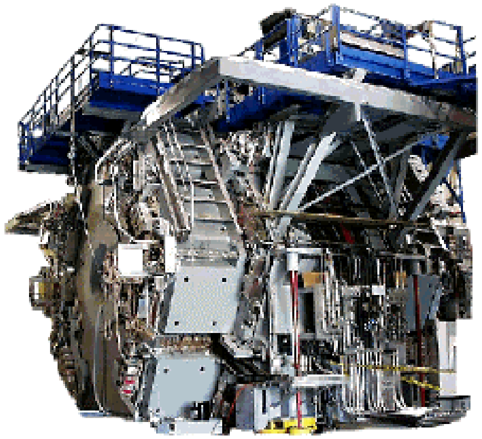


BABAR physics program

Marcello A. Giorgi

on behalf of

M.A.G. and Livio Lanceri

SLAC Annual Program Review

Some Fundamental Questions

CP violation and matter-antimatter asymmetry

- SM: 3 generations of quarks, mixing between quarks (CKM mechanism)
- CP symmetry violation, very specific pattern from a single phase
- Large violation predicted by SM in some rare B decays: observed at the B-factories by BaBar and Belle !
- But: SM not enough to explain why our universe is matter-dominated
- a systematic investigation of CKM is needed to test “small effects”

Rare B meson decays and new physics

- Mediated by loop diagrams: sensitive to new virtual quanta
- higher rates, asymmetries: indirect signatures of new physics

Charm, tau decays and new physics

- Also here: loop diagrams as keys for physics beyond SM

Results: overview

- CP Violation and the Standard Model
  - CKM quark mixing matrix: summarized by Unitarity Triangle
  - angles and sides from B decays
  - *13 journal papers + 9 in preparation*

In this talk: a few highlights

- Rare B decays
  - Charmless decays, Radiative Penguins, Leptonic decays
  - *7 journal papers + 9 in preparation*
- Other properties of B decays
  - Lifetime, mixing, decays to charm and charmonium, semileptonic decays
  - *20 journal papers + 2 in preparation*
- charm, tau, photon-photon, ISR, ...
  - *7 journal papers in preparation*
- 20 new results at the winter conferences 2003

CPV and the Standard Model

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}l^2 & l & Al^3(r-ih) \\ -l & 1-\frac{1}{2}l^2 & Al^2 \\ Al^3(1-r-ih) & -Al^2 & 1 \end{pmatrix} + O(l^4)$$

CP Violating phase

New phases from new physics may reshape the Unitarity Triangle

CKM quark mixing matrix: unitarity

b ® ul n
B ® (p, r, w) l n

B⁰ Mixing
B ® (r, w) g

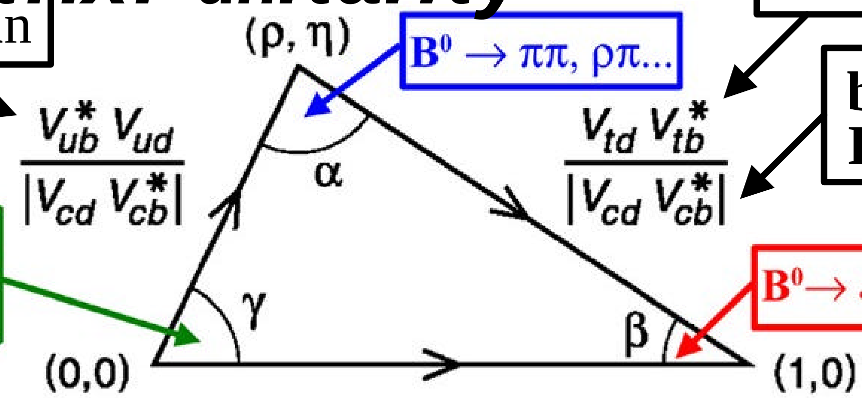
b ® cl n
B ® $D^{(*)}$l n

Both angles and sides are accessible to measurements at the B factories

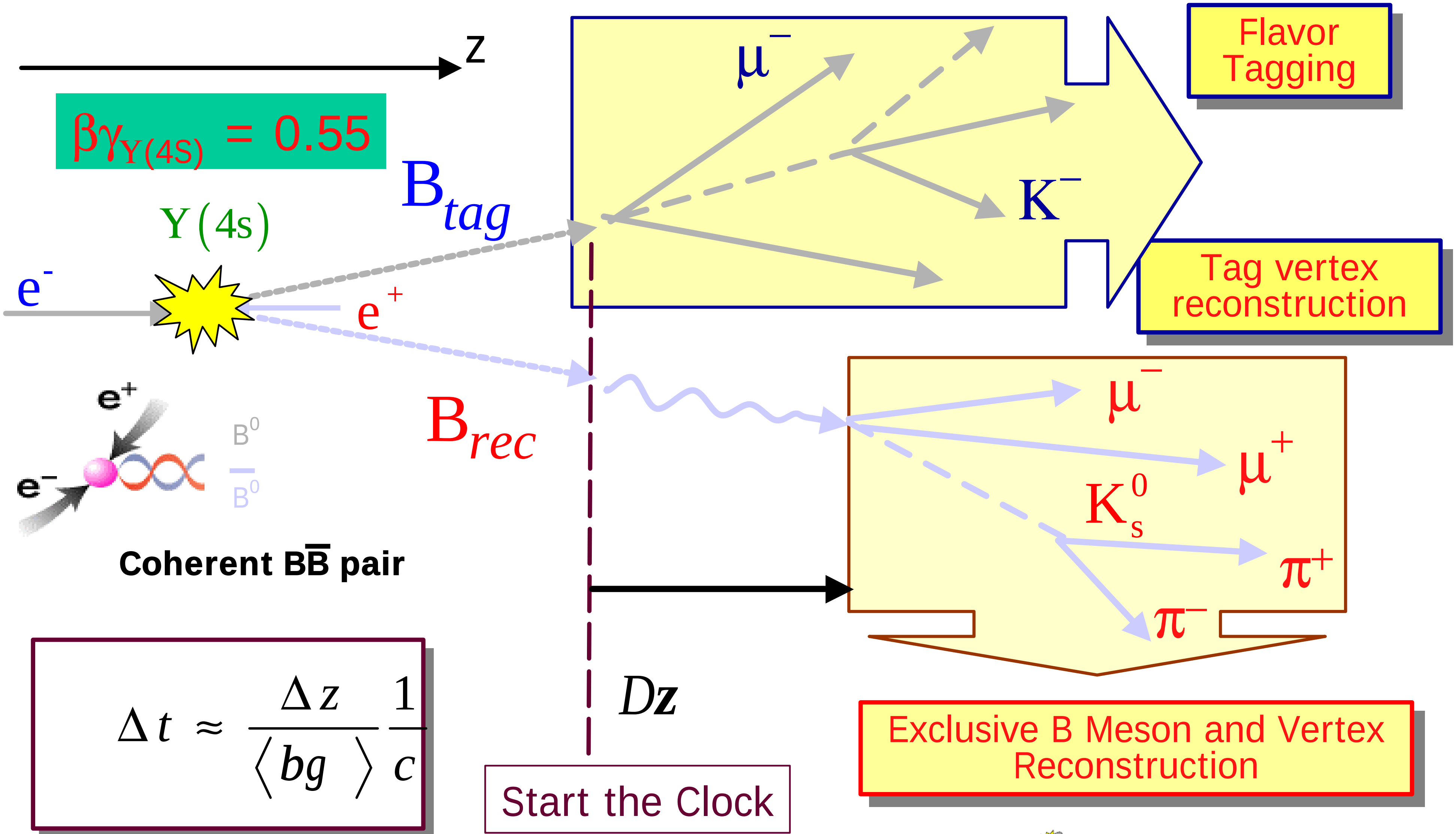
$B^0 \to \pi\pi, \rho\pi...$

$B \to D^*\pi, DK, \pi K, ...$

$B^0 \to J/\psi K_s, D^*\bar{D}^*, ...$



Experimental ingredients: BaBar optimized for time dependent CP asymmetries



$$\Delta t \approx \frac{\Delta z}{\langle bg \rangle} \frac{1}{c}$$

CP asymmetries: Time Dependence

CPV in mixing-decay interference ***direct CPV***

dN µ exp(–|Dt|/t_B) (1 ± D (S sin(DmDt) - C cos(DmDt))) Ä R

$$S = \frac{2\Im l}{1+|l|^2} \qquad C = \frac{1-|l|^2}{1+|l|^2}$$

Flavour tag

$$\lambda = \eta_{cp} \frac{q}{p} \frac{\overline{A}}{A}$$

Amplitude ratio
B^0 ® f_{cp} / B^0 ® f_{cp}

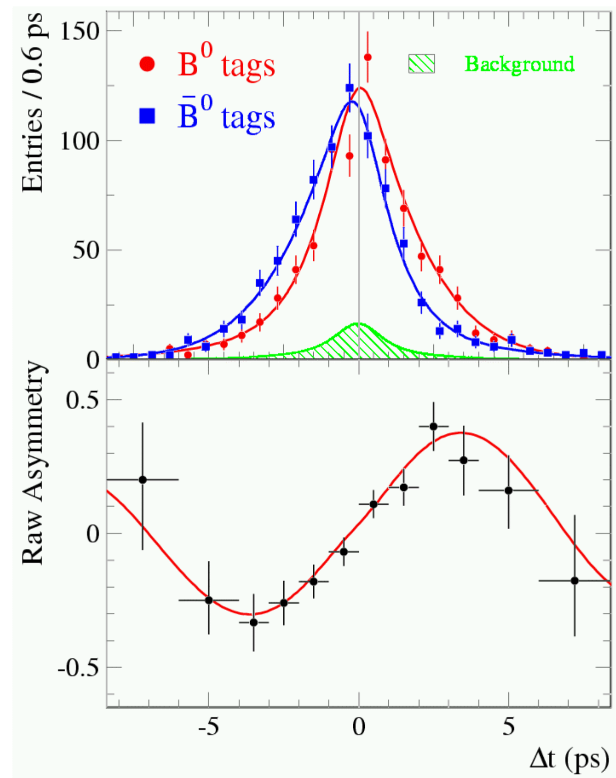
$$|B_\pm\rangle = p|B^0\rangle \pm q|\overline{B^0}\rangle$$

CP eigenvalue

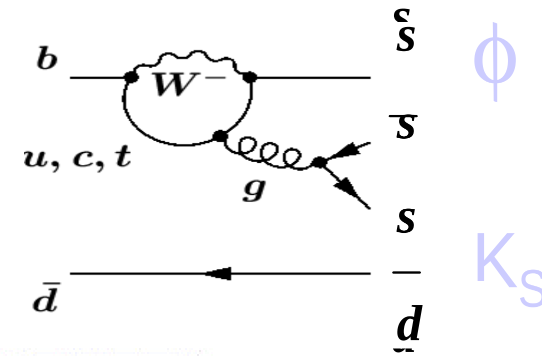
B mixing $\frac{q}{p} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} = e^{2if_M}$

D mis-tag dilution
R time resolution

Measured from data (Flavour sample)!



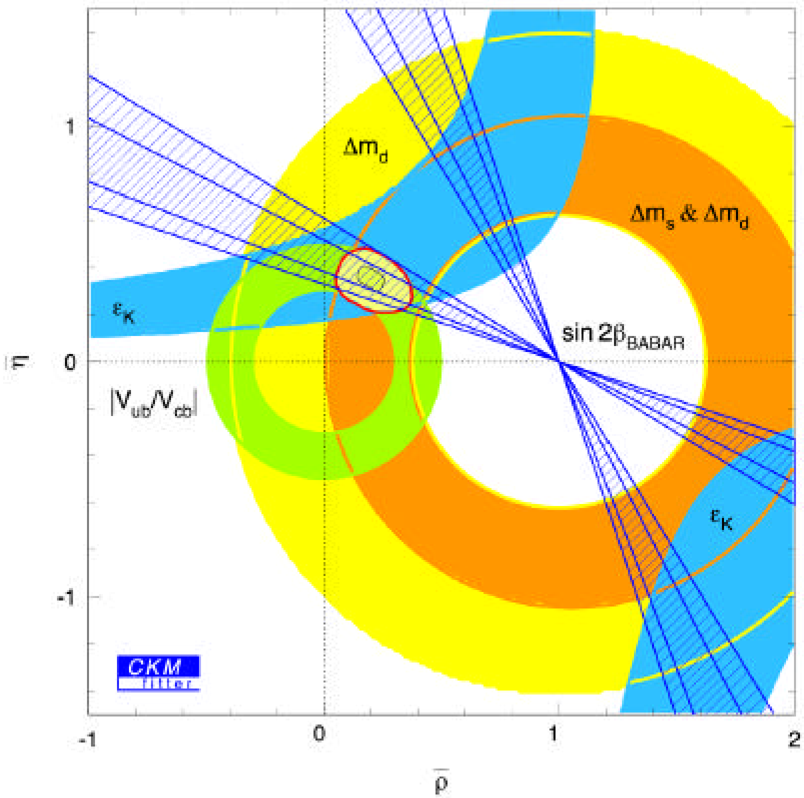
sin2b: Test N.P. in Loops?

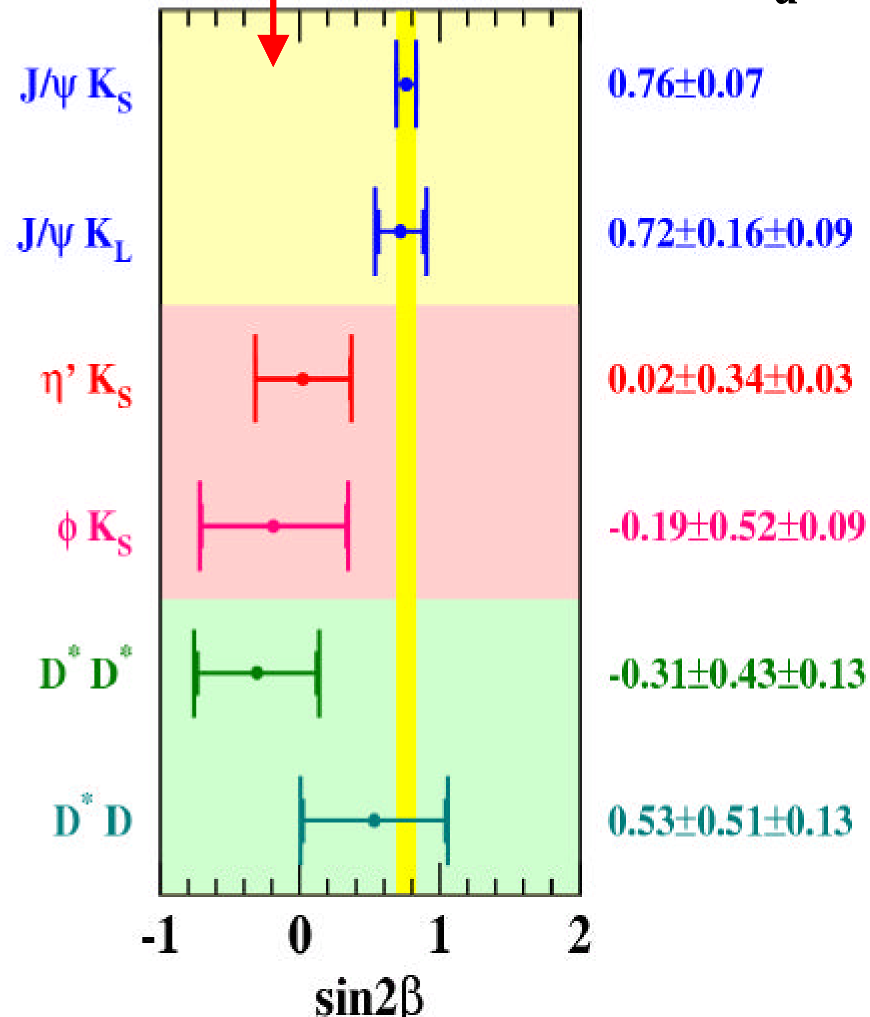


sin(2b) = 0.741 ± 0.067$_{stat}$ ± 0.033$_{syst}$

from charmonium channels

Results are so far CKM compatible but…





Flavour mixing and CP,T,CPT

$\Delta m = m_H - m_L \approx 2|M_{12}| \approx 0.5 ps^{-1}$ $\quad 1/\Gamma \approx 1.6$ ps

$\Delta\Gamma = \Gamma_H - \Gamma_L \approx |M_{12}| Re(\Gamma_{12}/M_{12})$ $\quad \Delta\Gamma << \Gamma$

$$\frac{\Gamma_{12}}{M_{12}} \simeq -3\pi \frac{m_b^2}{m_t^2}\left(1 + \frac{8}{3}\frac{m_c^2}{m_b^2}\frac{V_{cb}V_{cd}^*}{V_{tb}V_{td}^*}\right)$$

SM

$$\left|\frac{q}{p}\right| \neq 1$$

→ CP and T Violation in mixing

As in K sector where $\varepsilon_k = (p-q)/(p+q)$ $\quad \varepsilon \sim O(10^{-3})$

$$\left|\frac{q}{p}\right| - 1 \approx 4p \frac{m_c^2}{m_t^2} \sin b \approx 5 \times 10^{-4}$$

SM

Flavour mixing and CP,T,CPT

CP an CPT conservation if $H_{11}=H_{22}$

$$z = 2\frac{dM - (i/2)d\Gamma}{\Delta m - (i/2)\Delta\Gamma}$$

$$d\Gamma = \frac{(\Gamma_{11} - \Gamma_{22})}{2}$$

$$dM = \frac{(M_{11} - M_{22})}{2}$$

$z \neq 0$

$$Prob((B^0 \to B^0),t) \neq Prob((\bar{B}^0 \to \bar{B}^0),t)$$

CP and CPT VIOLATION

Assumptions made in the usual sin2β analysis:

$$\Delta\Gamma \equiv \Gamma_H - \Gamma_L \approx 0$$

$$\frac{q}{p} \equiv \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \approx 1$$

$$z \equiv \frac{M_{11} - M_{22} - \frac{i}{2}(\Gamma_{11} - \Gamma_{22})}{\Delta m - \frac{i}{2}\Delta\Gamma} \approx 0$$

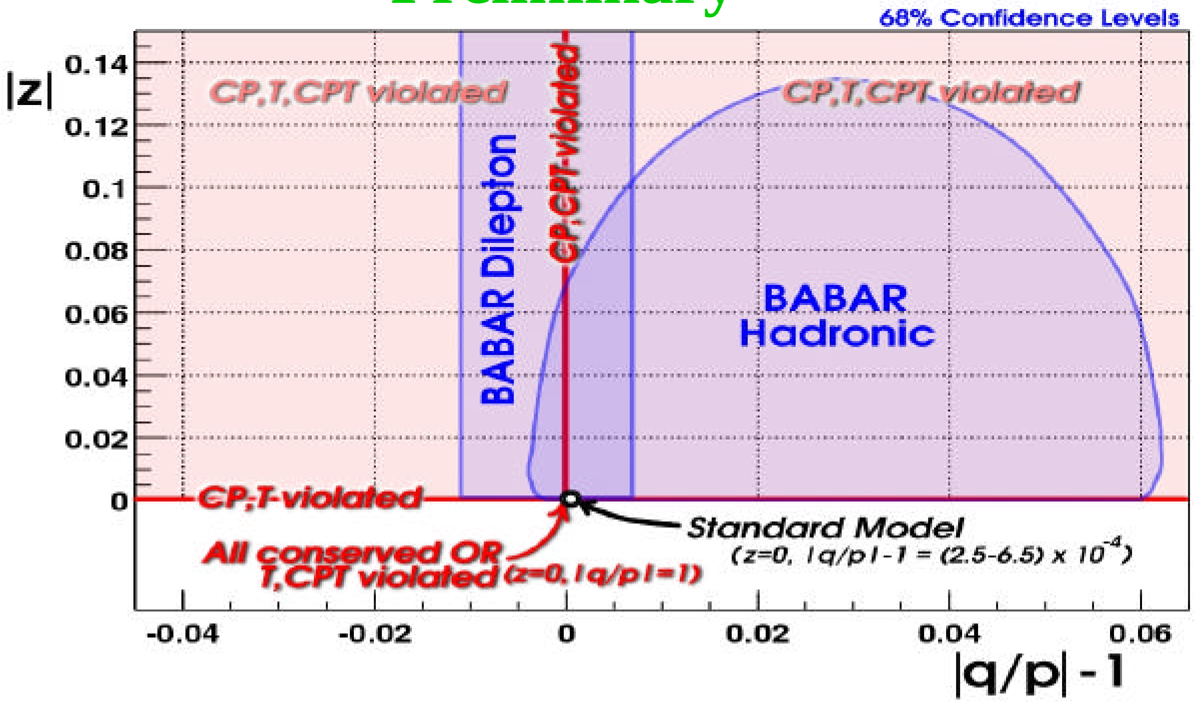
Fit without the "usual assumptions"!

Fit B→CP and B^0→flavor eigenstates ($\Delta\Gamma/\Gamma$, q/p, z and λ_{CP} left FREE)

$$\begin{array}{rcll}
\mathrm{sgn}(\mathrm{Re}\, l_{CP})\,\Delta\Gamma/\Gamma & = & -0.008 \pm 0.037(\mathrm{stat.}) \pm 0.018(\mathrm{syst.}) & [-0.084, 0.068] \\
|q/p| & = & 1.029 \pm 0.013(\mathrm{stat.}) \pm 0.011(\mathrm{syst.}) & [1.001, 1.057] \\
(\mathrm{Re}\, l_{CP}/|l_{CP}|)\,\mathrm{Re}\, z & = & 0.014 \pm 0.035(\mathrm{stat.}) \pm 0.034(\mathrm{syst.}) & [-0.072, 0.101] \\
\mathrm{Im}\, z & = & 0.038 \pm 0.029(\mathrm{stat.}) \pm 0.025(\mathrm{syst.}) & [-0.028, 0.104]
\end{array}$$

90% C.L.

Preliminary



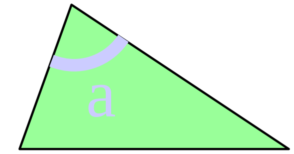
→ Direct limit on $\Delta\Gamma/\Gamma$

→ Test of CPT invariance

→ Indirect CP in mixing

The "usual assumptions" work!

B^0 ® p^+p^- Þ sin2a_{eff}



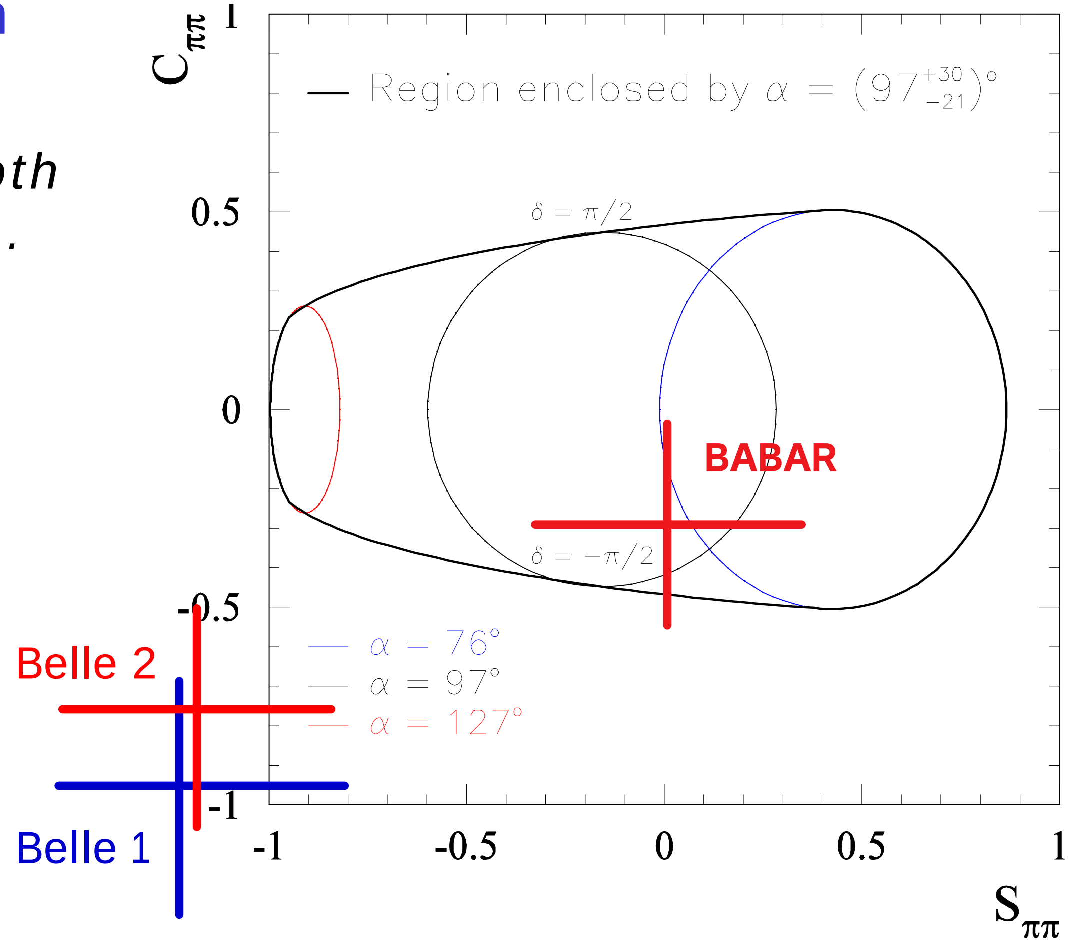
With incomplete information on Penguin contamination:

- *Measure S_{pp} and C_{pp} from both sinDmDt and cosDmDt terms.*
- *Compare with predicted S_{pp} and C_{pp} values for given a, b, |P/T|, and d. Assume for instance:* $a = (97^{+30}_{-21})^\circ$

$$b = 26^\circ$$

$$|P/T| = 0.28$$

$$-\tfrac{p}{2} < d < \tfrac{p}{2}$$



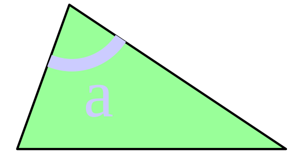
From sin2α_{eff} to sin2α?

isospin analysis, needs

B^0 ® p^0p^0

cf. Gronau and Rosner, *Phys. Rev. D65, 093012 (2002)*

$B^0 \rightarrow r^{\pm} p^{\mp} (K^{\mp})$: the CP fit



- Time integrated direct CP:

$$A_{CP}^{rK} = 0.28 \pm 0.17 \pm 0.08$$

$$A_{CP}^{rp} = -0.18 \pm 0.08 \pm 0.03$$

- Time dependent CP:

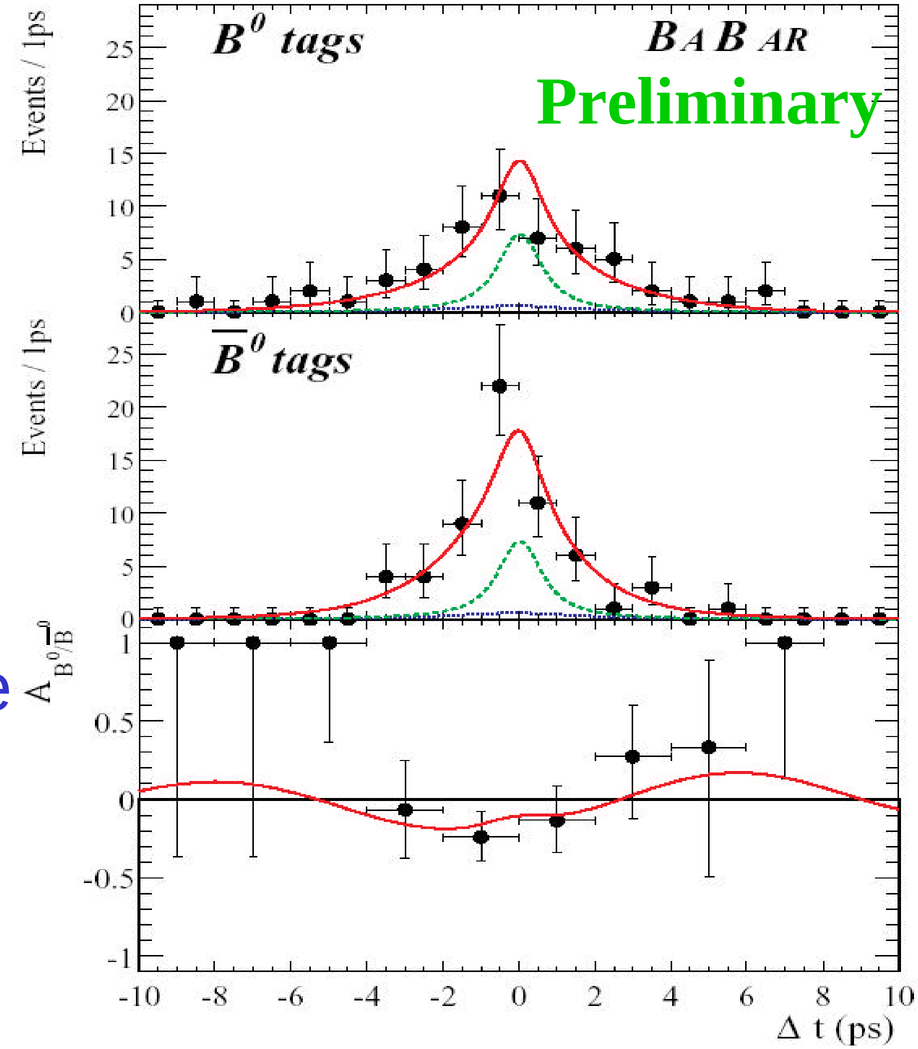
$$C_{rp} = 0.36 \pm 0.18 \pm 0.04$$

$$S_{rp} = 0.19 \pm 0.24 \pm 0.03$$

- Asymmetry between rate

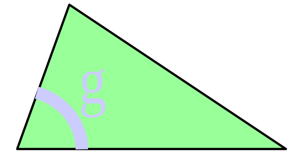
$$\Delta C_{rp} = 0.28 \,^{+0.18}_{-0.19} \pm 0.04$$

$$\Delta S_{rp} = 0.15 \pm 0.25 \pm 0.03$$

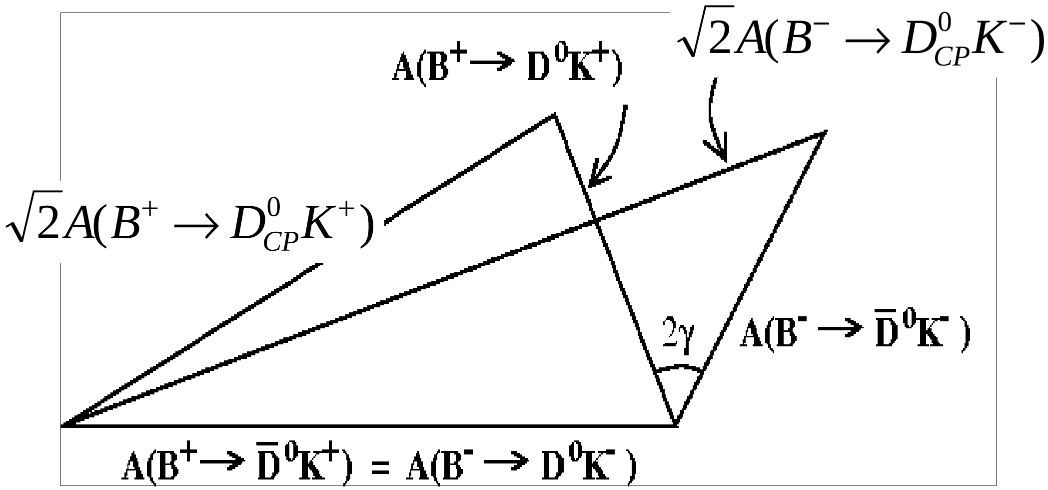


First step towards α in B→ρπ.
Full Dalitz analysis in progress.

g: the $B^{\pm} \to D^0_{CP} K^{\pm}$ approach



$\sin^2\gamma$ from the triangles (Gronau-Wyler method):



where D^0_{CP} are CP eigenstates :

$$D_{CP\pm} = \frac{D^0 \pm \overline{D}^0}{\sqrt{2}}$$

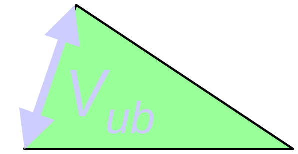
BaBar measurements:

Preliminary

$$R = \frac{BF(B^- \to D^0K^-)}{BF(B^- \to D^0p^-)} = (8.31 \pm 0.35 \pm 0.20)\%$$

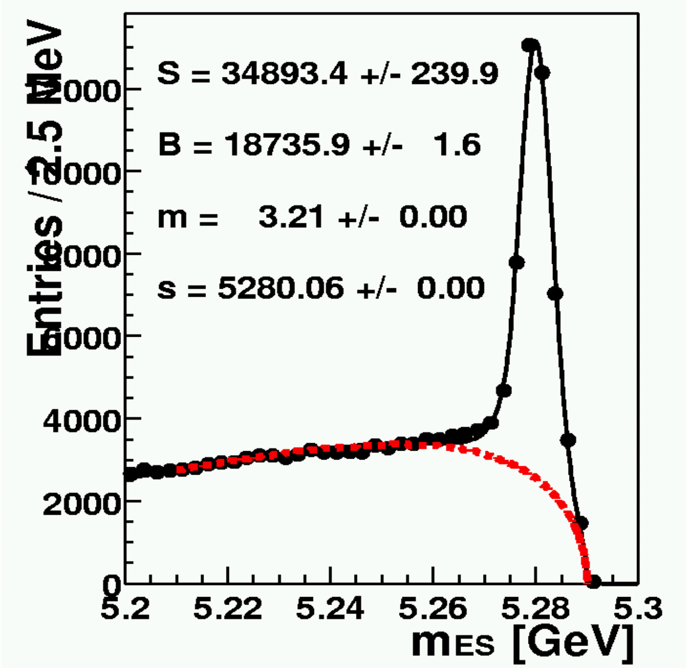
$$R_{CP} = \frac{BF(B^- \to D^0{}_{CP}K^-) + BF(B^+ \to D^0{}_{CP}K^+)}{BF(B^- \to D^0_{CP}p^-) + BF(B^+ \to D^0_{CP}p^+)} = (8.8 \pm 1.6 \pm 0.5)\%$$

$$A_{CP} = \frac{BF(B^- \to D^0{}_{CP}K^-) - BF(B^+ \to D^0{}_{CP}K^+)}{BF(B^- \to D^0_{CP}K^-) + BF(B^+ \to D^0_{CP}K^+)} = 0.06 \pm 0.17 \pm 0.06$$



Preliminary

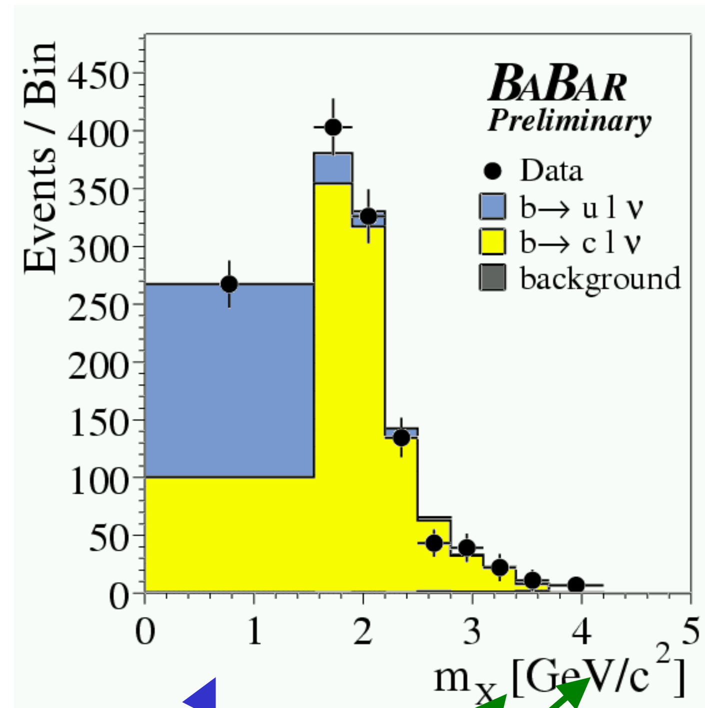
$$|V_{ub}| = (4.52 \pm 0.31(stat) \pm 0.27(syst) \pm 0.40(theo) \pm 0.09(pert) \pm 0.24(1/m_b^3)) \times 10^{-3}$$

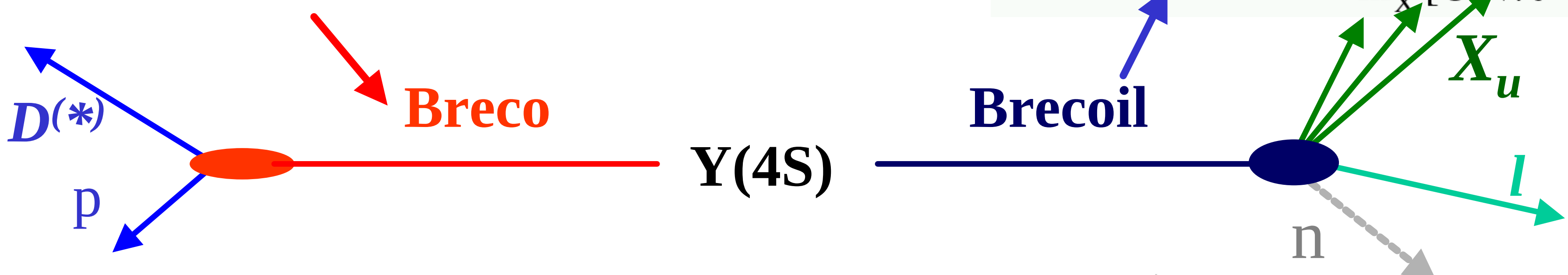


Recoil of fully reconstruted B
(~4KB / fb^{-1})

$b \to ul\nu$ signal:
M_X (< M_D)
(e ~ 60-80%)

S/B ≈ 1.7: good!

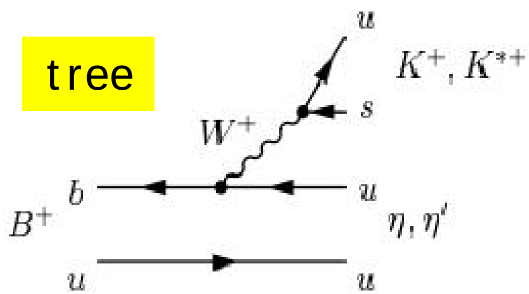


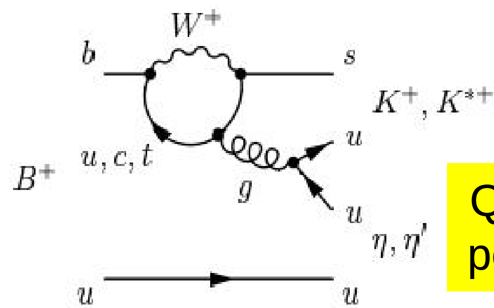


Rare B decays

b → u : tree, CKM suppressed

tree



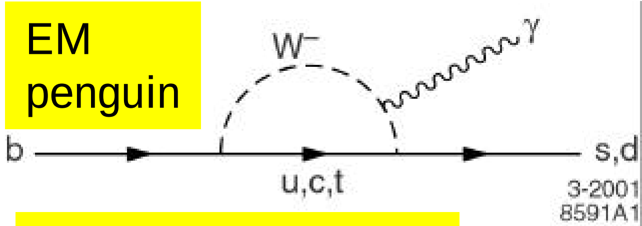


QCD penguin

Possible New Physics signatures: rates and phases from virtual particles in the loops

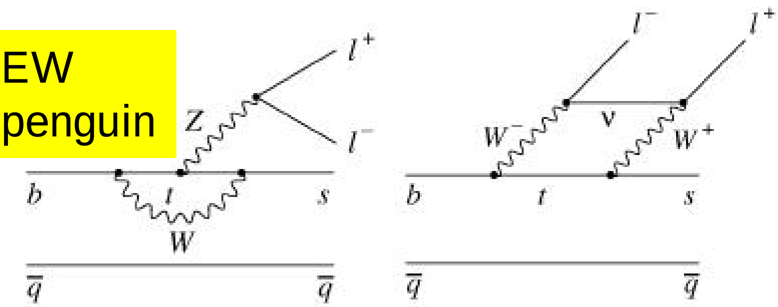
b → s,d: Radiative (QCD, EM, EW) Penguins FCNC

EM penguin

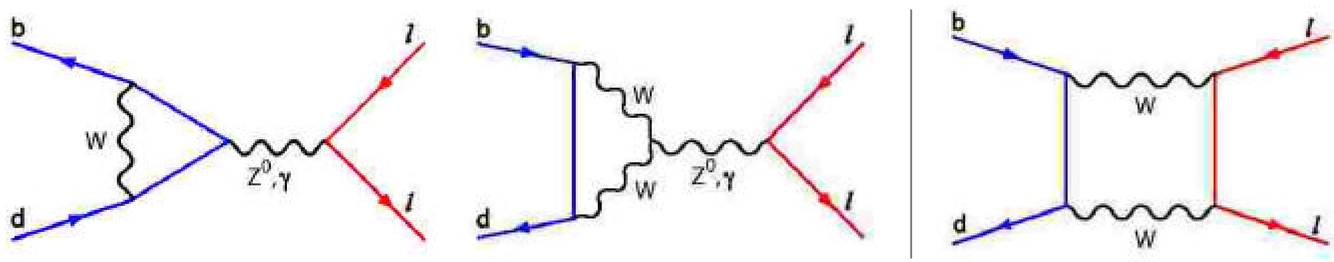


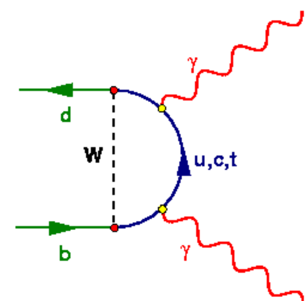
γ probes b inside B

EW penguin

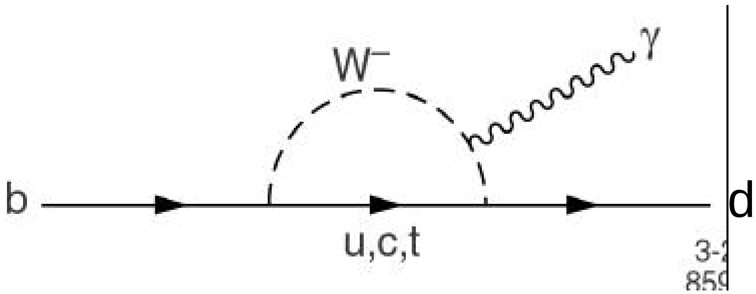


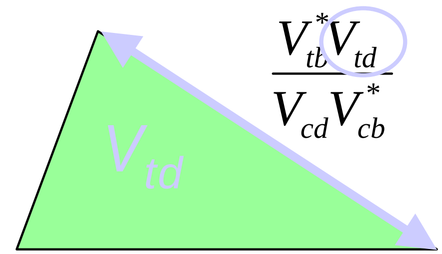
Leptonic decays: $B^0 \to l^+l^-$, $B \to \gamma\gamma$, $B \to l^+\nu$, ...





B→ργ and B→ωγ





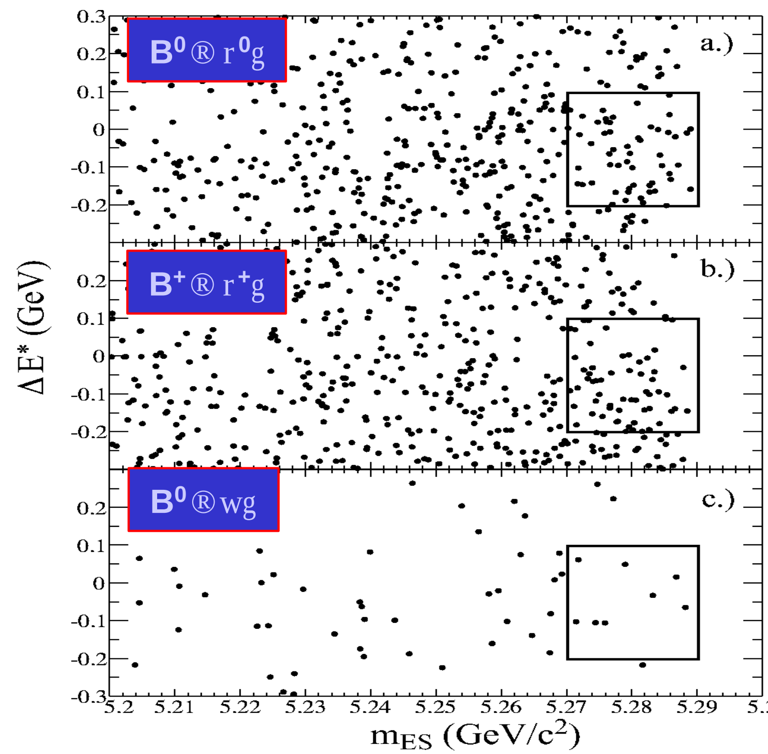
EW penguin dominated by t quark:

BF(b→dg) ~ $|V_{td}|^2$

Mode	90% CL (10^{-6})	SM Expectation (10^{-6})
$B(B^0 \to \rho^0\gamma)$	<1.2	0.49 ± 0.21
$B(B^+ \to \rho^+\gamma)$	<2.1	0.85 ± 0.40
$B(B^0 \to \omega\gamma)$	<1.0	~ 0.5

$$\frac{BF(B \to r g)}{BF(B \to K^{*} g)} < 0.047 \;\rightarrow\; \left|\frac{V_{td}}{V_{ts}}\right| < 0.36$$

Ali and Parkhomenko (hep-th 0105302)



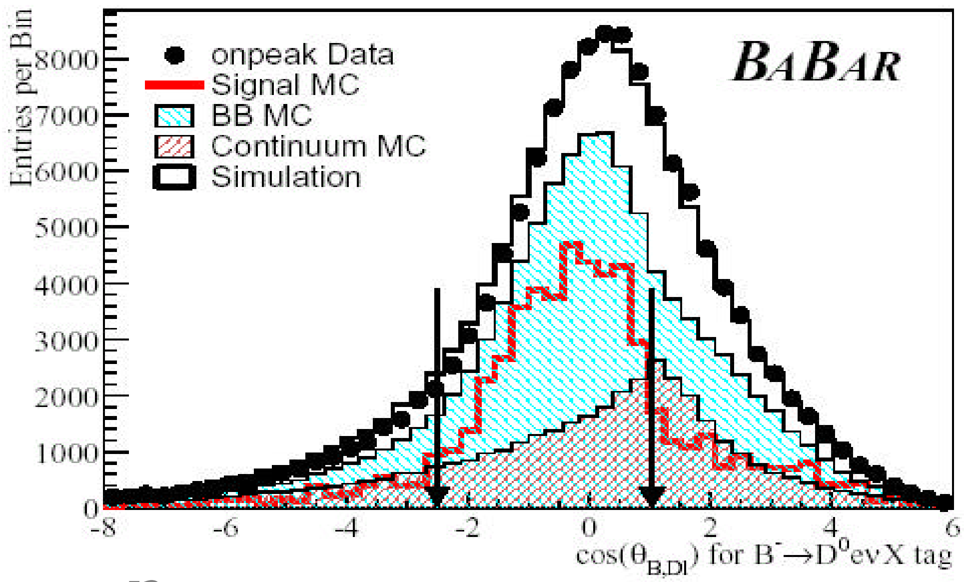
Search for B+ ® t+n

Preliminary

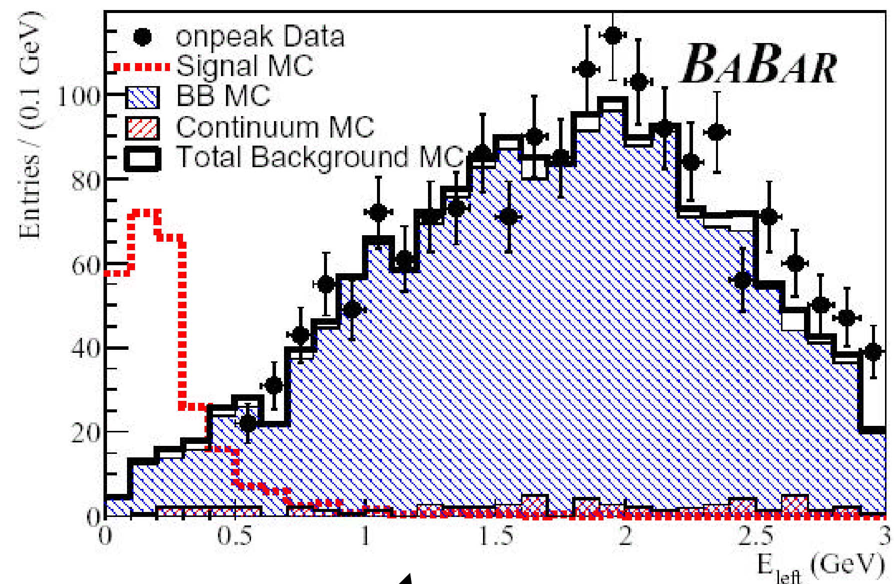
Semileptonic tags: ***BF*(B+ ® t+n) < 4.9´10-4 (90% CL)**
Fully reco tags: ***BF*(B+ ® t+n) < 7.7´10-4 (90% CL)**

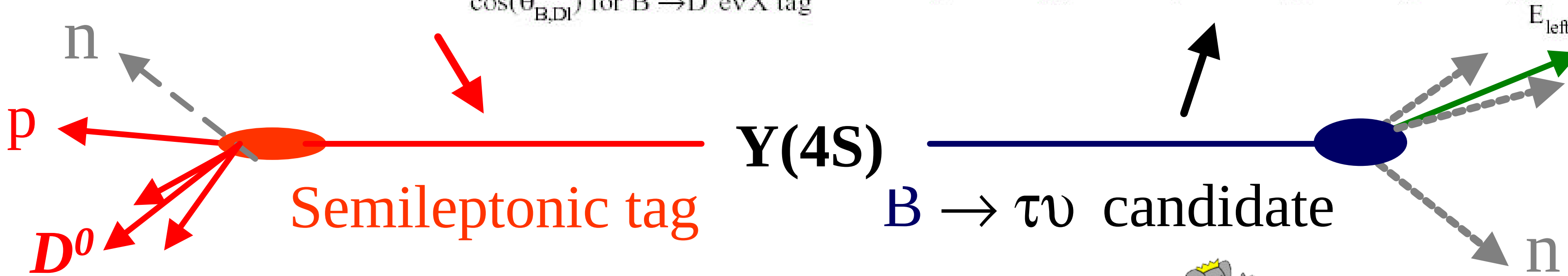
combined:
< **4.1 ´ 10-4**

cosq_B,Dl for B ® D0pnX tags



Total signal-side neutral energy





Charm, tau discovery potential

An example: D mixing

Very small in the S.M.

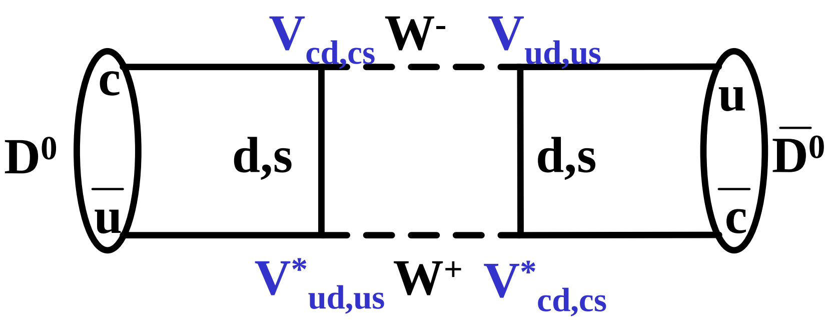
$\propto\ 1^{2} \times$ additional suppression

$$0.05\times\left(m_s^2 - m_d^2\right)/m_W^2 \rightarrow 0$$

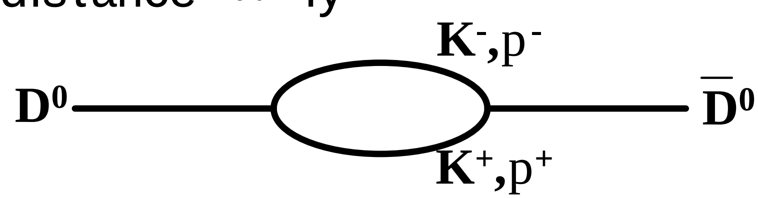
$$SU(3)\ \text{limit}$$

$\Rightarrow$ A window for new physics

"short distance" $\propto$ x



"long distance" $\propto$ -iy

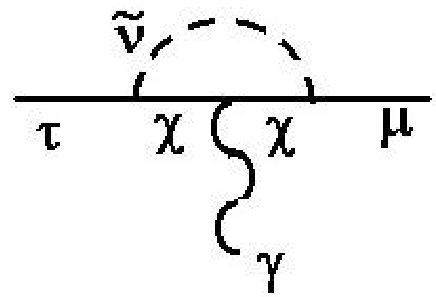


Another example:

lepton flavour violation

S.M., extended to include ν mixing and mass:

BR($\tau \rightarrow \mu\gamma$) ~ O($10^{-34}$)



lepton number is violated in many extensions of the S.M.

(present limits, O(10^{-6}) are not far from some model predictions)

Summary: FY2002, results

- Run1+Run2 was very successful:
  - in total Babar recorded 83.9 fb^{-1} (on-peak) + 9.6 fb^{-1} (off-peak)
  - About 40 conference papers and 17 journal papers submitted, more results reported at conferences
- Some physics highlights:
  - CPV in B decays to CP eigenstates with charmonium established with a precision measurement of $\sin 2\beta$
  - CPV explored also in charmless decays ($\sin 2\alpha_{eff}$);
  - search for direct CPV in many rare decay modes;
  - Measurements of many decay modes, including:
    - Rare decays (charmless, radiative penguins, …)
    - Decays to charm, charmoniun and semileptonic decays.
  - Measurements of B lifetime and mixing improved with respect to the world average

Summary: FY2003, program

- Run 3 expectations:
  - Until summer 2003: ≈ 50% relative increase in integrated luminosity
  - 11 conference papers and 10 journal papers submitted up to now; about 20 new results presented at the winter conferences; many analyses in preparation for the summer
- Highlights
  - Study of sin2β extended to modes dominated by penguin diagrams, basic assumptions (CPT, CP/T) released and tested with higher statistics
  - Study of $\sin 2\alpha_{eff}$ extended from 2- to 3-body final states and Dalitz analysis
  - Exclusive tagging "recoil" technique developed and applied both to inclusive semileptonic decays (|Vub|) and to searches of rare decays
  - D^0 mixing and spectroscopy in the charm sector
  - Rare decays…

Up to FY2005 and beyond

- Luminosity expectations
  - 500 fb^{-1} by end 2006
  - 1÷2 ab^{-1} by the end of the decade

sin2b: projected errors (BaBar)

- Extrapolated statistical and systematic uncertainties

Param.	Channel	s(stat)/s(syst) 0.08 ab^{-1}	s(stat)/s(syst) 0.5 ab^{-1}	s(stat)/s(syst) 2.0 ab^{-1}
sin2b	J/y K_S	0.08 / 0.03	0.037 / 0.018	0.018 / 0.018
	Golden	0.07 / 0.03	0.031 / 0.018	0.015 / 0.018
Im(l_+)	D*D*	0.43 / 0.13	0.16 / 0.07	0.08 / 0.03
S	J/y p^0	0.49 / 0.16	0.20 /	0.10 /
S	f K_S	0.50 / 0.09	0.20 /	0.10 /
S	h' K_S	0.34 / 0.03	0.14 /	0.07 /

Statistical uncertainty $\propto L^{-1/2}$

For "golden" modes only $s_{stat} \approx s_{syst}$ at $L \approx 2\,\mathrm{ab}^{-1}$

Results and extrapolations for $\sin 2a_{eff}$

Results *(0.08 ab^{-1})*

Param.	BaBar	Belle
S_{pp}	0.02 ± 0.34 ± 0.05	-1.23 ± 0.41 (+ 0.05-0.07)
C_{pp}	-0.30 ± 0.25 ± 0.04	-0.77 ± 0.27 ± 0.08

Extrapolated errors (BaBar)

Param.	Channel	s(stat)/s(syst) 0.08 ab^{-1}	s(stat)/s(syst) 0.5 ab^{-1}	s(stat)/s(syst) 2.0 ab^{-1}
S_{pp}	p^+p^-	0.34 / 0.05	0.12 / 0.03	0.06 /
C_{pp}		0.25 / 0.04	0.10 / 0.03	0.05 /

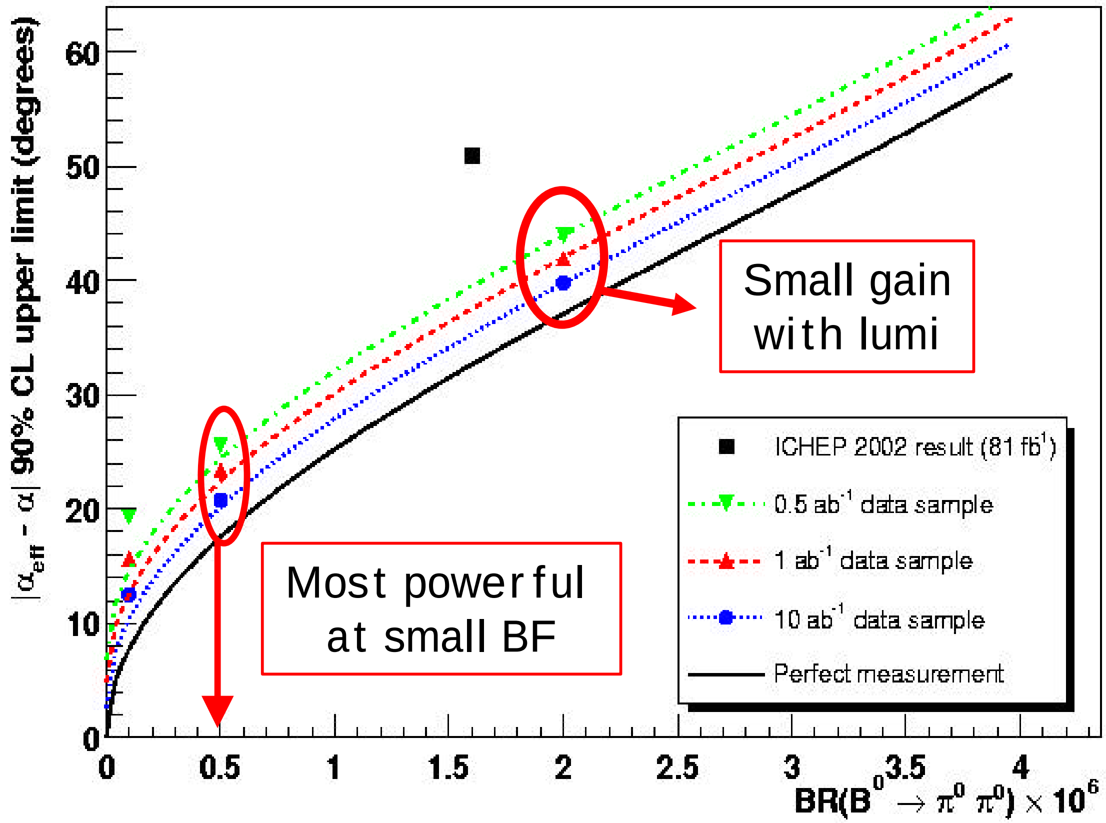
Upper bounds on $\kappa_{\pi\pi} = 2\alpha_{eff} - 2\alpha$

Grossman-Quinn bound:

$$\sin^2 \kappa_{\pi\pi} \le \frac{\mathrm{BF}\left(B^0 \to \pi^0 \pi^0\right)}{\mathrm{BF}\left(B^+ \to \pi^+ \pi^0\right)}$$

BaBar, present data: $\kappa_{\pi\pi} \le 51^0$

BaBar, extrapolations:
vs BF($\pi^0\pi^0$),
at fixed Luminosity



Isospin analysis: projections - 2

- BaBar sensitivity on k_{pp} : summary
  - (4-fold ambiguity not included)

Model	BF ´ 10^6 B® p^0p^0	BF ´ 10^6 Bbar® p^0p^0	s(k) 0.5 ab^{-1}	s(k) 2.0 ab^{-1}	s(k) 10 ab^{-1}
A	2.5	1.5	0.409	0.177	0.075
B	1.5	0.5	0.452	0.258	0.132
C (no bkgd)	2.5	1.5	0.286	0.106	0.045
D	0.6	0.4	0.436	0.316	0.175

- Assumptions:
  - $\pi^0\pi^0$ reconstruction efficiency: ε_{rec} = 0.18
  - For each B tagging category:
    - Tagging performance ε, D = 1-2w
    - Bkgd effective cross sect. B ($\times 10^6$)

Tag	*e*	*D*	*B*
1	*0.09*	*0.93*	*2.0*
2	*0.16*	*0.82*	*4.0*
3	*0.20*	*0.56*	*5.0*
4	*0.20*	*0.41*	*6.0*

g from $B^- \to D^0_{(CP)} K^-$: projections

Recent experimental results (BaBar)

$$n_1 \equiv \frac{\Gamma(B^- \to D_1 K^-)}{\Gamma(B^- \to D_0 K^-)} = 1.02 \pm 0.29 \pm 0.02$$

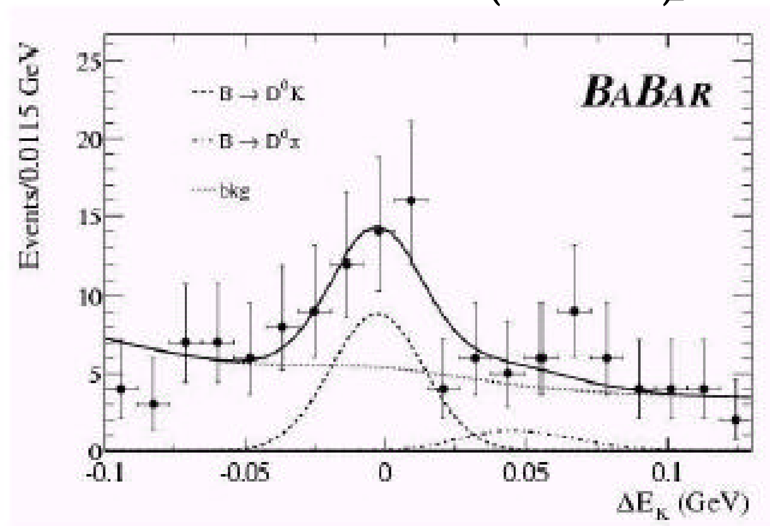
$$p_1 \equiv \frac{\Gamma(B^+ \to D_1 K^+)}{\Gamma(B^- \to D_0 K^-)} = (0.72 \pm 0.26 \pm 0.02)$$

$$A_{CP} = 0.17 \pm 0.23 \pm 0.08$$

$$r \equiv \left| \frac{A(B^- \to \overline{D}_0 K^-)}{A(B^- \to D_0 K^-)} \right| = O(0.1)$$

- $B^\pm \to D^0[K^+K^-]\, K^\pm$
  - $36.8 \pm 8.4 \pm 4.0$ signal events

$\approx 500 \quad D^0 (K^+K^-) p^\pm$



Toy MC projections: **(Fit unreliable for r = 0.1)**

r=0.3 (0.5 ab^{-1}), $\sin^2\gamma = 0.75 \Rightarrow$ fit: $\sin^2\gamma = 0.72 \pm 0.23$, $\gamma = (59.9 \pm 10.2)^o$

r=0.2 (2ab^{-1}), $\sin^2\gamma = 0.75 \Rightarrow$ fit: $\sin^2\gamma = 0.71 \pm 0.14$, $\gamma = (58.5 \pm 7.4)^o$

r=0.2 $\gamma=60^o$ $\Delta\delta=30^o$ (2ab^{-1}) $A_{CP}=0.174 \pm 0.031$

projected errors for $|V_{ub}|$

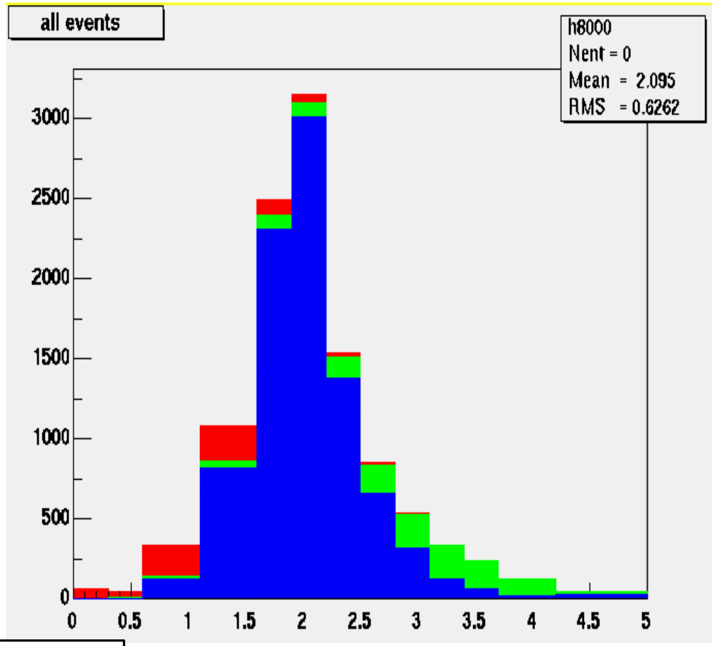
Selection:

One B reconstructed in $D^{(*)}X$

Lepton momentum and neutrino mass

Kaon veto, charge balance

Fit M_x with constraints



M_X distribution fit:

$b\rightarrow ul\nu$, $b\rightarrow cl\nu$, background

Errors:

Statistical

$L(ab^{-1}) = 0.08$	0.5	2.0	10
$\sigma_{stat}(\%) = 7.0$	2.8	1.4	0.6

Experim. Systematic ~5% (now) $\Rightarrow$ 2.5% ($b\rightarrow cl\nu$ bkgd)

Theoretical ~ 9% ($\sigma(m_b)$=90MeV) $\Rightarrow$ 5% ($b\rightarrow ul\nu$ above cut)

M_x cut, b quark Fermi motion from $b \rightarrow s\gamma$, M_x bins

Further improvements from lattice QCD, restricted phase space ulν above cut)

Some extrapolated yields (BaBar)

- Extrapolated yields for $B^+ \to \tau^+\nu$ and $B^+ \to K^+\nu\nu$

Channel	e_{sig}	e_{tag}	Theor. pred.	Yield (0.1ab^{-1})	Yield (0.5ab^{-1})	Yield (2ab^{-1})
$B^+ \to \tau^+\nu$	0.2 0.2	1×10^{-3} 5×10^{-3}	5×10^{-5}	1 6	6 36	24 144
$B^+ \to K^+\nu\nu$	0.3 0.2	1×10^{-3} 5×10^{-3}	4×10^{-6}	0.1 0.4	0.7 2	3 9

Present analysis: backgrounds:
τν 280 events in 80fb-1
Kνν 2 events in 56MBB pairs

Integrated luminosity vs physics

Expected 1000 rec $X_s l^+ l^-, K^* l^+ l^-$

with ε=0.2% and BF(6 10-6and 2 10-6)

Snowmass 2001

2002 **2006** » **2009 ? BaBar**

$t \rightarrow mg$ - - - - →

0.1 0.5 1.0 2.0 10. $\int L dt \left[ab^{-1} \right]$

$|V_{ub}/V_{cb}|$ $\sin 2b$ $\sin 2a$ g - - - - →

$X_s l^+ l^-, K^* l^+ l^-$

$r(w)g$

$X_s n\bar{n}, K^* n\bar{n}$ - - - - →

tn, mn - - - - →

$\sin(2b + g)$ - - - - →

Continuous improvement

A very exciting physics program

Higher the integrated luminosity.

And more precise and stringent test of the models can be carried out.

Look for an open window on new physics!