Radiative b decays: a goldmine for uncovering new phenomena

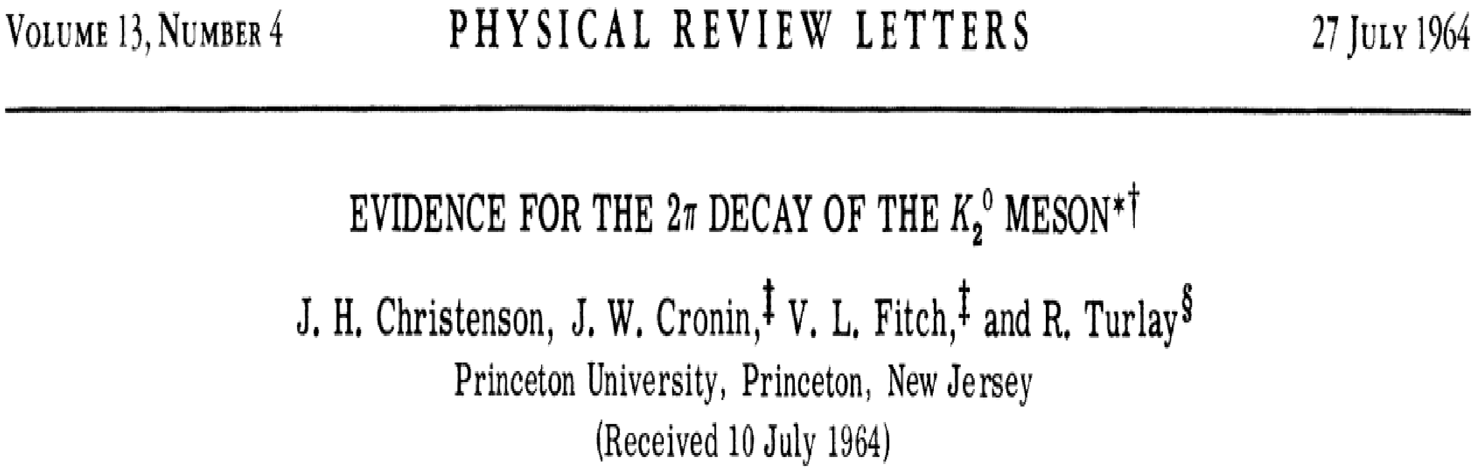
Valencia, Spain

Amarjit Soni

BNL-HET

[**5th workshop on Radiative b decays**]

BNL’64



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)

(Christenson) Cronin, Fitch (& Turlay), PRL’64

- **KL => 3 pi, most of the time but once in a purple moon it also goes to 2 pi**

- **This is an example of indirect CPV**
- **Nevertheless it has the profound consequence that CP is not a symmetry of nature!**
- **=> Weak shall “inherit the earth”**

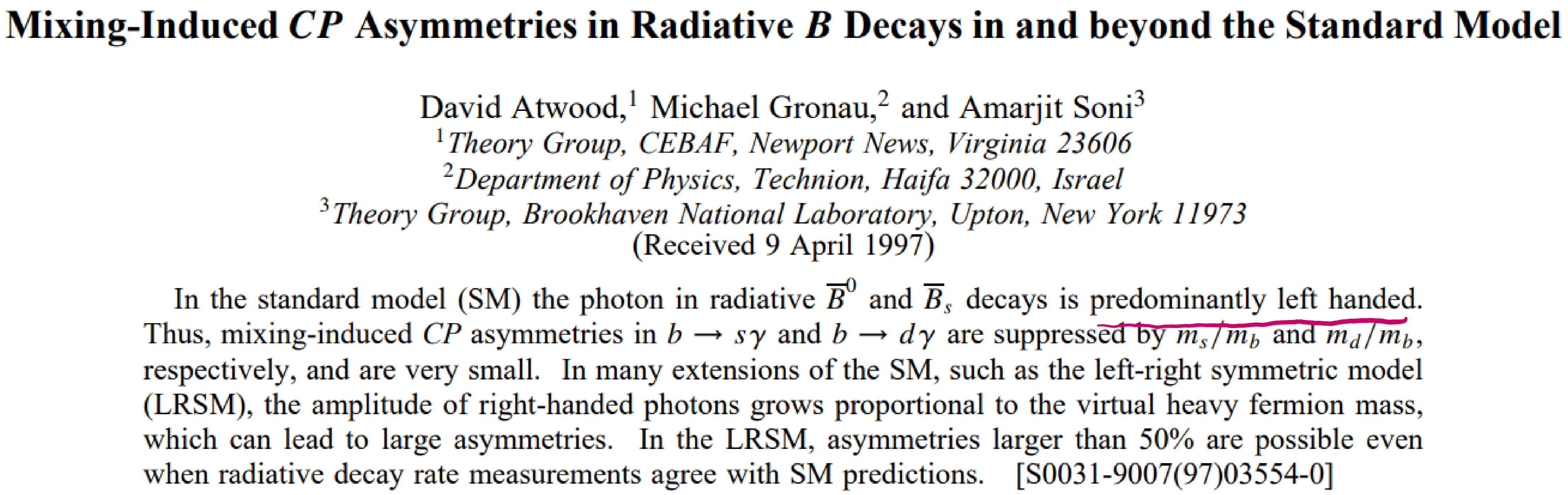
Outline

- **BNL'64 Cronin+Fitch, Br (KL =>2 pi) => not eq 0; CP is not a symmetry of nature**

- **Naturalness arguments then suggest any new physics scenario to entail BSM CP-odd-phase(s)**
- **Explicit examples of popular BSM back that assertion: 2 Higss DMs, LRSM, warped XM, SUSY r RPV-Susy or LQ Ms**

- **In radiative b decays just about the best search may well be via (mixing-induced) time-dependent CP [TDCP]**

- **However, in b decays searching for direct CP [DCP] or for that matter other types of CP also may well be very useful**



Mixing-Induced *CP* Asymmetries in Radiative *B* Decays in and beyond the Standard Model

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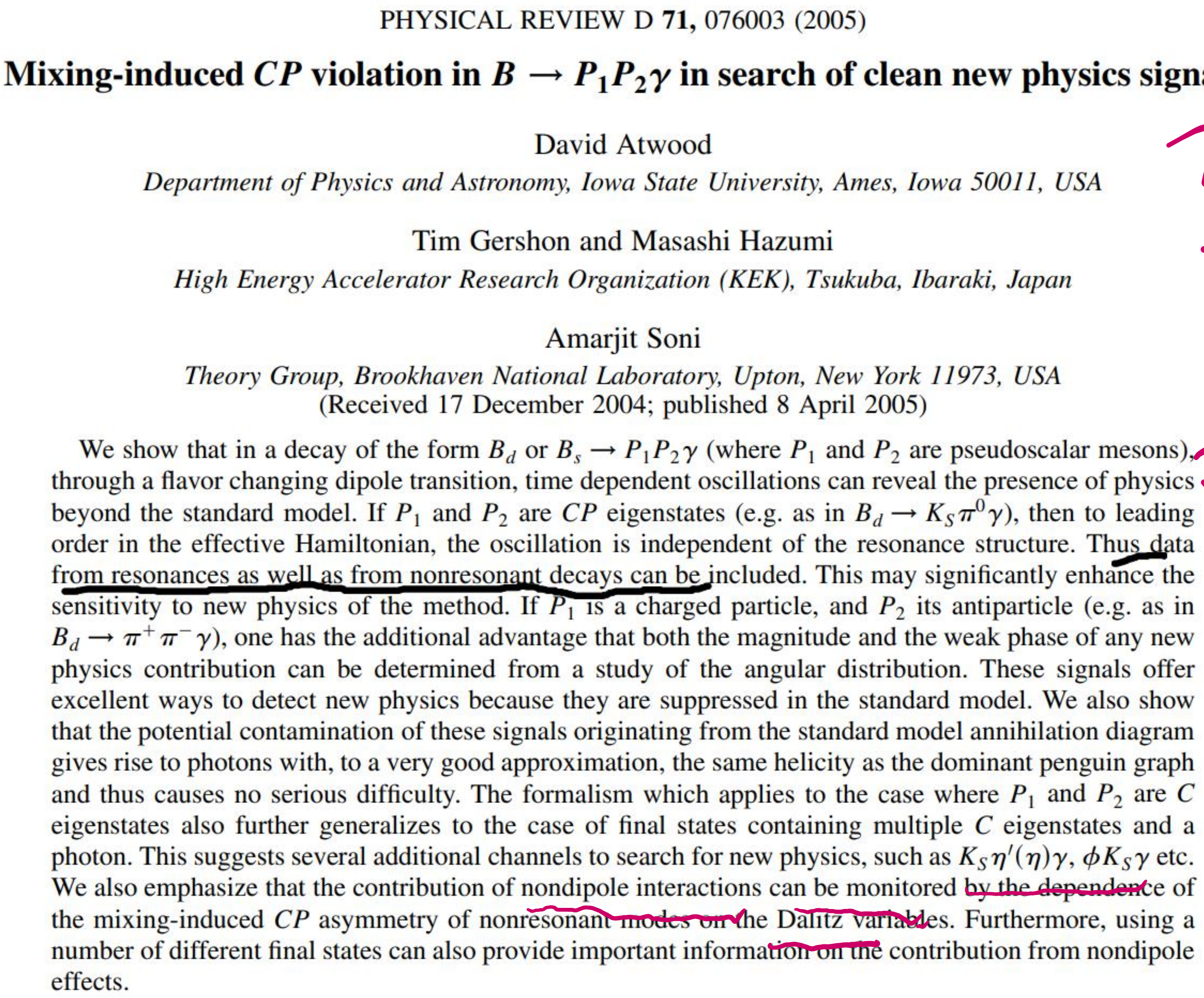
(Received 9 April 1997)

In the standard model (SM) the photon in radiative $\overline{B}^0$ and $\overline{B}_s$ decays is predominantly left handed. Thus, mixing-induced *CP* asymmetries in $b \to s\gamma$ and $b \to d\gamma$ are suppressed by m_s/m_b and m_d/m_b, respectively, and are very small. In many extensions of the SM, such as the left-right symmetric model (LRSM), the amplitude of right-handed photons grows proportional to the virtual heavy fermion mass, which can lead to large asymmetries. In the LRSM, asymmetries larger than 50% are possible even when radiative decay rate measurements agree with SM predictions. [S0031-9007(97)03554-0]



PHYSICAL REVIEW D **71,** 076003 (2005)

Mixing-induced *CP* violation in $B \to P_1 P_2 \gamma$ in search of clean new physics signals

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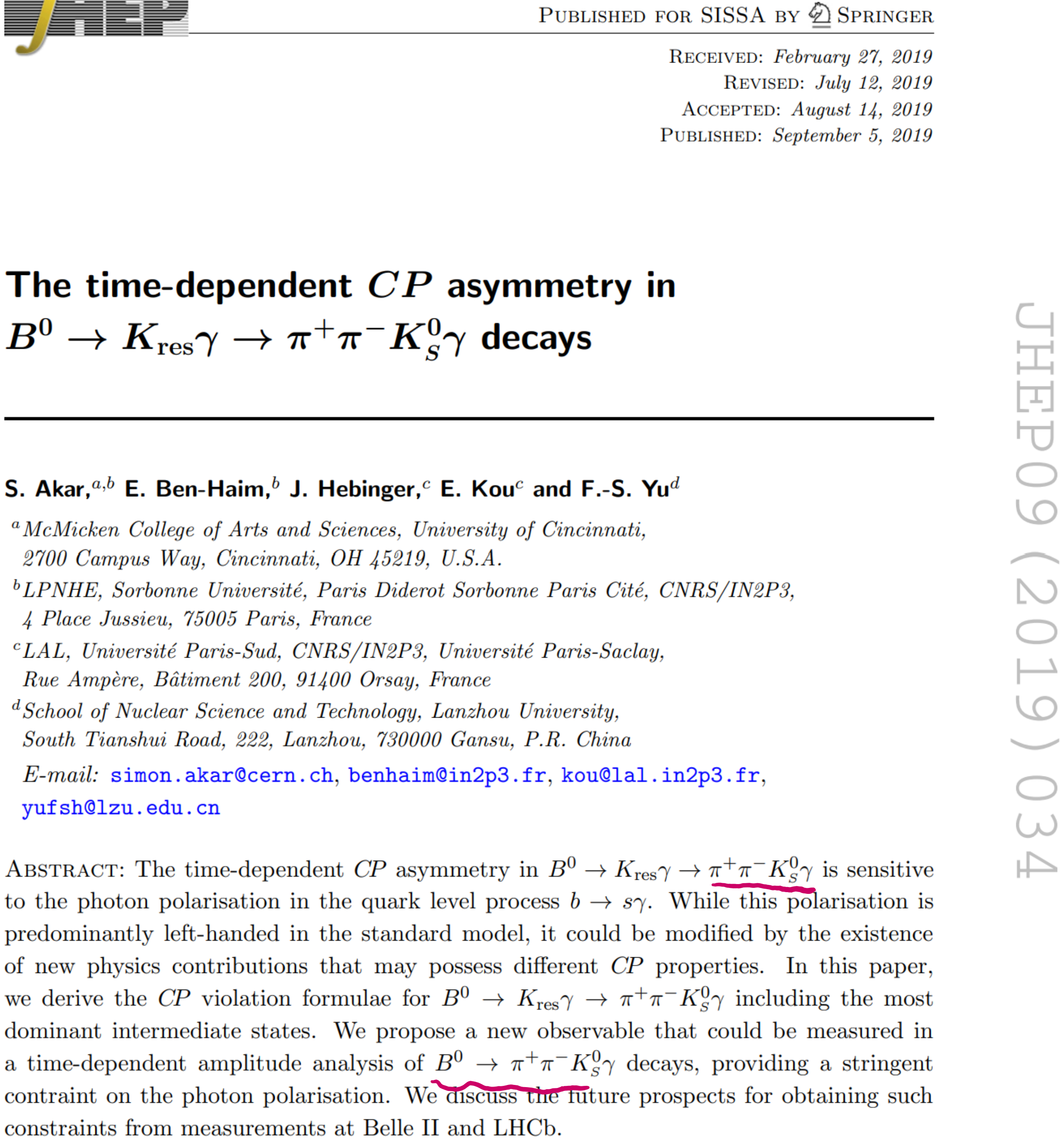
(Received 17 December 2004; published 8 April 2005)

We show that in a decay of the form B_d or $B_s \to P_1 P_2 \gamma$ (where P_1 and P_2 are pseudoscalar mesons), through a flavor changing dipole transition, time dependent oscillations can reveal the presence of physics beyond the standard model. If P_1 and P_2 are *CP* eigenstates (e.g. as in $B_d \to K_S \pi^0 \gamma$), then to leading order in the effective Hamiltonian, the oscillation is independent of the resonance structure. Thus data from resonances as well as from nonresonant decays can be included. This may significantly enhance the sensitivity to new physics of the method. If P_1 is a charged particle, and P_2 its antiparticle (e.g. as in $B_d \to \pi^+ \pi^- \gamma$), one has the additional advantage that both the magnitude and the weak phase of any new physics contribution can be determined from a study of the angular distribution. These signals offer excellent ways to detect new physics because they are suppressed in the standard model. We also show that the potential contamination of these signals originating from the standard model annihilation diagram gives rise to photons with, to a very good approximation, the same helicity as the dominant penguin graph and thus causes no serious difficulty. The formalism which applies to the case where P_1 and P_2 are *C* eigenstates also further generalizes to the case of final states containing multiple *C* eigenstates and a photon. This suggests several additional channels to search for new physics, such as $K_S \eta'(\eta) \gamma$, $\phi K_S \gamma$ etc. We also emphasize that the contribution of nondipole interactions can be monitored by the dependence of the mixing-induced *CP* asymmetry of nonresonant modes on the Dalitz variables. Furthermore, using a number of different final states can also provide important information on the contribution from nondipole effects.

THIS
SEQUEL
PROVIDES
MANY
DETAILS

NICE TO SEE
MORE
ATTENSION



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The time-dependent CP asymmetry in $B^0 \to K_{\rm res}\gamma \to \pi^+\pi^- K_S^0\gamma$ decays

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Abstract: The time-dependent CP asymmetry in $B^0 \to K_{\rm res}\gamma \to \underline{\pi^+\pi^- K_S^0\gamma}$ is sensitive to the photon polarisation in the quark level process $b \to s\gamma$. While this polarisation is predominantly left-handed in the standard model, it could be modified by the existence of new physics contributions that may possess different CP properties. In this paper, we derive the CP violation formulae for $B^0 \to K_{\rm res}\gamma \to \pi^+\pi^- K_S^0\gamma$ including the most dominant intermediate states. We propose a new observable that could be measured in a time-dependent amplitude analysis of $\underline{B^0 \to \pi^+\pi^- K_S^0\gamma}$ decays, providing a stringent contraint on the photon polarisation. We discuss the future prospects for obtaining such constraints from measurements at Belle II and LHCb.

JHEP09(2019)034

Only go after CP: surest way to see real NP& grab the NP and run!

Generalities of CP tests

- While mixing induced or time-dependent CP studies must be restricted to (neutral) i.e. B^0, Bs (and their anti-particles) direct CP tests can be done on all B's: charged or neutral
- Many properties of B^- are related to B^0 by isospin.

Although as a rule effects of isospin are small i.e. O(alpha/pi) or

O(mu/md), significantly larger (i.e. ~10 X alpha/pi) effects can arise

in some cases esp. when CP asymmetries are concerned

- charged B are related by SU3 to Bs..Breaking usually tends to be

(mu/ms) O(~10%), formally Bd and Bs can be related by U-spin O(md/ms) but the can be roughly as big as in SU3

Subtleties of QCD

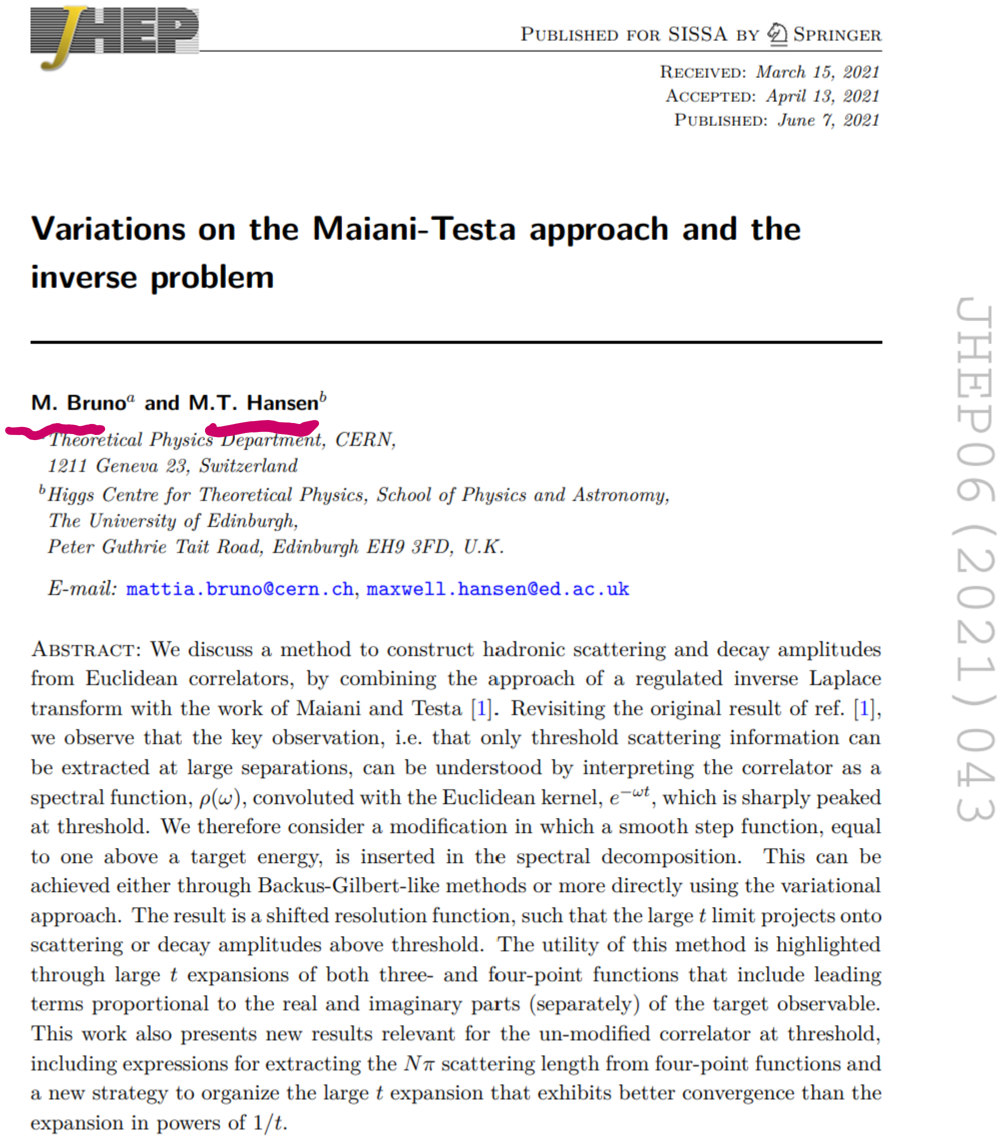
- **Much has been learned from intense lattice studies of K => 2 pi**

- **A very good example is that the amplitude that goes as O(N) largely cancels another one that goes as (N^2) [N=3 for QCD] around the physical mass of pion causing significant suppression of the Delta I=3/2 transition. This 'accidental' cancellation plays an important role in the classic puzzle known as 'The Delta I=1/2 Rule'.**

- **There are very good reasons to think that similar subtleties may well be the underlying reasons for some long standing puzzles in B decays**

For a very long time it seemed lattice will not be able to handle hadronic B-decays: some recent glimmer of hope

MATTIA
BRUNO
Now @
MILANO



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Variations on the Maiani-Testa approach and the inverse problem

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Abstract: We discuss a method to construct hadronic scattering and decay amplitudes from Euclidean correlators, by combining the approach of a regulated inverse Laplace transform with the work of Maiani and Testa [1]. Revisiting the original result of ref. [1], we observe that the key observation, i.e. that only threshold scattering information can be extracted at large separations, can be understood by interpreting the correlator as a spectral function, $\rho(\omega)$, convoluted with the Euclidean kernel, $e^{-\omega t}$, which is sharply peaked at threshold. We therefore consider a modification in which a smooth step function, equal to one above a target energy, is inserted in the spectral decomposition. This can be achieved either through Backus-Gilbert-like methods or more directly using the variational approach. The result is a shifted resolution function, such that the large t limit projects onto scattering or decay amplitudes above threshold. The utility of this method is highlighted through large t expansions of both three- and four-point functions that include leading terms proportional to the real and imaginary parts (separately) of the target observable. This work also presents new results relevant for the un-modified correlator at threshold, including expressions for extracting the $N\pi$ scattering length from four-point functions and a new strategy to organize the large t expansion that exhibits better convergence than the expansion in powers of $1/t$.

JHEP06(2021)043

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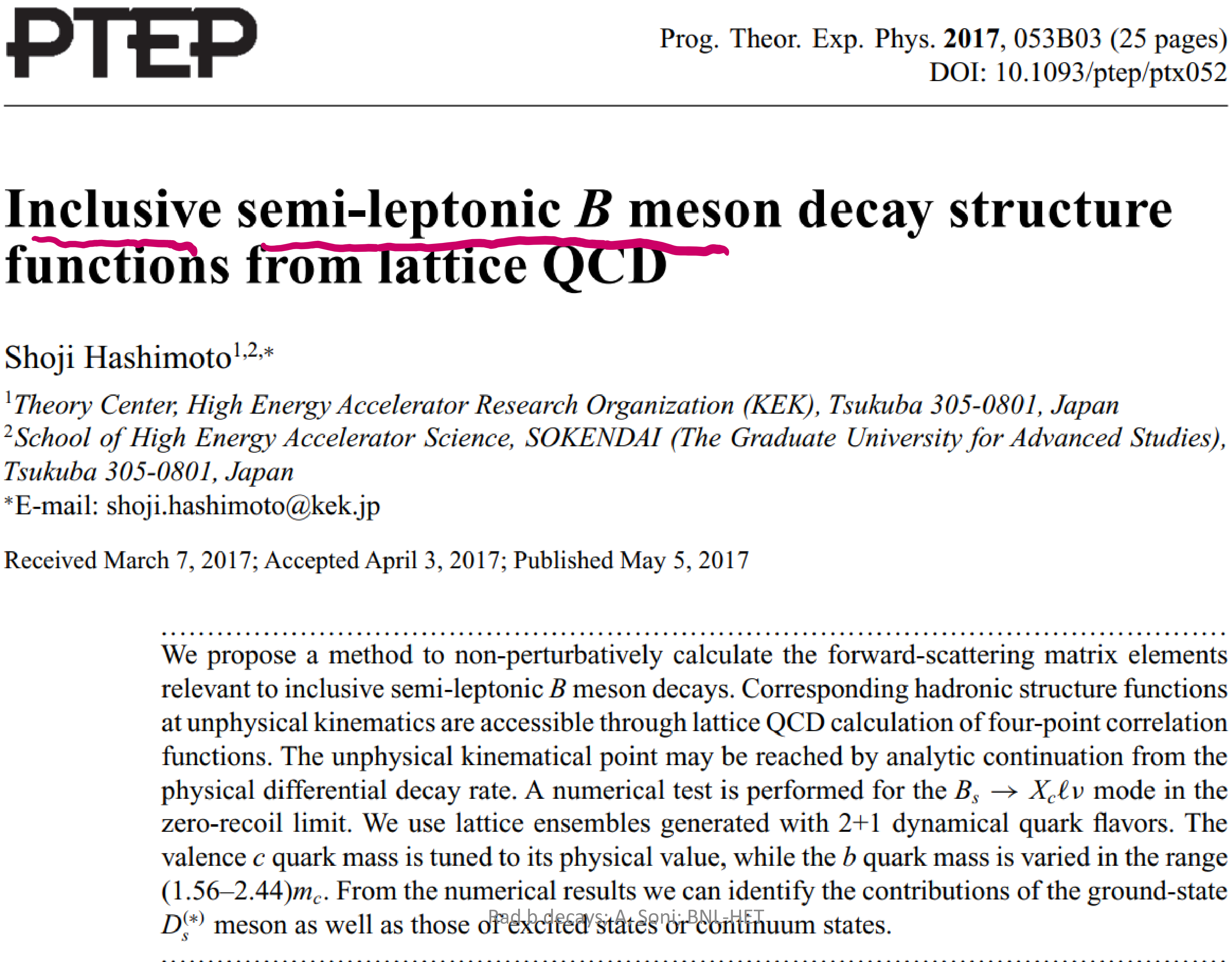

PTEP
Prog. Theor. Exp. Phys. **2017**, 053B03 (25 pages)
DOI: 10.1093/ptep/ptx052

Inclusive semi-leptonic *B* meson decay structure functions from lattice QCD

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We propose a method to non-perturbatively calculate the forward-scattering matrix elements relevant to inclusive semi-leptonic *B* meson decays. Corresponding hadronic structure functions at unphysical kinematics are accessible through lattice QCD calculation of four-point correlation functions. The unphysical kinematical point may be reached by analytic continuation from the physical differential decay rate. A numerical test is performed for the $B_s \to X_c \ell \nu$ mode in the zero-recoil limit. We use lattice ensembles generated with 2+1 dynamical quark flavors. The valence c quark mass is tuned to its physical value, while the b quark mass is varied in the range $(1.56\text{–}2.44)m_c$. From the numerical results we can identify the contributions of the ground-state $D_s^{(*)}$ meson as well as those of excited states or continuum states.

Few remarks on direct CP [DCP] tests

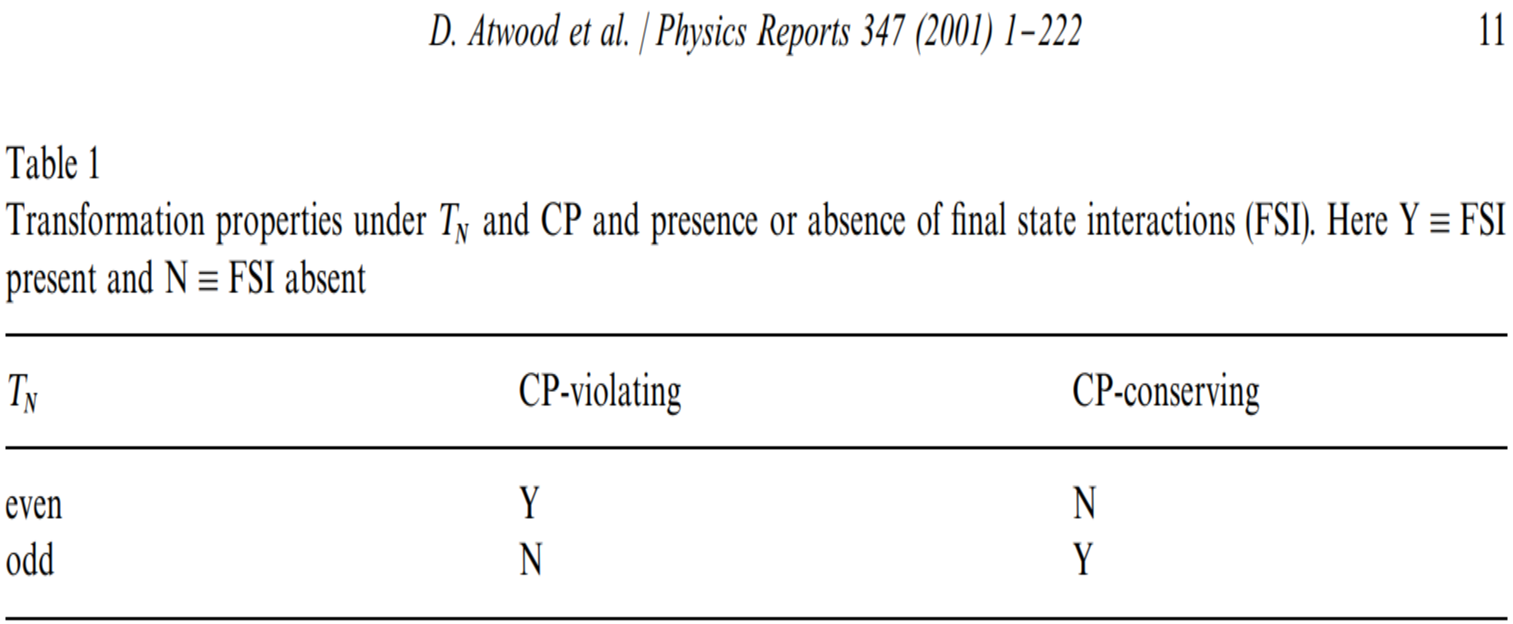
- [Br - \Br]/[Br + /Br] …..PRA available when you compare 2 conjugate processes……….REQUIRES FSI phase X CP-odd phase
- In perturbation theory FSI phases usually arise by (QCD) loops

- D

- When FS has 3 or more particles Energy asymmetry (EA) between conjugate particles can also be used and can be a powerful test of CPV
- EA can be a lot larger than PRA as they can balance among different regions of phase space
- FSI phases (are always CP-conserving) can arise even with EW loops NOT just QCD loops
- For a genuine DCPV effect one needs both a CPV phase and a CP conserving phase

TCA: triple correlation asymmetry

- **This is relevant when FS involves 3 or more particles in radiative b decays**
- **Or in general non-vanishing TN- correlations can arise whenever 4 linearly Independent momenta (spins, or 3-momenta) are involved**
- **But they are not necessarily CP violating**
- **If you find no-vanishing TCA, conjugate process MUST be studied to make sure it is a genuine CP violation and its not being faked by TN (naïve Time Reversal)TN- odd effects.**
- **See Table 1 in this Physics Reports**



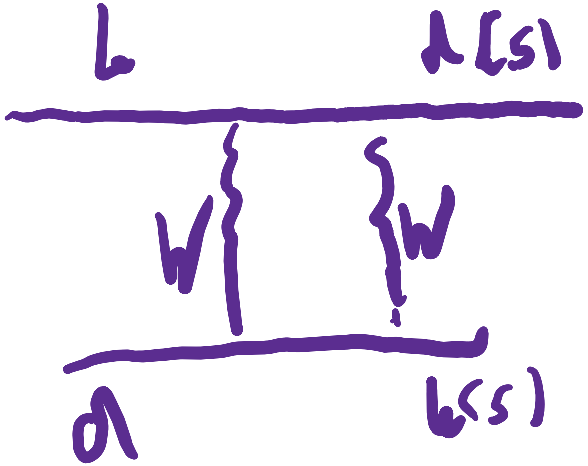
D. Atwood et al. / Physics Reports 347 (2001) 1–222 11

Table 1
Transformation properties under T_N and CP and presence or absence of final state interactions (FSI). Here Y ≡ FSI present and N ≡ FSI absent

T_N	CP-violating	CP-conserving
even	Y	N
odd	N	Y

Essential point: TDCP [see Atwood,Gronau+AS,PRL’97]

$$H_{\text{eff}} = -\sqrt{8}\, G_F \,\frac{e m_b}{16\pi^2}\, F_{\mu\nu}\Big[\frac{1}{2}\, F_L^q \bar{q}\sigma^{\mu\nu}(1 + \gamma_5)b + \frac{1}{2}\, F_R^q \bar{q}\sigma^{\mu\nu}(1 - \gamma_5)b\Big]. \tag{1}$$



Mixings must go to γ of same handedness

In the SM this is extremely suppressed

SOME DETAILS FROM Atwood, Gershon, Hazumi + AS PRD '05

MULTITUDE OF POSSIBLE FS

Just a few examples

TABLE I. Final states which can be used to probe $b \to s\gamma$ and $b \to d\gamma$ transitions in B_d and B_s decays. This list is not exhaustive; in particular, other neutral (pseudo-)scalar particles (η, η', f_0) may be used in the place of π^0.

	$K_S\pi^0\gamma$	$K_SK_S\gamma$	$\pi^+\pi^-\gamma$	$K^+K^-\gamma$	$K_SK_L\gamma$
$B_d/\overline{B}_d$	$b \to s\gamma$	$b \to d\gamma$	$b \to d\gamma$	$b \to d\gamma$	$b \to d\gamma$
$B_s/\overline{B}_s$	$b \to d\gamma$	$b \to s\gamma$	$b \to s\gamma$	$b \to s\gamma$	$b \to s\gamma$

FOR LHCb Replacing π^0 with ρ^0 may be worth it

IV. $B_d \to K_S\pi^0\gamma$ AND $B_d \to \pi^+\pi^-\gamma$

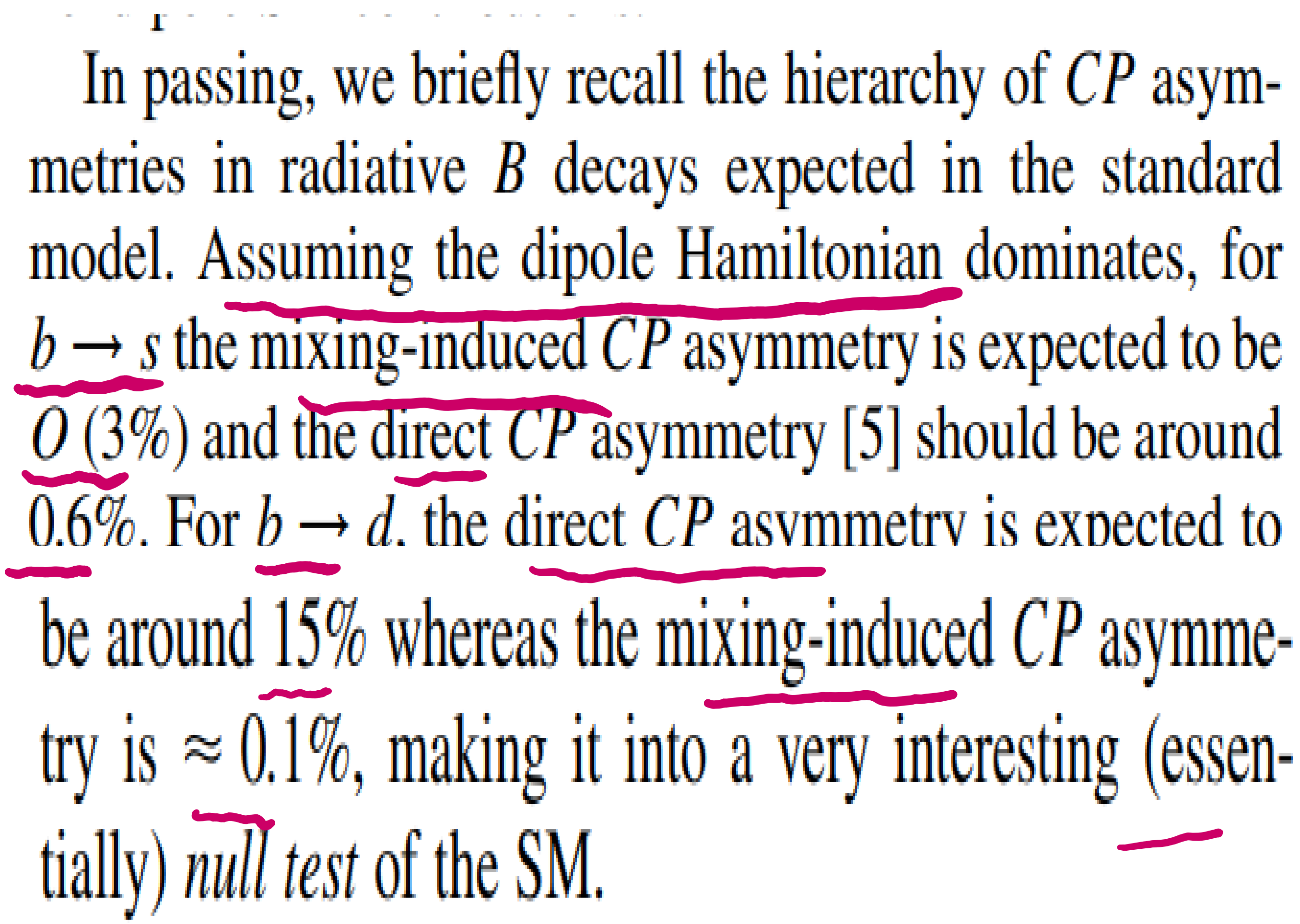
Only 2 of These DALITZ VARIABLES ARE Linearly independent

$$\left\{\begin{aligned} s_1 &= (p_{K_S} + p_{\pi_0})^2, \\ s_2 &= (p_{K_S} + p_{\gamma})^2, \\ s_3 &= (p_{\gamma} + p_{\pi_0})^2, \end{aligned}\right.$$
$$z = \frac{s_3 - s_2}{s_3 + s_2}. \tag{16}$$

In particular the amplitude can be expressed as a function of s_1 and z, where s_1 is the invariant mass squared of the $K_S\pi^0$ system, and z is the cosine of the angle between the B_d and π^0 in the $K_S\pi^0$ frame.

Estimated hierarchy of CP asymmetries

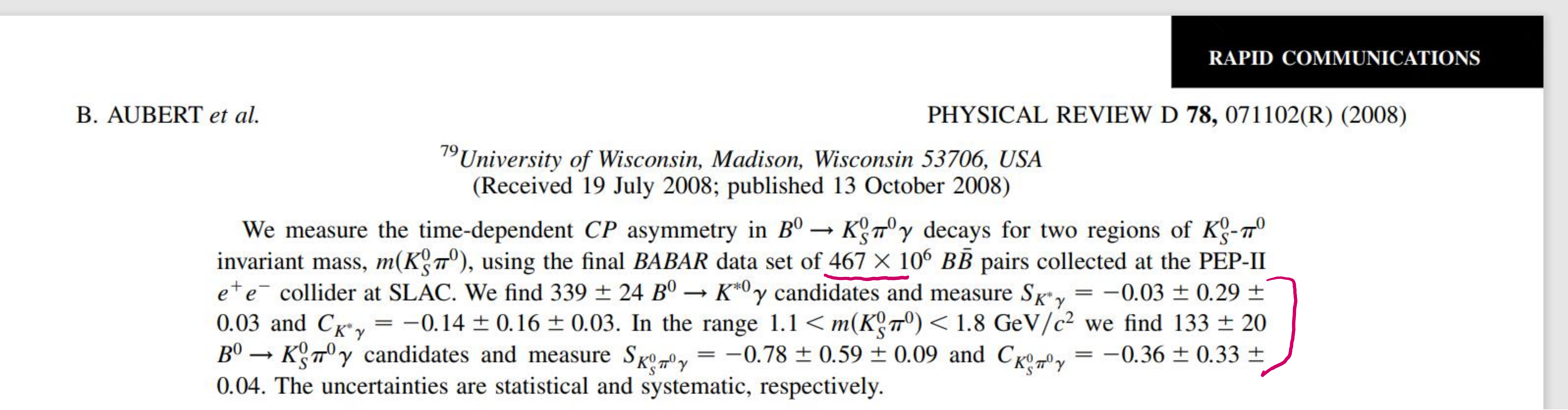
AGHS PRD



In passing, we briefly recall the hierarchy of CP asymmetries in radiative B decays expected in the standard model. Assuming the dipole Hamiltonian dominates, for $b \to s$ the mixing-induced CP asymmetry is expected to be O (3%) and the direct CP asymmetry [5] should be around 0.6%. For $b \to d$. the direct CP asymmetry is expected to be around 15% whereas the mixing-induced CP asymmetry is $\approx 0.1\%$, making it into a very interesting (essentially) *null test* of the SM.

Experimental Prospects for TDCP

- **BABAR and BELLE collaborations demonstrated the measurement feasibility of TDCP around 2006-07**



RAPID COMMUNICATIONS

B. AUBERT *et al.* PHYSICAL REVIEW D **78,** 071102(R) (2008)

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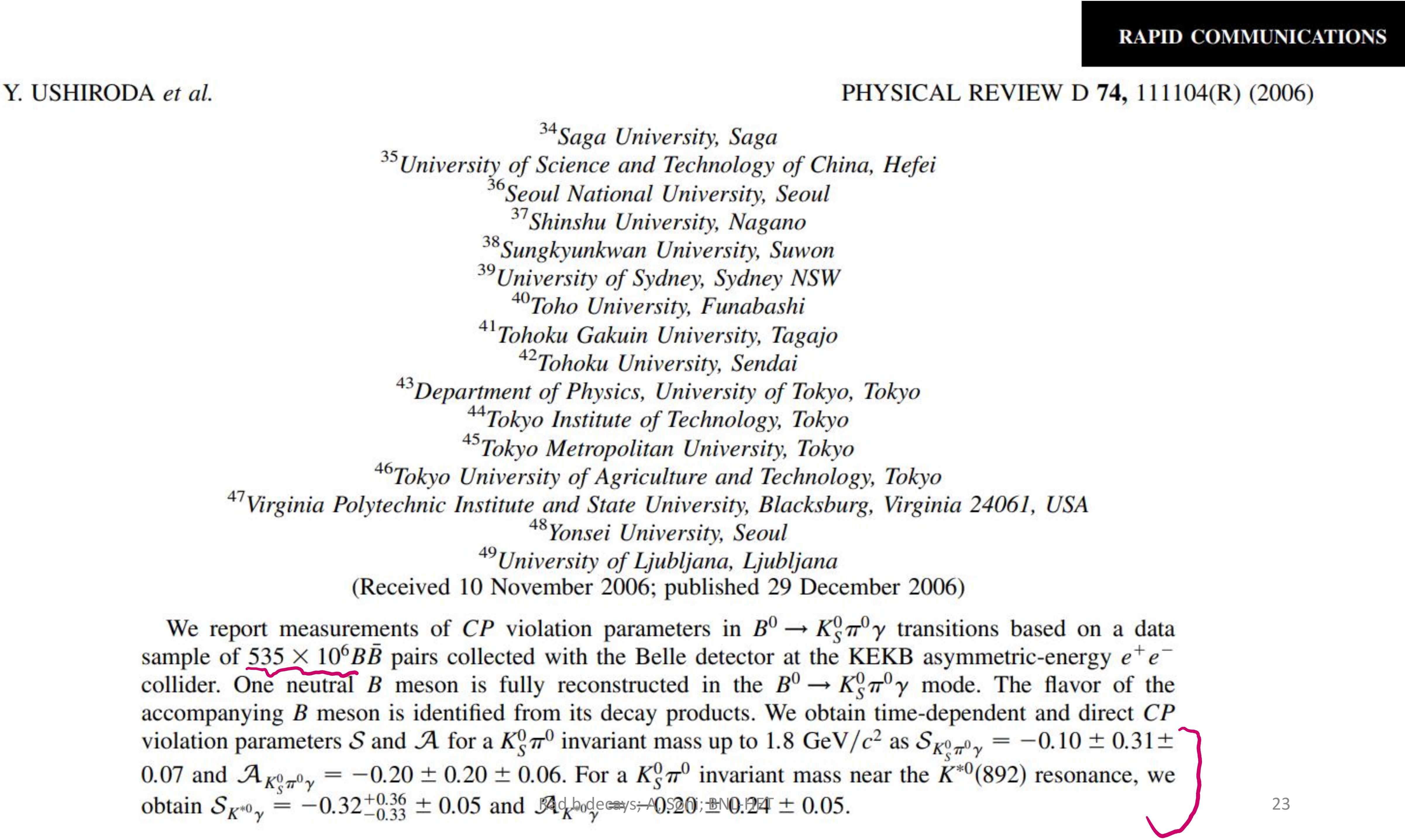
We measure the time-dependent *CP* asymmetry in $B^0 \to K_S^0 \pi^0 \gamma$ decays for two regions of K_S^0-π^0 invariant mass, $m(K_S^0 \pi^0)$, using the final *BABAR* data set of 467×10^6 $B\bar{B}$ pairs collected at the PEP-II e^+e^- collider at SLAC. We find 339 ± 24 $B^0 \to K^{*0}\gamma$ candidates and measure $S_{K^*\gamma} = -0.03 \pm 0.29 \pm 0.03$ and $C_{K^*\gamma} = -0.14 \pm 0.16 \pm 0.03$. In the range $1.1 < m(K_S^0 \pi^0) < 1.8\ \mathrm{GeV}/c^2$ we find 133 ± 20 $B^0 \to K_S^0 \pi^0 \gamma$ candidates and measure $S_{K_S^0 \pi^0 \gamma} = -0.78 \pm 0.59 \pm 0.09$ and $C_{K_S^0 \pi^0 \gamma} = -0.36 \pm 0.33 \pm 0.04$. The uncertainties are statistical and systematic, respectively.



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We report measurements of *CP* violation parameters in $B^0 \to K_S^0 \pi^0 \gamma$ transitions based on a data sample of $535 \times 10^6 B\bar{B}$ pairs collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. One neutral B meson is fully reconstructed in the $B^0 \to K_S^0 \pi^0 \gamma$ mode. The flavor of the accompanying B meson is identified from its decay products. We obtain time-dependent and direct *CP* violation parameters $\mathcal{S}$ and $\mathcal{A}$ for a $K_S^0\pi^0$ invariant mass up to 1.8 GeV$/c^2$ as $\mathcal{S}_{K_S^0\pi^0\gamma} = -0.10 \pm 0.31 \pm 0.07$ and $\mathcal{A}_{K_S^0\pi^0\gamma} = -0.20 \pm 0.20 \pm 0.06$. For a $K_S^0\pi^0$ invariant mass near the $K^{*0}(892)$ resonance, we obtain $\mathcal{S}_{K^{*0}\gamma} = -0.32^{+0.36}_{-0.33} \pm 0.05$ and $\mathcal{A}_{K^{*0}\gamma} = -0.20 \pm 0.24 \pm 0.05$.

BABAR and BELLE initial measurements highly limited by statistics

- **Each uses about ½   ab and gets conservatively ~0.80 for S**

- **Down the road with ~50 ab, optimistically S may result around .05**

- **That's around where it could get interesting**

- **For LHCb it may pay to focus on FS with only 1 photon:**

Bs => phi + gamma; K+ K- gamma; phi + rho^0 +gamma=>K+ K- pi+ pi- + gamma…

B0 => Ks rho gamma (for b=>s)

Summary + Conclusion p. 1 of 2

- **Naturalness arguments suggest existence of BSM phase**
- **Besides does not seem SM phase is enough to a/c for baryogenesis**
- **In this regard it is important to keep in mind our past experience:**

Indirect CP epsilon_K ~10^-3 ; several experiments gave up too soon

- **Much can be learned from focusing on CP studies, mixing-induced (time-dependent) as well as direct in radiative B, Bs decays using highest luminosities possible both with BELLE-II and also with LHCb runs**

Bottom line: Radiative b decays are extremely rich; they can teach us a lot

- **SU(N) gauge theories [Yang-Mills!] are very important.**
- **QCD is a very simple theory (# of parameters=1, theta’), hugely rich**

- **In particular for expts in IF …non-perturbative simulations have and will continue to teach us a lot…..supporting these is well worth the cost**

EXTRAS

Strategies for either definite gold or 0 gold

- Once Br (B => Xs gamma) is abot 0.1 SM open a separate pot for
- B=> K + pi + gamma ; Once Br (B=> K + pi + gamma) is about 0.2 of SM
- Once you are ~ 0.1 of SM soon start separating K vs no K;
- How many pots now?

- Ex BeLLe-II….2 sUbgroups….Yes CP and no CP

- Tables in Tim G + A S => Tables in T. Browder et al RMP => Tables in SBS + DA et al PR => Meaning of Life (NP) => CORRECTED & IMP. MOL –BSM CP