Searching for New Physics in Flavour Observables

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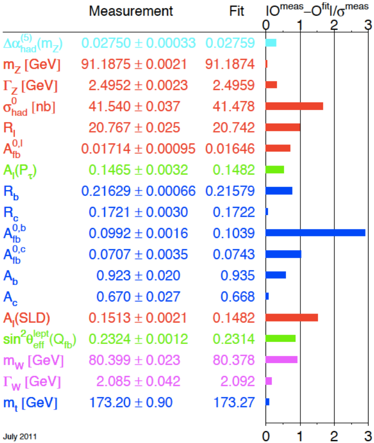
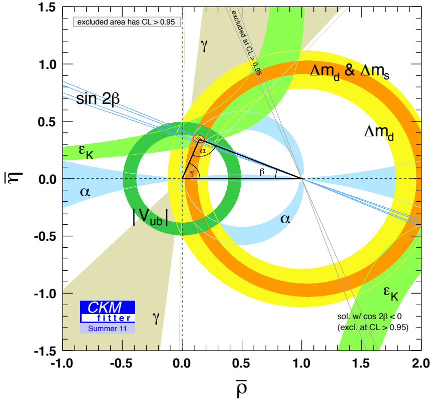
Contents

Why Study Flavour Physics?

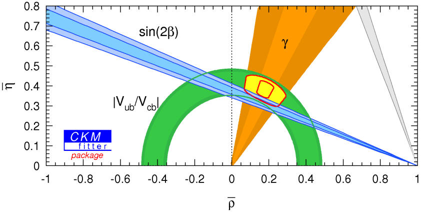
- The Standard Model passed all tests
  up to the 100 GeV Scale:
- LEP: test of the gauge Structure
- Flavour factories: test of the Flavour Sector



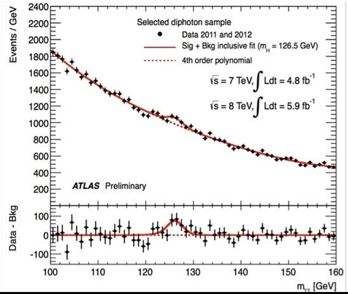


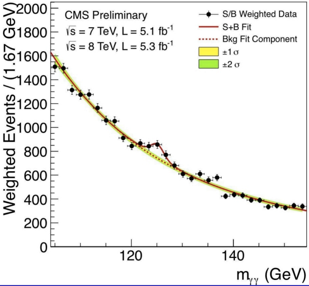
No significant deviation has been found (yet)!

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



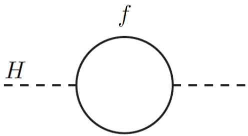
LHC will perform a direct test of the TeV Scale





Why do we believe in TeV Physics?

- Theoretical argument:
- Stabilization of the electroweak scale:

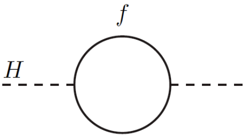


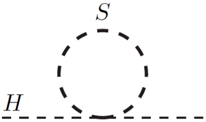
- Quadratic Dependence on the cut-off

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

- 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?

- Effective field theory picture:
- Standard model (without right handed ν's) is the (dim-4) starting point.
- Any new physics manifests itself as higher dimensional operators:

$$\mathcal{L} = \mathcal{L}^{SM}_{\mathrm{dim}\,4} + \mathcal{L}_{\mathrm{dim}\,5} + \mathcal{L}_{\mathrm{dim}\,6} + \cdots$$

- $\mathcal{L}_{\mathrm{dim\,n}}$ are suppressed by large mass scales

$$\mathcal{L}_{\mathrm{dim\,n}} = \frac{1}{\Lambda^{n-4}} \sum_i C_n^{(i)} O_n^{(i)}$$

$O_n^{(i)}$: Operators of dimension n,
$SU(3)_C \times SU(2)_W \times U(1)_Y$ gauge invariant
$C_n^{(i)}$: dimensionless couplings

Quark Flavour Physics

- For Quarks there is no contribution to $\mathcal{L}_{\mathrm{dim}\,5}$
- Some of the $O_j^{(n)}$ mediate $\Delta F = 2$ flavour transitions:

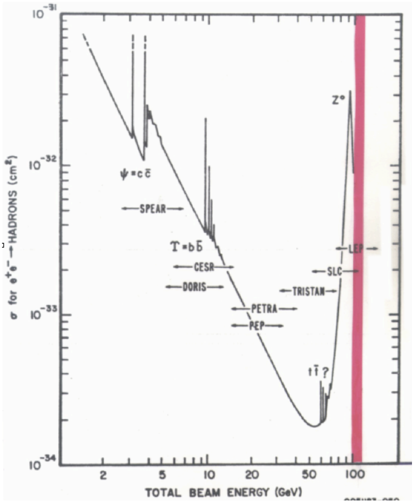
$$
\begin{aligned}
O_1^{(6)} &= (\bar{s}_L \gamma_\mu d)(\bar{s}_L \gamma^\mu d) && \text{(Kaon Mixing)} \\
O_2^{(6)} &= (\bar{b}_L \gamma_\mu d)(\bar{b}_L \gamma^\mu d) && (B_d \text{ Mixing}) \\
O_3^{(6)} &= (\bar{b}_L \gamma_\mu 2)(\bar{b}_L \gamma^\mu s) && (B_s \text{ Mixing}) \\
O_4^{(6)} &= (\bar{c}_L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

- $\Lambda \sim 1000$ 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

- "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)

Hints from the leptonic sector

- $\mathcal{L}^{SM}_{\dim 4}$ does not have a right handed neutrino
- ... thus no mixing for the leptons
- Discovery of Neutrino Oscillations:
  Nontrivial Flavour Physics of Leptons
- Important observation: The combination

$$N_i = (H^{c,\dagger} L_i) \,, \quad L_i = \begin{pmatrix} \nu_{L,i} \\ \ell_{L,i} \end{pmatrix} \,, \; H^c = (i\tau^2) H^* \,, H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

has no SM Quantum numbers

- This allows for a Unique dim -5 Operator:
  Generates Majorana masses for the ν's

$$\mathcal{L}_{\dim 5} = \frac{1}{\Lambda_{\rm LNV}} \sum_{ij} C_5^{ij} (\bar{L}_j H^c)^c (H^{c,\dagger} L_i)$$

- Generates a mixing matrix for the leptons (PMNS Matrix), analogous to the CKM Matrix
- This term is Lepton Number Violating, related to the scale $\Lambda_{\rm LNV}$
- Small Neutrino masses: $\Lambda_{\rm LNV}$ must be high, almost as big as the GUT scale?
- Hopefully $\Lambda_{\rm QFV}$ and $\Lambda_{\rm LFV}$ is not that high!

CP Violation

Two sources of CP violation in the SM:

- Strong CP violation:
  The QCD Vacuum generates the "θ term":

$$\mathcal{L}_{\text{strong CP}} = \theta \frac{\alpha_s}{8\pi} G^{\mu\nu,a} \tilde{G}^a_{\mu\nu}$$

  Natural size would be $\theta \sim 1$, Limit from Neutron EDM:

$$d_N \sim \theta \times 10^{-15} \mathrm{e\,cm} \quad \text{thus} \quad \theta \leq 10^{-10}$$

- CKM CP Violation from the phase of the CKM matrix:
  CKM CP violation is proportional to

$$\Delta = \mathrm{Im}\, V^*_{cs} V_{us} V_{cd} V^*_{ud}$$

  There is only a single 4^{th} order rephasing invariant

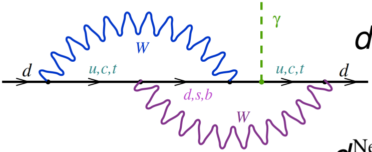
- Strong CP remains a mystery, can be removed by an additional symmetry (Peccei Quinn Symmetry)
- CKM CP Violation is established now from the flavor experiments
  (see the fit to the unitarity triangle)
- CKM CP does not seem to be large enough for the Matter Antimatter asymmetry of the universe
- CP Phases in the leptonic sector are still unexplored

??? 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?
- Is there an underlying principle for the flavor structure?
  like the gauge principle for the fundamental forces?
  such as
  - ... a broken (how?) flavour symmetry
  - ... extra dimensions

- Why is CP Violation in Flavour-diagonal Processes not observed? (e.g. electric dipole moments of electron and neutron)
  CKM contribution for quarks is at least three loops

  (Shabalin)



$$d_e^{\mathrm{quark}} \sim e\,\frac{\alpha_s}{\pi}\,\frac{G_F^2}{(16\pi^2)^2}\,\frac{m_t^2}{M_W^2}\,\mathrm{Im}\Delta\,\mu^3$$
$$\sim 10^{-32} e\,cm \quad \text{with } \mu \sim 0.3\,\mathrm{GeV}$$
$$d_{\mathrm{exp}}^{\mathrm{Neutron}} \leq 3.0 \times 10^{-26} e\,cm$$

- 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

$$\boxed{\mathcal{F}(1) = 0.906 \pm 0.013}$$

$$\boxed{\mathcal{G}(1) = 1.0528 \pm 0.0082}$$

Numbers from PDG 2016

$B \to D^{(*)}$ 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,...)

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

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

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

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

- 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

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

$\rightarrow$ 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

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

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):

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

- $d\Gamma_3 \propto \ln(m_c^2/m_b^2)$
- 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
- $\mathcal{O}(\alpha_s)$ for the μ_G^2/m_b^2 has been computed recently
  Alberti, Healy, Nandi, Gambino; M. Pivovarov, Rosenthal

Sample Application: V_{cb} Determination

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

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

$$\boxed{V_{cb,excl} = (38.7 \pm 0.7) \times 10^{-3}} \text{ (Lattice, 2008)}$$

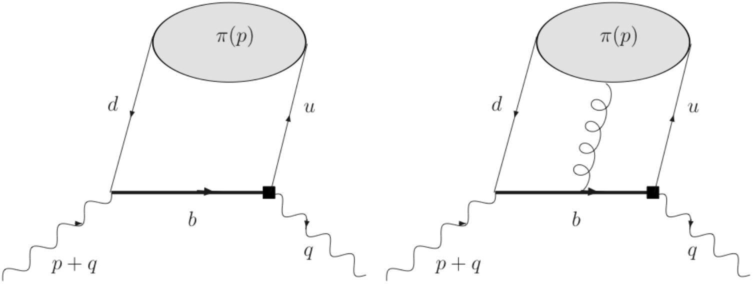
$$\boxed{V_{cb,excl} = (39.7 \pm 1.1) \times 10^{-3}} \text{ (Lattice, 2010)}$$

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

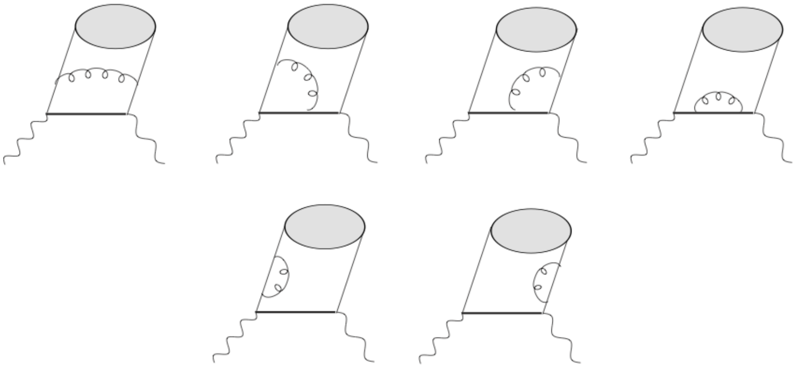
Tension between $V_{cb,incl}$ and $V_{cb,excl}$ is about to disappear!

Tools III: QCD Sum Rules

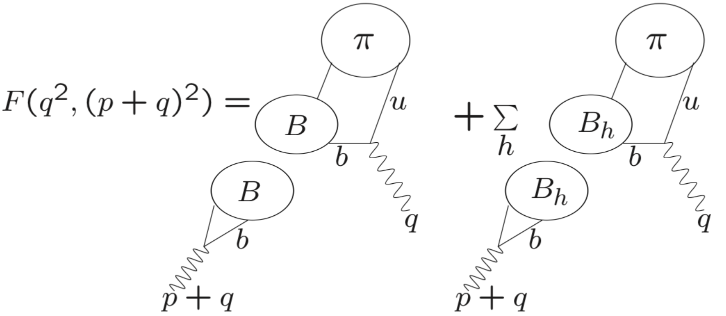
- QCDSR: Quantitative method to esimate hadronic matrix elements
- For form factors: Light Cone Sum Rules



- QCD corrections systematically accessible



- Insert a complete set of states



$f_B f^{+}_{B\pi}(q^2)$

$\sum_{B_h} \to duality$

Sample Application: Determination of: V_{ub}

- Recent LCQCDSR Calculation for $B \to \pi \ell \bar{\nu}$

$$\Delta\zeta(0, q^2_{max}) = \frac{1}{|V_{ub}|^2 \tau_{B^0}} \int_0^{q^2_{max}} dq^2 \frac{d\mathcal{B}(B \to \pi \ell \nu_\ell)}{dq^2},$$

including

- Full $\mathcal{O}(\alpha_s)$ QCD corrections
- Subleading twists
- a_2 and a_4 corrections to the pion DA, fitted from the electromagnetic pion form factor

$$|V_{ub}| = (3.50^{+0.38}_{-0.33}\Big|_{th.} \pm 0.11\Big|_{exp.}) \times 10^{-3}$$ (LCQCD $\otimes$ Lattice QCD)

Tools IV: Approximate Flavour Symmetries

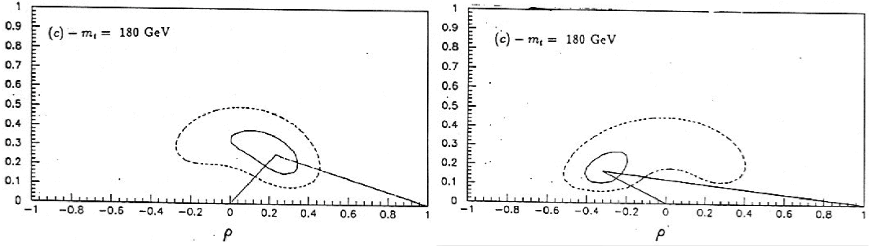
- Avoid to deal with QCD dynamics:
  Use symmetries of QCD
- I-spin, V-Spin, U-Spin or full Flavour SU(3)
- Discuss breaking of SU(3)
- Supplement group theory by
  "diagrammatic considerations"
  such as "Penguins are smaller than trees"
- Improvement by more data possible

Tools V: Lattice QCD

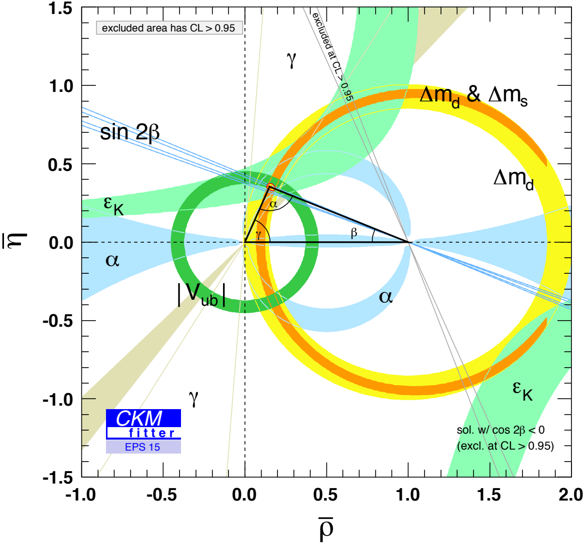
... ask the lattice experts ...

Status

- 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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excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
$|V_{ub}|$
α
ε_K
γ
CKM fitter
EPS 15
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
$\bar{\eta}$
$\bar{\rho}$

Towards understanding Flavour

Broken Flavour Symmetries

- Consider the Standard Model w/o Yukawa Couplings:
- Largest Quark Flavour Symmetry commuting with the Gauge Group of the Standard Model

$$G_F = U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R} / U(1)_B$$

with

$$Q_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix} \sim (3,1,1) \quad U_R \sim (1,3,1) \quad D_R \sim (1,1,3)$$

- G_F is *explicitely* broken by the Yukawa couplings

$$\mathcal{L}_{\text{Yuk}} = \bar{Q}_L H Y_D D_R + \bar{Q}_L \widetilde{H} Y_U U_R$$

- In the SM: Y_U and Y_D are the only sources of (explicit) G_F breaking!

Spurions

- Trick to parametrize explicit symmetry breaking: Introduce “Spurions”
- Spurion: Field with a well defined transformation under the symmetry to be explicitely broken.
- Write all terms that are allowed by the symmetry including a finite number of insertions of the spurion field(s)
- “Freeze” the spurion field(s) to a nonzero value: “vacuum expectation value”

- Explicit Symmetry breaking = Spontaneous Symmetry Breaking without the Higgs degrees of freedom
- Small symmetry breaking: Power counting for the spurion insertions is needed.

Spurion Analysis: Minimal Flavour Violation

- Interpret the Yukawa couplings as spurion fields transforming as

$$Y_U \sim (3, \bar{3}, 1) \quad Y_D \sim (3, 1, \bar{3})$$

- In this way the Yukawa terms become formally invariant under G_F
- “Freezing” the Yukawa couplings to the observed values breaks G_F explicitely.
- Minimal Flavour Violation: The two spurions Y_U and Y_D are the only sources of flavour violation.
- The flavour transitions of the new-physics contributions are still suppressed by the same CKM factors and masses as in the Standard Model

- Problem: The Top Yukawa Coupling is $\mathcal{O}(1)$
- Spurion Expansion can be problematic
- "Nonlinear Realization" of MFV (Feldmann, ThM; Zupan et al.)
- MFV can be extended by including other spurions
- $\rightarrow$ "Next to minimal flavour violation"
- Hierarchy of the CKM structure can be mapped into a sequence of broken flavor symmetries Jung, Feldmann, ThM)

These are all more or less nice parametrizations

Bottom-Up Approach

What if we take spontaneous instead of explicit breaking?

- Promote the Yukawa Couplings to be fields:
- $\rightarrow$ Canonical dimension of the Yukawa fields: Yukawa coupling term to fermions is dim 5!
- $\rightarrow$ Additional degrees of freedom. (Grinstein et al.)
- Invent a potential $V(Y_U, Y_D)$ which has a minimum generating the appropriate VEV's dynamically:
- $\rightarrow$ Introduces (many) Goldsone modes along the "flat directions", phenomenologically not wanted!
- $\rightarrow$ Gauge this symmetry: "Flavons"
- Kill the Anomlies: (Albrecht, Feldmann, ThM)
- $\rightarrow$ Additional fermions (Grinstein et al.)
- ... This is in Progress

- The potential $V(Y_U, Y_D)$ can depend only on G_F invariant combinations
- For two families: 5 independent invariants, eg.:

$$I_1 = Tr[Y_U^\dagger Y_U] \quad I_2 = Tr[Y_D^\dagger Y_D] \quad I_3 = Tr[Y_U^\dagger Y_U Y_U^\dagger Y_U]$$
$$I_4 = Tr[Y_D^\dagger Y_D Y_D^\dagger Y_D] \quad I_5 = Tr[Y_D^\dagger Y_D Y_U^\dagger Y_U]$$

- corresponds to the five physical parameters (4 Quark masses and the Cabbibo angle)
- For three families: 10 Invariants, 10 Parameters
- Embedding into a GUT?
  Relations between invariants?
  Renomalization group flow? ... etc

Where do we go?

- We all hope that LHC will find something beyond the SM Higgs particle!
- Unfortunately there is NO hint from flavor pointing to such an effect!
- Scenario 1: LHC finds TeV mass particles
  - The new particles will have new flavor physics
  - needs to be compatible with the low-energy data
- Scenario 2: Nothing except the 125 GeV Higgs
  - Flavour will serve as an indirect test of high scales
  - Needs very large samples of B and K mesons
  - Search for “impossible” decays like $B \to e\mu$, $B \to \bar{\Lambda}\mu$
- Flavour Physics remains interesting ...