Precision Flavour Physics as a Probe beyond the Standard Model

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Introduction: Why Study Flavour Physics?
- Why do we believe in TeV Physics?
- What can Flavour tell us?

Theory Tools for Precision Flavour Physics
- Effective Weak Hamiltonian
- Heavy Quark Expansions
- Approximate Flavour Symmetries

Achievements
- Semileptonic Decays
- Nonleptonic Decays
- Rare Decays
Why Study Flavour Physics?
The Standard Model passed all tests up to the 100 GeV Scale:
- LEP: test of the gauge Structure
- Flavour factories: test of the Flavour Sector
No significant deviation has been found (yet)!

... only a few “tensions”
(= Observables off by 2σ or even less)

LHC will perform a direct test of the TeV Scale
Why do we believe in TeV Physics?

- Theoretical argument:
- Stabilization of the electroweak scale:
  \[ \Delta m_H^2 = -\frac{\lambda_f^2}{8\pi^2} \Lambda_{\text{UV}}^2 \]
  \[ \Lambda_{\text{UV}} \sim M_{\text{PL}} \]

- Quadratic Dependence on the cut-off
Stabilization at the TeV scale: e.g. through SUSY:

\[ \Delta m_H^2 = m_{soft}^2 \frac{\lambda}{16\pi^2} \ln \left( \frac{\Lambda_{UV}}{m_{soft}} \right) \]

- Only logarithmic divergence

- \( m_{soft} \sim \mathcal{O}(\text{TeV}) \):
  
  Splitting between particles and particles
How strong are these arguments?

Could there something be wrong with our understanding of

- electroweak symmetry breaking?
- scale and conformal invariance?
  (c.f. Lee Wick Model)
- ...

Does flavour tell us something about this?
.... and what?
What can Flavour tell us?

- Flavour Physics $\leftrightarrow$ No new physics at the TeV scale with a generic flavour structure
- Parametrization of new physics:
  - Higher Dimensional Operators:
    \[
    \mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \mathcal{L}^{(5)} + \frac{1}{\Lambda^2} \mathcal{L}^{(6)} + \cdots
    \]
    \[\mathcal{L}^{(n)} = \sum_{j} C_j O_j^{(n)}\]

- $\Lambda$: New Physics scale
- $O_j^{(n)}$: Local Operators of dimension $n$
Some of the $O^{(n)}_j$ may mediate flavour transitions: e.g.

\[
\begin{align*}
O^{(6)}_1 &= (\bar{s}_L \gamma_\mu d)(\bar{s}_L \gamma^\mu d) \quad \text{(Kaon Mixing)} \\
O^{(6)}_2 &= (\bar{b}_L \gamma_\mu d)(\bar{b}_L \gamma^\mu d) \quad \text{(B}_d \text{ Mixing)} \\
O^{(6)}_3 &= (\bar{b}_L \gamma_\mu 2)(\bar{b}_L \gamma^\mu s) \quad \text{(B}_s \text{ Mixing)} \\
O^{(6)}_4 &= (\bar{c}_L \gamma_\mu u)(\bar{c}_L \gamma^\mu u) \quad \text{(D Mixing)}
\end{align*}
\]

\begin{itemize}
  \item $\Lambda \sim 1000$ TeV from Kaon mixing ($C_i = 1$)
  \item $\Lambda \sim 1000$ TeV from $D$ mixing
  \item $\Lambda \sim 400$ TeV from $B_d$ mixing
  \item $\Lambda \sim 70$ TeV from $B_s$ mixing
\end{itemize}
Recent LHCb result on CP violation in $D$ decays:

$$\Delta A_{\text{CP}} = A_{\text{CP}}(D^0 \rightarrow K^+ K^-) - A_{\text{CP}}(D^0 \rightarrow \pi^+ \pi^-)$$

$$= \begin{cases} -(0.82 \pm 0.21 \pm 0.11)\% & \text{LHCb} \\ -(0.68 \pm 0.18)\% & \text{world average} \end{cases}$$
“New physics” is around the corner??
Are the flavour data a hint at a new physics scale well above the TeV scale?
... there are a few corners where $\mathcal{O}(1)$ flavour effects are still possible, c.f. Charm CPV
Are there lessons from history?
The Top Quark Story

- First indirect hint to a heavy top quark: $B - \bar{B}$ Oscillation of ARGUS (1987)
- The world in 1987 (“PETRA Days”): The top was believed to be at $\sim 25$ GeV ... based on good theoretical arguments
- ARGUS could not have seen anything with a 25 GeV Top (within SM)
The consequences:

(−) No Toponium
(−) No Top quark discovery at LEP and SLC
(−) No “New Physics $\mathcal{O}(30 \text{ GeV})$” just around the corner
(+ ) CP violation in the $B$ sector may become observable
(+ ) GIM is weak for bottom quarks

This was actually good for Flavour Physics ...

GIM suppressed decays as a probe for large scales
From current data: TeV “New Physics” must have a flavour structure close to the one of the SM

Concept of “Minimal Flavour Violation” (MFV)
Strong CP remains mysterious
Flavour diagonal CP Violation is well hidden:
- e.g electric dipole moments:
  For quarks at least three loops (Shabalin)

\[
d_e^{\text{quark}} \sim e \frac{\alpha_s}{\pi} \frac{G_F^2}{(16\pi^2)^2} \frac{m_t^2}{M_W^2} \text{Im}\Delta \mu^3
\]
\[
\sim 10^{-32} \text{e cm} \quad \text{with} \quad \mu \sim 0.3 \text{GeV}
\]
\[
d_{\text{Neutron}}^{\text{exp}} \leq 3.0 \times 10^{-26} \text{e cm}
\]
Pattern of mixing and mixing induced CP violation determined by GIM: Tiny effects in the up quark sector

- $\Delta C = 2$ is very small
- Mixing with third generation is small: charm physics basically “two family”
- $\rightarrow$ CP violation in charm should be small in the SM

Fully consistent with particle physics observations
... but inconsistent with matter-antimatter asymmetry
Our Understanding of Flavour is unsatisfactory:

- 22 (out of 27) free Parameters of the SM originate from the Yukawa Sector (including Lepton Mixing)
- Why is the CKM Matrix hierarchical?
- Why is CKM so different from the PMNS?
- Why are the quark masses (except the top mass) so small compared with the electroweak VEV?
- Why do we have three families?

Why is CP Violation in Flavour-diagonal Processes not observed? (e.g. z.B. electric dipolmoments of electron and neutron)

Where is the CP violation needed to explain the matter-antimatter asymmetry of the Universe?
Theory Tools for Precision Flavour Physics
Tools I: Effective Weak Hamiltonian

- Integrate out the weak bosons and the top:

\[ H_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \lambda_{\text{CKM}} \sum_k \hat{C}_k(\mu)O_k(\mu) \]

\[ \begin{align*}
O_1 &= (\bar{c}_L,i\gamma_\mu s_L,i)\left(\bar{d}_L,i\gamma_\mu u_L,i\right), & O_2 &= (\bar{c}_L,i\gamma_\mu s_L,i)\left(\bar{d}_L,i\gamma_\mu u_L,i\right), \\
O_3 &= (\bar{s}_L,i\gamma_\mu b_L,i) \sum_{q=u,d,s,c,b} (\bar{q}_L,j\gamma_\mu q_{L,j}), & O_4 &= (\bar{s}_L,i\gamma_\mu b_L,i) \sum_{q=u,d,s,c,b} (\bar{q}_L,j\gamma_\mu q_{L,i}), \\
O_5 &= (\bar{s}_L,i\gamma_\mu b_L,i) \sum_{q=u,d,s,c,b} (\bar{q}_R,j\gamma_\mu q_{R,j}), & O_6 &= (\bar{s}_L,i\gamma_\mu b_L,i) \sum_{q=u,d,s,c,b} (\bar{q}_R,j\gamma_\mu q_{R,i}).
\end{align*} \]

\[ \begin{align*}
O_7 &= \frac{e}{16\pi^2} m_b(\bar{s}_L,\alpha \sigma_{\mu\nu} b_{R,\alpha}) F_{\mu\nu}, & O_8 &= \frac{g}{16\pi^2} m_b(\bar{s}_L,\alpha \gamma^a T^a_{\alpha\beta} \sigma_{\mu\nu} b_{R,\alpha}) G^{a\mu\nu}, \\
O_9 &= \frac{1}{2} (\bar{s}_L \gamma_\mu b_L)(\bar{\ell} \gamma^\mu \ell), & O_{10} &= \frac{1}{2} (\bar{s}_L \gamma_\mu b_L)(\bar{\ell} \gamma^\mu \gamma_5 \ell).
\end{align*} \]

- Coefficients in the SM are known to NLO!

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Precision Flavour Physics
**Tools II: Heavy Quark Expansions**

- Main development for precision flavour physics of heavy quarks: **Heavy Mass Expansion Methods:** HQET, HQE, SCET ...
- Remarkable Progress:
  In many cases this has pushed hadronic uncertainties back to the $1/m_b$ corrections
- Systematic calculations of radiative corrections is possible in these effective theories
- Works well for leptonics and semi-leptonics
  Exclusive as well as Inclusive
- Still a few problems with non-leptonics
  ... in particular for exclusive non-leptonics
Heavy Quark Symmetries: Exclusive Decays

- Kinematic variable for a heavy quark: Four Velocity $\nu$
- Differential Rates

$$
\frac{d\Gamma}{d\omega} (B \to D^* \ell \bar{\nu}_\ell) = \frac{G_F^2}{48\pi^3} |V_{cb}|^2 m_{D^*}^3 (\omega^2 - 1)^{1/2} P(\omega)(\mathcal{F}(\omega))^2
$$

$$
\frac{d\Gamma}{d\omega} (B \to D \ell \bar{\nu}_\ell) = \frac{G_F^2}{48\pi^3} |V_{cb}|^2 (m_B + m_D)^2 m_D^3 (\omega^2 - 1)^{3/2} (\mathcal{G}(\omega))^2
$$

- with $\omega = \nu \nu'$ and
- $P(\omega)$: Calculable Phase space factor
- $\mathcal{F}$ and $\mathcal{G}$: Form Factors
Heavy Quark Symmetries

- Normalization of the Form Factors is known at $v v' = 1$: (both initial and final meson at rest)
- Corrections can be calculated / estimated

\[
\mathcal{F}(\omega) = \eta_{\text{QED}} \eta_A \left[ 1 + \delta_1/\mu^2 + \cdots \right] + (\omega - 1)\rho^2 + O((\omega - 1)^2)
\]

\[
\mathcal{G}(1) = \eta_{\text{QED}} \eta_V \left[ 1 + O \left( \frac{m_B - m_D}{m_B + m_D} \right) \right]
\]

- Parameter of HQS breaking: $\frac{1}{\mu} = \frac{1}{m_c} - \frac{1}{m_b}$
- $\eta_A = 0.960 \pm 0.007$, $\eta_V = 1.022 \pm 0.004$,
  $\delta_1/\mu^2 = -(8 \pm 4)\%$, $\eta_{\text{QED}} = 1.007$
B → D(∗) Form Factors from the Lattice

- Unquenched Calculations become available!
- Heavy Mass Limit is not used
- Lattice Calculations of the deviation from unity

\[ F(1) = 0.908 \pm 0.016 \]

\[ G(1) = 1.074 \pm 0.018 \pm 0.016 \]

$B \rightarrow D^{(*)}$ Form Factors: Non-Lattice Results

- $B \rightarrow D^*$ Form Factor:
  - Based on Zero Recoil Sum Rules (Uraltsev, also Ligeti et al.)
  - Including full $\alpha_s$ and up to $1/m_b^5$

  $$\mathcal{F}(1) = 0.86 \pm 0.04$$
  (Gambino, Uraltsev, M (2010))

- $B \rightarrow D$ Form Factor:
  - Based on the “BPS limit” $\mu_\pi^2 = \mu_G^2$

  $$\mathcal{G}(1) = 1.04 \pm 0.02$$
  (Uraltsev)
Heavy Quark Expansion = Operator Product Expansion

\[ \Gamma \propto \sum_{X} (2\pi)^4 \delta^4 (P_B - P_X) |\langle X | \mathcal{H}_{\text{eff}} | B(v) \rangle|^2 \]

\[ = \int d^4 x \, \langle B(v) | \mathcal{H}_{\text{eff}}(x) \mathcal{H}_{\text{eff}}^\dagger(0) | B(v) \rangle \]

\[ = 2 \text{ Im} \int d^4 x \, \langle B(v) | T \{ \mathcal{H}_{\text{eff}}(x) \mathcal{H}_{\text{eff}}^\dagger(0) \} | B(v) \rangle \]

\[ = 2 \text{ Im} \int d^4 x \, e^{-im_b v \cdot x} \langle B(v) | T \{ \tilde{\mathcal{H}}_{\text{eff}}(x) \tilde{\mathcal{H}}_{\text{eff}}^\dagger(0) \} | B(v) \rangle \]

- Last step: \( b(x) = b_v(x) \exp(-im_b v x), \) corresponding to \( p_b = m_b v + k \)

Expansion in the residual momentum \( k \)
Perform an “OPE”: \( m_b \) is much larger than any scale appearing in the matrix element

\[
\int d^4 x e^{-i m_b v x} T \{ \tilde{\mathcal{H}}_{\text{eff}}(x) \tilde{\mathcal{H}}^\dagger_{\text{eff}}(0) \} = \sum_{n=0}^{\infty} \left( \frac{1}{2 m_Q} \right)^n C_{n+3}(\mu) \mathcal{O}_{n+3}
\]

→ The rate for \( B \to X_c \ell \bar{\nu}_\ell \) can be written as

\[
\Gamma = \Gamma_0 + \frac{1}{m_Q} \Gamma_1 + \frac{1}{m_Q^2} \Gamma_2 + \frac{1}{m_Q^3} \Gamma_3 + \cdots
\]

The \( \Gamma_i \) are power series in \( \alpha_s(m_Q) \):

→ Perturbation theory!

→ Works also for differential rates!
\( \Gamma_0 \) is the decay of a free quark ("Parton Model")
\( \Gamma_1 \) vanishes due to Heavy Quark Symmetries
\( \Gamma_2 \) is expressed in terms of two parameters

\[
2M_H \mu_\pi^2 = -\langle H(v) | \bar{Q}_v (iD)^2 Q_v | H(v) \rangle
\]
\[
2M_H \mu_G^2 = \langle H(v) | \bar{Q}_v \sigma_{\mu\nu} (iD^\mu)(iD^\nu) Q_v | H(v) \rangle
\]

\( \mu_\pi \): Kinetic energy and \( \mu_G \): Chromomagnetic moment
\( \Gamma_3 \) two more parameters

\[
2M_H \rho_D^3 = -\langle H(v) | \bar{Q}_v (iD_\mu)(ivD)(iD^\mu) Q_v | H(v) \rangle
\]
\[
2M_H \rho_{LS}^3 = \langle H(v) | \bar{Q}_v \sigma_{\mu\nu} (iD^\mu)(ivD)(iD^\nu) Q_v | H(v) \rangle
\]

\( \rho_D \): Darwin Term and \( \rho_{LS} \): Spin-Orbit Term

\( \Gamma_4 \) and \( \Gamma_5 \) have been computed Bigi, Uraltsev, Turczyk, TM, ...
Structure of the expansion (@ tree):

\[ d\Gamma = d\Gamma_0 + \left( \frac{\Lambda_{QCD}}{m_b} \right)^2 d\Gamma_2 + \left( \frac{\Lambda_{QCD}}{m_b} \right)^3 d\Gamma_3 + \left( \frac{\Lambda_{QCD}}{m_b} \right)^4 d\Gamma_4 \]

\[ + d\Gamma_5 \left( a_0 \left( \frac{\Lambda_{QCD}}{m_b} \right)^5 + a_2 \left( \frac{\Lambda_{QCD}}{m_b} \right)^3 \left( \frac{\Lambda_{QCD}}{m_c} \right)^2 \right) \]

\[ + \ldots + d\Gamma_7 \left( \frac{\Lambda_{QCD}}{m_b} \right)^3 \left( \frac{\Lambda_{QCD}}{m_c} \right)^4 \]

\[ d\Gamma_3 \propto \ln(m_c^2/m_b^2) \]

\[ \text{Power counting } m_c^2 \sim \Lambda_{QCD} m_b \]
Present state of the $b \rightarrow c$ semileptonic Calculations

- Tree level terms up to and including $1/m_b^5$ known
  Bigi, Zwicky, Uraltsev, Turczyk, TM, ...

- $\mathcal{O}(\alpha_s)$ and full $\mathcal{O}(\alpha_s^2)$ for the partonic rate known
  Melnikov, Czarnecki, Pak

- Proper mass definitions for $m_b$ and $m_c$ and precise input values have been given
  Hoang, Gambino, Kühn Steinhauser

- $\mathcal{O}(\alpha_s)$ for the $\mu_\pi^2/m_b^2$ is known
  Becher, Boos, Lunghi, Gambino

- In the pipeline:
  - Complete $\alpha_s/m_b^2$, including the $\mu_G$ terms
  - More on the “Intrinsic charm” and “weak annihilation” contributions
Avoid to deal with QCD dynamics:
Use symmetries of QCD
I-spin, V-Spin, U-Spin or full Flavour SU(3)
Discuss breaking of SU(3)
Supplement group theory by “diagrammatic considerations” such as “Penguins are smaller than trees”
Improvement by more data possible
Tools IV: Lattice QCD

... ask the lattice experts ...
Introduction: Why Study Flavour Physics?

Theory Tools for Precision Flavour Physics

Achievements

Semileptonic Decays

- The $1/m_b$ Expansion: an enormous progress

$$V_{cb, incl} = (41.54 \pm 0.72) \times 10^{-3}$$ (HQE)

A theo. uncertainty of 1% in $V_{cb, incl}$ looks plausible!

$$V_{cb, excl} = (38.7 \pm 1.1) \times 10^{-3}$$ (Lattice, 2008)

$$V_{cb, excl} = (39.7 \pm 1.1) \times 10^{-3}$$ (Lattice, 2010)

$$V_{cb, excl} = (41.0 \pm 1.5) \times 10^{-3}$$ (ZR Sum Rules. prelim.)

Tension between $V_{cb, incl}$ and $V_{cb, excl}$ is about to disappear!
Nonleptonic Decays

- The golden modes $B \to J/\psi K_s$ and $B_s \to J/\psi \phi$:
- How golden are these golden modes?
- Look at a decay $B \to f$, ($f$: Some CP eigentstate)

$$A(B^0 \to f) = A \left[ 1 + r_f e^{i\delta_f} e^{i\theta_f} \right]$$

- $\delta_f$: Weak Phase and $\theta_f$: Strong phase
- Penguin-over-Tree ratio:

$$r_f = \lambda_{\text{CKM},f} a_f$$

- $a_f$: Modulus of a ratio of hadronic matrix elements
- $\lambda_{\text{CKM},f}$: Modulus of a ratio of CKM matrix elements
Key Observable: Time-Dependent CP Asymmetries

\[ A_{\text{CP}}(t; f) \equiv \frac{\Gamma(B^0(t) \to f) - \Gamma(\bar{B}^0(t) \to f)}{\Gamma(B^0(t) \to f) + \Gamma(\bar{B}^0(t) \to f)} \]

General Expression

\[ A_{\text{CP}}(t; f) = A_D^f \cos(\Delta M_q t) + A_M^f \sin(\Delta M_q t) \frac{\cosh(\Delta \Gamma_q t/2) - A_{\Delta \Gamma}^f}{\cosh(\Delta \Gamma_q t/2) - A_{\Delta \Gamma}^f \sinh(\Delta \Gamma_q t/2)} \]

Neglecting the lifetime difference (for the \( B_d \))

\[ A_{\text{CP}}(t; f) = A_D^f \cos(\Delta M_q t) + A_M^f \sin(\Delta M_q t) \]
In terms of the parameters of the amplitude and the mixing phase $\phi_s$

\[ A_D^f = -2r_f \sin \theta_f \sin \delta_f \]
\[ A_M^f = \left[ \sin \phi_s + 2r_f \cos \theta_f \sin(\phi_s + \delta_f) + r_f^2 \sin(\phi_s + 2\delta_f) \right] \]
\[ A_{\Delta\Gamma}^f = \ldots \text{not needed here} \]

Golden Modes: For $B_d \to J/\psi K_s$ and $B_s \to J/\psi \phi$:

\[ \lambda_{\text{CKM},f} = \left| \frac{V_{ub} V_{us}^*}{V_{cb} V_{cs}^*} \right| \sim 5\% \]

(Bigi, Sanda)
Thus: In the Standard Model $r_{J/\psi K} \leq 5\%$:

$$C(J/\psi K_{S,L}) \approx 0, \quad S(J/\psi K_{S,L}) \approx -\eta_{S,L} \sin 2\beta$$

Penguin contamination small, suppressed by $\lambda_{\text{CKM}}$

Is it really small?

If not, what can be the sensitivity to a new physics contribution?
Use of data: **Employ Flavour Symmetries**
(M. Ciuchini, M. Pierini and L. Silvestrini, Phys. Rev. Lett. 95, 221804 (2005),

Problem: Flavour $SU(3)$ is severely broken

Two Strategies:
- Assume $SU(3)$, allow for generous uncertainties
- Try to get a hand on $SU(3)$ breaking

In the case at hand:
Compare $b \rightarrow s \bar{c}c$ with its $SU(3)$ friend $b \rightarrow d \bar{c}c$

Parametrize ($\phi_d = B - \bar{B}$ Mixing phase)

$$S(J/\psi K_S) = \sin(\phi_d + \Delta \phi_d)$$

$$\tan \Delta \phi_d = \frac{2 \lambda_{\text{CKM}} a \cos \theta \sin \gamma + \lambda_{\text{CKM}}^2 a^2 \sin 2\gamma}{1 + 2 \lambda_{\text{CKM}} a \cos \theta \cos \gamma + \lambda_{\text{CKM}}^2 a^2 \cos 2\gamma}$$
Using $SU(3)$ for $a$ and $\theta$: $\Delta \phi_d \in [-3.9, -0.8]^{\circ}$

Allowing 50% $SU(3)$ breaking in $a$ and $\theta, \theta' \in [90, 270]^{\circ}$ independently: $\Delta \phi_d \in [-6.7, 0.0]^{\circ}$

Hints at negative $\Delta \phi_d$

Softens the tension with the SM fit

However, still quite debatable $SU(3)$ assumptions

This is likely much larger then the perturbative estimate! (Ala Boos, Reuter, TM.)

Also significantly larger than other estimates (e.g. Gronau Rosner 2008)
Rare \((b \rightarrow s)\) Semileptonics

- Theory of \(B \rightarrow K^{(*)}\ell^+\ell^-\) is substantially different from the one for \(B \rightarrow D\ell\bar{\nu}\):

- Effective Interaction:

\[
H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) O_i(\mu),
\]

- Dominant \(b \rightarrow s\) effective operators: \(O_{7,9,10}\)

\(C_7(m_b) \approx -0.3, C_9(m_b) \approx 4.4, C_{10}(m_b) \approx = -4.7\)

- ... can be expressed in terms of form factors

\[
O_{7,9,10} \propto \langle K^{(*)}(p)|\bar{s} \Gamma b|B(p + q)\rangle
\]
Charm Loops


- Charm-loop effect: a combination of the $\langle \bar{s}c \rangle \langle \bar{c}b \rangle$ weak interaction ($O_{1,2}$) and e.m.interaction $\langle \bar{c}c \rangle \langle \ell \ell \rangle$

- new hadronic matrix elements, not a form factor
Light cone expansion of the charm loop

Expansion parameter $\frac{\Lambda^2_{\text{QCD}}}{(4m_c^2 - q^2)}$

Leads to a non-local operator ("shape-function-like" operator)

$$\tilde{O}_\mu(q) = \int d\omega \, l_{\mu\rho\alpha\beta}(q, m_c, \omega) \bar{s}_L \gamma^\rho \left( \delta[\omega - \frac{(in + D)}{2}] \tilde{G}_{\alpha\beta} \right) b_L,$$

Matrix element can be calculated in a LCSR for $q^2 \leq 0$
Results on $B \rightarrow K^{(*)} \ell^+ \ell^-$

$10^{-7}dBR/dq^2(B_0 \rightarrow K^0 \mu^+ \mu^-)$

$q^2(\text{GeV}^2)$

$N(q^2)(B_0 \rightarrow K^0 \mu^+ \mu^-)$

$q^2(\text{GeV}^2)$
Problem to compute above the charm threshold?
Problem also below charm threshold: \( B \rightarrow K\phi \rightarrow K\ell^+\ell^- \)
... currently under consideration  
Khodjamirian, Wang, TM
Concluding Remarks

- In 1993 we did not know $f_B$ nor the top mass.

- Enormous Progress over the past twenty years!
- ... experimentally as well as theoretically.
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Nonleptonic Decays
Rare Decays

\[ \bar{d} m_6 \]

\[
\sin 2\beta < 0 \quad \text{excluded at CL > 0.95}
\]

\[ V_{ub} \]

\[ |\Delta m_d| \]

\[ |\Delta m_s| \]

\[ \alpha, \beta \]

\[ \epsilon_K \]

\[ |V_{ub}| \]

\[ \gamma \]

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Precision Flavour Physics
• Yet there are a few tensions in $B$ decays
• ... and an interesting hint in charm decays
• ... which may be the first glimpse of the BSM era
• Flavour Physics turns out to be a sensitive indirect probe of “new physics” if
  • we have appropriate theoretical tools
    at least for some interesting processes
  • we have sufficient data on all types of heavy hadrons
  • ... in particular also for charm

The discovery of the Higgs may be a triumph, but not discovering the Higgs will be a revolution
Yet there are a few tensions in $B$ decays
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Flavour Physics turns out to be a sensitive indirect probe of “new physics” if
  - we have appropriate theoretical tools at least for some interesting processes
  - we have sufficient data on all types of heavy hadrons
  - ... in particular also for charm

The discovery of the Higgs may be a triumph, but Flavour Physics may initiate a revolution