CP Violation

Tom Browder (University of Hawaii)

Tsukuba

Honolulu

Detroit

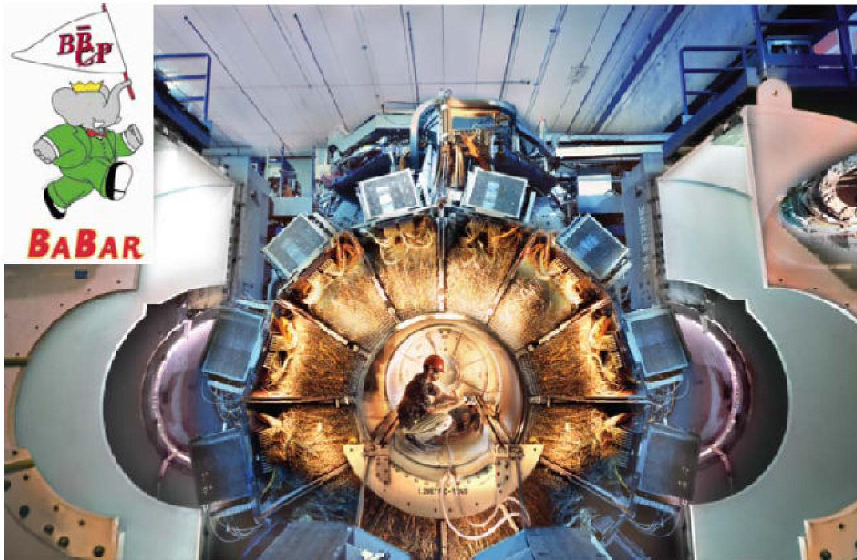
Will comment on the 2008 Nobel Prize in Physics

Will focus on CP Violation and its connection to NP in the weak interaction: B and D physics

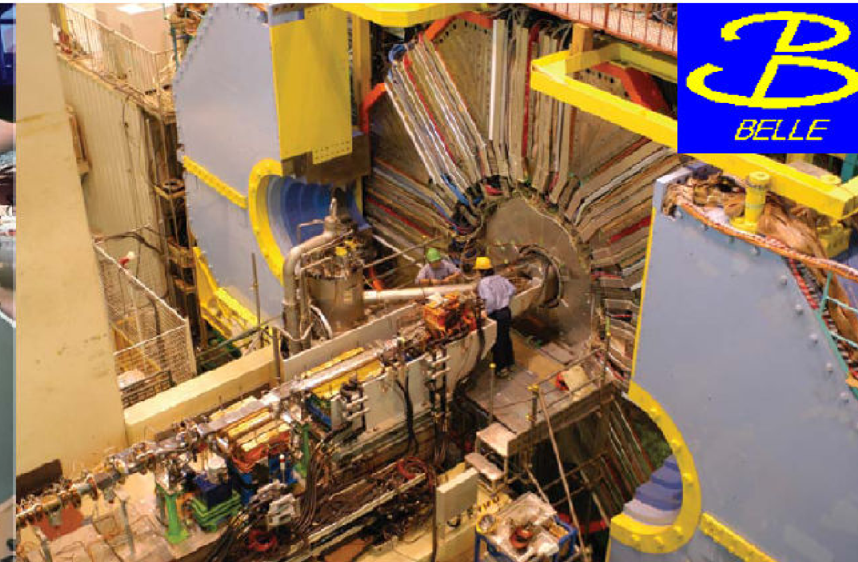
Dave Hitlin and Ben Grinstein will cover other aspects of flavor physics

Apologies: a talk with a bias towards B physics. *I have borrowed and benefited from the slides of many others. This talk is aimed at non-specialists and only covers a handful of possible topics with little detail.*

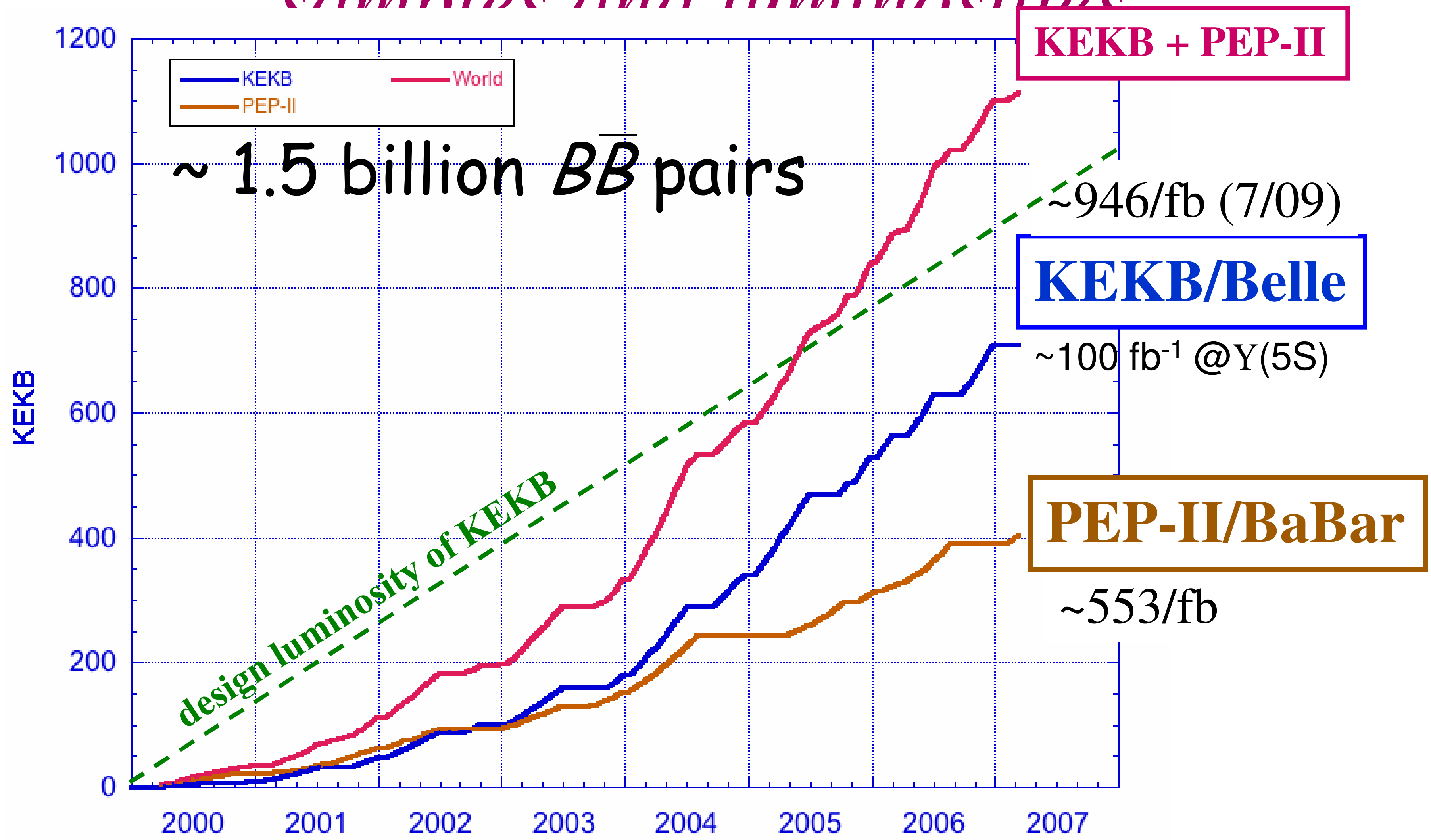
PEP-II and BaBar



KEKB and Belle



B factories: extraordinary data samples and luminosities



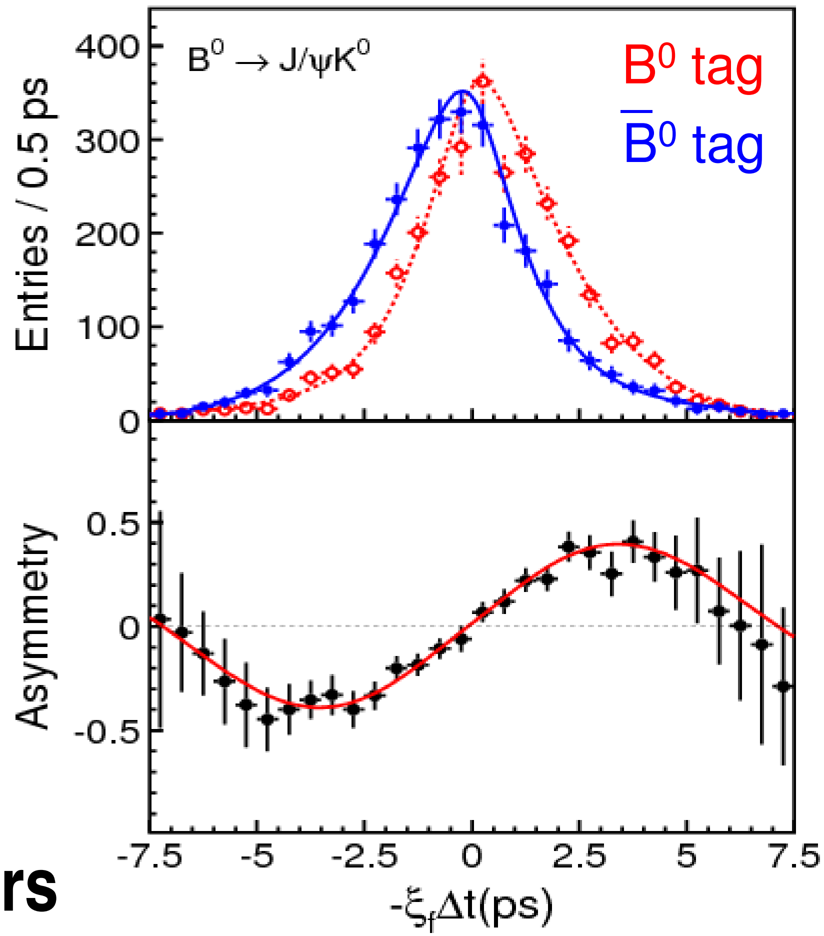
Recent progress at KEKB: L=2.1 x 10^{34}/cm^2/sec with crab cavities.

Critical Role of the B factories in the verification of the KM hypothesis was recognized and cited by the Nobel Foundation

A single irreducible phase in the weak interaction matrix accounts for most of the CPV observed in kaons and B's.

CP violating effects in the B sector are O(1) rather than O(10^{-3}) as in the kaon system.

The cartoon refers to $B^0 \rightarrow J/\psi K^0$ data



535 M $B\overline{B}$ pairs

previous measurement
$\sin 2\phi_1 = 0.652 \pm 0.044$
(388 M $B\overline{B}$ pairs)

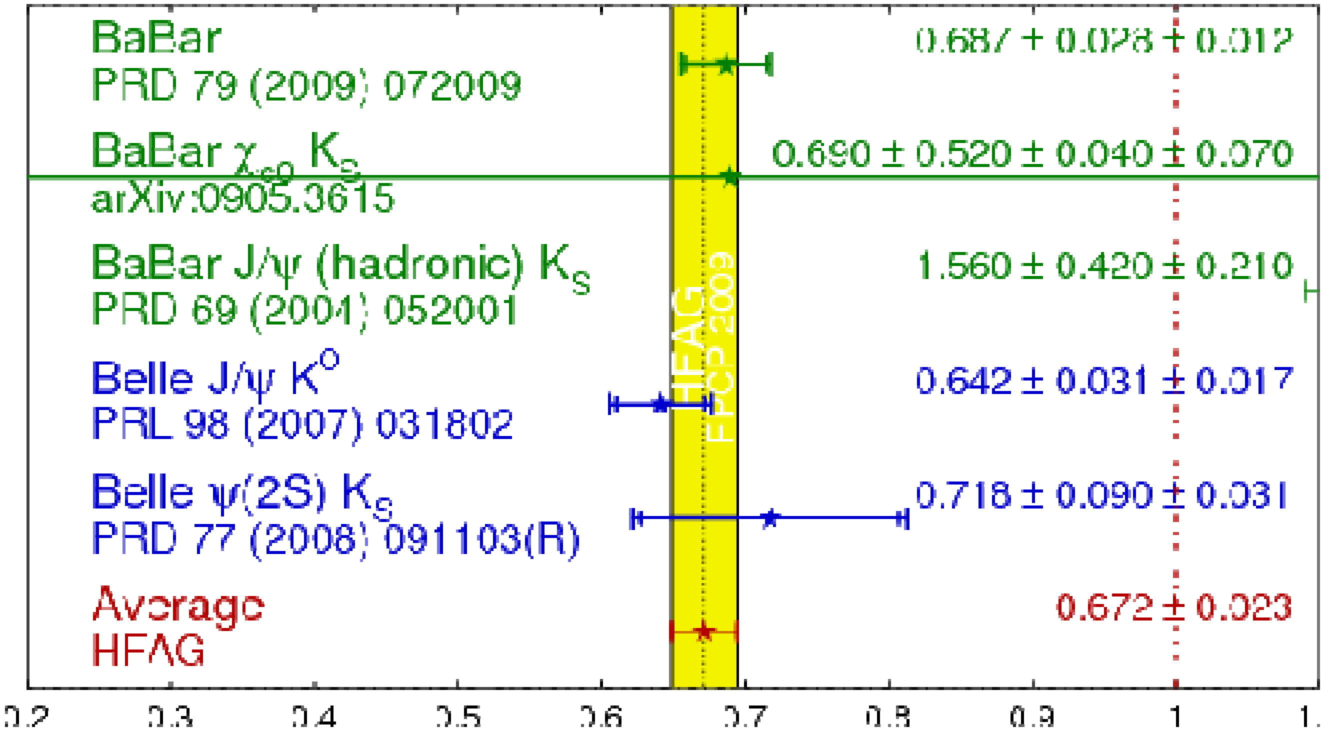
$\sin 2\phi_1 = 0.642 \pm 0.031$ (stat) ± 0.017 (syst)
A = 0.018 ± 0.021 (stat) ± 0.014 (syst)

hep-ex/0608039, PRL

BaBar + Belle

$\sin(2\beta) \equiv \sin(2\phi_1)$

HFAG
FPCP 2009
PRELIMINARY



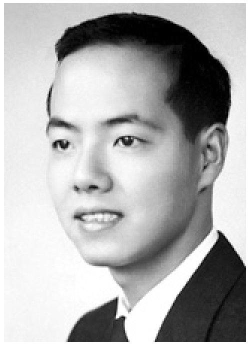
0.672 ± 0.023

A precise measurement of the phase of B_d mixing (< 4 % error)

"Yesterday's sensation is today's calibration and tommorow's background." - Val Telegdi

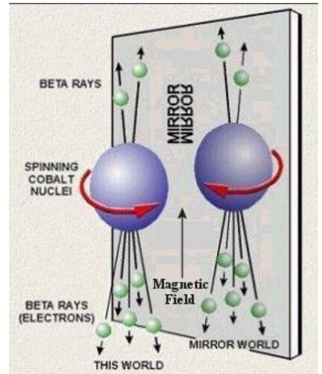
Reference Point for NP search

Nobel Prizes from Surprising Discoveries about
Weak Interactions of Quarks



T.D. Lee

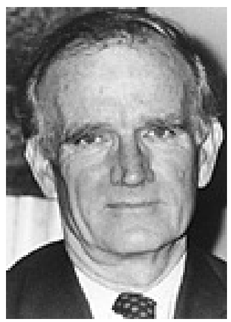
C.N. Yang



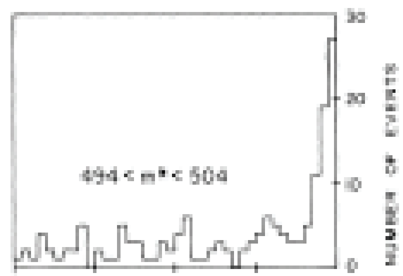
Maximal P violation

1957

J. Cronin



V. Fitch

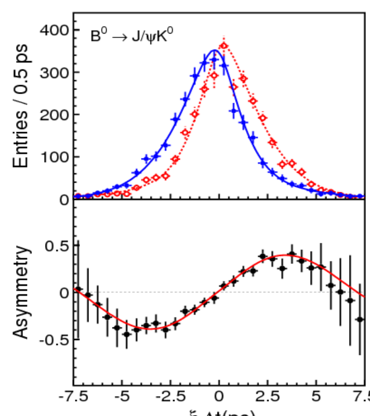


Small CP violation

1980

M. Kobayashi

T. Maskawa



O(1) CP violation and 3 generations

2008

Some experimental signatures of CP Violation in K, B, D……

$K_L \rightarrow$ Wrong CP Final State (e.g. $K_L \rightarrow \pi\pi$)

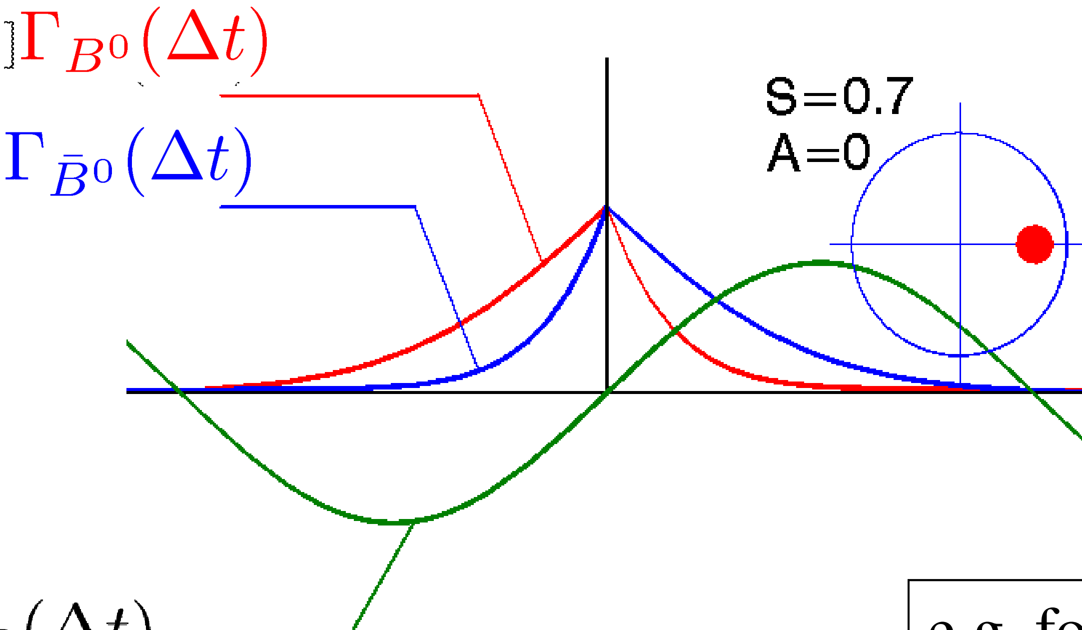
$$A = \frac{N(\overline{B}) - N(B)}{N(\overline{B}) + N(B)}$$

$$A(\Delta t) = \frac{N(\overline{B}, \Delta t) - N(B, \Delta t)}{N(\overline{B}, \Delta t) + N(B, \Delta t)}$$

The asymmetry can also be dependent on Dalitz plot variables in a 3-body decay or on both time and Dalitz plot variables. (some examples later). *In addition, triple product asymmetries (talk by A. Datta)*

Quick Review of time-dependent CP violation measurements

Time Dependent CPV in B^0 decays



$$A_{CP}(\Delta t)$$

$$\equiv \frac{\Gamma_{\bar{B}^0}(\Delta t) - \Gamma_{B^0}(\Delta t)}{\Gamma_{\bar{B}^0}(\Delta t) + \Gamma_{B^0}(\Delta t)}$$

$$= \mathcal{S} \sin \Delta m \Delta t + \mathcal{A} \cos \Delta m \Delta t$$

Mixing-induced CPV | Direct CPV

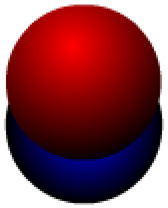
e.g. for B→J/ψ *Ks*
$\mathcal{S} = -\xi_{CP}\sin 2\phi_1 = +\sin 2\phi_1$
$\mathcal{A} \sim 0$

(ξ_{CP} : CP eigenvalue ± 1)

N.B. Time integrated mixing-induced asymmetries vanish

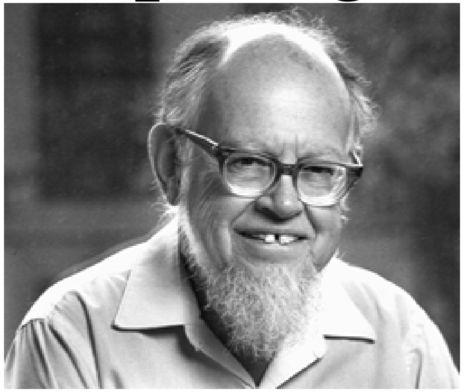
Time-Dependent CPV (*BaBar boost*)

B Decay Topology in the Boosted $\Upsilon(4S)$ Environment



Weak Interaction coupling constants

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



$\lambda \sim 0.22$
$\sin\theta_C$
Cabibbo angle

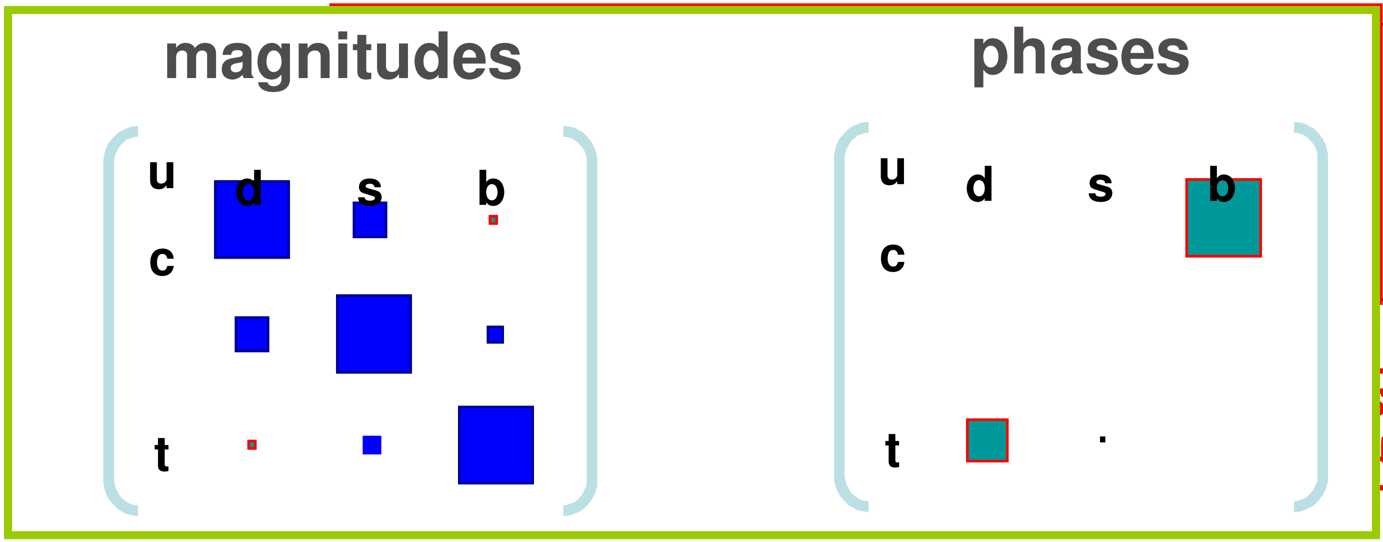
Gell-mann ,Levy

Wolfenstein parameterization:

Observed experimental hierarchy

2x2 submatrix: u,d,s,c quarks only

3x3 matrix: 3 quark generations



3 → 1
$\sim\lambda^3$

3 → 1
$\sim\lambda^3$

3 → 2
$\sim\lambda^2$

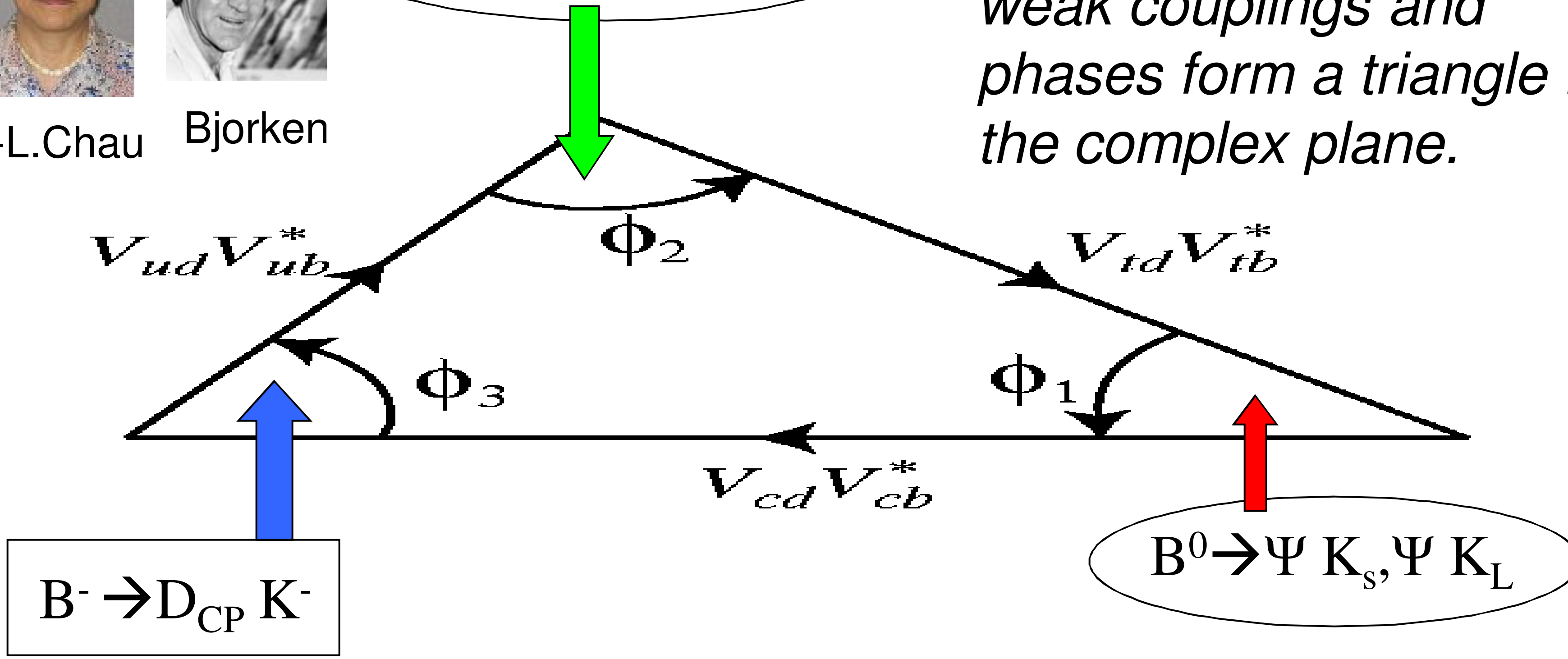
se: changes
under CP

Three Angles: (φ_1,φ_2,φ_3) or (β, α, γ)

L-L.Chau

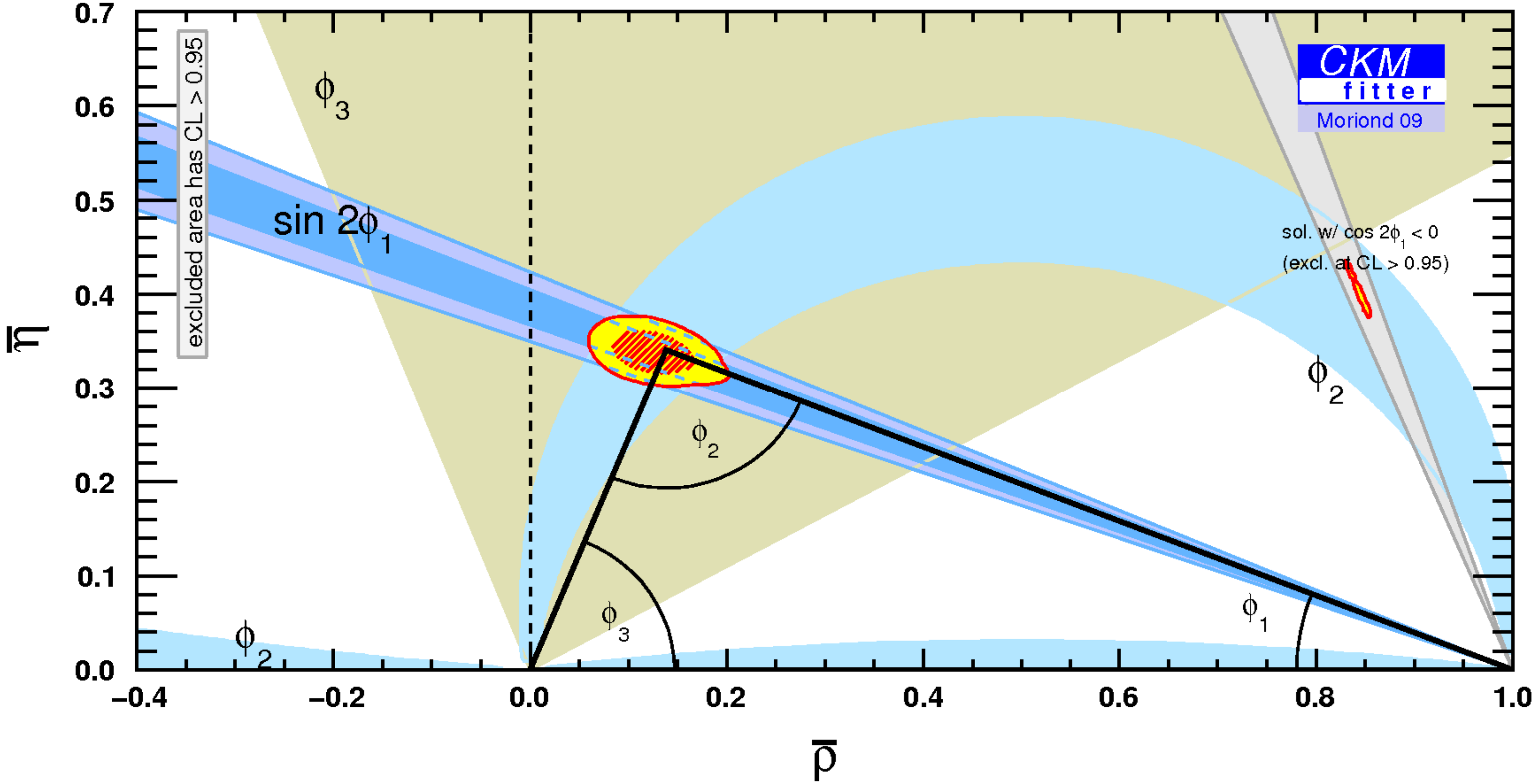
Bjorken

Unitarity implies that the weak couplings and phases form a triangle in the complex plane.



Big Question(s): *Are determinations of angles consistent with determinations of the sides of the triangle ? Are angle determinations from loop and tree decays consistent ?*

Current status of CP violating *angle* measurements



Note the large allowed region for the angle ϕ_3 (also known as γ)

Latest BaBar ADS and Belle Dalitz Results related to the angle ϕ_3 or γ

Need to pick off the phase of V_{ub}

Ratio of BFs:

$$R_{ADS}=\frac{\Gamma(B^- \to D[K^+\pi^-]K^-)+\Gamma(B^+ \to D[K^-\pi^+]K^+)}{\Gamma(B^- \to D[K^-\pi^+]K^-)+\Gamma(B^+ \to D[K^+\pi^-]K^+)} = r_B^2+r_D^2+2r_Br_D\cos\gamma(\cos\delta_B+\delta_D)$$

CP violating charge asymmetry:

$$A_{ADS}=\frac{\Gamma(B^- \to D[K^+\pi^-]K^-)+\Gamma(B^+ \to D[K^-\pi^+]K^+)}{\Gamma(B^- \to D[K^+\pi^-]K^-)+\Gamma(B^+ \to D[K^-\pi^+]K^+)} = 2r_Br_D\sin\gamma\sin(\delta_B+\delta_D)/R_{ADS}$$

Inputs:

$$r_D=\frac{|A(\bar{D}^0\to K^+\pi^-)|}{|A(D^0\to K^+\pi^-)|}$$ (HFAG)

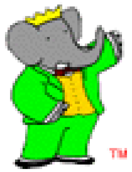
$$\delta_D=\arg\left[\frac{A(\bar{D}^0\to K^+\pi^-)}{A(D^0\to K^+\pi^-)}\right]$$ (CLEO-C)

- 2 eq. and 3 unknowns + r_D and δ_D
  - no γ determination by itself
  - improved sensitivity to γ when combined with other methods

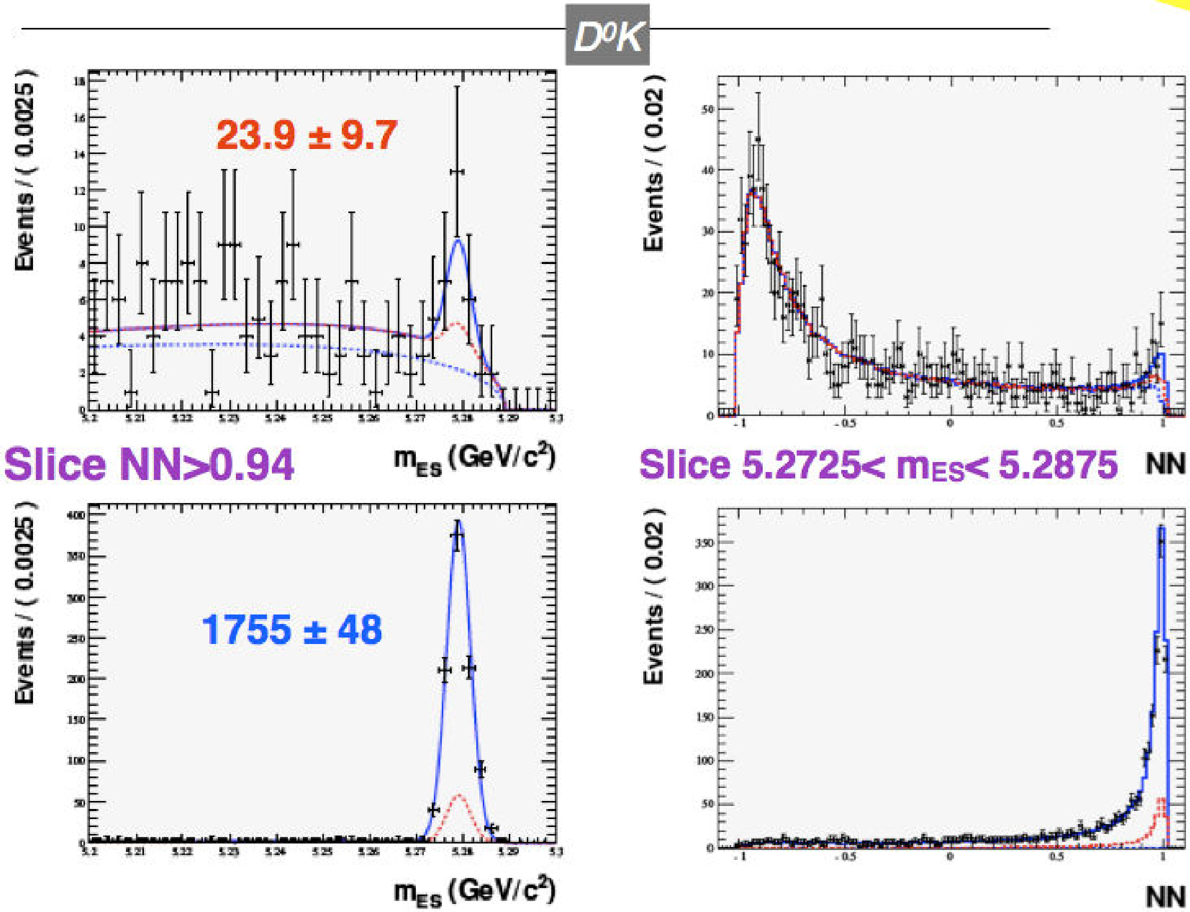
Method proposed by Atwood, Dunietz, Soni in PRL 78, 3257 (1997)

New

BaBar reports the first evidence for the highly suppressed ADS mode (preliminary)



ADS Ratio of BF's: DK results



Note the D mode is doubly Cabibbo suppressed while the B mode is singly Cabibbo suppressed.

$R_{ADS}(DK) = 0.0136 \pm 0.0055_{stat} \pm 0.0027_{syst}$

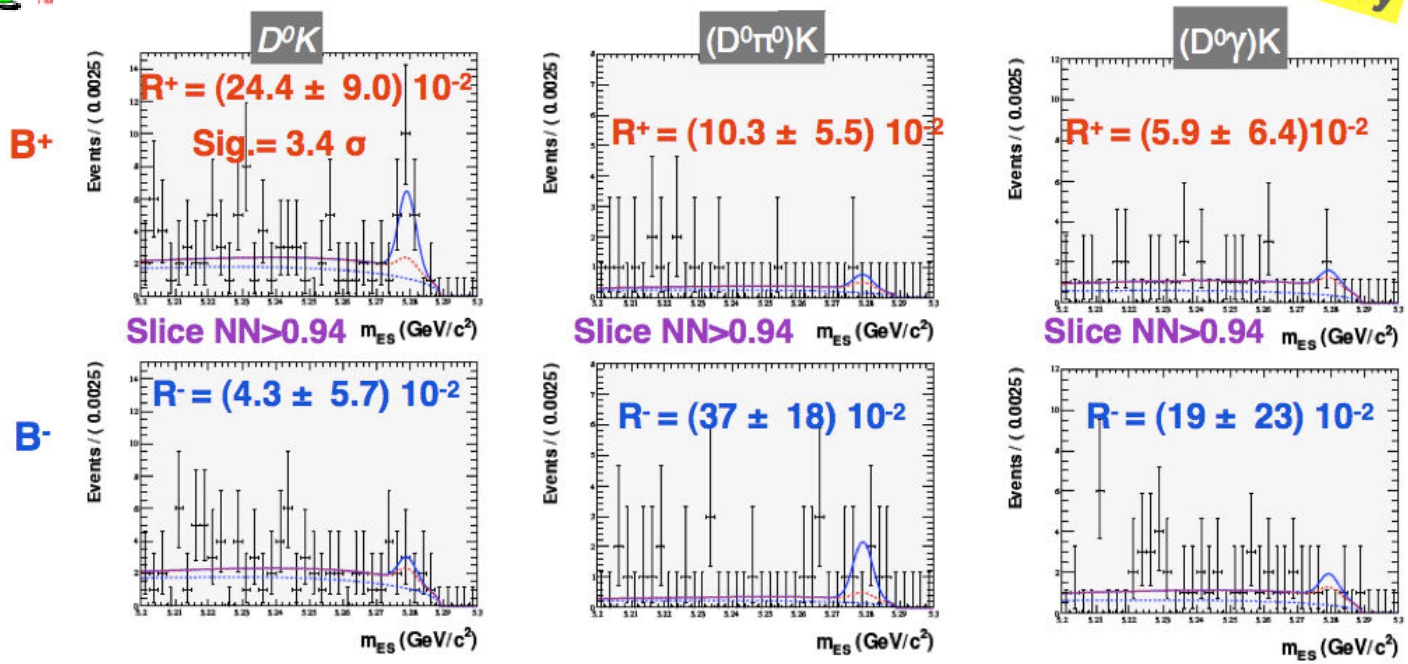
See talk by R. Kass

New

BaBar also reports a CP asymmetry for the new ADS mode

ADS Charge asymetry: $D^{(*)}K$ results

NEW!! Preliminary



$A_{ADS}(DK) = -0.70 \pm 0.35 {}^{+0.09}_{-0.14}$

$A_{ADS}([D\pi^0]K) = 0.77 \pm 0.35 \pm 0.12$

$A_{ADS}([D\gamma]K) = 0.36 \pm 0.94_{\text{stat}} {}^{+0.25}_{-0.41}{}_{\text{syst}}$

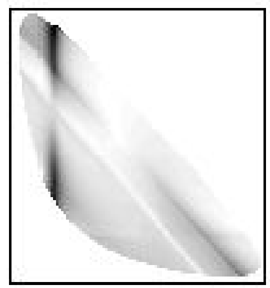
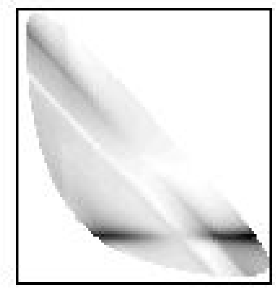
Although statistics are very low, the CP asymmetries *could be* very large in these modes.

Determination of ϕ_3/γ via CP asymmetries in Dalitz plots of $B \rightarrow D\ K$ modes, with $D \rightarrow K_S\pi^+\pi$

Use $B^\pm \to D^{(*)}K^{(*)\pm}$ modes with 3-body decay $D \to K_S\pi^+\pi^-$.
Dalitz plot density: $d\sigma_\pm(m_+^2, m_-^2) \sim |M_\pm|^2 dm_+^2 dm_-^2$

$$|M_\pm(m_+^2, m_-^2)|^2 = |f_D(m_+^2, m_-^2) + re^{i\delta_B \pm i\phi_3} f_D(m_-^2, m_+^2)|^2$$

A. Bondar

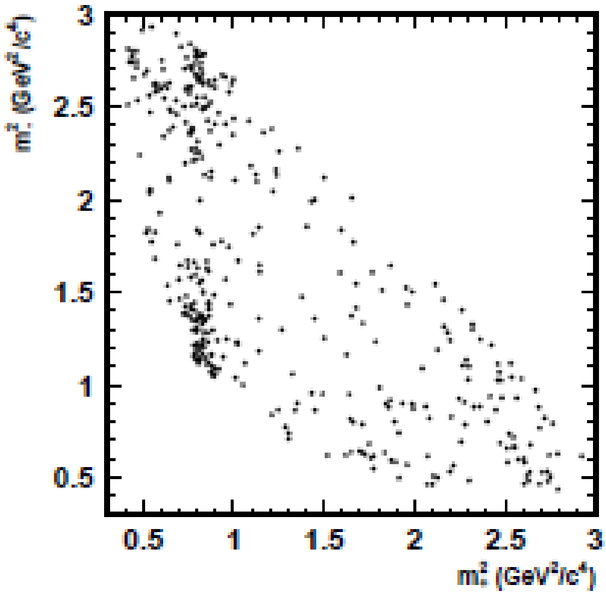
$$= \Big|$$  $$+ re^{i\delta_B \pm i\phi_3}$$  $$\Big|^2$$

$\overline{D}^0 \to K_S^0\pi^+\pi^-$ amplitude f_D is extracted from continuum ($D^{*\pm} \to D\pi^\pm$), parametrized as a set of two-body amplitudes.

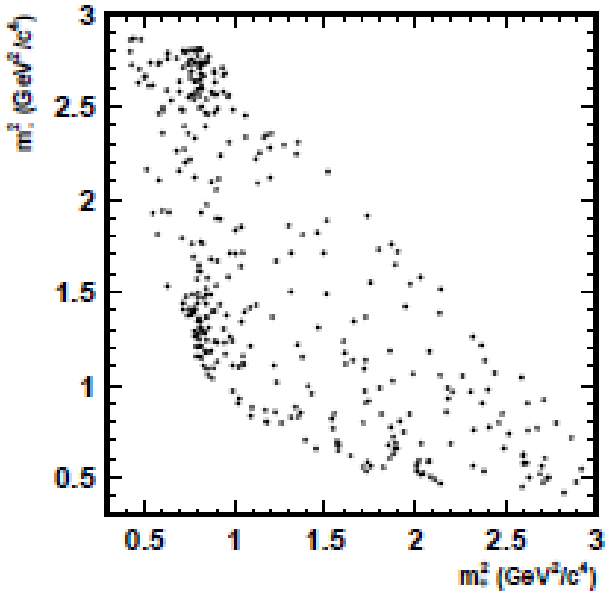
Only $|f_D|^2$ is observable $\Rightarrow$ Model dependence as a result .

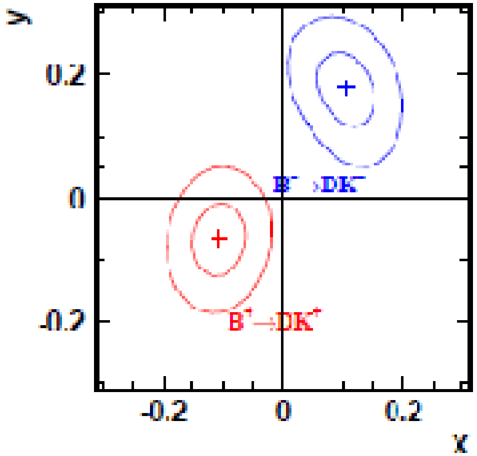
Fit variables: $x_\pm = r\cos(\delta_B \pm \phi_3)$, $y_\pm = r\sin(\delta_B \pm \phi_3)$.

$B^+ \to DK^+$



$B^- \to DK^-$





3.5σ CP asymmetry

update

ϕ_3	$78.4^{\circ}{}^{+10.8^{\circ}}_{-11.6^{\circ}} \pm 3.6^{\circ}(\text{syst}) \pm 8.9^{\circ}(\text{model})$
r_{DK}	$0.160^{+0.040}_{-0.038} \pm 0.011(\text{syst})^{+0.050}_{-0.010}(\text{model})$
δ_{DK}	$136.7^{\circ}{}^{+13.0^{\circ}}_{-15.8^{\circ}} \pm 4.0^{\circ}(\text{syst}) \pm 22.9^{\circ}(\text{model})$
r_{D^*K}	$0.196^{+0.072}_{-0.069} \pm 0.012(\text{syst})^{+0.062}_{-0.012}(\text{model})$
δ_{D^*K}	$341.9^{\circ}{}^{+18.0^{\circ}}_{-19.6^{\circ}} \pm 3.0^{\circ}(\text{syst}) \pm 22.9^{\circ}(\text{model})$

New Physics
(in the Weak Interaction)

Attempt to go beyond Kobayashi-Maskawa

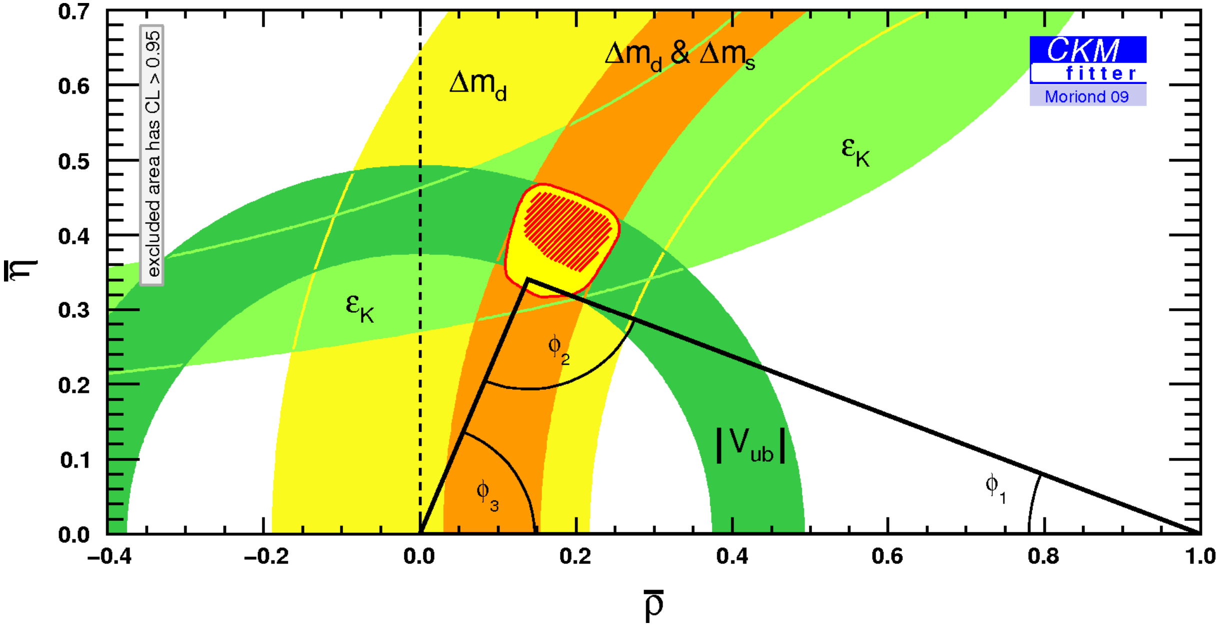
Are there new particles beyond those in the SM, which have different couplings (either in magnitude or in phase) ?

Supersymmety is an example (~40 new phases)

Is there a small NP phase in B^0-antiB^0 mixing ?

CKMFitter

No $\sin(2\,\phi_1)/\sin(2\,\beta)$ measurements used



See talks by A. Soni, E. Lunghi.

Indirect meas:

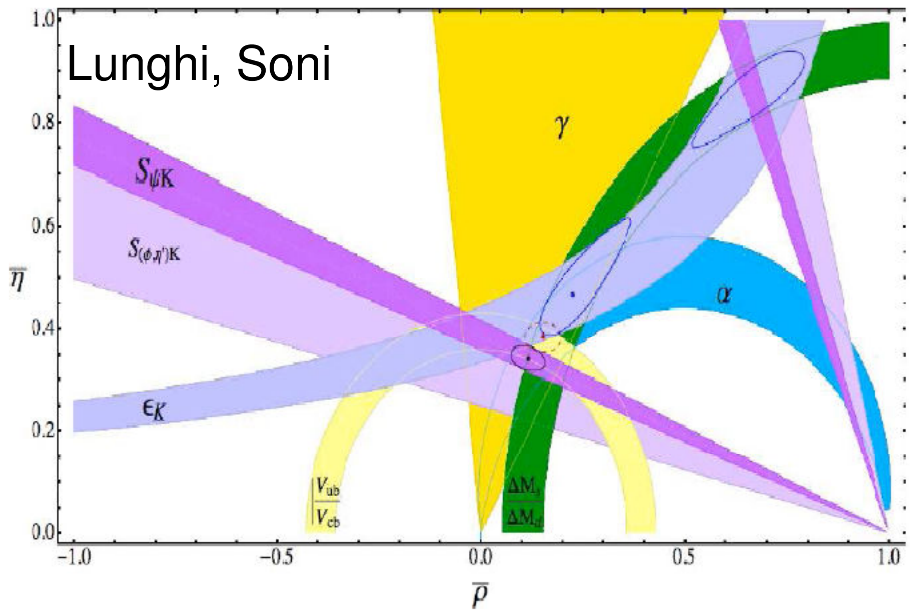
$\sin(2\phi_1)$=0.87±0.09

(about ~2σ deviation)

c.f. direct 0.672±0.023

Larger diff

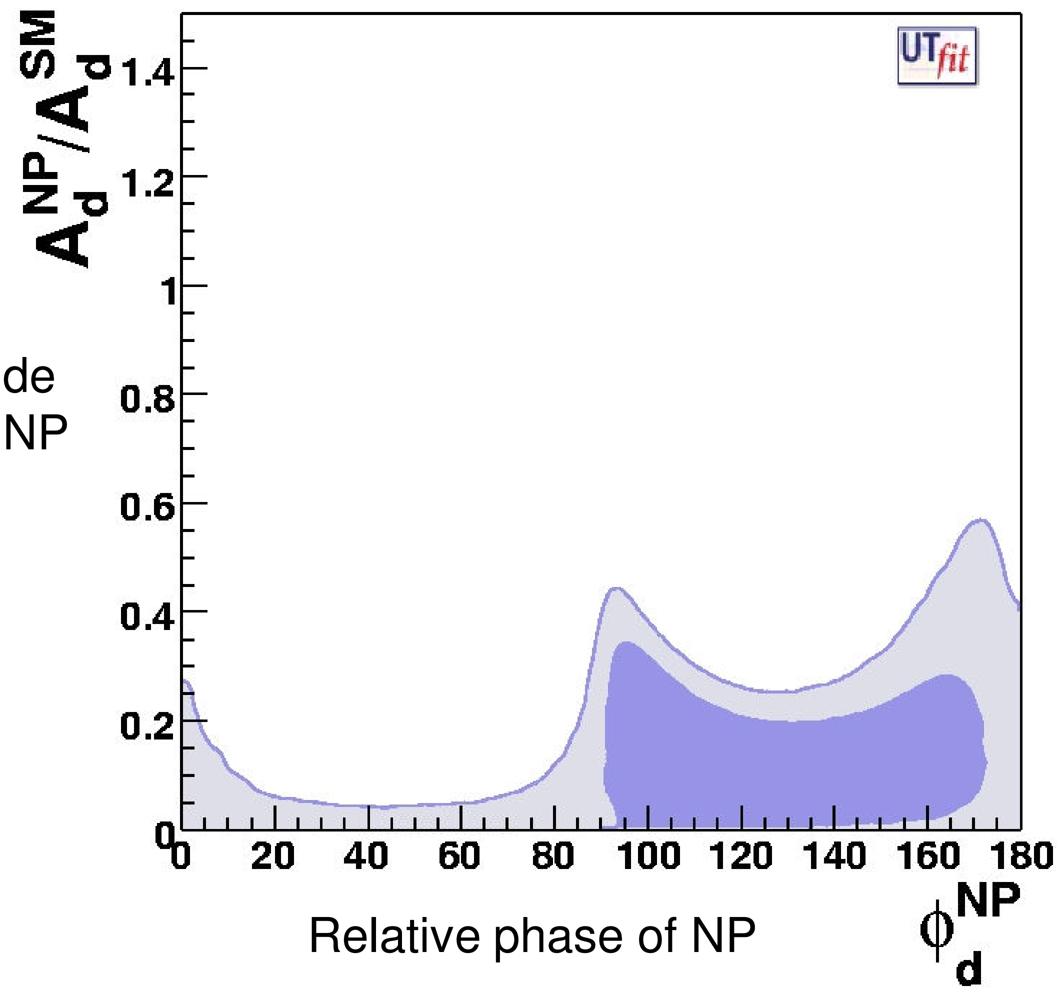
Penguin 0.58±0.06



Use the latest lattice results for ε_K

Similiarly, the UTfit and the CKMfitter groups find that a 10-20% NP contribution in B_d mixing is consistent with all data.

Amplitude ratio of NP to SM



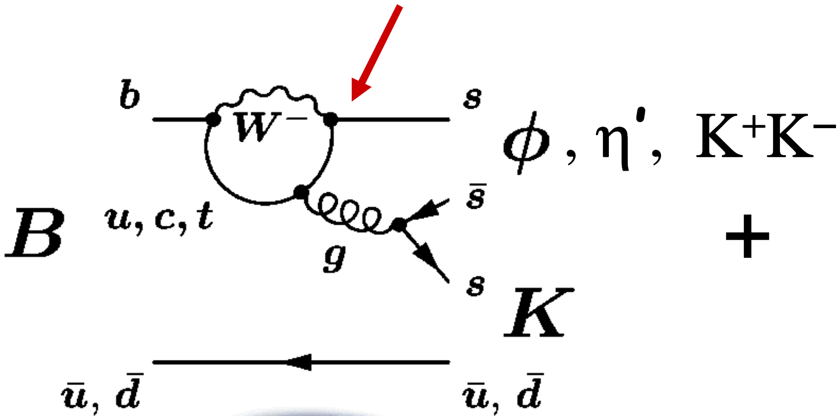
Relative phase of NP

Will need much more data to find or rule out a O(10%) NP contribution

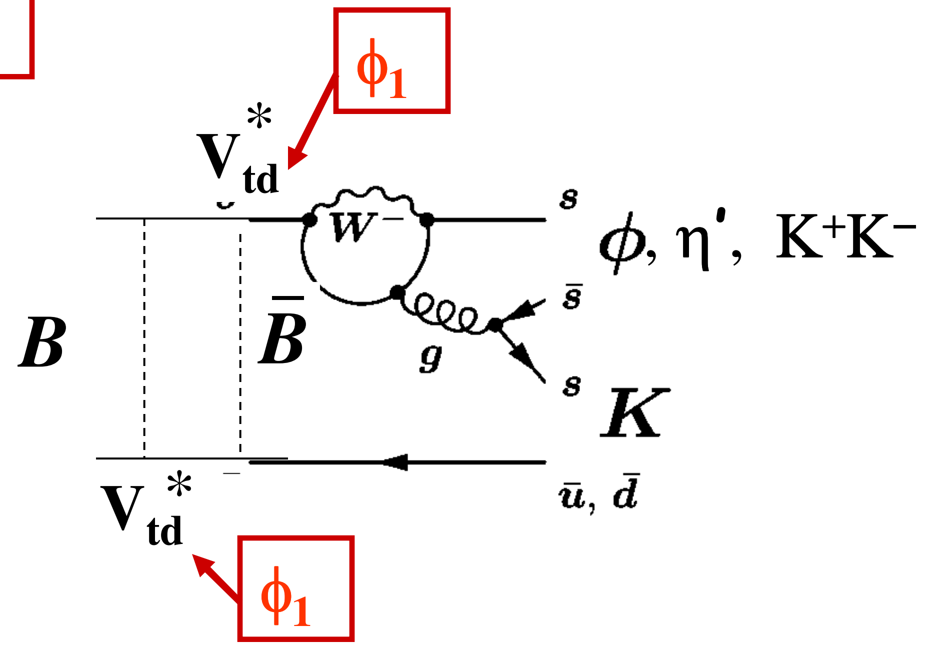
Another method to find New Physics (NP) Phases

Example:

V_{ts}: no KM phase



+

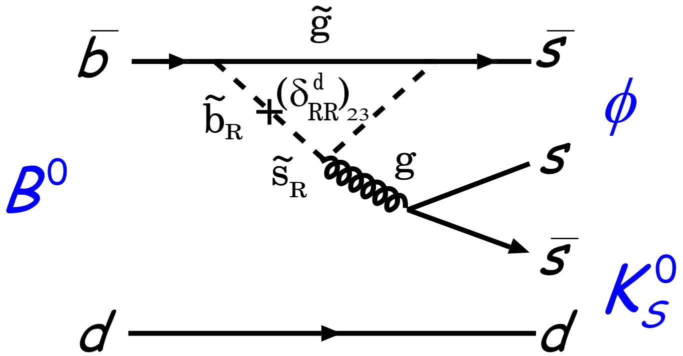


SM: $\sin 2\phi_1^{eff} = \sin 2\phi_1$ *from* $B \rightarrow J/\psi K^0$ $(b \rightarrow c\,\bar{c}\,s)$

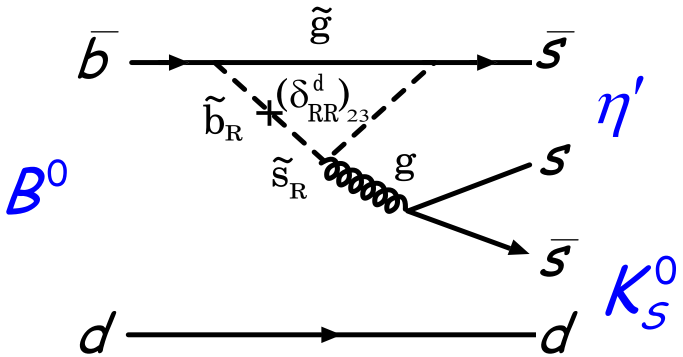
unless there are other, non-SM particles in the loop

How New Physics may enter in b→s loops

New physics in loops?



Many new phases are possible in SUSY



O(1) effect allowed even if SUSY scale is above 2TeV.

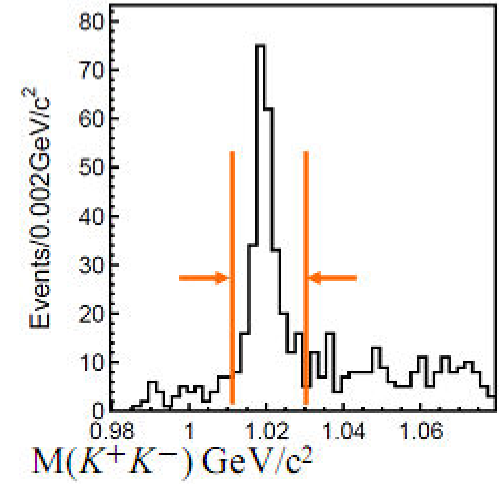
Large effects, O(0.1-0.2), are also possible in extra dimensional models e.g.with a 3 TeV KK gluon

(In 2003, >3 sigma effect seen in $B \rightarrow \phi K_S$ with low stats)

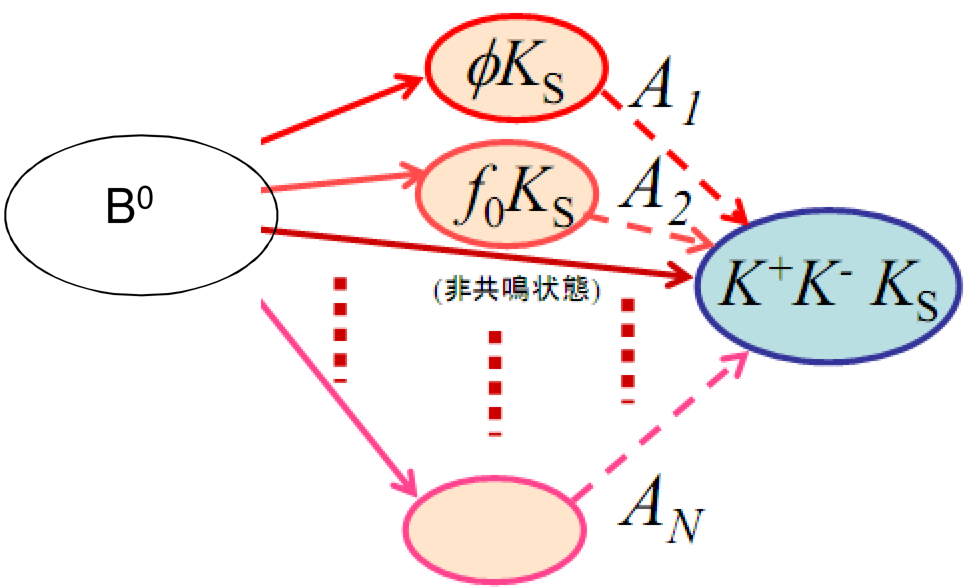
Latest generation of b→s time dependent CPV analyses

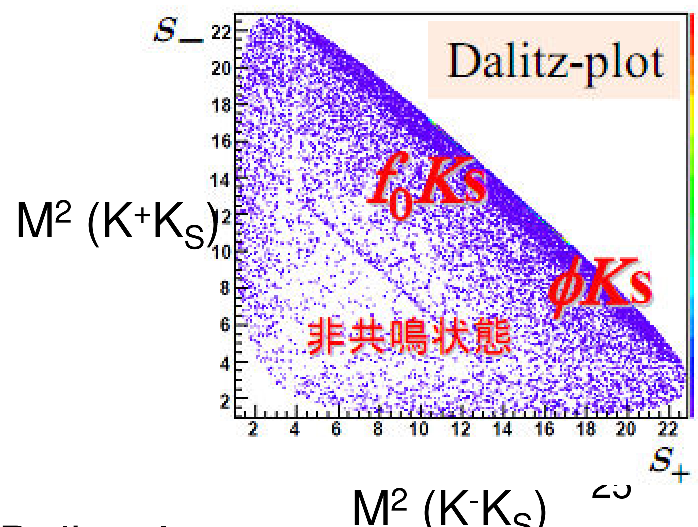
(~20% more data than 08) and **advanced analysis** for three-body decay modes

(Quasi-2body アプローチ)



Previous SAD (slice and dice) analyses have been modified. Now use time-dependent Dalitz analyses with interference between multiple common final states for tCPV in ϕK_S and $f_0 K_S$





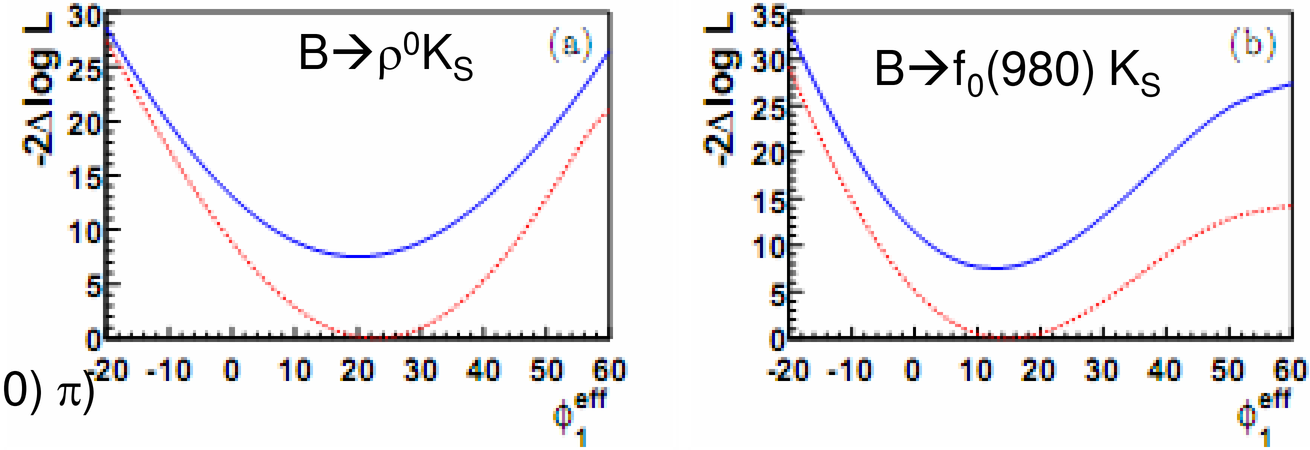
But need a model of resonances that contribute in the Dalitz plot

Generic *technical* problem for coherent t-dependent Dalitz analyses

For example,

$B \to K_S \pi\pi$

Multiple solutions for resonance fit fractions (corresponding to different interference terms)

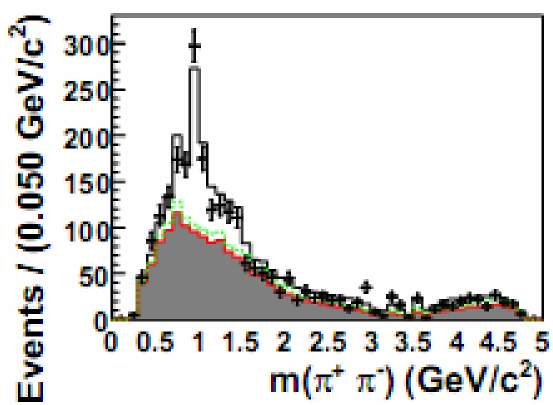


$f(B \to K^{*0}(1430)\ \pi)$ =17%, 62%

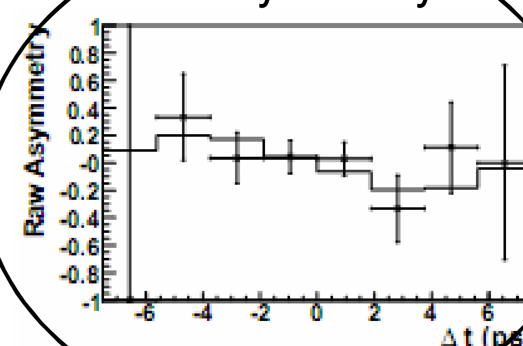
CPV phase 12.7^0 or 14.8^0

FIG. 4: Statistical likelihood scan of $\phi_1^{\rm eff}$ for $B^0 \to \rho^0(770) K_S^0$ (a), and $B^0 \to f_0(980) K_S^0$ (b) where the solid (dashed) curve represents Solution 1 (2).

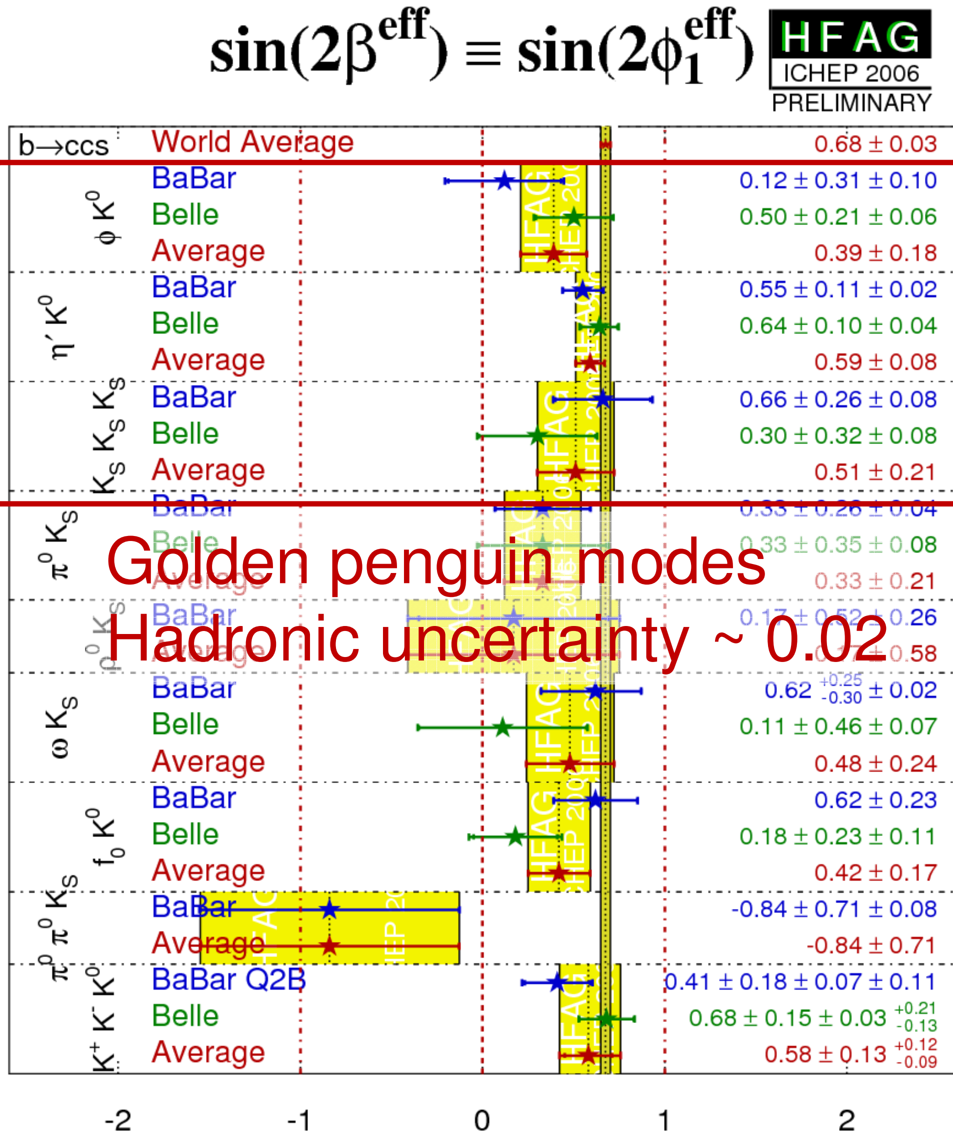
$B \to K_S \pi\pi$ fit projection



CP asymmetry



A possible hint for NP: $b \to s\bar{q}q$



Golden penguin modes

Hadronic uncertainty ~ 0.02

See talk by B. Dutta

Recent updates

BaBar

Belle

HFAG average

0.26±0.25±0.04

$0.67\pm^{0.25}_{0.27}\pm0.07$

0.44±0.18

0.57±0.08±0.02

0.64±0.10±0.04

0.59±0.07

$0.90\pm0.19\,^{+0.69}_{-0.04}$

0.30±0.32±0.08

0.74±0.17

For NP need to find a significant effect in a golden mode

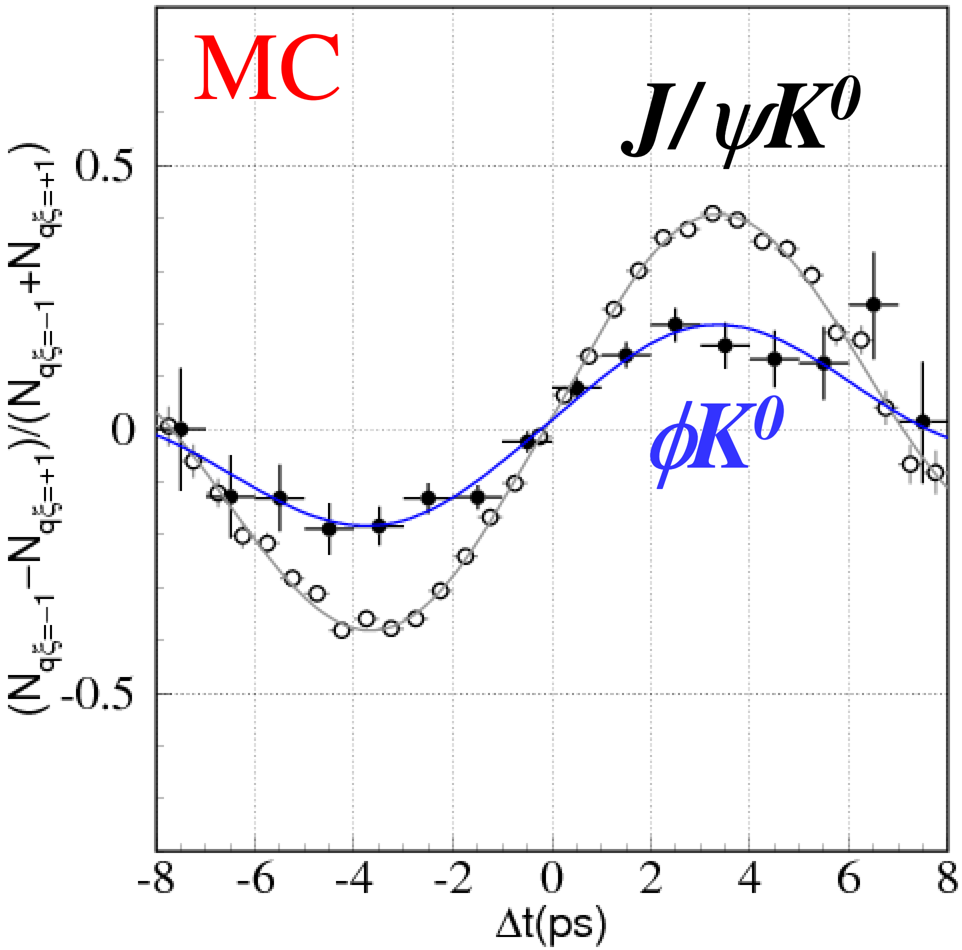
Need much more data to clarify this issue

Not such a wild extrapolation:

(See talk by K. Kinoshita on Belle-II, SuperKEKB)

$B \to \phi K^0$ at 50/ab with ~present WA values

Time dependent asymmetry



This would establish the existence of a NP phase

Compelling measurement in a clean mode

"Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed" –A. Soni@SuperKEKB Proto-collaboration meeting

A lesson from history

"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \rightarrow \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

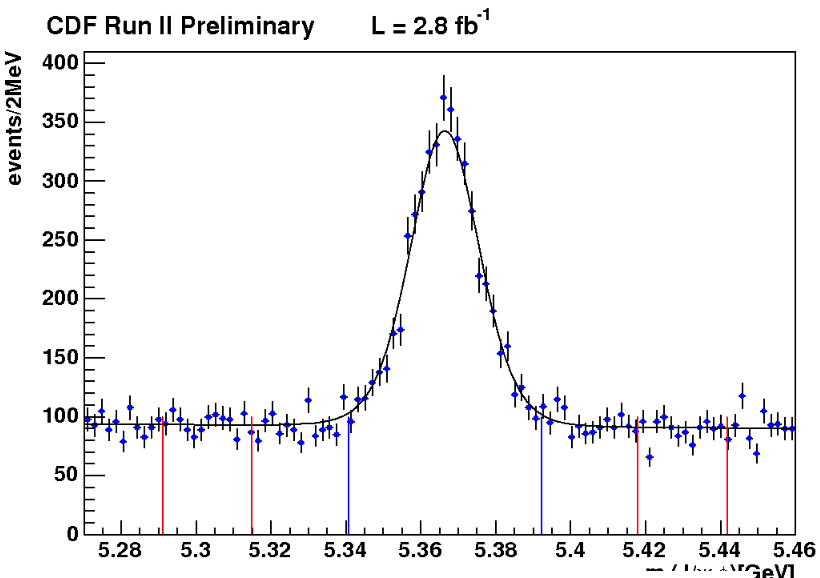
-Lev Okun, "The Vacuum as Seen from Moscow"

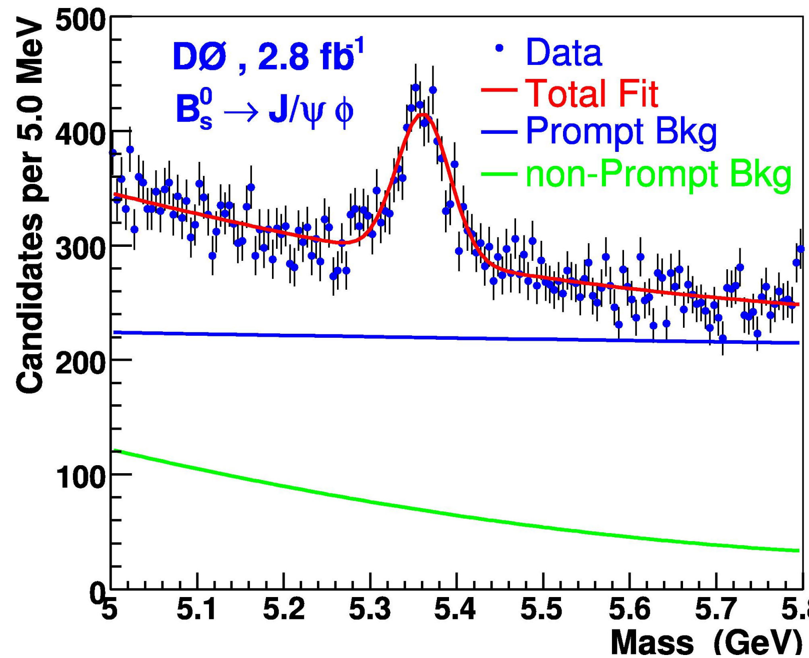
1964: BF= 2×10^{-3}

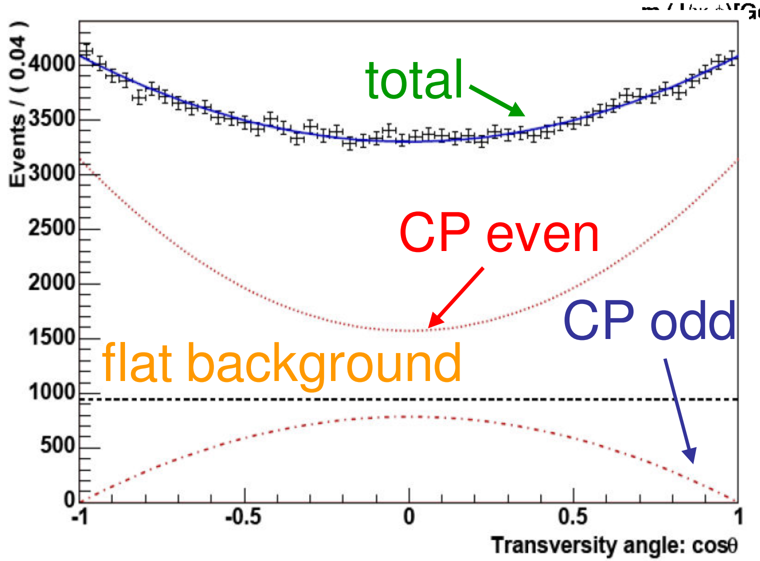
A failure of imagination ? Lack of patience ?

Is there a large NP phase in B_S mixing ?

Some current hadron collider data samples are shown below. (also see talks by I. Redondo, S.W. Youn)



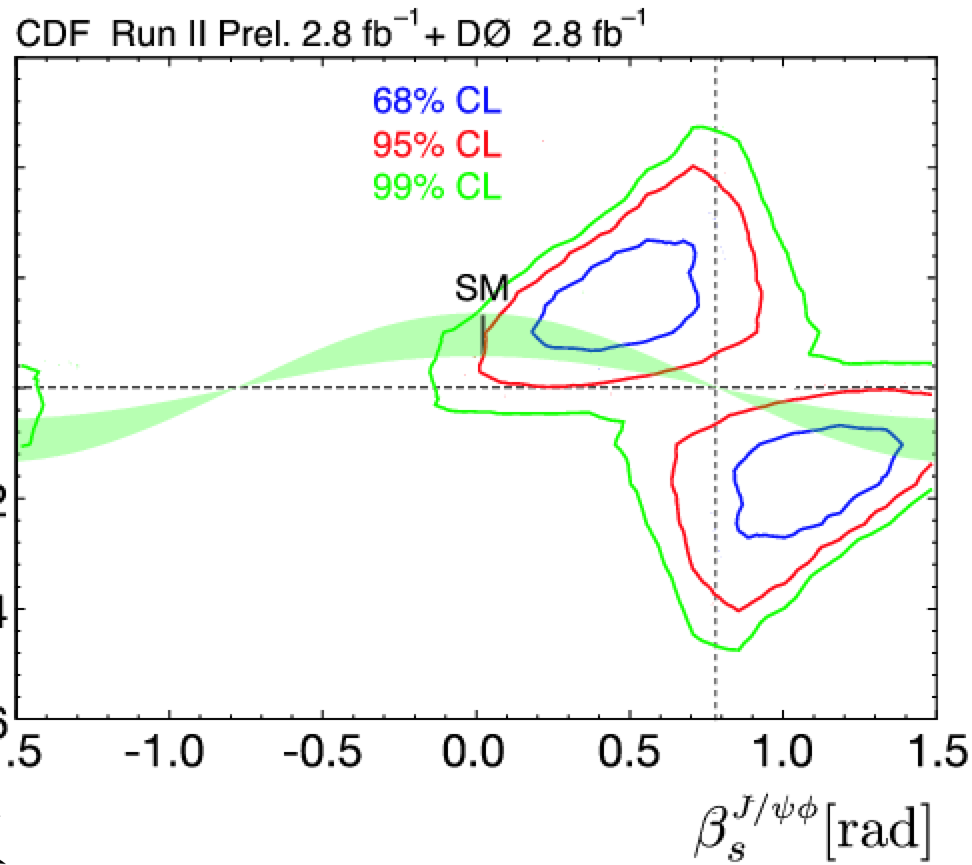


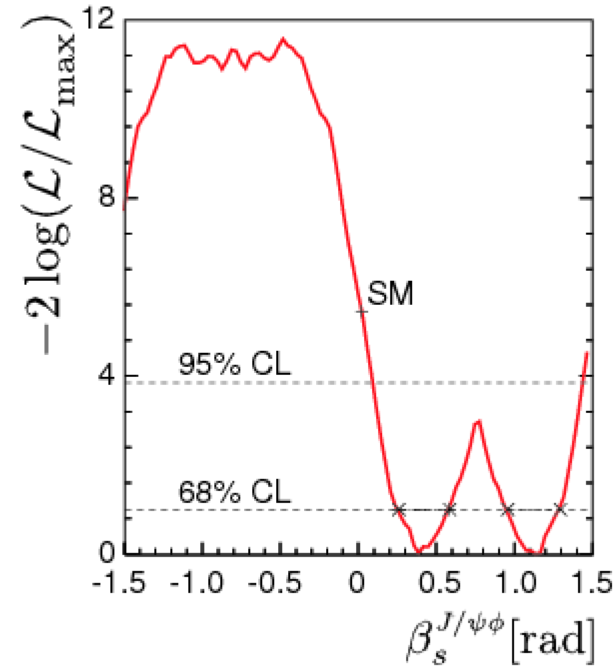


($B_S \rightarrow J/\psi\phi$ <u>not a pure CP eigenstate</u> so angular analysis is needed for CPV)

Hint: Phase of B_s (V_{ts}) mixing

(N.B. we are looking at a box diagram rather than a penguin)





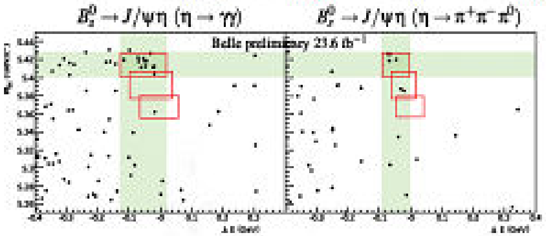
New world average (ref. notes: CDF9787, D05928). The deviation from the SM is currently about 2.1σ

New B_s CP eigenstates from Belle 5S Data

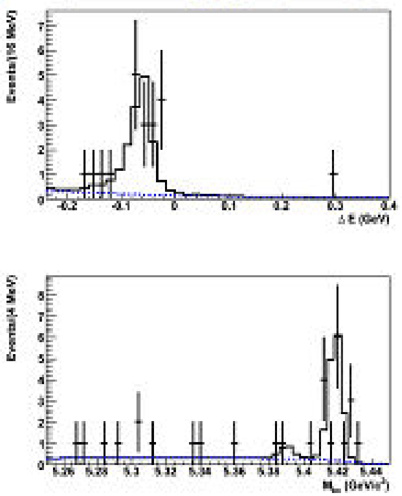
Observation of $B_s \to J/\psi\eta$

$\eta = (uu + dd - ss)/\sqrt{3} \Rightarrow$

$\mathcal{B}(B_s \to J/\psi\eta) \approx 1/3\,\mathcal{B}(B \to J/\psi\phi)$



Projection in $B_s^*B_s^*$ signal region:



$\mathcal{B}(B_s \to J/\psi\eta)$:

$\eta \to \gamma\gamma$ 5.9σ

$(3.44 \pm 1.07(\text{stat.})\,^{+0.62}_{-0.30}(\text{syst.}))\times 10^{-4}$

$\eta \to \pi^+\pi^-\pi^0$ 4.0σ

$(4.60 \pm 2.06(\text{stat.})\,^{+0.89}_{-0.30}(\text{syst.}))\times 10^{-4}$

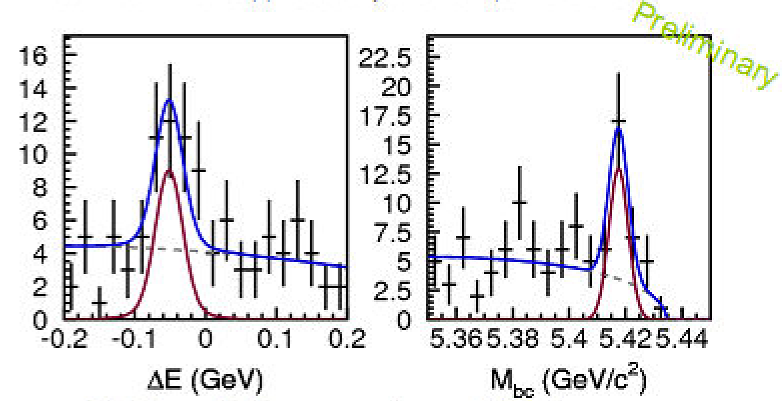
Combined

$(3.69 \pm 0.95(\text{stat.})\,^{+0.65}_{-0.30}(\text{syst.}))\times 10^{-4}$

Requires good neutral detection.

$B_s \to hh$: Observation of $B_s \to K^+K^-$

Continuum BG suppressed by event-shape variables.



23±6 Bs→ K+K− events observed (5.8σ).

$\mathcal{B}(B_s^0 \to K^+K^-) = (3.8^{+1.0}_{-0.9} \pm 0.7)\times 10^{-5}$

CDF: $(3.3\pm0.6\pm0.7)\times10^{-5}$ (PRL97, 211802)

5S kinematics and particle id eliminate bkgs from other B_d and B_s decays

No angular analysis required for these pure CP eigenstates

(See talk by Li Jin)

Belle will accumulate more CP eigenstates and have some $\Delta\Gamma$, CP sensitivity from their 120 fb^{-1} dataset. Later LHCb will come online (See talk by S. Blusk)

Glossary

"Direct CP Violation" (DCPV):
CPV in $\Delta S=1$ or $\Delta B=1$ transitions.

"Indirect" or "Mixing Induced" CPV:
CPV in $\Delta B=2$ transitions.

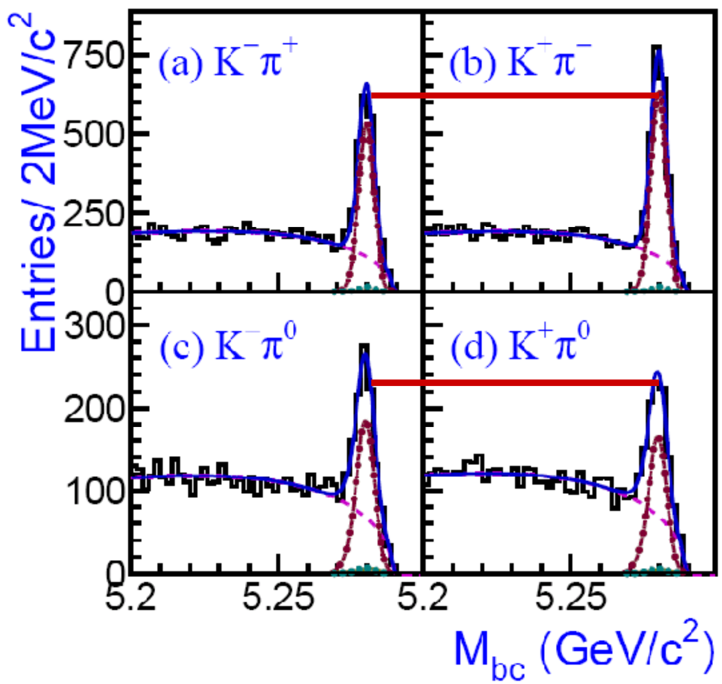
In some B meson decays, the $\Delta B=2$ CPV effects are O(1). For certain B decays, direct CPV effects are also large as we will see. Compare to the kaon system, $\varepsilon \sim 2 \times 10^{-3}$ and $\varepsilon' \sim 5 \times 10^{-6}$

Final KTeV ε'/ε result on kaon direct CPV (See talk by E. Worcester)

Direct CP Violation in B→Kπ Decays (NP Hint ?)

$$\mathcal{A}_{CP}(B \to f) = \frac{|\overline{A}|^2 - |A|^2}{|\overline{A}|^2 + |A|^2} \propto \sum_{i,j} A_i A_j \sin(\delta_i - \delta_j) \sin(\phi_i - \phi_j)$$

Belle Results: Nature 452, 332 (2008)



Recent Update ↓

$A_{cp}(K^+\pi^-) = \begin{cases} -0.107 \pm 0.016 \,^{+0.006}_{-0.004} & \textbf{BaBar} \\ -0.094 \pm 0.018 \pm 0.008 & \textbf{Belle} \\ -0.086 \pm 0.023 \pm 0.009 & \textbf{CDF} \\ -0.04 \pm 0.16 \pm 0.02 & \textbf{CLEO} \end{cases}$

$\Rightarrow -0.098 \,^{+0.012}_{-0.011}$ @ 8.1σ **AVG**

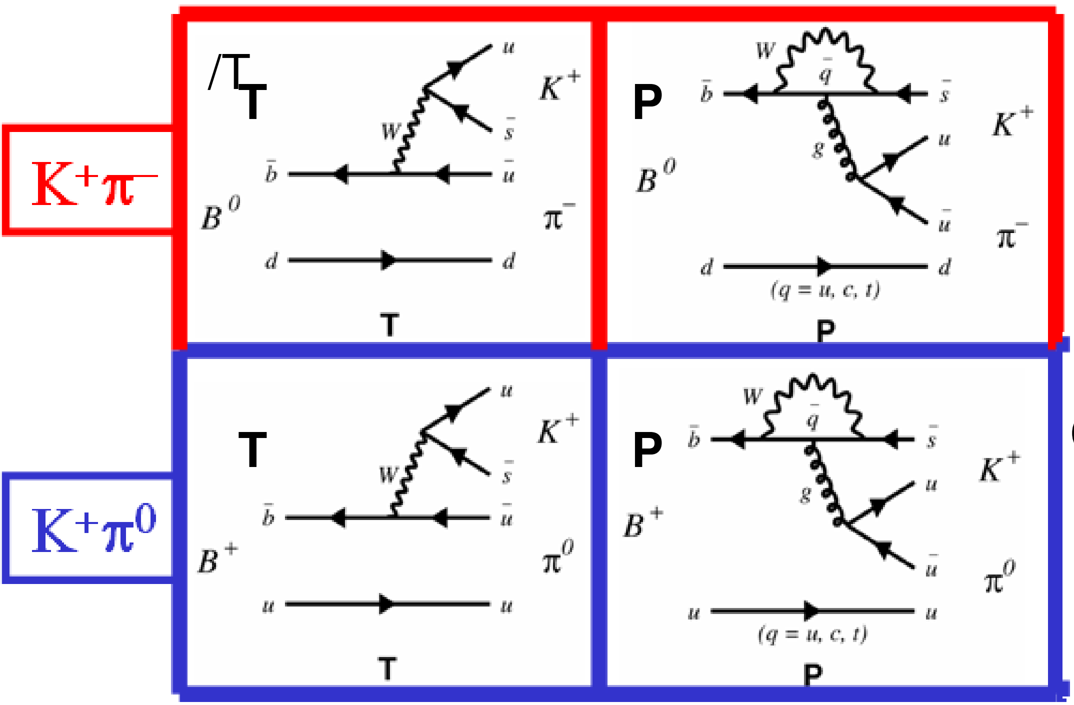
$A_{cp}(K^+\pi^0) = \begin{cases} +0.030 \pm 0.039 \pm 0.010 & \textbf{BaBar} \\ +0.07 \pm 0.03 \pm 0.01 & \textbf{Belle} \\ -0.29 \pm 0.23 \pm 0.02 & \textbf{CLEO} \end{cases}$

$\Rightarrow +0.050 \pm 0.025$ @**2.0**σ **AVG**

$\Delta A_{K\pi} = A_{cp}(K^+\pi^-) - A_{cp}(K^+\pi^0)$
$= -0.147 \pm 0.028$ @ **5.3**σ

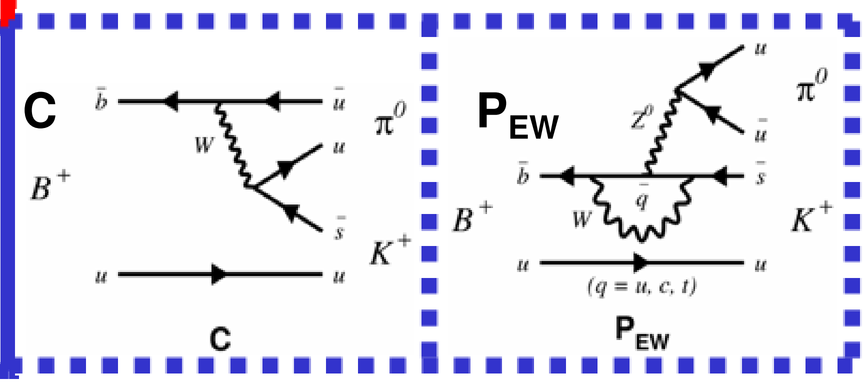
Solutions to the $\Delta A_{K\pi}$ Puzzle

See Nature commentary by Michael Peskin



Expectation from current theory

T & P are dominant $\Rightarrow \Delta A_{K\pi} \sim 0$



- **Enhancement of large C with large strong phase to T $\Rightarrow$ strong inter. !?**

Chiang et. al. 2004
Li, Mishima & Sanda 2005

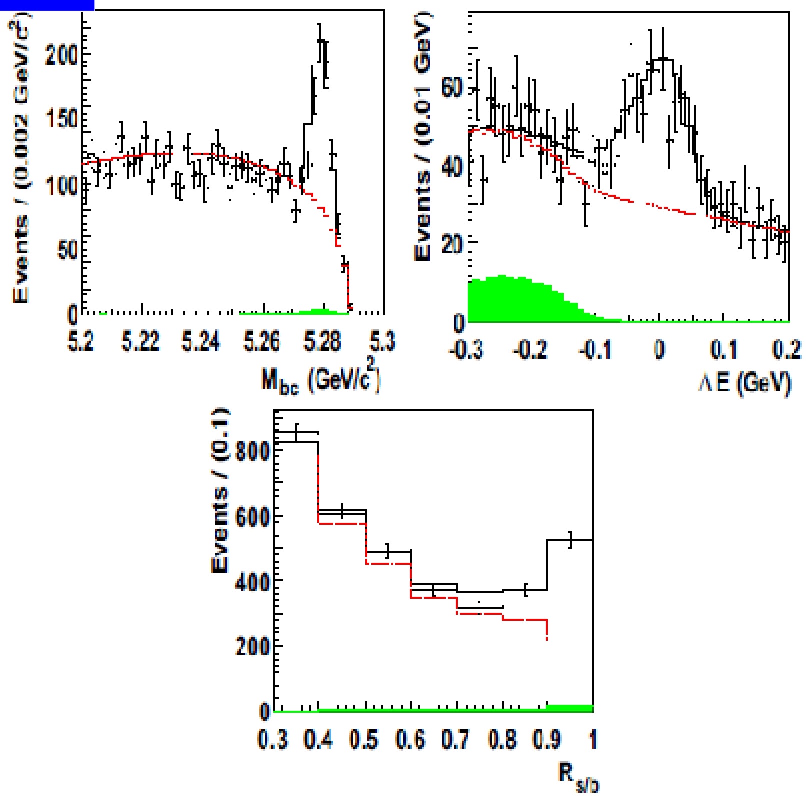
- **Enhancement of large P_{EW} $\Rightarrow$ New physics**

Yoshikawa 2003; Mishima & Yoshikawa 2004;
Buras et. al. 2004, 2006; Baek & London 2007;
Hou et. al. 2007; Feldmann, Jung & Mannel 2008

Can this issue be resolved in a model-independent way by experiment ?

One important but poorly constrained piece in the puzzle

$B \rightarrow K_S \pi^0$ Signal

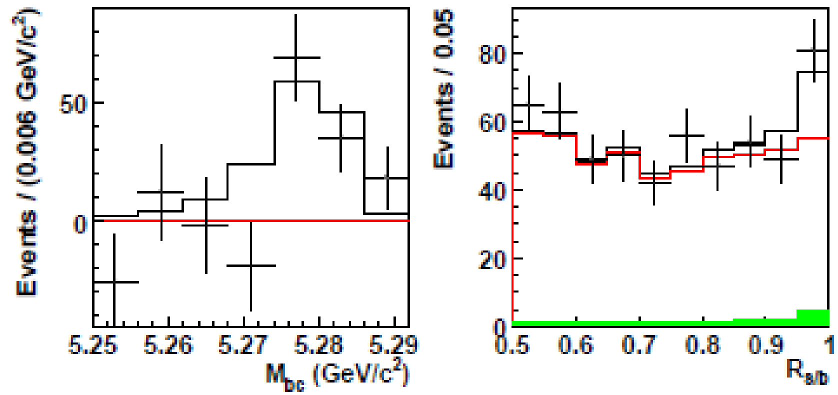


3-d fit gives a signal of 657±37 events

Use flavor tagging to distinguish B^0 and anti-$B^{\wedge 0}$

(Using K_S decays that are inside the silicon, we measure TCPV)

$+1^{st}$ $B \rightarrow K_L \pi^0$ Signal



285±52±57 (3.7σ incl. systematics)

These modes will be very difficult at a hadron machine

Model independent detection of NP in the $B \to K\pi$ system

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

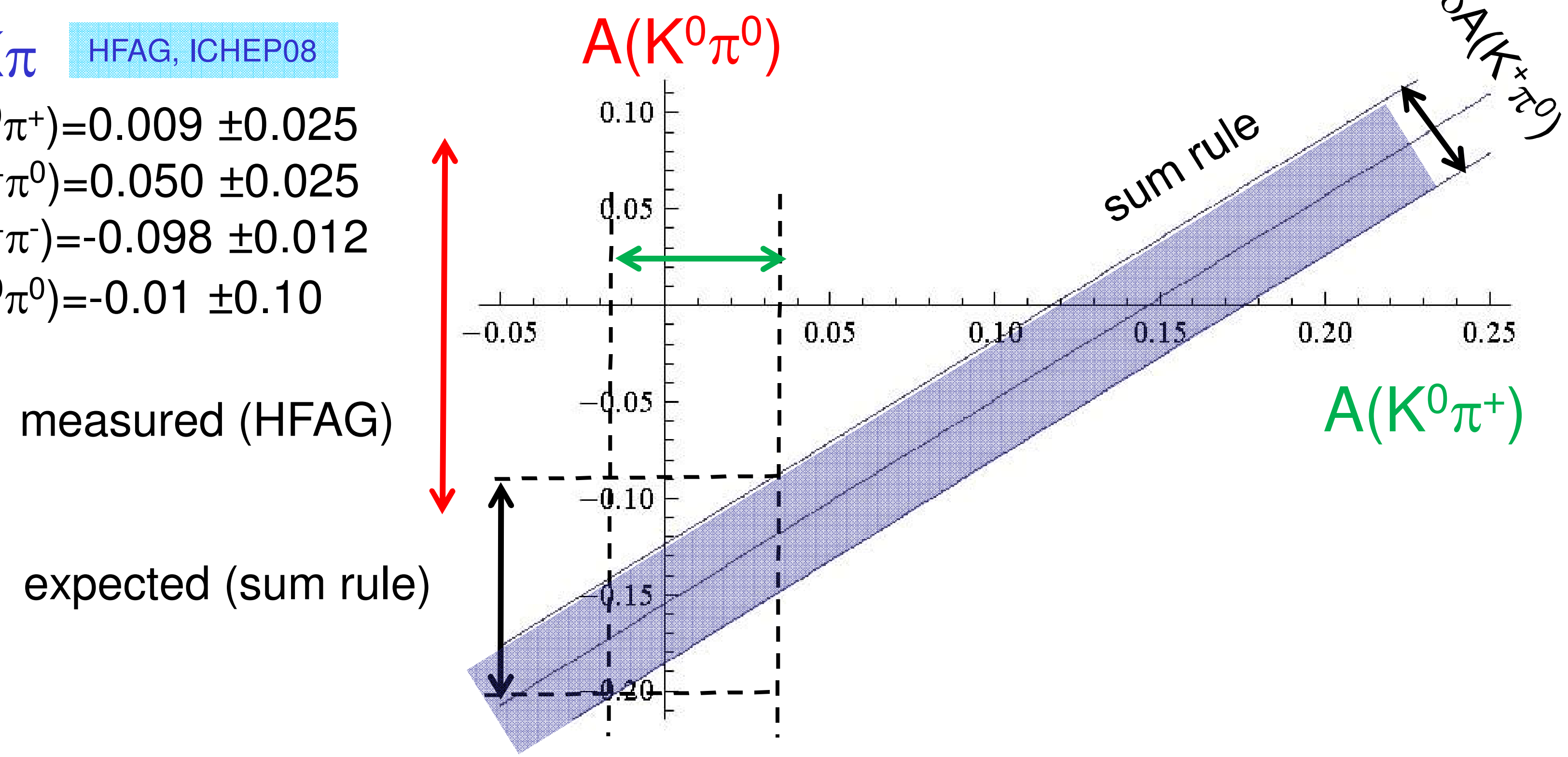
$B \to K\pi$ HFAG, ICHEP08

$A(K^0\pi^+)=0.009 \pm 0.025$

$A(K^+\pi^0)=0.050 \pm 0.025$

$A(K^+\pi^-)=-0.098 \pm 0.012$

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

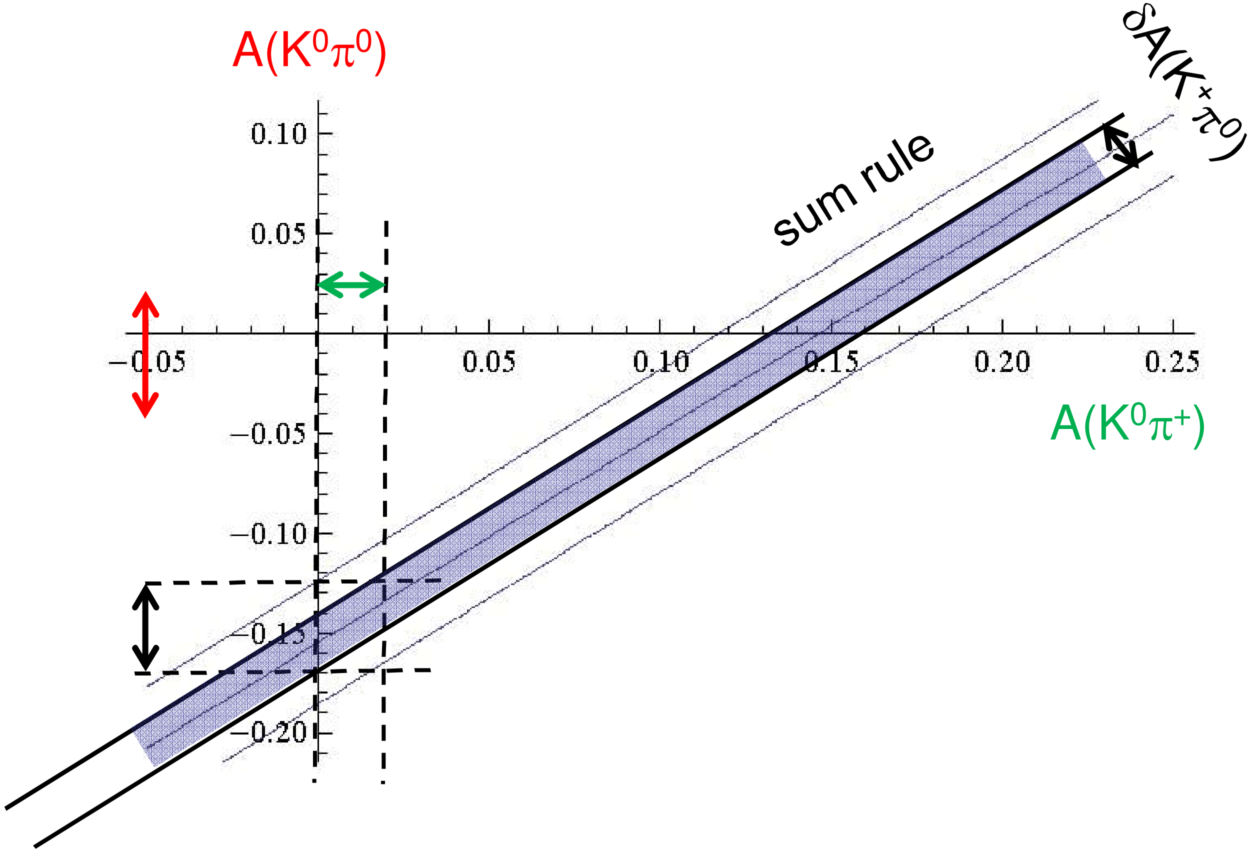


Sum rule proposed by:

M. Gronau, PLB 627, 82 (2005); D. Atwood & A. Soni, Phys. Rev. D 58, 036005(1998).

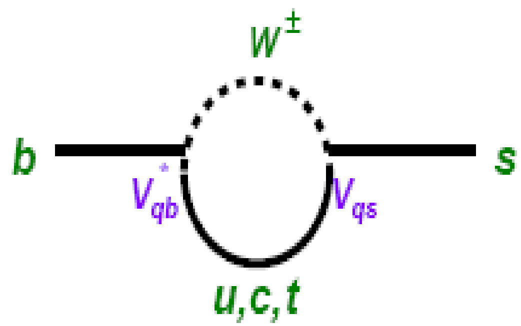
Model independent detection of NP in the B→K π system at coming Super B factories

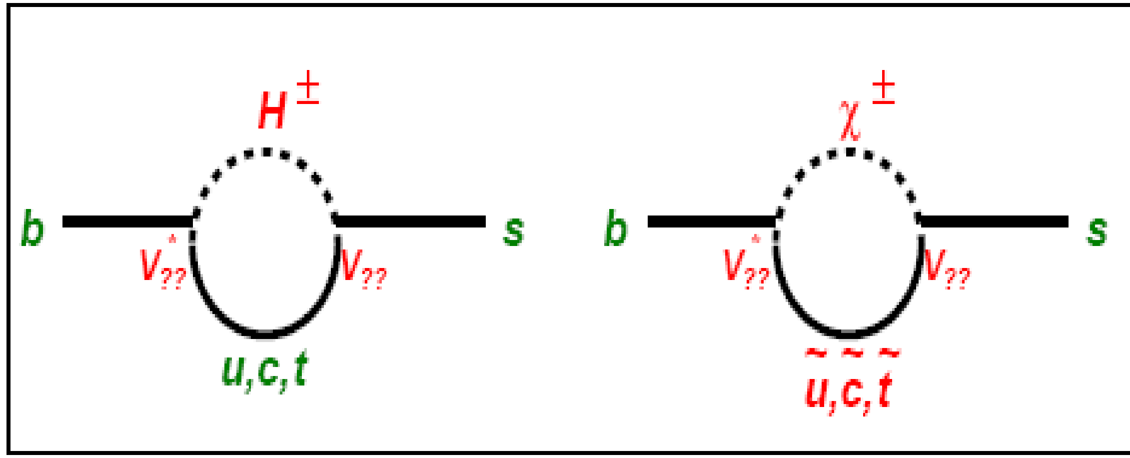
e.g. Belle-II, 50 ab^{-1}



B →$K^0\pi^0$:
main syst. uncertainty
full systematics treated
as non-scaling

CP Violation in Radiative Penguins



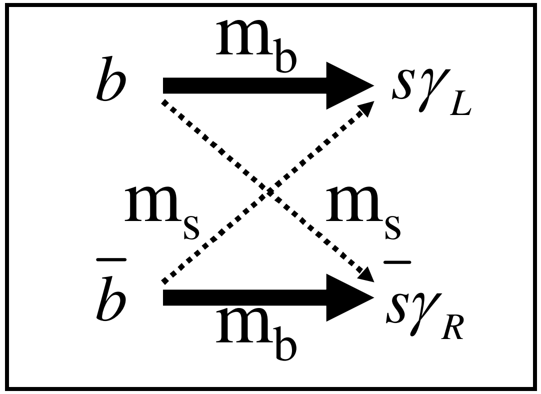


New heavy particles may contribute in the loop

Modifications to rates as well as direct and <u>time-dependent CP asymmetries</u> in b→s γ

Right-handed currents *in exclusive b→sγ processes*

D.Atwood, M.Gronau, A.Soni, PRL79, 185 (1997)
D.Atwood, T.Gershon, M.Hazumi, A.Soni, PRD71, 076003 (2005)



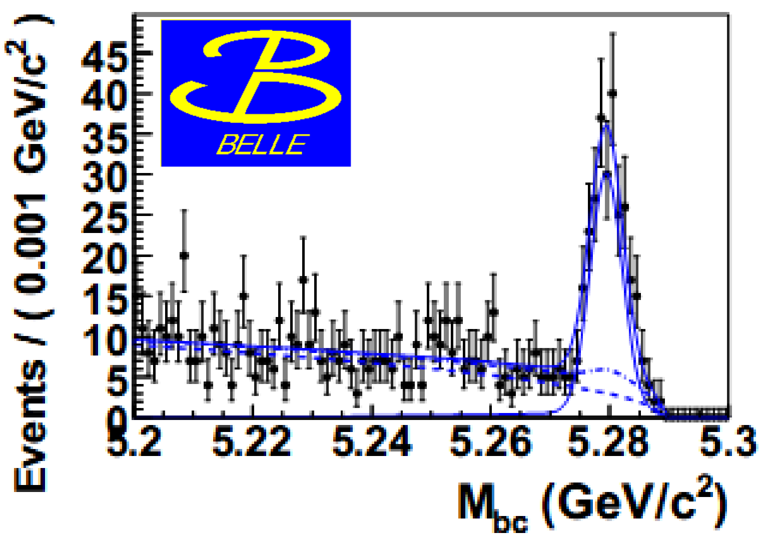
- Time dependent CPV in $B^0 \to (K_S\pi^0)_{K^*}\gamma$
  - SM: γis polarized, the final state almost flavor-specific.
    $S(K_S\pi^0\gamma) \sim -2m_s/m_b \sin2\phi_1$
  - m_{heavy}/m_b enhancement for right-handed currents in many new physics models (*left-right symmetric, extra dimensions etc*)
  - **No need for a new CPV** **suffice)**

Photon polarization measurement via time dependent CPV

Right handed currents ? e.g. new mode $B \rightarrow K_S \rho^0 \gamma$

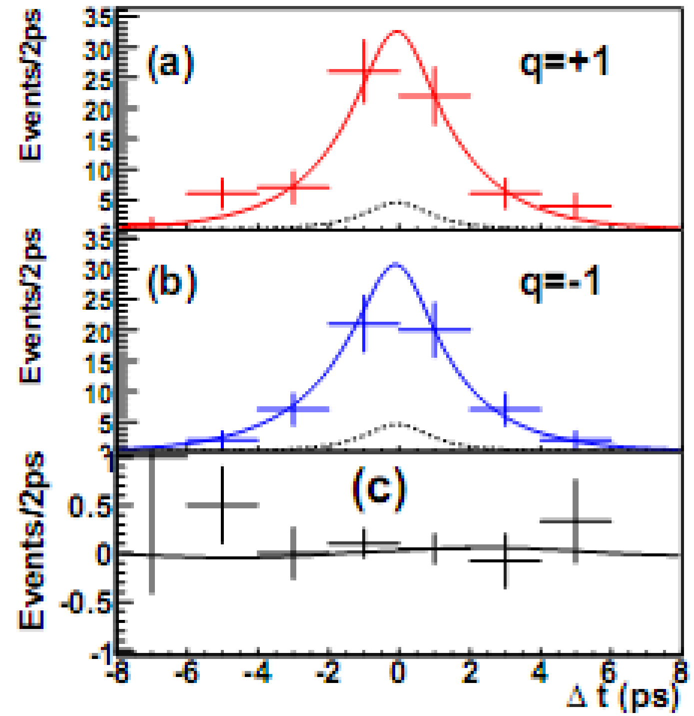
Use the $\rho^0 \rightarrow \pi^+ \pi^-$ decay for the vertex in the silicon. Does not require K_S vertexing in the silicon c.f $B \rightarrow K_S \pi^0 \gamma$

$B \rightarrow K_S \pi^+ \pi^- \gamma$



Require $M(\pi\pi)$ consistent with a ρ^0 meson

Good tags:



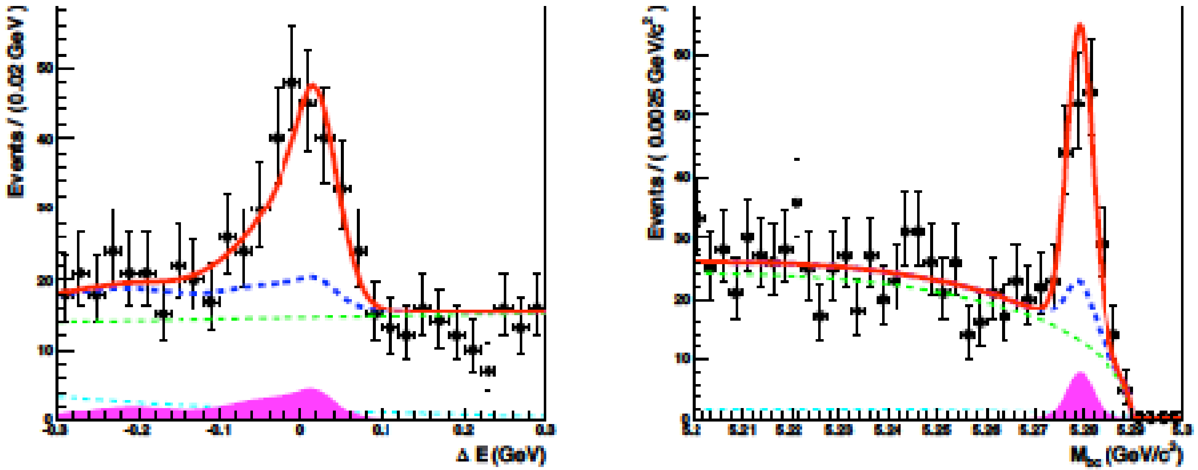
Effective CP parameters in the ρ^0 region

Applying the dilution factor,

$$S_{K_S \rho^0 \gamma} = S_{\text{eff}} / D = 0.11 \pm 0.33 (stat.)^{+0.05}_{-0.09} (syst.)$$

Another new mode for right-handed currents

$\mathcal{B}(B^+ \to \phi K^+ \gamma) = (2.34 \pm 0.29 \pm 0.23) \times 10^{-6}$

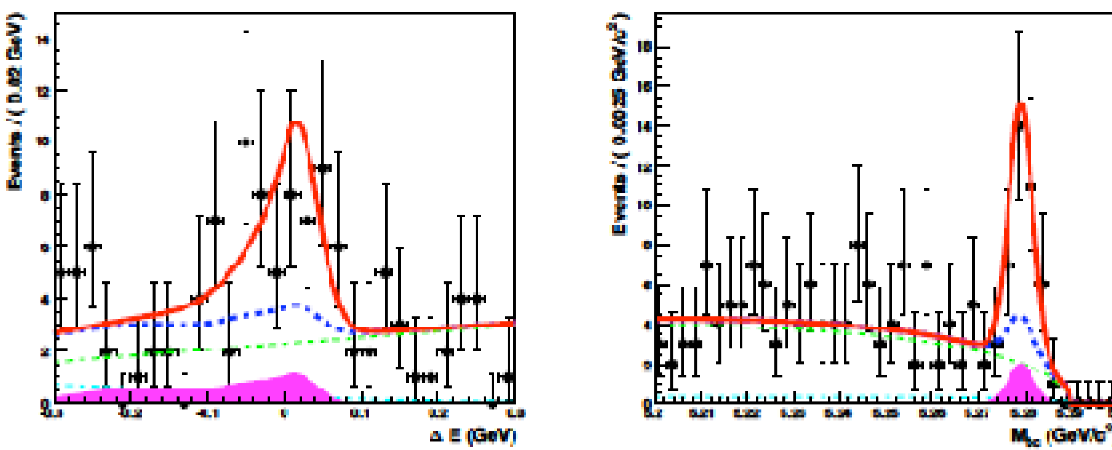


B→φ K⁺ γ

10.5σ(stat)

$\mathcal{B}(B^0 \to \phi K^0 \gamma) = (2.66 \pm 0.60 \pm 0.32) \times 10^{-6}$

New

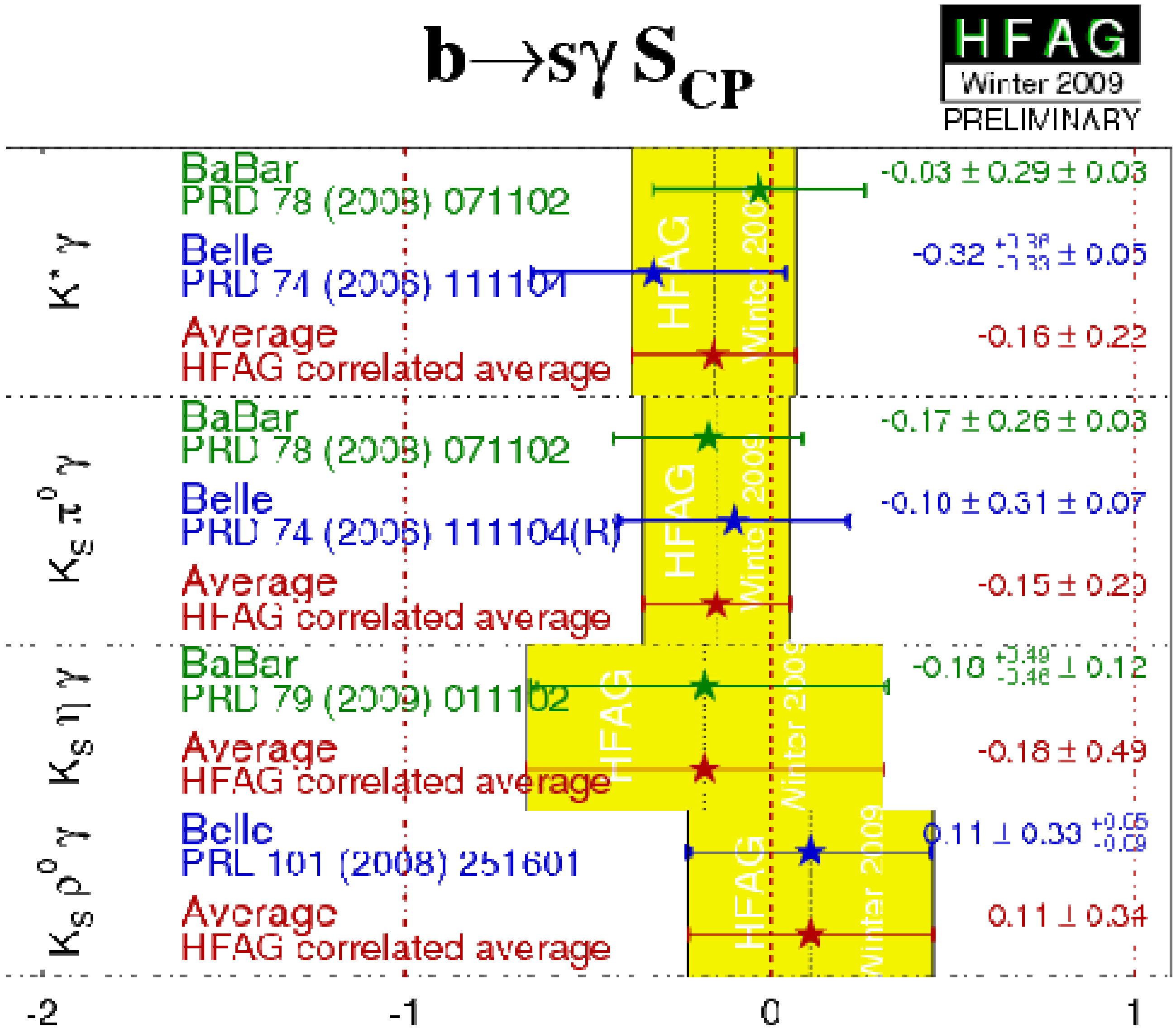


$B \to \phi K_S \gamma$

5.8σ(stat)

A prompt charged vertex from $\phi \to K^- K^+$

See talk by H. Sahoo

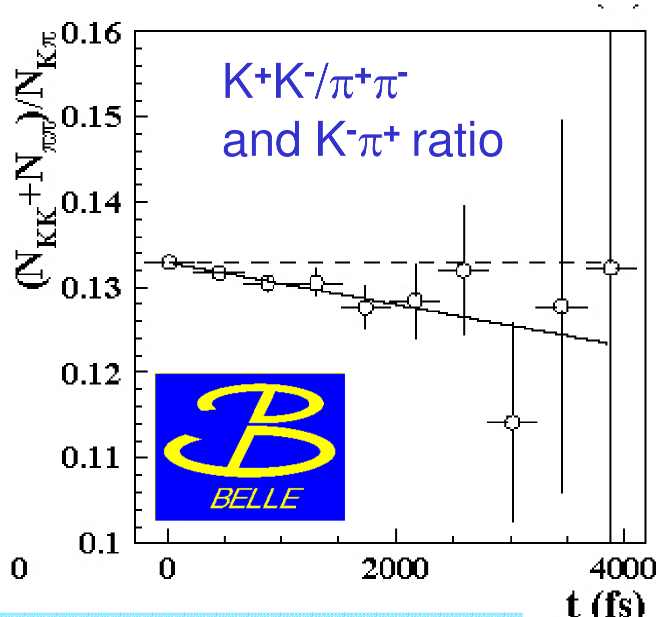


Opposite CP

Little evidence for NP right-handed currents *at current sensitivity*

First signals for D^0 Mixing were reported in spring 2007

Belle: $D^0 \rightarrow K^+K^- / \pi^+\pi^-$ vs $K^-\pi^+$



PRL 98, 211803 (2007), 540fb^{-1}

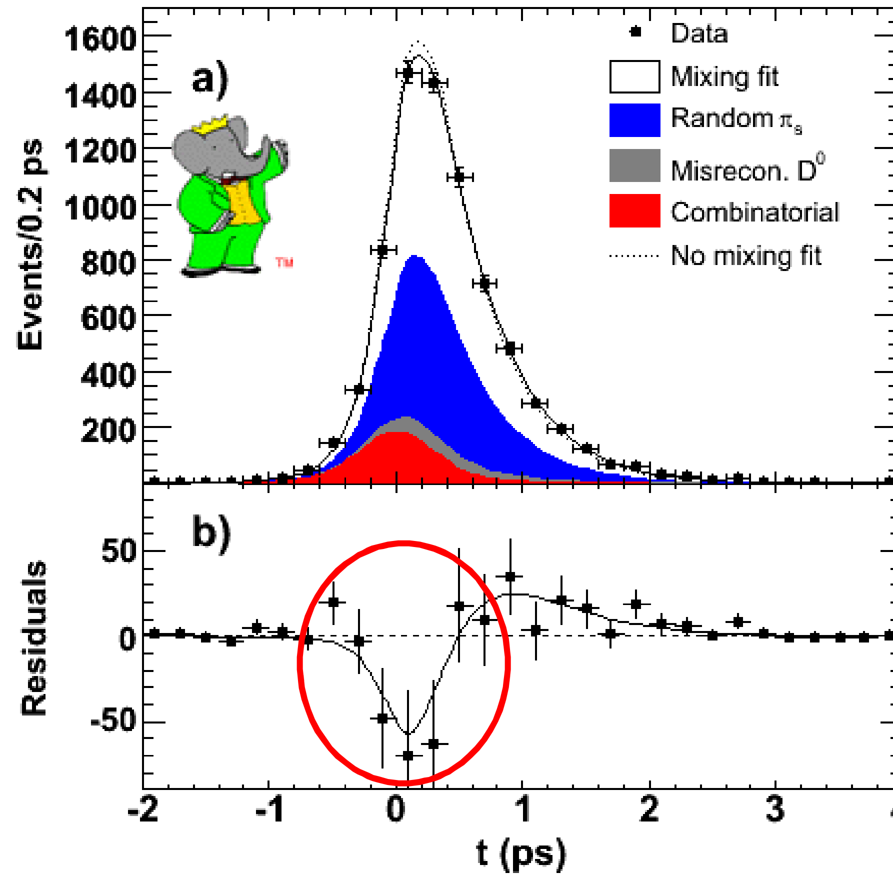
Difference of lifetimes visually observable

$$y = \Delta\Gamma/(2\Gamma)$$

3.2 σ from zero

(4.1 σ stat. only)

BaBar: Wrong sign $D^0 \rightarrow K^+\pi^-$



R_D: $(3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$

x'^2: $(-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$

y': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

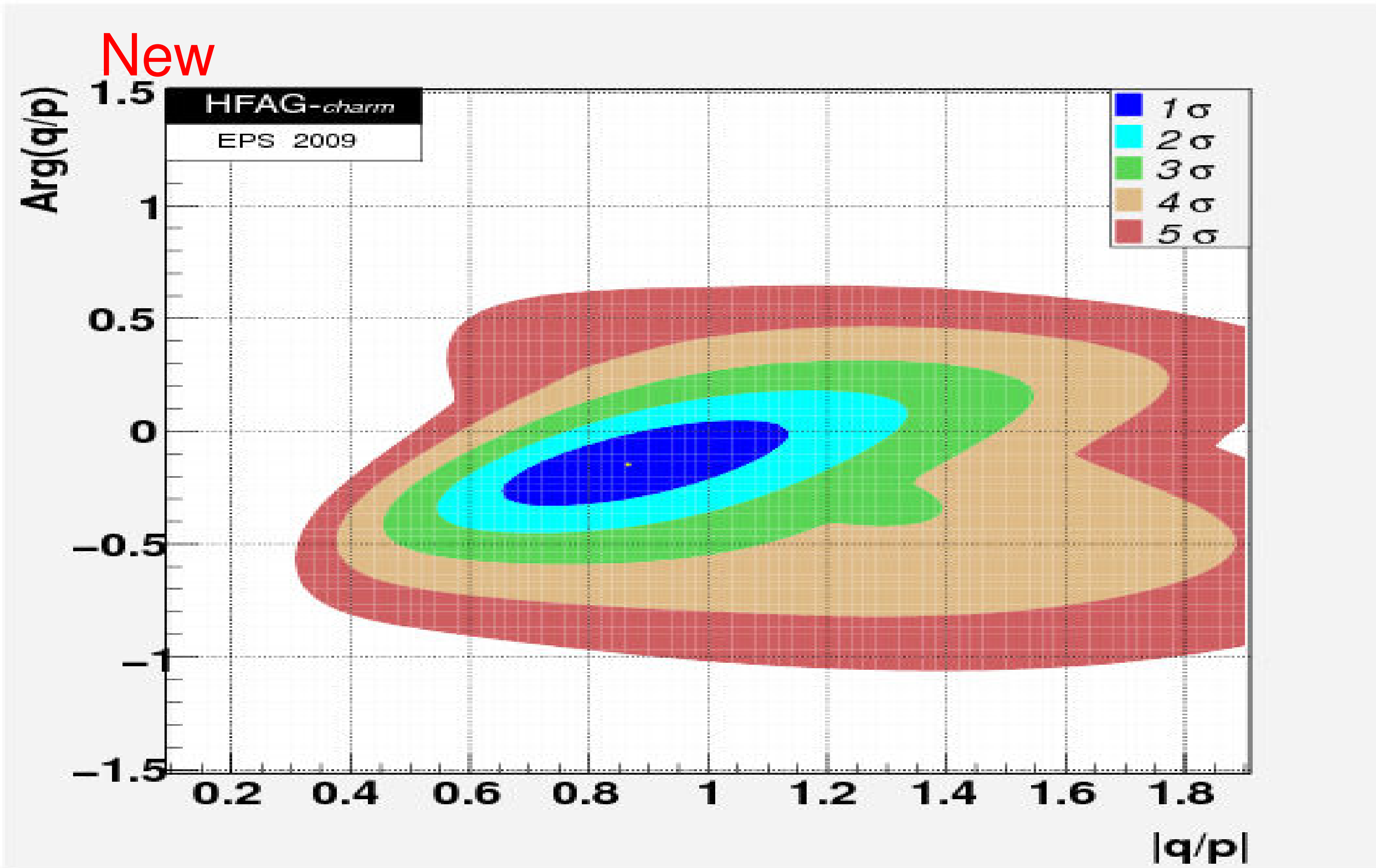
Evidence for D^0 mixing

(regardless of possible CPV)

(See talks by M. Sokoloff, M.Kulkarni and A. Lincoln)

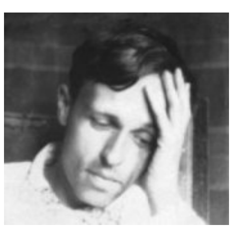
Why then is D^0 mixing important for finding NP ?

New



See talks by Petrov and Sokoloff for more details and discussion

BAU:=Baryon Asymmetry of the Universe



A. Sakharov

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

НАРУШЕНИЕ *CP*-ИНВАРИАНТНОСТИ, *C*-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует

The most compelling hint for new physics in the weak interaction is the BAU

$$\frac{n_{\mathcal{B}}}{n_\gamma} = (5.1^{+0.3}_{-0.2}) \times 10^{-10}$$ WMAP

$$\text{KM} \sim 10^{-20}$$

Too small by 10 orders of magnitude in the SM

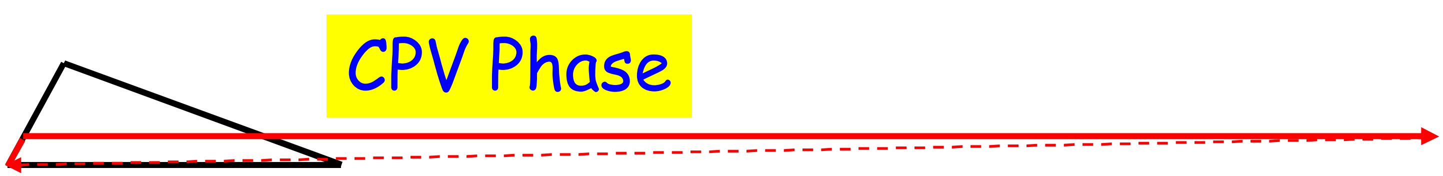
Why? Jarlskog Invariant in the SM (only 3 generations in KM)

$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)\, A$$

Normalize by T ~ 100 GeV ⟶ $J/T^{12} \sim 10^{-20}$

Mass factors in J too small !

$A \sim 3\times10^{-5}$ is common (unique) area of triangle in SM



Pedagogical slide adapted from W.S. (George) Hou

Some popular theoretical solutions to this BAU problem and their experimental implications:

Leptogenesis: requires M~O(10^{10} GeV) RH neutrinos AND CP violation in the neutrino sector.

(See talk by B. Kayser)

May produce lepton flavor violation such as $\tau \rightarrow \mu\gamma$ or $\mu \rightarrow e$ conversion

"Enhanced Baryogenesis": add massive 4th generation quarks (e.g. Hou, Soni et al) or add new SUSY particles in the MSSM (light scalars e.g. stop). Both will lead to new CPV phases.

(See talks by T. Cohen, Soni)

Phases in B_s mixing, $b \rightarrow s$ or $b \rightarrow d$ mixing, anomalous EW penguins (K π puzzle) etc..

Looking for low energy echoes of the primordial *CP violation produced at energy scales that are beyond the reach of accelerators*

Some Conclusions

There are some tantalizing hints of NP in the weak interaction of quarks and BAU but much more data will be needed to establish signals to go beyond KM.

>2020

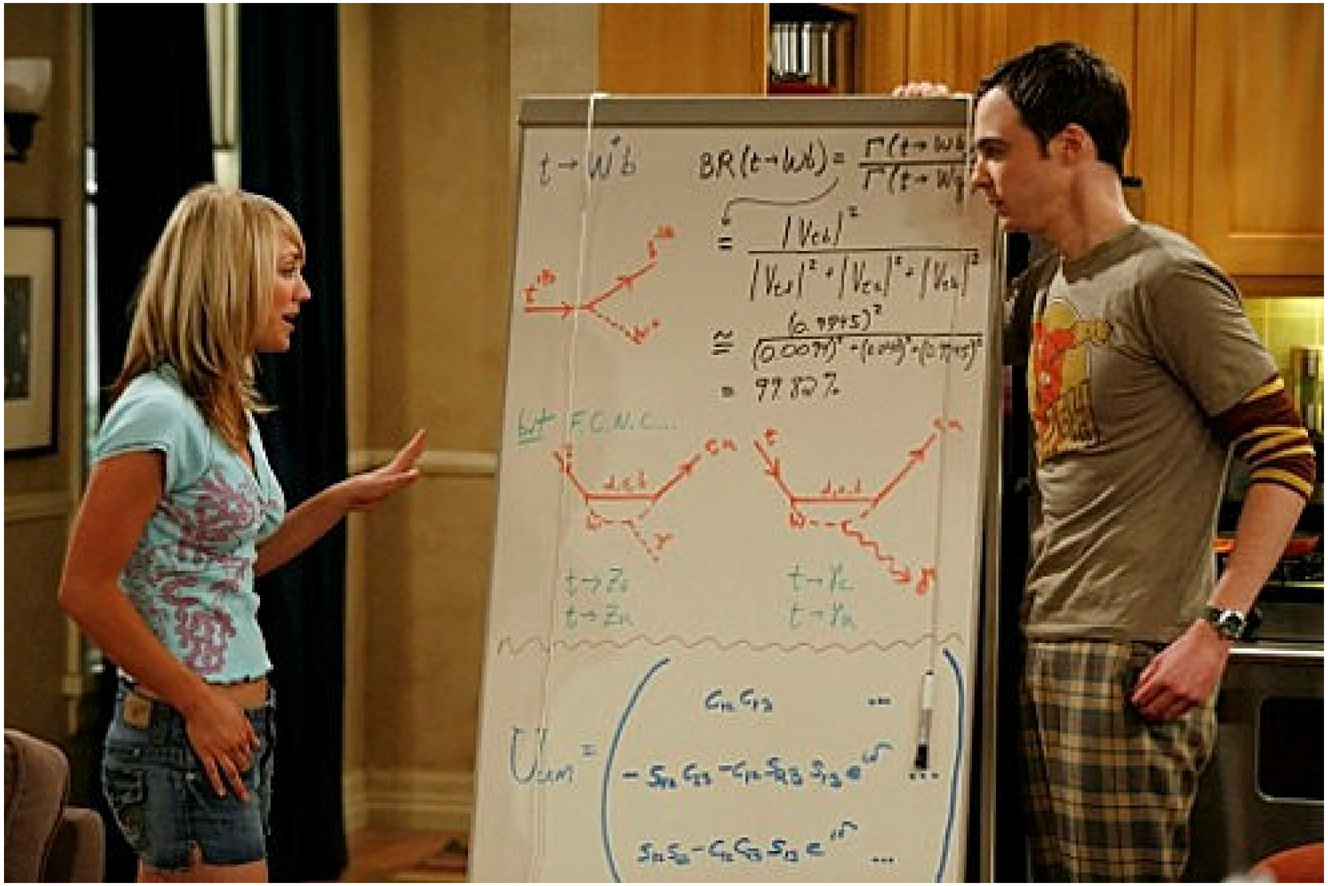
???

<u>However, we will need new facilities</u> (such as Super B factories, JPARC, FNAL Project X) and new experiments (LHCb, Belle-II, etc…) to find and establish these signals of NP (new sources of CPV and FCNC)

Bonus Slides

LHC/Super B factory synergy discussion on US TV comedy

D. Saltzberg, Science Advisor



CBS, "Big Bang Theory", averages 9 million viewers per episode.

23 SPIRES citations so far

Deciphering top flavor violation at the LHC with B factories.
Patrick J. Fox, Zoltan Ligeti, Michele Papucci , Gilad Perez, Matthew D. Schwartz 17pp.
Published in **Phys.Rev.D78:054008,2008**.

Table of Super B sensitivities at 50-75 ab^{-1}

New Physics at a Super Flavor Factory

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Faculty of mathematics and physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia and
J. Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

To appear in Reviews of Modern Physics (RMP)

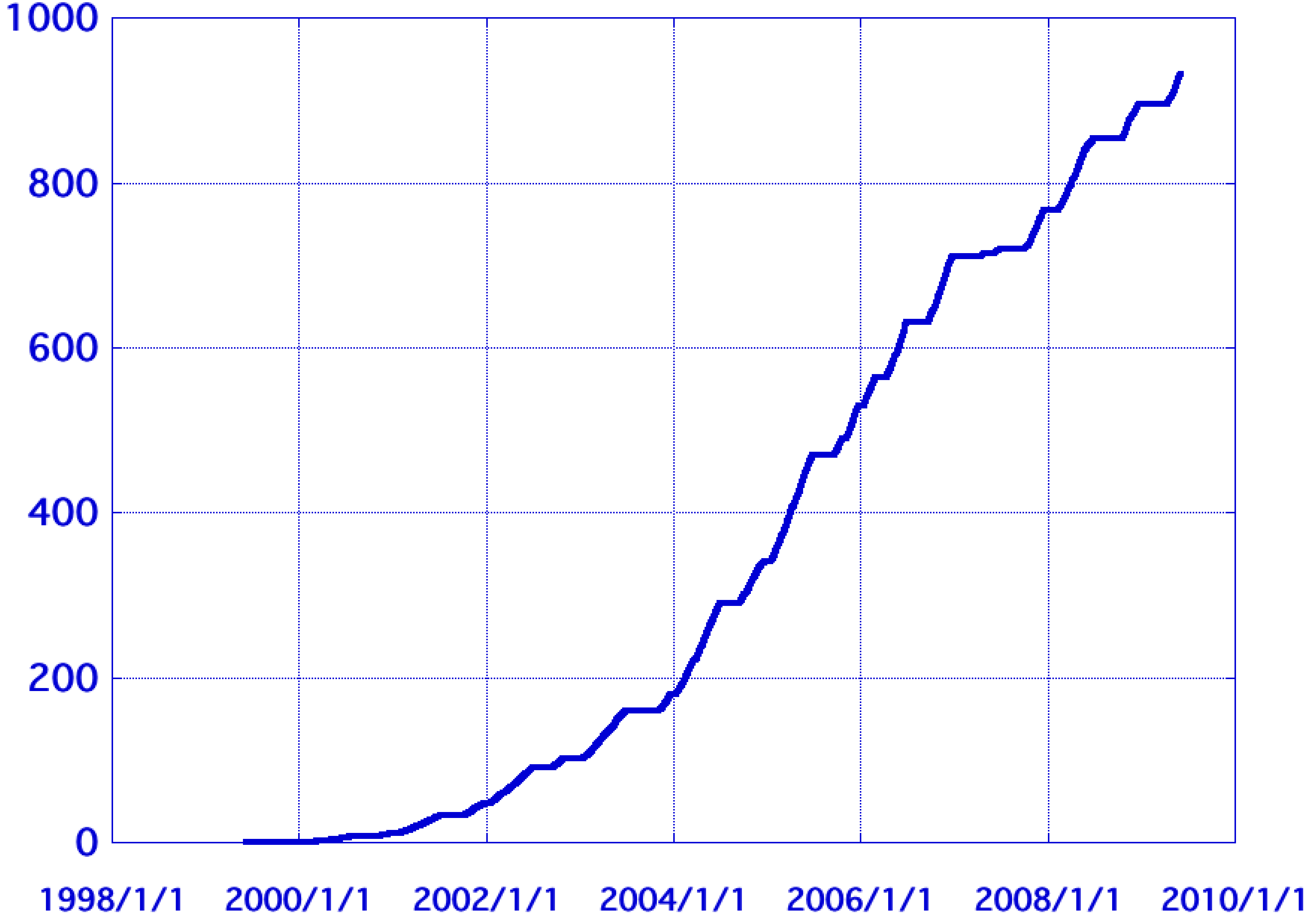
(hep-ph/0802.3201)

26 SPIRES citations so far

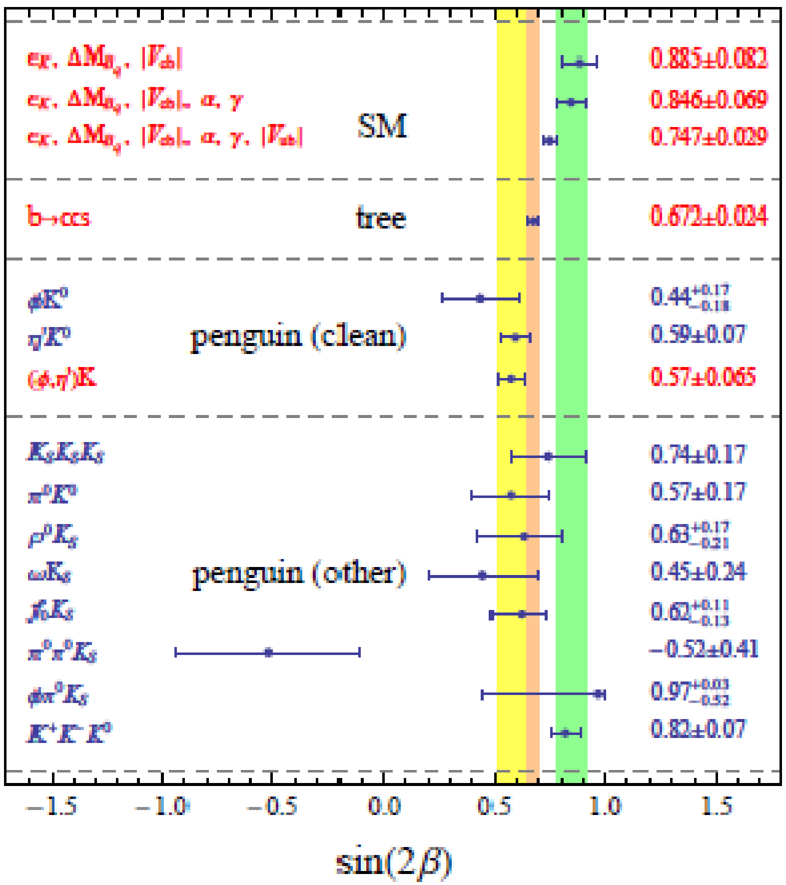
Observable	SFF sensitivity	Current sensitivity
$\sin(2\beta)\ (J/\psi K^0)$	0.005–0.012	0.025
$\gamma\ (DK)$	1–2°	$\sim 31°$ (CKMfitter)
$\alpha\ (\pi\pi,\ \rho\pi,\ \rho\rho)$	1–2°	$\sim 15°$ (CKMfitter)
$\|V_{ub}\|$(excl)	3–5%	$\sim 18\%$ (PDG review)
$\|V_{ub}\|$(incl)	3–5%	$\sim 8\%$ (PDG review)
$\bar{\rho}$	1.7–3.4%	$^{+20\%}_{-12\%}$
$\bar{\eta}$	0.7–1.7%	4.6%
$S(\phi K^0)$	0.02–0.03	0.17
$S(\eta' K^0)$	0.01–0.02	0.07
$S(K_S K_S K^0)$	0.02–0.03	0.20
$\mathcal{B}(B \to \tau\nu)$	3–4%	30%
$\mathcal{B}(B \to \mu\nu)$	5–6%	not measured
$\mathcal{B}(B \to D\tau\nu)$	2–2.5%	31%
$A_{CP}(b \to s\gamma)$	0.004–0.005	0.037
$A_{CP}(b \to s\gamma + d\gamma)$	0.01	0.12
$\mathcal{B}(B \to X_d\gamma)$	5–10%	$\sim 40\%$
$\mathcal{B}(B \to \rho\gamma)/\mathcal{B}(B \to K^*\gamma)$	3–4%	16%
$S(K_S\pi^0\gamma)$	0.02–0.03	0.24
$S(\rho^0\gamma)$	0.08–0.12	0.67
$\mathcal{B}(B \to X_s\ell^+\ell^-)$	4–6%	23%
$A^{FB}(B \to X_s\ell^+\ell^-)_{s0}$	4–6%	not measured
$\mathcal{B}(B \to K\nu\bar{\nu})$	16–20%	not measured
ϕ_D	1–2°	$\sim 20°$
$\mathcal{B}(\tau \to \mu\gamma)$	$2\text{–}8 \times 10^{-9}$	not seen, $< 5.0 \times 10^{-8}$
$\mathcal{B}(\tau \to \mu\mu\mu)$	$0.2\text{–}1 \times 10^{-9}$	not seen, $< (2\text{–}4) \times 10^{-8}$
$\mathcal{B}(\tau \to \mu\eta)$	$0.4\text{–}4 \times 10^{-9}$	not seen, $< 5.1 \times 10^{-8}$

Backup Slides

Integrated Luminosity (KEKB only)



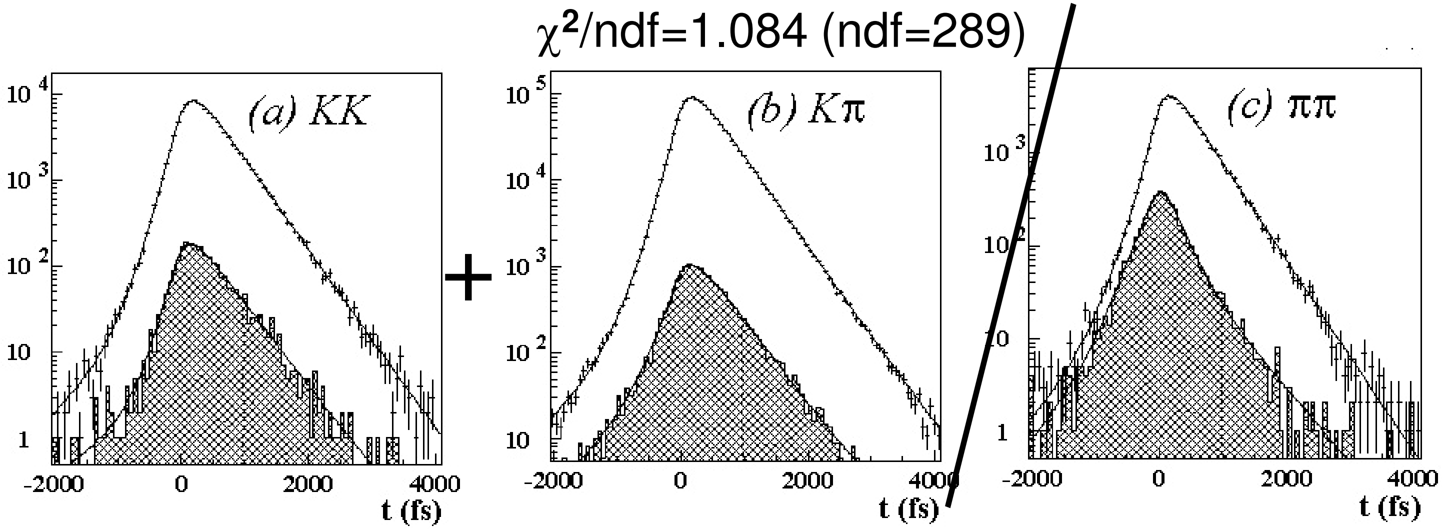
From Lunghi and Soni, arXiv:0903:5059v1



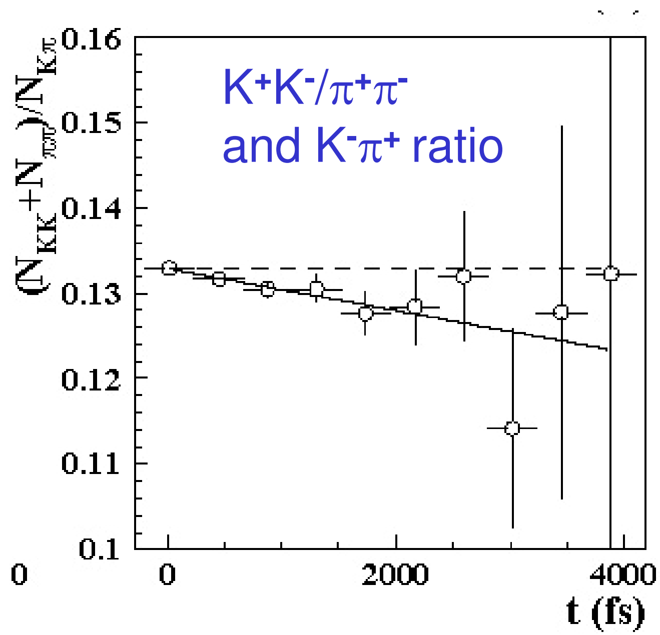
mode	w/out V_{ub}	with V_{ub}
$S_{\psi K_S}$	$2.4\,\sigma$	$2.0\,\sigma$
$S_{\phi K_S}$	$2.2\,\sigma$	$1.8\,\sigma$
$S_{\eta' K_S}$	$2.6\,\sigma$	$2.1\,\sigma$
$S_{(\phi+\eta')K_S}$	$2.9\,\sigma$	$2.5\,\sigma$

PRL 98, 211803 (2007), 540fb^{-1}

Belle $D^0 \to K^+K^- / \pi^+\pi^-$



Difference of lifetimes visually observable



$y_{CP} = (1.31 \pm 0.32 \pm 0.25)\%$

$y = \Delta\Gamma/(2\Gamma)$

3.2 σ from zero

(4.1 σ stat. only)

Also confirmed by BaBar

Evidence for D^0 mixing

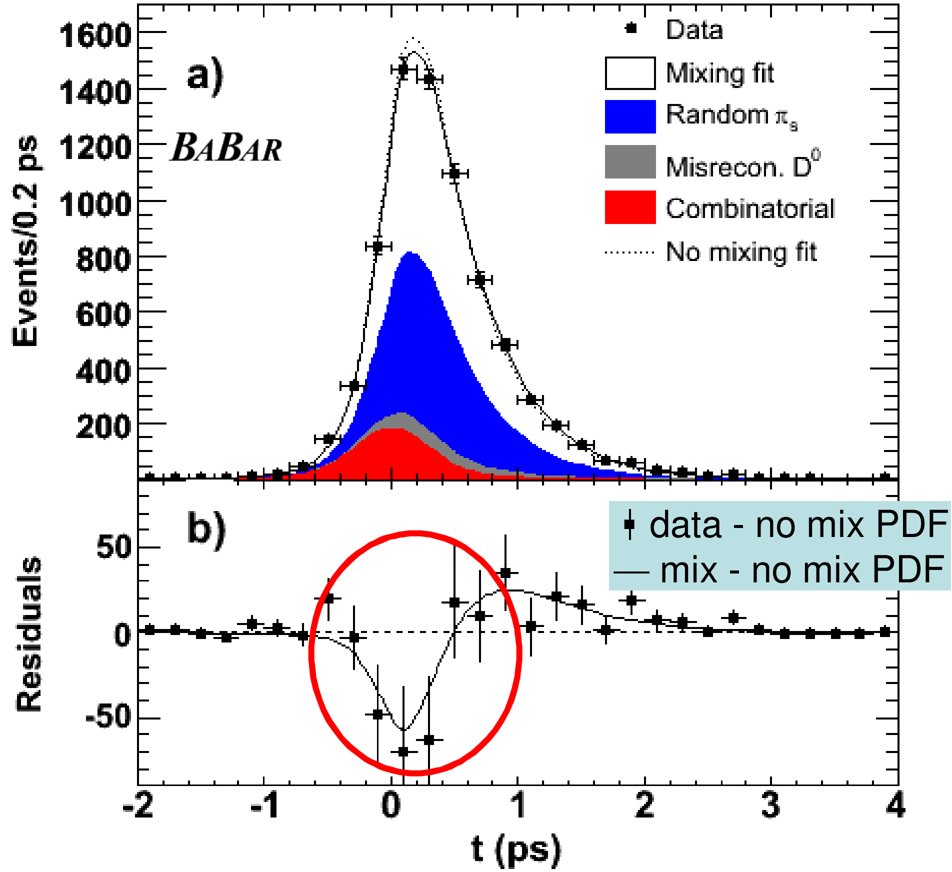
(regardless of possible CPV)

negligible CPV, $y_{CP}=y$

BaBar D-mixing Signal in $D^0 \rightarrow K^+\pi^-$

- Fit results:

R_D: $(3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$
x'^2: $(-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$
y': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$



WS *mixing* fit projection in signal region
1.843 GeV/c^2 < m < 1.883 GeV/c^2
0.1445 GeV/c^2 < Δm < 0.1465 GeV/c^2

$x = \Delta m / \Gamma$

$y = \Delta\Gamma / (2\Gamma)$

The quantities x', y' are rotated versions of x, y
The rotation angle is an unknown strong phase

(which can be measured at tau-charm factories)

CDF confirmation as well

Important Discovery(2007): D^0 mixing

D中間子の混合現象を発見

新理論の可能性に期待

高エネ研

反粒子に高確率で「変身」

D中間子 標準理論に変更も

高エネ研 確認

反粒子経て崩壊「D中間子」観測

国際研究チーム

高エネルギー加速器研究機構などの国際共同研究チームは十三日、韓国で開かれている国際会議で、「D中間子」という粒子の特殊な現象を世界で初めて観測したと発表した。素粒子物理学の新しい理論を構築する手掛かりになるという。

世界十四の国・地域から約四百人の研究者が参加している国際共同による加速器実験の成果。

D中間子は電子と、その反粒子（質量は同じだが、電気的性質などが反対の粒子）である陽電子が衝突したときに生じる微小な粒子。発生しても一兆分の一秒で壊れて別の粒子になるが、まれに反粒子にいったんなってから崩壊することがあり、この現象を観測することに成功した。

国際チームは一九九九年からD中間子の観測を重ね、約百回に一回の割合で、反粒子を経て崩壊することが分かった。

「現在の理論では、D中間子が反粒子を経て崩壊する割合に幅がある。実験で割合が確定したことで、新理論を作る道筋が与えられた」と山内正則高エネルギー加速器研究機構教授は話している。

D中間子の"混合現象"

高エネ機構加速器で観測

国際研究グループ

反粒子の「混合」D中間子で発見

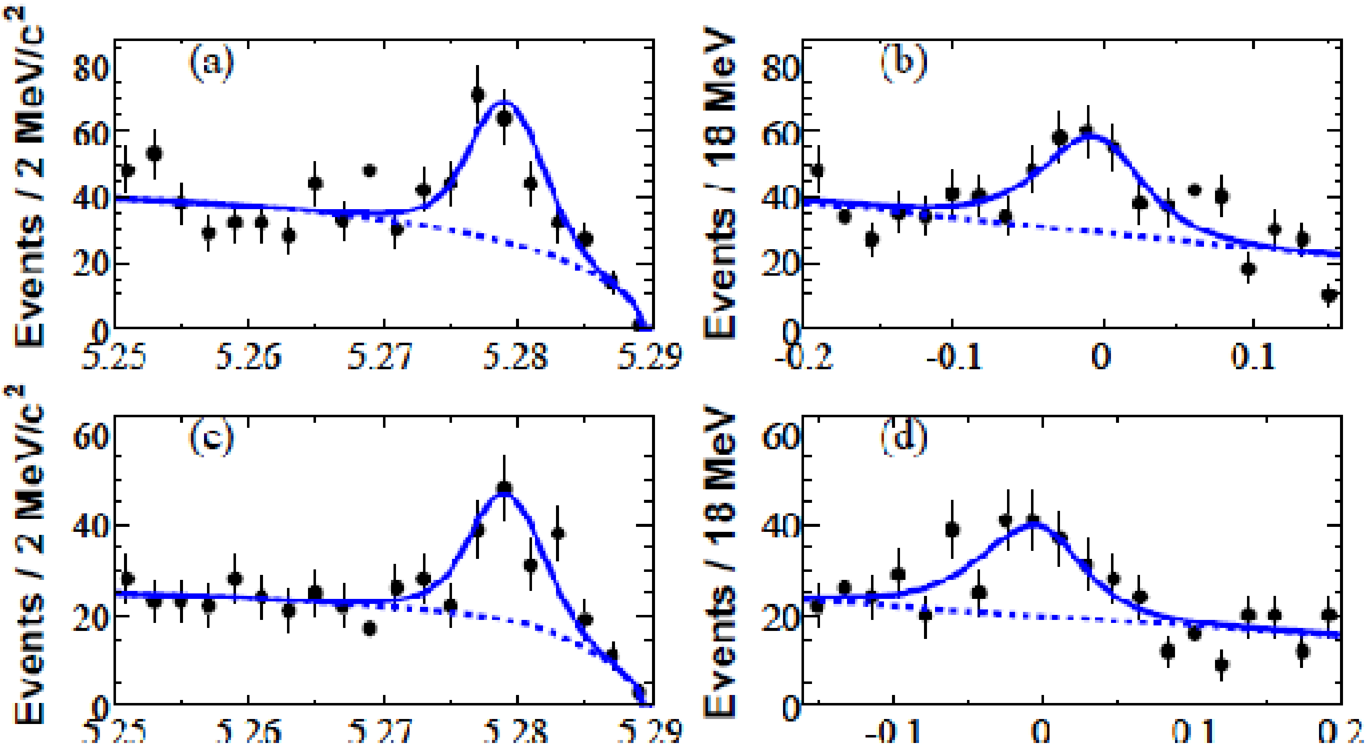
高エネ研チーム

宇宙に現在存在する粒子と、電気的な性質などが反対の反粒子が移り変わる「混合現象」が、D中間子で初めて見つかった。高エネルギー加速器研究機構（茨城県つくば市）の大型加速器「Bファクトリー」の国際実験チームが十三日、韓国で開かれた国際会議で発表した。米スタンフォード線形加速器センターの国際実験チームも別の測定方法で発見し、同会議で発表した。Bファクトリー実験の共同代表、山内正則高エネ研教授は「現在の素粒子物理学の標準理論を超える新理論や未知の新粒子を探る手掛かりになる」と話している。

混合現象は、電気的に中性で、素粒子のクォーク二個で構成される中間子に特有の現象。K中間子ではほぼ100%、B中間子では約70%の確率で起こることが知られるが、残るD中間子では未発見だった。

But not reported by the New York Times, Washington Post..

BaBar B→η K Direct CPV Hint

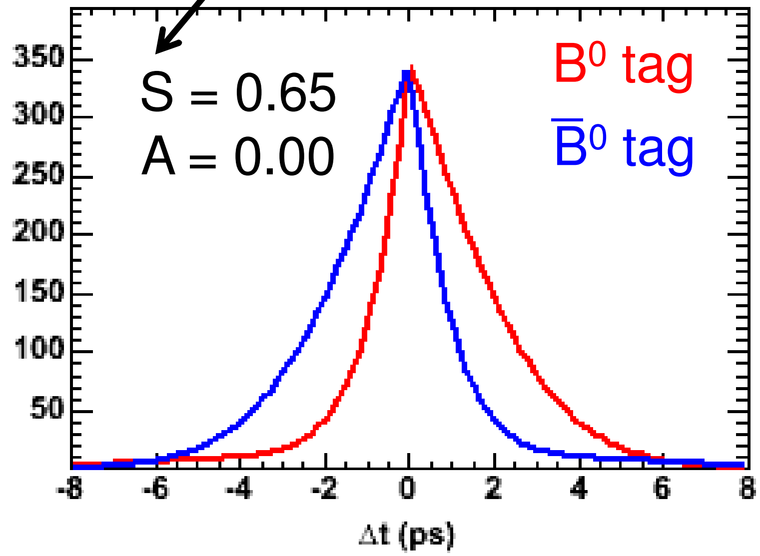


B→η π

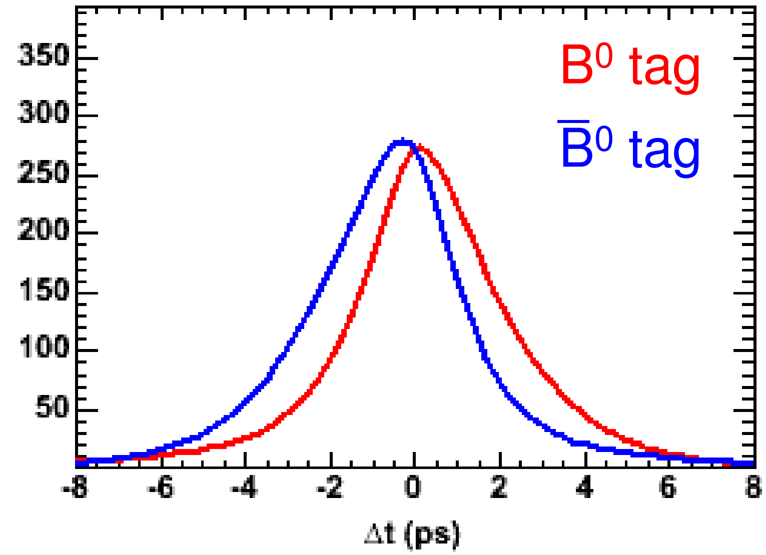
B→η K

Mode	Yield (ev)	Fit bias (ev)	ϵ (%)	$\prod \mathcal{B}_i$ (%)	$\mathcal{B}(10^{-6})$	$\mathcal{A}_{ch}$	$\mathcal{S}_{\mathcal{A}}(\sigma)$
$\eta_{\gamma\gamma}\pi^+$	286^{+31}_{-30}	+18	35.1	39.3	$4.16^{+0.48}_{-0.47}$	$-0.02^{+0.10}_{-0.11}$	0.4
$\eta_{3\pi}\pi^+$	95^{+19}_{-18}	+7	23.4	22.7	$3.53^{+0.77}_{-0.73}$	$+0.06 \pm 0.18$	0.4
$\boldsymbol{\eta\pi^+}$					$\mathbf{4.00 \pm 0.40 \pm 0.24}$	$\mathbf{-0.03 \pm 0.09 \pm 0.03}$	**0.3**
$\eta_{\gamma\gamma}K^+$	215^{+31}_{-30}	+21	34.0	39.3	$3.11^{+0.50}_{-0.48}$	-0.37 ± 0.12	3.1
$\eta_{3\pi}K^+$	69^{+16}_{-15}	+6	22.9	22.7	$2.60^{+0.68}_{-0.62}$	-0.32 ± 0.22	1.5
$\boldsymbol{\eta K^+}$					$\mathbf{2.94^{+0.39}_{-0.34} \pm 0.21}$	$\mathbf{-0.36 \pm 0.11 \pm 0.03}$	**3.3**
$\eta'_{\eta\pi\pi}\pi^+$	96^{+20}_{-19}	+1	29.4	17.5	4.0 ± 0.8	-0.25 ± 0.19	1.3
$\eta'_{\rho\gamma}\pi^+$	111^{+31}_{-29}	+7	25.9	29.4	$2.9^{+0.9}_{-0.8}$	$+0.56^{+0.29}_{-0.27}$	2.1
$\boldsymbol{\eta'\pi^+}$					$\mathbf{3.5 \pm 0.6 \pm 0.2}$	$\mathbf{+0.03 \pm 0.17 \pm 0.02}$	**0.2**
$\eta'_{\eta\pi\pi}K^+$	1601^{+44}_{-43}	−5	28.7	17.5	$68.5^{+1.9}_{-1.8}$	-0.004 ± 0.027	0.2
$\eta'_{\rho\gamma}K^+$	2991^{+72}_{-71}	−10	29.3	29.4	74.6 ± 1.8	$+0.016 \pm 0.023$	0.7
$\boldsymbol{\eta' K^+}$					$\mathbf{71.5 \pm 1.3 \pm 3.2}$	$\mathbf{+0.008^{+0.017}_{-0.018} \pm 0.009}$	**0.4**

$-\xi_{CP}\sin2\phi_1$

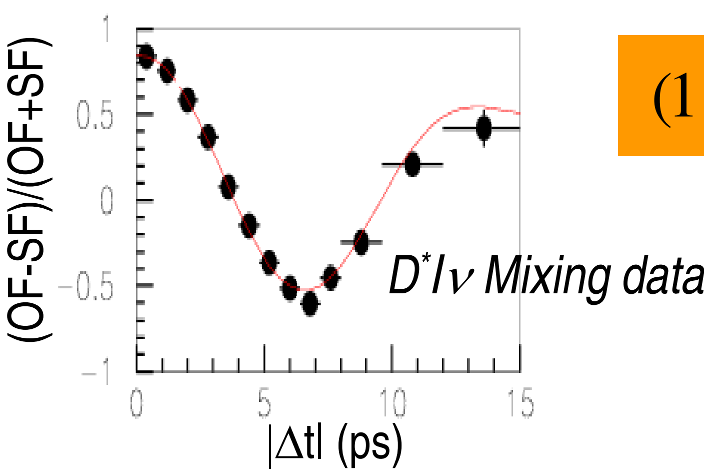


Experimental Complications (MC)



$$P(q=\pm1,\Delta t)=\frac{1}{4\tau}e^{-\frac{|\Delta t|}{\tau}}\left[1\pm(S\sin\Delta m\Delta t+A\cos\Delta m\Delta t)\right]\otimes R$$

$(1-2w)$



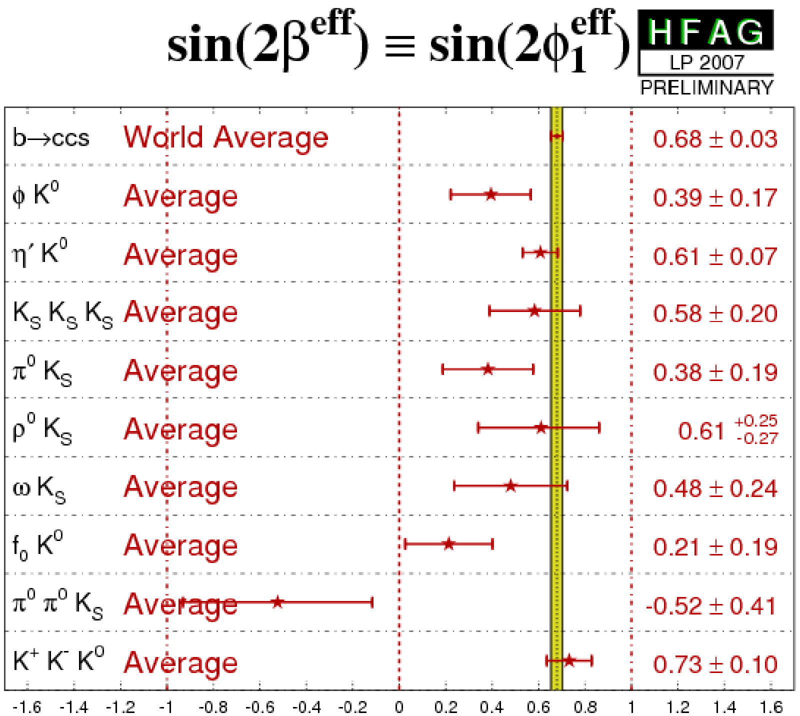
R : detector resolution

w : wrong tag fraction
(misidentification of flavor)

⇔ (1-2w) quality of flavor tagging

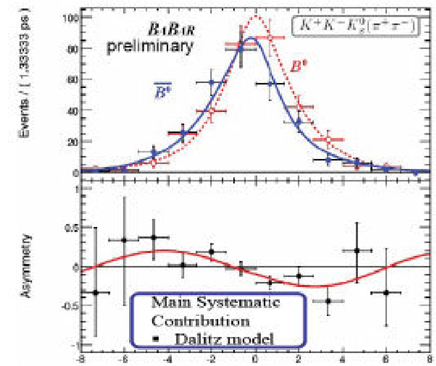
These are well determined by using data control samples: $D^*l\nu$, $D^{(*)}\pi$ etc…

ΔS results before summer 2008



For most modes, ΔS(SM) is positive.

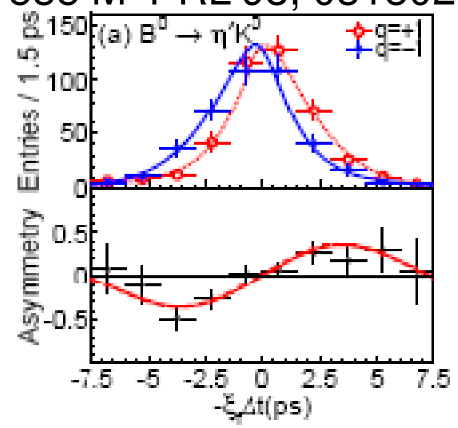
347M $B\bar{B}$ PRL 99, 161802 (2007)



Based on KKK Dalitz analysis

ϕK^0: $\sin 2\beta_{eff} = +0.12 + 0.31(stat) + 0.10\ (syst)$

535 M PRL 98, 031802 (2007)

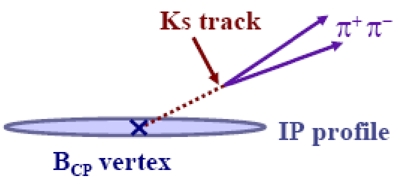


$\eta' K^0$: $\sin 2\phi_{1eff}$: +0.64± 0.10 ± 0.04

Updates of b→s penguin modes

- Class A: $\eta' K^0$, $\omega K_S \Rightarrow$ Same method as $J/\Psi\ K^0$
- Class B: $K^0\pi^0$

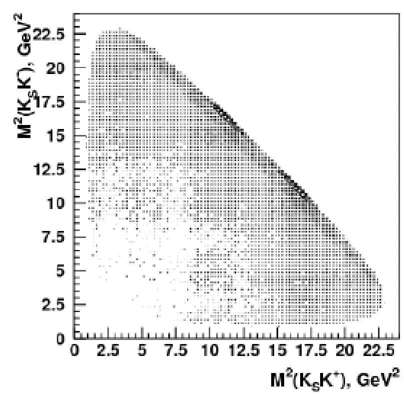
•No tracks on B decay vertex.
Require tracks with SVD hits.
• Perform fit by constraining C.



- Class C: $\pi^+\pi^-K_S$, $K^+K^-K_S$

Class is characterized by the analysis complexity

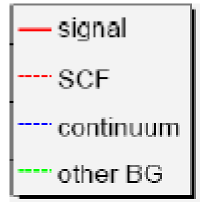
Model the Dalitz distributions.
Many parameters: phases,
S and C for each mode ….



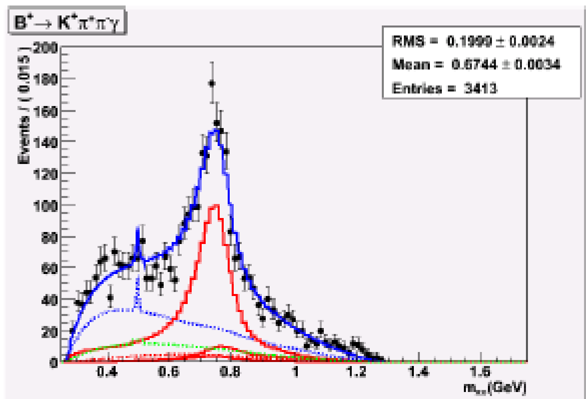
Multiple Solutions !

$M(\pi^+ \pi^-)$ distribution in $B \rightarrow K_S \pi^+ \pi^- \gamma$

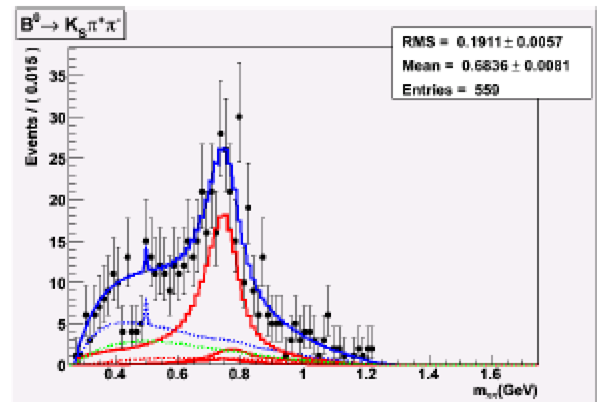
Find that the $B \rightarrow K_S \rho^0 \gamma$ component is dominant



$K^+\pi^+\pi^-\gamma$



$K_S\pi^+\pi^-\gamma$



Applying the dilution factor,

BELLE

$$S_{K_S \rho^0 \gamma} = S_{\text{eff}} / D = 0.11 \pm 0.33(stat.)^{+0.05}_{-0.09}(syst.)$$

No evidence for NP right-handed currents in this mode

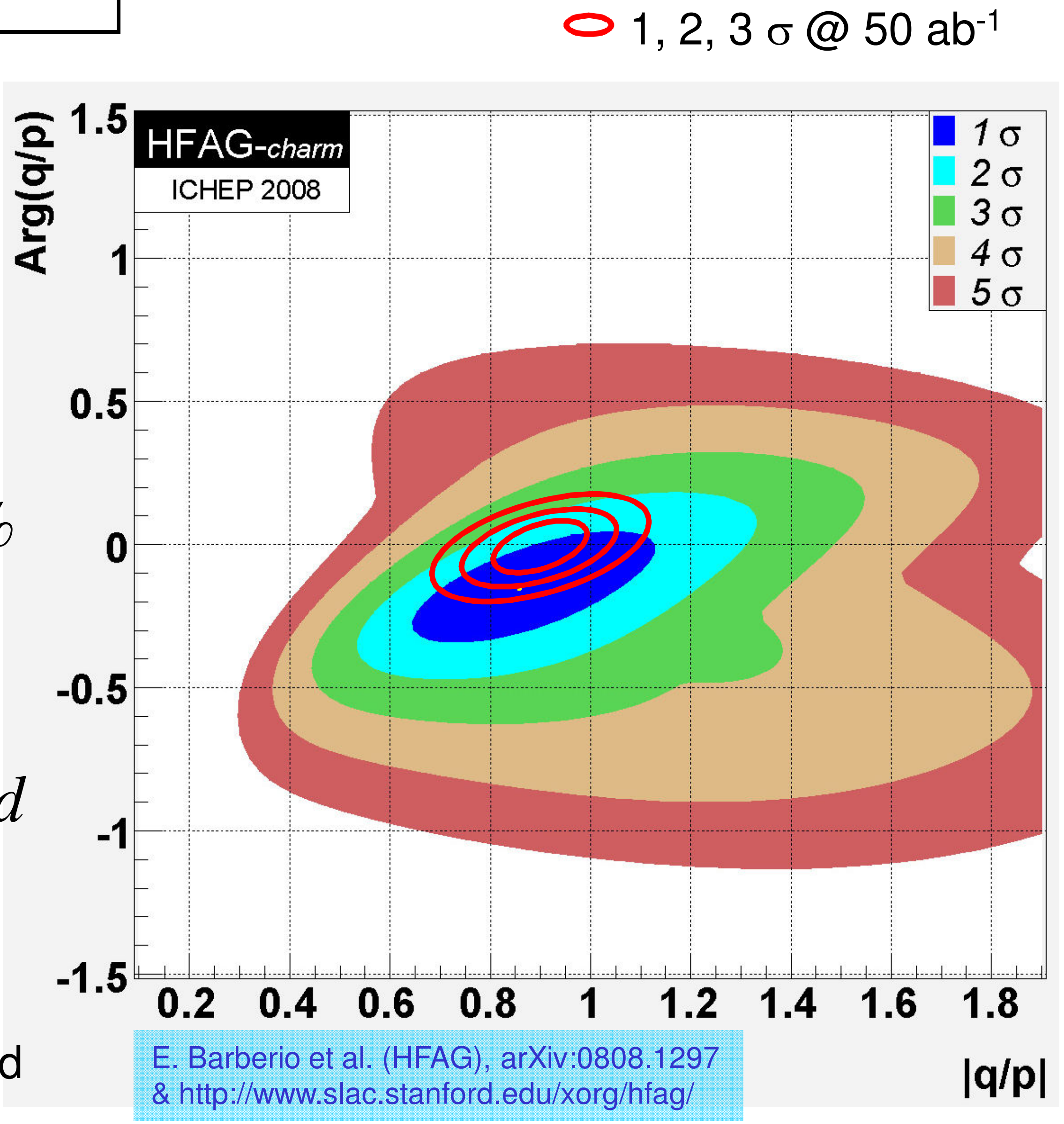
D^0 CPV @ 50 ab^{-1}

HFAG χ^2 fit

50 ab^{-1}

$$x = (0.832 \pm 0.095)\%$$
$$y = (0.813 \pm 0.064)\%$$
$$\delta_{K\pi} = 24.6° \pm 4.9°$$
$$R_D = (0.336 \pm 0.003)\%$$
$$\frac{|q|}{|p|} = 0.894 \pm 0.054$$
$$\varphi = -0.004 \pm 0.049\ rad$$
$$A_D = (-0.1 \pm 0.8)\%$$

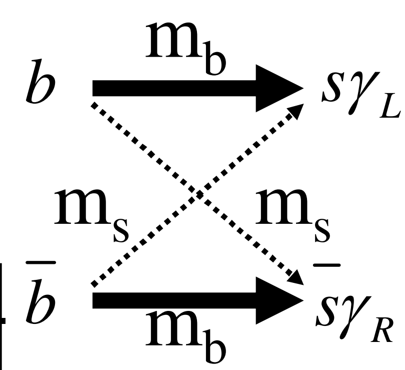
only KK/ππ, Kπ and $K_s\pi\pi$ projected sensitivities included



E. Barberio et al. (HFAG), arXiv:0808.1297
& http://www.slac.stanford.edu/xorg/hfag/

Right-handed currents in $b \to s\gamma$

D.Atwood, M.Gronau, A.Soni, PRL79, 185 (1997)
D.Atwood, T.Gershon, M.H, A.Soni, PRD71, 076003 (2005)



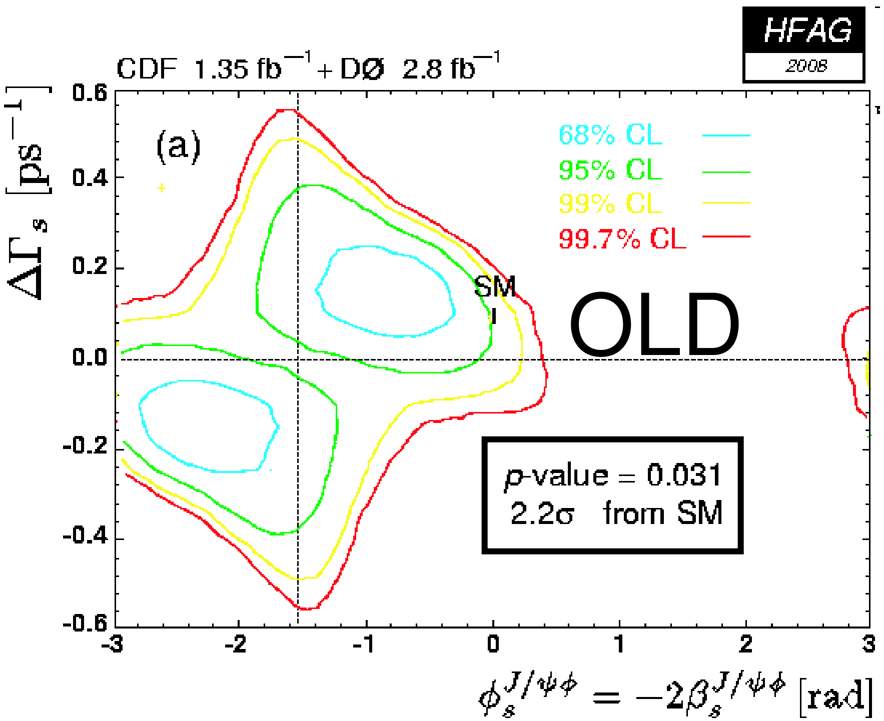
- tCPV in $B^0 \to (Ks\pi^0)_{K^*}\gamma$
  - SM: γ is polarized, the final state almost flavor-specific.
    $S(Ks\pi^0\gamma) \sim -2m_s/m_b \sin 2\phi_1$
  - m_{heavy}/m_b enhancement for right-handed currents in many new physics models

    e.g. LRSM, SUSY, Randall-Sundrum (warped extra dimension) model
  - LRSM: $SU(2)_L \times SU(2)_R \times U(1)$
    - Right-handed amplitude $\propto \zeta m_t/m_b$: ζ is W_L-W_R mixing parameter
    - for present exp. bounds ($\zeta < 0.003$, W_R mass > 1.4TeV)
      $|S(Ks\pi^0\gamma)| \sim 0.5$ is allowed.
  - **No need for a new CPV phas**

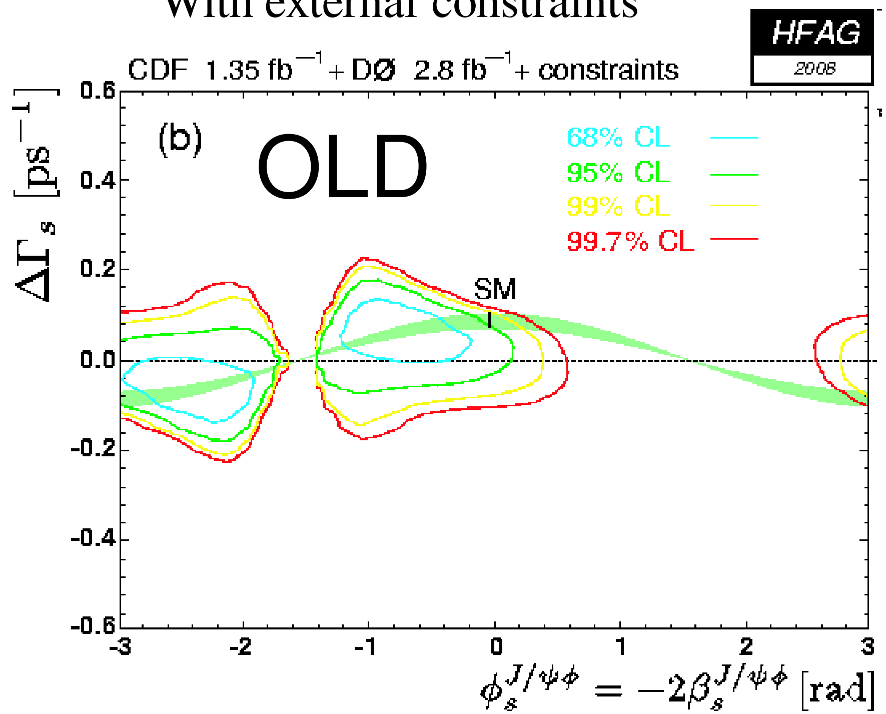
Photon polarization measurement via time dependent CPV

Hint: Phase of B_S (V_{ts}) mixing

(N.B. we are looking at a box diagram rather than a penguin)



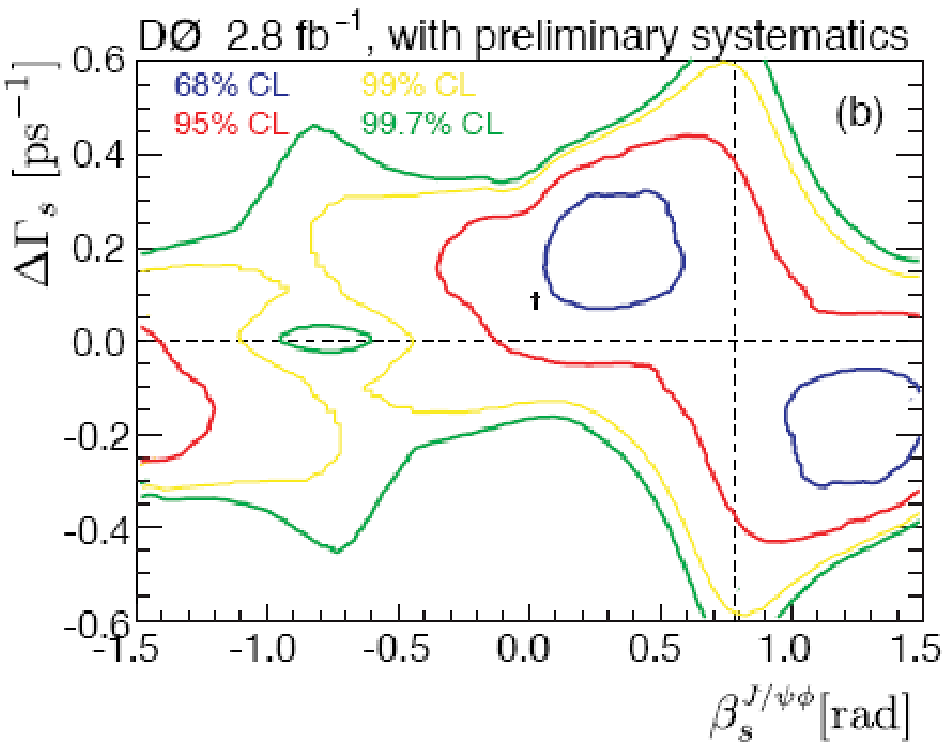
With external constraints

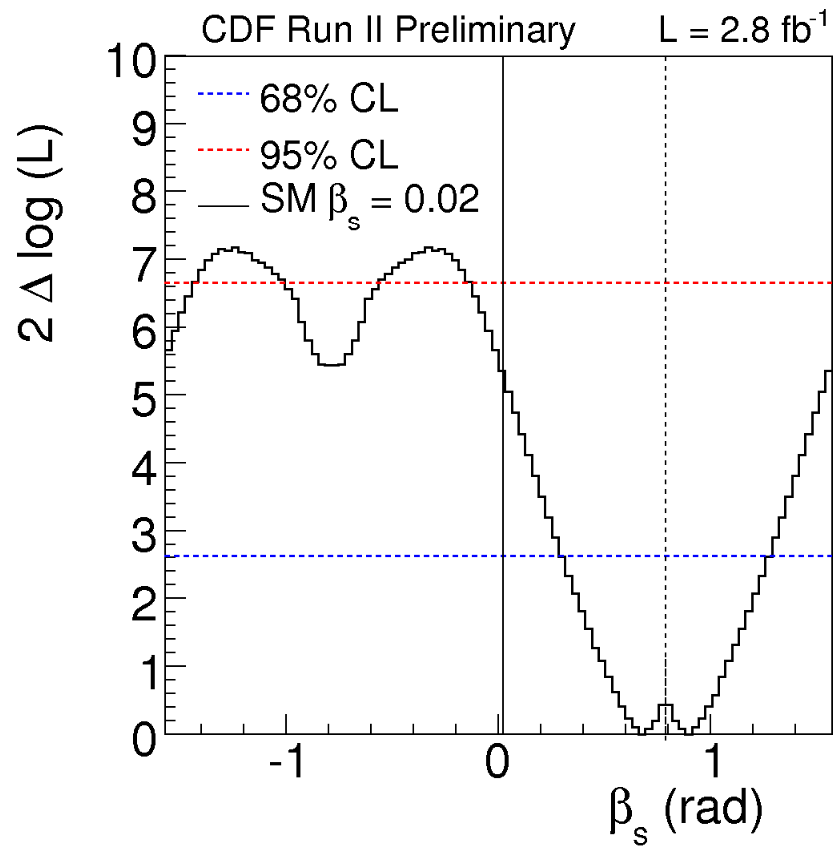


More data will be analyzed by CDF and D0. Belle will have some ΔΓ sensitivity from their 120 fb^{-1} Upsilon(5S) dataset . Later LHCb will come online.

Hint: Phase of B_s (V_{ts}) mixing

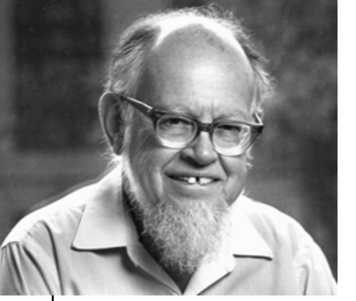
(N.B. we are looking at a box diagram rather than a penguin)





More data will be analyzed by CDF and D0. No up to date average. Last HFAG average of older CDF data and newer D0 data give a 2.2σ discrepancy from the SM

Old Motivation



> *"The final, completely definitive death of any superweak theory will come from the observation of direct CP violation in the B system…"*
>
> *Lincoln Wolfenstein, 1999*

[All CPV in the B system is due to a *new superweak* interaction. Expect no CPV in $\Delta B=1$ transitions.]

[e.g. J.M. Soares +L.Wolfenstein, PRD 27,421 1993.]

Direct CP Violation in B→ππ

Summary of $C_{\pi\pi}$

Year	BaBar	Belle	Difference
2001	$-0.25 \pm 0.45 \pm 0.14$ PRD 65, 051502 (33M)		
2002	$-0.30 \pm 0.25 \pm 0.04$ PRL 89, 281802 (88M)	$-0.94\,^{+0.25}_{-0.31} \pm 0.09$ PRL 89, 071801 (45M)	
2003	$-0.19 \pm 0.19 \pm 0.05$ preliminary LP2003 (123M)	$-0.77 \pm 0.27 \pm 0.08$ PRD 68, 012001 (85M)	2.0σ
2004	$-0.09 \pm 0.15 \pm 0.04$ PRL 95, 151803 (227M)	$-0.58 \pm 0.15 \pm 0.07$ PRL 93, 021601 (152M)	3.2σ
2005		$-0.56 \pm 0.12 \pm 0.06$ PRL 95, 101801 (275M)	2.3σ
2006	$-0.16 \pm 0.11 \pm 0.03$ ArXiv:0607106 (347M)	$-0.55 \pm 0.08 \pm 0.05$ PRL 98, 211801 (535M)	2.3σ
2007	$-0.21 \pm 0.09 \pm 0.02$ PRL 99, 021603 (383M)		2.1σ
2008	$-0.25 \pm 0.08 \pm 0.02$ ArXiv:0807.4226 (467M)		1.9σ