Physics reach of future flavor physics experiments

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- Flavor physics — current status
  ... Sizable NP contributions still possible
- Forthcoming progress
  ... Measurements and interpretations
- Some key processes
  ... Flavor as a probe of NP
- Conclusions

Which future experiments? Aren't we done yet?

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

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

- What are the theoretical uncertainties?

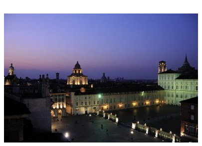
  Highly process dependent; some measurements already limited by theoretical uncertainties, while in other cases theory uncertainties are smaller than the expected sensitivity of future experiments.

- What can we expect in terms of experimental precision?

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

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

  The new flavor physics data will be complementary with the high-pT part of the LHC program. The synergy of both data sets can teach us a lot about the new physics at the TeV scale.



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What is flavor physics?

- The SM is consistent with a vast amount of particle physics phenomena

  special relativity $+$ quantum mechanics, local symmetry $+$ spontaneous breaking

- What breaks $SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$ "Electroweak symmetry breaking"

  What is the physics of Higgs condensate? What generates it? What else is there?

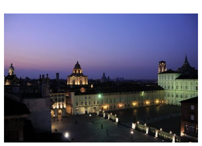
  The LHC will directly address this (make h)

- What breaks $U(3)_Q \times U(3)_u \times U(3)_d \to U(1)_{\rm Baryon}$ "Flavor physics"

  Which interactions distinguish generations (e.g., d, s, b identical if massless)?

  How do the fermions see the condensate and the physics associated with it?

- TeV-scale new physics models typically have new sources of flavor & CP violation which may be possible to probe in flavor physics but not directly at the LHC



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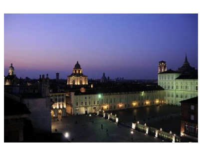
Why is flavor physics interesting?

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

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

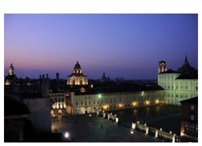
  - Many extensions of the SM have new sources of CP and flavor violation
  - The observed baryon asymmetry of the Universe requires CPV beyond the SM
    Not necessarily in flavor changing processes, nor necessarily in quark sector
    Flavor suppression destroys KM baryogenesis; flavor matters for leptogenesis
- Flavor sector can be tested a lot better, many NP models have observable effects



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

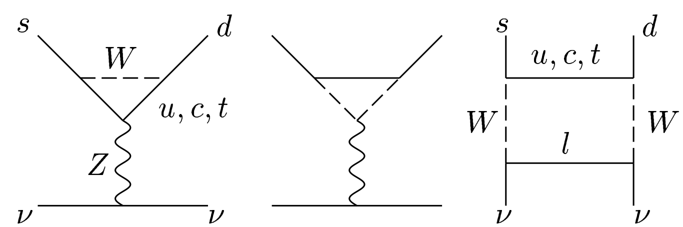


Current status

The “first” meson mixing: K^0

- CPV in K system is at the right level (ϵ_K accommodated with $\mathcal{O}(1)$ CKM phase)
- Hadronic uncertainties preclude precision tests (ϵ'_K notoriously hard to calculate)
- $K \to \pi\nu\overline{\nu}$: Theoretically clean, but small rates $\mathcal{B} \sim 10^{-10}(K^{\pm}),\ 10^{-11}(K_L)$

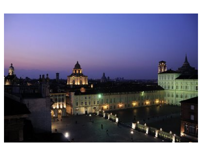
$$\mathcal{A} \propto \begin{cases} (\lambda^5\, m_t^2) + i(\lambda^5\, m_t^2) & t: \text{CKM suppressed} \\ (\lambda\, m_c^2) + i(\lambda^5\, m_c^2) & c: \text{GIM suppressed} \\ (\lambda\, \Lambda_{\rm QCD}^2) & u: \text{GIM suppressed} \end{cases}$$



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

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

Proposals: CERN NA62: $K^+ \to \pi^+\nu\bar{\nu} \sim 50$ events/yr, 2013 – 2015
FNAL: get about a thousand (few hundred) events with(out) project-X
KEK E391a & J-PARC E14



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

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

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

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

- Classes of models to suppress each factors

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

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

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

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

The standard model CKM fit

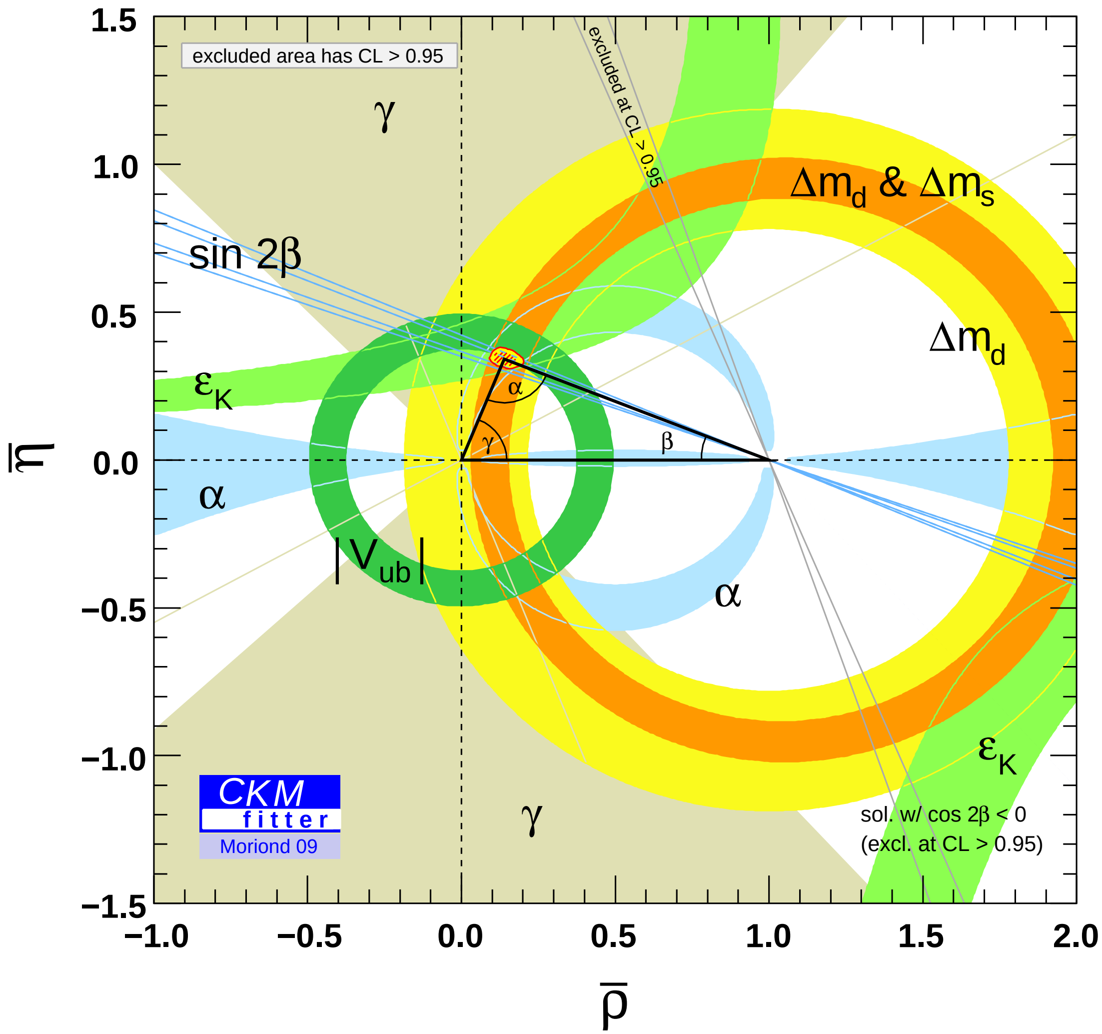
- Very impressive accomplishments

  $\mathcal{O}(20)$ CPV measurements at $> 3\sigma$

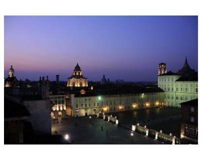
- The level of agreement between the various measurements is often misinterpreted

- Plausible TeV scale NP scenarios, consistent with all low energy data

- 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.)



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

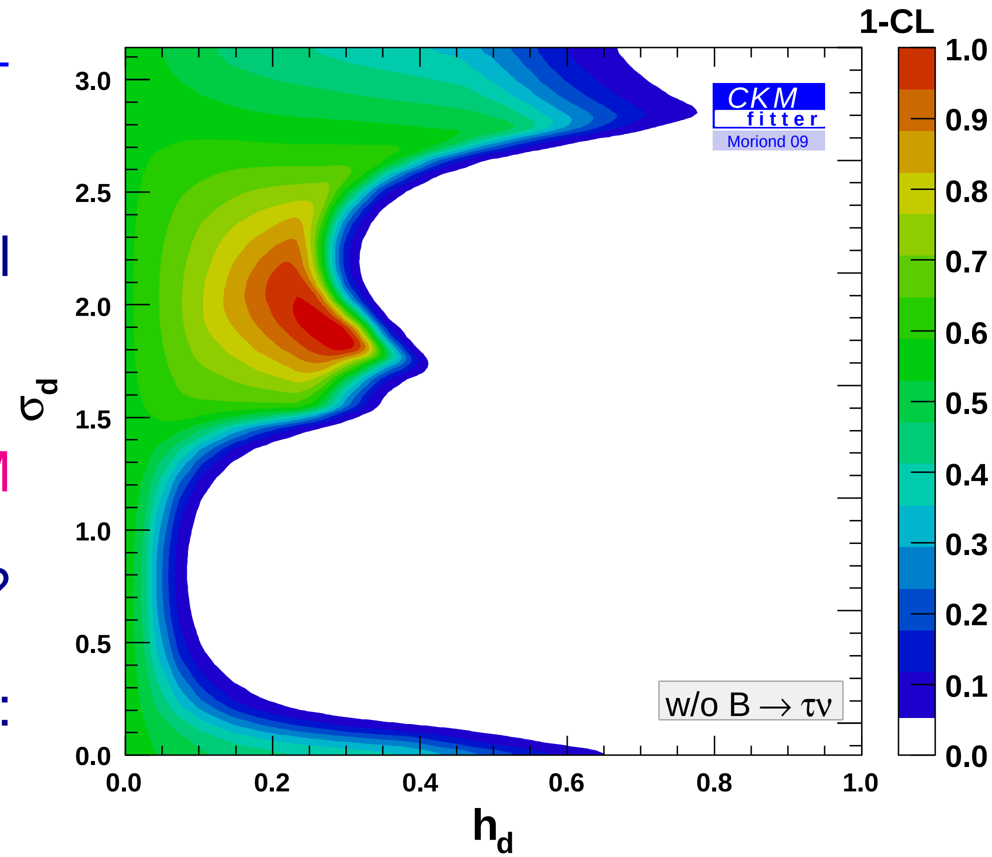
- Overconstraining ("redundant") measurements are crucial to bound new physics

  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 $\pi/2$)



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

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

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

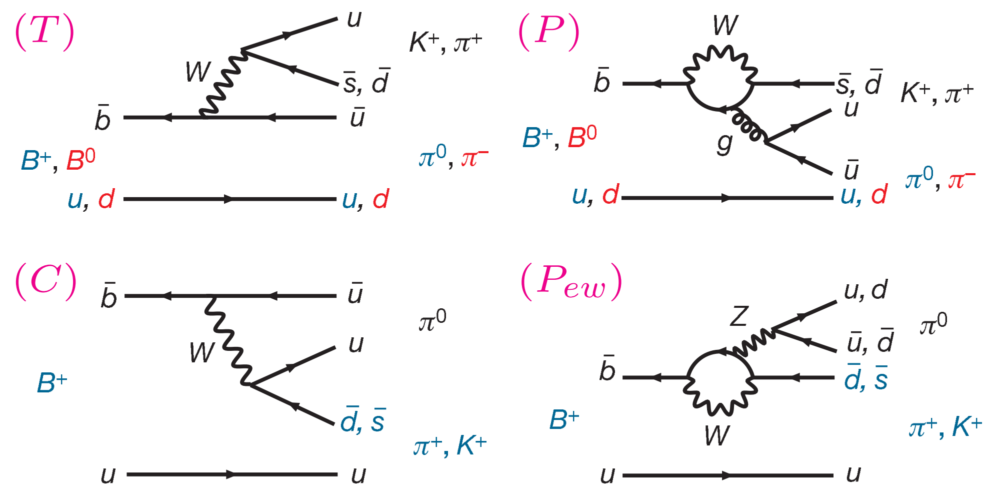
- **Q**: Have we seen new physics in CPV?

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

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

What's the reason for large difference?

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



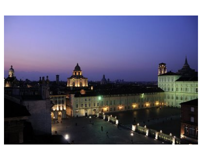
(Annihilation not shown) [Belle, Nature 452, 332 (2008)]

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

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

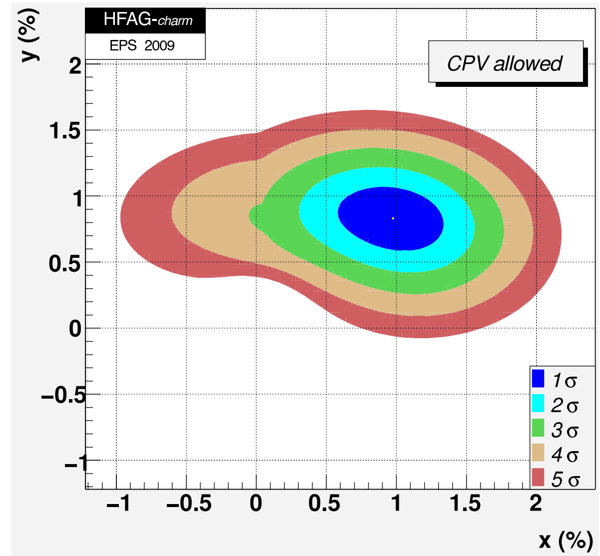
- No similarly clear tension in branching ratios, e.g., Lipkin sum rule is OK by now:

$$2\,\frac{\bar\Gamma(B^- \to \pi^0 K^-) + \bar\Gamma(\overline{B}{}^0 \to \pi^0 \overline{K}{}^0)}{\bar\Gamma(B^- \to \pi^- \overline{K}{}^0) + \bar\Gamma(\overline{B}{}^0 \to \pi^+ K^-)} = 1.05 \pm 0.05 \qquad \text{(should be near 1)}$$

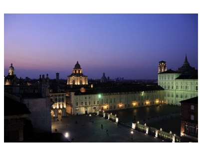


The “last” meson mixing: D^0

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



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



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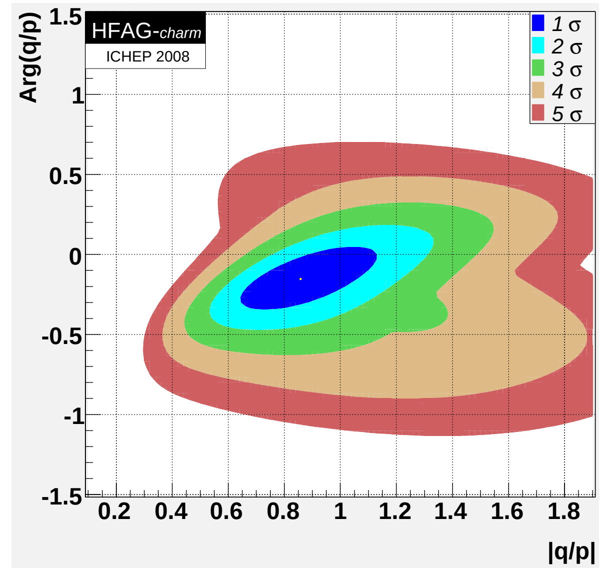
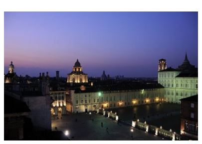
  - CPV (mixing or direct) $> 10^{-3}$ would be sign of NP
  - To do: Precise values of Δm and $\Delta\Gamma$?
    Is CPV absent in mixing and decays?



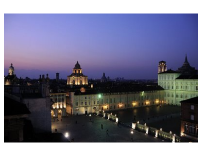
Not yet known if $|q/p| \simeq 1$

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



Summary — current status

- The SM flavor sector has been tested with impressive & increasing precision
  KM phase is the dominant source of CP violation in flavor changing processes
- 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



Future progress

The name of the game in the LHC era

- The question has been who sees NP first; once it's seen, how to understand it? [Assume the LHC sees more than a Higgs ...]
- Concentrate on topics where sensitivity can improve significantly (by an order of magnitude, or at least a factor of many)
  - Skip $B \to X_s\gamma$ rate, not far from "theory wall" (best bound on many models!)
    ... Possible tension between $\sin 2\beta$ and $|V_{ub}|$ (or $B \to \tau\nu$)
    ... The 3.2σ effect in $A_{\rm SL}$ by DØ
  - 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 new physics to duplicate GIM and CKM suppressions

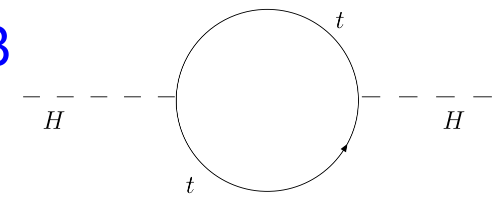
Reasons to pursue flavor physics

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

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

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

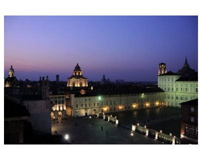
  Motivated models: NP $\Leftrightarrow$ 3rd gen. $\neq$ NP $\Leftrightarrow$ 1st & 2nd gen.



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

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

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



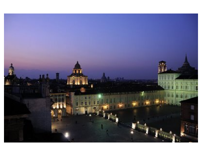
Where to look? Suppressed / forbidden processes

- SM suppressed / forbidden processes:
  - FCNC processes ($\Delta F = 2$ and $\Delta F = 1$)
  - CP violation

  Combine several measurements for optimal sensitivity (more of the same? recall Babar physics book: compare sides & angles, "redundant" measurements of β)

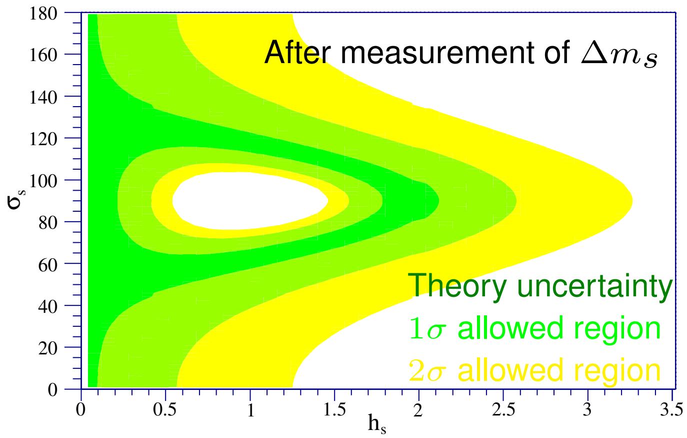
- "Standalone" discovery channels (way smaller SM backgrounds):
  - Lepton flavor / number violation (μ and τ decays)
  - Electric dipole moments (flavor diagonal / off-diagonal CPV?)
  - top FCNCs

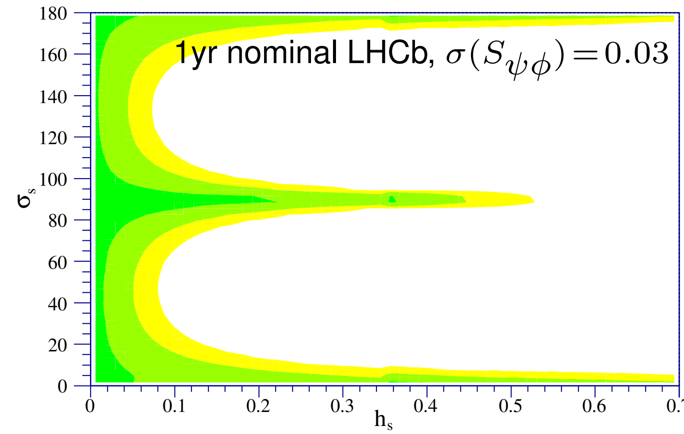
- Even if TeV-scale NP has the same loop + GIM suppressions in FCNC's as the SM, still expect deviations at the percent level



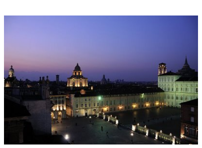
Some LHCb highlights

- LHCb will probe new physics in B_s decays comparable to the tests for B_d mesons
- After CDF measurement of Δm_s, large new physics contribution was still allowed





  - $B_s \to \mu^+\mu^-$ ($\propto \tan^6\beta$), 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 $B_s \to D_s^{\pm}K^{\mp}$ & other modes, α from $\rho\pi$ (probably super-B/KEKB wins)
  - Precisely measure τ_{Λ_b} — affects how much we trust $\Delta\Gamma_{B_s}$ calculation, etc.



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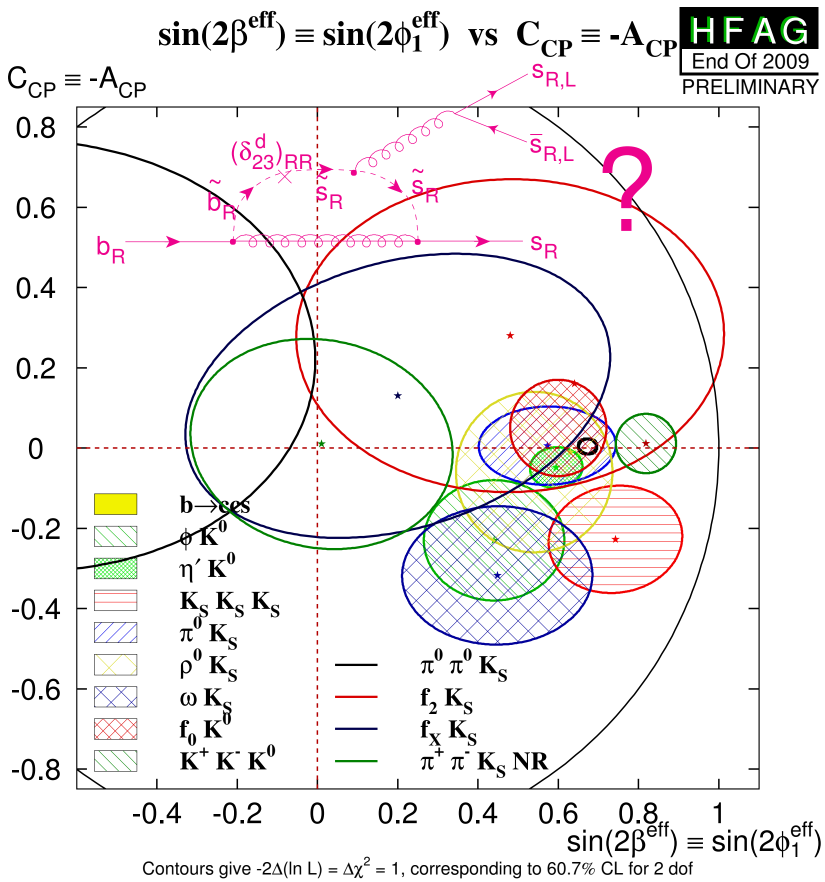
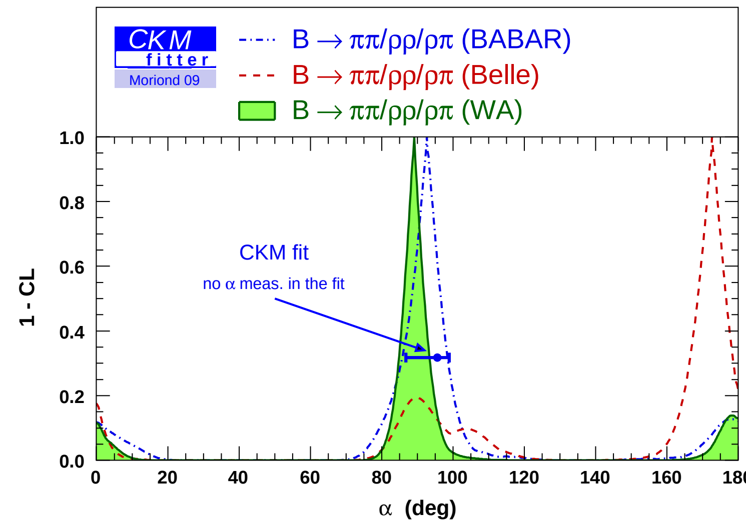
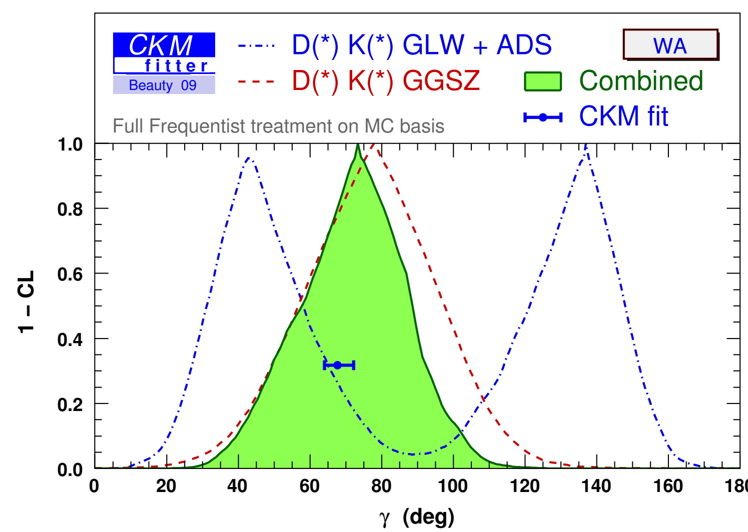
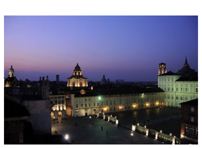
$\sin 2\beta_{\rm eff}$, α, γ — large improvements possible







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



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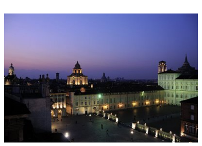
The rare B decay landscape

- Important probes of new physics (a crude guide, $\ell = e$ or μ)

Decay	$\sim$ SM rate	present status	expected
$B \to X_s\gamma$	3.2×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	4%
$B \to \tau\nu$	1×10^{-4}	$(1.67 \pm 0.39) \times 10^{-4}$	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}	$(3.7 \pm 0.8) \times 10^{-6}$	6%
$B_s \to \tau^+\tau^-$	1×10^{-6}	$<$ few $\%$	$\Upsilon(5S)$ run ?
$B \to X_s\,\tau^+\tau^-$	5×10^{-7}	$<$ few $\%$	?
$B \to \mu\nu$	4×10^{-7}	$< 1.0 \times 10^{-6}$	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}	$< 4 \times 10^{-8}$	LHCb
$B \to \mu^+\mu^-$	1×10^{-10}	$< 1.5 \times 10^{-8}$	LHCb

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

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



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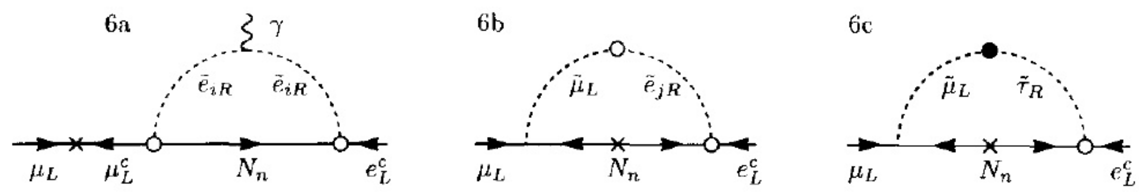
Lepton flavor violation (in τ decays)

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

  Very large model dependence

  $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma) \sim 10^{3\pm2}$



  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

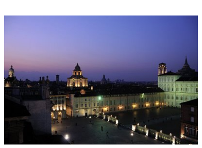
Super B sensitivity with $75\,\mathrm{ab}^{-1}$

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

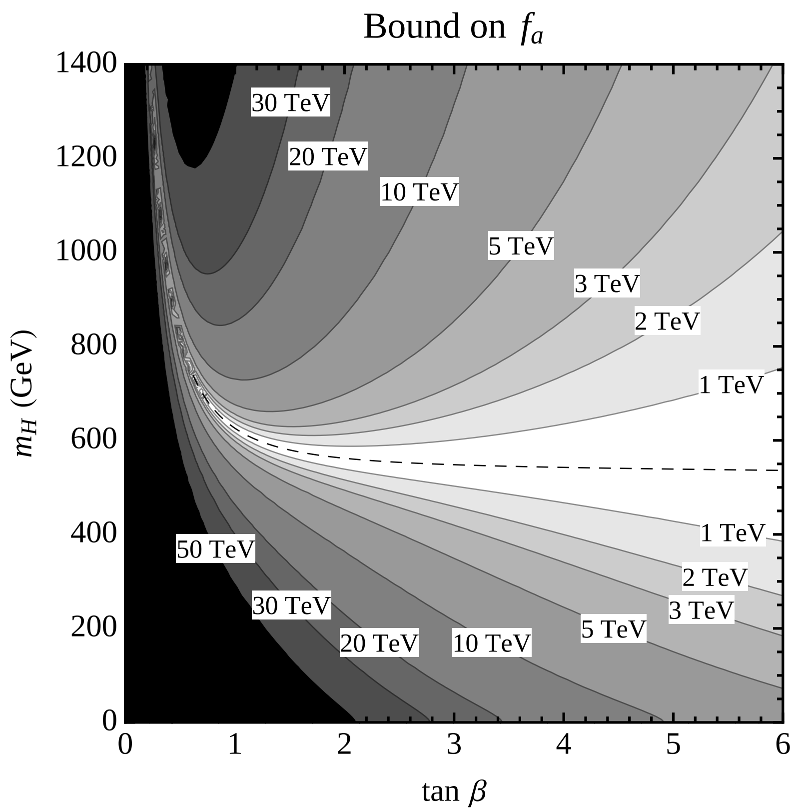
  If $(g-2)_\mu$ is due to NP, large hierarchy of coefficients ($\Rightarrow$ model building lessons)



“Odd” searches: probe DM models with B decays

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

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

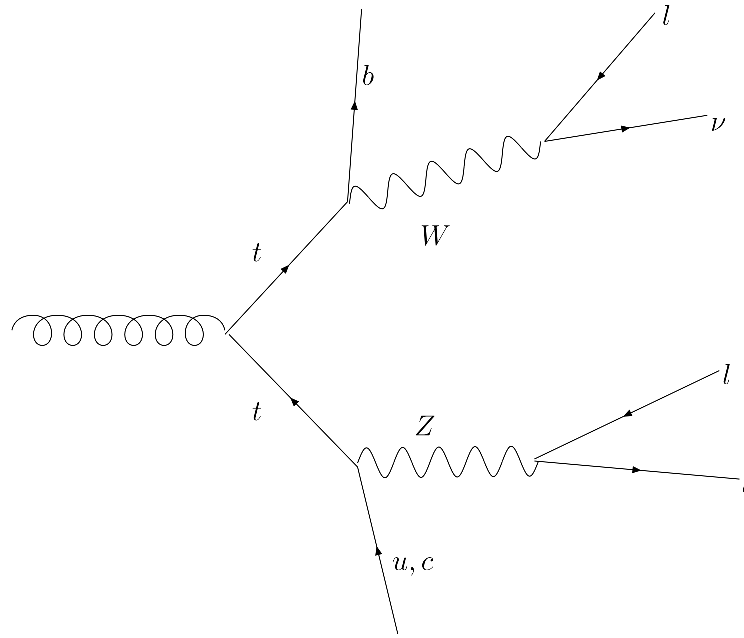


[Freytsis, ZL, Thaler, arXiv:0911.5355]

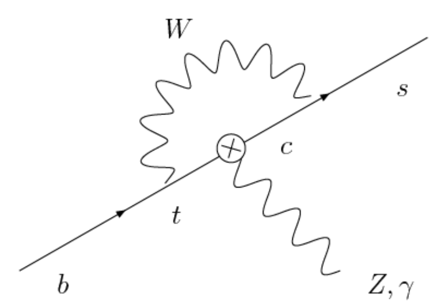
- Best bound in most of parameter space is from $B \to K\ell^+\ell^-$; can be improved

Flavor @ high p_T

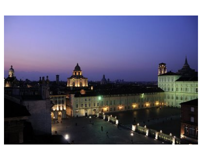
FCNC top decays at the LHC?



- 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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Supersymmetry and flavor at the LHC

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

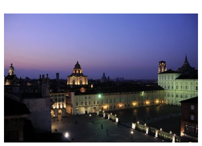
  What are their properties: mass, decay modes, spin, production cross section?

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

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

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

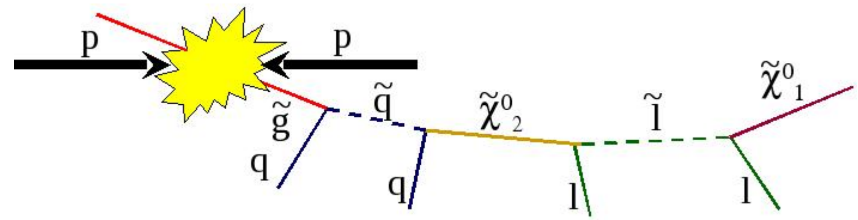
- Does flavor matter at ATLAS & CMS? Can we probe Sflavor directly at high p_T?



Flavor effects at the TeV scale

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

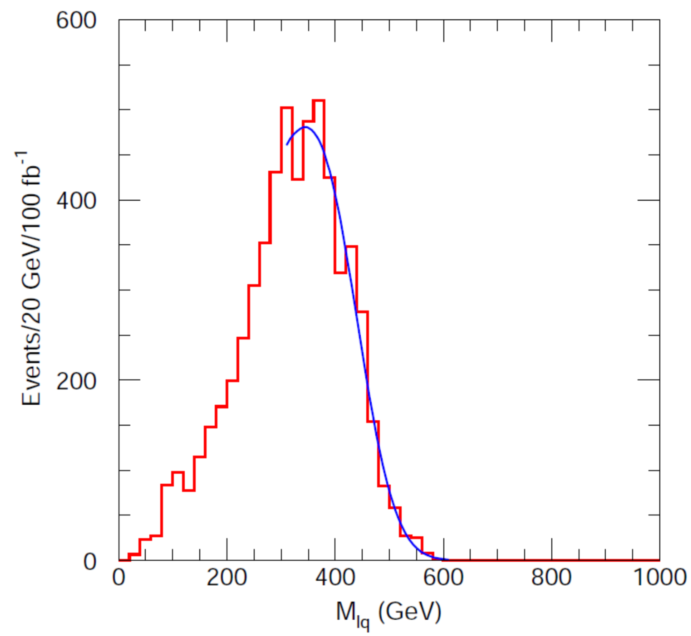
Detection of SUSY particles



- At each vertex two supersymmetric particles

  Lightest SUSY particle (LSP) undetected

- Reconstruct masses via kinematic endpoints

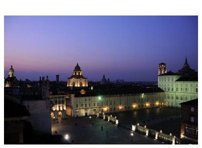


- Most experimental studies use reference points which set flavor (i.e., generation) off-diagonal rates to zero (and $\tilde{m}_1^2 = \tilde{m}_2^2 \neq \tilde{m}_3^2$)

- Some off-diagonal rates can still be $10-20\%$ or more, consistent with all low energy data

- Flavor can complicate determination of sparticle masses from cascade decays

  ... can modify the discovery potential of some particles



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Recent trends: flavorful SUSY models

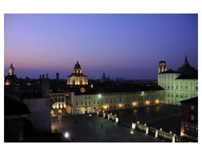
- Emerging non-MFV models w/ interesting flavor structure, consistent with all data

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

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

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

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



Final comments

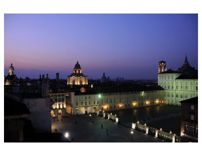
Theoretical limitations (continuum methods)

- 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



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Looking for unknown unknowns[1]

- Will NP be seen in the quark sector?

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

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

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

- Will NP be seen in the lepton sector?

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

- Will LHC see new particles beyond a Higgs?

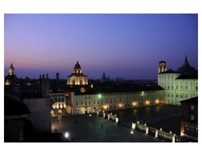
  SUSY, something else, understand in detail?

- I don't know, but I'm sure it's worth finding 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]



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Conclusions

- Consistency of precision flavor measurements with SM is a problem for NP @ TeV
- Despite huge progress, not yet known if NP $\ll$ SM in FCNCs (probe scale $\gg$ LHC)
- Low energy tests will improve a lot in next decade, by 10–1000 in some channels
  Exploring influence of NP requires LHCb, super-B factories, K, lepton flavor viol.
- 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

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:

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

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

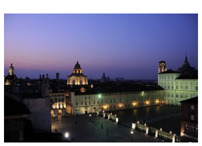
$$S_{\rho\rho} = \sin(2\alpha - 2\theta_d)$$

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

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

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

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



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Neutral meson mixings

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

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

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

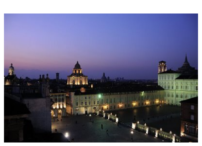
$$B_s\text{: long-lived} = CP\text{-odd } (1.5\sigma) = \text{heavy in the SM}$$

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

Before 2006, we only knew experimentally the kaon line above

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

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



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Some key CPV measurements

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

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

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

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

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

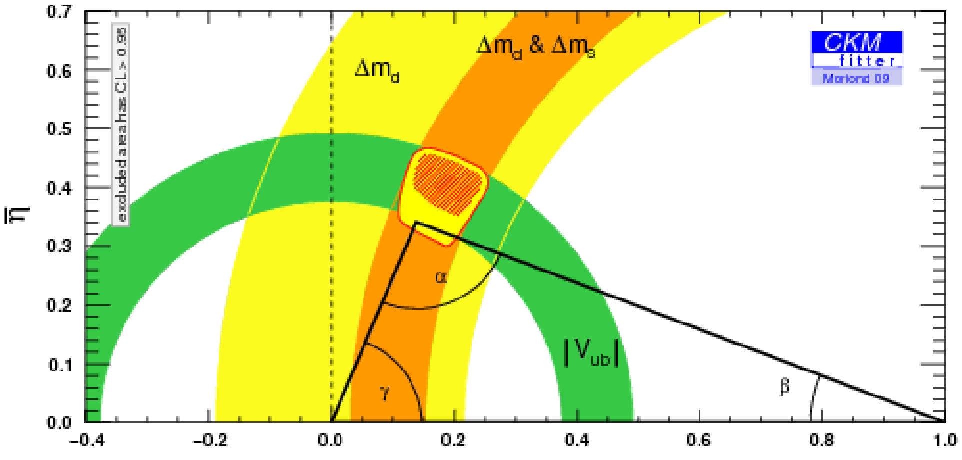
  CLEO 1997: $K\pi$ large, $\pi\pi$ small $\Rightarrow P_{\pi\pi}/T_{\pi\pi}$ large $\Rightarrow$ pursue all $\rho\rho$, $\rho\pi$, $\pi\pi$ modes

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

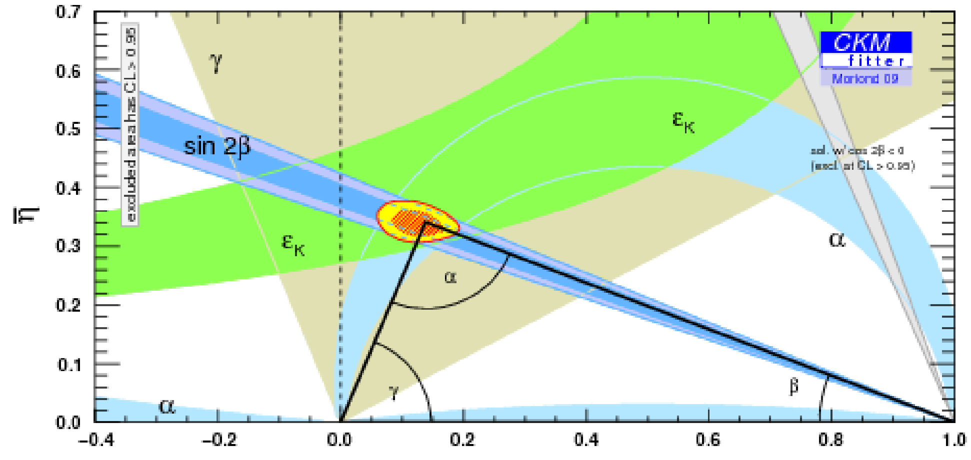
  Several difficult measurements ($D \to K_S \pi^+\pi^-$, D_{CP}, CF vs. DCS)

- Need a lot more data to approach irreducible theoretical limitations

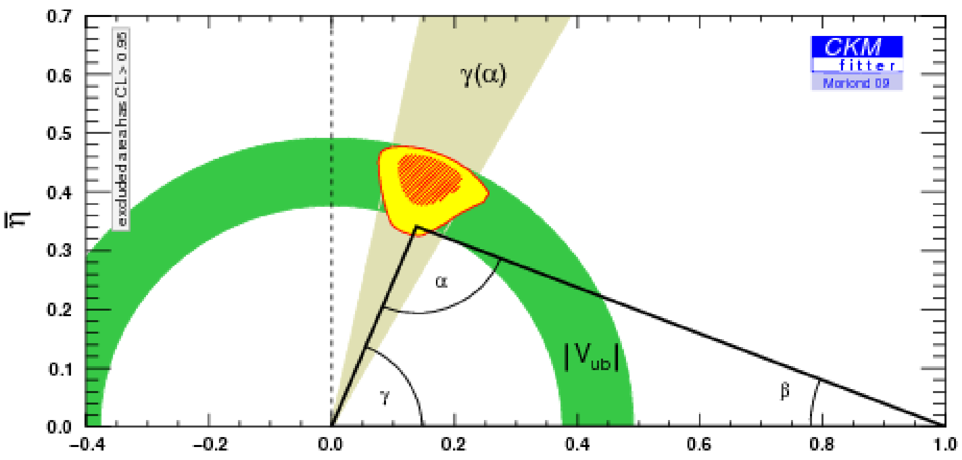
Overconstraining the standard model



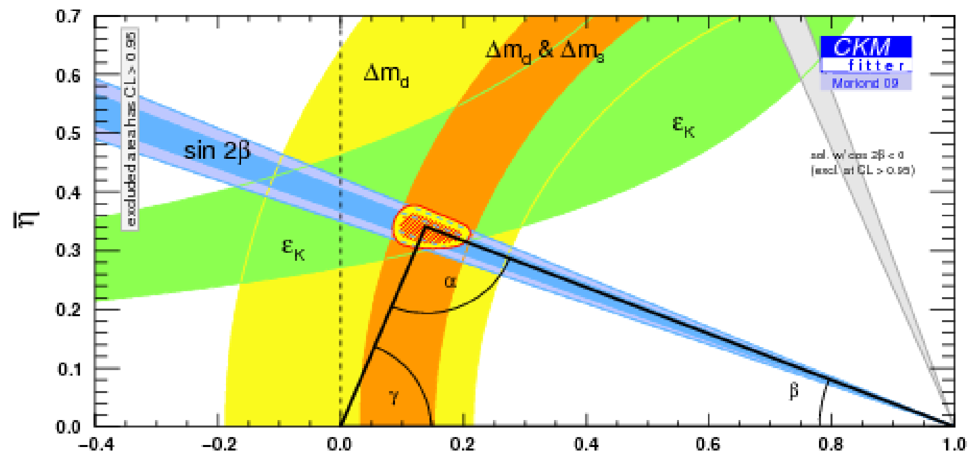
(CP conserving)



(CP violating)

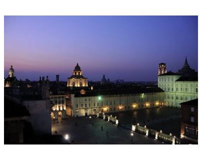


(tree-level)



(loop-dominated)

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



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Recent trends: (i) minimal flavor violation

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

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

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

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

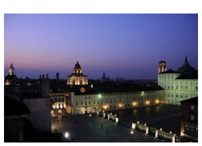
- CKM and GIM (m_q) suppressions similar to SM; allows EFT-like analyses

  Imposing MFV, best constraints from:

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

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

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



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Many interesting processes

- Complementarity of pp and e^+e^- b factories

Observable	Approximate SM prediction	Present status	Uncertainty / number of events	
			Super-B ($50\,\text{ab}^{-1}$)	LHCb ($10\,\text{fb}^{-1}$)
$S_{\psi K}$	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_{SL}	-5×10^{-4}	$-(5.8 \pm 3.4) \times 10^{-3}$	10^{-3}	10^{-3}
A^s_{SL}	2×10^{-5}	$(1.6 \pm 8.5) \times 10^{-3}$	$\Upsilon(5S)$ run?	10^{-3}
$A_{CP}(b \to s\gamma)$	< 0.01	-0.012 ± 0.028	0.005	—
$\lvert V_{cb}\rvert$	input	$(41.2 \pm 1.1) \times 10^{-3}$	1%	—
$\lvert V_{ub}\rvert$	input	$(3.93 \pm 0.36) \times 10^{-3}$	4%	—
$B \to X_s\gamma$	3.2×10^{-4}	$(3.52 \pm 0.25) \times 10^{-4}$	4%	—
$B \to \tau\nu$	1×10^{-4}	$(1.73 \pm 0.35) \times 10^{-4}$	5%	—
$B \to X_s\nu\bar\nu$	3×10^{-5}	$< 6.4 \times 10^{-4}$	only $K\nu\bar\nu$?	—
$B \to X_s\ell^+\ell^-$	6×10^{-6}	$(4.5 \pm 1.0) \times 10^{-6}$	6%	not studied
$B_s \to \tau^+\tau^-$	1×10^{-6}	$<$ few %	$\Upsilon(5S)$ run?	—
$B \to X_s\tau^+\tau^-$	5×10^{-7}	$<$ few %	not studied	—
$B \to \mu\nu$	4×10^{-7}	$< 1.3 \times 10^{-6}$	6%	—
$B \to \tau^+\tau^-$	5×10^{-8}	$< 4.1 \times 10^{-3}$	$\mathcal{O}(10^{-4})$	—
$B_s \to \mu^+\mu^-$	3×10^{-9}	$< 5 \times 10^{-8}$	—	$> 5\sigma$ in SM
$B \to \mu^+\mu^-$	1×10^{-10}	$< 1.5 \times 10^{-8}$	$< 7 \times 10^{-9}$	not studied
$B \to K^*\ell^+\ell^-$	1×10^{-6}	$(1 \pm 0.1) \times 10^{-6}$	15k	36k
$B \to K\nu\bar\nu$	4×10^{-6}	$< 1.4 \times 10^{-5}$	20%	—

[Grossman, ZL, Nir, arXiv:0904.4262]