Quark Flavor Physics

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- Introduction & IF Workshop report
- Status: sizable new physics allowed
- Key measurements, opportunities, conclusions

http://www.ph.utexas.edu/quarkflavor

2011 – 2012 IF Workshop activities

- Heavy Quarks Working Group:

  http://www.ph.utexas.edu/~heavyquark

- Contacted world-wide all relevant experimental groups + many theorists
- Solicited and received written contributions from many experiemnts (13)

  Solicited and received inputs from many theorists (7)

- 1.5 days of well-attended sessions at Rockville on B, K, and charm physics

  Covered theory, experiment, detector, accelerator advances + lots of discussions

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- Report has 67 authors, went through several iterations

Experimental input specifically for IF Workshop

- NA62: Ultra Rare Kaon Decays ($K^+ \to \pi^+ \nu \bar{\nu}$ at CERN)
  KOTO: The KOTO Experiment at J-PARC
  The TREK Program at J-PARC
  Measuring $K^+ \to \pi^+ \nu \bar{\nu}$ at Fermilab, The ORKA Collaboration
  Measuring $K_L^0 \to \pi^0 \nu \bar{\nu}$ at Project X, Bryman and Littenberg

- LHCb: Physics opportunities with LHCb and its planned upgrade
  SuperB Report for Intensity Frontier Workshop
  The Physics of the SuperKEKB/Belle II Super Flavor Factory
  CMS Prospects for Heavy Flavor Physics

- BES-III: Overview of the Key BES-III Physics Opportunities
  TAPAS: Heavy Quark Physics at the Antiproton Intensity Frontier
  Liquid Argon TPC as a means to study rare mu and K decays , Cline and Lee

- Also considered ~ 20 recent physics & technical reports (~ 3000 pages, ~ 200 MB)

Discussed even more experiments

1.) KLOE-2, NA62, KOTO, TREK, ORKA, Project-X opportunities

2.) Belle-II at SuperKEKB, SuperB in Italy, LHCb and upgrades, CMS, ATLAS

3.) BES III, and charm capabilities of 2.) above

- Theorists' inputs:

"A Letter from the Energy Frontier to the Intensity Frontier,"	Sundrum
"Benchmarks in Quark Flavor Physics,"	Blanke
"The Need to Advance the Intensity Frontier,"	Zupan
"The Future Quark Flavor Physics Program,"	Van de Water, Kronfeld, Mackenzie, Sharpe
"Lattice QCD and High-Intensity Flavor Physics,"	USQCD Collaboration
"Kaon Physics: Looking Beyond the Standard Model,"	Christ and Soni
"$B \to VV$ and $B \to V\ell^+\ell^-$ Angular Analysis,"	Datta and Duraisamy

Discussions at Rockville

- Allocated time between talks + additional 3 hours of discussions / brainstorming

  With moderators and fairly provocative questions...

  - Complementarity / redundancy / necessity? Strong and specific motivations?
  - What are the most important theoretical issues?
  - Any quantitative metrics to compare measurements of different processes?
  - Are there enough cross checks in the currently planned program?
    Is one measurement of key modes enough?
  - What do we learn from "new" $Q\bar{Q}$ states?
  - What would be lost without US program / US participation?
  - What accelerator R&D is needed? What facilities are needed?

“Heavy Quarks” — IF Workshop report

- Table of contents:

1. Quark Flavor as a Tool for Discovery
2. Strange, Charm, and Bottom Quarks as probes of New Physics
   - 2.1 K Decays
   - 2.2 B and B_s Decays
   - 2.3 D Decays
   - 2.4 Effective Theories, Hadronic Physics, and Exotic States
3. A World-wide Program of Quark Flavor Experiments
   - 3.1 Kaon Experiments
   - 3.2 B-meson Experiments
   - 3.3 Charm Experiments
   - 3.4 Exotic States
4. The Need for New Experiments and Facilities

(Preliminary) plans for "Snowmass"

- We want your input, but please look at report before telling us what to do

  Major changes since IF report? Something forgotten? New boundary conditions?

- Past planning:

  Jim Siegrist yesterday: "Stringing together projects that build upon previous investments either scientifically or through recycling of infrastructure is generally well received."

  Practically the opposite was done in flavor physics in the US: world leading K and B experiments abandoned / not pursued, while other regions are charging ahead — Can the US recover?

- Future planning: Clear physics case, how to make it more crisp / compelling to non-experts?

  – The interesting messages are not simple to explain [Not just one critical measurement; theory can be complicated]

  – The simple messages are not interesting [Lincoln Wolfenstein doesn't care what ρ and η are, so why should you?]

- Exciting flavor physics projects in Europe & Asia; US has an opportunity in Kaons

  Interpretation of "situation analysis" — "decision tree" — "pilot studies" for us? [Siegrist]

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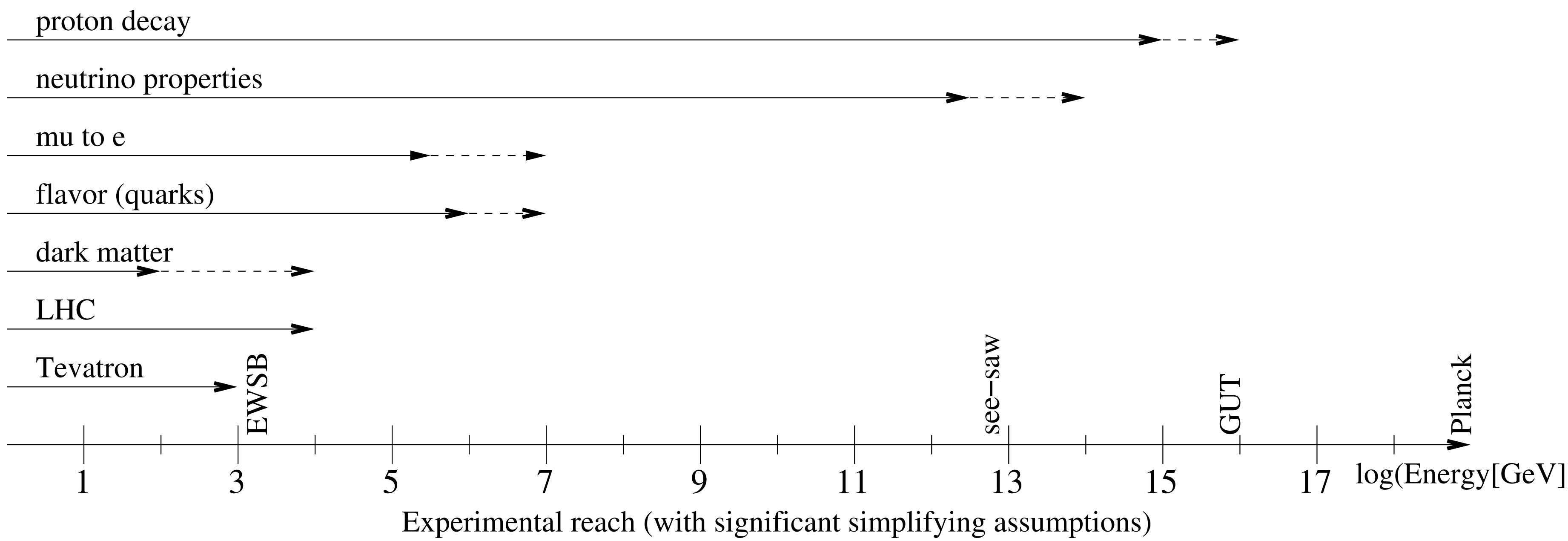
The big picture

Experiments and energy scales



Dashed arrows show anticipated improvements in next generation of experiments

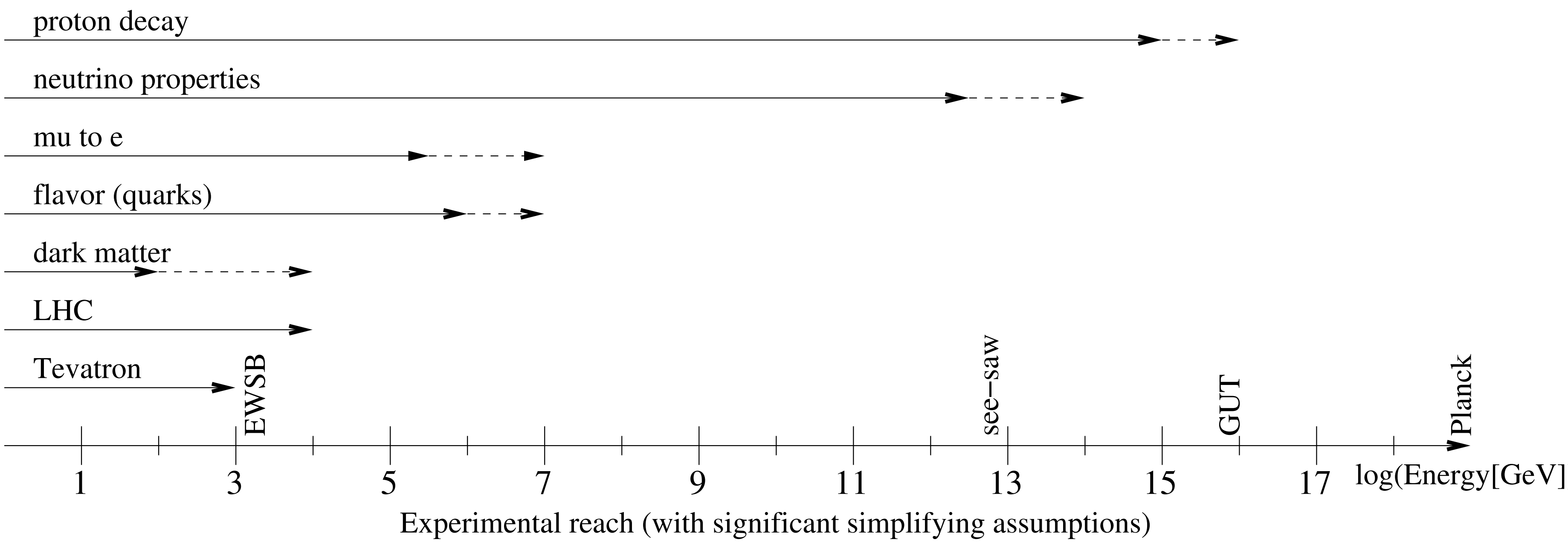
- Goal: Higher energy — Shorter distances — Earlier in the Universe

  Energy, Intensity, Cosmic frontiers all address these in different and complementary ways

Energy frontier: accelerator energy gives upper limit on mass of new particles produced

Intensity frontier: very heavy particles can affect the measurements via quantum effects

Experiments and energy scales



Dashed arrows show anticipated improvements in next generation of experiments

- proton decay already ruled out simplest version of grand unification
- neutrino experiments hope to probe see-saw mechanism
- flavor physics is getting to the level that even suppressed TeV-scale physics could show up
- LHC was in a unique situation that a discovery was virtually guaranteed (known since the 80's)

Can do or cannot do?

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

J. W. Cronin, V. L. Fitch, R. Turlay

(April 10, 1963)

I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of K^o_1 mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^o_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$. In addition, if time permits, the coherent regeneration of K_1's in dense materials can be observed with good accuracy.

II. EXPERIMENTAL APPARATUS

Fortuitously the equipment of this experiment already exists in operating condition. We propose to use the present 30° neutral beam at the A.G.S. along with the di-pion detector and hydrogen target currently being used by Cronin, et al. at the Cosmotron. We further propose that this experiment be done during the forthcoming μ-p scattering experiment on a parasitic basis.

The di-pion apparatus appears ideal for the experiment. The energy resolution is better than 4 Mev in the m^* or the Q value measurement. The origin of the decay can be located to better than 0.1 inches. The 4 Mev resolution is to be compared with the 20 Mev in the Adair bubble chamber. Indeed it is through the greatly improved resolution (coupled with better statistics) that one can expect to get improved limits on the partial decay rates mentioned above.

III. COUNTING RATES

We have made careful Monte Carlo calculations of the counting rates expected. For example, using the 30°, beam with the detector 60-ft. from the A.G.S. target we could expect 0.6 decay events per 10^{11} circulating protons if the K_2 went entirely to two pions. This means that one can set a limit of about one in a thousand for the partial rate of $K_2 \to 2\pi$ in one hour of operation. The actual limit is set, of course, by the number of three-body K_2 decays that look like two-body decays. We have not as yet made detailed calculations of this. However, it is certain that the excellent resolution of the apparatus will greatly assist in arriving at a much better limit.

If the experiment of Adair, et al. is correct the rate of coherently regenerated K_1's in hydrogen will be approximately 80/hour. This is to be compared with a total of 20 events in the original experiment. The apparatus has enough angular acceptance to detect incoherently produced K_1's with uniform efficiency to beyond 15°. We emphasize the advantage of being able to remove the regenerating material (e.g., hydrogen) from the neutral beam.

IV. POWER REQUIREMENTS

The power requirements for the experiment are extraordinarily modest. We must power one 18-in. x 36-in. magnet for sweeping the beam of charged particles. The two magnets in the di-pion spectrometer are operated in series and use a total of 20 kw.

⇒ Cronin & Fitch, Nobel Prize, 1980

⇒ 3 generations, Kobayashi & Maskawa, Nobel Prize, 2008

Spectacular track record

- Uncertainty principle $\Rightarrow$ heavy particles, which cannot be produced, affect lower energy processes (typically suppressed by E^2/M^2) $\Rightarrow$ can probe very high scales
  - ϵ_K predicted 3rd generation (Kobayashi & Maskawa)
  - Absence of $K_L \to \mu\mu$ predicted charm (Glashow, Iliopoulos, Maiani)
  - Δm_K predicted m_c (Gaillard & Lee)
  - Δm_B predicted large m_t
- Were critical to develop the SM, probably crucial to understand LHC physics, too
- Flavor physics and CP violation are excellent probes of BSM physics
- Already learned that TeV-scale NP must have very special features — flavor has mainly been an input to model building (structures imposed to satisfy bounds)

Flavor physics — the modern view

- "Flavor physics": what breaks $U(3)_Q \times U(3)_u \times U(3)_d \to U(1)_{\text{Baryon}}$?
- SM flavor problem: hierarchy of masses and mixing angles; why ν's are different
- NP flavor problem: TeV scale (hierarchy problem) $\ll$ flavor & CPV scale

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

  - Most TeV-scale new physics models have new sources of CP and flavor violation, which may be observable in flavor physics but not directly at the LHC
  - The observed baryon asymmetry of the Universe requires CPV beyond the SM (Not necessarily in flavor changing processes, nor necessarily in quark sector)
  - Hope: new source of symmetry violation $\Rightarrow$ new interactions / particles
- Flavor sector can be tested a lot better, many NP models have observable effects

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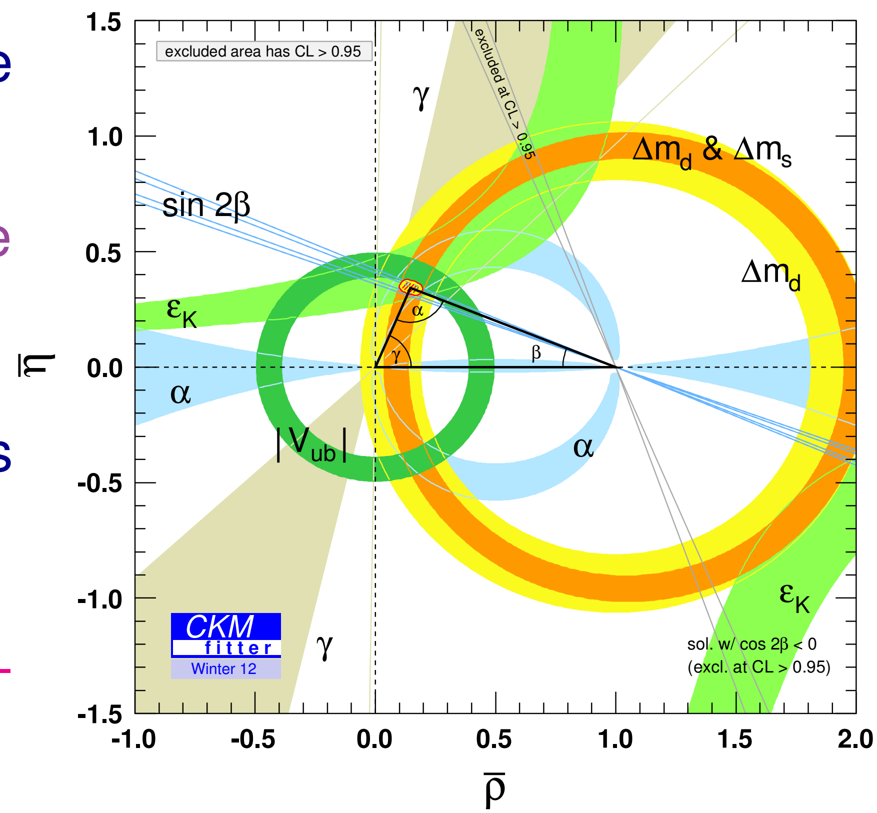
Current status: CKM fit in the SM

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

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

- There are no significant deviations from SM, a number of tensions, many measurements where huge improvements are possible

- Allowed region is much larger using only tree-level information γ and $|V_{ub}|$



- This picture makes things look more constrained than they really are; allowing for NP (more flavor parameters) can change the fit completely

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

Constraints on $\Delta F = 2$ (mixing)

- Bounds with $\mathcal{O}(1)$ couplings are in the $10^2 - 10^5\,\mathrm{TeV}$ range

Operator	Bounds on Λ [TeV] ($C = 1$) Re	Im	Bounds on C ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	2.2×10^2	7.6×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2	7.4×10^2	1.3×10^{-5}	3.0×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

- Guaranteed to give key information in any scenario — what flavor tells us?

Evidence for BSM?		FLAVOR yes	FLAVOR no
ATLAS & CMS	yes	complementary information	distinguish models
	no	tells us where to look next	flavor is the best telescope

The Future

What can flavor physics teach us about BSM physics?

Reasons to seek higher precision

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

  Generic flavor structure already ruled out by orders of magnitudes — can find any size deviations below the current bounds. In a large class of scenarios expect observable deviations.

- What are the theoretical uncertainties?

  Highly process dependent — in many key measurements theory uncertainties are smaller than the expected sensitivity of future experiments.

- What to expect in terms of experimental precision?

  Useful data sets will increase by $\sim 10^{2\pm1}$, and will probe fairly generic BSM predictions

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

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

- $\Rightarrow$ Very rich program of measurements & searches

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K physics

In many NP models, the K constraints are the strongest, since so are the SM suppressions

These are built into all NP models since the 70's — models constructed to evade the flavor bounds!

Precision tests with kaons

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

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

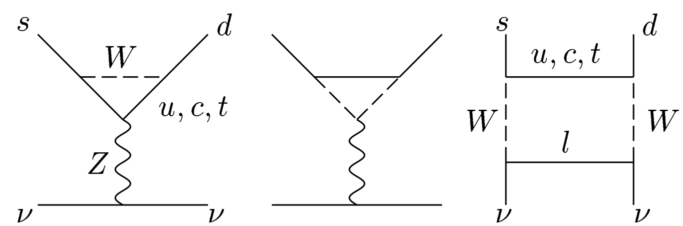
  We cannot rule out (nor prove) that the measured value of ϵ'_K is dominated by NP

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

- With lattice QCD improvements, ϵ_K has become more sensitive, hopes for ϵ'/ϵ

- $K \to \pi\nu\bar{\nu}$: Theory error $\sim$ few %, but very small rates $10^{-10}\,(K^\pm),\ 10^{-11}\,(K_L)$

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



So far $\mathcal{O}(1)$ uncertainty in $K^+ \to \pi^+\nu\bar{\nu}$, and $\mathcal{O}(10^3)$ in $K_L \to \pi^0\nu\bar{\nu}$

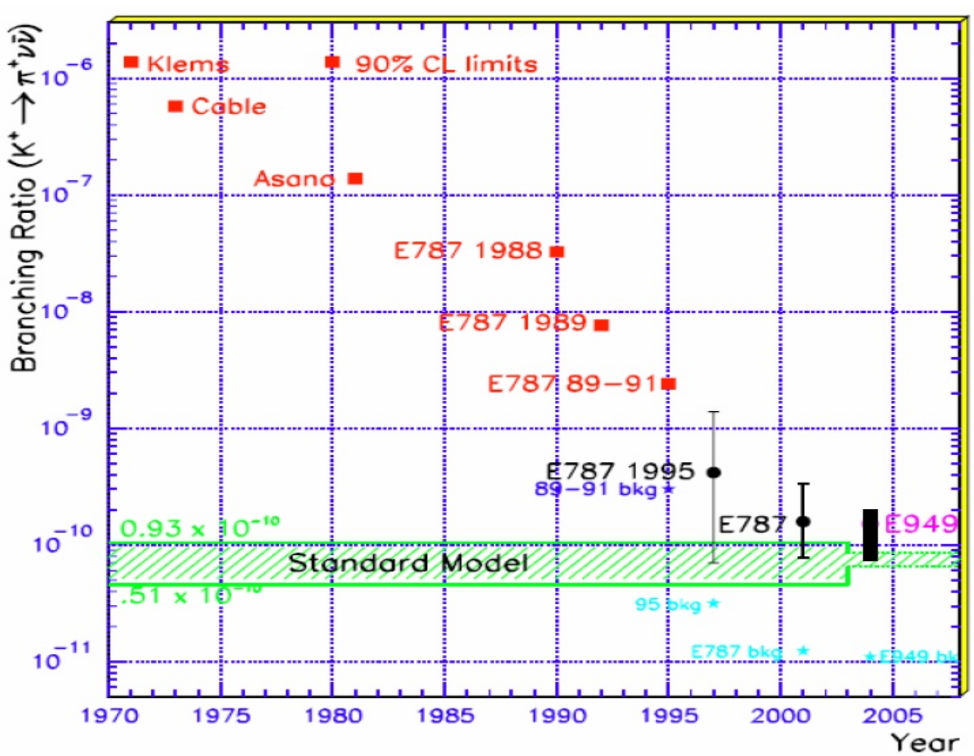
- $\Rightarrow$ Need much more data to achieve ultimate sensitivity

The quest for $K \to \pi\nu\bar{\nu}$

- Long history of ingenious experimental progress (huge backgrounds)

E787/E949: 7 events observed, $\mathcal{B}(K \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

SM: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (0.78 \pm 0.08) \times 10^{-10}$, $\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu}) = (0.24 \pm 0.04) \times 10^{-10}$



CERN NA62: ~ 100 $K^+ \to \pi^+\nu\bar{\nu}$ events in 2012–2016/7

FNAL ORKA proposal: ~ 1000 $K^+ \to \pi^+\nu\bar{\nu}$ events [Stage-1 approval]

J-PARC KOTO: observe $K_L^0 \to \pi^0\nu\bar{\nu}$ at SM level

FNAL w/ project-X: proposal for ~ 1000 event $K_L^0 \to \pi^0\nu\bar{\nu}$

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$K \to \pi\nu\bar{\nu}$ and other measurements

- Very clean: single operator $(\bar{s}d)_V(\bar{\nu}\nu)_{V-A}$, form factor measured in $K \to \pi\ell\nu$

  One complex param., $K^+ \to \pi^+\nu\bar{\nu}$ measures $|X|$, $K_L \to \pi^0\nu\bar{\nu}$ measures $\mathrm{Im}X$

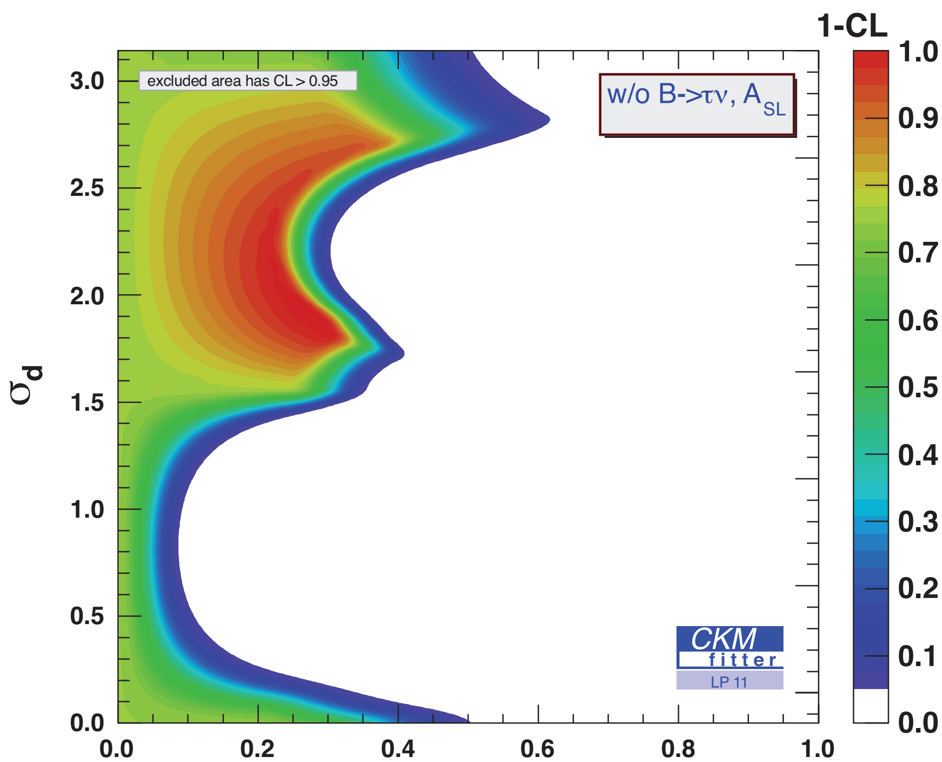
  Rates $\propto |V_{cb}|^4$, drops out from ratio (but then less discriminating power), so want highest precision

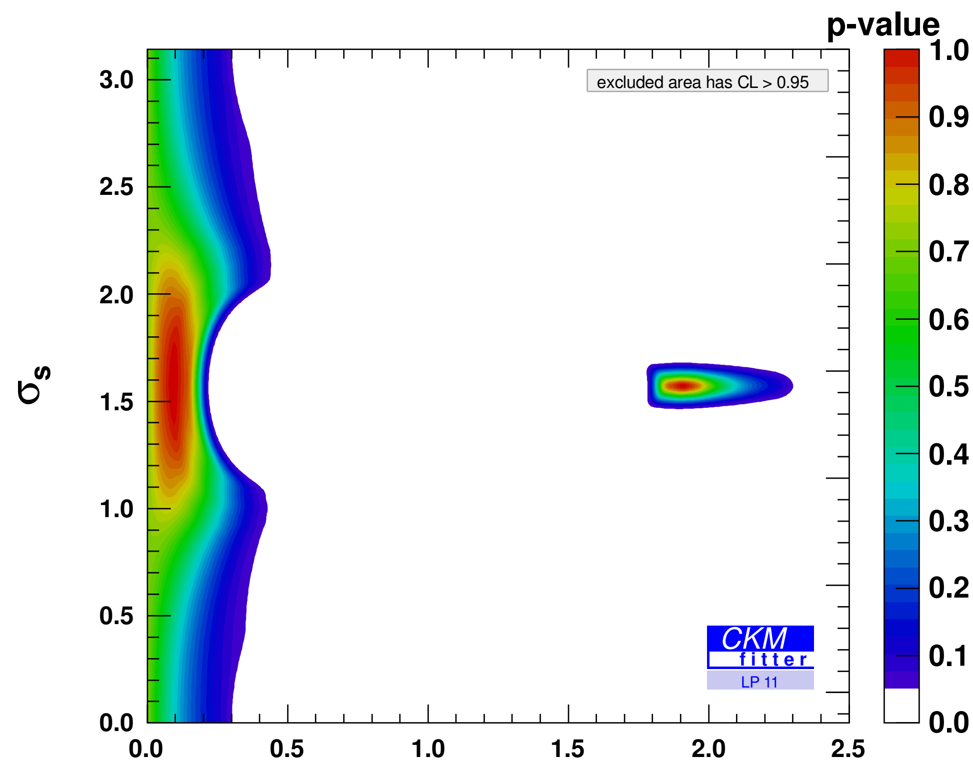
Observable	SM Theory	Current Expt.	Future Experiments
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	7.8×10^{-11}	$1.73^{+1.15}_{-1.05} \times 10^{-10}$	$\sim$10% measurement from NA62 $\sim$5% measurement from ORKA $\sim$2% with Project X
$\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu})$	2.43×10^{-11}	$< 2.6 \times 10^{-8}$	1^{st} observation from KOTO $\sim$5% measurement with Project X
$\mathcal{B}(K_L^0 \to \pi^0 e^+e^-)_{SD}$	1.4×10^{-11}	$< 2.8 \times 10^{-10}$	$\sim$10% measurement with Project X
$\mathcal{B}(K_L^0 \to \pi^0 \mu^+\mu^-)_{SD}$	3.5×10^{-11}	$< 3.8 \times 10^{-10}$	$\sim$10% measurement with Project X
$\lvert P_T\rvert$ in $K^+ \to \pi^0\mu^+\nu$	$\sim 10^{-7}$	< 0.0050	< 0.0003 from TREK < 0.0001 with Project X
$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$	2.477×10^{-5}	$(2.488 \pm 0.080) \times 10^{-5}$	$\pm 0.054 \times 10^{-5}$ from TREK $\pm 0.025 \times 10^{-5}$ with Project X
$\mathcal{B}(K_L^0 \to \mu^\pm e^\mp)$	$< 10^{-25}$	$< 4.7 \times 10^{-12}$	$< 2 \times 10^{-13}$ with Project X

B physics

Sizable BSM in $B_{d,s}$ mixing still allowed

- Few notable tensions, otherwise no preference for NP contributions (lots of room)





$$M_{12} = M_{12}^{\rm SM}\,(r\,e^{2i\theta}) = M_{12}^{\rm SM}\,(1 + h\,e^{2i\sigma})$$

- In many cases, we do not yet know if BSM $\ll$ SM! A must to find out!
- Need a lot more data from LHCb and Super-(KEK-)B, and lattice QCD progress

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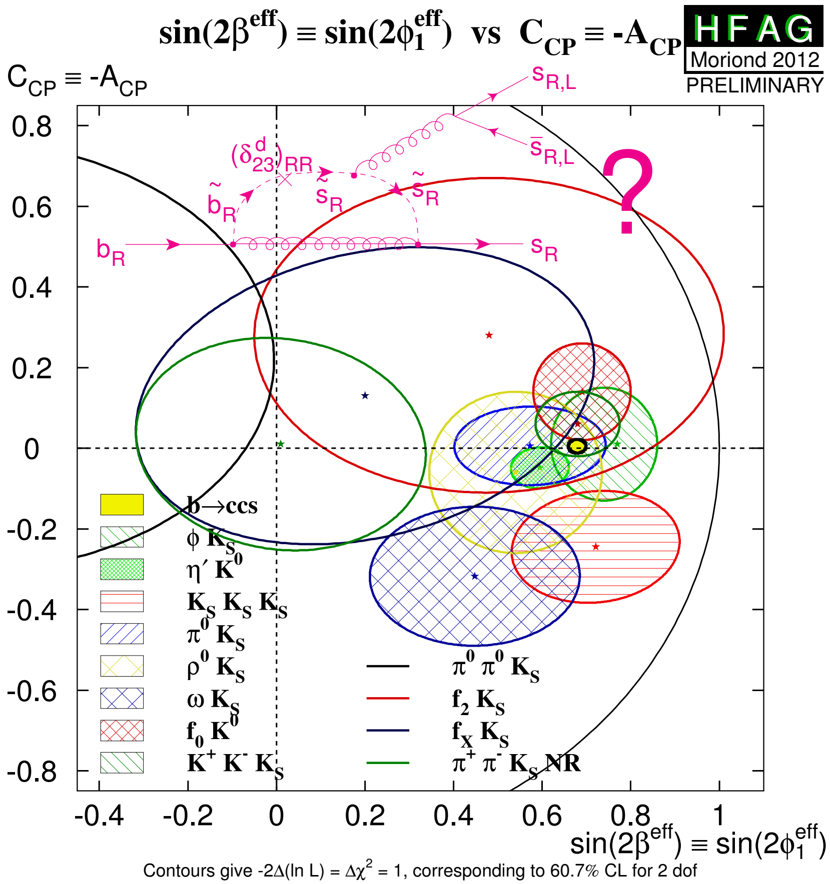
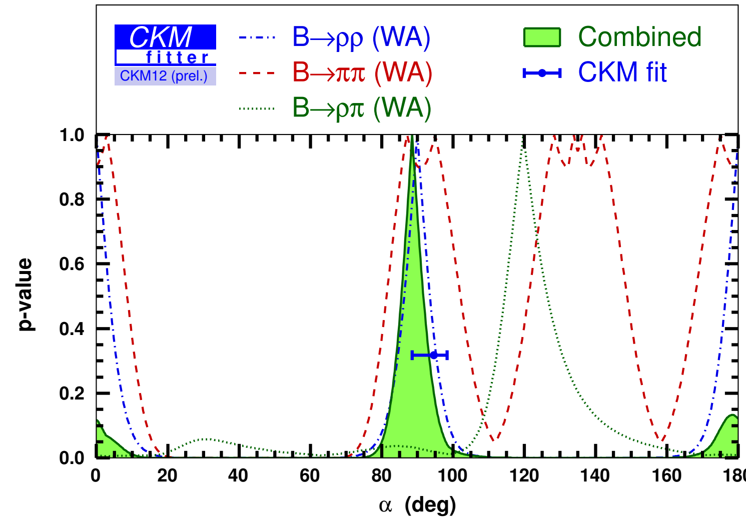
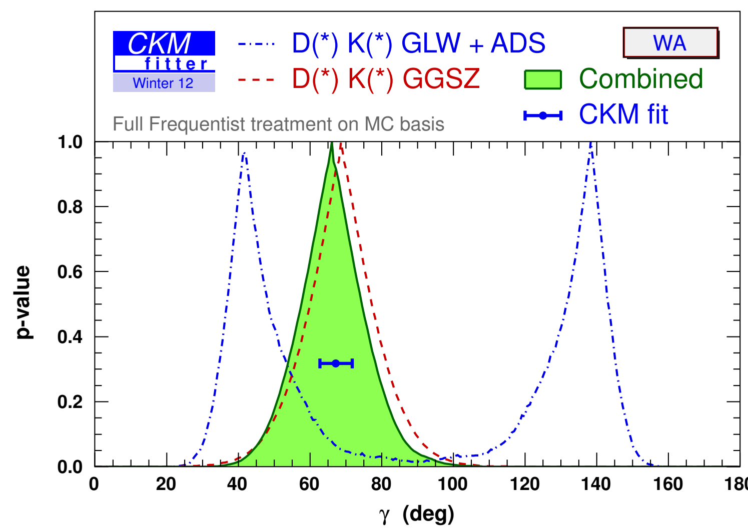
β, β_s, α, γ — large improvements possible







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

Unexpected developments will continue

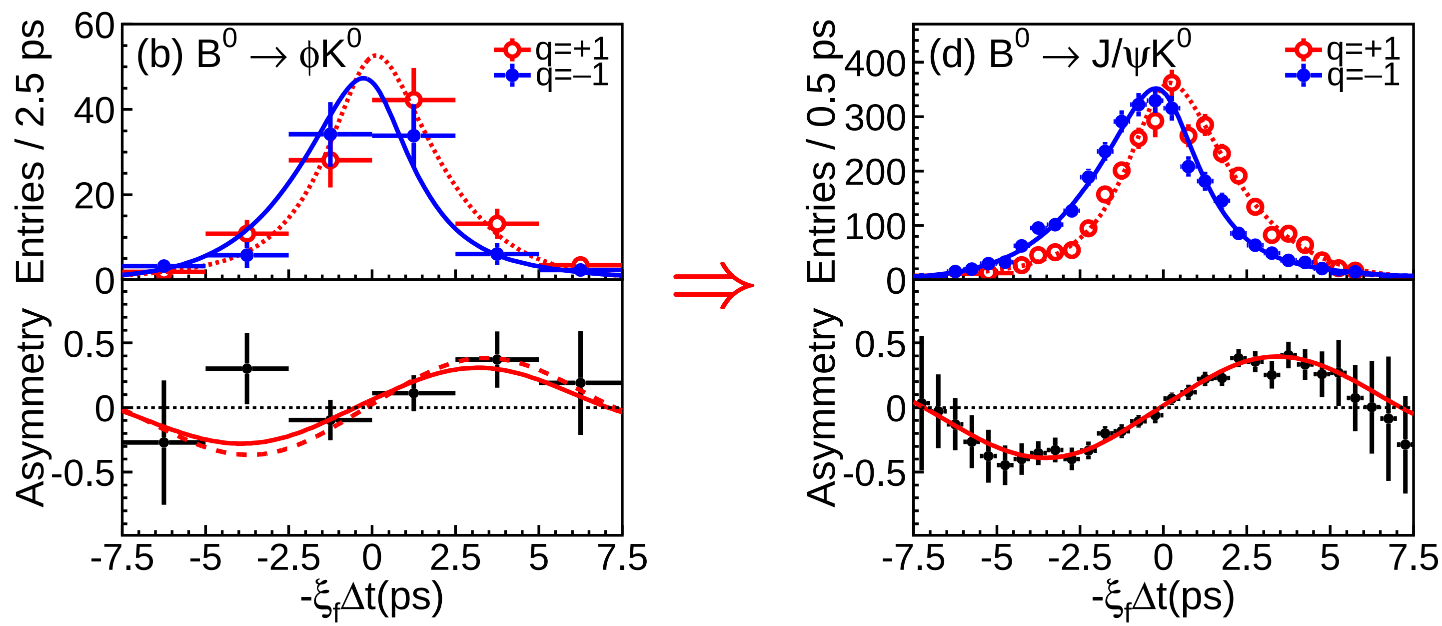
- Plethora of observables — cannot overestimate value of broad program (D_{CP})

  E.g.: Best α & γ measurements at BaBar/Belle not in previously expected modes

  Even less expected: "new" $Q\overline{Q}$ and $D_s(2317, etc.)$ narrow states

- Experimentalists & theorists challenge each other $\Rightarrow$ new ideas / methods (α, γ)

- E.g., $B \to \phi K_S$ will get roughly as good as $B \to \psi K_S$ is now



Substantial discovery potential in many modes

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

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

- In some decay modes, even in 2025:

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

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

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

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

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An LHCb best buy list

- LHCb will probe B_s sector at a level comparable to B_d
  - The CP asymmetry, $S_{B_s \to \psi\phi}$
  - Difference of CP asymmetries, $S_{B_s \to \psi\phi} - S_{B_s \to \phi\phi}$
  - $B_s \to \mu^+\mu^-$ ($\propto \tan^6\beta$), search for $B_d \to \mu^+\mu^-$, other rare / forbidden decays
  - 10^{4-5} events in $B \to K^{(*)}\ell^+\ell^-$, $B_s \to \phi\gamma$, ... — test Dirac structure, BSM op's
  - γ from $B \to DK$ and $B_s \to D_s K$
  - Search for charged lepton flavor violation, $\tau \to 3\mu$ and other modes if possible
  - Search for CP violation in $D^0 - \overline{D}{}^0$ mixing
  - [Precisely measure τ_{Λ_b} — affects how much we trust $\Delta\Gamma_{B_s}$ calculation, etc.]
- Very broad program, complementary to Super-(KEK-)B
- With large BSM discovery potential

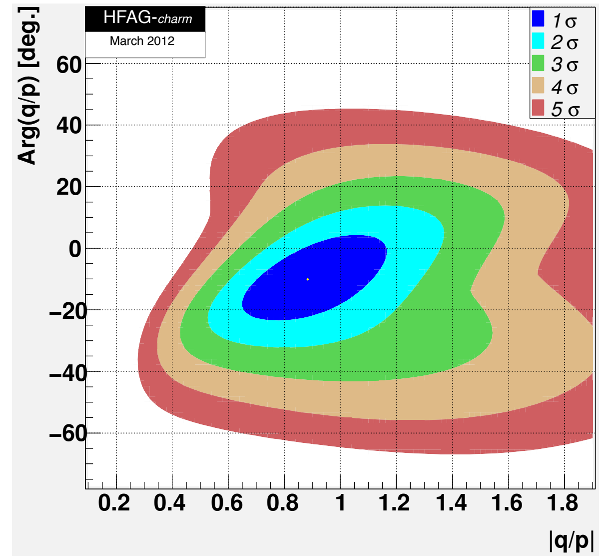
A Super-(KEK-)B best buy list

- Include observables: (i) sensitive to different NP, (ii) measurements can improve order of magnitude, (iii) not limited by hadronic uncertainties
  - Difference of CP asymmetries, $S_{\psi K_S} - S_{\phi K_S}$
  - γ from CP asymmetries in tree-level decays vs. γ from $S_{\psi K_S}$ and $\Delta m_d/\Delta m_s$
  - Search for charged lepton flavor violation, $\tau \to \mu\gamma$, $\tau \to 3\mu$, and similar modes
  - Search for CP violation in $D^0 - \overline{D}^0$ mixing
  - CP asymmetry in semileptonic decay (dilepton asymmetry), $A_{\rm SL}$
  - CP asymmetry in the radiative decay, $S_{K^*\gamma}$
  - Rare decay searches and refinements: $b \to s\nu\bar{\nu}$, $B \to \tau\bar{\nu}$, etc.
- Complementary to LHCb
- Any one of these measurements has the potential to establish new physics

charm physics

D^0: mixing in up sector

- Complementary to K, B: CPV, FCNC both GIM & CKM suppressed $\Rightarrow$ tiny in SM
  - 2007: observation of mixing, now $\gtrsim 10\sigma$ [HFAG combination]
  - Only meson mixing generated by down-type quarks (SUSY: up-type squarks)
  - SM suppression: $\Delta m_D,\, \Delta\Gamma_D \lesssim 10^{-2}\,\Gamma$, since doubly-Cabibbo-suppressed and vanish in flavor $SU(3)$ limit
  - How small CPV would still unambiguously establish new physics?



Don't known if $|q/p|$ is near 1!

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

Direct CP violation in D decay?

- LHCb: $\Delta a_{CP} \equiv a_{K^+K^-} - a_{\pi^+\pi^-} = -(8.2 \pm 2.1 \pm 1.1) \times 10^{-3}$

  CDF: $\Delta a_{CP} = -(6.2 \pm 2.1 \pm 1.0) \times 10^{-3}$

  $$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

- World average: $\Delta a_{CP} = -(6.78 \pm 1.47) \times 10^{-3}$ $(> 4\sigma)$ [HFAG]

  $$a_{K^+K^-} = (-2.3 \pm 1.7) \times 10^{-3}, \quad a_{\pi^+\pi^-} = (2.0 \pm 2.2) \times 10^{-3}$$

- Would Δa_{CP} central value be a sign of NP? (It is beyond all prior SM estimates)

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

  How do we tell? Use many measurements... separate asymmetries, etc.

- What kind of new physics could explain it? [many recent papers]

Impacts on broader program

- Determination of CKM elements from leptonic and semileptonic modes
- Phases from CP-tagged decays: very useful for B factories (γ)
- Test lattice QCD predictions
- Spectroscopy (charmonia, glueballs, etc.)

- Several experiments will pursue charm physics:
  - LHCb and super-(KEK-)B are charm factories
  - Dedicated charm experiments: BES III, Panda

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Final comments

Flavor information useful in all scenarios

- Nima @ Rockville (Nov. 30, 2011):

(a) There are no guarantees, but ...

(b) In my view, due to expt. + th. developments, the argument for seeing new flavor physics now, are both stronger and more diverse than the ones made before B-factories, and,

(c) The new physics that could be uncovered is more varied + interesting, and, in some cases, could be CRITICAL to future of HEP.

Main points (1)

- Flavor physics is an essential part of the future HEP program

  Crucial in all scenarios — whether LHC sees BSM or not:

  To understand structure of new interactions / to probe mass scales beyond LHC

- New physics in most FCNC processes may still be $\sim 20\%$ of the SM or more

- Few hints of discrepancies in SM fit; some (or others) may become decisive

- In many modes, theory is good enough — need high(er) statistics measurements

- Theory will also improve (continuum $+$ lattice), and as larger data sets become available, interplay between measurements and theory will add to this list

- Enables doing lots of hadronic physics

- This program will address key issues, and provide important complement to LHC

Main points (2)

- A rich program of heavy quark experiments is being pursued World-wide

  Some key processes to search for new physics:

  $K^+ \to \pi^+ \nu\bar\nu$ and $K_L^0 \to \pi^0 \nu\bar\nu$ aiming at 1000 event level

  CP violation in $B_s \to \psi\phi$

  β from $b \to c\bar{c}s$ vs. from loop-dominated decays

  γ and $|V_{ub}|$ — tree-level “reference” to compare NP with

  $B_{s,d} \to \ell^+\ell^-$, $B \to \ell\nu$, $A_{\rm SL}$

  Many $b \to s\gamma$, $s\ell^+\ell^-$, $s\nu\bar\nu$ observables (and $s \leftrightarrow d$)

  CP violation in D mixing, direct CP violation in charm decays

- Having >1 experiment is very valuable: competition, cross-checks, confirmation

  Especially critical if deviations from the SM are seen

- Exploring NP requires LHCb upgrade, super-(KEK-)B, and K experiments

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Exciting journey ahead

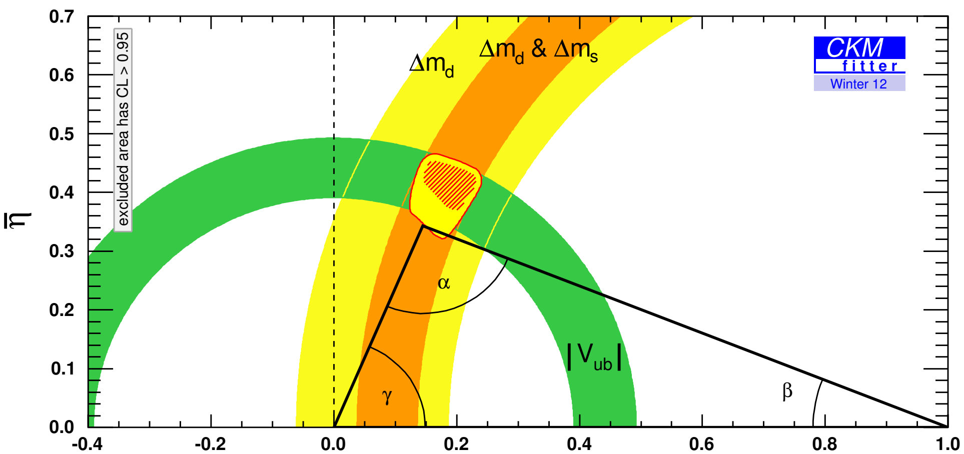
Many opportunities to reveal and constrain new physics using flavor physics in next decades

[Only way to avoid this: not to carry out the experiments]

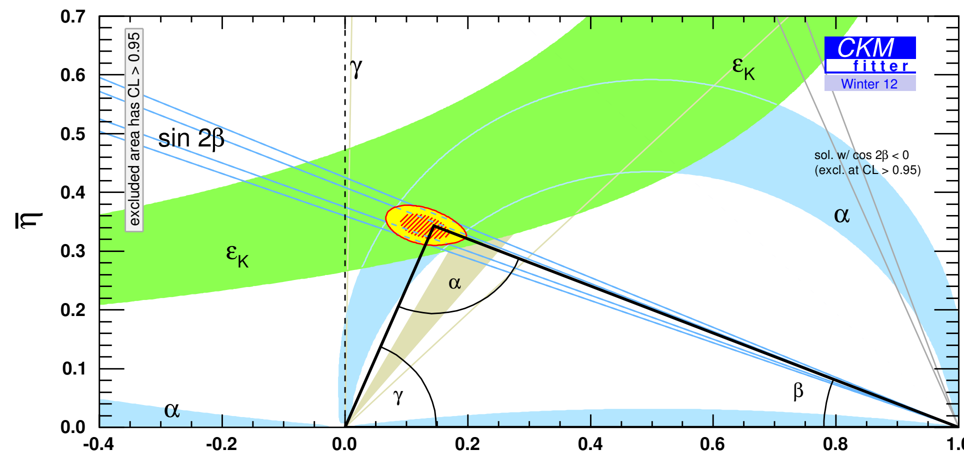
Persis @ Rockville: opportunities for paradigm changing scientific advances ✓

Backup slides

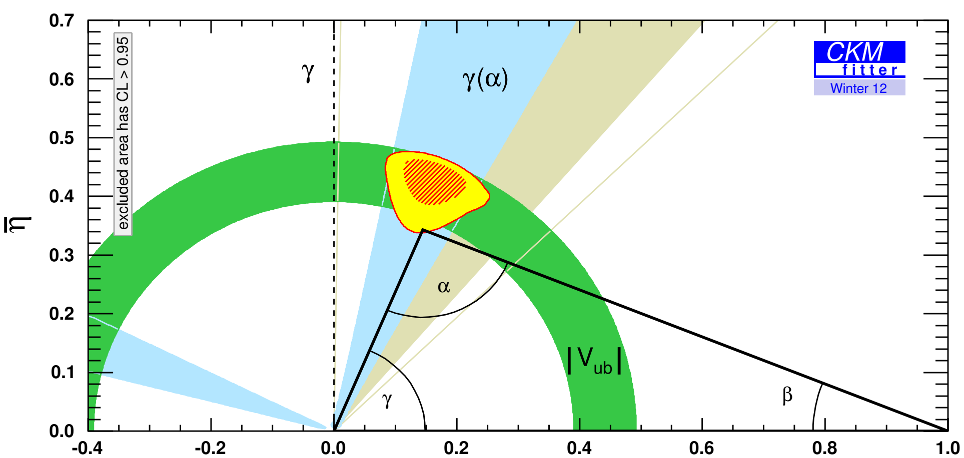
Overconstraining the standard model



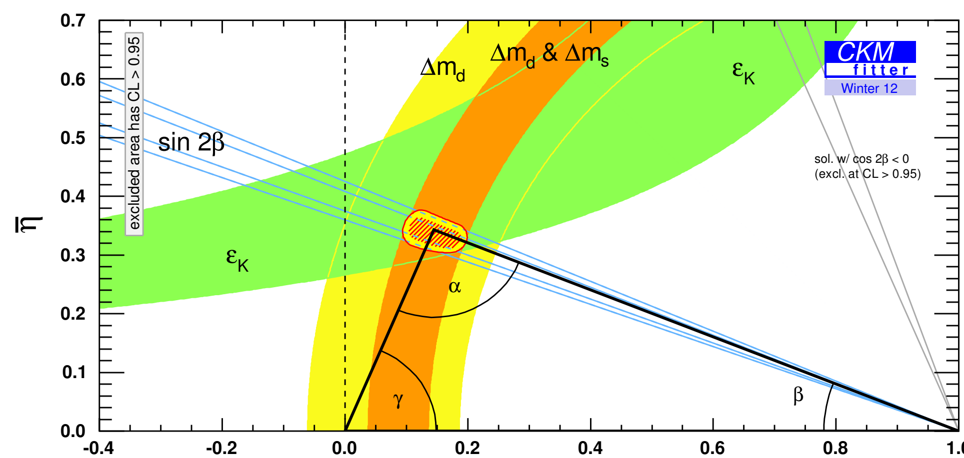
(CP conserving)



(CP violating)



(tree-level)

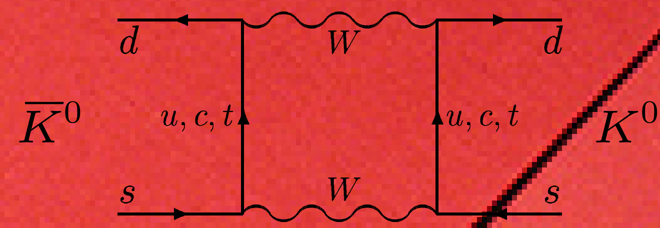


(loop-dominated)

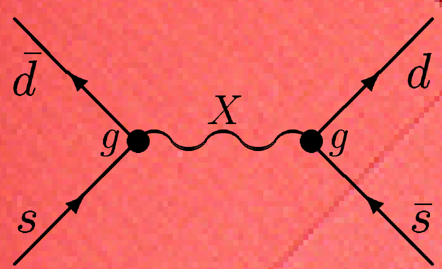
- Consistent determinations from subsets of measurements ⇒ bound extra terms

Back of an envelope calculation of Δm_K

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



- Tree-level exchange of a hypothetical boson:



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

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

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

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

Δm_K and ϵ_K in SUSY (oversimplified)

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

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

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

- Classes of models to suppress each factors

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

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

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

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

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

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Parameters of the MSSM

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

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

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

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

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

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

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

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

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

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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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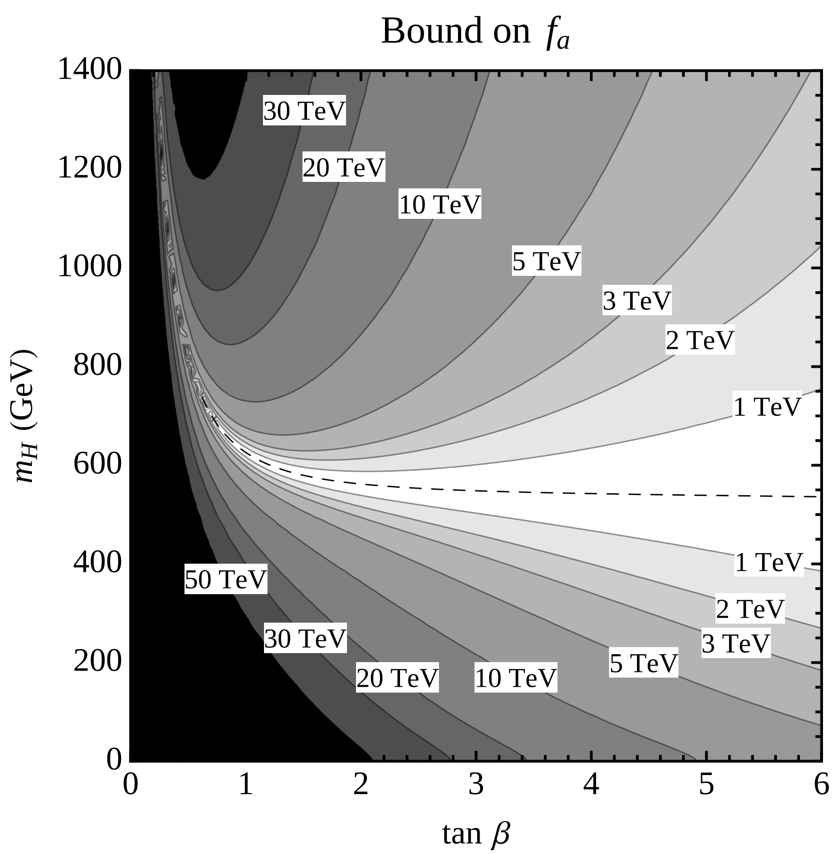
"Odd" searches: probe DM models with B decays

- Observations of cosmic ray excesses lead to flurry of DM model building

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



[Freytsis, ZL, Thaler, 0911.5355]

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

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Special features of the SM flavor sector

- All flavor changing processes depend only on a few parameters in the SM
  $\Rightarrow$ correlations between large number of s, c, b, t decays

- The SM flavor structure is very special:
  - Single source of CP violation in charged current interactions
  - Suppressions due to hierarchy of mixing angles
  - Suppression of FCNC processes from loops ($\Delta F = 2$ and $\Delta F = 1$)
  - Suppression of FCNC chirality flips by quark masses (e.g., $S_{K^*\gamma}$)

  Many suppressions that NP may not respect $\Rightarrow$ sensitivity to high scales

- It is interesting and possible to test each of these

- However, a general operator analysis has too many terms, no one has come up with a really useful STU-like parameterization

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Matter – antimatter asymmetry

- Gravity, electromagnetism, strong interaction are the same — but not the weak interaction

- At present: $\dfrac{N(\text{baryon})}{N(\text{photon})} \sim 10^{-9} \Rightarrow \dfrac{N_q - N_{\overline{q}}}{N_q + N_{\overline{q}}} \sim 10^{-9}$

  when universe was $T \sim 1\,\mathrm{GeV} \sim 10^{11}\,\mathrm{K}$

- CP violation in the SM is $\sim 10^{10}$ times too small

- Two scenarios — both require new physics:

  Baryogenesis: asymmetry formed during electroweak phase transition

  SM: ruled out; LHC: explore remaining model space (SUSY, 4th generation, ...)

  Leptogenesis: asymmetry formed in the decay of a heavy "neutrino"

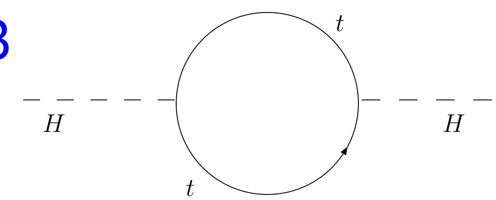
  Connected to light neutrino properties — in a model dependent way

Will become very plausible if see: i) $0\nu\beta\beta$; ii) CP viol. in ν oscillation; iii) baryogenesis ruled out

What we may hope to learn

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

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



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

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

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

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

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