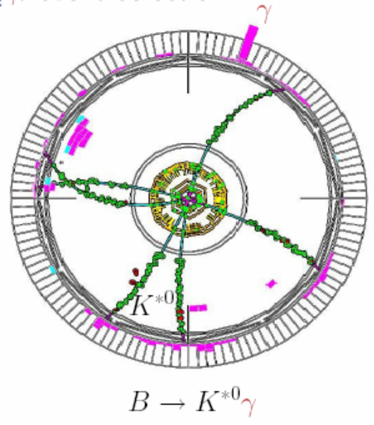


THE UNIVERSITY of LIVERPOOL

Physics at the B-factories

Particle Physics 2004
Birmingham
5th-7th April

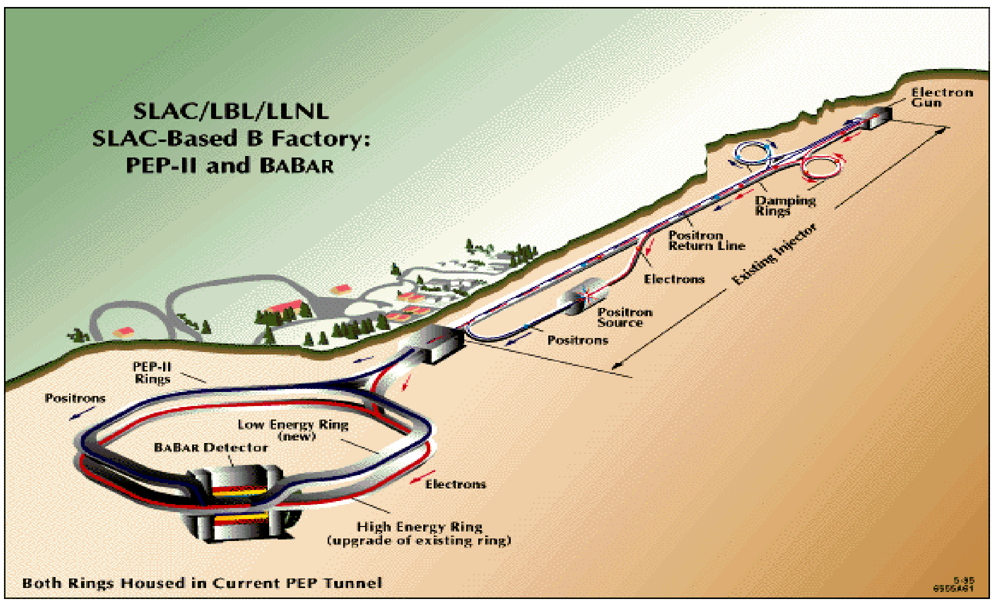
Adrian Bevan

Talk Outline

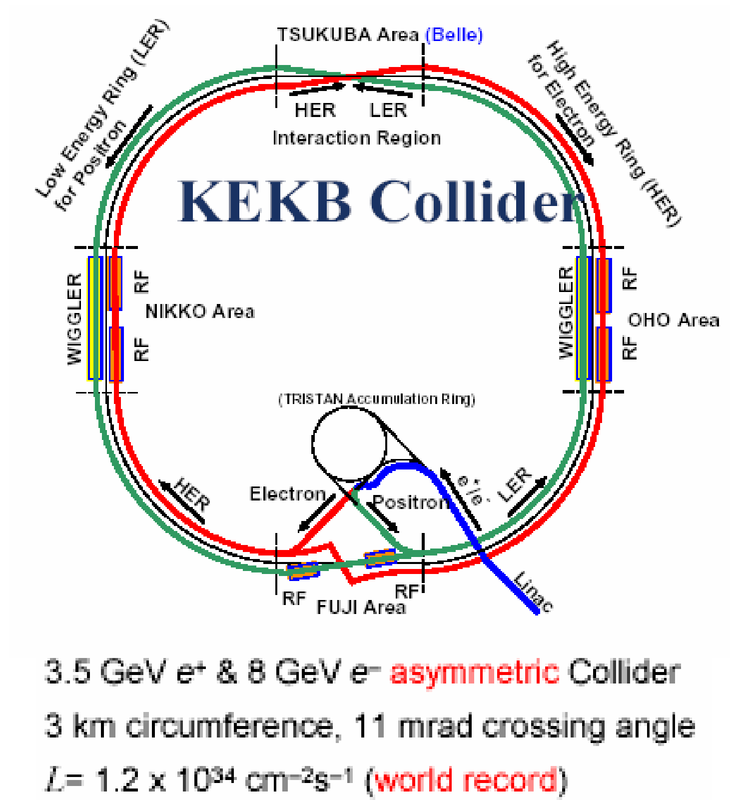
- Current generation of B-factories
- CP Violation Studies: α, β, γ
- Rare Decays
- New Particle Searches
- τ Physics
- Conclusions

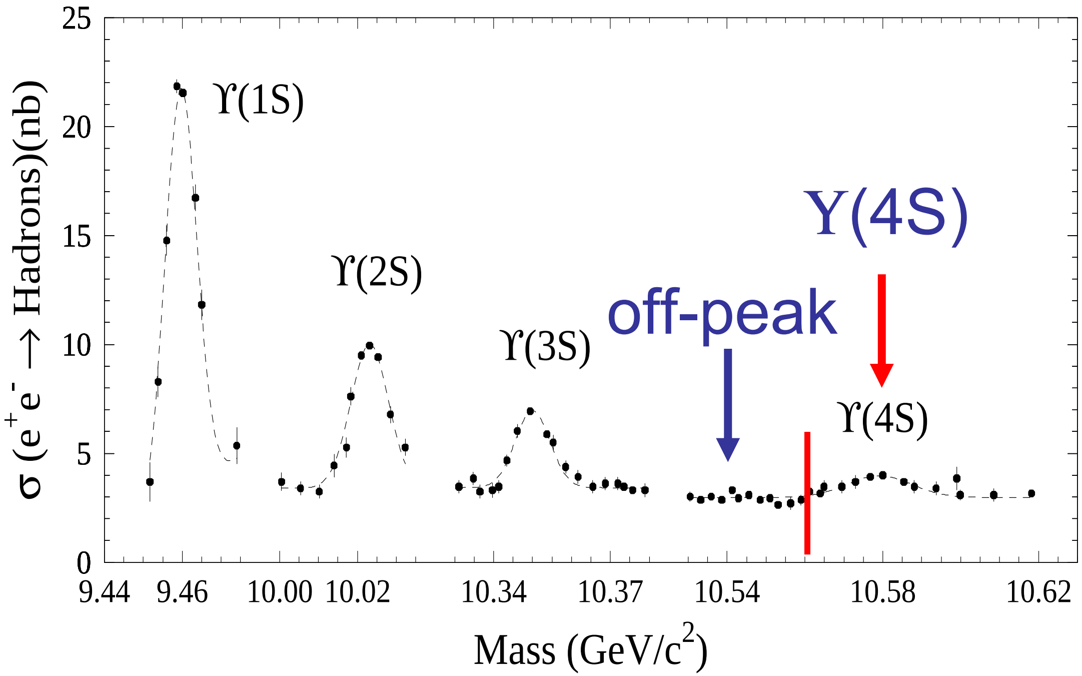
The B-factories

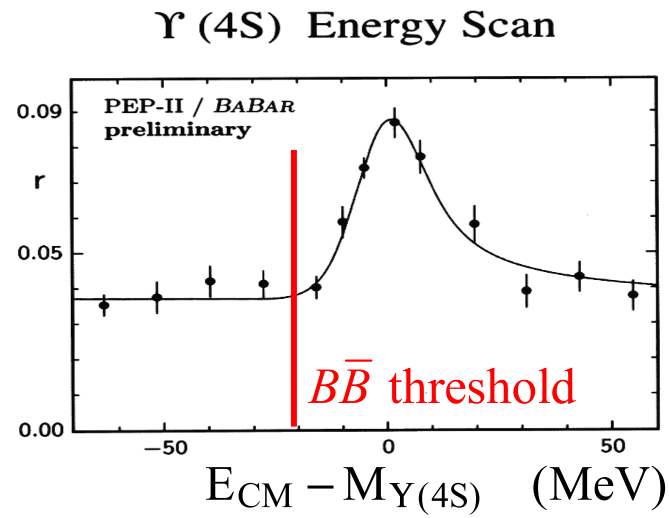
- PEP-II and KEK-B at SLAC and KEK, respectively
- Collide e^+ and e^- with a 10.58 GeV CM energy
- Detectors: BaBar and Belle
- Started data taking in 1999



- 9GeV e^- on 3.1GeV e^+
- $\Upsilon(4S)$ boost: $\beta\gamma=0.56$







- Υ(4S) decays into B^+B^- or $B^0\overline{B}^0$

$$\frac{BF(\Upsilon(4S) \to B^+B^-)}{BF(\Upsilon(4S) \to B^0\overline{B}^0)} = 1.04 \pm 0.07 \ (PDG2003)$$

- Cross Sections at Υ(4S):

$$b\overline{b} = 1.1nb$$

$$c\overline{c} = 1.3nb$$

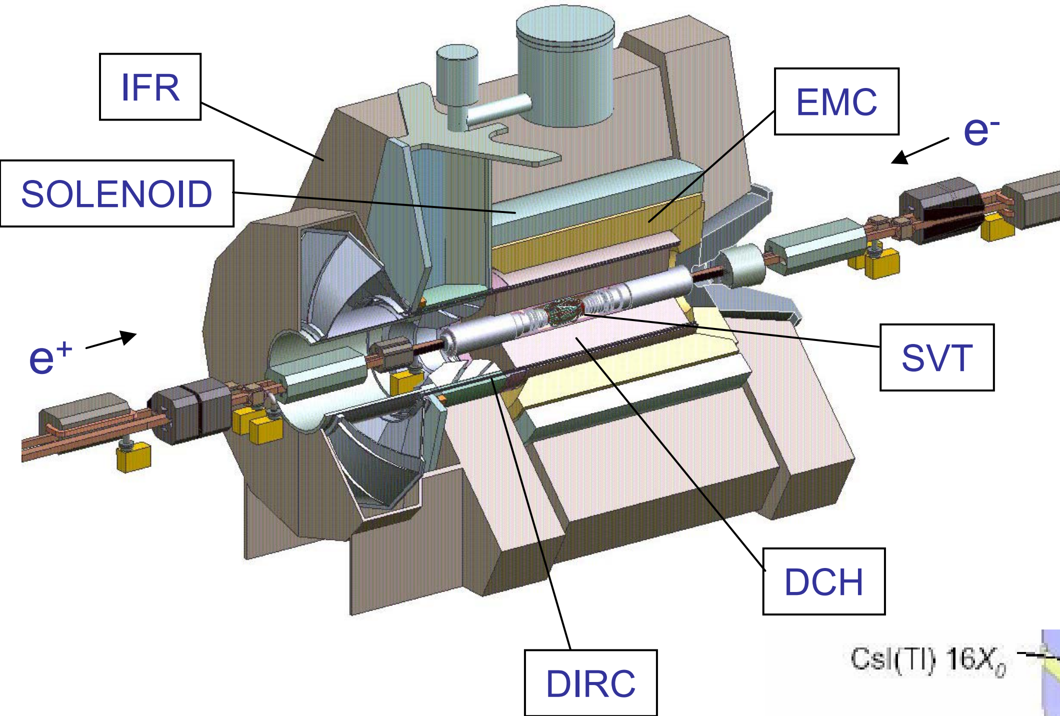
$$d\overline{d}, s\overline{s} = 0.3nb$$

$$u\overline{u} = 1.4nb$$

"continuum background"

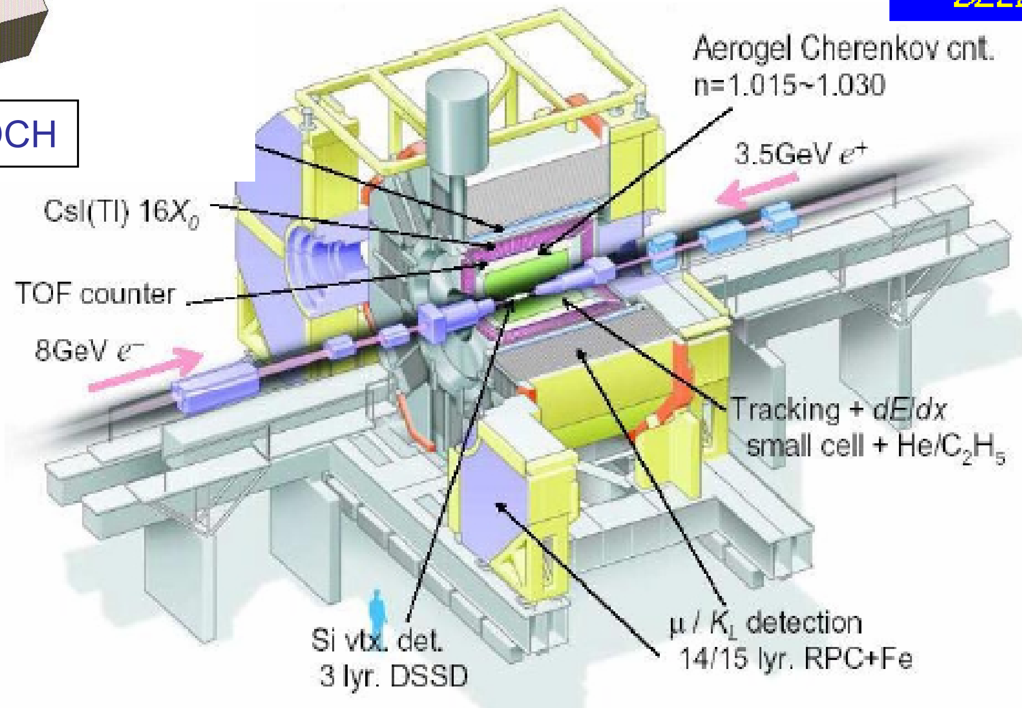
The Detectors

BaBar

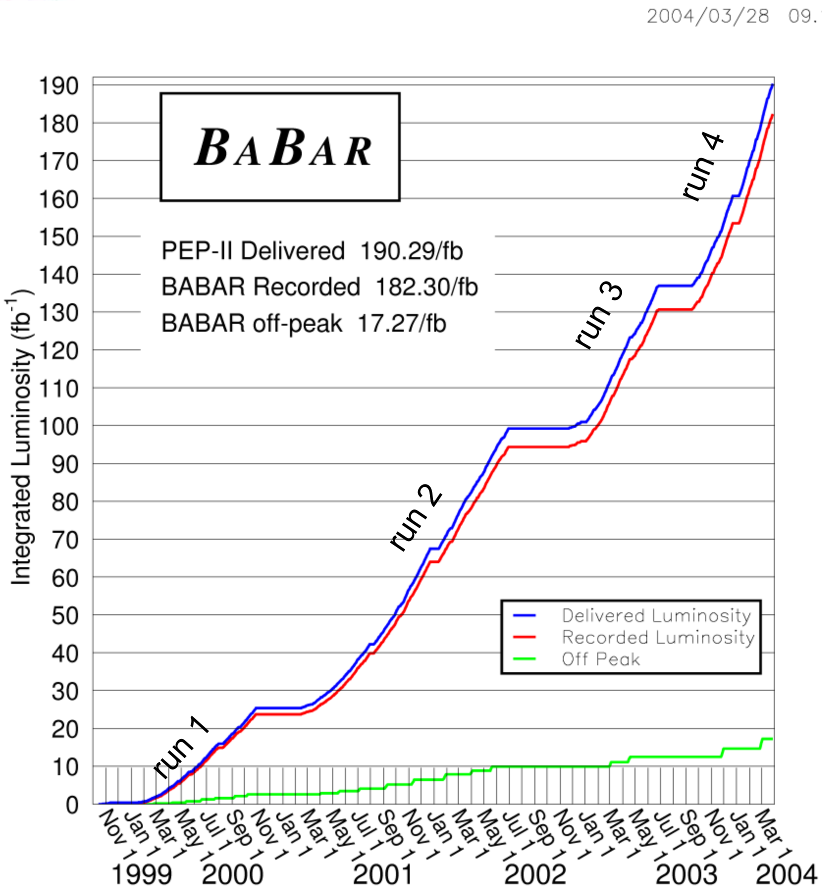


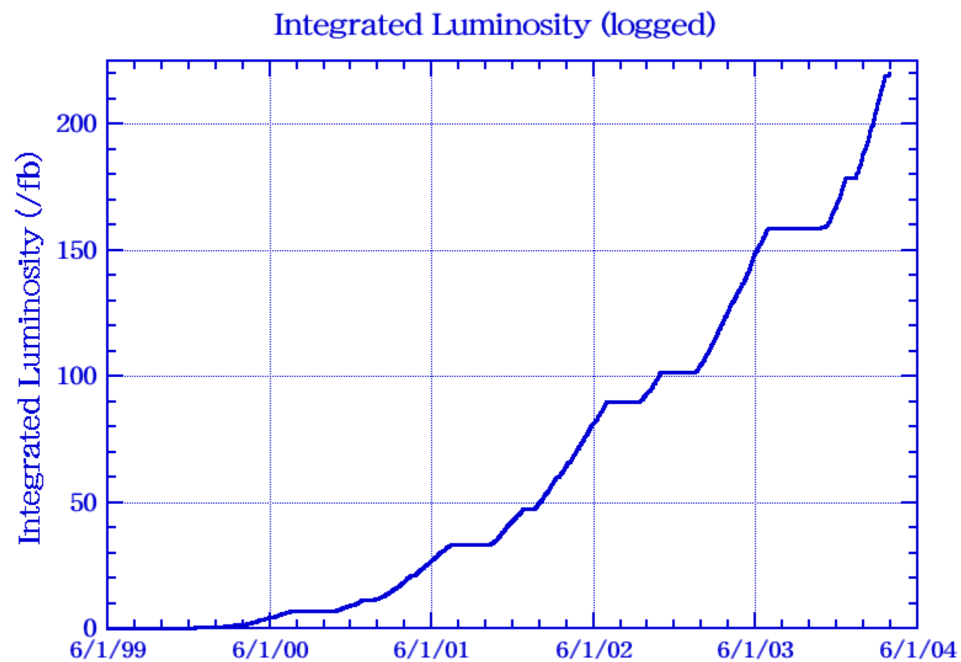
Differences between BaBar and Belle are small

Belle



Data Samples





Peak Lumi: 12×10^{33} cm^{-2} sec^{-1}

Number of B pairs approx: 220×10^{6}

Peak Lumi: 8.16×10^{33} cm^{-2} sec^{-1}

Number of B pairs approx: 200×10^{6}

CP Violation Studies:

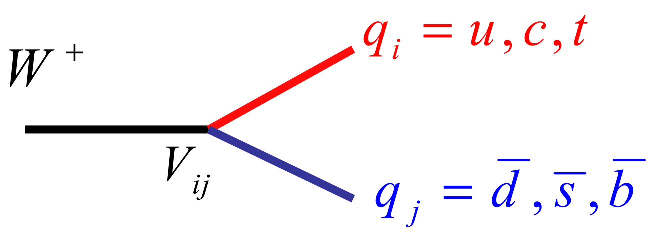
Why is CP Violation so important?

- Matter/anti-matter asymmetry in the universe requires CP Violation
  → known level of CPV is 10^9 times too small for cosmology

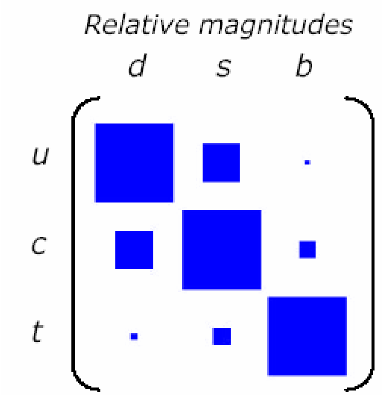
- Standard Model describes all CPV with a single complex phase
  → need to test

- Flavour physics BSM has many parameters
  → can search indirectly for new physics and try to (further) constrain models before the LHC

CP Violation in meson decay



$V =$



The couplings, V_{ij}, form a 3×3 matrix: The CKM Matrix;

Wolfenstein Parameterisation:

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$\lambda \sim 0.22$

$A \sim 0.8$

$\rho \sim 0.2 - 0.27$

$\eta \sim 0.28 - 0.37$

Understanding Standard Model CP Violation means accurate measurements of ρ and η

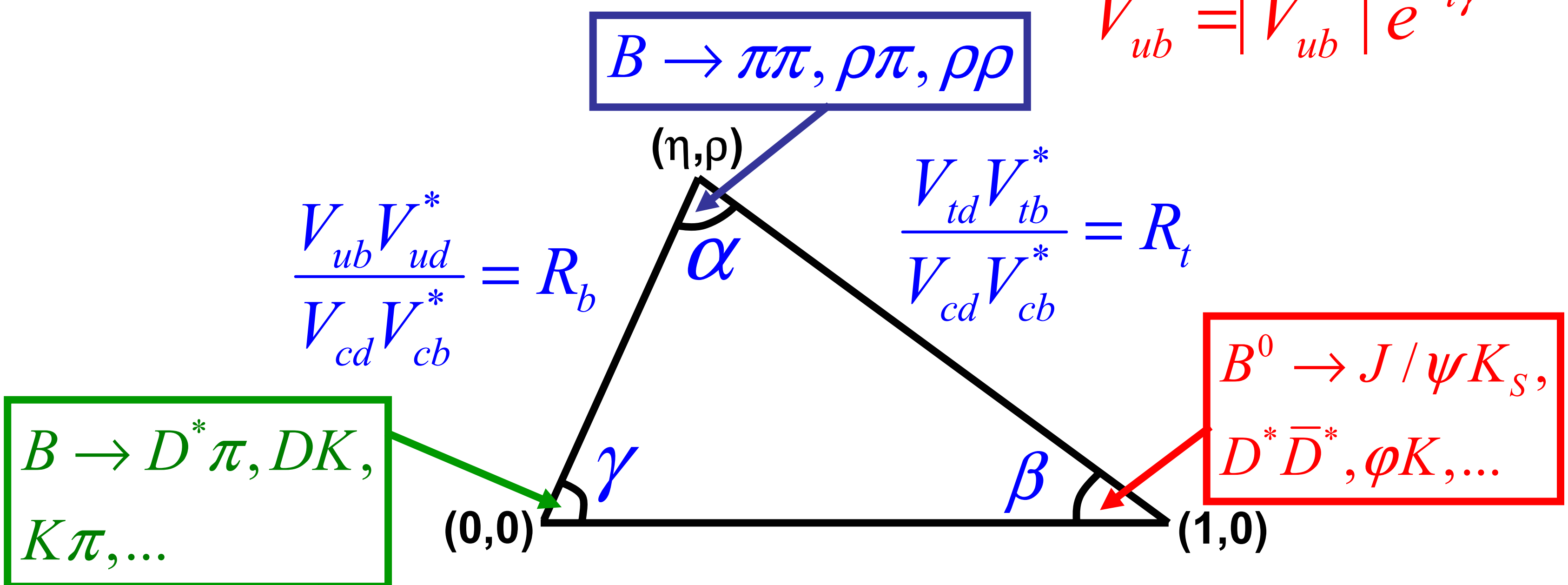
The Unitarity Triangle

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

$B^{0}\overline{B}^{0}$ mixing

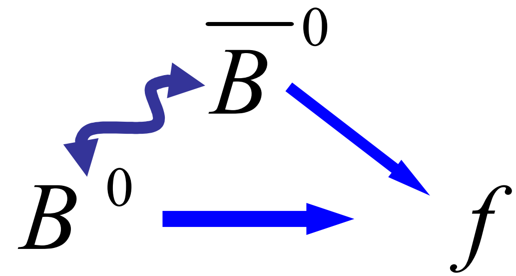
$$V_{td}=|V_{td}|e^{-i\beta}$$

$$V_{ub}=|V_{ub}|e^{-i\gamma}$$

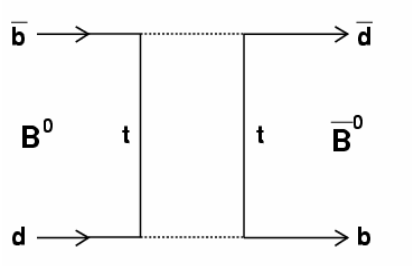


SM Predicts a closed triangle with two independent phase angles: β & γ

CP violation at the ϒ(4S)



- Three observable interference effects:
  - CP violation in mixing:



$$\Pr(B^0 \to \overline{B}^0) \neq \Pr(\overline{B}^0 \to B^0)$$

time dependent effect

  - (direct) CP violation in decay

$$\Pr(B^0 \to f) \neq \Pr(\overline{B}^0 \to f)$$

time integrated effect – number counting

CP violation in interference of mixing and decay (Im$\lambda \neq 0$)

time dependent effect – relevant for measuring CKM angles!

Analyse time evolution of $B^0\overline{B}^0$ system (assume $\Delta\Gamma=0$):

$$f(B^0/\overline{B}^0_{phys} \rightarrow f/\overline{f}, \Delta t) =$$

$$\tfrac{\Gamma}{4} e^{-\Gamma|\Delta t|}\left[1 + nS\sin(\Delta m_d \Delta t) - nC\cos(\Delta m_d \Delta t)\right]$$

$$n = +1(-1) \text{ for } B^0(\overline{B}^0)$$

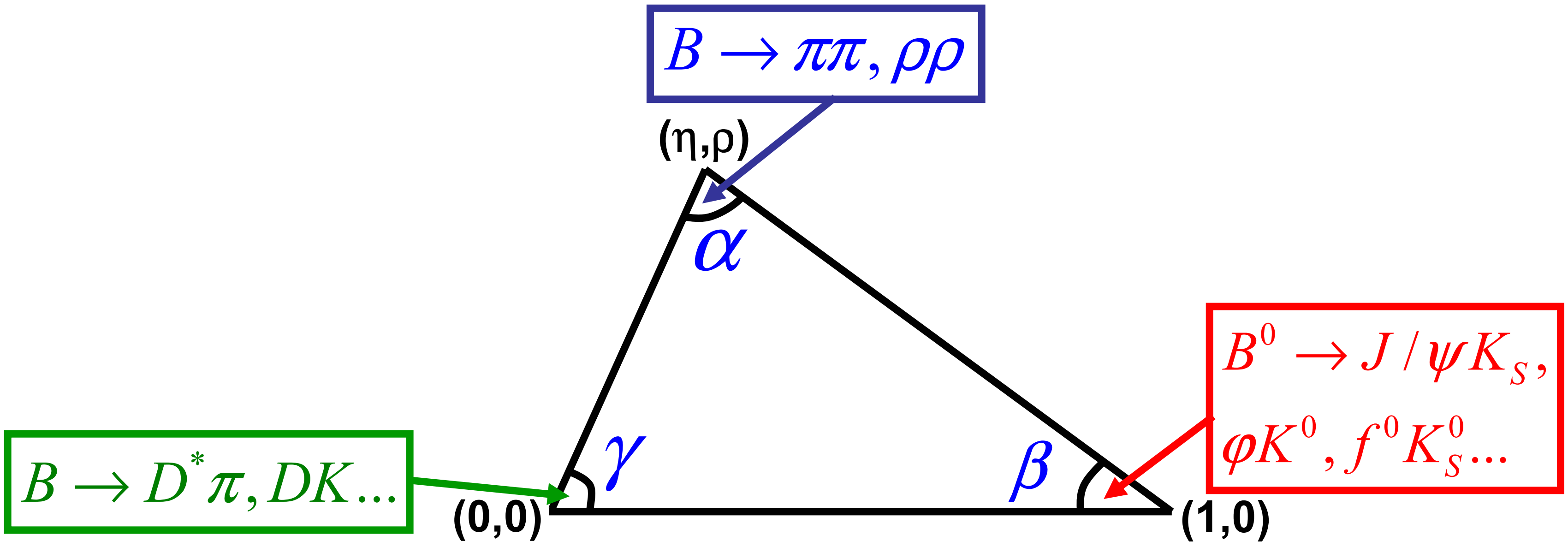
Indirect CP violation ➡ S ≠ 0

Direct CP violation ➡ C ≠ 0

$$A_{CP}(t) = \frac{\Gamma(B^0_{phys}(t) \rightarrow f) - \Gamma(\overline{B}^0_{phys}(t) \rightarrow f)}{\Gamma(B^0_{phys}(t) \rightarrow f) + \Gamma(\overline{B}^0_{phys}(t) \rightarrow f)}$$

$$= S\sin(\Delta m \Delta t) - C\cos(\Delta m \Delta t)$$

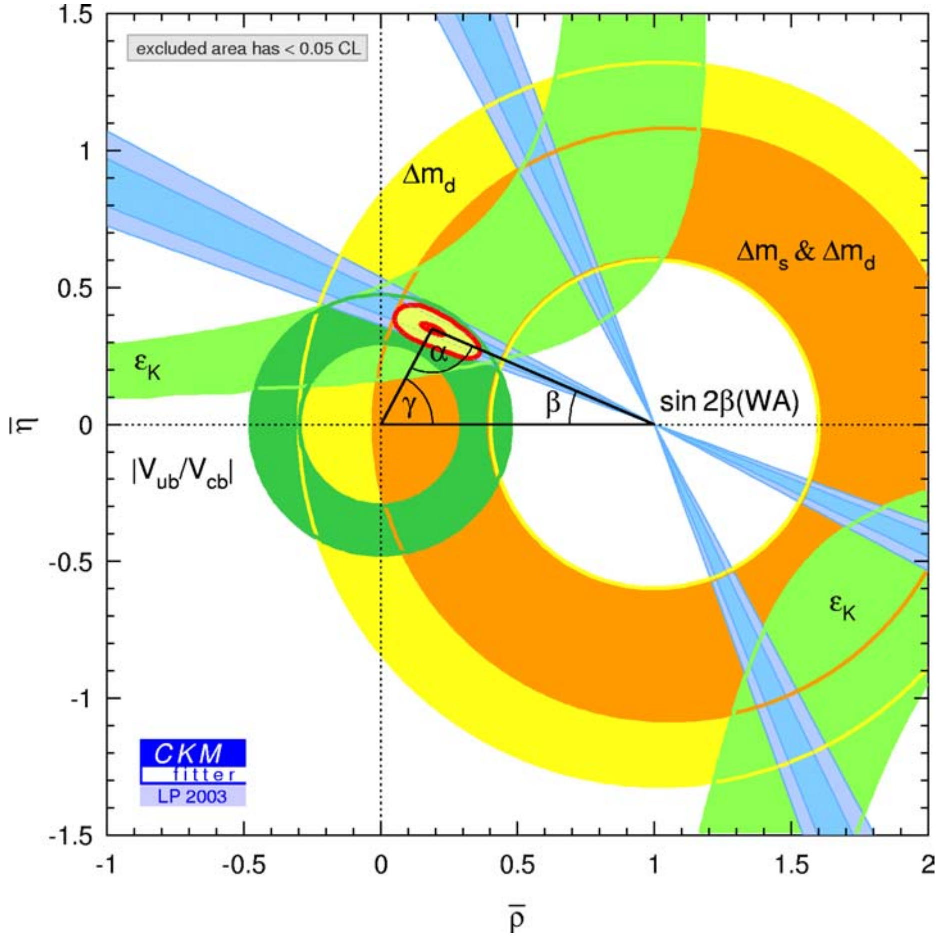
Measurements Related to the angles of the Unitarity Triangle



The CKM Angle β:

$$\sin 2\beta = 0.736 \pm 0.049$$

(Belle & BaBar)

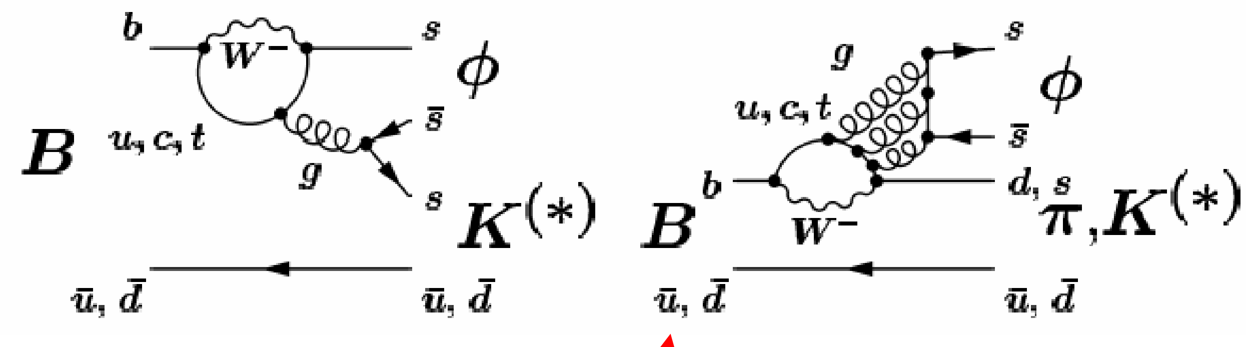


→ Precision measurement of β from $b \to c\bar{c}s$

→ Perfect agreement with the SM Prediction

→ Alternate measurements of β probe NP at TeV scale

The CKM Angle β: $B^0 \rightarrow \phi K^0$

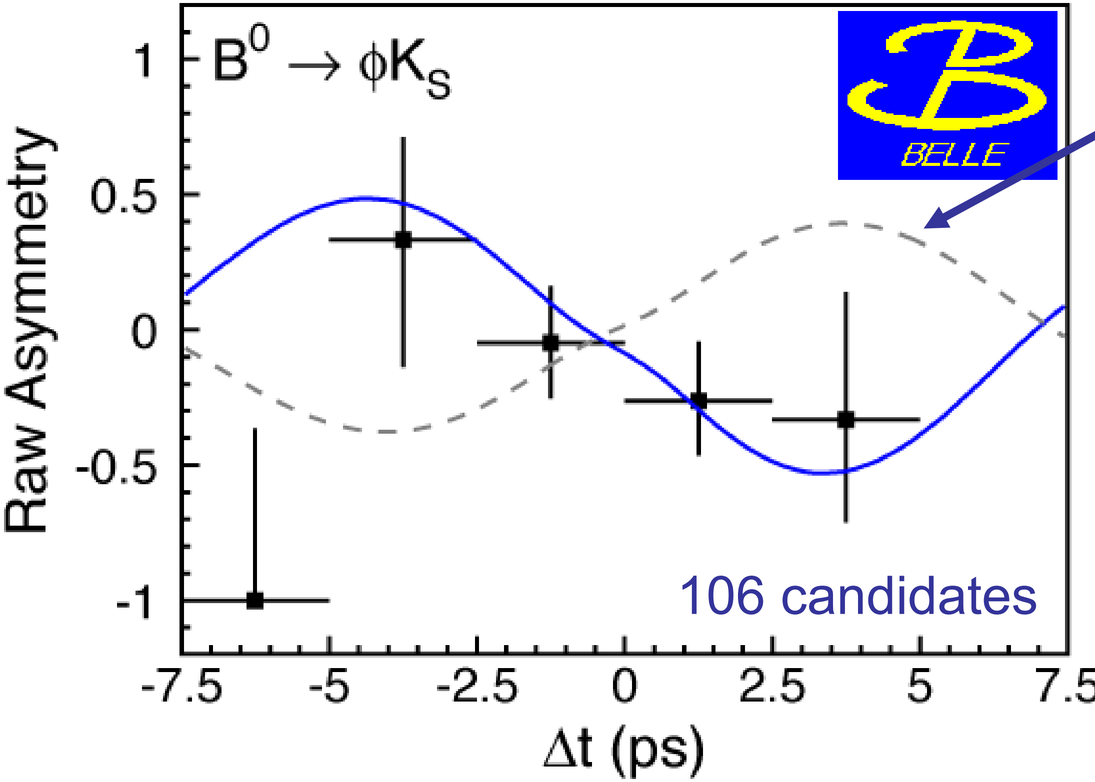


- Rare Decay
- loop or "pure penguin"
- sensitive to new physics
- measured β in this mode should agree with $b \rightarrow c\bar{c}s(J/\psi K_S^0)$

  $$[\sin 2\beta(b \rightarrow c\bar{c}s) = 0.736 \pm 0.049]$$

- So in SM: $S_{\phi K_s} = \sin 2\beta, C_{\phi K_s} = 0$

$B^0 \to \phi K^0_S$ $(b \to s\bar{s}s)$



SM=+0.74

$S = -0.96 \pm 0.50 \pm 0.10$

$C = -0.15 \pm 0.29 \pm 0.07$

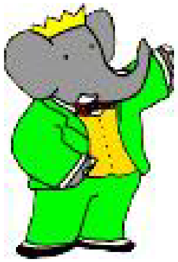
3.5σ deviation for S in φK_S
Belle Claim
"evidence for new physics"

(from 152×10^6 B pairs)

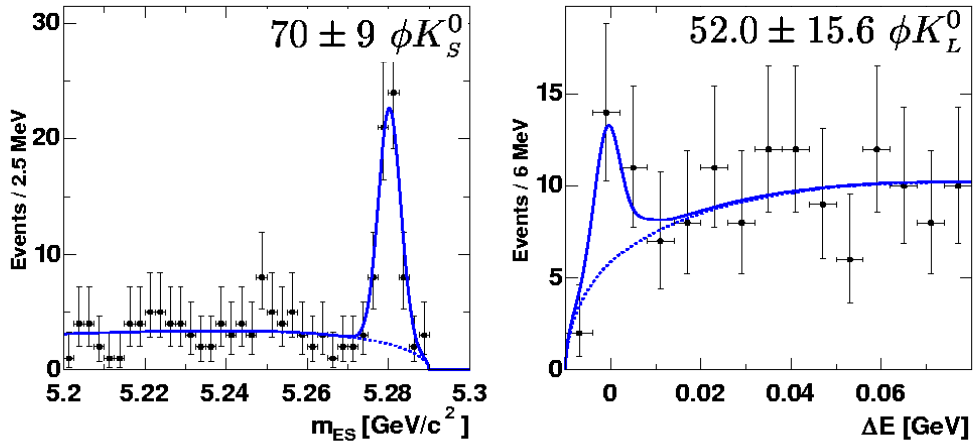
PRL. 91 (2003) 261602

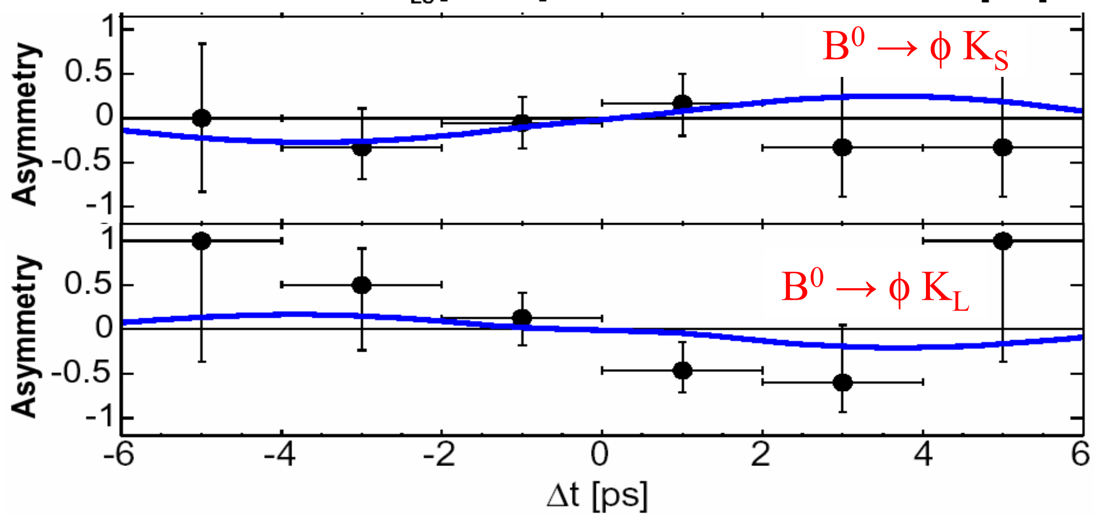
$B^0 \to \phi K^0$

Preliminary



120 M $B\bar{B}$





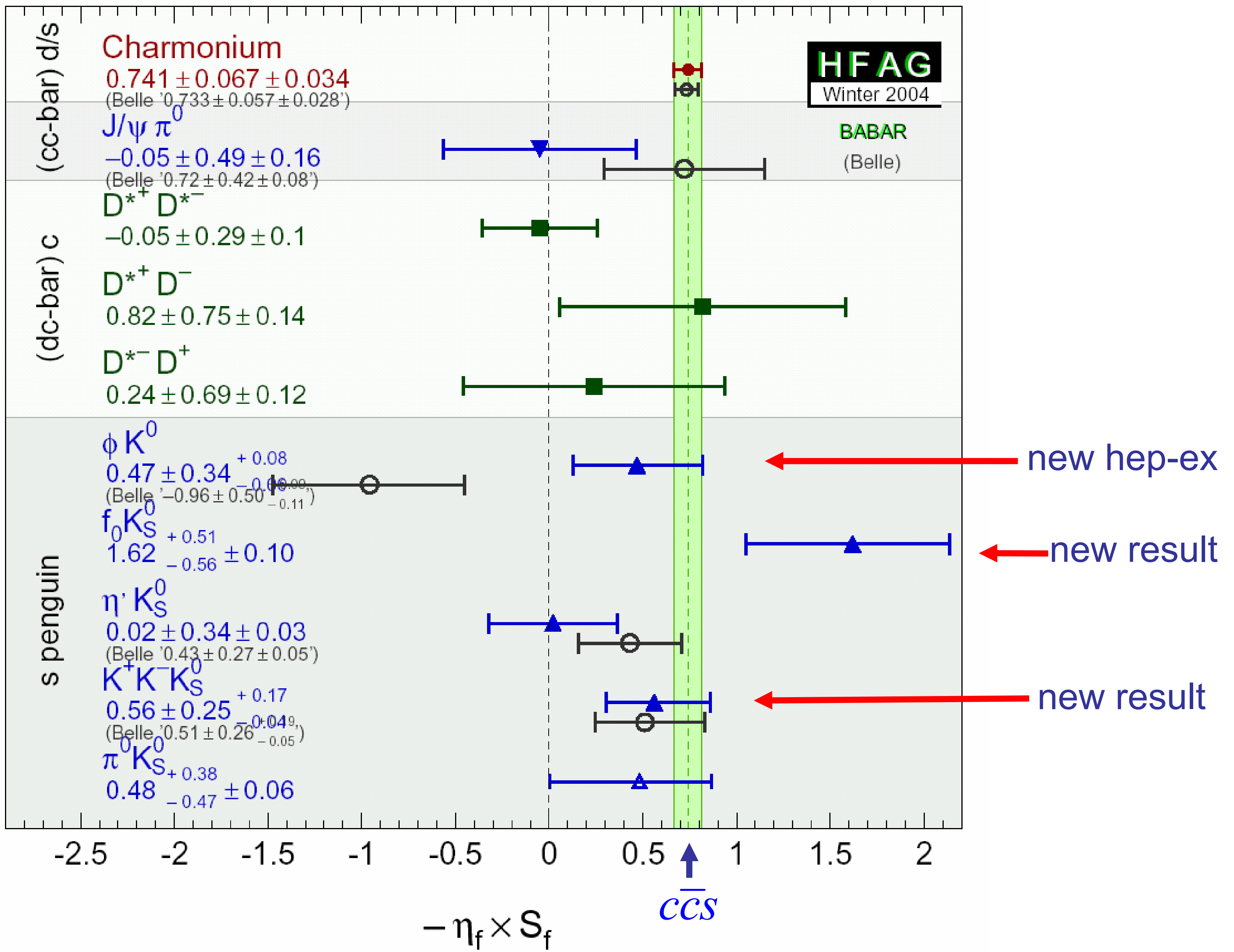
$$S_{\phi K} = 0.47^{+0.32}_{-0.36}(stat) \pm 0.06(syst)$$

$$C_{\phi K} = 0.01 \pm 0.33(stat) \pm 0.10(syst)$$

BaBar Result consistent with SM

hep-ex/0403026, submitted to PRL

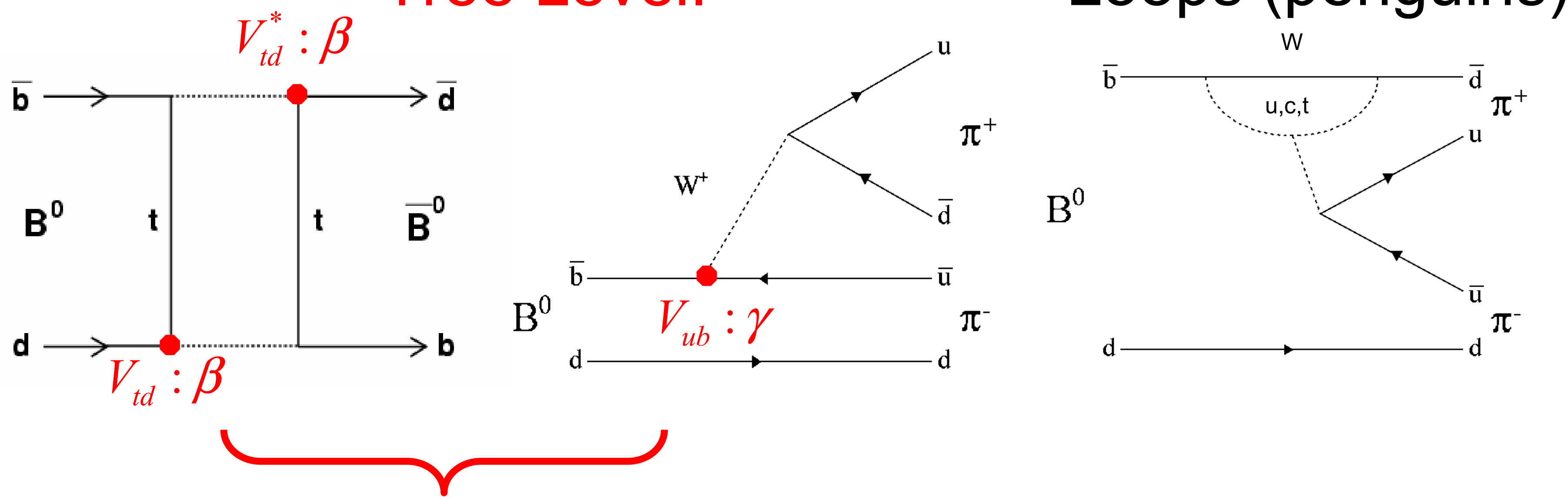
The CKM Angle β:



The CKM Angle α:

CP Violation in $B^0 \to h^+h^-$; h=ρ,π

Tree Level: +Loops (penguins)



$$C_{\pi\pi} = 0$$

$$S_{\pi\pi} = \sin(2\alpha)$$

$$C_{\pi\pi} \propto \sin(\delta)$$

$$S_{\pi\pi} = \sqrt{1 - C_{\pi\pi}^2}\,\sin(2\alpha_{\text{eff}})$$

→ measure α_{eff}

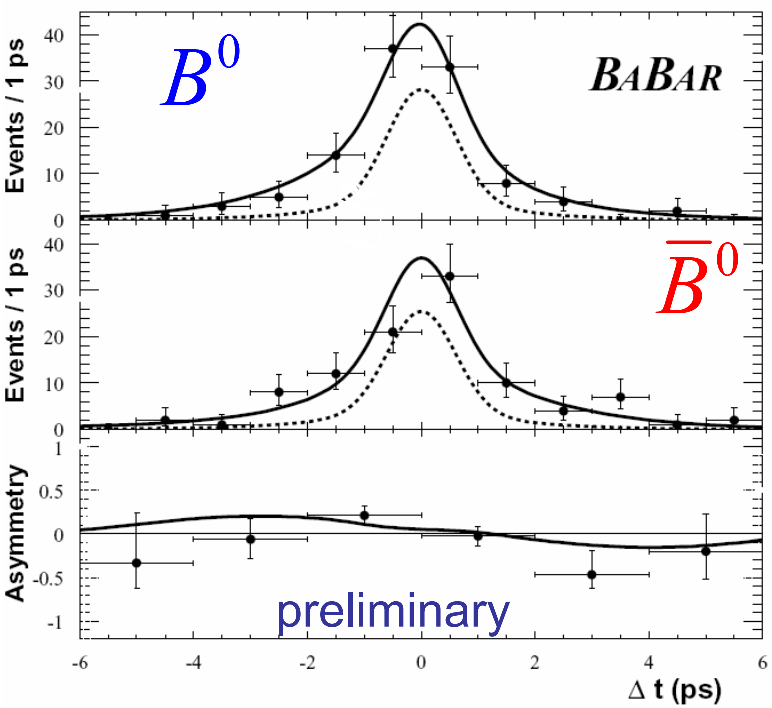
→ need to bound $|\alpha_{\text{eff}} - \alpha|$ (shift from loops)

→ different |Penguin/Tree| for different decays

$\pi^+\pi^-$ results for S and C

124×10^6 B pairs

266 signal events



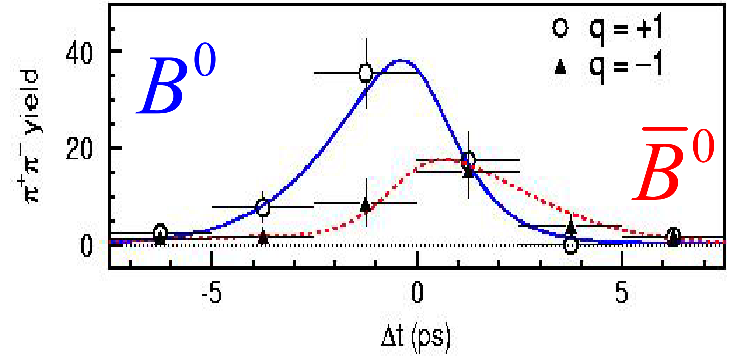
$$S_{\pi\pi} = -0.40 \pm 0.22 \pm 0.03$$

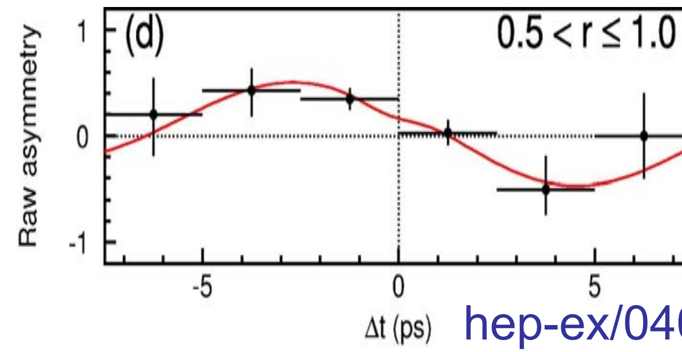
$$C_{\pi\pi} = -0.19 \pm 0.19 \pm 0.05$$

$$A_{K\pi} = -0.107 \pm 0.041 \pm 0.013$$

152×10^6 B pairs

372 signal events





hep-ex/0401029

$-A_{\pi\pi} = -0.58 \pm 0.15 \pm 0.07 = C$

$S_{\pi\pi} = -1.00 \pm 0.21 \pm 0.07$

→Observation of CPV

→Evidence for DCPV

$\pi\pi$ Isospin Analysis: need $B\to\pi^+\pi^-$, $\pi^+\pi^0$ and $\pi^0\pi^0$

➡ limiting factor is $B^0\to\pi^0\pi^0$

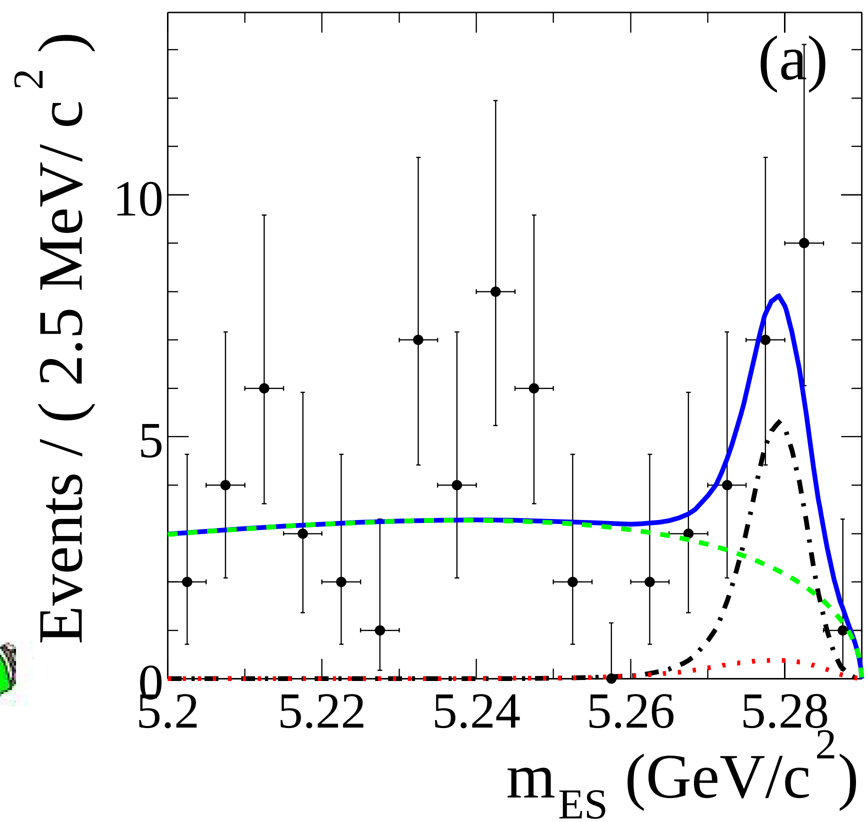
- Small signal BR
- $q\bar{q}$ and $\rho\pi^0$ background

124×10⁶ B pairs

$$N_{\pi^0\pi^0} = 46^{+14}_{-13} \pm 3$$

$$BR(B^0 \to \pi^0\pi^0) = (2.1 \pm 0.6 \pm 0.3)\times 10^{-6}$$

Significance including systematic errors = 4.2σ



➡ $|\alpha_{eff} - \alpha| < 48^0$ $(90\% C.L.)$

➡ Can't do Isospin analysis in $\pi\pi$ without a super B factory

➡ Stuck with model dep. interpretation in $\pi\pi$

PRL 91 (2003) 241801

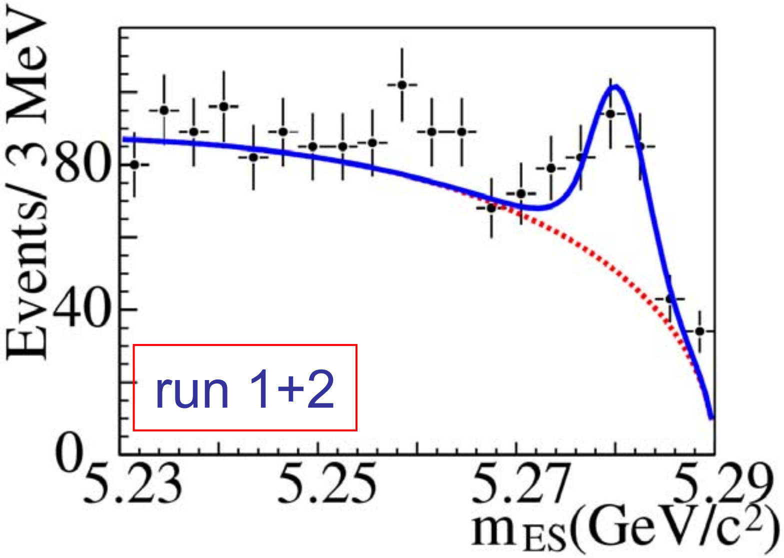
$B \to \rho\rho$

→ No observation published prior to last year
→ now have measurements of all modes

$B^0 \to \rho^+\rho^-$ (BaBar)

$$BF = (30 \pm 4 \pm 5) \times 10^{-6}$$

$$f_L = 0.99 \pm 0.03 \pm 0.04$$



$B^0 \to \rho^+\rho^0$ (Belle & BaBar)

$$BF = (26.4 \pm 6.4) \times 10^{-6}$$

$$f_L = 0.96^{+0.05}_{-0.07}$$

$B^0 \to \rho^0\rho^0$ (BaBar)

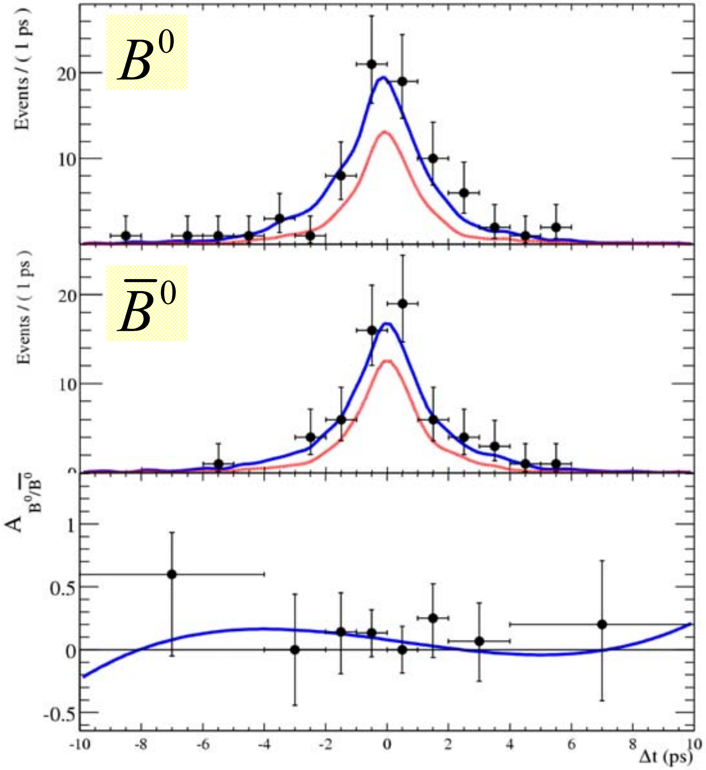
$$BF < 2.1 \times 10^{-6} (90\% C.L.)$$

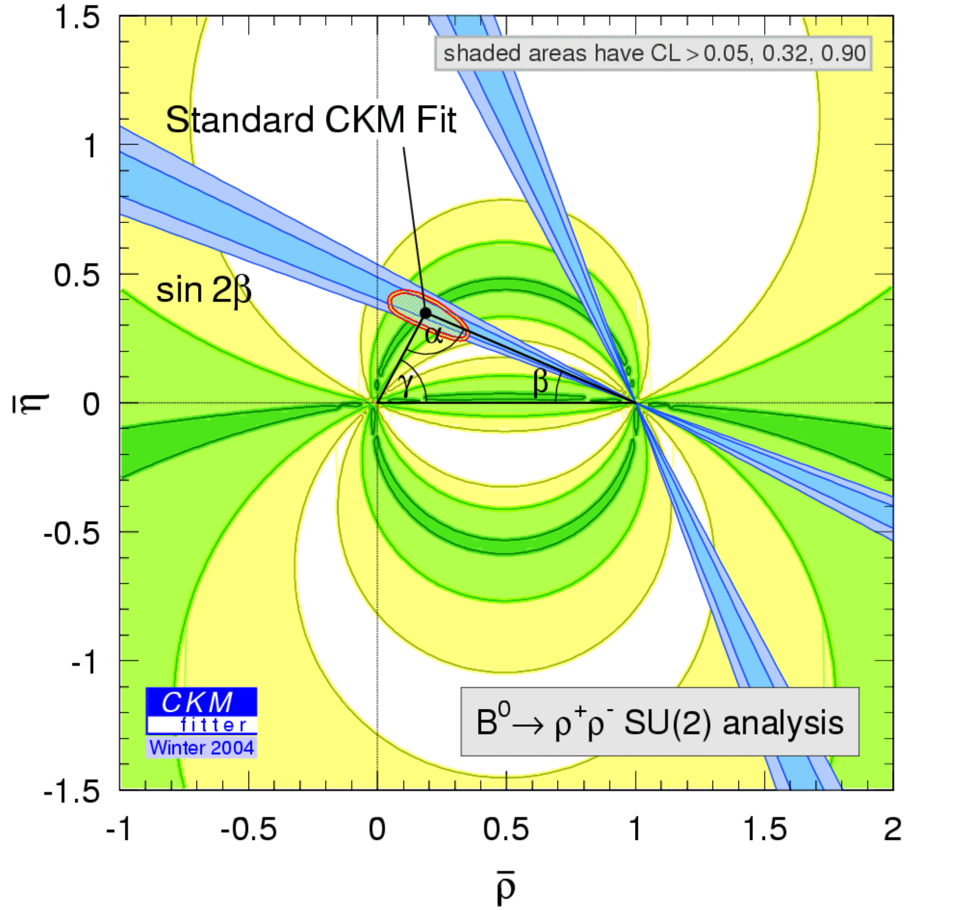
Penguins are small in B→ρρ

$$|\alpha_{eff} - \alpha| < 13° (68\% CL)$$

$B \to \rho\rho$ Preliminary Result

run 1+2+3





- ~113/fb
- 314 signal events

$$S_{long} = -0.19 \pm 0.33_{stat} \pm 0.11_{syst}$$

$$C_{long} = -0.23 \pm 0.24_{stat} \pm 0.14_{syst}$$

Isospin analysis gives:

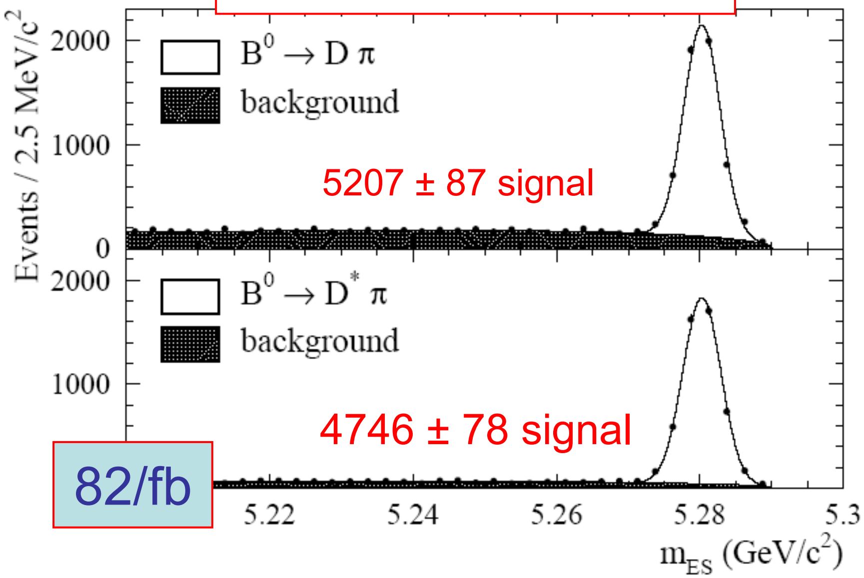
$$\alpha = 96 \pm 10_{stat} \pm 4_{syst} \pm 13_{theory}$$

The CKM Angle γ:

hep-ex/0308048 & *hep-ex/0310037 (BaBar)*
hep-ex/0308048 (Belle)

2 of many methods under study:
Full & Partial reconstruction of $B \to D^{(*)}\pi$: $\sin(2\beta+\gamma)$

Full Reconstruction

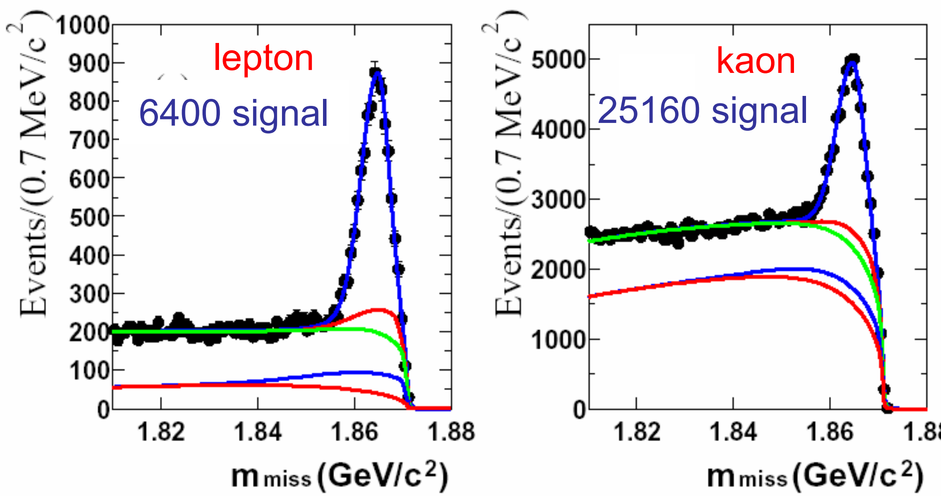


82/fb

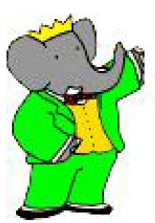
→ High Purity
→ Lower Statistics

Partial Reconstruction

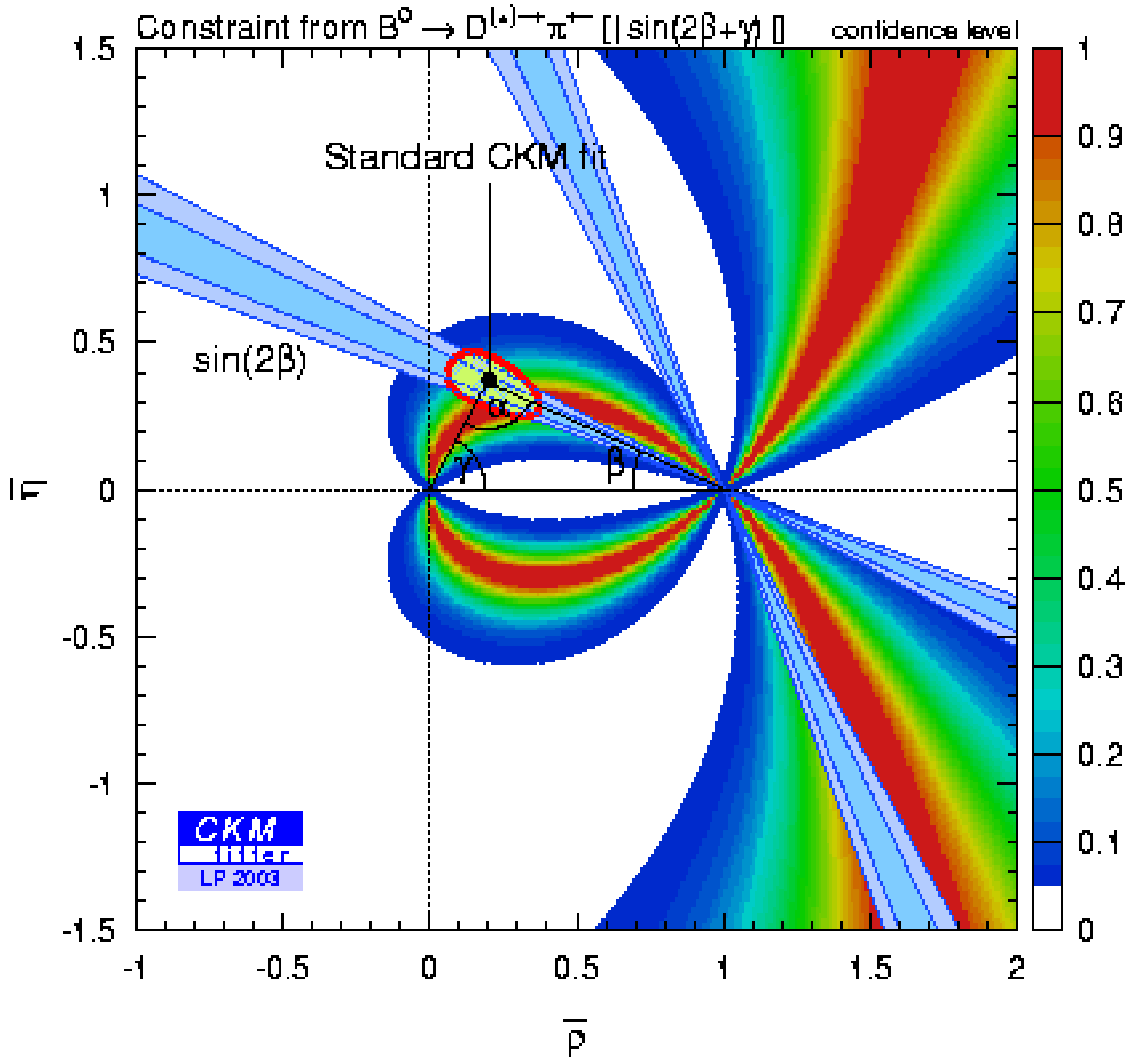
using 78/fb
→Only consider D*π with *l* or *K* in other B



→O(50%) purity
→use hard pion from B decay and soft pion from D* decay.
→No low efficiency from D^0 reconstruction



Preliminary



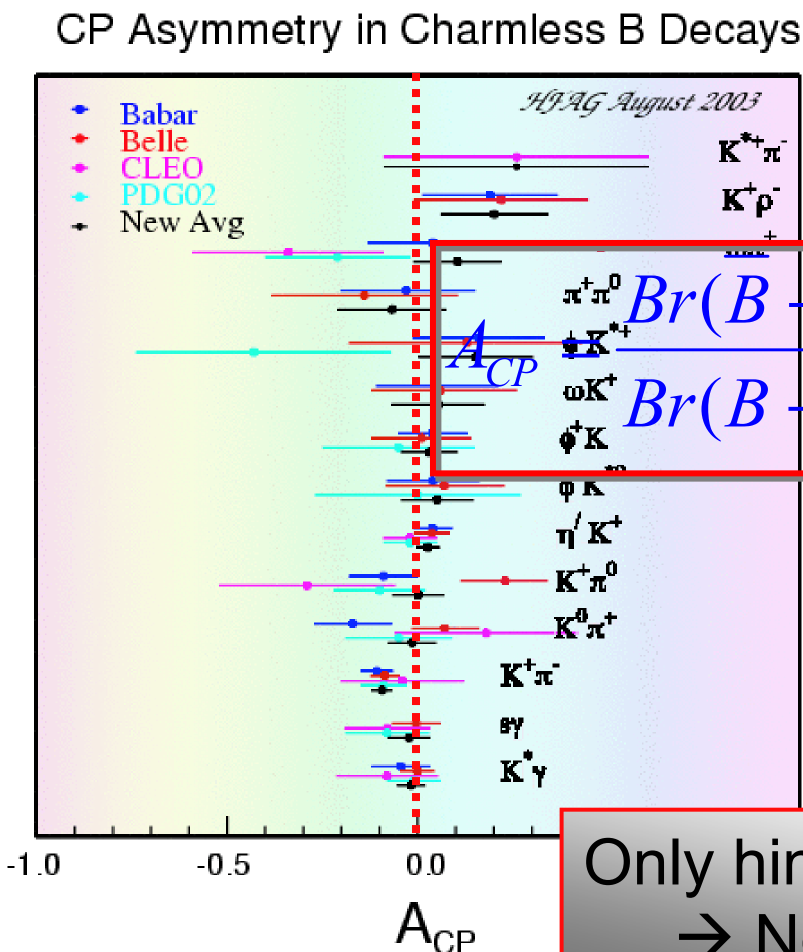
Combining results of both BaBar methods

sin(2β+γ) > 0.87 (68% CL)

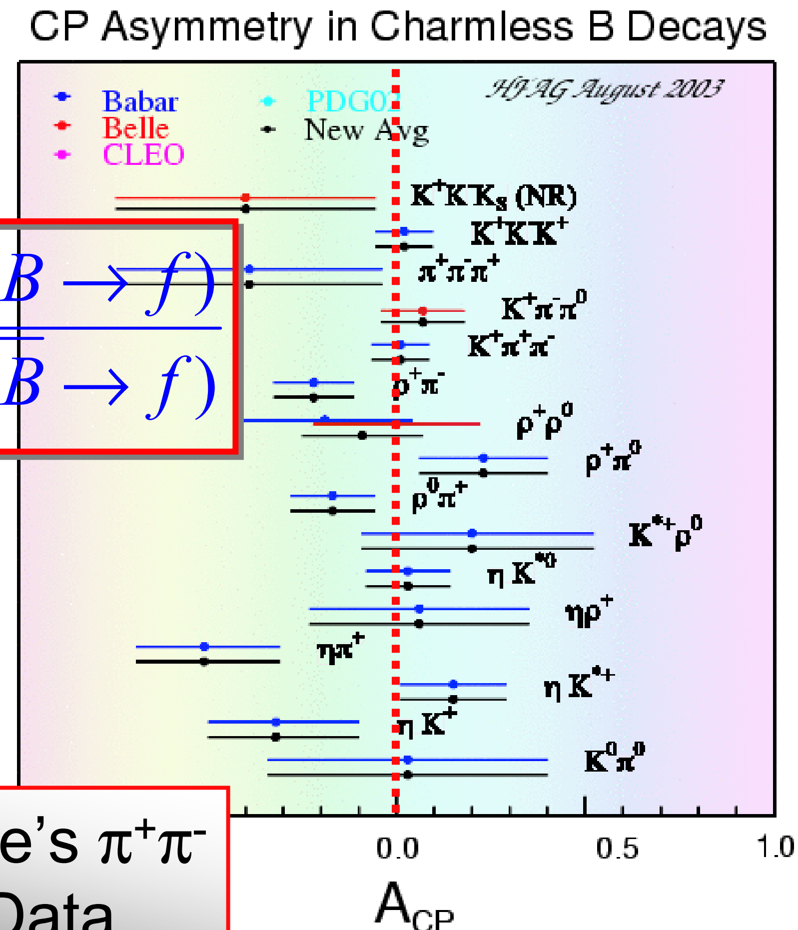
sin(2β+γ) > 0.58 (95% CL)

Direct CP Violation

- Interference of diagrams with different strong and weak phases
- ε' in kaon system only observed manifestation



$$A_{CP} = \frac{Br(B \to f) - Br(\bar{B} \to \bar{f})}{Br(B \to f) + Br(\bar{B} \to \bar{f})}$$



Only hint from Belle's $\pi^+\pi^-$

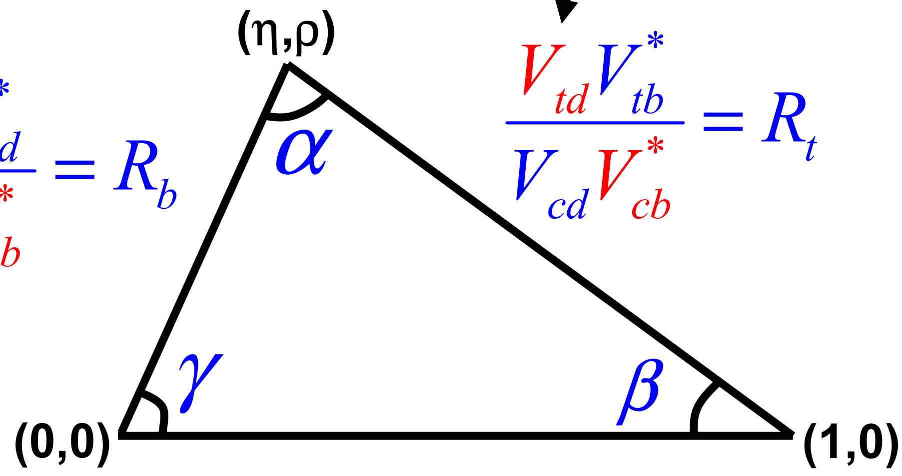
→ Need More Data

Measurements Related to Sides of the Unitarity Triangle

$$b \rightarrow s\gamma$$

$$\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = R_t$$

$$\frac{V_{ub}V_{ud}^*}{V_{cd}V_{cb}^*} = R_b$$



semi-leptonic B decays

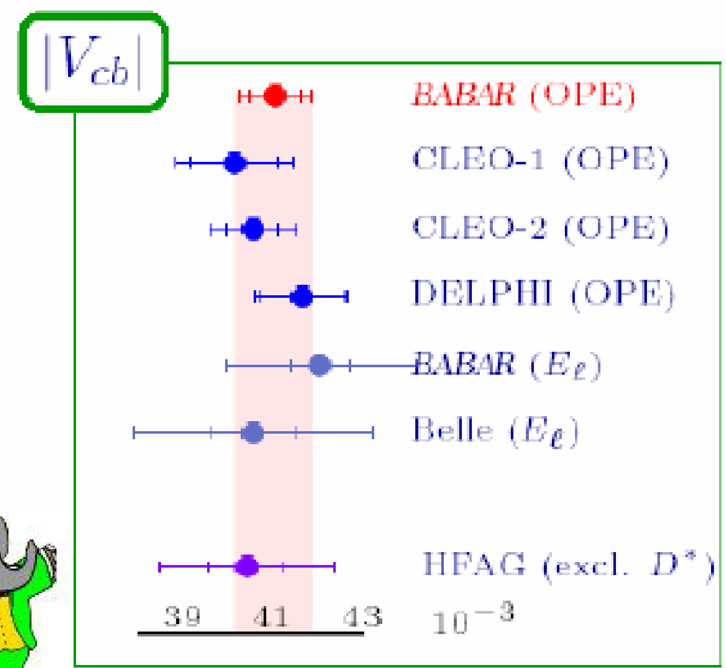
Measurement of V_{cb} from semileptonic B decays

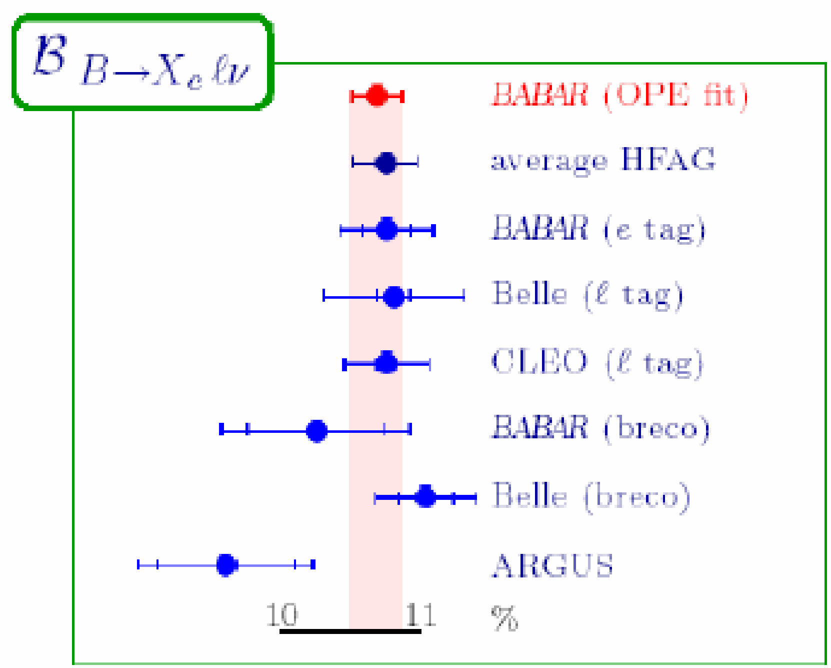
Use model from Gambino and Uraltsev → hep-ph/0401063, hep-ph/0403166

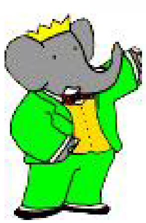
8 parameter fit includes: $|V_{cb}|$, $BR(X_C e\nu)$, m_b and m_c

$$|V_{cb}| = (41.4 \pm 0.4_{\rm exp} \pm 0.4_{\rm HQE} \pm 0.2_{\alpha_s} \pm 0.6_{\Gamma_{SL}}) \times 10^{-3}$$
$$Br(B \to X_c e\nu) = (10.61 \pm 0.16_{\rm exp} \pm 0.06_{\rm HQE})\%$$
$$m_b(1\ GeV) = (4.61 \pm 0.05_{\rm exp} \pm 0.04_{\rm HQE} \pm 0.02_{\alpha_s})\ GeV$$
$$m_c(1\ GeV) = (1.18 \pm 0.07_{\rm exp} \pm 0.06_{\rm HQE} \pm 0.02_{\alpha_s})\ GeV$$

$B(B \to X_c l\nu)$, $|V_{cb}|$ and m_b determined with precision of 2% or better!







Thanks to Henning Flaecher

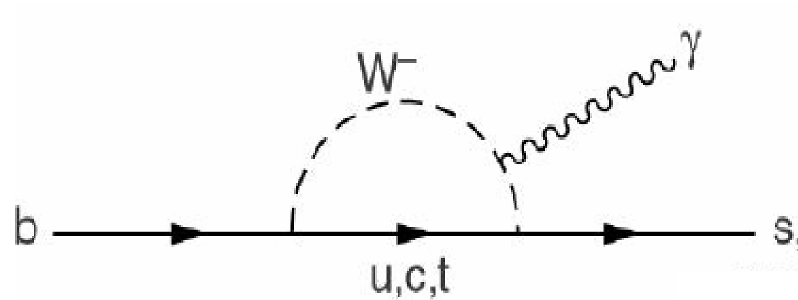
Preliminary

hep-ex/0403031, hep-ex/0403030

$B \to K^*\gamma$

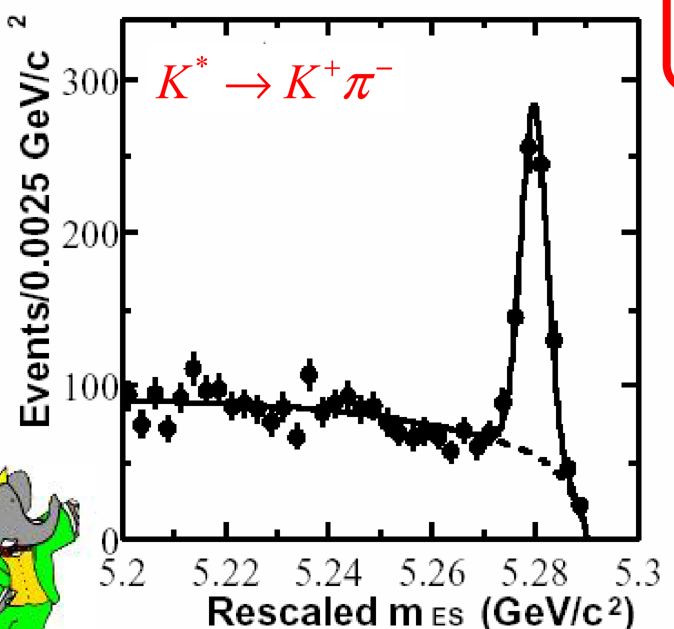
88×10^6 B pairs

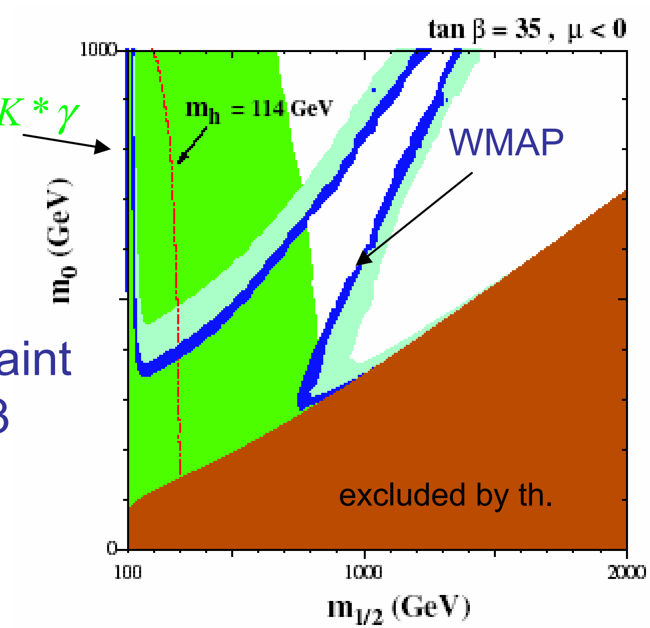
- $A_{cp} \le 1\%$ in SM.
- SUSY can enhance to ~20%



Reconstruct ~1150 signal in: $K^* \to K^+\pi^-, K^+\pi^0, K_s\pi^0, K_s\pi^+$

$$A_{CP} = -0.013 \pm 0.036(\mathrm{stat.}) \pm 0.010(\mathrm{sys.})$$





e.g. MSSM constraint
hep-ph/0303043
(Ellis et al)

Non CP/UT physics from BaBar

➔ Too much physics activity to do justice to all areas: We have work published/under study in many areas including:

- New Particle Searches
- Rare B decays
- Direct CP Violation Searches
- τ physics

→lots more areas under study that I don't have time to discuss.

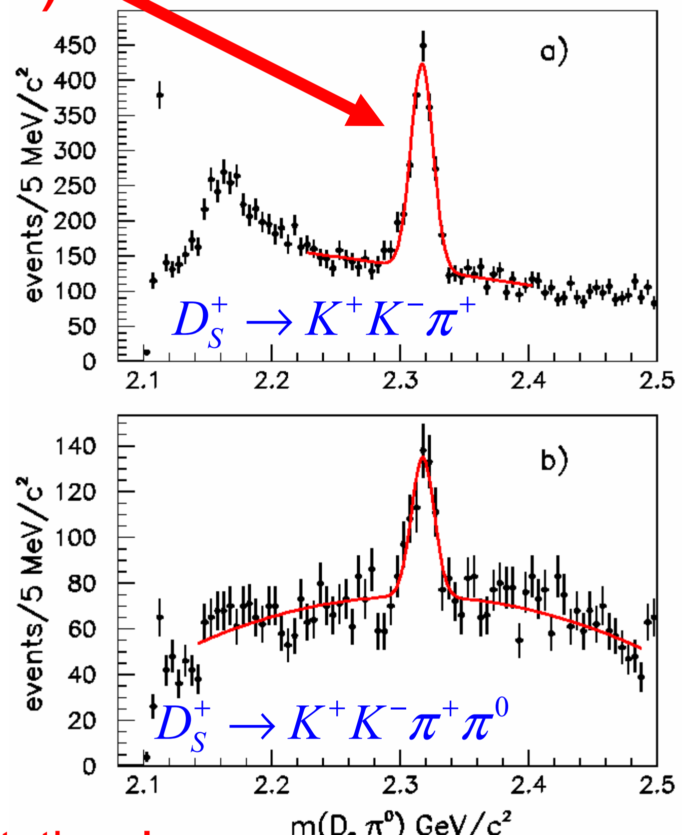
New Particle Searches

- Last Spring from BaBar:

  discovery of $\bar{c}s$ state: $D_{sJ}(2317)$

  evidence for $D_s(2458)$

data favour $J^P=0^+$



→revitalised charm meson spectroscopy

→Belle and CLEO confirmed this discovery

→led to improvement in theoretical models

→ State was found below DK threshold (previously assumed to be above threshold)

→ Now have many $B \to D_{sJ}X$ branching fractions

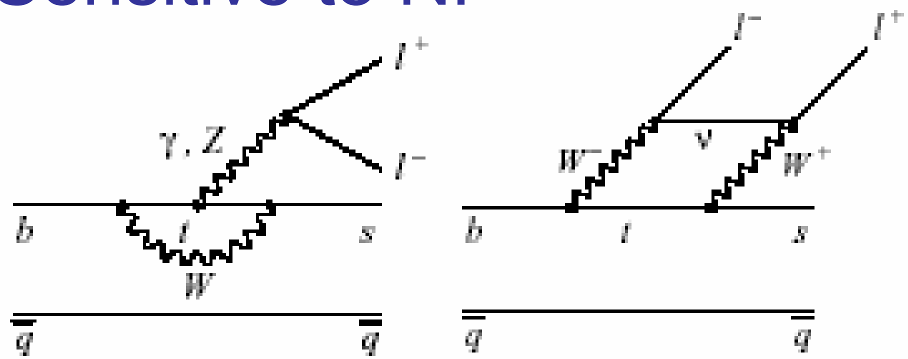
See: 2317: Phys.Rev.Lett. 90 (2003) 242001 ➔ 105 citations!
2458: Phys.Rev. D69 (2004) 031101

- Ongoing work searching for Pentaquarks

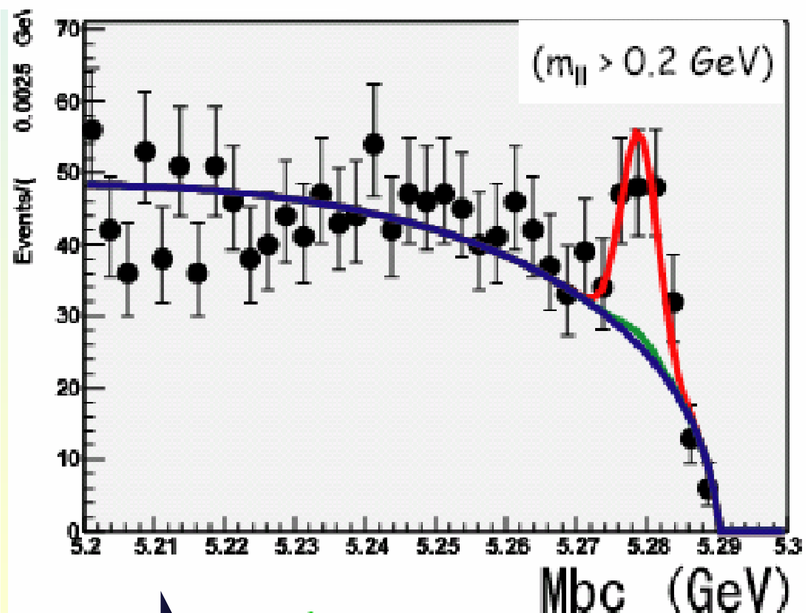
Belle Observe $B \to X_S ll$, $X_S = K, K_S$

from Iwasaki's talk at
http://moriond.in2p3.fr/EW/2004/

- Rare Decay (FCNC)
- Sensitive to NP



72 Signal Events
6.2σ significance
140/fb, 152×10^6 B pairs



$$Br(B \to Xsee) = [4.45 \pm 1.32^{+0.84}_{-0.79}]\times10^{-6}$$

$$Br(B \to Xs\mu\mu) = [4.31 \pm 1.06^{+0.74}_{-0.70}]\times10^{-6}$$

$$Br(B \to Xsll) = [4.39 \pm 0.84^{+0.78}_{-0.73}]\times10^{-6}$$

Also study $B \to K^{*}ll$ where BF~7×10^{-7}

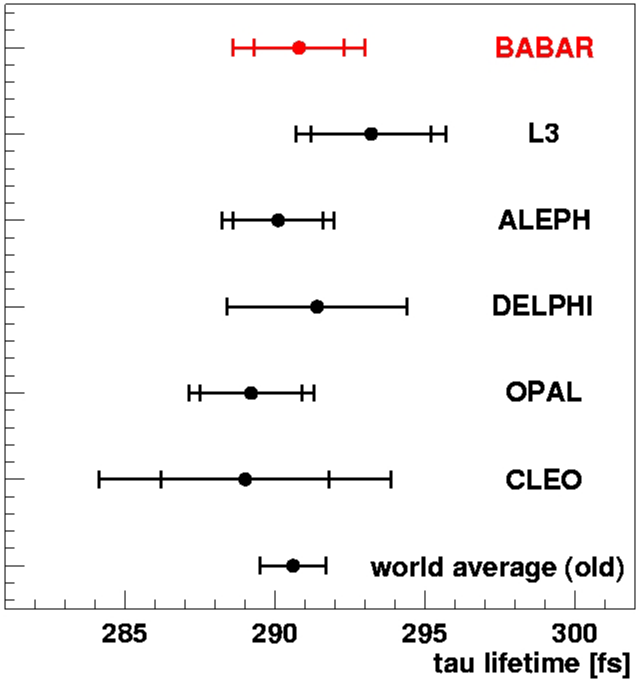
(results available from both expts)

Preliminary

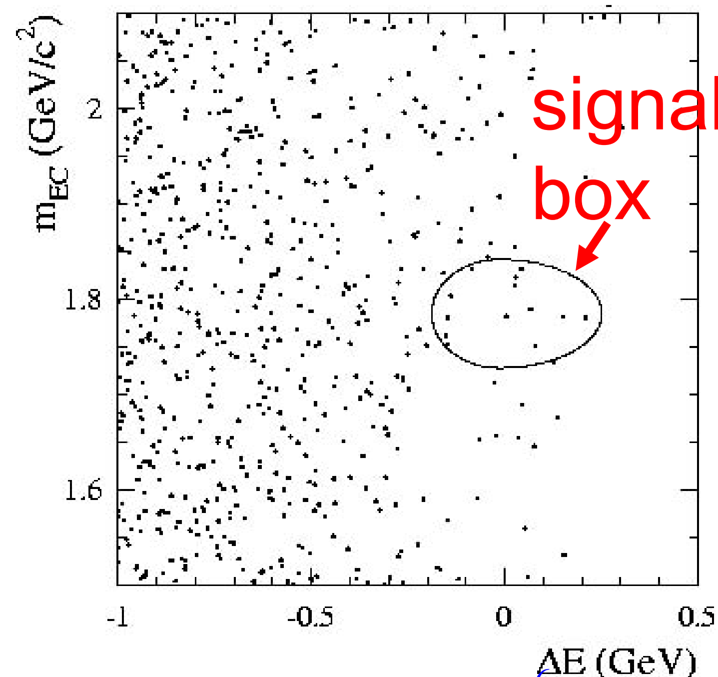
τ Physics: Overview

τ lifetime: 30/fb

$\tau_\tau = 290.8 \pm 1.5_{stat} \pm 1.6_{syst}$ fs

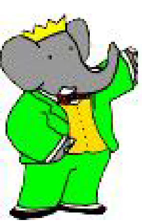


Rare τ decays



$BF(\tau \to \mu\gamma) < 2.0 \times 10^{-6}$ (90% C.L.)

(56×10^6 τ pairs)



LFV decay searches: 91.5/fb

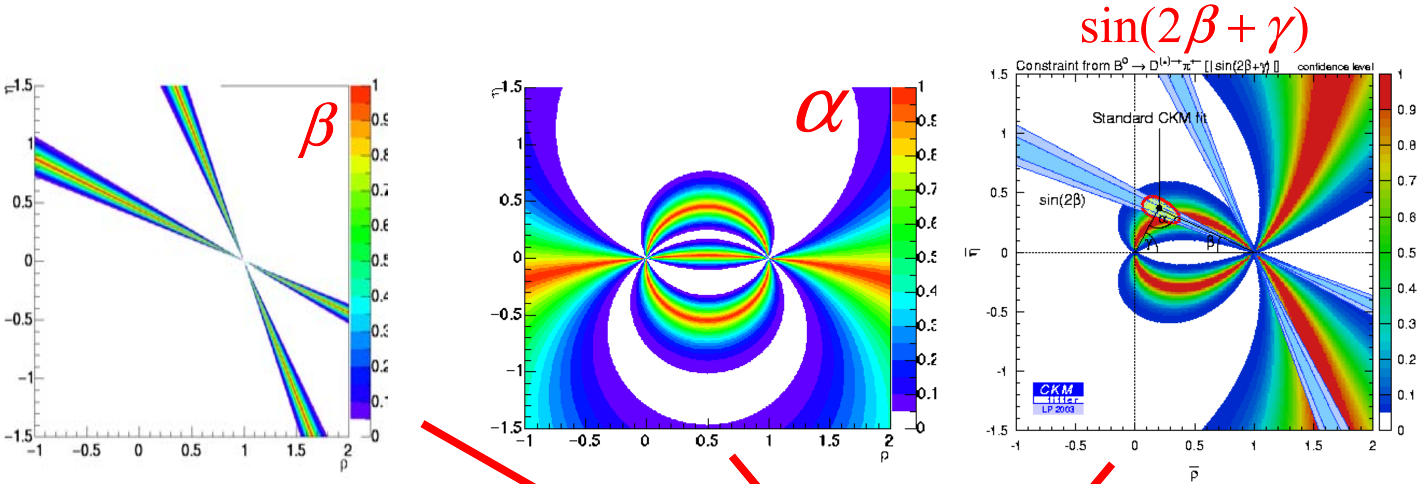
Decay mode	$e^-e^+e^-$	$\mu^+e^-e^-$	$\mu^-e^+e^-$
$\mathcal{B}^{90}_{UL}$	1.3×10^{-7}	3.3×10^{-7}	1.9×10^{-7}

→ hep-ex/0312027

Conclusions

- BaBar has first measurement of α from $B\rightarrow\rho\rho$
- Belle Observes CPV in $B\rightarrow\pi\pi$
  & sees hint of Direct CPV
- Starting to test closure of the Unitarity triangle
- Everything measured so far consistent with SM
- Searching for New Physics at higher order: looking closely at $b\rightarrow s$ penguins: new measurements of β
- Will have ~200-250/fb per experiment for ICHEP '04 (approx ×2-3 increase in stats over results shown)

Knowledge of η,ρ from direct measurements



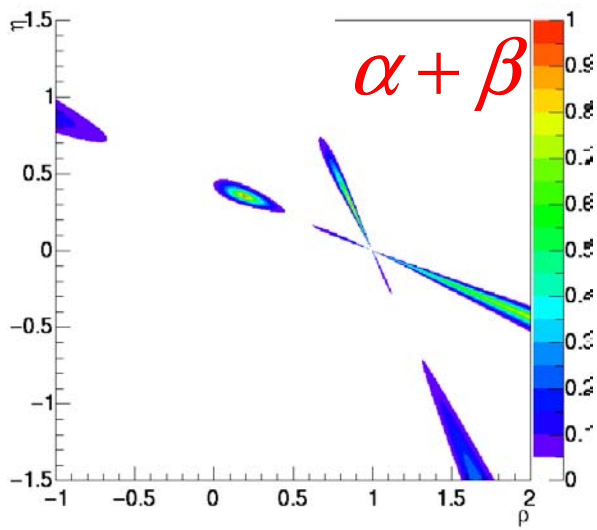
Constraints from:

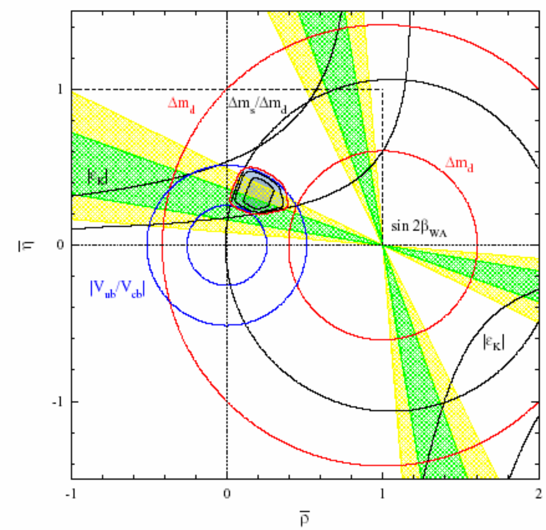
$b \to c\bar{c}s$

$B \to \rho\rho$

$B \to D^{(*)}\pi$

$B \to J/\psi K^*$

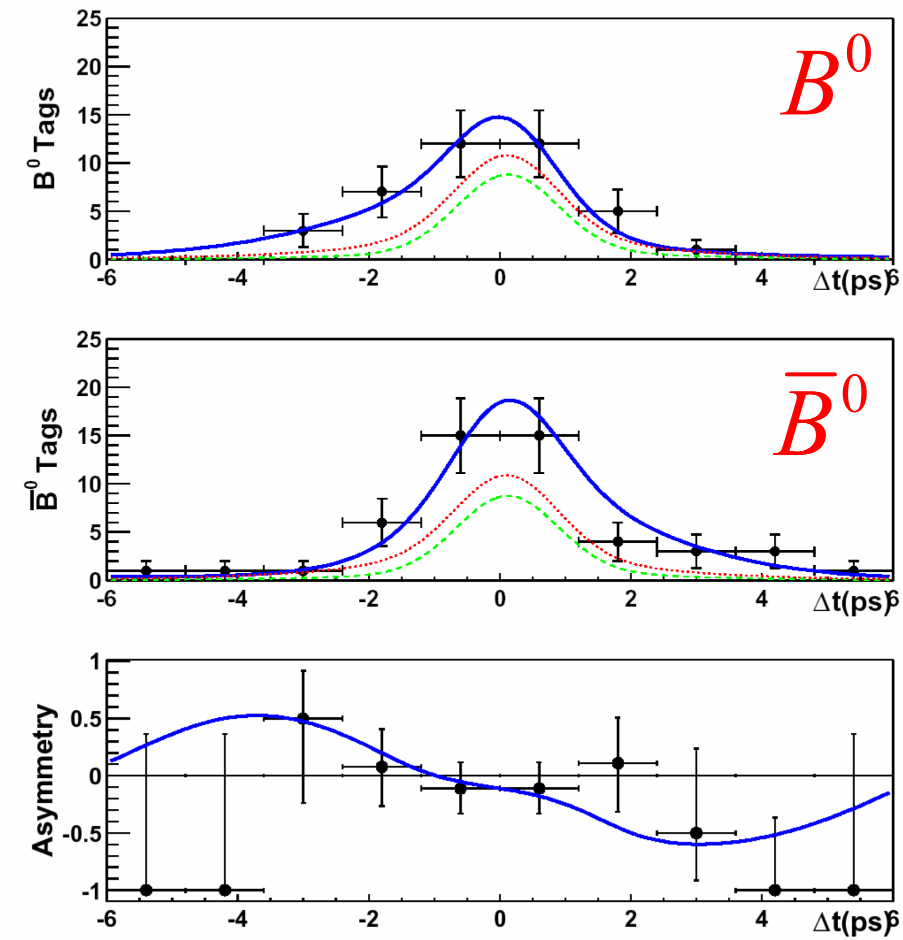




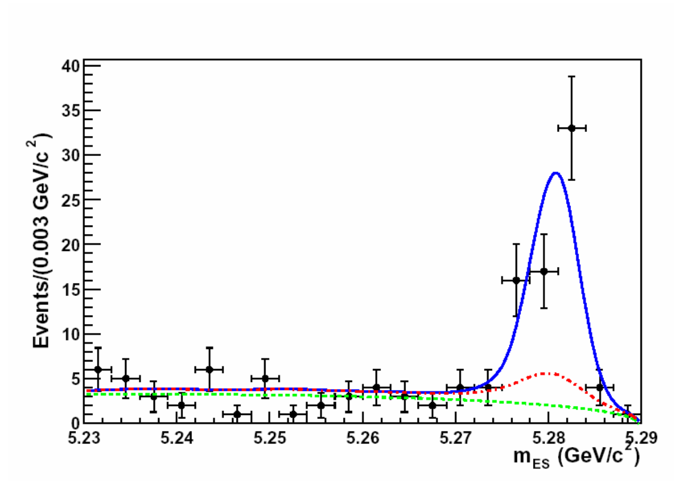
CPV from B system is consistent with SM

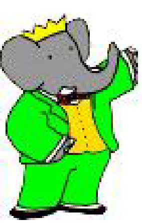
Additional Material:

$B^0 \rightarrow f^0\, K^0$ (CP even decay)



$$N_{f_0 K^0_S} = 94 \pm 14(\mathrm{stat}) \pm 6(\mathrm{syst})$$



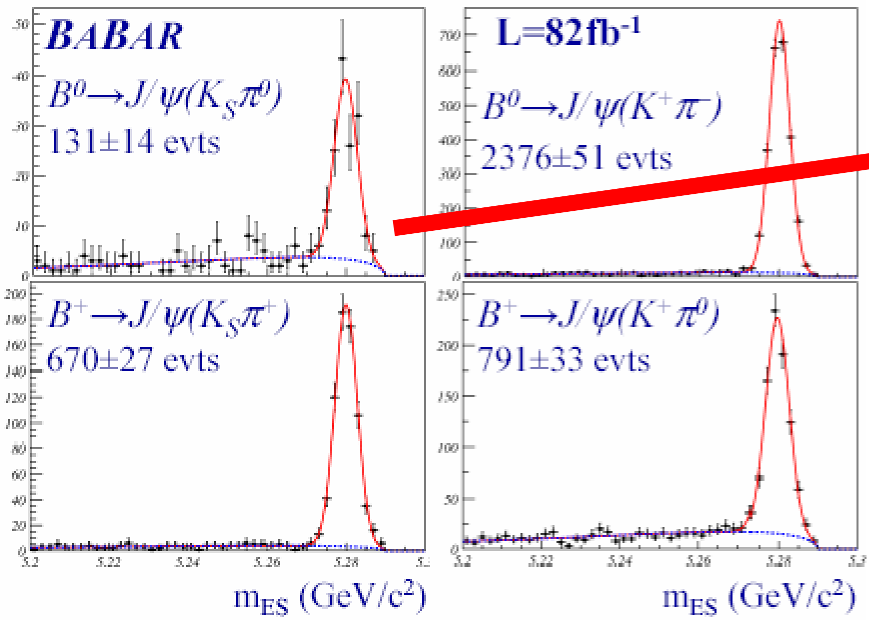


$$S = -1.62\ {}^{+\,0.56}_{-\,0.51}(\mathrm{stat}) \pm 0.10(\mathrm{syst})$$
$$C = 0.27 \pm 0.36(\mathrm{stat}) \pm 0.12(\mathrm{syst})\,.$$

$B \to J/\psi K^*$ $(\cos 2\beta)$

$B \to J/\psi K^*$ is a VV decay - has both CP even and CP odd parts

- $\cos(2\beta)$ comes from interference between helicity states



104 tagged events ($K_S\pi^0$)

$$\cos 2\beta = \pm 3.32^{+0.76}_{-0.96}(stat) \pm 0.27(syst)$$

$$\sin 2\beta = -0.10 \pm 0.57$$

With WA $\sin 2\beta$

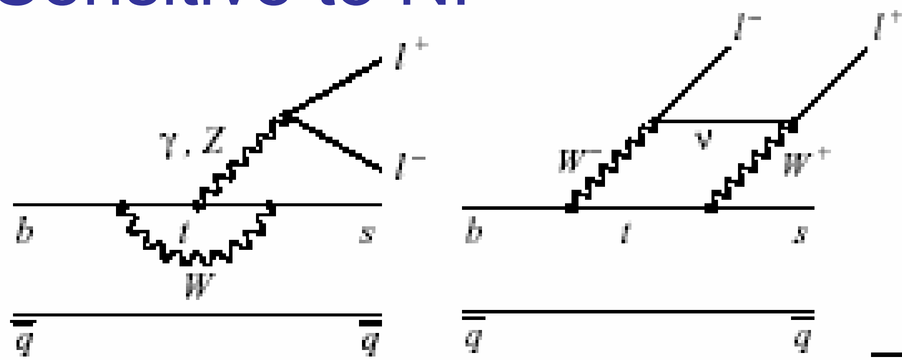
$$\cos 2\beta = +2.72^{+0.50}_{-0.79} \pm 0.27$$

Preliminary

$b \to sll$ → e^+e^- or $\mu^+\mu^-$

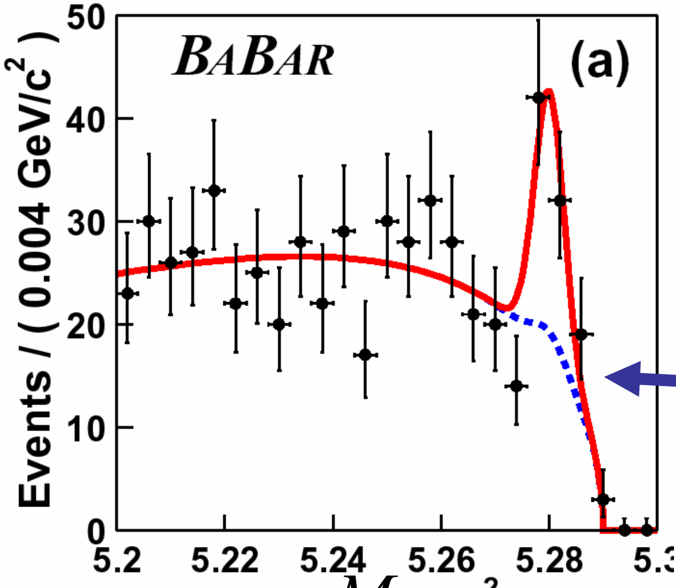
→ $K^\pm$ or K_S^0

- Rare Decay (FCNC)
- Sensitive to NP



Ali: PRD 66 034002 (2002)
Ali: hep-ph/0210183

SM BF~$7(1)\times10^{-6}$ (ee)
~$4(1)\times10^{-6}$ ($\mu\mu$)



M_{ES}

	N_{sig}	$\mathcal{B}$ $(\times10^{-6})$
(e)	$29.2 \pm 8.3 \pm 1.3$	$7.3 \pm 2.1^{+1.0+1.6}_{-0.8-1.4}$
(μ)	$11.2 \pm 6.2 \pm 0.9$	$5.5 \pm 3.0^{+0.8+1.4}_{-0.7-1.0}$
(ℓ)	$40.1 \pm 10.4 \pm 1.7$	$6.6 \pm 1.7^{+0.9+1.5}_{-0.7-1.3}$

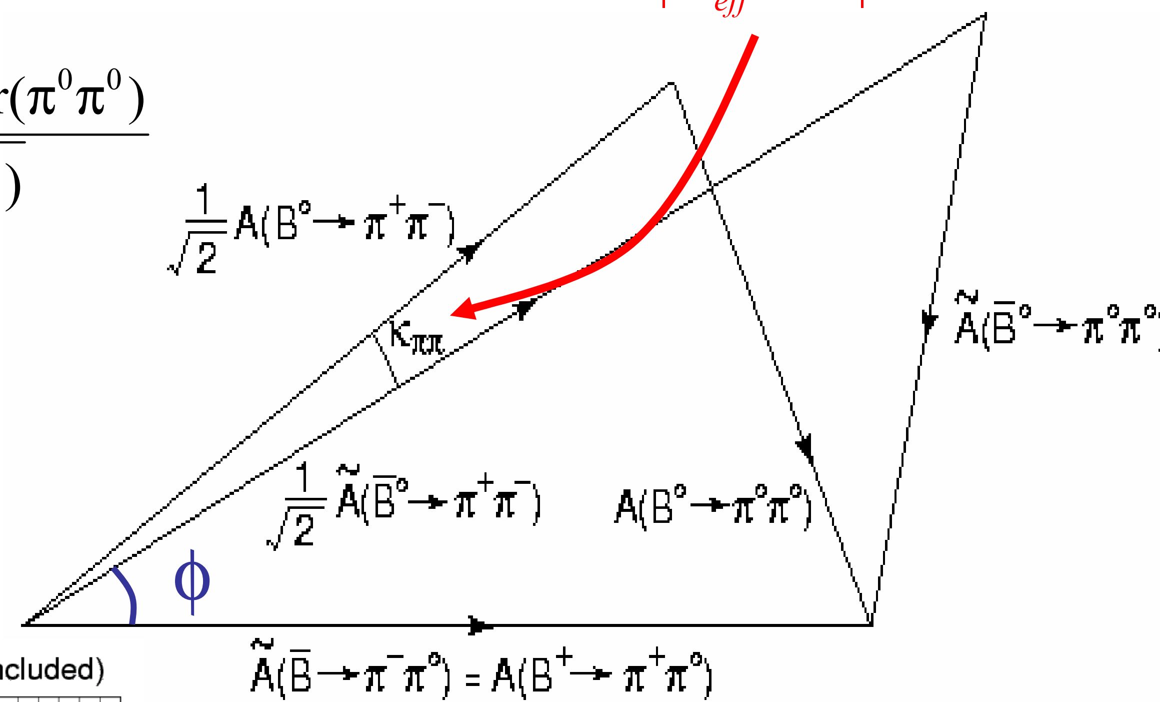
peaking BG component from charmonium and hadronic B decays

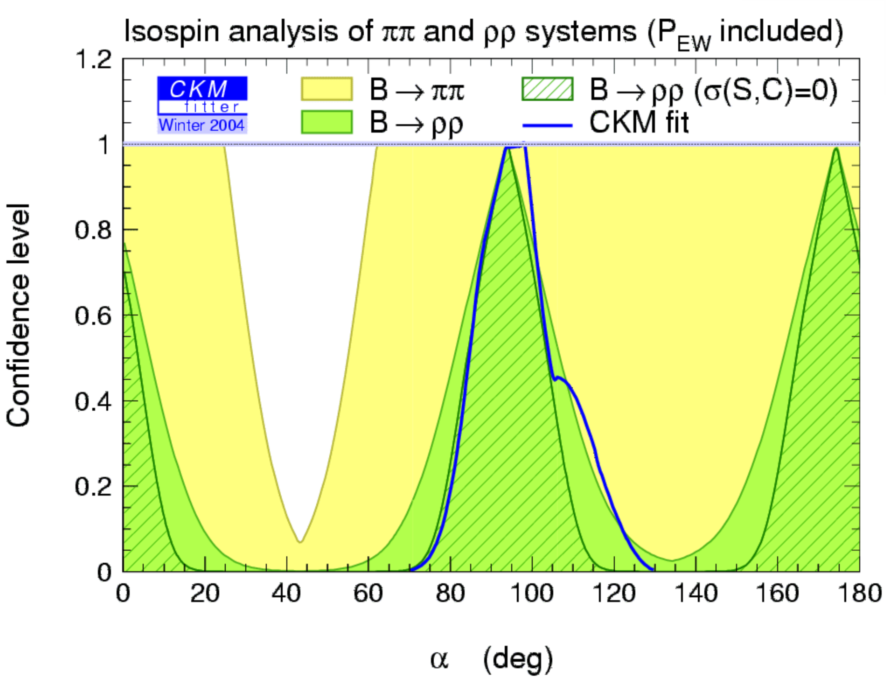
$$A_{CP} = -0.22 \pm 0.26(\text{stat}) \pm 0.02(\text{syst})$$ c.f. 0.02(0.20) in SM

Isospin Analysis

$$\cos\phi = \frac{\mathrm{Br}(\pi^+\pi^0) + \frac{1}{2}\mathrm{Br}(\pi^+\pi^-) - \mathrm{Br}(\pi^0\pi^0)}{\sqrt{2\,\mathrm{Br}(\pi^+\pi^-)\,\mathrm{Br}(\pi^+\pi^0)}}$$

$\kappa = |\alpha_{eff} - \alpha|$





Grossman Quinn bound

$$\sin^2(\alpha_{eff} - \alpha) \le \frac{Br\left(B^0 \to \pi^0\pi^0\right)}{Br\left(B^+ \to \pi^+\pi^0\right)}$$

Also see Charles, GLSS, Buchalla et al…

$B^0 \to \rho\pi / \rho K$: Not A CP Eigenstate

- ➔ doing analysis in region near ρ
- ➔ Dalitz Plot analysis goal

direct CPV

$$f_{B^0}^{\rho^\pm X^\mp}(\Delta t) = (1 \pm A_{CP}^X) e^{-|\Delta t|/\tau} \left[(S_{\rho X} \pm \Delta S_{\rho X}) \sin(\Delta m \Delta t) - (C_{\rho X} \pm \Delta C_{\rho X}) \cos(\Delta m \Delta t) \right]$$

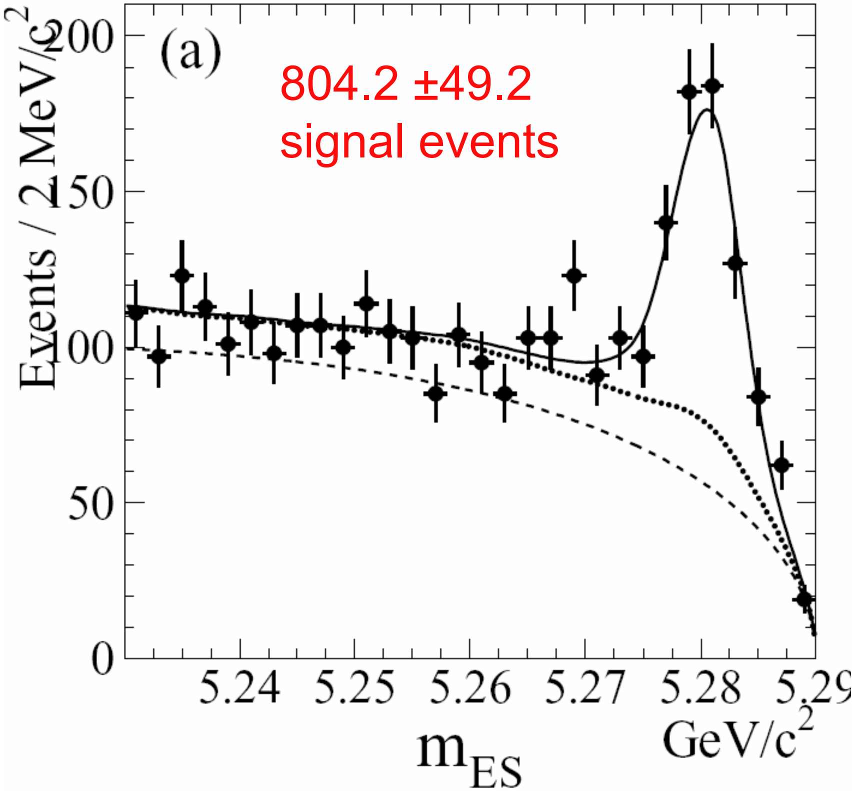
related to α

- ρK is self tagging

  $C_{\rho K}, S_{\rho K}, \Delta S_{\rho K} = 0, \Delta C_{\rho K} = -1$

- large expected:

  $A_{CP}(\rho\pi)$ & $A_{CP}(\rho K)$



$$B(B \to \rho^\pm \pi^\mp) = (22.6 \pm 1.8 \pm 2.2) \times 10^{-6}$$

$$B(B \to \rho^\pm K^\mp) = (7.3^{+1.3}_{-1.2} \pm 1.3) \times 10^{-6}$$

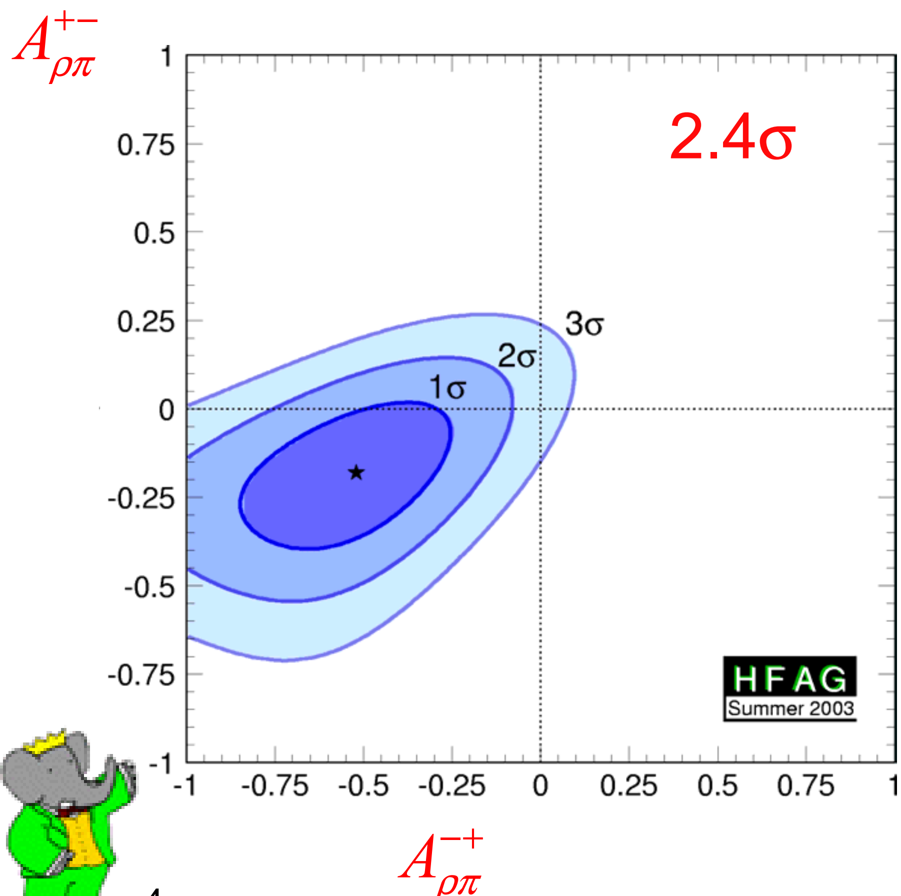
BF From Winter ’03 (82/fb)

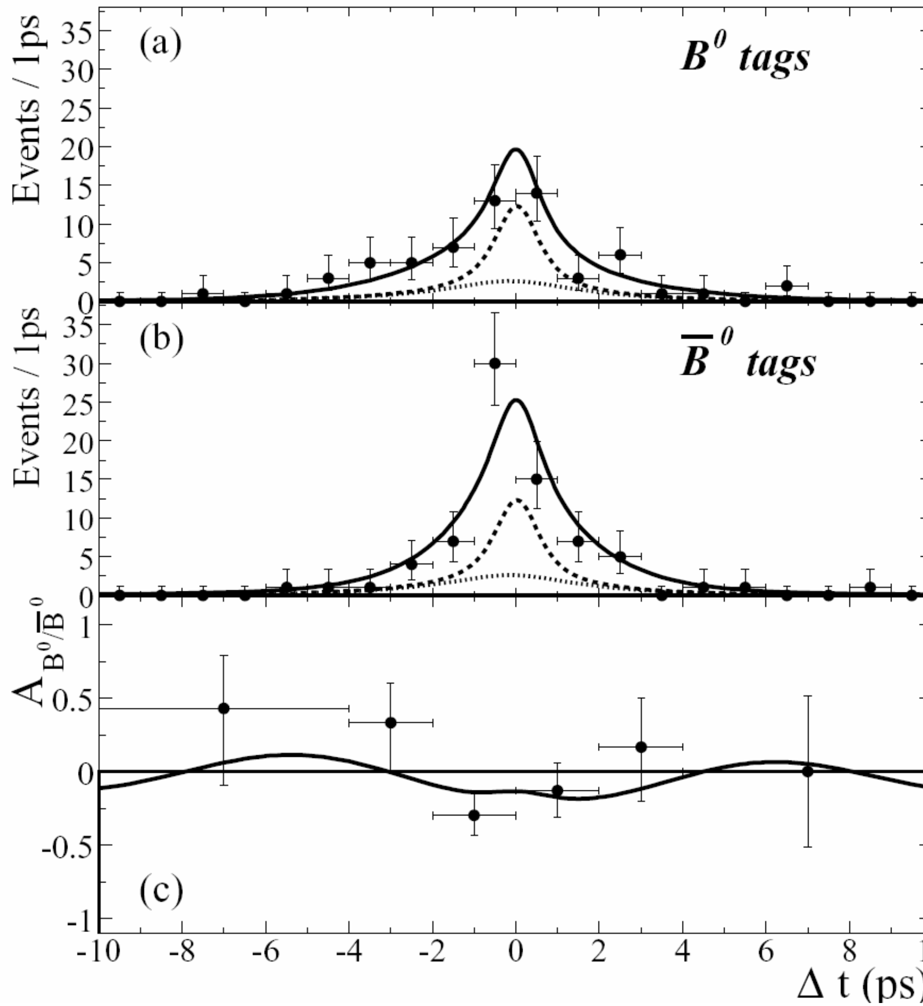
LP '03 result (113 /fb)

~123×10^6 B pairs

$$A_{CP}^{\rho\pi} = -0.114 \pm 0.062\,(\mathrm{stat}) \pm 0.027\,(\mathrm{syst})\ ,$$
$$S_{\rho\pi} = -0.13 \pm 0.18\,(\mathrm{stat}) \pm 0.04\,(\mathrm{syst})\ ,$$

$$A_{CP}^{\rho K} = 0.18 \pm 0.12\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst})\ ,$$
$$C_{\rho\pi} = 0.35 \pm 0.13\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst})\ ,$$

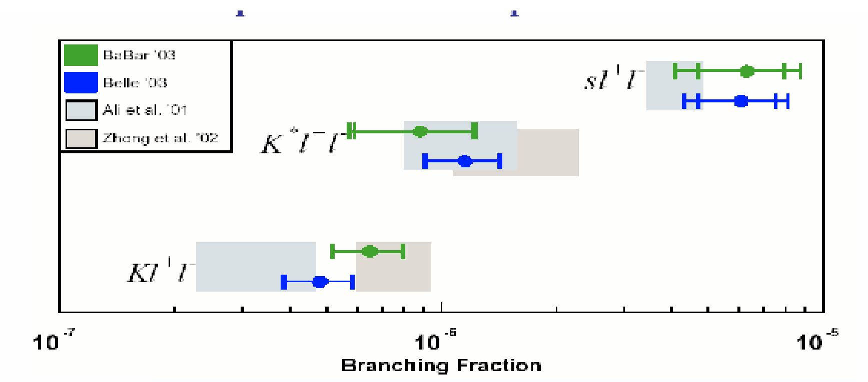


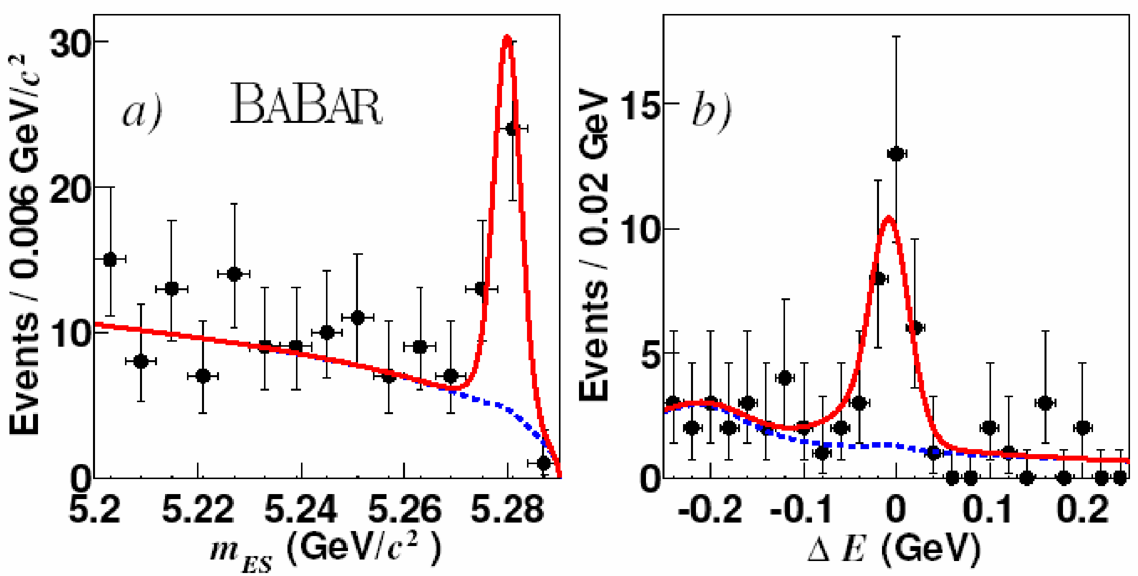


$$-C_{\rho\pi}\cos(\Delta m\Delta t) + S_{\rho\pi}\sin(\Delta m\Delta t)$$

Difficult to relate to α without DP analysis

$B \to K^* ll$

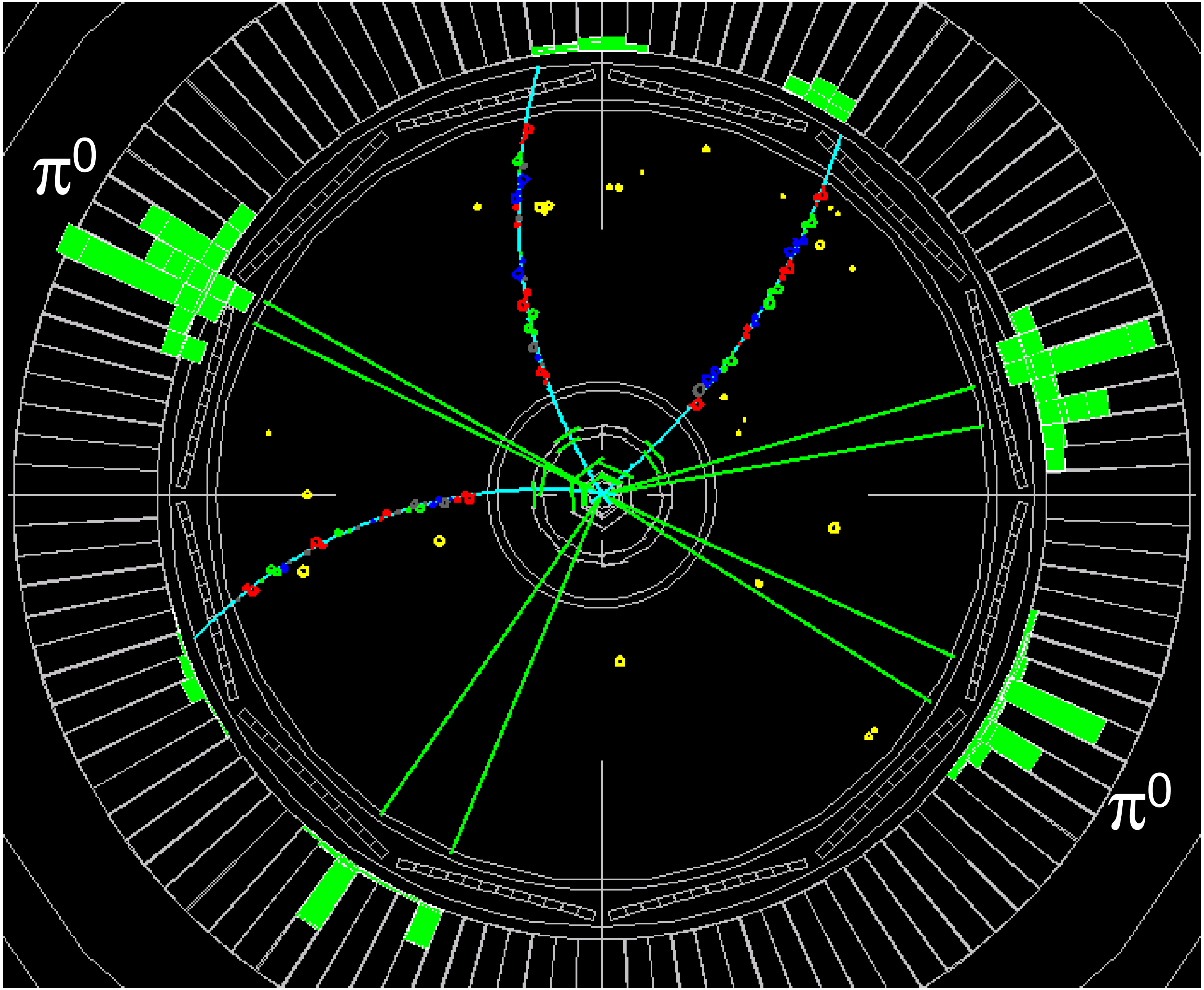




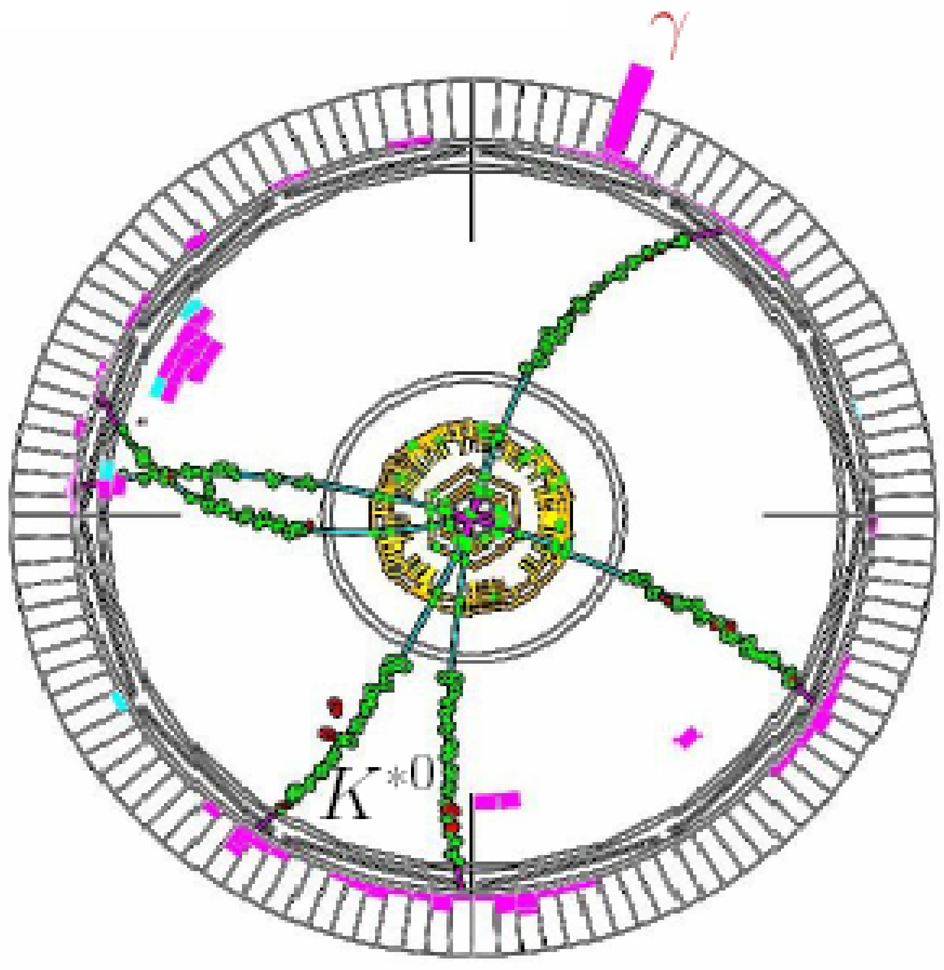
$$\mathcal{B}(B \to K\ell^+\ell^-) = (6.5^{+1.4}_{-1.3} \pm 0.4) \times 10^{-7}$$

⇑ Smallest measured B.R. of B mesons!⇑

$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (8.8^{+3.3}_{-2.9} \pm 1.0) \times 10^{-7}$$



π^0
π^0



$B \to K^{*0}\gamma$

The whole picture for B-meson decay:

CP Violation in mixing:

- $\frac{\Pr(B^0 \to \overline{B}^0)}{\Pr(\overline{B}^0 \to B^0)} \approx 1$ so this is small

Direct CP Violation:

- So far only seen in kaon decays
- this can be a large effect in rare B decay
  - Belle claim ‘evidence for’ in $\pi\pi$ decay

Indirect CP Violation – CPV in interference

- Need to measure the unitarity triangle angles

  α, β, γ