Flavor physics in the LHC era

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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**

Why is flavor physics interesting?

- SM flavor problem: hierarchy of masses and mixing angles; why ν's are different
- Empirical evidence that SM is incomplete:
  baryon asymmetry, dark matter, neutrino mass — at least two related to flavor
- NP flavor problem: TeV scale (hierarchy problem) $\ll$ flavor & CPV scale

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

  – Many extensions of the SM have new sources of CP and flavor violation
  – 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

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 flavor physics topics where sensitivity can improve significantly (by an order of magnitude, or at least a factor of many)

  – Skip $B \to X_s \gamma$ rate, near "hitting the theory wall" (best bound on many models)

    ... some tension between $\sin 2\beta$ and $|V_{ub}|$ [emphasized, e.g., by UTfit]

    ... $> 3\sigma$ tension between LQCD f_{D_s} and $D_s^+ \to \ell^+ \nu$ [Dobrescu & Kronfeld, arXiv:0803.0512]

  – Many measurements with complementary sensitivity will improve a lot

  – If all flavor effects $< 1\%$ in your favorite model (what is it?), I'll have little to say

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

SUSY contributions to $K^0 - \overline{K}^0$ mixing

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

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

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

- 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)

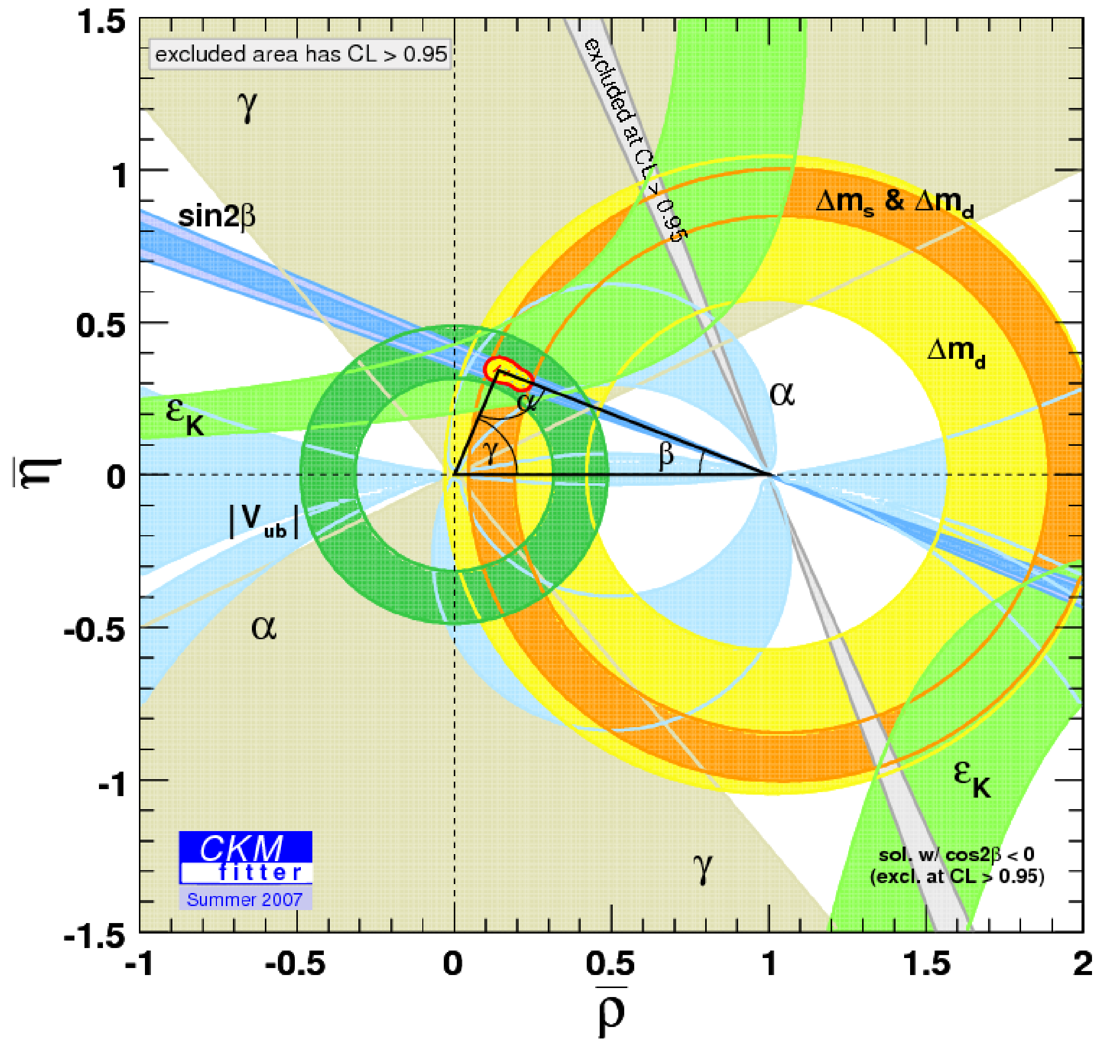
  (iii) Alignment: $|(K^d_{L,R})_{12}| \ll 1$ (e.g., horizontal symmetries)

- All SUSY models incorporate some of the above

Where are we now?

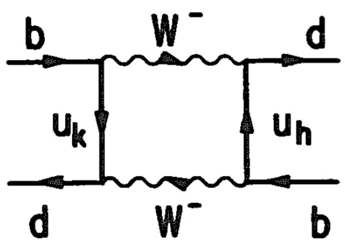
The standard model CKM fit

- Very impressive accomplishment
- The level of agreement between the various measurements is often misinterpreted
- Plausible TeV scale NP scenarios, consistent with all low energy data, w/o minimal flavor violation (MFV)
- CKM is inevitable; the question is not if it's correct, but is it sufficient?



New Physics in FCNC processes

- Mixing



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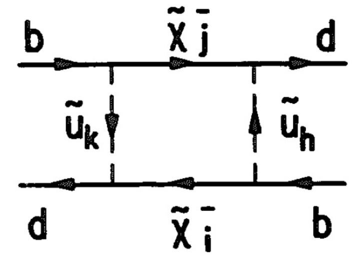
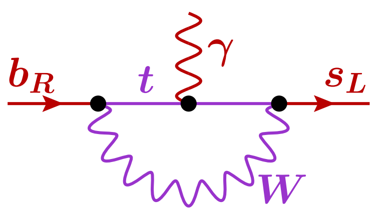


Simple parameterization for each neutral meson: $M_{12} = M_{12}^{\rm SM}\,(1 + h e^{2i\sigma})$

- Penguin decays



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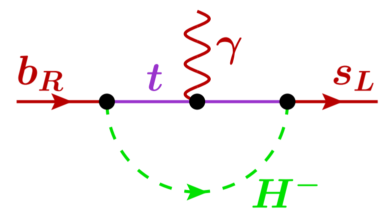


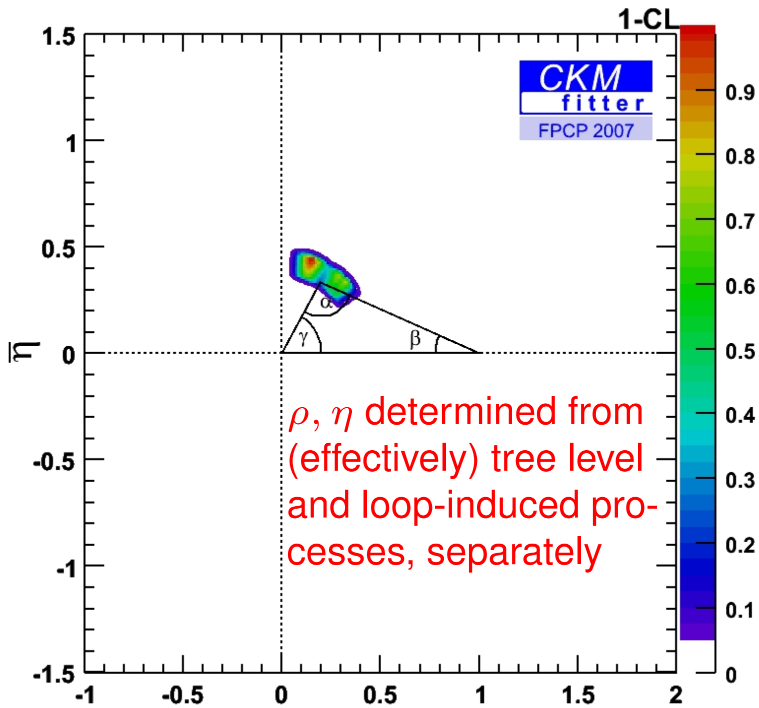
Many operators for $b \to s$ transitions — no simple parameterization of NP

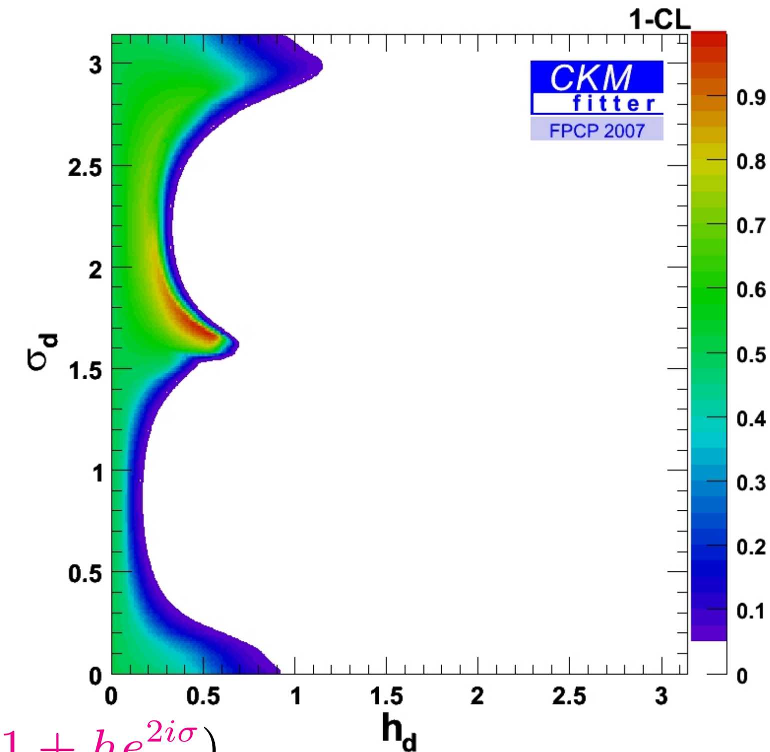
- $V_{td,\,ts}$ only measurable in loops; likely also subleading couplings of new particles

- Isolating modest NP contributions requires many measurements
  Compare NP-independent (tree) with NP-dependent (loop) processes

Constraints on NP in B_d^0 mixing

- Overconstraining ("redundant") measurements are crucial to bound new physics





$$M_{12} = M_{12}^{\rm SM}\left(1 + h e^{2i\sigma}\right)$$

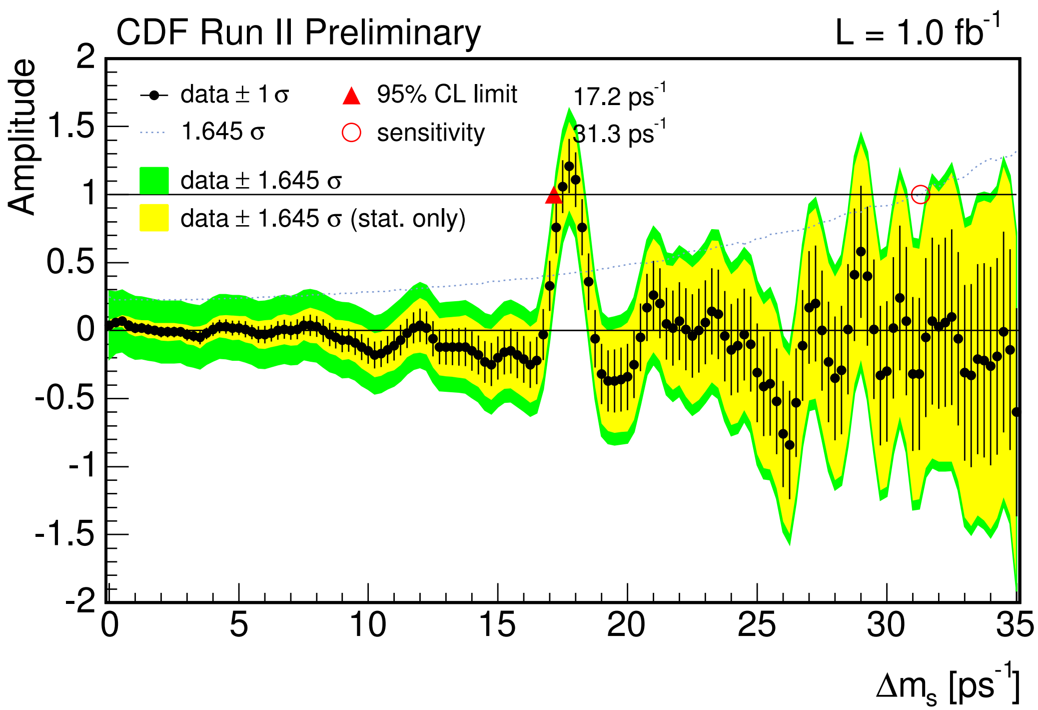
Only the SM-like region is allowed, even in the presence of NP in mixing

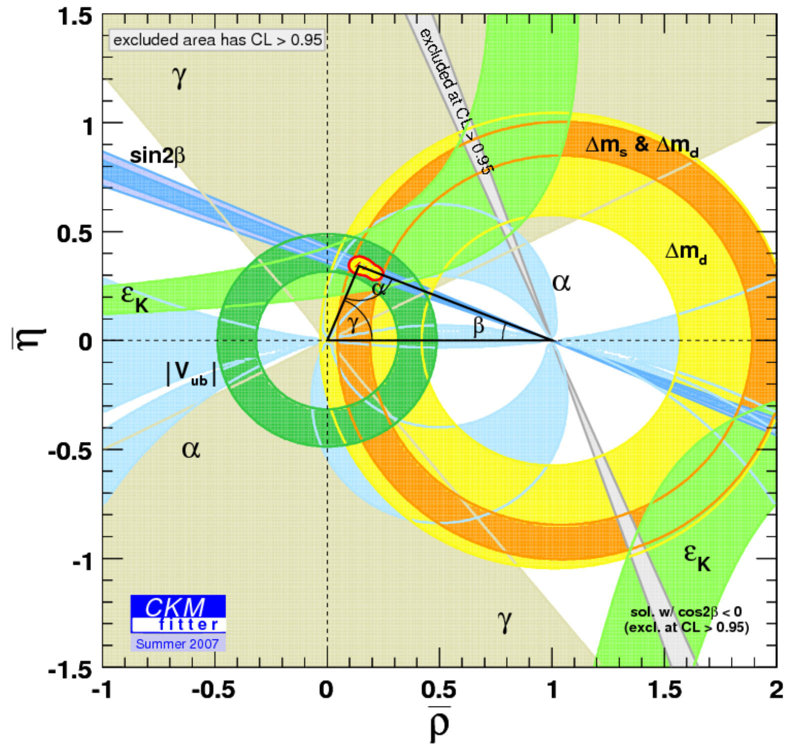
NP $\sim$ SM is still allowed; Think "MFV": $h \sim (4\pi v/\Lambda_{\rm flav.})^2$; is $\Lambda_{\rm flav.} \gg \Lambda_{\rm EWSB}$?

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

B_s mixing — Δm_s

- B_s^0–$\overline{B}_s^0$ oscillate 25 times on average before they decay — challenge to measure





- $\Delta m_s = (17.77 \pm 0.10 \pm 0.07)\,\mathrm{ps}^{-1}$

[CDF, hep-ex/0609040]

Uncertainty $\sigma(\Delta m_s) = 0.7\%$ is already smaller than $\sigma(\Delta m_d) = 0.8\%$

Largest uncertainty: $\xi = \dfrac{f_{B_s}\sqrt{B_s}}{f_{B_d}\sqrt{B_d}}$

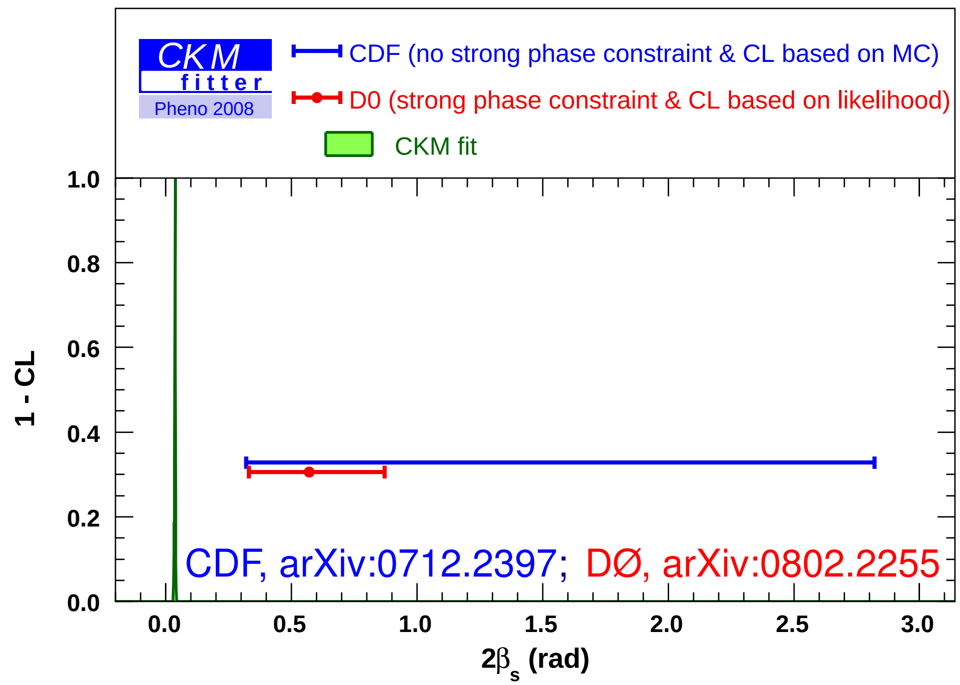
Lattice QCD: $\xi = 1.24 \pm 0.04 \pm 0.06$

B_s mixing phase — $\sin 2\beta_s$

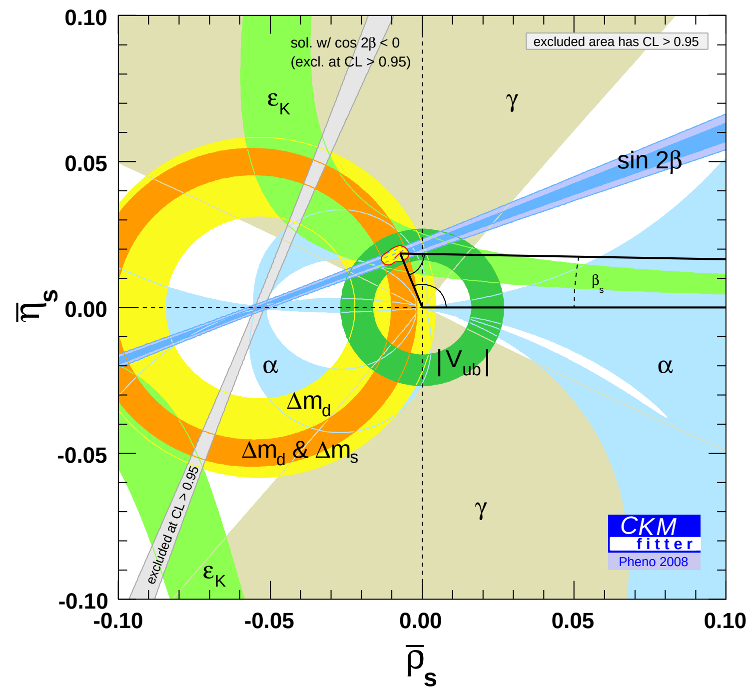
- Next key measurement: time dep. CP asymmetry in $B_s \to \psi\phi$ (as clean as $\sin 2\beta$)

  In the SM: $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) = 0.019 \pm 0.001$

- CDF & DØ disfavor large negative values:



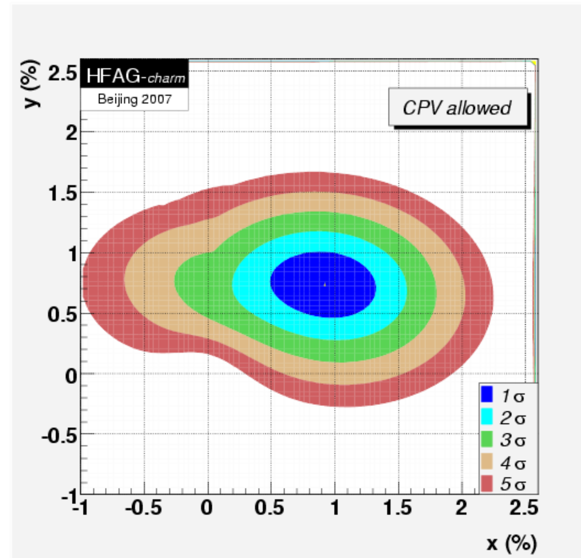
Testing a "squashed" UT:



Averaging complicated due to different assumptions, hopefully fixed by summer

The D meson system

- Complementary to K, B: CPV, FCNC both GIM & CKM suppressed $\Rightarrow$ tiny in SM
  - 2007: signal for 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) $\gg 10^{-3}$ 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 $|q/p| \simeq 1$)



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

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

The old/new $B \to K\pi$ puzzle

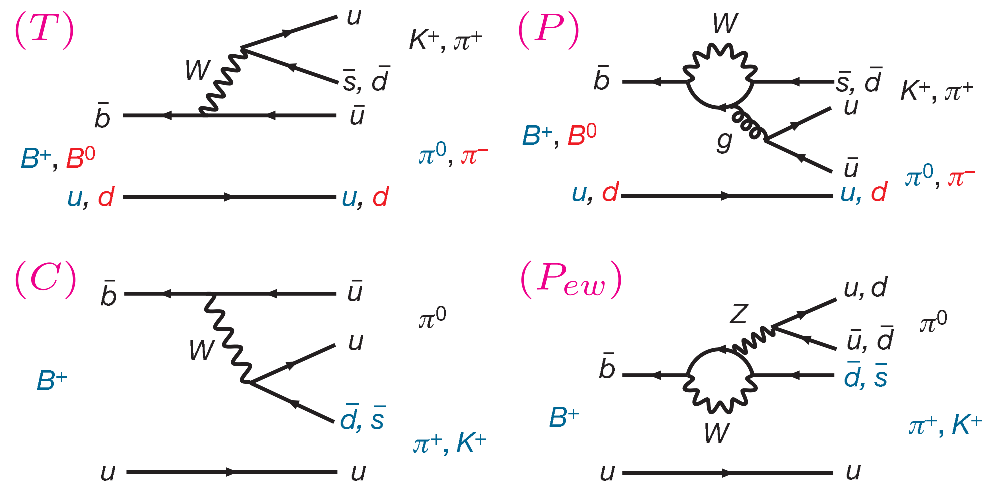
- **Q**: new physics in CPV in $B \to K\pi$?

$$A_{K^+\pi^-} = -0.097 \pm 0.012 \quad (P+T)$$

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

What is the reason for large difference?

$$A_{K^+\pi^0} - A_{K^+\pi^-} = 0.147 \pm 0.028 \quad (> 5\sigma)$$



(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 transparent problem with branching ratios, e.g., Lipkin sum rule looks OK by now:

$$2\,\frac{\bar\Gamma(B^- \to \pi^0 K^-) + \bar\Gamma(\overline{B}^0 \to \pi^0 \overline{K}^0)}{\bar\Gamma(B^- \to \pi^- \overline{K}^0) + \bar\Gamma(\overline{B}^0 \to \pi^+ K^-)} = 1.07 \pm 0.05$$

(should be near 1)

Forthcoming progress

Questions we hope to gain insights on

- The 3rd generation may differ from the 1st and 2nd by more than we know so far

  Large top Yukawa $\Rightarrow$ maybe non-universal coupling to EWSB and NP sector

  Want to compare 3rd–1st and 3rd–2nd generation data with precision kaon data

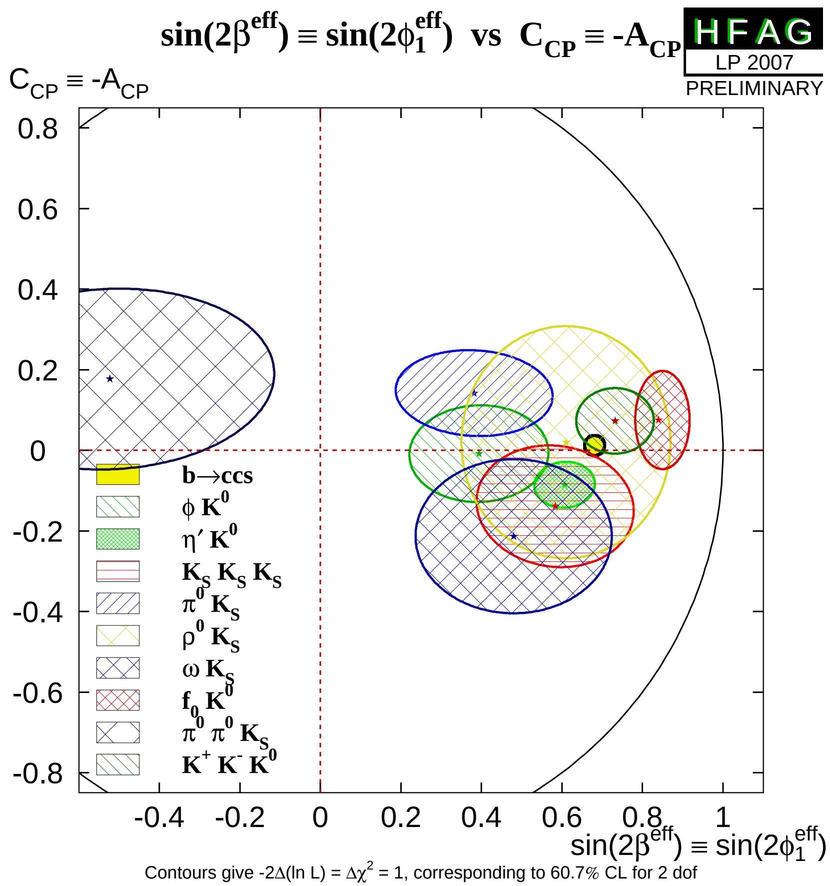
- Many processes have different sensitivities to various NP scenarios

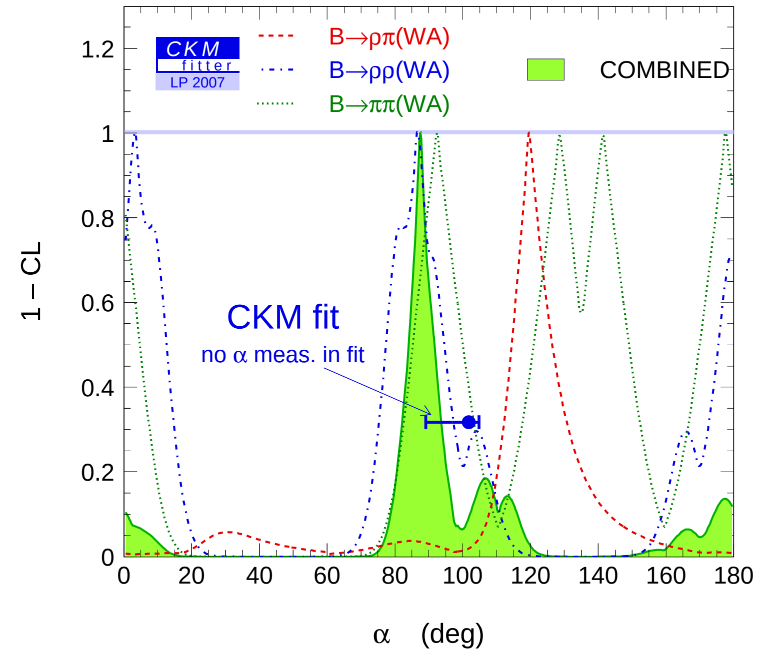
  In SM: CPV only in flavor changing, charged current interactions of quarks
  With NP: possible in flavor diagonal processes, neutral currents, in lepton sector

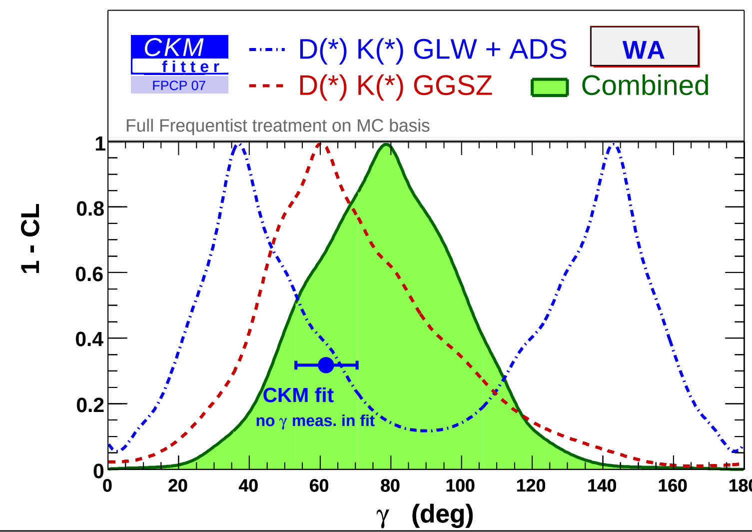
  Does new physics give rise to operators forbidden (highly suppressed) in the SM?
  E.g., $O_7 = \bar{s}\,\sigma^{\mu\nu} F_{\mu\nu} P_R\, b$ vs. $O_7' = \bar{s}\,\sigma^{\mu\nu} F_{\mu\nu} P_L\, b$

- Try to distinguish NP scenarios: One / many sources of CPV? Only in CC interactions? Couples to up / down sector? 3rd / all generations? $\Delta F = 2$ and / or 1?

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



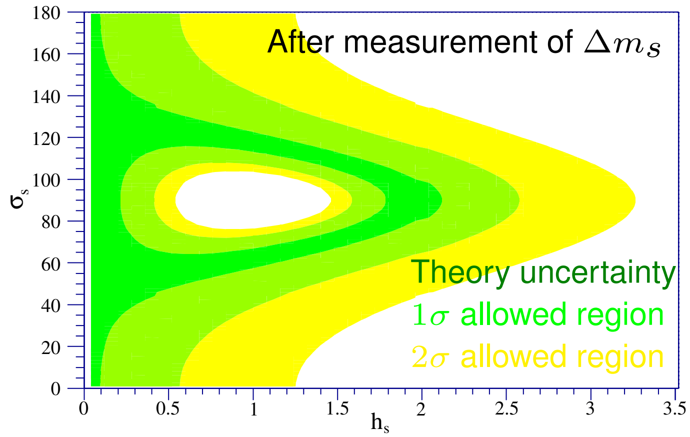


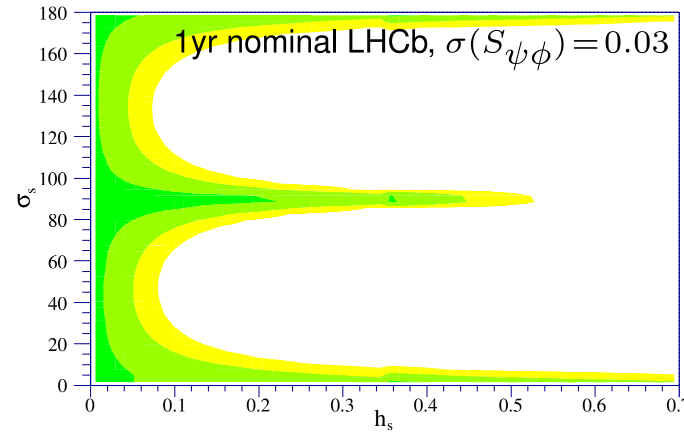


- E.g., $S_{\psi K} - S_{\phi K} = 0.29 \pm 0.17$; also for α & γ: want $\sim 10\times$ smaller error $\Rightarrow \sim 100\times$ more data
- Need both LHCb and e^+e^- super B factory

Some LHCb highlights / expectations

- After Δm_s measurement, large NP contribution to B_s^0 mixing is still allowed





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

LHCb will probe B_s sector at a level comparable to B_d

- $B_s \to \mu^+\mu^-$ ($\propto \tan^6\beta$), search for $B_d \to \mu^+\mu^-$, other rare / forbidden decays
- 10^{4-5} events in $B \to K^{(*)}\ell^+\ell^-$, $B_s \to \phi\gamma, \ldots$ — test Dirac structure, BSM op's
- γ from $B_s \to D_s^\pm K^\mp$ and other modes, α from $\rho\pi$ (probably super-(KEK)B wins)
- Precisely measure τ_{Λ_b} — affects how much we trust $\Delta\Gamma_{B_s}$ calculation, etc.

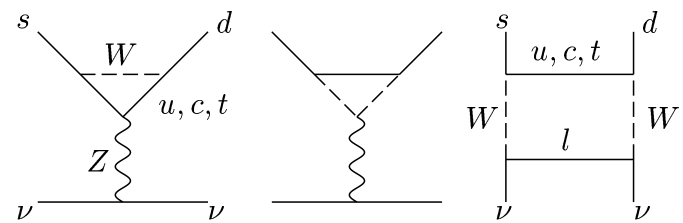
Skipping $\mu \to e\gamma$ and $K \to \pi\nu\bar{\nu}$

- $\mu \to e\gamma$: MEG (PSI) sensitivity to $\sim 10^{-13}$

  $\mu N \to eN$: PRISM/PRIME (J-PARC) sensitivity to $\sim 10^{-17}$ (and maybe project-X)

- $K \to \pi\nu\bar{\nu}$: 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: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ [BNL E787/E949]

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

Proposals: CERN NA62: $K^+ \to \pi^+\nu\bar{\nu} \sim 60$ events/yr, 2011–2013

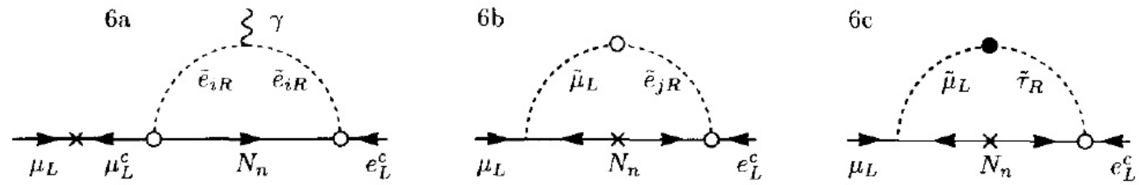
FNAL: get about a thousand (few hundred) events with(out) project-X

KEK E391a & J-PARC E14

Lepton flavor violation (in τ decays)

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

  Simplest $SU(5)$ expectation is $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma) \sim 3 \times 10^3$



  In many models best bet is $\mu \to e\gamma$, but this is model dependent, many 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)

Rare (semi)leptonic FCNC B decays

- Important probes of new physics
  - $B \to X_s\gamma$: Best $m_{H^\pm}$ limits in 2HDM — in SUSY many parameters
  - $B \to X_s\ell^+\ell^-$ or $K^{(*)}\ell^+\ell^-$: bsZ penguins, SUSY, right handed couplings

A crude guide ($\ell = e$ or μ)

Decay	$\sim$ SM rate	physics examples
$B \to s\gamma$	3×10^{-4}	$\lvert V_{ts}\rvert$, $H^\pm$, SUSY
$B \to \tau\nu$	1×10^{-4}	$f_B \lvert V_{ub}\rvert$, $H^\pm$
$B \to s\nu\nu$	4×10^{-5}	new physics
$B \to s\ell^+\ell^-$	6×10^{-6}	new physics
$B_s \to \tau^+\tau^-$	1×10^{-6}	$\Downarrow$
$B \to s\tau^+\tau^-$	5×10^{-7}	
$B \to \mu\nu$	5×10^{-7}	
$B_s \to \mu^+\mu^-$	4×10^{-9}	
$B \to \mu^+\mu^-$	2×10^{-10}	

Replacing $b \to s$ by $b \to d$ costs a factor ~ 20 (in SM); interesting to test in both: rates, CP asymmetries, etc.

In $B \to q\, l_1\, l_2$ decays expect 10–20% K^*/ρ, and 5–10% K/π (model dept)

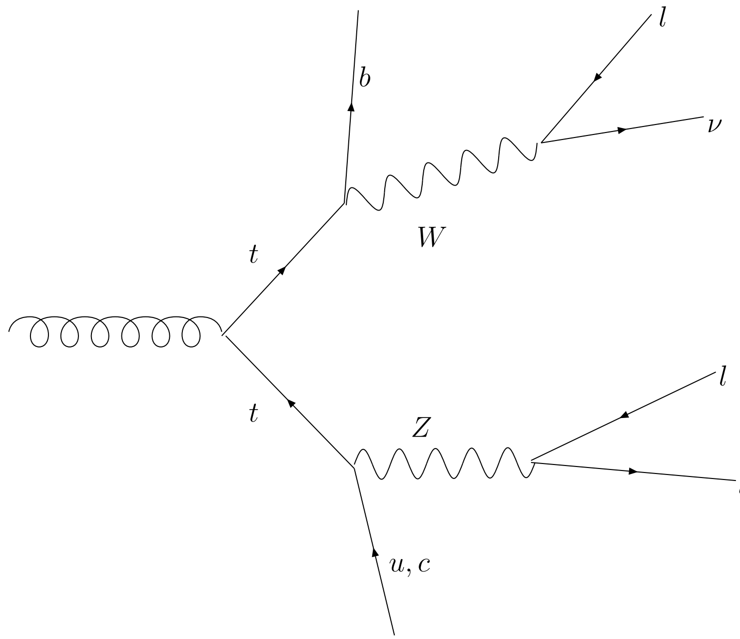
Many interesting modes will first be seen at LHCb and/or super-(KEK)B

Some of the theoretically cleanest (ν, τ, inclusive) only possible at e^+e^-

Flavor @ high p_T

LHC is a top factory: $1\ t\bar{t}$ pair / sec

- Improve bounds on FCNC top decays by more than 10^3 ($\sigma_{t\bar{t}} \sim 800$ pb)



channel	$t \to Zu(c)$	$t \to \gamma u(c)$	$t \to gu(c)$		
			(3 jets)	(4 jets)	(combined)
upper limit on BR ($L = 10$ fb^{-1})	3.4×10^{-4}	6.6×10^{-5}	1.7×10^{-3}	2.5×10^{-3}	1.4×10^{-3}
upper limit on BR ($L = 100$ fb^{-1})	6.5×10^{-5}	1.8×10^{-5}	5.0×10^{-4}	8.0×10^{-4}	4.3×10^{-4}

$\Uparrow$ $\Uparrow$

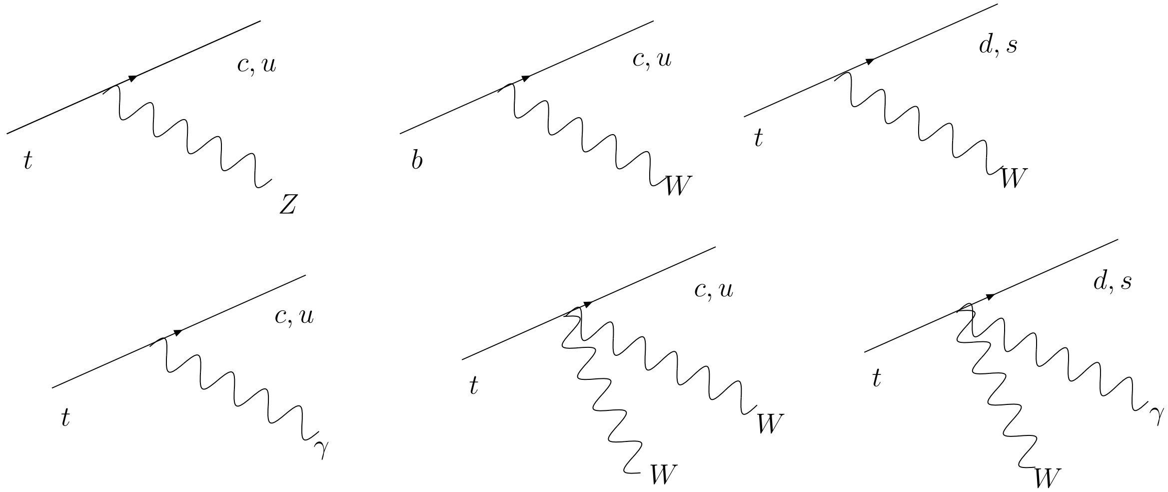
[Carvalho, Castro, Onofre, Veloso, ATLAS note, 2005]

- Probe FCNC top decays down to a few $\times 10^{-5}$ (now $> 10^{-2}$; SM $\sim 10^{-13}$)

FCNC top decays: $t \to c(u)\,\gamma, Z$

- The NP involved in EWSB may induce new flavor violation observable in top decay

[recent review: Han, arXiv:0804.3178]



- Start from $SU(2)\times U(1)$ invariant operators [Fox, ZL, Papucci, Perez, Schwartz, arXiv:0704.1482]
  - EW precision tests: $T,\ U,\ V$
  - B decays: semileptonic decays ($B \to X_{c,u}\ell\bar{\nu}$, $D^{(*)}\ell\bar{\nu}$, $\pi\ell\bar{\nu}$), mixing ($\Delta F = 2$)
    rare decays: $B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$, $B \to \rho\gamma$, $B \to \ell^+\ell^-$
- Subtlety: tree-level measurements modified — whole CKM fit has to be redone

Constraints on top FCNC operators

	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

Flavor effects at the TeV scale

- Questions: 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
- What flavor data the LHC can give us:
  - Spectrum (degeneracies)
  - Information on some (dominant?) decay widths
  - Production cross sections

Minimal flavor violation (MFV)

- How strongly can effects of NP at scale $\Lambda_{\rm NP}$ be (sensibly) suppressed?
- SM global flavor symmetry $U(3)_Q \times U(3)_u \times U(3)_d$ broken by Yukawa's

$$\mathcal{L}_Y = -Y_u^{ij}\, \overline{Q_{Li}^I}\, \widetilde\phi\, u_{Rj}^I - Y_d^{ij}\, \overline{Q_{Li}^I}\, \phi\, d_{Rj}^I \qquad \widetilde\phi = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \phi^*$$

- MFV: Assume Y's are the only source of flavor and CP violation (cannot demand all higher dimension operators to be flavor invariant and contain only SM fields)

[Chivukula & Georgi '87; Hall & Randall '90; D'Ambrosio, Giudice, Isidori, Strumia '02]

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

  Imposing MFV, best constraints come 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 few $\%$ deviations from SM in B, D, K
- In some scenarios high-p_T LHC data may rule out MFV or make it more plausible

Some MFV predictions

- Spectra: $y_{u,d,s,c} \ll 1$, so there is an approximate $SU(2)_q^3$ symmetry

  Indeed, in GMSB, the first two generation squarks are quasi-degenerate

- Mixing: Only source is CKM matrix

$$V_{\rm CKM}^{\rm (LHC)} = \begin{pmatrix} 1 & 0.2 & 0 \\ -0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

  $\Rightarrow$ New particles decay to either 3rd or non-3rd generation quarks, but not to both

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- How to test MFV at the LHC in specific models with an extended particle content

  [E.g.: Grossman, Nir, Thaler, Volansky, Zupan, arXiv:0706.1845]

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

Hitchhiker's guide to recent flavor models

- Models with hierarchical fermion wave functions yield partial alignment of NP flavor violation with Yukawas in down sector (NMFV, problems w/ ϵ_K)

  [Agashe *et al.*, hep-ph/0509117; Bona *et al.*, arXiv:0707.0636]

  Party in up sector? CPV in D mixing & decay, $D \to \pi\ell^+\ell^-$, FCNC t decays, etc. e.g., RS [Agashe, Perez, Soni, hep-ph/0408134; Davidson, Isidori, Uhlig, arXiv:0711.3376; Csaki, Falkowski, Weiler, arXiv:0804.1954]

- Down-quark alignment 5D MFV $\neq$ 4D MFV (more BSM in MFV than usual lore)

  [Fitzpatrick, Perez, Randall, arXiv:0710.1869]

- Suppression from heavy Dirac-gauginos (gluinos) $\Rightarrow$ OK with low energy observables (ϵ_K?), still plenty of high-p_T flavor violation [Kribs, Poppitz, Weiner, arXiv:0712.2039]

- Allow for modest subleading flavor-non-universal contributions in a natural way; maybe easiest to discover in slepton flavor violation

  [Feng *et al.*, arXiv:0712.0674; Nomura, Papucci, Stolarski, arXiv:0712.2074]

- Expect more on lepton flavor models [Cirigliano *et al.*, hep-ph/0507001; Chen, Yu, arXiv:0804.2503]

Implications for mass reconstructions

- Flavor (i.e., generation) off-diagonal rates can be $\mathcal{O}(10\%)$ and even more

E.g.:

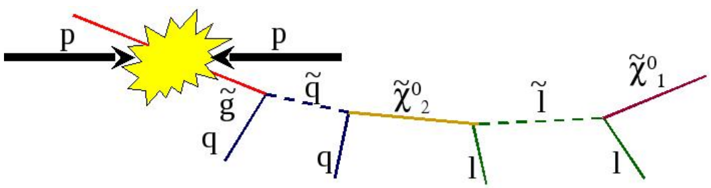

Table 2. Branching ratios (in %) of u-type squarks for the point specified in Table 1

	$\tilde{\chi}^0_1 c$	$\tilde{\chi}^0_1 t$	$\tilde{\chi}^0_2 c$	$\tilde{\chi}^0_2 t$	$\tilde{\chi}^0_3 c$	$\tilde{\chi}^0_3 t$	$\tilde{\chi}^0_4 c$	$\tilde{\chi}^0_4 t$	$\tilde{\chi}^+_1 s$	$\tilde{\chi}^+_1 b$	$\tilde{\chi}^+_2 s$	$\tilde{\chi}^+_2 b$
$\tilde{u}_1$	4.7	18	5.2	9.6	6×10^{-3}	0	0.02	0	11.3	46.4	2×10^{-3}	4.7
$\tilde{u}_2$	19.6	1.1	0.4	17.5	2×10^{-2}	0	6×10^{-2}	0	0.5	57.5	3×10^{-3}	2.9
$\tilde{u}_3$	7.3	3.7	20	1.4	6×10^{-2}	0	0.6	0	40.3	3.1	1	18.5
$\tilde{u}_6$	5.7	0.4	11.1	5.3	4×10^{-2}	5.7	0.6	13.2	22.9	13.1	0.6	8.0

- Sizable off-diagonal rates still allowed, consistent with low energy data, incl. $b \to s\gamma$

Table 3. Branching ratios (in %) of d-type squarks for the point specified in Table 1

	$\tilde{\chi}^0_1 s$	$\tilde{\chi}^0_1 b$	$\tilde{\chi}^0_2 s$	$\tilde{\chi}^0_2 b$	$\tilde{\chi}^0_3 s$	$\tilde{\chi}^0_3 b$	$\tilde{\chi}^0_4 s$	$\tilde{\chi}^0_4 b$	$\tilde{\chi}^-_1 b$	$\tilde{\chi}^-_1 t$	$\tilde{\chi}^-_2 b$	$\tilde{\chi}^-_2 t$	$\tilde{u}_1 W^-$
$\tilde{d}_1$	1.2	5.7	8.4	30.6	2×10^{-2}	1.5	0.2	0.9	16.6	34.1	0.6	0	0
$\tilde{d}_2$	17.4	5.8	5.1	15.7	7×10^{-2}	7.4	0.3	09.2	9.7	19.7	0.7	0	8.8
$\tilde{d}_4$	14.7	21.7	11.3	2.2	5×10^{-2}	10.6	0.5	8.4	22.1	3.6	1.2	0	3.4
$\tilde{d}_6$	1.7	0.5	20.5	6.9	0.1	0.9	1.2	1.3	40.3	10.2	3.4	11.1	1.8

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

- Could complicate determination of sparticle masses from kinematical endpoints in cascade decays — most LHC studies assume MFV, i.e., $\tilde{m}_1^2 = \tilde{m}_2^2 \neq \tilde{m}_3^2$

Final comments

Summary — low energy

- The SM flavor sector has been tested with impressive & increasing precision
  KM phase is the dominant source of CP violation in flavor changing processes
- Measurements probe scales $> \mathrm{TeV}$; sensitivity limited by statistics, not theory
- New physics in most FCNC processes may still be $\gtrsim 10\%$ of the SM contributions
- Tests of 3-2 generation transitions will approach precision of 3-1, approaching 2-1
  LHCb will constrain B_s sector at a level similar to B_d
- Sensitivity to lepton flavor violation will improve by 10–1000 in many channels
- If no NP is seen in flavor sector, similar constraints as LEP tests of gauge sector

Summary — high energy

- The consistency of precision flavor measurements at $E_{\rm exp} \sim \text{few GeV}$ with the SM poses problems for NP at $\Lambda_{\rm NP} \sim \text{few TeV}$
- If new particles discovered, their flavor properties can teach us about $\gg \text{TeV}$ NP: masses (degeneracies), decay rates (flavor decomposition), cross sections
- LHC data may rule out MFV or make it more plausible (so can LHCb & super-B)
- Direct and indirect probes of NP:
  – synergy in reconstructing the fundamental theory (distinguish between models)
  – complementary coverage of param. space (subleading couplings, $\gg$TeV scales)
- Flavor physics will provide important clues to model building in the LHC era

Backup slides

Spectacular track record

- Flavor and CP violation are excellent probes of new physics
  - 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
- If there is NP at the TEV scale, it must have a special flavor and CP structure

  Did we misinterpret the fine-tuning problem? Will the LHC find just a SM Higgs?
- If $\Lambda_{\rm CPV} \gg \Lambda_{\rm EW}$: no observable effects in B decays $\Rightarrow$ precise SM measurements

  If $\Lambda_{\rm CPV} \sim \Lambda_{\rm EW}$: sizable effects possible $\Rightarrow$ could get detailed information on NP

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 $\pi - \beta - \alpha$)

Flavor and CP violation in SUSY

- 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)

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

	$x = \Delta m/\Gamma$		$y = \Delta\Gamma/(2\Gamma)$		$A = 1 - \lvert q/p\rvert^2$	
	SM theory	data	SM theory	data	SM theory	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	$4\,{\rm Re}\,\epsilon$	$(6.6 \pm 1.6)10^{-3}$
D	< 0.01	< 0.016	$\mathcal{O}(0.01)$	$y_{CP} = 0.011 \pm 0.003$	$< 10^{-4}$	$\mathcal{O}(1)$ bound only

Some of the 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: $\sin 2\beta = 0.681 \pm 0.025$ — 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: $S_{\psi K} - S_{\phi K_S} = 0.29 \pm 0.17$

- 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

Exciting theoretical developments

- B physics has been and continues to be fertile ground for theory developments
- HQET & OPE — model independent description of certain exclusive and inclusive decays; nonperturbative matrix elements of higher dimensional operators are being extracted from the data, and used for precision measurements
- SCET — developed to address complicated kinematic regions in B decays, new and simplified proofs of factorization theorems, some new results for power suppressed processes; may have important applications for jets at the LHC as well
- Lattice QCD — in principle, fully model independent nonperturbative information
  No longer need model dependent assumptions for practical applications

  Large investment worldwide, flavor physics provides some of the most important applications and testing grounds