Flavor Physics, CP Violation, and Physics Beyond the Standard Model

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The Many Threads of Flavor Physics

The differing masses and electroweak couplings of the quarks give rise to appreciable effects: Enter "flavor physics".

The decipherment of the flavor and spin structure of the proton and neutron continues to be of intense interest — and at this meeting it has been a central theme:

strange quarks: D. Geesaman, D. Leinweber, J.C. Peng, A. Signal, R. Young
up/down quarks (and CSB): J.C. Peng, T. Londergan, W. Melnitchouk, I. Cloet

Flavor physics also has far-flung implications for the search for physics beyond the Standard Model.

I will offer a broad overview of these and then focus on its implications for the study of CP violation.

Interesting Questions, circa 2010 CE

There is much theoretical “evidence” that the Standard Model is incomplete — *it leaves many questions unanswered.* Here are a few.

- Where is gravity? [It does not include it by design.]
- What are dark matter, dark energy?
- Why are there 3 generations? What explains the observed pattern of fermion masses and mixings?
- Why is the weak mass scale $\mathcal{O}(100\,\mathrm{GeV})$?

  [The Planck scale is $M_P = (G_N)^{-1/2} \approx 10^{19}$ GeV – why this “hierarchy”?]
- Why is neutron electric dipole moment so small?

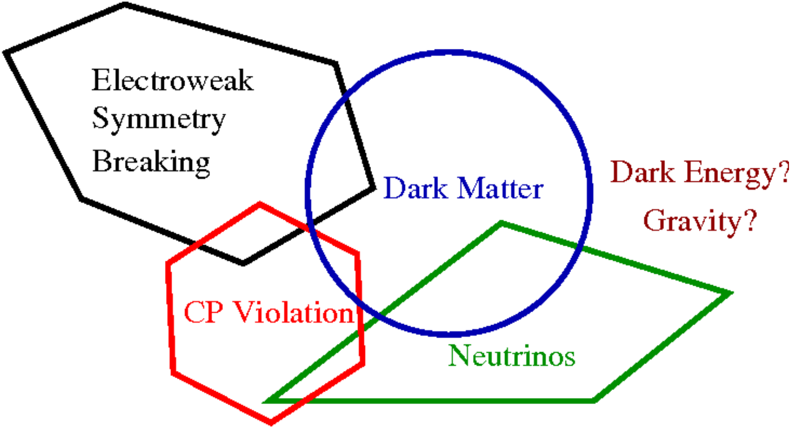
  [QCD has its own source of CP violation – but it doesn’t operate! Why?]
- What makes the baryon asymmetry of the Universe its observed value?

Most notably, the Standard Model only explains 5% of the known Universe.

There is much observational evidence for dark matter.

[Clowe et al., astro-ph/0608407]

Themes in the Search for New Physics



Electroweak Symmetry Breaking

Dark Matter

Dark Energy?

Gravity?

CP Violation

Neutrinos

How does flavor enter?

Flavor and the Search for New Physics

We have already seen some examples...

EWSB:

- of the impact of CSB and medium effects on the determination $\sin^2\theta_W$ from the NuTeV experiment [Londergan, Cloet]
- of the impact of strange quarks in the proton on the determination of the weak couplings of the *u* and *d* quarks from PVES [Young]

In each case the flavor-breaking effects required explicit evaluation.

Dark Matter: [Young]

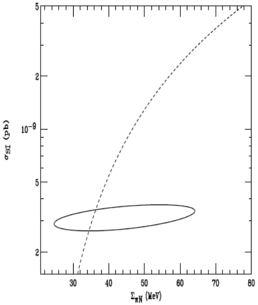
The neutralino-nucleon cross section is particularly sensitive to the strange scalar density.

Earlier studies consider fixed

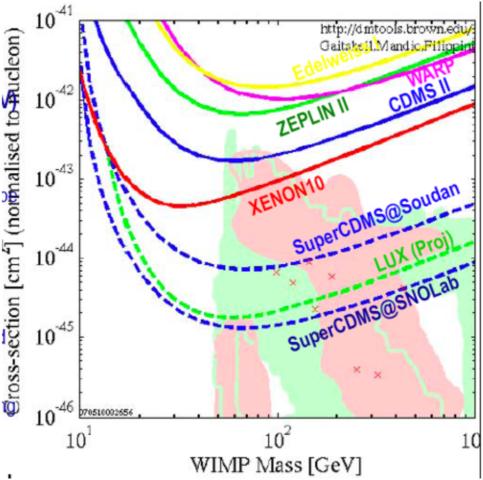
$\sigma_0 \equiv \langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle$

[Ellis, Olive, and Savage, Phys. Rev. D 77, 065026 (2008).]

Note [Giedt, Thomas, and Young, arXiv:0907.4177]



Flavor and Dark Matter



The strange scalar density impacts the discovery potential of WIMP searches!

Flavor and CP Violation

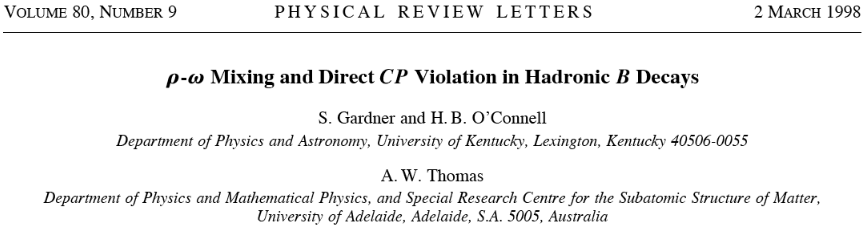
Flavor can impact (or has impacted)...

- the discovery of CP-violating effects

  What is the best discovery mode?
- the interpretation of CP-violating observables

  In what modes are Standard Model uncertainties smallest?
- the pattern of new physics itself

  To what extent does experiment allow new physics to be flavorful?



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ρ-ω Mixing and Direct CP Violation in Hadronic B Decays

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The Cabibbo-Kobayashi-Maskawa (CKM) Matrix

The decay $K^- \to \mu^- \bar{\nu}_\mu$ occurs: the quark mass eigenstates *mix* under the weak interactions. By convention

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{\text{weak}} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}} \quad ; \quad V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

In the Wolfenstein parametrization (1983)

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

where $\lambda \equiv |V_{us}| \simeq 0.22$ and is thus “small”. A, ρ, η are real.

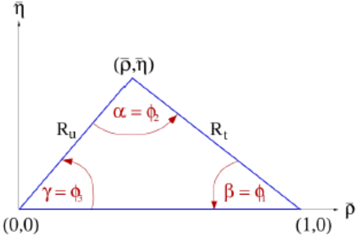
All CP-violating phenomena are encoded in η.

To test the SM picture of CP violation we must test the relationships it entails.

The Appeal of Beauty...

Intergenerational mixing is controlled by $V_{us} \sim 0.2$.
CKM unitarity compels — N.B. all terms are $\mathcal{O}(\lambda^3)$

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



$\phi_1 \equiv \beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$, $\phi_2 \equiv \alpha = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$, $\phi_3 \equiv \gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$
CP-violating effects need not be *small* — η can be $\mathcal{O}(1)$!

CP-Violation in B-Meson Decay

Different CP-violating phenomena can exist in the B meson system.

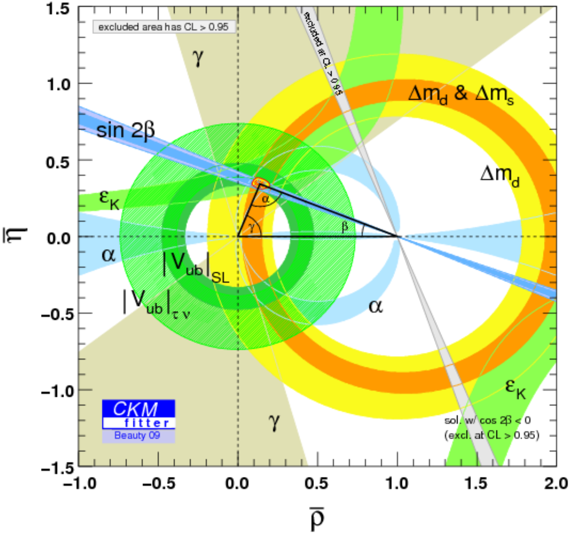
- CP violation in $B - \bar{B}$ mixing
- CP violation in the interference of $B - \bar{B}$ mixing and direct decay

$$\begin{tikzcd}
\mathrm{B} \arrow[rr] \arrow[dr] & & \mathrm{f}_{\mathrm{CP}} \\
& \bar{\mathrm{B}} \arrow[ur] &
\end{tikzcd}$$

  $|B^0(\tau)\rangle$... a state which is “tagged” as a B^0 meson at proper time $\tau = 0$ has a finite probability of being $\bar{B}$ at proper time τ.
  The $B - \bar{B}$ mixing oscillation frequency is small compared to the decay rate!

- CP violation in direct decay
  N.B. partial rate asymmetry $|A(B \to h_1 h_2)|^2 - |A(\bar{B} \to \bar{h}_1 \bar{h}_2)|^2 \neq 0$

The Success of the CKM Mechanism



[CKMfitter: hep-ph/0104062, hep-ph/0406184 ; http://ckmfitter.in2p3.fr – Beauty 2009 update]

On the Discovery of Direct CP Violation

Direct CP violation was observed in the B-meson system in 2004 via $B \to K^+\pi^-$. This mode is special.
To leading order in G_F, the sign of the $K^\pm$ "tags" the flavor of the decaying B ($\bar{B}$) meson. The rate asymmetry is [BaBar, hep-ex/0407057]

$$\mathcal{A}_{K\pi} \equiv \frac{n_{K^-\pi^+} - n_{K^+\pi^-}}{n_{K^-\pi^+} + n_{K^+\pi^-}} = -0.133 \pm 0.030(\mathrm{stat}) + 0.009(\mathrm{sys})$$

where $n_{K^-\pi^+}$ is the measured yield for the $K^-\pi^+$ final state.
The size of the asymmetry is uncomfortably large for theory. Is it a sign of BSM physics? Discussion continues....
The observation of direct CP violation in the D meson system, however, would signal new physics.
Analogous "untagged" studies in D decay are possible.
Enter $D \to K_S\pi^+\pi^-$.
The breaking of mirror symmetry in the untagged Dalitz plot would signal direct CP violation. [SG, PLB 2003; SG and Tandean, PRD 2004]

On the Interpretation of CP-Violating Observables

Flavor-based assumptions can be used to eliminate some sensitivity to Standard Model physics but can induce other uncertainties.

i) Measurement of β with $b \to s$ penguins

Is $\sin(2\beta)$ *universal?* [Grossman, Worah, 1996]

$$\Gamma(B^0(t) \to f_{CP}) \propto e^{-\Gamma t}\left[\frac{1+|\lambda_{f_{CP}}|^2}{2} + \frac{1-|\lambda_{f_{CP}}|^2}{2}\cos(\Delta m\, t) - \mathrm{Im}\lambda_{f_{CP}}\sin(\Delta m\, t)\right]$$

where $\lambda_{f_{CP}} \equiv \eta_{f_{CP}}(q/p)(A(\bar{B} \to \bar{f}_{CP})/A(B \to f_{CP}))$.
If the decay amplitude can be characterized by an unique weak phase, the strong dynamics cancels entirely!
This is true of $B \to J/\psi K_S$... and thus it is the "golden" mode.
$\mathrm{Im}\lambda_{\psi K_S}$ measures $\sin(2\beta)$.

For other modes, computation, or estimation, of the SM-induced shift from $\sin(2\beta)$ is crucial.

In $B \to \phi K_S$ [Grossman, Isidori, Worah, 1997] and $B \to f_0(980)K_S$ [Dutta, SG, PRD 2008] the corrections are very small.

On the Interpretation of CP-Violating Observables

ii) Measurement of γ (given β) with the $b \to u$ amplitude ($B \to \pi\pi$, $B \to n\pi$) These measurements yield α.

Here an assumption of isospin symmetry is essential.

[Gronau, London, PRL 1990; Snyder and Quinn, 1993]

Isospin-breaking effects are particularly important in $B \to \pi\pi$.

In this case transition amplitudes can emerge which did not appear in the isospin symmetric limit. [SG, 1999]

It is possible to assess all leading, strong isospin-breaking effects.

[SG, 1999, 2005; Gronau and Zupan, 2005].

However, current limits are driven by $B \to \rho\rho$ data.

And what of the flavor of possible New Physics?

At current levels of precision, the CKM mechanism dominates flavor violation as well.

Summary and Outlook

The pattern of CP violation in Nature can be described by a single parameter in the quark mixing (CKM) matrix to the $\mathcal{O}(10\%)$ level.

One can find evidence for physics BSM by observing

i) processes which are highly forbidden in the SM...

- Direct CP violation in the D system
- A permanent electric dipole moment

— and/or —

ii) decided failures of “Unitarity Triangle” tests

Flavor physics has played and will continue to play a crucial role in these developments.

Happy Birthday, Tony!!!

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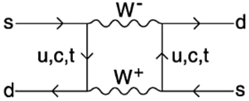
Backup Slides

The SUSY Flavor and CP Problems

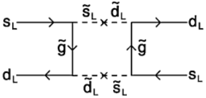
The MSSM is weakly coupled at the TeV scale and thus confronts precision electroweak measurements well if the superpartners are at the weak scale.
However, there are severe constraints from flavor and CP studies....

Flavor-Changing Neutral Current (FCNC) Constraints:

Note, e.g., $K_L - K_S$ mass difference: [Baer and Tata]

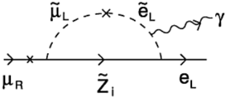


Standard Model



Additional effects from the MSSM

Constraints come from the mass differences from $B - \bar{B}$ and $D - \bar{D}$ mixing, too, as well as $b \to s\gamma$, $\mu \to e\gamma$, $\tau \to e\gamma$,....



Note the change in fermion *chirality*.
Constraints on chirality-changing effects also come from $(g-2)_\mu$.

All place constraints on the scalar masses and mixings in the soft breaking terms.

Can remove systematically through degeneracy or alignment or decoupling....

The SUSY CP Problem

The MSSM generically has many additional sources of CP violation because all the soft breaking terms can be complex.

Many constraints come from the non-observation of flavor-changing CP-violating effects beyond those of the SM:

in *K*'s:
$\Gamma(K_L \to 2\pi)$ (ϵ_K) and from the pattern of isospin-breaking in $\Gamma(K_L, K_S \to \pi^+\pi^-, \pi^0\pi^0)$ (ϵ').

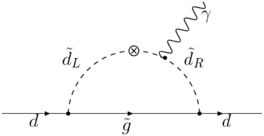
in *B*'s:
$A_{CP}(b \to s\gamma)$, $\Gamma(B, \bar{B}(t)) \to \psi K_S, \ldots$, $B_s \to \mu^+\mu^-$

We can study flavor-conserving, CP-violating processes also.
$\Longrightarrow$ Enter the EDM of the neutron, electron,....

In the case of the μ, this is the “complex”, i.e., CP-violating, analogue of the study of $(g-2)_\mu$. We can compute $(g-2)_\mu$ in the SM.

We cannot employ the measurement of the anomalous magnetic moment of the neutron to similar use because lattice QCD techniques are too primitive.

The leading contribution to the neutron EDM in the MSSM:



on the Electric Dipole Moment

The electric dipole moment d and magnetic moment μ of a nonrelativistic particle with spin S is defined via $\mathcal{H} = -d\frac{\mathbf{S}}{S}\cdot\mathbf{E} - \mu\frac{\mathbf{S}}{S}\cdot\mathbf{B}$

Assuming CPT invariance, the relativistic generalization is:

$\mathcal{L} = -d\frac{i}{2}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu} - \mu\frac{i}{2}\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}$

Thus through the EDM d, a P-odd, T-odd observable, we probe CP-violating effects in the Lagrangian (of everything?).

Both d and μ can be computed from spin-flip matrix elements of the nucleon.

In principle, we can test for CPT invariance by checking whether $d_N = d_{\bar{N}}$ or $d_{e^-} = d_{e^+}$ or $d_{\mu^-} = d_{\mu^+}$.

In the MSSM we compute $d_d = \langle n|\bar{\psi}_d\sigma^{\mu\nu}\gamma_5\psi_d F_{\mu\nu}|n\rangle$ and note $d_n \approx d_d$.

On dimensional grounds, under SU(2)$_L\times$ U(1) gauge invariance

[de Rujula et al., Nucl Phys B 357, 311 (1991)]

$d_d \sim 10^{-3} e\frac{m_d(\mathrm{MeV})}{\Lambda(\mathrm{TeV})^2} \sim 10^{-25}/\Lambda(\mathrm{TeV})^2$ e-cm.

Λ is the scale CP is broken.

Thus $|d_n^{\mathrm{expt}}| < \mathcal{O}(2.9\times 10^{-26})$ e-cm at 90%CL [Baker et al., PRL 97, 131801 (2006)] implies that the $\Lambda \sim 1$ TeV.

This makes the n EDM a sensitive probe of TeV-scale physics.

N.B. our estimate is not special to the MSSM (nor to the n)!!

The Effective CP-Violating Lagrangian at $\Lambda \sim 2$ GeV

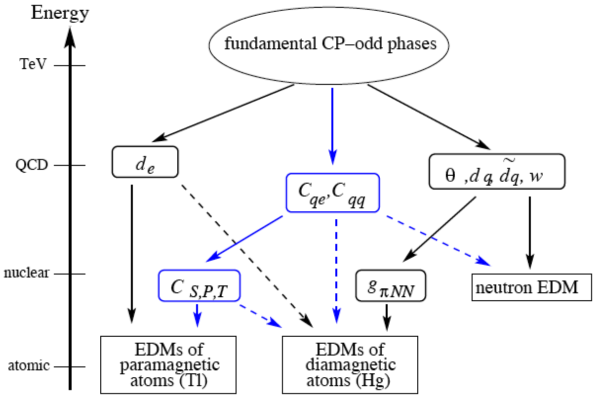
Here we organize the expected contributions to the low-energy $\mathcal{L}$ in terms of the mass dimension of the possible operators. We choose $\Lambda \sim m_c$ so that we can use QCD perturbation theory.
Note a mass dimension of $d - 4 > 0$ enters with a suppression factor of $\Lambda_{\rm CP}^{4-d}$, where $\Lambda_{\rm CP}$ is presumably not less than ~ 1 TeV.
Aside: $[\mathcal{L}] = 4$ so that $\int d^4x\mathcal{L}$ is dimensionless.
Thus $[A] = 1\,, [\psi] = 3/2\,, [\partial_\mu] = 1\,, [\phi] = 1$.
We have

$$\begin{aligned}\mathcal{L}_\Lambda \;=\; & \frac{\alpha_s\bar\theta}{8\pi}\epsilon^{\alpha\beta\mu\nu}F^a_{\alpha\beta}F^a_{\mu\nu} \\ & -\frac{i}{2}\sum_i d_i\bar\psi_i F_{\mu\nu}\sigma^{\mu\nu}\gamma_5\psi_i - \frac{i}{2}\sum_i \tilde d_i\bar\psi_i F^a_{\mu\nu}t^a\sigma^{\mu\nu}\gamma_5\psi_i \\ & +\frac{1}{3}wf^{abc}F^a_{\mu\nu}\epsilon^{\nu\beta\rho\delta}F^b_{\rho\delta}F_\beta^{\;\mu,c} + \sum_{i,j}C_{ij}(\bar\psi_i\psi_i)(\bar\psi_j i\gamma_5\psi_j) + \ldots\end{aligned}$$

with $i, j \in u, d, s, e, \mu$
and we neglect terms higher than dimension 6.

EDMs of Complex Systems

There is a hierarchy of scales to consider:



[Pospelov and Ritz]

At $\Lambda \sim 1$ MeV we have $\mathcal{L}_\Lambda = \mathcal{L}_{\mathrm{edm},\Lambda}(e,p,n) + \mathcal{L}_{\pi NN} + \mathcal{L}_{eN}$

All terms act as sources of CP violation.

EDMs in neutrons, nuclei, atoms, and molecules are broadly complementary.

EDMs in the Standard Model

There are two CP-violating parameters in the SM:
$\bar{\theta}$ in QCD and δ_{KM} (η) in the CKM matrix.

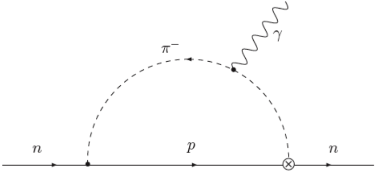
The Strong CP Problem

Since $\bar{\theta}$ accompanies a term of mass dimension 4, it is not suppressed by a large scale!

$\mathcal{L}_{\mathrm{CP}} = \frac{\alpha_s \bar{\theta}}{8\pi} \epsilon^{\alpha\beta\mu\nu} F^a_{\alpha\beta} F^a_{\mu\nu}$ can be rewritten as a total divergence, but it contributes in QCD nonetheless.

The needed matrix element $\langle n | \bar{q} i \gamma_5 q | n \rangle$ [Baluni, Phys Rev D19, 2227 (1979)] can be estimated using chiral Lagrangian techniques.

As $M_\pi \to 0$ limit one expects



to dominate, yielding $5.2 \cdot 10^{-16} \bar{\theta}$ e-cm.

[Crewther, Di Vecchia, Veneziano, Witten, PLB88, 123 (1979); PLB91, 487 (1980)]

Comparing to the exptl limit on d_n at 90%CL (Baker et al., ILL, 2007) yields $\bar{\theta} < 10^{-10}$.

Why is $\bar{\theta}$ so small?? Perhaps there is a spontaneously broken symmetry [Peccei and Quinn, 1979] (enter the axion) or $\Lambda_{\mathrm{CP}} \gg \Lambda_{\mathrm{SUSY}}$. [Hiller and Schmaltz, 2001]

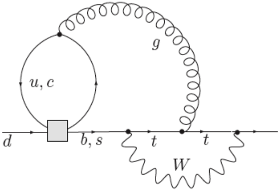
EDMs in the Standard Model

EDMs sourced from δ_{KM}

The structure of the CKM matrix guarantees that d_q is zero at two-loop order.

[Shabilin, Sov. J. Nucl. Phys. 28, 75 (1978)]

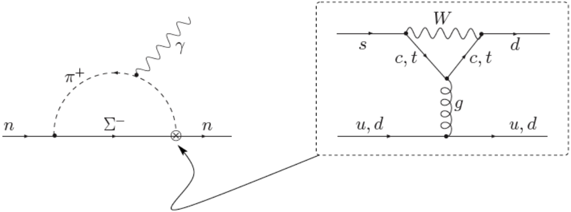
The first non-trivial contributions come at 3 loops, the largest involving a gluon [Khriplovich, PLB 173, 193 (1986)]



In leading logarithmic order at three loops $d_d^{\mathrm{KM}} \simeq 10^{-34}$ e-cm.

[Czarnecki and Krause, PRL 78, 4339 (1997)]

The π-loop contributions can be $1/m_\pi$ enhanced



and lead to the estimate $d_n^{\mathrm{KM}} \simeq 10^{-32}$ e-cm.

[Gavela et al., PLB 109, 215 (1982); Khriplovich and Zhitnitsky, PLB 109, 490 (1982).]

The estimates are so much smaller than the current experimental limits that the window for new physics is HUGE!

QCD matrix elements

How well can we interpret an EDM limit?

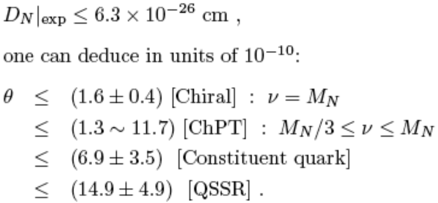
Let compare matrix element calculations for $\bar{\theta}$-QCD:

chiral: $d_n(\bar{\theta}) = 5.2 \cdot 10^{-16} \bar{\theta}$ e-cm [Crewther et al., 1979]

QCD sum rules: [Pospelov and Ritz, PRL 1999]

$$d_n(\bar{\theta}) = (1 \pm 0.5) \frac{\langle \bar{q} q \rangle}{(225\,\mathrm{MeV})^3} 2.5 \cdot 10^{-16} \bar{\theta}\ \text{e-cm}$$

They are crudely comparable, but... [Narison, PL B666, 455 (2008)]



$$D_N|_{\rm exp} \leq 6.3 \times 10^{-26}\ \mathrm{cm}\ ,$$

one can deduce in units of 10^{-10}:

$$\begin{aligned} \theta &\leq (1.6 \pm 0.4)\ [\text{Chiral}]\ :\ \nu = M_N \\ &\leq (1.3 \sim 11.7)\ [\text{ChPT}]\ :\ M_N/3 \leq \nu \leq M_N \\ &\leq (6.9 \pm 3.5)\ [\text{Constituent quark}] \\ &\leq (14.9 \pm 4.9)\ [\text{QSSR}]\ . \end{aligned}$$

cf. claimed 50% error in QSR method for CP-violating ops. w/ dimension ≤ 5

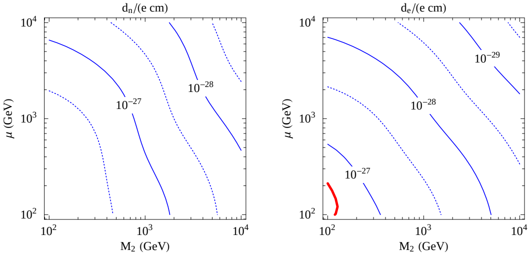
[Pospelov & Ritz, PRL 1999]

N.B. The nucleon matrix element computations needed can be tested by confronting the empirical anomalous moments. [Brodsky, SG, Hwang, PRD 2006]

Electric Dipole Moments in Split Supersymmetry

Can resolve SUSY CP problem by making superpartners heavy or CP phases small....

Models with "split" supersymmetry (heavy scalars!) can still produce significant EDMs at two-loop order: [Chang, Chang, Keung, 2005; Giudice and Romanino, 2006]



n and "e" EDMs are complementary! [see also Pospelov and Ritz]

Both d_e and d_n are expected to improve.

$|d_n| \leq 2.9 \cdot 10^{-26}$ e-cm (90% CL) [Baker et al., PRL 97, 131801 (2006)]

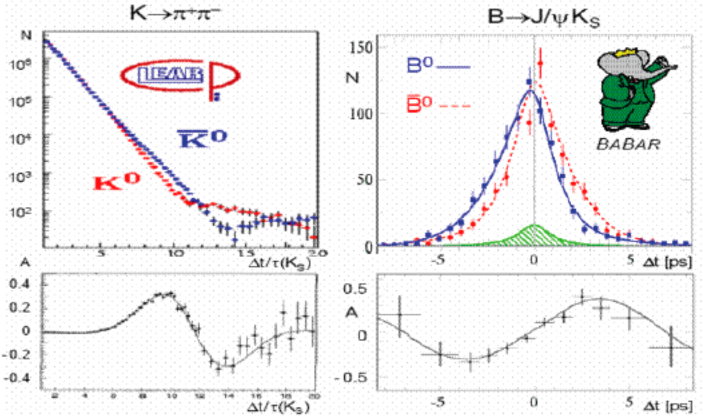
$|d_e| \leq 1.6 \cdot 10^{-27}$ e-cm [Regan et al., PRL 88, 071805 (2002)]

Some supersymmetric models (from "M Theory") realize CP violation only in the quark and lepton Yukawas $\Longrightarrow$ EDMs are SM-like [Kane, Kumar, Shao, arXiv:0905.2986]

Matter and Antimatter are Distinguishable

The decay rates for $K^0, \bar{K}^0 \rightarrow \pi^+\pi^-$ and $B^0, \bar{B}^0 \rightarrow J/\psi K_S$ are appreciably different. CP is violated!

[I.I. Bigi, arXiv:0703132v2 and references therein.]

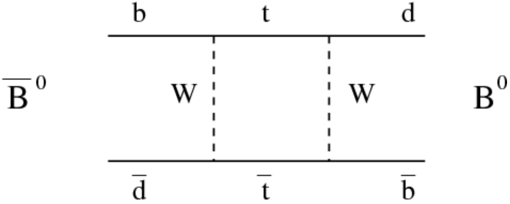


The Appeal of Beauty...

We can study the B-meson system at an $e^- e^+$ collider:

$$\boxed{e^- e^+ \to \Upsilon(4S) \to B_d \bar{B}_d}$$

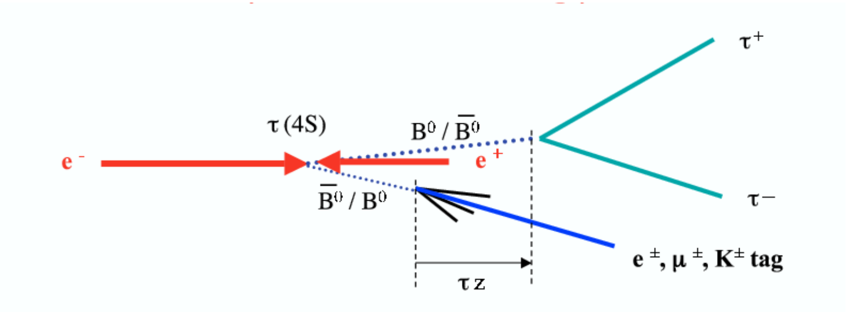
This produces *$B\bar{B}$ pairs*, and the B and $\bar{B}$ mix as well!



EPR correlations guarantee that the B and $\bar{B}$ change flavor in a *completely correlated* way.
If $B_d \to l^+ \nu X$ [$\bar{B}_d \to l^- \nu X$], then the other B meson was $\bar{B}_d$ [B_d] at *that* time.

Physics at a B-“Factory”

Enter the asymmetric B-factory, to facilitate the study of the time-dependence of CP violation. Such exist at SLAC and KEK.



Strong Interaction Obfuscation

Want to learn about underlying CKM parameters, but strong-interaction dynamics can confound this goal. Consider

$$\mathcal{A}_{direct} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2}$$

$A: \; M \to h_1 h_2$ and $\bar{A}: \; \bar{M} \to \bar{h}_1 \bar{h}_2$ An interference effect...

$$A = A_1 + A_2 \equiv A_1[1 + re^{i\delta}e^{i\phi}]$$

$$\bar{A} = \bar{A}_1 + \bar{A}_2 \equiv \bar{A}_1[1 + re^{i\delta}e^{-i\phi}]$$

$$\text{so that } \mathcal{A}_{direct} = \frac{-2r\sin\delta\sin\phi}{1 + 2r\cos\delta\cos\phi + r^2}$$

$\mathcal{A}_{direct}$ determines a combination of r, δ, ϕ . Note δ strong phase, ϕ weak phase.

Flavor symmetries (SU(2), SU(3)) can be used to relate r and δ of various decays in an approximate way. Precision studies may ultimately demand better?