Flavor physics in the LHC era

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- **Introduction**
- **Current status: sizable new physics allowed**
- **Some key probes at LHCb and super-(KEK-)B**
- **Flavor at high-p_T: top and new particles**
- **Conclusions**

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

Every end is a new beginning — transition era

- Past: Ten years ago we did not know that the CKM picture was (essentially) correct

  $\mathcal{O}(1)$ deviations / modifications were possible

- End: Nobel Prize in 2008 is formal recognition that the KM phase is the dominant source of CPV in flavor changing transitions of quarks

- Present: No significant deviations from SM

  $\mathcal{O}(1)$ effects in B_s FCNCs less and less viable

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: Kyodo/Reuters

Makoto Kobayashi

Photo: Kyoto University

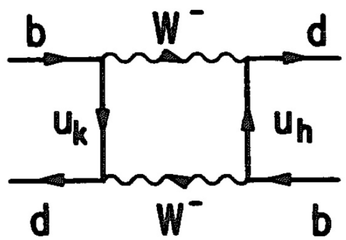
Toshihide Maskawa

- Begin: Looking for corrections to the SM picture of flavor and CP violation

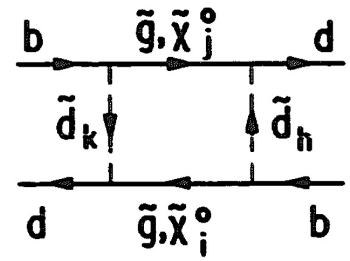
- Future: What can flavor physics teach us about BSM physics?

How to “see” virtual heavy particles

- Neutral meson mixing:

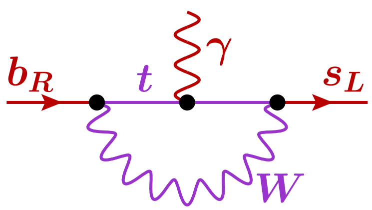


SM or (SM + NP)?

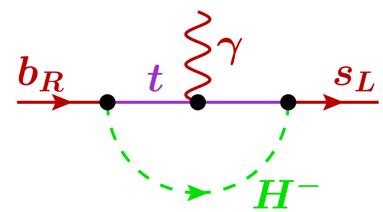


Simple parameterization for each neutral meson: $M_{12} = M_{12}^{\rm SM}\,(1 + h e^{2i\sigma})$

- Loop-dominated decays:



SM or (SM + NP)?



Many operators for $b \to s$ transitions — no simple parameterization of NP

To see NP, compare with predictions from SM tree-level decays (many measurements, precision)

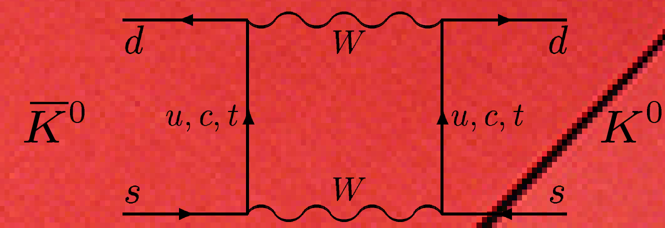
- New particles (even if much heavier than m_W, m_t) may have observable effects

May be the only way to see subleading couplings of new particles (like V_{ts}, V_{td}) [an example ⇒]

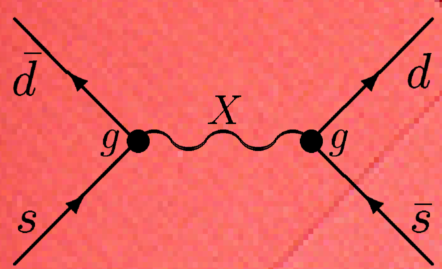
Back of an envelope calculation of Δm_K

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

  (severe suppressions!)



- Tree-level exchange of a hypothetical boson:



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

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

- New TeV-scale particles can have large contributions even in loops $(g\sim 0.01)$

- In many NP models, the Δm_K and ϵ_K constraints are the strongest, since so are the SM suppressions — these are built into the models since the 70's

Precision tests with kaons

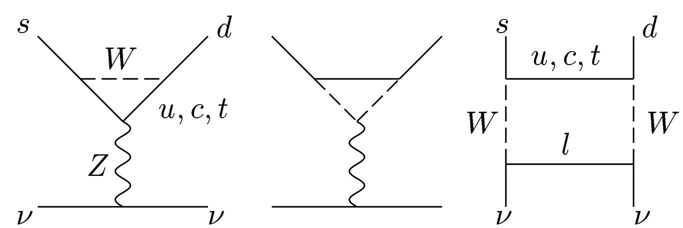
- CPV in K system is at the right level (ϵ_K accommodated with $\mathcal{O}(1)$ KM phase)
- Hadronic uncertainties preclude precision tests (ϵ'_K notoriously hard to calculate)

  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 $\mathcal{O}(1)$ uncertainty: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ [BNL E787/E949]

- Need much higher statistics for precision tests (another issue: rates $\propto A^4 \sim |V_{cb}|^4$)

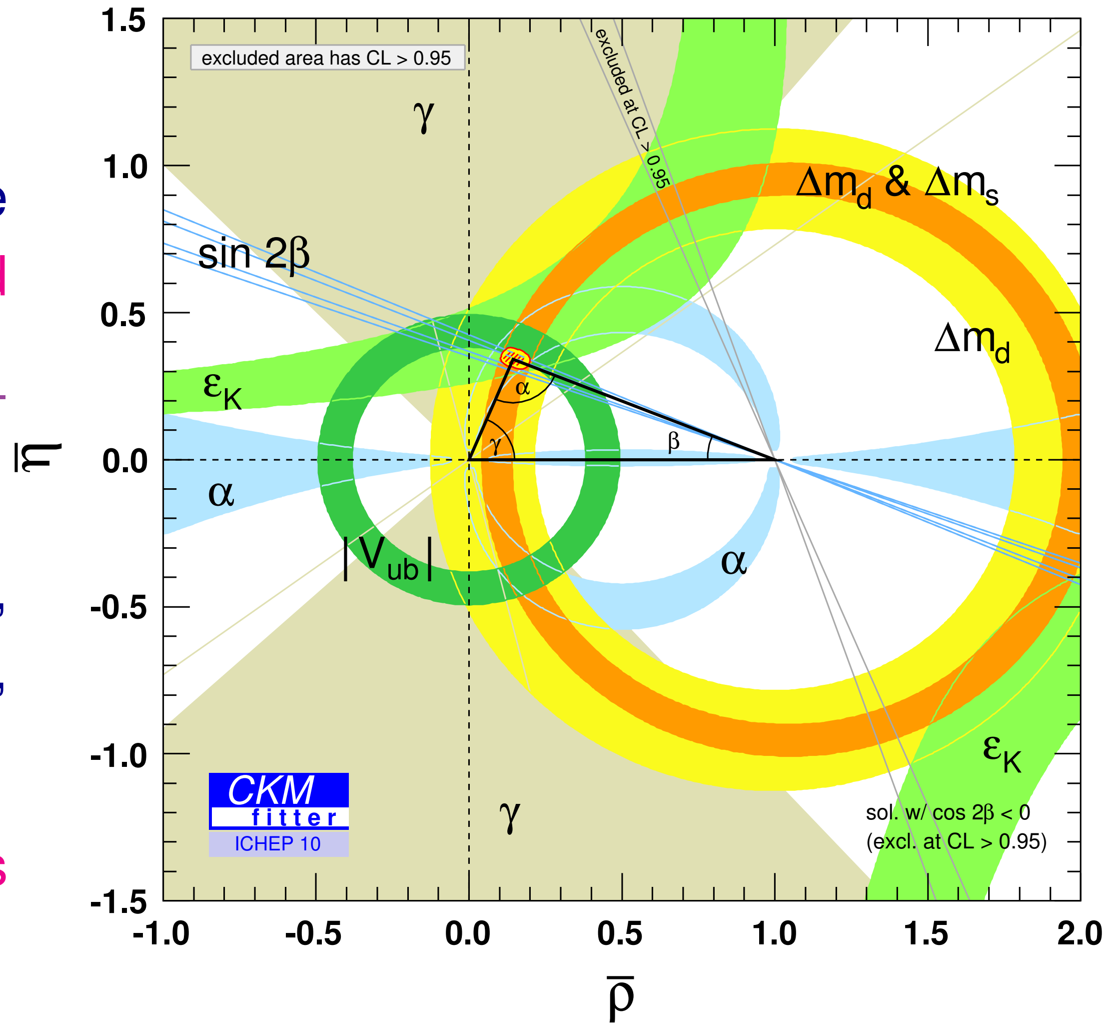
Spectacular track record

- Most parameters of the SM (and in many of its extensions) are related to flavor
- Flavor physics was crucial to develop the SM:
  - β-decay predicted neutrino (Pauli)
  - ϵ_K predicted 3rd generation (Kobayashi & Maskawa)
  - Absence of $K_L \to \mu\mu$ predicted charm (Glashow, Iliopoulos, Maiani)
  - Δm_K predicted m_c (Gaillard & Lee)
  - Δm_B predicted large m_t
- Flavor physics will be important to figure out $\mathcal{L}_{\rm LHC}$ as well
- 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 standard model CKM fit

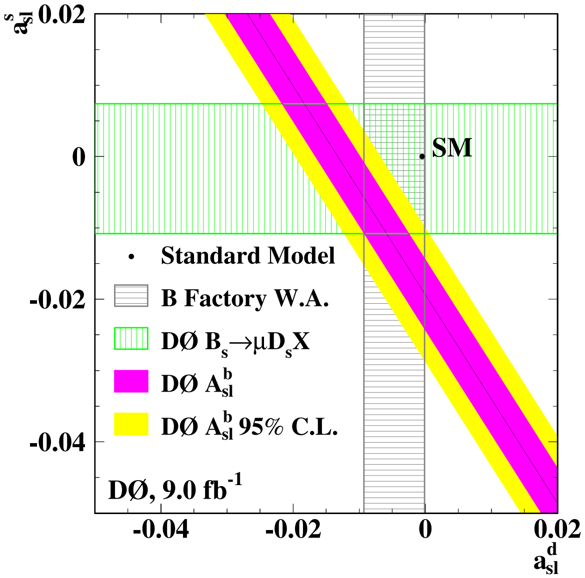
- Very impressive accomplishments
- The level of agreement between the measurements often misinterpreted
- Increasing the number of parameters can alter the fit completely
- Plausible TeV scale NP scenarios, consistent with all low energy data, with sizable flavor physics effects
- CKM is inevitable;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



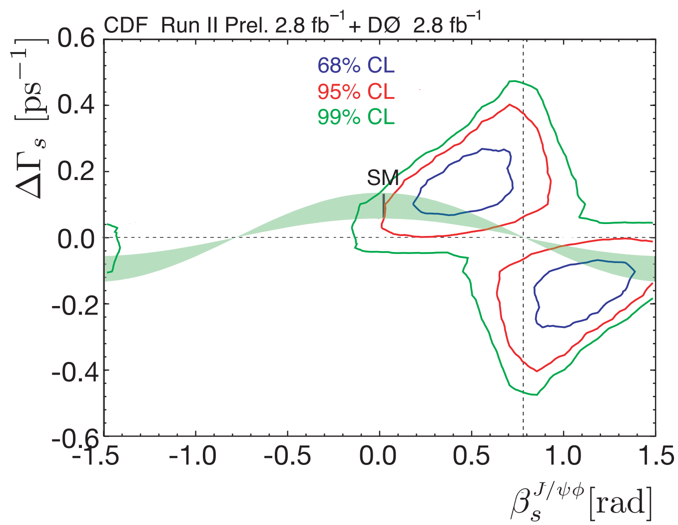
- Isolating small NP effects requires many measurements (compare tree / loop, etc.)

Intriguing anomalies — early 2011

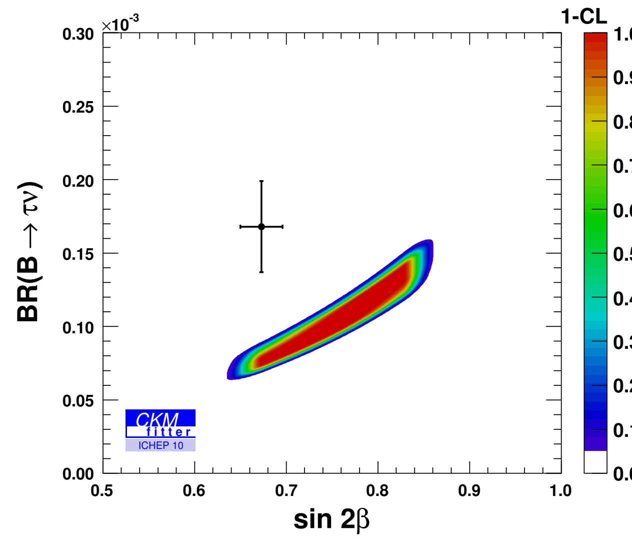
- $A_{\rm SL}$ — CP violation in $B_{d,s}$ mixing: $\sim 4\sigma$



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

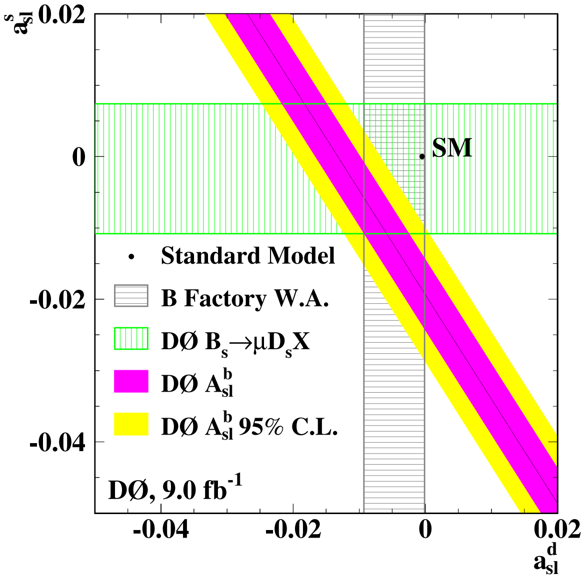


$\mathcal{B}(B \to \tau\nu)$ — above the SM prediction: $\sim 2.5\sigma$



Intriguing anomalies — late 2011

- $A_{\rm SL}$ — CP violation in $B_{d,s}$ mixing: $\sim 4\sigma$



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

LHCb consistent with SM

Most importantly, theory uncertainty $\ll$ measurement uncertainty

$\Rightarrow$ remains very important

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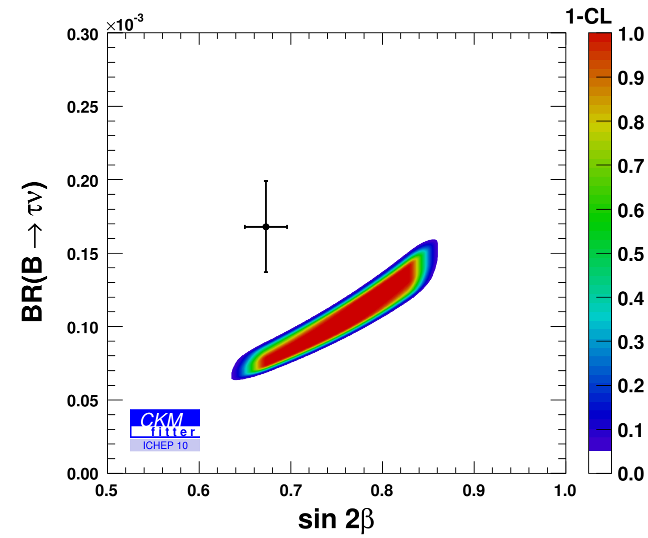


- $B \to K\pi$ CP asymmetries: theoretically less clean, but very puzzling (many "σ")

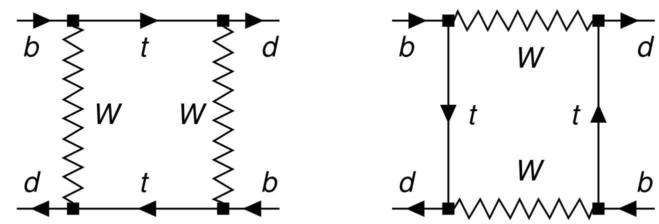
- Improved sensitivity can establish BSM physics in many other observables

As for Tevatron $t\bar{t}$ and Wjj anomalies, flavor properties will be important to understand what does (and what does not!) explain the high-p_T data

Differences between B and D mixing

- Evolution: $i\,\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|B^0(t)\rangle\\|\overline{B}^0(t)\rangle\end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix}|B^0(t)\rangle\\|\overline{B}^0(t)\rangle\end{pmatrix}$

  $M,\,\Gamma$: 2×2 Hermitian matrices



  Mass eigenstates: $|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$ $\quad |B_{H,L}(t)\rangle = e^{-(iM_{H,L}+\Gamma_{H,L}/2)t}\,|B_{H,L}\rangle$

- General solution for q/p:

$$\frac{q^2}{p^2} = \frac{2M_{12}^* - i\Gamma_{12}^*}{2M_{12} - i\Gamma_{12}}$$

- $B^0_{d,s}$: $|\Gamma_{12}| \ll |M_{12}|$ model independently, so $q/p = e^{iX}$ to a good approximation

  X determined by M_{12} (+ phase conventions) $\Rightarrow$ sensitive to NP

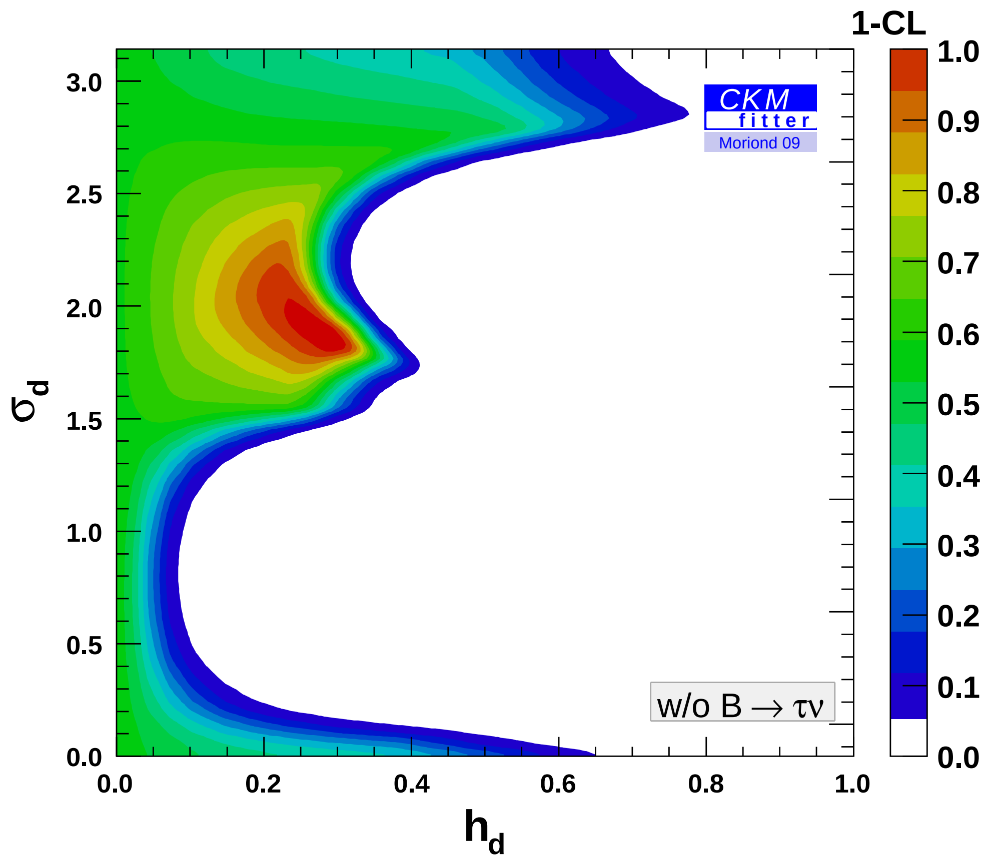
- D^0: $|\Gamma_{12}/M_{12}| = \mathcal{O}(1)$, so q/p depends on both Γ_{12} and M_{12}

- In the D^0 system, $|q/p| - 1$ is much less constrained than in B^0 and K^0 mixing

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

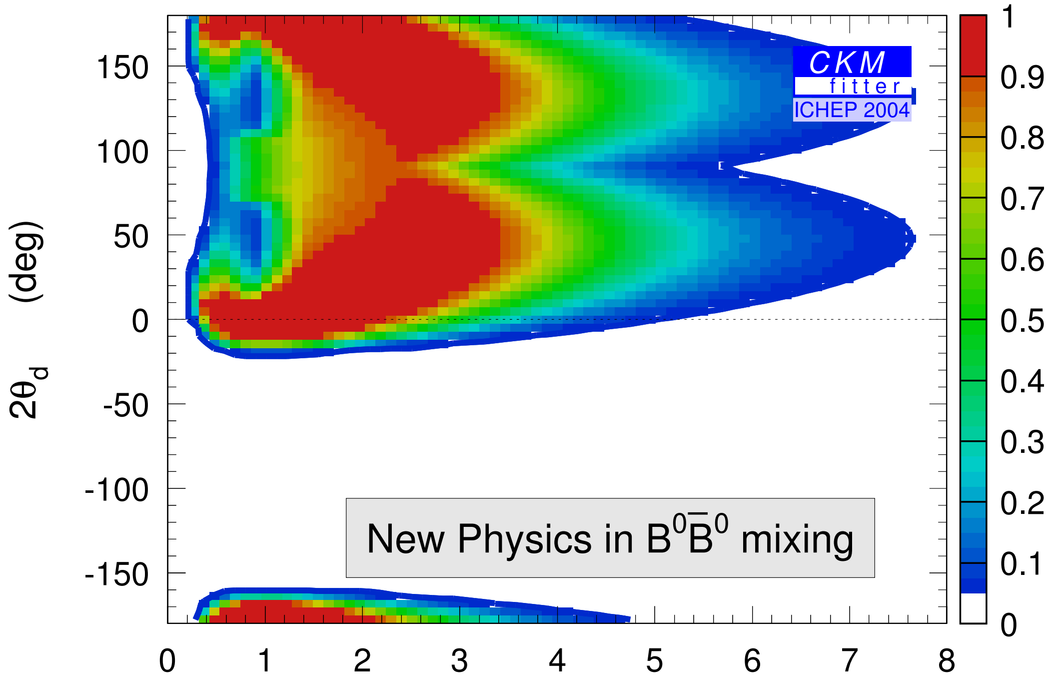
  Overconstraining measurements crucial

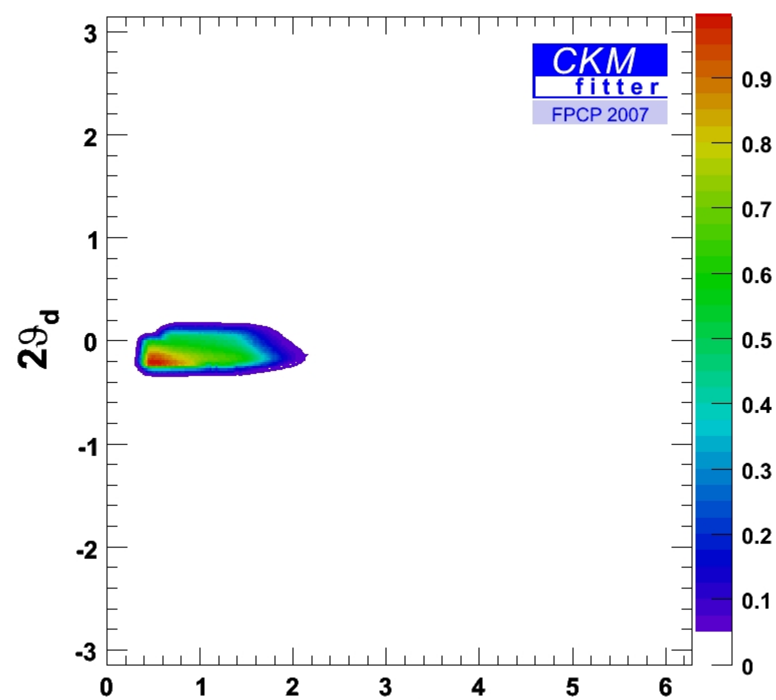
- Q: Is $\Lambda_{\rm flavor} \gg \Lambda_{\rm EWSB}$?
  Is NP $\ll$ SM unless $\sigma_d = 0$ (mod $\pi/2$)?

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

The one-page highlight of BaBar & Belle

- Strong bounds on new physics in many FCNC amplitudes (mixing, $B \to X_s\gamma$, etc.)
- Constrain (NP / SM) in $B^0 - \overline{B}^0$ mixing changed from < 10 to < 1, approaching $\ll 1$





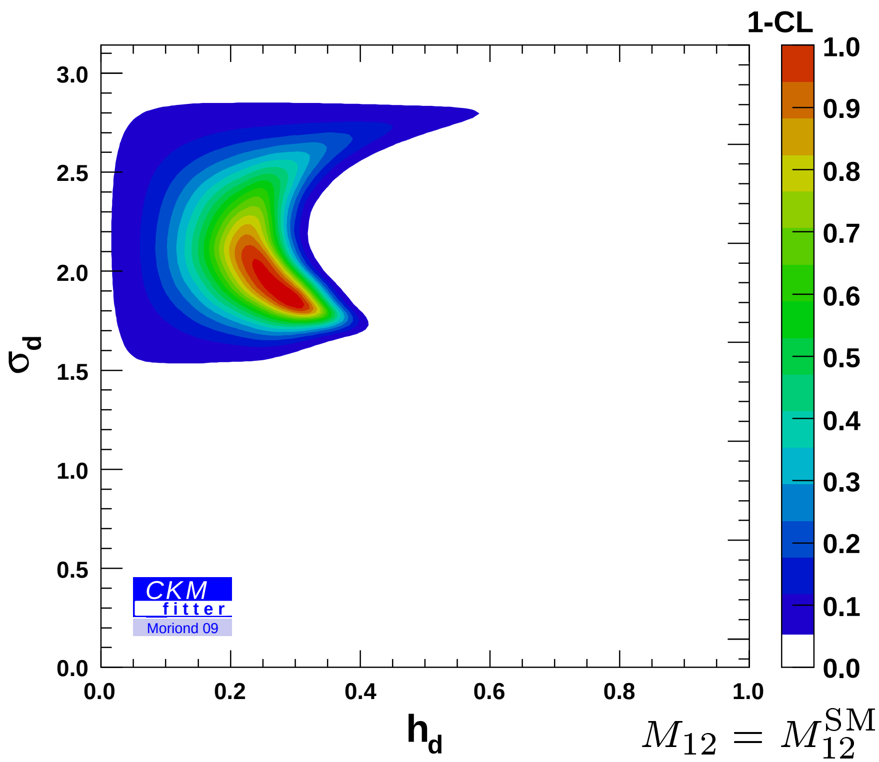
r_d^2 $\quad M_{12} = M_{12}^{\rm SM}\,(r_d\, e^{2i\theta_d}) = M_{12}^{\rm SM}\,(1 + h_d\, e^{2i\sigma_d})$ $\quad r_d^2$

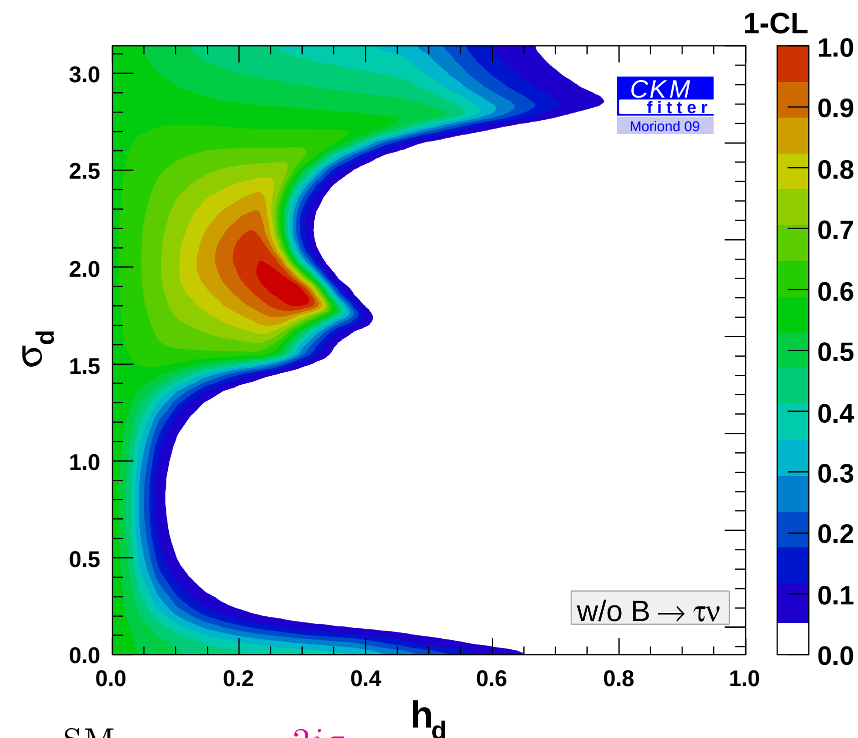
Qualitative change before vs. after 2004 — the main justification for the KM Nobel Prize

- $\mathcal{O}(20\%)$ NP contributions to most loop processes still possible; is $\Lambda_{\rm flavor} \gg \Lambda_{\rm weak}$?

B_d: does $B \to \tau\nu$ hint at BSM?

- One of the interesting tensions (I don't think ϵ_K is) — very hard measurement





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

- Tree-level measurements $|V_{xb}|$ and γ are crucial — need more data to be definitive

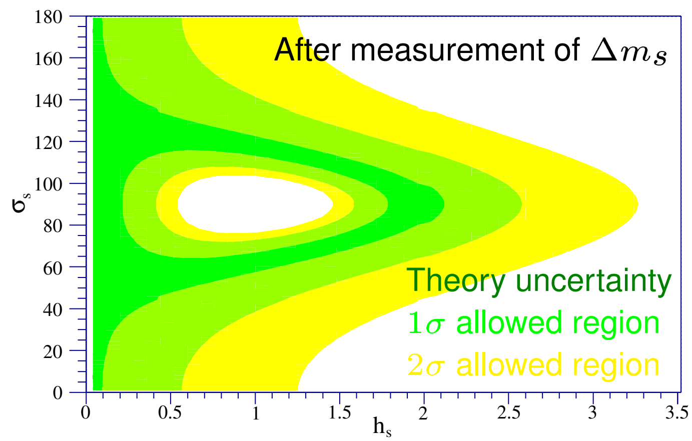
- Need precise γ measurement in order to substantially improve constraint on BSM

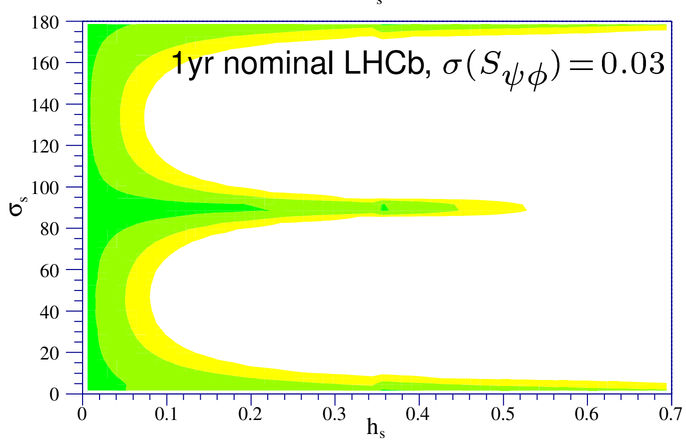
B_s: implication of $B_s \to \psi\phi$ for BSM

- Is B_s mixing different from B_d? We may approach the “BSM $\ll$ SM limit” faster

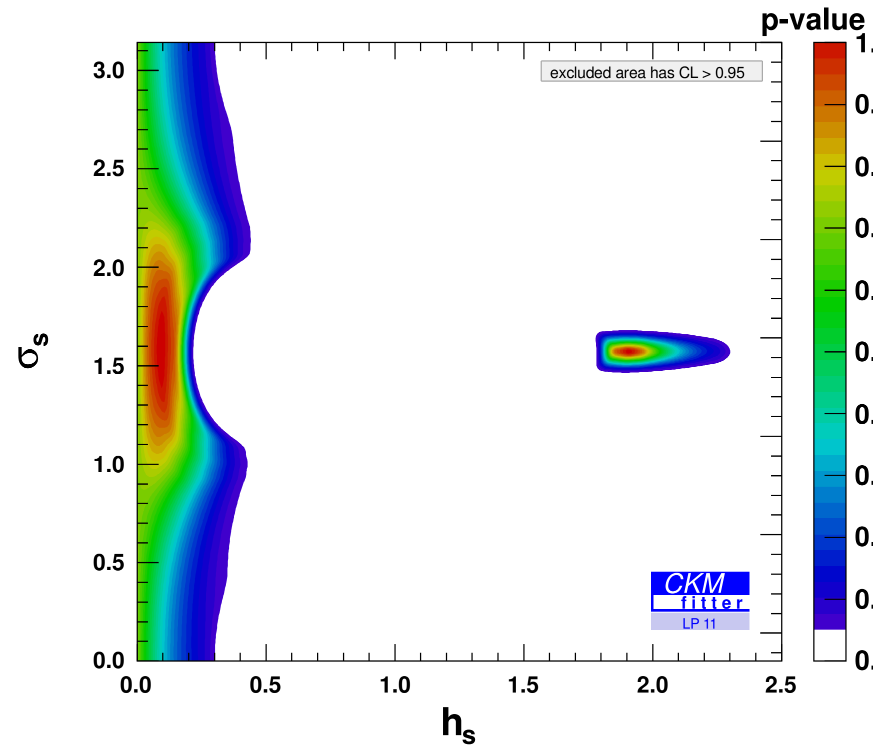
[ZL, Papucci, Perez, hep-ph/0604112]

Since the SM prediction of β_s is much better known (suppressed by λ^2) than that of β



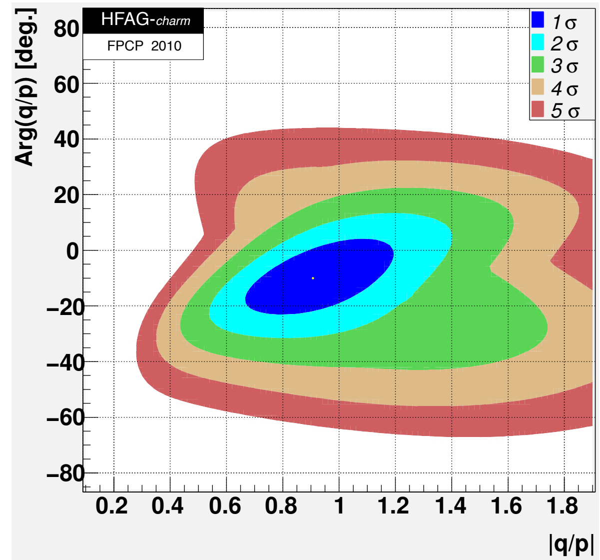


Current CKMfitter result



D^0: mixing in up sector

- Complementary to K, B: CPV, FCNC both GIM & CKM suppressed $\Rightarrow$ tiny in SM
  - 2007: observation of mixing, now $\gtrsim 10\sigma$ [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
  - Direct CPV bounds are approaching the 10^{-3} level
  - How small CPV would still unambiguously establish new physics?



Don't known if $|q/p|$ is near 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)

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 $B \to K\pi$ puzzle

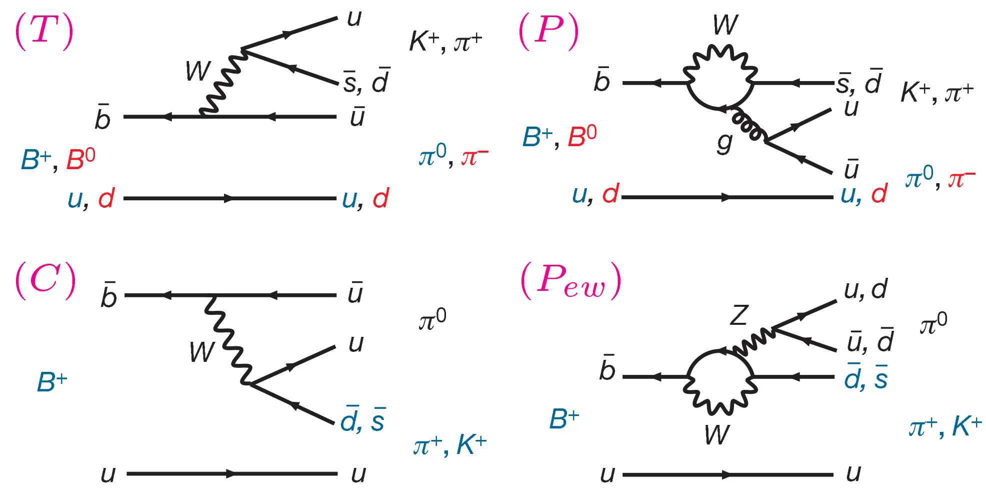
- **Q**: Have we seen new physics in CPV?

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

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

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)

Korea Institute for Advanced Study

Berkeley Lab

The news of the week: CPV in D decay

- LHCb announced on Monday (HCP, Paris):

$$\Delta a_{CP} \equiv a_{K^+K^-} - a_{\pi^+\pi^-} = -(0.82 \pm 0.21 \pm 0.11)\% \qquad a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

World average: $\Delta a_{CP} = (-0.69 \pm 0.18)\,\%$

This central value is beyond all SM calculations I know of

In the SM Δa_{CP} suppressed by $|V_{cb}V_{ub}|/|V_{cs}V_{us}| \simeq 0.07\%$; however, an enhancement, like the $\Delta I = \frac{1}{2}$ rule could accommodate the data [Grinstein & Golden, 1989]

- There will be a flood of model building papers: RPV, flavor off-diagonal Z's, etc.
- The important question is:
  How do we convince ourselves that we do not see a “fluke” like the $\Delta I = \frac{1}{2}$ rule?
- How do we get from: “NP could show up” $\Longleftrightarrow$ “Must be NP” or “Must be SM”

Future

Rich experimental future

- LHCb collects $2\,\mathrm{fb}^{-1}$/yr until $\sim 10\,\mathrm{fb}^{-1}$; plan upgrade for ~ 10 times the rate
- KEK-B / Belle upgrade in progress in Japan, Super-B approved in Italy
- $\mu \to e\gamma$: MEG (PSI) sensitivity to 10^{-13}, maybe 10^{-14} later

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

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

  EDM experiments
- $K \to \pi\nu\bar\nu$: 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: proposals for $K^+ \to \pi^+\nu\bar\nu$ and $K_L \to \pi^0\nu\bar\nu$ at ~ 1000 events
- Neutrino experiments

Reasons to seek higher precision

- What are the expected deviations from the SM, induced by TeV-scale NP?

  Generic flavor structure already ruled out by orders of magnitudes — can find any size deviations below the 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 to expect in terms of experimental precision?

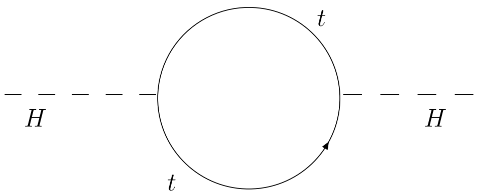
  Useful data sets can increase by a factor of $\sim 10^2$ at LHCb and a super-B factory. Such improvements will probe into the region of fairly generic new physics predictions.

- 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 measurements can teach us about what the new physics at the TeV scale is [not].

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

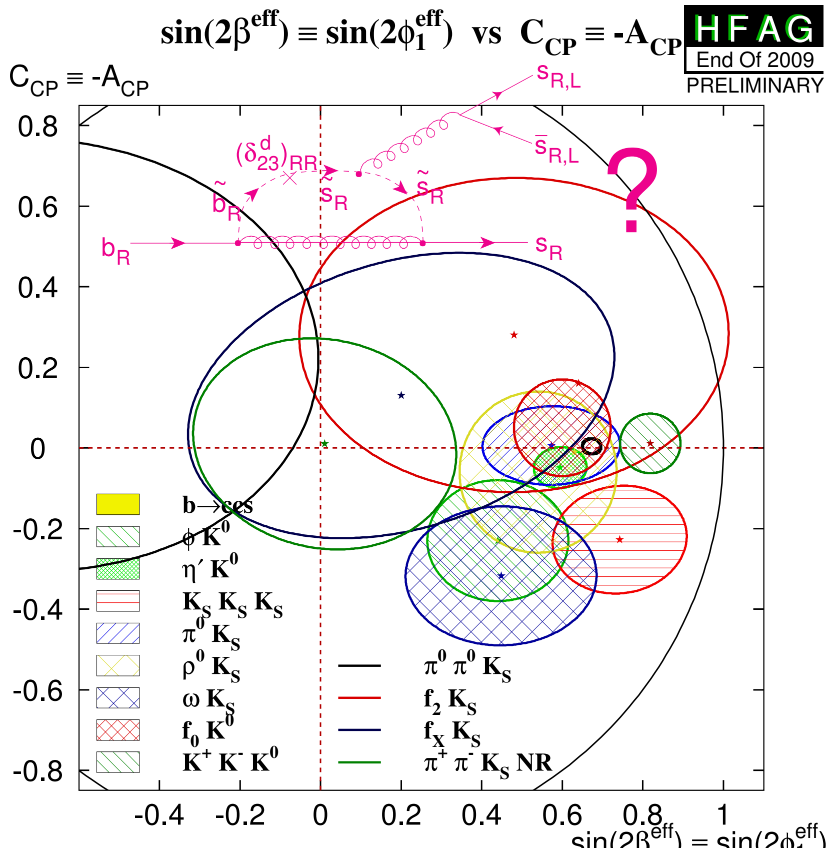


  Motivated models: NP $\Leftrightarrow$ 3rd gen. $\neq$ NP $\Leftrightarrow$ 1st & 2nd gen.

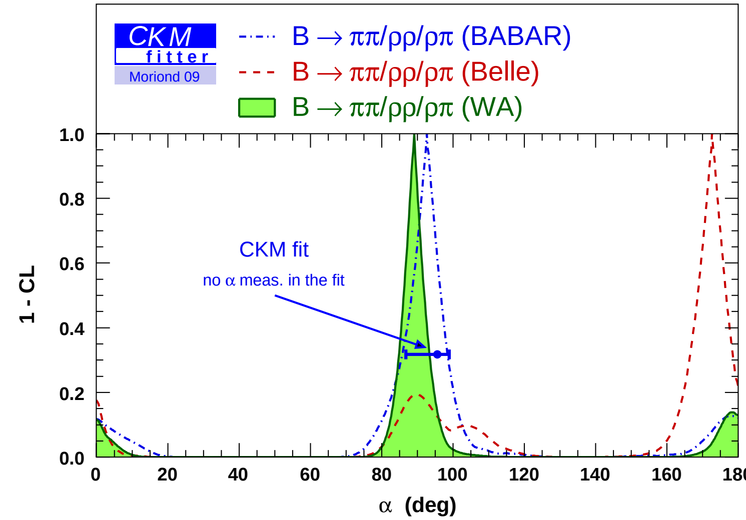
  Is the physics of 3rd–1st, 3rd–2nd, and 2nd–1st generation transitions the same?

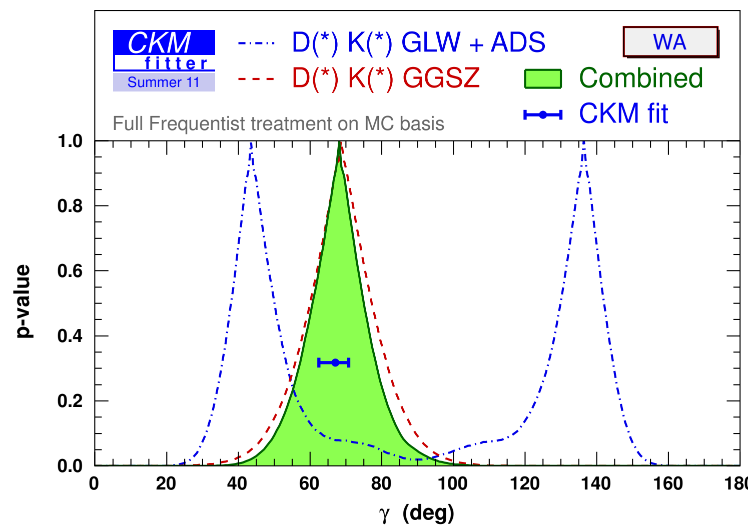
- If no NP is seen in flavor sector, similar constraints as LEP tests of gauge sector
- If non-SM flavor physics is seen, try to distinguish between classes of models:
  - One / many sources of CPV?
  - In charged / neutral currents?
  - Modify SM operators / new operators?
  - Couples to up / down sector?
  - To 3rd / all generations?
  - Quarks / leptons / other sectors?

$\sin 2\beta_{\rm eff}$, α, γ — large improvements possible



Contours give $-2\Delta(\ln L) = \Delta\chi^2 = 1$, corresponding to 60.7% CL for 2 dof





- Key masurements will benefit from ~ 100 times more data $\Rightarrow$ 10 times smaller error
- Will improve bounds on NP substantially [need both LHCb and super-(KEK-)B]

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Substantial discovery potential in many modes

- Some of the theoretically cleanest modes (ν, τ, inclusive) only possible at e^+e^-
- Many modes first seen at super-(KEK-)B or LHCb
- In some decay modes, even in 2025:

  (Exp. bound) / SM $\gtrsim 10^3$

  (E.g.: $B_{(s)} \to \tau^+\tau^-$, e^+e^- unlimited "muddle" building)

[Grossman, ZL, Nir, arXiv:0904.4262, Prog. Theor. Phys. special issue commemorating the KM Nobel Prize]

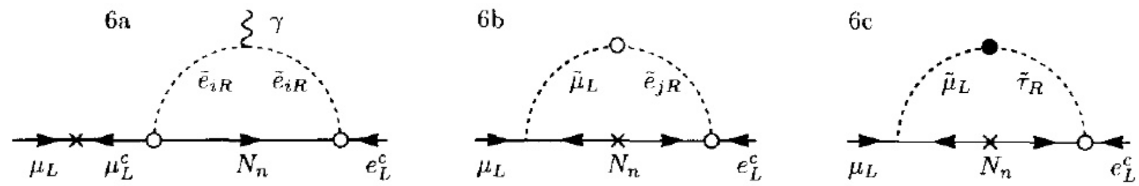
Observable	Approximate SM prediction	Present status	Uncertainty / number of events Super-B (50 ab^{-1})	LHCb (10 fb^{-1})
$S_{\psi K}$	input	0.671 ± 0.024	0.005	0.01
$S_{\phi K}$	$S_{\psi K}$	0.44 ± 0.18	0.03	0.1
$S_{\eta' K}$	$S_{\psi K}$	0.59 ± 0.07	0.02	not studied
$\alpha(\pi\pi, \rho\rho, \rho\pi)$	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%	—

Charged lepton flavor violation

- $\mu \to e\gamma, eee$ vs. $\tau \to \mu\gamma, \mu\mu\mu$

  Very large model dependence

  $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma) \sim 10^{4\pm3}$



  If a positive signal is seen, it's the tip of an iceberg $\Rightarrow$ trigger broad program

- $\tau^- \to \ell_1^- \ell_2^- \ell_3^+$ (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 of $\mu\gamma$ and $\mu\mu\mu$ final states by $\alpha_{\rm em}$ opposite for these two operators $\Rightarrow$ winner is model dependent

sensitivity with $75\,{\rm ab}^{-1}$ e^+e^- data

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 are comparable, $\mu \to e\gamma$ gives much stronger bound already

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

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An LHCb best buy list

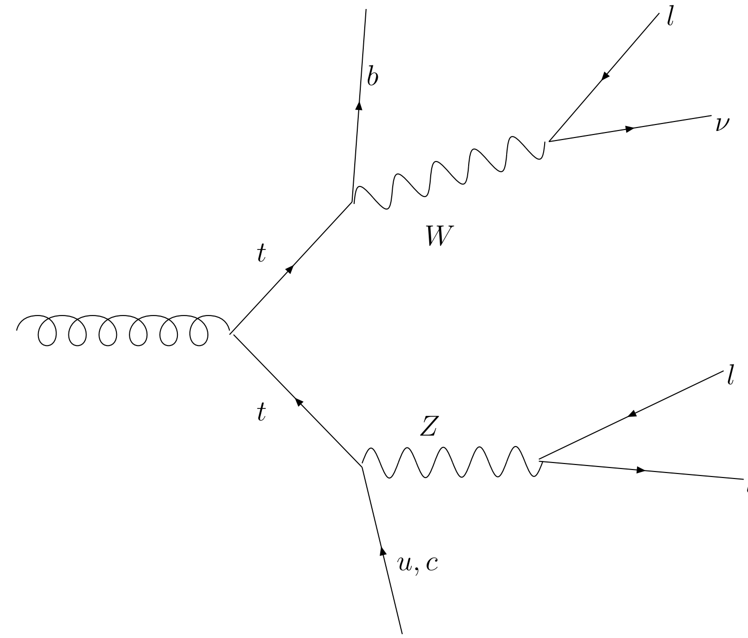
- LHCb will probe B_s sector at a level comparable to B_d
  - The CP asymmetry, $S_{B_s \to \psi\phi}$
  - Difference of CP asymmetries, $S_{B_s \to \psi\phi} - S_{B_s \to \phi\phi}$
  - $B_s \to \mu^+\mu^-$ ($\propto \tan^6\beta$), search for $B_d \to \mu^+\mu^-$, other rare / forbidden decays
  - 10^{4-5} 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)
  - Search for charged lepton flavor violation, $\tau \to 3\mu$ and similar modes
  - Search for CP violation in $D^0 - \overline{D}^0$ mixing
  - [Precisely measure τ_{Λ_b} — affects how much we trust $\Delta\Gamma_{B_s}$ calculation, etc.]
- Very broad physics program, with large discovery potential

A super-(KEK-)B best buy list

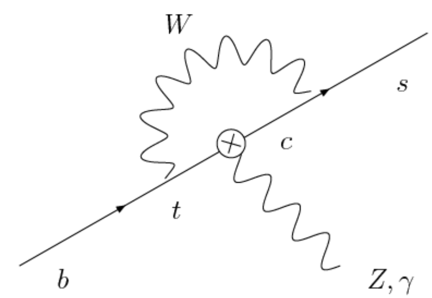
- Include observables: (i) sensitive to different NP, (ii) measurements can improve order of magnitude, (iii) not limited by hadronic uncertainties
  - Difference of CP asymmetries, $S_{\psi K_S} - S_{\phi K_S}$
  - γ from CP asymmetries in tree-level decays vs. γ from $S_{\psi K_S}$ and $\Delta m_d/\Delta m_s$
  - 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
  - CP asymmetry in semileptonic decay (dilepton asymmetry), $A_{\rm SL}$
  - 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

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

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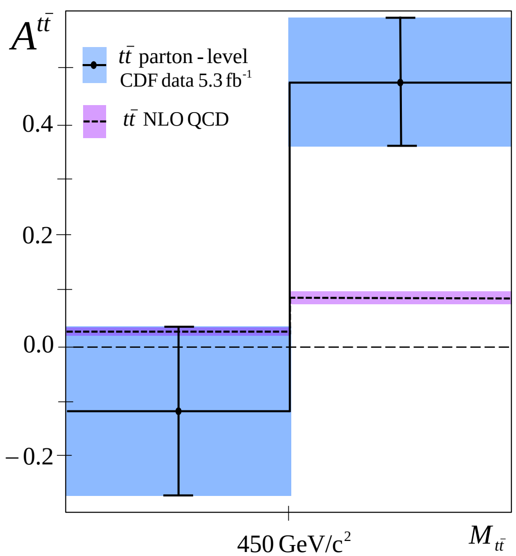
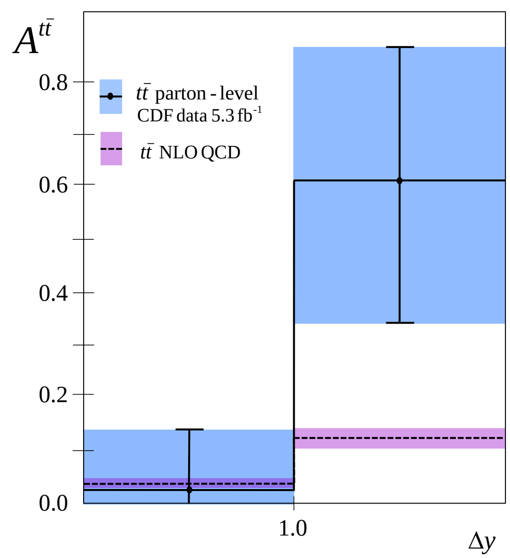
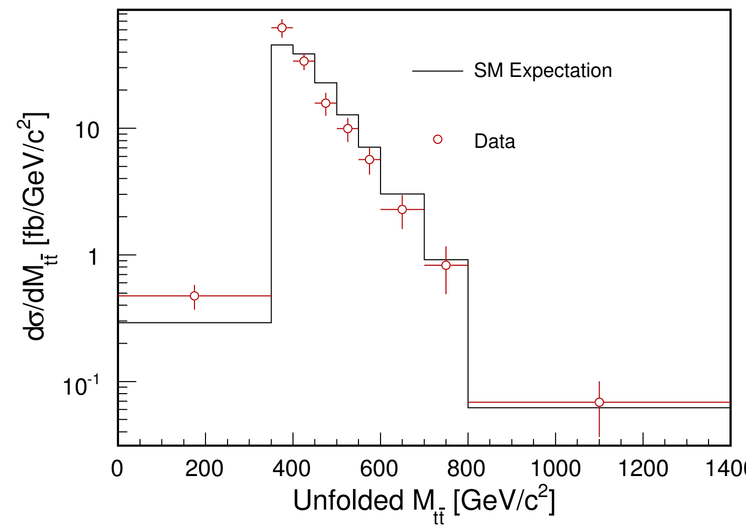
Tevatron $t\bar{t}$ forward-backward asymmetry

- CDF: $A^{t\bar{t}}(m_{t\bar{t}} > 450\,\text{GeV}) = 0.475 \pm 0.114, \qquad A^{t\bar{t}}(|\Delta y| \geq 1) = 0.611 \pm 0.256$
  (Consistent with DØ integrated over full phase space)







- Spectrum and $\sigma_{t\bar{t}} = (7.5 \pm 0.5)$ pb agree reasonably well with the expectations
  Discussions in literature about resummations, probably a conservative theory error is substantial

- Flavor conserving models can fit the data & satisfy low- and high-energy bounds
  [ZL, Schmaltz, Tavares, arXiv:1103.2757]

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The $t\bar{t}$ asymmetry at the LHC

- LHC: no forward-backward asymmetry, but charge asymmetry as a function of rapidity sensitive to same physics

  Tevatron: $q\bar{q} \to t\bar{t}$ dominates

  LHC: $gg \to t\bar{t}$ dominates, no asym.

- Enhance $q\bar{q}$ [Arguin, Freytsis, ZL, arXiv:1107.4090]

  R_1 : $|\eta_{1,2}| < 2.5$

  R_2 : $|\eta_1| < 2.5$ and $|\eta_2| < 4.5$

  R_3 : $|\eta_1| < 2.5$ and $2.5 < |\eta_2| < 4.5$

  M_1 : $m_{t\bar{t}} > 450\,\text{GeV}$

  M_2 : $m_{t\bar{t}} > 550\,\text{GeV}$

- Significantly increases LHC sensitivity to these models with 2011 – 2012 data

Cuts	SM MCFM	new physics models		
		Z'	Axigluon	Scalar **3**
R_1	$A_c = 0.011$	$A_c = 0.019$ $\varepsilon = 0.77$	$A_c = 0.025$ $\varepsilon = 0.78$	$A_c = 0.038$ $\varepsilon = 0.79$
R_2	$A_c = 0.018$	$A_c = 0.034$ $\varepsilon = 0.95$	$A_c = 0.031$ $\varepsilon = 0.94$	$A_c = 0.044$ $\varepsilon = 0.95$
R_3	$A_c = 0.028$	$A_c = 0.10$ $\varepsilon = 0.18$	$A_c = 0.058$ $\varepsilon = 0.17$	$A_c = 0.072$ $\varepsilon = 0.16$
R_1 & M_1	$A_c = 0.018$	$A_c = 0.038$ $\varepsilon = 0.44$	$A_c = 0.040$ $\varepsilon = 0.42$	$A_c = 0.059$ $\varepsilon = 0.48$
R_2 & M_1	$A_c = 0.021$	$A_c = 0.064$ $\varepsilon = 0.54$	$A_c = 0.046$ $\varepsilon = 0.50$	$A_c = 0.068$ $\varepsilon = 0.57$
R_3 & M_1	$A_c = 0.037$	$A_c = 0.18$ $\varepsilon = 0.10$	$A_c = 0.080$ $\varepsilon = 0.082$	$A_c = 0.12$ $\varepsilon = 0.087$
R_1 & M_2	$A_c = 0.022$	$A_c = 0.075$ $\varepsilon = 0.21$	$A_c = 0.061$ $\varepsilon = 0.19$	$A_c = 0.089$ $\varepsilon = 0.25$
R_2 & M_2	$A_c = 0.029$	$A_c = 0.12$ $\varepsilon = 0.27$	$A_c = 0.10$ $\varepsilon = 0.22$	$A_c = 0.10$ $\varepsilon = 0.29$
R_3 & M_2	$A_c = 0.041$	$A_c = 0.29$ $\varepsilon = 0.057$	$A_c = 0.10$ $\varepsilon = 0.036$	$A_c = 0.16$ $\varepsilon = 0.041$

Supersymmetry and flavor

- 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?

Δm_K and ϵ_K in SUSY (oversimplified)

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

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

  For ϵ_K, replace: $10^4\,{\rm Re}\big[(K^d_L)_{12}(K^d_R)_{12}\big] \;\Rightarrow\; 10^6\,{\rm Im}\big[(K^d_L)_{12}(K^d_R)_{12}\big]$

- 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

Flavor effects at the TeV scale

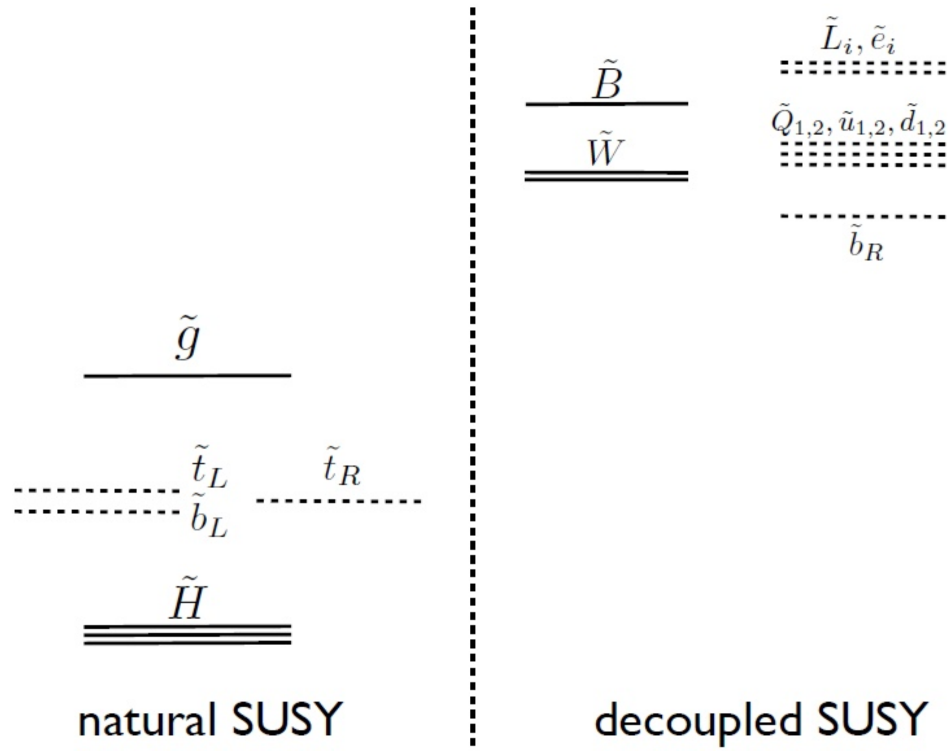
- Does flavor matter? Can we access flavor at high p_T?
- Some flavor aspects of LHC:
  - $p = g + u, d, s, c, b, \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}$ — has flavor
  - Hard to bound flavor properties of new particles (e.g., $Z' \to b\bar{b}$ vs. $Z' \to b\bar{s}$?)
  - Little particle ID: b (displaced 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

Flavor information useful in all scenarios

- Simplest bottom-up approach to keep SUSY as natural as possible, in light of ATLAS & CMS constraints

  [Papucci, Ruderman, Weiler, 1110.6926; Brust, Katz, Lawrence, Sundrum, 1110.6670; Kats, Meade, Reece, Shih, 1110.6444; Essig, Izaguirre, Kaplan, Wacker, 1110.6443]

  Can have approximate MFV, GIM, etc., but as the first two generations are pushed heavier, expect larger flavor non-universality, and increasing signals



- Another scenario: LHC sees what looks like GMSB — will want lots of precision tests to understand, at a detailed level, what the underlying theory really is

(As in SM: CPV + absence of $K_L \to \mu\mu \Rightarrow$ GIM & CKM, but decades to establish it with precision)

Summary

Conclusions

- Consistency of precision flavor measurements with SM is a problem for NP @ TeV
  However, new physics in most FCNC processes may still be $\gtrsim 20\%$ of the SM
- Few hints of discrepancies — hopefully LHCb will confirm some and find new ones (theoretical uncertainties won't be limiting in many cases)
- Low energy tests will improve a lot in next decade, by 10–1000 in some channels
  Exploring influence of NP requires LHCb, super-B, K, lepton flavor violation
- If LHC discovers "only" the Higgs, precision measurements are the only possibility to show the way ahead (sensitive to $\gg \mathrm{TeV}$), and point to the next energy scale
- If new particles are discovered, their flavor properties will be important to understand the underlying physics in all scenarios
- We shall learn an incredible amount in the next decade!

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: long-lived $=$ CP-odd $=$ heavy

D: long-lived $=$ CP-odd (3.5σ) $=$ light (2σ)

B_s: long-lived $=$ CP-odd (1.5σ) $=$ heavy in the SM

B_d: yet unknown, same as B_s 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

Recent trends: 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): $\mathcal{L}_Y = -Y_e^{ij}\, \overline{L_{Li}^I}\, \phi\, e_{Rj}^I - \frac{Y_\nu^{ij}}{M}\, L_{Li}^I L_{Lj}^I\, \phi\, \phi \qquad (Y_\nu^{ij} = Y_\nu^{ji})$
  $U(3)_L \times U(3)_e$ 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

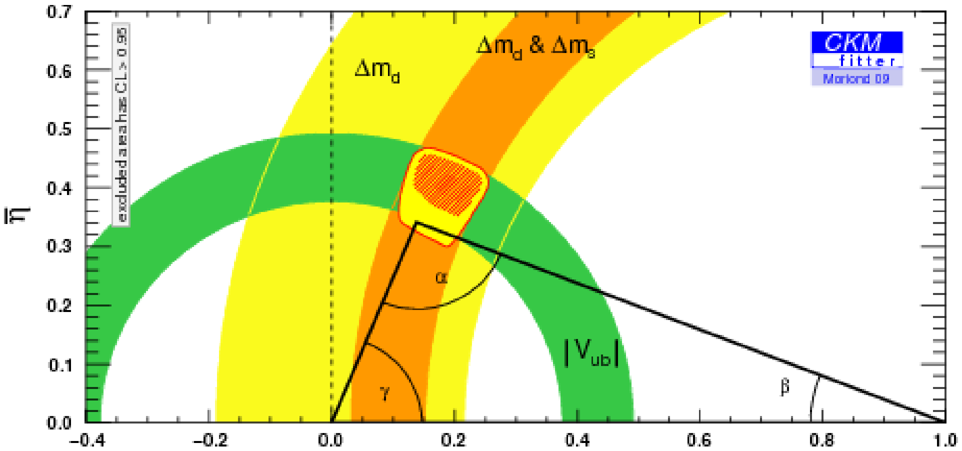
$5\ m_S^2$ hermitian sfermion mass-squared matrices — $5 \times (6$ real $+\ 3$ imag.) param's

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.

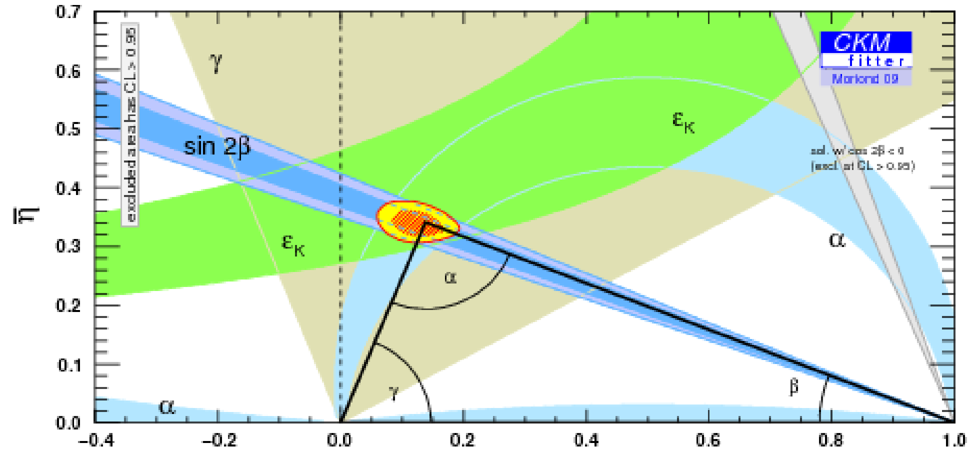
Parameters: $(95 + 74) - (15 + 30)$ from $U(3)^5 \times U(1)_{\rm PQ} \times U(1)_R \to U(1)_B \times U(1)_L$

- 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)

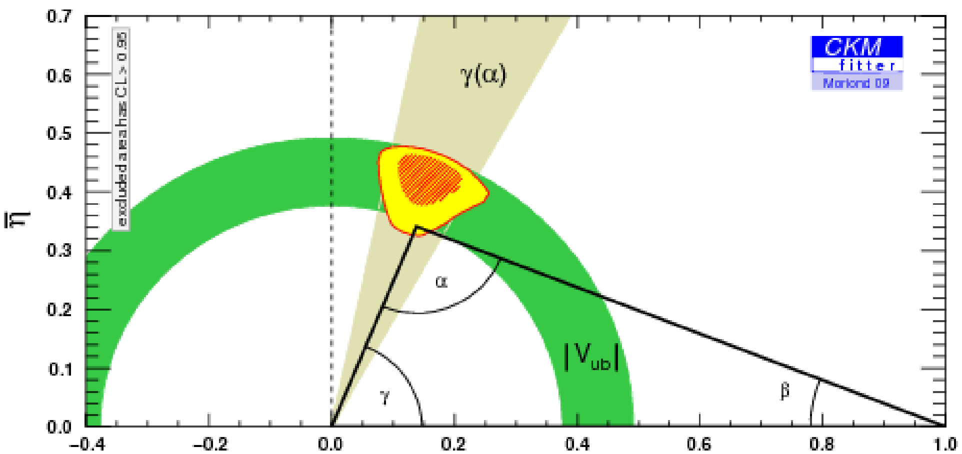
Overconstraining the standard model



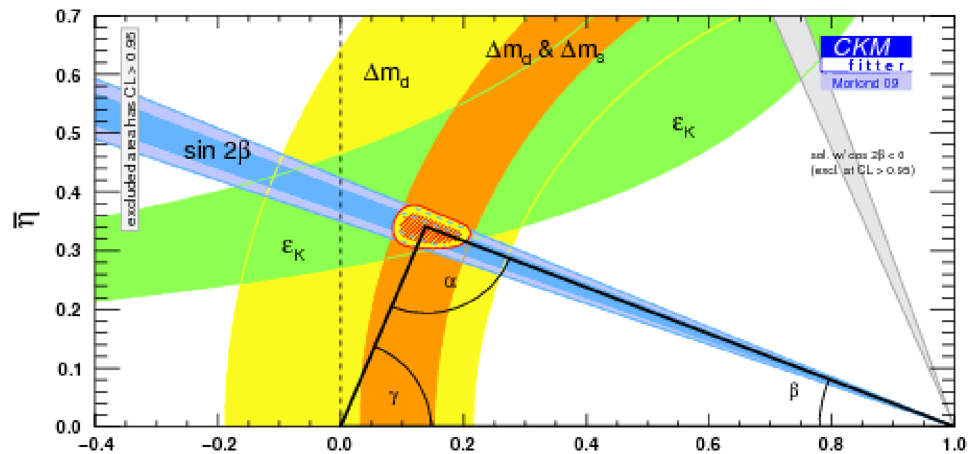
(CP conserving) ρ̄



ρ̄ (CP violating)



(tree-level) ρ̄



ρ̄ (loop-dominated)

- Consistent determinations from subsets of measurements ⇒ 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
$B \to \psi K \ (\beta)$	$\sim 0.2^\circ$	$\sim 1^\circ$
$B \to \eta' K, \ \phi K \ (\beta)$	$\sim 2^\circ$	$\sim 5, \ 10^\circ$
$B \to \rho\rho, \ \rho\pi, \ \pi\pi \ (\alpha)$	$\sim 1^\circ$	$\sim 5^\circ$
$B \to DK \ (\gamma)$	$\ll 1^\circ$	$\sim 15^\circ$
$B_s \to \psi\phi \ (\beta_s)$	$\sim 0.2^\circ$	$\sim 10^\circ$
$B_s \to D_s K \ (\gamma - 2\beta_s)$	$\ll 1^\circ$	—
$\lvert V_{cb} \rvert$	$\sim 1\%$	$\sim 2\%$
$\lvert V_{ub} \rvert$	$\sim 5\%$	$\sim 10\%$
$B \to X_s \gamma$	$\sim 4\%$	$\sim 7\%$
$B \to X_s \ell^+ \ell^-$	$\sim 5\%$	$\sim 25\%$
$B \to K^{(*)} \nu\bar{\nu}$	$\sim 5\%$	—
Many more, plus D and τ decays sensitive to new physics		

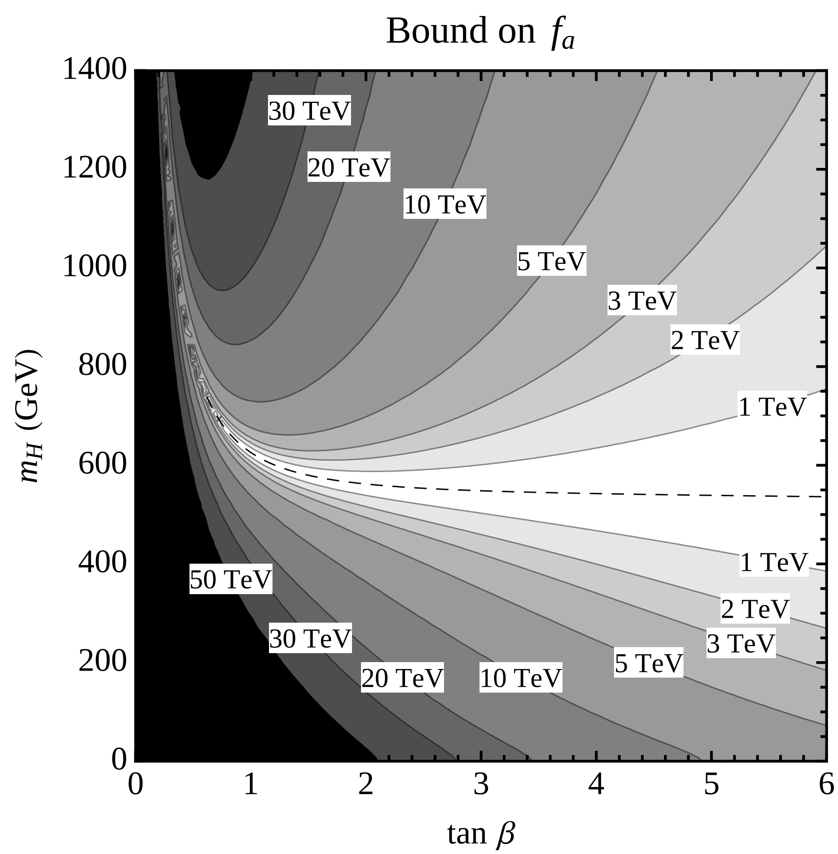
For some entries, the above theoretical limits require more complicated analyses

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

"Odd" searches: probe DM models with B decays

- Observations of cosmic ray excesses lead to flurry of 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]

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

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

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

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

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 $A_{\rm SL}^s$, $B_s \to \mu^+\mu^-$, or...?

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

  B: $B \to \tau\nu$) in increasing tension 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]