CP Violation for the Heaven and the Earth — Sighting the 4th Generation?

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February 2, 2009, Seminar @ Virginia

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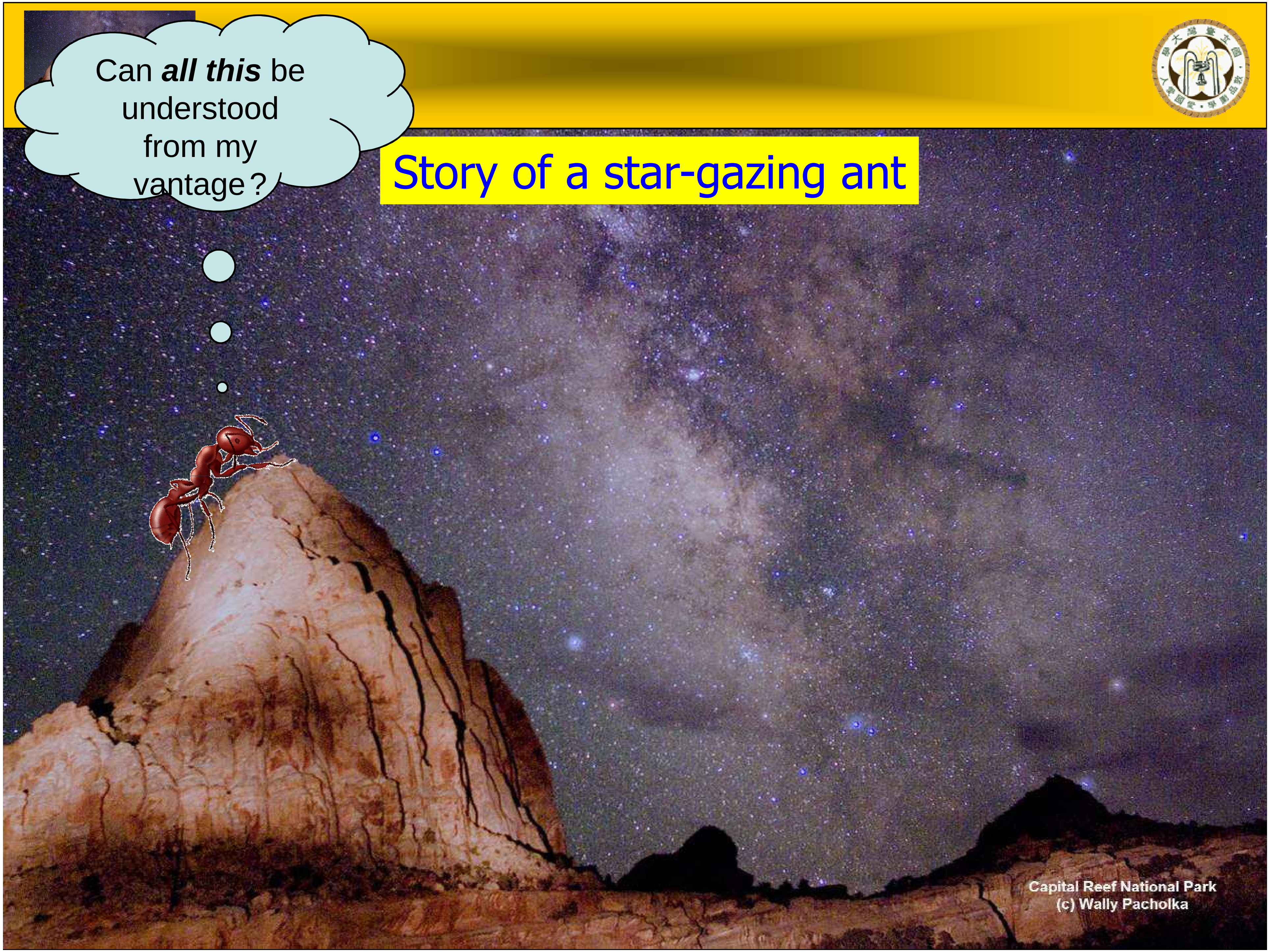
National Taiwan University

BELLE

Story of a star-gazing ant



Outline

I. Intro: the Heavenly Attraction

II. $\Delta A_{K\pi}$ Problem — Z Penguin and t′ Loop

b → s // b ↔ s CPV

III. Δm_{B_s} Measurement → Prediction for $\sin 2\Phi_{B_s}$

IV. Soaring to the Heavens : Enough CPV for BAU ?

V. Direct Sighting @ Tevatron vs LHC

VI. Conclusion: Know in 3-5 Years

WSH, Nagashima, Soddu,
PRL'05; PRD'05; PRD'07
Belle, Nature, 452, 20 (2008)
WSH, arXiv:0803.1234 [hep/ph]

I. Intro: the Heavenly Attraction

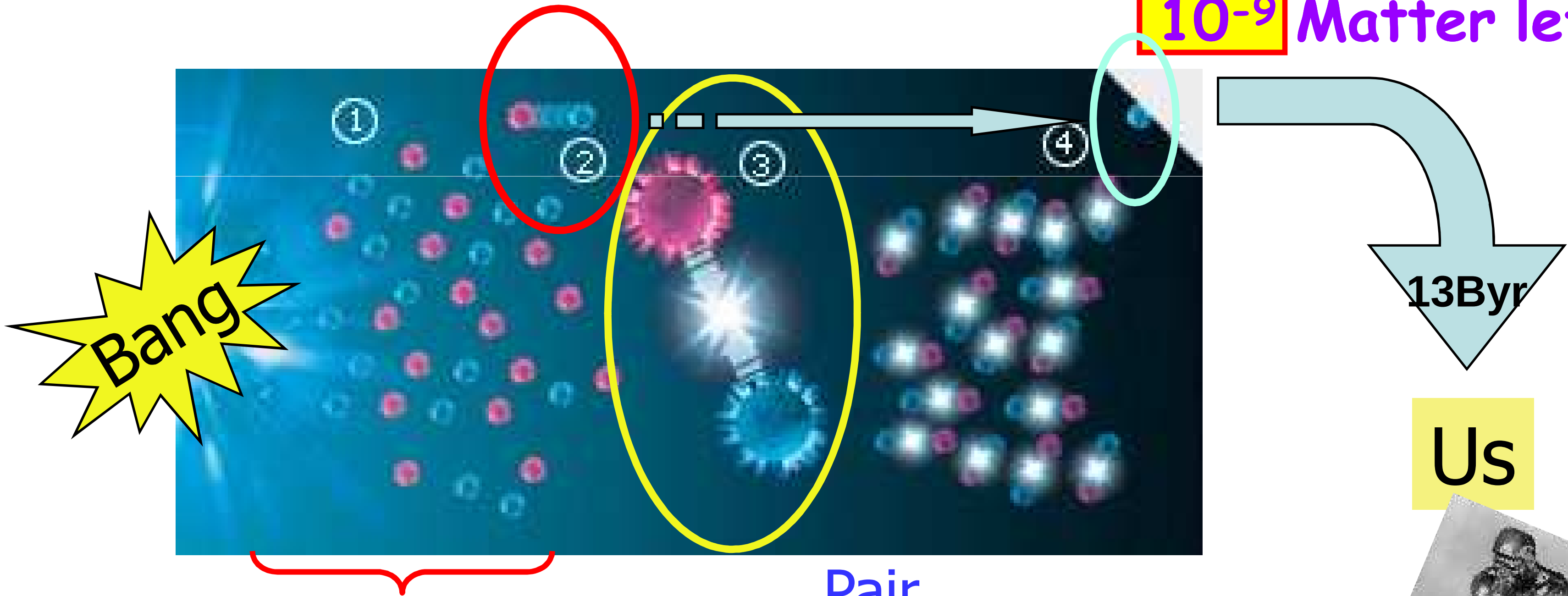

In the beginning God created the heaven and the earth.
Matter (?)
Matter!
— Genesis 1:1 (KJV)
Antimatter: 0%

(1967)

CPV & BAU (& U): The Sakharov View

- *Baryon Number Violation*
- *CP Violation*
- Deviation from Equilibrium

10^{-9} **Matter left !**



Equal Matter
-Antimatter

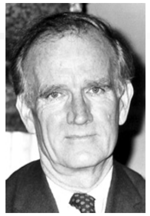
Pair
Annihilation

Us

Sakharov Stimulated by …

Discovery of CP Violation

- Phys. Rev. Lett. 13, 138 (1964)




VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

1980 Nobel

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey

(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, K_2^0 mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in.$\times 1\frac{1}{2}$-in.$\times$ 48-in. collimator at an average distance of 14.5 ft. from

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion. In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu 3}$, from 280 to ~516; and the $K_{\pi 3}$, from 280 to 363 MeV. We emphasize that m^* equal to the K^0 mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, θ, between it and the direction of the K_2^0 beam were determined. This

$2\times 1\ ^{-3}$: *T S . f S !*

Kobayashi-Maskawa Model (1973)

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

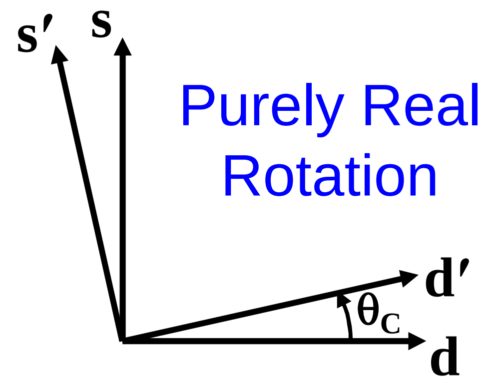
CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

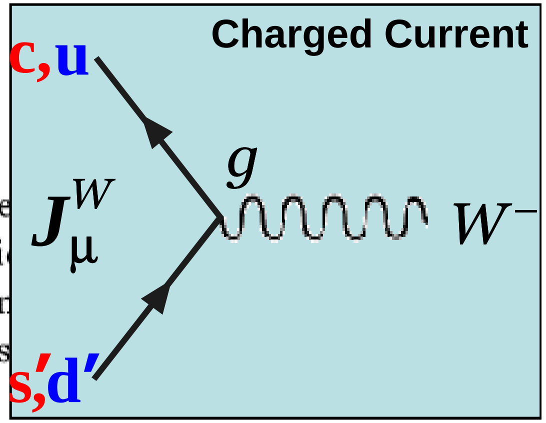
In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.



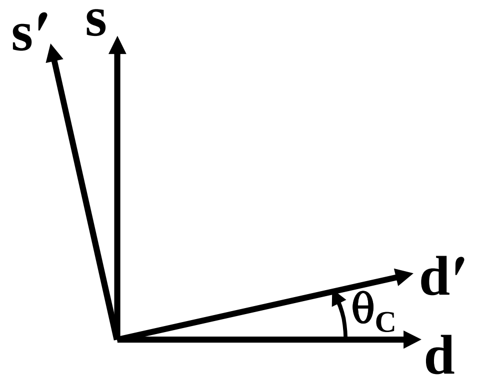
field corresponding to $U(1)$ which is irrelevant to our discussion. With an appropriate phase convention of the quartet field we can take U as

$$U=\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}. \qquad (6)$$

Therefore, if $\mathscr{L}'=0$, no *CP*-violations occur in this case. It should be note however, that this argument does not hold when we introduce one more fermi doublet with the same charge assignment. This is because all phases of elemen of a 3×3 unitary matrix cannot be absorbed into the phase convention of s fields. This possibility of *CP*-violation will be discussed later on.



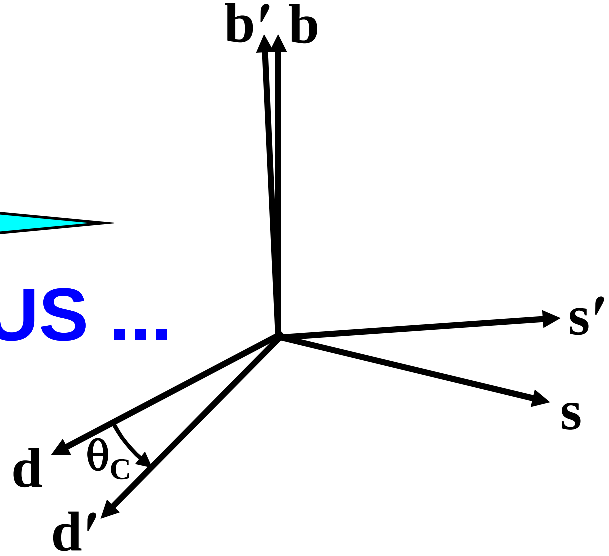
KM Model : 2 x 2 → 3 x 3



$$\begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix}, \begin{pmatrix} t \\ b' \end{pmatrix}$$

3x3 Rotation !

PLUS ...

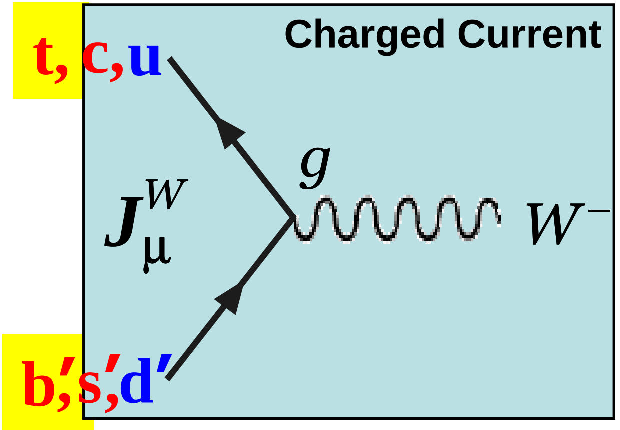


ponents, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\cos\theta_3 e^{i\delta} \end{pmatrix}. \quad (13)$$

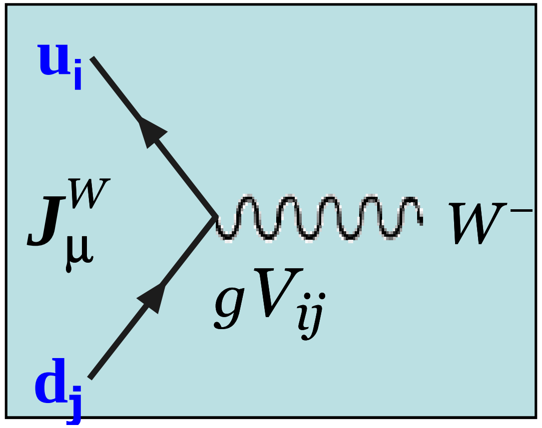
Then, we have CP-violating effects through the interference among these different current components. An interesting feature of this model is that the CP-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

3 "Generations"



Complex Dynamics: KM Sector of SM

only charged current interactions change flavor



Wolfenstein parametrization

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

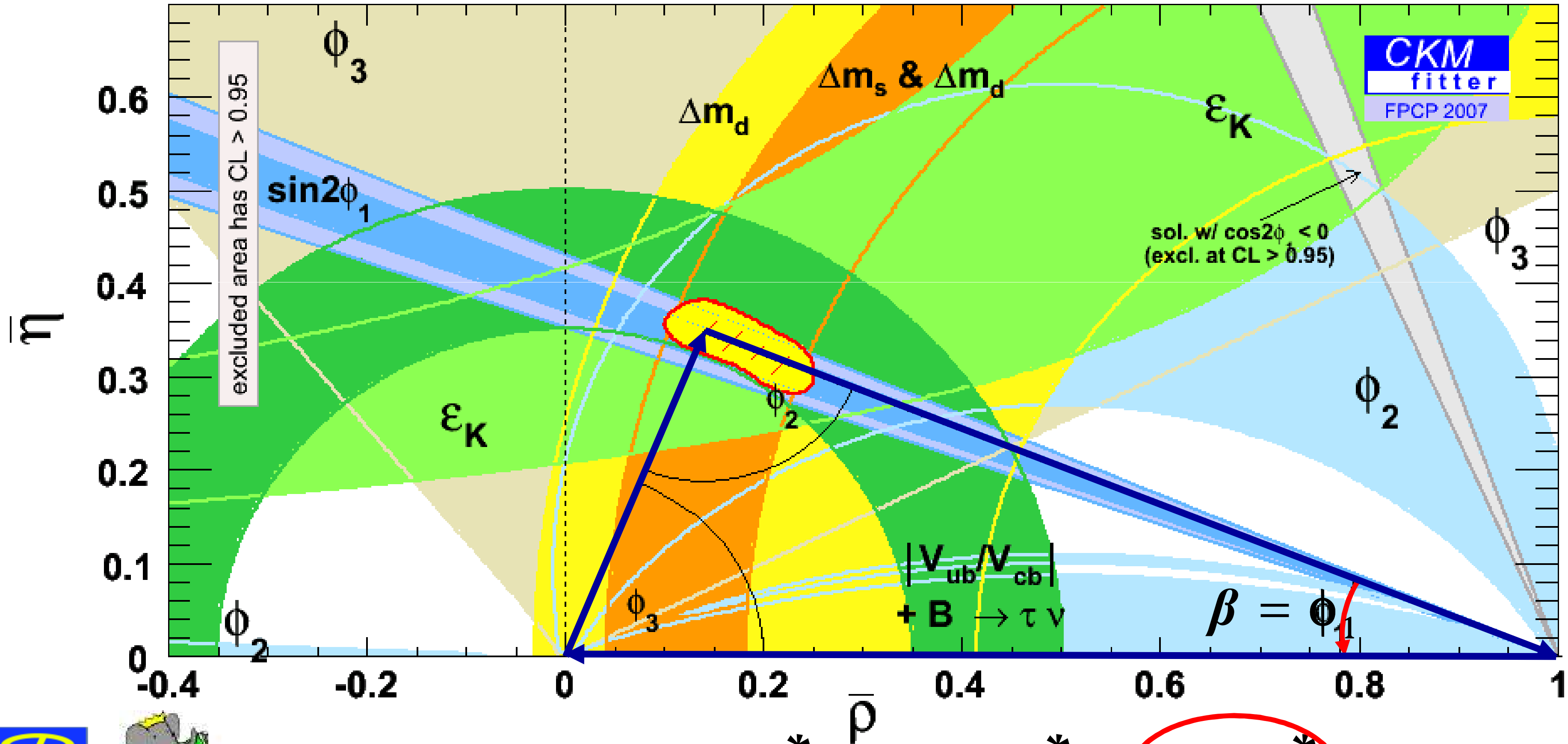
3x3 “Rotation”

Unitary

Need presence of all 3 generations to exhibit CPV in Standard Model

KM CPV Confirmed ~ 2001

the MOMA plot



"Nontrivial"

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

 The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

CP Violation in SM

Photo: Universtity of Chicago

Yoichiro Nambu

1/2 of the prize

USA

Enrico Fermi Institute, University of Chicago
Chicago, IL, USA

b. 1921
(in Tokyo, Japan)

Photo: KEK

Makoto Kobayashi

1/4 of the prize

Japan

High Energy Accelerator Research Organization (KEK)
Tsukuba, Japan

b. 1944

Photo: Kyoto University

Toshihide Maskawa

1/4 of the prize

Japan

Kyoto Sangyo University;
Yukawa Institute for Theoretical Physics (YITP), Kyoto University
Kyoto, Japan

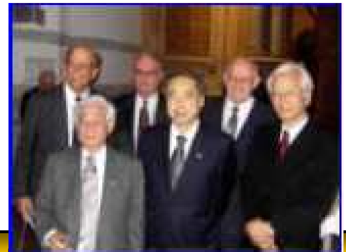
b. 1940

naturenews
7 October 2008

The Belle detector in Japan helped to confirm the symmetry breaking effects predicted by theoretical physicists.

KEK

B Factories
(BaBar & Belle)

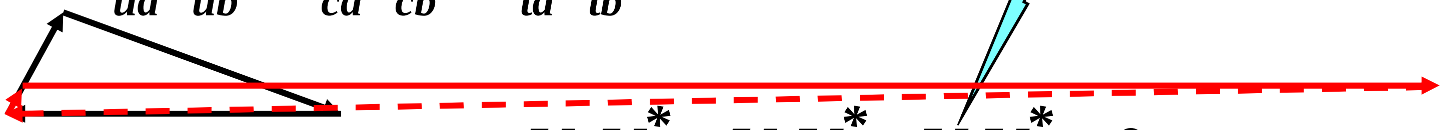


Wolfenstein Parametrization to O(λ^5)

$$V \cong \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+A^2\lambda^5(\frac{1}{2}-\rho-i\eta) & 1-\frac{1}{2}\lambda^2-(\frac{1}{8}+\frac{1}{2}A^2)\lambda^4 & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2+A\lambda^4(\frac{1}{2}-\rho-i\eta) & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

Unique CPV Phase: Common Area of Triangle

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



$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

N.B. geometric picture

CPV so far only observed in KM ...

- Nontrivial CPV Phase: A

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

- All like-charge quark pairs nondegenerate,

Otherwise → Back to 2-gen. and CPV vanish

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

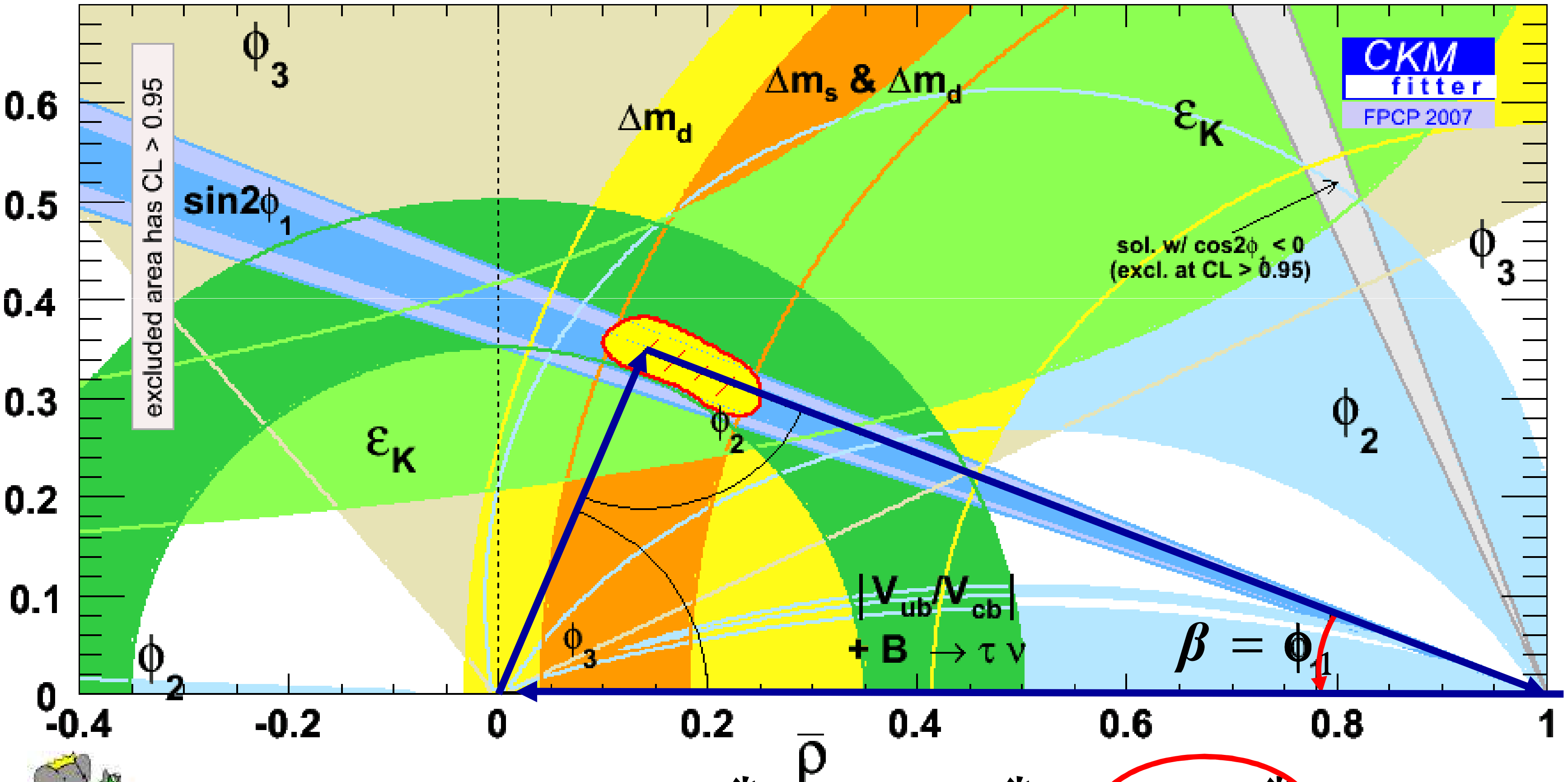
Jarlskog Invariant (1985) for CPV

$$\mathrm{Im}\,\det\left[m_u m_u^{\dagger},\ \ m_d m_d^{\dagger}\right]$$

b → d transitions consistent with SM

b → s: the Current Frontier

the MOMA plot



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

A Real Hint , ... or Not !?

Belle 2008 Nature: Simple Bean Count

$\Delta A_{K\pi} = A_{K^+\pi^0} - A_{K^+\pi^-} = +0.164\pm0.037 \quad 4.4\sigma$

LETTERS

$+0.07\pm0.03$ vs -0.094 ± 0.020

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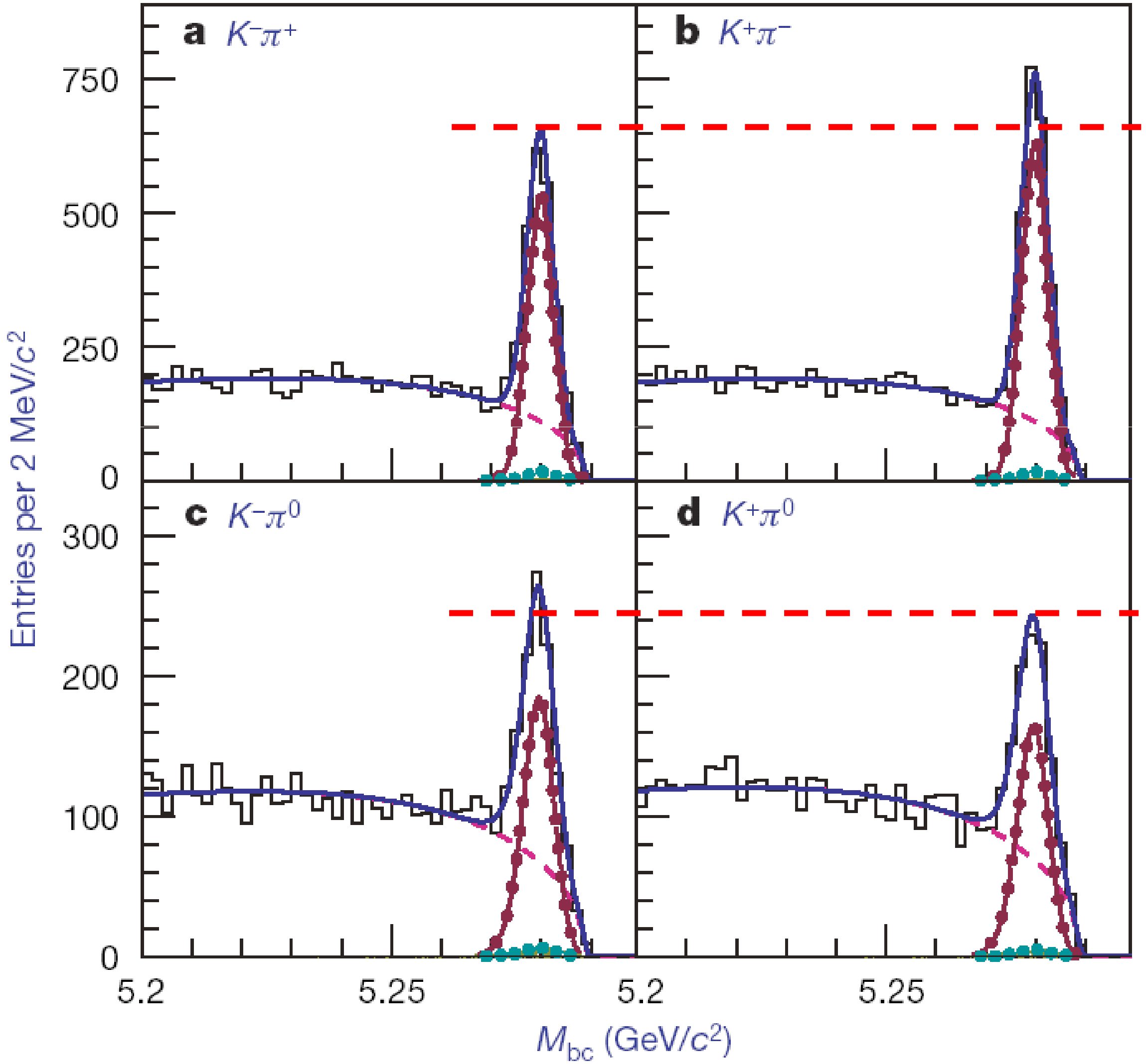


b → s CPV

Difference Is Large !

And Established

Belle + BaBar (+ CDF)

Vol 452 | 20 March 2008 | doi:10.1038/nature06827

LETTERS

Obligé

Dispair

Difference in direct charge-parity violation between charged and neutral B meson decays

The Belle Collaboration: S.-…
Aihara[4], K. Akai[3], K. Arinstein…
Balagura[7], E. Barberio[10], A. B…

Equal amounts of matter and antimatter are predicted to have been produced in the Big Bang, but our observable Universe is clearly matter-dominated. One of the prerequisites[1] for understanding this elimination of antimatter is the nonconservation of charge-parity (CP) symmetry. So far, two types of CP violation have been observed in the neutral K meson (K^0) and B meson (B^0) systems: CP violation involving the mixing[2] between K^0 and its antiparticle $\bar{K}^0$ (and likewise[3,4] for B^0 and $\bar{B}^0$), and direct CP violation in the decay of each meson[5–8]. The observed effects for both types of CP violation are substantially larger for the B^0 meson system. However, they are still consistent with the standard model of particle physics, which has a unique source[9] of CP violation that is known to be too small[10] to account for the matter-dominated Universe. Here we report that the direct CP violation in charged $B^{\pm} \to K^{\pm}\pi^0$ decay is different from that in the neutral B^0 counterpart. The direct CP-violating decay rate asymmetry, $\mathcal{A}_{K^{\pm}\pi^0}$ (that is, the difference between the number of observed $B^- \to K^- \pi^0$ event versus $B^+ \to K^+ \pi^0$ events, normalized to the sum of these events) is measured to be about +7%, with an uncertainty that is reduced by a factor of 1.7 from a previous measurement[7]. However, the asymmetry $\mathcal{A}_{K^{\pm}\pi^{\mp}}$ for $B^0 \to K^- \pi^+$ versus $\bar{B}^0 \to K^+\pi^-$ is at the −10% level[7,8]. Although it is susceptible to strong interaction effects that need further clarification, this large deviation in direct CP violation between charged and neutral B meson decays could be an indication of new sources of CP violation—which would help to explain the dominance of matter in the Universe.

It would seem that we are well on the way to understanding the basis of particle–antiparticle asymmetry in the early Universe.

In fact, we are not. The KM predictions depend crucially on the masses of the intermediate-mass s and c quarks. But the high temperature of the Universe just after the Big Bang makes these masses irrelevant in calculations of the cosmic-matter excess. The degree of asymmetry predicted by the KM model is ten orders of magnitude too small.

elementary particles of matter — has an antimatter counterpart with exactly the same mass and exactly the opposite electric charge. Over the past 20 years, the theories of the weak and strong nuclear forces that have been built up on this basis have passed numerous rigorous experimental tests. The mathematical form of these theories allows little space for interactions that treat particles and antiparticles differently.

And yet the Universe, as far out as we can see, is made of matter, not of antimatter. We see no signals of the matter–antimatter annihilation that would happen on the edge of our local region if only this region were dominated by matter. So did the initial conditions of the Big Bang perhaps contain more matter than antimatter? It is possible. But in inflationary cosmology, the model that has successfully

process (shown here from left to right). a, In a 'standard box' diagram of weak quark-mixing interactions, quarks change type by exchanging a pair of particles, for example a heavy top (t) quark and a W boson, the intermediary of the weak force. Here, a $\bar{B}^0$ meson (quark content $d\bar{b}$) converts into a B^0 ($\bar{b}d$). b, In a penguin process, the change of quark type occurs via a particle loop, which connects via a boson (wavy line; a gluon, g, gives a 'strong penguin'; a Z^0 an 'electroweak penguin'; γ is a photon) to a further particle. Here, for example, a $\bar{B}^0$ or B^0 could be decaying into a K^- ($s\bar{u}$) or $\bar{K}^0$ ($d\bar{s}$), plus an additional u or d quark that combines with the u or d antiquark in the B meson. The other end product is a π^0 particle, which can have quark content $u\bar{u}$ or $d\bar{d}$. In both penguin and box processes, the particles represented by the heavy lines (square in a, circle in b) could be as-yet-undiscovered exotic particles. Recent results

Since then, evidence accumulated by BaBar and Belle, in a data set of more than 1.2 billion B-meson decays, has been used to fix the two crucial parameters of the KM theory to an accuracy of about 5%. Complementary measurements from other processes involving B mesons[10-12] have confirmed these parameters to accuracies of between 10% and 20%.

It would seem that we are well on the way to understanding the basis of particle–antiparticle asymmetry in the early Universe.
In fact, we are not. The KM predictions depend crucially on the masses of the intermediate-mass s and c quarks. But the high temperature of the Universe just after the Big Bang makes these masses irrelevant in calculations of the cosmic-matter excess. The degree of asymmetry predicted by the KM model is ten orders of magnitude too small.

the experimentalist

The Lore/Lure that Despairs the Experimenter

The Abyss: CPV in KM and B.A.U.

The Lore

$$\frac{n_{\bar{\mathcal{B}}}}{n_\gamma} \cong 0 \qquad \frac{n_{\mathcal{B}}}{n_\gamma} = (6.2 \pm 0.2) \times 10^{-10}$$

WMAP

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

Too Small in SM

Jarlskog Invariant in SM3 (need 3 generation 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 ⟹ $J/T^{12} \sim 10^{-20}$

EW Phase Transition Temperature

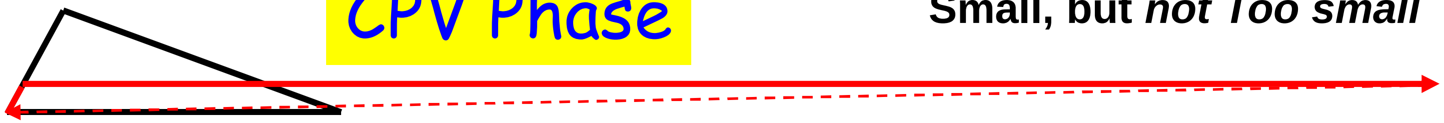
~ v.e.v.

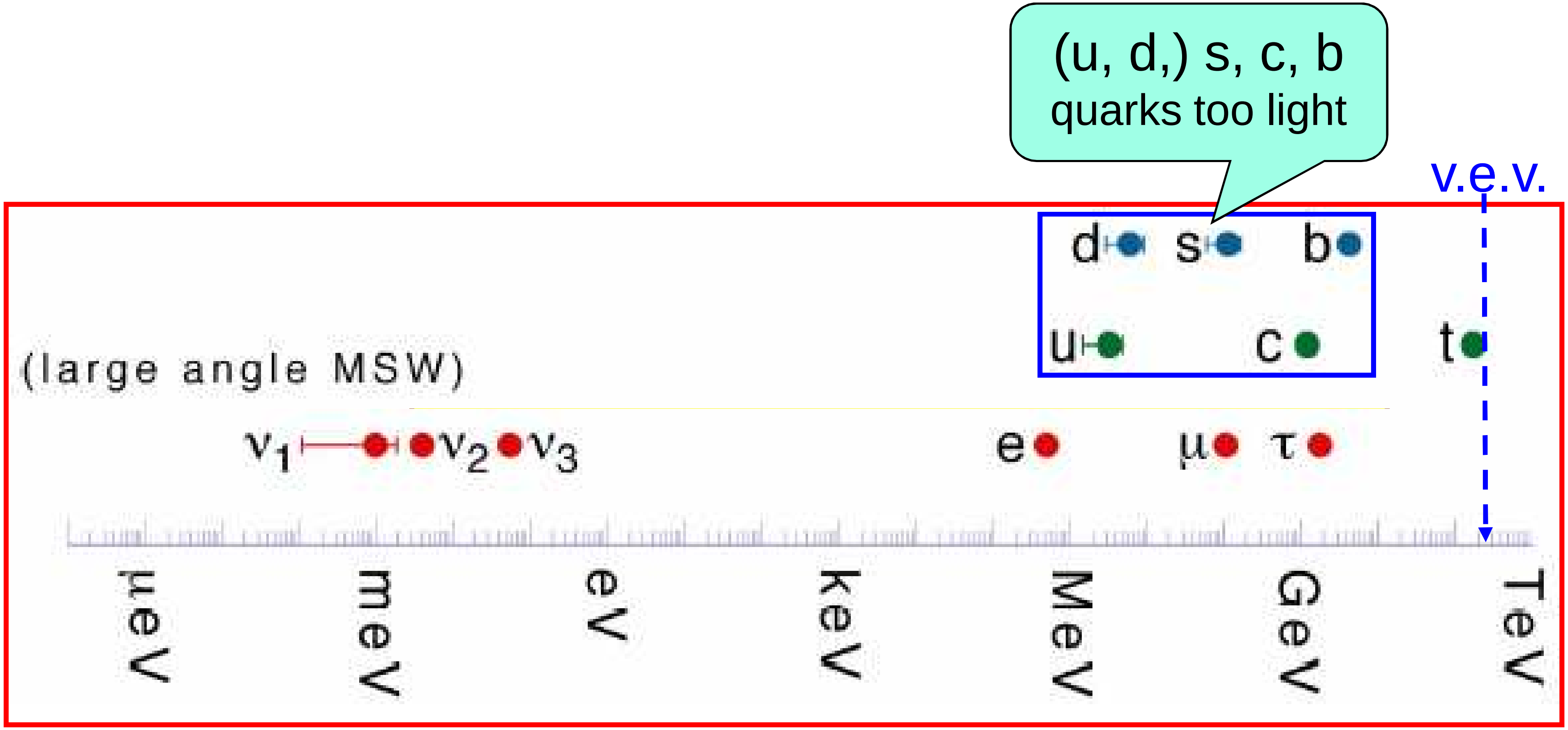
Masses too Small!

$A \sim 3 \times 10^{-5}$ is common (unique) area of triangle in SM

CPV Phase

Small, but *not Too small*





(u, d,) s, c, b
quarks too light
v.e.v.
d
s
b
u
c
t
(large angle MSW)
ν_1
ν_2
ν_3
e
μ
τ
μeV
meV
eV
keV
MeV
GeV
TeV

Wisdom from Peskin on $\Delta A_{K\pi}$

"hadronic"

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b quark or its antiparticle. The lighter d or $\bar{d}$ does not participate. Given this fact, one would expect that replacing the d or $\bar{d}$ in the B meson by the similarly light u or $\bar{u}$ would produce the same asymmetry. But Belle observes that the equivalent decays of the mesons corresponding to those quark compositions, $B^+ \to K^+\pi^0$ and $\bar{B}^- \to K^-\pi^0$, have an asymmetry of the opposite sign. Together with the same asymmetries recently announced by BaBar[2,3], the effect has a statistical significance greater than five standard deviations — the 'gold standard' of particle physicists for proof that an effect is real.

Unlike the decays of the neutral B mesons B^0 and $\bar{B}^0$, the decays of the charged B mesons B^+ and $\bar{B}^-$ produce two u quarks or antiquarks. This means that other processes that preferentially produce u quarks rather than d quarks might affect the asymmetry. The electroweak penguin is just such an effect — but to alter the asymmetry, this process must differ from the standard electroweak penguin, which affects the decay rates symmetrically. A contribution from an exotic loop is required. There are admittedly other possibilities that might explain the anomaly in the asymmetry: a direct weak-interaction decay process, the so-called 'colour-suppressed' contribution, also has the required properties. The size of this contribution depends on the quarks involved. In decays of mesons containing the c quark, it is substantial. For the heavier B mesons, however, it is indeed expected to be suppressed.

C

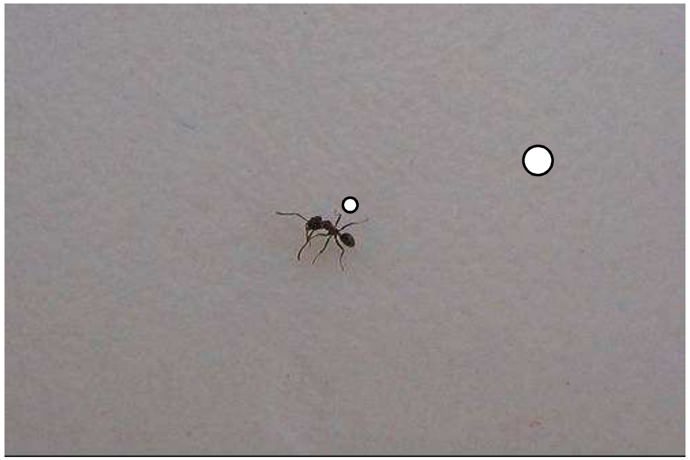
The new results[1–3] are not conclusive, but they are tantalizing. They might be due to properties of standard b-quark weak interactions that we cannot quite yet estimate precisely, but it is equally possible that this is the first hint of an entirely new mechanism for particle–antiparticle asymmetry. In the next few years, these ideas will be tested, both through the analysis of the huge Belle and BaBar data set, and from the hunt for exotic particles at the LHC. We do not yet know whether it is penguins or even more unusual creatures that produce our Universe made of matter and not antimatter. ■

Michael E. Peskin is in the Theoretical Physics Group, Particle Physics and Astrophysics, SLAC

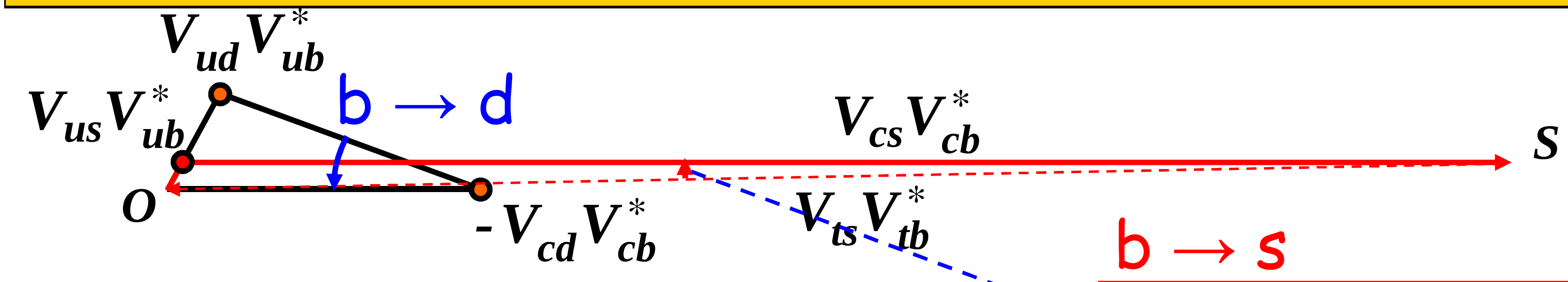
P_{EW}

Peskin (private communication)

"I must say that I am very skeptical that the new Belle result is new physics -- a larger than expected color suppressed amplitude is an explanation that is ready at hand. On the other hand, I felt that it was necessary to push the new physics interpretation when writing for the Nature audience, people outside of high energy physics, because this is why the result is potentially newsworthy."



Mixing-dep. CPV in B_d and B_s in SM



$\sin 2\,\phi_1 = \sin 2\,\beta$

Measured by Belle/BaBar
in $B_d \to J/\psi K_S$

$\sin 2\Phi_{B_s} \simeq -0.04$ in SM3

Measure in $B_s \to J/\psi\phi$
"possible only at LHCb"

- Recent Hint @ Tevatron
  $\sin 2\Phi_{B_s} < 0$!! ($\lesssim 3\sigma$)
- Consistent with 4th generation Prediction from $\Delta A_{K\pi}$
- BSM w/o hadronic uncertainty *iff* true.
- So what!? The 10^{-10} Abyss ...

II. $\Delta A_{K\pi}$ Problem — Z Penguin and t′ Loop

the Experimentalist

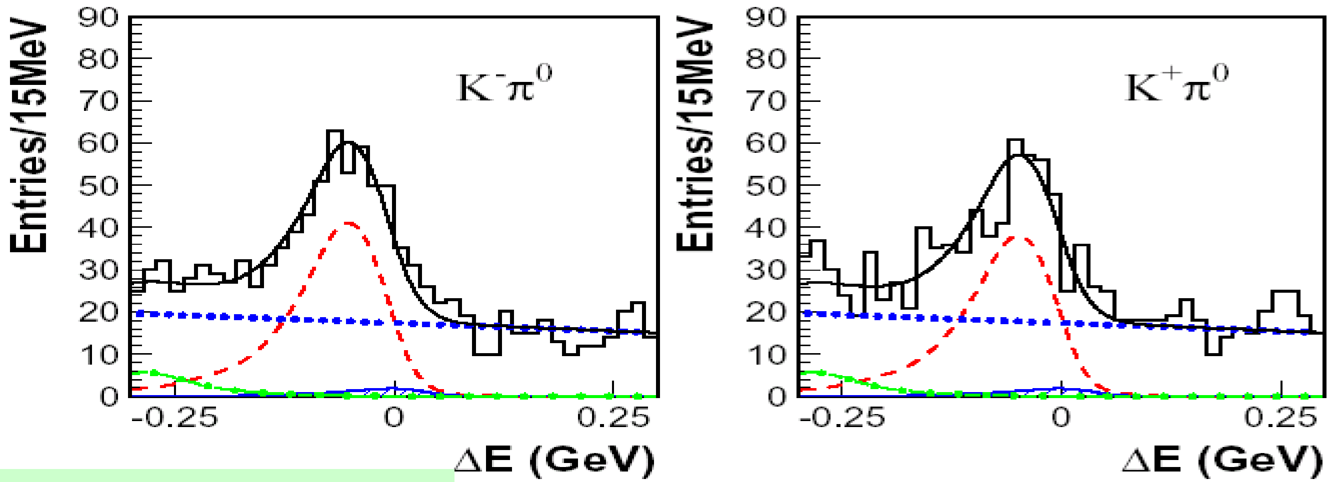
Just when $\Delta S_{\phi K}$ "disappeared"...

$A_{CP}(B \to K^+\pi^0)$

Sakai

275M $B\bar{B}$
New

$K^{\pm}\pi^0$: 728 ±53

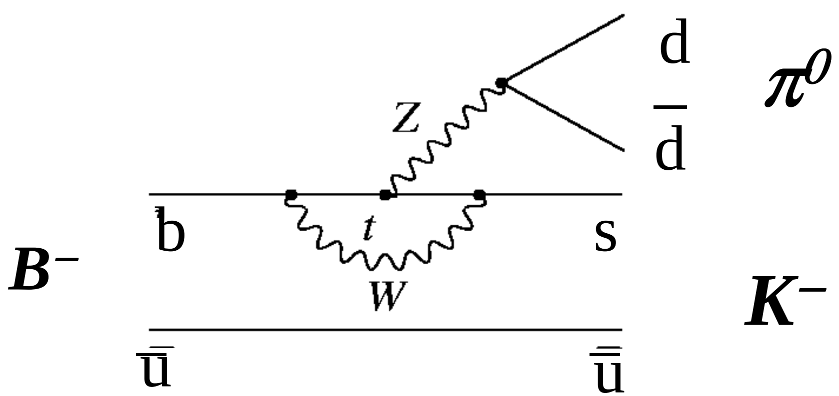


$A_{CP}(K^{\pm}\pi^0) = 0.04 \pm 0.05 \pm 0.02$

hint that $A_{CP}(K^+\pi^-) \neq A_{CP}(K^{\pm}\pi^0)$? (2.4σ) [also seen by BaBar]

Large EW penguin (Z^0) ?

New Physics ?



Belle 2004 PRL: Seed

Y. Chao, P. Chang et al.

BELLE

The partial rate asymmetry $\mathcal{A}_{CP}(K^+\pi^-)$ is found to be $-0.101 \pm 0.025 \pm 0.005$, which is 3.9σ from zero. The significance calculation includes the effects of systematic uncertainties. Our result is consistent with the value reported by *BABAR*, $\mathcal{A}_{CP}(K^+\pi^-) = -0.133 \pm 0.030 \pm 0.009$ [7]. The combined experimental result has a significance greater than 5σ, indicating that direct *CP* violation in the *B* meson system is established. Our measurement of $\mathcal{A}_{CP}(K^+\pi^0)$ is consistent with no asymmetry; the central value is 2.4σ away from $\mathcal{A}_{CP}(K^+\pi^-)$. If this result is confirmed with higher statistics, the difference may be due to the contribution of the electroweak penguin diagram or other mechanisms [16]. No evidence of

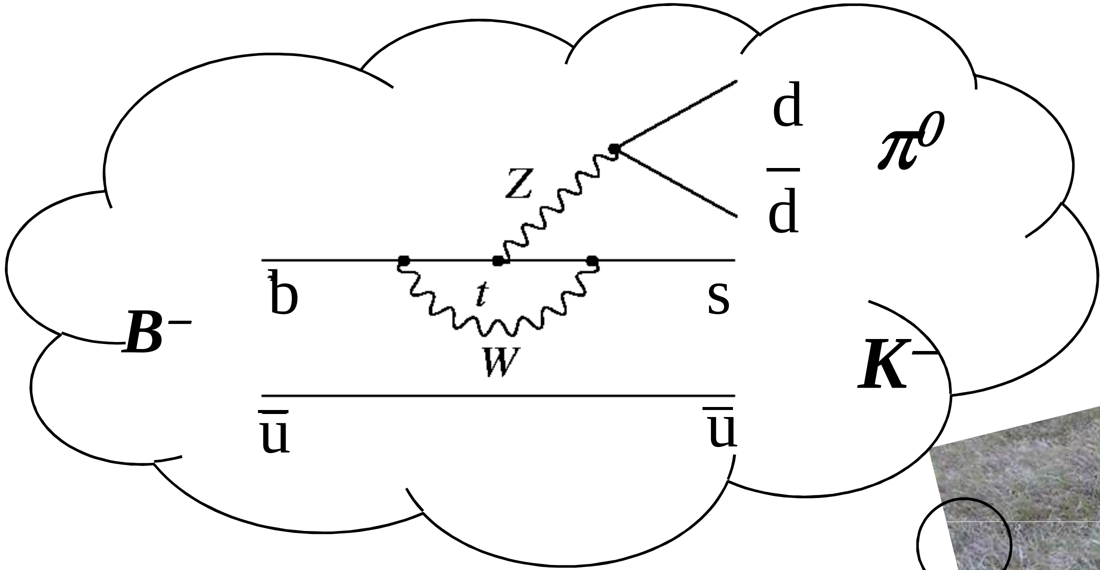
by "yours truly"

[16] A. J. Buras, R. Fleischer, S. Recksiegel, and F. Schwab, hep-ph/0402112; V. Barger, C.W. Chiang, P. Langacker, and H.S. Lee, Phys. Lett. B **598**, 218 (2004).

P_{EW}

Z'

The Crawlin' of one Ant



Going Up a Hill ...

My first B paper

WSH, Willey, Soni

VOLUME 58, NUMBER 16 PHYSICAL REVIEW LETTERS 20 APRIL 1987

an by Inami and Lim,[9] and we follow their notation. The effective Lagrangean arising from Fig. 1 is

$$\mathcal{L}_{\rm eff}^{b\bar{s}\to l^+l^-} = 2\sqrt{2}G_F\chi v_i\{\bar{C}_i(\bar{s}\gamma_\mu Lb)(\bar{l}\gamma_\mu Ll) - s_W^2(F_1^i + 2\bar{C}_i^Z)(\bar{s}\gamma_\mu Lb)(\bar{l}\gamma_\mu l)$$
$$- s_W^4 F_2^i[\bar{s}i\sigma_{\mu\nu}(q_\nu/q^2)(m_s L + m_b R)b](\bar{l}\gamma_\mu l)\}, \quad (1)$$

$$\mathcal{L}_{\rm eff}^{b\bar{s}\to\nu\bar{\nu}} = -2\sqrt{2}G_F\chi v_i\bar{D}_i(\bar{s}\gamma_\mu Lb)(\bar{\nu}\gamma_\mu L\nu), \quad (2)$$

where $\chi = g^2/16\pi^2$, $v_i \equiv V_{is}^* V_{ib}$, i is summed from 2 to n (where n is the number of generations),[10] s_W is the sine of the Weinberg angle, and we exhibit[11]

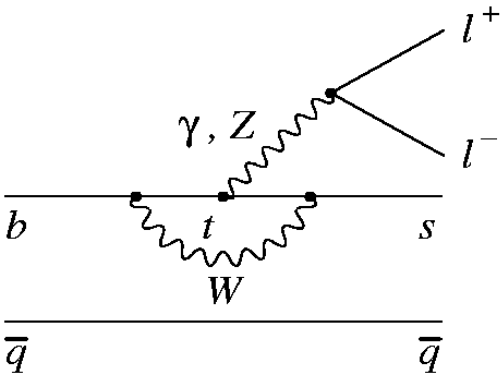
$$\bar{C}_i \equiv \bar{C}_i^Z + \bar{C}_i^{\rm box} = \frac{1}{4}x_i + \frac{3}{4}\left(\frac{x_i}{x_i-1}\right)^2 \ln x_i - \frac{3}{4}\frac{x_i}{x_i-1}, \quad (3)$$

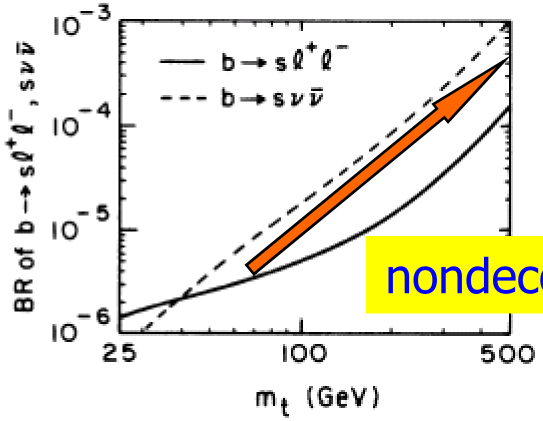
$$\bar{D}_i \equiv \bar{D}_i^Z + \bar{D}_i^{\rm box} = \frac{1}{4}x_i + \frac{3}{4}\frac{x_i(x_i-2)}{(x_i-1)^2}\ln x_i + \frac{3}{4}\frac{x_i}{x_i-1}, \quad (4)$$

where $x_i = m_i^2/M_W^2$, and m_i is the internal quark mass. The important feature of Eqs. (3) and (4) is the term $x_i/4$,[8]

dimensions

γ	Z
αG_F <	$G_F^2 m_t^2$





nondecoupling

Nondecoupling

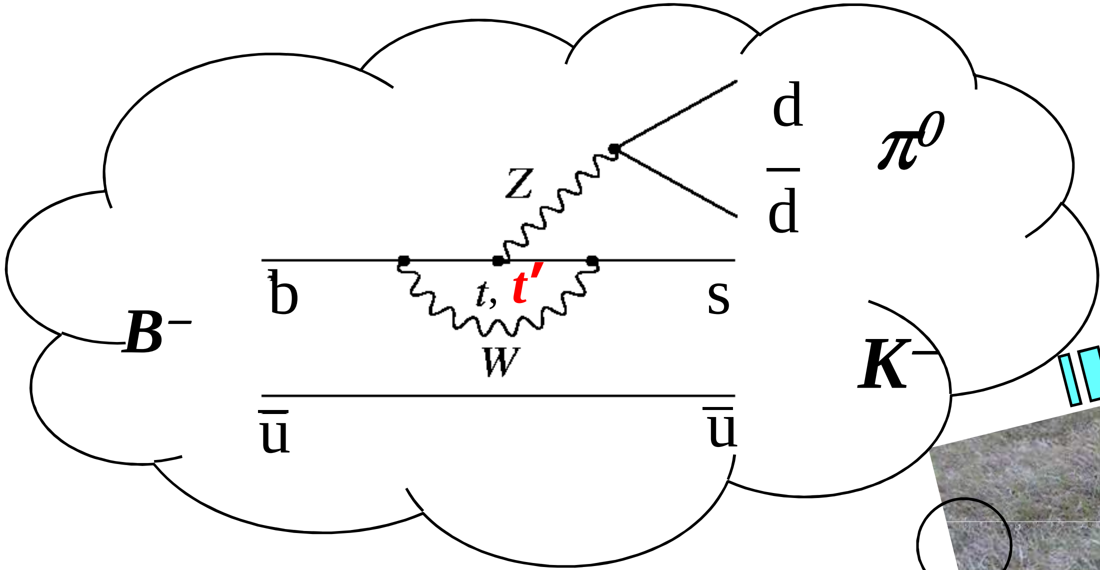
Decoupling Thm: Heavy Masses are decoupled in QED/QCD

∵ Appear in Propagator

Nondecoupling: Yukawa Couplings λ_Q Appear in Numerator

dynamical

Subtlety of Spont. Broken Gauge Theory



Going Up a Hill ...

My first B paper

... on 4th generation also ☺

VOLUME 58, NUMBER 16 PHYSICAL REVIEW LETTERS 20 APRIL 1987

Implications of a Heavy Top Quark and a Fourth Generation on the Decays $B \to Kl^+l^-$, $K\nu\bar{\nu}$

Wei-Shu Hou and R. S. Willey

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260

and

A. Soni

Department of Physics, University of California, Los Angeles, Los Angeles, California 90024

(Received 12 November 1986)

We point out the importance of the Z and box diagram to the decays $B \to Kl^+l^-$, $K\nu\bar{\nu}$. The rate for $B \to Kl^+l^-$ grows rapidly for internal quark masses >100 GeV. With three generations and 25 GeV $\lesssim m_t \lesssim$ 200 GeV the branching ratio ranges roughly from 10^{-6} to 10^{-5}. With four generations, this rate could go up another order of magnitude. The mode $B \to K\nu\bar{\nu}$ typically has a higher branching ratio, but is harder to detect experimentally. The rare B decays combined with information from $K \to \pi\nu\bar{\nu}$ studies may provide a test of the symmetry-breaking mechanism of the standard model and/or evidence for a fourth generation.

4th Generation Still?

- N_ν counting? 4th "neutrino" heavy

  Massive neutrinos call for new Physics

- Disfavored by EW Precision (see e.g. **J. Erler hep-ph/0604035; PDG06**

An extra generation of ordinary fermions is excluded at the 99.999% CL on the basis arameter alone, corresponding to $N_F = 2.81 \pm 0.24$ for the number of families. t assumes that there are no new contributions to T or U and therefore that amilies are degenerate. In principle this restriction can be relaxed by allowing

July 14, 2006 10:37

10. Electroweak model and constraints on new physics **37**

as well, since $T > 0$ is expected from a non-degenerate extra family. However, urrently favor $T < 0$, thus strengthening the exclusion limits. A more detailed required if the extra neutrino (or the extra down-type quark) is close to nass limit [208]. This can drive S to small or even negative values but at the expense of too-large contributions to T. These results are in agreement with a fit to the number of light neutrinos, $N_\nu = 2.986 \pm 0.007$ (which favors a larger value for $\alpha_s(M_Z) = 0.1231 \pm 0.0020$ mainly from R_ℓ and τ_τ). However, the S parameter fits are valid even for a very heavy fourth family neutrino.

- 4th generation **not** in such great conflict with EWPrT

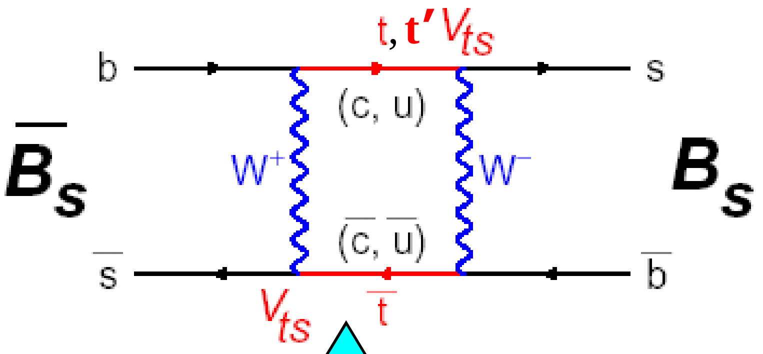
  Kribs, Plehn, Spannowsky, Tait, PRD'07

This is Still the Standard Model

$$\lambda_{t'} \equiv V^*_{t's} V_{t'b} \equiv r_{sb}\, e^{i\phi_{sb}}$$

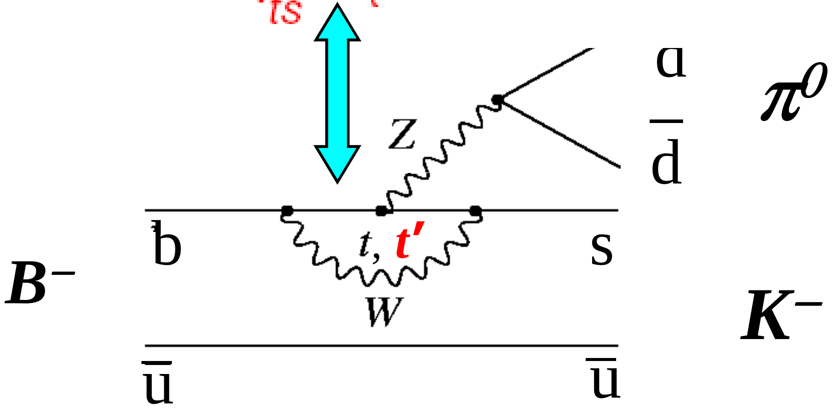
Arhrib and WSH, EPJC'03

t ⇨ t, t′

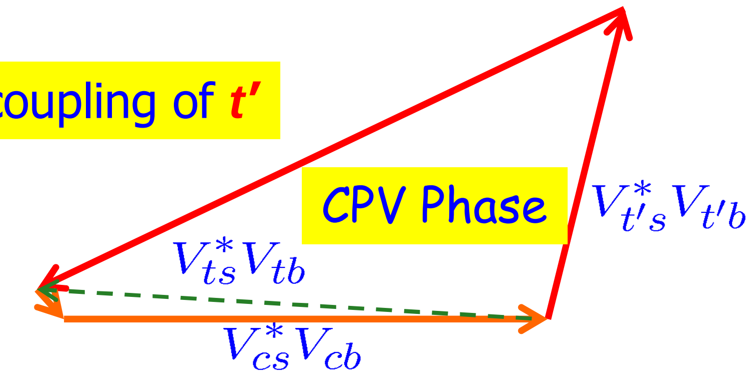


$$\lambda_u + \lambda_c + \lambda_t + \lambda_{t'} = 0$$

$$\lambda_t \cong -\lambda_c - \lambda_{t'}$$



Nondecoupling of *t′*



$$M_{12} \propto f_{B_s}^2 B_{B_s} \{ \lambda_c^2 S_0(t,t) + 2\lambda_c \lambda_{t'} [S_0(t,t) - S_0(t,t')] + \lambda_{t'}^2 [S_0(t,t) - 2S_0(t,t') + S_0(t',t')] \}$$

GIM Respecting

$$H_{\rm eff}^4 = \frac{G_F}{\sqrt{2}} \left[\lambda_u (C_1 O_1 + C_2 O_2) + \sum_{i=3}^{10} (\lambda_c C_i^t - \lambda_{t'} (C_i^{t'} - C_i^t)) O_i \right]$$

EWP/Box Sensitivity to 4th Gen.

γ, g less sensitive

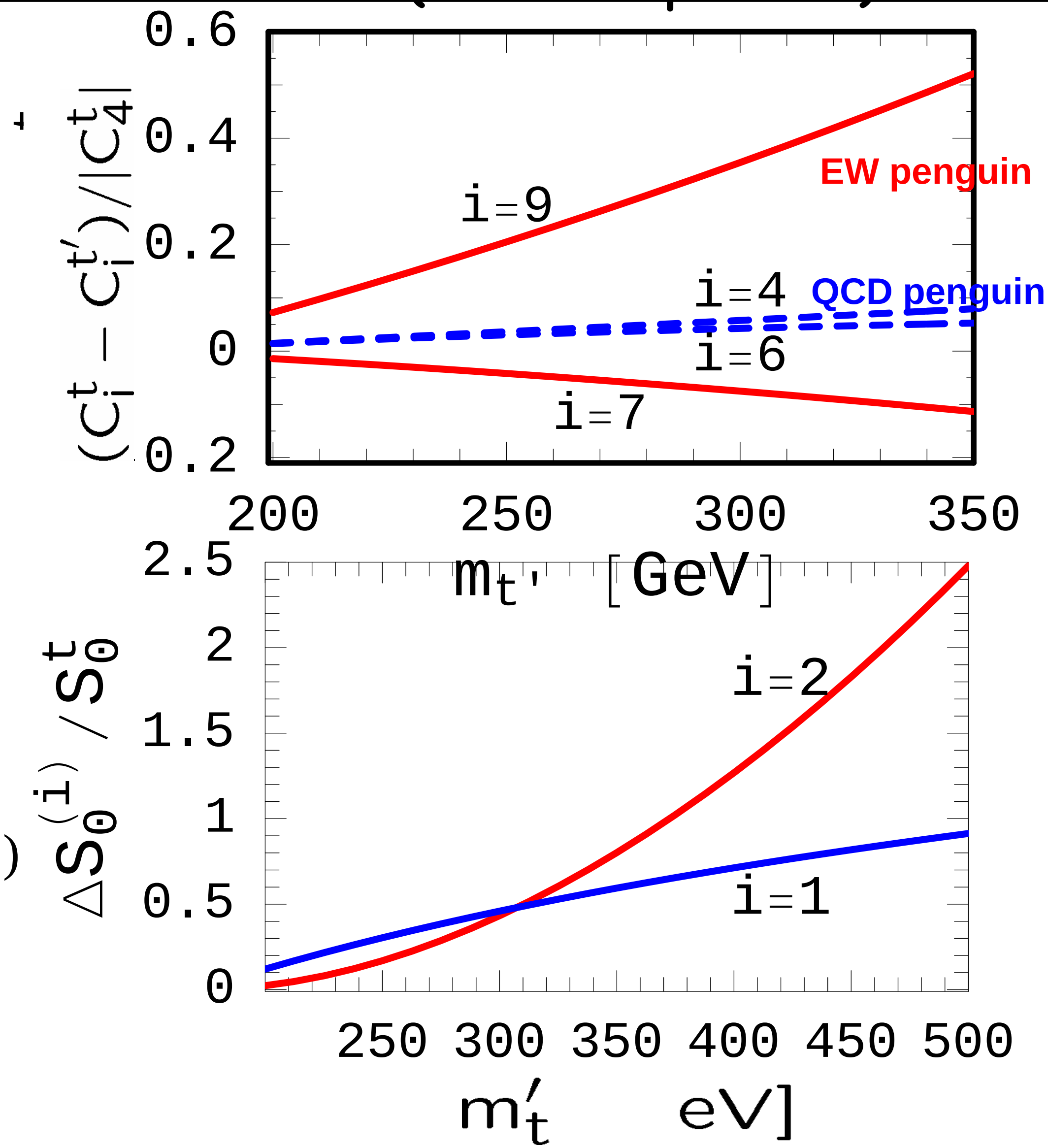
(No New Operators)

$$C_9^t - C_9^{t'} \propto x_t - x_{t'}$$

nondecoupling

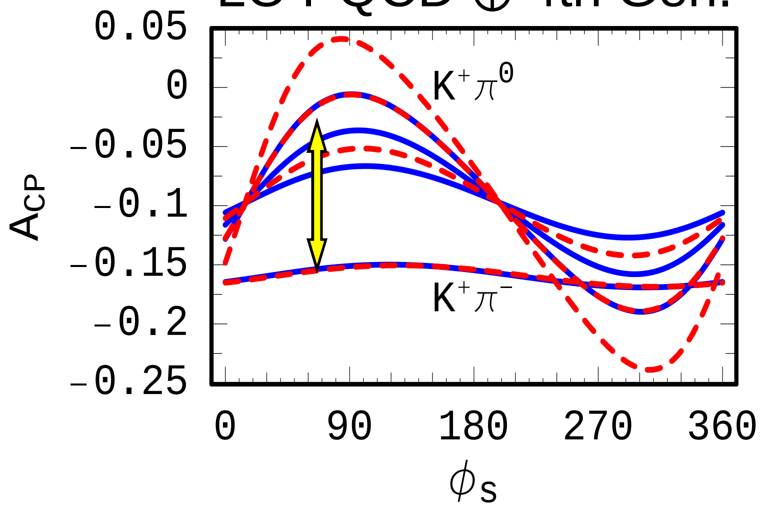
$$\Delta S_0^{(1)} = S_0(t,t') - S_0(t,t)$$

$$\Delta S_0^{(2)} = S_0(t',t') + S_0(t,t) - 2S_0(t,t')$$



$\Delta A = A_{K^+\pi^0} - A_{K^+\pi^-} \sim 15\%$ and $P_{EW}^{b\to s}$

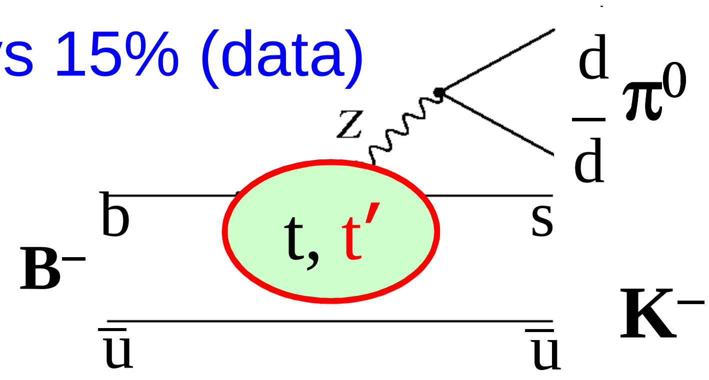
LO PQCD ⊕ 4th Gen.



WSH, Nagashima, Soddu, PRL'05

$\Delta A \approx 12\%$ vs 15% (data)

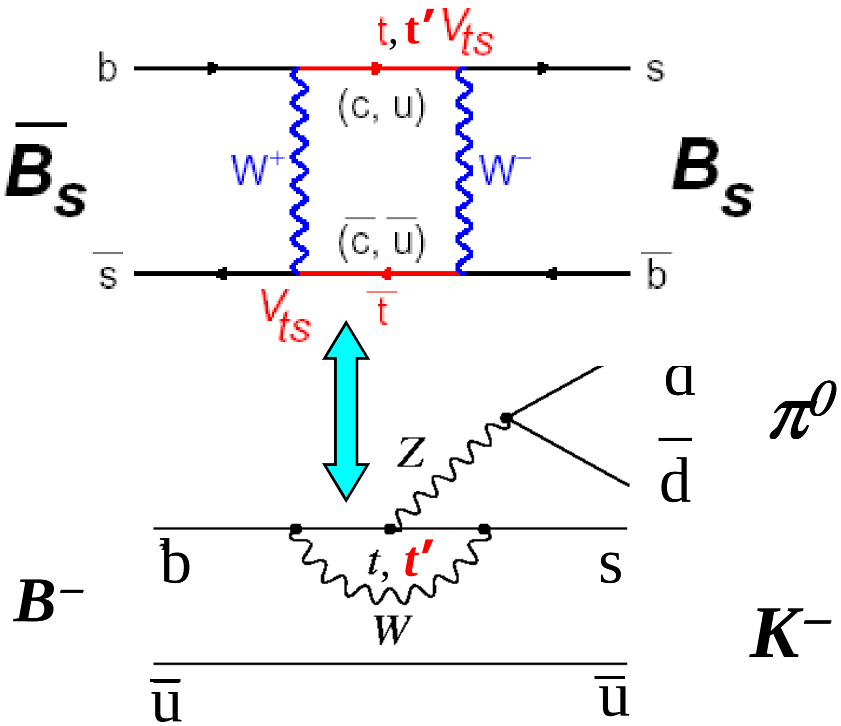
$m_{t'} = 300$ GeV
(illustration)



$$\lambda_{t'} \equiv V^*_{t's} V_{t'b} \equiv r_{sb}\, e^{i\phi_{sb}}$$

Arhrib and WSH, EPJC'03

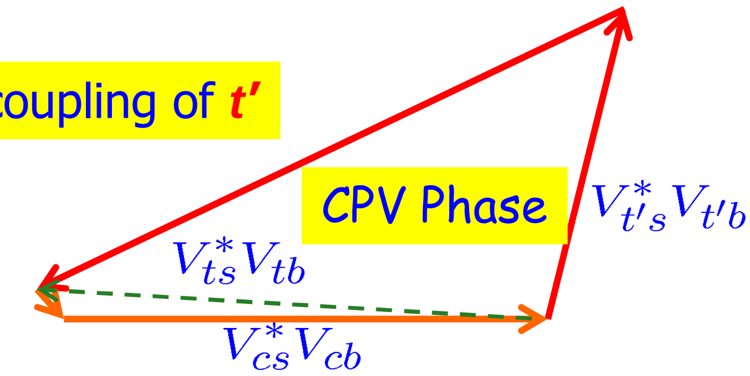
t ⇨ t, t′



$$\lambda_u + \lambda_c + \lambda_t + \lambda_{t'} = 0$$

$$\lambda_t \cong -\lambda_c - \lambda_{t'}$$

Nondecoupling of *t′*



$$M_{12} \propto f^2_{B_s} B_{B_s} \{\lambda_c^2 S_0(t,t) + 2\lambda_c \lambda_{t'} [S_0(t,t) - S_0(t,t')] + \lambda_{t'}^2 [S_0(t,t) - 2S_0(t,t') + S_0(t',t')]\}$$

GIM Respecting

$$H^4_{\rm eff} = \frac{G_F}{\sqrt{2}} \left[\lambda_u (C_1 O_1 + C_2 O_2) + \sum_{i=3}^{10} (\lambda_c C_i^t - \lambda_{t'}(C_i^{t'} - C_i^t)) O_i\right]$$

PRL 95, 141601 (2005) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2005

Difference in B^+ and B^0 Direct CP Asymmetry as an Effect of a Fourth Generation

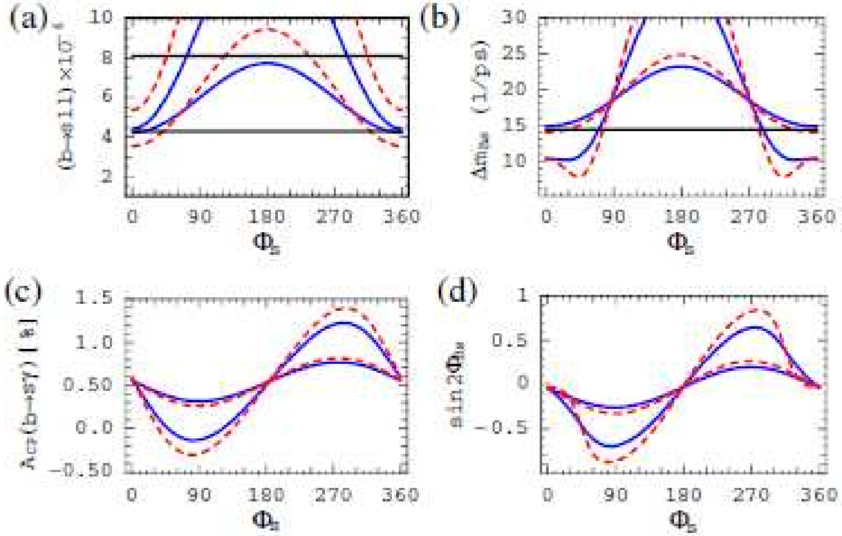
Wei-Shu Hou, Makiko Nagashima, and Andrea Soddu

Department of Physics, National Taiwan University, Taipei, Taiwan 106, Republic of China

(Received 8 March 2005; revised manuscript received 20 June 2005; published 30 September 2005)

Direct CP violation in $B^0 \to K^+\pi^-$ decay has emerged at the -10% level, but the asymmetry in $B^+ \to K^+\pi^0$ mode is consistent with zero. This difference points towards possible new physics in the electroweak penguin operator. We point out that a sequential fourth generation, with sizable $V^*_{t's}V_{t'b}$ and near maximal phase, could be a natural cause. We use the perturbative QCD factorization approach for $B \to K\pi$ amplitudes. While the $B^0 \to K^+\pi^-$ mode is insensitive to t', we critically compare t' effects on direct CP violation in $B^+ \to K^+\pi^0$ with $b \to s\ell^+\ell^-$ and B_s mixing. If the $K^+\pi^0 - K^+\pi^-$ asymmetry difference persists, we predict $\sin 2\Phi_{B_s}$ to be negative.

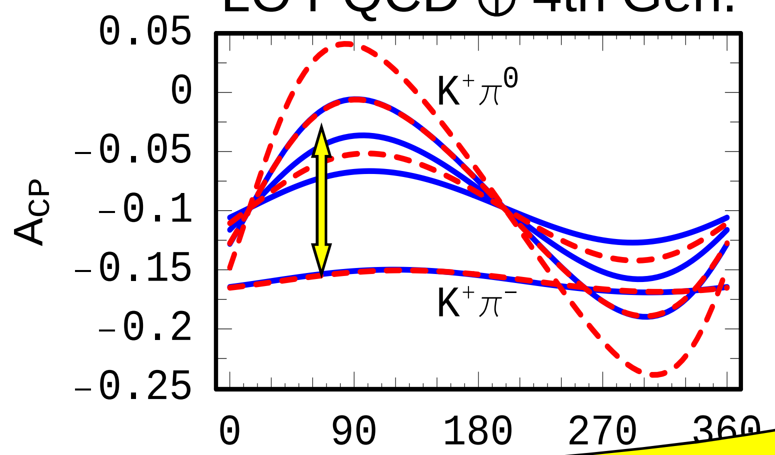
As prediction, we find $\sin 2\Phi_{B_s} < 0$ for CPV in B_s mixing, which is plotted versus ϕ_s in Fig. 3(d). We find $\sin 2\Phi_{B_s}$ in the range of -0.2 to -0.7 and correlating with $\mathcal{A}_{K\pi^0} - \mathcal{A}_{K\pi}$. Three generation SM predicts zero. Note that refined measurements of $\mathcal{B}(b \to s\ell\ell)$ and future measurements of Δm_{B_s} and $\sin 2\Phi_{B_s}$, together with theory improvements, can pinpoint $m_{t'}$, r_s, and ϕ_s. We note further that [6] $14.4\ \mathrm{ps}^{-1} < \Delta m_{B_s} < 21.8\ \mathrm{ps}^{-1}$ cannot yet be excluded because data are compatible with a signal in this region. We eagerly await B_s mixing and associated CPV measurement in the near future.



$\Delta A = A_{K^+\pi^0} - A_{K^+\pi^-} \sim 15\%$ and $P_{EW}^{b\to s}$

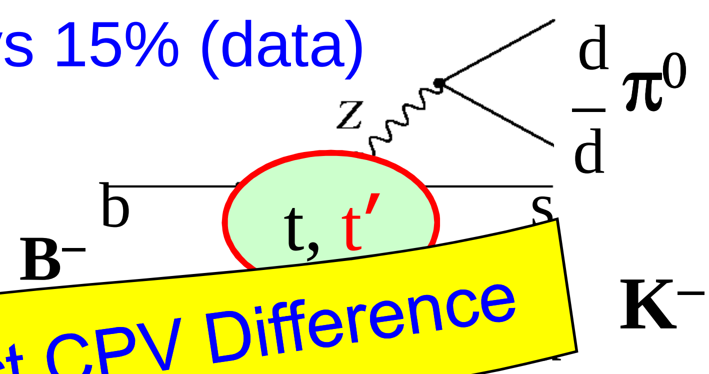
LO PQCD ⊕ 4th Gen.

WSH, Nagashima, Soddu, PRL'05



$\Delta A \approx 12\%$ vs 15% (data)

$m_{t'} = 300$ GeV (illustration)



Can Account for Belle/BaBar Direct CPV Difference

r_{sb} = 0.03: red, dash
0.02: blue, solid
0.01: green, dot-dash

WSH, Li, Mishima, Nagashima, PRL'07

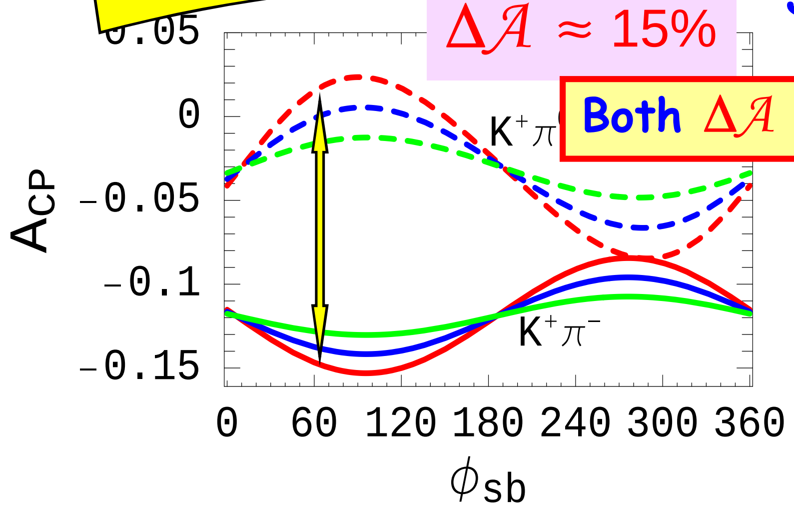
Joining C & P_{EW}

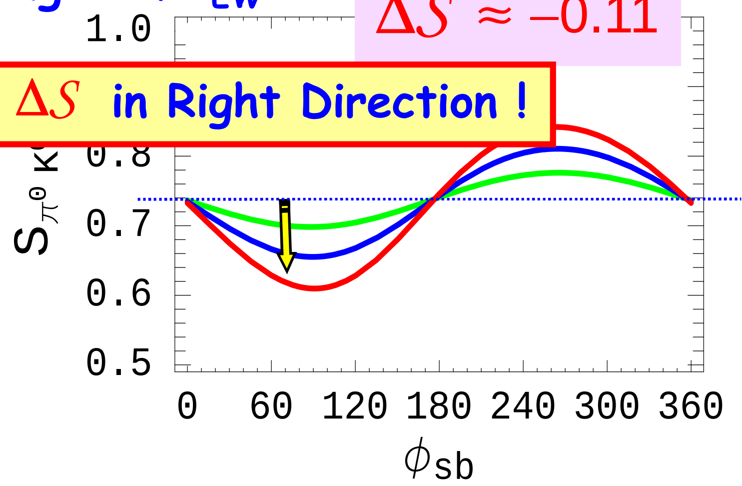
$\Delta\mathcal{A} \approx 15\%$

$\Delta\mathcal{S} \approx -0.11$

consistent with data

Both $\Delta\mathcal{A}$ and $\Delta\mathcal{S}$ in Right Direction !





WSH, Nagashima, Soddu, PRD'05

"Typical" CKM Matrix

$m_{t'} = 300\,\text{GeV}$

$V^4_{CKM} =$

0.9745	0.2225	$0.0038\, e^{-i\, 60^\circ}$	… 61°
-0.2241 …	…	…	$0.1164\, e^{i\, 66^\circ}$
0.0 …	$-0.0555\, e^{-i\, 25^\circ}$	0.9746	$0.2168\, e^{-i\, 1^\circ}$
$-0.0044\, e^{-i\, 10^\circ}$	$-0.1136\, e^{-i\, 70^\circ}$	-0.2200	0.9688

Extract Information from Constraints

$s \leftarrow b$

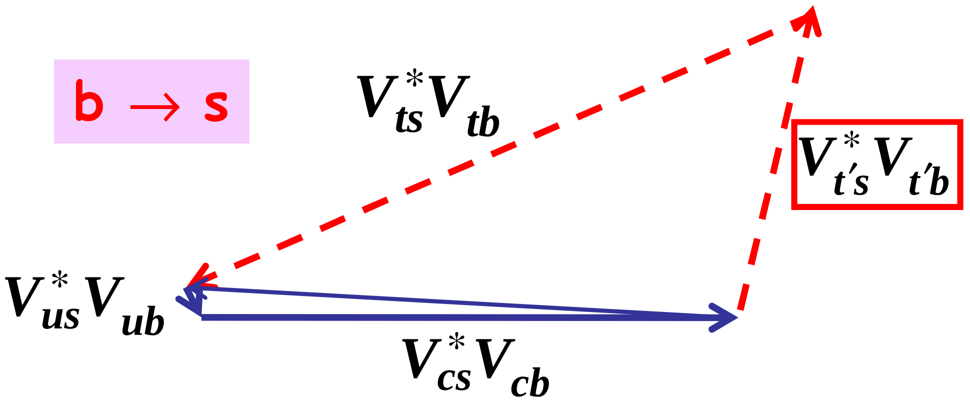
$d \leftarrow s$

$Z \to b\bar{b}$

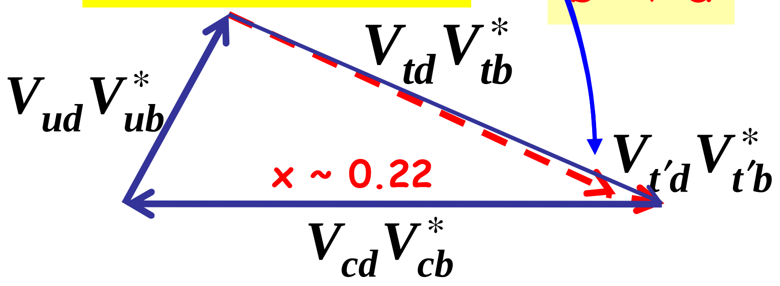
Nontrivial

Satisfy b → d: ✓
Cannot tell triangle from quadrangle

b → s



b → d

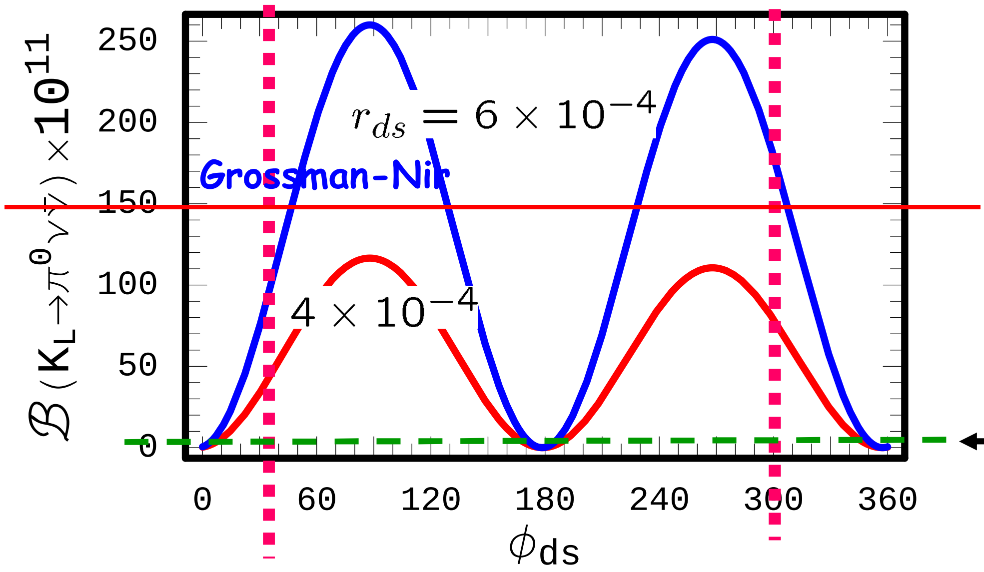


$\mathcal{A}_{FB}(B \to K^* l^+ l^-)$ and Other Predictions

sent to Backup

Implication for $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$

Nontrivial (phase) $V^*_{t'd} V_{t's}$



Current E391A U.L.

2.86×10^{-7} (90% c.l.)

Very hard to measure

$\leftarrow \mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \simeq 3 \times 10^{-11}$

SM3

Rate could be enhanced by up to almost two orders !!

$K_L \to \pi^0 \nu\bar{\nu}$ **enhanced to** 5×10^{-10} **or even higher !!**

In general larger than $K^+ \to \pi^+ \nu\bar{\nu}$ $(2\text{–}3 \times 10^{-10})$

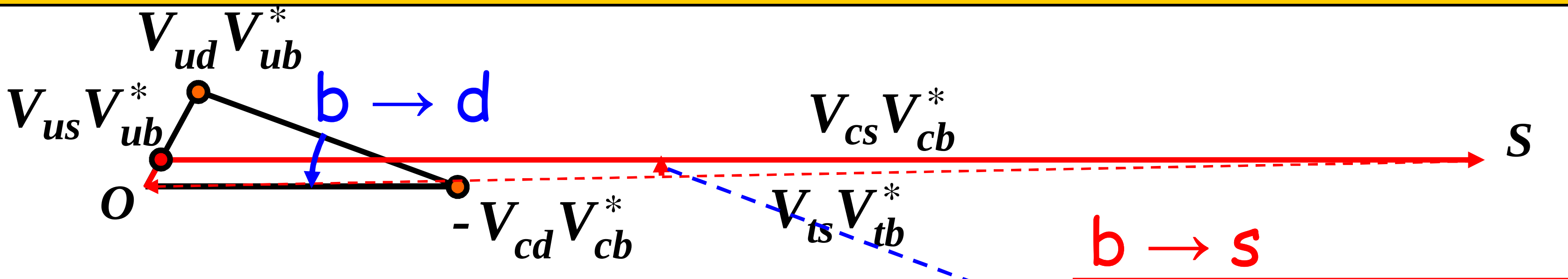
∵ Large CPV Phase

b ↔ s CPV

III. Δm_{B_s} Measurement → Prediction for $\sin 2\Phi_{B_s}$

the Experimentalist

Mixing-dep. CPV in B_d and B_s in SM



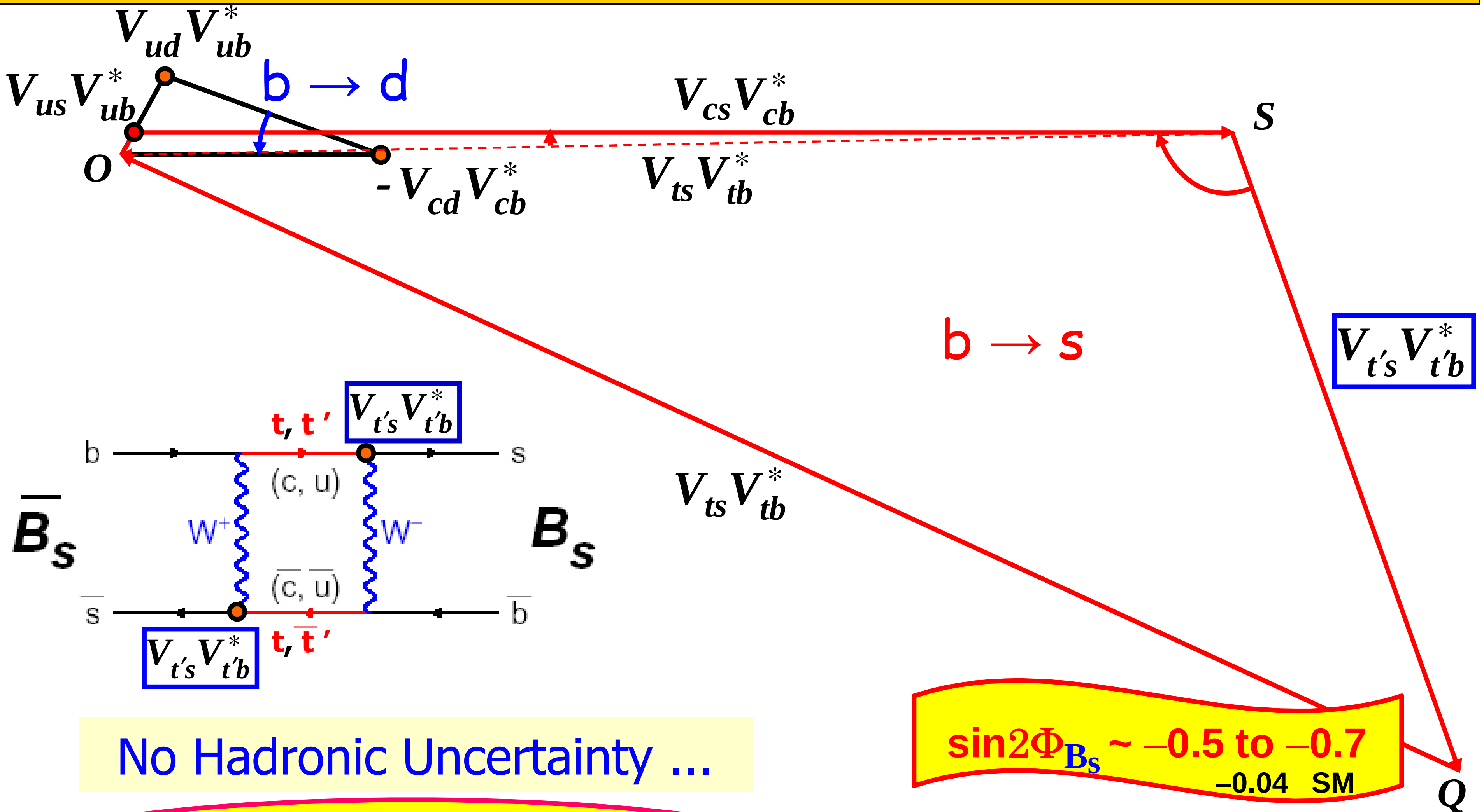
$\sin 2\phi_1 = \sin 2\beta$

Measured by Belle/BaBar

$\sin 2\Phi_{B_s} \simeq -0.04$ in SM3

Measure in $B_s \to J/\psi\phi$

Prediction: Large CPV in B_s Mixing



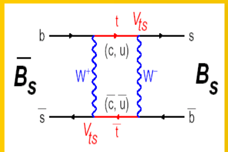
$\sin 2\Phi_{B_s} \sim -0.5$ to -0.7
-0.04 SM

No Hadronic Uncertainty ...

Despite Δm_{B_s}, $\mathcal{B}(b \to s\ell\ell)$ SM-like

Strength and Size of $\sin 2\Phi_{B_s}$

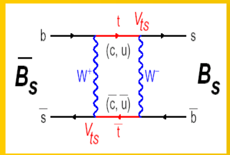
WSH, Nagashima, Soddu, PRD'07
PRL'05



$\mathbf{B_s}$ Mixing vs $\mathbf{B \to X_s \ell^+ \ell^-}$

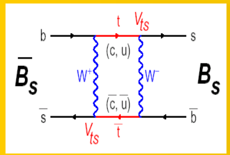
different nondecoupl. functions

Large CPV in B_s Mixing



Use nominal $m_{t'}$ = 300 GeV
Change $m_{t'}$, Change parameter range
Effect the Same.

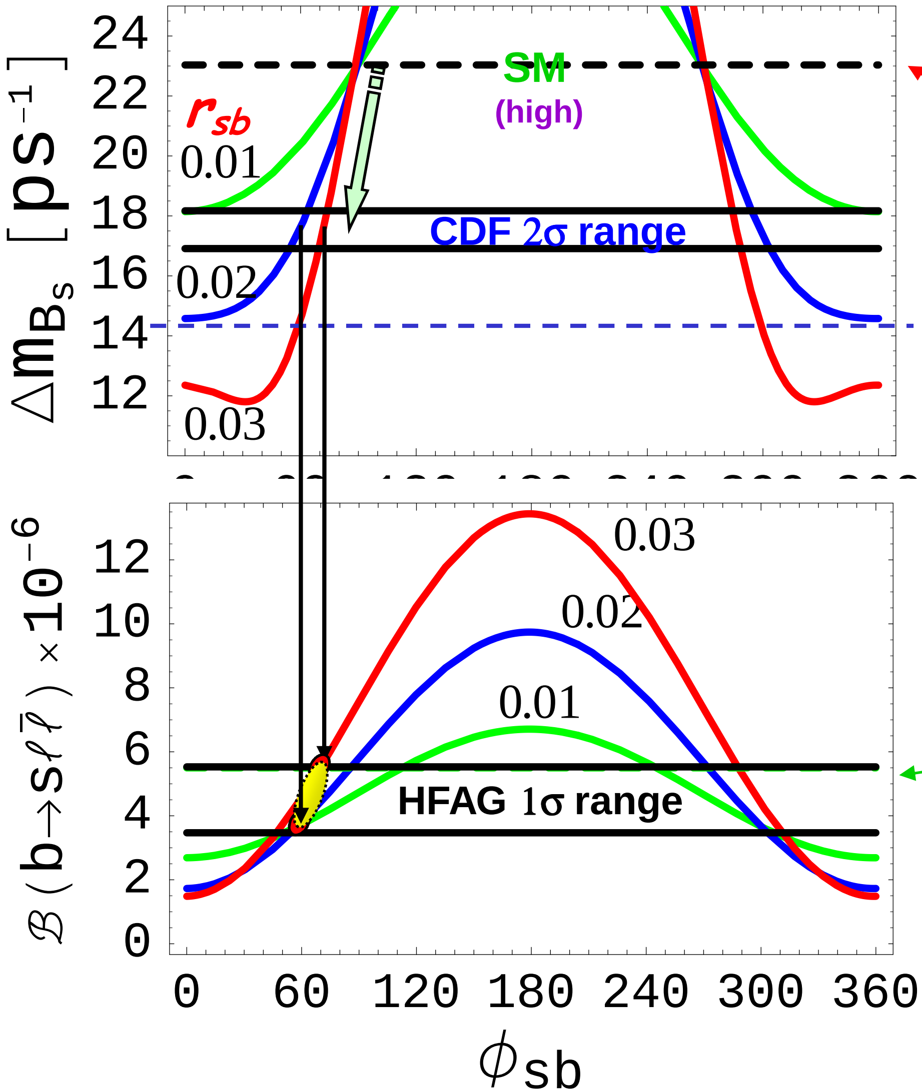
(Similar)



$$\lambda_{t'} \equiv V^*_{t's} V_{t'b} \equiv r_{sb}\, e^{i\phi_{sb}}$$

WSH, Nagashima, Soddu, hep-ph/0610385 (PRD'07)

$$f_{B_s}\sqrt{B_{B_s}} = 295 \pm 32 \text{ MeV}$$



- Fixed r_{sb} ⇨ Narrow ϕ_{sb} Range
  destructive with top
- For r_{sb} ~ 0.02 – 0.03, [V_{cb} ~ 0.04

ϕ_{sb} Range ~ 60° - 70°

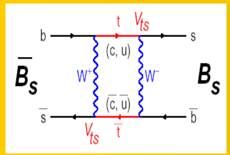
Finite CPV Phase

Consistent w/ $\mathcal{B}(b \to s\ell\ell)$

SM-like !

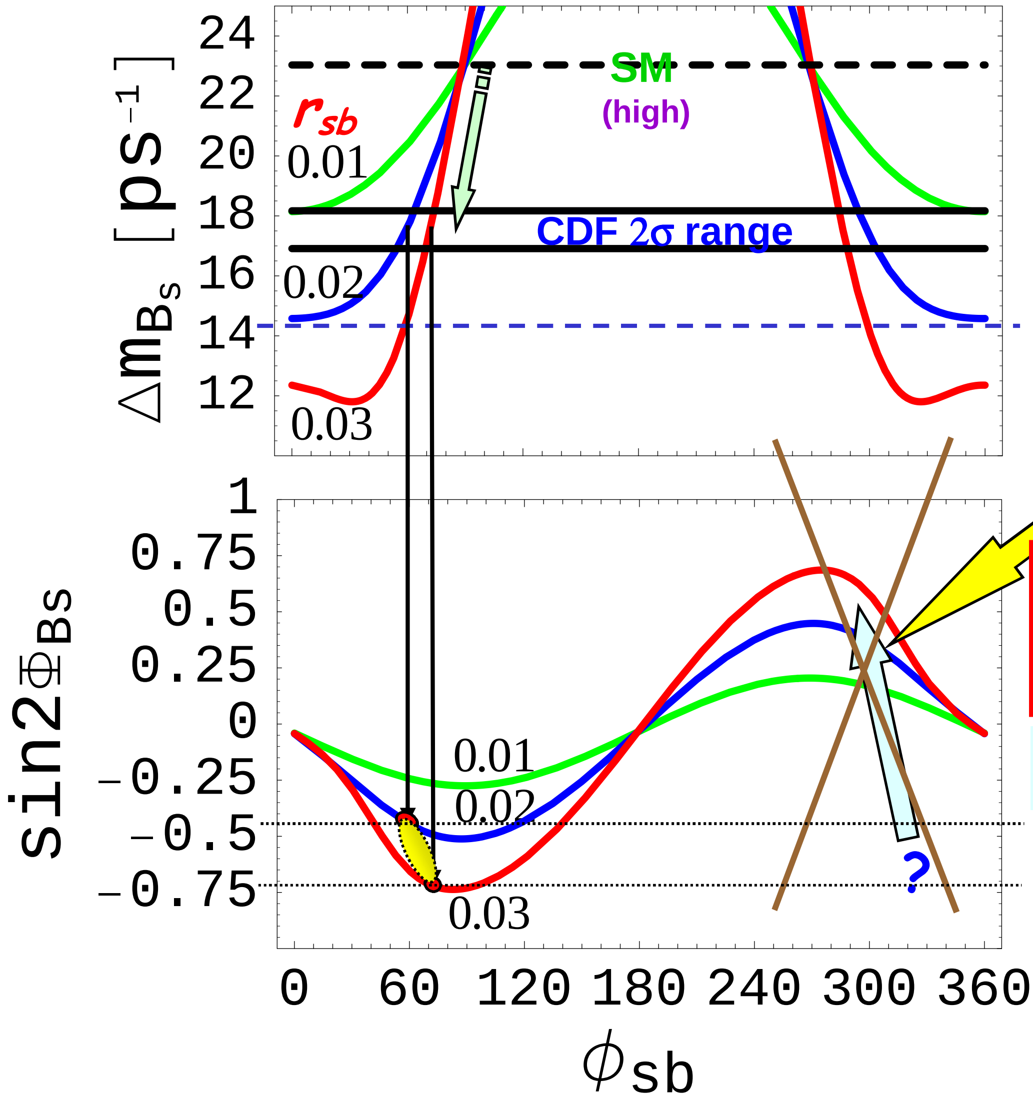
Large CPV Possible !

Despite Δm_{B_s}, $\mathcal{B}(b \to s\ell\ell)$ SM-like



Large CPV in B_s Mixing

WSH, Nagashima, Soddu, hep-ph/0610385



$\Delta\mathcal{A}_{K\pi}$, $\Delta\mathcal{S}$

Can Large CPV in B_s Mixing Be Measured @ Tevatron ?

Sign Predicted !

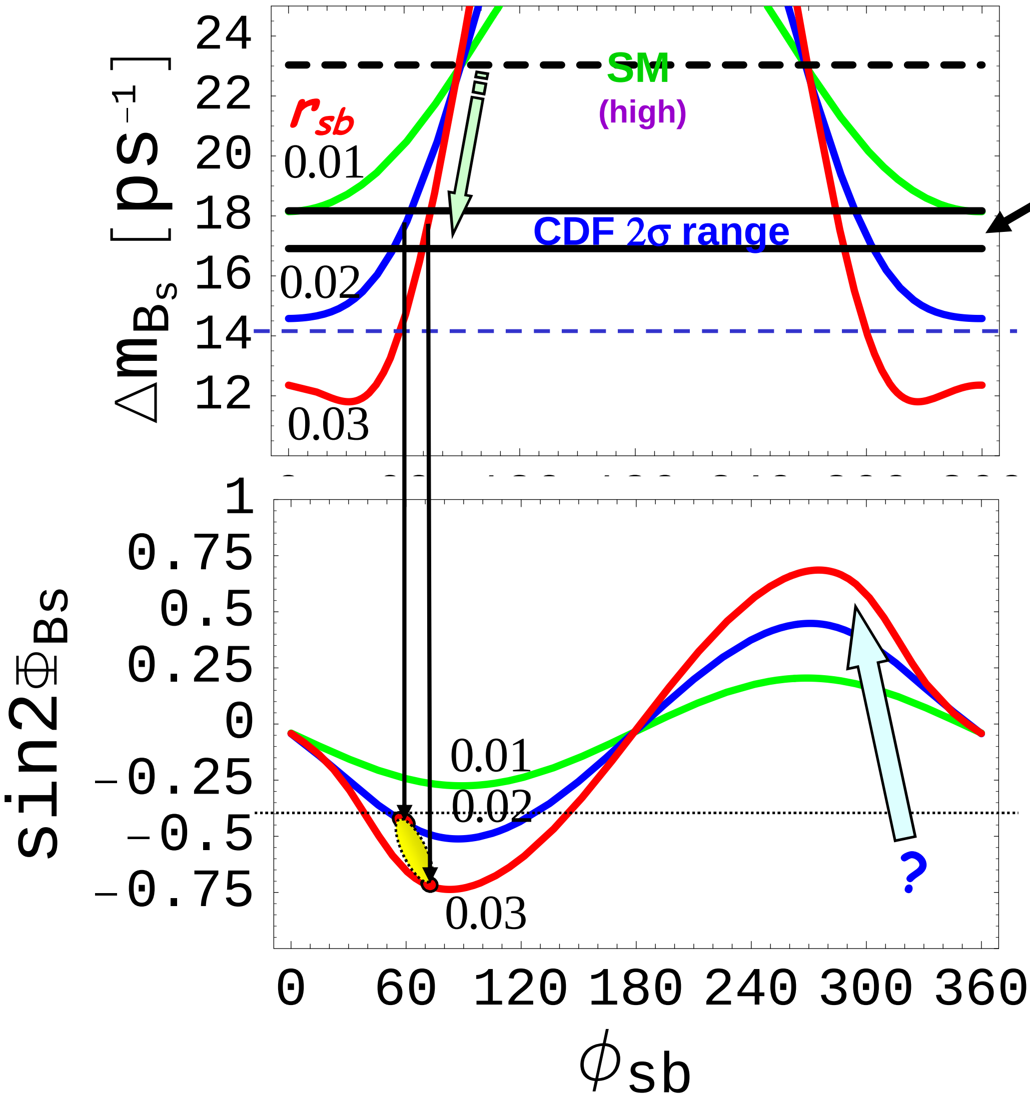
Sure thing by LHCb ca. 2008

$\sin 2\Phi_{B_s}$ ~ ±0.5 - ± 0.7

Despite Δm_{B_s}, $\mathcal{B}(b \to s\ell\ell)$ SM-like

Prediction: Large CPV in B_s Mixing

WSH, Nagashima, Soddu, PRD'07



$f_{B_s}\sqrt{B_{B_s}} = 295 \pm 32$ MeV

B_s Mixing Measured @ Tevatron in 4/2006

- For r_{sb} ~ 0.02 – 0.03, [V_{cb} ~ 0.04

ϕ_{sb} Range ~ 60˚ - 70˚

Finite CPV Phase

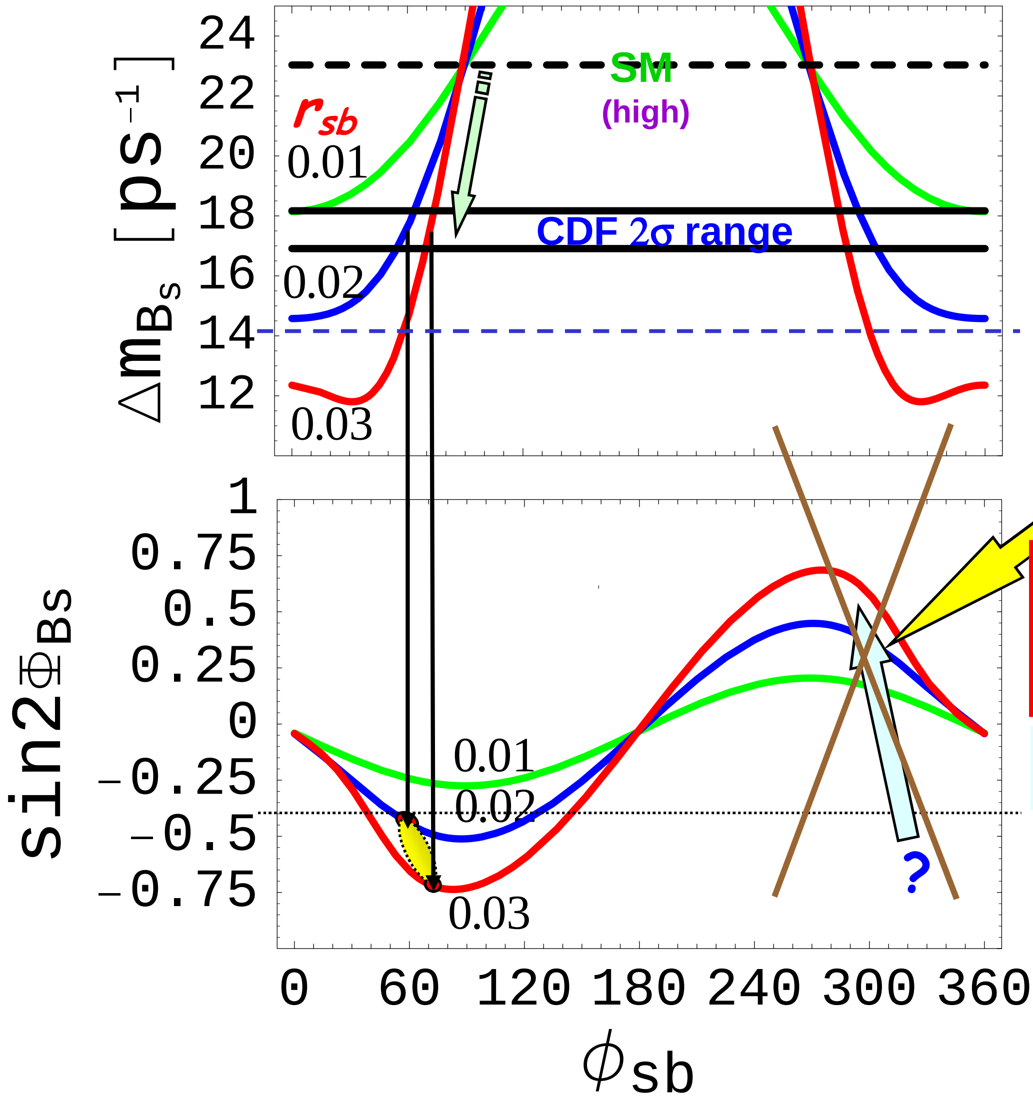
$\sin 2\Phi_{B_s}$ ~ –0.5 - –0.7
–0.04 SM

Despite Δm_{B_s}, $\mathcal{B}(b \to s\ell\ell)$ SM-like

WSH, Nagashima, Soddu, PRL'05

Prediction: Large CPV in B_s Mixing

WSH, Nagashima, Soddu, PRD'07



$\Delta\mathcal{A}_{K\pi}$, ΔS

Can Large CPV in B_s Mixing Be Measured @ Tevatron ?

Sign Predicted !

Sure thing by LHCb ca. 2010 (?)

$\sin 2\Phi_{B_s} \sim -0.5$ - -0.7

−0.04 SM

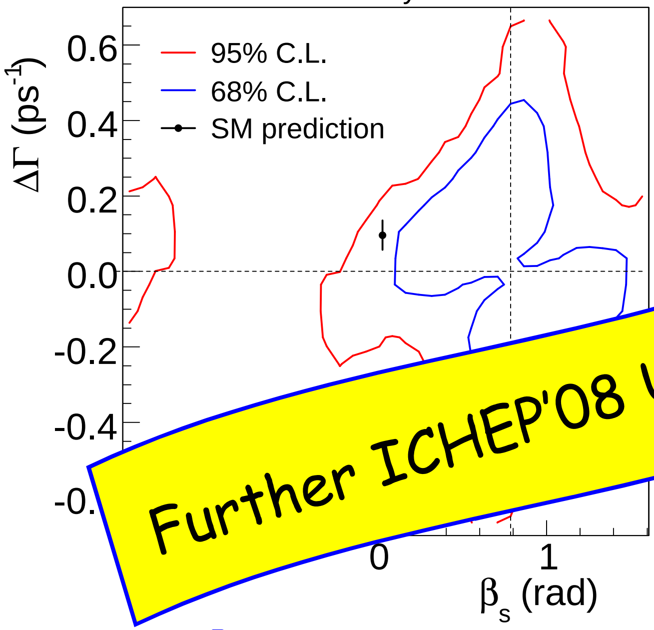
Despite Δm_{B_s}, $\mathcal{B}(b \to s\ell\ell)$ SM-like

WSH, Nagashima, Soddu, PRL'05

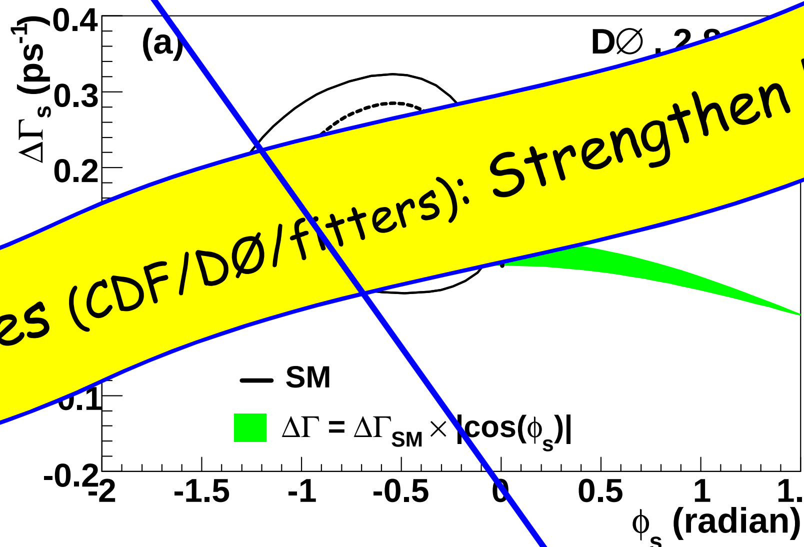
$\sin 2\Phi_{B_s} \sim -0.5 - -0.7$

WSH, Nagashima, Soddu, PRD'07 (already in 05)

PRL'08
arXiv:0712.2397 [hep.ex]



PRL'08
arXiv:0802.2255 [hep.ex]



Further ICHEP'08 Updates (CDF/DØ/fitters): Strengthen !

Observable	68% Prob.	95% Prob.
ϕ_{B_s} [°]	-19.9 ± 5.6	[illegible]
	-68.2 ± 4.9	[-78.45,-58.2]

UTfit

arXiv:0803.0659 [hep.ph]

$\sin 2\Phi_{B_s} = -0.64$ ~2.8σ ± ?

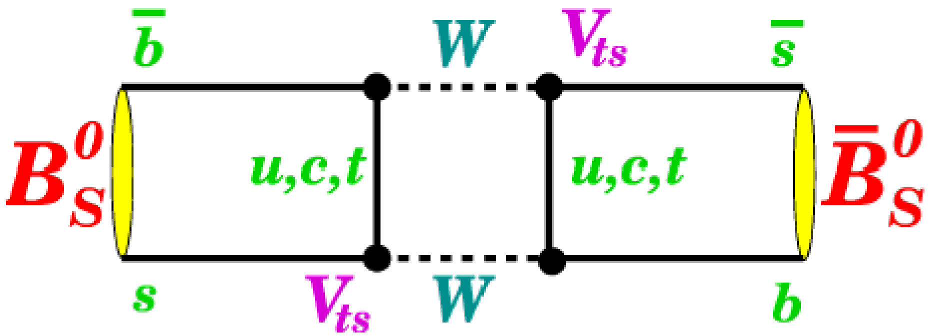
Incredible !!!

An Updated Measurement of the CP Violating Phase $\beta_s^{J/\psi\phi}$

The CDF Collaboration[1]

CDF/ANAL/BOTTOM/PUBLIC/9458
Version 1.0
August 7, 2008

It is interesting to note that the Belle and *BABAR* collaborations have observed an asymmetry between direct CP asymmetries of charged and neutral $B \to K\pi$ decays with 5σ significance [5, 6]. In the absence of an under-estimation of the contribution from color-suppressed tree decays, it is difficult to explain this discrepancy without some source of new physics contributing to the electroweak penguin which governs the $b \to s$ transition.In the standard model, this isospin-violating diagram should be highly suppressed, but if a new source of physics is indeed present in these transitions it may be enough to cause the different CP asymmetries that have been observed.. In the $B_s^0 \to J/\psi\,\phi$ decay, the $b \to s$ transition occurs through the mixing box diagram shown in Fig. 1. It is possible that new particles could enter this transition through the $b \to s$ quark transition. While there are surely a number of possible sources of new physics that might give rise to such discrepancies, George Hou predicted the presence of a t' quark with mass between ~ 300 and 1,000 GeV/c^2 in order to explain the Belle result and predicted *a priori* the observation of a large CP-violating phase in $B_s^0 \to J/\psi\,\phi$ decays [7, 8]. Another result of interest in the context of these measurements is the excess observed at ~ 350 GeV/c^2 in the recent t' search at CDF using 2.3 fb^{-1} of data [9]. In this direct search for a fourth generation up-type quark, a significance of less than 2σ is obtained for the discrepancy between the data and the predicted backgrounds, so that the effect, while intriguing, is presently consistent with a statistical fluctuation. A updated search with more data would also clearly be of interest, particularly if a large value of $\beta_s^{J/\psi\phi}$ persists with the addition of more data.



$\sin 2\Phi_{B_s} = -\sin\beta_s = \sin\phi_s$

(Conservative) outlook

% of CDF 'clones' that would observe a 5σ-effect, as a function of βs

Assumptions

✓ $\Delta\Gamma_s$ = 0.1 ps⁻¹

✓ Co… …g efficiency

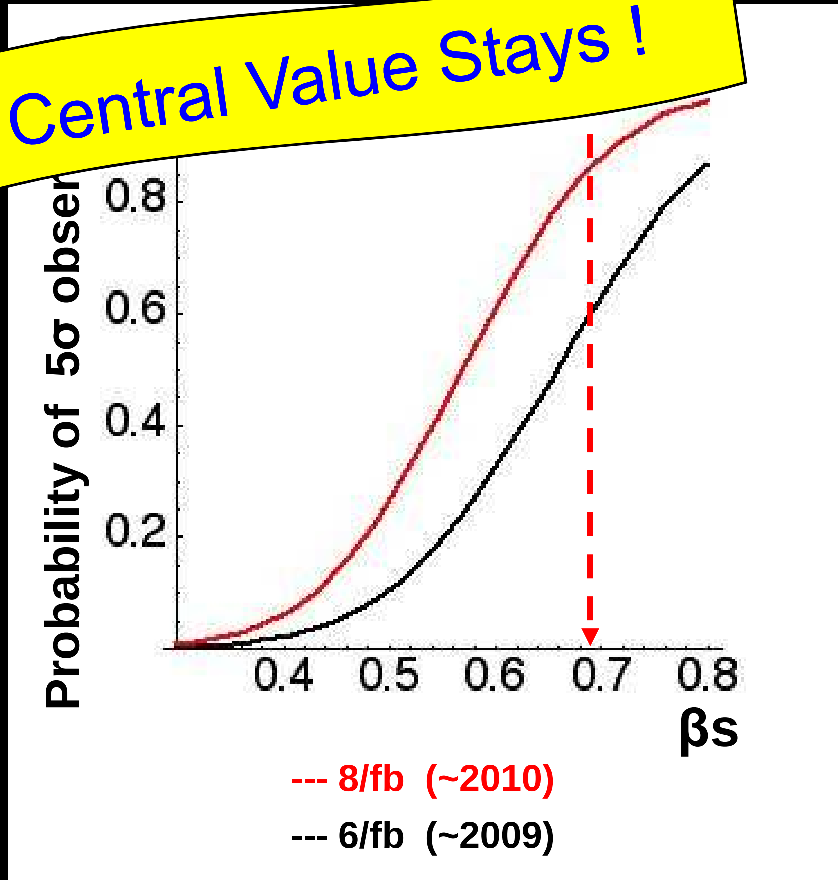
✓ No analysis improvements.

✓ No external constraints (A_{SL}, lifetimes) used.

CDF future will probably be better than that.

And DØ will contribute too.

Observation by 2010 if Central Value Stays !



IV. Soaring to the Heavens: Enough CPV for BAU?

If ... KM4

B.A.U. from CPV in KM ?

$\dfrac{n_{\bar{\mathcal{B}}}}{n_\gamma} \cong 0$

$$\frac{n_{\mathcal{B}}}{n_\gamma} = (6.2 \pm 0.2)\times 10^{-10}$$

WMAP

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

Too Small in SM

Why? Jarlskog Invariant in SM3 (need 3 generation in KM)

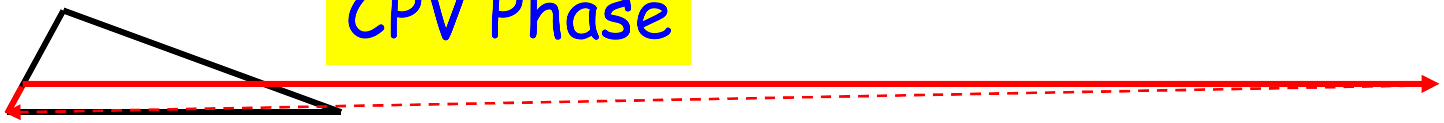
$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)\,A$$

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

masses too small !

$A \sim 3\times 10^{-5}$ in SM is common (unique) area of triangle

CPV Phase



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WMAP

KM ~ Enough CPV?

~~Too Small in SM~~

If shift by One Generation in SM4 (need 3 generation in KM)

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

Providence

WSH, arXiv:0803.1234 [hep/ph]

Moriond QCD

$$J^{sb}_{(2,3,4)} \simeq (m_{t'}^2 - m_c^2)(m_{t'}^2 - m_t^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_s^2)(m_{b'}^2 - m_b^2)(m_b^2 - m_s^2)\, A^{sb}_{234}$$

$$\sim \frac{m_{t'}^2}{m_c^2}\left(\frac{m_{t'}^2}{m_t^2} - 1\right)\frac{m_{b'}^4}{m_b^2 m_s^2}\frac{A^{sb}_{234}}{A} J$$

~ 10^{+15} Gain

Order 1 ~ 30

CPV Phase

Gain mostly in Large Yukawa Couplings !

Nature would likely use this !?

The Abyss between CPV in SM3 vs BAU
bridged in SM4 by *Heaviness of t' and b'*

Why wasn't this clearly
pointed out in past 20 years?

4th Generation Still?

- N_ν counting? 4th "neutrino" heavy

  Massive neutrinos call for new Physics

- Disfavored by EW Precision (see e.g. **J. Erler hep-ph/0604035; PDG06**

An extra generation of ordinary fermions is excluded at the 99.999% CL on the basis ...ameter alone, corresponding to $N_F = 2.81 \pm 0.24$ for the number of famili... assumes that there are no new contributions to T or U and the... ...ilies are degenerate. In principle this restriction...

Jul...

...traints on new physics **37**

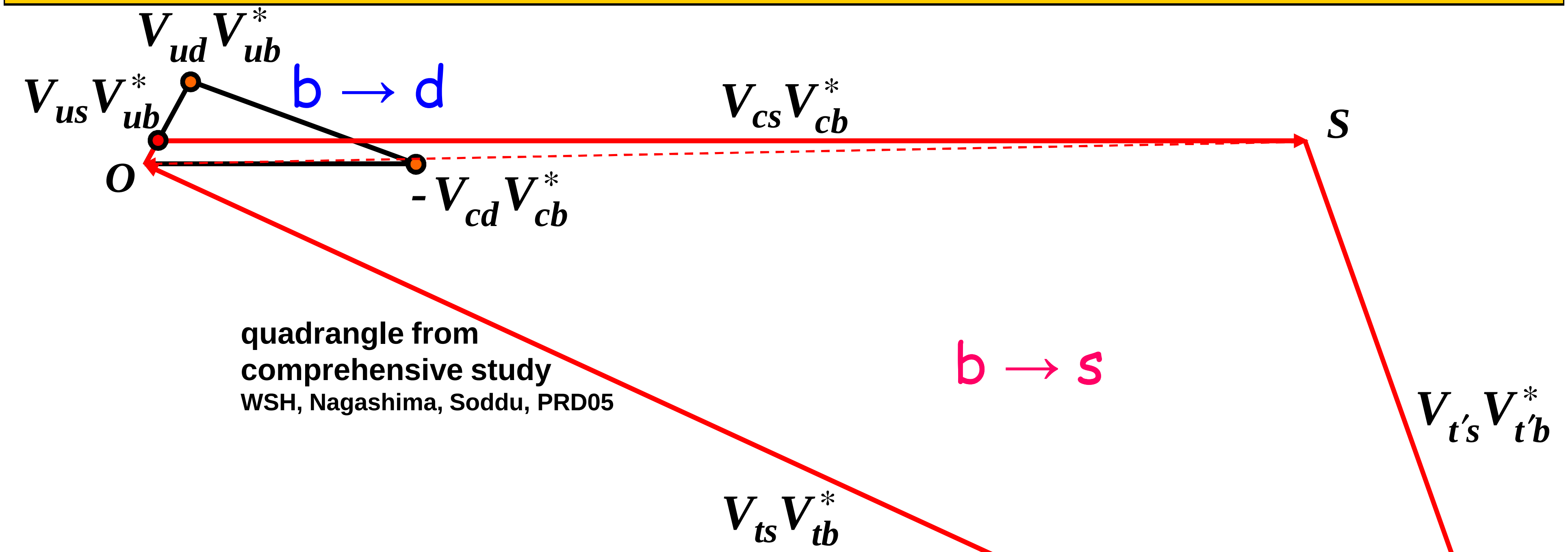
...cted from a non-degenerate extra family. However, ... < 0, thus strengthening the exclusion limits. A more detailed ...equired if the extra neutrino (or the extra down-type quark) is close to ...ass limit [208]. This can drive S to small or even negative values but at the expense of too-large contributions to T. These results are in agreement with a fit to the number of light neutrinos, $N_\nu = 2.986 \pm 0.007$ (which favors a larger value for $\alpha_s(M_Z) = 0.1231 \pm 0.0020$ mainly from R_ℓ and τ_τ). However, the S parameter fits are valid even for a very heavy fourth family neutrino.

(To Me) CPV Source for BAU Overrides These Concerns !

- 4th generation **not** in such great conflict with EWPrT

  Kribs, Plehn, Spannowsky, Tait, PRD'07

Gain mostly in Large Yukawa Couplings !



$$J^{sb}_{(2,3,4)} \simeq (m_{t'}^2 - m_c^2)(m_{t'}^2 - m_t^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_s^2)(m_{b'}^2 - m_b^2)(m_b^2 - m_s^2)\, A^{sb}_{234}$$

$$\sim \frac{m_{t'}^2}{m_c^2}\left(\frac{m_{t'}^2}{m_t^2} - 1\right)\frac{m_{b'}^4}{m_b^2 m_s^2}\,\frac{A^{sb}_{234}}{A}\, J$$

~ 10^{+15} Gain

$m_{b'}, m_{t'} \cong$ 300 GeV 10^{+13}

~ 600 GeV 10^{+15}

Only fac. 30 in CPV per se

This part will shrink a bit.

CPV for BAU: 2-3-4 Dominance

Jarlskog'85, 3 generations

$$\mathrm{Im}\,\det\left[\underbrace{m_u m_u^\dagger}_{S},\ \underbrace{m_d m_d^\dagger}_{S'}\right]$$

Jarlskog'87, n generations

$$\mathrm{Im}\,\mathrm{tr}[S, S']^3$$

"3 cycles"

also Gronau, Kfir, Loewy '87

4 generations: 3 indep. phases

long and short

d-*s* degenerate

(on v.e.v. scale)

2-3-4 generation only !

Effectively 3 generations

$$J^{sb}_{(2,3,4)} \simeq (m_{t'}^2 - m_c^2)(m_{t'}^2 - m_t^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_s^2)(m_{b'}^2 - m_b^2)(m_b^2 - m_s^2)\, A^{sb}_{234}$$

$$\sim \frac{m_{t'}^2}{m_c^2}\left(\frac{m_{t'}^2}{m_t^2} - 1\right)\frac{m_{b'}^4}{m_b^2 m_s^2}\,\frac{A^{sb}_{234}}{A}\,J$$

J(1,2,3) very small

suppressed by m_s, m_c

1st Order EW Phase Trans. for BAU ?

0803.1234 will appear in Chin. J. Phys.

Ran out of time, and knowledge ...

(perturbative)

- Fok & Kribs: Not possible in 4th generation — PRD'08 arXiv:0803.4207 [hep-ph]
- Conjecture: Could Strong Yukawa's do it ?

Beyond Unitarity Limit

arXiv:0901.1962v1 [hep-ph]

The strongly coupled fourth family and a first-order electroweak phase transition (I) quark sector

Not quite conclusive (?)

Yoshio Kikukawa,[1,*] Masaya Kohda,[2,†] and Junichiro Yasuda[3,‡]

[1] *Institute of Physics, University of Tokyo Tokyo 153-8092, Japan*
[2] *Department of Physics, Nagoya University Nagoya 464-8602, Japan*
[3] *Center for the Studies of Higher Education, Nagoya University Nagoya 464-8601, Japan*

(Dated: January 14, 2009)

In models of dynamical electroweak symmetry breaking due to strongly coupled fourth-family quarks and leptons, their low-energy effective descriptions may involve multiple composite Higgs fields, leading to a possibility that the electroweak phase transition at finite temperature is first order due to the Coleman-Weinberg mechanism. We examine the behavior of the electroweak phase transition based on the effective renormalizable Yukawa theory which consists of the fourth-family quarks and two SU(2)-doublet Higgs fields corresponding to the bilinear operators of the fourth-family quarks with/without imposing the compositeness condition. The strength of the first-order

SSB

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

Photo: Universtity of Chicago

Yoichiro Nambu

1/2 of the prize

USA

Enrico Fermi Institute,
University of Chicago
Chicago, IL, USA

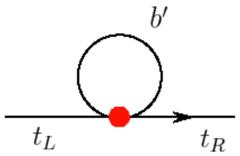
b. 1921
(in Tokyo, Japan)

$\langle \bar{Q}Q \rangle$ can Condense by Large Yukawa !

Could EWSB be
due to b′ and t′
above unitarity bound ~ 500-600 GeV ?

Bob Holdom: N–J-L

[Bardeen, Hill, Lindner



Gustavo Burdman: “Holographic” 4th gen.

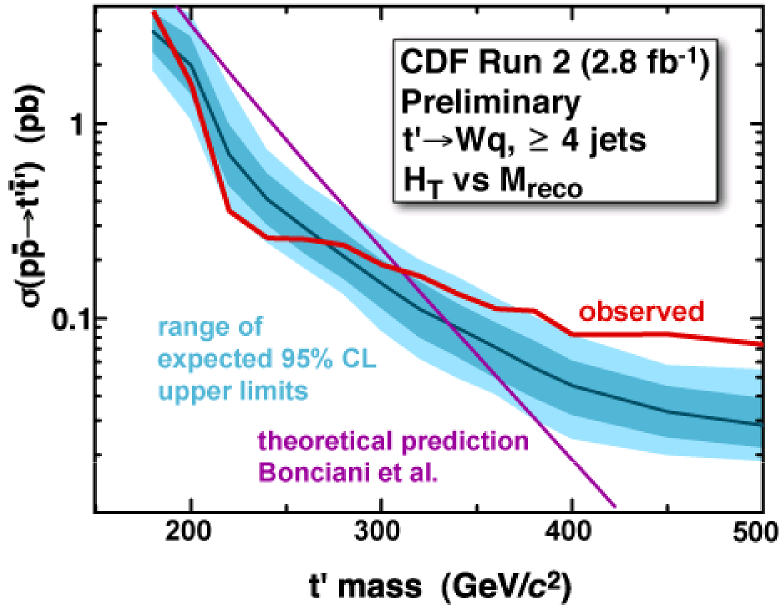
V. Direct Sighting @ Tevatron vs LHC

the Experimentalist

Tevatron/LHC Verification

Tevatron *Unequivocal BSM* ... if true

- $\sin 2\Phi_{B_s}$ "Evidence" by 2009 ?
  "Observe" by 2010 ?
- t′ Search Ongoing:
  $m_{t'}$ > 311 GeV @ 95% CL



LHC

- $\sin 2\Phi_{B_s}$ "Confirmation" — "Easy" for LHCb
- b′, t′ Discovery — Straightforward/full terrain

But when ?

Agenda of Taiwan-CMS

Sighting

Vision ~ Early '06

4th generation? — The jury is out …

In era of LHC, can Directly Search for b′, t′
Once and For All !

Find b′, t′, or Rule Out @ LHC

It's a Duty.

Strategy Considerations (漢中策略)

- **Well shielded training ground — All Tools**
  - ☞ Move on to Greener Pastures ~ in 2 years
- **Publish early — Large Cross Section**
  - **- If "Limits", then easy to publish**
  - **- If "Signal", Lucked Out!**

b′ Signatures

For $m_{b'} < m_t + M_W$ = 255 GeV

b′ → cW dominance — for sizable $V_{cb'}$

b′ → tW* dominance — for suppressed $V_{cb'}$

Kinematic suppressed for $m_{b'} \lesssim$ 230 GeV

Initial discovery should consider

b′ → cW ~ b′ → bZ, bH ~ b′ → tW*

Rich Signature

cc(bar)WW; cWbZ; cWbH; ← Bonus !!

tc(bar)WW*;

tt(bar)W*W*; tW*bZ; tW*bH;

For $m_{b'} > m_t + M_W$ = 255 GeV

b′ → tW dominance; FCNC searchable

tt(bar)WW → bb(bar)$W^+W^-W^+W^-$

Heavy Q related To EWSB ?

4 W's + 2b's

Available on the CMS information server

CMS PAS EXO-08-09

CMS Physics Analysis Summary

2008/08/29

Search for Heavy Bottom-like Fourth Generation Quark Pair at CMS in pp Collisions at $\sqrt{s} = 14$ TeV

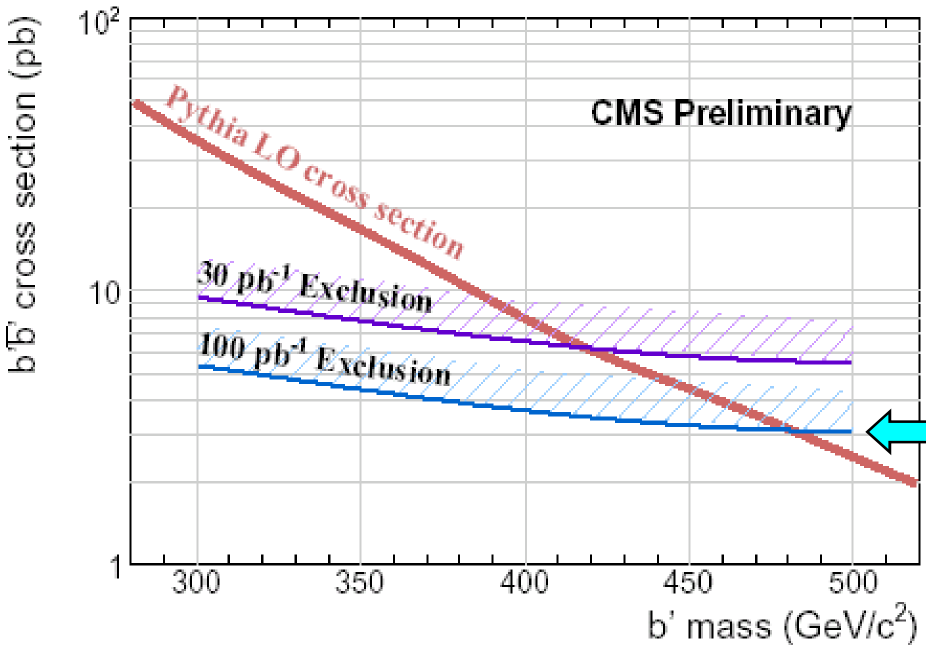
The CMS collaboration

$$pp \to b'\bar{b}' \to t\bar{t}W^+W^-$$

$100\ \mathrm{pb}^{-1}$

same-sign dilepton and trilepton

b' Mass	300 GeV/c^2	400 GeV/c^2	500 GeV/c^2
$b'\bar{b}'$ LO cross section	34.9 pb	8.05 pb	2.45 pb
Expected signal yield	68.2	22.2	8.0
Expected background yield		$7.3^{+10.5}_{-4.8}$	
S_{12}	7.5σ	2.0σ	0.0σ
S_{cP}	N/A	2.1σ	0.0σ



Limit to 480 GeV w/ $100\ \mathrm{pb}^{-1}$

$$J^{sb}_{(2,3,4)} \simeq (m_{t'}^2 - m_c^2)(m_{t'}^2 - m_t^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_s^2)(m_{b'}^2 - m_b^2)(m_b^2 - m_s^2)\, A^{sb}_{234}$$

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~ 10^{+15} Gain

Even if $O(1)$

$m_{b'}, m_{t'} \cong$ 300 GeV 10^{+13}

~ 600 GeV 10^{+15}

Enough CPV for B.A.U.

Maybe there is a 4th Generation !

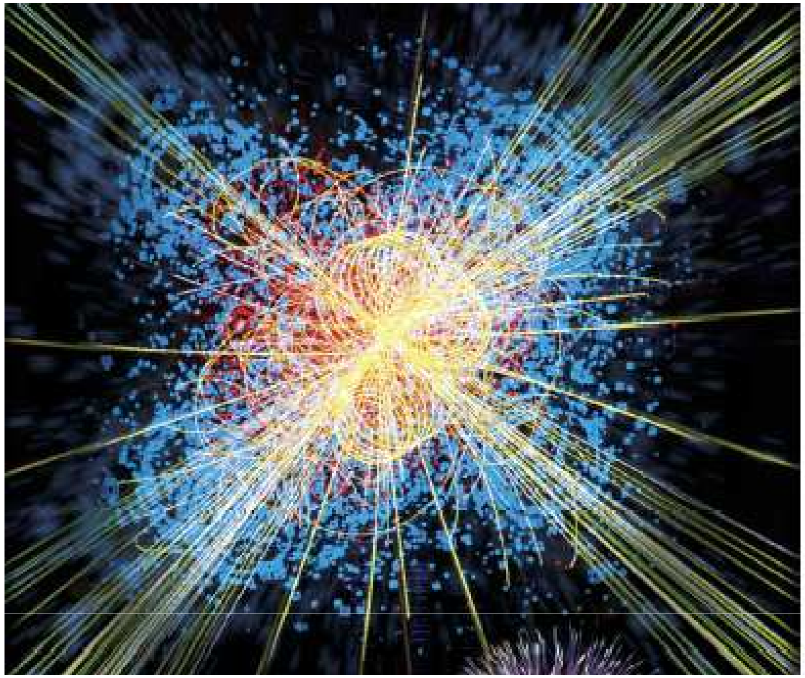
$\sin 2\Phi_{B_s}$ @ Tevatron by 2010

Will Really Know in ~ 3–5 years !

@ LHC

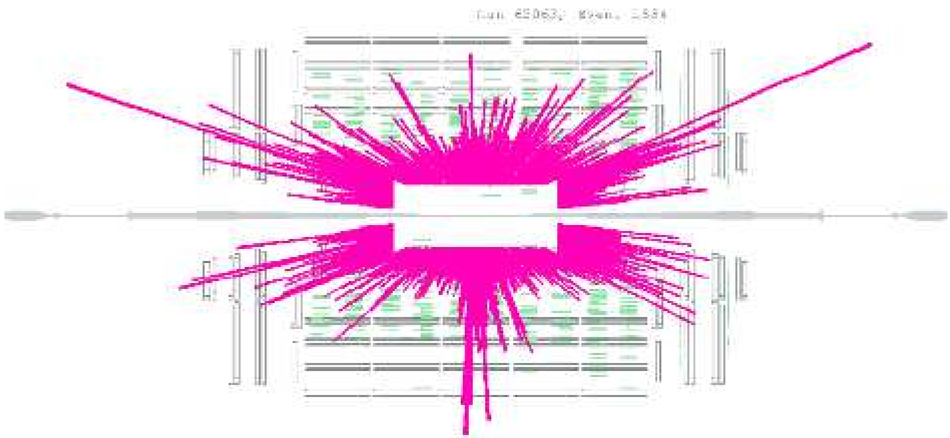
⇒ *Heaven on Earth?*

Universe (Genesis)



CPV

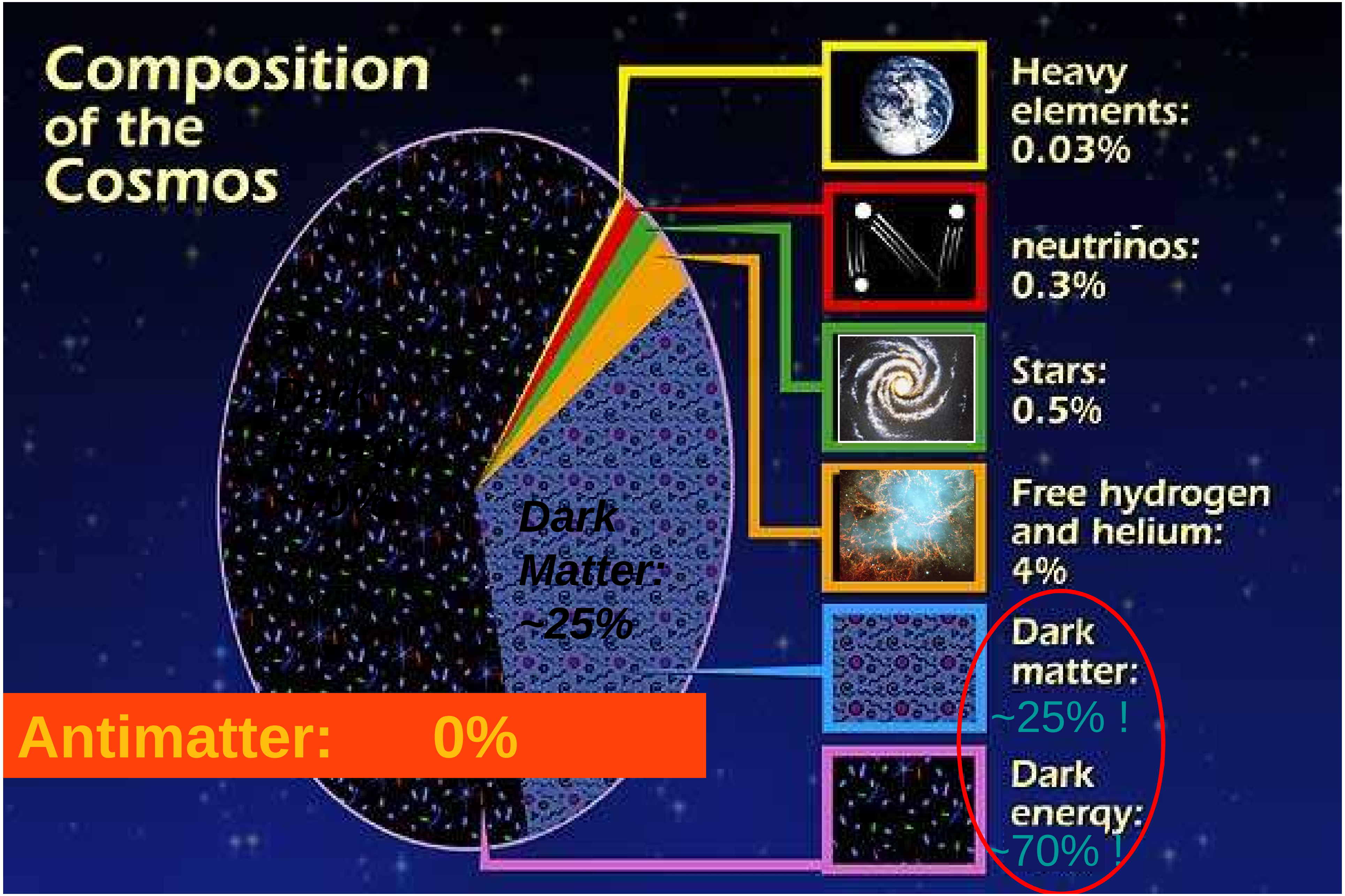
BAU



Earth (EW + KM4)

Backup

Matter (and More !!) Universe: No Antimatter



"Affleck-Dine", SUSY etc.:

Extra *Scalars* (strongly) coupled to H^0

More Scalars!

Let's first find One Scalar.

Leptogenesis:

Heavy Majorana Neutrinos

$\oplus$ **LFV/CPV Decay**

$\oplus$ B/L Violation (**"EW Baryogenesis"**)

Popular ! Driving θ_{13} study for neutrinos.

But, "Heavenly" — Could be(come) Metaphysics

i in Dynamics: Source of CPV

ElectroMagnetism: (everyone can feel

Charge *e* is *Real*.

"We" Understand: *Gauge* Charge is Real.

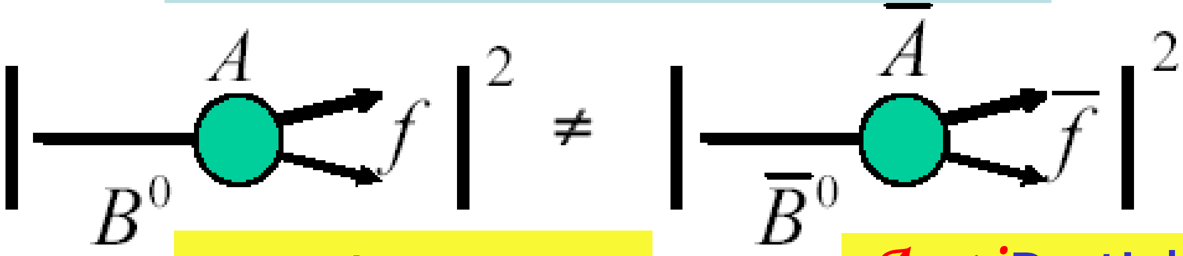
Imagine a Complex Coupling :

True, or, Possible, for Yukawa (湯川) Coupling of quarks/leptons to Higgs boson(s)...

Quantum Interference in ***Amplitude*** More Interesting

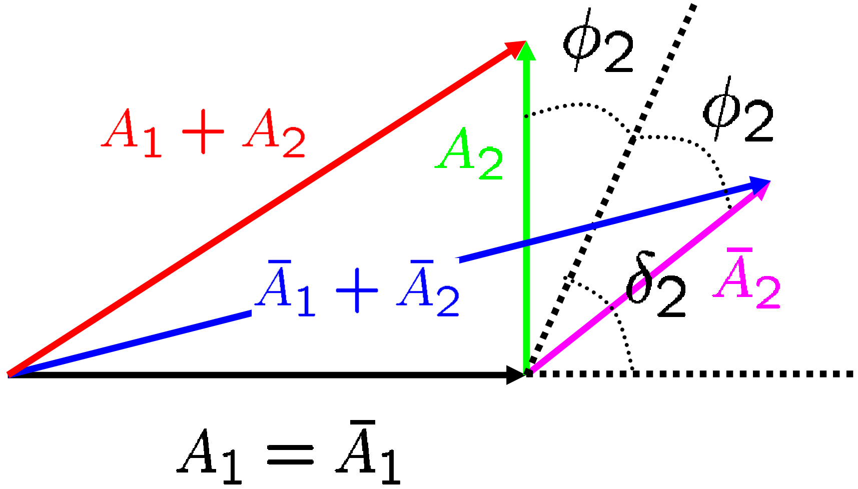
→ How CP Violation Appears

CP Violation Primer



Particle Process

*Anti*Particle Process



$$A = A_1 + A_2 = a_1 + a_2 e^{i\delta_2} e^{i\phi_2}$$

$$\bar{A} = \bar{A}_1 + \bar{A}_2 = a_1 + a_2 e^{i\delta_2} e^{-i\phi_2}$$

$$A^{CP} = \frac{\Gamma(\bar{B}^0 \to \bar{f}) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to \bar{f}) + \Gamma(B^0 \to f)} = \frac{2a_1 a_2 \sin\phi_2 \sin\delta_2}{a_1^2 + a_2^2 + 2a_1 a_2 + 2a_1 a_2 \cos\phi_2 \cos\delta_2}$$

CP Asymmetry needs *both* CP Conserv/Violating Phase

i_{QM} i_{dyn}

$$\Delta A_{K\pi} = \overset{+0.050\pm0.025}{A_{B\to K^+\pi^0}} - \overset{-0.097\pm0.012}{A_{B\to K^+\pi^-}} \neq 0$$

World

$= +0.147\pm0.028 \quad > 5\sigma$

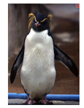
Experiment is Firm

Why a Puzzle ?

$\Delta A_{K\pi} \sim 0$ expected

$$\mathcal{M}(B^0 \to K^+\pi^-) \propto (T + P) = re^{i\phi_3} + e^{i\delta}$$

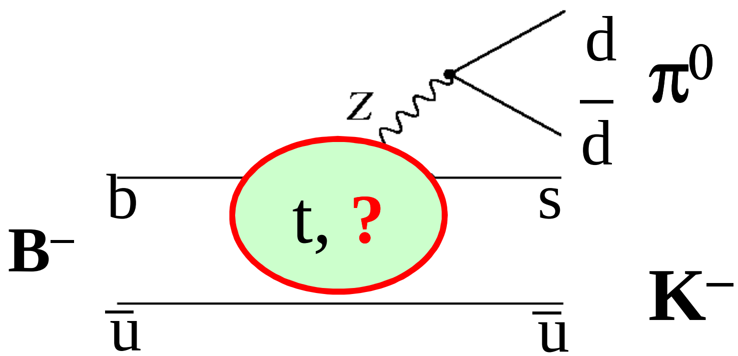
$$\sqrt{2}\mathcal{M}_{K^+\pi^0} - \mathcal{M}_{K^+\pi^-} \propto (P_{EW} + C)\ ?$$

$r =$  / 

Large C ? ⇒ ***A lot of (hadronic) finesse***

Baek, London, PLB653, 249 (2007)

Large EWPenguin ? ⇒ ***Need NP CPV Phase***



P_{EW} has practically no weak phase in SM

$$\Delta A_{K\pi} = \overset{+0.050\pm0.025}{A_{B\to K^+\pi^0}} - \overset{-0.097\pm0.012}{A_{B\to K^+\pi^-}} \neq 0$$

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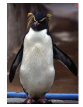
$r =$  / 

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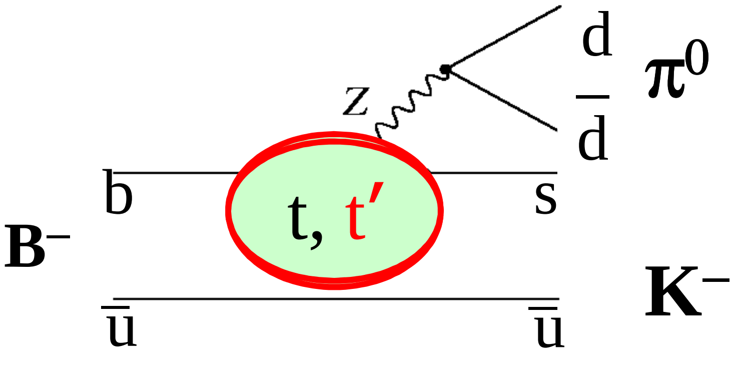
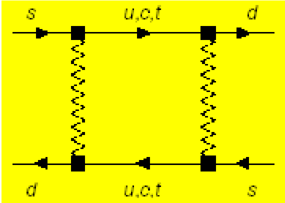


P_{EW} has practically no weak phase in SM

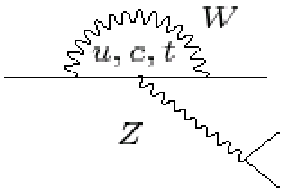
4th Gen. in EWP Natural

nondecoupling

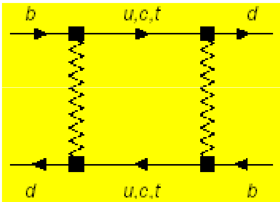
On Boxes and Z Penguins



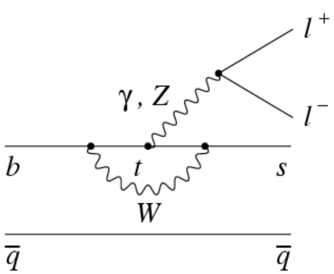
GIM, charm, ε_K

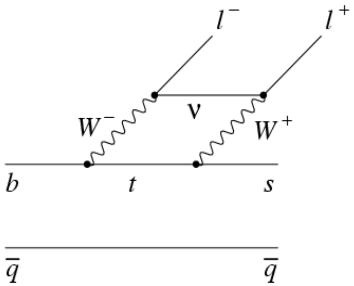


small ε'/ε, $K \to \pi\nu\nu$ (still waiting)



heavy top, $\sin 2\phi_1/\beta$





Z dominance for heavy top

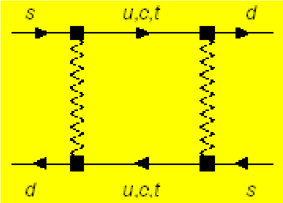
1986 $\to$ 2002

Most Flavor/CPV learned from these diagrams/processes

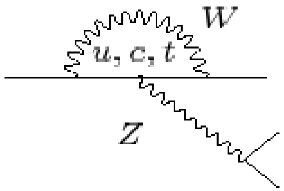
On Boxes and Z Penguins

Nondecoupling

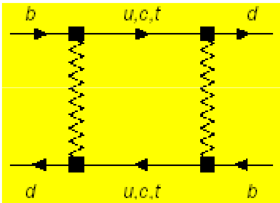
∵ Large Yukawa !



⇒ GIM, charm, ε_K

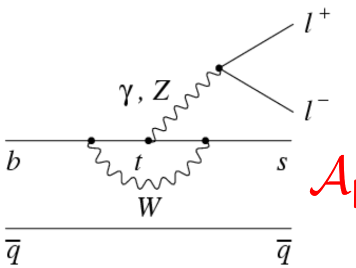


⇒ small ε'/ε, K → πνν (still waiting)

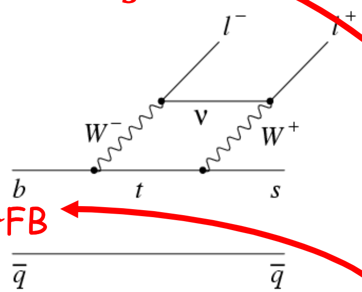


⇒ heavy top, sin$2\phi_1/\beta$

B_s



$\mathcal{A}_{FB}$



⇒ Z dominance for heavy top

1986 → 2002

All w/ 3-generations,
Just wait if there's a 4th

D !

b′, **t′** @ LHC

4 x 4 Unitarity ⇨ Constraints

	d	s	b	b'
u	$c_{12}c_{13}c_{14}$ $-c_{13}s_{12}s_{14}s_{24}\exp[-i(\phi_{db}-\phi_{sb})]$ $-c_{24}s_{13}s_{14}s_{34}\exp[-i(\phi_{db}+\phi_{ub})]$	$c_{13}c_{24}s_{12}$ $-s_{13}s_{24}s_{34}\exp[-i(\phi_{sb}+\phi_{ub})]$	$c_{34}s_{13}\exp[-i\phi_{ub}]$ **SM3**	$c_{12}c_{13}s_{14}\exp[i\phi_{db}]$ $+c_{13}c_{14}s_{12}s_{24}\exp[i\phi_{sb}]$ $+c_{14}c_{24}s_{13}s_{34}\exp[-i\phi_{ub}]$
c	$-c_{14}c_{23}s_{12}$ $-c_{12}c_{14}s_{13}s_{23}\exp[i\phi_{ub}]$ $-c_{12}c_{23}s_{14}s_{24}\exp[-i(\phi_{db}-\phi_{sb})]$ $+s_{12}s_{13}s_{14}s_{23}s_{24}\exp[-i(\phi_{db}-\phi_{sb}-i\phi_{ub})]$ $-c_{13}c_{24}s_{14}s_{23}s_{34}\exp[-i\phi_{db}]$	$c_{12}c_{23}c_{24}$ $-c_{24}s_{12}s_{13}s_{23}\exp[i\phi_{ub}]$ $-c_{13}s_{23}s_{24}s_{34}\exp[-i\phi_{sb}]$	$c_{13}c_{34}s_{23}$	$-c_{23}s_{12}s_{14}\exp[i\phi_{db}]$ $-c_{12}s_{13}s_{14}s_{23}\exp[i(\phi_{db}+\phi_{ub})]$ $+c_{12}c_{14}c_{23}s_{24}\exp[i\phi_{sb}]$ $-c_{14}s_{12}s_{13}s_{23}s_{24}\exp[i(\phi_{sb}+\phi_{ub})]$ $+c_{13}c_{14}c_{24}s_{23}s_{34}$
t	$-c_{12}c_{14}c_{23}s_{13}\exp[i\phi_{ub}]$ $+c_{14}s_{12}s_{23}$ $+c_{23}s_{12}s_{13}s_{14}s_{24}\exp[-i(\phi_{db}-\phi_{sb}-i\phi_{ub})]$ $+c_{12}s_{14}s_{23}s_{24}\exp[-i(\phi_{db}-\phi_{sb})]$ $-c_{13}c_{23}c_{24}s_{14}s_{34}\exp[-i\phi_{db}]$	$-c_{23}c_{24}s_{12}s_{13}\exp[i\phi_{ub}]$ $-c_{12}c_{24}s_{23}$ $-c_{13}c_{23}s_{24}s_{34}\exp[i\phi_{sb}]$	$c_{13}c_{23}c_{34}$	$-c_{12}c_{23}s_{13}s_{14}\exp[i(\phi_{db}+\phi_{ub})]$ $+s_{12}s_{14}s_{23}\exp[i\phi_{db}]$ $-c_{14}c_{23}s_{12}s_{13}s_{24}\exp[i(\phi_{sb}+\phi_{ub})]$ $-c_{12}c_{14}s_{23}s_{24}\exp[i\phi_{sb}]$ $+c_{13}c_{14}c_{23}c_{24}s_{34}$
t'	$-c_{24}c_{34}s_{14}\exp[-i\phi_{db}]$	$-c_{34}s_{24}\exp[-i\phi_{sb}]$	$-s_{34}$	$c_{14}c_{24}c_{34}$

We need to deal with mixing matrix in detail to keep Unitarity

$$V^*_{t's}V_{t'd} = c_{24}c_{34}^2 s_{14}s_{24}e^{i(\phi_{sb}-\phi_{db})} \equiv r_{ds}\ \phi_{ds}$$

Kaon

$$V^*_{t's}V_{t'b} = c_{34}s_{24}s_{34}e^{i\phi_{sb}} \equiv r_{sb}$$

b → s

$$V^*_{t'd}V_{t'b} = c_{24}c_{34}s_{14}s_{34}e^{i\phi_{db}} = \frac{r_{ds}s_{34}^2}{r_{sb}}e^{i\phi_{db}}$$

b → d

Cross Check !

$\Gamma(Z \to \text{hadrons})$

impose $s_{34} = 0.22 \simeq V_{us}$

$|V_{tb}|^2 + 3.4|V_{t'b}|^2 < 1.14$ for $m_{t'} = 300$ GeV $\Rightarrow s_{34} < 0.25$

From b → s study $r_{sb}\, e^{i\phi_{sb}} \simeq 0.025\, e^{i\,70^\circ}$

Constrain s ↔ d from K Physics

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (14.7^{+13.0}_{-8.9}) \cdot 10^{-11}$$ (shaded)

$$BR(K_L \to \mu^+\mu^-)_{SD} < 3.75 \cdot 10^{-9}$$

$$\epsilon_K = (2.284 \pm 2 \times 0.014) \cdot 10^{-3}$$

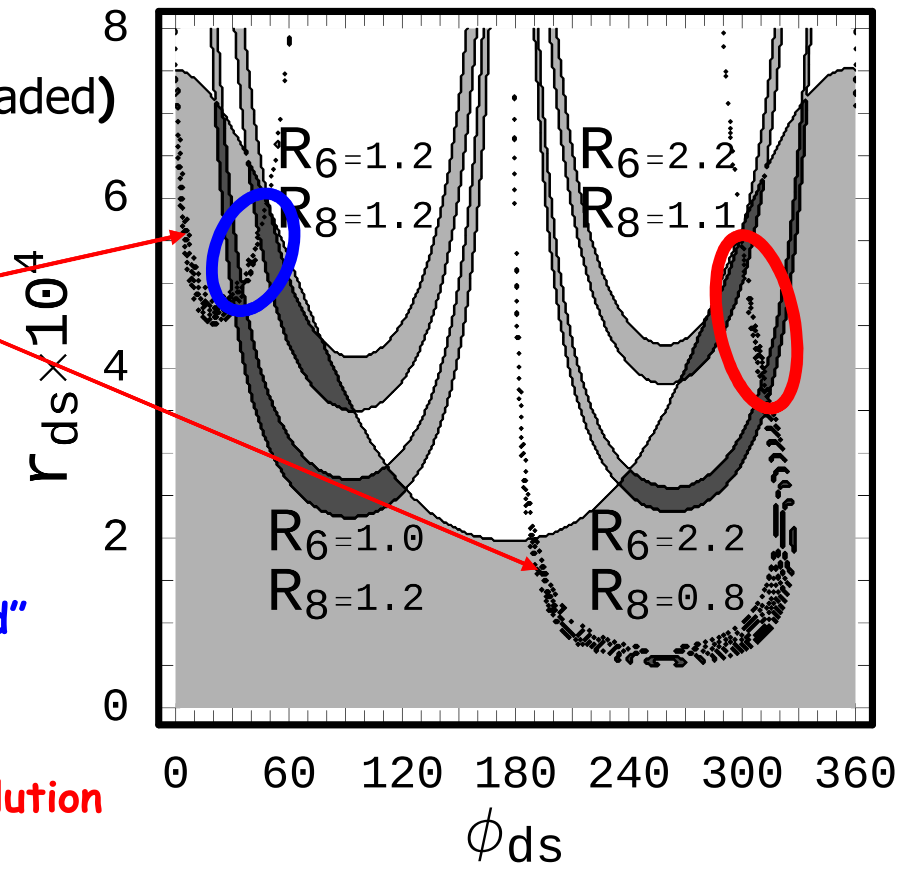
$$\frac{\epsilon'}{\epsilon} = (16.6 \pm 2 \times 1.6) \cdot 10^{-4}$$

$R_6 = 1.2$ **(E. Pallante et al.)**

$R_8 = 0.7 - 1.3$ **"Standard"**

$R_6 = 2.2$ **(J. Bijnens et al.)**

$R_8 = 0.8 - 1.4$ **No SM3 solution**



Therefore….

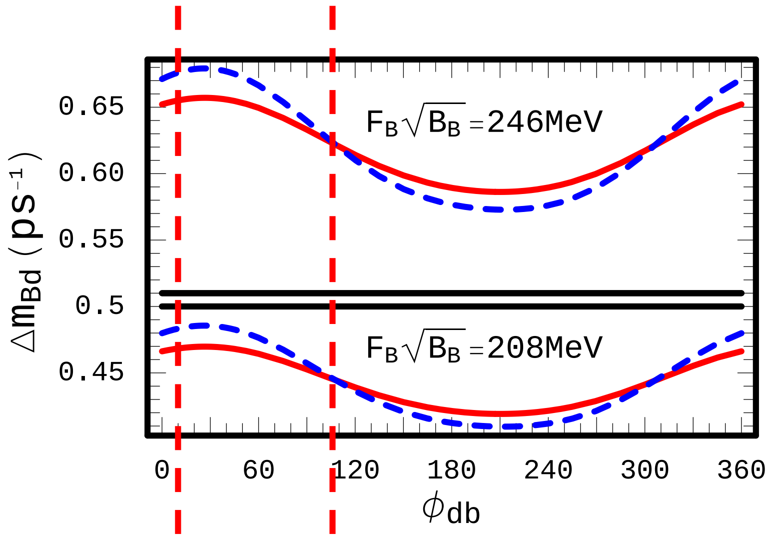
$$r_{ds} \sim 5 \times 10^{-4}, \quad \phi_{ds} \sim -60^\circ \text{ or } +35^\circ$$

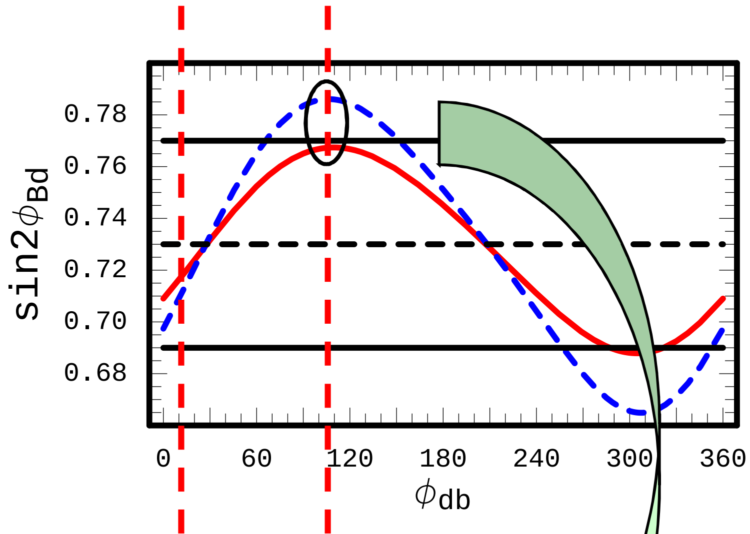
well-satisfy Δm_{B_d} and $\sin 2\phi_1$ **!**

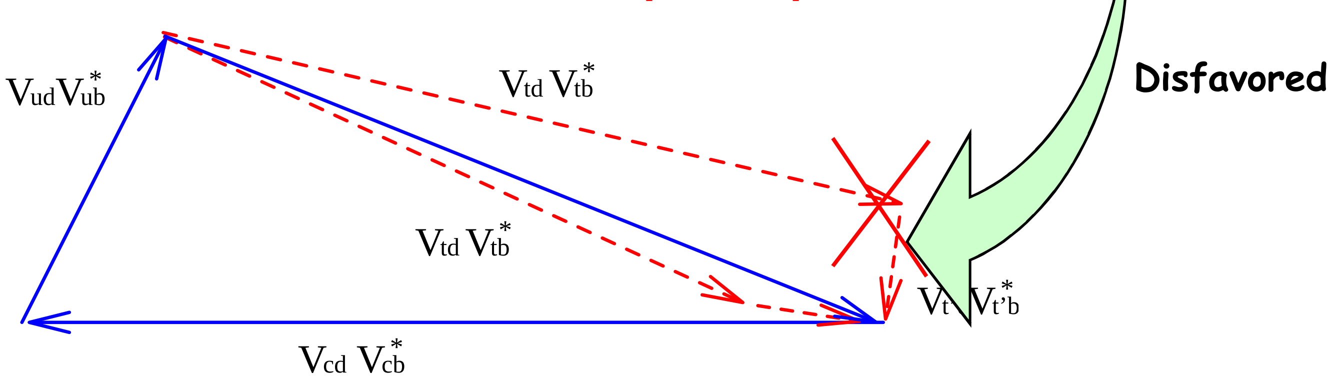
$$r_{ds} \sim 5 \times 10^{-4}, \quad \phi_{ds} \sim -60^\circ \text{ or } +35^\circ$$

$$r_{db} \sim 1 \times 10^{-3}, \quad \phi_{db} \sim 10^\circ \ (105^\circ)$$

well-satisfy Δm_{B_d} and $\sin 2\phi_1$ vs $V_{ub} \sim 0.01\, e^{-i\gamma}$







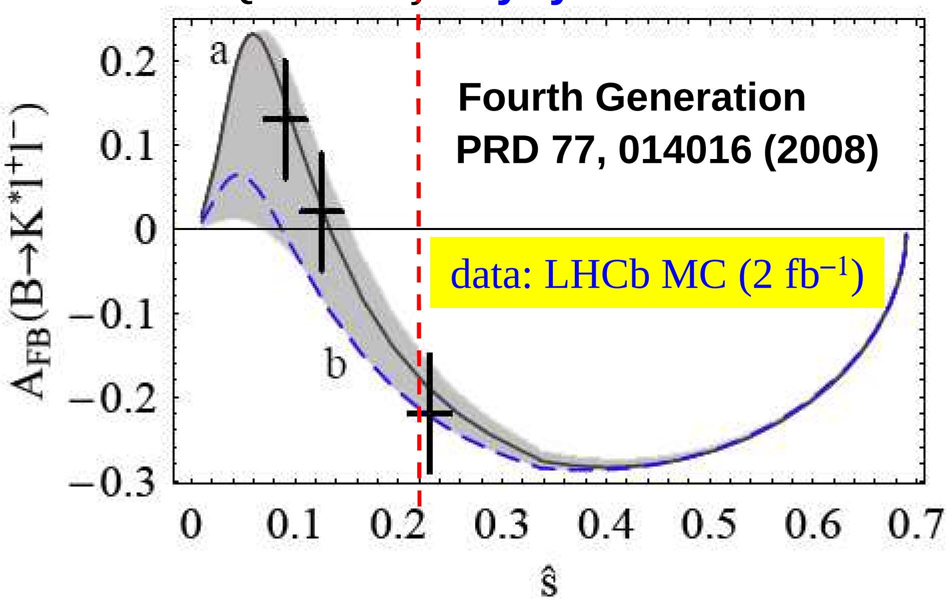
Hard to tell apart (non-trivial) with present precision

∵ stringent s → d

$\mathcal{A}_{FB}(B \to K^* l^+ l^-)$ and Other Predictions

sent to Backup

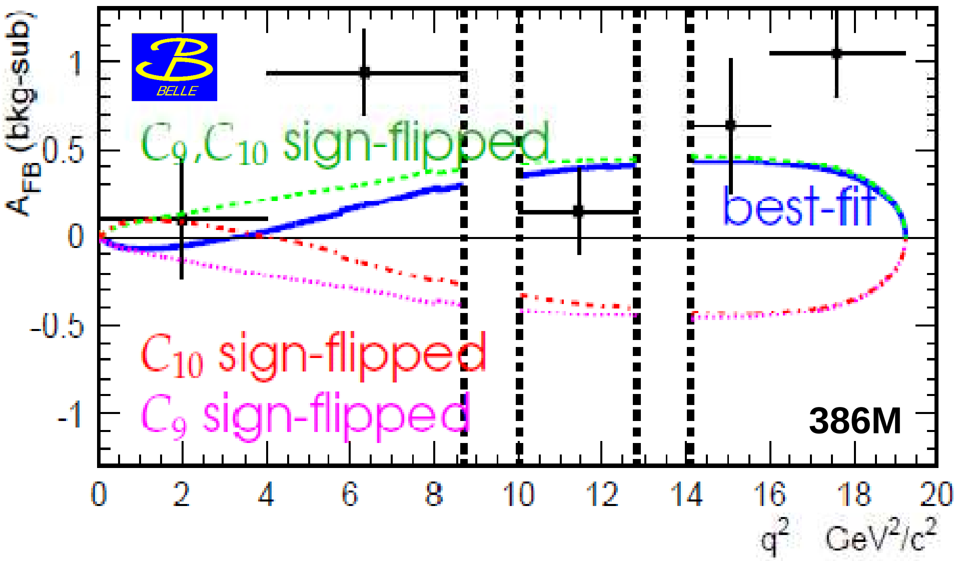
Quoted by **Tsybychev at FPCP08**

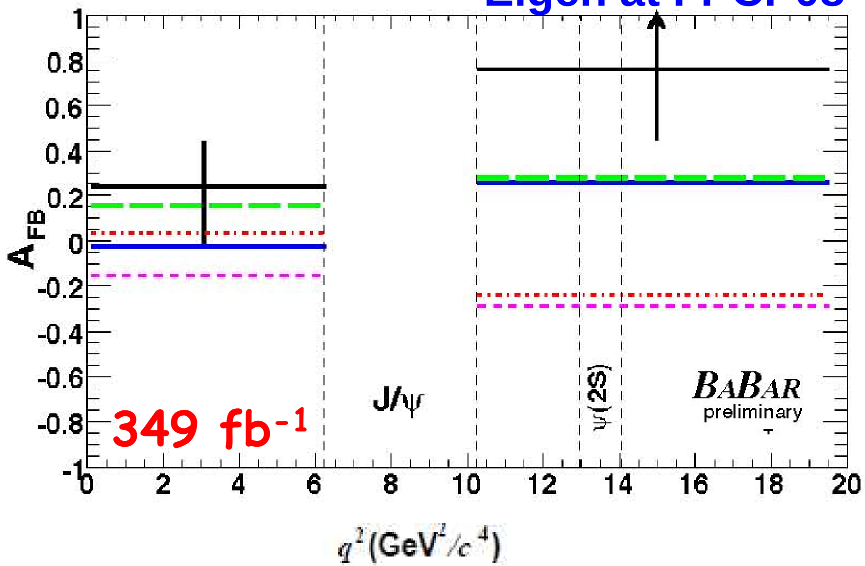


a: SM; b: 4 Gen. better

- $\mathcal{F}_L$ and) $\mathcal{A}_{FB}$ (and A_I) favor the "opposite-sign C_7 model"

Eigen at FPCP08



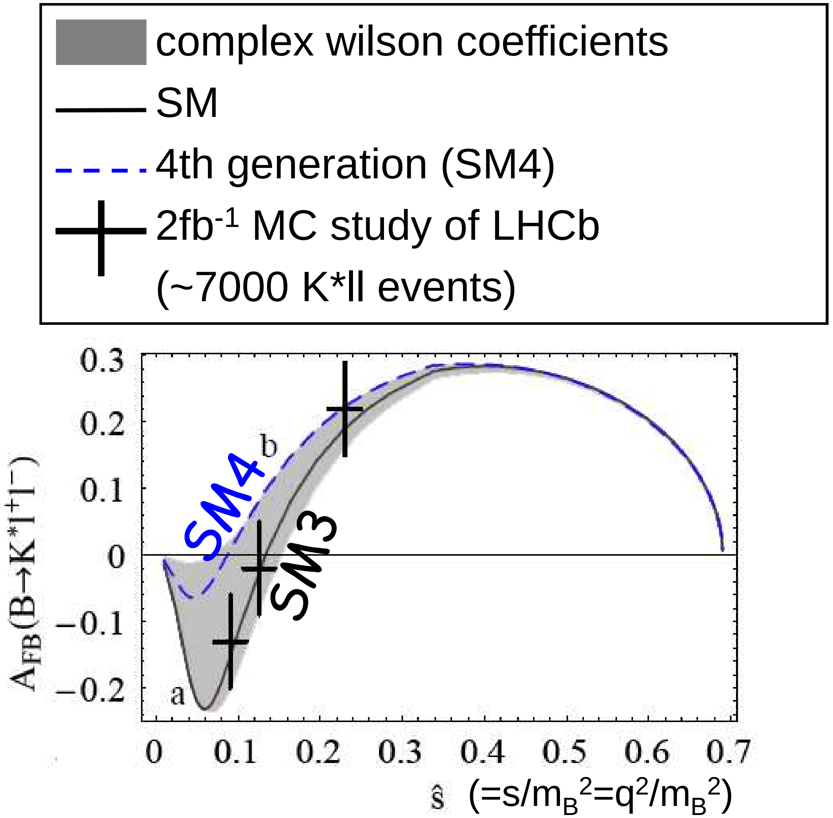


Instead flipped C_7 ...

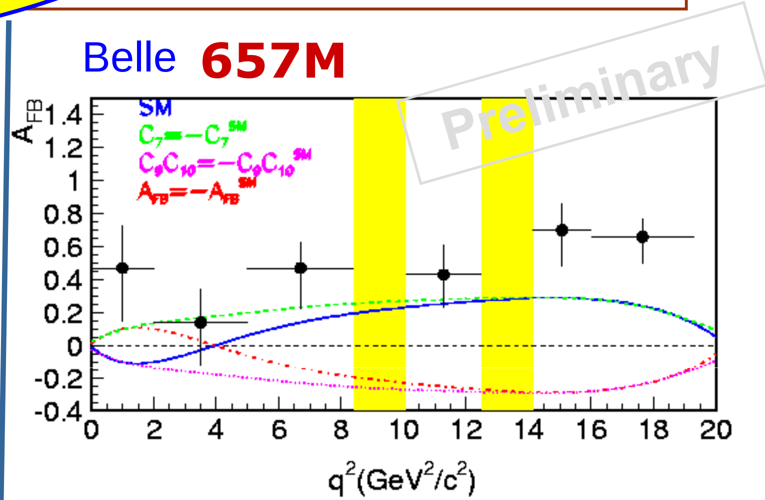
Deviation from SM3 Strengthened !

$$\frac{dA_{FB}}{d\hat{s}} \propto -\Big\{ \mathrm{Re}(C_9^{eff} C \ldots \hat{m} \ldots m_{K^*}) + A_1 T_1 (1+\hat{m}_{K^*})] \Big\}$$

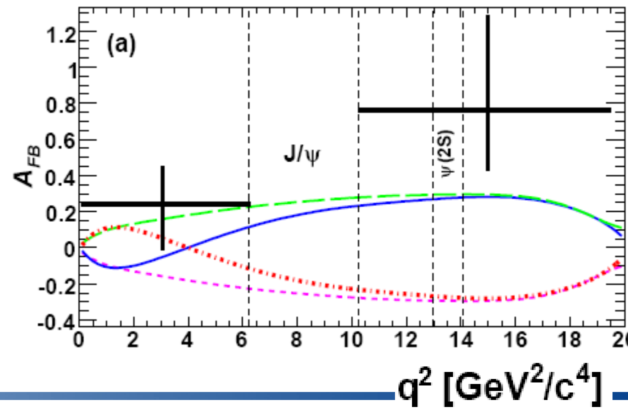
W.-S. Hou, A. ... ...yan, and N. Mahajan, PRD 77, 014016 (2008)



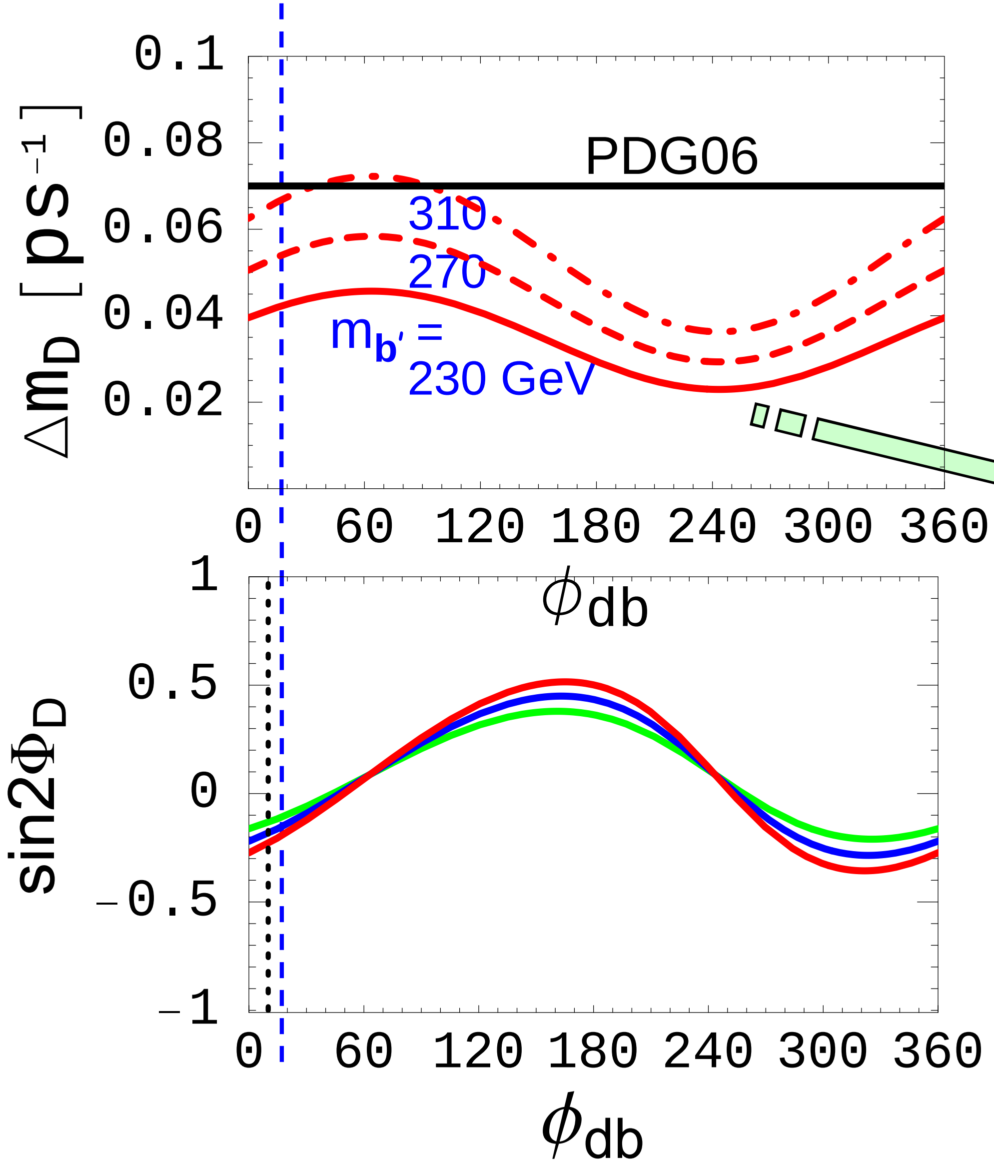
Belle **657M**



BABAR, arXiv:0804.4412 **386M**



D Mixing (Short-distance Only)



$$f_D\sqrt{B_D} = 200\ \text{MeV}$$

$$V^*_{t'd}V_{t'b} \equiv r_{db}e^{i\phi_{db}}$$

⇕ From 4 x 4 Unitarity

$$V_{ub'}V^*_{cb'}$$

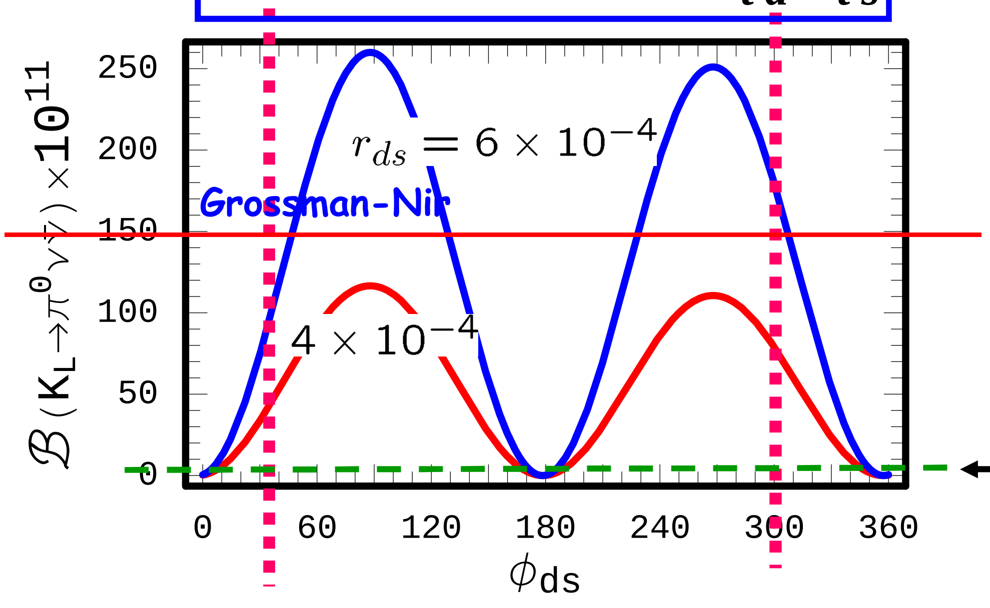
x = Δm/Γ ~ 1 - 3 plausible

w/ Sizable (but not huge)
CPV in Mixing ~ –15%

N.B. SM LD could generate
y ~ 1%, x ≈ y
[**Falk, Grossman, Ligeti, (Nir,) Petrov**]

Implication for $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$

Nontrivial (phase) $V^*_{t'd} V_{t's}$



Current E391A U.L.

2.86×10^{-7} (90% c.l.)

Very hard to measure

$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \simeq 3 \times 10^{-11}$

SM3

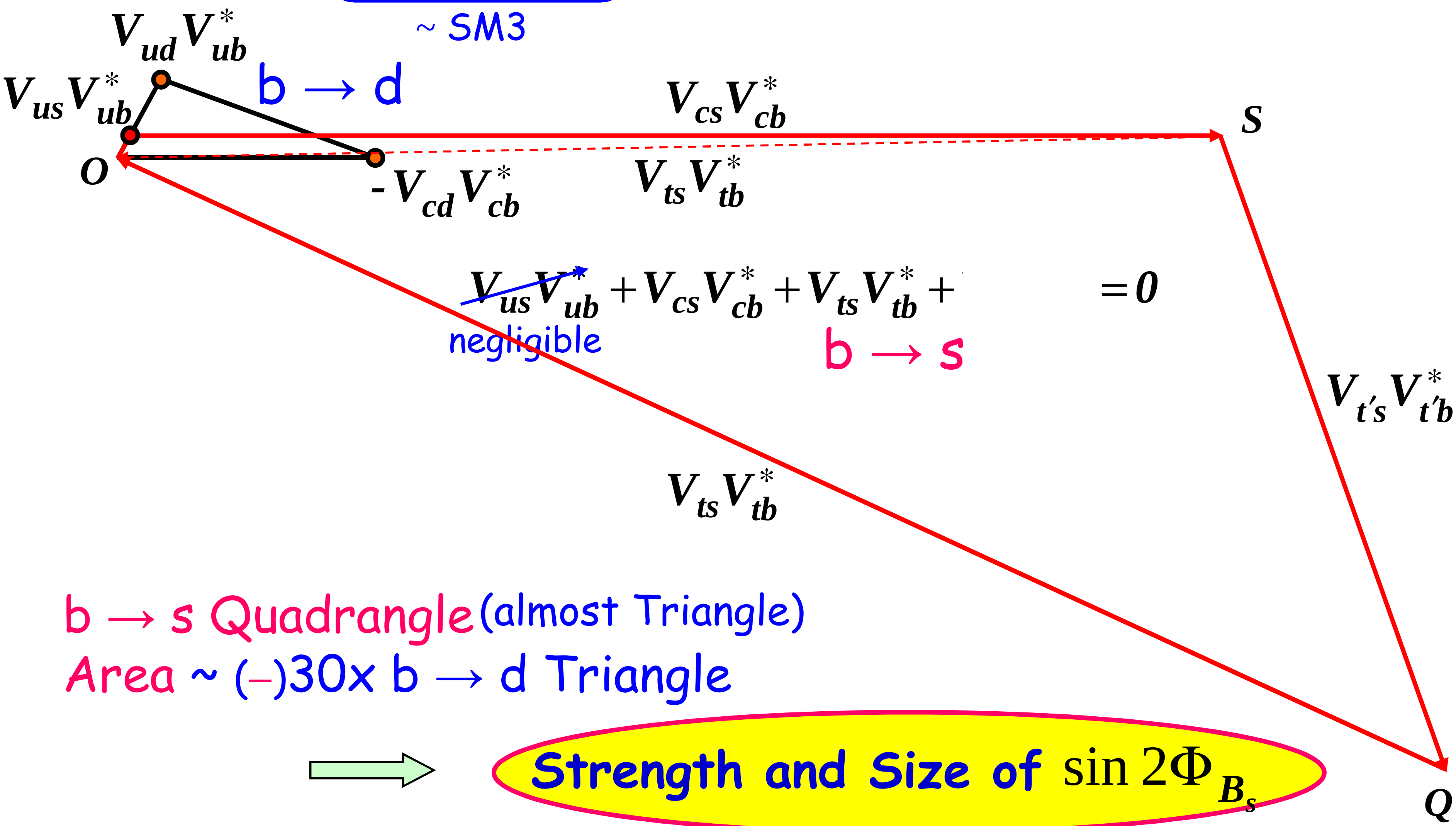
Rate could be enhanced by up to almost two orders !!

$K_L \to \pi^0 \nu\bar{\nu}$ **enhanced to** 5×10^{-10} **or even higher !!**

In general larger than $K^+ \to \pi^+ \nu\bar{\nu}$ $(2\text{–}3 \times 10^{-10})$

∵ Large CPV Phase

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + \underbrace{V_{td}V_{tb}^* + V_{t'd}V_{t'b}^*}_{\sim\ \text{SM3}} = 0$$



$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* + \quad = 0$$

negligible

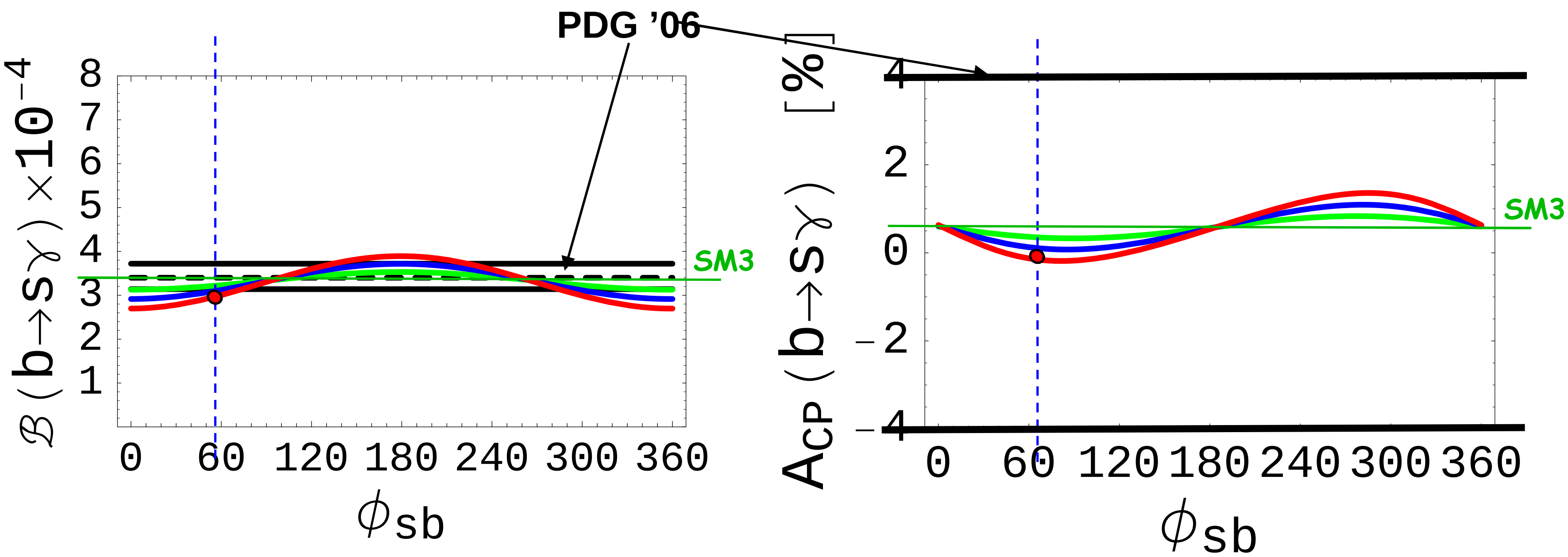
b → s

b → s Quadrangle (almost Triangle)

Area ~ (–)30x b → d Triangle

⇨ **Strength and Size of** $\sin 2\Phi_{B_s}$

Consistency and b → sγ Predictions

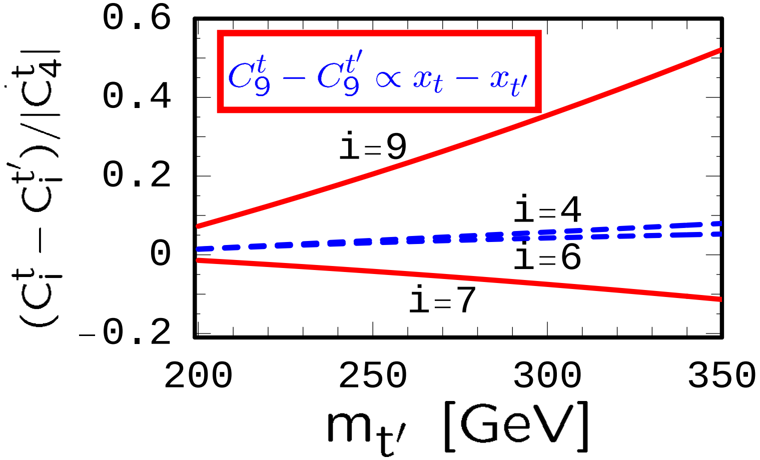


BR OK

A_{CP} ~ 0 far away

beyond SuperB

Heavy t′ effect decoupled for b → sγ



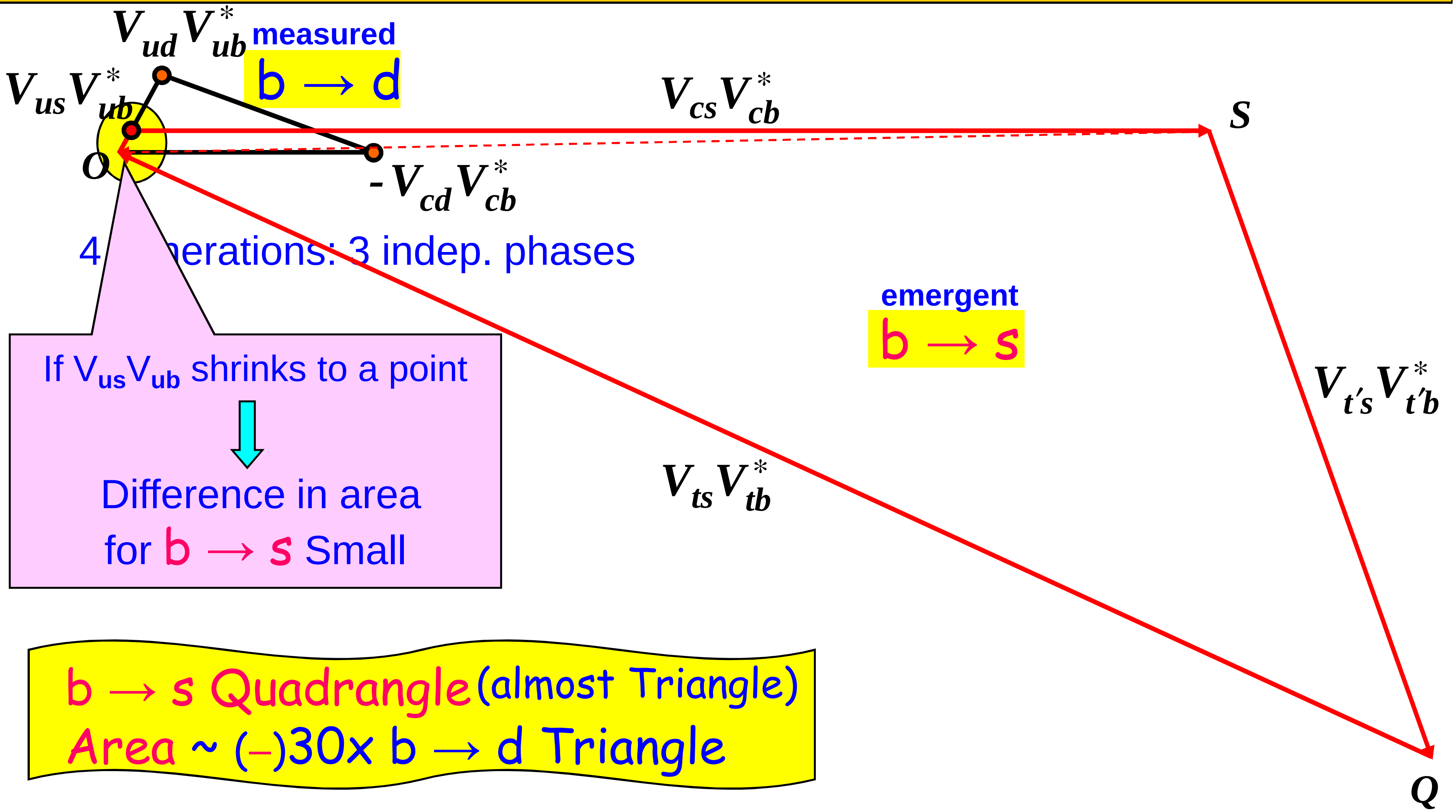
Large t, t′ Yukawa

ca. late summer 2007 ...

Large Yukawa !

YuReKawa !

4 generations: 3 indep. phases



2nd argument that $J^{sb}_{(2,3,4)}$ is predominant CPV