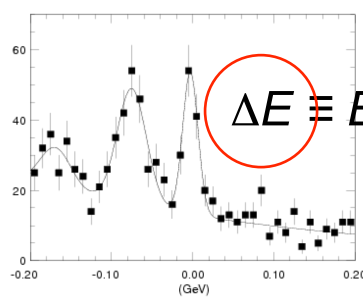
$$M_{bc} \equiv m_{ES} \equiv \sqrt{(E_{beam})^2 - (p^*_B)^2}$$

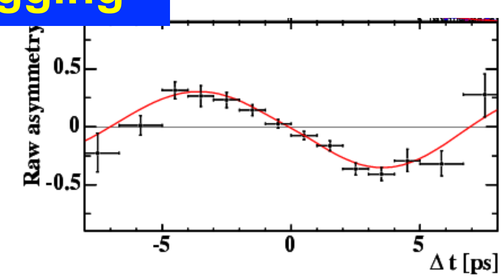
$\Delta t \approx \Delta z/\beta\gamma c$

B-Flavor Tagging

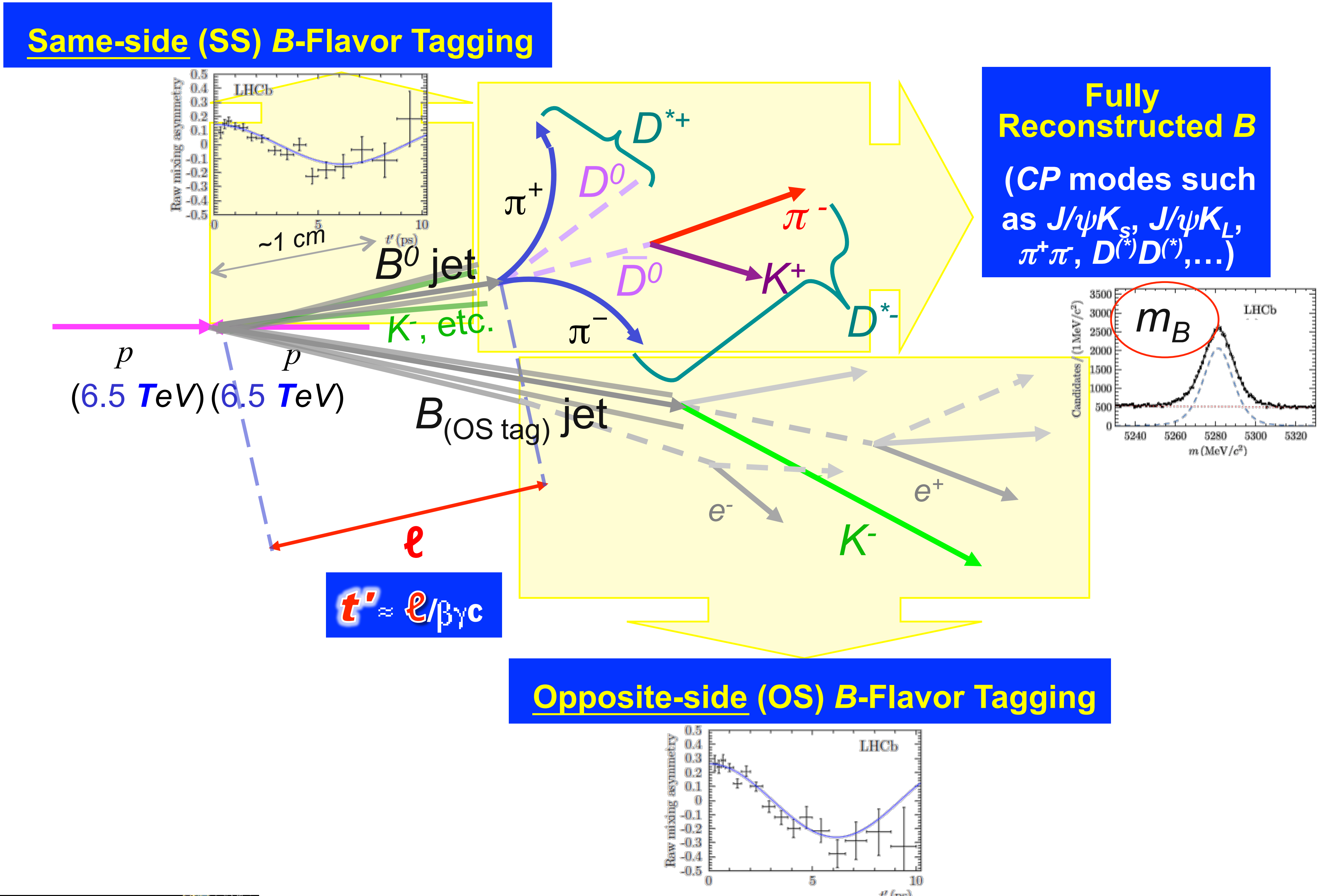
$$\Delta E \equiv E^*_B - E_{beam}$$







How it's measured at LHC(*b*):



3 (of *Many*) Selected Recent α/ϕ_2 and β/ϕ_1 Results

1) BABAR + **Belle** measurements of α from three-body charmless decays.

PRD **88**, 012003 (2013);
PRD **77**, 072001 (2008), PRL **98**, 221602 (2007)

2) LHCb measurements of **sin(2β)** in $B^0 \to J/\psi K^0_S$ and $B^0 \to D^+D^-$ decays.

PRL **115**, 031601 (2015);
PRL **117**, 261801 (2016)

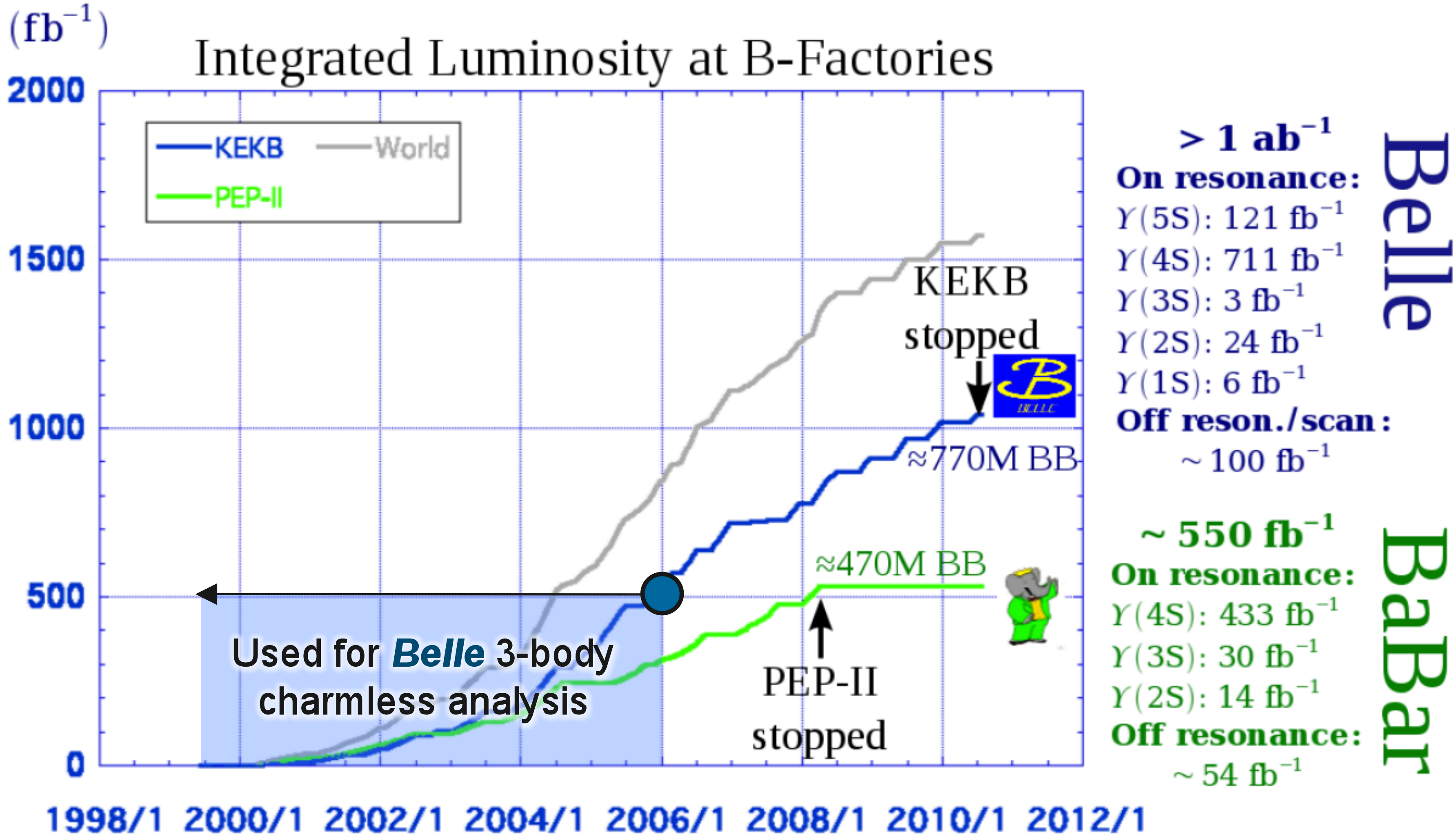
3) Combined BABAR + **Belle** measurement of the Unitarity Triangle parameters **sin(2β)** and **cos(2β)** in $B^0 \to D^{(*)0}h^0$ decays.

First Combined BABAR-Belle Experimental Data Analysis
To be submitted to PRL; initial (non-Dalitz) combined measurement of sin(2β) from this analysis published as PRL **115**, 121604.

1) BABAR + *Belle* measurements of α from three-body charmless decays

BABAR: PRD **88**, 012003 (2013);
Belle: PRD **77**, 072001 (2008), PRL **98**, 221602 (2007)

BABAR + *Belle* Datasets



- The *BaBar* and *Belle* measurements of α using 3-body charmless *B* decays use **471 x 10^6** $B\bar{B}$ pairs (*BaBar* analysis), and **449 x 10^6** $B\bar{B}$ pairs (*Belle* analysis).
- The **combined** *BaBar* + *Belle* measurement of sin(2β) and cos(2β) using $B^0 \to D^{(*)0}h^0$ decays utilizes **all** 1.1 ab^{-1} ≈ **1240 x 10^6** $B\bar{B}$ pairs from both experiments.

Snyder-Quinn method for *α*

- The initial ***Gronau-London*** method for measuring ***α*** uses both neutral and charged **2-body** charmless decays $B \to \pi\pi$ to remove "penguin pollution" from the estimation of ***α***, by utilizing isospin relations between the different decays. PRL 65 (1990) 3381

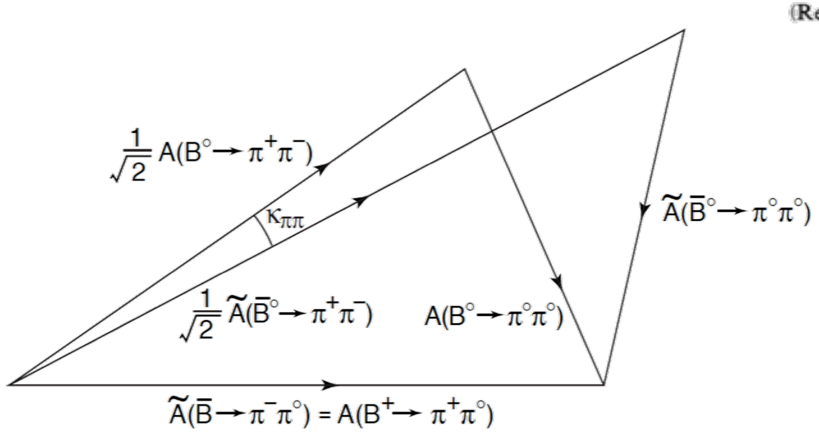
- The ***Snyder-Quinn*** method is a *revision* for **3-body** charmless decays $B^0 \to \pi^+\pi^-\pi^0$, utilizing a decay-time-dependent Dalitz plot to measure ***α***. PRD 48 (1993) 2139

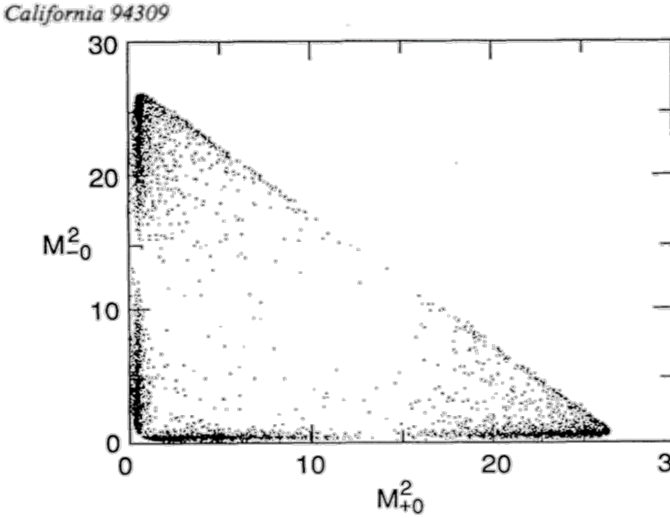
PHYSICAL REVIEW D VOLUME 48, NUMBER 5 1 SEPTEMBER 1993

Measuring *CP* asymmetry in $B \to \rho\pi$ decays without ambiguities

Arthur E. Snyder and Helen R. Quinn
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

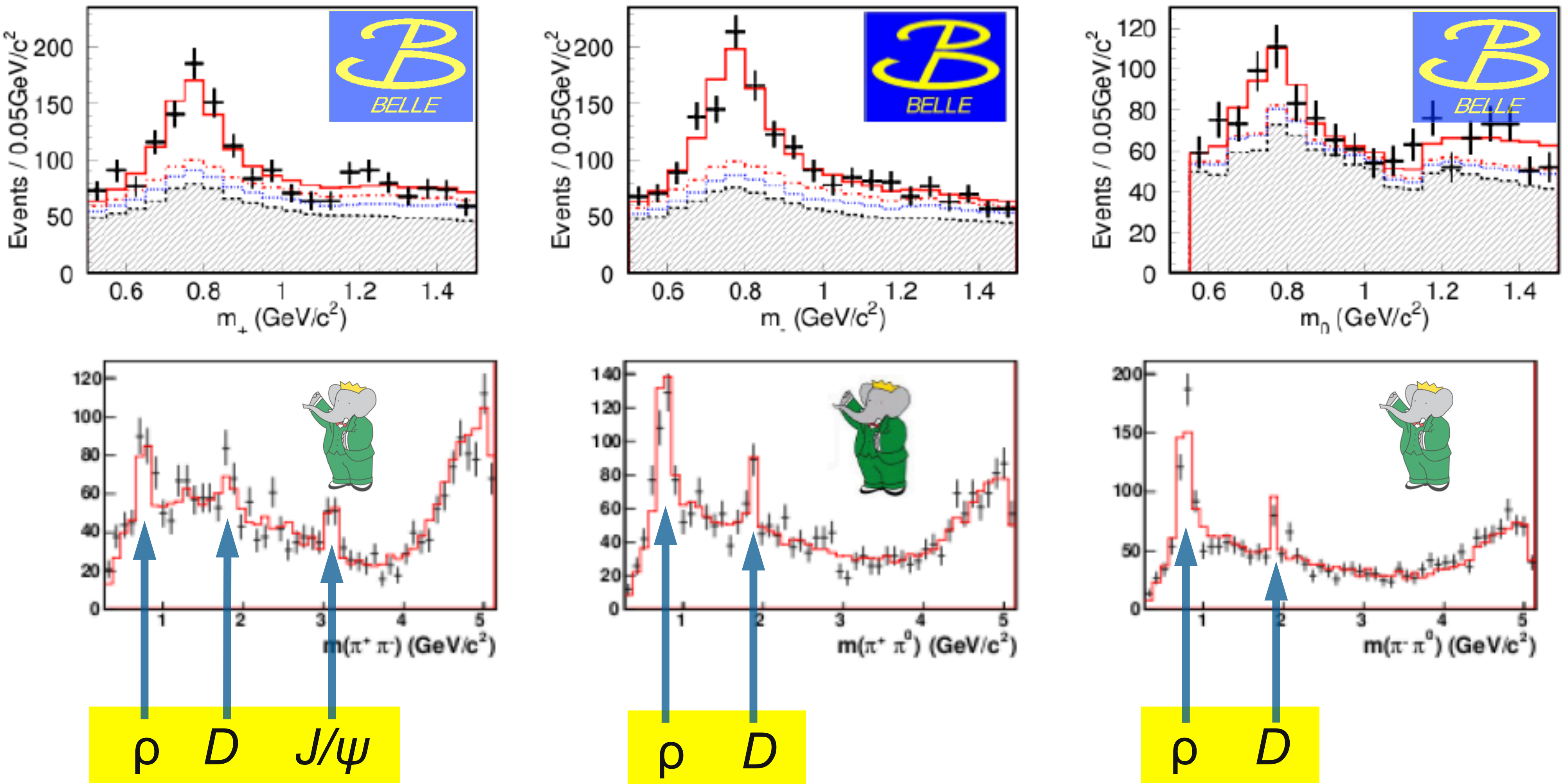
(Received 24 February 1993)





$B^0 \rightarrow \pi^+\pi^-\pi^0$: *B*-factory results

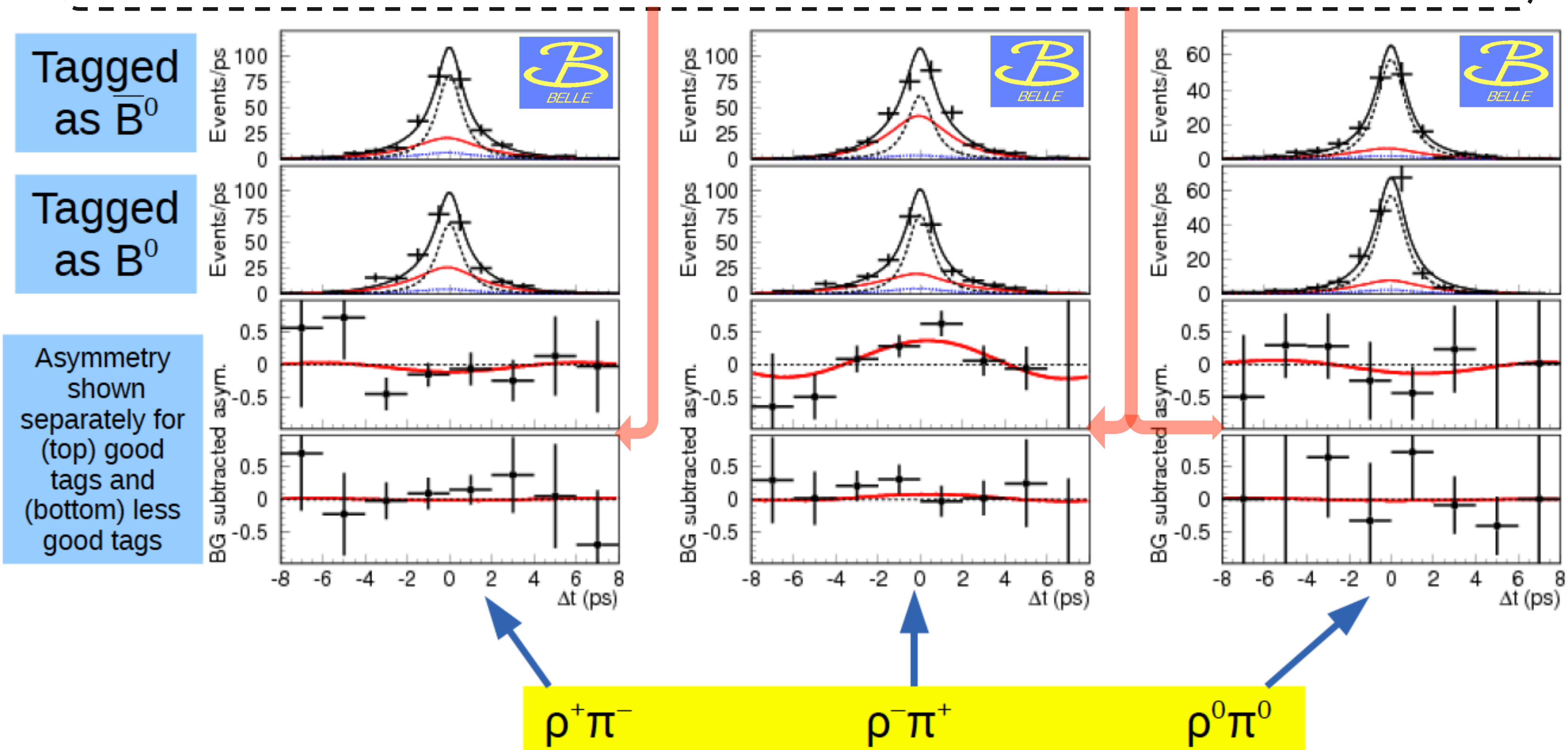
- ***Belle***: **449 x 10^6** $B\bar{B}$ pairs : PRL **98**, 221602 (2007); PRD **77**, 072001 (2008)
- **BABAR**: **471 x 10^6** $B\bar{B}$ pairs : PRD **88**, 012003 (2013)



$B^0 \rightarrow \pi^+\pi^-\pi^0$: *B*-factory results (II)

- ***Belle***: **449 x 10^6** $B\bar{B}$ pairs : PRL **98**, 221602 (2007); PRD **77**, 072001 (2008)
- **BaBar**: **471 x 10^6** $B\bar{B}$ pairs : PRD **88**, 012003 (2013)

"(Raw) Asymmetry" ≡ $\left[(n_{\bar{B}^0\text{ tags}} - n_{B^0\text{ tags}})/(n_{\bar{B}^0\text{ tags}} + n_{B^0\text{ tags}})\right]$, as a function of $\boldsymbol{\Delta t}$



Resulting 3-body constraints on α

- ➢ ***Belle***: **449 x 10^6** $B\bar{B}$ pairs : PRL **98**, 221602 (2007); PRD **77**, 072001 (2008)
- ➢ **BABAR**: **471 x 10^6** $B\bar{B}$ pairs : PRD **88**, 012003 (2013)

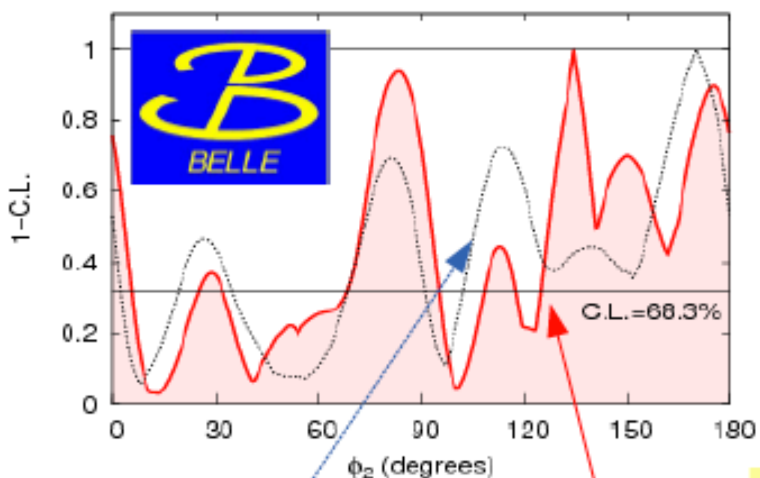
Belle

$A_{\rho\pi}$ = –0.12 ± 0.05 ± 0.04
C = –0.13 ± 0.09 ± 0.05
ΔC = +0.36 ± 0.10 ± 0.05
S = +0.06 ± 0.13 ± 0.05
ΔS = –0.08 ± 0.13 ± 0.05

BABAR

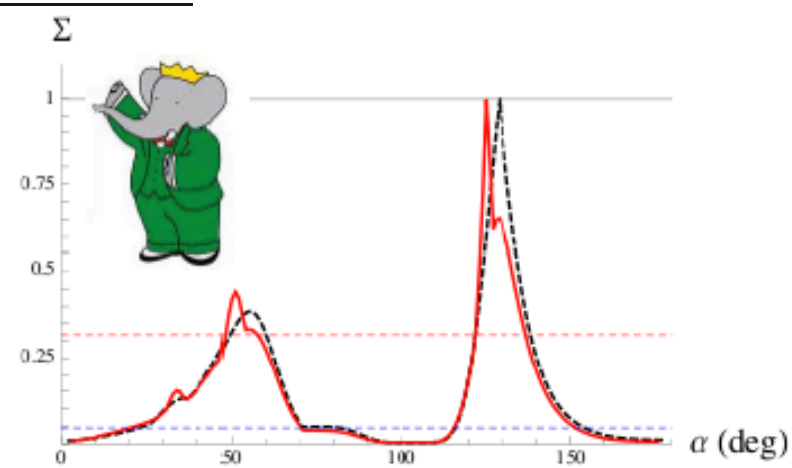
$A_{\rho\pi}$ = –0.10 ± 0.03 ± 0.02
C = +0.16 ± 0.06 ± 0.04
ΔC = +0.23 ± 0.06 ± 0.05
S = +0.05 ± 0.08 ± 0.03
ΔS = +0.05 ± 0.08 ± 0.04

however …



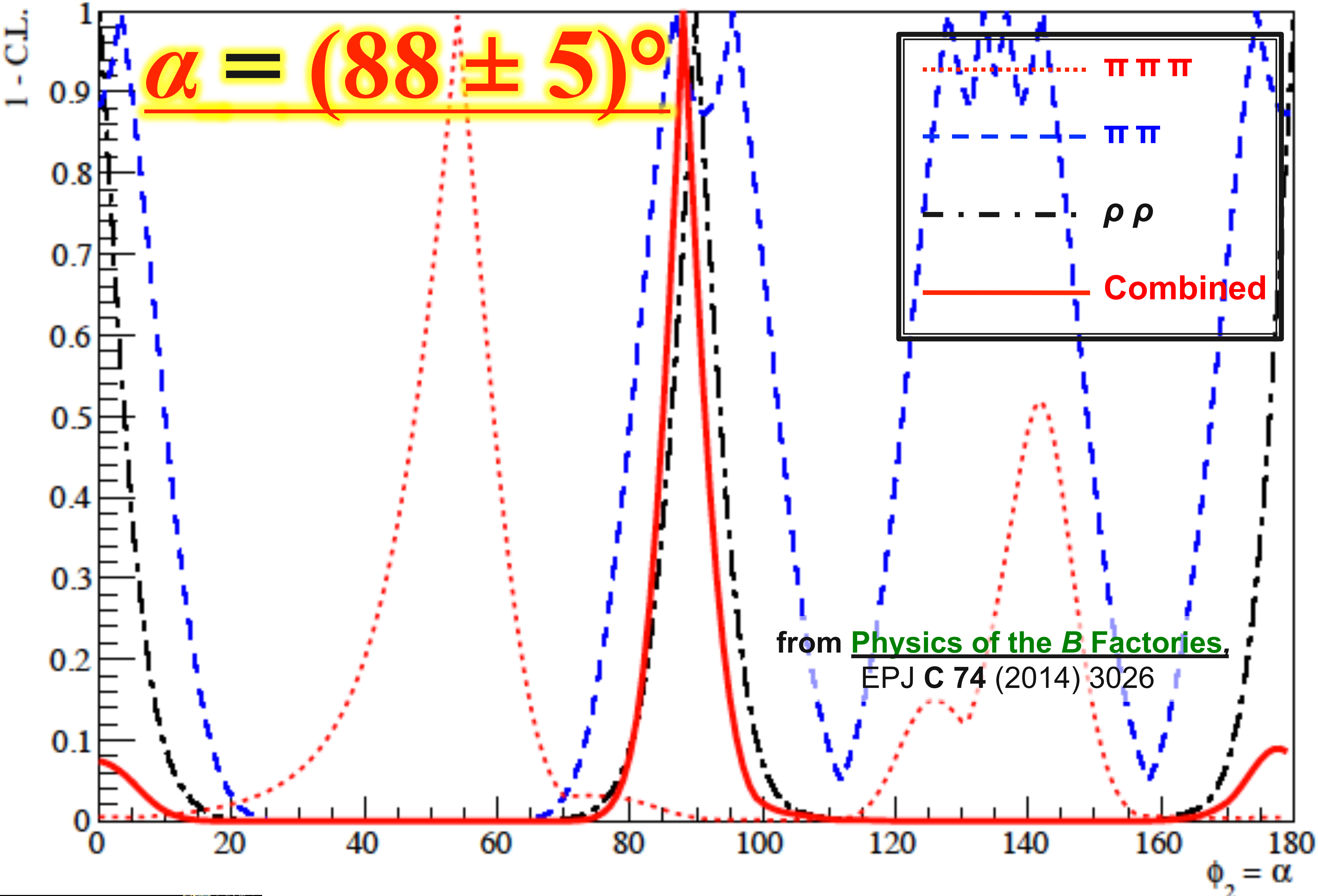
Contour from $B \to \pi^+\pi^-\pi^0$ only

Including also information on $B^+ \to \rho^+\pi^0$ and $B^+ \to \rho^0\pi^+$



"the extraction of α with our current sample size is not robust"

… but when combined with 2-body decay results:



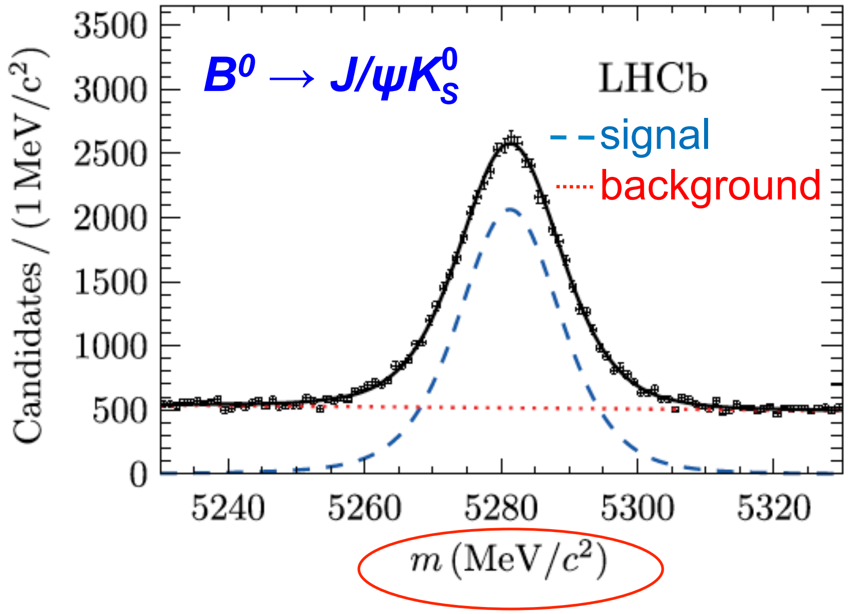
from **Physics of the *B* Factories**,
EPJ **C 74** (2014) 3026

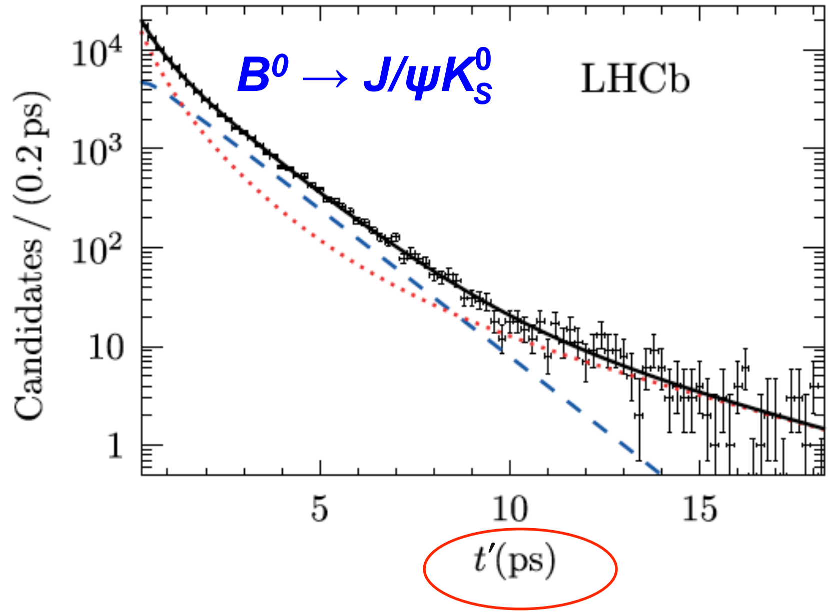
2) LHCb measurements of *CP* violation in $B^0 \to J/\psi K_S^0$ and $B^0 \to D^+D^-$ decays

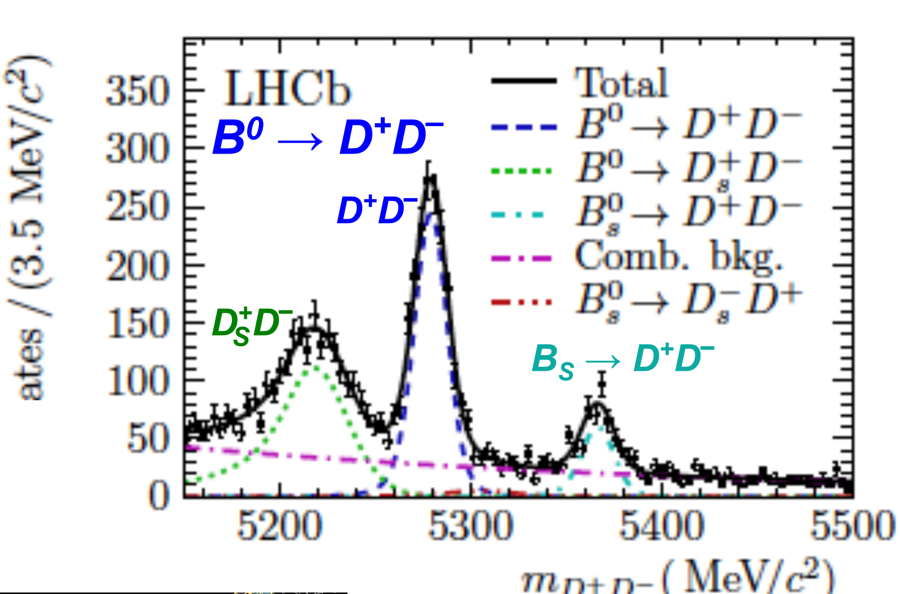
PRL 115, 031601 (2015); PRL 117, 261801 (2016)

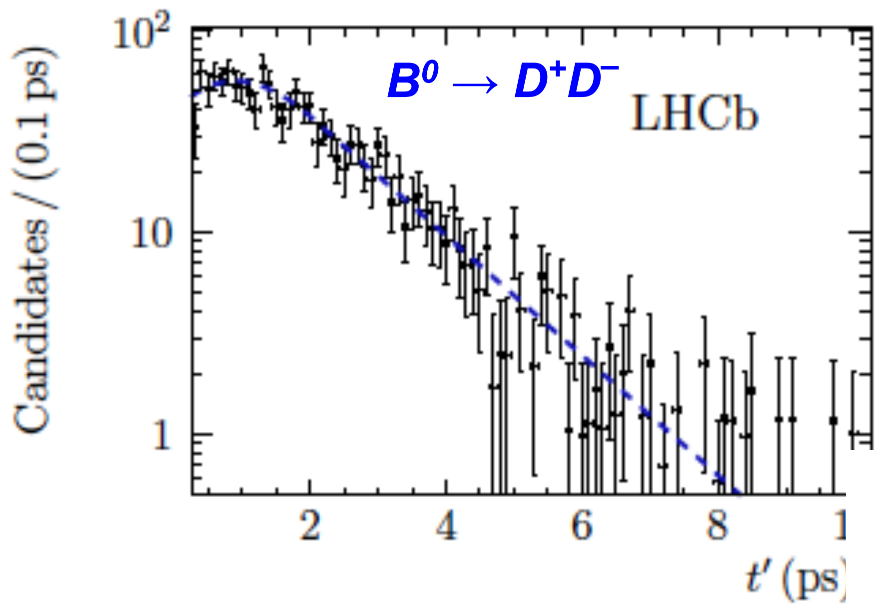
$B^0 \to J/\psi K_S^0$ and $B^0 \to D^+D^-$ Data Samples & Decay Time Distributions

➢ Distributions of reconstructed mass, and logarithmic distributions of decay time:





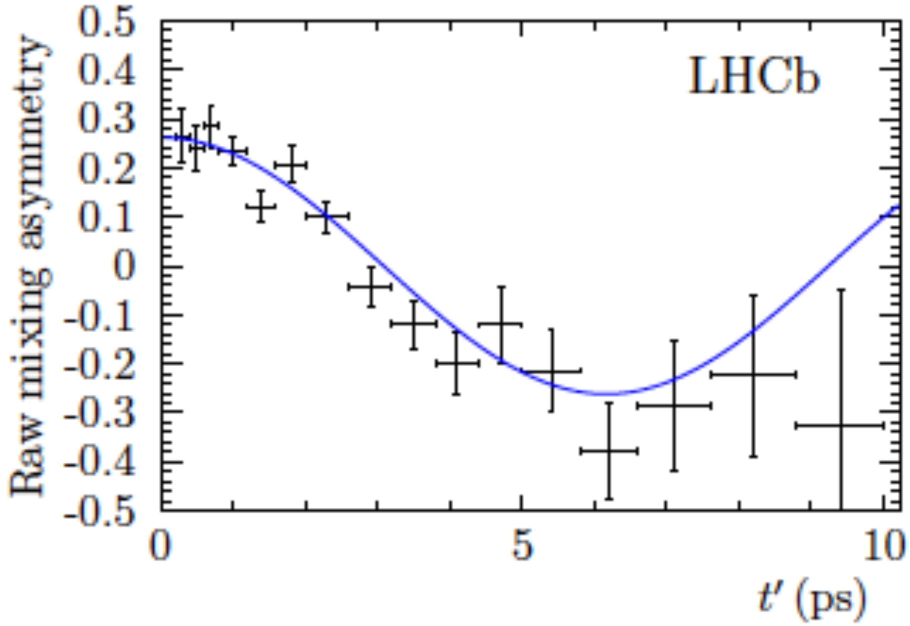




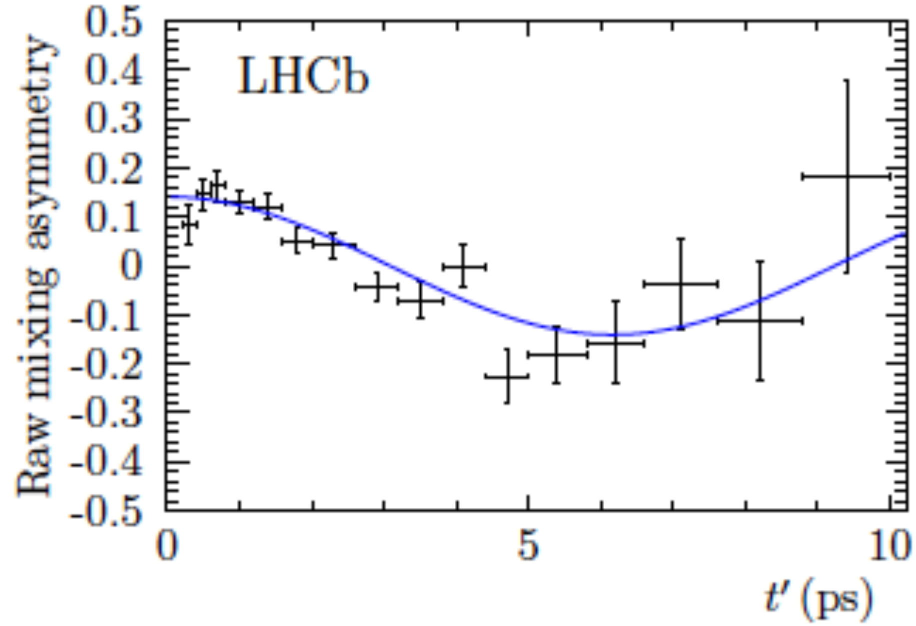
Opposite-Side (OS) and Same-Side (SS) Tagging

- Decay-time-dependent raw mixing asymmetries, with fit projections superimposed:

OS



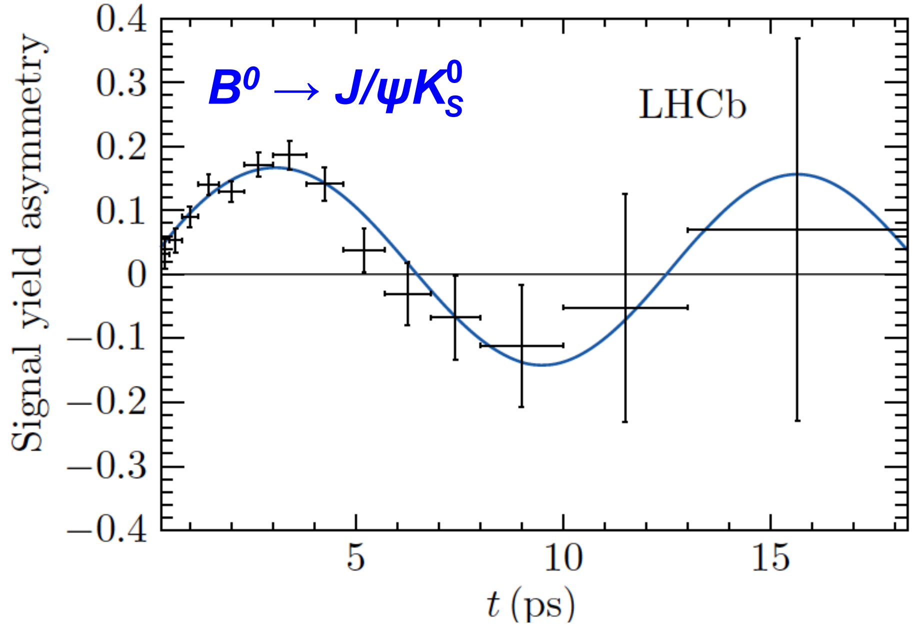
SS



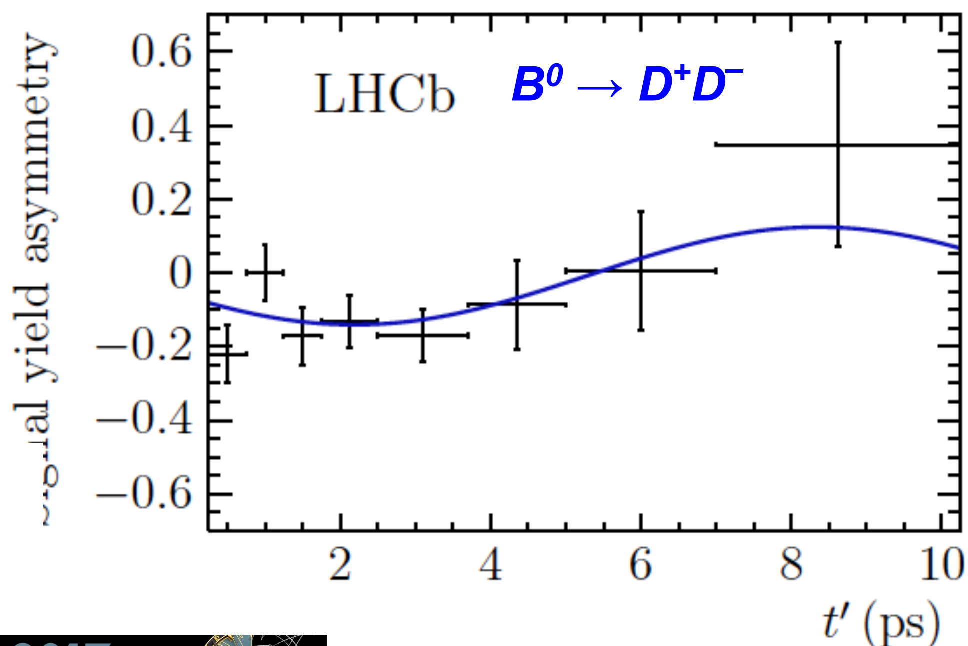
from $B^0 \to D_s^{\pm} D^{\mp}$ tagging and mixing test sample

$B^0 \to J/\psi K^0_S$ and $B^0 \to D^+D^-$ *CP* Asymmetry Measurements

➢ Decay-time-dependent raw signal yield asymmetries, with fit projections superimposed:



$$\sin(2\beta)_{meas} = 0.73 \pm 0.04 \pm 0.02$$



$$\sin(2\beta_{eff})_{meas} = 0.54^{+0.17}_{-0.15} \pm 0.05$$

$$\beta_{\text{LHCb}}\ \text{meas} = (23.5 \pm 1.8)°$$

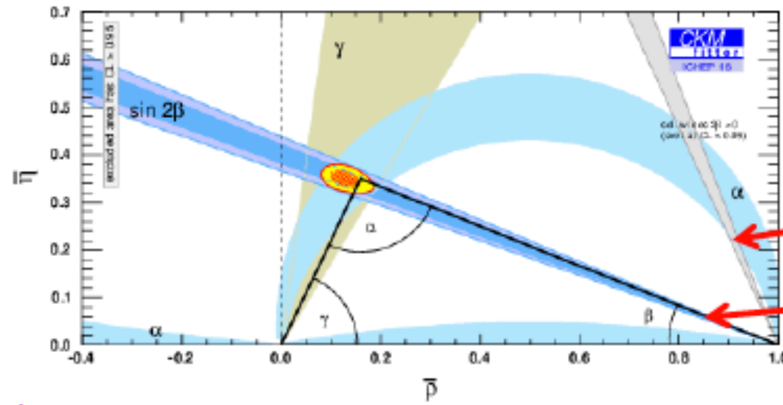
3) Combined BABAR + ***Belle*** measurement of the Unitarity Triangle parameters $\mathbf{sin(2\beta)}$ and $\mathbf{cos(2\beta)}$ in $B^0 \to D^{(*)0} h^0$ decays

First Combined BABAR-Belle Experimental Data Analysis

To be submitted to PRL; initial (non-Dalitz) combined measurement of sin(2β) from this analysis published as PRL 115, 121604.

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

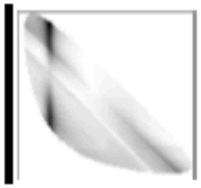
- The determination of β from sin(2β) measurements leads to a trigonometric ambiguity:



β=(π/2-21.9°)=68.1°

β=21.9°

- $B^0 \to D^{(*)0}h^0$, with $D \to K^0\pi^+\pi^-$ decays, enables the extraction of both sin(2β) and cos(2β):

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

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

[A. Bondar, P. Krokovny, T. Gershon PLB **624** 1 (2005)]

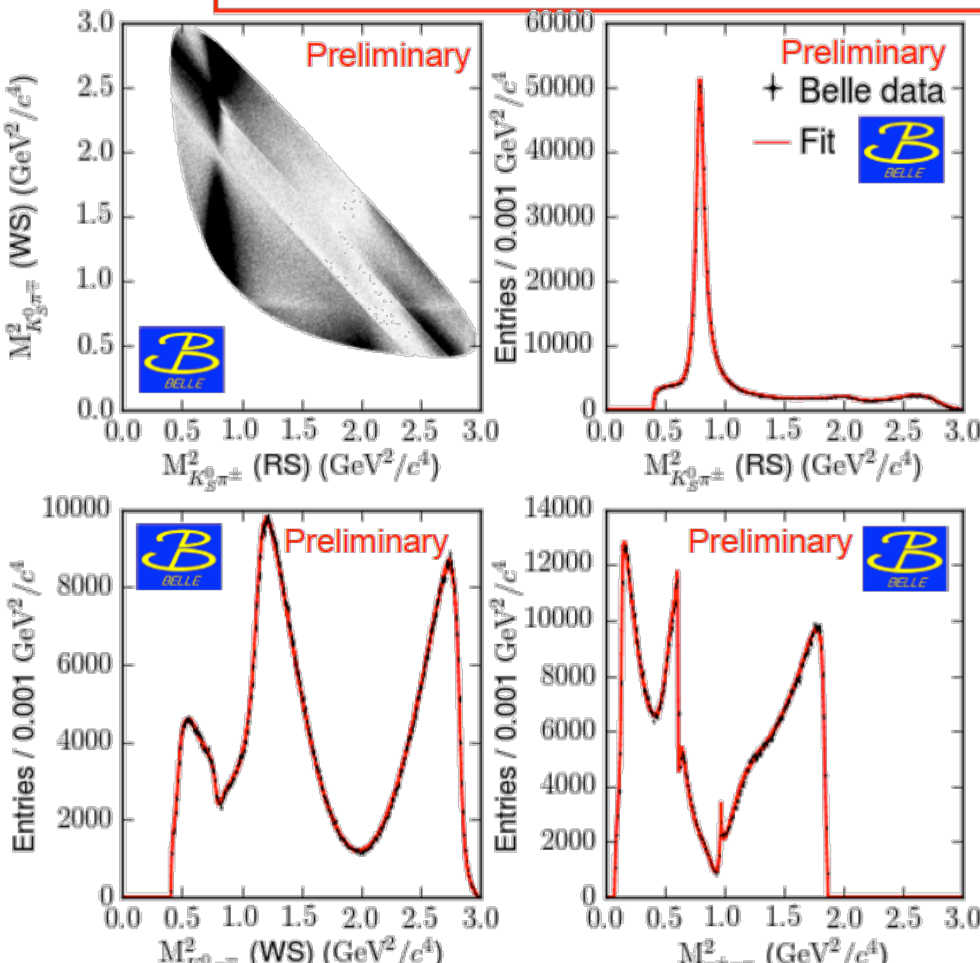
- The current best single experimental uncertainty on cos(2β) is ±0.36 [PRD 94, 052004 (2016)]

⇒ Perform time-dependent Dalitz analysis, combining BABAR + *Belle* data, to improve the sensitivity to cos(2β).

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

- The $D \to K^0_S\pi^+\pi^-$ Dalitz model is directly obtained from $e^+e^- \to c\bar{c}$ data.

$$\mathcal{A}_{D^0}(m_+^2, m_-^2) = \sum_{r \neq (K\pi/\pi\pi)_{L=0}} \underbrace{a_r e^{i\phi_r} \mathcal{A}_r(m_+^2, m_-^2)}_{\text{Isobar model for L≠0}} + \underbrace{\mathcal{A}_{K\pi_{L=0}}(s)}_{\text{LASS}} + \underbrace{F_1(s)}_{\text{K-matrix}}$$



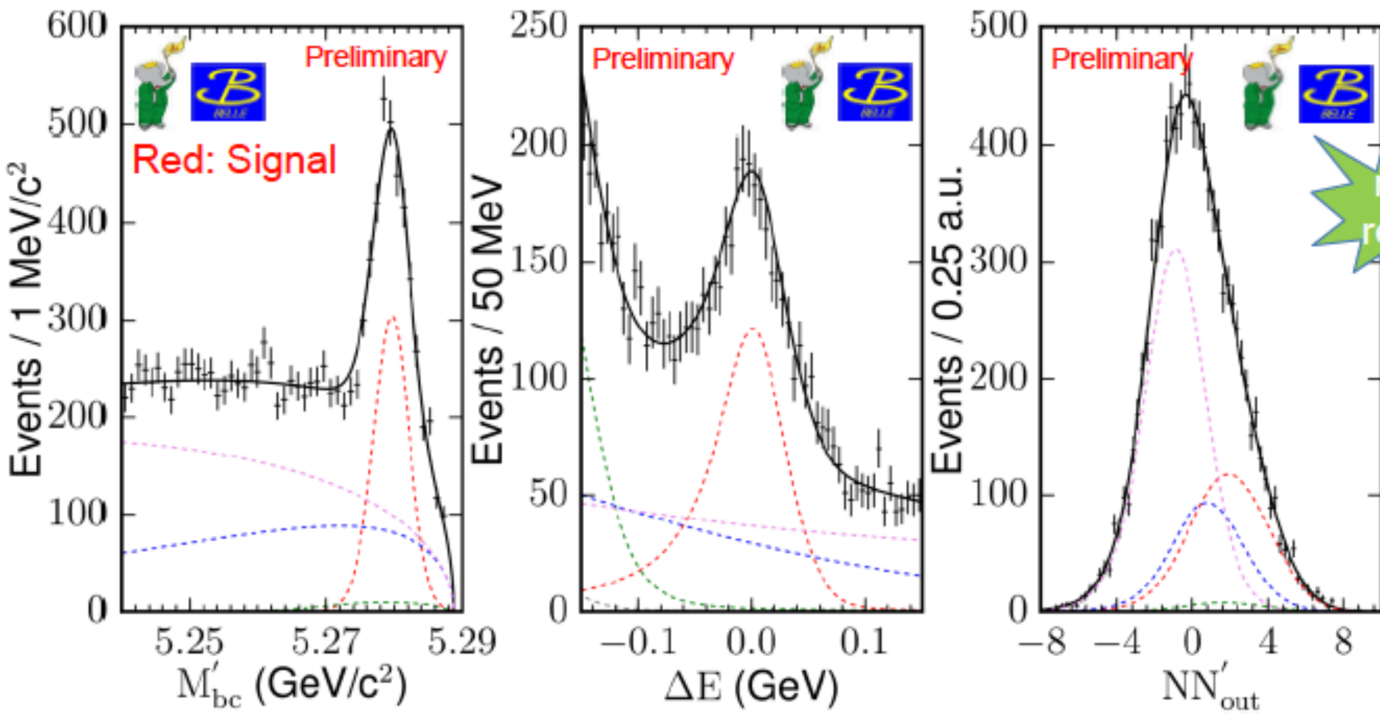
- The $D \to K^0_S\pi^+\pi^-$ Dalitz model that is extracted from ***Belle*** $e^+e^- \to c\bar{c}$ data accounts for 14 intermediate 2-body resonances.

- The *K*-matrix and LASS parameterizations are used to model the non-resonant $\pi\pi$ and $K\pi$ *S*-waves.

Principle of the Combined Analysis

- We reconstruct $B^0 \to D^{(*)0} h^0$ with $h^0 \in \{\pi^0 \to \gamma\gamma,\ \eta \to \gamma\gamma \text{ or } \pi^+\pi^-\pi^0,\ \omega \to \pi^+\pi^-\pi^0\}$

  $D^0 \to K^0\pi^+\pi^-$ and $D^{*0} \to D\pi^0$
- In total, 5 B^0 decay modes are reconstructed.
- Continuum background from $e^+e^- \to q\bar{q}$ ($q \in \{u, d, s, c\}$) is identified by a neural network.
- Coherent analysis strategy, applying essentially same selection on BABAR & *Belle* data.
- We extract signal via a 3-D fit of M_{bc} ($\equiv m_{ES}$), energy difference (ΔE), and NN_{out}.



new result

BABAR
1129 ± 48 signal events

Belle
1567 ± 56 signal events

1240 x 10^6 $B\bar{B}$ decays

CP Violation Results

- We perform the measurement by maximizing the combined log-likelihood function:

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

- The physics PDFs are convolved with experiment-specific resolution functions:

$$\mathcal{P}^{\text{Exp.}} = \sum_{\text{k}} \text{f}_{\text{k}} \int \left[\text{P}_{\text{k}}\left(\Delta\text{t}'\right) \text{R}_{\text{k}}\left(\Delta\text{t} - \Delta\text{t}'\right)\right] \text{d}\left(\Delta\text{t}'\right)$$

- We also apply **BABAR** and ***Belle***-specific flavor-tagging algorithms.
- We apply a **common** signal model:

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

BABAR + ***Belle*** with **1.1 ab^{-1}**:

Preliminary

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

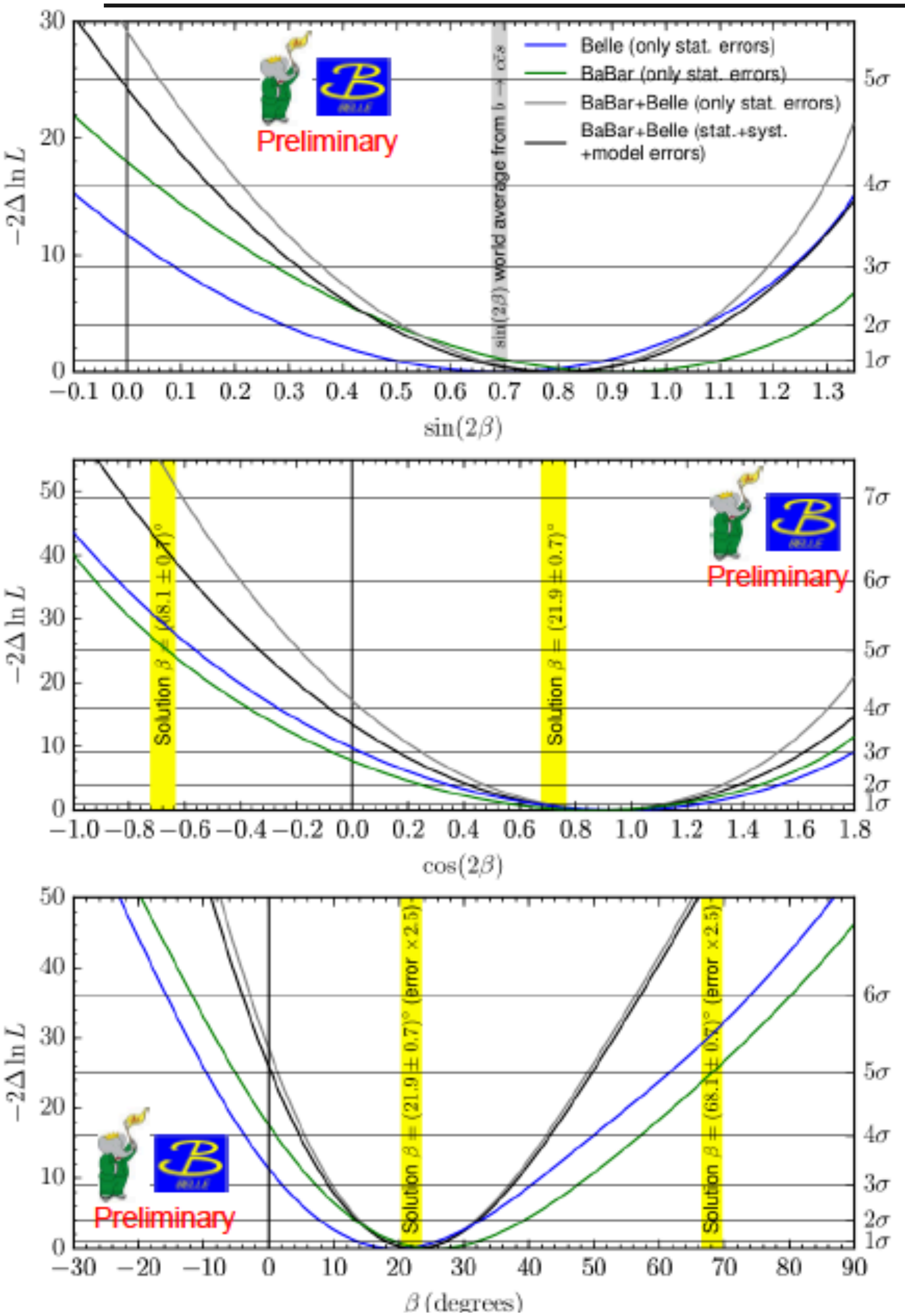
$$\cos(2\beta) = 0.91 \pm 0.22\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model})$$

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

new result

1240×10^6 $B\bar{B}$ decays

Significance of the Results



- First evidence for $\cos(2\beta) > 0$ (3.7σ)

- Direct exclusion of the 2nd solution

$$\pi/2 - \beta = (68.1 \pm 0.7)^\circ$$

  of the CKM Unitarity Triangle (7.3σ)

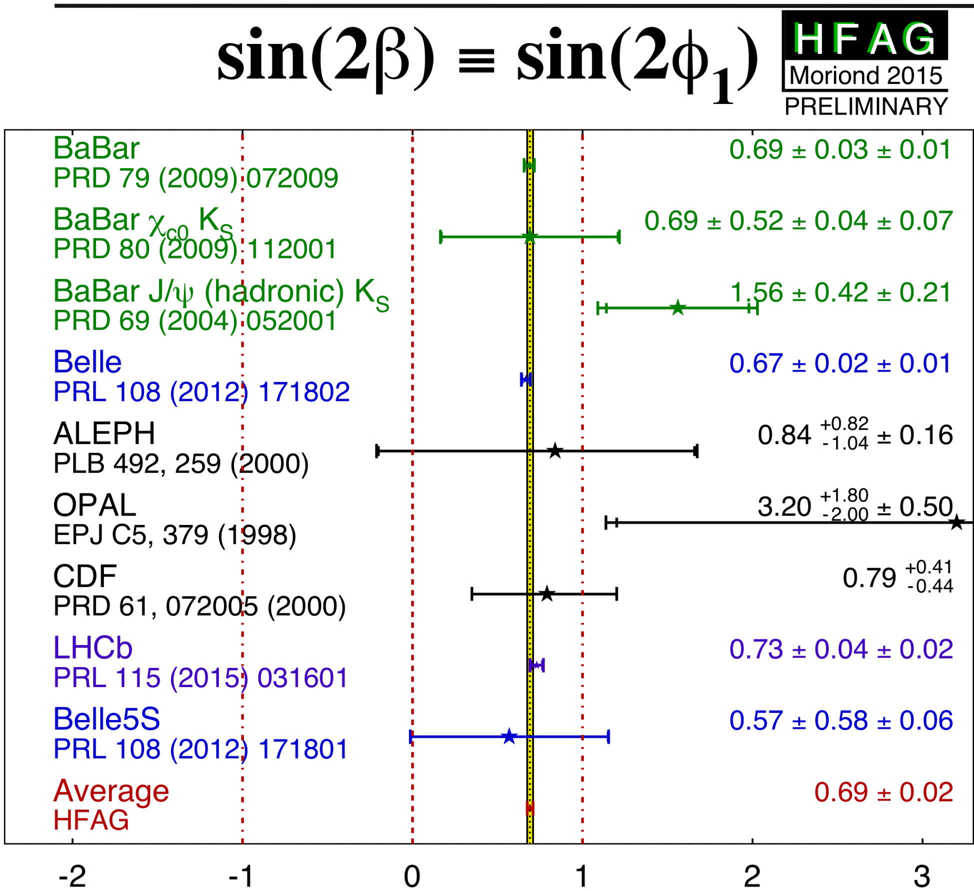
  → Reduction of the trigonometric ambiguity of the CKM Unitarity Triangle

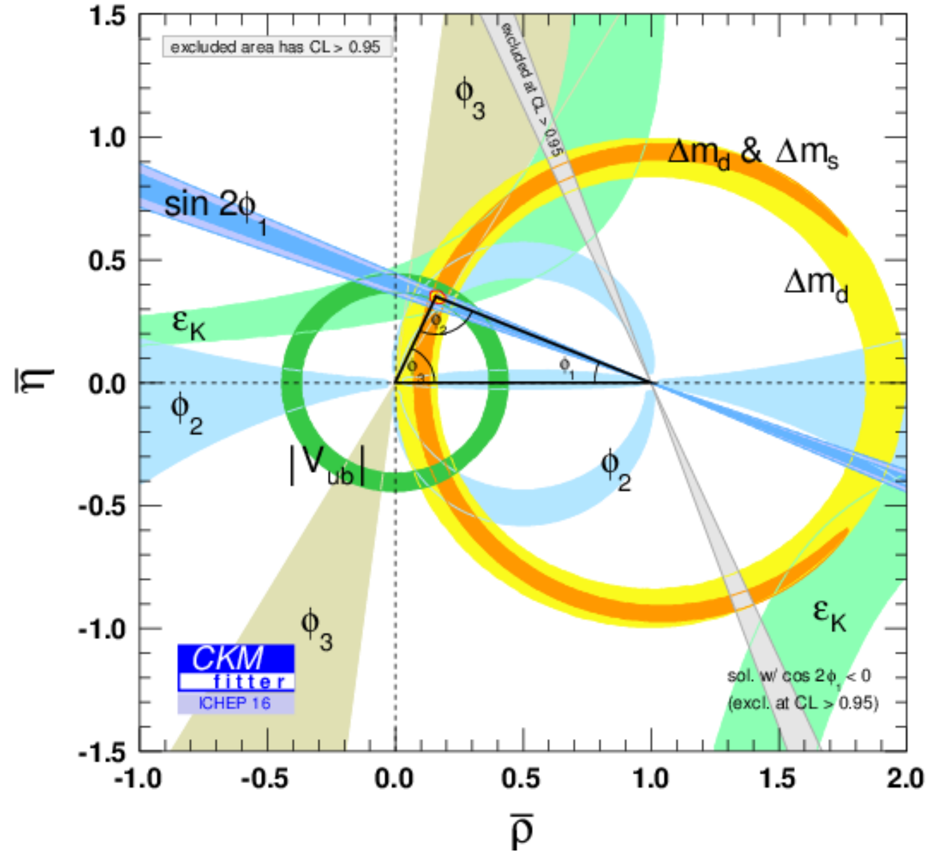
- Exclusion of $\beta = 0^\circ$ (5.1σ)

  → Observation of CP violation in $B^0 \to D^{(*)}h^0$ decays

new result

Overall status of β/ϕ_1





$$\sin(2\beta)_{ave} = \underline{0.69 \pm 0.02}$$

$$\Rightarrow \quad \beta_{ave} = \underline{(21.9 \pm 0.7)^\circ}$$

Summary

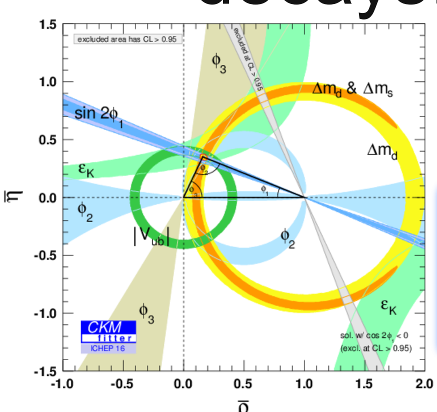
1) BABAR + *Belle* measurements of α from three-body charmless decays.

PRD **88**, 012003 (2013);
PRD **77**, 072001 (2008), PRL **98**, 221602 (2007)

2) LHCb measurements of $\mathbf{sin(2\beta)}$ in $B^0 \rightarrow J/\psi K^0_S$ and $B^0 \rightarrow D^+D^-$ decays.

PRL **115**, 031601 (2015);
PRL **117**, 261801 (2016)

3) Combined BABAR + *Belle* measurement of Unitarity Triangle parameters $\mathbf{sin(2\beta)}$ & $\mathbf{cos(2\beta)}$ in $B^0 \rightarrow D^{(*)0}h^0$ decays.



First Combined BABAR-Belle Experimental Data Analysis
To be submitted to PRL; initial analysis published as PRL **115**, 121604.

$$\alpha/\Phi_2 = \underline{(88 \pm 5)^\circ} \text{ and } \beta/\Phi_1 = \underline{(21.9 \pm 0.7)^\circ}$$

Backup Slides

The 3-body Dalitz plane: A Toy Model

Contributions only from $\rho^+\pi^-$, $\rho^-\pi^+$ and $\rho^0\pi^0$

27 parameters renamed "U" and "I" in commonly used notation

H.Quinn and J.Silva, PRD 62 (2000) 054002

PRD 48 (1993) 2139

Time dependence	Kinematic form	Amplitude measured	α dependence (all $P_i=0$)
1	f^+f^{+*}	$S_3S_3^*+\bar{S}_4\bar{S}_4^*$	1
$\cos(\Delta Mt)$	f^+f^{+*}	$S_3S_3^*-\bar{S}_4\bar{S}_4^*$	1
$\sin(\Delta Mt)$	f^+f^{+*}	$\mathrm{Im}(q\bar{S}_4S_3^*)$	$\sin(2\alpha)$
1	f^-f^{-*}	$S_4S_4^*+\bar{S}_3\bar{S}_3^*$	1
$\cos(\Delta Mt)$	f^-f^{-*}	$S_4S_4^*-\bar{S}_3\bar{S}_3^*$	1
$\sin(\Delta Mt)$	f^-f^{-*}	$\mathrm{Im}(q\bar{S}_3S_4^*)$	$\sin(2\alpha)$
1	f^0f^{0*}	$(S_5S_5^*+\bar{S}_5\bar{S}_5^*)/4$	1
$\cos(\Delta Mt)$	f^0f^{0*}	$(S_5S_5^*-\bar{S}_5\bar{S}_5^*)/4$	1
$\sin(\Delta Mt)$	f^0f^{0*}	$\mathrm{Im}(q\bar{S}_5S_5^*)/4$	$\sin(2\alpha)$
1	$\mathrm{Re}(f^+f^{-*})$	$\mathrm{Re}(S_3S_4^*+\bar{S}_4\bar{S}_3^*)$	1
$\cos(\Delta Mt)$	$\mathrm{Re}(f^+f^{-*})$	$\mathrm{Re}(S_3S_4^*-\bar{S}_4\bar{S}_3^*)$	1
$\sin(\Delta Mt)$	$\mathrm{Re}(f^+f^{-*})$	$\mathrm{Im}(q\bar{S}_4S_4^*-q^*S_3\bar{S}_3^*)$	$\sin(2\alpha)$
1	$\mathrm{Im}(f^+f^{-*})$	$\mathrm{Im}(S_3S_4^*+\bar{S}_4\bar{S}_3^*)$	1
$\cos(\Delta Mt)$	$\mathrm{Im}(f^+f^{-*})$	$\mathrm{Im}(S_3S_4^*-\bar{S}_4\bar{S}_3^*)$	1
$\sin(\Delta Mt)$	$\mathrm{Im}(f^+f^{-*})$	$\mathrm{Re}(q\bar{S}_4S_4^*-q^*S_3\bar{S}_3^*)$	$\cos(2\alpha)$
1	$\mathrm{Re}(f^+f^{0*})$	$\mathrm{Re}(S_3S_5^*+\bar{S}_4\bar{S}_5^*)/2$	1
$\cos(\Delta Mt)$	$\mathrm{Re}(f^+f^{0*})$	$\mathrm{Re}(S_3S_5^*-\bar{S}_4\bar{S}_5^*)/2$	1
$\sin(\Delta Mt)$	$\mathrm{Re}(f^+f^{0*})$	$\mathrm{Im}(q\bar{S}_4S_5^*+q^*S_3\bar{S}_5^*)/2$	$\sin(2\alpha)$
1	$\mathrm{Im}(f^+f^{0*})$	$\mathrm{Im}(S_3S_5^*+\bar{S}_4\bar{S}_5^*)/2$	1
$\cos(\Delta Mt)$	$\mathrm{Im}(f^+f^{0*})$	$\mathrm{Im}(S_3S_5^*-\bar{S}_4\bar{S}_5^*)/2$	1
$\sin(\Delta Mt)$	$\mathrm{Im}(f^+f^{0*})$	$\mathrm{Re}(q\bar{S}_4S_5^*-q^*S_3\bar{S}_5^*)/2$	$\cos(2\alpha)$
1	$\mathrm{Re}(f^-f^{0*})$	$\mathrm{Re}(S_4S_5^*+\bar{S}_3\bar{S}_5^*)/2$	1
$\cos(\Delta Mt)$	$\mathrm{Re}(f^-f^{0*})$	$\mathrm{Re}(S_4S_5^*-\bar{S}_3\bar{S}_5^*)/2$	1
$\sin(\Delta Mt)$	$\mathrm{Re}(f^-f^{0*})$	$\mathrm{Im}(q\bar{S}_3S_5^*-q^*S_4\bar{S}_5^*)$	$\sin(2\alpha)$
1	$\mathrm{Im}(f^-f^{0*})$	$\mathrm{Im}(S_4S_5^*+\bar{S}_3\bar{S}_5^*)/2$	1
$\cos(\Delta Mt)$	$\mathrm{Im}(f^-f^{0*})$	$\mathrm{Im}(S_4S_5^*-\bar{S}_3\bar{S}_5^*)/2$	1
$\sin(\Delta Mt)$	$\mathrm{Im}(f^-f^{0*})$	$\mathrm{Re}(q\bar{S}_3S_5^*-q^*S_4\bar{S}_5^*)/2$	$\cos(2\alpha)$

Note: physical observables depend on either sin(2α) or cos(2α) – never "directly" on α

f terms contain hadronic physics (lineshape, spin)

$S_3 = A(\rho^+\pi^-)$, $S_4 = A(\rho^-\pi^+)$, $S_5 = A(\rho^0\pi^0)$,

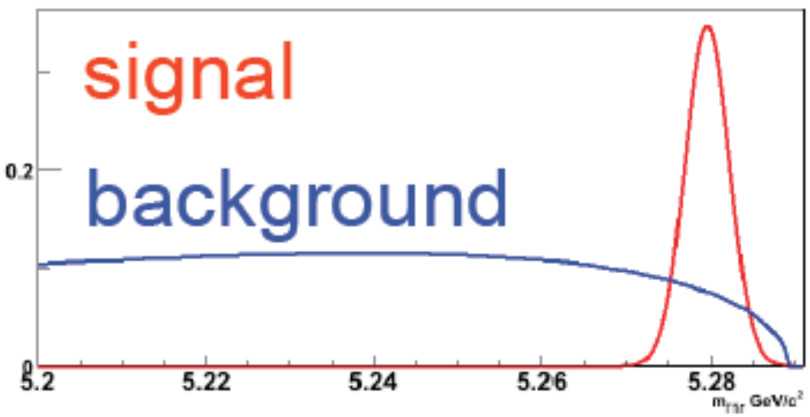
m_{ES} and ΔE

$$\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$$

$$m_{ES} = \sqrt{(\tfrac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2 / E_0^{*2} - \mathbf{p}_B^2}$$ = M_{bc} in Belle terminology!

Energy substituted mass

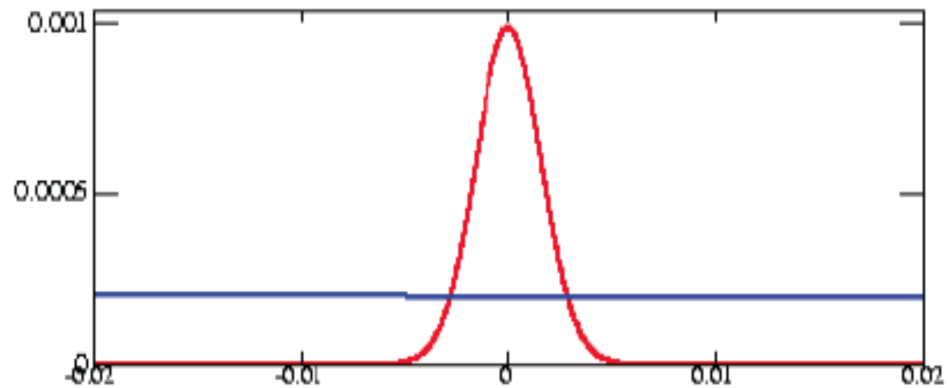
$$m_{ES} = \sqrt{E_{\mathrm{beam}}^2 - p_B^2}$$



Typical experimental resolution ~2.6 MeV/c²

Beam-energy difference

$$\Delta E = E_B - E_{\mathrm{beam}}$$



Typical experimental resolution [15-20] MeV

Overview of Joint Babar-Belle Analyses

- Allows for combined use of all **1.24 x 10^9** $B\bar{B}$ pairs collected by *both* experiments on the $\Upsilon(4S)$.
- Analyses can take advantage of this joint approach for **systematics cross-checks between datasets**, as well as for the increased statistics.
- These are not combination of two separate analyses from the two experiments; this are *single* analyses, done by one set of analysts, using both datasets, who have *full access to the relevant raw events and cross-check data from both experiments*.
- **More joint analyses coming** in the future.