CP Violation for the Heavens and the Earth

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October 2, 2008 @ IPMU

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Story of a star-gazing ant

Outline

I. Genesis 1:1 and BAU

II. The Abyss: BAU and CPV in Standard Model

III. The Heavenly Observation: KM Sufficient？

IV. Walking on Earth

V. Discussion

VI. Conclusion: Carried to Heaven？

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

I. Genesis 1:1 and BAU

In the beginning God created the heaven and the earth.

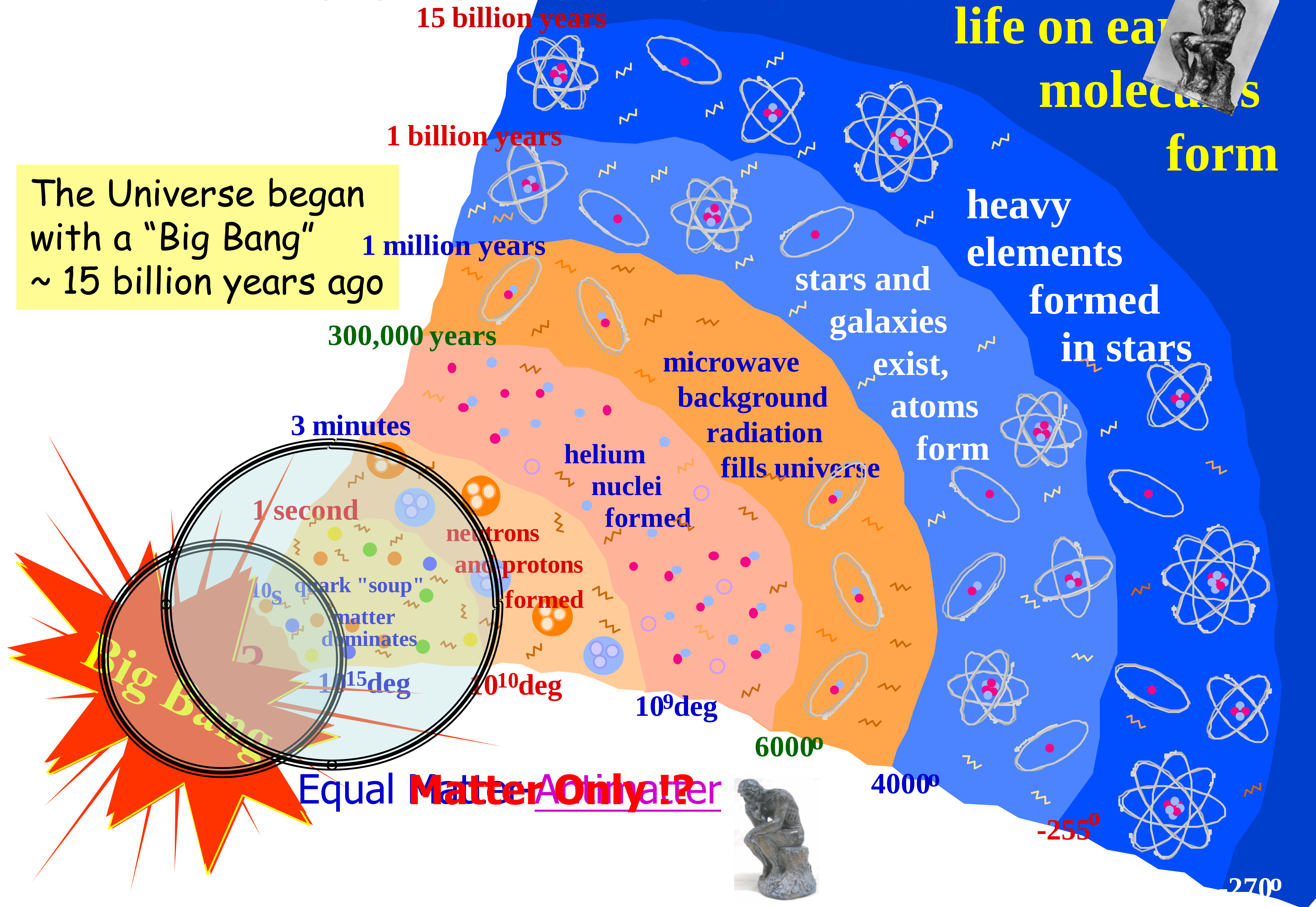
Matter (?)

Matter!

— Genesis 1:1 (KJV)

Evolution of the Universe

The Universe began with a "Big Bang" ~ 15 billion years ago

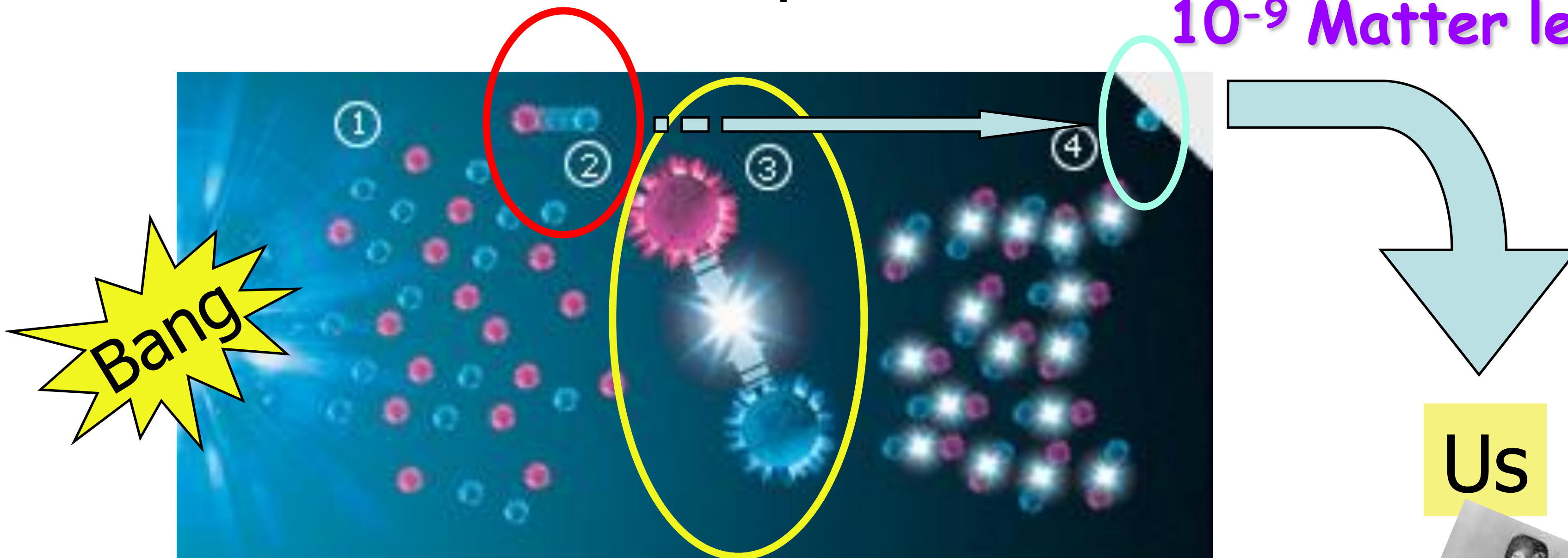


(1966)

CPV & BAU (& U): The Sakharov View

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

10^{-9} Matter left !



Equal Matter -Antimatter

Pair Annihilation

Us

Sakharov Stimulated by …
Discovery of CP Violation

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

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

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

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

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

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

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

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

Heavenly TH

"Affleck-Dine", SUSY etc.:

Extra *Scalars* (strongly) 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

II. The Abyss: BAU and CPV in Standard Model

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

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

WMAP

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

Too Small in SM

Complex Dynamics: KM Sector of SM

In mass basis, charged current ($W^\pm$) weak interactions become complicated:

$$-\frac{g}{2}\,\overline{Q^I_{Li}}\,\gamma^\mu\,W^a_\mu\,\tau^a\,Q^I_{Li} + \text{h.c.} \;\Rightarrow\; -\frac{g}{\sqrt{2}}\left(\overline{u_L},\,\overline{c_L},\,\overline{t_L}\right)\gamma^\mu\,W^+_\mu\,V_{\rm CKM}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$$

⇑

Cabibbo-Kobayashi-Maskawa matrix: $V_{\rm CKM}$

Only source of CPV in flavor changing processes in the SM

only charged current interactions change flavor

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

3x3 “Rotation”

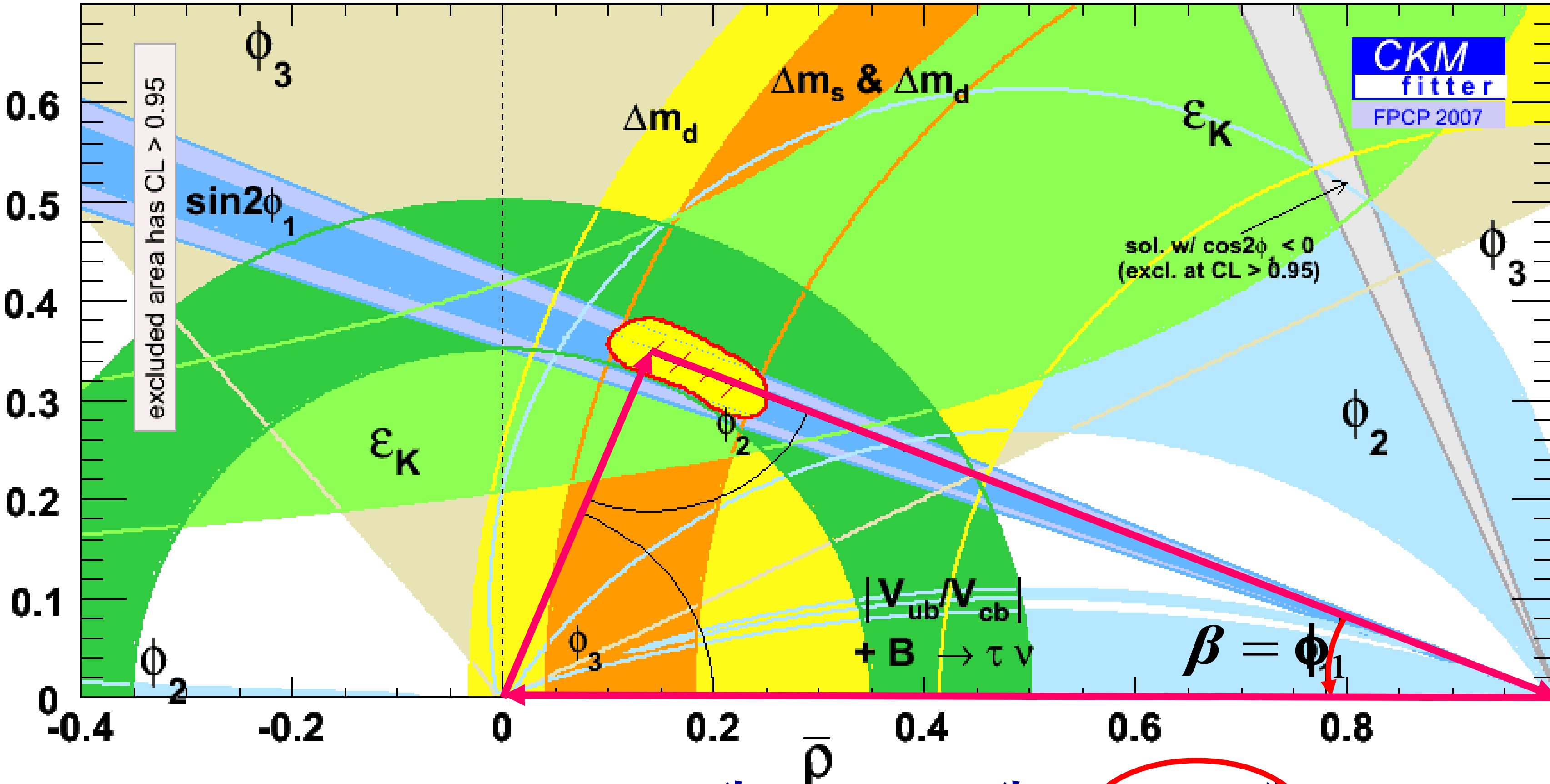
Unitary

CPV so far only observed in KM ...

- Nontrivial CPV Phase

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

Could this be the Year of CKM ?



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3x3 "Rotation"

Unitary

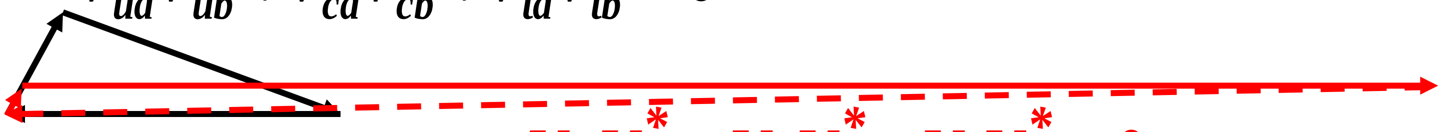
Need presence of all 3 generations to exhibit CPV in Standard Model

$$V \cong$$

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

Unique CPV Phase: Common Area of Triangle

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



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

CPV so far only observed in KM ...

- Nontrivial CPV Phase

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

- All like-charge quark pairs nondegenerate,

Otherwise → Back to 2-gen. and CPV vanish.

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

Jarlskog's Invariant for CPV

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

Jarlskog Invariant in SM3 (need 3 generation in KM)

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

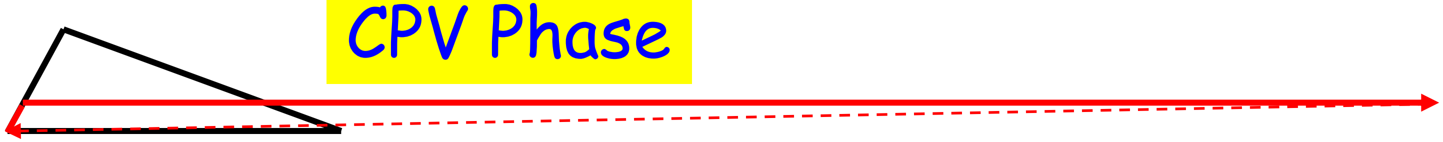
Normalize by T ~ 100 GeV ⟹ $J/T^{12} \sim 10^{-20}$

Masses too Small !

Small, but not *Too* small

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

CPV Phase



III. The Heavenly Observation: KM Sufficient?

If …

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 ~ 10^{-20}

Too Small in SM

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

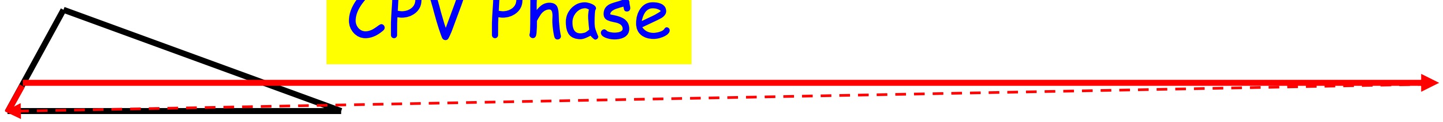
$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)A$$

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

masses too small !

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

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 ~ Enough CPV?

~~Too Small in SM~~

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

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

Providence

WSH, arXiv:0803.1234 [hep/ph]

Moriond QCD

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

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

~ 10^{+15} Gain

If ~ SM in CPV per se

CPV Phase

Gain mostly in Large Yukawa Couplings !

Nature would likely use this !?

The Abyss between CPV in SM3 vs BAU
bridged in SM4 by *Heaviness of t′ and b′*

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

IV. Walking on Earth

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*

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 $\bar{B}^0 \to K^- \pi^+$ versus $B^0 \to K^+ \pi^-$ 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.

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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
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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
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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.

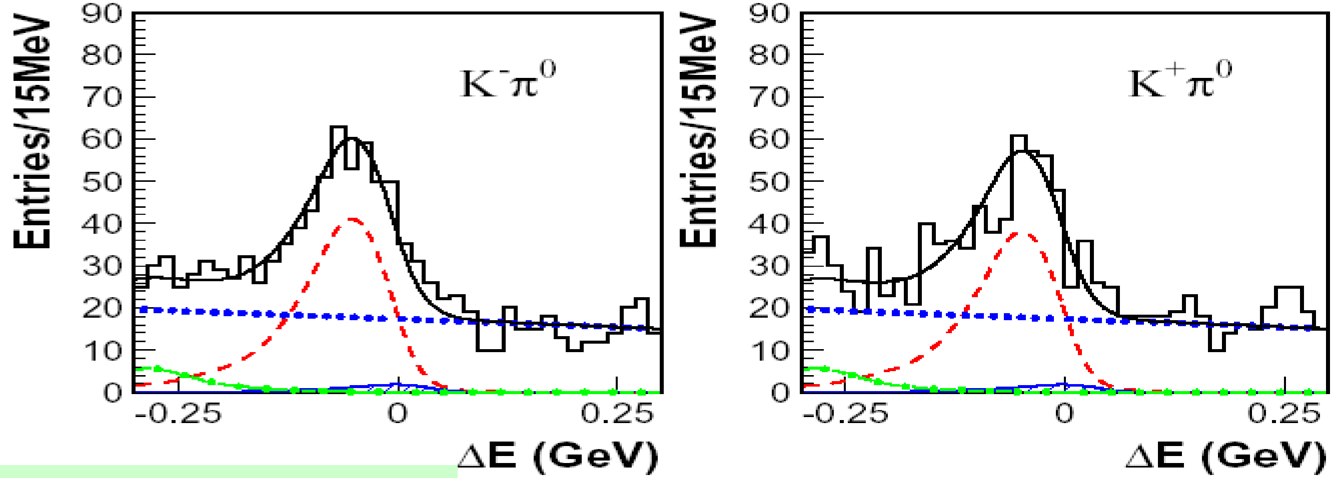
Saga Towards Belle Nature Paper ...

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

Sakai

275M $B\bar{B}$ New

$K^{\pm}\pi^0$: 728 ±53

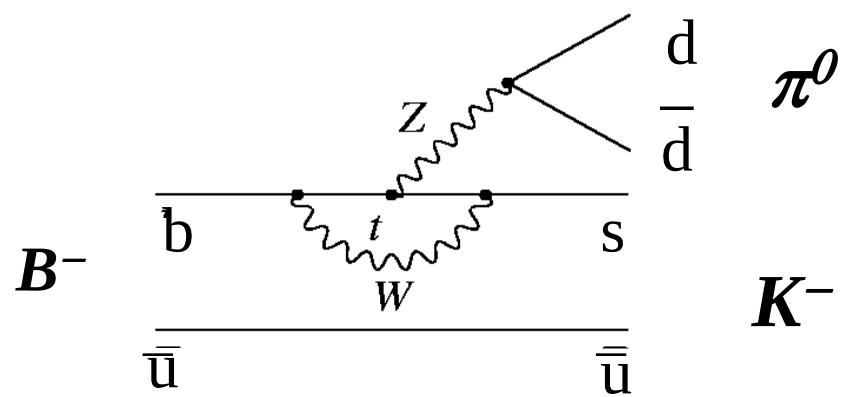


$A_{CP}(K^{\pm}\pi^0) = 0.04 \pm 0.05 \pm 0.02$

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.

BELLE

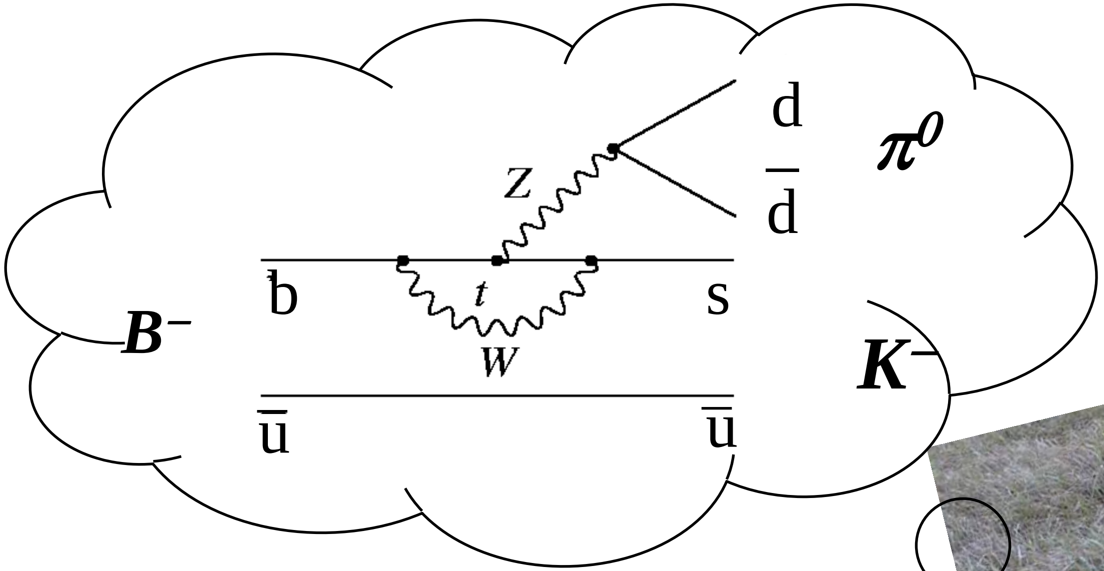
by "yours truly"

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'



Going Up a Hill ...

My first B paper

WSH, Willey, Soni

VOLUME 58, NUMBER 16 PHYSICAL REVIEW LETTERS 20 APRIL 1987

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

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

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

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

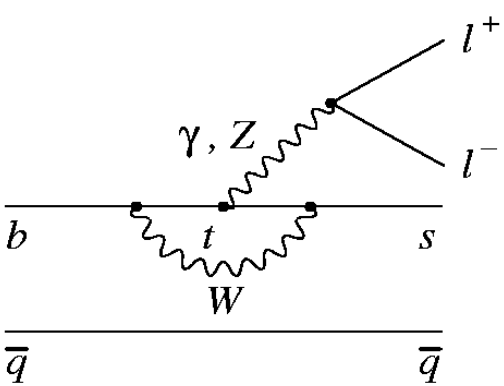
$$\bar{C}_i \equiv \bar{C}_i^Z + \bar{C}_i^{\rm box} = \tfrac{1}{4}x_i + \frac{3}{4}\left(\frac{x_i}{x_i-1}\right)^2 \ln x_i - \frac{3}{4}\frac{x_i}{x_i-1}, \quad (3)$$

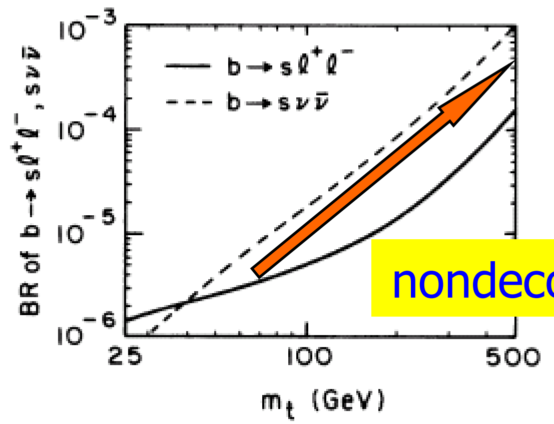
$$\bar{D}_i \equiv \bar{D}_i^Z + \bar{D}_i^{\rm box} = \tfrac{1}{4}x_i + \frac{3}{4}\frac{x_i(x_i-2)}{(x_i-1)^2}\ln x_i + \frac{3}{4}\frac{x_i}{x_i-1}, \quad (4)$$

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

dimensions

γ	Z
αG_F	$G_F^2\, m_t^2$





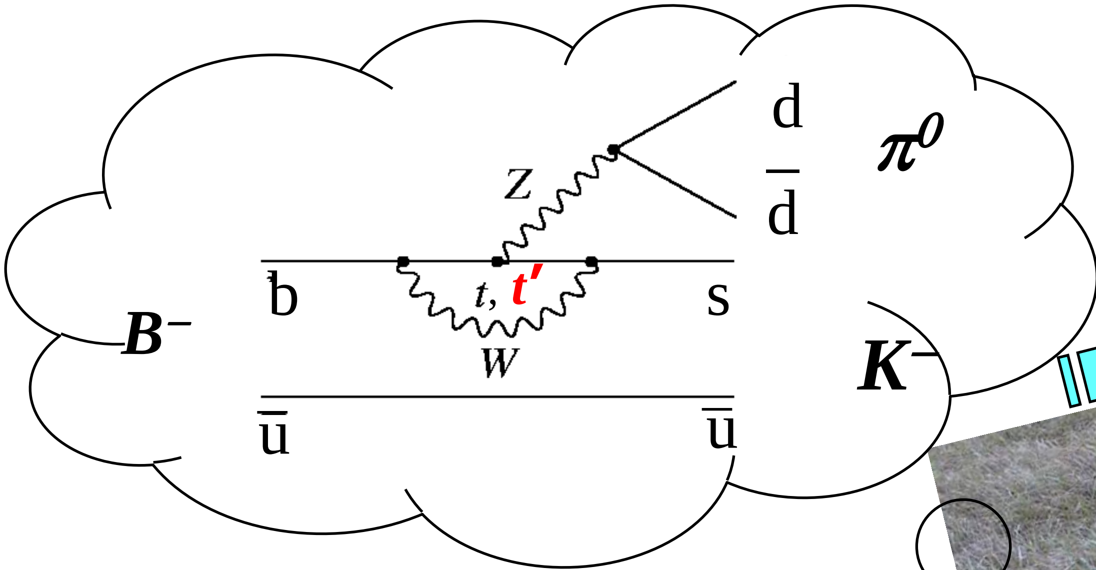
nondecoupling

Decoupling Thm: Heavy Masses are decoupled in QED/QCD
$\because$ 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 $B \to Kl^+l^-$, $K\nu\bar{\nu}$

Wei-Shu Hou and R. S. Willey
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260

and

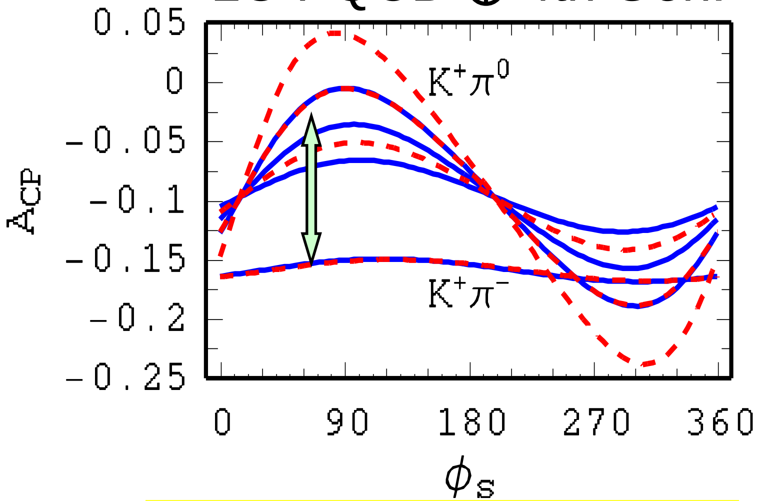
A. Soni
Department of Physics, University of California, Los Angeles, Los Angeles, California 90024
(Received 12 November 1986)

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

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

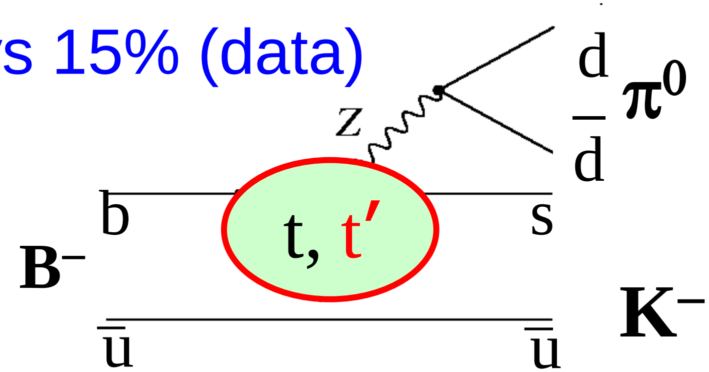
LO PQCD ⊕ 4th Gen.

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

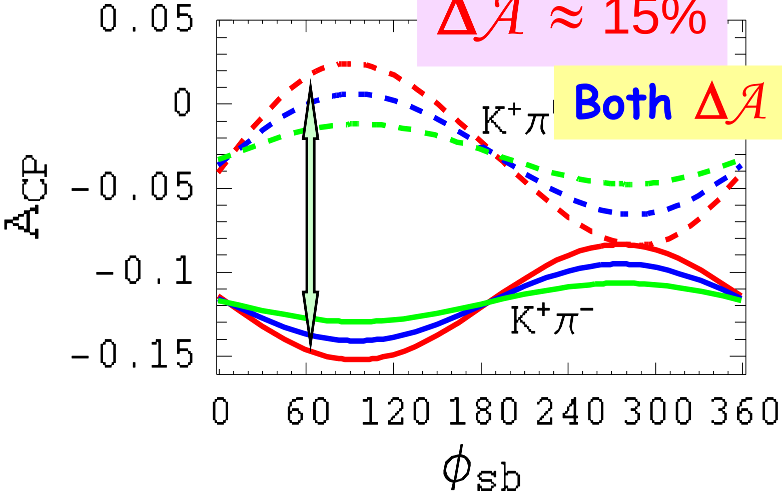
$\Delta\mathcal{A} \approx 15\%$

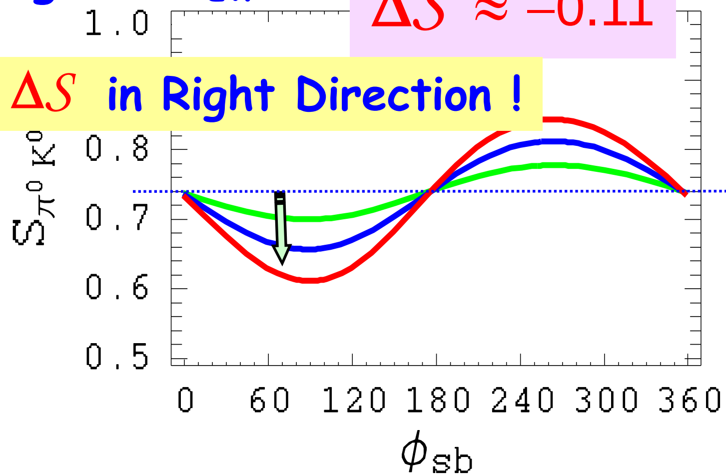
Joining C & P_{EW}

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

consistent with data

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





4 x 4 Unitarity ⇨ Z/K Constraints

"Typical" CKM Matrix

WSH, Nagashima, Soddu, PRD'05

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

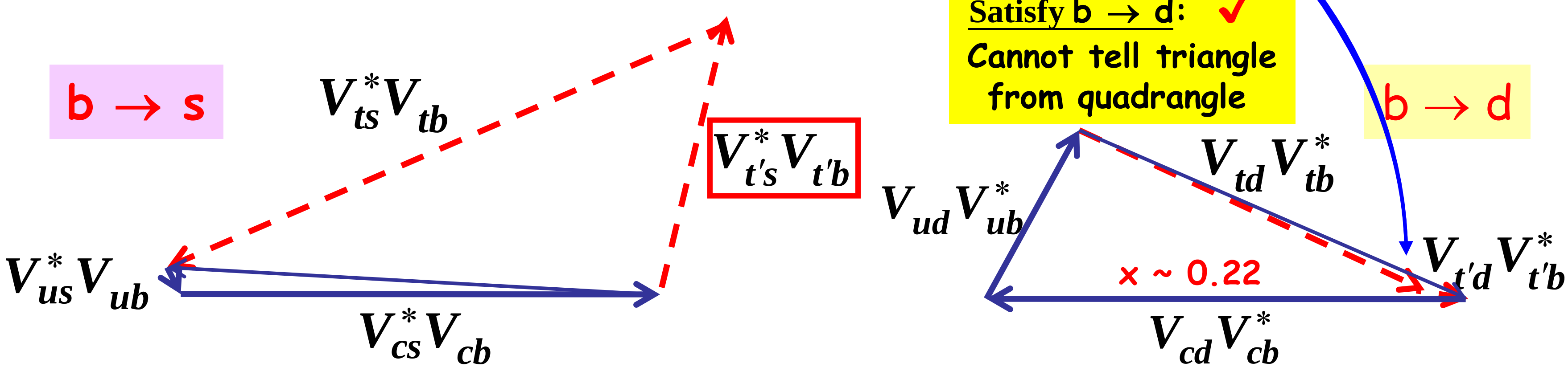
$$V^4_{CKM} = \begin{pmatrix} 0.9745 & 0.2225 & 0.0038\,e^{-i\,60^\circ} & 0.0281\,e^{i\,61^\circ} \\ -0.2241 & 0.9667 & 0.0415 & 0.1164\,e^{i\,66^\circ} \\ 0.0073\,e^{-i\,25^\circ} & -0.0555\,e^{-i\,25^\circ} & 0.9746 & 0.2168\,e^{-i\,1^\circ} \\ -0.0044\,e^{-i\,10^\circ} & -0.1136\,e^{-i\,70^\circ}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

$s \leftarrow b$

$d \leftarrow s$

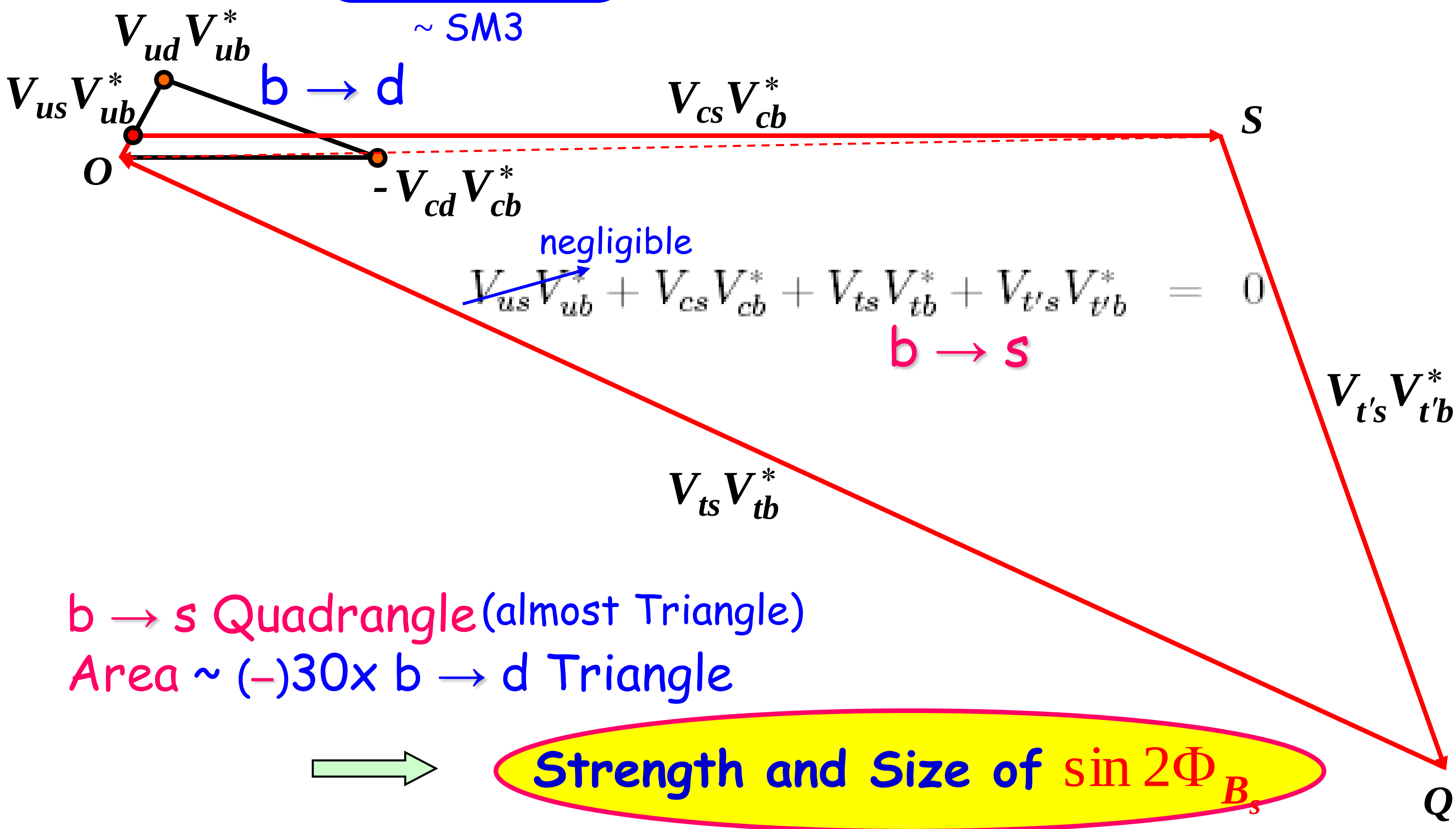
$Z \to b\bar{b}$

Satisfy $b \to d$: ✓
Cannot tell triangle from quadrangle



b → d "Triangle" and b → s Quadrangle

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



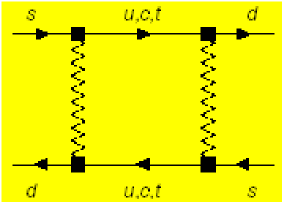
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* + V_{t's}V_{t'b}^* = 0$$

b → s Quadrangle (almost Triangle)

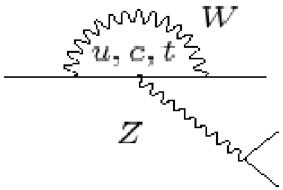
Area ~ (–)30x b → d Triangle

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

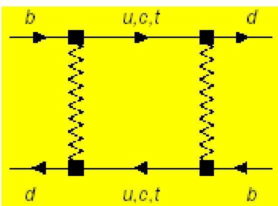
On Boxes and Z Penguins



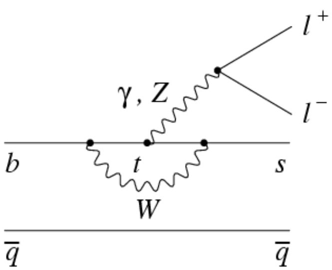
GIM, charm, ε_K

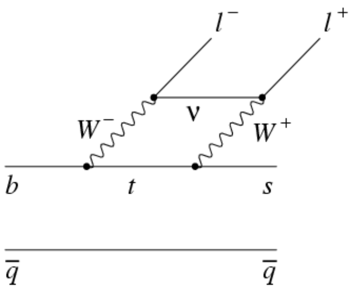


small ε'/ε, K $\to$ $\pi\nu\nu$ (still waiting)



heavy top, sin2ϕ_1/β





Z dominance for heavy top

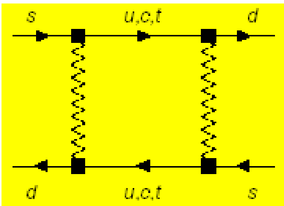
1986 $\to$ 2002

Most Flavor/CPV learned from these diagrams/processes

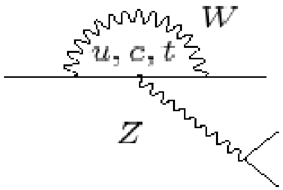
On Boxes and Z Penguins

Nondecoupling

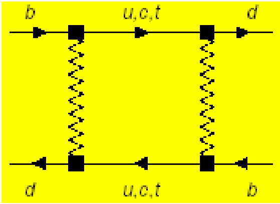
∵ Large Yukawa!



⇒ GIM, charm, ε_K

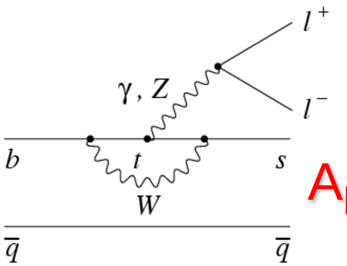


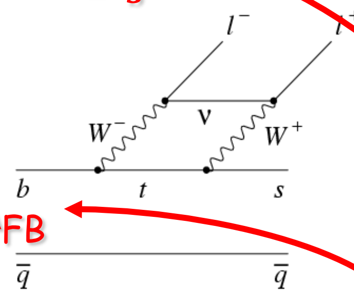
⇒ small ε'/ε, $K \to \pi\nu\nu$ (still waiting)



⇒ 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

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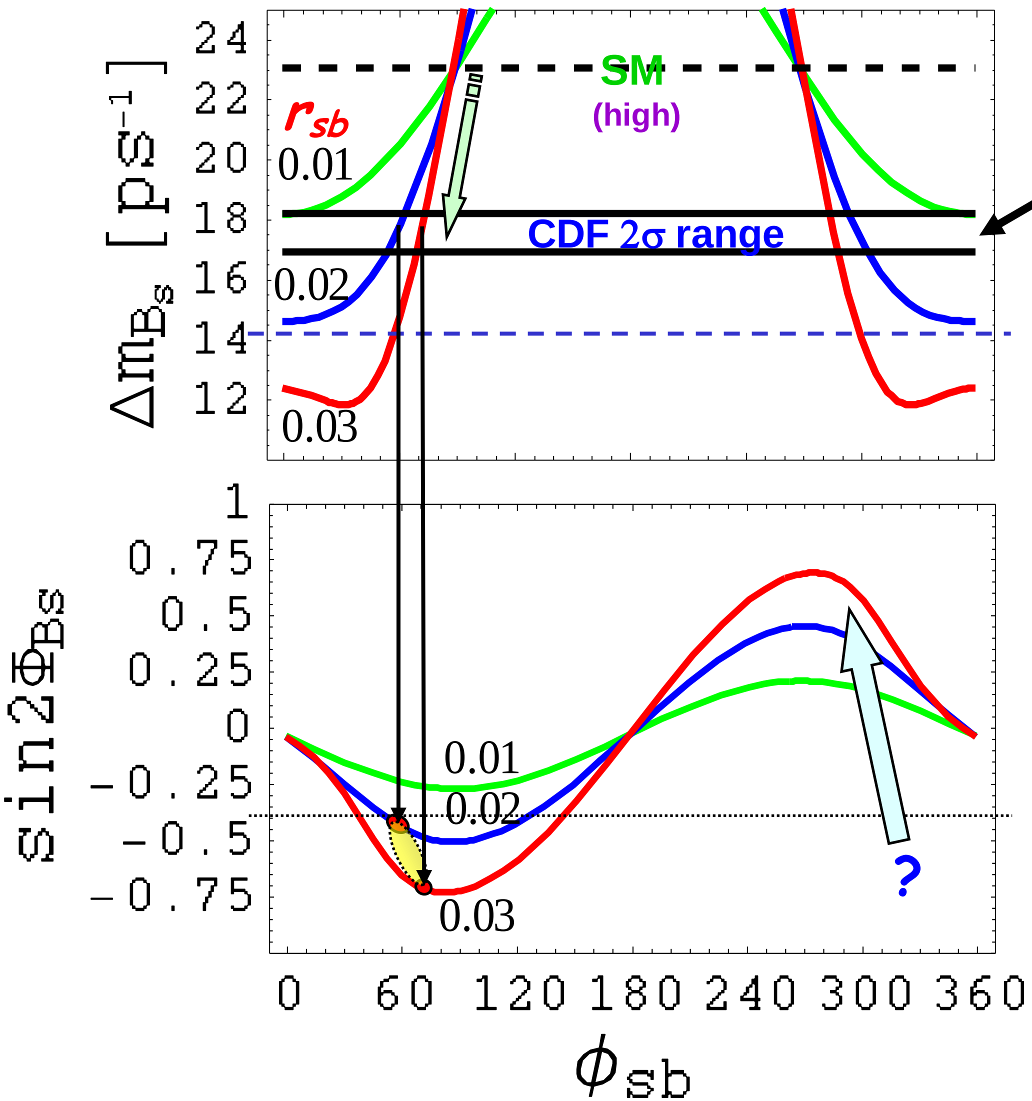
Large CPV in B_s Mixing

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} ~ 0.04

ϕ_{sb} Range ~ 60˚ - 70˚

Finite CPV Phase

$\sin 2\Phi_{B_s}$ ~ –0.5 - –0.7

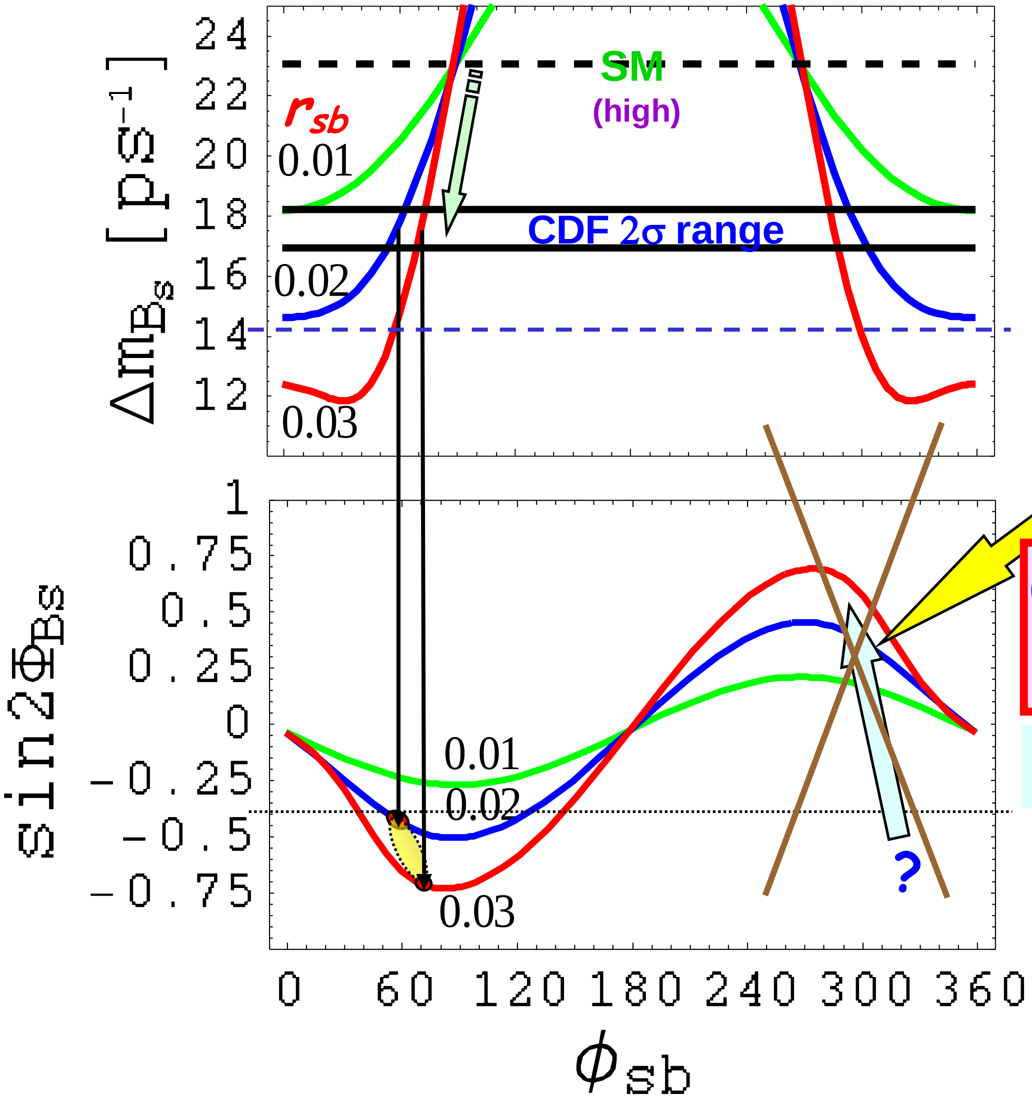
–0.04 SM

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

WSH, Nagashima, Soddu, PRL'05

Large CPV in B_s Mixing

WSH, Nagashima, Soddu, PRD'07



Can Large CPV in B_s Mixing Be Measured @ Tevatron ?

Sign Predicted !

Sure thing by LHCb ca. 2009-10

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

-0.04 SM

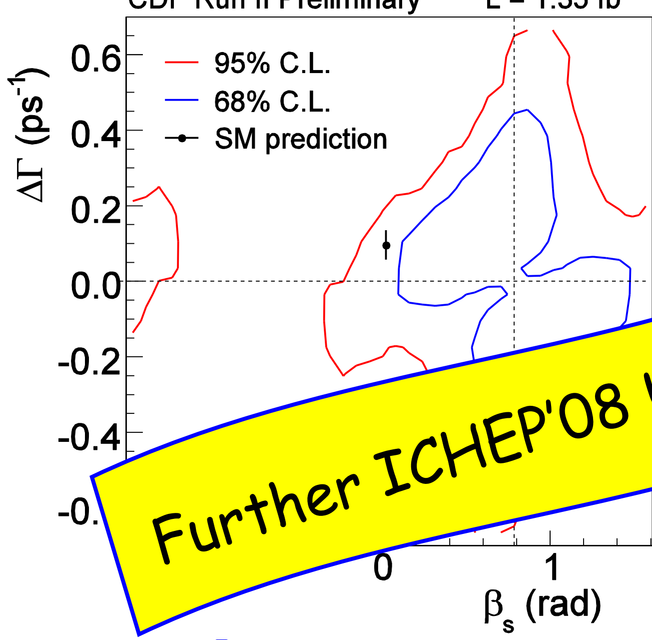
Despite Δm_{B_s}, $\mathcal{B}(b\to s\ell\ell)$ SM-like

WSH, Nagashima, Soddu, PRL'05

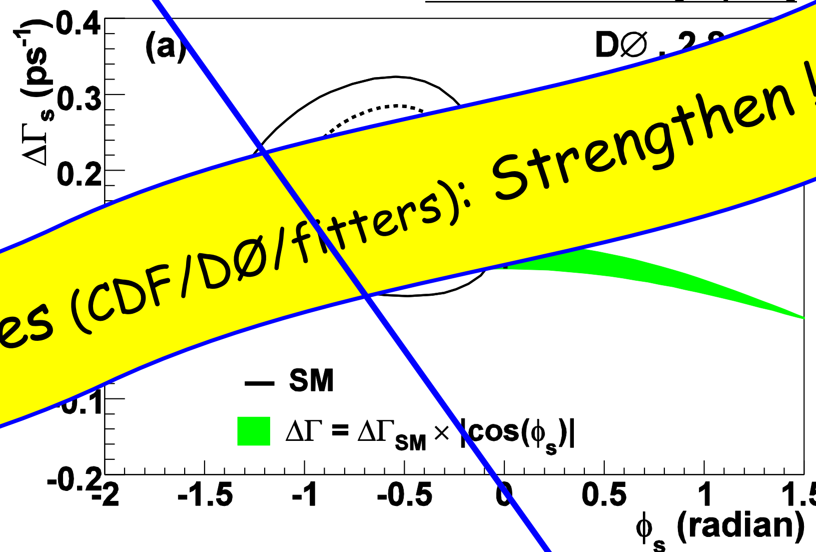
$\sin 2\Phi_{B_s} \sim -0.5$ - -0.7

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

PRL'08
arXiv:0712.2397 [hep.ex]



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]

UT*fit*

arXiv:0803.0659 [hep.ph]

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

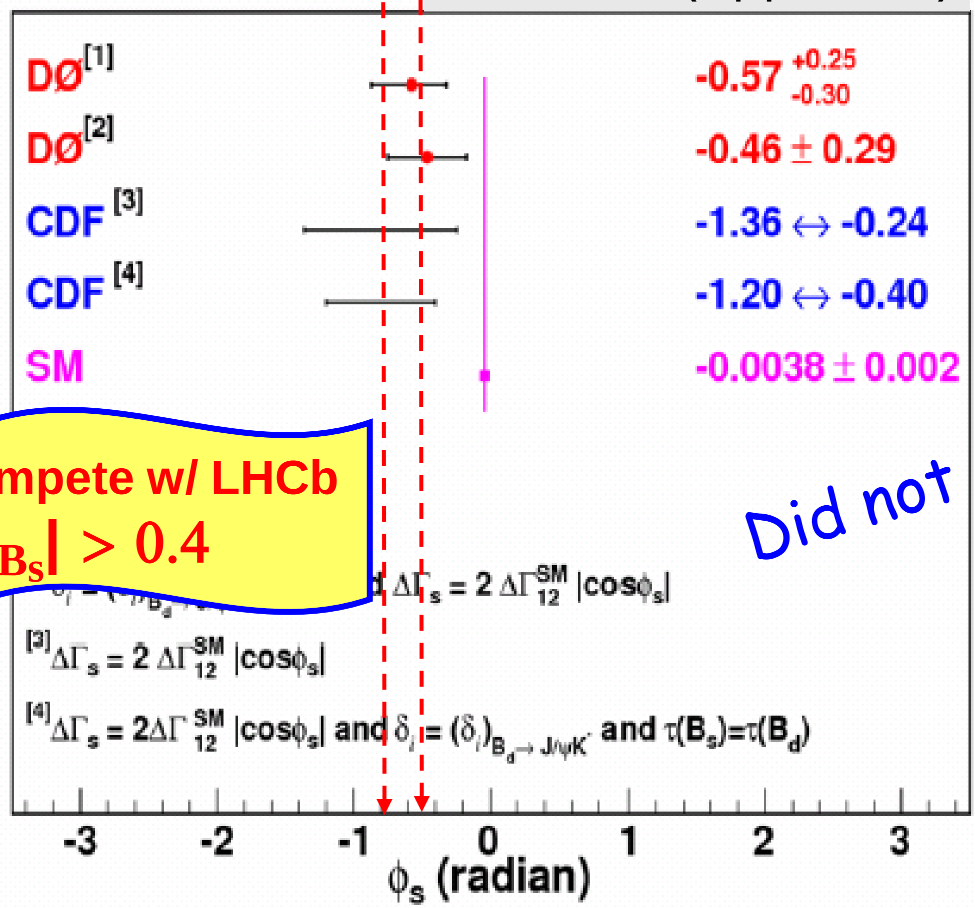
~2.5σ

Incredible !!!

Results with Flavor Tagging

4th Generation ?

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

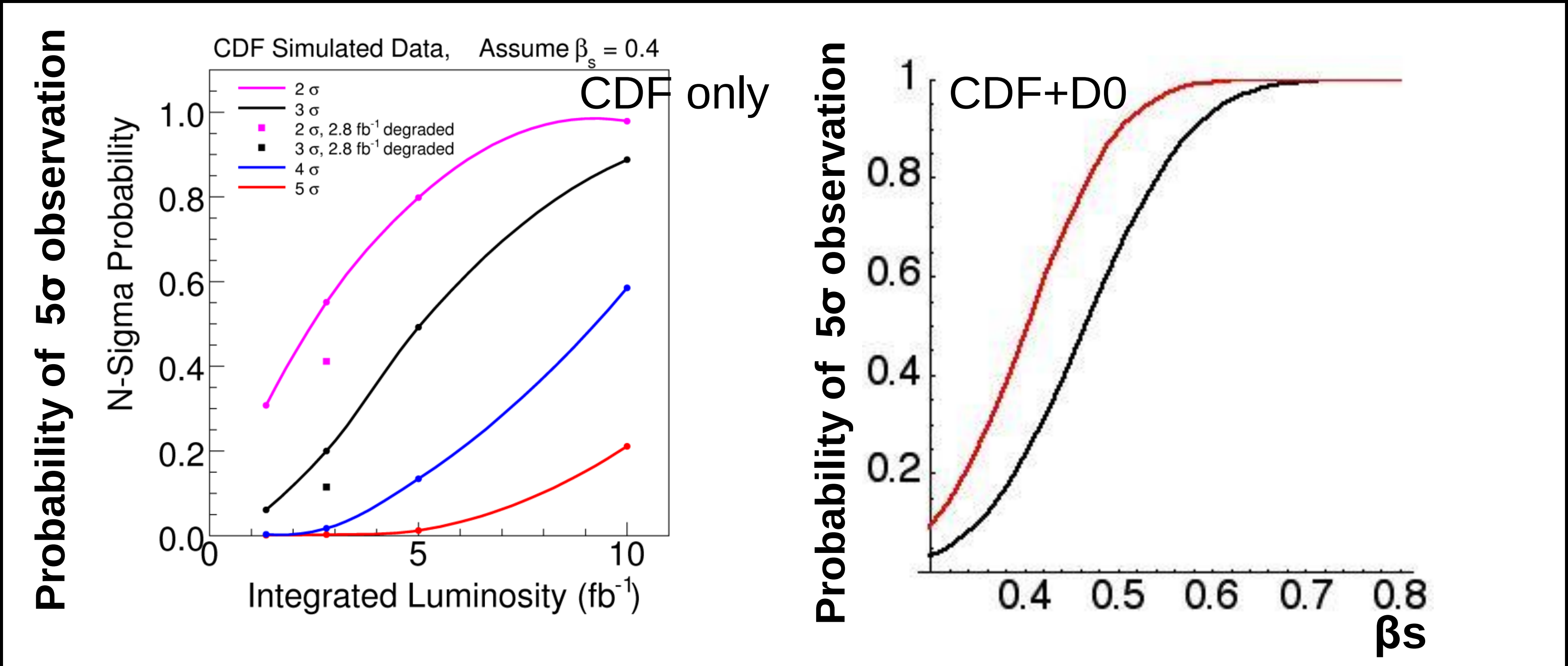


Tevatron can compete w/ LHCb
iff $|\sin 2\Phi_{B_s}| > 0.4$

Did not ask for this !

(Conservative) outlook

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



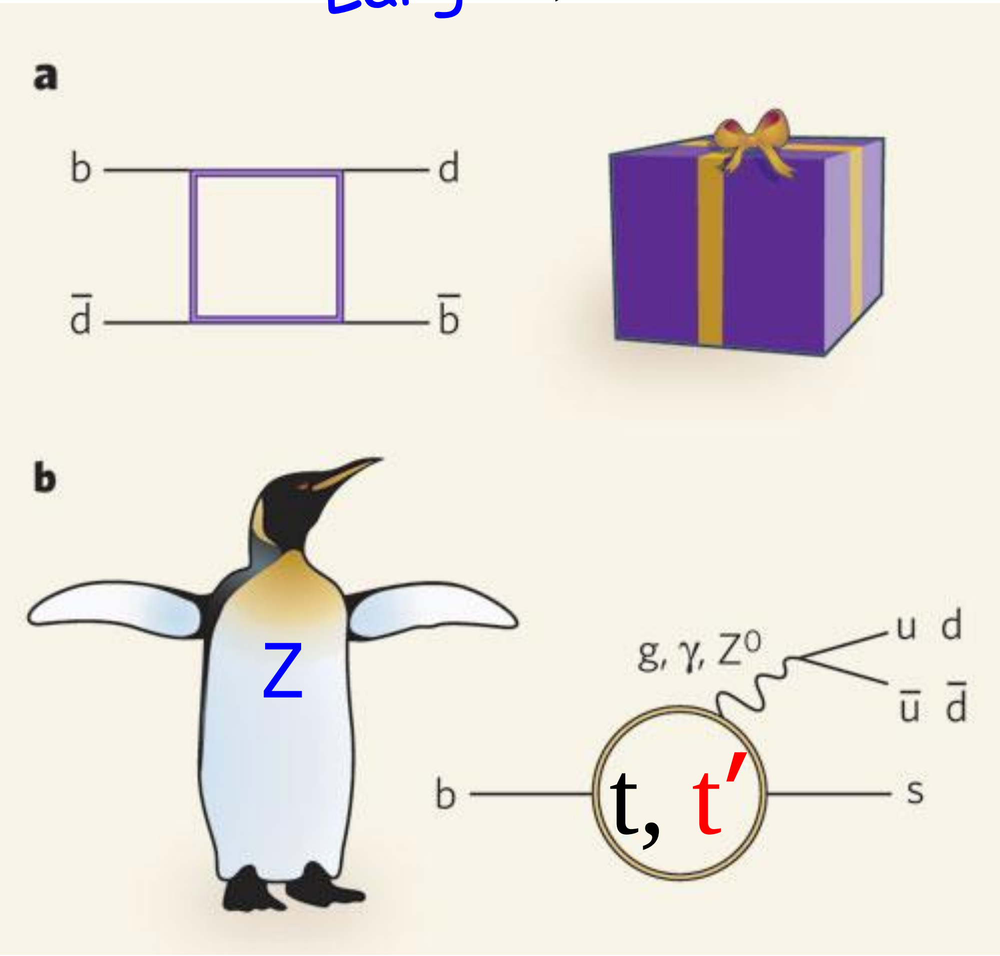
Assumes constant data-taking efficiency and no analysis improvements. No external constraints (Asl, lifetimes) used.

V. Discussion

- The Eureka Moment
- 2-3-4 Dominance of CPV/BAU
- Tevatron/LHC Verification

The Eureka Moment

Large t, t′ Yukawa !



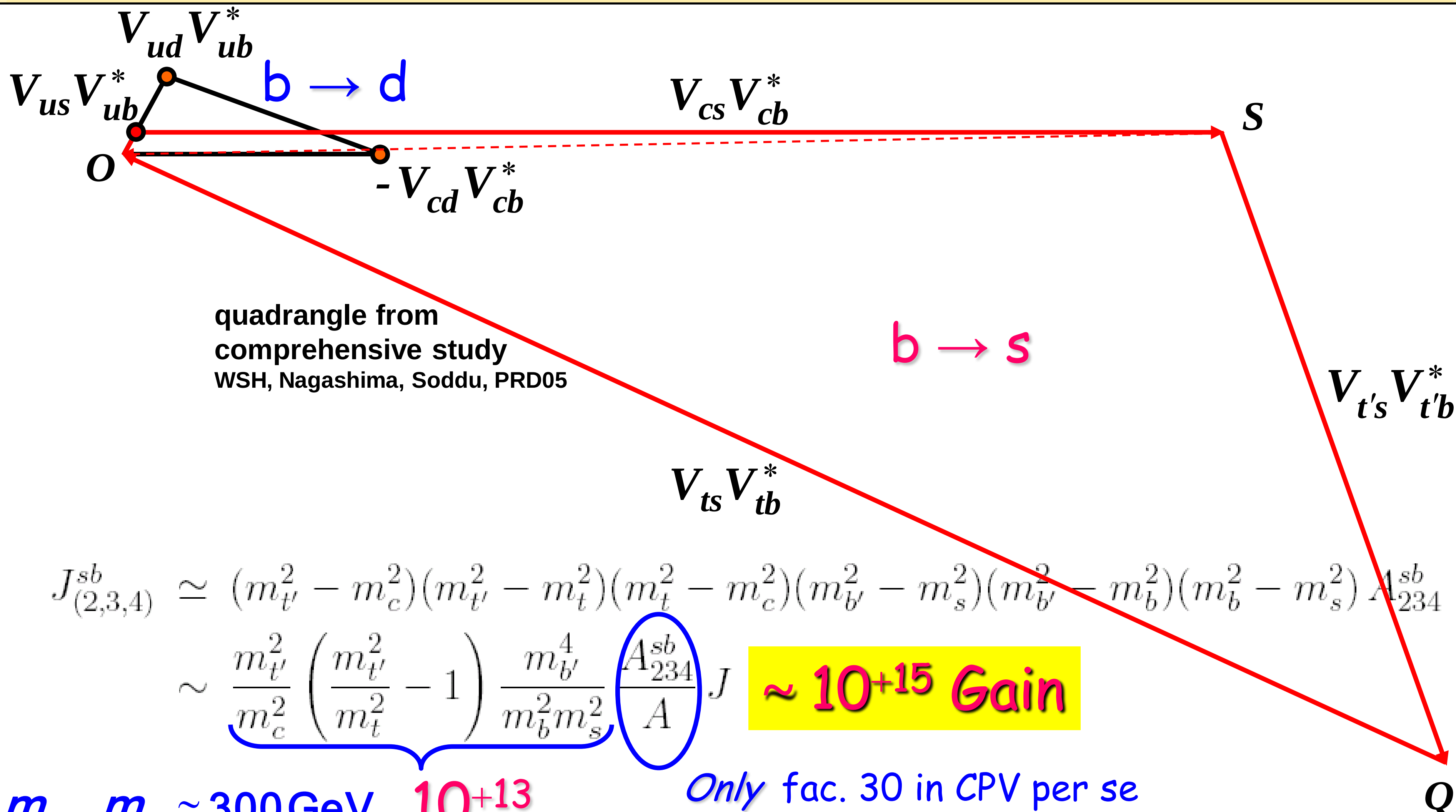
ca. late summer 2007 …

Large Yukawa !

YuReKawa !

Soaring to the Starry Heavens

Gain mostly in Large Yukawa Couplings !



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

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

$\sim 10^{+15}$ Gain

Only fac. 30 in CPV per se

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

$\sim 600\,\text{GeV}$ $\quad 10^{+15}$

CPV for BAU: 2-3-4 Dominance

Jarlskog'85, 3 generations

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

S S'

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 !

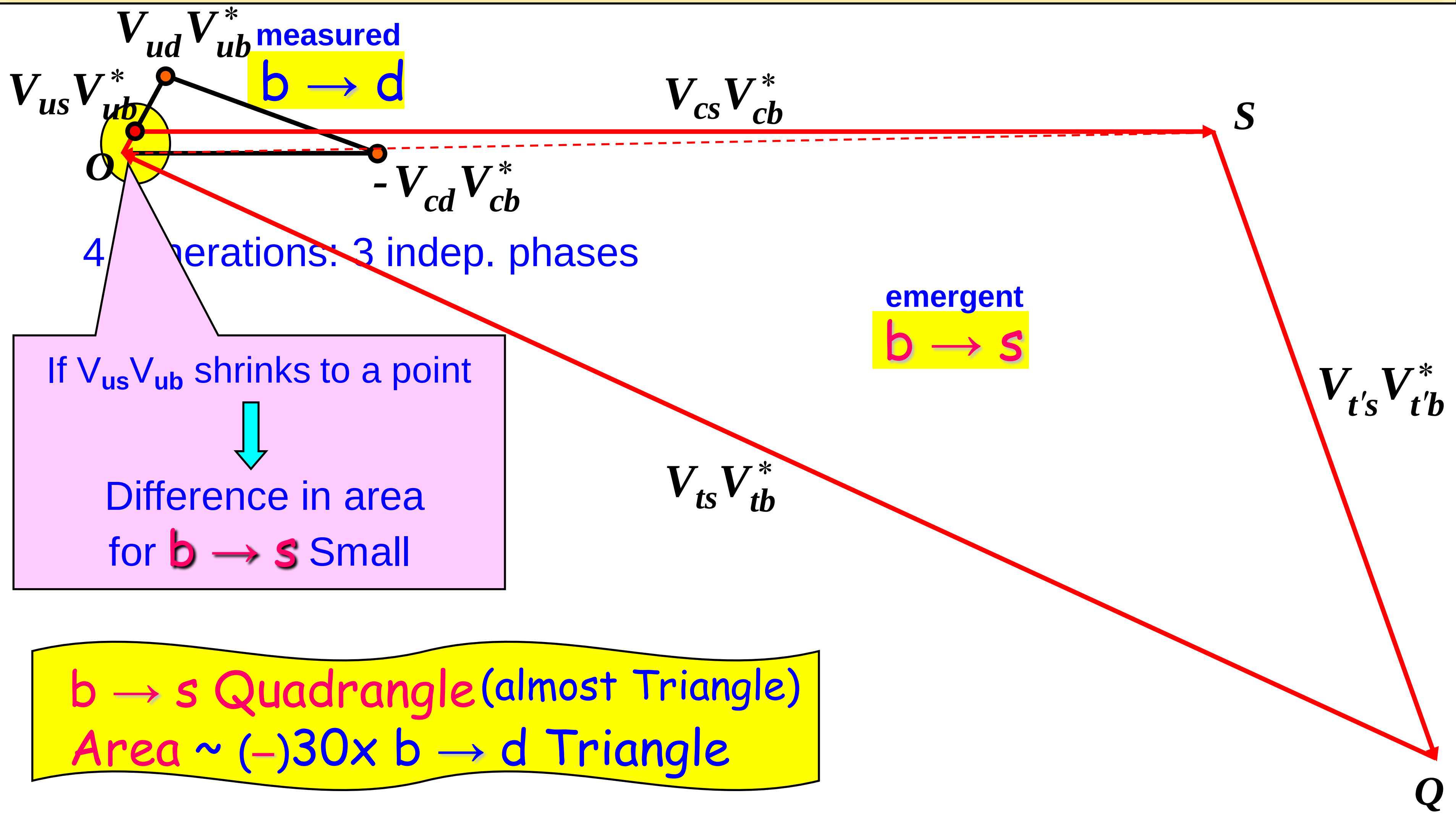
Effectively 3 generations

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

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

J(1,2,3) very small

4 generations: 3 indep. phases

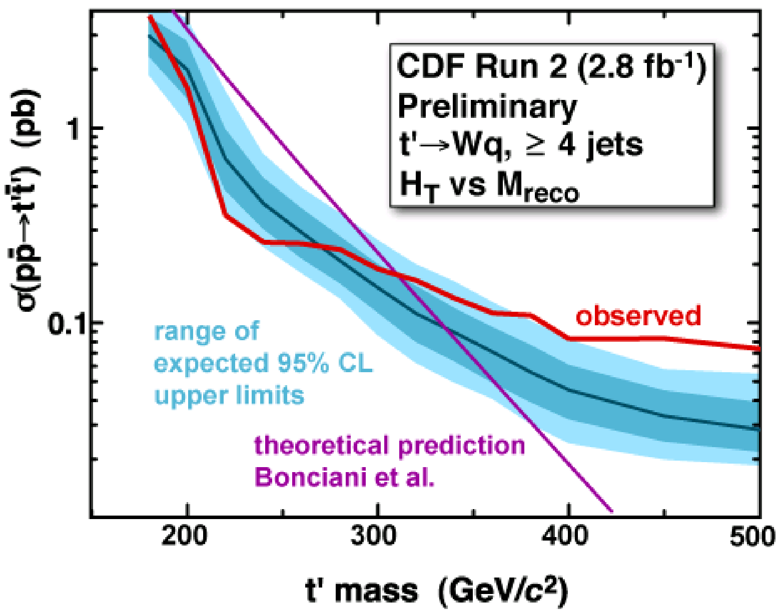


2nd argument that $J^{sb}_{(2,3,4)}$ is predominant CPV

Tevatron/LHC Verification

Tevatron

- **sin2Φ$_{B_s}$** "Evidence" by 2010 ?
- t′ Search Ongoing:
  $m_{t'}$ > 311 GeV @ 95% CL



LHC

Vincenzo Vagnoni (LHCb)

- **sin2Φ$_{B_s}$** "Confirmation" — "Easy" for LHCb
- b′, t′ Discovery — Straightforward/full terrain

talks by Erkcan Ozcan (ATLAS) and Yuan Chao (CMS), at 4th Generation meeting @ CERN, Sept. 4-5, 2008

VI. Conclusion: Heaven Ho

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

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

~ 10^{+15} Gain

Even if $O(1)$

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

$\sim 600\,\mathrm{GeV}$ 10^{+15}

Enough CPV for B.A.U.

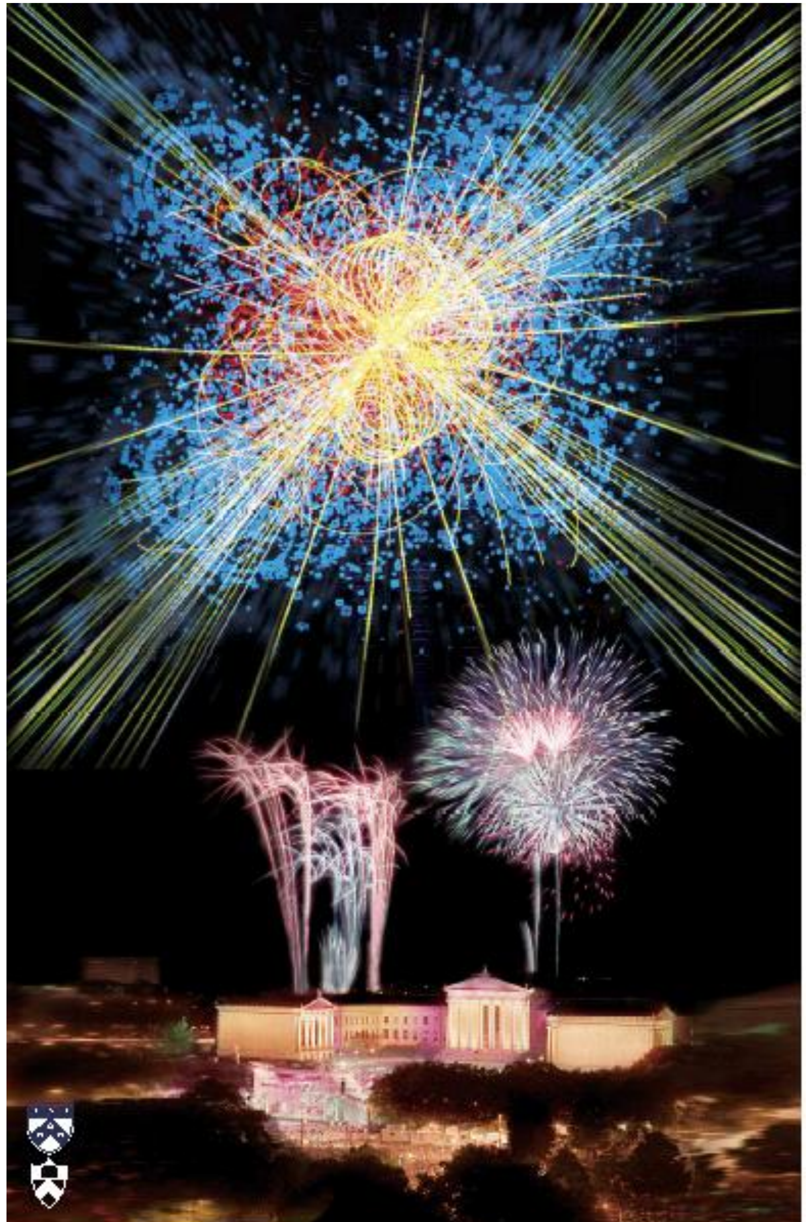
Maybe there is a 4th Generation !

Will know in ~ 3–5 years !

⇨ *Heaven on Earth?*

Universe (Genesis)

CPV



BAU

Earth (EW + KM4)

Backup

i in Dynamics: Source of CPV

ElectroMagnetism: (everyone can feel

Charge ***e*** is ***Real***.

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

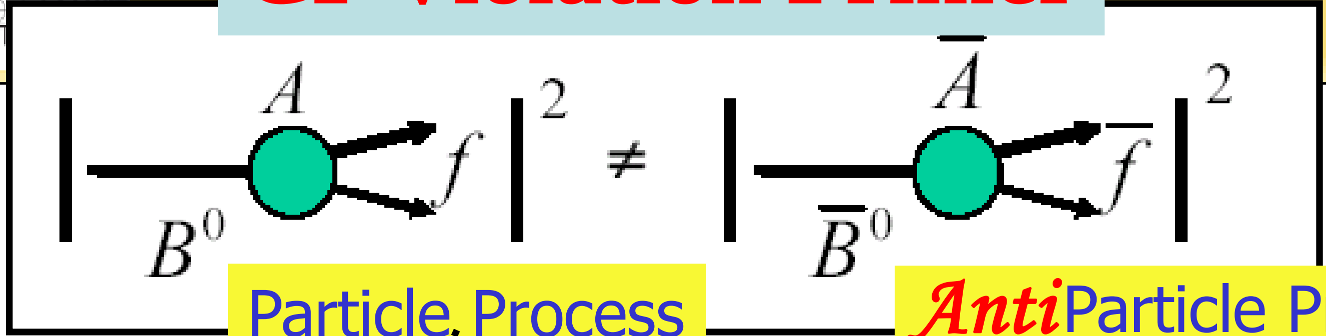
Imagine a Complex Coupling :

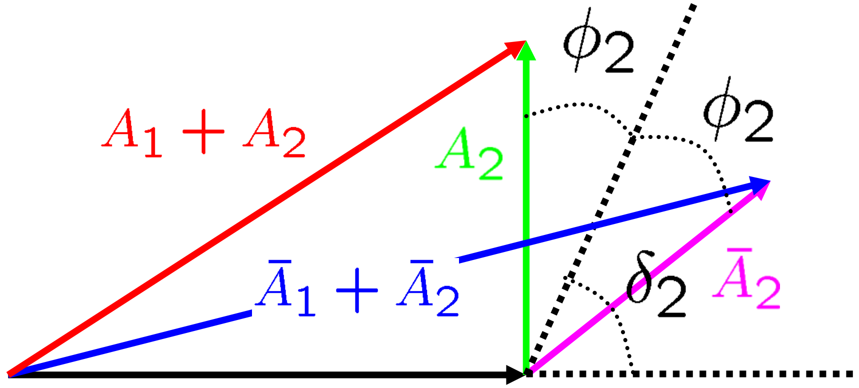
True, or, Possible, for Yukawa (湯川) Coupling of quarks/leptons to Higgs boson(s)...

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

⇒ How CP Violation Appears

CP Violation Primer





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

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

$$A_1 = \bar{A}_1$$

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

CP Asymmetry needs *both* CP Conserv/Violating Phase

i_{QM} i_{dyn}

i in Quantum Mechanics

$$-\frac{\hbar^2}{2m}\nabla^2\Psi + V\Psi = -i\hbar\frac{\partial}{\partial t}\Psi$$

Schrödinger Eq.

Diffusion Eq., except for *i*

prot*on*/neutr*on*
electr*on*
phot*on*

→ Waves: Particle-Waves

Everything is **Wave Phenomena**,
but also "corpuscular" (Newton not wrong)
Waves Interfere: Add in ***Amplitude***

Even for Particle, or High Energy Physics

Wisdom from Peskin

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, $B^+ \rightarrow K^+\pi^0$ and $\bar{B}^- \rightarrow K^-\pi^0$, have an asymmetry of the opposite sign. Together with the same asymmetries recently announced by BaBar[2,3], the effect has a statistical significance greater than five standard deviations — the 'gold standard' of particle physicists for proof that an effect is real.

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

C

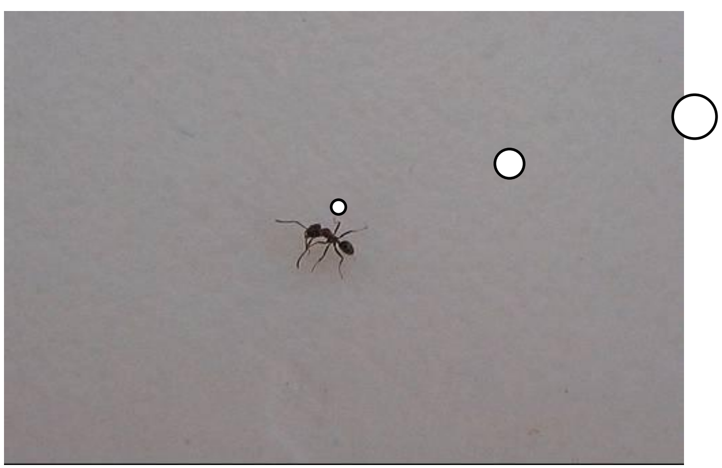
The new results[1–3] are not conclusive, but they are tantalizing. They might be due to properties of standard b-quark weak interactions that we cannot quite yet estimate precisely, but it is equally possible that this is the first hint of an entirely new mechanism for particle–antiparticle asymmetry.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

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

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."



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

World

$= +0.147 \pm 0.028 \quad > 5\sigma$

Experiment is Firm

Why a Puzzle ?

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

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

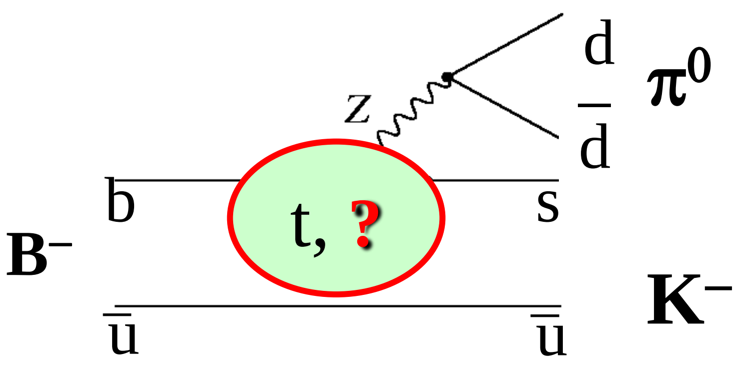
$$\sqrt{2}\mathcal{M}_{K^+\pi^0} - \mathcal{M}_{K^+\pi^-} \propto (P_{EW} + C) \; ?$$

$r =$  / 

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

Baek, London, PLB653, 249 (2007)

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



P_{EW} has practically no weak phase in SM

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

$+0.050\pm0.025$ $\quad -0.097\pm0.012$ **World**

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

Experiment is Firm

Why a Puzzle ?

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

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

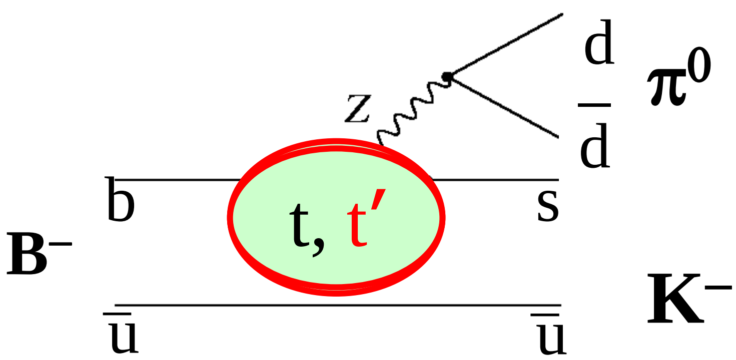
$r =$  / 

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

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

4th Gen. in EWP Natural

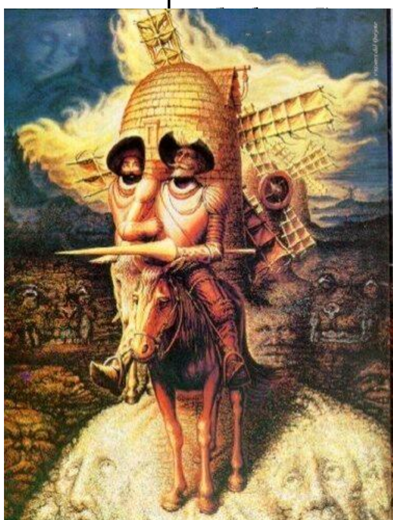
nondecoupling

4th Generation Still?

- N_ν counting? 4th "neutrino" heavy

  Massive neutrinos call for new Physics

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



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

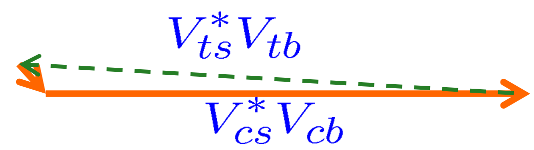
  Kribs, Plehn, Spannowsky, Tait, PRD'07

Effective b → s Hamiltonian and t′ Effect

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

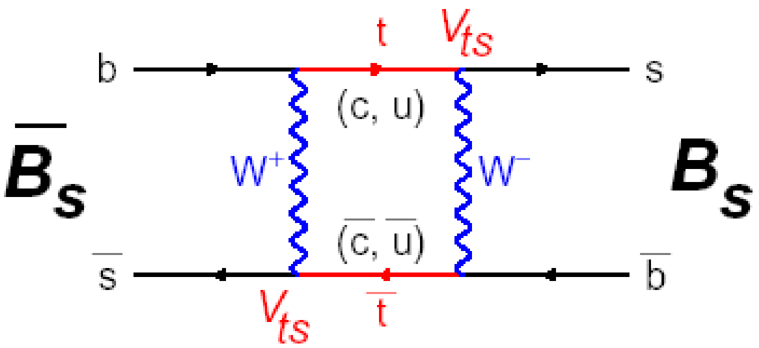
SM 3

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



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

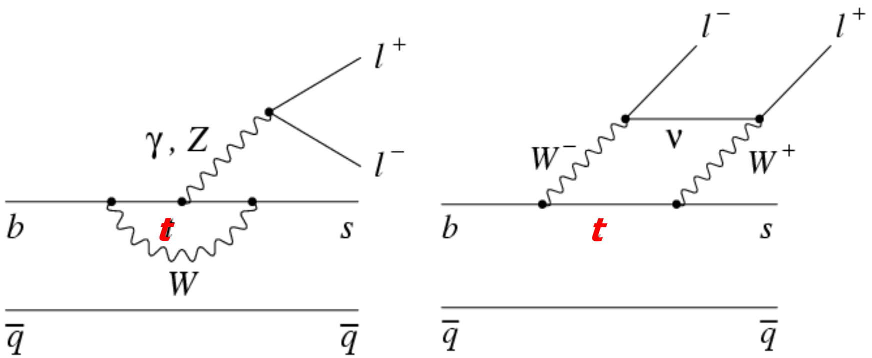
Arhrib and WSH, EPJC'03

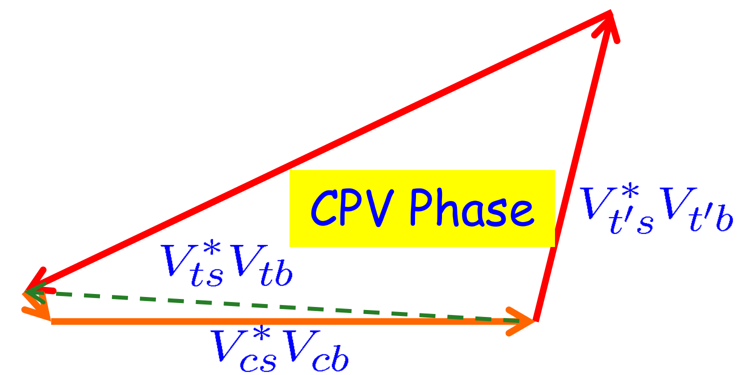


t ⇨ t, t′

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

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



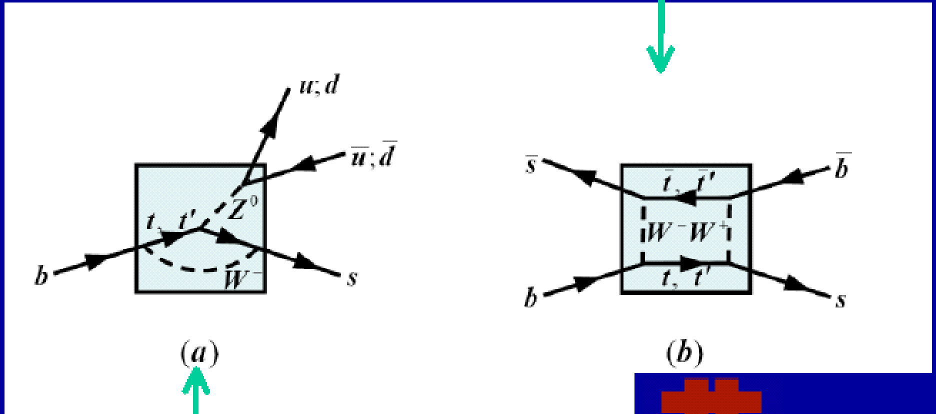


$$\mathrm{M}_{12} \propto f^2_{B_s} B_{B_s} \{\lambda_c^2 S_0(t,t) + 2\lambda_c \lambda_{t'} [S_0(t,t) - S_0(t,t')] + \lambda_{t'}^2 [S_0(t,t) - 2S_0(t,t') + S_0(t',t')]\}$$

GIM Respecting

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

Example of New Physics: a 4th generation quark that contributes to the mixing phase



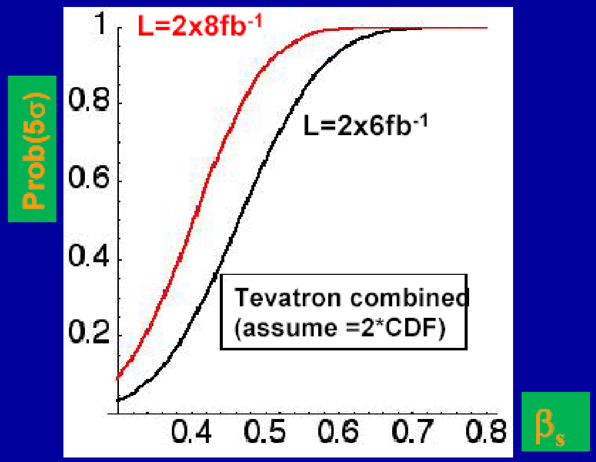
CDF now interested in 4th generation.

Would have other measureable consequenc
direct CP violation in $B^0 \to K^+\pi^-$ and $B^+ \to K^+$

Wei-Shu Hou, arXiv:hep-ph/0803.1234

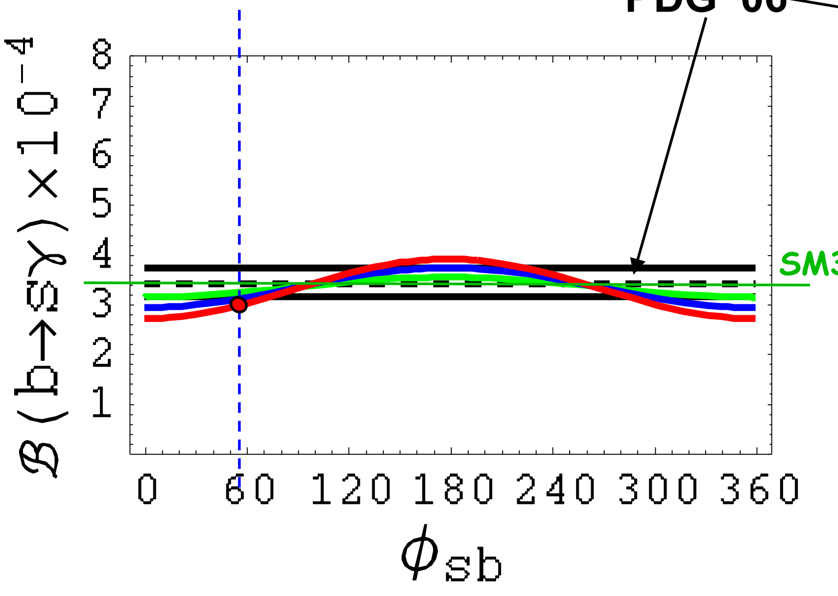
Tevatron outlook for β_s

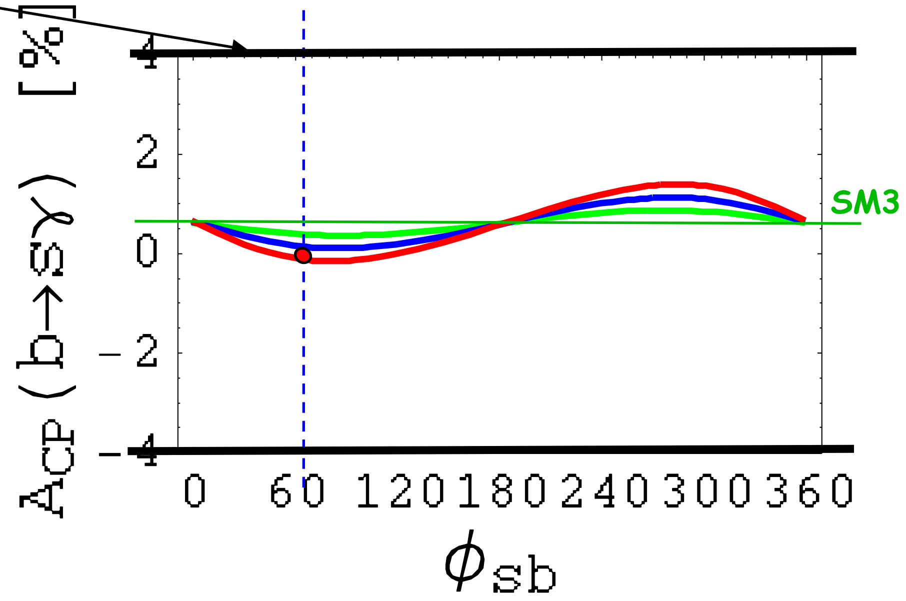
- This assumes no analysis improvements, and no external constraints, but same signal yield and experimental resolution.
- Further improvements can be realized by adding more signals (triggers) or by tagging improvements.



If $\beta_s \geq 0.4$, the Tevatron can discover New Physics

Consistency and $b \to s\gamma$ Predictions



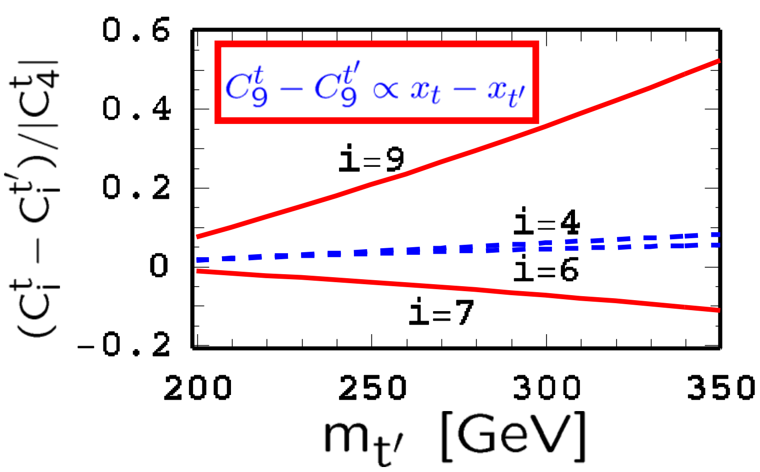


BR OK

A_{CP} ~ 0 far away

beyond SuperB

Heavy t′ effect decoupled for $b \to s\gamma$

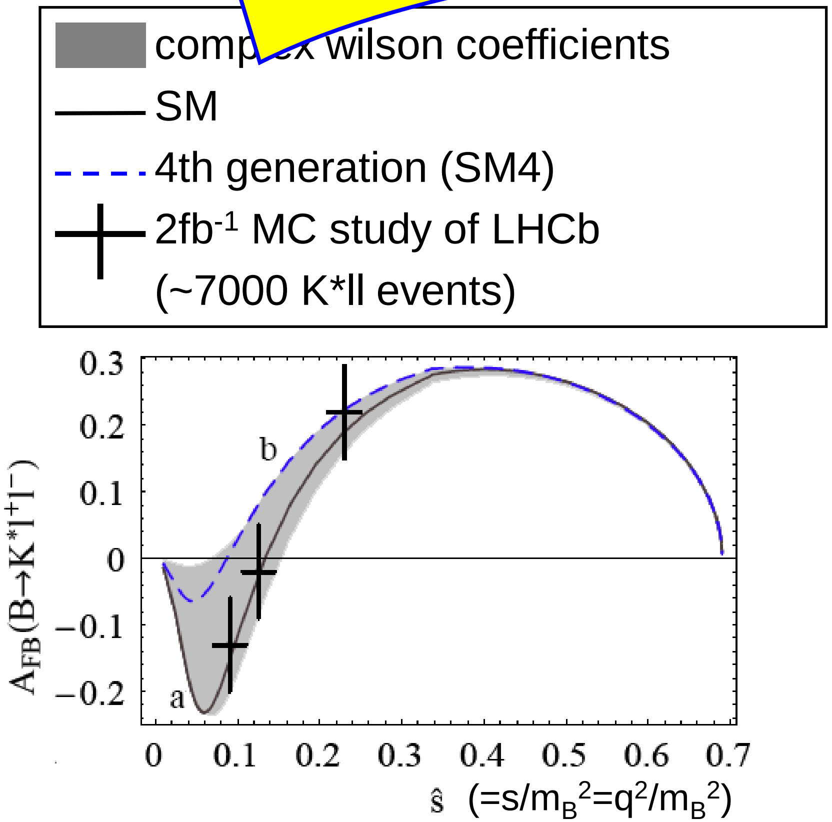


Instead flipped C_7

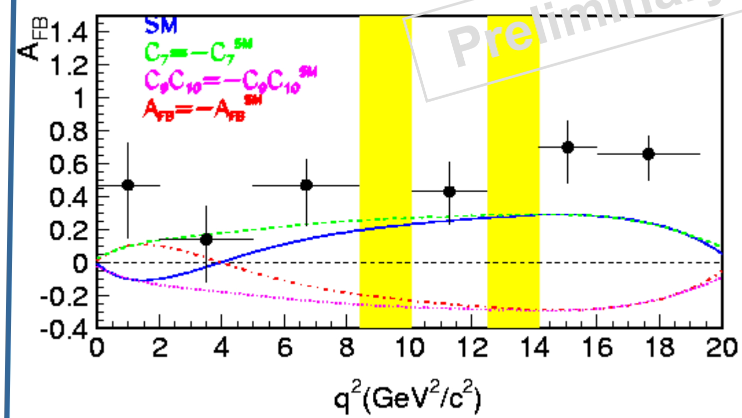
$$\frac{dA_{FB}}{d\hat{s}} \propto -\left\{ \mathrm{Re}(C_9^{eff} C_{10}) V A_1 + \frac{\hat{m}_b}{\ldots} \ldots (1 - \hat{m}_{K^*}) + A_1 T_1 (1 + \hat{m}_{K^*}) \right] \right\}$$

Deviation from SM3 Strengthened !

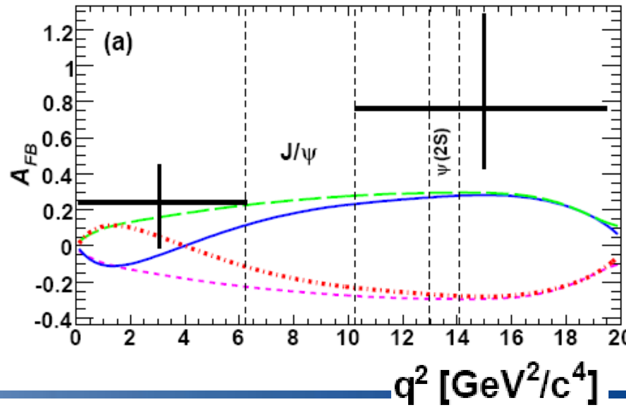
W.-S. ... N. Mah... , 014016 (2008)



Belle **657M**



BABAR, arXiv:0804.4412 **386M**



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

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

$$pp \to t'\overline{t'} \to W^+W^- b\bar{b}$$
and/or
$$pp \to b'\overline{b'} \to W^+W^- t\bar{t}$$

- 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

(or, **Holographic**)