Theoretical Overview of B Physics

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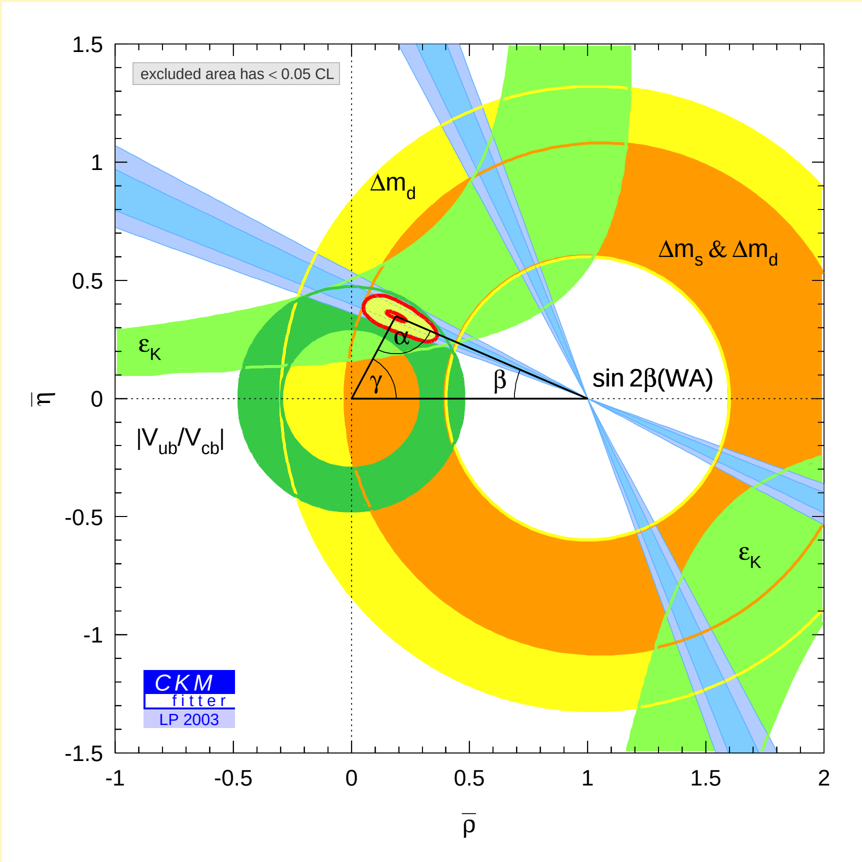


Edinburgh 4/2/04

(Some) Goals of B Physics

- precision determination of CKM matrix elements
  - $|V_{cb}|$ from $B \to D(*)e\nu$ and $B \to X_c e\nu$
  - $|V_{ub}|$ from $B \to \pi e\nu$ and $B \to X_u e\nu$
- new sources of CP violation?
  $\rightsquigarrow$ info about scalar sector of SM and BSM
- new physics in flavour changing neutral currents (FCNC)?
- B physics at B factories complementary to LHC:
  once new physics (e.g. SUSY) is established, measure couplings
  (to which LHC is not that sensitive)

Deserves more study!

Theoretical Tools

- treatment of large scales (m_W, m_t, $m_{\rm SUSY}$, even m_b) by effective field theory methods
- resummation of large (perturbative) QCD logarithms by renormalization group methods

  $\rightsquigarrow$ talk by M. Gorbahn
- treatment of low-energy nonperturbative QCD effects
  - on the lattice (*calculation from first principles*)

    $\rightsquigarrow$ talk by K. Foley
  - by QCD sum rules

    (*QCD-based calculation with a certain degree of model dependence*)
  - within heavy quark expansion

    (*parton model for inclusive decays, QCD factorisation for exclusive decays*)

What We CANNOT Expect from B Physics

- discovery of SUSY!
  (FCNC) B decays sensitive to new physics, but interpretation model-dependent.
  Instead, once SUSY with sparticle masses <1 TeV found at LHC, use B decays to constrain couplings.

- new physics from small effects:
  QCD effects (perturbative and nonperturbative) relevant in most cases, but in general not known to accuracy better than $\sim 10\%$

$\longrightarrow$ new-physics unambiguously detectable in B decays
only if effects larger $\sim 10\%$

Vita brevis, Ars longa. . .

Time limited $\longrightarrow$ selection of topics:

- Effective Field Theory Description
- $B \to \pi, \rho, \eta, K, K^*$ Form Factors
- CP Violation
- QCD Factorisation

E(ffective) F(ield) T(heory)

- hierarchy of scales $\mu \sim m_b \ll m_W, m_t \ll m_{\rm new\ physics}$
- separate scales:
  $\mathcal{H}_{\rm eff} = \sum_i C_i(\text{large scale}/\mu, \alpha_s)\, O_i(\mu) + O(1/\text{large scale})$
- Wilson coefficients C_i to encode short-distance (QCD + EW + NP) effects
- operators O_i to encode long-distance nonperturbative QCD effects
- complications: (cf. talk by M. Gorbahn)
  - ⋈ generation of new operators by radiative corrections (penguin etc. operators)
  - ⋈ large corrections $\sim \alpha_s \ln(m_W^2/\mu^2)$ etc. to C_i:
    need for resummation (renormalisation group improvement)
  - ⋈ operator mixing: large anomalous dimension matrices, complicated μ-dependence

Outline

- Effective Field Theory Description
- $B \longrightarrow \pi, \eta, K$ **Form Factors**
- CP Violation
- QCD Factorisation

Setting the Stage for $B \longrightarrow \pi$

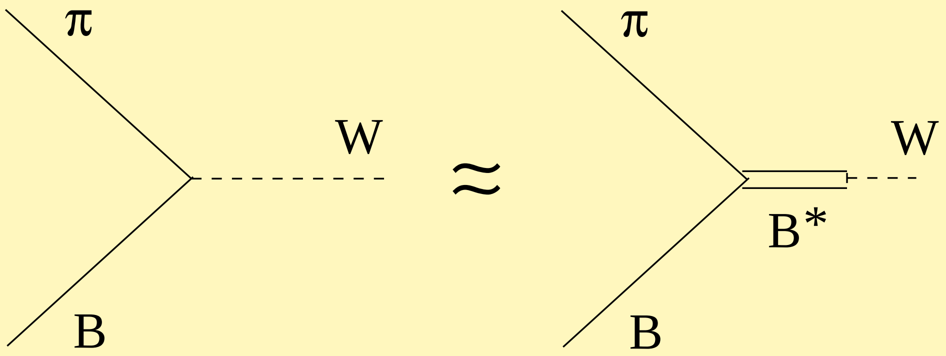
Definition of form factors $(0 \le q^2 \le (m_B - m_\pi)^2)$:

$$\langle \pi | \bar{u} \gamma_\mu b | B \rangle = f_+(q^2)(p_{B\mu} + p_{\pi\mu}) + f_-(q^2) q_\mu \quad [q_\mu = p_{B\mu} - p_{\pi\mu}]$$

$B \to \pi e \nu$: f_- suppressed by m_e^2/m_B^2, i.e. get $|V_{ub}|$ from experiment once f_+ is known

Naïve expectation: f_+ dominated by B^*-pole ($m_{B^*} = 5.32\,\text{GeV}$):

$$f_+(q^2) \propto \frac{1}{m_{B^*}^2 - q^2}$$



Correct expression: $f_+(q^2) = \dfrac{c}{m_{B^*}^2 - q^2} + \displaystyle\int_{(m_B + m_\pi)^2}^{\infty} dt \, \frac{\rho(t)}{t - q^2}$

Why $f_+^{B\to\pi}$?

- physical observable:
  - no dependence on renormalisation scale μ
  - direct comparison between theory and experiment
- q^2 dependence accessible experimentally, need only normalisation
  $\rightsquigarrow$ additional check of theory
- clean experimental signature
  (as compared to inclusive decays with huge $b \to c$ background)

But:

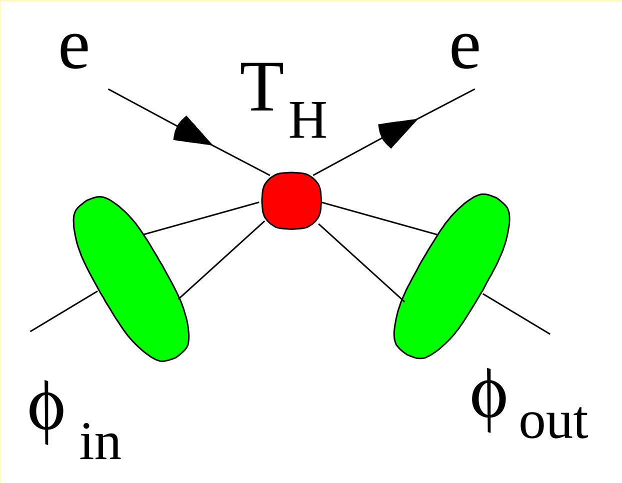
- challenging, as large range of momentum transfer: $0 \leq q^2 \leq 25\,\mathrm{GeV}^2$
- accessible in different theoretical limits:
  large momentum transfer $m_b \to \infty$ ($\to$ QCD sum rules, SCET)
  small energy ($\to$ lattice, talk by K. Foley)

Factorisation à la Brodsky/Lepage

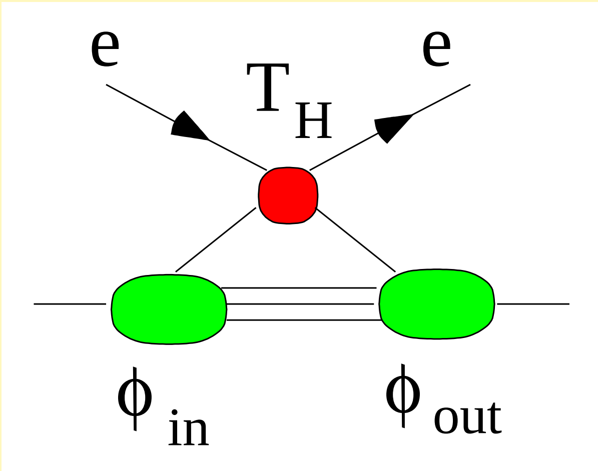
At large momentum transfer Q^2, exclusive QCD processes dominated by states with "valence" quark content; process amplitude factorises:

$$M = \prod_j \phi_{\mathrm{out},j}(n_j) \otimes T_H(n_j, n_i) \otimes \prod_i \phi_{\mathrm{in},i}(n_i)$$

$\phi(u)$, $0 \le u \le 1$: probability amplitude for collinear quarks with momentum up and $(1-u)p$, resp., to form hadron with momentum p ($p^2 \ll Q^2$)



Purely hard process: dominant in "classical" applications of pQCD, e.g. EM π FF; explicitly O(α_s)



Soft (Feynman) mechanism: strongly asymmetric kinematical configuration of partons

Apply to B Physics: $Q^2 \sim m_b^2 \to \infty$

Both hard and soft mechanisms contribute!

$\rightsquigarrow$ SCET (soft collinear effective theory) (Bauer/Fleming/Pirjol/Stewart)

- identify (uncalculable) soft/nonperturbative terms order by order in $1/m_b$ expansion
- construct perturbatively calculable (hard) relations between form factors (to given accuracy in $1/m_b$) with uncalculable soft terms *dropping out*

$\rightsquigarrow$ QCD sum rules on the light-cone (Ball/Braun)

- calculate both soft and hard terms within the same method, using the techniques of QCD sum rules
- obtain numerical predictions (and estimates of theoretical systematic (model-dependent) uncertainty)

QCD Sum Rules on the Light-Cone

$$i\int d^4y e^{iqy}\langle\pi(p)|T[\bar{u}\gamma_\mu b](y)[m_b\bar{b}i\gamma_5 d](0)|0\rangle \stackrel{\text{LCE}}{=} \sum_n T_H^{(n)}\otimes\phi_\pi^{(n)}$$

LCE = light-cone expansion

- $\phi_\pi^{(n)}$: π distribution amplitudes (DAs)
- n: twist
- $T_H^{(n)}$: perturbative amplitudes

$$= 2p_\mu\left(f_+(q^2)\,\frac{m_B^2 f_B}{m_B^2-p_B^2} + \text{higher poles and cuts}\right) \ + \ \text{terms contrib. to other FF}$$

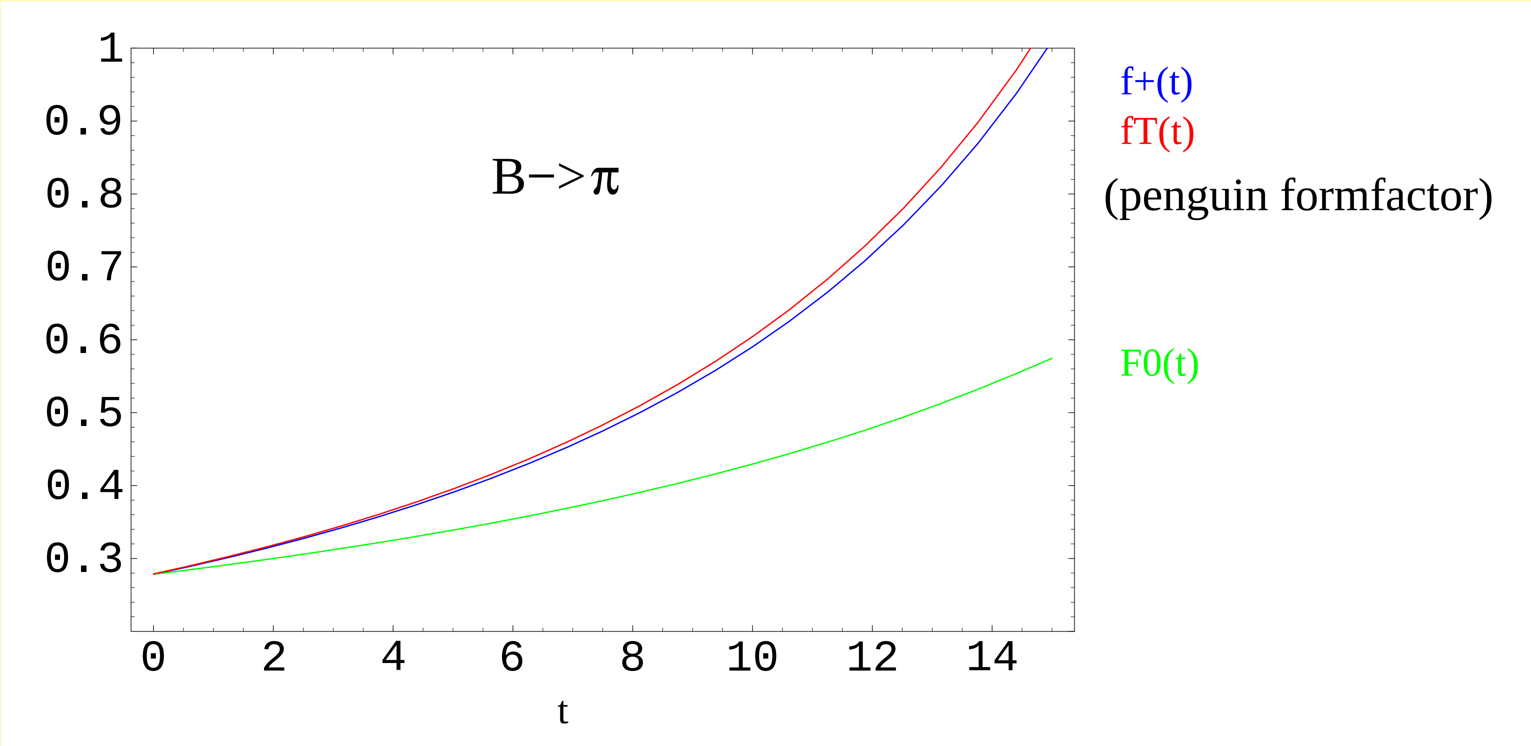
$\rightsquigarrow$ avoid B-meson DA as B described not as real particle, but via analytic continuation

$\rightsquigarrow$ LC-expansion starts at $O(1)$, not $O(\alpha_s)$ $\to$ soft terms included

And now, Ladies and Gentlemen:

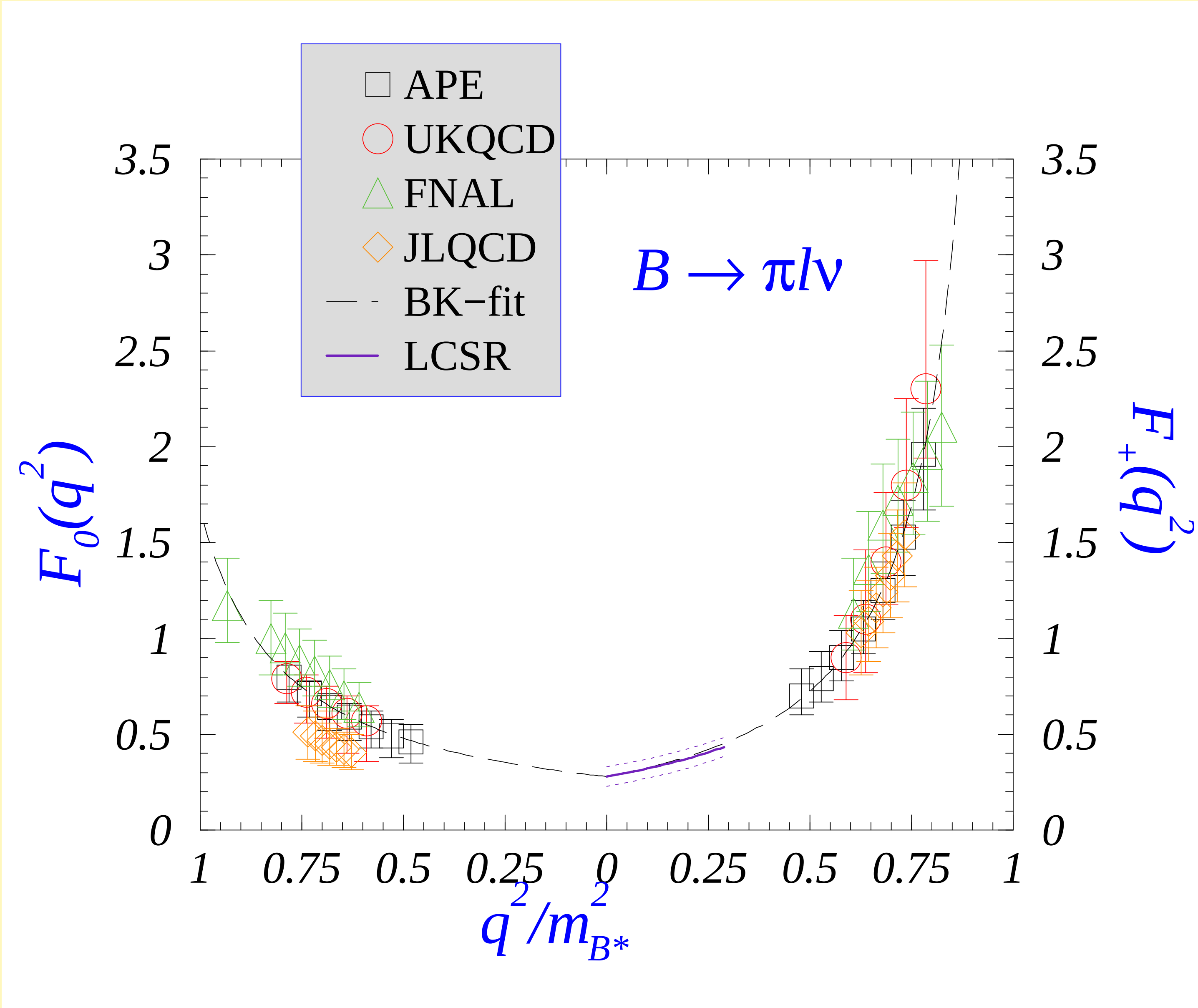
New (& Preliminary) Results!

Ball/Zwicky 2004



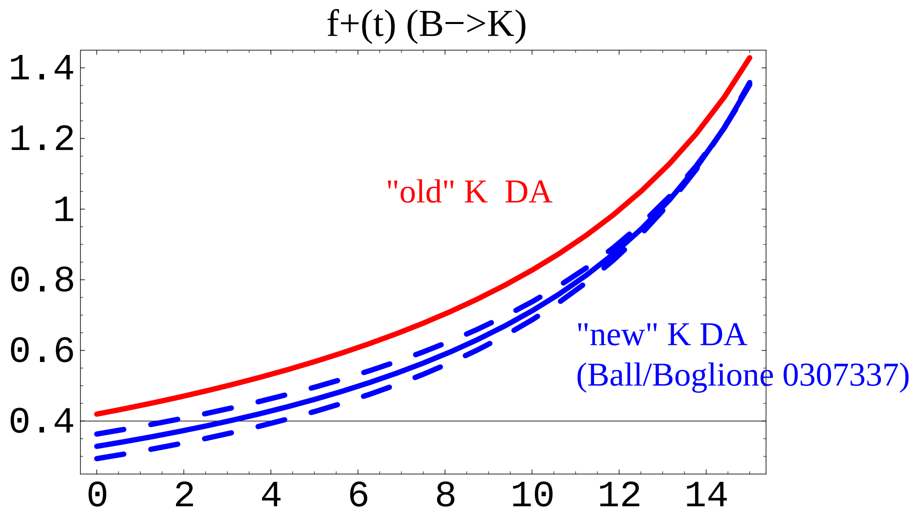
- LCSRs only valid for $E_\pi \gg \Lambda_{QCD}$, i.e. $t = m_B^2 - 2m_B E_\pi < m_B^2$.
  Choose $E_\pi^{min} \approx 1.2$ GeV.

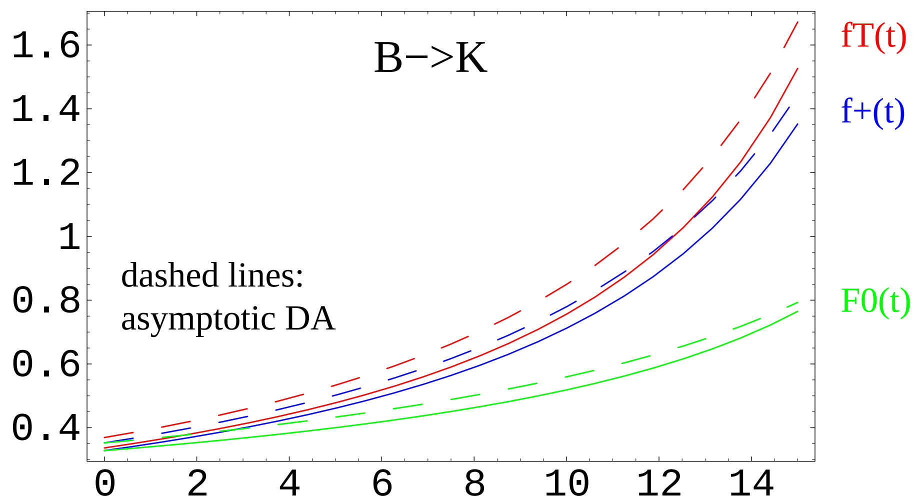
Compare to lattice: (Becirevic 2002)



$B \to K$

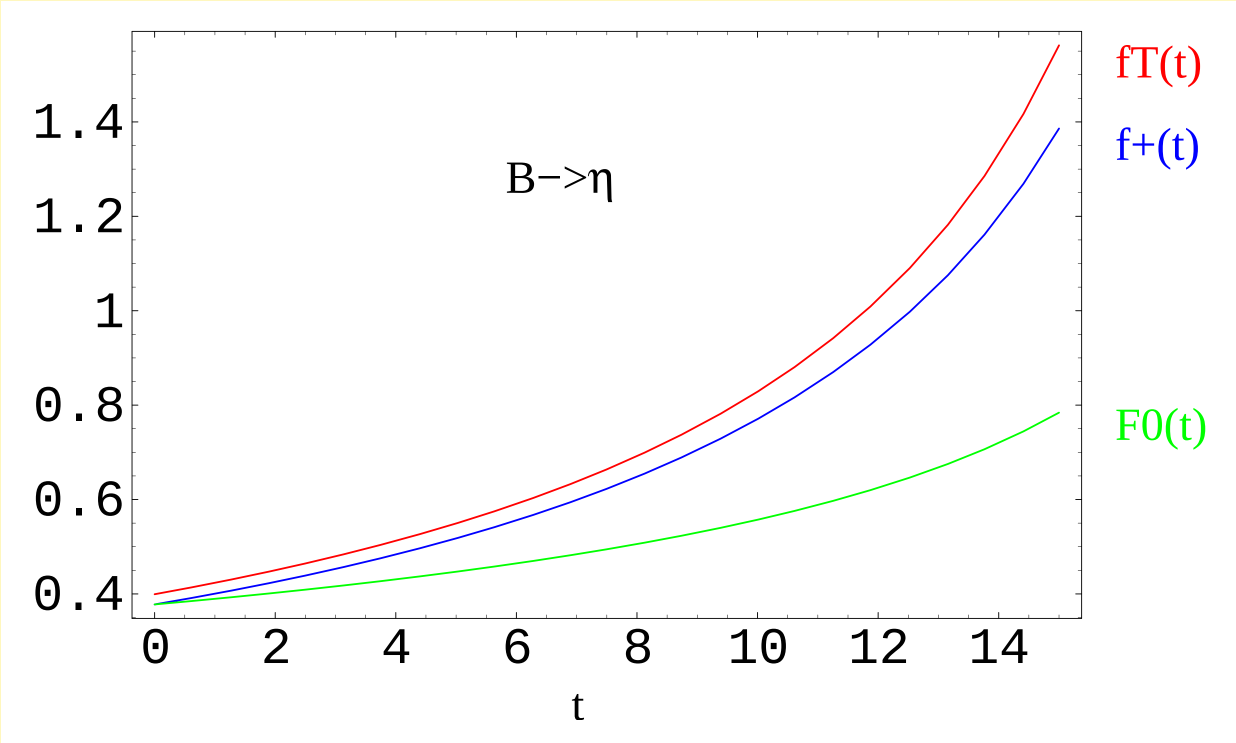
Recent redetermination of distribution amplitude ϕ for K: $f_+^{B\to K}$ becomes smaller!





Ball/Zwicky 2004

$B \to \eta$



Ball/Zwicky 2004

Only flavour octet included.

Outline

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- **CP Violation**
- QCD Factorisation

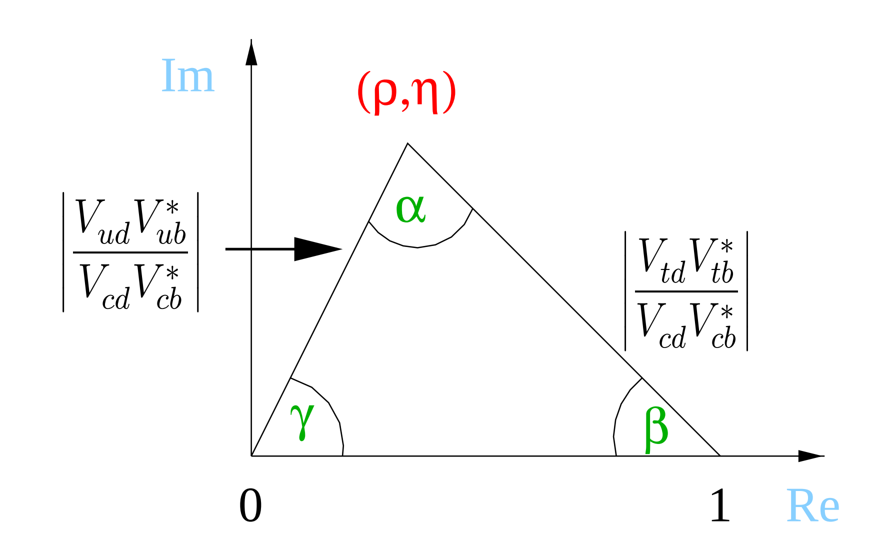
CP Violation in the SM

→ quark mass-eigenstates mix under weak interactions

→ mixing described by Cabibbo-Kobayashi-Maskawa (CKM) matrix V (3×3, unitary)

→ parametrized in terms of 3 rotation angles and

one complex phase of V $\rightarrow$ unique source of CP violation in SM



$\Longleftrightarrow$

Picture unitarity relation

$$\sum V_{dj} V_{jb}^* = 0$$

as triangle in the complex plane:

unitarity triangle (UT)

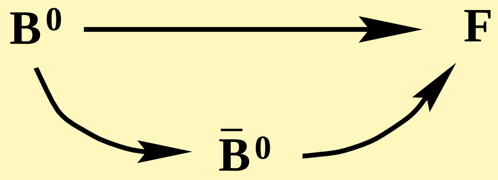
(There are of course 6 triangles: 4 are pretty much squashed, the other 2 nearly identical.)

Goal: test SM by overconstraining the unitarity triangle!

CP Violation in $B^0_{d,s}$ Decays into CP Eigenstates

Measure time-dependent CP-asymmetry: $(\mathrm{CP}|F\rangle = n_F|F\rangle)$:

$$\mathcal{A}_{\mathrm{CP}} = \frac{\Gamma(B^0_q(t)\to F) - \Gamma(\bar{B}^0_q(t)\to F)}{\Gamma(B^0_q(t)\to F) + \Gamma(\bar{B}^0_q(t)\to F)}$$



$$= \mathcal{A}^{\mathrm{dir}}_{\mathrm{CP}}(B_q\to F)\cos(\Delta M_q t) + \mathcal{A}^{\mathrm{mix}}_{\mathrm{CP}}(B_q\to F)\sin(\Delta M_q t)$$

$\mathcal{A}^{\mathrm{dir,mix}}_{\mathrm{CP}}$ depend on $\xi_F^{(q)} = -n_F e^{-i\phi_q}\frac{\langle F|\mathcal{H}^{\mathrm{weak}}_{\mathrm{eff}}|\bar{B}^0\rangle}{\langle F|\mathcal{H}^{\mathrm{weak}}_{\mathrm{eff}}|B^0\rangle}$

B^0–$\bar{B}^0$ mixing phase

$$\phi_q = \arg M_{12}^{(q)} = \begin{cases} +2\beta & (q=d) \\ \approx 0 & (q=s) \end{cases}$$

$\mathcal{H}^{\mathrm{weak}}_{\mathrm{eff}}(b\to r) = \sum_{j=u,c} V^*_{jr}V_{jb}Q^{jr} + \mathrm{c.c} \rightsquigarrow$ sum over weak amplitudes

Special case: dominance of one single amplitude

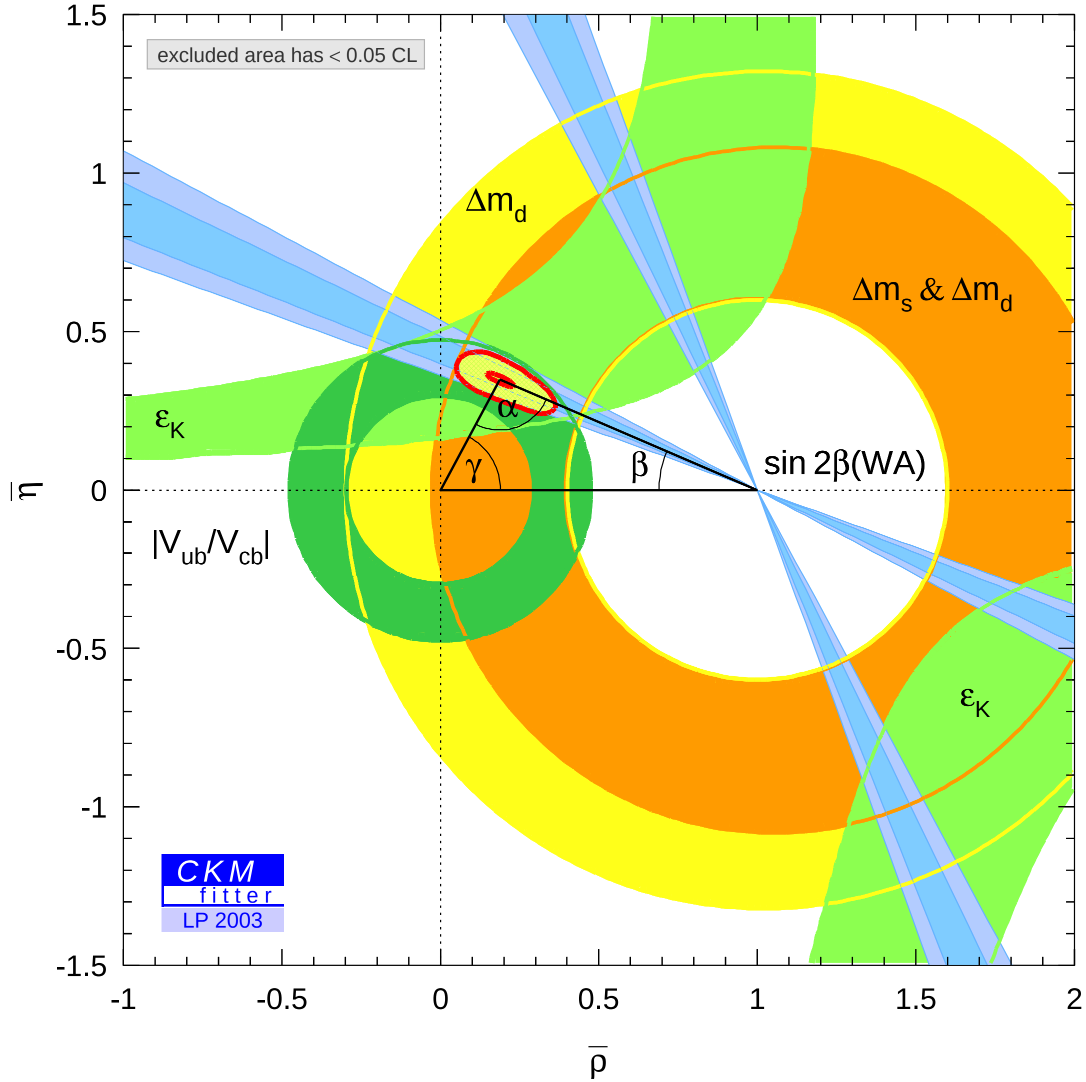
$\rightsquigarrow$ hadronic MEs cancel: $\xi_F^{(q)} = -n_F e^{-i(\phi_q - \phi_D^{(F)})}$

weak decay phase

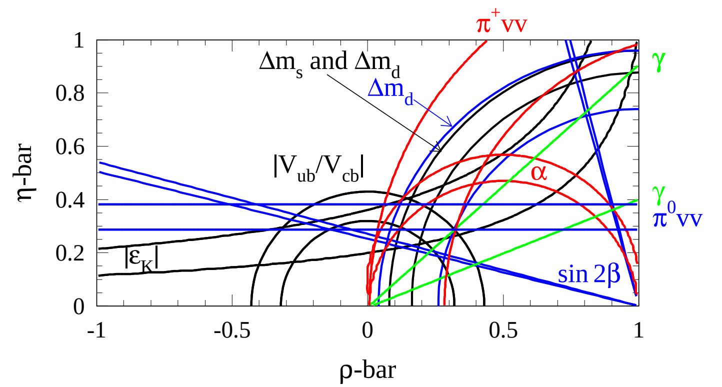
$\phi_D^{(F)} = 0$ for dominant $b\to c\bar{c}r$

$\Rightarrow$ "Gold-plated" decays, e.g. $B\to J/\psi K_S \rightsquigarrow \beta$

Present Status of UT



Prophecy for 2010:



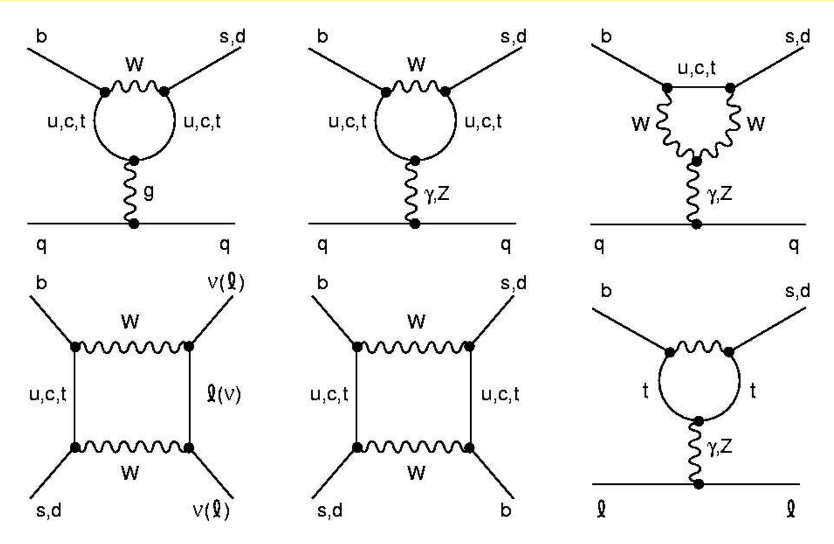
by courtesy of CKM-fitter group,
`http://ckmfitter.in2p3.fr/`

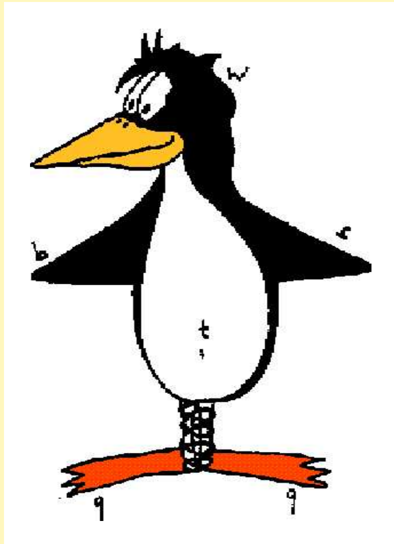
Expect measurements of ΔM_s, α, γ; improvement on β; in addition constraints from rare K decays: $K \to \pi\nu\bar{\nu}$.

The General Case: Penguin Pollution: e.g. $B \longrightarrow \pi\pi$

Interference of two weak amplitudes $A_{1,2}$, one (often) generated by penguin diagrams:

Flavour-changing neutral current (FCNC) $b \to s, d$ transitions:





- loop- and (in principle) GIM-suppressed in SM
- GIM-suppression largely relaxed because $m_t \gg m_W$
  $\rightsquigarrow$ experimentally accessible BRs $\sim 10^{-5}$, to be compared with FCNC K or D decays: BRs $\sim 10^{-10}$

The General Case: Penguin Pollution: e.g. $B \longrightarrow \pi\pi$

Interference of two weak amplitudes $A_{1,2}$, one (often) generated by penguin diagrams:

$$A_F = |A_1| e^{i(\phi_{A_1}+\delta_1)} + |A_2| e^{i(\phi_{A_2}+\delta_2)}, \quad \xi_F = -n_F e^{-2i\phi_1} \frac{1 + r e^{i(\Delta - \phi_2 + \phi_1)}}{1 + r e^{i(\Delta + \phi_2 - \phi_1)}}$$

with $\phi_{1,2} = \phi_{A_{1,2}} - \frac{1}{2}\phi_d$: weak phase, $\Delta = \delta_2 - \delta_1$: strong phase, $r = |A_2/A_1|$.

Assume r small :

$$\mathcal{A}_{\rm CP}^{\rm dir} \approx 2r \sin(\phi_1 - \phi_2) \sin\Delta$$

$$\mathcal{A}_{\rm CP}^{\rm mix} \approx n_F \left[\sin 2\phi_1 - 2r\cos 2\phi_1 \sin(\phi_1 - \phi_2)\cos\Delta\right]$$

No clean measurement of ϕ_1, ϕ_2!

r, Δ not (yet?) accessible to calculation from first principles; try to exploit symmetries ($\mathrm{SU_F}(3)$) and limits.
Or use QCD factorisation. . .

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- CP Violation
- **QCD Factorisation**

Factorization à la BBNS

Beneke/Buchalla/ Neubert/Sachrajda, PRL 83 (1999) 1914

Generic amplitude for heavy-to-light transitions:

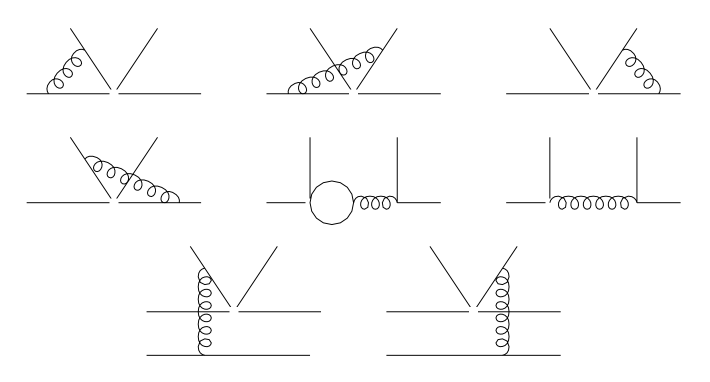
$$A(B \to \pi\pi) = f_+^{B\to\pi}(0) \int_0^1 dx\, T^I(x)\phi_\pi(x) + \int_0^1 d\xi dx dy\, T^{II}(\xi, x, y)\phi_B(\xi)\phi_\pi(x)\phi_\pi(y)$$

$$= A(B \to \pi\pi)_{\rm fact} \times (1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\Lambda_{\rm QCD}/m_b))$$

$f_+^{B\to\pi}$: weak decay form factor

- shown to be valid at 1-loop in QCD
- naive factorization works up to (calculable) radiative corrections and (uncalculable) power-suppressed terms

$T^{I,II}$: process-dependent hard scattering amplitudes



$\phi_{B,\pi}(x)$: universal light-cone distribution amplitudes

- describe collinear momentum-distribution of quarks in meson
- obtained from Bethe-Salpeter WFs by integration over transverse momenta
- well-studied for light mesons (e.g. π EM form factor)

Résumé

- primary objective of B physics: obtain info on quark mixing (i.e. scalar sector), bounds & constraints on new physics ($\not{C}\!\!\not{P}$, rare decays)

- experimental results extremely impressive already, and always improving. . .

- primary obstacle: contamination by (nonperturbative) QCD; for the moment, th. QCD uncertainties on par (or below) exp. ones; situation bound to change (very) soon. . .

- era of precision fits: reminds of LEP: electroweak p.f. $\rightsquigarrow$ info on m_t, m_H, yields bounds on SUSY etc.; main difference: presently, cannot match th. and exp. accuracy to arbitrary precision

- prospects: developments in npQCD: lattice: unquenched B calculations? Further development of pQCD methods? $\rightarrow$ need $1/m_b$!