Flavor Physics: the next decade(s)

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Journeys Through the
SSI2013 FRONTIER

What is particle physics?

- Central question of particle physics:

$$\mathcal{L} = ?$$

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

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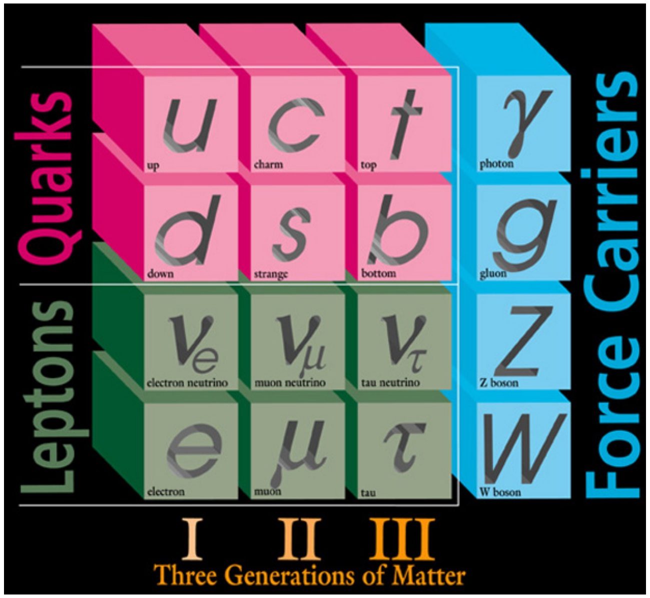
- Most experimentally observed phenomena consistent with standard model (SM)



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- Central question of particle physics:

$$\mathcal{L} = ?$$

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

- Most experimentally observed phenomena consistent with standard model (SM)
- Clearest empirical evidence that SM is incomplete:
  - Dark matter
  - Baryon asymmetry of the Universe

May be at
TeV scale

  - Neutrino mass [can add in a straightforward way]
  - Hierarchy problem [$126\,\mathrm{GeV}$ scalar $=$ SM Higgs? why so light? why so heavy?]
  - Dark energy [cosmological constant? need to know more to understand?]

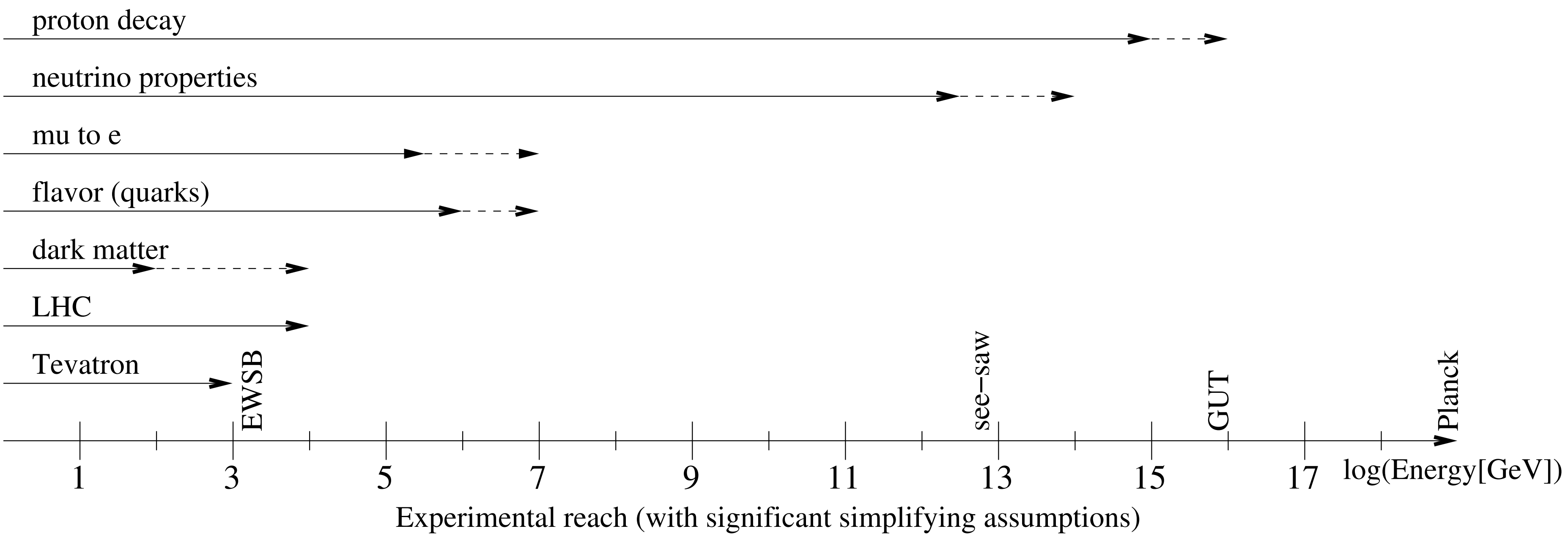
The matter–antimatter asymmetry

- Sakharov conditions (1967):
  1. baryon number violating interactions
  2. C and CP violation
  3. deviation from thermal equilibrium
- SM contains 1–3, but:
  - i. CP violation is too small
  - ii. deviation from thermal equilibrium too small at the electroweak phase transition

New TeV-scale physics can enhance both (supersymmetry, etc.) and may have observable CPV effects (possibly only in flavor-diagonal processes, e.g., EDM-s)

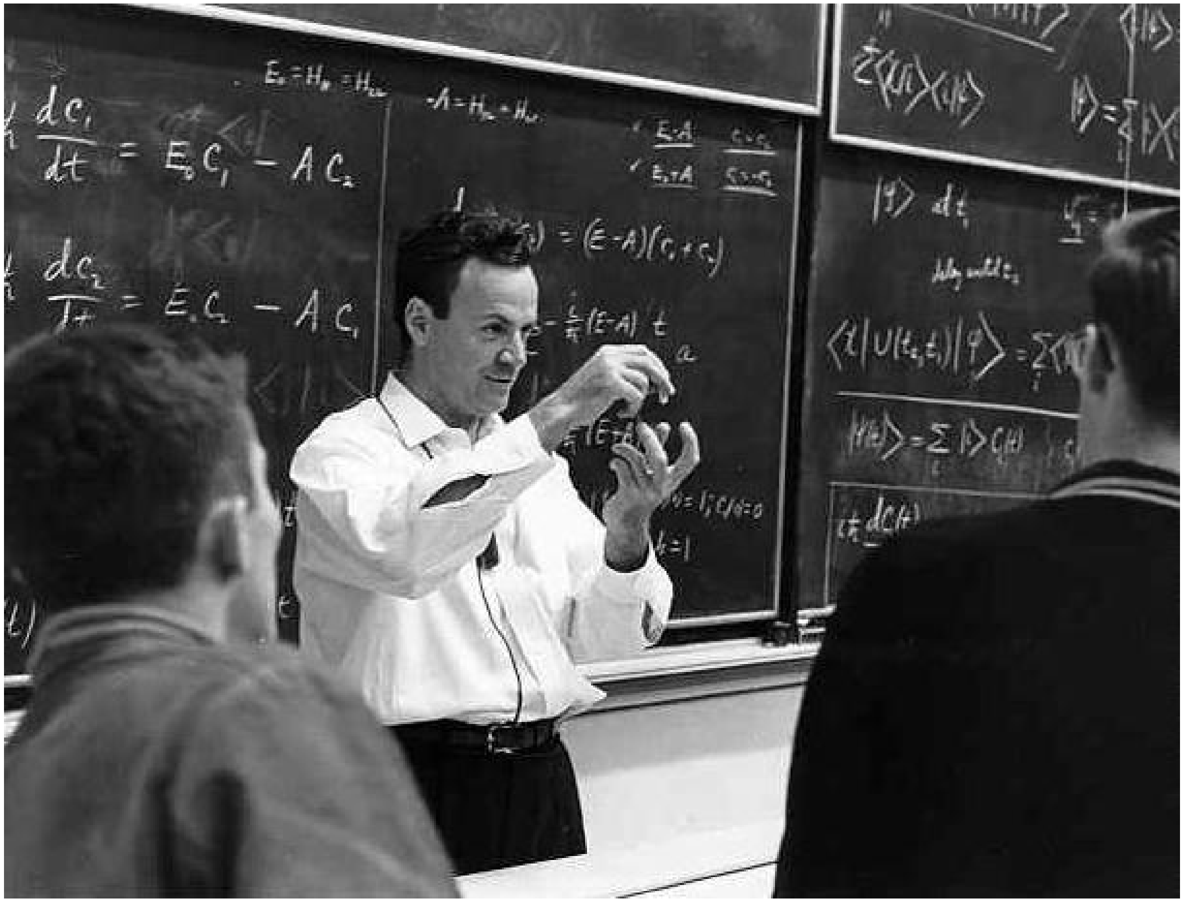
- What is the microscopic theory of CP violation? How precisely can we test it?

The big question: where is new physics?



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 (evidence for a dim-5 operator...)
- flavor physics probes TeV-scale new physics with even SM-like suppressions
- LHC was in a unique situation that a discovery was virtually guaranteed (known since 80’s)



“It doesn’t matter how beautiful your theory is, it doesn’t matter how smart you are. If it doesn’t agree with experiment, it’s wrong.”

[R.P. Feynman]

What is flavor physics?

- Theorist: flavor physics (quarks) $\equiv$ what breaks $U(3)_Q \times U(3)_u \times U(3)_d \;\to\; U(1)_{\text{Baryon}}$
- Experimentalist: rich and sensitive way to probe the SM and search for NP
- SM flavor problem: hierarchy of masses and mixing angles? why 3 generations?
- NP flavor problem: TeV scale (hierarchy problem) $\ll$ "naive" flavor & CPV scale

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

  - Most TeV-scale new physics contains 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 sector will be tested a lot better, many NP models have observable effects

Going from: $\underset{(2003)}{\text{NP} \lesssim (\text{few} \times \text{SM})} \;\to\; \underset{(2013)}{\text{NP} \lesssim (0.3 \times \text{SM})} \;\to\; \underset{(2023)}{\text{NP} \lesssim (0.05 \times \text{SM})}$

Outline

- ~~Physics beyond the SM must exist, good reasons to hope it's at the TeV scale~~
- Brief introduction to the standard model

  Weak interactions, flavor, CKM
- Testing the flavor sector

  CP violation, K and D mesons
- Clean information from B physics

  Constraining new physics in mixing

- Flavor symmetries and new physics

  Lepton flavor violation
- Flavor physics at high-p_T

  top FCNC, MFV, SUSY flavor vs. LHC
- Conclusions

Preliminaries

- Dictionary:
  SM $=$ standard model NP $=$ new physics
  CPV $=$ CP violation UT $=$ unitarity triangle

- Disclaimers: I will not talk about: the strong CP problem $\frac{\theta_{\rm QCD}}{16\pi^2}\, F_{\mu\nu}\widetilde{F}^{\mu\nu}$
  lattice QCD
  detailed new physics scenarios

- Most importantly: If I do not talk about your favorite process [the one you are working on...], it does not mean that I think it's not important!

- Many reviews and books, e.g.:

Y. Grossman, ZL, Y. Nir, arXiv:0904.4262; A. Hocker, ZL, hep-ph/0605217; ZL, hep-lat/0601022
G. Branco, L. Lavoura and J. Silva, *CP Violation*, Clarendon Press, Oxford, UK (1999)

“Ancient” past

Crucial role of symmetries: C, P, and T

- Intimate connection between symmetries and conservation laws

$C =$ charge conjugation (particle $\leftrightarrow$ antiparticle)

$P =$ parity ($\vec{x} \leftrightarrow -\vec{x}$)

$T =$ time reversal ($t \leftrightarrow -t$, initial $\leftrightarrow$ final states)

CPT cannot be violated in a relativistically covariant local quantum field theory

- Once upon a time, “Tau – Theta puzzle”: $\theta^+ \to \pi^+\pi^0$

$$\tau^+ \to \pi^+\pi^+\pi^- \qquad \pi:\ J^P = 0^-$$

If parity was conserved in decay: $P(\pi\pi) = (-1)^{J(\theta^+)}$ and $P(\pi\pi\pi) = -(-1)^{J(\tau^+)}$

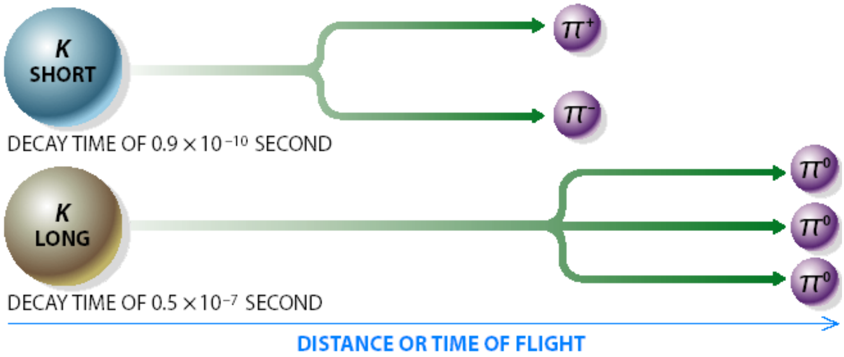
Assumed: $\tau^+ \neq \theta^+$ but by 1955 precise mass & lifetime measurements (now: K^+)

- Lee and Yang: test if weak interactions violate parity? (Nobel prize, 1957)

$\Rightarrow$ Modern theory of weak interactions

1964: CP symmetry is broken

- The CP symmetry was expected to hold
- Two neutral states, nearly equal mass, but lifetime ratio > 500 — understood as coming from phase space difference



If CP were conserved: CP eigenstates $=$ mass eigenstates $(K_L,\, K_S)$

$\pi\pi$ in $J = 0$ state has $CP = +1$, so only one of the states can decay to it (K_S)

- Discovered in 1964:

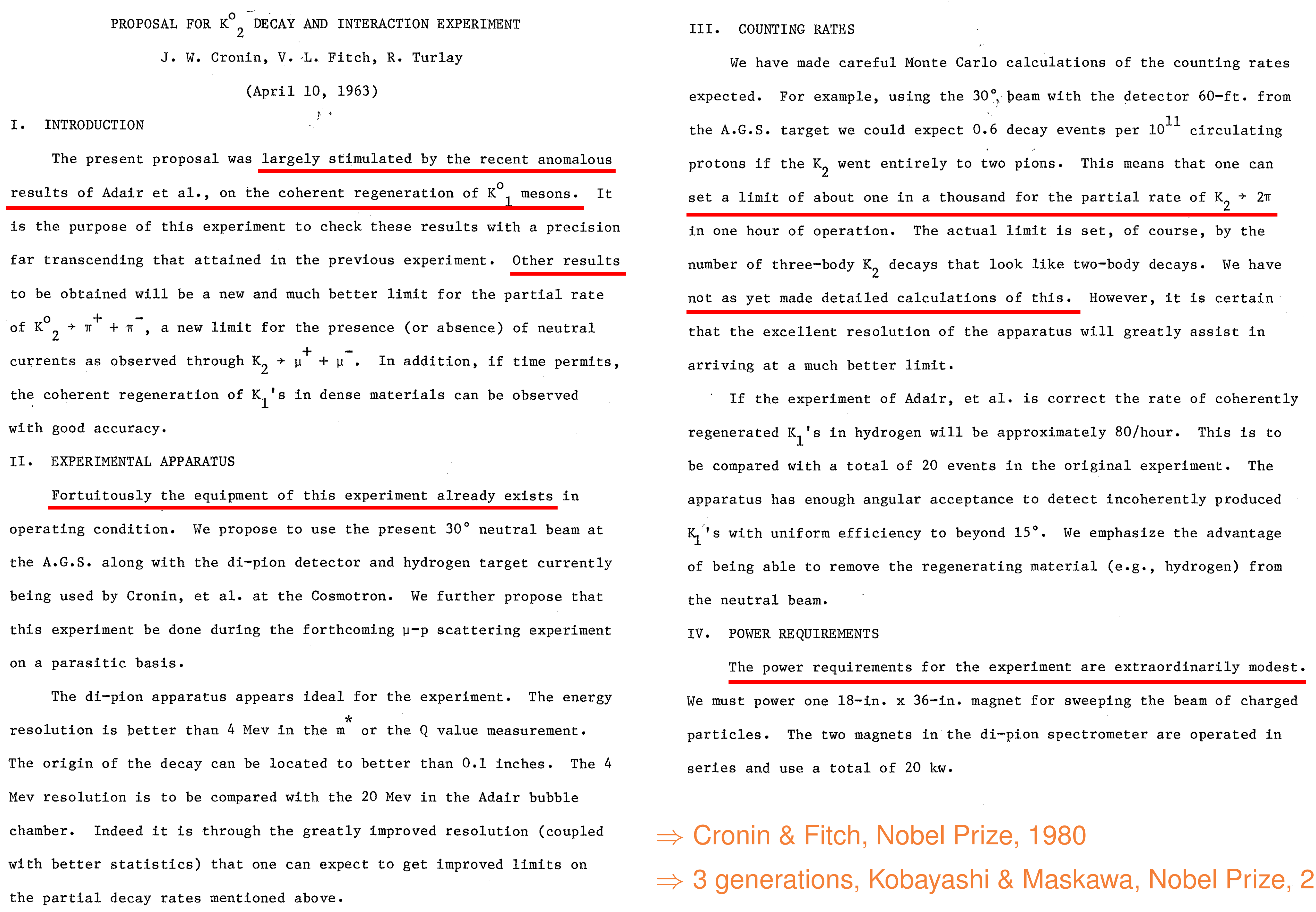
(0.2%) (Nobel prize, 1980)

- A new CP violating interaction? Is CP an approximate symmetry?

[Before charm and much of the SM — could involve new particles / new sectors of the theory]

Many options... No other independent observation of CP violation until 1999

Aside: the experimental proposal



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 $K^o_2 \rightarrow \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \rightarrow \mu^+ + \mu^-$. 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 $K_2 \rightarrow 2\pi$ 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.

$\Rightarrow$ Cronin & Fitch, Nobel Prize, 1980

$\Rightarrow$ 3 generations, Kobayashi & Maskawa, Nobel Prize, 2008

Hitchhiker’s guide to the SM

Ingredients of a model

- Need to specify: (i) gauge (local) symmetries
  (ii) representations of fermions and scalars
  (iii) vacuum — spontaneous symmetry breaking

- $\mathcal{L} =$ all gauge invariant terms (renormalizable, $dim \leq 4$)

  "Everything" follows, after a finite number of parameters are fixed from experiment

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- Implicit assumptions: Lorentz symmetry and QFT;
  No global symmetries imposed; accidental symmetries can arise

- Higher dimension terms are suppressed at low energies

  (We are modest and don't worry about details of physics at much higher scales)

  If higher dimension operators $(dim > 4)$ present ⇒ new physics at high energy

The standard model

- Gauge symmetry: $SU(3)_c \times SU(2)_L \times U(1)_Y$ parameters

  8 gluons $W^\pm$, Z^0, γ 3

- Particle content: 3 generations of quarks and leptons

  $Q_L(3,2)_{1/6},\ u_R(3,1)_{2/3},\ d_R(3,1)_{-1/3}$ 10

  $L_L(1,2)_{-1/2},\ \ell_R(1,1)_{-1}$ 12 (?)

  quarks: $\begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix}$ leptons: $\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \\ e & \mu & \tau \end{pmatrix}$

- Symmetry breaking: $SU(2)_L \times U(1)_Y \ \to \ U(1)_{\text{EM}}$

  $\phi(1,2)_{1/2}$ with a vev: $\langle\phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$ 2

- Strongly interacting particles observed in Nature have no color; quarks confined

  mesons: $\pi^+\,(u\bar{d}),\ K^0\,(\bar{s}d),\ B^0\,(\bar{b}d),\ B^0_s\,(\bar{b}s)$; baryons: $p\,(uud),\ n\,(udd)$

From Yukawa couplings to CKM matrix

- SM is the simplest scenario: Higgs background $=$ single scalar field ϕ

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

- Quark masses: from Yukawa couplings after ϕ acquires vev $(Y_{u,d} = 3{\times}3$ complex)

$$\mathcal{L}_{\rm mass} = -\overline{u_{Li}^I}\, M_u^{ij}\, u_{Rj}^I - \overline{d_{Li}^I}\, M_d^{ij}\, d_{Rj}^I\,, \qquad M_{u,d} = Y_{u,d}\,(v/\sqrt{2})$$

Diagonalize: $M_f^{\rm diag} \equiv V_{fL}\, M_f\, V_{fR}^\dagger$ $(f = u, d;$ four V matrices unitary)

Mass eigenstates: $f_{Li} \equiv V_{fL}^{ij}\, f_{Lj}^I\,, \quad f_{Ri} \equiv V_{fR}^{ij}\, f_{Rj}^I$

- Different unitary transformations get u_{Li} and d_{Li} into mass basis, but these are part of the same $SU(2)_L$ doublet: $Q_{Li}^I = \begin{pmatrix} u_{Li}^I \\ d_{Li}^I \end{pmatrix} = (V_{uL}^\dagger)_{ij} \begin{pmatrix} u_{Lj} \\ (V_{uL} V_{dL}^\dagger)_{jk}\, d_{Lk} \end{pmatrix}$

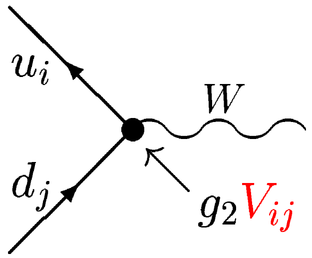
- Charged current weak interactions become off-diagonal: CKM matrix

$$-\frac{g}{2}\, \overline{Q_{Li}^I}\, \gamma^\mu\, W_\mu^a\, \tau^a\, Q_{Li}^I + \text{h.c.} \;\Rightarrow\; -\frac{g}{\sqrt{2}} \left(\overline{u_L},\, \overline{c_L},\, \overline{t_L}\right) \gamma^\mu\, W_\mu^+ (V_{uL} V_{dL}^\dagger) \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$$

Weak interaction properties

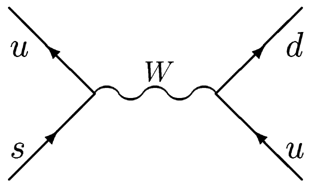
- Only the $W^\pm$ interactions change the type of quarks

  Interaction strength is given by Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, V_{ij}, 3×3 unitary matrix



- Flavor changing charged currents at tree level

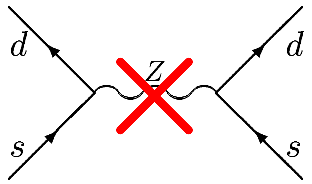
  e.g.: $K \to \pi\pi$ or $K \to \pi \ell \bar{\nu}$



  No flavor changing neutral currents (FCNC) at tree level

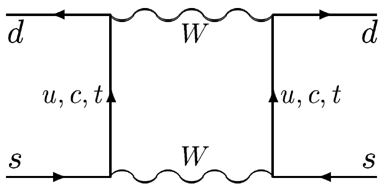
  e.g.: no $K^0 - \overline{K}^0$ mixing, $K \to \mu^+\mu^-$, etc.

  (Show that Z^0 interactions are flavor conserving in the mass basis)



- FCNC only at loop level in SM; suppressed by $(m_i^2 - m_j^2)/m_W^2$

  e.g.: $K^0 - \overline{K}^0$ mixing used to predict m_c before its discovery



- FCNCs probe difference between the generations (typically small in the SM)

Quark mixing and the unitarity triangle

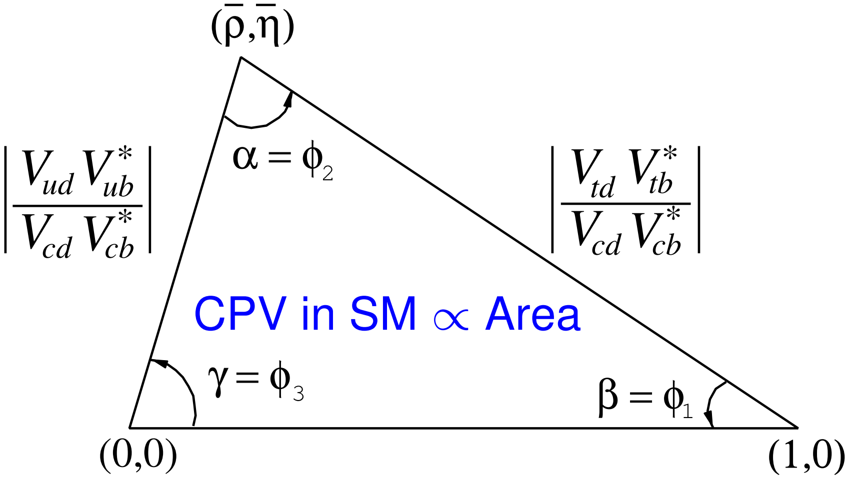
- The $(u,\ c,\ t)\ \ W^{\pm}\ (d,\ s,\ b)$ couplings: (Wolfenstein parm., $\lambda \sim 0.23$)

$$V_{\rm CKM} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\text{CKM matrix}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \ldots$$

One complex phase in $V_{\rm CKM}$: only source of CP violation in quark sector

9 complex couplings depend on 4 real parameters $\Rightarrow$ many testable relations

- Unitarity triangles (6): visualize SM constraints and compare measurements



$$V_{ud}\,V_{ub}^* + V_{cd}\,V_{cb}^* + V_{td}\,V_{tb}^* = 0$$

Sides and angles measurable in many ways

Goal: overconstrain by many measurements sensitive to different short distance physics

Determinations of CKM elements

- Magnitudes of CKM elements (sides of UT): semileptonic decays; $B_{d,s}$ oscillation
- Relative phases of CKM elements (angles of UT-s): CP violation
  (Any physical CP violating quantity must depend on at least 4 CKM elements)

Measure hadrons, but interested in quark properties, parameters in Lagrangian

Need to deal with strong interactions, at scales at which perturbation theory is of limited use

- The name of the game: do “redundant” / “overconstraining” measurements of processes sensitive to different short-distance physics — if inconsistent ⇒ NP

Lincoln Wolfenstein: *‘I do not care what the values of the Wolfenstein parameters are, so you should not either; the only question is if their independent determinations give the same results’*

- Need experimental precision and theoretical cleanliness to increase NP sensitivity

Summary — standard model

- The SM is consistent with a vast amount of particle physics phenomena
  - special relativity $+$ quantum mechanics
  - local symmetry $+$ spontaneous breaking

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

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

  $\Rightarrow$ The LHC started to directly address this (produce h and test its couplings)

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

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

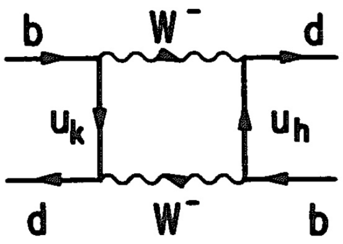
  How do the fermions see the condensate and the physics associated with it?

  $\Rightarrow$ CP violation and flavor changing neutral currents are very sensitive probes

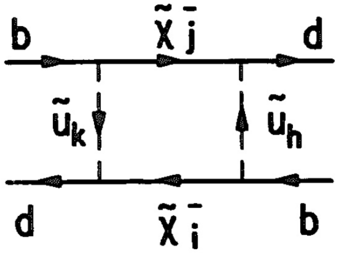
New physics and flavor

What are we after?

- Meson mixing:

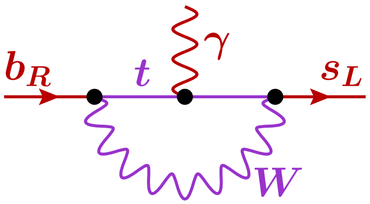


~~OR~~ ⇒ AND?



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

- FCNC decays:



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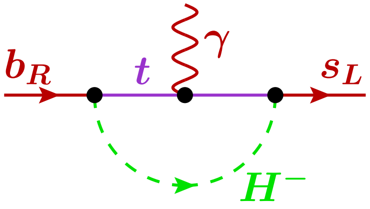


Many operators for $b \to s$ transitions — no similarly simple parameterization

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

- Complication: isolating modest NP contributions requires many measurements

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

Spectacular track record

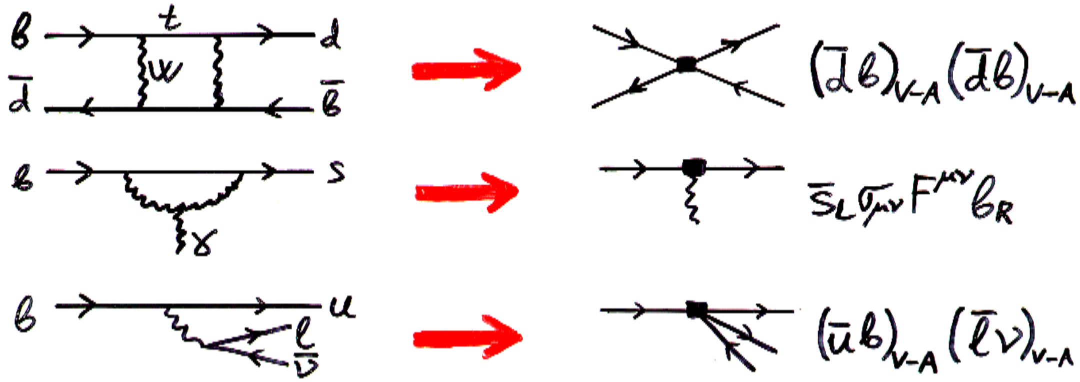
- Most parameters of the SM (and in many of its extensions) are related to flavor
- Flavor physics was crucial to figure out $\mathcal{L}_{\rm SM}$:
  - β-decay predicted neutrino (Pauli)
  - Absence of $K_L \to \mu\mu$ predicted charm (Glashow, Iliopoulos, Maiani)
  - ϵ_K predicted 3rd generation (Kobayashi & Maskawa)
  - Δm_K predicted m_c (Gaillard & Lee)
  - Δm_B predicted large m_t
- Likely to be important to figure out $\mathcal{L}_{\rm LHC}$ as well
- If there is NP at the TEV scale, it must have a very special flavor & CP structure

The low energy viewpoint

- At scale m_b, flavor changing processes are mediated by dozens of higher dimension operators

  Depend only on a few parameters in the SM $\Rightarrow$ correlations between s, c, b, t decays

weak / NP scale $\qquad\qquad$ $\sim 5\,$GeV



E.g.: in SM $\dfrac{\Delta m_d}{\Delta m_s}, \dfrac{b \to d\gamma}{b \to s\gamma}, \dfrac{b \to d\ell^+\ell^-}{b \to s\ell^+\ell^-} \propto \left|\dfrac{V_{td}}{V_{ts}}\right|$, but test different short dist. physics

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- Does the SM (i.e., integrating out virtual W, Z, and quarks in tree and loop diagrams) explain all flavor changing interactions? Right coefficients and operators?
  - Changes in correlations (B vs. K constraints, $S_{\psi K_S} \neq S_{\phi K_S}$, etc.)
  - Enhanced or suppressed CP violation (sizable $S_{B_s\to\psi\phi}$ or $A_{b\to s\gamma}$, etc.)
  - Compare tree and loop processes — FCNC's at unexpected level

Flavor probes $10^2 - 10^5$ TeV scale

- Neutral meson mixings: dimension-6 operators, come with coefficients C/Λ^2

  If $\Lambda = \mathcal{O}(1\,\mathrm{TeV})$ then $C \ll 1$; alternatively, if $C = \mathcal{O}(1)$ then $\Lambda \gg 1\,\mathrm{TeV}$

Operator	Bounds on Λ [TeV] $(C = 1)$		Bounds on C $(\Lambda = 1$ TeV$)$		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\, \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\, \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\, \lvert q/p\rvert,\, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\, \lvert q/p\rvert,\, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d};\, S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_{B_d};\, S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\, S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\, S_{\psi\phi}$

- Flavor has mainly been input to NP models (structures imposed to satisfy bounds)

- If NP is $10 - 100\,\mathrm{TeV}$ (split, spread, ...), flavor crucial (less constraints, high reach)

Important features of flavor in SM

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

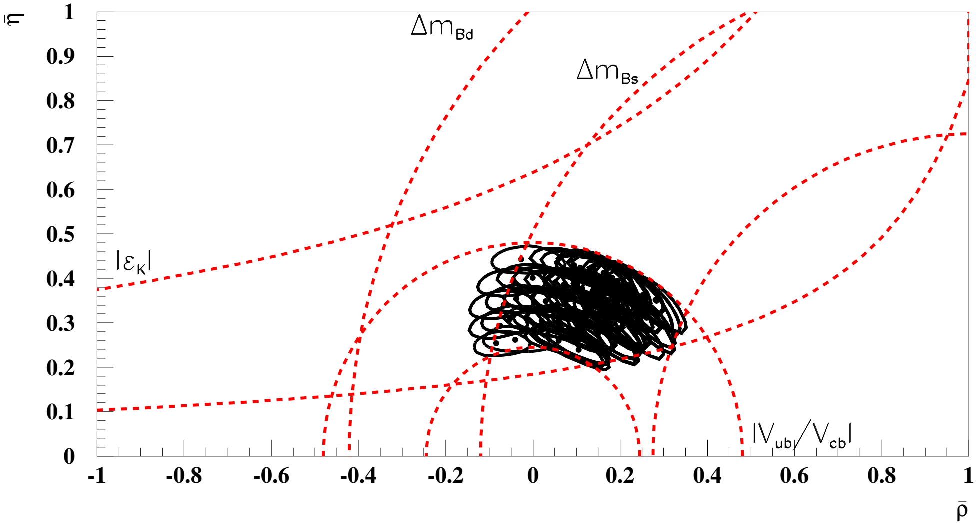
- The SM flavor structure is very special:
  - Single source of CP violation in CC interactions
  - Suppressions due to hierarchy of CKM elements
  - Suppression of FCNC processes (loops)
  - Suppression of FCNC chirality flips by quark masses (e.g., $B \to K^*\gamma$)

  Many suppressions that NP might not respect $\Rightarrow$ probe very high scales

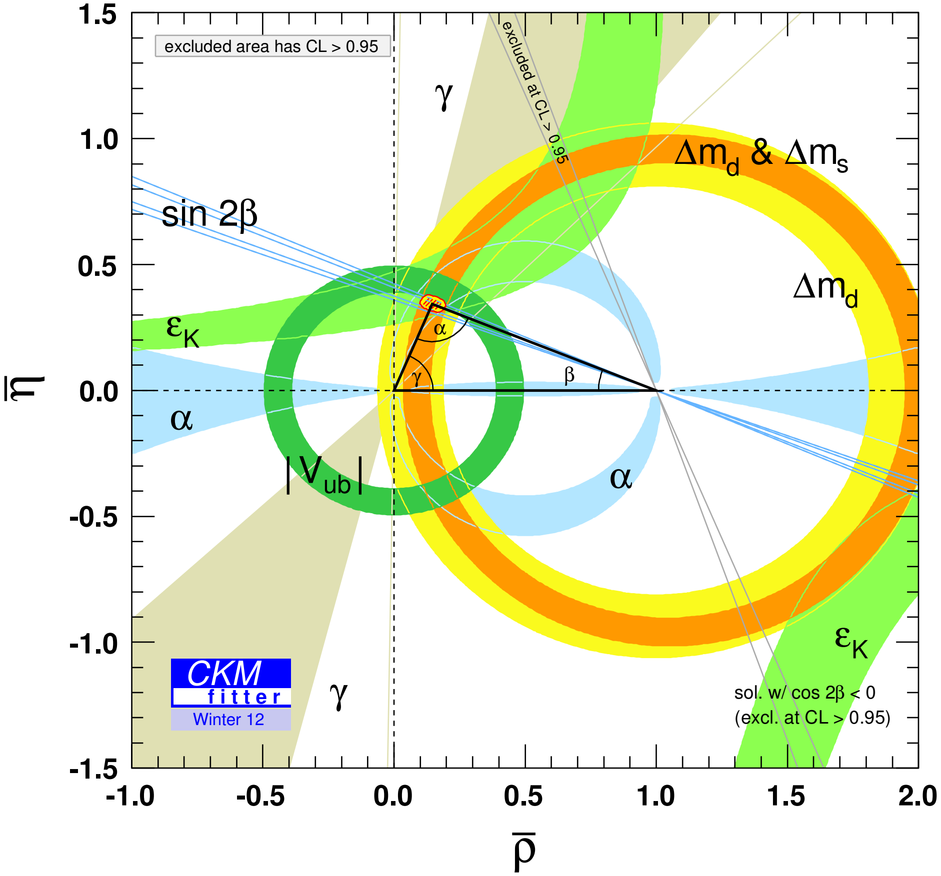
- It is interesting and possible to look for NP contributions with better sensitivity

CP violation before the B factories

- For 35 years (untill 1999), only unambiguous CPV measurement was in K mixing



(BABAR Physics Book, 1998)

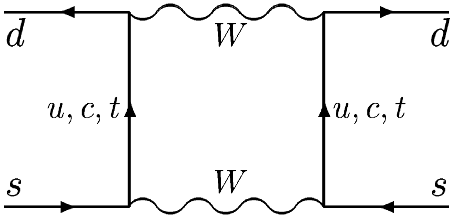


- CP vioaltion used to be interesting in itself; by now dozens of measurements

  ⇒ In which cases can both theory and experiment be precise?

Bits of K physics

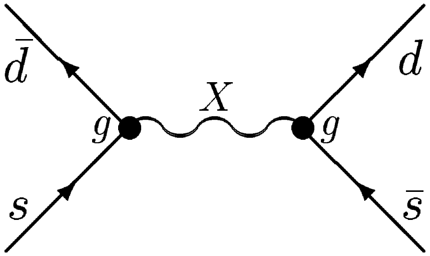
Δm_K — built in NP models since 60's



- In the SM: $\Delta m_K \sim \alpha_w^2 \, |V_{cs} V_{cd}|^2 \, \frac{m_c^2}{m_W^4} \, f_K^2 \, m_K$

  (severe suppressions!)

- If tree-level exchange of a heavy gauge boson was responsible for a significant fraction of the measured value of Δm_K



$$\left| \frac{M_{12}^{(X)}}{\Delta m_K} \right| \sim \left| \frac{g^2 \, \Lambda_{\rm QCD}^3}{M_X^2 \, \Delta m_K} \right| \Rightarrow M_X \gtrsim g \times 2 \cdot 10^3 \ \text{TeV}$$

- TeV-scale new particles can have large contributions even in loops $[g \sim \mathcal{O}(10^{-2})]$

In many NP scenarios the constraits from kaons are the strongest, since so are the SM suppressions — these are built into models since the 70's

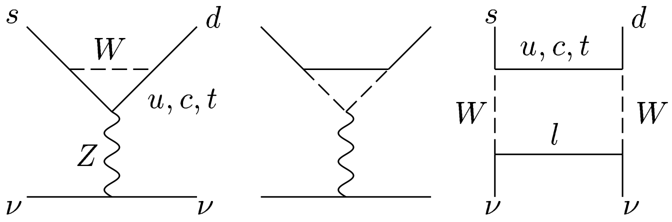
Precision CKM tests with kaons

- 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
- $K \to \pi\nu\overline{\nu}$: 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 $K_L \to \pi^0\nu\bar\nu$

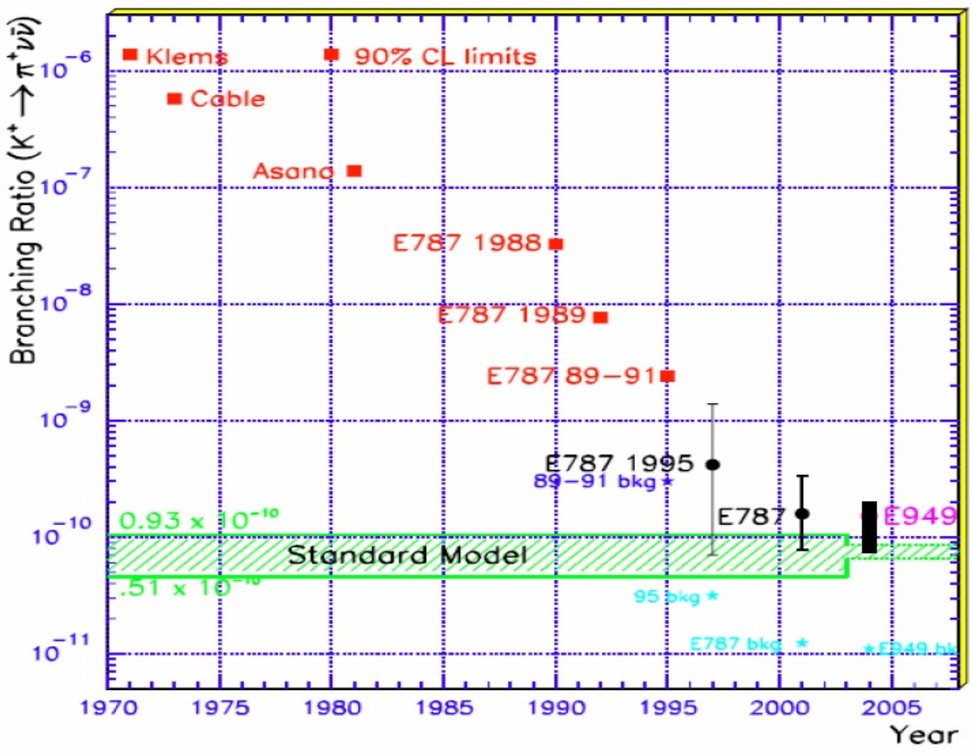
- $\Rightarrow$ Need much more data to achieve ultimate sensitivity

The holy grail: $K \to \pi\nu\bar{\nu}$

- 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: expect to get ~ 100 $K^+ \to \pi^+\nu\bar{\nu}$ events

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 $K_L^0 \to \pi^0\nu\bar{\nu}$

Many interesting measurements

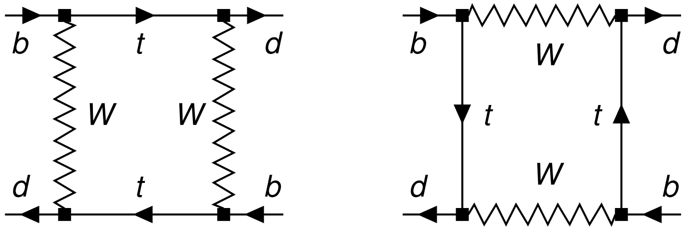
Observable	SM Theory	Current Status	Future Experiments
$\mathcal{B}(K^+ \to \pi^+\nu\bar\nu)$	$7.81(75)(29) \times 10^{-11}$	$1.73^{+1.15}_{-1.05} \times 10^{-10}$ E787/E949	$\sim$10% at NA62 $\sim$5% at ORKA $\sim$2% at Project-X
$\mathcal{B}(K_L^0 \to \pi^0\nu\bar\nu)$	$2.43(39)(6) \times 10^{-11}$	$< 2.6 \times 10^{-8}$ E391a	1st observation at KOTO $\sim$5% at Project-X
$\mathcal{B}(K_L^0 \to \pi^0 e^+ e^-)$	$(3.23^{+0.91}_{-0.79}) \times 10^{-11}$	$< 2.8 \times 10^{-10}$ KTeV	$\sim$10% at Project-X
$\mathcal{B}(K_L^0 \to \pi^0 \mu^+ \mu^-)$	$(1.29^{+0.24}_{-0.23}) \times 10^{-11}$	$< 3.8 \times 10^{-10}$ KTeV	$\sim$10% at Project-X
$\lvert P_T \rvert$ in $K^+ \to \pi^0\mu^+\nu$	$\sim 10^{-7}$	< 0.0050	< 0.0003 at TREK < 0.0001 at Project-X
$\Gamma(K_{e2})/\Gamma(K_{\mu2})$	$2.477(1) \times 10^{-5}$	$2.488(12) \times 10^{-5}$ (NA62, KLOE)	$\pm 0.0054 \times 10^{-5}$ at TREK $\pm 0.0025 \times 10^{-5}$ at Project-X
$\mathcal{B}(K_L^0 \to \mu^\pm e^\mp)$	$< 10^{-25}$	$< 4.7 \times 10^{-12}$	$< 2 \times 10^{-13}$ at Project-X

- Broad program, beyond measuring the $K \to \pi\nu\bar\nu$ rates [More: Tschirhart, tomorrow]
- Unique opportunity for U.S. to have world-leading kaon program: ORKA @ FNAL

$B^0 - \overline{B}^0$ mixing and CPV

B meson mixing

- Quantum mechanical two-level system; flavor eigenstates: $|B^0\rangle = |\bar{b}d\rangle,\ |\overline{B}^0\rangle = |b\bar{d}\rangle$
- Evolution: $i\,\dfrac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|B^0(t)\rangle\\ |\overline{B}^0(t)\rangle\end{pmatrix} = \left(M - \dfrac{i}{2}\Gamma\right)\begin{pmatrix}|B^0(t)\rangle\\ |\overline{B}^0(t)\rangle\end{pmatrix}$



Mass eigenstates: $|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$

$M,\ \Gamma$: 2×2 Hermitian matrices (*CPT* implies $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$)

- Off-diagonal elements dominated by box diagrams with top ⇒ short distance

In the SM: $M_{12} = (V_{tb}V_{td}^*)^2\,\dfrac{G_F^2}{8\pi^2}\,\dfrac{m_W^2}{m_B}\,S\!\left(\dfrac{m_t^2}{m_W^2}\right)\eta_B\,b_B(\mu)\,\langle B^0|(\bar{b}_L\gamma^\nu d_L)^2|\overline{B}^0\rangle$

CKM calculable perturbatively nonperturbative

- Time dependence involves mixing & decay: $|B_{H,L}(t)\rangle = e^{-(iM_{H,L}+\Gamma_{H,L}/2)t}|B_{H,L}\rangle$
- Hadronic uncertainties in Δm (LQCD helps) and especially $\Delta\Gamma$, but not $\arg(q/p)$

The four neutral mesons

- Physical observables: $x = \Delta m/\Gamma,\ y = \Delta\Gamma/(2\Gamma),\ |q/p|$
- In the absence of CP violation: $\Delta m = 2|M_{12}|,\ \Delta\Gamma = 2|\Gamma_{12}|$

Order of magnitudes of SM predictions:

meson	x	y	$\lvert q/p\rvert - 1$
K	1	1	10^{-3}
D	10^{-2}	10^{-2}	$10^{-2(-3?)}$
B_d	1	10^{-2}	10^{-3}
B_s	10^{1}	10^{-1}	10^{-3}

- General sol. for eigenvalues is complicated; an important part: $\dfrac{q^2}{p^2} = \dfrac{2M_{12}^* - i\Gamma_{12}^*}{2M_{12} - i\Gamma_{12}}$

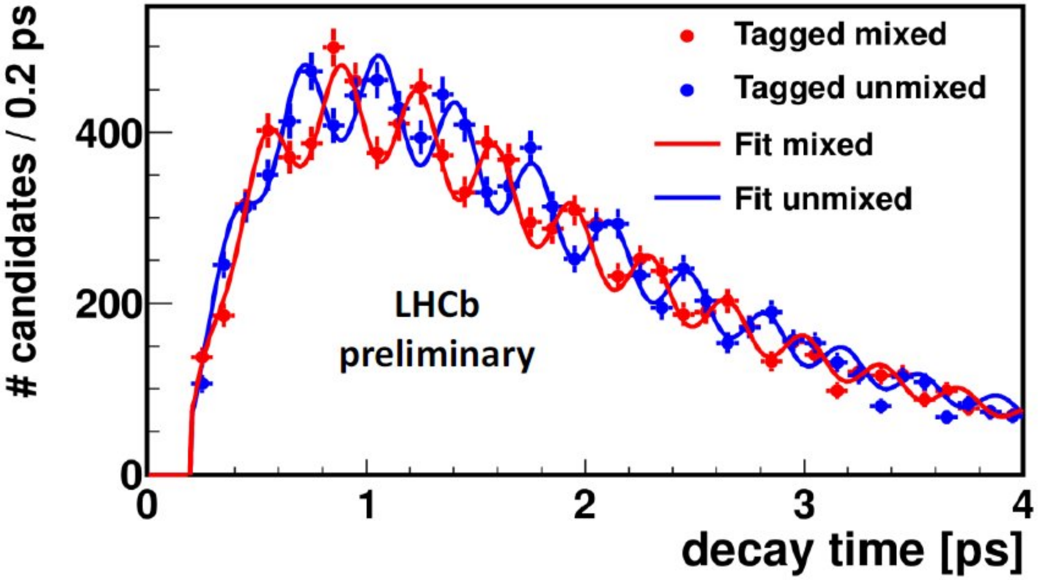
CPV in mixing $\leftrightarrow$ mass eigenstates $\neq CP$ eigenstates $\leftrightarrow$ $|q/p| \neq 1$ $\leftrightarrow$ $\mathrm{Im}(\Gamma_{12}/M_{12}) \neq 0$

- In $B_{d,s}$ mixing, $|M_{12}| \gg |\Gamma_{12}|$ $\Rightarrow$ $q/p =$ pure phase, no hadronic uncertainty

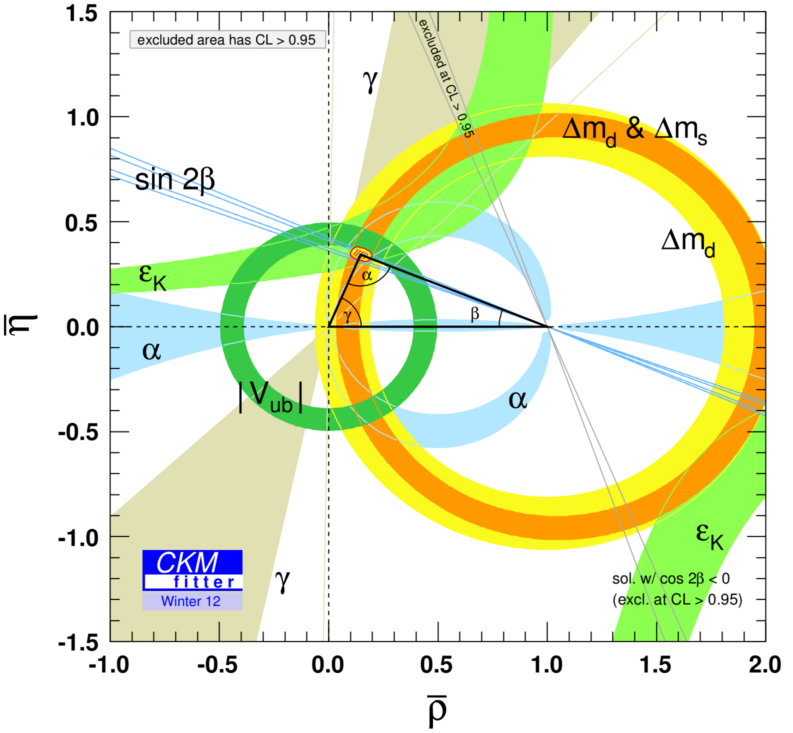
A key to allow many model independent measurements from CPV

B_s^0 mixing and $|V_{td}/V_{ts}|$

- $B_s^0 - \overline{B}_s^0$ oscillate ~ 25 times before they decay (first measured by CDF in 2007)



$$\Delta m_s = (17.768 \pm 0.024)\,\mathrm{ps}^{-1}$$



- Uncertainty $\sigma(\Delta m_s) = 0.13\%$ is much 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: $\xi = 1.24 \pm 0.03 \pm 0.02$

Three types of CP violation

- CPV in decay: simplest, possible for charged and neutral mesons, and baryons

$$\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})$$

Requires interference of amplitudes with ≥ 2 different weak and strong phases

$$A_f = \langle f|\mathcal{H}|B\rangle = \sum_k A_k\, e^{i\delta_k}\, e^{i\phi_k} \qquad \overline{A}_{\overline{f}} = \langle \overline{f}|\mathcal{H}|\overline{B}\rangle = \sum_k A_k\, e^{i\delta_k}\, e^{-i\phi_k}$$

weak phases ϕ_k from Lagrangian, CP-odd — strong phases δ_k from rescattering, CP-even

In case of two amplitudes: $|A|^2 - |\overline{A}|^2 = 4A_1A_2\, \sin(\phi_1 - \phi_2)\, \sin(\delta_1 - \delta_2)$

- Unambiguously established by $\epsilon'_K \neq 0$, and also in B and B_s decays

Theoretical understanding insufficient to either prove or to rule out that NP enters

Nevertheless, ϵ'_K is still a very strong constraint on NP

- Two other ways for CP violation in neutral mesons — can be theoretically cleaner

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CPV in mixing

- If CP is conserved then $|q/p| = 1$ and $\mathrm{Im}(M_{12}/\Gamma_{12}) = 0$

  CPV iff (mass eigenstates) $\neq$ (CP eigenstates) — physical states not orthogonal!

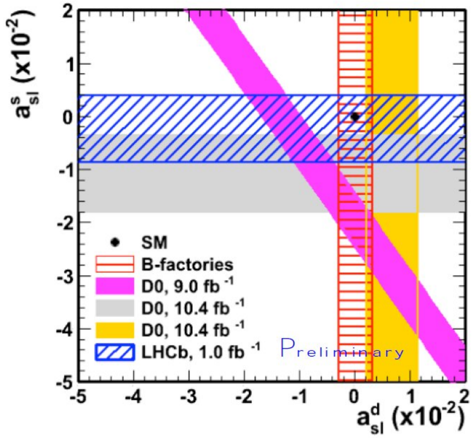
  $|q/p| \neq 1 \ \Leftrightarrow$ CPV in mixing   implies: $\langle B_H | B_L \rangle = |p|^2 - |q|^2 \neq 0$

- Simplest example: decay to “wrong sign” lepton (“dilepton asymmetry”)

$$A_{\mathrm{SL}} = \frac{\Gamma[\overline{B}^0(t) \to \ell^+ X] - \Gamma[B^0(t) \to \ell^- X]}{\Gamma[\overline{B}^0(t) \to \ell^+ X] + \Gamma[B^0(t) \to \ell^- X]} = \frac{|p/q|^2 - |q/p|^2}{|p/q|^2 + |q/p|^2} = \frac{1 - |q/p|^4}{1 + |q/p|^4} = \mathrm{Im}\,\frac{\Gamma_{12}}{M_{12}}$$

  Observed in K decay in agreement with SM (CPLEAR @ CERN)

  Intriguing 4σ hint of an effect from DØ



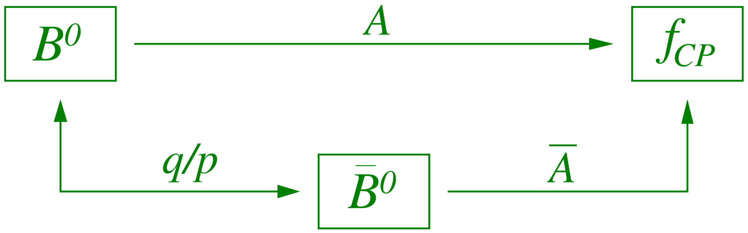
- Hadronic uncertainties in Γ_{12}, but interesting to look for NP:

  $|\Gamma_{12}/M_{12}| = \mathcal{O}(m_b^2/m_W^2)$ model independently

  $\arg(\Gamma_{12}/M_{12}) = \mathcal{O}(m_c^2/m_b^2)$ in SM, maybe $\mathcal{O}(1)$ with NP

CPV in interference between decay and mixing

- Can get theoretically clean information in some cases when B^0 and $\overline{B}^0$ decay to same final state



$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle \qquad \lambda_{f_{CP}} = \frac{q}{p}\,\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

- Time dependent CP asymmetry:

$$a_{f_{CP}} = \frac{\Gamma[\overline{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\overline{B}^0(t) \to f] + \Gamma[B^0(t) \to f]} = \underbrace{\frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}}_{S_f} \sin(\Delta m\, t) - \underbrace{\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}}_{C_f\ (-A_f)} \cos(\Delta m\, t)$$

- If amplitudes with one weak phase dominate a decay, hadronic physics drops out

- Measure a phase in the Lagrangian theoretically cleanly:

$$a_{f_{CP}} = \eta_{f_{CP}}\, \sin(\text{phase difference between decay paths})\ \sin(\Delta m\, t)$$

Aside: D^0 — mixing in up sector

- Complementary to K, B: CPV, FCNC both GIM & CKM suppressed $\Rightarrow$ tiny in SM

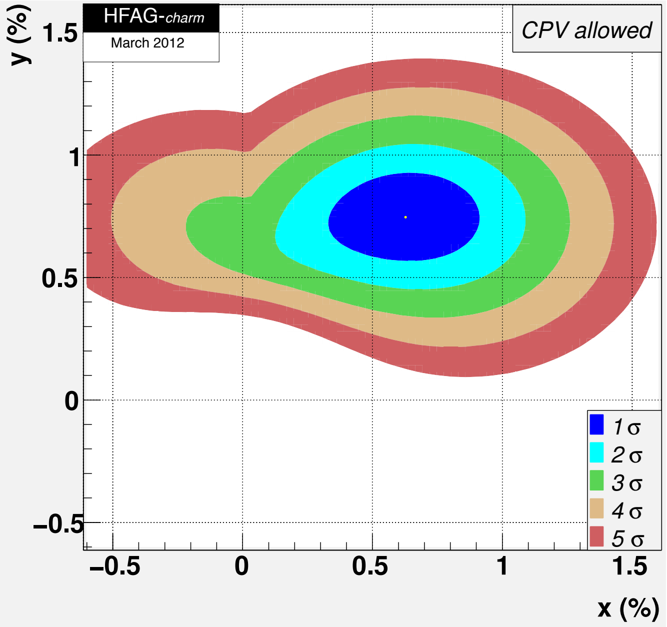
- 2007: observation of mixing, now $\gtrsim 10\sigma$ [HFAG combination]

  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 & vanish in $SU(3)$ limit

- $y = (0.75 \pm 0.12)\%$ and $x = (0.63 \pm 0.20)\%$

  ... suggest long distance dominance



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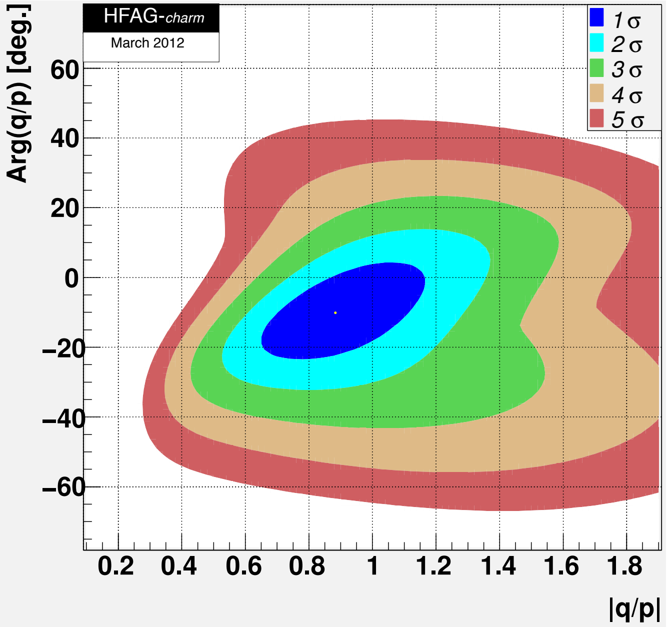


Don’t known yet if $|q/p|$ is near 1!

- How small CPV would unambiguously establish NP?

- Interesting inerplay in SUSY between Δm_D and Δm_K constraints
  Possible connections to top FCNC top decays

Looking for NP with B decays

LHCb

Super KEKB
Quest for BSM

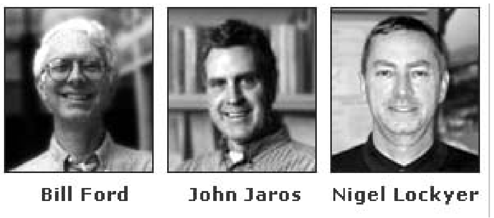
BELLE

CDF II

D0

What's special about B's?

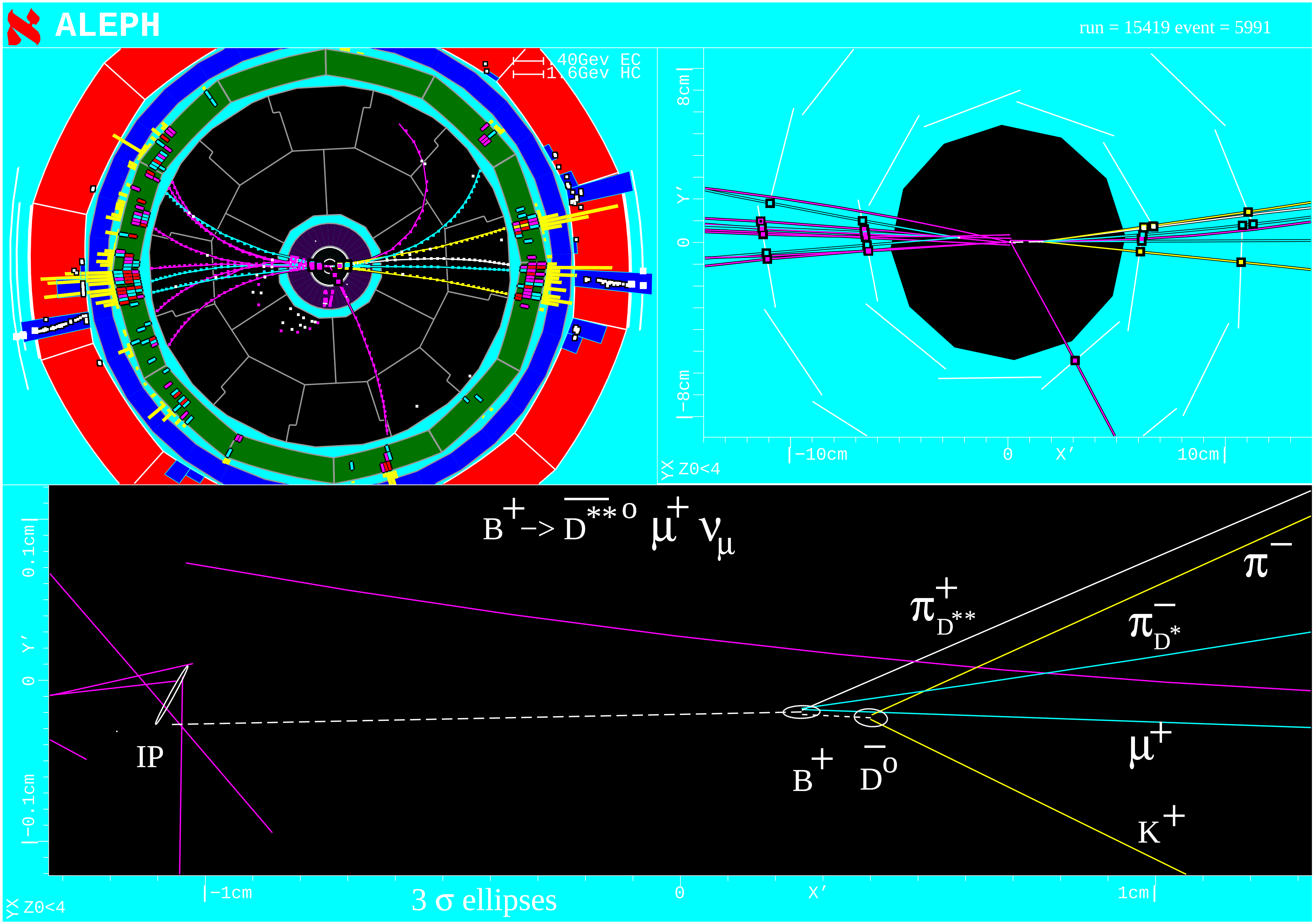
- Large variety of interesting processes:
  - Top quark loops neither GIM nor CKM suppressed
  - Large CP violating effects possible, some with clean interpretation
  - Some of the hadronic physics understood model independently $(m_b \gg \Lambda_{\text{QCD}})$
- Experimentally feasible to study:
  - $\Upsilon(4S)$ resonance is clean source of B mesons
  - Long B meson lifetime



    If $|V_{cb}|$ were as large as $|V_{us}|$, probably BaBar and Belle would not have been built, these lectures would not take place, etc.

  - Comparable timescale of oscillation and decay: $\Delta m/\Gamma \simeq 0.77 \, [= \mathcal{O}(1)]$ (and $\Delta\Gamma \ll \Gamma$)

You can “see” B decays



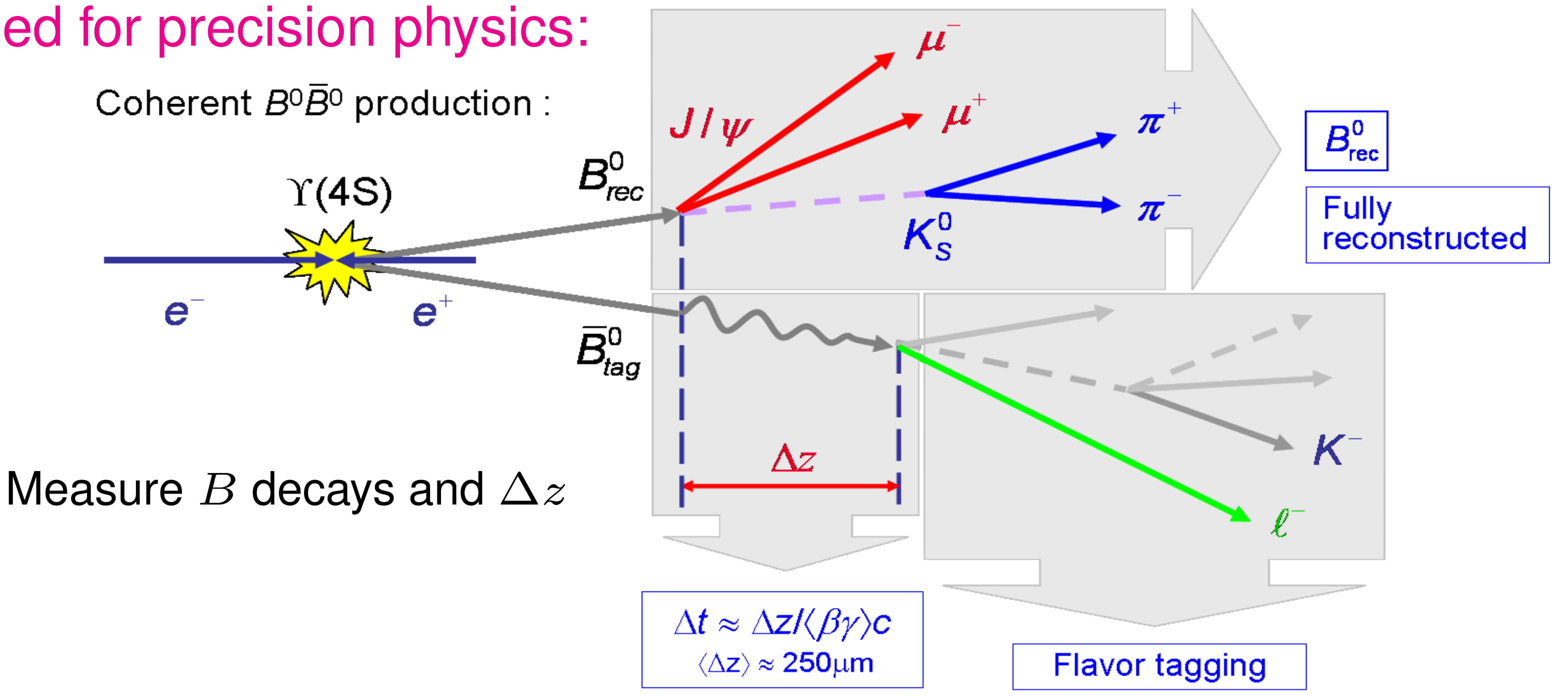
Quantum entanglement in $\Upsilon(4S) \to B^0\overline{B}^0$

- $B^0\overline{B}^0$ pair created in a p-wave ($L=1$) evolve coherently and undergo oscillations

  Two identical bosons cannot be in an antisymmetric state

  If one B decays as a B^0, then at the same time the other is a $\overline{B}^0$ (and vice versa)

- EPR effect used for precision physics:

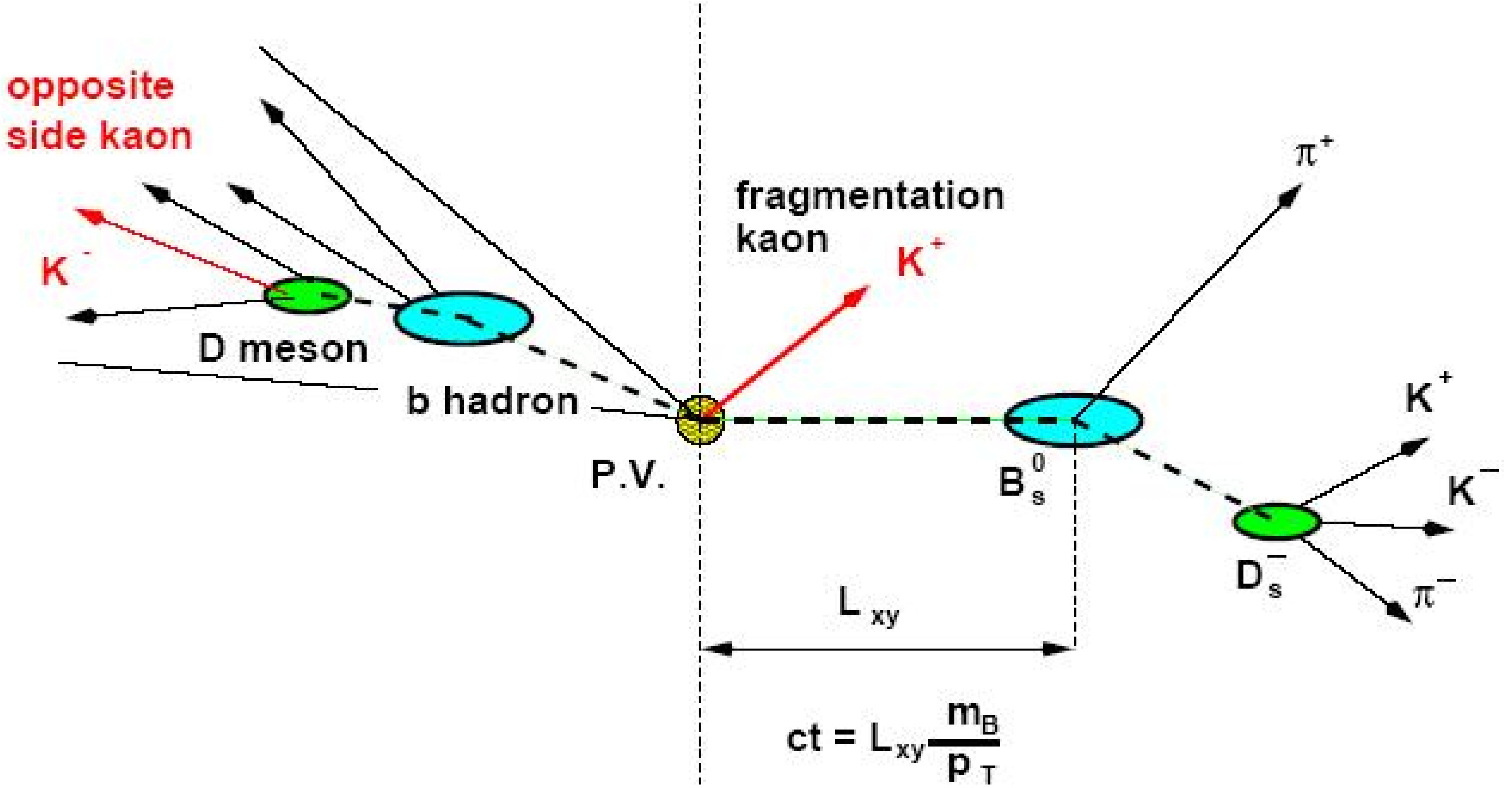


Measure B decays and Δz

- First decay ends quantum correlation and tags the flavor of the other B at $t = t_1$

Hadron colliders — no quantum correlation

- Opposite side tagging $+$ same side tagging (at LHCb, both are boosted forward)



- Much smaller ϵD^2 than at $\Upsilon(4S)$ ($\epsilon =$ tagging efficiency, $D = 1 - 2\omega_{\rm mistag} =$ "dilution")

  Need good time resolution, and fully reconstructed B on signal side to know boost

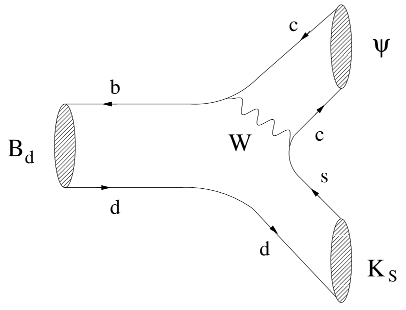
One of the cleanest cases: $B \to \psi K_S$

- Interference of $\overline{B} \to \psi \overline{K}^0$ $(b \to c\bar{c}s)$ with $\overline{B} \to B \to \psi K^0$ $(\bar{b} \to c\bar{c}\bar{s})$

  Amplitudes with one weak phase dominate by far

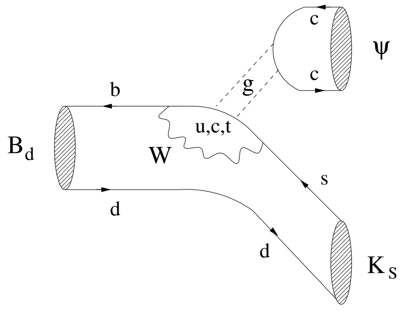
  unitarity: $V_{tb}V_{ts}^* + V_{cb}V_{cs}^* + V_{ub}V_{us}^* = 0$

$$\overline{A}_{\psi K_S} = \underbrace{V_{cb}V_{cs}^*}_{\mathcal{O}(\lambda^2)} \underbrace{\langle \text{“}T\text{”} \rangle}_{\text{“1”}} + \underbrace{V_{ub}V_{us}^*}_{\mathcal{O}(\lambda^4)} \underbrace{\langle \text{“}P\text{”} \rangle}_{\alpha_s(2m_c)}$$



  First term $\gg$ second term $\Rightarrow$ theoretically very clean

$$\lambda_{\psi K_{S,L}} = \mp \underbrace{\left(\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\right)}_{B-\text{mixing}} \underbrace{\left(\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\right)}_{\text{decay}} \underbrace{\left(\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}\right)}_{K-\text{mixing}} = \mp e^{-2i\beta}$$



  Corrections: $|\overline{A}/A| \neq 1$ (main uncertainty), $\epsilon_K \neq 0$, $\Delta\Gamma_B \neq 0$

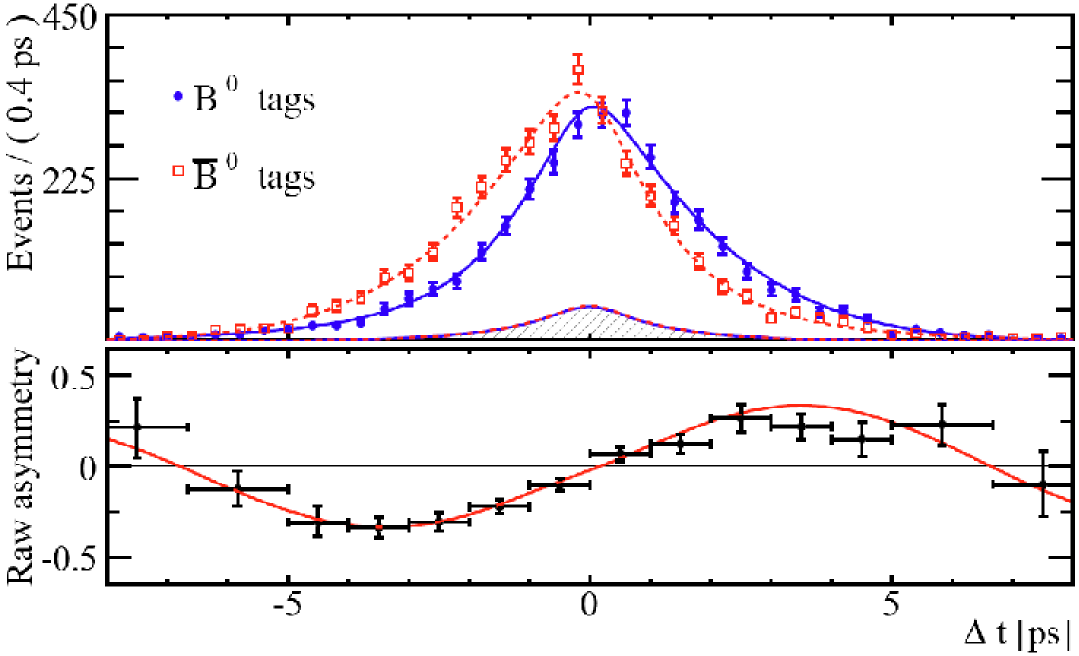
  all are few $\times 10^{-3}$ $\Rightarrow$ accuracy $< 1\%$

- World average: $\sin 2\beta = \pm S_{\psi K_{S,L}} = 0.677 \pm 0.020$ — a 3% uncertainty!

- Large deviations from CKM excluded; CPV is not small in general, only in K

CP violation in $B \to \psi K_S$ by the naked eye

- CP violation is an $\mathcal{O}(1)$ effect: $\sin 2\beta = 0.677 \pm 0.020$

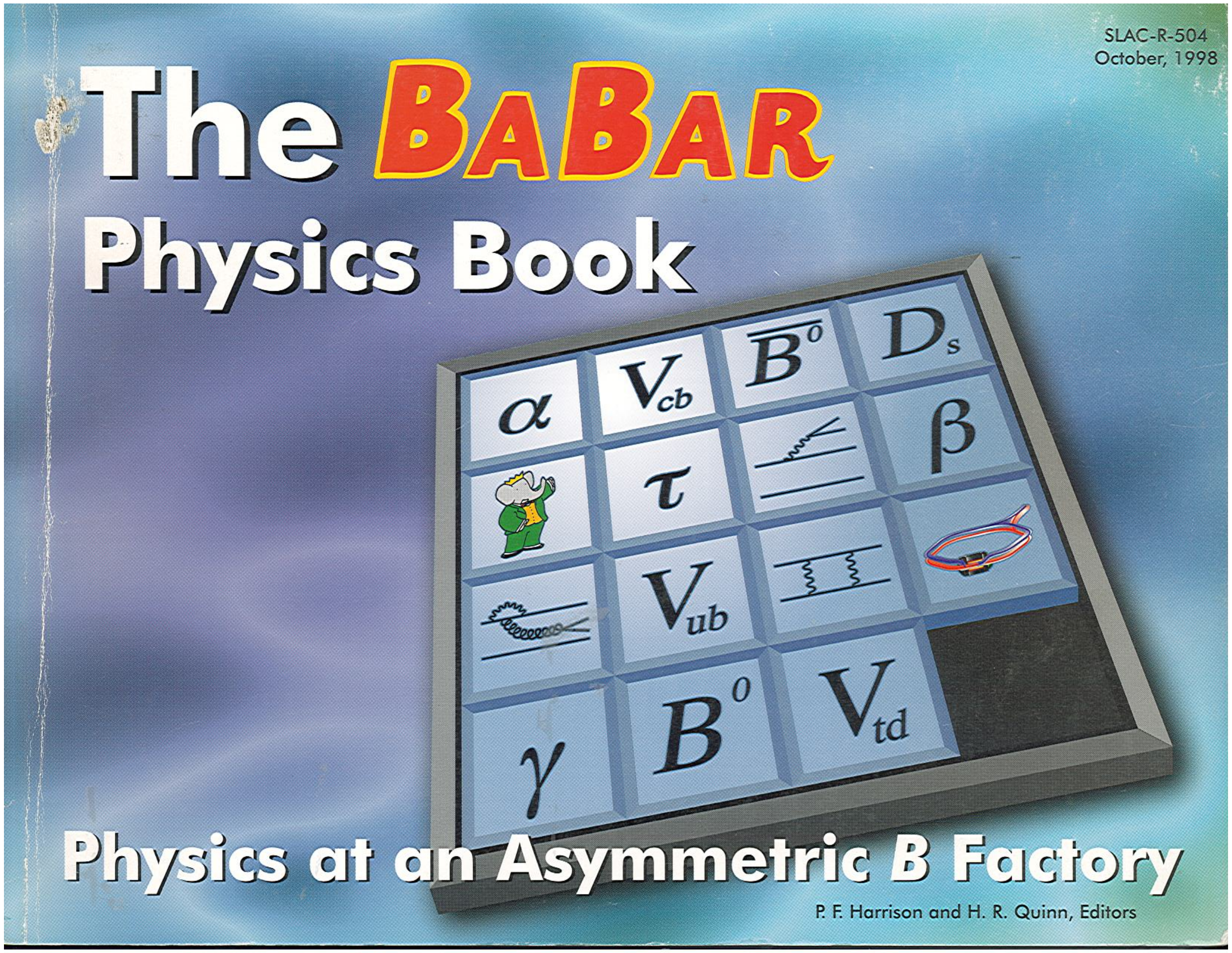


$$a_{f_{CP}} = \frac{\Gamma[\overline{B}^0(t) \to \psi K] - \Gamma[B^0(t) \to \psi K]}{\Gamma[\overline{B}^0(t) \to \psi K] + \Gamma[B^0(t) \to \psi K]} = \sin 2\beta\ \sin(\Delta m\, t)$$

- CP violation is large in some B decays, not a small effect in general

  Small kaon CPV is simply due to small CKM elements (involving 3rd generation)

Aside: “Killer app” in BaBar Physics Book?



SLAC-R-504
October, 1998

The BaBar
Physics Book

Physics at an Asymmetric *B* Factory

P. F. Harrison and H. R. Quinn, Editors

- There was no executive summary... Neither a list of gold-plated measurements...

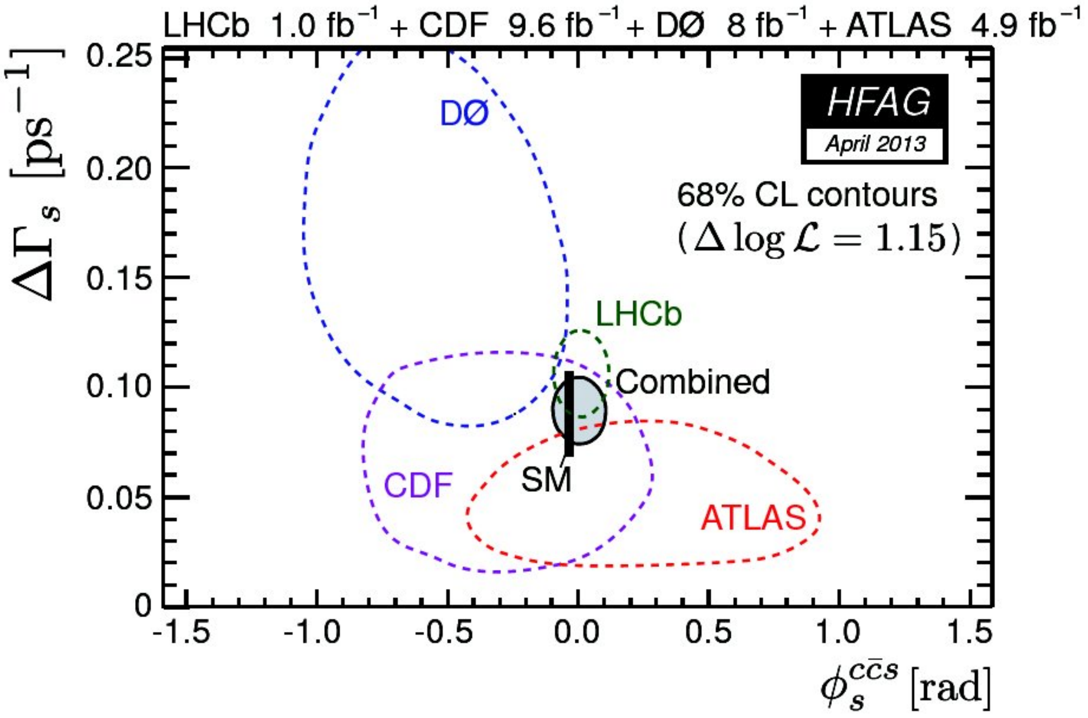
Similarly: β_s from $B_s \to \psi\phi$

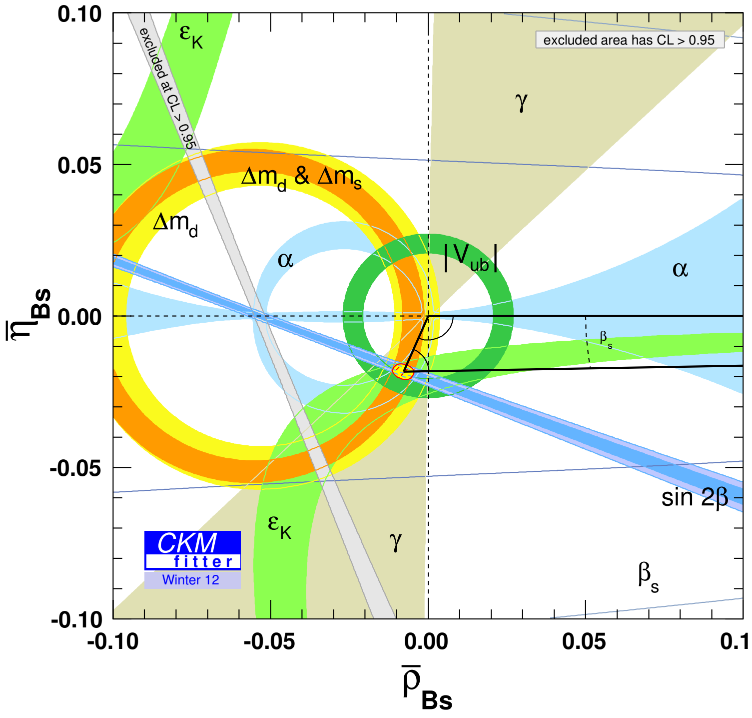
- Time dependent $B_s \to \psi\phi$ CP asymmetry (analog of $B \to \psi K$ + angular anal.)

  In SM: $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) = 0.019 \pm 0.002$ (λ^2 suppressed compared to β)

- LHCb 2013: $\phi_s \equiv -2\beta_s = 0.01 \pm 0.07$

The B_s "squashed" UT:

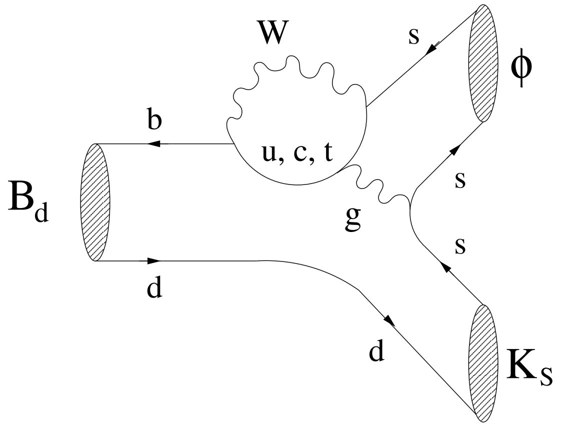




- Uncertainty of the SM prediction ≪ current experimental error (⇒ LHCb upgrade)

$B \to \phi K$ and $B_s \to \phi\phi$ — window to NP?

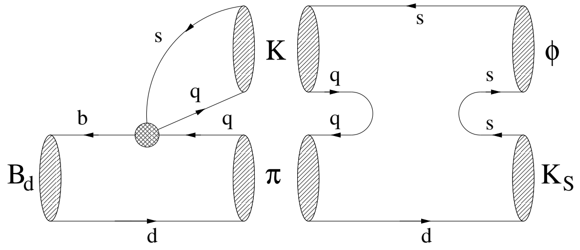
- Measuring same angle in decays sensitive to different short distance physics give good sensitivity to NP (sensitive to NP–SM interference)



Same physics: $S_{\phi K_S} - S_{\psi K}$ vs. $S_{B_s \to \psi\phi} - S_{B_s \to \phi\phi}$

- Amplitudes with one weak phase expected to dominate:

$$\overline{A} = \underbrace{V_{cb}V_{cs}^*}_{\mathcal{O}(\lambda^2)} \underbrace{[P_c - P_t + T_c]}_{\text{“1”}} + \underbrace{V_{ub}V_{us}^*}_{\mathcal{O}(\lambda^4)} \underbrace{[P_u - P_t + T_u]}_{\mathcal{O}(1)}$$



SM: $S_{\phi K_S} - S_{\psi K}$ and $C_{\phi K_S}$ < 0.05

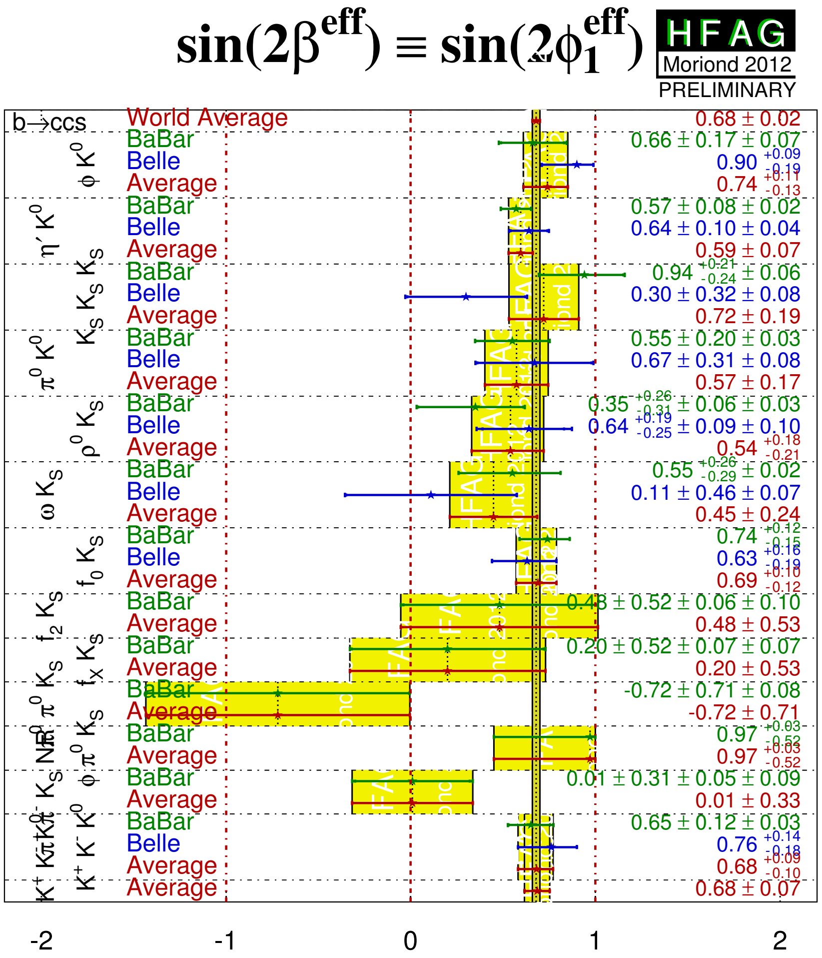
NP: $S_{\phi K_S} \neq S_{\psi K}$ possible

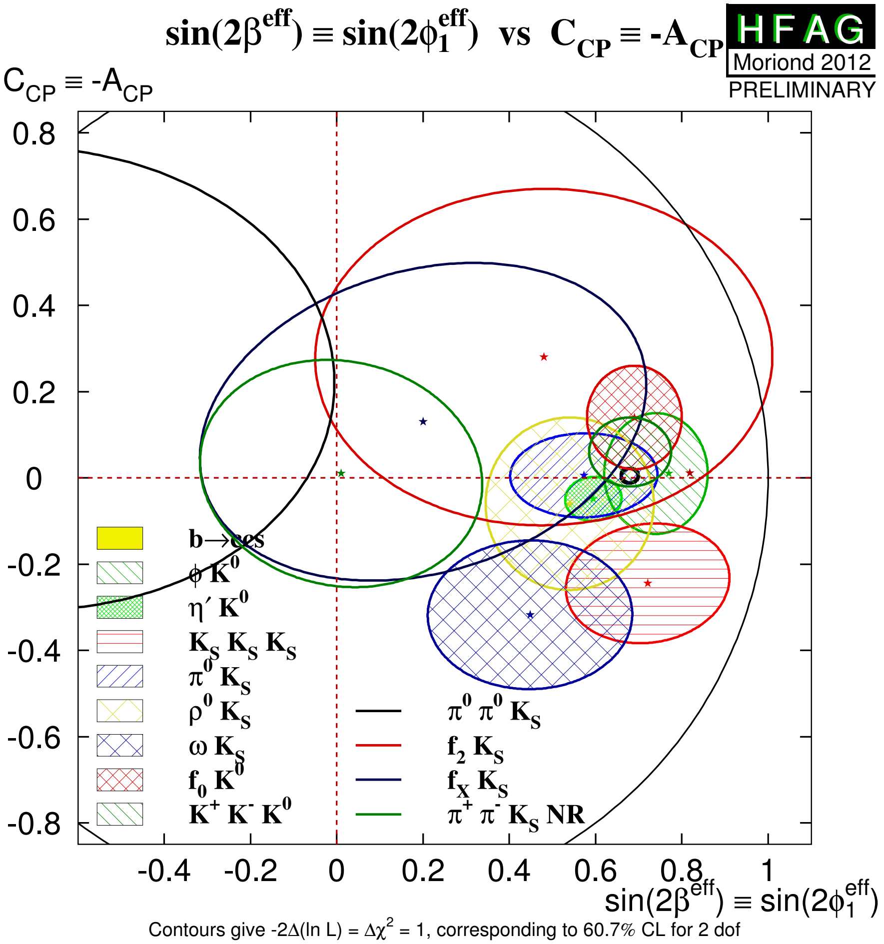
Expect different S_f for each $b \to s$ mode

NP could enter $S_{\psi K}$ mainly in mixing, while $S_{\phi K_S}$ through both mixing and decay

- Interesting to pursue independent of present results — plenty of room left for NP

Status of $\sin 2\beta_{\rm eff}$ measurements





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

- Earlier hints of deviations reduced, e.g., in $S_{\phi K}$ and $S_{\eta' K}$

It is still interesting to significantly reduce these experimental uncertainties

γ from $B^{\pm} \to DK^{\pm}$

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

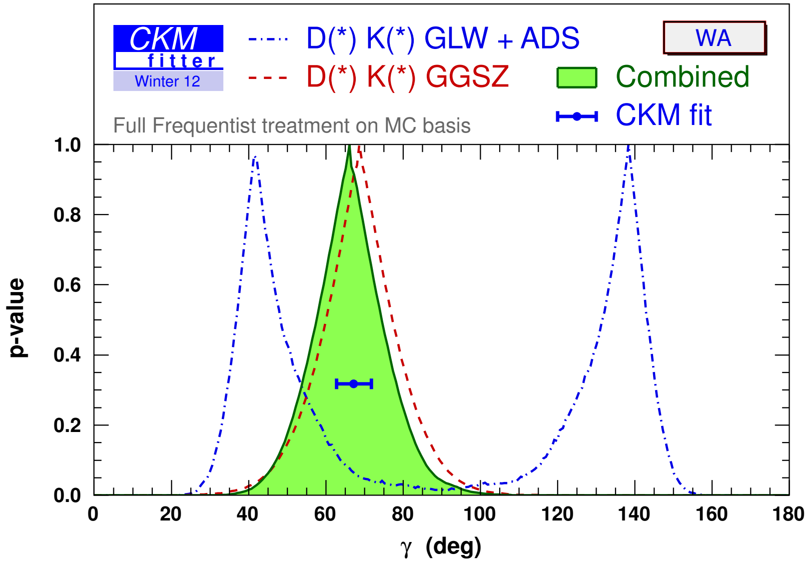
  Final states that both D^0 and $\overline{D}^0$ can decay into

  Measure both B & D decay amplitudes — many variants depending on D decay

- Challenge: large ratio of interfering amplitudes, sensitivity crucially depends on:

  $$r_B = |A(B^- \to \overline{D}^0K^-)/A(B^- \to D^0K^-)| \approx 0.1$$

- Best measurement so far: $D^0, \overline{D}^0 \to K_S\,\pi^+\pi^-$
  - Both amplitudes Cabibbo allowed;
  - Can integrate over regions in Dalitz plot



Other variants: GLW (Gronau–London–Wyler), ADS (Atwood–Dunietz–Soni)

- Measurement will not be theory limited at any conceived future experiment

Only LHCb: γ from $B_s \to D_s^\pm K^\mp$

- Same weak phase in each $B_s, \overline{B}_s \to D_s^\pm K^\mp$ decay ⇒ the 4 time dependent rates determine 2 amplitudes, a strong, and a weak phase (clean, although $|f\rangle \neq |f_{CP}\rangle$)

  Four amplitudes: $\overline{B}_s \overset{A_1}{\to} D_s^+ K^- \quad (b \to c\bar{u}s)\,, \qquad \overline{B}_s \overset{A_2}{\to} K^+ D_s^- \quad (b \to u\bar{c}s)$

  $$B_s \overset{A_1}{\to} D_s^- K^+ \quad (\bar{b} \to \bar{c}u\bar{s})\,, \qquad B_s \overset{A_2}{\to} K^- D_s^+ \quad (\bar{b} \to \bar{u}c\bar{s})$$

  $$\frac{\overline{A}_{D_s^+ K^-}}{A_{D_s^+ K^-}} = \frac{A_1}{A_2} \left(\frac{V_{cb} V_{us}^*}{V_{ub}^* V_{cs}} \right), \qquad \frac{\overline{A}_{D_s^- K^+}}{A_{D_s^- K^+}} = \frac{A_2}{A_1} \left(\frac{V_{ub} V_{cs}^*}{V_{cb}^* V_{us}} \right)$$

  Magnitudes and relative strong phase of A_1 and A_2 drop out if four time dependent rates are measured ⇒ no hadronic uncertainty:

  $$\lambda_{D_s^+ K^-}\, \lambda_{D_s^- K^+} = \left(\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*} \right)^2 \left(\frac{V_{cb} V_{us}^*}{V_{ub}^* V_{cs}} \right) \left(\frac{V_{ub} V_{cs}^*}{V_{cb}^* V_{us}} \right) = e^{-2i(\gamma - 2\beta_s - \beta_K)}$$

- Similarly, $B_d \to D^{(*)\pm} \pi^\mp$ determines $\gamma + 2\beta$, since $\lambda_{D^+\pi^-}\, \lambda_{D^-\pi^+} = e^{-2i(\gamma+2\beta)}$

  ... ratio of amplitudes $\mathcal{O}(\lambda^2)$ ⇒ small asymmetries (tag side interference)

What’s ahead?

[skip to end]

Cast a wide net — look for “surprises”

- Obvious! most cited Belle paper: $X(3872)$, most cited BaBar paper: $D_{s0}^*(2317)$
- Many interesting searches can be done a lot better at Belle II & LHCb:

$B \to (\gamma+)\,\text{invisible}$ [Belle, 1206.5948; BaBar, 1206.2543]

$B \to X_s + \text{invisible}$

$\Upsilon(1S) \to \text{invisible}$ [Belle, hep-ex/0611041; BaBar, 0908.2840]

$\Upsilon(nS) \to \gamma + \text{invisible}$ [e.g., for $1S$ and $3S$: BaBar, 0808.0017, 1007.4646]

$e^+e^- \to (\gamma+)\,\text{invisible}$

- Also include “invisible” replaced by a new resonance; may decay to $\ell^+\ell^-$, etc.
- τ and μ lepton flavor violation
- Searches for violations of conservation laws

Jump on the data, or wait for it to change...?

- Many people thought it was a serious challenge to theory for 20 years

PDG (1996): $\tau_{\Lambda_b} = (1.14 \pm 0.08)\ \mathrm{ps}$ (first time $\sigma_{\mathrm{WA}} < 0.1\ \mathrm{ps}$)

PDG (2006): $\tau_{\Lambda_b} = (1.230 \pm 0.074)\ \mathrm{ps}$

PDG (2008): $\tau_{\Lambda_b} = (1.383^{+0.049}_{-0.048})\ \mathrm{ps}$

CDF: $\tau_{\Lambda_b} = (1.593^{+0.089}_{-0.085})\ \mathrm{ps}$ [hep-ex/0609021]

PDG (2010): $\tau_{\Lambda_b} = (1.391^{+0.038}_{-0.037})\ \mathrm{ps}$

PDG (2012): $\tau_{\Lambda_b} = (1.425 \pm 0.032)\ \mathrm{ps}$

CDF: $\tau_{\Lambda_b} = (1.537 \pm 0.051)\ \mathrm{ps}$ [arXiv:1012.3138]

ATLAS: $\tau_{\Lambda_b} = (1.449 \pm 0.040)\ \mathrm{ps}$ [arXiv:1207.2284]

CMS: $\tau_{\Lambda_b} = (1.503 \pm 0.061)\ \mathrm{ps}$ [arXiv:1304.7495]

LHCb: $\tau_{\Lambda_b} = (1.482 \pm 0.022)\ \mathrm{ps}$ [arXiv:1307.2476] $[\tau_{\Lambda_b}/\tau_{B^0} = 0.976 \pm 0.013]$

- We might never really know why, but “old” measurements not using fully reconstructed hadronic decays will probably be quite far from future averages

[There are examples of strongly time-dependent theory predictions — will leave it for another talk]

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].

Key question — to me, now

- 2012: SM-like Higgs, SM-like $B_s \to \mu^+\mu^-$ rate
  Do not know if and what LHC-14 will discover — if there is NP, fantastic $\to 2050+$

- Compelling future flavor physics experimental program, even w/o theory progress

1) Processes not yet observed, suppressed, or forbidden in the SM

2) Measurements sensitive to highest scales, and how much they can improve

3) Measurements when "room" can shrink the most between experiment and SM

- Study NP in mixing: consider NP w/ unitary 3×3 CKM, tree amplitudes unchanged
  [Relatively mature field — fits 2) above, but not 1) or 3)]

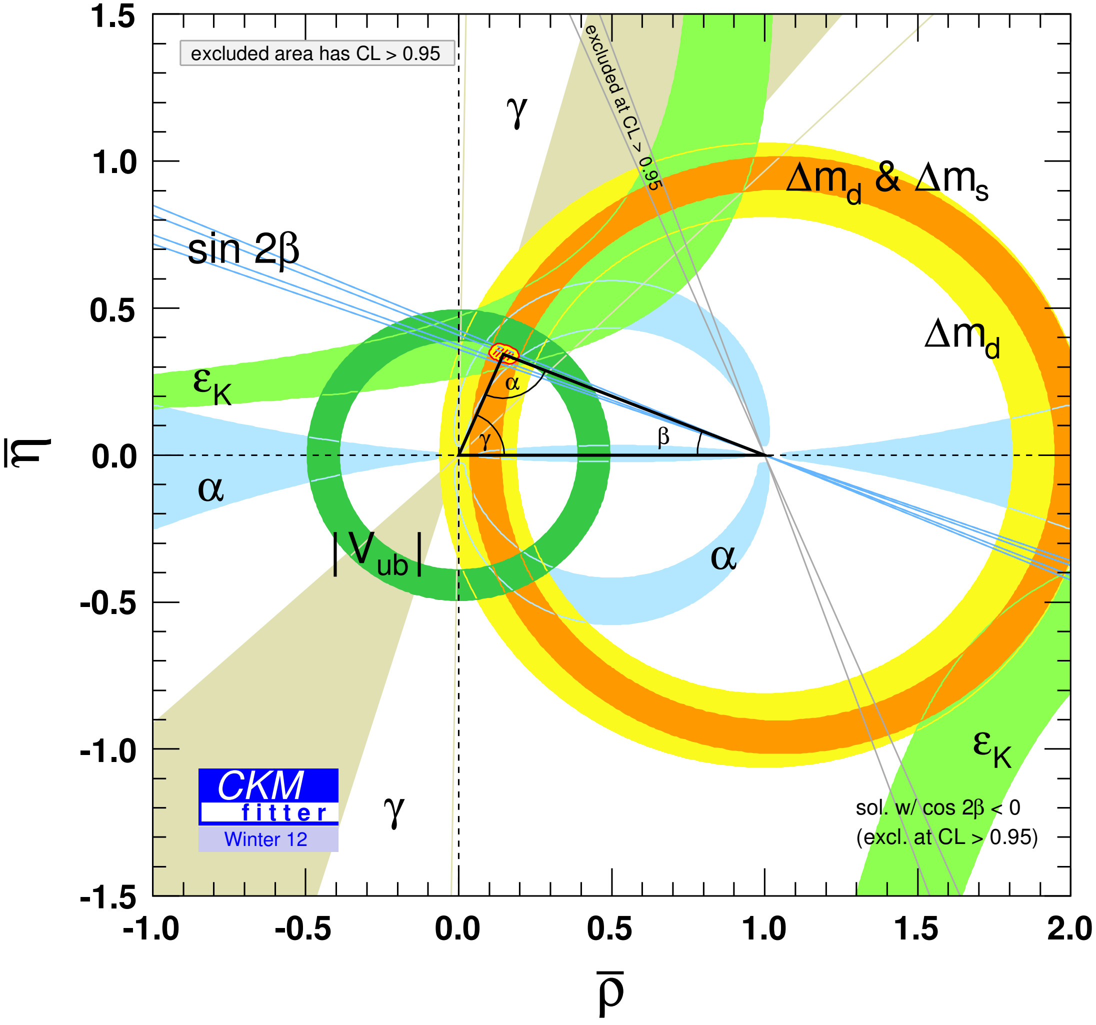
  Gives a conservative picture of the anticipated future progress

New physics in B mixing

[skip to end]

The standard model CKM fit

- Looks impressive...
- Level of agreement between the measurements often misinterpreted
- Increasing the number of parameters can alter the fit completely
- Plausible TeV scale NP scenarios, consistent with all low energy data, w/o minimal flavor violation (MFV)
- CKM is inevitable; the question is not if it's correct, but is it sufficient?



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

- Assume: (i) 3×3 CKM matrix is unitary; (ii) tree-level decays dominated by SM

  Concentrate on NP in mixing amplitude; two parameters for each neutral meson:

$$M_{12} = \underbrace{M_{12}^{\rm SM}\, r^2\, e^{2i\theta}}_{\text{easy to relate to data}} \equiv \underbrace{M_{12}^{\rm SM}(1 + h\, e^{2i\sigma})}_{\text{easy to relate to models}}$$

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

- $B\overline{B}$ mixing dependent observables sensitive to NP: $\Delta m_{d,s}$, S_{f_i}, $A_{\rm SL}^{d,s}$, $\Delta\Gamma_s$

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

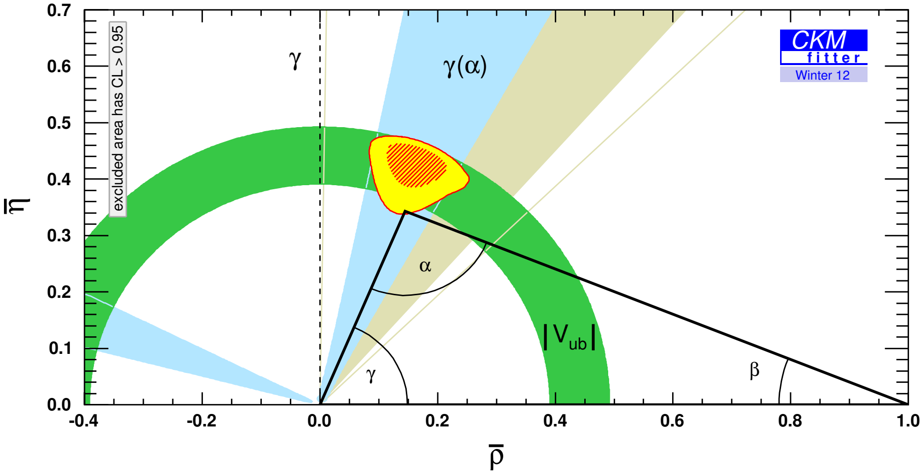
$$S_{\psi K} = \sin(2\beta + 2\theta_d) = \sin[2\beta + \arg(1 + h_d e^{2i\sigma_d})] \qquad S_{\rho\rho} = \sin(2\alpha - 2\theta_d)$$

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

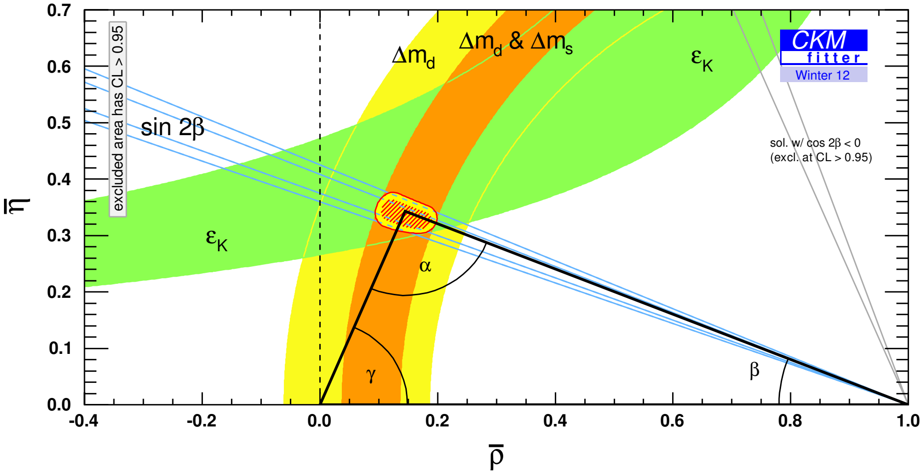
$$A_{\rm SL}^q = {\rm Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q r_q^2\, e^{2i\theta_q}}\right) = {\rm Im}\left[\frac{\Gamma_{12}^q}{M_{12}^q(1 + h_q e^{2i\sigma_q})}\right] \qquad \Delta\Gamma_s^{CP} = \Delta\Gamma_s^{\rm SM} \cos^2 2\theta_s$$

New physics in B meson mixing

- Tree-dominated measurements:

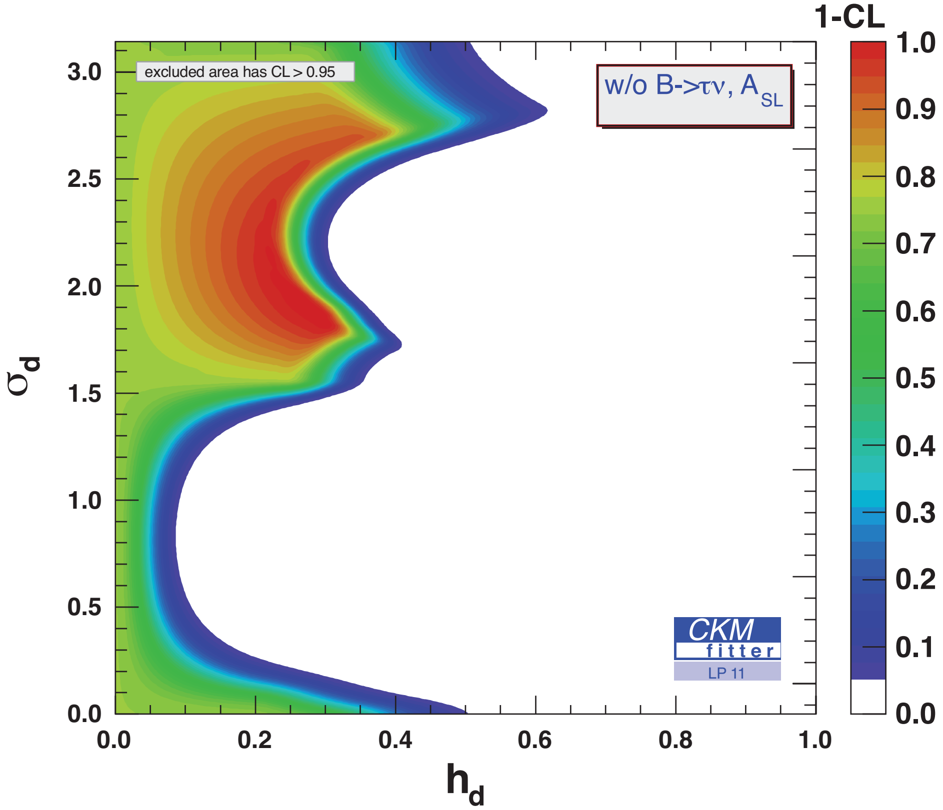


- Loop-dominated measurements:



Until 2004, $h_d \sim 10$ was allowed

Better tree-level measurements crucial

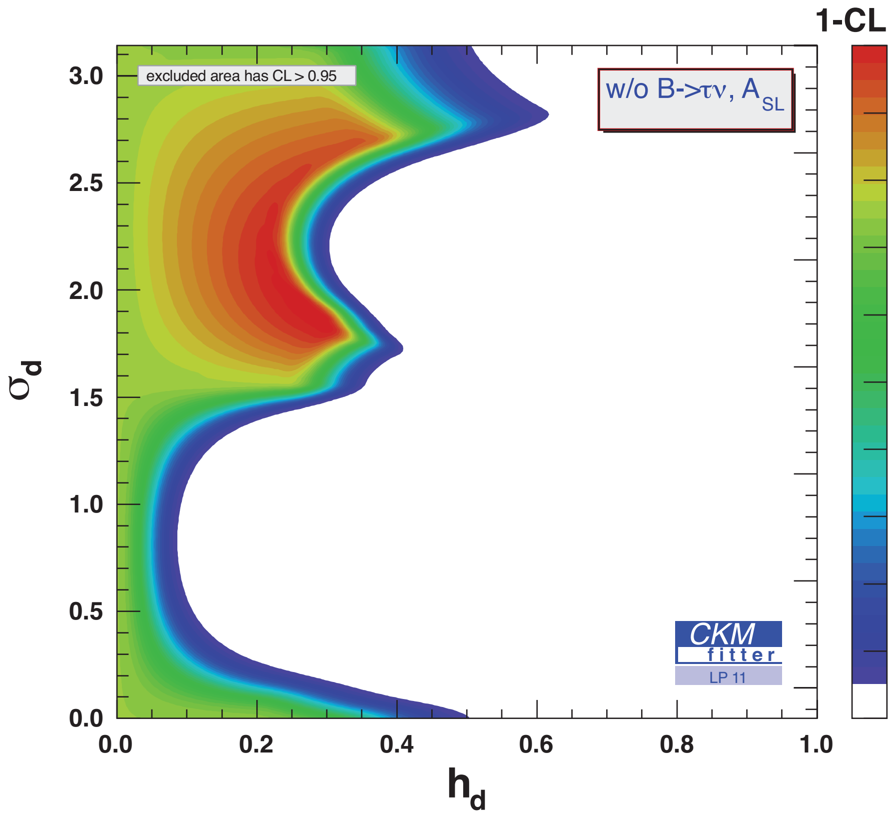


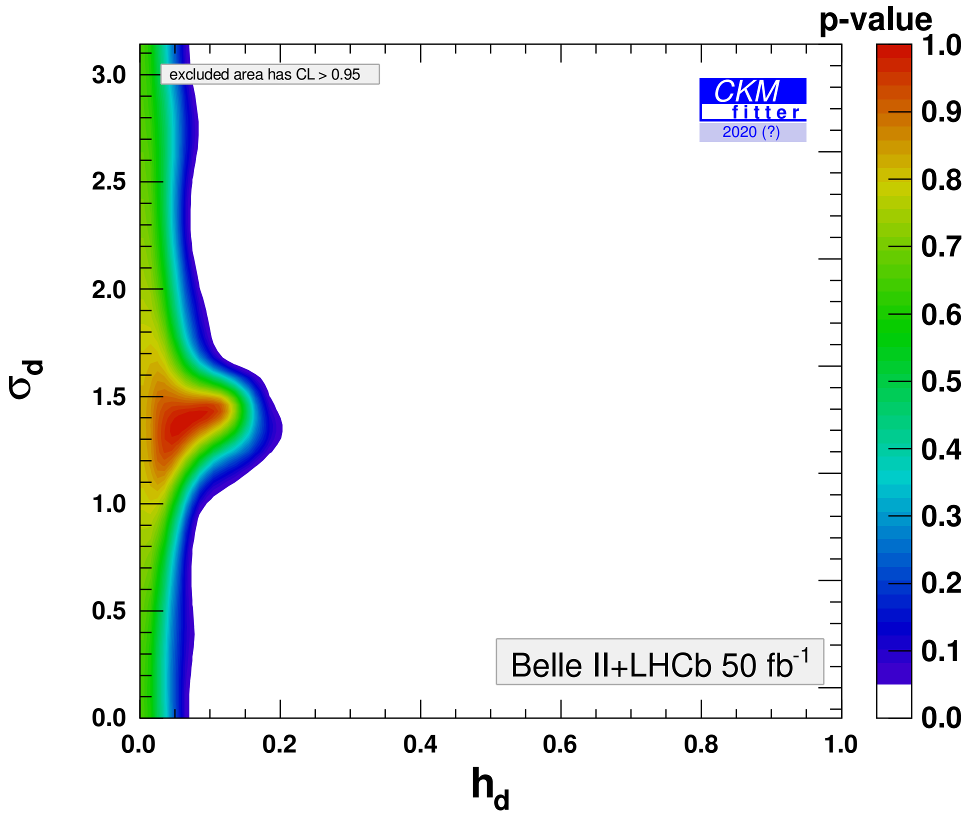
A goal: assume $h \sim (4\pi v/\Lambda_{\text{flav.}})^2$

Can we probe $\Lambda_{\text{flav.}} \gtrsim \Lambda_{\text{EWSB}}$?

Preliminary — sensitivity in ~ 10 years?

- Rough predictions to illustrate increased sensitivity



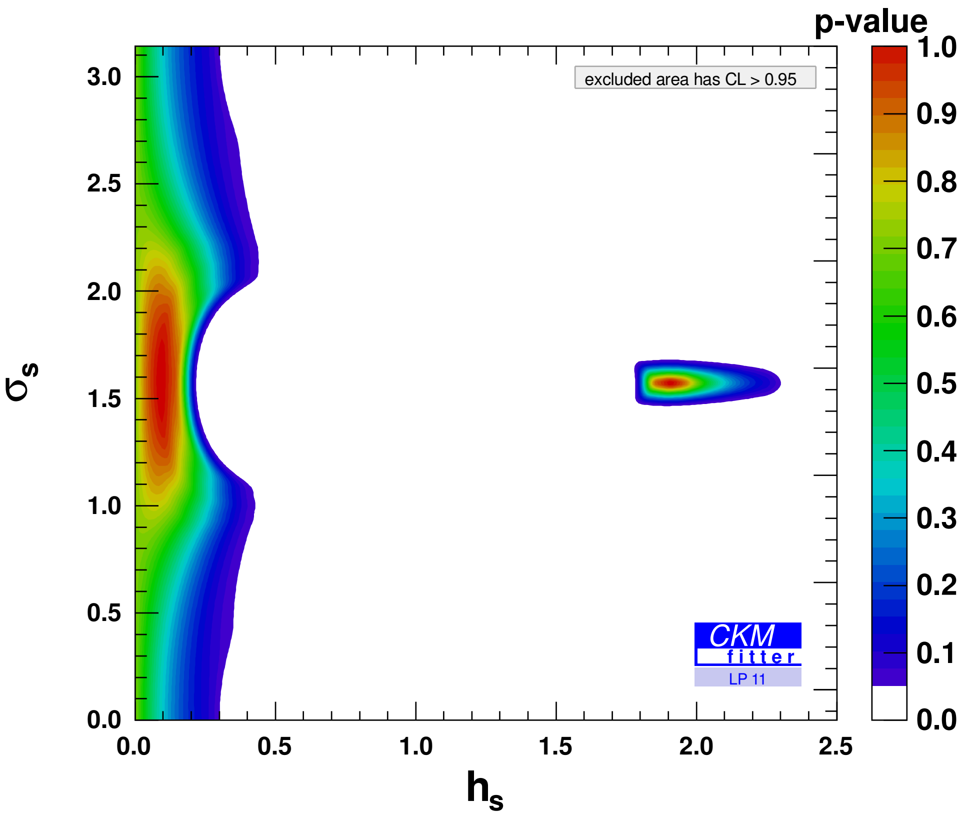


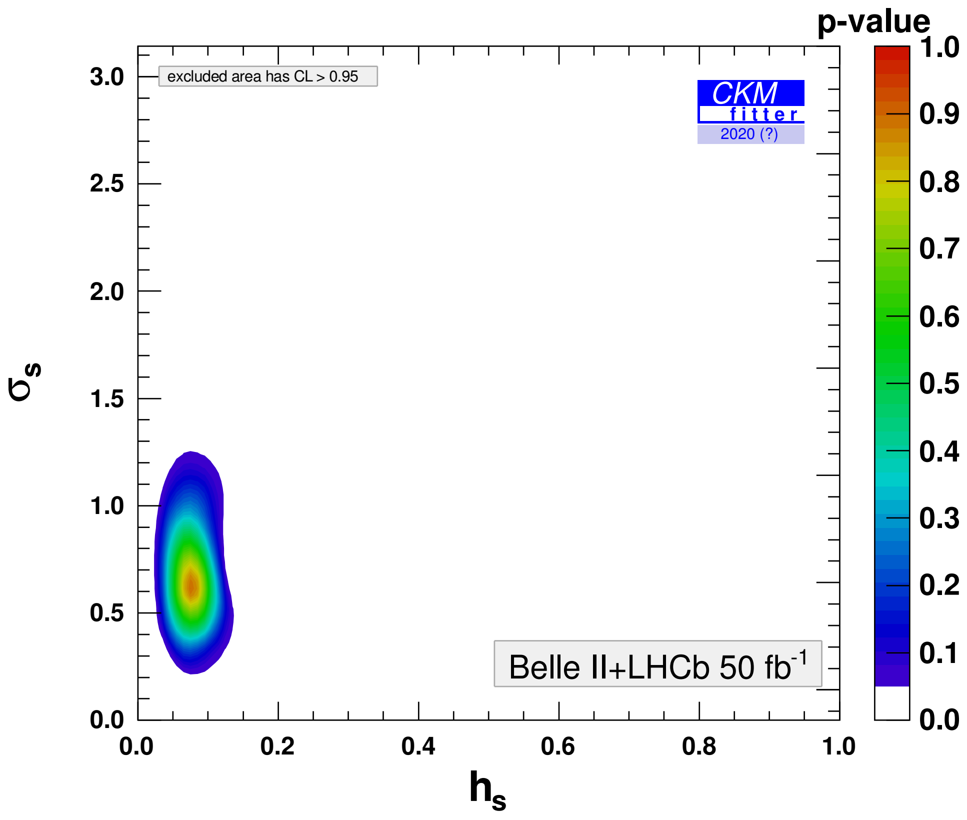
right plot will actually look better

[Charles, Descotes-Genon, ZL, Monteil, Papucci Trabelsi, to appear]

Preliminary — sensitivity in ~ 10 years?

- Rough predictions to illustrate increased sensitivity





The $h_s \sim 2$ region excluded by now

[Charles, Descotes-Genon, ZL, Monteil, Papucci Trabelsi, to appear]

Summary

[back1] [back2]

A Belle II “best buy” list

- Key observables: (i) sensitive to different NP, (ii) measurements can improve by order of magnitude, (iii) not limited by hadronic uncertainties
  - Difference of CP asymmetries, $S_{\psi K_S} - S_{\phi K_S}$, $S_{\psi K_S} - S_{\eta' K_S}$, etc.
  - 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
  - Search for CP violation in mixing, $A_{\rm SL}^d$
  - CP asymmetry in the radiative decay, $S_{K_S\pi^0\gamma}$
  - Rare decay searches and refinements: $b \to s\nu\bar{\nu}$, $B \to \tau\bar{\nu}$, etc.
  - Improve magnitudes of CKM elements
- Complementary to LHCb
- Any one of these measurements has the potential to establish new physics

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, $S_{B_s \to \psi\phi} - S_{B_s \to \phi\phi}$
  - $B_s \to \mu^+\mu^-$, search for $B_d \to \mu^+\mu^-$, other rare / forbidden decays
  - γ from $B \to DK$ and $B_s \to D_s K$
  - Search for CP violation in $D^0 - \overline{D}^0$ mixing
  - Search for charged lepton flavor violation, $\tau \to 3\mu$ and other modes if possible
  - Search for CP violation in mixing, $A_{\rm SL}^s$
  - 10^{4-5} events in $B \to K^{(*)}\ell^+\ell^-$, $B_s \to \phi\gamma$, $\ldots$ — test Dirac structure, BSM op’s
- Very broad program, complementary to Belle II
- With large BSM discovery potential

Substantial discovery potential: Belle II

Observable	SM theory	Current measurement (early 2013)	Belle II ($50\,\mathrm{ab}^{-1}$)
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.03
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.02
α from $B \to \pi\pi,\ \rho\rho$		$\pm 5.4^\circ$	$\pm 1.5^\circ$
γ from $B \to DK$		$\pm 11^\circ$	$\pm 1.5^\circ$
$S(B \to K_S \pi^0 \gamma)$	< 0.05	-0.15 ± 0.20	± 0.03
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.15
$A_{\mathrm{CP}}(B \to X_{s+d}\, \gamma)$	< 0.005	0.06 ± 0.06	± 0.02
A_{SL}^d	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 0.05 \times 10^{-4}$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\pm 0.2 \times 10^{-7}$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 0.13 \times 10^{-4}$
$\mathcal{B}(B \to X_s \ell^+ \ell^-)$	1.6×10^{-6}	$(3.66 \pm 0.77) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$\mathcal{B}(B \to K \nu\overline{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 1.0 \times 10^{-6}$
$A_{\mathrm{FB}}(B \to K^* \ell^+ \ell^-)_{q^2 < 4.3\,\mathrm{GeV}^2}$	-0.09	0.27 ± 0.14	± 0.04
$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0} \ell^+ \ell^-)$	0.16	0.029	0.008
$\lvert V_{ub}\rvert$ from $B \to \pi \ell^+ \nu$ ($q^2 > 16$ GeV^2)	$9\% \to 2\%$	11%	2.1%

[More: Browder, tomorrow]

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

Substantial discovery potential: LHCb

Observable	SM theory uncertainty	Precision as of 2013	LHCb (6.5 fb^{-1})	LHCb Upgrade (50 fb^{-1})
$2\beta_s(B_s \to J/\psi\phi)$	~ 0.003	0.09	0.025	0.008
$\gamma(B \to D^{(*)}K^{(*)})$	$< 1^\circ$	8°	4°	0.9°
$\gamma(B_s \to D_s K)$	$< 1^\circ$	—	$\sim 11^\circ$	2°
$\beta(B^0 \to J/\psi K^0_S)$	small	0.8°	0.6°	0.2°
$2\beta_s^{\rm eff}(B_s \to \phi\phi)$	0.02	1.6	0.17	0.03
$2\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}^{*0})$	< 0.02	—	0.13	0.02
$2\beta_s^{\rm eff}(B_s \to \phi\gamma)$	0.2%	—	0.09	0.02
$2\beta^{\rm eff}(B^0 \to \phi K^0_S)$	0.02	0.17	0.30	0.05
$A^s_{\rm SL}$	0.03×10^{-3}	6×10^{-3}	1×10^{-3}	0.25×10^{-3}
$\mathcal{B}(B_s \to \mu^+\mu^-)$	8%	42%	15%	5%
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s \to \mu^+\mu^-)$	5%	—	$\sim 100\%$	$\sim 35\%$
$s_0\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	7%	18%	6%	2%

[More: Artuso, today]

- Many modes first seen at Belle II or LHCb; complementarity between them
- In some decay modes, even in 2025 we'll have (Exp. bound)/SM $\gtrsim 10^3$

  E.g.: $B_{(s)} \to \tau^+\tau^-,\ e^+e^-$, can build many models...

Summary (1)

- Flavor physics $\equiv$ what distinguishes generations (break $U(3)^5$ global symmetry)
- Flavor changing neutral currents and neutral meson mixing probe high scales
  ... strong constraints on TeV-scale NP, many synergies (hard to avoid)
- CP violation is always the result of interference phenomena; no classical analog
- Past: Ten years ago $\mathcal{O}(1)$ deviations from the SM predictions were possible
  Present: $\mathcal{O}(20\%)$ corrections to most FCNC processes are still allowed
  Future: Few $\%$ sensitivities. Corrections to SM? What can we learn about NP?
- KM phase is the dominant source of CP violation in flavor changing processes
- The point is not measuring CKM elements, but to overconstrain flavor many ways
- Measurements probe scales $\gg 1\,\mathrm{TeV}$; sensitivity limited by statistics, not theory

2nd Lecture
Flavor at the TeV scale

- Known particles: leptons, top, Higgs
- SUSY and flavor

  MFV, squark searches
- Final thoughts

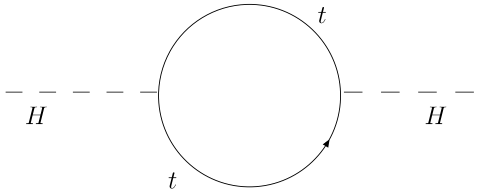
Reasons to pursue flavor physics

- 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 ⇒ SUSY breaking, mediation

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

  Motivated models: NP ⇔ 3rd gen. ≠ NP ⇔ 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?

Seeking indirect signals of NP

- Precision electroweak T parameter ("little hierarchy problem"):

$$\frac{(\phi D^\mu \phi)^2}{\Lambda^2} \quad \Rightarrow \quad \Lambda > \text{ several TeV}$$

- Flavor and CP violating operators ("new physics flavor problem"), e.g.:

$$\frac{QQQQ}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^{(1\ldots4)}\ \mathrm{TeV}$$

Flavor and custodial symmetry are broken already in the SM

There cannot be an exact symmetry forbidding NP to generate these operators

- Baryon and lepton number violating operators (lack of proton decay), e.g.:

$$\frac{QQQL}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^{16}\,\mathrm{GeV}$$

- Unique set of dimension-5 terms composed of SM fields:

$$\mathcal{L}_{\text{dim-5}} = \frac{1}{\Lambda}(L\phi)(L\phi) \to m_\nu\, \nu\nu\,, \qquad\qquad m_\nu \propto \frac{v^2}{\Lambda} \quad \text{(see-saw mechanism)}$$

And the winner is... (for now?)

- Unique set of dimension-5 terms composed of SM fields:

$$\mathcal{L}_{\text{dim-5}} = \frac{1}{\Lambda}(L\phi)(L\phi) \to m_\nu\,\nu\nu\,, \qquad m_\nu \propto \frac{v^2}{\Lambda} \quad \text{(see-saw mechanism)}$$

  ... Gives lepton number violating ("Majorana") neutrino mass terms

- Neutrino oscillations imply that SM has to be extended:
  - Lepton number conserving mass: need "sterile" right haded neutrinos
  - Lepton number violating mass: need nonrenormalizable BSM terms

- Majorana mass: natural expectation if SM viewed as a low energy effective theory

  Suggests very high scales (assuming $\mathcal{O}(1)$ couplings), far beyond reach

---

- Hierarchy $\Rightarrow \Lambda \sim 1\text{TeV}$; flavor / $CP \Rightarrow \Lambda \gtrsim 10^3\text{TeV}$; neutrino mass $\Rightarrow \Lambda \sim 10^{10}\text{TeV}$

  All have assumptions — we do not really know; hope to find NP at a TeV

Related to TeV scale physics?

- In its simplest version with $m_\nu = 0$, SM predicted lepton flavor conservation

  This is now known not to be the case — so there is no reason to impose it as a symmetry on new physics

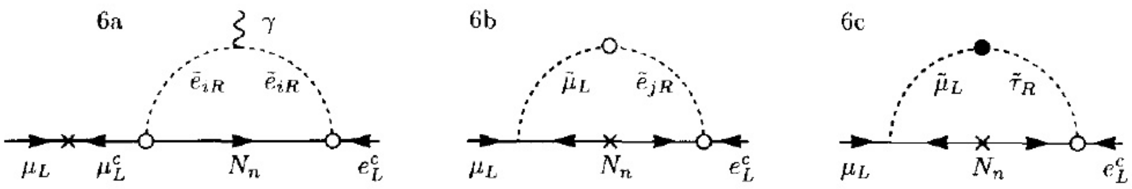
- If there are new TeV-scale particles that carry lepton number (sleptons), then they have their own mixing matrices and give rise to charged lepton flavor violation

  Most often discussed: $\mu \to e\gamma$, $\mu \to e\bar{e}e$, $\tau \to \mu\gamma$, $\tau \to \ell\ell\ell$

  SM predictions (penguins w/ neutrinos) are incredibly small and always negligible

Lepton flavor violation (in τ decays)

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

  Very large model dependence

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

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

- $\tau^- \to \ell_1^- \ell_2^- \ell_3^+$ (few $\times 10^{-10}$) vs. $\tau \to \mu\gamma$?

  Consider operators: $\bar\tau_R \sigma_{\alpha\beta} F^{\alpha\beta} \mu_L, \; (\bar\tau_L \gamma^\alpha \mu_L)(\bar\mu_L \gamma_\alpha \mu_L)$

  Suppression of $\mu\gamma$ and $\mu\mu\mu$ final states by α_{em} opposite for these two operators ⇒ winner is model dependent

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

Process	Sensitivity
$\mathcal{B}(\tau \to \mu\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\,\mu\,\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}

- $\mu \to e\gamma$ and $(g-2)_\mu$ operators are very similar: $\dfrac{m_\mu}{\Lambda^2}\, \bar\mu \sigma_{\alpha\beta} F^{\alpha\beta} e\,, \quad \dfrac{m_\mu}{\Lambda^2}\, \bar\mu \sigma_{\alpha\beta} F^{\alpha\beta} \mu$

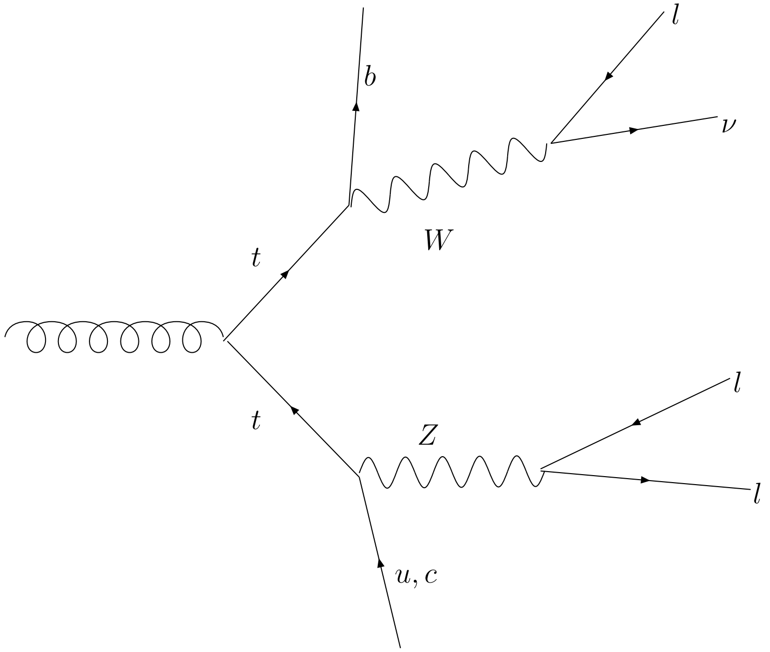
  If coefficients are comparable, $\mu \to e\gamma$ gives much stronger bound already

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

Heavy SM particles: t and h

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

- The best place to probe FCNC top decays



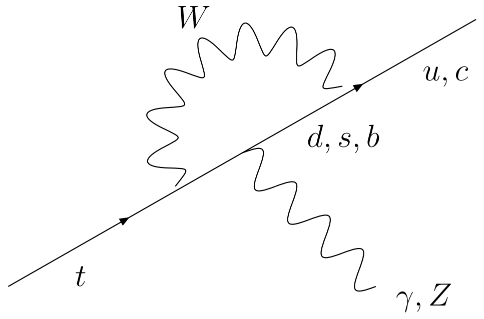
channel	$t \to Zu(c)$	$t \to \gamma u(c)$	$t \to gu(c)$		
			(3 jets)	(4 jets)	(combined)
upper limit on BR ($L = 10$ fb^{-1})	3.4×10^{-4}	6.6×10^{-5}	1.7×10^{-3}	2.5×10^{-3}	1.4×10^{-3}
upper limit on BR ($L = 100$ fb^{-1})	6.5×10^{-5}	1.8×10^{-5}	5.0×10^{-4}	8.0×10^{-4}	4.3×10^{-4}

$\Uparrow$ $\Uparrow$

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

FCNC in top decays

- Rare top decays
  - $t \to qZ \qquad (q = u, c)$
  - $t \to q\gamma$
  - $t \to qg$
  - $t \to qh \qquad \longleftarrow$ more model dependent

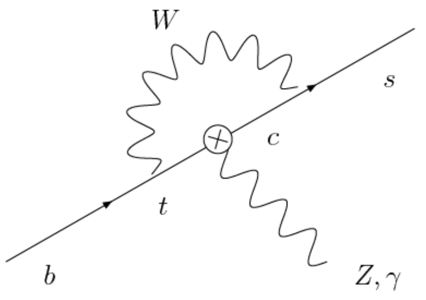


- Tiny in SM: $\mathcal{B}(t \to cZ) \sim \mathcal{B}(t \to c\gamma) \sim 10^{-13}$ — good place to look for NP
- Direct bounds on top FCNC's are weak (95% CL)
  - LEP2: $e^+e^- \to tc: \quad \mathcal{B}(t \to qZ) < 13.7\%$
  - Hera: $e^-p \to te^-: \quad \mathcal{B}(t \to u\gamma) < 0.6\%$
  - CDF, DØ: $\mathcal{B}(t \to qZ) < 3\%$
  - CMS, ATLAS: $\mathcal{B}(t \to qZ) < 0.3\%$

NP in the top sector?

- Indirect constraints: $t_L \leftrightarrow b_L$ — tight bounds from B decays

  Top FCNC's could affect other observables



[e.g., arXiv:0704.1482]

- B factory data constrain some of the relevant operators (some beyond the LHC reach)

  Right-handed operators may still give rise to LHC signals

- If top FCNC is seen, LHC & B decay data will probe the NP responsible for it

  Similarly large body of literature on $t \to cg$, single top production, etc.

- Forward-backward asymmetry: I fear we may never understand Tevatron signals

  Models have implications and are constrained by both flavor and collider data especially if want flavor structure (MFV, etc.), and not postulate something ad-hoc

Higgs couplings

- Many papers on constraining flavor non-universal and non-diagonal couplings

  Measuring $hf\bar{f}$ couplings is by definition flavor physics (distinguish generations)

- We know that $\mathcal{B}(h \to \mu^+\mu^-) < 10\times$ SM, so $\ll \mathcal{B}(h \to \tau^+\tau^-)$ [ATLAS-CONF-2013-010]

  Of the tree-level couplings (NP can enter in loops), I think this is the first / strongest evidence of non-universal coupling to fermions

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- One can also search for $h \to \mu^+\tau^-$ and other modes absent in the SM

  It's all interesting. It's all flavor physics. We'll skip it.

SUSY and flavor

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 seems to be the most interesting
  - How is supersymmetry broken?
  - How is SUSY breaking mediated to MSSM?
  - Predict soft SUSY breaking terms?

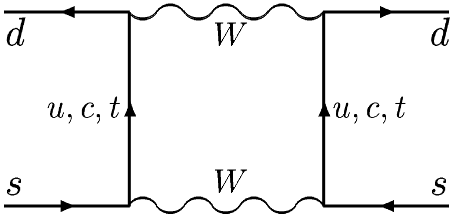
- Details of interactions of new particles with quarks and leptons will be important to understand underlying physics

- In SUSY, CP violation possible in squark & slepton couplings, flavor diagonal processes (e, n EDM's), neutral currents; may enhance FCNCs ($b \to s\gamma$, $\mu \to e\gamma$)

Saw this: Δm_K, ϵ_K built in NP models since 70's

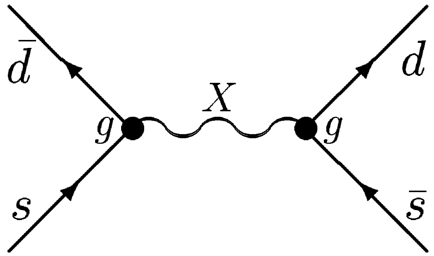
- In the SM: $\Delta m_K \sim \alpha_w^2 \, |V_{cs}V_{cd}|^2 \, \frac{m_c^2}{m_W^4} \, f_K^2 \, m_K$

  (severe suppressions!)



... Even more suppressions for ϵ_K, which involves all 3 generation

- If tree-level exchange of a heavy gauge boson was responsible for a significant fraction of the measured value of Δm_K



$$\left|\frac{M_{12}^{(X)}}{\Delta m_K}\right| \sim \left|\frac{g^2\,\Lambda_{\rm QCD}^3}{M_X^2\,\Delta m_K}\right| \;\Rightarrow\; M_X \gtrsim g \times 2 \cdot 10^3\ {\rm TeV}$$

- TeV-scale new particles can have large contributions even in loops $[g \sim \mathcal{O}(10^{-2})]$

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

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

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

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

- Classes of models to suppress each factors

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

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

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

- All models incorporate some of the above — has been known since the ’70s

Flavor and CP violation in SUSY

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

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

- 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)

Minimal flavor violation

Minimal flavor violation (MFV)

- What are the minimal flavor physics effects of new physics at $\Lambda_{\rm NP}$ scale?

  Assume that only source of flavor violation are the SM Yukawa couplings

  Unrealistic to demand that all higher dimension operators are flavor invariant and contain only SM fields (and not Y), since $U(3)^3$ is not a symmetry of the SM

- MFV: treat Y's as spurions [Chivukula & Georgi '87; Hall & Randall '90; D'Ambrosio, Giudice, Isidori, Strumia '02]

  $$Y_u \sim (3,\overline{3},1)\,, \quad Y_d \sim (3,1,\overline{3})$$ [under $SU(3)_Q \times SU(3)_u \times SU(3)_d$]

  ... their background values are the only source of $U(3)^3$ breaking and CPV

- EFT like analyses, e.g., terms for down quarks

$$\bar{Q}_L Y_u Y_u^\dagger Q_L, \quad \bar{d}_R Y_d^\dagger Y_u Y_u^\dagger Q_L, \quad \bar{d}_R Y_d^\dagger Y_u Y_u^\dagger Y_d d_R$$

Convenient to choose $Y_d \sim \mathrm{diag}(m_d, m_s, m_b)$, then $Y_u \sim V^\dagger\, \mathrm{diag}(m_u, m_c, m_t)$

Examples of MFV at work

- Δm_K: operator $(X/\Lambda_{\rm NP}^2)\,(\bar s_L \gamma_\mu d_L)^2$

  $\bar s_L(\bar 3,1,1),\ d_L(3,1,1) \Rightarrow (\bar s_L d_L) \in (8,1,1)$ must be $\propto (Y_u Y_u^\dagger)_{21} = y_c^2\, V_{cd}^* V_{cs}$

  $\Rightarrow$ In MFV: $X \propto y_c^4\,|V_{cd}^* V_{cs}|^2$ — similarly, $\Delta m_{B_{d,s}}$ are proportional to $y_t^4\,|V_{tb}^* V_{tq}|^2$

- $\Gamma(b \to s\gamma)$: operator $(X/\Lambda_{\rm NP})\,(\bar s_L \sigma_{\mu\nu} F^{\mu\nu} b_R)$

  $\bar s_L b_R$ is not invariant under $U(3)^3$

  $\bar s_L\, Y_d\, b_R \to \bar s_L\, m_d^{\rm diag}\, b_R$ is flavor diagonal

  $\bar s_L\, Y_u Y_u^\dagger Y_d\, b_R \to \bar s_L\, V^\dagger (m_u^{\rm diag})^2\, V m_d^{\rm diag}\, b_R \to \bar s_L\, V_{ts}^* V_{tb}\, y_t^2\, m_b\, b_R$

  $\Rightarrow$ In MFV: $X \propto (m_b/\Lambda_{\rm NP})\, y_t^2\,|V_{tb}^* V_{ts}|^2$

As in SM: Suppressed by m_b; FCNC's vanish for degenerate quark masses (GIM)
Need at least two CKM elements, one of which must be off-diagonal

MFV and flavor change in SUSY

- For generic parameters, way too much flavor change, unless scale $\gg \mathrm{TeV}$

  E.g., even if at some scale: $m_U^2 = \begin{pmatrix} m_{\tilde{u}}^2 & 0 & 0 \\ 0 & m_{\tilde{c}}^2 & 0 \\ 0 & 0 & m_{\tilde{t}}^2 \end{pmatrix}$

  – Run a little and $m_U^2 =$ generic... Why 0's are set at a certain scale?

  – How do these terms know about quark basis? SUSY breaking about Yukawas?

- Imposing MFV solves this in a RGE invariant way, e.g., $m_U^2 = \tilde{m}^2(a\,1 + b\,Y_u Y_u^\dagger + \ldots)$

- Even imposing MFV, some observables may still receive sizable corrections: precision electroweak, $B \to X_s\gamma,\ B_s \to \mu^+\mu^-,\ \Delta m_{B_s},\ B \to \tau\nu,\ g-2,\ \Omega h^2$

- Additional subtleties, e.g., in 2HDM at large $\tan\beta$

Flavor effects at the TeV scale

- Does flavor matter at ATLAS & CMS? Can we probe (s)flavor directly 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

Some MFV predictions

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

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

- Mixing: Only source is the CKM matrix

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

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

- More and more studies to test MFV in specific models with a given particle content

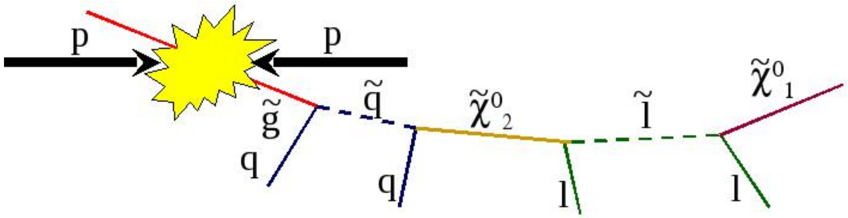
  Typically it's easier to rule out MFV than to prove it

  E.g.: extra down type quarks $B'_{L,R}(3,1)_{-1/3}$ [Grossman, Nir, Thaler, Volansky, Zupan, 0706.1845]

Detection of SUSY particles

- At each vertex two supersymmetric particles

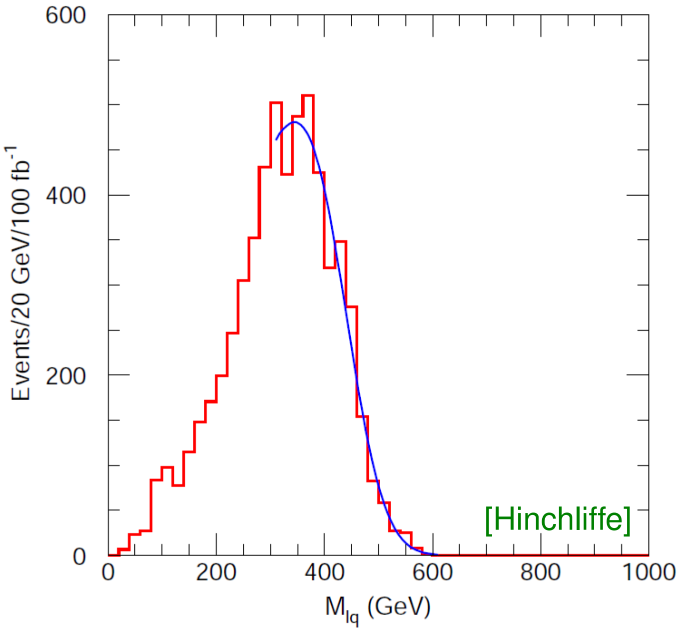
  Lightest SUSY particle (LSP) undetected



- 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 by smearing out endpoints ... can modify the discovery potential of some particles

Flavorful SUSY models

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

  Many studies over the last few years (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

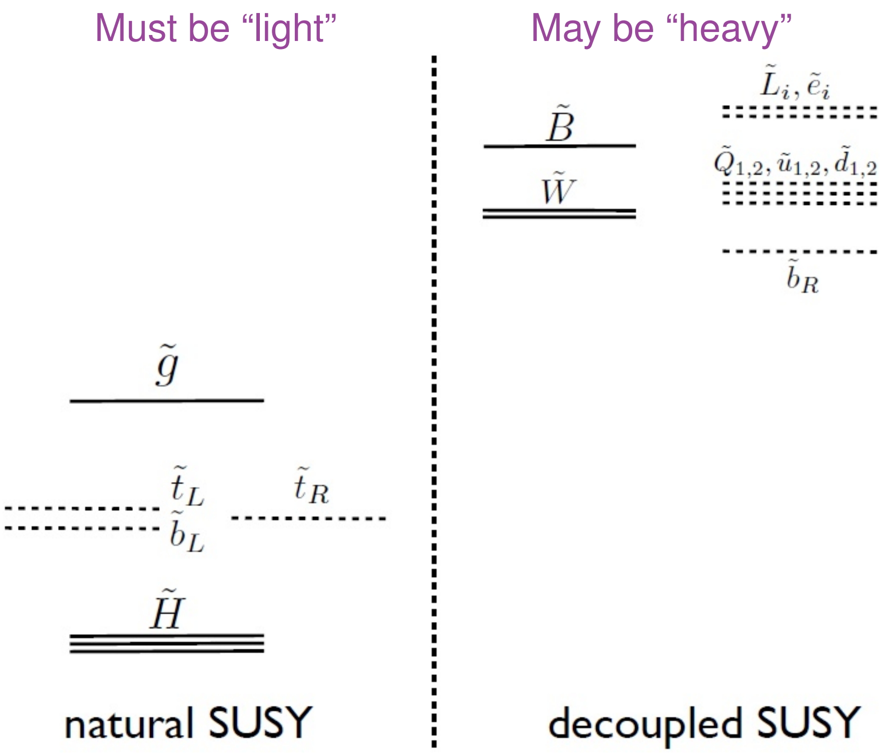
Natural SUSY and $m_h = 126\,\mathrm{GeV}$

- Naturalness has been main motivation for TeV-scale NP — leave no stone unturned!

  Simplest bottom-up approach:
  Light $\tilde{t}$, 1st & 2nd generation (a lot) heavier

  [Cohen, Kaplan, Nelson, 90-s; Papucci, Ruderman, Weiler, 1110.6926]

- Accommodating $m_h = 126\,\mathrm{GeV}$ pushes models toward NMSSM or large A terms; latter has interesting flavor implications



- LHC is probing weak-scale natural SUSY; with no BSM signal, increasing focus on RPV, stealth/squashed and split spectra (many models)

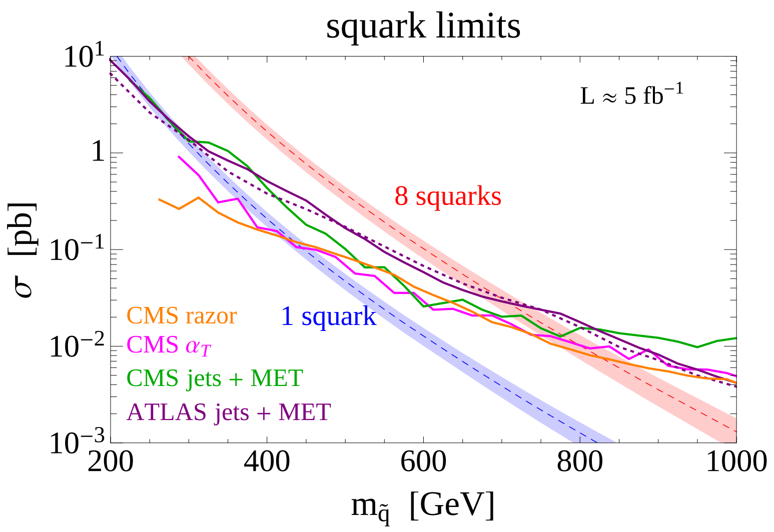
  Can have (SUSY) GIM, (approximate) MFV, etc., but as the first two generations are pushed heavier, expect larger flavor non-universality, and more flavor signals

Hide flavor signals ⇔ hide LHC signals

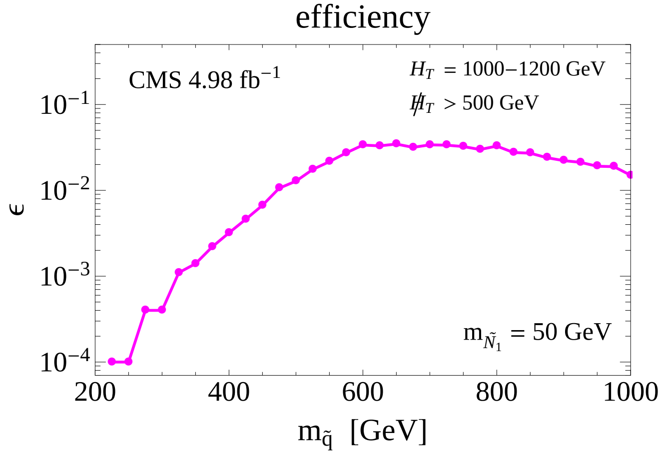
- Despite lore, squarks need not be nearly as degenerate as widely believed (triggered by studying charm CPV) [Gedalia, Kamenik, ZL, Perez, 1202.5038]

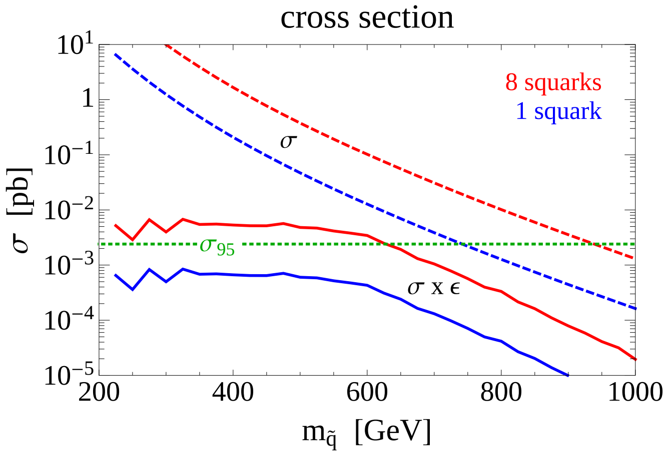
  Right plot: each LHC search gets much weaker

  [Mahbubani, Papucci, Perez, Ruderman, Weiler, 1212.3328]



- Not only due to cross sections, but steeply falling efficiencies at lower mass, due to hard cuts (below: CMS multijets $+$ MET search, but this is typical behavior)



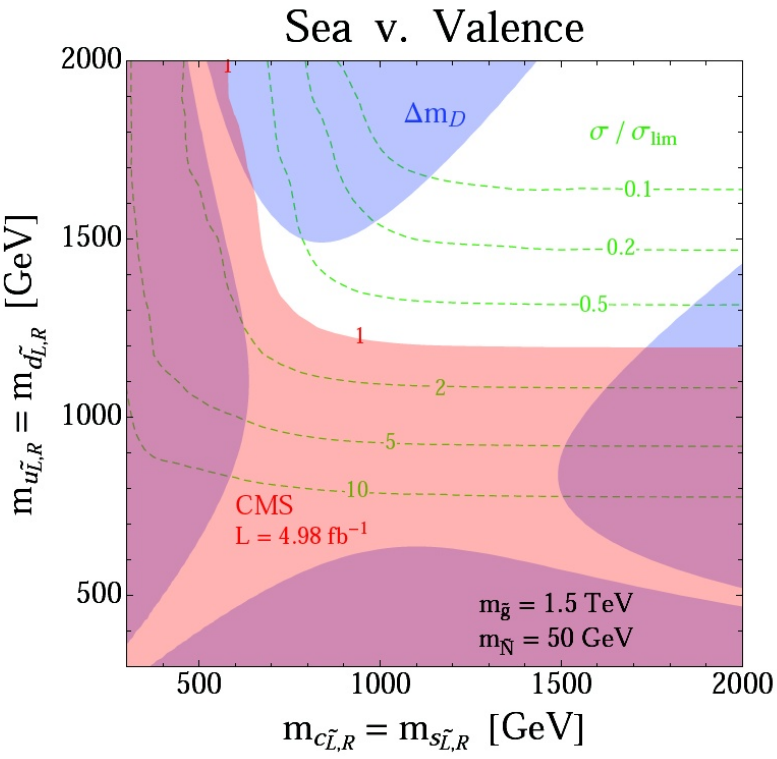


Hide flavor signals ⇔ hide LHC signals

- If 4 pairs of u, d, s, c squarks not degenerate, lot weaker LHC bounds: $1.2\,\mathrm{TeV} \;\Rightarrow \sim 0.5\,\mathrm{TeV}$

  E.g., assume that 4–4 squarks (1st and 2nd generation, but not all 8) are degenerate

  Unshaded region still allowed



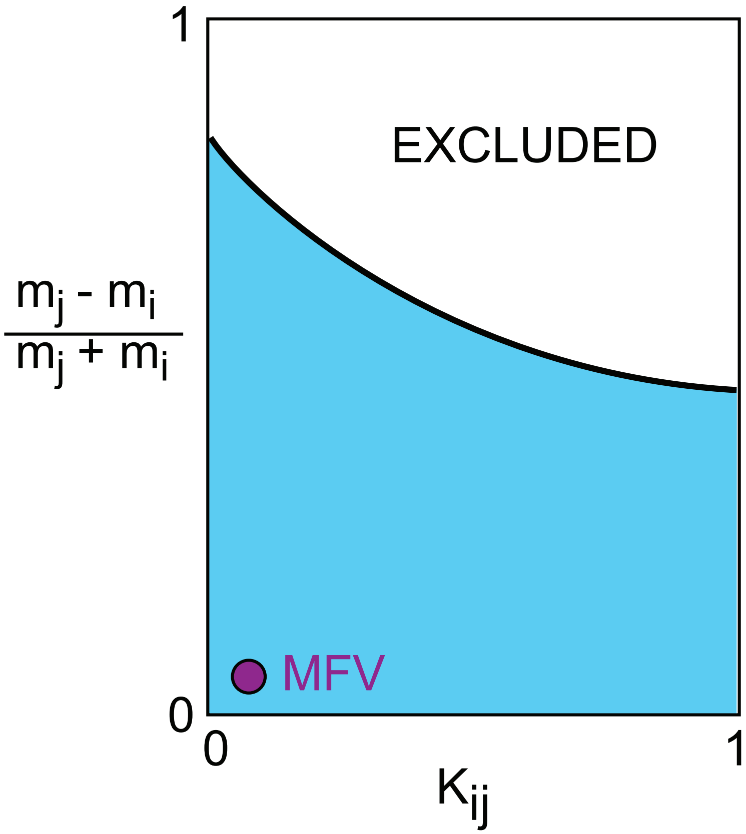
- Modify search strategies to improve coverage

- Ways for naturalness to survive — can give up many assumptions before abandoning key principles (many new LHC studies are yet to be devised and done)

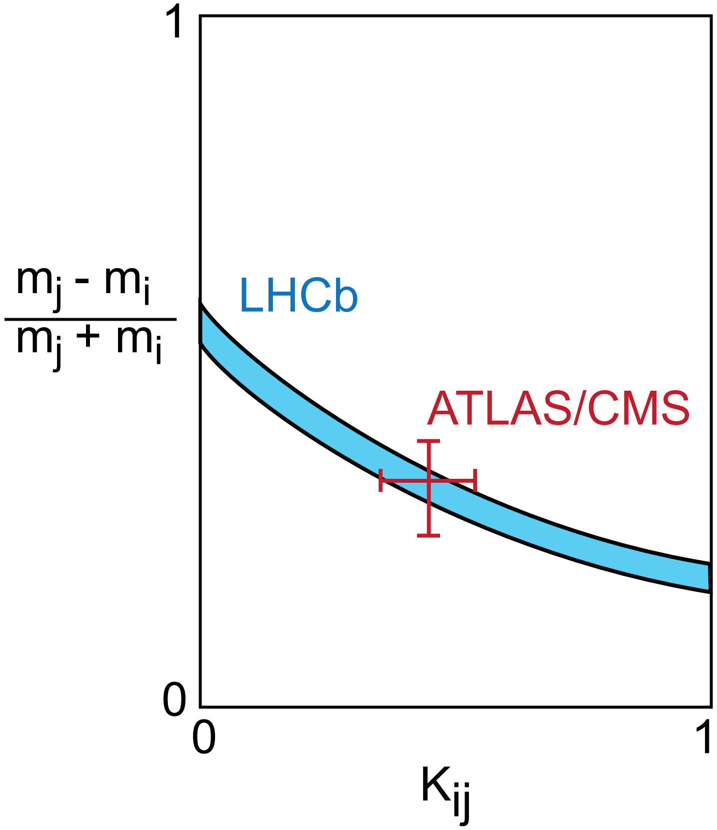
Possible pictures in a few years

- Combination of LHC and flavor physics measurements can be very powerful to discriminate between models

Constraints on masses & couplings now



Constraints in the future



Final comments

Conclusions — GeV scale

- CKM phase is the dominant source of CPV in flavor changing processes
  However, new physics in most FCNC processes may still be $\gtrsim 20\%$ of the SM

- Few hints of discrepancies — existing data could have shown new physics, compelling reasons to continue (theoretical uncertainties won't be limiting)

- If NP is seen: Study it in as many different operators as possible:

- If NP is not seen: Achieve what is theoretically possible; will teach us a lot about the NP seen (or not) at LHC

- Progress in theory toward model independently understanding more observables

- Low energy tests will improve a lot in next decade, by 10–1000 in some channels
  Exploring influence of NP requires LHCb upgrade, Belle II, K, lepton flavor viol.

Conclusions — TeV scale

- Consistency of precision flavor measurements with SM is a problem for NP @ TeV
  ⇒ New physics could show up any time measurements improve
- If new particles discovered, their flavor properties can teach us about $\gg \mathrm{TeV}$; masses (degeneracies), decay rates (flavor decomposition), cross sections
- We may learn how the NP flavor problem is (not) solved; MFV may be excluded
- Possible convergence between (s)quark and (s)lepton flavor physics
- Interplay between direct & indirect probes of NP will provide important information
  – synergy in reconstructing the fundamental theory (distinguish between models)
  – complementary coverage of param. space (subleading couplings, ≫TeV scales)