Measurement of $\sin 2\beta$ and $\cos 2\beta$

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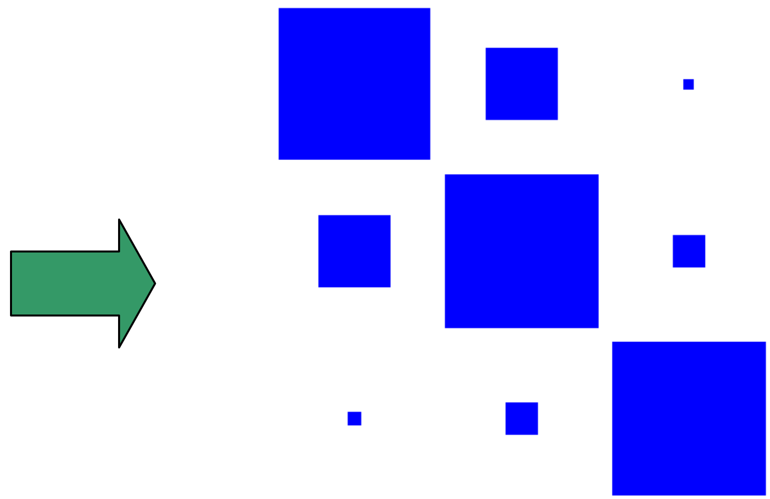
Representing the BABAR Collaboration

CP Violation in Standard Model from non-zero phase in CKM matrix

- Coupling for $Q \rightarrow W^{+} q$ is ~ V^{*}_{Qq}

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



Three generations:

4 fundamental parameters

1 phase

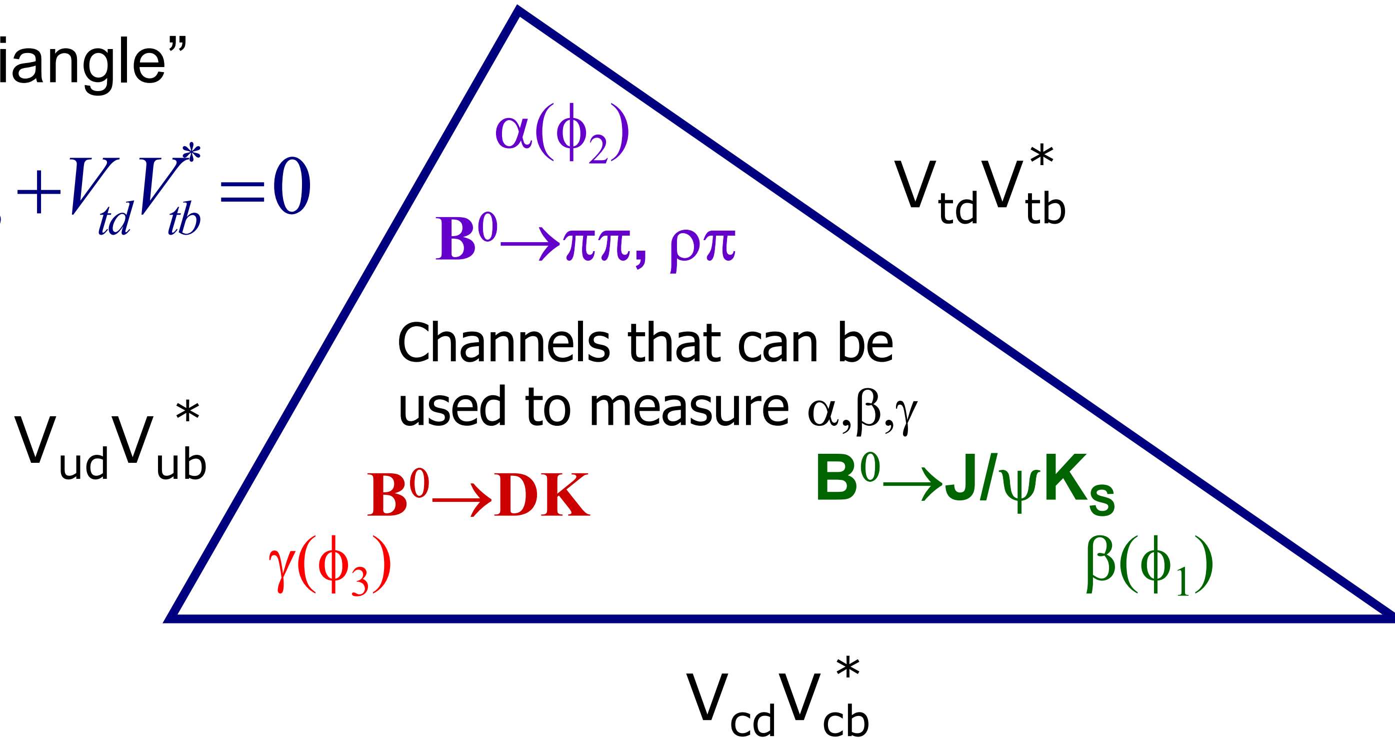
Test unitarity of matrix with B decays. Does

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

Overconstrain angles and sides of Unitarity Triangle to test the Standard Model

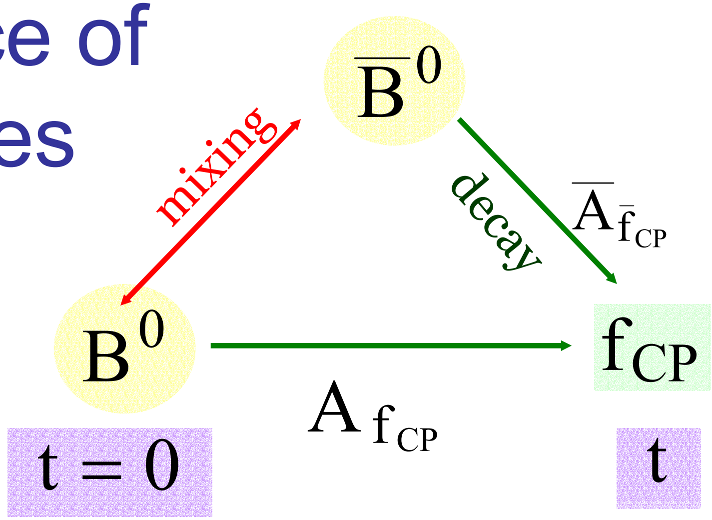
"Unitarity Triangle"

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



Measure β with "golden" modes $B \rightarrow J/\psi K^0$

CPV in $B \rightarrow J/\psi K^0$: Interference of decay and mixing amplitudes



$$\lambda = \frac{q}{p} \cdot \frac{\overline{A}}{A}$$

← Amplitude ratio

$$\lambda_{f_{CP}} \neq \pm 1 \quad \Rightarrow \quad \mathrm{Prob}(\overline{B}^0_{phys}(t) \rightarrow f_{CP}) \neq \mathrm{Prob}(B^0_{phys}(t) \rightarrow f_{CP})$$

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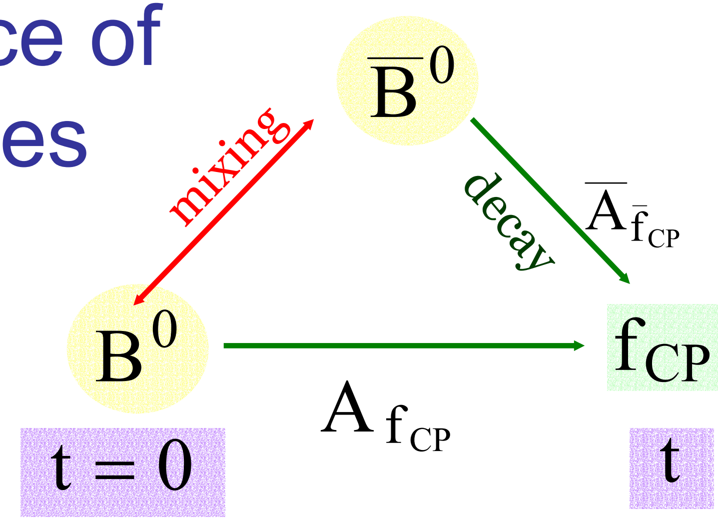


$$\lambda_{f_{CP}} \neq \pm 1 \quad \Rightarrow \quad \mathrm{Prob}(\overline{B}^0_{phys}(t) \rightarrow f_{CP}) \neq \mathrm{Prob}(B^0_{phys}(t) \rightarrow f_{CP})$$

$$A_{f_{CP}}(t) = \frac{\Gamma(\overline{B}^0_{phys}(t) \rightarrow f_{CP}) - \Gamma(B^0_{phys}(t) \rightarrow f_{CP})}{\Gamma(\overline{B}^0_{phys}(t) \rightarrow f_{CP}) + \Gamma(B^0_{phys}(t) \rightarrow f_{CP})}$$
$$= C_{f_{CP}} \cdot \cos(\Delta m_{B_d} t) + S_{f_{CP}} \cdot \sin(\Delta m_{B_d} t)$$

$(\Delta\Gamma = 0)$

$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$

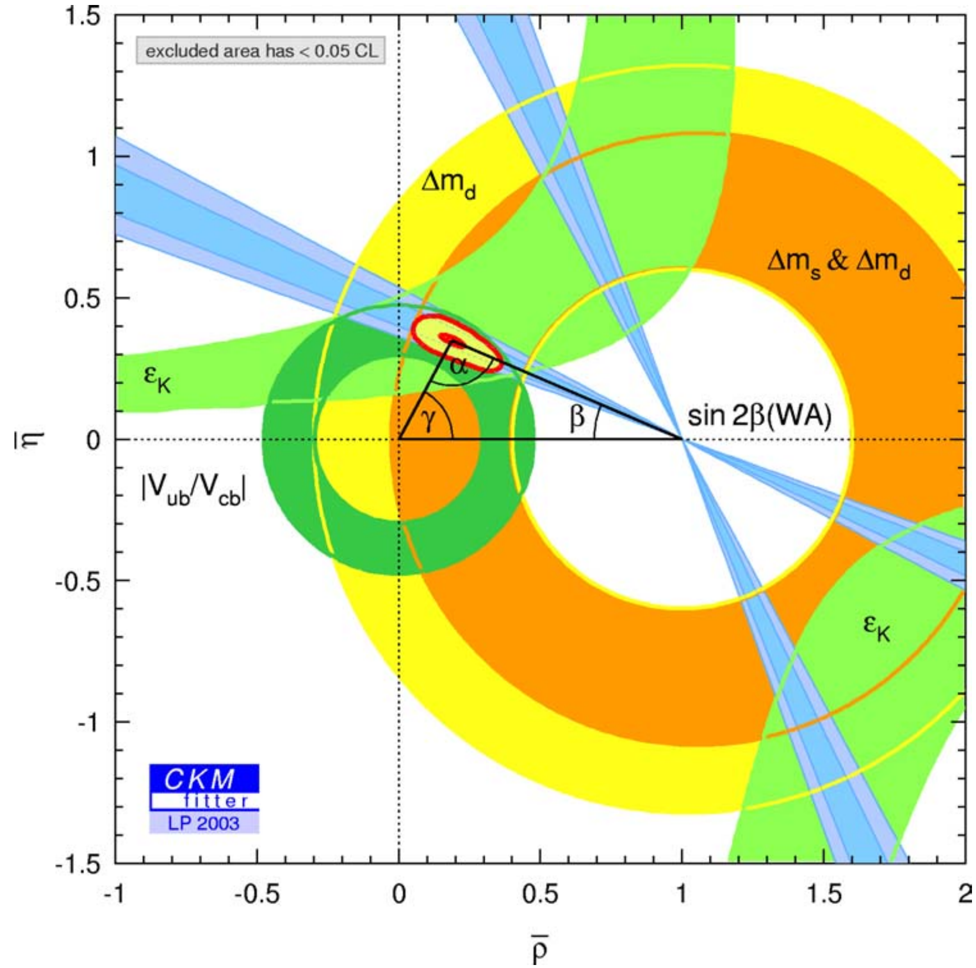
$$S_{f_{CP}} = \frac{2\,\mathrm{Im}\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}$$

C=0 and S=+/- sin2β for $B \rightarrow J/\psi K_S$ and $B \rightarrow J/\psi K_L$

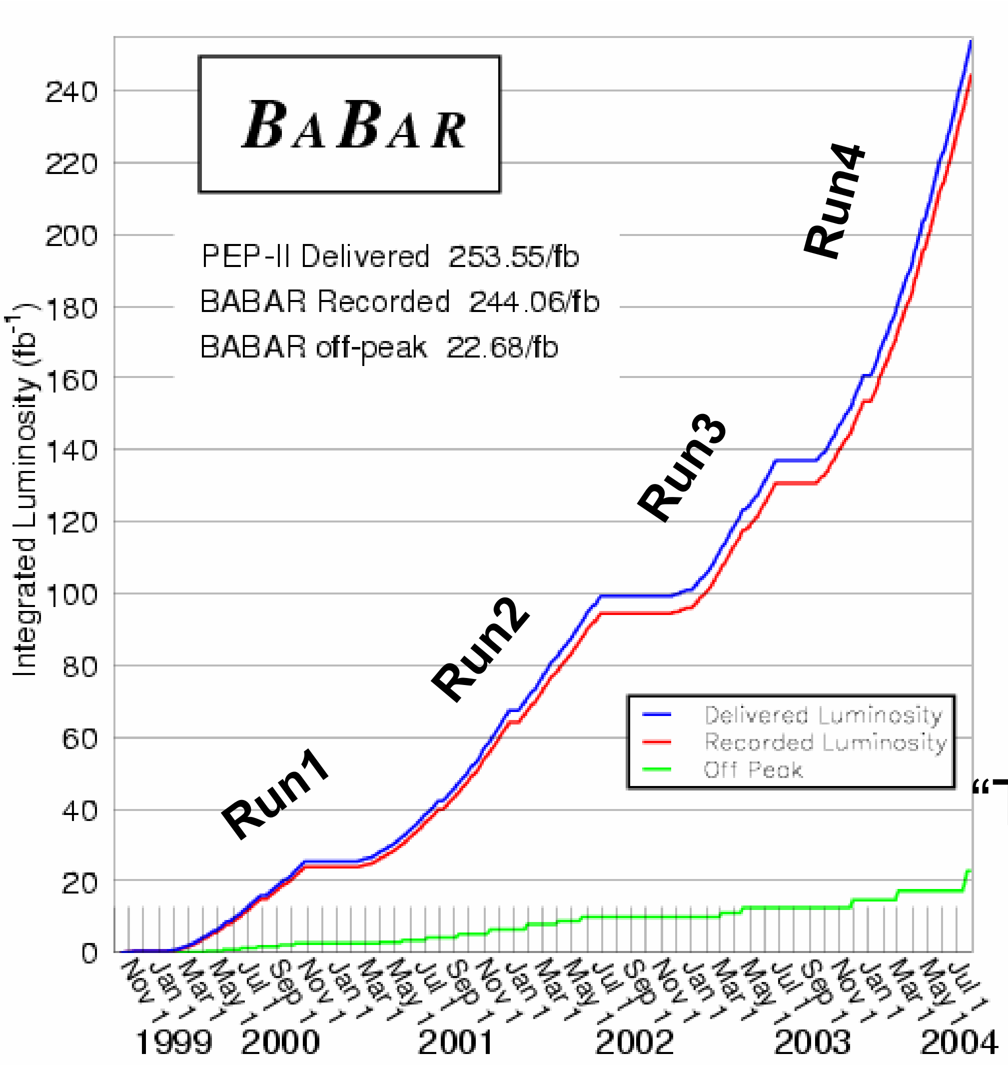
2002: BABAR and Belle experiments conclusively observe that sin2β!=0

- World average:

  0.731+/-0.056
- “Perfect” agreement between constraints of apex of the Unitarity Triangle.



BABAR has collected ~2.5x more data



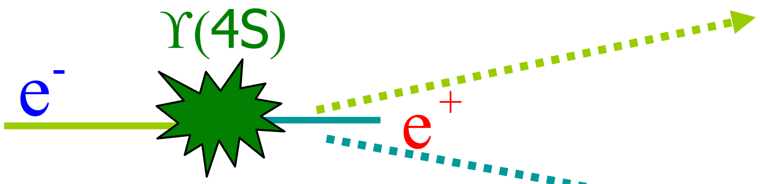
New results on full 1999-2004 sample

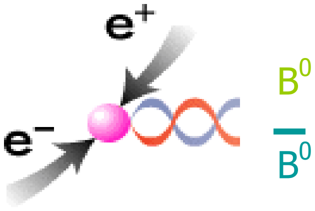
2002 results run1-2 only

"Theory" error on determination of sin2β from measurement of "S" on $J/\psi K_S$ is about +/-0.01

Experimental procedure to measure time-dependant CP Violation parameters

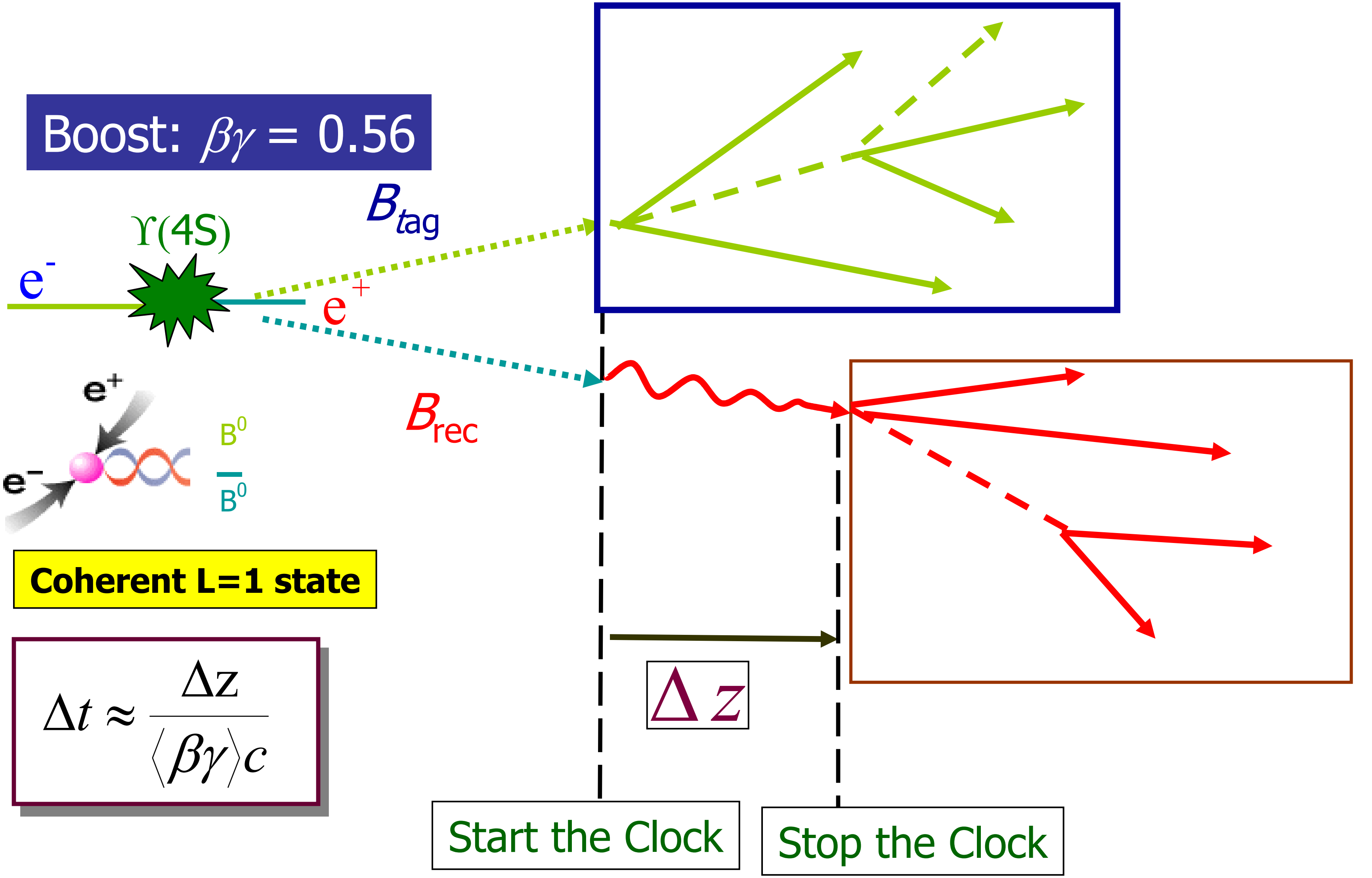
Boost: $\beta\gamma$ = 0.56





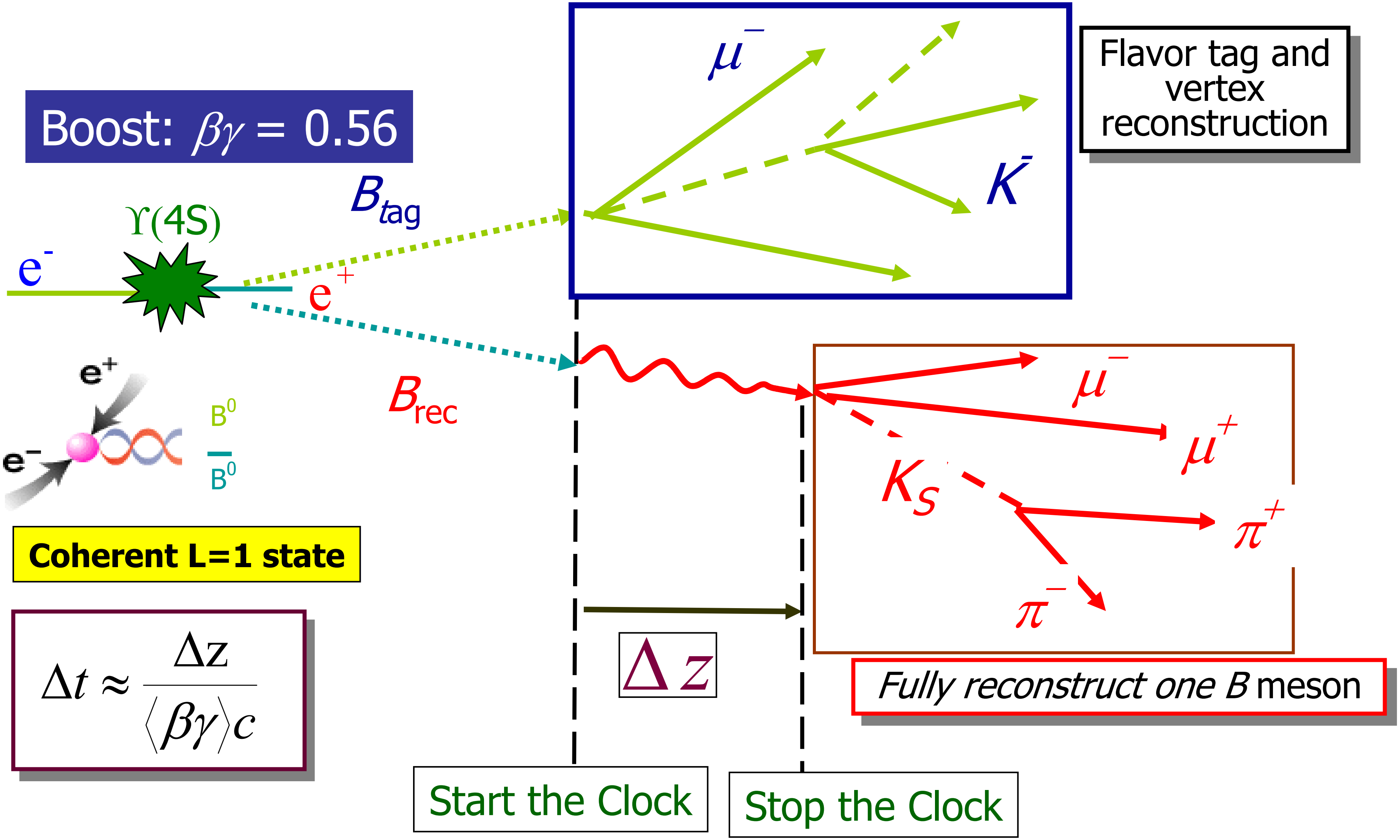
Coherent L=1 state

Experimental procedure to measure time-dependant CP Violation parameters



$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c}$$

Experimental procedure to measure time-dependant CP Violation parameters

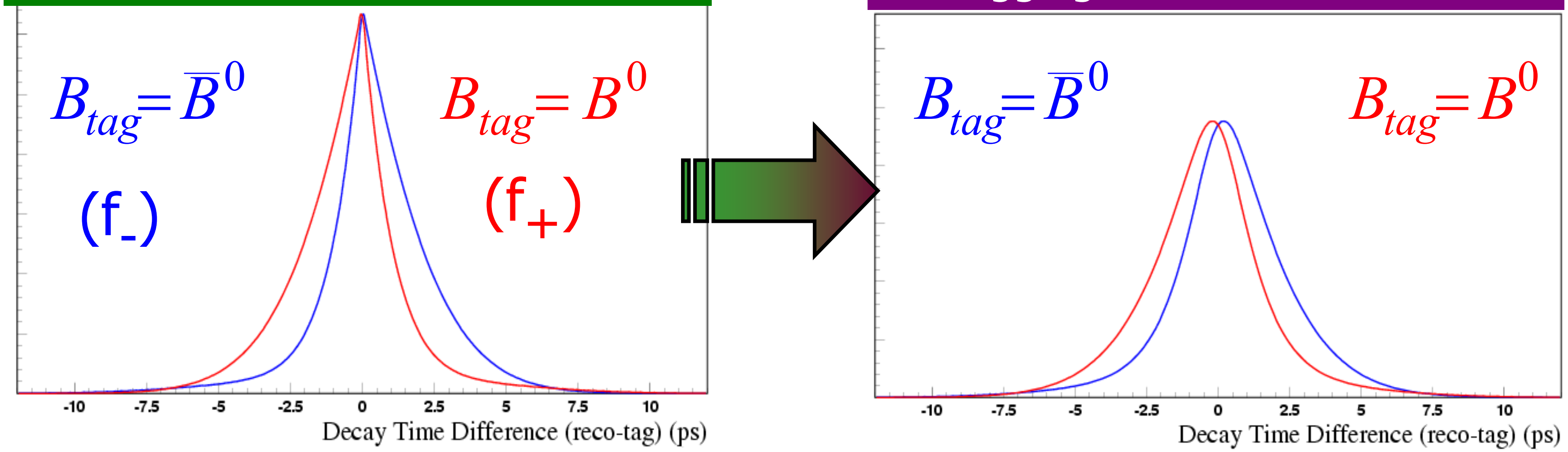


$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c}$$

Tagging and Δt resolution parameters are determined from data

perfect
tagging & time resolution

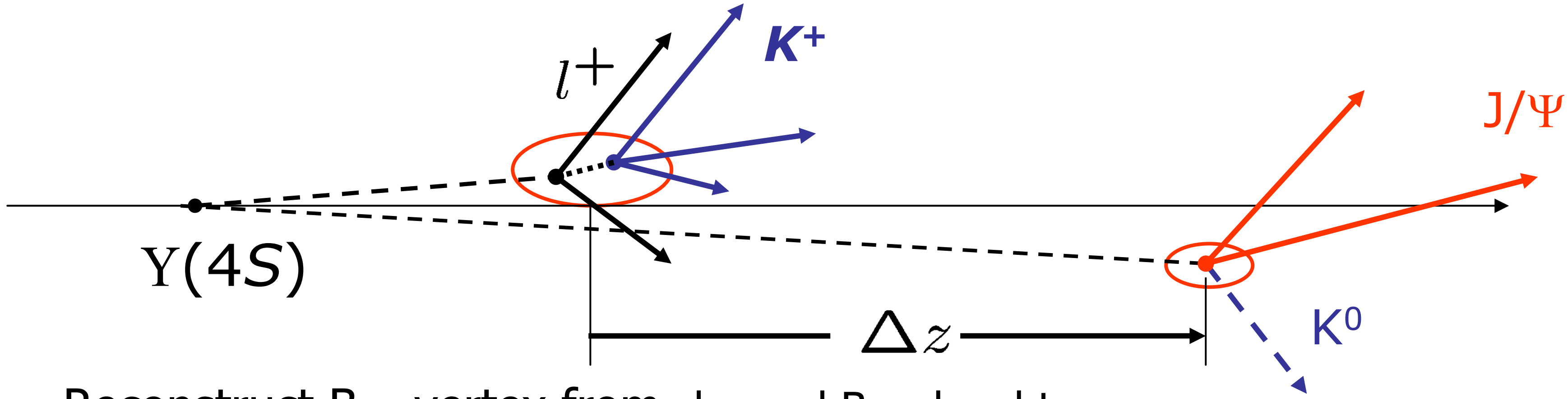
typical
mistagging & finite time resolution



$$f_{\pm} = \left[1 \mp (1-2w) S_{f_{CP}} \sin(\Delta m \Delta t)\right] \times R$$

Determine *w* and *R* parameters from more plentiful B^0-$\overline{B}^0$ decays to flavor eigenstates.

Boosted center-of-mass plus silicon vertex detector required for Δt determination



- Reconstruct B_{rec} vertex from charged B_{rec} daughters
- Determine B_{Tag} vertex from
  - All charged tracks not in B_{rec}
  - Constrain with B_{rec} vertex, beam spot, and Υ(4S) momentum
  - Remove high χ^2 tracks (to reject charm decays)
- High efficiency: 95%
- Average Δz resolution ~ 180 μm (dominated by B_{Tag})

  $<|\Delta z|>$ ~ 260 μm

  B mesons produced just above threshold: $<|\Delta z|>$ ~ 30 mm if no boost…

B decay properties used to determine if tagging B decayed as a B^0 or $\bar{B}^0$

Measure of tagging performance Q:

$$Q=\varepsilon(1-2w)^2$$

$$\sigma(\sin 2\beta) \propto \frac{1}{\sqrt{Q}}$$

	ε(%)	w(%)	Q(%)
Lepton	8.6+/-0.1	3.2+/-0.4	7.5+/-0.2
KaonI	10.9+/-0.1	4.6+/-0.5	9.0+/-0.2
KaonII	17.1+/-0.1	15.6+/-0.5	8.1+/-0.2
K-π	13.7+/-0.1	23.7+/-0.6	3.8+/-0.2
π	14.5+/-0.1	33.9+/-0.6	1.7+/-0.1
Other	10.0+/-0.1	41.1+/-0.8	0.3+/-0.1
Total	74.9+/-0.2		30.5+/-0.4

5% (relative) improvement in tagging algorithm.

Event sample for “Golden” channels

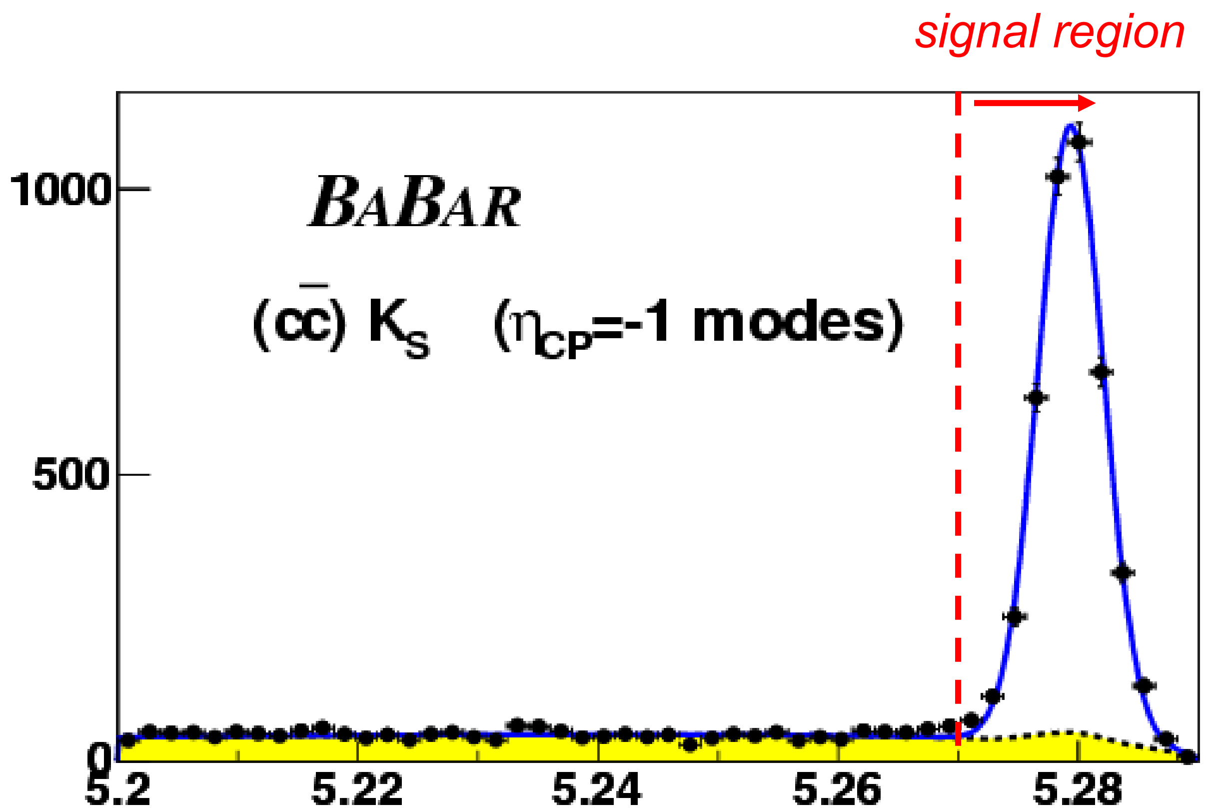
$B^0 \to J/\psi K_S\ (\pi^+\pi^-)$

$B^0 \to J/\psi K_S\ (\pi^0\pi^0)$

$B^0 \to \psi(2S) K_S$

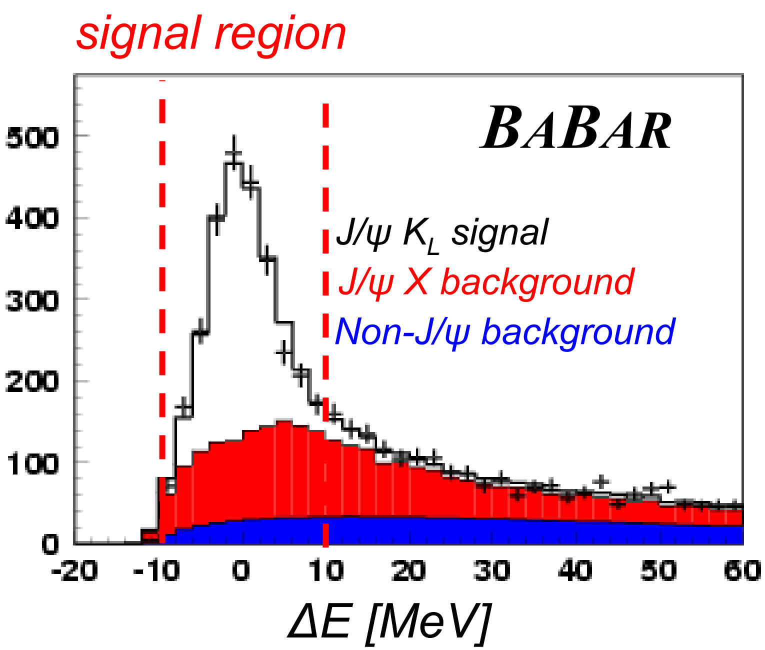
$B^0 \to \chi_{c1} K_S$

$B^0 \to \eta_c K_S$



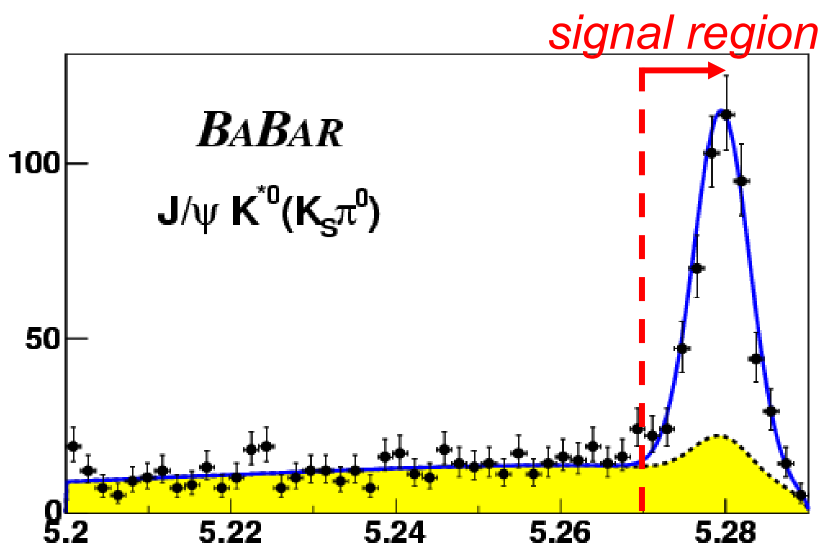
3900 $\eta_{CP} = -1$ tagged signal events

$B \rightarrow J/\psi K_L$ and $B \rightarrow J/\psi K^{*0}(K_S\pi^0)$

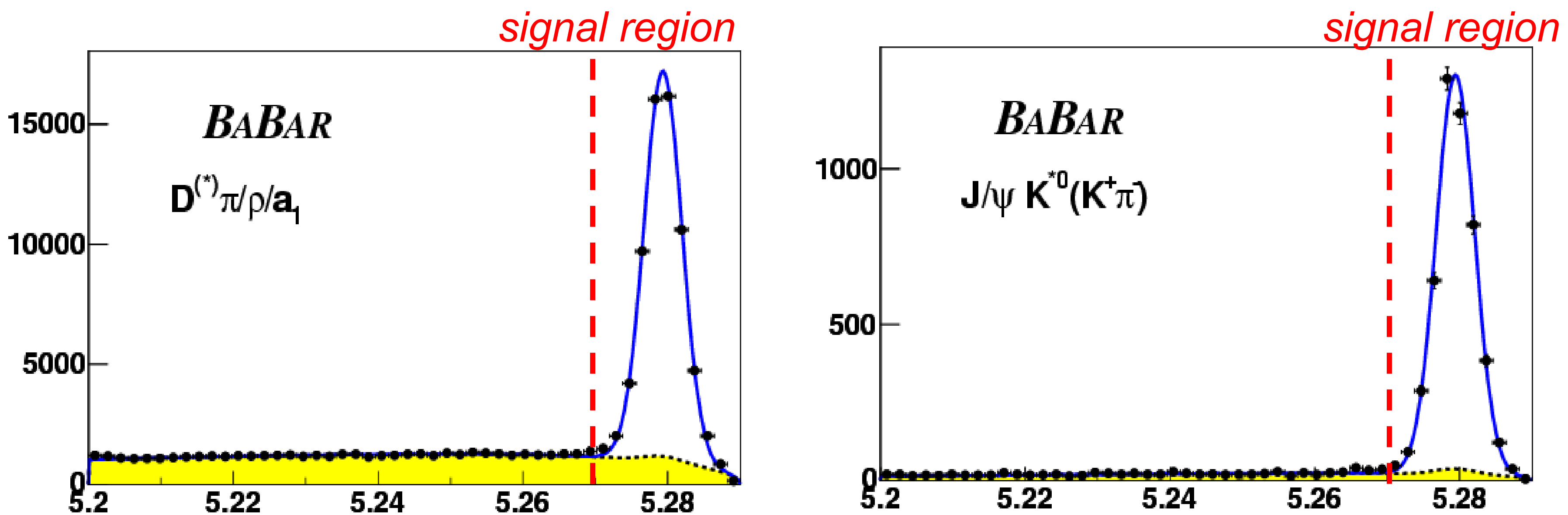


- 1600 $J/\psi K_L$ tagged signal events

- 400 $J/\psi K^{*0}$ tagged signal events

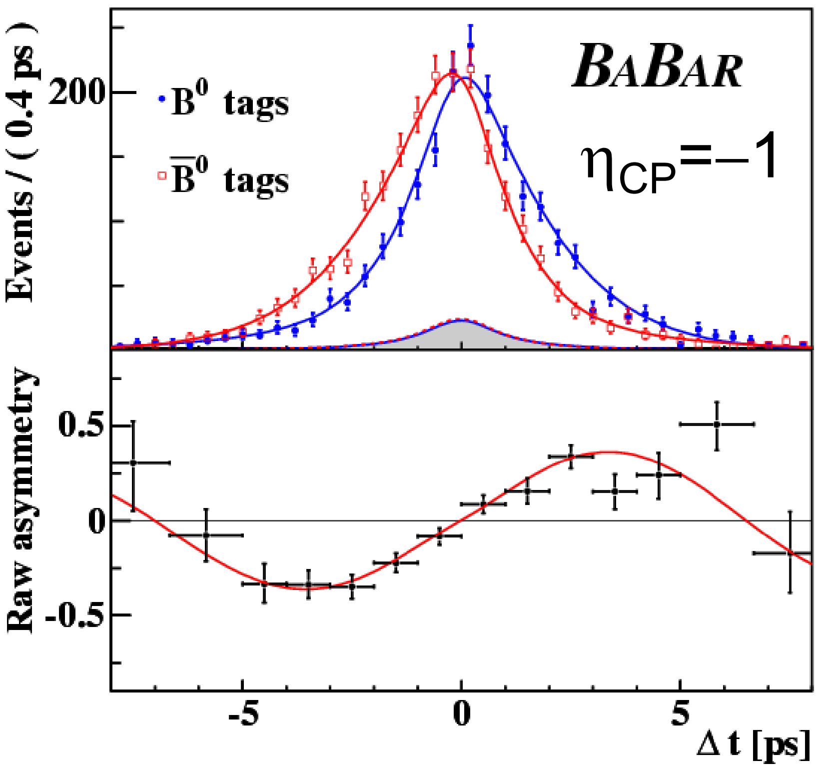


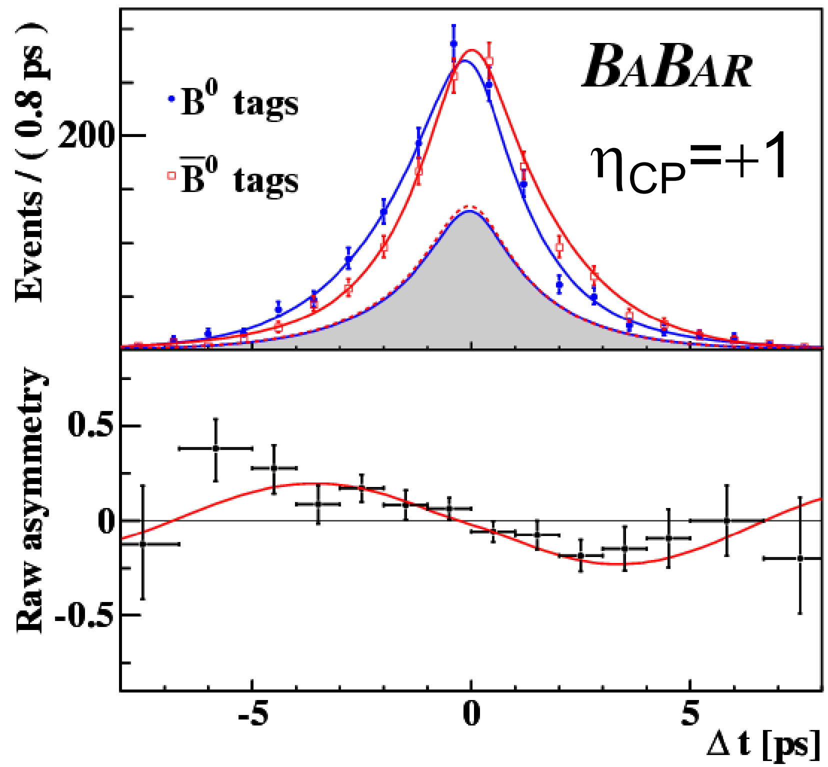
Large sample of B decays to flavor eigenstates: $B \rightarrow D^{(*)}\pi,\rho,a_1$ and $B \rightarrow J/\psi K^*$



- Resolution function parameters and dilution parameters are determined using high statistics sample with known Δt distribution.

New sin2β Results: 227 $B\bar{B}$ events





$\sin 2\beta = 0.722 \pm 0.040\ (\mathrm{stat}) \pm 0.023\ (\mathrm{sys})$

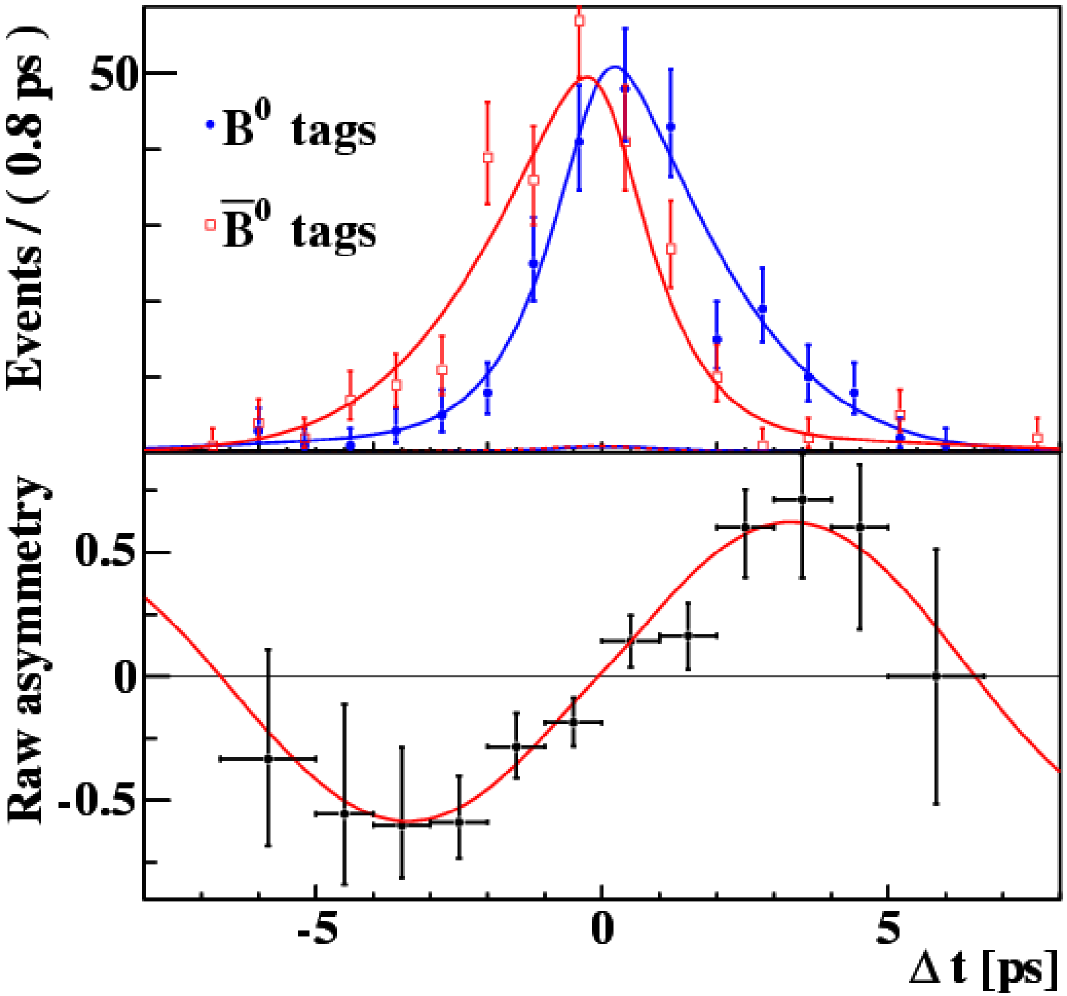
Best of the best: Lepton tagged $\eta_{CP}=-1$ events

Lower background

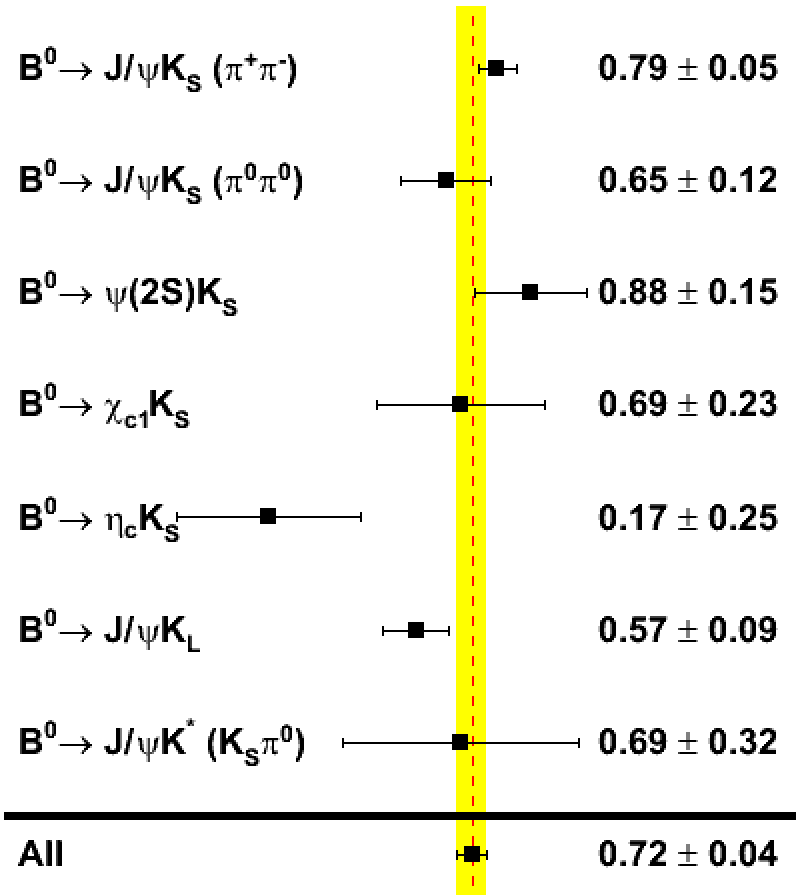
Close to perfect tagging

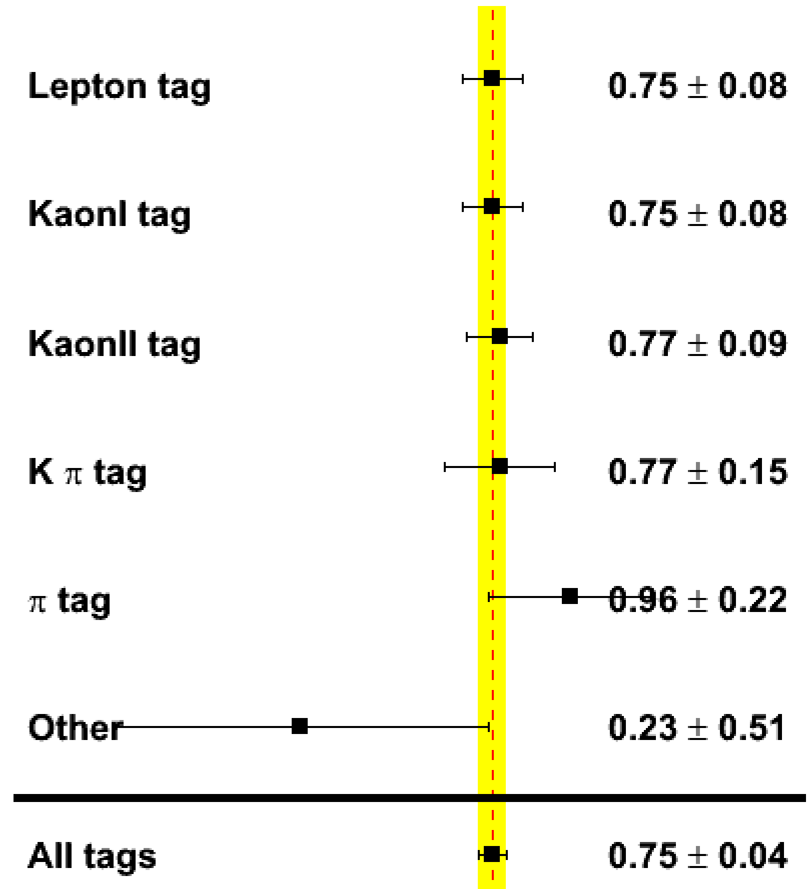
Better Δt determination

sin2β=0.75+/-0.08



Consistent results when data is split by decay mode and tagging category





X^2=11.7/6 d.o.f.
Prob (χ^2)=7%

X^2=1.9/5 d.o.f.
Prob (χ^2)=86%

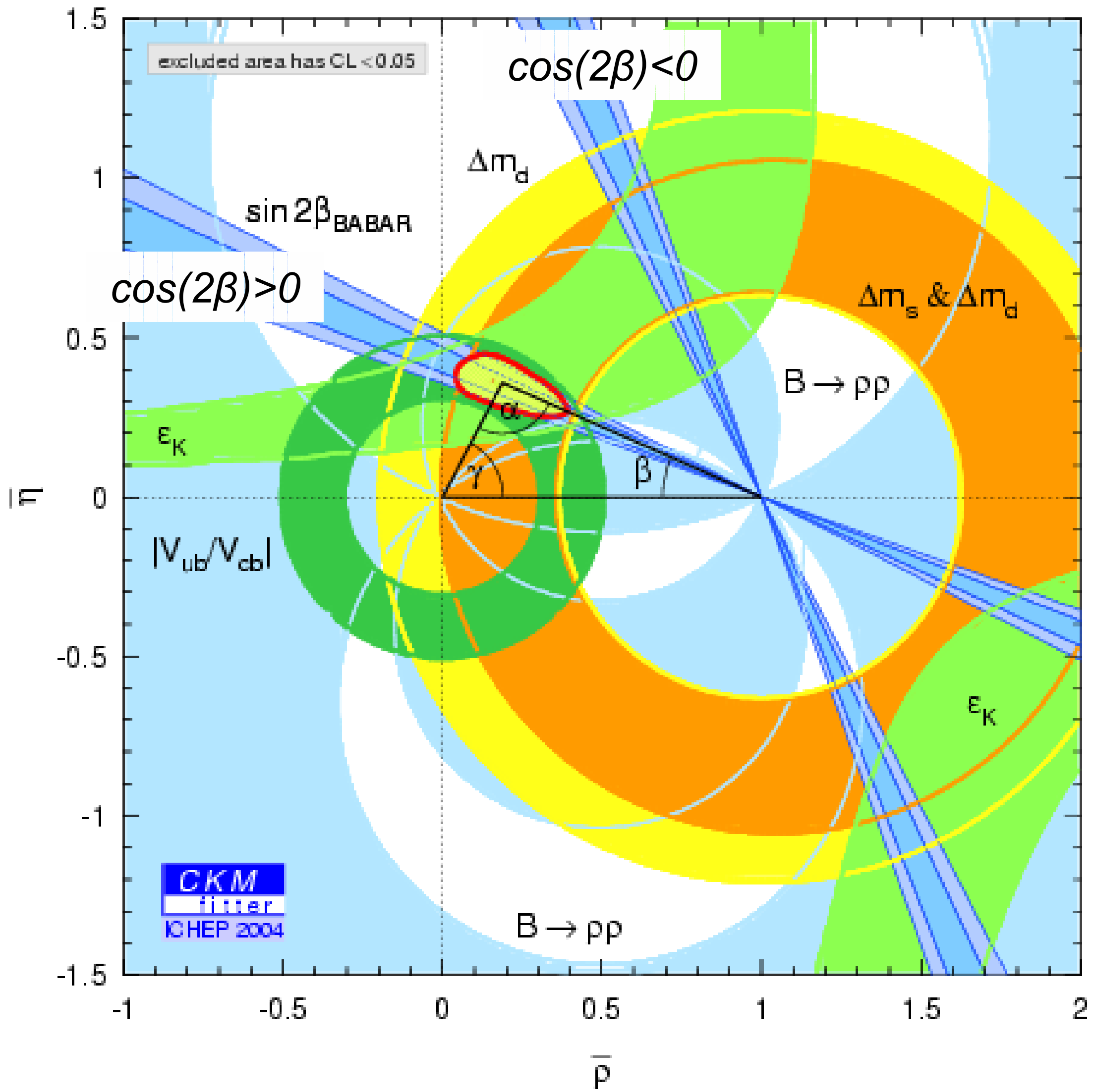
Decreasing systematic error: sin2β measurement still statistics limited.

	$\sigma(\sin 2\beta)$
Description of background events	0.012
CP content of peaking background	
Background shape uncertainties	
Mistag differences between B_{CP} and B_{flav} samples	0.007
Composition and content of $J/\psi\, K_L$ background	0.011
Δt resolution and detector effects	0.011
Silicon detector alignment uncertainty	
Δt resolution model	
Beam spot position	0.007
Fixed Δm, τ, $\Delta\Gamma/\Gamma$, $\lvert\lambda\rvert$	0.005
Tag-side interference/ DCSD decays	0.003
MC statistics/bias	0.003
TOTAL	**0.023**

Steadily reducing systematic error: July 2002 = 0.033
July 2001 = 0.05

CKM picture with new sin2β measurement

- 1 of 4 solutions for β overlays allowed region by other constraints.



B→J/ψK* channel sensitive to cos2β if angular variables are included in analysis

- CP even (L=0,2) and odd (L=1) amplitudes averaged over in nominal sin2β analysis.
- Terms proportional to cos2β also in full amplitude
  - Sign of cos2β mathematically ambiguous
    - Two-fold ambiguity in determination of strong phases

$$\pm e^{-\Gamma|\Delta t|} f_4(\vec{\omega}) |A_{\perp}||A_{\parallel}| \cos(\delta_{\perp} - \delta_{\parallel}) \cos(2\beta) \sin(\Delta m \Delta t)$$

$$\pm e^{-\Gamma|\Delta t|} f_6(\vec{\omega}) |A_{\perp}||A_{0}| \cos(\delta_{\perp} - \delta_{0}) \cos(2\beta) \sin(\Delta m \Delta t)$$

angular amplitudes

decay angles:

$$\vec{\omega} = (\cos(\theta_{K^*}), \cos(\theta_{tr}), \varphi_{tr})$$

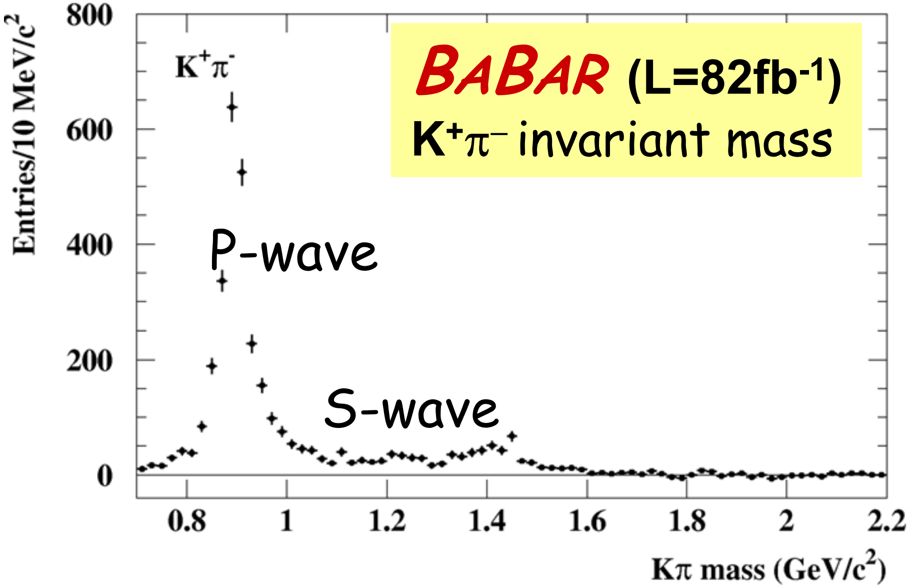
$$A_{\perp} = |A_{\perp}| e^{i\delta_{\perp}} \text{ (CP odd)}$$

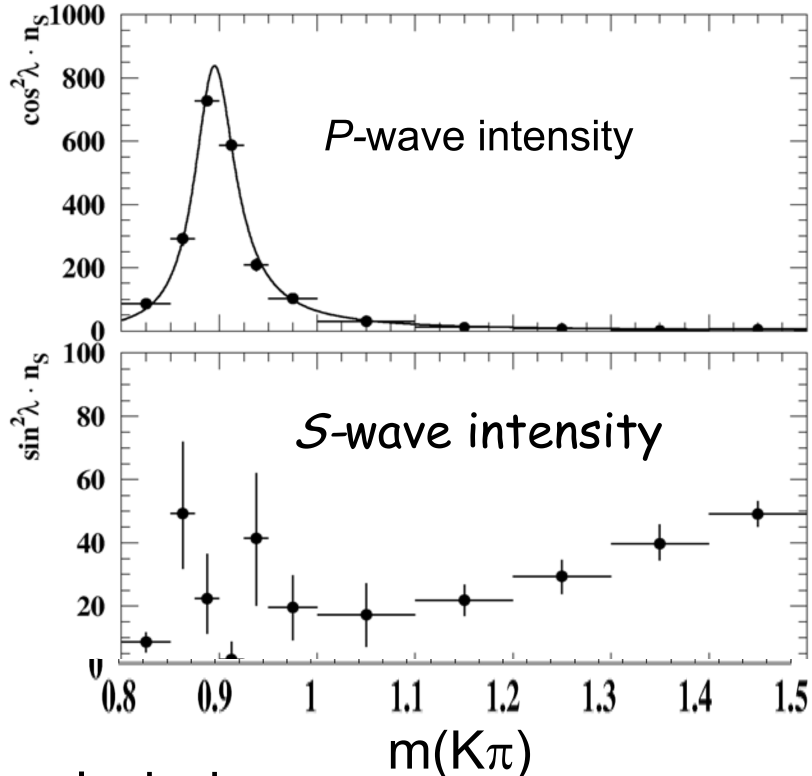
$$A_{0} = |A_{0}| e^{i\delta_{0}} \text{ (CP even)}$$

$$A_{\parallel} = |A_{\parallel}| e^{i\delta_{\parallel}} \text{ (CP even)}$$

angular amplitudes in transversity basis

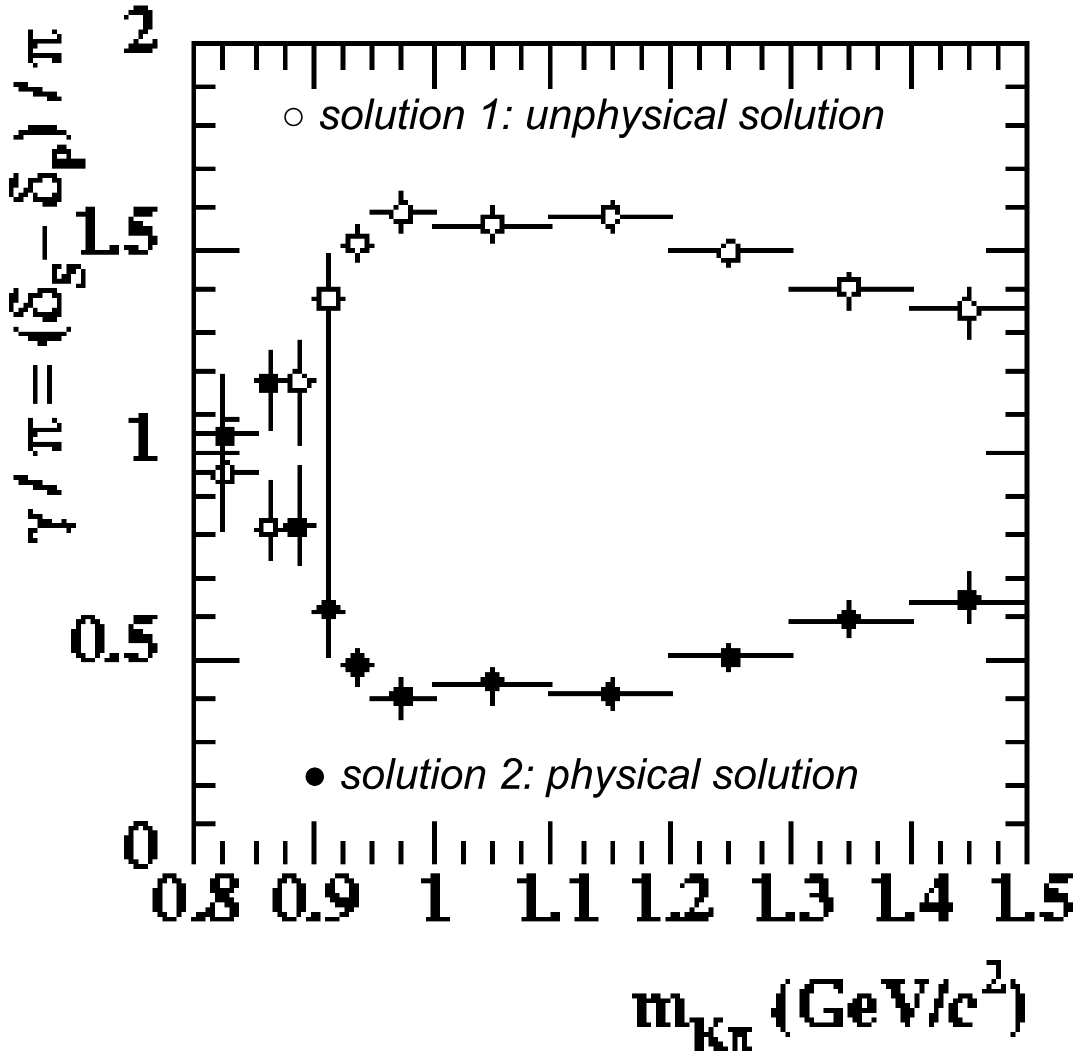
Ambiguity solved via S-wave – P-wave interference





- Wigner causality:
  - Resonance phase rotates counter-clockwise
  - P-wave moves "fast", S-wave moves "slow"
- Look at interference term in amplitude analysis
  - δ_S-δ_P vs. m(Kπ) : Which solution is physical?

Clear solution to strong phase ambiguity



"solution 1"

$$\delta_{\parallel} - \delta_0 = 2.729 \pm 0.0101 \pm 0.052$$

$$\delta_{\perp} - \delta_0 = 0.184 \pm 0.070 \pm 0.046$$

Preliminary

"solution 2"

$$\delta_{\parallel} - \delta_0 = -2.729 \pm 0.0101 \pm 0.052$$

$$\delta_{\perp} - \delta_0 = 2.958 \pm 0.070 \pm 0.046$$

$$|A_0|^2 = 0.566 \pm 0.012 \pm 0.005$$

$$|A_{\parallel}|^2 = 0.204 \pm 0.015 \pm 0.005$$

$$|A_{\perp}|^2 = 0.230 \pm 0.015 \pm 0.004$$

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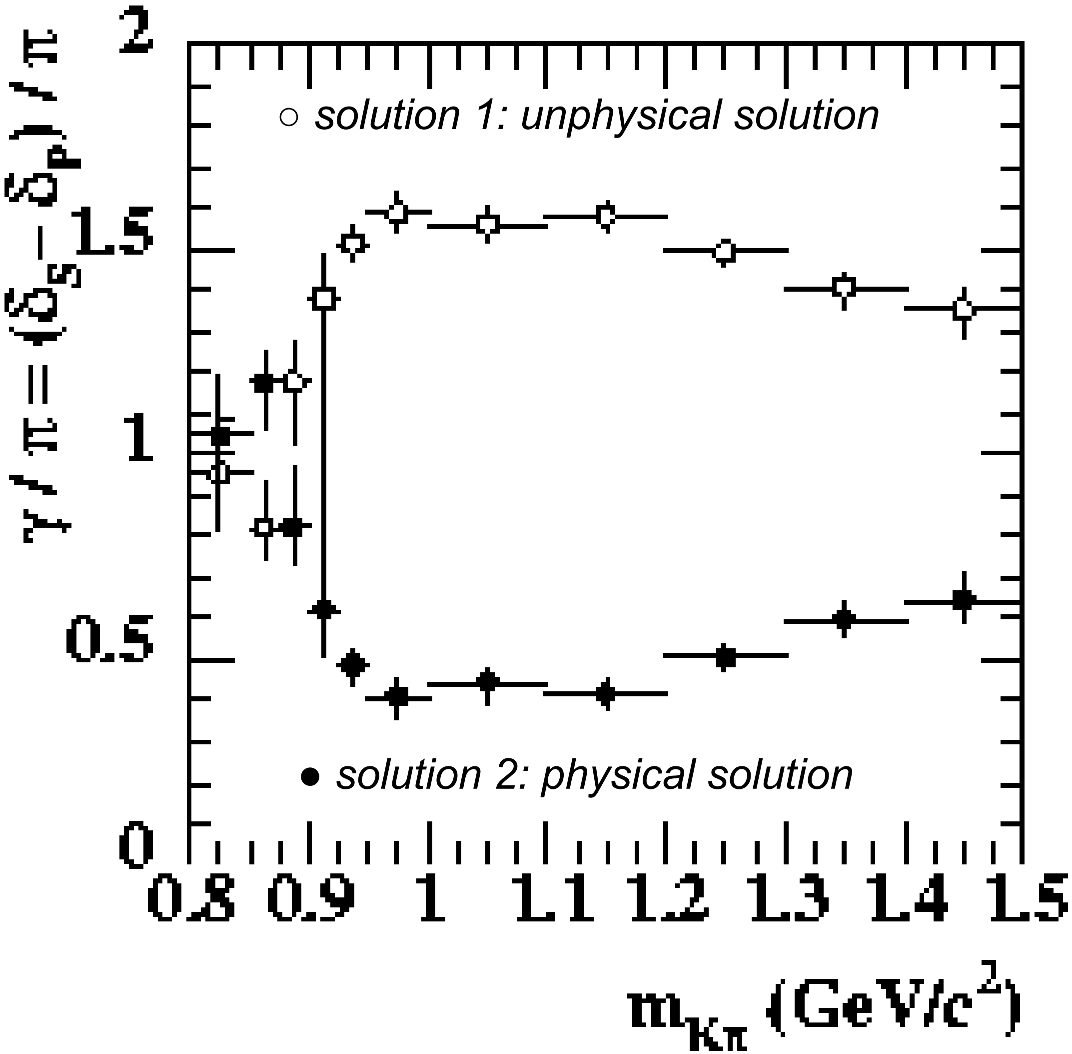

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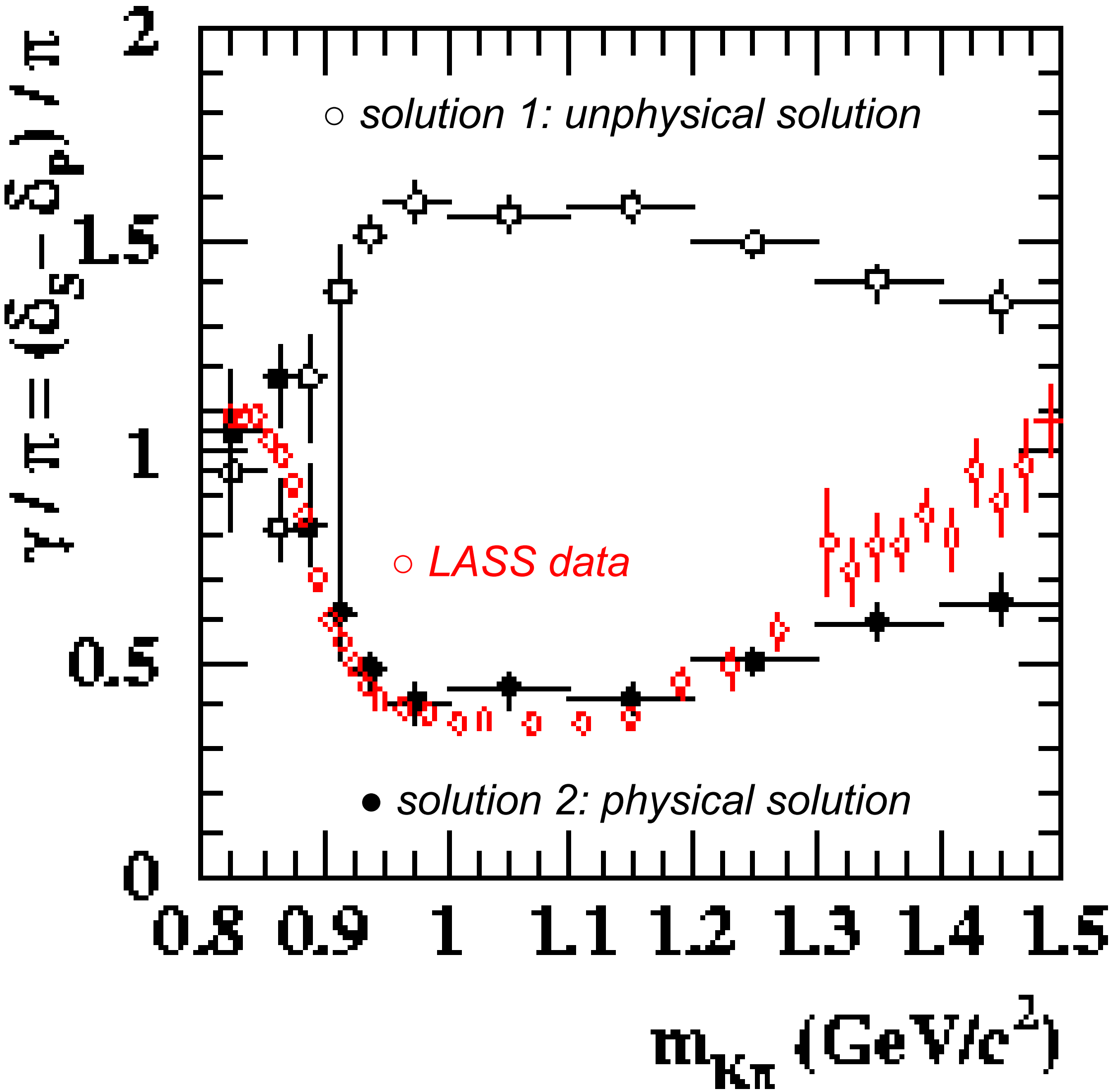
Comparison with LASS Kπ scattering data



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Measure cos2β with angular and time dependent analysis

- Current results on 88 million BB events.
  - 104 tagged signal events.

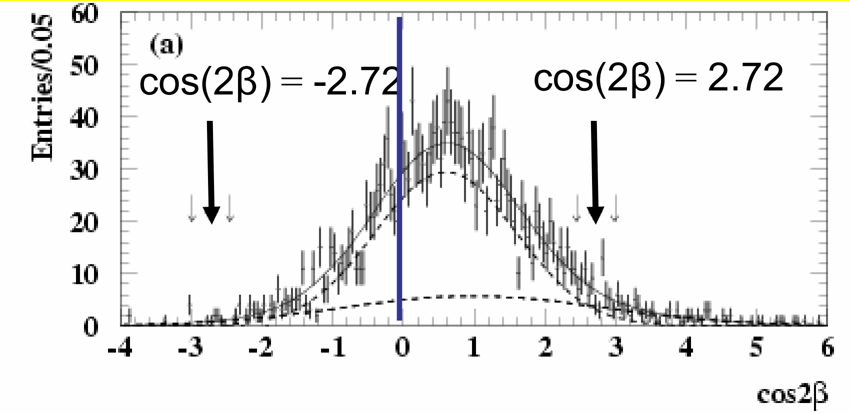
Preliminary

$$\cos(2\beta) = 2.72^{+0.50}_{-0.79}(stat.) \pm 0.27(syst.)$$

(with sin(2β) fixed to 0.731)

$$\cos(2\beta) = -\sqrt{1-\sin^2(2\beta)} = -0.68 \quad \text{excluded at 86.6\% CL}$$

Distribution of cos(2β) results from data-sized Monte Carlo samples, generated with cos(2β)=0.68



Standard Model sign of cos(2β) favored by our data.

Conclusion

- Updated measurement of sin2β with B→J/ψK^0 decays using full BABAR data sample

$$\sin 2\beta = 0.722 \pm 0.040\ (\text{stat}) \pm 0.023\ (\text{syst})$$

- Novel method to break strong phase ambiguity in measurement of cos2β in B→J/ψK* decays

$$\cos(2\beta) = 2.72^{+0.50}_{-0.79}(stat.) \pm 0.27(syst.)$$

- cos2β=-0.68 excluded at 86.6% level. More data to be included in this analysis.