Theorie Exklusiver B-Zerfälle

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DPG-Frühjahrstagung, Mainz, 1. April 2004

- Effective Hamiltonian for $|\Delta B| = 1$ transitions
- Heavy quark decays into soft particles $\longrightarrow$ HQET
- **Heavy quark decays into energetic particles $\longrightarrow$ SCET**
- **"Theory vs. Experiment" (Examples)**
- Conclusions

Goals of B-physics

Measurement of Standard Model parameters,
Precision test of CKM mechanism,
Hints/constraints on new physics

$\longleftarrow$ complementary to
electroweak precision tests (LEP)
and direct searches (LHC, Tevatron)

operator product expansion
effective field theories
factorization theorems $\longrightarrow$

Understanding strong interactions
on the quantum level (QCD)

Probing hadronic structure in
B-meson and its decay products

$\longleftarrow$ theoretical and phenomenological
input for other processes

Different faces of strong interactions in B-decays

Different energy scales $\leftrightarrow$ different dynamics $\leftrightarrow$ different methods:

$\mu^2 \sim M_X^2$ $\longrightarrow$ "new physics" ???

$\mu^2 \sim M_W^2$ $\longrightarrow$ standard-model flavour transitions

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effective electroweak Hamiltonian including perturbative QCD (QED) corrections

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$\mu^2 \sim m_b^2$
$\mu^2 \sim m_b\Lambda$ $\longrightarrow$ short-distance dynamics in hadronic matrix elements

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heavy quark expansion $\longrightarrow$ effective theories HQET/SCET

$\mu^2 \sim \Lambda^2$ $\longrightarrow$ long-distance hadronic parameters
(form factors, decay constants, parton distributions, . . .)

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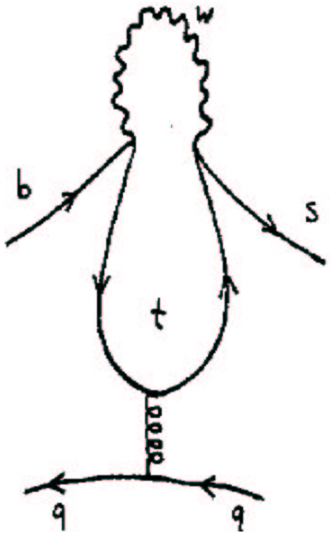
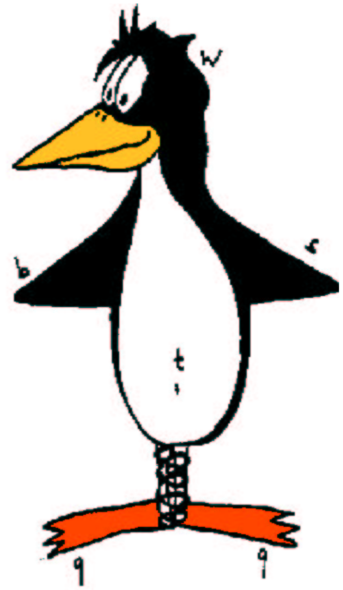
data / non-perturbative methods / approximate symmetries

Effective Hamiltonian for $|\Delta B| = 1$ transitions





References:

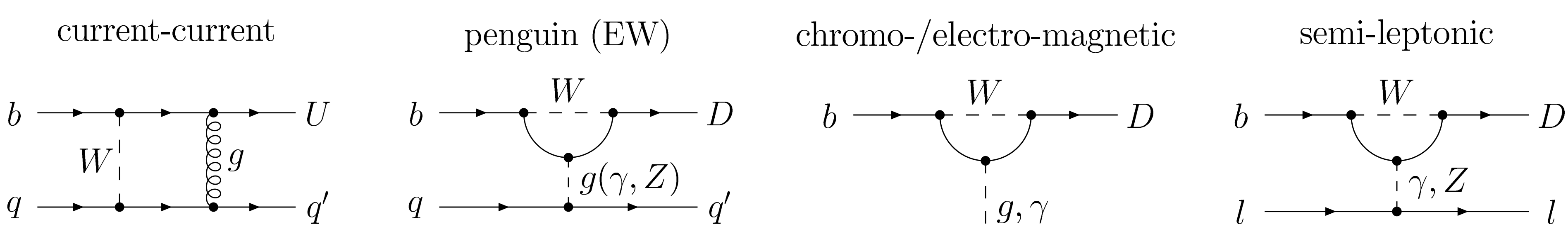
- see e.g. Buchalla/Buras/Lautenbacher, Rev.Mod.Phys.68, 1125 (1996), and ref's therein.

Effective Hamiltonian for b decays

$$H_{\mathrm{eff}} \sim \frac{G_F}{\sqrt{2}} \sum_i \lambda_{\mathrm{CKM}}\, C_i(\mu) \cdot \mathcal{O}_i \; + \; \text{terms suppressed by } m_b^2/M_W^2$$

Effect of heavy particles (W, Z, top, ...) in short-distance Wilson coefficients.

Long-distance modes with $p^2 \leq \mu^2$ in matrix elements of operators $\mathcal{O}_i$:



Matching and Running

- Calculation of matching coefficients c_i in fixed-order perturbation theory:

$$C_i(m_W) = c_i^{(0)} + \frac{\alpha_s}{4\pi} c_i^{(1)} + \ldots$$

$\longleftarrow$ SM! + New Physics?

- Perturbative calculation of anomalous dimensions γ_{ij} of operators in $H_{\rm eff}$

$$\gamma_{ij} = \gamma_{ij}^{(0)} + \frac{\alpha_s}{4\pi} \gamma_{ij}^{(1)} + \ldots$$

$\longleftarrow$ QCD (+QED)

- Use renormalization group to sum large logarithms $\ln \frac{m_b}{m_W}$:

$$C_i(m_W) \to C_i(m_b) = \left[\frac{\alpha_s(m_b)}{\alpha_s(m_W)}\right]^{-\gamma_{ij}^{(0)}/2\beta_0} C_j(m_W) + \ldots$$

$\longleftarrow$ RGE

Calculation of hadronic matrix elements at $\mu = m_b$

- Straight-forward for *fully inclusive* decays:
  - ⋆ Quark-hadron duality: dominance of perturbative physics.
  - ⋆ Heavy quark mass expansion: no Λ/m_b terms.
  - ⋆ Example: Wilson coefficient C_7 and $B \to X_s\gamma$.

- More involved for inclusive decay *spectra*:
  - ⋆ Breakdown of OPE in endpoint and resonance regions.
  - ⋆ $|V_{cb}|$ and $|V_{ub}|$ from semi-leptonic decays. → H. Lacker (T VII)
  - ⋆ Forward-backward asymmetry zero in $B \to X_s\ell^+\ell^-$.

- *Exclusive* decay channels even more challenging, see below.
  - ⋆ Effective theories / Factorization / Approximate symmetries:
    Express exclusive matrix elements in terms of (few) universal hadronic quantities.

Radiative decays – Recent developments

- 3-loop anomalous dimensions for $b \to s\ell^+\ell^-$: [Gambino et al. 238 (2003)]

  (and confirmation for $b \to s\gamma$)

- 2-loop matrix elements in $b \to d\ell^+\ell^-$
  - ⋆ Expansion in masses and small values of q^2: [Asatrian et al., hep-ph/0312063]
  - ⋆ Analytical, also for large q^2: [Seidel, hep-ph/0403185, T 108]

- 2-loop matrix elements in $b \to s\ell^+\ell^-$
  - ⋆ Semi-numerical, also for large q^2: [Ghinculov et al., hep-ph/0310187, hep-ph/0312128]
  - ⋆ Gluon bremsstrahlung corrections: [Asatrian et al., hep-ph/0311187]
  - ⋆ Higher-order electroweak effects: [Bobeth et al., hep-ph/0312090]

$\Rightarrow$ Theoretical basis for precision tests in radiative B decays

$|V_{cb}|$ and $|V_{ub}|$ from inclusive decays

- Status (winter 2003):
  - $\star$ $|V_{cb}|_{\text{incl.}} = 0.0421 \pm 0.0013$
  - $\star$ $|V_{ub}|_{\text{incl.}} = 0.00426 \pm 0.00013 \pm 0.00050$

[Schubert @ lepton-photon 2003]

$\longrightarrow$ for recent update, see H. Lacker (T VII)

- New theoretical developments:
  - $\star$ Better understanding of shape function effects in endpoint region (also using effective theory arguments)

$\longrightarrow$ Hope to improve theoretical control on $|V_{ub}|_{\text{incl.}}$

[Bauer/Luke/Mannel 02],[Bauer/Manohar 03]
[Neubert 02],[Bosch/Lange/Neubert/Paz 04]

Hadronic parameters (non-perturbative QCD effects)

Challenge: Give a reliable estimate of systematic uncertainties!

- Lattice QCD:
  - ⋆ several extrapolations required:
    (continuum limit, quenched approximation, chiral extrapolation, heavy quark extra-(inter-)polation)
  - ⋆ (slow but steady) progress to be expected:
    (improved actions, better understanding of unquenched systematics, computer power, better algorithms)

- QCD sum rules:
  - ⋆ relies on parton-hadron duality
  - ⋆ estimate of uncertainties from variation of threshold parameter s_0 and Borel mass.
  - ⋆ radiative corrections and power-suppressed effects from condensates can be included.

- Phenomenological models:
  - ⋆ Vague idea of uncertainties by comparing sufficiently many (independent) approaches.

Heavy quark decays into soft particles $\longrightarrow$ HQET

$$\boxed{m_b \gg \Lambda_{\rm QCD}}$$

References:

- see [Neubert, Phys.Rep.245, 259 (1994)] and ref's therein.

Heavy quark effective theory

- Consider heavy quark decays, like $b \to c\ell\nu$ or $b \to u\ell\nu$ for small energy transfer to final state hadronic system.

- Heavy quark mass is large compared to typical momenta of soft quarks/gluons:

  ⋆ $\alpha_s(m_Q) \ll 1$: dynamics at distances of order $1/m_Q$ is still perturbative
  ⋆ $\Lambda_{\rm QCD}/m_Q \ll 1$: new (approximate) symmetries in the limit $m_Q \to \infty$

⇒ construct effective theory in terms of $h_v(x) = e^{i m_Q v\cdot x}\,\frac{1+\not v}{2}\,Q(x)$
(b and c quarks ≈ static colour/flavour sources, moving with fixed velocity v^μ)

$$\mathcal{L}_{\rm HQET} = \bar h_v \left\{ iv\cdot D + \frac{(i\vec{D})^2}{2m_Q} + C_m(\mu)\,\frac{g_s}{4m_Q}\,\sigma_{\mu\nu}\,G^{\mu\nu} + \ldots \right\} h_v$$

- Perturbative matching of weak decay operators onto HQET
("integrating out" hard modes, expansion in $\Lambda_{\rm QCD}/m_Q$)

Applications of HQET in exclusive B decays

- Determination of $|V_{cb}|$ from $B \to D^{(*)} \ell \nu$ decays: ($\to$ H. Lacker, T VII)
  - ⋆ Approximate spin/flavour symmetry in HQET:
    $B \to D \ell \nu$ transitions described in terms of unique Isgur-Wise form factor, which is normalized at zero recoil, $\xi(v \cdot v' = 1) = 1$.
  - ⋆ Radiative corrections calculable from matching coefficients in HQET.
  - ⋆ $1/m_b$ corrections estimated from lattice / QCD sum rules.

  $\to$ Extract value of CKM matrix element: $|V_{cb}|_{\text{excl.}} = (40.2 \pm 0.9_{\text{exp}} \pm 1.8_{\text{th}})\, 10^{-3}$

  [from Schubert @ lepton-photon 2003]

  Improved lattice results may further reduce theoretical uncertainty.

- What about $|V_{ub}|$ from $B \to \pi \ell \nu$ and $B \to \rho \ell \nu$?
  - ⋆ No Isgur-Wise theorem for heavy-to-light form factors!
  - ⋆ Form factor uncertainties dominate error ($> 10\%$).
  - ⋆ Measure form factors for given value $|V_{ub}|_{\text{incl.}}$ $\to$ input for $B \to \pi\pi$ ...

Heavy quark expansion and new D_s resonances

- Unexpected new narrow D_s resonances at BaBar, BELLE, CLEO, CDF
  - ⋆ New D_s states below DK threshold $\longrightarrow$ no isospin-allowed strong decay channel
- In HQET hadrons are classified according to spin/parity j^P of light spectator:

$1/m_c$ corrections to heavy quark spin symmetry

j^P	heavy meson doublet	j^P	heavy meson doublet
$\frac{1}{2}^-$	$D_s(1968)$ $D_s^*(2112)$	$\frac{1}{2}^+$	$D_{sJ}^*(2317)$ $D_{sJ}(2460)$

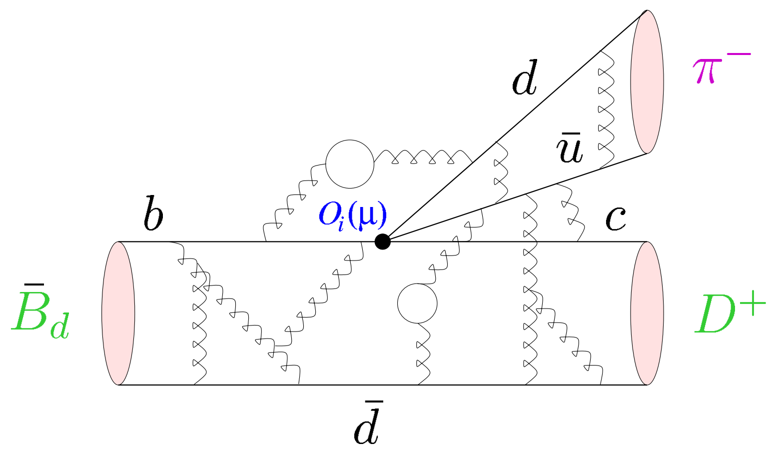
would-be chiral partners $\Delta m \propto \langle q\bar{q}\rangle$

- Issues related to soft dynamics within spectator system
  - ⋆ difficult to reproduce mass splitting in quark potential models
  - ⋆ situation in lattice QCD / sum rules not conclusive
  - ⋆ models with dynamical chiral symmetry breaking seem to work quite well
  - ⋆ exotic interpretations?

. . . $\longrightarrow$ Improve low-energy picture of QCD!

[many references]

Heavy quark decays into energetic particles $\longrightarrow$ SCET



References:

- QCD (improved) factorization / "BBNS approach":
  [Beneke/Buchalla/Neubert/Sachrajda, NPB591, 313 (2000), NPB606:245 (01)] . . .
- Soft-collinear effective theory:
  [Bauer *et al.*, PRD63:114020 (01); PRL87:201806 (01); PRD65:054022 (02); PRD67:071502 (03)];
  [Chay/Kim, PRD65:114016 (02)]; [Lunghi/Pirjol/Wyler, NPB649, 349 (03)];
  [Bosch/Hill/Neubert, PRD67:094014 (03)]; [Lange/Neubert, PRL91:102001 (03)];
  [Beneke/Chapovsky/Diehl/TF, NPB643, 431 (02)]; [Beneke/TF, hep-ph/0311335];
  [Beneke/Kiyo/Yang, hep-ph/0402241];
  [Hill/Neubert, NPB657, 229 (03); Becher/Lange/Neubert, PRD69:034013 (04)] . . .

Relevant degrees of freedom

Consider B-decays involving light energetic hadrons
($B \to D\pi$, $B \to \pi\pi$, $B \to K^*\gamma \ldots$)

- long-distance physics determined by two different types of light-quark and gluon modes: (in B meson rest frame)

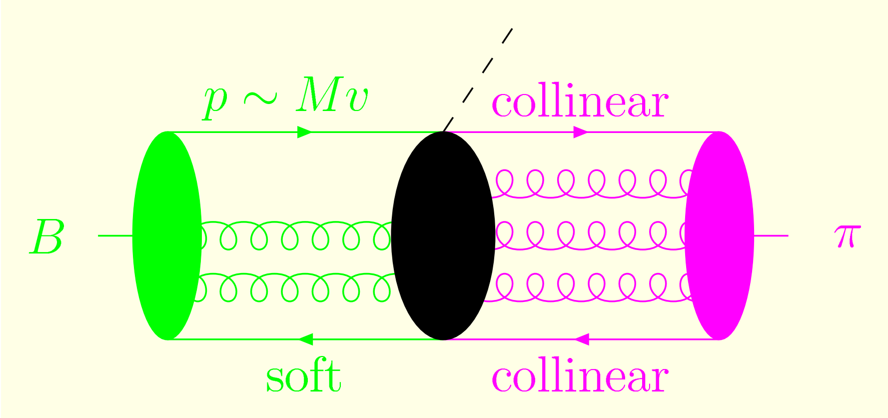
  ⋆ soft modes: $|p_s^\mu| \sim \Lambda_{\rm QCD}$ (as in HQET)
  ⋆ collinear modes: $E_c \sim m_b \,, \quad p_c^2 \sim \Lambda_{\rm QCD}^2$ (as in DIS)

- this implies two types of short-distance modes:

  ⋆ hard modes: $p_h^2 \sim m_b^2$
  ⋆ hard-collinear ("jet") modes: $E_{\rm hc} \sim m_b \,, \quad p_{\rm hc}^2 \sim (p_s + p_c)^2 \sim m_b \Lambda_{\rm QCD}$

  which one would like to treat perturbatively in hadronic matrix elements.

Example: $B \to \pi \ell \nu$ transition at large recoil



$E_\pi = \mathcal{O}(m_b)$

- low-virtuality modes:
  - ⋆ HQET fields: $p - m_b v \sim \mathcal{O}(\Lambda)$
  - ⋆ soft spectators in B meson:
    $p_s^\mu \sim \Lambda \ll m_b, \quad p_s^2 \sim \mathcal{O}(\Lambda^2)$
  - ⋆ collinear quarks and gluons in pion:
    $E_c \sim m_b, \quad p_c^2 \sim \mathcal{O}(\Lambda^2)$

- high-virtuality modes:
  - ⋆ hard modes:
    (heavy quark + collinear)$^2 \sim \mathcal{O}(m_b^2)$
  - ⋆ hard-collinear modes:
    (soft + collinear)$^2 \sim \mathcal{O}(m_b \Lambda)$

Soft-collinear effective theory

- Separation of short- and long-distance modes through virtuality:

$$p_c^2,\, p_s^2 \ll p_{\rm hc}^2 \ll p_{\rm h}^2$$

$\longrightarrow$ Use dimensional regularization: $d^4k \to \mu^{2\epsilon} d^{4-2\epsilon}k$

⋆ modes with $p^2 > \mu^2$ in short-distance coefficients
⋆ modes with $p^2 < \mu^2$ in matrix elements

- Presence of two perturbative scales implies two-step matching procedure

⋆ integrate out hard modes at $\mu_1^2 \sim m_b^2 \longrightarrow$ SCET$_I$
⋆ use renormalization group in SCET$_I$ to evolve to $\mu_2^2 \sim m_b \Lambda_{\rm QCD}$
⋆ integrate out hard-collinear modes $\longrightarrow$ SCET$_{II}$

Features of SCET

- Soft Lagrangian is a copy of QCD restricted to soft modes. (as in HQET)

- The collinear Lagrangian is expressed in terms of "good" light-cone components of light quark spinors. (⟶ new symmetries)

$$\mathcal{L}_c = -\frac{1}{2}\mathrm{tr}[F_{\mu\nu}F^{\mu\nu}]_c + \bar{\xi}_c\Big[(in_-D_c) + (i\not{D}_{\perp\,c} - m)\,\frac{1}{(in_+D_c)}\,(i\not{D}_{\perp\,c} + m)\Big]\frac{\not{n}_+}{2}\,\xi_c$$

- Effective-theory currents are non-local! (soft and collinear fields are separated by light-like distances)

  ⋆ matching coefficients ⟶ coefficient functions (dependent on particle energies)
  ⋆ multiplicative renormalization ⟶ convolutions

  (as in DIS)

- Since the theory contains two type of long-distance modes, the dependence on the renormalization scale is through "Sudakov" double-logarithms.

Factorization of soft and collinear degrees of freedom

- Factorization theorems for exclusive B-decays state that, in addition, long-distance dynamics from soft and collinear interactions can be separated:

$$\text{e.g.} \qquad \langle D\pi|H_{\rm eff}|B\rangle = \langle D|J_1|B\rangle \cdot T_{\rm I} \star \langle \pi|J_2|0\rangle \ ;$$

$$\langle \pi\pi|H_{\rm eff}|B\rangle = \langle \pi|J_1|B\rangle \cdot T_{\rm I} \star \langle \pi|J_2|0\rangle + \langle 0|J_1|B\rangle \star T_{\rm II} \star \langle \pi|J_2|0\rangle\langle \pi|J_3|0\rangle$$

- Hadronic matrix elements expressed in terms of simpler universal objects:
  - ⋆ transition form factors
  - ⋆ B-meson light-cone wave function
  - ⋆ light-cone wave functions for π etc.

- Short-distance functions $T_{\rm I,II}$ can be calculated in perturbation theory.

→ QCD-improved factorization (BBNS)

Generic statements of QCD-improved factorization

- Small strong (re-scattering) phases.
  (either perturbatively calculable, or suppressed by powers of $1/m_b$)

  (different to "pQCD" approach of Keum et al.)

- Radiative corrections to "naive" factorization can be calculated systematically.

  $\longrightarrow$ Eliminate scale ambiguities.

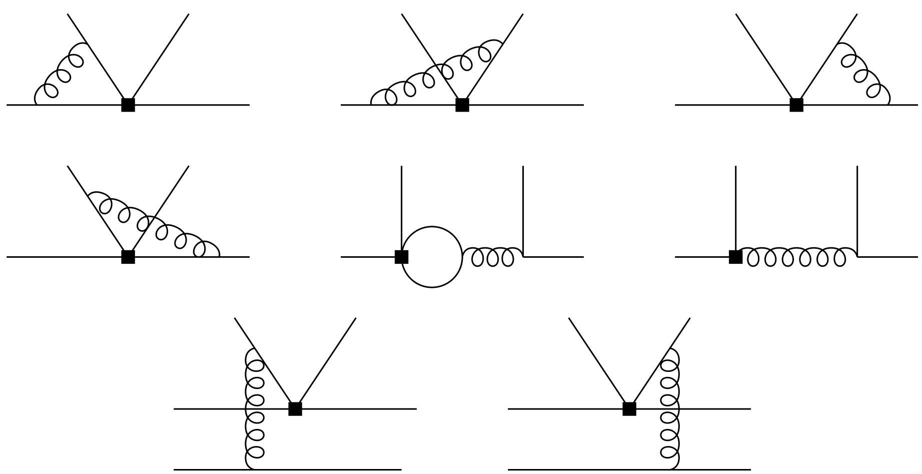
- Some formally power-suppressed terms are enhanced by numerical factors proportional to the quark condensate.

  $\longrightarrow$ limits the accuracy of theoretical predictions in this framework.

- Combination with traditional methods (isopsin, flavor symmetry) possible.

How to prove / disprove soft-collinear factorization?

- This is a highly non-trivial task: [Beneke/TF 03]
  - ⋆ Separation of soft and collinear degrees of freedom cannot be performed by dim. reg. !
  - ⋆ No factorization, if amplitudes are sensitive to endpoint behaviour of convolution integrals, where E_c becomes small or E_s becomes large.
  - ⋆ Factorization usually does not hold beyond the limit $m_b \to \infty$.
  - ⋆ Rigorous (all orders) factorization proofs (so far) only for particular examples $(B \to \gamma \ell \nu,\ B \to D\pi,\ B \to \pi \ell \nu)$
  - ⋆ In other cases: rely on diagrammatic analysis at fixed order of α_s (and $m_b \to \infty$):



“Theory vs. Experiment” (Examples)

$B \to \pi\pi$ and $B \to \pi K$ decays

1. $B \to \pi\pi$ data not well in line with QCD factorization (central values)
   - ⋆ Large modification of some hadronic input parameters (?) [Beneke/Neubert 03]
     $\longrightarrow$ enhancement of effective parameter $a_2 = C_2 + C_1/N_c + \mathcal{O}(\alpha_s) + \mathcal{O}(\Lambda/m_b)$
   - ⋆ Large phases by long-distance rescattering effects (?)
     - "charming penguins" (?) [Ciuccini et al.]
     - but only modest effect from QCD sum rules [Khodjamirian/Melic/Mannel 03]
   - ⋆ Take as input for $SU(3)$ analysis in $B \to \pi K$ (!) [Buras et al. 04]

2. Somewhat too large theoretical prediction for CP-averaged ratio

$$R_n = \frac{1}{2}\,\frac{\mathrm{BR}[B_d^0 \to \pi^- K^+] + \mathrm{BR}[\bar{B}_d^0 \to \pi^+ K^-]}{\mathrm{BR}[B_d^0 \to \pi^0 K^0] + \mathrm{BR}[\bar{B}_d^0 \to \pi^0 K^0]} = 1 + \mathcal{O}(10\%)\left\{1 + \mathcal{O}(\frac{\alpha_{\mathrm{em}}}{\epsilon_{\mathrm{CKM}}})\right\}$$

   - ⋆ Problem of experimental data?
   - ⋆ New physics contribution, showing up in EW penguins?
   - ⋆ Discrepancy appears to be independent of assumptions about factorization . . .

Ratios of $B \to \pi\pi$ and $B \to \pi K$ observables

Observable	QCD-F	SM Fit + $\mathrm{SU}(3)_{\mathrm{F}}$	EXP
$R_{+-}^{\pi\pi}$	$1.26^{+0.49}_{-0.33}$	input	2.12 ± 0.37
$R_{00}^{\pi\pi}$	$0.08^{+0.11}_{-0.05}$	input	0.83 ± 0.23
R	$0.91^{+0.13}_{-0.11}$	$0.94^{+0.03}_{-0.03}$	0.91 ± 0.07
R_{c}	$1.15^{+0.19}_{-0.17}$	$1.14^{+0.08}_{-0.07}$	1.17 ± 0.12
R_{n}	$1.16^{+0.22}_{-0.19}$	$1.11^{+0.06}_{-0.07}$	0.76 ± 0.10
Ref.	Beneke/Neubert 2003	Buras et al. 2004	HFAG

- Can we establish new physics from "R_n puzzle"?
- Are we sure about our understanding of hadronic effects?

$\longrightarrow$ to be taken into account when extracting CKM angle γ from $B \to PP$

CP violation in $B \to \phi K_s$

- Time-dependent CP-asymmetry
  for neutral B-meson decays into CP eigenstates:

$$\mathcal{A}_f(t) \equiv \frac{\Gamma[\bar{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\bar{B}^0(t) \to f] + \Gamma[B^0(t) \to f]} = -\boxed{C_f} \cos(\Delta m_B\, t) + \boxed{S_f} \sin(\Delta m_B\, t)$$

- If decay is dominated by a single weak phase, $C_f \simeq 0$

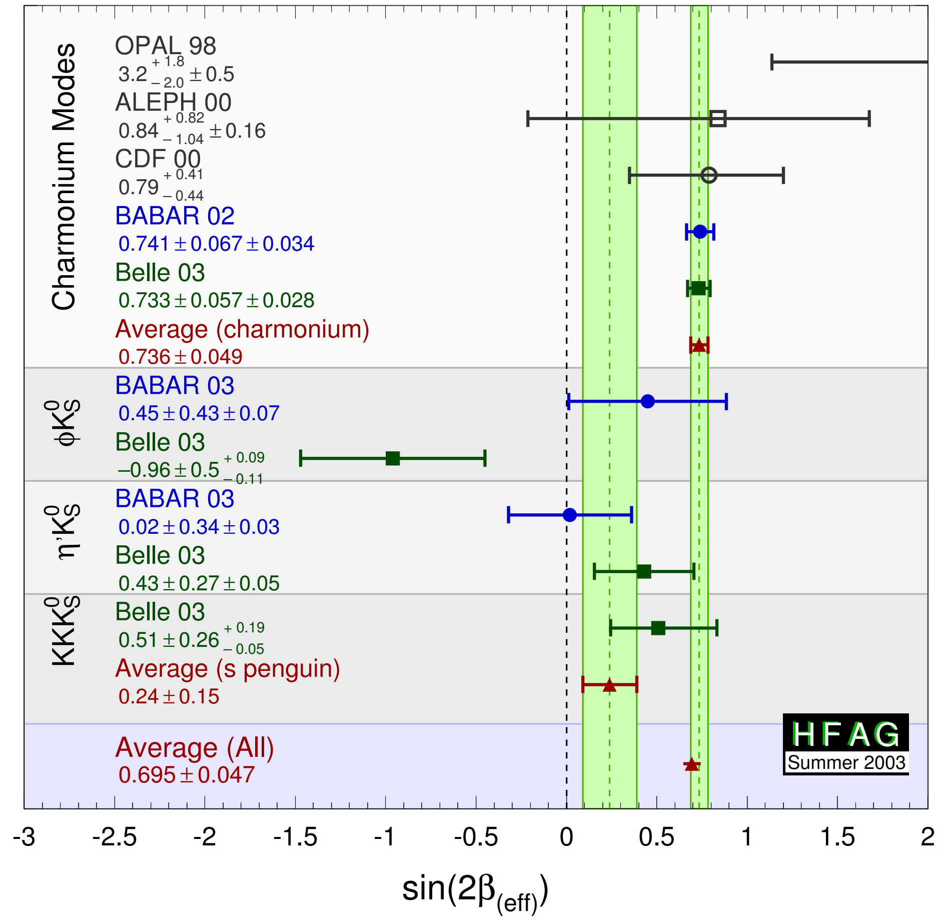
- For $B \to \phi K_s$ dominant contribution from penguin $b \to s s \bar{s}$ transition

$$\Rightarrow \quad S_{\phi K_s} \simeq \sin 2\beta$$

  measures the same angle of the CKM triangle as in $B \to J/\psi K_s$!

(also for $B \to \eta' K_s$, $B \to K^+ K^- K_s$)

Experimental Situation for $\sin(2\beta)_{\text{eff}}$ (HFAG)



- Too small S_f from $b \to s s \bar{s}$ channels!
  - ⋆ BELLE measurement of $S_{\phi K_s}$
  - ⋆ BABAR measurement of $S_{\eta' K_s}$
- Theoretical estimates of hadronic effects not sufficient to explain large discrepancy between $S_{\phi K_s}$ and $S_{J/\psi K_s}$.

  (QCD-F, [Beneke/Neubert 02])

  ($SU(3)_F$ analysis, [Grossmann et al. 03])

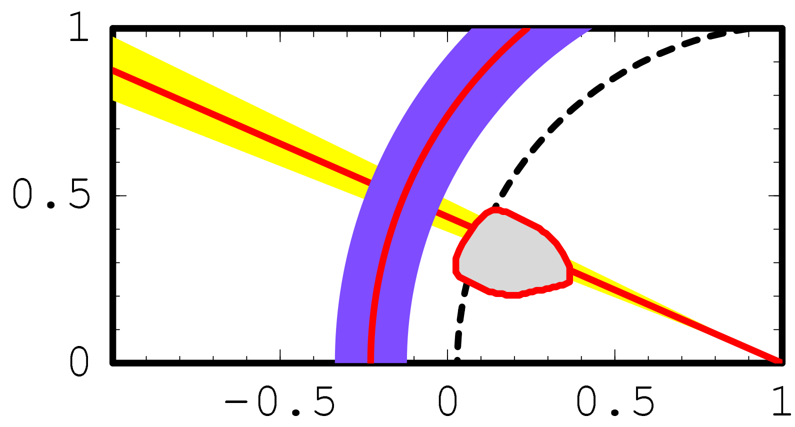
$\longrightarrow$ Experimental issue . . . ?

(new results $\longrightarrow$ R. Stamen, T II)

$\longrightarrow$ New physics in $b \to s s \bar{s}$?

Constraints on unitarity triangle from $\Gamma[B \to \rho\gamma]/\Gamma[B \to K^*\gamma]$

[Bosch/Buchalla 02, Ali et al. 02]



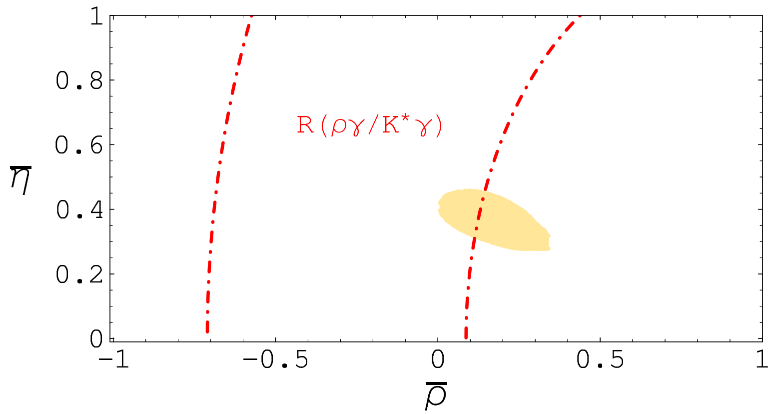
$$R_{00} \equiv \frac{\Gamma[B^0 \to \rho^0\gamma]}{\Gamma[B^0 \to K^{*(0)}\gamma]} \simeq \frac{1}{2}\frac{|V_{td}|^2}{|V_{ts}|^2}\left[\frac{F^{B\to\rho}}{F^{B\to K^*}}\right]^2 (1 + \delta(\rho,\eta))$$

- Experimental upper bound $R_{00} < 0.024$

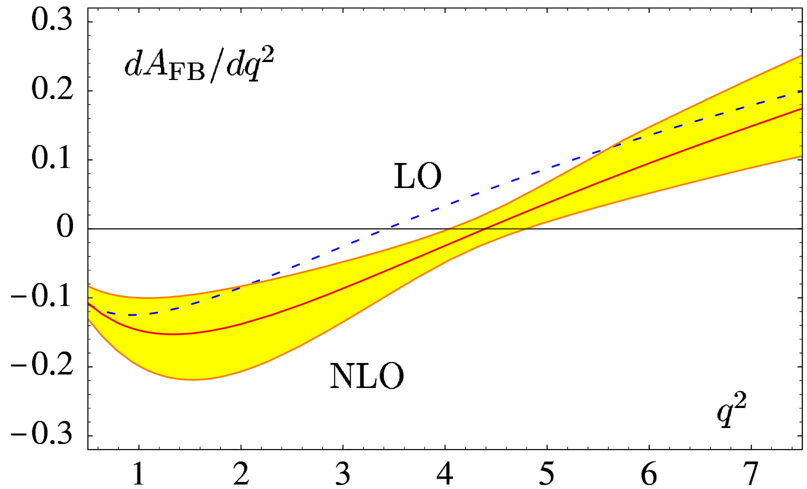
  $\longrightarrow$ Upper bound for length of one side of the unitarity triangle $R_t < 1.24$
- Becomes competitive with constraints from ΔM_B
- Dominating uncertainty from form factor ratio (dashed curve $= SU(3)_F$ limit)
- Function $\delta(\rho,\eta)$ can be calculated in QCD-F.

Including new experimental number for $B \to \rho/\omega\gamma$

Preliminary! — With kind help from Enrico Lunghi!



FB asymmetry zero in $B \to K^* \ell^+ \ell^-$



[from Beneke/TF/Seidel '01]

Our prediction:

$$q_0^2 = \begin{array}{ll} (4.39 \pm 0.35)\ \text{GeV}^2 & \text{excl. } 1/m_b \\ (4.2 \pm 0.6)\ \text{GeV}^2 & \text{incl. } 1/m_b \end{array}$$

[⟶ future experiments]

- For given value of C_7^{eff} (e.g. from $B \to X_s \gamma$), Wilson coefficient C_9 can be tested with $\sim 15\%$ accuracy!

[15% on loop-induced quantity to be compared with $\frac{15\%}{16\pi^2} \simeq 0.1\%$ accuracy for tree-level process.]

Conclusions

~~Goals~~ Achievements of B-physics

Measurement of Standard Model parameters, Precision test of CKM mechanism, Hints/constraints on new physics

$\longleftarrow$ complementary to electroweak precision tests (LEP) and direct searches (LHC, Tevatron)

operator product expansion
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Understanding strong interactions on the quantum level (QCD)

Probing hadronic structure in B-meson and its decay products

$\longleftarrow$ theoretical and phenomenological input for other processes