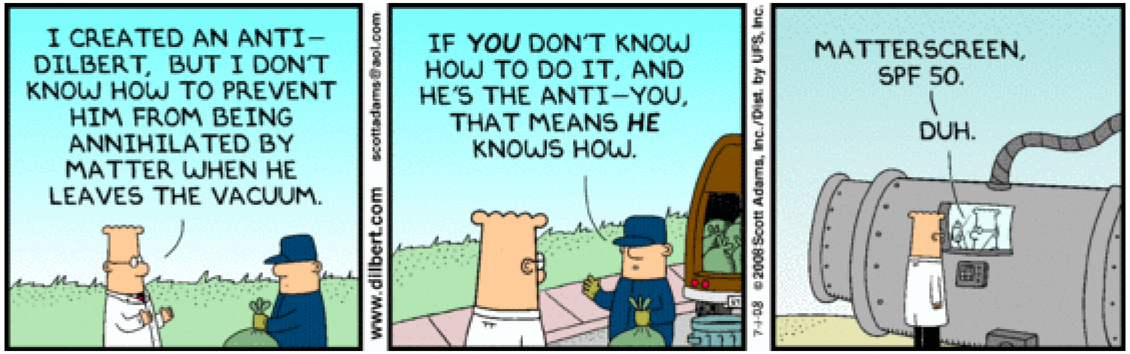
Source of CP Violation for Baryon Asymmetry of the Universe

George W.S. Hou (侯維恕)
National Taiwan University

(August 1, 2008, ICHEP'08 @ Penn)
September 4, 2008, Beyond 3SM @ CERN



Source of CP Violation

Outline

I. The Lore that Despairs the Experimenter

II. Going up a Hill … and (*maybe*) Becoming a Mountain

III. Soaring to the Starry Heavens

IV. Towards Solution of BAU

V. Tevatron/LHC Verification

VI. Conclusion

I. The Lore that Despairs the Experimenter

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

LETTERS

Obligé

Dispair

talk by Paoti Chang (Belle)

BELLE

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

The Belle Collaboration*

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.

Equal amounts of matter and a
been produced in the Big Bang,
clearly matter-dominated. One
standing this elimination of ant
of charge-parity (CP) symmetry.
have been observed in the neutral
systems: CP violation involving
antiparticle $\bar{K}^0$ (and likewise[3,4] fo
tion in the decay of each meson
types of CP violation are substa
system. However, they are sti
model of particle physics, which
tion that is known to be too sm
dominated Universe. Here we re
in charged $B^{\pm}\to K^{\pm}\pi^0$ decay is dif
counterpart. The direct CP-violati
(that is, the difference between th
event versus $B^+\to K^+\pi^0$ events,
events) is measured to be about +
reduced by a factor of 1.7 from a
ever, the asymmetry $\mathcal{A}_{K^{\pm}\pi^{\mp}}$ for B
the −10% level[7,8]. Although it is s
effects that need further clarificat
CP violation between charged a
be an indication of new sources
help to explain the dominance of

Electroweak Baryogenesis !?

Kuzmin, Rubakov, Shaposhnikov, 1986

Sakharov (1967)

Antimatter → Matter if:

(1) Proton Decay
(Baryon # Violation) ✓

(2) Matter-antimatter Asymm.
(CP Violation) Too Small !

(3) Out of Equilibrium EWPhT a crossover !
(not strong enough ...)

Challenge

Particle Physics  Astrophysics

Continue Search for CP Violation

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 $\bar{d}$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 $\bar{B}^-$ 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 from the Belle[1] and BaBar[2] collaborations invite

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.

B.A.U. from CPV in KM ?

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

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

WMAP

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

Too Small in SM

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

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

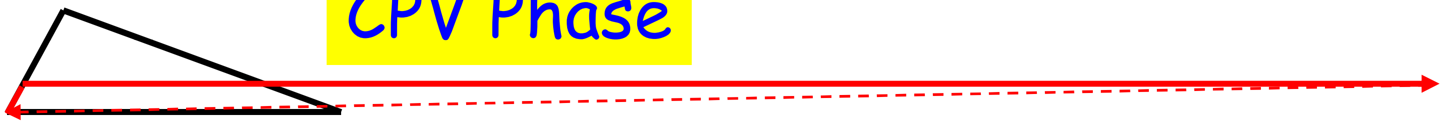
Normalize by T ~ 100 GeV ⟹ $J/T^{12} \sim 10^{-20}$

Masses too Small !

Small, but not *Too* small

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

CPV Phase



"Affleck-Dine", SUSY etc.:

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

More Scalars!

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

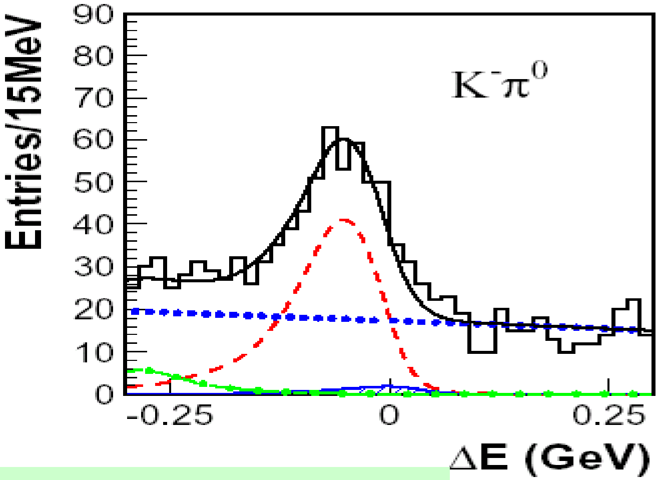
Saga Towards Belle Nature Paper ...

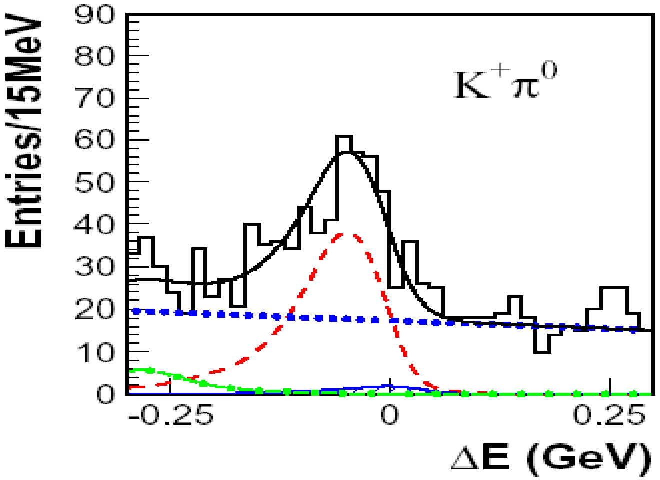
$A_{CP}(B \to K^+\pi^0)$

Sakai

275M $B\bar{B}$
New

$K^{\pm}\pi^0$: 728 ±53



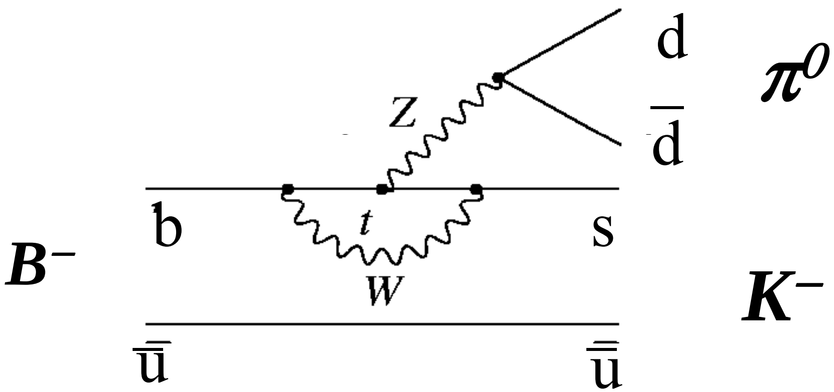


$A_{CP}(K^{\pm}\pi^0) = 0.04 \pm 0.05 \pm 0.02$

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.

by "yours truly"

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).

P_{EW}

Z'

NEWS & VIEWS NATURE|Vol 452|20 March 2008

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.

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. ■

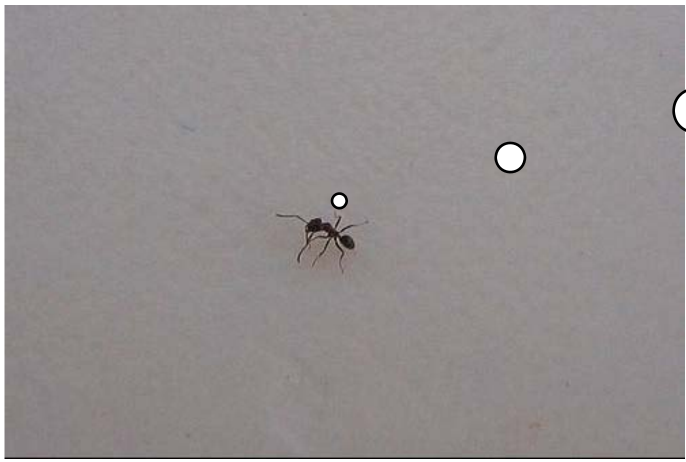
Michael E. Peskin is in the Theoretical Physics Group, Particle Physics and Astrophysics

C

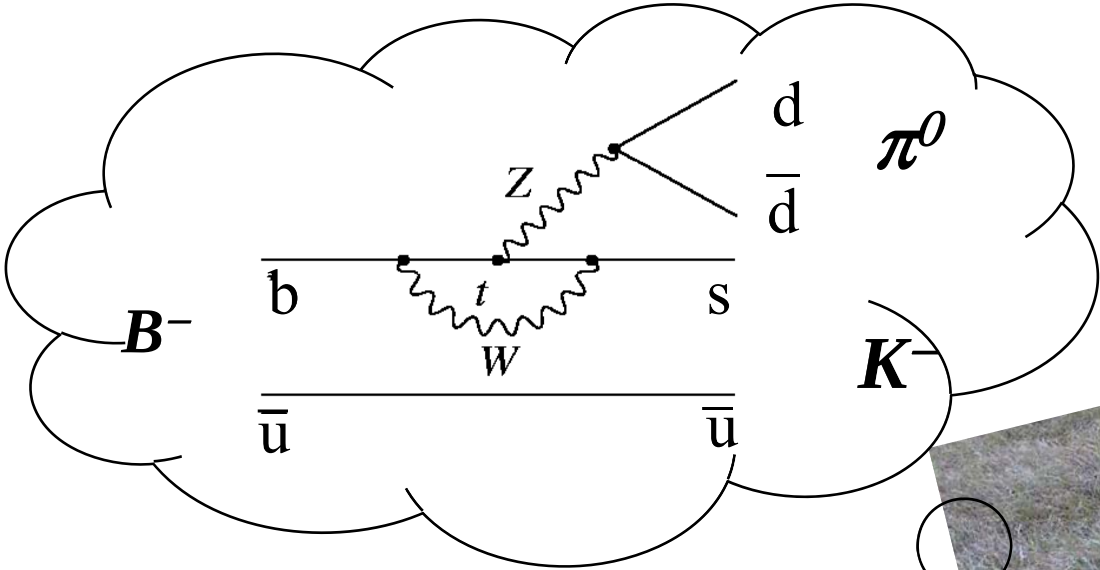
P_{EW}

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."



II. Going up a Hill … and (*maybe*) Becoming a Mountain



Going Up a Hill ...

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]

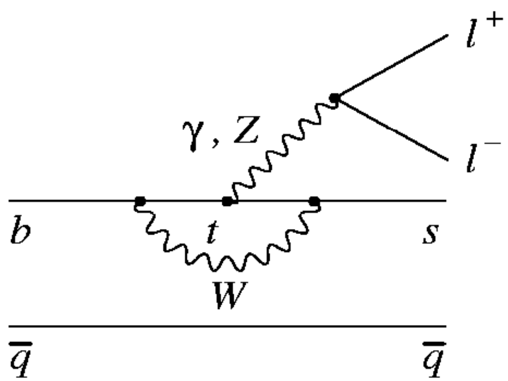
$$\bar{C}_i \equiv \bar{C}_i^Z + \bar{C}_i^{\rm box} = \tfrac{1}{4}x_i + \frac{3}{4}\left(\frac{x_i}{x_i-1}\right)^2 \ln x_i - \frac{3}{4}\frac{x_i}{x_i-1}, \quad (3)$$

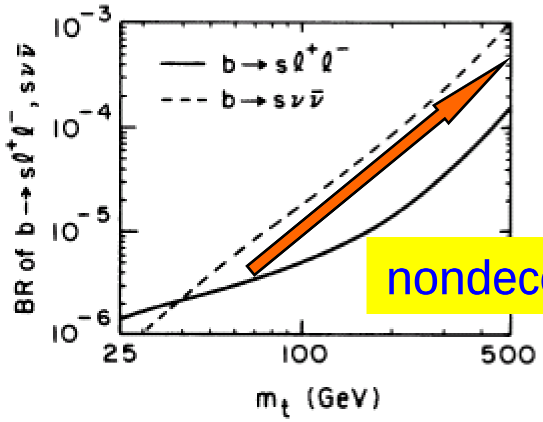
$$\bar{D}_i \equiv \bar{D}_i^Z + \bar{D}_i^{\rm box} = \tfrac{1}{4}x_i + \frac{3}{4}\frac{x_i(x_i-2)}{(x_i-1)^2}\ln x_i + \frac{3}{4}\frac{x_i}{x_i-1}, \quad (4)$$

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

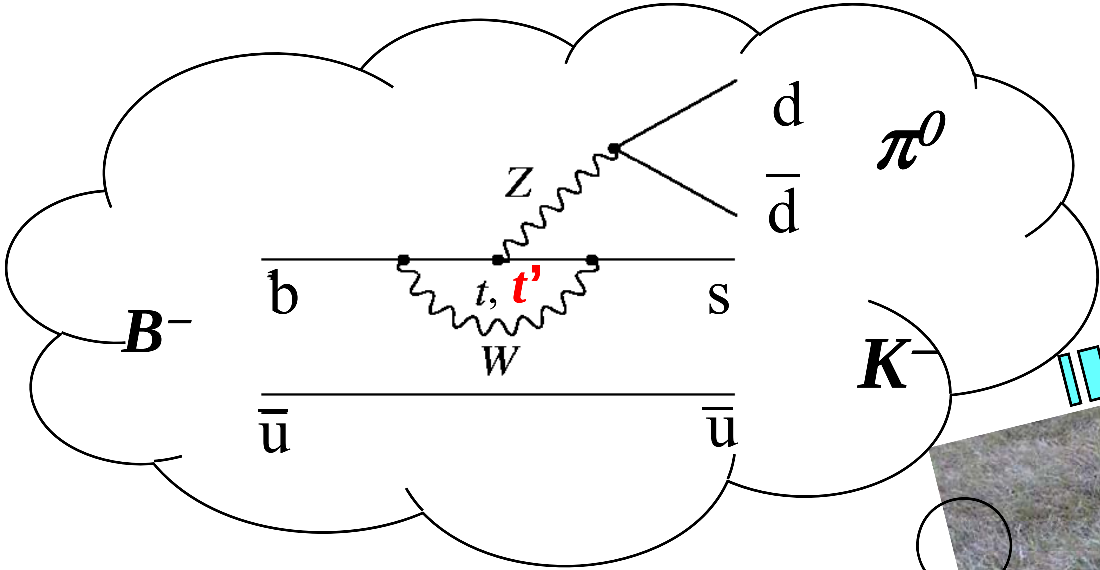
Decoupling Thm: Heavy Masses are decoupled in QED/QCD

∵ Appear in Propagator

Nondecoupling: Yukawa Couplings λ_Q Appear in Numerator

dynamical

Subtlety of Spont. Broken Gauge Th



Going Up a Hill ...

My first B paper

... also on 4th generation ☺

VOLUME 58, NUMBER 16 PHYSICAL REVIEW LETTERS 20 APRIL 1987

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

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 $B \to K l^+ l^-, K\nu\bar{\nu}$. The rate for $B \to K l^+ l^-$ 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?

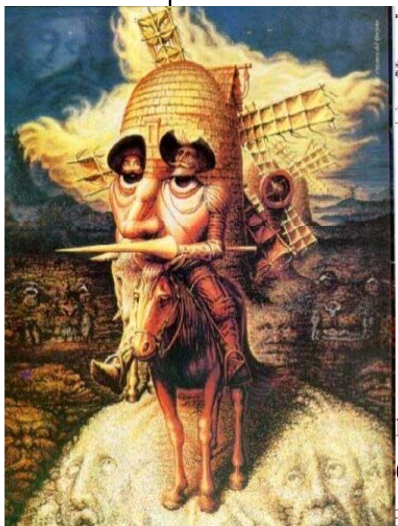
talks by Marc Sher & Mikhail Vysotsky

P.Q. Hung

- 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 …rameter alone, corresponding to $N_F = 2.81 \pm 0.24$ for the number of families. … assumes that there are no new contributions to T or U and therefore that …nilies 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**

… well, since $T > 0$ is expected from a non-degenerate extra family. However, …rently favor $T < 0$, 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.

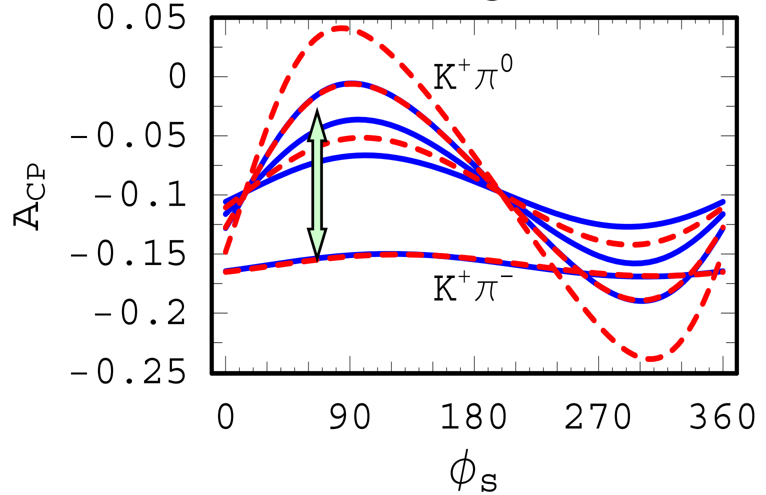
- 4th generation **not** in such great conflict with EWPrT

  Kribs, Plehn, Spannowsky, Tait, PRD'07

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

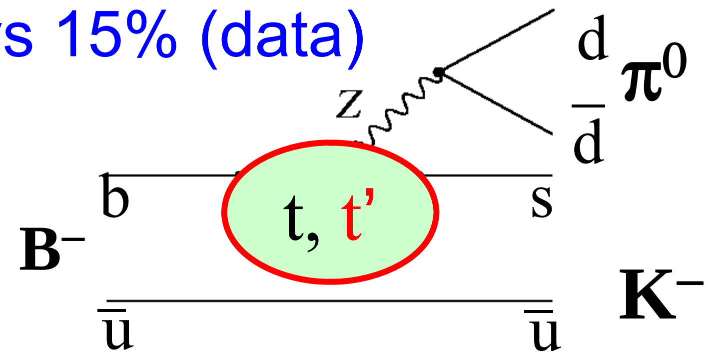
LO PQCD ⊕ 4th Gen.

WSH, Nagashima, Soddu, PRL'05



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

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



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

NLO PQCD ⊕ 4th Gen.

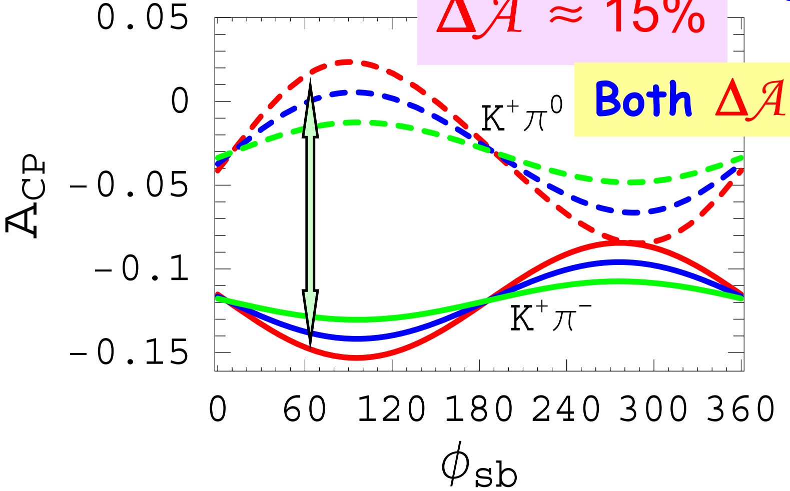
WSH, Li, Mishima, Nagashima, PRL'07

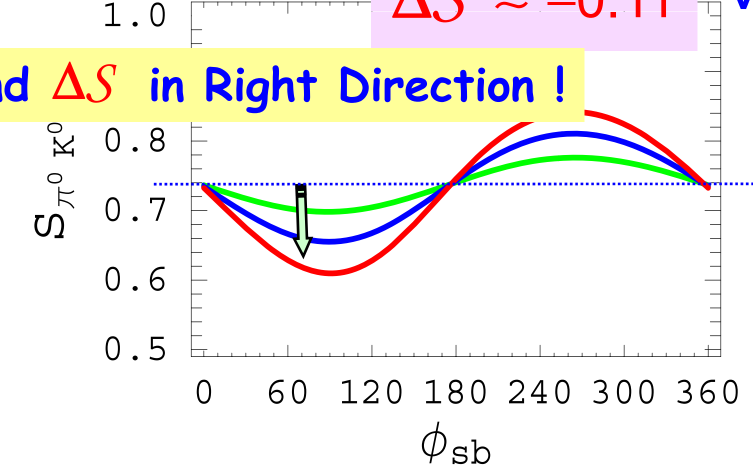
$\Delta\mathcal{A} \approx 15\%$

Joining C & P_{EW}

$\Delta\mathcal{S} \approx -0.11$ vs $-0.34\pm0.2x$ (data)

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





SM3 input

human ants

Recently ... (*maybe*) Becoming a Mountain

Conclusion

New Physics in Δm_{B_s}, Δm_D, and $\mathcal{A}(B^+ \to J/\psi K^+)$

I Intro: SM Reigns (?)

~~Flavor/CP Frontier and 4th Generation (?!)~~

II Large CPV in B_s Mixing — $\sin 2\Phi_{B_s} \sim -0.4$ - -0.7

Δm_{B_s} vs $\mathcal{B}(b \to s\ell\ell)$ $\Leftrightarrow$ $\Delta\mathcal{A}_{K\pi}$, $\Delta\mathcal{S}$;

Unitarity link to K/D

III D Mixing Prediction

IV DCPV in $B^+ \to J/\psi K^+$ — $\mathcal{A}_{J/\psi K^+} \sim$ couple % ?

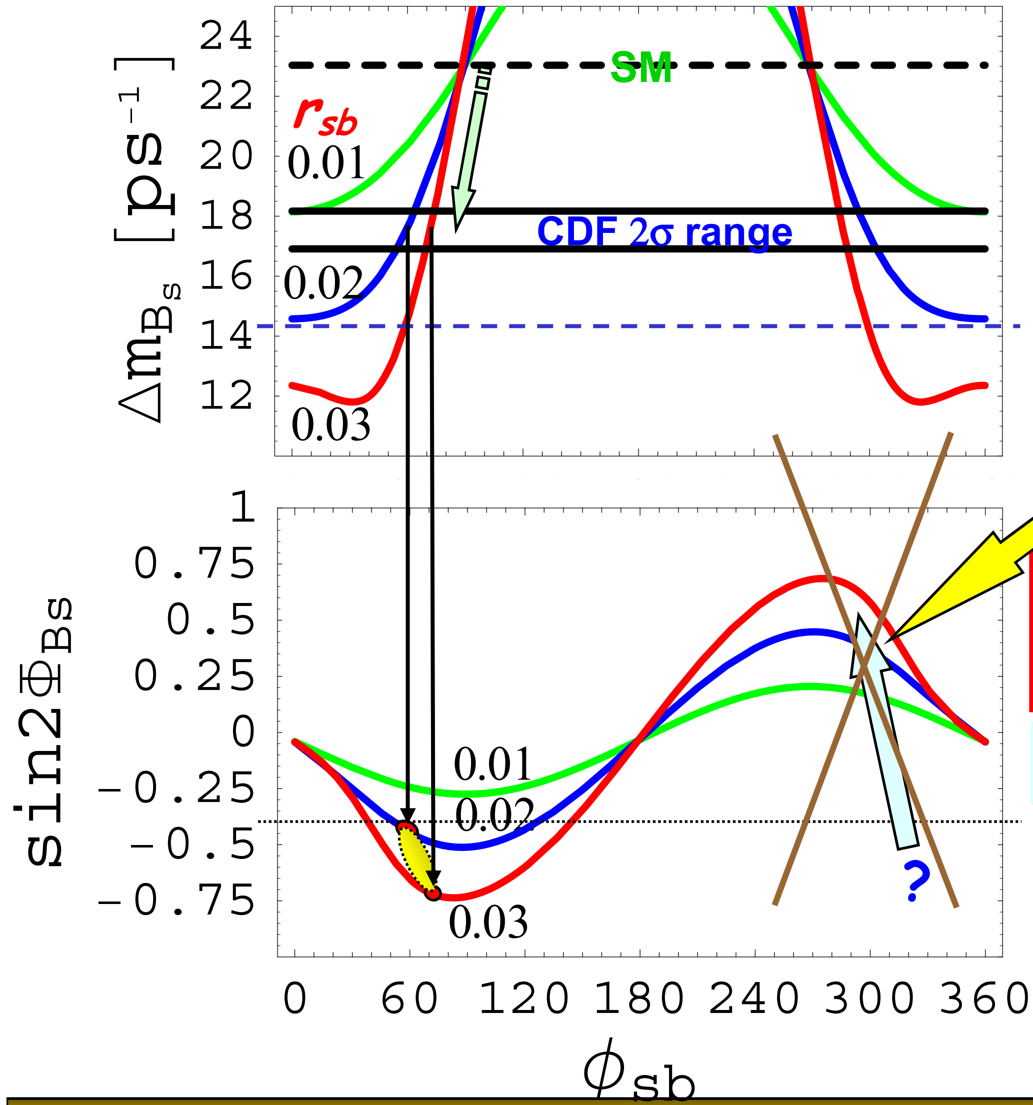
V Conclusion

coworkers

M. Nagashima, G. Raz, A. Soddu

[H.n. Li, S. Mishima]

Large CPV in B_s Mixing



$\Delta\mathcal{A}_{K\pi}$, ΔS

Can Large CPV in B_s Mixing Be Measured @ Tevatron ?

Sign Predicted !

Sure thing by LHCb ca. 2008

$\sin 2\Phi_{B_s} \sim -0.4 - -0.7$

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

WSH, Nagashima, Soddu, PRL'05

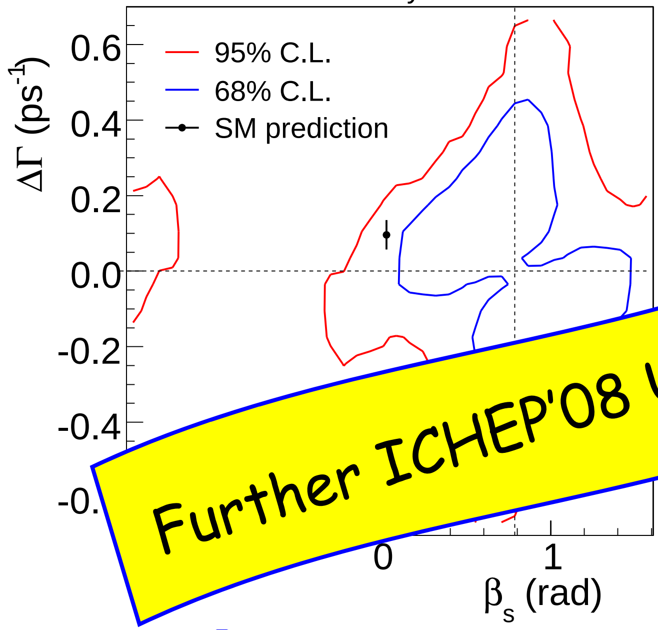
$\sin 2\Phi_{B_s} \sim -0.5$ - -0.7

talk by Juan Fernandez (CDF)

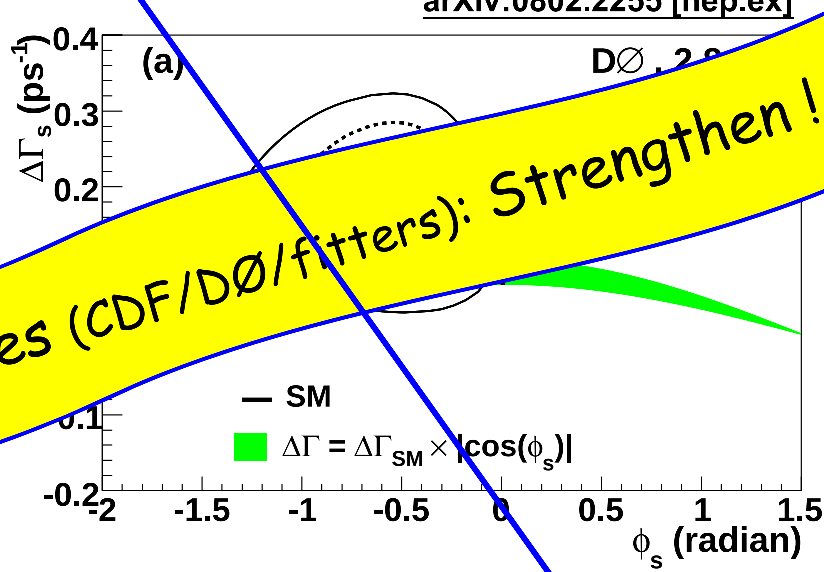
WSH, Nagashima, Soddu, PRD'07

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

arXiv:0712.2397 [hep.ex]



arXiv:0802.2255 [hep.ex]



Observable	68% Prob.	95% Prob.
ϕ_{B_s} [°]	-19.9 ± 5.6	[-30.45,-9.29]
	-68.2 ± 4.9	[-78.45,-58.2]

UT*fit*

arXiv:0803.0659 [hep.ph]

$\sin 2\Phi_{B_s} = -0.64$ ~2.5σ ± ?

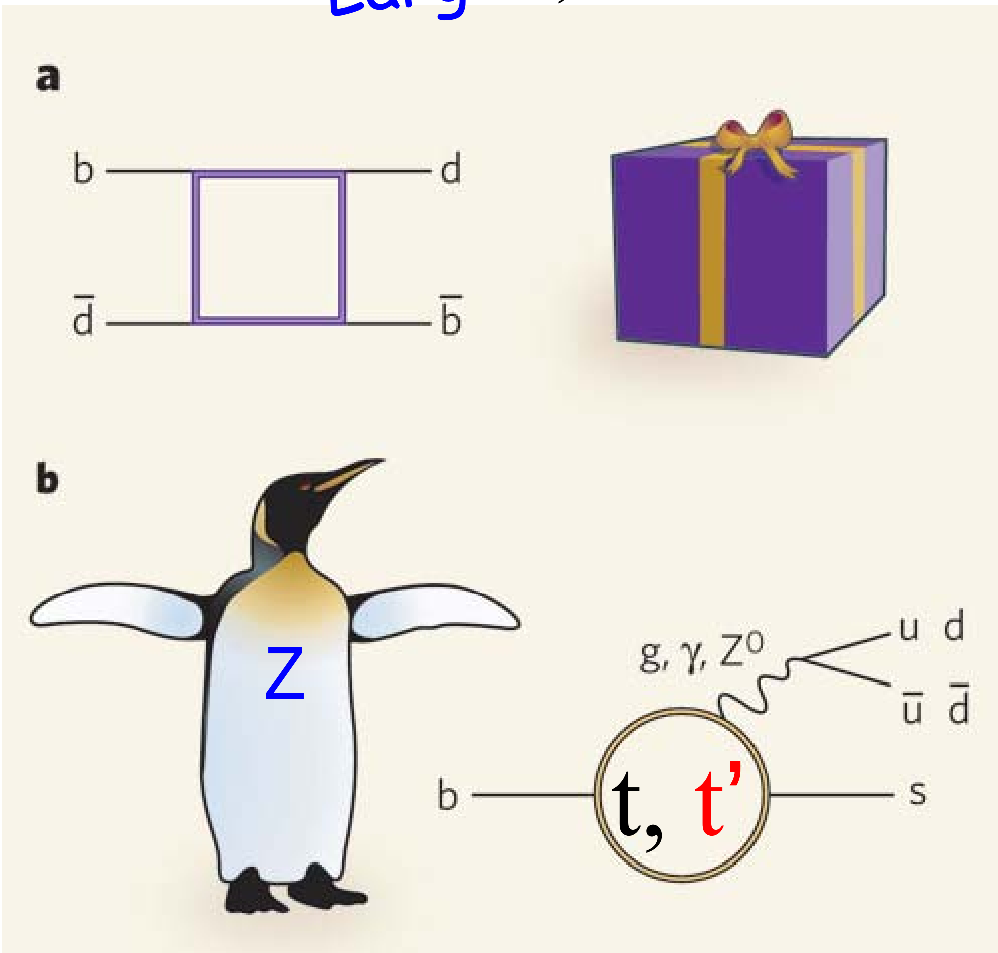
Incredible !!!

More breadth/depth tomorrow

III. Soaring to the Starry Heavens

On Boxes and Z Penguins

Large t, t′ Yukawa!



…

Large Yukawa !

YuReKawa !

B.A.U. from CPV in KM ?

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

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

WMAP

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

Too Small in SM

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

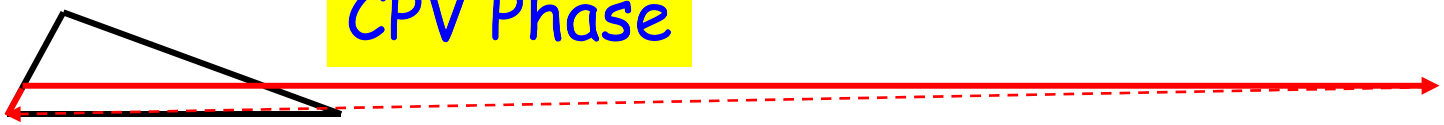
$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)\,A$$

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

Masses too Small !

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

CPV Phase



B.A.U. from CPV in KM

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

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

WMAP

KM ~ 1

Too ... in SM

Enough CPV?

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]

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

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

~ 10^{+15} Gain

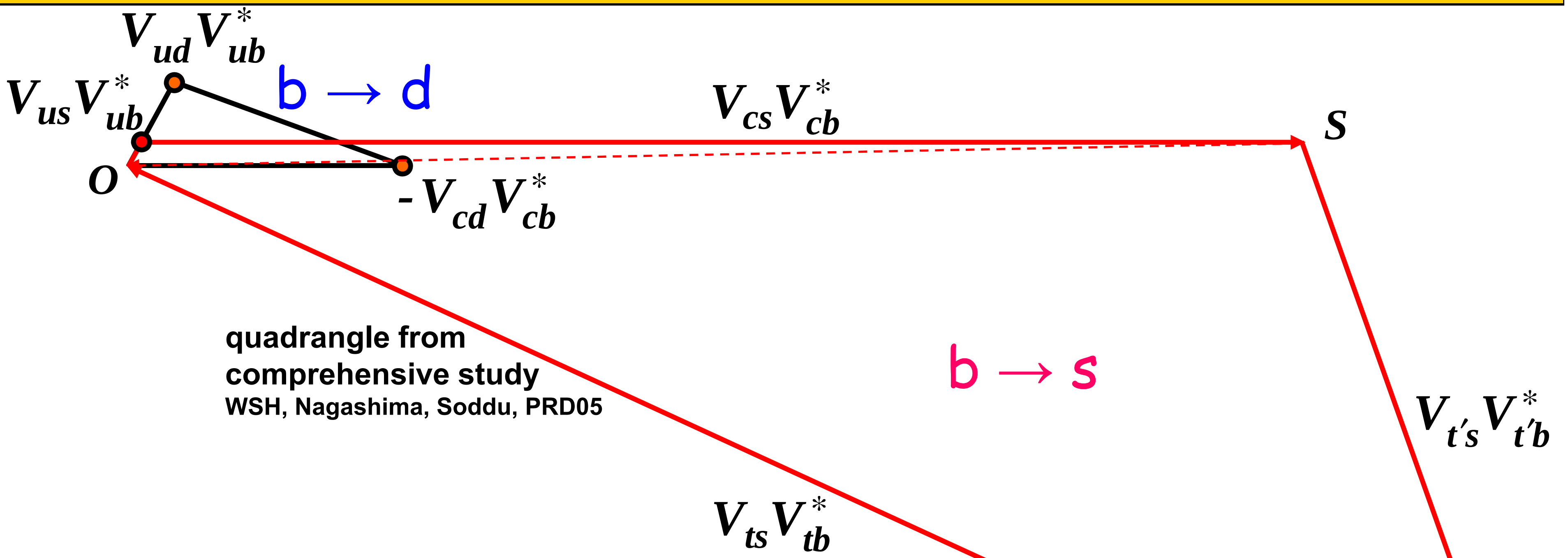
Only fac. 30 in CPV per se

CPV Phase

Gain mostly in Large Yukawa Couplings !

Nature would likely use this !?

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

Only fac. 30 in CPV per se

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

~600GeV 10^{+15}

IV. Towards Solution of BAU

CPV for BAU: 2-3-4 Dominance

Jarlskog'85, 3 generations

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

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)

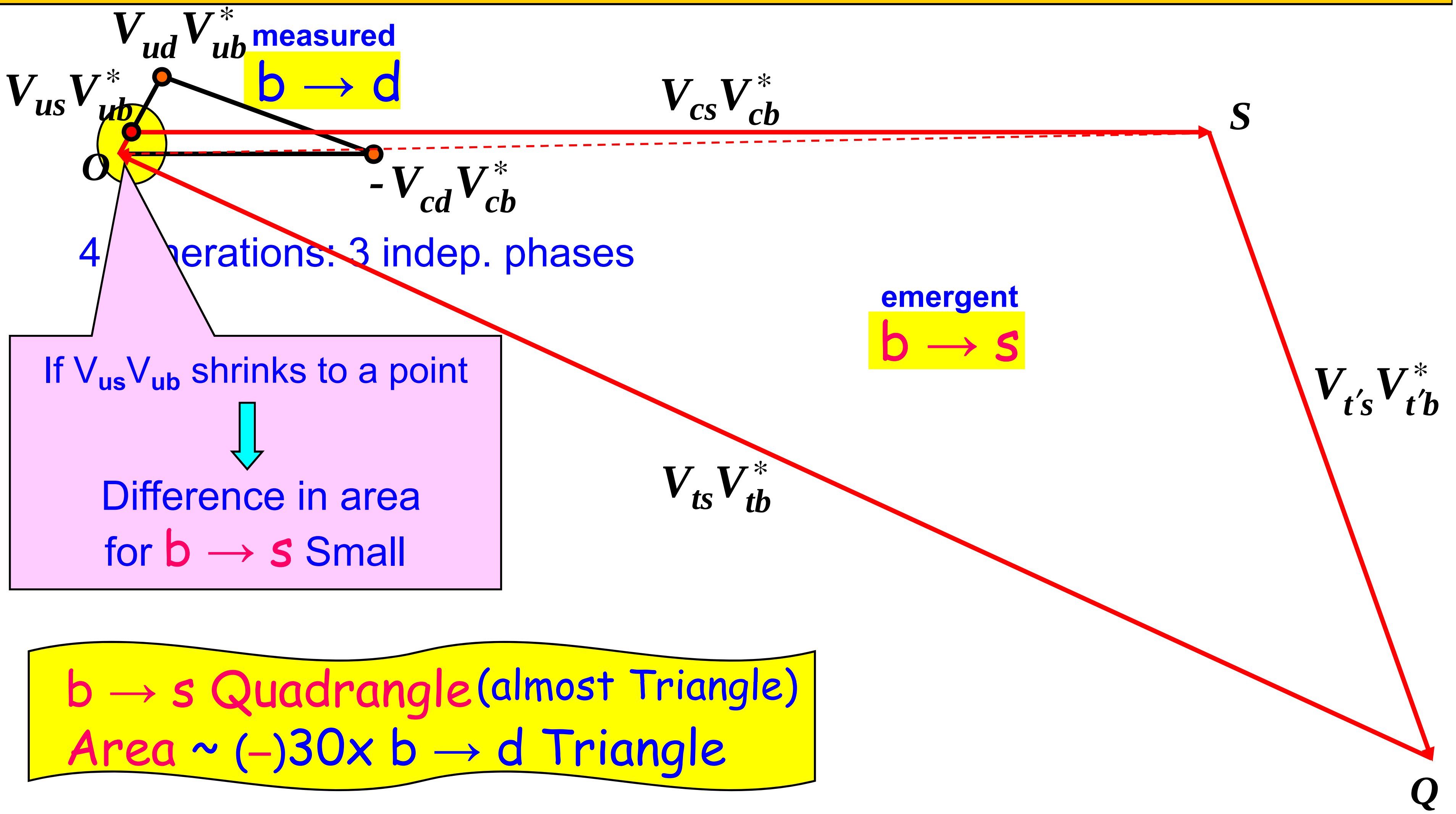
2-3-4 generation only !

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

4 generations: 3 indep. phases



b → s Quadrangle (almost Triangle)
Area ~ (–)30x b → d Triangle

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

1st Order EW Phase Trans. for BAU ?

Ran out of time, and knowledge ...

(perturbative)

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

Beyond Unitarity Limit

talks by Bob Holdom
& Leandro Da Rold,
also A. Soni

A fourth family ...

- sequential fourth family (with a heavy ν) with at least some CKM mixing
- pair production and weak decays of the fourth family quarks

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

and/or

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

- since colored fermions are involved, cross sections are decent at the LHC

... and no light Higgs

- suppose t' and b' masses are in the 600 GeV range
- then the Goldstone bosons of electroweak symmetry breaking couple strongly to these quarks
- strong interactions will unitarize WW scattering

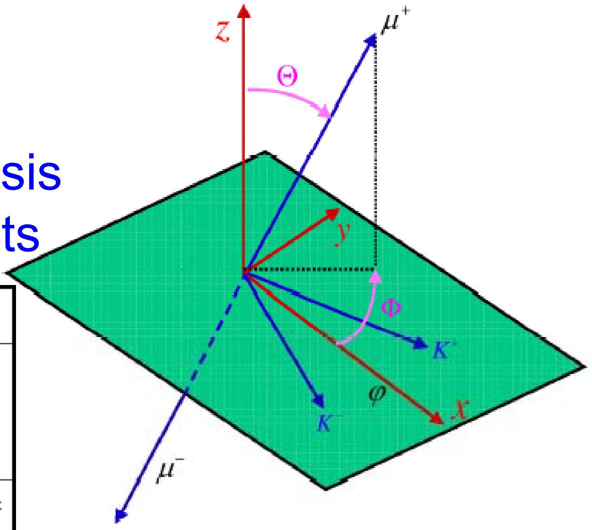
Holdom

V. Tevatron/LHC Verification

Φ_{B_s} Prospect (short term)

$B_s \to J/\psi\phi$ analogous to $B_d \to J/\psi K_S$

VV ⟹ Angular & Vertex Resolved Analysis to disentangle CP +/– components



- CDF/DØ: 8 fb^{-1} projected

  $\sigma(\sin 2\Phi_{B_s}) \simeq$ 0.2 (?)/exp

  similar →

Trigger	CDF	DØ
2-Track	p_T > 2.0 GeV/c $p_{T1}+p_{T2}$ > 5.5 GeV/c 100 μm<$\|d_{1,2}\|$< 1 mm	—
1-Muon	—	p_T (μ)>3,4,5 GeV/c
2-Muon	p_T(μ's) > 1.5 GeV/c	p_T(μ's)>2.0 GeV/c

- LHCb: 0.5 fb^{-1} (2008 ?)

  $\sigma(\sin 2\Phi_{B_s}) \simeq$ 0.04

- ATLAS: 2.5 fb^{-1} (2008 ?)

  $\sigma(\sin 2\Phi_{B_s}) \simeq$ 0.16

CMS ?

Nakada @ fLHC 3/07

€ LHCb the winner if ~ SM

$\sin 2\Phi_{B_s} \sim -0.04$ in SM

But 2009 looks interesting !

$ Tevatron could get lucky

if $\sin 2\Phi_{B_s}$ *large* ⟺ *New Physics !*

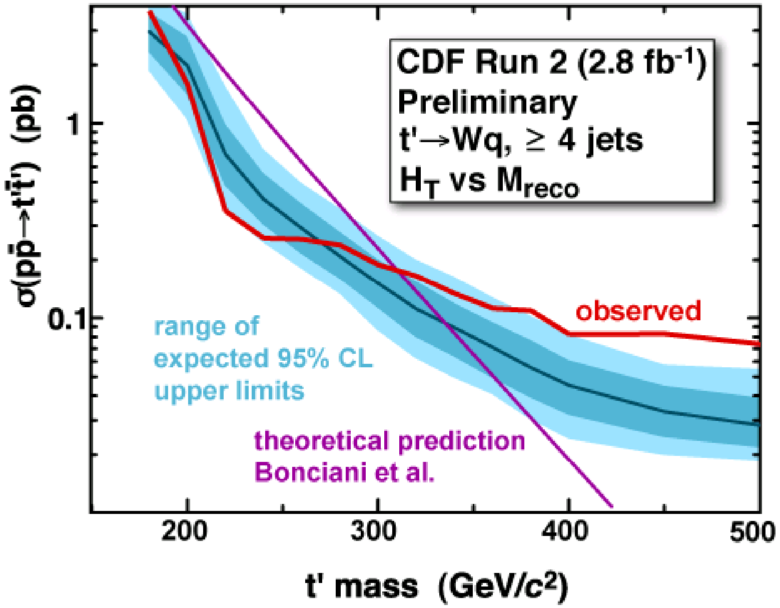
Could Tevatron run beyond 2008 ?

Tevatron

Juan Fernandez (CDF)

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

talk by Alison Lister (CDF)
also, Regina Demina (Dzero)



LHC

Vincenzo Vagnoni (LHCb)

- $\sin 2\Phi_{B_s}$ "Confirmation" — "Easy" for LHCb
- b', t' Discovery — Straightforward/full terrain

talks by Erkcan Ozcan (ATLAS)
Yuan Chao (CMS)

VI. Conclusion

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

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

~ 10^{+15} Gain

Even if $O(1)$

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

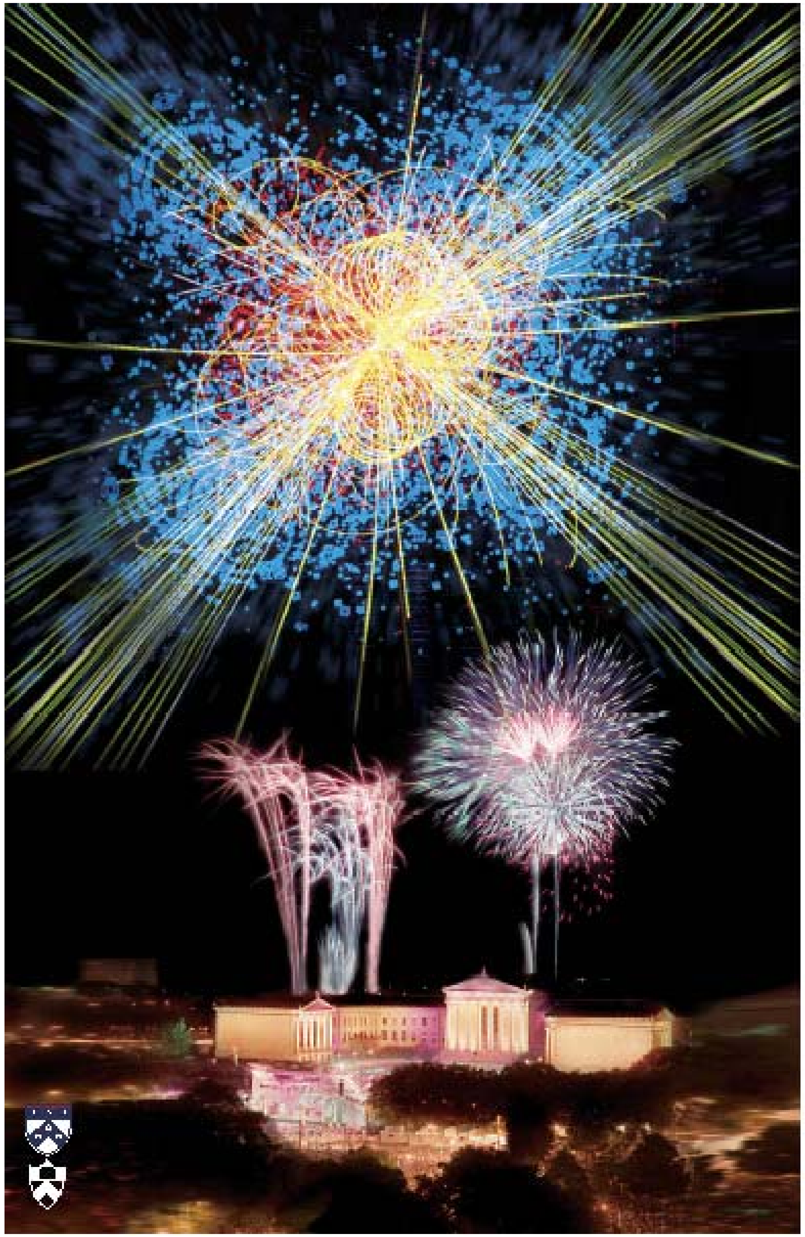
~600GeV 10^{+15}

Enough CPV for B.A.U.

Maybe there is a 4th Generation !

Universe (Genesis)

CPV



BAU

Earth (EW + KM4)

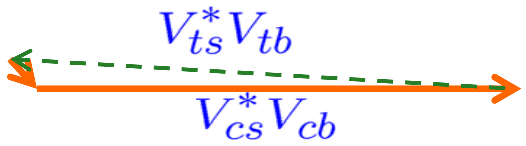
Backup

Effective b → s Hamiltonian and t' Effect

$$\left.\begin{array}{c} \lambda_u + \lambda_c + \lambda_t = 0 \\ |\lambda_u| \sim 10^{-3} \end{array}\right\} \Rightarrow \boxed{\lambda_t \cong -\lambda_c}$$

SM 3

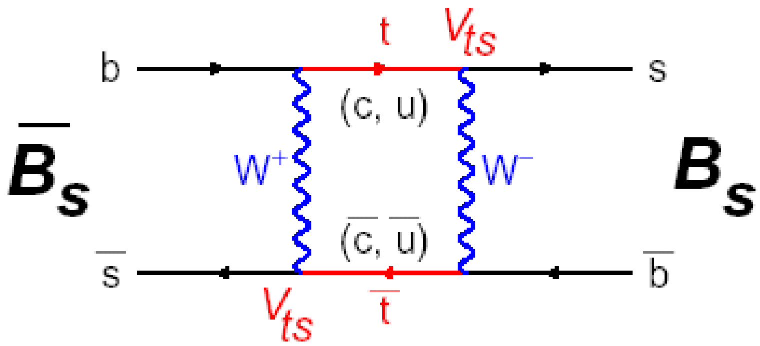
$$H_{\rm eff}^3 = \frac{G_F}{\sqrt{2}} \left[\lambda_u \left(C_1 O_1 + C_2 O_2 \right) + \sum_{i=3}^{10} \lambda_c C_i^t O_i \right]$$



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

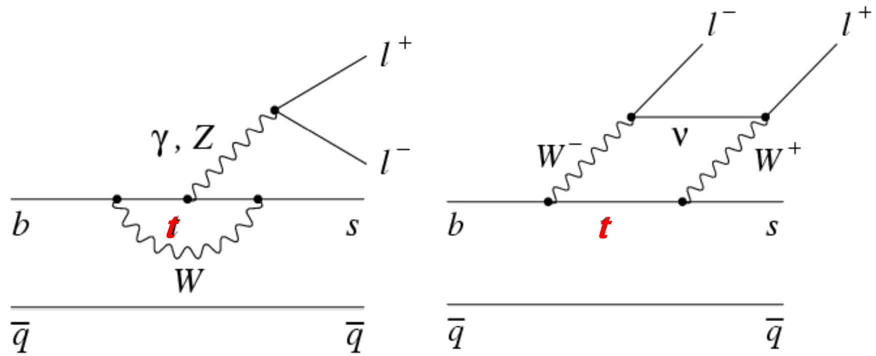
Arhrib and WSH, EPJC'03

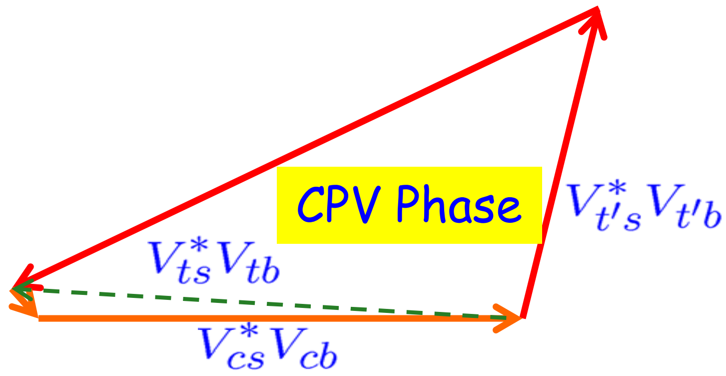
t ⇨ t, t'



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

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





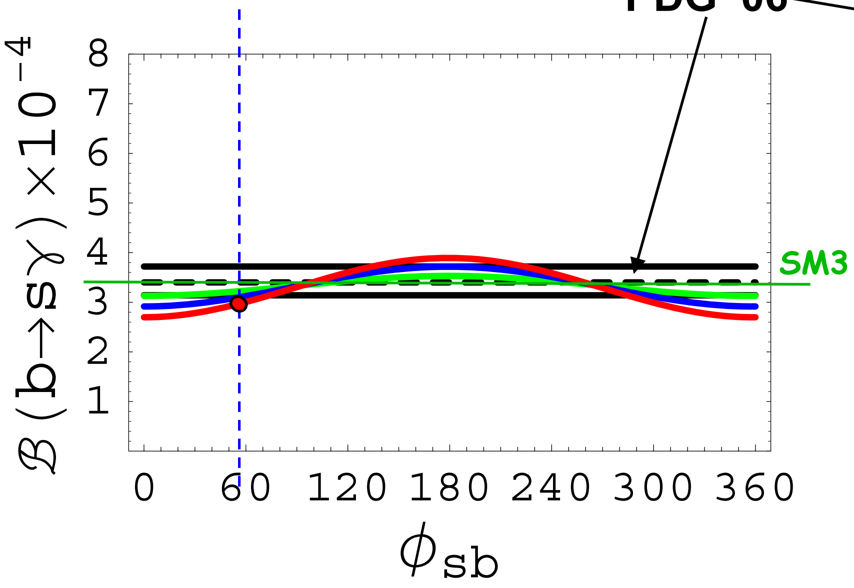
$$M_{12} \propto f_{B_s}^2 B_{B_s} \{ \lambda_c^2 S_0(t,t) + 2\lambda_c \lambda_{t'} [S_0(t,t) - S_0(t,t')] + \lambda_{t'}^2 [S_0(t,t) - 2S_0(t,t') + S_0(t',t')] \}$$

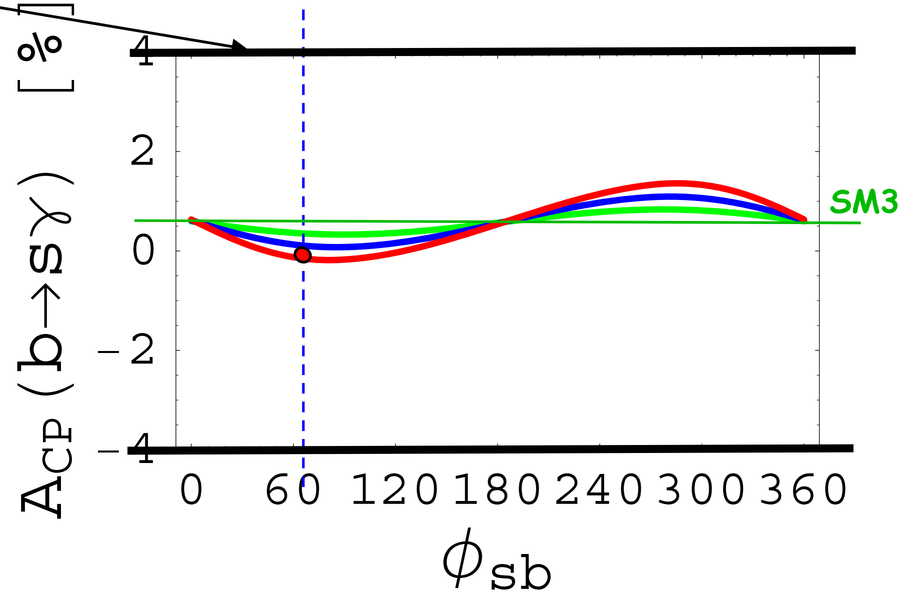
GIM Respecting

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

Consistency and b → sγ Predictions

PDG '06



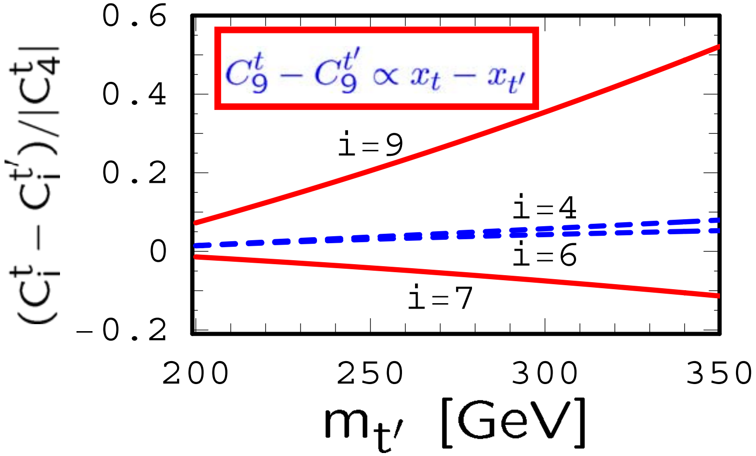


BR OK

A_{CP} ~ 0 far away

beyond SuperB

Heavy t' effect decoupled for b → sγ



4 x 4 Unitarity ⇨ Z/K Constraints

"Typical" CKM Matrix

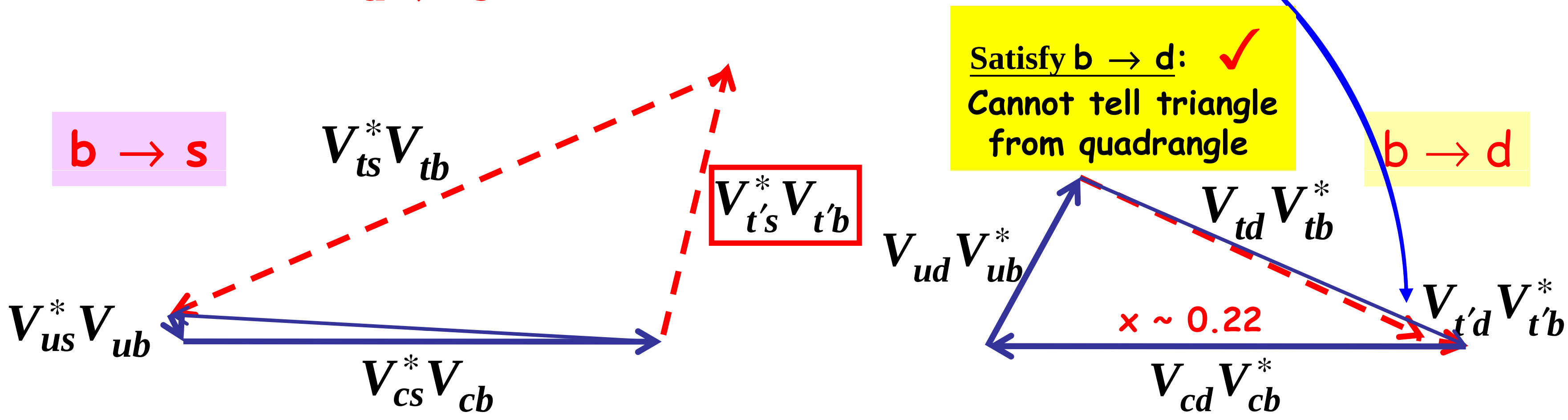
WSH, Nagashima, Soddu, PRD'05

$$V^4_{CKM} = \begin{pmatrix} 0.9745 & 0.2225 & 0.0038\, e^{-i\,60^\circ} & 0.0281\, e^{i\,61^\circ} \\ -0.2241 & 0.9667 & 0.0415 & 0.1164\, e^{i\,66^\circ} \\ 0.0073\, e^{-i\,25^\circ} & -0.0555\, e^{-i\,25^\circ} & 0.9746 & 0.2168\, e^{-i\,1^\circ} \\ -0.0044\, e^{-i\,10^\circ} & -0.1136\, e^{-i\,70^\circ} & -0.2200 & 0.9688 \end{pmatrix}$$

$s \leftarrow b$

$d \leftarrow s$

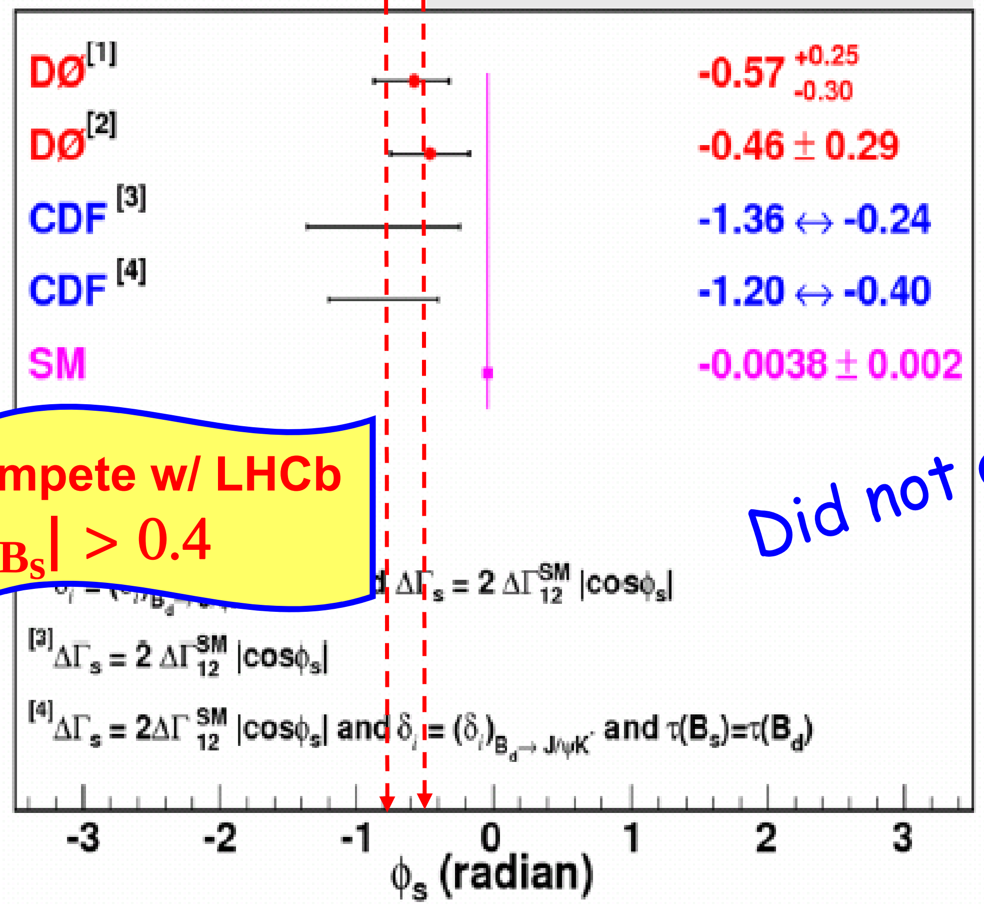
$Z \to b\bar{b}$



Results with Flavor Tagging

4th Generation ?

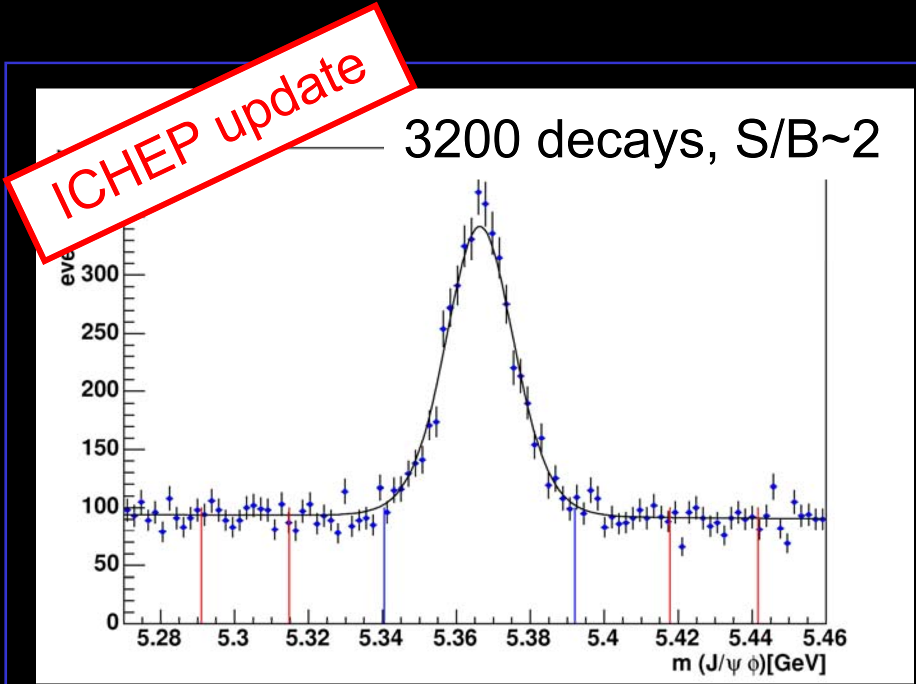
WSH, Nagashima, Soddu, PRD'07 (hep-ph/0610385)



Tevatron can compete w/ LHCb
iff $|\sin 2\Phi_{B_s}| > 0.4$

Did not ask for this !

Hot off the press…2.8/fb update!



Same-side tagger NOT yet used in second half of sample. PID calibrations still to be finalized.

Equivalent to reduced sample size 2.8/fb → 2/fb

www-cdf.fnal.gov/physics/new/bottom/080724.blessed-tagged_BsJPsiPhi_update_prelim/

Once the SST will be calibrated have:

+20% signal events – by using PID info in selection

x3 tagging power in second-half of the sample

ICHEP update

Increased dataset still hints at larger than SM values!

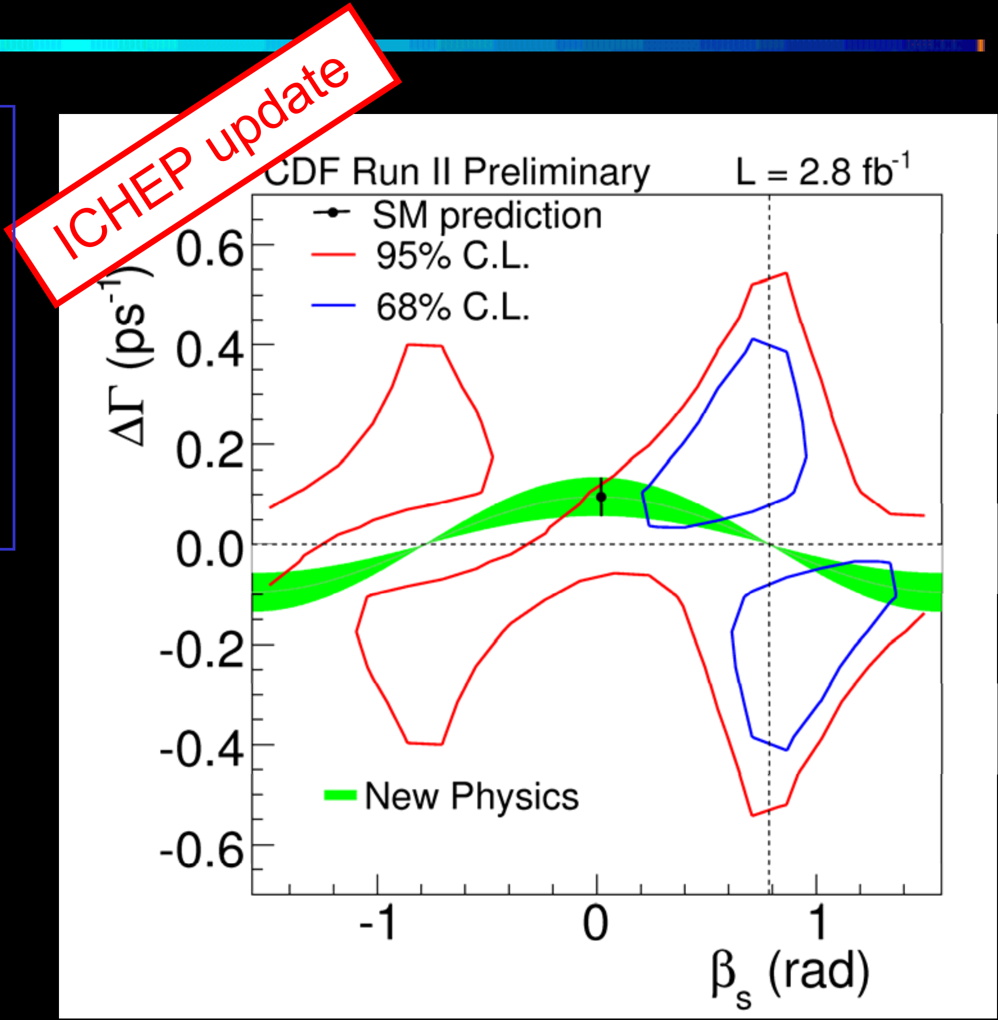
Consistency with SM decreased 15% → 7% (~1.8σ)

0.28 < βs < 1.29 at 68% CL

-pi/2 < βs < -1.45 OR

-1.01 < βs < -0.57 OR

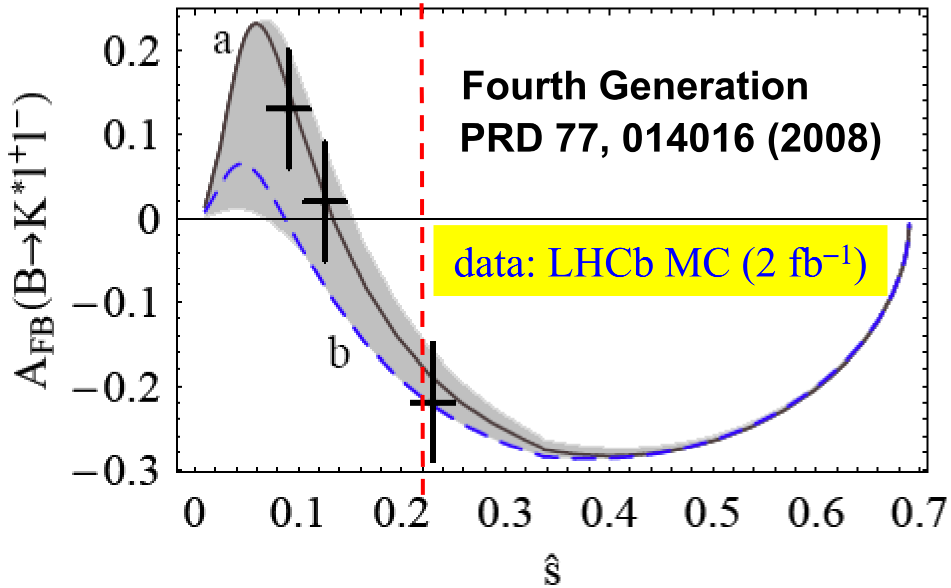
-0.13 < βs < pi/2 at 95% CL



www-cdf.fnal.gov/physics/new/bottom/080724.blessed-tagged_BsJPsiPhi_update_prelim/

Will shrink further with PID in the whole dataset

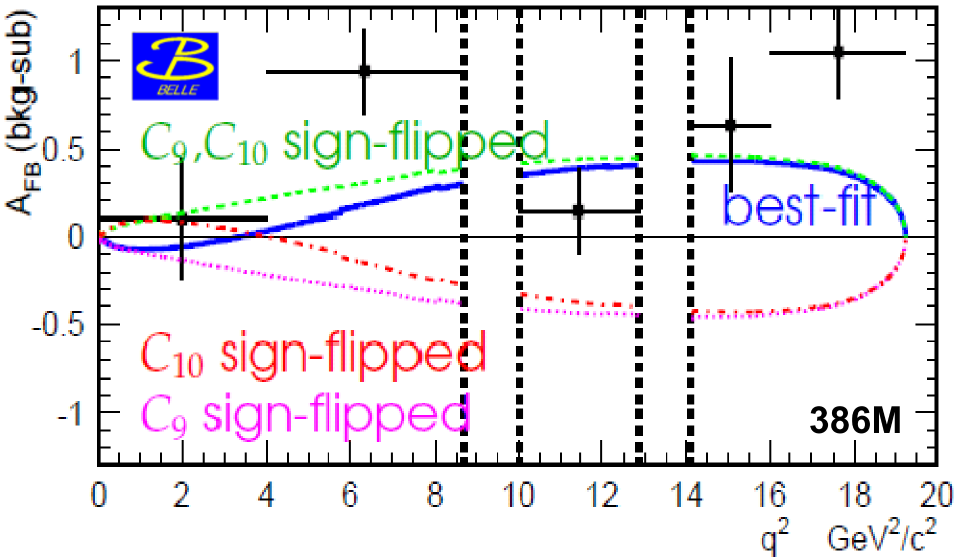
Quoted by **Tsybychev at FPCP08**

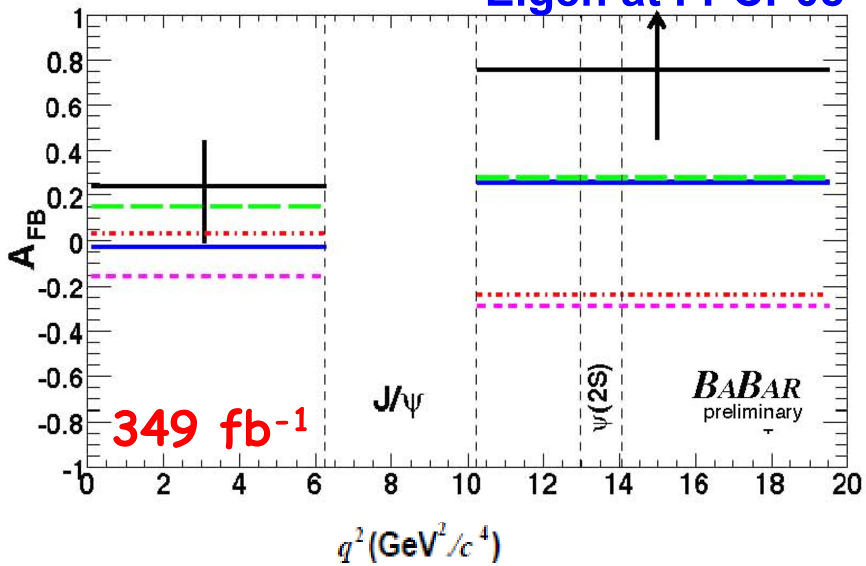


a: SM; b: 4 Gen. better

- (F$_L$ and) A_{FB} (and A_I) favor the "opposite-sign C_7 model"

Eigen at FPCP08

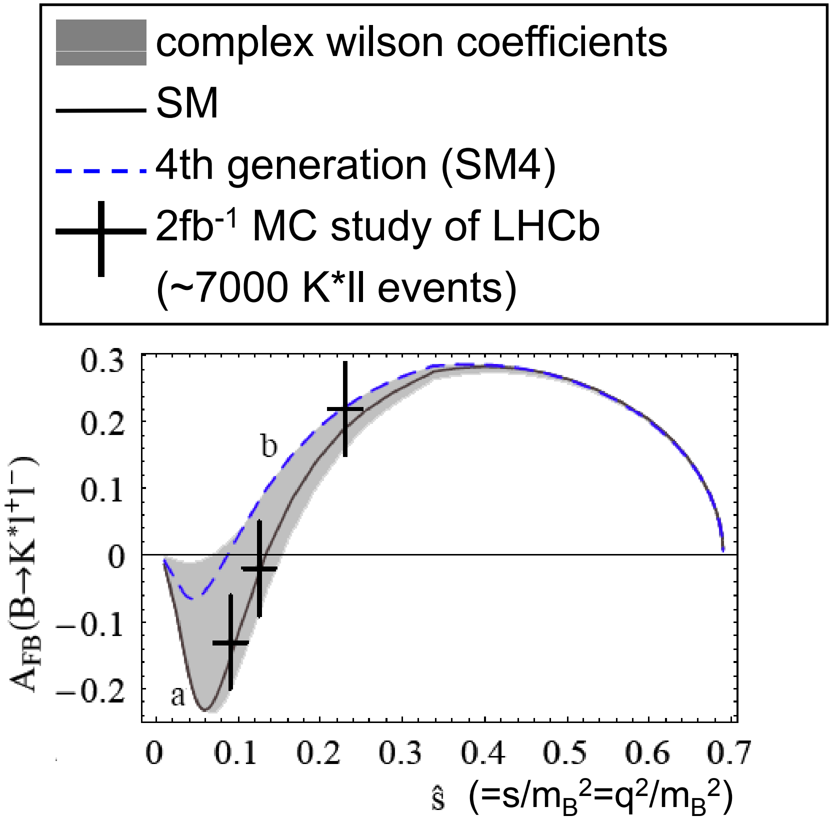




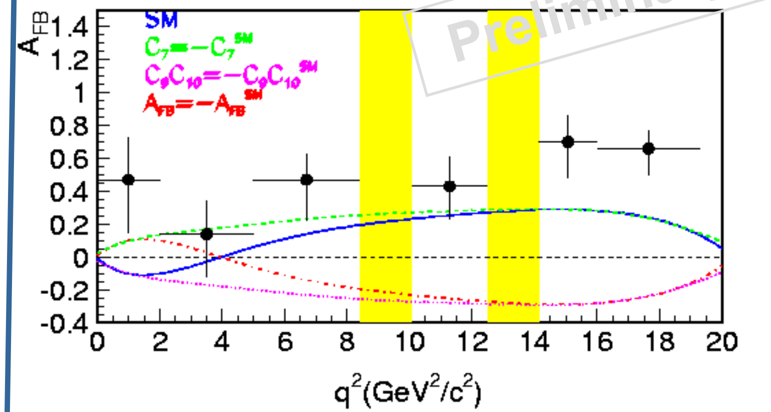
Instead flipped C_7 ...

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

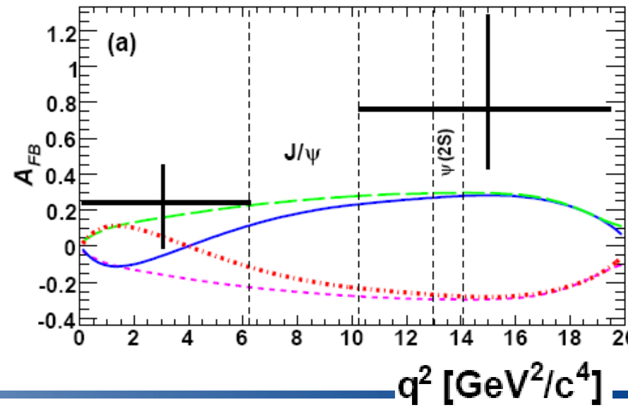
W.-S. Hou, A. Hovhannisyan, and N. Mahajan, PRD 77, 014016 (2008)



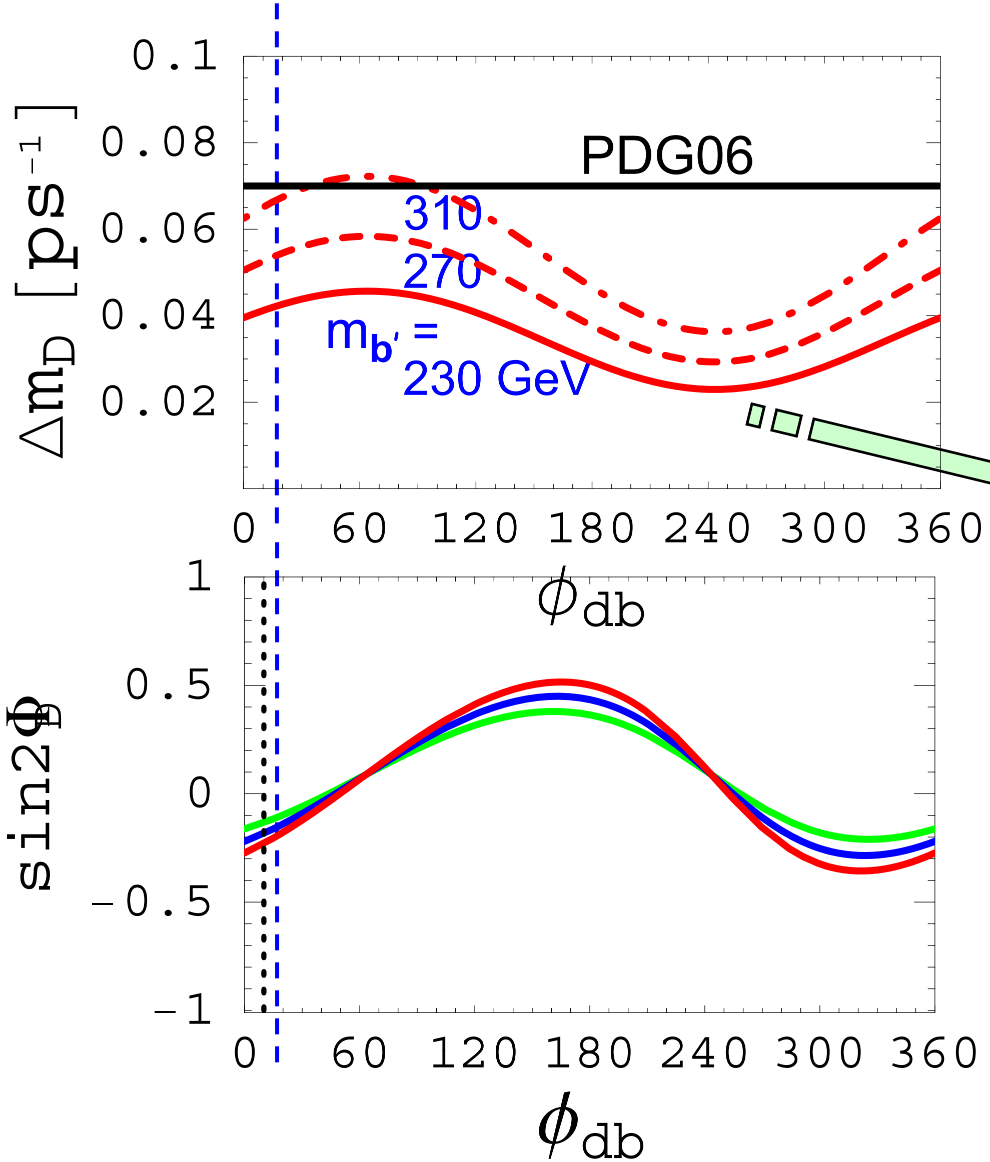
Belle **657M**



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

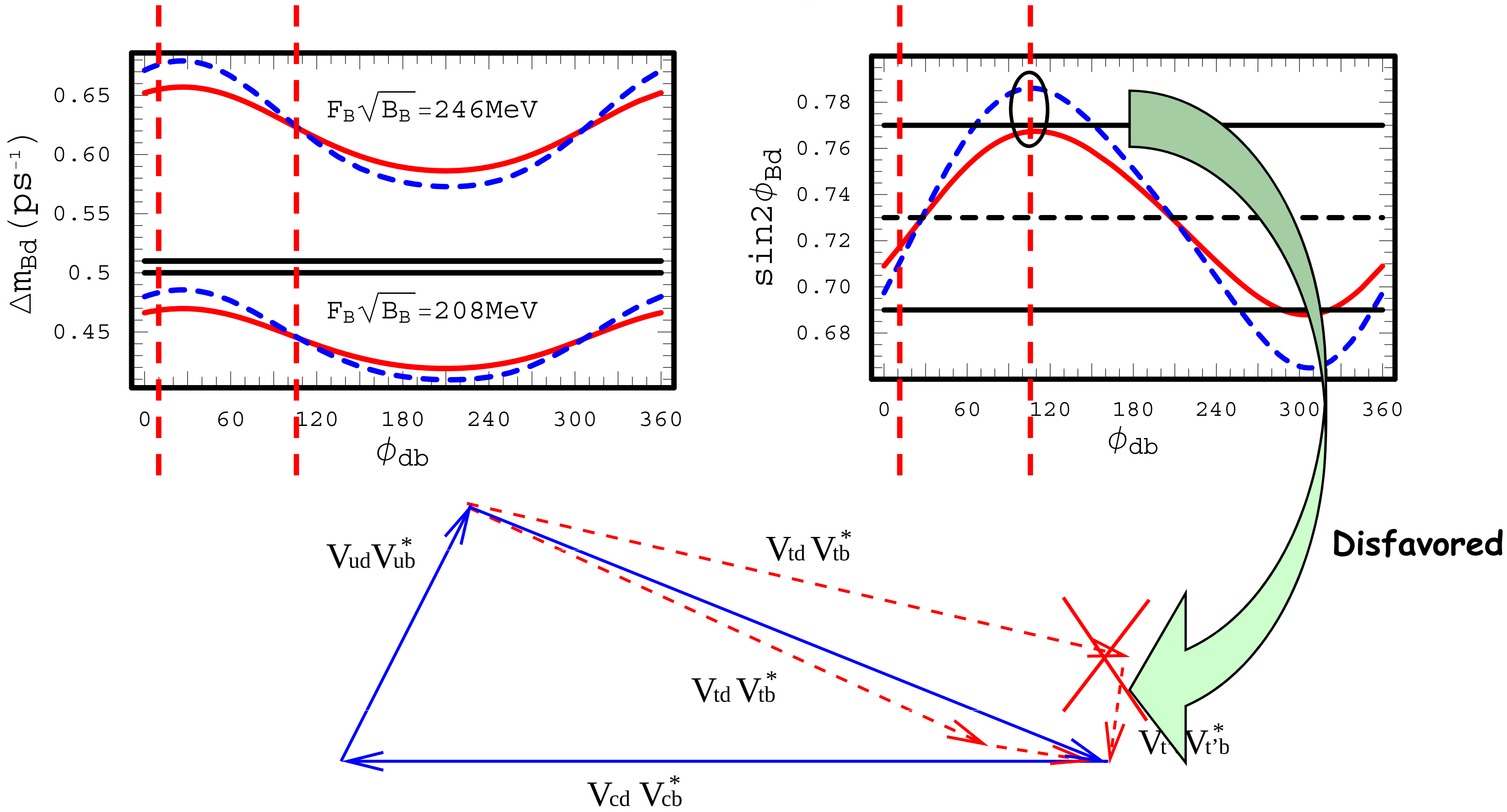
w/ Sizable (but not huge) CPV in Mixing ~ –15%

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

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

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

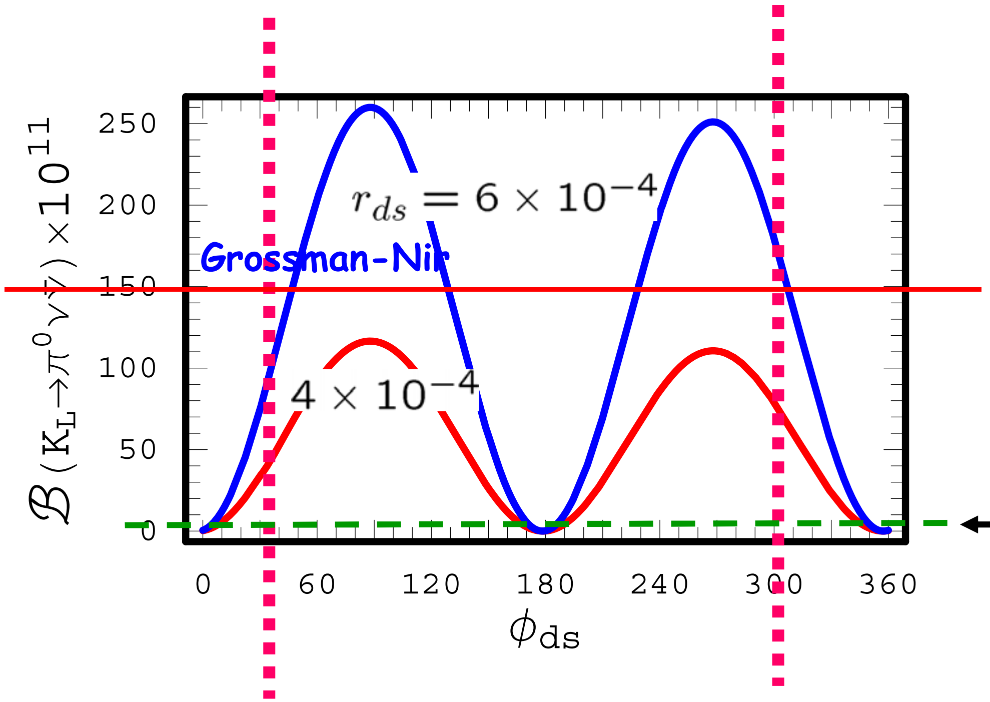
well-satisfy Δm_{B_d} and $\sin 2\phi_1$ vs $V_{ub} \sim 0.01\, e^{-i\gamma}$



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

∵ stringent $s \to d$

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



Current E391A U.L.

2.86×10^{-7} (90% c.l.)

Very hard to measure

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

SM 3

Rate could be enhanced 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

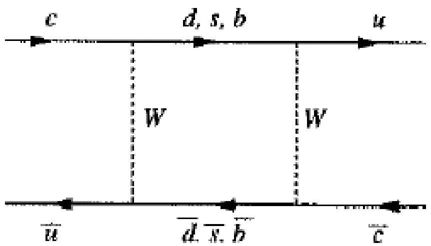
4 x 4 Unitarity ⇨ Z/K Connections

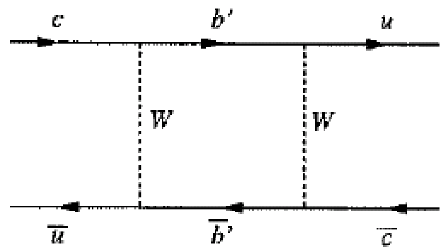
"Typical" CKM Matrix

(Too) Large/Imaginary

$$V^4_{CKM} = \begin{pmatrix} 0.9745 & 0.2225 & 0.0038\, e^{-i\,60^\circ} & 0.0281\, e^{i\,61^\circ} \\ -0.2241 & 0.9667 & 0.0415 & 0.1164\, e^{i\,66^\circ} \\ 0.0073\, e^{-i\,25^\circ} & -0.0555\, e^{-i\,25^\circ} & 0.9746 & 0.2168\, e^{-i\,1^\circ} \\ -0.0044\, e^{-i\,10^\circ} & -0.1136\, e^{-i\,70^\circ} & -0.2200 & 0.9688 \end{pmatrix}$$

Data Driven





SM LD — NP SD

$$V_{ud}V^*_{cd} + V_{us}V^*_{cs} + V_{ub}V^*_{cb} + V_{ub'}V^*_{cb'} = 0$$

-0.218 $+0.215$ $+0.0033\,e^{-i5^\circ}$