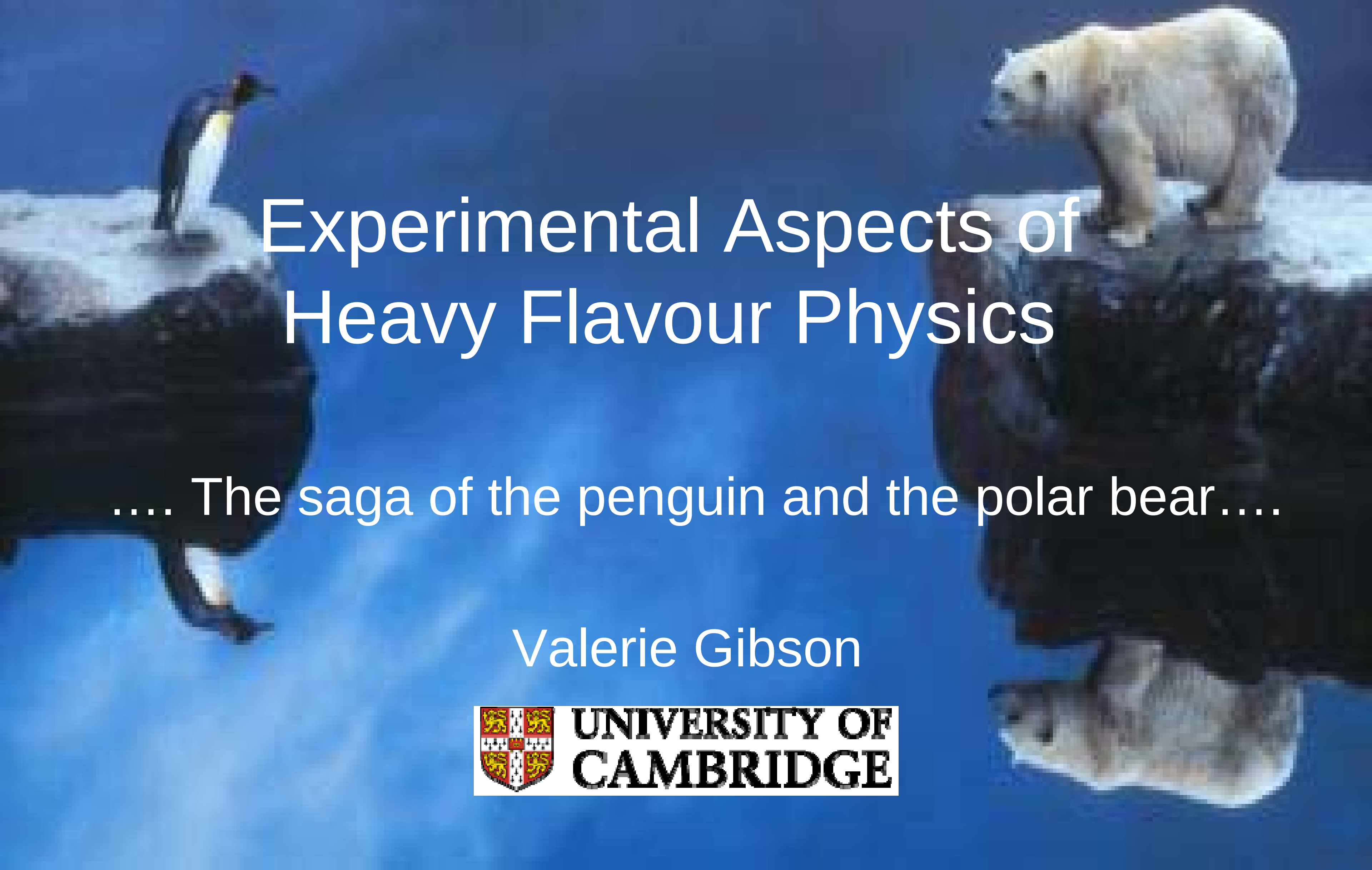
CERN-FNAL HCP 2009



Experimental Aspects of Heavy Flavour Physics

…. The saga of the penguin and the polar bear….

Valerie Gibson

UNIVERSITY OF CAMBRIDGE

Disclaimer….

The title “Experimental Aspects of Heavy Flavour Physics” covers an enormous range of topics. Therefore I can only present a very selective personal view. Concentrate on mostly experimental aspects of

The quest to understand the SM picture of Heavy Flavours and the search for New Physics.

Acknowledgements

I have taken my inspiration from many recent results and conference talks….If you would like to know more about the current status of Heavy Flavour Physics, have a look at…

Recontres de Moriond EW/QCD 2009

Heavy Flavor Averaging Group

http://www.slac.stanford.edu/xorg/hfag/

Many thanks to those who (un)knowingly help me:
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G.Hamel de Monchenault,
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and many more….

Flavor Physics &
CP Violation 2009

FPCP 2009

May 27– June 1, Lake Placid, NY

To integrate past results with recent developments in flavor physics and CP violation, both in theory and experiment. Among the topics included will be: Bottom, Charm and Kaon mixing and decays, determination of the CKM matrix elements, neutrino masses and mixings, new spectroscopy, and future facilities.

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Overview

- Introduction
- The Standard Model
- B Physics
- Celebrating the B factories

Lecture 1

- What have we learnt from the Tevatron ?
- The LHC era
- and beyond….
- Summary

Lecture 2

Role of Heavy Flavour Physics

Heavy flavour physics has led the way to

- The 3 generation Standard Model
- The CKM picture of flavour
- CP Violation

SM cannot be ultimate theory

- low-energy effective theory of a more fundamental theory at a higher energy scale (TeV range)
- Hierarchy problem: New Physics required to cancel radiative corrections to the Higgs mass but leave the SM EW predictions unaffected

NP needs to have a special flavour structure

- provide the suppression mechanism for FCNC processes already observed.
- we need to measure the flavour structure to distinguish between the NP models.

Flavour physics goes hand-in-hand with direct searches

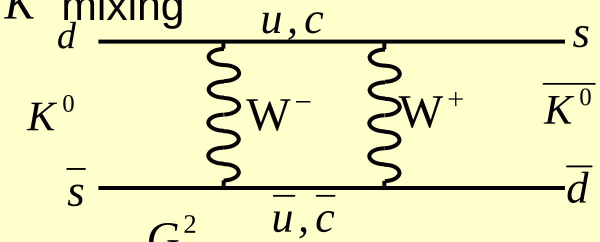
Historical Note

New Physics in box diagrams

1970’s

Glashow, Iliopoulos and Maini : existence of c quark (GIM mechanism)

Gaillard, Lee and Rosner : m_c~1.5 GeV from $K^0-\bar{K}^0$ mixing



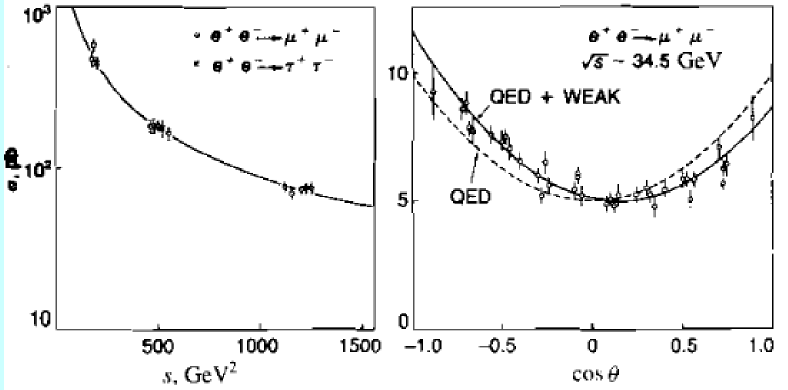
$$\Delta m_K = \frac{G_F^2}{4\pi} m_K f_K^2 m_c^2 \cos^2\theta_c \sin^2\theta_c$$

1974 c quark discovered

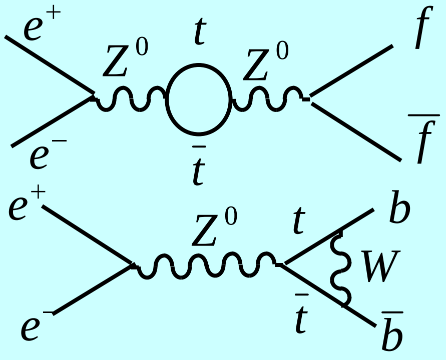
New Physics in interference

1980’s

$$\boxed{e^+e^- \to \mu^+\mu^-}$$



Existence of Z^0 at high $\sqrt{s}$

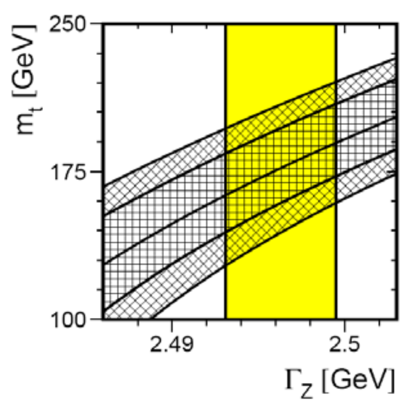


New Physics in loops

1990’s

Virtual effects at the Z^0
LEP

$$\boxed{m_t = 170 \pm 10^{+17}_{-19}\text{ GeV}}$$



The Standard Model

Physical quark states in the Standard Model

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L ,\ldots\ldots\, u_R, d_R, c_R, s_R, t_R, b_R$$

Lagrangian for charged current weak decays

$$L_{cc} = -\frac{g}{\sqrt{2}} J^{\mu}_{cc} W^{*}_{\mu} + h.c.$$

where

$$J^{\mu}_{cc} = (\bar{u}, \bar{c}, \bar{t})_L \, \gamma^{\mu} \, V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

CKM Matrix

V_{CKM} describes rotation between the weak eigenstates (d',s',b') and mass eigenstates (d,s,b)

weak states

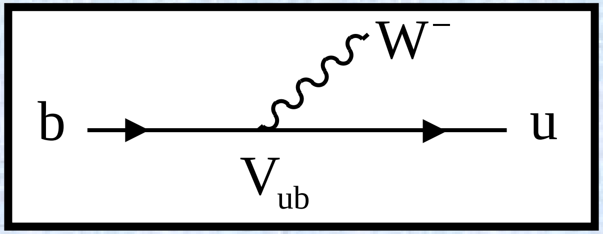
CKM matrix

mass states

Quarks

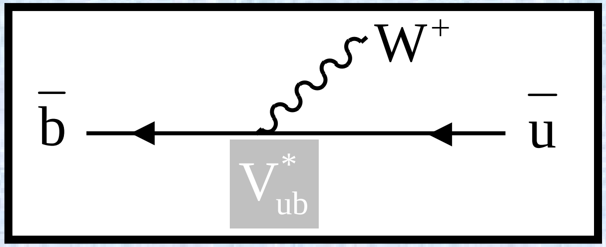
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

V_{ij} proportional to transition amplitude from quark j to quark i



Antiquarks

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$



CPV due to complex phases of CKM matrix elements

CKM Matrix

- CKM matrix is complex and unitary

$$\boxed{\hat{V}^{+}_{\text{CKM}}\hat{V}_{\text{CKM}} = 1}$$

- 4 independent parameters
  - These 4 numbers are fundamental constants of nature and must be determined from experiment
- Standard parametrization (PDG)
  - 3 angles $(\theta_{12}, \theta_{23}, \theta_{13})$ 1 phase δ

$$\boxed{V_{CKM} = R_{23} \times R_{13} \times R_{12}}$$

$$R_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \quad R_{13} = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij} \quad c_{ij} = \cos\theta_{ij}$$

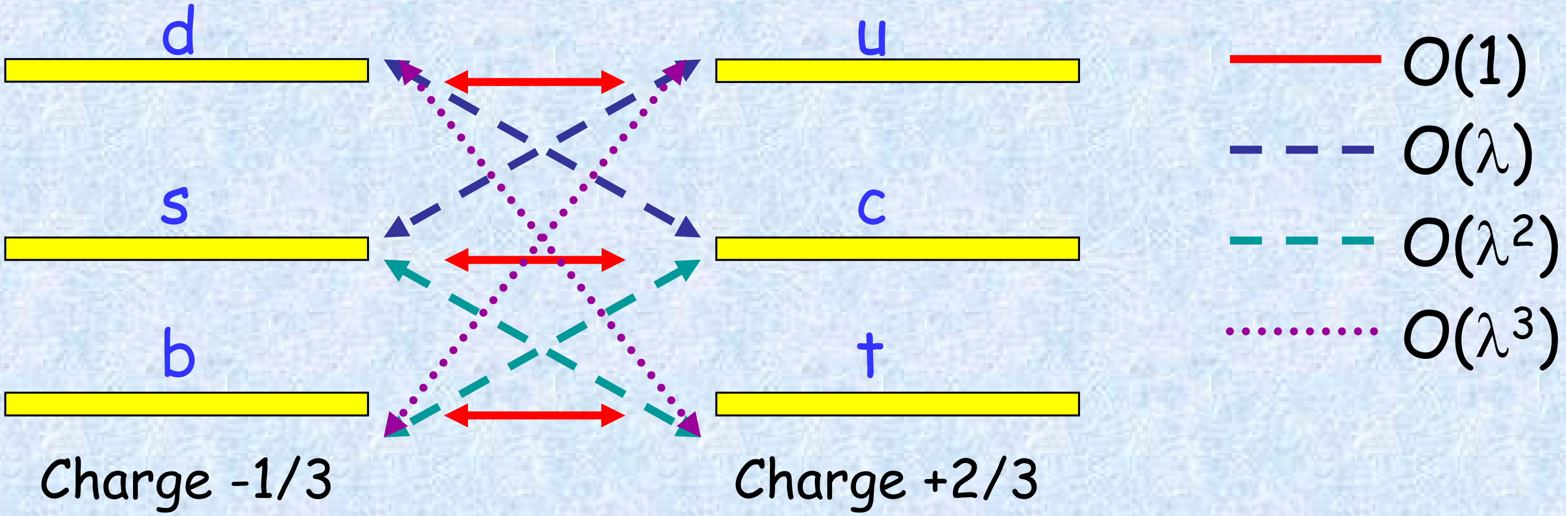
Wolfenstein Parameterization

Wolfenstein parameterization (perturbative form)

$$\boxed{\lambda = s_{12} \qquad A = \frac{s_{23}}{s_{12}^2} \qquad \rho = \frac{s_{13}\cos\delta}{s_{12}s_{23}} \qquad \eta = \frac{s_{13}\sin\delta}{s_{12}s_{23}}}$$

$\lambda = sin\,\theta_{12} \approx 0.23$

Reflects hierarchy of strengths of quark transitions



Wolfenstein Parameterization

Wolfenstein parameterization to O(λ^3):

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Next-to leading order corrections in λ will be important in LHC era:

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 - \lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5(1/2 - \rho - i\eta) & 1-\lambda^2/2 - \lambda^4/8\,(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 + A\lambda^4(1/2-\rho-i\eta) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^6)$$

$$(\bar{\rho},\bar{\eta}) \equiv (1-\lambda^2/2)(\rho,\eta)$$

CP Violation in the Standard Model

Requirements for CP violation

$$\boxed{\begin{aligned}&\left(m_t^2-m_c^2\right)\left(m_t^2-m_u^2\right)\left(m_c^2-m_u^2\right)\\ \times&\left(m_b^2-m_s^2\right)\left(m_b^2-m_d^2\right)\left(m_s^2-m_d^2\right)\times J_{CP}\neq 0\end{aligned}}$$

J_{CP} Jarlskog determinant

where $$\boxed{J_{CP}=\left|\mathrm{Im}\left\{V_{i\alpha}V_{j\beta}V_{i\beta}^{*}V_{j\alpha}^{*}\right\}\right| \quad (i\neq j,\alpha\neq\beta)}$$

Using parameterizations

$$\boxed{J_{CP}=s_{12}s_{13}s_{23}c_{12}c_{23}c_{13}\sin\delta=\lambda^6A^2\eta=O\left(10^{-5}\right)}$$

→ CP violation is small in the Standard Model

Unitarity Triangles

CKM matrix is unitary : 12 conditions (6 normalisation, 6 orthoganality)

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

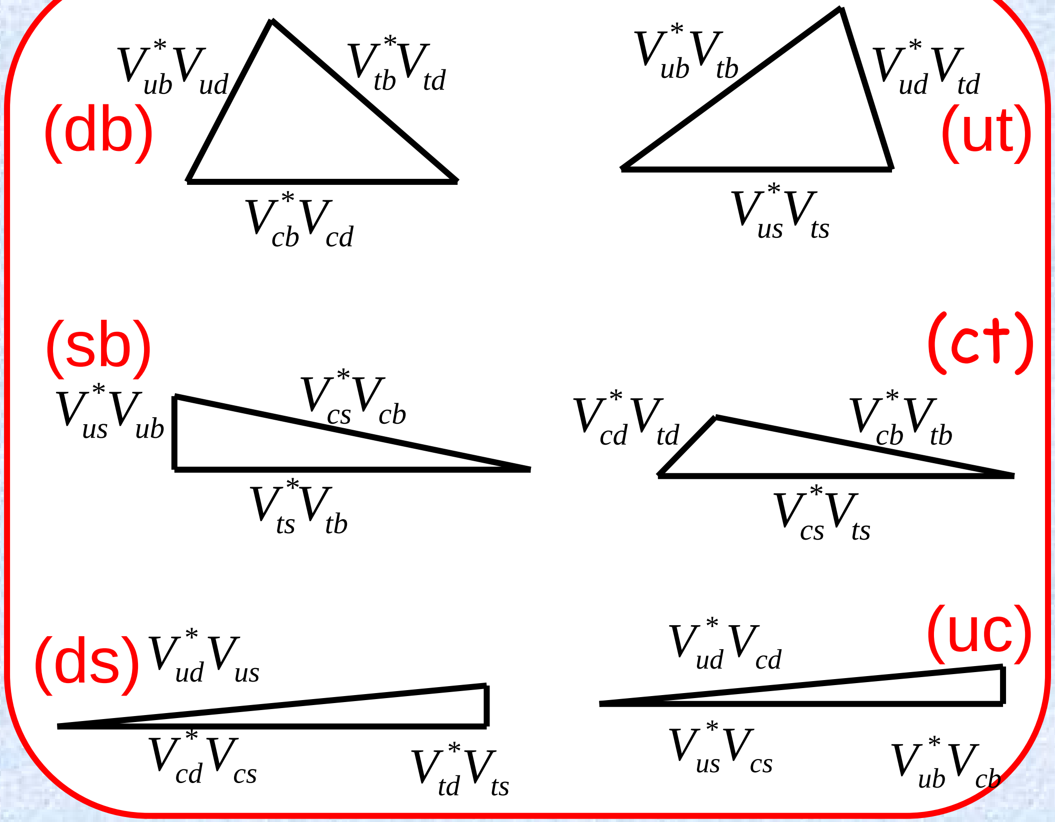
$$V_{us}V_{ub}^{*}+V_{cs}V_{cb}^{*}+V_{ts}V_{tb}^{*}=0 \text{ (sb)}$$

$$V_{ud}V_{us}^{*}+V_{cd}V_{cs}^{*}+V_{td}V_{ts}^{*}=0 \text{ (ds)}$$

$$V_{ud}V_{td}^{*}+V_{us}V_{ts}^{*}+V_{ub}V_{tb}^{*}=0 \text{ (ut)}$$

$$V_{cd}V_{td}^{*}+V_{cs}V_{ts}^{*}+V_{cb}V_{tb}^{*}=0 \text{ (ct)}$$

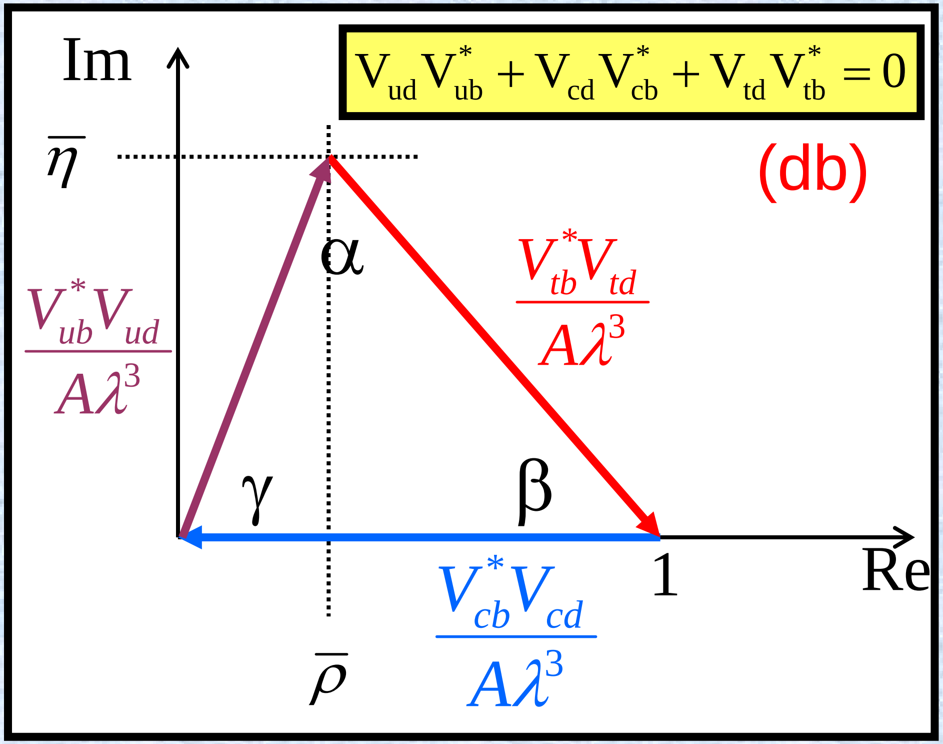
$$V_{ud}V_{cd}^{*}+V_{us}V_{cs}^{*}+V_{ub}V_{cb}^{*}=0 \text{ (uc)}$$



All 6 Δ's have the same area (= $J_{CP}/2$), a measure of CPV in the Standard Model.

The Unitarity Triangle

Redraw “unsquashed” Δ’s and take $V_{cb}^{*}V_{cd}$ real divide by $\left|V_{cb}^{*}V_{cd}\right|$



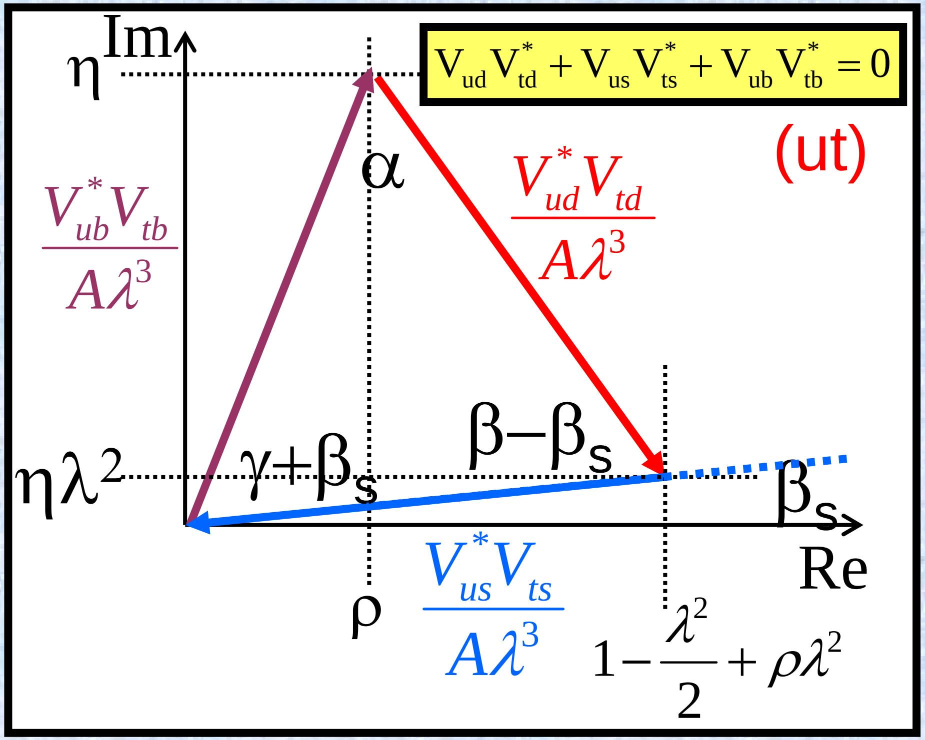
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

$$\alpha \equiv \pi - \beta - \gamma$$

$$\gamma \equiv \arg\left[-\frac{V_{ub}^{*}V_{ud}}{V_{cb}^{*}V_{cd}}\right] = \tan^{-1}\frac{\bar{\eta}}{\bar{\rho}} \sim 70^{o}$$

$$\beta \equiv \arg\left[-\frac{V_{cb}^{*}V_{cd}}{V_{tb}^{*}V_{td}}\right] = \tan^{-1}\frac{\bar{\eta}}{1-\bar{\rho}} \sim 21^{o}$$

The … other…Unitarity Triangle



$$\beta_s \equiv \arg\left[-\frac{V_{cb}^* V_{cs}}{V_{tb}^* V_{ts}}\right] \sim \eta\lambda^2 \sim 1^o$$

2 Δ's identical to O(λ^3)

The Ultimate Quest…

To discover New Physics

beyond the Standard Model

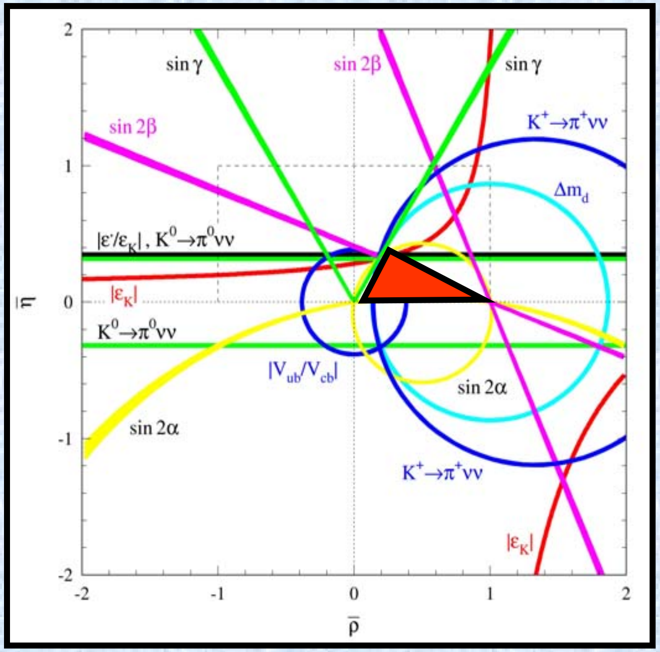
The Quest…

NP models introduce new particles which could

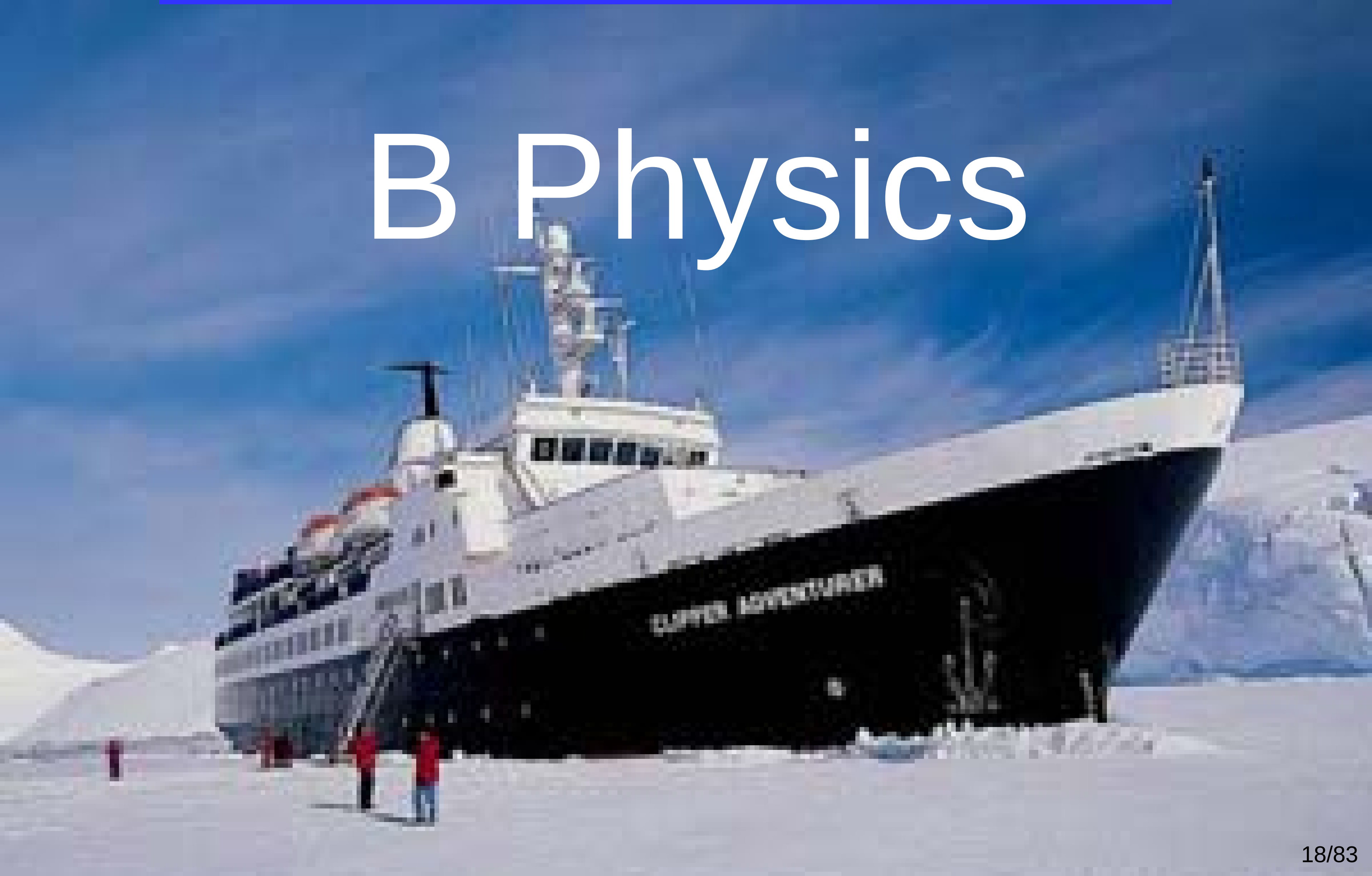
- be produced and discovered as real particles
- appear as virtual particles in loop processes → observable deviations from the SM expectations in flavour physics and CPV

Heavy flavour programme

- Precision measurements of CKM elements
- Compare tree level processes with loop processes sensitive to NP
- Measure all angles and sides in many different ways and look for inconsistencies
- Measure processes very suppressed in SM



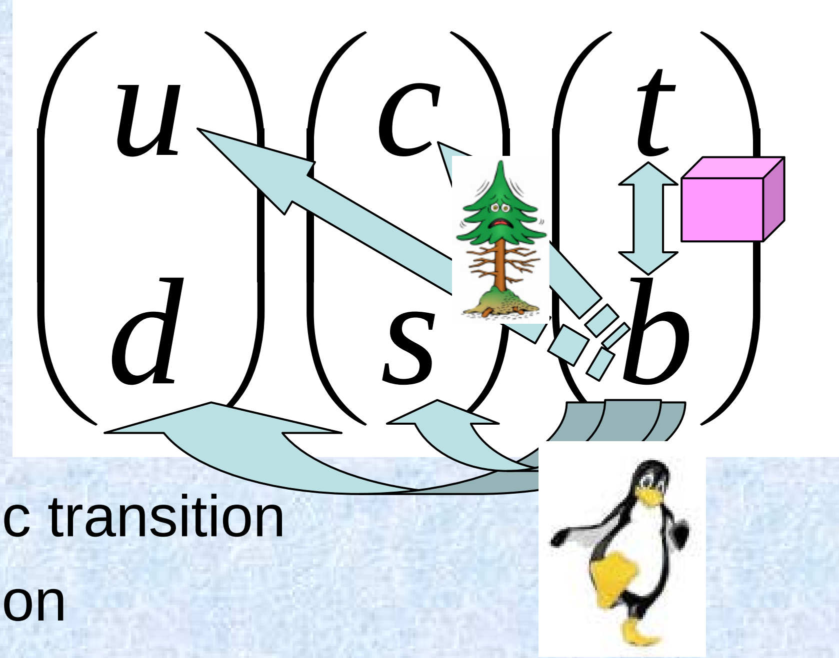
The Tools....



B Physics

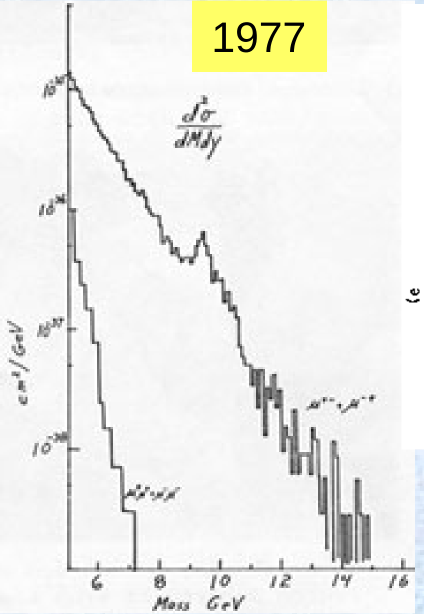
Why the b-quark ?

- Heaviest quark that forms hadronic bound states (m~4.7 GeV)
- Must decay outside 3rd family
  - All decays are CKM suppressed
  - Long lifetime (~1.6 ps)
- High mass: many accessible final states (all Br's are small)



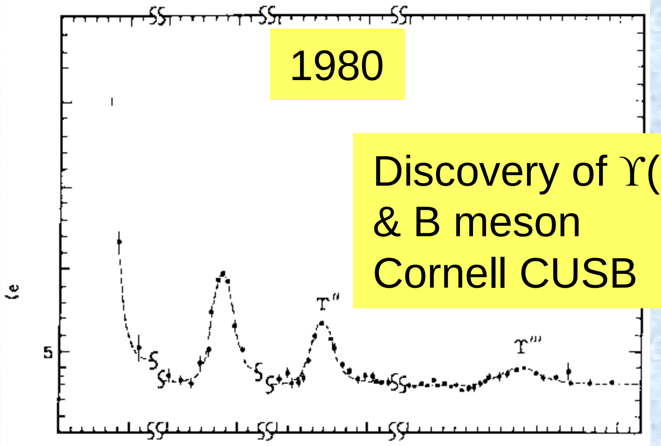
- Dominant decay process: "tree" b→c transition
- Very suppressed "tree" b→u transition
- FCNC: "penguin" b→s,d transition
- Flavour oscillations (b→t "box" diagram)
- CP violation – expect large CP asymmetries in some B decays

The Birth of B Physics



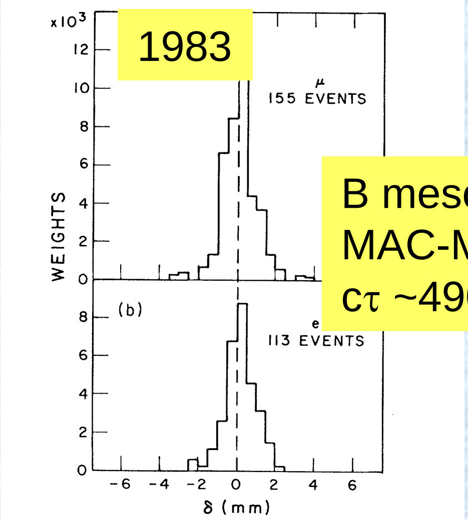
1977

Discovery of b quark
Fermilab fixed target



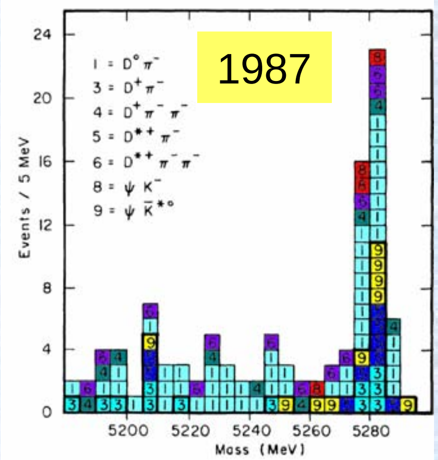
1980

Discovery of Υ(4s)
& B meson
Cornell CUSB



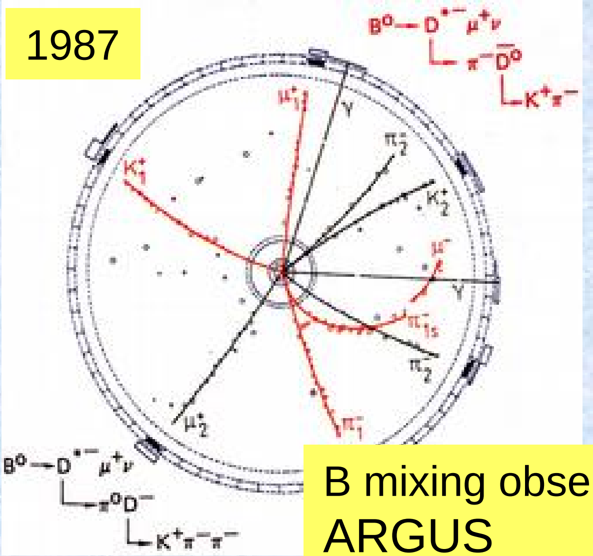
1983

B meson lifetime
MAC-Mark II
cτ ~490 μm



1987

Exclusive reconstruction of
several b→c decay modes
CLEO

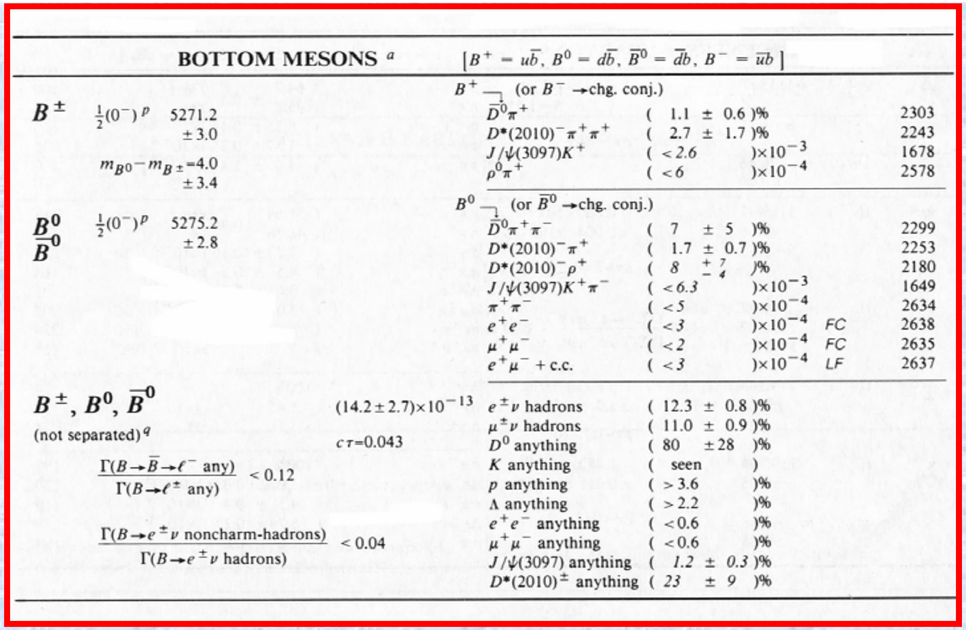


1987

B mixing observed
ARGUS

B Physics

PDG 1986



BOTTOM MESONS [a]				$[B^+ = u\bar{b},\ B^0 = d\bar{b},\ \bar{B}^0 = \bar{d}b,\ B^- = \bar{u}b]$			
				$B^+ \to$ (or $B^- \to$ chg. conj.)			
$B^\pm$	$\frac{1}{2}(0^-)$ [p]	5271.2 ±3.0		$\bar{D}^0\pi^+$	(1.1 ± 0.6)%		2303
				$D^*(2010)^-\pi^+\pi^+$	(2.7 ± 1.7)%		2243
		$m_{B^0}-m_{B^\pm}=-4.0$ ±3.4		$J/\psi(3097)K^+$	(<2.6)$\times10^{-3}$		1678
				$\rho^0\pi^+$	(<6)$\times10^{-4}$		2578
				$B^0 \to$ (or $\bar{B}^0 \to$ chg. conj.)			
B^0 $\bar{B}^0$	$\frac{1}{2}(0^-)$ [p]	5275.2 ±2.8		$\bar{D}^0\pi^+\pi^-$	(7 ± 5)%		2299
				$D^*(2010)^-\pi^+$	(1.7 ± 0.7)%		2253
				$D^*(2010)^-\rho^+$	(8 $^{+7}_{-4}$)%		2180
				$J/\psi(3097)K^+\pi^-$	(<6.3)$\times10^{-3}$		1649
				$\pi^+\pi^-$	(<5)$\times10^{-4}$		2634
				e^+e^-	(<3)$\times10^{-4}$	FC	2638
				$\mu^+\mu^-$	(<2)$\times10^{-4}$	FC	2635
				$e^+\mu^-$ + c.c.	(<3)$\times10^{-4}$	LF	2637
$B^\pm$, B^0, $\bar{B}^0$ (not separated) [q]			$(14.2\pm2.7)\times10^{-13}$	$e^\pm\nu$ hadrons	(12.3 ± 0.8)%		
				$\mu^\pm\nu$ hadrons	(11.0 ± 0.9)%		
			$c\tau=0.043$	D^0 anything	(80 ±28)%		
$\frac{\Gamma(B\to\bar{B}\to\ell^-\text{ any})}{\Gamma(B\to\ell^\pm\text{ any})} < 0.12$				K anything	(seen)		
				p anything	(>3.6)%		
				Λ anything	(>2.2)%		
				e^+e^- anything	(<0.6)%		
$\frac{\Gamma(B\to e^\pm\nu\text{ noncharm-hadrons})}{\Gamma(B\to e^\pm\nu\text{ hadrons})} < 0.04$				$\mu^+\mu^-$ anything	(<0.6)%		
				$J/\psi(3097)$ anything	(1.2 ± 0.3)%		
				$D^*(2010)^\pm$ anything	(23 ± 9)%		

PDG 2009

> 25 pages

1992	Evidence for Λ_b, B_s
1993	First observation of $B \to K^*\gamma, B \to \pi^+\pi^-$, time dependent B mixing
1994	Evidence for Ξ_b, B^{**}, measurement of exclusive B lifetime
1998	Discovery of B_c
2001	Discovery of CPV in B system
2004	Direct CPV in B system
2006	Measurement of B_s mixing

B Mixing

Mixing of neutral B mesons governed by

$$i\frac{\partial}{\partial t}\begin{pmatrix}a\\b\end{pmatrix}=H\begin{pmatrix}a\\b\end{pmatrix}=\begin{pmatrix}M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12}\\ M_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*} & M_{22}-\frac{i}{2}\Gamma_{22}\end{pmatrix}\begin{pmatrix}a\\b\end{pmatrix}$$

Physical mass eigenstates

$$\left|B_{L,H}\right\rangle = p\left|B^0\right\rangle \pm q\left|\overline{B^0}\right\rangle$$

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

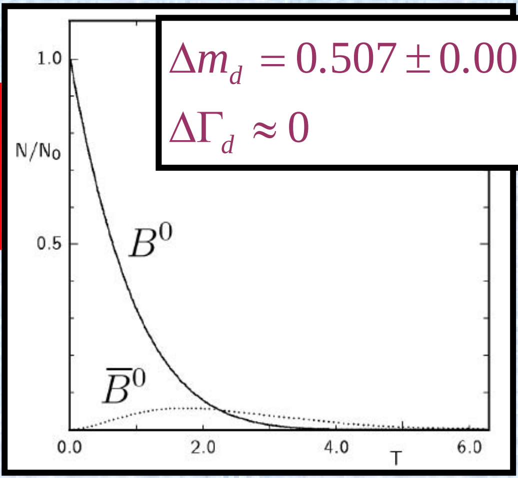
$$|p|^2+|q|^2=1$$

- p and q represent the amount of state mixing

$$\Delta m = m_H - m_L = 2|M_{12}|$$

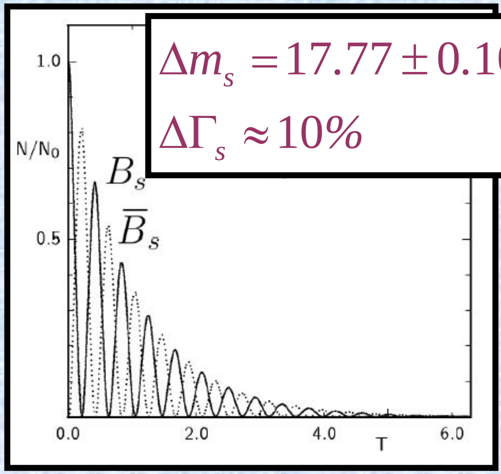
$$\Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|$$

$$|q/p| = 1$$



$$\Delta m_d = 0.507 \pm 0.005\ \mathrm{ps}^{-1}$$

$$\Delta\Gamma_d \approx 0$$



$$\Delta m_s = 17.77 \pm 0.10 \pm 0.007\ \mathrm{ps}^{-1}$$

$$\Delta\Gamma_s \approx 10\%$$

CP Violation in B System

Decay amplitudes of flavour states → final state f

$$\boxed{A_f = \langle f | H | B^0 \rangle \quad \overline{A_f} = \langle f | H | \overline{B^0} \rangle}$$

Define

$$\boxed{\lambda_f = \frac{q}{p}\frac{\overline{A_f}}{A_f}}$$

General time dependence of decay rate for initially pure flavour states

$$\boxed{\begin{aligned}\Gamma_f &\equiv \left|\langle f | H | B^0(t) \rangle\right|^2 = \frac{1+|\lambda_f|^2}{2}|A_f|^2 e^{-t/\tau}\left[\cosh y\, t/\tau + \Omega_f \sinh yt/\tau + C_f \cos xt/\tau - S_f \sin xt/\tau\right] \\ \overline{\Gamma}_f &\equiv \left|\langle f | H | \overline{B}^0(t) \rangle\right|^2 = \frac{1+|\lambda_f|^2}{2}\left|\frac{p}{q}A_f\right|^2 e^{-t/\tau}\left[\cosh yt/\tau + \Omega_f \sinh yt/\tau - C_f \cos xt/\tau + S_f \sin xt/\tau\right]\end{aligned}}$$

$$\boxed{S_f \equiv \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad \Omega_f^2 + S_f^2 + C_f^2 = 1}$$

$\tau \equiv 1/\Gamma$

$x \equiv \Delta m/\Gamma$

$y \equiv \Delta\Gamma/2\Gamma$

3 Types of CP Violation

CP violation if $\Gamma_f \neq \overline{\Gamma}_{f}$

CPV in Decay

Direct CP Violation

$$\left|\frac{\overline{A}_{\bar{f}}}{A_f}\right| \neq 1$$

CPV in Mixing

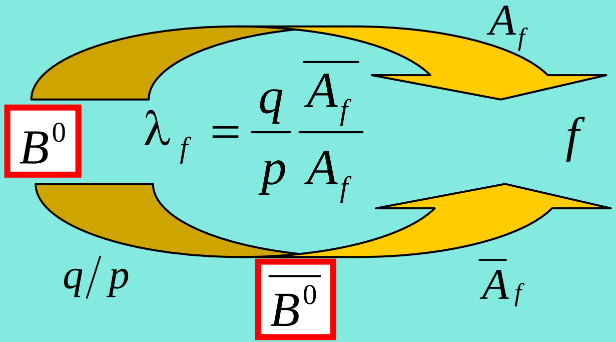
Indirect CP Violation

$$\left|\frac{q}{p}\right| \neq 1 \qquad \mathrm{Im}\left\{\Gamma_{12}^{*} M_{12}\right\} \neq 0$$

CPV in Interference between mixing and decay

Indirect CP Violation

$$\left|\lambda_f\right| = 1, \quad \mathrm{Im}\left\{\lambda_f\right\} \neq 0$$



$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

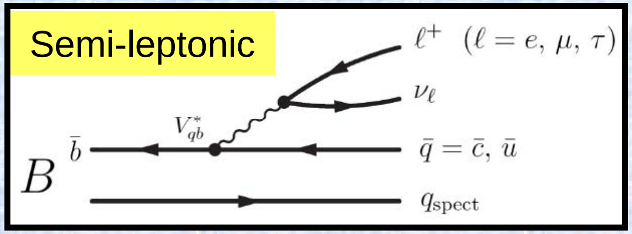
$$A_f^{CP}(t) = \frac{\Gamma_f(t) - \overline{\Gamma}_f(t)}{\Gamma_f(t) + \overline{\Gamma}_f(t)} = \frac{-C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) + \Omega_f \sinh(\Delta\Gamma t/2)}$$

Golden case: CP final state and single dominating amplitude

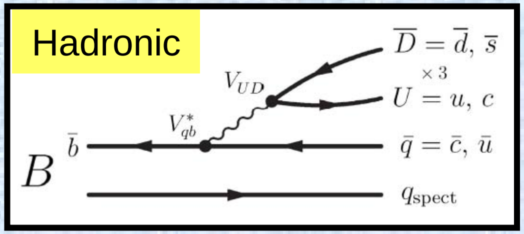
$$A_{f_{CP}}^{CP}(t) = \mathrm{Im}\,\lambda_{f_{CP}} \sin(\Delta m t)$$

B Decays

Dominant decays

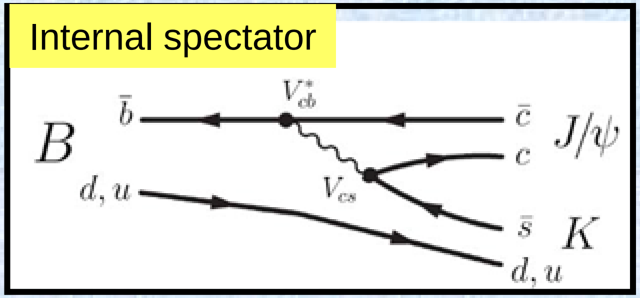


Semi-leptonic

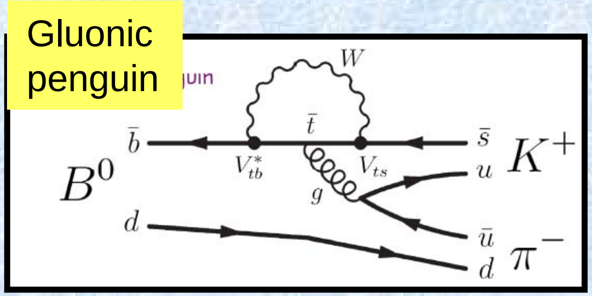


Hadronic

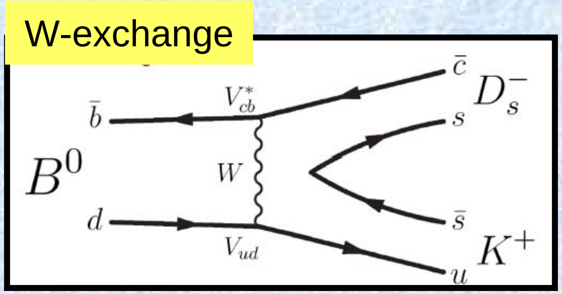
Rare hadronic decays



Internal spectator

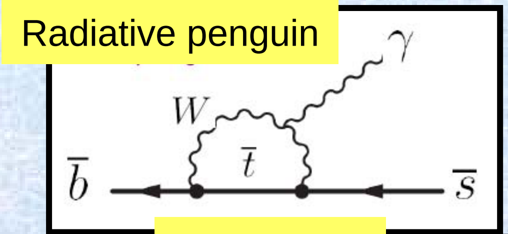


Gluonic penguin

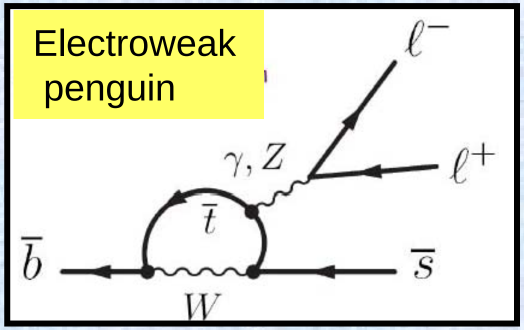


W-exchange

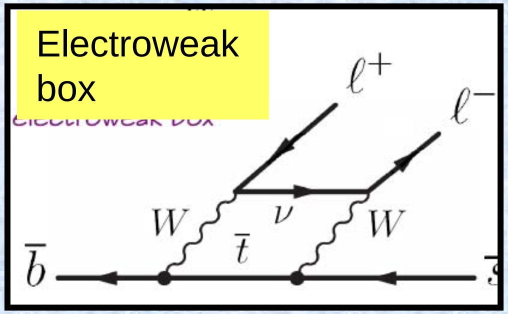
Radiative and leptonic decays



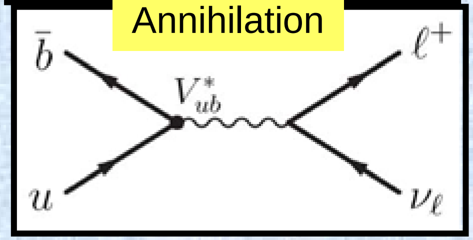
Radiative penguin



Electroweak penguin

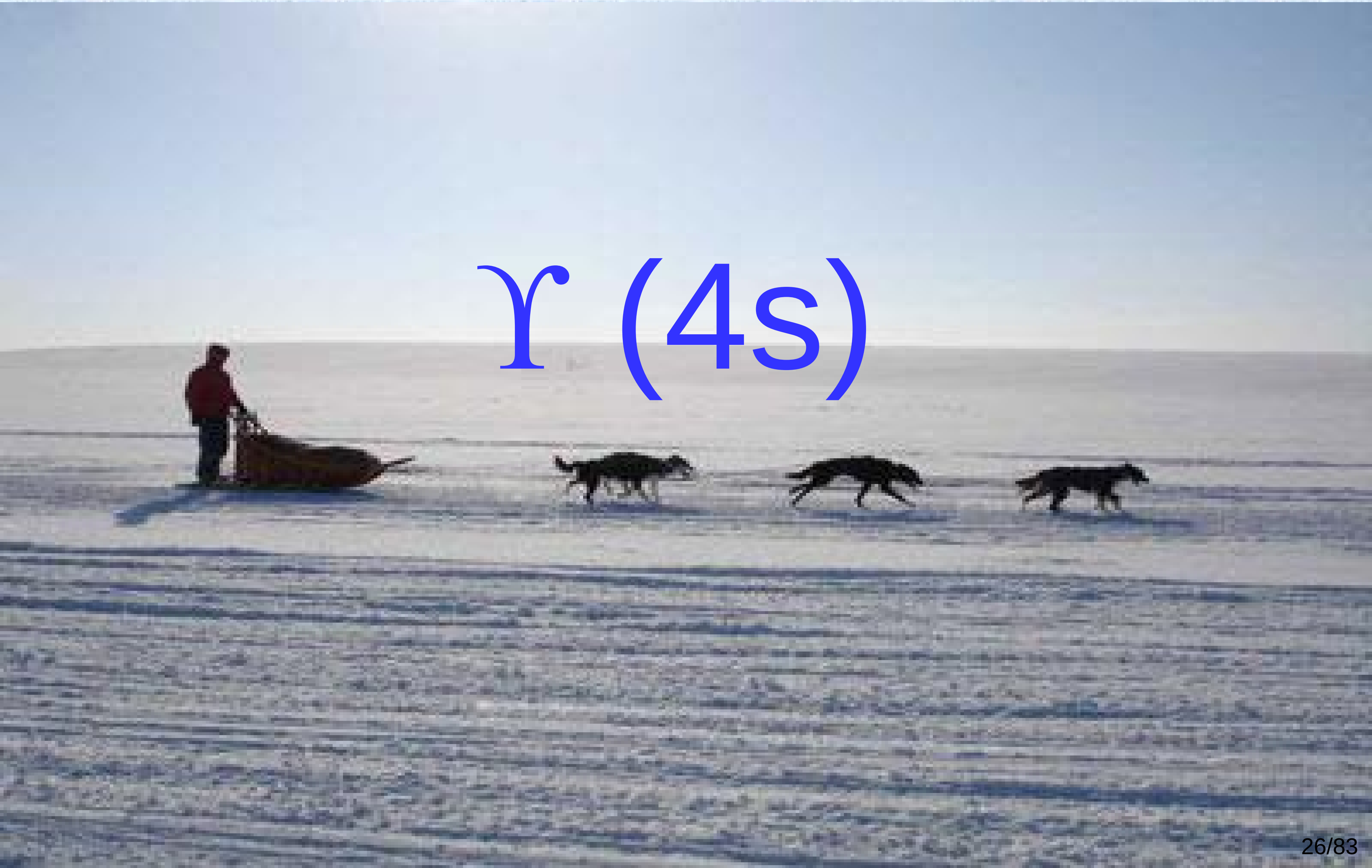


Electroweak box



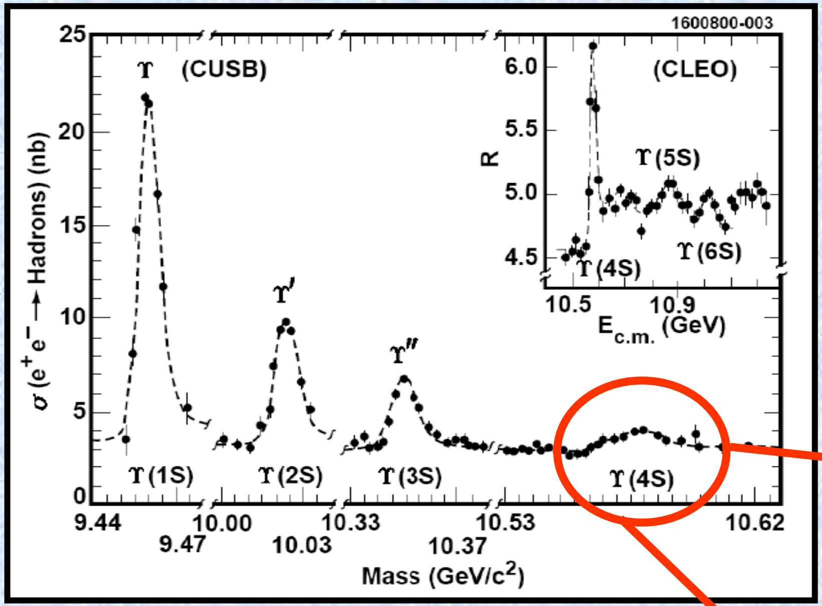
Annihilation

Where to start ?



$\Upsilon(4s)$

Υ (4s) Resonance



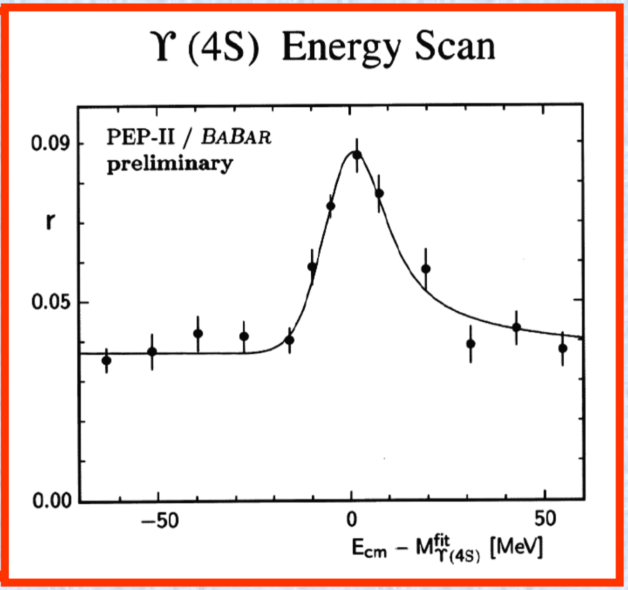
Cleanest way to produce B mesons

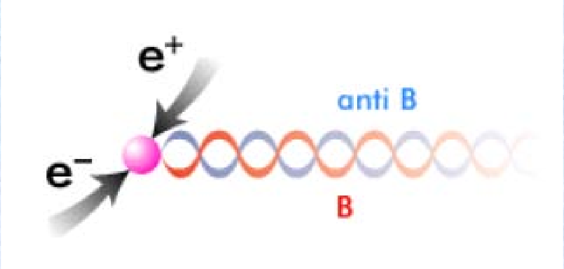
e^+e^- collisions around

$$\boxed{\sqrt{s} = 10.58\,\text{GeV}}$$

$\sigma_{b\bar{b}} = 1.1\,\text{nb}$ continuum ~ 3 nb

~1.1 million $B\bar{B}$ pairs per fb^{-1}





50% / 50%

$B^0 \overline{B^0} / B^+ B^-$

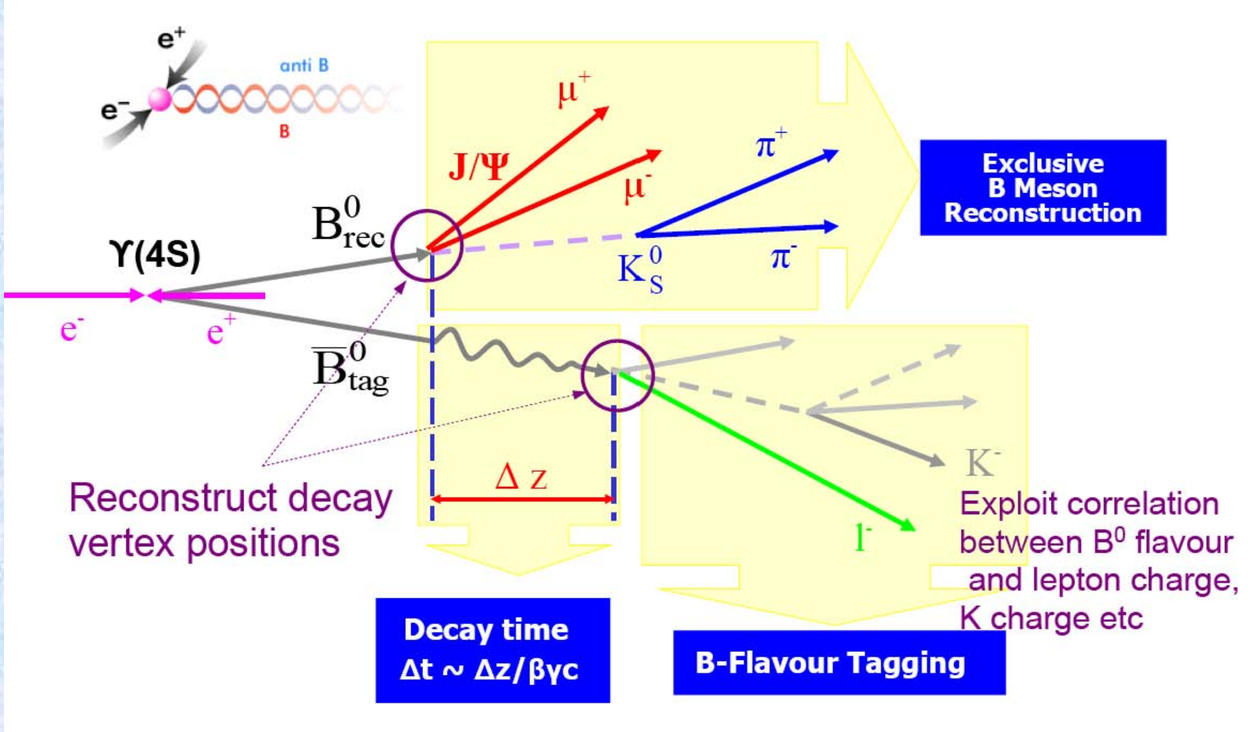
$B\overline{B}$ pair is produced in a coherent L=1 state

Two B mesons evolve until one decays

Υ (4s) Resonance

Symmetric-energy collider : B mesons produced ~ at rest in the CM frame which, combined with a short B lifetime (~1.5 ps), makes flight distance unmeasurably small.

Asymmetric-energy collider : with boost $\boxed{\beta\gamma \sim 0.6}$



Reconstruct decay vertex positions

Exploit correlation between B⁰ flavour and lepton charge, K charge etc

$$\boxed{\begin{gathered}\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c} \\ \langle |\Delta z| \rangle \approx 200\ \mu\mathrm{m}\end{gathered}}$$

Asymmetric B Factories

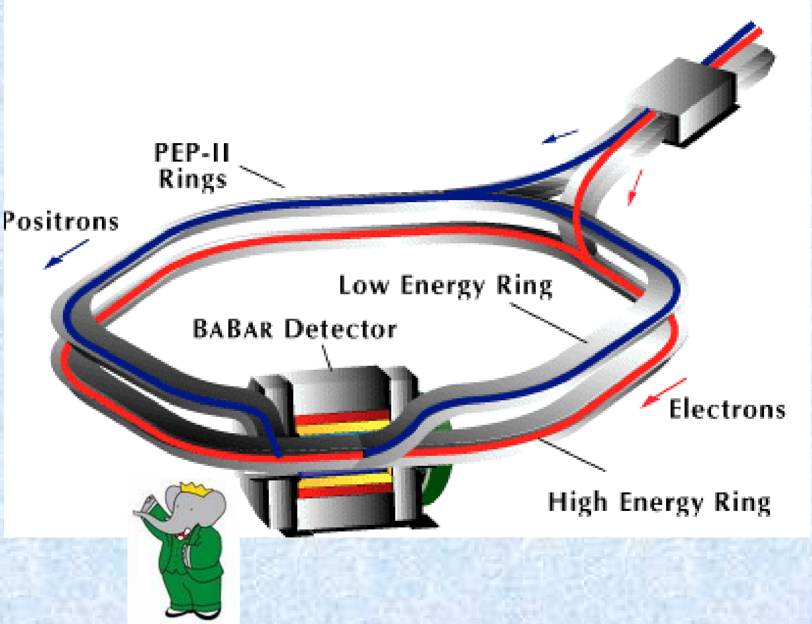
PEP-II @ SLAC

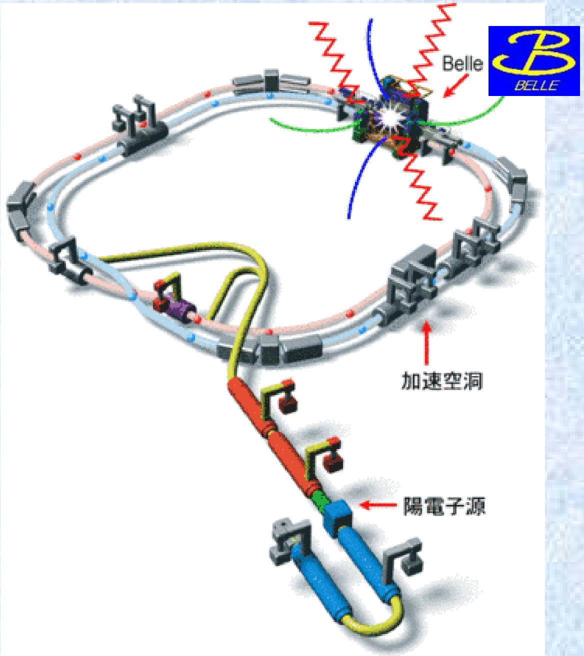
High Energy Ring : 9.0 GeV e^-
Low Energy Ring : 3.1 GeV e^+
Design luminosity : 3 x 10^{33} cm^{-2}s^{-1}
Peak luminosity : 1.207 x 10^{34} cm^{-2} s^{-1}

KEK-B @ KEK

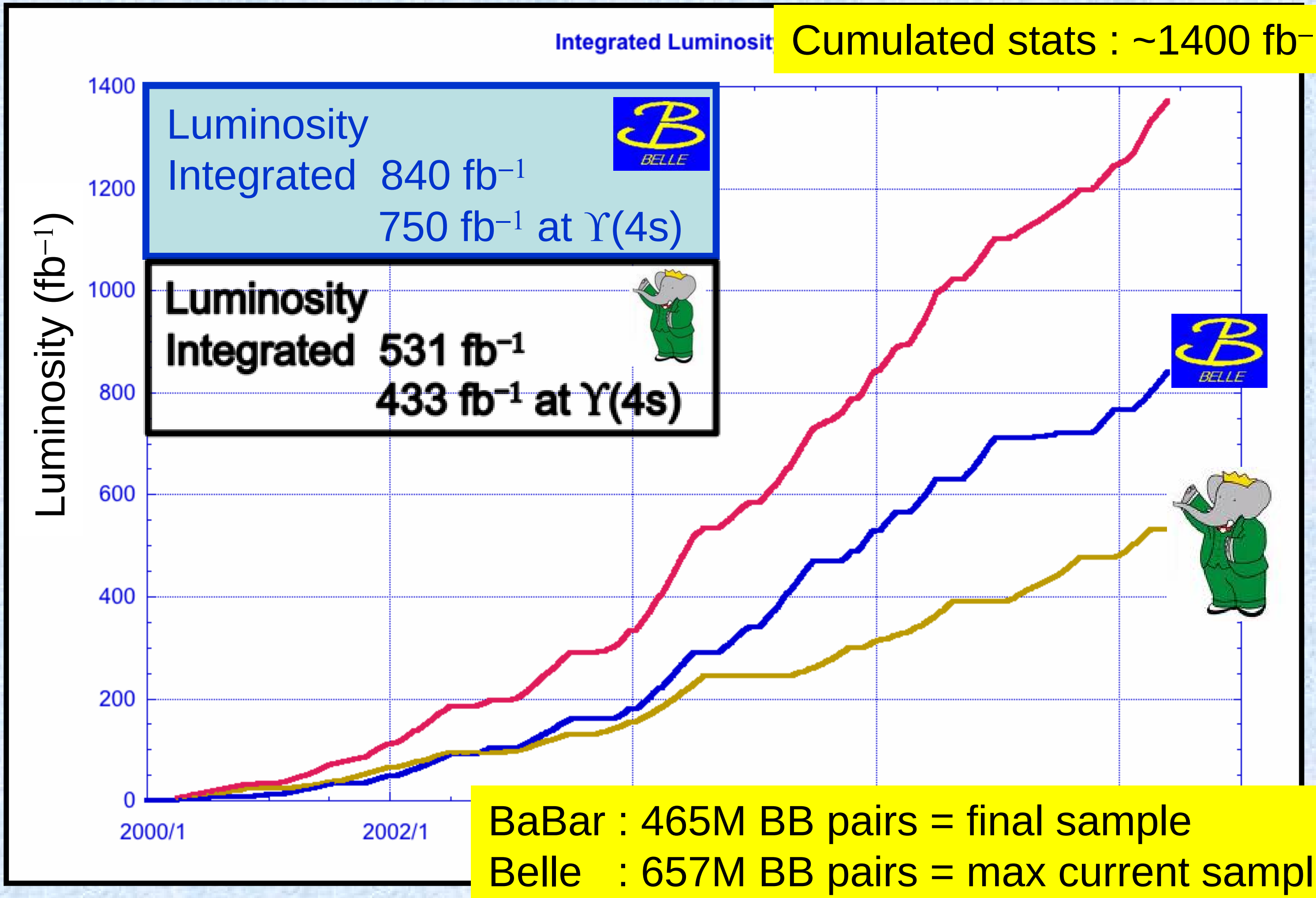
High Energy Ring : 8.0 GeV e^-
Low Energy Ring : 3.5 GeV e^+
Design luminosity : 1 x 10^{34} cm^{-2}s^{-1}
Peak luminosity : 1.71 x 10^{34} cm^{-2} s^{-1}

Beam crossing angle : 22 mrad





Luminosity at B Factories



Luminosity
Integrated 840 fb^{-1}
750 fb^{-1} at Υ(4s)

Luminosity
Integrated 531 fb^{-1}
433 fb^{-1} at Υ(4s)

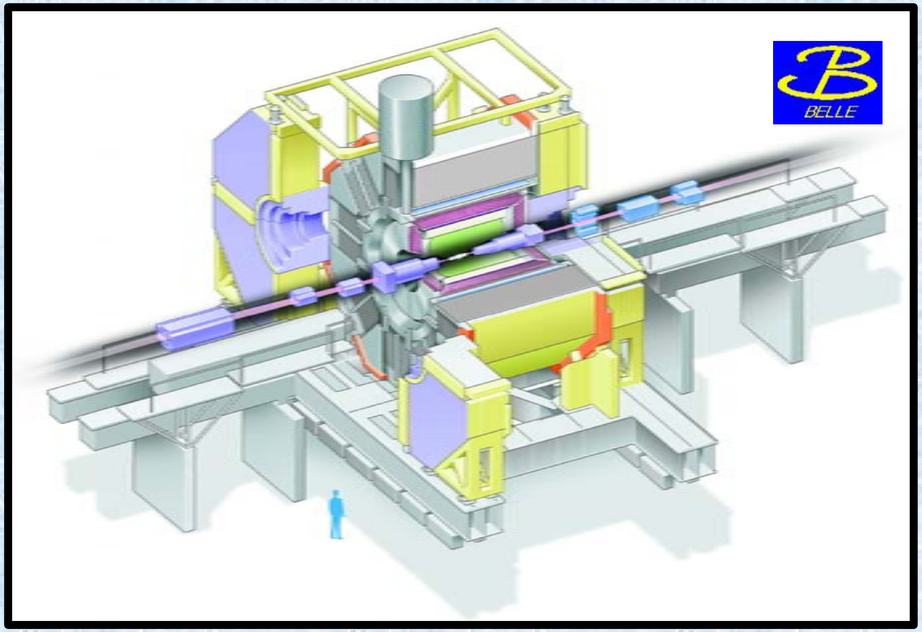
Cumulated stats : ~1400 fb^{-1}

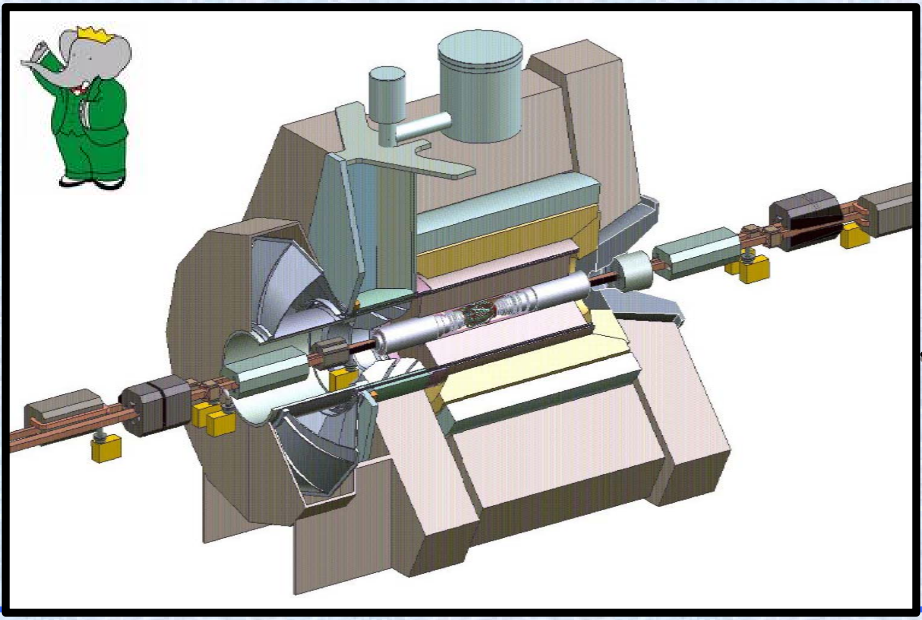
BaBar : 465M BB pairs = final sample
Belle : 657M BB pairs = max current sample
(final sample expected ~800M BB pairs)

K.Trabelsi, Moriond 2009

BELLE and BABAR

3/4 layers DSSD silicon detector
Threshold Cherenkov + TOF
Central drift chamber
EM Cal CsI
RPCs
1.5T solenoid





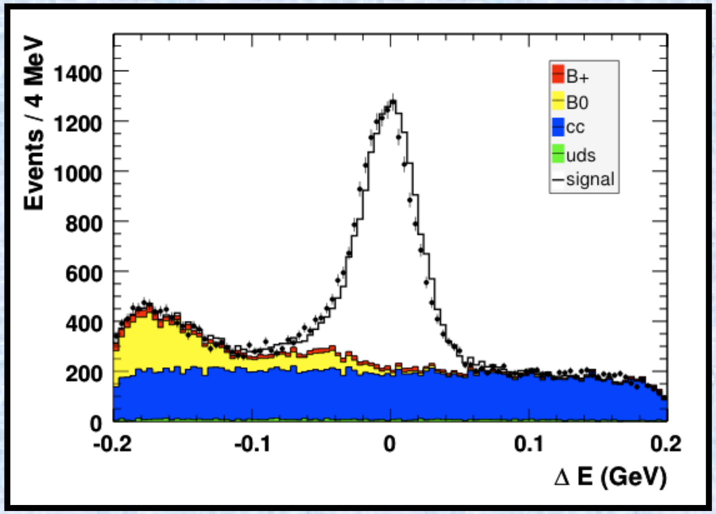
5 layers DSSD silicon detector
Ring-Imaging Cherenkov DIRC
Drift chamber
EM Cal CsI
RPCs
1.5T SC solenoid

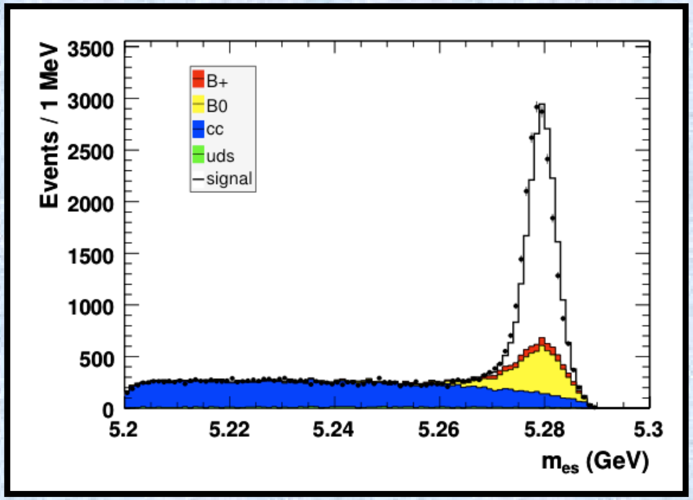
Kinematics at the ϒ (4s)

Precise knowledge of CM energy used to constrain kinematics of B system.

$$\boxed{\Delta E \equiv E_B^* - E_{beam}^*}$$

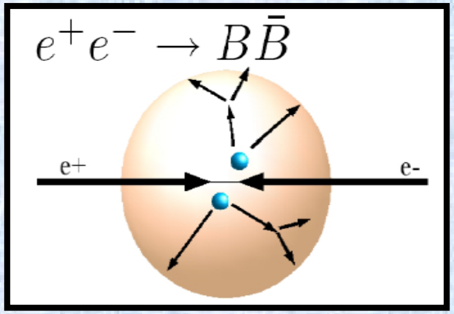
$$\boxed{m_{ES} \equiv \sqrt{E_{beam}^{*\,2} - p_B^{*\,2}}} \qquad E_{beam}^* = \sqrt{s}/2$$

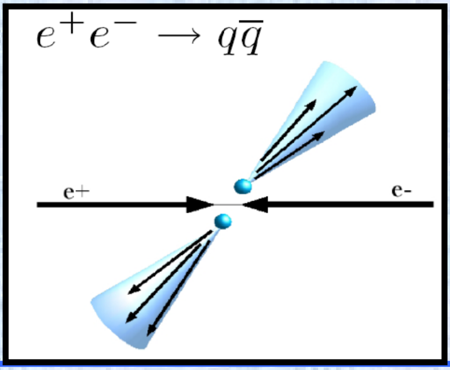




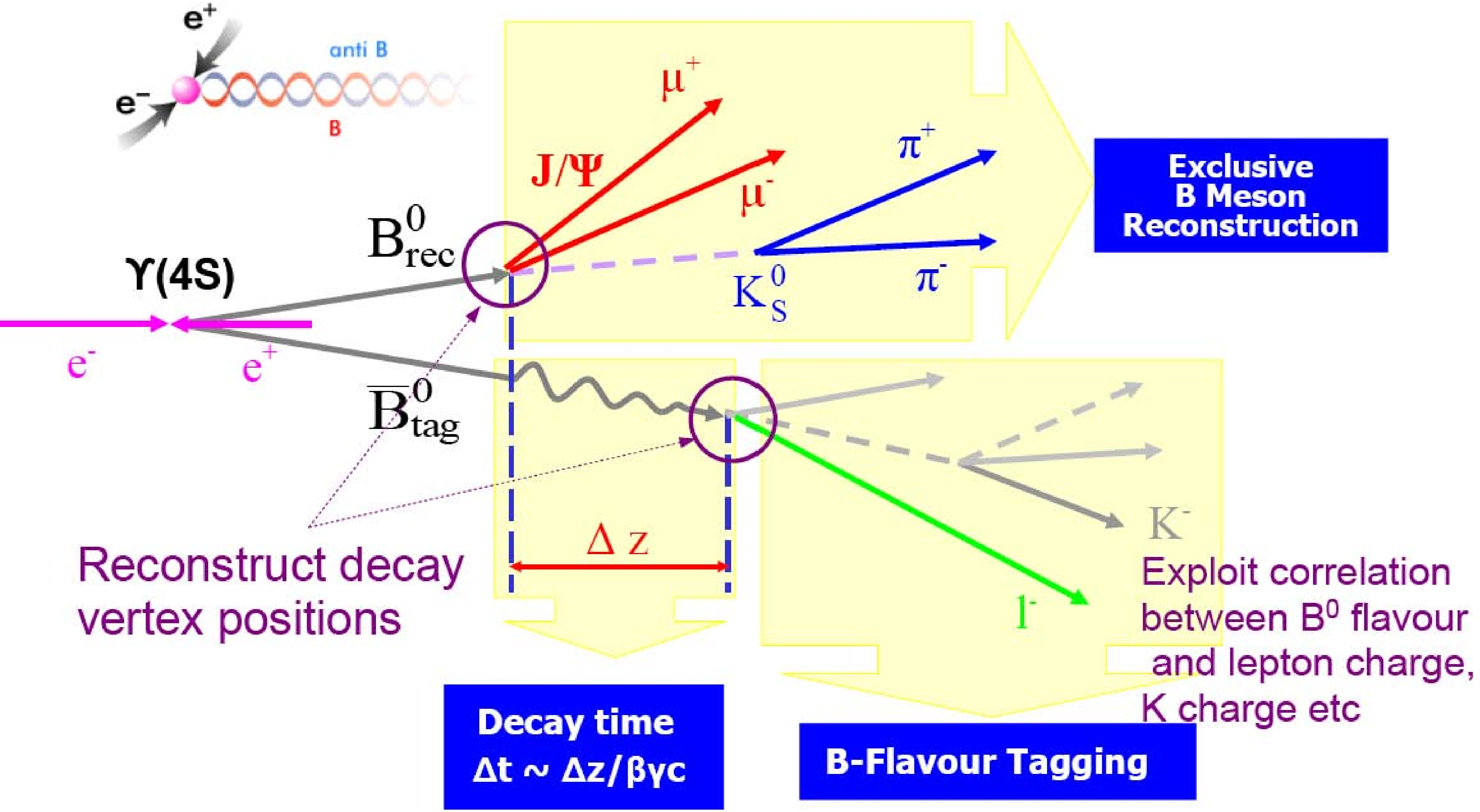
Estimate background from sidebands

Continuum background suppressed using event shape





Time-Dependent Analyses



Exclusive B Meson Reconstruction

Reconstruct decay vertex positions

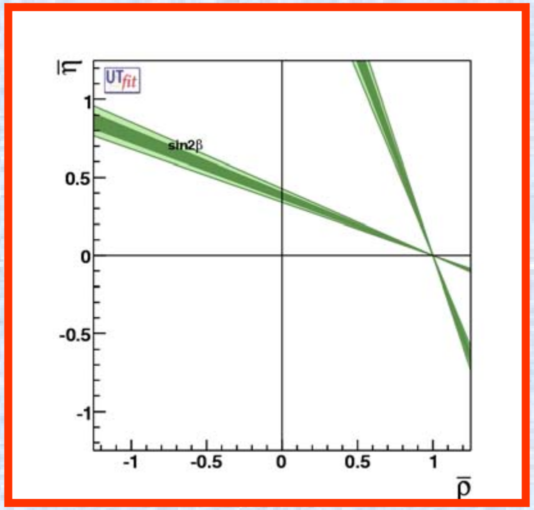
Decay time
$\Delta t \sim \Delta z/\beta\gamma c$

B-Flavour Tagging

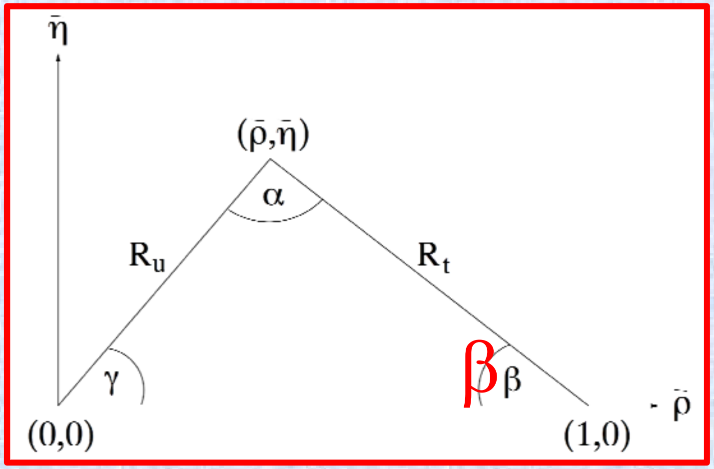
Exploit correlation between B^0 flavour and lepton charge, K charge etc

What to measure first ?

$\mathrm{Sin}\ (2\beta) \equiv \mathrm{Sin}\ (2\phi_1)$



$$\beta = \tan^{-1}\frac{\bar{\eta}}{1-\bar{\rho}}$$



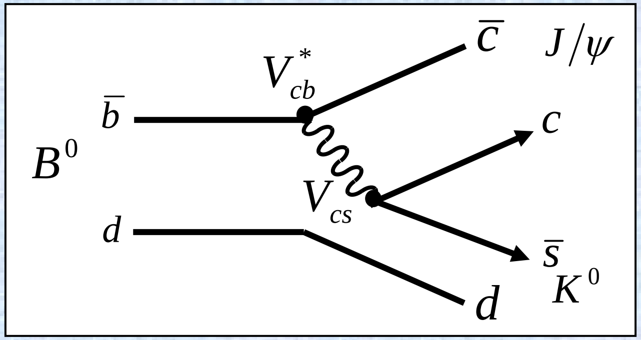
β : b→ccs modes

Golden decay mode: $B^0 \to J/\psi\, K^0$, final state CP eigenstate

Method:

Count number of signal events reconstructed with B^0 and $\overline{B}^0$ tags as a function of Δt

Observed asymmetry depends on time resolution and tagging purity of sample.



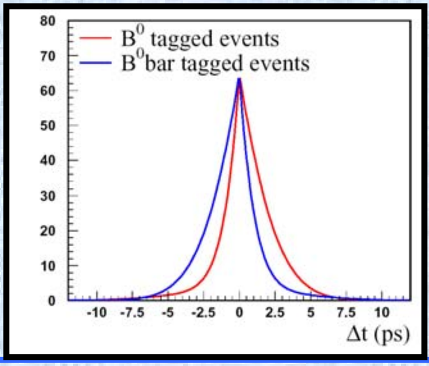
$$A_{CP}(t) = \frac{N\left(B_{tag} = B^0\right) - N\left(B_{tag} = \overline{B}^0\right)}{N\left(B_{tag} = B^0\right) + N\left(B_{tag} = \overline{B}^0\right)}$$

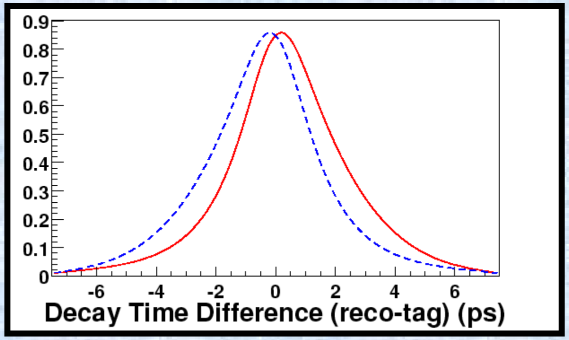
$$\approx \pm\left\{(1-2\omega)\times \sin 2\beta \times \sin(\Delta m \Delta t)\right\} \otimes \mathrm{R}(\Delta t)$$

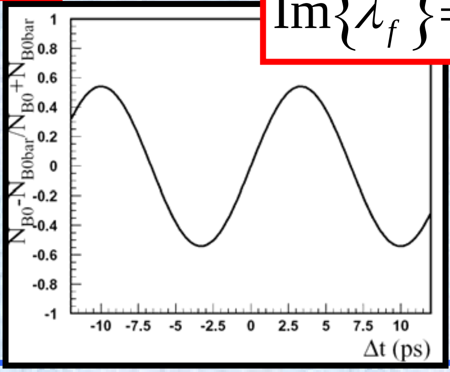
$$\lambda_f = \left(\frac{q}{p}\right)_{B^0}\left(\frac{q}{p}\right)_{K^0}\left(\frac{\overline{A}}{A}\right)_{J/\Psi K^0}$$

$$= -\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}\right)\left(\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\right)$$

$$\mathrm{Im}\{\lambda_f\} = \mathrm{Im}\{-e^{-2i\beta}\} = \sin 2\beta$$

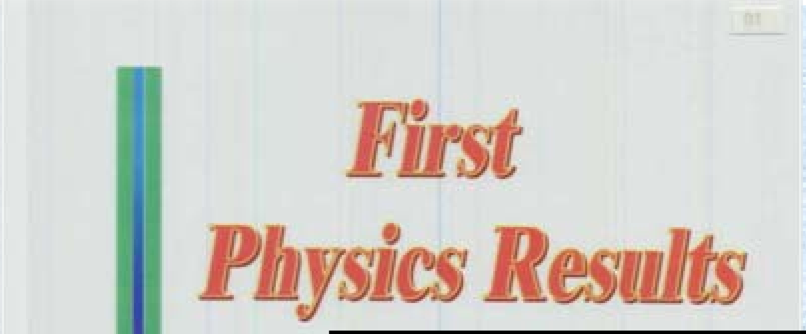




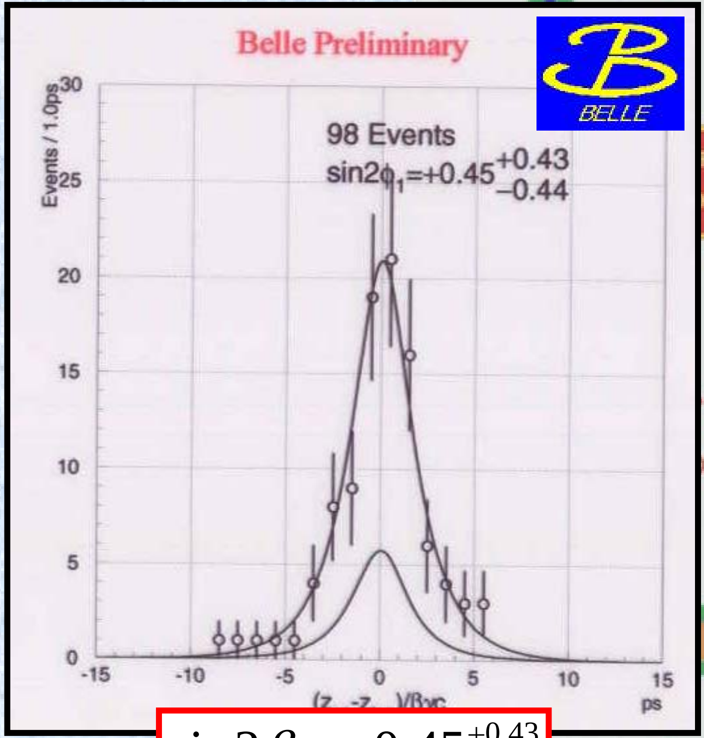


β : Then…

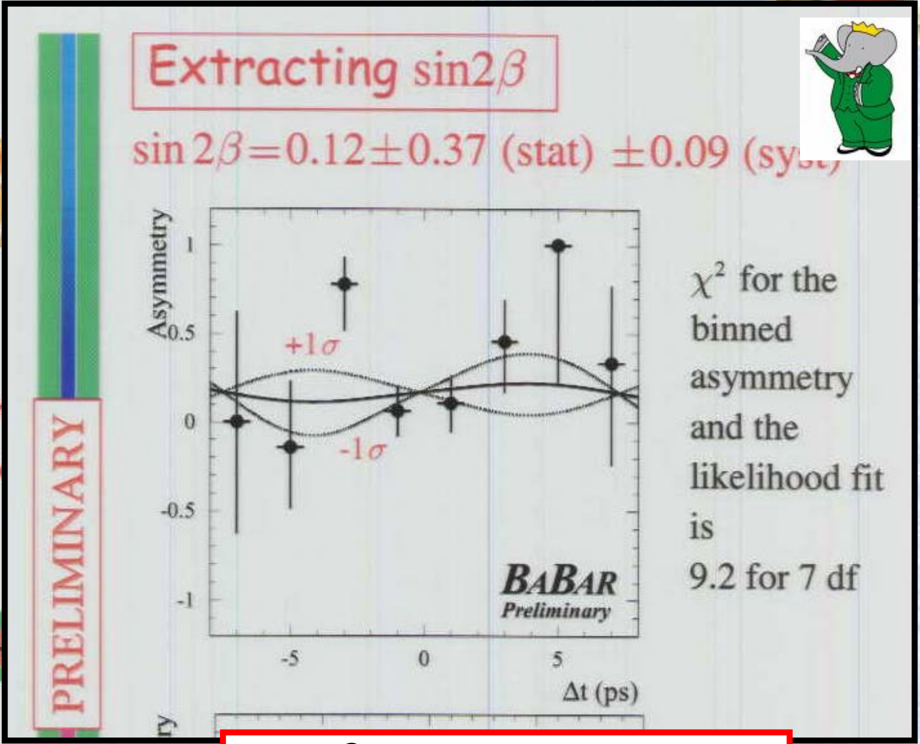
Year 2000


First

Physics Results



$$\sin 2\beta = +0.45^{+0.43}_{-0.44}$$


Extracting $\sin 2\beta$

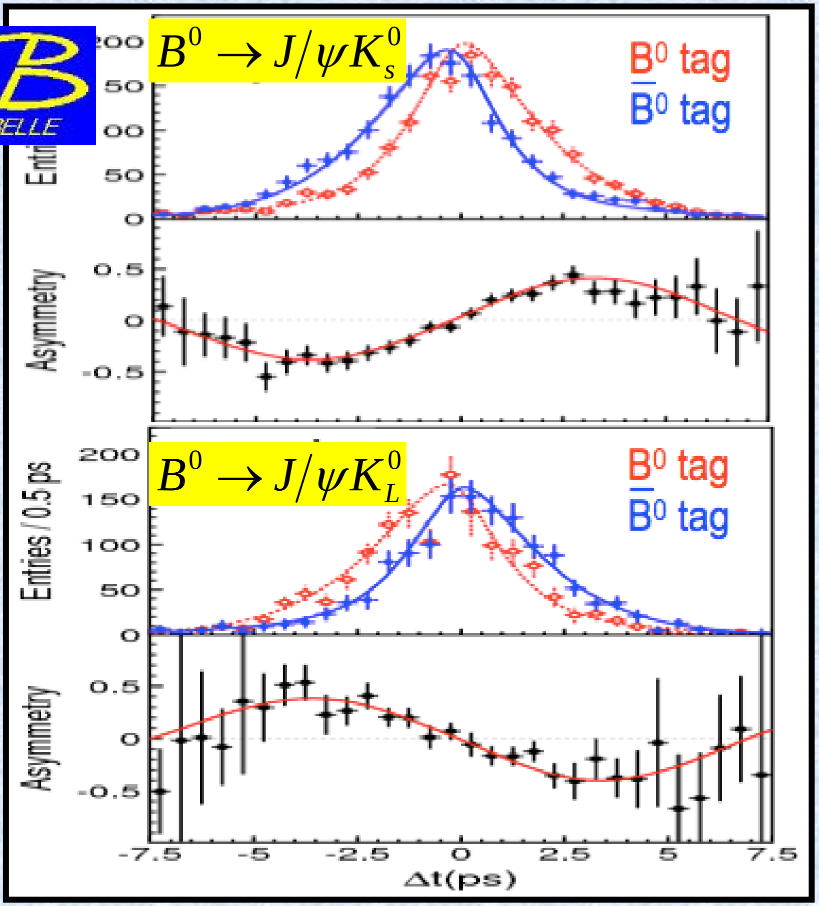
$\sin 2\beta = 0.12 \pm 0.37$ (stat) ± 0.09 (sy…

χ^2 for the binned asymmetry and the likelihood fit is 9.2 for 7 df

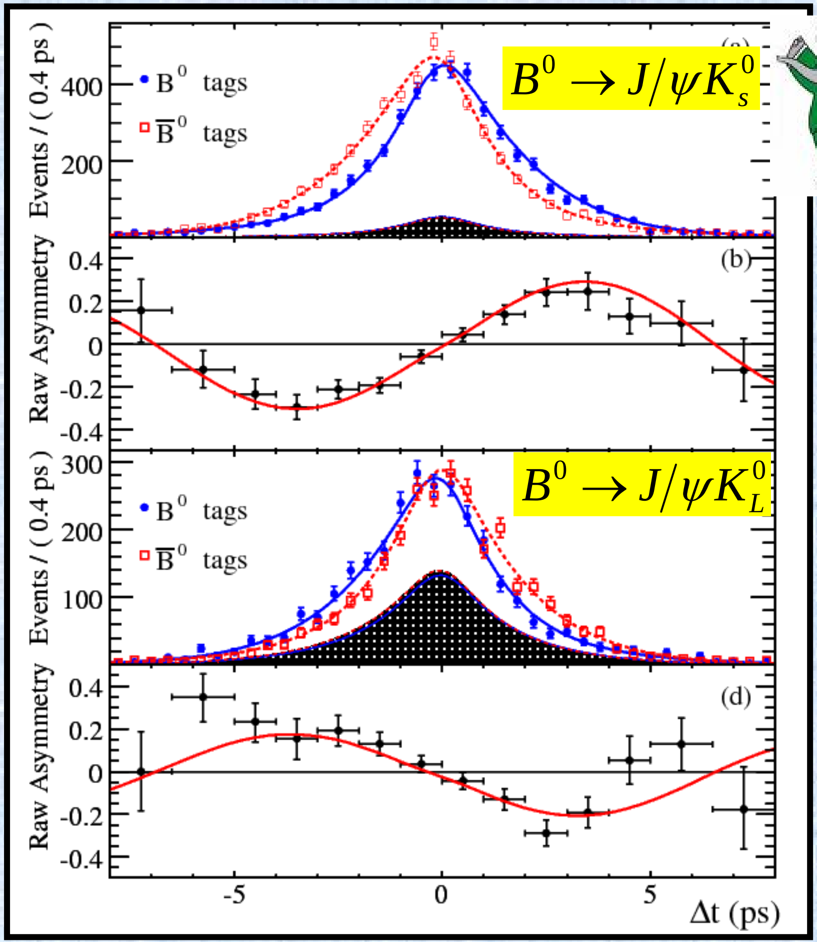
$$\sin 2\beta = 0.12 \pm 0.37 \pm 0.09$$

And now…

Belle : 535M BB; PRL98 (2007) 031802
BaBar : 465M BB; PRD79 (2009) 072009

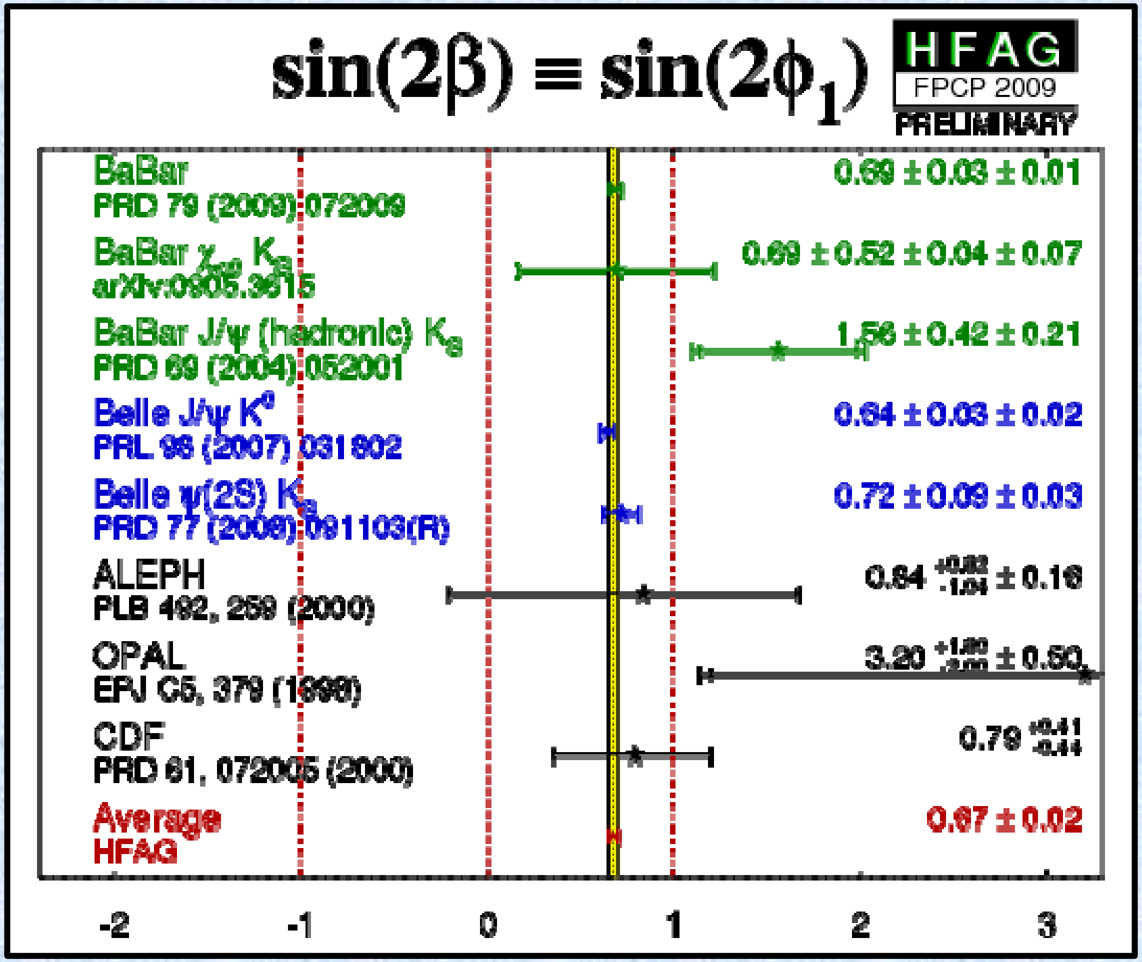


$$\sin 2\beta = 0.642 \pm 0.031 \pm 0.017$$

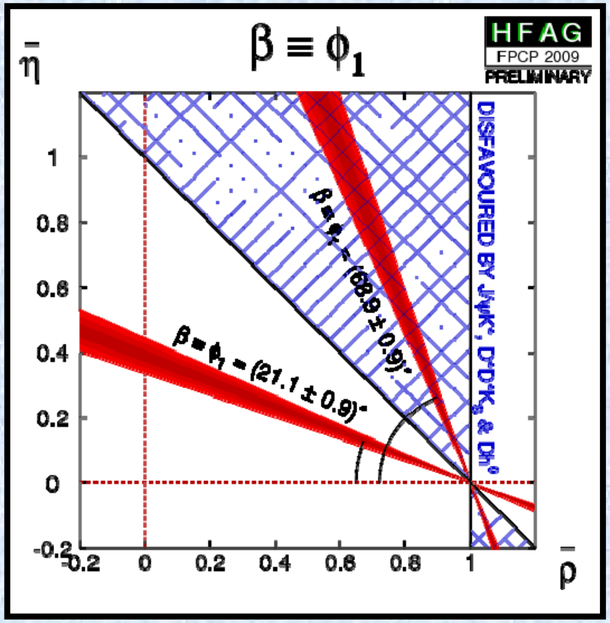


$$\sin 2\beta = 0.666 \pm 0.031 \pm 0.013$$

β : b→ccs modes



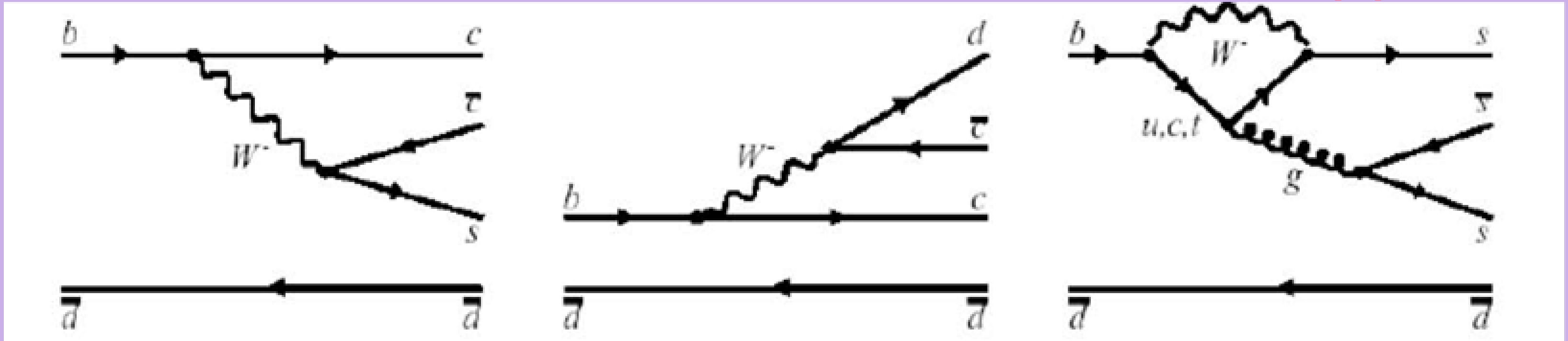
Other measurements sensitive to cos(2β) remove ambiguity



$$\boxed{\beta = (21.1 \pm 0.9)^{o}}$$

β_{eff} in other modes

$b \to cc\bar{s}$ $b \to c\bar{c}d$ $b \to sq\bar{q}$



$J/\psi K_s^0, \psi(2s)K_s^0, \chi_{c1}K_s^0,$
$\eta_c K_s^0, J/\psi K_L^0,$
$J/\psi K^{*0}\left(K^{*0} \to K_s^0 \pi^0\right)$

$D^{*+}D^-, D^+D^-,$
$J/\psi \pi^0, D^{*+}D^{*-}$

$\phi K^0, K^+K^-K_s^0,$
$K_s^0K_s^0K_s^0, \eta' K^0, K_s^0\pi^0,$
$\omega K_s^0, f_0(980)K_s^0$

Increasing tree diagram amplitude

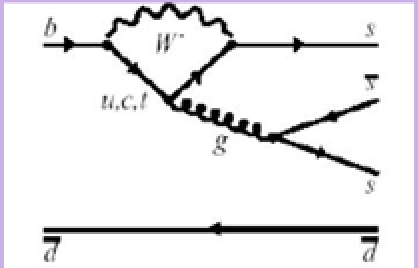
←

Increasing sensitivity to new physics

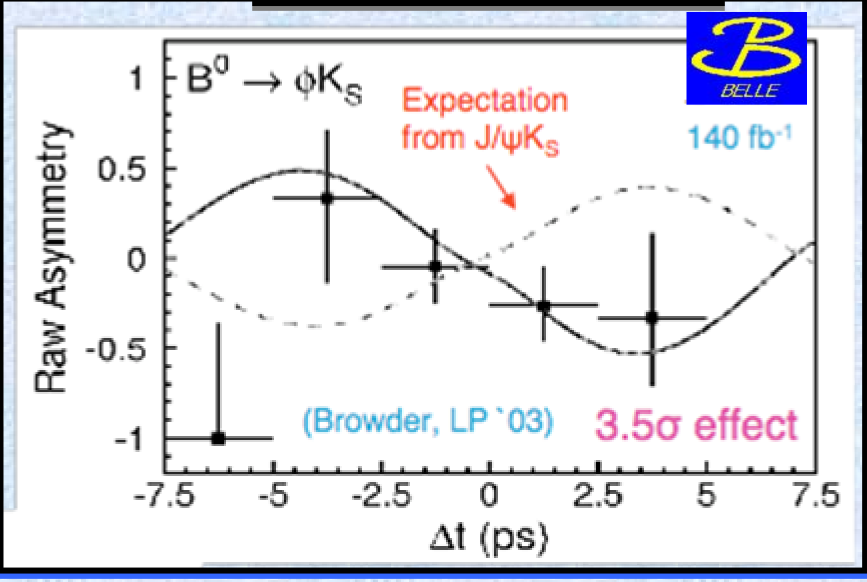
→

β_{eff} : b→sqq modes

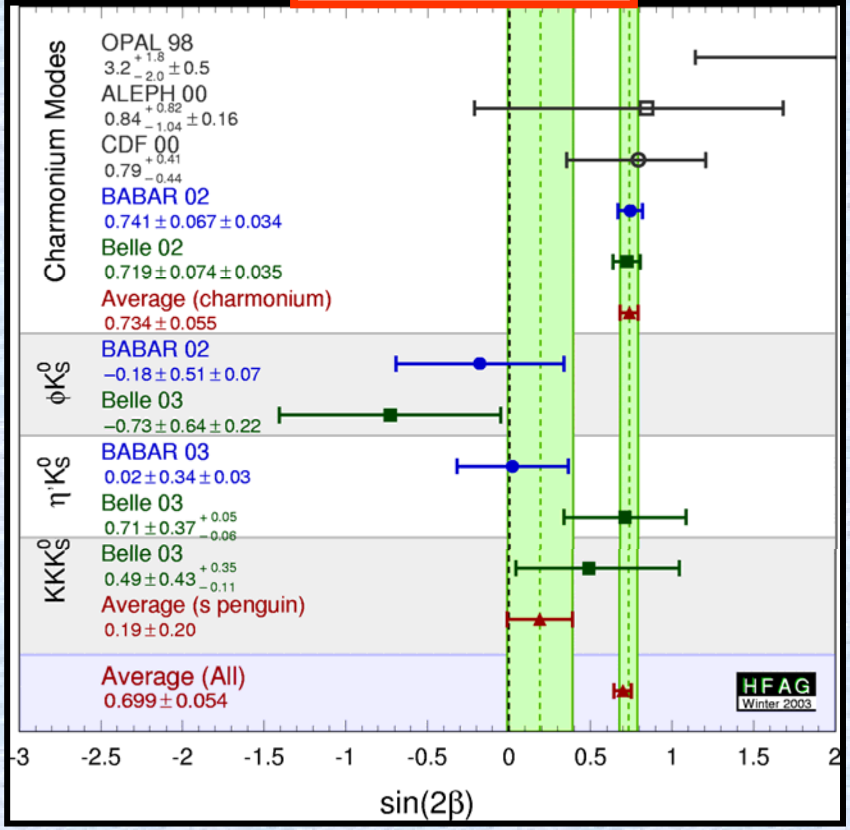
Most sensitive to new physics



$\phi K^0, K^+K^-K_s^0,$
$K_s^0K_s^0K_s^0, \eta' K^0, K_s^0\pi^0,$
$\omega K_s^0,\ f_0(980)K_s^0$



Moriond 2003



2.6 σ : Hint of New Physics ?

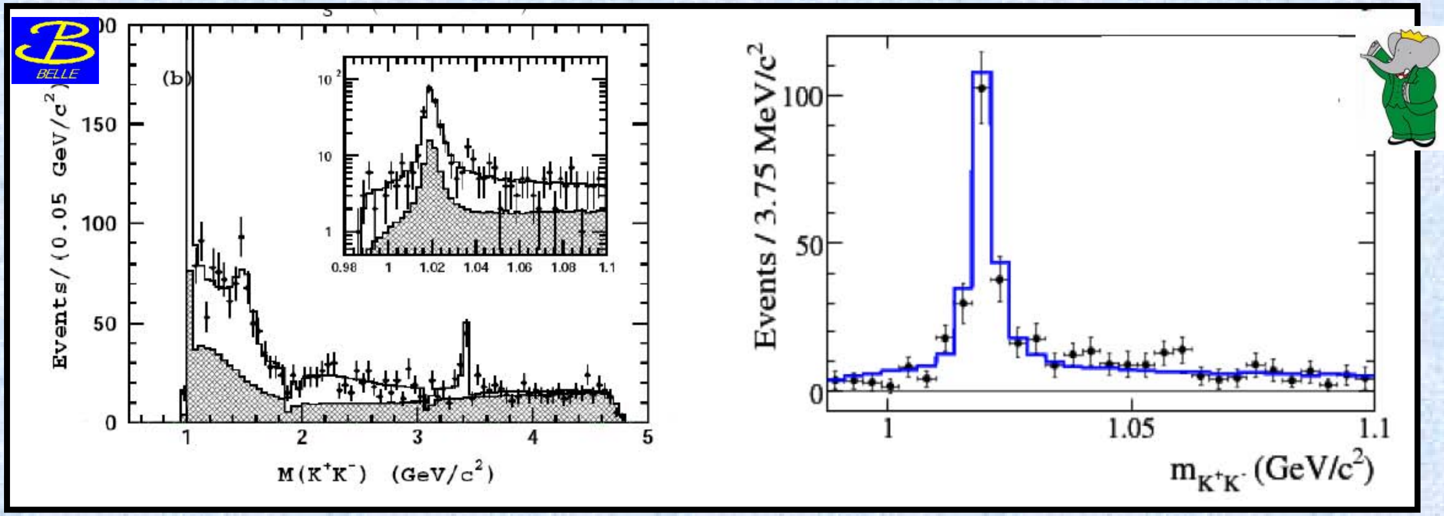
Belle : PRD67 (2003) 031102

β_{eff} : b→sqq modes

Time-dependent Dalitz plot analyses sensitive to $\sin(2\beta_{eff})$ and $\cos(2\beta_{eff})$

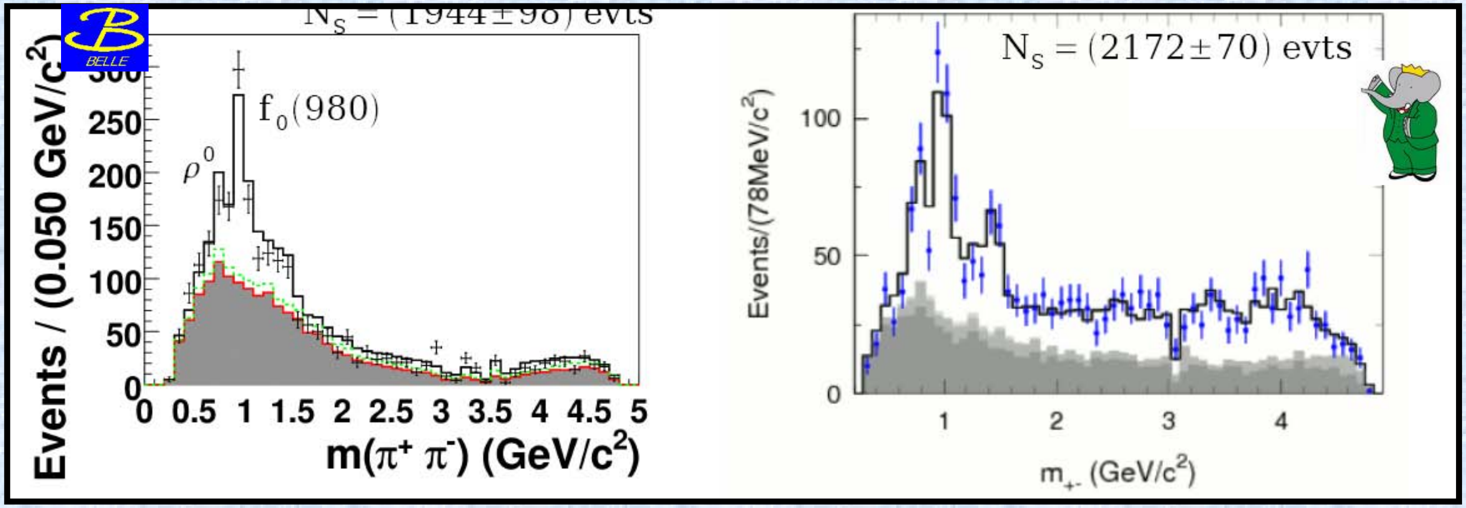
$B^0 \to K_s K^+ K^-$

BaBar : 465M BB;
ArXiv:0808.0700
Belle : 657M BB;
ICHEP 08

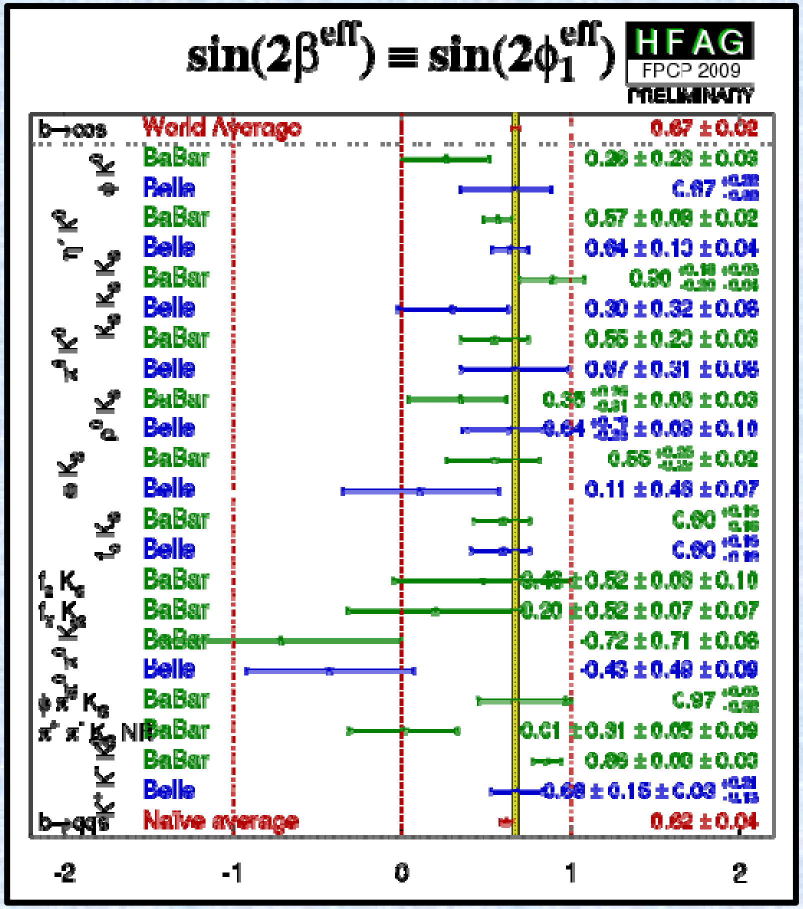


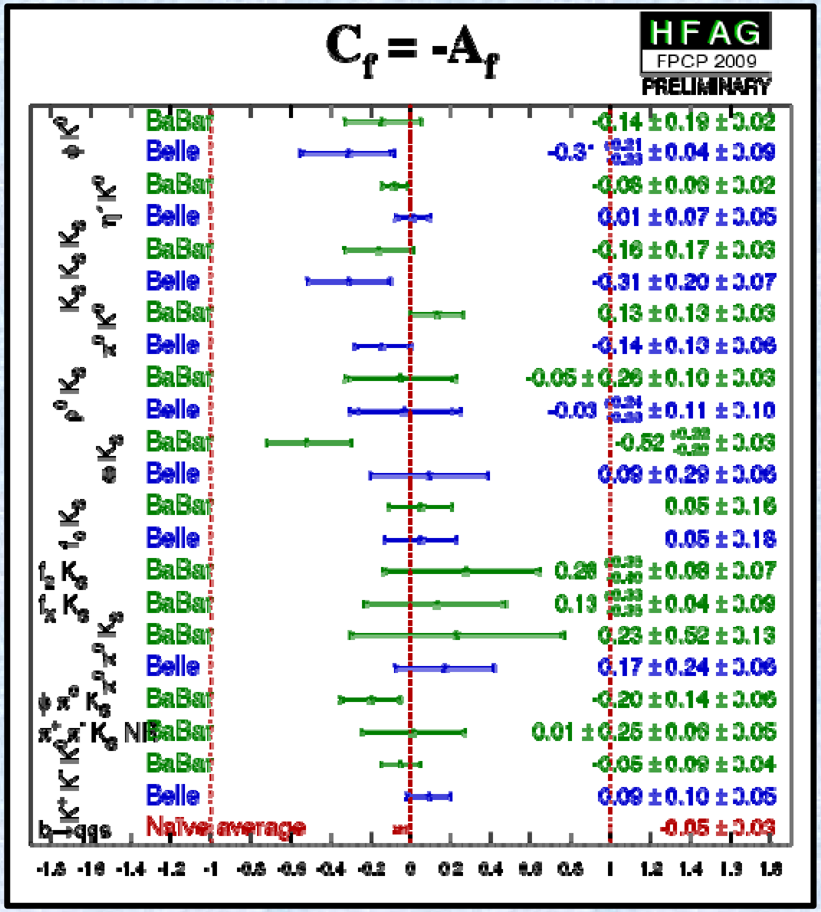
$B^0 \to K_s \pi^+ \pi^-$

BaBar : 383M BB;
ArXiv:0905.3615
Belle : 657M BB;
PRD79 (2009) 072004



β_{eff} : b→sqq modes

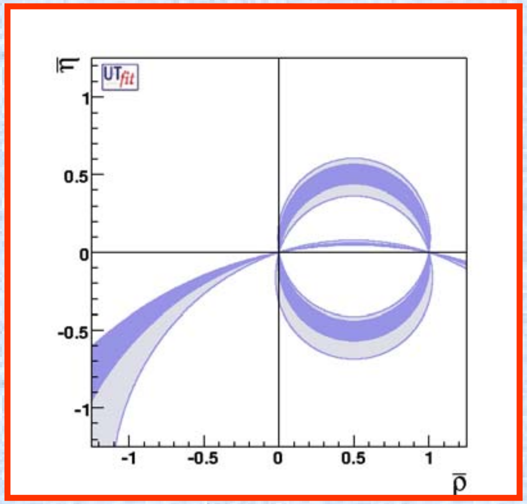




Non-zero β_{eff} is observed in b→sqq penguin transition

Smaller error is required to see any deviation between $\sin(2\beta_{eff})$ and $\sin(2\beta)$

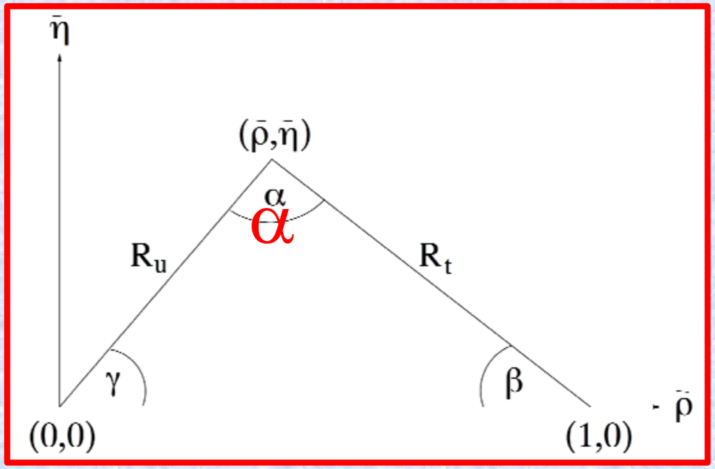
Angle $\alpha \equiv \phi_2$



$$\alpha = \pi - \beta - \gamma$$

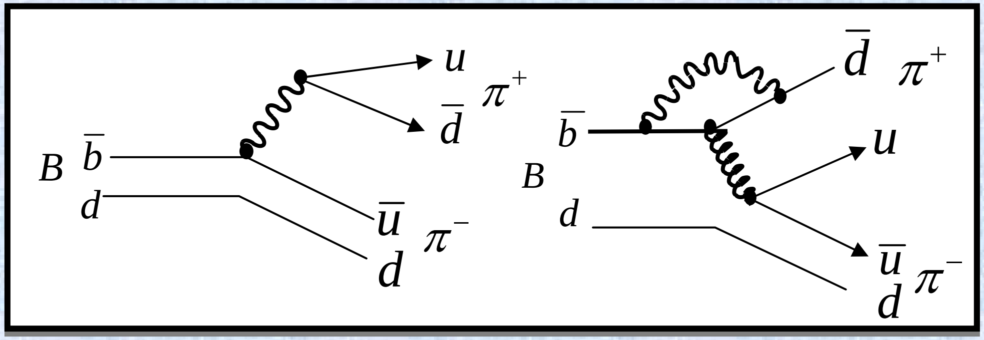
$$\beta = \tan^{-1}\frac{\overline{\eta}}{1-\overline{\rho}}$$

$$\gamma = \tan^{-1}\frac{\eta}{\rho}$$



$\alpha : B \to \pi^+\pi^-$

Strangeless-charmless two-body decay; $b \to uud$ transition, final state CP eigenstate.



If tree amplitude dominates

$$\boxed{\lambda^t_{\pi^+\pi^-} = +e^{-2i(\beta+\gamma)} = e^{2i\alpha}}$$

$$\boxed{S_{\pi^+\pi^-} = \sin 2\alpha \quad C_{\pi^+\pi^-} = 0}$$

$$S_f \equiv \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2} \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

… but penguin contributions cannot be neglected $\boxed{\left|P/T\right| \sim 30\%}$

$$\boxed{\lambda^{t+p}_{\pi^+\pi^-} \approx e^{2i\alpha}\left[1+2i\left|\tfrac{P}{T}\right|\sin\alpha\, e^{i(\delta_P-\delta_T)}\right]}$$

$$\boxed{S_{\pi^+\pi^-} = \sin 2\alpha - 2\left|\tfrac{P}{T}\right|\sin\alpha\cos 2\alpha\cos(\delta_P-\delta_T) + O\left(\left|\tfrac{P}{T}\right|^2\right)}$$

In general let $\lambda_{\pi^+\pi^-} \equiv |\lambda_{\pi^+\pi^-}|\,e^{2i\alpha_{eff}}$ and fit time-dependent CP asymmetry

$$\boxed{A_{CP}(t) = \sqrt{1-C^2_{\pi\pi}}\,\sin 2\alpha_{eff}\,\sin(\Delta m t) - C_{\pi\pi}\cos(\Delta m t)}$$

$\alpha : B \to \pi^+\pi^-$

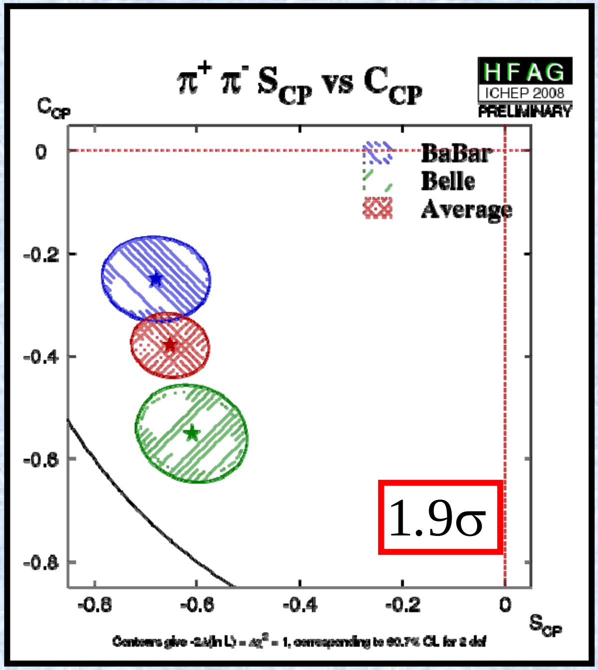
BaBar : 467M BB; ArXiv:0807.4226
Belle : 535M BB; PRL98 (2007) 211801

Two types of CP violation are observed

- Direct CP violation $C_{\pi^+\pi^-} \neq 0$
- Mixing induced CP violation $S_{\pi^+\pi^-} \neq 0$

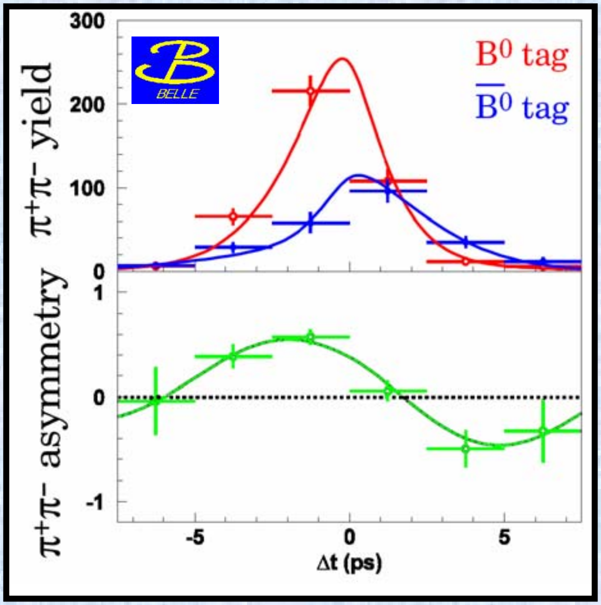
Need to estimate $\boxed{\Delta\alpha \equiv \alpha_{eff} - \alpha}$

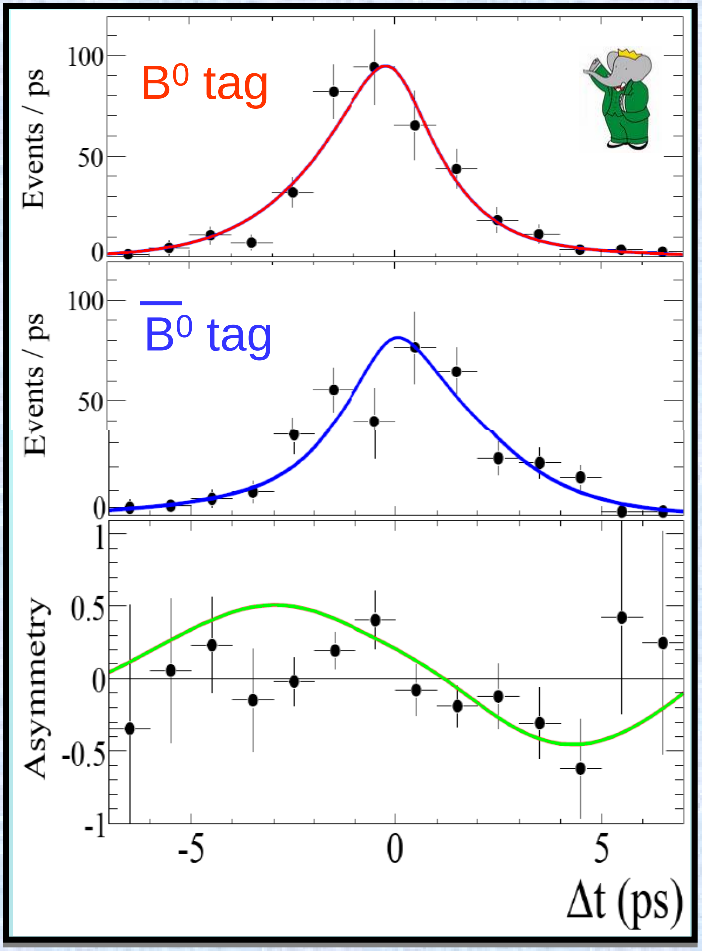
$\boxed{\sigma(\alpha_{eff}) \sim 4^o}$



Contours give $-2\Delta(\ln L) = \Delta\chi^2 = 1$, corresponding to 60.7% CL for 2 dof

1.9σ





Isospin Analysis B → ππ

Gronau and London, PRL65 (1990) 3381.

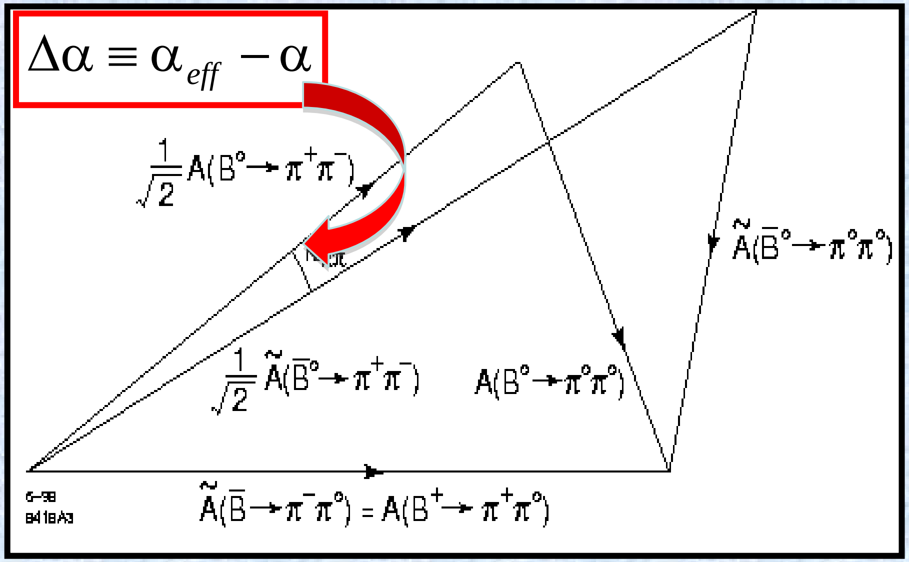
Isospin amplitude relations for

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

$B^0 \to \pi^0\pi^0$

$B^+ \to \pi^+\pi^0$

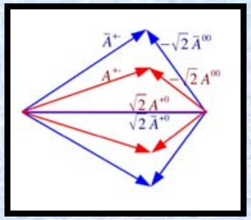
$$A_{+-} + \sqrt{2}A_{00} = \sqrt{2}A_{0+}$$
$$\bar{A}_{+-} + \sqrt{2}\,\bar{A}_{00} = \sqrt{2}\,\bar{A}_{0-}$$



$\Delta\alpha \equiv \alpha_{eff} - \alpha$

Neglecting EWP

$$|A_{0+}| = |\bar{A}_{0+}|$$



Ambiguities: 4 triangle orientations → 4-fold ambiguity for Δα

$\alpha \Leftrightarrow (\pi - \alpha) \Rightarrow$ 8–fold ambiguity for α

Need to measure $Br(B^0 \to \pi^0\pi^0)$ and $Br(\bar{B}^0 \to \pi^0\pi^0)$

$\sigma(\Delta\alpha)$ determines $\sigma(\alpha)$

Isospin Analysis B → ππ

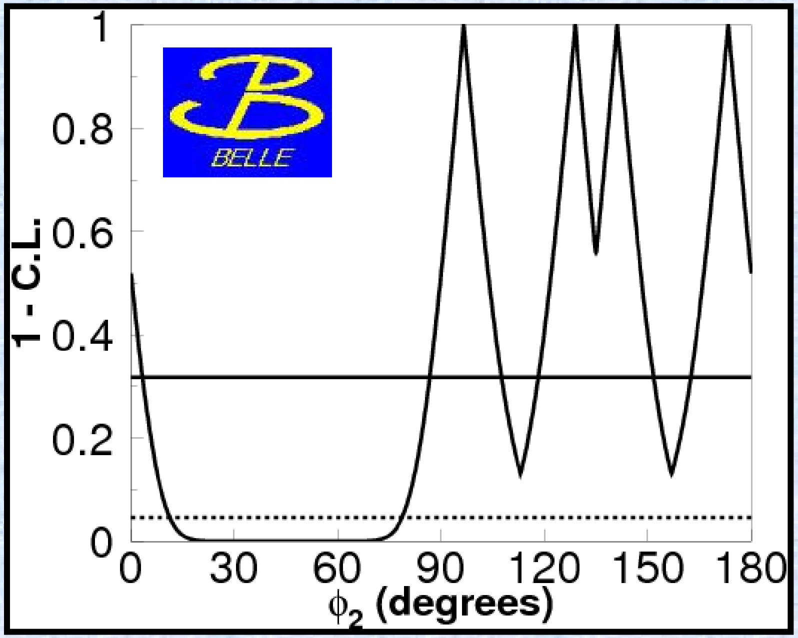
6 inputs : $Br(B^0 \to \pi^+\pi^-)$, $Br(B^+ \to \pi^+\pi^0)$, $Br(B^0 \to \pi^0\pi^0)$, C_{+-}, S_{+-}, C_{00}

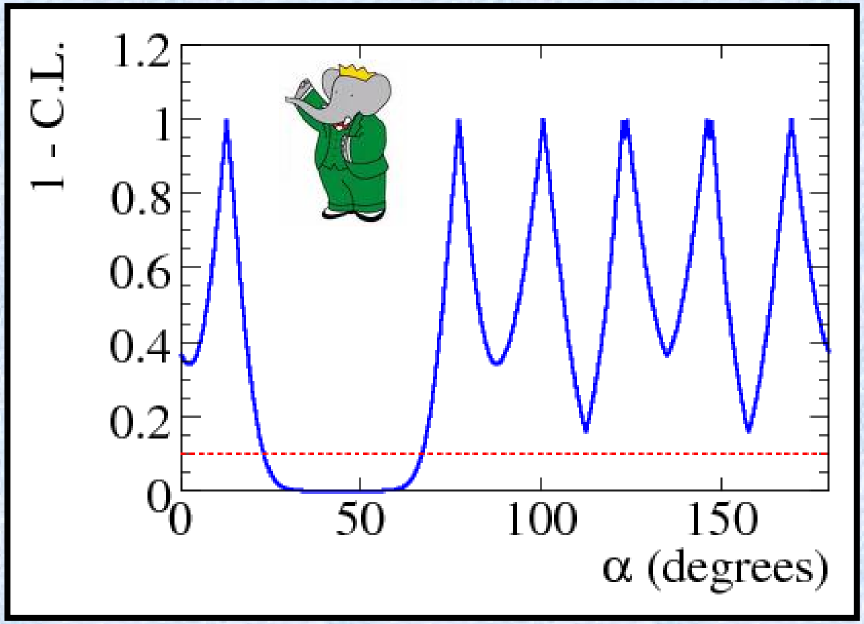
α scan : find minimum χ^2 in fit of isospin triangle to the measurements

convert to C.L. (frequentist)

BaBar : 467M BB; ArXiv:0807.4226

Belle : 535M BB; PRL98 (2007) 211801





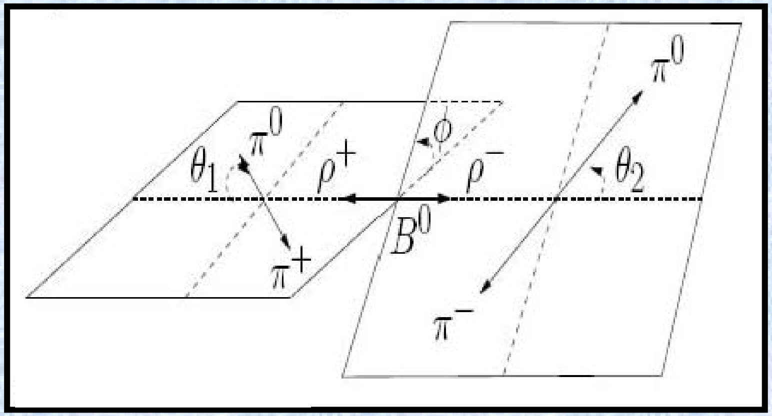
Belle: $11 < \alpha < 79^{o}$ excluded at 95% C.L.
BaBar : $23 < \alpha < 67^{o}$ excluded at 90% C.L.

α : B → ρρ

$B \to \rho\rho$ similar to $B \to \pi\pi$

- $Br\left(B^0 \to \rho^+\rho^-\right) \sim 5 \times Br\left(B^0 \to \pi^+\pi^-\right)$ and $Br\left(B^0 \to \rho^0\rho^0\right) \sim 4\% \times Br\left(B^0 \to \rho^+\rho^-\right)$
- $|P/T|$ smaller ~ 4%
- Time-dependent measurement for $B^0 \to \rho^0\rho^0$ possible → S_{00} lifts 4-fold ambiguity
- ρ has spin 1 → 3 polarization states

  Mixture CP odd and CP even



1 longitudinal $\propto \cos\theta_1 \cos\theta_2$
2 transverse $\propto \sin\theta_1 \sin\theta_2\, e^{\pm i\phi}$

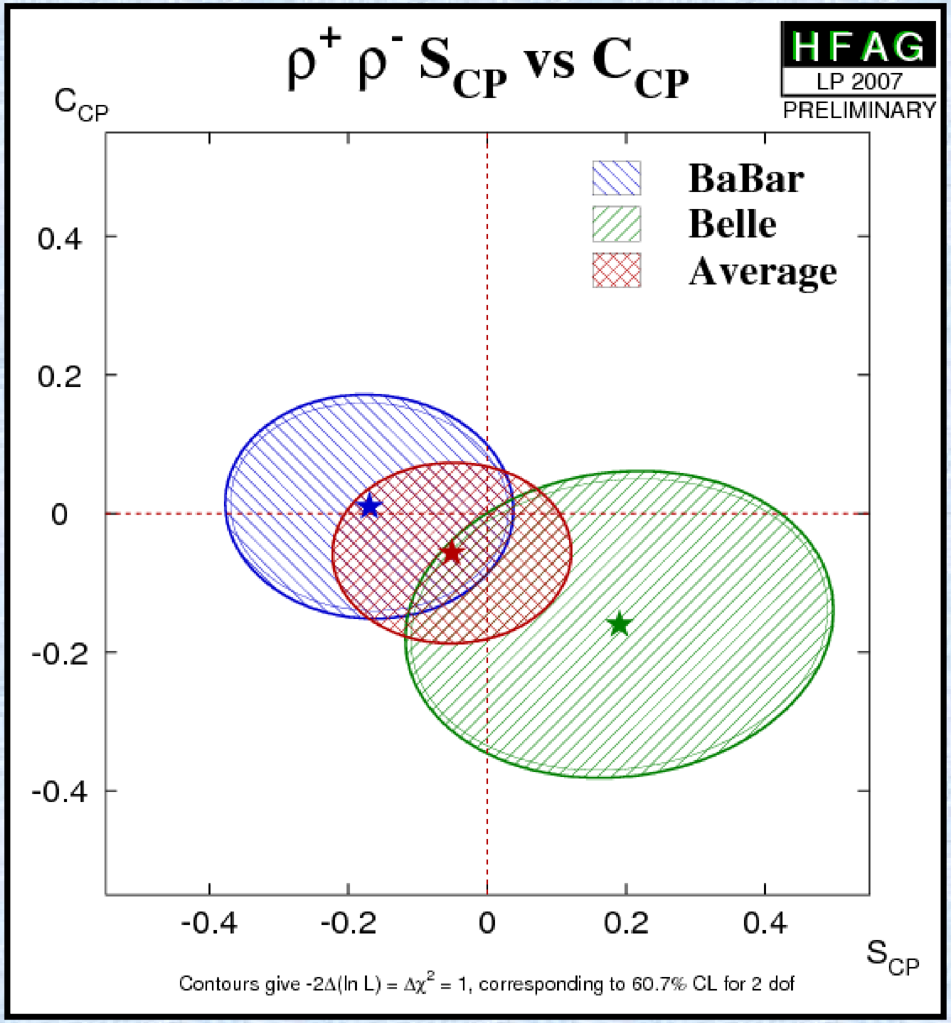
Integrate over ϕ

$$\boxed{\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_1\, d\cos\theta_2} = \frac{9}{16}\left[4\cos^2\theta_1\cos^2\theta_2\, f_L + \sin^2\theta_1\sin^2\theta_2\left(1 - f_L\right)\right]}$$

- is almost longitudinally polarized $\boxed{f_L\left(\rho^+\rho^-\right) = 0.992 \pm 0.024^{+0.026}_{-0.013}}$

$\alpha : B \to \rho\rho$

BaBar : 387M BB; PRD76 (2007) 052007
Belle : 535M BB; PRD76 (2007) 011104

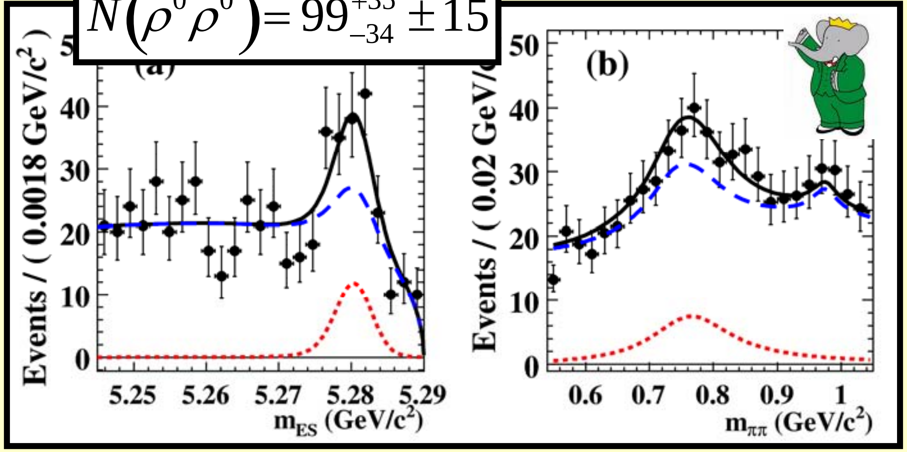


$$\boxed{\sigma(\alpha_{eff}) \sim 6^o}$$

α : $B \to \rho\rho$

$B^0 \to \rho^0\rho^0$

$N(\rho^0\rho^0) = 99^{+35}_{-34} \pm 15$



$Br(B \to \rho^0\rho^0) = (0.92 \pm 0.32 \pm 0.14) \times 10^{-6}$

$f_L = 0.75^{+0.11}_{-0.14} \pm 0.04$

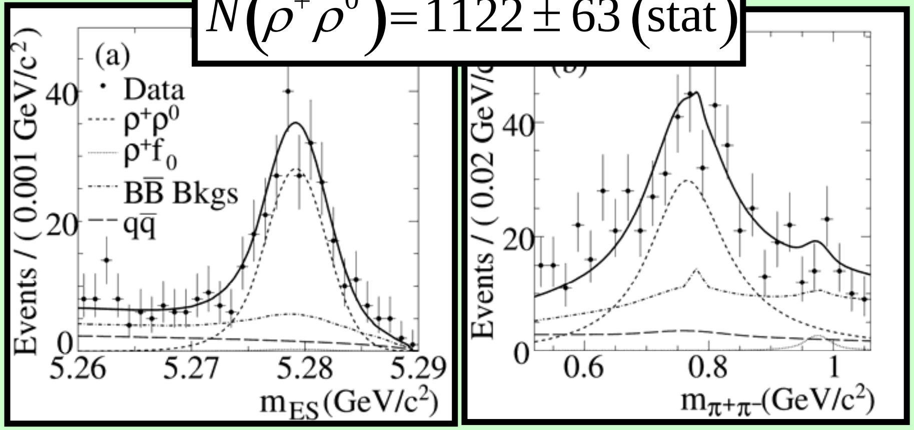
$S_L^{00} = 0.3 \pm 0.7 \pm 0.2$ $C_L^{00} = 0.2 \pm 0.8 \pm 0.3$

$Br(B \to \rho^0\rho^0) < 1.0 \times 10^{-6}$ @ 90% c.l.

BaBar : 465M BB; PRD78 (2008) 071104
Belle : 657M BB; PRD78 (2008) 111102

$B^+ \to \rho^+\rho^0$

$N(\rho^+\rho^0) = 1122 \pm 63\,(\text{stat})$



$Br(B^+ \to \rho^+\rho^0) = (23.7 \pm 1.4 \pm 1.4) \times 10^{-6}$

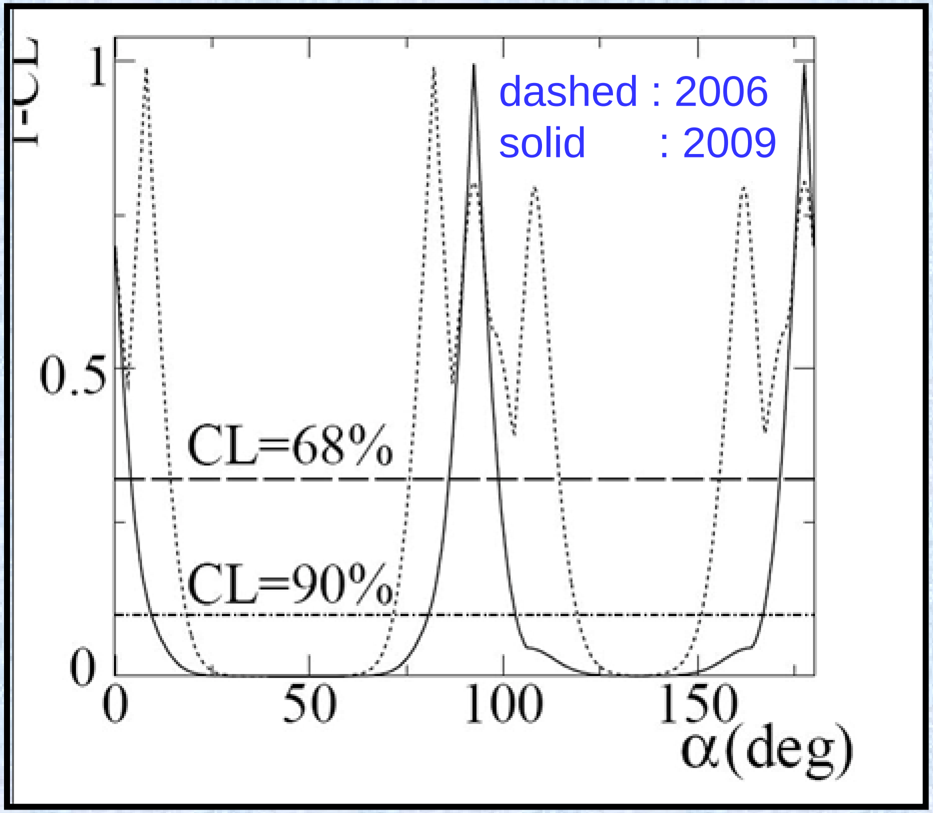
$f_L = 0.950 \pm 0.015 \pm 0.006$

New: Moriond 2009

BaBar : 465M BB; PRL102 (2009) 141802

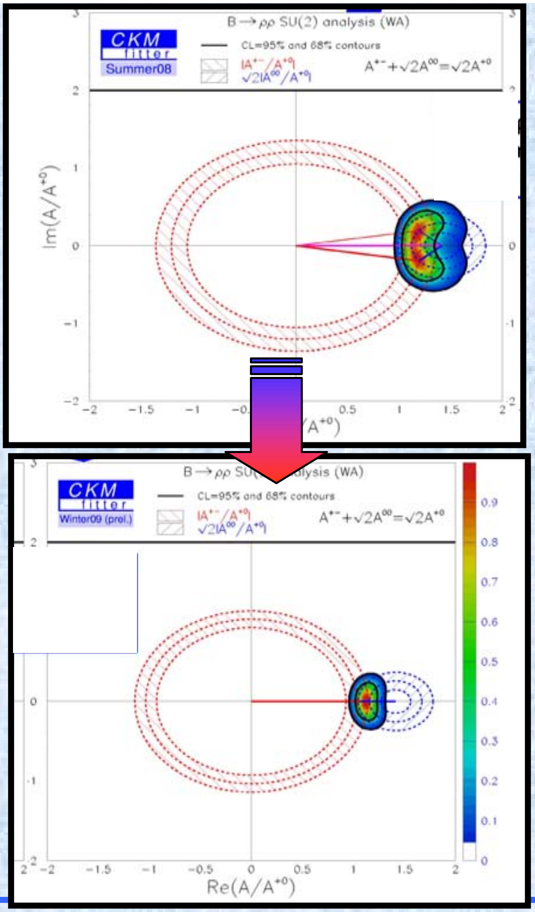
$B \to \rho\rho$

Perform isospin analysis:



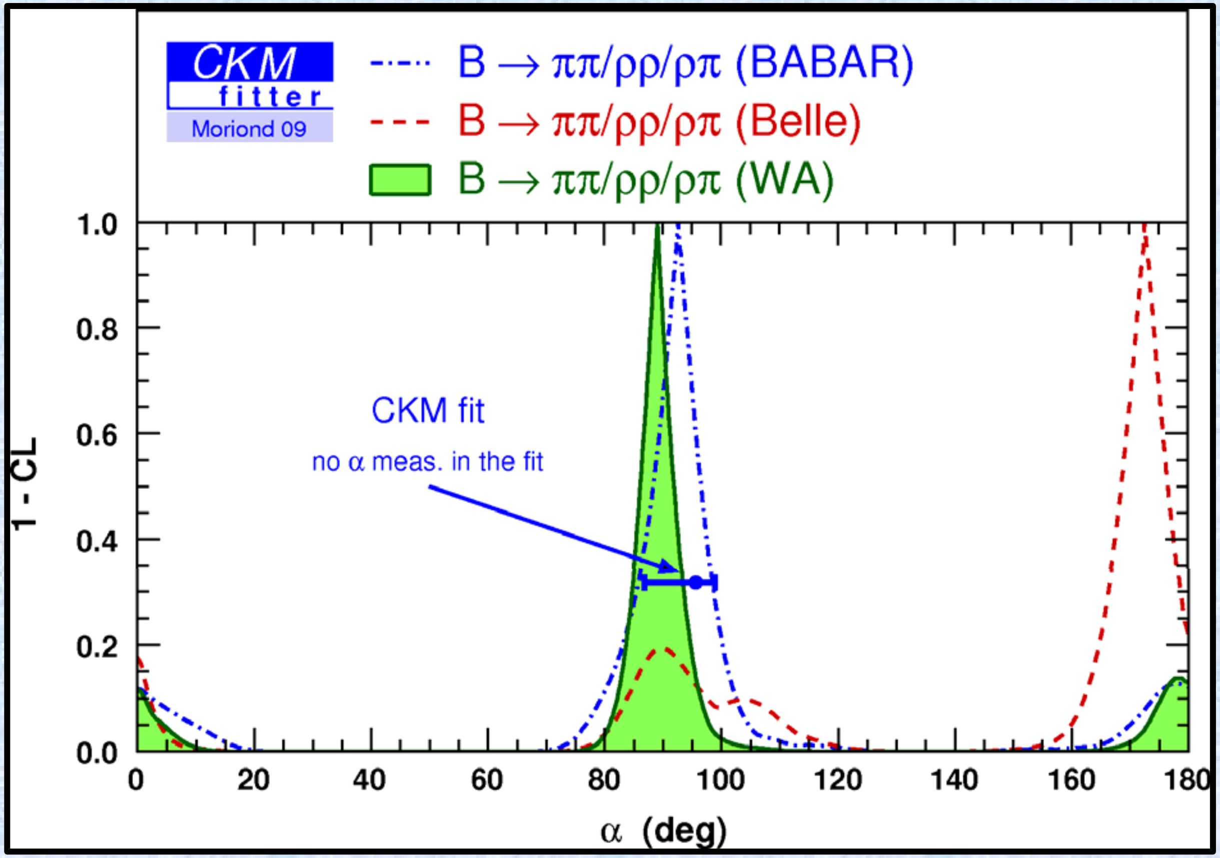
dashed : 2006
solid : 2009

Why the significant improvement?
Increase of $Br\left(B^{+} \to \rho^{+}\rho^{0}\right)$ by ~2σ flattens isospin triangle
Two distinct solutions → single solution



$$\alpha = \left(92.4^{+6.0}_{-6.5}\right)^{\mathrm{o}}$$

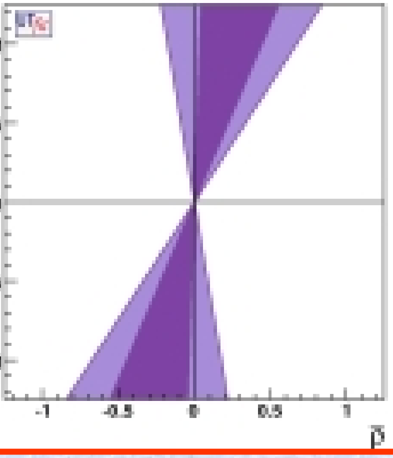
Summary α



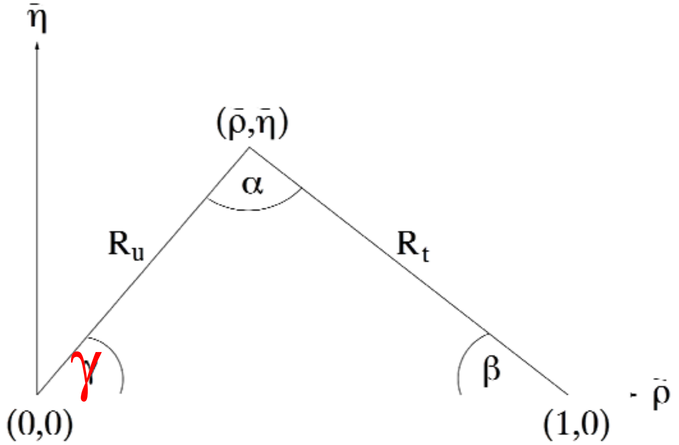
$$\boxed{\alpha = \left(89.0^{+4.4}_{-4.2}\right)^{o}\ \text{60\% c.l. interval}}$$

α is now a precision 4.8% measurement
Note: β @ 4.2%

Angle $\gamma \equiv \phi_3$



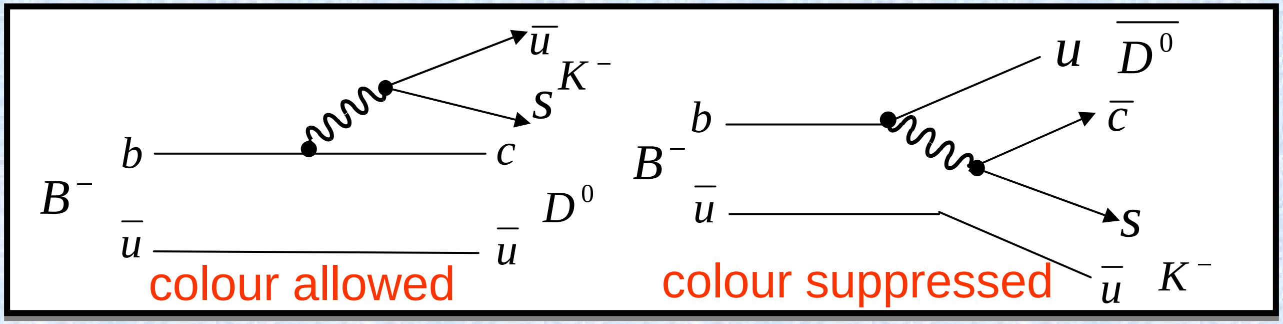
$$\gamma = \tan^{-1}\frac{\eta}{\rho}$$



γ : B→DK

The measurement of γ via tree processes provides a SM benchmark that must be met by any New Physics model

The theoretically cleanest method measures γ via the interference between $B \to D^0 K$ and $B \to \overline{D^0} K$



Common parameters:

- CKM angle γ
- Amplitude ratio, r_B
- Strong phase difference, δ_B

$$\frac{\langle B \to \overline{D^0} K \rangle}{\langle B \to D^0 K \rangle} = r_B e^{i(\delta_B - \gamma)}$$

γ precision very sensitive to value of r_B

$$r_B \sim \frac{|V_{ub} V_{cs}^*|}{|V_{cb} V_{us}^*|} \times |\text{col. supp}| = 0.1 - 0.2$$

γ : B$\to$DK

Reconstruct D in final states accessible to both D^0 and $\overline{D^0}$

“ADS” Method: Atwood, Dunietz, Soni; PRL78 (1997) 3257; PRD63 (2001) 036005.

D $\to$ Cabibbo favoured and doubly-suppressed decays e.g. $K^+\pi^-$, $K^+\pi^-\pi^0$

“GLW” Method: Gronau, London, Wyler; PLB253 (1991) 483; PLB265 (1991) 172.

D $\to$ CP Eigenstates e.g. K^+K^-, $\pi^+\pi^-$, $K_s\pi^0$

“Dalitz” or “GGSZ” Method: Giri, Grossman, Soffer, Zupan, PRD68 054018 (2003).

D $\to$ three-body decays e.g. $K_s\pi^+\pi^-$, $K_sK^+K^-$

Time-integrated analyses, tagging not required

Effects due to charm mixing and CP violation negligible

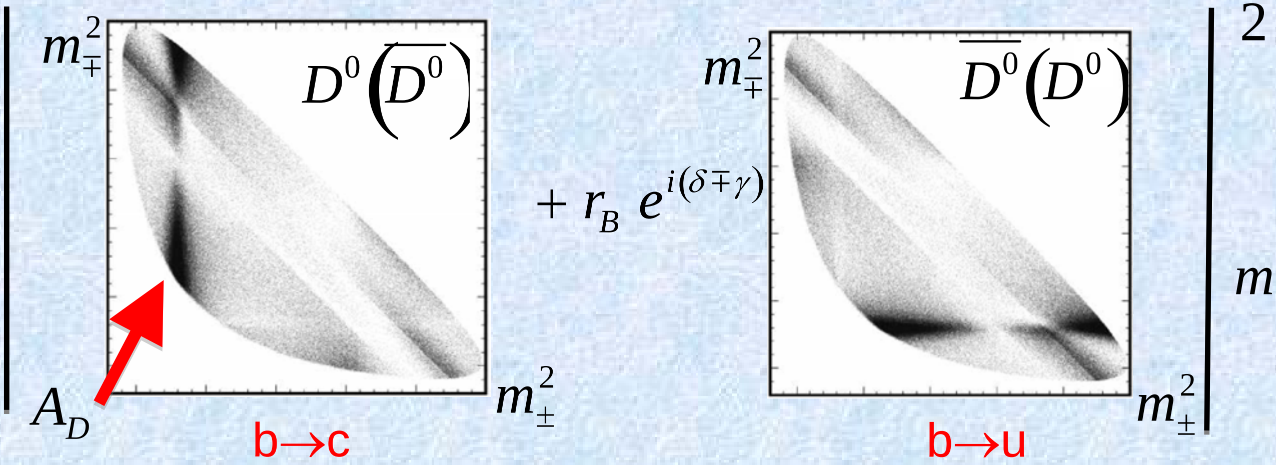
Different B decays (e.g. DK, D^*K, DK^*) have different hadronic factors r_B, δ_B

Strategy: combine as many channels as possible to improve γ sensitivity

GGSZ (Dalitz) Method

Currently most powerful method for extraction of γ

Exploit interference pattern in Dalitz plot for $B^{\mp} \to D(K_s h^+ h^-)K^{\mp}$



$$|A_{\mp}|^2 = \left| A_D + r_B\, e^{i(\delta \mp \gamma)} \right|^2$$

schematic

$$m^2_{\pm} = m^2\left(K_s h^{\pm}\right)$$

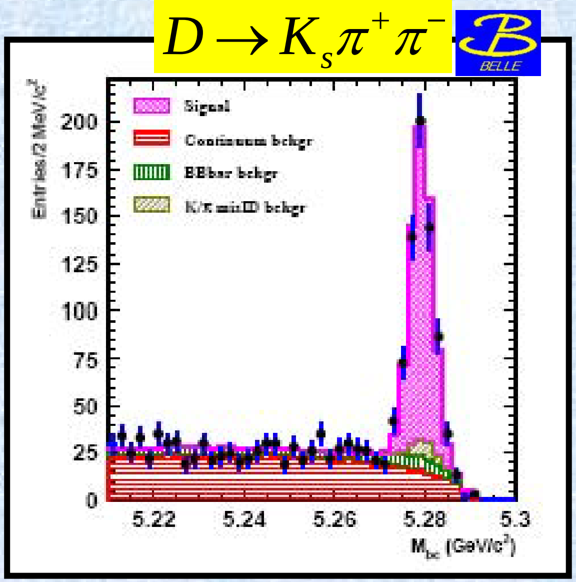
Sensitivity varies strongly over Dalitz plane (mixture ADS+GLW)

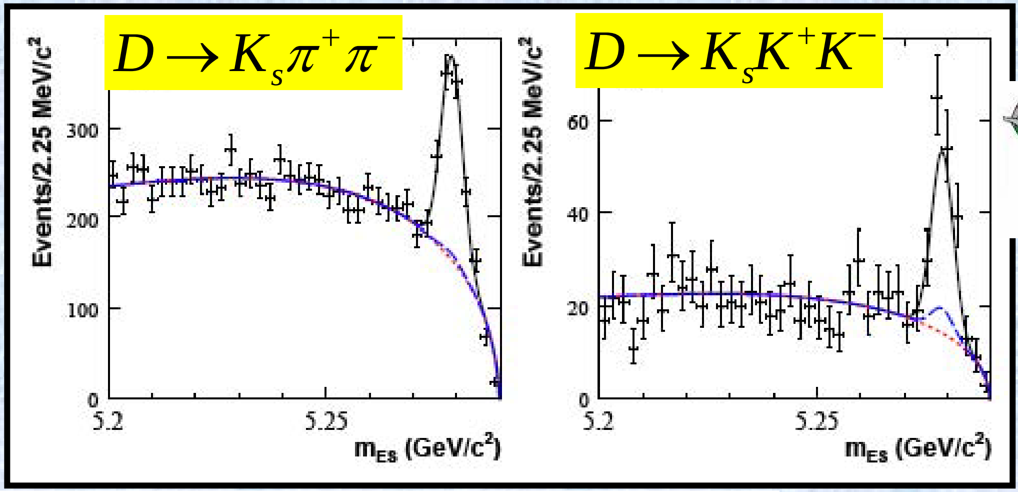
Input knowledge of D decay amplitude, introduces model uncertainty

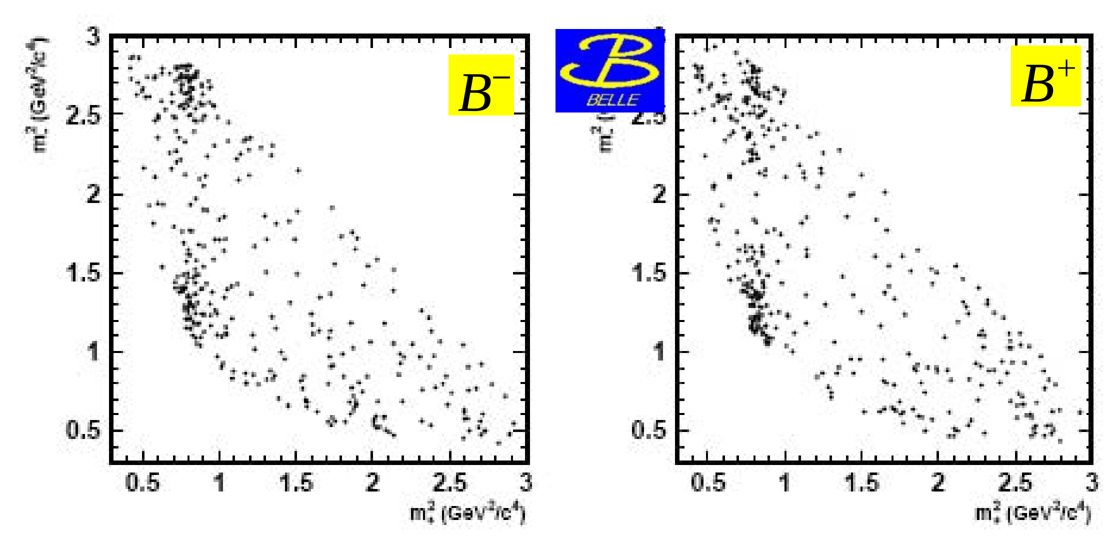
Simultaneous fit to Dalitz plot density for B^+/B^- data

GGSZ (Dalitz) Method

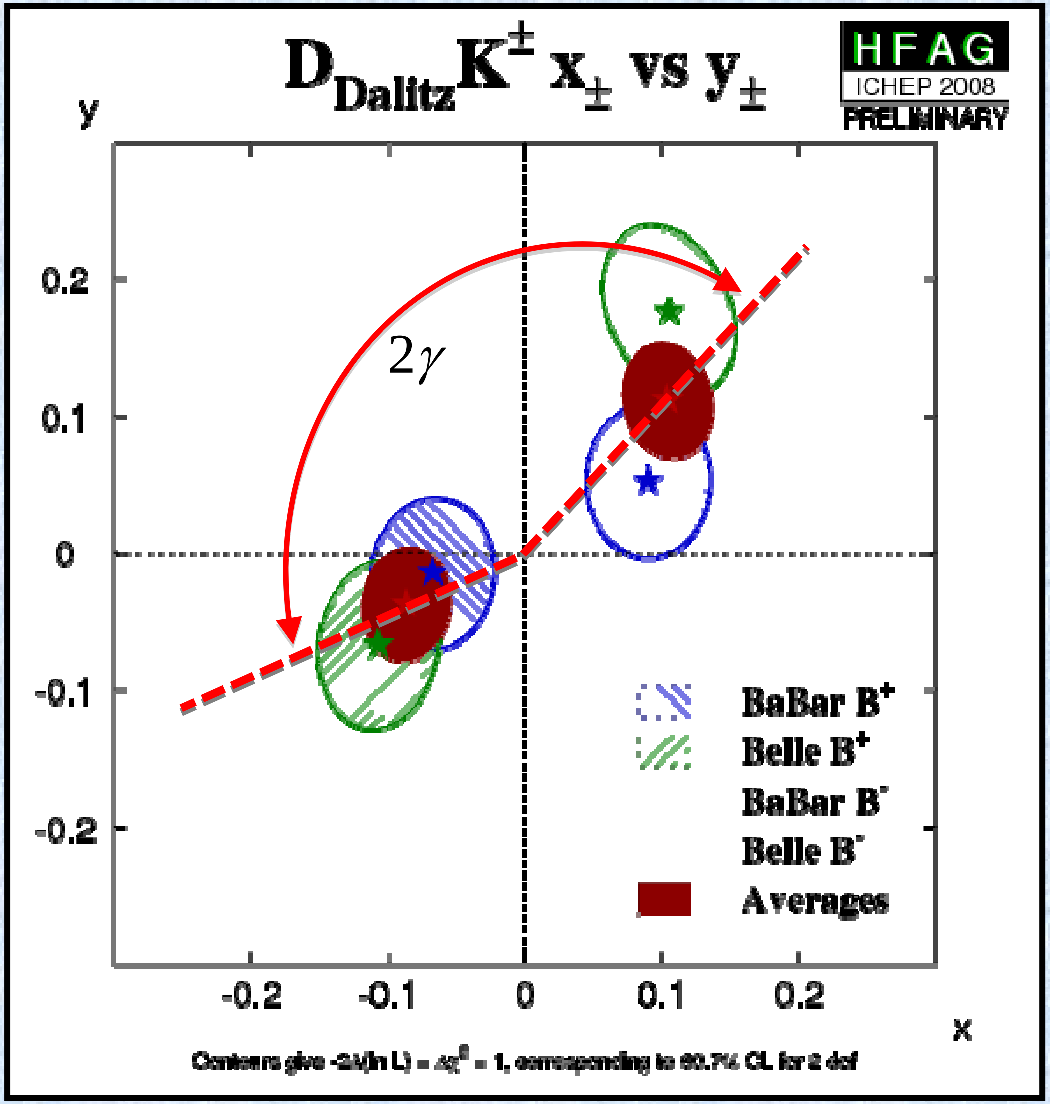
BaBar : 383M BB; PRD78 (2008) 034023
Belle : 657M BB; ArXiv:0803.3375







GGSZ (Dalitz) Method



BaBar : 383M BB; PRD78 (2008) 034023
Belle : 657M BB; ArXiv:0803.3375

$$x_{\pm} = r_B \cos(\delta_B \pm \gamma)$$

$$y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$

$$\gamma = \left(76^{+12}_{-13} \pm 4 \pm 9\right)^{o}$$

$$B \to DK, D^{*}K$$

$$D \to K_s\pi^{+}\pi^{-}$$

model error

$$\gamma = (76 \pm 22 \pm 5 \pm 5)^{o}$$

$$B \to DK, D^{*}K, DK^{*}$$

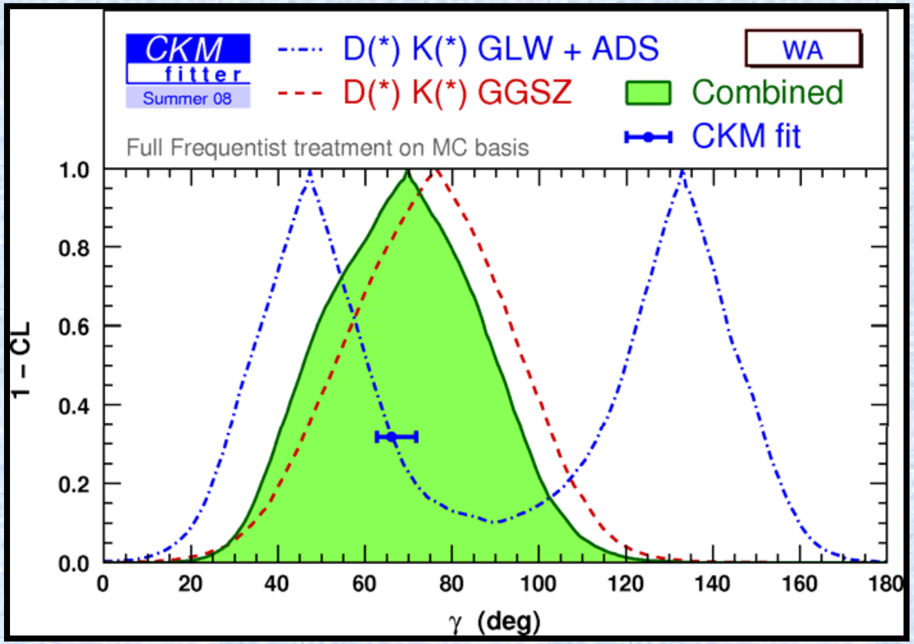
$$D \to K_s\pi^{+}\pi^{-}, K_sK^{+}K^{-}$$

Note: difference in Belle & BaBar stat errors due to values of r_B

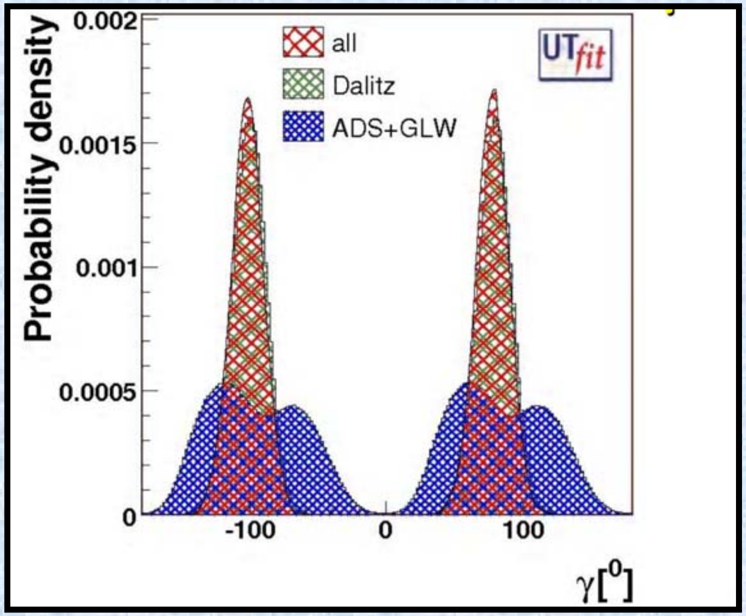
Summary γ

World average combinations vary according to statistics philosophy…

frequentist

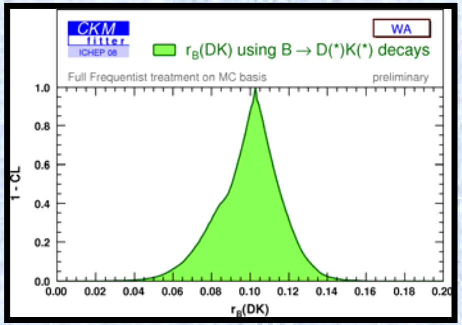


Bayesian



$$\gamma = (70^{+27}_{-29})^{\circ}$$

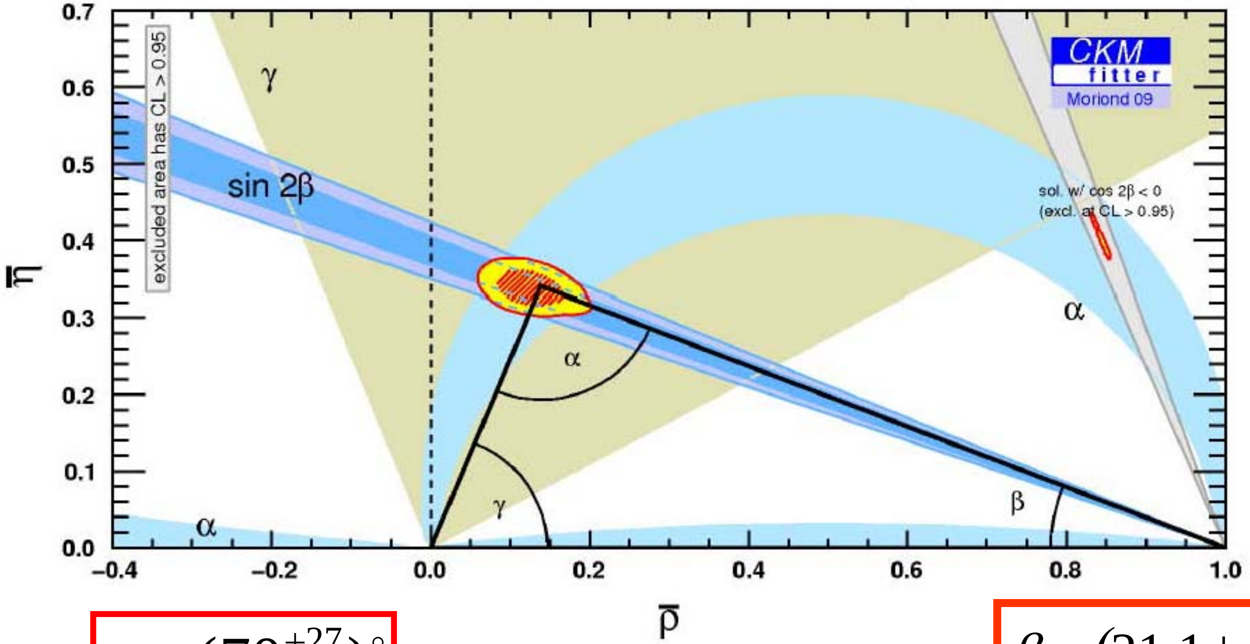
$$r_B = 0.103^{+0.017}_{-0.023}$$



$$\gamma = (78 \pm 12)^{\circ}$$

Summary of the Angles

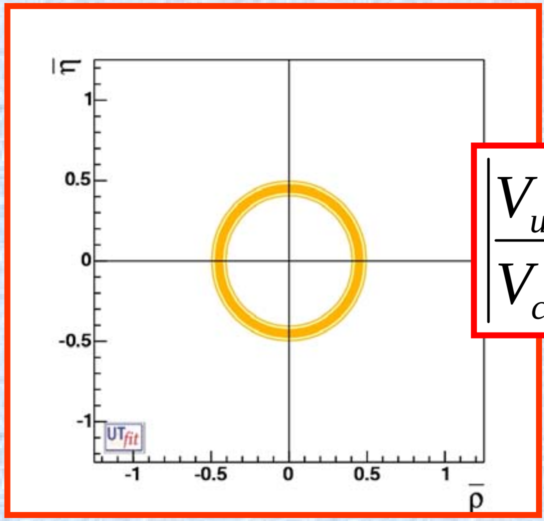
$$\alpha = \left(89.0^{+4.4}_{-4.2}\right)^{o}\ 60\%\ \text{c.l. interval}$$



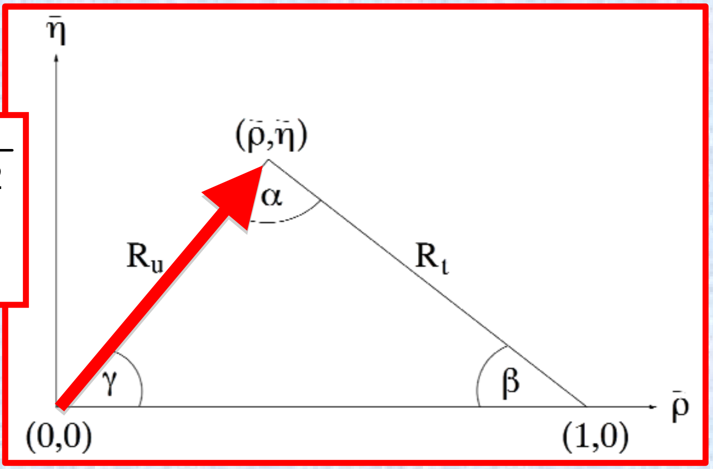
$$\gamma = \left(70^{+27}_{-29}\right)^{\circ}$$

$$\beta = \left(21.1 \pm 0.9\right)^{o}$$

$|V_{ub} / V_{cb}|$



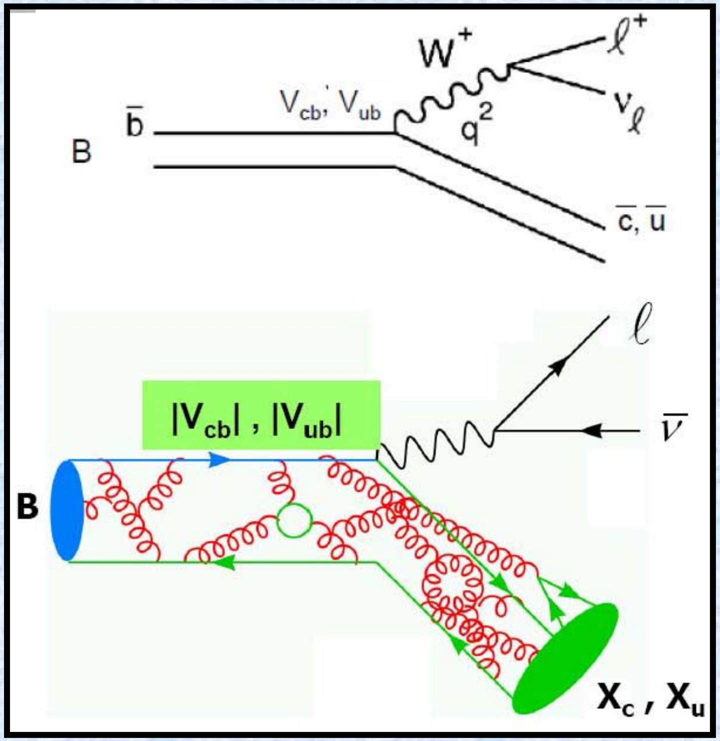
$$\left|\frac{V_{ub}}{V_{cb}}\right| = \frac{\lambda}{1-\lambda^2/2}\sqrt{\bar\rho^2+\bar\eta^2}$$



V_{ub} and V_{cb}

$|V_{ub}|$ and $|V_{cb}|$ determined from semi-leptonic B decays

At tree level everything is clean



QCD corrections must be included

- Inclusive measurements :

  OPE → total s.l. decay rate, moments
- Exclusive measurement :

  Form factors from LQCD

V_{ub} suffers from large b→c background

$$\frac{\Gamma(b\to u\ell\nu)}{\Gamma(b\to c\ell\nu)} \sim \left|\frac{V_{ub}}{V_{cb}}\right|^2 \sim \frac{1}{50}$$

Theory and experiment analyses are well advanced

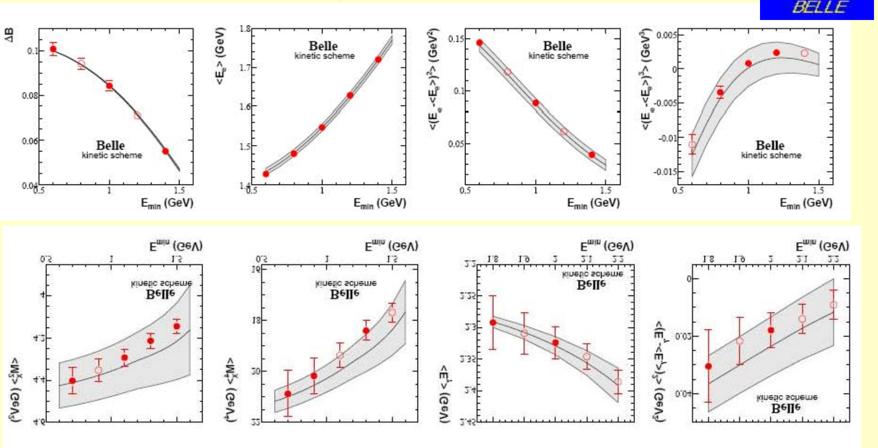
- Briefly comment on current status

CERN - FERMILAB HADRON COLLIDER PHYSICS SUMMER SCHOOL 2009

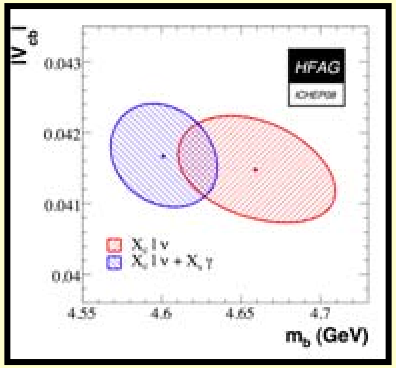
V_{cb}

Inclusive

Global fit to moments of E_ℓ, M_X^2 in $b \to c \ell \nu$ and E_γ in $b \to s\gamma$ decays



Belle : PRD78 (2008) 032016



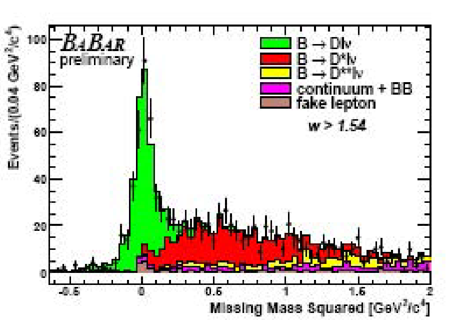
HFAG: Inclusion of $b \to s\gamma$ lowers m_b contrary to Belle moment analysis

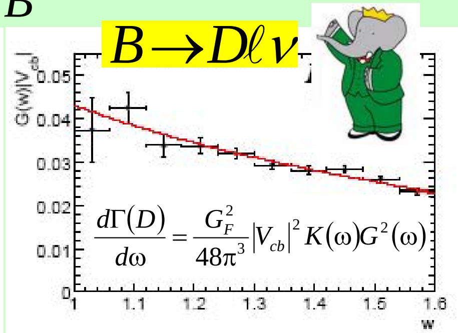
$$|V_{cb}| = (41.67 \pm 0.43 \pm 0.08 \pm 0.58) \times 10^{-3}$$

2.5σ

Exclusive

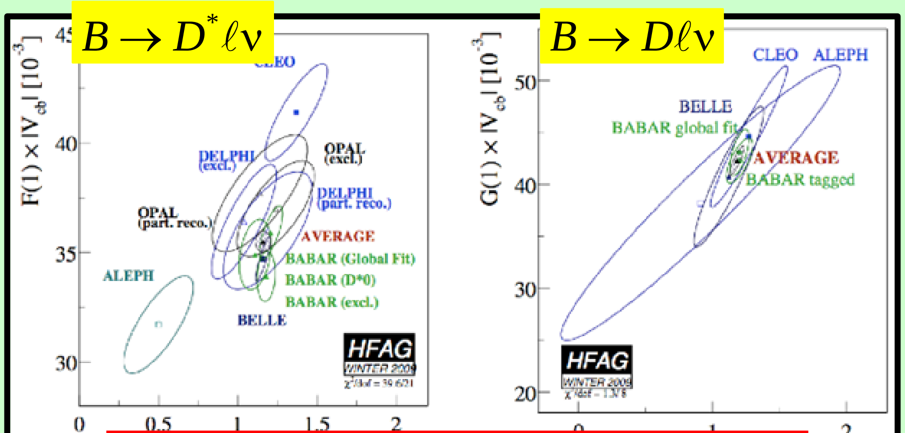
Select $D^{(*)}\ell\nu$ decays on the recoil of a fully reconstructed B





$$\frac{d\Gamma(D)}{d\omega} = \frac{G_F^2}{48\pi^3}|V_{cb}|^2 K(\omega) G^2(\omega)$$

BaBar : ArXiv:0807.4978



$$|V_{cb}| = (39.1 \pm 1.4 \pm 0.9) \times 10^{-3} \quad (D)$$

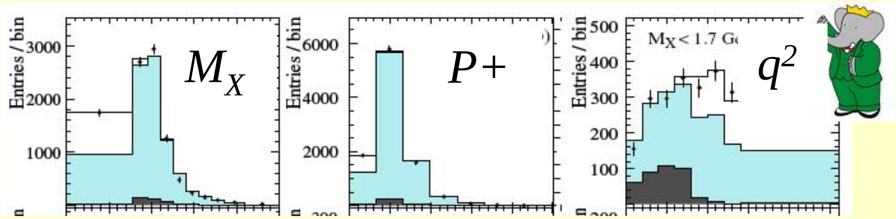
$$|V_{cb}| = (38.3 \pm 0.5 \pm 1.0) \times 10^{-3} \quad (D^*)$$

V_{ub}

Inclusive

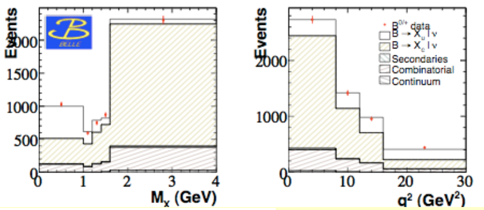
Experimental measurements of partial rates in regions of M_X, q^2, P_+....

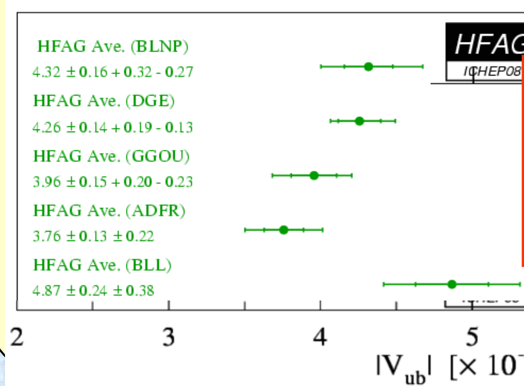
- Recoil analysis PRL100 (2008) 171802



- Multivariate analysis measures full $b\to u\ell\nu$ rate

FPCP09



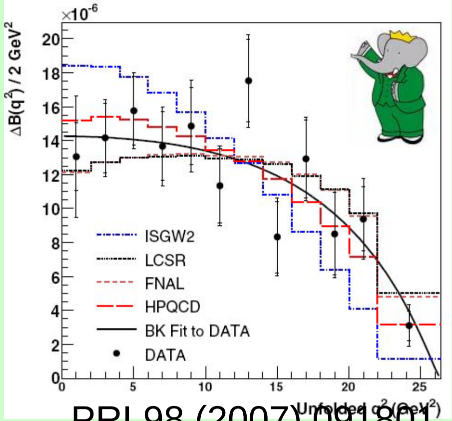


$$\frac{\Delta|V_{ub}|}{|V_{ub}|} \sim 4\%\,(exp)$$

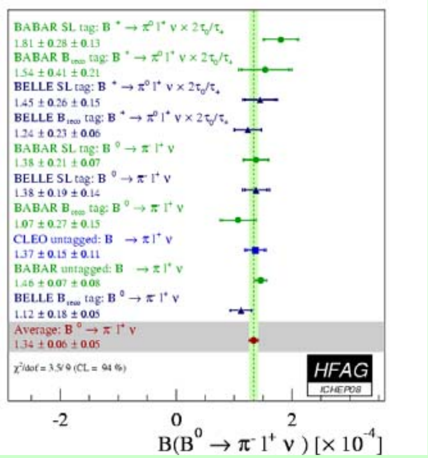
$$\sim 6-7\%\,(th)$$

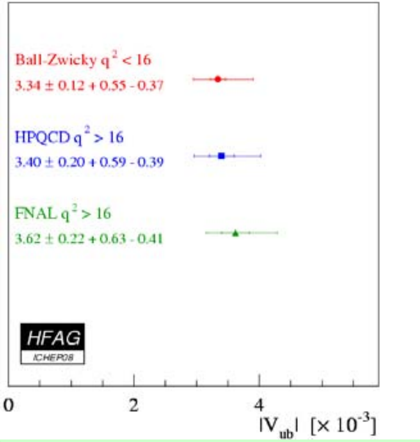
Exclusive

$B\to\pi\ell\nu$: reconstruct ν from whole event and extract signal yield in q^2 bins from fit to ΔE and M_{ES} distributions



PRL98 (2007) 091801





$$\frac{\Delta|V_{ub}|}{|V_{ub}|} \sim 5\%\,(exp)$$

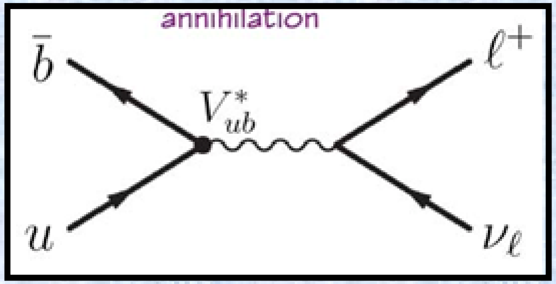
$$\sim^{+17\%}_{-11\%}\,(th)$$

Lower than inclusive V_{ub}

$B \to \tau\nu$

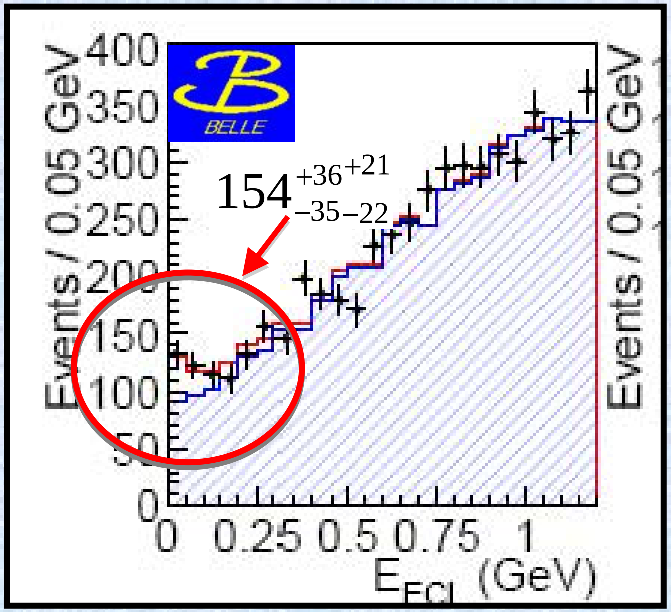
The helicity suppressed B→ τν annihilation decay sensitive to $f_B\,|V_{ub}|$

Also sensitive to tree-level charged Higgs



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

An excess of events is clearly visible in signal region of “Extra Energy in Calorimeter”



$$Br\left(B^+ \to \tau^+\nu\right) = \left(1.65^{+0.38+0.35}_{-0.37-0.37}\right)\times 10^{-4}$$

Semi-leptonic tag

$$Br\left(B^+ \to \tau^+\nu\right) = \left(1.2 \pm 0.4 \pm 0.3 \pm 0.2\right)\times 10^{-4}$$

hadronic tag

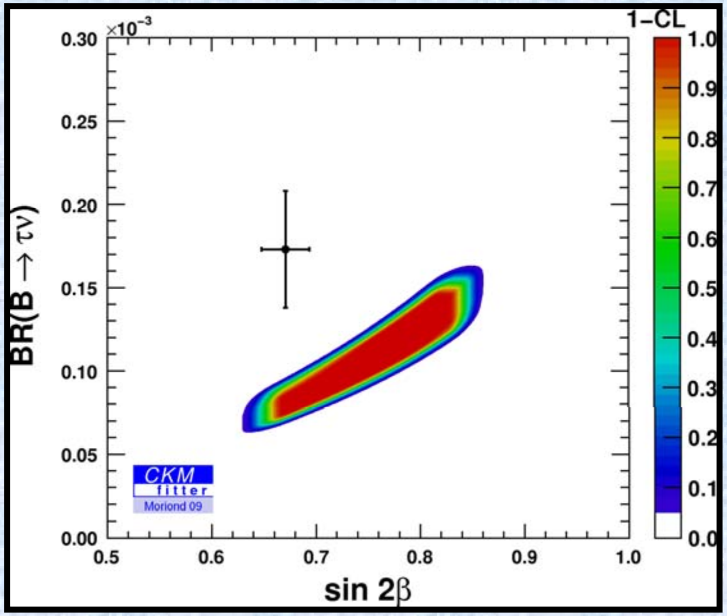
BaBar : 383M BB; PRD77 (2008) 011107

Belle : 657M BB; ArXiv:0809.3834

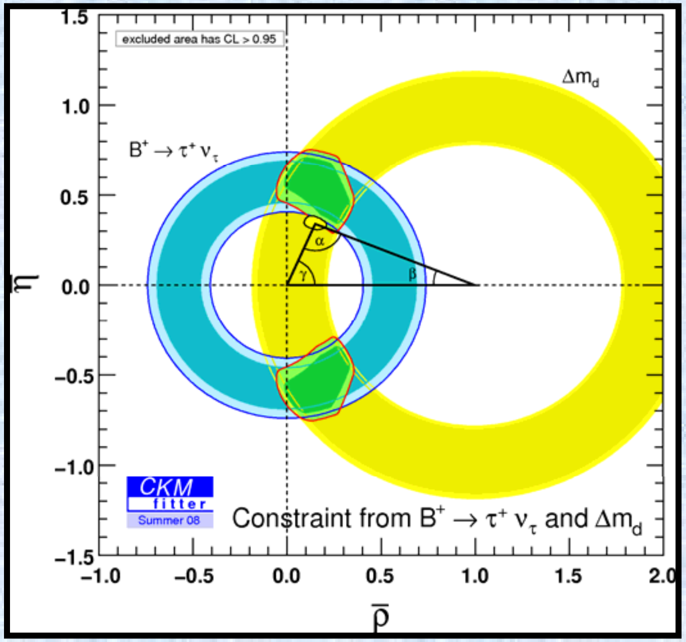
$B \to \tau\nu$

Within SM, $Br(B\to \tau\nu)$ determines $f_B\,|V_{ub}|$

- Input f_B from lattice $\to|V_{ub}|$



~2.5σ discrepancy between $Br(B\to \tau\nu)$ and CKM from other measurements



Constraint from $B^+\to\tau^+\nu_\tau$ and Δm_d

Combining with B mixing results removes dependence on f_B

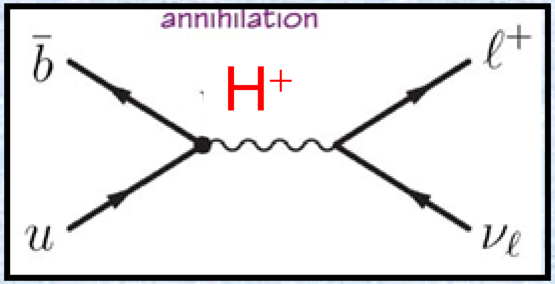
$$\frac{Br\left(B^+\to\tau^+\nu\right)}{\Delta m_d}=\frac{3\pi}{4}\,\frac{m_\tau^2\tau_B}{m_W^2 S(x_t)}\left(1-\frac{m_\tau^2}{m_B^2}\right)^2\frac{\sin^2\beta}{\sin^2\gamma}\,\frac{1}{|V_{ud}|^2 B_{B_d}}$$

Tension with sin2β persists.

Theory free prediction for B_{Bd} ~2.7σ from LQCD value

$B \to \tau\nu$

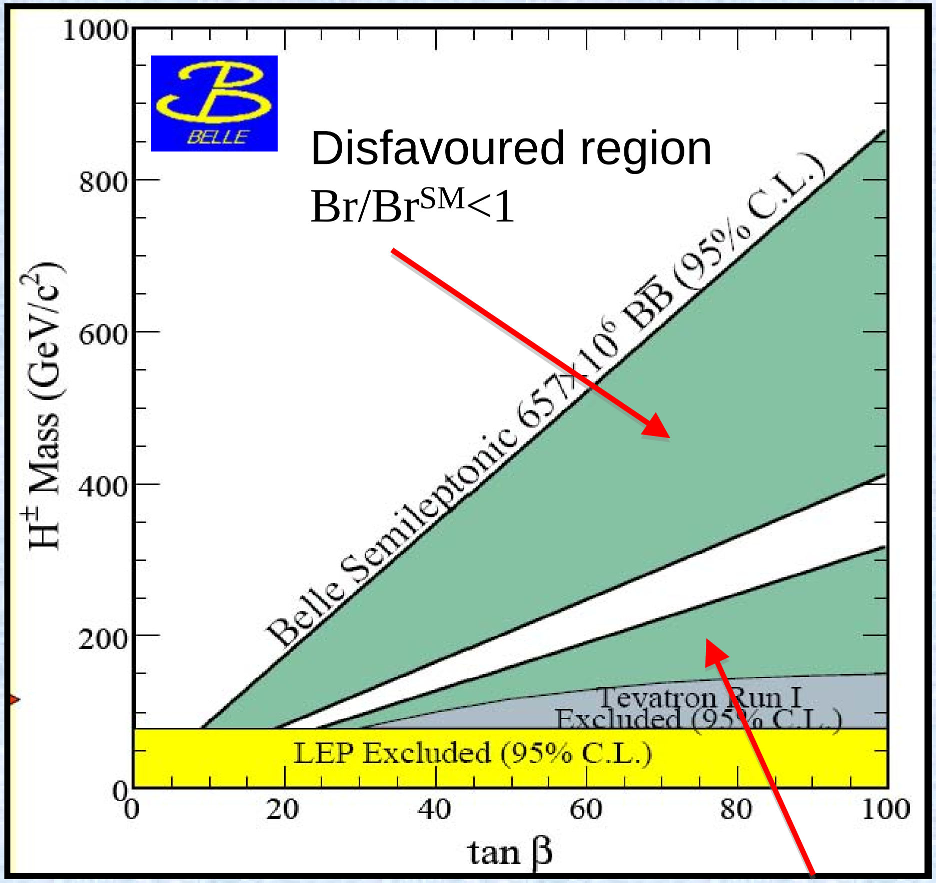
Tree-level charged Higgs contribution interferes destructively with SM W diagram



e.g. MSSM (G.Isidori; ArXiv:0710.5377)

$$Br\left(B^+ \to \tau^+ \nu\right) \approx Br^{SM} \times \left(1 - \frac{m_B^2}{m_H^2} \tan^2\beta\right)^2$$

$$\frac{Br\left(B^+ \to \tau^+ \nu\right)}{Br^{SM}} = 1.77 \pm 0.65$$

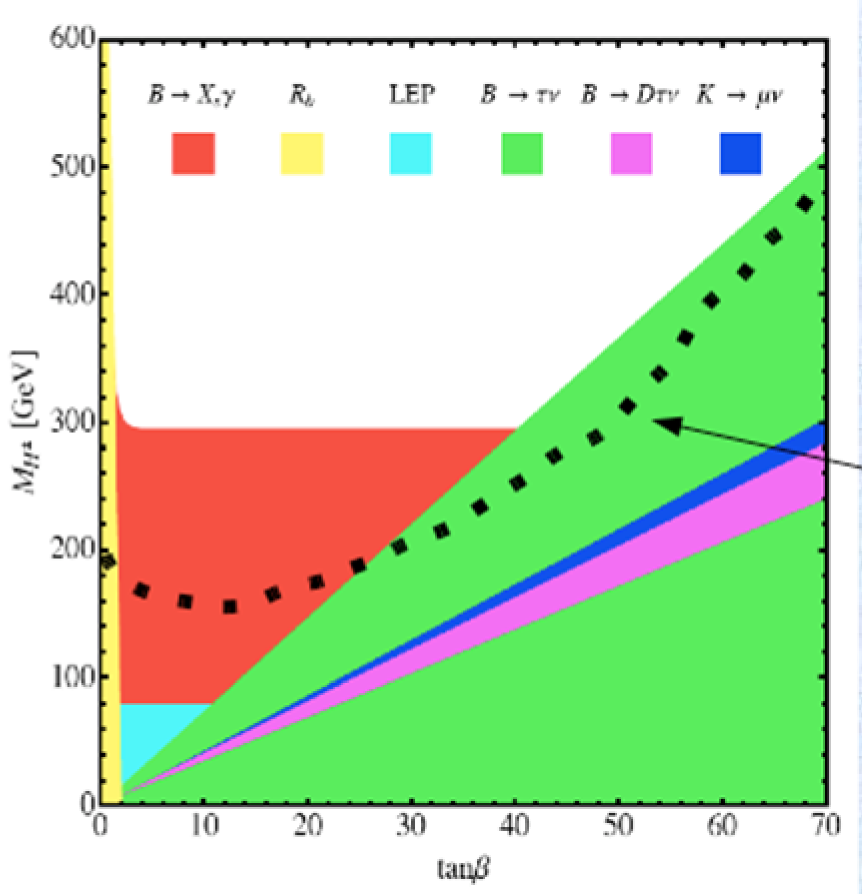


Disfavoured region $Br/Br^{SM}<1$

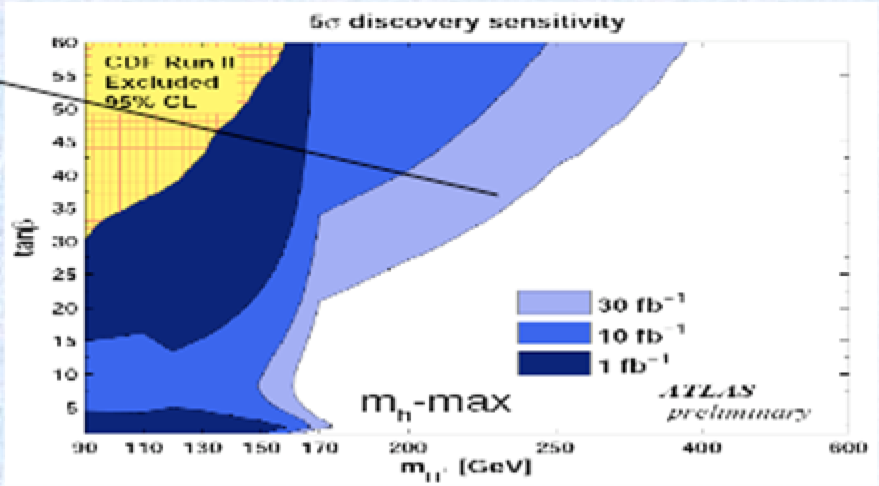
Large Br/Br^{SM} ruled out by Br upper limits

$B \to \tau\nu$

B factories versus LHC (ATLAS) for the charged Higgs

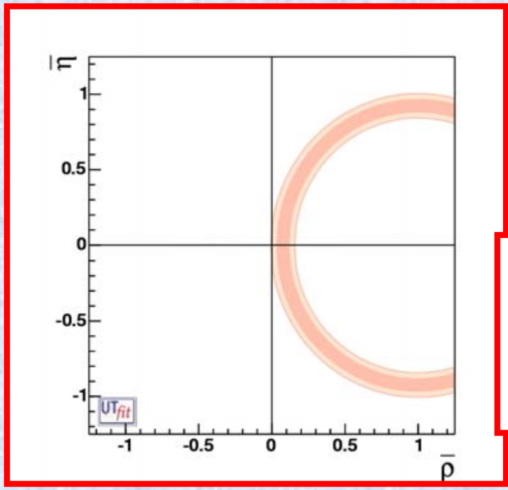


Current flavour constraints are already competitive with LHC direct search sensitivity for charged Higgs

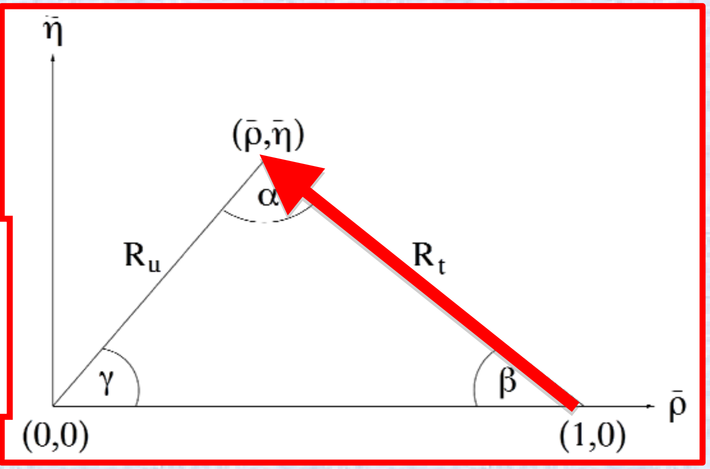


U.Haisch, hep-ph/0805.2141; ATLAS curve added by Steve Robertson (LLWI 2009)
D.Eriksson, F.Mahmoudi and O.Stal, JHEP 0811:0.35 (2008) for MSSM interpretation

$|V_{td} / V_{ts}|$

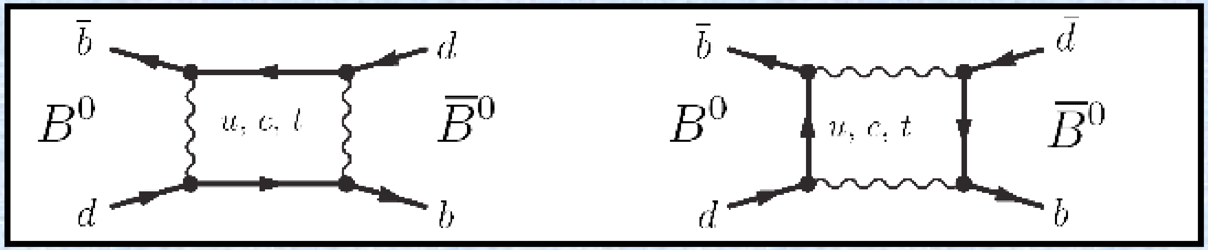


$$\left|\frac{V_{td}}{V_{ts}}\right| \approx \sqrt{\left(1-\bar{\rho}\right)^2 + \bar{\eta}^2}$$



B Mixing

Traditional method for measuring V_{td} and V_{ts} is through box diagrams



SM

$$\Delta m_q = 2|M_{12}| = \frac{G_F^2 m_W^2 \eta_{B_q} m_{B_q} B_{B_q} f_{B_q}^2}{6\pi^2} S\left(m_t^2/m_W^2\right)\left|V_{tq}^* V_{tb}\right|^2$$

$$|q/p| = 1$$

Measure oscillation rates for flavour eigenstates

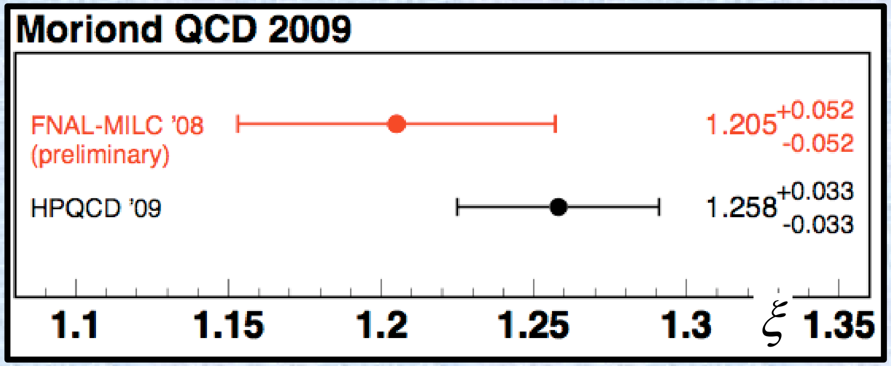
Input theory from LQCD for B_{Bq} and f_{Bq} to extract $|V_{td}|$ or $|V_{td}/V_{ts}|$

HPQCD; ArXiv:0902.1815

$$f_{B_d}\sqrt{B_{B_d}} = 216\,(15) \quad \text{MeV}$$

$$f_{B_s}\sqrt{B_{B_s}} = 266\,(18) \quad \text{MeV}$$

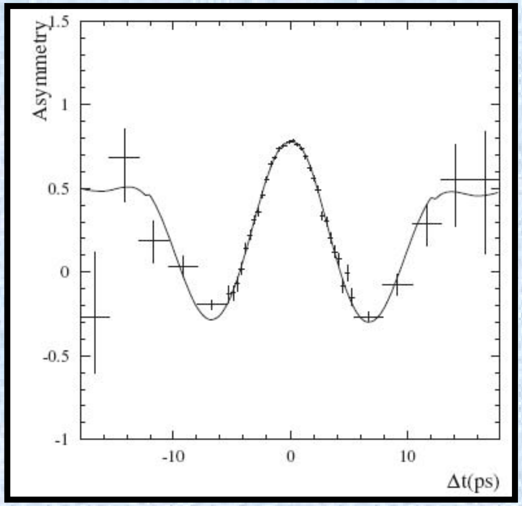
$$\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}} = 1.258\,(33)$$

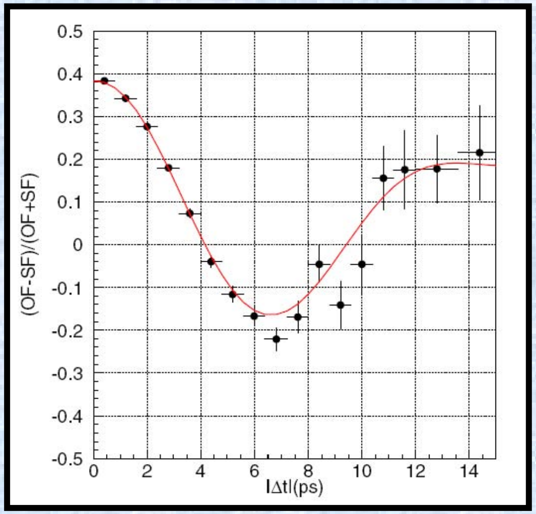


$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}}\xi^2\left|\frac{V_{ts}}{V_{td}}\right|^2$$

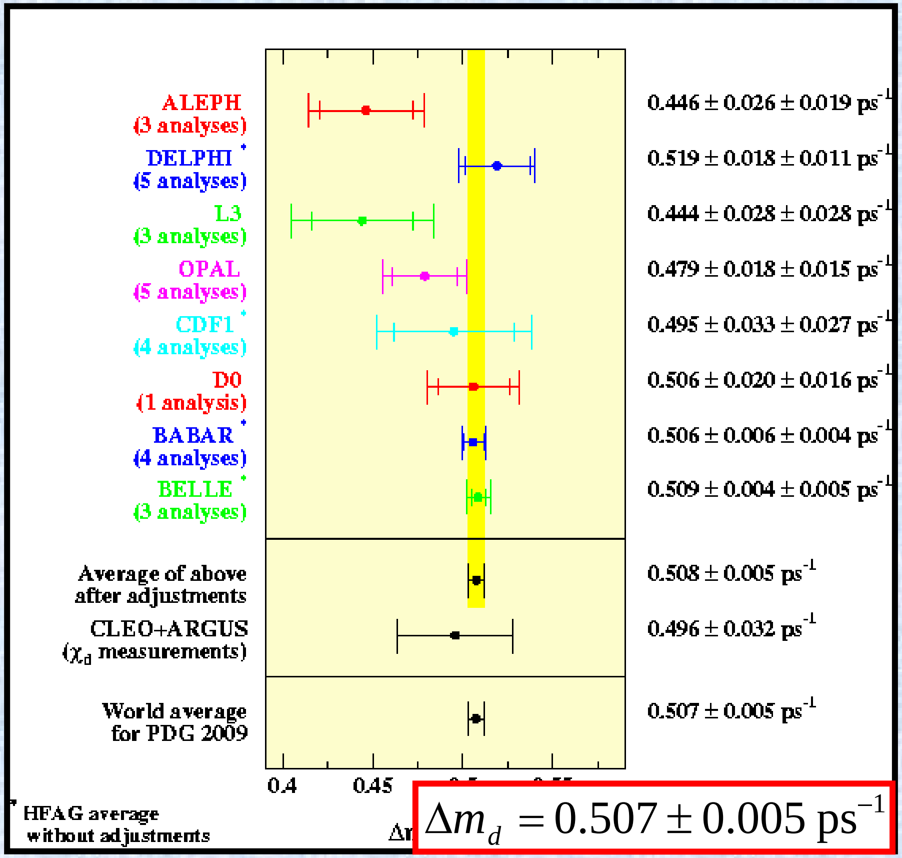
3%

B Mixing





$$A_{mix}(\Delta t) \cong \{(1-2\omega)\times\cos\Delta m\,\Delta t\}\otimes R(\Delta t)$$



$$\Delta m_d = 0.507 \pm 0.005\ \text{ps}^{-1}$$

$$\left|\frac{V_{ts}}{V_{td}}\right| = 0.214\ (1)_{\text{exp.}}\ (5)_{\text{lattice.}}$$

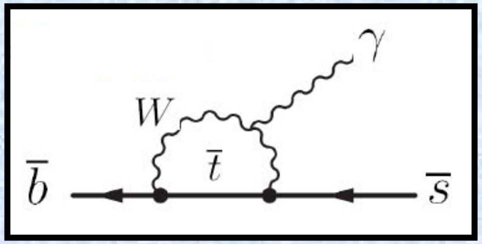
FPCP 09:
R.Van de Water

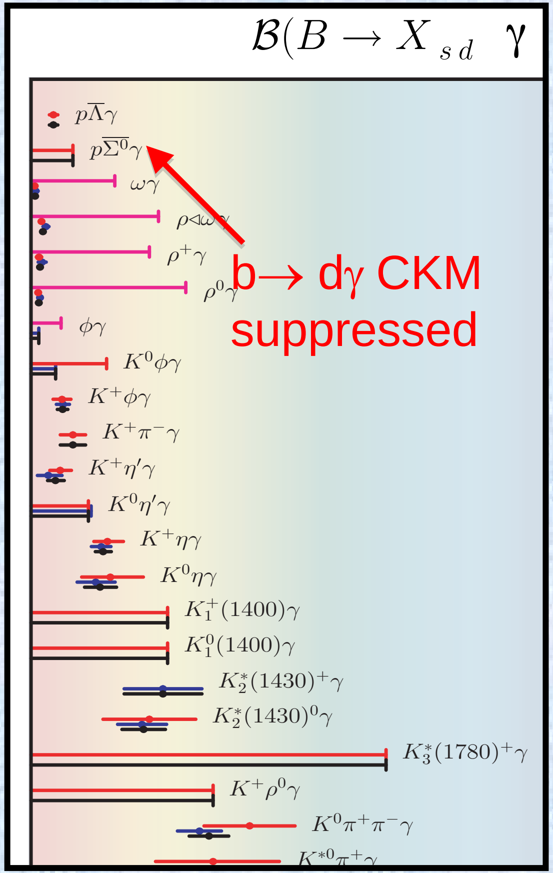
FCNC : B → $(\rho,\omega)\gamma$, $K^*\gamma$

Access to $|V_{td}/V_{ts}|$ through ratios of exclusive Br's.

Provides comparison between penguins vs box

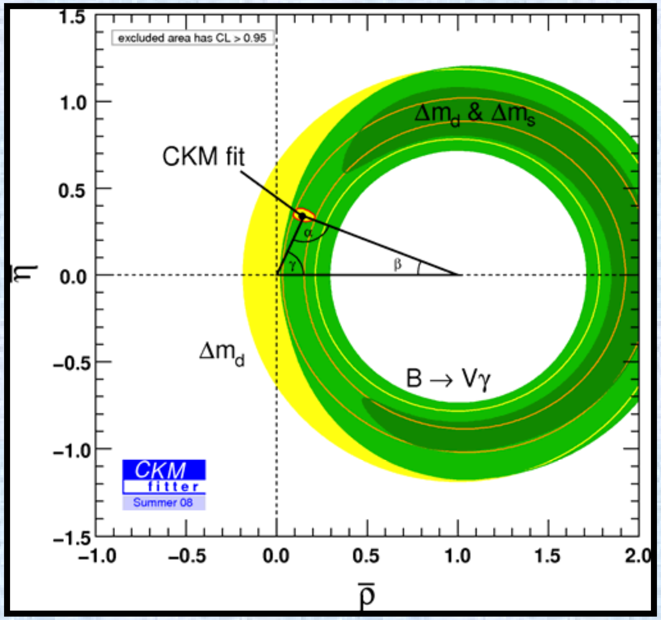
Many recent and accurate exclusive measurements





b→ dγ CKM suppressed

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

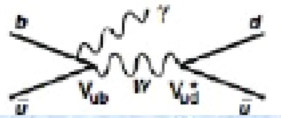


$\xi = 1.17 \pm 0.09$

Flavour SU(3) breaking

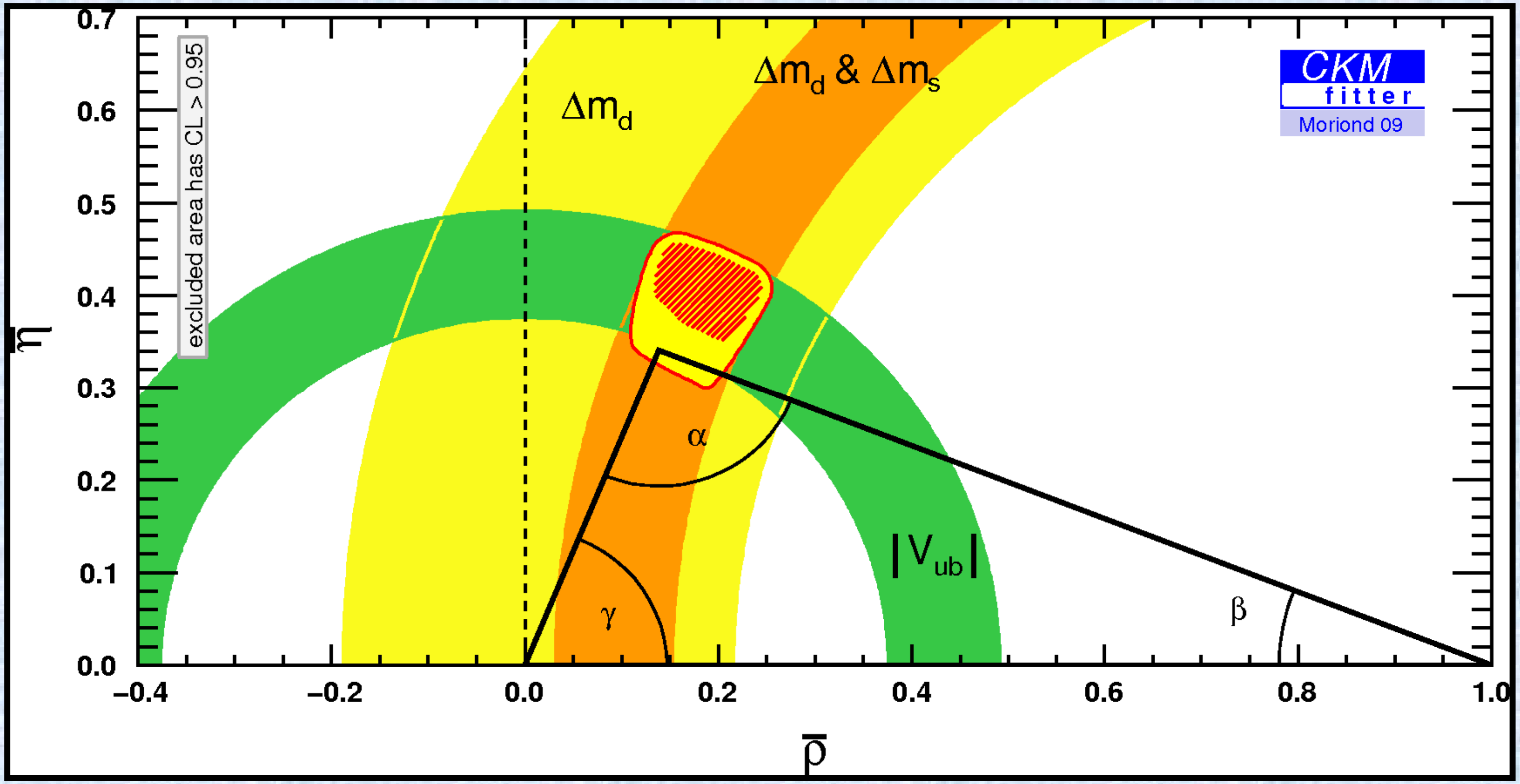
$\Delta R = 0.1 \pm 0.1$

Weak annihilation correction



Summary of Sides

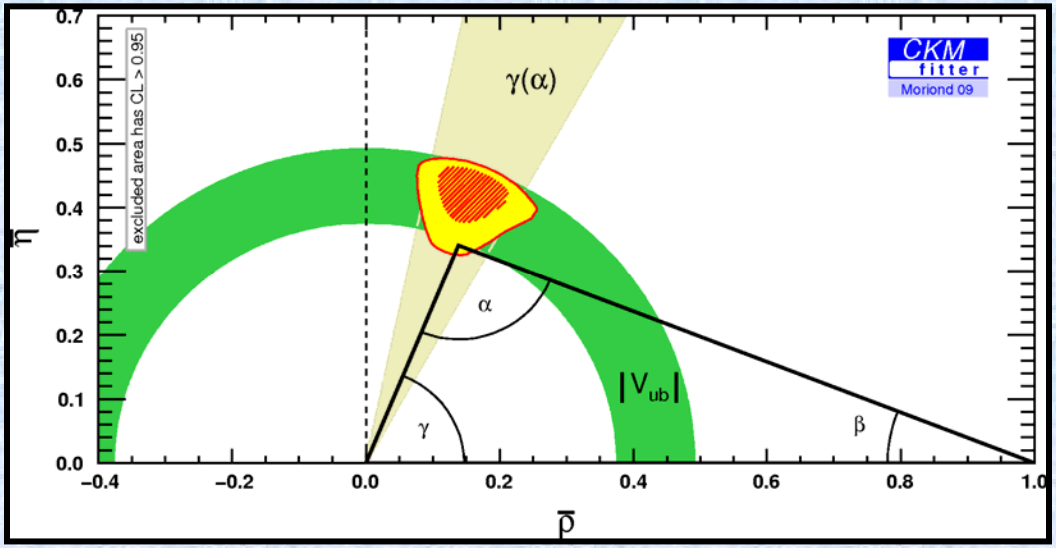
CP Conserving Measurements $\boxed{\left|V_{ub}/V_{cb}\right|, \quad \Delta m_d, \quad \left|\Delta m_d/\Delta m_s\right|, \quad B \to \tau\nu}$



Global CKM Fit

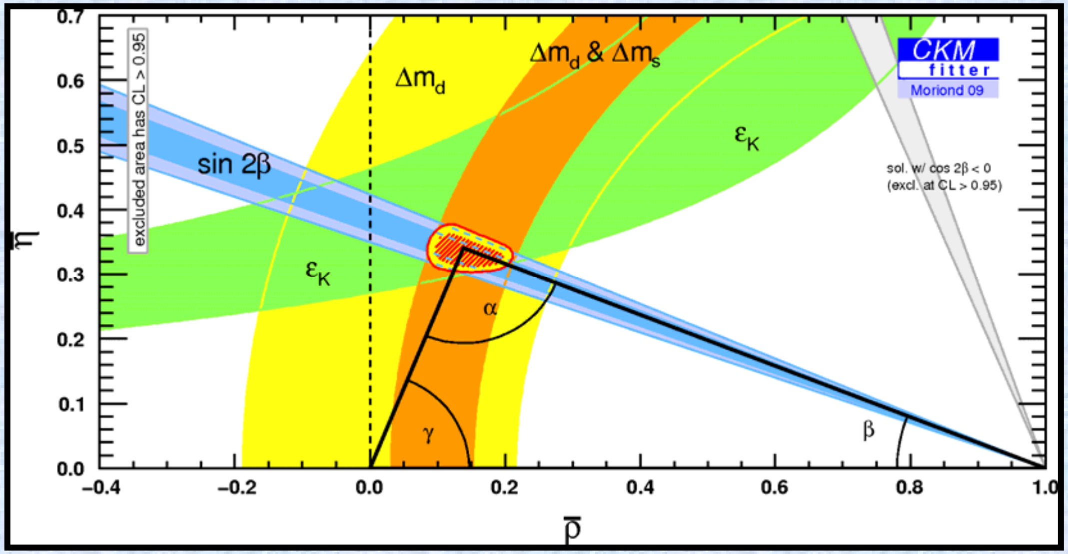
Tree processes only:

$$\left|V_{ub}/V_{cb}\right|,\ B\to\tau\nu,\ \gamma,\ \pi-\alpha-\beta$$



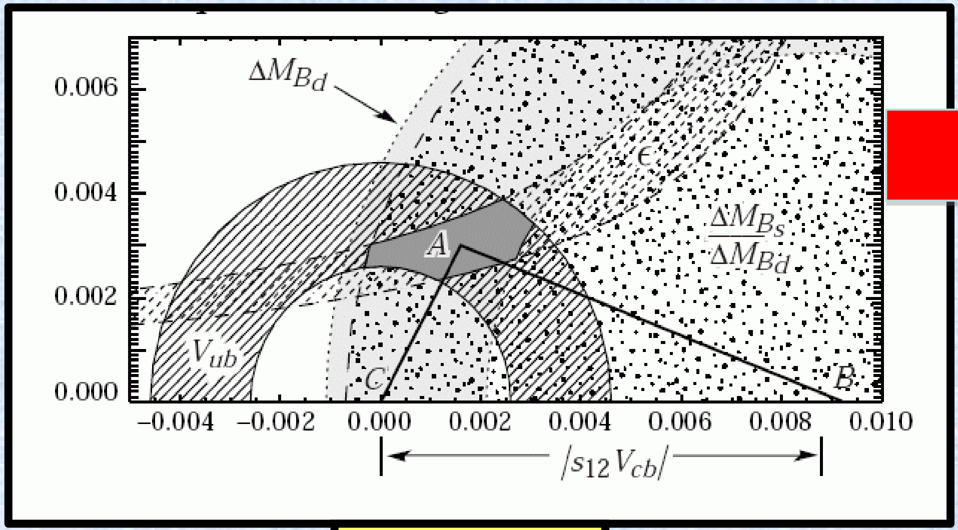
Loop processes only:

$$\left|\varepsilon_K\right|,\ \sin 2\beta,\ \Delta m_d,\ \Delta m_s$$

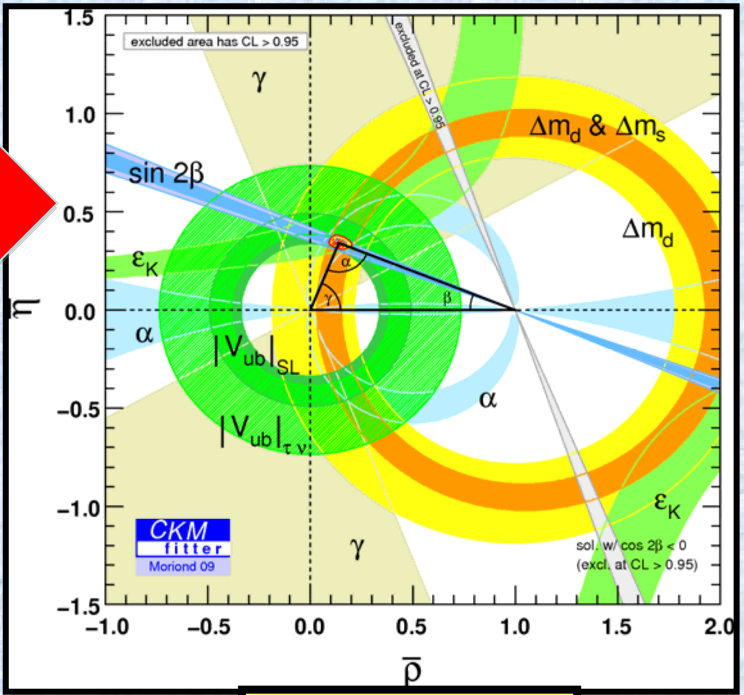


Tension between $B\to\tau\nu$ and $\sin 2\beta$ evident ($\sim 2.4\sigma$)

Global CKM Fit



PDG 1997



Moriond 2009

$$A = 0.8116^{+0.0097}_{-0.0241}$$

$$\lambda = 0.22521 \pm 0.00082$$

$$\bar{\rho} = 0.139^{+0.025}_{-0.027}$$

$$\bar{\eta} = 0.341^{+0.016}_{-0.015}$$

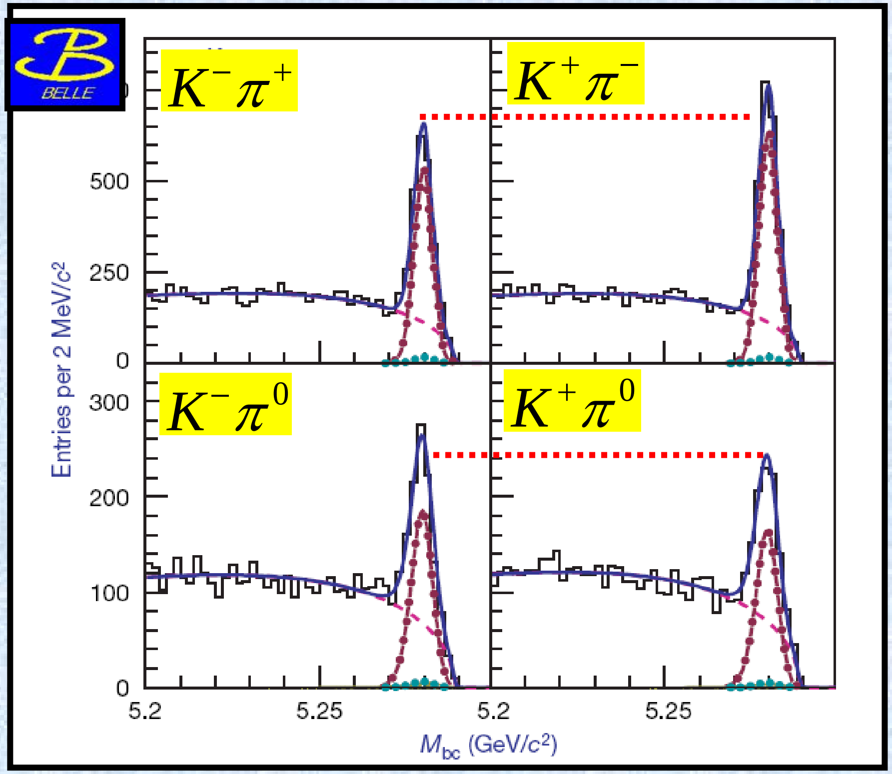
$$J_{CP} = (2.92 \pm 0.15) \times 10^{-5}$$

The “Kπ Puzzle”

“Kπ Puzzle” published by Belle in Nature 2008….

Belle : 535M BB; Nature 452 (2008) 332

Direct CPV asymmetry in B→$K^+\pi^-$ decays different to B→$K^+\pi^0$ decays ??



HFAG 2009

$$A_{CP}\left(K^+\pi^-\right) = -0.098^{+0.012}_{-0.011}$$

8.1σ

$$A_{CP}\left(K^+\pi^0\right) = +0.050 \pm 0.025$$

$$\Delta A_{K\pi} = A_{CP}\left(K^+\pi^-\right) - A_{CP}\left(K^+\pi^0\right)$$
$$= -0.147 \pm 0.028$$

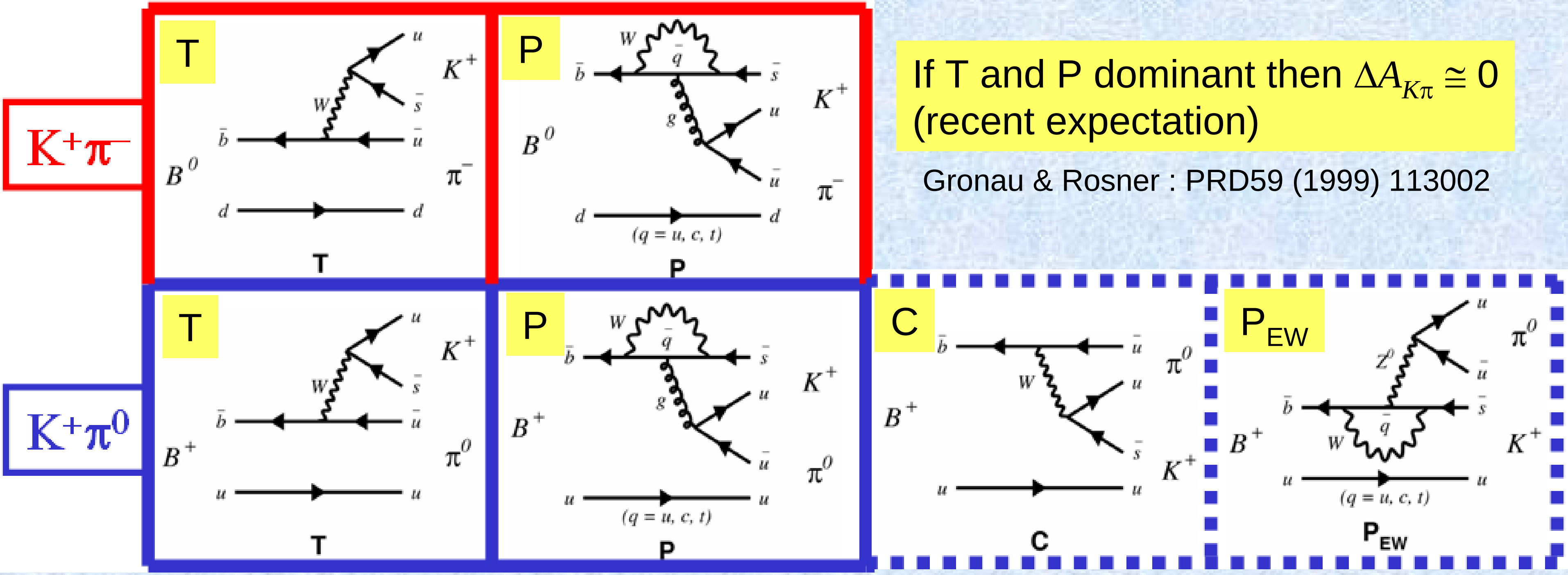
5.3σ

“Kπ Puzzle”

Solutions to the “Kπ Puzzle”

See Nature commentary by Michael Peskin

M.Peskin : Nature 452 (2008) 293



If T and P dominant then $\Delta A_{K\pi} \cong 0$ (recent expectation)

Gronau & Rosner : PRD59 (1999) 113002

Enhancement of C with large strong phase to T ⇒ strong Interactions ??

Enhancement of P_{EW} from ⇒ New Physics

Also explains pattern of B→ππ and B→ρρ Br’s

Fleischer et al (& ref therein) : ArXiv 0806.2900

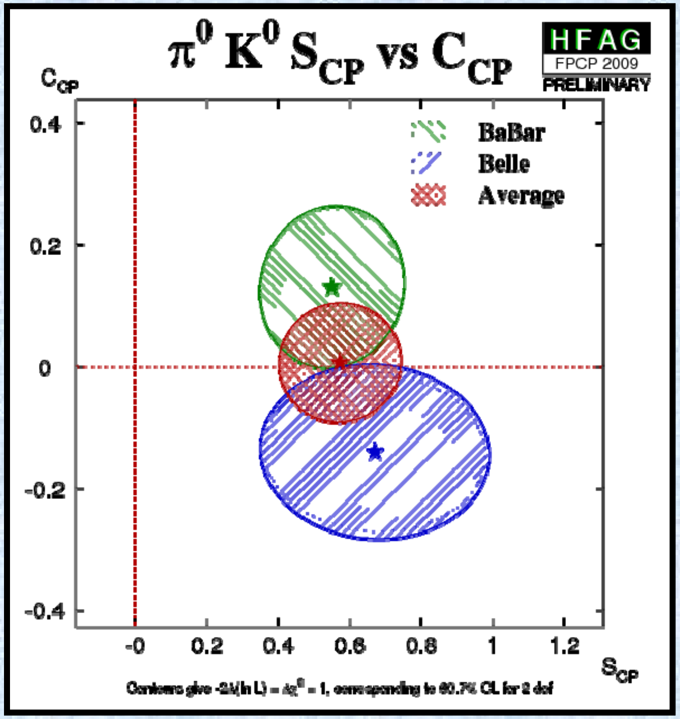
Li & Mishima : ArXiv 0901.1272

Solutions to the “Kπ Puzzle”

Model independent method to detect NP

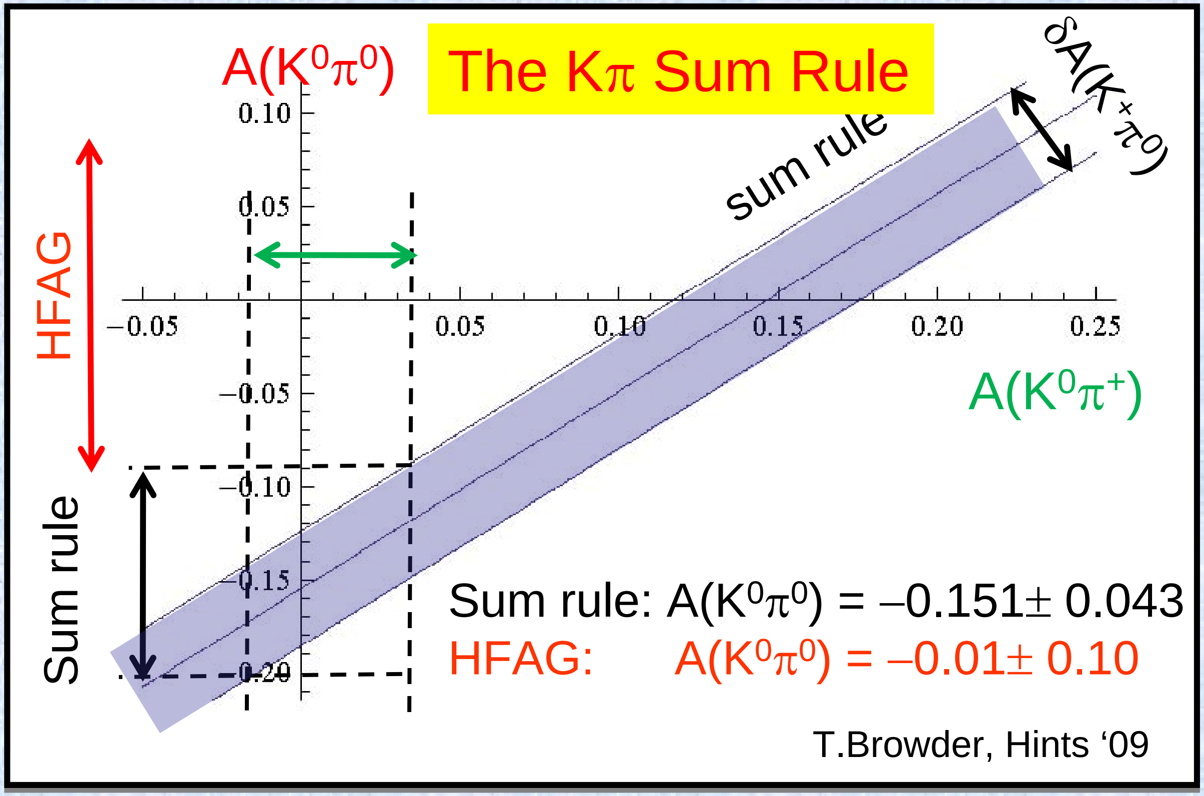
M.Gronau : PLB82 (2005) 627

$$\mathcal{A}_{CP}(K^+\pi^-) + \mathcal{A}_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = \mathcal{A}_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + \mathcal{A}_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$



BaBar : 467M BB; PRD79 (2009) 052003

Belle : 657M BB; ArXiv:0809.4366



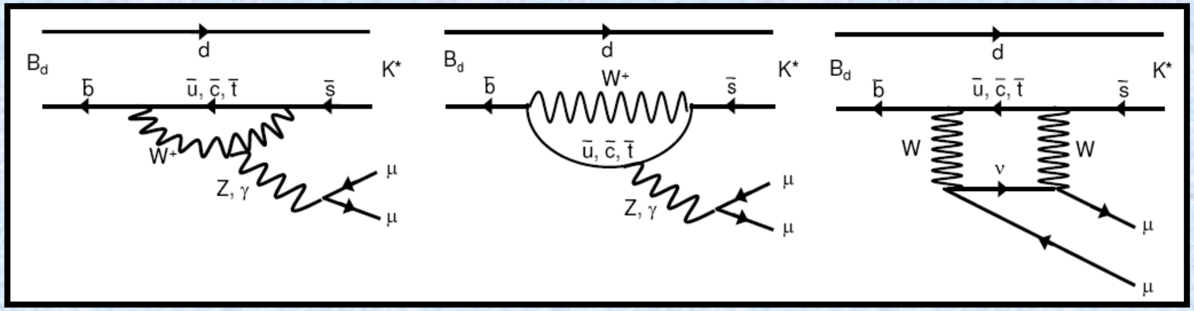
Sum rule: $A(K^0\pi^0) = -0.151 \pm 0.043$

HFAG: $A(K^0\pi^0) = -0.01 \pm 0.10$

T.Browder, Hints ‘09

FCNC Rare Decays: B →K*μμ

FCNC b→s transition, very sensitive to NP



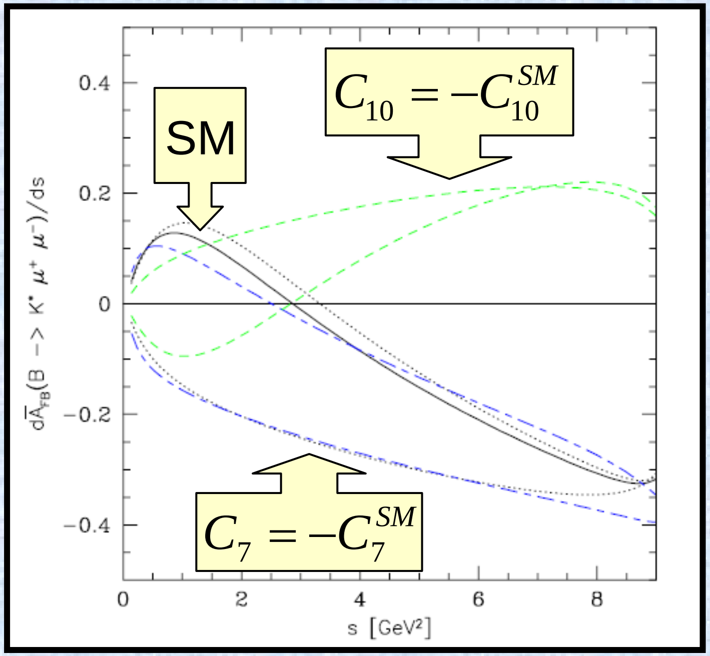
The forward-backward asymmetry arises from the interference between γ and Z^0 contributions

$$A_{FB}\left(s=m_{\mu\mu}^{2}\right)=-C_{10}\,\xi(s)\left[\mathrm{Re}(C_{9})F_{1}+\frac{1}{s}C_{7}F_{2}\right]$$

The zero crossing point is most theoretically clean

$$s_{0}^{SM}=4.36_{-0.31}^{+0.33}\ \mathrm{GeV}^{2}$$

Beneke et al; EPJC41 (2005) 173

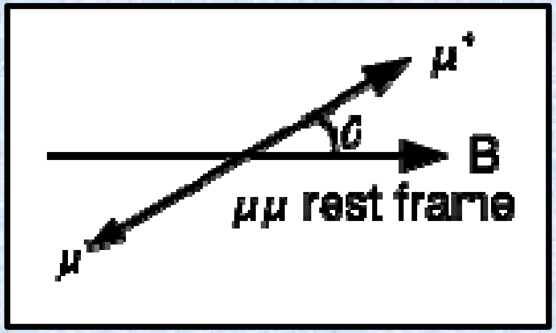


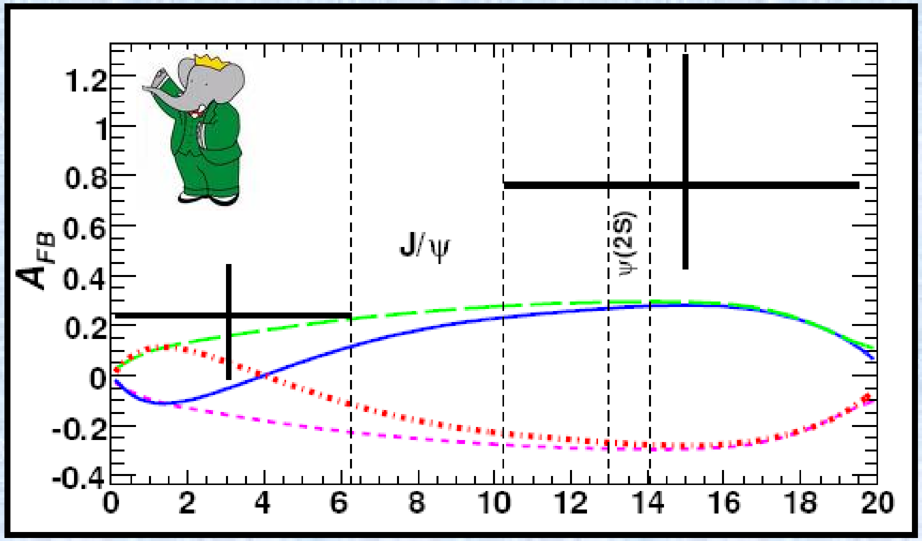
Ali et al; PLB273 (1991) 505

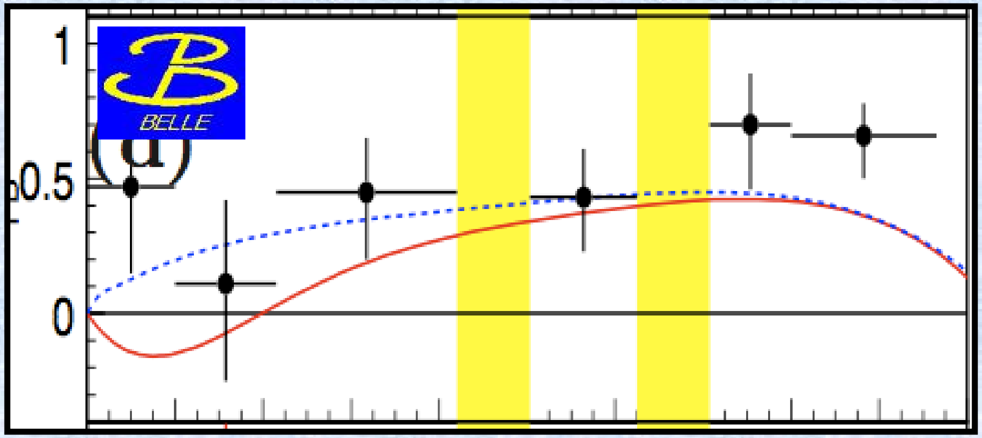
FCNC Rare Decays: B →K*μμ

Recent results of A_{FB} from the B factories show interesting behaviour

$$A_{FB}\left(s=m_{\mu\mu}^{2}\right)=\frac{N_F-N_B}{N_F+N_B}$$







BaBar : 384M BB; ArXiv:0804.4412

Belle : 657M BB; ArXiv:0904.0770

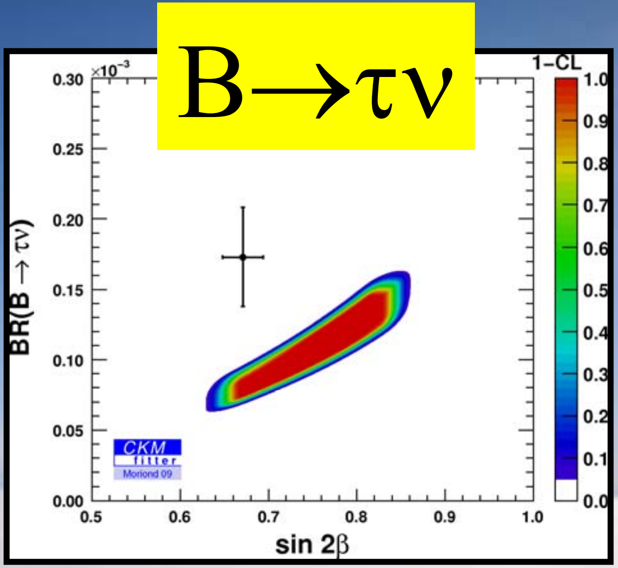
Note: opposite sign convention

Data points tend to be above the SM curve

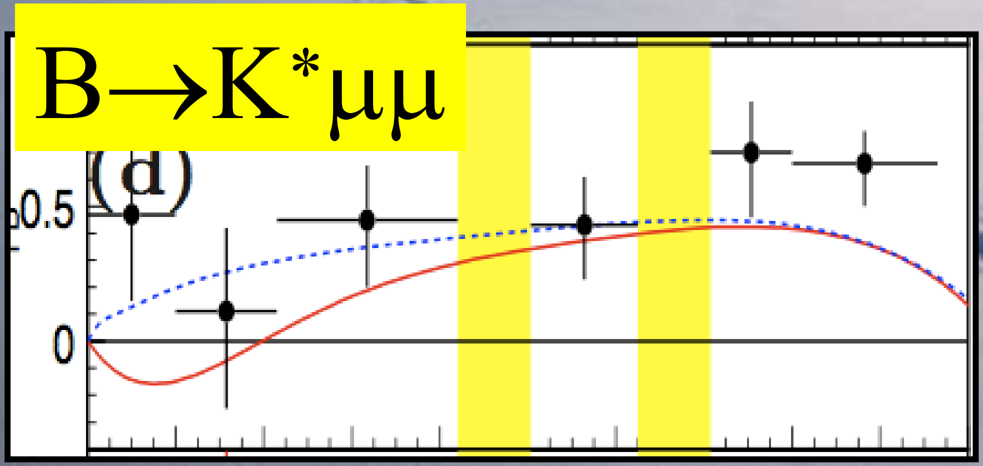
Is the sign of C7 wrong ? Need more statistics

Some hints/puzzles exist…?.

β_{eff}



$B \rightarrow \tau\nu$



$B \rightarrow K^{*}\mu\mu$

"Kπ Puzzle"

Summary

B factories have dramatically improved our understanding of flavour physics, far beyond expectations.

Clear demonstration of the SM CKM mechanism as the dominant source of CP violation

Overall good agreement in the global SM CKM fit

- A huge step forward on precision of α

A few puzzles remaining…..

- Tension between $\sin 2\beta$ and $|V_{ub}|$ with $B\to\tau\nu$
- $K\pi$ puzzle
- A_{FB} in $B\to K^*\mu\mu$

Next lecture:

- What have we learnt from the Tevatron ?
- Is there still room for NP ?
- If so, can it be discovered at the LHC and beyond ?

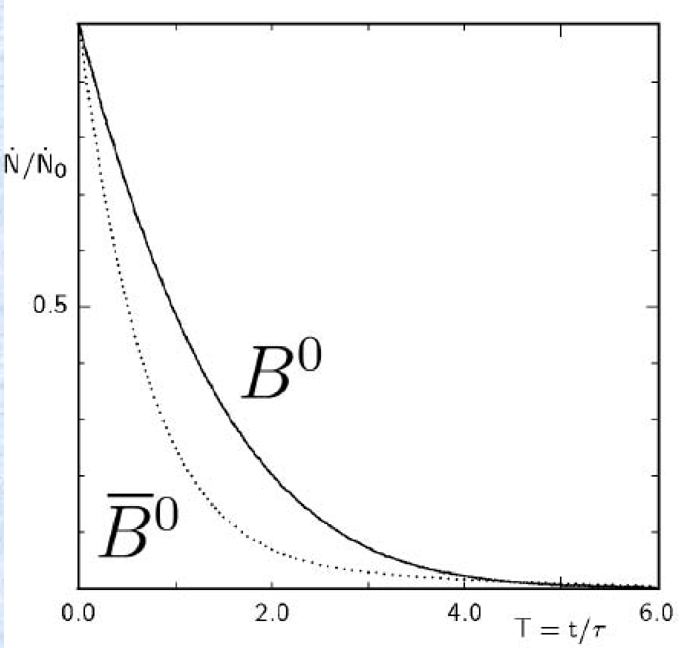
New Physics is still hiding…

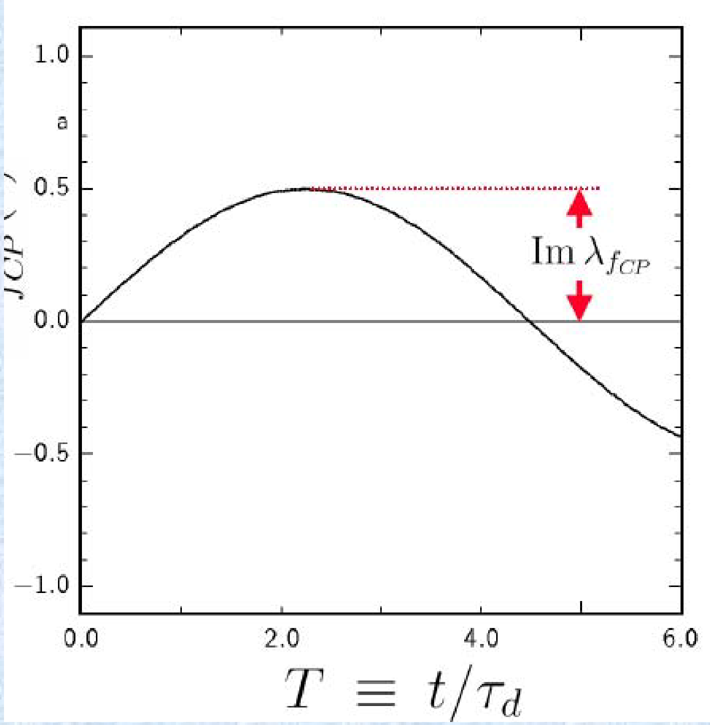

iStockphoto

CP Violation in Interference

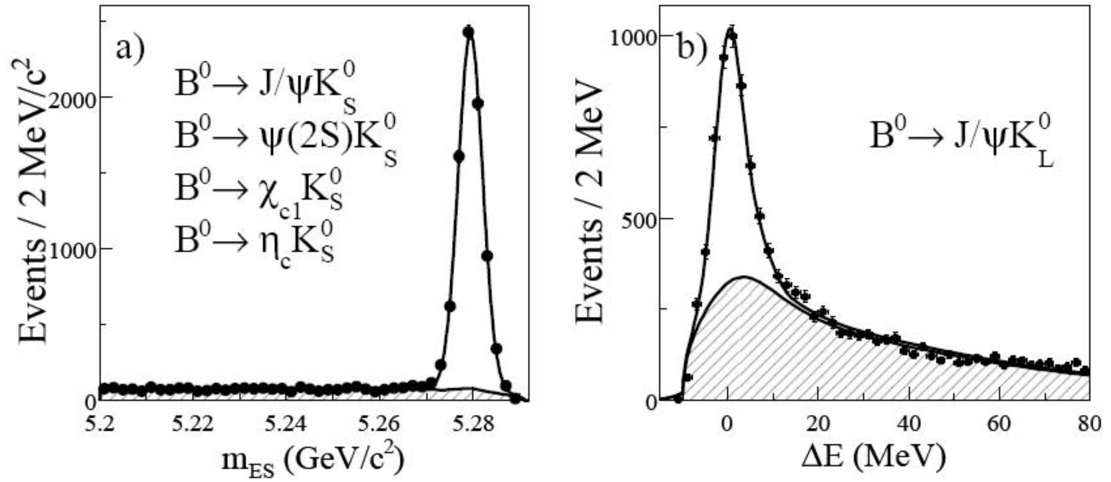
Golden case: CP final state and single dominating amplitude

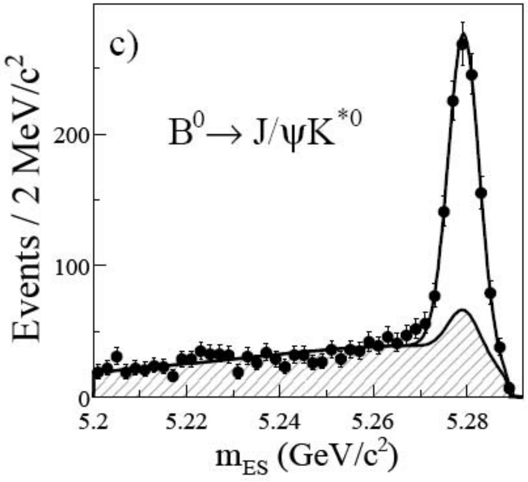
$$A_{f_{CP}}^{CP}(t) = \operatorname{Im}\lambda_{f_{CP}} \sin(\Delta m t)$$





β : b→ccs modes



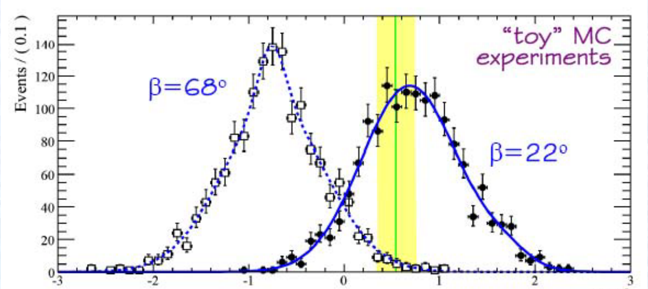


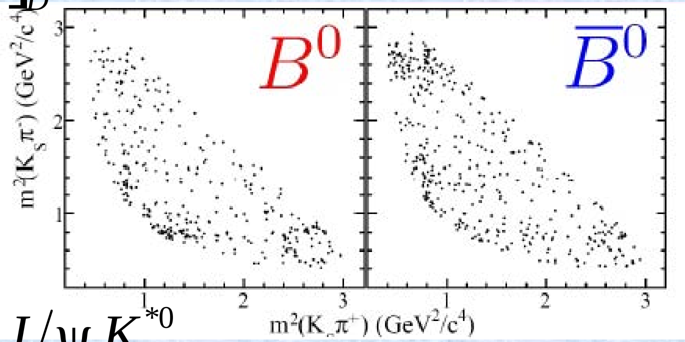
Mode	$\sin 2\beta$
$J/\psi K_S$	$0.657 \pm 0.036 \pm 0.012$
$J/\psi K_L$	$0.694 \pm 0.061 \pm 0.031$
$J/\psi K^0$	**$0.666 \pm 0.031 \pm 0.013$**
$\psi(2S) K_S$	$0.897 \pm 0.100 \pm 0.036$
$\chi_{c1} K_S$	$0.614 \pm 0.160 \pm 0.040$
$\eta_c K_S$	$0.925 \pm 0.160 \pm 0.057$
$J/\psi K^{*0}$	$0.601 \pm 0.239 \pm 0.087$
$c\bar{c}K^{(*)0}$	**$0.687 \pm 0.028 \pm 0.012$**

Resolve 2-fold sin 2β ambiguity

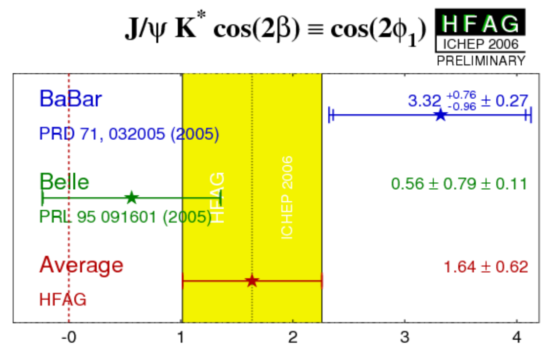
Belle : 386M BB; PRL97 (2006) 081801
BaBar : 383M BB; PRL99 (2007) 231802

- Amplitude analysis in $B^0 \to \left[K_s^0\pi^+\pi^-\right]_D \pi^0$

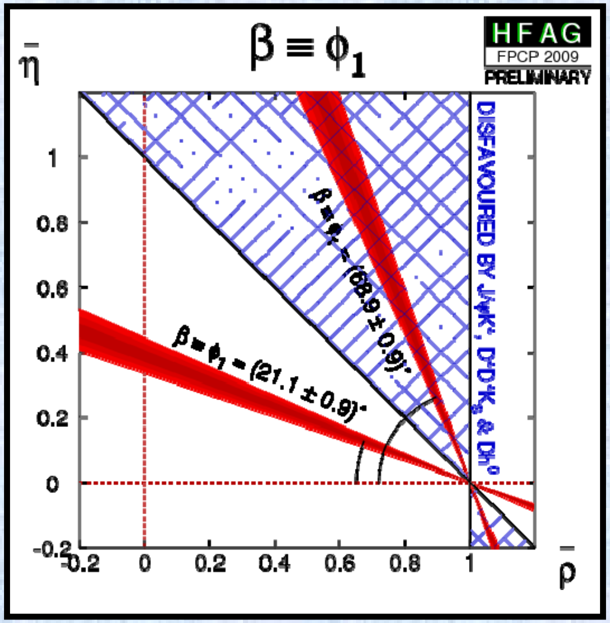




- Time-dependent analysis in $B^0 \to J/\psi K^{*0}$

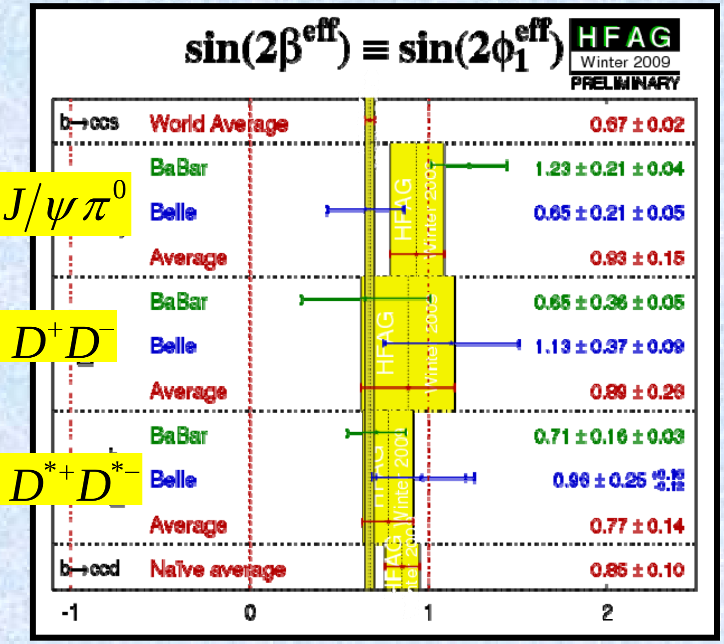


- Time-dependent analysis of $B^0 \to D^{*+}D^{*-}K_s^0$



BaBar : 230M BB; PRD74 (2006) 091101
Belle : 449M BB; PRD76 (2007) 072004

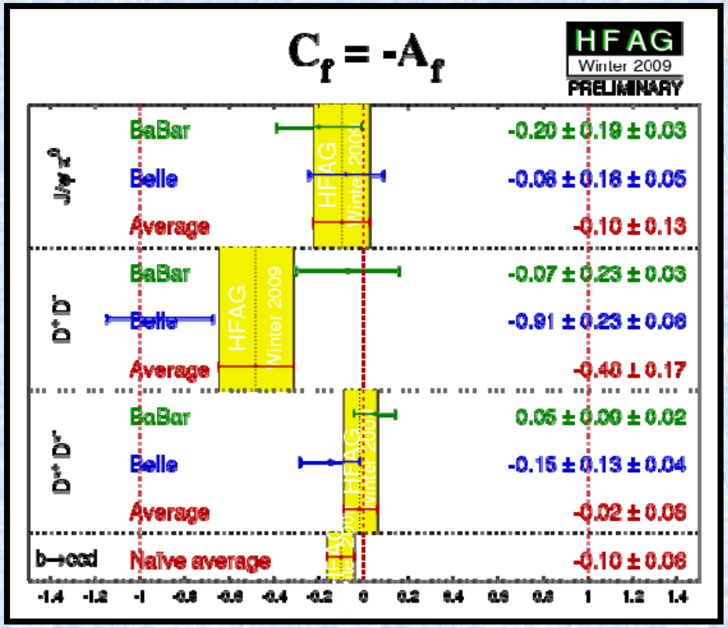
β_{eff} : b→ccd modes

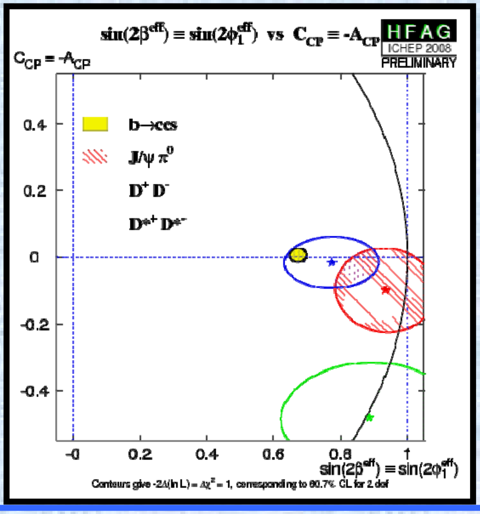


$B^0 \to J/\psi\pi^0$

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

$B^0 \to D^{*+}D^{*-}$



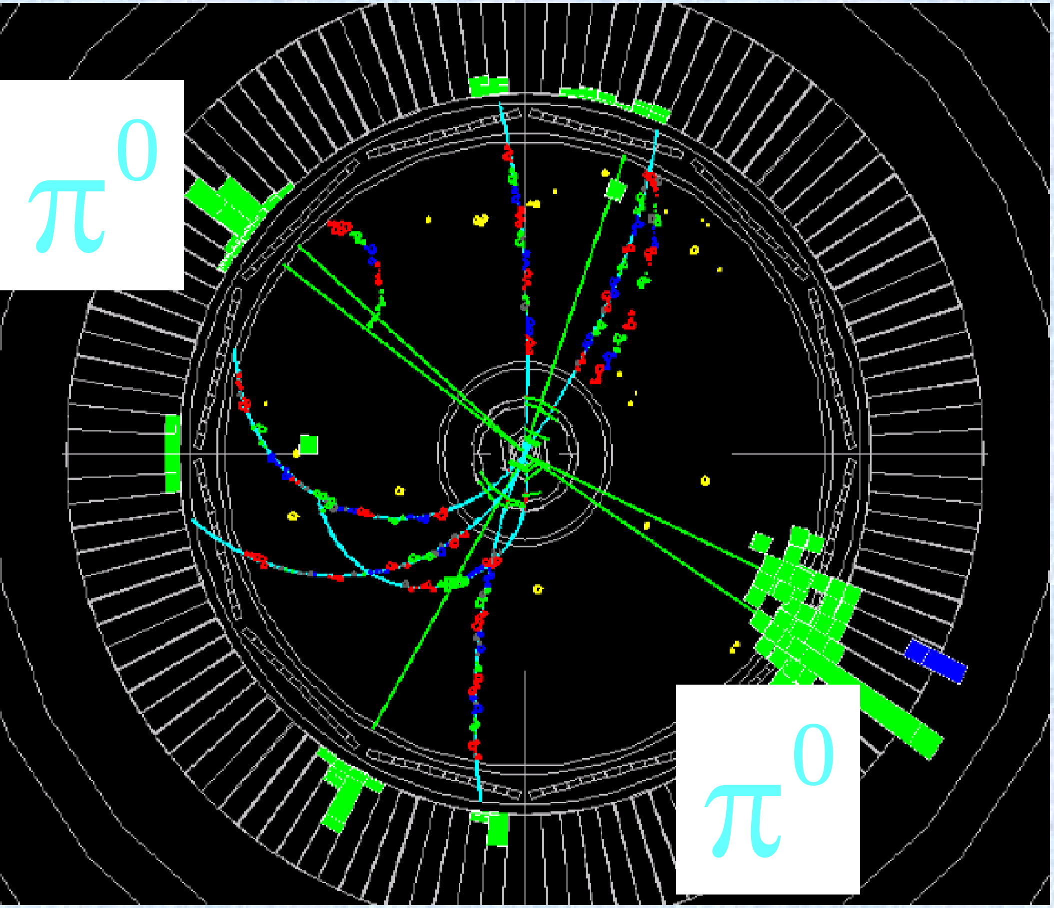


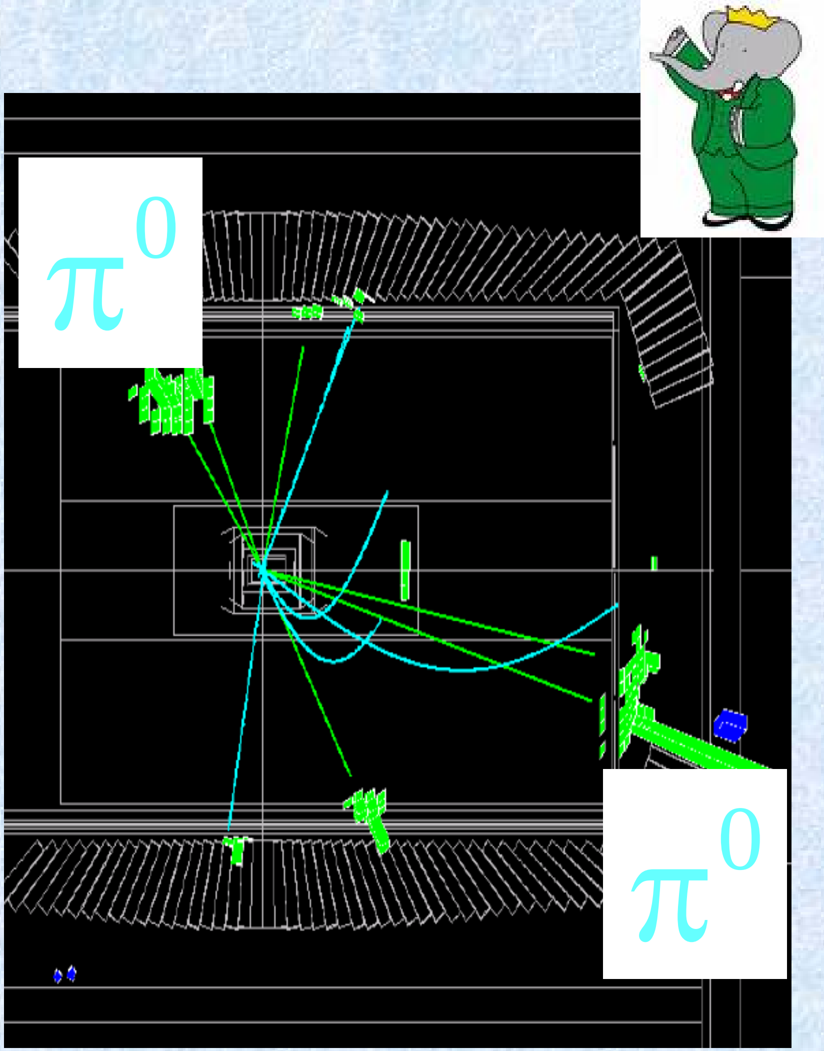
Good agreement with $b \to ccs$ modes

$$S = -\sin 2\beta \quad C = 0$$

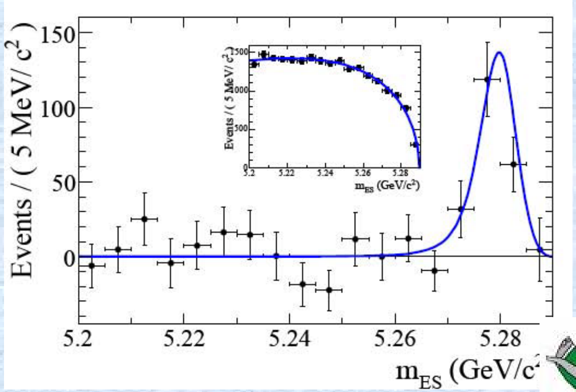
More info needed for C in D^+D^- mode

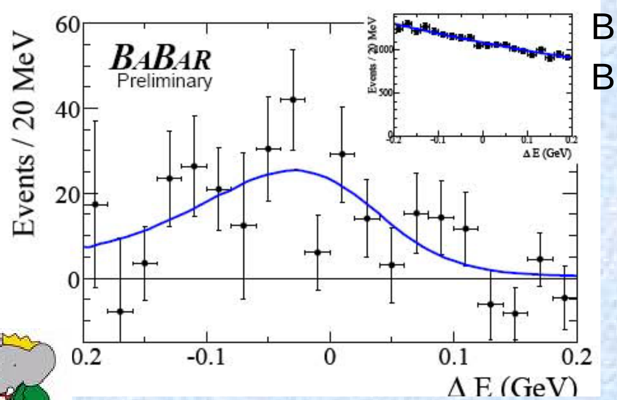
α : B $\rightarrow \pi^0\pi^0$





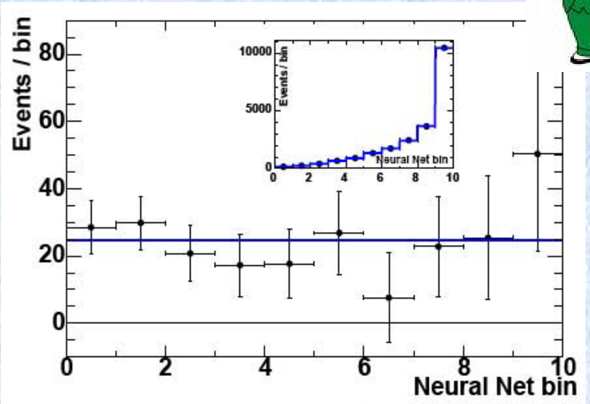
Isospin Analysis B → ππ





BaBar : 467M BB; ArXiv:0807.4226

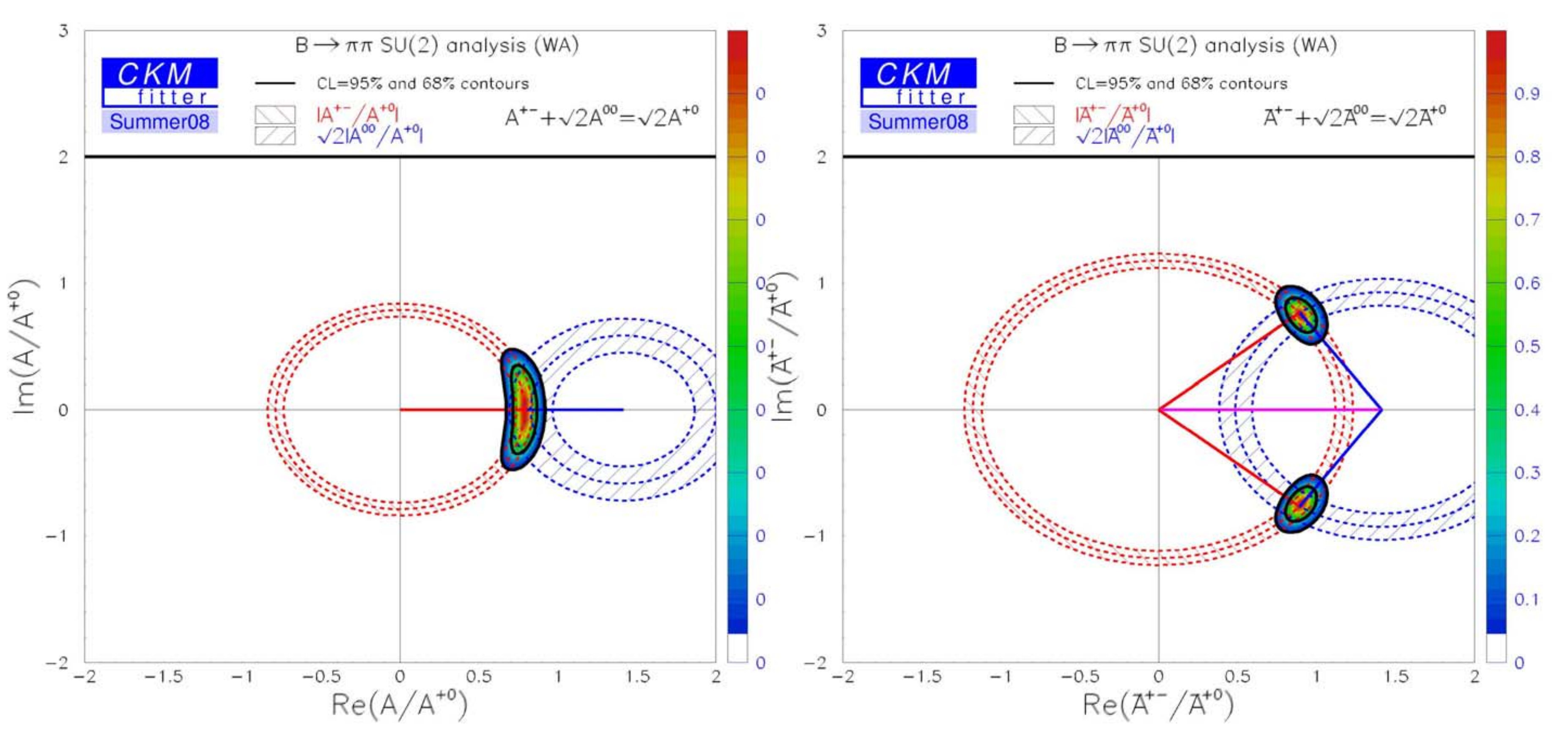
Belle : 535M BB; PRL98 (2007) 211801



	Br(10^{-6})	C	S
$\pi^+\pi^-$	5.5±0.4±0.3	-0.25±0.08±0.02	-0.68±0.10±0.03
$\pi^+\pi^0$	5.02±0.46±0.29		
$\pi^0\pi^0$	1.83±0.21±0.13	-0.43±0.26±0.05	No vertex Not possible

Isospin Analysis B → ππ

- Input $Br\left(B^0 \to \pi^+\pi^-\right), Br\left(B^+ \to \pi^+\pi^0\right), Br\left(B^0 \to \pi^0\pi^0\right), C_{+-}, S_{+-}, C_{00}$



Isospin Analysis $B \to \pi\pi$

- Grossmann-Quinn limit

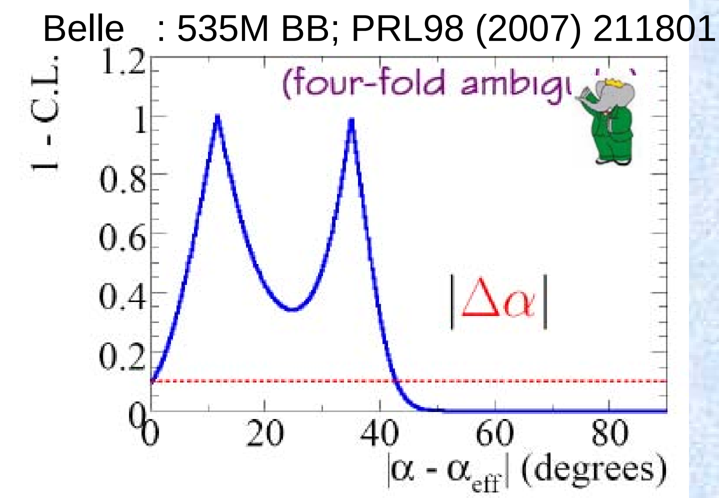
Grossmann, Quinn; arXiv:hep-ph/9712306

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

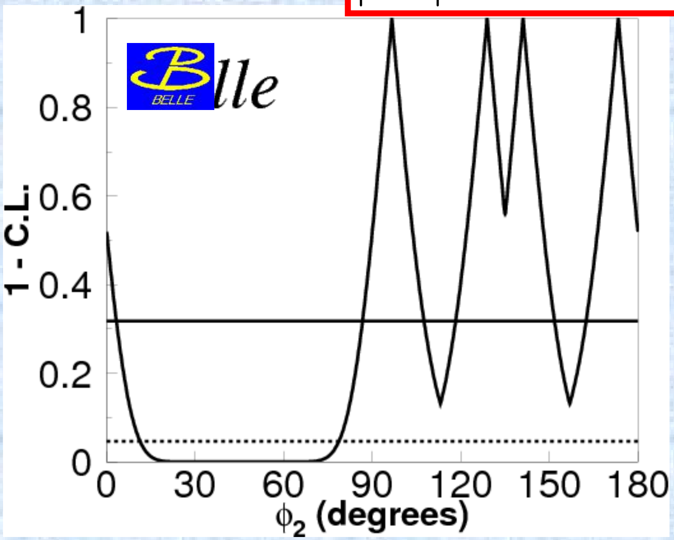
  - $\pi^0\pi^0$ rate too large to obtain useful limit
  - $\pi^0\pi^0$ rate too small for a precision CP mea

BaBar : 467M BB; ArXiv:0807.4226

Belle : 535M BB; PRL98 (2007) 211801

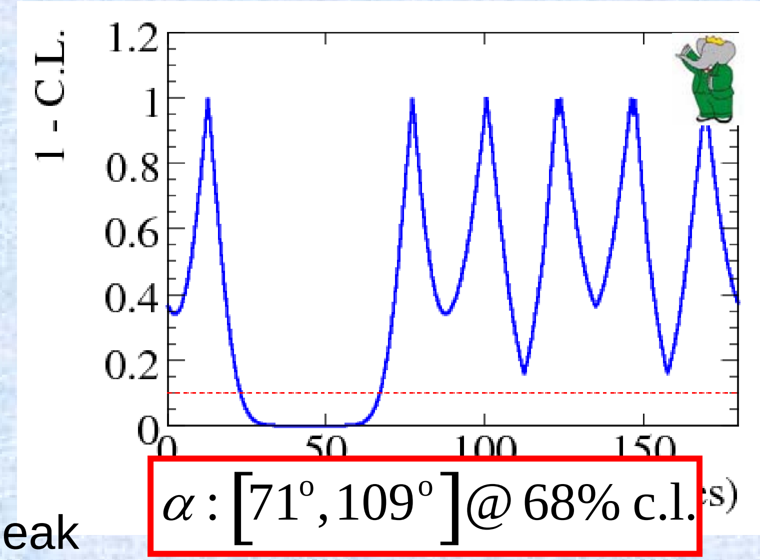


$$|\Delta\alpha| < 43^{o}\ @\ 90\%\ \text{c.l.}$$



$$\alpha : \left[86^{o}, 108^{o}\right] @\ 68\%\ \text{c.l.}$$

Standard peak



$$\alpha : \left[71^{o}, 109^{o}\right] @\ 68\%\ \text{c.l.}$$

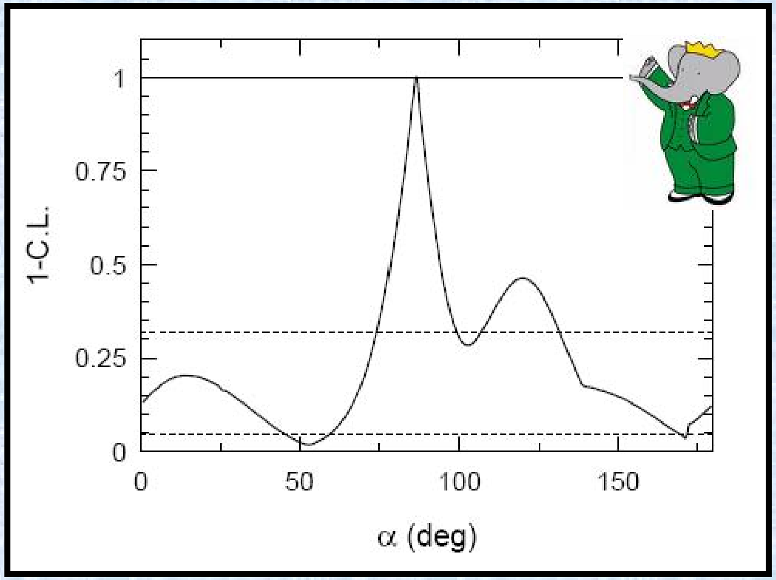
$B \rightarrow \pi^+\pi^-\pi^0$

Three-pion final state: dominated by transitions through ρ mesons

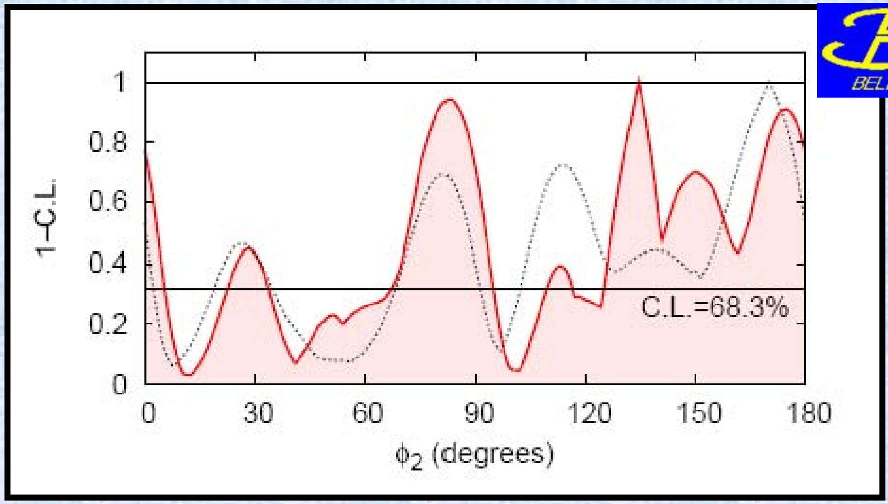
- Interfering contributions from $\rho^+\pi^-, \pi^+\rho^-$ (and $\rho^0\pi^0$)

Snyder-Quinn method Snyder&Quinn, PRD48 (1993) 2139; Quinn&Silva, PRD62 (2000) 054002

- Time-dependent Dalitz analysis of 6 decay amplitudes
- BW phase variations break degeneracy in solutions



$\alpha = \left(87^{+45}_{-13}\right)^{\circ}$ @ 68% c.l.



$68^{\circ} < \alpha < 95^{\circ}$ @ 68% c.l.

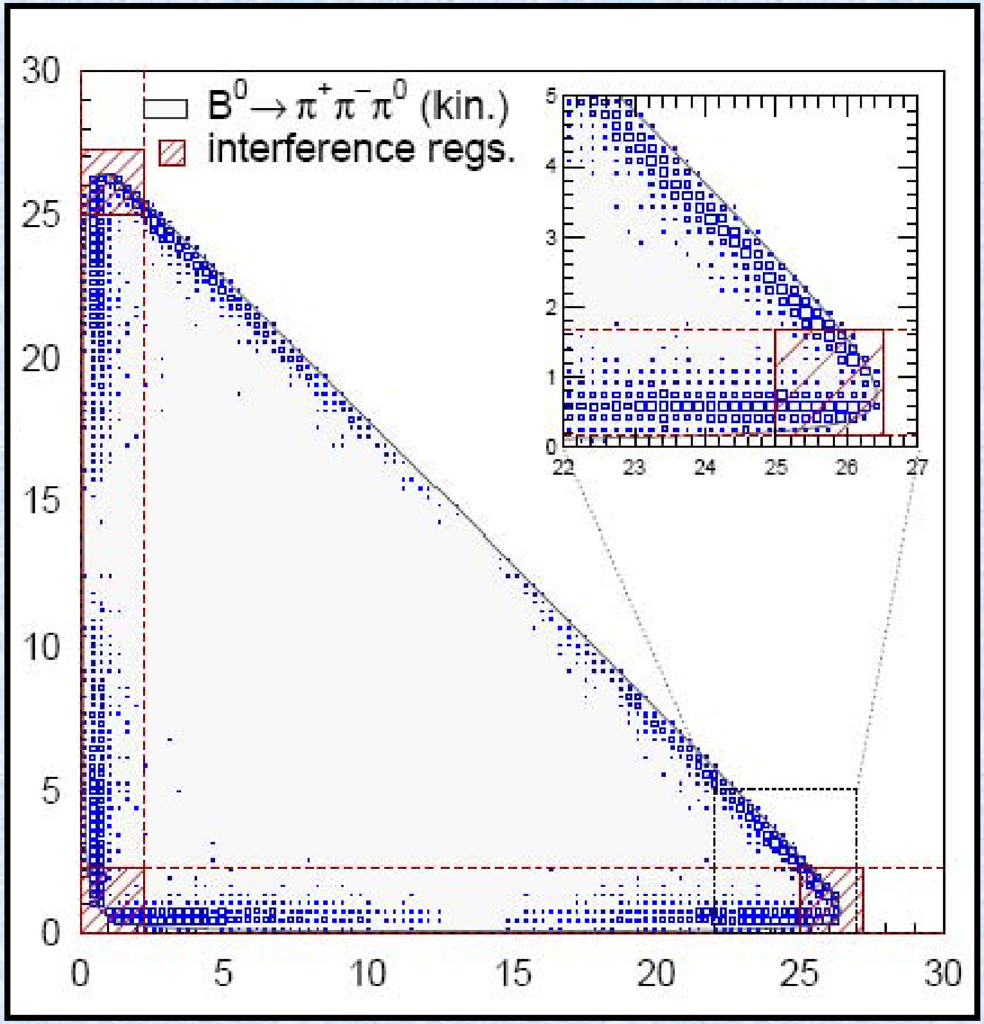
BaBar : 375M BB; PRD76 (2007) 012004

Belle : 449M BB; PRL98 (2007) 221602

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

Dalitz plot

$m^2(\pi^-\pi^0)\,\mathrm{GeV}^2$



$m^2(\pi^+\pi^0)\,\mathrm{GeV}^2$

ADS Method

Favoured and doubly-suppressed D decays e.g. $K^+\pi^-$, $K^+\pi^-\pi^0$

$$B^+ \to D^0 K^+ \quad + \quad D^0 \to f$$

suppressed favoured

$$B^+ \to \overline{D^0} K^+ \quad + \quad \overline{D^0} \to f$$

favoured suppressed

Same final state
Large interference
~O(1)

Measure B$^+$ and B$^-$ yields to determine ADS observables:

$$R_{ADS} \equiv \frac{\Gamma\left(B^- \to D[\to f]K^-\right) + \Gamma\left(B^+ \to D[\to \bar{f}]K^+\right)}{\Gamma\left(B^- \to D[\to \bar{f}]K^-\right) + \Gamma\left(B^+ \to D[\to f]K^+\right)} = r_B^2 + r_D^2 + 2 r_B r_D \cos\gamma \cos\left(\delta_B + \delta_D\right)$$

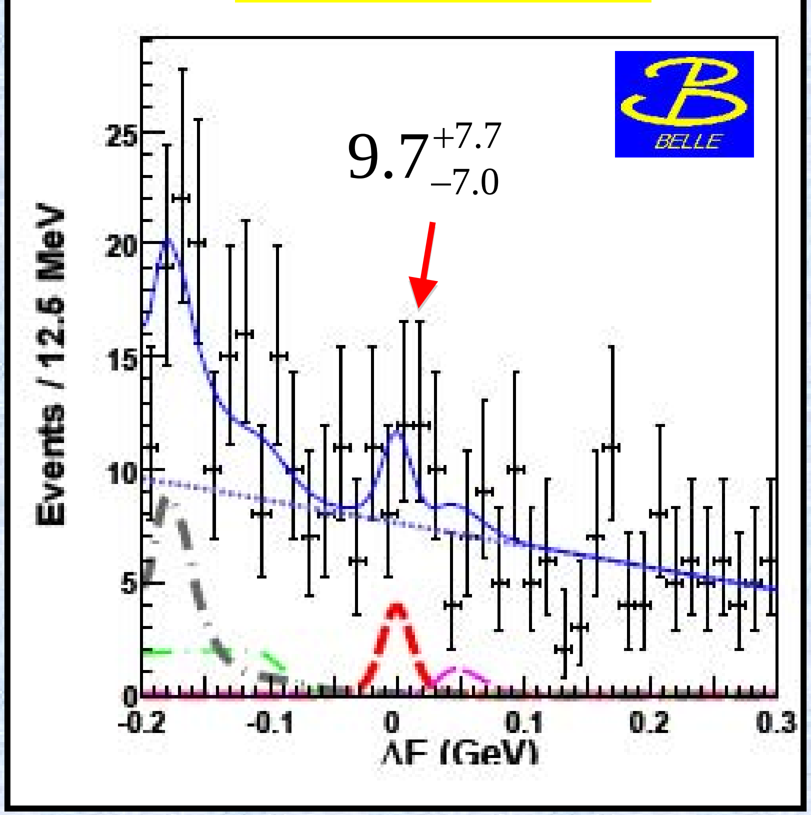
$$A_{ADS} \equiv \frac{\Gamma\left(B^- \to D[\to f]K^-\right) - \Gamma\left(B^+ \to D[\to \bar{f}]K^+\right)}{\Gamma\left(B^- \to D[\to f]K^-\right) + \Gamma\left(B^+ \to D[\to \bar{f}]K^+\right)} = 2 r_B r_D \sin\gamma \sin\left(\delta_B + \delta_D\right) / R_{ADS}$$

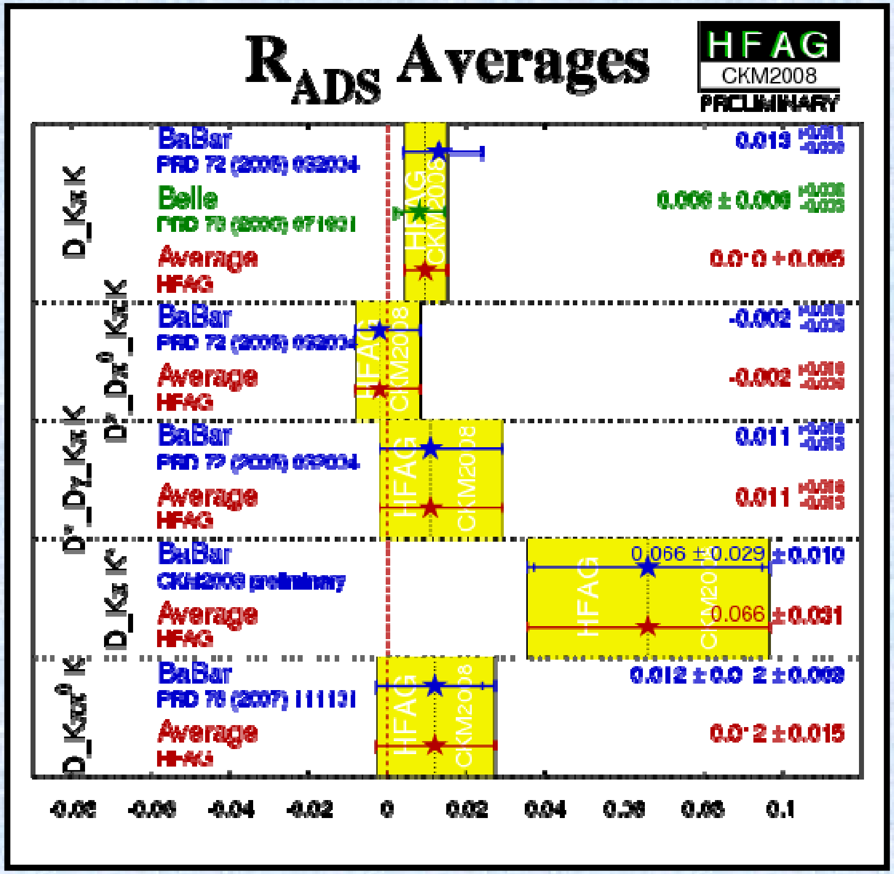
ADS method useful at present to constrain r_B

$$r_D = \left|\frac{A\left(\overline{D^0} \to f\right)}{A\left(D^0 \to f\right)}\right|, \quad \delta = \arg\left[\frac{A\left(\overline{D^0} \to f\right)}{A\left(D^0 \to f\right)}\right]$$

ADS Method

$$B^- \to D^0\left[K^+\pi^-\right]K^-$$





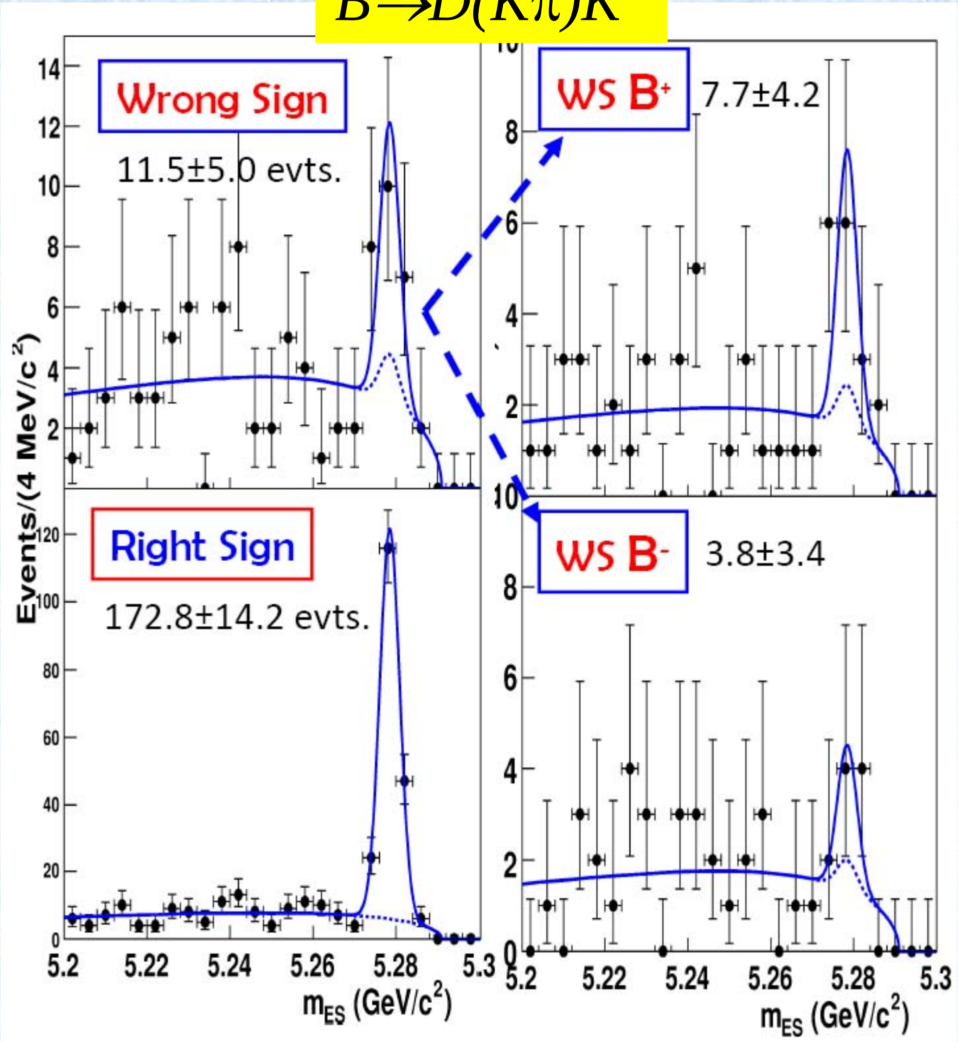
Belle : 657M BB; PRD78 (2008) 071901

No significant signal observed in any modes yet
Upper limits on R_{ADS} translated to constraint r_B

ADS Method

BaBar : 379M BB; CKM008 prelim.

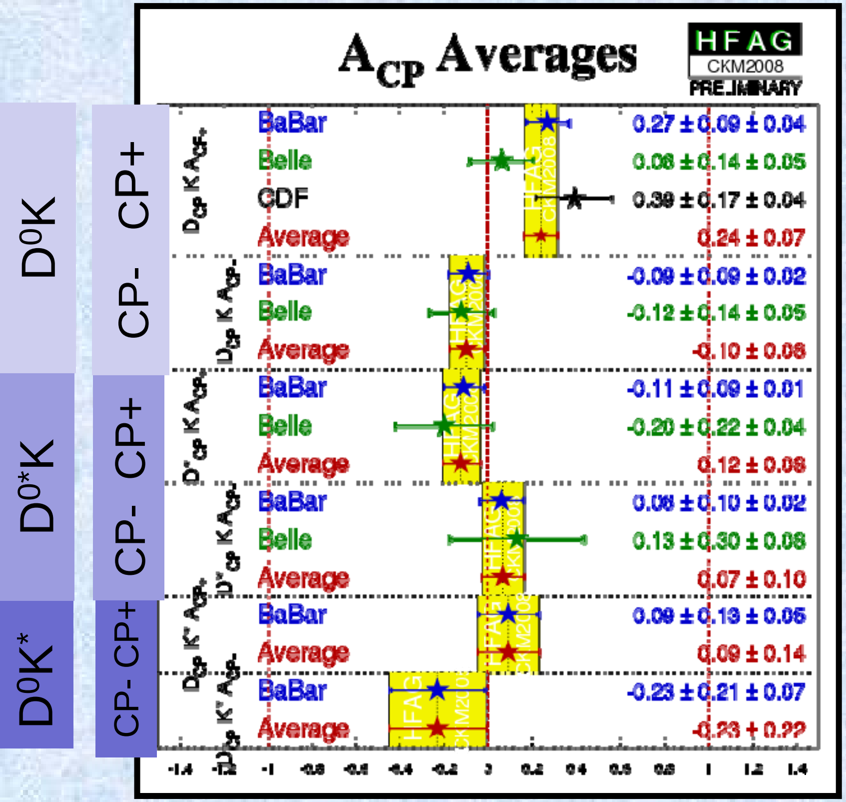
$B \to D(K\pi)K^*$

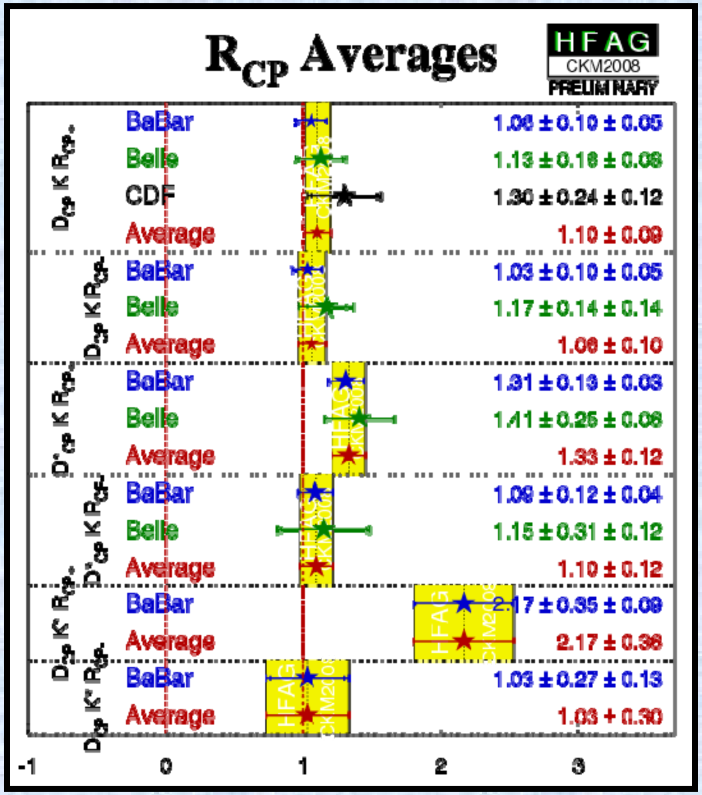


GLW Method

D → CP eigenstates e.g. K^+K^-, $\pi^+\pi^-$ (CP+) and $K_s\pi^0$ (CP-)

Measure B^+ and B^- yields to determine GLW observables, A_{CP} and R_{CP}





First result from CDF
ArXiv:0809.4809

No direct measurement of γ, but helps in combination with other methods.
Sensitivity to γ depends on strong phase.

GLW Method

- Observables

$$R_{CP\pm} \equiv \frac{\Gamma\left(B^- \to D^0_{CP\pm}K^-\right)+\Gamma\left(B^+ \to D^0_{CP\pm}K^+\right)}{2\Gamma\left(B^- \to D^0 K^-\right)} = 1 \pm 2r_B\cos\gamma\cos\delta_B + r_B^2$$

$$A_{CP\pm} \equiv \frac{\Gamma\left(B^- \to D^0_{CP\pm}K^-\right)-\Gamma\left(B^+ \to D^0_{CP\pm}K^+\right)}{\Gamma\left(B^- \to D^0_{CP\pm}K^-\right)+\Gamma\left(B^+ \to D^0_{CP\pm}K^+\right)} = \pm 2r_B\sin\gamma\sin\delta_B / R_{CP\pm}$$

- Alternate set

$$x_\pm = r_B\cos\left(\delta_B + \gamma\right) = \frac{R_{CP+}\left(1 \mp A_{CP+}\right) - R_{CP-}\left(1 \mp A_{CP+}\right)}{4}$$

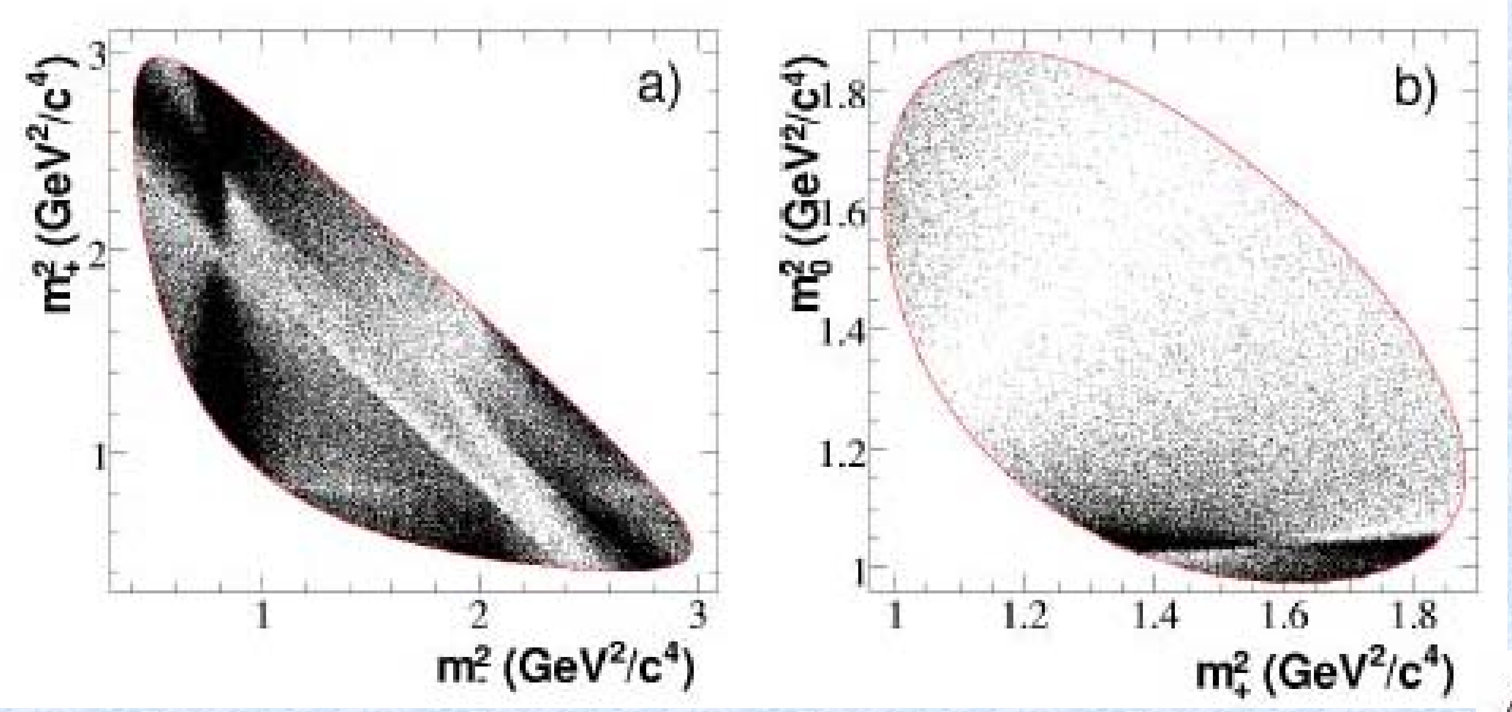
$$r_B^2 = x_\pm^2 + y_\pm^2 = \frac{R_{CP+} + R_{CP-} - 2}{2}$$

GGSZ (Dalitz) Method

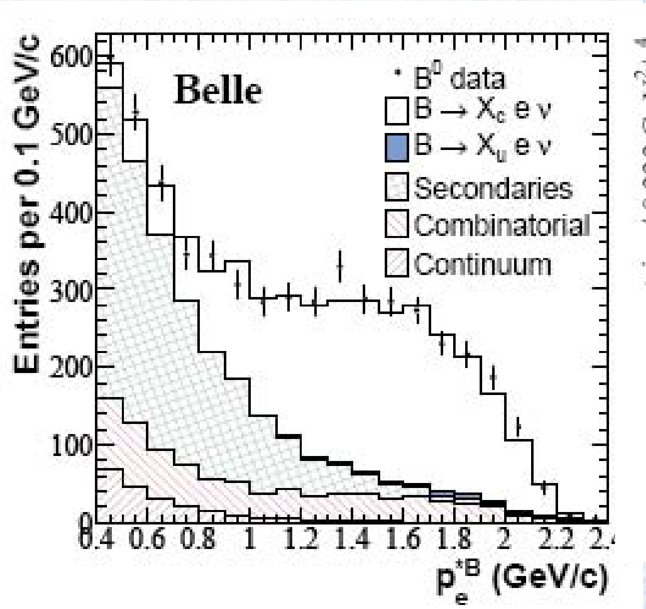
- Dalitz model

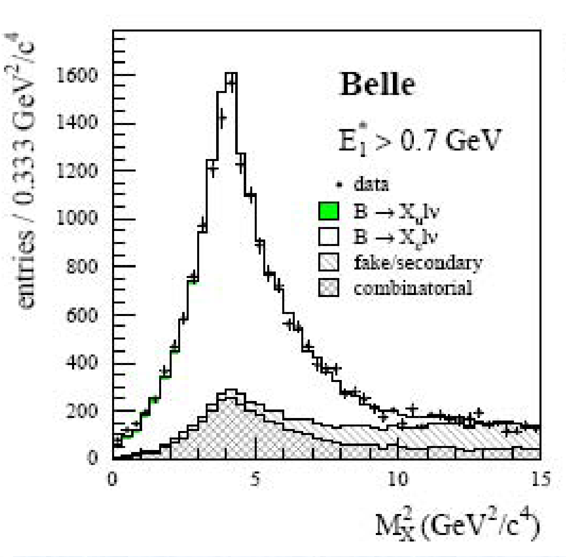
$K_s\pi^+\pi^-$

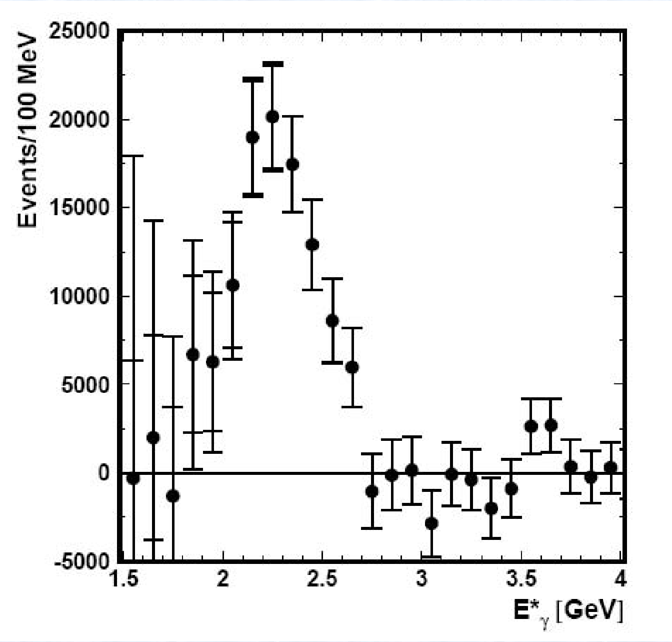
$K_sK^+K^-$



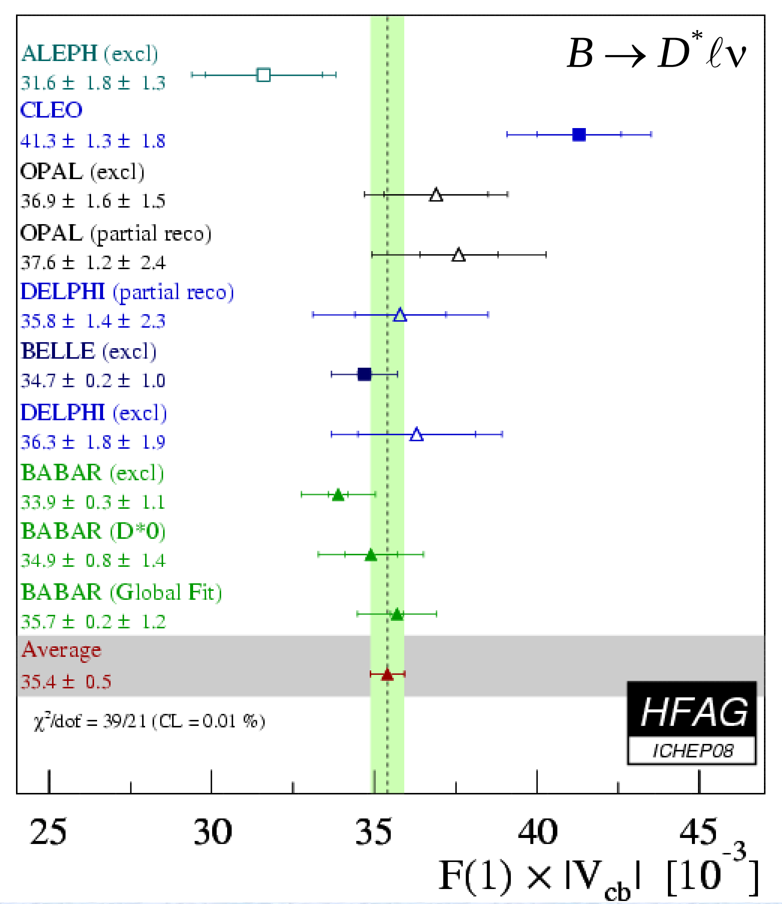
Inclusive Vcb

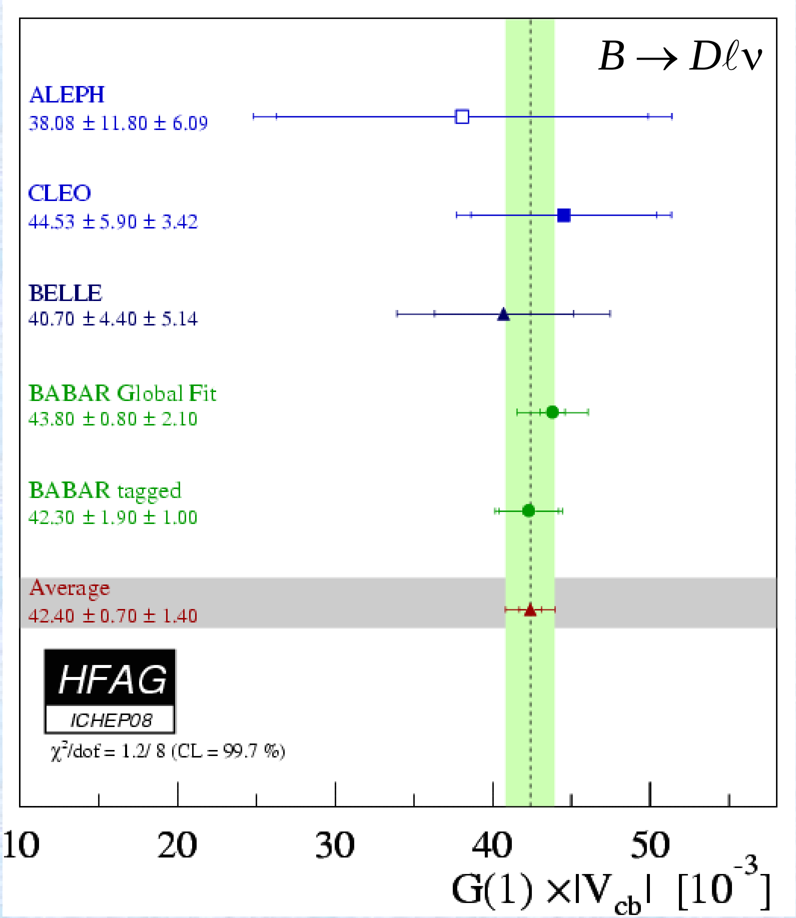






Exclusive Vcb





$$F(1) = 0.921 \pm 0.013 \pm 0.020$$

$$|V_{cb}| = (38.1 \pm 0.6 \pm 0.9) \times 10^{-3} \quad (D^*)$$

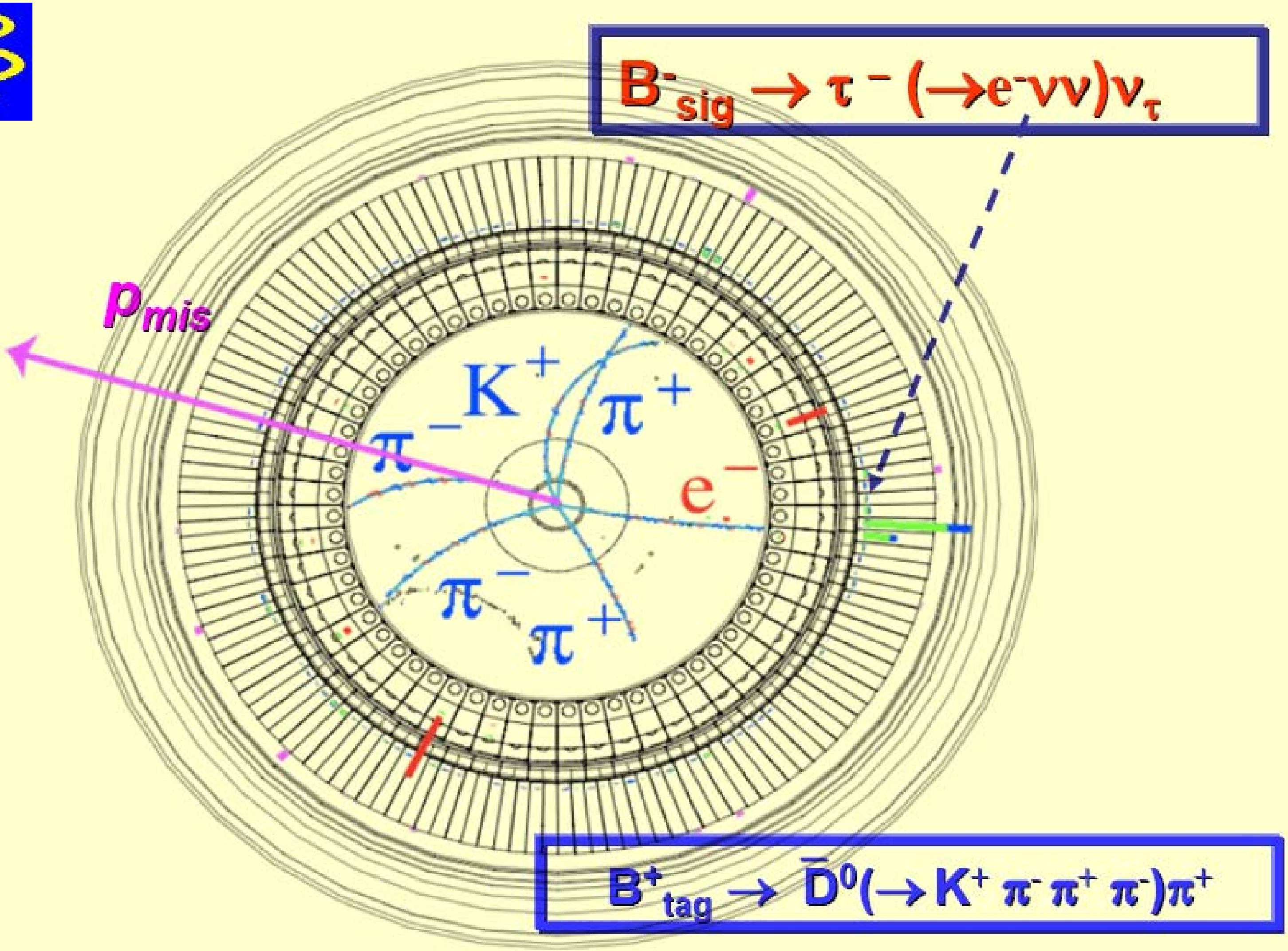
$$G(1) = 1.074 \pm 0.018 \pm 0.016$$

$$|V_{cb}| = (39.7 \pm 1.4 \pm 0.9) \times 10^{-3} \quad (D)$$

C.Bernard et al, ArXiv:0808.2519

M.Okamoto et al, NPPS140 (2005) 461

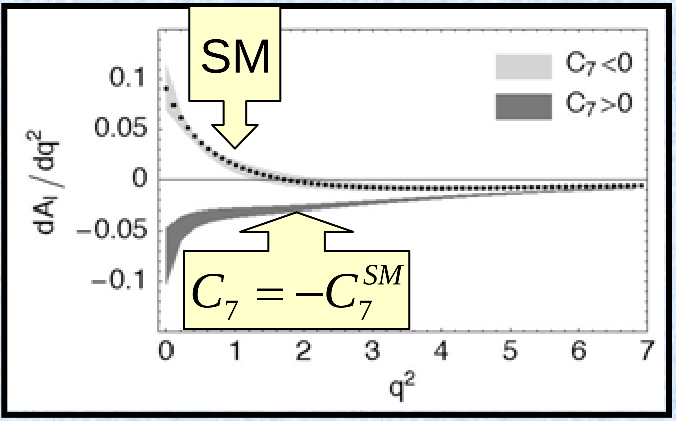
$B \to \tau\nu$


$B^-_{sig} \to \tau^-(\to e^-\nu\nu)\nu_\tau$
p_{mis}
K^+
π^+
π^-
e^-
π^-
π^+
$B^+_{tag} \to \bar{D}^0(\to K^+\pi^-\pi^+\pi^-)\pi^+$

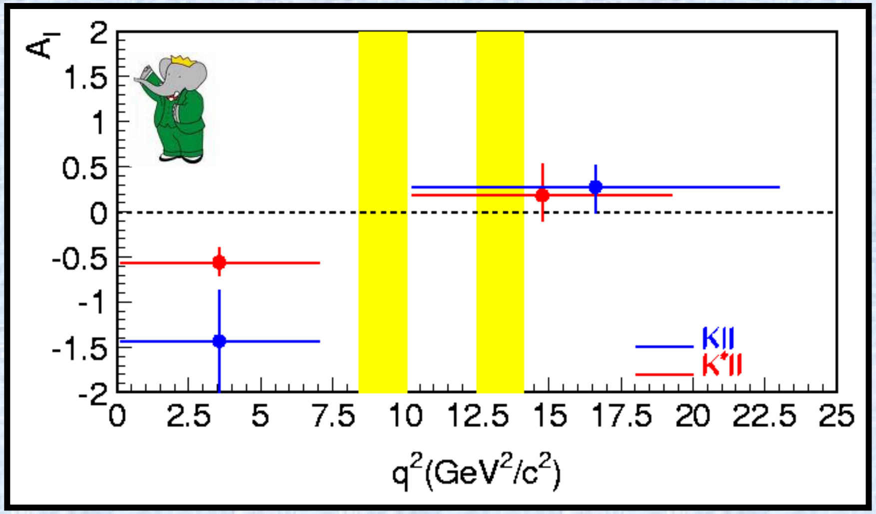
FCNC Rare Decays: B →$K^*\mu\mu$

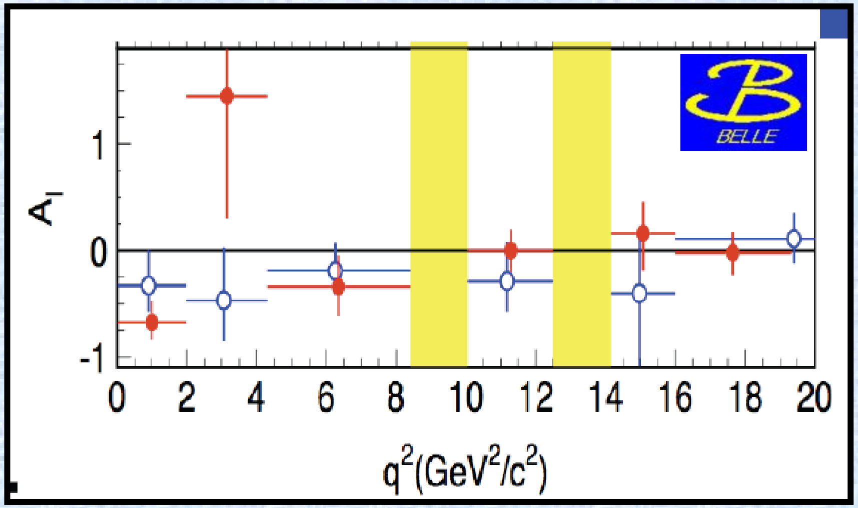
Expect Isospin asymmetry to be small (< 15%) in the SM

$$A_I\left(s=m_{\mu\mu}^2\right)=\frac{\left(\tau_{B^+}/\tau_{B^0}\right)N\left(B^0\rightarrow K^{(*)0}\ell^+\ell^-\right)-N\left(B^\pm\rightarrow K^{(*)\pm}\ell^+\ell^-\right)}{\left(\tau_{B^+}/\tau_{B^0}\right)N\left(B^0\rightarrow K^{(*)0}\ell^+\ell^-\right)+N\left(B^\pm\rightarrow K^{(*)\pm}\ell^+\ell^-\right)}$$



Feldmann & Matias JHEP 0301, 074 (2003)





Intriguing large and negative A_I

BaBar : 384M BB; ArXiv:0807.4119

Belle : 657M BB; ArXiv:0904.0770