Precision Flavour Physics as a Probe beyond the Standard Model

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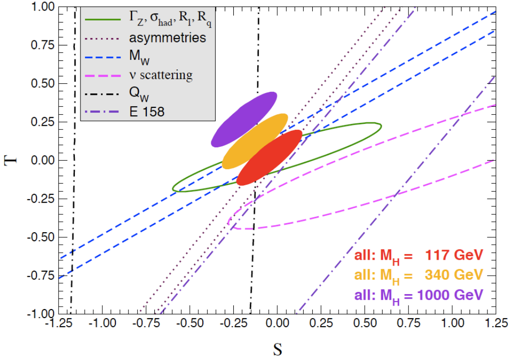
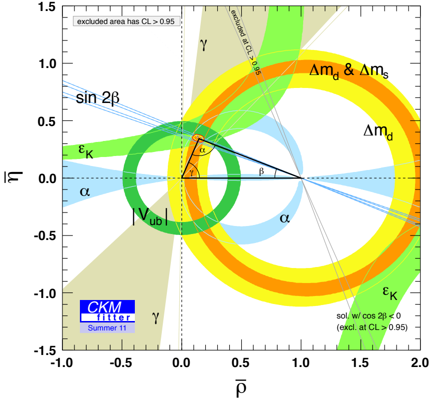
Contents

Why Study Flavour Physics?

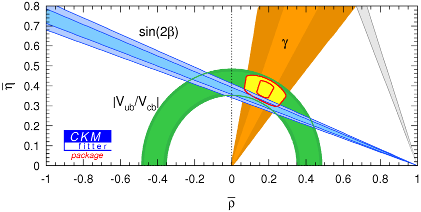
- The Standard Model passed all tests
  up to the 100 GeV Scale:
- LEP: test of the gauge Structure
- Flavour factories: test of the Flavour Sector



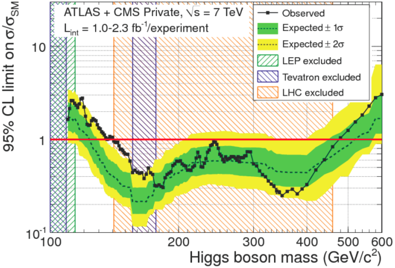


No significant deviation has been found (yet)!

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

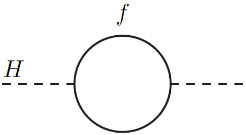


LHC will perform a direct test of the TeV Scale



Why do we believe in TeV Physics?

- Theoretical argument:
- Stabilization of the electroweak scale:

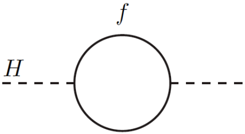


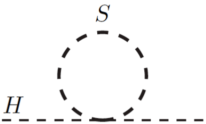
- Quadratic Dependence on the cut-off

$$\Delta m_H^2 = -\frac{\lambda_f^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2$$

- Drives the Higgs mass up to the UV cut off $\Lambda_{\mathrm{UV}} \sim M_{\mathrm{PL}}$

- Stabilization at the TeV scale: e.g. through SUSY:





- Only logarithmic divergence

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

- $m_{\rm soft} \sim \mathcal{O}(\text{TeV})$:
  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:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \cdots \qquad \mathcal{L}^{(n)} = \sum_j C_j O_j^{(n)}$$

- Λ: New Physics scale
- $O_j^{(n)}$: Local Operators of dimension n

- Some of the $O_j^{(n)}$ may mediate flavour transitions: e.g.

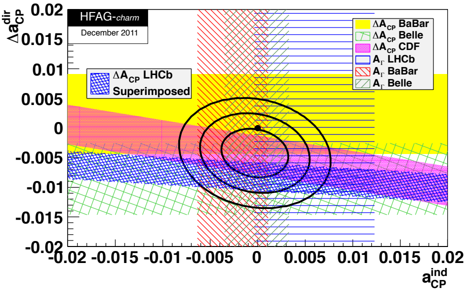
$$
\begin{aligned}
O_1^{(6)} &= (\bar{s}_L \gamma_\mu d)(\bar{s}_L \gamma^\mu d) && \text{(Kaon Mixing)} \\
O_2^{(6)} &= (\bar{b}_L \gamma_\mu d)(\bar{b}_L \gamma^\mu d) && (B_d \text{ Mixing}) \\
O_3^{(6)} &= (\bar{b}_L \gamma_\mu 2)(\bar{b}_L \gamma^\mu s) && (B_s \text{ Mixing}) \\
O_4^{(6)} &= (\bar{c}_L \gamma_\mu u)(\bar{c}_L \gamma^\mu u) && (D \text{ Mixing})
\end{aligned}
$$

- $\Lambda \sim 1000$ TeV from Kaon mixing ($C_i = 1$)
- $\Lambda \sim 1000$ TeV from D mixing
- $\Lambda \sim 400$ TeV from B_d mixing
- $\Lambda \sim 70$ TeV from B_s mixing

News from Charm: CP Violation?

- Recent LHCb result on CP violation in D decays :

$$\Delta A_{\rm CP} = A_{\rm CP}(D^0 \to K^+ K^-) - A_{\rm CP}(D^0 \to \pi^+ pi^-)$$
$$= \begin{cases} -(0.82 \pm 0.21 \pm 0.11)\% & \text{LHCb} \\ -(0.68 \pm 0.18)\% & \text{world average} \end{cases}$$

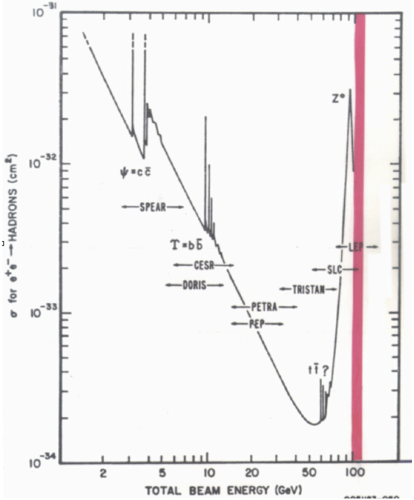


- “Old” or “New” Physics?

- “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

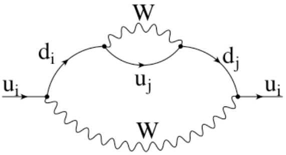
- First indirect hint to a heavy top quark: $B-\overline{B}$ Oscillation of ARGUS (1987)
- The world in 1987 (“PETRA Days”): The top was believed to be at $\sim$ 25 GeV
  ... based on good theoretical arguments
- ARGUS could not have seen anything with a 25 GeV Top (within SM)



- The consequences:
  - (–) No Toponium
  - (–) No Top quark discovery at LEP and SLC
  - (–) No “New Physcis $\mathcal{O}$(30 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
- $\rightarrow$ Concept of “Minimal Flavour Violation” (MFV)

Peculiarities of SM Flavour Parametrization

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



$$d_e^{\mathrm{quark}} \sim e\,\frac{\alpha_s}{\pi}\,\frac{G_F^2}{(16\pi^2)^2}\,\frac{m_t^2}{M_W^2}\,\mathrm{Im}\Delta\,\mu^3$$

$$\sim 10^{-32}\,e\,cm \quad \text{with } \mu \sim 0.3\,\mathrm{GeV}$$

$$d_{\mathrm{exp}}^{\mathrm{Neutron}} \leq 3.0 \times 10^{-26}\,e\,cm$$

- 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”
  - $\to$ CP violation in charm should be small in the SM
- Fully consistent with particle physics observations
- ... but inconsistent with matter-antimatter asymmetry

??? Many Open Questions ???

- 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:

$$H_{\rm eff} = \frac{4G_F}{\sqrt{2}} \lambda_{\rm CKM} \sum_k \hat{C}_k(\mu)\mathcal{O}_k(\mu)$$

$$\begin{aligned}
\mathcal{O}_1 &= \left(\bar{c}_{L,i}\gamma_\mu s_{L,j}\right)\left(\bar{d}_{L,j}\gamma_\mu u_{L,i}\right) \ , \quad \mathcal{O}_2 = \left(\bar{c}_{L,i}\gamma_\mu s_{L,i}\right)\left(\bar{d}_{L,j}\gamma_\mu u_{L,j}\right) \ , \\
\mathcal{O}_3 &= (\bar{s}_{\rm L,\it i}\gamma_\mu b_{\rm L,\it i}) \sum_{q=u,d,s,c,b} (\bar{q}_{\rm L,\it j}\gamma^\mu q_{\rm L,\it j}) \ , \quad \mathcal{O}_4 = (\bar{s}_{\rm L,\it i}\gamma_\mu b_{\rm L,\it j}) \sum_{q=u,d,s,c,b} (\bar{q}_{\rm L,\it j}\gamma^\mu q_{\rm L,\it i}) \ , \\
\mathcal{O}_5 &= (\bar{s}_{\rm L,\it i}\gamma_\mu b_{\rm L,\it i}) \sum_{q=u,d,s,c,b} (\bar{q}_{\rm R,\it j}\gamma^\mu q_{\rm R,\it j}) \ , \quad \mathcal{O}_6 = (\bar{s}_{\rm L,\it i}\gamma_\mu b_{\rm L,\it j}) \sum_{q=u,d,s,c,b} (\bar{q}_{\rm R,\it j}\gamma^\mu q_{\rm R,\it i}) \ . \\
\mathcal{O}_7 &= \frac{e}{16\pi^2} m_b (\bar{s}_{\rm L,\alpha}\sigma_{\mu\nu} b_{\rm R,\alpha}) F^{\mu\nu} \ , \quad \mathcal{O}_8 = \frac{g}{16\pi^2} m_b (\bar{s}_{\rm L,\alpha} T^a_{\alpha\beta}\sigma_{\mu\nu} b_{\rm R,\alpha}) G^{a\mu\nu} \ , \\
\mathcal{O}_9 &= \frac{1}{2}(\bar{s}_{\rm L}\gamma_\mu b_{\rm L})(\bar{\ell}\gamma^\mu \ell) \ , \quad \mathcal{O}_{10} = \frac{1}{2}(\bar{s}_{\rm L}\gamma_\mu b_{\rm L})(\bar{\ell}\gamma^\mu\gamma_5 \ell)
\end{aligned}$$

- Coefficients in the SM are known to NLO!

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 calculatons 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 Velovity v
- 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 $\omega = vv'$ 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 $vv' = 1$: (both initial and final meson at rest)
- Corrections can be calculated / estimated

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

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

- Parameter of HQS breaking: $\dfrac{1}{\mu} = \dfrac{1}{m_c} - \dfrac{1}{m_b}$
- $\eta_A = 0.960 \pm 0.007$, $\eta_V = 1.022 \pm 0.004$, $\delta_{1/\mu^2} = -(8 \pm 4)\%$, $\eta_{\mathrm{QED}} = 1.007$

$B \to D^{(*)}$ Form Factors from the Lattice

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

$$\boxed{\mathcal{F}(1) = 0.908 \pm 0.016}$$

$$\boxed{\mathcal{G}(1) = 1.074 \pm 0.018 \pm 0.016}$$

F(1): upd. from CKM2010 , G(1): A. Kronfeld et al. 2005

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

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

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

- $B \to D$ Form Factor:
  - Based on the "BPS limit" $\mu_\pi^2 = \mu_G^2$

$$\boxed{\mathcal{G}(1) = 1.04 \pm 0.02}$$ (Uraltsev)

Heavy Quark Expansion in Inclusive Decays

Heavy Quark Expansion = Operator Product Expansion
(Chay, Georgi, Bigi, Shifman, Uraltsev, Vainstain, Manohar. Wise, Neubert, M,...)

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

$$= \int d^4x \, \langle B(v)|\mathcal{H}_{eff}(x)\mathcal{H}^\dagger_{eff}(0)|B(v)\rangle$$

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

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

- Last step: $b(x) = b_v(x)\exp(-im_b vx)$, 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

$$\int d^4x e^{-im_b vx} T\{\widetilde{\mathcal{H}}_{eff}(x)\widetilde{\mathcal{H}}_{eff}^\dagger(0)\} = \sum_{n=0}^{\infty} \left(\frac{1}{2m_Q}\right)^n C_{n+3}(\mu)\mathcal{O}_{n+3}$$

$\rightarrow$ 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 Γ_i are power series in $\alpha_s(m_Q)$:
  $\rightarrow$ Perturbation theory!
- Works also for differential rates!

- Γ_0 is the decay of a free quark ("Parton Model")
- Γ_1 vanishes due to Heavy Quark Symmetries
- Γ_2 is expressed in terms of two parameters

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

μ_π: Kinetic energy and μ_G: Chromomagnetic moment

- Γ_3 two more parameters

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

ρ_D: Darwin Term and ρ_{LS}: Spin-Orbit Term

- Γ_4 and Γ_5 have been computed Bigi, Uraltsev, Turczyk, TM, ...

Structure of the HQE

- Structure of the expansion (@ tree):

$$
\begin{aligned}
d\Gamma = {} & d\Gamma_0 + \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^2 d\Gamma_2 + \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^3 d\Gamma_3 + \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^4 d\Gamma_4 \\
& + d\Gamma_5 \left(a_0 \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^5 + a_2 \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^3 \left(\frac{\Lambda_{\rm QCD}}{m_c}\right)^2 \right) \\
& + \ldots + d\Gamma_7 \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^3 \left(\frac{\Lambda_{\rm QCD}}{m_c}\right)^4
\end{aligned}
$$

- $d\Gamma_3 \propto \ln(m_c^2/m_b^2)$
- Power counting $m_c^2 \sim \Lambda_{\rm QCD} m_b$

Present state of the $b \to c$ 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 μ_π^2/m_b^2 is known
  Becher, Boos, Lunghi, Gambino
- In the pipeline:
  - Complete α_s/m_b^2, including the μ_G terms
  - More on the “Intrinsic charm” and “weak annihilation” contributions

Tools III: Flavour Symmetries and Diagramm Topologies

- 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 ...

Semileptonic Decays

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

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

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

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

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

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

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)

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

- δ_f: Weak Phase and θ_f: Strong phase
- Penguin-over-Tree ratio:

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

- a_f: Modulus of a ratio of hadronic matrix elements
- $\lambda_{\rm CKM,f}$: Modulus of a ratio of CKM matrix elements

- Key Observable: Time-Dependent CP Asymmetries

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

- General Expression

$$A_{\mathrm{CP}}(t;f) = \frac{A_{\mathrm{D}}^f \cos(\Delta M_q t) + A_{\mathrm{M}}^f \sin(\Delta M_q t)}{\cosh(\Delta\Gamma_q t/2) - \mathcal{A}_{\Delta\Gamma}^f \sinh(\Delta\Gamma_q t/2)}$$

- Neglecting the lifetime difference (for the B_d)

$$A_{\mathrm{CP}}(t;f) = A_{\mathrm{D}}^f \cos(\Delta M_q t) + A_{\mathrm{M}}^f \sin(\Delta M_q t)$$

- In terms of the parameters of the amplitude an the mixing phase ϕ_s

$$
\begin{aligned}
A^f_{\mathrm{D}} &= -2r_f \sin\theta_f \sin\delta_f \\
A^f_{\mathrm{M}} &= \left[\sin\phi_s + 2r_f \cos\theta_f \sin(\phi_s+\delta_f) + r_f^2 \sin(\phi_s + 2\delta_f)\right] \\
A^f_{\Delta\Gamma} &= \text{.... not needed here}
\end{aligned}
$$

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

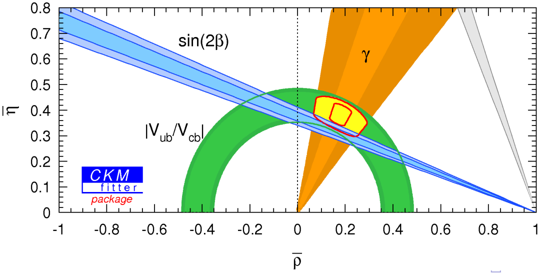
$$\lambda_{\mathrm{CKM,f}} = \left|\frac{V_{ub}V^*_{us}}{V_{cb}V^*_{cs}}\right| \sim 5\%$$

(Bigi, Sanda)

- Thus: In the Standard Model $r_{J/\psi K} \leq 5\%$:

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

- Penguin contamination small, suppressed by λ_{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),
S. Faller, R. Fleischer, M. Jung and T. M., Phys. Rev. **D79**:014030,2009.)
- 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 $b \to s\bar{c}c$ with its $SU(3)$ friend $b \to d\bar{c}c$
- Parametrize (ϕ_d = $B - \overline{B}$ Mixing phase)

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

$$\boxed{\tan \Delta\phi_d = \frac{2\lambda_{\rm CKM} a \cos\theta \sin\gamma + \lambda_{\rm CKM}^2 a^2 \sin 2\gamma}{1 + 2\lambda_{\rm CKM} a \cos\theta \cos\gamma + \lambda_{\rm CKM}^2 a^2 \cos 2\gamma}}$$

- Using $SU(3)$ for a and θ: $\boxed{\Delta\phi_d \in [-3.9, -0.8]^\circ}$
- Allowing 50% $SU(3)$ breaking in a and $\theta, \theta' \in [90, 270]^\circ$ indepedently: $\boxed{\Delta\phi_d \in [-6.7, 0.0]^\circ}$
- 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 ($b \to s$) Semileptonics

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

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

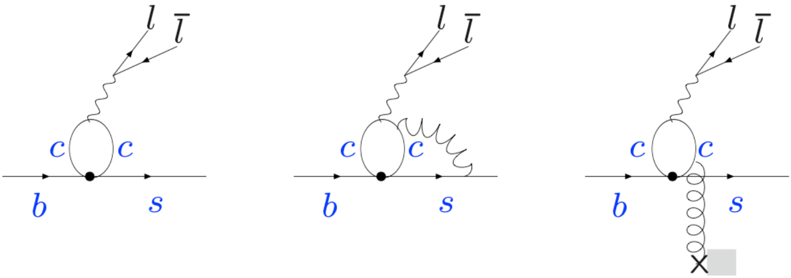
- Dominant $b \to s$ effective operators: $O_{7,9,10}$
  $C_7(m_b) \simeq -0.3$, $C_9(m_b) \simeq 4.4$, $C_{10}(m_b) \simeq= -4.7$
- ... can be expressed in terms of form factors

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

Charm Loops

Buchalla, Isidori, Feldmann, Khodjamirin, TM, Pivovarov, Wang

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



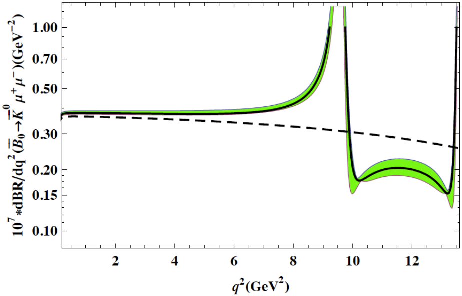
- new hadronic matrix elements, not a form factor

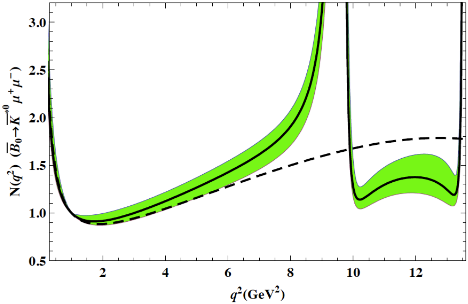
- Light cone expansion of the charm loop
- Expansion parameter $\dfrac{\Lambda^2_{\mathrm{QCD}}}{(4m_c^2 - q^2)}$
- Leads to a non-local operator ("shape-function-like" operator)

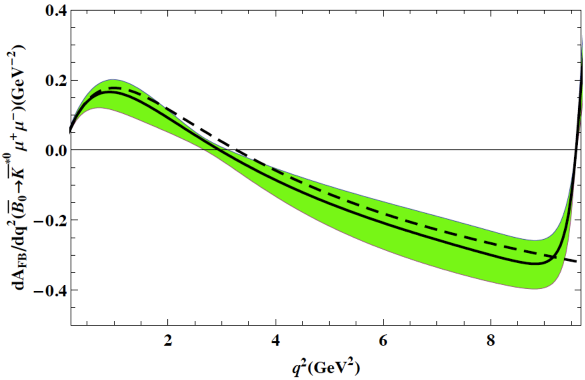
$$\widetilde{\mathcal{O}}_\mu(q) = \int d\omega \, I_{\mu\rho\alpha\beta}(q, m_c, \omega) \bar{s}_L \gamma^\rho \left(\delta[\omega - \frac{(in_+\mathcal{D})}{2}] \widetilde{G}_{\alpha\beta} \right) b_L \ ,$$

- Matrix element can be calculated in a LCSR for $q^2 \leq 0$

Results on $B \to K^{(*)}\ell^+\ell^-$







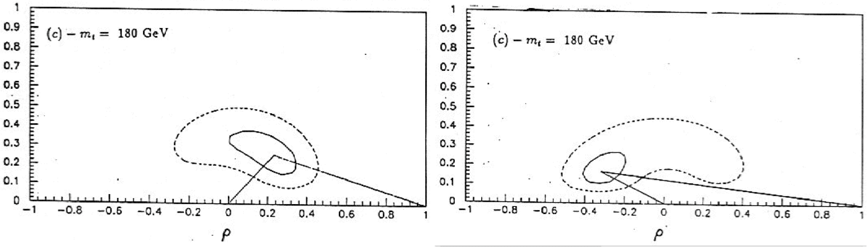
Problem to compute above the charm threshold?

Problem also below charm theshold: $B \to K\phi \to K\ell^+\ell^-$

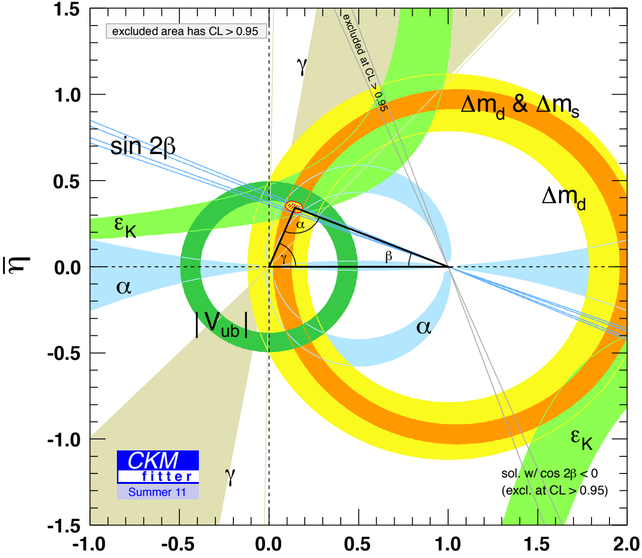
... currently under consideration Khodjamirian, Wang, TM

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


excluded area has CL > 0.95
γ
excluded at CL > 0.95
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
|V_ub|
CKM fitter
Summer 11
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
η̄
ρ̄
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
2.0

- 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

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