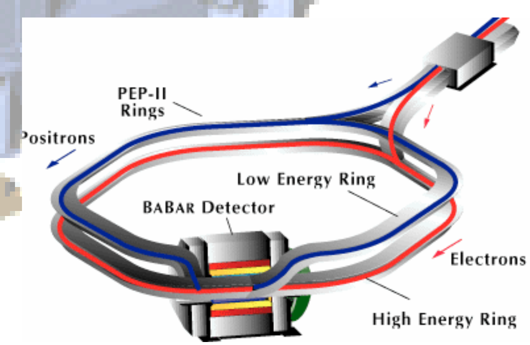
Measurement of CP Violation Parameter β and Search for New Physics from BaBar Experiment

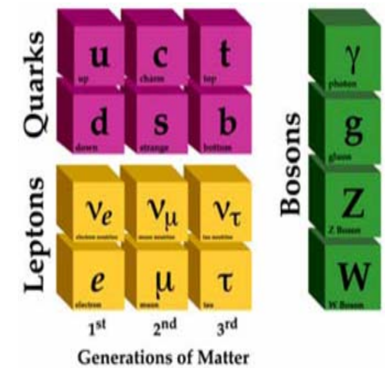
Chunhui Chen
Department of Physics
University of Maryland

Experimental HEP Seminar
University of Pennsylvania
January 18th, 2008



Open Questions in Particle Physics

Standard Model has explained almost all the experimental observables in high energy physics so far, but……



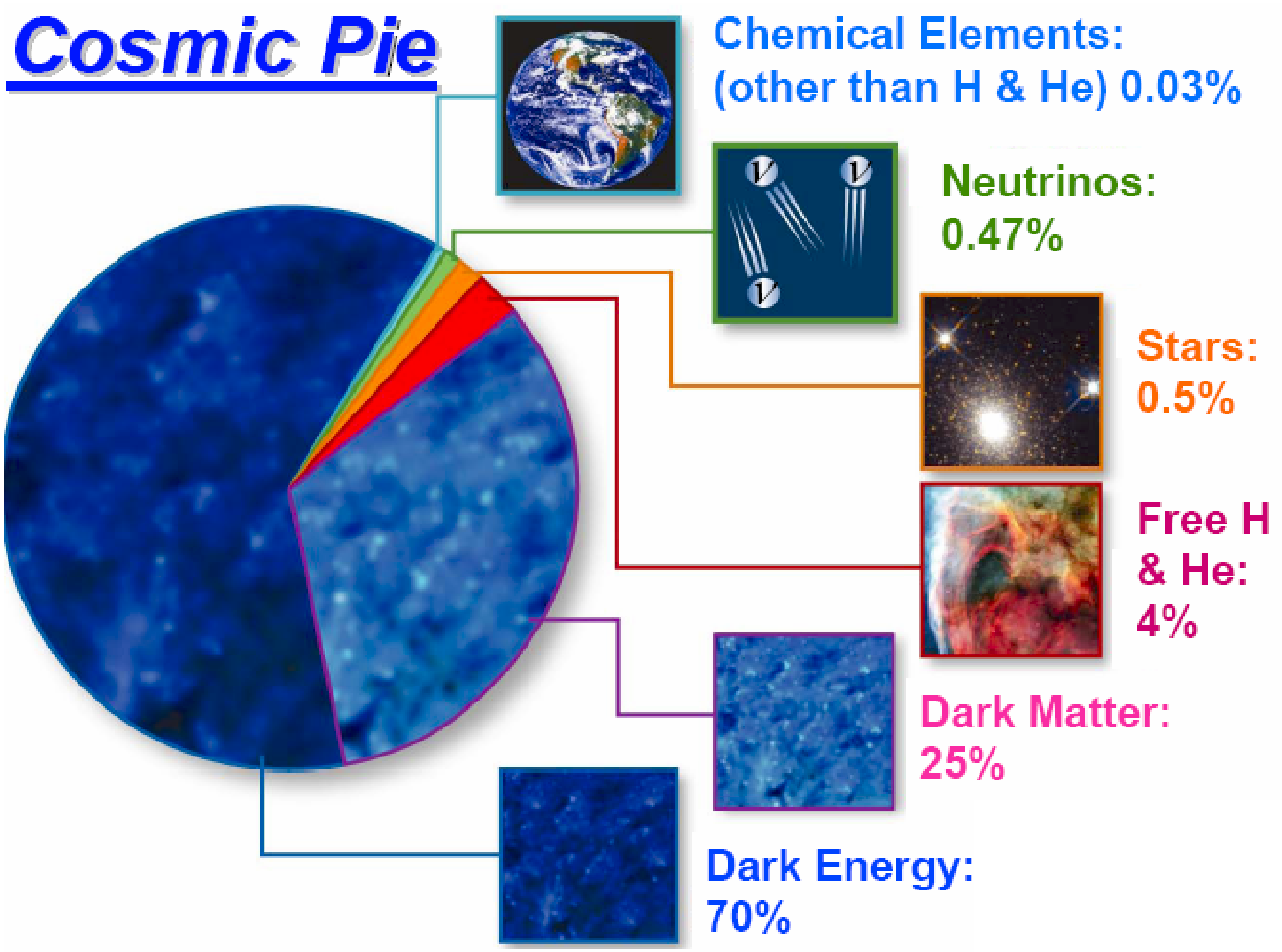
- ***The question of flavor:***
  - Why are there three families of matter?
  - Why are the neutrino masses so small?
  - Why asymmetry between matter & anti-matter (CP violation)?
- ***The question of mass:***
  - Does the Higgs boson in SM exist?
  - Mass hierarchy problems?
- ***The question of the dark universe:***
  - What is the dark matter in the universe?
  - What is the nature of dark energy?
- ***And more ……***

New Physics?

Are there undiscovered principles of nature:
New symmetries, new physical laws, new particles?

"New Physics": It's all around us !

Standard Model (25 free parameters):
extraordinarily successful explanation of only ~5% of Universe



History of the CP Violation

CP: left-handed particles ↔ right-handed anti-particles
C: charge conjugate; P: parity

←1964

CP conserved

CP-even: $K_S \rightarrow \pi^+\pi^-$ CP-odd: $K_L \rightarrow \pi^+\pi^-\pi^0$

1964

J. Cronin

V. Fitch

CP violated in neutral kaons

$K_L \rightarrow \pi^+\pi^-$ ($\sim 10^{-3}$)

Unexpected, not fitting existing models, changed understanding of weak interaction!
Is CP violation a fundamental feature of Nature or just an accident in kaons?

1987 Proposal to build asymmetric B factories to study CP violation in B decays
(first coll. meeting 1993
first collisions in 1999)

2001: CP violated in $B^0 \rightarrow J/\psi K_S$
($\sin 2\beta \neq 0$)
2004:CP violated $B^0 \rightarrow K^-\pi^+$
$Br(B^0 \rightarrow K^-\pi^+) \neq Br(B0 \rightarrow K+\pi^-)$

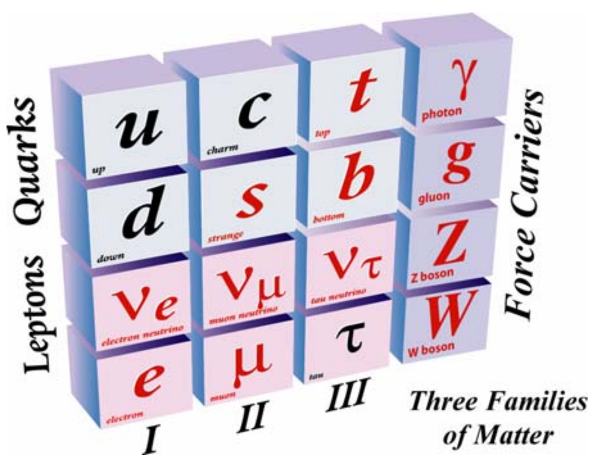
2004 →

Precise study of CP violation in B decays
(large effects, theoretically clean,
Important test of Standard Model).

Why Study CP Asymmetry

- ***CP violation (CPV) allowed in Standard Model (SM):***
  - Common origin with the quark mass and their mixing
    - ✓ Spontaneous electroweak symmetry breaking (EWSB) introduced by Higgs coupling
  - Probing the EW scale as well, complementary to other studies at energy frontier, e.g.: high P_T Physics at Tevatron & LHC
  - Excellent probe for new Physics (NP) beyond SM
  - Does the SM explain the observed CP violation effects?
- ***One of the conditions to generate matter dominated Universe:***
  - Sakharov conditions (1967):
    - ✓ **Violation of charge conjugation C & parity P asymmetries**
      - **CP Violation in SM is not large enough**
    - ✓ Baryon number violation, e.g., proton decay
    - ✓ Deviation from thermal equilibrium

CP Violation: CKM Matrix & EWSB



In the SM, electroweak symmetry breaking (EWSB) arises from the Higgs mechanism, which gives mass to the W and Z bosons via interaction with the Higgs boson:

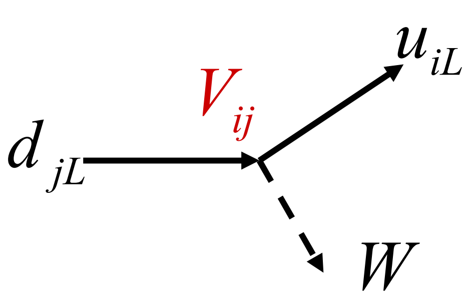
$$m_W = \tfrac{1}{2}\upsilon g = m_Z \cos\theta_W$$

v = "vacuum expectation value" ~ 250 GeV

Yukawa interaction of quarks with the Higgs field:

$$\mathcal{L}_Y = -Y^d_{ij}\overline{Q^I_{Li}}\phi d^I_{Rj} - Y^u_{ij}\overline{Q^I_{Li}}\varepsilon\phi^* u^I_{Rj} + \text{h.c.}$$

Quark mixing: flavor (weak) eigenstate $\neq$ mass eigenstate related by CKM matrix



V_{ij} : the CKM matrix that coupling the left-handed i^{th} generation of up-quark (u,c,t) with the left-handed j^{th} generation of down-quark (d,s,b)

CKM Matrix Phenomenology

weak eigenstates = V_{CKM} mass eigens,

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

- 3x3 complex unitary matrix: $V^{+}V=1$
- 4 free parameters
  - ✓ 3 angles
  - ✓ 1 phase, change sign under CP
- Observed experimental hierarchy

Wolfenstein parameterization:

L. Wolfenstein, PRL, **51**, p. 1945 (1983)

Expanded **matrix in small parameter:** $\lambda = V_{us} = \sin\theta_{Cabibbo} \approx 0.22$

$$V_{CKM} \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

Complex Phase: changes sign under CP (Origin of CP violation in SM)

$$\begin{pmatrix} 0.9739 \text{ to } 0.9751 & 0.221 \text{ to } 0.227 & 0.0029 \text{ to } 0.0045 \\ 0.221 \text{ to } 0.227 & 0.9730 \text{ to } 0.9744 & 0.039 \text{ to } 0.044 \\ 0.0048 \text{ to } 0.014 & 0.037 \text{ to } 0.043 & 0.9990 \text{ to } 0.9992 \end{pmatrix}$$

Range are 95% CL, PDG: PL. B 592, 1 (2004)

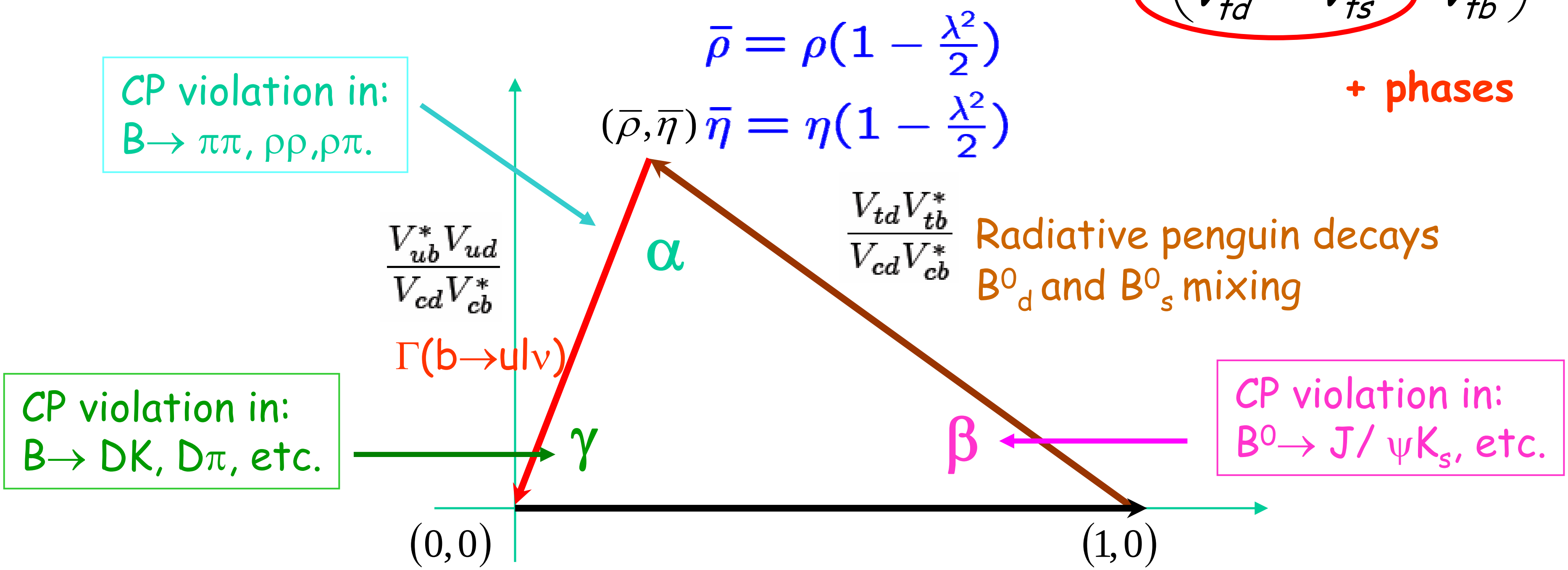
Unitarity Triangle & Search NP in B Decays

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

UT as a summary of SM B Physics

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

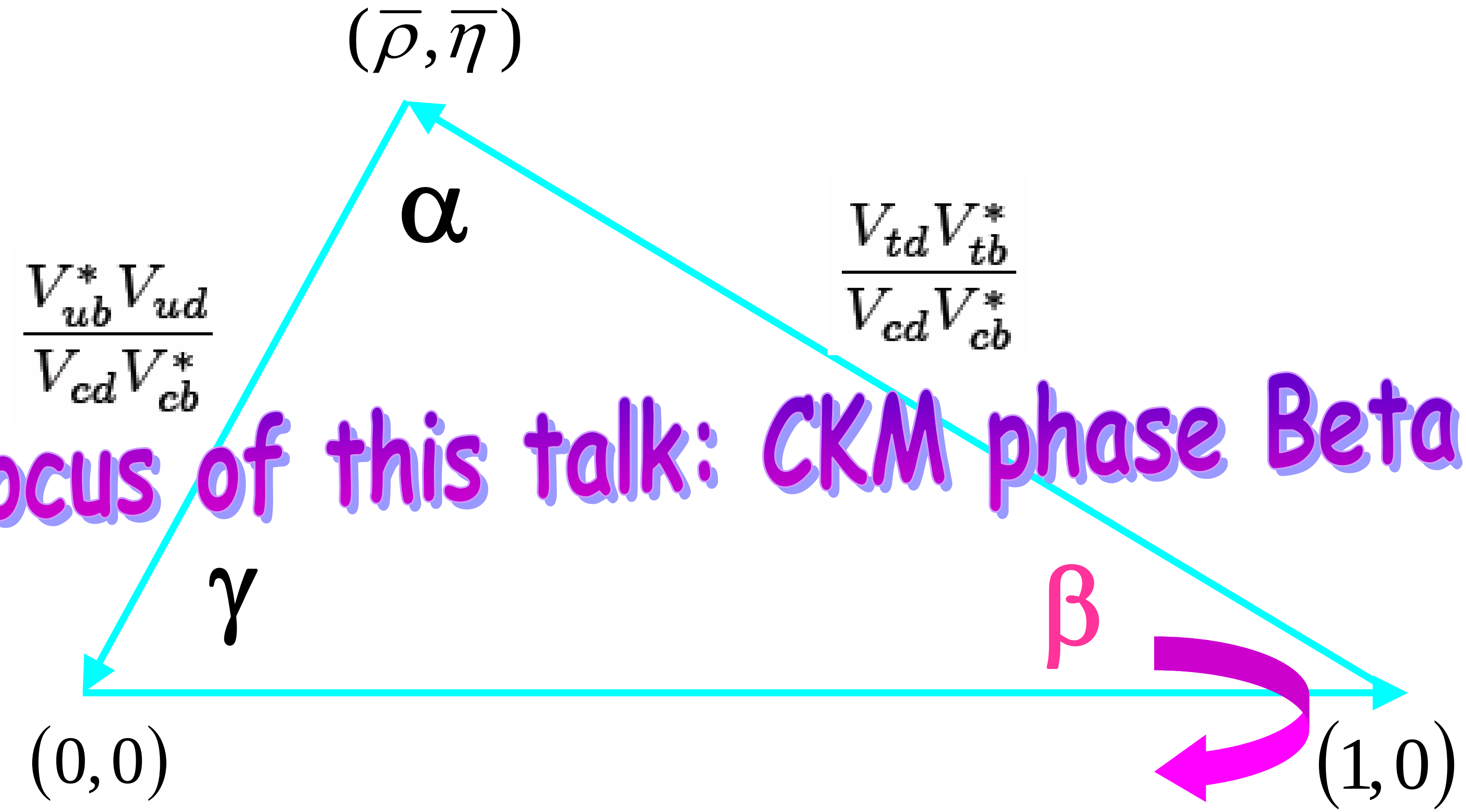
+ phases



Model Independent test SM & search for NP:

- Overconstarint of unitarity triangle
- Redundant measurement of same CKM phases: $\sin 2\beta$

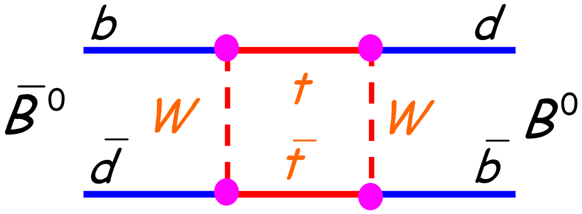
Focus of this talk: CKM phase Beta



- Most precisely measured CKM angle
- Important measurements for the test of SM and search for NP
  - ✓ Overconstraint unitarity triangle
  - ✓ Possible deviation of measured sin2β in different modes due to NP

B Physics v.s. Conventional Search of NP

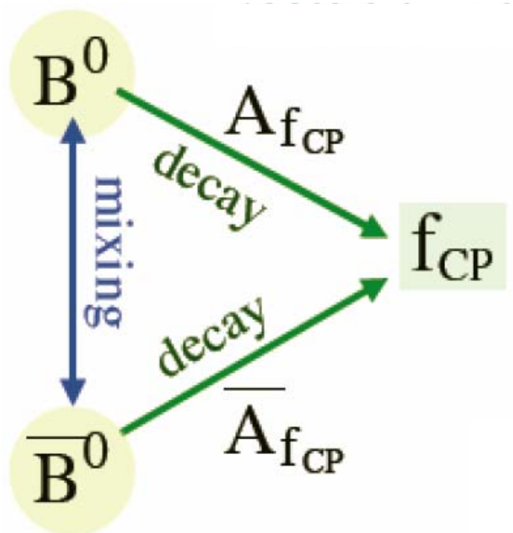
- ***Conventional search: direct observation***
  - Eg: observation of Higgs or new particles at LHC
- ***Approach in B physics:***
  - m_B=5.28GeV, New Physics scale $\Lambda_{NP} \sim$ TeV
  - FCNC forbidden at tree level in SM
  - Deviation from SM due to "virtual loops" effect
  - sensitive to NP $\Lambda_{NP} >> E_{experiment}$
- ***Lesson learned in B^0 mixing:***
  - Observation of B^0 mixing in ARGUS experiment in 1987



  - Quantum loop process: rate depends on mass of *virtual* top quarks and W bosons circulating in loop and quark couplings
  - Implication: m_{top}>50 GeV/c^2, heavier than "expected"
  - First evidence of "heavy top", long before it is directly observed at 170 GeV/c^2 in Tevatron

How to Measure CKM angles (β)

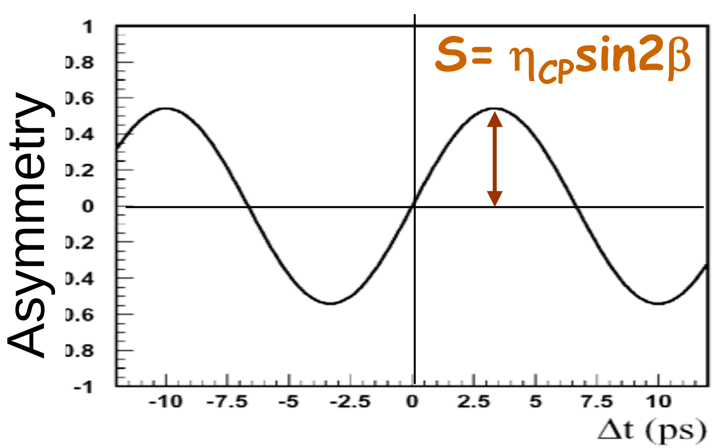
Use mixing induced CPV: CPV through interference between mixing and decay amplitude



- B^0 and $\overline{B}^0$ decay differently:
- Non-exponential decay
- Time-dependent decay rate asymmetry:

$$A_{CP} \equiv \frac{\Gamma(\overline{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})}$$

$$= \underbrace{S\sin(\Delta m \Delta t)}_{\text{Indirect CPV}} - \underbrace{C\cos(\Delta m \Delta t)}_{\text{Direct CPV}}$$

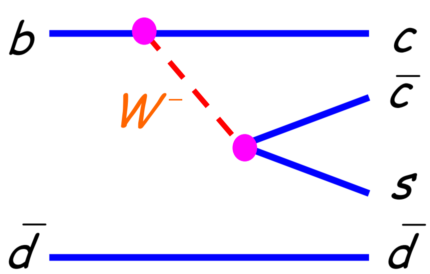


- C: direct CP violation
  - ✓ $C \neq 0$ $\Gamma(B \to f) \neq \Gamma(\overline{B} \to \bar{f})$
- S: mixed inducted CP violation
  - ✓ related to CKM angles
- Special case: one weak phase in decay amplitude
  - ✓ C=0
  - ✓ S=constant×sin2β (eg: $B^0 \to J/\psi K^0$)
  - ✓ Clean way to extract CKM phases

Independent Measurement of β

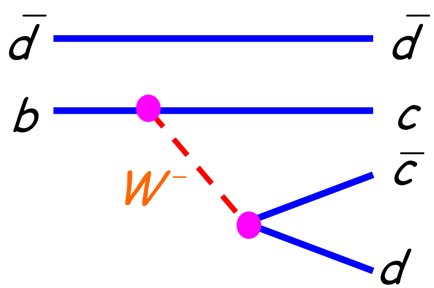
Determination angle β by measuring sin2β:
Can use three different categories of B^0 decays

$b \to c\bar{c}s$ (charmonium)



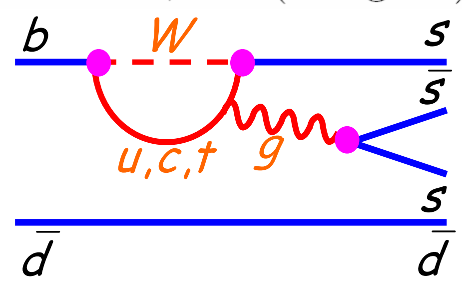
$B^0 \to J/\psi K^0, \psi(2S)K_S, \eta_c K_S, \chi_{c1}K_S, J/\psi K^{*0}(K^{*0} \to K_S\pi^0)$

$b \to c\bar{c}d$ (charm & charmonium)



$B^0 \to D^{*+}D^{*-}, D^+D^-, D^{*+}D^-$,
$B^0 \to J/\psi\pi^0$

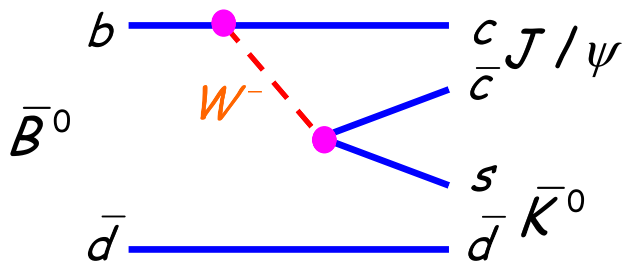
$b \to s\bar{s}s, d\bar{d}s$ (Penguin)

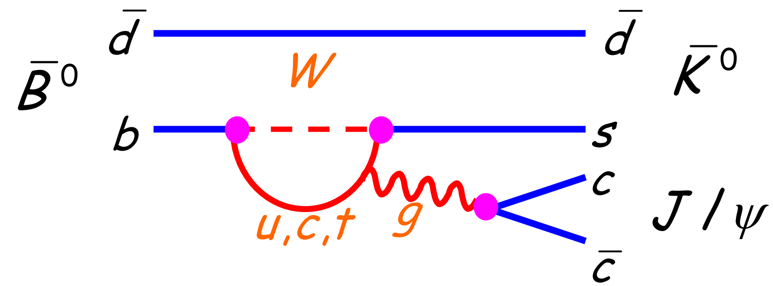


$B^0 \to \phi K^0, K^+K^-K_S, \eta' K_S$,
$K_SK_SK_S, \omega K_S, \rho K_S$ ……

Measure sin2β in $b \to c\bar{c}s$ Modes

$B^0 \to J/\psi K^0$ ($K^0 \to K_S$ or K_L), $\psi(2S)K_S$, $\eta_c K_S$, $\chi_{c1}K_S$, $J/\psi K^{*0}$($K^{*0} \to K_S\pi^0$)





Golden Channel

- Decay dominated by Single Weak Phase:
  - ✓ **C=0 and S= η_{CP}sin2β**
  - ✓ η_{CP}=+1(-1) for CP even: $J/\psi K_L$ (odd: $J/\psi K_S$) state

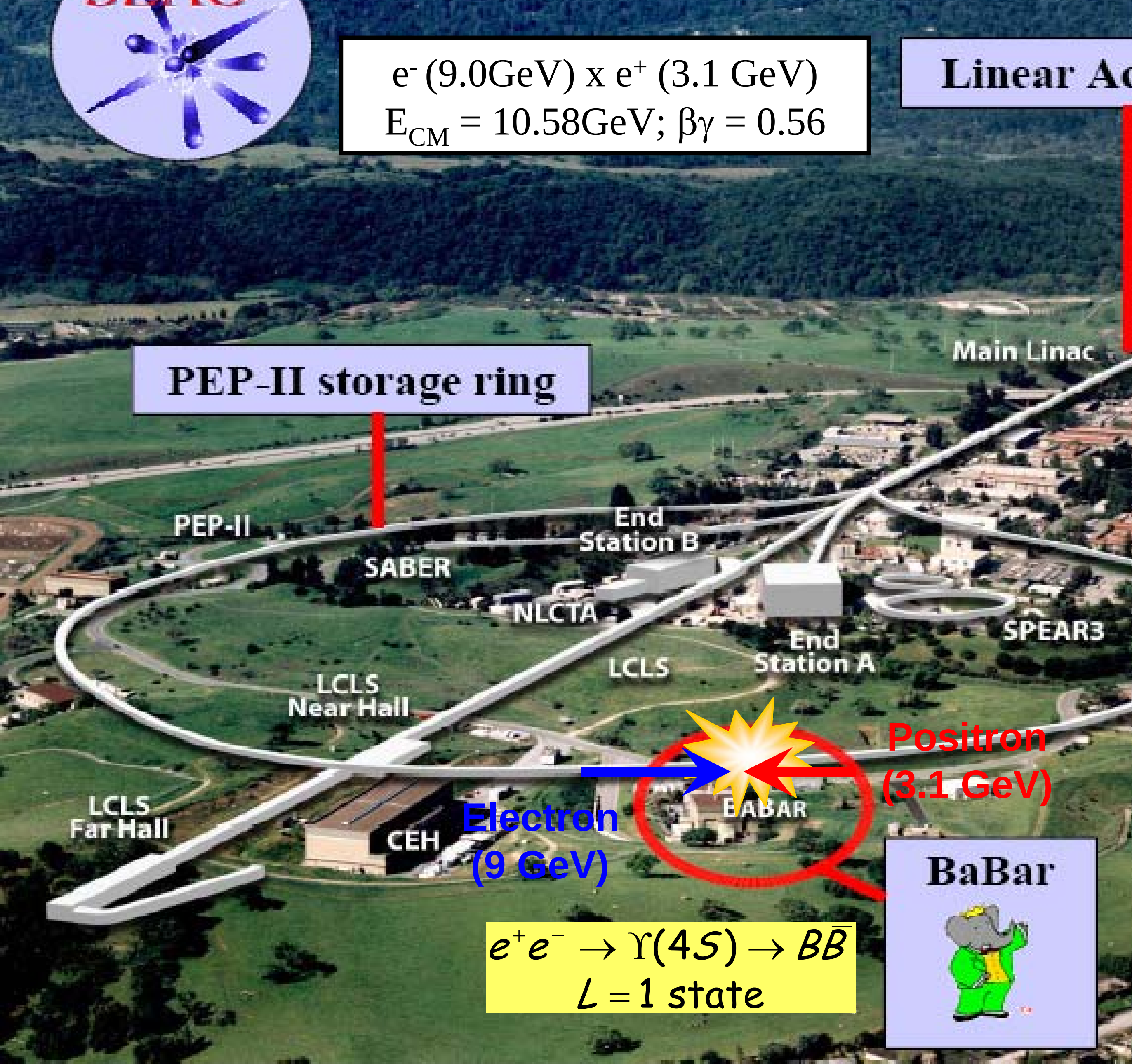
- Correction due to penguin diagram is small
  - ✓ $|\Delta S| \sim 10^{-3}$ & $|\Delta C| \sim 10^{-3}$ (hep-ph/0610120 : Factorization + Perturbative QCD)
- Theoretically clean way to measure sin2β
- Same principle for $B^0 \to \psi(2S)K_S$, $\eta_c K_S$, $\chi_{c1}K_S$, $J/\psi K^{*0}$($K^{*0} \to K_S\pi^0$)

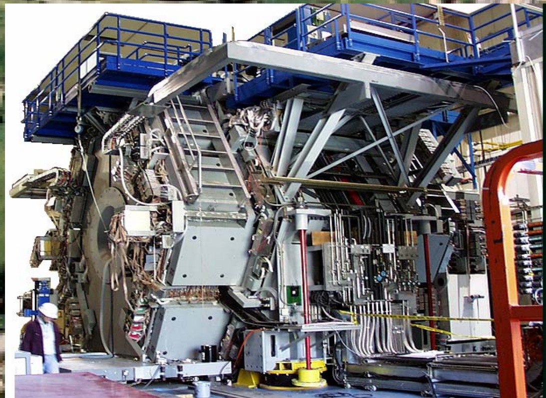
Experimental Methods

- ***Produce and reconstruct B mesons***
- ***Measure decay time of reconstructed B meson***
  - Mean decay proper time of $B^0 \sim 1.5$ ps (10^{-12} second)
  - Need precise position measurement (vertexing)
- ***Determine initial flavor of reconstructed B meson:***
  - B Flavor Tagging

The PEP-II B Factory (SLAC)

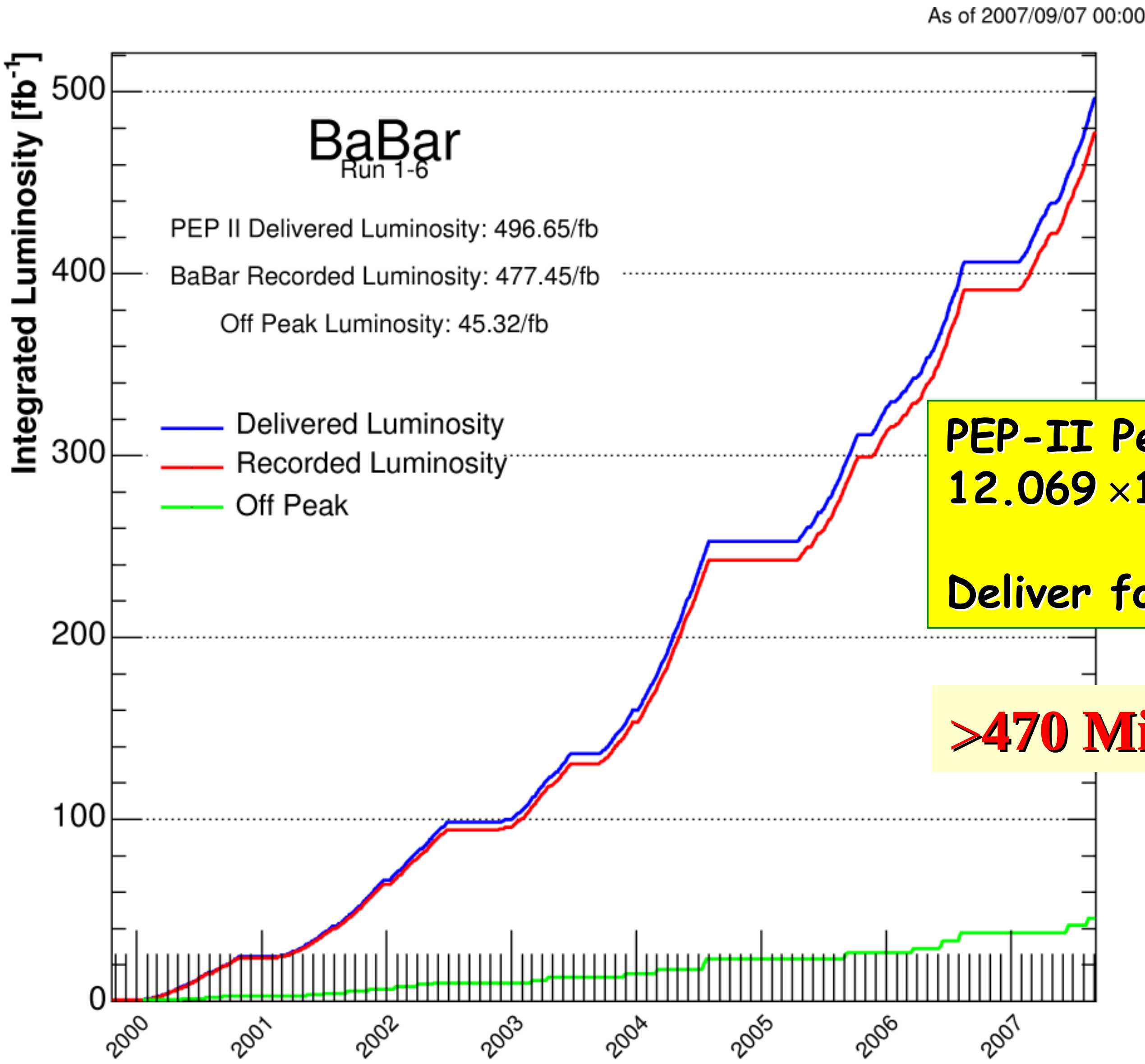
e^- (9.0GeV) x e^+ (3.1 GeV)
E_{CM} = 10.58GeV; $\beta\gamma$ = 0.56





$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$
$$L = 1 \text{ state}$$

PEPII Performance: Integrated Luminosity



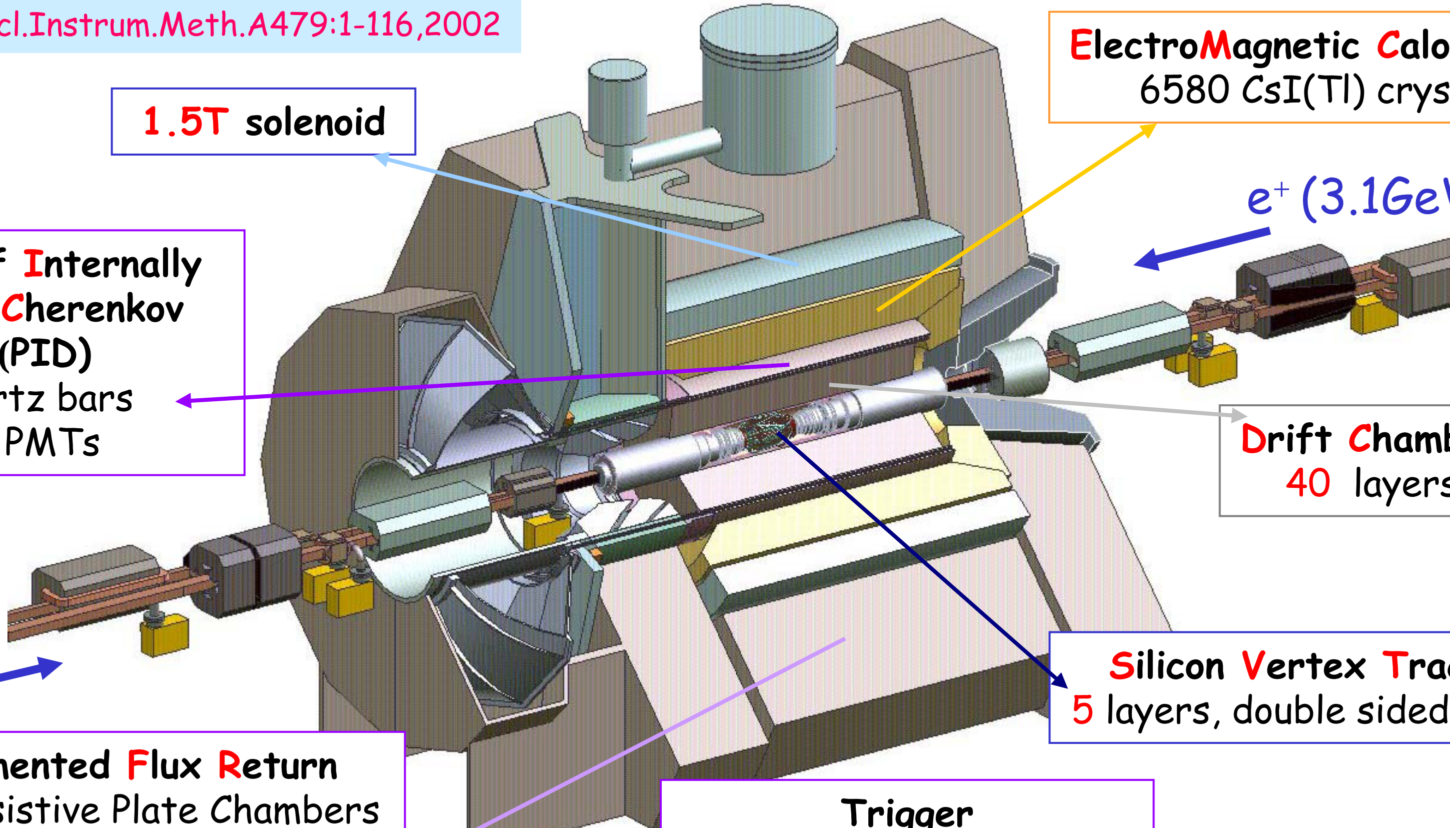
PEP-II Peak lum:
$12.069 \times 10^{33} cm^{-2} sec^{-1}$

Deliver for BaBar >496fb^{-1}

>470 Million $B\bar{B}$ pairs !!

BaBar Detector

Detail see: Nucl.Instrum.Meth.A479:1-116,2002



1.5T solenoid

ElectroMagnetic Calorimeter
6580 CsI(Tl) crystals

Detector of Internally Reflected Cherenkov light (PID)
144 quartz bars
11000 PMTs

Drift Chamber
40 layers

Silicon Vertex Tracker
5 layers, double sided strips

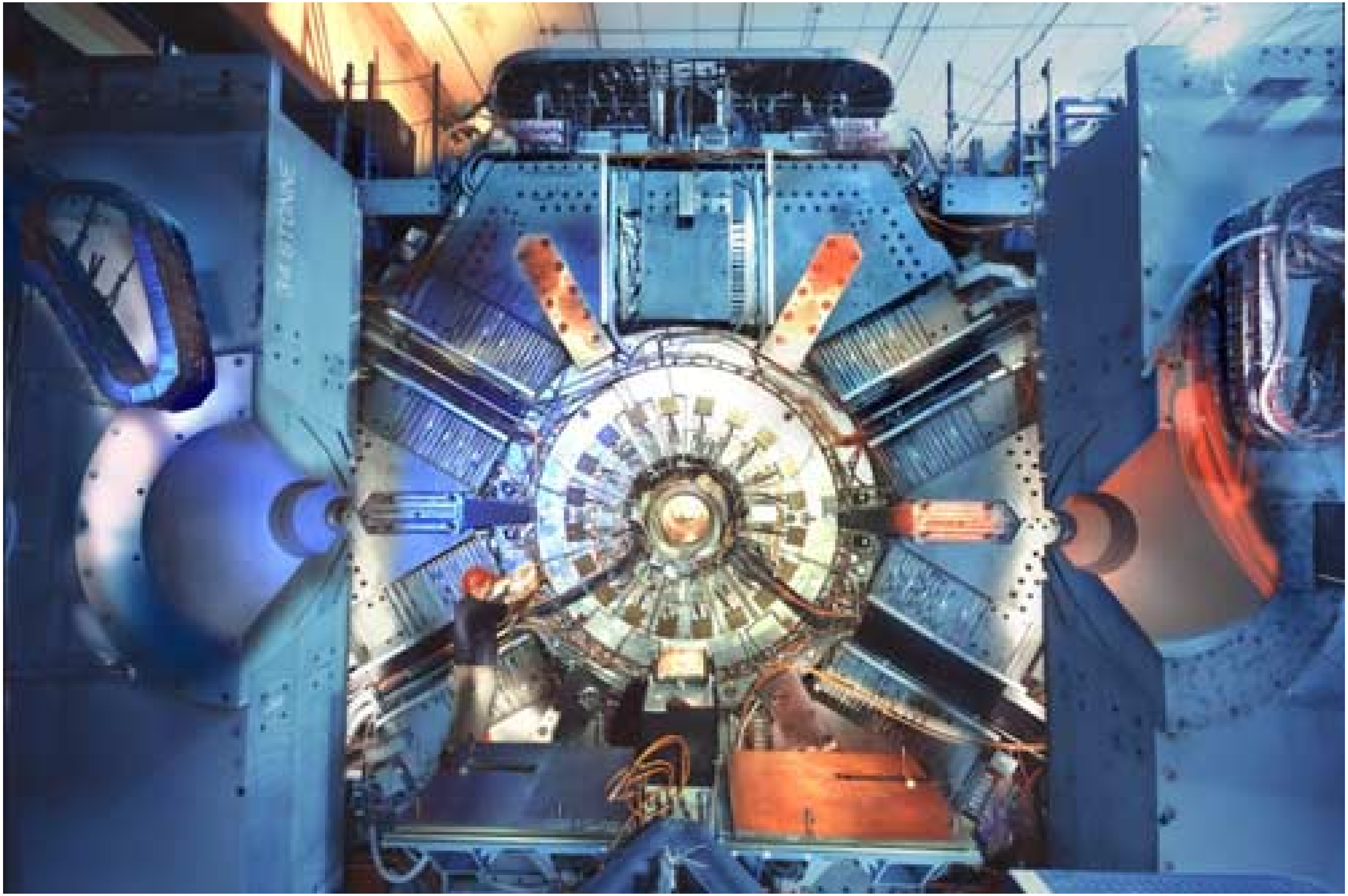
Instrumented Flux Return
Iron / Resistive Plate Chambers
or Limited Streamer Tubes
(muon / neutral hadrons)

Trigger
L1 ~2KHz, L3 120Hz
Trigger eff. ~98%

High luminosity offer great challenges to our detector

Collaboration founded in 1993
Detector commissioned in 1999
80 institutes, 11 countries, ~600 physicists

BaBar Detector



Reconstruction of B Decays

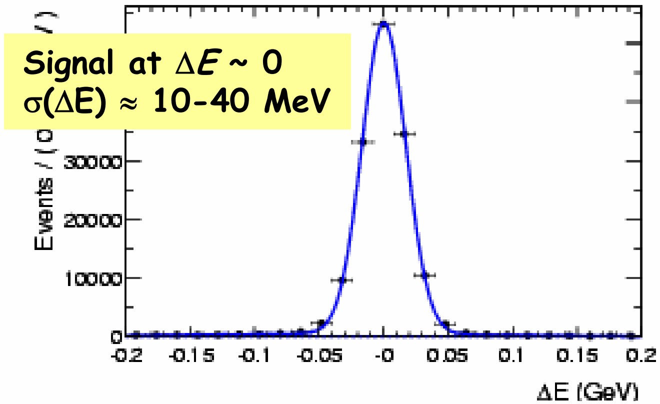
For exclusive B reconstruction, two nearly uncorrelated kinematic variables are used:

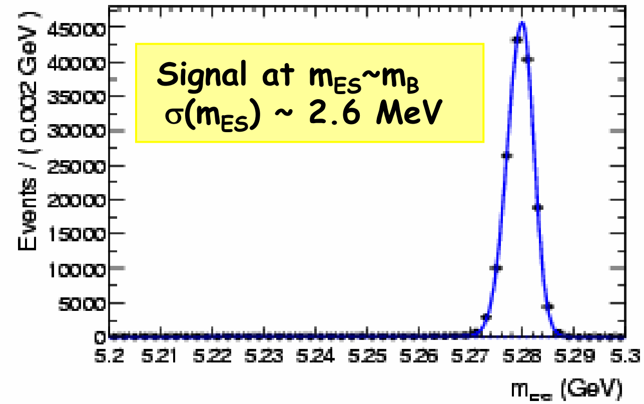
"Energy Difference"

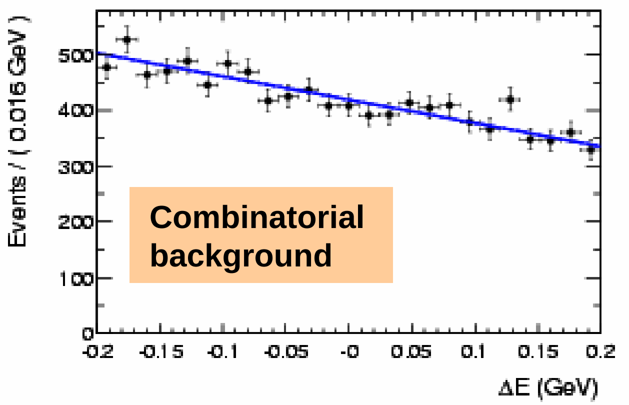
$$\Delta E = E_B^* - E_{beam}^*$$

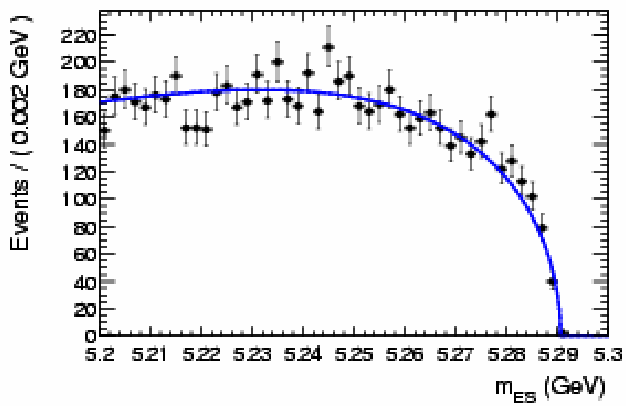
"Energy-substituted mass"

$$m_{ES} = \sqrt{\left(E_{beam}^*\right)^2 - \left(\mathbf{p}_B^*\right)^2}$$



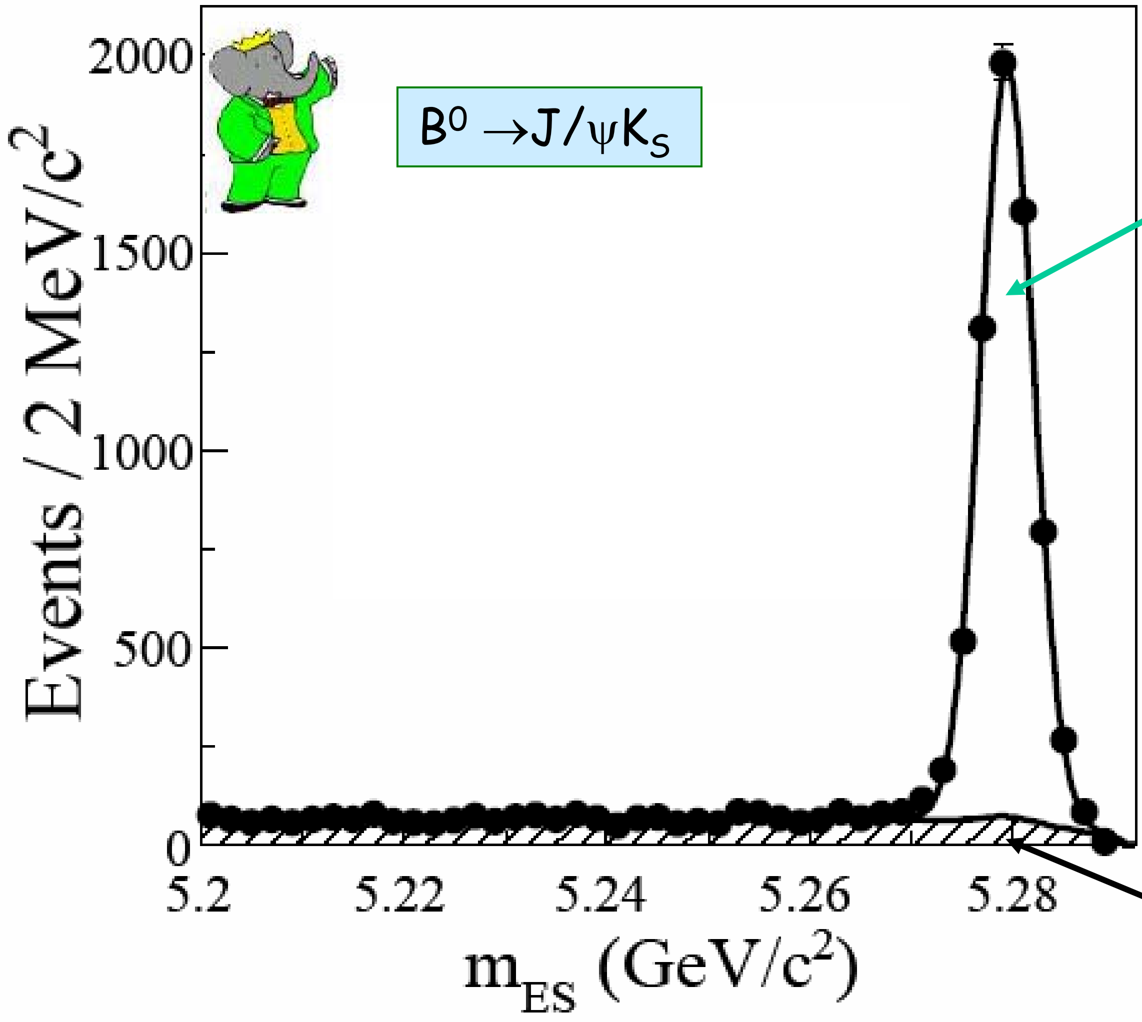






Signal Yield and Purity

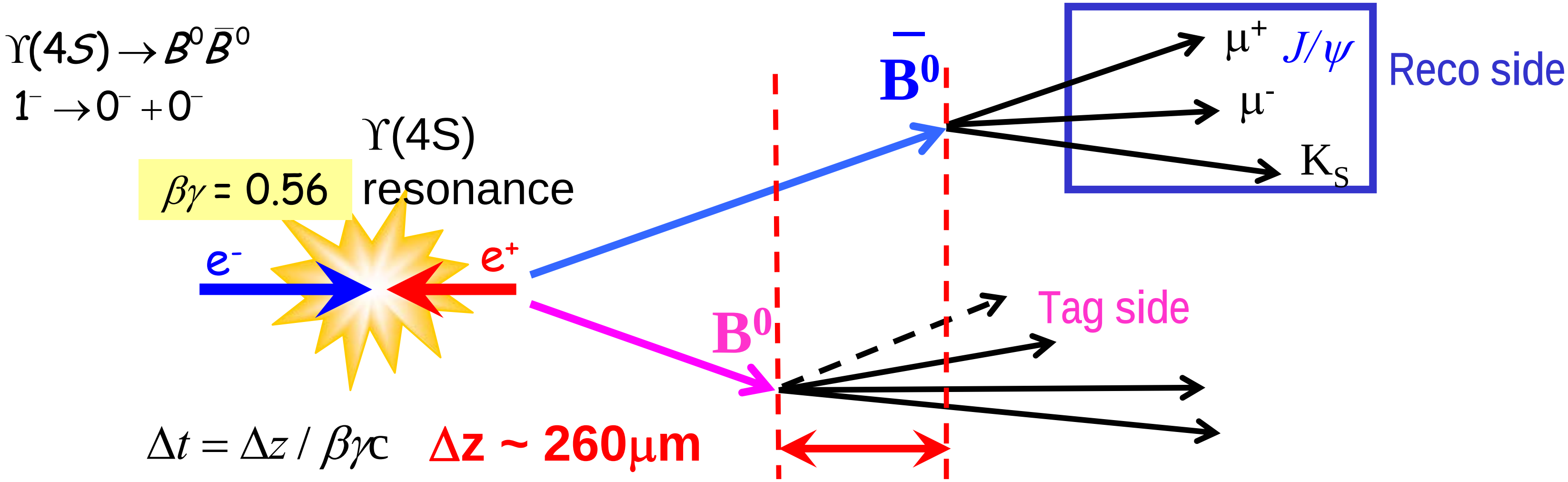
383×10^6 BBbar pairs



Signal:
N~7000
Purity > 92%

Background

Determine Δt and B Flavour



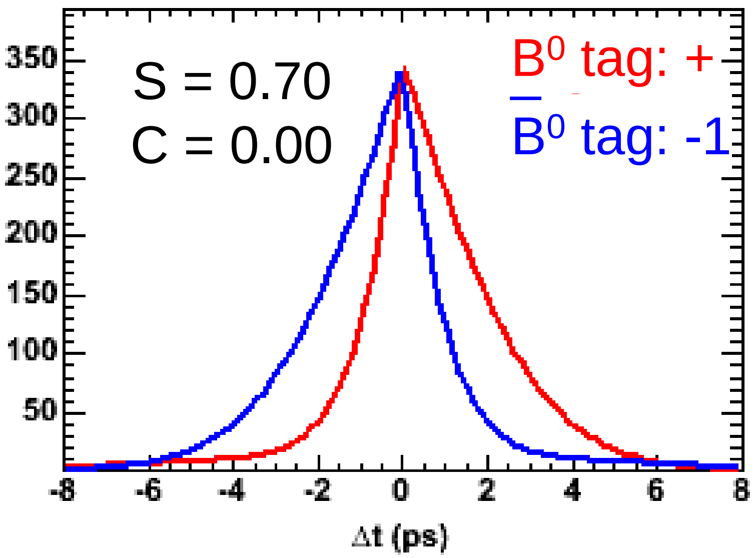
- Fully reconstruct a B meson (B_{rec}) that decays to CP/Flavor eigenstate
- Reconstruct inclusively vertex of other B meson (B_{tag}) with remaining charged tracks
- Compute decay proper time difference (Δt) between B_{rec} and B_{tag}
  - ✓ Use their vertex (Δz) difference: $\Delta t \approx \Delta z / \langle\beta\gamma\rangle c$
  - ✓ σ(Δz) ~ 60μm for B_{reco} and σ(Δz) ~ 170μm for B_{tag}

- Υ(4S) produce coherent B pair
- B^0 meson decays to flavor eigenstates ~ 100%
- Determine the flavor of B_{tag} ⇒ infer the initial flavor of B_{rec}
  - ✓ Eg: $b \rightarrow c \rightarrow e^-$ or $b \rightarrow c \rightarrow s \rightarrow K^-$
  - ✓ Effective tagging efficiency at BaBar: 30.4 ±0.3%

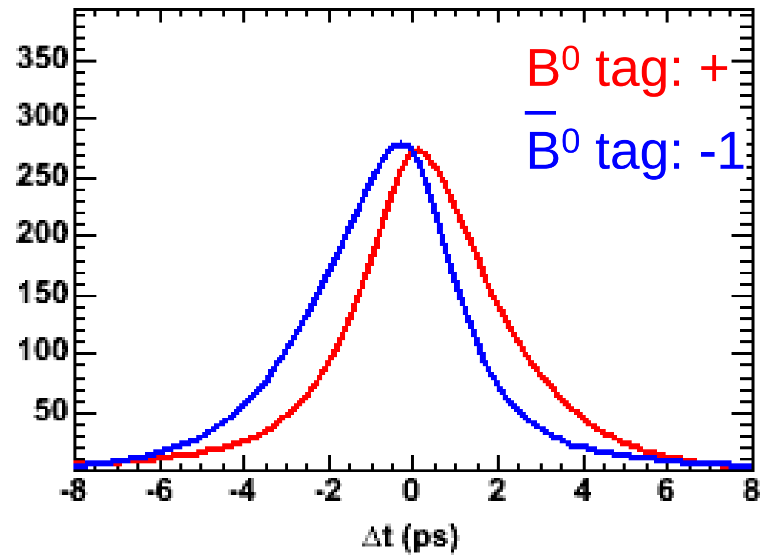
(same technique used for all time-dependent CP analyses)

CP Analysis: Time Distribution

Perfect flavor tagging & time resolution



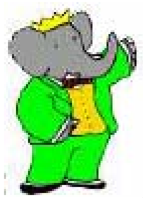
Realistic mistag probability & finite time resolution



$$f_{CP=\pm}(\Delta t) = \frac{1}{4\tau} e^{-\frac{|\Delta t|}{\tau}} \left[1 \pm (1-2w)\cdot(-C\cos\Delta m\Delta t + S\sin\Delta m\Delta)\right] \otimes R$$

- R: detector Δt resolution, w: wrong tag fraction
  - ✓ BFlav and CP sample have the same w and R
- Combined unbinned maximum likelihood fit to Δt spectra of *B*flav and *CP* samples
  - ✓ Float both sin2β and C: 66 free parameters
  - ✓ All parameters extracted from data

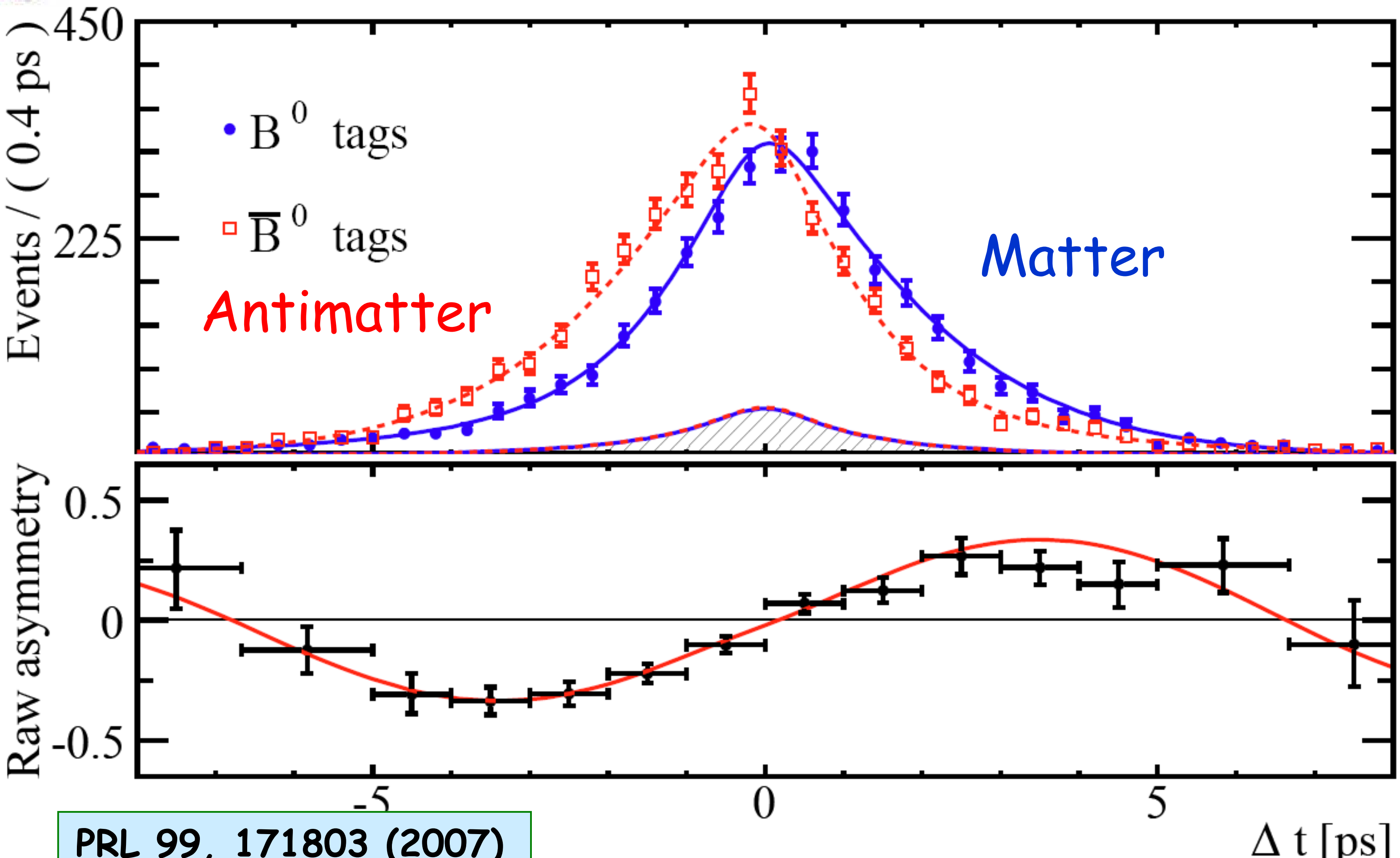
CP violation fit result from $B^0 \rightarrow (c\bar{c})K^{(*)0}$



$\sin 2\beta = 0.714 \pm 0.032 \pm 0.018$
$C = 0.049 \pm 0.022 \pm 0.017$

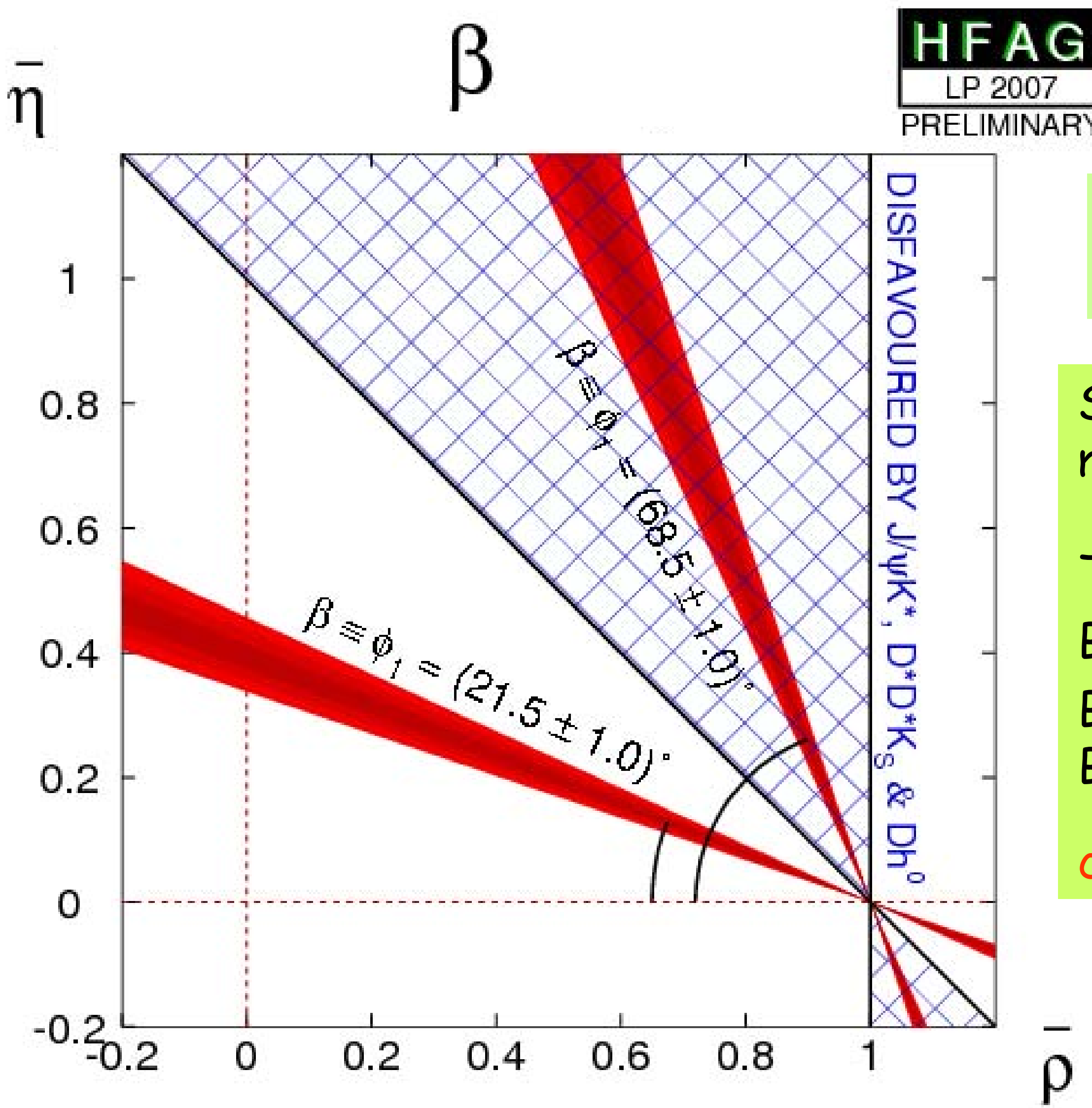
(World Average)

$\sin 2\beta = 0.68 \pm 0.025$
$C = 0.012 \pm 0.020$



PRL 99, 171803 (2007)

From sin2β to β: cos2β Measurement



2 solutions of β
β and π/2-β ambiguity

Solved by several cos2β measurement:

Time-dependent CP violation:

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

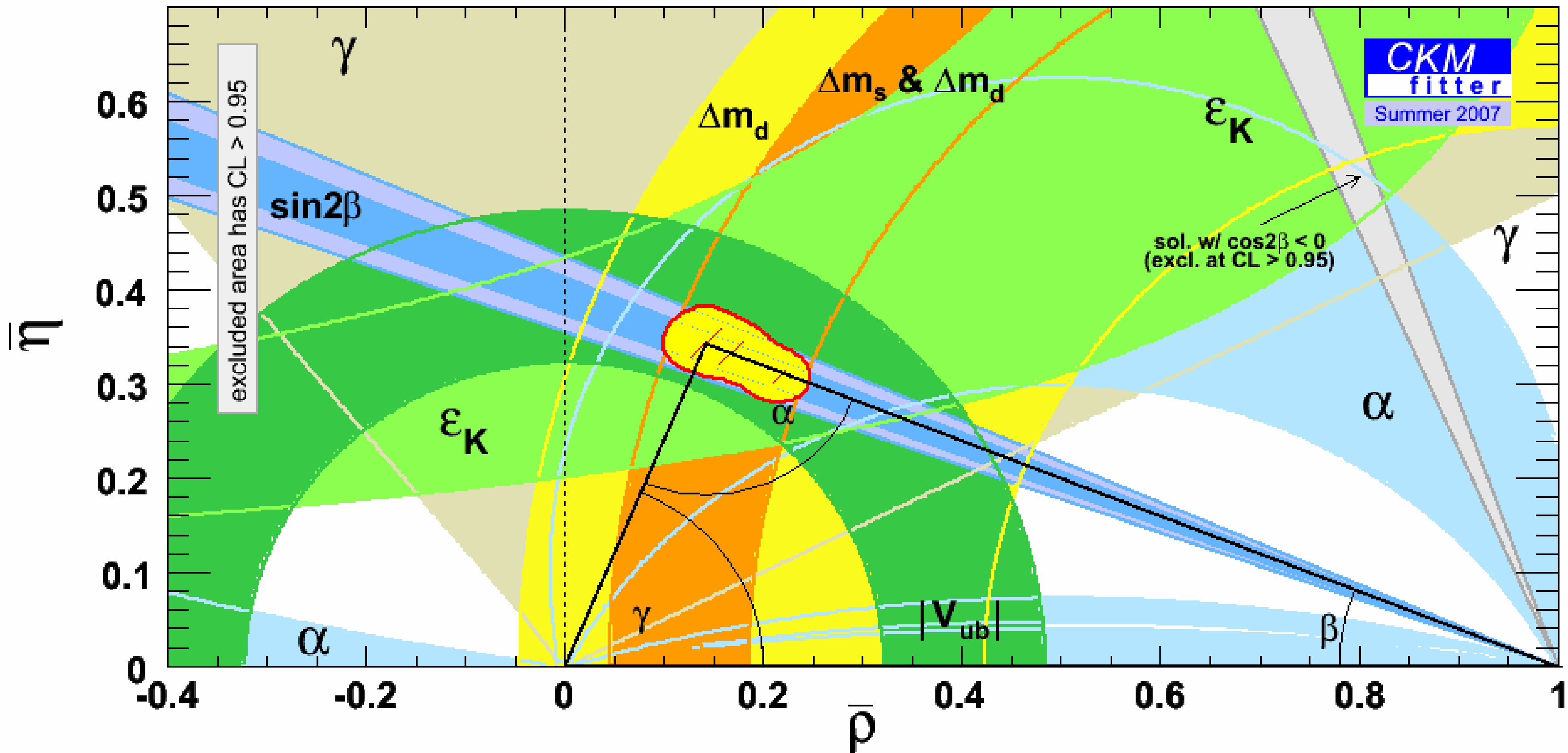
$B^0 \rightarrow D^{(*)0}h^0$ $(D^0 \rightarrow K_S\pi\pi)$

$B^0 \rightarrow D^{*+}D^{*-}K_S$

cos2β > 0 as expected in SM

PRD71:032005,2005
PRL99:231802,2007
PRD74:091101,2006

UT from CP Violation & Indirect Measurement



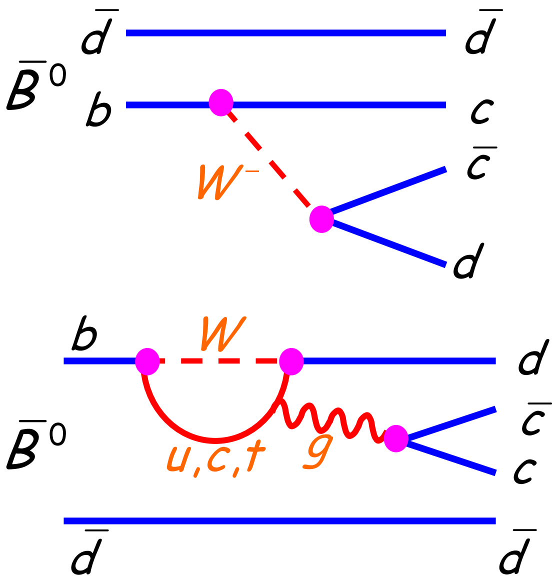
Overconstrained: growing set of independent measurements are consistent with CKM picture

Now: looking for New Physics as correction to CKM

Measure sin2β in $b \to c\bar{c}d$ ($B^0 \to D^{(*)+}D^{(*)-}$) mode

Another implication of overconstrained: redundant approaches to same CKM parameter

$B^0 \to$ $D^{*+}D^{*-}$, D^+D^-, $D^{*+}D^-$, $D^{*-}D^+$

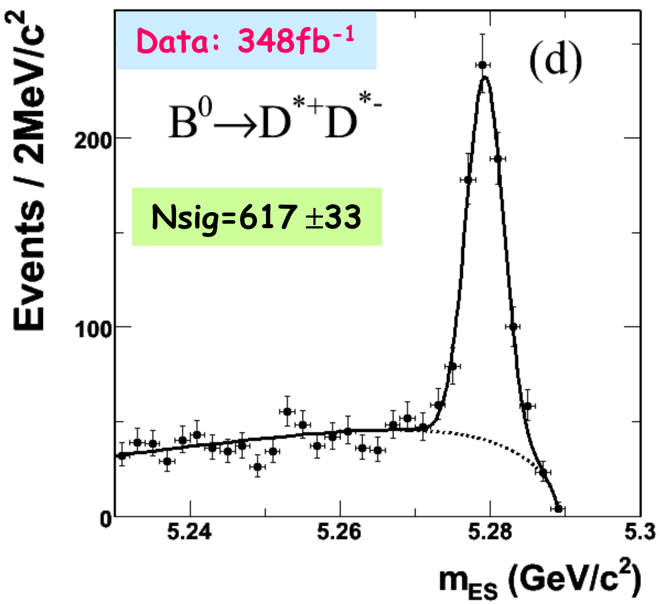


- If no penguin contribution
  - ✓ C=0 and S=-sin2β
- Penguin contribution: not negligible
  - ✓Expected to be small (Phys.Rev.D61:014010,2000)
  - ✓~5% for $B^0 \to D^{(*)+}D^{(*)-}$ (HQET + factorization)
- Possible NP contribution in loop (Phys.Lett.B395:241,1997)
  - ✓ sin2β significant different from $J/\psi K_S$ mode
  - ✓ Large non zero direct CP violation

$B^0 \to D^{*+}D^{*-}$

- P→VV decay, Mixed CP-even (L=0,2) and CP-odd (L=1) state
- $S=-(1-2R_T)\sin 2\beta$,
- Need angular analysis to extract R_T (CP odd fraction)

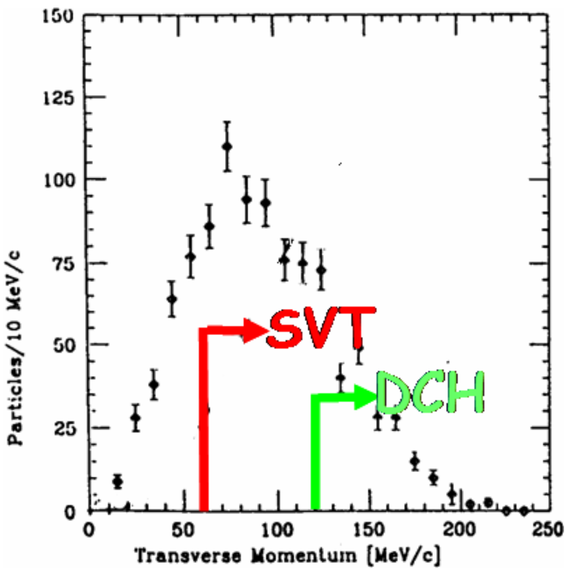
$B^0 \to D^{*+}D^{*-}$ Signal Yield

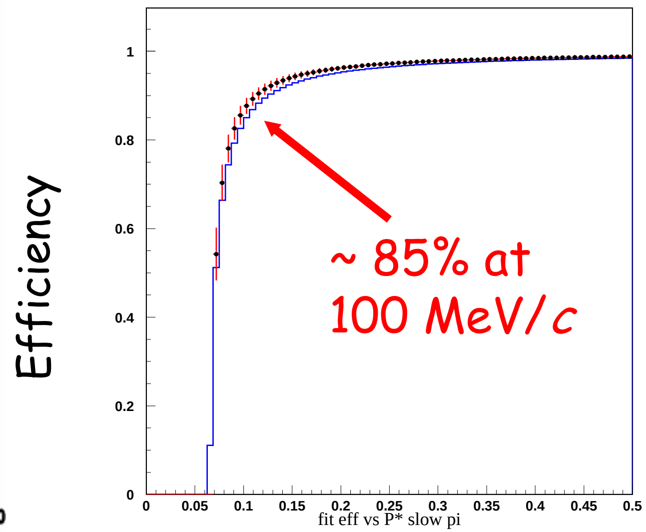


Signal eff. 2 times of Belle's:

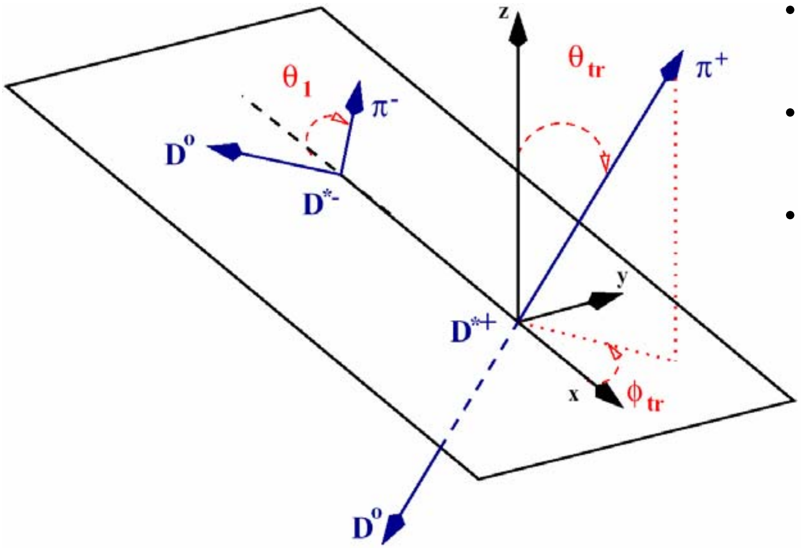
Better Reconstruction of soft π^+ from $D^{*+} \to D^0 \pi^+$ Decay at Babar due to SVT

Five double sided Silicon layer
Small mass ~4% interaction length
Large ~90% geometrical coverage in $\Upsilon(4S)$ C.M.
Standalone tracking ability
(Design studied in the R&D, not a coincidence)

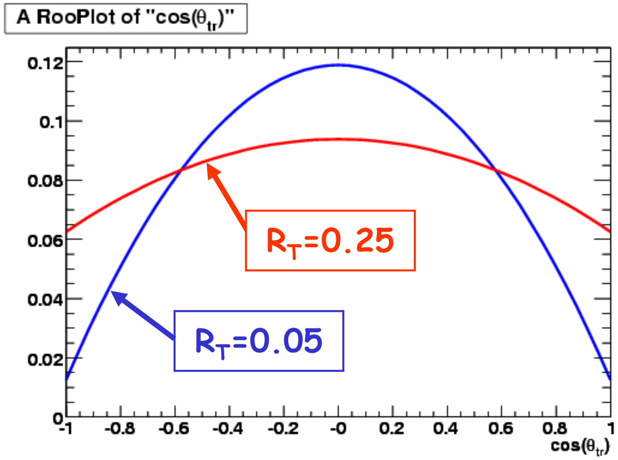




Time-integrated Transversity Analysis ($B^0 \to D^{*+}D^{*-}$)



Phy.Rev.D43:2193,1991



- θ_1: angle between π^- momentum in D^{*-} rest frame and D^{*-} flight direction in B rest frame
- θ_{tr}: angle between normal z to D^{*-} decay plane and π^+ flight direction in D^{*+} rest frame
- ϕ_{tr}: corresponding azimuthal angle

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_1 \mathrm{d}\cos\theta_{\mathrm{tr}}\mathrm{d}\phi_{\mathrm{tr}}} = \frac{9}{16\pi}\frac{1}{|A_0^0|^2+|A_\parallel^0|^2+|A_\perp^0|^2}$$

$$\Big\{ 2\cos^2\theta_1\sin^2\theta_{\mathrm{tr}}\cos^2\phi_{\mathrm{tr}}|A_0^0|^2$$

$$+\sin^2\theta_1\sin^2\theta_{\mathrm{tr}}\sin^2\phi_{\mathrm{tr}}|A_\parallel^0|^2$$

$$+\sin^2\theta_1\cos^2\theta_{\mathrm{tr}}|A_\perp^0|^2$$

$$+\frac{1}{\sqrt{2}}\sin 2\theta_1\sin^2\theta_{\mathrm{tr}}\sin 2\phi_{\mathrm{tr}}\ \Re e(A_0^{0*}A_\parallel^0)\Big\} \ ,$$

Integrated over θ_1 and ϕ_{tr}:

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{tr}}} = \frac{3}{4}(1-R_t)\sin^2\theta_{\mathrm{tr}} + \frac{3}{2}R_t\cos^2\theta_{\mathrm{tr}}.$$

Acceptance Effect

Different transversity component has different acceptance

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{tr}}} =$$
$$\frac{3}{4}(1-R_t)\sin^2\theta_{\mathrm{tr}} \times \left\{\frac{1+\alpha}{2} I_{0,0}(\cos\theta_{\mathrm{tr}}) + \frac{1-\alpha}{2} I_{\|,\|}(\cos\theta_{\mathrm{tr}})\right\}$$
$$+ \quad \frac{3}{2} R_t \cos^2\theta_{\mathrm{tr}} \times I_{\perp,\perp}(\cos\theta_{\mathrm{tr}})$$

$$R_t = \frac{|A_\perp|^2}{|A_0|^2 + |A_\||^2 + |A_\perp|^2}. \qquad \alpha = \frac{|A_0^0|^2 - |A_\|^0|^2}{|A_0^0|^2 + |A_\|^0|^2}$$

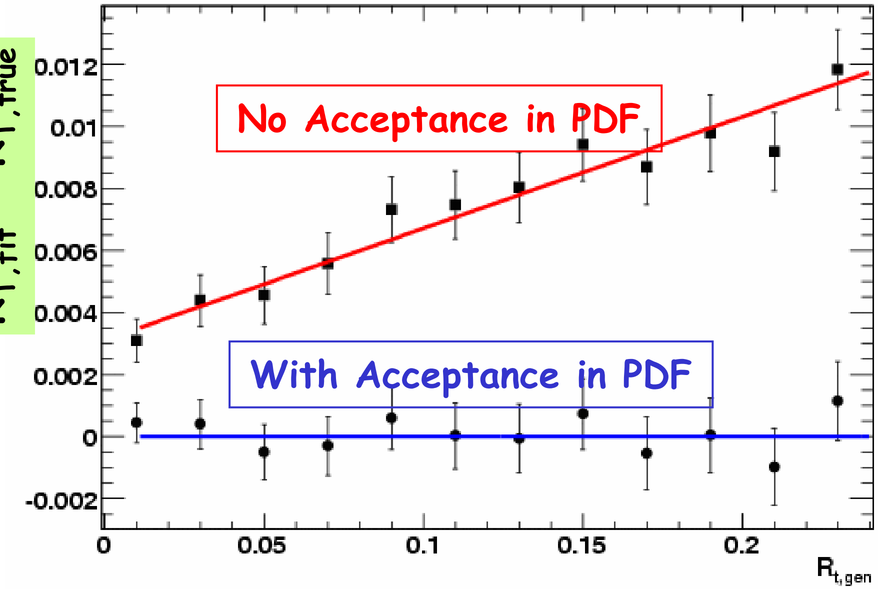
$I_0, I_\perp, I_{II}$ acceptance moments: (eff. Integral over phase space)

- CP even and odd terms may have different acceptance efficiencies
- Equal to same constant $\Rightarrow$ acceptance is uniform
- Model acceptance moments from the MC and fixed the parameter in the fit
- Acceptance moments does not deviate much from uniform

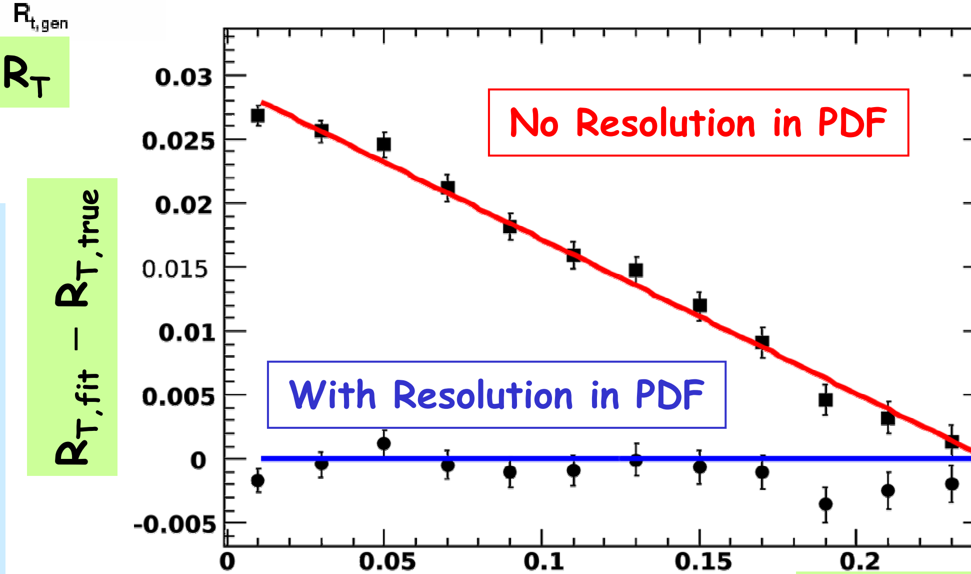
α parameter:

- Fixed to zero by default
- R_T sensitive to α only if $I_0, I_\|$ are significant different

Acceptance & Angular Resolution Effect

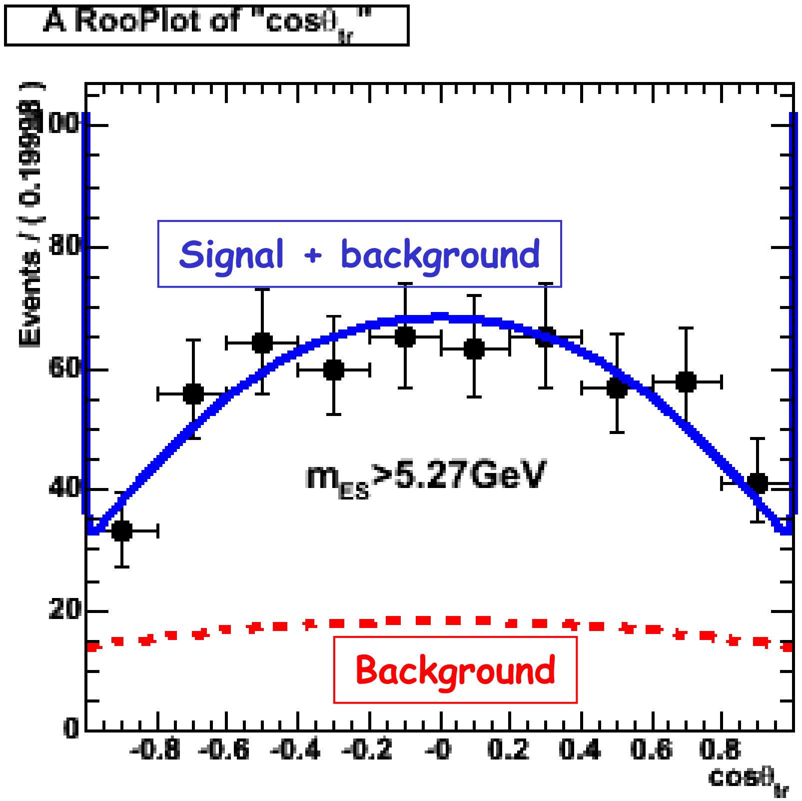


- Acceptance effect by soft pion reco. Eff.
  - ✓ Depends on minimum p_T of track that can be reconstructed
- A small effect due to BaBar SVT performance:
  - ✓ High eff. for low momentum charged tracks
- Reco eff. measured from data (D^{*+} helicity angle)
- Small corresponding sysmatic uncertainties



- Angular resolution not negligible:
  - ✓ Unlike other angular analysis
  - ✓ Large uncertainties of soft pion tracking parameters
  - ✓ Significant bias for small R_T
- Model resolution using MC simulation
- Semi-numerical convolution

Measurement Result of CP-odd Fraction



PRD-RC 76,111102 (2007) ($348fb^{-1}$)

$R_T=0.143 \pm 0.034 \pm 0.008$

Systematic Uncertainty

Angular resolution	0.0056
Acceptance Moments	0.0035
α Parameter scan	0.0026
Floating bg parameter	0.0006
Peaking background	0.0039
Total	0.0084

- Good agreement with previous BaBar & Belle results:
  - ✓ $R_T=0.125 \pm 0.044 \pm 0.007$ (BaBar: Phys.Rev.Lett.95:151804,2005, $209fb^{-1}$)
  - ✓ $R_T=0.19 \pm 0.08 \pm 0.01$ (Belle: Phys.Lett.B618:34-42,2005,$140fb^{-1}$)
- Good agreement with the theoretical calculation (Factorization)
  - ✓ $R_T \sim 0.06$ Phys.Rev.D61:014010,2000, Phy.Rev.D42:3732,1990
  - ✓ $R_T \sim 0.1$ Eur.Phys.J.C46:367-377,2006

Time-dependent CP + Angular Analysis

- If CP analysis by fit Δt only:
  - ✓ $S=-(1-2R_T)\sin 2\beta$
  - ✓ Loss of statistical power
  - ✓ Need to assume the same C and S for CP-even and Odd components
- Solution: time-dependent CP and angular analysis (2D PDF)
  - ✓ Correction for acceptance not necessary if float "R_T"
  - ✓ No bias for CP parameters

2-Dimentional signal PDF

$$\frac{1}{\Gamma}\frac{d^2\Gamma(\overset{(-)}{B^0}\to D^{*+}D^{*-})}{dz\,dt} = \frac{9}{32\pi}e^{-\Gamma t}\{ [(1-R_t)G_+(z)+R_tG_-(z)] \overset{(-)}{+} [C_+(1-R_t)G_+(z)+C_-R_tG_-(z)]\cos\Delta m_d t \overset{(+)}{-} [S_+(1-R_t)G_+(z)-S_-R_tG_-(z)]\sin\Delta m_d t\};$$

$z=\cos\theta_{tr}$

$$G_+(z) = \frac{8\pi}{3}(1-z^2) = \frac{8\pi}{3}\sin^2\theta_{tr}$$
$$G_-(z) = \frac{16\pi}{3}z^2 = \frac{16\pi}{3}\cos^2\theta_{tr},$$

$$C_+ = \frac{C_\parallel|A_\parallel^0|^2 + C_0|A_0^0|^2}{|A_0|^2+|A_\parallel|^2}$$
$$S_+ = \frac{S_\parallel|A_\parallel^0|^2 + S_0|A_0^0|^2}{|A_0|^2+|A_\parallel|^2}$$

CP parameters for CP-even states

CP parameters for CP-odd state

$$C_- = C_\perp$$
$$S_- = S_\perp.$$

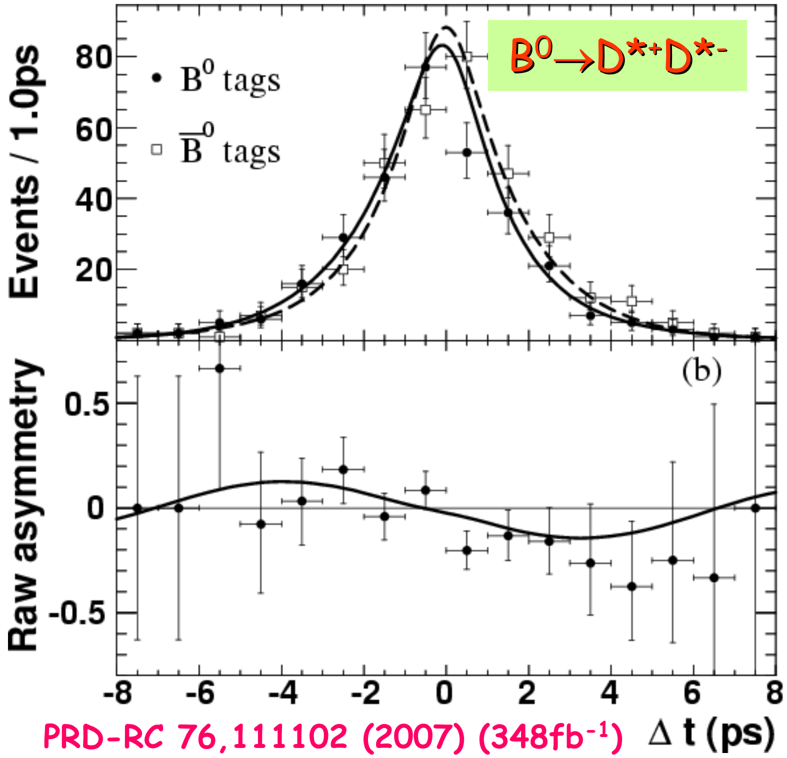
CP violation fit result from $B^0 \to D^{*+}D^{*-}$

- Unbinned maximum likelihood fit to m_{ES},Δt, and $\cos\theta_{tr}$ distributions (79 parameters)
  - ✓ Tagging and Δt resolution parameters fixed from BFlav
  - ✓ Most parameters are determined from data, except
    - Angular resolution
- Validate fitting procedure using signal & generic MC
  - ✓ No biased for CP parameters

$C_+=-0.05 \pm 0.14 \pm 0.02$ $C_-=-0.23 \pm 0.67 \pm 0.10$
$S_+=-0.72 \pm 0.19 \pm 0.05$ $S_-=-1.83 \pm 1.04 \pm 0.23$

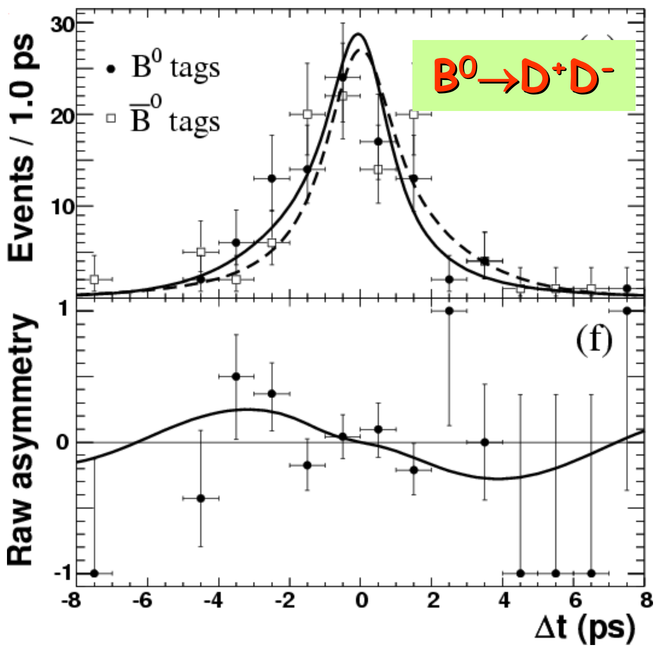
Assume same C and S for CP-even & odd terms
$C=-0.02 \pm 0.11 \pm 0.02$ $S=-0.66 \pm 0.19 \pm 0.04$

- Result consistent with SM expectation
  - ✓ No evidence of direct CP violation
  - ✓ Mix induced CP violation: 3.7σ



PRD-RC 76,111102 (2007) ($348fb^{-1}$)

CP Violation in $B^0 \to D^+D^-$, $D^{*+}D^-$ & $D^{*-}D^+$

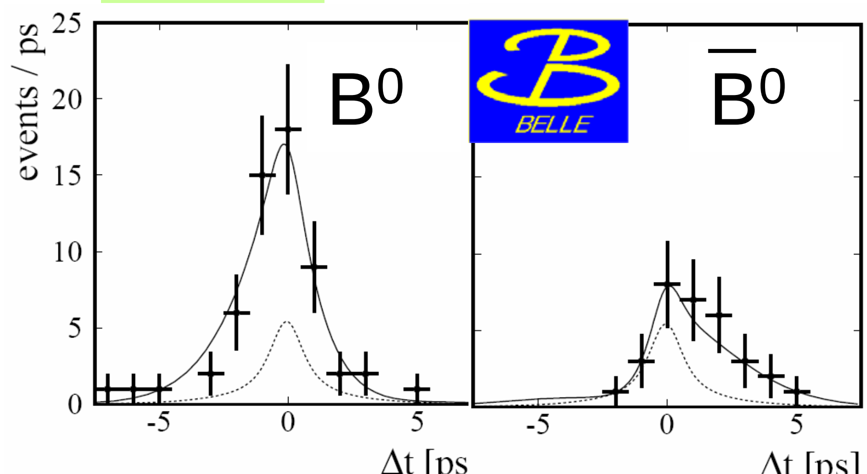


$B^0 \to D^+D^-$

Phys. Rev. Lett. 99, 071801 (2007) (348fb^{-1})

- Result consistent with SM expectation
  - ✓ C=0.11±0.22±0.07, S=-0.54±0.34±0.06
  - ✓ No evidence of direct CP violation seen by Belle
    - ✓ C=-0.91±0.23±0.09 (Belle)
    - ✓ S=-1.13±0.37±0.09 (Belle)
- Inconsistent with Belle's result: > 3σ
  - ✓ Need more data

$B^0 \to D^+D^-$



PRL98:221802,2007

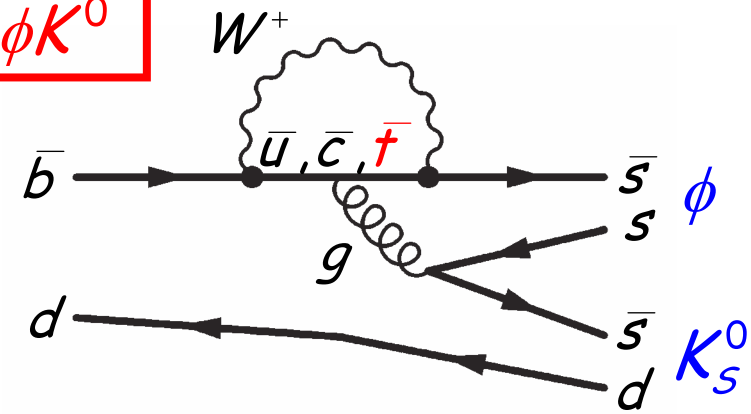
$B^0 \to D^{*+}D^-$ & $D^{*-}D^+$

- Significance of CP violation: > 4σ
- Result consistent with SM expectation
- No evidence of direct CP violation

Measure sin2β in $b \to s\bar{s}s$ (Penguin) Modes

QCDF (Beneke, PLB620 (2005) 143-150; Cheng, Chua, Soni, PRD72 (2005) 094003; …) and SCET (Williamson, Zupan, hep-ph/0601214) allows to estimate ΔS: *expect positive deviation for almost all modes*

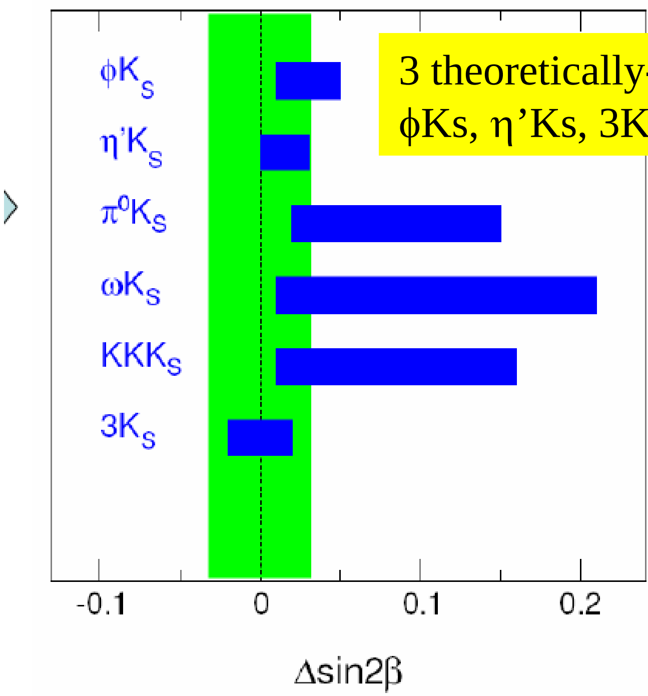
$B^0 \to \phi K^0$



"Internal Penguin"

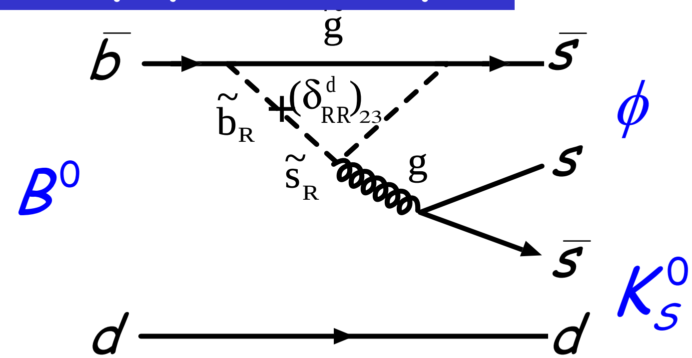
some of recent QCDF estimates

$\sin 2\beta^f_{eff} - \sin 2\beta$



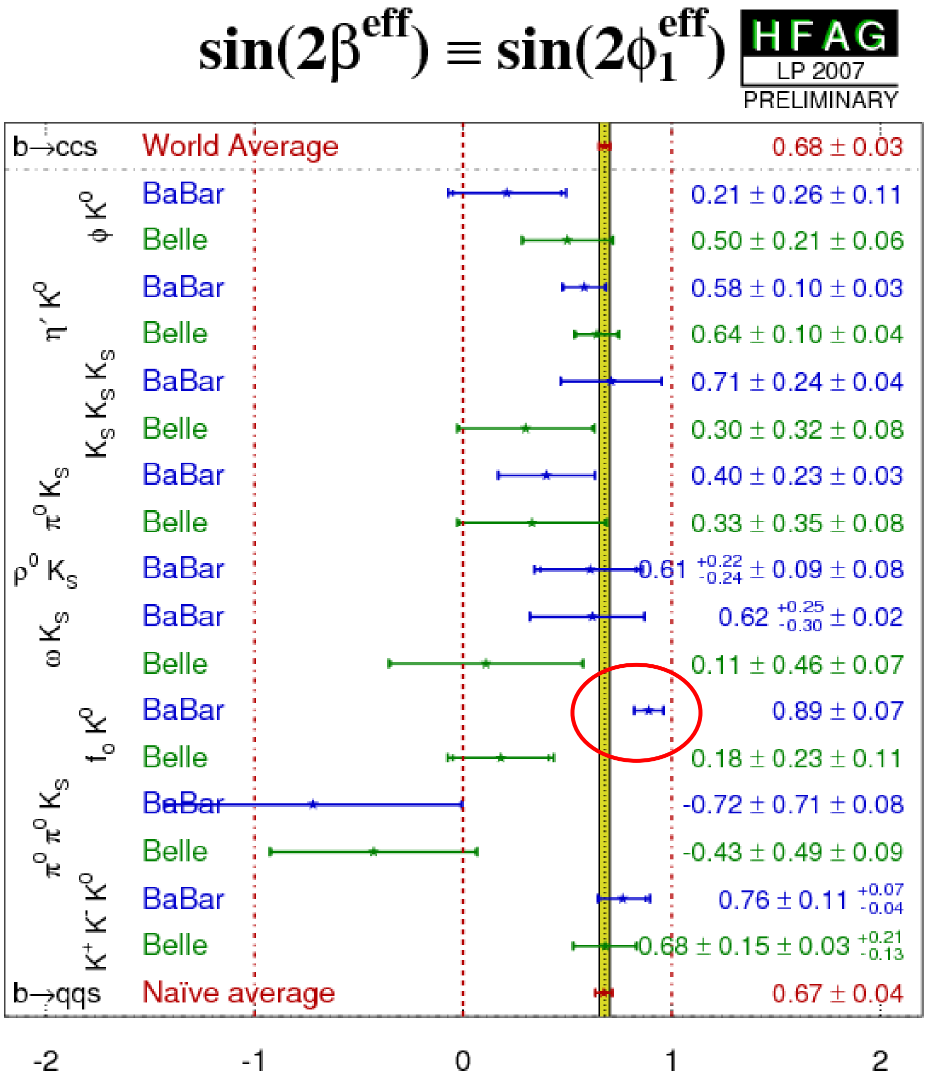
3 theoretically-clean modes
φKs, η'Ks, 3Ks

New physics in loops?



E.g.: SUSY contribution with new phases

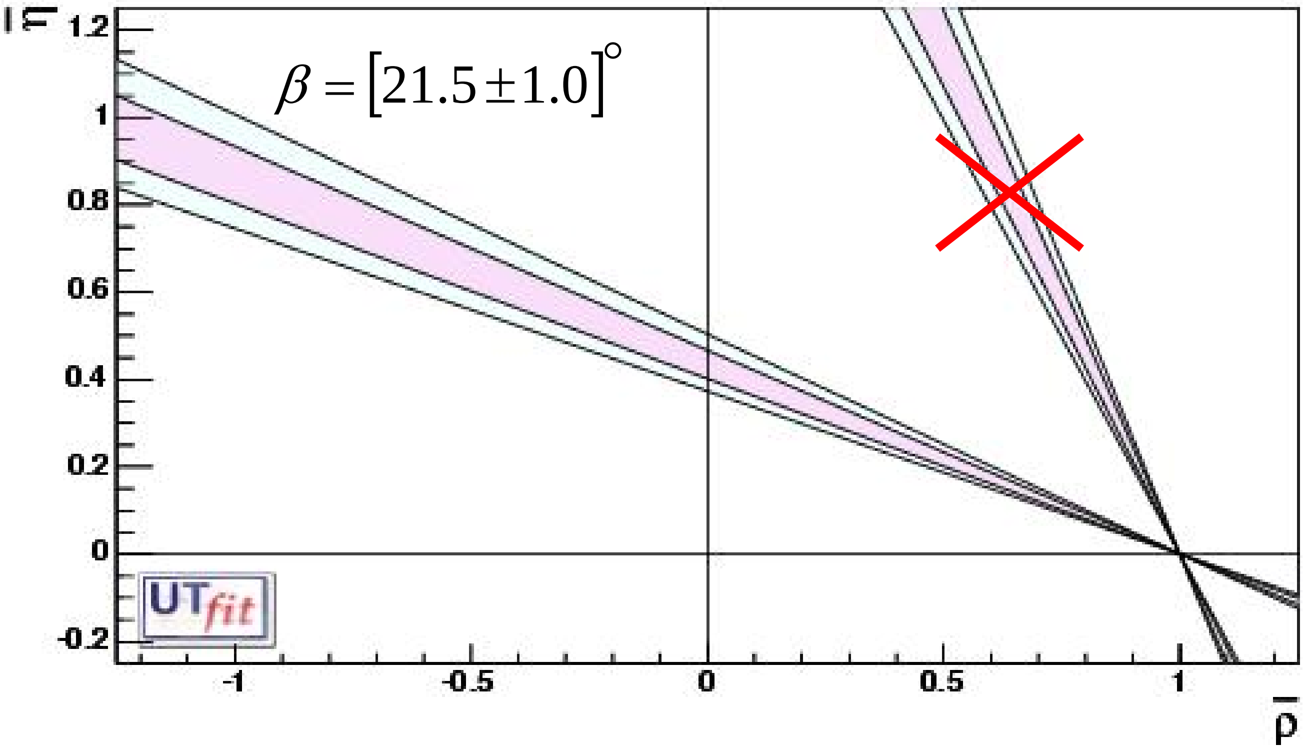
Summary of BaBar/Belle b→s Results



- Naïve average of all b→s modes (BaBar+Belle)
  - ✓ $\sin 2\beta^{eff}$=0.67±0.04
  - ✓ Consistent with $\sin 2\beta$ in Golden modes
  - ✓ Poor fit: χ^2=32/16 dof (C.L. 0.01)
- Need extremely cautious when interoperating the average
  - ✓ Assumption of Gaussian errors not justified for all measurements
- Average without f^0K^0 mode:
  - ✓ $\sin 2\beta$eff=0.56±0.05
  - ✓ χ^2=16/15 dof (C.L. 0.25)
  - ✓ 2σ from the one in charmonium modes

More statistics crucial for mode-by-mode studies

Summary of CKM Phase β Measurement

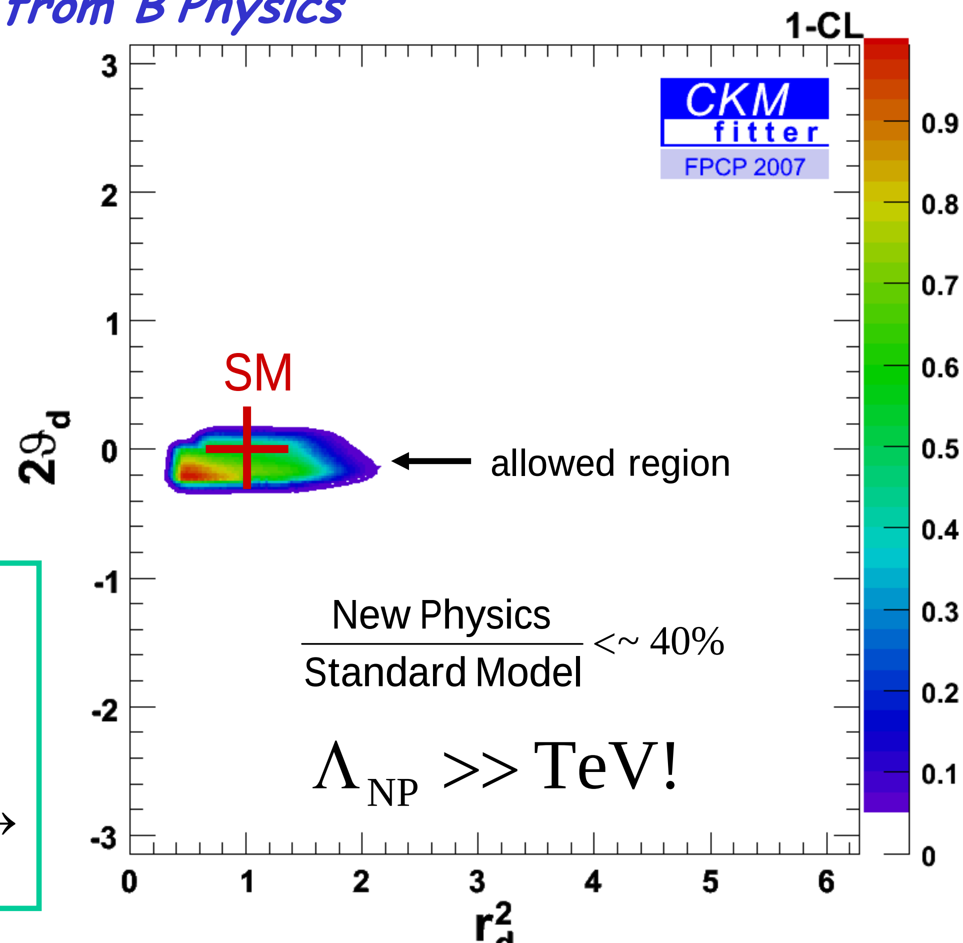


- β determined at 1 degree precision
  - ✓ Based on sin2β in charmonium modes and cos2β > 0
- No sign of NP from $\sin 2\beta_{eff}$ measured in $B^0 \to D^{(*)+} D^{(*)-}$
- Possible hints of NP effect from $\sin 2\beta_{eff}$ in penguin mode:
  - ✓ **hits of 1-2σ deviation from SM** (need more statistics)

Constraining NP from Flavor (B) Physics

- *New Physics ⇒ New source of CP violation*
  - E.g. SUSY: 59(41) new CP-conserving (violating) parameters (phases)
  - New Physics scale is expected to be ~ 1 TeV
- *"Model-Independent" constraint from B Physics*
  - Assume 3 generation of CKM,
  - no NP in tree level
  - Add new amplitude to B_d mixing

$$r_d^2 e^{i2\theta_d} \equiv \frac{A_{SM} + A_{NP}}{A_{SM}}$$



New Physics Flavor Problem:

Why no NP effect in B decays?

If new physics lives at the TeV scale, a generic flavor structure is disfavored → Minimal Flavor Violation

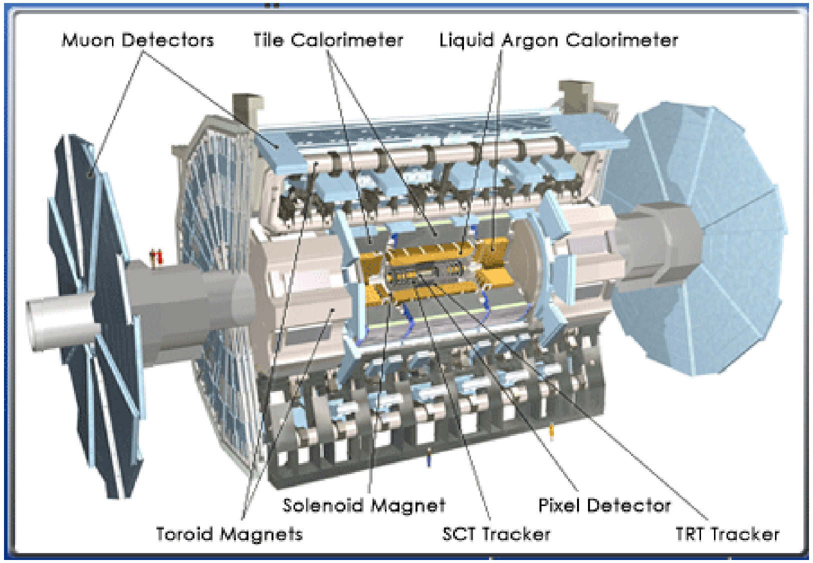
Current Status of B Physics

- ***Significant understanding of CP violation in last 10 years***
  - Firmly established CKM mechanism as the primary source of CP violation we have observed so far in the quark sector.
  - Test SM with precise measurements from B factories.
  - No obvious sign of deviation from SM.
  - Too small to explain the matter & anti-matter asymmetry in Universe
  - Any new physics found at the LHC has to obey constraints provided by BaBar and Belle

- ***More open questions aroused:***
  - New Physics flavor puzzle: (why no NP evidence in B if Λ_{NP}~1TeV?)
  - CP violation in the lepton sectors ?
  - ……

Looking into the Future

- The ultimate frontier machine will be the LHC. We may finally have a first clean glimpse of the physics beyond the Standard Model
- Many interesting physics programs:
- The ("one of") highest priority (ies):
  - ✓ Search for & observe SM Higgs
  - ✓ Search for & discover NP beyond SM:
    - Pay attention to flavor physics sector:
    - Help disentangle different NP scenarios using precision measurements from flavor physics



- Understand LHC detector
  - ✓ Essential to achieve "ground breaking" discoveries at LHC
- Ongoing detector R&D for the future HEP experiments
  - ✓ LHC upgrade, ILC and new neutrino experiments etc.
  - ✓ Key to understand the NP seen in LHC and future of particle physics

Conclusion and Prospect

…… the beginning of the 21st century will be as important for physics as the beginning, the first 50 years, of the 20th century, and the LHC is going to be the first machine to make the first discovery ……

- T.D. Lee

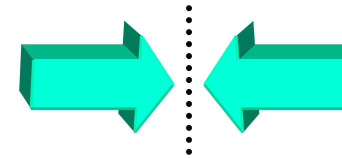
A bright future for particle physics !

We are lucky to be here to make it happen !

Additional Slides for Reference

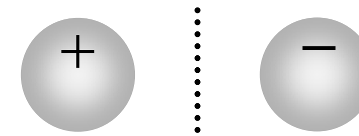
Important Discrete Symmetries

- ***Parity, P:***
  - Reflect a system through the origin, thereby converting right-handed into left-handed coordinate systems
  - Thought to be conserved by all the interactions just as C & T symmetries before 1956 (C.S.Wu experiment demonstrate P violation in weak interaction)



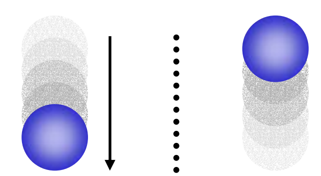
$$\mathbf{r} \to -\mathbf{r}$$
$$\mathbf{p} \to -\mathbf{p}$$
$$\mathbf{L} \to \mathbf{L}$$

- ***Charge Conjugate, C:***
  - Change particles into anti-particles and vice versa



$$e^- \to e^+$$
$$\gamma \to \gamma$$

- ***Time Reversal, T:***
  - Reverse the arrow of time, reversing all time-dependent quantities, e.g. momentum



$$t \to -t$$

Good symmetries of strong and electromagnetic forces

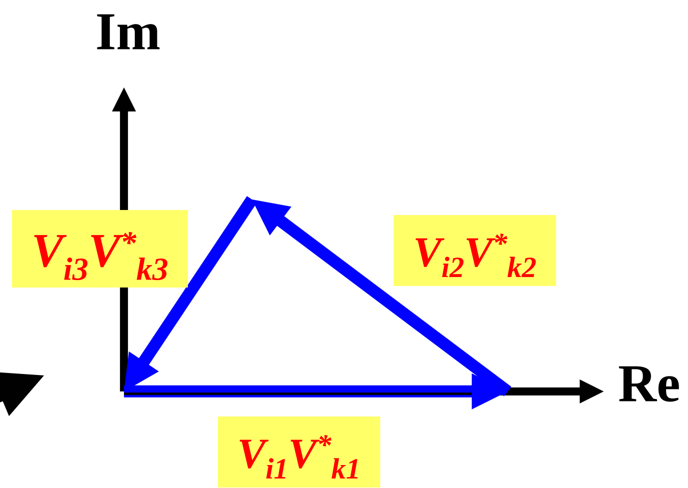
The Unitarity Triangle

V is unitarity ⇒

$$\sum_{j=1}^{3} V_{ij} V_{ji}^{*} = 1$$

$$\sum_{j=1}^{3} V_{ij} V_{kj}^{*} = 0 \ (k \neq i)$$

geometric representation:
triangle in complex plane



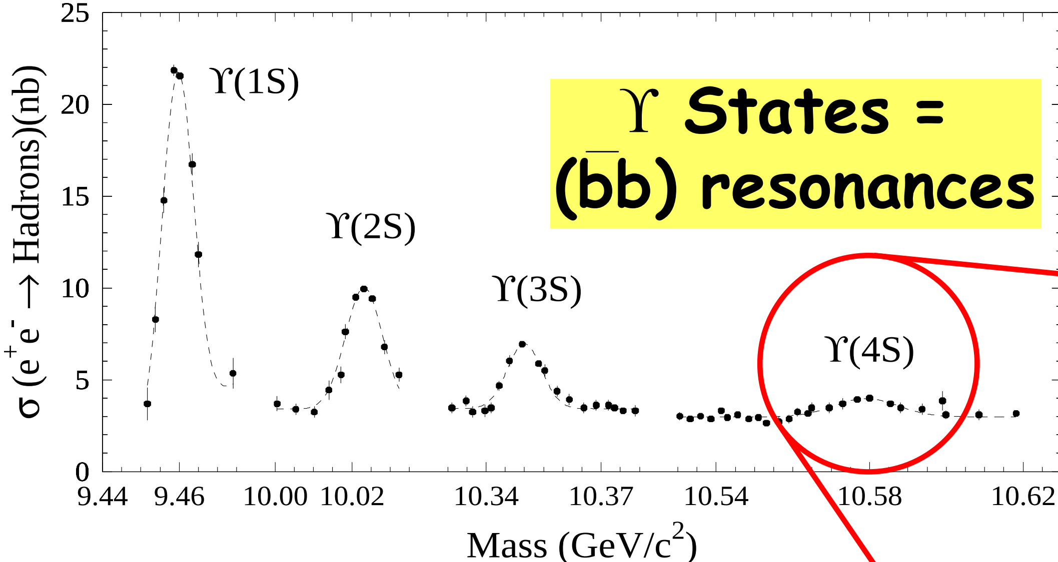
There are 6 triangles

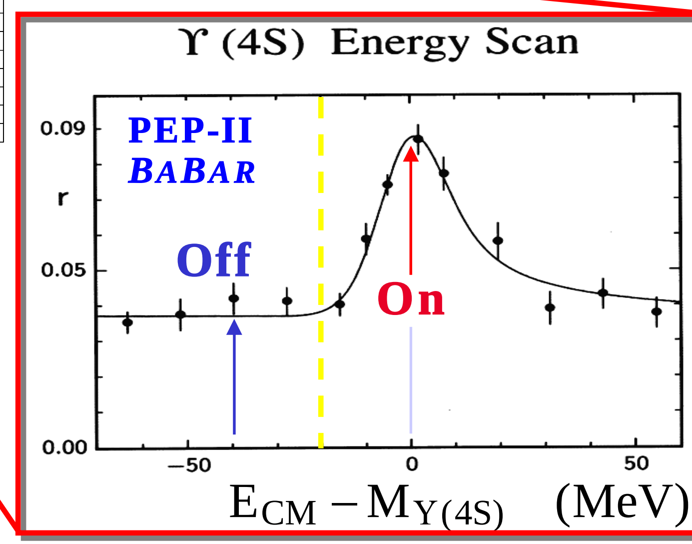
Kaon UT $0 = \frac{V_{ud}V_{us}^*}{V_{cd}V_{cs}^*} + \frac{V_{cd}V_{cs}^*}{V_{cd}V_{cs}^*} + \frac{V_{td}V_{ts}^*}{V_{cd}V_{cs}^*} \sim O\left(\frac{\lambda}{\lambda}\right) + O(1) + O\left(\frac{A^2\lambda^5}{\lambda}\right)$ flat

Beauty UT $\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{cd}V_{cb}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$

n.b. these triangles are ***rescaled*** by one of the sides

Production of B Mesons





Cross Section at ϒ(4S):

$b\overline{b} \sim 1.1\,\text{nb}$

$c\overline{c} \sim 1.3\,\text{nb}$

$d\overline{d}, s\overline{s} \sim 0.3\text{nb}$

$u\overline{u} \sim 1.4\,\text{nb}$

$\tau\overline{\tau} \sim 0.9\,\text{nb}$

Collect 11 BB pairs/second

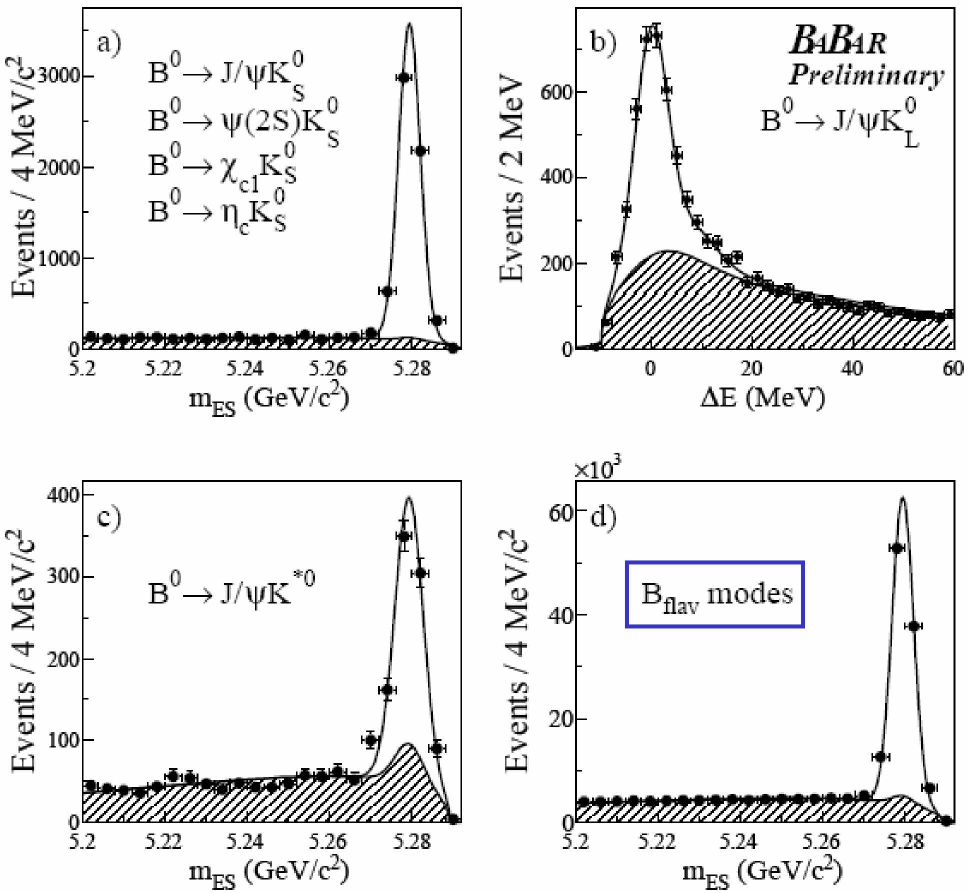
@ Luminosity=1.0 $\times 10^{34}$ cm^{-2}sec^{-1}

B factory is also a Charm/Tau factory

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$$

$$L = 1 \text{ state}$$

Signal Yield and Purity



PRL 99, 171803 (2007)
348 fb^{-1} data

- Signal Model: single Gaussian
- Background: η_f=-1 and BFlav
  - ✓ Argus function
  - ✓ $[1-(m_{ES}-m_0)^2]^{1/2}\exp[\kappa(1-(m_{ES}-m_0)^2]$
  - ✓ endpoint m_0 fixed to 5.2892GeV
- Background: η_f=+1
  - ✓ Using MC and sideband
- Peaking background
  - ✓ Small contributions
  - ✓ Estimated using large MC

BFlav sample:

✓ $B^0 \to D^{(*)-} h^+ (h^+ = \pi^+, \rho^+, a_1^+)$

✓ Used for tag & resolution determination

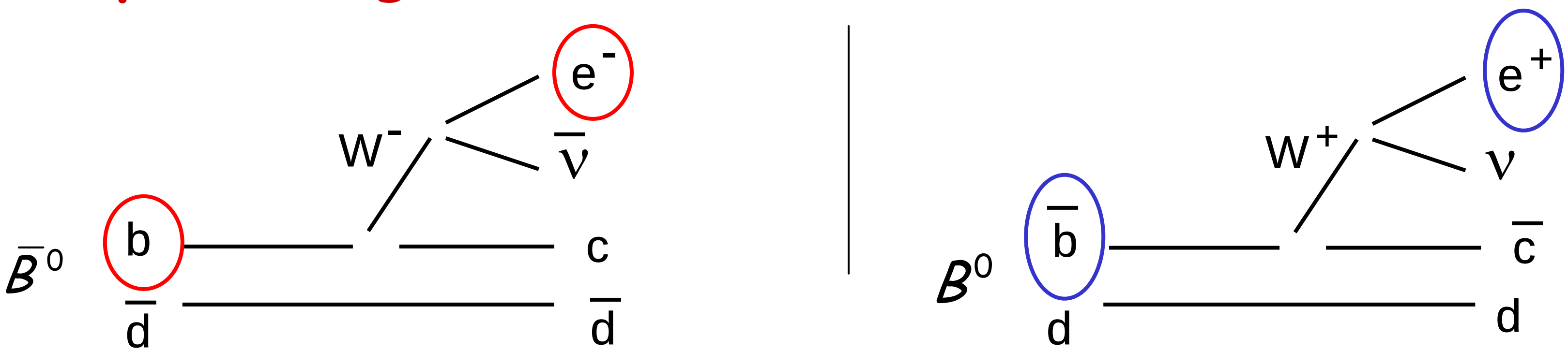
✓ See later slides

Sample	N_{tag}	$P(\%)$
Full CP sample	12677	75
$J/\psi K^0_S, \psi(2S)K^0_S, \chi_{c1}K^0_S, \eta_c K^0_S$	6863	92
$J/\psi K^0_L$	4748	55
$J/\psi K^{*0}$	1056	66
B_{flav} sample	123893	85

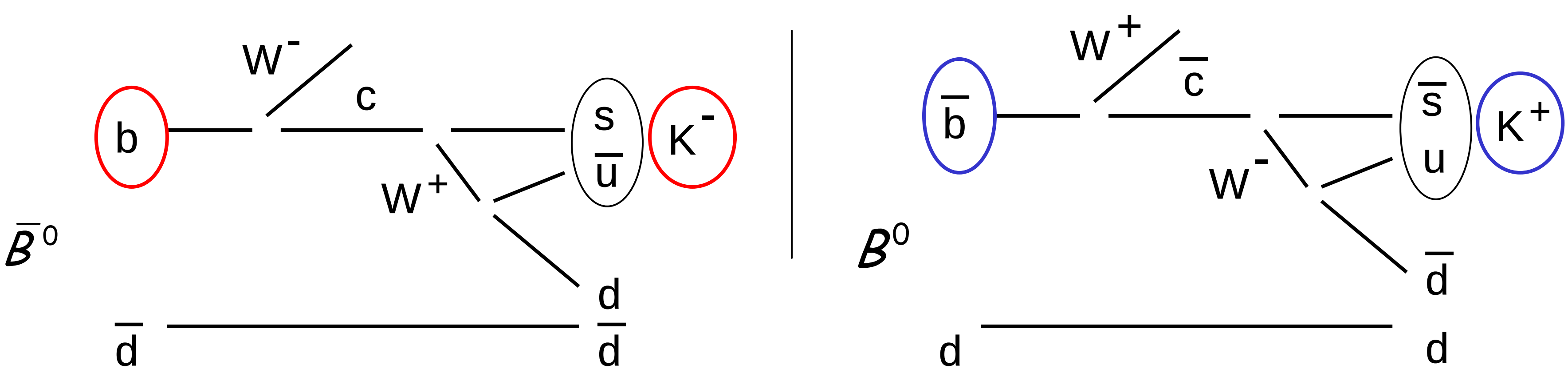
Identify B Flavor (B tagging)

- $\Upsilon(4S)$ produce coherent B pair: $\Upsilon(4S) \to B^0 \bar{B}^0$
- B^0 meson decays to flavor eigenstates ~ 100%
- Determine the flavor of B_{tag} $\Rightarrow$ infer the initial flavor of B_{rec}
- Effective tagging efficiency at BaBar: 30.4 ±0.3%

Leptons Tag:



Kaons Tag:



Flavour Tagging Performance

- Multivariate algorithms (neural network) to identify B_{tag} flavor
- 6 tagging categories defined:

$\Delta w = w(B^0) - w(\bar{B}^0)$

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

Category	ε (%)	w (%)	Δw (%)	Q (%)
Lepton	8.67 ± 0.08	3.0 ± 0.3	-0.2 ± 0.6	7.67 ± 0.13
Kaon I	10.96 ± 0.09	5.3 ± 0.4	-0.6 ± 0.7	8.74 ± 0.16
Kaon II	17.21 ± 0.11	15.5 ± 0.4	-0.4 ± 0.7	8.21 ± 0.19
Kaon-Pion	13.77 ± 0.10	23.5 ± 0.5	-2.4 ± 0.8	3.87 ± 0.14
Pion	14.38 ± 0.10	33.0 ± 0.5	5.2 ± 0.8	1.67 ± 0.10
Other	9.61 ± 0.08	41.9 ± 0.6	4.6 ± 0.9	0.25 ± 0.04
All	74.60 ± 0.12			30.4 ± 0.3

Efficiency — From m_{ES} fit of BFlav sample

Average Mistag Fraction

Mistag Fraction Difference

Effective Tagging Efficiency

From Δt fit of BFlav sample

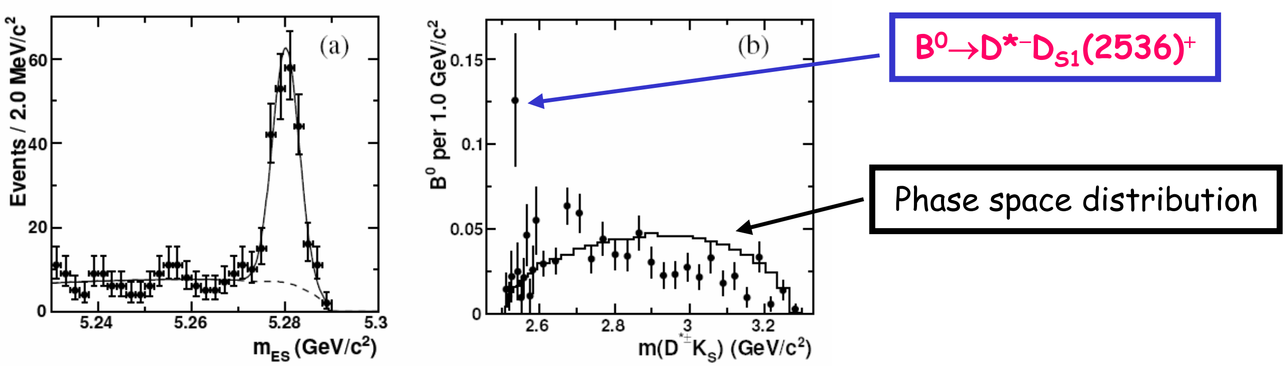
Resolve β & $\pi/2-\beta$ ambiguity in $B^0 \to D^{*+}D^{*-}K_S$

- Time-dependent decay rate asymmetry in half $D^{*\pm}K_S$ Dalitz plane
  - ✓ Phys.Rev.D61:054009,2000.
  - ✓ J_0, J_c, J_{s1} and J_{s2}: Amplitude integral over half Dalitz plane $s_\pm = m^2(D^{*\pm}K_S)$

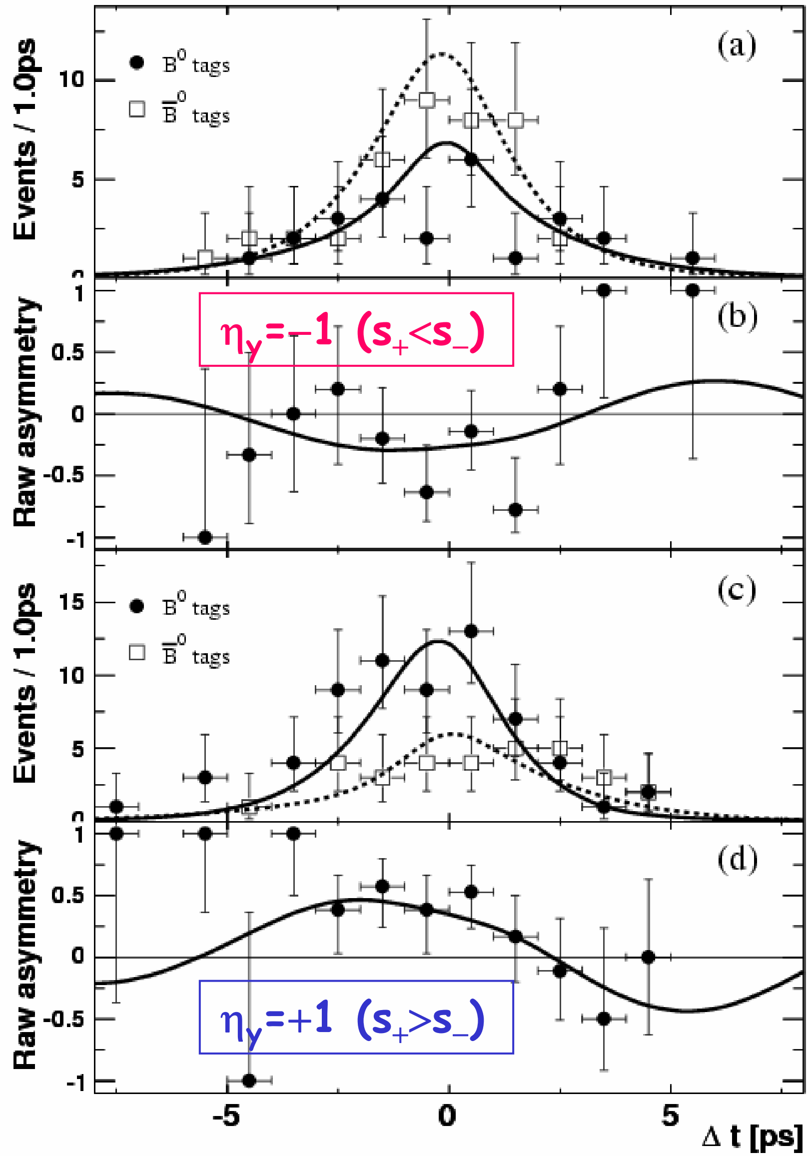
$$A(t) \equiv \frac{\Gamma_{\overline{B}^0} - \Gamma_{B^0}}{\Gamma_{\overline{B}^0} + \Gamma_{B^0}} = \eta_y \frac{J_c}{J_0}\cos(\Delta m_d t) - \left(\frac{2J_{s1}}{J_0}\sin 2\beta + \eta_y \frac{2J_{s2}}{J_0}\cos 2\beta\right)\sin(\Delta m_d t),$$

  - ✓ $\eta_y = +1(-1)$ for $s_+ > s_-$ ($s_+ < s_-$)
  - ✓ **J_c/J_0**: $|a|^2 - |\bar{a}|^2$ decay asymmetry in half Dalitz plane between B^0 & $\overline{B}^0$
  - ✓ **$2J_{s1}/J_0$**: $\mathcal{R}e(\bar{a}a^*)$ dilution due to mixing of CP-even and odd states
  - ✓ **$2J_{s2}/J_0$**: $\mathcal{I}m(\bar{a}a^*)$ predicted to be positive in theory
- Model-dependent interpretation:
  - ✓ depending on the existence of broad D^+_{s1} resonance contribution
  - ✓ Measure $J_c/J_0 \neq 0$ indicate "unknown" broad D_{s1} resonance

Phys.Rev.D74:091101,2006
201±17 event
$209 fb^{-1}$ data



Resolve β & π/2-β ambiguity in $B^0 \to D^{*+}D^{*-}K_S$



Phys.Rev.D74:091101,2006 (209fb^{-1} data)

Significantly ≠ 0 ⇒ evidence of broad resonance D^+_{s1} with large Contribution to the decay

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

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

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

cos2β>0 at 94% CL if $J_{s2}/J_0>0$
Model dependent interoperation
Consistent with SM expectation
Consistent with other measurements

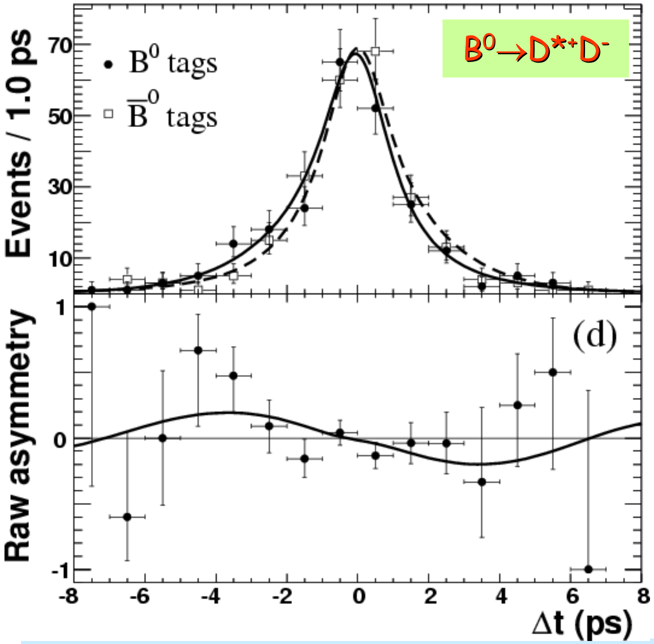
$B^0 \to D^{(*)+}D^{(*)-}$ Signal Reconstruction

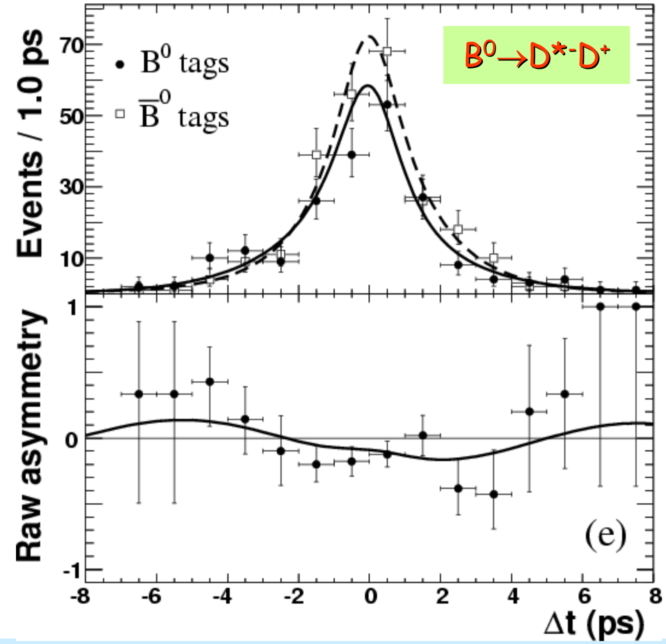
- Many sub decay modes used for $B^0 \to D^{(*)+}D^{(*)-}$ reconstruction (22 modes)
  - ✓ D^{*-} modes: $D^0\pi^-$, $D^-\pi^0$
  - ✓ D^+ modes: $K^-\pi^+\pi^+$, $K_S\pi^+$, $K^-K^+\pi^+$
  - ✓ D^0 modes: $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K_S\pi^+\pi^-$
  - ✓ At least one of $D^{*+} \to D^0\pi^+$

- Reduce background using ΔE and "mass Likelihood" L_{mass}
  - ✓ $L_{MASS} = G(m_{D0}) \times G(m_{D0}) \times G(m_{D^{*+}}) \times G(m_{D^{*-}})$
  - ✓ Mass constraint for D^0 and D^+ afterwards
  - ✓ Optimize ΔE and L_{mass} cuts using MC for each sub decay modes
  - ✓ After applying cuts, select best candidate based on L_{mass} per event
  - ✓ ~1.1-1.8 candidate per event, >95% correct selection

- Other variables: CLEO fisher, Dalitz weight, D decay length significance
  - ✓ Not necessary for $B^0 \to D^{*+}D^{*-}$ mode
  - ✓ Useful for $B0 \to D^{*+}D^-$, $D^{*-}D^+$, and D^+D^- modes

CP violation result from $B^0 \to D^{*+}D^-$ & $D^{*-}D^+$





- $D^{*+}D^-$ & $D^{*-}D^+$: not CP eigenstates

  $A(D^{*+}D^-)/A(D^{*-}D^+)=Re^{i\delta}$

  $S^{\pm}=2R\sin(2\beta\pm\delta)/(1+R^2)$

  $(S^++S^-)/2=2R\cos\delta\sin2\beta/1+R^2$

- Analyze $D^{*+}D^-$ and $D^{*-}D^+$ separately: Phys. Rev. Lett. 99, 071801 (2007) ($348fb^{-1}$)

$B^0 \to D^{*+}D^-$	$B^0 \to D^{*-}D^+$
$C^+=+0.18 \pm 0.15 \pm 0.04$	$C^-=+0.23 \pm 0.15 \pm 0.04$
$S^+=-0.79 \pm 0.21 \pm 0.06$	$S^-=-0.44 \pm 0.22 \pm 0.06$

- If no CP violation: $C^+=-C^-$ and $S^+=-S^-$
  - ✓ Significance of CP violation: $> 4\sigma$