Flavor physics in the LHC era

Zoltan Ligeti

Physics at the Dawn of the LHC Era

January 27–29, 2011, TRIUMF

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- Introduction
- Current status: sizable NP contributions allowed
- Some key probes at LHCb and super-(KEK)B
- High-p_T flavor physics
- Conclusions

What future experiments? Aren't we done yet?

- Expected deviations from SM predictions induced by new TeV-scale physics?

  Generic flavor structure already ruled out by orders of magnitudes; can thus expect any size deviation below current bounds. In a large class of scenarios expect deviations at the 10^{-2} level.

- What are the theoretical uncertainties?

  Highly process dependent; some measurements already limited by theoretical uncertainties, while in other cases theory uncertainties are smaller than the expected sensitivity of future experiments.

- What can we expect in terms of experimental precision?

  Useful data sets can increase by a factor of $\sim 10^2$ at LHCb and a super-B factory. Such improvements will probe into the region of fairly generic new physics predictions.

- What will the measurements teach us if deviations from the SM are [not] seen?

  The new flavor physics data will be complementary with the high-p_T part of the LHC program. The synergy of data sets can teach us about what the new physics at the TeV scale is [not].

Future (1)

SuperKEKB groundbreaking

- Unless the proposal is denied by the Diet, we will have a groundbreaking ceremony on April 8, 2011.
  - Symposium
  - Press conference
  - Contributions to CERN Courier, Symmetry, interactions.org, etc.
  - Party
- All of you are cordially invited to the party.

[Yamauchi @ Belle II Collaboration meeting last November]

Future (2)

The act of Minister is linked to the Plan of INFN

Componenti Super B	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Sviluppo Acceleratore (150 M€) • Costruzione infrastrutture, Sviluppo damping rings, Sviluppo transfer lines, Messa in funzione linac, damping lines transfer lines Costruzione facility end-user • Disegno e costruzione labs end user e primo set di beam lines	20	60	70							
Sviluppo Centri Calcolo (43 M€) • Sviluppo progettazione costruzione centro dii calcolo per analisi dati	5	15	23							
Completamento Acceleratore (156 M€) • Installazione componenti negli archi acceleratore , Installazione zona di interazione, Messa in funzione acceleratore • Disegno e costruzione secondo set di beam lines				52	52	52				
Utilizzo installazione (120 M€) • Costi operazione e manutenzione acceleratore • Costi e manutenzione beam lines							30	30	30	30
Totale Infrastrutture tecniche (469 M€)	25	75	93	52	52	52	30	30	30	30
Overheads INFN (45.1 M€ pari al 9%)	2.3	6.8	8.4	4.7	4.7	4.7	2.7	2.7	2.7	2.7
Cofinanziamento INFN (150 M€)	15	15	15	15	15	15	15	15	15	15
Cofinanziamento IIT (100 M€)	10	10	10	10	10	10	10	10	10	10
Costo Totale del progetto (764.1 M€)	84	95	103.[illegible]	80.8	80.8	80.8	56.8	56.8	56.8	56.8

20 50 60

140

[Giorgi @ Babar Collaboration meeting this Monday]

Future (3)

- LHCb collects $2\,\mathrm{fb}^{-1}$ / yr until $\sim 10\,\mathrm{fb}^{-1}$; plan upgrade for ~ 10 times the rate

- $\mu \to e\gamma$: MEG (PSI) sensitivity to 10^{-13}, maybe 10^{-14} later

- $K \to \pi\nu\bar{\nu}$: CERN NA62: about 60 $K^+ \to \pi^+\nu\bar{\nu}$ events / yr in 2012–2014

  plans for $K_L \to \pi^0\nu\bar{\nu}$ mode later

  J-PARC E14 KOTO 10^{-11} $K_L \to \pi^0\nu\bar{\nu}$ sensitivity, later 100 events

  FNAL: maybe get ~ 1000 $K^+ \to \pi^+\nu\bar{\nu}$ events with project-X

$\mu N \to eN$: Fermilab MECO/mu2e sensitivity 2×10^{-17}, maybe 10^{-18} later

J-PARC: COMET sensitivity to 10^{-16}, later PRISM/PRIME to 10^{-18}

- EDM experiments

Neutrino experiments

Why is flavor physics interesting?

- "Flavor physics": what breaks $U(3)_Q \times U(3)_u \times U(3)_d \to U(1)_{\text{Baryon}}$?

- SM flavor problem: hierarchy of masses and mixing angles; why ν's are different

- NP flavor problem: TeV scale (hierarchy problem) $\ll$ flavor & CPV scale

$$\epsilon_K\text{:}\ \frac{(s\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4\,\text{TeV}, \quad \Delta m_B\text{:}\ \frac{(b\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^3\,\text{TeV}, \quad \Delta m_{B_s}\text{:}\ \frac{(b\bar{s})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^2\,\text{TeV}$$

  - TeV-scale new physics models typically have new sources of CP and flavor violation, which may be observable in flavor physics but not directly at the LHC

  - The observed baryon asymmetry of the Universe requires CPV beyond the SM
    Not necessarily in flavor changing processes, nor necessarily in quark sector
    Flavor suppression destroys KM baryogenesis; flavor matters for leptogenesis

- Flavor sector can be tested a lot better, many NP models have observable effects

Spectacular track record

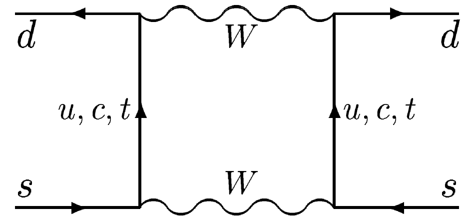
- Most parameters of the SM (and in many of its extensions) are related to flavor
- Flavor physics was crucial to figure out $\mathcal{L}_{\rm SM}$:
  - β-decay predicted neutrino (Pauli)
  - Absence of $K_L \to \mu\mu$ predicted charm (GIM)
  - ϵ_K predicted 3rd generation (KM)
  - Δm_K predicted m_c (GL)
  - Δm_B predicted large m_t
- Flavor physics is likely to be crucial to figure out $\mathcal{L}_{\rm LHC}$, strong constraints already
- TeV-scale NP must have special flavor & CP structure — flavor has mainly been an input to model building, not an output (structures imposed to satisfy bounds)

Current status

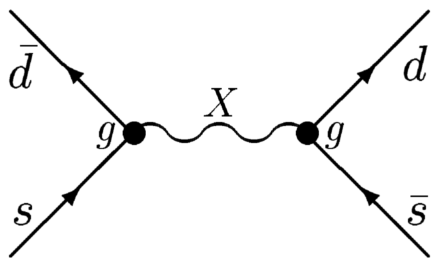
The power of Δm_K (ϵ_K is similar)

- In the SM: $\Delta m_K \sim \dfrac{g^4\,|V_{cs}V_{cd}|^2}{16\pi^2}\,\dfrac{m_c^2}{m_W^4}\,f_K^2\,m_K$

  (severe suppressions!)



- If tree-level exchange of a heavy gauge boson was responsible for a significant fraction of the measured value of Δm_K



$$\frac{\Delta m_K^{(X)}}{\Delta m_K^{(\mathrm{exp})}} \sim \frac{g^2\,\Lambda_{\mathrm{QCD}}^3}{M_X^2\,\Delta m_K} \;\Rightarrow\; M_X > g \times 2\cdot 10^3\ \mathrm{TeV}$$

Similarly, from $B^0 - \overline{B}{}^0$ mixing: $M_X > g \times 3 \cdot 10^2\ \mathrm{TeV}$

- Or new particles at TeV scale can have large contributions in loops $(g \sim 0.01)$

In many NP models the constraints from kaons are the strongest, since so are the SM suppressions — these are built into models since the 70's

Δm_K and ϵ_K in SUSY (oversimplified)

- $$\frac{(\Delta m_K)^{\rm SUSY}}{(\Delta m_K)^{\rm exp}} \sim 10^4 \left(\frac{1\,{\rm TeV}}{\tilde m}\right)^2 \left(\frac{\Delta \tilde m_{12}^2}{\tilde m^2}\right)^2 {\rm Re}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$$

  $K^d_{L(R)}$: mixing in gluino couplings to left-(right-)handed down quarks and squarks

  For ϵ_K, replace: $10^4\,{\rm Re}\big[(K_L^d)_{12}(K_R^d)_{12}\big] \Rightarrow 10^6\,{\rm Im}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$

- Classes of models to suppress each factors

  (i) Heavy squarks: $\tilde m \gg 1\,{\rm TeV}$ (e.g., split SUSY)

  (ii) Universality: $\Delta m^2_{\tilde Q, \tilde D} \ll \tilde m^2$ (e.g., gauge mediation)

  (iii) Alignment: $|(K^d_{L,R})_{12}| \ll 1$ (e.g., horizontal symmetries)

- All SUSY models incorporate some of the above; 50 years of K ($+30$ years of B) constraints led to many models with suppressed FCNCs in down sector

- Smallness of $D^0 - \overline{D}{}^0$ mixing (BaBar & Belle, ’07) ruled out (iii) as sole explanation

Precision tests with kaons

- CPV in K system is at the right level (ϵ_K accommodated with $\mathcal{O}(1)$ CKM phase)

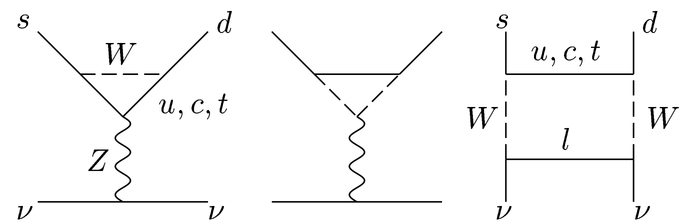
- Hadronic uncertainties preclude precision tests (ϵ'_K notoriously hard to calculate)

  We cannot rule out (nor prove) that the measured value of ϵ'_K is dominated by NP

  (N.B.: bad luck in part — heavy m_t enhanced hadronic uncertainties, but helps for B physics)

- $K \to \pi\nu\bar\nu$: Theoretically clean, but small rates $\mathcal{B} \sim 10^{-10}(K^\pm),\ 10^{-11}(K_L)$

$$\mathcal{A} \propto \begin{cases} (\lambda^5\, m_t^2) + i(\lambda^5\, m_t^2) & t: \text{CKM suppressed} \\ (\lambda\, m_c^2) + i(\lambda^5\, m_c^2) & c: \text{GIM suppressed} \\ (\lambda\, \Lambda_{\rm QCD}^2) & u: \text{GIM suppressed} \end{cases}$$

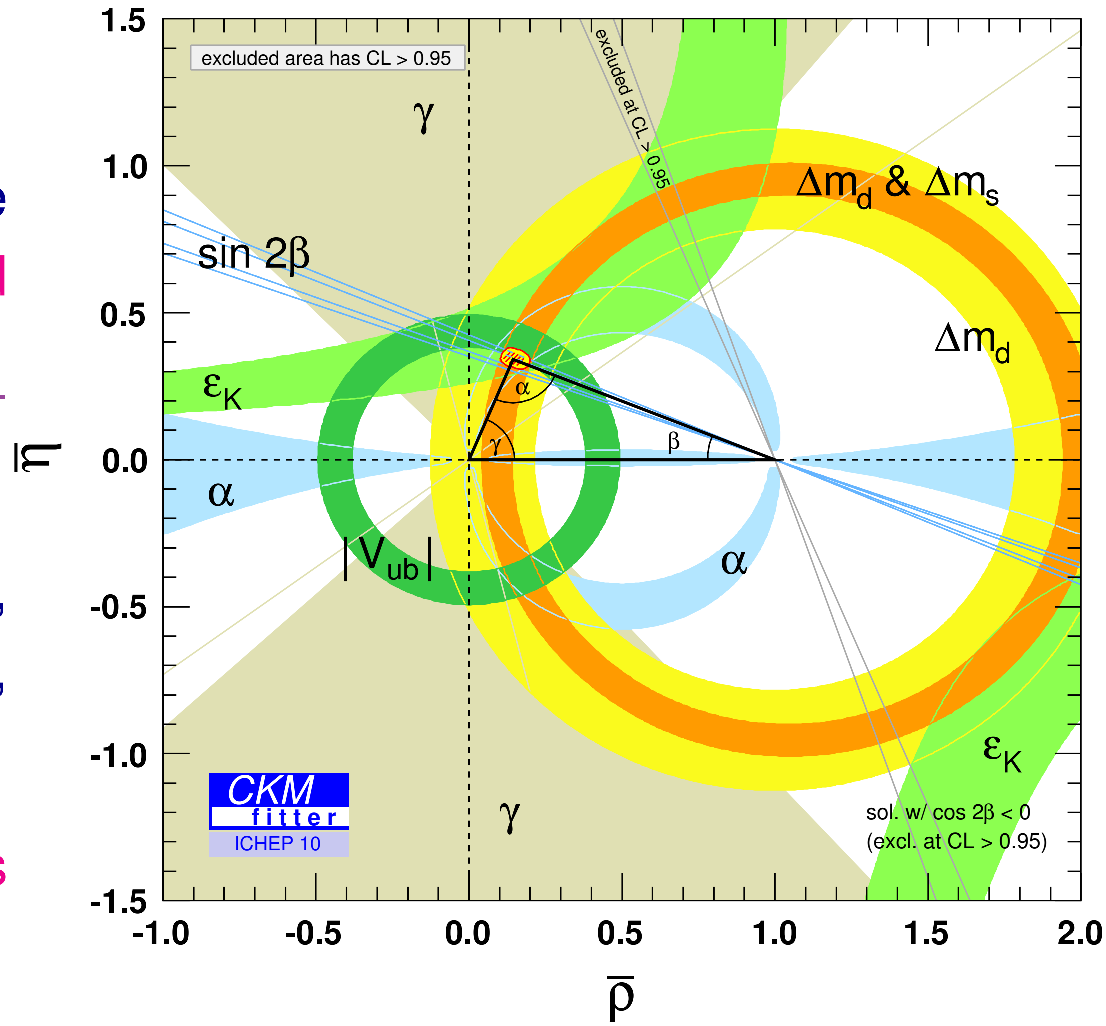


So far 3 events: $\mathcal{B}(K^+ \to \pi^+\nu\bar\nu) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ [BNL E787/E949]

- Need more statistics for precision tests (rates $\propto A^4 \sim |V_{cb}|^4$)

The standard model CKM fit

- Very impressive accomplishments
- The level of agreement between the measurements often misinterpreted
- Increasing the number of parameters can alter the fit completely
- Plausible TeV scale NP scenarios, consistent with all low energy data, with sizable flavor physics effects
- CKM is inevitable; the question is not if it's correct, but is it sufficient?

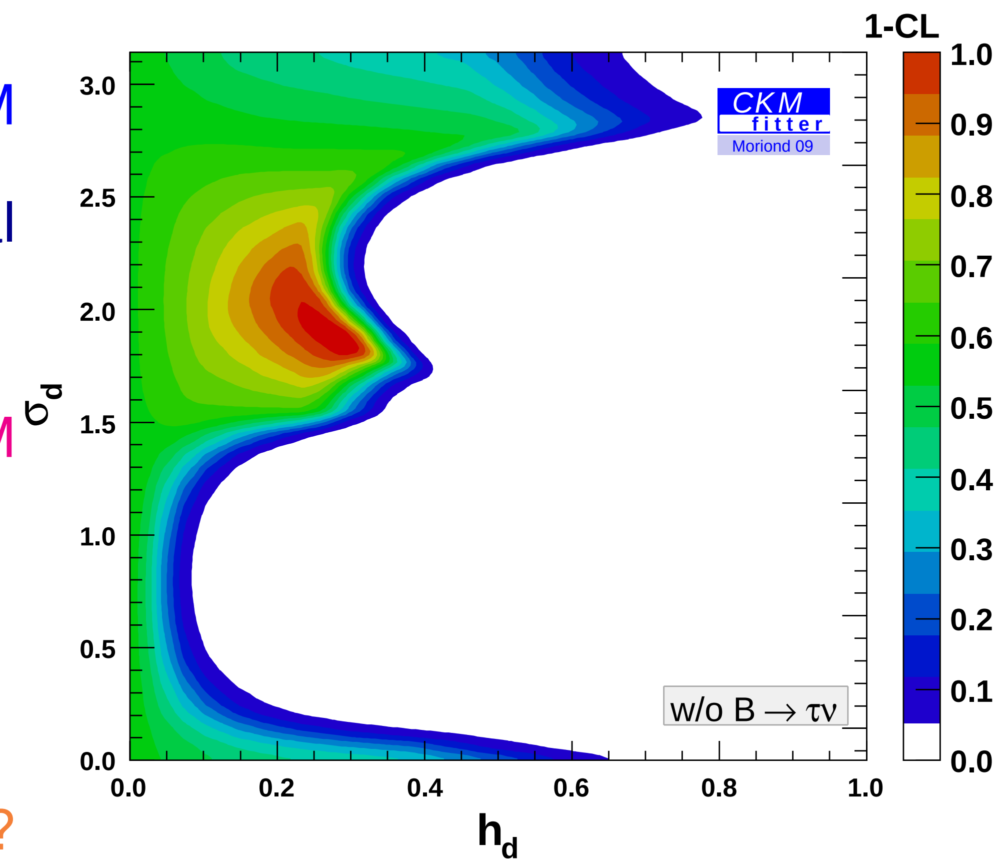


- Isolating small NP effects requires many measurements (compare tree / loop, etc.)

Constraining new physics in $B^0 - \overline{B}^0$ mixing

- Assume: (i) 3×3 CKM matrix is unitary
  (ii) tree-level decays dominated by SM

  Simple parameterization for each neutral meson: $M_{12} = M_{12}^{\rm SM}\,(1 + h_d\, e^{2i\sigma_d})$



- Non-SM terms not yet bound to be $\ll$ SM

  Need a lot more data to be able to tell

  Overconstraining measurements crucial

- Q: Is $\Lambda_{\rm flavor} \gg \Lambda_{\rm EWSB}$?

  Is NP $\ll$ SM unless $\sigma_d = 0$ (mod $\pi/2$)?

E.g.: $(z/\Lambda^2)(\bar{b}_L \gamma^\mu s_L)^2 \;\Rightarrow\; \Lambda \gtrsim (5\,{\rm TeV})\, \dfrac{h_d^{1/2}}{|V_{tb}V_{td}|/|z|^{1/2}}$

- 10–20% non-SM contributions to most loop-mediated transitions are still possible

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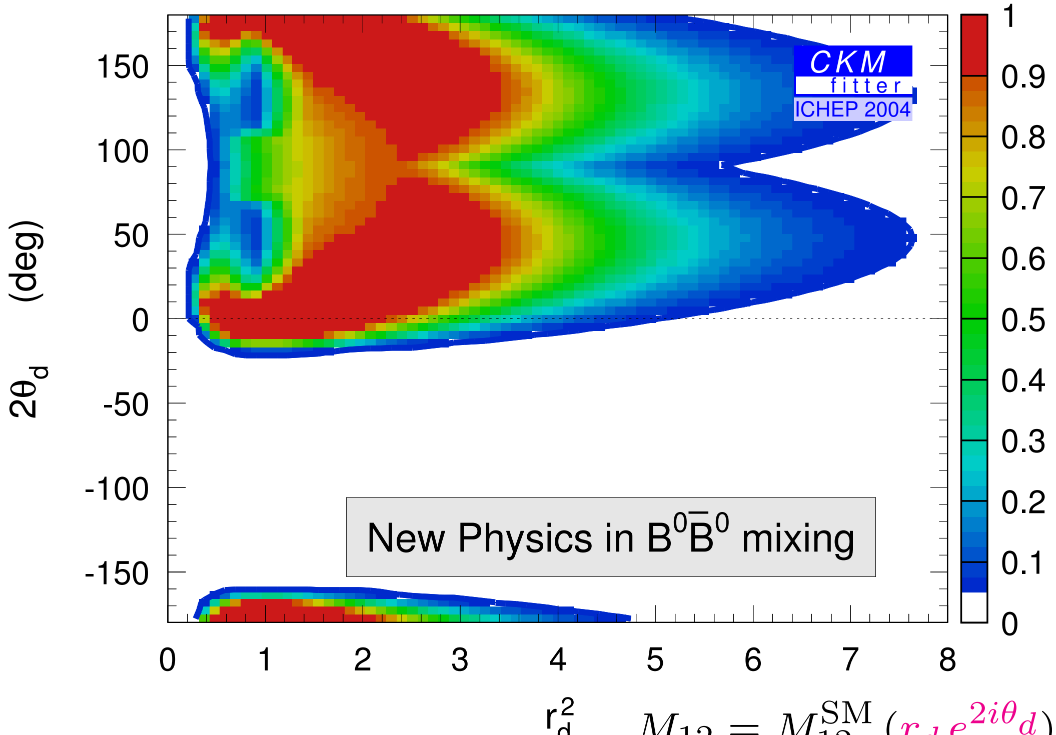
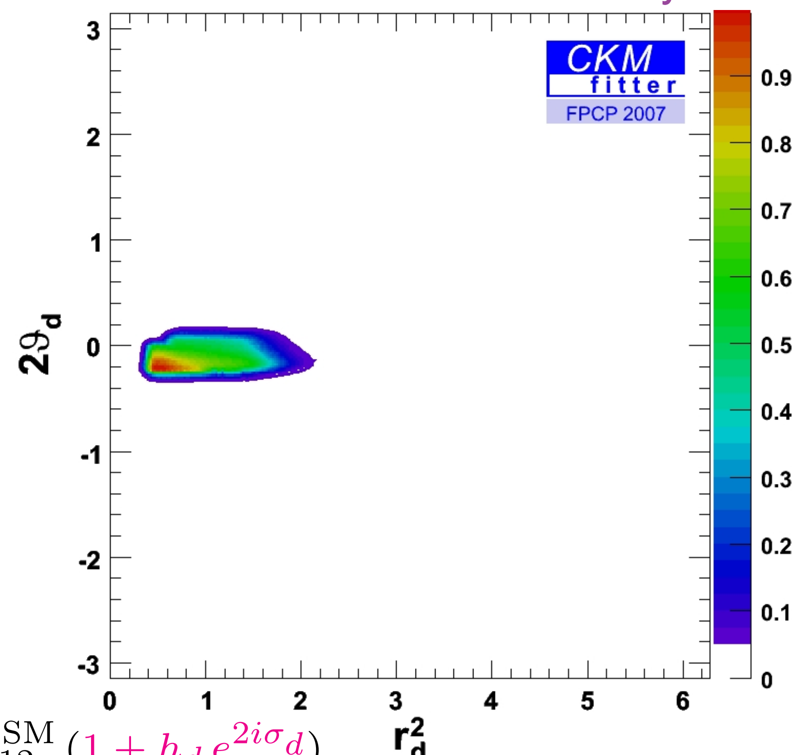
The one-page summary of BaBar & Belle

- Strong constraints on NP in many FCNC amplitudes — much more progress in this (and more interesting) than just the uncertainties of the SM parameters

Qualitative change before vs. after 2004 — the real justification for the Nobel Prize in my mind





$$M_{12} = M_{12}^{\rm SM}\,(r_d\, e^{2i\theta_d}) = M_{12}^{\rm SM}\,(1 + h_d\, e^{2i\sigma_d})$$

And a lot more: the B factory decade

- Q: How many CP violating quantities are measured with $> 3\sigma$ significance?

  A: 15; B: 19; C: 23; D: 27 (with different sensitivity to new physics)

And a lot more: the B factory decade

- Q: How many CP violating quantities are measured with $> 3\sigma$ significance?

  C: 23 (with different sensitivity to new physics)

ϵ_K, ϵ'_K,

$S_{\psi K}$, $S_{\eta' K}$, $S_{f_0 K}$, $S_{\pi K}$, $S_{K^+K^-K^0}$, S_{3K_S}, $S_{\psi\pi^0}$, $S_{D^+D^-}$, $S_{D^{*+}D^{*-}}$, $S_{D^{*+}D^-}$, $S_{\pi^+\pi^-}$

$A_{\rho^0 K^+}$, $A_{\eta K^+}$, $A_{f_2 K^+}$, $A_{K^+\pi^-}$, $A_{\eta K^{*0}}$, $A_{\pi^+\pi^-}$, $A_{\rho^\pm\pi^\mp}$, $\Delta C_{\rho^\pm\pi^\mp}$, $a_{D^{*\pm}\pi^\mp}$, $A_{D_{\rm CP^+}K^-}$

- Just because a measurement determines a CP violating quantity, it no longer automatically implies that it is interesting

  (E.g., if $S_{\eta' K}$ was still consistent with 0, it would be a many σ discovery of NP!)

- It doesn't matter if one measures a side or an angle — only experimental precision and theoretical cleanliness for interpretation for short distance physics do

Penguins: the old/new $B \to K\pi$ puzzle

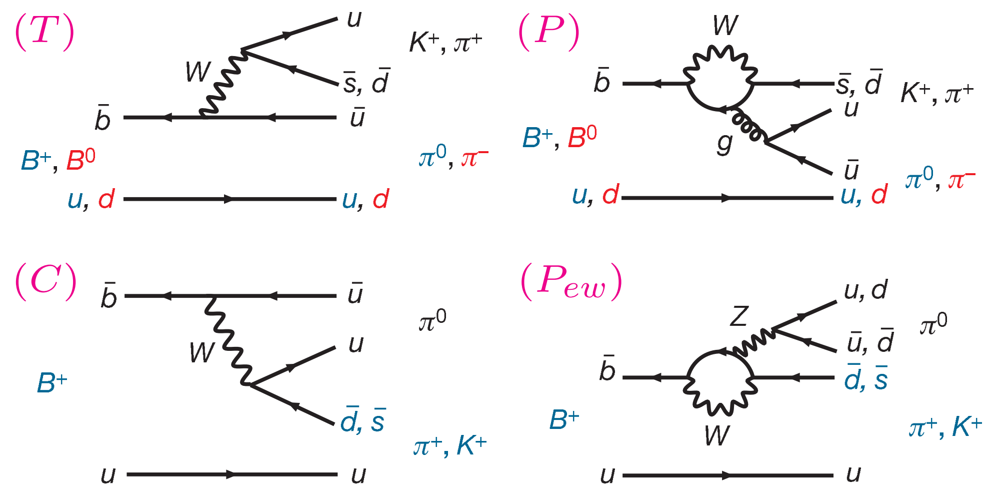
- **Q**: Have we seen new physics in CPV?

$$A_{K^+\pi^-} = -0.098 \pm 0.012 \quad (P+T)$$

$$A_{K^+\pi^0} = 0.050 \pm 0.025 \quad (P+T+C+A+P_{ew})$$

What's the reason for large difference?

$$A_{K^+\pi^0} - A_{K^+\pi^-} = 0.148 \pm 0.028$$



(Annihilation not shown) [Belle, Nature 452, 332 (2008)]

SCET / factorization predicts: $\arg(C/T) = \mathcal{O}(\Lambda_{\rm QCD}/m_b)$ and $A + P_{ew}$ small

- **A**: huge fluctuation, breakdown of $1/m$ exp., missing something subtle, new phys.

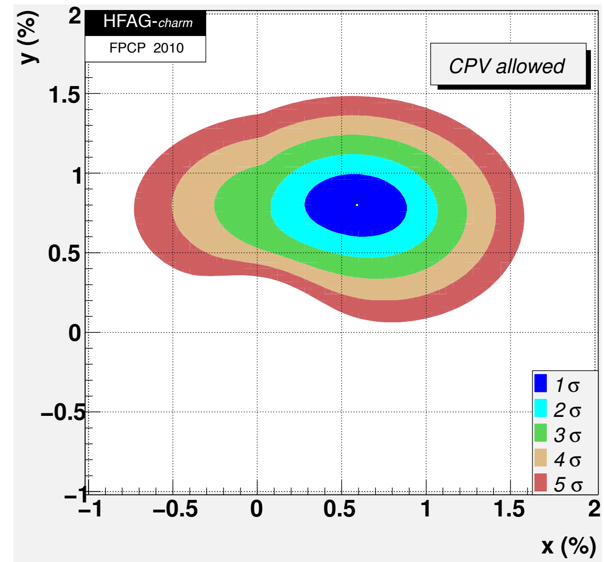
- No similarly clear tension in branching ratios, e.g., Lipkin sum rule is OK by now:

$$2\,\frac{\bar\Gamma(B^- \to \pi^0 K^-) + \bar\Gamma(\overline{B}^0 \to \pi^0 \overline{K}^0)}{\bar\Gamma(B^- \to \pi^- \overline{K}^0) + \bar\Gamma(\overline{B}^0 \to \pi^+ K^-)} = 1.05 \pm 0.05$$

(should be near 1)

The "last" meson mixing: D^0

- Complementary to K, B: CPV, FCNC both GIM & CKM suppressed $\Rightarrow$ tiny in SM
  - 2007: significance of mixing $> 5\sigma$ [HFAG combination]
  - Only meson mixing generated by down-type quarks (SUSY: up-type squarks)
  - SM suppression: $\Delta m_D,\ \Delta\Gamma_D \lesssim 10^{-2}\,\Gamma$, since doubly-Cabibbo-suppressed and vanish in flavor $SU(3)$ limit
  - CPV (mixing or direct) $> 10^{-3}$ would be sign of NP



$(x = \Delta m/\Gamma,\ y = \Delta\Gamma/2\Gamma)$

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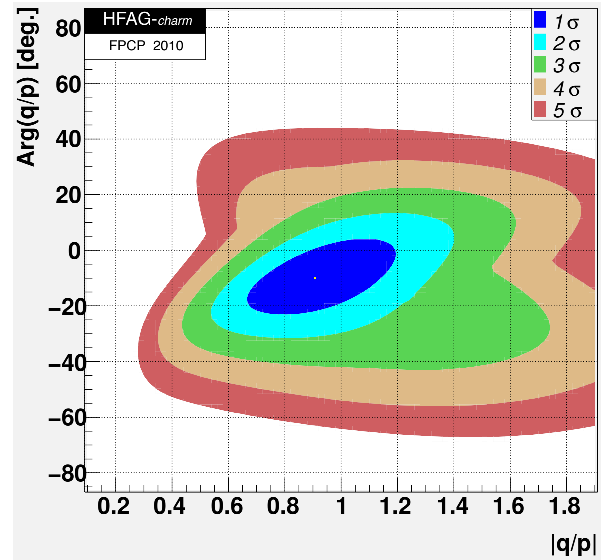
  - CPV (mixing or direct) $> 10^{-3}$ would be sign of NP
  - To do: Precise values of Δm and $\Delta\Gamma$?
    Is CPV absent in mixing and decays?



Not yet known if $|q/p| \simeq 1$

- Particularly interesting for SUSY: Δm_D and $\Delta m_K \Rightarrow$ if first two squark doublets are within LHC reach, they must be quasi-degenerate (alignment alone not viable)

Summary — current status

- The SM flavor sector has been tested with impressive & increasing precision
  KM phase is the dominant source of CP violation in flavor changing processes
- New physics in most FCNC processes may still be $\gtrsim 10\%$ of the SM contributions
- Measurements probe scales $\gg 1\,\mathrm{TeV}$; sensitivity limited by statistics, not theory
- Few hints of discrepancies; need more data and / or improved theory to resolve

Where do we go from here?

Future progress

The name of the game in the LHC era

- The question has been who sees NP first; once it's seen, how to understand it? [Assume the LHC sees more than a Higgs ...]

- Concentrate on topics where sensitivity can improve significantly

  Many measurements with different sensitivities will improve an order of magnitude

  Skip: $B \to X_s\gamma$ rate, not far from "theory wall" (best bound on many models!)

  Tension between $\sin 2\beta$ and $|V_{ub}|$ or $B \to \tau\nu$

  DØ's 3.2σ effect in $A_{\rm SL}$

- Lack of a "flavor theory" — there isn't an obviously right / natural way for TeV-scale new physics to duplicate GIM and CKM suppressions

- Even if TeV-scale NP has the same loop + GIM suppressions in FCNC's as the SM, still expect deviations at the percent level

Special features of the SM flavor sector

- All flavor changing processes depend only on a few parameters in the SM
  $\Rightarrow$ correlations between large number of s, c, b, t decays
- The SM flavor structure is very special:
  - Single source of CP violation in charged current interactions
  - Suppressions due to hierarchy of mixing angles
  - Suppression of FCNC processes from loops ($\Delta F = 2$ and $\Delta F = 1$)
  - Suppression of FCNC chirality flips by quark masses (e.g., $S_{K^*\gamma}$)

  Many suppressions that NP may not respect $\Rightarrow$ sensitivity to high scales
- It is interesting and possible to test each of these
- However, a general operator analysis has too many terms, no one has come up with a really useful STU-like parameterization

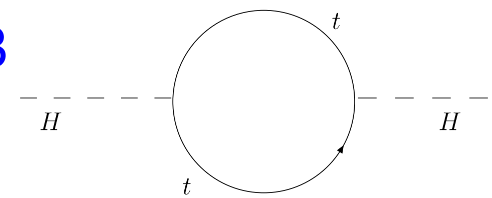
What we may hope to learn

- Hopefully the LHC will discover new particles; some subleading couplings probably not measurable directly (we know V_{td} & V_{ts} only from B and not t decays)

  Important to figure out soft SUSY breaking terms $\Rightarrow$ SUSY breaking, mediation

- In many models: large $m_t \Rightarrow$ non-universal coupling to EWSB

  Motivated models: NP $\Leftrightarrow$ 3rd gen. $\neq$ NP $\Leftrightarrow$ 1st & 2nd gen.

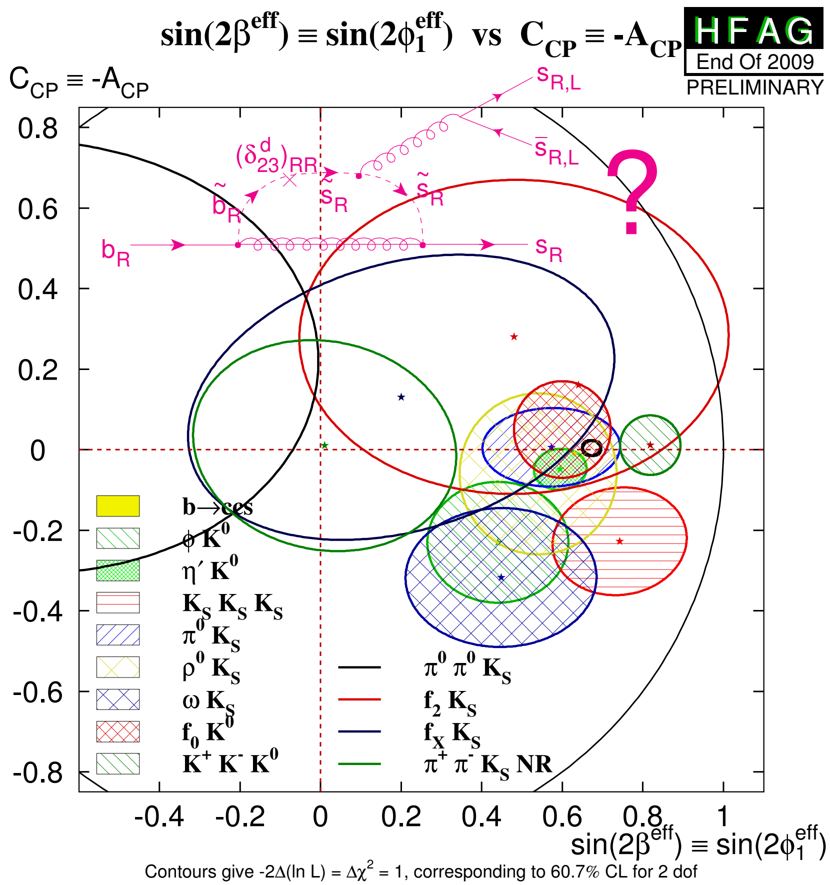


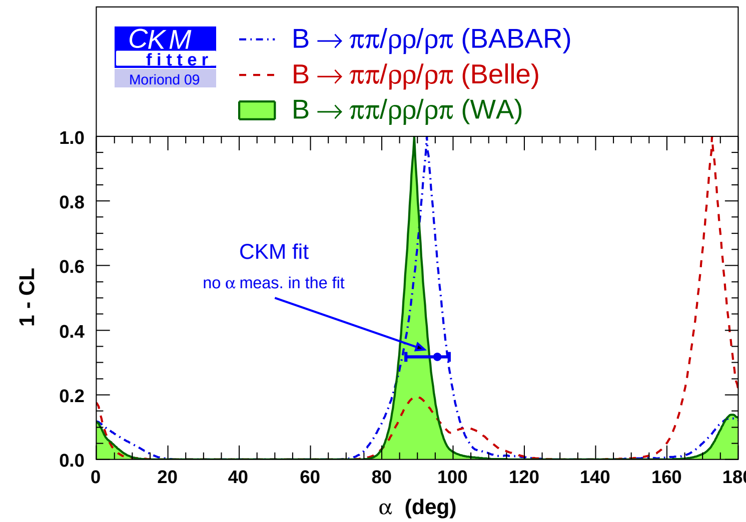
  Is the physics of 3rd–1st, 3rd–2nd, and 2nd–1st generation transitions the same?

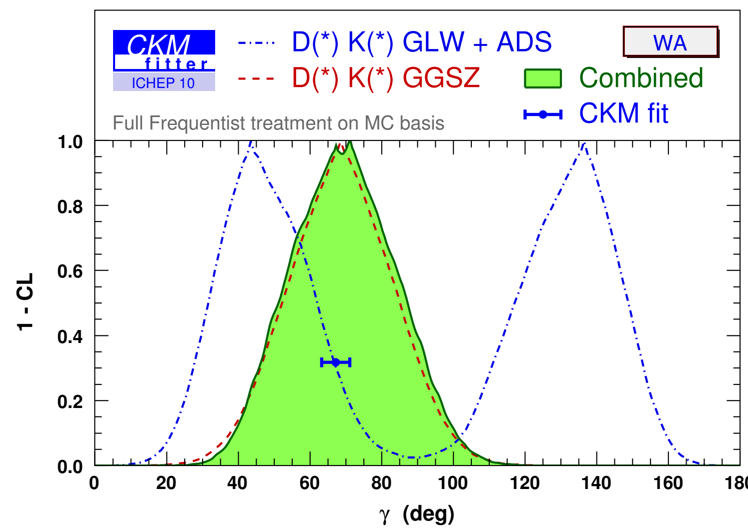
- If no NP is seen in flavor sector, similar constraints as LEP tests of gauge sector

- If non-SM flavor physics is seen, try to distinguish between classes of models:
  - One / many sources of CPV?
  - In charged / neutral currents?
  - Modify SM operators / new operators?
  - Couples to up / down sector?
  - To 3rd / all generations?
  - Quarks / leptons / other sectors?

$\sin 2\beta_{\text{eff}}, \alpha, \gamma$ — large improvements possible







- E.g., $S_{\psi K} - S_{\phi K} = 0.23 \pm 0.17$; also for α & γ: want $\sim 10\times$ smaller error $\Rightarrow \sim 100\times$ more data
- Need both LHCb and e^+e^- super-B/KEKB

Many interesting processes

- Complementarity of pp and e^+e^- B factories
- Some of the theoretically cleanest modes (ν, τ, inclusive) only possible at e^+e^-
- Many modes first seen at super-(KEK-)B or LHCb

Observable	Approximate SM prediction	Present status	Uncertainty / number of events Super-B (50 ab^{-1})	LHCb (10 fb^{-1})
$S_{\psi K}$	input	0.671 ± 0.024	0.005	0.01
$S_{\phi K}$	$S_{\psi K}$	0.44 ± 0.18	0.03	0.1
$S_{\eta' K}$	$S_{\psi K}$	0.59 ± 0.07	0.02	not studied
$\alpha(\pi\pi, \rho\rho, \rho\pi)$	α	$(89 \pm 4)^\circ$	2°	4°
$\gamma(DK)$	γ	$(70^{+27}_{-30})^\circ$	2°	3°
$S_{K^*\gamma}$	few $\times$ 0.01	-0.16 ± 0.22	0.03	—
$S_{B_s \to \phi\gamma}$	few $\times$ 0.01	—	—	0.05
$\beta_s(B_s \to \psi\phi)$	1°	$(22^{+10}_{-8})^\circ$	—	0.3°
$\beta_s(B_s \to \phi\phi)$	1°	—	—	1.5°
$A^d_{\rm SL}$	-5×10^{-4}	$-(5.8 \pm 3.4) \times 10^{-3}$	10^{-3}	10^{-3}
$A^s_{\rm SL}$	2×10^{-5}	$(1.6 \pm 8.5) \times 10^{-3}$	$\Upsilon(5S)$ run?	10^{-3}
$A_{CP}(b \to s\gamma)$	< 0.01	-0.012 ± 0.028	0.005	—
$\lvert V_{cb} \rvert$	input	$(41.2 \pm 1.1) \times 10^{-3}$	1%	—
$\lvert V_{ub} \rvert$	input	$(3.93 \pm 0.36) \times 10^{-3}$	4%	—
$B \to X_s\gamma$	3.2×10^{-4}	$(3.52 \pm 0.25) \times 10^{-4}$	4%	—
$B \to \tau\nu$	1×10^{-4}	$(1.73 \pm 0.35) \times 10^{-4}$	5%	—
$B \to X_s\nu\bar\nu$	3×10^{-5}	$< 6.4 \times 10^{-4}$	only $K\nu\bar\nu$?	—
$B \to X_s\ell^+\ell^-$	6×10^{-6}	$(4.5 \pm 1.0) \times 10^{-6}$	6%	not studied
$B_s \to \tau^+\tau^-$	1×10^{-6}	$<$ few %	$\Upsilon(5S)$ run?	—
$B \to X_s\tau^+\tau^-$	5×10^{-7}	$<$ few %	not studied	—
$B \to \mu\nu$	4×10^{-7}	$< 1.3 \times 10^{-6}$	6%	—
$B \to \tau^+\tau^-$	5×10^{-8}	$< 4.1 \times 10^{-3}$	$\mathcal{O}(10^{-4})$	—
$B_s \to \mu^+\mu^-$	3×10^{-9}	$< 5 \times 10^{-8}$	—	$> 5\sigma$ in SM
$B \to \mu^+\mu^-$	1×10^{-10}	$< 1.5 \times 10^{-8}$	$< 7 \times 10^{-9}$	not studied
$B \to K^*\ell^+\ell^-$	1×10^{-6}	$(1 \pm 0.1) \times 10^{-6}$	15k	36k
$B \to K\nu\bar\nu$	4×10^{-6}	$< 1.4 \times 10^{-5}$	20%	—

[Grossman, ZL, Nir, arXiv:0904.4262]

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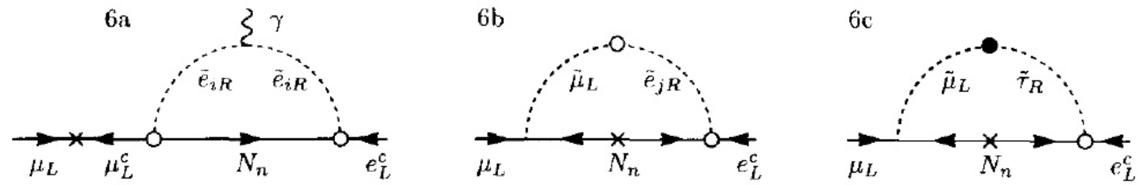
Lepton flavor violation (in τ decays)

- $\mu \to e\gamma$ vs. $\tau \to \mu\gamma$ (few $\times\, 10^{-9}$)

  Very large model dependence

  $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma) \sim 10^{3\pm 2}$



  In many models best bet is $\mu \to e\gamma$, but there are lots of exceptions

- $\tau^- \to \ell_1^- \ell_2^- \ell_3^+$ (few $\times\, 10^{-10}$) vs. $\tau \to \mu\gamma$

  Consider operators: $\bar\tau_R \sigma_{\alpha\beta} F^{\alpha\beta} \mu_L,\ (\bar\tau_L \gamma^\alpha \mu_L)(\bar\mu_L \gamma_\alpha \mu_L)$

  Suppression by $\alpha_{\rm em}$ opposite in two cases $\Rightarrow$ model dependent which process gives the best sensitivity

Super B sensitivity with $75\,\text{ab}^{-1}$

Process	Sensitivity
$\mathcal{B}(\tau \to \mu\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\,\mu\,\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}

- $\mu \to e\gamma$ and $(g-2)_\mu$ operators are very similar: $\dfrac{m_\mu}{\Lambda^2}\, \bar\mu \sigma_{\alpha\beta} F^{\alpha\beta} e\,, \quad \dfrac{m_\mu}{\Lambda^2}\, \bar\mu \sigma_{\alpha\beta} F^{\alpha\beta} \mu$

  If coefficients comparable, $\mu \to e\gamma$ gives much stronger bound

  If $(g-2)_\mu$ is due to NP, large hierarchy of coefficients ($\Rightarrow$ model building lessons)

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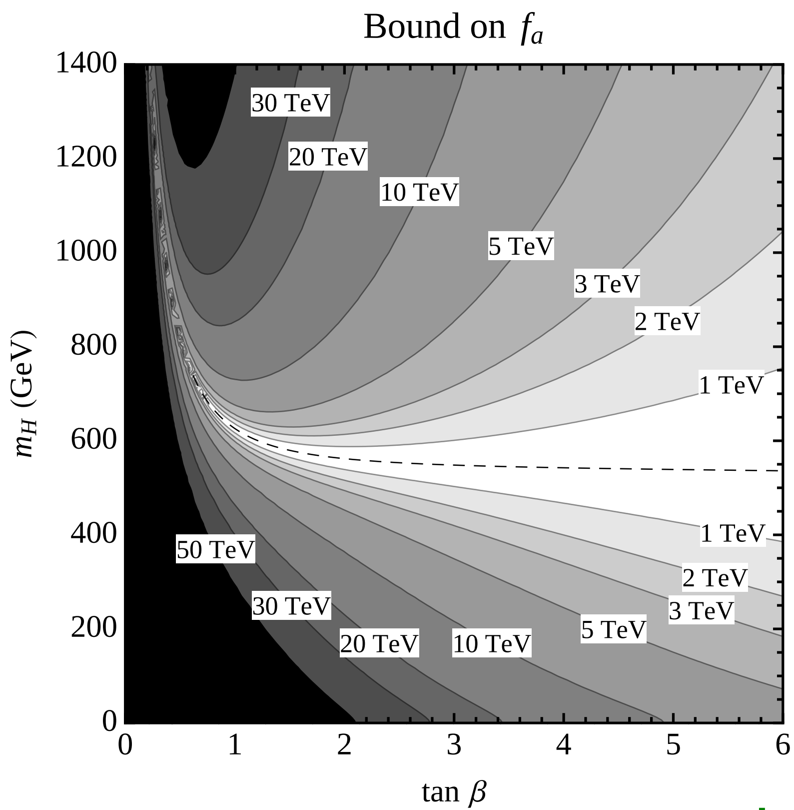
"Odd" searches: probe DM models with B decays

- Recent observations of cosmic ray excesses lead to flurry DM model building

  E.g., "axion portal": light ($\lesssim 1\,\mathrm{GeV}$) scalar particle coupling as $(m_\psi/f_a)\,\bar\psi\gamma_5\psi\,a$



[Freytsis, ZL, Thaler, 0911.5355]

[see also: Batell, Pospelov, Ritz, 0911.4938]

- Best bound in most of parameter space is from $B \to K\ell^+\ell^-$; can be improved

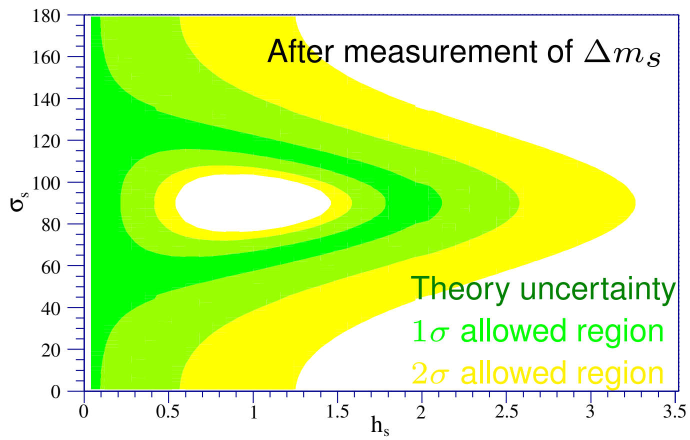
A super(-KEK)-B best buy list

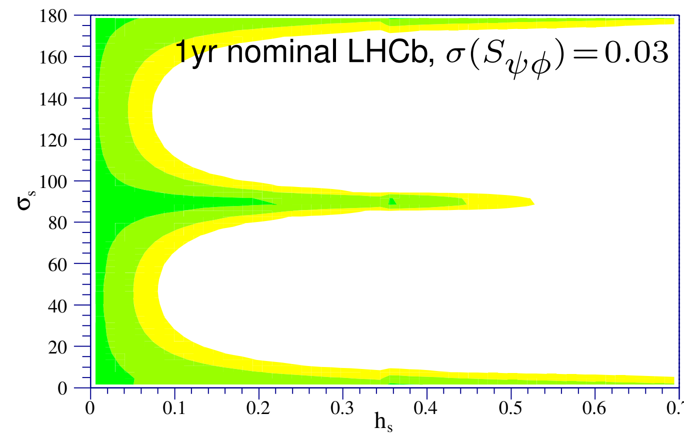
- Want observables: (i) sensitive to different NP, (ii) measurements can improve by an order of magnitude, and (iii) not limited by hadronic uncertainties:
  - Difference of CP asymmetries, $S_{\psi K_S} - S_{\phi K_S}$
  - γ from CP asymmetries in tree-level decays vs. γ from $S_{\psi K_S}$ and $\Delta m_d/\Delta m_s$
  - 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, $S_{K^*\gamma}$
  - Rare decay searches and refinements: $b \to s\nu\bar{\nu}$, $B \to \tau\bar{\nu}$, etc.
- Complementary to LHCb
- Any one of these measurements has the potential to establish new physics

An LHCb best buy list

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

  [We may approach the “MFV limit” sooner for B_s than B_d mixing]





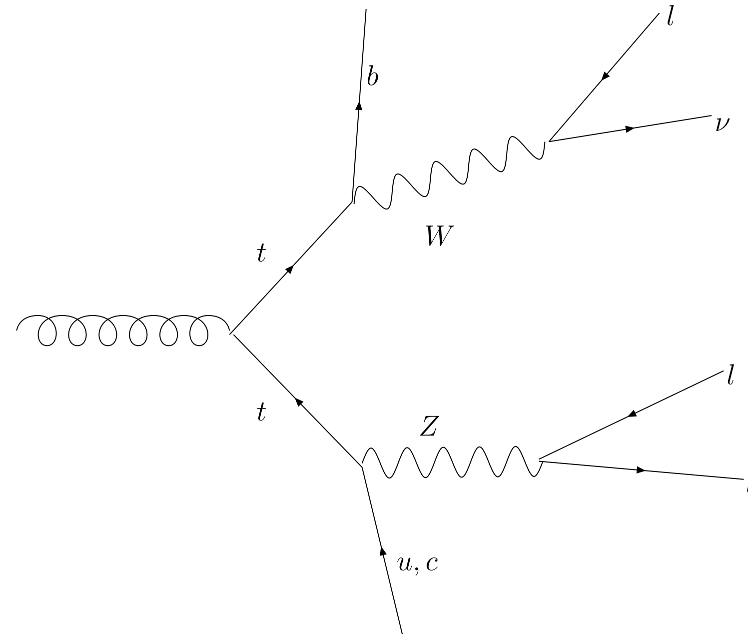
[ZL, Papucci, Perez, hep-ph/0604112]

- 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)

Flavor @ high p_T

FCNC top decays at the LHC?

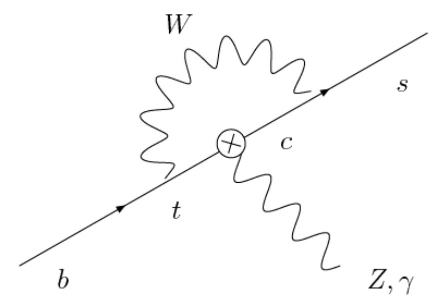
- Flavor violation in top decays not well explored
  SM $\sim 10^{-13}$, current bound $> 10^{-2}$



- Observable top FCNC possible in extensions of the SM and still allowed by B-factory constraints
  [Fox, ZL, Papucci, Perez, Schwartz, arXiv:0704.1482]

- LHC: $1\, t\bar{t}$ pair / sec $\Rightarrow$ sensitivity $\lesssim 10^{-5}$

- Indirect constraints: $t_L \leftrightarrow b_L$ — tight bounds from B decays
  Top FCNC's could affect other observables
  Strong bounds on operators with left-handed fields
  Right-handed operators could give rise to LHC signals



- If top FCNC is seen, LHC & B factories will both probe the NP responsible for it

Constraints on top FCNC operators

- SM + dimension-6 $SU(2)\times U(1)$ invariant operators (e.g., $O^u_{RR} = i\,\bar{t}_R\gamma^\mu c_R[H^\dagger D_\mu H]$)

  Assume a valid perturbative expansion in v/Λ; consider all bounds

	C^u_{LL}	C^h_{LL}	C^w_{RL}	C^b_{RL}	C^w_{LR}	C^b_{LR}	C^u_{RR}
direct bound	9.0	9.0	6.3	6.3	6.3	6.3	9.0
LHC sensitivity	0.20	0.20	0.15	0.15	0.15	0.15	0.20
$B\to X_s\gamma,\ X_s\ell^+\ell^-$	$[-0.07,\ 0.036]$	$[-0.017,\ -0.01]$ $[-0.005,\ 0.003]$	$[-0.09, 0.18]$	$[-0.12, 0.24]$	$[-14, 7]$	$[-10, 19]$	—
$\Delta F=2$	0.07	0.014	0.14	—	—	—	—
semileptonic	—	—	—	—	$[0.3, 1.7]$	—	—
best bound	0.07	0.014	0.15	0.24	1.7	6.3	9.0
Λ for $C_i=1$ (min)	3.9 TeV	8.3 TeV	2.6 TeV	2.0 TeV	0.8 TeV	0.4 TeV	0.3 TeV
$\mathcal{B}(t\to cZ)$ (max)	7.1×10^{-6}	3.5×10^{-7}	3.4×10^{-5}	8.4×10^{-6}	4.5×10^{-3}	5.6×10^{-3}	0.14
$\mathcal{B}(t\to c\gamma)$ (max)	—	—	1.8×10^{-5}	4.8×10^{-5}	2.3×10^{-3}	3.2×10^{-2}	—
LHC Window	Closed*	Closed*	Ajar	Ajar	Open	Open	Open

[Fox, ZL, Papucci, Perez, Schwartz, arXiv:0704.1482]

- B factory data constrain some of the operators beyond the LHC reach
- If top FCNC seen, LHC & B factories together can probe the NP responsible for it

Supersymmetry and flavor at the LHC

- After the LHC discovers new particles (and the champagne is gone):

  What are their properties: mass, decay modes, spin, production cross section?

- My prejudice: I hope the LHC will discover something unexpected
  Of the known scenarios, supersymmetry may be the most interesting

  – How is supersymmetry broken?
  – How is SUSY breaking mediated to MSSM?
  – Predict soft SUSY breaking terms?

- Details of interactions of new particles with quarks and leptons will be important to understand underlying physics

- Does flavor matter at ATLAS & CMS? Can we probe Sflavor directly at high p_T?

Flavor effects at the TeV scale

- Does flavor matter? Can we access flavor at high p_T?
- Some flavor aspects of LHC:
  - $p = g + u, d, s, c, b, \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}$ — has flavor
  - Hard to bound flavor properties of new particles (e.g., $Z' \to b\bar{b}$ vs. $Z' \to b\bar{s}$?)
  - Little particle ID: b (displaced vertex), t (which p_T range?), and all the others
- Flavor data the LHC can give us:
  - Spectrum (degeneracies) which mass splittings can be probed?
  - Information on some (dominant?) decay widths
  - Production cross sections
- As in QCD, spectroscopy can give dynamical information

Detection of SUSY particles

- At each vertex two supersymmetric particles

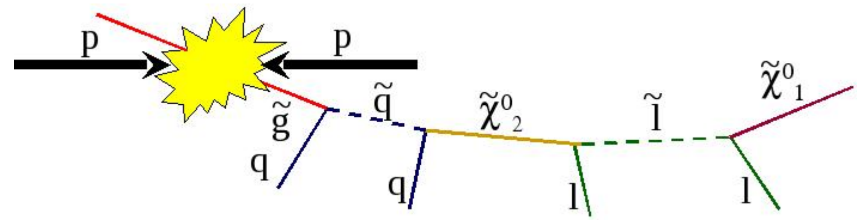
  Lightest SUSY particle (LSP) undetected

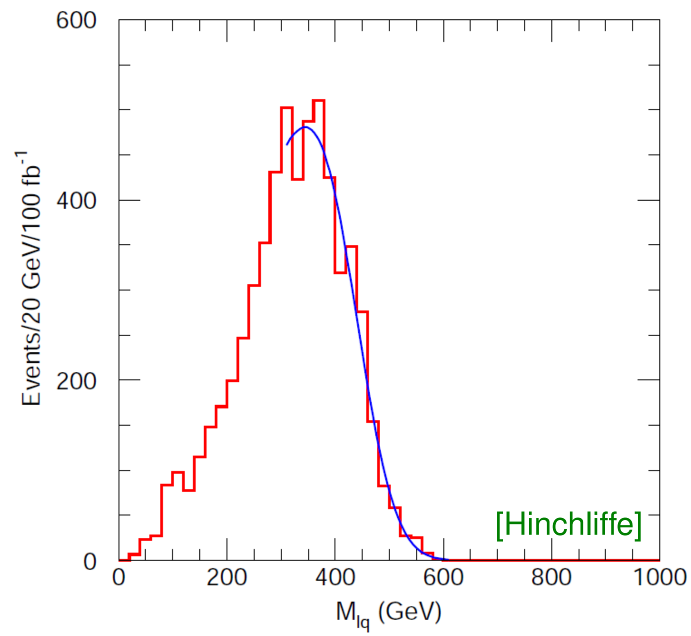
- Reconstruct masses via kinematic endpoints

- Most experimental studies use reference points which set flavor (i.e., generation) off-diagonal rates to zero (and $\tilde{m}_1^2 = \tilde{m}_2^2 \neq \tilde{m}_3^2$)

- Some off-diagonal rates can still be $\sim 20\%$ or more, consistent with all low energy data

  [E.g.: Hurth & Porod, hep-ph/0311075]





- Flavor can complicate determination of sparticle masses from cascade decays

  ... can modify the discovery potential of some particles

Recent trends: flavorful SUSY models

- Emerging non-MFV models w/ interesting flavor structure, consistent with all data

  Many studies over the last year (and in progress), mostly based on SUSY

- "Dilute" (but not completely eliminate) SUSY flavor violation with
  - mixed gauge / gravity mediated SUSY breaking [Feng *et al.*; Nomura, Papucci, Stolarski; Hiller *et al.*]
  - heavy Dirac gaugino masses (going beyond the MSSM) [Kribs, Poppitz, Weiner]

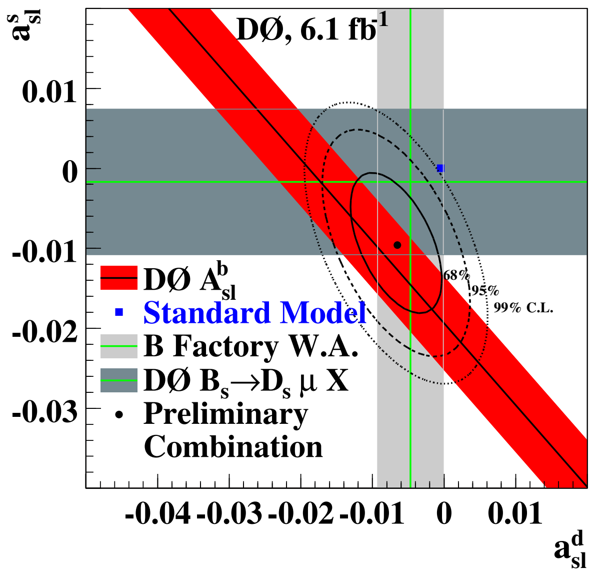
- Emerging themes:
  - Viable model space $\gg$ often thought; sizable flavor non-universalities possible
  - Easier to tag lepton than quark flavor $\Rightarrow$ slepton sflavor violation probably more accessible than squark sflavor violation

- Slepton spectrum and branching ratios may contain useful info on flavor physics

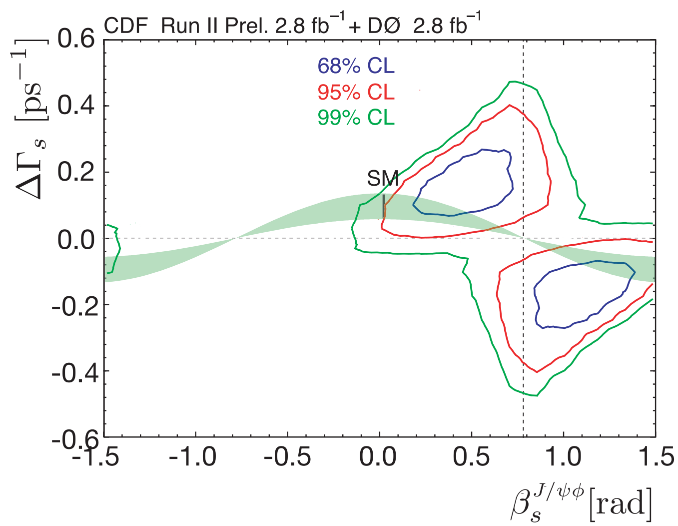
Final comments

Anomalies on the watch list

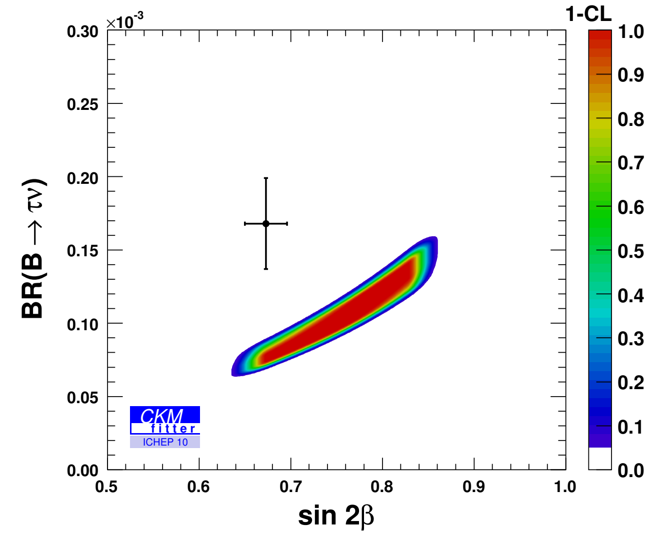
- $A_{\rm SL}$ — CP violation in $B_{d,s}$ mixing: $\sim 3\sigma$



- 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 many other measurements where improved experimental sensitivity could unambiguously establish non-SM physics

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Conclusions

- Consistency of precision flavor measurements with SM is a problem for NP @ TeV
  However, NP in most FCNC processes may still be $> 10\%$ of the SM contributions
- Few hints of discrepancies — existing data could have shown new physics, compelling reasons to want a lot more data (theoretical uncertainties won't be limiting)
- Low energy tests will improve a lot in next decade, by 10–1000 in some channels
  Exploring influence of NP requires LHCb, super-B factory, K, lepton flavor viol.
- If new particles are discovered, their flavor properties can teach us about $\gg \mathrm{TeV}$
  masses (degeneracies), decay rates (flavor decomposition), cross sections
  Will also make interpretation of low energy data a whole new game
- Expect exciting synergies between high-p_T LHC and low energy flavor physics

Backup slides

Parameterization of NP in mixing

- Assume: (i) 3×3 CKM matrix is unitary; (ii) Tree-level decays dominated by SM

  NP in mixing — two new param's for each neutral meson:

$$M_{12} = \underbrace{M_{12}^{\rm SM}\, r_q^2\, e^{2i\theta_q}}_{\text{easy to relate to data}} \equiv \underbrace{M_{12}^{\rm SM}(1 + h_q\, e^{2i\sigma_q})}_{\text{easy to relate to models}}$$

- Observables sensitive to $\Delta F = 2$ new physics:

$$\Delta m_{B_q} = r_q^2\, \Delta m_{B_q}^{\rm SM} = |1 + h_q e^{2i\sigma_q}| \Delta m_q^{\rm SM}$$

$$S_{\psi K} = \sin(2\beta + 2\theta_d) = \sin[2\beta + \arg(1 + h_d e^{2i\sigma_d})]$$

$$S_{\rho\rho} = \sin(2\alpha - 2\theta_d)$$

$$S_{B_s \to \psi\phi} = \sin(2\beta_s - 2\theta_s) = \sin[2\beta_s - \arg(1 + h_s e^{2i\sigma_s})]$$

$$A_{\rm SL}^q = {\rm Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q r_q^2\, e^{2i\theta_q}}\right) = {\rm Im}\left[\frac{\Gamma_{12}^q}{M_{12}^q (1 + h_q e^{2i\sigma_q})}\right]$$

$$\Delta\Gamma_s^{CP} = \Delta\Gamma_s^{\rm SM} \cos^2(2\theta_s) = \Delta\Gamma_s^{\rm SM} \cos^2[\arg(1 + h_s e^{2i\sigma_s})]$$

- Tree-level constraints unaffected: $|V_{ub}/V_{cb}|$ and γ (or $\pi - \beta - \alpha$)

Neutral meson mixings

- Identities, neglecting CPV in mixing (not too important, surprisingly poorly known)

$$K\text{: long-lived} = CP\text{-odd} = \text{heavy}$$

$$D\text{: long-lived} = CP\text{-odd } (3.5\sigma) = \text{light } (2\sigma)$$

$$B_s\text{: long-lived} = CP\text{-odd } (1.5\sigma) = \text{heavy in the SM}$$

$$B_d\text{: yet unknown, same as } B_s \text{ in SM for } m_b \gg \Lambda_{\rm QCD}$$

Before 2006, we only knew experimentally the kaon line above

- We have learned a lot about meson mixings — good consistency with SM

	$x = \Delta m/\Gamma$ SM theory	$x = \Delta m/\Gamma$ data	$y = \Delta\Gamma/(2\Gamma)$ SM theory	$y = \Delta\Gamma/(2\Gamma)$ data	$A = 1 - \lvert q/p\rvert^2$ SM theory	$A = 1 - \lvert q/p\rvert^2$ data
B_d	$\mathcal{O}(1)$	0.78	$y_s\,\lvert V_{td}/V_{ts}\rvert^2$	-0.005 ± 0.019	$-(5.5 \pm 1.5)10^{-4}$	$(-4.7 \pm 4.6)10^{-3}$
B_s	$x_d\,\lvert V_{ts}/V_{td}\rvert^2$	25.8	$\mathcal{O}(-0.1)$	-0.05 ± 0.04	$-A_d\,\lvert V_{td}/V_{ts}\rvert^2$	$(0.3 \pm 9.3)10^{-3}$
K	$\mathcal{O}(1)$	0.948	-1	-0.998	$4\,\mathrm{Re}\,\epsilon$	$(6.6 \pm 1.6)10^{-3}$
D	< 0.01	< 0.016	$\mathcal{O}(0.01)$	$y_{CP} = 0.011 \pm 0.003$	$< 10^{-4}$	$\mathcal{O}(1)$ bound only

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Some key CPV measurements

- β: $S_{\psi K_S} = -\sin[(B\text{-mix} = -2\beta) + (\text{decay} = 0) + (K\text{-mix} = 0)] = \sin 2\beta$

  World average: $\sin 2\beta = 0.673 \pm 0.023$ — 4% precision (theory uncertainty $< 1\%$)

- $S_{b\to s}$ "penguin" dominated modes: NP can enter in mixing (as $S_{\psi K}$), also in decay

  Earlier hints of deviations reduced: $S_{\psi K} - S_{\phi K_S} = 0.23 \pm 0.17$

- α: $S_{\pi^+\pi^-} = \sin[(B\text{-mix} = 2\beta) + (\overline{A}/A = 2\gamma + \ldots)] = \sin[2\alpha + \mathcal{O}(P/T)]$

  CLEO 1997: $K\pi$ large, $\pi\pi$ small $\Rightarrow$ $P_{\pi\pi}/T_{\pi\pi}$ large $\Rightarrow$ pursue all $\rho\rho$, $\rho\pi$, $\pi\pi$ modes

- γ: interference of tree level $b \to c\bar{u}s$ $(B^- \to D^0 K^-)$ and $b \to u\bar{c}s$ $(B^- \to \overline{D}^0 K^-)$

  Several difficult measurements ($D \to K_S\pi^+\pi^-$, D_{CP}, CF vs. DCS)

- Need a lot more data to approach irreducible theoretical limitations

Recent trends: (i) minimal flavor violation

- MFV: a class of models which solves the NP flavor puzzle (GMSB, mSUGRA, ...)

  Assume SM Yukawas are only source of flavor and CP violation (cannot demand all higher dimension operators to be flavor invariant and contain only SM fields)

- Spectra: $y_{u,d,s,c} \ll 1$, so first two generation squarks are quasi-degenerate

  Mixing: CKM $\Rightarrow$ new particles decay to 3rd or non-3rd generation quarks, not both

- CKM and GIM (m_q) suppressions similar to SM; allows EFT-like analyses

  Imposing MFV, best constraints from:

  $B \to X_s\gamma,\ B \to \tau\nu,\ B_s \to \mu^+\mu^-,\ \Delta m_{B_s},\ \Omega h^2,\ g-2$, precision electroweak

- Even with MFV and TeV-scale NP, expect $\%$ level deviations from SM in B, D, K

- In some scenarios high-p_T LHC data may rule out MFV or make it more plausible

Flavor parameters in the SM

- Nonzero Yukawa couplings break flavor symmetries — masses and mixings are determined by the interactions of fermions with the Higgs background

- Quark sector: $U(3)_Q \times U(3)_u \times U(3)_d \to U(1)$ quark (baryon) number

$$[36 \text{ couplings}] - [26 \text{ broken symmetries}] = 10 \text{ parameters with physical meaning}$$
$$= [6 \text{ masses}] + \overbrace{[3 \text{ angles}] + \underbrace{[1 \text{ phase}]}_{\text{Single source of } CP \text{ violation in the quark sector in the SM}}}^{\text{parameters in } V_{\text{CKM}}}$$

- Lepton sector (Majorana ν's): $\mathcal{L}_Y = -Y_e^{ij}\, \overline{L_{Li}^I}\, \phi\, e_{Rj}^I - \dfrac{Y_\nu^{ij}}{M}\, L_{Li}^I L_{Lj}^I\, \phi\, \phi \qquad (Y_\nu^{ij} = Y_\nu^{ji})$

  $U(3)_L \times U(3)_e$ completely broken

$$[30 \text{ couplings}] - [18 \text{ broken symmetries}] = 12 \text{ parameters with physical meaning}$$
$$= [6 \text{ masses}] + [3 \text{ angles}] + \underbrace{[3\text{CPV phases}]}_{\text{One CPV phase measurable in } \nu \text{ oscillations, others in } 0\nu\beta\beta \text{ decay}}$$

Parameters of the MSSM

- Superpotential: [Haber, hep-ph/9709450]

$$W = \sum_{i,j} \left(Y^u_{ij} H_u \, Q_{Li} \bar{U}_{Lj} + Y^d_{ij} H_d \, Q_{Li} \bar{D}_{Lj} + Y^\ell_{ij} H_d \, L_{Li} \bar{E}_{Lj} \right) + \mu H_u H_d$$

- Soft SUSY breaking terms: $(S = \tilde{Q}_L, \tilde{\bar{D}}_L, \tilde{\bar{U}}_L, \tilde{L}_L, \tilde{\bar{E}}_L)$

$$\mathcal{L}_{\rm soft} = -\left(A^u_{ij} H_u \tilde{Q}_{Li} \tilde{\bar{U}}_{Lj} + A^d_{ij} H_d \tilde{Q}_{Li} \tilde{\bar{D}}_{Lj} + A^\ell_{ij} H_d \tilde{L}_{Li} \tilde{\bar{E}}_{Lj} + B H_u H_d \right)$$
$$- \sum_{\rm scalars} (m_S^2)_{ij} \, S_i \bar{S}_j - \frac{1}{2} \left(M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g} \tilde{g} \right)$$

$3 \; Y^f$ Yukawa and $3 \; A^f$ matrices — $6 \times (9$ real $+ \; 9$ imaginary) parameters

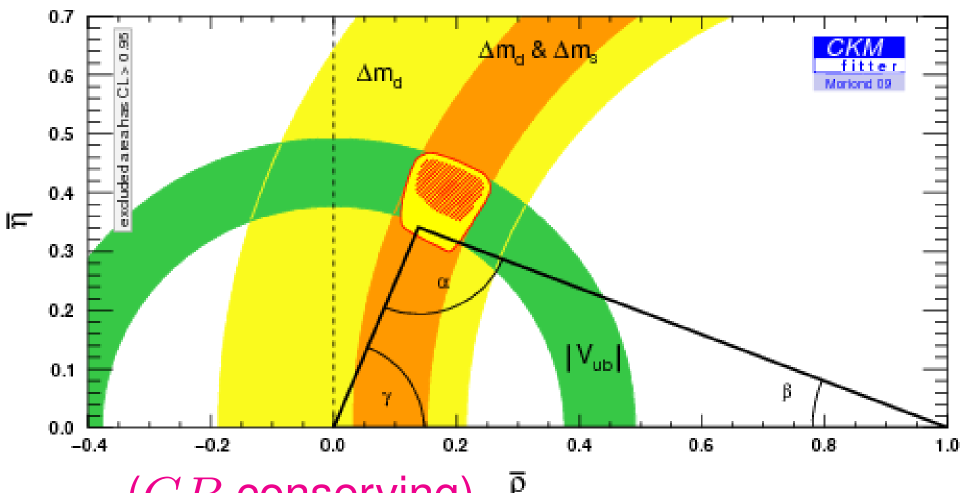
$5 \; m_S^2$ hermitian sfermion mass-squared matrices — $5 \times (6$ real $+ \; 3$ imag.) param's

Gauge and Higgs sectors: $g_{1,2,3}, \theta_{\rm QCD}, M_{1,2,3}, m^2_{h_{u,d}}, \mu, B$ — 11 real $+ \; 5$ imag.

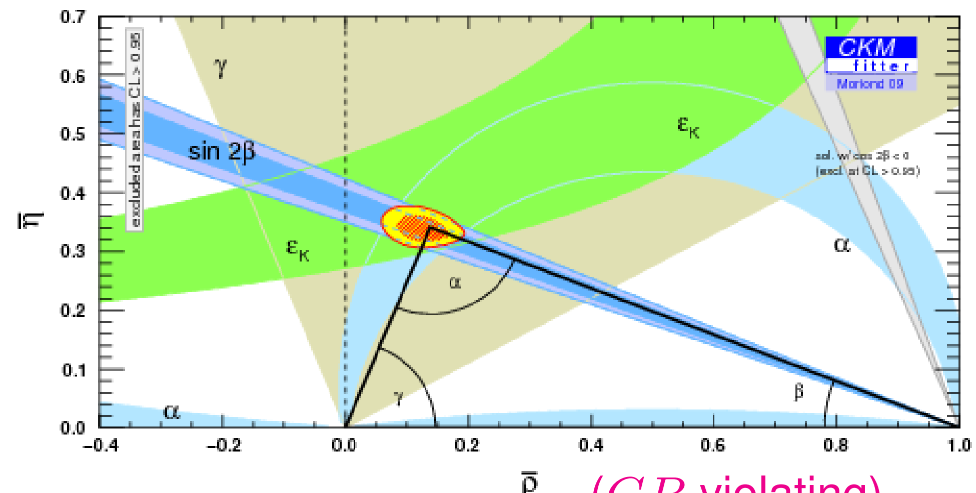
Parameters: $(95 + 74) - (15 + 30)$ from $U(3)^5 \times U(1)_{\rm PQ} \times U(1)_R \to U(1)_B \times U(1)_L$

- 44 CPV phases: CKM $+ \; 3$ in M_1, M_2, μ (set $\mu B^*, M_3$ real) $+ \; 40$ in mixing matrices of fermion-sfermion-gaugino couplings ($+80$ real param's)

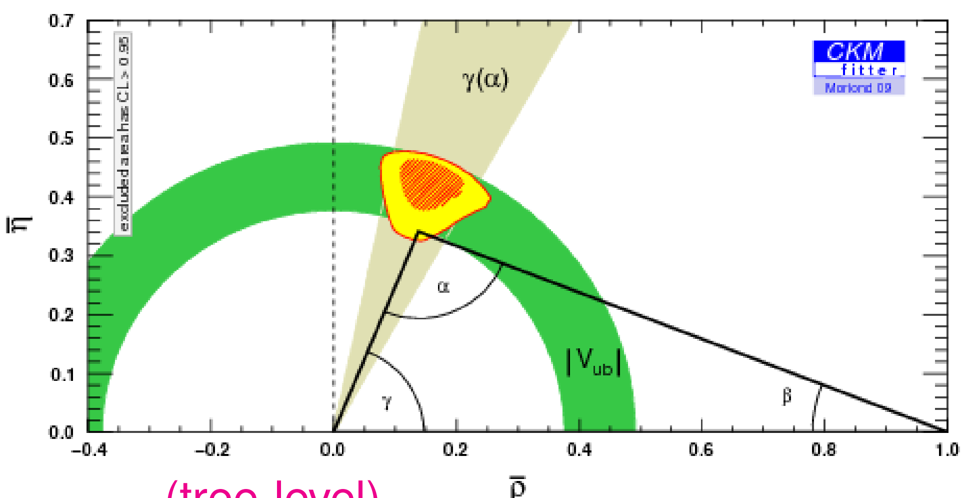
Overconstraining the standard model



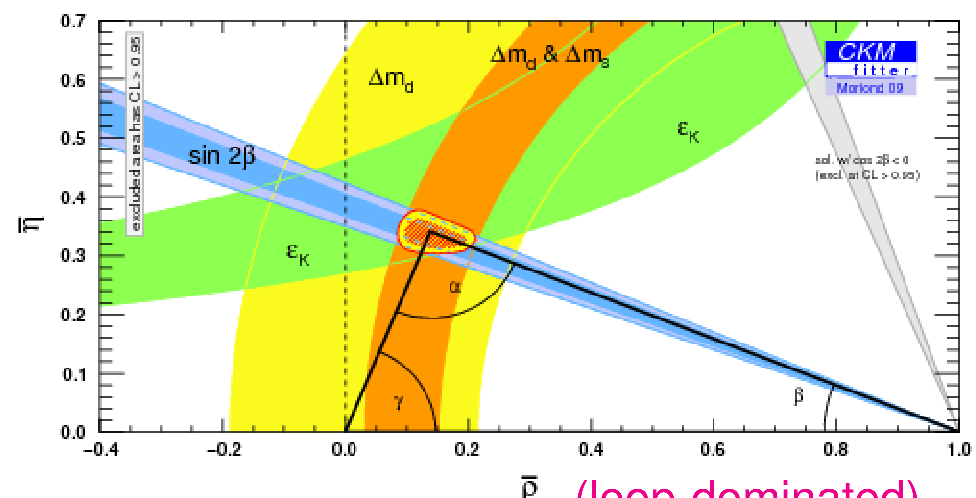
(CP conserving)



(CP violating)



(tree-level)



(loop-dominated)

- Consistent determinations from subsets of measurements $\Rightarrow$ bound extra terms

Theoretical limitations (continuum methods)

- Many important measurements are not theory limited even with $100\times$ current data

Measurement (in SM)	Theoretical limit	Present error
$B\to\psi K$ (β)	$\sim 0.2^\circ$	$\sim 1^\circ$
$B\to\eta' K,\ \phi K$ (β)	$\sim 2^\circ$	$\sim 5,\ 10^\circ$
$B\to\rho\rho,\ \rho\pi,\ \pi\pi$ (α)	$\sim 1^\circ$	$\sim 5^\circ$
$B\to DK$ (γ)	$\ll 1^\circ$	$\sim 15^\circ$
$B_s\to\psi\phi$ (β_s)	$\sim 0.2^\circ$	$\sim 10^\circ$
$B_s\to D_s K$ $(\gamma-2\beta_s)$	$\ll 1^\circ$	—
$\lvert V_{cb}\rvert$	$\sim 1\%$	$\sim 2\%$
$\lvert V_{ub}\rvert$	$\sim 5\%$	$\sim 10\%$
$B\to X_s\gamma$	$\sim 4\%$	$\sim 7\%$
$B\to X_s\ell^+\ell^-$	$\sim 5\%$	$\sim 25\%$
$B\to K^{(*)}\nu\bar\nu$	$\sim 5\%$	—
Many more, plus D and τ decays sensitive to new physics		

For some entries, the above theoretical limits require more complicated analyses

Theory will also improve: past breakthroughs motivated by data, lattice will help

Outlook

- Measurements sensitive to scales $> \mathrm{TeV}$; sensitivity limited by statistics

  The non-observation of NP at $E_{\rm exp} \sim m_B$ is a problem for NP at $\Lambda_{\rm NP} \sim \mathrm{TeV}$

  $\Rightarrow$ New physics could show up any time measurements improve

- If NP is seen: Study it in as many different operators as possible

  One / many sources of CPV? Only in CC interactions? NP couples mostly to up / down sector? 3rd / all generations? $\Delta(F) = 2$ or 1?

- If NP is not seen: Achieve what is theoretically possible

  Could teach us a lot whether or not NP is seen at LHC

- Flavor physics will provide important clues to model building in the LHC era

Looking for unknown unknowns[1]

- Will LHC see new particles beyond a Higgs?

  SUSY, something else, understand in detail?

- Will NP be seen in the quark sector?

  B_s: large $A^s_{\rm SL}$, β_s, or $B_s \to \mu^+\mu^-$?

  D: CPV in $D^0-\overline{D}^0$ mixing?

  B: Convergence in $|V_{ub}|$ extractions (incl., excl., $B \to \tau\nu$), in conflict with $\sin 2\beta$?

- Will NP be seen in the lepton sector?

  $\mu \to e\gamma$, $\mu \to eee$, $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$, ...?

- I don't know, but I would like to find it out...

[1]**unknown unknowns:**

"There are known knowns. There are things we know that we know.
There are known unknowns. That is to say, there are things that we now know we don't know.
But there are also unknown unknowns. There are things we do not know we don't know."

[Rumsfeld, DOD briefing, Feb 12, 2002]