The CKM quark mixing matrix

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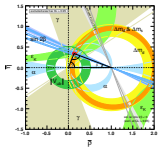
- Written from scratch for RPP 2006, biannual updates / iterations / referees since
- Structure:
  1. Introduction
  2. Magnitudes of CKM elements
  3. Phases of CKM elements
  4. Global fit in the Standard Model
  5. Implications beyond the SM (rewritten for 2010)

Where we are at present

- Ten years ago we did not know that the CKM picture was (essentially) correct
  $\mathcal{O}(1)$ deviations in CP violation were possible
- Nobel Prize in 2008 is a formal recognition that the KM phase is esablished as the dominant source of CP violation in flavor changing transitions of quarks



- Present: no significant deviations from SM, several hints of possible NP signals



Issues (1): HFAG

- After more than 10 years of BaBar & Belle, still no HFAG average for α and γ

  Here 2006: *"results this April make constraints on α and γ weaker (hopefully HFAG will provide ... averages by 2008)"*

- CKMfitter (frequentist) vs. UTfit (bayesian) have both been doing fits for us with our inputs, we mainly quote frequentist results, comment on consistency

  Differences due to method & dependence on priors (far from infinite statistics limit)

- α : Major conceptual differences CKMfitter / UTfit [hep-ph/0703073, hep-ph/0607246 / hep-ph/0701204]

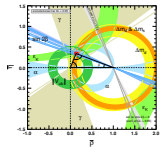
- γ : Uncertainties in frequentist / bayesian results differ by factor ~ 2

  $\left(71^{+21}_{-25}\right)^\circ$ vs. $(74 \pm 11)^\circ$

  [N.B.: all BaBar & Belle results on α and γ use frequentist statistics]

- Fit results in the SM are very similar, but the impact on NP fits is significant

  (Comparing loop-mediated and tree-dominated processes)



Issues (2): inputs from minireviews

- Most important for us: (i) V_{cb} and V_{ub}; and (ii) V_{ud} and V_{us}
- Persistent tension in determination of V_{cb} and V_{ub} from inclusive and exclusive semileptonic decays — and then the interesting tension between V_{ub} and $\sin 2\beta$

  Since 2008, minireview inflates uncertainty, and we accept it

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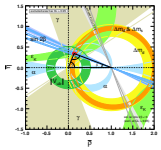
- Another important input is V_{us} (Cabibbo angle)

  Minireview quotes: $f_+(0) = 0.9644 \pm 0.0049$ [PRL 100 (2008) 141601, arXiv:0710.5136]

  What to do when one lattice QCD calculation dominates the average?

  "The broadly used classic calculation of $f_+(0)$ [Leutwyler–Roos] is in good agreement with this value, while other calculations differ by as much as 2%"
- As I told Michael (and probably Yoshi and Augusto, too) if I wrote a CKM review now, not in the PDG, I would not quote this error — I feel very uneasy about this



Issues (3): lattice QCD

- No official lattice QCD averages — plenary talks at annual Lattice Conferences sometimes provide reasonable values, sometimes not [we only use unquenched]

  We have used these, and for 2010 a recently started project: [arXiv:0910.2928]
  `http://latticeaverages.org` — not beyond criticism either

- An example: f_{D_s} and possible NP in $D_s \to \ell\bar{\nu}$

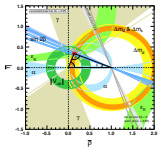
  HPQCD & UKQCD: $f_{D_s} = (241.0 \pm 3)\,\mathrm{MeV}$ [PRL 100 (2008) 062002, arXiv:0706.1726]
  was $> 3\sigma$ from data; generated a lot of interest, 185 citations

  same authors: $f_{D_s} = (248.0 \pm 2.5)\,\mathrm{MeV}$ [arXiv:1008.4018]

- As in $f_+(0)$ case (previous page), one lattice QCD calculation dominates

  It is very hard to judge from the outside the quoted errors, let alone "correct" them

- How we treat each case should not depend on whether result agrees with SM fit



Refereeing and other feedback

- Included many useful comments — and have disagreed with some
- Some comments I remember that have made us think:
  - Some of the lattice inputs may be viewed as too optimistic
  - Amount of beyond SM discussion / interpretation / implications
    (Not a single typical BSM model for flavor; too many new parameters in general)
  - Quantify uncertainty from $\sin 2\beta$ "penguin" modes
  - Balance between best determinations of a certain quantity and reflecting on the state of the field (best one now may not be the next time around)
  - Improved PDFs may make $|V_{cs}|$ from neutrino scattering competitive
    (Does not affect SM fit, but it does, e.g., constraints on 4th generation)
  - More introduction & explanation of details $\Rightarrow$ lengthen?
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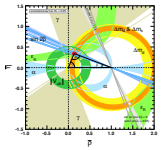
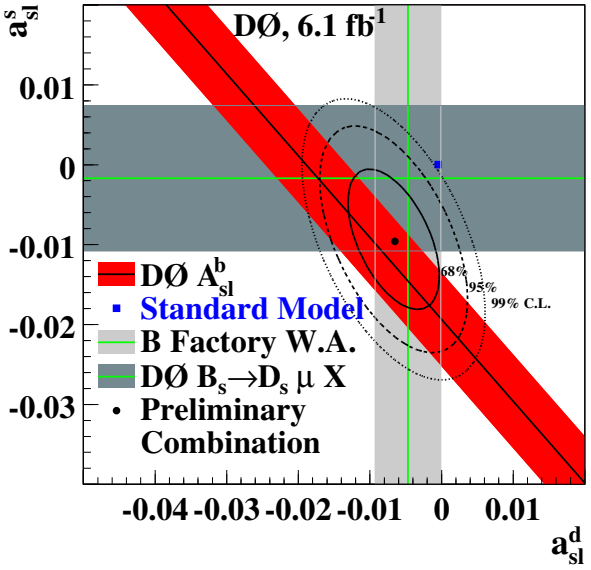
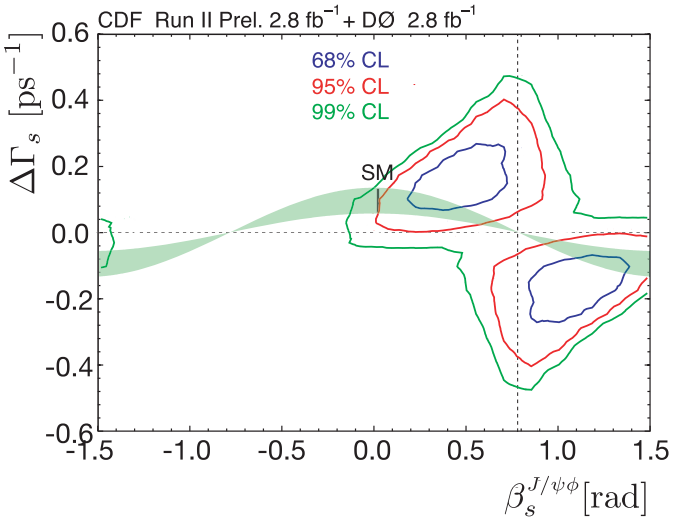


Possible hints to watch

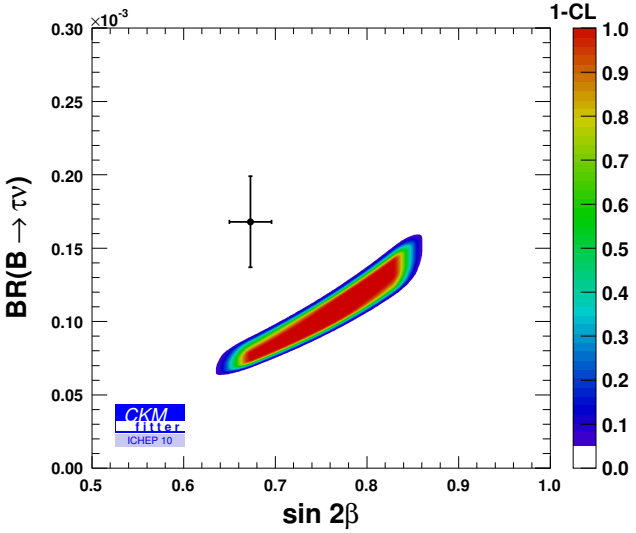
- $A_{\rm SL}$ — CP violation in $B_{d,s}$ mixing: $\sim 3\sigma$



- β_s — analog of β, measured in $B_s \to \psi\phi$: $\sim 2\sigma$

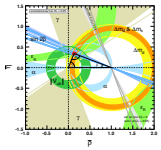


- $\mathcal{B}(B \to \tau\nu)$ — above the SM prediction: $\sim 2.5\sigma$



- $B \to K\pi$ CP asymmetries: theoretically less clean, but very puzzling (many σ)

- In addition, there are several other measurements where improved experimental sensitivity could unambiguously establish non-SM physics $\Rightarrow$ super(-KEK)-B



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The future...

- Looking for corrections to the SM picture of flavor and CP violation
- What can flavor physics teach us about beyond SM physics?
- Many new experiments with exciting discovey potentials:

  NA62: $K \to \pi\nu\bar{\nu}$, the long-awaited complementarity with B decays

  LHCb: Bring constraints on NP in B_s mixing and FCNCs to same level as in B

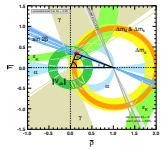
  [extra slide]

  Belle II and maybe Super-B: many measurements improve an order of magnitude

  [extra slide]

- If the LHC sees new physics, it will tell us the scale of the new operators, which will make the interpretation of flavor physics data even more interesting

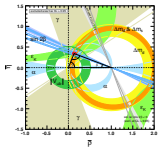
  (And pose new challenges to the PDG — how to present information on flavor structure of NP?)



Backup slides

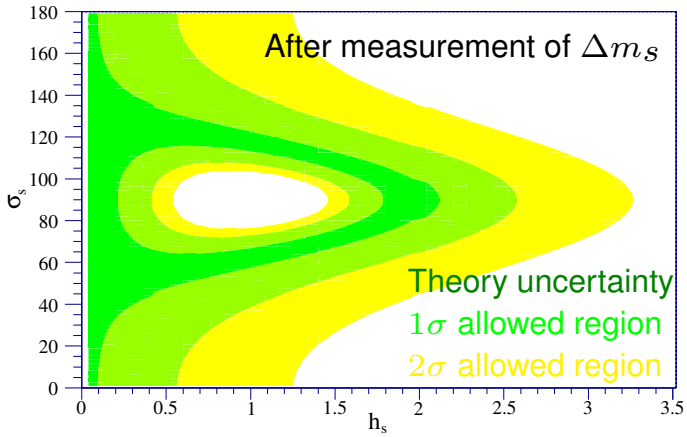
A personal super(-KEK)-B best buy list

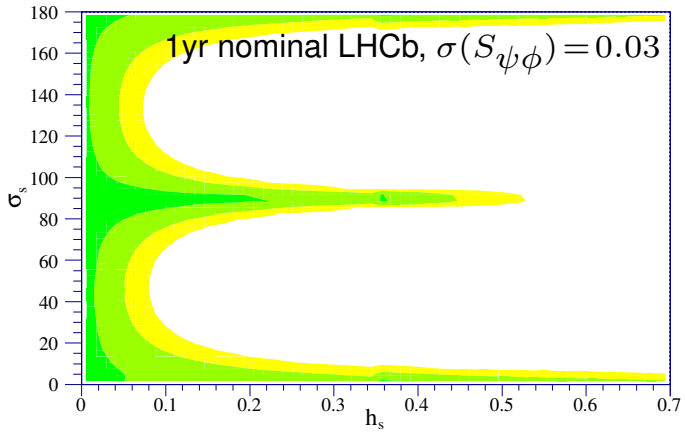
- Want observables: (i) sensitive to different NP, (ii) measurements can improve by an order of magnitude, and (iii) not limited by hadronic uncertainties:
  - Difference of CP asymmetries, $S_{\psi K_S} - S_{\phi K_S}$
  - γ from CP asymmetries in tree-level decays vs. γ from $S_{\psi K_S}$ and $\Delta m_d/\Delta m_s$
  - Search for charged lepton flavor violation, $\tau \to \mu\gamma$, $\tau \to 3\mu$, and similar modes
  - Search for CP violation in $D^0 - \overline{D}^0$ mixing
  - The CP asymmetry in semileptonic decay, $A_{\rm SL}$
  - The CP asymmetry in the radiative decay, $S_{K^*\gamma}$
  - Search for not yet seen FCNC decays and refinements: $b \to s\nu\bar{\nu}$, $B \to \tau\bar{\nu}$, etc.
- Any one of these measurements has the potential to establish new physics



LHCb highlights

- After Δm_s measurement, large NP contribution to B_s mixing is still allowed





[ZL, Papucci, Perez, hep-ph/0604112]

- LHCb will probe B_s sector at a level comparable to B_d
  - Difference of CP asymmetries, $S_{B_s \to \psi\phi} - S_{B_s \to \phi\phi}$
  - $B_s \to \mu^+\mu^-$ ($\propto \tan^6\beta$), search for $B_d \to \mu^+\mu^-$, other rare / forbidden decays
  - 10^{4-5} events in $B \to K^{(*)}\ell^+\ell^-$, $B_s \to \phi\gamma$, ... — test Dirac structure, BSM op's
  - γ from $B \to DK$ and $B_s \to D_s K$ (for α probably super-B wins)
  - [Precisely measure τ_{Λ_b} — affects how much we trust $\Delta\Gamma_{B_s}$ calculation, etc.]