天 地

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

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February 9, 2009, Seminar @ LLR, Paris

LeCosPA

臺灣大學

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BELLE

Can ***all this*** be understood from my vantage？

Capital Reef National Park
(c) Wally Pacholka

Outline

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b → s // b ↔ s CPV

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WSH, Nagashima, Soddu,
PRL’05; PRD’05; PRD’07; PRD’08
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.

— Genesis 1:1 (KJV)

Matter (?)

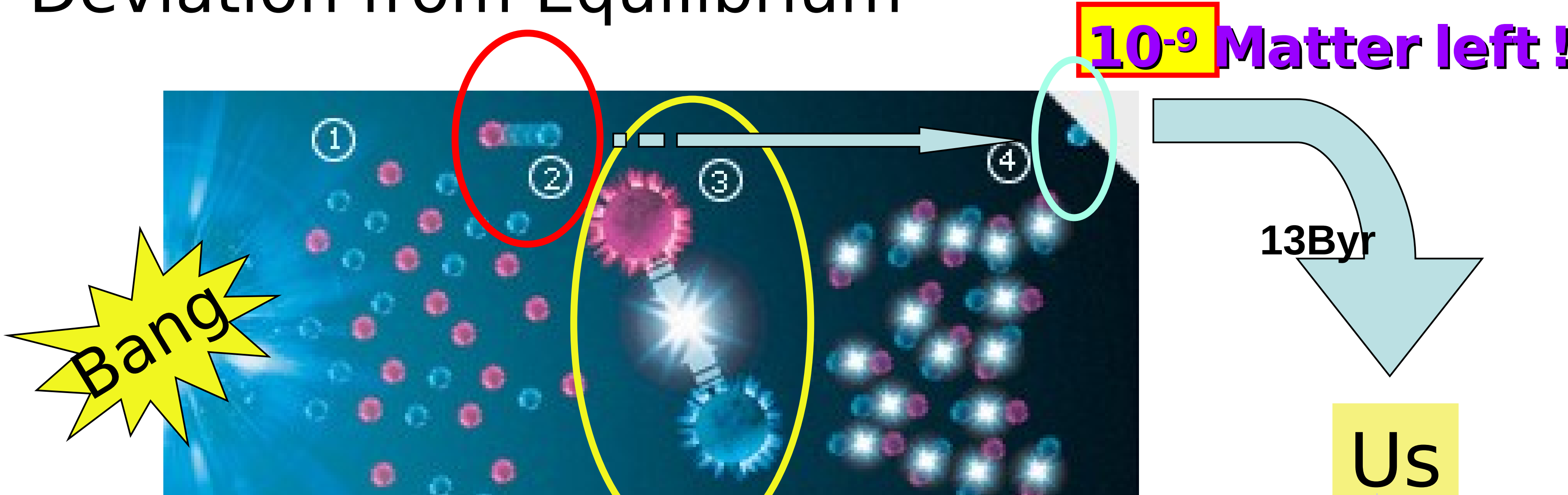
Matter !

Antimatter: 0%

(1967)

CPV & BAU (& U): The Sakharov View

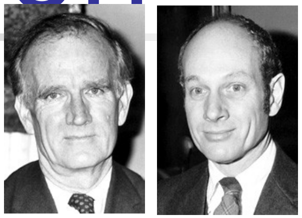
- **Baryon Number Violation**
- *CP Violation*
- Deviation from Equilibrium



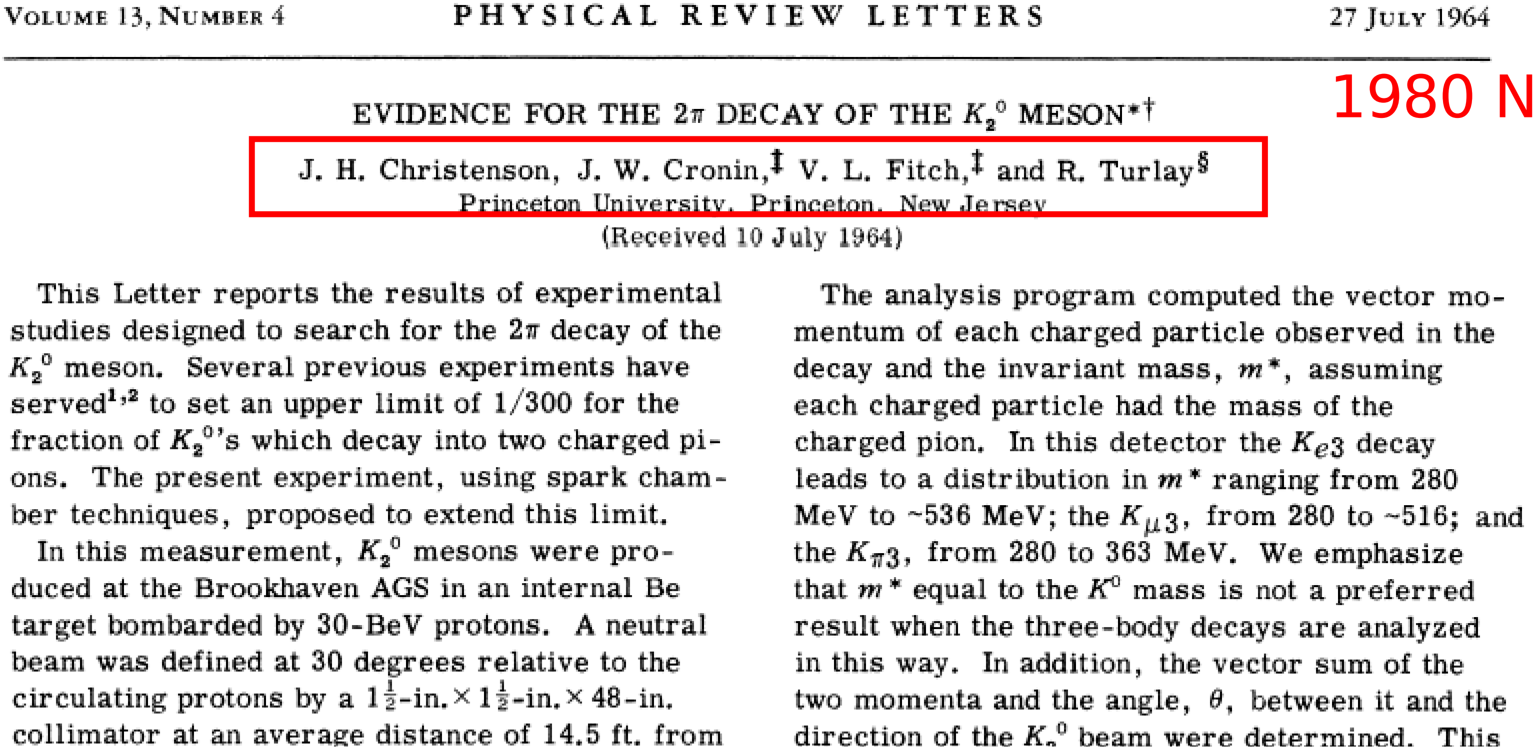
Sakharov Stimulated by ...

Discovery of CP Violation

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



1980 Nobel



VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

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)

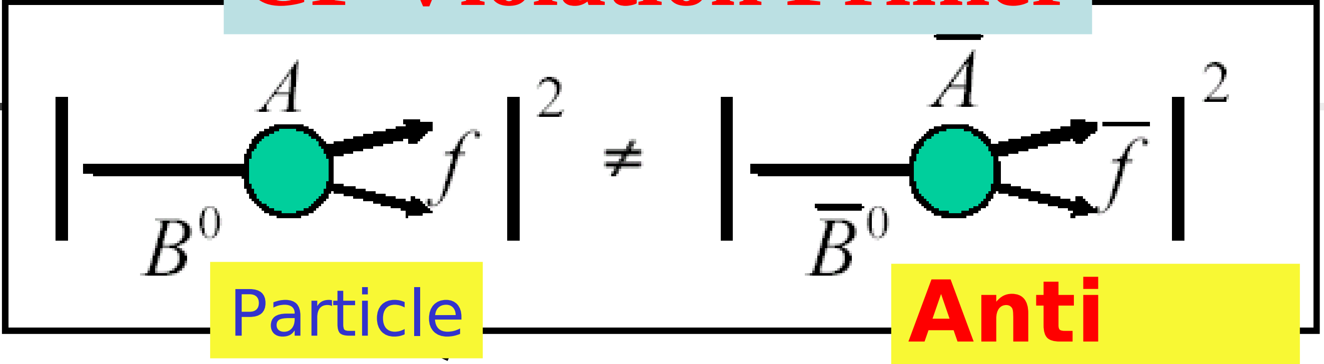
This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, 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 $K_{\mu3}$, from 280 to ~516; and the $K_{\pi3}$, 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

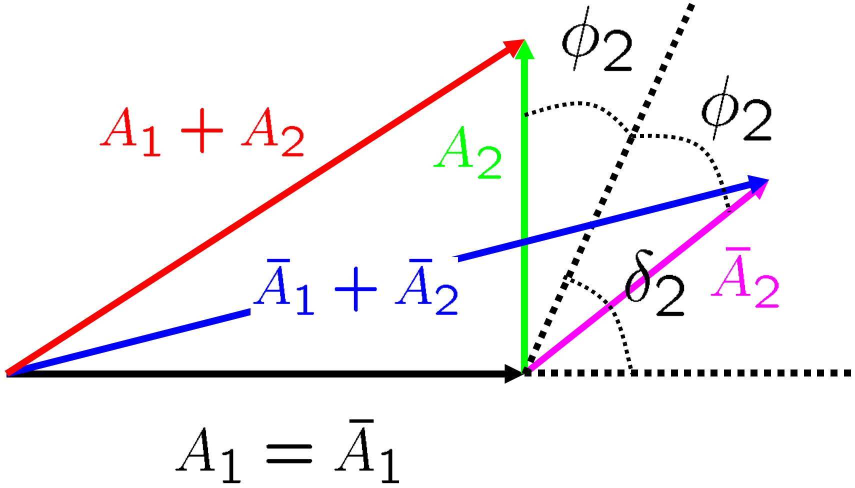
2×10^{-3}: *Too Small .... for Sakharov!*

CP Violation Primer



Particle

Anti Particle



CPV

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

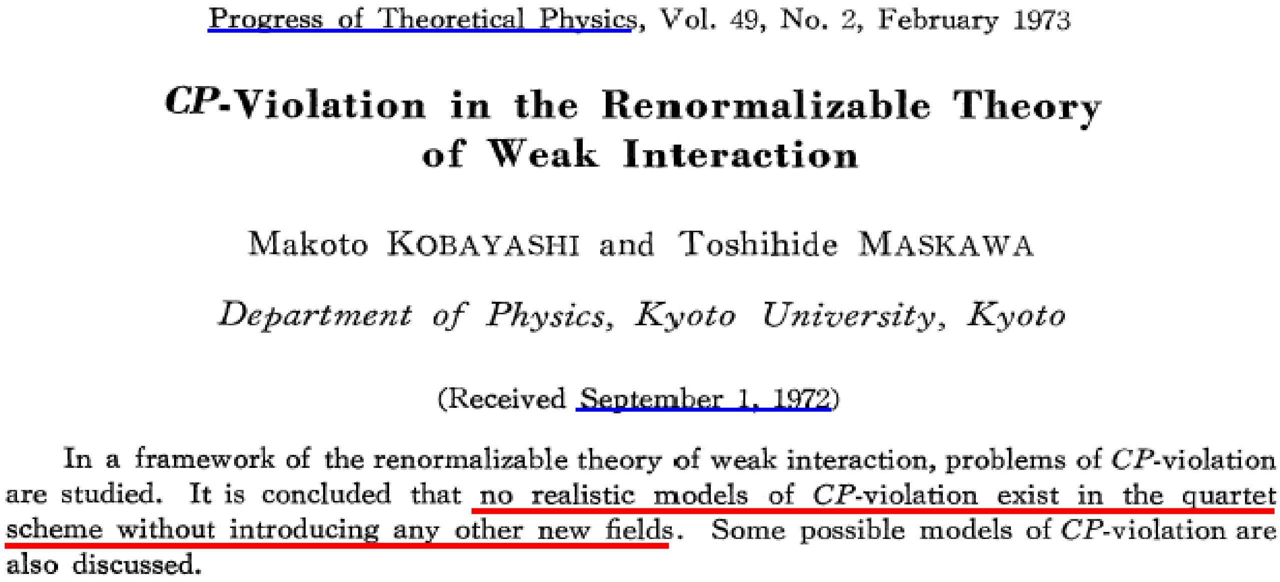
$$\bar{A} = \bar{A}_1 + \bar{A}_2 = a_1 + a_2 e^{i\delta_2} e^{-i\phi_2}$$

QM

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

CP Asymmetry needs both CP Conserv/Violating Phase

Kobayashi-Maskawa Model (1973)



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

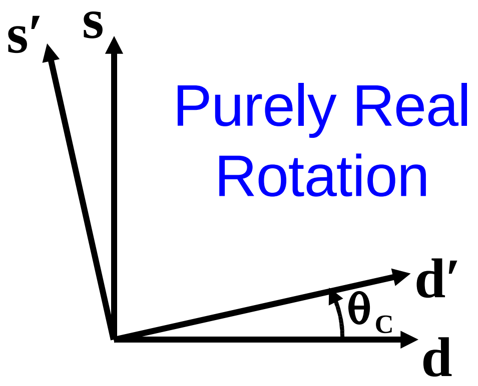
CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

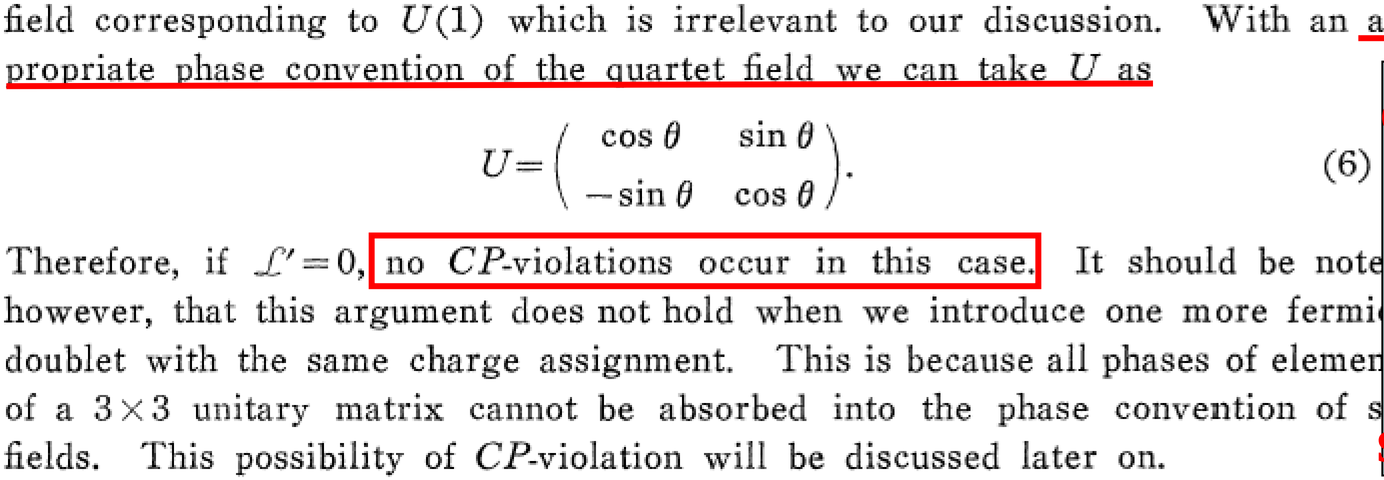
Department of Physics, Kyoto University, Kyoto

(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.



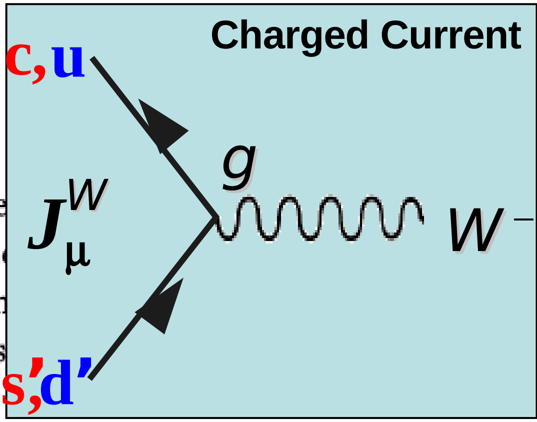
Purely Real Rotation



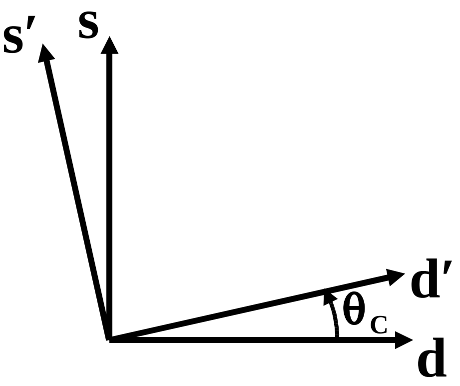
field corresponding to $U(1)$ which is irrelevant to our discussion. With an appropriate phase convention of the quartet field we can take U as

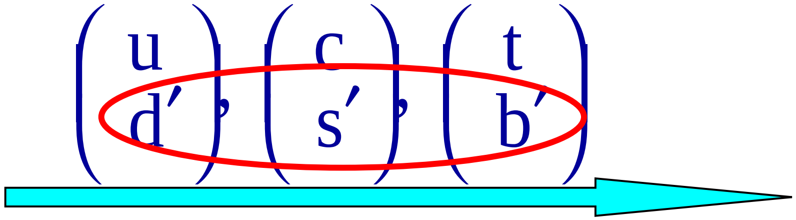
$$U=\begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}. \qquad (6)$$

Therefore, if $\mathcal{L}'=0$, 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.


Charged Current

KM Model : 2 x 2 → 3 x 3

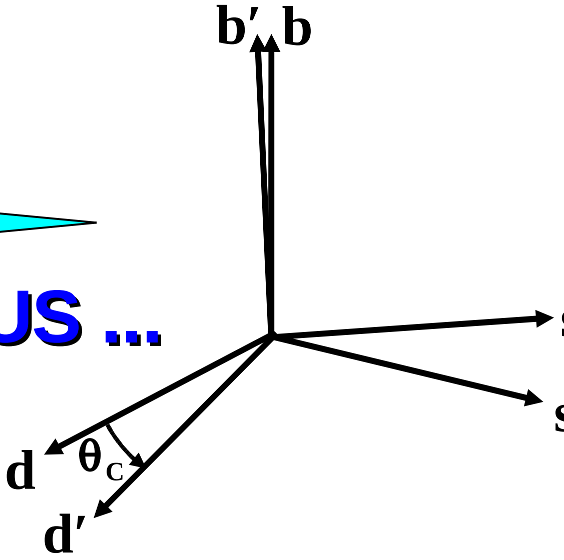


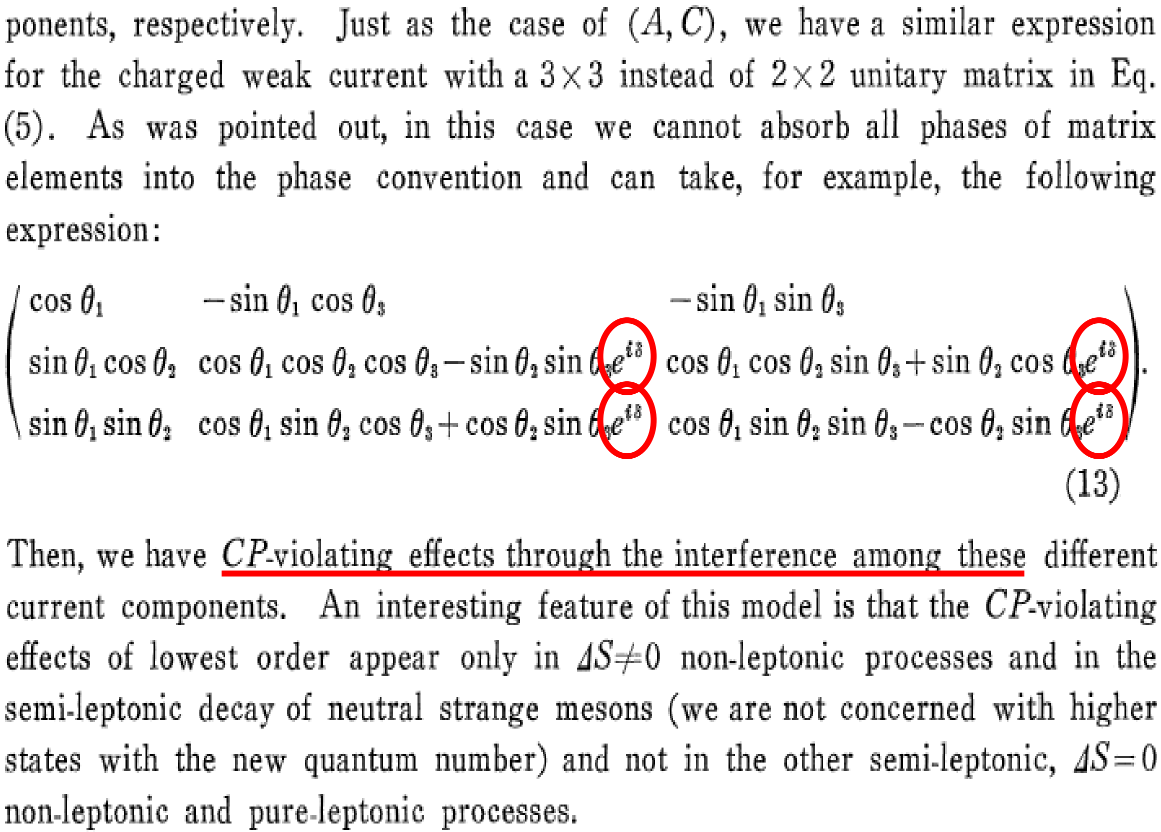


$$\begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix}, \begin{pmatrix} t \\ b' \end{pmatrix}$$

3x3 Rotation !

PLUS ...



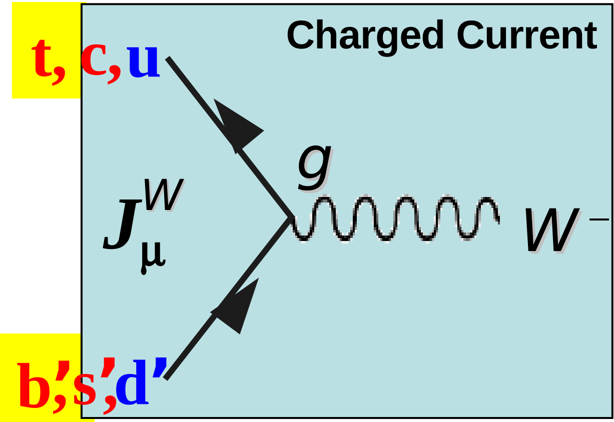


ponents, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following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

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

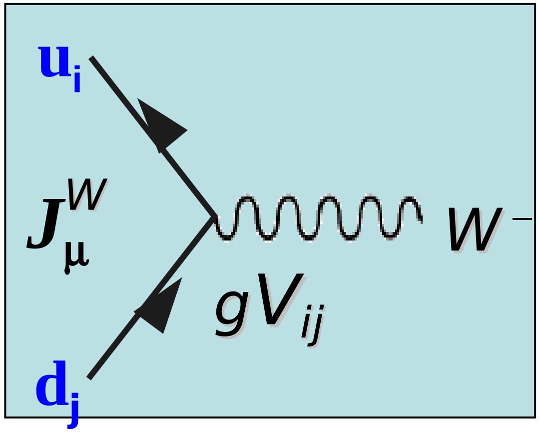
Then, we have CP-violating effects through the interference among these different current components. An interesting feature of this model is that the CP-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we 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

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

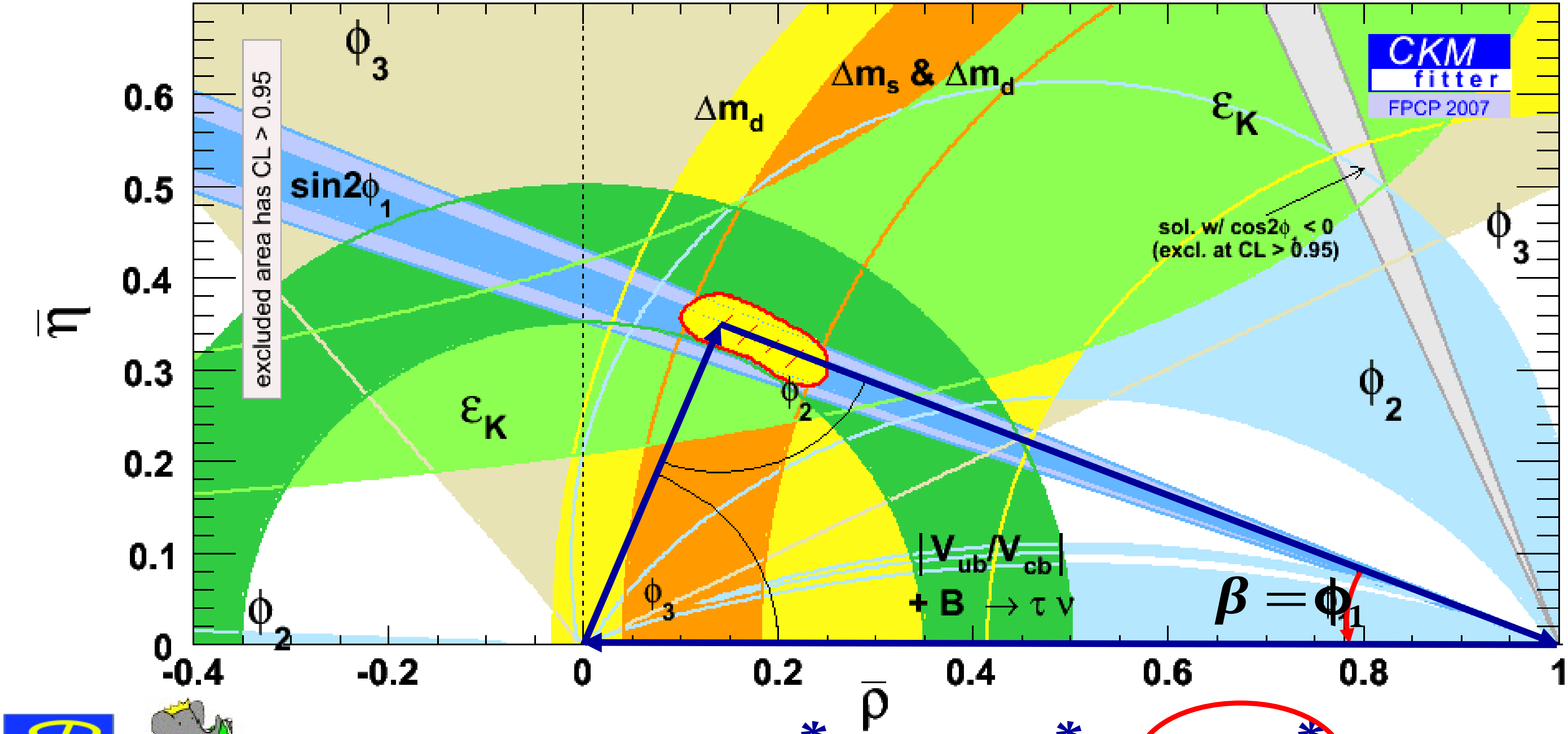
3x3 “Rotation”

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"

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)

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

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

CP Violation in SM

naturenews
7 October 2008

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

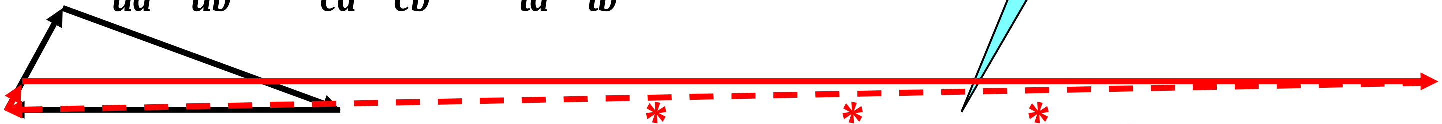
KEK

B Factories (BaBar & Belle)

Wolfenstein Parametrization to O(λ⁵)

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

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 (area)

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

- All like-charge quark pairs nondegenerate,

  Otherwise → Back to 2-gen. and CPV vanish

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

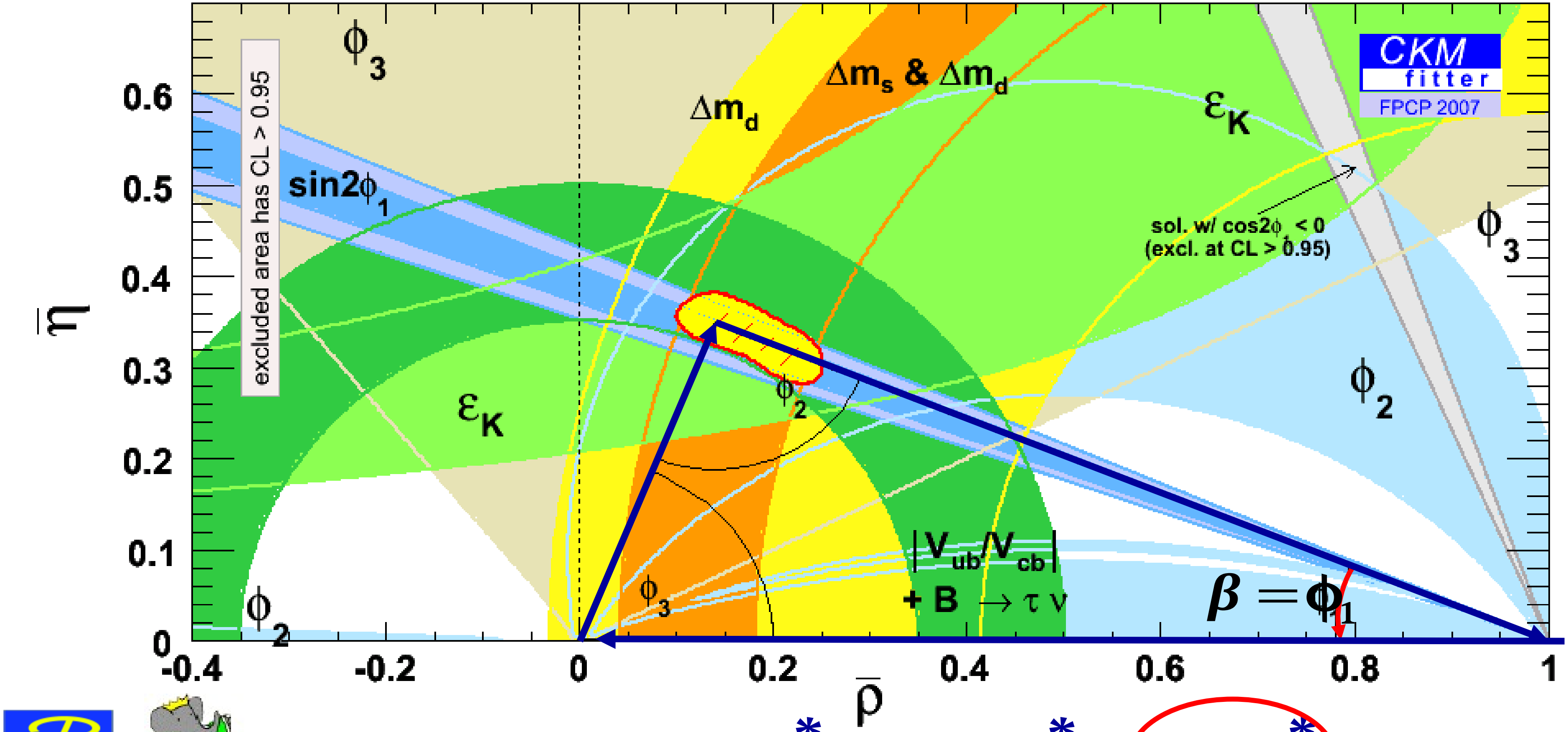
Jarlskog Invariant (1985) for CPV

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

b → d transitions consistent with SM

b → s: the Current Frontier

the MOMA plot



“Nontrivial”

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

A Real Hin , … or Not !?

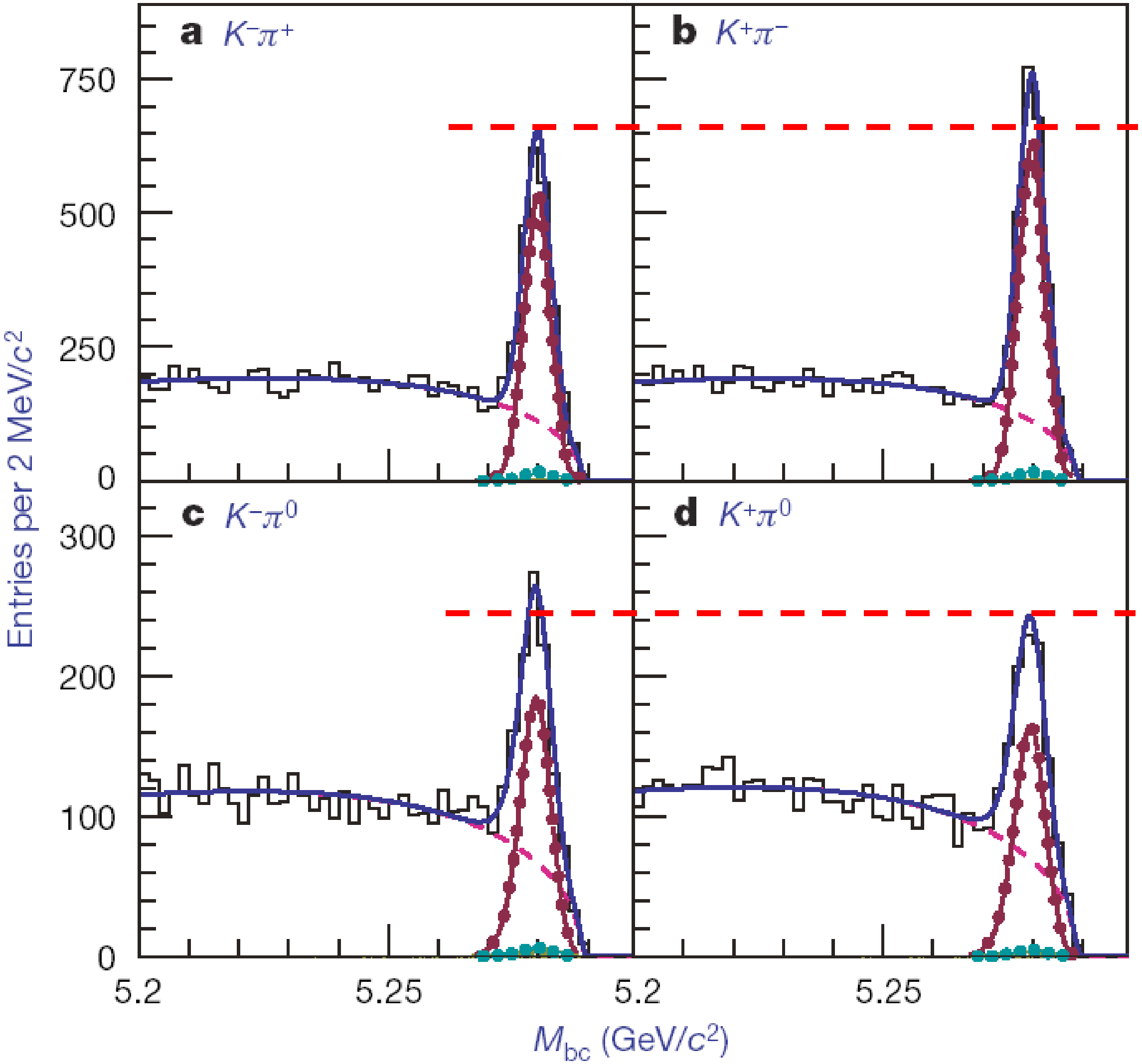
Belle 2008 Nature: Simple Bean Count

$$\Delta A_{K\pi} = A_{K^+\pi^0} - A_{K^+\pi^-} = +0.164 \pm 0.037 \qquad 4.4\sigma$$

LETTERS

$+0.07 \pm 0.03$ **vs** -0.094 ± 0.020

NATURE | Vol 452 | 20 March 2008

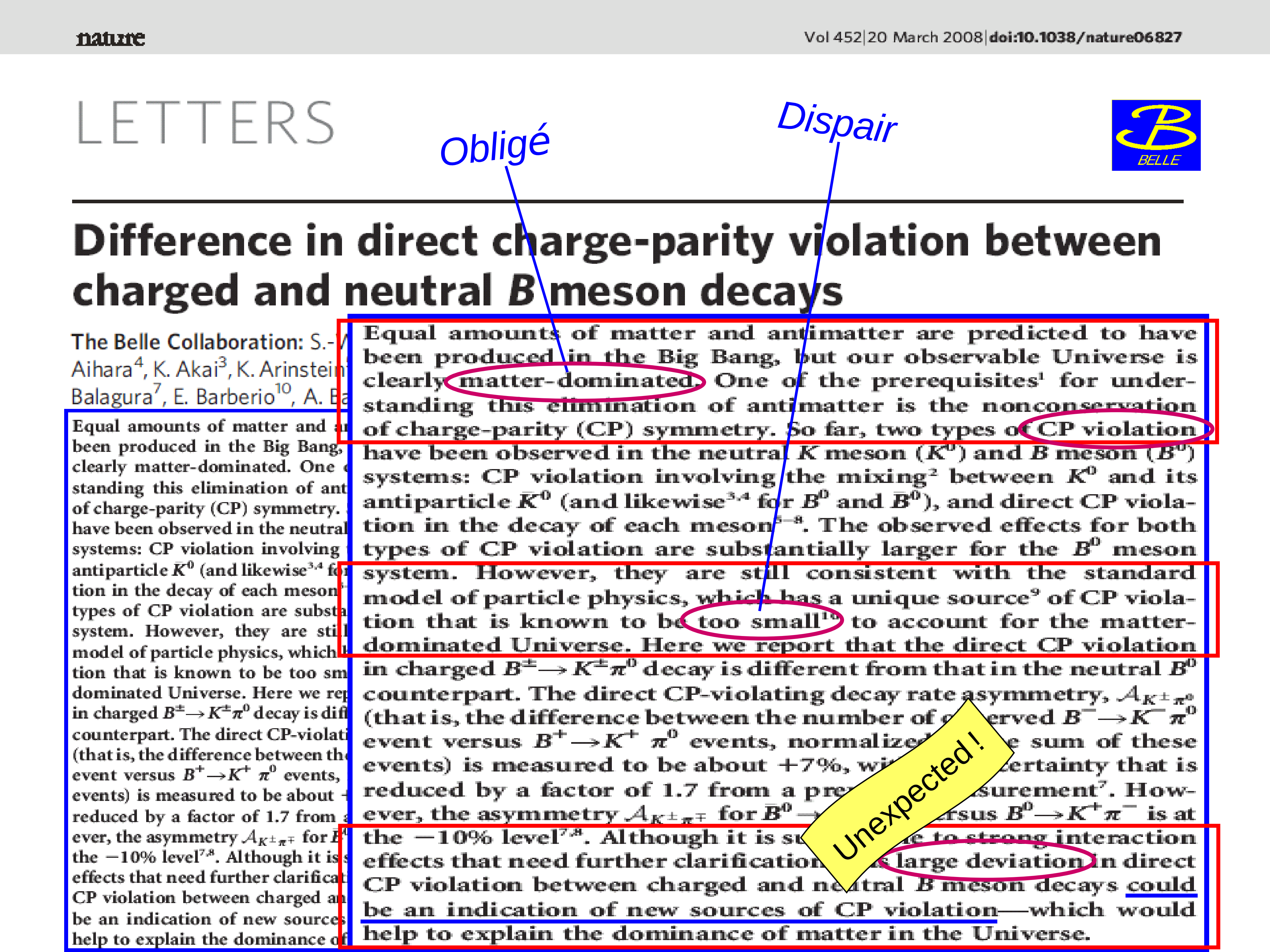


b → s CPV

Difference
Is
Large !

And Established

Belle + BaBar (+ CDF)



nature 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

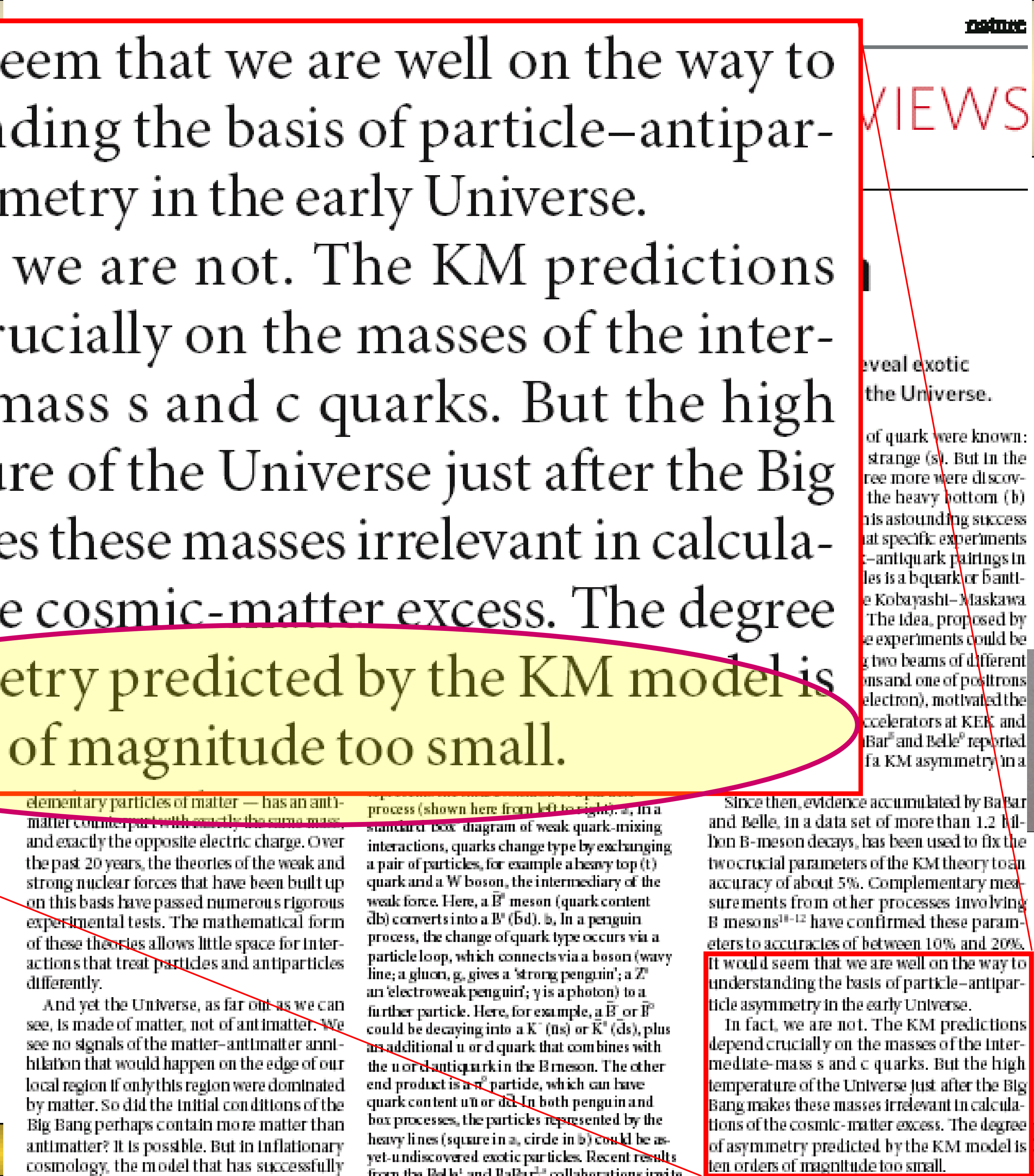
The Belle Collaboration: S.-
Aihara[4], K. Akai[3], K. Arinstein
Balagura[7], E. Barberio[10], A. Ba

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 o[illegible]erved $B^- \to K^- \pi^0$ event versus $B^+ \to K^+ \pi^0$ events, normalized [illegible] sum of these events) is measured to be about +7%, wi[illegible]ertainty that is reduced by a factor of 1.7 from a pre[illegible]surement[7]. However, the asymmetry $\mathcal{A}_{K^{\pm}\pi^{\mp}}$ for $\bar{B}^0 \to$ [illegible]ersus $B^0 \to K^+\pi^-$ is at the −10% level[7,8]. Although it is su[illegible]e to strong interaction effects that need further clarification[illegible] 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.

Unexpected !

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.



nature

VIEWS

eveal exotic
the Universe.

of quark were known:
strange (s). But in the
ree more were discov-
the heavy bottom (b)
his astounding success
hat specific experiments
–antiquark pairings in
les is a b quark or $\bar{b}$ anti-
e Kobayashi–Maskawa
The idea, proposed by
e experiments could be
g two beams of different
ons and one of positrons
electron), motivated the
ccelerators at KEK and
Bar[8] and Belle[9] reported
f a KM asymmetry in a

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

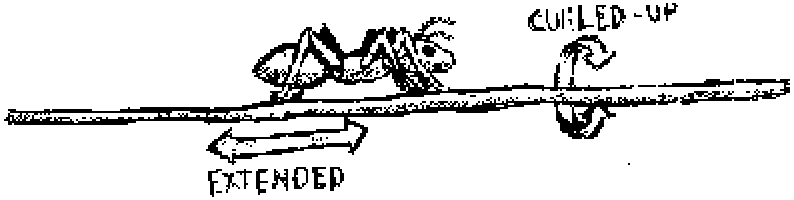
process (shown here from left to right). a, In a standard 'box' diagram of weak quark-mixing interactions, quarks change type by exchanging a pair of particles, for example a heavy top (t) quark and a W boson, the intermediary of the weak force. Here, a $\bar{B}^0$ meson (quark content $\bar{d}b$) converts 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 B^- or $\bar{B}^0$ could be decaying into a K^- ($\bar{u}s$) or $\bar{K}^0$ ($\bar{d}s$), 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

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

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

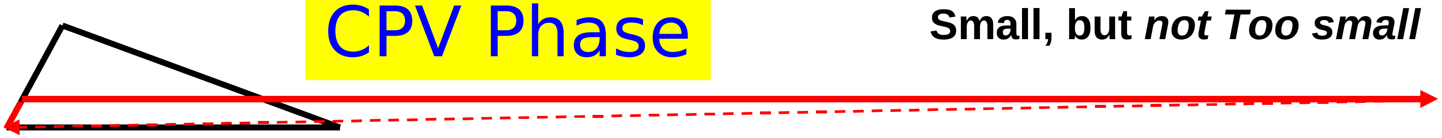
$$\boxed{J/T^{12} \sim 10^{-20}}$$

EW Phase Transition Temperature

~ v.e.v.

Masses too Small !

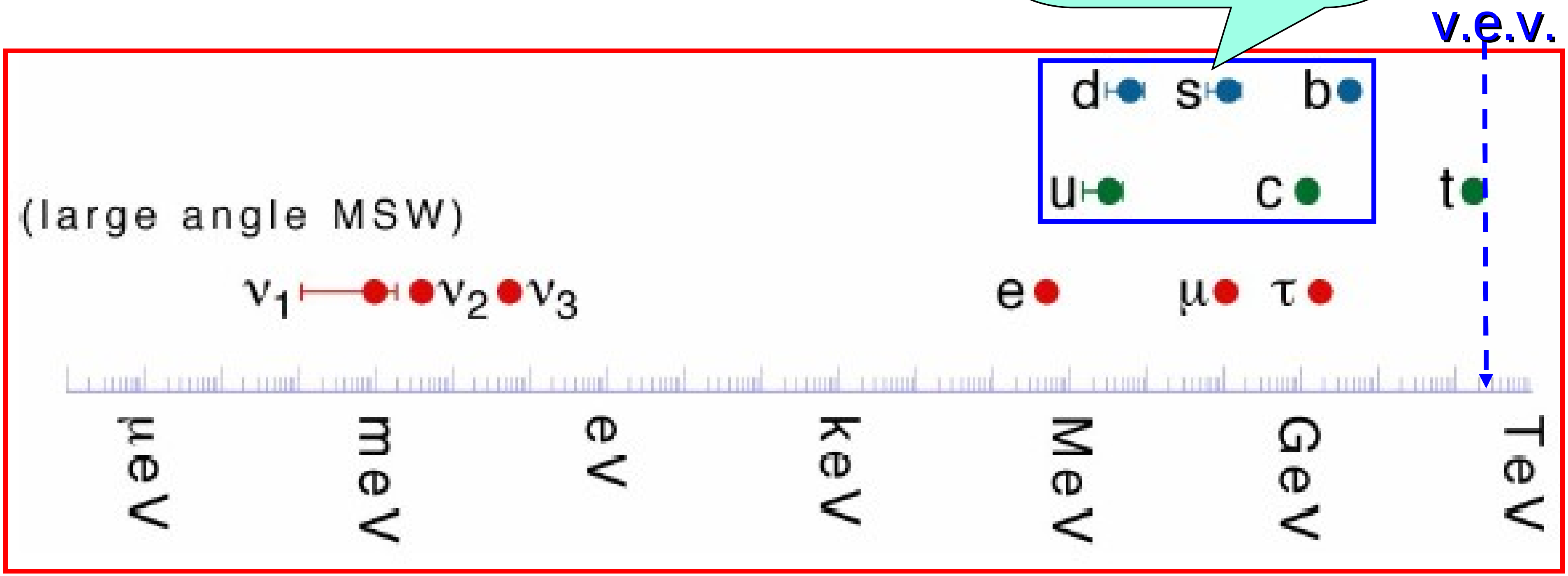
$$A \sim 3 \times 10^{-5} \text{ is common } \overset{\text{in SM}}{\text{(unique)}} \text{ area of triangle}$$



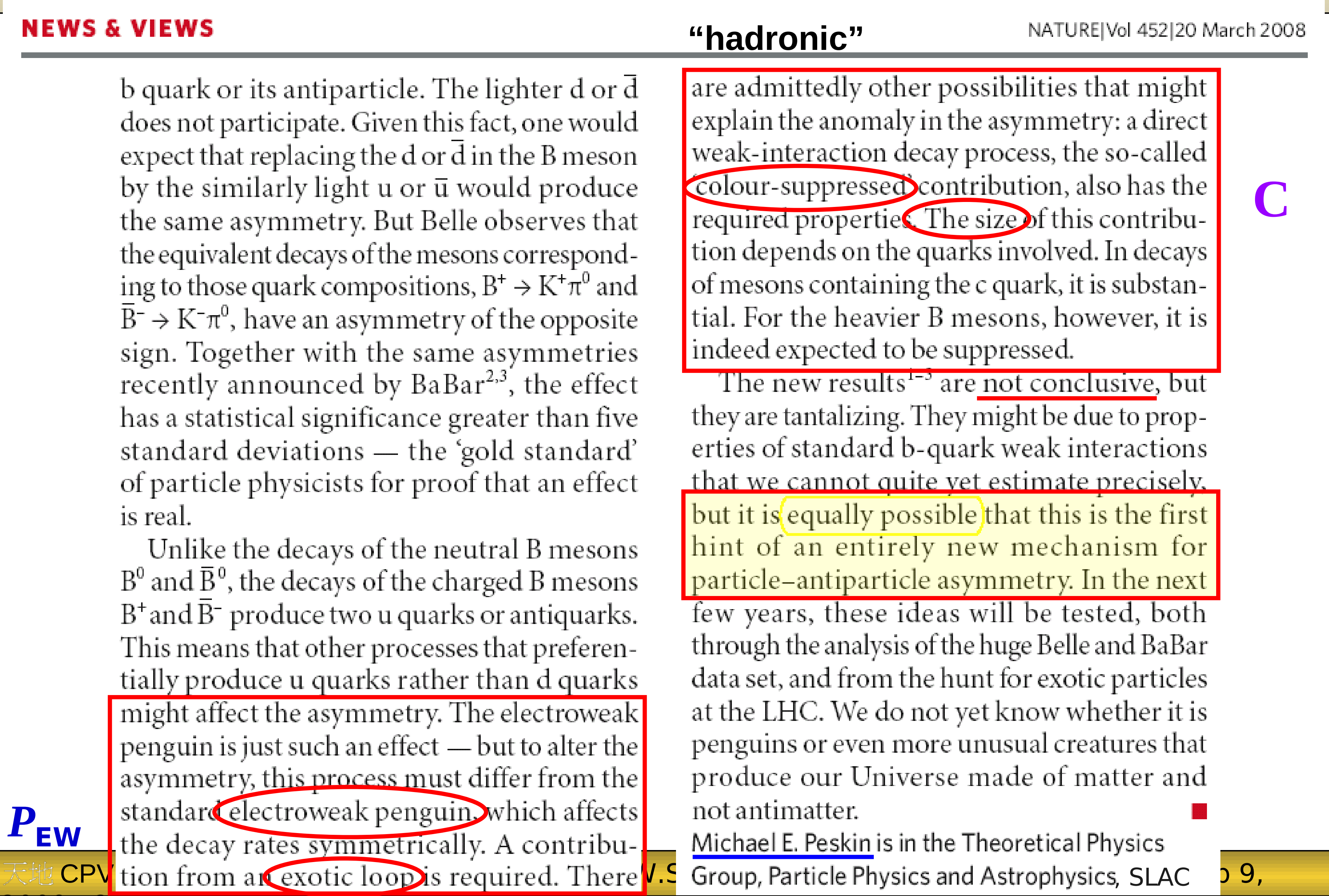
CPV Phase

Small, but *not Too small*

(u, d,) s, c, b
quarks too light



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



NEWS & VIEWS

NATURE|Vol 452|20 March 2008

“hadronic”

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.

P_{EW}

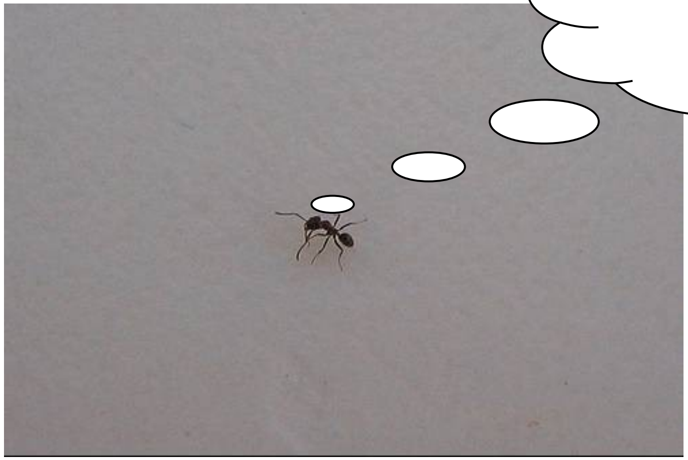
C

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

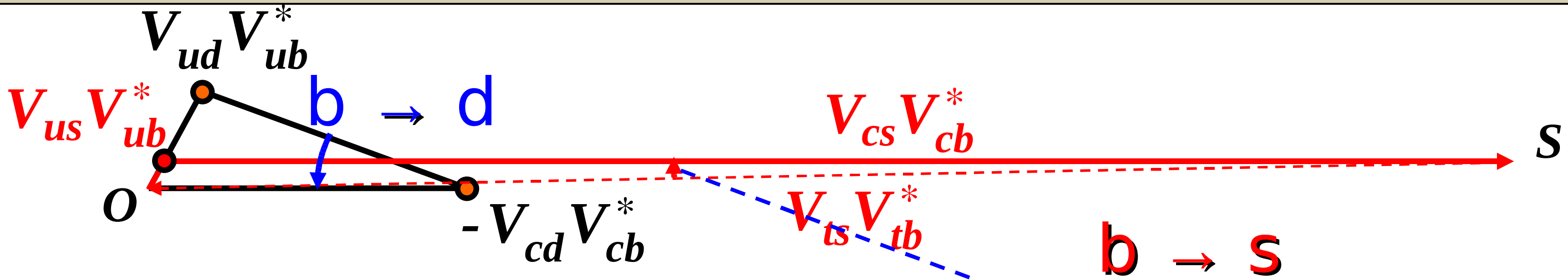
M. Peskin (private communication)

"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."



Ya, ya!
Need 10^{10}
anyway !
Me keep
crawlin'...

Mixing-dep. CPV in B_d and B_s in SM



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

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

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

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

"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”...

Saga Towards Belle Nature Paper ...

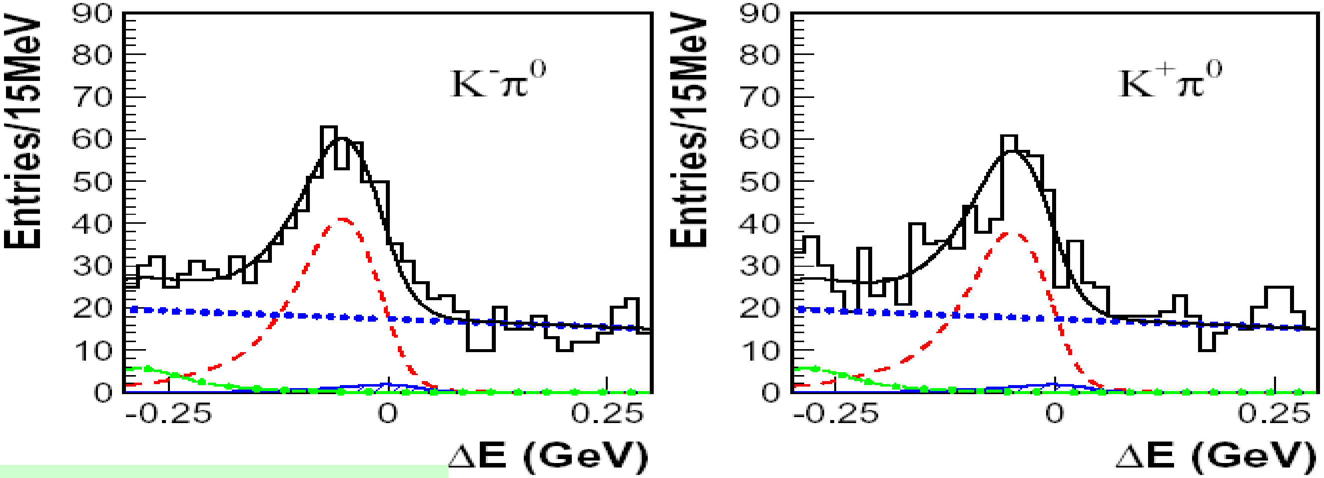
$A_{CP}(B \to K^+\pi^0\ )$

Sakai

275M $B\bar{B}$

New

$K^{\pm}\pi^0$: 728 ±53



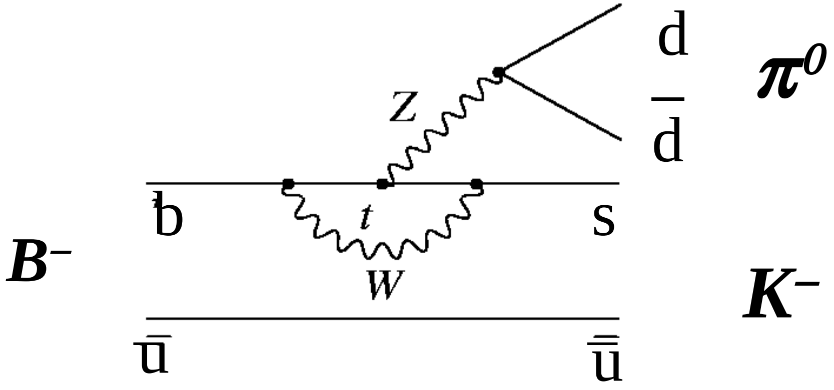
$$A_{CP}(K^{\pm}\pi^0\ ) = 0.04 \pm 0.05 \pm 0.02$$

hint that $A_{CP}(K^+\pi^-\ ) \neq A_{CP}(K^{\pm}\pi^0\ )$? (2.4σ)

[also seen by BaBar]

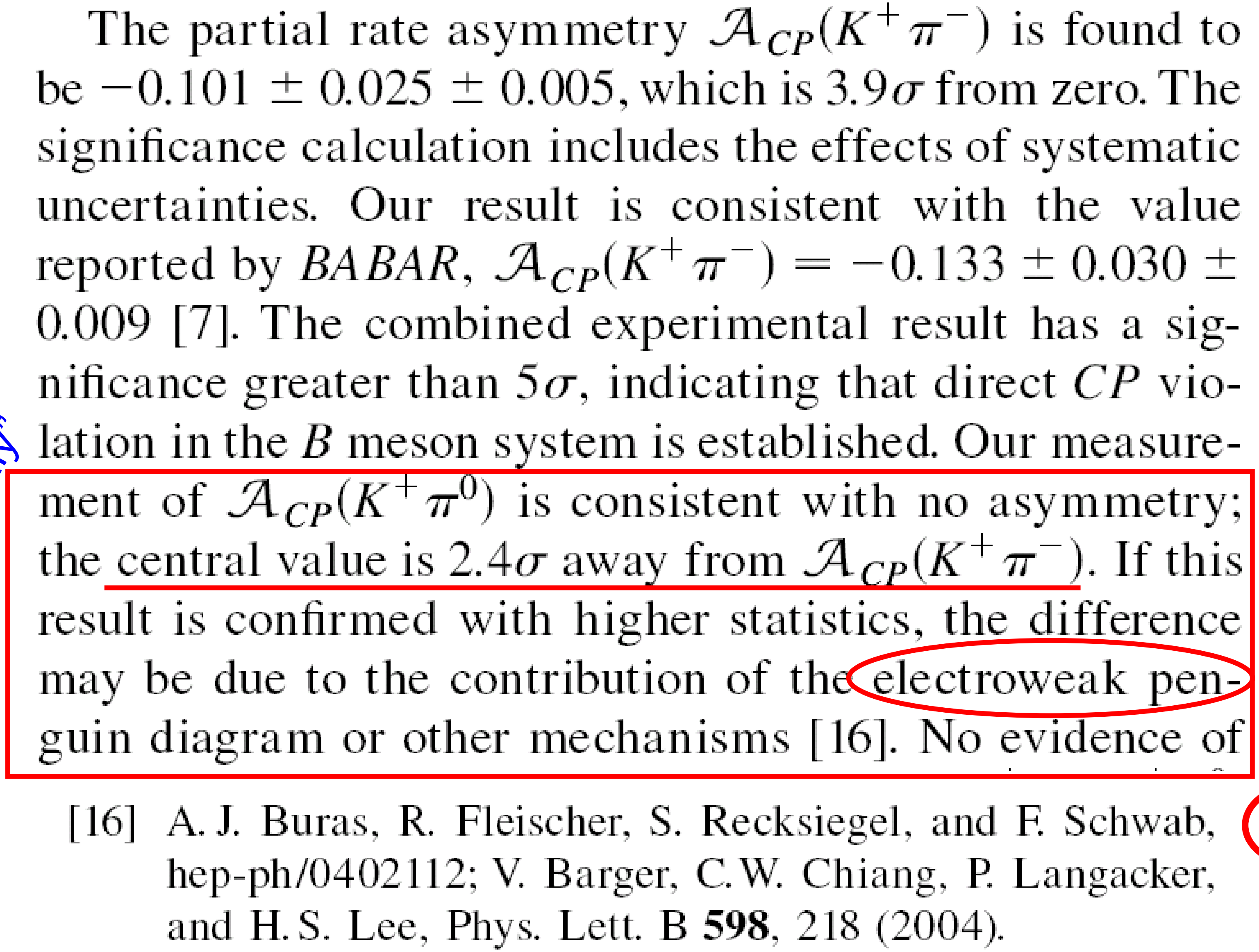
Large EW penguin (Z^0) ?

New Physics ?



Belle 2004 PRL: Seed

Y. Chao, P. Chang et al.



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

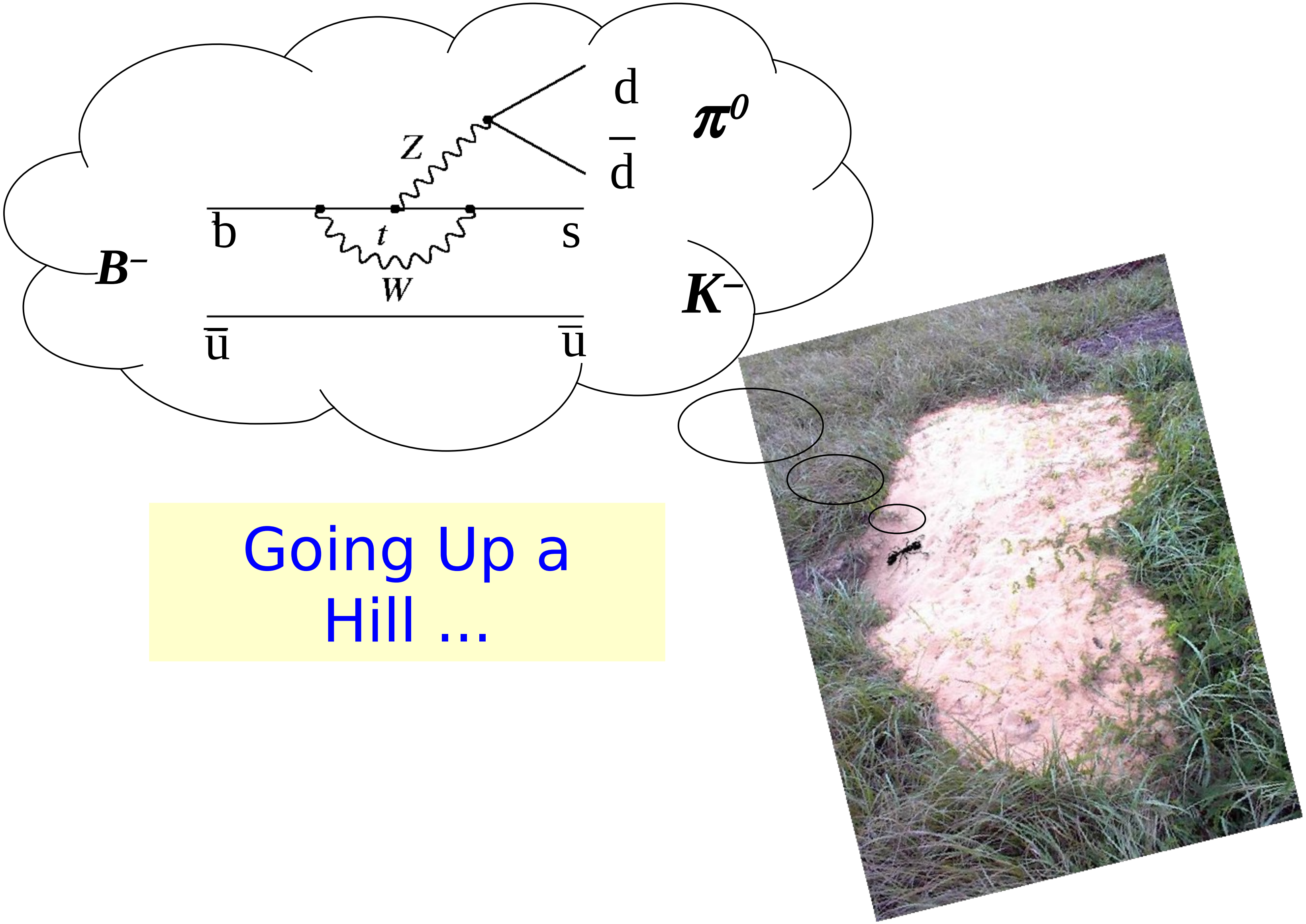
[16] A. J. Buras, R. Fleischer, S. Recksiegel, and F. Schwab, hep-ph/0402112; V. Barger, C. W. Chiang, P. Langacker, and H. S. Lee, Phys. Lett. B **598**, 218 (2004).

by "yours truly"

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

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

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

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]

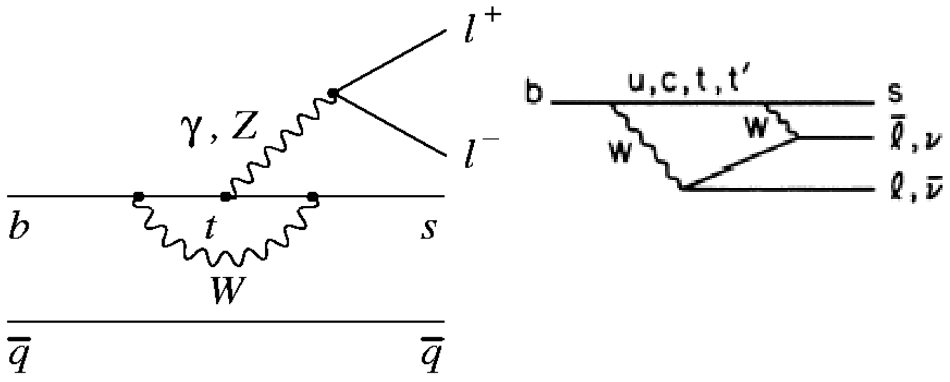
$$\bar{C}_i\equiv\bar{C}_i^Z+\bar{C}_i^{\rm box}=\tfrac{1}{4}x_i+\frac{3}{4}\left(\frac{x_i}{x_i-1}\right)^2\ln x_i-\frac{3}{4}\frac{x_i}{x_i-1}, \quad (3)$$

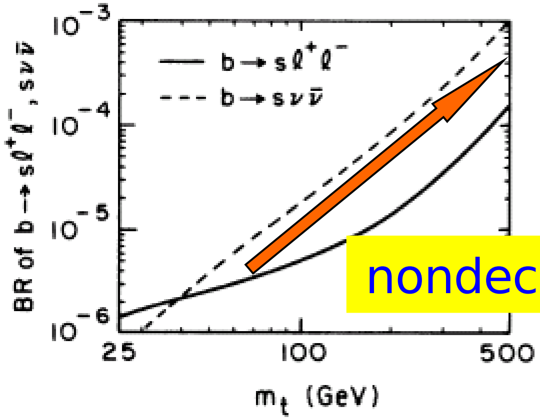
$$\bar{D}_i\equiv\bar{D}_i^Z+\bar{D}_i^{\rm box}=\tfrac{1}{4}x_i+\frac{3}{4}\frac{x_i(x_i-2)}{(x_i-1)^2}\ln x_i+\frac{3}{4}\frac{x_i}{x_i-1}, \quad (4)$$

dimensions

γ		Z
αG_F	$<$	$G_F^2\, m_t^2$

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]





nondecoupling

Nondecoupling

Decoupling Thm: Heavy Masses are decoupled in QED/QCD

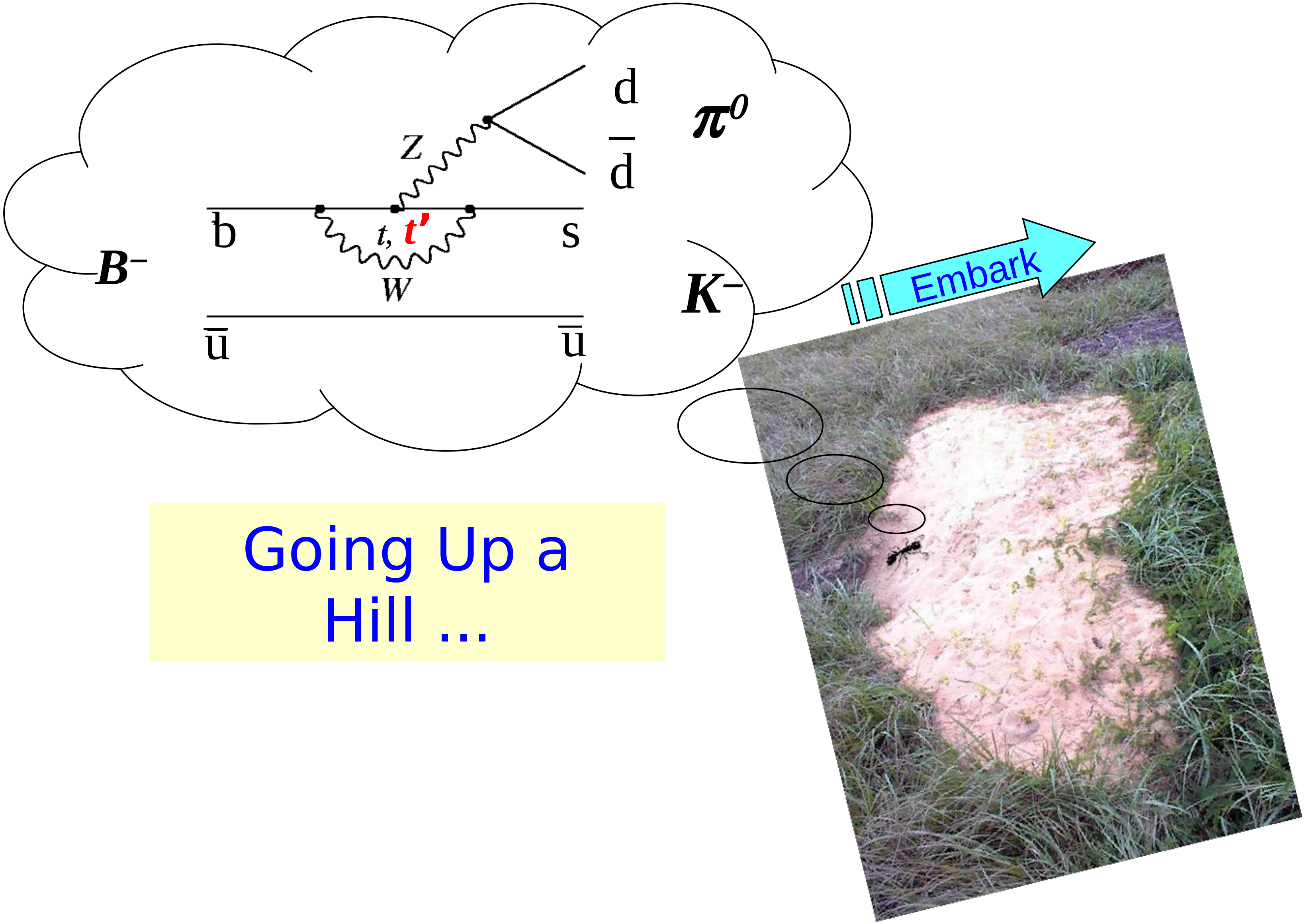
∵ Appear in Propagator

Nondecoupling: Yukawa Couplings λ_Q Appear in Numerator

dynamical

Subtlety of Spont. Broken Gauge Theory

The Crawlin' of one Ant



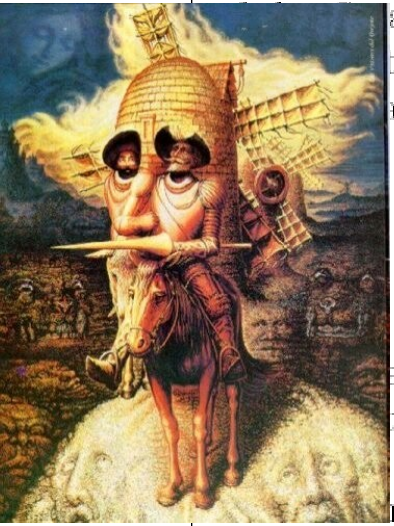
Going Up a Hill ...

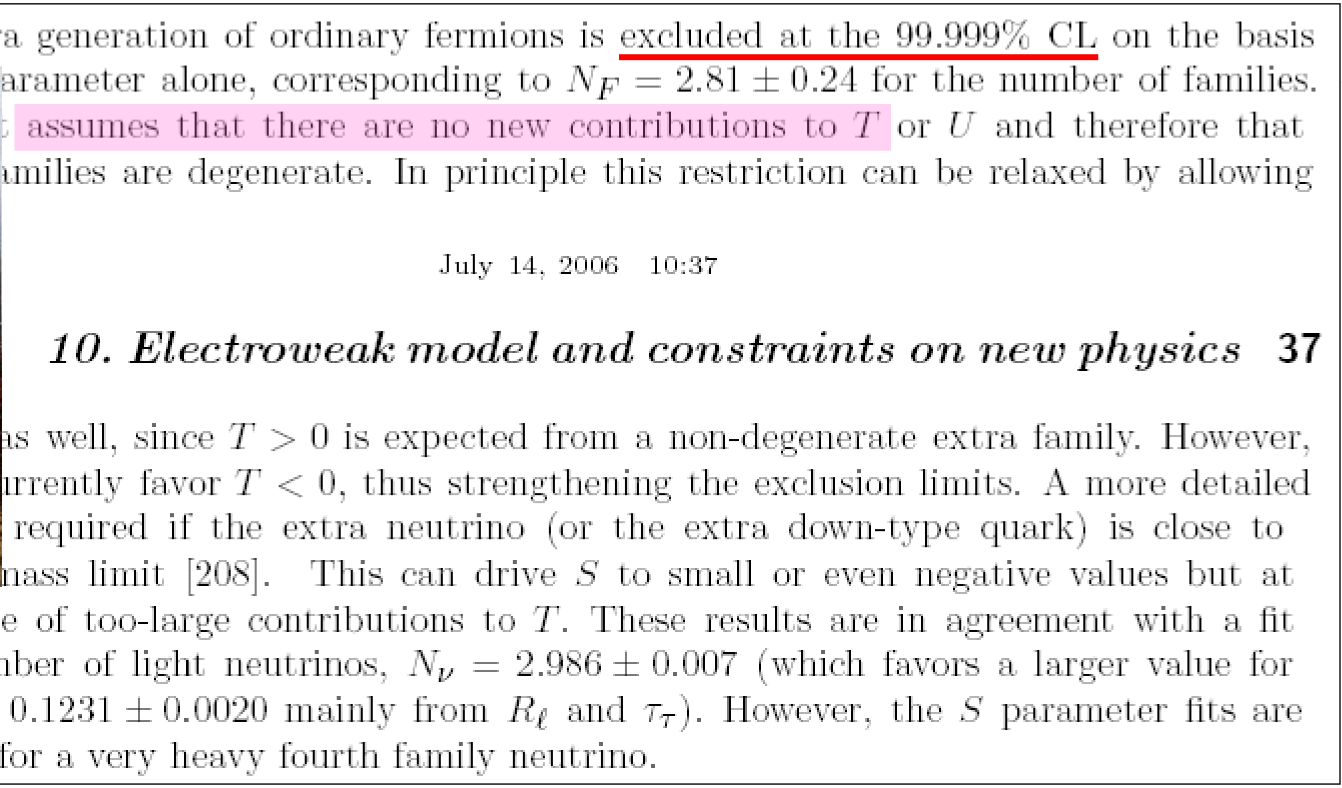
4th Generation Still?

- N_ν counting? 4th "neutral lepton" 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

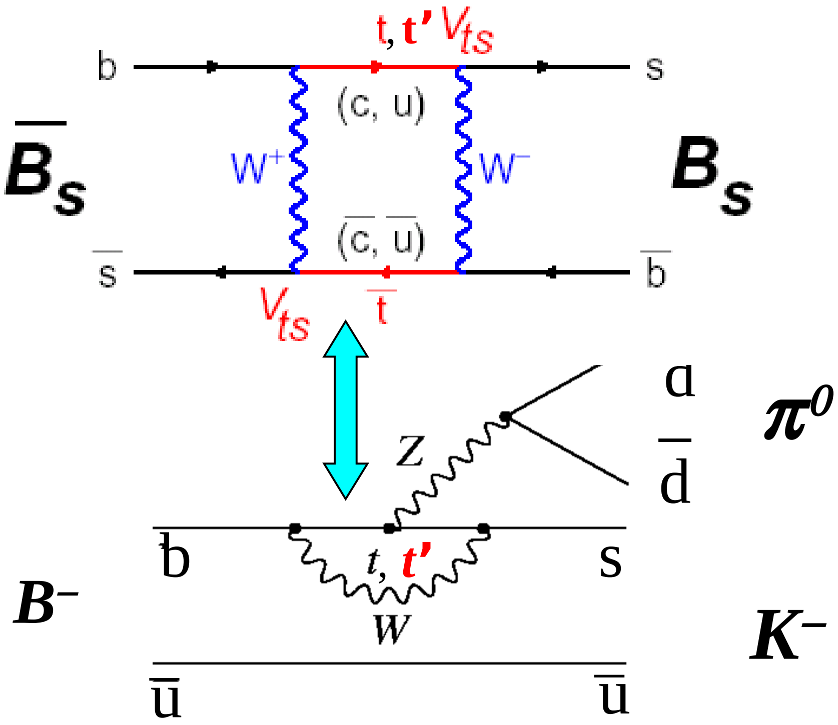
Kribs, Plehn, Spannowsky, Tait,

This is Still the Standard Model

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

Arhrib and WSH, EPJC'03

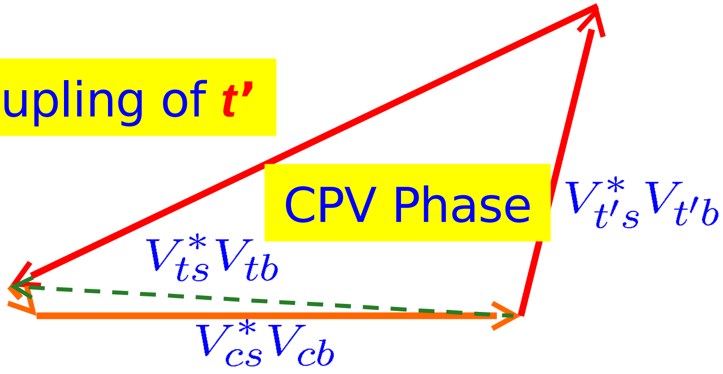
t ⇨ t, t'



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

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

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

$$H^4_{\rm eff} = \frac{G_F}{\sqrt{2}}\left[\lambda_u(C_1O_1 + C_2O_2) + \sum_{i=3}^{10}(\lambda_c C_i^t - \lambda_{t'}(C_i^{t'} - C_i^t))O_i\right]$$

EWP/Box Sensitivity to 4th Gen.

γ, g less sensitive

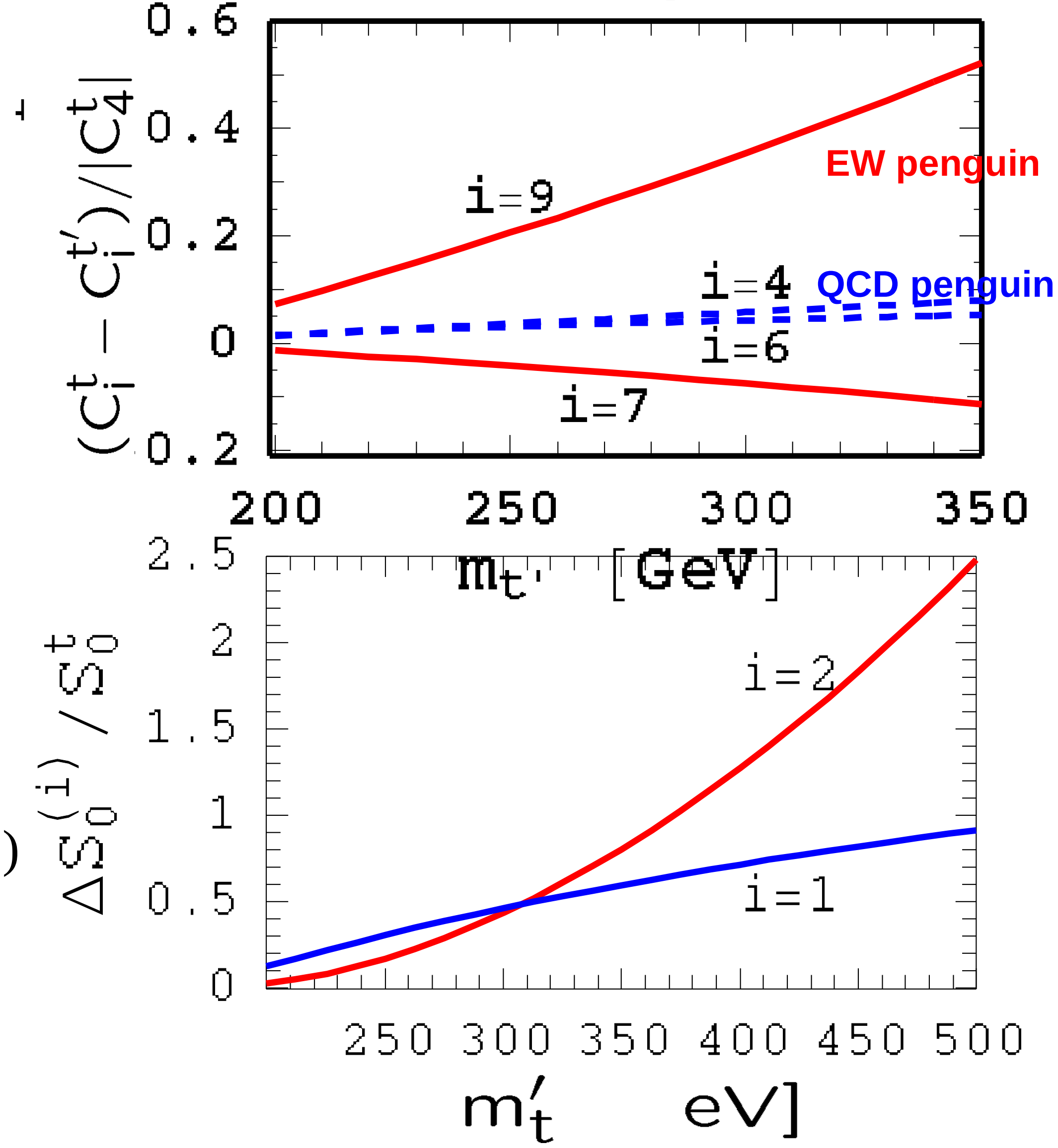
(No New Operators)

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

nondecoupling

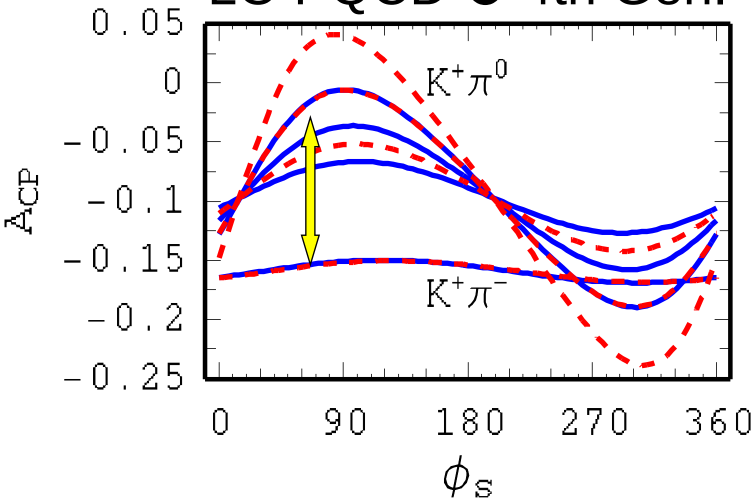
$$\Delta S_0^{(1)} = S_0(t,t') - S_0(t,t)$$

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



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

LO PQCD ⊕ 4th Gen.

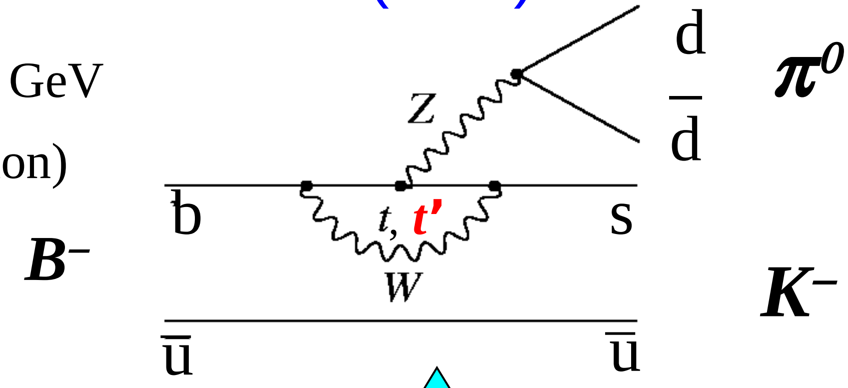


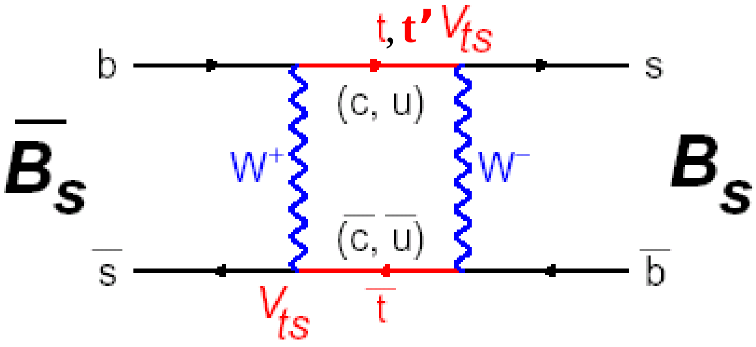
WSH, Nagashima, Soddu, PRL'05

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

$m_{t'} = 300$ GeV

(illustration)





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

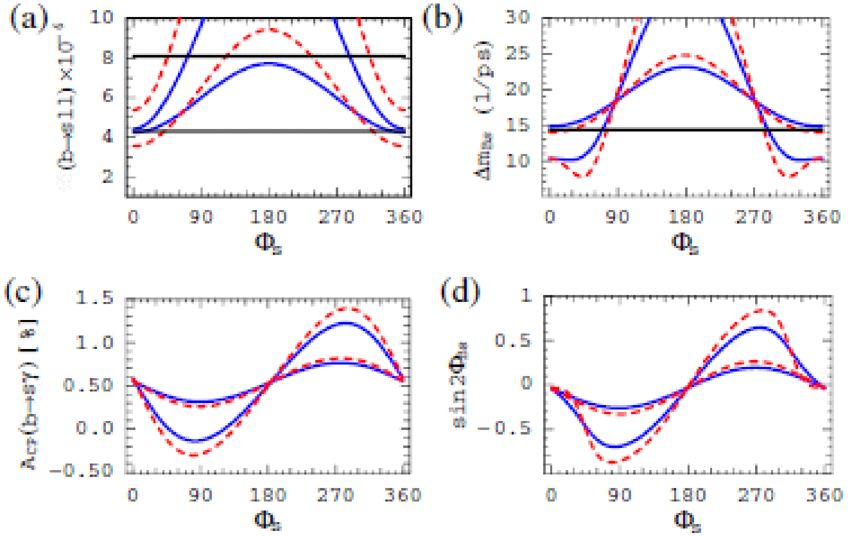
Wei-Shu Hou, Makiko Nagashima, and Andrea Soddu

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)

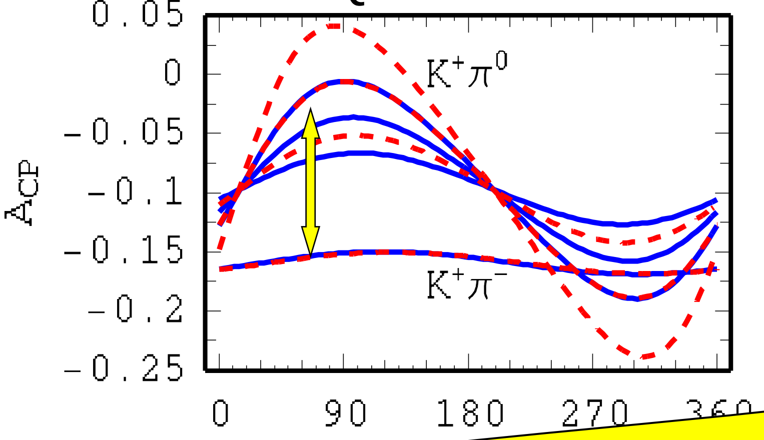
Direct *CP* violation in $B^0 \to K^+\pi^-$ decay has emerged at the -10% level, but the asymmetry in $B^+ \to K^+\pi^0$ mode is consistent with zero. This difference points towards possible new physics in the electroweak penguin operator. We point out that a sequential fourth generation, with sizable $V_{t's}^* V_{t'b}$ 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] $14.4\ \text{ps}^{-1} < \Delta m_{B_s} < 21.8\ \text{ps}^{-1}$ 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.

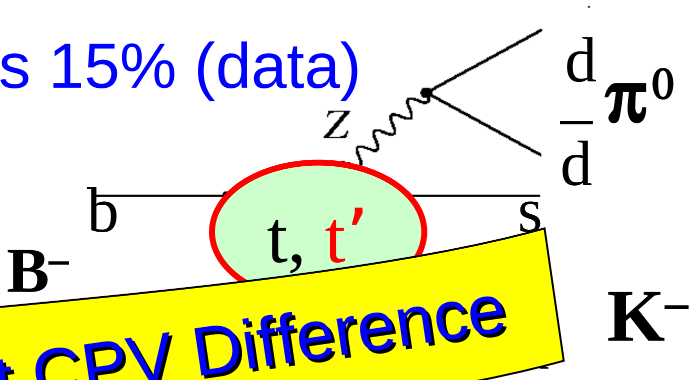


WSH, Nagashima, Soddu, PRL'05

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

$m_{t'} = 300$ GeV

(illustration)



Can Account for Belle/BaBar Direct CPV Difference

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

, Li, Mishima, Nagashima, PRL'07

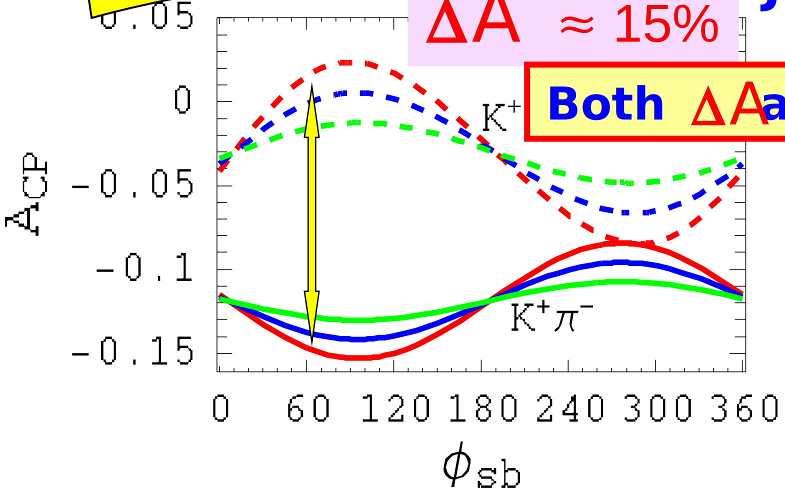
$\Delta A \approx 15\%$

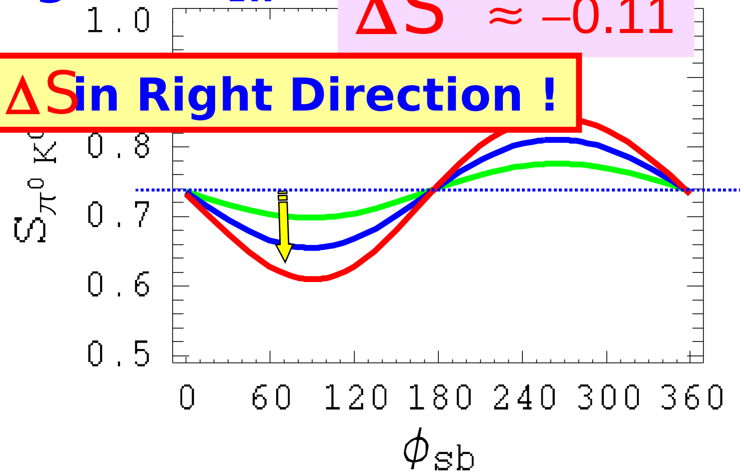
Joining C & P$_{EW}$

$\Delta S \approx -0.11$

consistent with data

Both ΔA and ΔS in Right Direction !





SM3 input

4 x 4 Unitarity

WSH, Nagashima, Soddu, PRD'05

"Typical" CKM Matrix

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

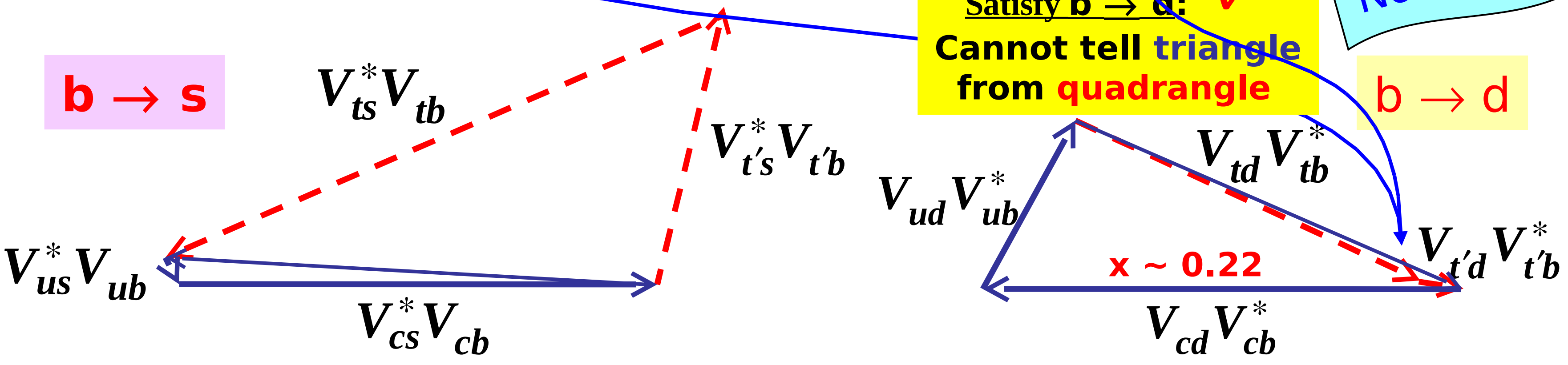
$$V_{CKM}^4 = \begin{pmatrix} 0.9745 & 0.2225 & 0.0038\,e^{-i\,60^\circ} & [illegible]\,61^\circ \\ -0.22[illegible] & [illegible] & [illegible] & 0.1164\,e^{i\,66^\circ} \\ 0.0[illegible] & -0.0555\,e^{-i\,25^\circ} & 0.9746 & 0.2168\,e^{-i\,1^\circ} \\ -0.0044\,e^{-i\,10^\circ} & -0.1136\,e^{-i\,70^\circ} & -0.2200 & 0.9688 \end{pmatrix}$$

Extract Information from Constraints

s ← b

d ← s

$Z \to b\bar{b}$



b → s

$V_{ts}^*V_{tb}$

$V_{t's}^*V_{t'b}$

$V_{us}^*V_{ub}$

$V_{cs}^*V_{cb}$

Satisfy **b → d:** ✓

Cannot tell triangle from quadrangle

Nontrivial

b → d

$V_{td}V_{tb}^*$

$V_{ud}V_{ub}^*$

x ~ 0.22

$V_{t'd}V_{t'b}^*$

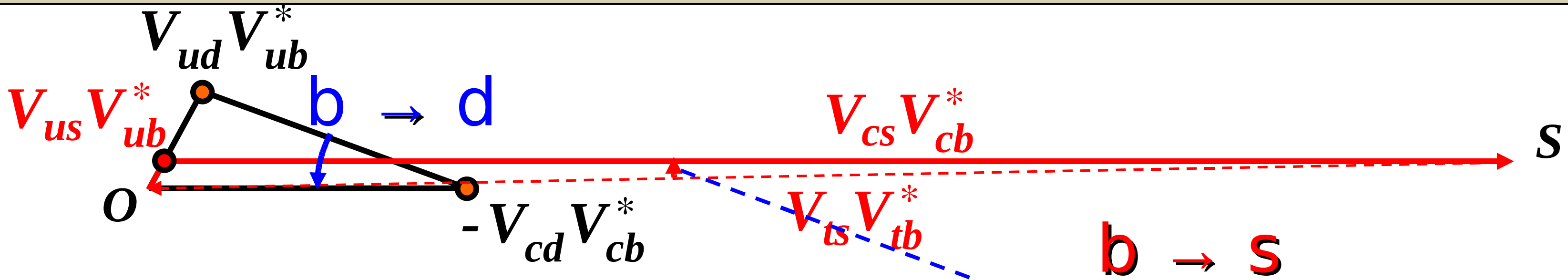
$V_{cd}V_{cb}^*$

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



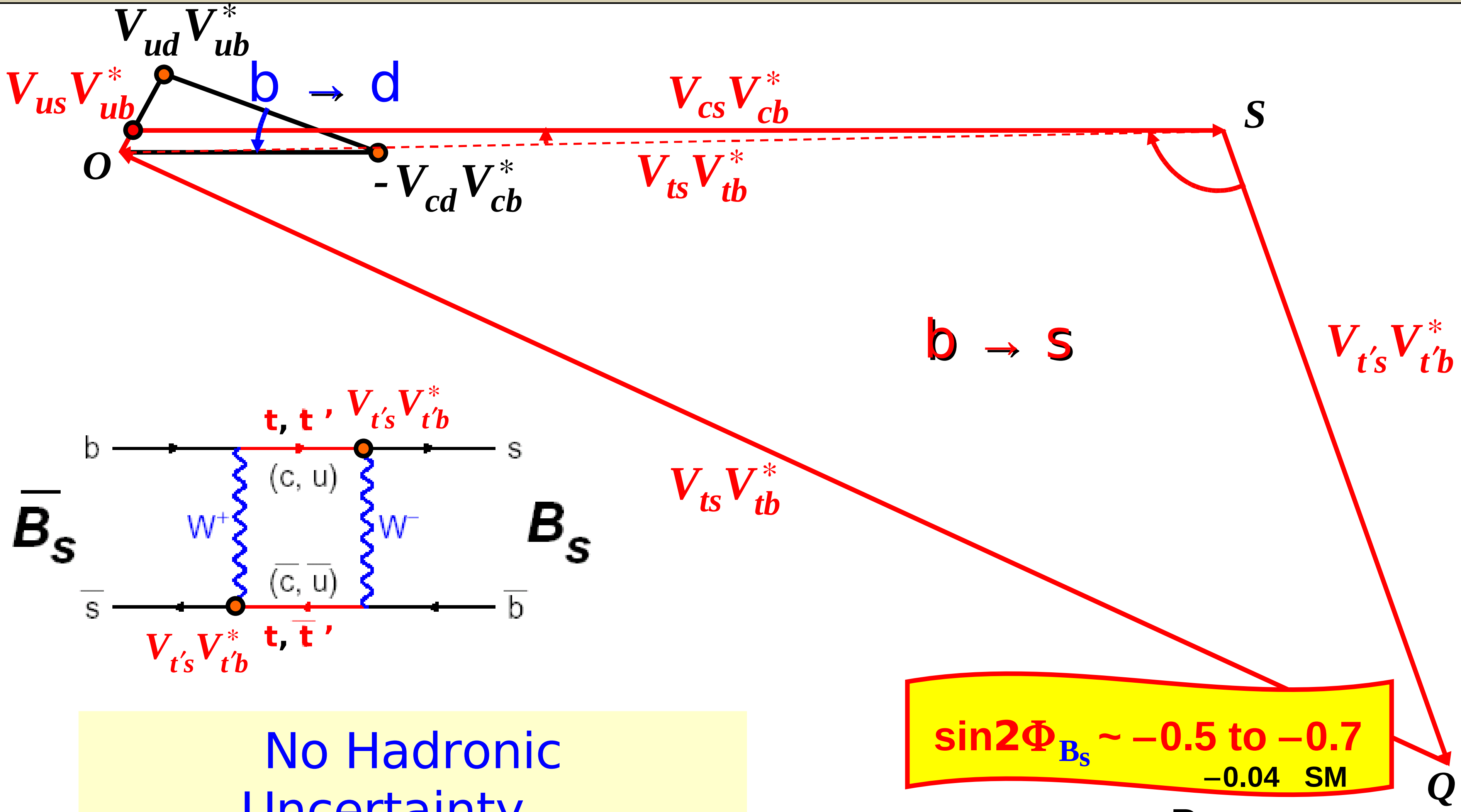
$$\sin 2\phi_1 = \sin 2\beta$$

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

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

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

Prediction: Large CPV in B_s Mixing



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

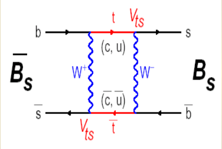
-0.04 SM

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

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

No Hadronic Uncertainty ...

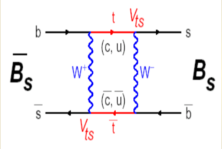
Strength and Size of $\sin 2\Phi_{B_s}$



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

different nondecoupl. functions

Large CPV in B_s Mixing

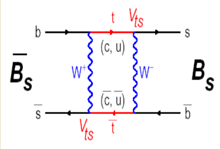


Use nominal $m_{t'}$ = 300 GeV

Change $m_{t'}$, Change parameter range

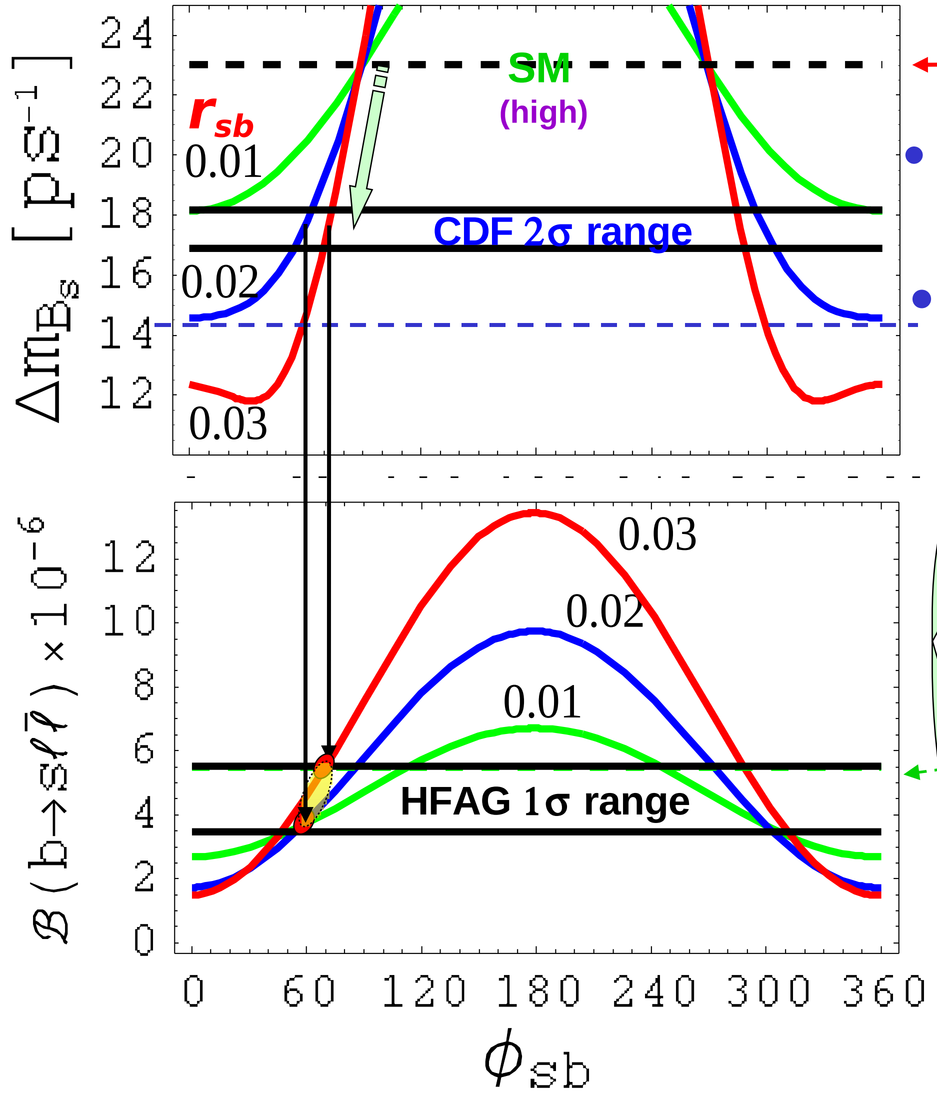
Effect the Same.

(Similar)



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

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, [$V_{cb} \sim 0.0$

  ϕ_{sb} Range ~ 60° - 70°

Finite CPV

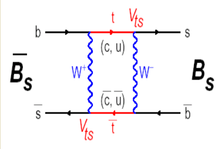
Phase

Consistent w/ **B**(b→sll)

SM-like !

Large CPV Possible !

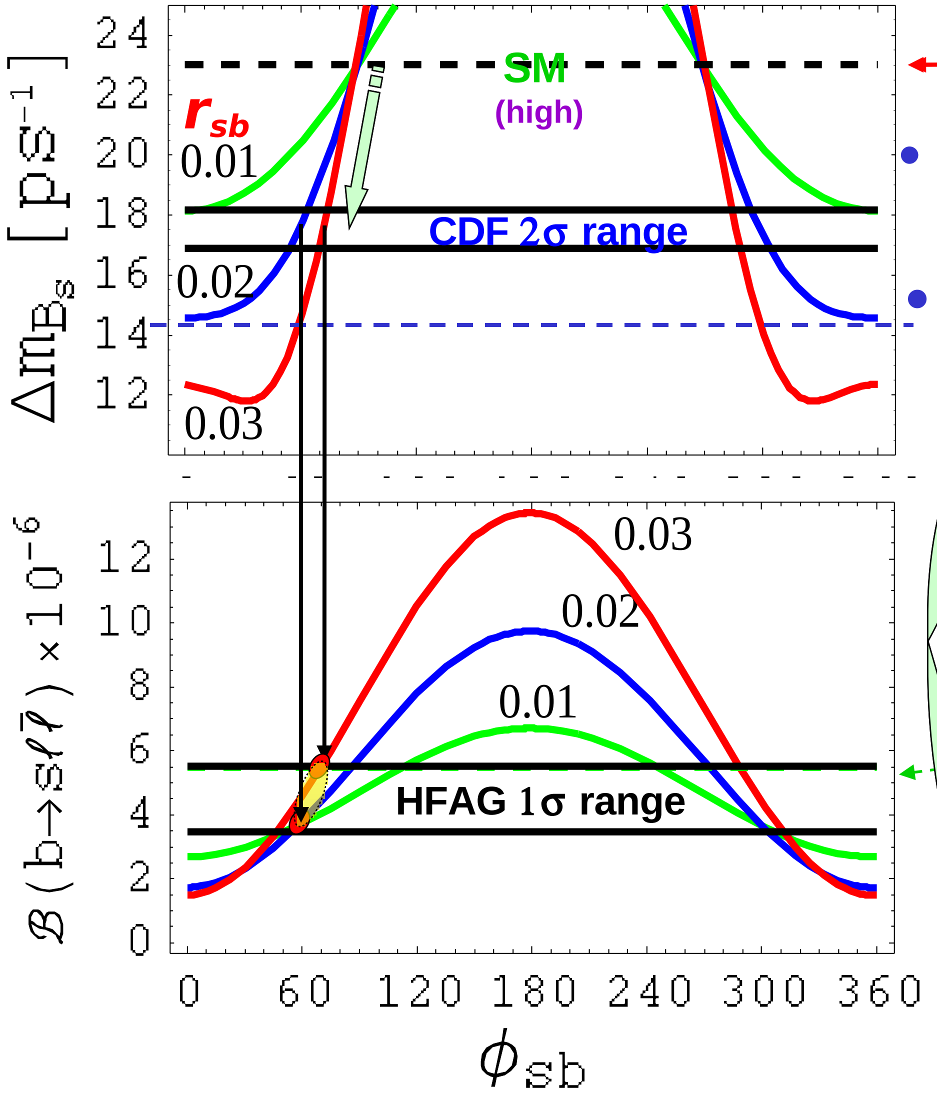
Despite Δm_{B_s}, B(b→sll) SM-like



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

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,

  [$V_{cb} \sim 0.0$

  ϕ_{sb} Range ~ 60° - 70°

Finite CPV

Phase

Consistent w/ **B**(b→sll)

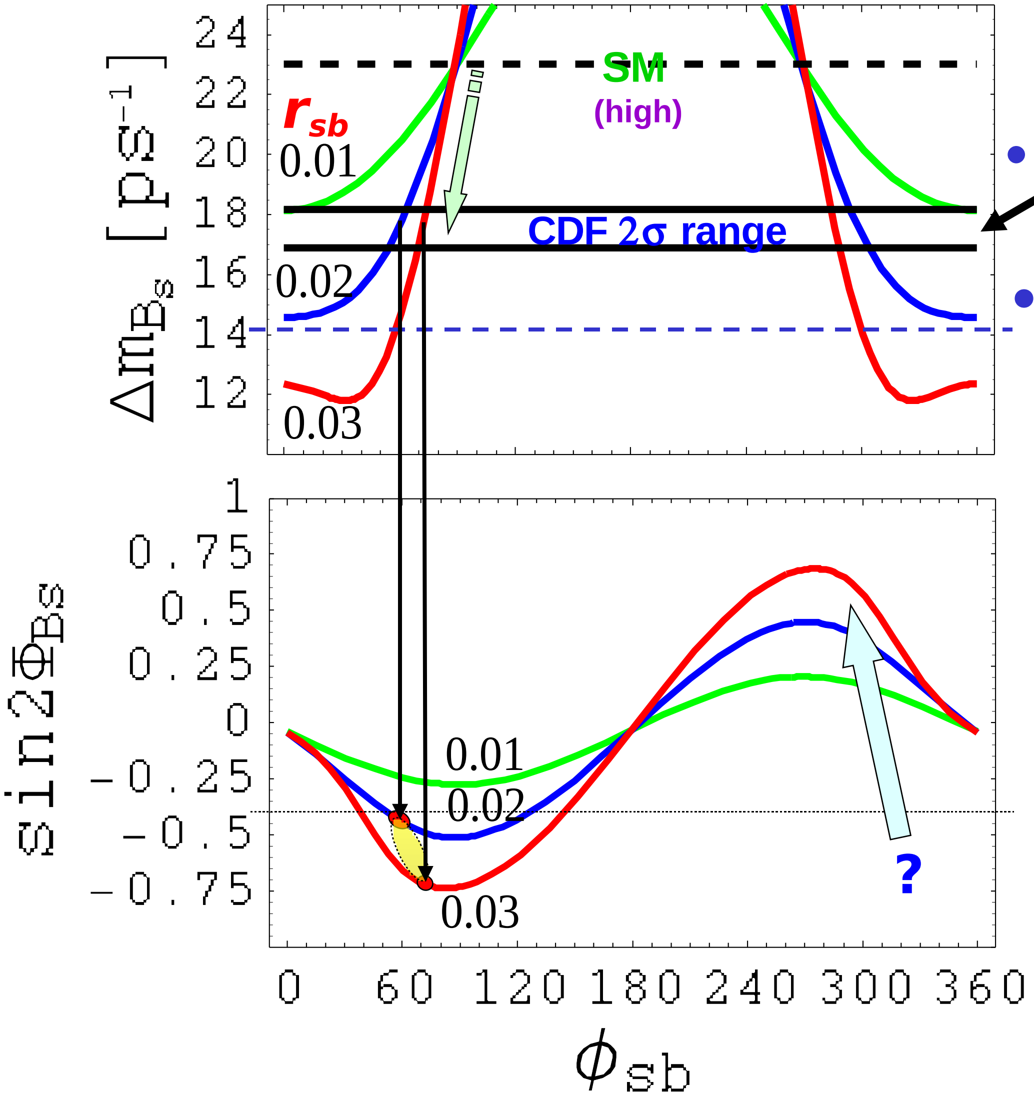
SM-like !

Large CPV Possible !

Despite Δm_{B_s}, B(b→sll) SM-like

Prediction: Large CPV in B_s Mixing

WSH, Nagashima, Soddu, PRD'07



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

- B_s Mixing Measured @ Tevatron in 4/2006
- For r_{sb} ~ 0.02 – 0.03, [V_{cb} ~ 0.0

ϕ_{sb} Range ~ 60° - 70°

Finite CPV

Phase

$\sin 2\Phi_{B_s}$ ~ −0.5 - −0.7

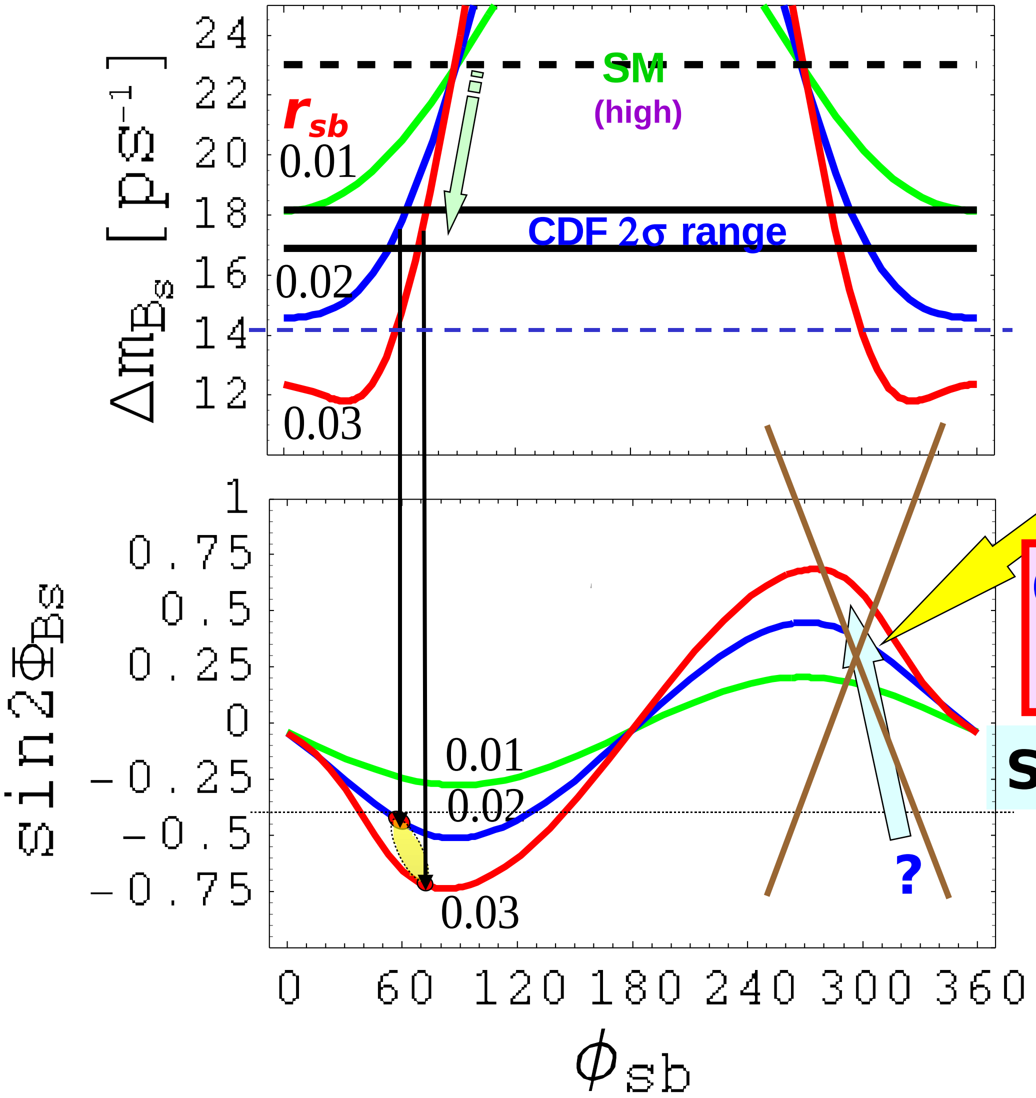
−0.04 SM

Despite Δm_{B_s}, B(b→sll) SM-like

WSH, Nagashima, Soddu, PRL'05

Prediction: Large CPV in B_s Mixing

WSH, Nagashima, Soddu, PRD'07



$\Delta A_{K\pi}$, ΔS

Can **Large CPV in B_s Mixing**

Be Measured @ Tevatron ?

Sign Predicted !

Sure thing by
HCb ca. 2010 (?)

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

-0.04 SM

Despite Δm_{B_s}, B(b→sll) SM-like

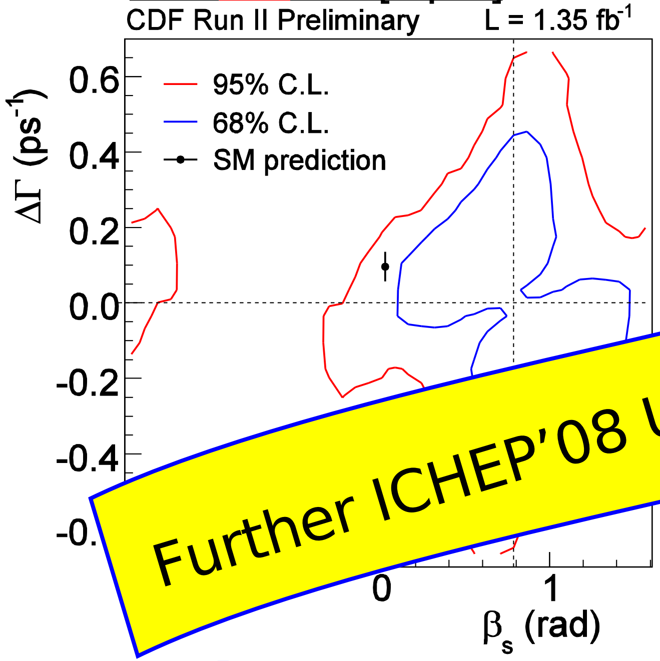
WSH, Nagashima, Soddu, PRL'05

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

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

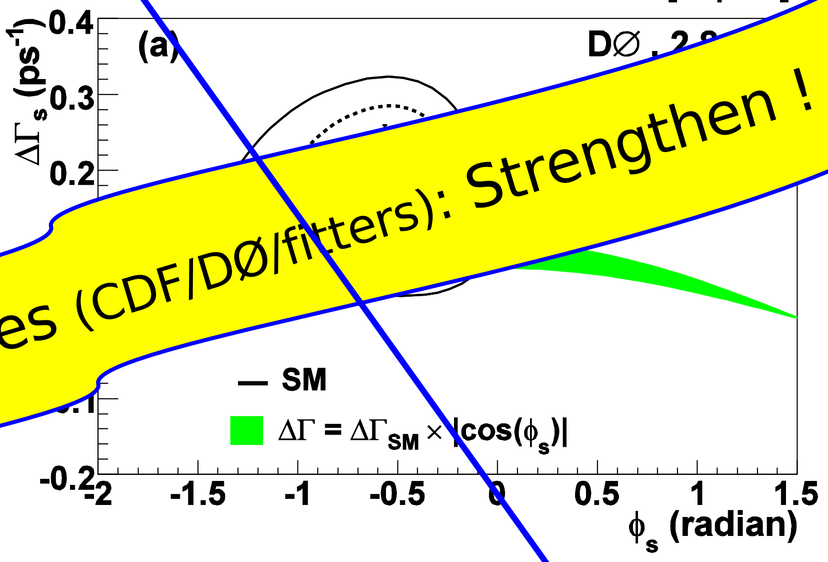
PRL'08

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	[-30.45, -9.29]
	-68.2 ± 4.9	[-78.45,-58.2]

UTfit

arXiv:0803.0659 [hep.ph]

$\sin 2\Phi_{B_s} = -0.64$

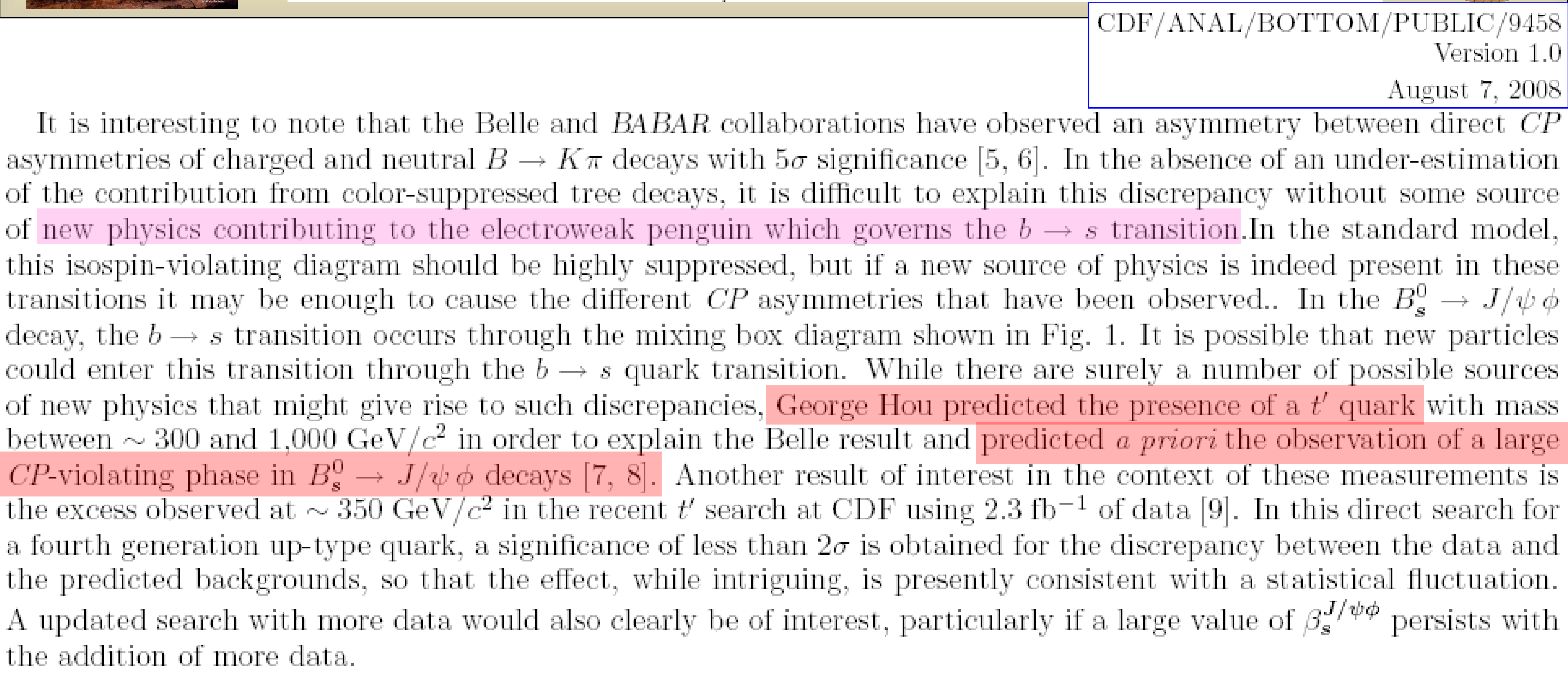
~2.8σ

± ?

Incredible !!!

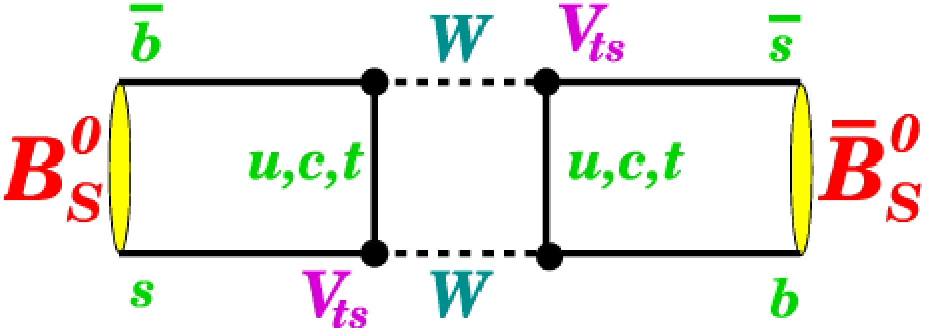
An Updated Measurement of the CP Violating Phase $\beta_s^{J/\psi\phi}$

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

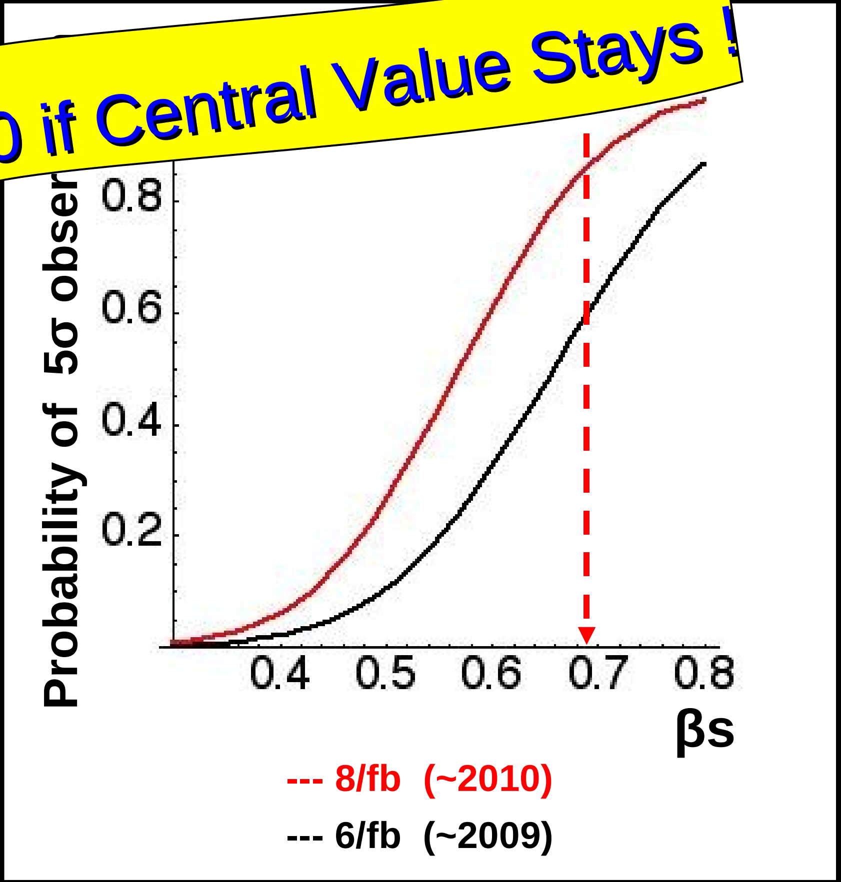
✓ $\Delta\Gamma_s = 0.1$

✓ Co taking efficiency

✓ No analysis improvements.

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

Observation by 2010 if Central Value Stays !



CDF future will probably be better than that.

And DØ will contribute too.

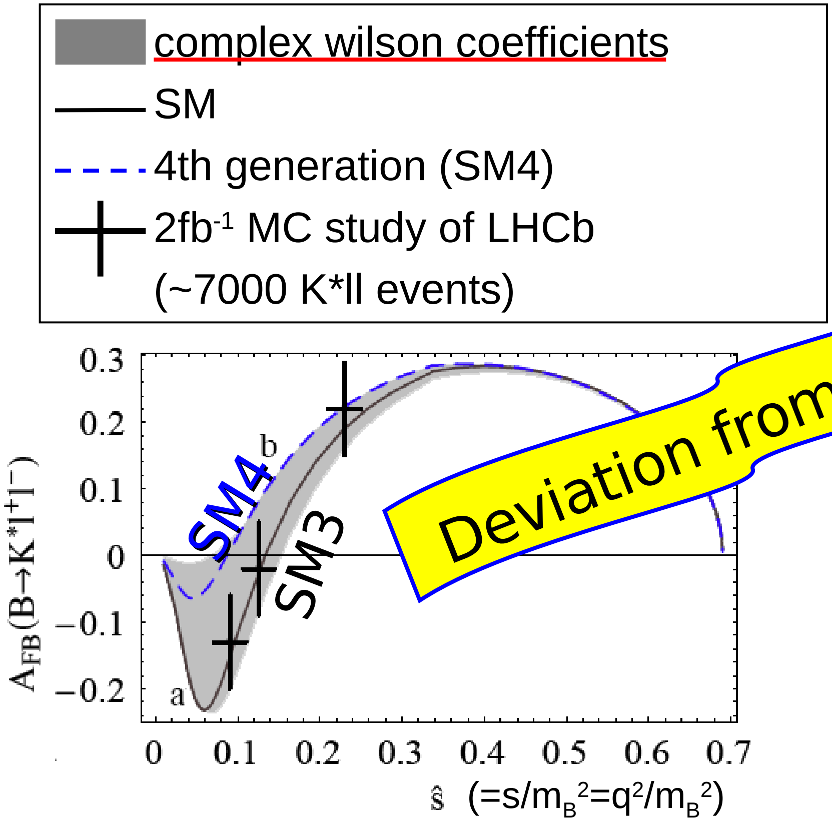
$A_{FB}(B \to K^*l^+l^-)$ and Other Predictions

sent to Backup

Instead flipped C_7 ...

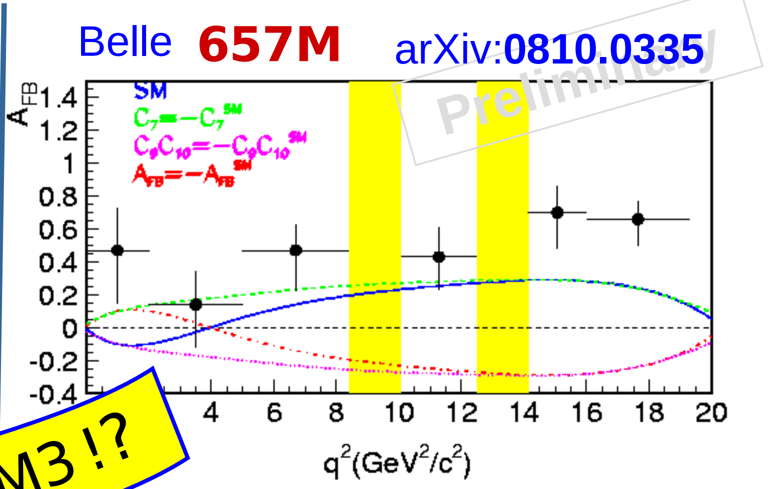
$$\frac{dA_{FB}}{d\hat{s}} \propto -\left\{ \mathrm{Re}(C_9^{eff} C_{10}) V A_1 + \frac{\hat{m}_b}{\hat{s}} \mathrm{Re}(C_7^{eff} C_{10}) \left[V T_2 (1 - \hat{m}_{K^*}) + A_1 T_1 (1 + \hat{m}_{K^*}) \right] \right\}$$

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

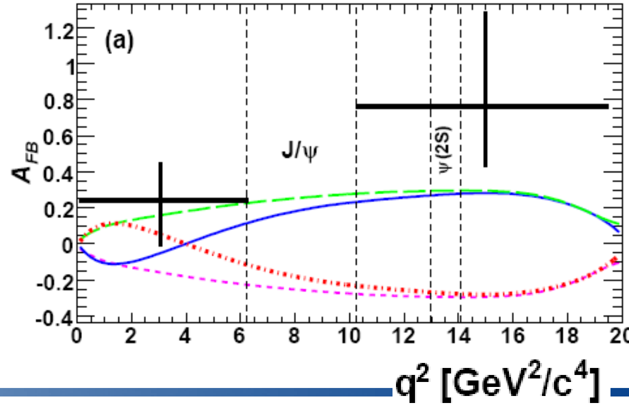


Deviation from SM3 !?

Belle **657M** arXiv:**0810.0335**



BABAR, arXiv:**0804.4412** **386M**



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

If … KM4

B.A.U. from CPV in KM ?

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

WMAP

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

Too Small in SM

Why? Jarlskog Invariant in SM3

(need 3 generation in KM)

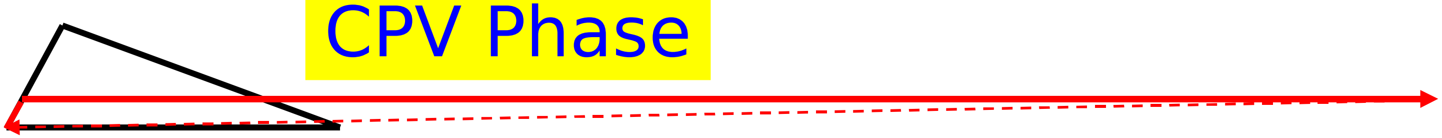
$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2) A$$

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

masses too small !

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

CPV Phase



B.A.U. from CPV in KM

$$\frac{n_B}{n_\gamma} \cong 0$$

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

WMAP

KM ~

Enough CPV?

~~Too Small in SM~~

If shift by One Generation in SM4 (need 3 generation n 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]

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

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

~ 10^{+15} Gain

Order 1 ~ 30

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

arameter alone, corresponding to $N_F = 2.81 \pm 0.24$ for the number of familie

assumes that there are no new contributions to T or U and the

ilies are degenerate. In principle this restriction

July

on new physics **37**

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

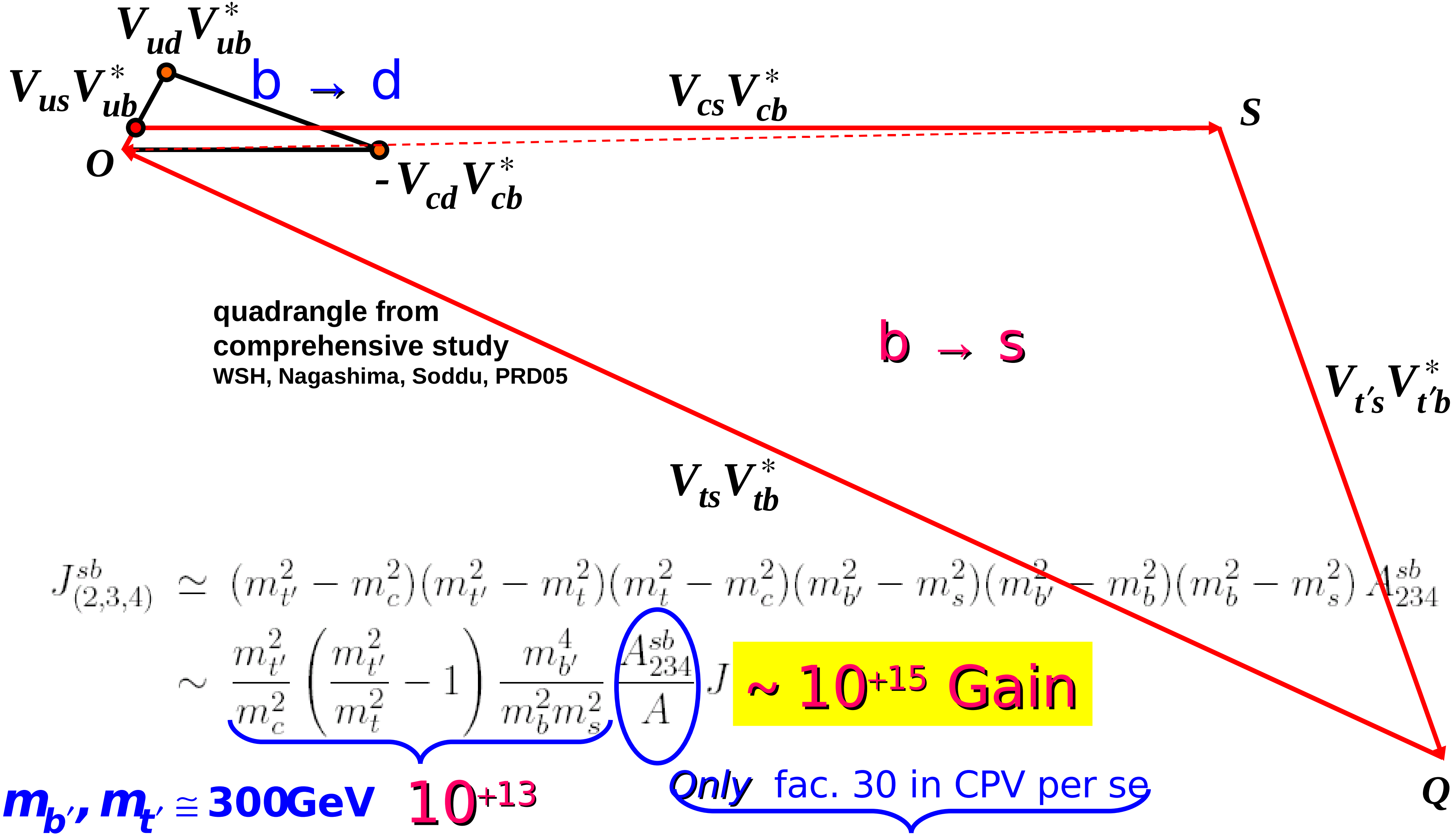
ass limit [208]. This can drive S to small or even negative values but at the expense of too-large contributions to T. These results are in agreement with a fit to the number of light neutrinos, $N_\nu = 2.986 \pm 0.007$ (which favors a larger value for $\alpha_s(M_Z) = 0.1231 \pm 0.0020$ mainly from 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,

Gain mostly in Large Yukawa Couplings !



quadrangle from comprehensive study
WSH, Nagashima, Soddu, PRD05

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

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

~ 10^{+15} Gain

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

~600GeV 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

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

$\longrightarrow$

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

$\longrightarrow$

d-*s* degenerate

(on v.e.v. scale)

2-3-4 generation only !

Effectively 3 generations

$$\boxed{\begin{aligned} J^{sb}_{(2,3,4)} &\simeq (m_{t'}^2 - m_c^2)(m_{t'}^2 - m_t^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_s^2)(m_{b'}^2 - m_b^2)(m_b^2 - m_s^2)\, A^{sb}_{234} \\ &\sim \frac{m_{t'}^2}{m_c^2}\left(\frac{m_{t'}^2}{m_t^2} - 1\right)\frac{m_{b'}^4}{m_b^2 m_s^2}\,\frac{A^{sb}_{234}}{A}\,\enclose{circle}{J} \end{aligned}}$$

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.

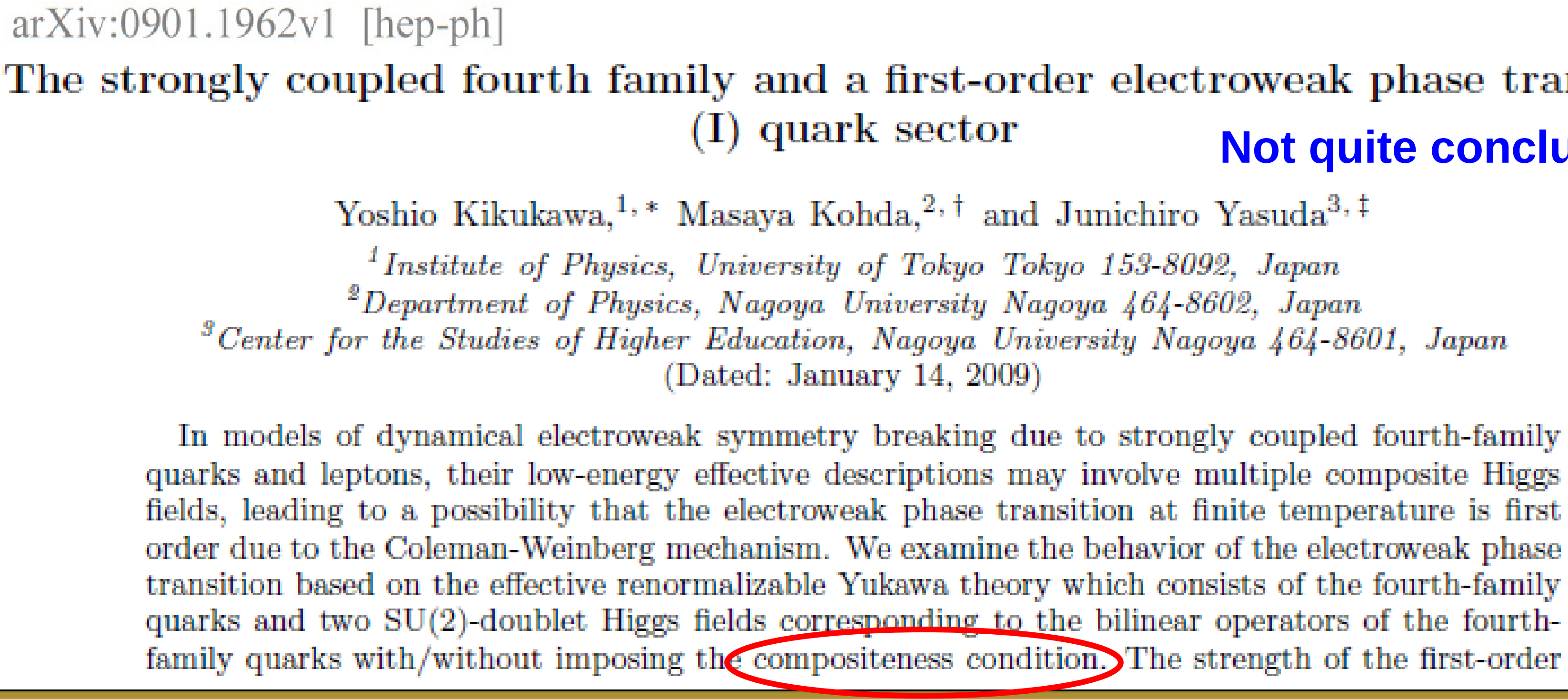
Ran out of time, and knowledge ...

(perturbative)

- Fok & Kribs: Not possible in 4th generation
- Conjecture: Could Strong Yukawa's do it ?

PRD'08
arXiv:0803.4207 [hep-ph]

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

Thoughts on the other 1/2 Nobel Prize

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)

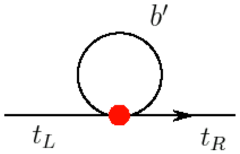
$\langle \bar{\boldsymbol{Q}}\boldsymbol{Q} \rangle$ can Condense

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

Unequivocal BSM

... if true

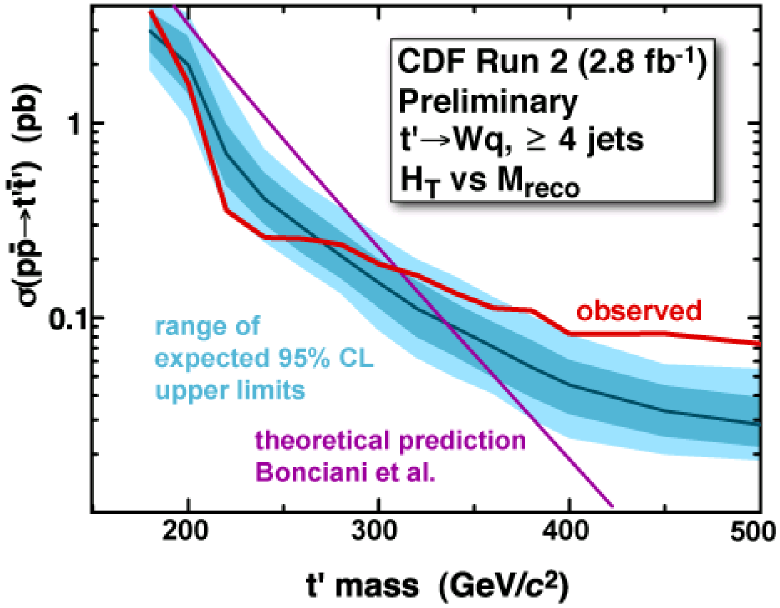
Tevatron

- **$\sin 2\Phi_{B_s}$** “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 ?

Glimpse of agenda at 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**
Well shielded
  - ☞ **Move on to Greener Pastures ~ in 2 years**
- **Publish early — Large Cross Section**
Publish early
  - **- 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

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;

tc(bar)WW*;

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

Bonus !!

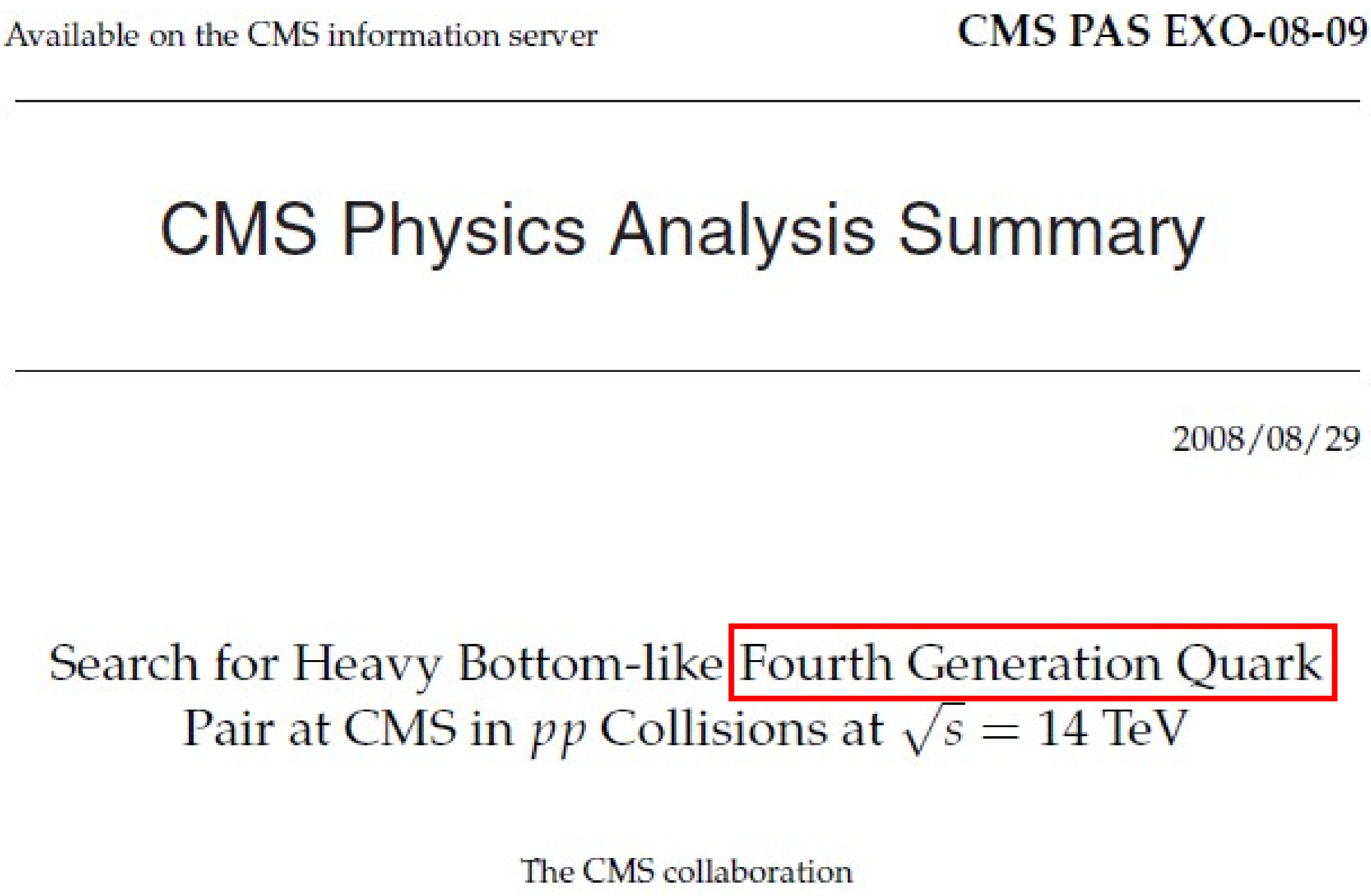
For $m_{b'} > m_t + M_W = 255$ GeV

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

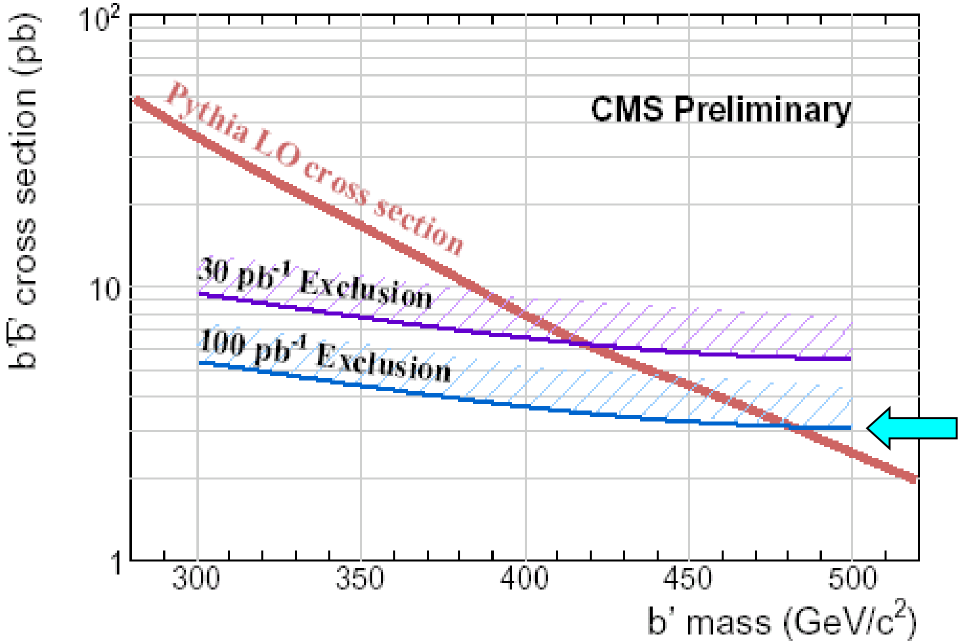
The CMS collaboration

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

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

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

VI. Conclusion: Know in 3-5 Years

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

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

~ 10^{+15} Gain

Even if O(1)

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

~600GeV 10^{+15}

Enough CPV for B.A.U.

Maybe there is a 4th Generation !

sin2Φ_{B_s}

@ Tevatron

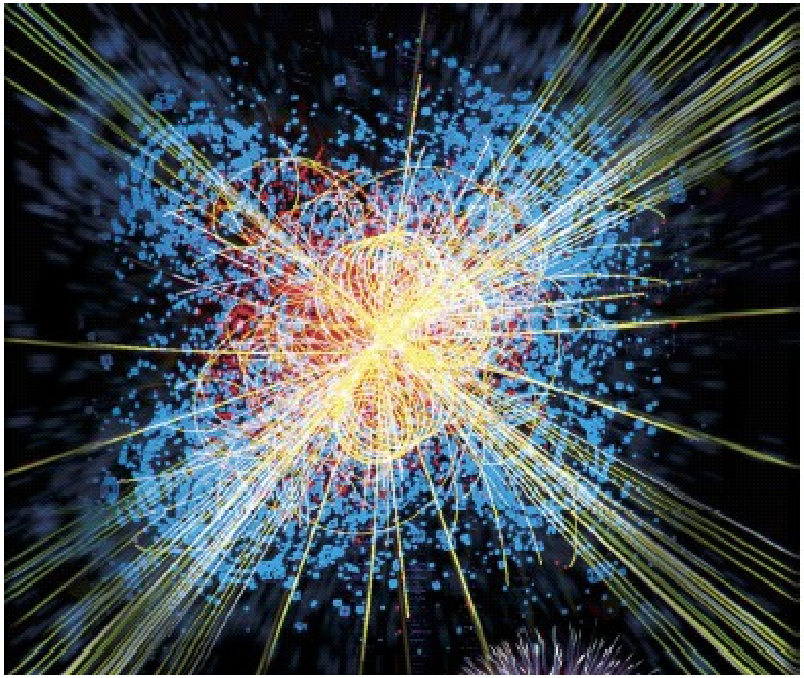
by 2010

Will Really Know in ~ 3–5 years !

@ LHC

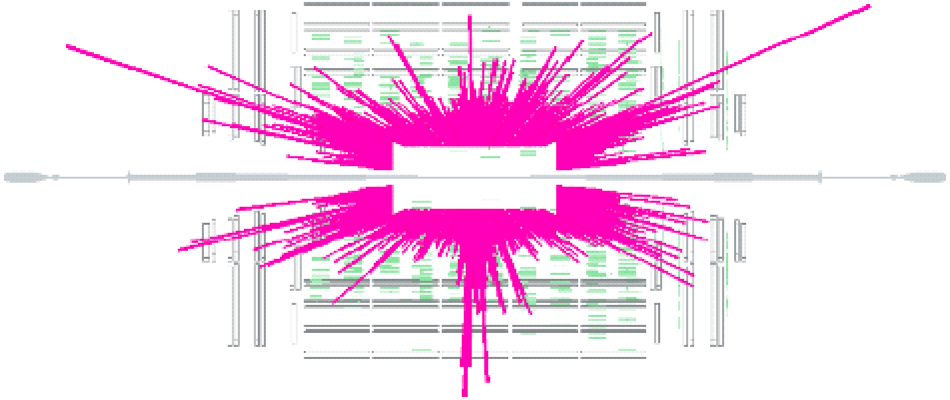
⇨ Heaven on Earth?

Universe (Genesis)



CPV

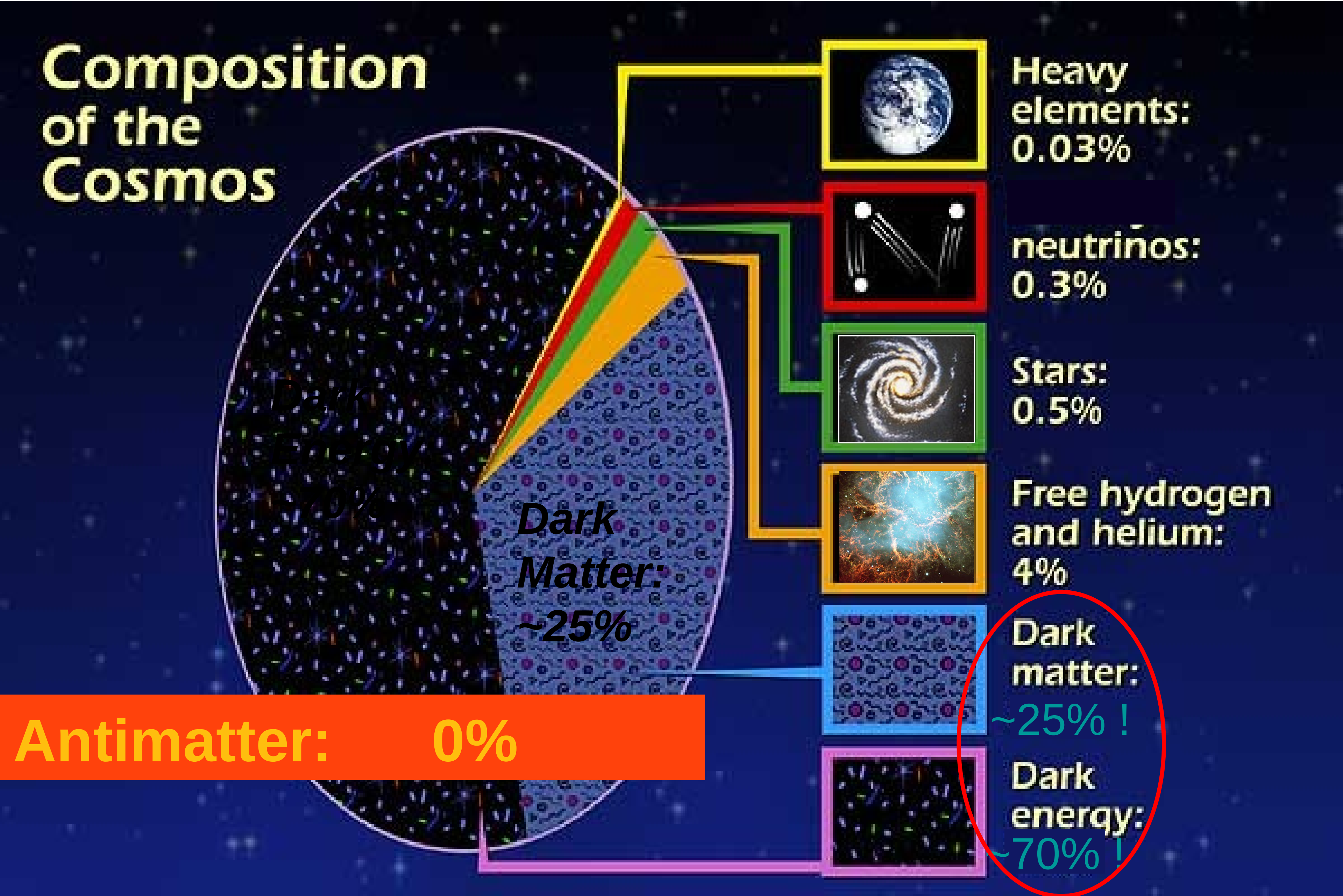
BAU



Earth (EW + KM4)

Backup

Matter (and More !!) Universe: No Antimatter



Dark Energy: ~70%

Dark Matter: ~25%

~25% !

~70% !

Antimatter: 0%

Heavenly TH

“Affleck-Dine”, SUSY etc.:

Extra S **Scalars** trongly) coupled to H^0

More Scalars!

Let’**s** first find One Scalar.

Leptogenesis:

Heavy **Majorana Neutrinos**

⊕ LFV/CPV Decay

⊕ **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.

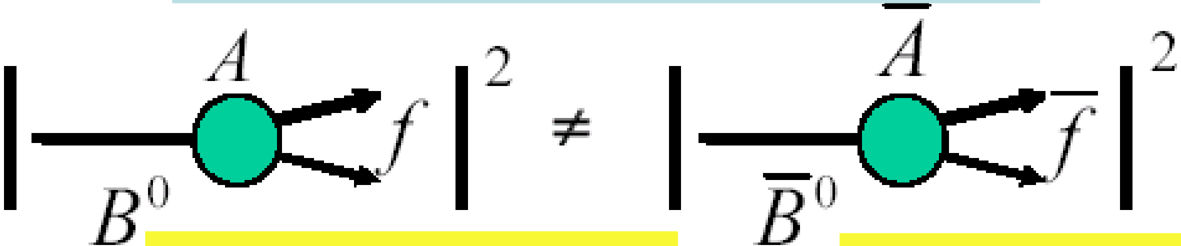
Imagine a Complex Coupling :

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

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

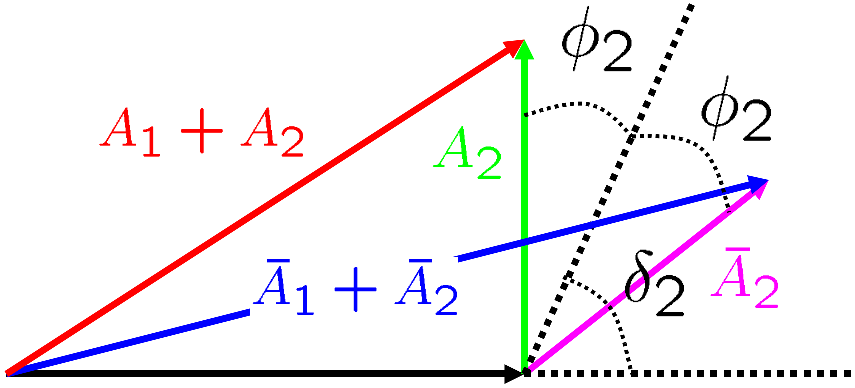
→ How CP Violation Appears

CP Violation Primer



Particle Process

Anti Particle Process



$$A_1 = \bar A_1$$

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

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

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

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

$= +0.147\pm0.028$ $> 5\sigma$ Experiment is Firm

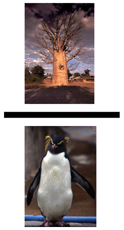
Why a Puzzle ?

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

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

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

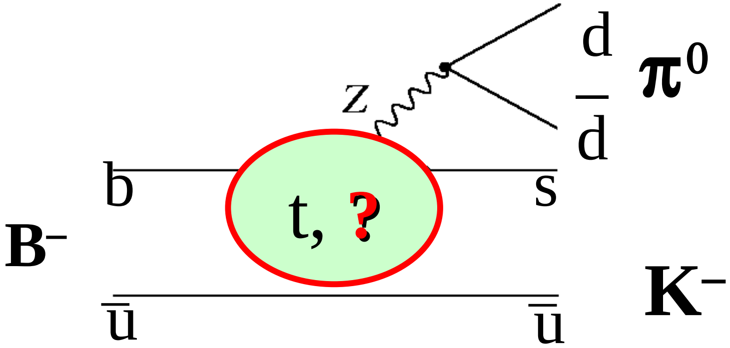
$r =$



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

$+0.050\pm0.025$ -0.097 ± 0.012 **World**

$$\Delta A_{K\pi} = A_{B\to K^+\pi^0} - A_{B\to K^+\pi^-} \neq 0$$

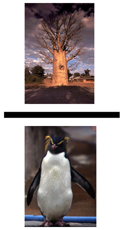
$= +0.147\pm0.028 \quad > 5\sigma$ Experiment is Firm

Why a Puzzle ?

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

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

$r =$

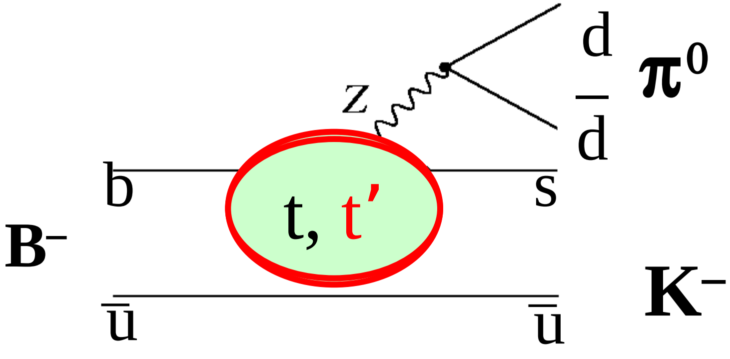


$$\sqrt{2}\mathcal{M}_{K^+\pi^0} - \mathcal{M}_{K^+\pi^-} \propto (P_{\rm EW} + C)$$?

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

Baek, London, PLB653, 249 (2007)

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

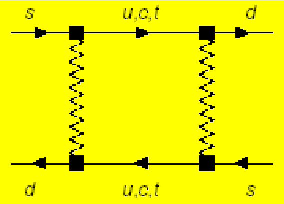


$P_{\rm EW}$ has practically no weak phase in

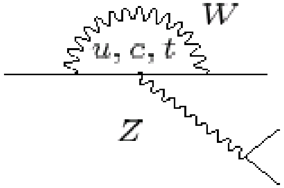
4th Gen. in EWP Natural

nondecoupling

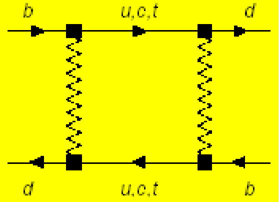
On Boxes and Z Penguins



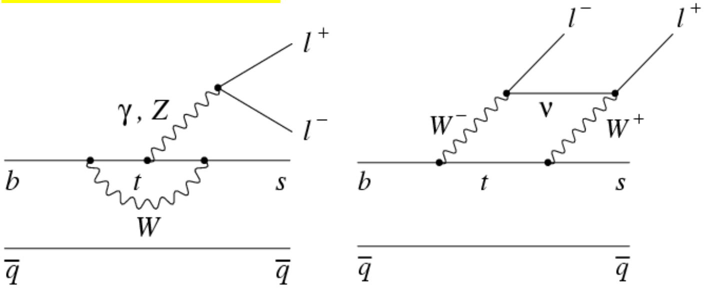
GIM, charm, ε_K



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



heavy top, sin2ϕ_1/β



Z dominance for heavy top

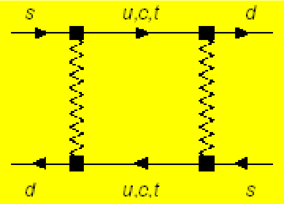
1986 → 2002

Most Flavor/CPV learned from these diagrams/processes

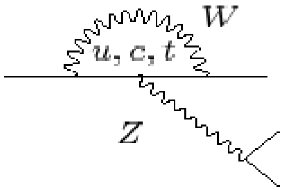
On Boxes and Z Penguins

Nondecoupling

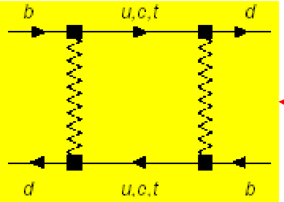
∵ Large Yukawa !



⇒ GIM, charm, ε_K

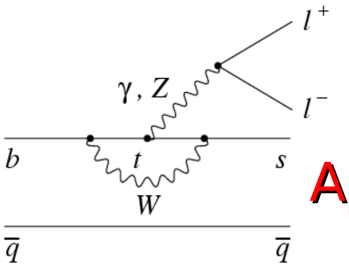


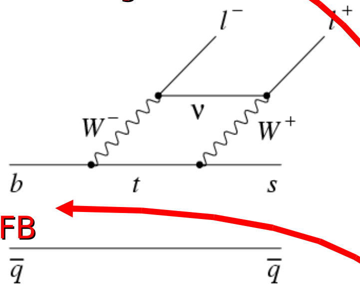
⇒ small ε'/ε, $K \to \pi\nu\nu$ (still waiting)



⇒ heavy top, sin$2\phi_1/\beta$

B_s





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

$$
\begin{array}{c|llll}
 & d & s & b & b' \\
\hline
u & \begin{array}{l} 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})] \end{array} & \begin{array}{l} c_{13}\,c_{24}\,s_{12} \\ -s_{13}\,s_{24}\,s_{34}\exp[-i(\phi_{sb}+\phi_{ub})] \end{array} & c_{34}\,s_{13}\exp[-i\phi_{ub}] & \begin{array}{l} 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}] \end{array} \\
c & \begin{array}{l} -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}] \end{array} & \begin{array}{l} 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}] \end{array} & c_{13}\,c_{34}\,s_{23} & \begin{array}{l} -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} \end{array} \\
t & \begin{array}{l} -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}] \end{array} & \begin{array}{l} -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}] \end{array} & c_{13}\,c_{23}\,c_{34} & \begin{array}{l} -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} \end{array} \\
t' & -c_{24}\,c_{34}\,\boxed{s_{14}}\exp[-i\phi_{db}] & -c_{34}\,\boxed{s_{24}}\exp[-i\phi_{sb}] & \boxed{-s_{34}} & c_{14}\,c_{24}\,c_{34}
\end{array}
$$

SM3

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

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

$$\equiv r_{ds} \quad \phi_{ds}$$

Kaon

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

b → s

$$\equiv r_{sb}$$

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

b → d

Cross Check !

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

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

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

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

Constrain s ↔ d from K Physics

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

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

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

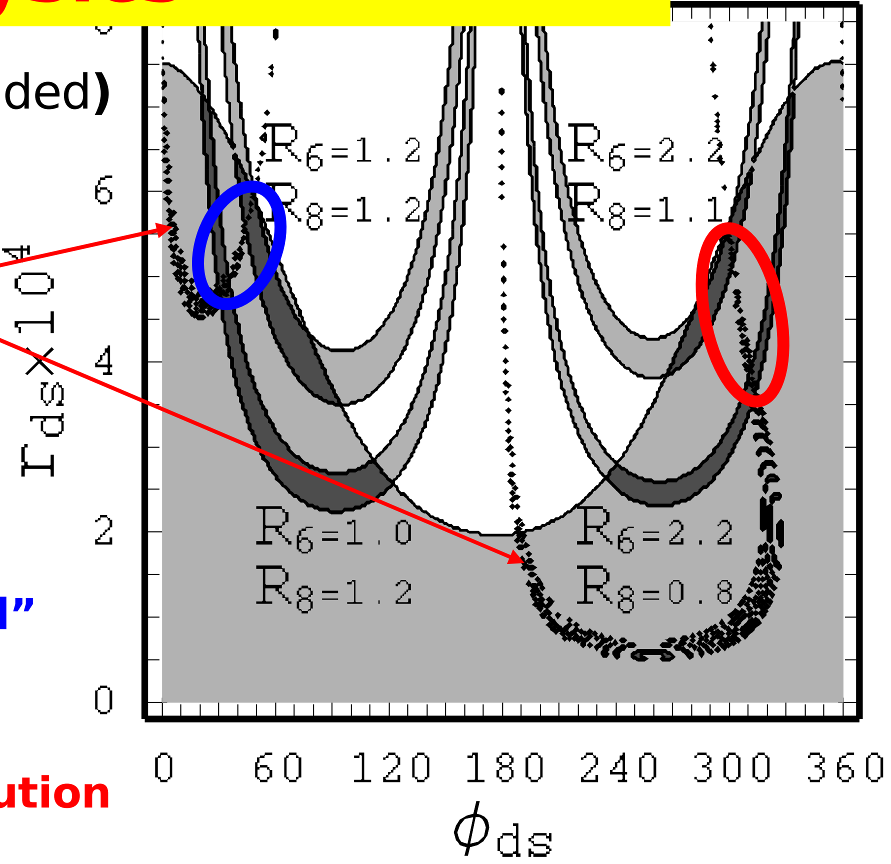
$\frac{\epsilon'}{\epsilon} = (16.6 \pm 2 \times 1.6) \cdot 10^{-4}$

$R_6 = 1.2$ **(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….

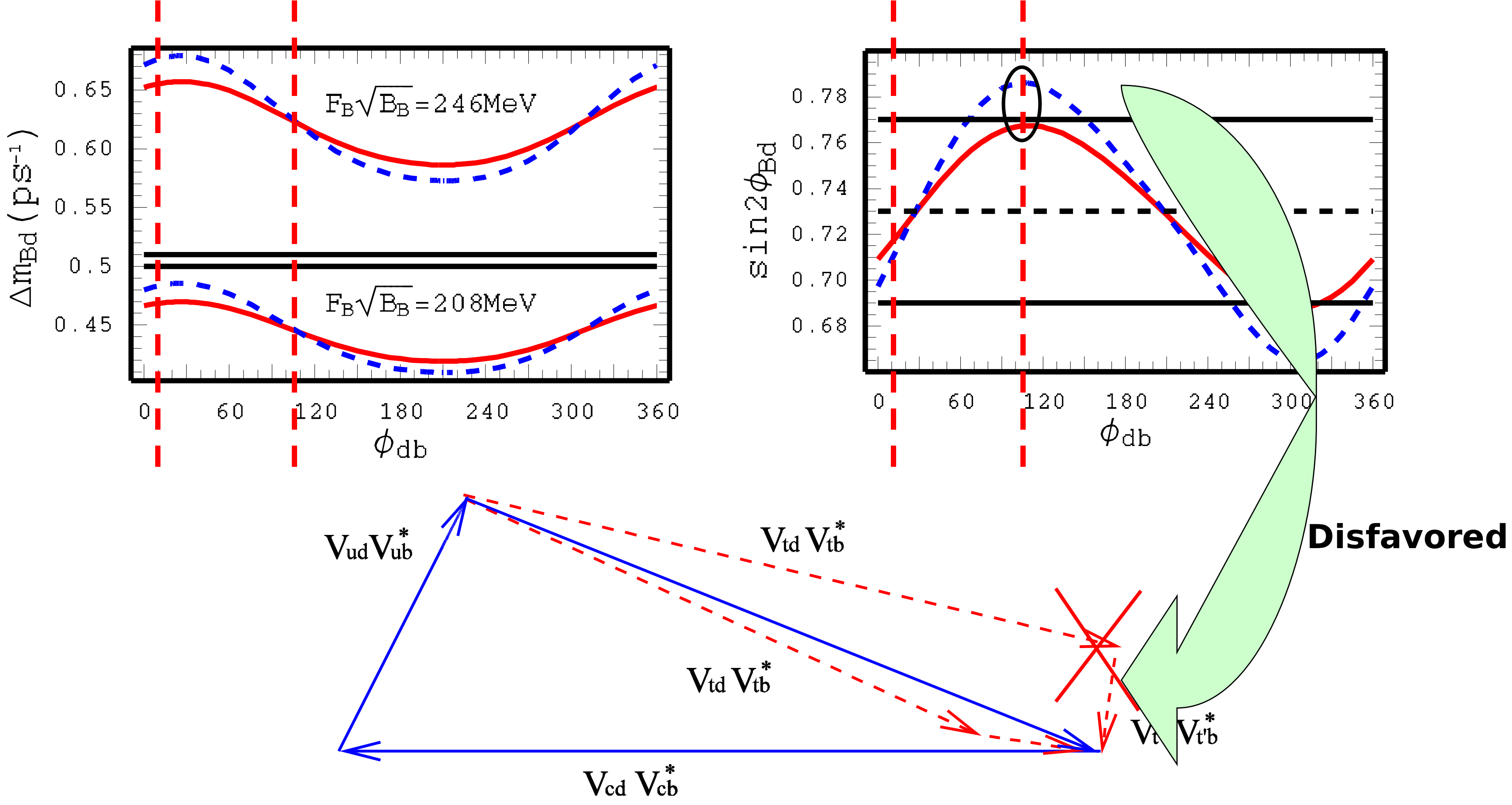
$$\boxed{r_{ds} \sim 5 \times 10^{-4}, \quad \phi_{ds} \sim -60^\circ \text{ or } +35^\circ}$$

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

$r_{ds} \sim 5 \times 10^{-4}, \quad \phi_{ds} \sim -60^\circ$ 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 $V_{ub} \sim 0.01\, e^{-i\gamma}$



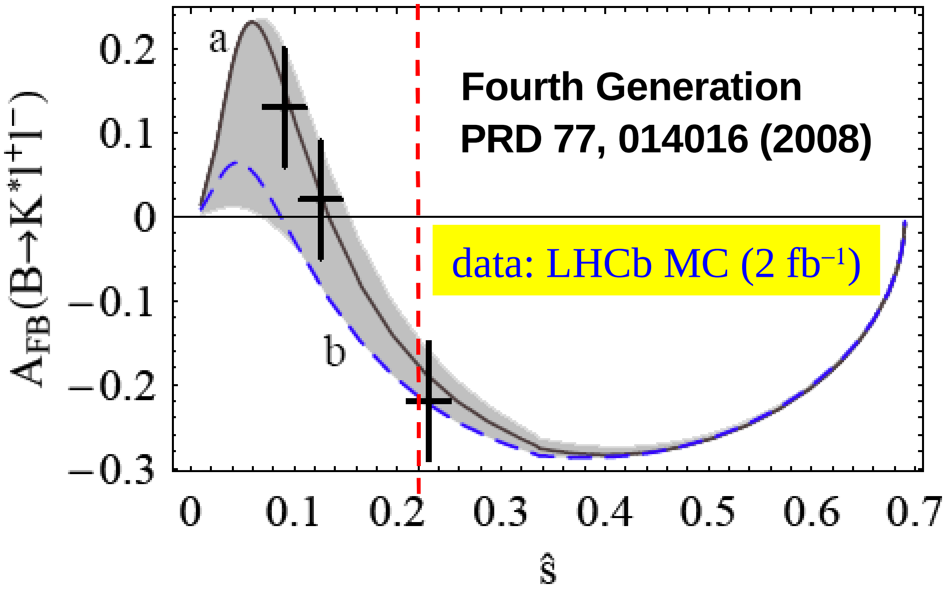
Hard to tell apart (non-trivial) with present precision

∵ stringent s → d

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

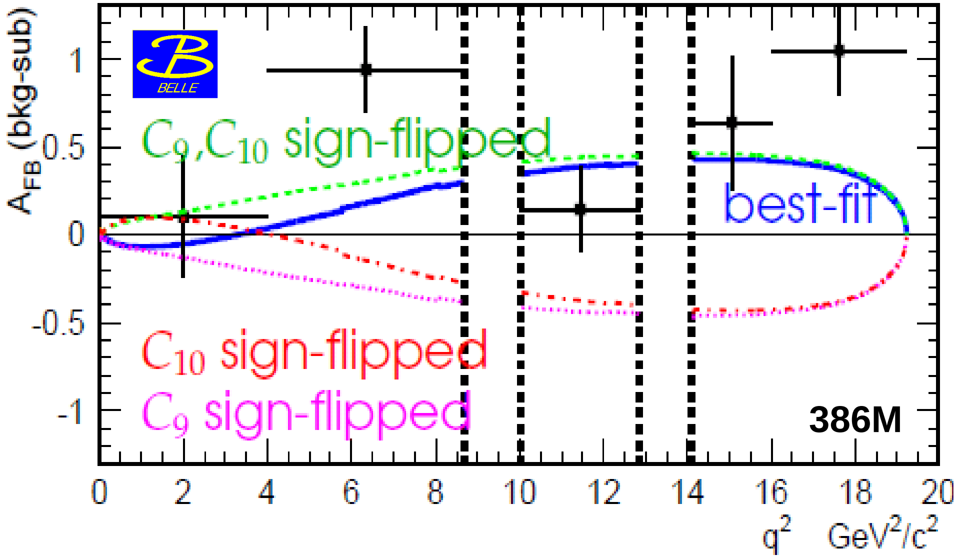
sent to Backup

Quoted by **Tsybychev at FPCP08**

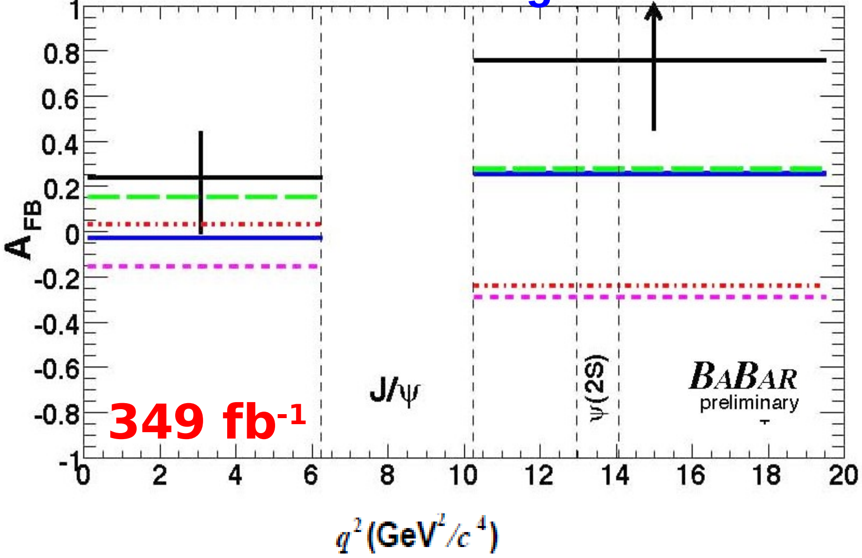


a: SM; b: 4 Gen.
better

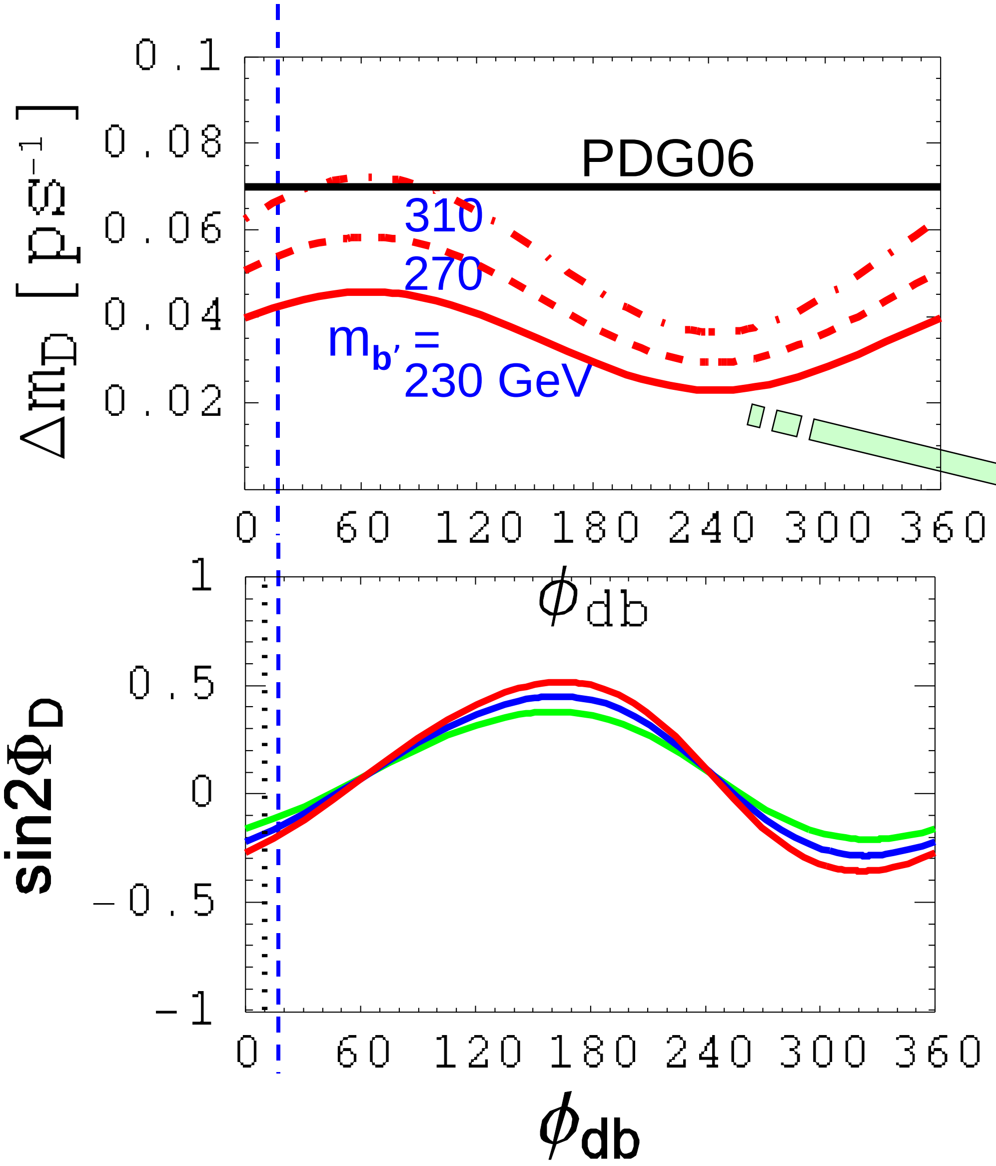
- (F$_L$ and) A$_{FB}$ (and A$_l$) favor the “opposite-sign C$_7$ model”



Eigen at FPCP08



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

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

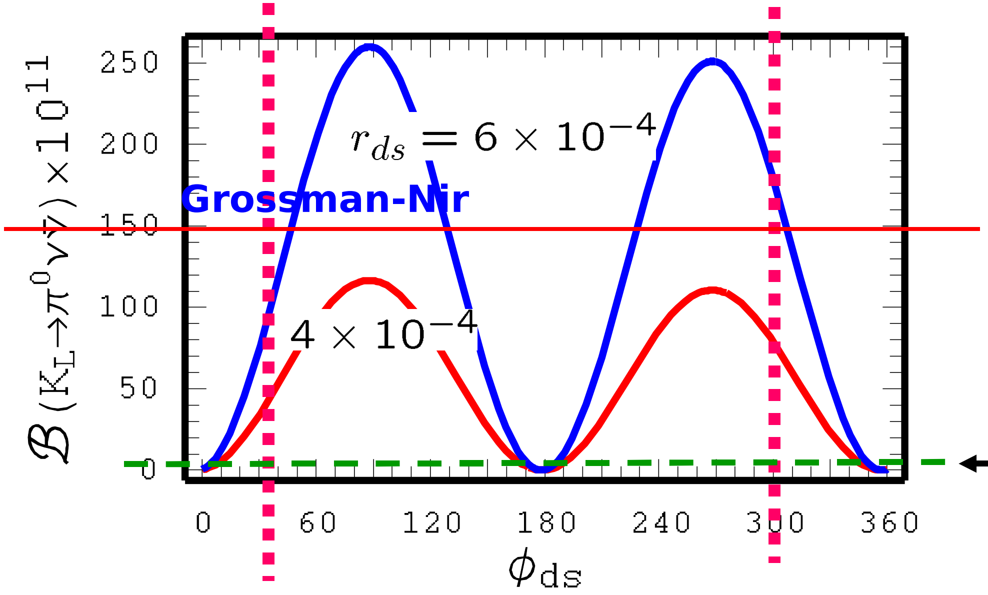
x = Δm/Γ ~ 1 - 3 plausible

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 !!

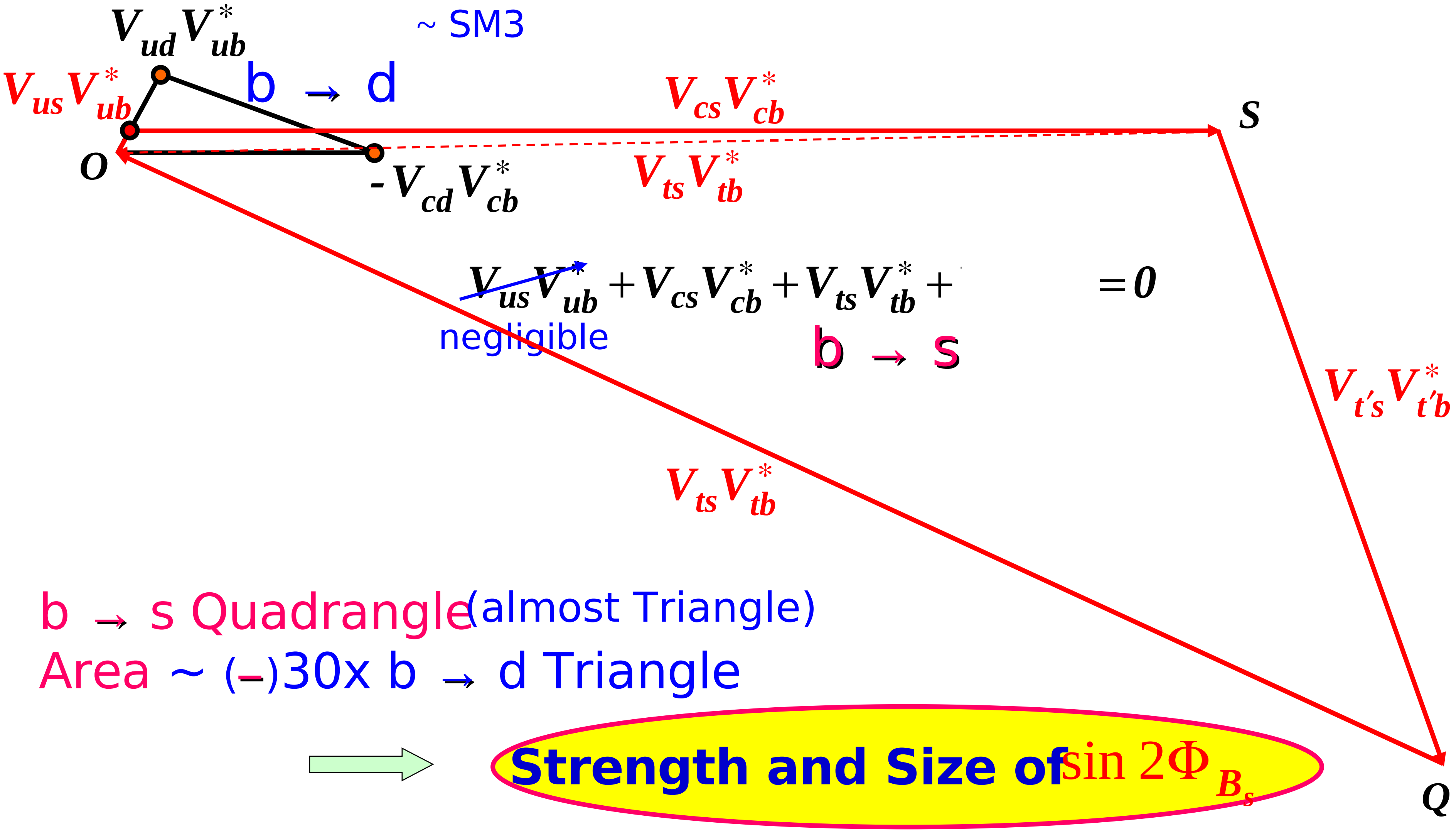
$K_L \to \pi^0\nu\bar{\nu}$ **enhanced to** 5×10^{-10} **or even higher !!**

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

∵ Large CPV Phase

b → d "Triangle" and b → s Quadrangle

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



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

negligible

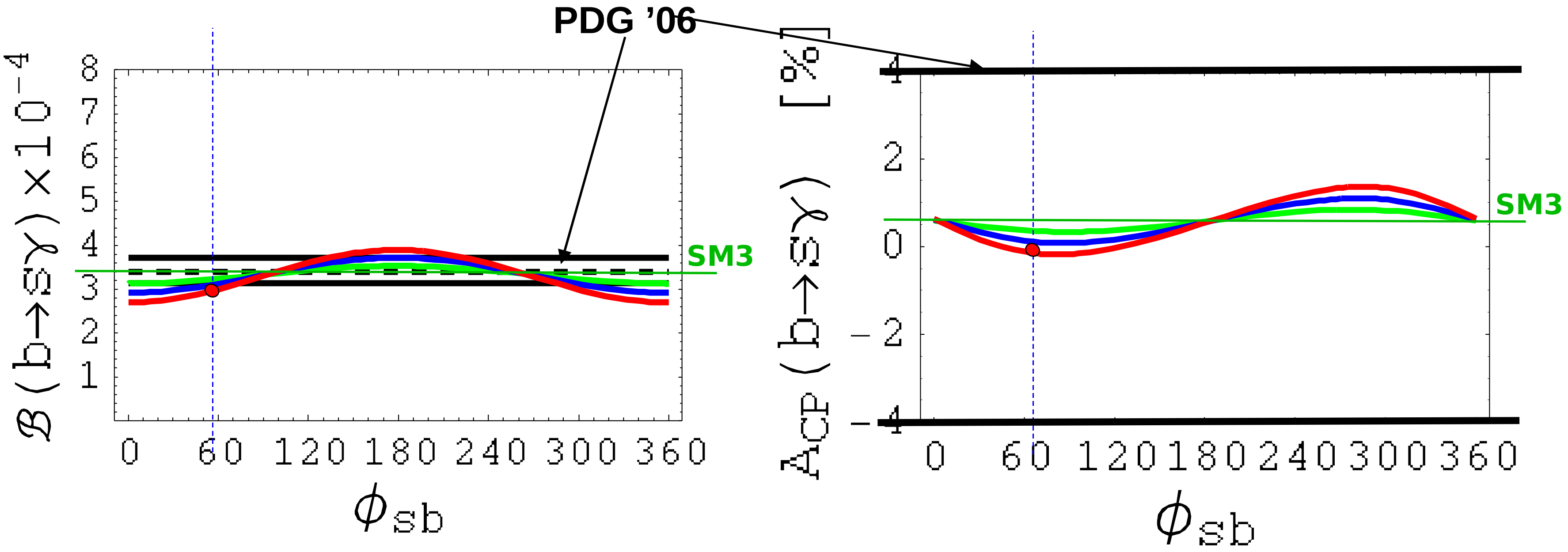
b → s

b → s Quadrangle(almost Triangle)

Area ~ (–)30x b → d Triangle

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

Consistency and b → sγ Predictions

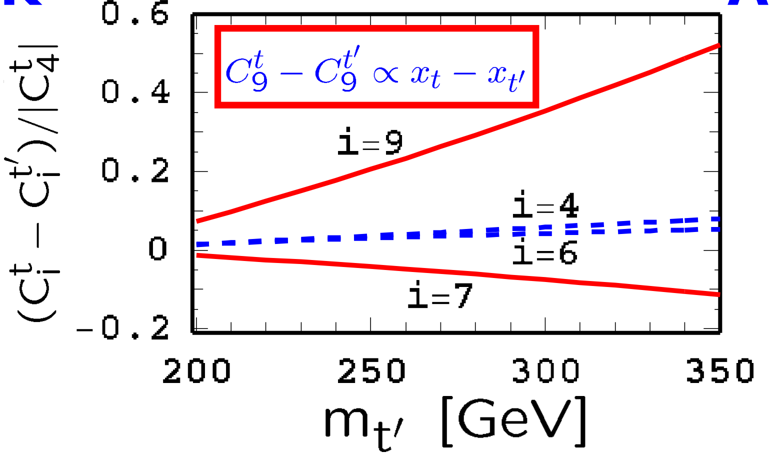


BR OK

A_{CP} ~ 0 far away

beyond SuperB

Heavy t' effect decoupled for b → sγ



The Eureka Moment

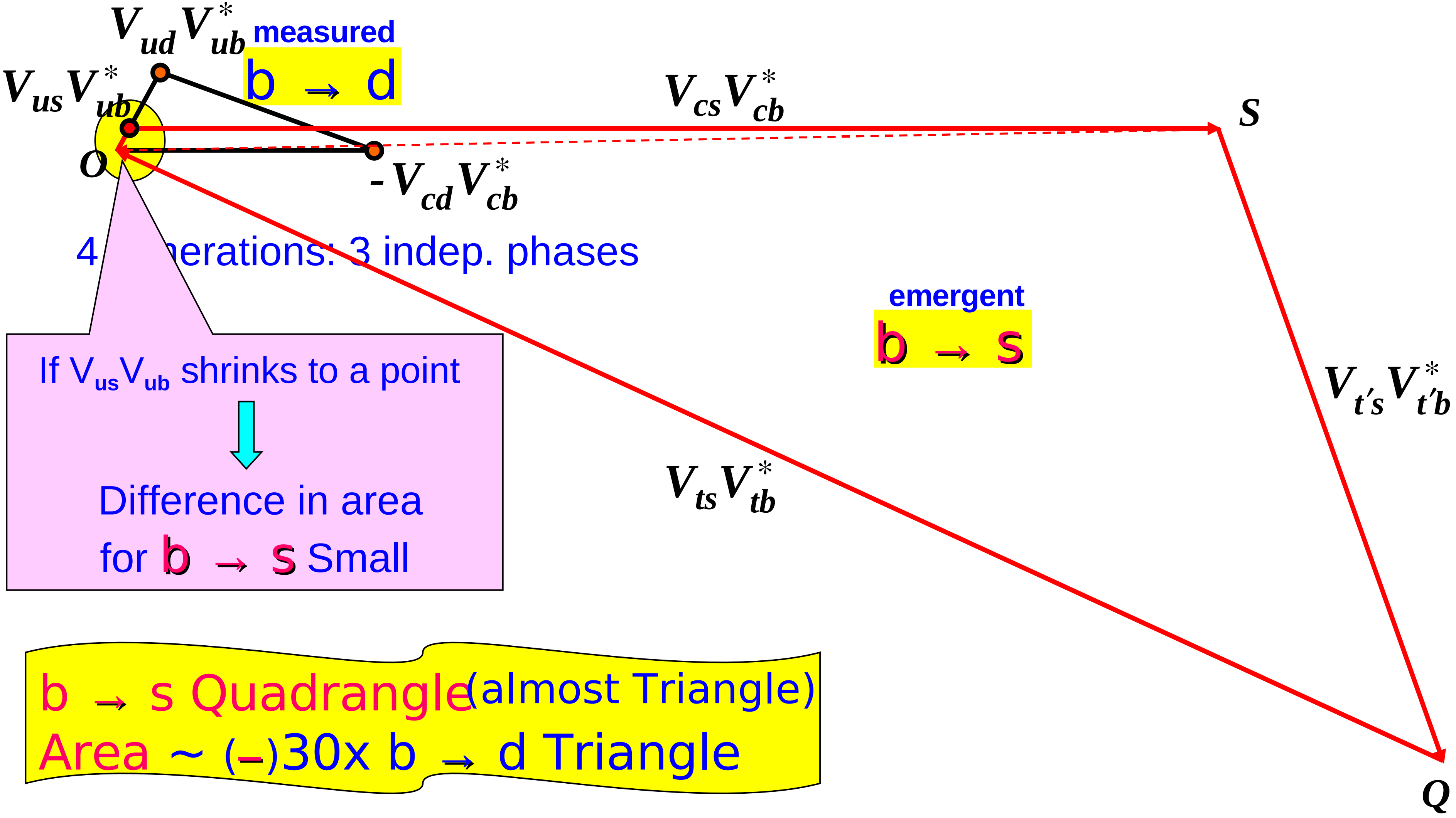
Large t, t’ Yukawa

ca. late summer 2007 …

Large Yukawa !

YuReKawa !

4 generations: 3 indep. phases



If $V_{us}V_{ub}$ shrinks to a point

⇓

Difference in area

for b → s Small

b → s Quadrangle (almost Triangle)

Area ~ (–)30x b → d Triangle

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