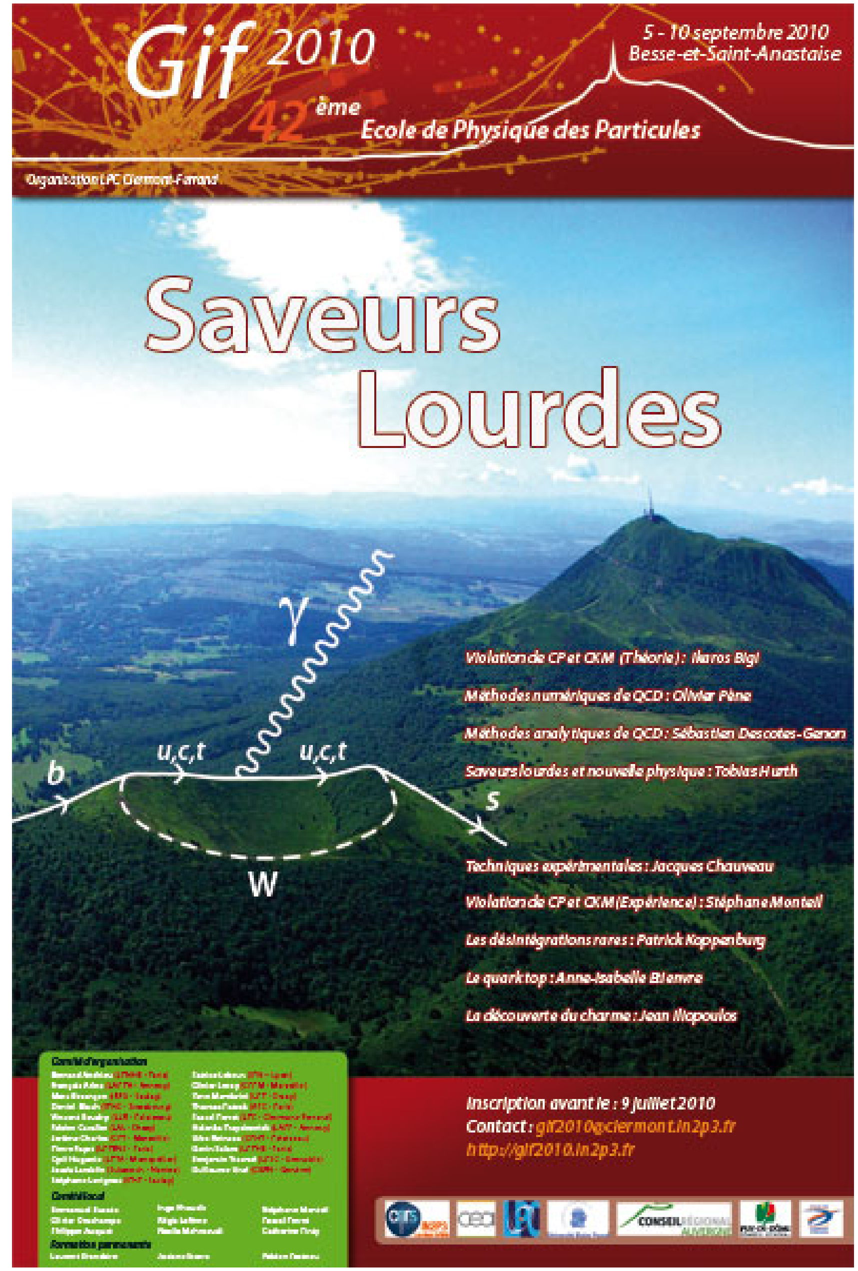
CP violation and CKM

Zoltan Ligeti

(ligeti@lbl.gov)

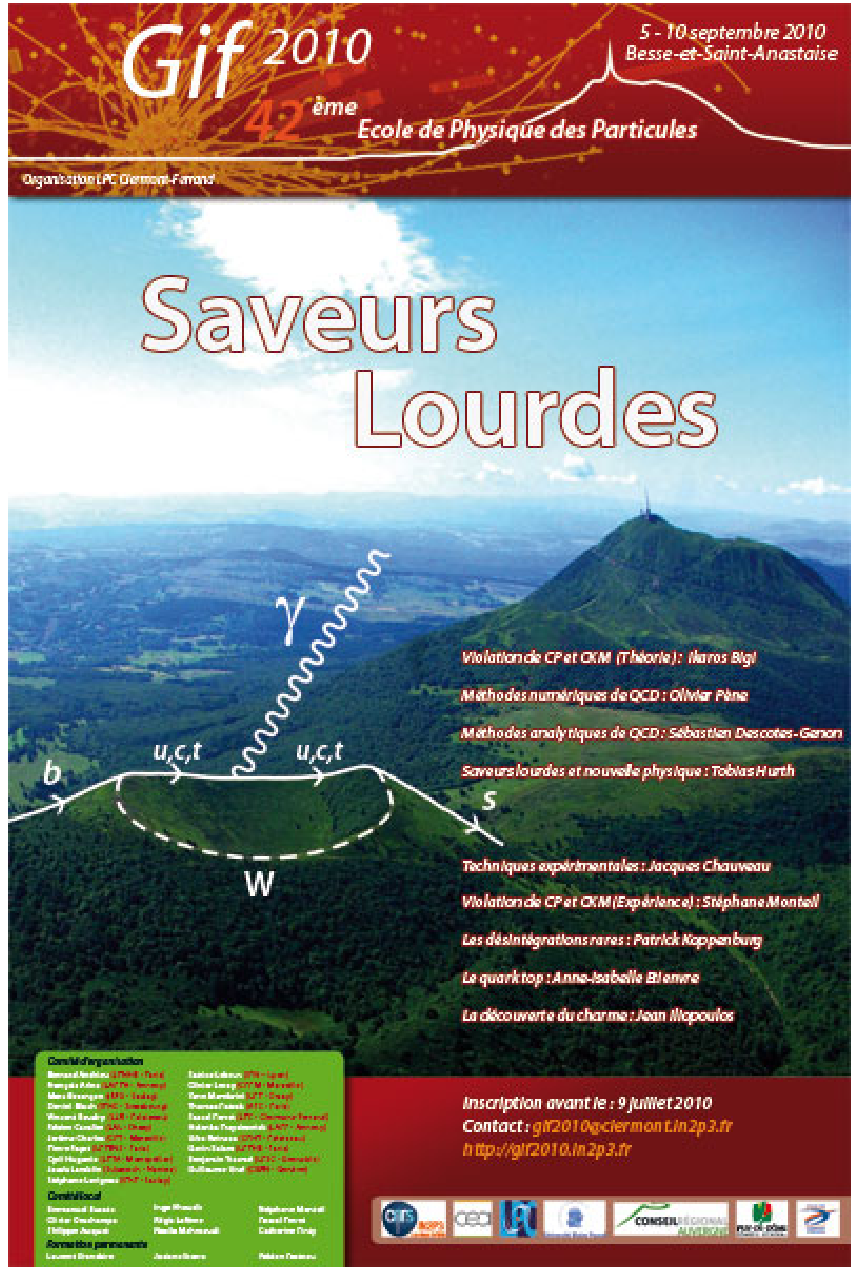
Lawrence Berkeley National Laboratory



Besse-et-Saint-Anastaise, Sep 5–10, 2010

CP violation and CKM

(in the next decade)



Zoltan Ligeti

(ligeti@lbl.gov)

Lawrence Berkeley National Laboratory

Besse-et-Saint-Anastaise, Sep 5–10, 2010

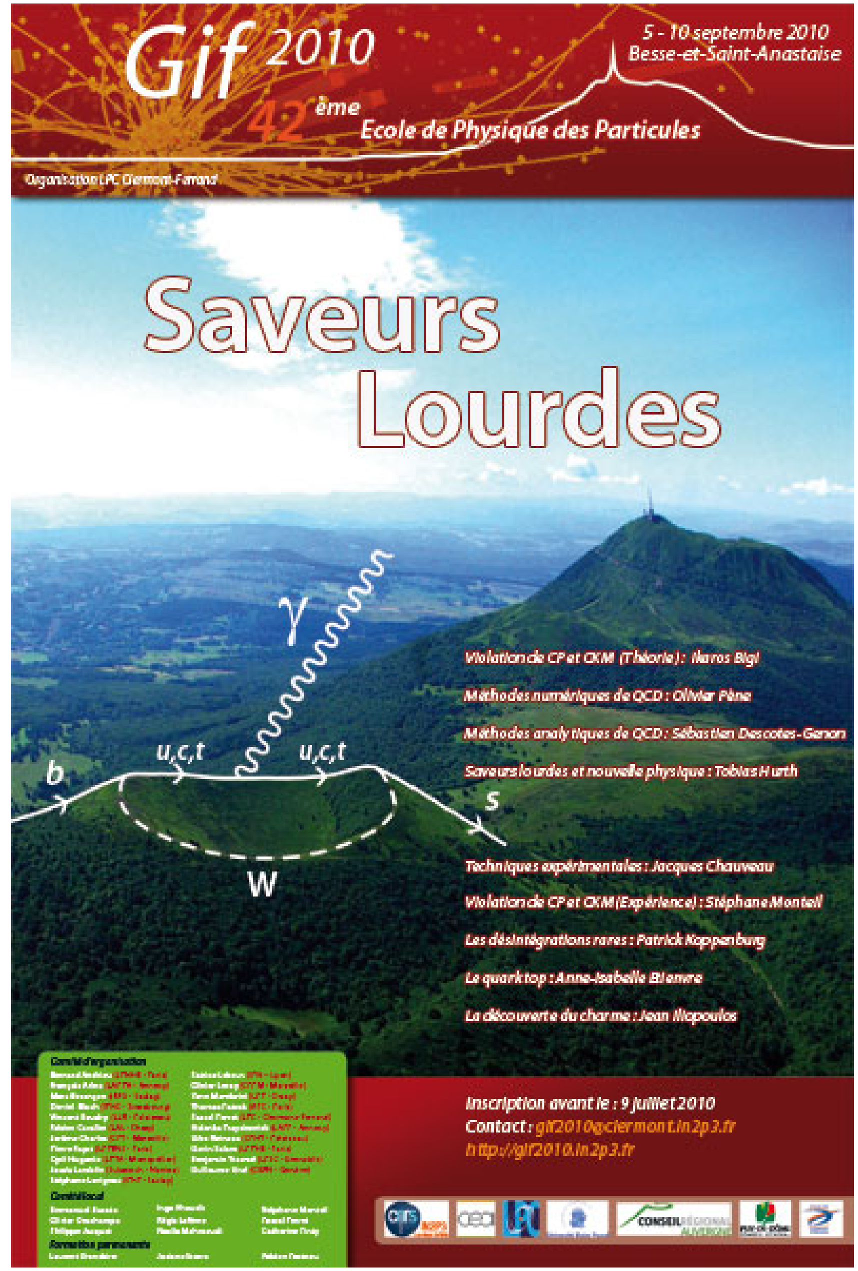
Flavor Physics

in the next decade

Zoltan Ligeti

(ligeti@lbl.gov)

Lawrence Berkeley National Laboratory



Besse-et-Saint-Anastaise, Sep 5–10, 2010

Every end is a new beginning...

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

  $\mathcal{O}(1)$ deviations in CP violation were possible

- End: Nobel Prize in 2008 is formal recognition that the KM phase is esablished as the dominant source of CPV in flavor changing transitions of quarks

- Present: No significant deviations from SM

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: Kyodo/Reuters

Makoto Kobayashi

Photo: Kyoto University

Toshihide Maskawa

- Begin: Looking for corrections to the SM picture of flavor and CP violation

- Future: What can flavor physics teach us about beyond SM physics?

What is particle physics?

- Central question:

$$\mathcal{L} = ?$$

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

What is particle physics?

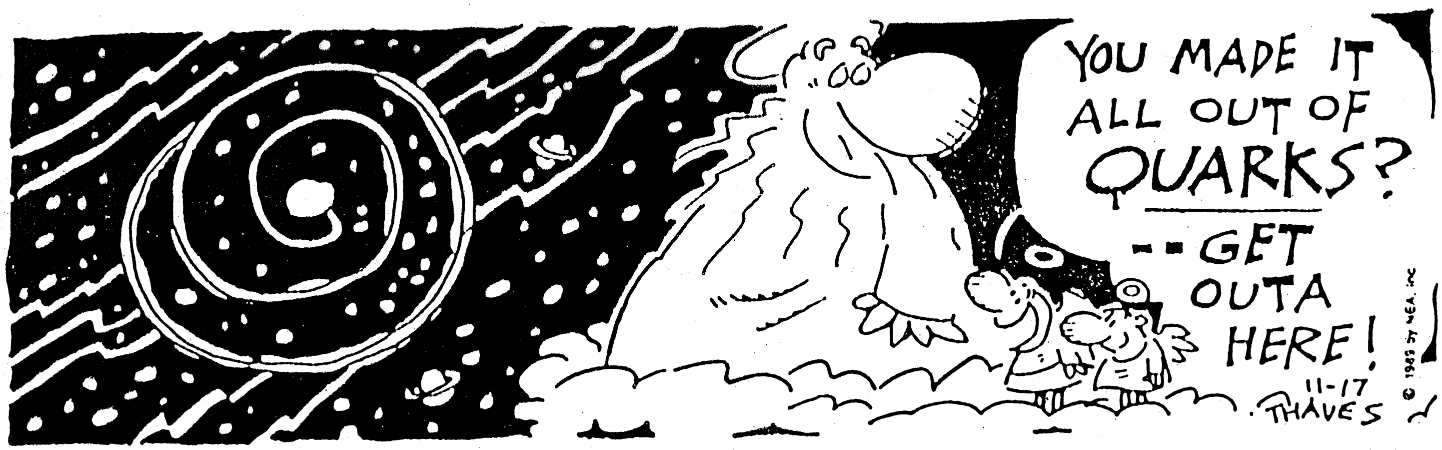
- Central question:

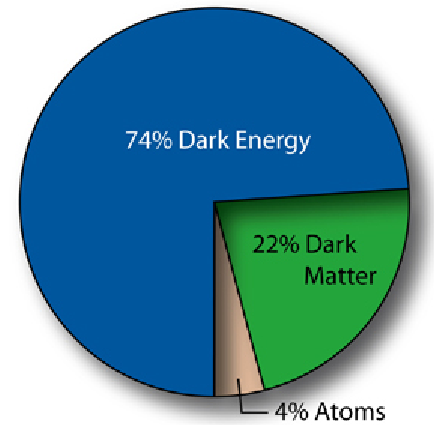
$$\mathcal{L} = ?$$

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

- Most of the observed phenomena consistent with the standard model (SM)
- Clearest empirical evidence that SM is incomplete:
  - Dark matter
  - Baryon asymmetry of the Universe
  - Neutrino mass [can add in straightforward (albeit unnatural) way]
  - Dark energy [cosmological constant? need to know more to understand?]
  - Hierarchy problem [is there an elementary Higgs? why so light? aesthetical?]

What is dark matter?





- Overwhelming evidence for DM: rotation curves, gravitational lensing, cosmology
- It cannot be a SM particle

  Know: non-baryonic (BBN), long lived, neutral (charge, color), abundance

  Don't know: interactions, mass, quantum numbers, one/many species
- Maybe thermal relic of early universe: weakly interacting massive particle (WIMP)
- Required WIMP interaction strength is at TeV scale — LHC may directly probe it

Matter–antimatter asymmetry

- Gravity, electromagnetism, strong interaction are same for matter and antimatter

- Soon after the big bang, quarks and anti-quarks were in thermal equilibrium

$$\frac{N(\text{baryon})}{N(\text{photon})} \sim 10^{-9} \quad \Rightarrow \quad \frac{N_q - N_{\bar{q}}}{N_q + N_{\bar{q}}} \sim 10^{-9}$$

$$\text{at } t < 10^{-6}\,\mathrm{s} \ \ (T > 1\,\mathrm{GeV})$$

- The SM prediction is 10^{10} times smaller

- Solution may lie at the TeV scale

  May learn about it at the LHC and from precision flavor physics measurements

Discrete symmetries: P, C, and T

- Discovering "new" symmetries / violation of "old" symmetries often lead to more fundamental understanding — may imply presence of new interactions

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

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

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

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

Discrete symmetries: P, C, and T

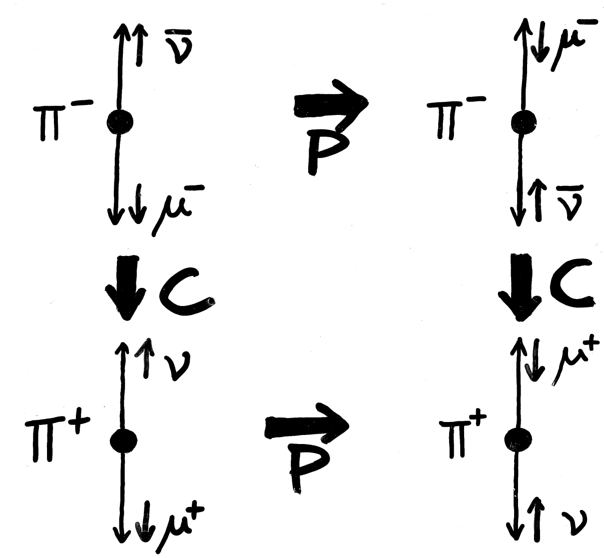
- Discovering "new" symmetries / violation of "old" symmetries often lead to more fundamental understanding — may imply presence of new interactions

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

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

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

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



Discrete symmetries: P, C, and T

- Discovering “new” symmetries / violation of “old” symmetries often lead to more fundamental understanding — may imply presence of new interactions

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

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

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

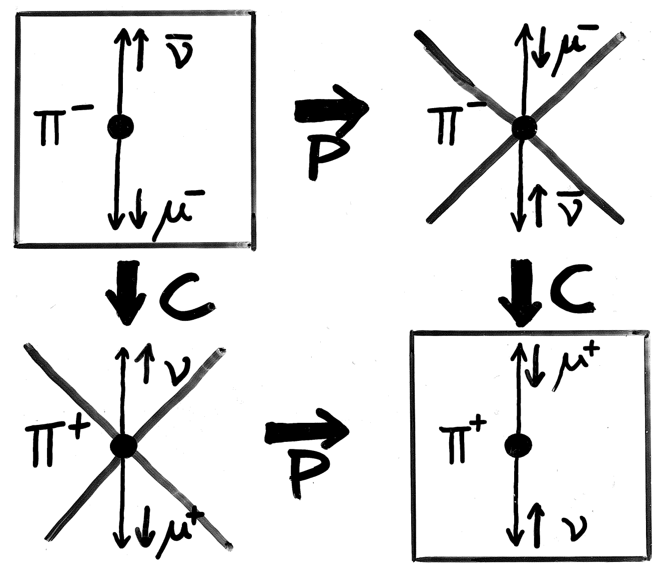
  CPT cannot be violated in a relativistically covariant local quantum field theory

- Only ν_L and $\bar{\nu}_R$ participate in weak interaction (1956)

  Weak interactions maximally violate C and P

  ($\Rightarrow$ Nobel prize 1957)

- CP conservation was widely believed / assumed



Telling matter from anti-matter

- CP violation well established in kaon decays since 1964 (⇒ Nobel prize 1980)

  Roughly consistent with SM, but theoretical uncertainties preclude precision tests

  Simplest example: $\Gamma(K_L^0 \to e^+ + X) > \Gamma(K_L^0 \to e^- + X)$

  Can "define" matter: smaller probability to produce e^- than e^+ in K_L decay

Telling matter from anti-matter

- CP violation well established in kaon decays since 1964 ($\Rightarrow$ Nobel prize 1980)

  Roughly consistent with SM, but theoretical uncertainties preclude precision tests

  Simplest example: $\Gamma(K_L^0 \to e^+ + X) > \Gamma(K_L^0 \to e^- + X)$

  Can "define" matter: smaller probability to produce e^- than e^+ in K_L decay

- "Practical" issues:

  Can tell if spaceship is made of matter or anti-matter... to avoid annihilation

  Matter / antimatter are distinguishable

Matter–antimatter asymmetry

- How could $\dfrac{N(\text{baryon})}{N(\text{photon})} \sim 10^{-9}$ be generated dynamically?
- Sakharov conditions:
  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 electroweak phase transition
- New TeV-scale physics can enhance both (e.g., SUSY)
- What is the microscopic theory of CP violation? How can we test it?

Outline (1)

- Brief introduction to the standard model

  Weak interactions, flavor, CKM

- Testing the flavor sector

  Bits of history, K decays, recent D mixing results

- Mixing and CPV in neutral mesons

  Types of CPV, how to get clean information

  Examples: β from $B \to \psi K_s$, ϕK, $B_s \to \phi\phi$; γ from $B \to DK$ and $B_s \to D_s^{\pm} K^{\mp}$

- Constraining new physics in mixing

  Sizable corrections to the SM are still allowed

Outline (2–3)

- Isospin and $SU(3)$: α from $B \to \pi\pi$ and $\rho\rho$
- Heavy quark symmetry and OPE

  Spectroscopy, exclusive / inclusive decays, $|V_{cb}|$, $|V_{ub}|$

  Rare decays, $B \to X_s\gamma$, and friends
- Nonleptonic decays, factorization

  B decays to final states with & without charm

- Flavor symmetries and new physics
- Lepton flavor violation
- FCNC top decays
- Minimal flavor violation

  Flavor at high-p_T
- 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 $\dfrac{\theta_{\rm QCD}}{16\pi^2}\, F_{\mu\nu}\widetilde{F}^{\mu\nu}$
  lattice QCD
  detailed new physics scenarios

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

- Many books and reviews, e.g.:

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

The Standard Model briefly

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, $d \leq 4$)

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

---

- Implicit assumptions: Lorentz symmetry and QFT; No global symmetries imposed; Accidental symmetries can arise in absence of higher dimension terms

- Higher dimension terms are suppressed at low energies

  (We are modest and not worry about details of physics we cannot probe)

  If higher dimension operators are present $\Rightarrow$ new physics at a higher scale

Standard model tidbits

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

  "forces" strong & electroweak interactions

  Carriers: 8 gluons, $W^\pm$, Z^0, γ [spin-1]

- Particle content: 3 generations of fermions (indistinguishable to start)

  "charges" quarks: $\begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix}$ leptons: $\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \\ e & \mu & \tau \end{pmatrix}$ [spin-$\frac{1}{2}$]

  ↖ 3 colors, strong int.

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

  Nonzero vev of an $SU(2)$ doublet scalar: $\langle\phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$

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

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

The identities of quarks

- Hamiltonian $\Rightarrow$ want to determine eigenstates, eigenenergies

  Degeneracy $=$ unresolved ambiguity in naming things

  – degeneracy broken by perturbations $\Rightarrow$ "good" states

  – degeneracy unbroken $\Rightarrow$ symmetry?

  Some perturbations break degeneracies and assign identities

---

- The quantum numbers of u, c, t are identical, so are those of d, s, b

  Degeneracy under choosing "good" combinations: $\widetilde{q}^{\,i} = \sum_j U_{ij}\, q^j$

  Ambiguity in assigning identities to particles: are q^i or $\widetilde{q}^{\,i}$ fundamental?

- Degeneracy broken by quark masses — where do they come from?

  [Only known difference between the 3 generations of particles $\Rightarrow$ "flavor physics"]

Masses of elementary particles

- Quark and lepton representations of $SU(3)_c \times SU(2)_L \times U(1)_Y$

  quarks: $\left[Q_L(3,2)_{1/6}, \quad u_R(3,1)_{2/3}, \quad d_R(3,1)_{-1/3}\right] \times 3$ copies

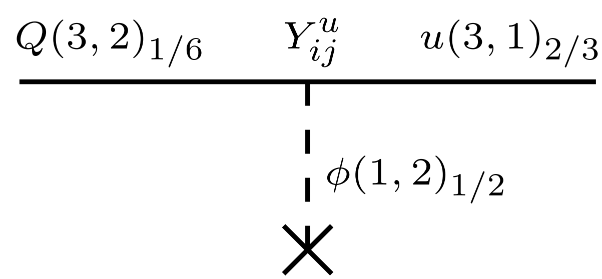
  leptons: $\left[L_L(1,2)_{-1/2}, \quad \ell_R(1,1)_{-1}\right] \times 3$ copies $\qquad [\nu_R(1,1)_0\,?]$

- Problem: SM gauge symmetries forbid $m\bar\psi\psi$ fermion mass terms (also $W^\pm$, Z^0)

  Loophole: the vacuum can also be charged

  “Higgs condensate” has $SU(2) \times U(1)$ charge

  (also gives mass to $W^\pm$, Z^0, but not to γ)



- Mass is an interaction with something unknown

- Simplest explicit model: Higgs $= SU(2)_L$ doublet scalar field

  after it acquires a vev $\Rightarrow$ one physical Higgs boson

The missing piece: Higgs

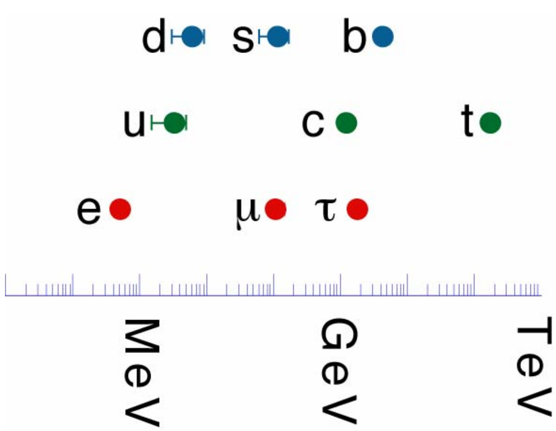
- In the SM: $m_H < 1\,\mathrm{TeV}$

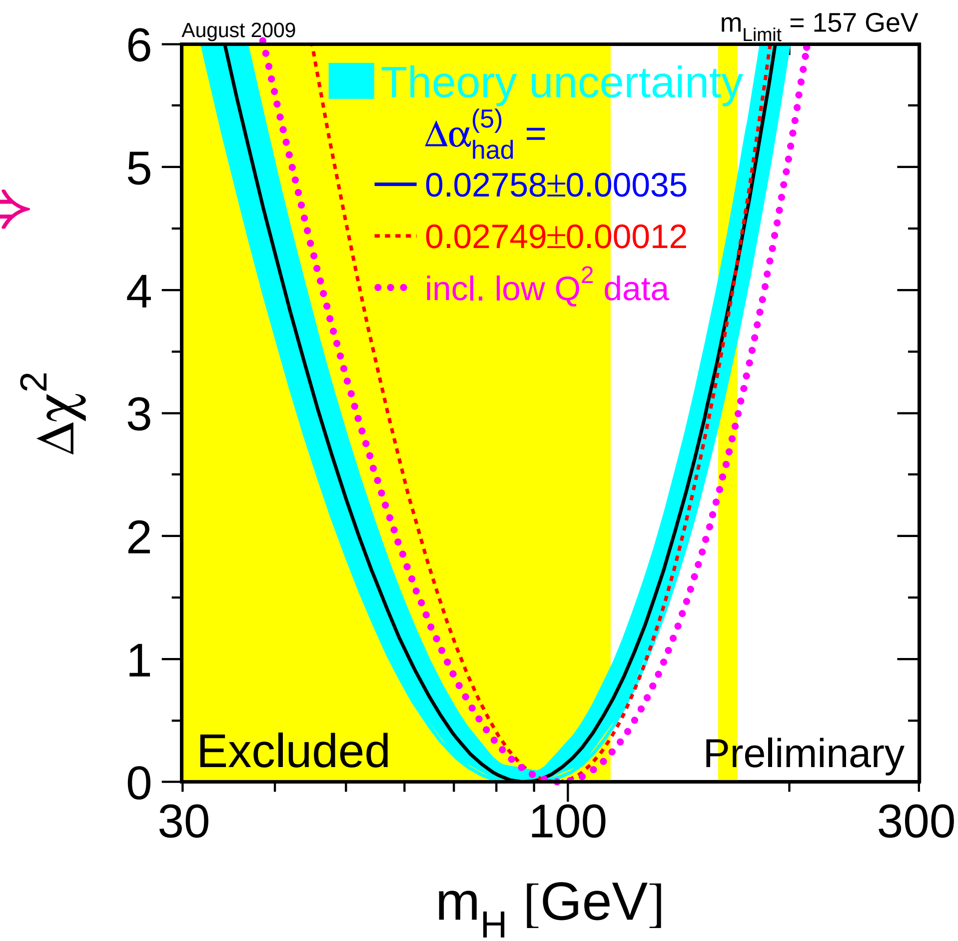
  No known spin-0 elementary particles

  Electroweak precision measurements $\Rightarrow$
  (LEP, SLC, Tevatron): $m_H \lesssim 200\,\mathrm{GeV}$

- If H has SM-like production cross sections and decays, the LHC will find it

- Quark masses: couplings to Higgs





Terms in the SM Lagrangian

- Kinetic terms: $\mathcal{L}_{\rm kin} = -\frac{1}{4}\sum_{\rm groups} (F^a_{\mu\nu})^2 + \sum_{\rm rep's} \overline{\psi}\, i\not{D}\, \psi$ (3 param's: g, g', g_s)

  always CPC (ignoring $F\widetilde{F}$)

- Higgs terms: $\mathcal{L}_{\rm Higgs} = |D_\mu\phi|^2 + \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$ (2 param's; $v^2 = \mu^2/\lambda$)

  CPC if $\exists$ only one Higgs doublet — CPV possible with extended Higgs sector

- Yukawa couplings in interaction basis: (this is where flavor is)

$$\mathcal{L}_Y = -Y^d_{ij}\,\overline{Q^I_{Li}}\,\phi\, d^I_{Rj} - Y^u_{ij}\,\overline{Q^I_{Li}}\,\widetilde{\phi}\, u^I_{Rj} - Y^\ell_{ij}\,\overline{L^I_{Li}}\,\phi\,\ell^I_{Rj} + \text{h.c.}$$

  $i, j \sim$ generations

  (cannot write such mass term for ν_i)

  $\searrow \; = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \phi^*$

- CPV is related to unremovable phases of Yukawa couplings:

$$Y_{ij}\,\overline{\psi_{Li}}\,\phi\,\psi_{Rj} + Y^*_{ij}\,\overline{\psi_{Rj}}\,\phi^\dagger\,\psi_{Li}$$

$\Downarrow$ CP exchanges fermion bilinears

$$Y_{ij}\,\overline{\psi_{Rj}}\,\phi^\dagger\,\psi_{Li} + Y^*_{ij}\,\overline{\psi_{Li}}\,\phi\,\psi_{Rj}$$

Yukawa couplings and CKM matrix

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

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

- $Y_{u,d}^{ij} = 3 \times 3$ are complex matrices $\Rightarrow$ mass terms after ϕ acquires VEV

$$\mathcal{L}_{\rm mass} = -M_u^{ij}\, \overline{u_{Li}^I}\, u_{Rj}^I - M_d^{ij}\, \overline{d_{Li}^I}\, d_{Rj}^I\,, \qquad M_{u,d} \propto Y_{u,d}$$

Diagonalize: $M_f^{\rm diag} \equiv V_{fL}\, M_f\, V_{fR}^\dagger \qquad (f = u, d)$

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

- Mass matrices diagonalized by different transformations for u_{Li} and d_{Li}, which are part of the same $SU(2)_L$ doublet, Q_L, so: $\begin{pmatrix} u_{Li}^I \\ d_{Li}^I \end{pmatrix} = (V_{uL}^\dagger)_{ij} \begin{pmatrix} u_{Lj} \\ (V_{uL} V_{dL}^\dagger)_{jk}\, d_{Lk} \end{pmatrix}$

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

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

Aside: counting flavor parameters

- Nonzero Yukawa couplings break flavor symmetries — pattern of masses and mixings are inherited from the interactions of fermions with the Higgs background

- Quark sector: $U(3)_Q \times U(3)_u \times U(3)_d \to U(1)$ quark (baryon) number

$$[36 \text{ couplings}] - [26 \text{ broken symmetries}] = 10 \text{ parameters with physical meaning}$$

$$= [6 \text{ masses}] + \overbrace{[3 \text{ angles}] + \underbrace{[1 \text{ phase}]}_{\text{Single source of } CP \text{ violation in the quark sector in the SM}}}^{\text{parameters in } V_{\text{CKM}}}$$

- Lepton sector (Majorana ν's): $\mathcal{L}_Y = -Y_e^{ij}\, \overline{L_{Li}^I}\, \phi\, e_{Rj}^I - \dfrac{Y_\nu^{ij}}{M}\, L_{Li}^I L_{Lj}^I\, \phi\, \phi \qquad (Y_\nu^{ij} = Y_\nu^{ji})$

  $U(3)_L \times U(3)_e$ completely broken

$$[30 \text{ couplings}] - [18 \text{ broken symmetries}] = 12 \text{ parameters with physical meaning}$$

$$= [6 \text{ masses}] + [3 \text{ angles}] + \underbrace{[3\text{CPV phases}]}_{\text{One CPV phase measurable in } \nu \text{ oscillations, others in } 0\nu\beta\beta \text{ decay}}$$

Quark mixing and the unitarity triangle

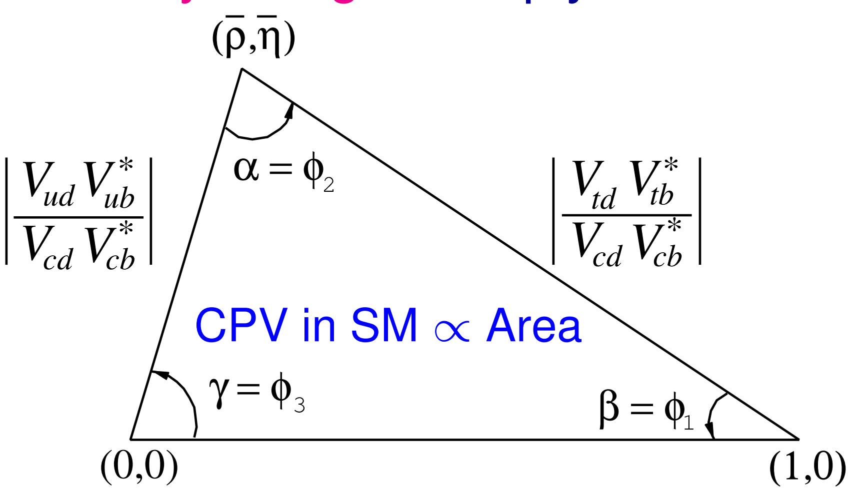
- The $W^\pm$ couples $(u,\, c,\, t)$ and $(d,\, s,\, b)$ with strength: $(\lambda \sim 0.23)$

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

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 relations

- Unitarity triangle: simply visualize SM constraints and compare measurements



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

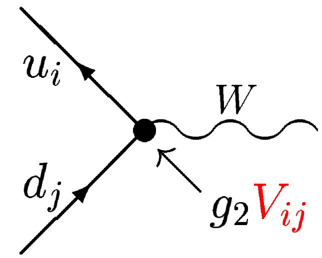
Sides and angles measurable in many ways

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

Weak interaction properties

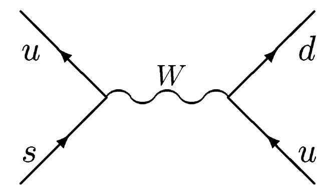
- Only the $W^{\pm}$ interactions change the type of quarks

  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

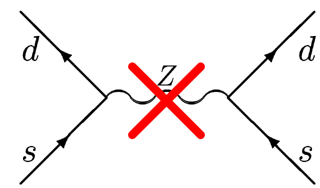
  e.g.: $K \to \pi\pi$ or $K \to \pi\ell\bar{\nu}$



  No flavor changing neutral currents (FCNC) at tree level

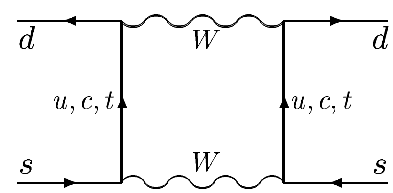
  e.g.: no $K^0 - \overline{K}^0$ mixing, $K \to \mu^+\mu^-$, etc.

  (Show that Z^0 interactions remain 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 differences between the generations

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" what breaks $SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$

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

  $\Rightarrow$ The LHC will directly address this (produce h)

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

  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

Testing the flavor sector

Spectacular track record

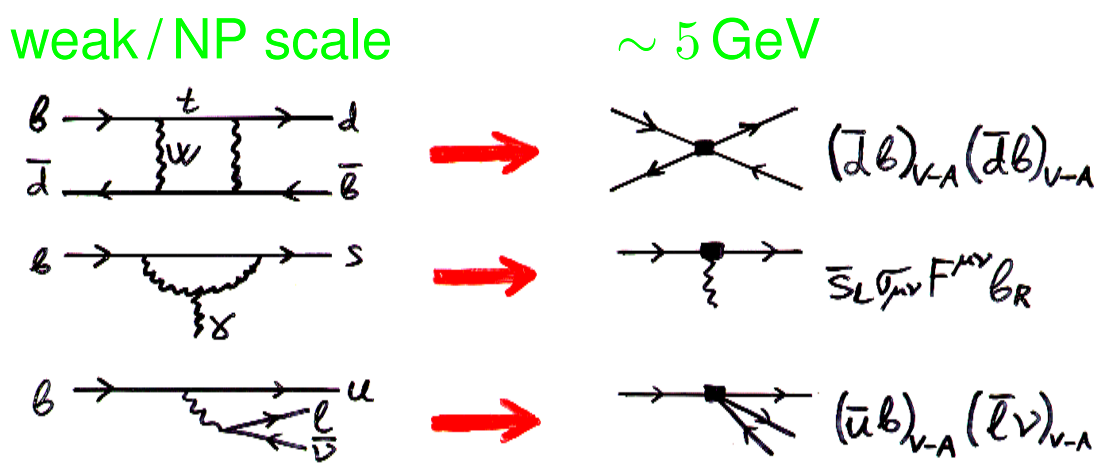
- Most parameters of the SM (and in many of its extensions) are related to flavor
- Flavor physics was crucial to figure out $\mathcal{L}_{\mathrm{SM}}$:
  - β-decay predicted neutrino (Pauli)
  - Absence of $K_L \to \mu\mu$ predicted charm (GIM)
  - ϵ_K predicted 3rd generation (KM)
  - Δm_K predicted m_c (GL)
  - Δm_B predicted large m_t
- Likely to be important to figure out $\mathcal{L}_{\mathrm{LHC}}$ too — excellent probes of new physics

  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



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

---

- 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

How do we know that CP is violated?

- Prior to 1964, the explanation of the large lifetime ratio of the two neutral kaons was CP symmetry (before 1956, it was C alone...)

$$|K^0\rangle = \bar{s}\,d\,, \qquad |\overline{K}^0\rangle = \bar{d}\,s\,, \qquad CP|K^0\rangle = +|\overline{K}^0\rangle$$ (convention dependent)

states of definite CP: $|K_{1,2}\rangle = \frac{1}{\sqrt{2}}\,(|K^0\rangle \pm |\overline{K}^0\rangle)$

$$CP|K_1\rangle = |K_1\rangle\,, \qquad CP|K_2\rangle = -|K_2\rangle$$

If CP were an exact symmetry: only $K_1 \to \pi\pi$, both $K_{1,2} \to \pi\pi\pi$ $\Big\}$ $\Rightarrow\ \tau(K_1) \ll \tau(K_2)$

- But $K_L \to \pi\pi$ was observed (1964) at the 10^{-3} level! (not the goal of the exp!)

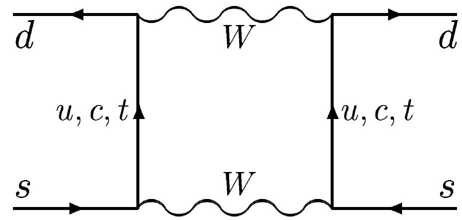
$$\eta_{00} = \frac{\langle\pi^0\pi^0|\mathcal{H}|K_L\rangle}{\langle\pi^0\pi^0|\mathcal{H}|K_S\rangle} \quad \eta_{+-} = \frac{\langle\pi^+\pi^-|\mathcal{H}|K_L\rangle}{\langle\pi^+\pi^-|\mathcal{H}|K_S\rangle} \quad \epsilon_K \equiv \tfrac{1}{3}\,(\eta_{00} + 2\eta_{+-}) \quad \epsilon'_K \equiv \tfrac{1}{3}\,(\eta_{+-} - \eta_{00})$$

Took <1 yr to propose superweak, but 9 till KM (before 2nd generation complete!)

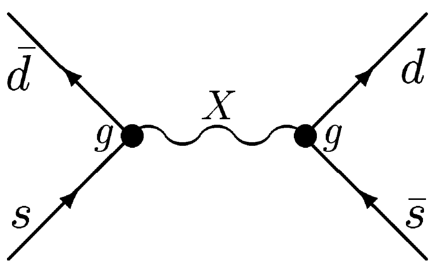
Δm_K, ϵ_K are built in NP models since 70's

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

  (severe suppressions!)



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



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

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

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

(In many scenarios the constraits from kaons are the strongest, since so is the SM suppression, and these are built into models since the 70's)

Aside: $K^0 - \overline{K}^0$ mixing in supersymmetry

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

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

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

- Classes of models to suppress each factors

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

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

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

- Has driven SUSY model building — all models incorporate some of the above

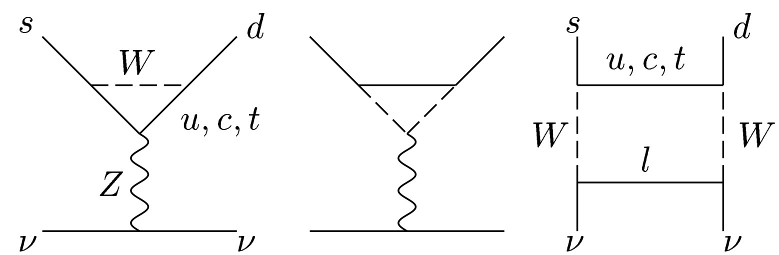
- $D^0 - \overline{D}^0$ mixing discovery (BaBar & Belle, 2007) ruled out (iii) as sole explanation

Testing CKM with Kaons

- CPV in K system is at the right level (ϵ_K accommodated with $\mathcal{O}(1)$ CKM phase)
- Hadronic uncertainties preclude precision tests (ϵ'_K notoriously hard to calculate)

- $K \to \pi\nu\bar{\nu}$: Theoretically clean, but rates small $\mathcal{B} \sim 10^{-10}(K^{\pm}),\ 10^{-11}(K_L)$

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



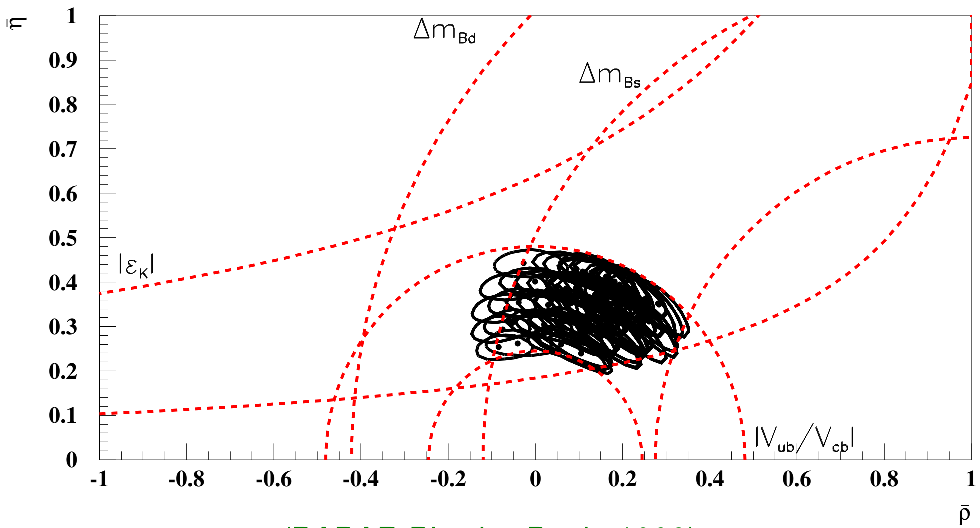
So far 3 events observed: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

Only an upper bound: $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < (2.6 \times 10^{-8} \quad (90\%\,\mathrm{CL})$

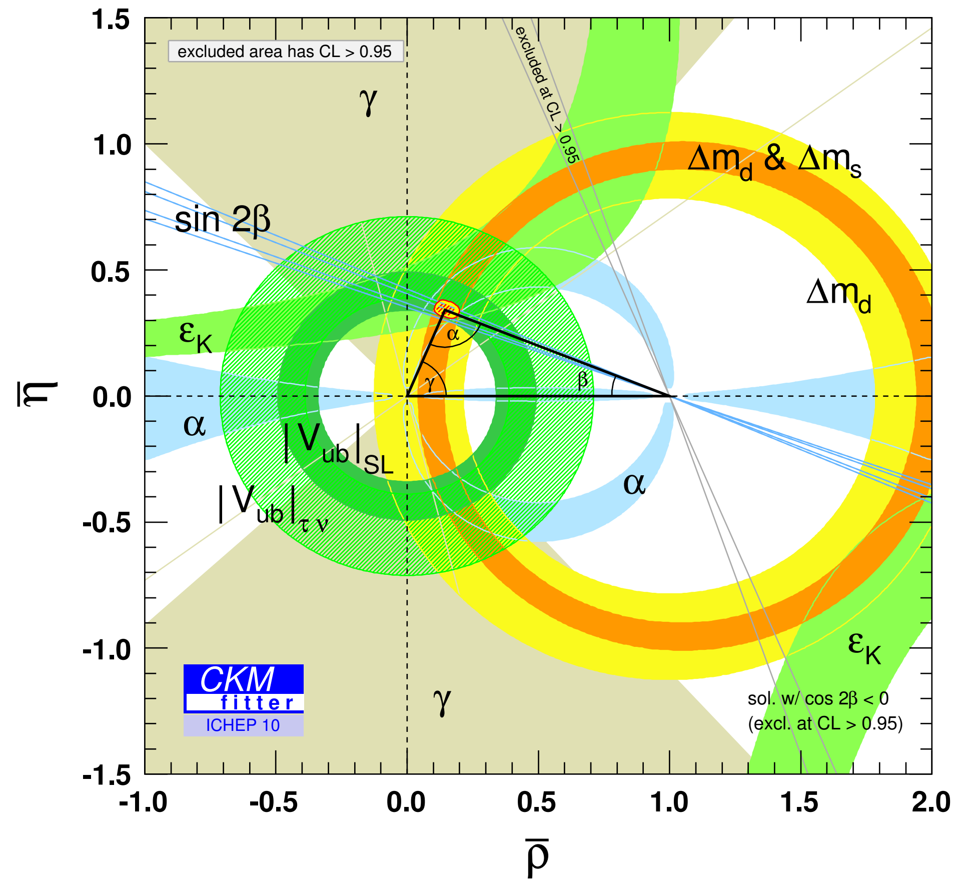
- Need much higher statistics to make definitive tests

Constraints on CKM matrix

- For 35 years, untill 1999, the only unambiguous measurement of CPV was ϵ_K



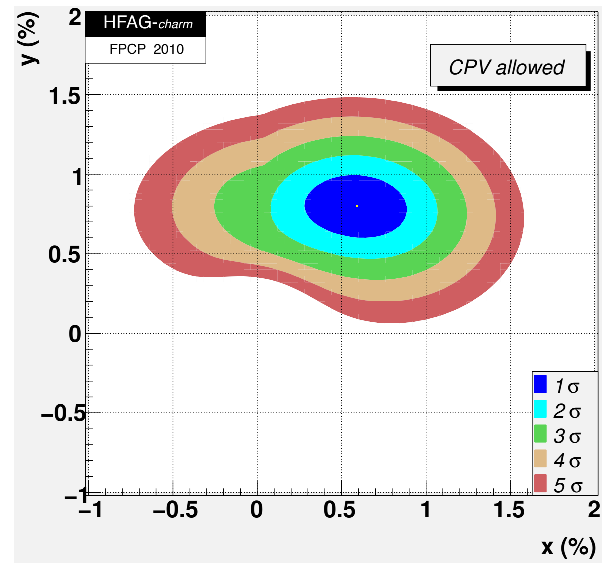
(BABAR Physics Book, 1998)



- $\sin 2\beta = 0.673 \pm 0.023$ — by now dozens of CPV measurements, so the interesting question is in which cases can both theory and experiment be precise

The D meson system

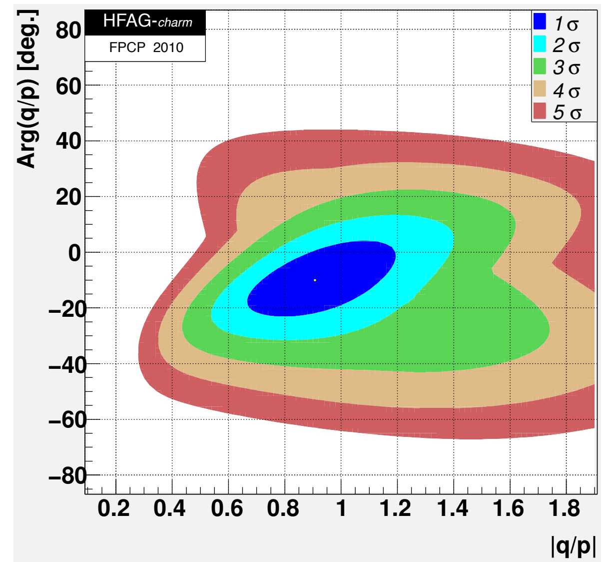
- Complementary to K, B: CPV, FCNC both GIM & CKM suppressed $\Rightarrow$ tiny in SM
  - 2007: significance of mixing $> 5\sigma$ [HFAG combination]
  - Only meson mixing generated by down-type quarks (SUSY: up-type squarks)
  - SM suppression: $\Delta m_D,\ \Delta\Gamma_D \lesssim 10^{-2}\,\Gamma$,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



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

The D meson system

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



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

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

Important features of the 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 mixing angles
  - Suppression of FCNC processes (loops)
  - Suppression of FCNC chirality flips by quark masses (e.g., $S_{K^*\gamma}$)

  Many suppressions that NP might not respect $\Rightarrow$ sensitivity to very high scales
- It is interesting and possible to test all of these

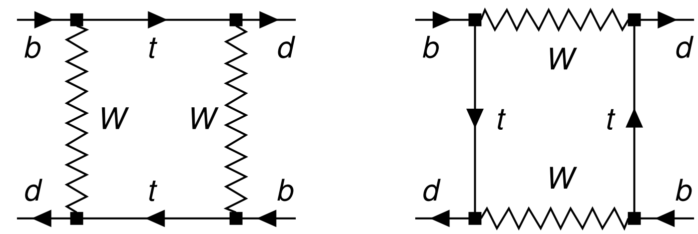
What's special about B's?

- 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 $(m_b \gg \Lambda_{\rm QCD})$
- Experimentally feasible to study:
  - $\Upsilon(4S)$ resonance is clean source of B mesons
  - Long B meson lifetime
  - Timescale of oscillation and decay comparable: $\Delta m/\Gamma \simeq 0.77\, [= \mathcal{O}(1)]$ (and $\Delta\Gamma \ll \Gamma$)

Mixing and CPV in neutral mesons

Neutral 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: $i\,\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|B^0(t)\rangle\\ |\overline{B}^0(t)\rangle\end{pmatrix} = \left(M - \frac{i}{2}\,\Gamma\right)\begin{pmatrix}|B^0(t)\rangle\\ |\overline{B}^0(t)\rangle\end{pmatrix}$



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 $\Gamma_{11} = \Gamma_{22}$)

M_{12} dominated by box diagrams with top quarks $\Rightarrow$ sensitive to high scales

Time dependence involves mixing and decay: $|B_{H,L}(t)\rangle = e^{-(iM_{H,L}+\Gamma_{H,L}/2)t}|B_{H,L}\rangle$

- For $B_{d,s}$: $|\Gamma_{12}| \ll |M_{12}| \Rightarrow \Delta m = 2|M_{12}|,\ \ \Delta\Gamma = 2|\Gamma_{12}|\cos\phi_{12},\ \ \phi_{12} = \arg(-M_{12}/\Gamma_{12})$

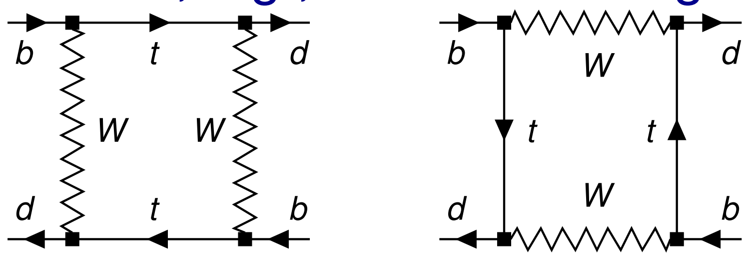
In SM: $(q/p)_{B_d} = e^{-2i\beta + \text{conv.dep.}} + \mathcal{O}(10^{-3})$ $\qquad (q/p)_{B_s} = e^{\text{tiny}+\text{conv.dep.}}$

- Sizable hadronic uncertainties in Δm and especially $|q/p|$, but not in $\arg(q/p)$

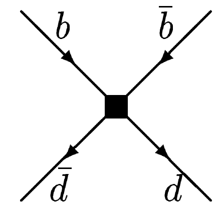
Effective Hamiltonians

- Interactions at high scale (weak or new physics) produce local operators at lower scales (hadron masses)

  Consider, e.g., $B^0 - \overline{B}^0$ mixing:



$\Rightarrow$



$$Q(\mu) = (\bar{b}_L\, \gamma_\nu\, d_L)\, (\bar{b}_L\, \gamma^\nu\, d_L)$$

  New physics can modify coefficients and/or induce new operators

- Going from operators to observables is equally important

  In SM: $$M_{12} = (V_{tb} V_{td}^*)^2\, \frac{G_F^2}{8\pi^2}\, \frac{M_W^2}{m_B}\, S\left(\frac{m_t^2}{M_W^2}\right) \eta_B\, b_B(\mu)\, \langle B^0 | Q(\mu) | \overline{B}^0 \rangle$$

  what we are after — calculable perturbatively — nonperturbative

  $\eta_B\, b_B(\mu)$: Resumming $\alpha_s^n \ln^n(m_W/\mu)$, where $\mu \sim m_b$, is often very important

  $\langle B^0 | Q(\mu) | \overline{B}^0 \rangle = \frac{2}{3}\, m_B^2\, f_B^2 \frac{\widehat{B}_B}{b_B(\mu)}$: hadronic uncertainties enter here

Aside: importance of $|\Gamma_{12}| \ll |M_{12}|$

- New physics in mixing modifies M_{12}; new CPV phases may alter $\phi \equiv \arg(q/p)$
  Observing ϕ different from the SM prediction may be the best hope to find NP

  $B_{d,s}$: $\Gamma_{12} \ll M_{12}$, K: $M_{12} \sim \Gamma_{12}$, D: $\Gamma_{12} \sim$ or $> M_{12}$

  Solving the eigenvalue equation:

  – If $\Delta m \gg \Delta\Gamma$, the CPV phase can be **LARGE**: $\phi = \arg(M_{12}) + \mathcal{O}(\Gamma_{12}^2/M_{12}^2)$

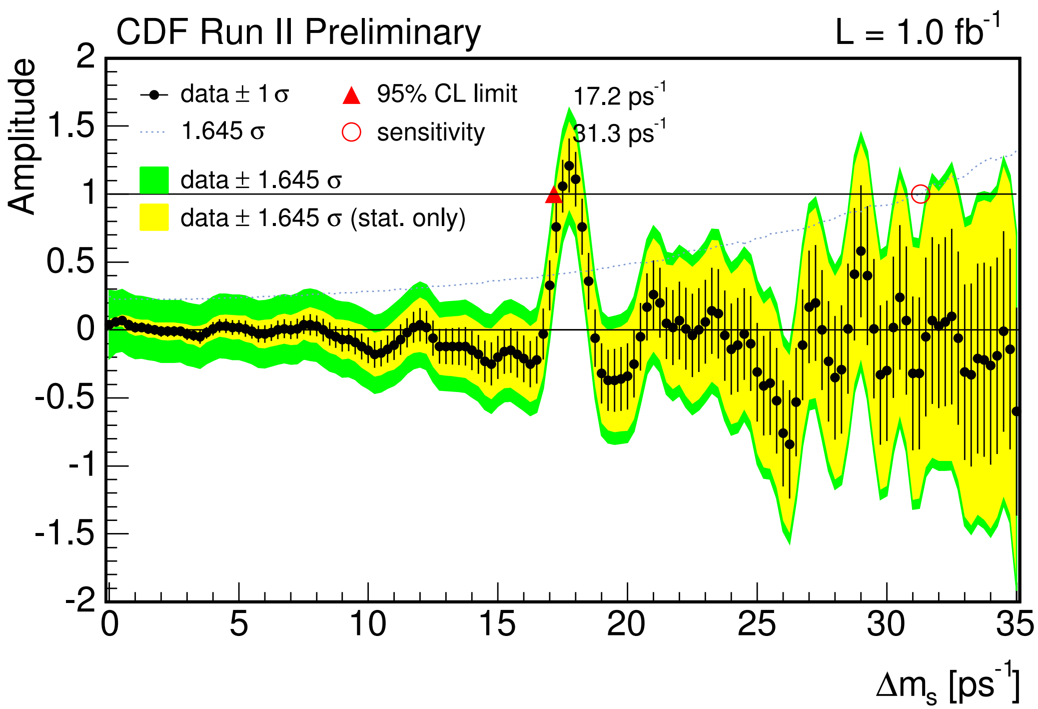
  – If $\Delta\Gamma \gg \Delta m$, the CPV phase is **SMALL**: $\phi = \mathcal{O}(M_{12}^2/\Gamma_{12}^2) \times \sin(2\,\phi_{12})$

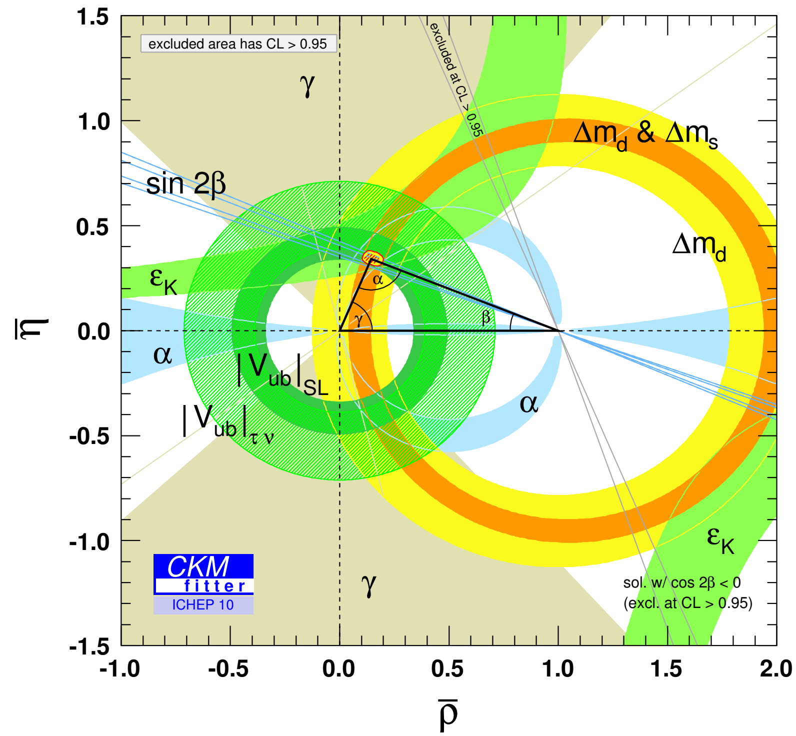
- If $\Delta\Gamma \gg \Delta m$ then even if new physics dominates M_{12}, the sensitivity of any physical observable to it is suppressed by $\Delta m/\Delta\Gamma$

- Another reason to pin down Δm_D; while $\Delta\Gamma_D \neq 0$ at $> 5\sigma$, $\Delta m_D \neq 0$ is barely more than 2σ — will affect sensitivity to NP

B_s mixing: V_{td}/V_{ts} from Δm_s

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





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

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

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

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

CPV in decay

- CPV in decay: simplest form of CPV — count events

  $|\overline{A}_{\overline{f}}/A_f| \neq 1$: need amplitudes with different weak (ϕ_k) & strong (δ_k) phases

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

- Unambiguously established by $\epsilon'_K \neq 0$, and since 2004 also in B decays:

$$A_{K^-\pi^+} \equiv \frac{\Gamma(\overline{B} \to K^-\pi^+) - \Gamma(B \to K^+\pi^-)}{\Gamma(\overline{B} \to K^-\pi^+) + \Gamma(B \to K^+\pi^-)} = -0.098 \pm 0.012$$

  – After "K-superweak", also "B-superweak" excluded: CPV is not only in mixing

  – There are large strong phases (also in $B \to \psi K^*$); challenge to some models

- Theoretical understanding for both ϵ'_K and $A_{K^-\pi^+}$ insufficient to either prove or to rule out that NP enters (3.6σ signal also in $B \to \rho\pi$)

  Sensitive to NP in cases when SM prediction is model independently small

CPV in mixing

- If CP is conserved then physical states are $\frac{1}{\sqrt{2}}(|B^0\rangle \pm |\overline{B}^0\rangle)$, corresponding to $|q/p| = 1$ and $\arg(M_{12}/\Gamma_{12}) = 0$ — CPV if (mass eigenstates) $\neq$ (CP eigenstates)

  $\left|\frac{p}{q}\right| \neq 1 \;\Rightarrow$ CPV in mixing — occurs iff: $\langle B_H | B_L \rangle = |p|^2 - |q|^2 \neq 0$

- Simplest example: decay to "wrong sign" lepton ("dimuon asymmetry")

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

  Observed in K decay in agreement with SM — intriguing hint at DØ in B_s mixing

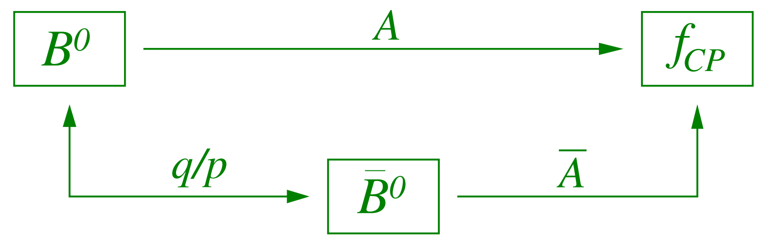
- Large hadronic uncertainties in calculation of Γ_{12}, but interesting to look for NP:

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

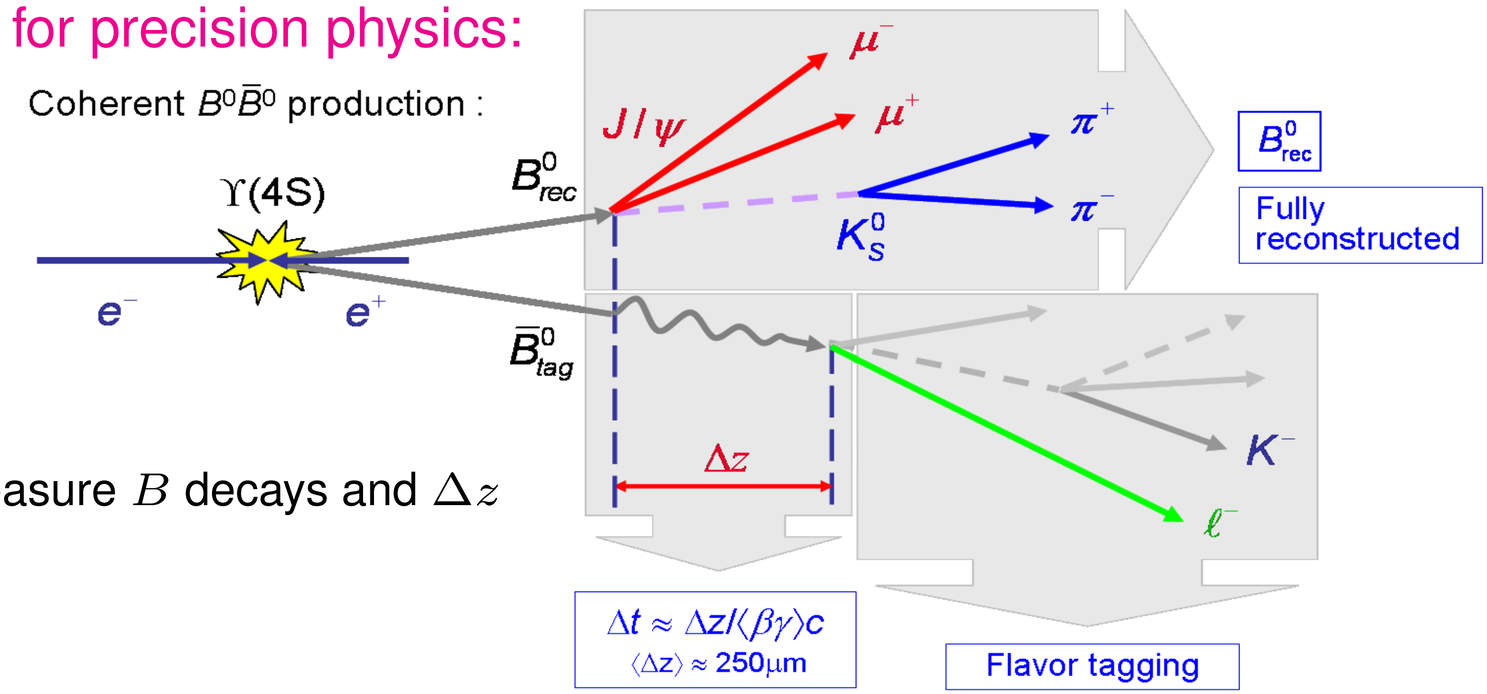
$$a_{f_{CP}} = \eta_{f_{CP}} \sin(\text{phase difference between decay paths})\ \sin(\Delta m\, t)$$

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 ($\overline{B}^0$), then at the same time the other B must be $\overline{B}^0$ (B^0)

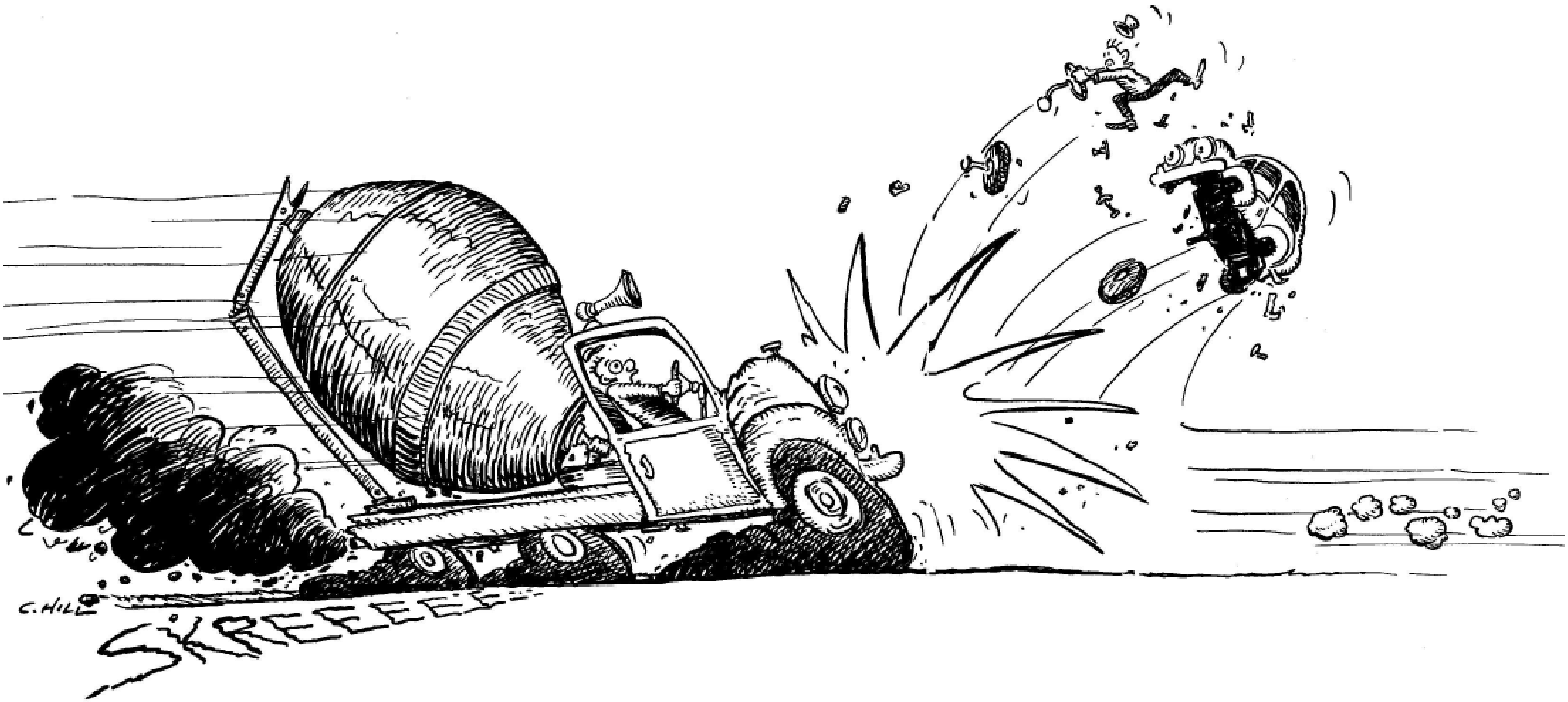
- EPR effect used for precision physics:



Measure B decays and Δz

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

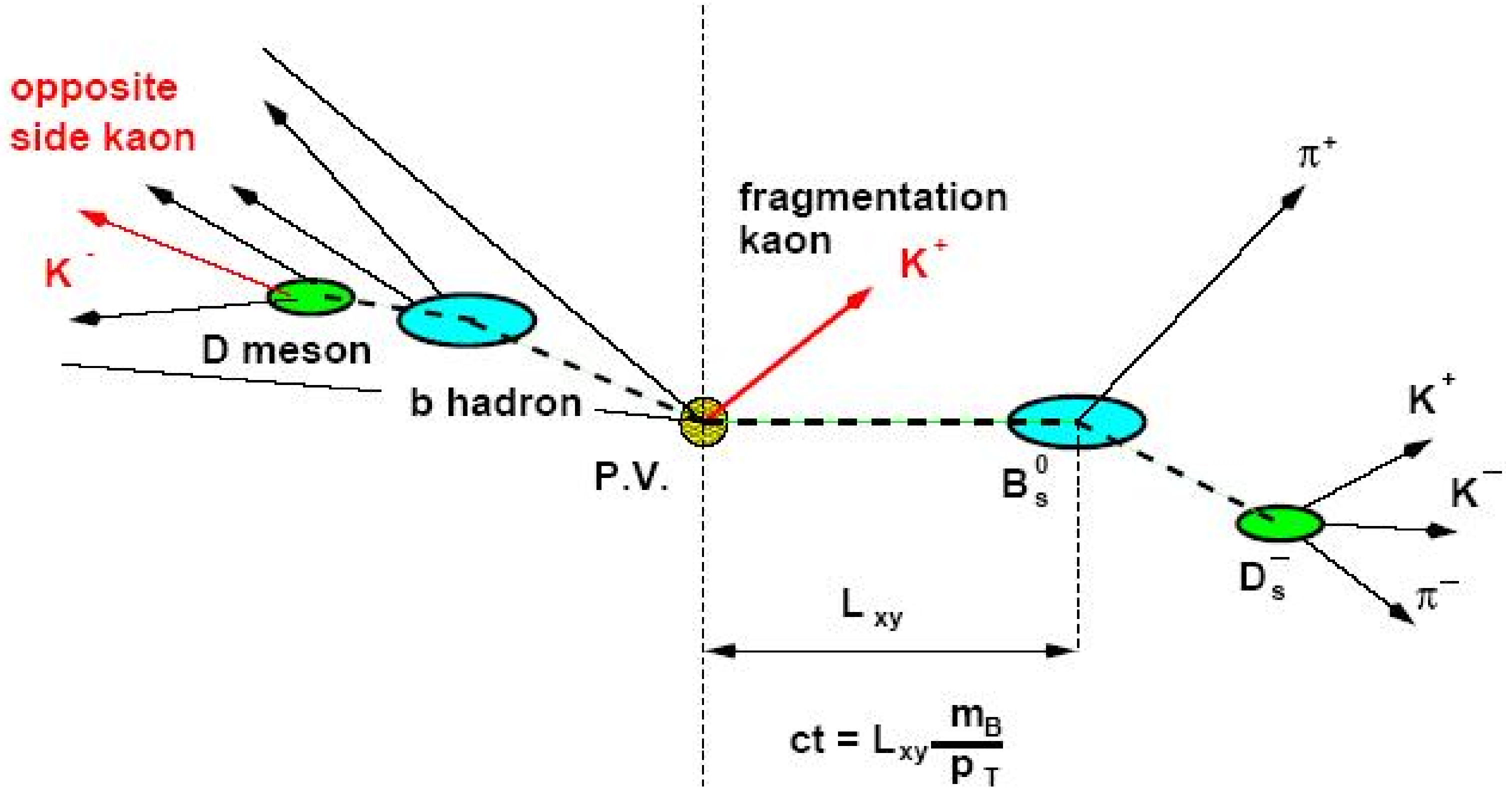
Asymmetric colliders



... to measure time dependence of decay after the collision

Hadron colliders — no quantum correlation

- B_s^0 with sufficient boost to study CPV at Tevatron & LHC (+ Belle data on rates)



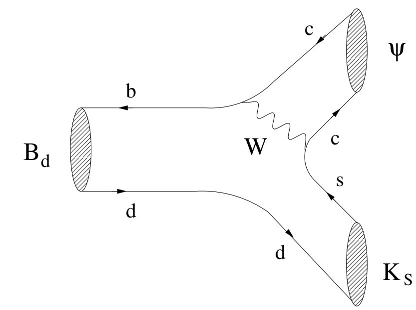
- $gg,\, q\bar{q} \to b\bar{b}$: measure flavor of a b hadron, and flavor of B_s^0 as a function of time

  Need excellent time resolution, and fully reconstructed B_s^0 to know its boost

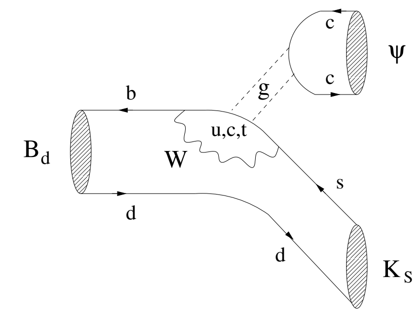
The cleanest case: $B \to \psi K_S$

- 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 a second weak phase strongly suppressed (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

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

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

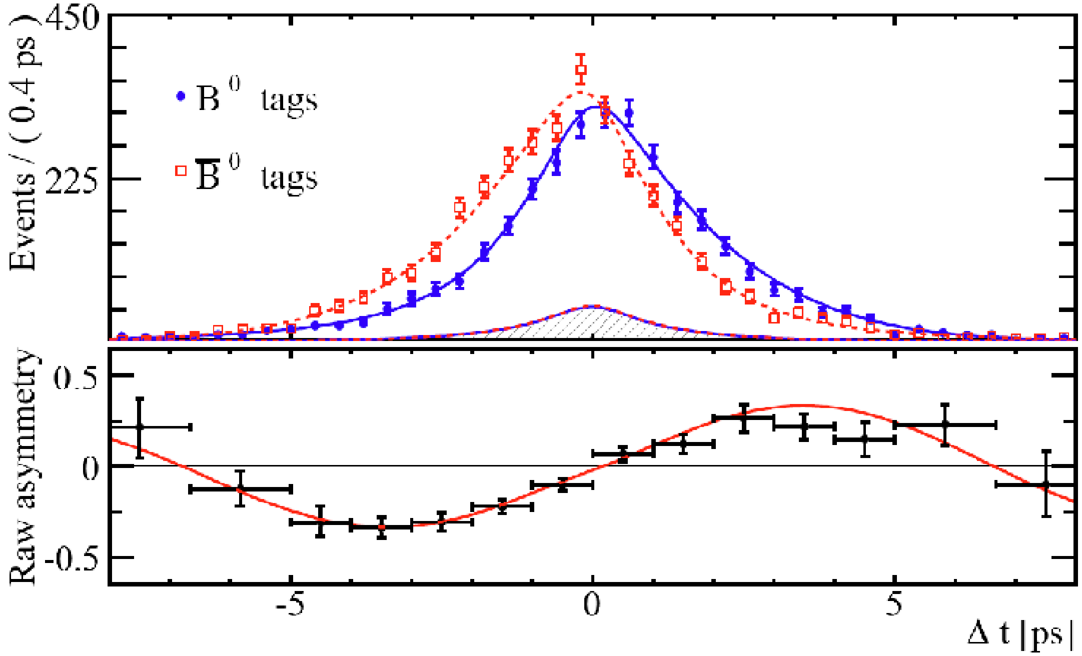
  all are few $\times 10^{-3} \Rightarrow$ accuracy $< 1\%$

- World average: $\sin 2\beta = 0.673 \pm 0.023$ — better than 4%!

- Large deviations from CKM excluded (e.g., approximate CP in the sense that all CPV phases are small) $\Rightarrow$ Look for corrections, rather than alternatives to CKM

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

- CP violation is an $\mathcal{O}(1)$ effect: $\sin 2\beta = 0.673 \pm 0.023$



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

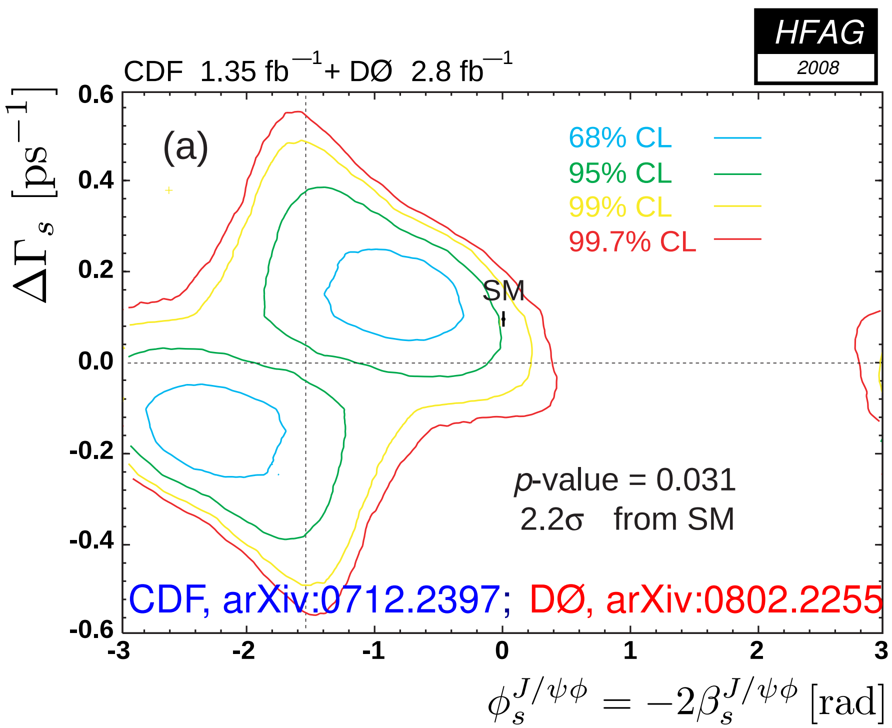
- CP violation is large in some B decays — in K decays it is small due to small CKM elements, not because CP violation is generically small

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

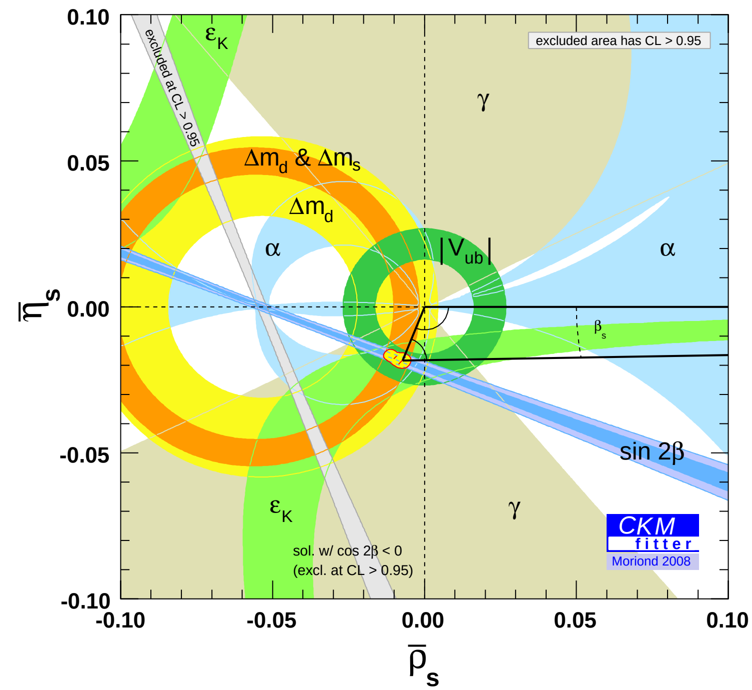
- Next key measurement: time dep. CP asymmetry in $B_s \to \psi\phi$ (analog of $\sin 2\beta$)

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

- CDF & DØ hints at possible deviation:



The B_s "squashed" UT:



- No big change in results at ICHEP, no combination yet ⇒ key LHCb measurement

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

- Measuring same angle in decays sensitive to different short distance physics may give best sensitivity to NP

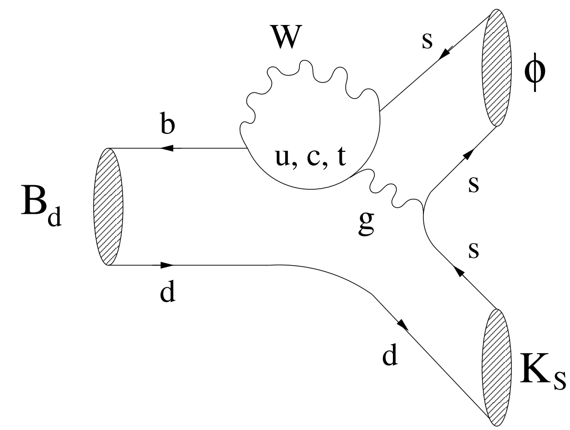
Amplitudes with one weak phase expected to dominate:

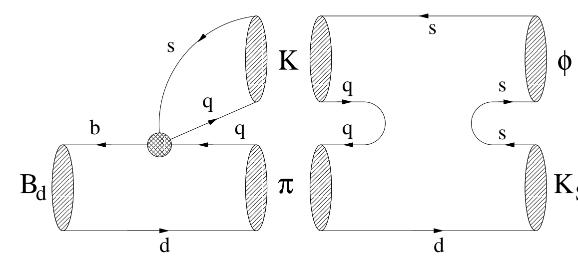
$$\overline{A} = \underbrace{V_{cb}V_{cs}^*}_{\mathcal{O}(\lambda^2)} \underbrace{[P_c - P_t + T_c]}_{\text{“1”}} + \underbrace{V_{ub}V_{us}^*}_{\mathcal{O}(\lambda^4)} \underbrace{[P_u - P_t + T_u]}_{\mathcal{O}(1)}$$

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

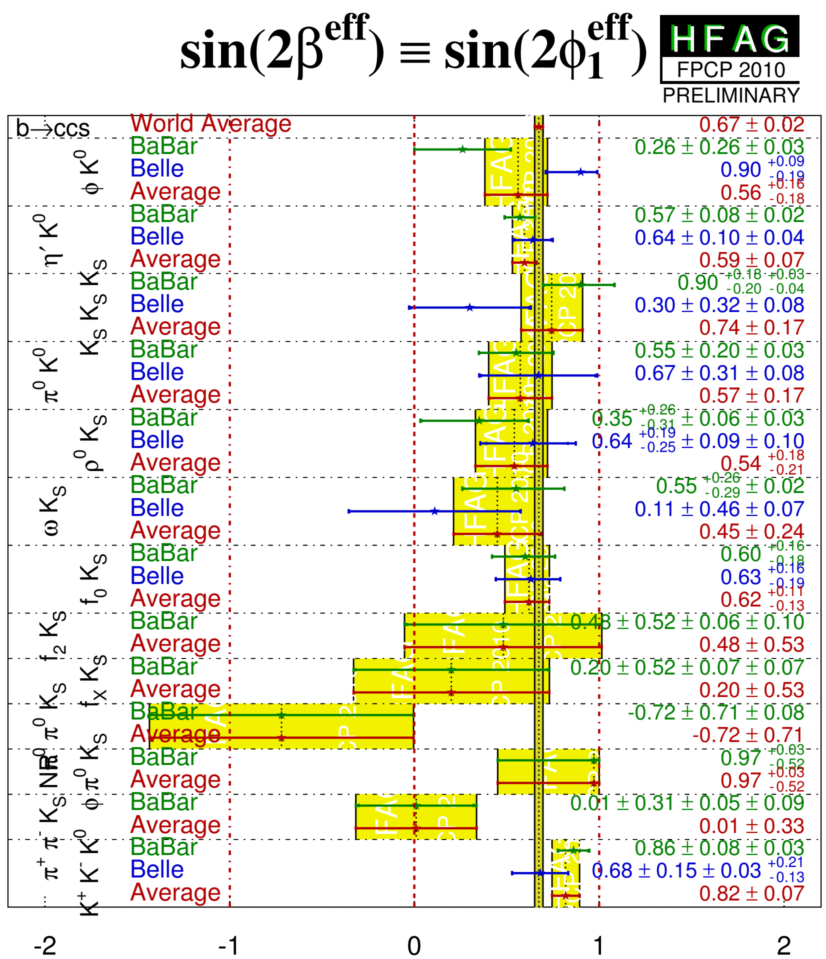


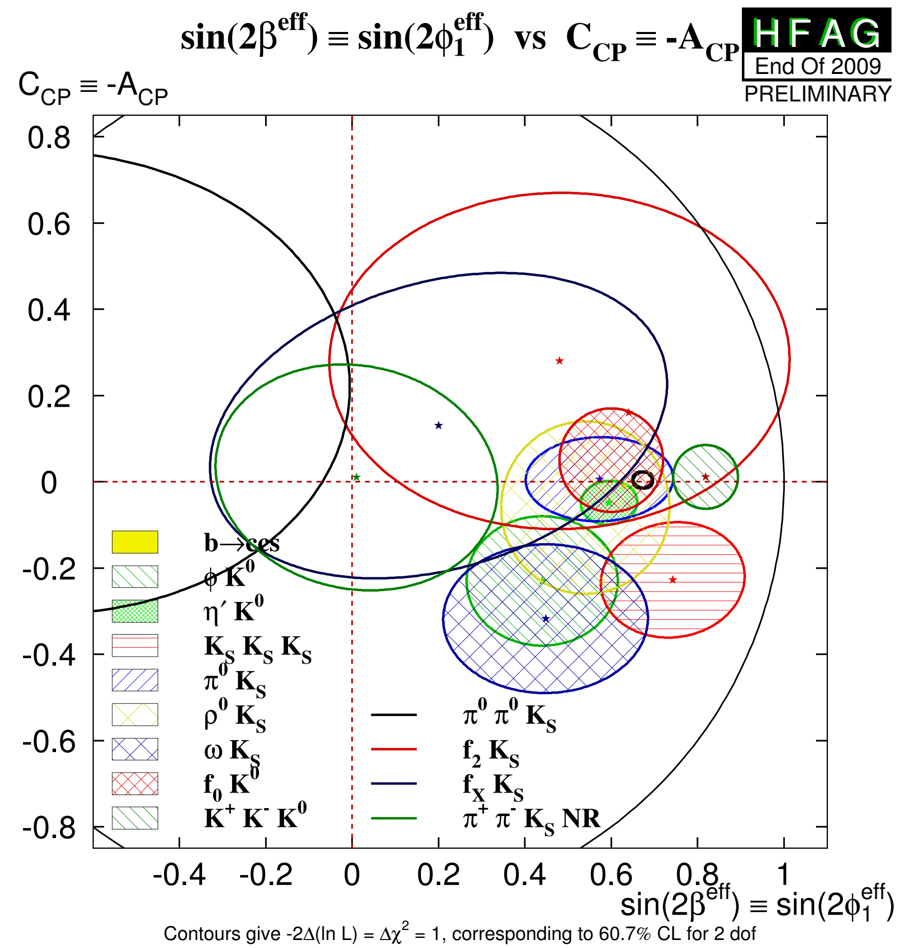


NP could enter $S_{\psi K}$ mainly in mixing, while $S_{\phi K_S}$ through both mixing and decay

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

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





- Earlier hints of deviations reduced, e.g., $S_{\psi K} - S_{\phi K_S} = 0.11 \pm 0.17$

It is still interesting to significantly reduce these experimental uncertainties

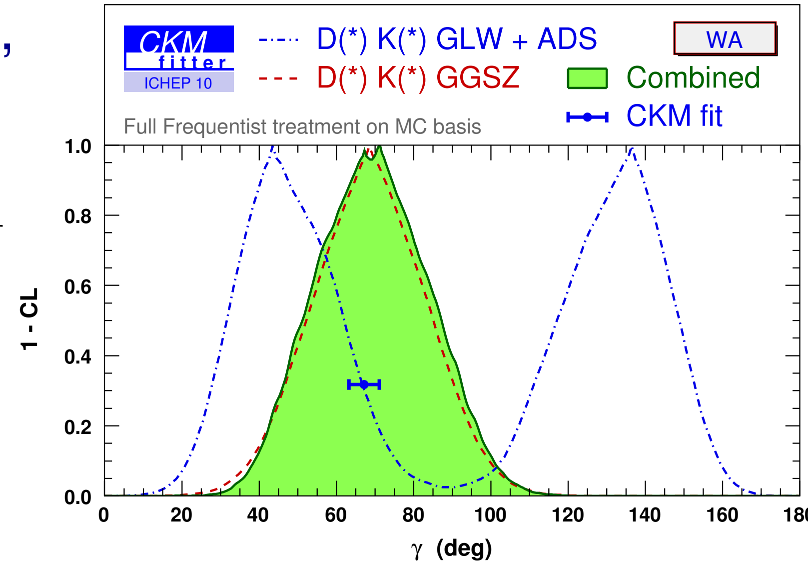
γ from $B^\pm \to DK^\pm$

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

  Extract B & D decay amplitudes from data; many variants depending on D decay

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

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



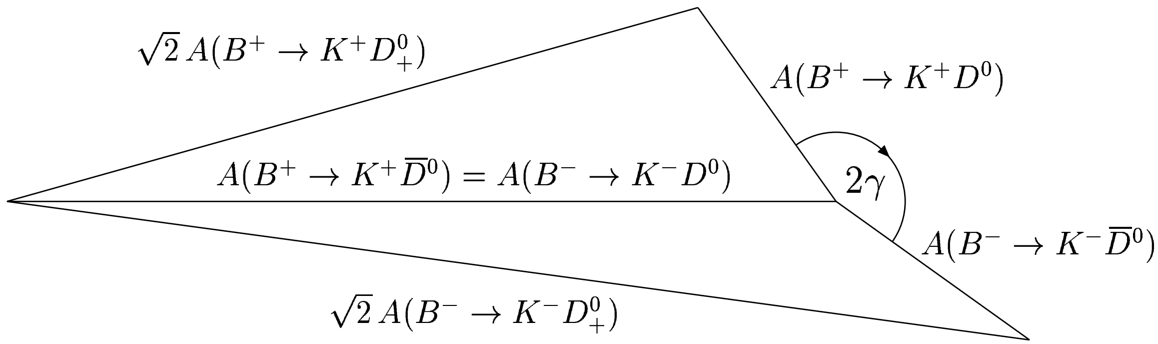
- Best measurement so far: $D^0, \overline{D}^0 \to K_S\,\pi^+\pi^-$
  - Both amplitudes Cabibbo allowed;
  - Can integrate over regions in Dalitz plot

  More data: besides reducing error of γ, test/refine the D decay model

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

γ: some other methods

- $B^\pm \to K^\pm D$ [GLW]: theoretically very clean, experimentally hard



(only assumes no CPV in D sector)

$$\frac{|A(B^+ \to K^+ D^0)|}{|A(B^+ \to K^+ \overline{D}{}^0|} \sim \frac{\lambda}{N_c}$$

- $B^\pm \to K^\pm (D^0, \overline{D}{}^0) \to K^\pm f$ [ADS] (f can be two- or multy-body)

Idea: $B^+ \to K^+ \overline{D}{}^0 \to K^+ f$ doubly Cabibbo suppressed } comparable amplitudes

$B^+ \to K^+ D^0 \to K^+ f$ Cabibbo allowed

Using n different $B \to D K X_i$ decays and k different $D \to f_j$ states, $n+k$ unknown amplitudes and $n \times k$ observables; or measure $D \to f$ amplitudes separately

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 $\Rightarrow$ 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 $\Rightarrow$ no hadronic uncertainty:

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

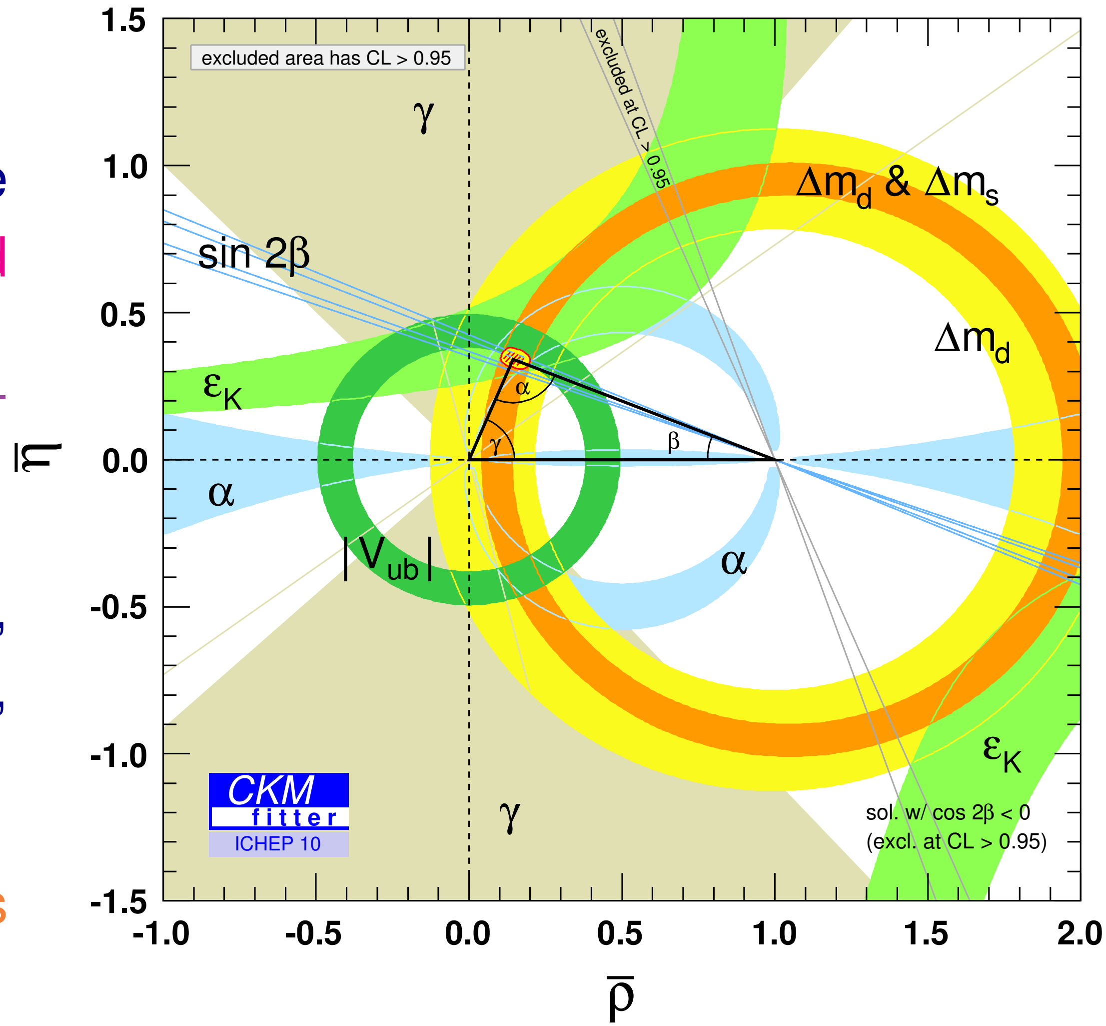
- Similarly, $B_d \to D^{(*)\pm}\pi^\mp$ determines $\gamma + 2\beta$, since $\lambda_{D^+\pi^-}\,\lambda_{D^-\pi^+} = e^{-2i(\gamma+2\beta)}$

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

Constraining new physics

The standard model CKM fit

- Very impressive accomplishments
- 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}, $A_{\rm SL}^{d,s}$, $\Delta\Gamma_s$

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}, $A_{\rm SL}^{d,s}$, $\Delta\Gamma_s$

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

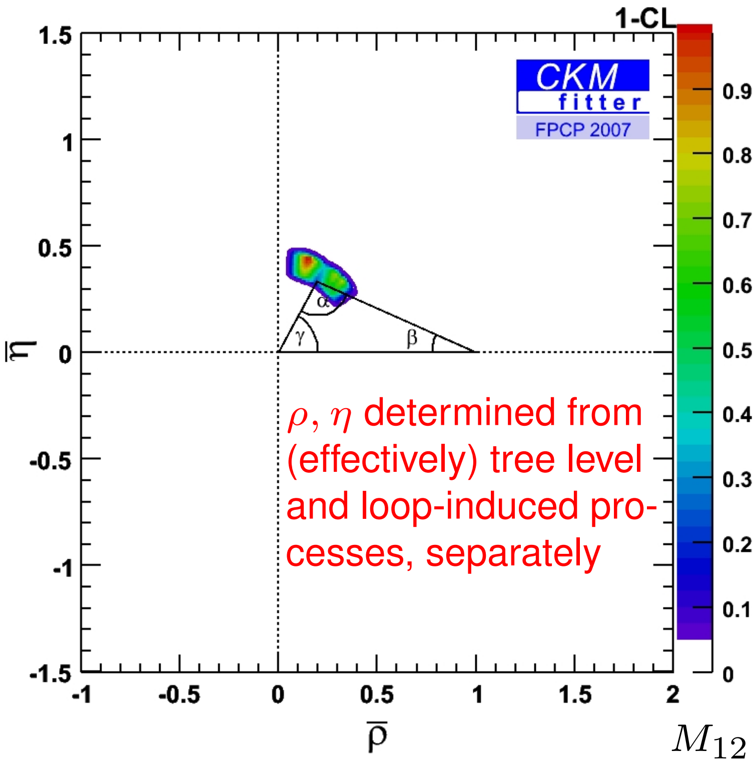
$$S_{\psi K} = \sin(2\beta + 2\theta_d) = \sin[2\beta + \arg(1 + h_d e^{2i\sigma_d})] \qquad S_{\rho\rho} = \sin(2\alpha - 2\theta_d)$$

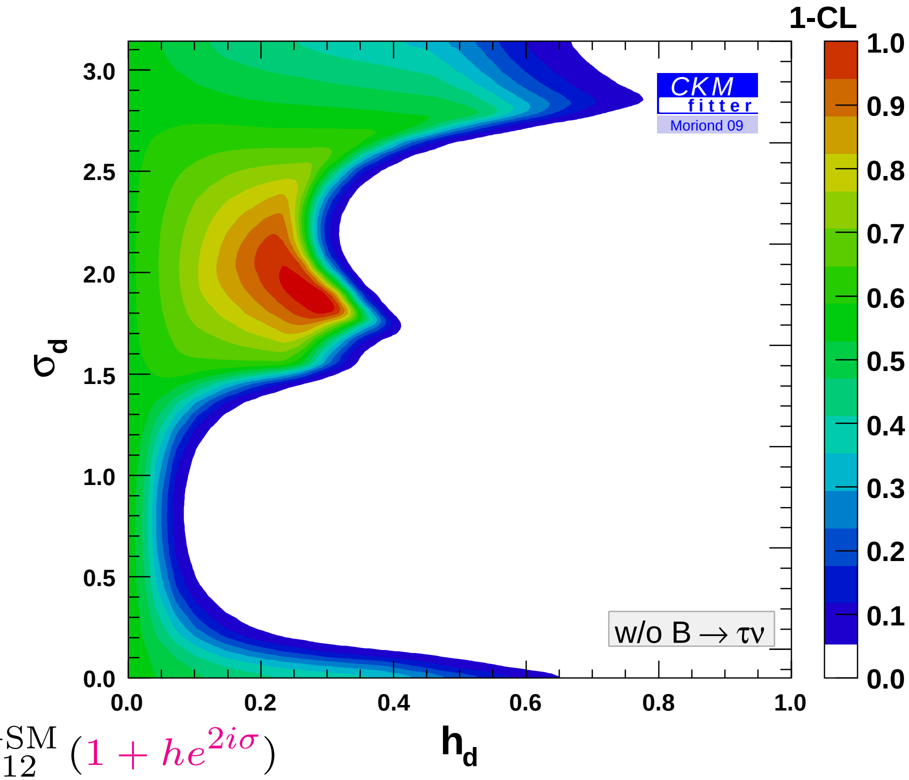
$$S_{\psi\phi} = \sin(2\beta_s - 2\theta_s) = \sin[2\beta_s - \arg(1 + h_s e^{2i\sigma_s})]$$

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

Constraints on new physics in B_d^0 mixing

- Overconstraining measurements (tree vs. loop) are crucial to bound new physics





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

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

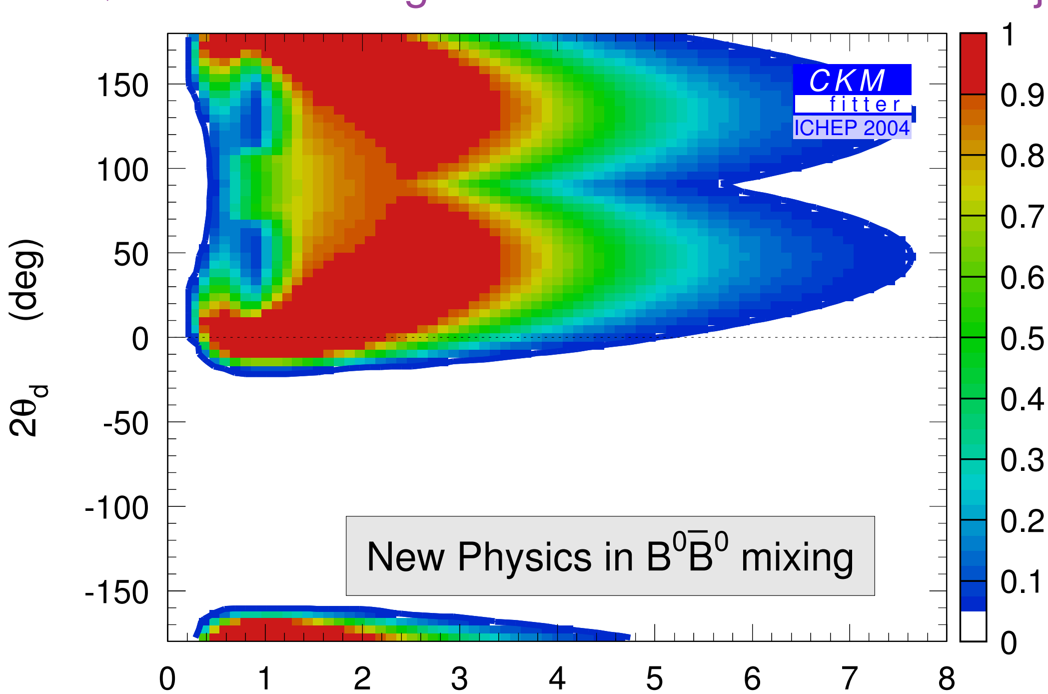
NP ∼ SM is still allowed, approaching NP ≪ SM unless $\sigma_d = 0 \pmod{\pi/2}$

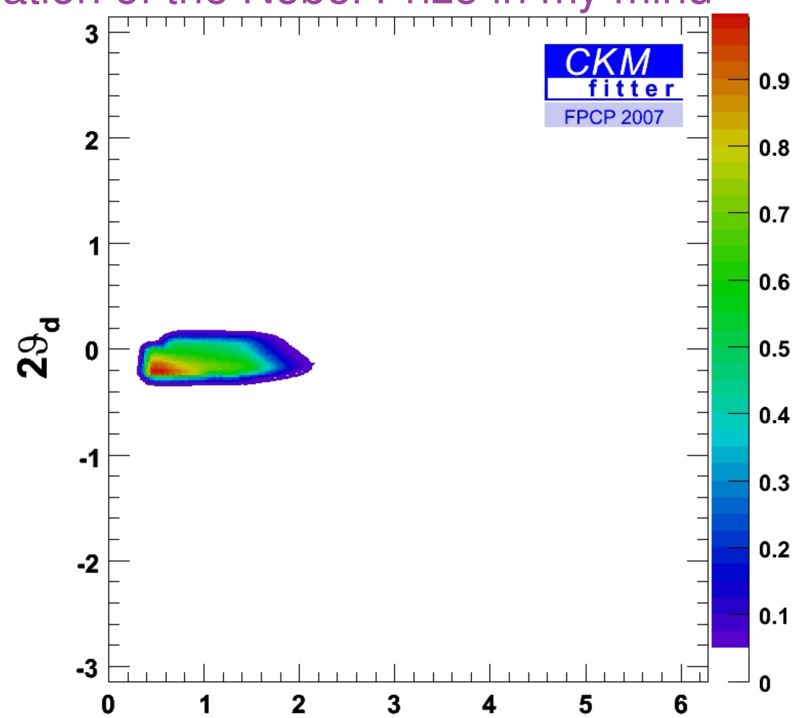
- What we really want to know: assume $h \sim (4\pi v/\Lambda_{\rm flav.})^2$, is then $\Lambda_{\rm flav.} \gg \Lambda_{\rm EWSB}$?

The one-page summary of BaBar & Belle

- Strong constraints on NP in many FCNC amplitudes — much more progress in this and more interesting than just the uncertainties of the SM parameters

Qualitative change before vs. after 2004 — the justification of the Nobel Prize in my mind





$$M_{12} = M_{12}^{\rm SM}\,(r_d\, e^{2i\theta_d}) = M_{12}^{\rm SM}\,(1 + h_d\, e^{2i\sigma_d})$$

- Despite huge progress $\sim 20\%$ NP contribution to most loop processes still allowed

Summary

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

- The point is not just to measure magnitudes and phases of CKM elements (or ρ, η and α, β, γ), but to probe the flavor sector by overconstraining it in many ways

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

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

- Few hints of discrepancies — existing data could have shown NP, and a lot more is needed to achieve theoretical limits