Direct CP: Challenges, Progress & Outlook

Amarjit Soni; HET-BNL

Myron Bander Memorial Symposium

UCI 6/8/13

outline

- **Prologue**
- **Challenges of Dir-CP**
- **Some Progress**
- **Insights from a candidate theory of flavor:**

  The importance of dir CP
- **Epilogue**

NOV 1977

PHYSICAL REVIEW LETTERS

Observation of Structure in the ϒ Region

Lem et al

Deserves a 2nd NP for inventing the reaction: junk + junk -> gems +X which has led to the discoveries of J, Upsilon, W, Z , top,…and remains the most powerful exploratory tool in our arsenal!!

CP Noninvariance in the Decays of Heavy Charged Quark Systems

Myron Bander, D. Silverman, and A. Soni
Department of Physics, University of California, Irvine, California 92717
(Received 9 May 1979)

Within the context of a six-quark model combined with quantum chromodynamics we study the asymmetry in the decay of heavy charged mesons into a definite final state as compared with the charge-conjugated mode. We find that, in decays of mesons involving the b quark, measurable asymmetries may arise. This would present the first evidence for CP noninvariance in charged systems.

Brands of CP

- Mixing

$|\epsilon_K| \approx 2.228 \times 10^{-3}$

$K_L \to \pi\pi$

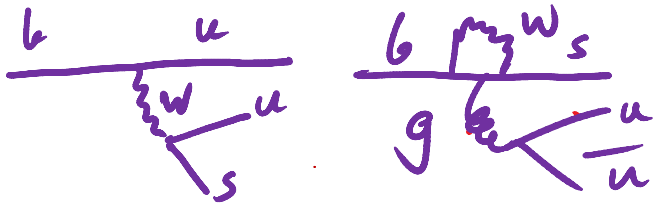
BNL '64

CRONIN + FITCH NOBEL

- Decay (direct, time-integrated)

Bander, Silverman, A.S, PRL'79

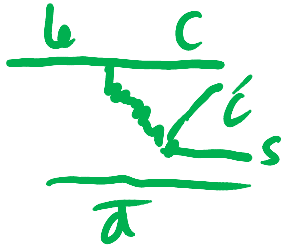
I e.g. $A_{CP}(B^0 \to K^+\pi^-)$, $A_{CP}(B^+ \to K^+\pi^0)$



II $R_e\, \epsilon'_K/\epsilon_K$ GILMAN + WISE '78

III $\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

- Mixing and decay (time-dependent)



$S(B^0 \to \psi K_0) \simeq \sin 2\beta \sim 0.673$

Leads to very accurate determination of sin 2β providing a very important test of CKM-paradigm

Carter & Sanda, PRL'80
Bigi & Sanda, NPB'81

Direct CP agalore!

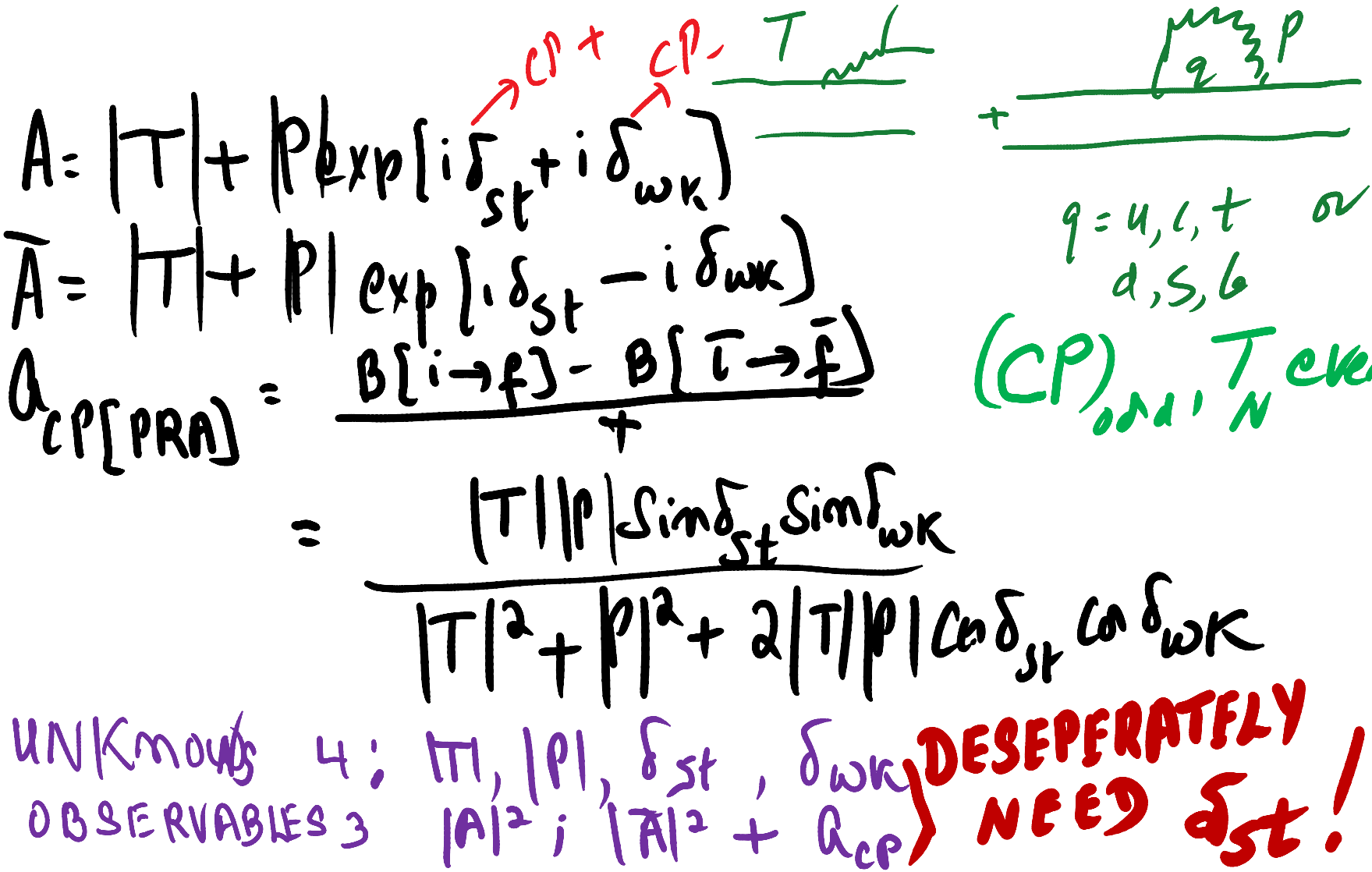
$\mathrm{Re}\,\epsilon'_K/\epsilon_K \sim 1.65\times10^{-3}$ Winstein et al KTEV + NA48 ....

- $A_{CP}(B^0 \to K^+\pi^-) = -0.098$
- $A_{CP}(B^+ \to K^+\pi^0) = +0.051 \pm 0.025$

} BABAR, BELLE '05-'06

- $\Delta A_{CP}(D^0) = -0.33 \pm 0.12\ \%$ LHCb, CDF, BELLE, BABAR

Direct CP: Long^2 standing challenge for theorists



Data driven "solutions"

- From Theory need non-perturbative framework..
- For K (ε'/ε) on going lattice efforts for ~30 years!
- [significant progress [by RBC-UKQCD]in related problem of the $\Delta I = 1/2$ PUZZLE , see arXiv:1212.1474;PRL] Lattice methods not available (yet) for D, B
- Resonance dominance ….width contains info of δ_{st}

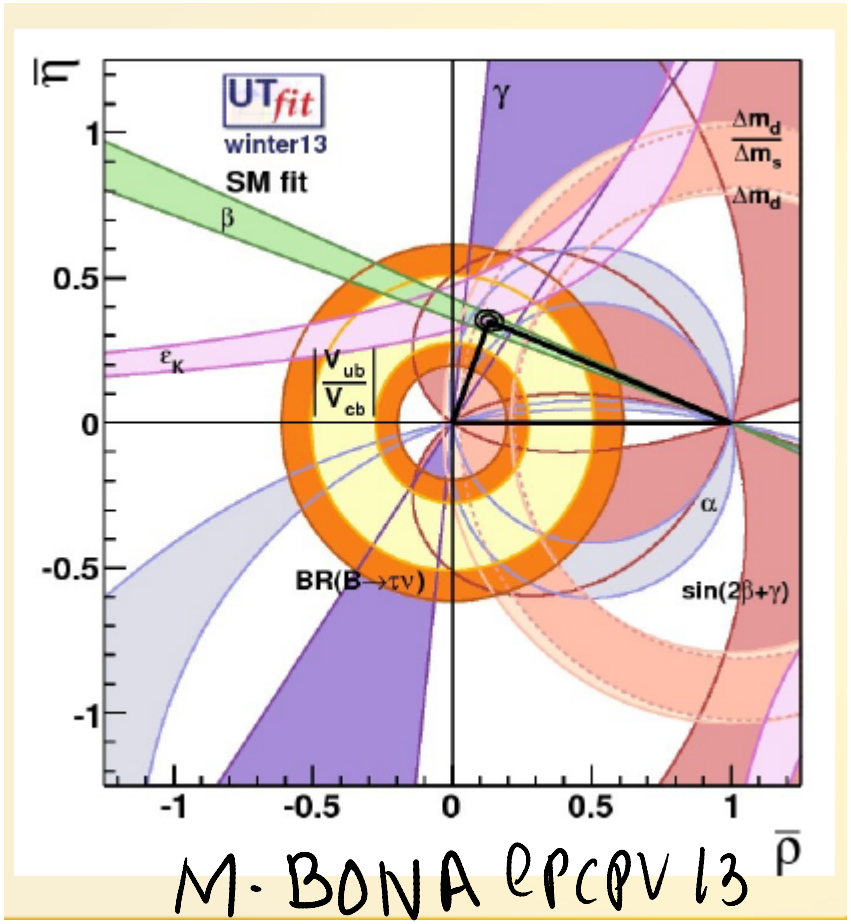
Eilam, Hewett, AS, PRL'91; Atwood+AS, Zphys'94

- $B^+ \Rightarrow D^0 K$ channels …..most precise determination of γ

Atwood,Dunietz,AS, PRL'97 ……

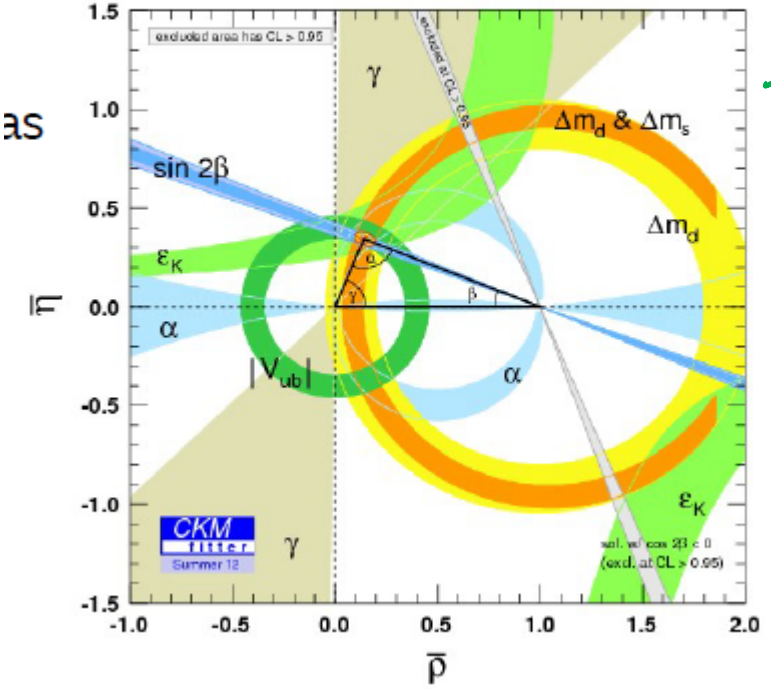
Now $\gamma \approx 70 \pm 10°$ S(LHCb)

Theory precision $\sim$ few $\times 10^{-3}$!! Belle II



M. BONA @PCPV 13

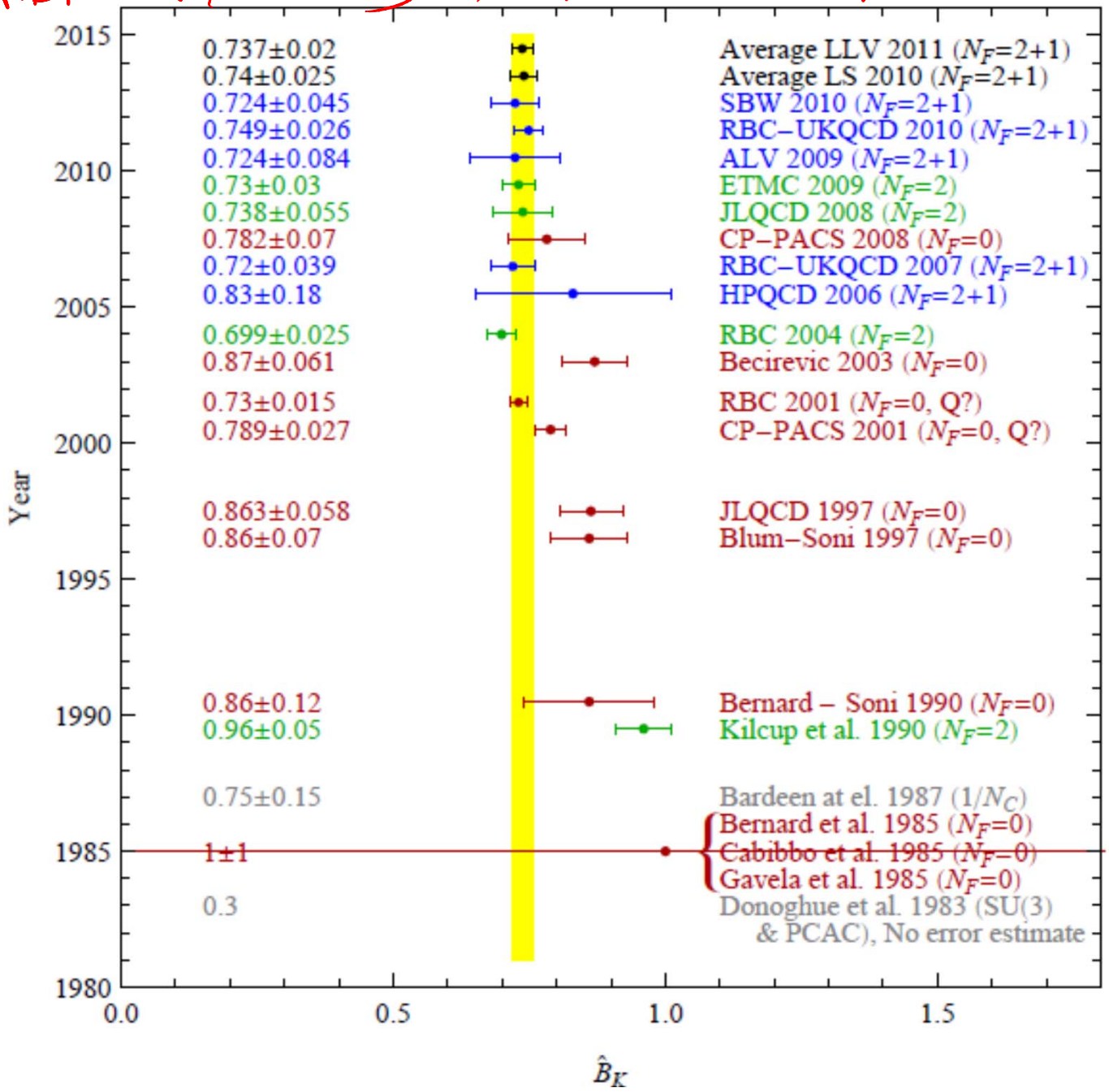
http://ckmfitter.in2p3.fr
see also http://www.utfit.org



T. GERSHON @BF2013

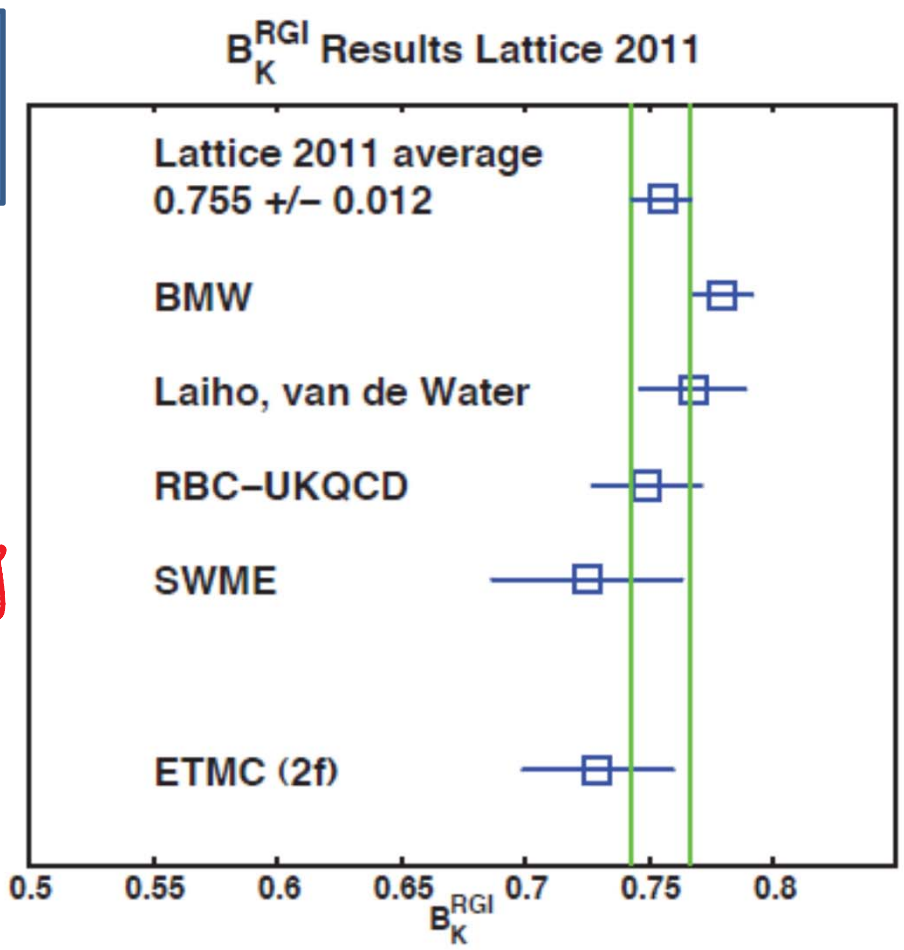
SM-CKM paradigm works rather well.
No glaring discrepancy
BTOH tests only ≈ 10–15% accuracy

A BRIEF (≈ 25 yrs) HISTORY OF B_K



Mawhinney, plenary LAT'11

Several Lattice groups using completely diff. methods reporting B_K with total error $\lesssim 3\%$!



HUGE STRIDES IN LATTICE CALCULATION OF BK!

- Average the four 2+1 flavor calculations presented
- Except for BMW, all are preliminary, although all groups have recently published B_K results from earlier datasets, so preliminary work should be fairly reliable.

See also recent summary by FLAG working group of FLAVIANET (arXiv:1011.4408)
They quote $\hat{B}_K = 0.728(20)$ for $N_f = 2+1$

Some of the issues/anomalies

- sin2β(measured-tree)=0.665 pm 0.024 vs
  Predicted from SM ~ 0.76 –0.82 (pm 0.05)
[depending on input used]

- sin2β (penguin) tends to be bit low ~0.58pm 0.07
- [extremely important test of flavor alignment]

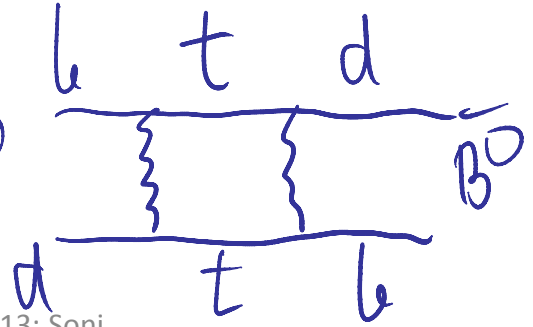
- V_{ub} excl ~(29.7 pm 3.1) vs (40.1 pm 4.7) incl X10^{-4}

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

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

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

OSC is COMMON



Grossman & Worah, hepph/9612269; London & AS,hepph/9704277

Persisting anomalies/puzzles

- Δ ACP : $A_{CP}(B^- \to K^-\pi^0) - A_{CP}(\bar{B}^0 \to K^-\pi^+)$ ≈ 5−(−9) ≃ 14%
- Sin2 β from SM fits tends to be higher than the "gold-plated" measurement by B-factories

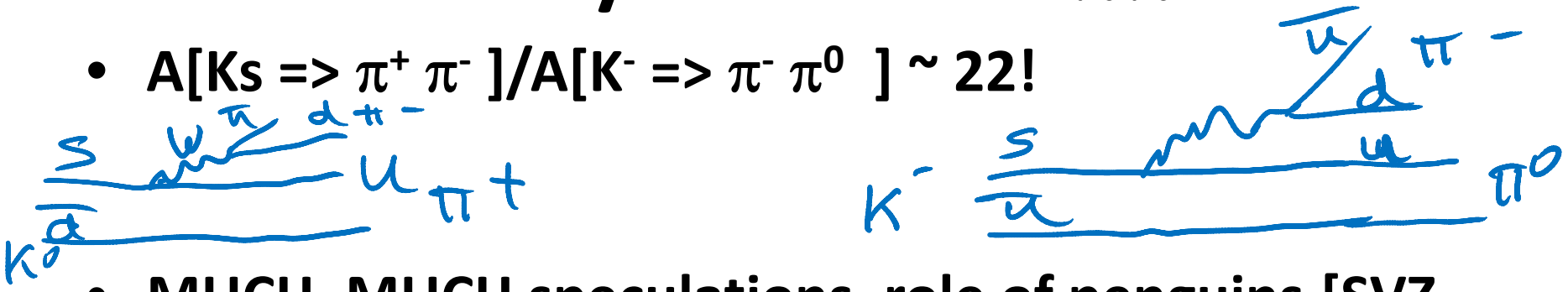
- Sin2 β from gold-plated (tree) modes tends to a bit higher than from penguin modes
- B=>τ ν ; B=> D(*) τ ν
- Charm direct CP seen is somewhat bigger than naïve quark-level expectations…..
- In all of these important issues, effects of QCD are providing a huge challenge for theory
- Lattice understanding of an ancient puzzle….

  FOOD FOR THOUGHT

CULPRIT: DIRECT CP!

$\Delta I=1/2$ Rule $K=>\pi\pi$

- **A[Ks => $\pi^+ \pi^-$]/A[K^- => $\pi^- \pi^0$] ~ 22!**



- **MUCH, MUCH speculations, role of penguins,[SVZ and the like]**

- **Folklore[see e.g. DGH book: section VIII-4]:**

"the factorization hypothesis works reasonably well in reproducing the experimental value of A2"

$$A(K^- \to \pi^- \pi^0) \sim f_\pi \langle K^- | \bar{u} \gamma_\mu s | \pi^- \rangle$$

Semi-leptonic

Ultimate goal (for ~30 yrs!) epsilon'/epsilon

Four stages

PhD

- ~1982 – 1994 .with Claude Bernard

WF, ChPT, QA

TD

- ~ 1995-1998 with Tom Blum

DWF, ChPT, QA

- 1998---2008 RBC

DWF, ChPT, QA → $N_F = 2$

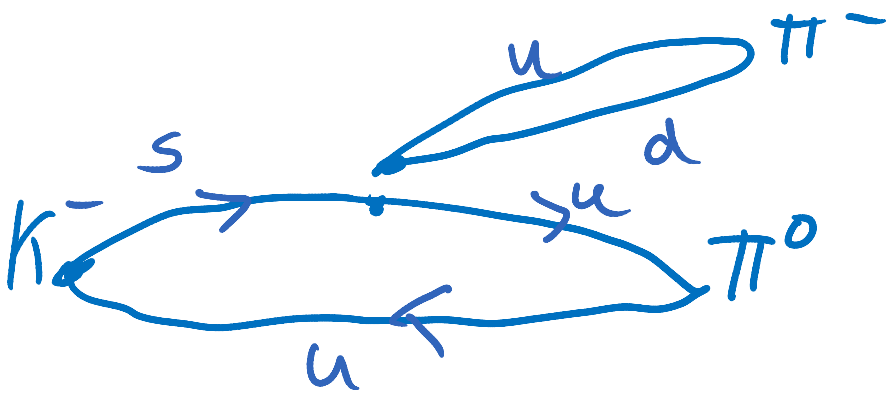
I.C
S.L
S.L

- 2008 -> present RBC-UKQCD

DWF, LL, $N_F = 2+1$ (Full QCD)

Q L

Dissecting 3/2 Amp on the lattice



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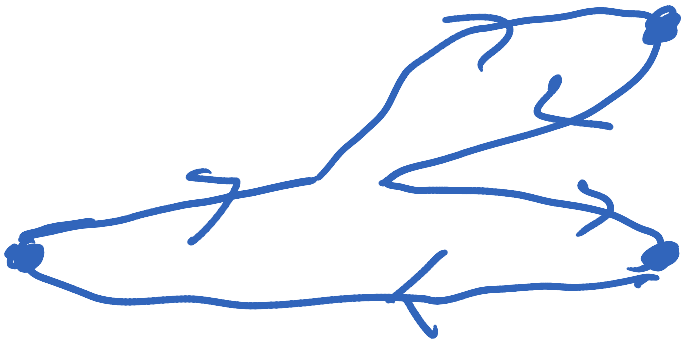
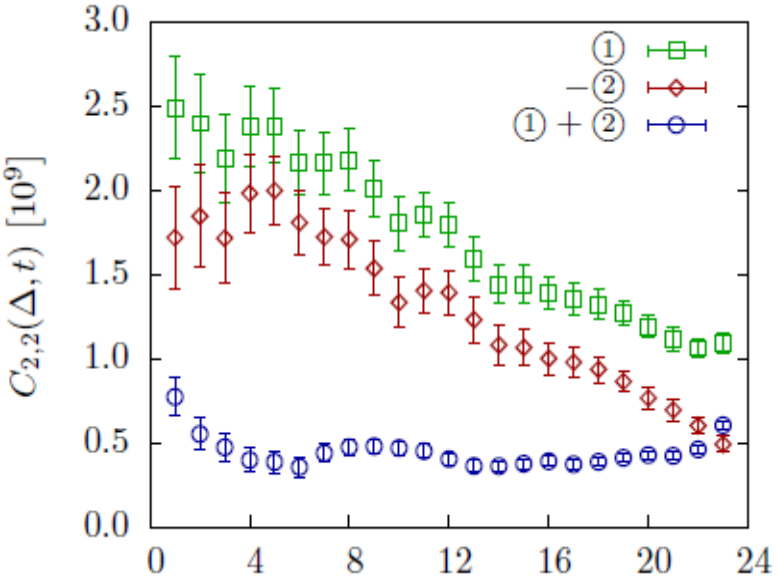


$T_1 \times T_1$

(N^2)

T_2 (N)

Simplest basic step is Significantly different from phenomenological expectations



DRAMATIC CANCELLATION!

RBC-UKQCD arXiv:1212.1474

Current status

	Experiment	$32^3 \times 64$ (IDSDR)	$24^3 \times 64$ (Iwasaki)	$16^3 \times 32$ (Iwasaki)
a^{-1}/GeV	-	1.375(9)	1.73(3)	1.73(3)
m_K/MeV	498	511	662	877
m_π/MeV	137	142.9	329	421
$\lvert\vec{p}_\pi\rvert/\mathrm{MeV}$	207	200	0	0
$\mathrm{Re}(A_2)/(10^{-8}\ \mathrm{GeV})$	1.479(4)	1.436(63)(258)	2.668(14)	4.911(31)
$\mathrm{Im}(A_2)/(10^{-12}\ \mathrm{GeV})$	-	-0.629(46)(120)	-0.6509(34)	-0.5502(40)
$\mathrm{Re}(A_0)/(10^{-8}\ \mathrm{GeV})$	33.20(2)	-	32.1(45)	45(10)
$\mathrm{Im}(A_0)/(10^{-12}\ \mathrm{GeV})$	-	-	-33(15)	-41(26)
$\mathrm{Re}(A_0)/\mathrm{Re}(A_2)$	22.45(6)	-	12.0(17)	9.1(21)
$\mathrm{Re}(\varepsilon'/\varepsilon)/10^{-3}$	1.65(26)	-	2.0(17)	2.7(26)

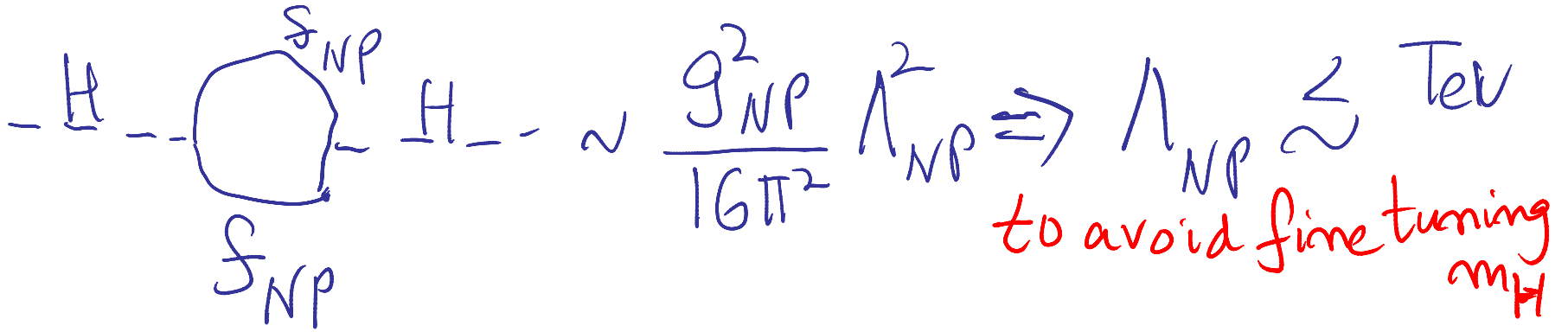
15%
50%

Stolen from Christoph Lehner

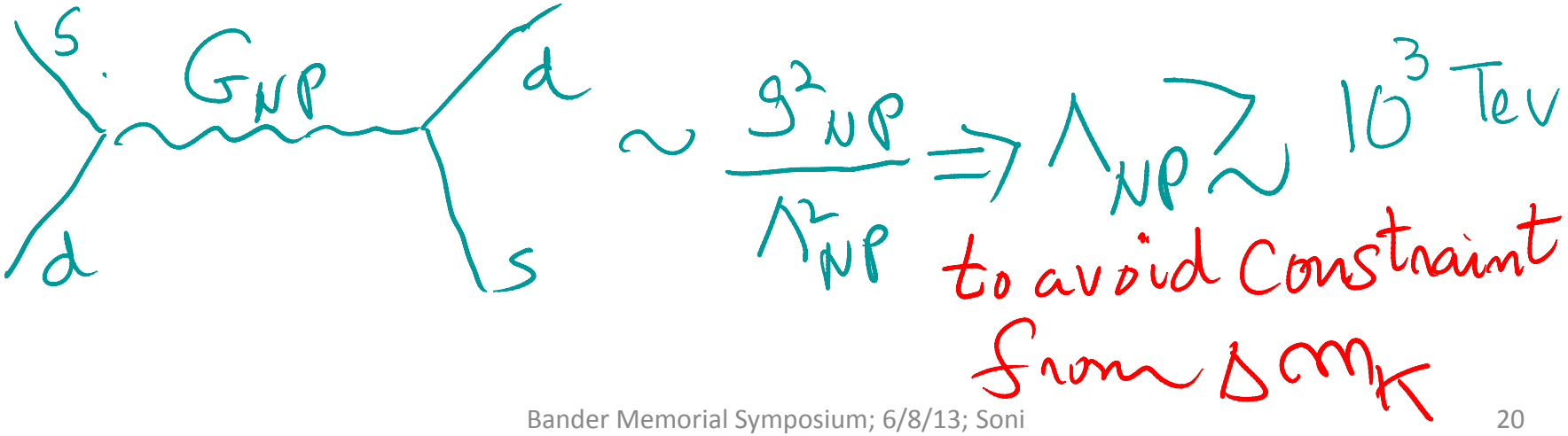
27 / 29

Outstanding Th.puzzles of our times

- **Hierarchy puzzle**

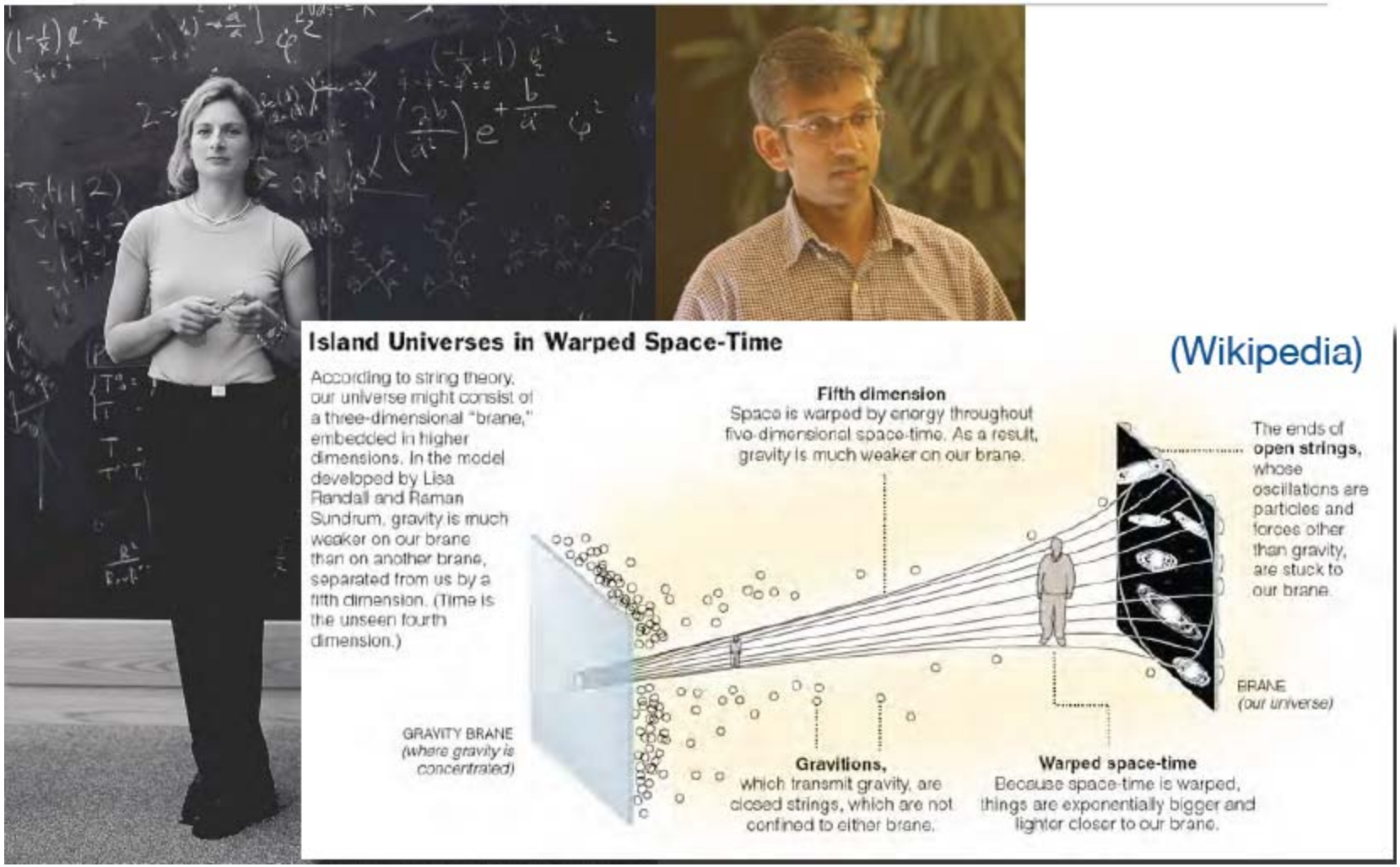


- **Flavor puzzle** $\Delta flavor = 2$ e.g.



INSIGHTS FROM A MODERN THEORY OF FLAVOR

The Randall-Sundrum (RS) idea

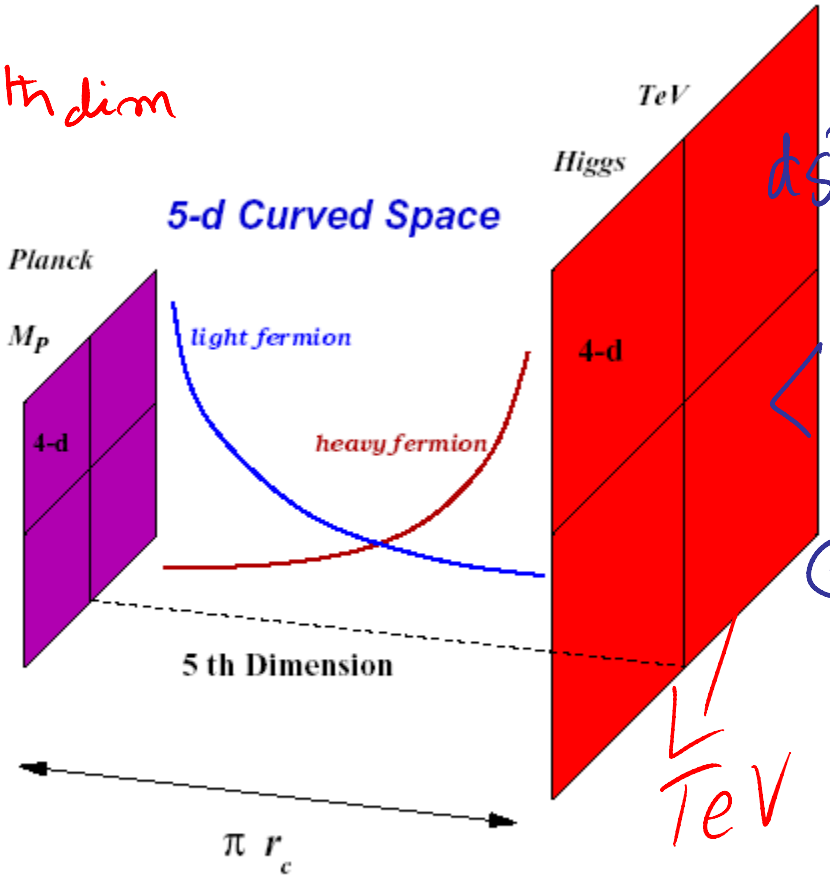


[Stolen from Neubert]

RANDALL+SUNDRUM '99

[FIG BY H DAVOUDIASL]

Points along 5th dim correspond to diff. eff. 4d scale!



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

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

$\sigma = k r_c \pi$

~ 12

TeV

M_P

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

Simultaneous resolution to hierarchy and flavor puzzles

Localization parameters of the 3-families of quarks

$$c_{Q_1} = -0.579\,, \quad c_{Q_2} = -0.517\,, \quad c_{Q_3} = -0.473$$

$$c_{u_1} = -0.742\,, \quad c_{u_2} = -0.558\,, \quad c_{u_3} = +0.339$$

$$c_{d_1} = -0.711\,, \quad c_{d_2} = -0.666\,, \quad c_{d_3} = -0.553$$

Table from M. Neubert @Moriond09

$\Rightarrow$ masses of the 6 quarks in RS!

Fermion "geography" (localization) naturally explains:

Grossman&Neubert; Gherghetta&Pomarol; Davoudiasl, Hewett & Rizzo

- **Why they are light (or heavy)**
- **FCNC for light quarks are severely suppressed automatically**
- **RS-GIM MECHANISM (Agashe, Perez,AS'04)** flavor changing transitions though at the *tree level* (resulting from rotation from interaction to mass basis)are suppressed roughly to the same level as the loop in SM=> CKM hierarchy
- **O(1) CP ubiquitous;…..nedm, in fact ALL DIR-CP [ε'/ε,ΔACP(B=>Kπ),Δ(Sin2β);S[B=>K* $\rho\gamma$]; ΔACP(D)..] are an exceedingly important path to BSM-phase and new physics**
- **Most flavor violations are driven by the top**

-> ENHANCED t-> cZ(h) ….A VERY IMPORTANT "GENERIC" PREDICTION..Agashe, Perez, AS'06

$\Delta m_K : 10^3$ TeV $\Rightarrow \sim 10$ TeV

EXTENSIVE RECENT STUDIES by BURAS et al and NEUBERT et al

Agashe, Perez, AS; Assumed $m_{KK} \sim 3$ TeV

TABLE I. Contrasting signals from RS1 with 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	$\Delta m_{B_s}^{\rm SM}[1 + O(1)]$	$O(1)$	$\sin 2\beta \pm O(0.2)$	$Br^{\rm SM}[1 + O(1)]$	$O(1)$	$O(1)$
SM	$\Delta m_{B_s}^{\rm SM}$	λ_c^2	$\sin 2\beta$	$Br^{\rm SM}$	$\frac{m_s}{m_b}(\sin 2\beta, \lambda_c^2)$	$\frac{m_d}{m_b}(\lambda_c^2, \sin 2\beta)$

→ Beall, Bander, AS PRL '82

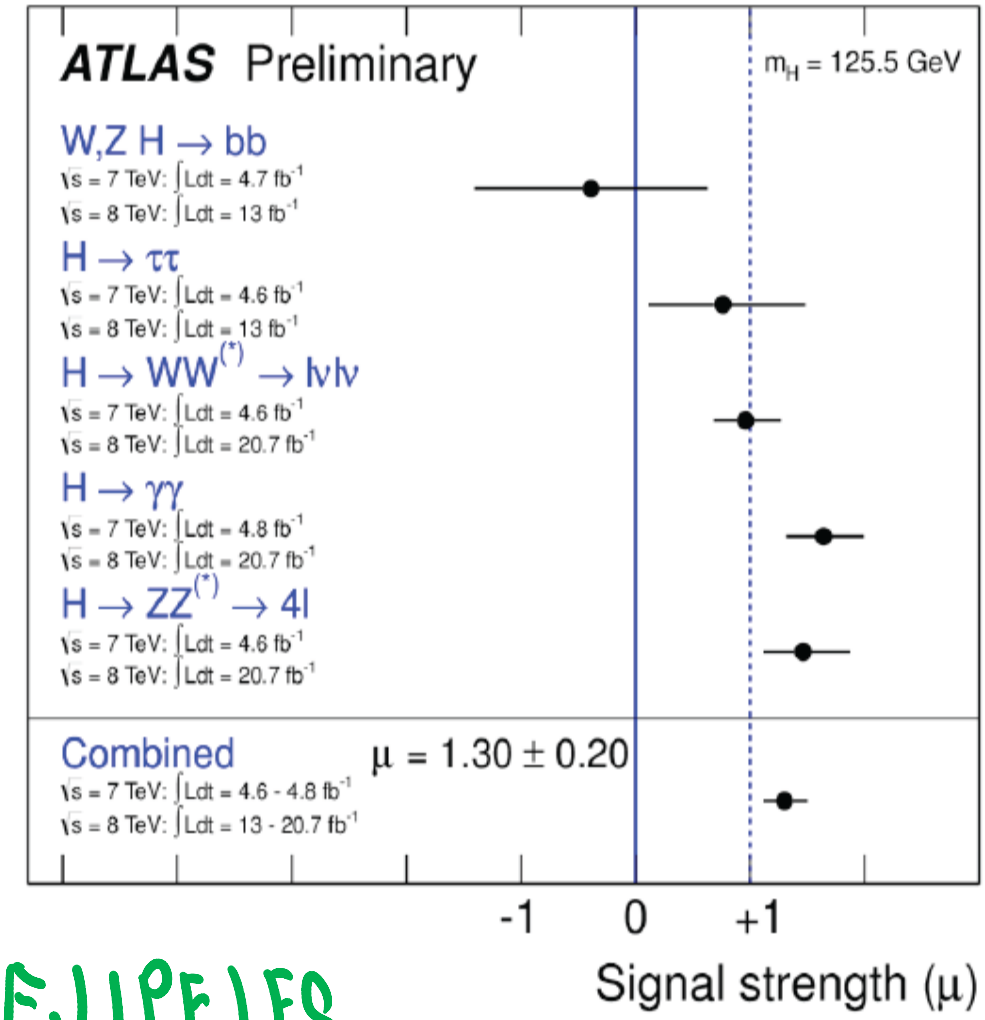
But LR currents cause conflict with $\Delta m_K, \epsilon_K$

$\Rightarrow m_{KK} \gtrsim 10$ TeV

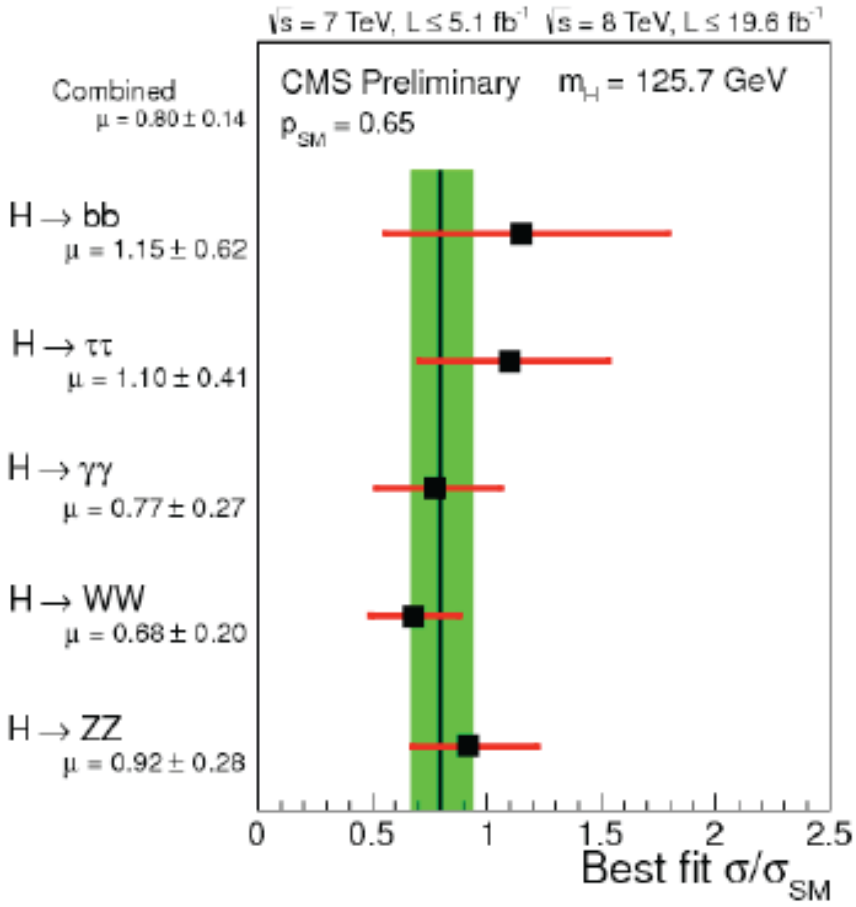
Above signals all become a lot smaller.

Messages from a candidate theory of flavor

- **Direct CP is an extremely powerful probe of flavor alignment and holds the key to unlocking new physics**
- **In a candidate theory, the gigantic tension between hierarchy and flavor puzzles gets dramatically amielorated.**



E. LIPELES CBF2013



μ=0.80±0.14

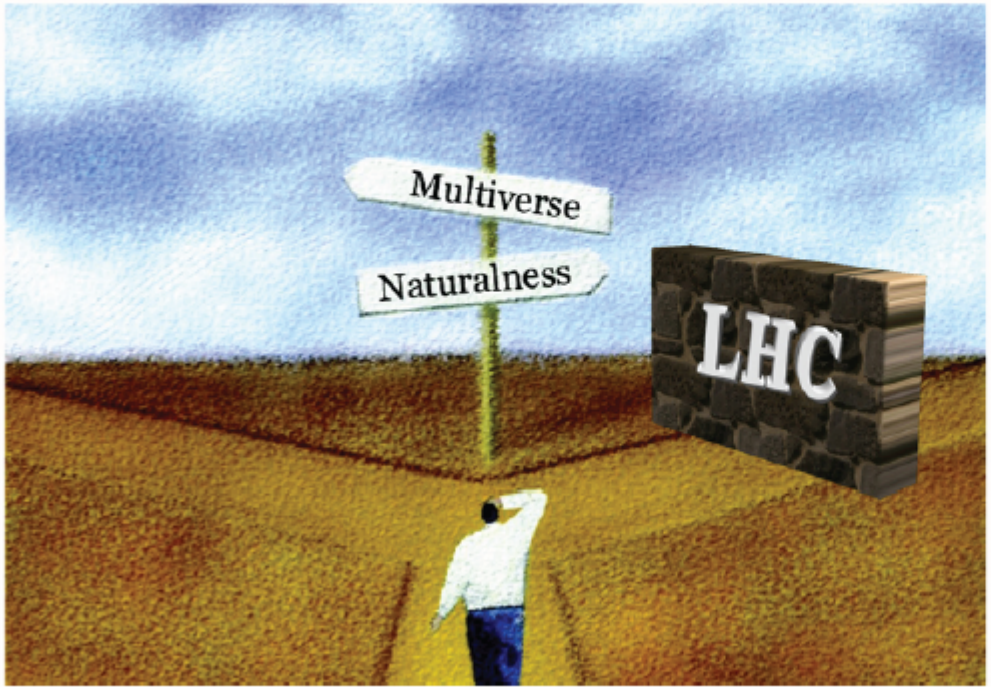
S. BOSE CBF2013

Is Nature Unnatural?

Decades of confounding experiments have physicists considering a startling possibility: The universe might not make sense.

by: Natalie Wolchover

May 24, 2013 email print



Is the universe natural or do we live in an atypical bubble in a multiverse? Recent results at the Large Hadron Collider have forced many physicists to confront the latter possibility. (Illustration: Giovanni Villadoro)

Solid or Liquid? Physicists Redefine States of Matter

Glass and other strange materials have long confounded textbook definitions of what it means to be solid. Now, two groups of physicists propose a new solution to the...

learn more

Computer Scientists Take Road Less Traveled

An infinitesimal advance in the traveling salesman problem breathes new life into the search for improved approximate...

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GEE, DON'T SEE NO NP SIGNALS
FLAVOR: TOLD YOU SO

Higgs is SM-like =>

- **Light SM-like Higgs strengthens case for mKK > ~ 10 TeV in warped framework**

See Azatov, Toharia, Zhu, arXiv 1006.5939
Goertz, Haisch, Neubert, 1204.0008
Davoudiasl, McElmurry, A. S. 1206.4062

- **With mKK> 10 TeV resulting set up is simpler and economical but at LHC only (at best) radion (Higgs-like scalar) possible**

Restate

- **Light SM-like Higgs strengthens case for mKK > ~ 10 TeV in warped framework; a conclusion that actually results from flavor physics**
- **RS framework provides a compelling simultaneous resolution of weak-planck hierarchy and flavor puzzle via an elegant geometric interpretation**
- **Provides a strong rationale for higher energy hadron collider for direct experimental verification**

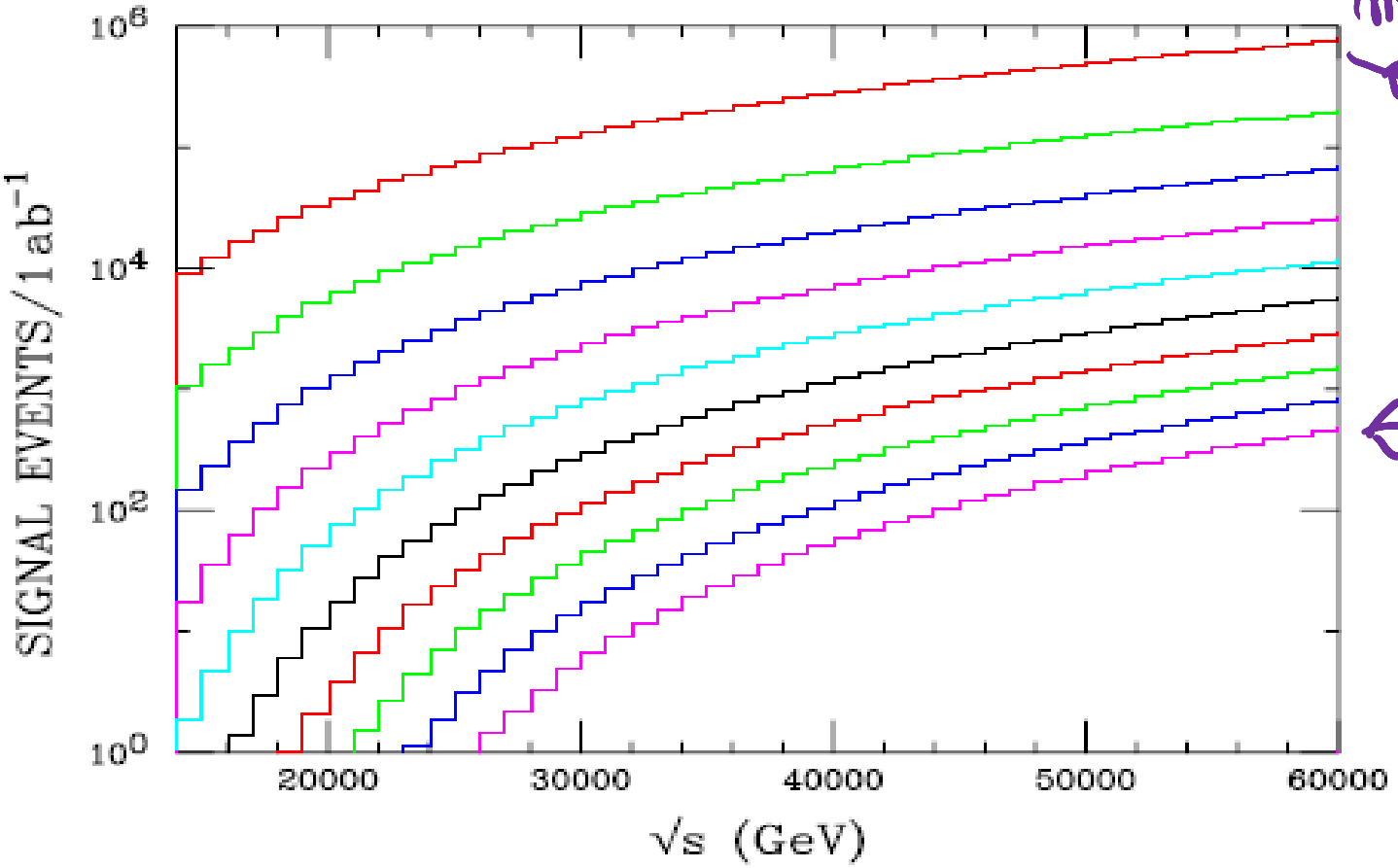


FIG. 10 (color online). Signal rate for a possible gluon KK resonance as a function of the collider energy employing the cuts described in the text. Branching fractions and efficiencies have been neglected. From top to bottom, the results are shown for gluon KK masses in the range from 3 to 12 TeV in steps of 1 TeV.

Davoudiasl,Rizzo,AS,PRD'08

KKg → tt̄

Lesson learnt from ν's

~ Circa 1983, after long and arduous efforts, Δm^2 upper bound used to be around a few ev^2 but efforts to Search oscillations continued basically because there was no good theoretical reason for m_ν to be zero.

- ***Recall it took more than a decade beyond '83*** **and Δm^2 had to be lowered by almost 4 orders of magnitude (!) before osc were discovered.**
- **Moral: Physical "principles" shouldn't be abandoned easily …..We'll just have to work harder to get to it**

Recall SSC ~40 TeV 1990 technologically completely feasible.

We should be SERIOUSLY THINKING of

GIGANTIC INTERNATIONAL HADRON COLLIDER [GIHC]

~ 100 TeV CM

"GEEK"

Adapted from Browder

A lesson from history (I)

"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \rightarrow \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

-Lev Okun, "The Vacuum as Seen from Moscow"

1964: BF= 2×10^{-3}

A failure of imagination ? Lack of patience ?

Christenson, Cronin, FITCH + TURLAY BNL '64

DRAWING STRONG CONCLUSIONS BASED on 20% tests is too risky.

Expected Progress

- **Expect more data from LHCb => …..S(LHCb)**

- **SuperKeKB/BellII X 40 more Lumi….**
  [A HUGE DEVELOPMENT FOR OUR FIELD!]

- **In addition lattice (more powerful computers + numerous theoretical & technical developments), for the 1st time simulations with physical m_π …….**

- **So in ~ 5 years expect significantly tighter tests**

Crucial message from an illustrative modern theory of flavor

- **O(1) CP ubiquitous;…..nedm, in fact ALL DIRCP[ε'/ε,ΔACP(B=>Kπ),Δ(Sin2β); S[B=>K* $\rho\gamma$], ΔACP(D)..] are an exceedingly important path to BSM-phase and new physics**
- **Precision tests should be given high priority**

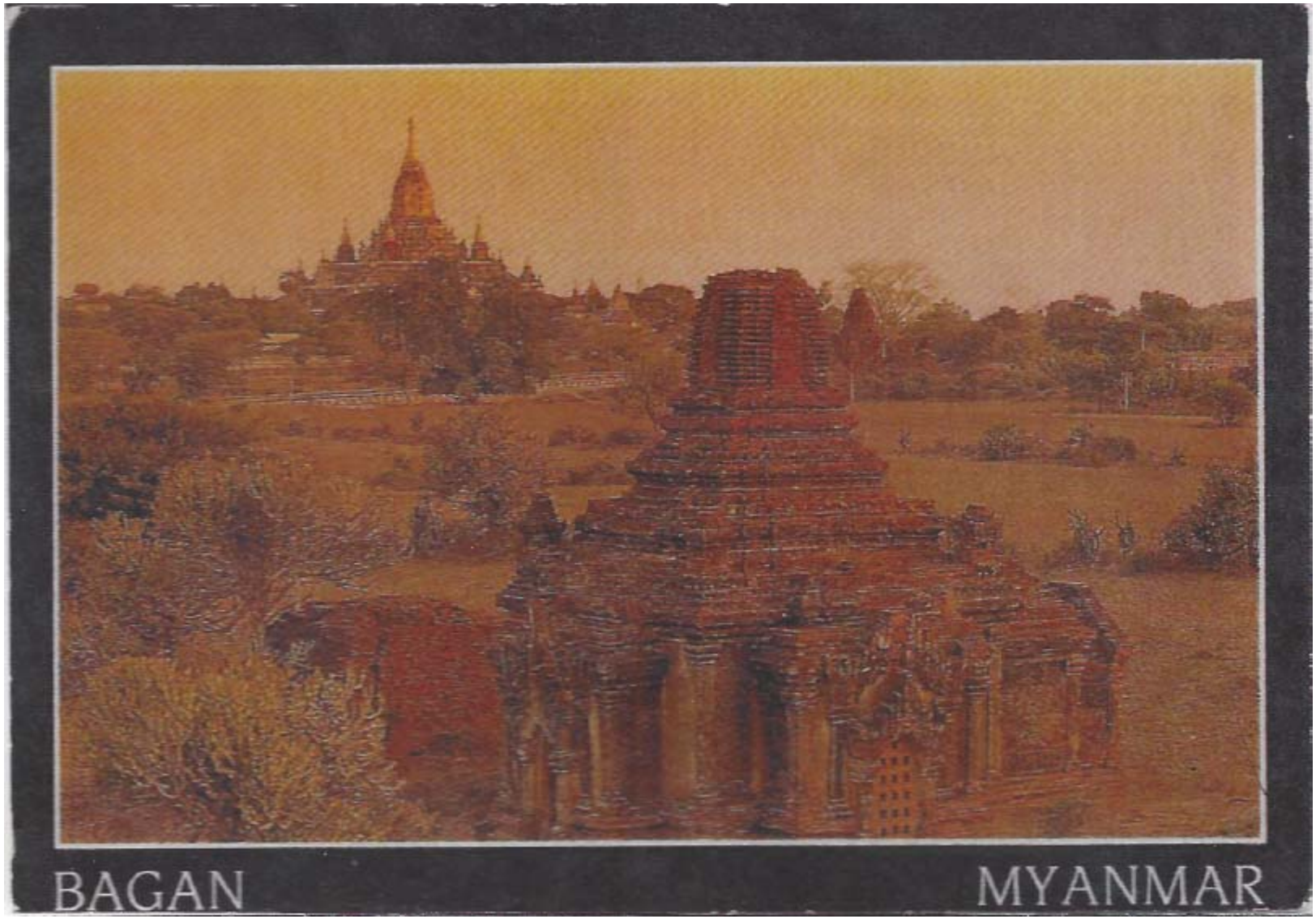
Thank You MYRON for starting me off on an interesting path!

Drop A Pebble In The Water

Drop a pebble in the water:
just a splash, and it is gone;
But there's half-a-hundred ripples
circling on and on and on,
Spreading, spreading from the center,
flowing on out to the sea.
And there is no way of telling
where the end is going to be.

Drop a pebble in the water:
in a minute you forget,
But there's little waves a-flowing,
and there's ripples circling yet,
And those little waves a-flowing
to a great big wave have grown;
You've disturbed a mighty river
just by dropping in a stone.

James W Foley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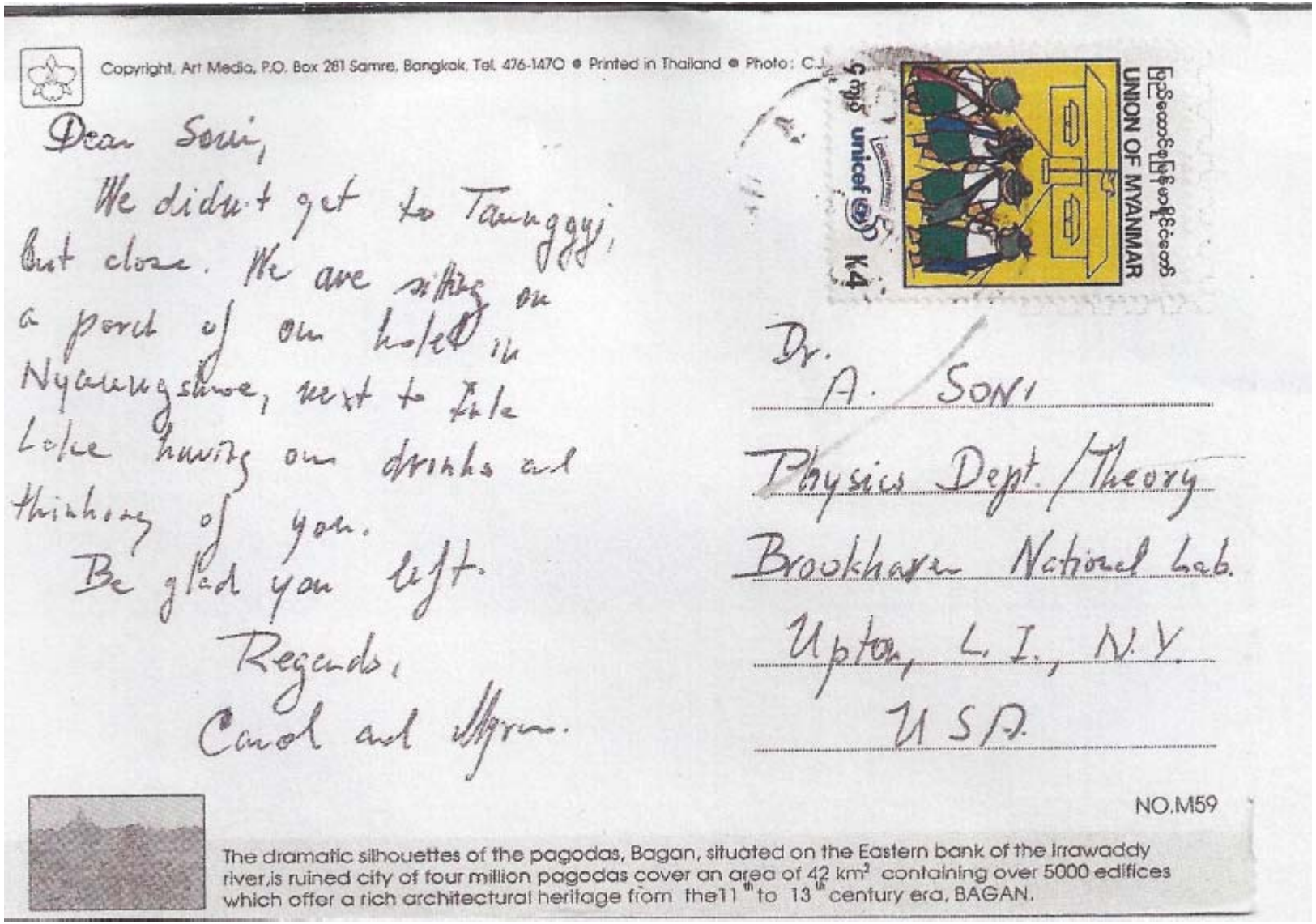
MYANMAR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UNION OF MYANMAR
unicef
K4
Dear Soni,
We didn't get to Taunggyi, but close. We are sitting on a porch of our hotel in Nyaungshwe, next to Inle Lake having our drinks and thinking of you.
Be glad you left.
Regards,
Carol and Myron.
Dr. A. Soni
Physics Dept./Theory
Brookhaven National Lab.
Upton, L.I., N.Y.
U.S.A.
NO.M59
The dramatic silhouettes of the pagodas, Bagan, situated on the Eastern bank of the Irrawaddy river, is ruined city of four million pagodas cover an area of 42 km² containing over 5000 edifices which offer a rich architectural heritage from the 11th to 13th century era. BAGAN.

Chalets

INLE PRINCESS RESORT, INLE LAKE, Near Tamegyi, Myanmar