The Physics of Flavor: Half a Billion b Quarks for BaBar

TM

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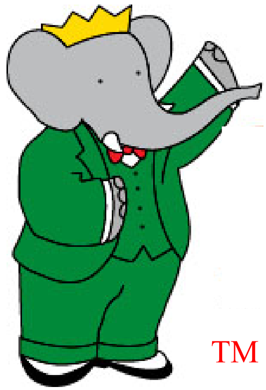


Quarks, Flavor Violation, and CP Violation

Quarks and the problem of mass

Standard Model "explanation" of quark mass:
Six quark species with unpredicted masses
Spanning almost six orders of magnitude

Up type (q=+2/3)		Mass (GeV/c^2)
Up	u	10^{-3}
Charm	c	1
Top	t	175

Down type (q=-1/3)		Mass (GeV/c^2)
Down	d	5 10^{-3}
Strange	s	10^{-1}
Bottom	b	5

The origin of different fermion generations, masses, flavor violation, and CP violation are all arbitrary parameters of electroweak symmetry breaking.
A comparative physics of the quark flavors directly probes this little-known sector.

Quarks and their Strong Interactions

Quarks cannot be detected in isolation, only as bound states
A quark/anti-quark pair forms a bound state (mesons)

Flavor	u,d	s	c	b	t
spin 0 mesons	$\pi^+ (u\bar{d})$ $\pi^0 (u\bar{u}-d\bar{d})$	$K^+ (u\bar{s})$ $K_S^0 (d\bar{s}+s\bar{d})$	$D^+ (c\bar{d})$ $D^0 (c\bar{u})$	$B^0 (d\bar{b})$ $B^+ (u\bar{b})$	none
spin 1 mesons	$\rho^+ (u\bar{d})$ $\rho^0 (u\bar{u}-d\bar{d})$ $\omega (u\bar{u}+d\bar{d})$	$K^{*+} (u\bar{s})$ $K^{*0} (d\bar{s})$ $\phi (s\bar{s})$	$D^{*+} (c\bar{d})$ $D^{*0} (c\bar{u})$ $J/\psi (c\bar{c})$	$\Upsilon (b\bar{b})$	none

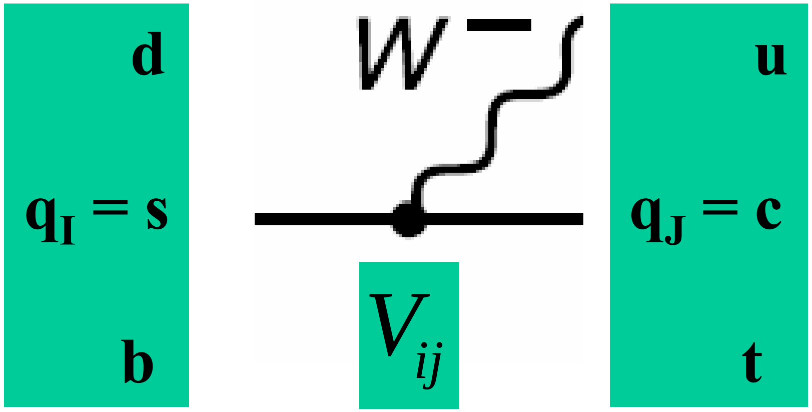
b quarks are the heaviest flavor with measureable bound states→

B mesons are a natural starting point for studying the other flavors

Quarks and Flavor Violation

Photon, gluon or Z boson: quark flavor conserving interactions

W boson: changes any down type flavor to any up type flavor



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

The (Cabibbo-Kobayashi-Maskawa) CKM matrix: complex amplitude of each possible transition

Conservation of probability → CKM matrix is unitary

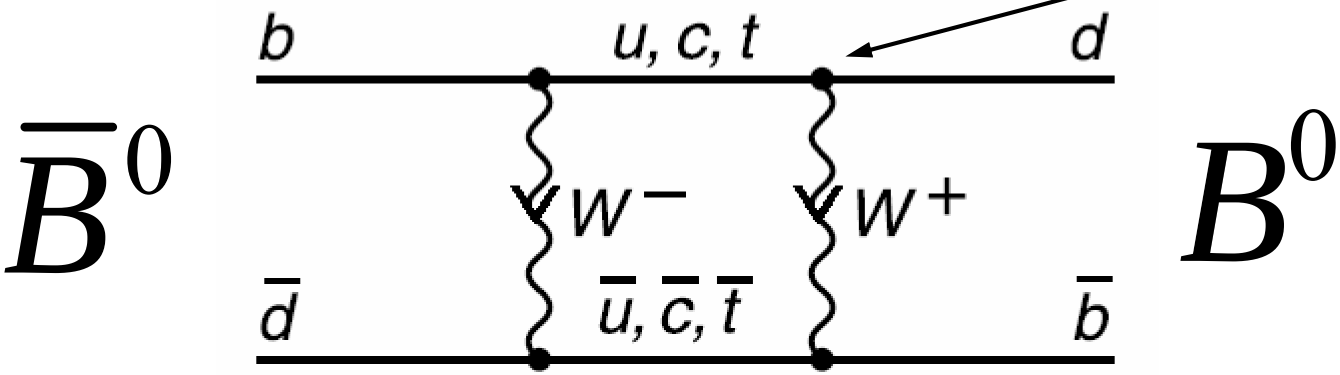
3X3 unitary matrix has (effectively) four degrees of freedom:
3 angles + 1 complex phase

Quarks and Flavor Violation: Mixing

Pairs of down (or pairs of up) type quarks can spontaneously swap flavor for anti-flavor via two flavor-violating exchanges

"Meson Mixing" aka "Flavor oscillation"

Sensitive to $V_{td,}$ top quark!



$$\mathbf{Prob(\overline{B}^0 \rightarrow B^0) \approx exp(-\Gamma\ t)/2 * (1 - cos(\Delta m\ t))}$$

Similar to neutrino oscillation, except decay term added

Mixing time ~few ps

Quarks and CP Violation

For a particle(s) f with momentum p and helicity λ

C : Charge conjugation operator $\quad C\ f(p, \lambda) = \bar{f}(p, \lambda)$

P : Parity reversal operator $\quad P\ f(p, \lambda) = f(-p, -\lambda)$

$\quad CP\ f(p, \lambda) = \bar{f}(-p, -\lambda)$

CP eigenstate: particle = anti-particle (Ex: $q\bar{q}$ mesons)

CP conservation → left-handed particles have the same physics as right-handed anti-particles

Obviously violated for our (baryon-asymmetric) local universe!

In the Standard Model CP violation originates from complex phase in CKM matrix → in general, $V_{ij} \neq V_{ij}^*$

Three Paths to CP Violation

CP violation → an observable O of particles (f1,f2,…) such that
$O(f1,f2,\ldots) \neq O(CP(f1,f2,\ldots)) = O(\overline{f1}, \overline{f2}, \ldots)$

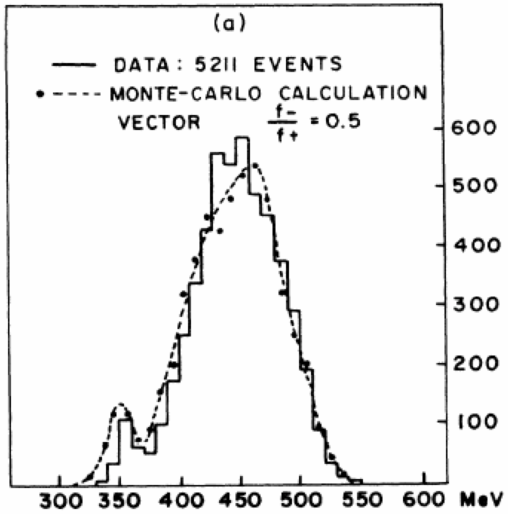
1. CP violation in meson mixing

$$\left| \overline{B}^0 \to B^0 \to f \right|^2 \neq \left| B^0 \to \overline{B}^0 \to \overline{f} \right|^2$$

Mixing rate of meson to final state f not the same as
Mixing rate of anti-meson to same final anti-state

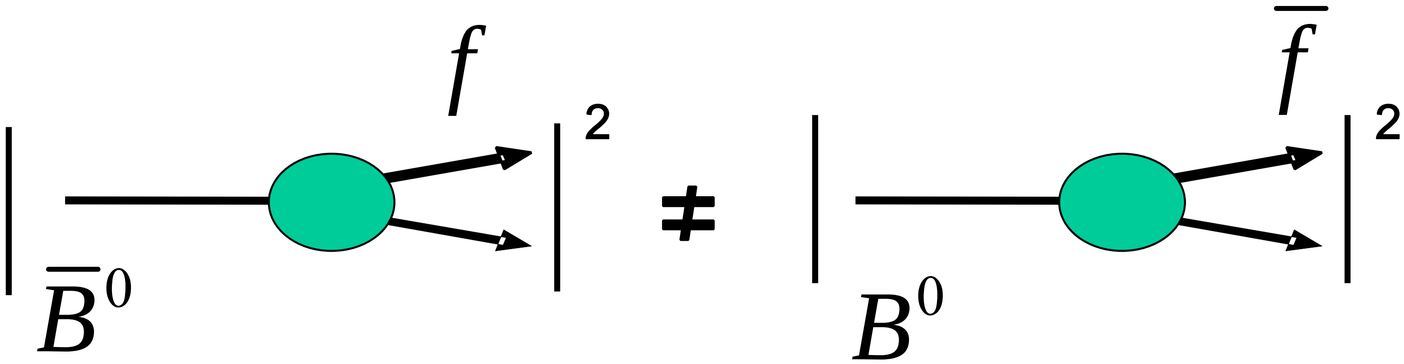
In the Standard Model, very small ~10^{-3}

CP violation in K^0 decays first observed through this path forty years ago!

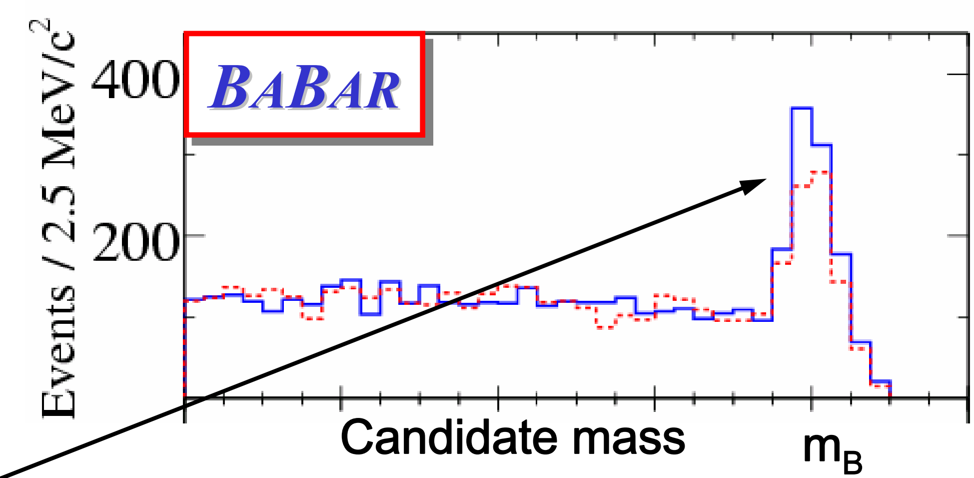


Three Paths to CP Violation

2. CP violation in meson decay → "Direct CP violation"



Decay rate of meson to final state f not the same as Decay rate of anti-meson to same final anti-state



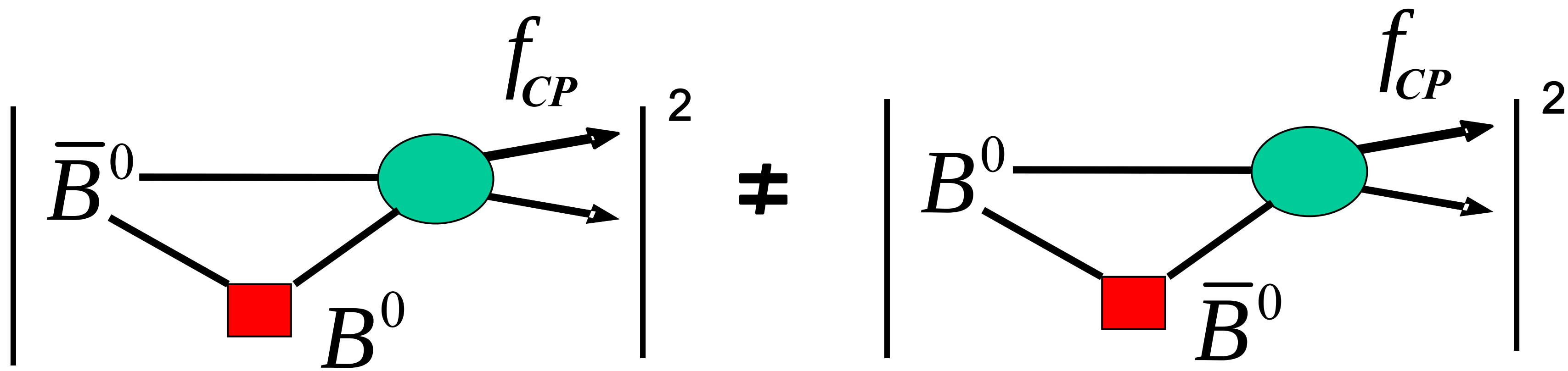
Blue $B^0 \to K^+\pi^-$

Red $\bar{B}^0 \to K^-\pi^+$

Recently observed in $B^0 \to K^+ \pi^-$ at the 10% level!

Three Paths to CP Violation

3.Time dependent asymmetry of meson/anti-meson decay rate to a common final state



If $\overline{B}^0$ and B^0 decay to the same final state f_{CP}, there is interference between
amplitude of direct decay and
amplitude of mixing followed by decay

In the presence of CP violating phases in these amplitudes, can induce large time-dependent asymmetry with frequency equal to mixing frequency:

$$A_{f_{CP}} = -C_{f_{CP}} \cos(\Delta m t) + S_{f_{CP}} \sin(\Delta m t)$$

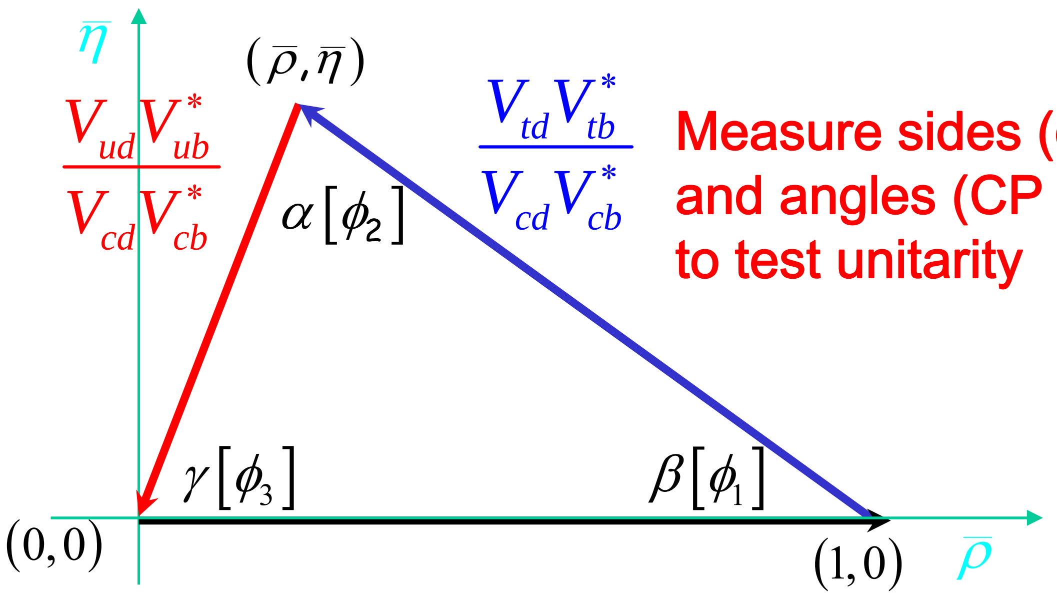
$C_{f_{CP}} \neq 0$ implies Direct *CP* Violation

CKM Unitarity

Inner product of first and third columns of CKM matrix is zero:

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

Rescale, rotate and reparameterize to describe a Unitarity Triangle in the complex plane



b Quarks and CKM Unitarity

B decay rates, CP asymmetries measure the entire triangle!

Triangle sides:

$B^+ \to \rho^0\, l^-\, \nu$ decay rate measures $b \to u$ transition ($|V_{ub}|$)

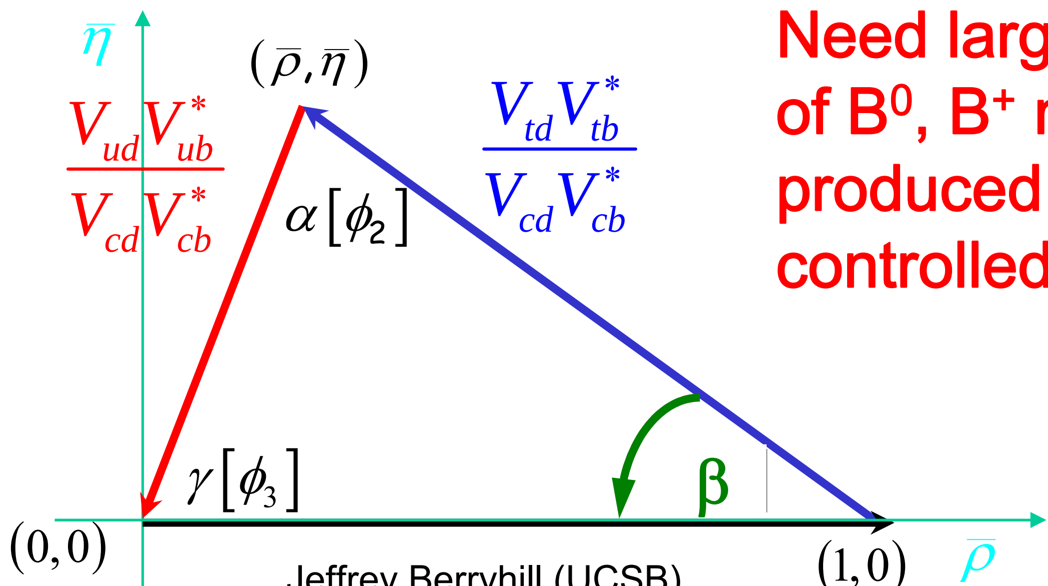
B^0 mixing rate measures $|V_{td}|$

Angles:

$B^0 \to \rho^+ \rho^-$ time dependent CP asymmetry measures $\sin 2\alpha$

$B^0 \to J/\psi\, K_S^0$ time dependent CP asymmetry measures $\sin 2\beta$

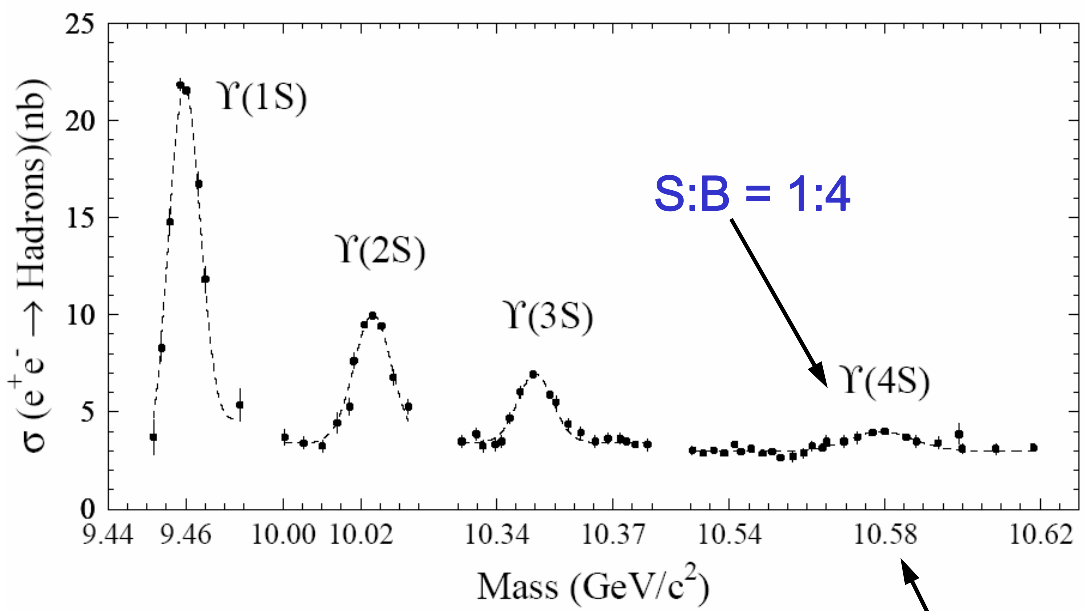
$B^+ \to D(^*)K^+$ decay rates measure γ

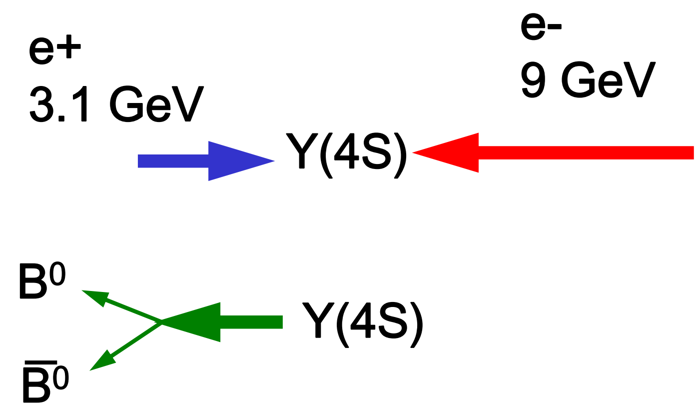


Need large sample of B^0, B^+ mesons produced under controlled conditions

B Factory Experiments

Asymmetric B Factories





Y(4S) meson: $b\bar{b}$ bound state with mass 10.58 GeV/c^2

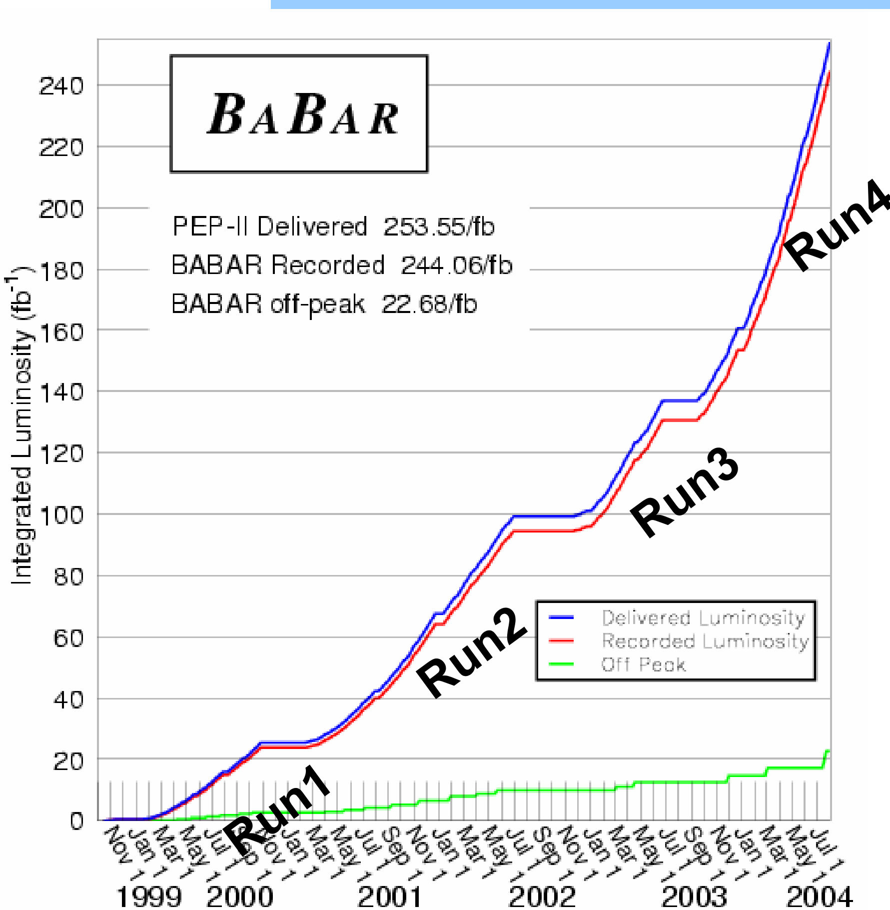
Just above 2 x mass of B meson → decays exclusively to $B^0\,\bar{B}^0$ (50%) and $B^+\,B^-$ (50%)

B factory: intense e+ and e- colliding beams with E_{CM} tuned to the Y(4S) mass

Use e beams with asymmetric energy → time dilation due to relativistic speeds keeps B's alive long enough to measure them (decay length ~0.25mm)

PEP-II at the Stanford Linear Accelerator Center

PEP-II performance



PEP-II top luminosity:
9.2 x 10^{33}cm^{-2}s^{-1}
(more than 3x design goal 3.0 x 10^{33})

1 day record : 681 pb^{-1}

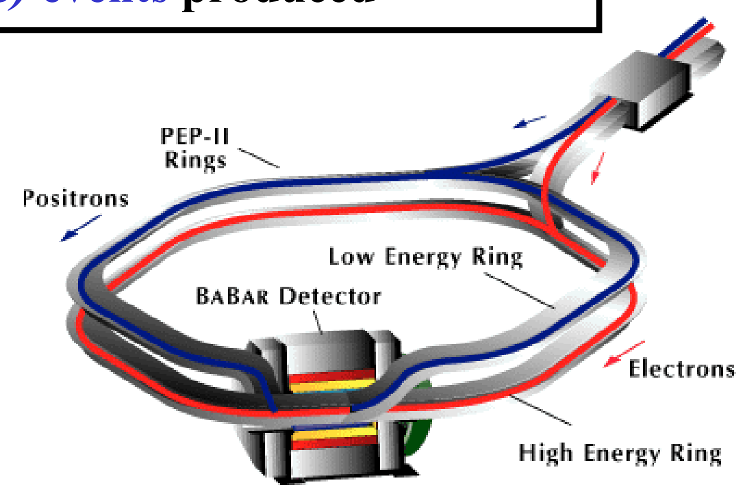
About 1 Amp of current per beam, injected continuously

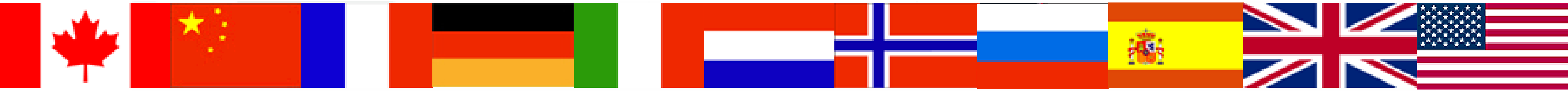
<u>Run1-4 data: 1999-2004</u>
On peak 205 fb^{-1}

σ(e+e- →Y(4S)) = 1.1 nb →
227M *Y(4S)* events produced

454 million b quarks produced!

Also ~10^8 each of u, d, s, c, and τ





The *BABAR* Collaboration

11 Countries

80 Institutions

593 Physicists

USA [38/300]

California Institute of Technology
UC, Irvine
UC, Los Angeles
UC, Riverside
UC, San Diego
UC, Santa Barbara
UC, Santa Cruz
U of Cincinnati
U of Colorado
Colorado State
Florida A&M
Harvard
U of Iowa
Iowa State U
LBNL
LLNL
U of Louisville
U of Maryland
U of Massachusetts, Amherst
MIT
U of Mississippi
Mount Holyoke College
SUNY, Albany
U of Notre Dame
Ohio State U
U of Oregon
U of Pennsylvania
Prairie View A&M U
Princeton U
SLAC
U of South Carolina
Stanford U
U of Tennessee
U of Texas at Austin
U of Texas at Dallas
Vanderbilt
U of Wisconsin
Yale

Canada [4/20]

U of British Columbia
McGill U
U de Montréal
U of Victoria

China [1/5]

Inst. of High Energy Physics, Beijing

France [5/51]

LAPP, Annecy
LAL Orsay
LPNHE des Universités Paris VI et VII
Ecole Polytechnique, Laboratoire Leprince-Ringuet
CEA, DAPNIA, CE-Saclay

Germany [5/31]

Ruhr U Bochum
U Dortmund
Technische U Dresden
U Heidelberg
U Rostock

Italy [12/101]

INFN, Bari
INFN, Ferrara
Lab. Nazionali di Frascati dell' INFN
INFN, Genova & Univ
INFN, Milano & Univ
INFN, Napoli & Univ
INFN, Padova & Univ
INFN, Pisa & Univ & ScuolaNormaleSuperiore
INFN, Perugia & Univ
INFN, Roma & Univ "La Sapienza"
INFN, Torino & Univ
INFN, Trieste & Univ

The Netherlands [1/5]

NIKHEF, Amsterdam

Norway [1/3]

U of Bergen

Russia [1/11]

Budker Institute, Novosibirsk

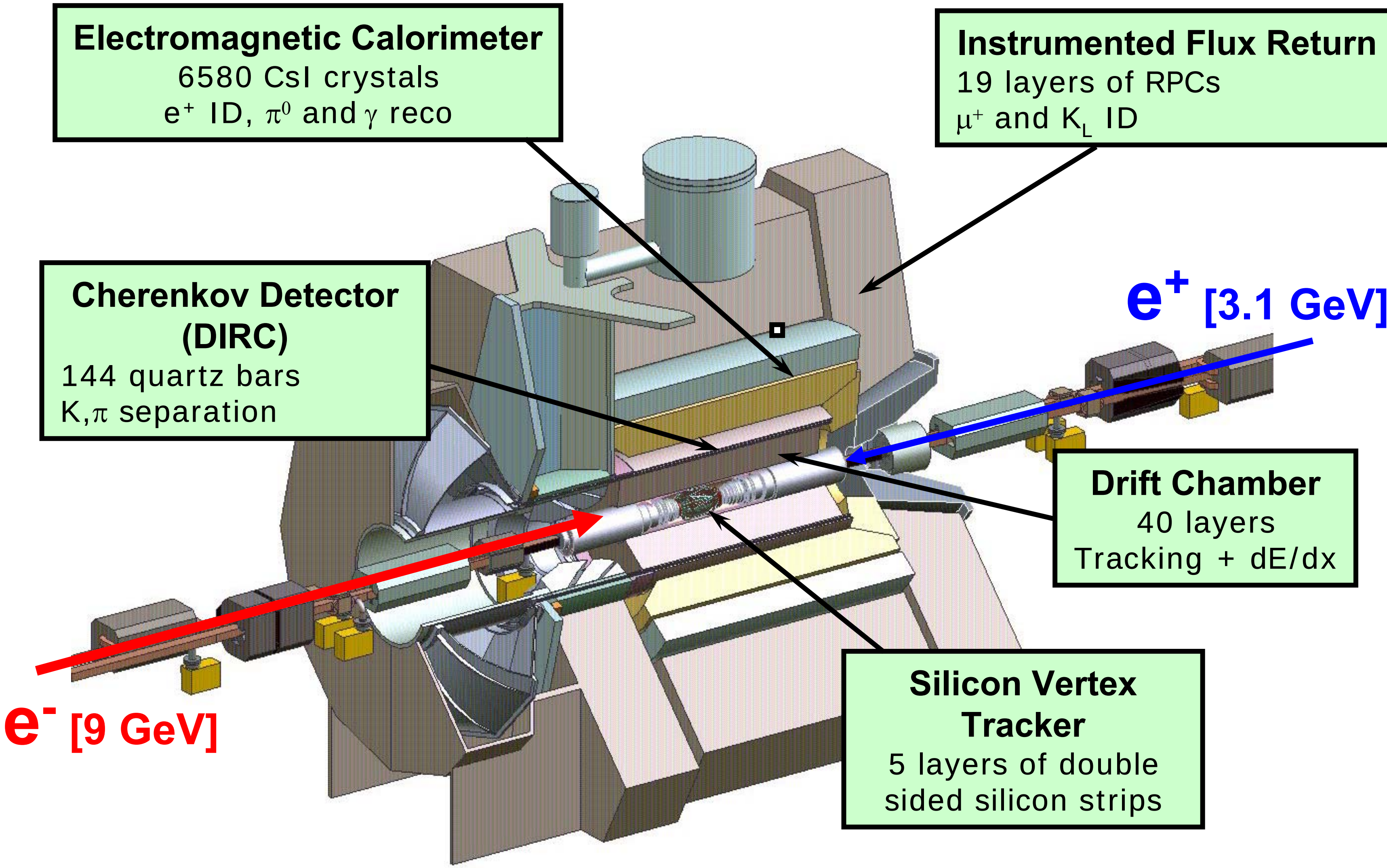
Spain [2/2]

IFAE-Barcelona
IFIC-Valencia

United Kingdom [10/66]

U of Birmingham
U of Bristol
Brunel U
U of Edinburgh
U of Liverpool
Imperial College
Queen Mary , U of London
U of London, Royal Holloway
U of Manchester
Rutherford Appleton Laboratory

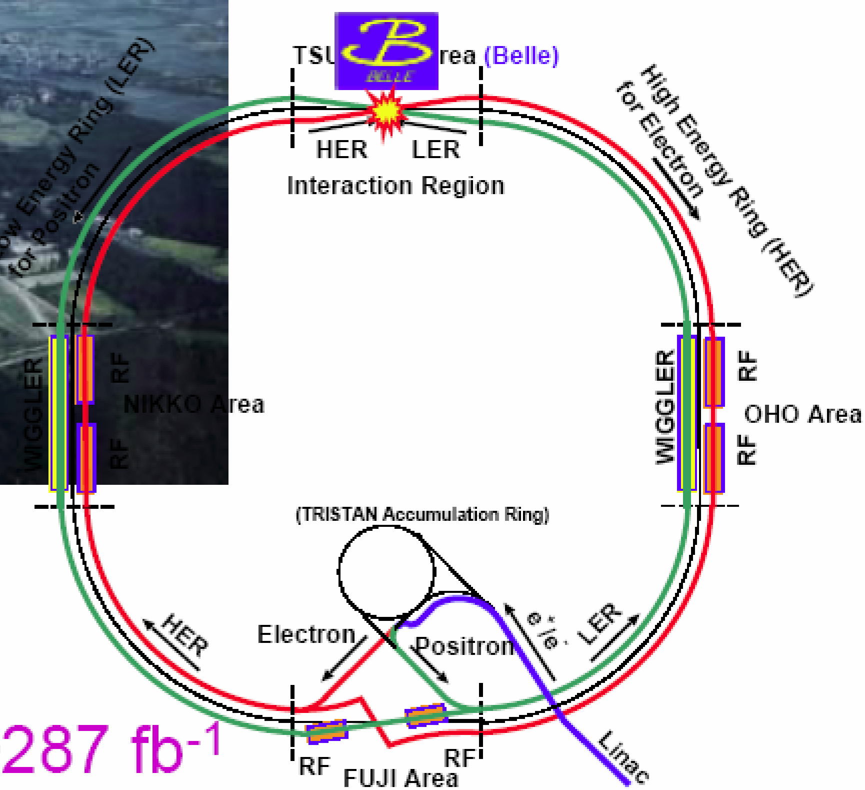
The BaBar detector



Our Friendly Competitors

8 GeV e^- x 3.5 GeV e^+

±11mrad crossing

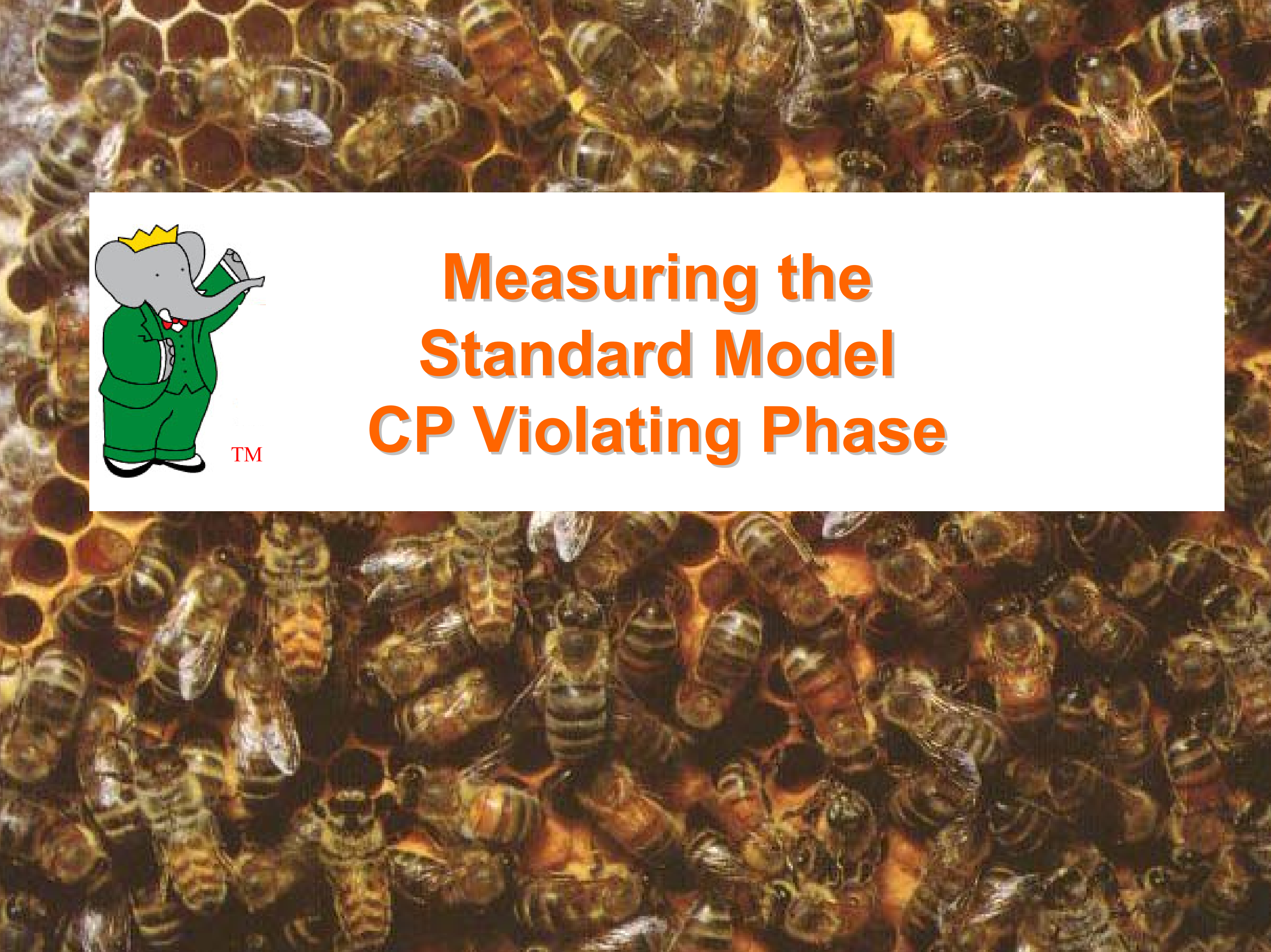


$L_{peak} = 1.39 \times 10^{34}\ sec^{-1}cm^{-2}$

@ 1.2A x 1.6A

253 fb^{-1} on Υ(4S)   274M $B\bar{B}$
28 fb^{-1} below Υ(4S)

~287 fb^{-1}

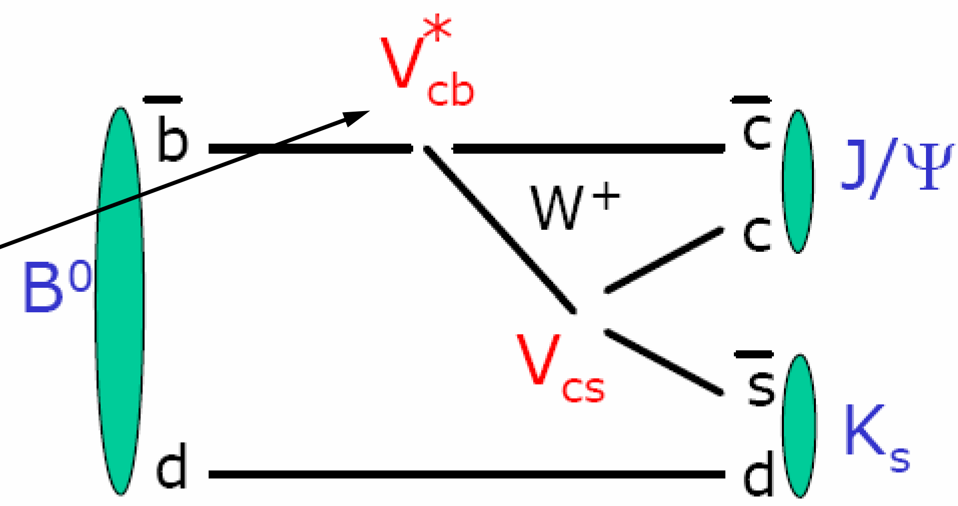


Measuring the Standard Model CP Violating Phase

$B^0 \rightarrow J/\psi\ K_S^0$ and sin 2β

Decay dominated by a single "tree-level" Feynman diagram: b → c$\bar{c}$s

$$\beta \equiv \varphi_1 \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$



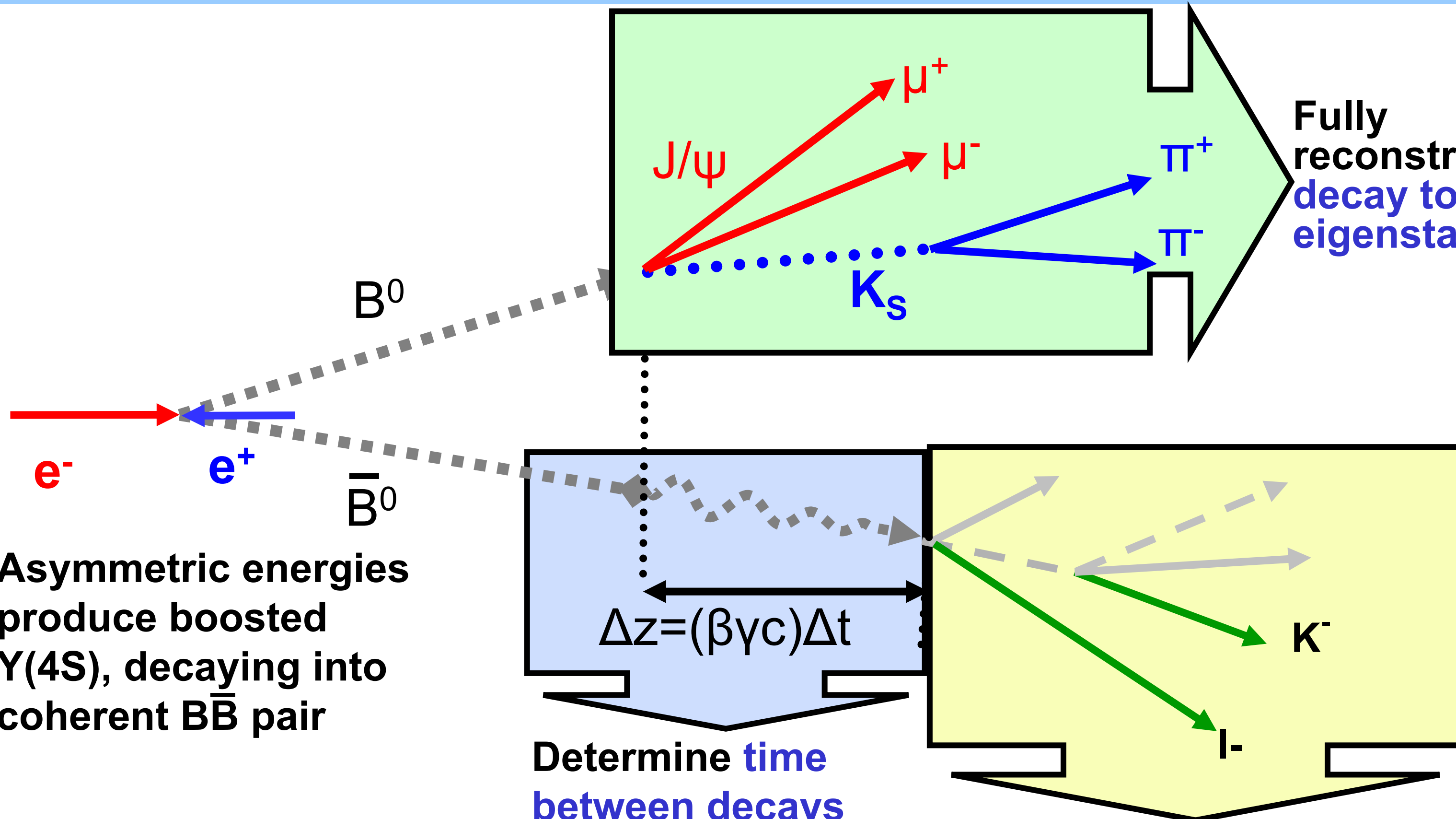
J/ψ identified cleanly by decay to a lepton pair;
K_S identified cleanly by decay to pion pair.
Both particles are CP eigenstates → both B^0 and $\bar{B}^0$ decay to them

Time-dependent CP violation has amplitude sin 2β and frequency Δm

$$A_{CP}(J/\psi K_s;t) = \sin 2\beta\ \sin \Delta m_d\, t$$

Works for several other b →c$\bar{c}$s decays as well; results can be combined

Time-Dependent CP Violation: Experimental technique



Fully reconstruct decay to CP eigenstate f

Asymmetric energies produce boosted Y(4S), decaying into coherent $B\bar{B}$ pair

Determine time between decays from vertices

$\sigma(\Delta t) \approx 1$ ps

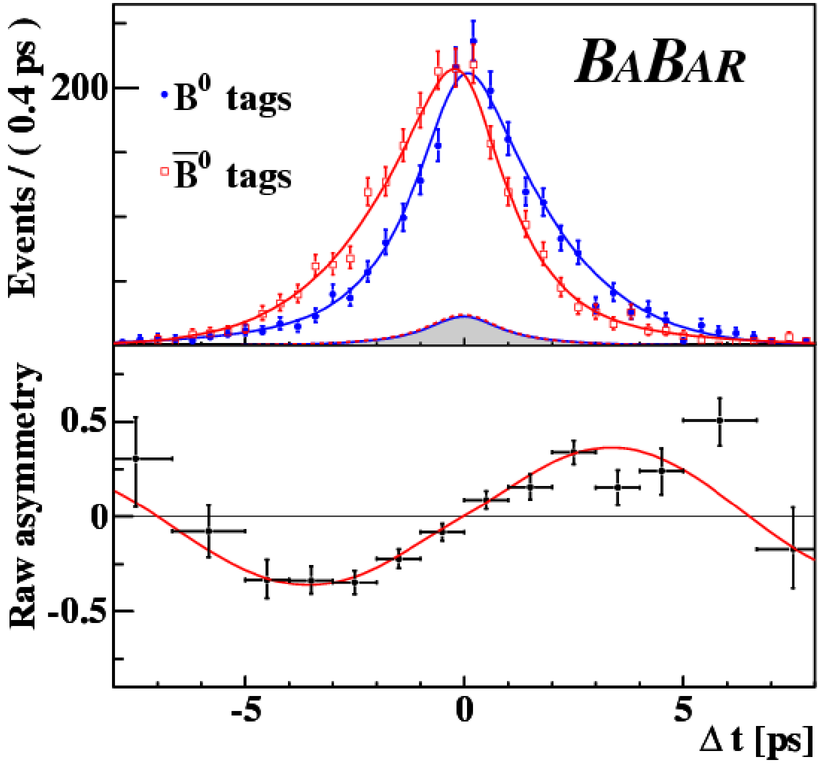
Determine flavor and vertex position of other B decay

Compute CP violating asymmetry $A(\Delta t) = \dfrac{N(\bar{f}\,;\Delta t) - N(f\,;\Delta t)}{N(\bar{f}\,;\Delta t) + N(f\,;\Delta t)}$

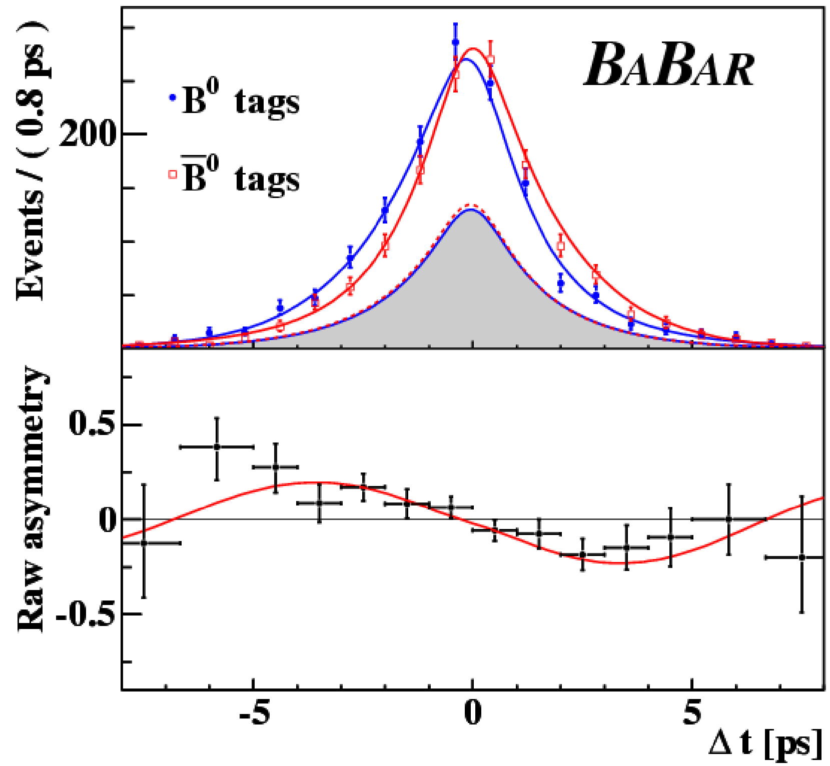
sin 2β fit results

Raw asymmetry $A(\Delta t) \approx (1 - 2w)\ \sin 2\beta\ \ \sin \Delta m \Delta t$

($c\bar{c}$) K_S (CP odd) modes



J/ψ K_L (CP even) mode

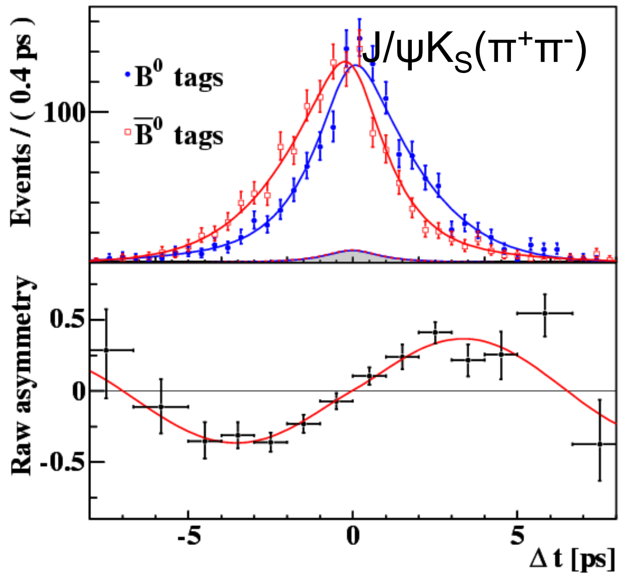


Signal yield, background yield, sin 2β, flavor tagging, Δt resolution function all from simultaneous maximum likelihood fit to signal+control samples

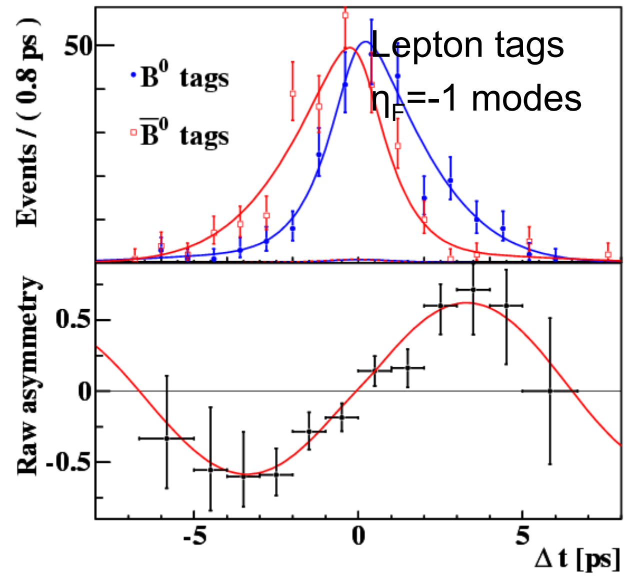
$\sin 2\beta = 0.722 \pm 0.040\ (\text{stat}) \pm 0.023\ (\text{sys})$

Consistency checks

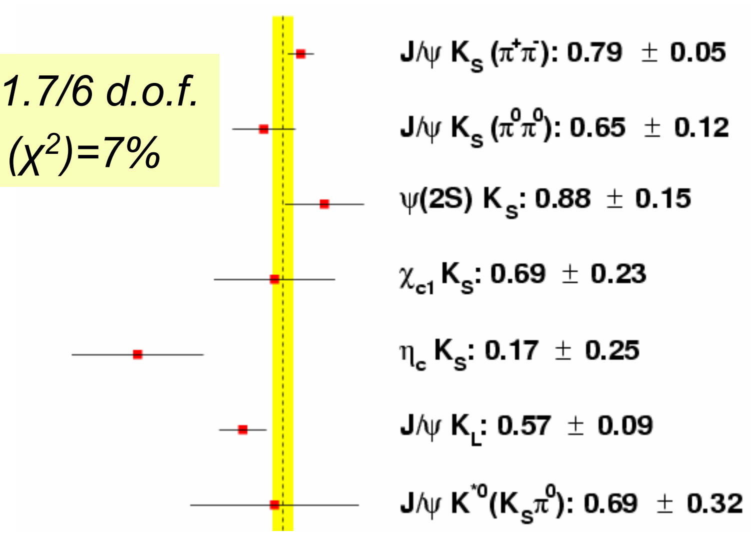
Cleanest charmonium sample →



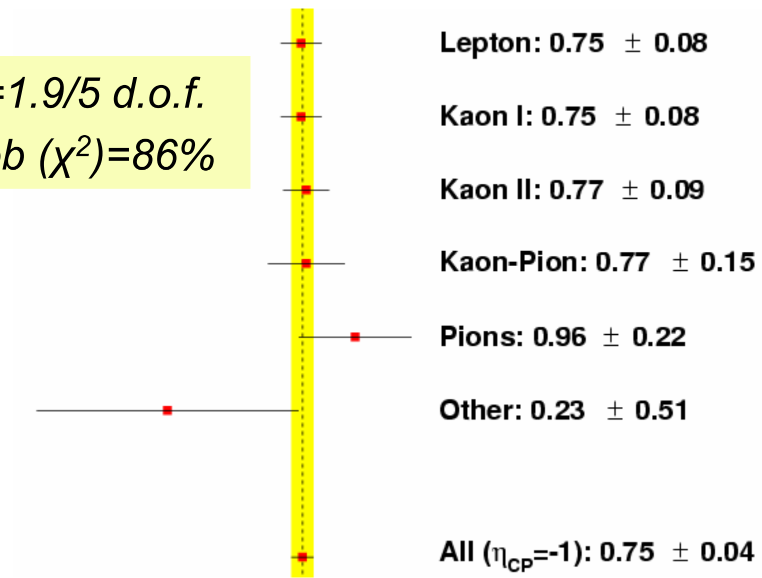
Purest flavor tagging mode →



X^2=11.7/6 d.o.f.
Prob (χ^2)=7%



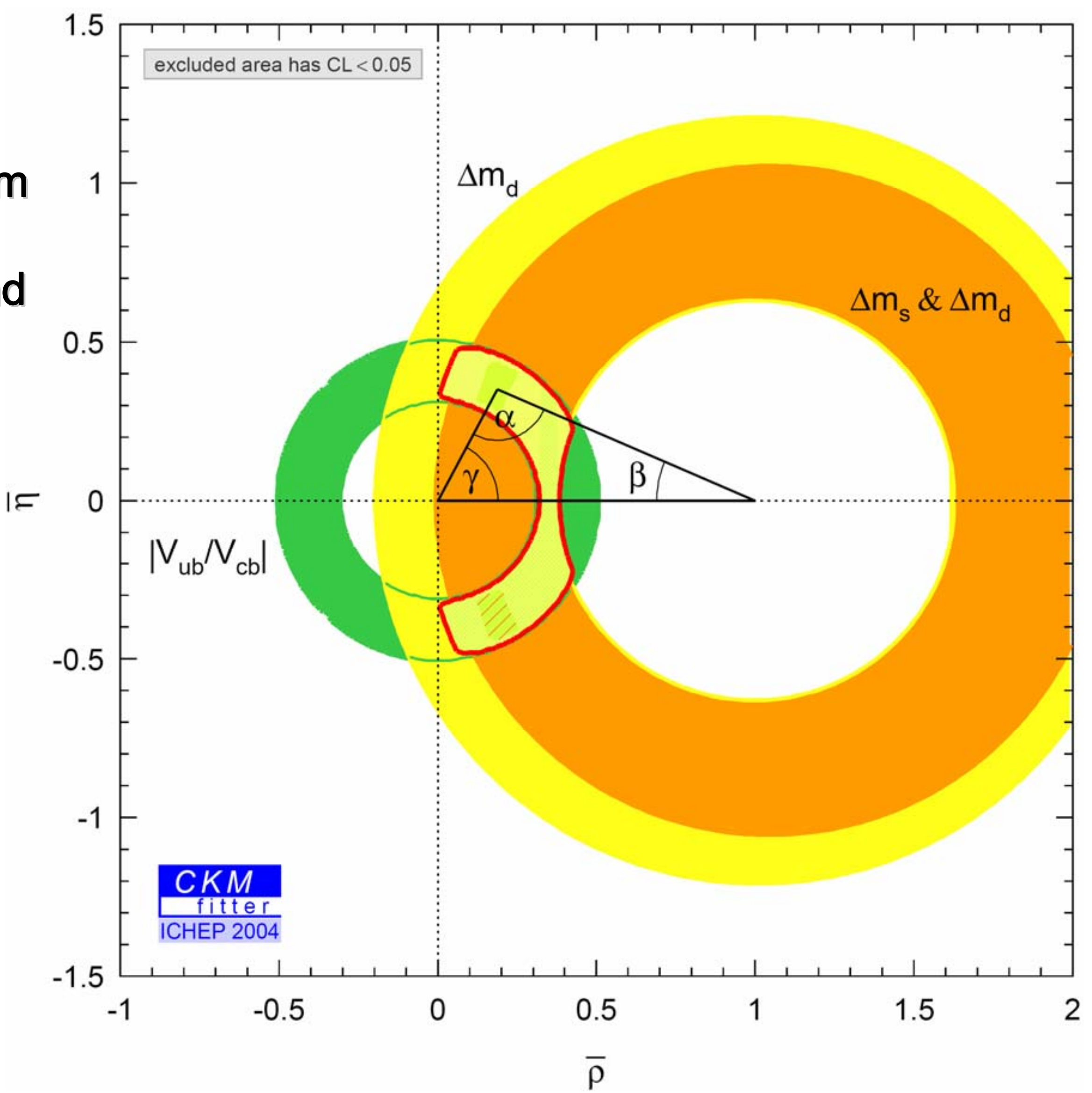
X^2=1.9/5 d.o.f.
Prob (χ^2)=86%



CKM Unitarity Triangle: Experimental Constraints

Constraints from

Decay rates and
Mixing Rates

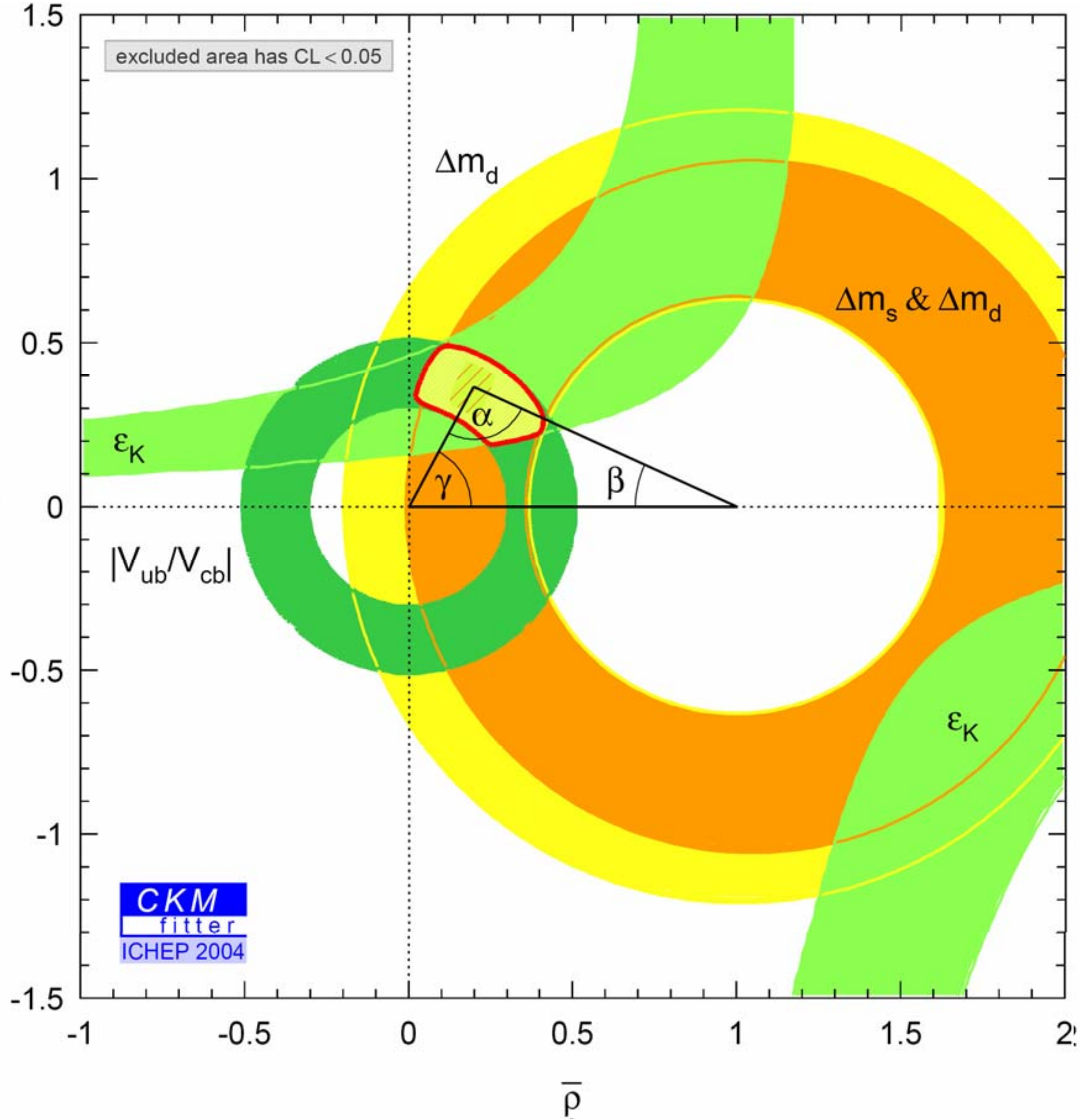


CKM Unitarity Triangle: Experimental Constraints

Constraints from

Decay rates and
Mixing Rates

CP violation in
Kaon decay



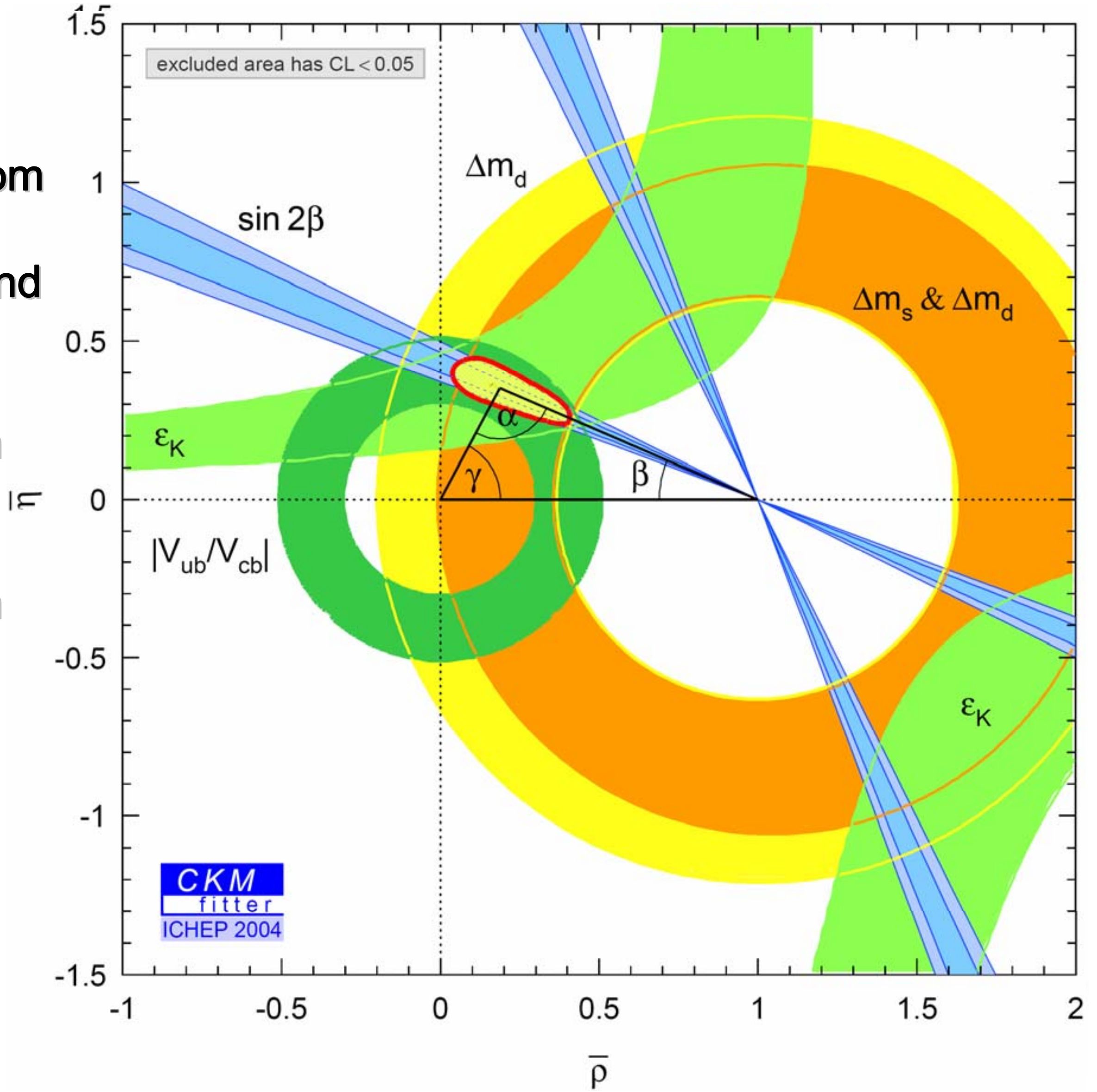
CKM Unitarity Triangle: Experimental Constraints

Constraints from

Decay rates and Mixing Rates

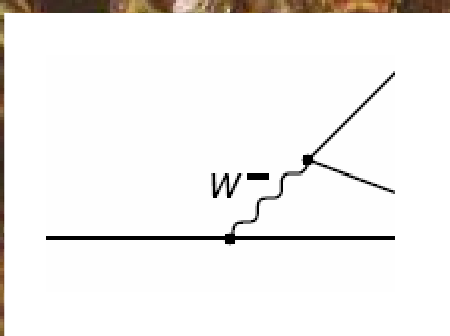
CP violation in Kaon decay

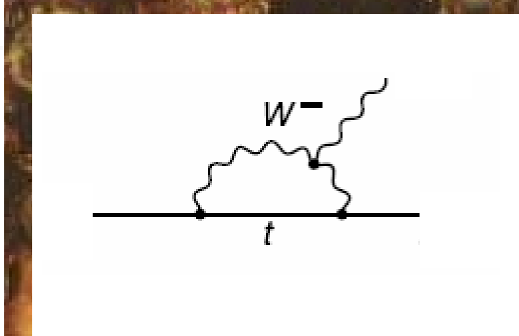
CP violation in b→ ccs



Remarkable validation of the CKM mechanism for both flavor violation and CP violation!

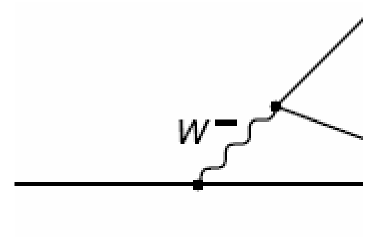
CP Violation Redux: Trees vs. Penguins



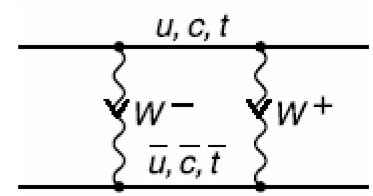


A Third Path to Flavor Violation

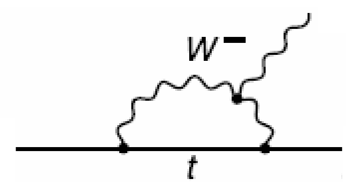
1. Tree diagram decay: down → up



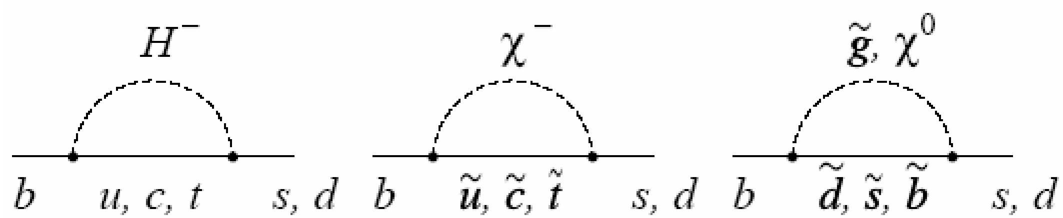
2. Box diagram: neutral meson mixing



3. Penguin diagram: down-type changes to down-type via emission & reabsorption of W; top-quark couplings V_{td}, V_{ts} dominate

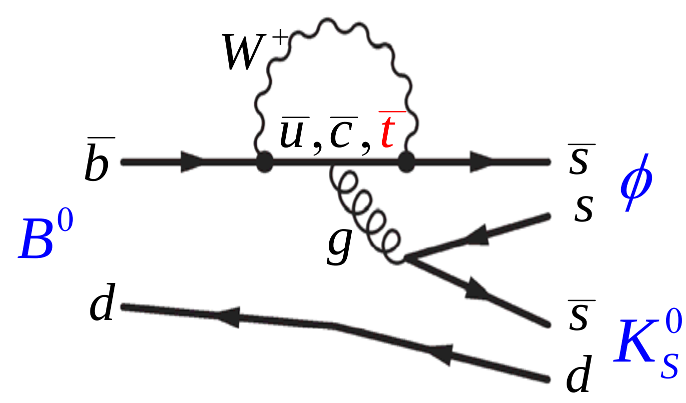


SM penguins are suppressed; new physics can compete directly!



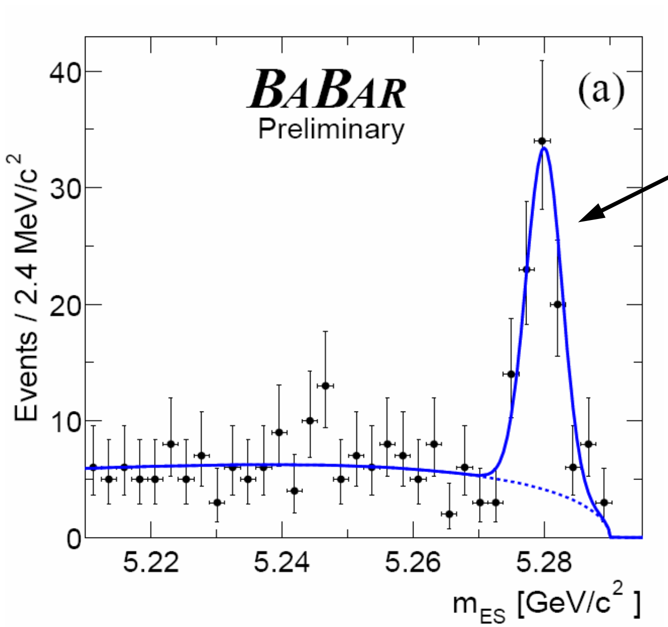
$B^0 \to \phi\, K_S^0$ and sin 2β

Decay dominated by a single "gluonic penguin" Feynman diagram: $b \to s\bar{s}s$



ϕ identified cleanly by decay to a kaon pair;
K_S identified cleanly by decay to pion pair.
Both particles are CP eigenstates

Decay rate 100X smaller than $J/\psi\, K_S$
→ small signal, large background

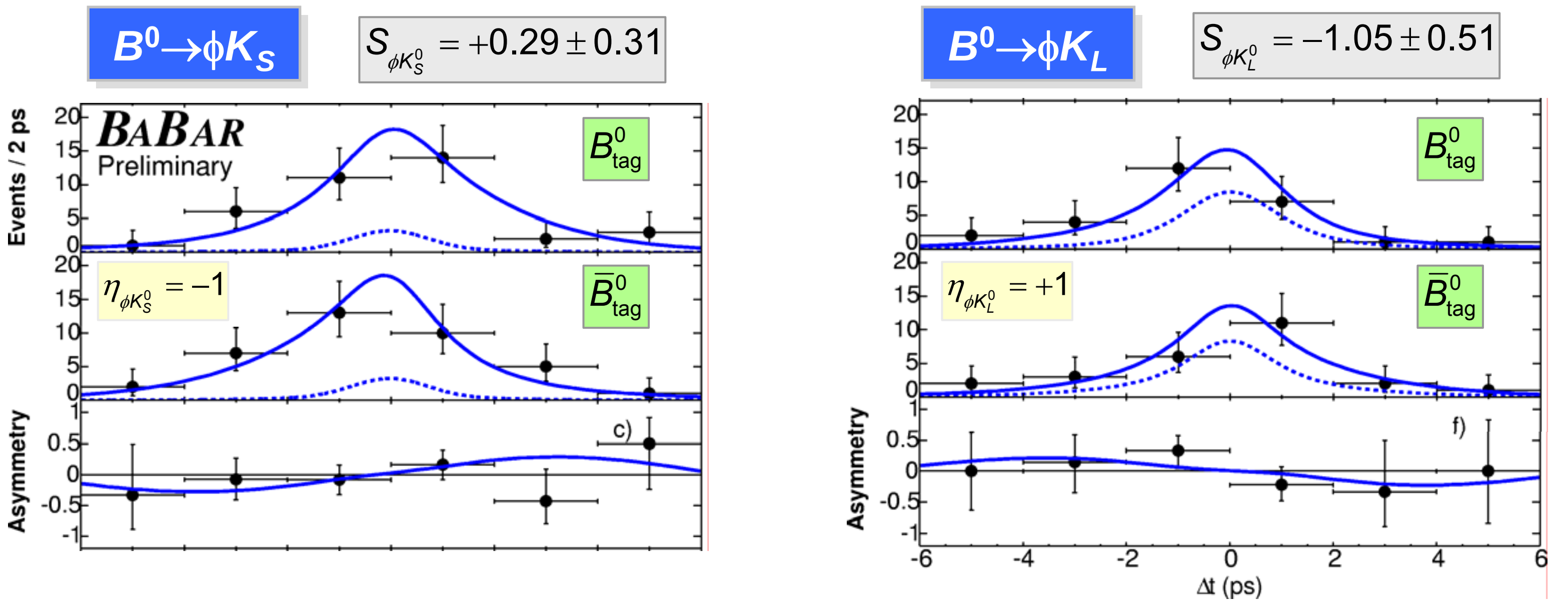


114 ± 12 $B^0 \to \phi\, K_S$ events out of ½ billion b quarks produced!

Time-dependent CP violating asymmetry A can be measured in the same way as $J/\psi\, K_S$

Same combination of CKM complex phases as $J/\psi\, K_S$ → same relation between A and sin 2β

$B^0 \rightarrow \phi K^0$ and sin 2β: Fit Result

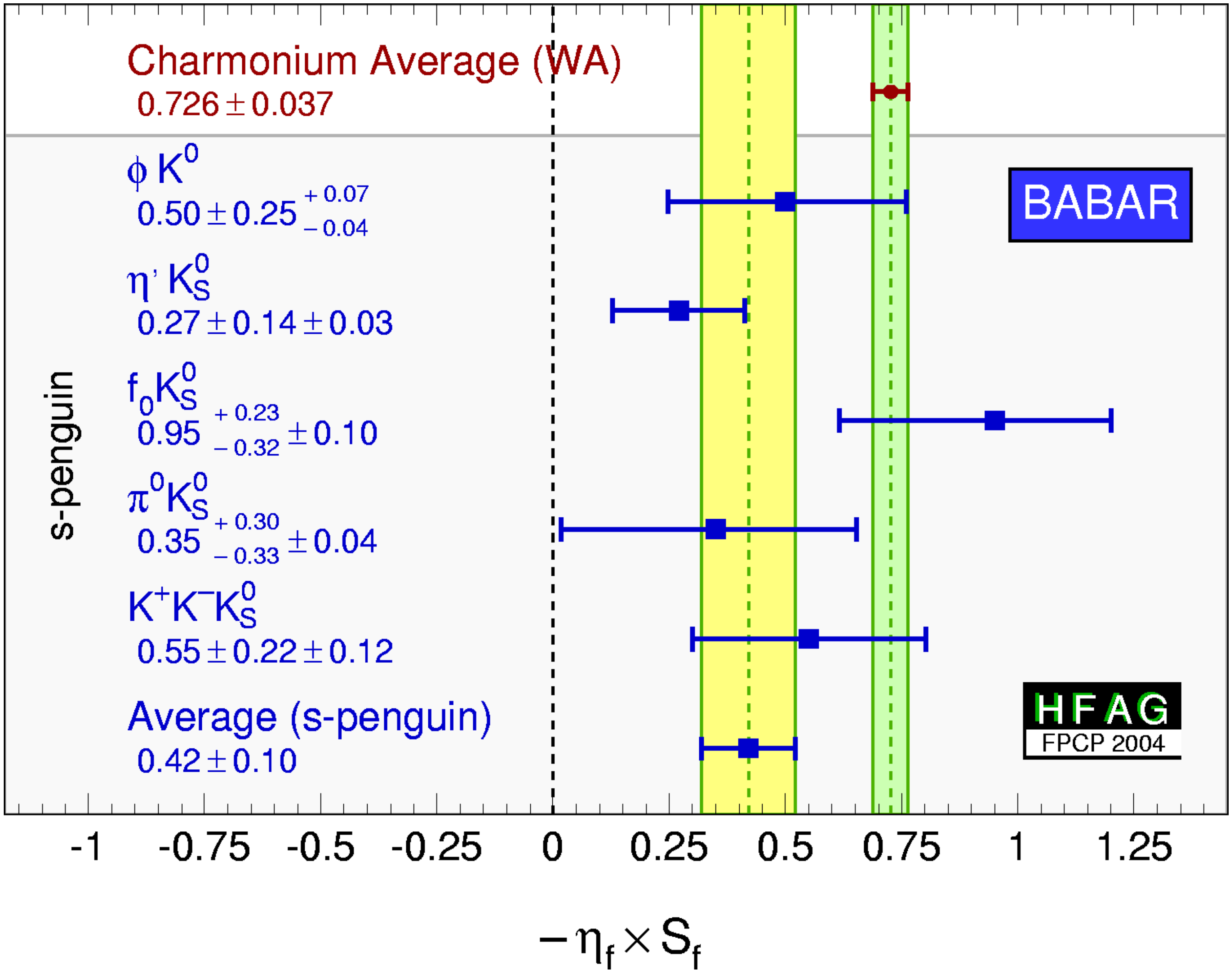


sin 2β = S(ϕ K^0) = +0.50 ± 0.25 ±0.07

vs. S(ψ K^0) = +0.72 ± 0.04 ±0.02

Consistent with tree decays, about 1 σ low

Trees(green) vs. Penguins(yellow): BaBar Data

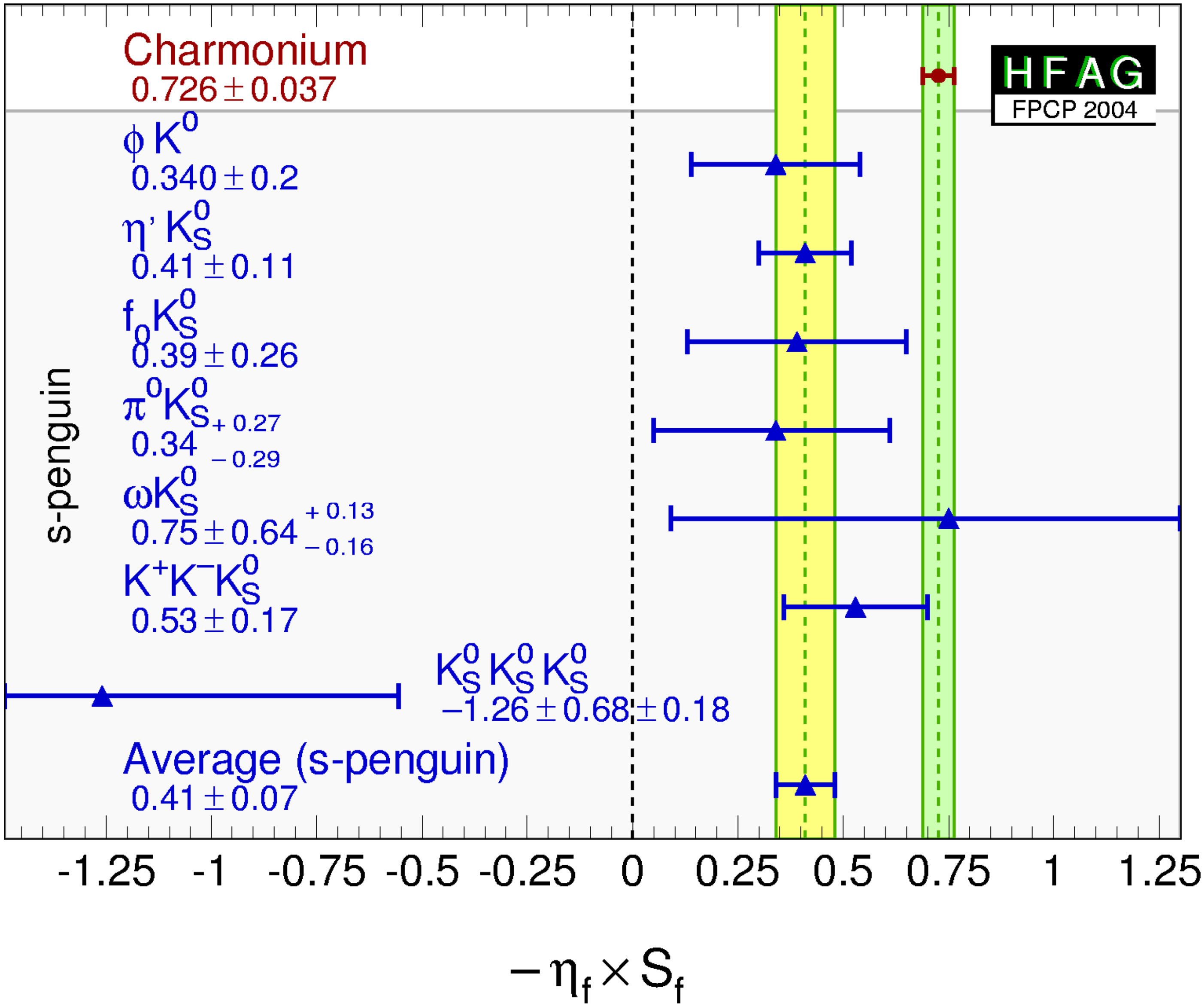


Averaging over many penguin decays:

BaBar discrepancy with tree decays

= -2.7 σ

Trees(green) vs. Penguins(yellow): World Average

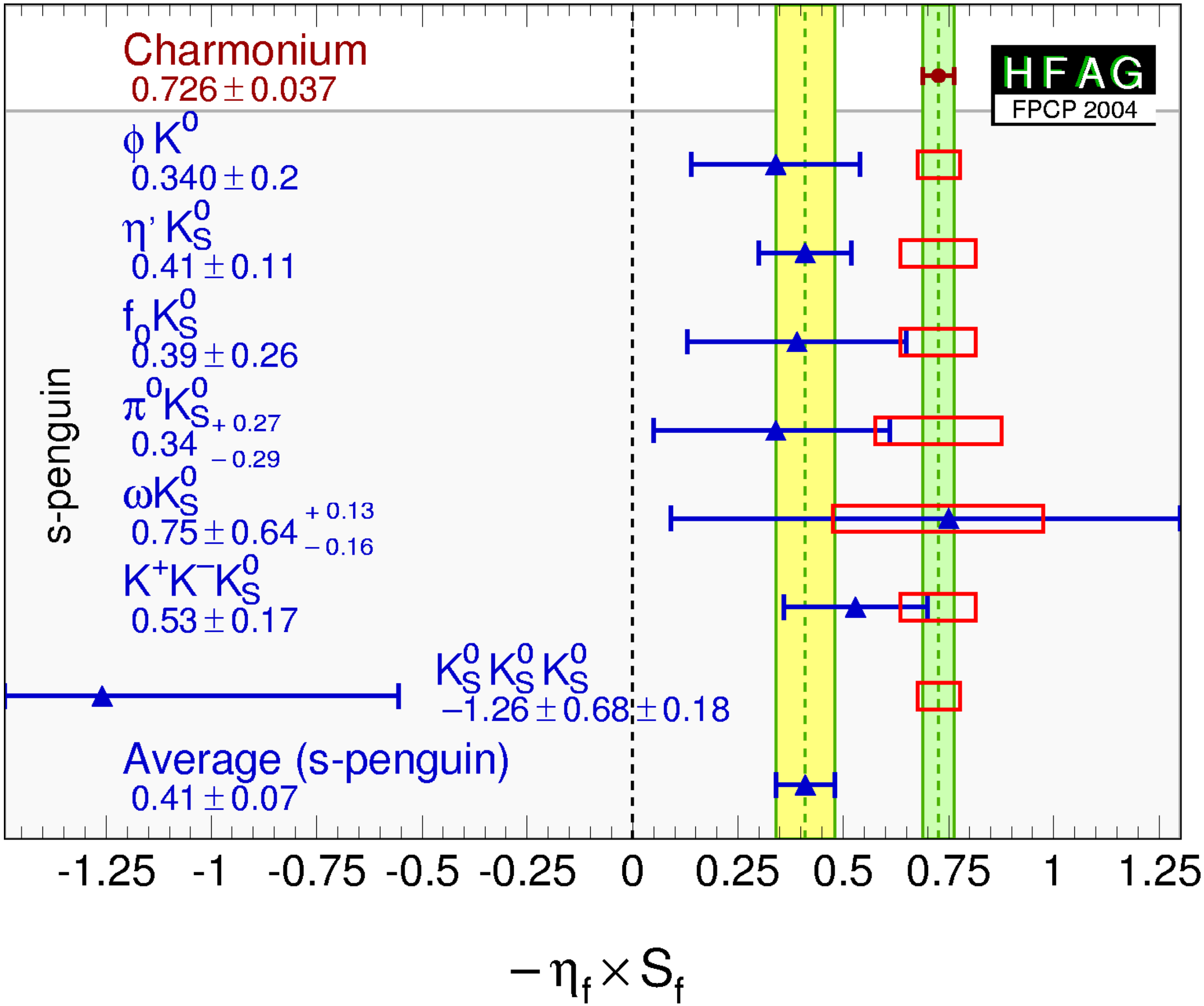


Averaging over many penguin decays:

World discrepancy with tree decays

= -3.5 σ

Trees(green) vs. Penguins(yellow): World Average



Averaging over many penguin decays:

World discrepancy with tree decays

= -3.5 σ

Red boxes: estimate from theory of errors due to neglecting other decay amplitudes

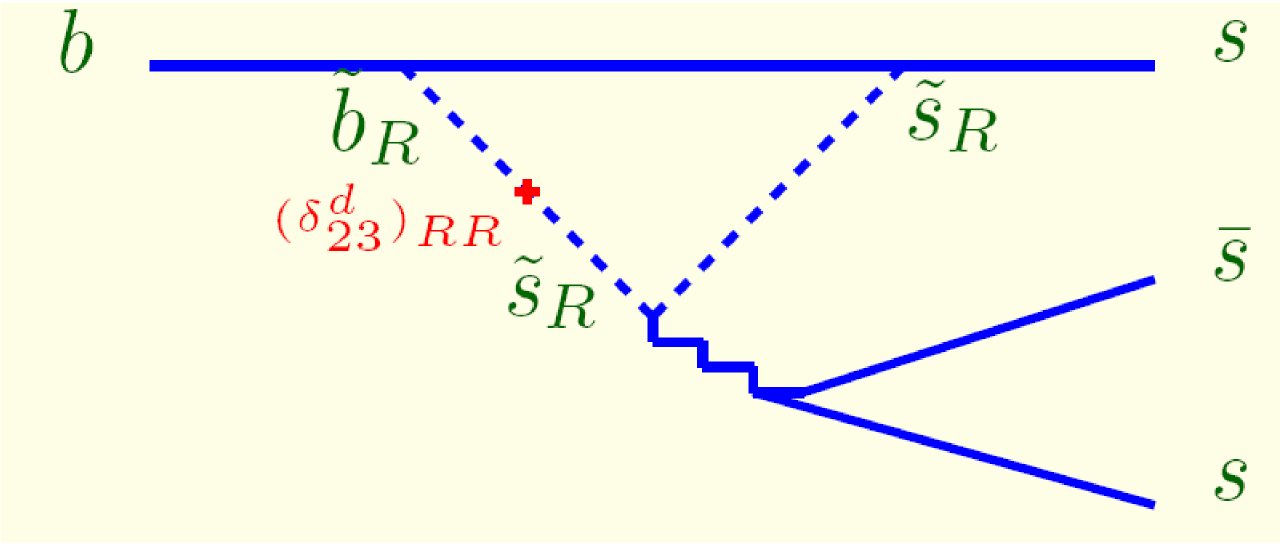
New Physics Scenarios

•**New physics at the electroweak scale generically introduces new large flavor-violating or CP-violating couplings to quarks**

→Existing flavor physics measurements severely limit types of new physics!

• **The great number of possible new couplings can give rise to many different combinations of effects**

Ex: Right handed (b →s) squark mixing in gluino penguins could introduce a new phase in b → s$\bar{s}$s penguins without affecting B mixing nor b → c$\bar{c}$s nor b → sγ



Future and Follow-up Measurements

- Both B factories hope to collect 4-5 X more data over the next 4-5 years
    - Significance of the penguin problem could double and unambiguously falsify the Standard Model!

- Improved measurements of rates and asymmetries in other penguin decays ($b \to s\, \gamma$, $b \to d\, \gamma$, $b \to s\, l\, l$, $B \to \phi\, K^*$, ……)

- Fermilab Tevatron can measure B_s , Λ_b decays

- LHCb, BTeV: scheduled to produce billions of B's in pp collisions

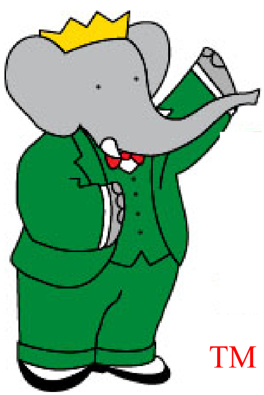
- Super B Factory: 50X version of B factories

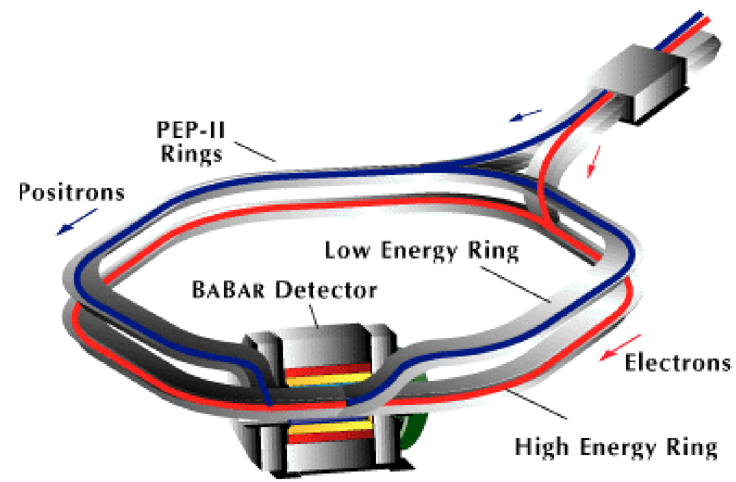
Summary

•The physics of quark flavor, as seen through the b quark, is a rich area of study with wide-ranging implications

•The Standard Model CKM theory of flavor and CP violation holds up well for tree-level processes

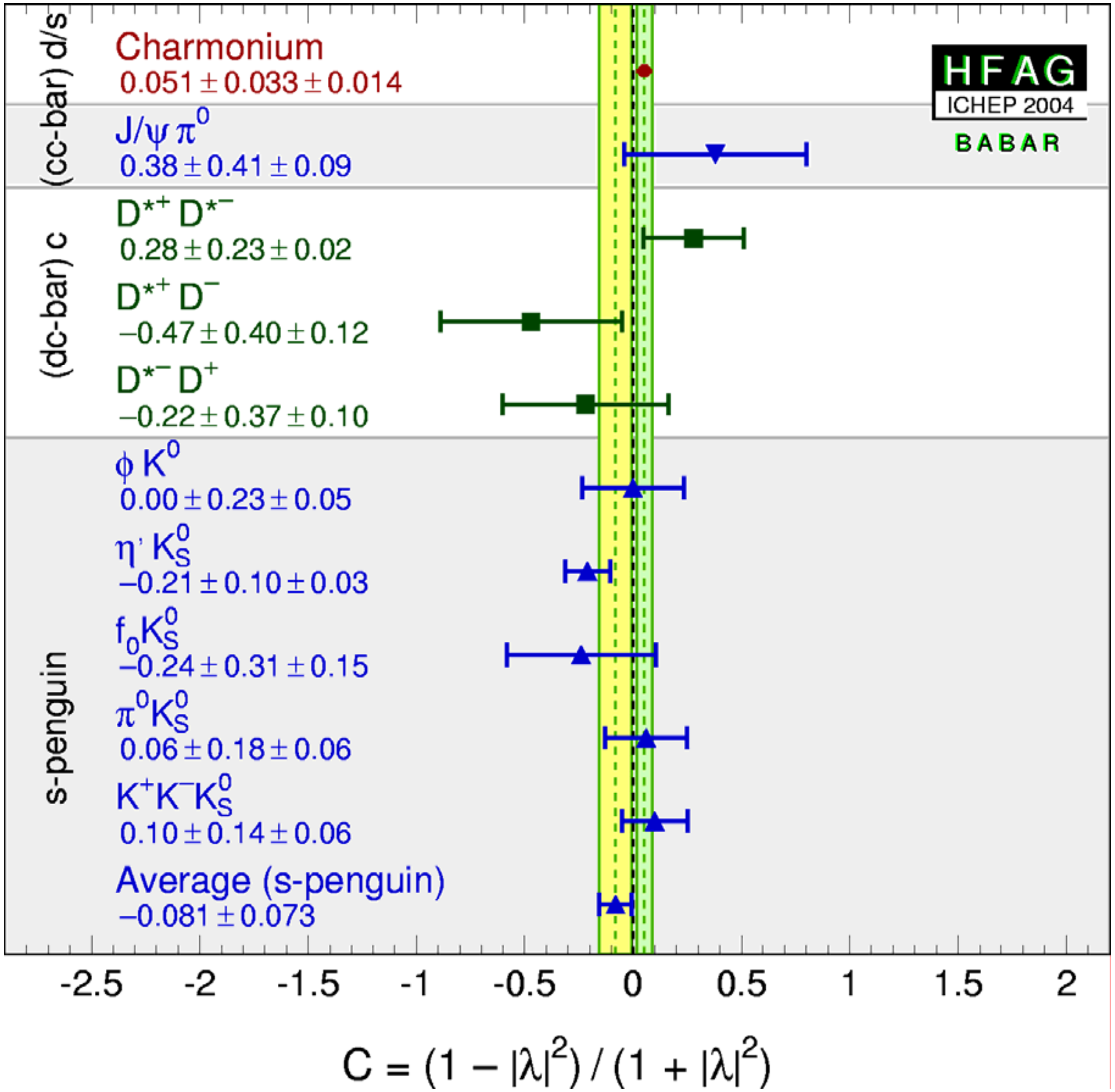
•Penguin processes, which are especially sensitive to new physics, could prove to be the lever which cracks the Standard Model wide open





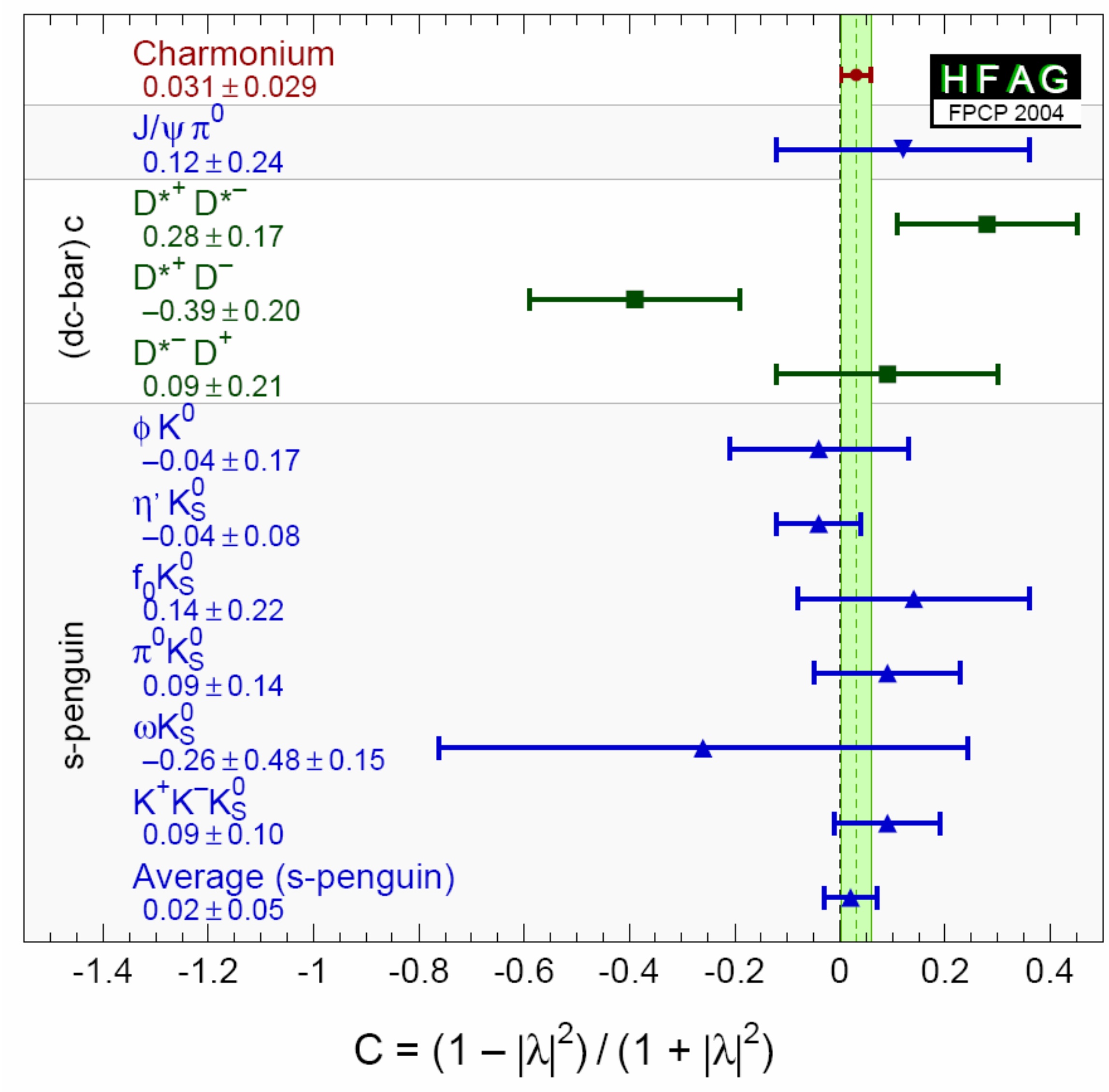
Backups

Direct CP Violation: BaBar Data



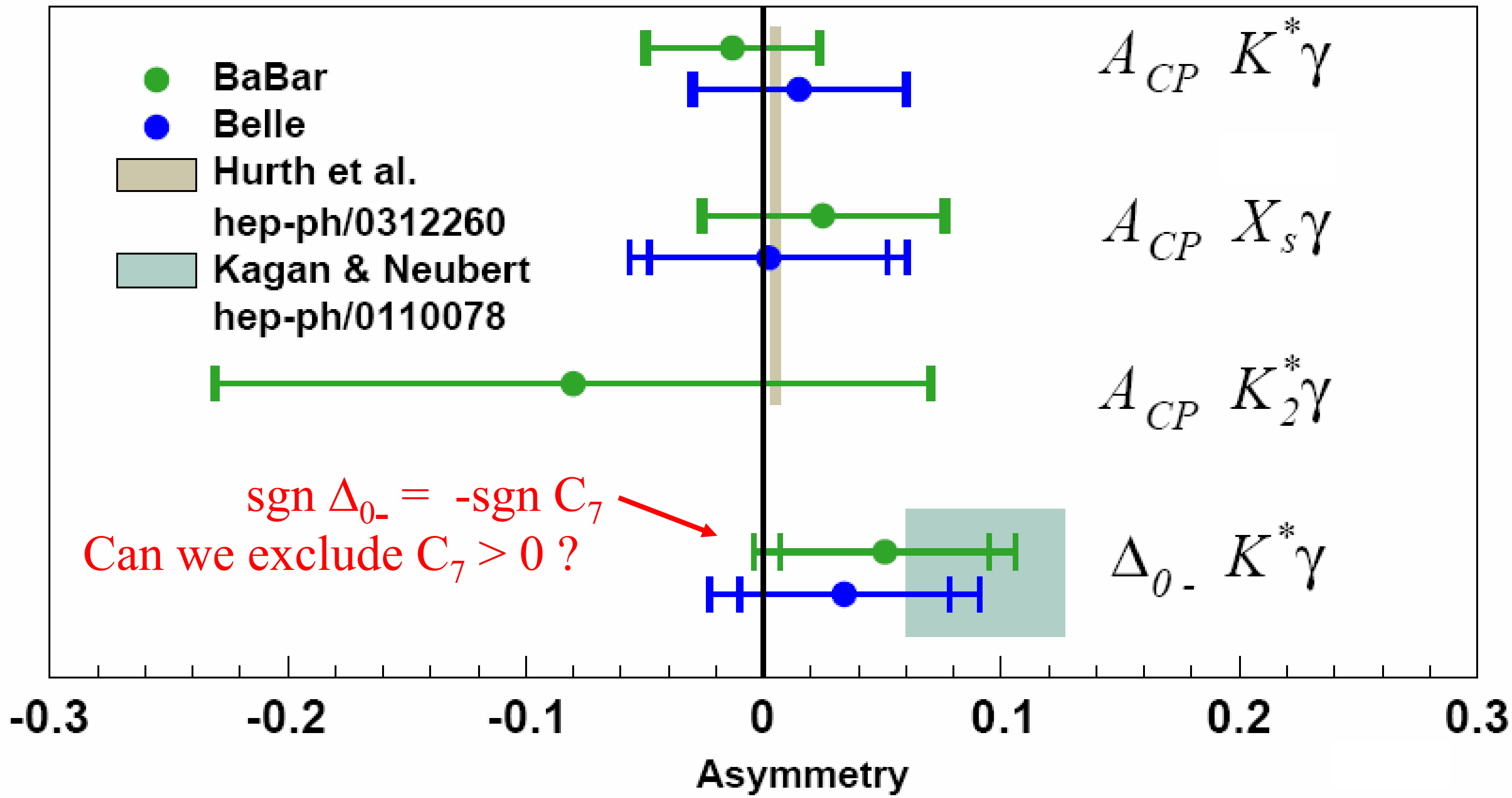
Direct CP violation consistent with 0 for all modes

Direct CP Violation: World Average

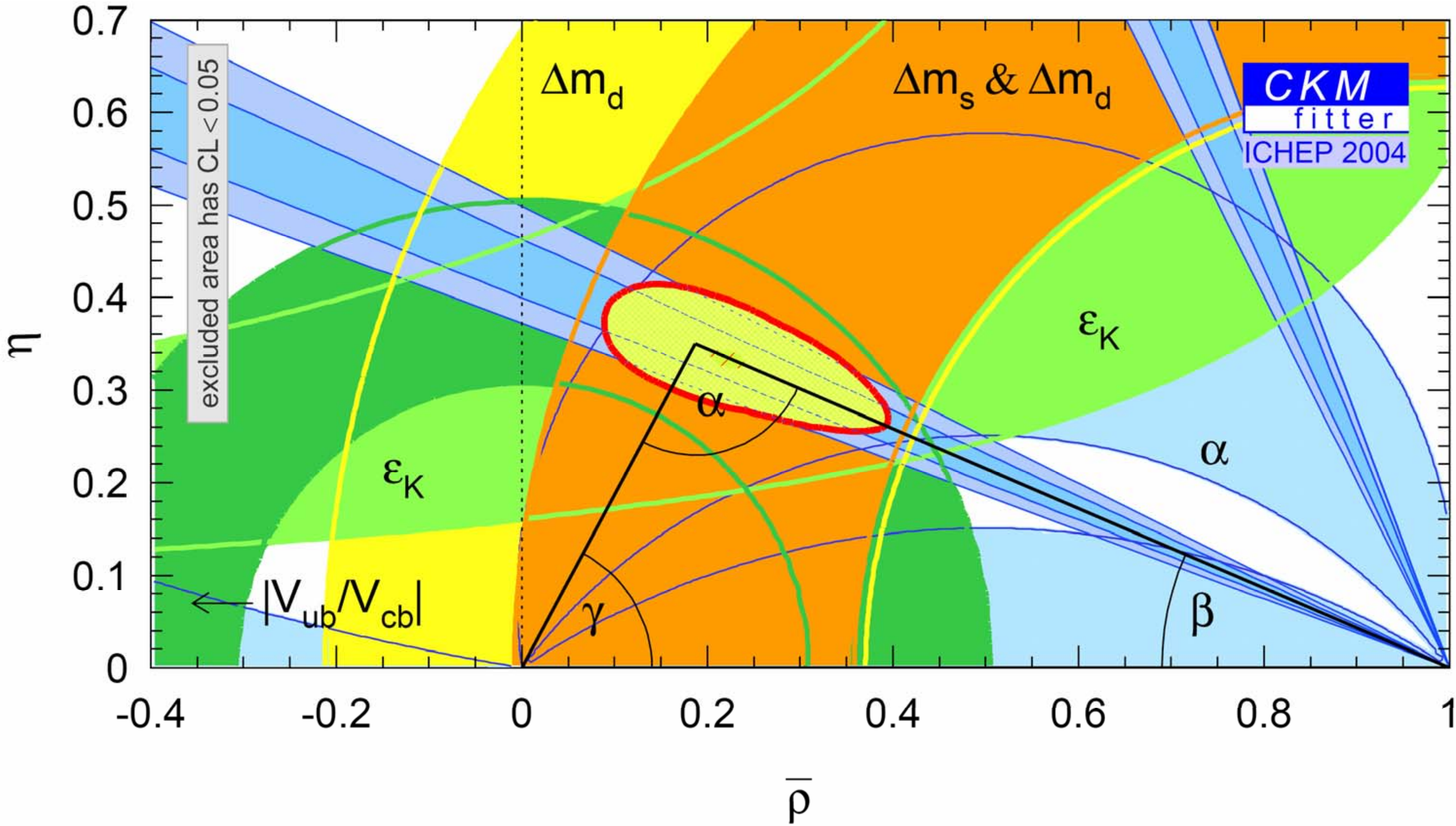


$b \to s\,\gamma$ Asymmetries: Summary

- BaBar measurements on 82 fb^{-1}
  $K^*\gamma$, $K_2^*\gamma$ preliminary; $X_s\gamma$ published
- CP asymmetries consistent with SM (0.4%) at the ~5% level
- $K^*\gamma$ isospin asymmetry Δ_{0-} consistent with $C_7 < 0$
- **Statistics limited** up to ~1 ab^{-1}



CKM Constraints



CKM matrix constraint

SU(3) breaking of form factors $\zeta^2 = 0.85 \pm 0.10$

weak annhilation correction $\Delta R = 0.1 \pm 0.1$

Ali et al. hep-ph/0405075

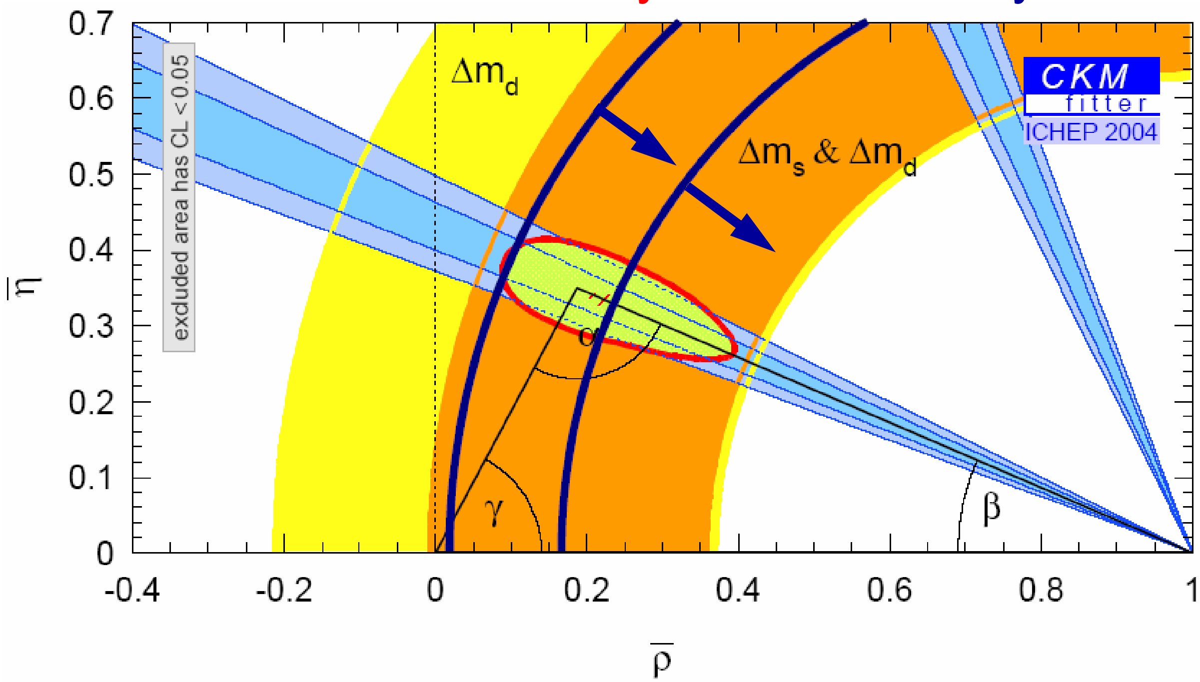
$$\frac{\overline{\mathcal{B}}[B \to (\rho/\omega)\gamma]}{\overline{\mathcal{B}}(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - m_\rho^2/M_B^2}{1 - m_{K^*}^2/M_B^2}\right)^3 \zeta^2[1 + \Delta R]$$

$(\zeta^2,\Delta R) = (0.75,0.00)$ theory error

$(\zeta^2,\Delta R) = (0.85,0.10)$ no theory error

Penguins are starting to provide meaningful CKM constraint

Reduction of theory errors necessary to be competitive with B_d,B_s mixing

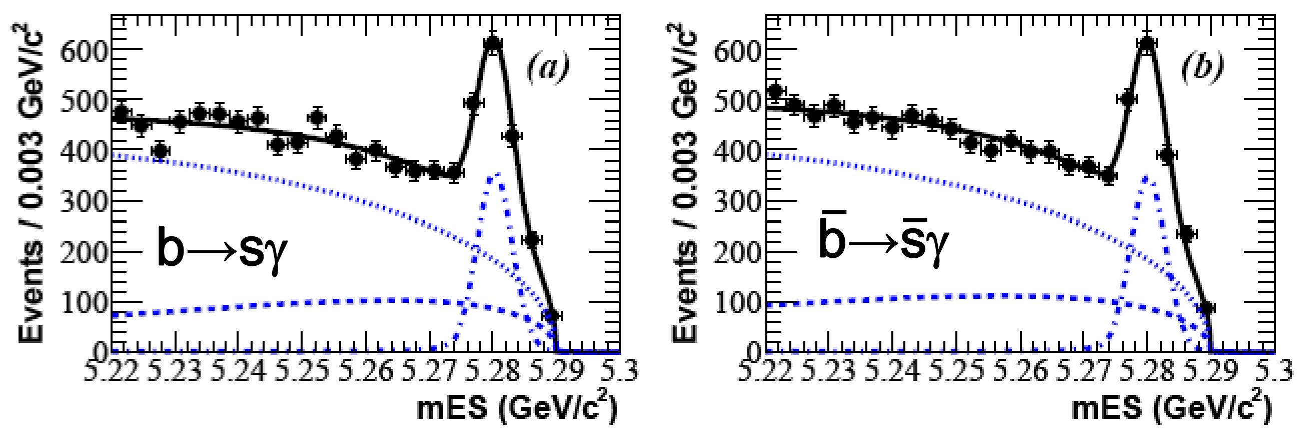


$\rho\gamma$ 95% C.L. BaBar allowed region (inside the blue arc)

Direct CP Asymmetry: b →sγ and $B \rightarrow K^* \gamma$

< 1% in the SM, could receive ~10% contributions from new EW physics
Either inclusive or exclusive decays could reveal new physics

B or K charge tags the flavor of the b quark with ~1-2% asymmetry systematic



Sum of 12 exclusive, self-tagging $B \rightarrow X_s\ \gamma$ final states

X_s = K/K_s + 1-3 pions
$E\gamma^*$ > 2.14 GeV

b →sγ $A_{CP} = (N - \bar{N})/(N + \bar{N}) = 0.025 \pm 0.050 \pm 0.015$

PRL 93 (2004) 021804, hep-ex/0403035

Asymmetries also measured precisely in exclusive K*γ decays:

B →K*γ $A_{CP} = -0.013 \pm 0.036 \pm 0.010$

submitted to PRL, hep-ex/0407003

$$\Delta_{0-} = \frac{\Gamma(\bar{K}^{*0}\gamma) - \Gamma(K^{*-}\gamma)}{\Gamma(\bar{K}^{*0}\gamma) + \Gamma(K^{*-}\gamma)} = 0.050 \pm 0.045 \pm 0.028 \pm 0.024$$

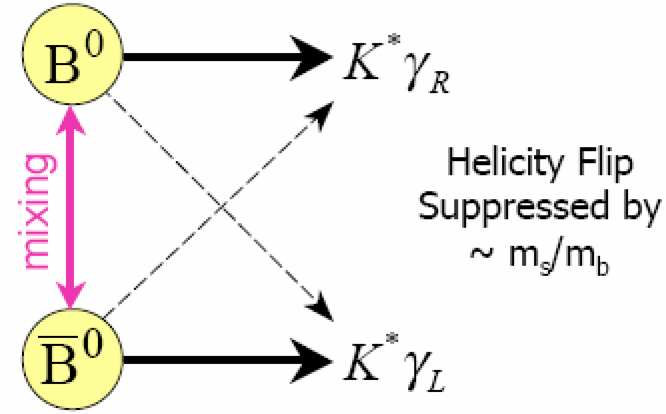
preliminary

Time-Dependent CP Asymmetry in $B \to K^*\gamma$ (113 fb^{-1})

As in $B^0 \to J/\psi\, K_S$, interference between mixed and non-mixed decay to same final state required for CPV.

In the SM, mixed decay to $K^*\gamma$ requires wrong photon helicity, thus CPV is suppressed:

In SM: $C = -A_{CP} \approx -1\%$ $\quad S \approx 2(m_s/m_b)\sin 2\beta \approx 4\%$

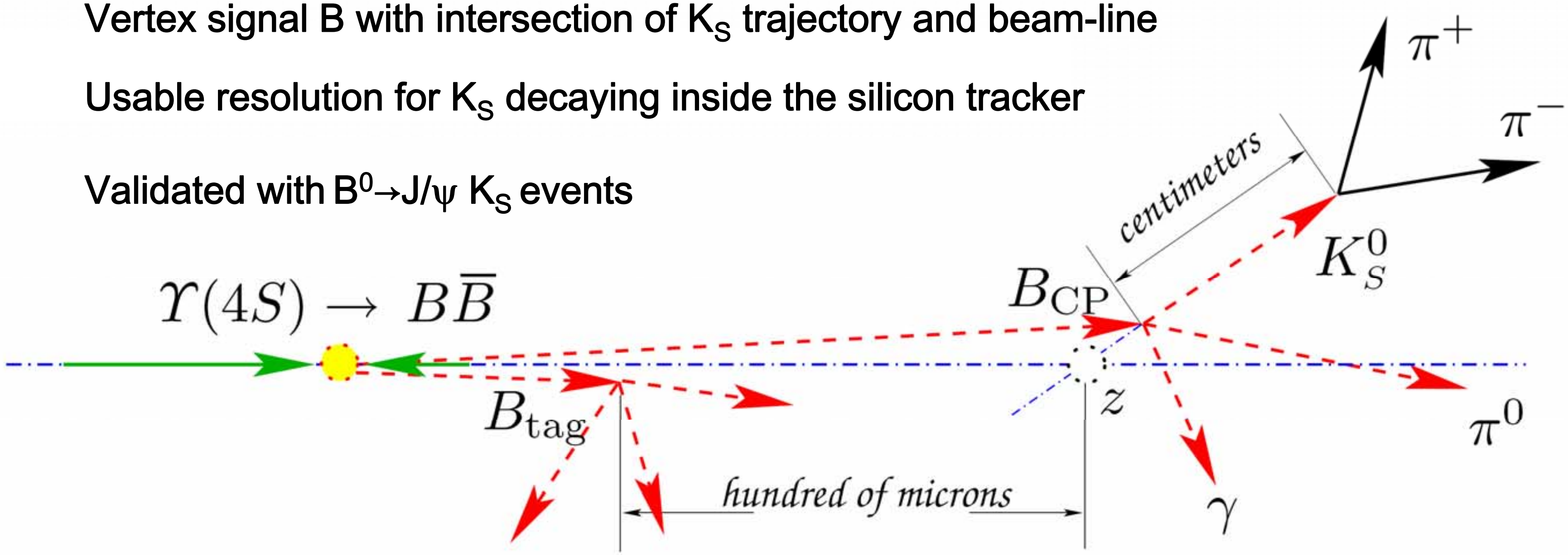


Measuring Δt of $K^*(\to K_S\pi^0)\,\gamma$ events requires novel beam-constrained vertexing techinque:

Vertex signal B with intersection of K_S trajectory and beam-line

Usable resolution for K_S decaying inside the silicon tracker

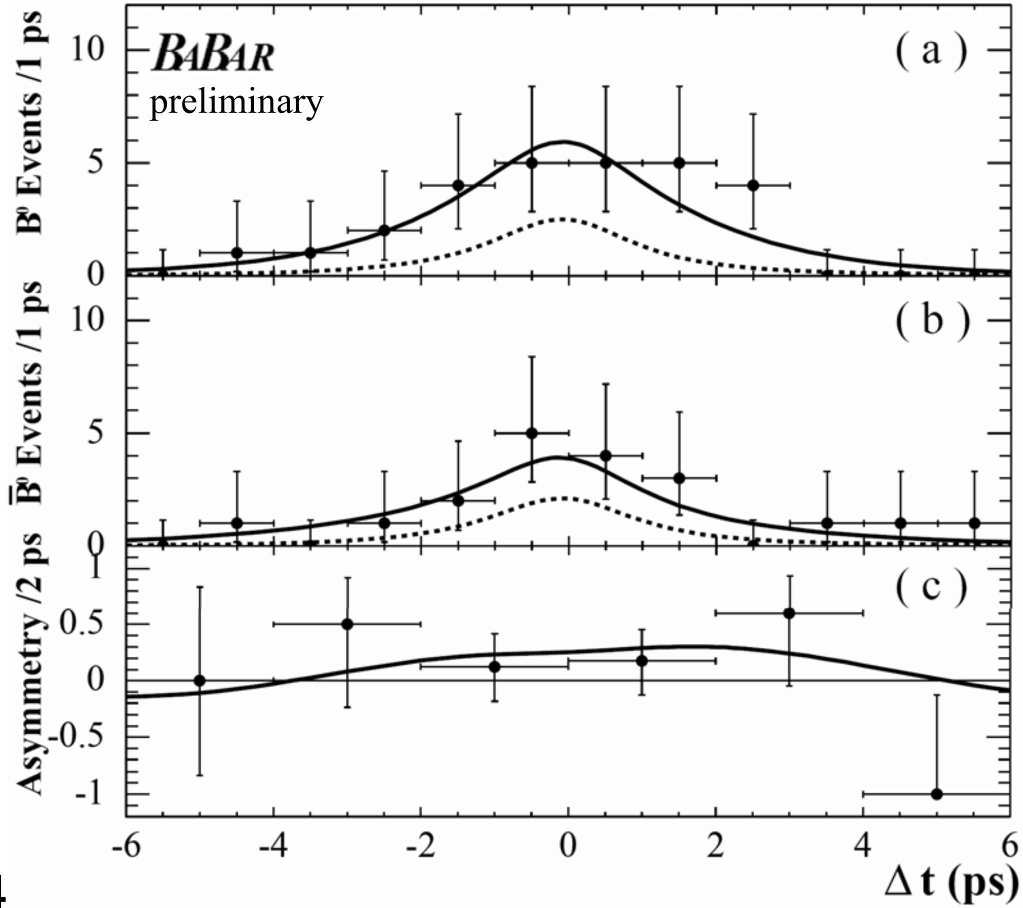
Validated with $B^0 \to J/\psi\, K_S$ events



Time-Dependent CP Asymmetry in $B \to K^*\gamma$ (113 fb^{-1})

Likelihood fit of three components ($q\bar{q}$, $B\bar{B}$, $K^*\gamma$) to 5D data (m_{ES},ΔE,Fisher,m_{K^*},Δt)

$K^*\gamma$ signal = 105 ± 14 events



S = +0.25 ± 0.63 ± 0.14

C = -0.57 ± 0.32 ± 0.09

submitted to PRL, hep-ex/0405082

Consistent with SM

For C fixed to 0, S = 0.25 ± 0.65 ± 0.14

First ever measurement of time-dependent CP asymmetries in radiative penguins!

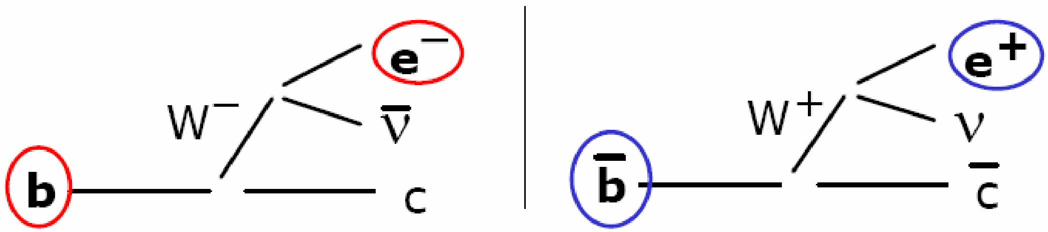
Flavor tagging

CP asymmetry is between $B^0 \rightarrow f$ and $\overline{B^0} \rightarrow f$

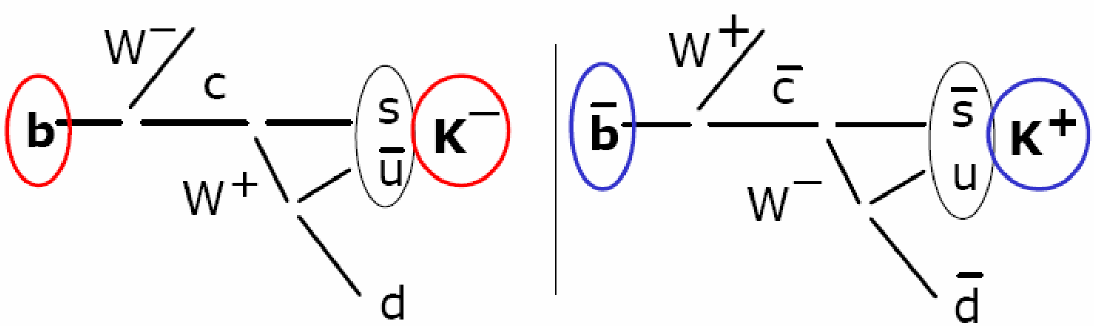
Must tag flavor at $\Delta t=0$ (when we know flavor of two Bs is opposite).

Use decay products of *other* (tag) B.

Leptons : Cleanest tag. Correct >95%



Kaons : Second best. Correct 80-90%



Full tagging algorithm combines all in neural network

Four categories based on particle content and NN output.

Tagging performance

$$\sum_i \epsilon_i (1-2\omega_i)^2$$

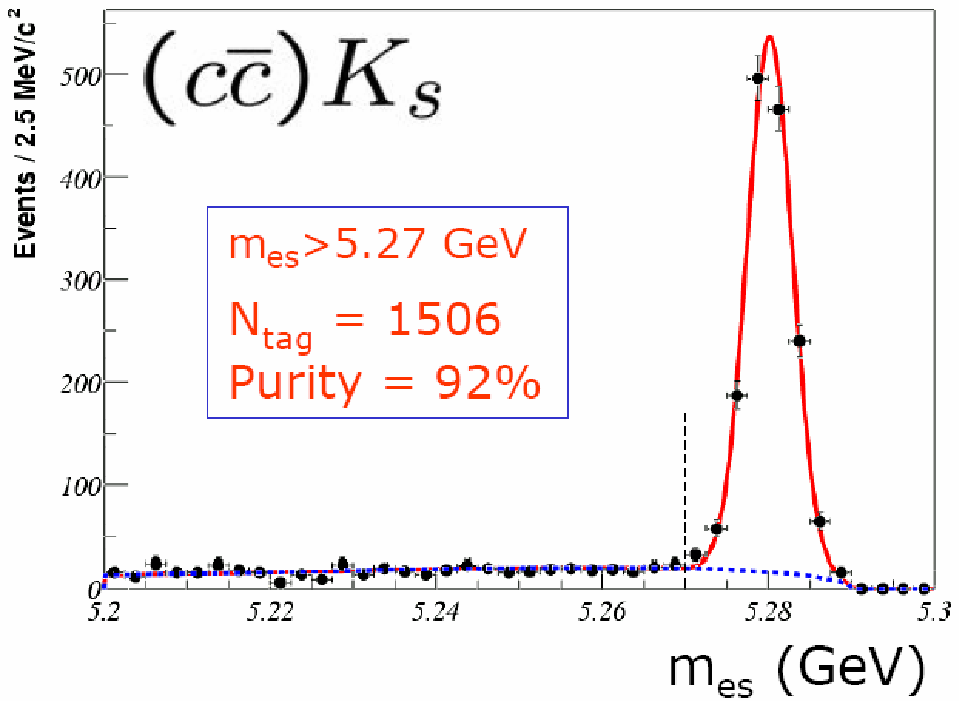
= 28% !

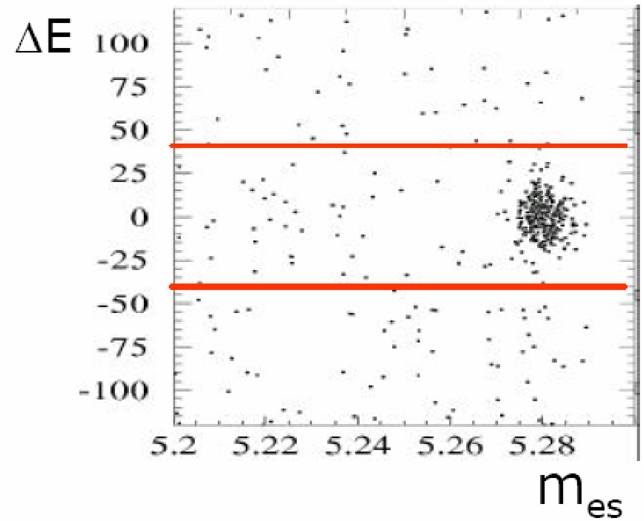
Kinematic variables at the $\Upsilon(4S)$

Variables for signal/BG discrimination

$$m_{es} = \sqrt{E^{*2}_{\text{beam}} - \sum \vec{p^*_i}^{\,2}}$$

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





$\sigma m_{es} \approx 3$ MeV

$\sigma\ \Delta E \approx 15$ MeV

J/ψ Ks $(\pi^+\pi^-)$
m_{es} > 5.27 GeV
N_{tag} = 974
Purity 97%

Measurement of Δt

- $J/\Psi \rightarrow l^+l^-$ dominates in determination of CP vertex.
- Tracks not from CP B combined to form tag vertex.
  - Tracks with large χ^2 iteratively removed.
  - Long-lived particles (K_s , Λ) explicitly reconstructed.
  - Photon conversions ($\gamma \rightarrow e^+e^-$) removed.
- Vertex incorporates constraint from average beam position.
- Efficiency for CP sample 97 % (95% after $|\Delta t|<20$ ps, $\sigma_{\Delta t}<2.5$ ps)