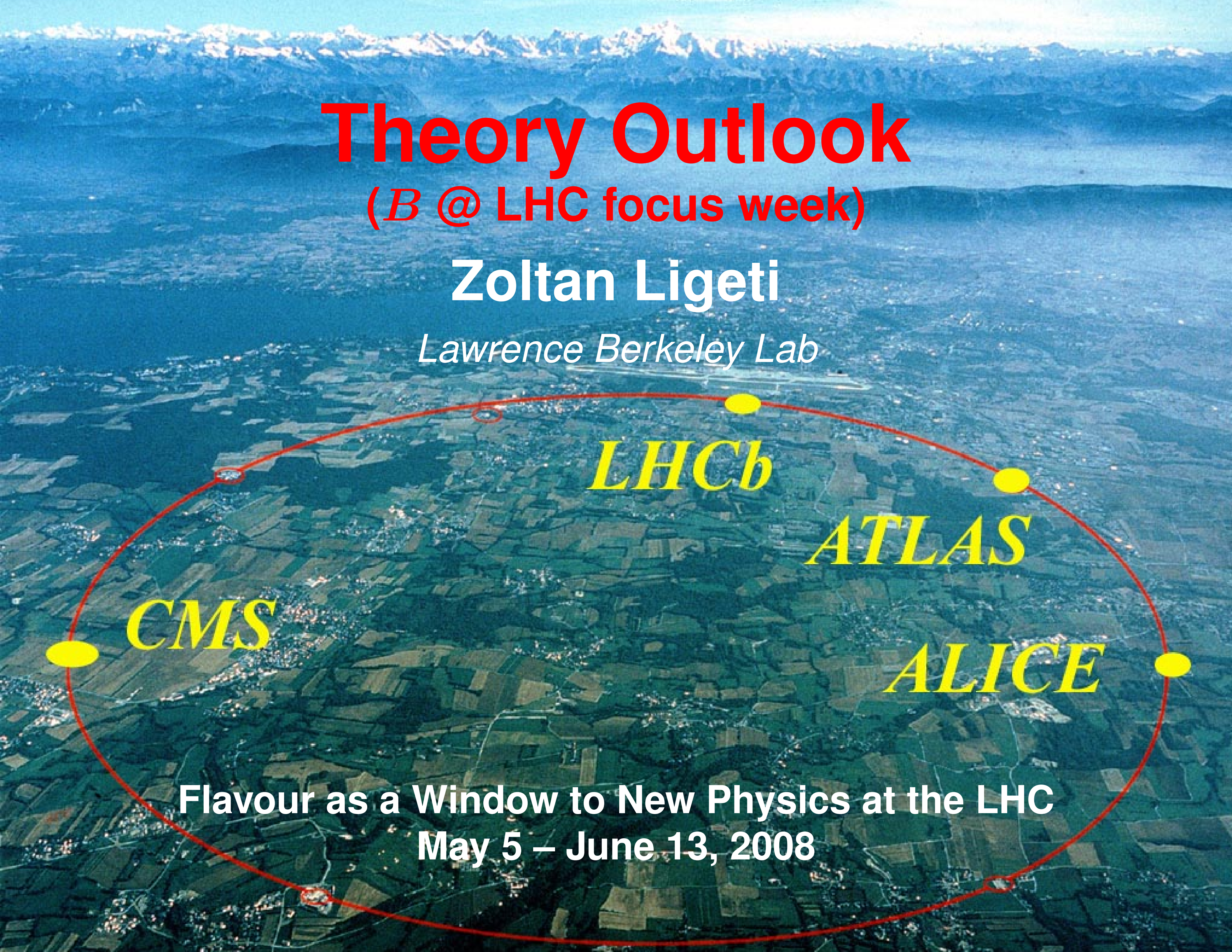
Theory Outlook

(B @ LHC focus week)

Zoltan Ligeti

Lawrence Berkeley Lab



Flavour as a Window to New Physics at the LHC
May 5 – June 13, 2008

Theory Outlook

(B @ LHC focus week)

Zoltan Ligeti

Lawrence Berkeley Lab

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

I suppose, we all want to know...

- The question:

$$\mathcal{L} = ?$$

"Everything should be made as simple as possible, but not simpler" A. Einstein

... what are the elementary degrees of freedom and how they interact?

- Empirical evidence that SM is incomplete:
  - Baryon asymmetry
  - Dark matter
  - Neutrino mass
  - Dark energy

Spectacular track record

- 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

If there is NP at the TEV scale, it must have a very special flavor & CP structure

Why is flavor physics interesting?

- 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

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

  - Almost all extensions of the SM have new sources of CPV & flavor conversion
  - A major constraint for model building
  - 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 has only been tested at the 10% level and can be done a lot better
  Many NP models proposed to solve the hierarchy puzzle have observable effects

SUSY in $K^0 - \overline{K}^0$ mixing (oversimplified)

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

  $K^d_{L(R)}$: 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

- Last year, BaBar & Belle Δm_D results ruled out alignment as the sole explanation

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]

    ... some 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

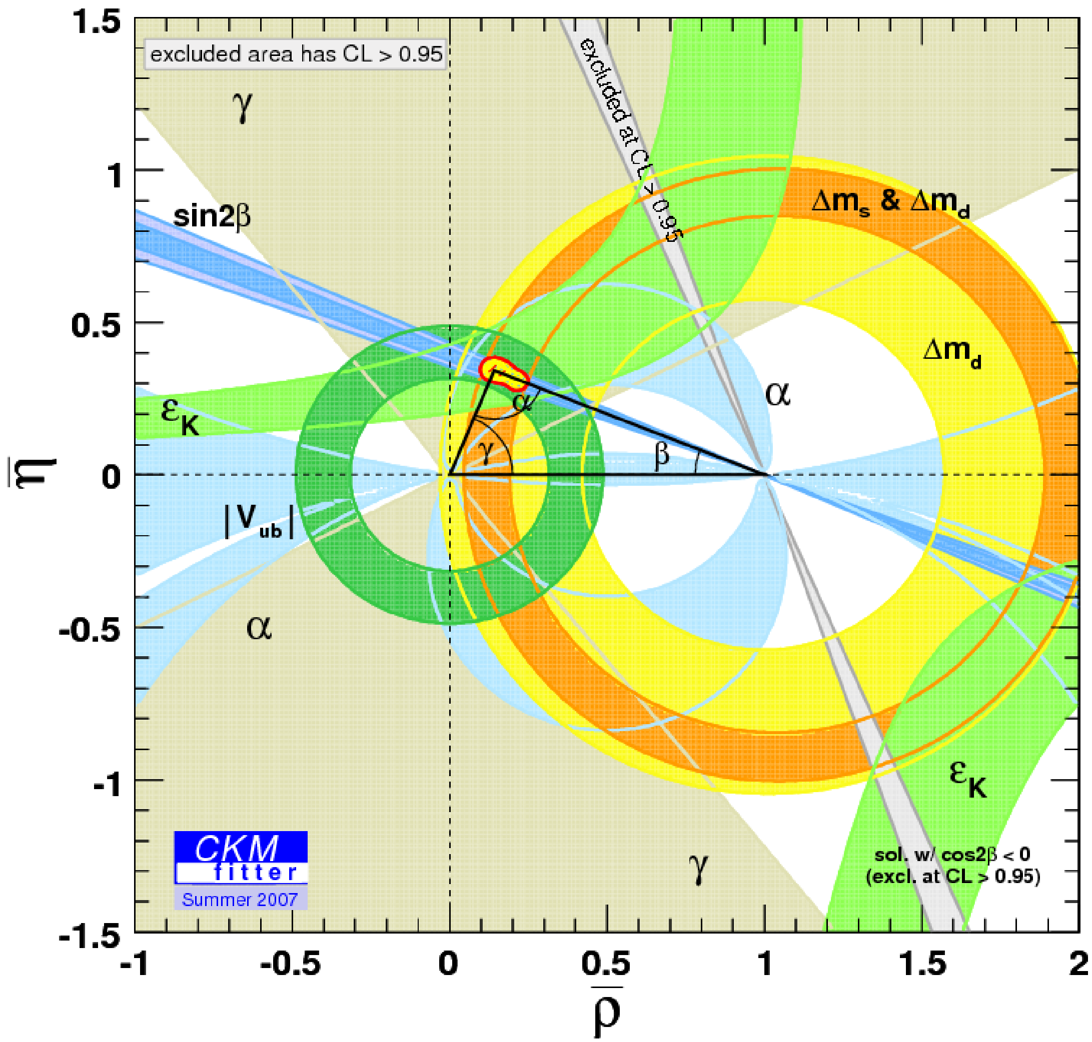
  – If all flavor effects $< 1\%$ in your favorite model (what is it?), I'll have little to say

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

Where are we now?

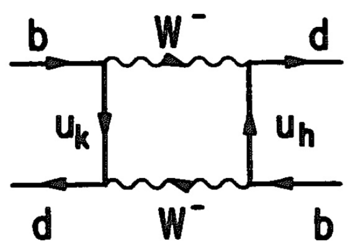
The standard model CKM fit

- 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?

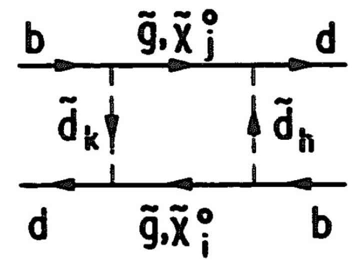


New Physics in FCNC processes

- Mixing

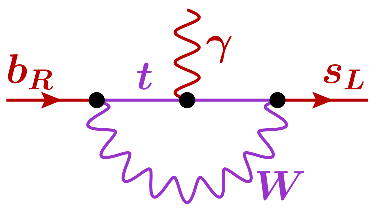


~~OR~~ $\Rightarrow$ AND?

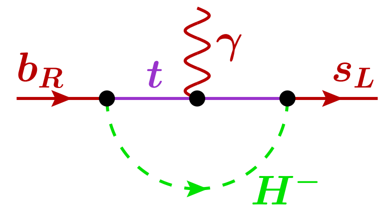


Simple parameterization for each neutral meson: $M_{12} = M_{12}^{\rm SM}\,(1 + h e^{2i\sigma})$

- Penguin decays



~~OR~~ $\Rightarrow$ AND?



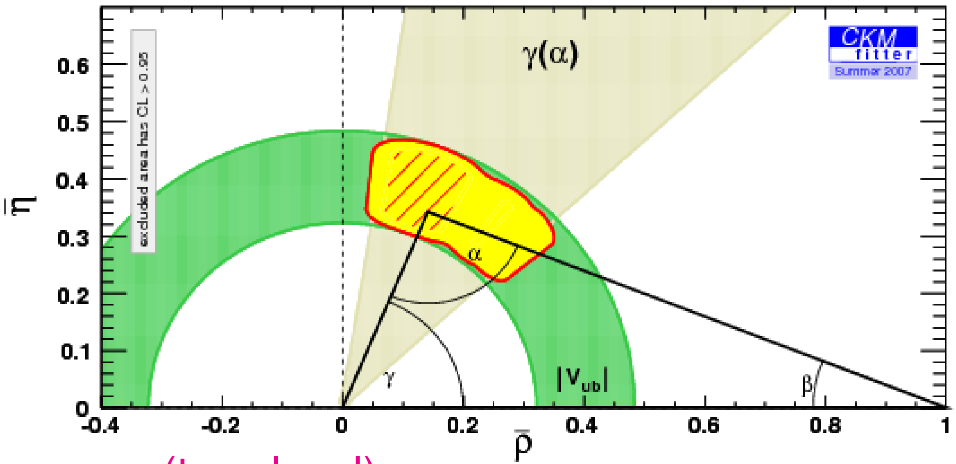
Many operators for $b \to s$ transitions — no simple parameterization of NP

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

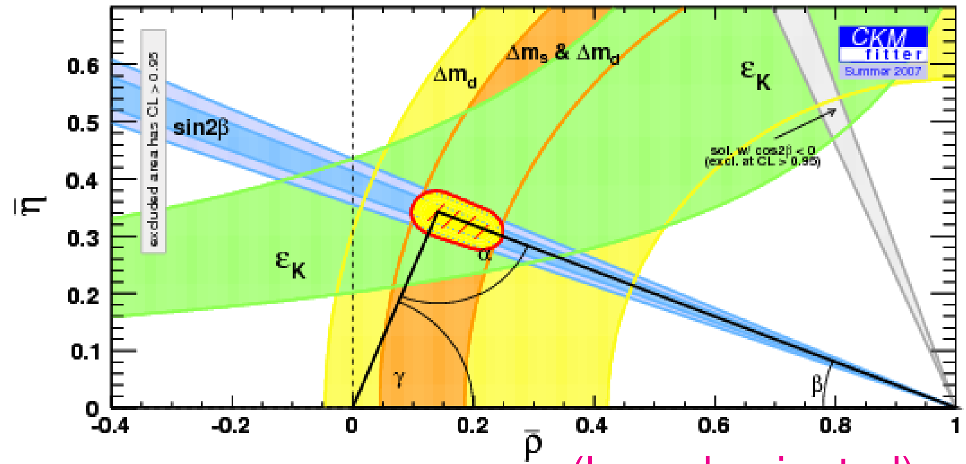
- Isolating modest NP contributions requires many measurements

  Compare NP-independent (tree) with NP-dependent (loop) processes

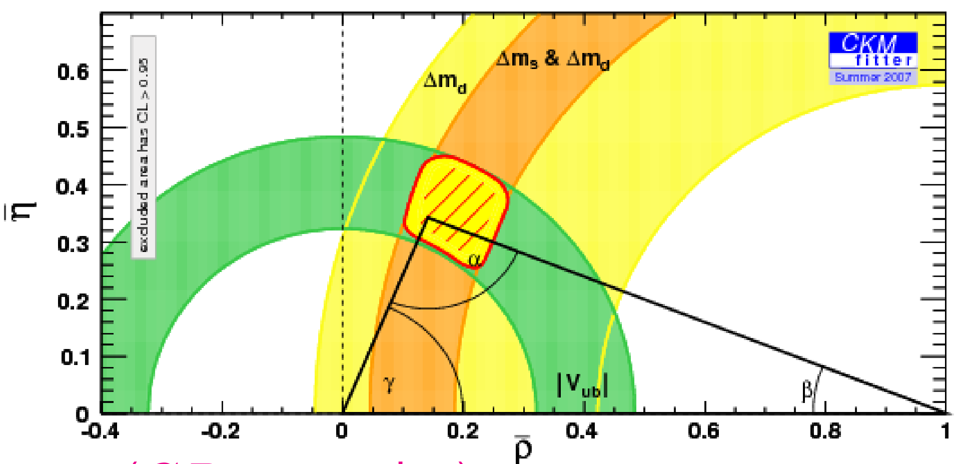
Overconstraining the standard model



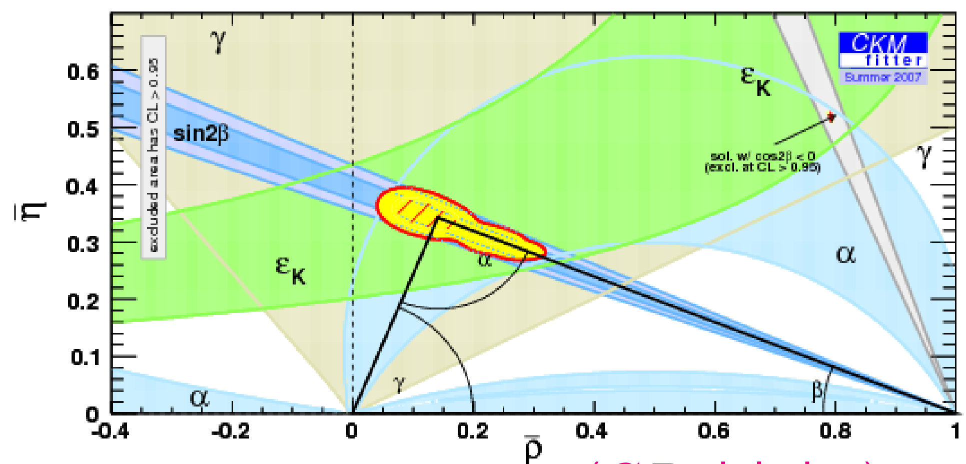
(tree-level)



(loop-dominated)



(CP conserving)



(CP violating)

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

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

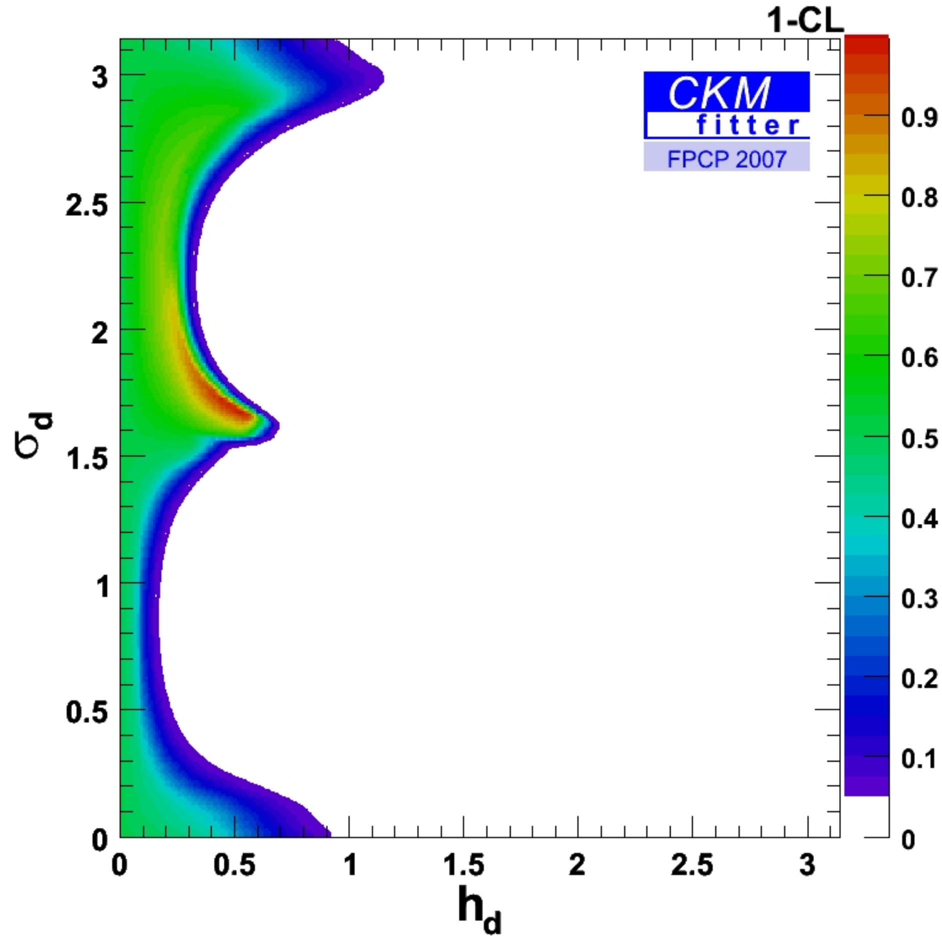
- Overconstraining ("redundant") measurements are crucial to bound new physics

  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

  What we really ask: is $\Lambda_{\rm flavor} \gg \Lambda_{\rm EWSB}$?

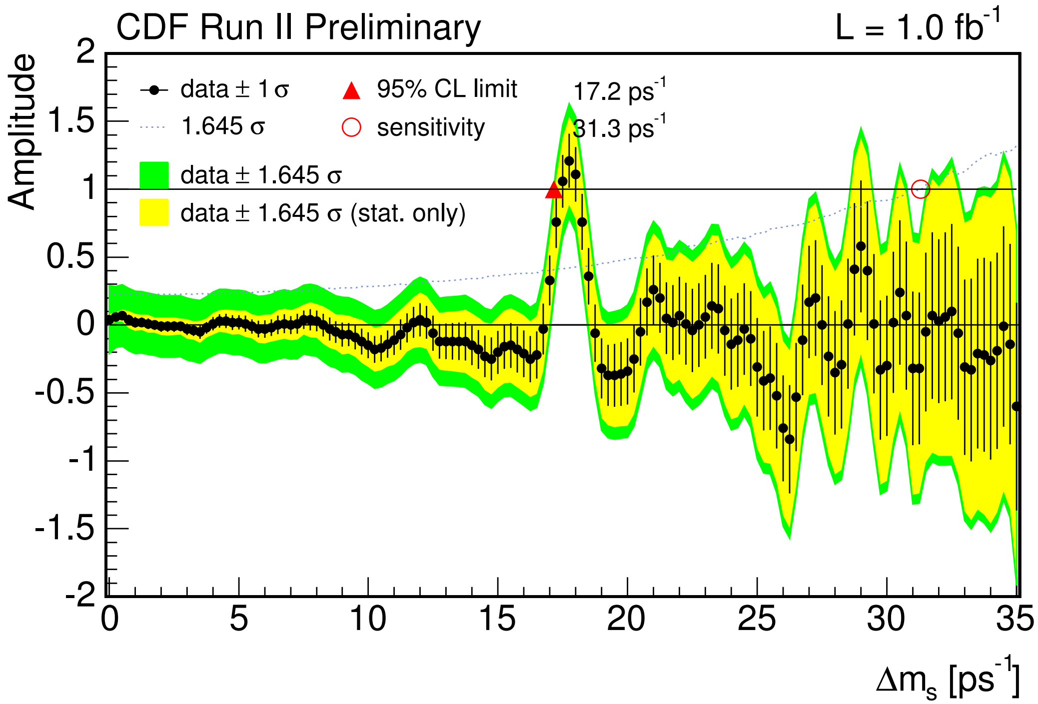
  Need a lot more data to be able to test if: NP $\ll$ SM unless $\sigma_d = 0$ (mod $\pi/2$)

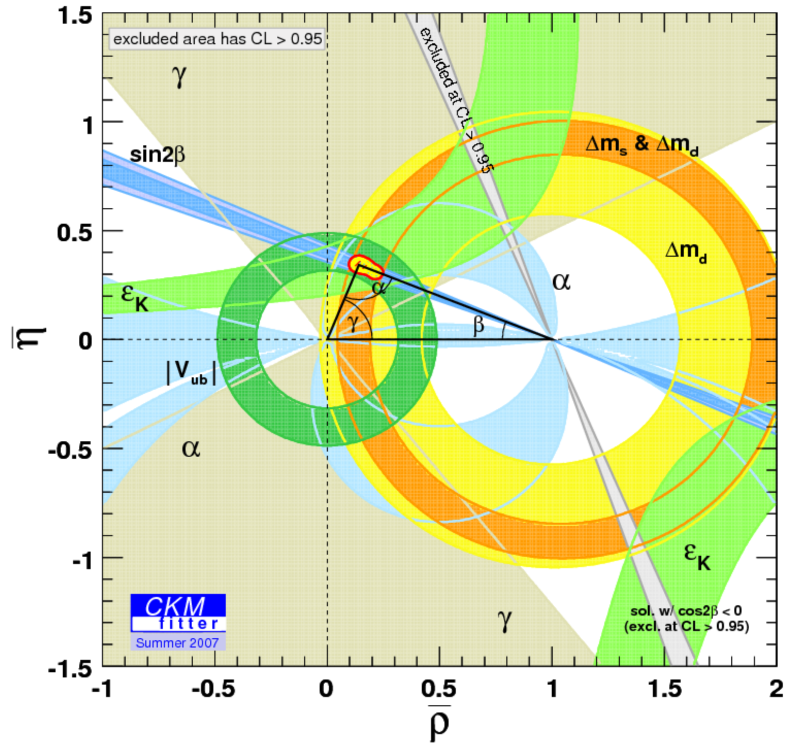


- 10–20% non-SM contributions to most loop-mediated transitions are still possible

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

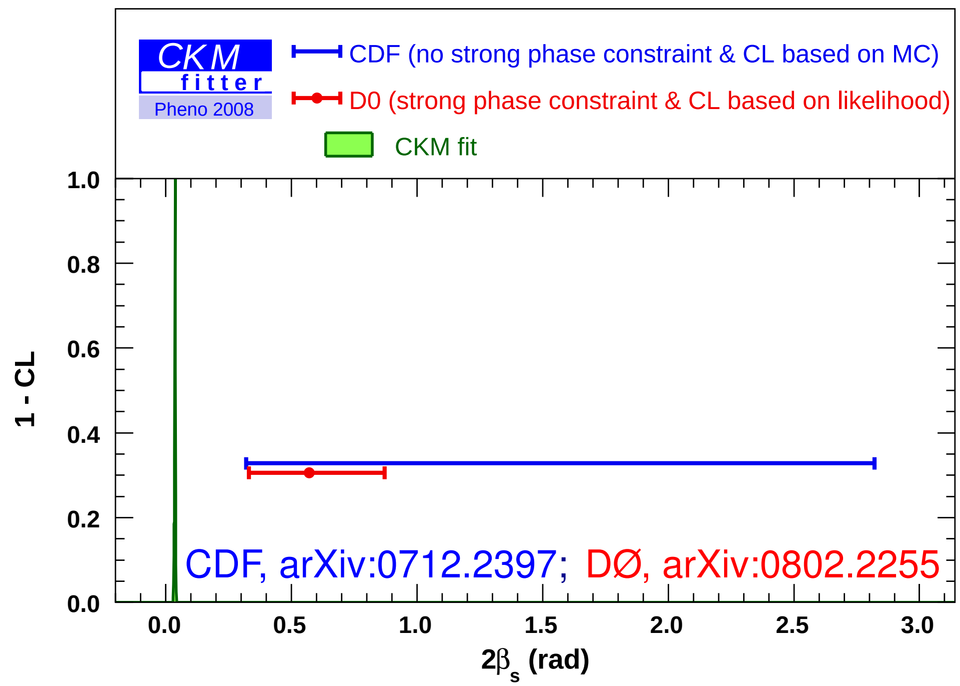
Lattice QCD: $\xi = 1.24 \pm 0.04 \pm 0.06$

B_s mixing: CP violation in $S_{\psi\phi}$ and $2\beta_s$

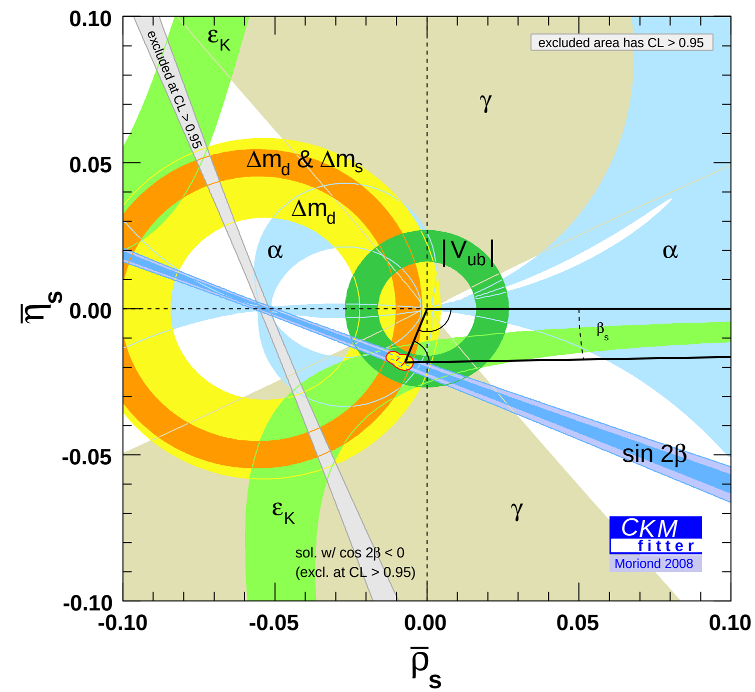
- Next key measurement: time dep. CP asymmetry in $B_s \to \psi\phi$ (as clean as $\sin 2\beta$)

  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:



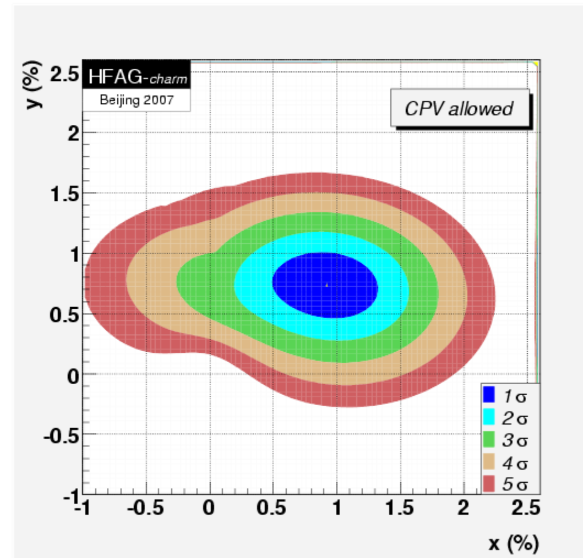
The B_s "squashed" UT:



Averag complicated due to different assumptions; should be available soon

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) $> 10^{-3}$ 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

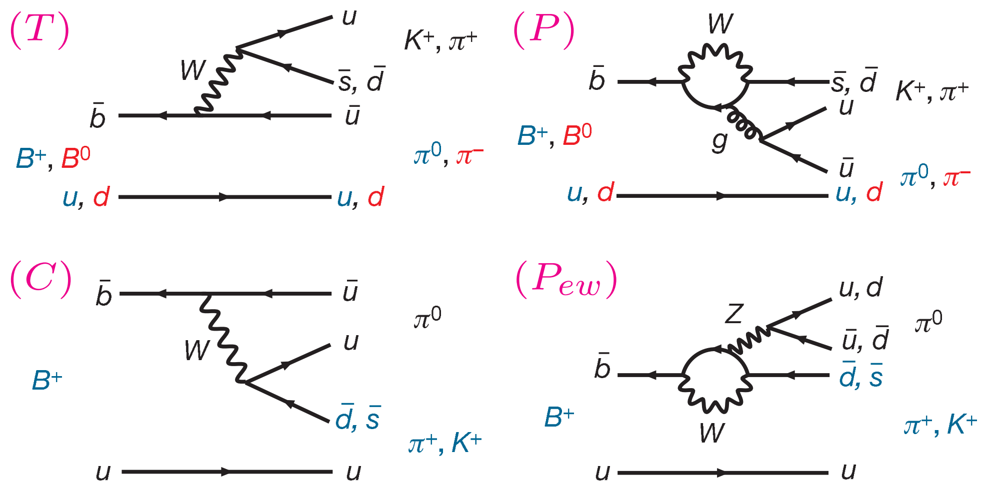
- **Q**: Have we seen new physics in CPV?

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

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

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)

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

- Measurements probe scales $\gg 1\,\mathrm{TeV}$; sensitivity limited by statistics, not theory

- New physics in most FCNC processes may still be $\gtrsim 10\%$ of the SM contributions

- Few hints of discrepancies; need more data and / or improved theory to resolve

- Great synergy between theoretical and experimental developments to learn both about electroweak and strong interactions

Forthcoming progress

Physics goals for LHCb & super-(KEK)B

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

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

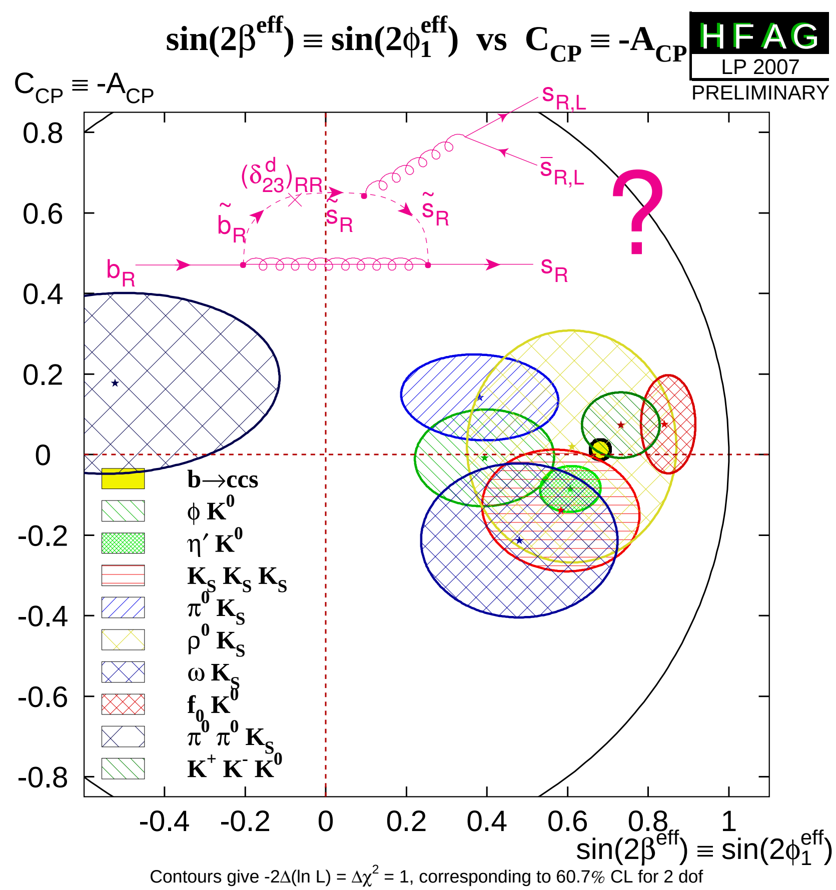
  Is the physics of 3rd–1st, 3rd–2nd, and 2nd–1st generation transitions the same?

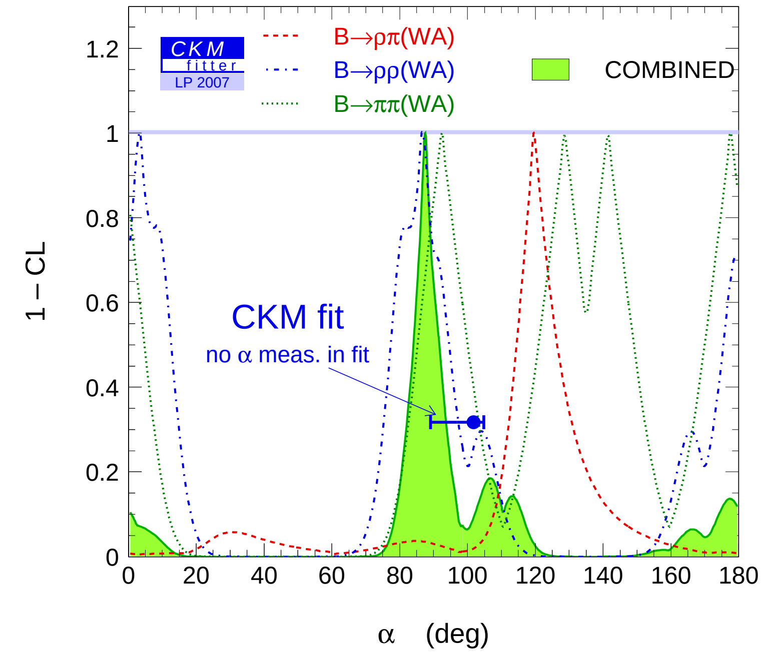
- If no NP is seen in flavor sector, similar constraints as LEP tests of gauge sector

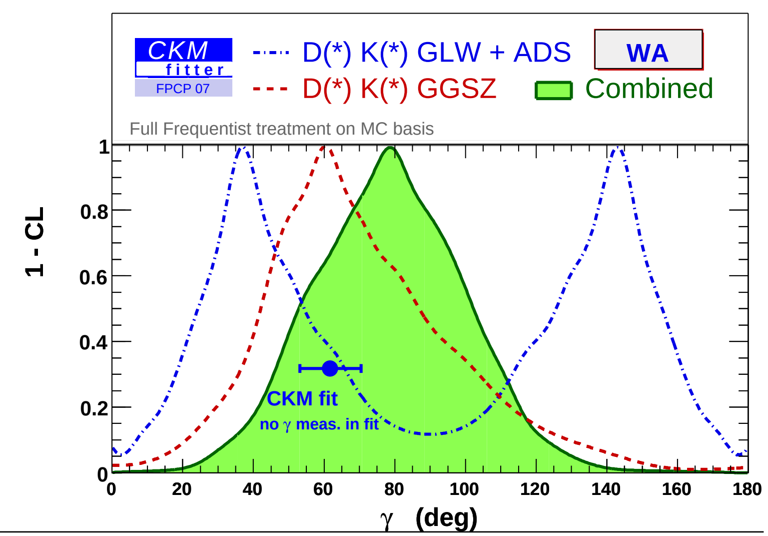
- If non-SM flavor physics is seen, try to distinguish between classes of models:
  - One / many sources of CPV?
  - In charged / neutral current interactions?
  - Modify SM operators / new operators?
  - Couples to up / down sector?
  - 3rd / all generations? $\Delta F = 2$ and / or 1?
  - Only to quarks / leptons?

  } Many interesting probes

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



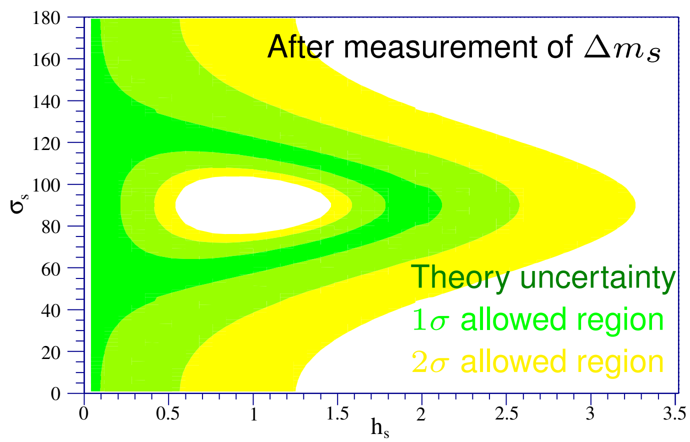


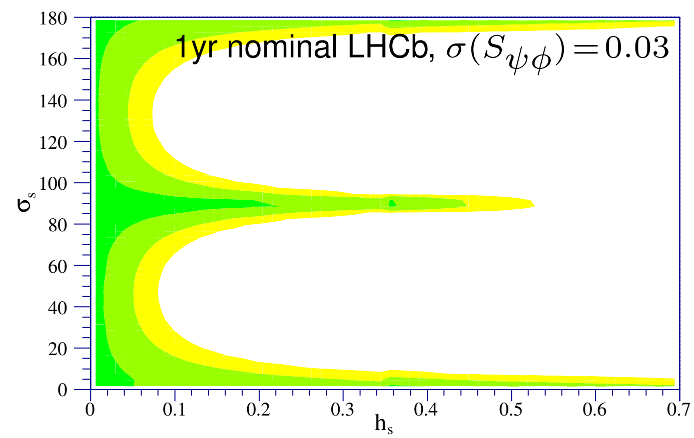


- E.g., $S_{\psi K} - S_{\phi K} = 0.29 \pm 0.17$; also for α & γ: want $\sim 10\times$ smaller error $\Rightarrow \sim 100\times$ more data
- Need both LHCb and e^+e^- super B factory

Some LHCb highlights

- 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.

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^-

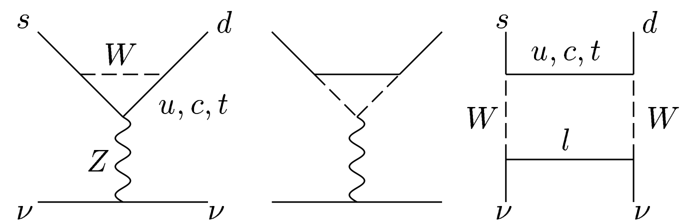
Skipping $\mu \to e\gamma$ and $K \to \pi\nu\bar{\nu}$

- $\mu \to e\gamma$: 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 $\mathcal{B} \sim 10^{-10}(K^\pm)$, $10^{-11}(K_L)$

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



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 $\propto A^4 \sim |V_{cb}|^4$)

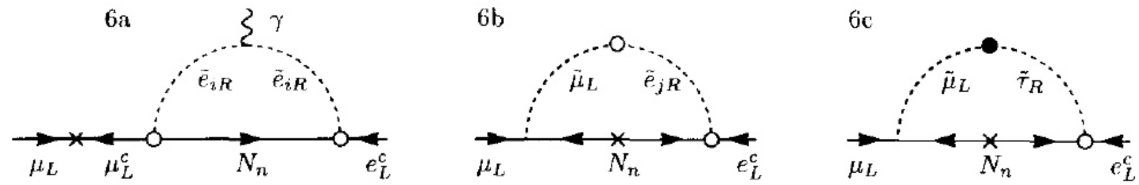
Proposals: CERN NA62: $K^+ \to \pi^+\nu\bar{\nu} \sim 60$ events/yr, 2011–2013
FNAL: get about a thousand (few hundred) events with(out) project-X
KEK E391a & J-PARC E14

Lepton flavor violation (in τ decays)

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

  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 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 $75\,\mathrm{ab}^{-1}$

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

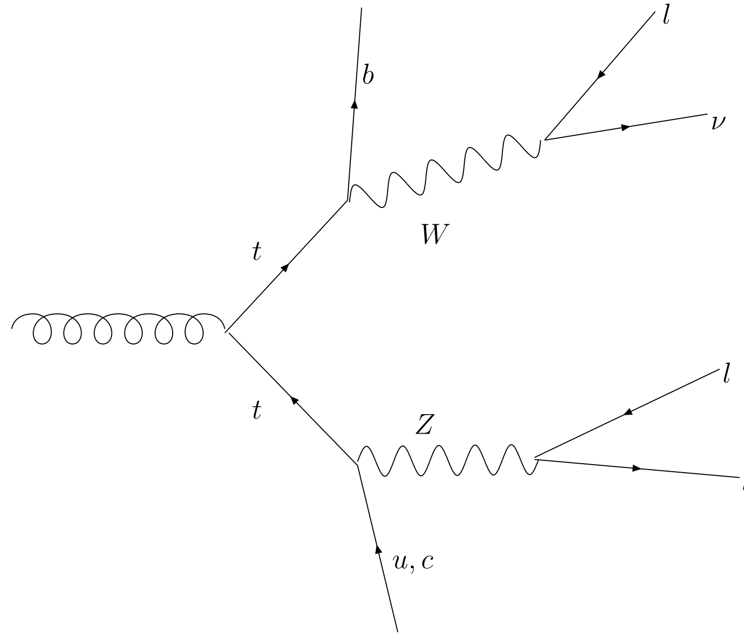
  If $(g-2)_\mu$ is due to NP, large hierarchy of coefficients ($\Rightarrow$ model building lessons)

Flavor @ high p_T

The LHC will be a top quark factory

- Flavor violation in top decays not well explored
  SM $\sim 10^{-13}$, current bound $> 10^{-2}$ [CDF, 0805.2109]

- Observable top FCNC possible in extensions of the SM and still allowed by B factory constraints
  [Fox *et al.*, 0704.1482; Botella *et al.*, 0805.3995; etc.]



- LHC: $1\, t\bar{t}$ pair / sec ($\sigma_{t\bar{t}} \sim 800\,$pb)
  Improve bounds on FCNC top decays by $> 10^3$

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 $\times 10^{-5}$

- If top FCNC seen, LHC & B factories together can probe the NP responsible for it

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

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 I view supersymmetry as 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?

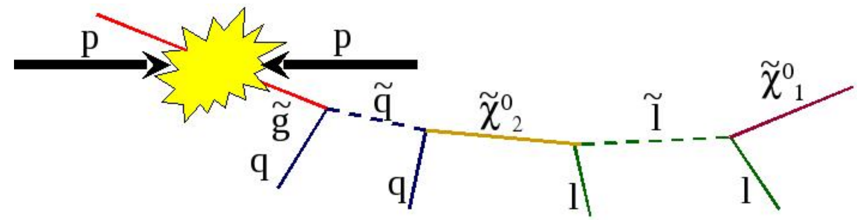
Flavor effects at the TeV scale

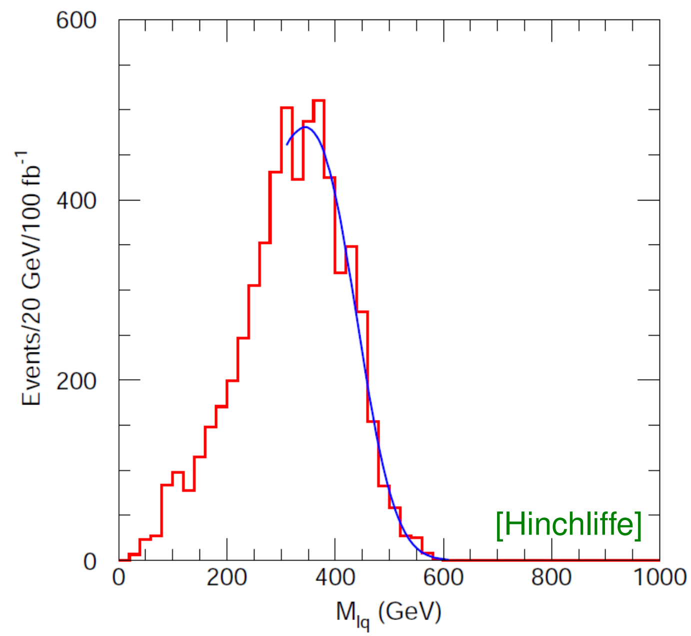
- Does flavor matter? Can we access flavor at high p_T?
- Some flavor aspects of LHC:
  - $p = g + u, d, s, c, b, \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}$ — has flavor
  - Hard to bound flavor properties of new particles (e.g., $Z' \to b\bar{b}$ vs. $Z' \to b\bar{s}$?)
  - Little particle ID: b (displaced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

- Long cascade decays, 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 $10 - 20\%$ 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: (i) minimal flavor violation

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

  [Chivukula & Georgi; Hall & Randall; D'Ambrosio, Giudice, Isidori, Strumia; Buras *et al.*]

  Assume SM Yukawa interactions are the only source of flavor and CP violation (global symmetry... how weakly / strongly broken?)

- 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 automatically occur as in the SM

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

- LHC data may rule out MFV or make it more plausible (so can LHCb & super-B)

  Explicit models with extended particle content where LHC can test (rule out) MFV

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

Recent trends: (ii) 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
  - flavor blind SUSY breaking at a lower scale [Feng *et al.*; Nomura, Papucci, Stolarski]
  - 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

Back to the beginning...

- Wanted to understand matter – antimatter asymmetry
  The LHC may help (new particles, new CP violation)

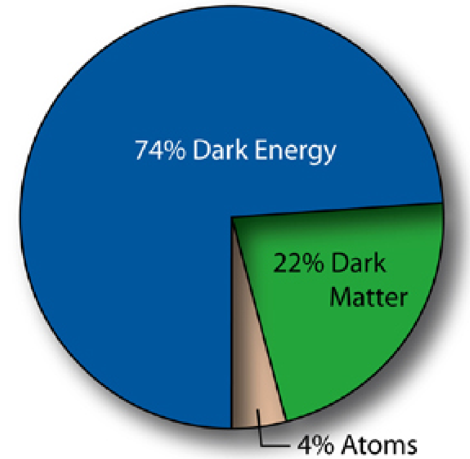
- We hope to also understand what dark matter is
  Perfect candidate: lightest supersymmetric particle

- Neutrino mass: may gain insights to relation between (s)quark and (s)lepton flavor

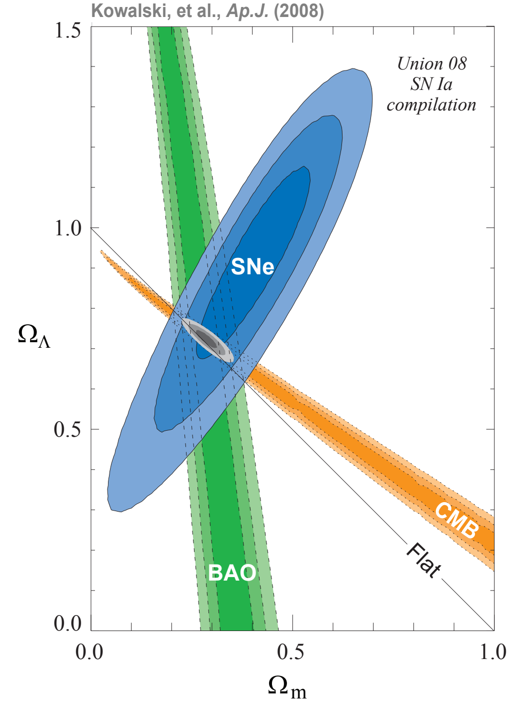
- Dark energy: accelerating expansion discovered (1998)
  $\Lambda_{\rm cc} \sim 10^{-29}\,{\rm g/cm^3} = 10^{-47}\,{\rm GeV^4} = 10^{-120}$ (Planck units)

  The LHC won't directly address the cosmological constant problem, but it may tell us if we (mis)understand fine-tuning

  Is it a coincidence that $\Lambda_{cc} \sim (1\,{\rm TeV}^2/M_{\rm Pl})^4$?



Supernova Cosmology Project
Kowalski, et al., *Ap.J.* (2008)



Back to the beginning...

- Wanted to understand matter – antimatter asymmetry
  The LHC may help (new particles, new CP violation)

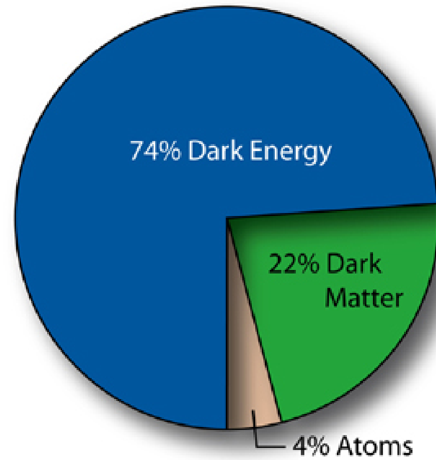
- We hope to also understand what dark matter is
  Perfect candidate: lightest supersymmetric particle

- Neutrino mass: may gain insights to relation between (s)quark and (s)lepton flavor

- Dark energy: accelerating expansion discovered (1998)
  $\Lambda_{\rm cc} \sim 10^{-29}\,{\rm g/cm^3} = 10^{-47}\,{\rm GeV^4} = 10^{-120}$ (Planck units)

  The LHC won't directly address the cosmological constant problem, but it may tell us if we (mis)understand fine-tuning

  Is it a coincidence that $\Lambda_{cc} \sim (1\,{\rm TeV}^2/M_{\rm Pl})^4$?



AMERICAN HYDROPONICS
Crop Performance Products Since 1984

Is it going to be Heaven?

- Last two years' discoveries: 2006: $B_s^0 - \overline{B}_s^0$ mixing, 2007: $D^0 - \overline{D}^0$ mixing will they be followed by...

Is it going to be Heaven?

- Last two years' discoveries: 2006: $B_s^0 - \overline{B}_s^0$ mixing, 2007: $D^0 - \overline{D}^0$ mixing will they be followed by...
  - Summer '08: CDF & DØ measure (no strong phase assumption): $2\beta_s = 0.9 \pm 0.3$

Is it going to be Heaven?

- Last two years' discoveries: 2006: $B_s^0 - \overline{B}_s^0$ mixing, 2007: $D^0 - \overline{D}^0$ mixing will they be followed by...
  - Summer '08: CDF & DØ measure (no strong phase assumption): $2\beta_s = 0.9 \pm 0.3$
  - Moriond '09: BaBar & Belle discover CP violation in $D^0 - \overline{D}^0$ mixing

Is it going to be Heaven?

- Last two years' discoveries: 2006: $B_s^0 - \overline{B}_s^0$ mixing, 2007: $D^0 - \overline{D}^0$ mixing will they be followed by...
  - Summer '08: CDF & DØ measure (no strong phase assumption): $2\beta_s = 0.9 \pm 0.3$
  - Moriond '09: BaBar & Belle discover CP violation in $D^0 - \overline{D}^0$ mixing
  - Summer '09: ATLAS & CMS: stat. insignificant, but peculiar events / accesses

Is it going to be Heaven?

- Last two years' discoveries: 2006: $B_s^0 - \overline{B}_s^0$ mixing, 2007: $D^0 - \overline{D}^0$ mixing
  will they be followed by...
  - Summer '08: CDF & DØ measure (no strong phase assumption): $2\beta_s = 0.9 \pm 0.3$
  - Moriond '09: BaBar & Belle discover CP violation in $D^0 - \overline{D}^0$ mixing
  - Summer '09: ATLAS & CMS: stat. insignificant, but peculiar events / accesses
  - Moriond 2010: LHCb discovers $\mathcal{B}(B_s \to \mu^+\mu^-) = (1.2 \pm 0.3) \times 10^{-8}$

Is it going to be Heaven?

- Last two years' discoveries: 2006: $B_s^0 - \overline{B}_s^0$ mixing, 2007: $D^0 - \overline{D}^0$ mixing will they be followed by...
  - Summer '08: CDF & DØ measure (no strong phase assumption): $2\beta_s = 0.9 \pm 0.3$
  - Moriond '09: BaBar & Belle discover CP violation in $D^0 - \overline{D}^0$ mixing
  - Summer '09: ATLAS & CMS: stat. insignificant, but peculiar events / accesses
  - Moriond 2010: LHCb discovers $\mathcal{B}(B_s \to \mu^+\mu^-) = (1.2 \pm 0.3) \times 10^{-8}$
  - Summer 2010: ATLAS & CMS: evidence for what appears like $\tilde{\mu}$ NLSP

Is it going to be Heaven?

- Last two years' discoveries: 2006: $B_s^0 - \overline{B}_s^0$ mixing, 2007: $D^0 - \overline{D}^0$ mixing
  will they be followed by...

  – Summer '08: CDF & DØ measure (no strong phase assumption): $2\beta_s = 0.9 \pm 0.3$

  – Moriond '09: BaBar & Belle discover CP violation in $D^0 - \overline{D}^0$ mixing

  – Summer '09: ATLAS & CMS: stat. insignificant, but peculiar events / accesses

  – Moriond 2010: LHCb discovers $\mathcal{B}(B_s \to \mu^+\mu^-) = (1.2 \pm 0.3) \times 10^{-8}$

  – Summer 2010: ATLAS & CMS: evidence for what appears like $\tilde{\mu}$ NLSP

... would settle for less

Conclusions

- Consistency of precision flavor measurements with SM is a problem for NP @ TeV
- Low energy tests will continue to improve in the next decade
  Sensitivity to lepton flavor violation will improve by 10–1000 in many channels
- If no NP signal is found in the flavor sector, constraints will give important clues to model building in the LHC era (similar to tests of the gauge sector at LEP)
- 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
- Interplay between direct & indirect probes of NP will provide important information
  – synergy in reconstructing the underlying theory (distinguish between models)
  – complementary coverage of param. space (subleading couplings, $\gg$TeV scales)

Backup slides

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]

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: $(S = \tilde{Q}_L, \tilde{\bar{D}}_L, \tilde{\bar{U}}_L, \tilde{L}_L, \tilde{\bar{E}}_L)$

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

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

$5\ m^2_S$ 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)

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

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

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

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

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

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: $\sin 2\beta = 0.681 \pm 0.025$ — 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

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