1. Introduction
   a. Standard Model and why we love it
   b. Standard Model and why we hate it
2. Flavor-changing neutral currents and meson mixing
3. Need for New Physics
4. Conclusions
Flavour, also spelled flavor, in particle physics, property that distinguishes different members in the two groups of basic building blocks of matter, the quarks and the leptons. There are six flavours of subatomic particle within each of these two groups: six leptons (the electron, the muon, the tau, the electron-neutrino, the muon-neutrino, and the tau-neutrino), and six quarks (designated up, down, charm, strange, top, and bottom).

In this presentation I will mainly talk about quarks.

The secret of being a bore is to tell everything (Voltaire).
Le secret d’ennuyer est celui de tout dire.

(consult Prof. T. Weiler about leptons)
Why flavor?
Amos Williams Visits Criminal Justice

Aging and being a dedicated war veteran, a former Detroit Police Chief, spoke about being an accomplished attorney with some 35 years of practice. Alexey A Petrov visited another Detroit police officer, Amos Williams, in his office on 9/11. The former police chief and national police and law enforcement professionals discussed ways to help police and how to improve public perceptions of the police. He emphasized the importance of training and education for police officers.

Inside
- Physics Department Wins NSF CAREER Award
- CSEA Welcomes New Faculty to Development
- CSEE Welcomes New Faculty to Development
- College of Liberal Arts & Sciences News
- Inside the Clas Notes
-clstnews.wayne.edu
- Spring 2007

For the benefit of the students in the audience who plan on becoming police officers, the professor stressed that integrity counts above all. Cops volunteer for the job, and he hopes that the future law officers in the audience would be "volunteers to do the job correctly."
## CLAS Faculty Grants and Awards

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**CLAS Notes**

Alexey A Petrov (WSU & MCTP)  
Vanderbilt U Colloquium, 22 September 2011

Wednesday, September 21, 11
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### CLAS Notes

**Alexey A Petrov** (WSU & MCTP)

Vanderbilt U Colloquium, 22 September 2011
★ In case DOE reviewers of my grant are in the room, this work was really supported by...

NSF CAREER award PHY-0547794

DOE grant DE-FG02-96ER41005

Faculty Competition for Post-Doctoral Fellows
1. Introduction

The Standard Model of particle physics is a remarkably simple and powerful construct.
1. Introduction

The Standard Model of particle physics is a remarkably simple and powerful construct.

Gauge symmetries: all particles are (initially) massless.
The Ultimate Equation?

Something is needed to give masses to all particles
The Ultimate Equation?

Something is needed to give masses to all particles
The Ultimate Equation?

Something is needed to give masses to all particles

\[ \text{Standard Model} = \text{Elementary Particles} \]

Alexey A Petrov (WSU & MCTP)

Vanderbilt U Colloquium, 22 September 2011
Something is needed to give masses to all particles

\[ \mathcal{L}_{SM} = \sum_{\psi} \bar{\psi} \gamma^\mu \left( i \partial_\mu - \frac{g_1}{2} Y_W B_\mu - \frac{g_2}{2} \vec{\tau}_L \vec{W}_\mu \right) \psi + \mathcal{L}_B, \text{kin} + \mathcal{L}_W, \text{kin} + \mathcal{L}_{Higgs} \]

★ Part of the Lagrangian related to matter interaction with Higgs: flavor
Matter sector: experimental data

★ Ratios of masses of quarks and leptons

- quarks

\[
\frac{m_d}{m_u} \approx 2, \quad \frac{m_s}{m_d} \approx 21, \quad \frac{m_t}{m_c} \approx 267, \quad \frac{m_c}{m_u} \approx 431, \quad \frac{m_t}{m_u} \approx 1.2 \times 10^5.
\]

- leptons

\[
\frac{m_\tau}{m_\mu} \approx 17, \quad \frac{m_\mu}{m_e} \approx 207.
\]

★ Quark mixing (Cabibbo-Kobayashi-Maskawa) matrix parameters

\[
V_{CKM} = V_L^* V_L^\dagger = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}
\]

\[V_{ud} \sim 1, \ V_{us} \sim 0.2, \ V_{cb} \sim 0.04, \ V_{ub} \sim 0.004\]
Note that gauge forces in SM do not distinguish between fermions of different generations:
- \( e, \mu, \tau \) have same electrical charge
- quarks have same color charge

★ Why generations? Why only 3? Are there only 3?★ Why hierarchies of masses and mixings?★ Can there be transitions between quarks/leptons of the same charge but different generations?
A couple of questions...

Note that gauge forces in SM do not distinguish between fermions of different generations:
- $e$, $\mu$, $\tau$ have same electrical charge
- quarks have same color charge

★ Why generations? Why only 3? Are there only 3?
★ Why hierarchies of masses and mixings?
★ Can there be transitions between quarks/leptons of the same charge but different generations?

The flavor puzzle
Standard Model “solution”

1. Why generations? Why only 3? Are there only 3?
1. Why generations? Why only 3? Are there only 3?
1. Why generations? Why only 3? Are there only 3?
1. Why generations? Why only 3? Are there only 3?
   › ???

2. Why hierarchies of masses and mixings?

\[ \mathcal{L}_1 = -y_\psi \bar{\psi}_L \psi_R \phi + h.c. - \frac{y_\psi v}{\sqrt{2}} (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L), \]

\[ m_\psi = \frac{y_\psi v}{\sqrt{2}} \]

No explanation of the hierarchy, but mass hierarchy is related to hierarchy of Yukawa couplings

\[ y_u \sim 10^{-5}, \quad y_c \sim 10^{-2}, \quad y_t \sim 1, \]
\[ y_d \sim 10^{-5}, \quad y_s \sim 10^{-3}, \quad y_b \sim 10^{-2}, \]
\[ y_e \sim 10^{-6}, \quad y_\mu \sim 10^{-3}, \quad y_\tau \sim 10^{-2}. \]

3. Can there be transitions between quarks/leptons of the same charge but different generations?

No transitions at tree level (no interactions that change flavor w/out changing electric charge), but...
FCNC in the SM: GIM-mechanism

Glashow-Iliopoulos-Maiani (GIM) mechanism

- There are no $\Delta Q=2$ interactions in the Standard Model...
- ... but we can make them via a “two-step process” (loop diagram):

![Diagram](image)

- Let’s calculate them! For each internal quark type we get

$$\sim g^4 \left(V_{is}V_{id}^\dagger V_{js}^\dagger V_{jd}\right) \int \frac{d^4k}{(4\pi)^4} \frac{(\text{some gamma matrices}) (k^2)}{(k-m_i)(k-m_j)(k^2-m_W^2)^2}$$
FCNC in the SM: GIM-mechanism

Glashow-Iliopoulos-Maiani (GIM) mechanism

- There are no $\Delta Q=2$ interactions in the Standard Model...
- ... but we can make them via a “two-step process” (loop diagram):

![Diagram showing the two-step process]

- Let’s calculate them! For each internal quark type we get

$$\sim g^4 \left( V_{is} V_{id}^\dagger V_{js} V_{jd}^\dagger \right) \int \frac{d^4 k}{(4\pi)^4} \frac{(\text{some gamma matrices}) (k^2)}{(k - m_i)(k - m_j)(k^2 - m_w^2)^2}$$

Divergent: not good...
GIM-mechanism

- However, CKM matrix is unitary:
  
  contribution of different internal flavors comes with different signs!

- Thus, in the limit where $k \gg m_i, m_j, M_W$:

  \[
  \begin{align*}
  \text{top:} & \quad (V_{tb}V_{td}^*V_{tb}^*V_{td}^*) \sim (1 \times A\lambda^3)(1 \times A\lambda^3) \\
  \text{top-charm:} & \quad (V_{tb}V_{td}^*V_{cb}V_{cd}^*) \sim (1 \times A\lambda^3)(A\lambda^2 \times (-\lambda))
  \end{align*}
  \]

\[
\begin{align*}
\text{top:} & \quad g^4 \left(A\lambda^3\right)^2 \int \frac{d^4 k}{(4\pi)^4} \frac{(\text{some gamma matrices})(k^2)}{(k)(k)(k^2)^2} \\
\text{top-charm:} & \quad -g^4 \left(A\lambda^3\right)^2 \int \frac{d^4 k}{(4\pi)^4} \frac{(\text{some gamma matrices})(k^2)}{(k)(k)(k^2)^2}
\end{align*}
\]

... and similarly for other quarks

\[ A \propto \sum_i m_i^2 (V_{is}V_{ib}^*)^2 g_k(m_i^2) \]

Cancellation of divergences!

Glashow-Iliopulous-Maiani

Wednesday, September 21, 11
Experimental consequences of FCNC

- **FCNC can be seen experimentally**
  - $\Delta F = 1$ processes ($b \rightarrow s\gamma, c \rightarrow u\gamma$, etc)
  - $\Delta F = 2$ processes (BB-mixing, KK-mixing, DD-mixing)
2. Basics of meson mixing

$\Delta Q=2$: only at one loop in the Standard Model: possible new physics particles in the loop

$\Delta Q=2$ interaction couples dynamics of $D^0$ and $\overline{D}^0$

\[ |D(t)\rangle = \begin{bmatrix} a(t) \\ b(t) \end{bmatrix} = a(t)|D^0\rangle + b(t)|\overline{D}^0\rangle \]

- Time-dependence: coupled Schrödinger equations

\[ i \frac{\partial}{\partial t} |D(t)\rangle = \left( M - \frac{i}{2} \Gamma \right) |D(t)\rangle = \begin{bmatrix} A \\ \frac{P^2}{q^2} \end{bmatrix} |D(t)\rangle \]

- Diagonalize: mass eigenstates $\neq$ flavor eigenstates

\[ |D_{1,2}\rangle = p |D^0\rangle \pm q |\overline{D}^0\rangle \]

Mass and lifetime differences of mass eigenstates:

\[ x = \frac{M_2 - M_1}{\Gamma}, \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma} \]
2. Basics of meson mixing

\( \Delta Q=2 \): only at one loop in the Standard Model: possible new physics particles in the loop

\( \Delta Q=2 \) interaction couples dynamics of \( D^0 \) and \( \bar{D}^0 \)

\[
|D(t)\rangle = \begin{bmatrix} a(t) \\ b(t) \end{bmatrix} = a(t)|D^0\rangle + b(t)|\bar{D}^0\rangle
\]

- Time-dependence: coupled Schrödinger equations

\[
i \frac{\partial}{\partial t} |D(t)\rangle = \left( M - \frac{i}{2} \Gamma \right) |D(t)\rangle = \begin{bmatrix} A \\ Q^2 \\ P \end{bmatrix} |D(t)\rangle
\]

- Diagonalize: mass eigenstates \( \neq \) flavor eigenstates

No CPV: \( |D_{1,2}\rangle \Rightarrow |D_{CP \pm}\rangle = \frac{1}{\sqrt{2}} \left[ |D^0\rangle \pm |\bar{D}^0\rangle \right] \)

Mass and lifetime differences of mass eigenstates:

\[
x = \frac{M_2 - M_1}{\Gamma}, \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}
\]

Alexey A Petrov (WSU & MCTP)

Vanderbilt U Colloquium, 22 September 2011

Wednesday, September 21, 11
Mixing: charm and beauty

$D^0 - D^0$ mixing (hard)

- intermediate down-type quarks
- SM: $b$-quark contribution is negligible due to $V_{cd}V_{ub}^*$
  
  \[
  \text{rate} \propto f(m_s) - f(m_d)
  \]
  
  (zero in the SU(3) limit)

1. Sensitive to long distance QCD
2. Small in the SM: New Physics!
   (must know SM $x$ and $y$)

$B^0 - B^0$ mixing (easy)

- intermediate up-type quarks
- SM: $t$-quark contribution is dominant
  
  \[
  \text{rate} \propto m_t^2
  \]
  
  (expected to be large)

1. Computable in QCD (*)
2. Large in the SM: CKM!

(*) up to matrix elements of 4-quark operators

2nd order effect!!!
Lifetime differences in mesons

This is "theoretical data"
Lifetime differences in mesons

K

\begin{align*}
K_{\text{mixing}}(E) &= \frac{1}{2} \left( 1 + \cos \theta \right) \\
K_{\text{mixing}}(E) &= \frac{1}{2} \left( 1 - \cos \theta \right)
\end{align*}

B_d

\begin{align*}
B_d^{\text{mixing}}(E) &= \frac{1}{2} \left( 1 + \cos \theta \right) \\
B_d^{\text{mixing}}(E) &= \frac{1}{2} \left( 1 - \cos \theta \right)
\end{align*}

B_s

\begin{align*}
B_s^{\text{mixing}}(E) &= \frac{1}{2} \left( 1 + \cos \theta \right) \\
B_s^{\text{mixing}}(E) &= \frac{1}{2} \left( 1 - \cos \theta \right)
\end{align*}

D

\begin{align*}
D_{\text{mixing}}(E) &= \frac{1}{2} \left( 1 + \cos \theta \right) \\
D_{\text{mixing}}(E) &= \frac{1}{2} \left( 1 - \cos \theta \right)
\end{align*}

This is "theoretical data"
Mixing in mesons

This is “real data”
Mixing in mesons

This is “real data”
Easy case: $B_s$ system

Mixing parameters are sensitive probes of flavor physics

★ Time development of $B_s$ system

$$i \frac{d}{dt} \left( \frac{B_q(t)}{B_q(t)} \right) = \left[ M - \frac{i}{2} \Gamma \right]_{ij} \left( \frac{B_q(t)}{B_q(t)} \right)$$

★ Mixing parameters (concentrate on $B_s$)

$$\Delta M_{B_s} = 2 |M_{12}|, \quad \Delta \Gamma_{B_s} = \frac{4 \text{Re}(M_{12}\Gamma_{12}^*)}{\Delta M_{B_s}}$$

⇒ Theoretical predictions?
Bs system: Standard Model contributions

Both $\Delta M_{Bs}$ and $\Delta \Gamma_{Bs}$ can be computed in the limit $m_b \to \infty$:

$\Delta M_{Bs}$:

$$M_{12}(B_s) = \frac{G_F^2 M_{Bs}}{12\pi^2} M_W^2 (V_{tb} V_{ts}^*)^2 \hat{\eta}_B S_0(x_t)f_{Bs}^2 B$$

$\Delta \Gamma_{Bs}$:

$$\Gamma_{21}(B_s) = \sum_k \frac{C_k(\mu)}{m_b^k} \langle B_s | O_k^{\Delta B=2}(\mu) | B_s \rangle.$$
Not so easy: SM contributions to $\Delta \Gamma_{B_s}$

$\Delta \Gamma_{B_s}$: a calculation yields:

$$
\Gamma_{21}(B_s) = - \frac{G_F^2 m_b^2}{12\pi(2M_{B_s})} (V_{cb}^* V_{cs})^2 \left[ [F(z) + P(z)] \langle Q \rangle ight.
+ [F_S(z) + P_S(z)] \langle Q_S \rangle + \delta_{1/m} + \delta_{1/m^2} \left. \right]
$$

★ ... with operators

$$
Q = (\bar{b}_i s_i)_{V-A} (\bar{b}_j s_j)_{V-A}, \quad Q_S = (\bar{b}_i s_i)_{S-P} (\bar{b}_j s_j)_{S-P}
$$

$$
\tilde{Q} = (\bar{b}_i s_j)_{V-A} (\bar{b}_j s_i)_{V-A}, \quad \tilde{Q}_S = (\bar{b}_i s_j)_{S-P} (\bar{b}_j s_i)_{S-P}
$$

★ ... so the result (up to $1/m_b^2$) is:

$$
\Delta \Gamma_{B_s} = \left[ 0.0005B + 0.1732B_s + 0.0024B_1 - 0.0237B_2 - 0.0024B_3 - 0.0436B_4 
+ 2 \times 10^{-5} \alpha_1 + 4 \times 10^{-5} \alpha_2 + 4 \times 10^{-5} \alpha_3 + 0.0009 \alpha_4 - 0.0007 \alpha_5 
+ 0.0002 \beta_1 - 0.0002 \beta_2 + 6 \times 10^{-5} \beta_3 - 6 \times 10^{-5} \beta_4 - 1 \times 10^{-5} \beta_5 
- 1 \times 10^{-5} \beta_6 + 1 \times 10^{-5} \beta_7 + 1 \times 10^{-5} \beta_8 \right] \langle ps^{-1} \rangle.
$$

A.Badin, F. Gabbiani, A.A.P.  
SM contributions to $\Delta \Gamma_{B_s}$

Compare to experimental measurements

Lifetime difference:

Mass difference:

$$\Delta M_{B_s}^{th} = (117.1^{+17.2}_{-16.4}) \times 10^{-13} \text{ GeV}$$

$$\Delta M_{B_s}^{exp} = (117.0 \pm 0.8) \times 10^{-13} \text{ GeV}$$

or $$x_{B_s} = \Delta M_{B_s}/\Gamma_{B_s} = 26.2 \pm 0.5.$$
Why is $\Delta \Gamma_{B_s}$ interesting?

★ Probes of NP phase in $B_s$ mixing in $B_s \rightarrow J/\psi \phi$

Standard Model: $\beta_s$ is tiny; NP: anything!

- $\beta_{J/\psi} \approx \frac{1}{2} \text{Arg} \left( \frac{(V_{cb}V_{ub}^*)^2}{M_{12s}} \right)$
- $\beta_{J/\psi}^{(SM)} = 0.019 \pm 0.001$

R. Van Kooten, LP-2011

- $\Delta \Gamma, L = 5.2 \text{ fb}^{-1}$
- $\Delta \Gamma_p = 44\%$

- $\Delta \Gamma, L = 400 \text{ pb}^{-1}$
- $\Delta \Gamma_p = 30\%$

G. Raven, LP-2011

- Assuming identical analysis performance + central values
Why is $\Delta \Gamma_{B_s}$ interesting?

★ Probes of NP phase in $B_s$ mixing in $B_s \rightarrow J/\psi \phi$

Standard Model: $\beta_s$ is tiny; NP: anything!

- $\beta_{s}^{J/\psi\phi} \approx \frac{1}{2} \text{Arg} \left( \frac{(V_{tb}V_{ts}^*)^2}{M_{12s}} \right)$
- $\beta_{s}^{J/\psi\phi}(SM) = 0.019 \pm 0.001$

CDF Run II Preliminary
L = 5.2 fb$^{-1}$

- 95% CL
- 68% CL
- SM prediction

SM $p$-value = 44%

CDF Public Note 10206

LHCb Preliminary
$\sqrt{s} = 7$ TeV, L = 337 pb$^{-1}$

- 68% C.L.
- 90% C.L.
- 95% C.L.

SM $p$-value = 30%

$\phi_s = 0.13 \pm 0.18 \text{ (stat)} \pm 0.07 \text{ (syst) rad}$

- 68% C.L.
- 90% C.L.
- 95% C.L.

R. Van Kooten, LP-2011
G. Raven, LP-2011
Difficult case: D-mixing

★ Predictions of $x$ and $y$ in the SM are complicated
- second order in flavor SU(3) breaking
- $m_c$ is not quite large enough for OPE
  - $x, y \ll 10^{-3}$ (“short-distance”)
  - $x, y \sim 10^{-2}$ (“long-distance”)

★ Short distance:
- assume $m_c$ is large
  - combined $m_s, 1/m_c, a_s$ expansions
  - leading order: $m_s^2, 1/m_c^6$!

★ Long distance:
- assume $m_c$ is NOT large
  - sum of large numbers with alternating signs, SU(3) forces zero!
  - multiparticle intermediate states dominate

Resume: a contribution to $x$ and $y$ of the order of 1% is natural in the SM
D-mixing predicted in the Standard Model...

- $y \sim 1\%$
- $|x| \sim [0.1\%, 1\%]$

... and observed in 2007!

- no-mixing is excluded at $10.1\sigma$
  $x = 0.63^{+0.19}_{-0.20}\%$
  $y = 0.75 \pm 0.12 \%$

HFAG 2011

- observations consistent with no-CP-violation

$\Rightarrow$ Consistent with Standard Model!!!
Since all FCNC cases are adequately described by the Standard Model contributions, do we need New Physics???
Do we need to search for New Physics?

★ Standard Model has intrinsic problem related to Higgs mechanism (stabilization of quantum effects)
  - BSM stabilization (e.g. SUSY), other mechanisms of EWSB

★ Standard Model does not have enough CP-violation to describe generation of baryon asymmetry
  - need for BSM sources of CP-violation

★ Standard Model adequately describes experimental FCNC data, but does not provide solution to the flavor puzzle
  - BSM solution to the flavor problem?
Solutions to the flavor problem?

“Frankly, I even find it hard to believe some of the things I’ve been coming up with.”
Need for New Physics...

★ New Physics is needed!!!

★ But of what kind?
  ★ Multi-Higgs/LR models?
  ★ Supersymmetry (SUSY)?
  ★ Large extra dimensions?
  ★ Technicolor?
  ★ Compositeness?
  ★ ... other weird theory?

★ Ultimately: strings, M-theory?
Solutions to the flavor problem?

"I think he's crossed that thin line from speculative fiction into outright fantasy."
3. Need for New Physics

★ New Physics is needed!!!

★ But of what kind?
  ★ Multi-Higgs/LR models?
  ★ Supersymmetry (SUSY)?
  ★ Large extra dimensions?
  ★ Technicolor?
  ★ Compositeness?
  ★ … other weird theory?

★ Ultimately: strings, M-theory?

BUT: flavor is mainly an INPUT, not OUTPUT of models
Solutions to the flavor problem?

★ Standard Model adequately describes experimental FCNC data, but does not provide solution to the flavor puzzle

- BSM solution to the flavor problem?

- study FCNC ($\Delta F=2$ and $\Delta F=1$ processes) to get a glimpse of NP

Standard Model

Supersymmetric SM
Solutions to the flavor problem?

★ Standard Model adequately describes experimental FCNC data, but does not provide solution to the flavor puzzle

- BSM solution to the flavor problem?
- study FCNC ($\Delta F=2$ and $\Delta F=1$ processes) to get a glimpse of NP

\[ \begin{align*}
\text{Standard Model} & \quad \text{or} \quad \text{Supersymmetric SM}
\end{align*} \]
How does New Physics affect $x$ and $y$ in charm?

- Local $\Delta C=2$ piece of the mass matrix affects $x$:

$$\left( M - \frac{i}{2} \Gamma \right)_{ij} = m_D^{(0)} \delta_{ij} + \frac{1}{2m_D} \langle D_i^0 | H_W^{\Delta C=2} | D_j^0 \rangle + \frac{1}{2m_D} \sum_I \frac{\langle D_i^0 | H_W^{\Delta C=1} | I \rangle \langle I | H_W^{\Delta C=1} | D_j^0 \rangle}{m_D^2 - m_i^2 + i\epsilon}$$

- Double insertion of $\Delta C=1$ affects $x$ and $y$:

   Amplitude $A_n = \langle D_0^0 | (H_{SM}^{\Delta C=1} + H_{NP}^{\Delta C=1}) | n \rangle = A_n^{SM} + A_n^{NP}$

   Suppose $|A_n^{NP}|/|A_n^{SM}| : O(\text{exp. uncertainty}) \leq 10\%$

Example: $y = \frac{1}{2\Gamma} \sum_n \rho_n \left( A_n^{SM} + A_n^{NP} \right) \left( A_n^{SM} + A_n^{NP} \right) = \frac{1}{2\Gamma} \sum_n \rho_n A_n^{SM} A_n^{SM} + \frac{1}{2\Gamma} \sum_n \rho_n \left( A_n^{SM} A_n^{NP} + A_n^{NP} A_n^{SM} \right)$

Golowich, Pakvasa, A.A.P.
How does New Physics affect $x$ and $y$ in charm?

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$$

- Double insertion of $\Delta C=1$ affects $x$ and $y$:

Amplitude $A_{n} = \langle D_{i}^{0} | (H_{SM}^{\Delta C=1} + H_{NP}^{\Delta C=1}) | n \rangle \equiv A_{n}^{SM} + A_{n}^{NP}$

Suppose $|A_{n}^{NP}|/|A_{n}^{SM}| : O(\text{exp. uncertainty}) \leq 10\%$

Example:

$$
y = \frac{1}{2\Gamma} \sum_{n} \rho_{n} \left( A_{n}^{SM} + A_{n}^{NP} \right) \left( A_{n}^{SM} + A_{n}^{NP} \right) = \frac{1}{2\Gamma} \sum_{n} \rho_{n} A_{n}^{SM} A_{n}^{SM} + \frac{1}{2\Gamma} \sum_{n} \rho_{n} \left( A_{n}^{SM} A_{n}^{NP} + A_{n}^{NP} A_{n}^{SM} \right)
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How does New Physics affect $x$ and $y$ in charm?

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\left( M - \frac{i}{2} \Gamma \right)_{ij} = m_{D}^{(0)} \delta_{ij} + \frac{1}{2m_{D}} \langle D_{i}^{0} \left| H_{W}^{\Delta C=2} \right| D_{j}^{0} \rangle + \frac{1}{2m_{D}} \sum \langle D_{i}^{0} \left| H_{W}^{\Delta C=1} \right| I \rangle \langle I \left| H_{W}^{\Delta C=1} \right| D_{j}^{0} \rangle \frac{m_{D}^{2} - m_{i}^{2} + i\varepsilon}{m_{D}^{2} - m_{i}^{2} + i\varepsilon}
$$

- Double insertion of $\Delta C=1$ affects $x$ and $y$:

$$
\text{Amplitude} \quad A_{n} = \langle D_{i}^{0} \left| (H_{SM}^{\Delta C=1} + H_{NP}^{\Delta C=1}) \right| n \rangle \equiv A_{n}^{SM} + A_{n}^{NP}
$$

Suppose $|A_{n}^{NP}|/|A_{n}^{SM}| : O(\text{exp. uncertainty}) \leq 10\%$

Example:

$$
y = \frac{1}{2\Gamma} \sum_{n} \rho_{n} \left( A_{n}^{SM} + \overline{A}_{n}^{NP} \right) \left( A_{n}^{SM} + A_{n}^{NP} \right) = \frac{1}{2\Gamma} \sum_{n} \rho_{n} \overline{A}_{n}^{SM} A_{n}^{SM} + \frac{1}{2\Gamma} \sum_{n} \rho_{n} \left( A_{n}^{SM} A_{n}^{NP} + \overline{A}_{n}^{NP} A_{n}^{SM} \right)
$$

Golowich, Pakvasa, A.A.P. 
How does New Physics affect $x$ and $y$ in charm?

- Local $\Delta C=2$ piece of the mass matrix affects $x$:

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$$

- Double insertion of $\Delta C=1$ affects $x$ and $y$:

$$
\text{Amplitude} \quad A_n = \left< D_0 \left| \left( H_{SM}^{\Delta C=1} + H_{NP}^{\Delta C=1} \right) n \right. \right> = A_n^{SM} + A_n^{NP}
$$

Suppose $\left| A_n^{NP} \right| / \left| A_n^{SM} \right| : O(\text{exp. uncertainty}) \leq 10\%$

Example:

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y = \frac{1}{2\Gamma} \sum_n \rho_n \left( A_n^{SM} + A_n^{NP} \right) \left( A_n^{SM} + A_n^{NP} \right) = \frac{1}{2\Gamma} \sum_n \rho_n \bar{A}_n^{SM} A_n^{SM} + \frac{1}{2\Gamma} \sum_n \rho_n \left( A_n^{SM} A_n^{NP} + \bar{A}_n^{NP} A_n^{SM} \right)
$$

Zero in the SU(3) limit

Falk, Grossman, Ligeti, and A.A.P.
Phys.Rev. D65, 054034, 2002
2nd order effect!!!

Golowich, Pakvasa, A.A.P.
How does New Physics affect $x$ and $y$ in charm?

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$$

- Double insertion of $\Delta C=1$ affects $x$ and $y$:

Amplitude

$$A_n = \left< D^0 \left| (H_{SM}^{\Delta C=1} + H_{NP}^{\Delta C=1}) \right| n \right> = A_n^{SM} + A_n^{NP}$$

Suppose $|A_n^{NP}| / |A_n^{SM}| : O(\text{exp. uncertainty}) \leq 10\%$

Example:

$$y = \frac{1}{2\Gamma} \sum_n \rho_n \left( A_n^{SM} + A_n^{NP} \right) \left( A_n^{SM} + A_n^{NP} \right) = \frac{1}{2\Gamma} \sum_n \rho_n \left( A_n^{SM} A_n^{NP} + A_n^{NP} A_n^{SM} \right)$$

- Zero in the SU(3) limit

- Can be significant!!!
Global Analysis of New Physics: $\Delta C=2$

- Multitude of various models of New Physics can affect $x$

\[\begin{align*}
\mu &\geq 1\text{TeV} \\
\mu &\leq 1\text{TeV} \\
\mu &\leq 1\text{GeV}
\end{align*}\]
If all of those models of New Physics affect FCNC processes, how come all of them are described by the Standard Model so well???
If all of those models of New Physics affect FCNC processes, how come all of them are described by the Standard Model so well???

The “New Physics” flavor puzzle
Global Analysis of New Physics: $\Delta C=2$

Let's write the most general $\Delta C=2$ Hamiltonian

$$\langle f | \mathcal{H}_{NP} | i \rangle = G \sum_{i=1} C_i(\mu) \langle f | Q_i | i \rangle (\mu)$$

... with the following set of 8 independent operators...

$$Q_1 = (\bar{u}_L \gamma_\mu c_L) (\bar{u}_L \gamma^\mu c_L)$$
$$Q_2 = (\bar{u}_L \gamma_\mu c_L) (\bar{u}_R \gamma^\mu c_R)$$
$$Q_3 = (\bar{u}_L c_R) (\bar{u}_R c_L)$$
$$Q_4 = (\bar{u}_R c_L) (\bar{u}_R c_L)$$

$$Q_5 = (\bar{u}_R \sigma_{\mu\nu} c_L) (\bar{u}_R \sigma^{\mu\nu} c_L)$$
$$Q_6 = (\bar{u}_R \gamma_\mu c_R) (\bar{u}_R \gamma^\mu c_R)$$
$$Q_7 = (\bar{u}_L c_R) (\bar{u}_L c_R)$$
$$Q_8 = (\bar{u}_L \sigma_{\mu\nu} c_R) (\bar{u}_L \sigma^{\mu\nu} c_R)$$

RG-running relate $C_i(m)$ at NP scale to the scale of $m \sim 1 \text{ GeV}$, where ME are computed (on the lattice)

$$\frac{d}{d \log \mu} \tilde{C}(\mu) = \tilde{\gamma}^T(\mu) \tilde{C}(\mu)$$

Each model of New Physics provides unique matching condition for $C_i(L_{NP})$
Example: generic restrictions on FCNC from $\bar{D}D$-mixing

★ Comparing to experimental value of $x$, obtain constraints on FCNC in charm sector
- assume $x$ is dominated by New Physics
- assume no accidental strong cancellations b/w SM and NP

$$H_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu)Q'_i$$

$$Q_1^{cu} = \bar{u}_L \gamma_\mu C_L \bar{d}_L \gamma^\mu C_L,$$
$$Q_2^{cu} = \bar{u}_R C_L \bar{u}_R \gamma^\beta C_L,$$
$$Q_3^{cu} = \bar{u}_R C_L \bar{u}_R \gamma^\alpha C_L,$$

★ ... which are

$$|z_1| \lesssim 5.7 \times 10^{-7} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2,$$
$$|z_2| \lesssim 1.6 \times 10^{-7} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2,$$
$$|z_3| \lesssim 5.8 \times 10^{-7} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2,$$
$$|z_4| \lesssim 5.6 \times 10^{-8} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2,$$
$$|z_5| \lesssim 1.6 \times 10^{-7} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2.$$ 

New Physics is either at a very high scales

- tree level: $\Lambda_{NP} \geq (4 - 10) \times 10^3 \text{ TeV}$
- loop level: $\Lambda_{NP} \geq (1 - 3) \times 10^2 \text{ TeV}$

or have highly suppressed couplings to charm!

★ Constraints on particular NP models available

E.Golowich, J. Hewett, S. Pakvasa and A.A.P. 
Imaginary parts (CP-violation)

★ Assume that direct CP-violation is absent \((\text{Im}(\Gamma_1^*H_f/A_f) = 0, |\tilde{A}_f/A_f| = 1)\)
- experimental constraints on \(x, y, \varphi, |q/p|\) exist
- can obtain generic constraints on \(\text{Im}\) parts of Wilson coefficients

\[
\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu)Q'_i
\]

★ In particular,

\[
\begin{align*}
\text{Im}(z_1) & \lesssim 1.1 \times 10^{-7} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2, \\
\text{Im}(z_2) & \lesssim 2.9 \times 10^{-8} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2, \\
\text{Im}(z_3) & \lesssim 1.1 \times 10^{-7} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2, \\
\text{Im}(z_4) & \lesssim 1.1 \times 10^{-7} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2, \\
\text{Im}(z_5) & \lesssim 3.0 \times 10^{-8} \left( \frac{\Lambda_{NP}}{1 \text{ TeV}} \right)^2.
\end{align*}
\]

New Physics is either at a very high scales
- tree level: \(\Lambda_{NP} \geq (4 - 10) \times 10^3\) TeV
- loop level: \(\Lambda_{NP} \geq (1 - 3) \times 10^2\) TeV

or have highly suppressed couplings to charm!

★ Constraints on particular NP models possible as well

Gedalia, Grossman, Nir, Perez
Phys.Rev.D80, 055024, 2009

Bigi, Blanke, Buras, Recksiegel,
JHEP 0907:097, 2009
New Physics in \( \times \): lots of extras

New Physics contributions do not suffer from QCD uncertainties as much as SM contributions since they are short-distance dominated.

- **Extra gauge bosons**
  - Left-right models, horizontal symmetries, etc.

- **Extra scalars**
  - Two-Higgs doublet models, leptoquarks, Higgsless, etc.

- **Extra fermions**
  - 4\(^{th}\) generation, vector-like quarks, little Higgs, etc.

- **Extra dimensions**
  - Universal extra dimensions, split fermions, warped ED, etc.

- **Extra symmetries**
  - SUSY: MSSM, alignment models, split SUSY, etc.
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**Total:** 21 models considered
Consider an example: FCNC $Z^0$-boson

appears in models with
extra vector-like quarks
little Higgs models

1. Integrate out $Z$: for $\mu < M_Z$ get

$$\mathcal{H}_{2/3} = \frac{g^2}{8 \cos^2 \theta_w M_Z^2} (\lambda_{uc})^2 \bar{u}_L \gamma_\mu c_L \bar{u}_L \gamma^\mu c_L$$

2. Perform RG running to $\mu \sim m_c$ (in general: operator mixing)

$$\mathcal{H}_{2/3} = \frac{g^2}{8 \cos^2 \theta_w M_Z^2} (\lambda_{uc})^2 r_1(m_c, M_Z) Q_1$$

3. Compute relevant matrix elements and $x_D$

$$x_D^{(2/3)} = \frac{2 G_F f_D^2 M_D}{3 \sqrt{2} \Gamma_D} B_D (\lambda_{uc})^2 r_1(m_c, M_Z)$$

4. Assume no SM - get an upper bound on NP model parameters (coupling)
Consider another example: warped extra dimensions

FCNC couplings via KK gluons

1. Integrate out KK excitations, drop all but the lightest

\[ \mathcal{H}_{RS} = \frac{2\pi k r_c}{3 M_1^2} g_s^2 (C_1(M_n)Q_1 + C_2(M_n)Q_2 + C_6(M_n)Q_6) \]

2. Perform RG running to \( \mu \sim m_c \)

\[ \mathcal{H}_{RS} = \frac{g_s^2}{3 M_1^2} (C_1(m_c)Q_1 + C_2(m_c)Q_2 + C_3(m_c)Q_3 + C_6(m_c)Q_6) \]

3. Compute relevant matrix elements and \( x_D \)

\[ x_D^{(RS)} = \frac{g_s^2 f_D B_D M_D}{\Gamma_D} \left( \frac{2}{3} [C_1(m_c) + C_6(m_c)] - \frac{1}{6} C_2(m_c) - \frac{5}{12} C_3(m_c) \right) \]

Constrains LHC parameter space!!!
Consider another example: warped extra dimensions

FCNC couplings via KK gluons

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3. Compute relevant matrix elements and \( x_D \)

\[ x_D^{(RS)} = \frac{g_s^2 \ f_D^2 B_D M_M}{\Gamma_D} \left( \frac{2}{3} |C_1(m_c) + C_6(m_c)| - \frac{1}{6} C_2(m_c) - \frac{5}{12} C_3(m_c) \right) \]

Implies: \( M_{1KKg} > 2.5 \text{ TeV}! \)

Constrains LHC parameter space!!!
Summary: New Physics in mixing

✓ Considered 21 well-established models

✓ Only 4 models yielded no useful constraints

★ Flavor physics provides good constraints on New Physics models!

★ ... especially if used in correlation with other measurements!

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.

A.A.P. and G. Yeghiyan

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
So, what about models of flavor?

★ Proposed BSM solutions to the flavor problem

- **SM Lagrangian is U(3)$^5$-invariant in the limit $y_i \to 0$**
  - Yukawas arise as a result of spontaneous breaking of a subgroup of U(3)$^5$?
  - continuous flavor symmetries
  - discrete flavor symmetries
  - accidental flavor symmetries

(consult Prof. T. Kephart about flavor models)

★ Dynamical mechanisms

- **two-Higgs doublet models: tan$\beta$ as a large parameter**

\[
\mathcal{L}_2 = -y_\psi \bar{\psi}_L \psi_R \phi_1 - y_X \bar{\chi}_L X_R \phi_2 + h.c. \\
\frac{m_X}{m_\psi} = \frac{y_X v_2}{y_\psi v_1} = \frac{y_X}{y_\psi} \tan \beta \gg 1
\]

★ Work is still continuing! LHC?

A. Blechman, A.A.P., G. Yeghiyan
JHEP 1011:075, 2010
Flavor as a probe of New Physics: anomalies?

Simplest decay of heavy-flavored meson: $B \rightarrow \tau \bar{\nu}$

Only one non-perturbative parameter

$f_{BS} = 250(12) \text{ MeV} (\sim 5\%)$

Harbinger of New Physics?

Two-Higgs doublet model:

$\Gamma(B \rightarrow \tau \nu_{\tau})_{2HDM} = \Gamma(B \rightarrow \tau \nu_{\tau})_{SM} \times \left(1 - \frac{m_{B}^{2}}{m_{H}^{2}} \tan^{2} \beta \right)^{2}$
**Before we conclude:**

★ Are there more than three generations of quarks?

Higgs production at LHC is via $gg \rightarrow H$
- extremely sensitive to 4th generation quarks

---

H. Bachacou, LP-2011
Before we conclude:

★ Are there more than three generations of quarks?

Sequential 4th generation is in trouble...

Higgs production at LHC is via $gg \rightarrow H$
- extremely sensitive to 4th generation quarks

H. Bachacou, LP-2011
4. Conclusions

- Flavor puzzle is still a big problem for particle physics
  - The reason(s) for generations and mass hierarchy are not known
  - Standard Models simply parameterizes the solution
  - New Physics models use flavor as input, not output

- Flavor-changing neutral current transitions provide great opportunities for studies of flavor in the SM and BSM
  - several anomalies in $B_s$ physics might point to New Physics “around the corner”
  - studies of charmed transitions experience explosive growth
    - unique access to up-type quark sector
    - large available statistics/in many cases small SM background
    - D-mixing is a second order effect in SU(3) breaking ($x,y \sim 1\%$ in the SM)
    - large contributions from New Physics are possible, but not seen

- Maybe flavor physics will be the first to see glimpses of New Physics
- Maybe flavor physics will be the only game in town to see New Physics...
Thank you for your attention!
Thank you for your attention!

Hopefully, I did better than him...
Additional slides
Full Standard Model contains CP violation!

- CP transformations on $\psi(x), H(x), V(\mu)(x), ...$
  \[
  C \psi(t, x) C = \gamma^0 \psi(t, -x)
  \]
  \[
  P \psi(t, x) P = -i (\psi(t, x) \gamma^0 \gamma^2)^T
  \]

  thus $\bar{\psi}_i \psi_k \xrightarrow{CP} \bar{\psi}_k \psi_i$, $\varphi \xrightarrow{CP} \varphi$, $V^{\mu\pm} \xrightarrow{CP} (-1)^{\mu} V^{\mu\mp}, ...$

- Consider a Yukawa-type interaction term

\[
L_{Yuk} = \zeta_{ik} \bar{\psi}_i \psi_k \varphi + \text{H.c.} \xrightarrow{CP} \not\sim L_{Yuk}!
\]

$\Rightarrow$ Complex $\zeta_{ik}$ may imply CP-nonconserving effects

Standard Model with three generations
Time Reversal \[ T|f\rangle = |f^*\rangle \]

The expectation value of an operator transformed by $T$ is

\[
\langle Q \rangle_K = \int \Psi_K^* Q \Psi_K \, dV = \int \Psi Q \Psi^* \, dV \\
= \int (Q \Psi)^* \Psi \, dV = \int \Psi^* Q^* \Psi \, dV \\
= \langle Q^* \rangle
\]

Operators with complex phases (e.g., $p$ and $L$), are not $T$ invariant (and therefore are not CP invariant).
Conditions for the asymmetry

Matter-antimatter imbalance in the Universe

✓ Baryon (and lepton) number - violating processes to *generate* asymmetry

✓ Universe that evolves out of thermal equilibrium to *keep* asymmetry from *being washed out*

✓ “Microscopic CP-violation” to *keep* asymmetry from *being compensated in the “anti-world”

$\Delta B = 3, \Delta L = 3,$

$B - L$ conserved
2. What is CP(T)?
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P: parity (inversion of space) \( P \): \( x \rightarrow -x \)
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P: parity (inversion of space) \[ \mathcal{P} : \bar{x} \rightarrow -\bar{x} \]

\[ P \left| \Psi \left( r, s \right) \right\rangle = \pm \left| \Psi \left( -r, s \right) \right\rangle \]

\[ \Gamma (K^+ \rightarrow \mu^+_l \nu_{\mu_l}) = \Gamma (K^+ \rightarrow \mu^+_R \nu_{\mu_R}) \]
2. What is CP(T)?

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C: charge conjugation  \[ C : \quad Q \rightarrow -Q \]
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2. What is CP(T)?

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\[ \Gamma(K^+ \rightarrow \mu^+_l \nu_{\mu_l}) = \Gamma(K^+ \rightarrow \mu^+_{R} \nu_{\mu_R}) \]

C: charge conjugation
\[ C : \quad Q \rightarrow -Q \]

\[ C \left| e^- \right\rangle = \left| e^+ \right\rangle, \quad C \left| p \right\rangle = \left| p \right\rangle, \quad C \left| \gamma \right\rangle = -\left| \gamma \right\rangle \]

\[ \Gamma(K^+ \rightarrow \mu^+_l \nu_{\mu_l}) = \Gamma(K^- \rightarrow \mu^-_{l} \nu_{\mu_l}) \]
2. What is CP(T)?

P: parity (inversion of space)  \[ P \Psi(r, s) = \pm \Psi(\tilde{r}, s) \]

\[ \Gamma(K^+ \rightarrow \mu^+_l \nu_{\mu_l}) = \Gamma(K^+ \rightarrow \mu^+_R \nu_{\mu_R}) \]

C: charge conjugation

\[ C | e^- \rangle = | e^+ \rangle, \quad C | p \rangle = | \bar{p} \rangle, \quad C | \gamma \rangle = -| \gamma \rangle \]

\[ \Gamma(K^+ \rightarrow \mu^+_l \nu_{\mu_l}) = \Gamma(K^- \rightarrow \mu^-_l \bar{\nu}_{\mu_l}) \]

T: time reversal

\[ \mathcal{T} : \quad \bar{t} \rightarrow -t \]
2. What is CP(T)?

P: parity (inversion of space)
\[ P | \Psi \left( r, s \right) \rangle = \pm | \Psi \left( -r, s \right) \rangle \]
\[ \Gamma (K^+ \to \mu^+_l \nu_{\mu_l}) = \Gamma (K^+ \to \mu^+_R \nu_{\mu_R}) \]

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\[ C | e^- \rangle = | e^+ \rangle, \quad C | p \rangle = | p \rangle, \quad C | \gamma \rangle = -| \gamma \rangle \]
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T: time reversal
\[ T : \quad \bar{t} \to -\bar{t} \]
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C: charge conjugation \( C: Q \rightarrow -Q \)

\[ C |e^-\rangle = |e^+\rangle, \quad C |p\rangle = |-p\rangle, \quad C |\gamma\rangle = -|\gamma\rangle \]

\[ \Gamma(K^+ \rightarrow \mu^+_l \nu_{\mu_l}) = \Gamma(K^- \rightarrow \mu^-_l \nu_{\mu_l}) \]

T: time reversal \( T: \bar{t} \rightarrow -\bar{t} \)

\[ \Gamma(K^+ \rightarrow \mu^+_l \nu_{\mu_l}) = \Gamma(\mu^+_l \nu_{\mu_l} \rightarrow K^+) \]
Can Standard Model violate CP?

- Strong and electromagnetic interactions conserve $C$, $P$ and $T$
- All interactions (local QFT) conserve combination $CPT$
- Weak interactions violate $P$ and $C$...
  what about $CP$?

$$\Gamma(K^+ \rightarrow \mu^+_L \nu_{\mu_L}) = \Gamma(K^- \rightarrow \mu^-_R \nu_{\mu_R})$$

But: if SM contains operators with complex phases then there just might be $CP$ violation in the Standard Model!
I. Intrinsic particle properties

✓ electric dipole moments:

\[ \vec{d} = \int d^3x \, \bar{x} \rho(\bar{x}) \]

should be (anti-)aligned with spin \( \vec{s} \)!

\[ \begin{align*}
\vec{d} &\rightarrow \vec{d} \quad \parallel \quad \vec{s} &\rightarrow -\vec{s} \\
\vec{d} &\rightarrow -\vec{d} \quad \parallel \quad \vec{s} &\rightarrow \vec{s}
\end{align*} \]

however

\[ \begin{align*}
\text{Experimental limits:} \\
\begin{array}{|c|c|c|}
\hline
\text{Particle} & \text{Exp Limit, } e\text{ cm} & \text{Theory (SM), } e\text{ cm} \\
\hline
\text{neutron} & |d_n| < 6.3 \times 10^{-26} & |d_n| \sim 10^{-32} \\
\text{electron} & |d_e| < 4 \times 10^{-27} & |d_e| \sim 10^{-37} \\
\text{muon} & |d_\mu| < 7 \times 10^{-19} & |d_\mu| \sim 10^{-35} \\
\hline
\end{array}
\end{align*} \]

thus, if \( \vec{d} \neq 0 \Rightarrow \mathcal{T} \) or \( CP \) is broken
How to observe CP-violation?

I. Intrinsic particle properties

✓ electric dipole moments:

\[ \vec{d} = \int d^3 x \, \bar{x} \rho(x) \]

should be (anti-)aligned with spin \( \vec{s} \)!

\[ \vec{d} \xrightarrow{\mathcal{T}} -\vec{d} \parallel \vec{s} \xrightarrow{\mathcal{T}} -\vec{s} \]

however

\[ \vec{d} \xrightarrow{\mathcal{P}} -\vec{d} \parallel \vec{s} \xrightarrow{\mathcal{P}} \vec{s} \]

thus, if \( \vec{d} \neq 0 \Rightarrow \mathcal{T} \) or \( \mathcal{CP} \) is broken

Low energy strong interaction effects might complicate predictions!
5. CP-violation (preliminary)

- In any quantum field theory CP-symmetry can be broken
  1. Explicitly through dimension-4 operators ("hard")
     
     Example: Standard Model (CKM):
     \[
     \mathcal{L}_{Yuk} = \xi_{ik} \bar{\psi}_i \psi_k \varphi + \text{H.c.} \quad \not\sim \mathcal{L}_{Yuk}
     \]
     
  2. Explicitly through dimension <4 operators ("soft")
     
     Example: SUSY
  3. Spontaneously (CP is a symmetry of the Lagrangian, but not of the ground state)
     
     Example: multi-Higgs models, left-right models

- These mechanisms can be probed in charm transitions
Possible sources of CP violation in charm transitions:

- CPV in $\Delta c = 1$ decay amplitudes ("direct" CPV)

$$A(D \to f) = A_f = |A_1| e^{i \delta_1} e^{i \phi_1} + |A_2| e^{i \delta_2} e^{i \phi_2}, \quad \Delta \delta \neq 0, \Delta \phi \neq 0$$

- CPV in $D^0 - \bar{D}^0$ mixing matrix ($\Delta c = 2$)

$$R_m^2 = \left( \frac{p}{q} \right)^2 = \frac{2M_{12} - i \Gamma_{12}}{2M_{12}^* - i \Gamma_{12}^*} \neq 1$$

- CPV in the interference of decays with and without mixing

$$\lambda_f = \frac{q}{p} \frac{\overline{A_f}}{A_f} = R_m e^{i(\phi + \delta)} \left| \frac{\overline{A_f}}{A_f} \right|$$

- One can separate various sources of CPV by customizing observables
A comment

- Generic expectation is that CP-violating observables in the SM are small

**$\Delta c = 1$ amplitudes**

- The Unitarity Triangle for charm:

\[
V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0
\]

\[\sim \lambda \sim \lambda \sim \lambda^5\]
A comment

- Generic expectation is that CP-violating observables in the SM are small

\[ \Delta c = 1 \text{ amplitudes} \]

\[ V_{ud} V_{cd}^* + V_{us} V_{cs}^* + V_{ub} V_{cb}^* = 0 \]

\[ \sim \lambda \quad \sim \lambda \quad \sim \lambda^5 \]

- The Unitarity Triangle for charm:

\[ \begin{align*}
V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* &= 0 \\
\sim \lambda &= \lambda^5
\end{align*} \]

Any CP-violating signal in the SM will be small, at most \( O(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim 10^{-3} \)

Thus, \( O(1\%) \) CP-violating signal can provide a “smoking gun” signature of New Physics
How to observe CP-violation?

- There exists a variety of CP-violating observables
  1. "Static" observables, such as electric dipole moment
  2. "Dynamical" observables:
     a. Transitions that are forbidden in the absence of CP-violation
        \[ CP[\text{initial state}] \neq CP[\text{final state}] \]
     b. Mismatch of transition probabilities of CP-conjugated processes
        \[ \Gamma(D \to f) \neq \Gamma(\bar{D} \to \bar{f}) \]
     c. Various asymmetries in decay distributions, etc.

- Depending on the initial and final states, these observables can be affected by all three sources of CP-violation
a. Transitions forbidden w/out CP-violation

★ Recall that CP of the states in $D^0\bar{D}^0 \rightarrow (F_1)(F_2)$ are anti-correlated at $\psi(3770)$:
★ a simple signal of CP violation: $\psi(3770) \rightarrow D^0\bar{D}^0 \rightarrow (CP_\pm)(CP_\pm)$

$CP[F_1] = CP[F_2]$

$\Gamma_{F_1F_2} = \frac{\Gamma_{F_1} \Gamma_{F_2}}{R_m^2} \left[ (2 + x^2 + y^2) |\lambda_{F_1} - \lambda_{F_2}|^2 + (x^2 + y^2) |1 - \lambda_{F_1} \lambda_{F_2}|^2 \right]$
What if $F_1$ or $F_2$ is not a CP-eigenstate

★ If CP violation is neglected: mass eigenstates = CP eigenstates
★ CP eigenstates do NOT evolve with time, so can be used for “tagging”

$\tau$-charm factory (BES/CLEO-c)

★ CP anti-correlated $\psi(3770)$: CP(tag) $(-1)^L = [CP(K_S) CP(\pi^0)] (-1) = +1$
★ CP correlated $\psi(4140)$

Can measure $(y \cos \phi)$:

$$B^l_\pm = \frac{\Gamma(D_{CP\pm} \rightarrow Xl\nu)}{\Gamma_{tot}}$$

$$y \cos \phi = \frac{1}{4} \left( \frac{B^l_+ - B^l_-}{B^l_+} \right)$$

D. Atwood, A.A.P., hep-ph/0207165
D. Asner, W. Sun, hep-ph/0507238

Alexey A Petrov (WSU & MCTP)
b. Mismatch of transition probabilities

- At least two components of the transition amplitude are required

\[ A(D^+ \rightarrow f) = A_f = |A_1| e^{i\delta_1} e^{i\phi_1} + |A_2| e^{i\delta_2} e^{i\phi_2} \]

Look at charged D’s:

Then, charge asymmetry will provide a CP-violating observable

\[ a_f = \frac{\Gamma(D^+ \rightarrow f) - \Gamma(D^- \rightarrow \bar{f})}{\Gamma(D^+ \rightarrow f) + \Gamma(D^- \rightarrow \bar{f})} = \frac{2 \text{Im} A_1 A_2^* \sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2 \text{Re} A_1 A_2^* \cos(\delta_1 - \delta_2)} \]

...or, introducing \( r_f = \left| \frac{A_2}{A_1} \right| \):

\[ a_f = 2r_f \sin\phi \sin\delta \]

Prediction sensitive to details of hadronic model

- Same formalism applies if one of the amplitudes is generated by New Physics

need \( r_f \sim 1\% \) for O(1%) charge asymmetry
b. Mismatch of transition probabilities - II

- This can be generalized for neutral D-mesons too:

\[ a_f = \frac{\Gamma(D \rightarrow f) - \Gamma(D \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(D \rightarrow \bar{f})} \quad \text{and} \quad a_{\bar{f}} = \frac{\Gamma(D \rightarrow \bar{f}) - \Gamma(D \rightarrow f)}{\Gamma(D \rightarrow \bar{f}) + \Gamma(D \rightarrow f)} \]

- Each of those asymmetries can be expanded as

\[ a_f = a_f^d + a_f^m + a_f^i \]

- Similar formulas available for \( \bar{f} \)

1. for CP-eigenstates: \( f = \bar{f} \) and \( y_f' \rightarrow y \)

Those observables are of the first order in CPV parameters, but require tagging.