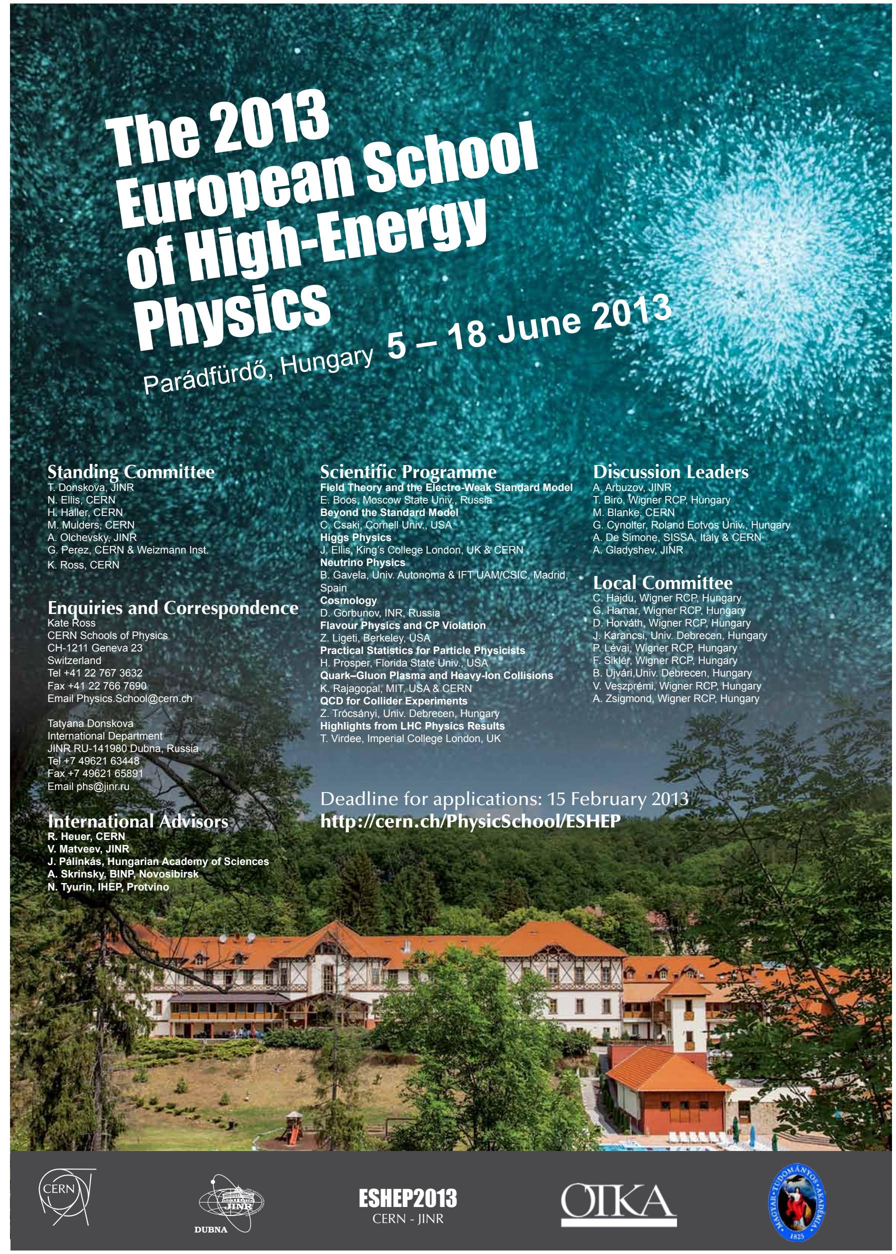
Flavor Physics and CP Violation

Zoltan Ligeti

(ligeti@lbl.gov)

Lawrence Berkeley Laboratory



Parádfürdő, Hungary, June 5–18, 2013

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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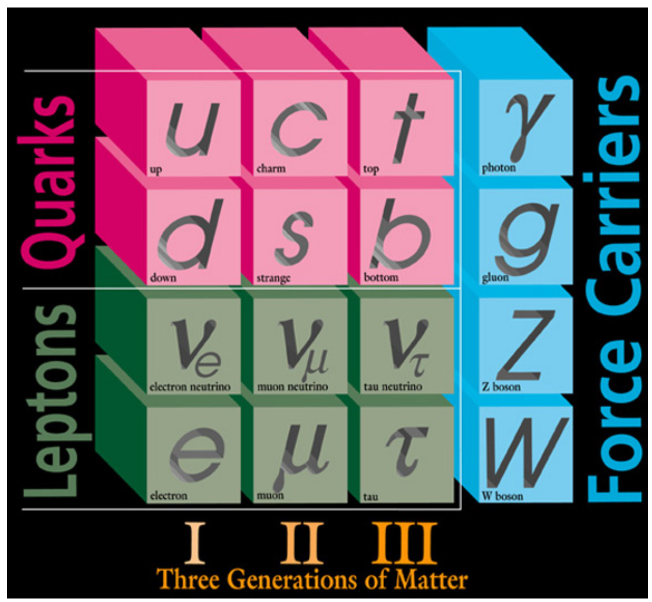

What is particle physics?

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

Maybe at the TeV scale?

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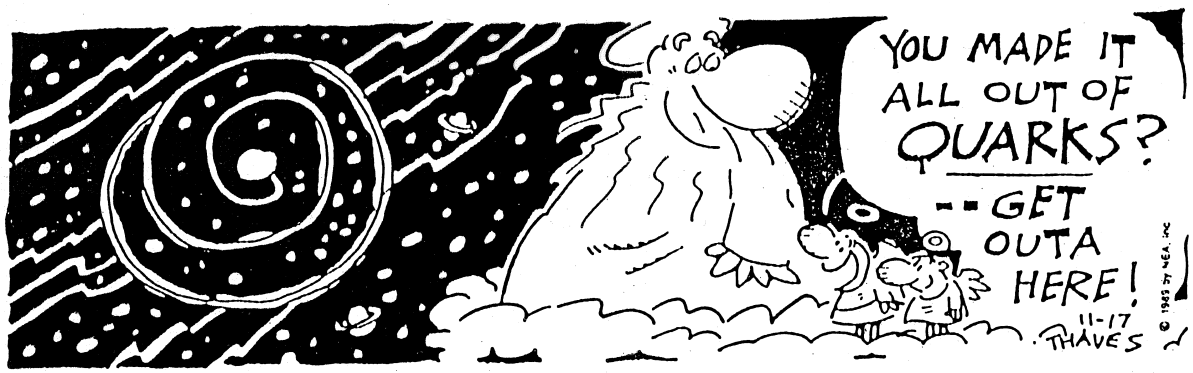
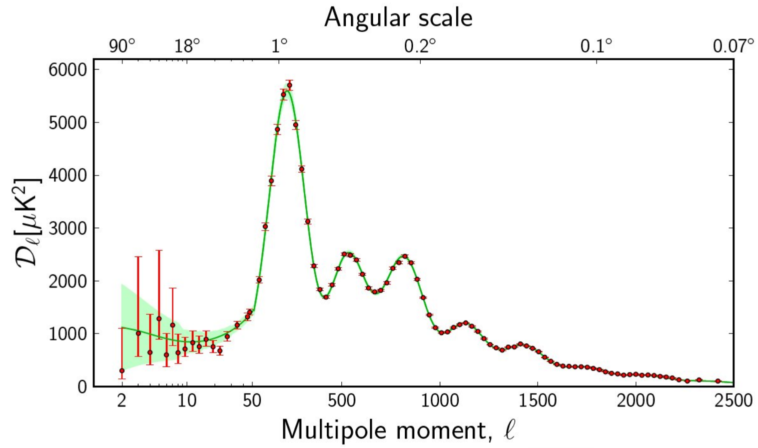
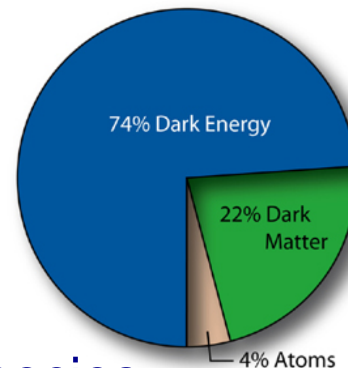
The Universe: what is dark matter?

- Homogeneous, isotropic, spatially flat, expanding





- Dark matter: rotation curves, gravitational lensing, cosmology



- DM cannot be a SM particle:

  Know: non-baryonic, long lived, neutral, abundance

  Don't know: interactions, mass, quantum numbers, one/many species

- Maybe thermal relic of early universe: weakly interacting massive particle (WIMP)

  If so, WIMP mass has to be around the TeV scale — LHC may directly produce it

The Universe: matter vs. antimatter

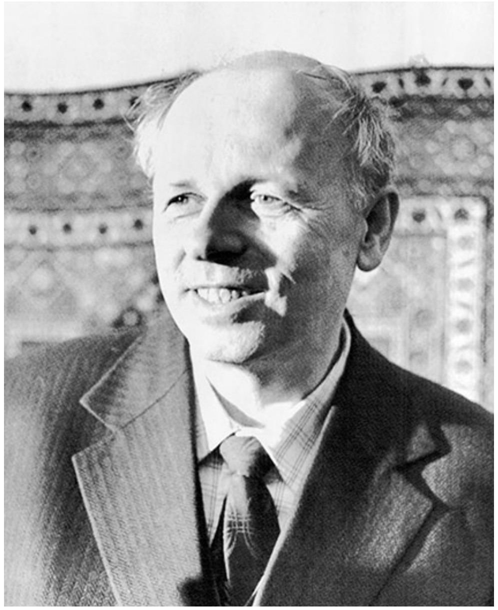
- Gravity, electromagnetism, strong interaction are same for matter and antimatter
- Soon after the big bang, quarks and anti-quarks were in thermal equilibrium

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

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

- The SM prediction is $\sim 10^{10}$ times smaller
- Solution may lie at the TeV scale, and the LHC may shed light on it

The matter–antimatter asymmetry



- How could the asymmetry be generated dynamically?
- 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 electroweak phase transition

  New TeV-scale physics can enhance both (supersymmetry, 4th generation, etc.)
- What is the microscopic theory of CP violation? How precisely can we test it?

What is flavor physics?

- Flavor physics (quarks) $\equiv$ what breaks $U(3)_Q \times U(3)_u \times U(3)_d \to U(1)_{\text{Baryon}}$
- SM flavor problem: hierarchy of masses and mixing angles
- NP flavor problem: TeV scale (hierarchy problem) $\ll$ flavor & CPV scale

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

  – Most TeV-scale new physics models have new sources of CP and flavor violation, which may be observable in flavor physics but not directly at the LHC

  – The observed baryon asymmetry of the Universe requires CPV beyond the SM (Not necessarily in flavor changing processes, nor necessarily in quark sector)

- Flavor sector will be tested a lot better, many NP models have observable effects

[Going from: NP $\lesssim$ (few $\times$ SM) $\to$ NP $\lesssim$ $(0.3 \times$ SM$)$ $\to$ NP $\lesssim$ $(0.05 \times$ SM$)$]

Outline (1)

- ~~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 and neutral meson mixing

  The K and D meson systems

- Clean information from B physics

  Constraining new physics in mixing

Outline (2–3)

- Heavy quark symmetry and OPE

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

  Rare decays, $B \to X_s\gamma$, and friends

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

- Nonleptonic decays, factorization

  B decays to final states with & without charm

- Flavor symmetries and new physics

- Lepton flavor violation

- Flavor physics at high-p_T

  top FCNC, minimal flavor violation, SUSY flavor

- 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

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- 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

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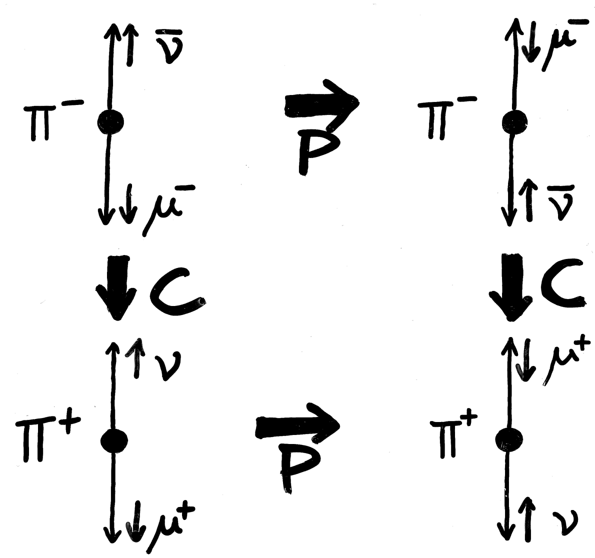
- Charge & angular momentum: 4 possibilities



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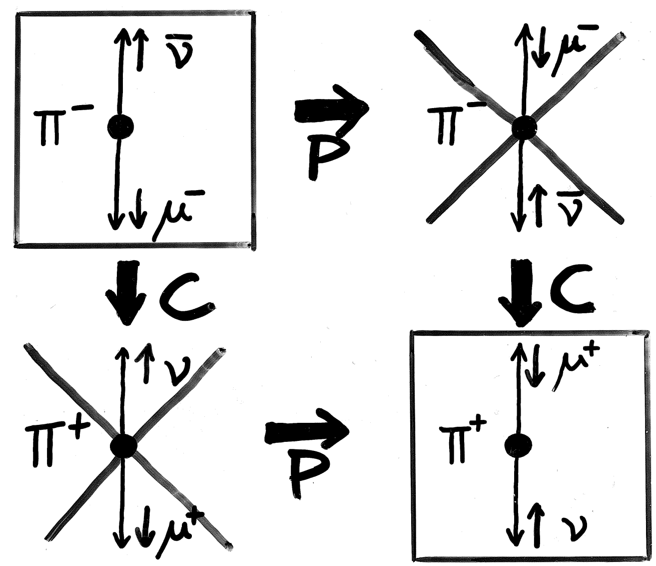
- Charge & angular momentum: 4 possibilities

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

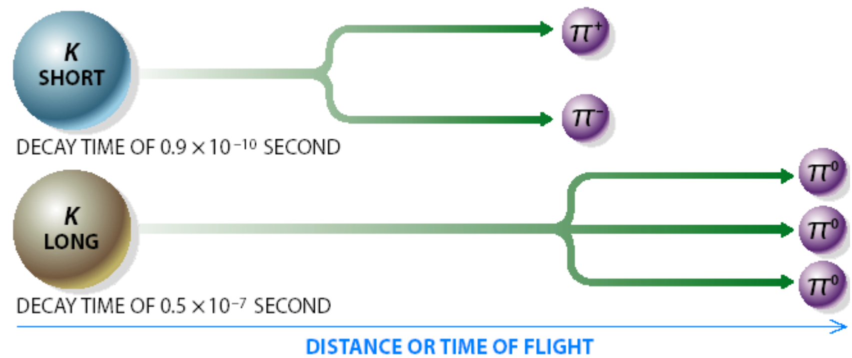
  Weak interactions maximally violate C and P

- However, CP could still be a good symmetry



1964: CP symmetry is also 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.

⇒ Cronin & Fitch, Nobel Prize, 1980

⇒ 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 are present $\Rightarrow$ 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

  $L_L(1,2)_{-1/2},\ \ell_R(1,1)_{-1}$ — 3(+9)

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

  $\phi(1,2)_{1/2}$ Higgs scalar, $\langle\phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$ — 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: $p\,(uud),\ n\,(udd)$

SM: where can CP violation occur?

- 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 for one Higgs doublet; CPV constrains extended Higgs sector

- Yukawa couplings in interaction basis: (where flavor comes from)

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

$i, j \sim$ generations

(cannot write such mass term for ν_i)

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

- 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

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

From Yukawa couplings to CKM matrix

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

$$\mathcal{L}_Y = -Y_u^{ij}\,\overline{Q^I_{Li}}\,\widetilde{\phi}\,u^I_{Rj} - Y_d^{ij}\,\overline{Q^I_{Li}}\,\phi\,d^I_{Rj} \qquad \widetilde{\phi} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \phi^*$$

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

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

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

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

- 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: $\begin{pmatrix} u^I_{Li} \\ d^I_{Li} \end{pmatrix} = (V^\dagger_{uL})_{ij} \begin{pmatrix} u_{Lj} \\ (V_{uL}V^\dagger_{dL})_{jk}\,d_{Lk} \end{pmatrix}$

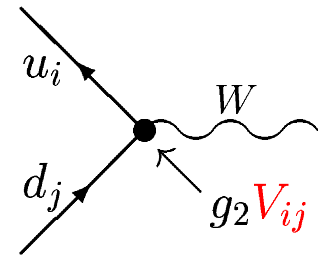
- Charged current weak interactions become off-diagonal: $\longleftrightarrow$ CKM matrix

$$-\frac{g}{2}\,\overline{Q^I_{Li}}\,\gamma^\mu\,W^a_\mu\,\tau^a\,Q^I_{Li} + \text{h.c.} \;\Rightarrow\; -\frac{g}{\sqrt{2}}\left(\overline{u_L},\,\overline{c_L},\,\overline{t_L}\right)\gamma^\mu\,W^+_\mu\,(V_{uL}V^\dagger_{dL}) \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$$

Weak interaction properties

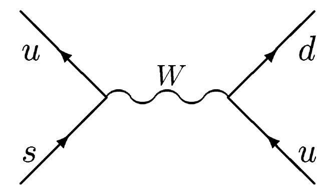
- Only the $W^\pm$ interactions change the type of quarks

  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

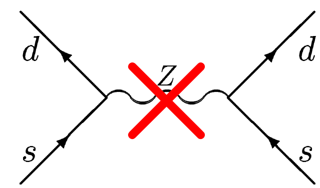
  e.g.: $K \to \pi\pi$ or $K \to \pi\ell\bar{\nu}$



  No flavor changing neutral currents (FCNC) at tree level

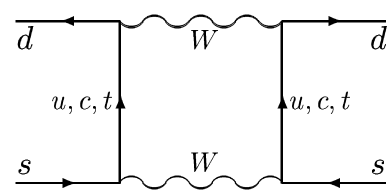
  e.g.: no $K^0 - \overline{K}^0$ mixing, $K \to \mu^+\mu^-$, etc.

  (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

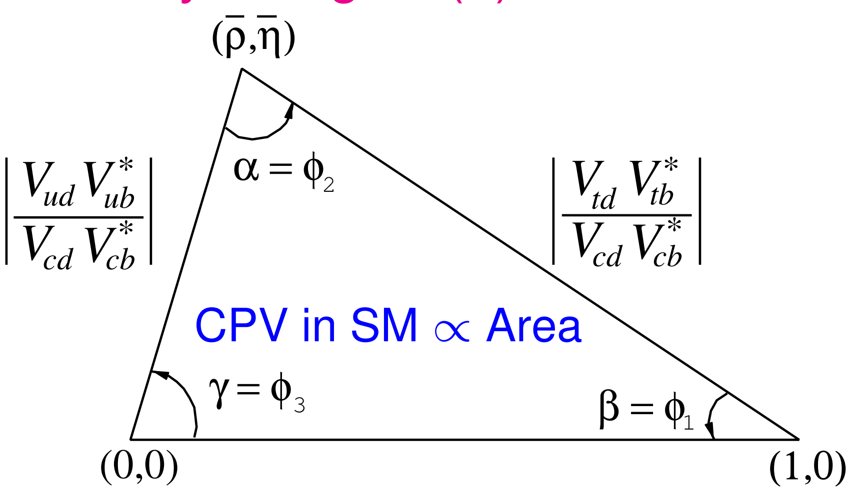
- The $(u,\ c,\ t)\ W^{\pm}\ (d,\ s,\ b)$ couplings: (Wolfenstein parm., $\lambda \sim 0.23$)

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

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

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

$$[36 \text{ couplings in } Y_{u,d}] - [26 \text{ broken generators}] = 10 \text{ parameters with physical meaning}$$

$$= [6 \text{ masses}] + \overbrace{[3 \text{ angles}] + \underbrace{[1 \text{ phase}]}}^{\text{parameters in } V_{\rm CKM}}$$

Single source of CP violation in the quark sector in the SM

- Lepton sector (if 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

$$[30 \text{ couplings in } Y_{e,\nu}] - [18 \text{ broken generators}] = 12 \text{ parameters with physical meaning}$$

$$= [6 \text{ masses}] + [3 \text{ angles}] + \underbrace{[3 \text{ phases}]}$$

One CPV phase measurable in ν oscillations, others in $0\nu\beta\beta$ decay

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 using processes sensitive to different short-distance physics — if inconsistent $\Rightarrow$ NP

  Lincoln Wolfenstein: *'I do not care what the values of the Wolfenstein parameters are, so you should not either; the only thing that matters is if their independent determinations are consistent'*

- Combination of experimental feasibility and theoretical cleanliness is the key

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

Seeking indirect signals of NP

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

$$\frac{(\phi D^\mu \phi)^2}{\Lambda^2} \Rightarrow \Lambda > \text{few} \times 10^3\,\text{GeV}$$

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

$$\frac{QQQQ}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{(4\ldots7)}\,\text{GeV}$$

Flavor and custodial symmetry broken in SM already, so cannot forbid NP to generate these op's

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

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

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

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

Suggests very high scales (assuming $\mathcal{O}(1)$ couplings) — unless there are "sterile" neutrinos...

Testing the flavor sector

Spectacular track record

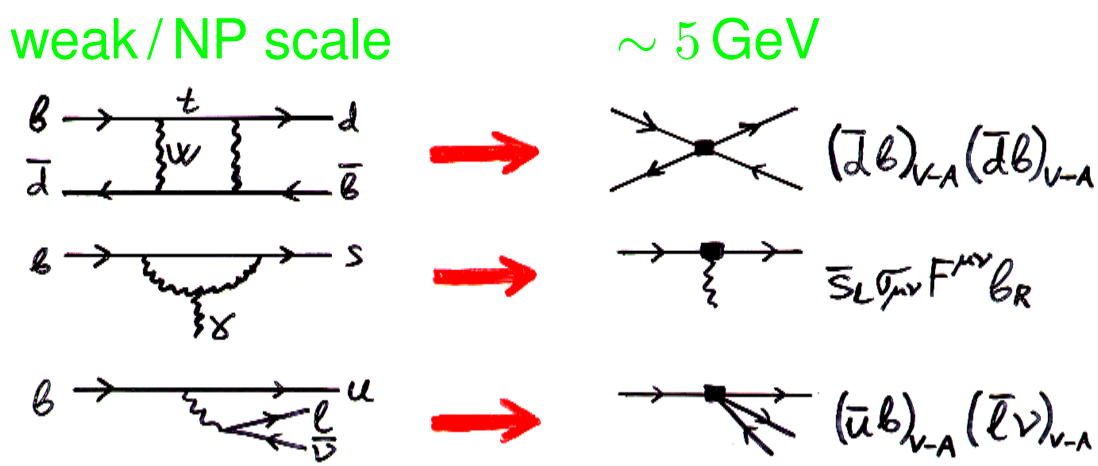
- Most parameters of the SM (and in many of its extensions) are related to flavor
- Flavor physics was crucial to figure out $\mathcal{L}_{\rm SM}$:
  - β-decay predicted neutrino (Pauli)
  - Absence of $K_L \to \mu\mu$ predicted charm (Glashow, Iliopoulos, Maiani)
  - ϵ_K predicted 3rd generation (Kobayashi & 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



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

Constraints on $\Delta F = 2$ operators

- Neutral meson mixings: dimension-6 operators, come with coefficients C/Λ^2
- If $\Lambda = \mathcal{O}(1\,\text{TeV})$ then $C \ll 1$; alternatively, if $C = \mathcal{O}(1)$ then $\Lambda \gg 1\,\text{TeV}$

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

- Large SM suppressions — excellent probes of NP

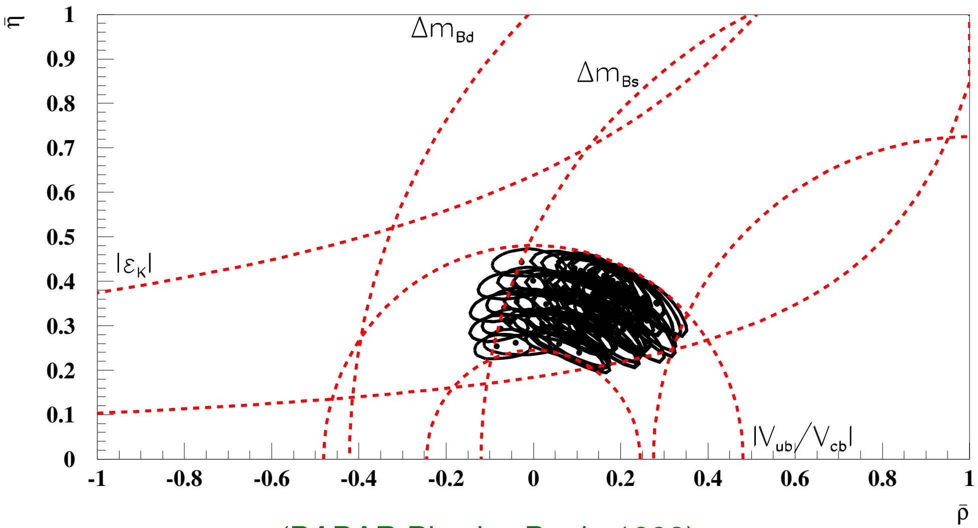
Important features of SM-flavor

- 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., $B \to K^*\gamma$)

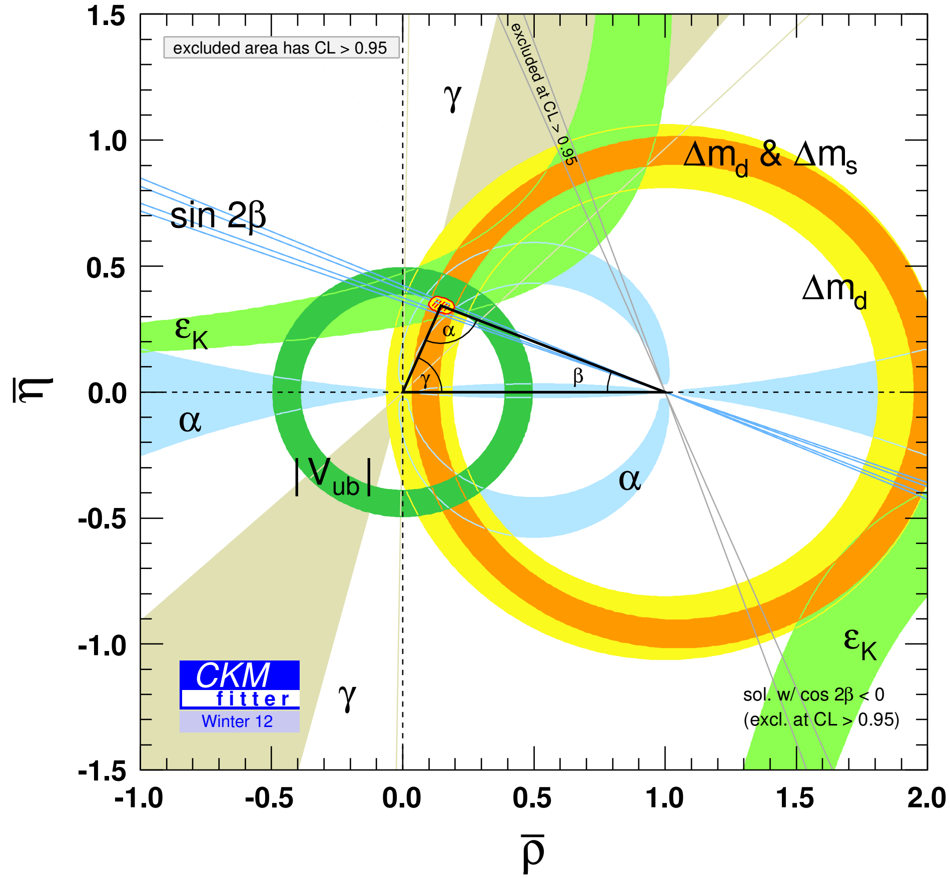
  Many suppressions that NP might not respect $\Rightarrow$ probe very high scales
- It is interesting and possible to look for NP contributions with better sensitivity

Brief history of CKM constraints

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



(BABAR Physics Book, 1998)



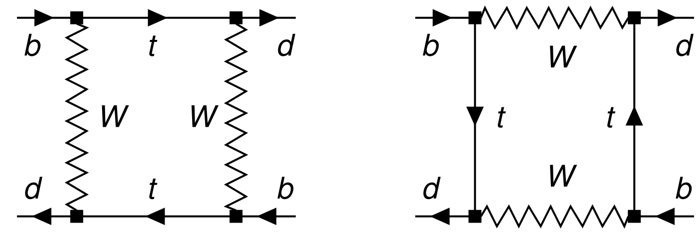
- CP vioaltion used to be interesting in itself; by now dozens of measurements

  $\Rightarrow$ In which cases can both theory and experiment be precise?

Mixing and CP violation

Neutral meson mixing

- Quantum mechanical two-level system; flavor eigenstates: $|B^0\rangle = |\overline{b}d\rangle,\ |\overline{B}^0\rangle = |b\overline{d}\rangle$
- 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 $\Gamma_{11} = \Gamma_{22}$)

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

- CP violation: $|q/p| \neq 1 \ \Leftrightarrow$ mass eigenstates $\neq CP$ eigenstates
- GIM mechanism: $M_{12} \propto \sum\limits_{i,j} V_{ib}V_{id}^*\,V_{jb}V_{jd}^*\,f(m_i, m_j) \to \dfrac{m_\alpha^2 - m_\beta^2}{m_W^2}$ suppression

  since m-independent terms in f cancel due to CKM unitarity
- Hadronic uncertainties in Δm (LQCD helps) and especially $|q/p|$, but not $\arg(q/p)$

Aside: time evolition

- If you like to calculate things, maybe derive (start with $\Delta\Gamma = 0$)

$$|B^0(t)\rangle = g_+(t)\,|B^0\rangle + \frac{q}{p}\,g_-(t)\,|\overline{B}^0\rangle$$

$$|\overline{B}^0(t)\rangle = \frac{p}{q}\,g_-(t)\,|B^0\rangle + g_+(t)\,|\overline{B}^0\rangle$$

$$g_+(t) = e^{-it(m-i\Gamma/2)}\left[\cosh\frac{\Delta\Gamma\,t}{4}\,\cos\frac{\Delta m\,t}{2} - i\sinh\frac{\Delta\Gamma\,t}{4}\,\sin\frac{\Delta m\,t}{2}\right]$$

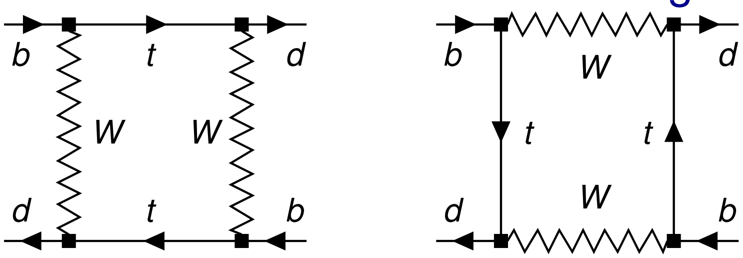
$$g_-(t) = e^{-it(m-i\Gamma/2)}\left[-\sinh\frac{\Delta\Gamma\,t}{4}\,\cos\frac{\Delta m\,t}{2} + i\cosh\frac{\Delta\Gamma\,t}{4}\,\sin\frac{\Delta m\,t}{2}\right]$$

(We defined $\Delta m > 0$, but the sign of $\Delta\Gamma$ is physical)

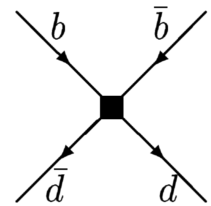
Aside: Effective Hamiltonians (M_{12} in B mixing)

- Interactions at high scale (weak or new physics) produce local operators at lower scales (hadron masses) — mixing dominated by intermediate top quarks

SM contributions to $B^0 - \overline{B}^0$ 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 $\alpha_s^n \ln^n(m_W/\mu)$ is often very important $(\mu \sim m_b)$

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

The four neutral mesons

- Physical observables: $x = \Delta m/\Gamma$, $y = \Delta\Gamma/(2\Gamma)$, $|q/p| - 1$

  Order of magnitudes of SM predictions:

meson	x	y	$\|q/p\| - 1$
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: $\dfrac{q^2}{p^2} = \dfrac{2M_{12}^* - i\Gamma_{12}^*}{2M_{12} - i\Gamma_{12}}$

  [CP violation in mixing $\leftrightarrow \mathrm{Im}(\Gamma_{12}/M_{12}) \neq 0$]

- In the absence of CP violation: $\Delta m = 2|M_{12}|$, $\Delta\Gamma = 2|\Gamma_{12}|$

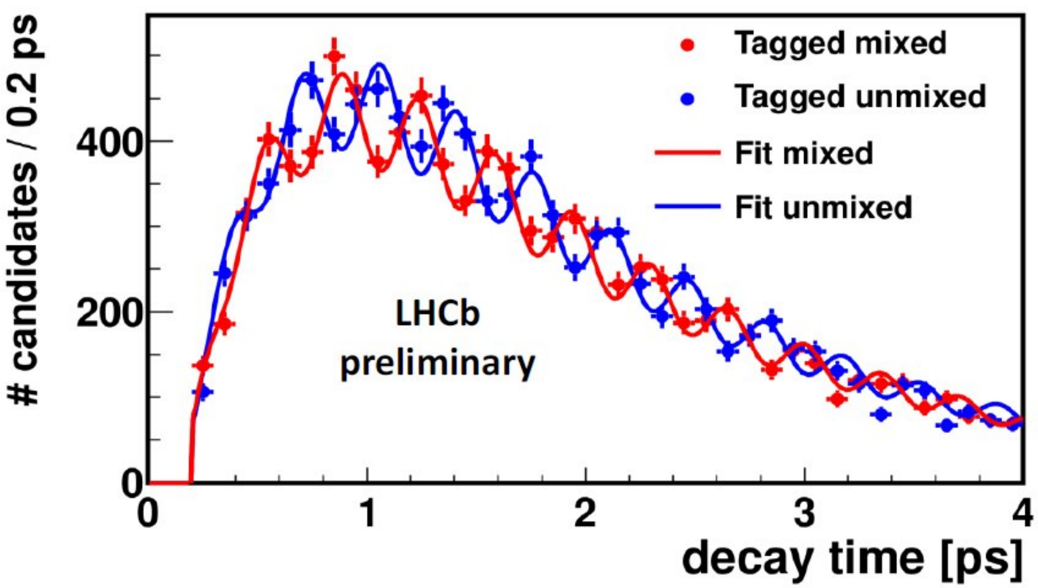
- If $|M_{12}| \gg |\Gamma_{12}|$, valid for B_d and B_s mixing:

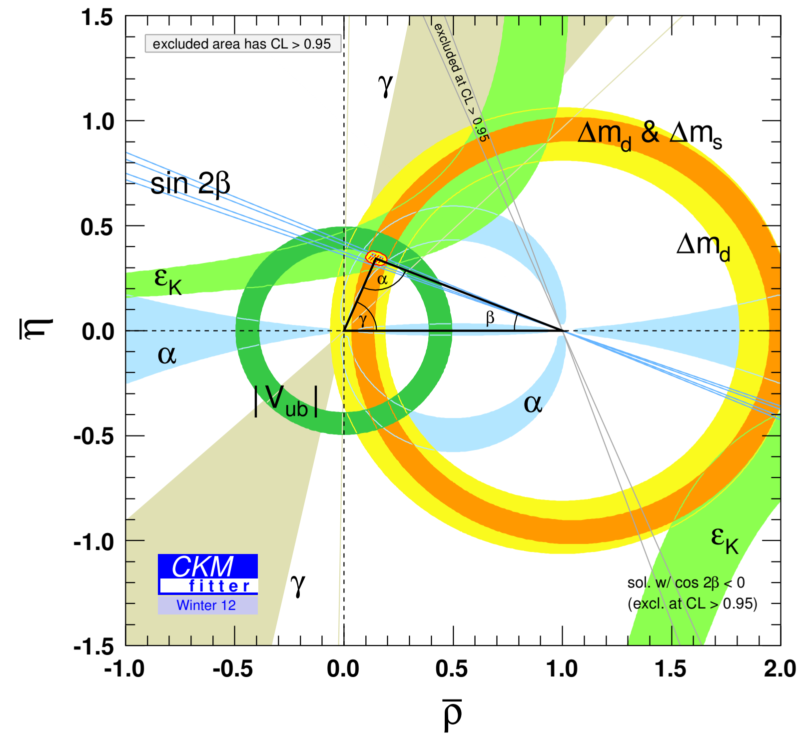
$$\Delta m = 2|M_{12}|, \quad \Delta\Gamma = 2|\Gamma_{12}| \cos\phi_{12}, \quad \phi_{12} = \arg(-M_{12}/\Gamma_{12})$$

$q/p =$ pure phase — a key to allow 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)





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

- 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: $\xi = 1.24 \pm 0.03 \pm 0.02$

Types of CP violation

- CP violation: $\Gamma(A \to B) \neq \Gamma(\bar{A} \to \bar{B})$

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

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

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

  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 $\epsilon'_K \neq 0$ in 1999, and since 2004 also in B decays

  Theoretical understanding for ϵ'_K, $A_{K^-\pi^+}$, etc., insufficient to either prove or to rule out that NP enters — still, ϵ'_K is a very strong constraint on NP

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

CPV in mixing

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

  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")

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

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

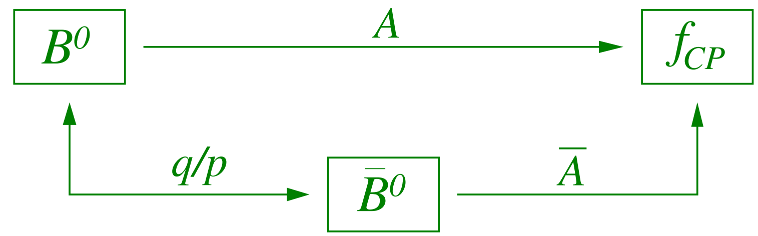
- Large hadronic uncertainties in calculation of Γ_{12}, but interesting to look for NP:

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

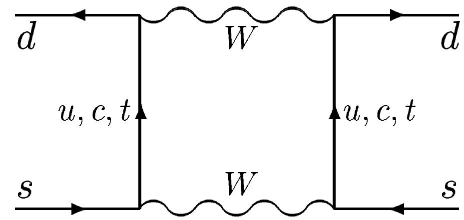
$$a_{f_{CP}} = \eta_{f_{CP}} \sin(\text{phase difference between decay paths}) \sin(\Delta m\, t)$$

Bits of K and D physics

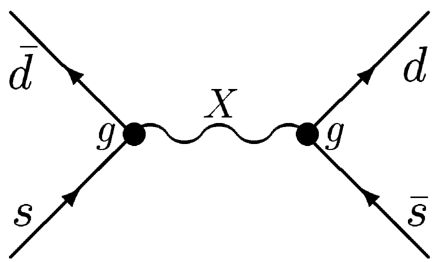
Δm_K — built in NP models since 60's

- 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



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

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

- 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)

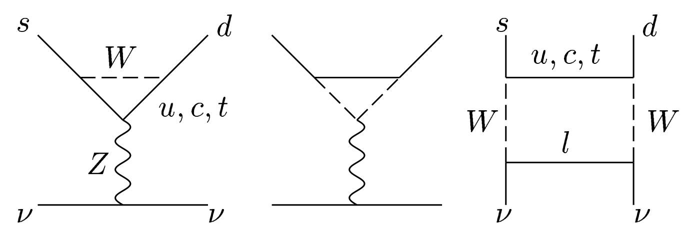
Precision CKM tests with kaons

- 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 $10^{-10}\,(K^\pm)$, $10^{-11}\,(K_L)$

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



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

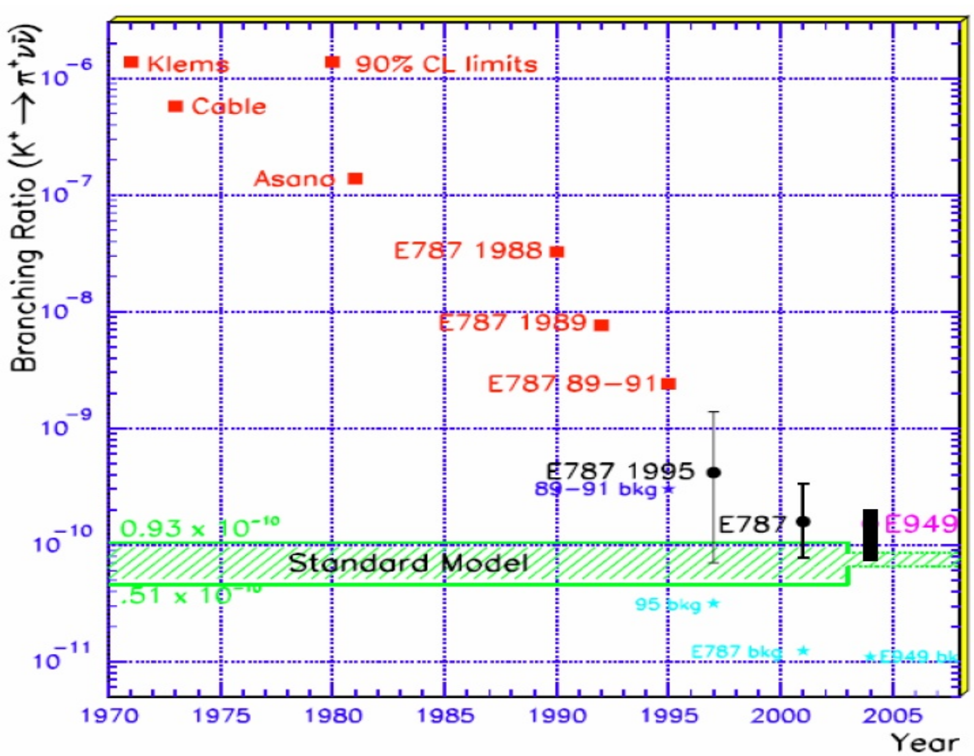
- $\Rightarrow$ Need much more data to achieve ultimate sensitivity

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

- Long history of ingenious experimental progress (huge backgrounds)

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

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



CERN NA62: 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 $K_L^0 \to \pi^0\nu\bar{\nu}$

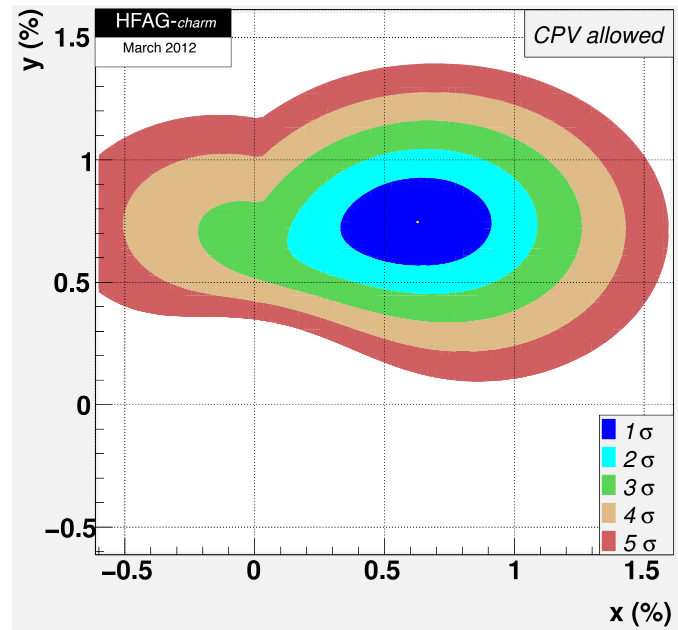
D^0: mixing in up sector

- 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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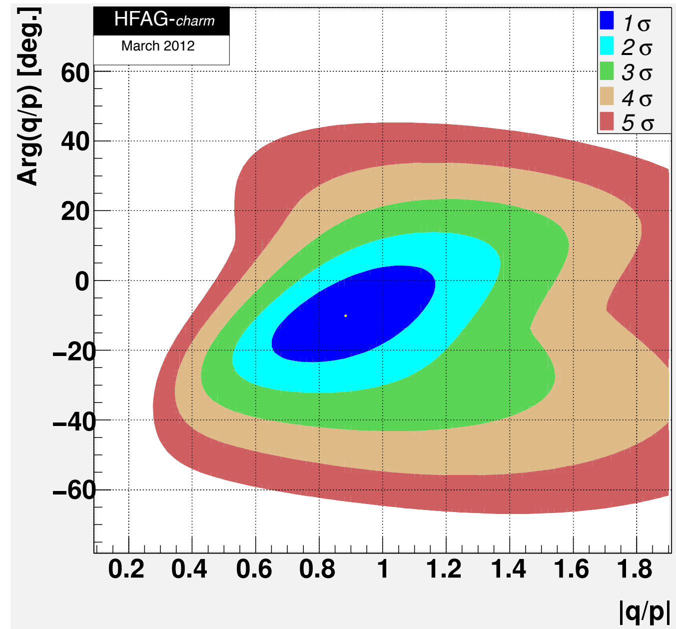


Don't known yet if $|q/p|$ is near 1!

- $y = (0.75 \pm 0.12)\%$ and $x = (0.63 \pm 0.20)\%$
  ... suggest long distance dominance

- 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

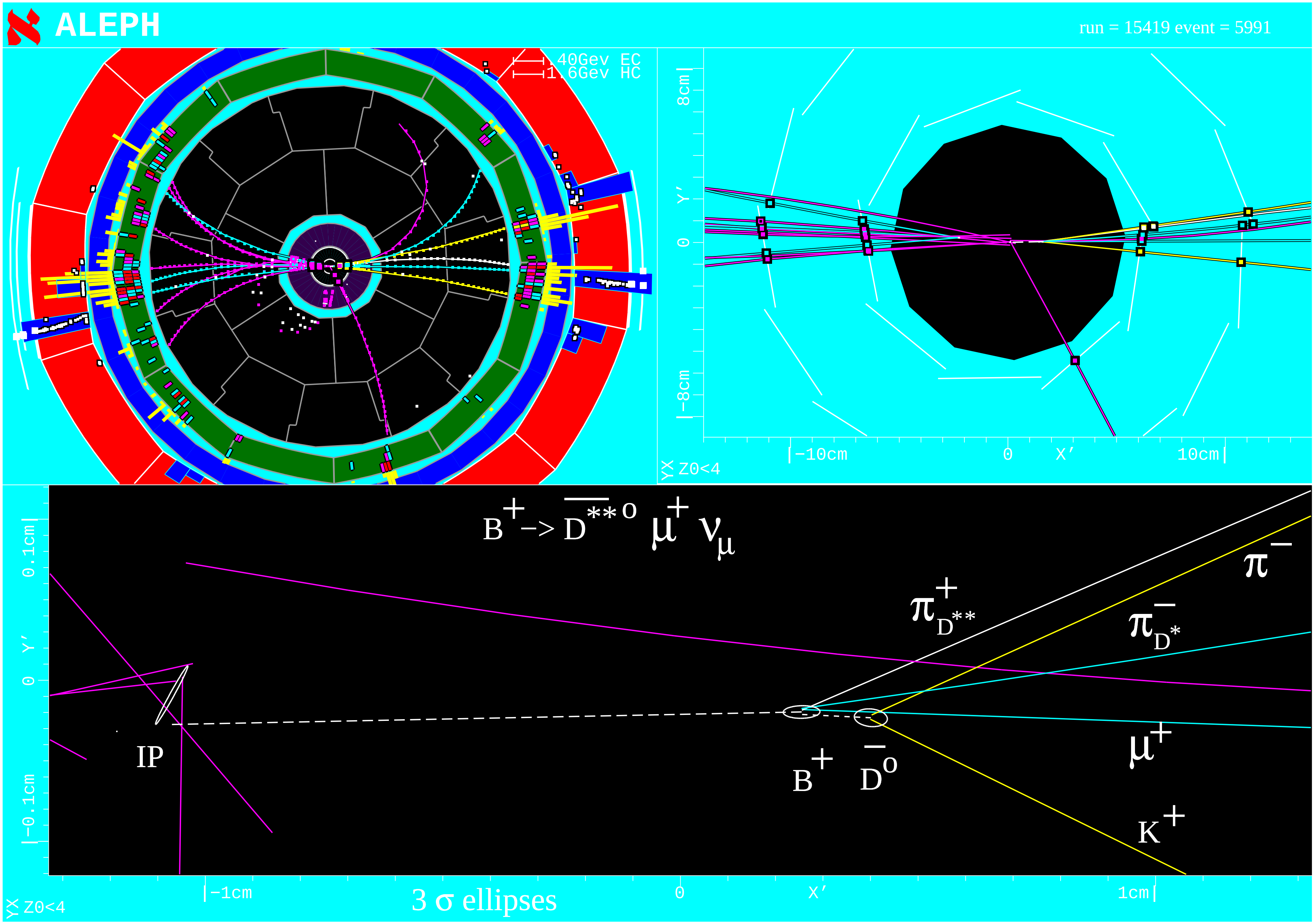
Looking for NP with B decays

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

    If $|V_{cb}|$ were as large as $|V_{us}|$, probably BaBar, Belle, LHCb would not have been built, these lectures would not take place, etc.
  - Timescale of oscillation and decay comparable: $\Delta m/\Gamma \simeq 0.77\, [= \mathcal{O}(1)]$ (and $\Delta\Gamma \ll \Gamma$)

You can "see" B decays

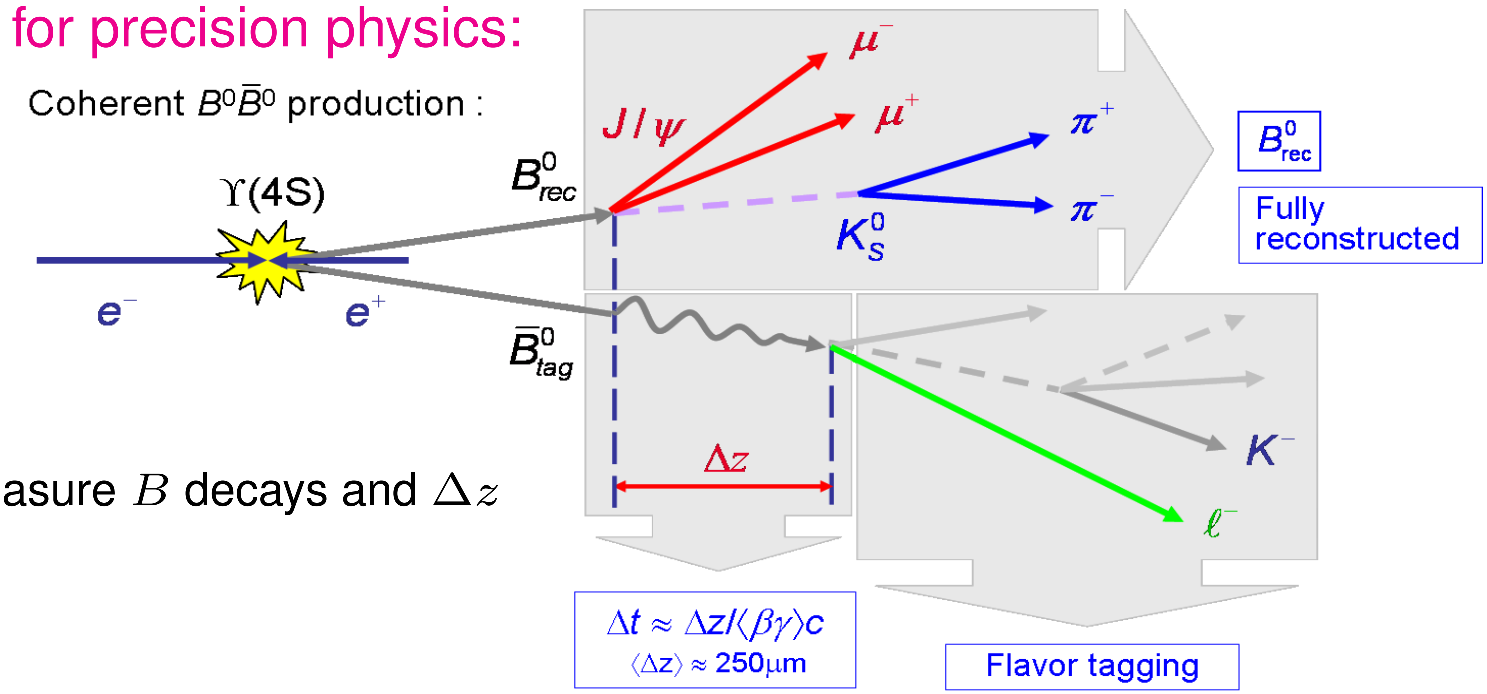


Quantum entanglement in $\Upsilon(4S) \to B^0\overline{B}^0$

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

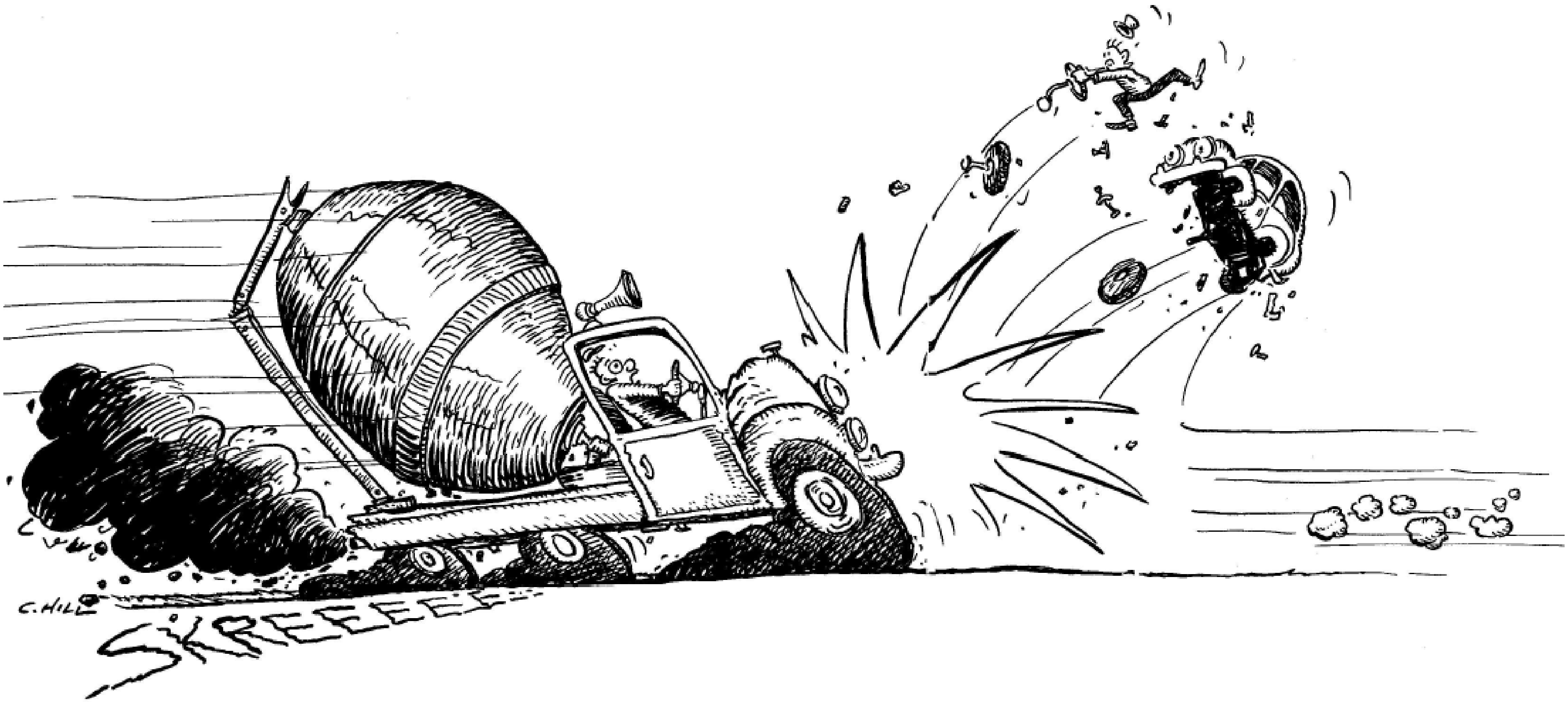
- EPR effect used for precision physics:



Measure B decays and Δz

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

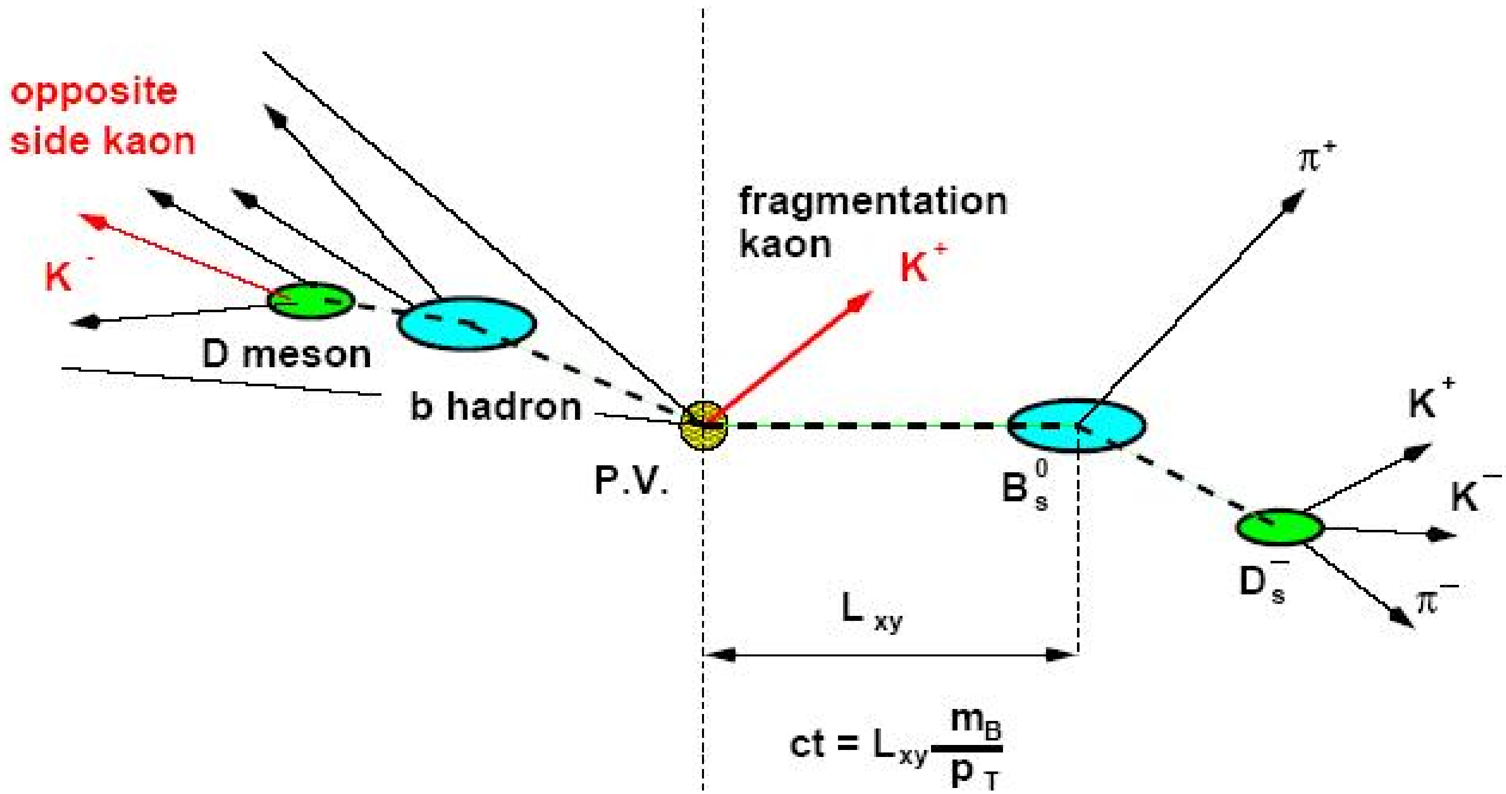
Asymmetric colliders



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

Hadron colliders — no quantum correlation

- 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

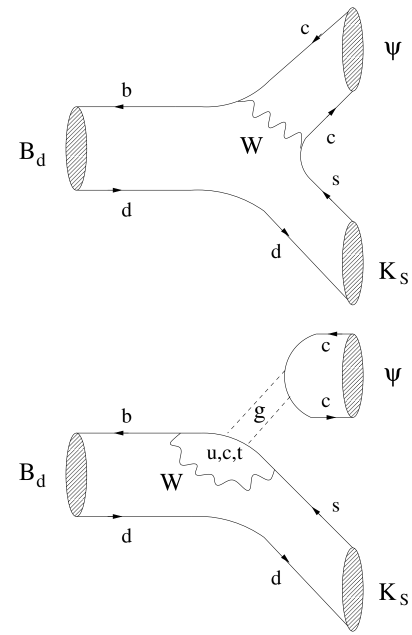
The cleanest case: $B \to \psi K_S$

- 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 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), $\epsilon_K \neq 0$, $\Delta\Gamma_B \neq 0$

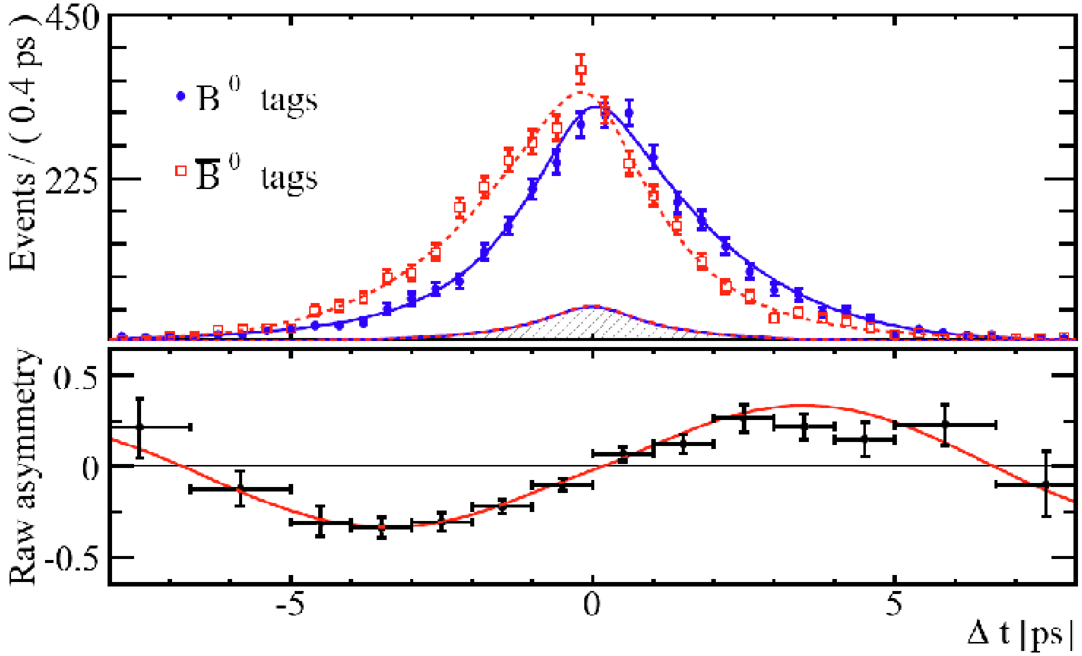
  all are few $\times 10^{-3}$ $\Rightarrow$ accuracy $< 1\%$

- 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 $B \to J/\psi\, K_S$ by the naked eye

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



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

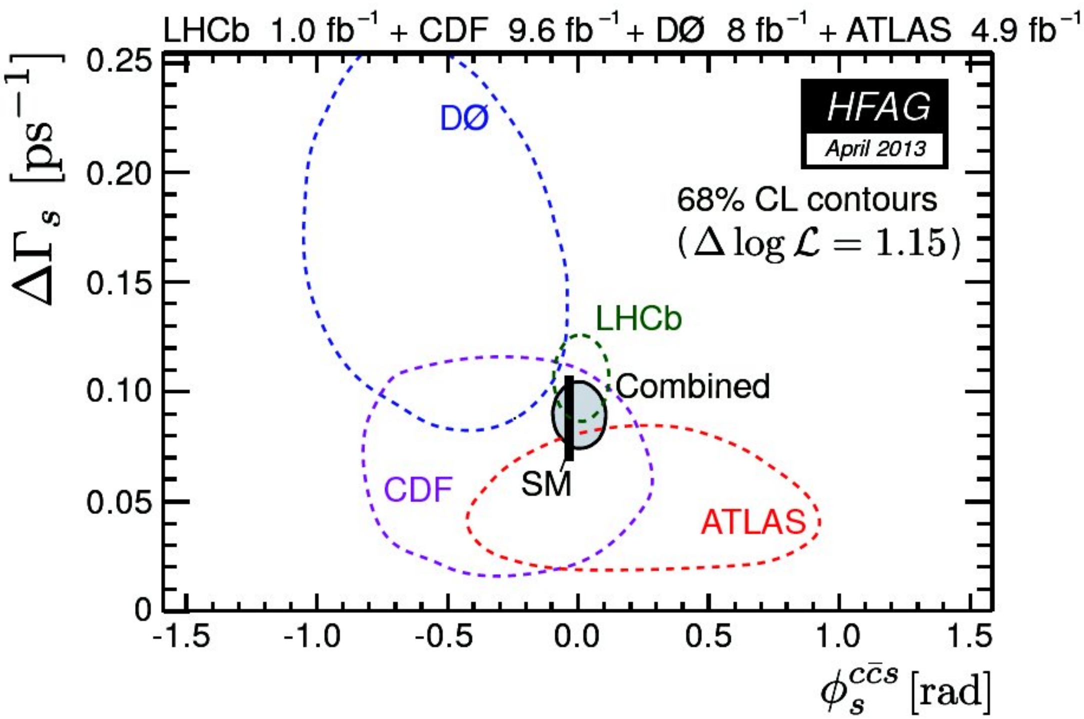
- CP violation is large in some B decays — in K decays it is small due to small CKM elements, not because CP violation is generically small

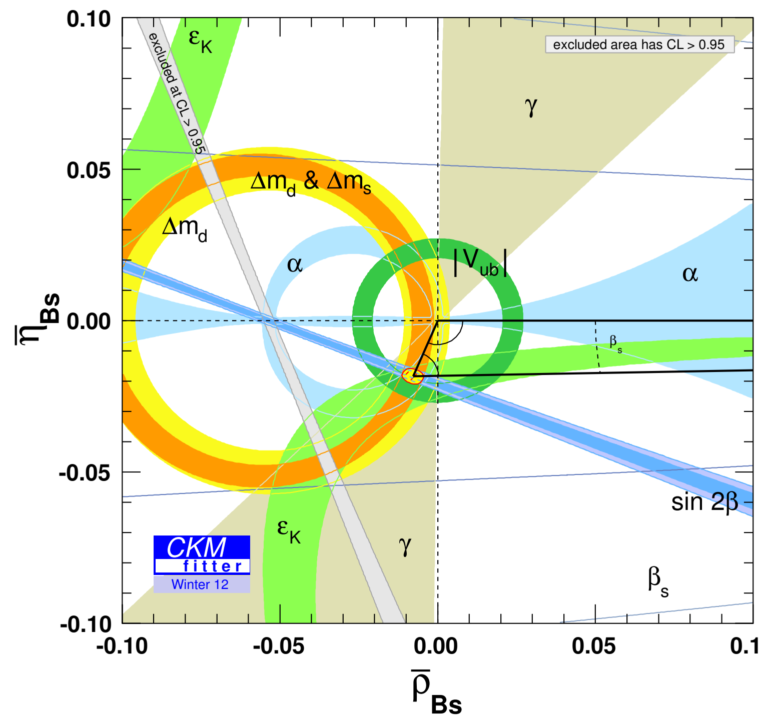
Similarly: β_s from $B_s \to \psi\phi$

- Analog in $B \to \psi K$: time dependent CP asymmetry in $B_s \to \psi\phi$

  In SM: $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) = 0.019 \pm 0.001$ (λ^2 suppressed compared to β)

- LHCb 2013: $\phi_s \equiv -2\beta_s = 0.01 \pm 0.07$ The B_s “squashed” UT:



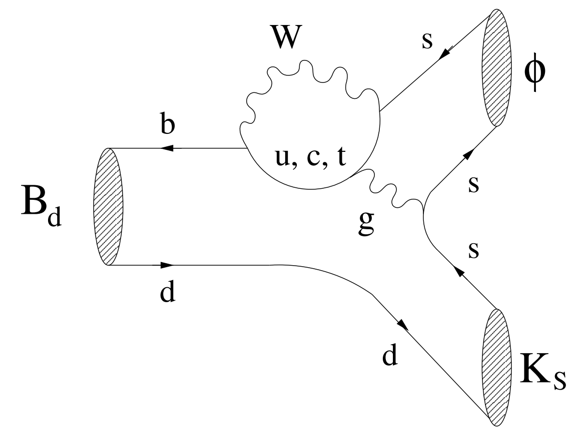


- Uncertainty of the SM prediction $\ll$ current experimental error ($\Rightarrow$ LHCb upgrade)

$B \to \phi K$ 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)

Amplitudes with one weak phase expected to dominate:

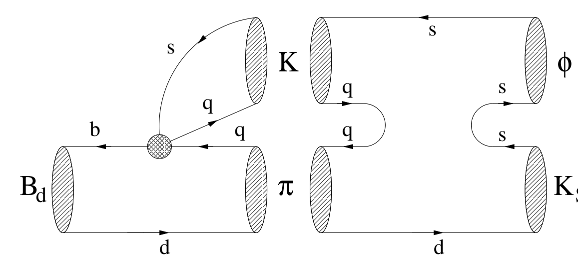


$$\overline{A} = \underbrace{V_{cb}V_{cs}^*}_{\mathcal{O}(\lambda^2)} \underbrace{[P_c - P_t + T_c]}_{\text{“1”}} + \underbrace{V_{ub}V_{us}^*}_{\mathcal{O}(\lambda^4)} \underbrace{[P_u - P_t + T_u]}_{\mathcal{O}(1)}$$

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

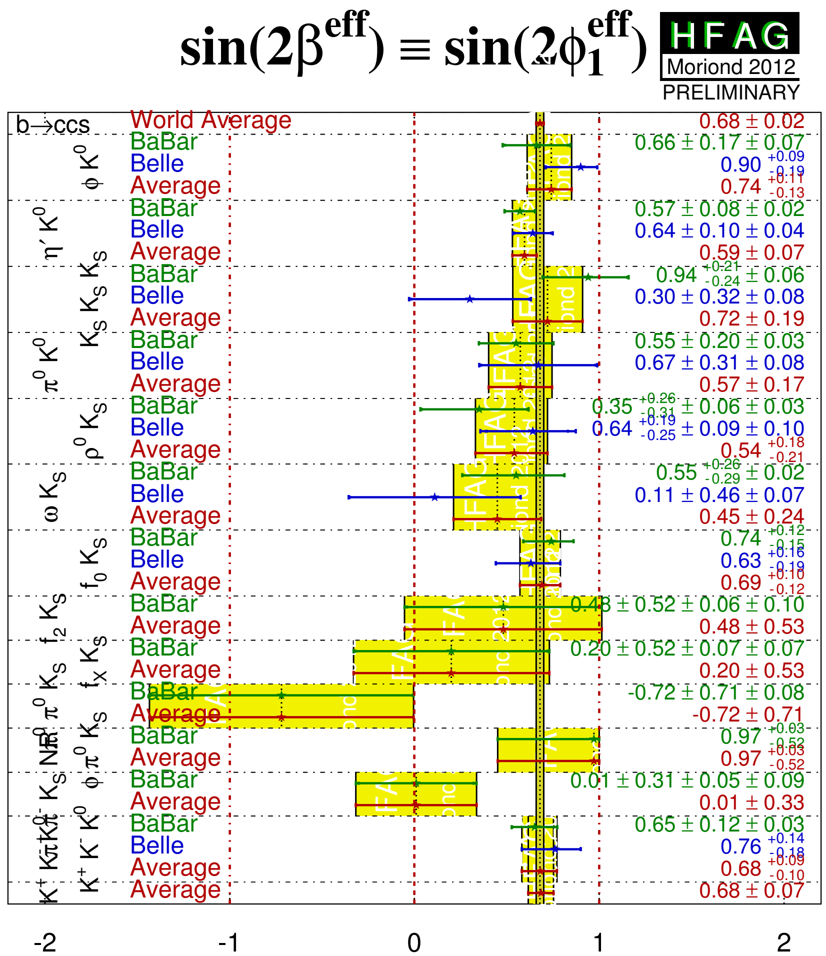
Expect different S_f for each $b \to s$ mode

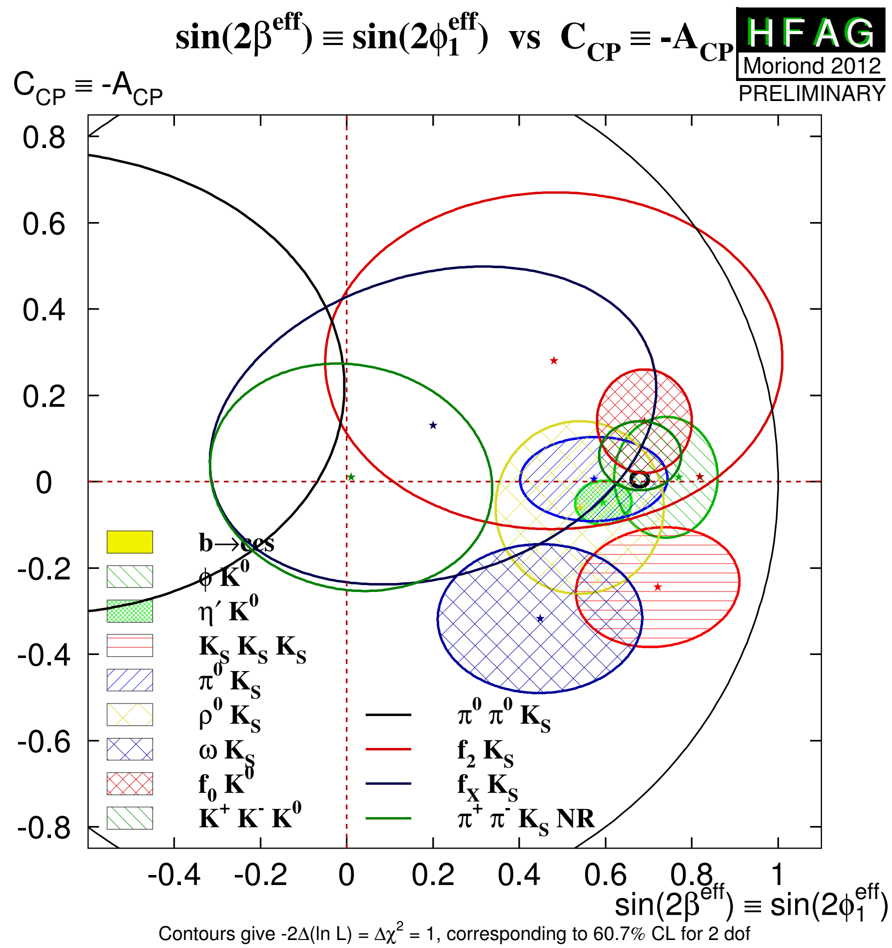


NP could enter $S_{\psi K}$ mainly in mixing, while $S_{\phi K_S}$ through both mixing and decay

- 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., in $S_{\phi K}$ and $S_{\eta' K}$

It is still interesting to significantly reduce these experimental uncertainties

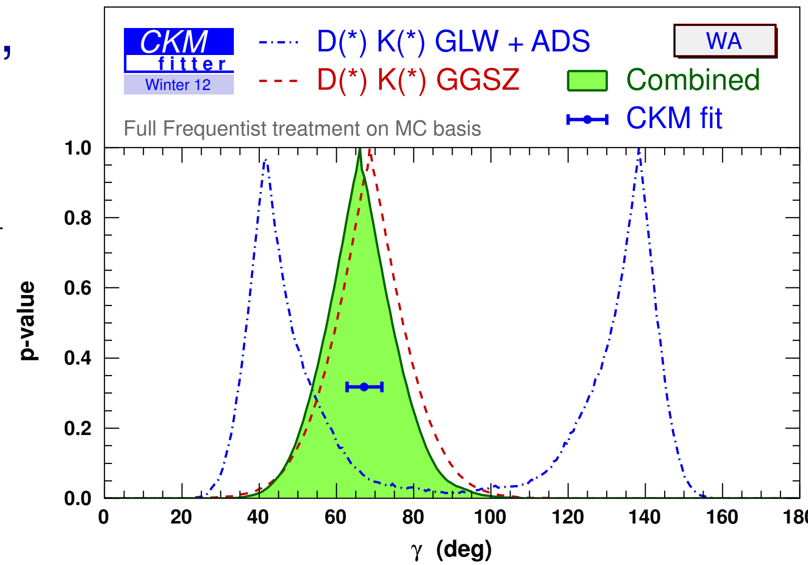
γ from $B^\pm \to DK^\pm$

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

  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 $\Rightarrow$ 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:

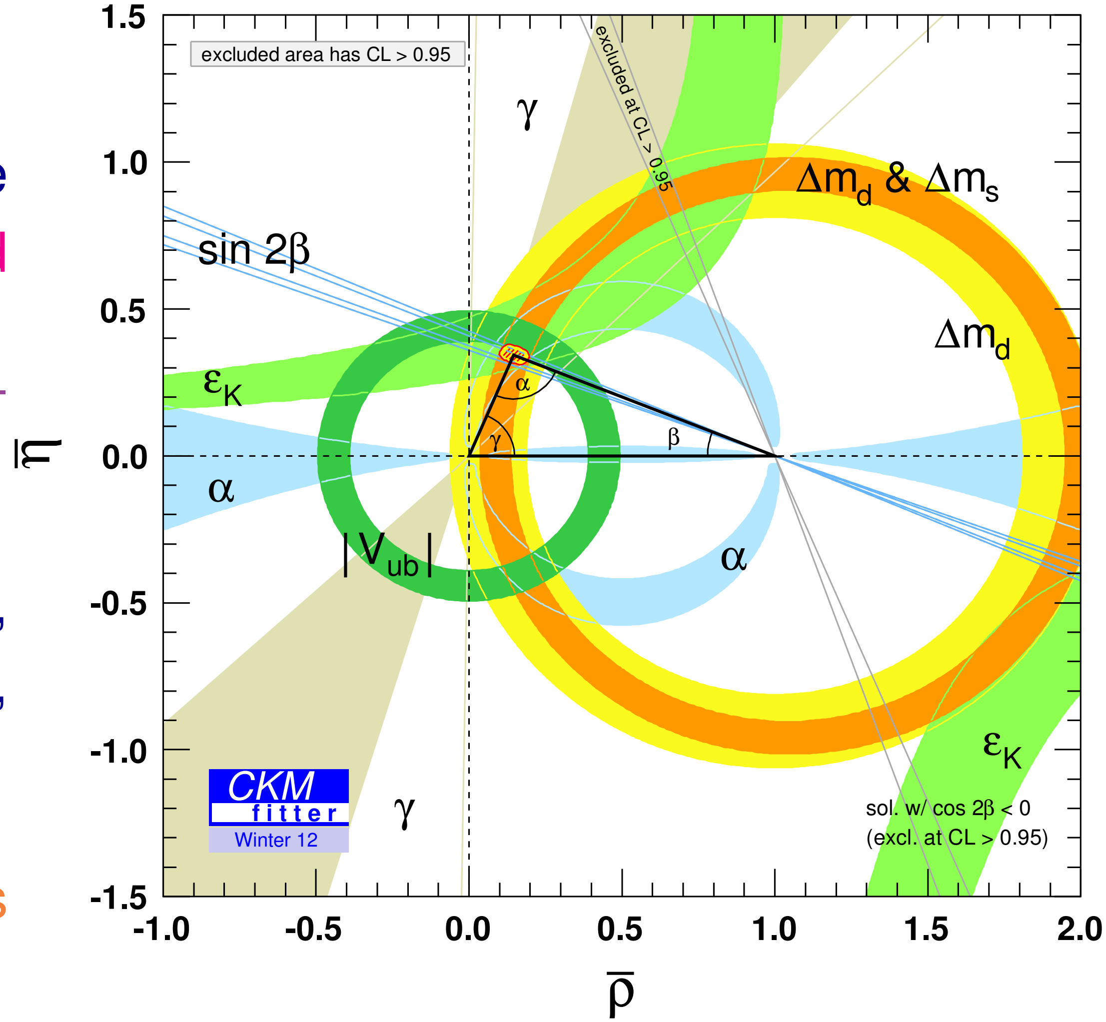
$$\lambda_{D_s^+ K^-} \lambda_{D_s^- K^+} = \left(\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*} \right)^2 \left(\frac{V_{cb} V_{us}^*}{V_{ub}^* V_{cs}} \right) \left(\frac{V_{ub} V_{cs}^*}{V_{cb}^* V_{us}} \right) = e^{-2i(\gamma - 2\beta_s - \beta_K)}$$

- 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)

New physics in B mixing

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

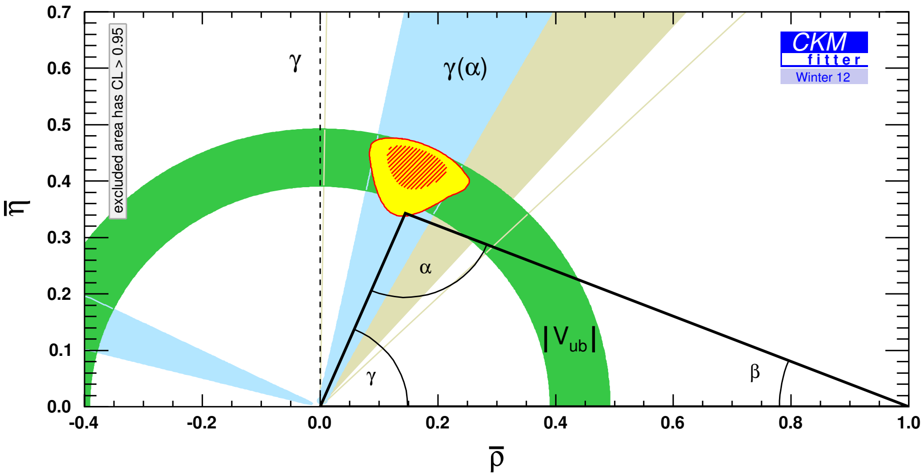
$$S_{\psi K} = \sin(2\beta + 2\theta_d) = \sin[2\beta + \arg(1 + h_d e^{2i\sigma_d})] \qquad S_{\rho\rho} = \sin(2\alpha - 2\theta_d)$$

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

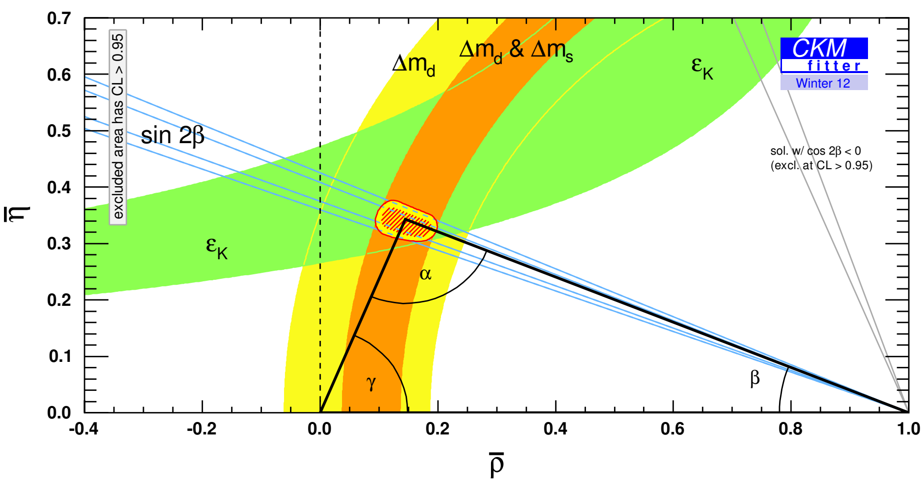
$$A_{\rm SL}^q = {\rm Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q r_q^2\, e^{2i\theta_q}}\right) = {\rm Im}\left[\frac{\Gamma_{12}^q}{M_{12}^q(1 + h_q e^{2i\sigma_q})}\right] \qquad \Delta\Gamma_s^{CP} = \Delta\Gamma_s^{\rm SM} \cos^2 2\theta_s$$

New physics in B meson mixing

- Tree-dominated measurements:

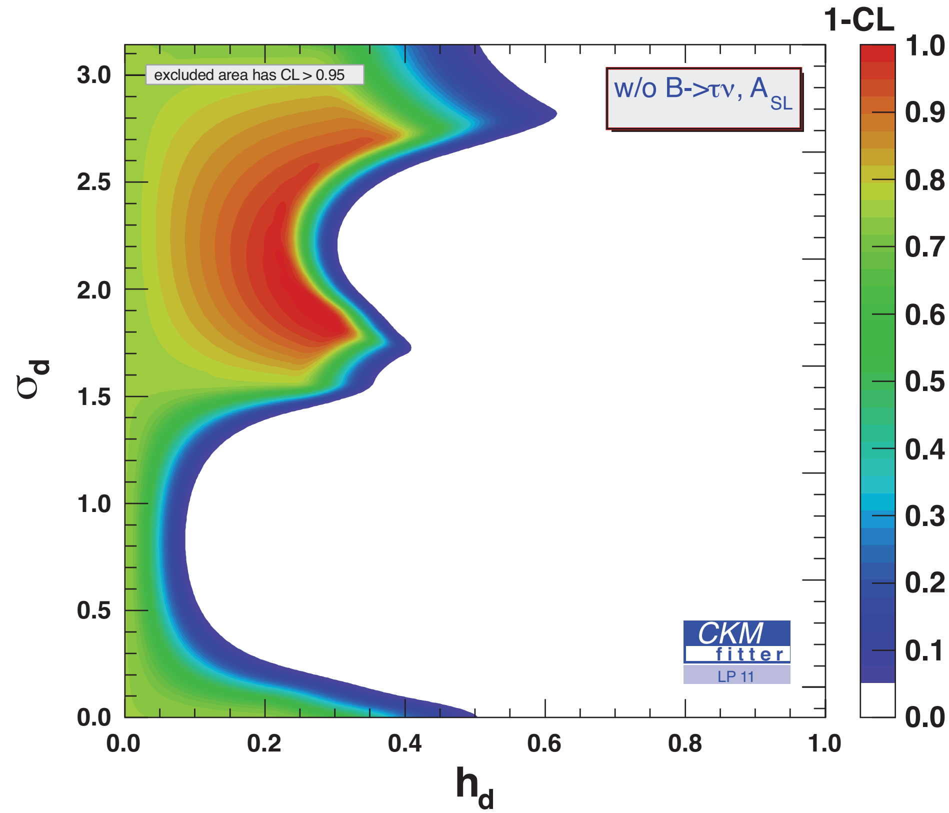


- Loop-dominated measurements:



Until 2004, $h_d \sim 10$ was allowed

Better tree-level measurements crucial

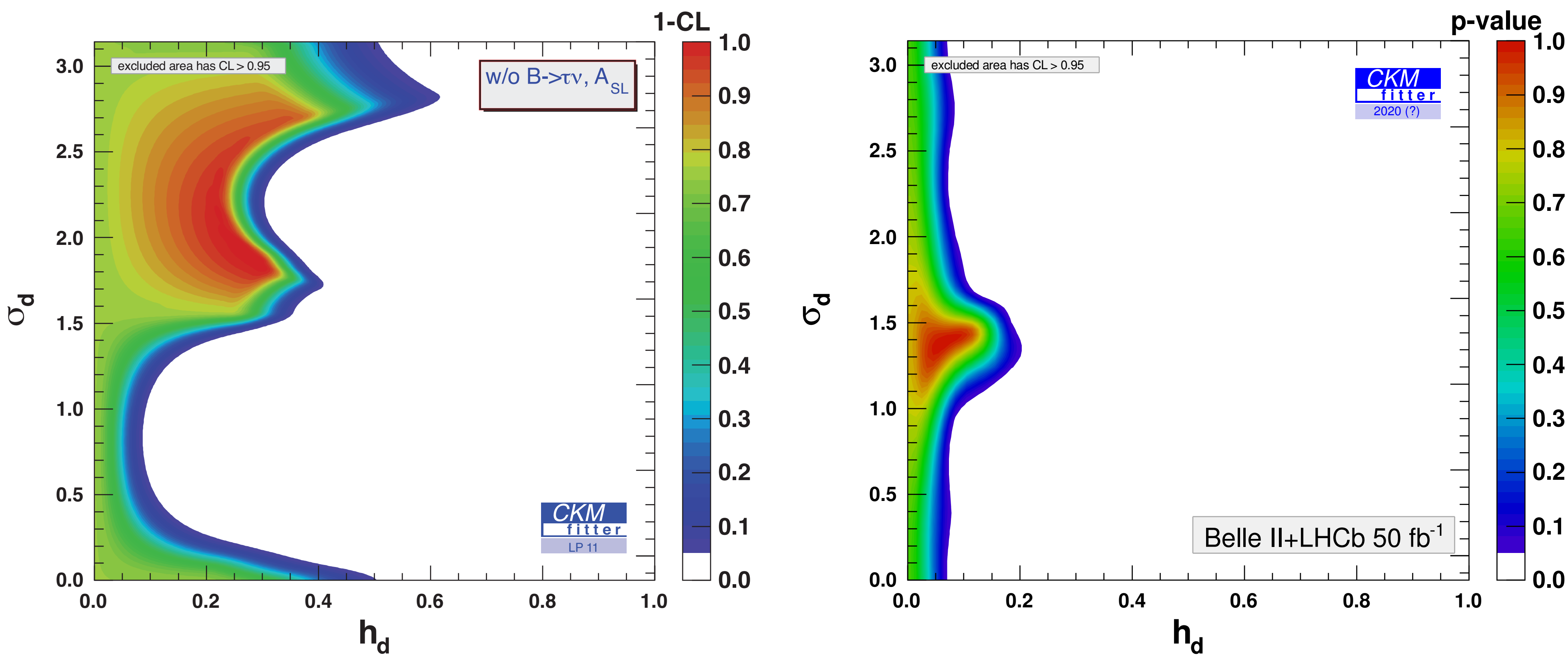


A goal: assume $h \sim (4\pi v/\Lambda_{\rm flav.})^2$

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

Preliminary — sensitivity in ~ 10 years?

- Rough predictions to illustrate increased sensitivity



Hot off the press (computers), since I gave the slides to Kate yesterday

[Thanks to S. Descotes-Genon and K. Trabelsi, CKMfitter]

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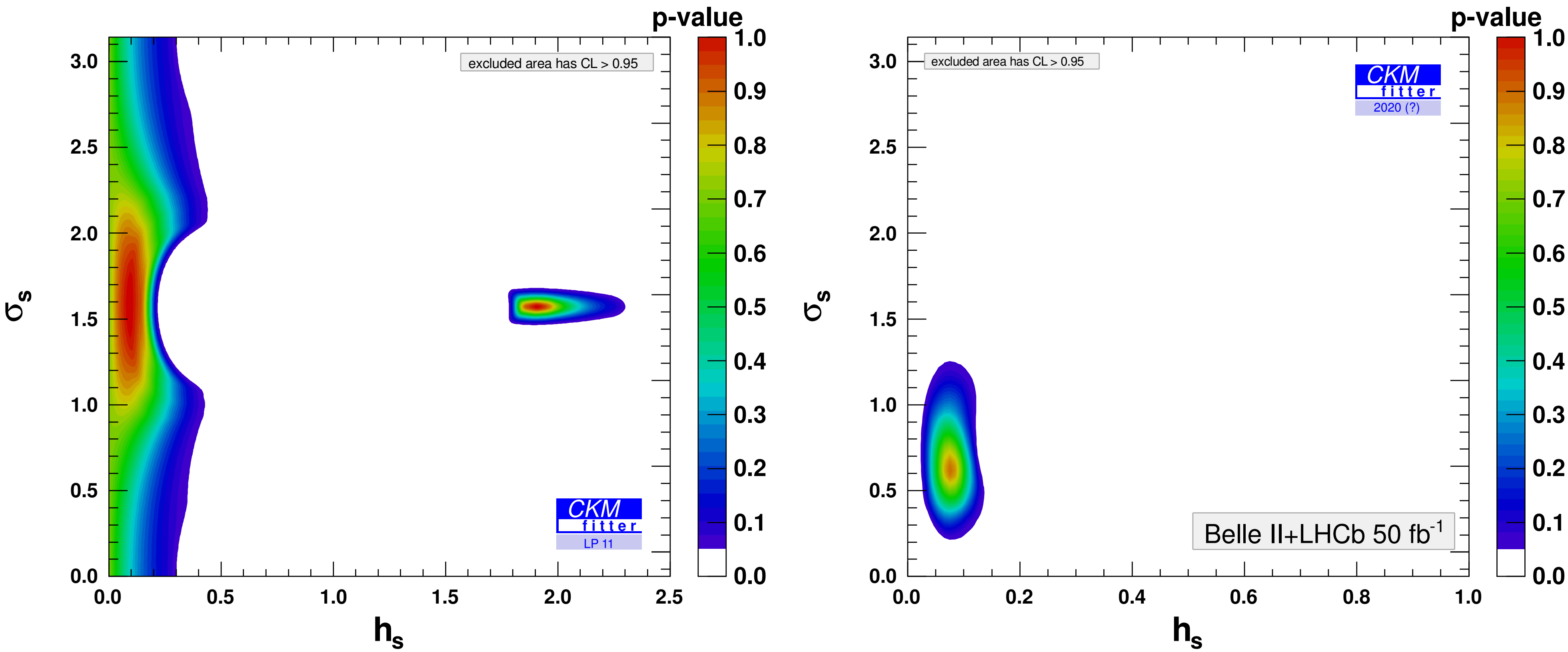

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Summary (1)

- 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 $\gg 1\,\text{TeV}$; sensitivity limited by statistics, not theory