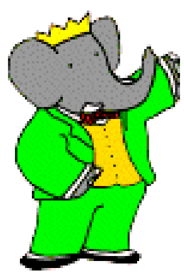
$\begin{bmatrix} u \end{bmatrix} \begin{bmatrix} c \\ s \end{bmatrix} \begin{bmatrix} b \end{bmatrix}$ *High Energy Physics*

Measurement of sin2β using B^0 Decays into a Charmonium State and a K^0 at BaBar

Stephen Levy, UCSB

APS / DPF

April 5, 2003



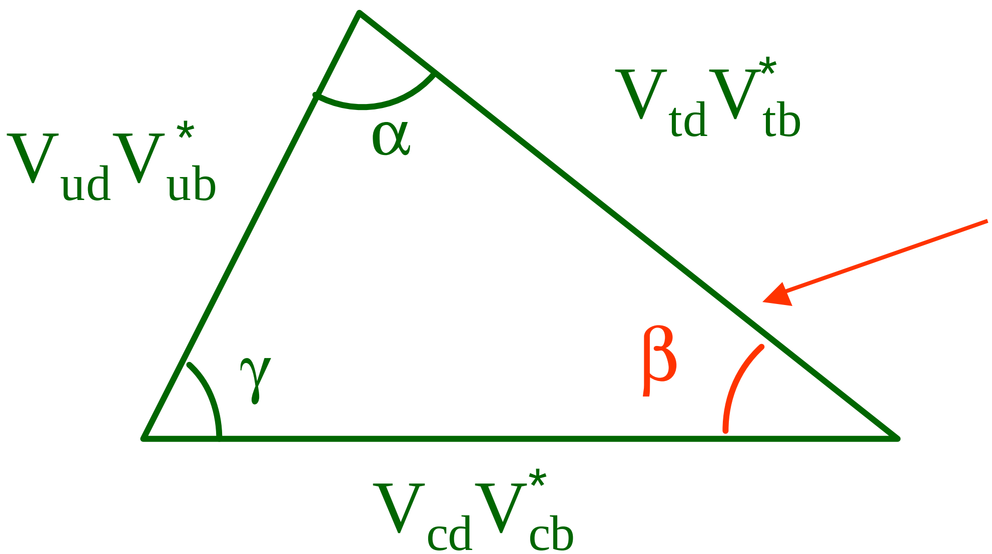
Origin of CP violation

Irreducible phase of CKM matrix only SM source of CP violation

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Unitarity constraint of CKM Matrix

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



Measure sin2β in

$B^0 \rightarrow J/\psi\ K_{S,L}, K^{*0}$

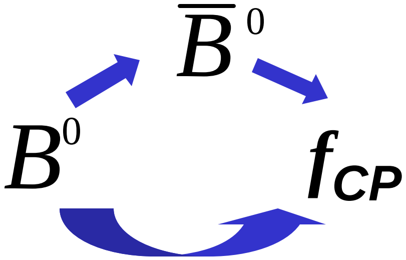
$B^0 \rightarrow \chi_c\ K_S$

$B^0 \rightarrow \eta_c\ K_S$

$B^0 \rightarrow D^*D^{(*)}$

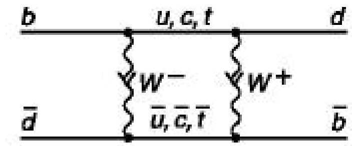
$B^0 \rightarrow \Phi\ K_s$

CP violation due to mixing and decay



$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle$$

$$l_f = \frac{q}{p}\frac{A(\overline{B}^0 \to f_{CP})}{A(B^0 \to f_{CP})}$$



$$\frac{q}{p} \sim \frac{V_{td}}{V_{td}^*}$$

$$\Delta m_d = m_H - m_L$$

$$f(B^0_{phys} \to f_{CP}, t) = \tfrac{\Gamma}{4} e^{-\Gamma|\Delta t|}\,[1 + C_f \cos(\Delta m_d t) - S_f \sin(\Delta m_d t)]$$

$$f(\overline{B}^0_{phys} \to f_{CP}, t) = \tfrac{\Gamma}{4} e^{-\Gamma|\Delta t|}\,[1 - C_f \cos(\Delta m_d t) + S_f \sin(\Delta m_d t)]$$

$$C_f = \frac{1 - |?_{f_{CP}}|^2}{1 + |?_{f_{CP}}|^2}$$

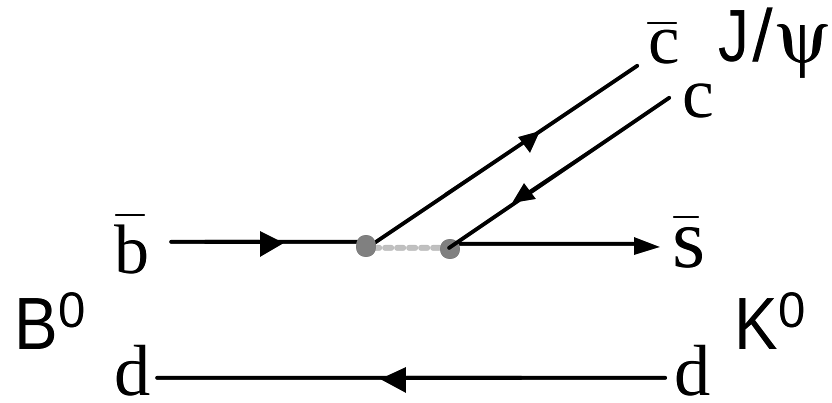
Probe of direct CP violation: $|?_{f_{CP}}| \neq 1$

$$S_f = \frac{2\,\mathrm{Im}\,?_{f_{CP}}}{1 + |?_{f_{CP}}|^2}$$

Sensitive to phase of λ even without direct CP Violation

CP asymmetry in $B^0 \to (c\bar{c})K^0$

- Theoretically clean
  - Tree level dominates
  - Phase only from mixing
- Relatively large branching fractions
- Clear experimental signatures



$$l_{CP} = \frac{q}{p}\frac{A(\overline{B}^0 \to f_{CP})}{A(B^0 \to f_{CP})} \Rightarrow \lambda_{CP} = h_{CP}\, e^{-i2b}, \quad h_{CP} = \pm 1$$

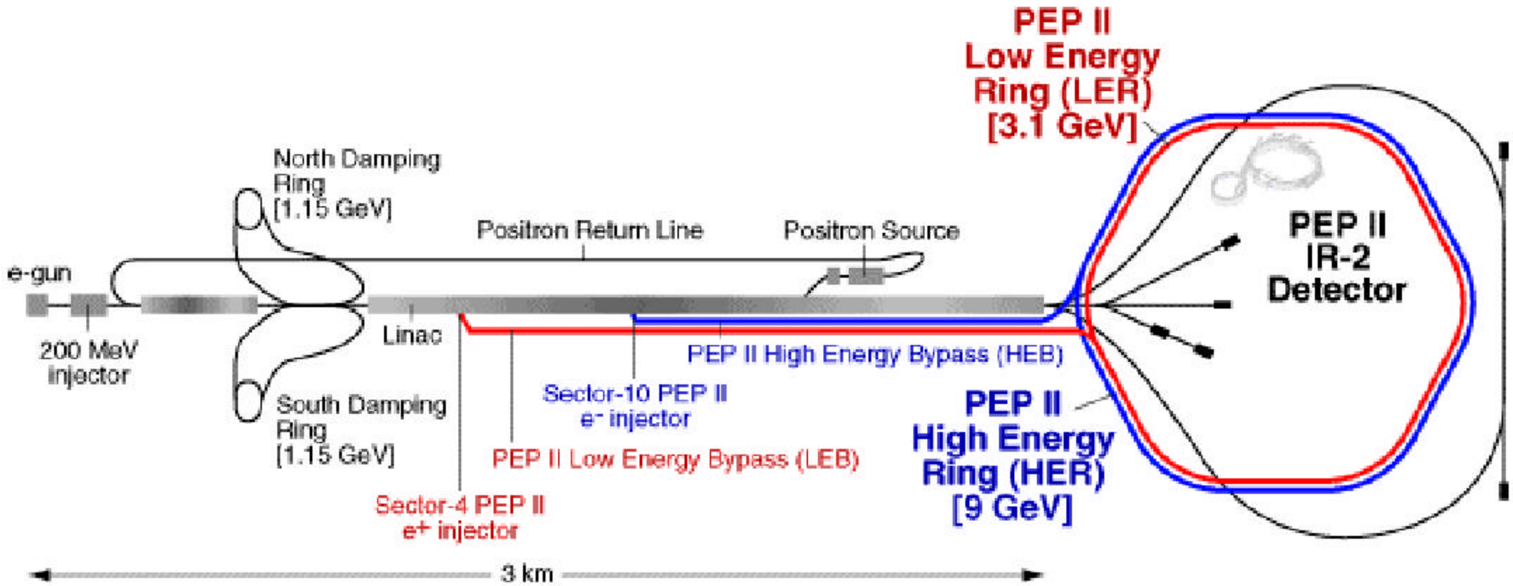
$$|\lambda_{CP}| = 1$$

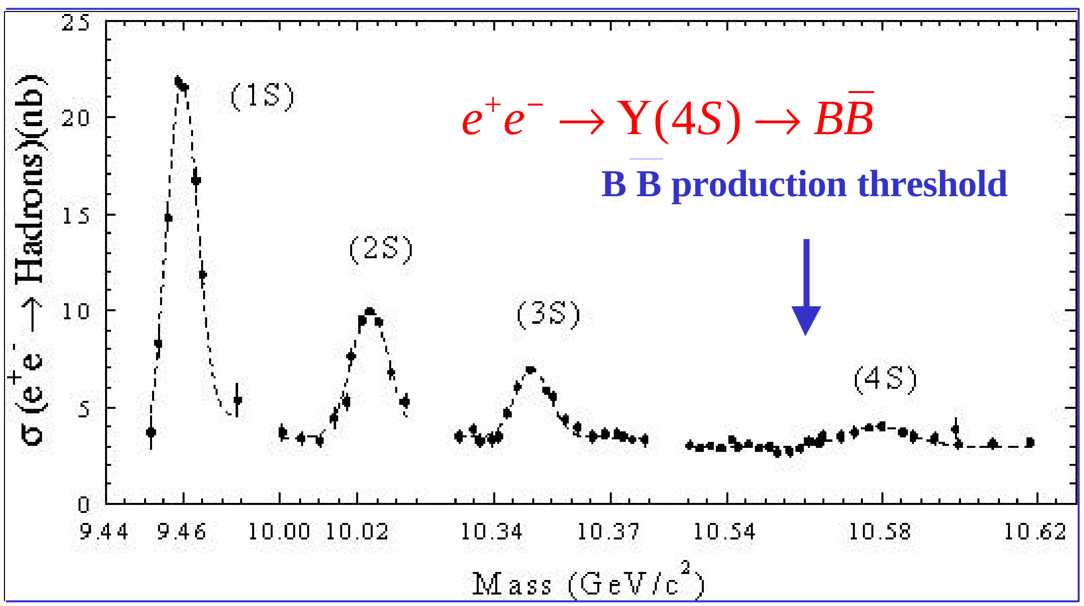
Holds to <1% in SM

$$A_{CP}(t) = \frac{f_+ - f_-}{f_+ + f_-} = -h_{CP} \sin 2b \sin(\Delta m_d t)$$

- $\eta_{CP} = -1$
  $B^0 \to J/\psi, \psi(2S), \chi_{c1}, \eta_c, K^0_S$
- $\eta_{CP} = +1$
  $B^0 \to J/\psi\ K^0_L$

PEP-II Asymmetric B-Factory





- 9 GeV e^- on 3.1 GeV e^+
- Υ(4S) boosted in lab frame

$$\beta\gamma = 0.55$$

Outstanding PEP-II performance

PEP-II has been a huge success!

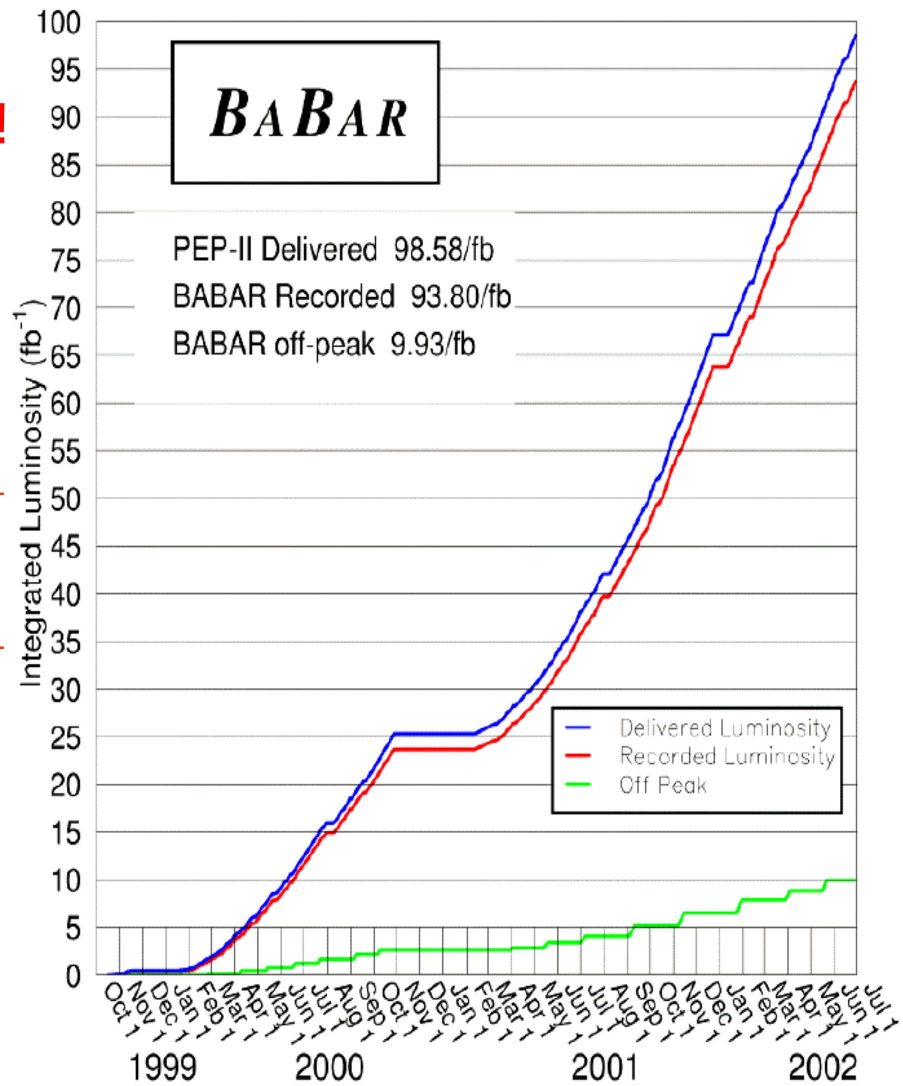
PEP-II top luminosity:
 $5.2 \times 10^{33} cm^{-2}s^{-1}$
 (design 3.0×10^{33})

Top recorded Lumi/week: $1.84\ fb^{-1}$

Top recorded Lumi/24h: $347\ pb^{-1}$

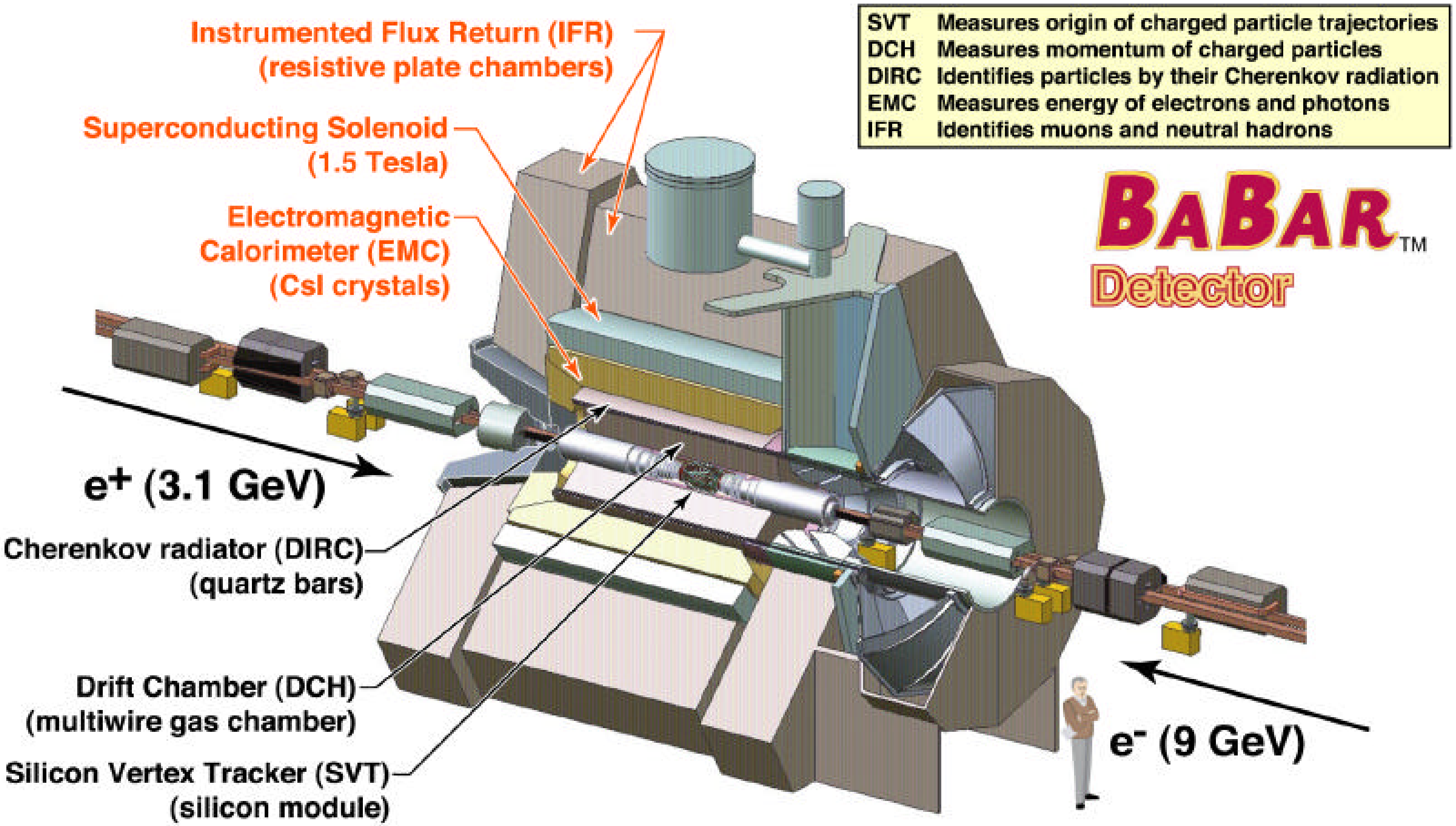
Top recorded Lumi/8h: $118\ pb^{-1}$

BaBar efficiency > 95%



Analysis sample
On peak: $81\ fb^{-1}$ (88 Million $B\bar{B}$)
Off peak: $10\ fb^{-1}$

BABAR Detector



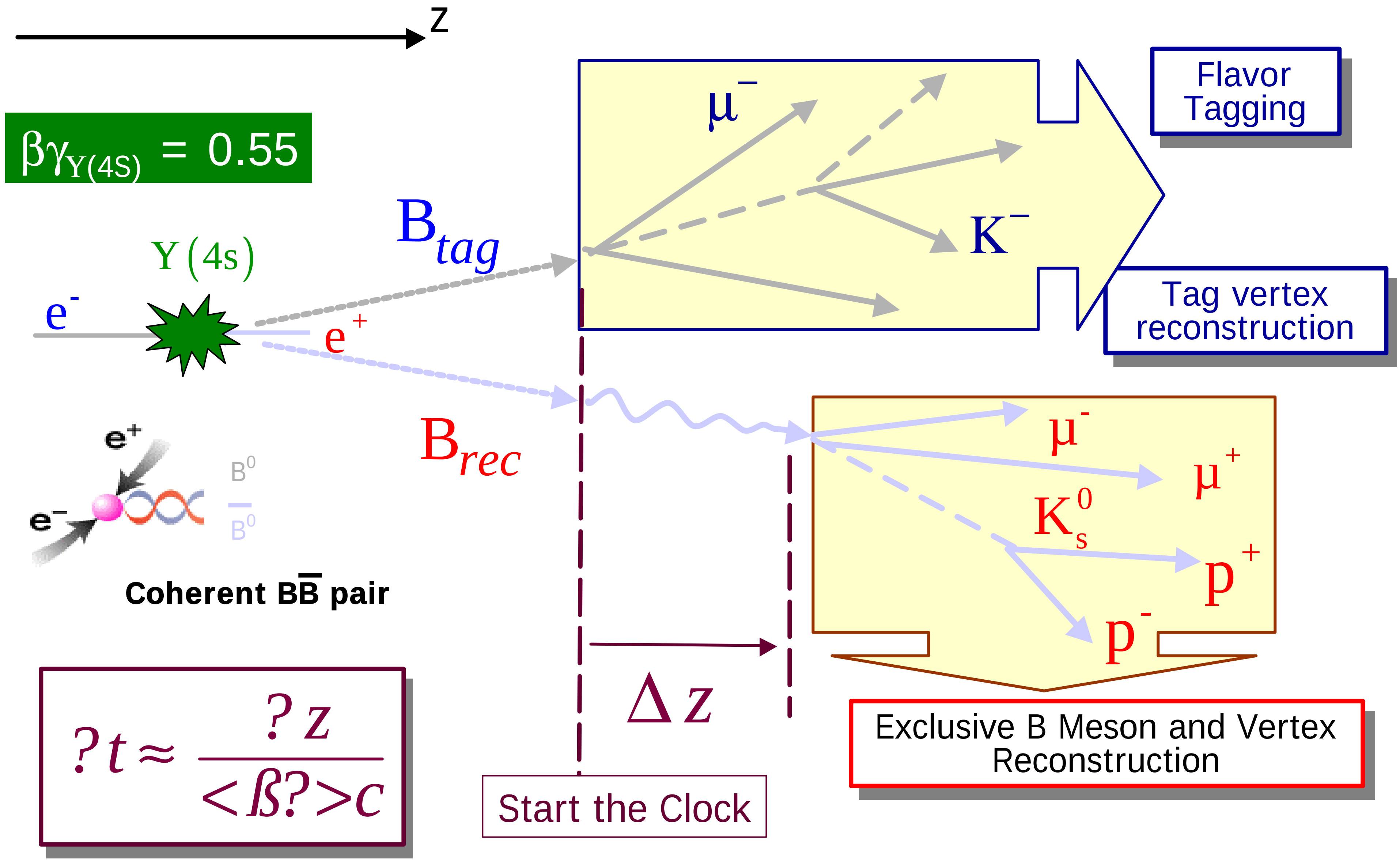
SVT: 97% efficiency, 15 μm z hit resolution (inner layers, perp. tracks)

SVT+DCH: $\sigma(p_T)/p_T = 0.13\,\% \times p_T \oplus 0.45\,\%$

DIRC: K-π separation 4.2 σ @ 3.0 GeV/c → 2.5 σ @ 4.0 GeV/c

EMC: $\sigma_E/E = 2.3\,\%\cdot E^{-1/4} \oplus 1.9\,\%$

Event topology



Ingredients for time-dependent sin2β analysis

Reconstruction of neutral B mesons in flavor eigenstates

Reconstruction of neutral B mesons in CP eigenstates

Δz vertex reconstruction

Flavor tagging

⇩

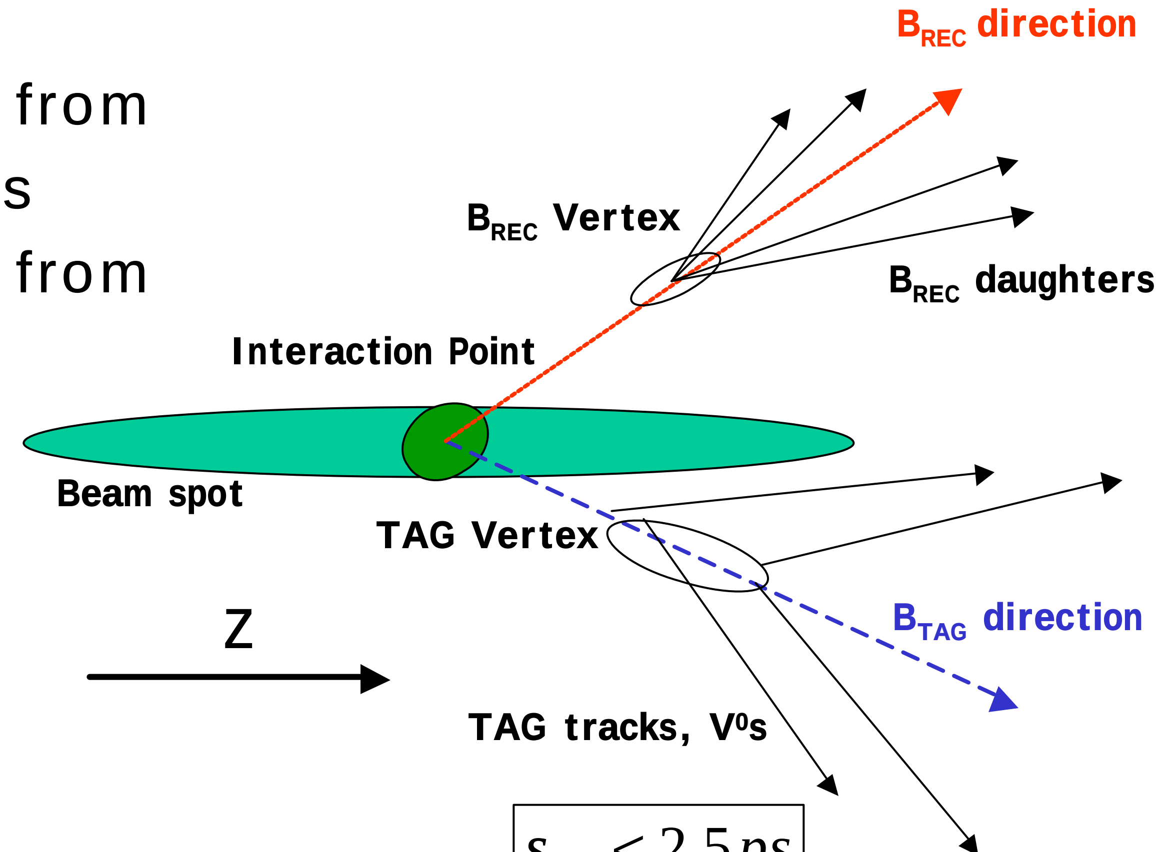
Maximum likelihood fit

⇩

CP Asymmety

Vertex and Δz Reconstruction

- Determine B_{rec} vertex from B_{rec} charged daughters
- Determine B_{tag} vertex from
  - Charged tracks not belonging to B_{rec}
  - B_{rec} vertex and momentum
  - Beam spot and Y(4S) momentum



$$s_{\Delta t} < 2.5\,ps$$
$$|\Delta t| < 20\,ps$$

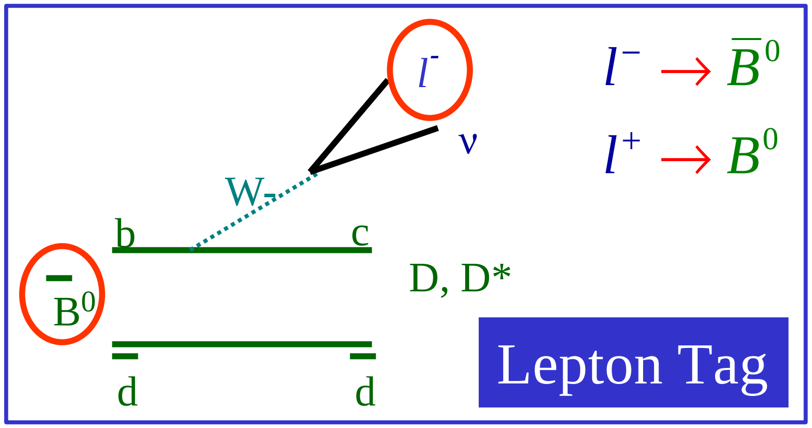
- 95% of events pass vtx requirements

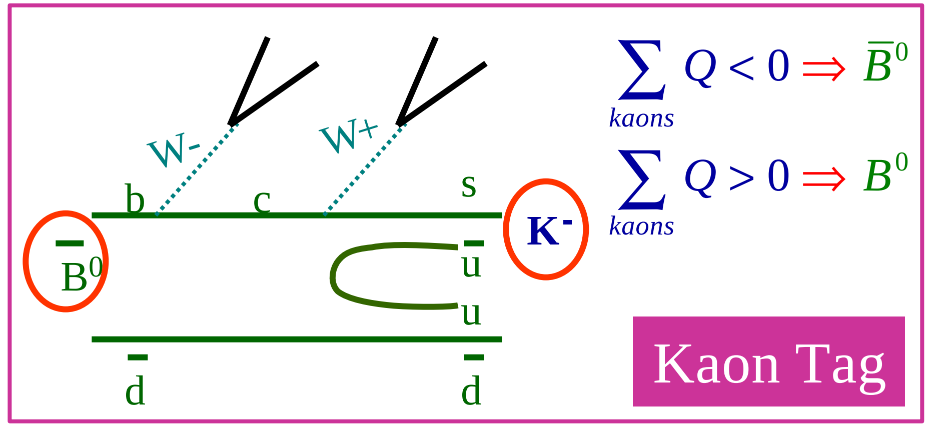
- Average Δz resolution 180 μm

  $<|\Delta z|> \sim \beta\gamma c\tau = 260\ \mu m$

Flavor tagging

For electrons, muons and Kaons use the charge correlation



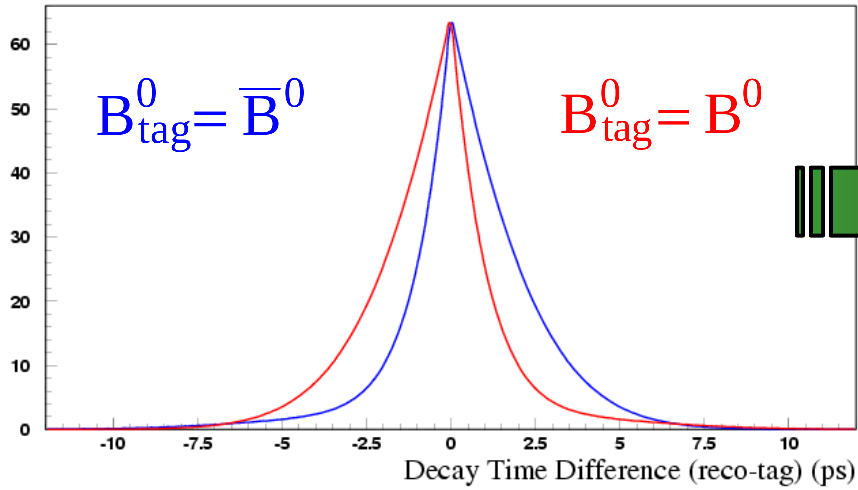


Multilevel neural network assigns each event to one of five mutually exclusive tagging categories

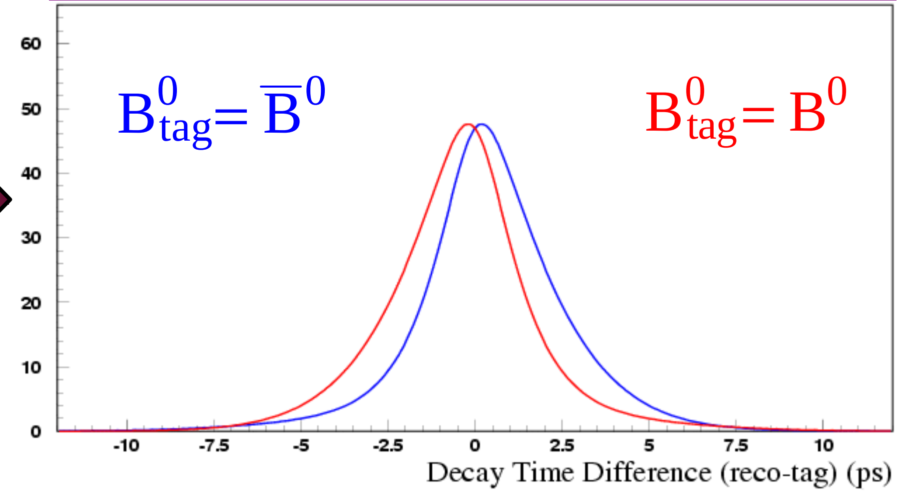
Each category is characterized by the probability of giving the wrong tag answer (mistag fraction *w*)

Δt Spectrum of CP Events

perfect
flavor tagging & time resolution



realistic
mis-tagging & finite time resolution



Mistag fractions w
and
resolution function R

determined by
flavor sample

CP PDF

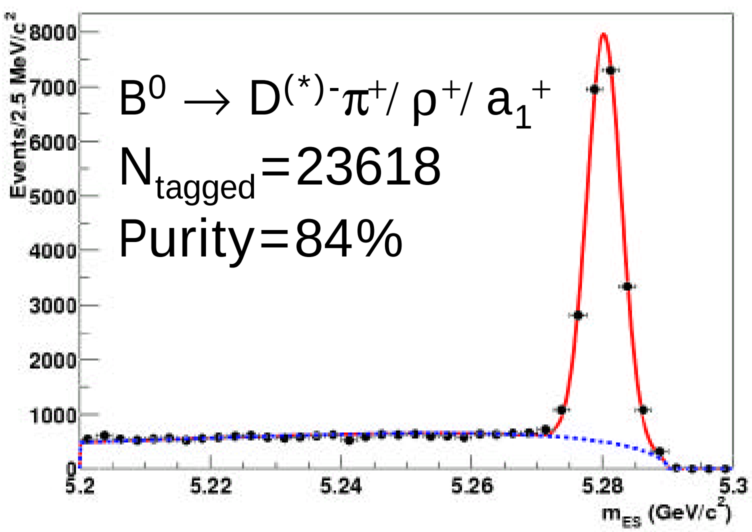
$$f_{B^0/\overline{B}^0}(\Delta t) = \left[\frac{e^{-|\Delta t|/\tau_{B_d}}}{4\tau_{B_d}} \times \left(1 \mp \eta_f (1-2w) \sin 2\beta \sin(\Delta m_d \Delta t) \right) \right] \otimes R$$

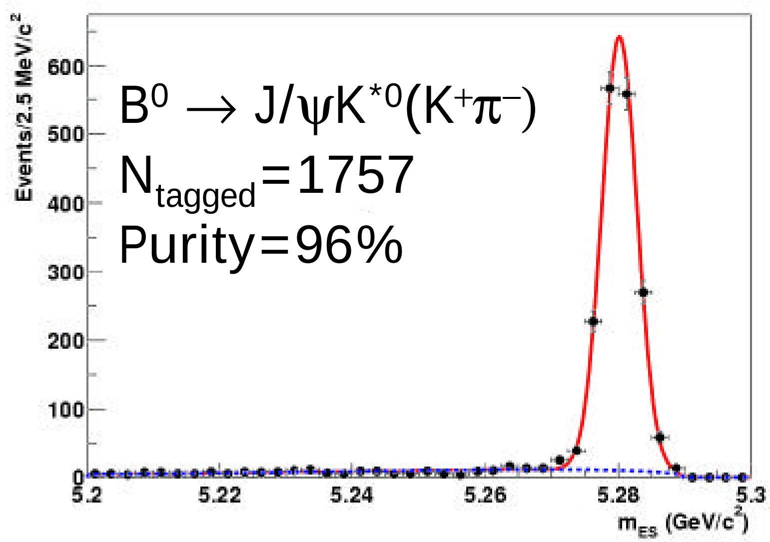
Mixing PDF

$$f_{mixing,\pm}(\Delta t) = \left[\frac{e^{-|\Delta t|/\tau_{B_d}}}{4\tau_{B_d}} \times \left(1 \pm (1-2w) \cos(\Delta m_d \Delta t) \right) \right] \otimes R$$

Use B_{flav} sample to measure *w* and *R*

- Fully reconstruct self-tagged modes: $m_{ES} = \sqrt{(E^{cm}_{beam})^2 - (p^{cm}_B)^2}$





- Apply B_{tag} to other side:

$$f_{\substack{\text{Unmixed}\\\text{Mixed}}}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/t_B}}{4t_B}\left[1 \pm (1-2w)\cos(\Delta m_d \Delta t)\right] \right\} \otimes R$$

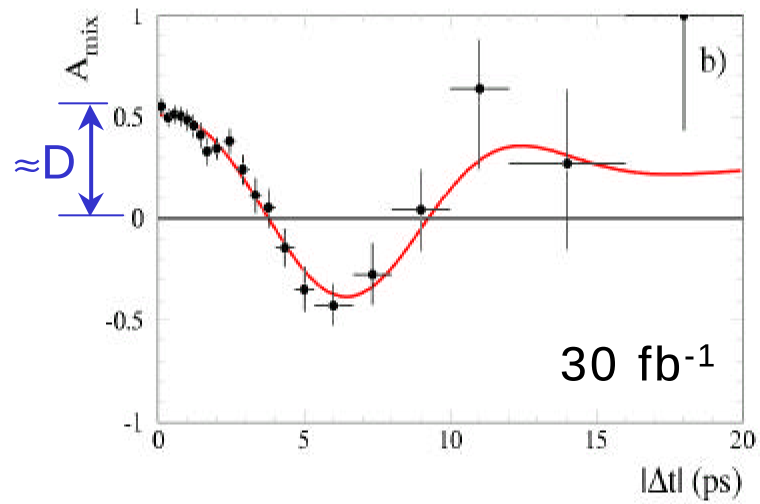
B_{flav} sample is x10 size of CP sample

Fit results: flavor tag Dilutions

Mixing fit with B^0 flav sample (30 fb^{-1})

Δm_d = 0.516 ± 0.016 ± 0.010 ps^{-1}.

- Lepton tag has lowest mistag rate
- Kaon1 tag contributes most.

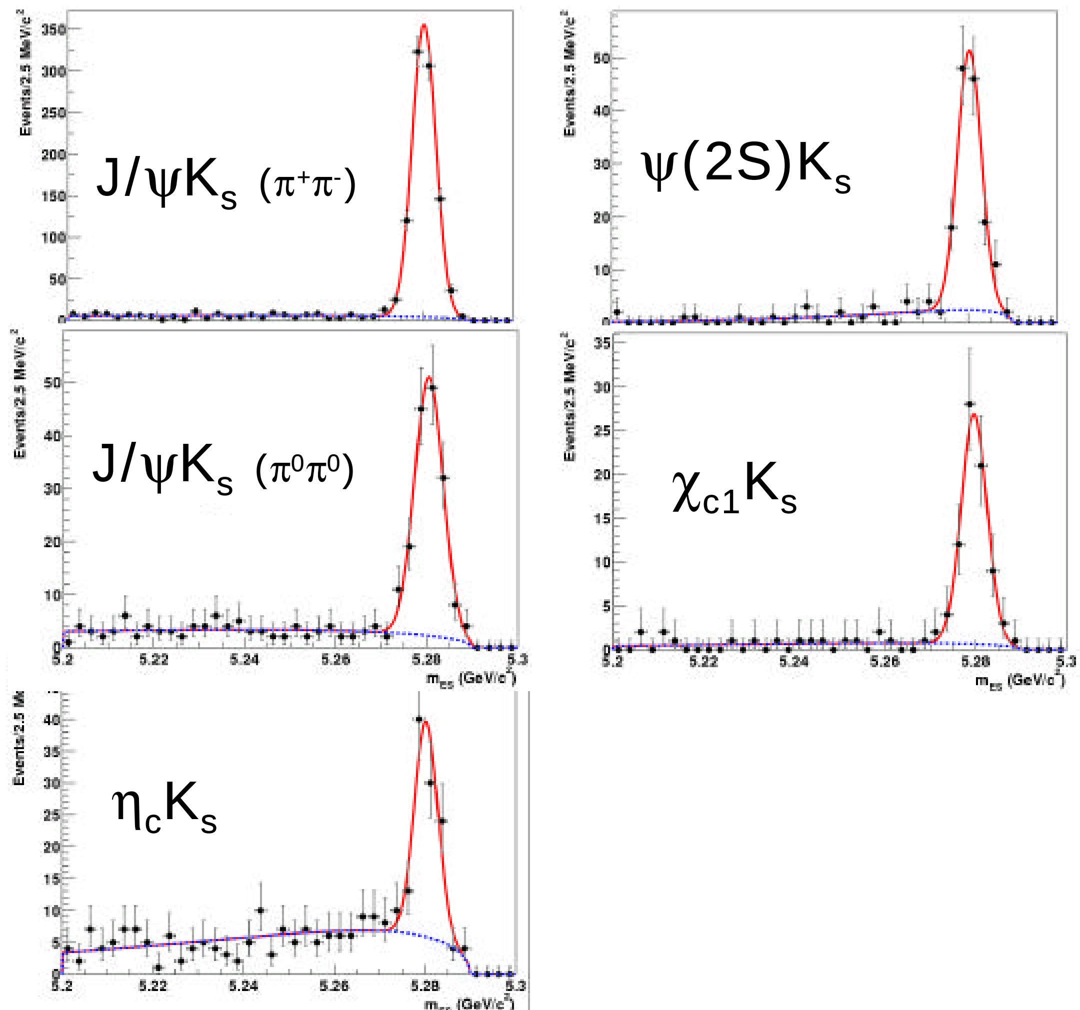


Flavor tag	Efficiency (ε)	Mistag fr. (ω)	D = 1-2ω	εD²
Lepton	9.1 ± 0.2 %	**3.3 ± 0.6 %**	**93.4 ± 1.2 %**	7.9 ± 0.3 %
Kaon1	16.7 ± 0.2 %	9.9 ± 0.7 %	80.2 ± 1.4 %	**10.7 ± 0.4 %**
Kaon2	19.8 ± 0.3 %	20.9 ± 0.8 %	58.2 ± 1.6 %	6.7 ± 0.4 %
Inclusive	20.0 ± 0.3 %	31.6 ± 0.9 %	36.8 ± 1.8 %	2.7 ± 0.3 %
Total	**65.6 ± 0.5 %**			**28.1 ± 0.7 %**

Error on sin2β Proportional to 1/sqrt(εD^2).

sin2β golden sample: $(c\bar{c})K_S$ (h_f = -1)

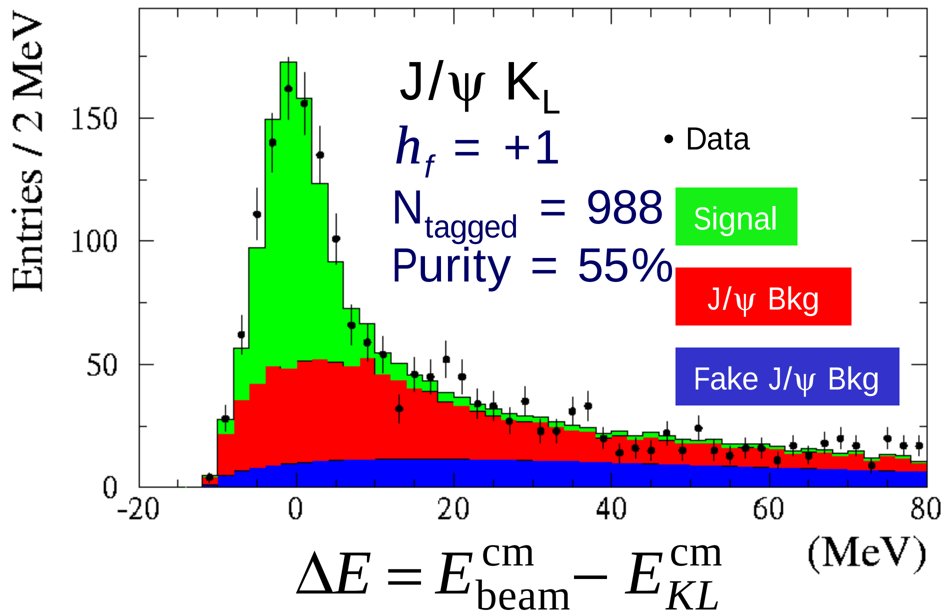
Sample	N_{tagged}	Purity
$J/\psi\ K_S(\pi^+\pi^-)$	**974**	**97%**
$J/\psi\ K_S(\pi^0\pi^0)$	**170**	**89%**
$\psi(2S)\ K_S$	**150**	**97%**
$\chi_{c1}\ K_S$	**80**	**95%**
$\eta_c\ K_S$	**132**	**73%**
Total	**1506**	**92%**

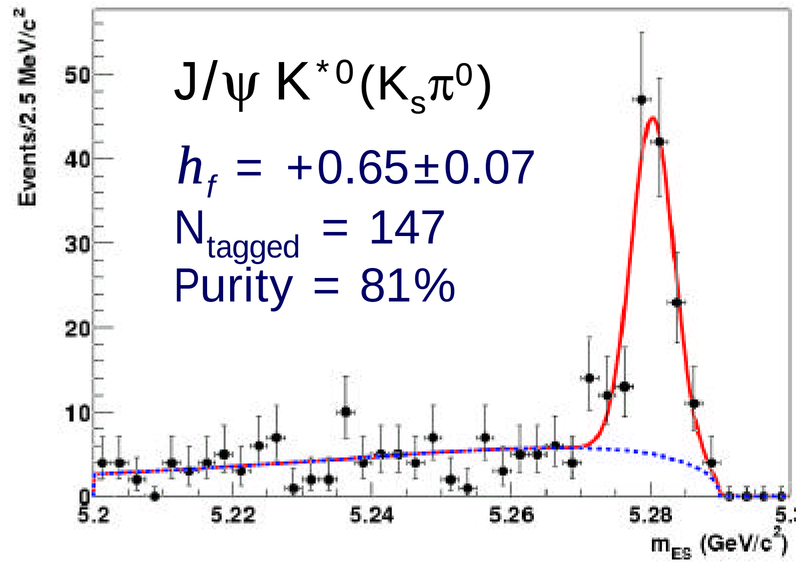


Latest addition:
$B^0 \to \eta_c K_S$
where $\eta_c \to K^+K^-\pi^0$ or
$K^+K_S\pi^-$

Energy-substituted mass $m_{ES} = \sqrt{\left(E^{cm}_{beam}\right)^2 + \left(p^{cm}_B\right)^2}$

sin2β samples: J/ψ K_L and J/ψ K^{*0}





- Use m_B constraint to determine p_{KL}
- J/ψ background shape estimated from Monte Carlo
- Fake J/ψ background shape estimated from data sidebands

- Vector-Vector mode: mixture of CP-even and CP-odd
- Use angular analysis to determine CP-odd fraction
- Treat CP-odd component as dilution → effective h_f

Fitting Strategy

Fit CP and B^0 flavor samples simultaneously.

- Unbinned maximum likelihood fit.
  - Use measured evt-by-evt error on Δt.
  - Use m_{es} evt-by-evt to determine signal probability.
- Simultaneous fit automatically propagates uncertainty on dilutions and Δt resolution.

Parameters	# free
$\sin 2\beta$	1
$\langle D \rangle$ and ΔD	8
Δt resolution function	8
Background Δt res fcn	3
Background D	8
Background Δt shape	6

CP sample ($\sin 2\beta$)

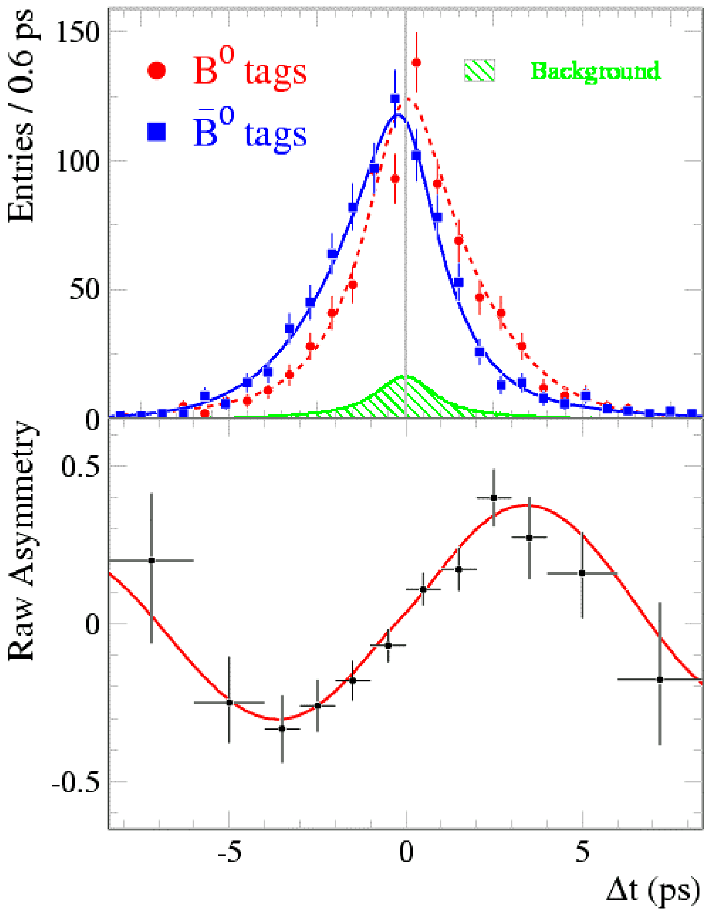
B^0 flav sample ($\langle D \rangle$ and ΔD; Δt resolution function)

m_{es} sideband (Background Δt res fcn; Background D; Background Δt shape)

Total: 34 free parameters.

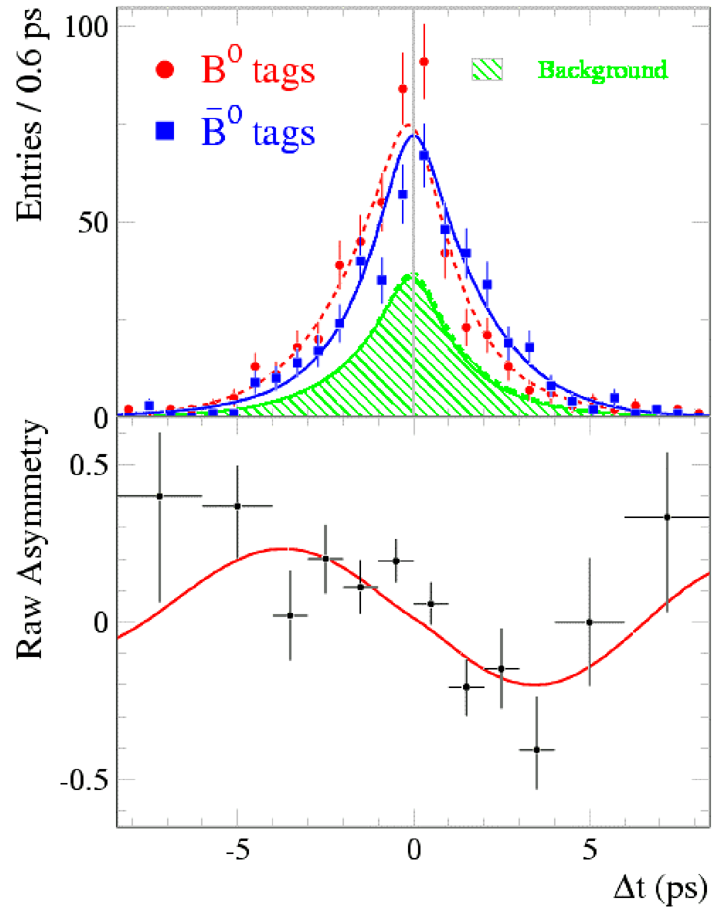
sin2β Fit Results

$(c\bar{c})K_s$ (η_{cp} = -1)



sin2b = 0.755 ± 0.074

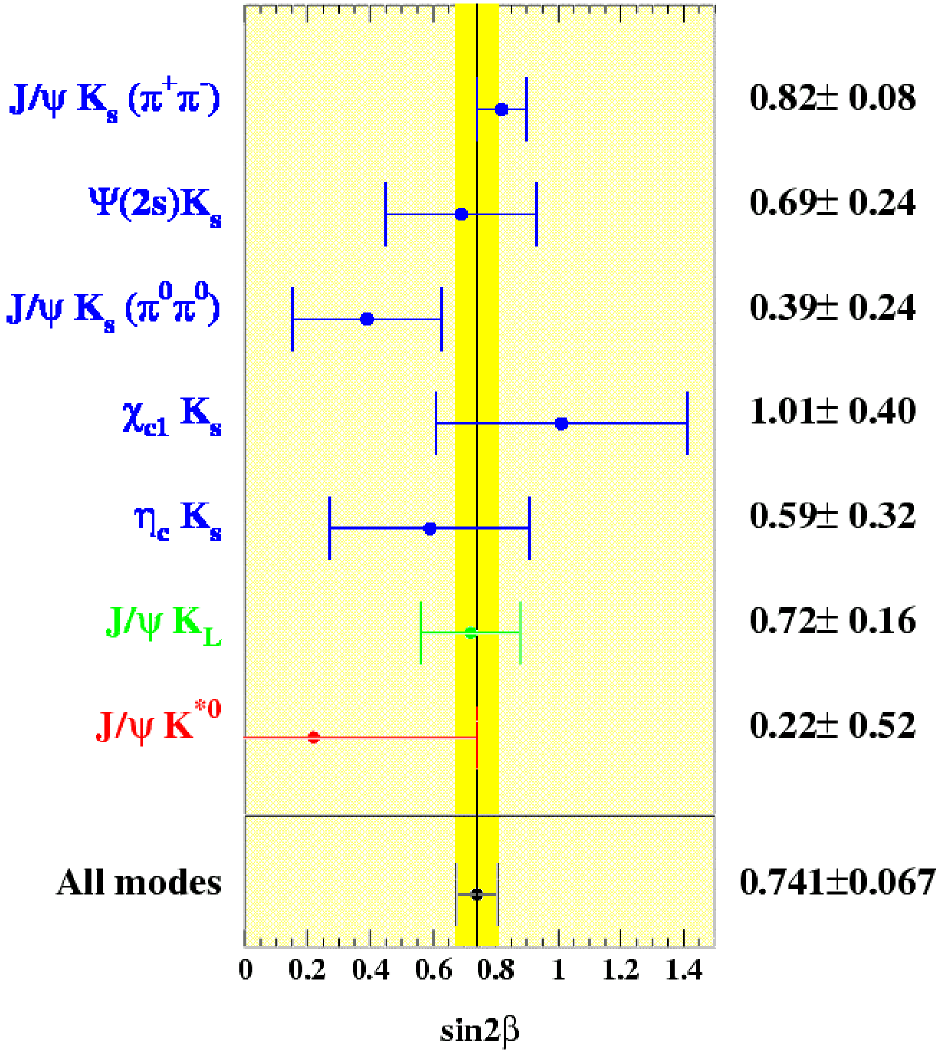
J/ψ K_L (η_{cp} = +1)



sin2b = 0.723 ± 0.158

All modes: sin2b = 0.741 ± 0.067 ± 0.034

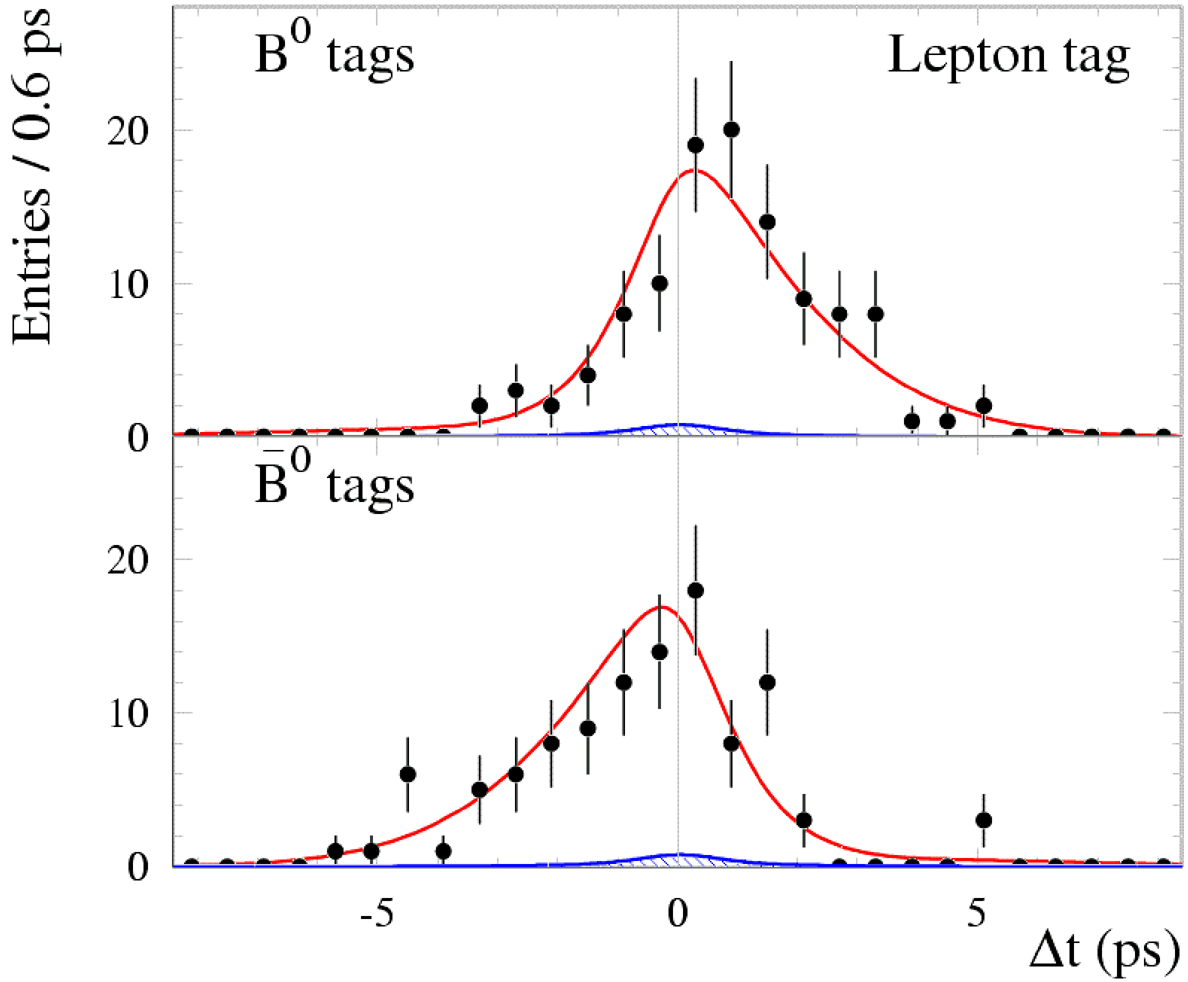
sin2β by Decay Mode



χ^2/d.o.f. = 4.8 / 6

Prob(χ^2) = 57%

Δt Distributions for lepton tagged $(c\bar{c})K_s$ sample



220 events, $\sin 2\beta = 0.79 \pm 0.11$

98% Pure

Mistag frac. 3.3%

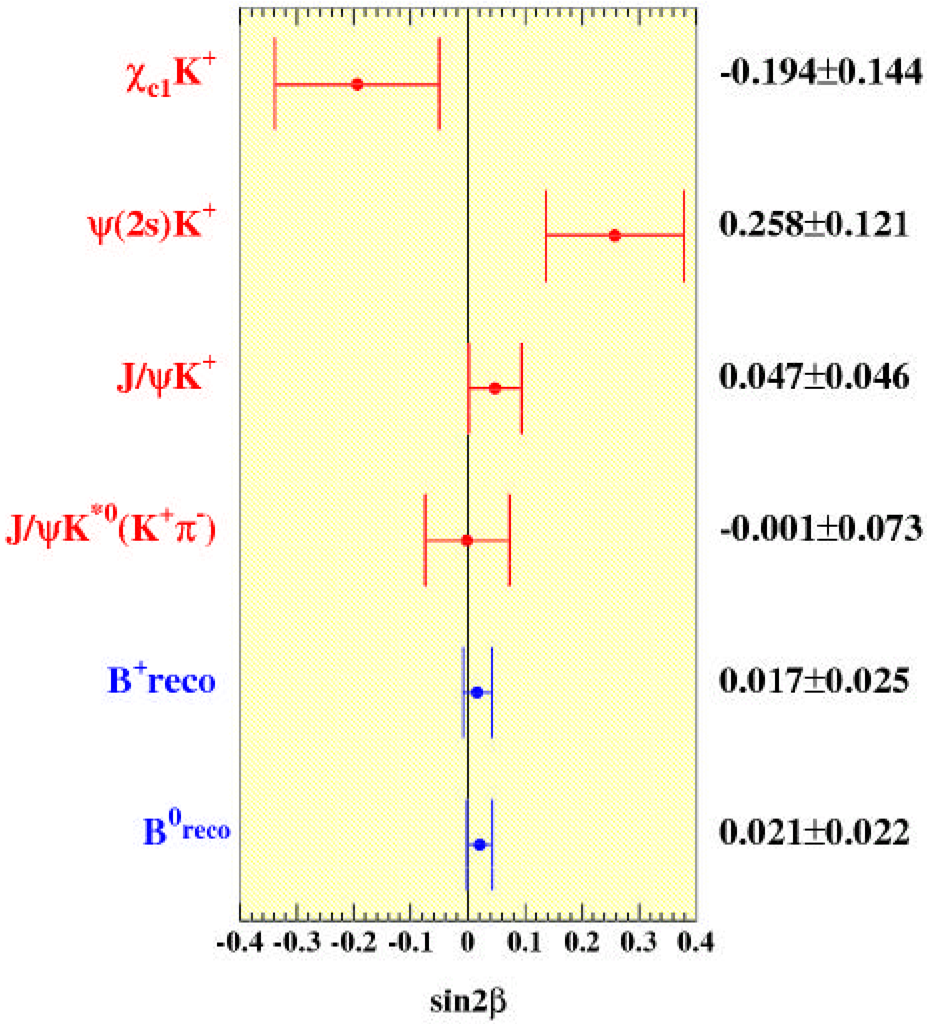
$\sigma_{\Delta t}$ 20% better than other tag categories

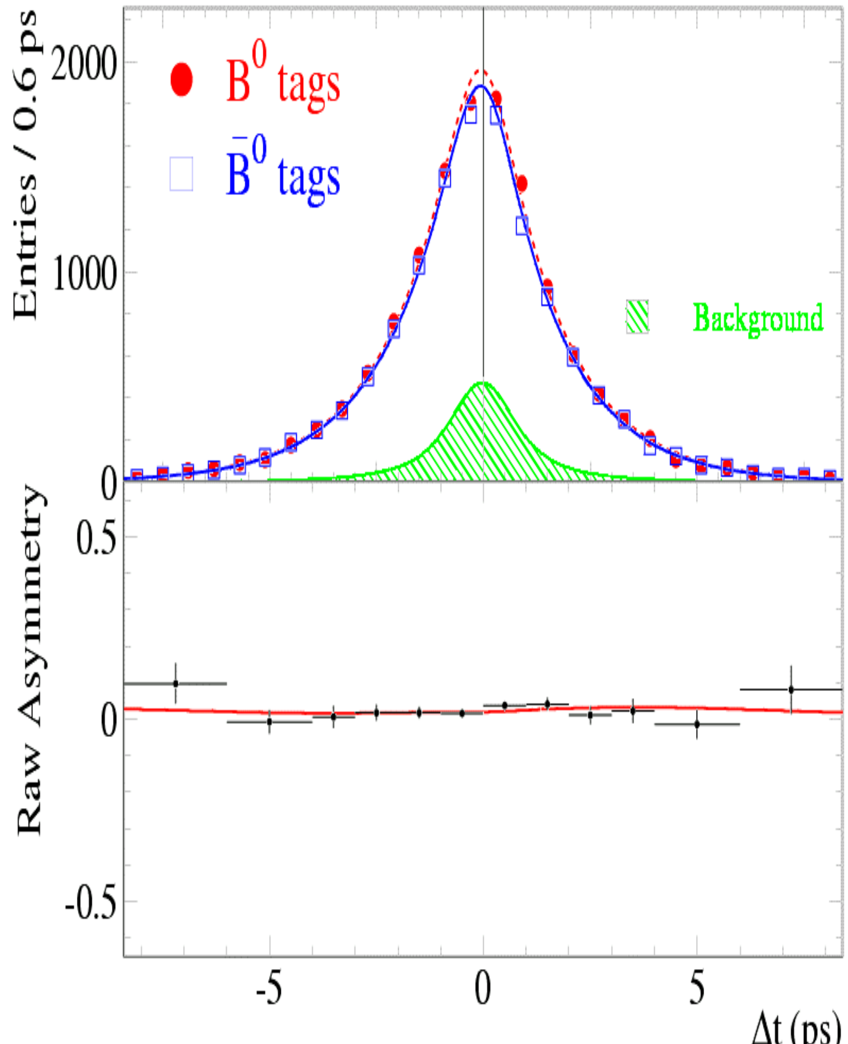
It doesn't get much better than this!

sin2β Control Samples

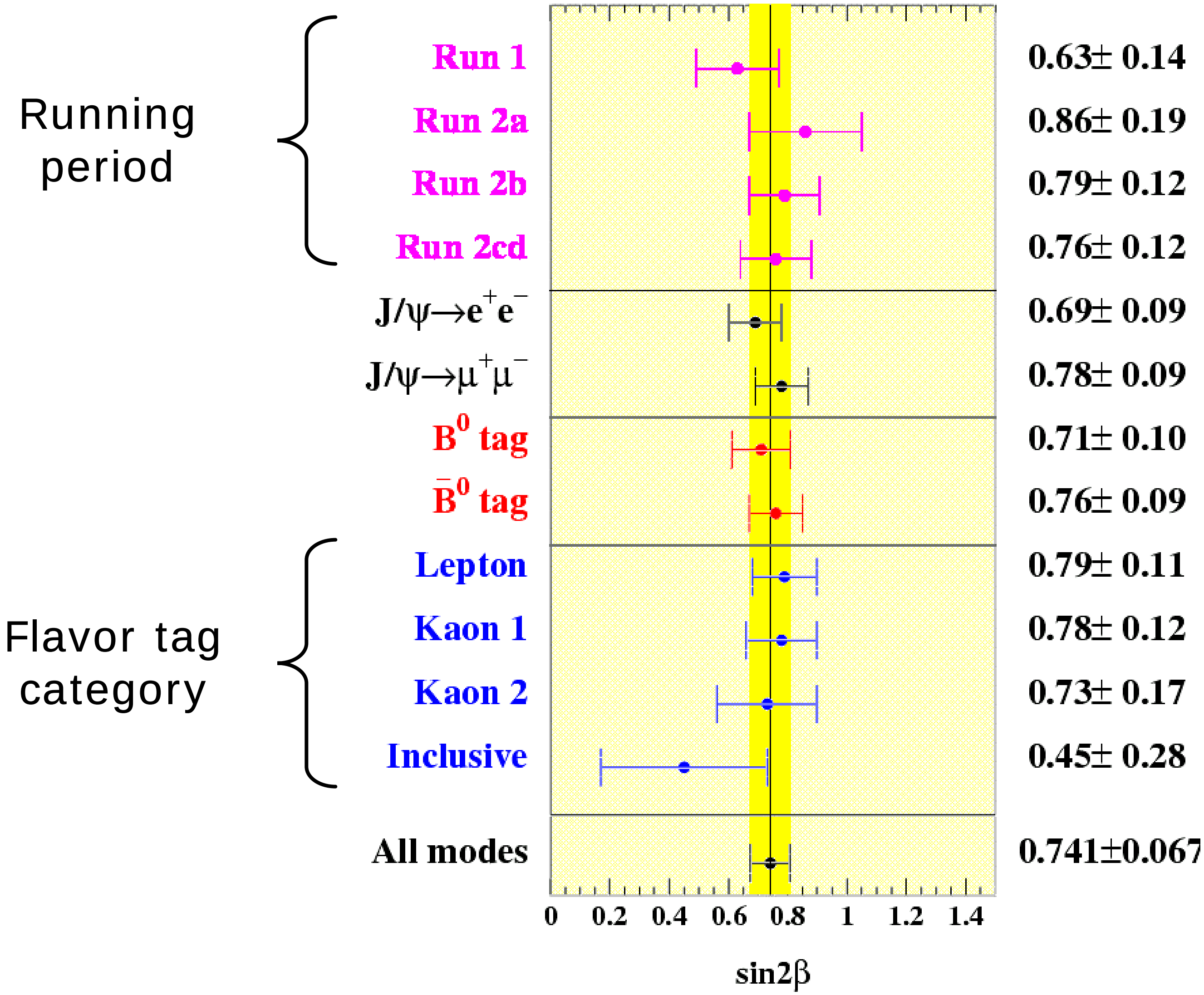
No asymmetry where none expected!

Fit B^0 reco for sin2β





Crosschecks: sin2β in subsamples

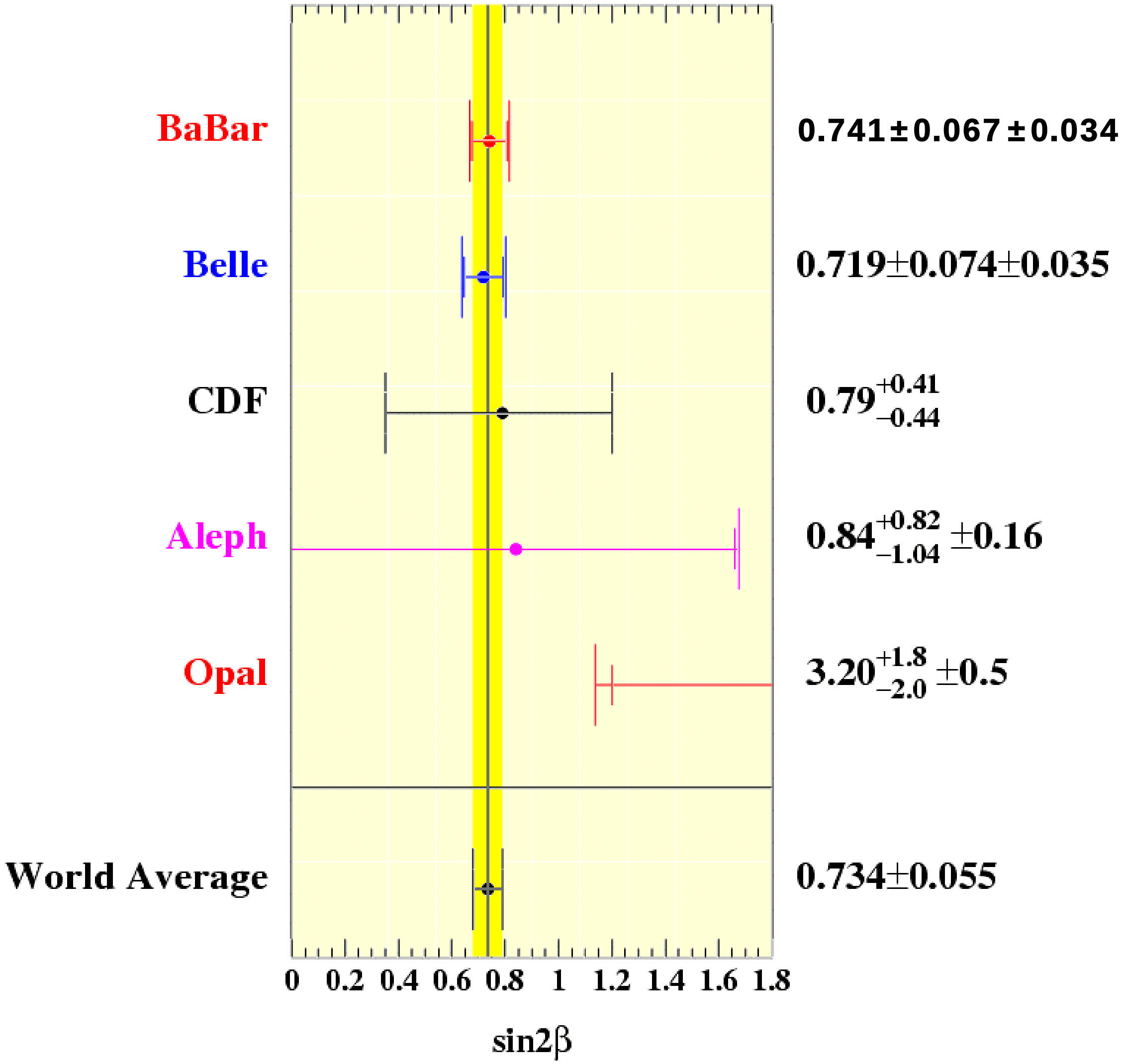


Sources of Systematic Error

	$\sigma(\sin 2\beta)$
Description of background events	0.017
CP content of background components	
Background shape uncertainties	
Composition and content of $J/\psi\ K_L$ background	0.015
Δt resolution and detector effects	0.017
Silicon detector alignment uncertainty	
Δt resolution model	
Mistag differences between B_{CP} and B_{flav} samples	0.012
Fit bias correction	0.010
Fixed lifetime and oscillation frequency	0.005
TOTAL	0.034

Steadily reducing systematic error: July 2002 = 0.034
July 2001 = 0.05

sin2β world average



Latest B-factory measurements are in good agreement.

Check for direct CP violation

In the nominal sin2β fit, we assume |λ| = 1 (as expected in SM)

where
$$\lambda = e^{-2i\beta}\frac{\overline{A}}{A}$$

We check this SM assumption by performing the fit with |λ| free.

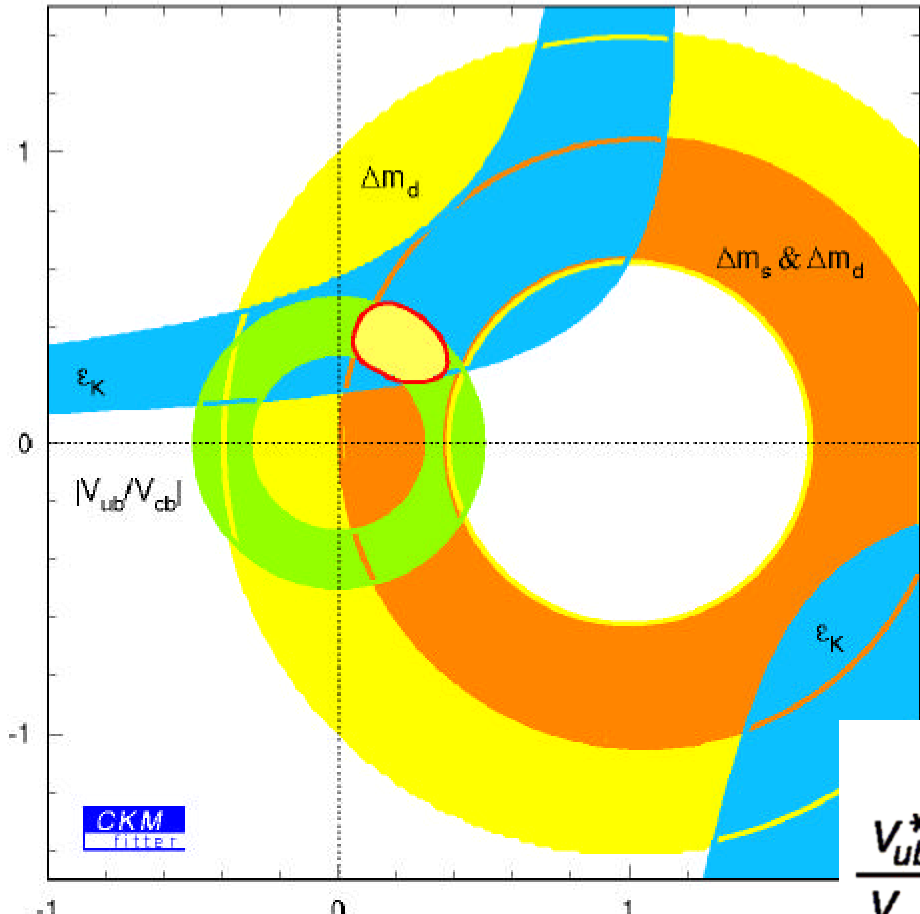
The fit was done only on the very clean ($c\overline{c}$)K_s sample which requires minimal background assumptions.

$$|\lambda| = 0.948 \pm 0.051 \text{ (stat)} \pm 0.030 \text{ (syst)}$$
$$\text{Im}\,\lambda\,/|\lambda| = 0.759 \pm 0.074 \text{ (stat)}$$

Consistent with the Standard Model expectation of |λ|=1.

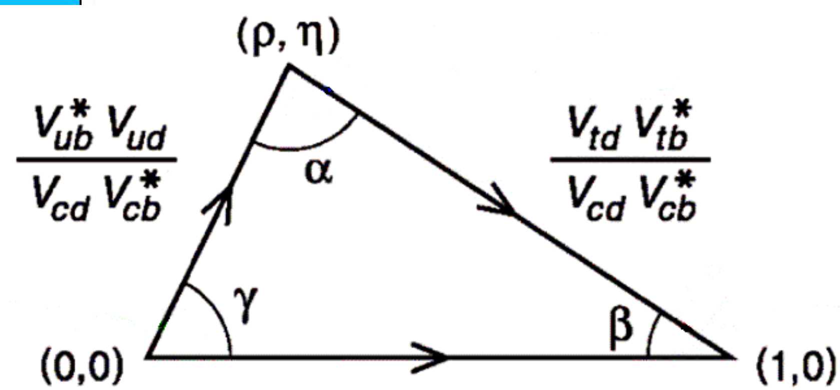
The Im λ /|λ| term, which is sin2β for the |λ|=1 case, is consistent with the nominal fit (sin2β = 0.755 ± 0.074 for ($c\overline{c}$)K_s modes alone).

Standard Model interpretation



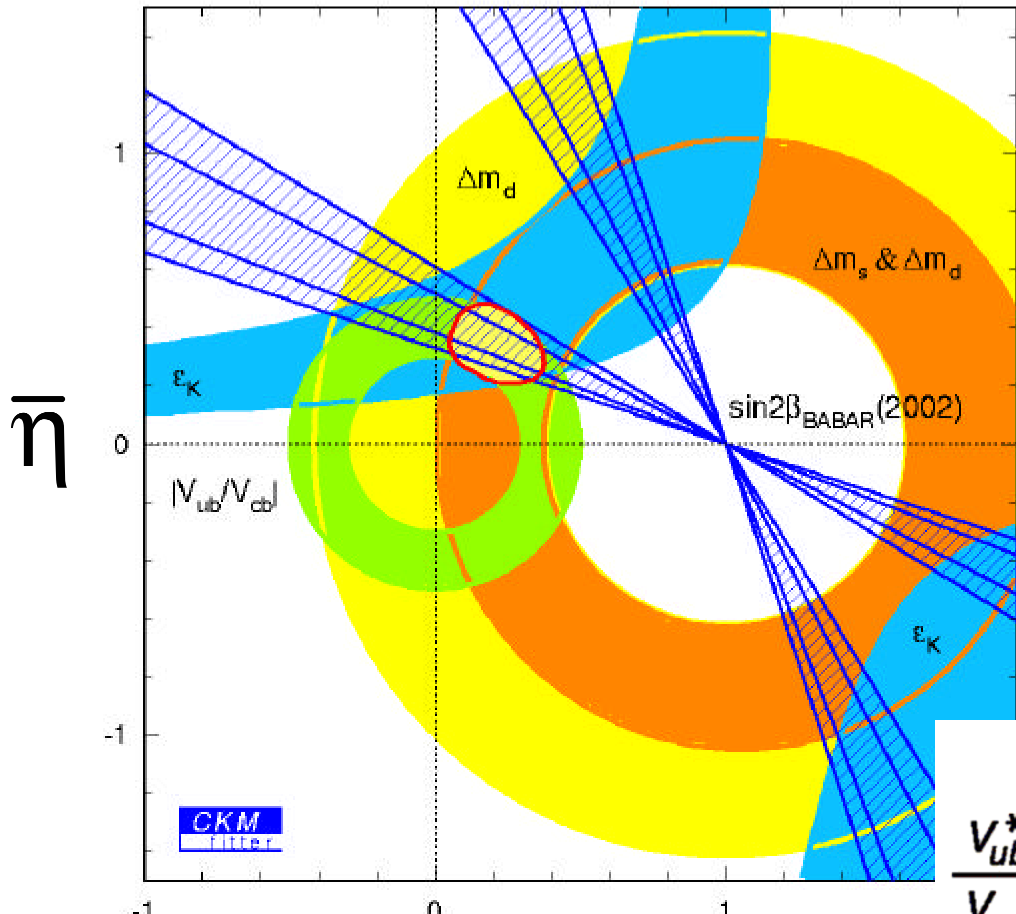
Constraints on the Wolfensten parameters ρ and η or the apex of the Unitarity Triangle.

$\bar{\rho} = \rho(1-\lambda^2/2)$
$\bar{\eta} = \eta(1-\lambda^2/2)$



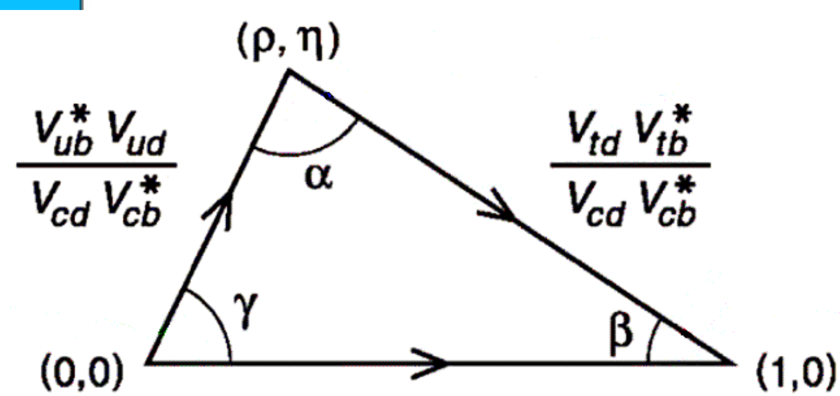
Method as in Höcker et al, Eur.Phys.J.C21:225-259,2001

Standard Model interpretation



Constraints on the Wolfensten parameters ρ and η or the apex of the Unitarity Triangle.

One solution for *b* is in excellent agreement with measurements of unitarity triangle apex



$\bar{\rho} = \rho(1-\lambda^2/2)$
$\bar{\eta} = \eta(1-\lambda^2/2)$

Method as in Höcker et al, Eur.Phys.J.C21:225-259,2001

Conclusions

- Latest measurement of $\sin 2\beta$ with BaBar PRL **89**, 201802 (2002)

$$\sin 2\beta = 0.741 \pm 0.067\,(\mathrm{stat}) \pm 0.034\,(\mathrm{syst})$$

- Next round will be precision measurement
- $\sin 2\beta$ remains interesting with possible SM deviations in penguin only decays
- *"The KM mechanism of CP violation has successfully passed its first precision test."* Y. Nir

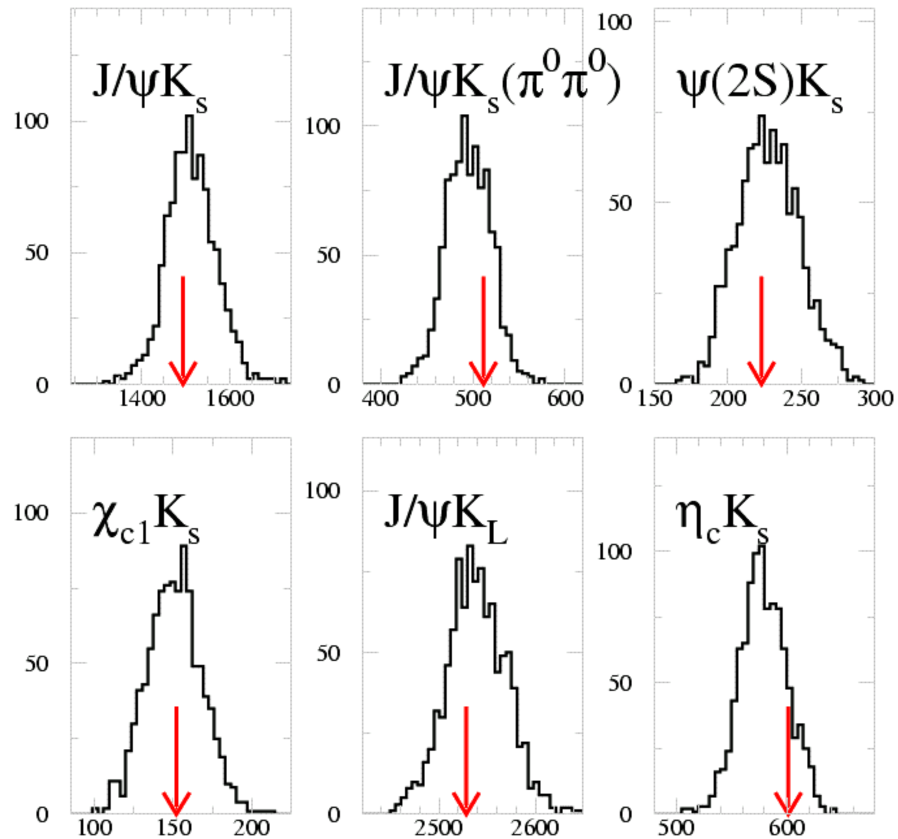
Backup Slides

Yields for CP (Ks) and B^0 flavor data sets

Mode	Ntag	Purity (%)
$J/\psi K_s$ $(\pi^+\pi^-)$	974	96.5
$J/\psi K_s$ $(\pi^0\pi^0)$	170	88.5
$\Psi(2S)K_s$	150	96.9
$\chi_c K_s$	80	94.5
$\eta_c K_s$	132	63.4
(cc)K_s	**1506**	**92.2**
Breco Hadronic	23618	84.2
$J/\psi K^{*0}(K^+\pi^-)$	1757	95.8
Bflavor	**25375**	**84.5**

Goodness of fit from toy MC

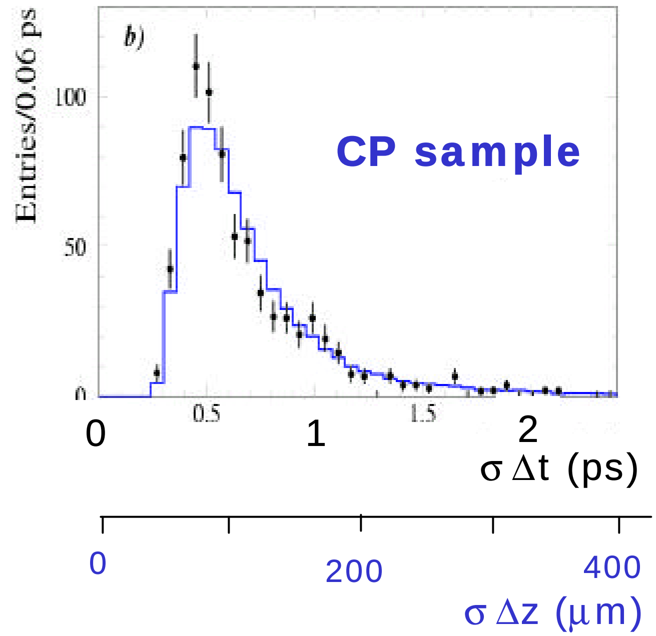
- Use toy MC to evaluate the expected statistical error and the goodness of fit from the log likelihood.
- Samples are generated with exactly the same statistics and per-event properties ($\sigma_{\Delta t}$, tag cat, tag val, m_{es}) as the data sample.
- The per-event Δt is regenerated based on the Δt PDF from the likelihood fit of the data, using the per-event properties above.

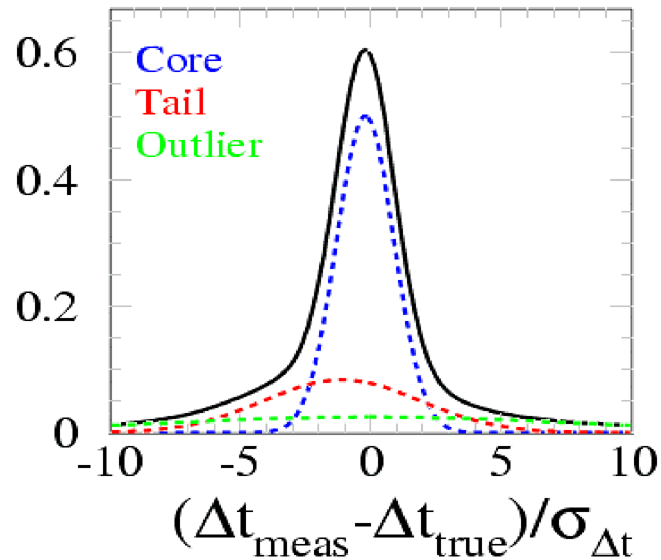


ln L

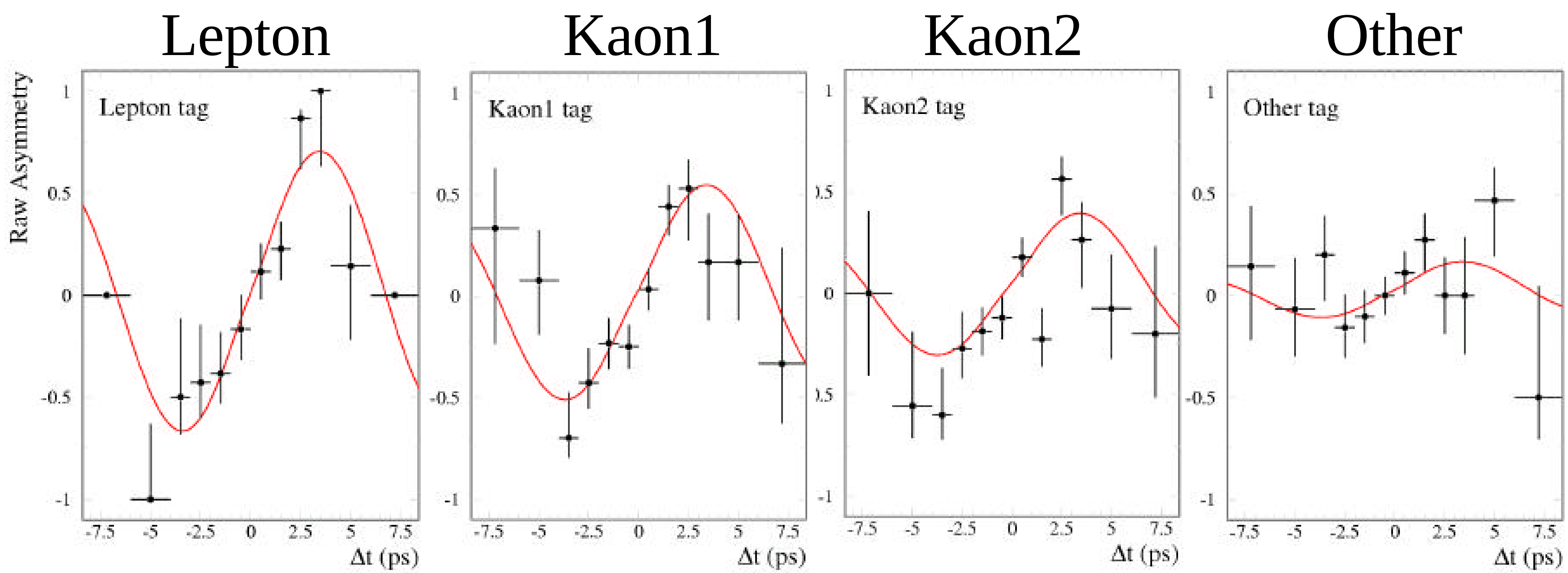
Δt resolution function

- Sum of 3 Gaussians (core, tail, outlier)
- **Core** and **tail** width scales with event error:
  - $s_{c} = S_c\, s_{Dt}$
  - $s_{t} = S_t\, s_{Dt}$ (S_t fixed to 3)
- Mean is free parameter. **Core** mean is flavor-tag dependent.
- **Core** and **tail** mean scale with s_{Dt}.
- **Outlier** has : s_{o} = 8 ps , mean = 0.
- BG resolution function is only **core** and **outlier**.



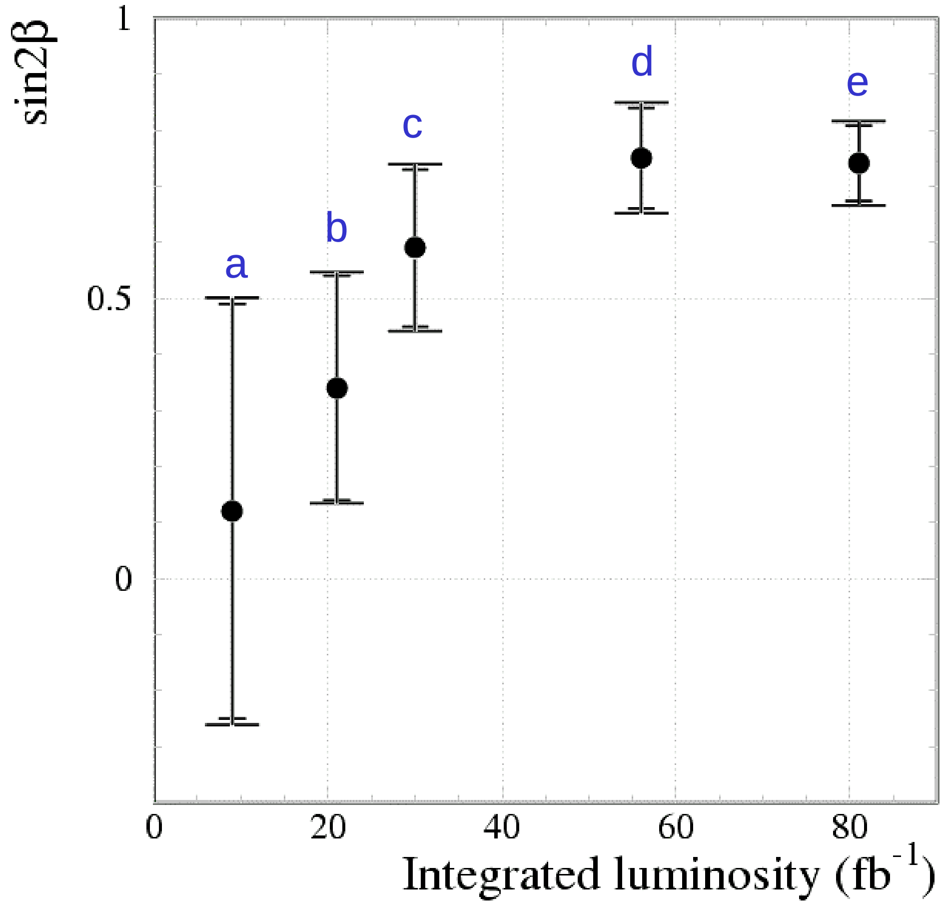


CP Asymmetry by Tagging Category for $(c\bar{c})\ K_s$



sin2β	Lepton	Kaon1	Kaon2	Other
	0.79 ± 0.11	0.78 ± 0.12	0.73 ± 0.17	0.45 ± 0.28

sin2β measurement history



a) "Osaka 2000" measurement. (hep-ex/0008048).
  - Only $J/\psi\ K_s$ and $\psi(2s)\ K_s$.

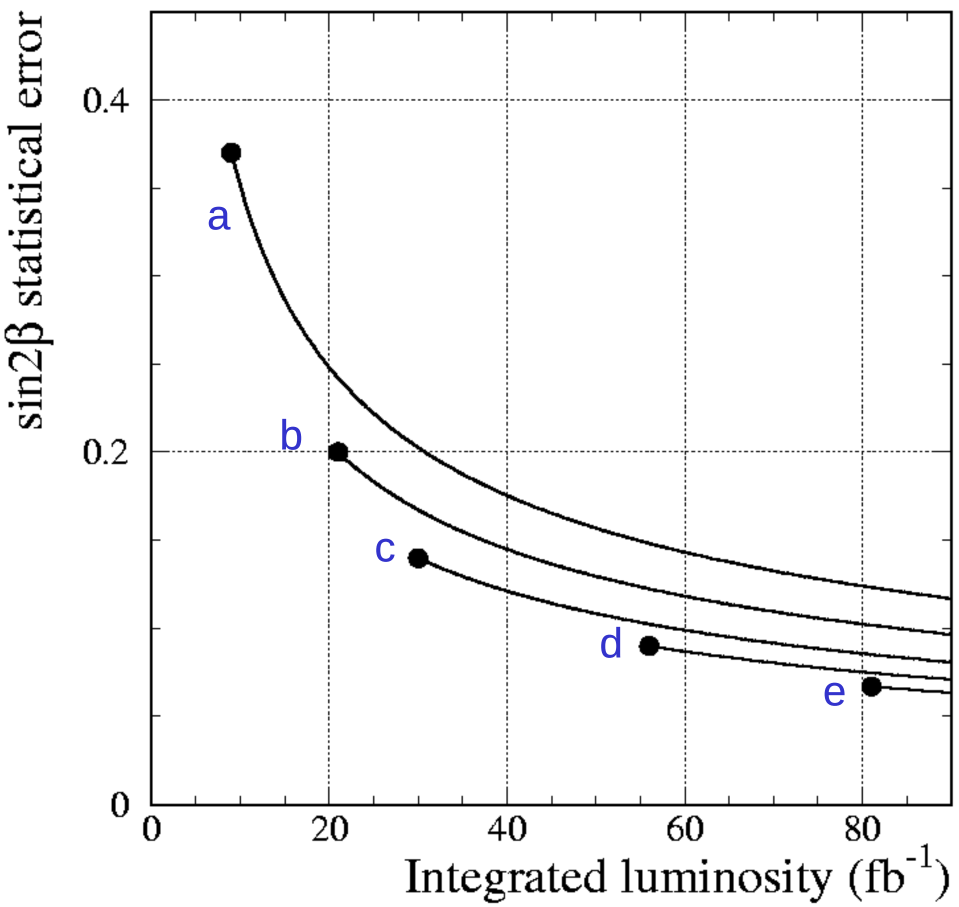
b) 1st Paper (PRL **86** (2001) 2515).
  - Added $J/\psi\ K_L$.
  - Simultaneous sin2β and mixing fit.

c) 2nd Paper (PRL **87** (2001) 201803).
  - Added $J/\psi\ K^{*0}$ and $\chi_c\ K_s$.
  - Better vertexing.
  - Better SVT alignment and higher K_s efficiency for new data.

d) Winter 2002 (hep-ex/0203007).
  - Improved event selection.
  - Reprocessed 1st 20 fb^{-1}.

e) Current measurement.
  - Improved flavor tagging.
  - One more CP mode: $\eta_c K_s$.

sin2β measurement history



a) "Osaka 2000" measurement. (hep-ex/0008048).
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Full expression for Δt from Δz

- The approximation $\Delta t \approx \Delta z/\beta\gamma c$ is very good but it ignores the B momentum (340 MeV/c) in the $\Upsilon(4S)$ frame.
- Can use the fully reconstructed B to improve it

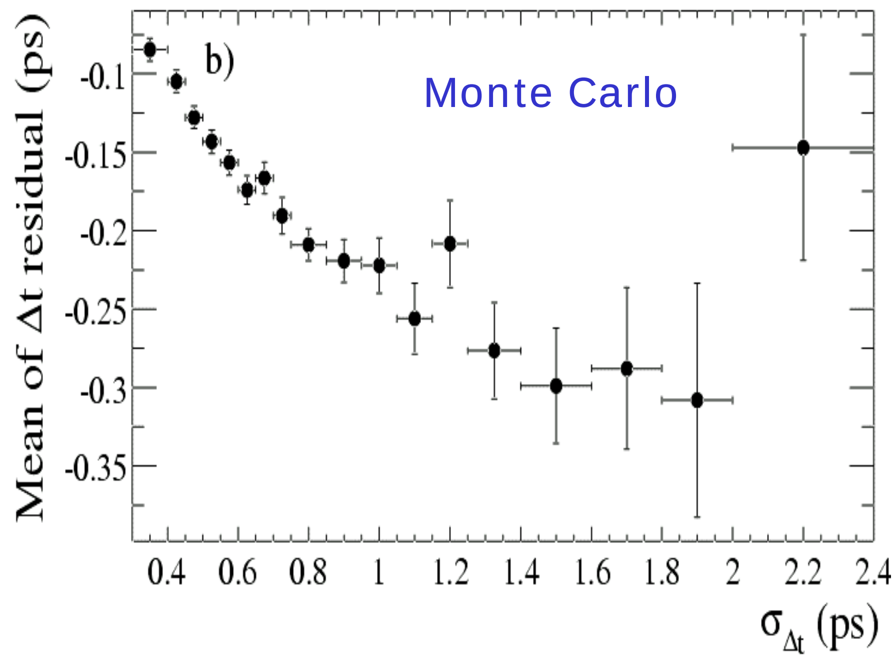
$$\Delta z = \beta\gamma\gamma^*_{\rm rec} c\Delta t + \gamma\beta^*_{\rm rec}\gamma^*_{\rm rec}\cos\theta^*_{\rm rec} c\left(\tau_B + |\Delta t|\right)$$

Where the B in the $\Upsilon(4S)$ frame has $\beta^*_{\rm rec} = 0.064$ and $\gamma^*_{\rm rec} = 1.002$

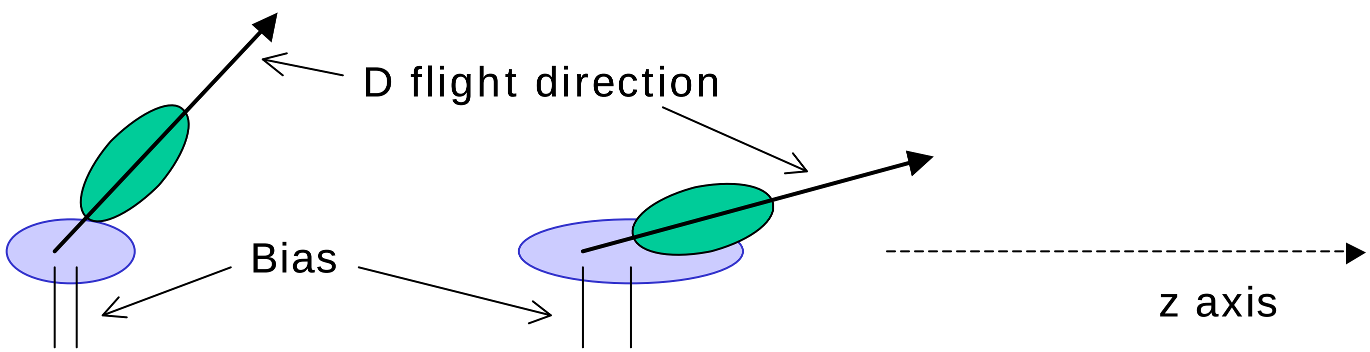
- Improves Δt resolution by about 5%.
- Removes a correlation between Δt and $\sigma_{\Delta t}$.

Δt bias correlation with $\sigma(\Delta t)$

- D vertex error ellipse aligned along its flight direction.
- D flight length in z is also correlated with D flight dir.



Two tag vertex scenarios.



Crosscheck: independent signal Δt resolution for CP and Breco

- The fit explicitly assumes that the charmonium and Breco modes share a common signal resolution function.
- MC supports this and the systematic is small:

  (0.002 this time).

Parameter	Breco	Charmonium
Scale core	1.10 ± 0.05	1.13 ± 0.15
Scale tail	3.0 (fixed)	3.0 (fixed)
Bias core, Lep	0.05 ± 0.07	0.03 ± 0.16
Bias core, Kaon1	-0.24 ± 0.05	-0.11 ± 0.13
Bias core, Kaon2	-0.25 ± 0.05	-0.16 ± 0.11
Bias core, Other	-0.21 ± 0.05	-0.25 ± 0.11
Bias tail	-1.1 ± 0.3	-1.1 ± 0.7
Fraction tail	0.11 ± 0.02	0.12 ± 0.07
Fraction outlier	0.003 ± 0.001	0.003 ± 0.003

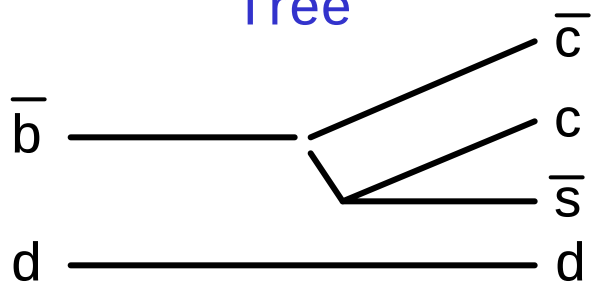
Good agreement!

$\Delta \sin 2\beta = +0.011$

$\sigma(\sin 2\beta)$ up 2%

Penguin terms in $(c\bar{c})K_s$

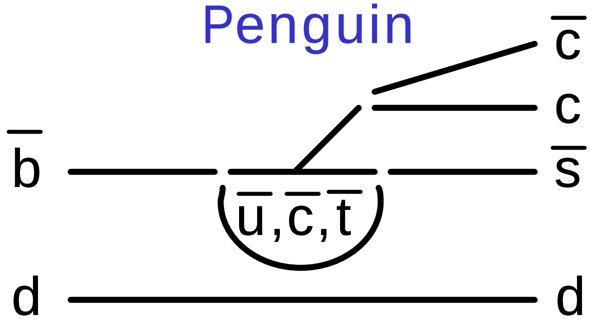
Tree



Tree amplitude proportional to

$$V^*_{cb}\, V_{cs} \approx A\, \lambda^3$$

Penguin



Three penguins

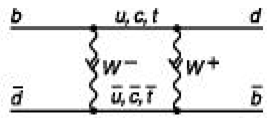
- c quark: same CKM factors as tree so same weak phase.
- u quark: suppressed by $\lambda^2 \approx 0.04$.
- t quark: same order as tree *but* can regroup this one with u and c terms assuming unitarity.

$$V^*_{tb}\, V_{ts} = -\, V^*_{cb}\, V_{cs} - V^*_{ub}\, V_{us}$$

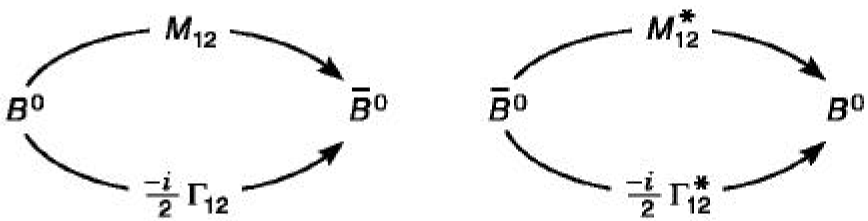
CP violation in $B^0 - \overline{B^0}$ mixing

CP violation if rate($B^0 \rightarrow \overline{B^0}$) $\neq$ rate($\overline{B^0} \rightarrow B^0$).

- Are there 2 separate amplitudes? Yes.
  - Virtual intermediate states (M_{12}) – Box diagram
  - On-shell intermediate states (Γ_{12}) – e.g. $\pi^+\pi^-$



- Are the necessary phase differences present? Yes.



The factor $-i = e^{-i\pi/2}$ plays the role of the strong phase: it does not change sign under CP.

- How big is it? *Tiny!*

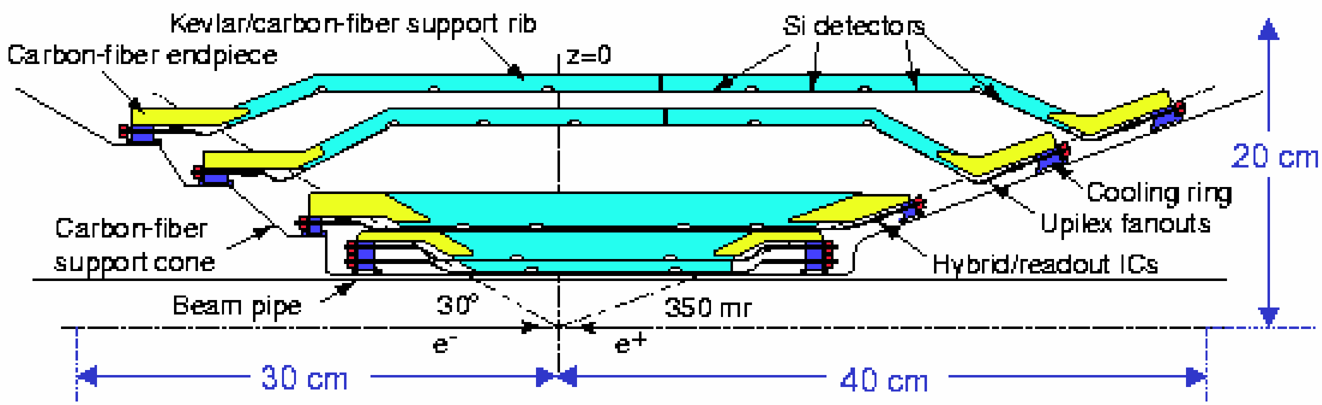
$$\mathcal{A}_{SL} \equiv \frac{\Gamma(\bar{B}^0_{\rm phys} \rightarrow \ell^+ X) - \Gamma(B^0_{\rm phys} \rightarrow \ell^- X)}{\Gamma(\bar{B}^0_{\rm phys} \rightarrow \ell^+ X) + \Gamma(B^0_{\rm phys} \rightarrow \ell^- X)} = (0.2 \pm 1.4) \times 10^{-2}$$

- Virtual path (M_{12}) totally dominates. *Neglect* CPV in mixing.

Vertex Detector

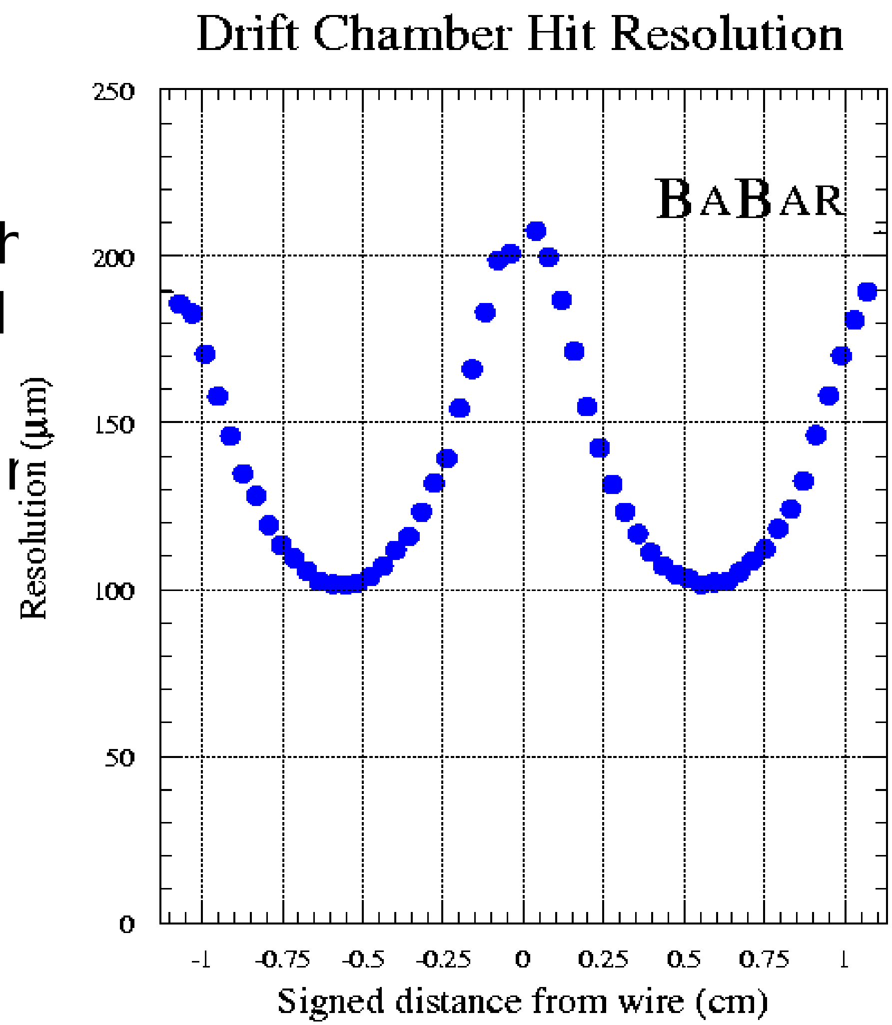
The BaBar Silicon Vertex Tracker

- 5 Layers of double-sided, AC-coupled Silicon.
- Custom rad-hard readout IC (the AToM chip).
- Low-mass design. (Pt < 2.7 GeV/c^2 for B daughters)
- Stand-alone tracking for slow particles.
  - Inner 3 layers for angle and impact parameter measurement.
  - Outer 2 layers for pattern recognition and low Pt tracking.



Drift Chamber

- Drift cells arranged in 10 superlayers of 4 layers each alternating stereo and axial
- 280 cm long cylinder with R_{in} = 23.6 cm, R_{out} = 80.9 cm
- Low Z He-Isobutane gas
- $\frac{s_{p_t}}{p_t} \approx 0.3\%$ in 1.5 T field



Detection of Internally Reflected Cherenkov Light (DIRC)

- Incident angle of Cherenkov photons maintained by internal reflection along quartz bars

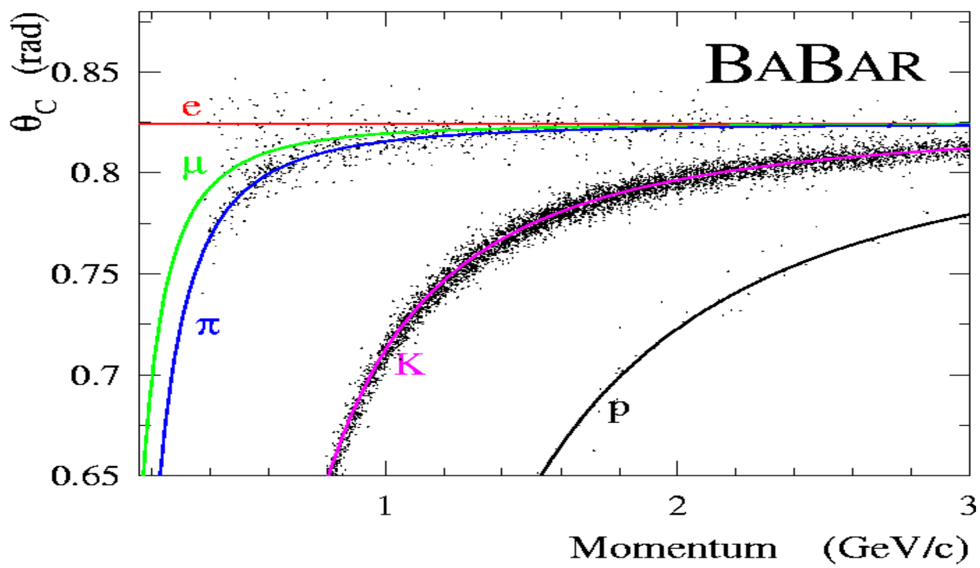
$$\cos q_c = (nb)^{-1}$$

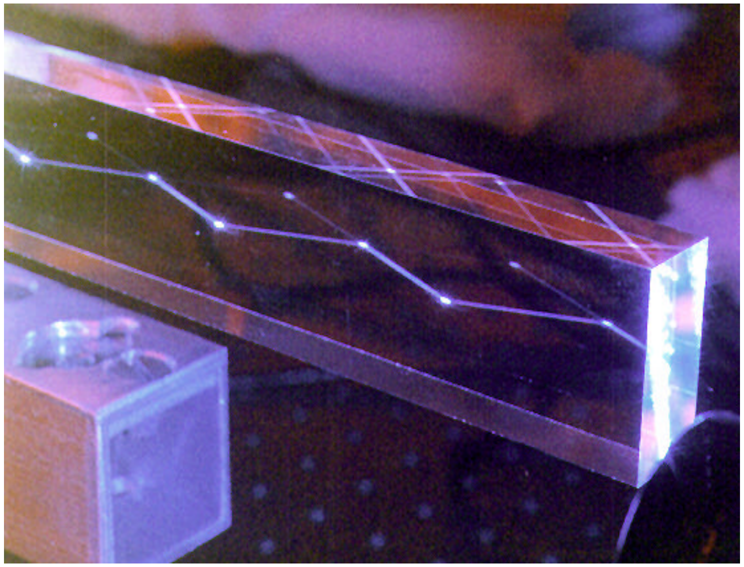
Measured in DIRC

$$p = mgbc$$

Measured in drift chamber

- Greater than 3σ K – π separation up to 3 GeV/c

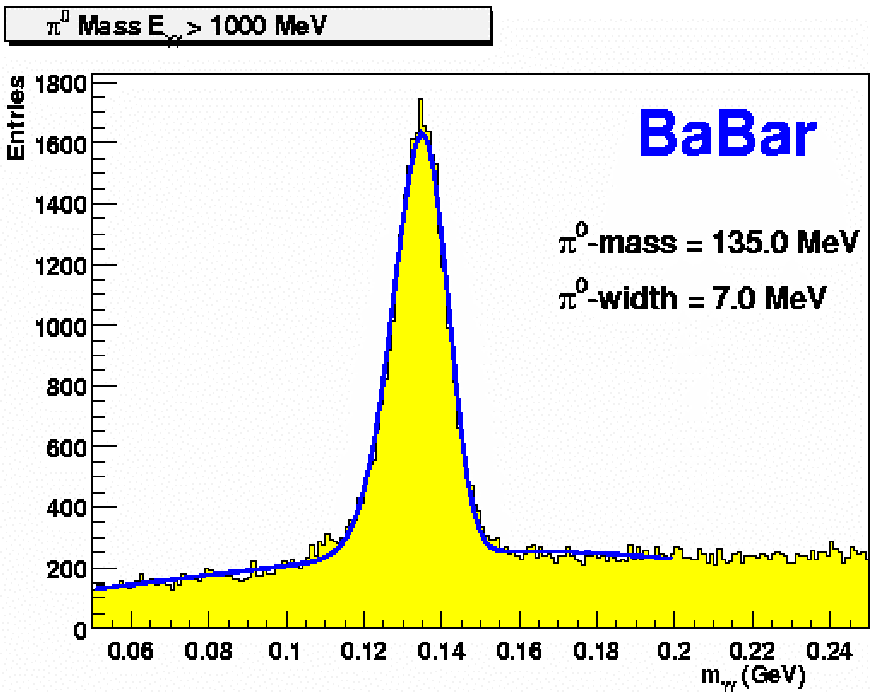




Shower Detectors

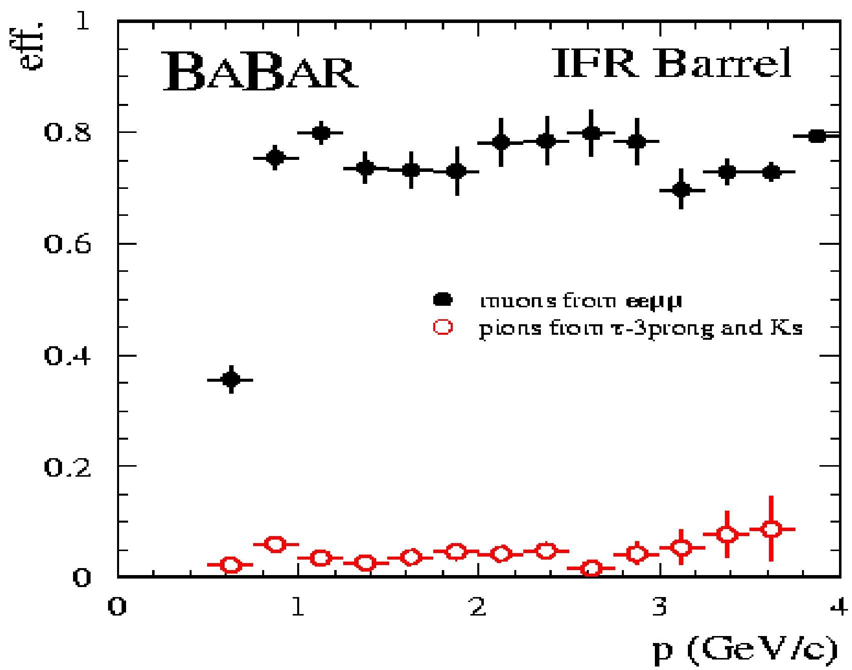
Electro-Magnetic Calorimeter

- 6580 CsI(Tl) crystals for good low energy resolutions (X_0 ~ 1.85 cm)
- Covers –0.78 < $\cos\theta_{lab}$ < 0.96
- Typical electron id efficiency of 90% with less than 1% fake pion rate



Instrumented Flux Return

- Identify muons and neutral hadrons (K_L)
- Iron structure segmented and instrumented with Resistive Plate Counters (RPCs)
- Iron plate thickness varies from 2 cm at innermost layers to 10



Maximum Likelihood Method

- Extract sin2β by maximizing likelihood fit to time distribution
- Determine parameter A with true value $\hat{A}$ fit with dataset $\{t_i\}$ assuming normalized PDF f $(A; t_i)$. Likelihood given by

$$L = \sum_i \ln f(A; t_i)$$

- As the number of data points increases

$$L \to N \int dt f(\hat{A}, t) \ln f(A, t)$$

- We find

$$\frac{\partial L}{\partial A} \to N \int dt f(\hat{A}, t) \frac{1}{f(A, t)} \frac{\partial f(A, t)}{\partial A}$$

evaluated at the true value of A vanishes

Asymptotically, the maximum likelihood occurs at true value of parameter