Update on BABAR Physics and Prospects

David B. MacFarlane

P5 Visit to SLAC

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Stanford Linear Accelerator Center

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Pillars of BABAR physics program

- *Highly constrained and redundant set of precision tests of weak interactions in the Standard Model*

  - Full program of flavor physics/CP violation measurements will provide a legacy of fundamental constraints on future New Physics discoveries

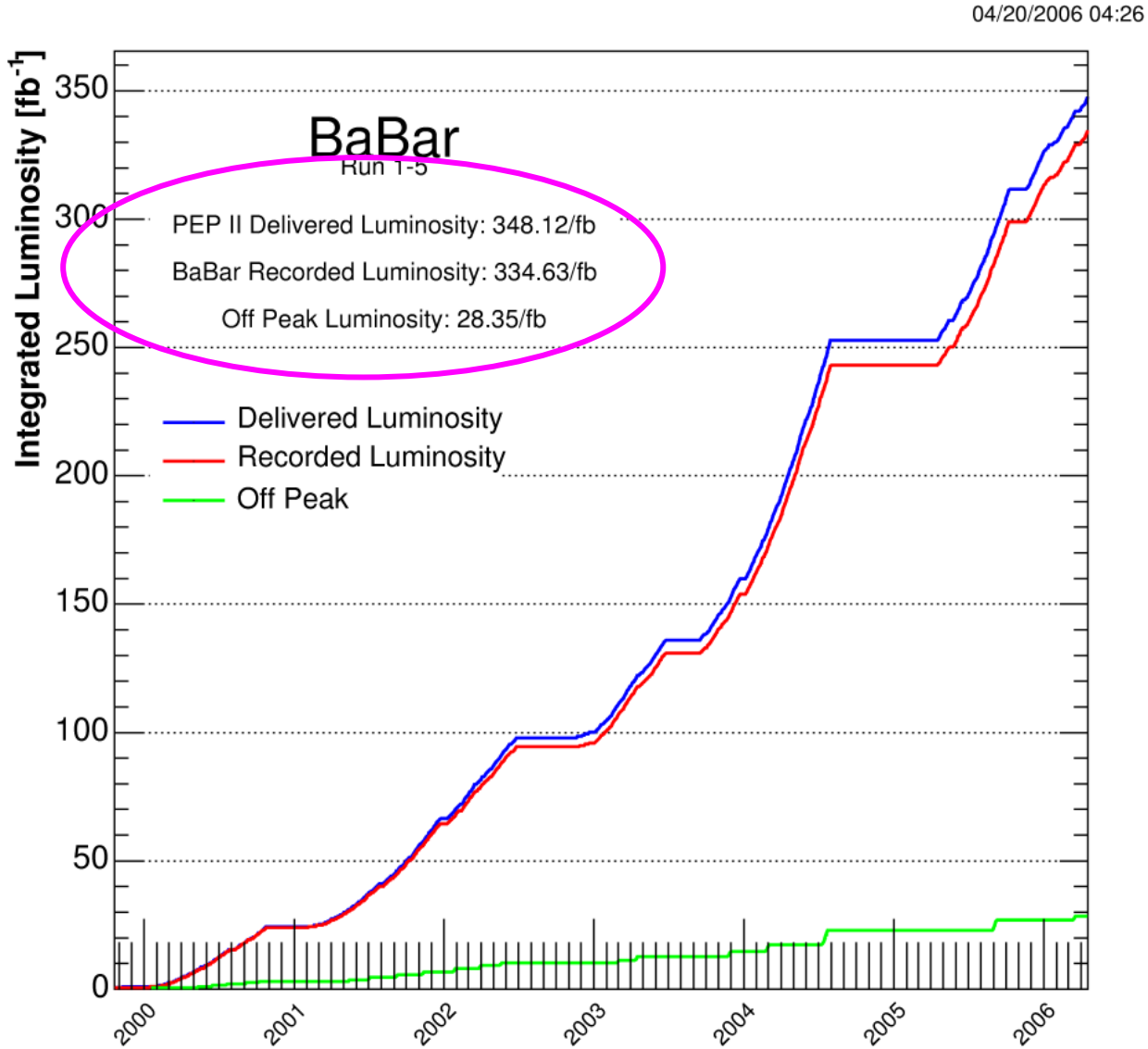
- *Searches for physics beyond the Standard Model in a well understood & characterized environment*

  - Sensitivity to New Physics at LHC mass scales through rare decays and *CP* violation
  - Discovery potential from large data sample across a whole range of beauty, charm, tau, two-photon, ISR physics

Challenging measurements at the edge of sensitivity benefit enormously from operation of both PEP-II & KEK B Factories

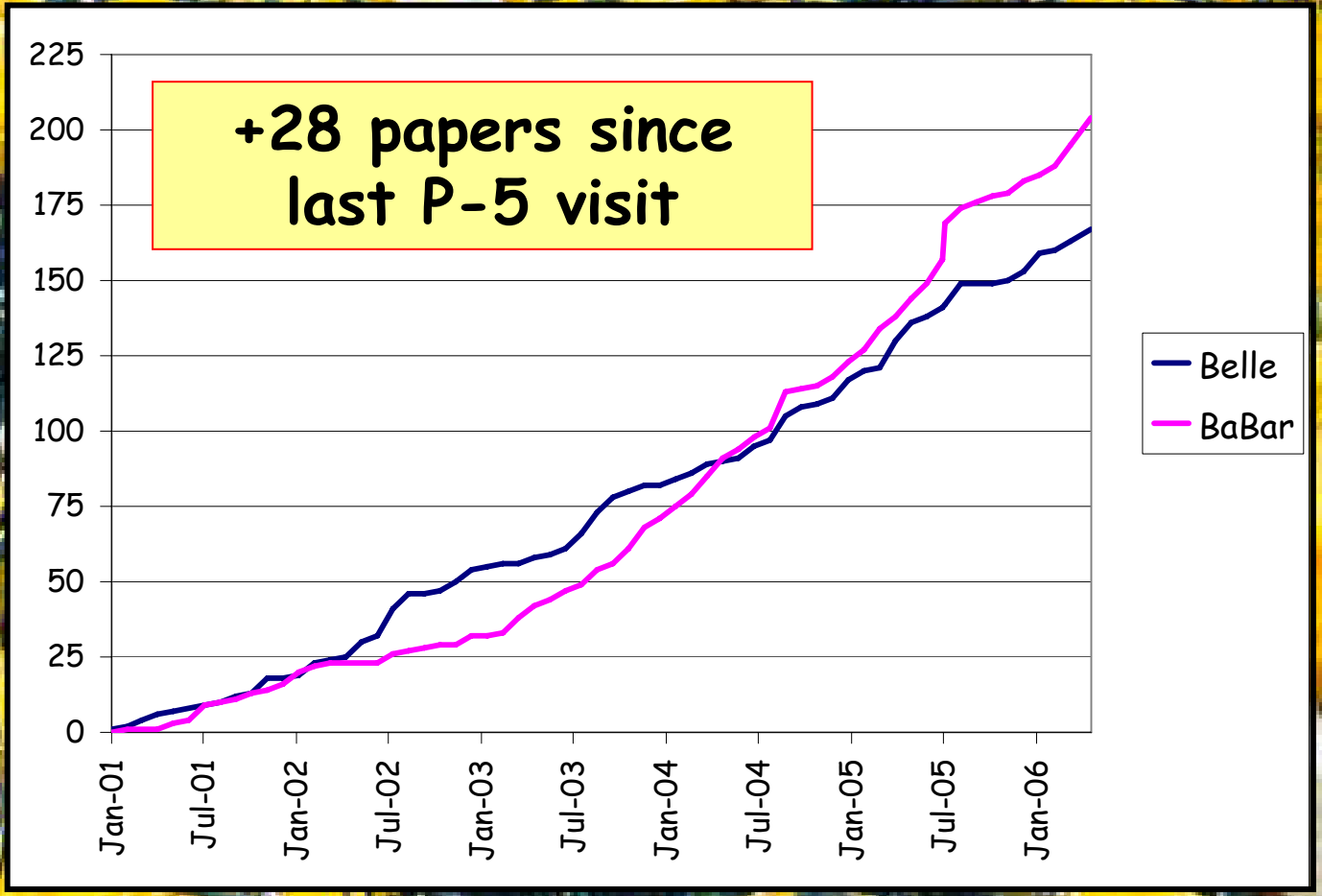
Integrated data sample to date

Project Run 5
at 405 fb^{-1} delivered



BABAR & Belle physics results

Journal Papers	BABAR	Belle
Total [Today]	204	167



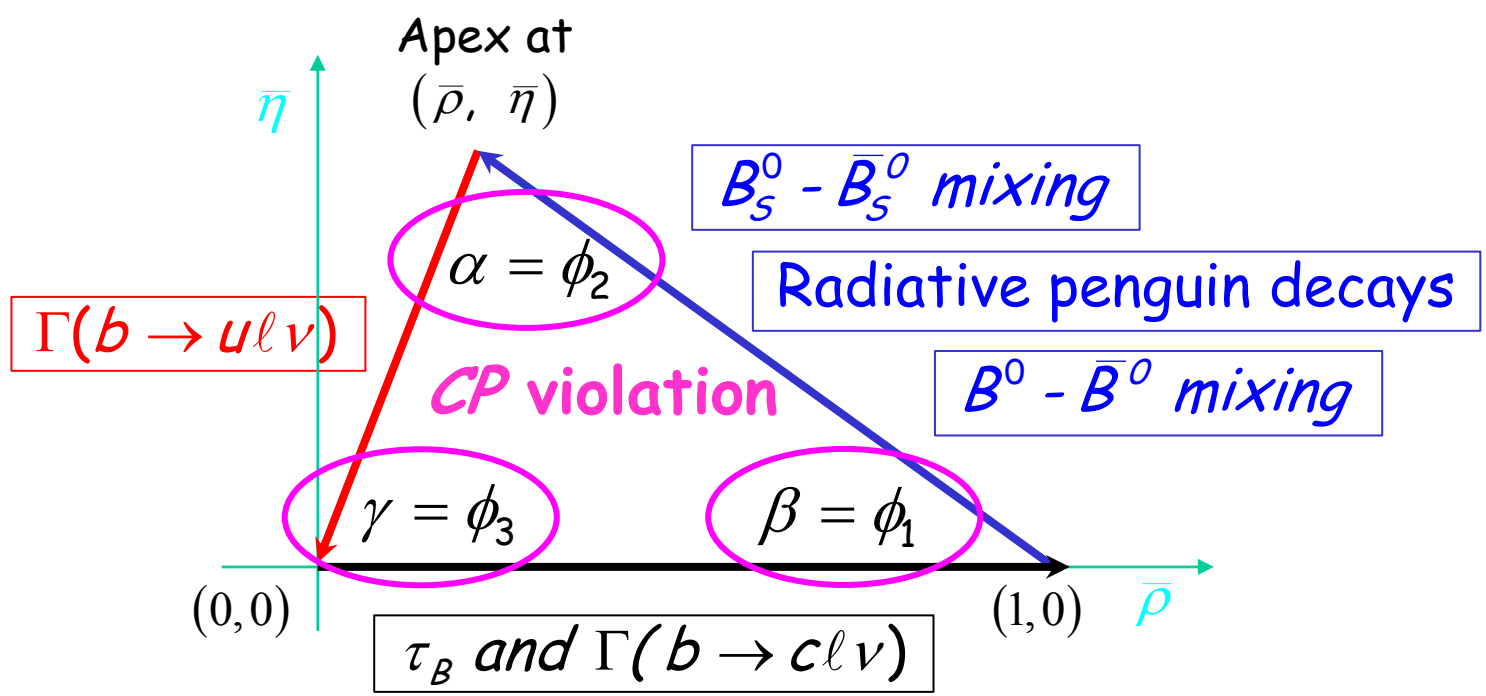
Weak Interaction in Standard Model

Unitarity Triangle as a summary of Standard Model *b* physics

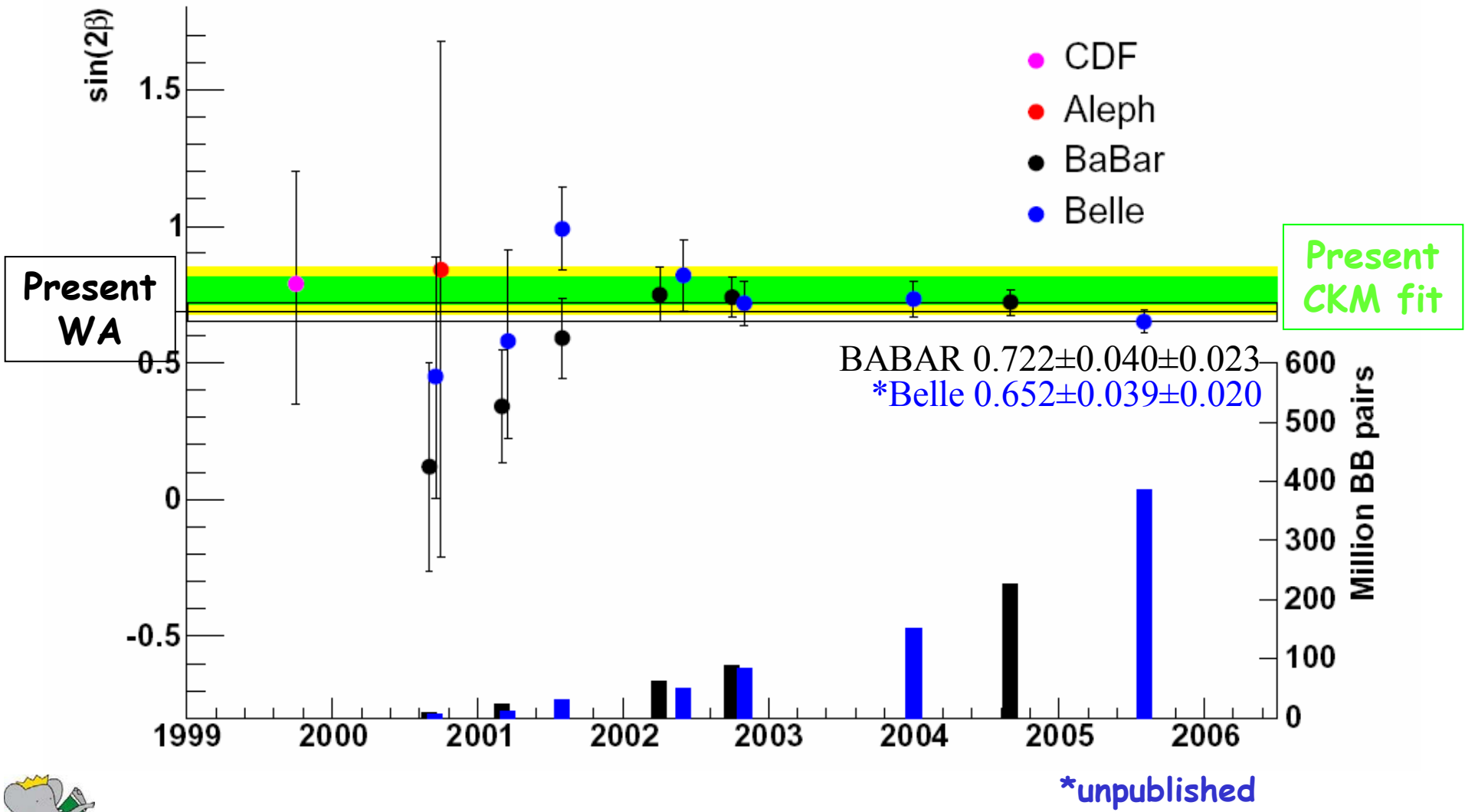
Unitarity: $V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$

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

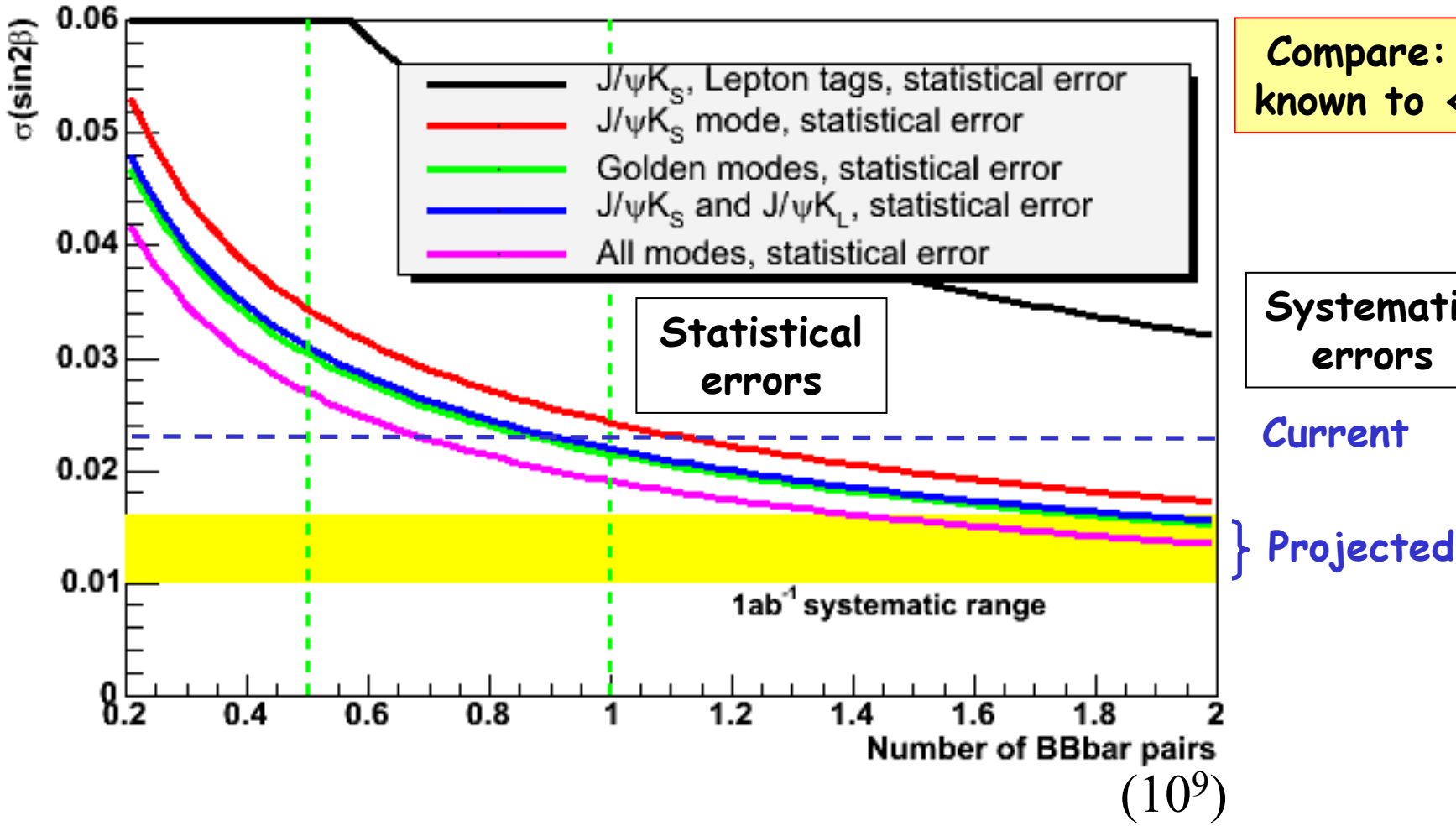
+ phases



Evolution of sin2β measurements



Projected uncertainties on sin2β



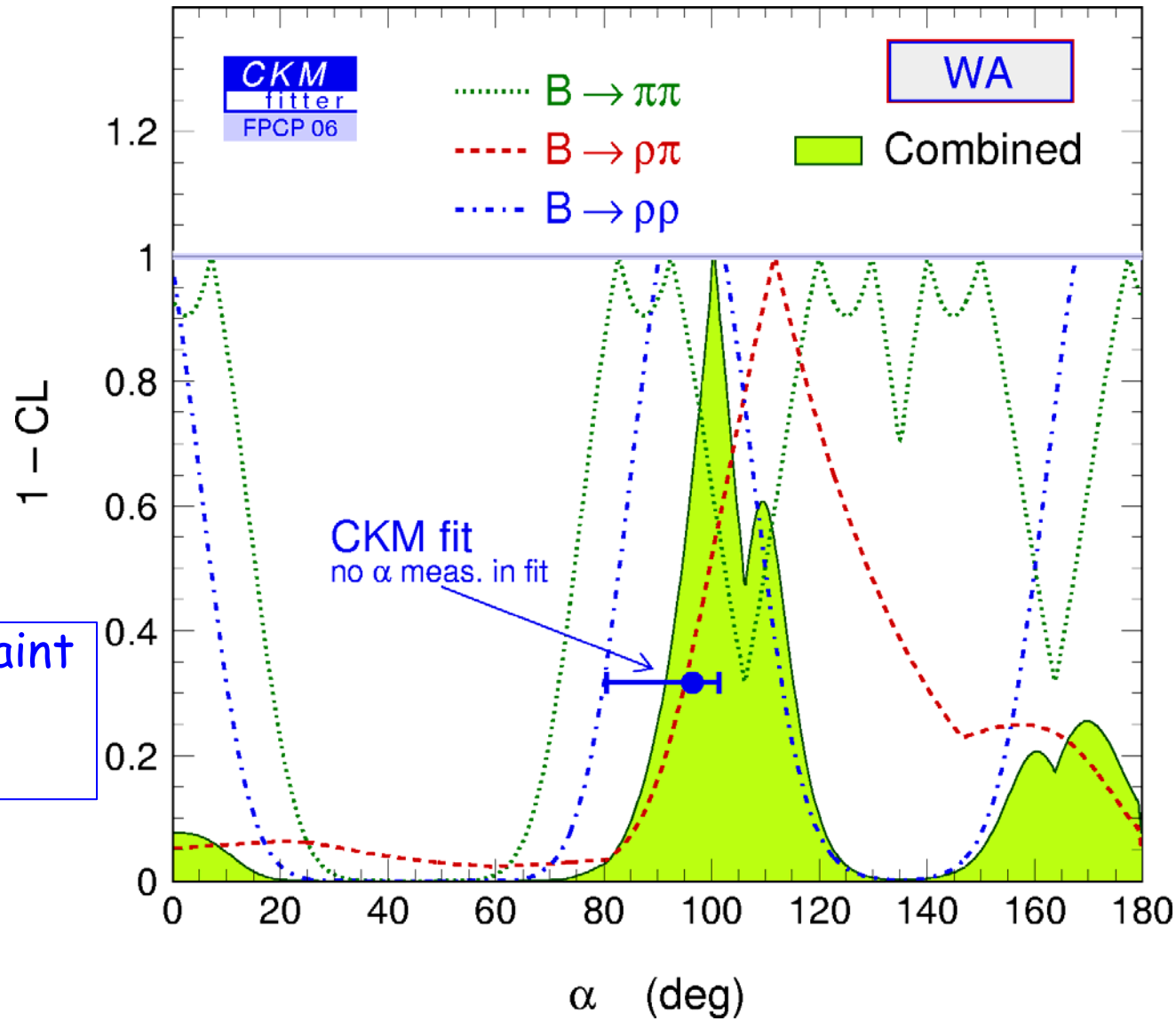
Summary of constraints on α

Mirror solutions disfavored

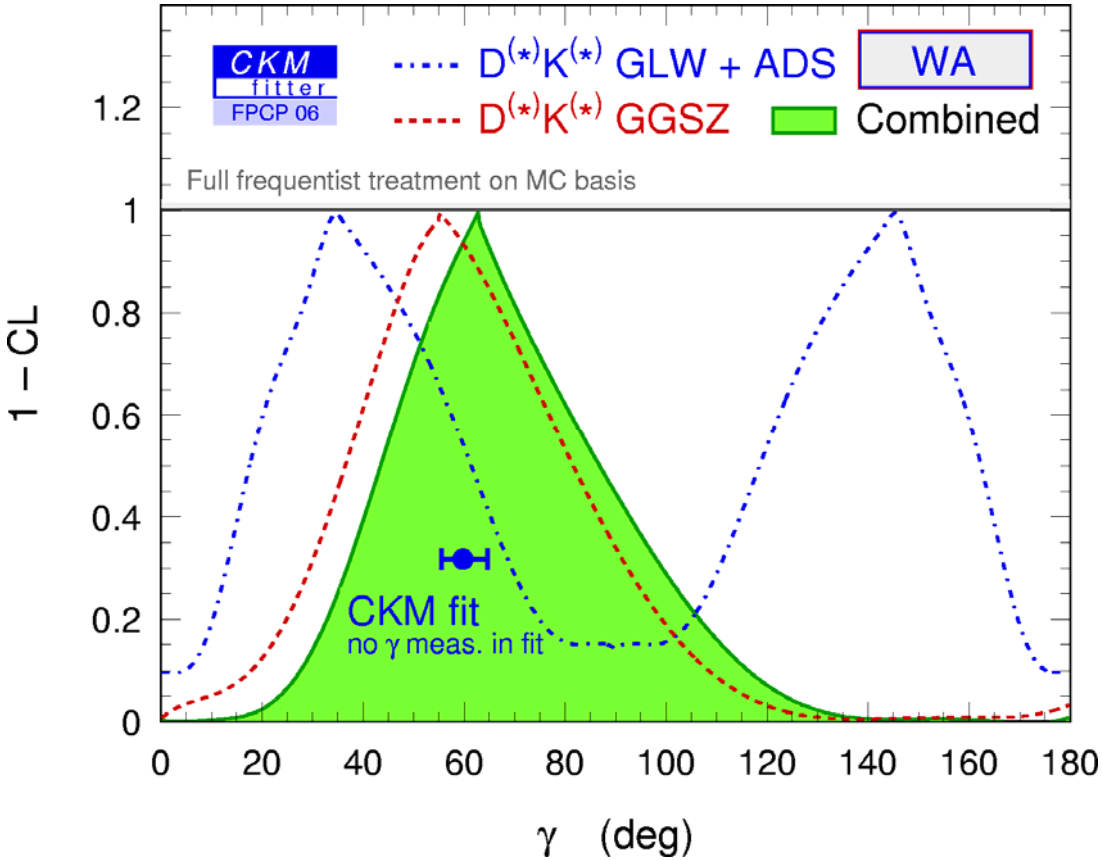
From combined $\pi\pi, \rho\pi, \rho\rho$ results:

$$\alpha = \left[100^{+15}_{-9}\right]^{\circ}$$

CKM indirect constraint fit: $\alpha = \left[97^{+5}_{-16}\right]^{\circ}$



Summary of constraints on γ



Interference:

$b \to c$ with $b \to u$

Ratio r_B of allowed to suppressed is critical

ADS

$$B^+ \to D^{(*)0}\left[\to D_{DCSD}\right]K^+$$

GLW

$$B^+ \to D^{(*)0}\left[\to D_{CP}\right]K^+$$

GGSZ

$$B^+ \to D^{(*)0}\left[\to K_S^0\pi^+\pi^-\right]K^+$$

From combined analysis:

$$\gamma = \left[62^{+35}_{-25}\right]^\circ$$

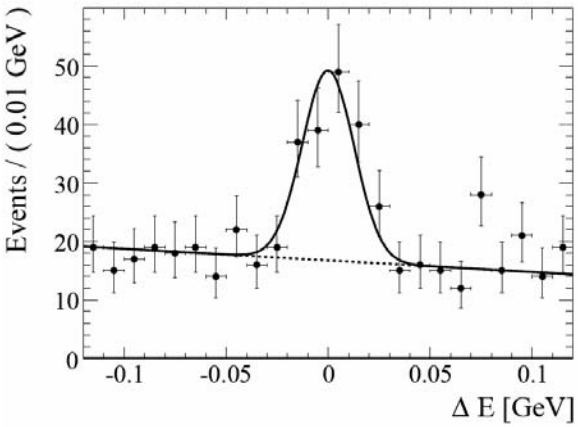
Indirect constraint:

$$\gamma = \left[60^{+5}_{-4}\right]^\circ$$

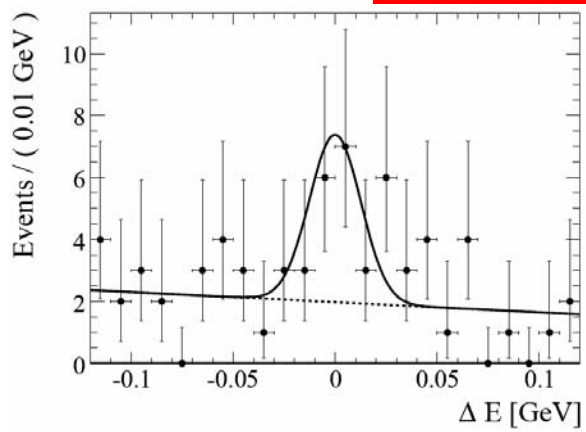
New results for $B^0 \to D^{(*)0} K^{(*)0}$

hep-ex/0604016

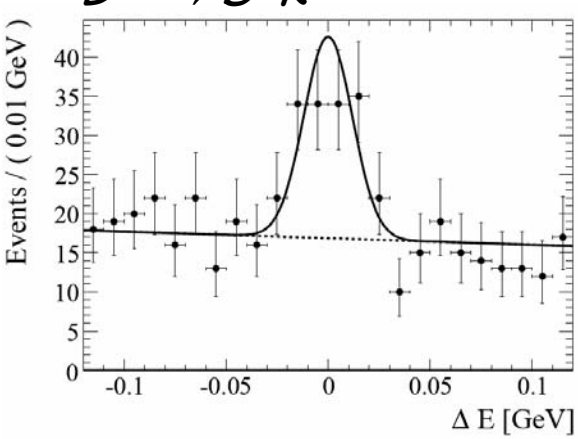
$B^0 \to D^0 K_S^0$



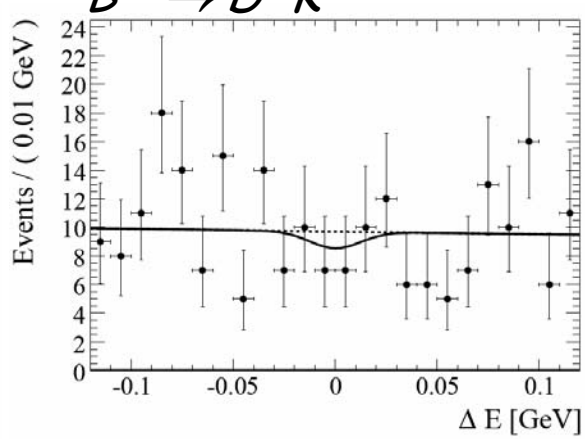
$B^0 \to D^{*0} K_S^0$ **First evidence**



$\bar{B}^0 \to D^0 \bar{K}^{*0}$



$\bar{B}^0 \to \bar{D}^0 \bar{K}^{*0}$

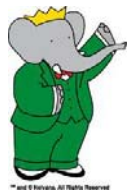


V_{cb} **transition**

V_{ub} **transition**

Measure r in self-tagging final state $D^0 K^{*0}$

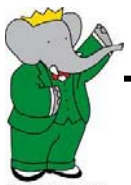
$$r_B \equiv \left| \frac{A(\bar{B}^0 \to \bar{D}^0 \bar{K}^{*0})}{A(\bar{B}^0 \to D^0 \bar{K}^{*0})} \right|$$



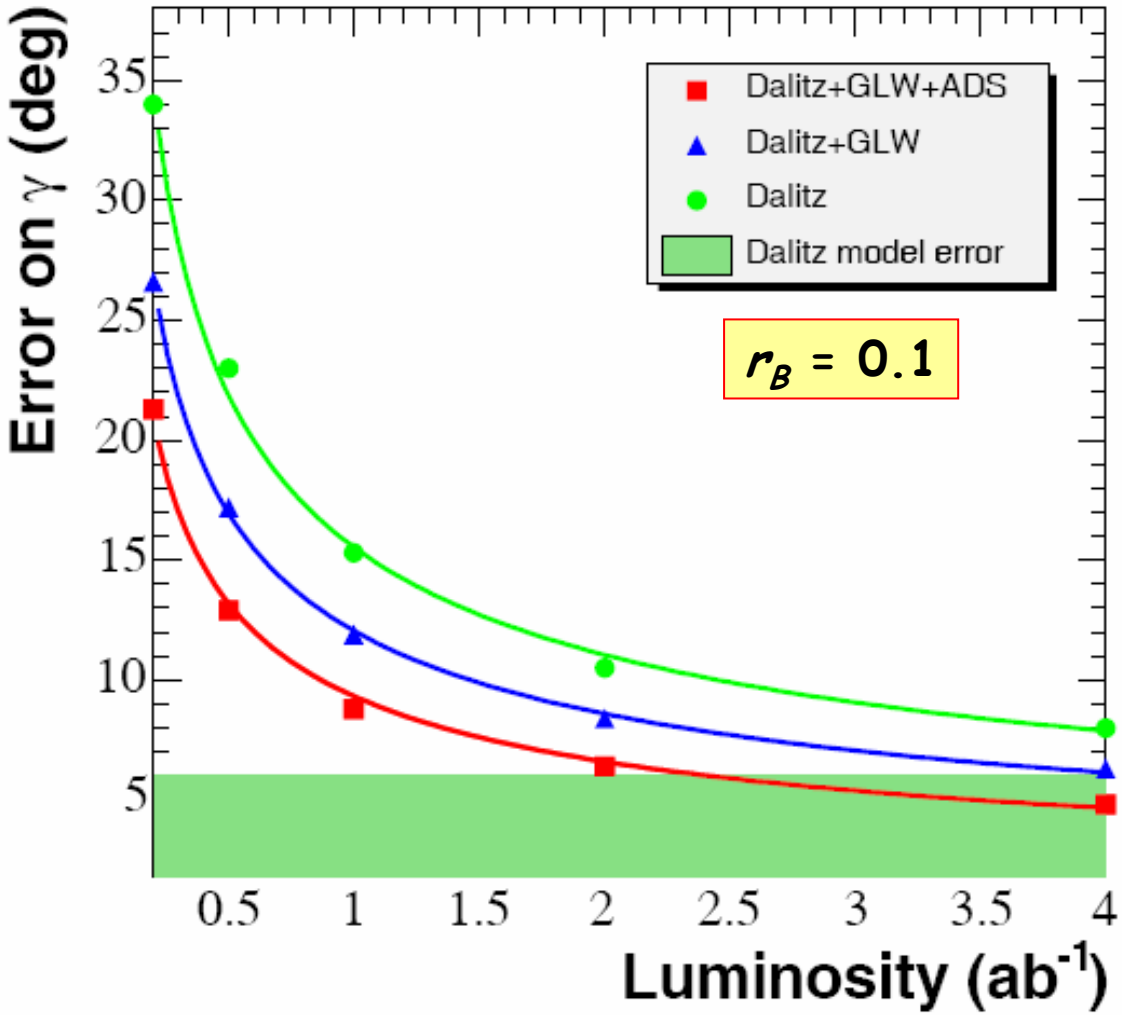
New!

No V_{ub}, r_B less than expected!

$r_B < 0.40 @ 90\% CL$



Projected uncertainty on γ

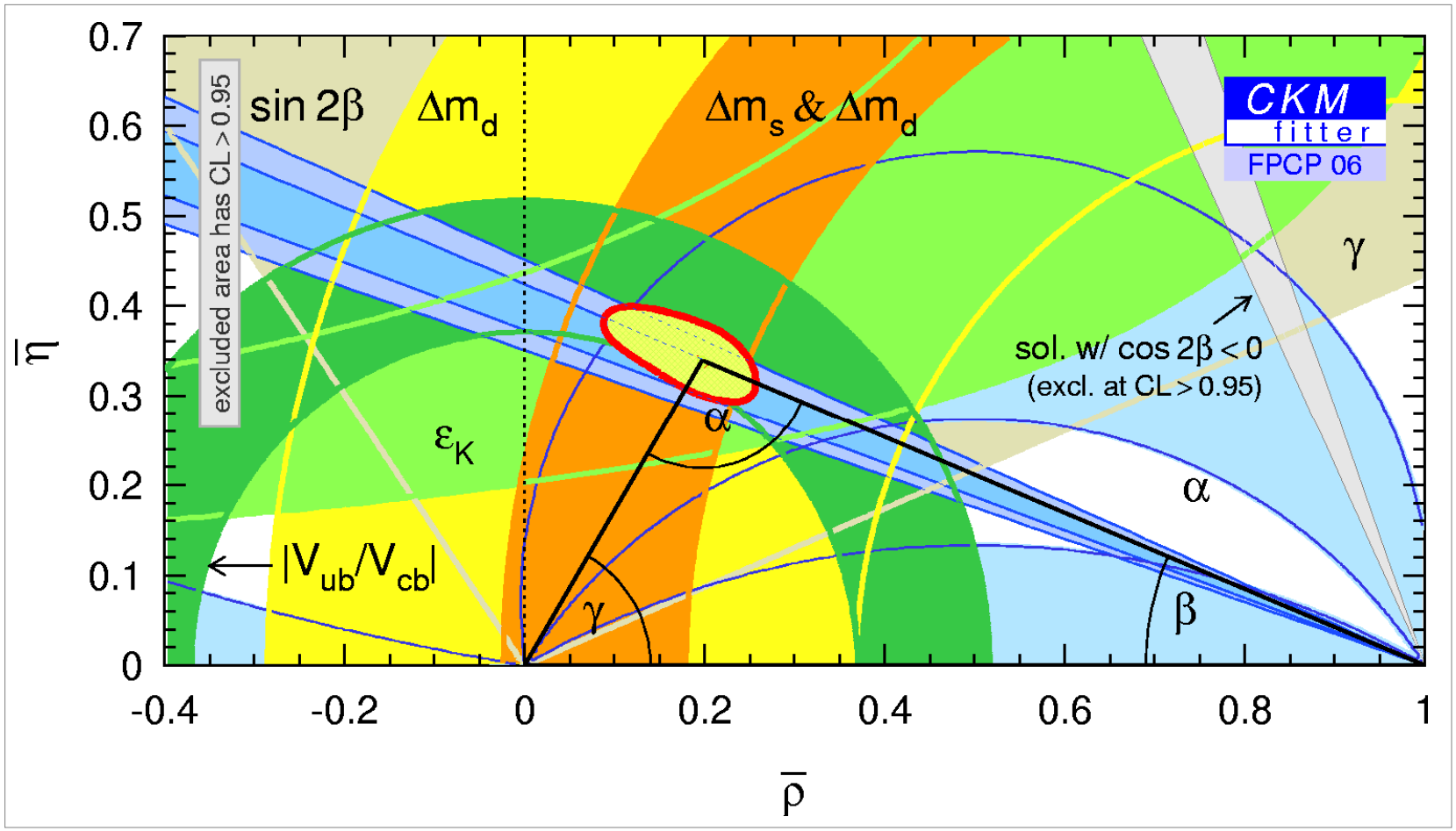


Based on original γ modes, but we are still hunting for more!

Projected sys error due to D^0 Dalitz plot

Global CKM fit: 2006

95% contours

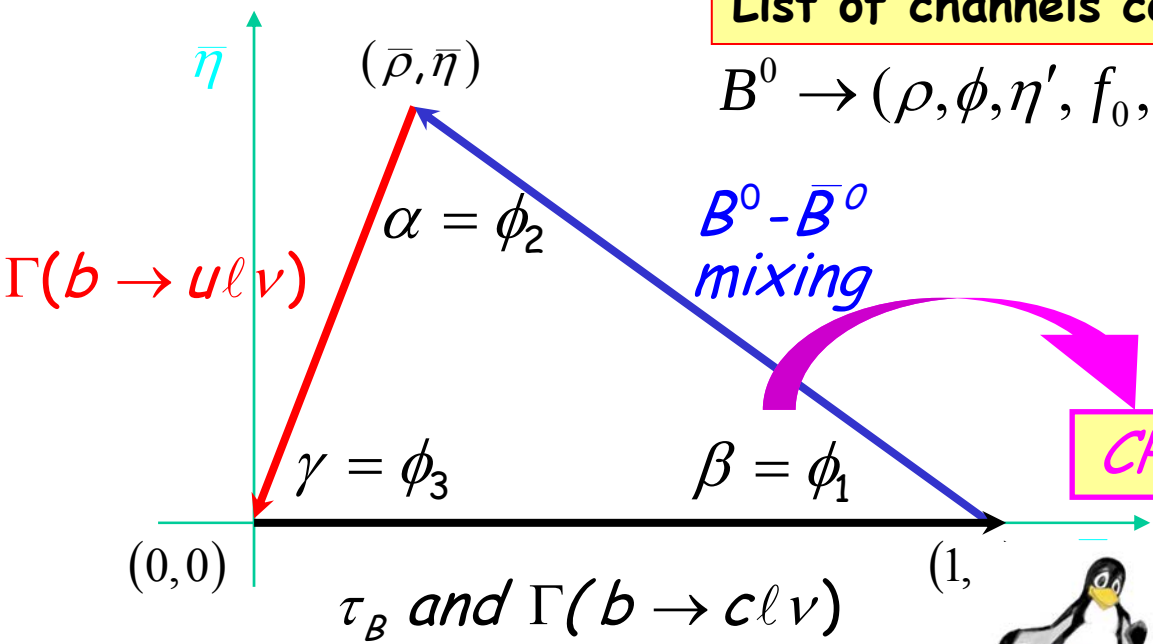


Includes CDF measurement of Δm_s

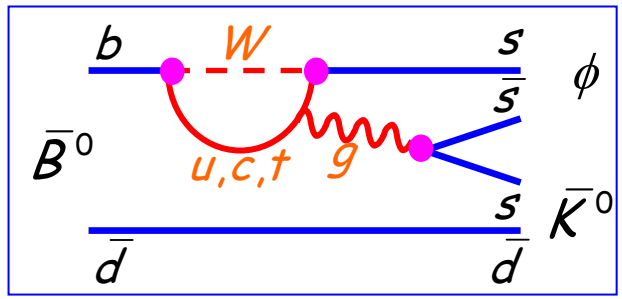
CPV in Penguin Modes

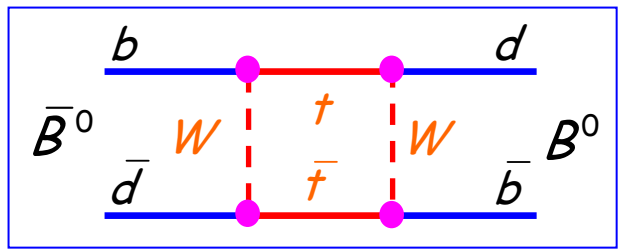
List of channels continues to expand…

$$B^0 \to (\rho, \phi, \eta', f_0, \pi^0, \pi^0\pi^0, K^+K^-, K_S^0 K_S^0) K^0$$



CPV in $B^0 \to \phi K_S^0, \eta' K_S^0, \ldots$





Interference of suppressed $b \to s$ Penguin decay with mixing

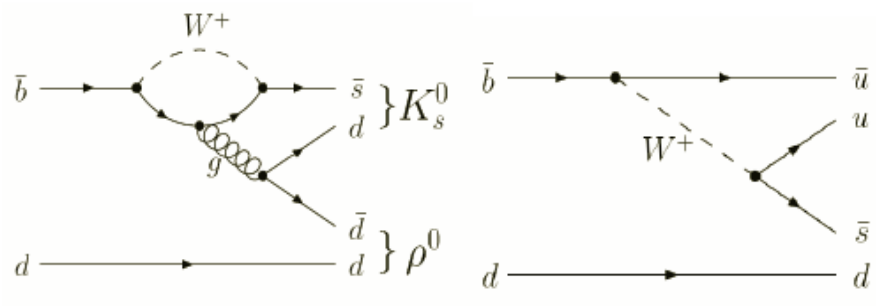
New: $\sin 2\beta_{eff}$ in $B \to \rho K_S$

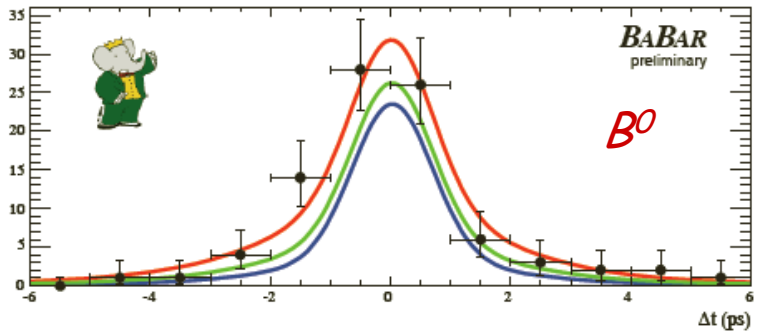
First Measurement!

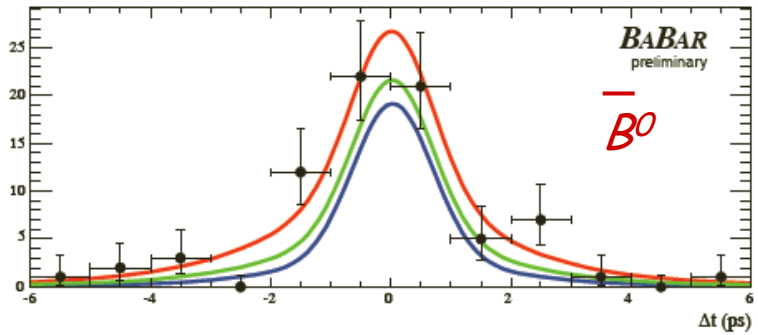
Challenges:

- Overlap of $f_0(1280)$ and ρ, $B\bar{B}$ & non-resonant backgrounds
- Possible color-suppressed tree

New!





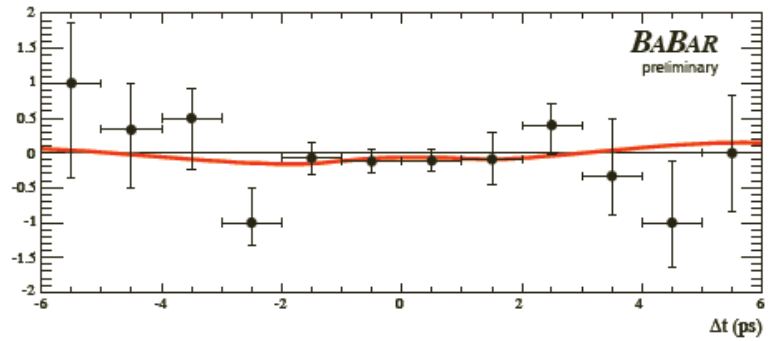


Related New Results from BABAR:

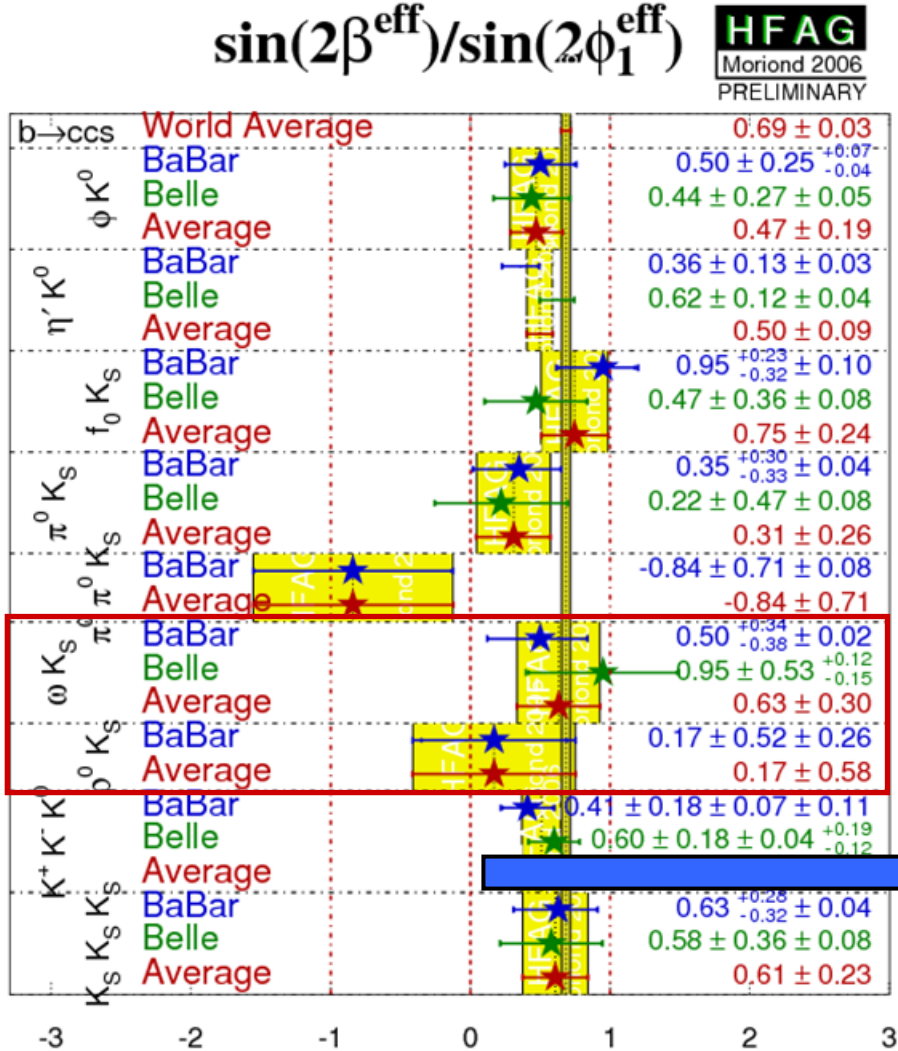
- Update in ωK_S
- Search for $B \to K_S K_S K_L$
- Many BF and A_{CP} measurements in related modes control hadronic uncertainties in $b \to s$ penguins

New!

Asymmetry

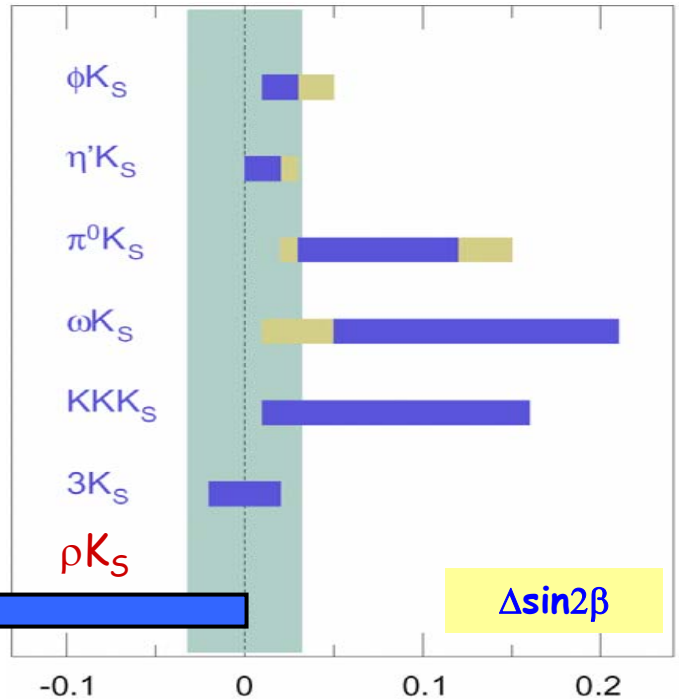


Summary of sin(2β) in Penguins



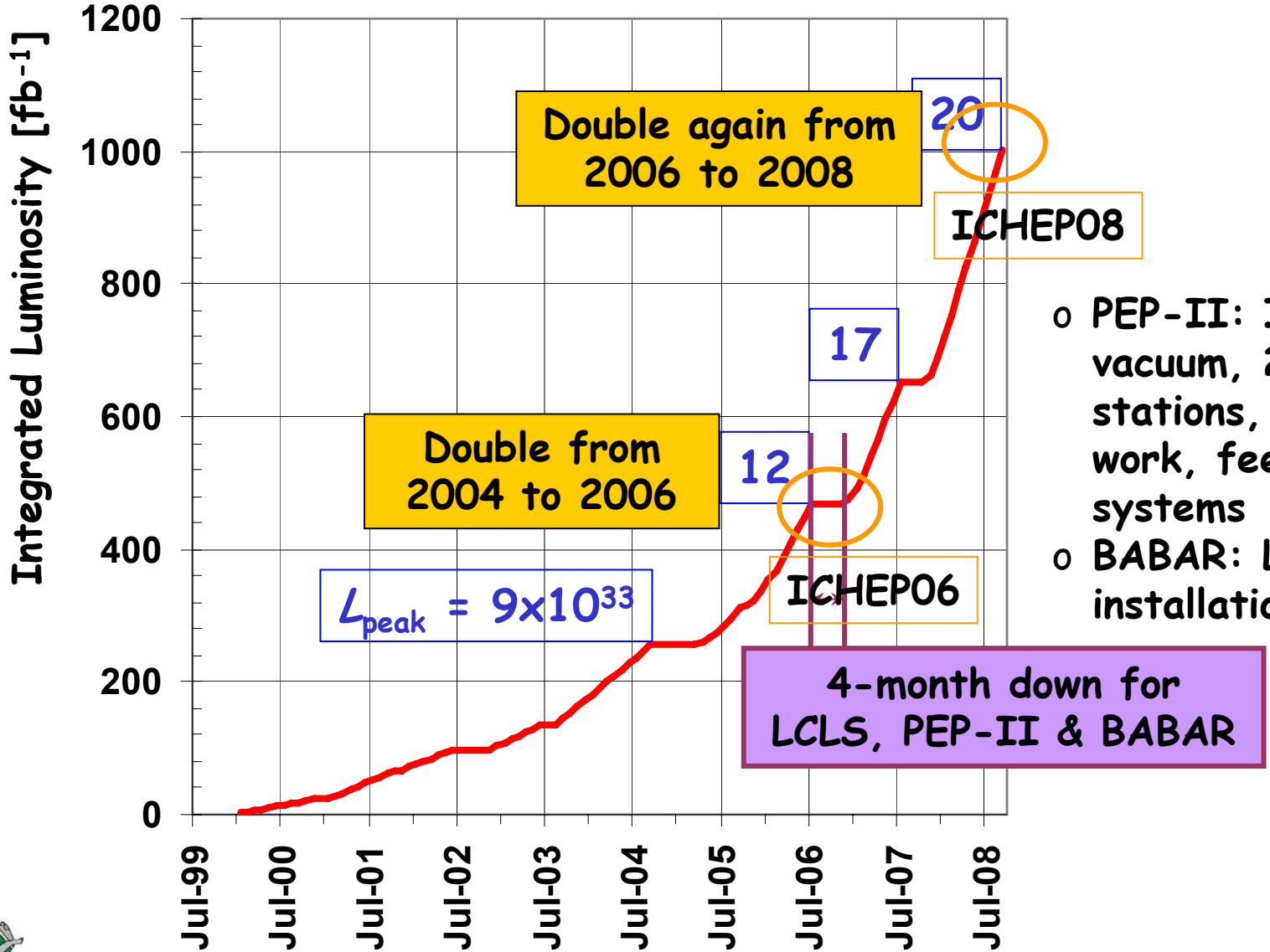
Naïve[2] Average: 0.50 ± 0.06 (2.8σ)

Representative theory estimates



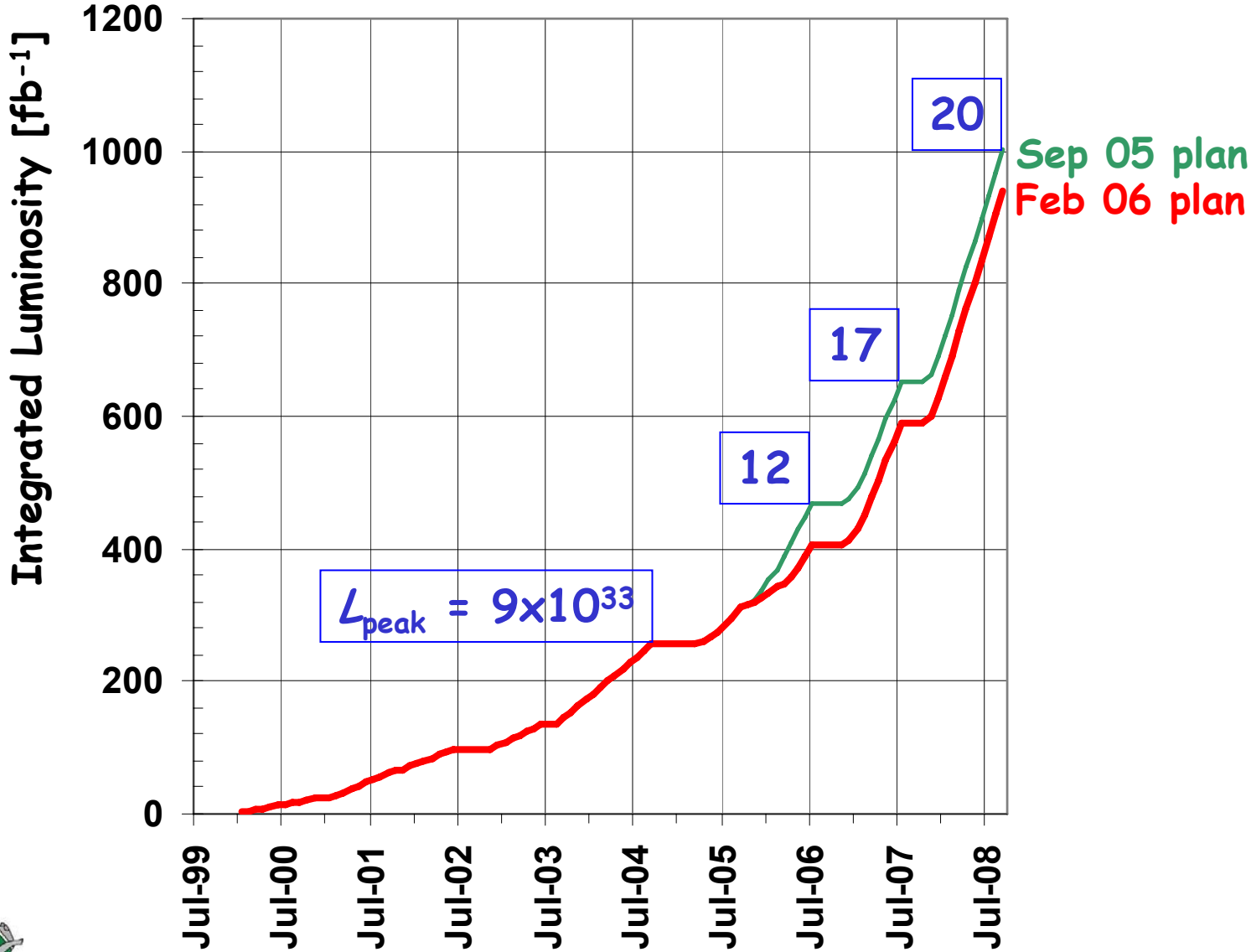
Example from recent calculations (QCD factorization)
2-body: [Beneke; PL B620, 143 (2005)]
3-body: [Cheng,Chua,Soni; PRD72, 094003 (2005)]

Projected data sample growth

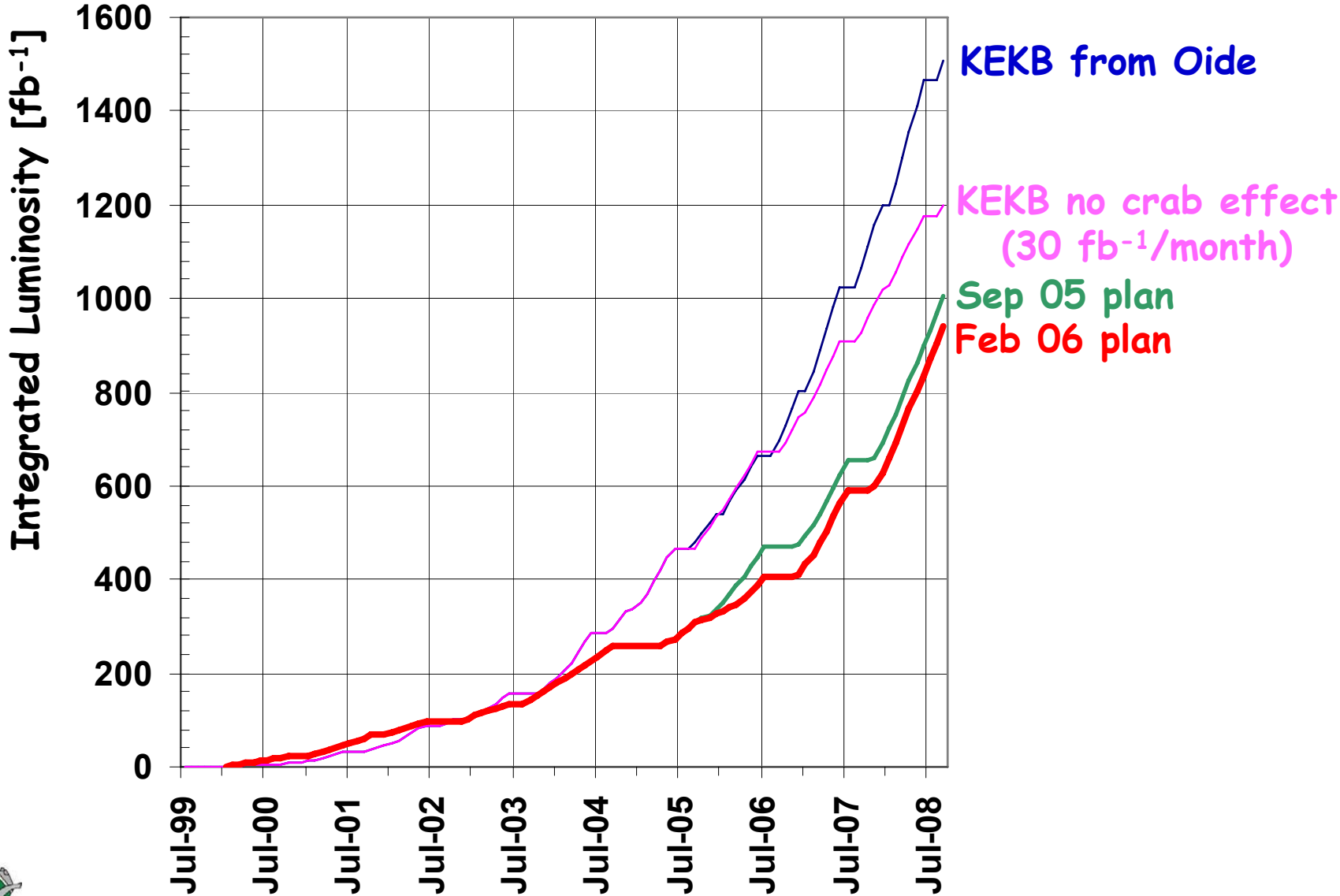


- PEP-II: IR-2 vacuum, 2xrf stations, BPM work, feedback systems
- BABAR: LST installation

Projected data sample growth



How does this compare with KEKB?



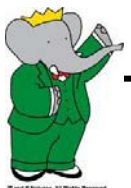
Updated performance comparison

Revised from 2005 results; conclusions unchanged from 2004 study

S	Belle				BABAR				Errors/Luminosity			
									Belle	BABAR		
Mode	S	stat err	lumi	Untag sample	S	stat err	lumi	Untag sample	st*sqrt(L)	st*sqrt(L)	Perf Ratio	Lumi Ratio
phiK0	0.440	0.270	357	258	0.500	0.250	205	212	5.101	3.579	1.425	2.031
etapK0	0.620	0.120	357	1017	0.270	0.140	205	819	2.267	2.004	1.131	1.279
KKK0	0.600	0.180	357	536	0.550	0.170	205	452	3.401	2.434	1.397	1.952
KSKSKS	0.580	0.360	357	105	0.630	0.320	205	129	6.802	4.582	1.485	2.204
f0K0	0.470	0.360	357	145	0.950	0.320	192	152	6.802	4.434	1.534	2.353
pi0K0	0.220	0.470	357	344	0.150	0.300	205	300	8.880	4.295	2.067	4.274
ccbarK0	0.652	0.039	357	5264	0.722	0.040	205	10320	0.737	0.573	1.287	1.655
pipi	-0.670	0.160	253	666	-0.300	0.170	205	467	2.545	2.434	1.046	1.093
rhopi S	-0.280	0.230	140	483	-0.100	0.140	192	1184	2.721	1.940	1.403	1.968
rhopi A+-	-0.020	0.160	140	483	-0.210	0.110	192	1184	1.893	1.524	1.242	1.543
rhopi A-+	-0.530	0.290	140	483	-0.470	0.140	192	1184	3.431	1.940	1.769	3.129
rhorho	0.090	0.420	253	142	-0.330	0.240	205	617	6.681	3.436	1.944	3.780
Averages											1.477	2.272

Typically better errors for BABAR despite larger Belle dataset

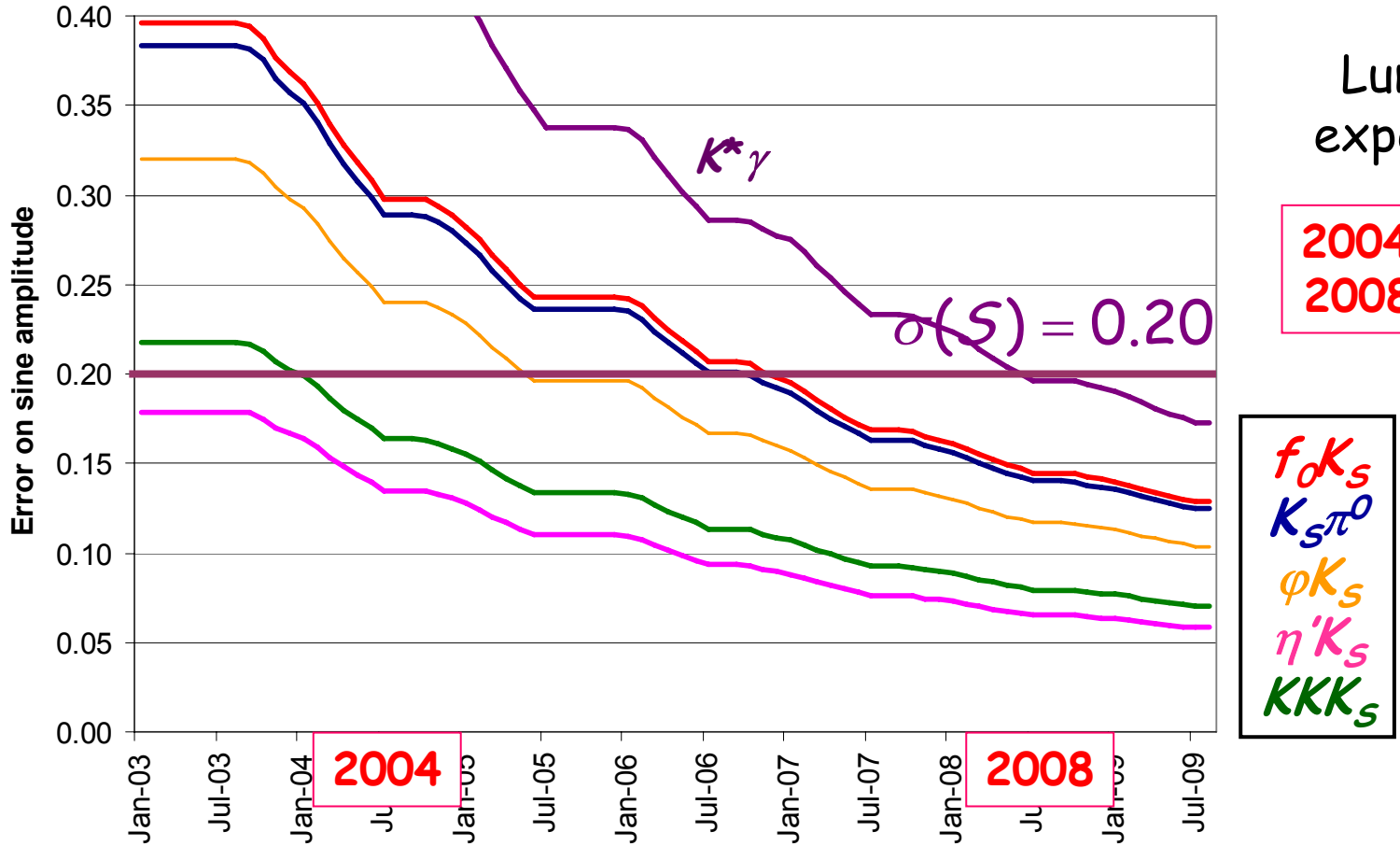
Normalized performance ratio



BABAR CKM physics goals

Physics	Impact	FY2006 450 fb^{-1}	FY2007 650 fb^{-1}	FY2008 1000 fb^{-1}
Precision measurement of sin2β	Fundamental constant of the SM, whose precision is only limited by statistics			Improve error by factor of two to 2%
Precision measurement of *CP* asymmetry in $b \to s\bar{q}q$ penguin modes	Primary approach to new physics in loop decays; $b \to s\bar{s}s$ presently discrepant with SM predictions at 2.4σ level when averaged over all available modes	Potentially reach the 4-5σ level for average of all $b \to s\bar{s}s$ modes		Could reach the 4-5σ level for individual theoretically-clean modes
Precision measurement of unitarity angle α	Fundamental constraint on the UT		Discovery of $B^0 \to \rho^0\rho^0$ if it has SM branching fraction	Isospin analysis in $B \to \rho\rho$ allows better than 10° measurement
Precision measurement of unitarity angle γ	Fundamental tree-level constraint on phases and amplitudes originating from any new physics beyond the SM	Pioneering measurements with 10-15° accuracy		Determine to 5-10° precision
Precision measurement of $\lvert V_{ub}\rvert$ with inclusive & exclusive semileptonc *B* meson decays	Fundamental tree-level constraint on amplitudes and phases originating from any new physics beyond the SM	Inclusive decays reach 6.5% precision		Exclusive decays reach 8% precision

Projections of sin2β from Penguin modes



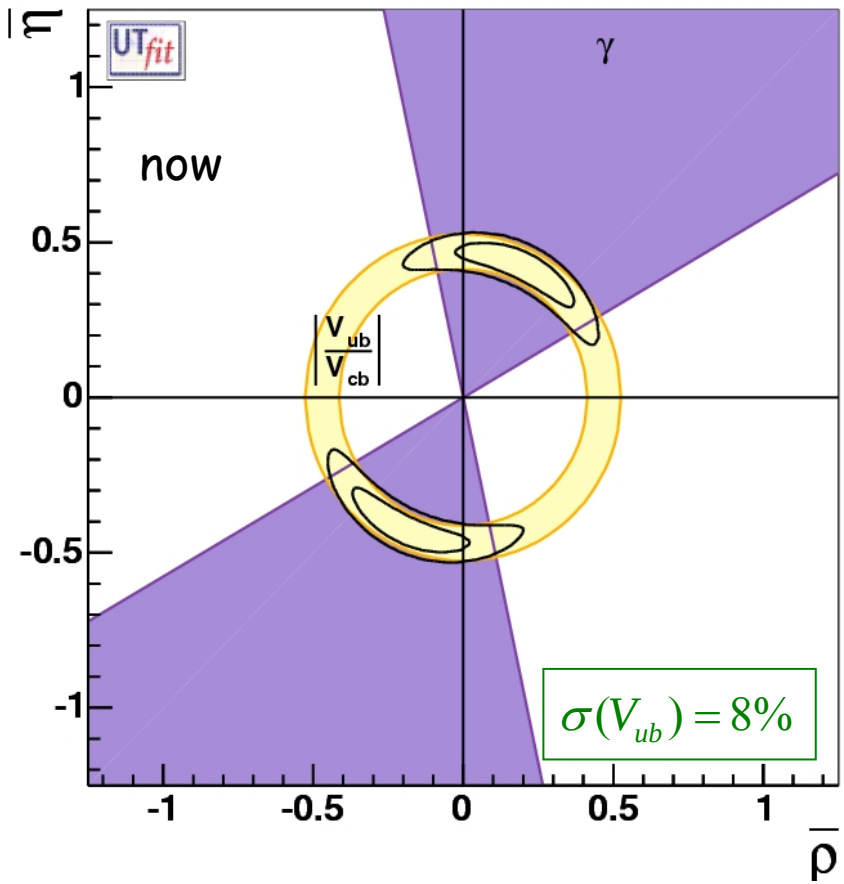
Luminosity expectations:

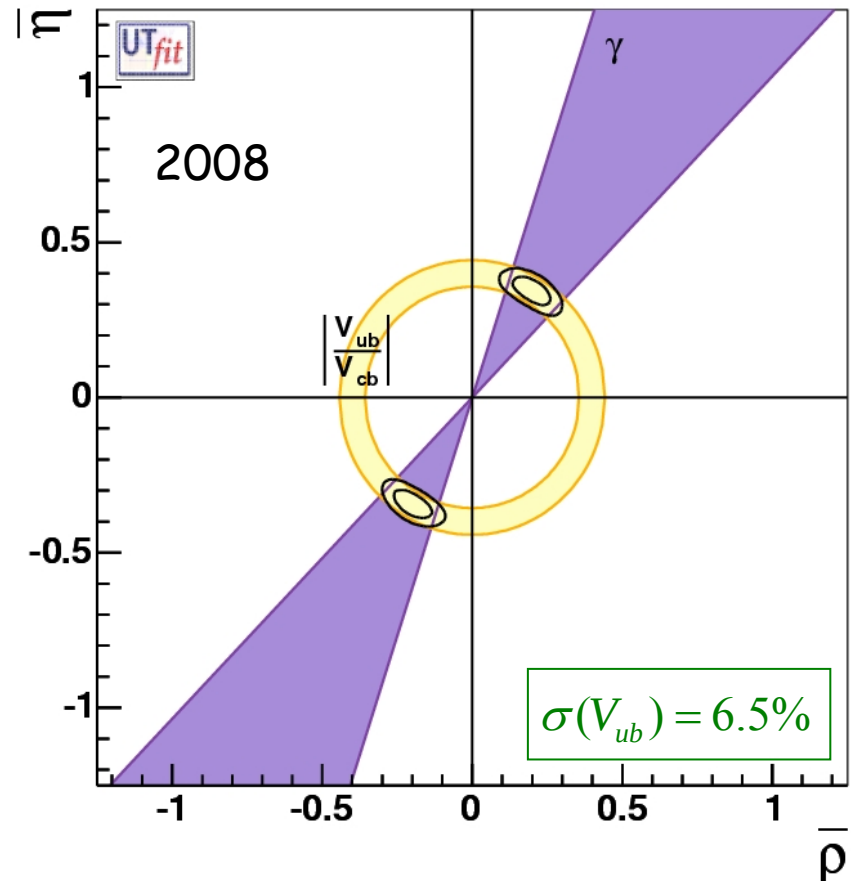
2004=240 fb^{-1}
2008=1.0 ab^{-1}

Projections are statistical errors only;
however systematic errors at few percent level

UT constraints in 2008

95% contours





Assumption: no NP in trees [almost any NP model]

Significant constraint on all New Physics models in LHC era

Bounds on new physics

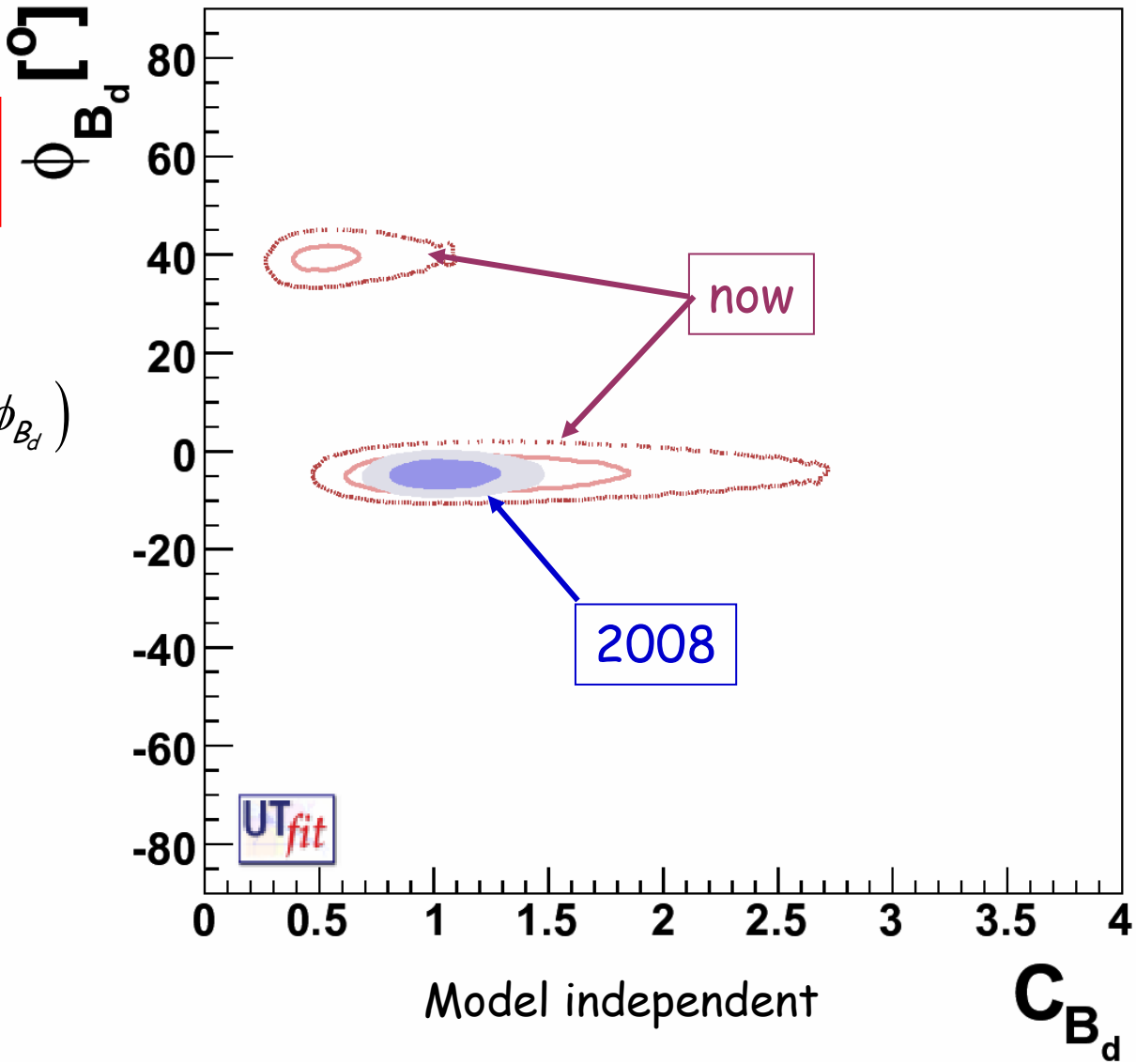
Introduce new physics in mixing diagram

$$\left(\Delta M_{B_d}\right) = C_{B_d}\left(\Delta M_{B_d}\right)^{SM}$$

$$A_{CP}\left(J/\psi K_S^0\right) = \sin 2\left(\beta + \phi_{B_d}\right)$$

Mass scale being probed for unit coupling:

Λ(now) ~ 5 TeV
Λ(2008) ~ 10TeV



New: T/CP/CPT Violation in B^0 mixing

Asymmetry in same-sign data:

$$A_{T/CP}(\Delta t) = \frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)} \approx \frac{1-|q/p|^4}{1+|q/p|^4} \approx 2\left(1-|q/p|\right)$$

$$\mathrm{Re}\, z \approx (m_{\overline{B}^0} - m_{B^0})/\Delta m$$
$$\mathrm{Im}\, z \approx (\Gamma_{\overline{B}^0} - \Gamma_{B^0})/\Delta m$$

Asymmetry in opposite-sign data:

$$A_{CP/CPT}(|\Delta t|) = \frac{N^{+-}(\Delta t > 0) - N^{+-}(\Delta t < 0)}{N^{+-}(\Delta t > 0) + N^{+-}(\Delta t < 0)} \quad (4)$$

$$\simeq 2\frac{\mathrm{Im}\, z \sin(\Delta m \Delta t) - \mathrm{Re}\, z \sinh(\frac{\Delta\Gamma\Delta t}{2})}{\cosh(\frac{\Delta\Gamma\Delta t}{2}) + \cos(\Delta m \Delta t)}.$$

hep-ex/0603053

$$|q/p| = 1.0008 \pm 0.0027(stat) \pm 0.0019(syst)$$
$$\mathrm{Im}(z) = 0.0139 \pm 0.0073(stat) \pm 0.0032(syst)$$
$$\Delta\Gamma x\, \mathrm{Re}(z) = -0.0071 \pm 0.0039(stat) \pm 0.0020(syst)$$

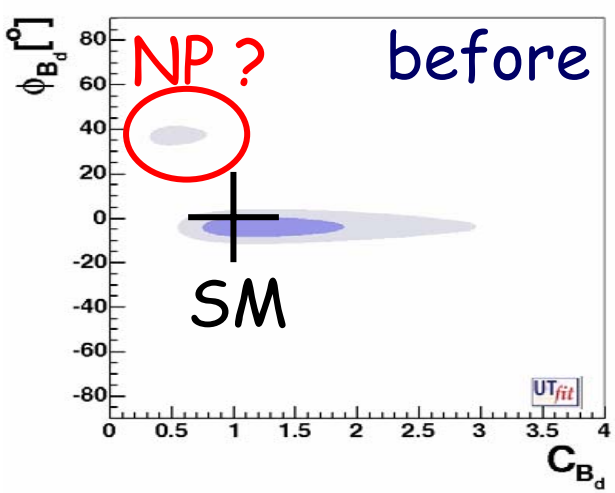
New!

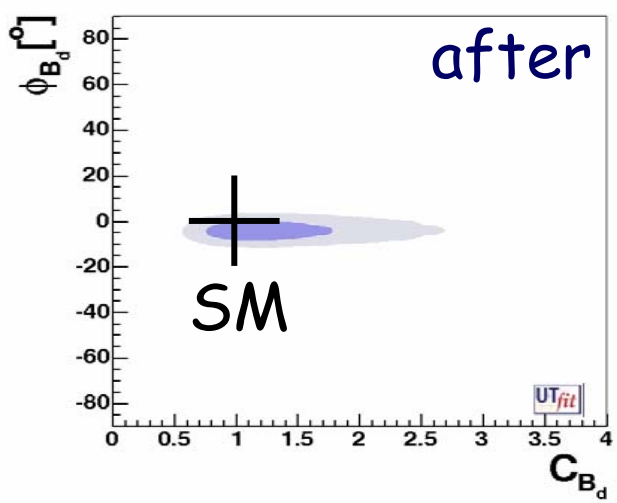
40% reduction in σ(q/p)

80% reduction in σ(Im(z))

First Measurement!

Constraints on New Physics from |q/p|





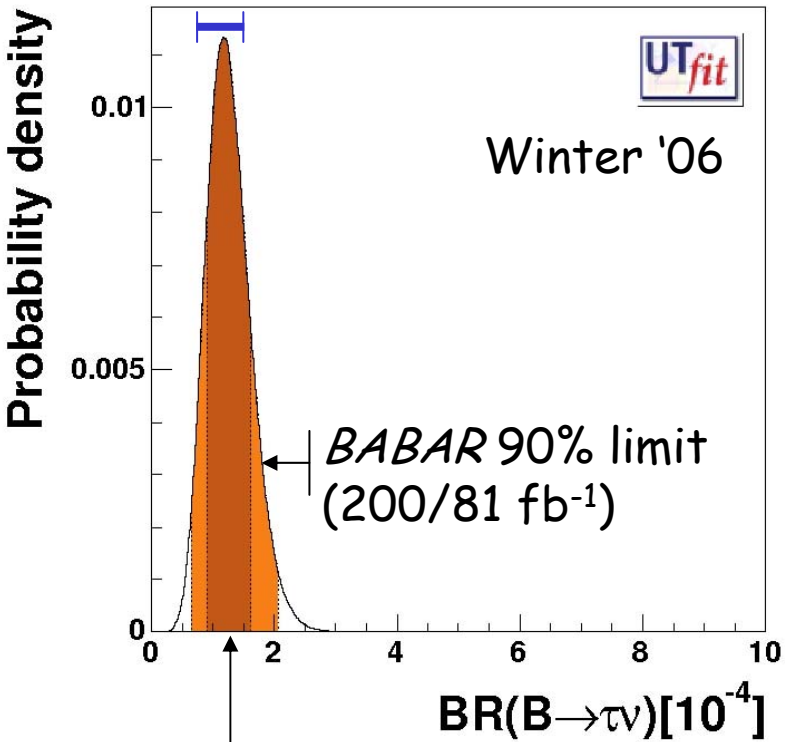
BABAR rare decay physics goals

Physics	Impact	FY2006 450 fb^{-1}	FY2007 650 fb^{-1}	FY2008 1000 fb^{-1}
Discovery of $B \to \tau \nu_\tau$	Provides a determination of $\lvert V_{ub} \rvert$ and constrains Higgs sector in MSSM and NP in a parameter regime that is complementary to LHC	Limit	First hints	Discovery if it has SM branching fraction
Precision determination of $b \to s\gamma$ branching fraction, *CP* asymmetry, and photon energy spectrum	Loop diagram that provides unique insight into *B* meson structure and constrains Higgs sector in MSSM and NP in a parameter regime that is complementary to LHC		Ultimate precision on photon energy spectrum	Strong constraints from 5% error on BF; 1-2% error on *CP* asymmetry
Precision determination of $b \to s\ell^+\ell^-$ branching fractions, *CP* and FB asymmetries	Contributions from Z-penguin and W-exchange loops that give additional constraints on MSSM and NP in a parameter regime that is complementary to LHC	Useful precision for constraints on NP		Strong constraint for NP from BF, *CP* and FB asymmetries
Discovery of $B \to \rho\gamma$	Provides a unique determination of CKM matrix elements $\lvert V_{td} \rvert / \lvert V_{ts} \rvert$; likely before B_S^0-$\bar{B}_S^0$ mixing discovery	First hints	Discovery if it has SM branching fraction	Precise measurement of BF

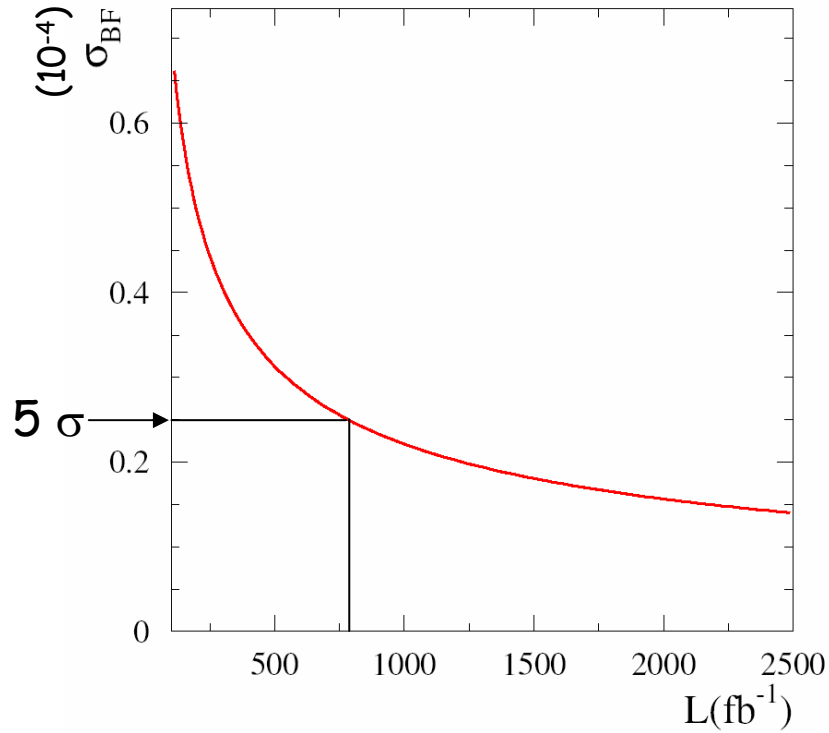
New Belle result

Developments in $B \to \tau\nu$

Belle at FPCP (400 fb^{-1})



SM prediction moved up ~30% due to V_{ub}, B_s mixing



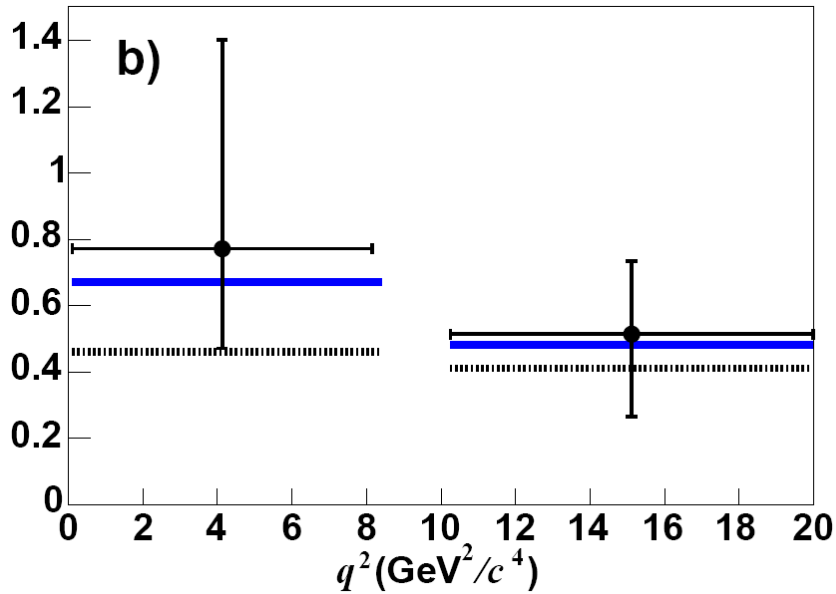
Example where Belle analysis is better than BABAR

Current analysis $\sigma_{Belle}=\sigma_{BaBar}*0.7$
Under investigation, but likely recoverable

New: angular analysis in $B \to K^{(*)}ll$

K^* polarization F_L

hep-ex/0604007

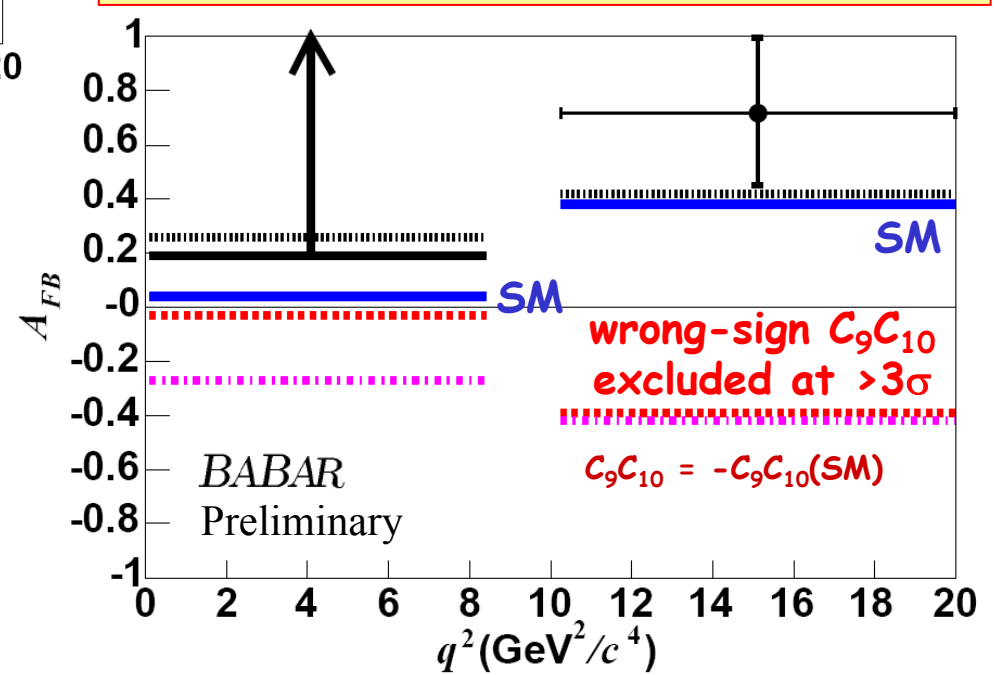


K^* polarization consistent with Standard Model

Possible to exclude $C_7 = -C_7(SM)$ with 1 ab^{-1}

New!

Forward-backward asymmetry A_{FB} vs q^2



Low q^2 limit excludes SM at 98% CL (2.1σ)

$$A_{FB} > 0.19 \ (95\% \ CL)$$
$$A_{FB}(SM) = 0.03$$

BABAR Physics Goals

Physics	Impact	FY2006 450 fb^{-1}	FY2007 650 fb^{-1}	FY2008 1000 fb^{-1}
Search for D^0-$\bar{D}^0$ mixing	Highly suppressed in the SM and therefore an ideal place to search for new physics in charm mixing diagram	Hint if 1% mixing amplitude		Discovery if 1% mixing amplitude
Search for lepton-flavor violation in $\tau \to \mu\gamma$ or other tau decays	Expected to be significantly enhanced in many extensions of the SM accommodating neutrino mass, but extremely small in the SM itself			Limits reach 2×10^{-8} sensitivity
New discovery in heavy hadron spectroscopy	Improved understanding of QCD in non-perturbative regime	Discoveries possible anytime	Discoveries possible anytime	Discoveries possible anytime

New: search for D mixing in $K\pi\pi^0$

SM predicts small effect: x,y < 10^{-5}

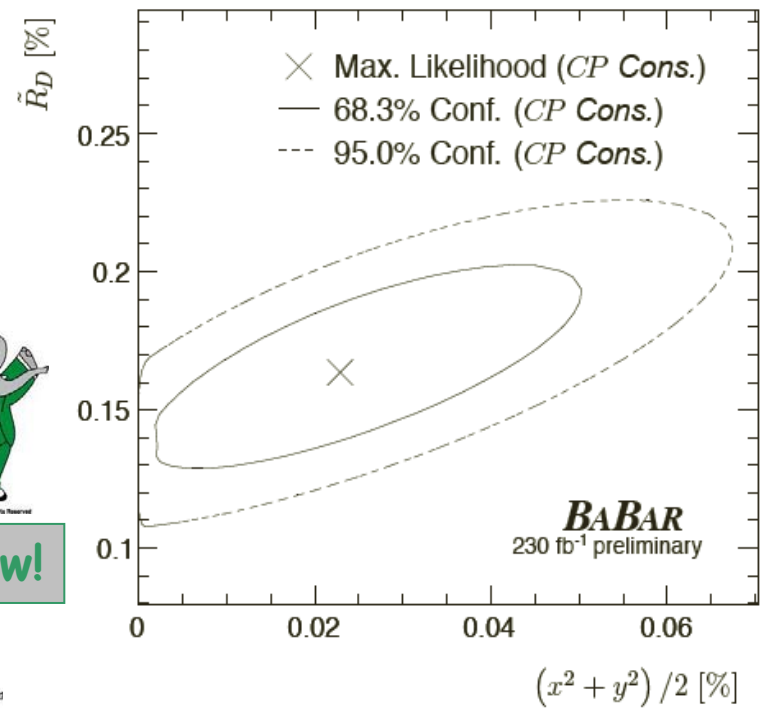
$$x \equiv 2\frac{m_2 - m_1}{\Gamma_2 + \Gamma_1},\ y \equiv \frac{\Gamma_2 - \Gamma_1}{\Gamma_2 + \Gamma_1}$$

$$R = \frac{\Gamma(D^0 \to K^+\pi^-\pi^0)}{\Gamma(D^0 \to K^-\pi^+\pi^0)} = (0.214 \pm 0.008 \pm 0.008)\%$$

Smaller DCS relative to $K\pi$

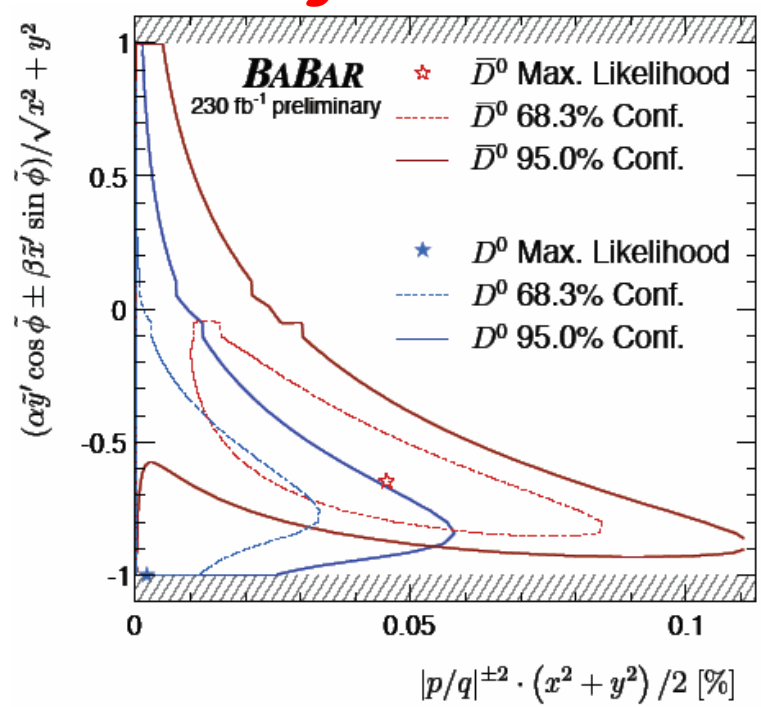
Search for New Physics:
CP violation in the *D* system

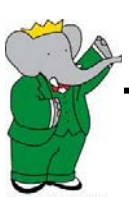
Result consistent with no mixing @ 4.5%



New!

Allowing for CP violation





Summary: Physics reach of BABAR

- ***Goal for 2005-2006: double current data set***
  - Delay in Run 5 can be overcome by summer 2006 with extended running period, with substantial reduction in errors on CP violation asymmetries in rare decay modes
  - Error on average of Penguin modes should reach 0.06
- ***Goal for 2007-2008: double again to ~1 ab^{-1}***
  - Individual Penguin modes with errors in range 0.06-0.12
  - Suite of fundamental Standard Model measurements with substantially improved levels of precision

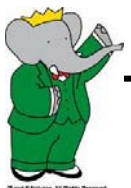
  - **Sensitivity to New Physics through rare decays, *CP* violation, & large data sample with a significant discovery potential**
  - **Full program of flavor physics/CP violation measurements provide fundamental constraints on future New Physics discoveries**

- ***Program will continue to be exciting and competitive through at least 2008***

Future opportunities in B physics

- ***Terminating PEP-II/BABAR in 2008 is premature***
  - Many important physics goals are on the edge of sensitivity; a further doubling beyond 2008 would be feasible & welcome
  - If there is new physics in Penguin modes then more data will almost certainly allow us to contribute to unraveling its nature
  - Belle has shown that a B_s^0 program on the $\Upsilon(5S)$ is feasible; running on $\Upsilon(5S)$ would be important & complementary to LHC*b*
- ***Ideas for Super B Factories are vigorously pursued***
  - Physics case based on sensitivity to new physics in beauty, charm and tau sectors
  - Super KEKB is a mature proposal to upgrade KEKB to 4×10^{35}
  - INFN is sponsoring a design study based on adopting linear collider ideas to a new very high luminosity facility (1×10^{36})

Interest in flavor physics at BABAR and beyond present *B* Factory programs remains strong



Backup Slides

The *BABAR* Collaboration

11 Countries
80 Institutions
623 Physicists

USA [38/311]

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
Harvard U
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 [4/24]

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

China [1/5]

Inst. of High Energy Physics, Beijing

France [5/53]

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

Germany [5/24]

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

Italy [12/99]

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 & Scuola Normale Superiore
INFN, Perugia & Univ
INFN, Roma & Univ "La Sapienza"
INFN, Torino & Univ
INFN, Trieste & Univ

The Netherlands [1/4]

NIKHEF, Amsterdam

Norway [1/3]

U of Bergen

Russia [1/13]

Budker Institute, Novosibirsk

Spain [2/3]

IFAE-Barcelona
IFIC-Valencia

United Kingdom [11/75]

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
U of Warwick

Evolution of $S_{\pi\pi}$ measurements

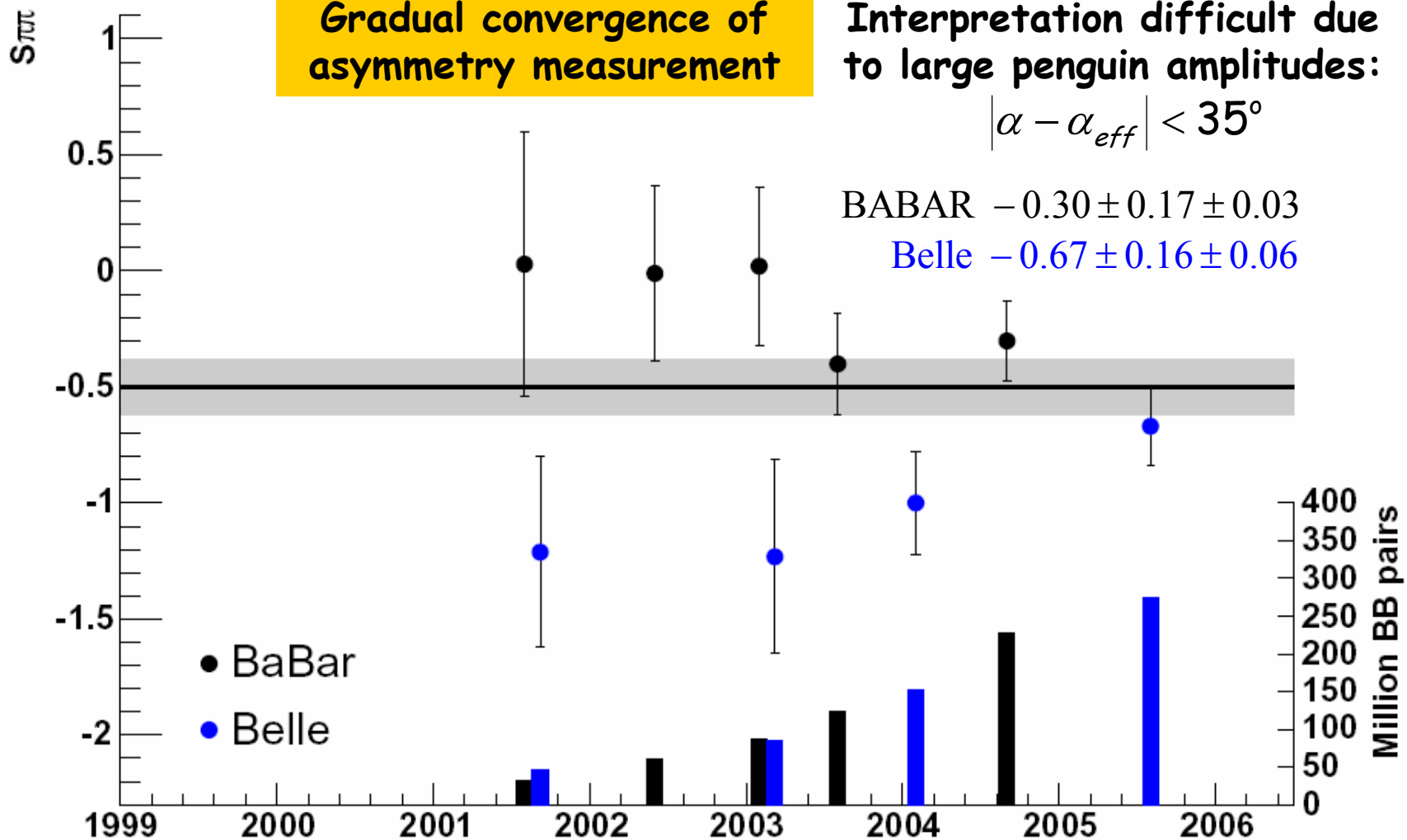
Gradual convergence of asymmetry measurement

Interpretation difficult due to large penguin amplitudes:

$$|\alpha - \alpha_{eff}| < 35^{\circ}$$

BABAR $-0.30 \pm 0.17 \pm 0.03$

Belle $-0.67 \pm 0.16 \pm 0.06$



Projected uncertainties on α

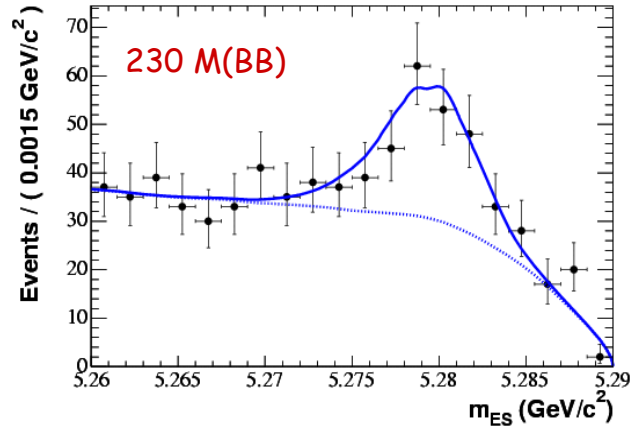
New!

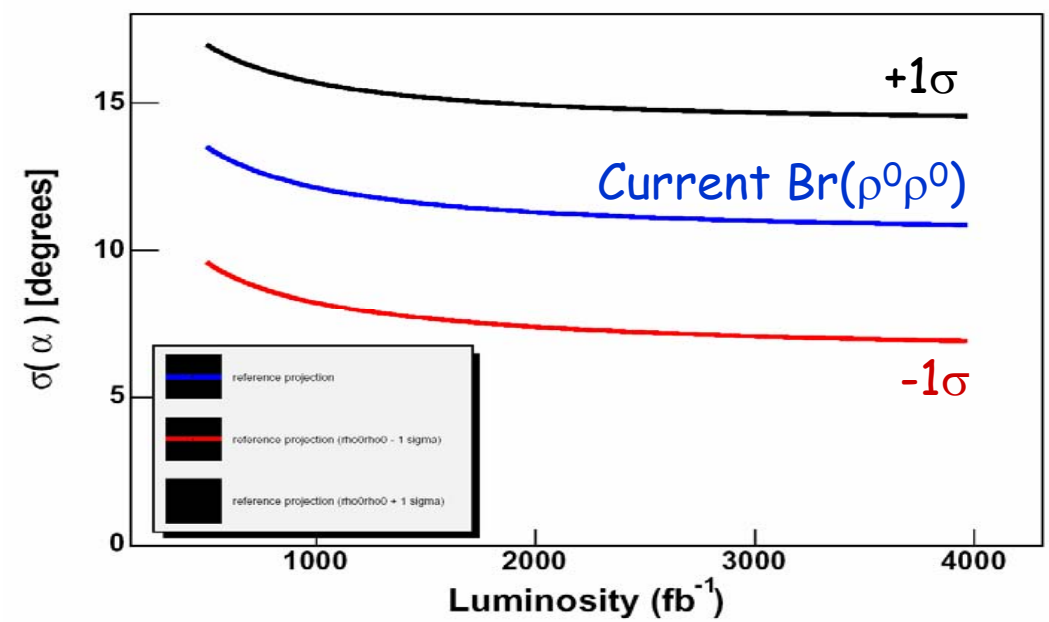
New measurement of $\rho^+\rho^0$:

$$\mathcal{B}(B^\pm \to \rho^\pm\rho^0) = (17.2 \pm 2.5 \pm 2.8) \times 10^{-6}$$

$$f_L(B^\pm \to \rho^\pm\rho^0) = 0.96 \pm 0.04 \pm 0.05$$

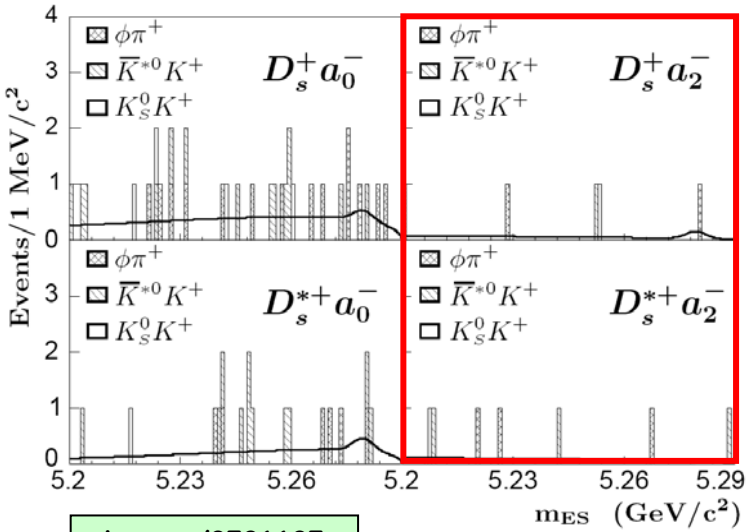
$$A_{CP}(B^\pm \to \rho^\pm\rho^0) = 0.10 \pm 0.14 \pm 0.09.$$





Projections depend on size of isospin corrections

Exploring other γ channels



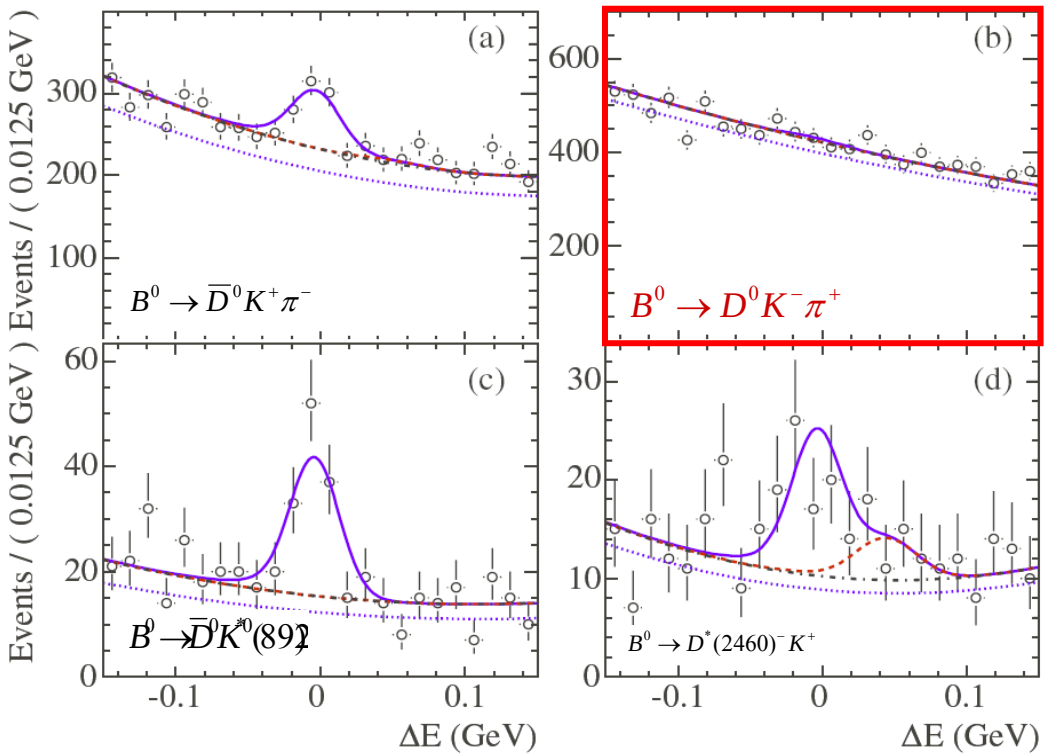
hep-ex/0501105

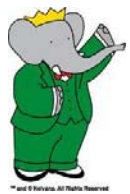
Looking for $b \to u$ in $D_s^{(*)}a_{0(2)}$

No sign of $b \to u$ signal, r_B smaller than expected!

New!

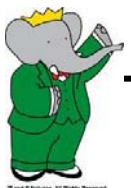
Phys. Rev. Lett. 96, 011803,2006



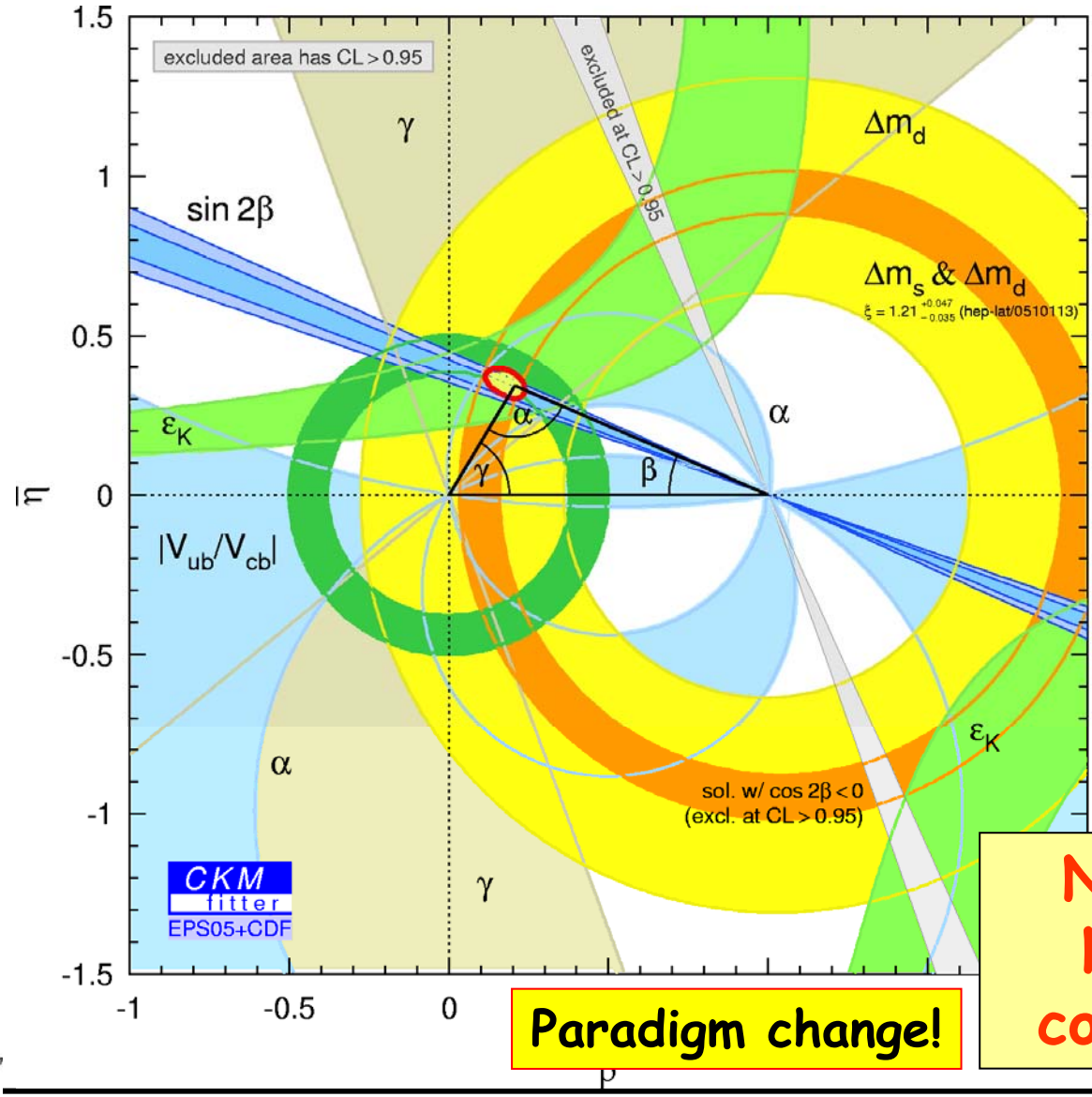


New!

No sign of $b \to u$ signal, r_B smaller than expected!



UT from sin2β & indirect constraints



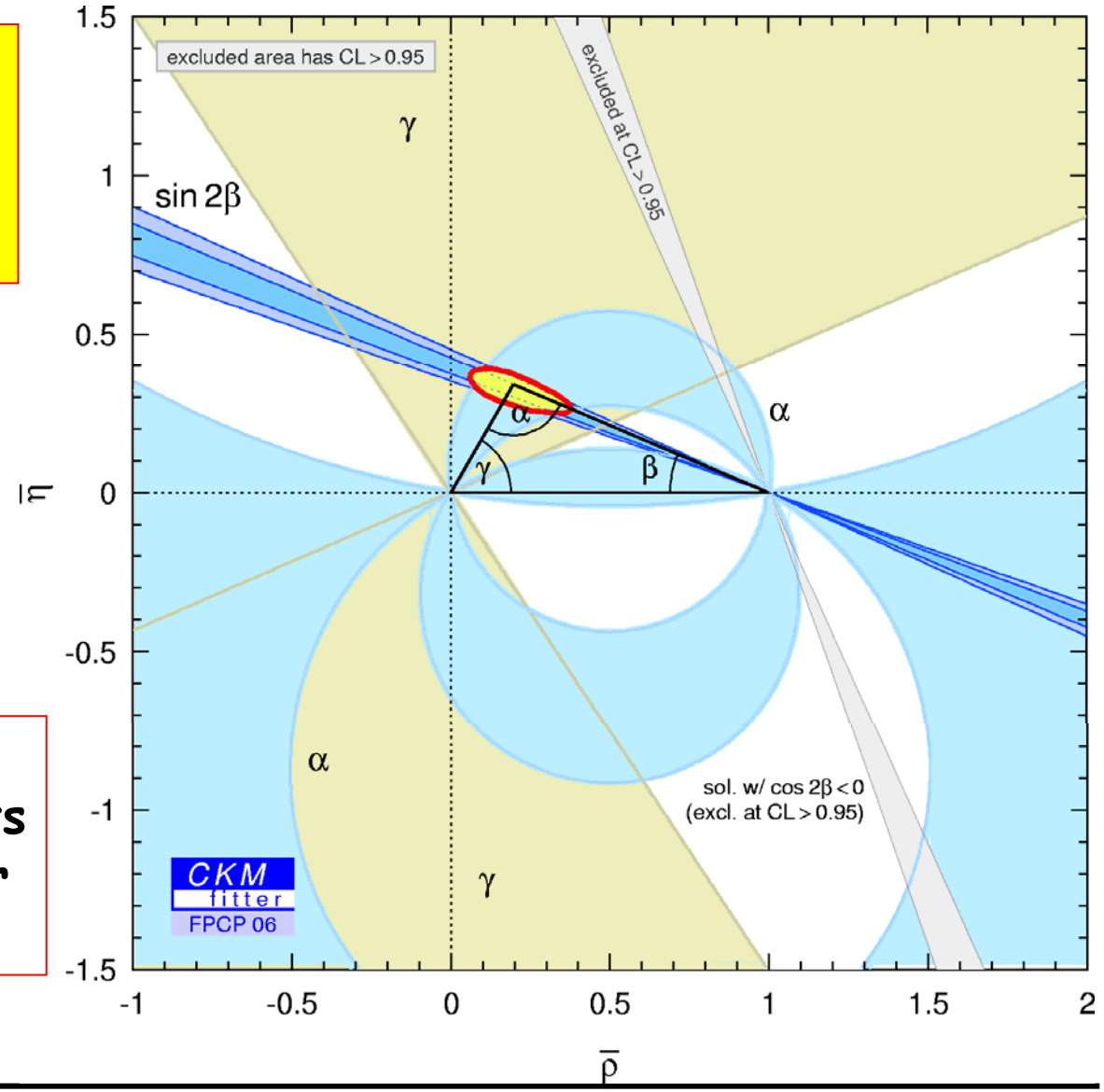
Overconstrained: growing set of independent measurements are consistent with CKM picture

Paradigm change!

Now: looking for New Physics as correction to CKM

UT from CP violation measurements alone

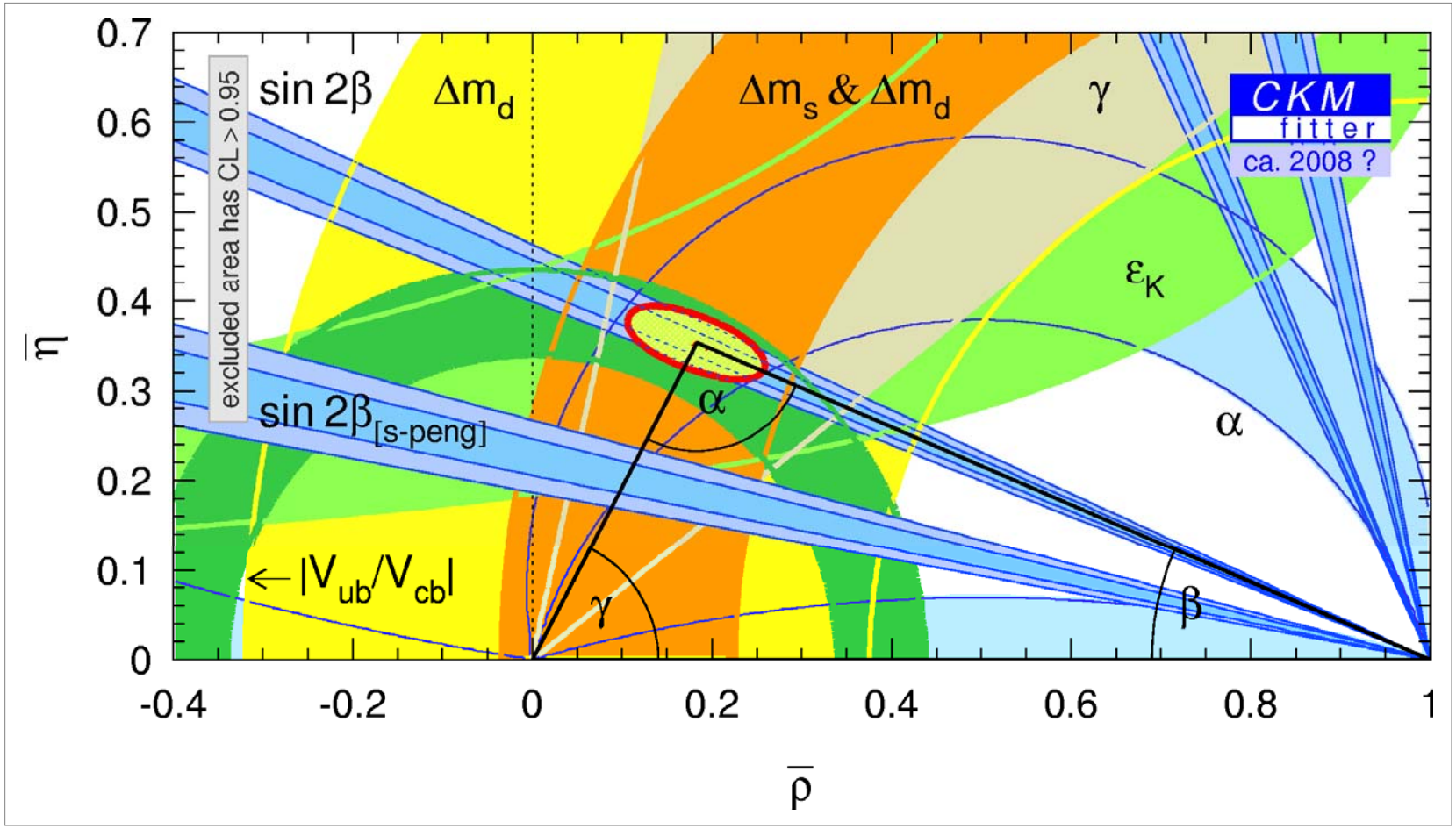
New *B* Factory milestone: Comparable UT precision from *CPV* in *B* decays alone



Overconstrained: subsets of measurements can be used to test for new physics

Global CKM fit: 2008

95% contours



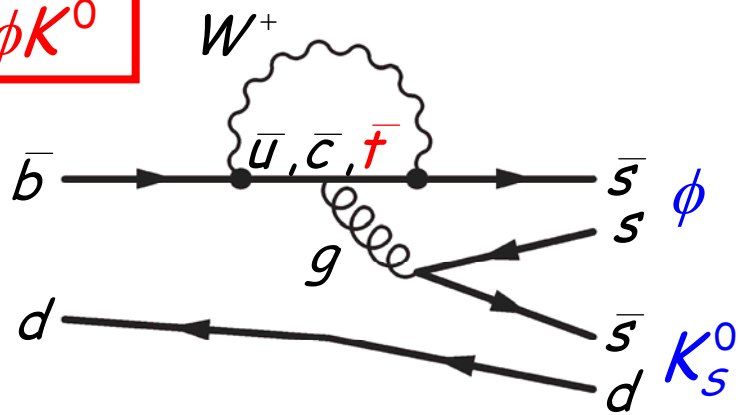
$\sigma(V_{ub}) = 6.5\%$

$\sigma(\Delta m_s) = 5\%$

$\sigma(\sin 2\beta) = 0.019 \quad \sigma(\alpha) = 8^{o} \quad \sigma(\gamma) = 10^{o}$

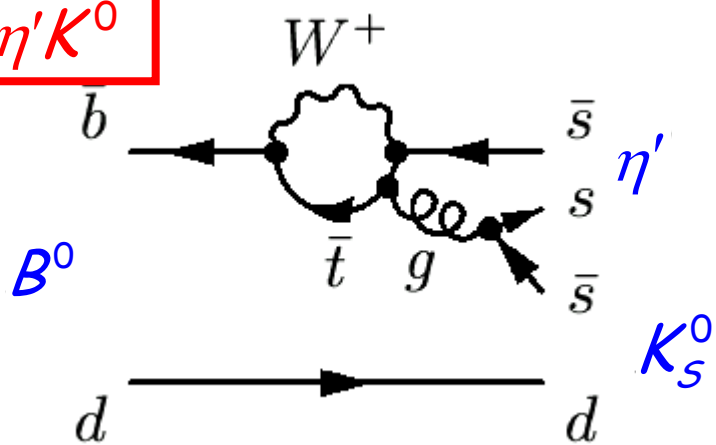
Potential New Physics contributions

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

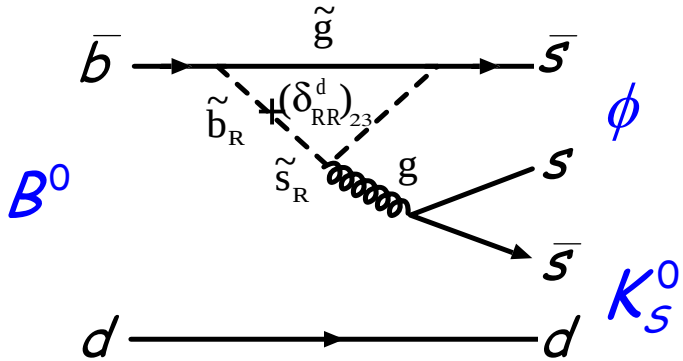


"Internal Penguin"

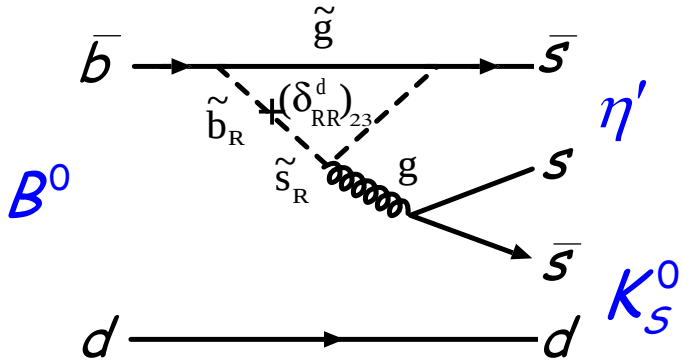
$B^0 \to \eta' K^0$

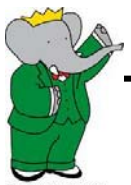


New physics in loops?



SUSY contribution with new phases





Possible evolution of measurements

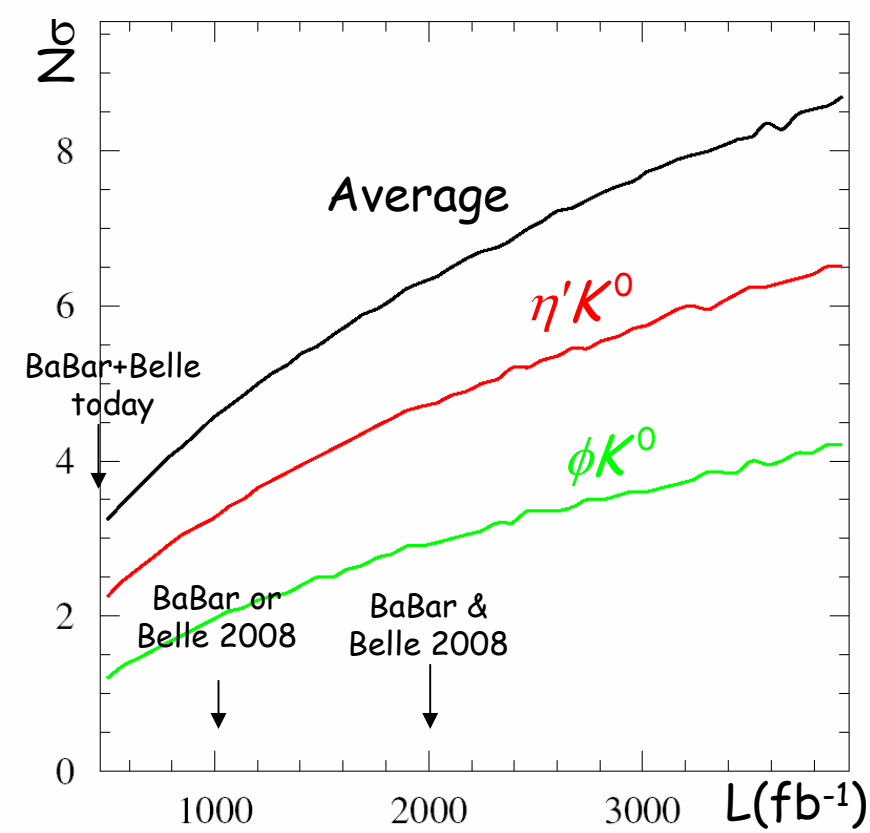
For each mode compare
S_f with $S_f^{exp} = S(X_{c\bar{c}}) + \Delta S_f$

Average: compare

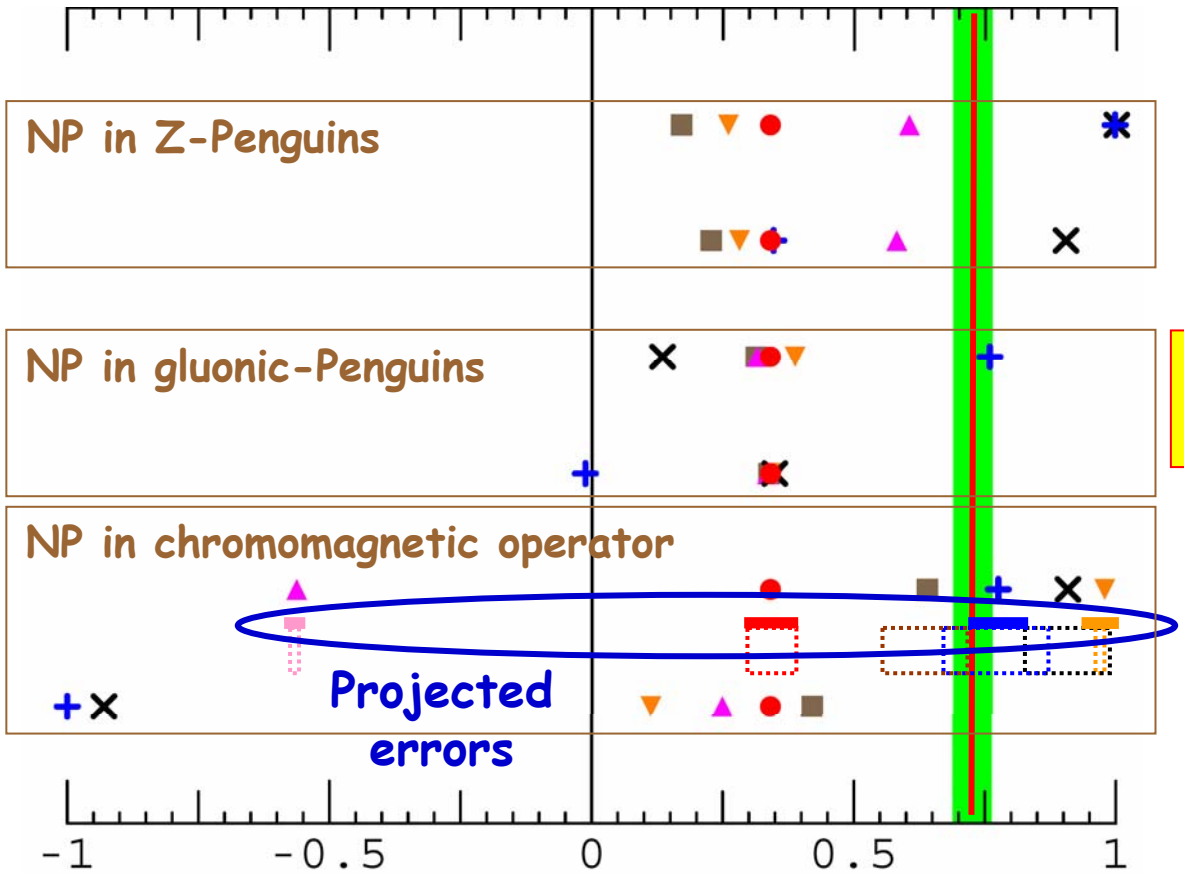
$$\frac{\sum \omega_f (S_f - S_f^{exp})}{\sum \omega_f} \text{ with } 0$$

$$\omega_f = \sigma_f^{ex} \oplus \sigma_f^{th}$$

Assume measurements will fluctuate around current world average central values



Snapshot II: Fall 2010?



$S_{B \to X K_S^0}$

SM + various New Physics

Present SM uncertainty "1 sigma"

$B^0 \to X K_S^0$

● $= \pi$

■ $= \eta$

▲ $= \eta'$

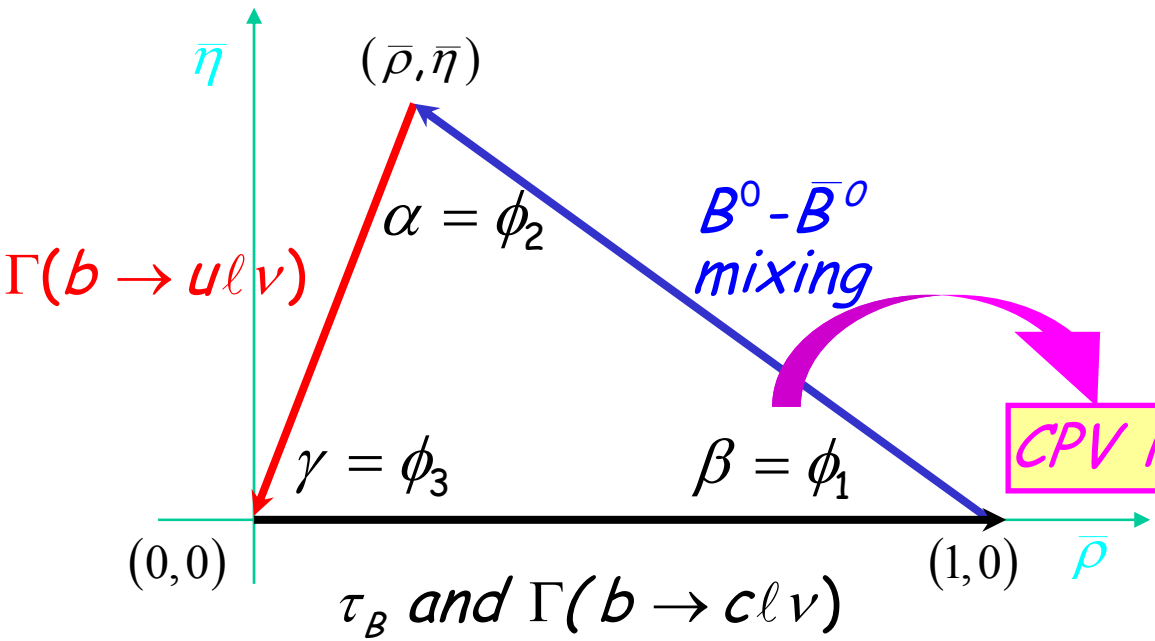
▼ $= \phi$

× $= \omega$

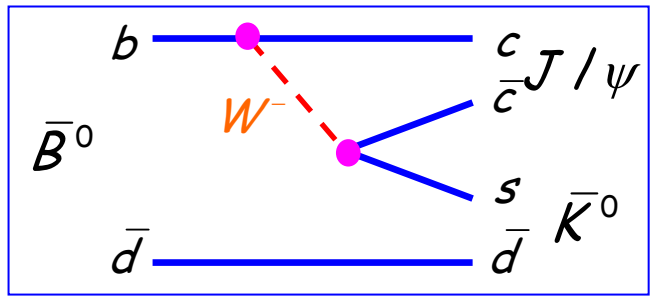
+ $= \rho$

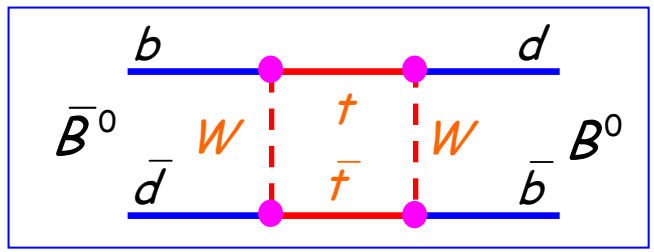
Buchalla, Hiller, Nir, Raz
hep-ph/0503151

CPV in charmonium modes



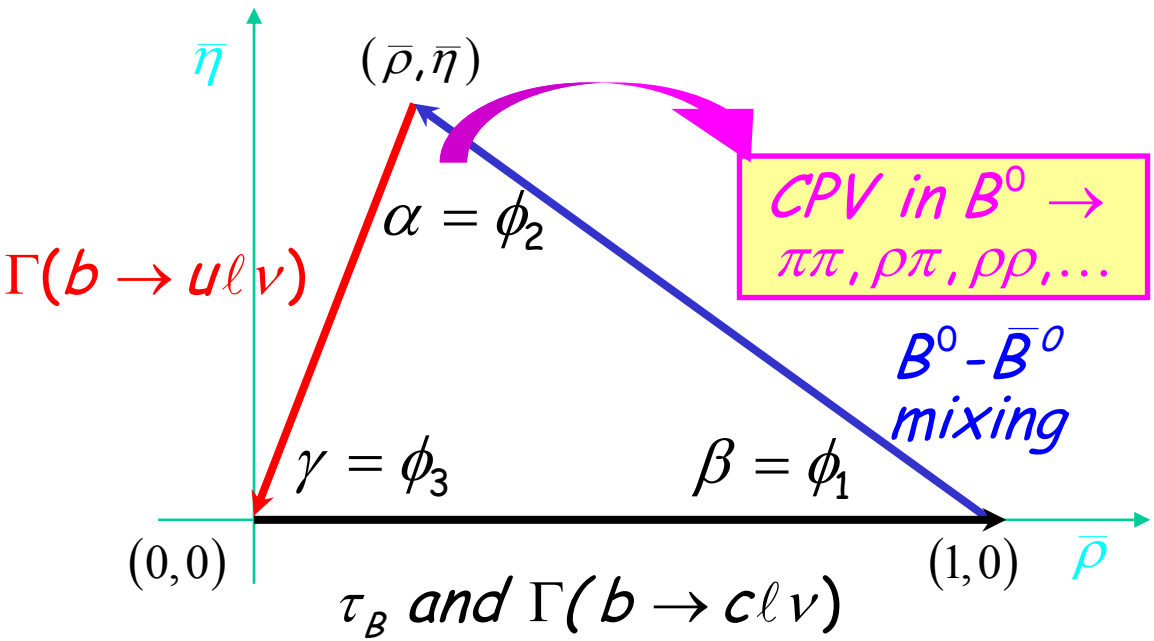
CPV in $B^0 \to J/\psi K^0_S$





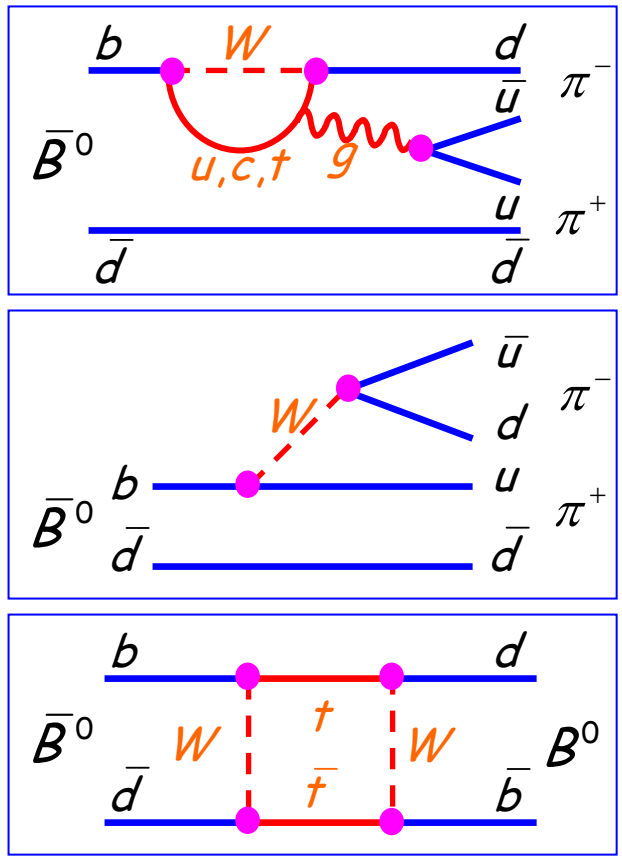
Interference of $b \to c$ tree decay with mixing

CPV in charmless modes

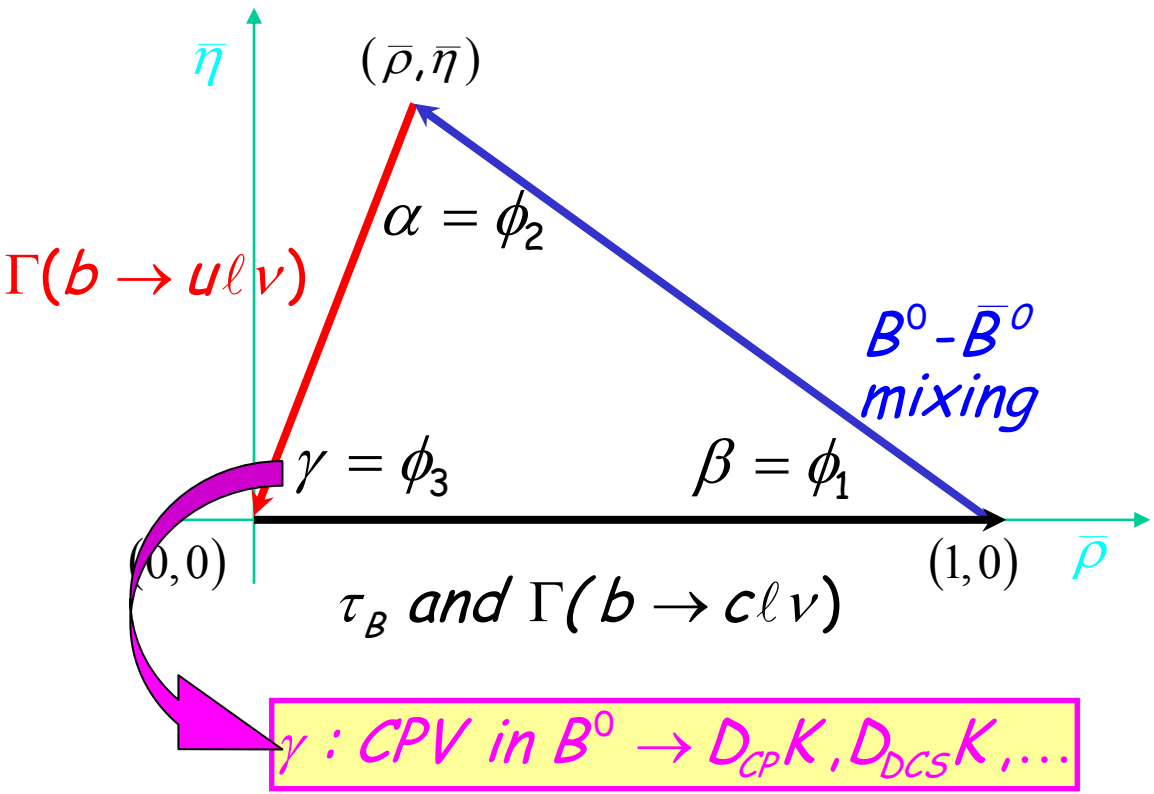


Interference of suppressed $b \to u$ tree decay with mixing

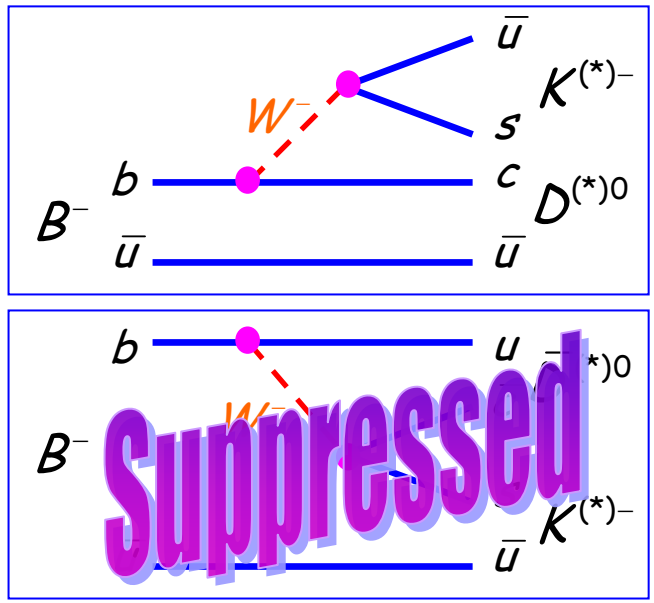
3rd component: sizable Penguin diagram



Remarkably good progress on gamma!



Effect depends on ratio of two diagrams



$+D(\bar{D})$ decay to common final state

$D_{CP}, D_{DCS}, D^0 \to K_S^0\pi^+\pi^-$

Interference of color-allowed and color-suppressed tree decays

BABAR publications since last P5 visit

1) A study of the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ mesons in inclusive c cbar production near sqrt(s) = 10.6 GeV
2) Study of the decay anti-B^0 -> D^{*+} omega pi^-
3) Observation of a Charmed Baryon Decaying to D^0p at a Mass Near 2.94 GeV/c^2
4) Measurements of *CP*-Violating Asymmetries and Branching Fractions in *B* Decays to omega *K* and omega pi
5) Measurements of branching fractions, rate asymmetries, and angular distributions in the rare decays *B* -> *K* l^+l^- and *B* -> *K** l^+l^-
6) Measurement of branching fractions and CP-violating charge asymmetries for *B* meson decays to $D^{(*)}$ anti-$D^{(*)}$, and implications for the CKM angle gamma
7) Measurement of Branching Fractions in Radiative *B* Decays to eta *K* gamma and Search for *B* Decays to eta' *K* gamma
8) Search for *T*, *CP* and *CPT* Violation in B^0-anti-B^0 Mixing with Inclusive Dilepton Events
9) Search for the decay tau- -> 3pi- $2pi^+$ $2pi^0$ nu_{tau}
10) Search for the charmed pentaquark candidate $Theta_c(3100)^0$ in e^+e^- annihilations at sqrt(s)=10.58 GeV

BABAR publications since last P5 visit

11) Observation of B^0 Meson Decay to $a_1^{+/-}$(1260) $pi^{-/+}$
12) Branching fraction limits for B^0 decays to eta' eta, eta' pi^0 and eta pi^0
13) Measurement of the B^- -> D^0 K^{*-} branching fraction
14) Measurement of anti-B^0 -> $D^{(*)0}$ anti-$K^{(*)0}$ branching fractions
15) Measurement of time-dependent *CP* asymmetries in B^0 -> $D^{(*)+/-}$ $pi^{-/+}$ and B^0 -> $D^{+/-}$ $rho^{-/+}$ decays
16) Measurements of the branching fraction and time-dependent *CP* asymmetries of B^0 -> J/psi pi^0 decays
17) The e^+e^- -> 3(pi^+pi^-), 2($pi^+pi^-pi^0$) and K^+K^-2(pi^+pi^-) cross sections at center-of-mass energies from production threshold to 4.5 GeV measured with initial-state radiation
18) Measurements of the *B* -> *D** form factors using the decay anti-B^0 -> $D^{*+}e^-$ anti-nu_e
19) Measurement of *CP* observables for the decays $B^{+/-}$ -> D^0_{CP} $K^{+/-}$
20) Study of e^+e^- -> *p* anti-*p* using initial state radiation with BABAR
21) Determinations of $|V_{ub}|$ from Inclusive Semileptonic *B* Decays with Reduced Model Dependence

BABAR publications since last P5 visit

22) Search for the rare decays B^0 -> $D_s^{(*)+}$ $a_0^{(2)-}$
23) Search for rare quark-annihilation decays, B^- -> $D_s^{(*)-}$ phi
24) Measurements of $Lambda^+_c$ Branching Fractions of Cabibbo-Suppressed Decay Modes involving Lambda and $Sigma^0$
25) Measurement of the inclusive electron spectrum in charmless semileptonic B decays near the kinematic end point and determination of $|V_{ub}|$
26) Study of the X(3872) and Y(4260) in B^0 -> J/psi pi^+ pi^- K^0 and B^- -> J/psi pi^+ pi^- K^- decays
27) Search for the decay B^+ -> tau^+ nu_{tau}
28) Measurement of *CP* observables for the decays $B^{+/-}$ -> D^0_{CP} $K^{*+/-}$