The CKM matrix : from the Standard Model to New Physics (II)

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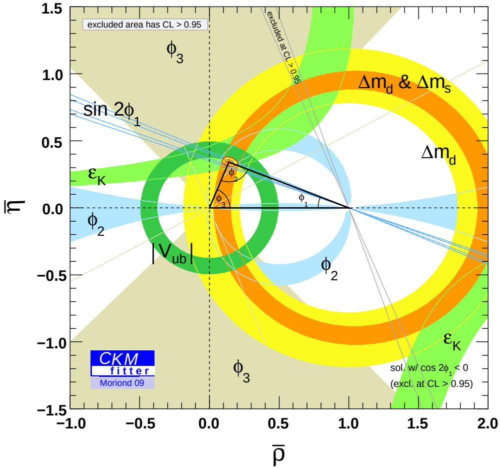
April 7 2009

The Global Fit



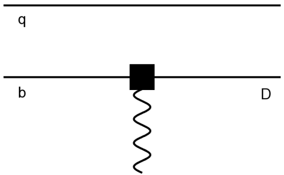
Standard Model

- An impressive global agreement
- The Kobayashi Maskawa mechanism describes CP violation in flavour physics
- Worth looking at other observables/sectors to find discrepancies
- And maybe find new physics ?

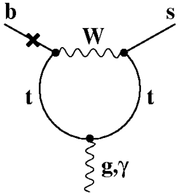
Topics

1. Looking for discrepancies : radiative decays
2. Looking for discrepancies : charm physics
3. A potential loophole : hadronic inputs
4. Testing a simple model of NP with flavour

Radiative decays



Introduction



$b \to D\gamma$ with $D = d, s$

- access to $|V_{t(d,s)}|$ within SM
- cross-check of neutral B mixing (box/penguin)
- loop processes very sensitive to NP

Inclusive: $B \to X_s\gamma$

- accurately measured
- computed perturbatively up to (N)NLO [Misiak et al.]
- constrains $|V_{ts}|$ only

Exclusive: $B \to K^*\gamma$ and $B \to (\rho, \omega)\gamma$

- Measurements available from Babar & Belle
- Hadronic effects difficult to estimate theoretically
- Naively : $A(B \to V\gamma) \propto V_{tD} V_{tb}^* C_7 T^{B\to V}$
  with magnetic operator $Q_7 = \frac{e}{8\pi^2} m_b \bar{D}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu} b + \ldots$

$B \to \rho\gamma$ and $B \to K^*\gamma$

$b \to d, s\gamma$: loop processes, give access to $|V_{t(d,s)}|$, complement $\Delta m_{d,s}$

Early days : focus on magnetic op. $Q_7 = (e/8\pi^2) m_b \bar{D}\sigma^{\mu\nu}(1+\gamma_5) F_{\mu\nu}\, b$
and assume short-distance dominance

$B \to \rho\gamma$ and $B \to K^*\gamma$

$b \to d, s\gamma$: loop processes, give access to $|V_{t(d,s)}|$, complement $\Delta m_{d,s}$

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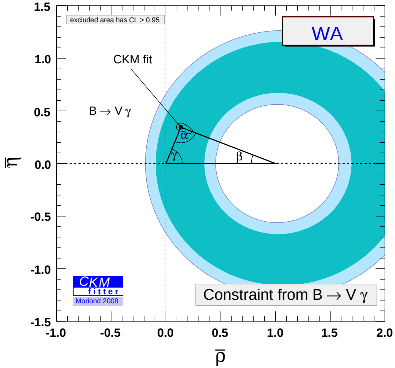

$$R_{\rho/\omega} = \frac{\bar{\mathcal{B}}(\rho^\pm\gamma) + \frac{\tau_{B^\pm}}{\tau_{B^0}}\left[\bar{\mathcal{B}}(\rho^0\gamma) + \bar{\mathcal{B}}(\omega\gamma)\right]}{\bar{\mathcal{B}}(K^{*\pm}\gamma) + \frac{\tau_{B^\pm}}{\tau_{B^0}}\left[\bar{\mathcal{B}}(K^{*0}\gamma)\right]}$$

$$= \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - m_\rho^2/m_B^2}{1 - m_{K*}^2/m_B^2}\right)^3 \frac{1}{\xi^2}\left[1 + \Delta R\right]$$

- ξ ratio of form factors
- ΔR estimated as $\Delta R = 0.1 \pm 0.1$

Ali,Lunghi,Parkhomenko 02,04,06

Many open questions : dependence of ΔR on CKM matrix ? isopin breaking ? weak annihilation (tree for $(\rho, \omega)\gamma$) ?

A more sophisticated analysis

For each final state, estimate all contributions, expressed as factor to the leading amplitude (magnetic operator Q_7)

$$\bar{\mathcal{A}} \equiv \frac{G_F}{\sqrt{2}} \left(\lambda_u^D a_7^u(V) + \lambda_c^D a_7^c(V) \right) \langle V\gamma | Q_7 | \bar{B} \rangle \qquad \lambda_U^D = V_{UD}^* V_{Ub}$$

$$a_7^U(V) = a_7^{U,\mathrm{QCDF}}(V) + a_7^{U,\mathrm{ann}}(V) + a_7^{U,\mathrm{soft}}(V) + \ldots$$

- QCDF : QCD factorisation for LO in $1/m_b$ up to $O(\alpha_s)$
  Bosch and Buchalla 02
- ann,soft : $1/m_b$-suppressed terms from light-cone sum rules
  Ball,Jones,Zwicky 06

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- each decay described individually
- u and c internal loops (short and long dist), not "buried" into ΔR
- other operators than Q_7 taken into account

Input parameters

Several series of input parameters involved in the analysis

- Hadronic parameters (nonperturbative)
  - Decay constants f_V
  - Form factors $T^{B\to V}(0)$
  - Moments of distribution amplitudes a_V^k, λ_B
- QCD parameters
  - Quark masses $m_{c,b,t}$
  - Strong coupling constant $\alpha_s(\mu)$
  - Factorisation scale $\mu_{m_b} = 4.2 \pm 1$ GeV (vertex) and $\mu_{had} = \sqrt{\Lambda_h \mu_{m_b}}$ (hard-spectator)
- Wilson coefficients
  - NLO for C_7 and C_8 (magnetic operators)
  - LO for the others

Output

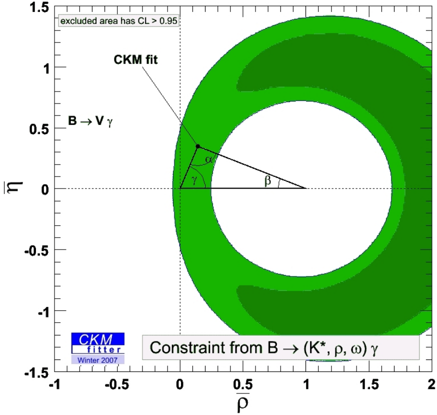
$$\mathcal{B}(\bar{B} \to V\gamma) = \frac{\tau_B}{c_V^2} \frac{G_F^2 \alpha m_B^3 m_b^2}{32\pi^4} \left(1 - \frac{m_V^2}{m_B^2}\right)^3 \left[T_1^{B\to V}(0)\right]^2$$
$$\times \left\{ \left|\sum_U \lambda_U^{(D)} a_{7L}^U(V)\right|^2 + \left|\sum_U \lambda_U^{(D)} a_{7R}^U(V)\right|^2 \right\}$$

Isospin factors $c_{\rho^\pm, K^*, \phi} = 1$ and $c_{\rho^0, \omega} = \sqrt{2}$

Output

- CP-averaged branching ratios
- CP asymmetries
- $B_{u,d}$ decays into $K^{*-}\gamma$, $K^{*0}\gamma$, $\rho\gamma$, $\rho^0\gamma$, $\omega\gamma$
- B_s decays into $\bar{K}^{*0}\gamma$, $\phi\gamma$

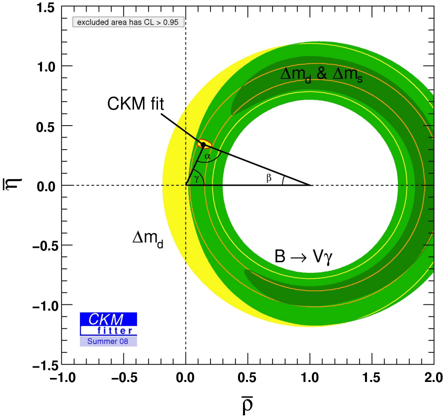
From 2007 to 2008



- $|V_{ud}|, |V_{us}|, |V_{cb}|$
- HFAG Winter 2007

$K^{*-}\gamma$	40.3 ± 2.6
$K^{*0}\gamma$	40.1 ± 2.0
$\rho^{+}\gamma$	$0.88^{+0.28}_{-0.26}$
$\rho^{0}\gamma$	$0.93^{+0.19}_{-0.18}$
$\omega\gamma$	$0.46^{+0.20}_{-0.17}$

From 2007 to 2008



- $|V_{ud}|, |V_{us}|, |V_{cb}|$
- HFAG Winter 2008

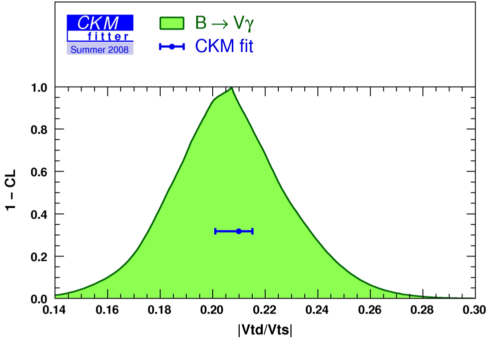
$K^{*-}\gamma$	45.7 ± 1.9
$K^{*0}\gamma$	44.0 ± 1.5
$\rho^+\gamma$	0.98 ± 0.25
$\rho^0\gamma$	0.86 ± 0.15
$\omega\gamma$	0.44 ± 0.17

- Belle 0804.4770 and 0712.2659

$B(B_s \to \phi\gamma)$	57 ± 22
$C(B^- \to \rho^-\gamma)$	$0.11 \pm 0.32 \pm 0.09$

$|V_{td}/V_{ts}|$

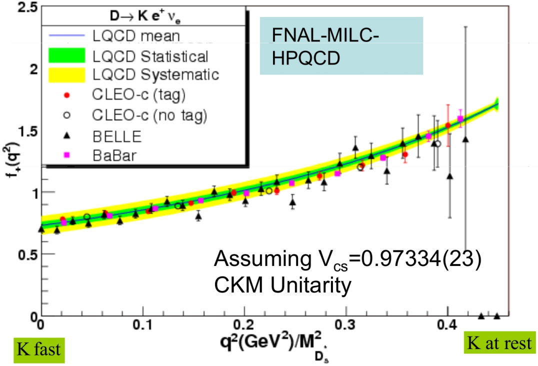
- Can be turned into a constraint on $|V_{td}/V_{ts}|$
- Test of the Standard Model in loops
- Excellent agreement between box (ΔM) and penguin ($B \to V\gamma$)



Can be extended to $B \to V\ell^+\ell^-$

- More observables (e.g., zero of A_{fb})
- Richer potential to find new physics
- In progress (just now and here !)

Charm physics



Charm as a test of CKM

Charm sector

- favourite place to test lattice QCD [$m_c \sim \Lambda_{QCD}$]
- null tests from the SM [GIM mechanism]
- access to NP large couplings to second family

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Current constraints on $|V_{cd}|$

- DIS of neutrinos on nucleons $|V_{cd}| = 0.2308 \pm 0.011 (5\%)$
- CLEO-c on $D \to \pi \ell \nu$

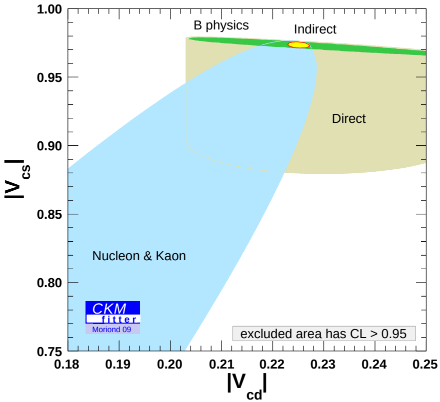
$|V_{cd}| = 0.222 \pm 0.008(stat) \pm 0.003(syst) \pm 0.023(latt)(3.8\% exp + 10\% th)$

Current constraints on $|V_{cs}|$

- Charm tagged W decays $|V_{cs}| = 0.97 \pm 0.09 \pm 0.07 (12\%)$
- CLEO-c on $D \to K \ell \nu$

$|V_{cs}| = 1.018 \pm 0.010(stat) \pm 0.008(syst) \pm 0.106(latt)(1.3\% exp + 10\% th)$

Charm as a test of CKM : semileptonic decays



- K and nucleon: $V_{ud} \simeq V_{cs}$ and $V_{cd} \simeq V_{us}$ only at first non trivial order in λ (need b-input to fix higher orders)
- B alone: rather constraining
- Indirect (combination of the two above): already quite well determined
- Unitarity constraint: $|V_{cd}|^2 + |V_{cs}|^2 \leq 1$

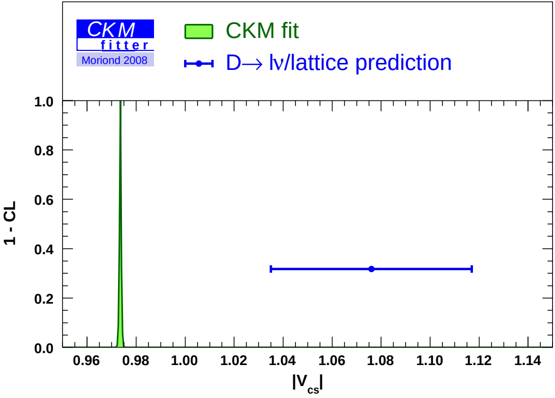
Direct

- $|V_{cd}|$ from νN scattering
- $|V_{cs}|$ from CLEO-c $D \to K\ell\nu$ + lattice

I. Shipsey CLEO-c Aspen workshop

The trouble with $|V_{cs}|$ (2008 !)

- $D_s \to \ell\nu$ (CLEO-c,Belle...)
- Unquenched (staggered) lattice $f_{D_s} = 241 \pm 3$ MeV (HPQCD+UKQCD)
- Combined : $|V_{cs}| = 1.076 \pm 0.041$
- compared to fit value (68% CL) $|V_{cs}| = 0.9735^{+0.00020}_{-0.00022}$

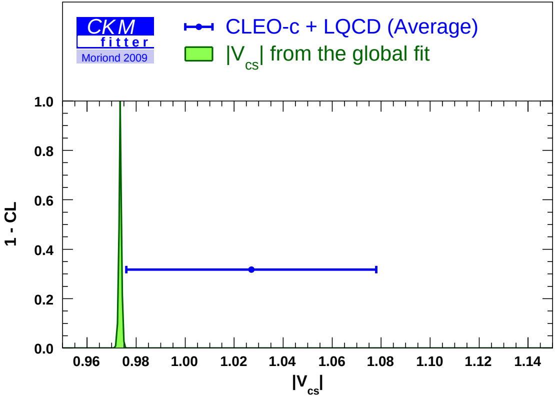


f_{D_s} supposedly ideal for lattice (charm strange) and far worse than f_K/f_π (light quarks) !?

Uncontrolled systematics in full (unquenched) QCD simulations ??

The trouble with $|V_{cs}|$? (2009)

- $D_s \to \mu\nu$ (CLEO-c) and $D_s \to \tau\nu$ (CLEO, Babar, Belle)
- Own lattice QCD average $f_{D_s} = 246.3 \pm 1.2 \pm 5.3$
- Combined : $|V_{cs}| = 1.032 \pm 0.049$
- compared to fit value (68% CL) $|V_{cs}| = 0.9735^{+0.0002}_{-0.0002}$



Agreement between theory and experiment ?

What has happened ?

Theoretical predictions more accurate than direct measurements, in marginal agreement

	$D_s \to \mu\nu$	$D_s \to \tau\nu$
CKMfitter	$5.17 \pm 0.28 \cdot 10^{-3}$	$5.05 \pm 0.27 \cdot 10^{-2}$
CLEOc 09	$5.65 \pm 0.48 \cdot 10^{-3}$	$5.62 \pm 0.44 \cdot 10^{-2}$
Babar	$6.38 \pm 0.92 \cdot 10^{-3}$	–
Belle	$6.74 \pm 1.09 \cdot 10^{-3}$	–

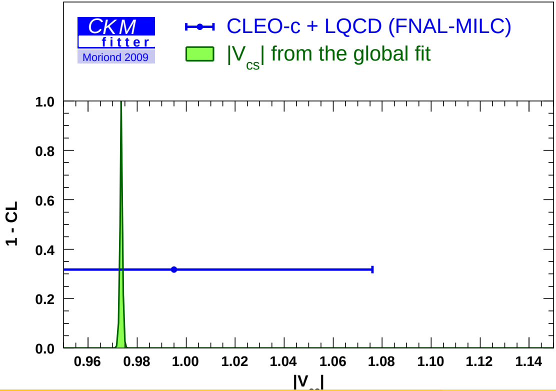
A few possible explanations

- Experimental issue
  - CLEO-c lower than before and disagreeing with Babar and Belle
  - BES could achieve 0.7% accuracy on these BRs
- Issue of f_{D_s} from lattice, though safer than other hadronic quantities
- New physics in $\Delta F = 1$ processes

How large a disagreement ?

Disagreement depends on which value you believe more...

f_{D_s}	Mean	Stat	Syst
FNAL-MILC07*	254	8	11
HPQCD07	241	1.4	5.3
Our average	246.3	1.2	5.3



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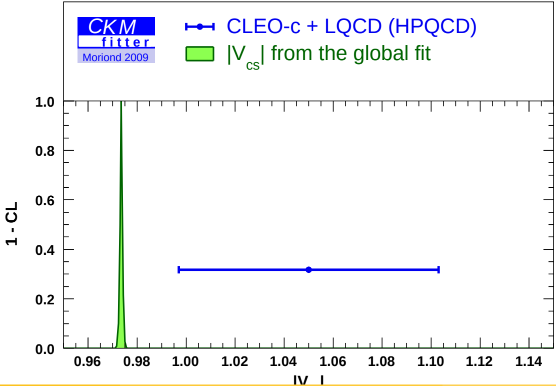

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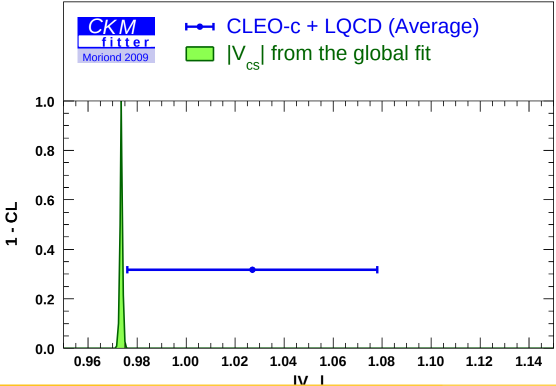
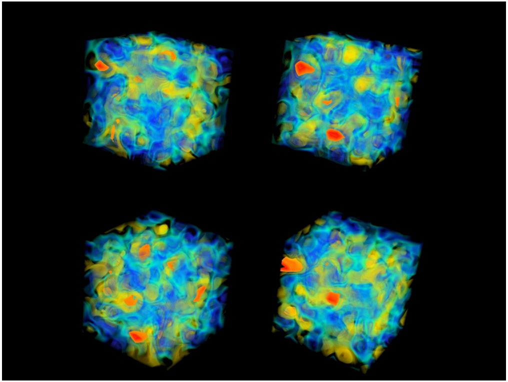


Hadronic inputs and lattice



The situation

- Several hadronic inputs required as inputs for CKMfitter

$$f_B, f_{B_s}, B_B, B_{B_s}, B_K \ldots$$

- Lattice QCD the almost only tool able to estimate them with uncertainties that can be checked and improved
- But many collaborations with different methods of simulations, results, and estimations of errors

Need to perform an average

- Up to now : use reviews from the lattice community (e.g., Tantalo CKM 06)
- Problem : averages often performed in a rather personal manner
- Recently, we attempted to perform our own averages

Sources of uncertainties

Euclidean, finite, discrete box
$\langle Q \rangle = \int [dA] \hat{Q}[A] (det S_f[A])^{N_f} \exp(-S_{YM}[A])$

observable = statistical average over gauge configurations weighted according to gauge and fermion actions

Statistical

- Size of the ensemble of gauge configurations
- Part of errors listed below (when scaling with size of gauge config)

Systematics

- Fermion action : $N_f = 2$, staggered fermions
- Continuum limit/discretisation error $a \to 0$
- Finite volume effects $L \to \infty$
- Quark mass extrapolation (chiral limit and heavy quark limit)

List the results

Include

- only unquenched results with 2 or 2+1 dynamical fermions (sea quarks)
- papers and proceedings (but not preliminary studies)
- split error estimates into stat and syst

Potential problems

- include staggered fermions, though status unclear (still QCD ?)
- proceedings not always followed by peer-reviewed papers
- preliminary studies superseded by other papers
- correlations among observables rarely given (e.g., neutral meson mixing with f_B, B_B, $f_B\sqrt{f_B}\ldots$)

A simple example

Let us take reported values for dynamical simulations of f_{B_s}

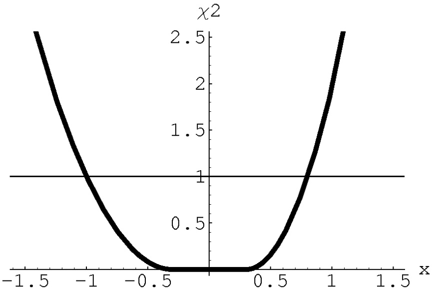
Reference	N_f	Mean	Stat	Syst
CP-PACS01	2	242	9	$^{+53}_{-34}$
MILC02	2	217	6	$^{+58}_{-31}$
JLQCD03	2	215	9	$^{+19}_{-15}$
HPQCD03	2+1	260	7	39
FNAL-MILC07$*$	2+1	240	5	26
Our average		?	?	?

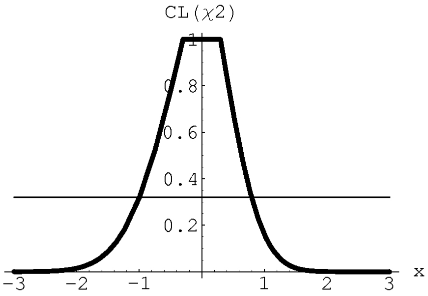
How to combine them ?

Rfit scheme

Each of these results is expressed in the Rfit scheme

- χ^2 with flat bottom (syst) and parabolic walls (stat)
- can be represented as CL assuming χ^2 distribution





$$x = 0^{+0.5}_{-0.7} \pm 0.3$$

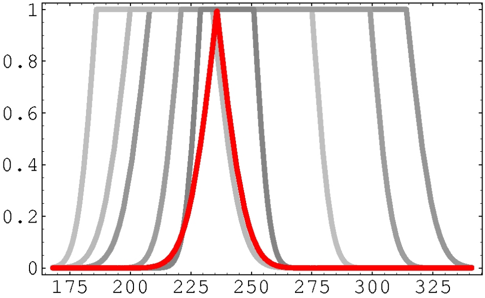
Four different ways of performing the average

For our averages, several methods have been considered

- “pure Gaussian”: all errors in quadrature + adding χ^2
- “splitted Gaussian”:
  - separate statistical and systematic errors
  - adding χ^2 separately for syst and stat
  - two errors interpreted as statistical and systematic uncertainties of the combination
- “naive Rfit”: take Rfit χ^2 and add them
- “educated Rfit”:
  - add *chi*^{2} with only the statistical errors
  - theoretical uncertainty of the combination = the one of the most precise method

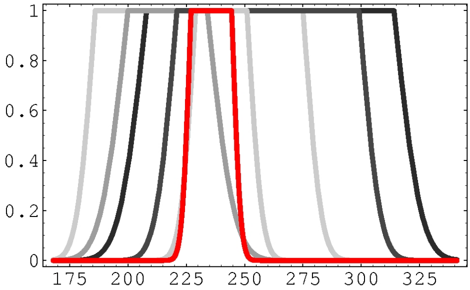
$\Longrightarrow$ Illustration on one quantity f_{B_s} (4 different lattice values)

Pure Gaussian



$$f_{B_s} = 236 \pm 9.5\ \mathrm{MeV}$$

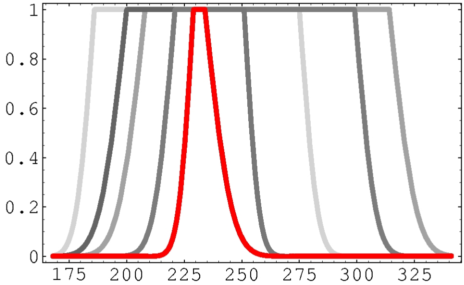
All errors combined in quadrature + sum of χ^2



$$f_{B_s} = 236 \pm 2.9 \pm 8.7 \text{ MeV}$$

Separate Gaussian treatment of stat and syst errors + sum of χ^2

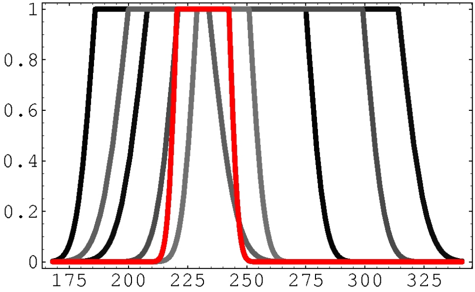
Naive Rfit



$$f_{B_s} = 232^{+9}_{-5} \pm 2.5 \text{ MeV}$$

Sum of Rfit χ^2

Educated Rfit



$$f_{B_s} = 232 \pm 3 \pm 11 \text{ MeV}$$

Sum of χ^2 for stat + min syst uncertainty among values

Final choice

- "Educated Rfit"
- If several Rfit errors, combined linearly (requires to go back to the papers, as it is often combined in quadrature)

Conservative, algorithmic procedure with an internal logic for systematics

- the present state of art cannot allow us to reach a better theoretical accuracy than the best of all estimates
- this best estimate should not be penalized by less precise methods (opposed to combined syst = dispersion of central values)

f_{B_s}

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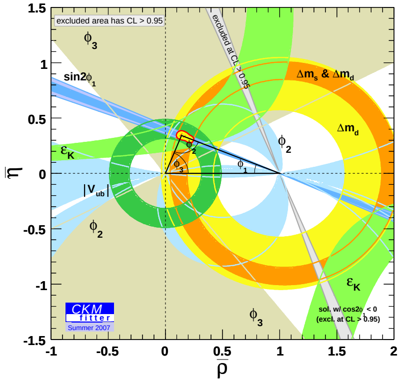
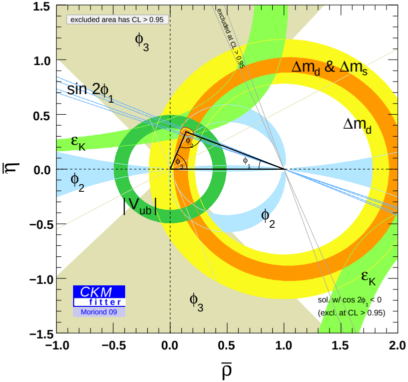
Our average		228	3	17

Used in global fit (and other analyses such as NP)

- currently : meson decay constants
- currently : bag parameters for K, B and B_s mixing
- soon : $K_{\ell 3}$ form factors
- maybe : exclusive semileptonic $b \to c$ and $b \to u$ decays

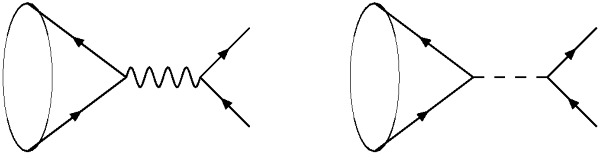
From 2007 to 2008





- Lattice-related obs: Δm_d, Δm_s, ϵ_K (also V_{ub} through $B \to \tau\nu$)
- Impact of change of lattice values (our own averages in 2008)

Beyond the Standard Model : 2HDM



Two Higgs doublet models

- In SM, Higgs mechanism from a single complex doublet for EWSB
- Not imposed by symmetry...one can take ϕ_1 and ϕ_2 of opposite hypercharge

Different 2HDM (two-Higgs doublet models)

- type I : ϕ_1 coupling to both up- and down-type, ϕ_2 to none
- type II : ϕ_1 coupling to up-type, ϕ_2 to down-type (and leptons)
- type III : ϕ_1 and ϕ_2 coupling both to both types of quarks

Focus on 2HDM(II) : looks like SM with 2 Yukawa matrices $y^{d,u}$

$$\mathcal{L}_{II,Y} = -\bar{Q}_L\phi_1 y^d D_R - \bar{Q}_L\phi_2 y^d U_R - \bar{L}_L\phi_2 y^e E_R + h.c.$$

(SM would be $\phi_2 = i\sigma_2\phi_1^*$).

Electroweak symmetry breaking

EWSB occurs through

$$|\langle 0|\phi_1|0\rangle| = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix} \qquad |\langle 0|\phi_2|0\rangle| = \begin{pmatrix} v_2/\sqrt{2} \\ 0 \end{pmatrix} \qquad v_1^2 + v_2^2 = v^2$$

Charged states: ϕ^+ (new W^+ polarisation) and H^+ (charged Higgs)

$$\begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi^+ \\ H^+ \end{pmatrix}$$

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EWSB occurs through

$$|\langle 0|\phi_1|0\rangle| = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix} \qquad |\langle 0|\phi_2|0\rangle| = \begin{pmatrix} v_2/\sqrt{2} \\ 0 \end{pmatrix} \qquad v_1^2 + v_2^2 = v^2$$

Charged states: ϕ^+ (new W^+ polarisation) and H^+ (charged Higgs)

$$\begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi^+ \\ H^+ \end{pmatrix}$$

The charged Higgs H^+ has the couplings

$$\mathcal{L}_{H^+} = \frac{gH^+}{\sqrt{2}} \sum_{ij} \left[\tan\beta \frac{m_{dj}}{M_W} \bar{u}_{Li} V_{ij} d_{Rj} + \cot\beta \frac{m_{ui}}{M_W} \bar{u}_{Rj} V_{ij} d_{Lj} + \tan\beta \frac{m_{\ell i}}{M_W} \bar{\nu}_{Lj} \ell_{Rj}\right]$$

CKM matrix V_{ij} from reexpression of quarks in mass eigenstates

2HDM(II) vs SM

Simple and predictive extension of the Standard Model (embedded in susy models)

- SM-like Yukawa terms for the quark sector
- CKM matrix only source of flavour-changing interactions
- No flavour-changing neutral currents at tree level
- New flavour-changing charged interactions : exchange of a charged Higgs rather than W, $S - P$ rather than $V - A$

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After EWSB, 5 scalars :

$H^\pm$ (charged), A (pseudoscalar), h^0 and H^0 (scalar)

Additional parameters:

- masses of $H^\pm$, H and A,
- ratio of vacuum expectation values $\tan\beta = v_2/v_1$
- angle describing the mixing between h^0 and H^0

Variables and inputs

Potential problems with leptonic decays ($B \to \tau\nu$, $D_s \to \ell\nu\ldots$)

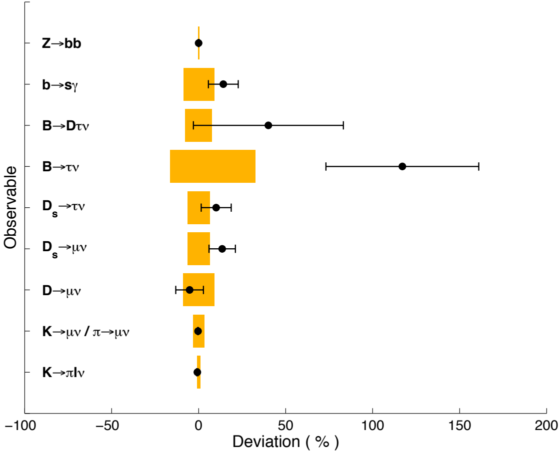
- Restrict analysis to $\Delta F = 1$ or electroweak processes receiving H^+ contributions
- Parameters : CKM matrix, M_{H^+}, $\tan\beta$ (none from neutral Higgses)

CKM matrix inputs

- Need some inputs to fix CKM matrix
- Take inputs where charged Higgs contribution suppressed because proportional to $\frac{m_{\text{light}} m_{\text{heavy}}}{M_{H^+}^2}$ or $\frac{m_{\text{light}}^2}{M_{H^+}^2}$
- Selects $|V_{ud}|$, $|V_{ub}|$, $|V_{cb}|$, γ (from combination of α and β)

Observables and deviations from SM

Observables chosen for the analysis with SM predictions



Orange band : SM pred with two standard deviations

Points : measurements with exp one standard deviation

Leptonic decays

For any meson M, SM leptonic decay rate [rad corr only for $M = K, \pi$]

$$\mathcal{B}[M \to \ell\nu_\ell]_{\rm SM} = \frac{G_F^2 m_M m_\ell^2}{8\pi}\left(1-\frac{m_\ell^2}{m_M^2}\right)^2 |V_{q_u q_d}|^2 f_M^2 \tau_M (1+\delta_{EM}^{M\ell 2})$$

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Charged Higgs contributions:

$$\mathcal{B}[M \to l\nu] = \mathcal{B}[M \to l\nu]_{\rm SM}(1+r_H)^2$$

$$r_H = \left(\frac{m_{q_u} - m_{q_d}\tan^2\beta}{m_{q_u}+m_{q_d}}\right)\left(\frac{m_M}{m_{H^+}}\right)^2 .$$

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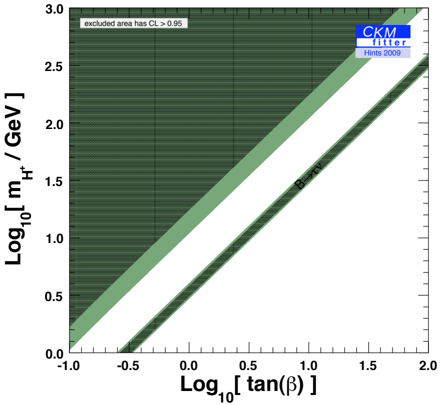
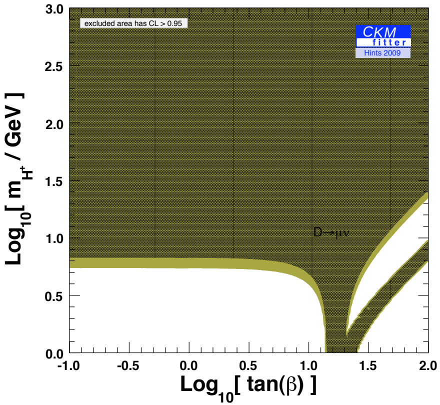
If perfect agreement SM-data, two distinct solutions in 2HDM(II)

- decoupling : $r_H = 0$ ($m_{H^+} \to \infty$, $\tan\beta$ small)
- fine-tuned : $r_H = -2$ (linear correlation between m_H^+ and large $\tan\beta$, depends on meson mass

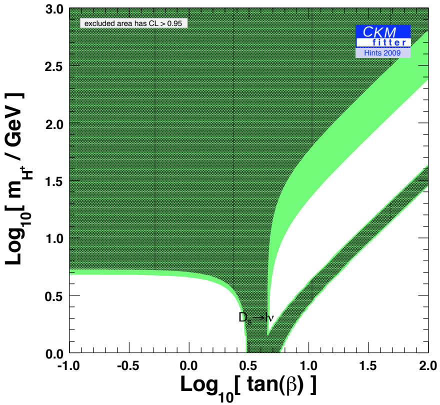
The 4 leptonic decays : $B \to \tau\nu$



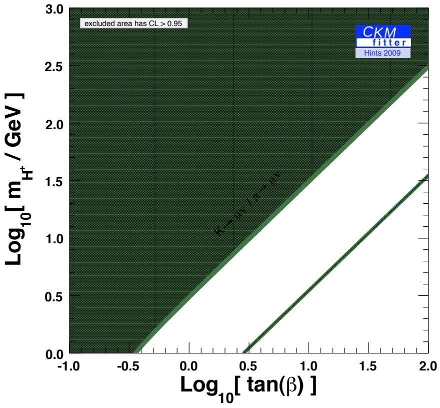
The 4 leptonic decays : $D \to \mu\nu$



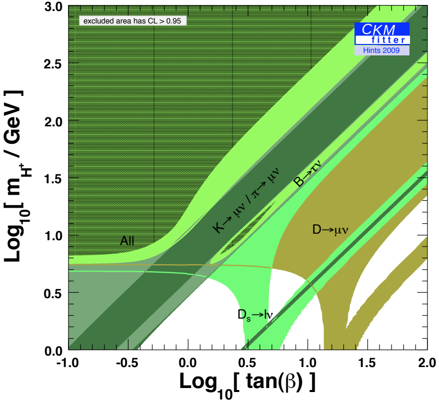
The 4 leptonic decays : $D_s \to \ell\nu$



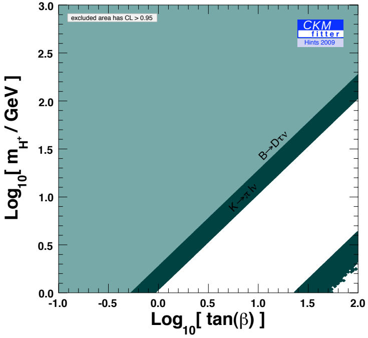
The 4 leptonic decays : $K \to \ell\nu/\pi \to \ell\nu$



The 4 leptonic decays combined



Semileptonic decays : heavy and light



Semileptonic decays help to remove fined-tuned solutions at 95% CL

$$\mathcal{B}[B \to D\tau\nu]/\mathcal{B}[B \to D\ell\nu]$$

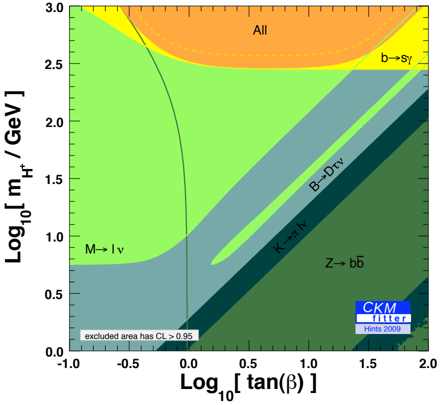
and

$$\mathcal{B}[K^0 \to \pi\mu\nu]/\mathcal{B}[K^0 \to \pi e\nu]$$

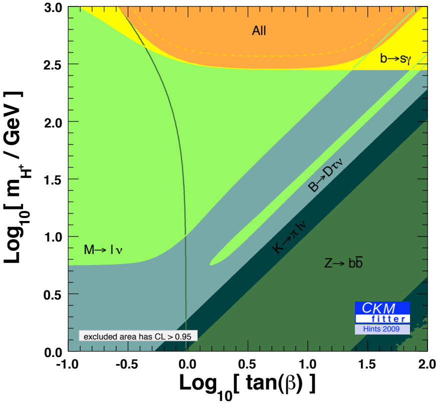
- Easier to study experimentally than purely leptonic decays
- Sensitive to scalar currents through helicity suppressed contribution (scalar form factor)
- Form factors constrained from lattice QCD (including scalar)
- Uses of effective theories (HQET and chiral pert theory)

Further observables and combined fit

- Further observables added : $R_b = \Gamma[Z \to b\bar{b}]/\Gamma[Z \to \text{hadrons}]$ and $b \to s\gamma$
- Charged Higgs contrib = shift in (perturbative) coefficients describing decays in SM



Further observables and combined fit

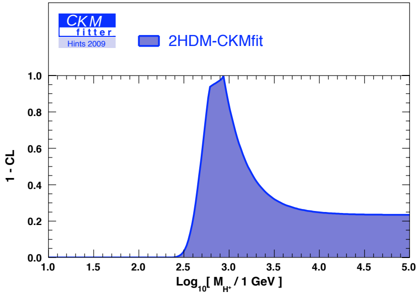


- $\chi^2_{min} \simeq 11$ obtained for $m_{H^+} > 600$ GeV
- At high H^+ mass and any tan β (decoupling limit), charged Higgs contributions negligible

Large χ^2_{min} value is due to the tension between

- large measured $\mathcal{B}[B \to \tau\nu]$ favouring fine-tuned sol at low m_{H^+}
- other observables agree with SM and select large m_{H^+}

Constraints on M_{H^+} and $\tan\beta$



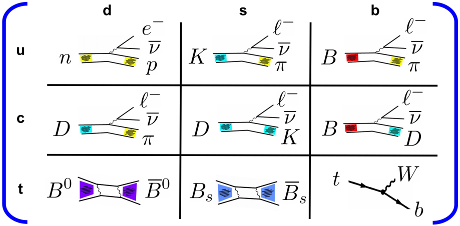
A limit on $m_{H^+} > 323$ GeV at 95% CL is obtained

- Large $\tan\beta$ (> 30), $B \to \tau\nu$ competes with $b \to s\gamma$ and sharpens its exclusion limit
- At small $\tan\beta$ (< 1), most stringent constraint from the $Z \to b\bar{b}$ partial width

and no constraint on $\tan\beta$ at 95%CL

Conclusions

V =



Conclusions (1)

SM very robust

- Kobayashi-Maskawa mechanism at work very efficiently for CP violation
- Fits also additional more invovled constraints, such as $B \to V\gamma$ (loop processes)
- Potential tensions from charm sector

Issue of hadronic inputs

- Lattice main conveyor of results from various collaborations
- What to do with systematic uncertainties ?
- How to combine them

Conclusions (2)

New physics in $\Delta F = 1$ processes

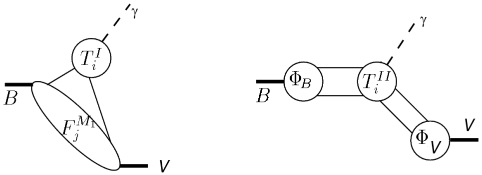
- Renewed interest due to troules with leptonic decays ($B \to \tau\nu$, $D_s \to \ell\nu$)
- Explicit example : Two Higgs Doublet Models with Charged Higgs contributions
- 2HDM(II) does not fare better than SM : favours slightly the decoupling limit
- More observables (mixing, $B_s \to \mu\mu$) to be considered, as well as other 2HDM models

Thank you for your attention !

Backup

$B \to V\gamma$ in QCDF (Buchalla and Bosch)

$$\langle V\gamma|Q_i|B\rangle = \epsilon^* \cdot \Big[T_1^{B\to V}(0)\, T_i^I + \int d\xi\, du\, T_i^{II}(\xi,u)\, \phi_B(\xi)\, \phi_{2;V}^{\perp}(u) \Big] \cdot \left\{ 1 + O\left(\frac{1}{m_b}\right) \right\}$$



- ϵ_μ photon's polarisation
- Q_i from effective Hamiltonian for $b \to (s,d)$
- $T_1^{B\to V}$ form factor ϕ_B, $\phi_{2;V}^{\perp}$ leading-twist distrib. ampl.

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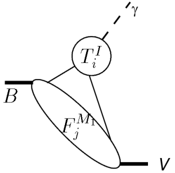

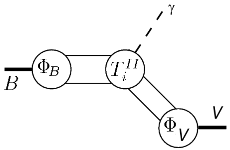

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- $T_1^{B\to V}$ form factor ϕ_B, $\phi_{2;V}^\perp$ leading-twist distrib. ampl.

Up to $1/m_B$ corrections, separation (factorisation) of

- Long distances : form factors, distribution amplitudes
- Short distances : hard-scattering kernels T_i^I and T_i^{II}.

Beyond QCDF (Ball et al.)

All expressed as factor to leading $Q_7 = \frac{e}{8\pi^2} m_b \bar{D}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b + \ldots$

$$\bar{\mathcal{A}}_{L(R)} \equiv \frac{G_F}{\sqrt{2}} \left(\lambda_u^D a^u_{7L(R)}(V) + \lambda_c^D a^c_{7L(R)}(V)\right) \langle V\gamma_{L(R)}|Q_7^{L(R)}|\bar{B}\rangle$$

- $\lambda_U^D = V_{UD}^* V_{Ub} \qquad \lambda_t^D + \lambda_c^D + \lambda_u^D = 0$
- L and R polarisation of the photon
- $a^{c,u}_{7L}(V) = C_7 + O(\alpha_s, 1/m_b) \qquad a^{c,u}_{7R}(V) = O(\alpha_s, 1/m_b)$

Beyond QCDF (Ball et al.)

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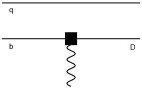
- L and R polarisation of the photon
- $a^{c,u}_{7L}(V) = C_7 + O(\alpha_s, 1/m_b) \qquad a^{c,u}_{7R}(V) = O(\alpha_s, 1/m_b)$

$$a_7^U(V) = a_7^{U,\mathrm{QCDF}}(V) + a_7^{U,\mathrm{ann}}(V) + a_{7L}^{U,\mathrm{soft}}(V) + \dots$$

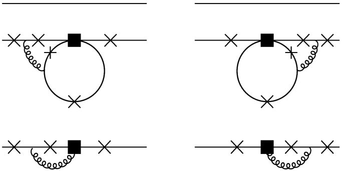
- QCDF : $O(\alpha_s)$ terms, but leading $1/m_b$
- ann,soft : $1/m_b$-suppressed terms large or for isospin/CP asym

$B \to V\gamma$: QCD factorisation part

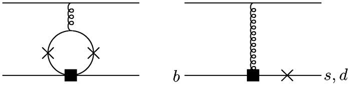
Bosch and Buchalla : explicit formulae for $a_{7L}^{U,\mathrm{QCDF}}$, complete to $O(\alpha_s)$



- LO contribution to T_1 from Q_7
- NLO from 4-quark $Q_{1\ldots6}$ and chromomagnetic Q_8

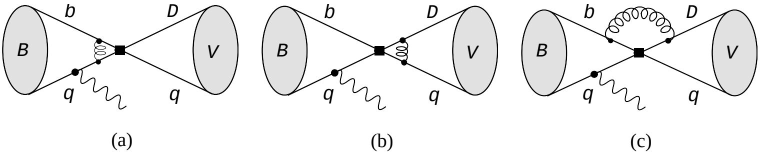


T_1 (vertex)



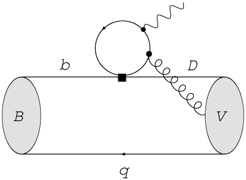
T_2 (hard-scattering)

$B \to V\gamma$: weak annihilation and soft gluons



Weak annihilation

- Short-distance part estimated within QCDF
- Long-distance contribution : photon emission from B meson through LCSR



Soft-gluon emission from a quark loop

- for light-quark loop : fairly complicated LCSR
- for heavy-quark loop : $1/m_Q$ expansion, then LCSR

$b \to s\gamma$ in 2HDM(II)

$$\mathcal{R}_{b\to s\gamma} = \frac{\mathcal{B}[\bar{B} \to X_s\gamma]}{\mathcal{B}[\bar{B} \to X_c\ell\bar{\nu}]} = \left|\frac{V_{ts}^\star V_{tb}}{V_{cb}}\right|^2 \frac{6\alpha_{\mathrm{EM}}}{\pi C}(P+N)$$

- P QCD perturbative corrections (leading contribution to the $1/m_b$ expansion, up to NNLO)
- N non-perturbative corrections (corresponding to higher orders in the $1/m_b$ expansion, starting at $1/m_b^2$)
- C phase space difference between charmed semileptonic decays and $\bar{B} \to X_s\gamma$

Charged Higgs estimated from SusyBSG package, fitting A and B

$$P + N = (C_{7,SM}^{\mathrm{eff},(0)} + B\Delta C_{7,H^+}^{\mathrm{eff},(0)})^2 + A,$$

where $\Delta C_{7,H^+}$ known function of m_{H^+} and $\tan\beta$

$Z \to b\bar{b}$ in 2HDM(II)

$R_b = \Gamma[Z \to b\bar{b}]/\Gamma[Z \to \mathrm{hadrons}]$ is

$$\frac{1}{R_b} = 1 + \frac{S_b}{[(\bar{g}_b^L - \bar{g}_b^R)^2(1-6\mu_b) + (\bar{g}_b^L + \bar{g}_b^R)^2]^2 C_b^{QCD} C_b^{QED}}$$

Charged Higgs contribution redefine coupling constants:

$$\begin{aligned}
\bar{g}_b^L &= \bar{g}_{b,SM}^L + \frac{2^{3/4} G_F^{3/2} m_W^3}{8\pi^2 \cos\theta_W} \left(\frac{m_t}{m_W} \frac{1}{\tan\beta}\right)^2 F_z\left[\frac{m_t}{m_{H^+}}\right] \\
\bar{g}_b^R &= \bar{g}_{b,SM}^R - \frac{2^{3/4} G_F^{3/2} m_W^3}{8\pi^2 \cos\theta_W} \left(\frac{m_b}{m_W} \tan\beta\right)^2 F_z\left[\frac{m_t}{m_{H^+}}\right]
\end{aligned}$$

where the function F_z is

$$F_z[x] = \frac{x^2 - x - x\ln(x)}{(x-1)^2}.$$

Prediction of $\bar{g}_b^L$ and $\bar{g}_b^R$ driven by $\sin^2\theta_W^{\mathrm{eff}}$, mostly insensitive to R_b