CERN, May 2008

I was asked to give a talk
"B-Physics Theory Overview".
I was told by somebody,
who prefers to remain anonymous
-- can you guess? --
this obviously means
"Buras-Physics Overview".
Since it is even more impossible to do that in 30 min.,
I decided to specify the title differently ---

CERN, May 2008

B Decay Dynamics -- an Overview

Ikaros Bigi, Notre Dame du Lac

First an appeal to LHC experiments:

Try very, very hard to search for

$$\tau \to 3\mu, \ldots$$

desirable range ~ 10^{-8} - 10^{-10}

Will address measurements that

- can be made at the LHC

- are relevant for LHC studies, even if cannot be done here

Prologue

- 3 inter-related aspects of B dynamics
  - indirect probes for New Physics (NP)

    observed rate ≠ predicted rate

  - ew SM decay dynamics

    SM parameters ⟹ accurate SM predictions

    {quarks, gluons, …} ⟺ {hadrons,…}

  - hadronization
    - validate theoret. control over QCD
    - learn (novel ?) lessons on QCD

☞ QCD might just be the first of theories realized in nature with essential nonperturb. dynamics

- We cannot count on numerically massive impact of TeV scale NP on B decays -- larger than anticipated operational success of B factories suggest typical impact smallish
  - → need reliability & accuracy
- ☞ sign of hope: $\bar{\Lambda}/m_b \ll 1$

Heavy Quark Symmetry ≈ Heavy Quark Expans.

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

i.e., infinitely heavy static quark, without spin dynamics, only colour Coulomb potential!

- classification of $m_b \to \infty$ — good!
- understand $1/m_b$ corrections — better!
- no $1/m_b$ correct., understand $1/m_b^2$ correct. — best!

- Heavy Quark Theory (HQT) mature, robust framework
  - (quark) model considerations
    - most useful as starting point
    - most helpful to train intuition
    - not satisfactory for final answers
    - should not replace interpretations based on HQT!
- We would have seen `generic' SUSY -- but
  - Nature has shown little taste for `generic' dynam.
  - the one certain aspect of SUSY -- that it is broken -- is the least understood one

➼ The statement "The data have led us to a world of Minimal Flavour Violation (MFV)" might be visionary --

but it is at least premature!

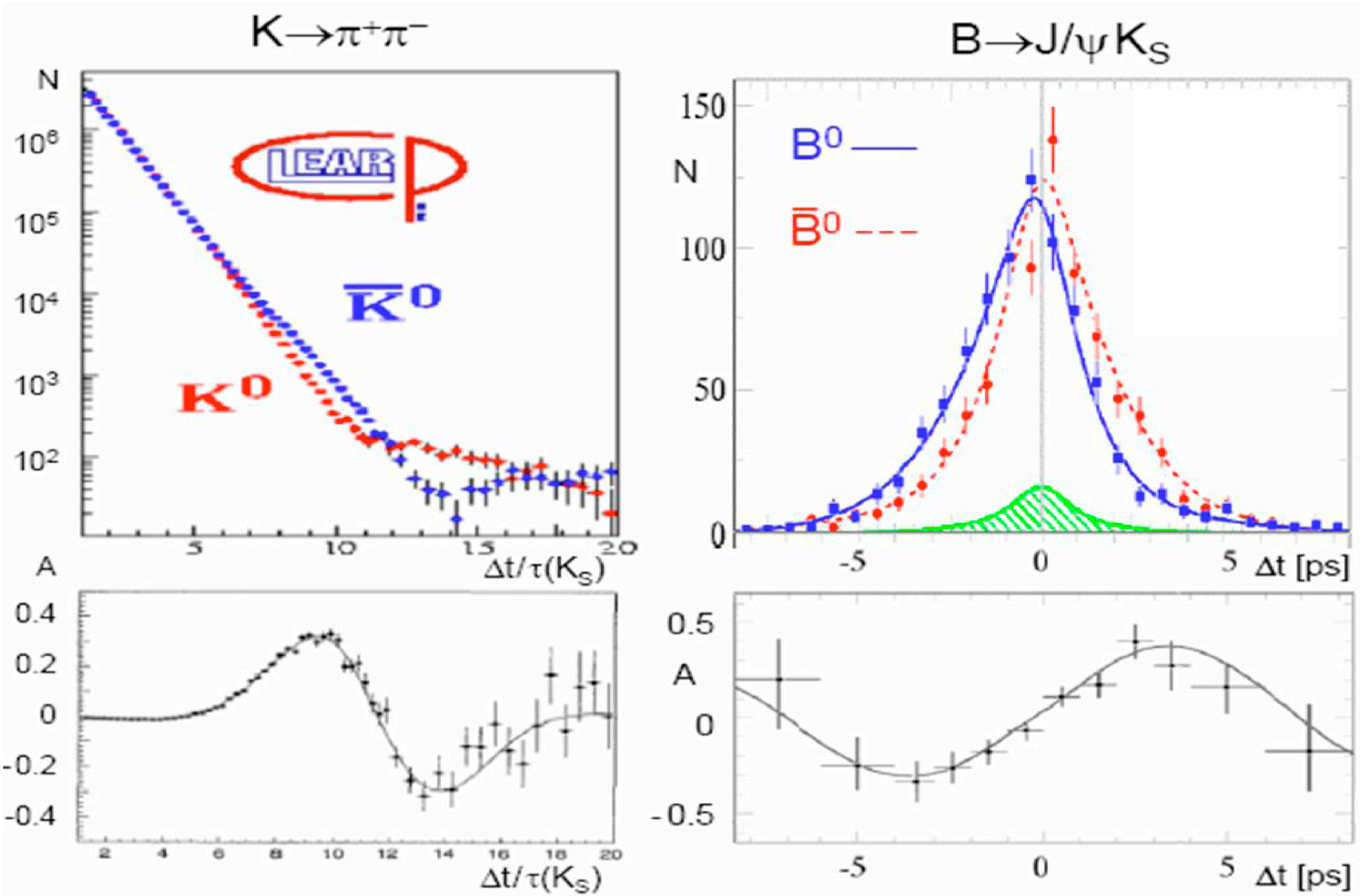
Inferring $T_{NP} \ll T_{SM}$ from $T_{NP} < T_{SM}$ needs some act of faith

- it is a classification scheme, not a model or theory -- analogous to the Superweak Model of ~~CP~~

- one must analyze to which degree a given theory implements this scheme dynamically:

  absolute vs. approximate; how approximate?

✍ When & if time dependent ~~CP~~ in $B_s \to \psi\phi$ found to be < 10%, then I will be more intrigued



[courtesy of K. Schubert]

- statement `~~CP~~ in B decays is much larger than in K decays' is an empirically verified fact

The Menu

I Basics of HQT and HQE

II On Beauty Lifetimes → Lenz

III On Extracting |V(cb)| and |V(ub)| → Uraltsev

IV "3/2 vs. 1/2"

V On the Autonomy of B_s Dynamics

VI On $B \to \tau\nu D, \tau\nu X$ → Uraltsev

VII Outlook

I Basics of HQT and HQE

One of the most active & most quickly progressing fields of QCD

- ✍ the goal: to treat nonperturbative dynamics quantitatively
- ☺ the hope: $m_b \gg \Lambda_{QCD}$
- central tool: Operator Product Expansion (OPE)
- most common application: inclusive rates

$$\Gamma(H_Q \to f) = \Sigma_i \, c_i^{(f)} \, (KM, M_W, m_Q, \alpha_S, \mu) \langle H_Q \,|\, O_i \,|\, H_Q \rangle_{(\mu)}$$

- short distance dynamics → coeff. $c_i^{(f)}$
- universal cast of local operators O_i
- $\langle H_Q|O_i|H_Q\rangle$ inferred from other observables or lattice QCD!
- expansion parameter

$$1/E_{release} \sim \begin{cases} 1/(m_b - m_c) & \text{for } b \to c \\ 1/m_b & \text{for } b \to u \end{cases}$$

- Wilson: auxiliary scale μ s.t.

short distance < μ^{-1} < long distance

- c_i ↔ short distance dynamics
- O_i active fields - long distance dynamics

- not all OPEs are created equal

caveat: $\mu_\pi^2 \neq -\lambda_1$, $\mu_G^2 \neq -\lambda_2$

will use `kinetic scheme': soft gluon effects lumped into HQP defined at $\mu \sim 1$ GeV

- total widths, total SL widths:

  - no contributions ~ $O(1/m_b)$ due to complete cancellations between initial and final state corrections

  - partial cancellations in ~ $O(1/m_b^2)$
    - ➥ somewhat smaller than `natural' scale

  - for $\Gamma_{SL}(B \to l\nu X_c)$ explicit analysis of $O(1/m_b^4)$

    Mannel et al.

  - can & will be improved with results from IC analysis

    Zwicky et al.

II On Beauty Lifetimes

→ Lenz

	$1/m_b$ predict.	comment	data
$\tau(B^-)/\tau(B_d)$	$1+0.05(f_B/0.2GeV)^2$ '92 1.06 ±0.02 '98-'03	PI in $\tau(B^-)$ fact. at low scale ~ 1 GeV	1.076±0.008 '05 1.071±0.009 '08
$<\tau(B_s)>/\tau(B_d)$	1 ± $\mathcal{O}$(0.01) '94		0.92±0.03 '05 0.961±0.018 '08
$\tau(\Lambda_b)/\tau(B_d)$	~0.9 - 1.0 '93 0.88 - 0.97 '98	quark model ME	0.806±0.047 '05 0.904±0.032 '08
$\tau(B_c)$	~ 0.5 psec '94	largest lifetime difference! no $1/m_Q$ crucial	0.45±0.12 ps '05 0.463±0.071 ps '08
$\Delta\Gamma(B_s)/\Gamma(B_s)$	$0.18(f_B/0.2GeV)^2$ '87 0.12±0.04 '04	less reliable than $\Delta M(B_s)$	0.07±0.06 '08

'93/'94: $\tau(\Lambda_b)/\,\tau(B_d) \sim 0.9 - 1.0$ ibiBlokShifUraltVainsh

'94ff: $\tau(\Lambda_b)/\,\tau(B_d) \sim 0.806 \pm 0.047$

'98: $\tau(\Lambda_b)/\,\tau(B_d) \sim 0.94^{+0.03}_{-0.06}$ [0.88 - 0.97] Uralt ⟸

if $\tau(\Lambda_b)/\,\tau(B_d) < 0.88$ ⟹ new paradigm for had. wavefct.

'04: $\tau(\Lambda_b)/\,\tau(B_d) \sim 0.86 \pm 0.05$ GOP

'05: $\tau(\Lambda_b)/\,\tau(B_d) \sim 0.87 \pm 0.17 \pm 0.03$ D0

$\tau(\Lambda_b)/\,\tau(B_d) \sim 0.944 \pm 0.086$ CDF

'06: $\tau(\Lambda_b)/\,\tau(B_d) \sim 1.037 \pm 0.058$ CDF

highly desirable to measure $\tau(\Xi^0_b)$ & $\tau(\Xi^-_b)$ to diagnose failure or confirm success

'93/'94: $\bar{\tau}(B_s)/\,\tau(B_d) = 1 \pm \mathcal{O}(1\,\%)$ ibiUralt

'08: $\bar{\tau}(B_s)/\,\tau(B_d) = 0.961 \pm 0.018$

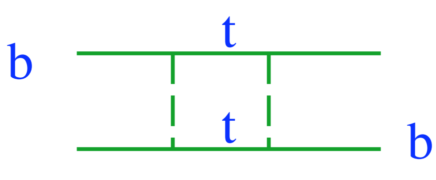
$\Delta\Gamma_s$

theoret. predict.
based on quark
box diagram

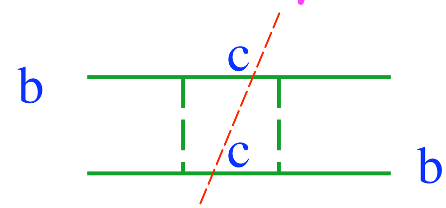
$\Delta\Gamma(B_s)/\Gamma(B_s)$		
	$0.18(f_B/0.2\,GeV)^2$	'87
	0.12 ± 0.04	'04

my heart wishes $\Delta\Gamma(B_s)/\Gamma(B_s) \sim 0.5$
yet my head tells me $\Delta\Gamma(B_s)/\Gamma(B_s) > 0.25$ very unlikely

$\Delta M(B)$



$\Delta\Gamma(B)$



onset of duality?

local operator — (at best) short-distance operator

☞ quark box diagram less reliable for $\Delta\Gamma(B)$ than for $\Delta M(B)$

➥ theoretical uncertainties might be sizable in $\Delta\Gamma(B)/\Delta M(B)$ even with the bag factor dropping out!

III On Extracting |V(cb)| and |V(ub)|

→Uraltsev

(3.1) |V(cb)|

$B \to l\nu X_c$

total width & normalized moments for $B \to l\nu X_c/\gamma X$

➥ $|V(cb)|_{incl} = (42.04 \pm 0.34|_{fit} \pm 0.59|_{\Gamma SL}) \times 10^{-3}$

$m_b^{kin} = (4.597 \pm 0.034|_{fit})$ GeV

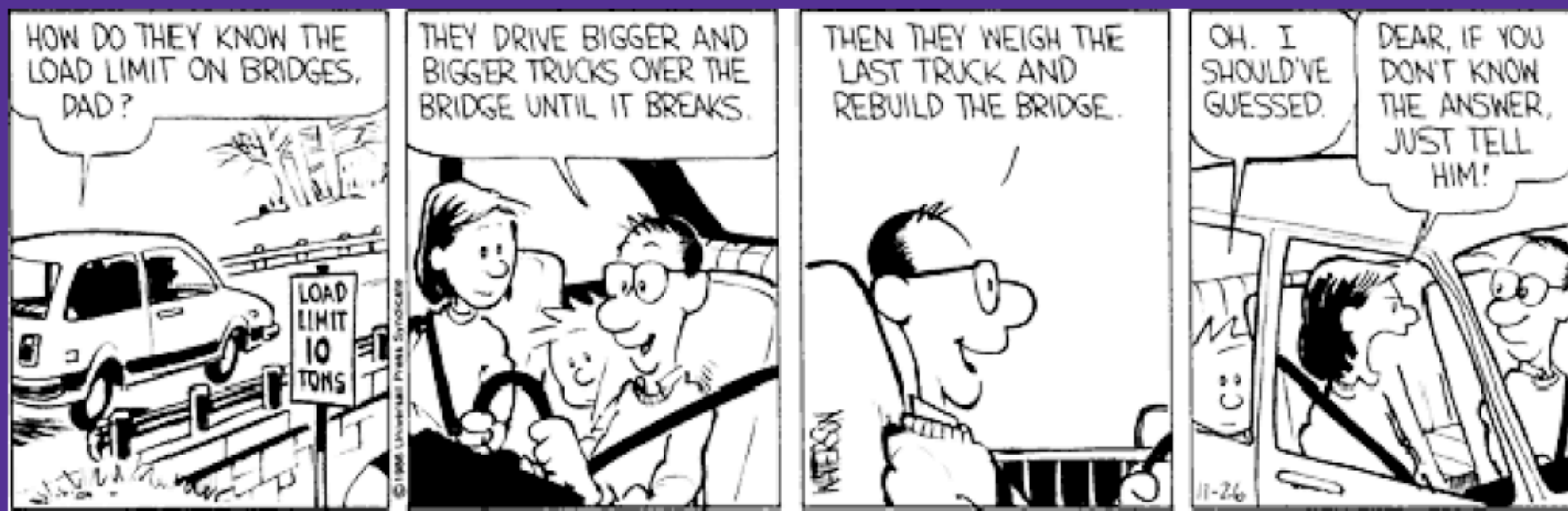
$m_c = (1.163 \pm 0.051|_{fit})$ GeV

$\mu_\pi^2 = (0.434 \pm 0.033|_{fit})$ GeV^2

$\rho_D^3 = (0.213 \pm 0.033|_{fit})$ GeV^3

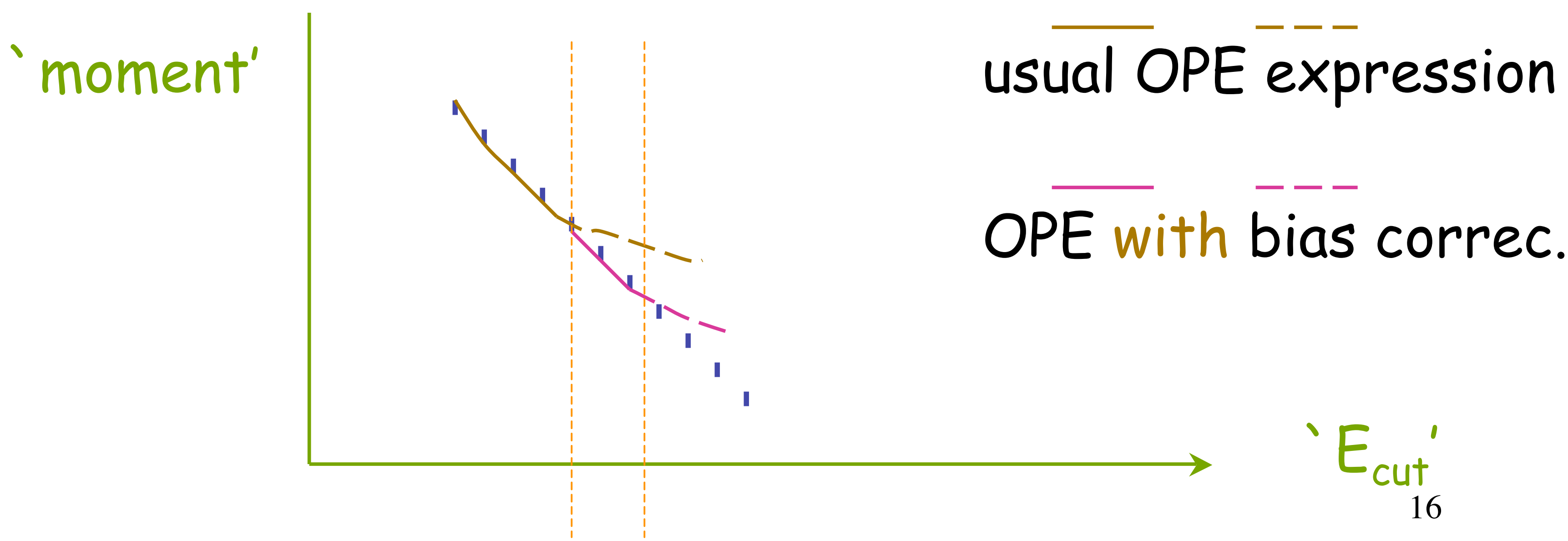
✍ theoretical error budget defensible since

- 4 HQP provide consistent fit to several moments with different cuts ⟹ high degree of overconstraints
- m_b^{kin} from weak $B \to l\nu X_c$ = m_b^{kin} from em&str. $\Upsilon(4S) \to b\bar{b}$
- fit values satisfy relations without them being imposed



http://www.geocities.com/Hollywood/Theater/9876/askdad1.html

\`defensible' ? --



$B \to l\nu D^*$

Extract $|F(1)||V(cb)|_{excl} = (36.2 \pm 0.6)\times 10^{-3}$

- LQCD: $|F(1)| = 0.924 \pm 0.023$
  - ➥ $|V(cb)|_{excl} = (39.2 \pm 0.6 \pm 1.0)\times 10^{-3}$
- $F(1) = 0.89 \pm 0.04 + \mathcal{O}(1/m_Q^3)$ Uraltsev '94
  - $F(1) < 0.89$ Uraltsev '07
- caveat concerning F(1)
  - leading expansion term $1/m_c$

  to consider when comparing

$$|V(cb)|_{incl} = (42.04 \pm 0.34|_{fit} \pm 0.59|_{\Gamma SL})\times 10^{-3}$$

vs.

$$|V(cb)|_{excl} = (39.2 \pm 0.6 \pm 1.0)\times 10^{-3}$$

(3.2) |V(ub)|

$B \to l\nu X_u$

no need to `re-invent the wheel':

- for $B \to l\nu X_u$ use same values of the HQP as determined in $B \to l\nu X_c$
- yet given enough data can check it anyway

- in principle $\Gamma(B \to l\nu X_u)$ under better theoretical control than $\Gamma(B \to l\nu X_c)$

Lepton energy endpoint spectrum ?

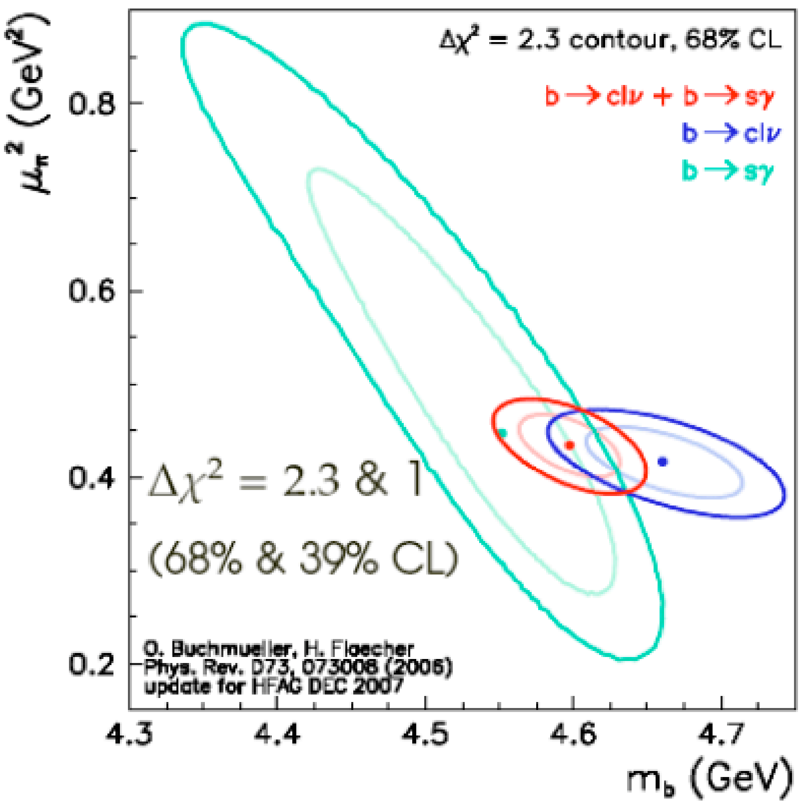
- ☹ model dependent!
- 😐 can get heavy quark distribution function from $B \to \gamma X$
  - 😐 but only to leading order in $1/m_b$
- 😐 endpoint spectrum different for SL B_u and B_d decays (WA)

Hadronic recoil mass spectrum !

$B \to l\nu X_u$

$M_X < M_D$ vs. $E_l > [\sim] (M_B^2 - M_D^2)/2M_B$ vs. $q^2 > (M_B - M_D)^2$

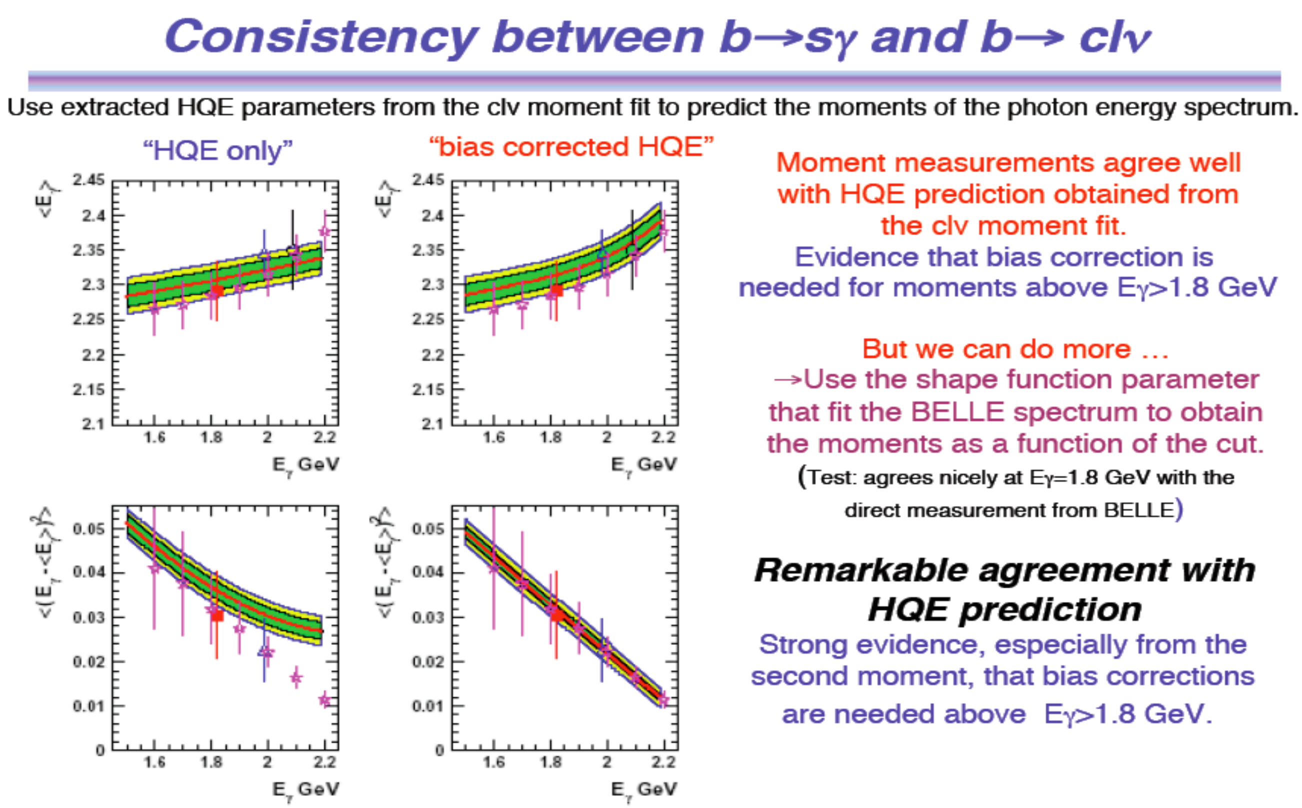
- ✍ cuts destroy straightforward applicability of OPE
- ✍ sensitivity to precise value of m_b



Should we `toss out' $B \to \gamma X$ moments due to severe cuts on E_γ?

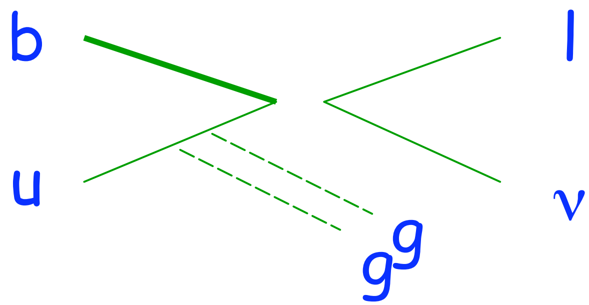
No!

- `Do not let the excellent be the enemy of the very good!'
- We have demonstrated that the cut dependence is under sufficient control -- the `bias corrections'

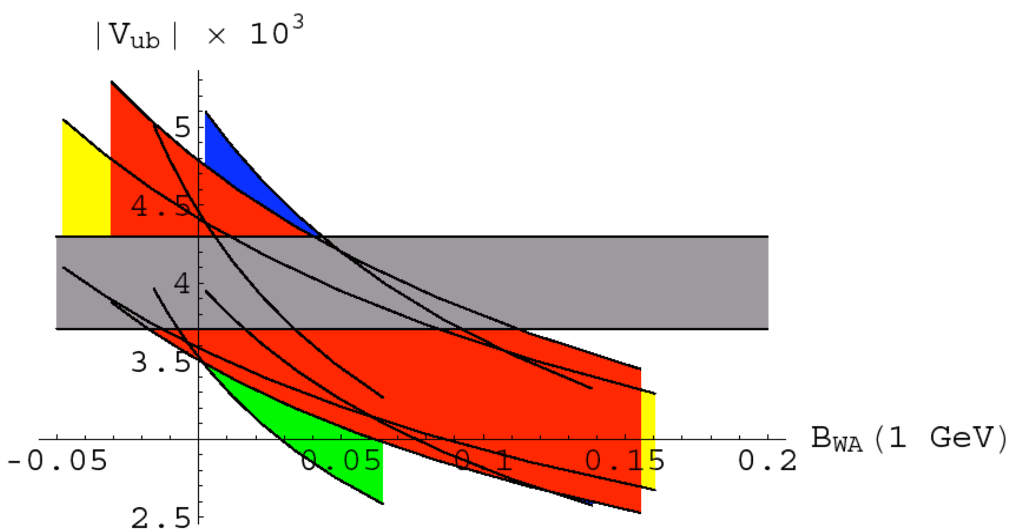


from O. Buchmueller

✍ Important concern: Weak Annihilation (WA)



- dominant contribution at high q^2
- unambiguous signature: difference in B_d & B_u endpoint spectrum
- yet can have also sizable isoscalar contribution
  - ➥ need careful modeling



Preliminary Babar analysis of the q^2 spectrum seems to suggest a Small WA contribution and V_{ub}~0.0040

P. Gambino, Valencia Super-B

From P. Gambino's FPCP talk

Kinetic scheme -- Gambino, Giordano, Ossola, Uraltsev --

$|V(ub)|_{incl} = (3.94 \pm 0.15|_{exp} {}^{+0.20}_{-0.23}|_{th})\times 10^{-3}$

-- BLNP --

$|V(ub)|_{incl} = (3.99 \pm 0.14|_{exp} {}^{+0.32}_{-0.27}|_{th})\times 10^{-3}$

[if same input values used in BLNP, $|V(ub)|_{incl} \sim 4.1 \times 10^{-3}$]

vs.

$|V(ub)|_{excl} = (3.5 \pm 0.4 \pm 0.1)\times 10^{-3}$

$|V(ub)|_{excl} = (3.5 \pm 0.4|_{th} \pm 0.2|_{sh} \pm 0.1|_{exp})\times 10^{-3}$

➥ no clear discrepancy between $|V(ub)|_{incl}$ & $|V(ub)|_{excl}$

➻ some tension with $|V(ub)|_{CKMfit} = (3.57 \pm 0.17)\times 10^{-3}$

My conclusions

- Theory error estimates for $|V(ub)|_{incl}$ have not reached same level of maturity as for $|V(cb)|_{incl}$
- ~ 5 % within reach in next few years
- need better understanding of WA
- need higher accuracy on m_b
- we are encountering a Calvinist scenario:

many paths to heaven -- only success reveals Heaven's blessing

- ~ 2 % conceivable with data set from Super-B factory!

IV "3/2 vs. 1/2"

Heavy Quark Symmetry ≈ Heavy Quark Expans.

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

i.e.,
infinitely heavy static quark, without spin dynamics,
only colour Coulomb potential!

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

- ground states: $[S|l_q|j_q] = [0,1|0|1/2]$:

  PS -- B or D -- & V -- B* or D*

- 1st excit. states: $[0,1|1|1/2]$ & $[1,2\ |1|3/2]$

4 P wave states: 2 $j_q=3/2$ narrow states

2 $j_q=1/2$ broad states

2/3 - 3/4 of $B \rightarrow l\nu X_c$ given by D/D*

➥ charm can act as a heavy flavour

✍ what is the rest of X_c made up from?

✒ P wave states

HQ SR: narrow `3/2' have to dominate over broad `1/2'

QM, LQCD: same prediction to different numerical degrees

Data: somewhat ambiguous findings

- agree with expectations on narrow states
- ~ 15 - 20 % of final states of different nature

☞ non-resonant D/D*π's forming ~15% a priori not surpris.

- no obvious non-resonant contribution in data
- if observed broad structures `1/2', then ~~`3/2' > `1/2'~~!

?? Novel lesson on QCD ??

Can LHCb contribute?

V On the Autonomy of B_s Dynamics

original paradigm: need B_d & B_s to determine all 3 angles

ϕ_2/α, ϕ_1/β from B_d vs. ϕ_3/γ from B_s

new paradigm: can get all angles from B_d

Furthermore NP in general will not obey SM relations between

B and B_s decays

➥ B_s decays a priori independent chapter in nature's book on fundamental dynamics

$B_s(t) \to \psi\phi, \psi\eta, \phi\phi$ not a repetition of lessons from B_d & B_u decays!

VI On $B \to \tau\nu D, \tau\nu X$

$B \to \tau\nu D$ could be affected by $H^{\pm}$-X

- hadronization effects do not drop out from

  $\Gamma(B \to \tau\nu D)/\Gamma(B \to \mu\nu D)$ at finite quark masses

  [1 FF for $B \to \mu\nu D$, 2 FFs for $B \to \tau\nu D$]

- Uraltsev's BPS approximation can help:
  - validate it in $B \to \mu\nu D$
  - apply it to $B \to \tau\nu D$

$B \to \tau\nu X_c$ could be affected by $H^{\pm}$-X

its SM size been evaluated in '94 (Neubert et al.)

- now we can do it much better: ingredients there to predict $\Gamma(B \to \tau\nu X)|_{SM}$ to within very few %
- even if no NP found there, novel lessons on onset of duality!

VII Outlook

We have come a long way in the last 15 years

- in B decay dynamics have established theoretical control

over non-pert. dynamics on the very few % level with

  - detailed theoretical error budgets
  - that can be defended

- Basis for this progress two-fold
  - robust theoretical framework
  - challenged & complemented by detailed high quality data
- emerging synergies between diff. theoret. technologies
- further progress likely[possible]: $\delta V_{cb} \sim 1\%$, $\delta V_{ub} \sim 5\%$ [2%]
- LHCb will be highly successful --

B_s = indep. chapter in nature's book on fundamental dynamics

-- but not complete the agenda of heavy flavour dynamics

A final thought:

Models with extra dimensions have several ad-hoc features

…

yet are sufficiently radical/crazy to push our thinking out of the comfort zone of a possible dead end into new fruitful directions --

i.e. are a most helpful `imagination stretcher'!