If you are interested in Greek & Roman Art, visiting Central Montemartini is a most definite must!

It being housed in an old power station makes it almost unique.

If you follow my advice & visit it, but do not like it -- I promise to never bother you with my advice again.

If you like it, tell the authorities how much you like it!

LNF 05

Hadronization -- the Hero rather than the Villain in the Tale of CP Violation

Ikaros Bigi, Notre Dame du Lac

SM has recently scored not merely more or even new successes, but novel ones!

predicted `Paradigm of large $\cancel{C}P$' in B decays confirmed:

indirect, direct $\cancel{C}P$ & $\cancel{T}$

$B \to \psi K_S$, $B \to \pi^+ \pi^-$, $B \to K\pi$

However -- these novel successes do not illuminate any of the mysterious features of the SM; if anything, they deepen the mysteries:

(i) electroweak symmetry breaking

$$SU(2)_L \times U(1) \rightarrow U(1)_{QED}$$

(ii) family structure

$$Q_e = 3\ Q_d$$

(iii) finite family replication

$$Z^0 \rightarrow 3\ \nu\nu$$

n.b.: (i), (ii), (iii) not necessarily related possible illuminations/explanations

for (i): `confidently predicted' NP at ~ 1 TeV = cpNP

e.g., SUSY

for (ii): `guaranteed' NP at ~ $\mathcal{O}(10^{11})$ TeV = gNP

e.g., SO(10)

for (iii): CKM pattern most unlikely accidental

➥ `strongly suspected' NP at ??? scale = ssNP

e.g., ??? (M theory ??)

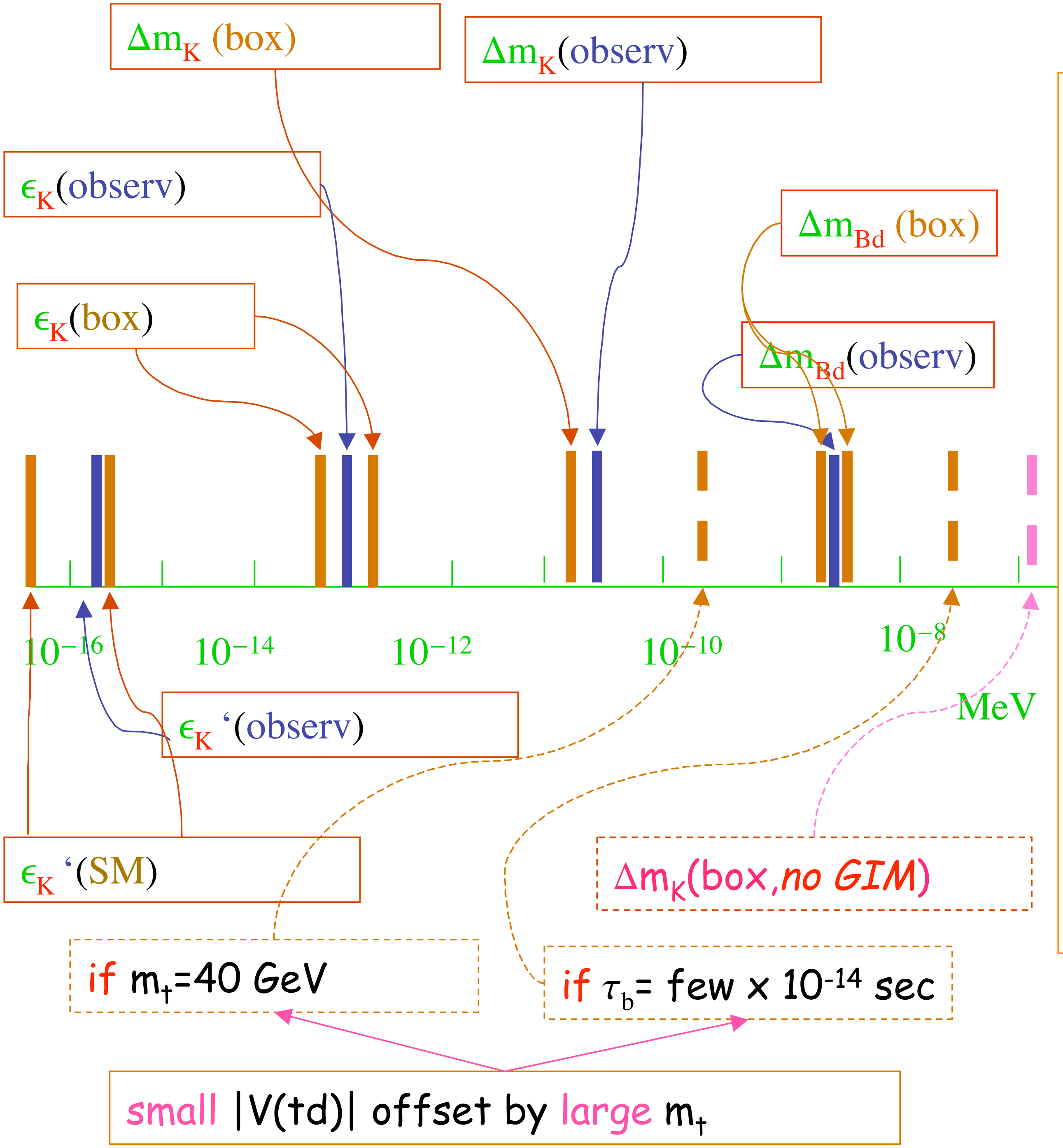
heavy flavour studies for q & l might -- just might -- provide insights into (iii) & (ii) -- but they will be crucial for identifying the cpNP

➥ heavy flavour studies complementary to high p_T studies at LHC & Linear Collider two-fold message

❶ ~ TeV scale dynamics likely to have some impact on B decays

❷ yet -- due to past `unlikely' success of CKM cannot count on massive manifestation of New Physics, at least not in B decays

- ➥ need presumably high experim. & theoret. accuracy in flavour studies
  - ➻ requires better quantitative understanding of hadronization to exhaust discovery potential in B decays!



Δm_K (box)

Δm_K(observ)

ϵ_K(observ)

ϵ_K(box)

Δm_{Bd} (box)

Δm_{Bd}(observ)

ϵ_K '(observ)

ϵ_K '(SM)

Δm_K(box,*no GIM*)

if m_t=40 GeV

if τ_b= few x 10^{-14} sec

small |V(td)| offset by large m_t

can be reproduced with

|V(us)|~ 0.22,|V(ts)|~0.04

|V(td)|~ 0.004

m_u~5 MeV,m_c~1.2 GeV

m_t≈180 GeV,m_d ~10 MeV

m_s~0.15 GeV,m_b≈4.6 GeV

observables spanning several orders of magnitude accommodated with

parameter choices that a priori would seem frivolous!

There could easily have been inconsistencies!

The Menu

Prelude: Singing the Praise of Hadronization

I Extracting V(cb) as a Lesson

II Case Studies of Hadronization as a Difficult Ally

III τ Decays -- the New Frontier

IV Summary

Prelude: Singing the Praise of Hadronization

hadronization (& nonperturbative dynamics in general) usually viewed as unwelcome complication (if not outright nuisance)

case in point:

$$\left.\begin{array}{l}\text{large fraction of } \Delta m_K,\ \epsilon_K,\ \Delta m_B \\ \text{most of } \epsilon_K' \end{array}\right\} \begin{array}{l}\text{could be due} \\ \text{to New Physics}\end{array}$$

correct --

yet such perspective misses the deeper truth without hadronization no formation of bound states

- no K^0-$\overline{K}^0$ oscillations
  - no indirect $\not{C}P$: Im M_{12} ~$\mathcal{O}(10^{-8}$ eV)!
  - no direct $\not{C}P$ a la ϵ'
- no B^0-$\overline{B}^0$ oscillations
  - no $\not{C}P$ in $\Delta B=2$: ~$\mathcal{O}(10^{-4}$ eV)
  - no New Physics in $\Delta B=2$

hadronization

- reduces CP √ $K_L \to 3\pi$ by ~ 500 due to hadronic PhSp
- awards `patience'; i.e. you can `wait' for pure K_L beam
- generates CP signal in existence rather than asymmetry

> hadronization -- the hero rather than the villain in the tale of $\not{C}P$!

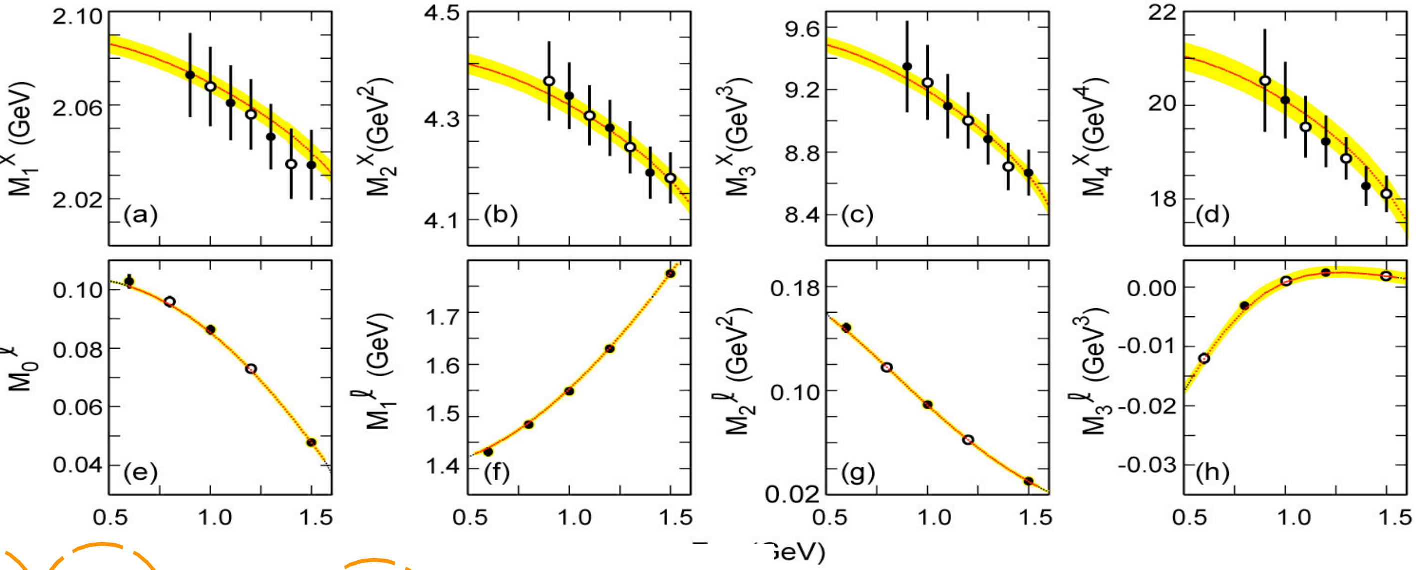
I Extracting V(cb) as a Lesson

need

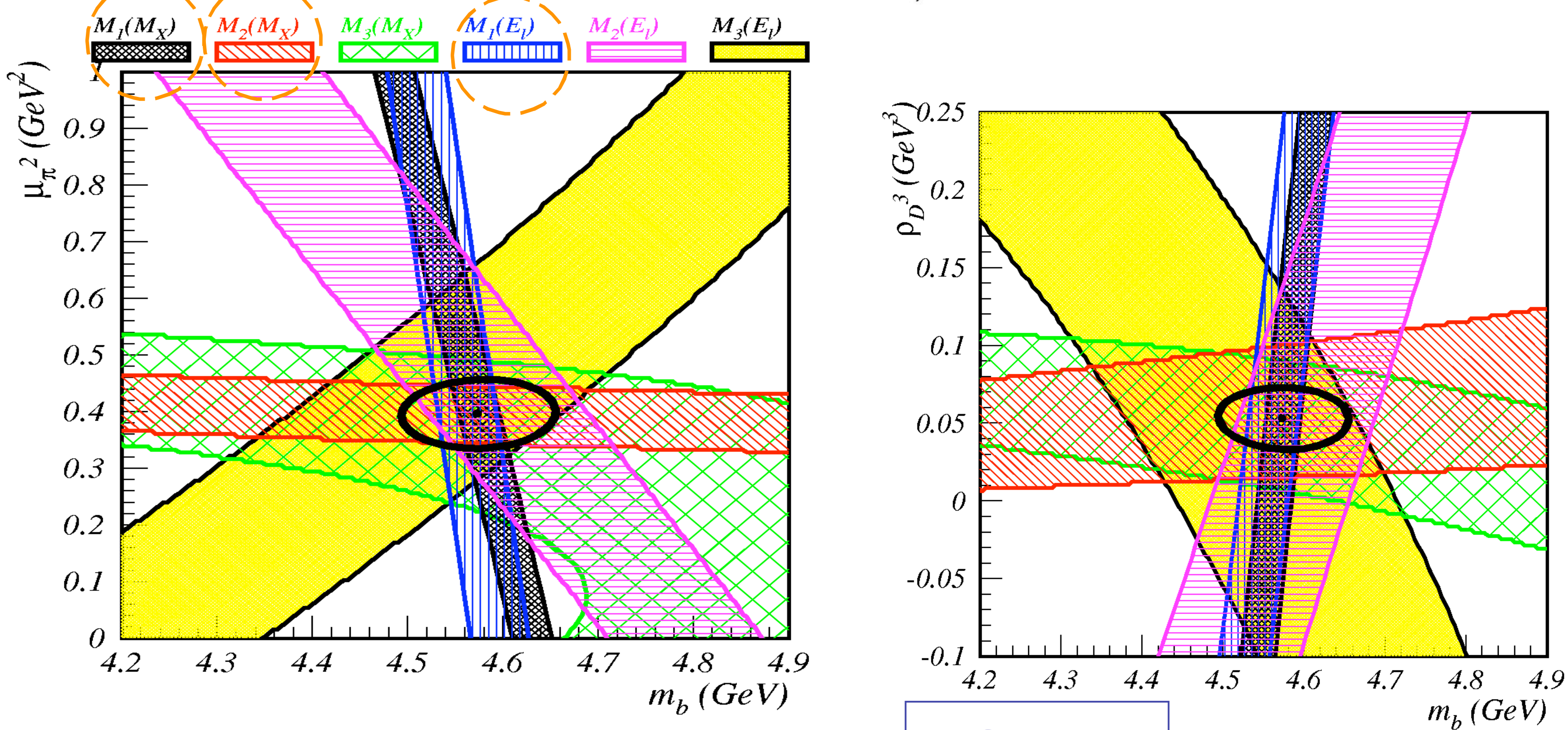
- robust theoretical framework:
  - ✔ $1/m_Q$ expansions, Sum Rules, LQCD
- comprehensive & detailed data
  - ✔ SL B decays, lepton spectra, moments …

❑ excellent description of large set of data points in terms of 6 or even merely 4 parameters: m_b, m_c, μ_π^2, ρ_D^3, (μ_G^2, ρ_{LS}^3)

❑ a priori free fit parameters assume values obeying various theoretical constraints and knowledge!



BABAR



DELPHI

$m_b(1\ \mathrm{GeV})|_{B\to l\nu X_c} = 4.61 \pm 0.068\ \mathrm{GeV}$ BaBar
$m_b(1\ \mathrm{GeV})|_{Hb\to l\nu X_c} = 4.575 \pm 0.069 \pm 0.043 \pm 0.005\ \mathrm{GeV}$ DELPHI
$m_b(1\ \mathrm{GeV})|_{\Upsilon(4S)\to bb} = 4.57 \pm 0.08\ \mathrm{GeV}$

$m_c(1\ \mathrm{GeV}))|_{B\to l\nu X_c} = 1.18 \pm 0.092\ \mathrm{GeV}$ BaBar
$m_c(1\ \mathrm{GeV})|_{Hb\to l\nu X_c} = 1.144 \pm 0.106 \pm 0.071 \pm 0.020\ \mathrm{GeV}$ DELPHI
$m_c(1\ \mathrm{GeV}))|_{cc\ SR} = 1.19 \pm 0.11\ \mathrm{GeV}$
$m_c(1\ \mathrm{GeV}))|_{cc\ SR} = 1.30 \pm 0.03\ \mathrm{GeV}$

$m_b(1\ \mathrm{GeV}) - m_c(1\ \mathrm{GeV})|_{B\to l\nu X_c} = 3.436 \pm 0.032\ \mathrm{GeV}$ BaBar
$m_b(1\ \mathrm{GeV}) - m_c(1\ \mathrm{GeV})|_{Hb\to l\nu X_c} = 3.431 \pm ?\ \mathrm{GeV}$ DELPHI
$m_b(1\ \mathrm{GeV}) - m_c(1\ \mathrm{GeV})|_{MB-MD} = 3.48 \pm 0.02 \pm ?\ \mathrm{GeV}$

$\mu_\pi^2(1\ \mathrm{GeV})|_{B\to l\nu X_c} = 0.447 \pm 0.053\ \mathrm{GeV}^2$ BaBar
$\mu_\pi^2(1\ \mathrm{GeV})|_{Hb\to l\nu X_c} = 0.399 \pm 0.047 \pm 0.039 \pm 0.020\ \mathrm{GeV}^2$ DELPHI
$\mu_\pi^2(1\ \mathrm{GeV})|_{QCDSR} = 0.45 \pm 0.1\ \mathrm{GeV}^2$
$\mu_G^2(1\ \mathrm{GeV})|_{HF} = 0.35 \pm 0.03\ \mathrm{GeV}^2$

Status '04

$m_b(1\ \text{GeV}) = (4.61 \pm 0.068)\ \text{GeV}$ ← 1.5 %

$m_c(1\ \text{GeV}) = (1.18 \pm 0.092)\ \text{GeV}$ ← 7.8 %

$m_b(1\ \text{GeV}) - 0.74\ m_c(1\ \text{GeV}) = (3.74 \pm 0.017)\ \text{GeV}$ ← 0.5 %

$|V(cb)| = (41.390 \pm 0.870)\times 10^{-3}$ ← 2.1 %

vs.

$|V(us)|_{KTeV} = 0.2252 \pm 0.0022$ ← 1.1 %

~ % level precision!

$\delta|V(ub)| = \pm 5$ % achievable

II Case Studies of Hadronization as a Difficult Ally

`classic' examples: ΔM_K, ϵ, ϵ'

role of $\pi-\pi$ phase shifts, η- η' wavefunctions, σ resonance etc.

four case studies concerning B decays, where hadronization can be employed as a powerful tool -- *if* applied judiciously:

❶ Semileptonic B decays and charm spectroscopy

❷ Extracting ϕ_1 from B → 3 kaons

❸ Extracting ϕ_2 from B → pions

❹ Extracting ϕ_3 from B → DK: the power of the Dalitz plot

II.1 Case I: `1/2 > 3/2 Puzzle'

3 motivations for understanding charm spectroscopy

- to extract $\Gamma_{SL}(B)$ and its error from data
- to extract $B \to l \nu D/D^*$ and their errors
- impact on sum rules for $B \to l \nu D(s_q = 1/2 \text{ or } 3/2)$
  relating HQP $\rho^2(\mu)$, $\Lambda(\mu)$, $\mu^2_\pi(\mu)$ with
  observables in SL B decays

Heavy hadrons H_Q labeled by total spin S and by $j_q = l_q + s_q$:

- ground states: $[S|l_q|j_q] = [0,1|0|1/2]$: P & V
- 1st excit. states: $[0,1|1|1/2]$ & $[1,2\ |1|3/2]$

$$\sim H_{Pauli} = - A_0 + (i\partial - \mathbf{A})^2/2m_Q + \sigma\mathbf{B}/2m_Q \quad \to - A_0 \quad \text{as } m_Q \to \infty$$

HQ Sum Rules

☞ $\rho^2(\mu) - 1/4 = \Sigma_n |\tau_{1/2}^{(n)}|^2 + 2\,\Sigma_m |\tau_{3/2}^{(m)}|^2$ Bj 1990

☞ $1/2 = -\,2\,\Sigma_n |\tau_{1/2}^{(n)}|^2 + 2\,\Sigma_m |\tau_{3/2}^{(m)}|^2$ U 2000

☞ $\overline{\Lambda}(\mu) = 2\,(\Sigma_n\, \epsilon_n |\tau_{1/2}^{(n)}|^2 + 2\,\Sigma_m\, \epsilon_m |\tau_{3/2}^{(m)}|^2)$ Vo 1992

☞ $\mu^2_\pi(\mu)/3 = \Sigma_n\, \epsilon_n^2 |\tau_{1/2}^{(n)}|^2 + 2\,\Sigma_m\, \epsilon_m^2 |\tau_{3/2}^{(m)}|^2$ BiSUVa 1994

☞ $\mu^2_G(\mu)/3 = -2\,\Sigma_n\, \epsilon_n^2 |\tau_{1/2}^{(n)}|^2 + 2\Sigma_m\, \epsilon_m^2 |\tau_{3/2}^{(m)}|^2$ BiSU 1997

where: $\tau_{1/2}$ & $\tau_{3/2}$ denote transition amplitudes for

$B \to l\,\nu\, D(s_q = 1/2 \text{ or } 3/2)$ with excitation energy $\epsilon_k \leq \mu$

➥ rigorous definitions, inequalities + experim. constraints

☞ “1/2 > 3/2” puzzle (Uraltsev, Orsay group):

SR: $\Sigma_n |\tau_{1/2}^{(n)}|^2 < 2 \Sigma_m |\tau_{3/2}^{(m)}|^2$

$\Sigma_n \epsilon_n^2 |\tau_{1/2}^{(n)}|^2 < 2\Sigma_m \epsilon_m^2 |\tau_{3/2}^{(m)}|^2$

experim. indications (DELPHI):

sum rules not saturated by lowest P wave states
(yet most recent BELLE data consistent with SR)

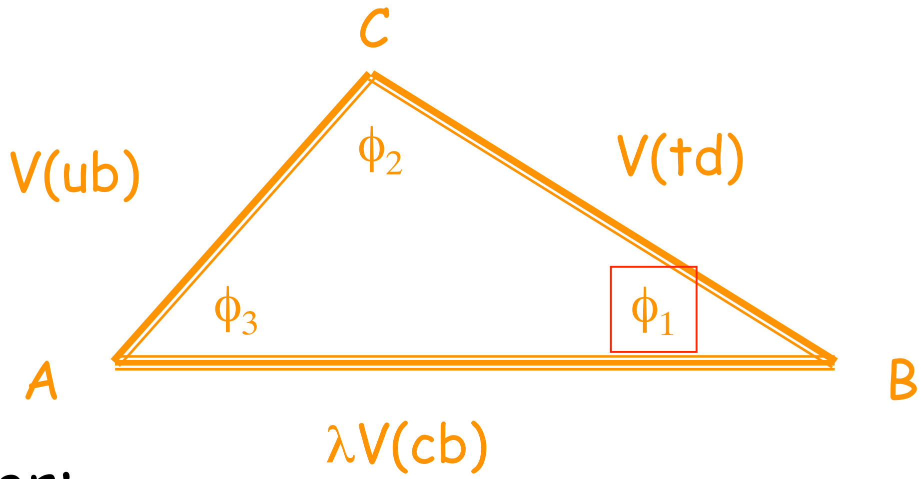
general lesson:

we need to understand charm spectroscopy

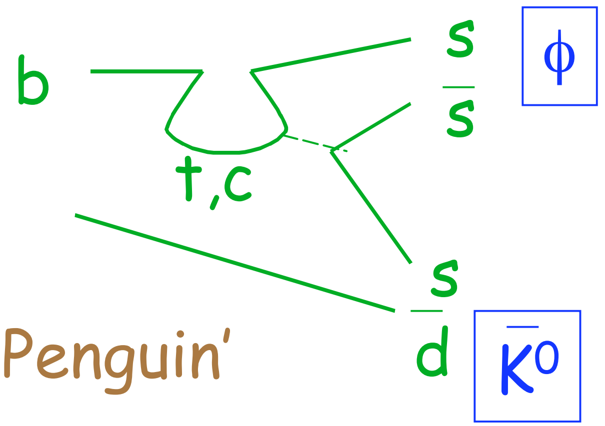
➼ to extract a precise value for V(cb) [& V(ub)]

➼ to avoid either faking a signal for a (V+A)x(V-A) component in SL B decays or missing a real signal

II.2 Case II: ϕ_1 from ~~CP~~ in $B_d \to$ 3 kaons



1 decay operator:



`Penguin'

predict in SM:

$\sin 2\phi_1 (B_d \to \psi K_S) \approx \sin 2\phi_1 (B_d \to \phi K_S)$

measure

$\sin 2\phi_1 = 0.726 \pm 0.037$ from $B_d \to \psi K_S$

Summer 2003

- BELLE: $\sin 2\phi_1^{eff} = -0.96 \pm 0.5 \pm 0.010$
- BABAR: $\sin 2\phi_1^{eff} = +0.45 \pm 0.43 \pm 0.07$

Summer 2004

[hep-ex/0408072]

“$\sin 2\phi_1$” $= +0.50 \pm 0.25 \, {}^{+0.07}_{-0.04}$

A $= 0.00 \pm 0.23 \pm 0.05$

[hep-ex/0409049]

“$\sin 2\phi_1$” $= +0.06 \pm 0.33 \pm 0.09$

A $= +0.08 \pm 0.22 \pm 0.09$

ϕK^0

SVD1:

S = −0.68 ± 0.46

A = −0.02 ± 0.28

4.5% (MC) ↔

SVD2:

S = +0.78 ± 0.45

A =+0.17 ± 0.33

many systematic checks, all ok

Summer 2005

measure

$\sin 2\phi_1 = 0.685 \pm 0.032 \pm ??$ from $B_d \rightarrow \psi K_S$

$$\text{“}\sin 2\phi_1\text{”} = +0.44 \pm 0.27 \pm 0.05$$
$$A = -0.14 \pm 0.17 \pm 0.07$$

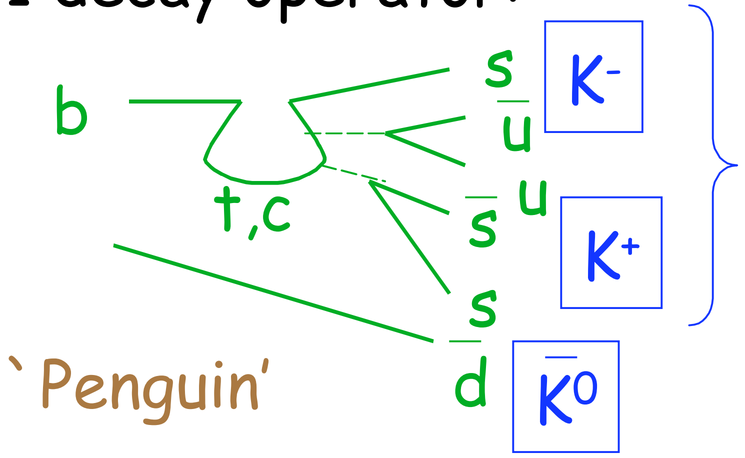
Summer 2003

- BELLE: $\sin 2\phi_1^{eff} = -0.96 \pm 0.5 \pm 0.010$

Summer 2004

$$\text{“}\sin 2\phi_1\text{”} = +0.06 \pm 0.33 \pm 0.09$$
$$A = +0.08 \pm 0.22 \pm 0.09$$

1 decay operator:



$\phi, f_0(980)$, …

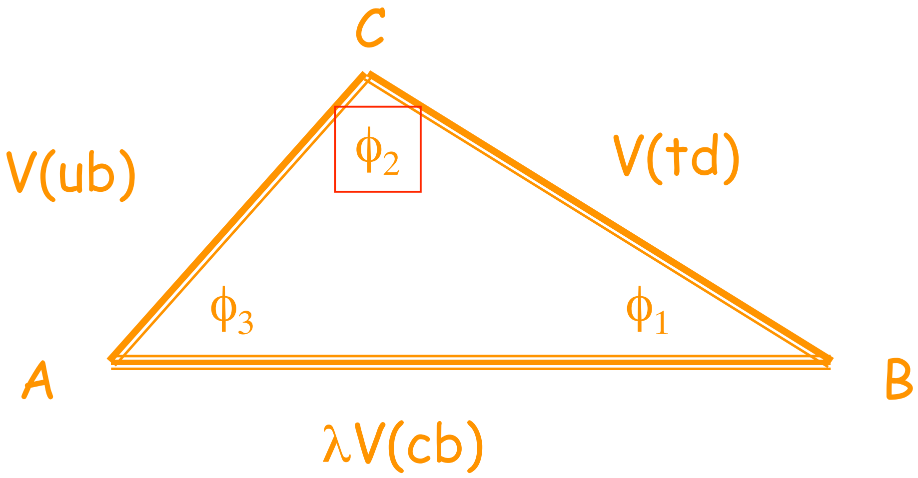
$\cancel{CP}(B_d \to \phi K_S) = - \cancel{CP}(B_d \to f_0(980) K_S)$

i.e., a smallish `pollution' by $f_0 K_S$

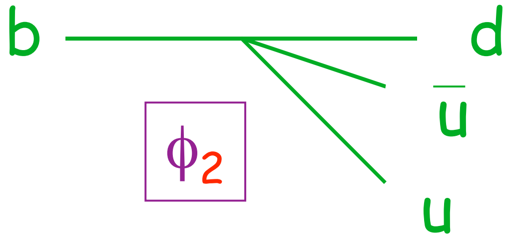
reduces $\cancel{CP}$ observed in ϕK_S

- ➥ need to perform full Dalitz plot analysis for
  - ❑ $B_d \to K^+ K^- K_S$,
  - ❑ $B_d \to K_S K_S K_S$
  - ❑ $B^+ \to K^+ K^- K^+$,
  - ❑ $B^+ \to K^+ K_S K_S$

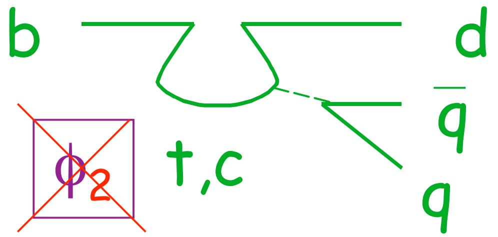
II.3 Case III: ϕ_2 from $\not{C}P$ in $B_d \to$ pions



2 operators contribute:



\`tree'



\`Penguin'

\`pollution'

blame us -- not the Penguins!

to isolate `pollution' through isospin decomposition:

- $B^{0,\pm} \to \pi^{+,0}\pi^{-,0}, \pi^{\pm}\pi^{0}$

  challenging experimentally, yet reliable theoretically

- $B^{0,\pm} \to \rho^{+,0}\pi^{-,0}, \rho^{\pm}\pi^{0}, \pi^{+,0}\rho^{-,0}, \pi^{\pm}\rho^{0}$

less challenging experimentally, yet reliable theoretically??

$B \to \pi\pi\pi$: $\rho\pi$ vs. $\sigma\pi$ vs. ?? (U. Meissner, S. Gardner)

- $B^{0,\pm} \to \rho^{+,0}\rho^{-,0}, \rho^{\pm}\rho^{0}$

even better experimentally, yet even worse theoretically

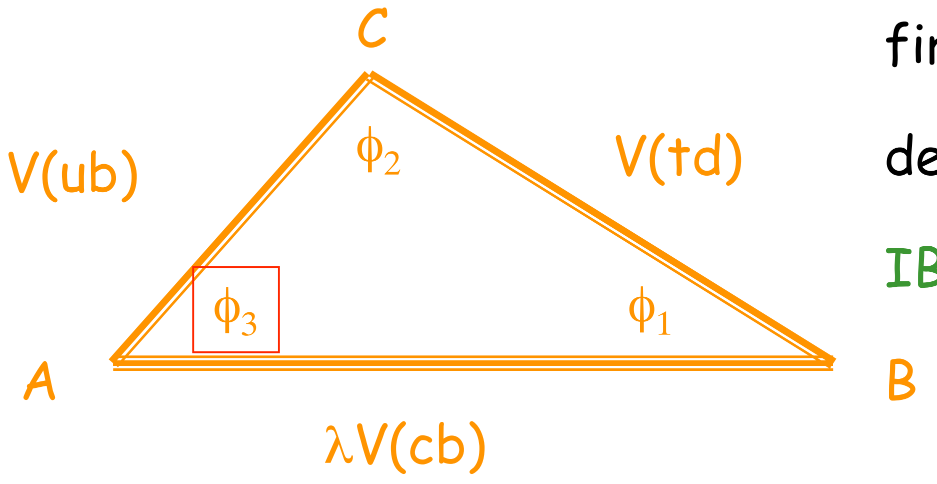
$B \to \pi\pi\pi\pi$: $\rho\rho$ vs. $\sigma\rho$ vs. $\sigma\sigma$ vs. $\rho\pi\pi$ vs. $\sigma\pi\pi$ vs. ...

memento: precision -- say ±5% --required!

➥ need expertise from low-energy hadronization

(chiral dynamics, Dalitz plot)

II.4 Case IV: ϕ_3 from $\cancel{C}P$ in $B^\pm \to D^{neut}K^\pm$



first mentioned by Sanda in '80

dedicated paper

IB, A.Sanda, PLB211 ('85)213

$$\begin{tikzcd} & D^0K^- \arrow[dr] & \\ B^- \arrow[ur] \arrow[dr, "\boxed{\phi_3}"'] & & f_{common} \\ & \overline{D}^0K^- \arrow[ur] & \end{tikzcd}$$

vs.

$$\begin{tikzcd} & D^0K^+ \arrow[dr] & \\ B^+ \arrow[ur, "\boxed{-\phi_3}"] \arrow[dr] & & f_{common} \\ & \overline{D}^0K^+ \arrow[ur] & \end{tikzcd}$$

original idea: $f_{common} = h_1h_2$ -- $K_S\pi^0, K^+K^-, \pi^+\pi^-, K^+\pi^-, K^-\pi^+$

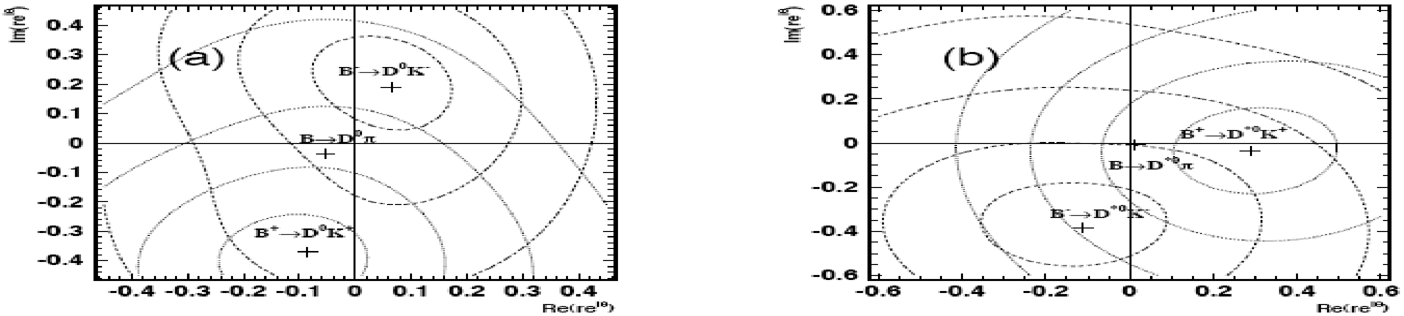
drawback: small BR's

new idea implemented by BELLE:
use $f_{common} = K_S\pi^+\pi^-$ coupled with Dalitz plot analysis
requires a lot of investment if effort -- yet pays
handsome profit in cross checks $\Longrightarrow$ confidence!

A. Poluektov *et al.* (Belle Collaboration), `hep-ex/0406067`, to appear in PRD.

Using $B^\pm \to DK^\pm$ and $B^\pm \to D^*K^\pm$ $(D^* \to D\pi^0)$

$$\phi_3 = 77^\circ\,{}^{+17^\circ}_{-19^\circ}(\text{stat}) \pm 13^\circ(\text{syst}) \pm 11^\circ(\text{model})$$



I consider it still a pilot study -- yet a very promising one -- showing the power of using hadronization as a (difficult) ally

III τ Decays -- the New Frontier

SM forbidden τ decays

$\tau \rightarrow \mu/e\,\gamma$

$\tau \rightarrow 3\,l$

if New Physics in $b \rightarrow sss$ ≈ New Physics in $\tau \rightarrow \mu\mu\mu$

then $BR(\tau \rightarrow \mu\mu\mu) \sim 10^{-8}$

$\cancel{CP}$ in τ decays

observed baryon # of Universe might be induced by primary leptogenesis

- ➥ need & want to observe CP in leptodynamics

3 \`promising' areas

- ν oscillations
- EDM's of electrons & atoms
- τ decays
  - ☞ CPT less restrictive
  - ☞ Higgs couplings less suppressed

~~CP~~ in τ decays

most promising channels: $\tau \to \nu K \pi$

- most sensitive to Higgs dynamics
- CP asymmetries possible also in final state distributions rather than integrated rates
- unique opportunity for $e^+e^- \to \tau^+\tau^-$

  pair produced with spins aligned:
  1 τ decays can `tag' the spin of the other
  ➥ can probe spin-dependent ~~CP~~ with unpolarized beams!
- confidently predicted ~~CP~~:

  0.0033 in $\Gamma(\tau^+ \to \nu K_S \pi^+)$ vs. $\Gamma(\tau^- \to \nu K_S \pi^-)$
  -- due to K_S's preference for antimatter

IV Summary

- persuasive evidence SM is incomplete pointing to New physics conceivably at the ~ TeV scale
  - ✍ goal must be not only to establish presence of New Physics, but also its features
    - ➼ justification for ILC
    - ➼ same justification applies also to flavour factories!
- in next 5-10 years huge data sets of unprecedented quality
  - ➥ theory can no longer hide behind experim. uncertainties!
- cannot count on massive intervention of New Physics
  - ➥ must add aspect of `high accuracy' to that of `high sensitivity'

- treat hadronization = nonperturbative dynamics as your ally -- albeit a complex and sometimes quirky one -- rather than as a nuisance

cannot be done by theory tools alone --

will need input from studies of ππ, KK, Kπ final state interact.

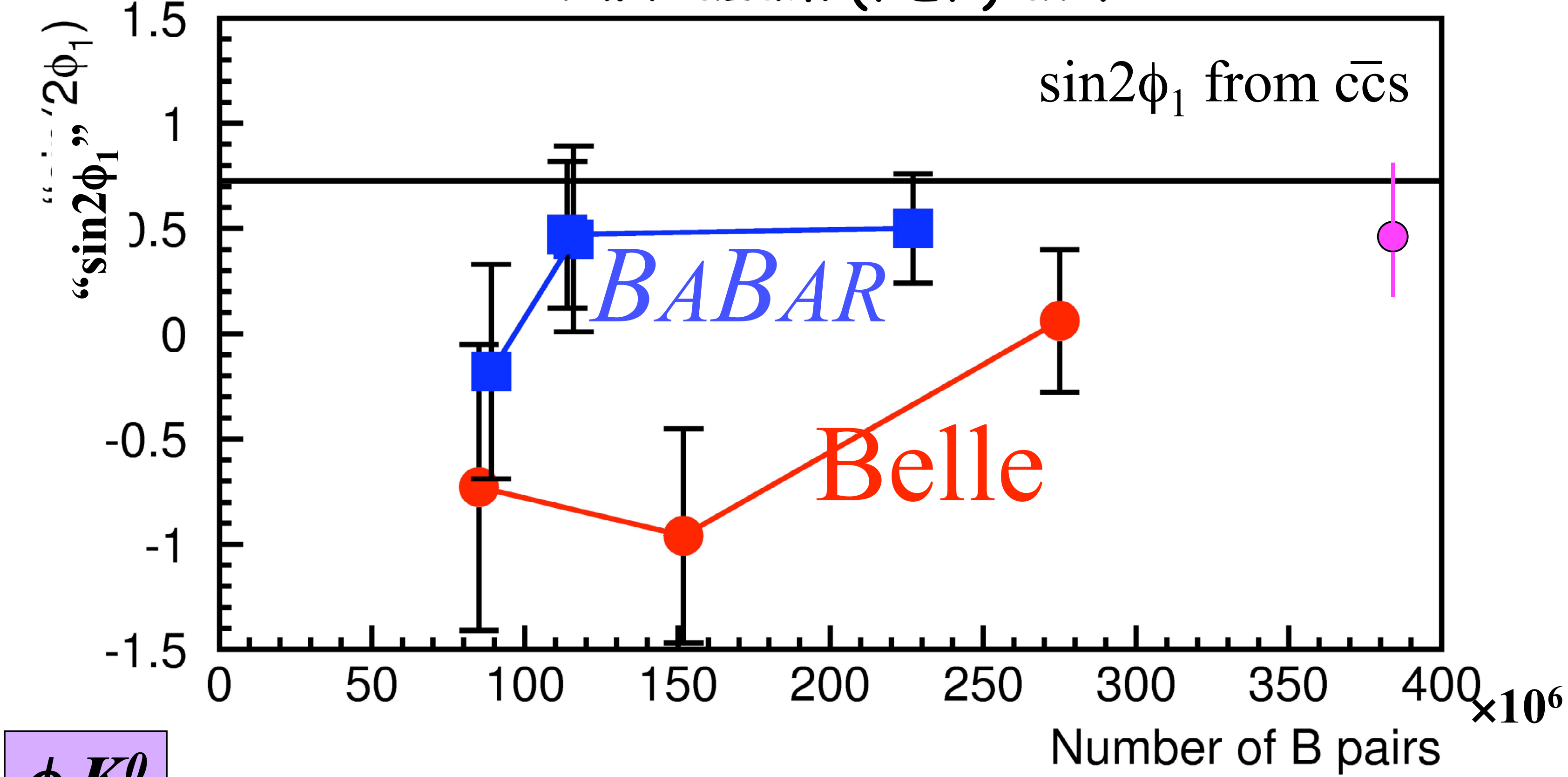
- at low energies
- in D → 3π, Kππ, KKπ, … lνKπ, lνππ
- B → multi-neutrals

i.e., complementarity with Mike Pennington's talk!

Memento: Swiss watches became famous by being reliable & sturdy, not necessarily elegant back-up slide item # 5

History of "$\sin2\phi_1$" with ϕK^0

M. Hazumi(KEK) at FPCP04



ϕK^0

SVD1:
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$A = -0.02 \pm 0.28$

4.5% (MC)

↔

SVD2:
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many systematic checks, all ok