CP Violation: SM & Beyond

Amarjit Soni

HET,BNL

(soni@bnl.gov,adlersoni@gmail.com)

Univ. of Southampton (6/19/07)

OUTLINE

- Status of SM CKM paradigm
- Why is precision of paramount importance?
- Prospects for needed precision
- Possible signs of BSM-CP-odd phase?
- Illustrative candidates for BSM
- BSMs & EDMs
- Summary

B-factories help attain an important milestone

- CKM constraints using expts. $[\epsilon_K, b \to ul\nu, \Delta m_d, \Delta m_s/\Delta m_d]$ + lattice + phenom. $\Rightarrow (\sin 2\beta)_{SM} \approx \cancel{0.70 \pm 0.10}$ $.79 \pm .10$
- $a_{CP}(B \to \psi K^0)$ [BELLE/BABAR/CDF....] $\Rightarrow \sin 2\beta = \cancel{0.731 \pm 0.055}$ $.67 \pm .03$ $\Rightarrow$ **CKM phase is the dominant contributor to a_{CP}** $\Rightarrow$ CP-odd phase(s) due BSM (χ_{BSM}) may well cause only small deviations from SM in B-Physics

Search must go on

Search for CP-odd phase(s) $[\chi_{BSM}]$ due BSM-physics is especially well motivated as there are essentially compelling reasons that they exist:

Extensions of SM invariably lead to new phase(s), besides baryogenesis is difficult to account for by the CKM paradigm

Lightning recap to SM-CKM paradigm of CPV

CKM unitary matrix

$\sim 1\%$ $\lambda = .2257 \pm .0021$

$\sim 2\%$ $A = .818 {}^{+.007}_{-.017}$

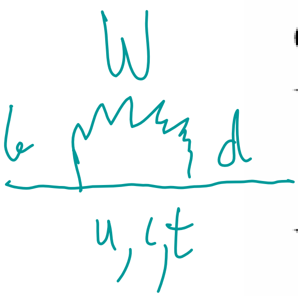
CKM matrix relates weak and mass eigenstates of quarks

Four physical parameters; fundamental constants of the SM

Complex elements allow (only source of) CP violation in SM

25% $\rho \sim .22$

20% $\eta \sim .34$



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

Wolfenstein expansion ($A \sim 0.82$, $\lambda \sim 0.23$, ρ, η) in powers of λ:

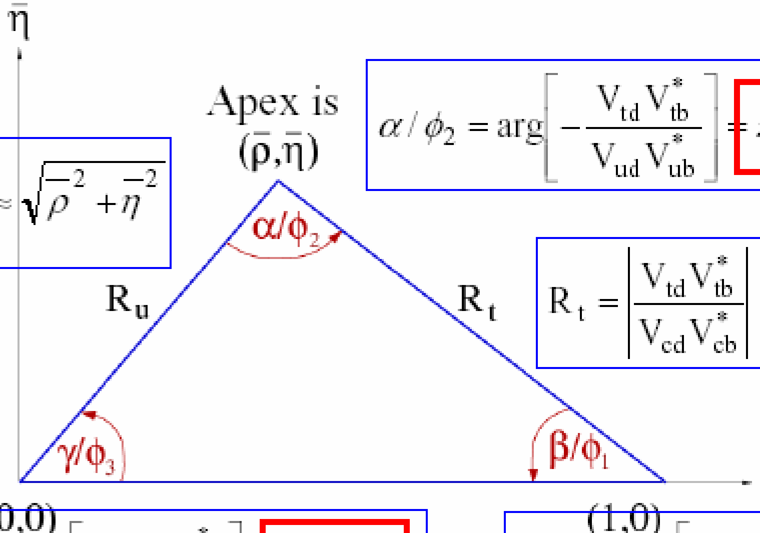
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Only two complex elements to this order; both small $\sim\lambda^3$

Unitarity triangle

Represent as "Unitarity Triangle" in complex ρ,η plane

To O(λ⁶), use corrected values: $\bar{\rho} = \rho(1-\lambda^2/2)$, $\bar{\eta} = \eta(1-\lambda^2/2)$



$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| \approx \sqrt{\bar{\rho}^2 + \bar{\eta}^2}$$

$$\alpha/\phi_2 = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] = \boxed{\pi - \beta - \gamma}$$

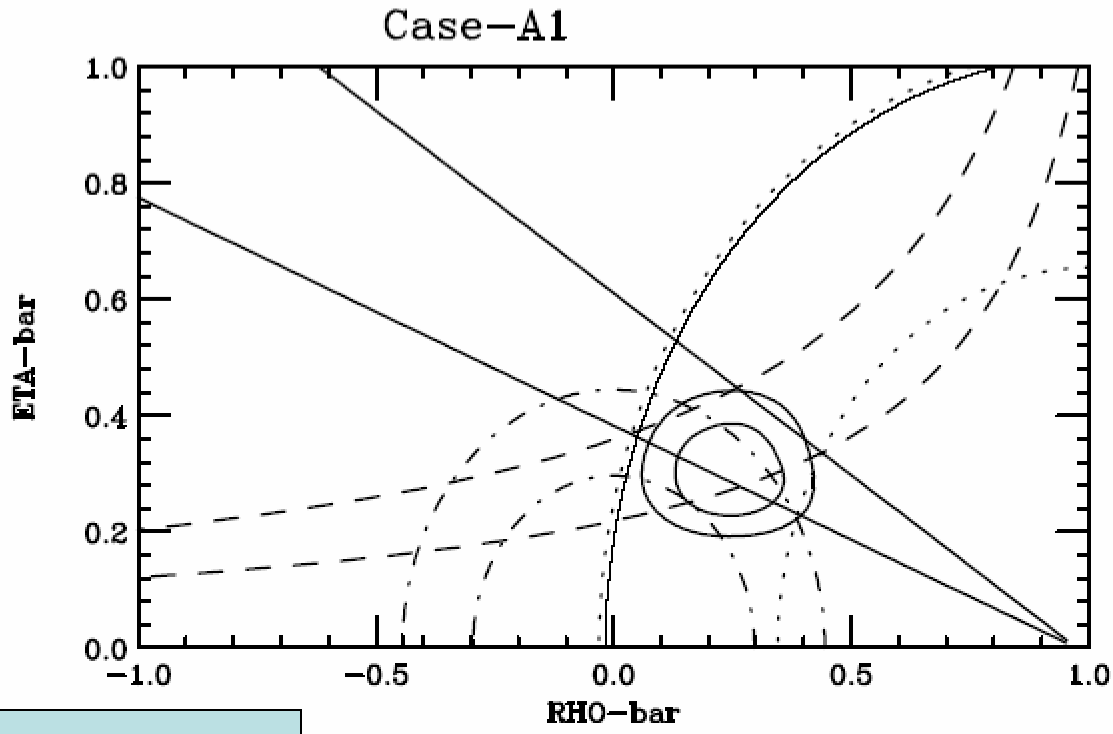
$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| \approx \sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2}$$

$$\gamma/\phi_3 = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right] \approx \boxed{\arg\left[V_{ub}^*\right]}$$

$$\beta/\phi_1 = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \approx \boxed{\arg\left[V_{td}^*\right]}$$

1st Hints of confirmation
Of CKM-CP violation

Atwood&A.S,
hep-ph/0103197



Most bands due
To theory errors

Theoretical Underpinnings (see e.g. Ciuchini et al, hep-ph/0012308)

- CP violation in the kaon system which is expressed by $|\varepsilon_K|$

$$|\varepsilon_K| = C_\varepsilon \; A^2\lambda^6 \; \bar{\eta} \left[-\eta_1 S(x_c) + \eta_2 S(x_t) \left(A^2\lambda^4 \left(1-\bar{\rho}\right)\right) + \eta_3 S(x_c, x_t)\right] \; \hat{B}_K \,, \tag{2.4}$$

where

$$C_\varepsilon = \frac{G_F^2 f_K^2 m_K m_W^2}{6\sqrt{2}\pi^2 \Delta m_K} \,. \tag{2.5}$$

$S(x_i)$ and $S(x_i, x_j)$ are the appropriate Inami-Lim functions [27] of $x_q = m_q^2/m_W^2$, including the next-to-leading order QCD corrections [28, 30]. The most uncertain parameter is $\hat{B}_K$.

- The $B_d^0 - \bar{B}_d^0$ time oscillation period which can be related to the mass difference between the light and heavy mass eigenstates of the $B_d^0 - \bar{B}_d^0$ system

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \; \eta_c S(x_t) \; A^2\lambda^6 \; \left[(1-\bar{\rho})^2 + \bar{\eta}^2\right] m_{B_d} \; f_{B_d}^2 \hat{B}_{B_d} \,, \tag{2.2}$$

where $S(x_t)$ is the Inami-Lim function [27] and $x_t = m_t^2/M_W^2$. m_t is the $\overline{MS}$ top mass, $m_t^{\overline{MS}}(m_t^{\overline{MS}})$, and η_c is the perturbative QCD short-distance NLO correction. The remaining factor, $f_{B_d}^2 \hat{B}_{B_d}$, encodes the information of non-perturbative QCD. Apart for $\bar{\rho}$ and $\bar{\eta}$, the most uncertain parameter in this expression is $f_{B_d}\sqrt{\hat{B}_{B_d}}$. The value of $\eta_c = 0.55 \pm 0.01$ has been obtained in [28] and we used $m_t = (167 \pm 5)$ GeV, as deduced from measurements of the mass by CDF and D0 Collaborations [29].

- The limit on the lower value for the time oscillation period of the $B_s^0 - \bar{B}_s^0$ system is transformed into a limit on Δm_s and compared with Δm_d

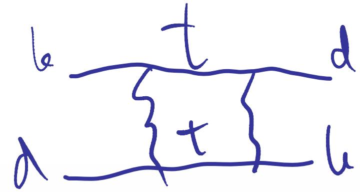
$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \left(\frac{\lambda}{1-\lambda^2/2}\right)^2 \left[(1-\bar{\rho})^2 + \bar{\eta}^2\right]. \qquad (2.3)$$

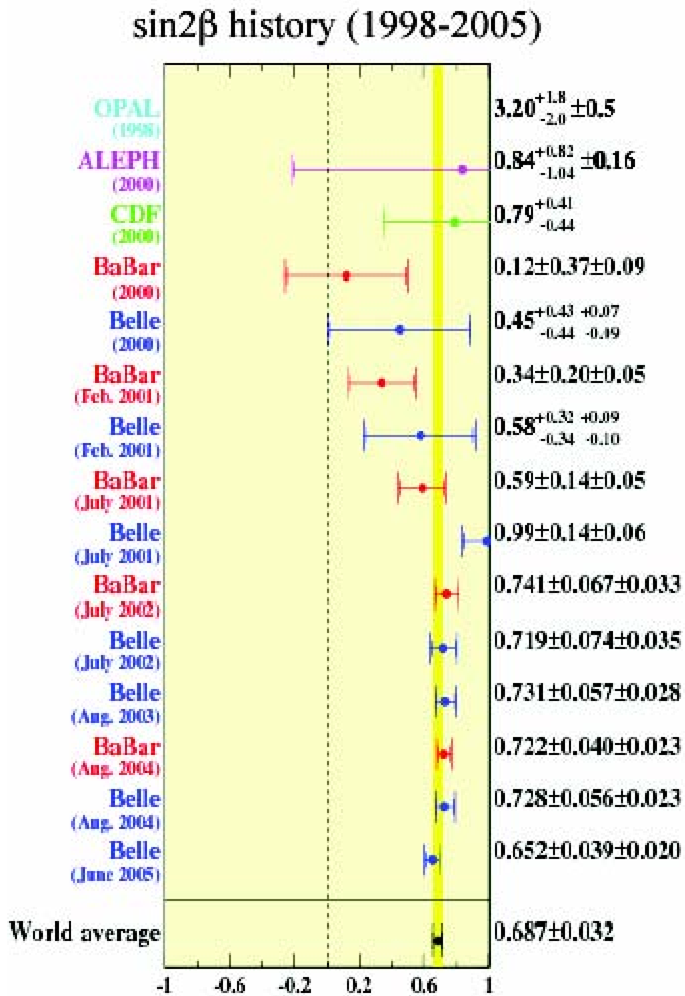
The ratio $\xi = f_{B_s}\sqrt{\hat{B}_{B_s}}/f_{B_d}\sqrt{\hat{B}_{B_d}}$ is expected to be better determined from theory than the individual quantities entering into its expression. In our analysis, we accounted for the correlation due to the appearance of Δm_d in both Equations (2.2) and (2.3).

- The relative rate of charmed and charmless b-hadron semileptonic decays which allows to measure the ratio

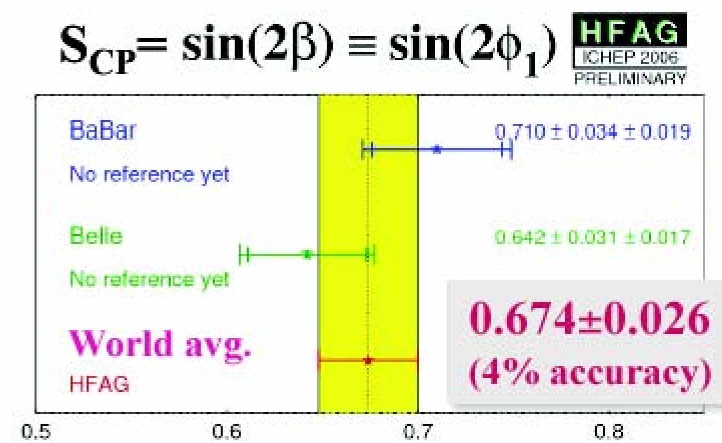
$$\left|\frac{V_{ub}}{V_{cb}}\right| = \frac{\lambda}{1-\lambda^2/2}\sqrt{\bar{\rho}^2 + \bar{\eta}^2}. \qquad (2.1)$$

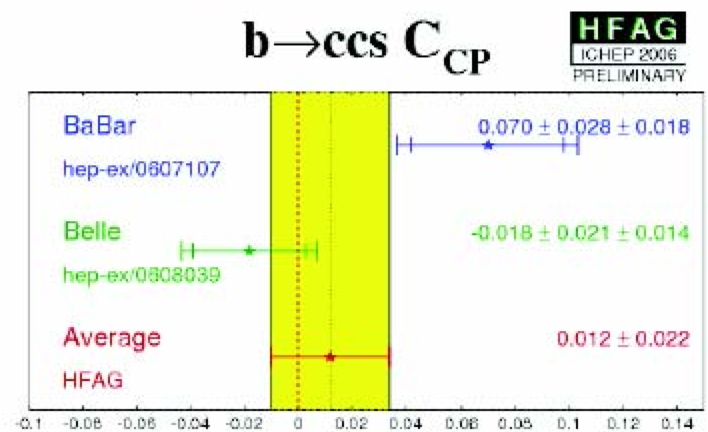
Measurement of β(φ1)





2006 BaBar + Belle



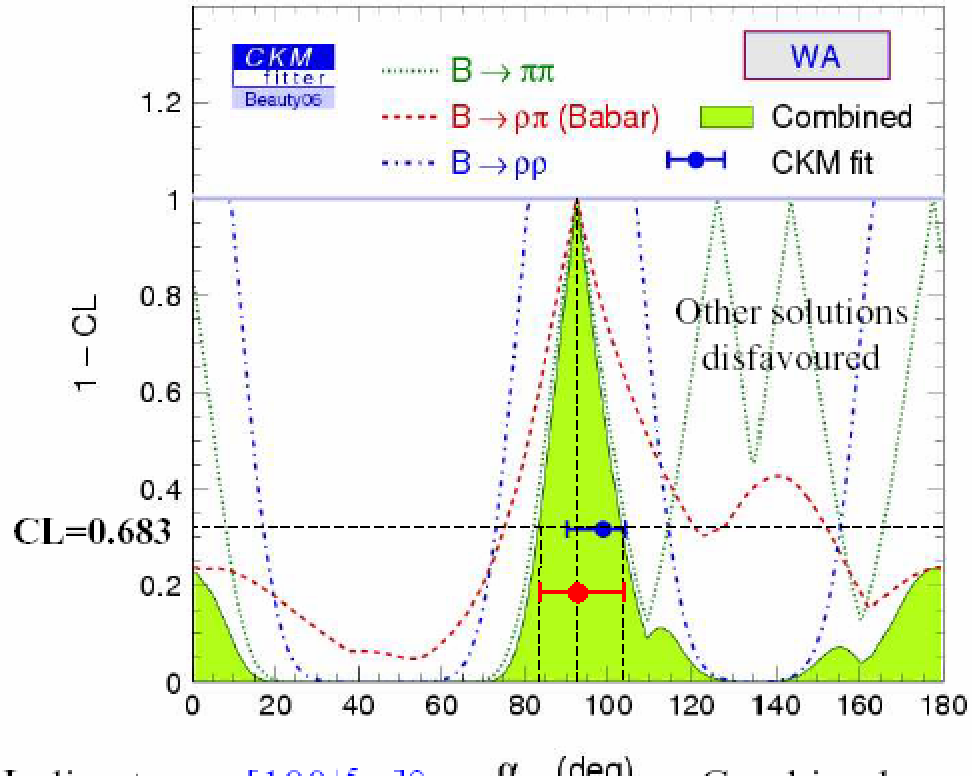


SM $\sin 2\beta = .79 \pm .10$

Youngjoon Kwon

Measurement of $\alpha(\phi_2)$

Overall result, including $\rho\pi$



Indirect: $\alpha = [100^{+5}_{-7}]^\circ$ Combined: $\alpha = [93^{+11}_{-9}]^\circ$

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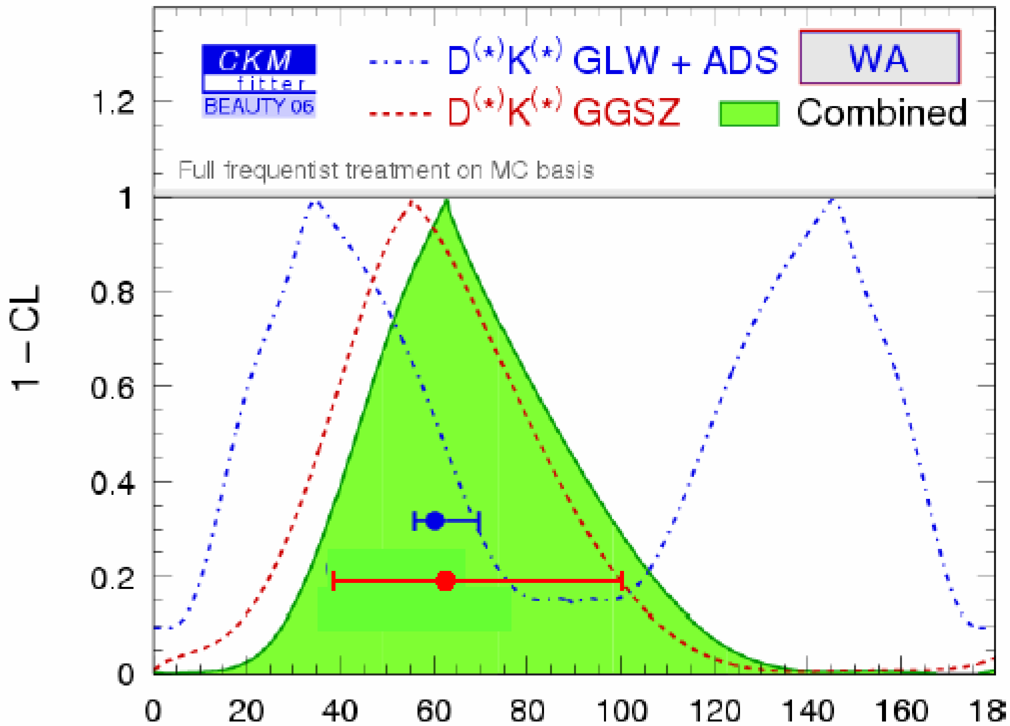
Measurement of γ (ϕ_3)

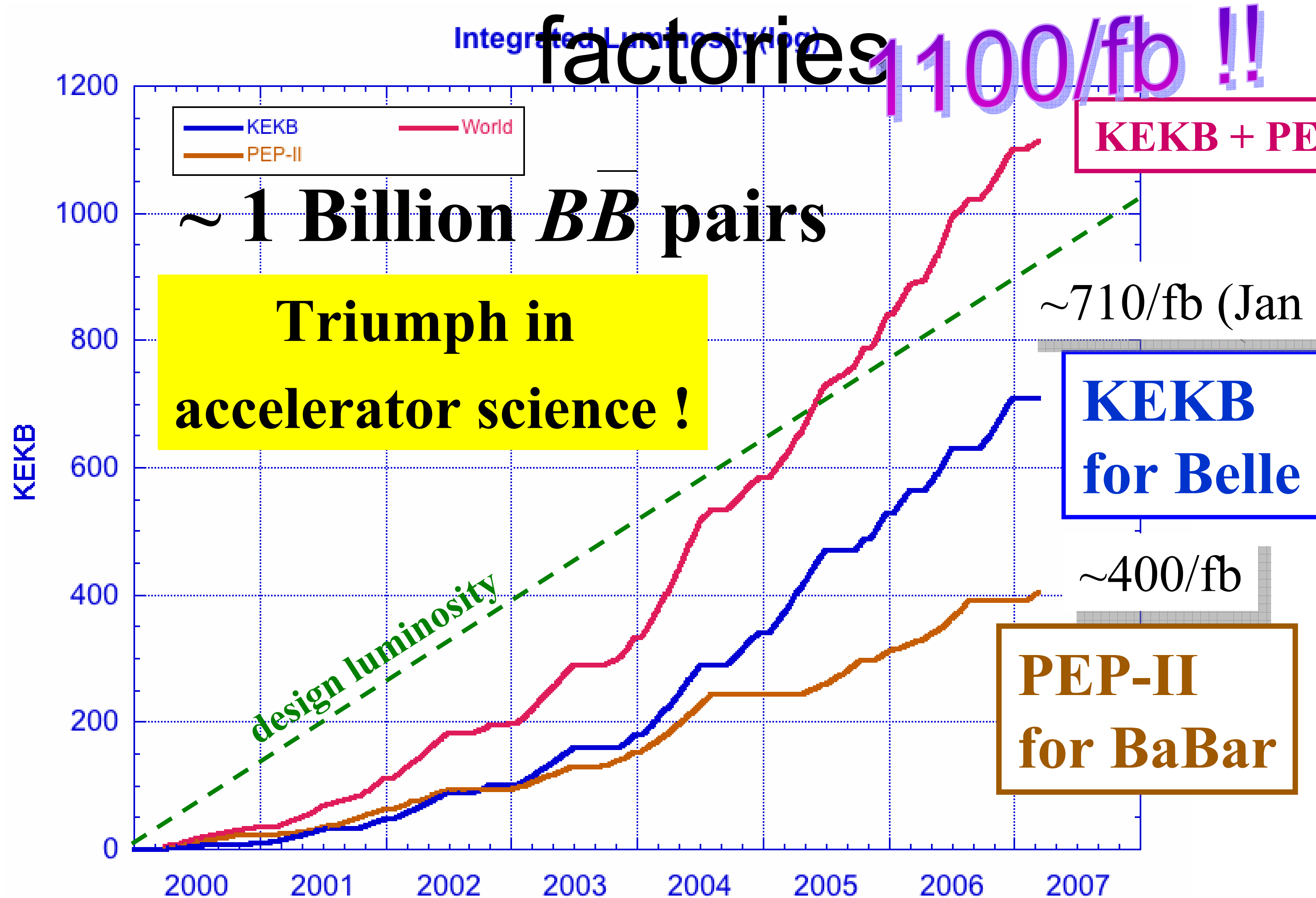
Overall result

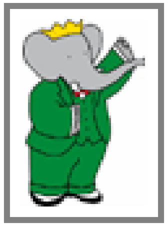


Indirect: $\gamma = [59^{+9}_{-4}]^\circ$ Combined: $\gamma = [62^{+38}_{-24}]^\circ$

Youngjoon Kwon

Integrated luminosity at B factories





M.Hazumi

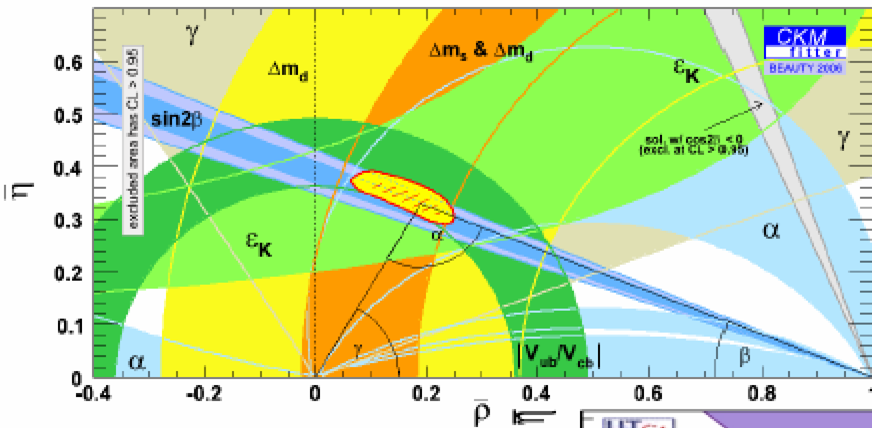
Overall CKM agreement

$S(t)(B^0 \to \psi K_S) \sim 70\%$

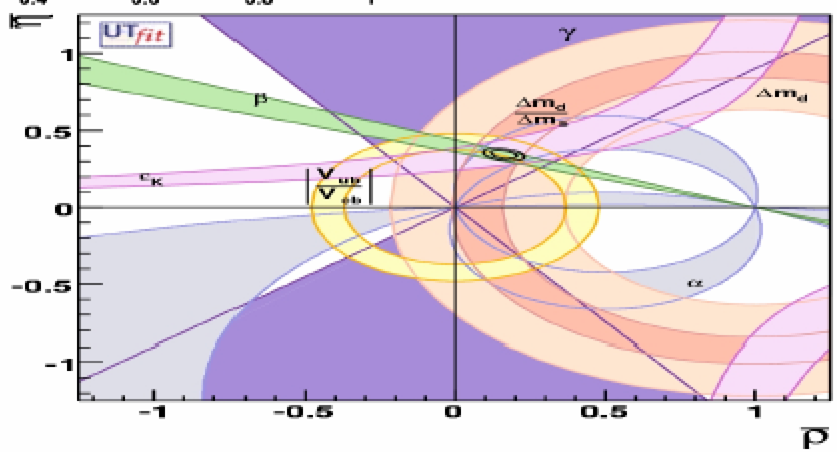
$\epsilon_K (K_L \to \pi\pi) \sim 10^{-3}$

BOTH Accounted by the KM phase!!

Frequentist



Bayesian



Conclusion is the same:

All measurements agree with SM picture of CKM matrix within errors

Celebration II: A beautiful theory paper which not only suggested the need for the 3rd family, before the discovery of charm and tau, its framework is vindicated in detail through exhaustive experimentation ~35 years later!!

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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.

And of course we must not forget the C!

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

We present here an analysis of leptonic decays based on the unitary symmetry for strong interactions, in the version known as "eightfold way,"[1] and the V-A theory for weak interactions.[2,3] Our basic assumptions on J_μ, the weak current of strong interacting particles, are as follows:

(1) J_μ transforms according to the eightfold representation of SU_3. This means that we neglect currents with $\Delta S = -\Delta Q$, or $\Delta I = 3/2$, which should belong to other representations. This limits the scope of the analysis, and we are not able to treat the complex of K^0 leptonic decays, or $\Sigma^+ \to n + e^+ + \nu$ in which $\Delta S = -\Delta Q$ currents play a role. For the other processes we make the hypothesis that the main contributions come from that part of J_μ which is in the eightfold representation.

(2) The vector part of J_μ is in the same octet as the electromagnetic current. The vector contribution can then be deduced from the electromagnetic properties of strong interacting particles. For $\Delta S = 0$, this assumption is equivalent to vector-

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Should 10% tests be good enough?

Vital Lessons from our past

- ***LESSON # 1: Remember ε_K***
- **Its extremely important to reflect on the severe and tragic consequences if**

Cronin et al had decided in 1963 that O(10%) searches for ε were good enough!

Imagine what an utter disaster for our field that would have been.

Note also even though CKM-CP-odd phase is O(1) (as we now know)
in the SM due to this O(1) phase only in B-physics we saw large effects…
in K (miniscule), D(very small), t(utterly negligible).

Understanding the fundamental SM parameters to accuracy only of O(10%) would leave us extremely vulnerable …..Improvement of our understanding should be our crucial HOLY GRAIL!

Lesson #2

Remember m_ν

Just as there was never any good reason for m_ν =0 there is none for BSM-CP-odd phase not to exist

$\Delta m^2 \sim 1 eV^2$ ~ 1980 -> $\Delta m^2 \sim 10^{-4} eV^2$ …'97

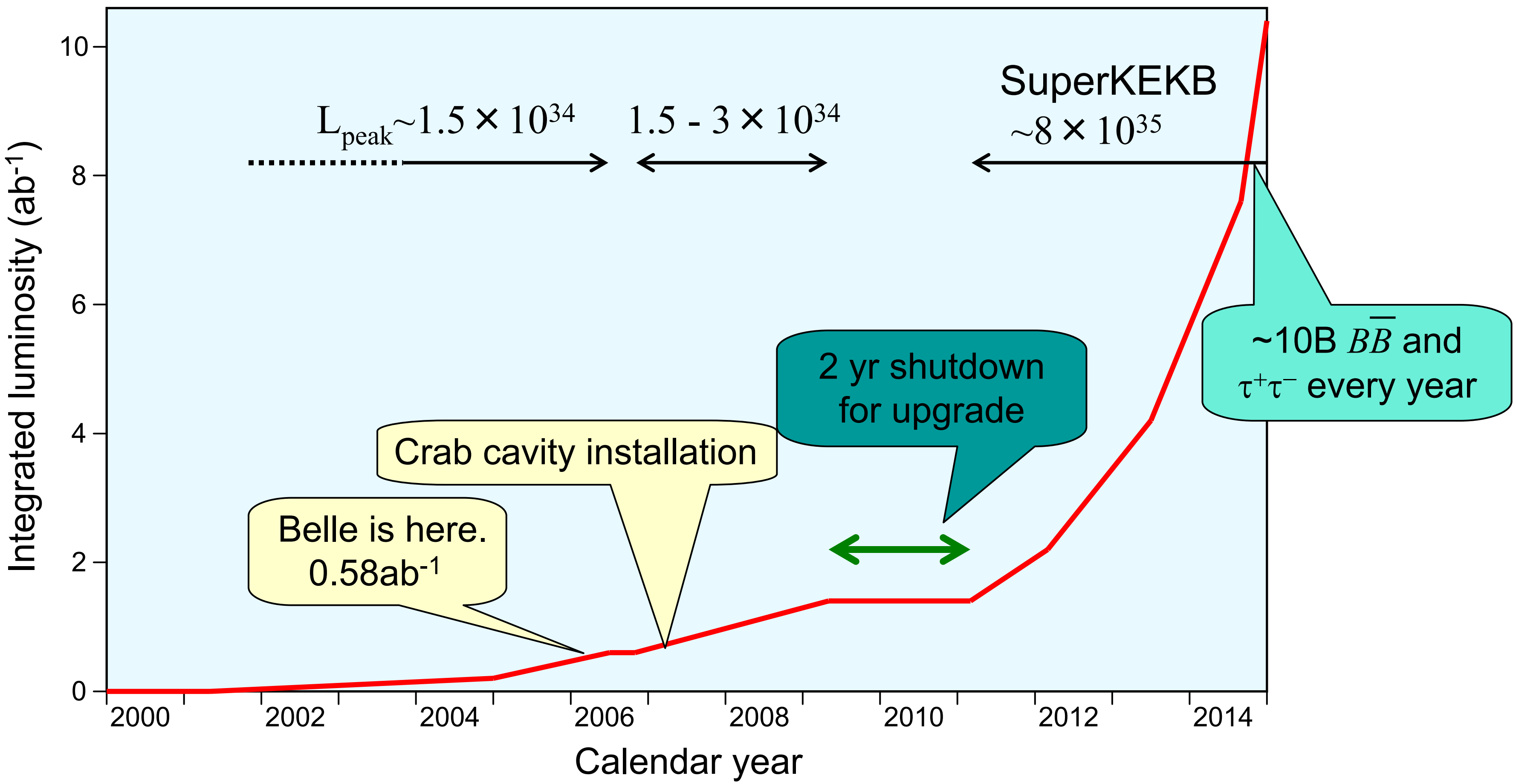
Osc. Discovered….

Similarly for BSM-CP-odd phase, we may need to look for much smaller deviations than the current O(10%)

demanding precision from expt. & theory

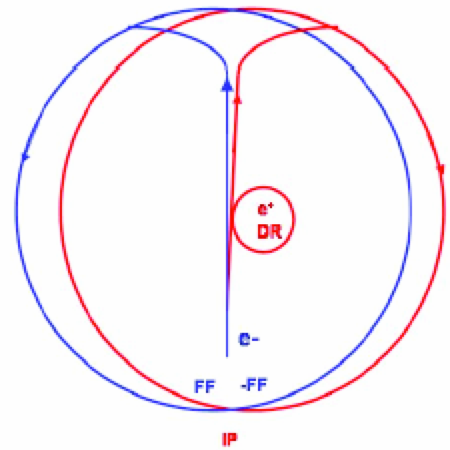
Prospects for improved exptal precision

Proposed schedule



SuperB @ INFN

	PEP-II	SuperB
σ_z	1cm	1cm
$\theta_{1/2}$	0	25 mrad
σ_x	100 μm	2.7 μm
σ_z^{Eff}	1cm	40 μm
β_v	0.8 cm	80 μm
σ_v	4 μm	12 nm
ξ_v	0.07	< 0.07
$\mathcal{L}$	$\sim 10^{34}$	$\sim 10^{36}$



Aaron Roodman @DPF06

SUMMARY on UTA

HOLY GRAIL

Angle	NOW (1/ab)	'09 (2/ab)	ITE
$\beta(\phi_1)$	4°%	$\sim 3.5^\circ$%	$\lesssim 1^\circ$%
$\alpha(\phi_2)$	$\approx 12^\circ$%	$\sim 9^\circ$%	$\sim$ few$^\circ$%
$\gamma(\phi_3)$	$\approx 50^\circ$%	$\simeq 25^\circ$%	$\sim 0.1^\circ$%

← EXPT. ERROR →

SBF is ESSENTIAL

Prospects for improved lattice calculations

~25 years of B_K

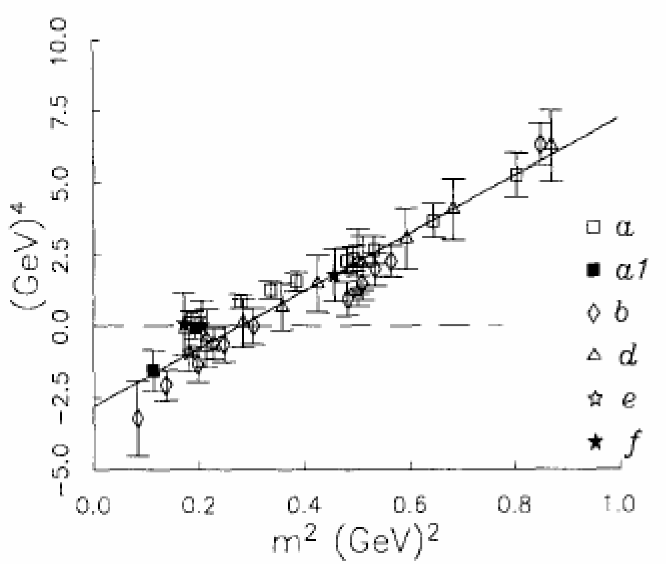


FIGURE 4
The amplitude $\langle \bar{K}^0 | (\Delta s = 2)_{LL} | K^0 \rangle \times 10^2$ vs. m^2. The solid line is a naive (uncorrelated) fit to the data.

$\langle \bar{K}^0 | (\Delta s = 2)_{LL} | K^0 \rangle$ with Wilson fermions has been proposed in Ref. 32. One starts by writing the CPTh form for the matrix elements of the continuum (physical) operator and for its Wilson lattice counterpart:

$$\langle \bar{K}^0 | (\Delta s = 2)_{LL} | K^0 \rangle^{cont} = \gamma (p_K \cdot p_{\bar{K}}) + \cdots$$
$$\langle \bar{K}^0 | (\Delta s = 2)_{LL} | K^0 \rangle^{latt} = \alpha + \beta m^2 + \gamma' (p_K \cdot p_{\bar{K}}) + \cdots, \qquad (8)$$

where the α and β terms in the lattice amplitude (and the change from γ to γ') are due to "bad" chirality operators such as $O'_\pm$ which have not been correctly removed by perturbation theory. Note that for K, $\bar{K}$ at rest, $p_K \cdot p_{\bar{K}} = m^2$; while for the crossed amplitude $\langle \bar{K}^0 \bar{K}^0 | (\Delta s = 2)_{LL} | 0 \rangle$, $p_K \cdot p_{\bar{K}} = -m^2$. Both the original $K^0 - \bar{K}^0$ amplitude and the crossed amplitude are then computed at rest on the lattice for various values of m, and the γ' term is extracted by a fit to the data. Finally, with the assumption $\gamma \simeq \gamma'$ (see below for a critique), the order m^2 term in the continuum ampli-

Bernard & A.S.
Lattice '88

Chiral Symmetery & fine tuning

$$\Delta S = 2 \quad (\bar{s}\gamma_{\mu L} d)^2 \equiv O^{cont}_{LL} \Rightarrow (V-A)\times(V-A)$$

$$O^{cont}_{LL} \Rightarrow \left(1 + C_{LL}\frac{g^2}{16\pi^2} \cdots\right) O^{latt}_{LL} + C_{PP}\frac{g^2}{16\pi^2}\, P\times P + \cdots$$

WRONG Chirality

ie lattice artefact

$$\langle K | O_{LL} | \bar{K} \rangle \xrightarrow[m_q \to 0]{} 0 \; ; \quad \langle K | P\times P | \bar{K} \rangle \xrightarrow[m_q \to 0]{} \text{Const}$$

Accurate evaluation of O_{LL} requires precise knowledge of C's
-> SEARCHING FOR A NEEDLE IN A HAYSTACK

ΔS=1, a deathbed w/o chiral symmetry

e.g. $(\bar{s}\gamma_{\mu L} d)(\bar{u}\gamma_{\mu L} u)$

MIXING WITH LDO

$\sim \frac{\bar{s}d}{a^3}$; $\sim \frac{\bar{s}\gamma_5 d}{a^3}$

DEATH-BED

MIXING WITH DIM 6 OPS of wrong χ

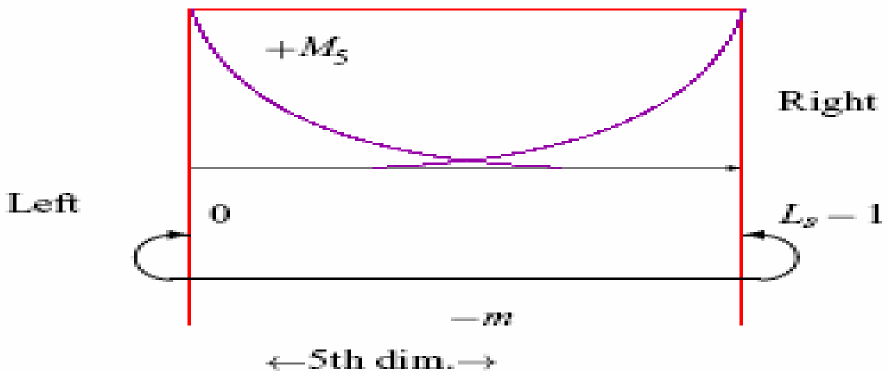
similar to $\Delta S=2$

UPHILL TASK

EXACT CHIRAL SYMMETRY ON THE LATTICE

Conventional fermions do not preserve chiral-flavor symmetry on the lattice (Nielsen - Ninomiya Theorem) $\Rightarrow \Delta S = 1, \Delta I = 1/2$ case mixing with lower dim. (power-divergent) operators & or mixing of 4-quark operators with wrong chirality ones makes lattice study of $K - \pi$ physics virtually impossible.

Domain Wall Fermions (Kaplan, Shamir, Narayanan and Neuberger)

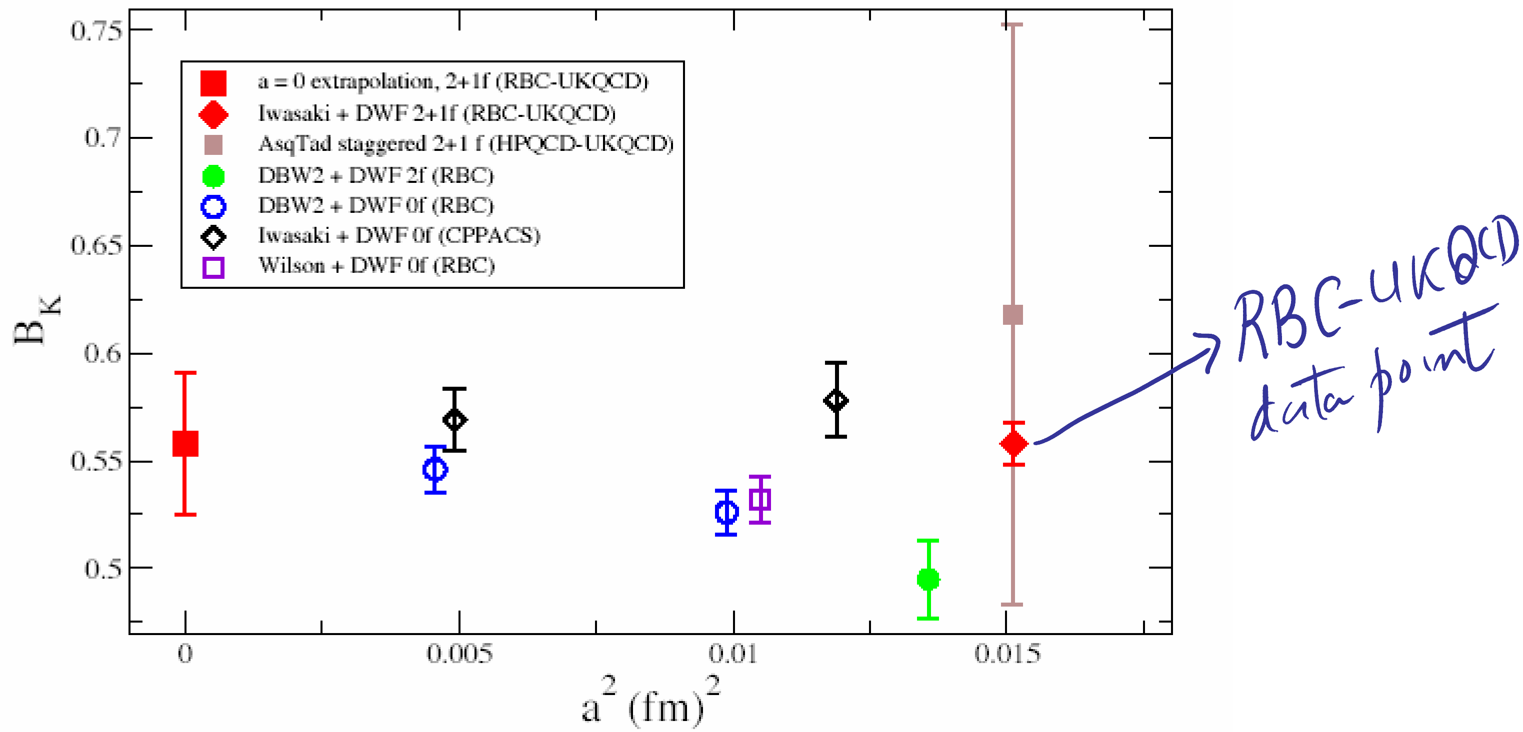


Practical viability of DWF for QCD demonstrated (96-97) Tom Blum & A. S.
Chiral symmetry on the lattice, $a \neq 0$! Huge improvement

$\Rightarrow$ Now widespread use at BNL and elsewhere

RBC-UKQCD's 2+1 dynamical DWQ
hep-ph/0702042

Final Result for B_K



$B_K^{(\overline{MS})}$(2 GeV) = 0.557(12)(29) extrapolated to continuum

~2% (Stat); ~5% syst

BROOKHAVEN
NATIONAL LABORATORY

HEP
office of high energy physics

Brief (~25 years) History of B_K

, ~'83 DGH use K^+ lifetime + LOChPT + SU(3)->
B_K ~0.33… no error estimate, no scale dependence… UNCONTROLLABLE APPROXIMATION

~'84 Lattice method for WME born…many attempts & improvements for B_K evaluations

~'98 JLQCDstaggered B_K (2GeV)= 0.628(42)quenched(~110).

~'97 1st B_K with DWQ(T.Blum&A.S),0.628(47) quenched.

~'01 RBC B_K with DWQ, quenched=0.532(11) quenched

~'05 RBC , nf=2, dyn. DWQ, B_K =0.563(21)(39)(30)

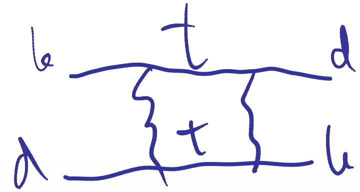
~'06 Gimnez et al (HPQCD; stagg.) 2+1, B_K =0.618(18)(19)(30)(130)

~07,RBC-UKQCD DWQ 2+1 …..0.557(12)(29)

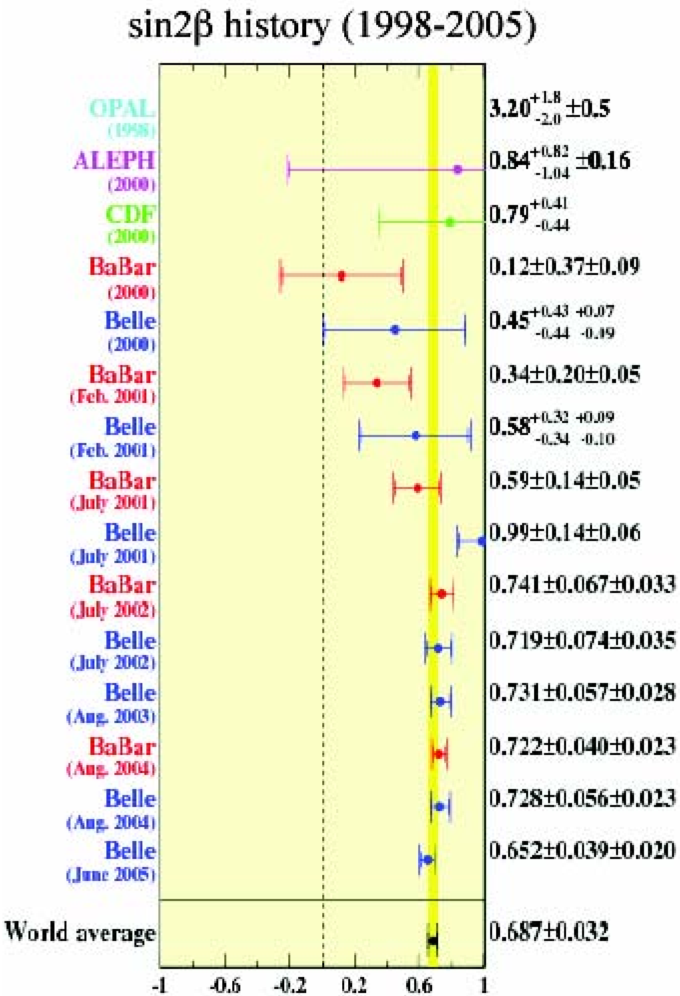
DWQ lower B_K -> requiring larger CKM-phase

~'08 Target 2+1 dyn. DWQ, B_K with total error 5%

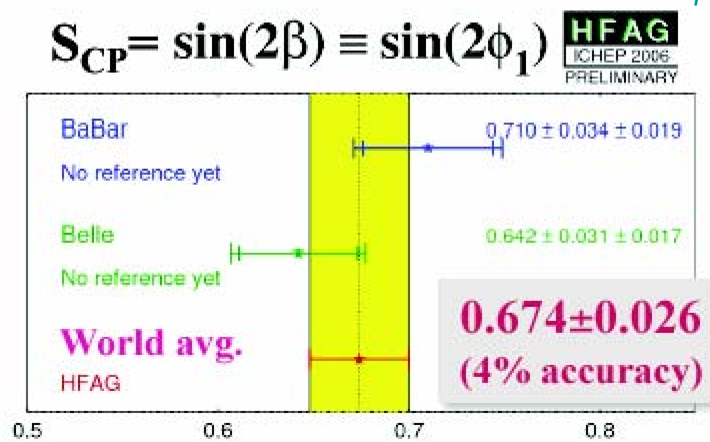
Measurement of β(φ₁)

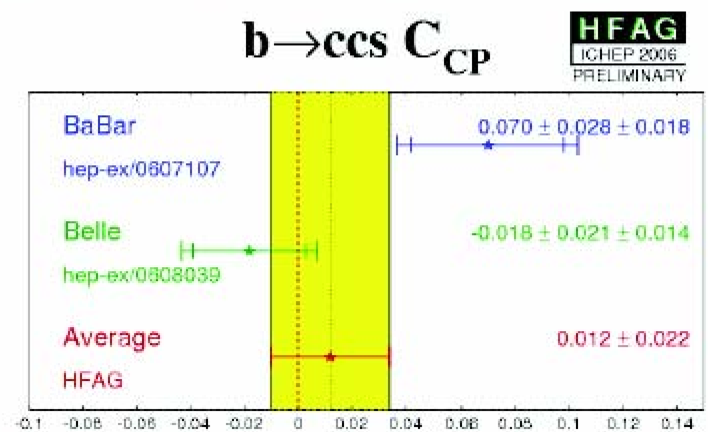


$10+5K M-y



2006 BaBar + Belle





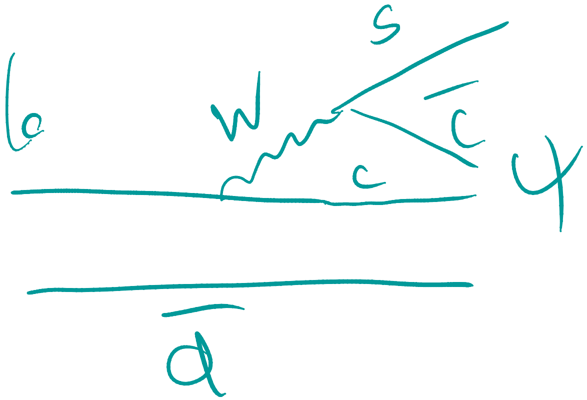
SM $\sin 2\beta = .79 \pm .10$

Youngjoon Kwon

Tantalizing (possible) signs of a BSM-CP phase

$$\Delta S \equiv S_{penguin} - S_{\psi K_S} = O(\lambda^2)$$

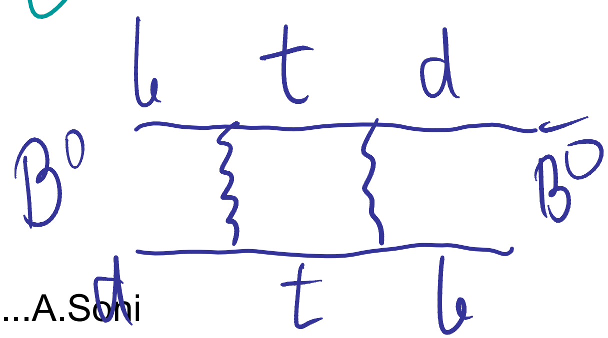
$$S^{Decay}_{peng} \simeq O(\lambda^2) \sim few\%$$



$$S^{Decay}_{\psi K_S} = 0$$

Grossman & Worah PLB'97;
London and A.S. PLB'97

OSC is COMMON



Testing the SM with penguin dominated modes

- $\Delta S = C_{MD}\ O(\lambda^2)$, expect $C_{MD} \sim O(1)$

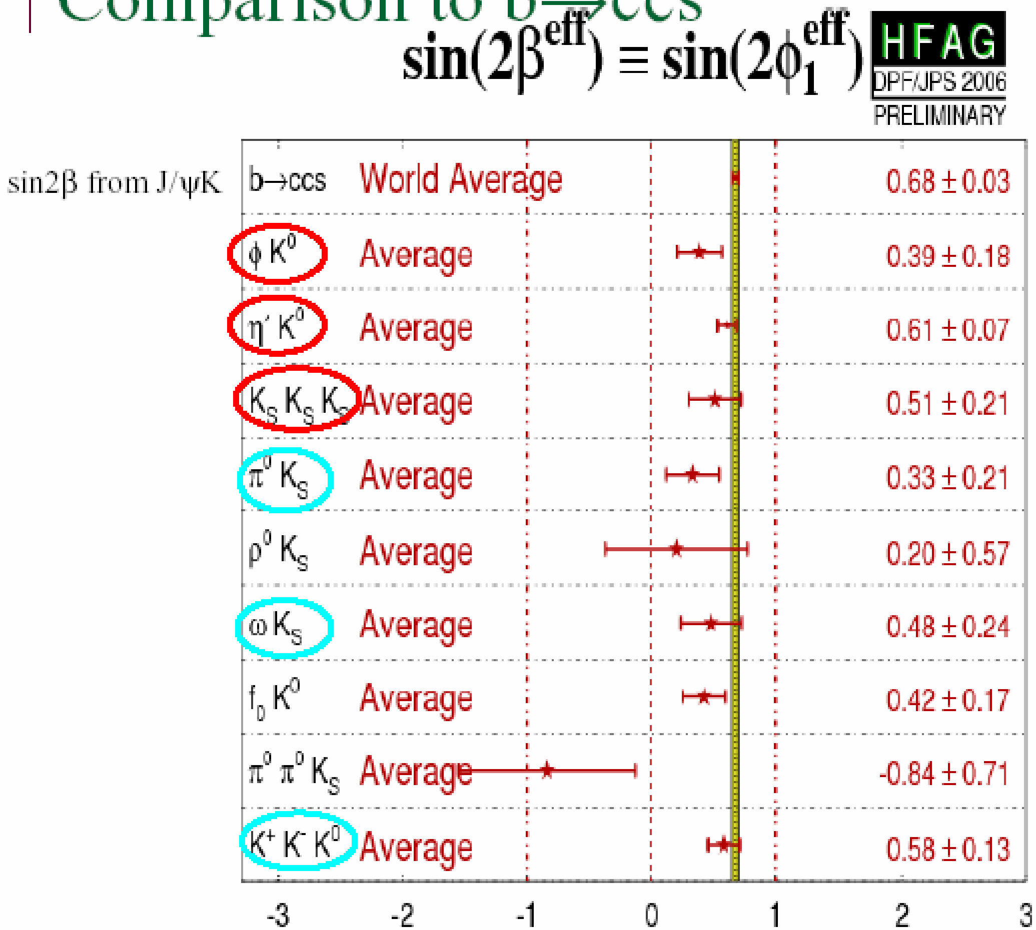
- Sigificant deviation from this expectation is a sign of BSM-CP-odd phase!
- Unfortunately C_{MD} is a (QCD) model dependent coefficient

TABLE I: Some expectations for ΔS in the cleanest modes.

Mode	QCDF+FSI [20, 21]	QCDF [23]	QCDF [24]	SCET [25]
$\eta' K^0$	$0.00^{+0.00}_{-0.04}$	0.01 ± 0.01	0.01 ± 0.02	-0.019 ± 0.009 -0.010 ± 0.001
ϕK^0	$0.03^{+0.01}_{-0.04}$	0.02 ± 0.01	0.02 ± 0.01	
$K_S K_S K^0$	$0.02^{+0.00}_{-0.04}$			

CLEANEST MODES

Comparison to b→$c\bar{c}s$



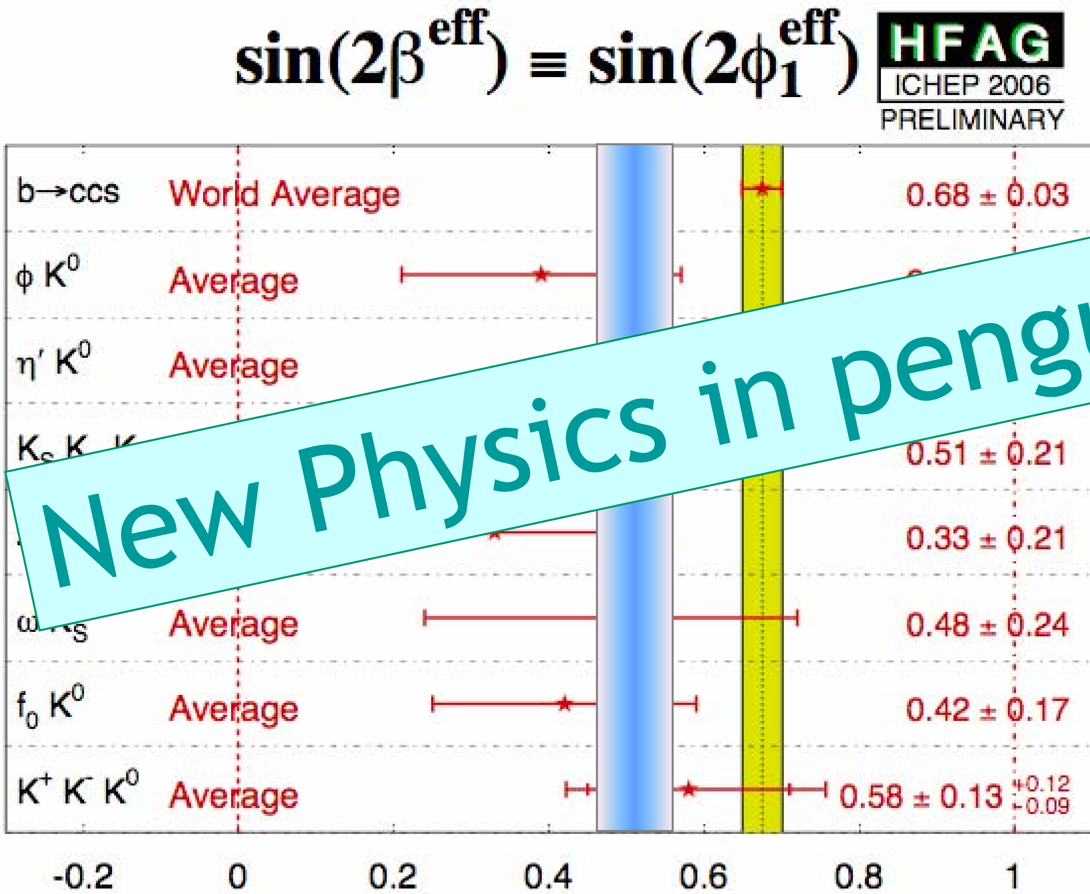
INTRIGUING!

NP?
More
data
needed!

SIGN of ΔS is (almost) systematically opposite to Theory

Youngjoon Kwon; c also Matthias Neubert

Current situation



New Physics in penguin processes?

- Reference value reduced to 0.68
- A… …odes increased to

0.52 ± 0.05

- Deviation reduced to 2.8σ ☹

oni

Matthias Neubert

On the issue of adding many modes
EXTRACT from David London + A.S PLB407, 61 (1997)
where $\eta' K_S$ and many peng dominated modes were 1st discussed.

To sum up this point, CP asymmetries in $b \to s$ penguins do indeed measure the CP angle β. The tree contributions to these decays are quite small, at most a few percent. It is therefore possible to add up the measured CP asymmetries in all these modes to obtain a larger signal. If the value of β extracted in this way differs by more than about 10% from that found in ΨK_s, then it is a clear signal of new physics, with new phases, in the $b \to s$ FCNC. If the difference is less than about 10%, it could in principle be due to the tree contamination. However, this can be checked by using only the final states ϕK_s and $\eta' K_s$ (to a very good approximation).

However, call from Stockholm will demand conclusive evidence for ΔS>0.10 in several separate modes

Although, at the moment it is not a conclusive effect,
it may well become a serious blunder on the part
of experimentalists to ignore it!
We can try learn some lessons from history.

It is extremely important to understand
that basically it is a very good test of the SM.

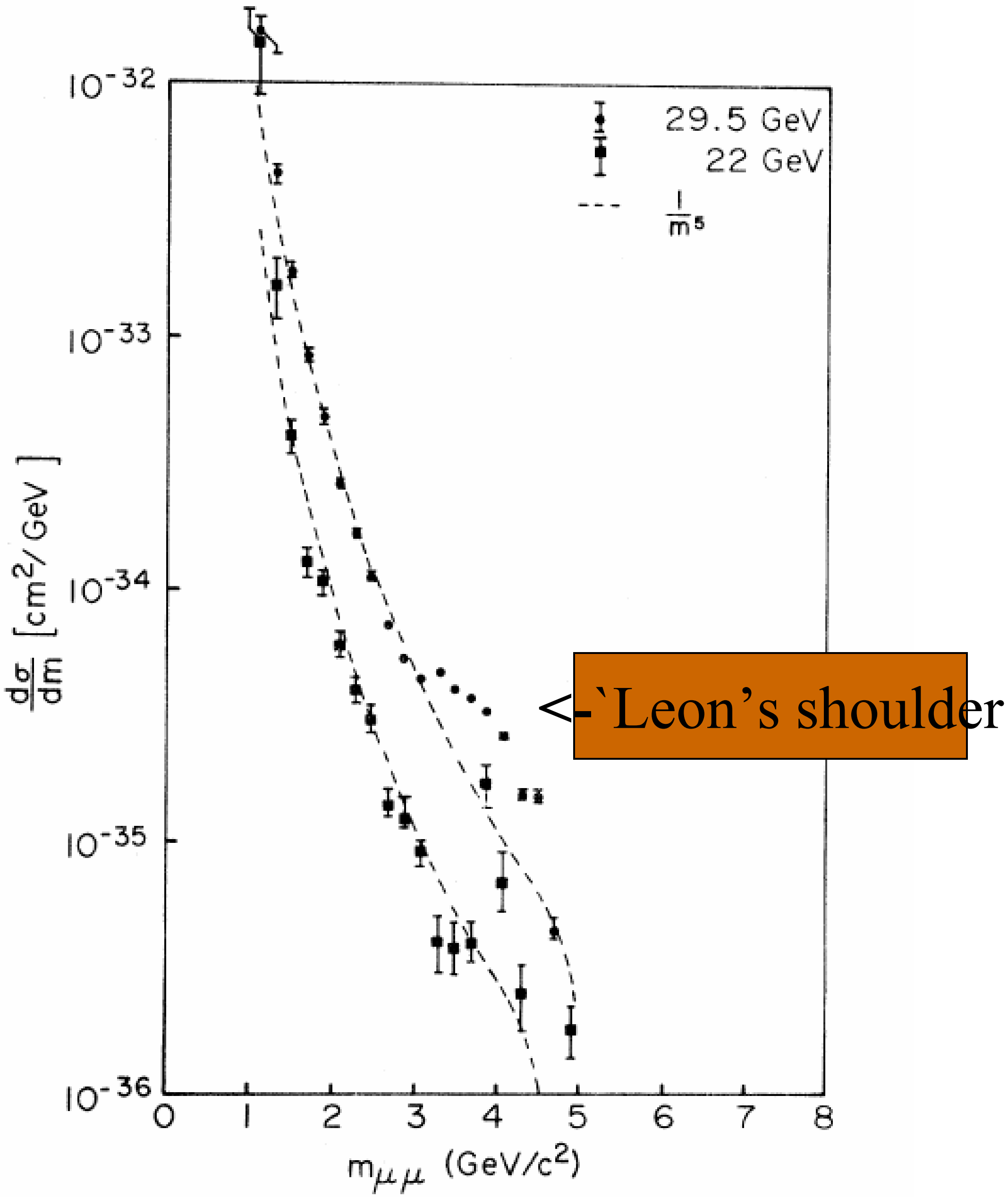


FIG. 15. Experimental cross sections at two energies compared with a simple $1/m^5$ continuum.

Christenson,Hicks,Lederman,Limon,Pope & Zavattini
PRD 8,2016 '72

mass range of 3–5 GeV/c^2, there is a distinct excess of the observed cross section over the reference curve. If this excess is assumed (certainly not required) to be the production of a resolution-broadened resonance, the cross-section–branching-ratio production σB would be approximately 6×10^{-35} cm^2, subject to the cross-section uncertainties discussed above. Alternatively the excess may be interpreted as merely a departure from the overly simplistic (and arbitrarily normalized) $1/m^5$ dependence. In this regard, we should remark that there may be two entirely different processes represented here: a low-Q^2 part which has to do with vector mesons, tail of the ρ, bremsstrahlung, etc., and a core yield with a slower mass dependence, which may be relevant to the scaling argument discussed below.

The "heavy photon" pole that has been postulated[32] to remove divergence difficulties in quan-

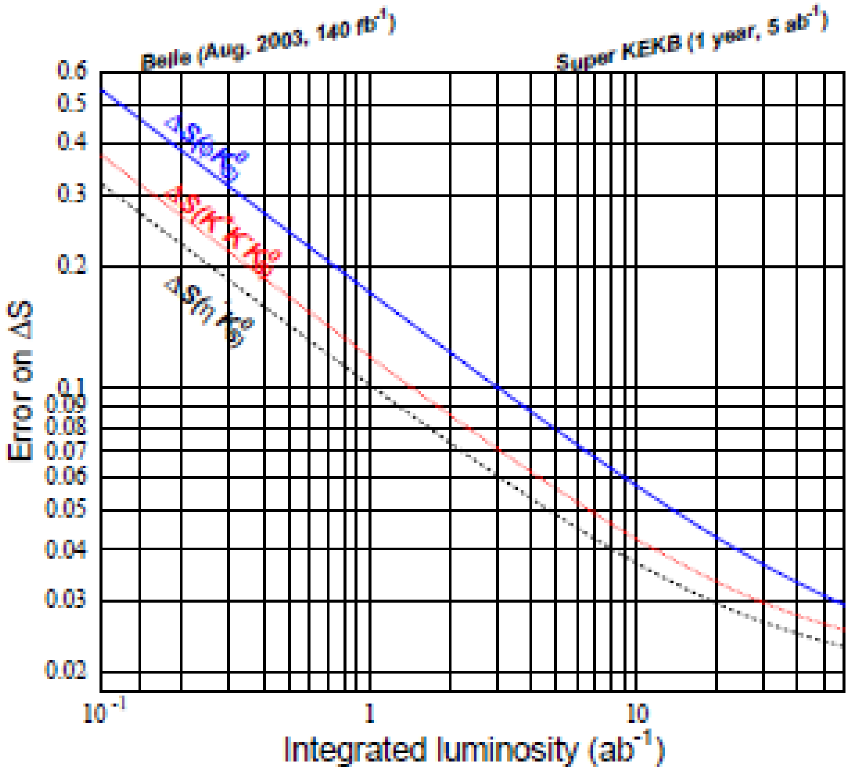
cles produced in the initial proton-uranium collision. In principle, these secondary particles could also create muon pairs. In this case, the observed spectrum would represent the inseparable product of the spectrum of the secondary particle and its own yield of muon pairs. In exploratory research of this kind this disadvantage is largely offset by the fact that the variety of initial states provides a more complete exploration of dimuon production in hadron collisions.

2. *Real Photons*

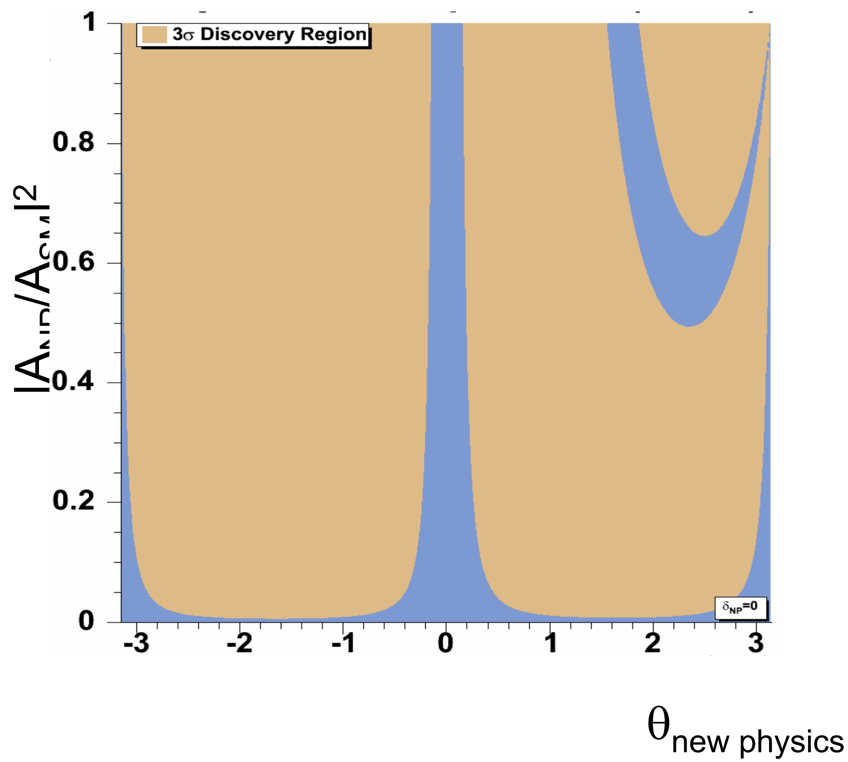
Real photons produced in the target (presumably from the decay of neutral pions) yield muon pairs by Bethe-Heitler or Compton processes. Estimates were made for the photon flux on the basis of pion-production models,[27,28] and this method of calculating the flux was checked against the experimental data of Fidecaro *et al.*[33] The argument

Sensitivity to new CP phases

Estimated error in the measurement of time dependent CP violation



Discovery region with 50 ab^{-1}



So far 3 numbers

- Expt [ε_K , B-mixing, b->ueν…] + Lattice WME -> $\sin 2\beta_{SM}$ =0.79+-0.10
- BF measurements [B -> "ψ" K_S]=0.674+-0.026
- BF measurements [B-> (φ, η'…) K_S]=0.52+-.05

- ***-> Deviations 2.8 -3.5 sigmas***

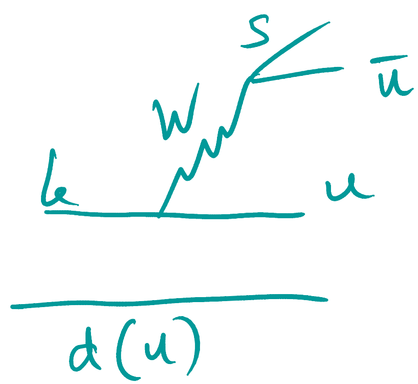
Last but quite significant #

$$A_{CP}(B^0 \to K^+\pi^-) = -9.7 \pm 1.2\,\%$$

$$A_{CP}(B^+ \to K^+\pi^0) = 4.7 \pm 2.6\,\%$$

$$\Delta A_{CP} = (14.4 \pm 2.9)\,\%$$

4th IMPORTANT #



CAVEAT

(Naively) SM predicts $\Delta A_{CP} \approx 0$

Summary so far

- The CKM-paradigm of CP violation accounts for the observed CP patterns to an accuracy ofabout 15%!
- Remarkably in the past few years several B-factories results exhibit 2.5 -3.5 σ deviations from the SM-CKM paradigm!!

WHODUNIT?

Honest answer &

- Don't really know (too many possibilities…)
- But theoretically the most interesting possibility is that we may be witnessing

  Dawning of the age of

"Warped Quantum Flavordynamics"

RANDALL+SUNDRUM '99

[FIG BY H DAVOUDIASL]

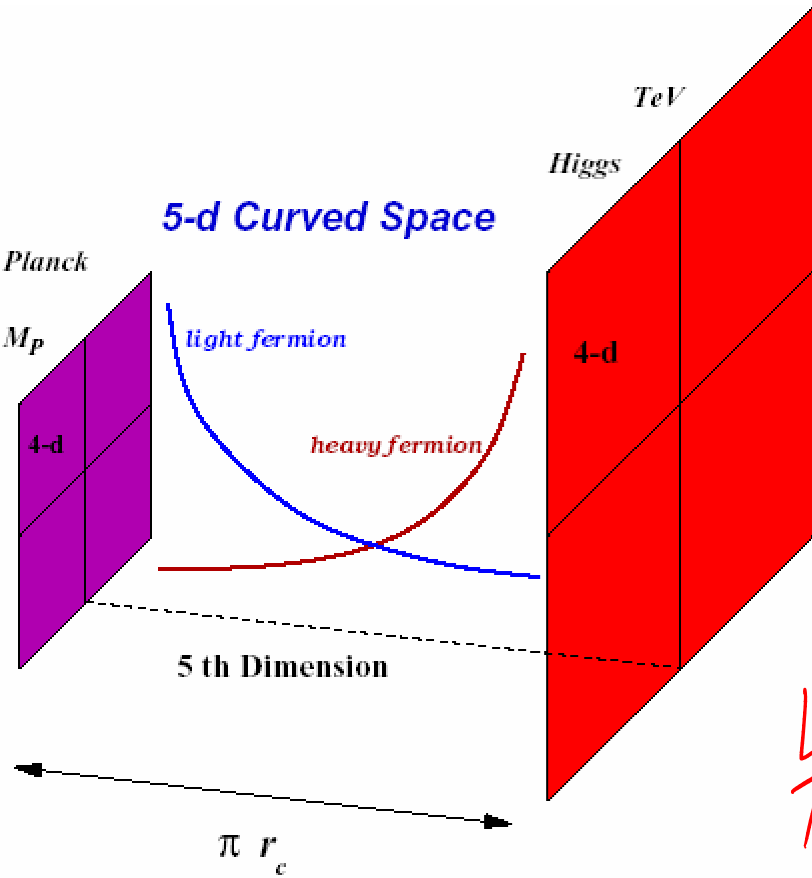


Figure 1: Warped geometry with flavor from fermion localization. The Higgs field resides on the TeV-brane. The size of the extra dimension is $\pi r_c \sim M_P^{-1}$.

$$ds^2 = e^{-2\sigma}\eta_{\mu\nu}\,dx^\mu dx^\nu - r_c^2\, d\phi^2$$

$$\langle H_4\rangle = e^{-\sigma}\langle H_5\rangle$$

TeV

M_P

$$\sigma = \underbrace{k r_c}_{\sim 12}\pi$$

Some other noteable effects

$B \to X_s\gamma$ branching fraction

NNLO TH $2.98 \pm .27 \times 10^{-4}$

~ 1.46

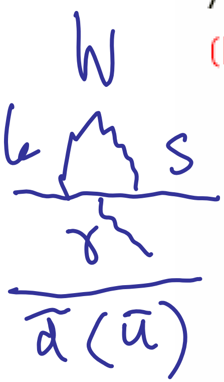
Average branching fraction for $E_\gamma > 1.6$ GeV

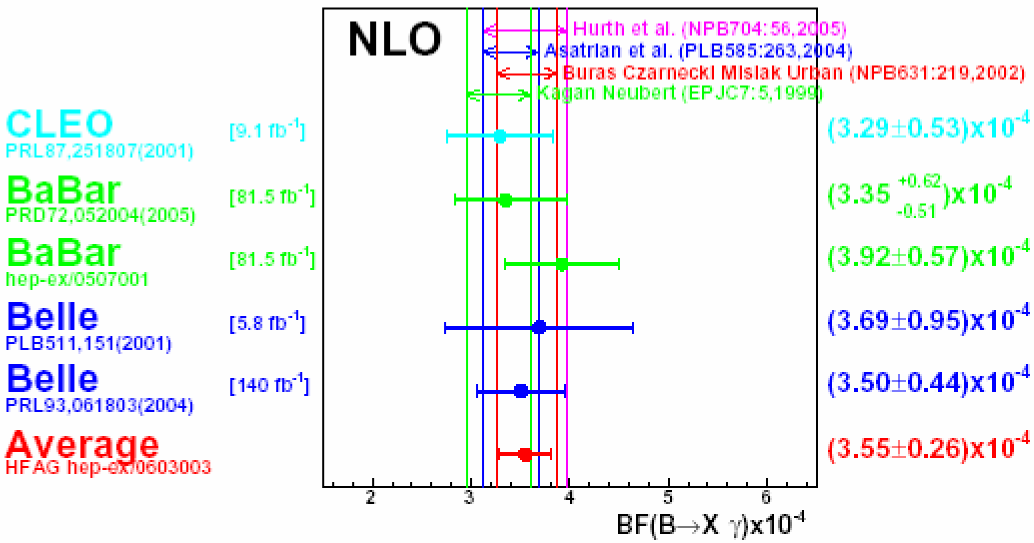
(Heavy Flavor Averaging Group (HFAG), hep-ex/0603003)

$$\mathcal{B}(B \to X_s\gamma;\, E_\gamma > 1.6\ \text{GeV}) = (355 \pm 24_{(\text{stat+sys})}\,{}^{+9}_{-10}(\text{shape}) \pm 3_{(d\gamma)}) \times 10^{-6}$$

M Neubert

M. MISIAK





- Very consistent with NLO SM, e.g., $(357 \pm 30) \times 10^{-6}$
- Many NLO SM calculations — theory error?

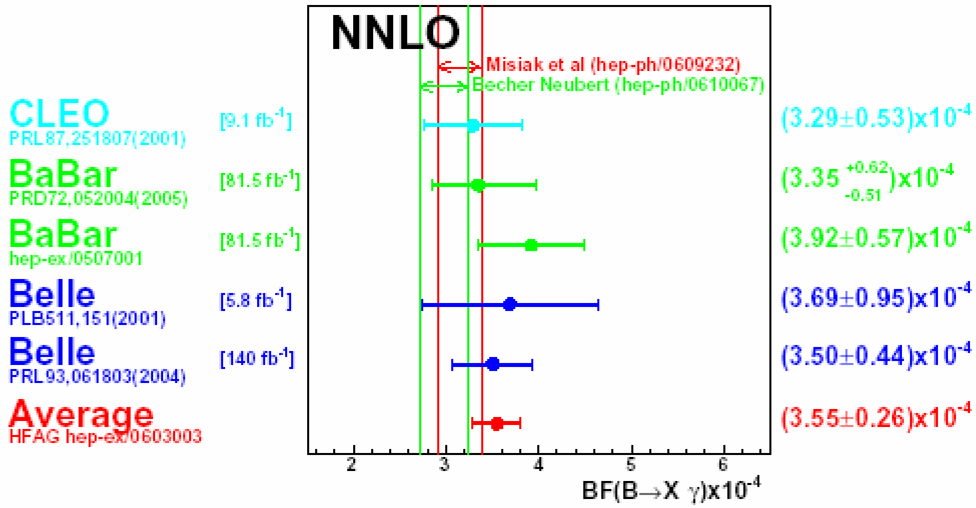
Mikihiko Nakao @ CKM06; c also Matthias Neubert

$B \to X_s\gamma$ branching fraction

with $\sim 2\times10^8$ $B\bar{B}$

Average branching fraction for $E_\gamma > 1.6$ GeV
(Heavy Flavor Averaging Group (HFAG), hep-ex/0603003)

$$\mathcal{B}(B \to X_s\gamma;\, E_\gamma > 1.6\ \text{GeV}) = (355 \pm 24_{(\text{stat+sys})}\, {}^{+9}_{-10}{}_{(\text{shape})} \pm 3_{(d\gamma)}) \times 10^{-6}$$



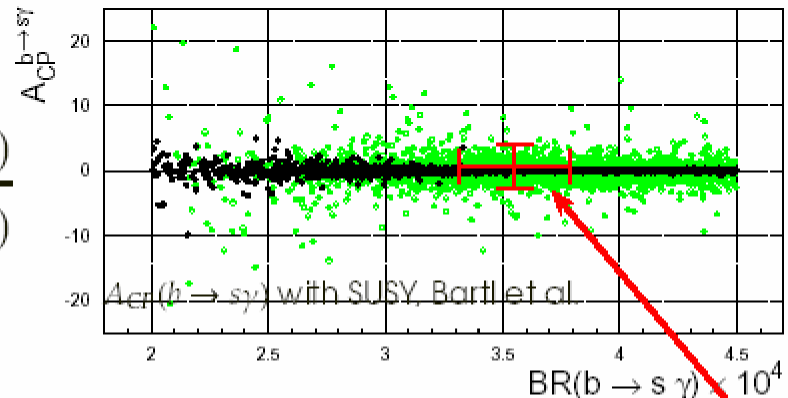
In view of theo. developments expt. stat error should be reduced by $\times 2-3$

- Very consistent with NLO SM, e.g., $(357 \pm 30) \times 10^{-6}$
- Many NLO SM calculations — theory error?
- Or slightly higher than first NNLO SM estimates?

Mikihiko Nakao @ CKM06 ; c also Matthias Neubert

Direct CP asymmetry

$$A_{CP} = \frac{\Gamma(b \to s\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma)}{\Gamma(b \to s\gamma) + \Gamma(\bar{b} \to \bar{s}\gamma)}$$



- Precisely measured: HFAG $A_{CP}(B \to X_s\gamma) = (5 \pm 36) \times 10^{-3}$
  Belle 140 fb^{-1}: $(2 \pm 50 \pm 30) \times 10^{-3}$, BaBar 82 fb^{-1}: $(25 \pm 50 \pm 15) \times 10^{-3}$
  but extremely small in SM: e.g., $A_{CP} = (4.2\,^{+1.7}_{-1.2}) \times 10^{-3}$ (T.Hurth et al)
  Only up to a few percent even in SUSY (with EDM constraints)
- BaBar 82 fb^{-1}: $A_{CP}(B \to X_{(s+d)}\gamma) = (-110 \pm 115 \pm 17) \times 10^{-3}$
  $b \to s\gamma$ and $b \to d\gamma$ are not separated — even smaller SM CPV (canceling)

$b \to s\gamma$ measurements from B factories — Mikihiko Nakao — p.14

Better A_{cp} highly desirable due to indications of 2HD

Mikihiko Nakao @ CKM06

Summary of CDF Results on B^0_s Mixing

A. Abulencia et al., hep-ex/0609040, accepted by Phys. Rev. Lett.

Observation of B_s Oscillations and precise measurement of Δm_s

$$\Delta m_s = 17.77 \pm 0.10\,(\text{stat.}) \pm 0.07\,(\text{syst.})\ \text{ps}^{-1}$$

Δm_s (SM) = 19.8 ± 3.5 Atwood + Soni PLB'01

Precision: 0.7% **Probability random fluctuation mimics signal: 8£10^{-8}**

IV EW '07: 18.6 ± 2.3 LUNGHI + AS

(2.83 THz, 0.012 eV)

USING Δm_d^{expt} & lattice info:

Most precise measurement of $|V_{td}/V_{ts}|$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007\,(\text{exp.})^{+0.0081}_{-0.0060}\,(\text{theo.})$$

Kevin Pitts

Two Higgs Doublet Models with Natural Flavor Conservation

The charged Higgs boson interactions with the quark sector are governed by the Lagrangian

$$\mathcal{L} = \frac{g}{2\sqrt{2}M_W} H^{\pm} \left[V_{ij} m_{u_i} A_u \bar{u}_i (1-\gamma_5) d_j + V_{ij} m_{d_j} A_d \bar{u}_i (1+\gamma_5) d_j \right] + h.c.\,,$$

where g is the usual SU(2) coupling constant and V_{ij} represents the appropriate CKM element. In model I, $A_u = \cot\beta$ and $A_d = -\cot\beta$, while in model II, $A_u = \cot\beta$ and $A_d = \tan\beta$, where $\tan\beta \equiv v_2/v_1$ is the ratio of vev

Part of SUSY

T2HDM: 2HiggsDM for the top quark

[see Das,Kao('96);Kirers,Wu,AS('99)…]

- **2nd doublet couples only to top (1st doublet**

to all else), so that with $V_2/V_1 >> 1$, natural

way to get a very heavy top

T2HDM Possibly disproves SUSY?

$$\mathcal{L}_Y = -\bar{L}_L \phi_1 E l_R - \bar{Q}_L \phi_1 F d_R - \bar{Q}_L \tilde{\phi}_1 G \mathbf{1}^{(1)} u_R - \bar{Q}_L \tilde{\phi}_2 G \mathbf{1}^{(2)} u_R + \mathrm{H.c.},$$

Here ϕ_1 are the two Higgs doublets; E, F and G are 3 X 3 Yukawa matrices giving masses respectively to the charged letptons, the down and up type quarks; $\mathbf{I}^{(1)} \equiv diag(1,1,0)$ and $\mathbf{I}^{(2)} \equiv diag(0,0,1)$ are the two orthogonal projectors onto the 1st two and third family respectively. Q_L and L_L are the usual left-handed quark and lepton doublets.

(b) T2HDM should be viewed as LEET that parametrizes through the yukawa interactions some high energy dynamics which generates the top quark mass as well as the weak scale...

(c) In addition to largish $\tan\beta$ the model has restrictive FCNC (since it belongs to type III) amongst only the up-type

H^{+-} phenomenology in T2HDM

H^{+-} interactions with U_R and D_L

$$\frac{g_2 m_c \tan\beta}{\sqrt{2} m_W}\begin{pmatrix} \xi'^* V_{td} & \xi'^* V_{ts} & \xi'^* V_{tb} \\ \xi^* V_{td} - V_{cd} & \xi^* V_{ts} - V_{cs} & \xi^* V_{tb} - V_{cb} \\ V_{td}\cot^2\beta/\epsilon_{ct} + \epsilon_{ct}\xi V_{cd} & V_{ts}\cot^2\beta/\epsilon_{ct} + \epsilon_{ct}\xi V_{cs} & V_{tb}\cot^2\beta/\epsilon_{ct} \end{pmatrix}$$

EXTENSIVE ANALYSIS: LUNGHI + A.S (TBP)

IMP. PARAMETERS: $m_{H^\pm}$, $\tan\beta$, $\xi = |\xi| e^{i\varphi_\xi}$, $\bar{\rho}$, $\bar{\eta}$

CLEAN INPUT PROCESSES

$|V_{ub}/V_{cb}|$, $\Delta M_{B_s}/\Delta M_{B_d}$, $a_{\psi K}$, ε_K, $B \to X_s\gamma$, $B \to \tau\nu$

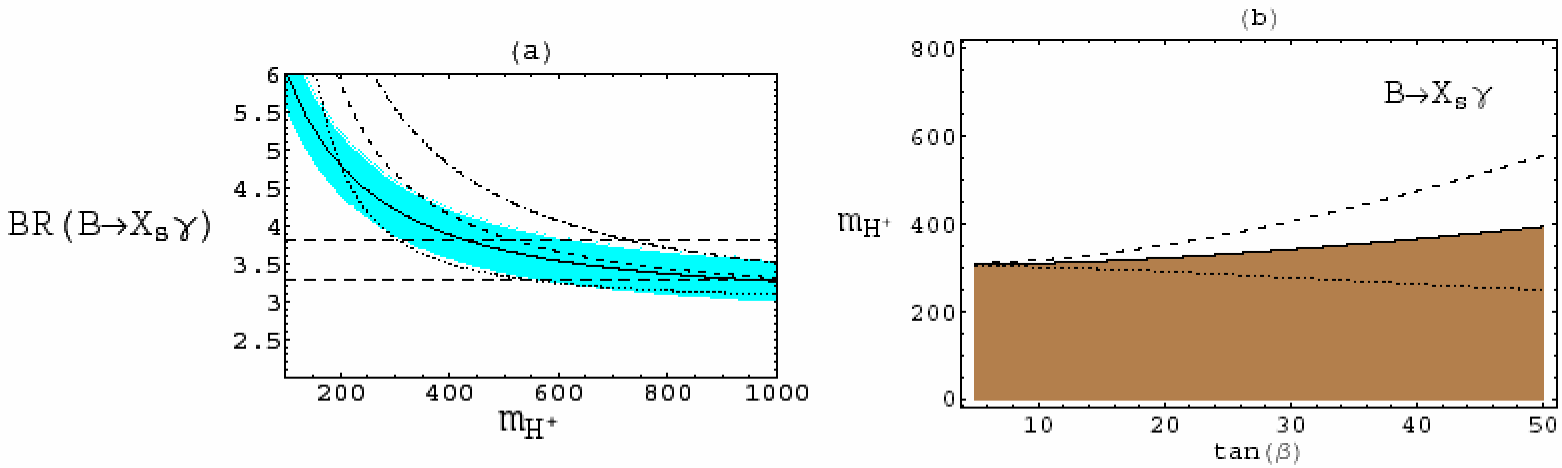


Figure 5: **Plot a.** $m_{H^\pm}$ dependence of the branching ratio $B \to X_s\gamma$ in units of 10^{-4}. Solid, dashed, dotted and dotted-dashed lines correspond to $(\tan\beta, \xi) = (10, 0)$, $(50, 0)$, $(50, 1)$ and $(50, -1)$, respectively. There is no appreciable dependence on ξ'. The two horizontal dashed lines are the experimental 68%C.L. allowed region. The blue region represents the theory uncertainty associated to the solid line (similar bands can be drown for the other cases). **Plot b.** Portion of the $(\tan\beta, m_{H^\pm})$ plane excluded at 68%C.L. by the $B \to X_s\gamma$ measurement. The shaded area corresponds to $\xi = 0$. The dotted and dashed lines show how this region changes for $\xi = 1$ and -1, respectively.

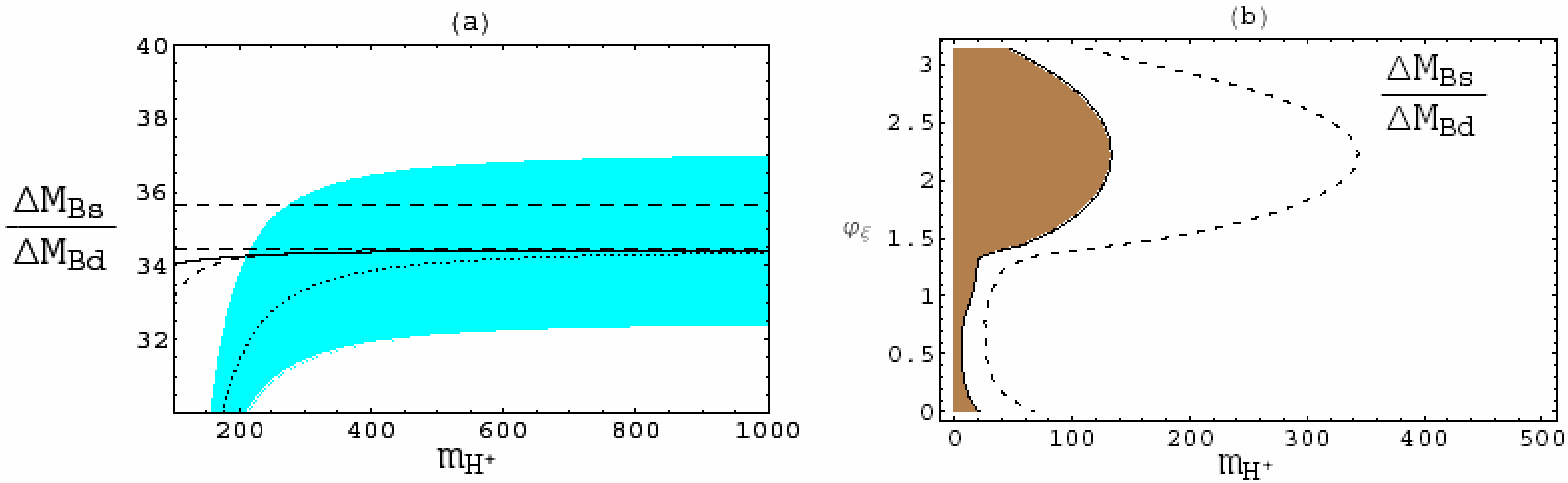


Figure 10: **Plot a.** $m_{H^\pm}$ dependence of the T2HDM contributions to $\Delta m_{B_{(s)}}/\Delta m_{B_{(d)}}$. See the caption in Fig. 9. **Plot b.** Excluded region in the $(\varphi_\xi, m_{H^\pm})$ plane. The solid and dashed contours correspond to $\tan\beta = 30$ and 50, respectively.

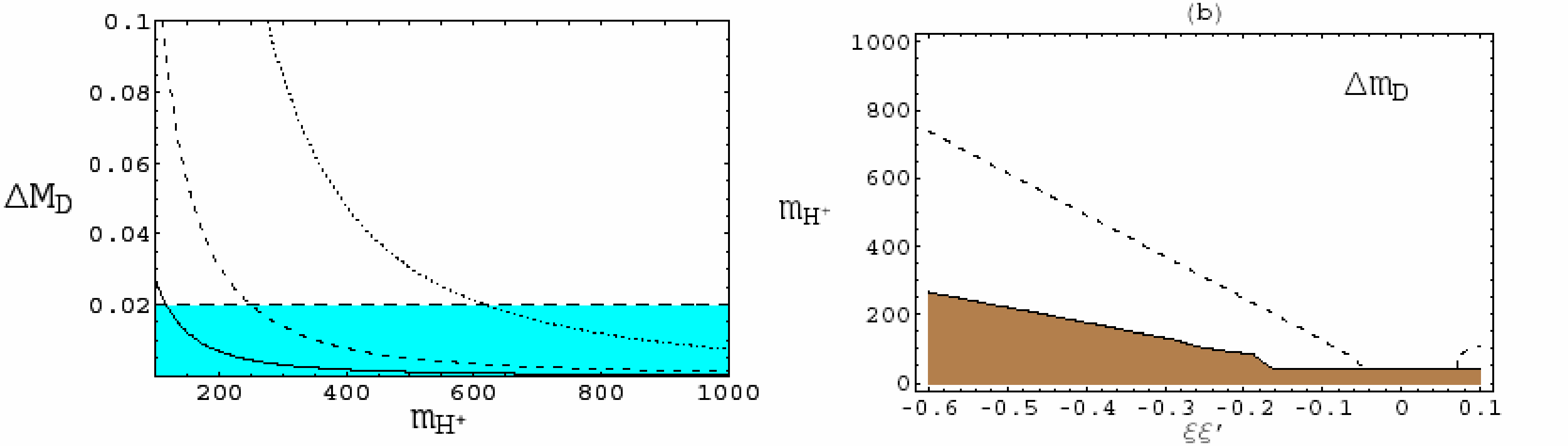
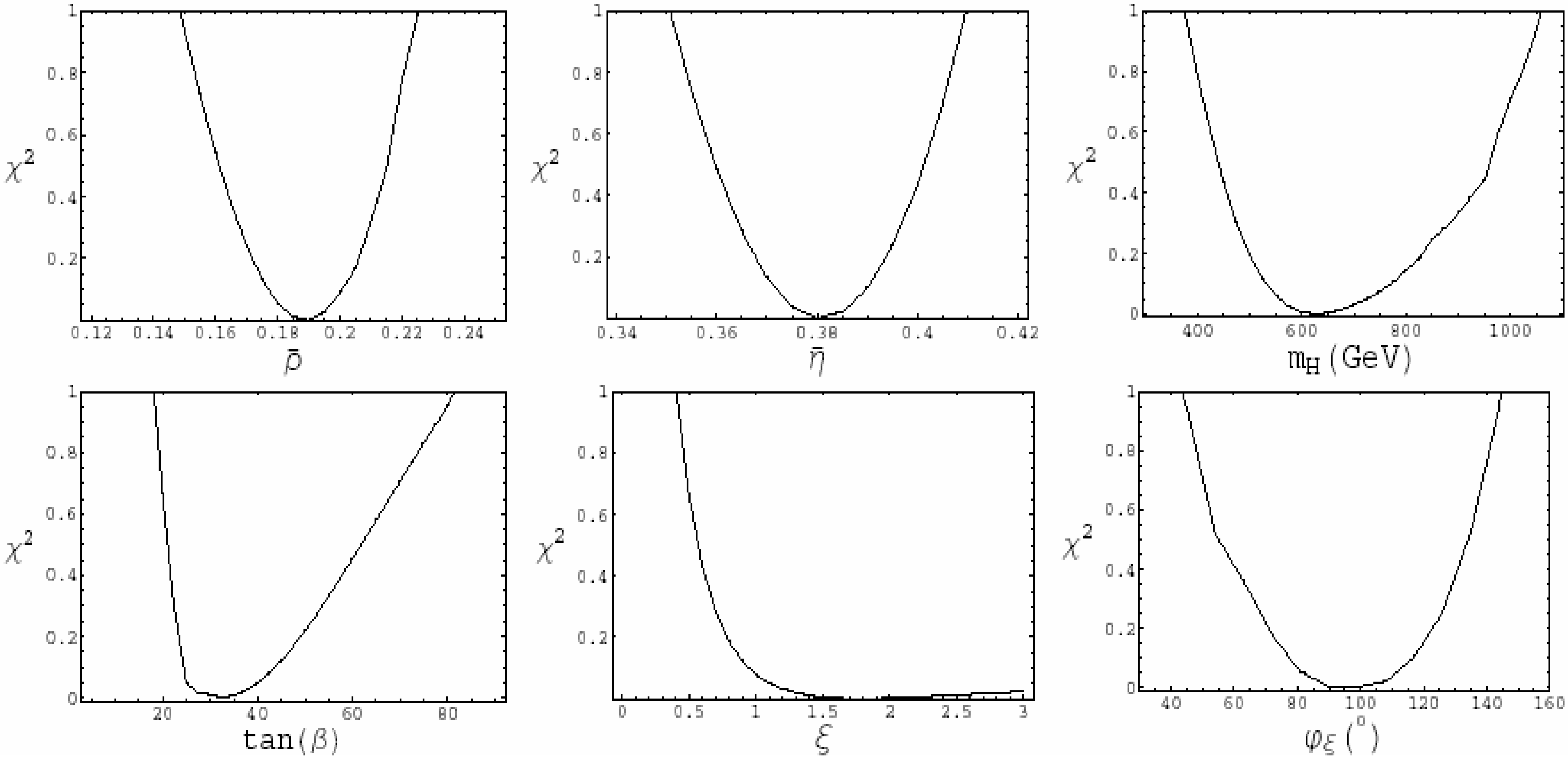
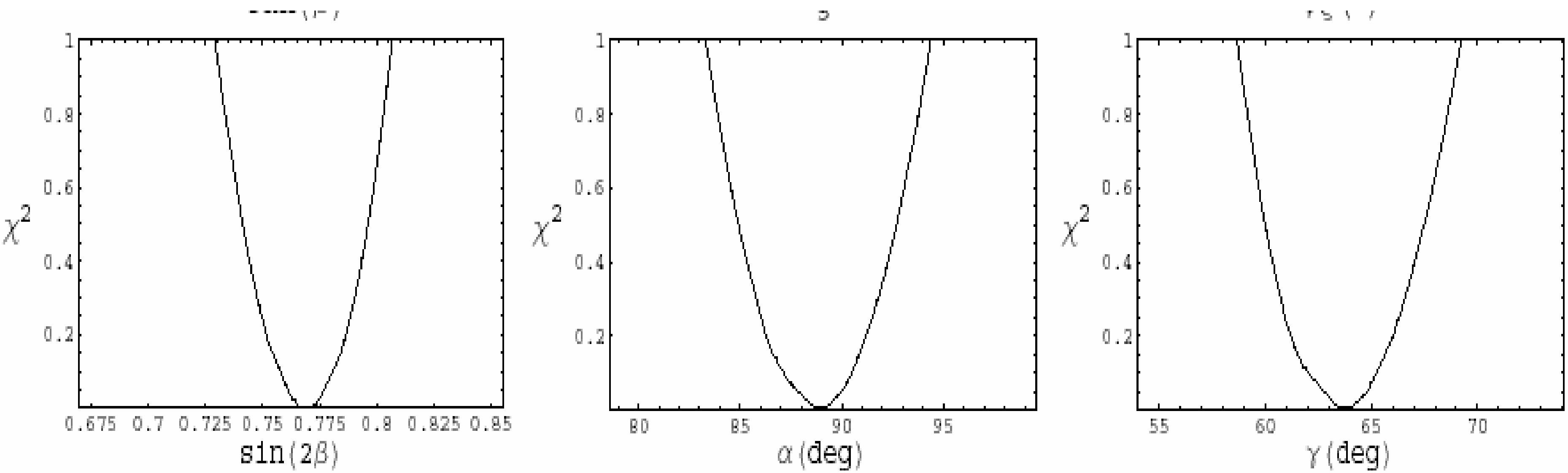


Figure 11: **Plot a.** $m_{H^\pm}$ dependence of the T2HDM contributions to Δm_D. Solid, dashed and dotted lines correspond to $|\xi\xi'| = 0.1$, 0.2 and 0.5, respectively. We fix $\tan\beta = 50$. The horizontal dashed line is the experimental upper limit. **Plot b.** Portion of the $(\xi\xi', m_{H^\pm})$ plane excluded by Δm_D. The shaded area corresponds to $\tan\beta = 30$. The dashed line to $\tan\beta = 50$.



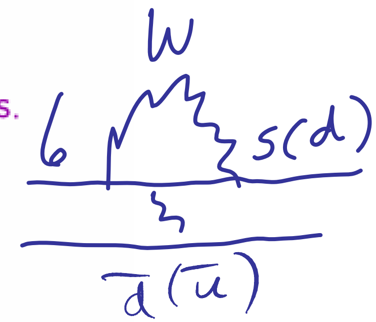
AT16 : $m_H = 600^{-200}_{+400}$ GeV; $\tan\beta = 30^{-10}_{+50}$; $\phi_\xi = 100^{-40}_{+40}$



χ²
1
0.8
0.6
0.4
0.2
0.675 0.7 0.725 0.75 0.775 0.8 0.825 0.85
sin(2β)
χ²
1
0.8
0.6
0.4
0.2
80 85 90 95
α(deg)
χ²
1
0.8
0.6
0.4
0.2
55 60 65 70
γ(deg)

Direct CP violation in Radiative B decays in and beyond the SM

Kiers,soni and Wu hep-ph/0006280 (some input from refs. below)



Model	$A_{CP}^{B\to X_s\gamma}(\%)$	$A_{CP}^{B\to X_d\gamma}(\%)$
SM	0.6	-16
2HDM (Model II)	≈ 0.6	≈ -16
3HDM	-3 to +3	-20 to +20
T2HDM	$\approx$ 0 to +0.6	$\approx$ -16 to +4
Supergravity[*]	$\approx$ -10 to +10	-(5 - 45) and (2
SUSY with squark mixing[+]	$\approx$ -15 to +15	
SUSY with R-parity violation[+*]	$\approx$ -17 to +17	

* : T. Goto et al hep-ph/9812369; M. Aoki et al, hep-ph/9811251. + : C.-K Chua et al hep-ph/9808431; Y.G.Kim et al NPB544,64(99); Kagan and Neubert,hep-ph/9803368.

B-Factory Signals for a WED

[Agashe,Perez,Soni,hep-ph/0406101(PRL);0408134(PRD)]

- **RS1 with a WARPED EXTRA DIMENSION (WED) provides an elegant solution to the HP**
- **In this framework, due to warped higher-dimensional spacetime, the mass scales (i.e. flavors) in an effective 4D description depend on location in ED. Thus, e.g. the light fermions are localized near the Plank brane where the effective cut-off is much higher than TeV so that FCNC's from HDO are greatly suppressed.. The top quark,on the other hand is localized on the TeV brane so that it gets a large 4D top Yukawa coupling**.
- **Thus, KK-masses >~ 3TeV become possible.**

Key features of WED

- **Amielorating the Flavor Problem. This provides an understanding of hierarchy of fermion masses w/o hierarchies in fundamental 5D params. Thus "solving" the SM flavor problem.**

Flavor violations Most flavor-violating effects arise due to the violation of RS-GIM mechanism by the large top mass.

This originates from the fact that $(t,b)_L$ is localized on the TeV brane.

Contrasting B-Factory Signals from WED with those from the SM

	Δm_{B_s}	$S_{B_s \to \psi\phi}$	$S_{B_d \to \phi K_s}$	$Br[b \to s l^+ l^-]$	$S_{B_{d,s} \to K^*, \phi\gamma}$	$S_{B_{d,s} \to \rho, K^* \gamma}$
RS1	$\Delta m_{B_s}^{SM}[1+O(1)]$	$O(1)$	$\sin 2\beta \pm O(.2)$	$Br^{SM}[1+O(1)]$	$O(1)$	$O(1)$
SM	$\Delta m_{B_s}^{SM}$	λ_c^2	$\sin 2\beta$	Br^{SM}	$\frac{m_s}{m_b}\left(\sin 2\beta, \lambda_c^2\right)$	$\frac{m_d}{m_b}\left(\lambda_c^2, \sin 2\beta\right)$

MODELS ARE NOT YET Developed to be precise.

BSM implications for edm's

Neutron EDM: a classic "null" test

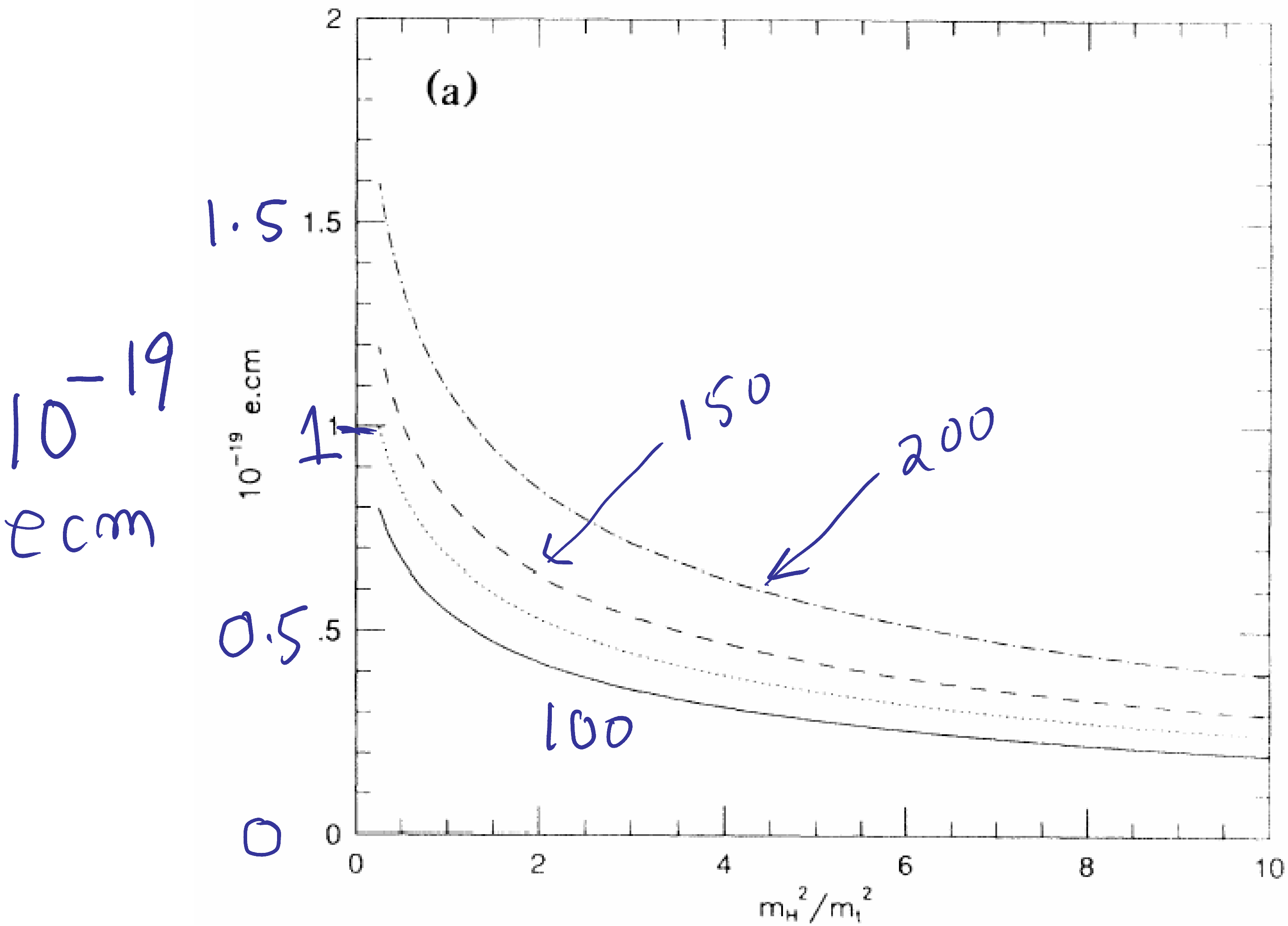
- In the SM NEDM cannot arise at least to two
- loops in EW……..expect < 10^{-31} ecm
- Long series of experiments now place
- a 90% CL bound, <6.3 X 10^{-26} ecm (Harris et
- al, '99)
- In numerous BSM, including SUSY, Warped
- extra-dimensions, …… neutron edm close
- to current bound is expected

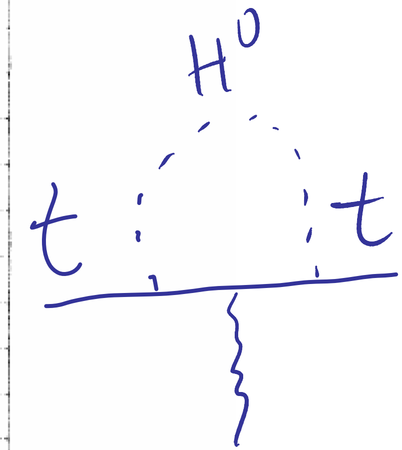
SHOULD BE PURSUED with very high priority!

Top quark EDM: a clean “null” test

- Top is so heavy compared to other quarks that
- GIM mechanism is super-effective -> all SM
- CP violation effects are vanishingly small.
- As one concrete illustration is the top quark
- Electric dipole moment….In the SM you need to
- Go to 2 loops in EW

R. Xu + A. S, PRL '92 {Electric dipole moment of top-quark with an extended Higgs sector}





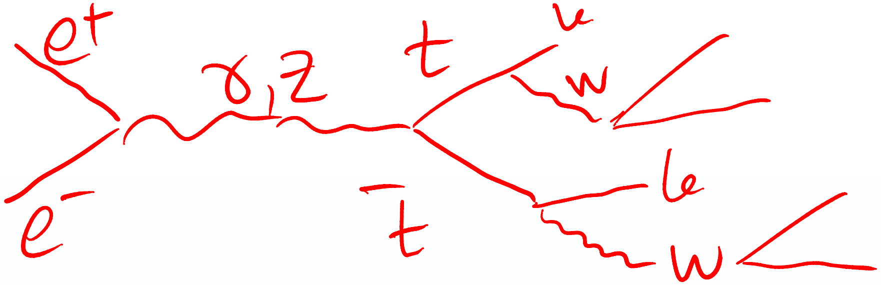
tedm $> 10^{-20}$ ecm possible.

Top quark dipole moment form factors in BSM scenarios {Atwood, Bar-Shalom, Eilam & A.S, Phys. Reports '01}

type of moment $(e-cm)$ ⇓	$\sqrt{s}$ (GeV) ⇓	Standard Model	neutral Higgs $m_h = 100-300$	charged Higgs $m_{H^+} = 200-500$	Supersymmetry $m_{\tilde{g}} = 200-500$
$\lvert\Im m(d_t^\gamma)\rvert$	500	$< 10^{-30}$	$(4.1-2.0)\times10^{-19}$	$(29.1-2.1)\times10^{-22}$	$(3.3-0.9)\times10^{-19}$
	1000		$(0.9-0.8)\times10^{-19}$	$(15.7-1.0)\times10^{-22}$	$(1.2-0.8)\times10^{-19}$
$\lvert\Re e(d_t^\gamma)\rvert$	500	$< 10^{-30}$	$(0.3-0.8)\times10^{-19}$	$(33.4-1.5)\times10^{-22}$	$(0.3-0.9)\times10^{-19}$
	1000		$(0.7-0.2)\times10^{-19}$	$(0.3-2.7)\times10^{-22}$	$(1.1-0.3)\times10^{-19}$
$\lvert\Im m(d_t^Z)\rvert$	500	$< 10^{-30}$	$(1.1-0.2)\times10^{-19}$	$(15.8-2.5)\times10^{-22}$	$(1.1-0.3)\times10^{-19}$
	1000		$(0.2-0.2)\times10^{-19}$	$(9.2-1.2)\times10^{-22}$	$(0.4-0.3)\times10^{-19}$
$\lvert\Re e(d_t^Z)\rvert$	500	$< 10^{-30}$	$(1.6-0.2)\times10^{-19}$	$(22.9-0.8)\times10^{-22}$	$(0.1-0.3)\times10^{-19}$
	1000		$(0.2-1.4)\times10^{-19}$	$(0.6-1.9)\times10^{-22}$	$(0.4-0.1)\times10^{-19}$

LARGE tedm also in RS

ILC



MANY OBSERVABLES

Table 5: *Attainable 1-σ sensitivities to the CP-violating dipole moment form factors in units of* 10^{-18} *e-cm, with* $(P_e = \pm 1)$ *and without* $(P_e = 0)$ *beam polarization.* $m_t = 180$ *GeV. Table taken from [175].*

10^{-19}

500

	20 fb^{-1}, $\sqrt{s} = 500$ GeV			50 fb^{-1}, $\sqrt{s} = 800$ GeV		
	$P_e = 0$	$P_e = +1$	$P_e = -1$	$P_e = 0$	$P_e = +1$	$P_e = -1$
$\delta(\Re d_t^\gamma)$	4.6	0.86	0.55	1.7	0.35	0.23
$\delta(\Re d_t^Z)$	1.6	1.6	1.0	0.91	0.85	0.55
$\delta(\Im d_t^\gamma)$	1.3	1.0	0.65	0.57	0.49	0.32
$\delta(\Im d_t^Z)$	7.3	2.0	1.3	4.0	0.89	0.58

PHY. Rep. "CPV in top-quark Physics"
Atwood, Barshalom, Eilam + A.S.

Summary & Outlook

- **Asym. B factories + Lattice -> KM phase is the dominant contributor to observed CP**
- **Search for BSM-CP-odd phase imposes greater demands of precision on expt. & on theory**
- **ΔS test of the CKM-paradigm extremely tantalizing with ~2.5 -3.5σ deviations-> EXCITING**
- **Given that such effects occur quite naturally in most BSMs the expt. situation needs to be clarified at the highest priority.**
- **Most of the BSMs also exhibit nedm ~ 10^{-26} ecm & tedm ~ 10^{-19} ecm; should pursue both vigorously.**

. ***B-factories are hinting an exciting LHC-era!***

EXTRAS

Basics of the framework

between the relevant models considered below. The basic set-up of our models is the RS1 framework [1]. The space time of the model is described by a slice of ADS_5 with curvature scale, $k \sim M_{Pl}$, the $4D$ Planck mass. The Planck brane is located at $\theta = 0$, where θ is the compact extra dimension coordinate. The TeV brane is located at $\theta = \pi$. The metric of RS1 can be written as:

$$(ds)^2 = \frac{1}{(kz)^2}\left[\eta_{\mu\nu}dx^\mu dx^\nu - (dz)^2\right], \tag{1}$$

where $kz = e^{kr_c\theta}$. We assume that $k\pi r_c \sim \log\left(M_{\rm Pl}/\mathrm{TeV}\right)$ to solve the hierarchy problem,

$$\left(z_h \equiv \frac{1}{k}\right) \leq z \leq \left(z_v \equiv \frac{e^{k\pi r_c}}{k}\right), \tag{2}$$

where $z_v \sim \mathrm{TeV}^{-1}$.

The gauge group of the models under study is given by [9, 10] $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The gauge symmetry is broken on the Planck brane down to the SM gauge group and in the TeV brane it is broken down to $SU(3)_c \times SU(2)_D \times U(1)_{B-L}$. $SU(2)_D$ is the diagonal subgroup of the two $SU(2)$'s present in the bulk.

NP Contributions due WED

There are essentially 3 types of top quark dominated FCNC contributions:

i) Contributions to FCNC processes arise

from a relatively large dispersion in the doublets 5D masses, specifically large coupling of $(t,b)_L$ to gauge modes due to

heaviness of the t..

ii) Contributions to FCNC processs (mostly semi-leptonic)

These arise from contribution of i) and mixing between the zero and KK states of the Z due to EWSB.

iii) Contribution to radiative B-decays via dipole operators arise from large 5D Yukawa required to obtain m_t

Flavor	f_Q^{-1}	f_u^{-1}	f_d^{-1}
I	$\frac{\lambda^3}{f_{Q^3}} \sim 0.4 \times 10^{-2}$	$\frac{m_u}{m_t} \frac{f_{u^3}^{-1}}{\lambda^3} \sim 10^{-3}$	$\frac{m_d}{m_b} \frac{f_{d^3}^{-1}}{\lambda^3} \sim 10^{-3}$
II	$\frac{\lambda^2}{f_{Q^3}} \sim 2 \times 10^{-2}$	$\frac{m_c}{m_t} \frac{f_{u^3}^{-1}}{\lambda^2} \sim 10^{-1}$	$\frac{m_s}{m_b} \frac{f_{d^3}^{-1}}{\lambda^2} \sim 0.3 \times 10^{-2}$
III	$\frac{f_{u^3} m_t}{v \lambda_{5D} k} \sim \frac{1}{3}$	$\mathrm{O}\left(\frac{5}{6}\right)$	$\frac{m_b}{m_t} f_{u^3}^{-1} \sim 0.6 \times 10^{-2}$

Table 3: The known quark masses and CKM mixing implies relation between the model flavor parameters, f_{x^i}, (11,12). The value of f_{u^3}, λ_{5D} is determined by requiring the theory is perturbative (13,14).

Notable FCNC characteristic (see table)

$f_{x^i}^{-1}$ apart from the ones related to the top mass are small. This implies that the model has a built-in approximate flavor symmetry for the light quarks. This is indeed the reason why the framework may avoid the severe constraint from FCNC processes with such a low KK masses. We can compare this with the flat extra dimension models which require KK masses of $\mathcal{O}(1000\,\mathrm{TeV})$.

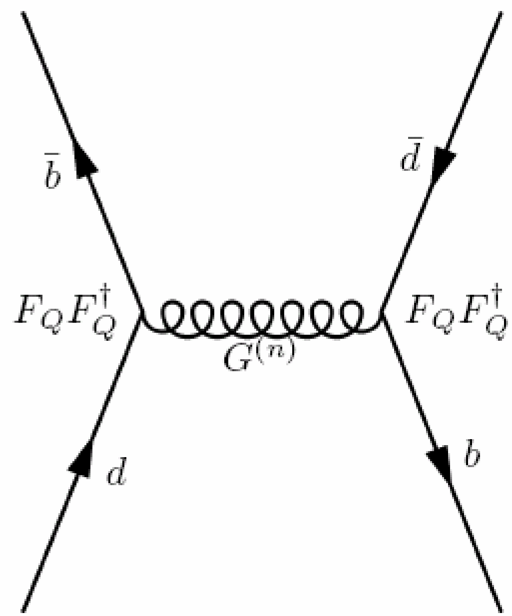


Fig. 1: Contributions to $\Delta F = 2$ processes from KK gluon exchange.