Searching for New Physics: Results from Belle and Babar

- Brief intro
  "Old physics," B-factory experiments
- Searches for New Physics
  - B decay: loops & annihilation
  - Charm
  - Tau
- Summary

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¿where/how to search for new physics?

- New particles - (mainly) energy frontier - **brute force**
- Deviations from the Standard Model:
  - where possible New Physics effect > (exp & th) precision of SM
    - precise and finite SM value
    - highly suppressed/forbidden in SM

- At the B factory
  - B decays
    - CKM magnitudes, angles of Unitarity Triangle
    - Rates & CP asymmetries in rare decays
  - Charm decays
    - Large suppressions in SM: mixing, flavor-changing-neutral-current (FCNC), CP asymmetry
  - Tau leptons
    - Lepton flavor/number, baryon number

The Old Physics

Cabibbo-Kobayashi-Maskawa (CKM) matrix

{weak<->mass} eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathcal{M} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{array}{c|ccc} & d & s & b \\ \hline u & V_{ud} & V_{us} & V_{ub} \\ c & V_{cd} & V_{cs} & V_{cb} \\ t & V_{td} & V_{ts} & V_{tb} \end{array}$$

to make W-couplings generation-conserving

$$g_F \times \begin{array}{c|ccc} & d' & s' & b' \\ \hline u & 1 & 0 & 0 \\ c & 0 & 1 & 0 \\ t & 0 & 0 & 1 \end{array}$$

complex
preserves metric
" orthogonality
} ≡ unitary

Unitarity conditions $V_{ji}^{*}V_{jk}=\delta_{ik}$ **-> 4 free parameters**

explicit parametrization(Wolfenstein):

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

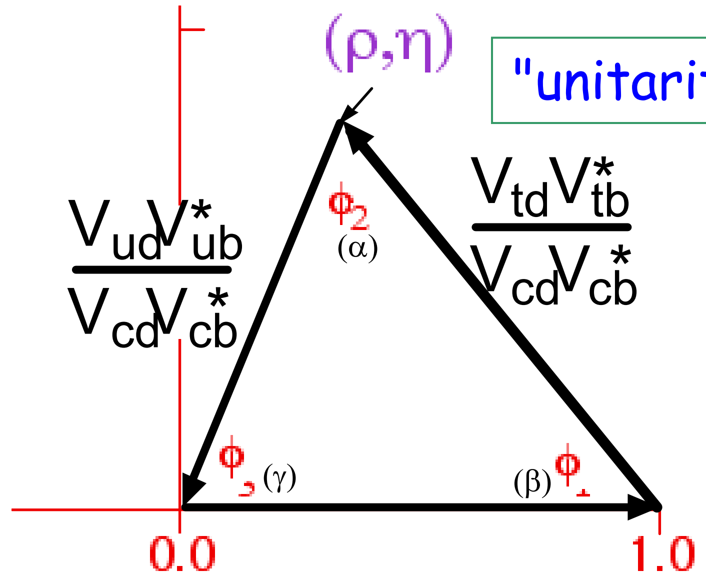
irreducibly complex! **-> CP violation**

Unitarity Triangle

Unitarity condition for {i=1,k=3} $V_{ub}^*V_{ud}+V_{cb}^*V_{cd}+V_{tb}^*V_{td}=0$

$$\Rightarrow \frac{V_{ub}^*V_{ud}}{V_{cb}^*V_{cd}} + 1 + \frac{V_{tb}^*V_{td}}{V_{cb}^*V_{cd}} = 0$$

$$-(\rho+i\eta) \qquad -(1-\rho-i\eta)$$



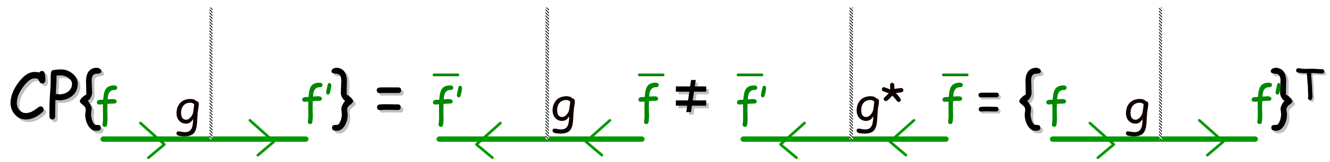
B-factories test self-consistency of UT

- fully constrained by 3 of {3 angles, 3 sides}

==> overconstrain to reveal any New Physics

Observing CP asymmetry

Complex coupling constant is CP-violating



BUT to <u>observe</u> CP asym, need 2+ interfering amplitudes {T,P}:

T=gA,P=g'A' -> |gA+g'A'| $\xrightarrow{CP}$ |gA*+g'A'*|

Equal only if <u>relative phase</u> of g,g'=0

AND for irreducibly complex weak coupling in CKM, need process w. all 3 generations

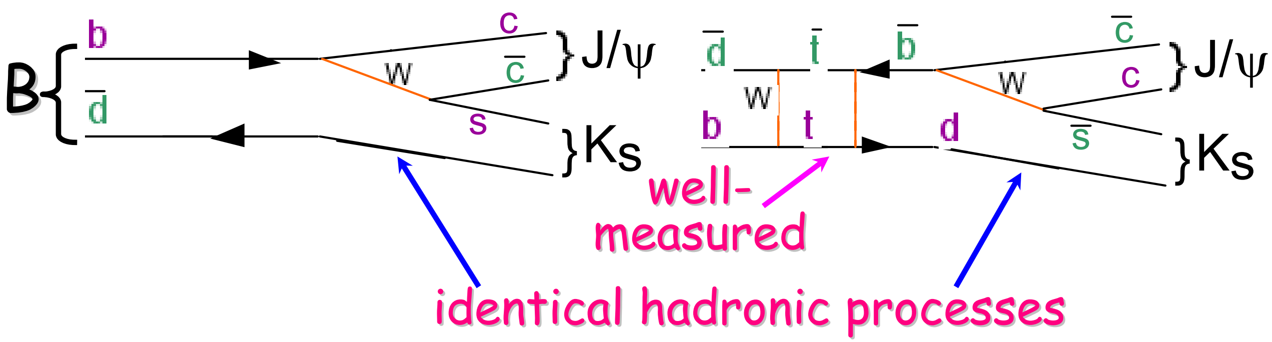
===>>> B Decays ===>>>

CP asymmetry in B decay: example

B -> J/ψ K_s(Sanda/Bigi/Carter)

mixing+tree ($\propto V_{td}^{*2}$)

tree (real V_{ij}) $\propto V_{cb}^{*}V_{cs}$ $\propto V_{tb}^{*2}V_{td}^{2}V_{cb}V_{cs}^{*}$



Bottom line: CP-dependent oscillation in time from x-term(s)
- no theoretical uncertainty: $\arg(V_{td}^2) = 2\varphi_1$

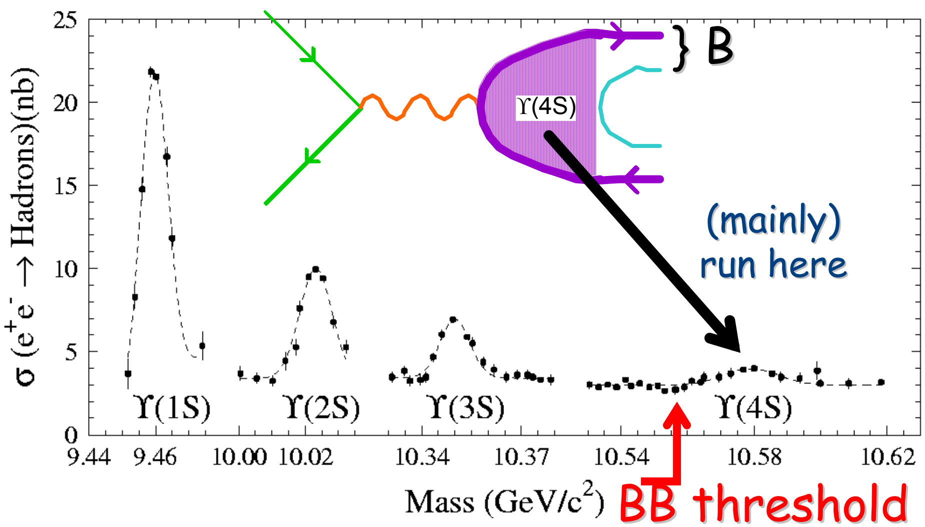
$$\frac{dN}{dt}(B \rightarrow f_{CP}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}(1 + \eta_b\eta_{CP}\sin 2\phi_1 \sin(\Delta m \Delta t));$$

$$\eta_b = \begin{pmatrix} +1 \text{ if } B_{t=0} = B^0 \\ -1 \text{ if } B_{t=0} = \bar{B}^0 \end{pmatrix} \quad \eta_{CP} = \begin{pmatrix} -1 \text{ if } CP\ odd \\ +1 \text{ if } CP\ even \end{pmatrix}$$

the B-factory experiments

- Luminosity & events, Belle + Babar combined
  - $\int L dt$ ~ 1100 fb^{-1} (~90% Υ(4S), ~10% off-resonance)
    - ~ 1.2 billion $B\overline{B}$ events
    - ~ 1.3 billion $c\overline{c}$ events
    - ~ 1.1 billion tau pairs
  - at Υ(5S){10.869 GeV} 1.86 fb^{-1} (Belle)
    - 9 x 10^4 $B_s\overline{B}_s$ events

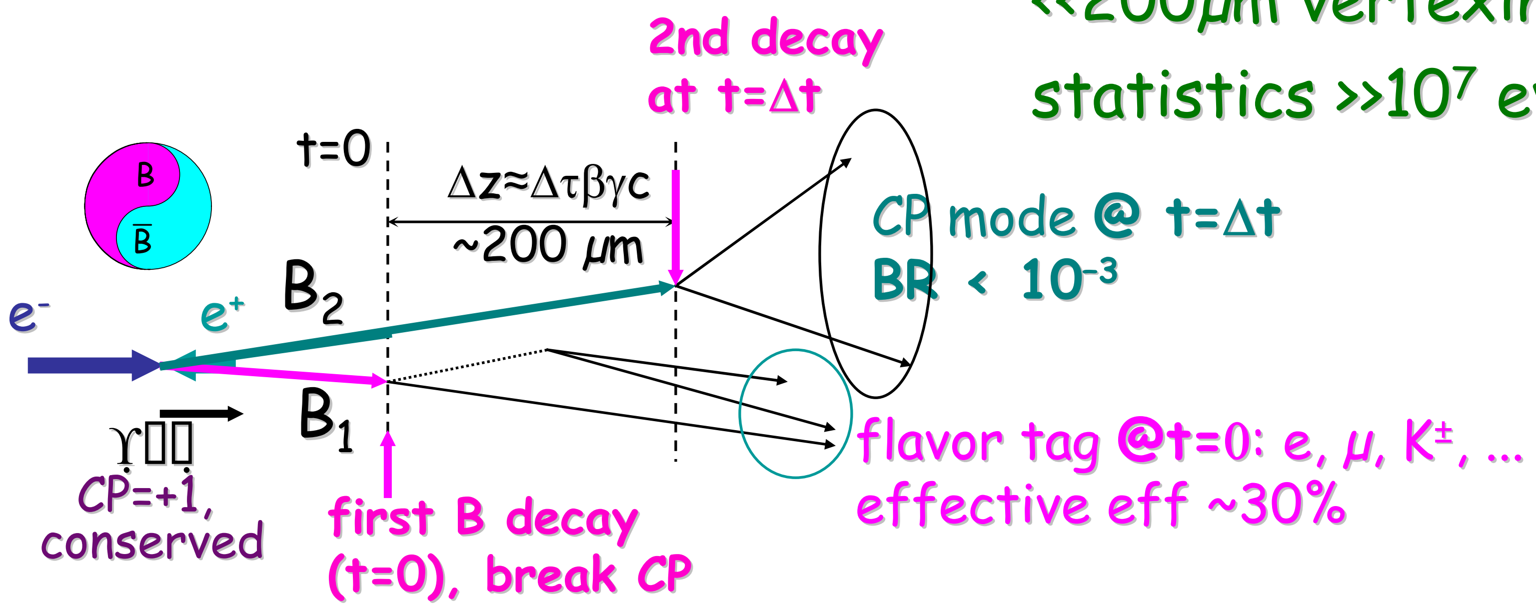
B factory: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$



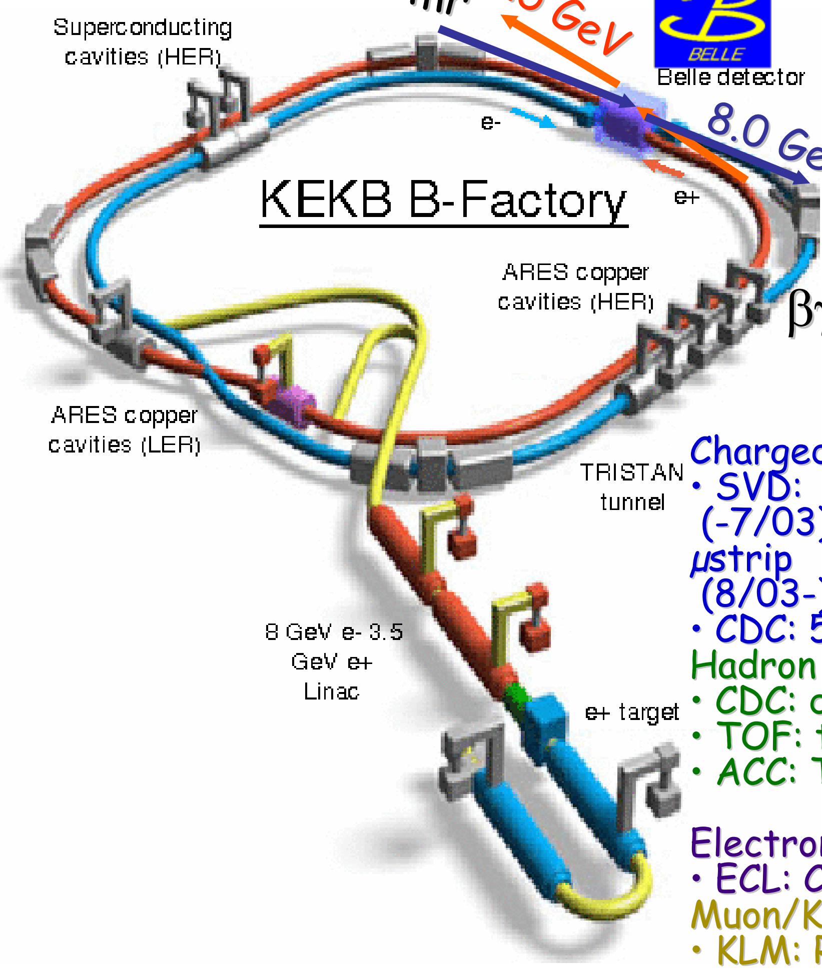
Δt [illegible] energy $e^+e^- \to \Upsilon(4S)$
(symmetric Υ(4S): CLEO 1979-2001)

Experimental design:

- hadron (K/π), lepton ID
- <<200μm vertexing
- statistics >>10^7 events



KEKB & Belle



- L_{max} = 1.65 X 10^{34} $cm^{-2}s^{-1}$ (world record)
- Data (6/1999–6/2006)
- $\int Ldt$ = 630 fb^{-1}@{Y(4S)+off(~10%)}
- (>6.4x10^8 B events)

SVD1: 152M B pairs
SVD2: 480M+

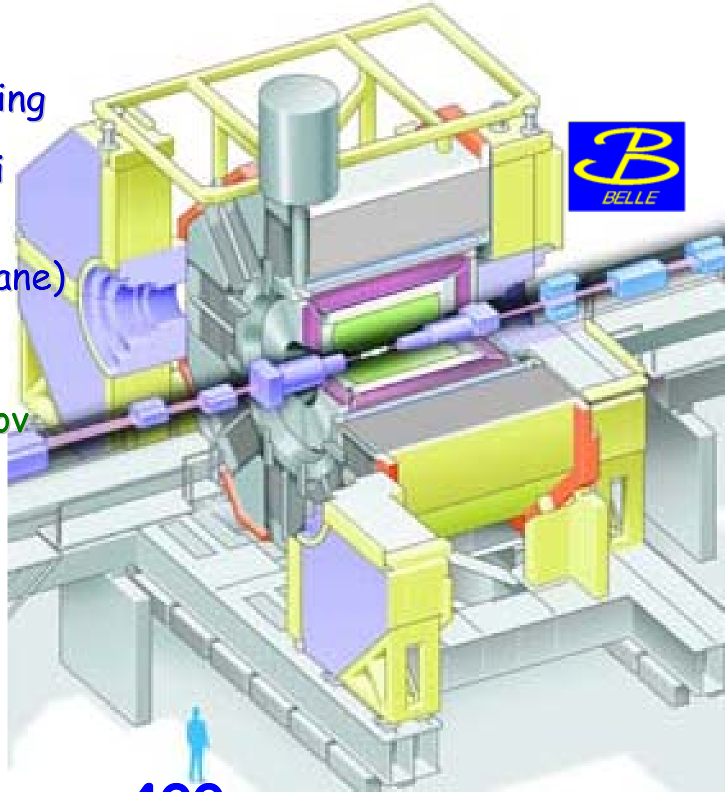
$\beta\gamma$ = 0.425

Charged tracking/vertexing
- SVD:
  (-7/03) 3-layer DSSD Si μstrip
  (8/03-) 4-layer
- CDC: 50 layers (He-ethane)

Hadron identification
- CDC: dE/dx
- TOF: time-of-flight
- ACC: Threshold Cerenkov (aerogel)

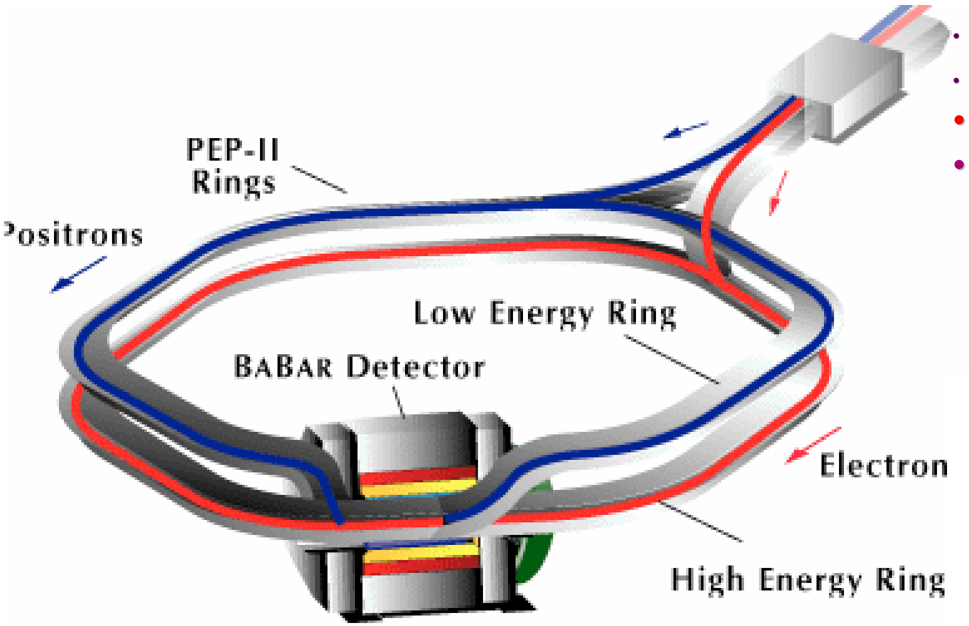
Electron/photon
- ECL: CsI calorimeter

Muon/K_L
- KLM: Resistive plate counter/iron

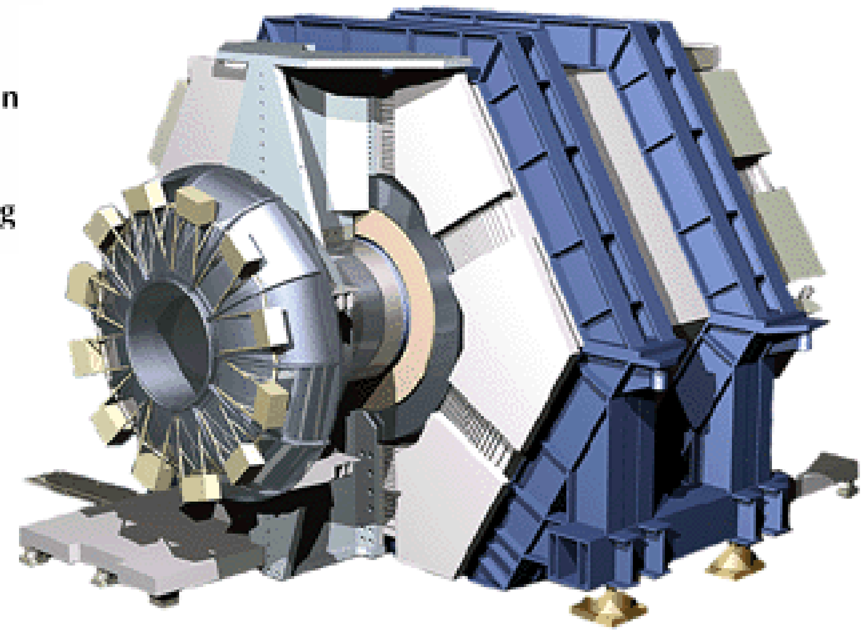


~13 nations, 55 institutes, ~400 persons

PEP-II & Babar



- L_{max} = 1.12 X 10^{34} $cm^{-2}s^{-1}$
- Data (1999–7/2006)
- $\int Ldt$ = 371 fb^{-1}@{Y(4S)+off(~10%)}
- (>3.7x10^{8} B events)



Charged tracking/vertexing
- 5-layer DSSD Si μstrip
- 40 layers (He-isobutane)

Hadron identification
- tracker: dE/dx
- DIRC imaging Cerenkov

Electron/photon
- CsI calorimeter

Muon/K_L
- Instrumented flux return

11 nations, 80 institutes, 623 persons

time-dependent CP analysis: overview

(Belle)

1) CP final state reconstruction

exploit

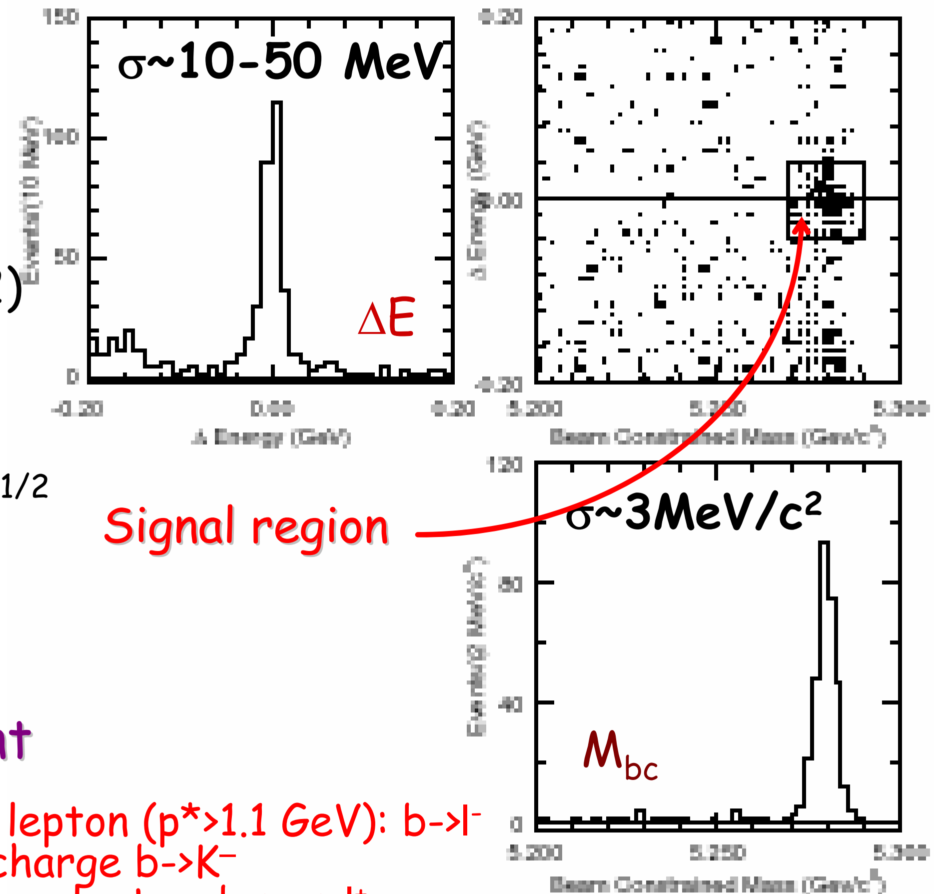
- exclusive pair production of B
- narrow resolution of collision energy

$\Delta E \equiv E^*_{cand} - E^*_{beam} \approx 0 \ (E^*_{beam} \equiv s^{1/2}/2)$

$\sigma \sim 10\text{-}50$ MeV, depending on mode

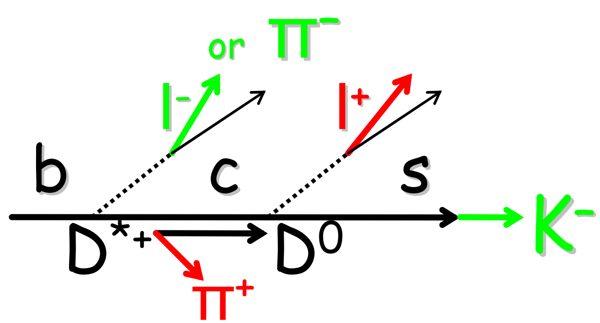
M_{bc} (Beam-constrained mass)

$M_{bc} \equiv (E^{*2}_{beam} - p^{*2}_{cand})^{1/2}$



2) Flavor tagging: sign of other b

all remaining particles in the event

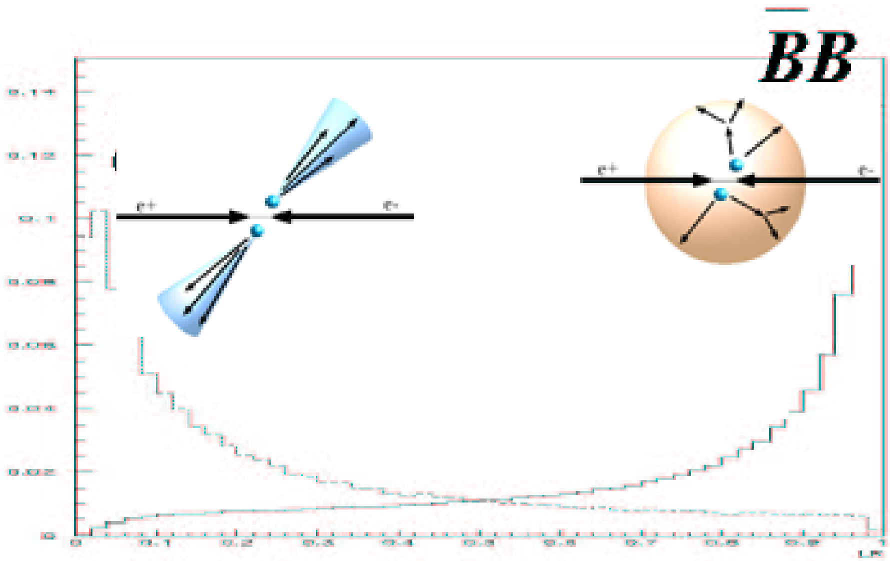


- high-p lepton ($p^*>1.1$ GeV): $b \to l^-$
- net K charge $b \to K^-$
- medium-p lepton, $b \to c \to l^+$
- soft π $b \to c\{D^{*+} \to D^0\pi^+\}$
- hard π $b \to \{c\}\pi^- X$

multidimensional likelihood, ε>99%

incorrect tag reduces ε, net (28.7±0.5)%

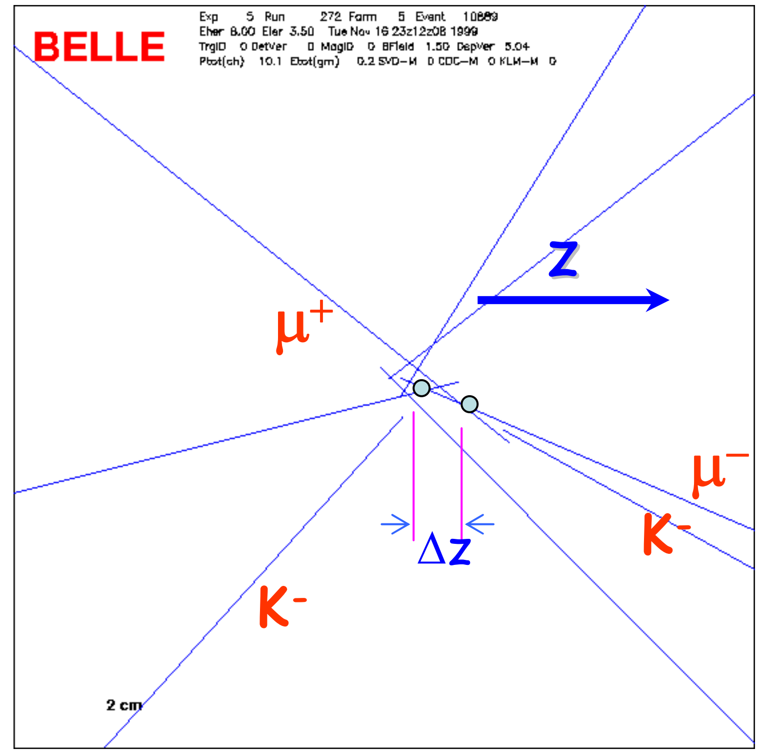
3) Continuum suppression: event parameters (“shape”)



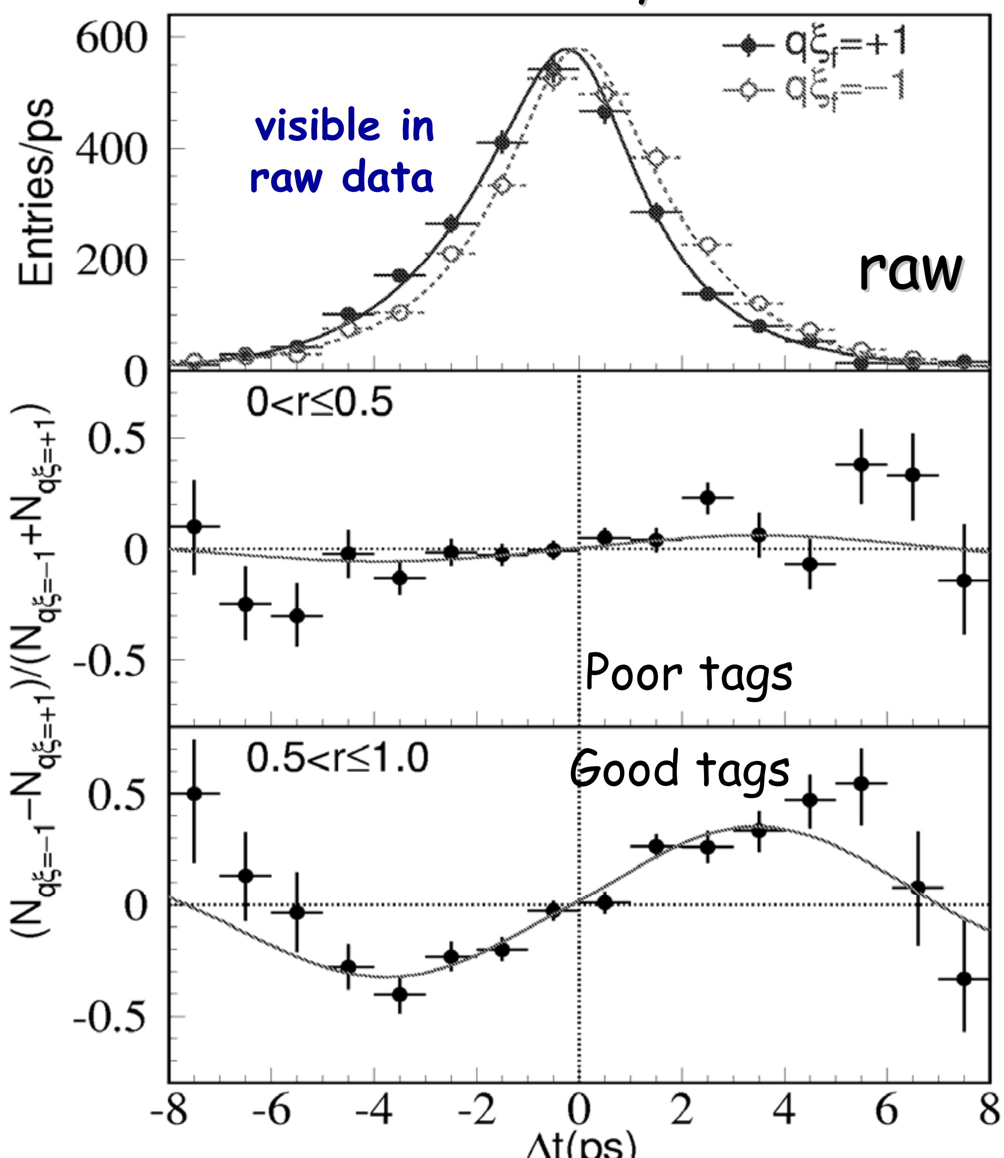
$$R \equiv \frac{\mathcal{L}_{sig}}{\mathcal{L}_{sig} + \mathcal{L}_{bg}}$$

4) Vertex reconstruction

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



Belle B->c$\bar{c}$s decays



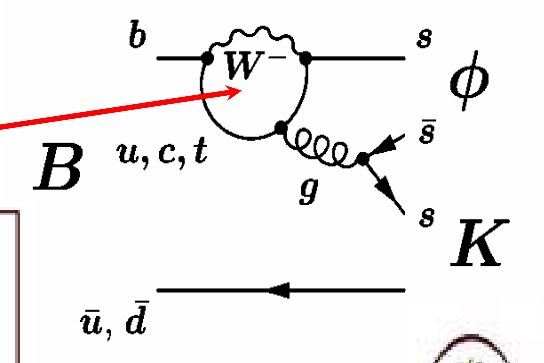
5) Fit to Δt distribution:
unbinned maximum likelihood

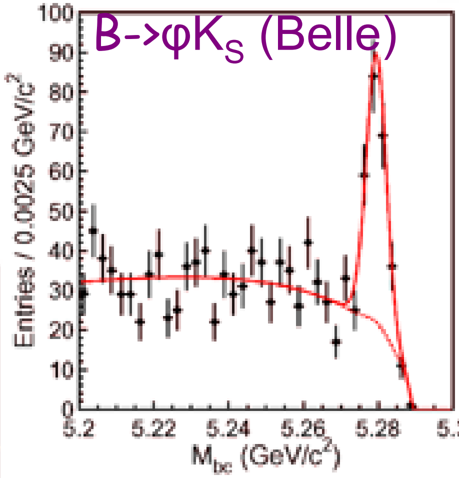
Measurements with sensitivity to New Physics
(many to be updated in a few days)

- CP asymmetry in b->$s s \bar{s}$, $s q \bar{q}$
- b->$s\ell^+\ell^-$: Wilson coefficients
- b->dγ/b->sγ
- CP, CPT asymmetry in dilepton events
  - (Belle) hep-ex/0505017 (Babar) hep-ex/0603053
- B-> τν
- B_d, B_s -> γγ
- Charm - mixing, flavor-changing neutral currents
- Tau - lepton flavor/number, baryon number violation

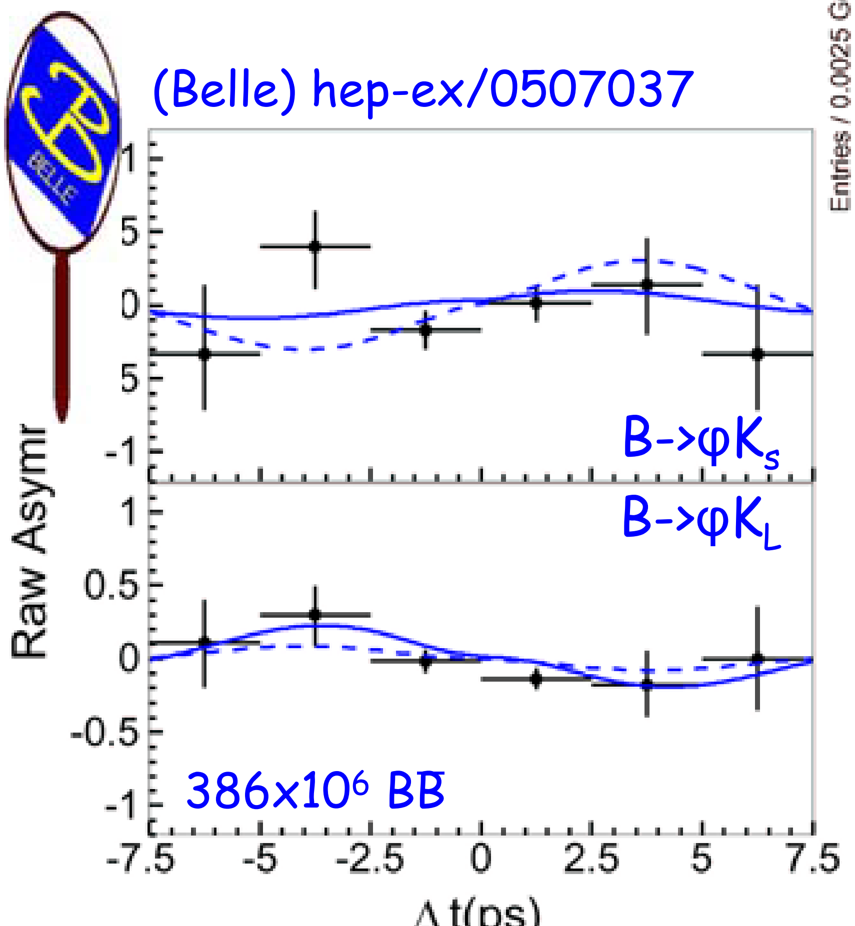
CP asymmetry in B->ss$\bar{s}$: sin2φ_1 in SM

- Dominated by penguin, ≠0 due to high t mass
  - SM: approx. cancellation in loop
  - NP w complex phase

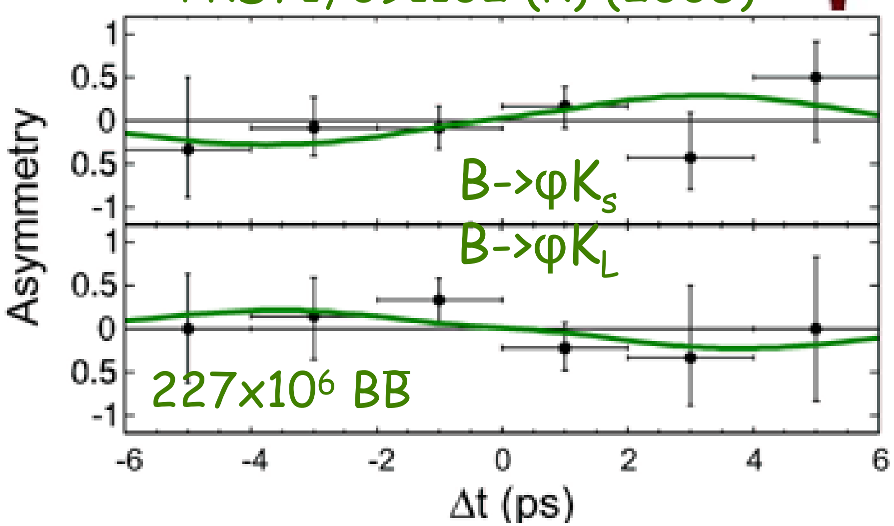




(Belle) hep-ex/0507037

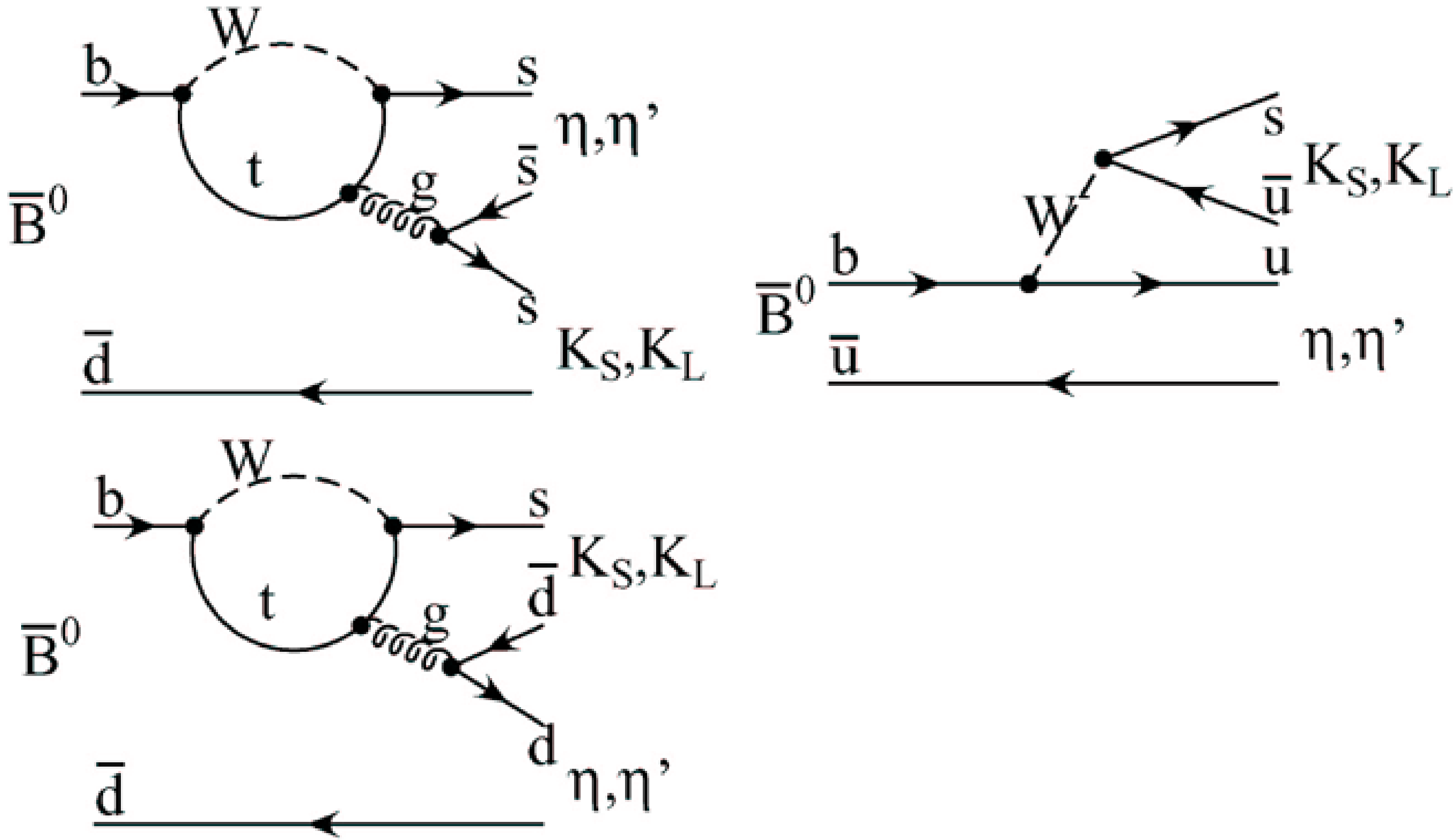


PRD71, 091102 (R) (2005)

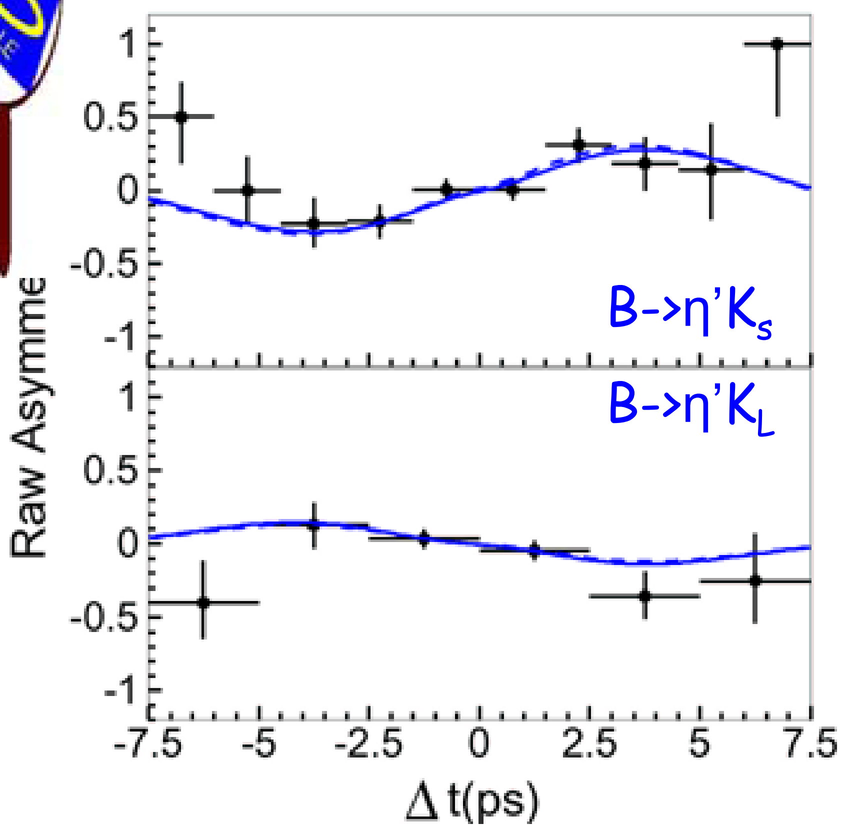


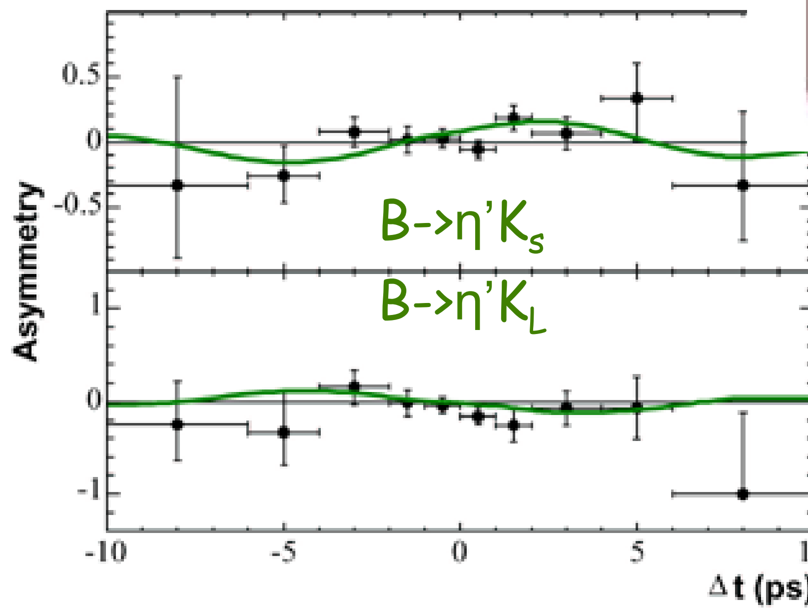
B->s$\bar{q}$q: e.g. Kη'

- Additional diagrams compared to pure sss, possible tree contributions -> not as theoretically tidy



B->s$q\bar{q}$: η'K^0


B->η'K_s
B->η'K_L
Raw Asymme
1
0.5
0
-0.5
-1
-7.5
-5
-2.5
0
2.5
5
7.5
Δ t(ps)


B->η'K_s
B->η'K_L
Asymmetry
0.5
0
-0.5
1
0
-1
-10
-5
0
5
10
Δ t (ps)

Average "sin2φ_1" from *b->s* penguins

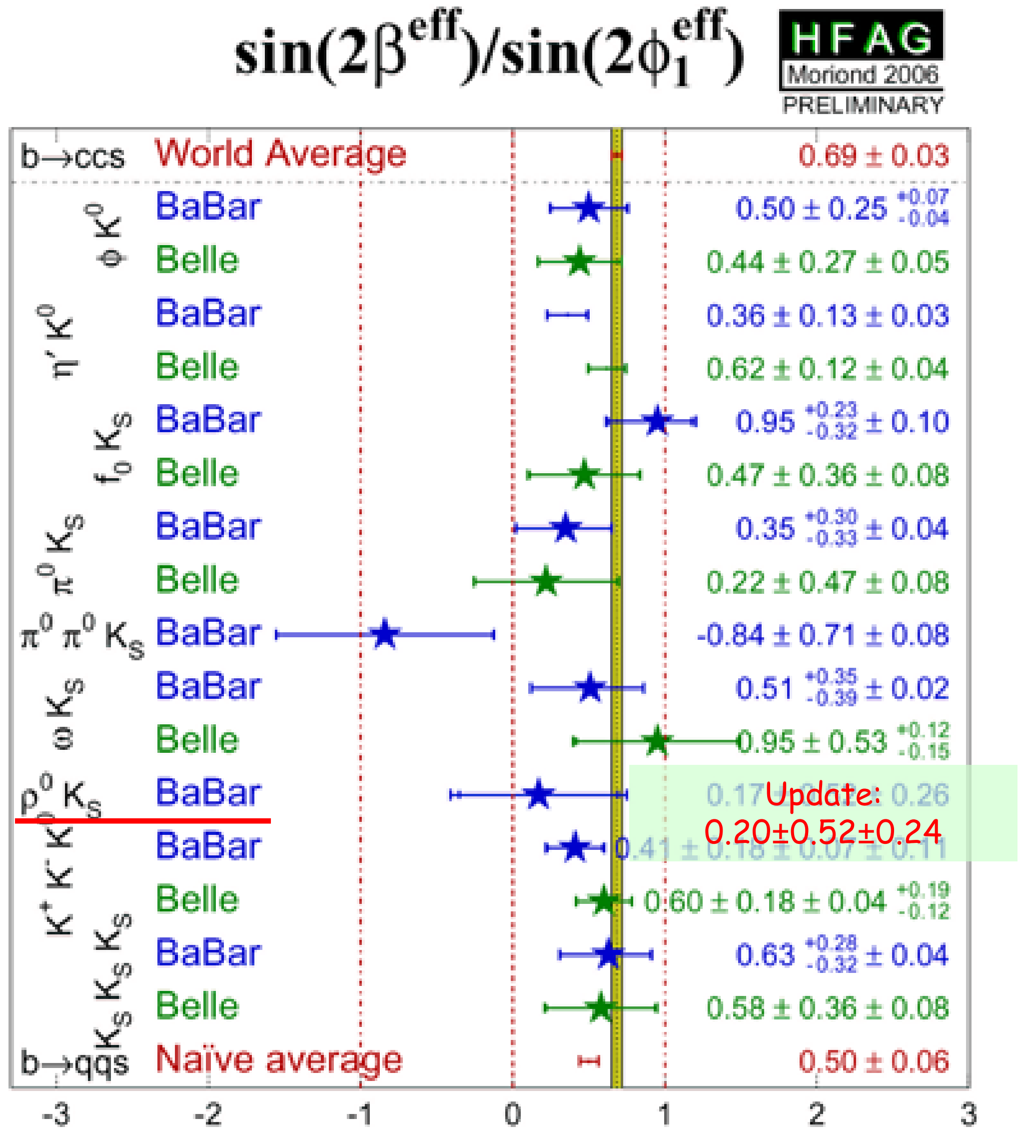
Only 1 update since Winter 2006 (more in a few days):
http://www.slac.stanford.edu/xorg/hfag/triangle/moriond2006/index.shtml#qqs

Naïve World Average
sin2φ_1($b \to sq\bar{q}$)= 0.50 ± 0.06

Compare to $c\bar{c}s$:
sin2φ_1($b \to c\bar{c}s$) = 0.685 ± 0.032

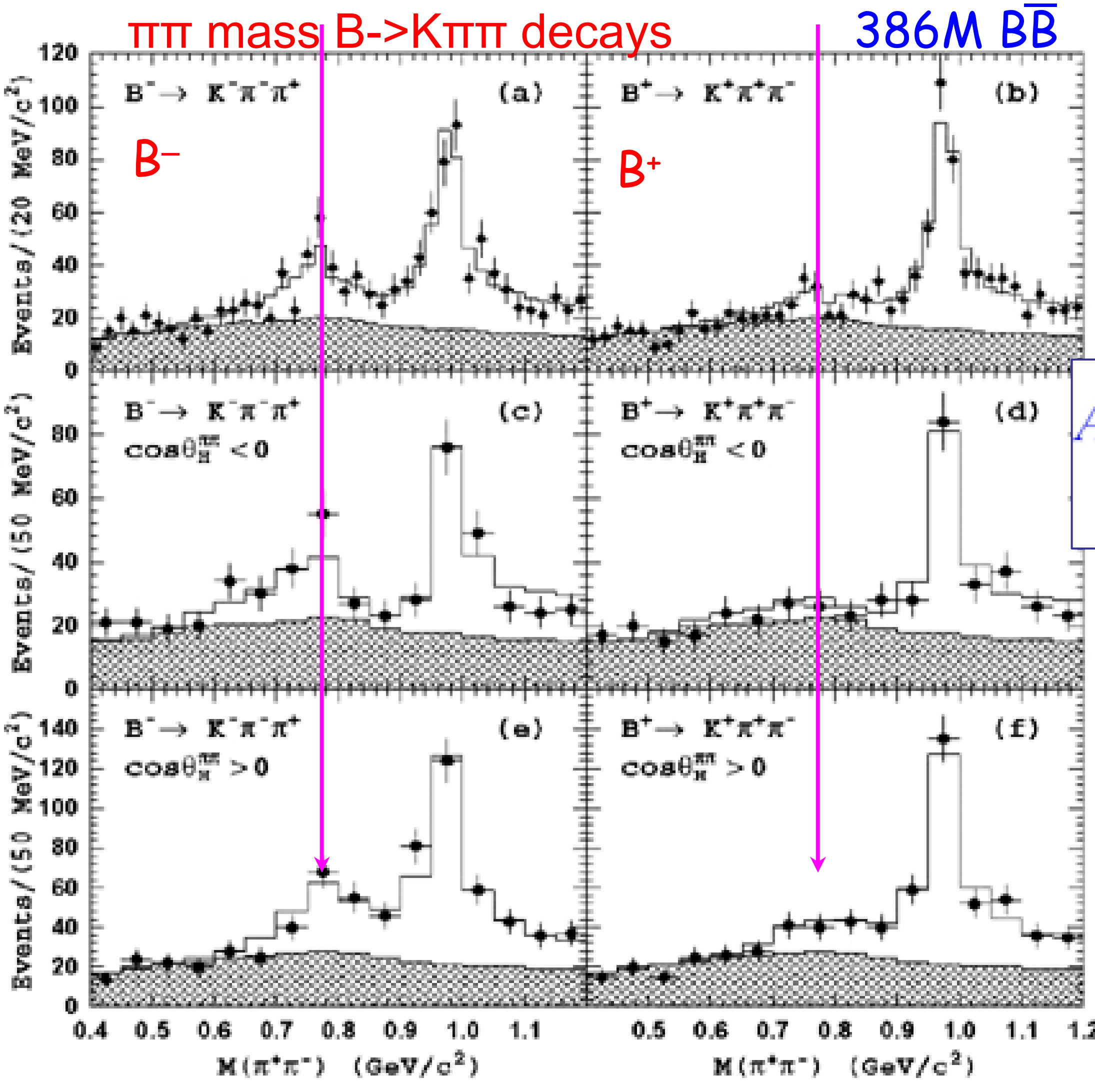
CL = 9.2×10^{-3} (2.6σ)

- statistics?
- experimental systematics?
- theory corrections?
- new physics?



B->$s\bar{q}q$: $K^-\rho^0$

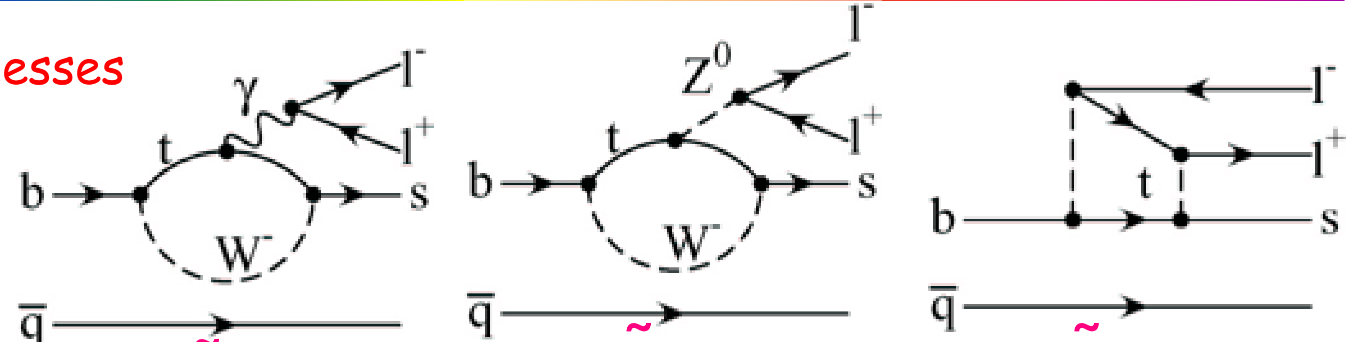
- hep-ex/0512066, to appear in PRL
- First observation of direct CP violation in charged B



$$A_{CP} \equiv \frac{N^- - N^+}{N^- + N^+} = +0.30 \pm 0.11 \pm 0.02^{+0.11}_{-0.04}$$

$B \to s\ell^+\ell^-$

- 3 dominant processes



$\tilde{C}_7^{eff}$ $\tilde{C}_9^{eff}$ $\tilde{C}_{10}^{eff}$

"effective Wilson coefficient:" short distance part of amplitude
(calculated in SM to NNLO)

{$|\tilde{C}_7^{eff}|$ from $B(B \to X_s\gamma)$, constraints from $B(B \to K^{(*)} l^+ l^-)$}

- Different distributions in
  - q^2
  - θ = "helicity angle" -> polarization, forward-backward asymmetry A_{FB}
  - Direct CP asymmetry

- => measure magnitudes, relative signs of $\tilde{C}_i^{eff}$ (may be altered by NP)
  Comparison w SM is more reliable than total rate
- Check lepton universality: rates to μμ vs ee (hep-ex/0604007)

B->K$^{(*)}\ell^+\ell^-$: Wilson coefficients

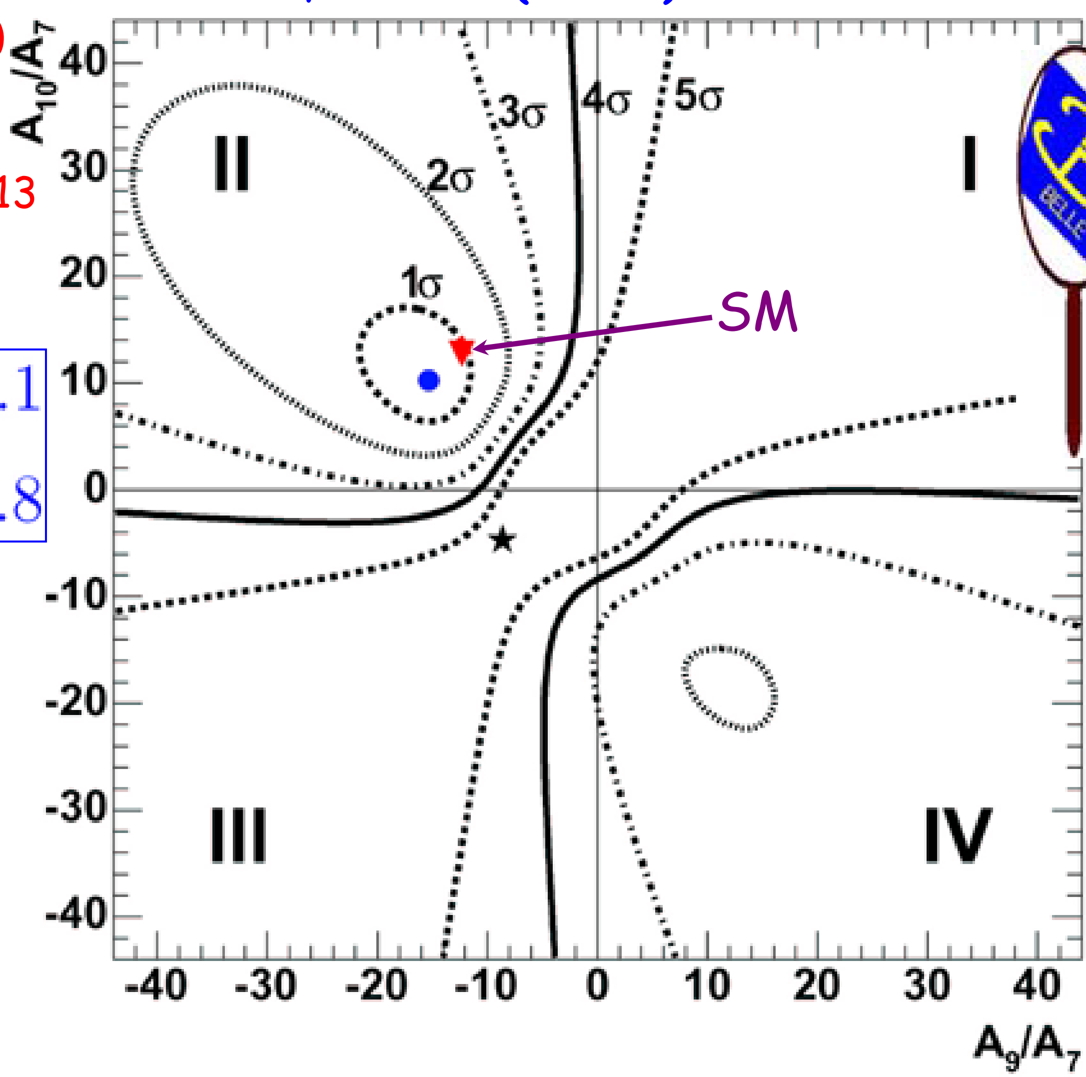
- Fit for A_9/A_7, A_{10}/A_7

A_i: $\tilde{C}_i^{eff}=A_i$+higher order (th)

SM: A_7=–0.330;A_9=4.069;A_{10}=–4.213

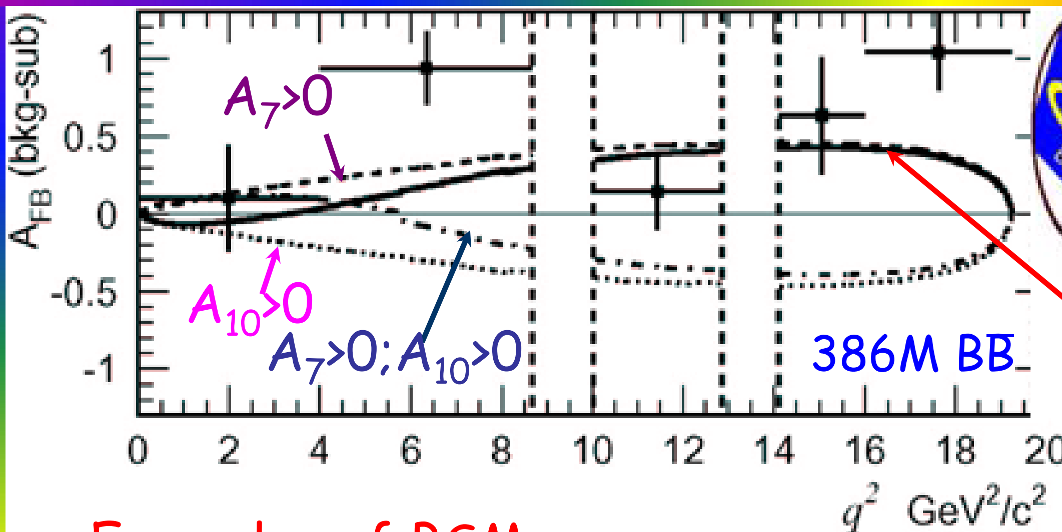
PRL 96, 251801(2006)

$$A_9/A_7 = -15.3^{+3.4}_{-4.8} \pm 1.1$$
$$A_{10}/A_7 = +10.3^{+5.2}_{-3.5} \pm 1.8$$



$A_9 \bullet A_{10}<0$ (98.2% CL)

$B \to K^{(*)}\ell^+\ell^-$: A_{FB}



Belle: PRL 96, 251801(2006)

A_{FB}=0.50±0.15±0.02 (3.4σ)

Babar: hep-ex/0604007

A_{FB}>0.55 (95% CL)

SM (solid):

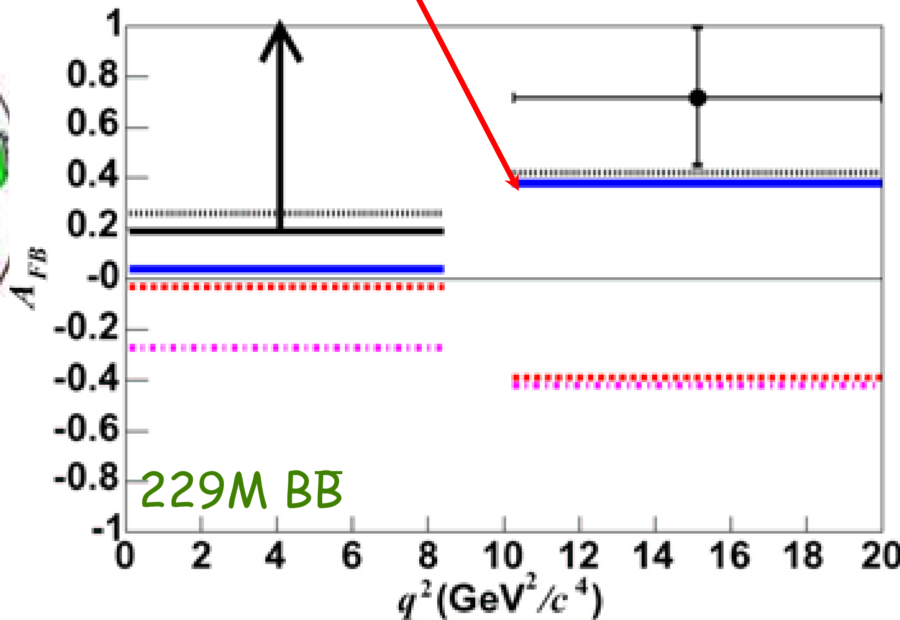
A_7=–0.330;A_9=4.069;A_{10}=–4.213

Examples of BSM:

A_7=0.330;A_9=4.609;A_{10}=–4.213

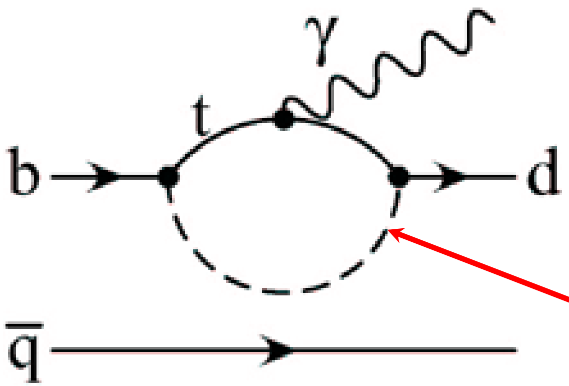
A_7=–0.280;A_9=2.219;A_{10}=1.317

A_7=0.280;A_9=2.219;A_{10}=3.817



Consistent with SM,
Eliminates many NP scenarios

B->dγ



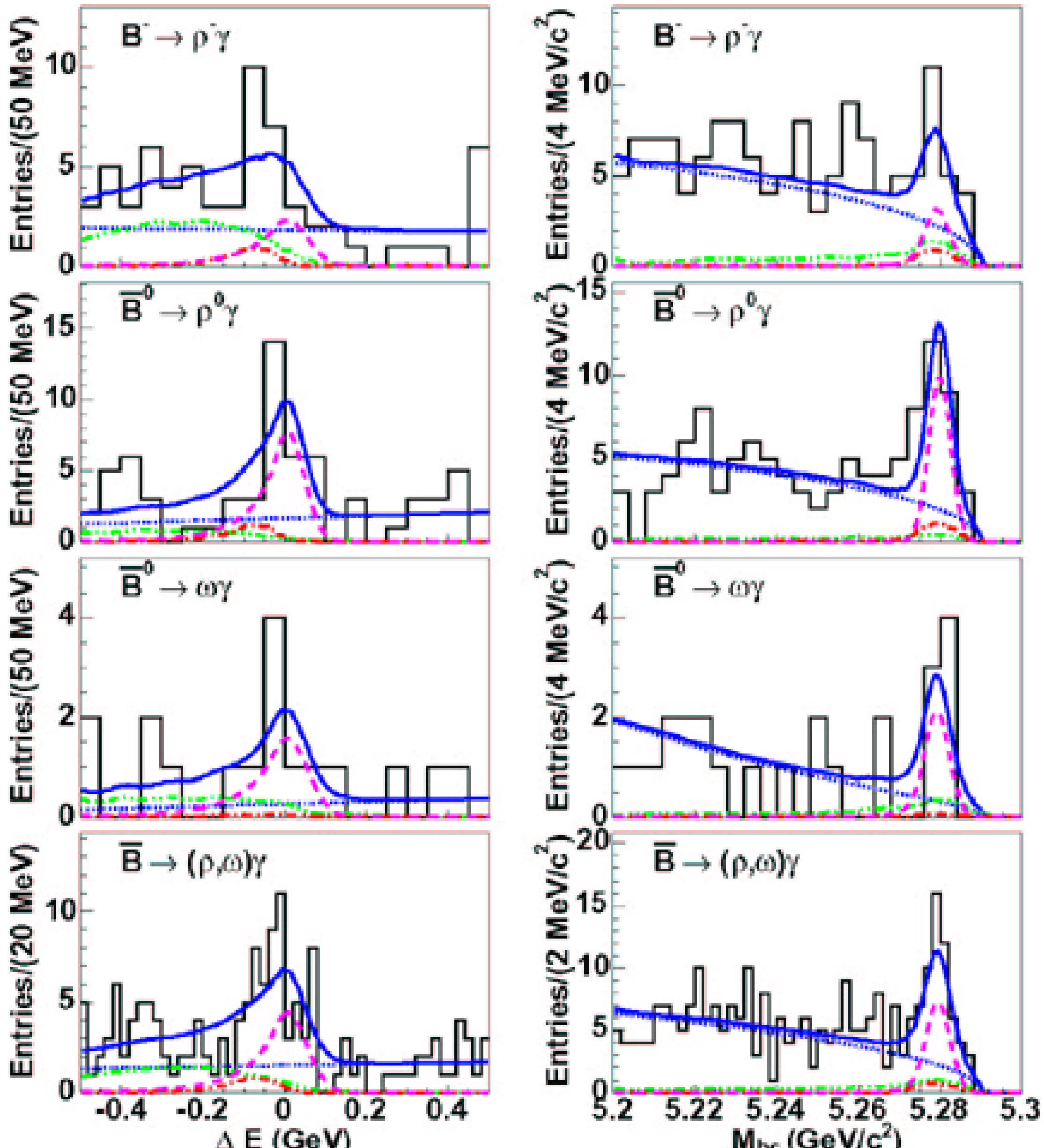
$$\frac{\Gamma(b \to d\gamma)}{\Gamma(b \to s\gamma)} \propto \left|\frac{V_{td}}{V_{ts}}\right|^2$$

Ratio -> reduced theory error ~10%

CKM cancellation: suppressed in SM
Modified via NP e.g.Higgs

- inclusive measurement - preferred by theory
  large (~30X) bg from b->sγ, similar kinematics
- exclusive B-> {ρ/ω}γ - experimentally feasible
  full reconstruction of decay

B->dγ: first observation



B->dγ : $|V_{td}/V_{ts}|$

386 M $B\bar{B}$ evts (5.1σ; first observation) PRL 96, 221601 (2006)

(use isospin relations $\Gamma(B^- \to \rho^-\gamma) = 2\Gamma(B^0 \to \rho^0\gamma) = 2\Gamma(B^0 \to \omega\gamma)$)

$$\mathcal{B}(B \to (\rho/\omega)\gamma) \; \{= \mathcal{B}(B^- \to \rho^-\gamma)\} = (1.32^{+0.34+0.10}_{-0.31-0.09}) \times 10^{-6}$$

$$\frac{\mathcal{B}(B^- \to \rho^-\gamma)}{\mathcal{B}(B^- \to K^{*-}\gamma)} = 0.032 \pm 0.008 \pm 0.002$$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.199^{+0.026}_{-0.025}(exp)^{+0.018}_{-0.015}(th)$$

211 M $B\bar{B}$ evts (2.1σ) PRL 94, 011801 (2005)

$$\mathcal{B}(B^- \to \rho^-\gamma) < 1.2 \times 10^{-6} (90\% \; CL)$$

$$\frac{\mathcal{B}(B^- \to \rho^-\gamma)}{\mathcal{B}(B^- \to K^{*-}\gamma)} < 0.029 (90\% \; CL)$$

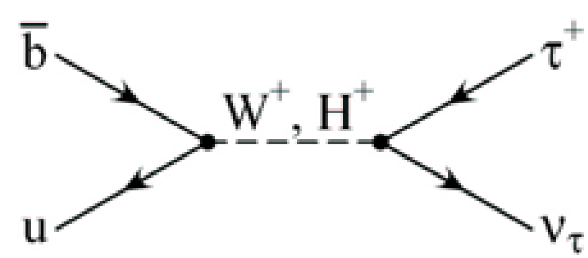
$$\left|\frac{V_{td}}{V_{ts}}\right| < 0.19 \; (90\% \; CL)$$

$B^+ \to \tau^+ \nu_\tau$

Theory:

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

$= (1.59 \pm 0.40) \times 10^{-4}$



- Experimentally nontrivial: ≥2ν's

Belle: hep-ex/0604018 447×10^6 $B\bar{B}$

Full reconstruction of hadronic B^+ decay -> what's left is B^-

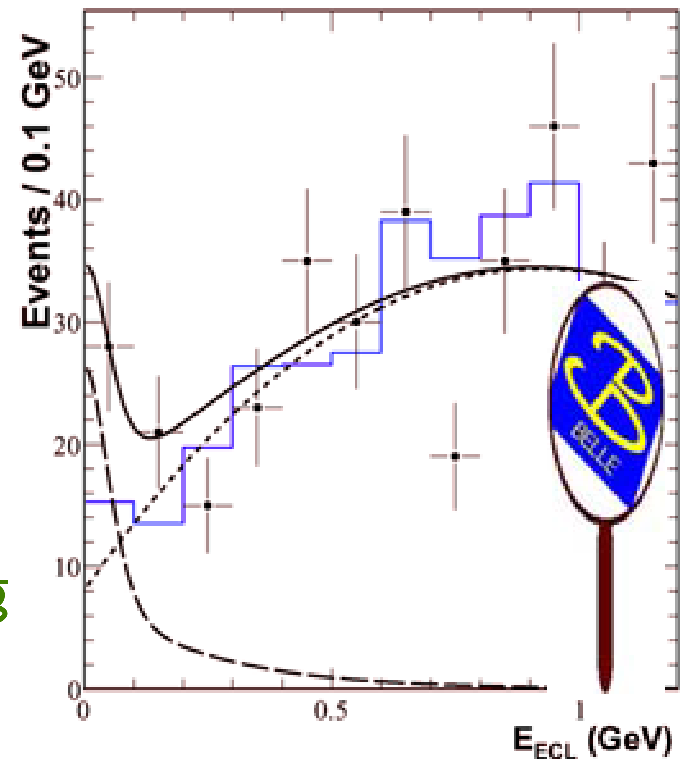
B^-:

$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$, $e^- \bar{\nu}_e \nu_\tau$, $\pi^- \nu_\tau$, $\pi^- \pi^0 \nu_\tau$, $\pi^- \pi^+ \pi^- \nu_\tau$ (81% of channels)

examine additional calorimeter energy, E_{ECL}

$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = (1.06^{+0.34}_{-0.28}{}^{+0.18}_{-0.16}) \times 10^{-4}$$

First evidence



Babar: PRD 73, 057101 (2006) 232×10^6 $B\bar{B}$

$B < 2.6 \times 10^{-4}$ (90% CL)

$B^+ \to \tau^+ \nu_\tau$: CKM constraint

theory:

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

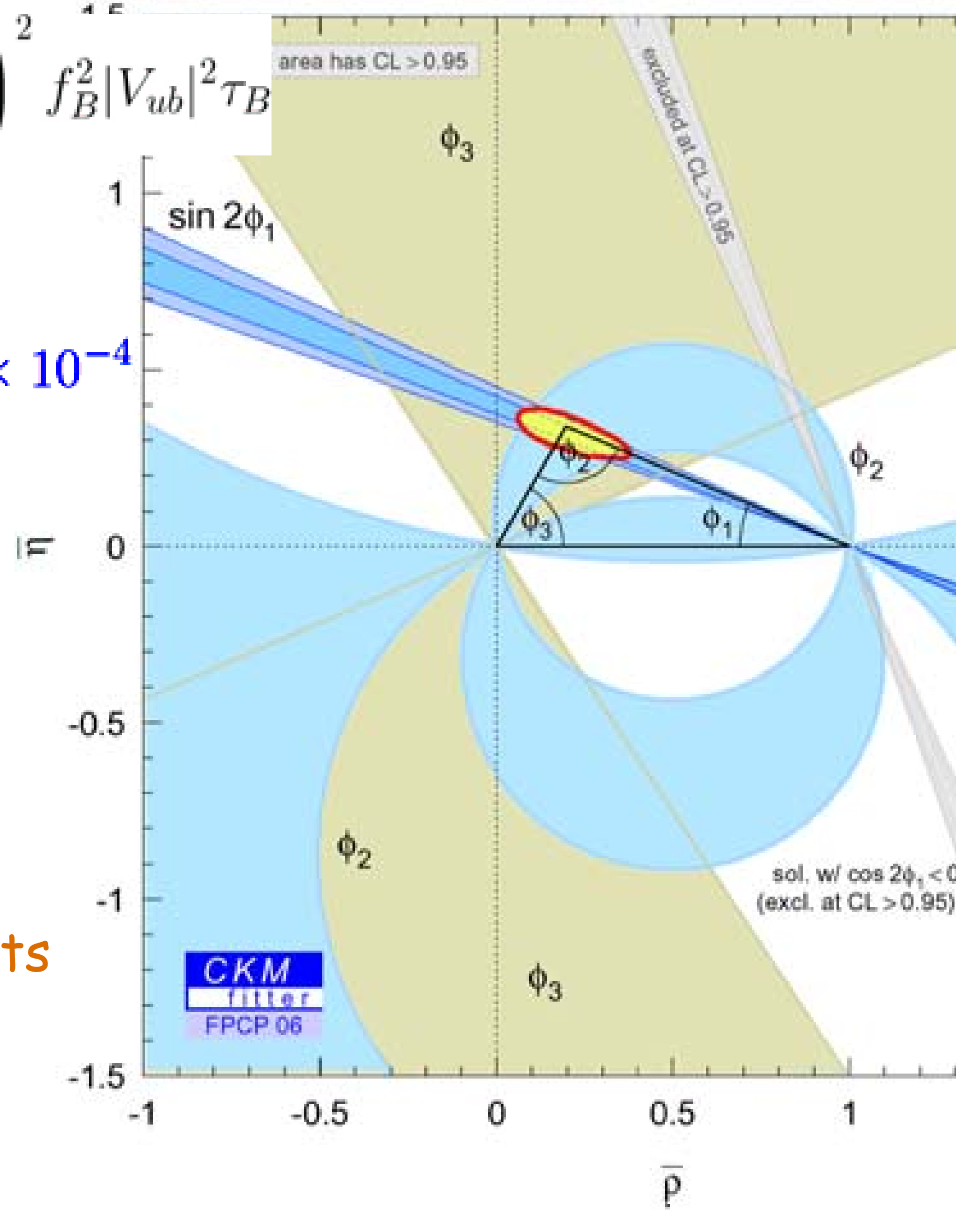
$= (1.59 \pm 0.40) \times 10^{-4}$

experiment:

$$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = (1.06^{+0.34+0.18}_{-0.28-0.16}) \times 10^{-4}$$

taking the difference
as being due to "$|V_{ub}|$,"
& using Δm_d,

Compare using only
CP asymmetry measurements

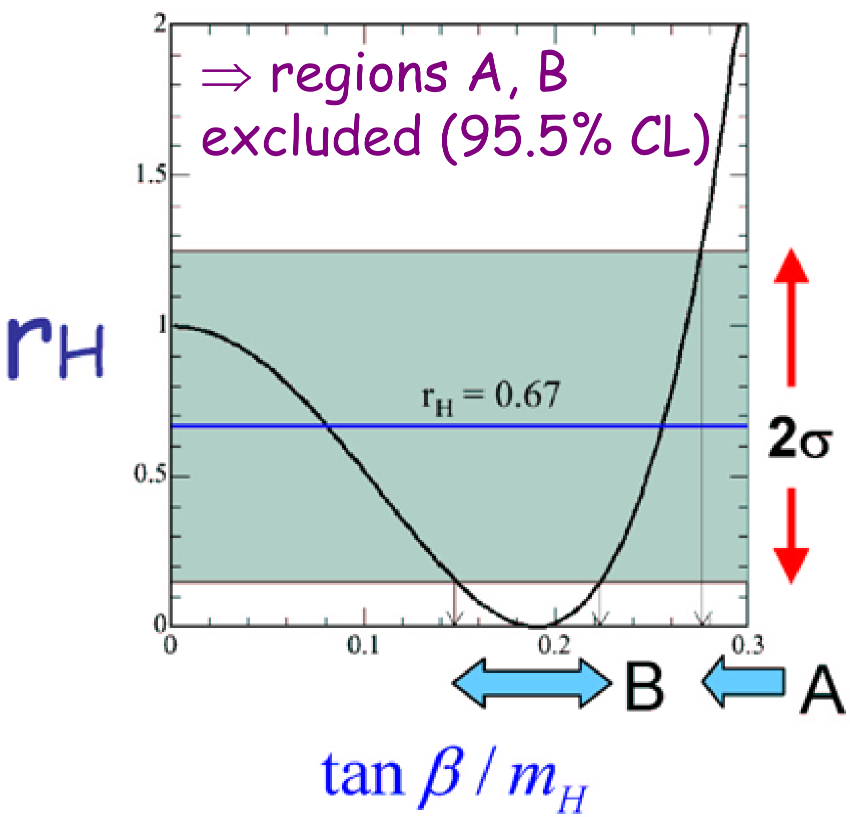


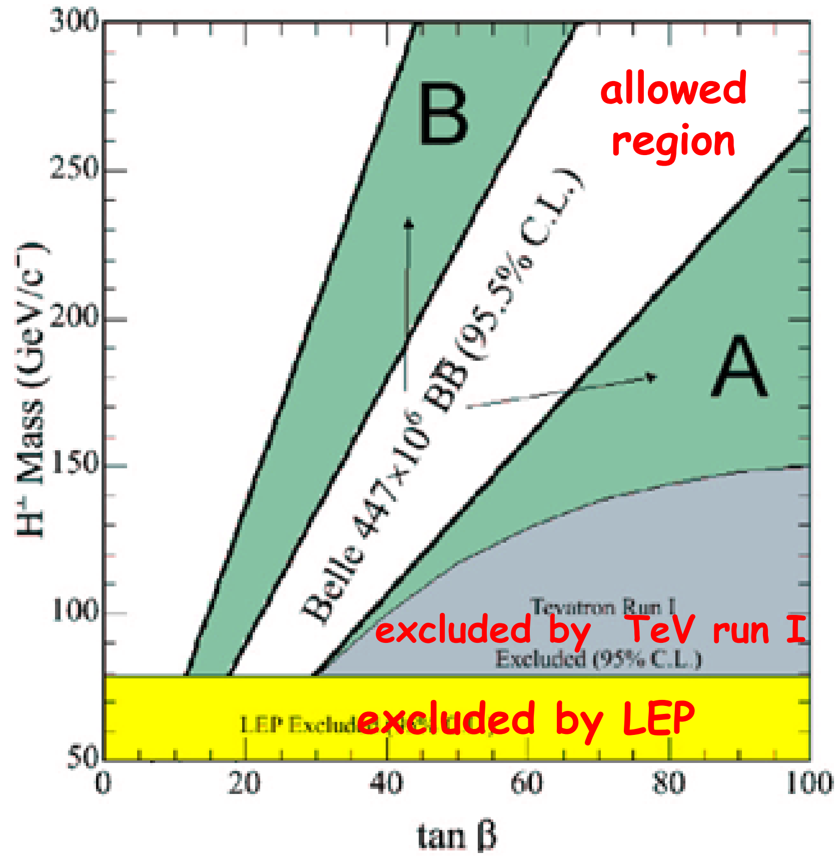
$B^+ \to \tau^+ \nu_\tau$: constraints on charged Higgs

$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\mathrm{SM}} \times r_H \qquad r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

$$\Rightarrow r_H = 0.67^{+0.29}_{-0.26}$$

{WS Hou, PRD 48, 2342 (1993)}





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

SM: $\mathcal{B} \sim 2 \times 10^{-7}$

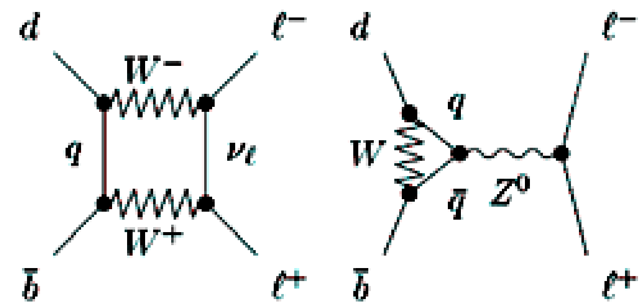
BSM: direct lepton-quark coupling

Babar: PRL 96, 241802 (2006) 232 x 10^6 $B\bar{B}$

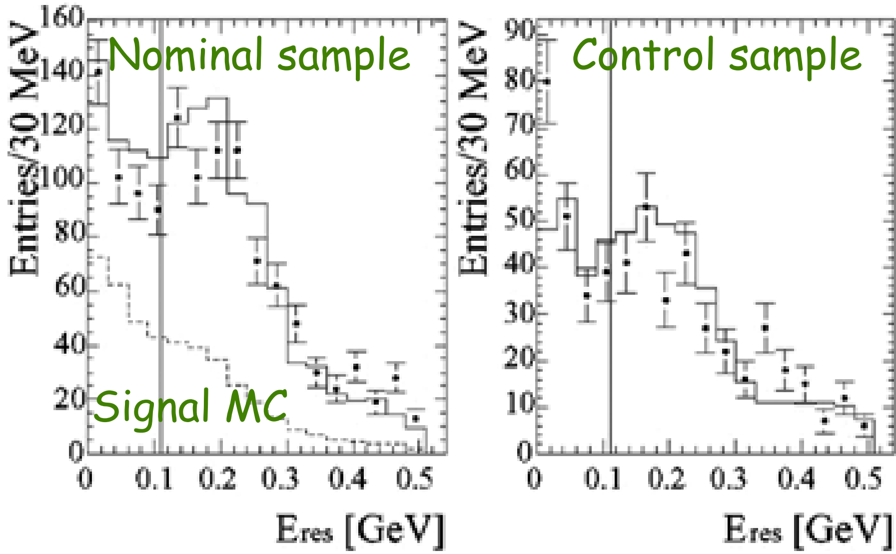
Full reconstruction of hadronic B^0 decay

Other ($\bar{B}^0$): $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$, $e^- \bar{\nu}_e \nu_\tau$, $\pi^- \nu_\tau$, $\rho^0 \nu_\tau$

examine residual calorimeter energy

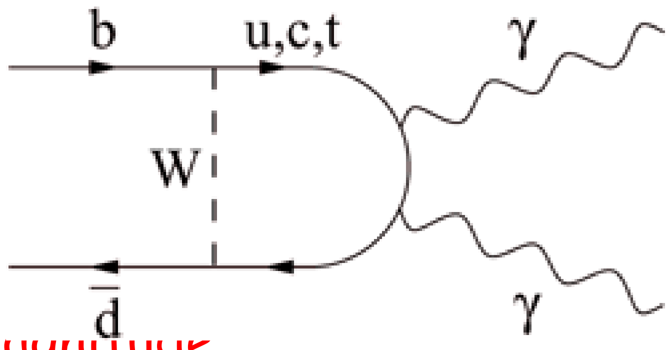


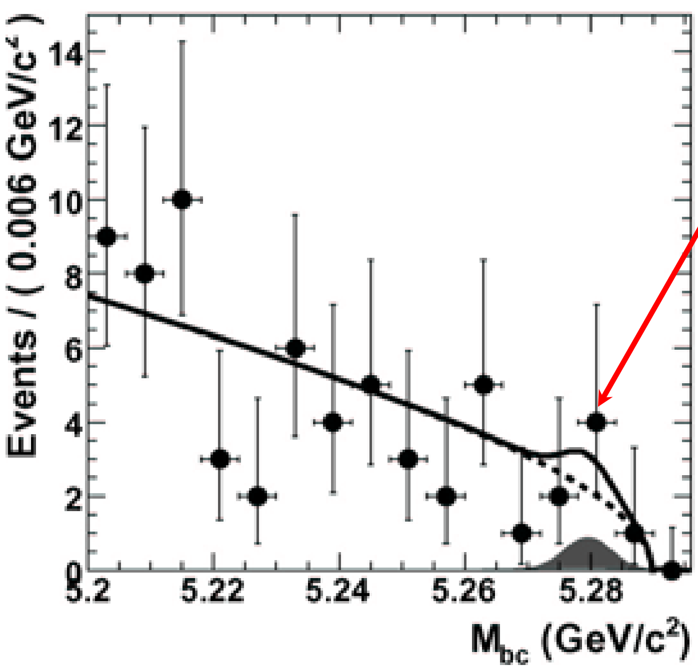
$\mathcal{B} < 4.1 \times 10^{-3}$ (90% CL)



B_d, B_s -> γγ

- W-loop, NP via e.g. H^+
- SM:
  - $B(B_d\text{->}\gamma\gamma) \sim 3 \times 10^{-8}$
  - $B(B_s\text{->}\gamma\gamma) \sim 0.5\text{-}1.0 \times 10^{-6}$
- BSM: enhanced up to 2 orders of magnitude





Belle: PRD 73, 051107 (2006) 111x10⁶ $B\bar{B}$

$B(B_d\text{->}\gamma\gamma) < 6.2 \times 10^{-7}$ (90% CL)

Belle-CONF-0615 9.0×10^4 $B_s\bar{B}_s$

$B(B_s\text{->}\gamma\gamma) < 5.6 \times 10^{-5}$ (90% CL)

1/3 x current PDG limit

Charm summary

Strong GIM suppression of

Mixing, Flavor-changing neutral currents (FCMC), CP violation

--> opportunity to reveal NP

- search for FCNC:

  Babar - D^+, D_s^+ -> {π/K}$\ell^+\ell^-$, Λ_c -> $p\ell^+\ell^-$

  (20 modes, 17 new limits)

- mixing

  Belle - PRL96, 151801 (2006) 400 fb^{-1}

  D^0->$K^+\pi^-$; flavor tag by D^{*+}-> $D^0\pi^+$;

  fit decay time dist (separate mixed from doubly-Cabibbo-suppressed);

  rate $R_M < 4 \times 10^{-4}$ (95% CL) (SM: ~ 10^{-4})

  Babar - 230.4 fb^{-1}

  D^0->$K^+\pi^-\pi^0$ Dalitz analysis of decay time dist

  Dalitz plot improves separation of mixing/DCSD

  $R_M < 5.4 \times 10^{-4}$ (95% CL)

Tau summary

Tau - SM clean, well understood -> look for violation of flavor, lep#, baryon#

- $\ell\gamma$
  - Babar: hep-ex/0508012 $B(e\gamma) < 1.1 \times 10^{-7}$ (90% CL)
  - Belle: BELLE-CONF-0653 (535 fb^{-1})
    - $B(e\gamma) < 1.2 \times 10^{-7}$ (90% CL)
    - $B(\mu\gamma) < 4.5 \times 10^{-8}$ (90% CL)
      - New MSSM constraint:

$$Br(\tau \to \mu\gamma) = 3.0 \times 10^{-6} \times \left(\frac{\tan\beta}{60}\right)^2 \times \left(\frac{M_{SUSY}}{1\text{TeV}}\right)^{-4}$$

- Baryonic
  - Belle hep-ex/0508044 $B(\bar{\Lambda}\pi^+) < 1.4\times10^{-7}$, $B(\Lambda\pi^-) < 0.72\times10^{-7}$ (90% CL)
- $\ell\, h^+h^-$ modes: ℓ {π/K}{π/K}, ℓ{$\rho^0/K^{*0}/\varphi$}:
  - Belle hep-ex/0603036 UL= $1\text{-}8\times10^{-7}$ (90% CL)
- ℓK_S:
  - Belle hep-ex/0605025 $B(eK_S) < 5.6\times10^{-8}$, $B(\mu K_S) < 4.9\times10^{-8}$ (90% CL)