New Physics from Flavour
Reasons for Physics Beyond the Standard Model

- **Dark Matter**

- **Dark Energy: Cosmological constant**

- **Hierarchy Problem:** Divergent quantum corrections to go from Electroweak scale $\sim 100$ GeV to Planck scale of Energy $\sim 10^{19}$ GeV without "fine tuning" quantum corrections

- *All of the above may only be related to Gravity*
Reasons for NP

- Flavor problem: Why 3 replications of quarks & leptons?
- Baryogenesis: The amount of CP Violation observed thus far in the quark sector is too small: \((n_B - n_{\bar{B}})/n_\gamma = \sim 10^{-20}\) but \(~6 \times 10^{-10}\) is needed. Thus New Physics must exist to generate needed CP Violation.

- To explain the values of CKM couplings, \(V_{ij}\), (both neutrino & quark)
- To explain the masses of fundamental objects. Are they related to the \(V_{ij}\)'s?
Why these values? Are the two related? Are they related to masses?
Masses

Three light $\nu$'s summed masses 0.04-0.3 eV

12 orders of magnitude differences not explained; t quark as heavy as Tungsten
Theorists task

- A given theoretical model must explain all the data

Model must thread through all experimental constraints (12 axe handles). One measurement can, in principle, defeat the theorist, but we seek a consistent pattern.
Flavor Physics as a NP discovery tool

- While measurements of CKM parameters & masses are fun, the main purpose of Flavor Physics is to find and/or define the properties of physics beyond the SM.
- FP probes large mass scales via virtual quantum loops. An example, of the importance of such loops are changes in the W mass:
  - $M_W$ changes due to $m_t$: $\frac{dM_W}{dm_t} \propto \frac{m_t}{M_W}$
  - $M_W$ changes due to $m_H$: $\frac{dM_W}{dm_H} \propto \frac{dm_H}{M_H}$
Ex. of Strong Constraints on NP

- **Inclusive $b \to s\gamma$, ($E_\gamma > 1.6$ GeV)**
  - Measured $(3.37\pm 0.23) \times 10^{-4}$
  - Theory $(3.15\pm 0.23) \times 10^{-4}$ (NNLL) Misiak arXiv:1010.4896
  - Ratio $= 1.07\pm 0.10$, Limits most NP models
  - Example 2HDM
    - $m(H^+) > 385$ GeV

New BaBar
$(3.31\pm 0.35) \times 10^{-4}$
See G. Eigen’s talk

Misiak et. al hep-ph/0609232,
See also A. Buras et. al,
arXiv:1105.5146
Limits on New Physics

- It is oft said that we have not seen New Physics, yet what we observe is the sum of Standard Model + New Physics. How to set limits on NP?

- One hypothesis: assume that tree level diagrams are dominated by SM and loop diagrams could contain NP.

Tree diagram example

Loop diagram example
Flavor as a High Mass Probe

- Already excluded ranges from box diagrams
  \[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda_i} O_i, \text{take } c_i \sim 1 \]

Ways out
1. New particles have large masses >> 1 TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constrains on NP

Neutral Meson Mixing

- Neutral mesons can transform into their anti-particles via 2nd order weak interactions.
- Short distance transition rate depends on
  - mass of intermediate $q_i$, the heavier the larger, favors s & b since t is allowed.
  - CKM elements $V_{ij}$.

$D^0$, $B^0_{d}$, $B^0_{s}$

$\text{Prob}[D^0](t)$, $\text{Prob}[B^0_{d}](t)$, $\text{Prob}[B^0_{s}](t)$

from Van Kooten
Mixing & CPV Definitions

- **Mixing & Decay:**

  \[
  |M_L\rangle = p|M^o\rangle + q|\overline{M}^o\rangle, \quad |M_H\rangle = p|M^o\rangle - q|\overline{M}^o\rangle,
  \]

  \[
  mB_s = (M_H + M_L)/2, \quad \Delta M = M_H - M_L,
  \]

  \[
  1/\tau_{B_s} = \Gamma = (\Gamma_H + \Gamma_L)/2, \quad \Delta \Gamma = \Gamma_L - \Gamma_H,
  \]

  \[
  y \equiv \Delta \Gamma / 2\Gamma
  \]

- \[
  i \frac{d}{dt} \begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_{11} - \Gamma_{11} / 2 & M_{12} - i\Gamma_{12} / 2 \\ M_{12}^* - i\Gamma_{12}^* / 2 & M_{22} - i\Gamma_{22} / 2 \end{pmatrix} \begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix}
  \]
Consider where $f$ is a CP eigenstate

\[ a[f(t)] = \frac{\Gamma(M \rightarrow f) - \Gamma(M \rightarrow f)}{\Gamma(M \rightarrow f) + \Gamma(M \rightarrow f)} \]

Define

\[ A_f \equiv A(M \rightarrow f), \quad \bar{A}_f \equiv A(M \rightarrow f), \quad \lambda_f = \frac{p}{q A_f} \]

\[ \lambda_f \text{ is a function of } V_{ij} \text{ in SM} \]

\[
\begin{align*}
\Gamma(M \rightarrow f) &= N_f |A_f|^2 e^{-\Gamma t} \left( \cosh \frac{\Delta \Gamma t}{2} - \text{Re} \lambda_f \sinh \frac{\Delta \Gamma t}{2} - \text{Im} \lambda_f \sin(\Delta M t) \right) \\
\Gamma(M \rightarrow \bar{f}) &= N_f |A_f|^2 e^{-\Gamma t} \left( \cosh \frac{\Delta \Gamma t}{2} - \text{Re} \lambda_f \sinh \frac{\Delta \Gamma t}{2} + \text{Im} \lambda_f \sin(\Delta M t) \right)
\end{align*}
\]

CPV in $B_s \rightarrow J/\psi X$

- Interference between mixing & decay

- For $f = J/\psi \phi$ or $J/\psi \pi^+ \pi^-$

$B_s^0 \{ b \bar{s} \}_{c\bar{c}} \rightarrow J/\psi$

$B_s \{ b \bar{s} \}_{c\bar{c}} \rightarrow J/\psi \phi$

$\pi^+ \pi^-$ or $K^+ K^-$

- Small CPV expected, good place for NP to appear

- $B_s \rightarrow J/\psi \phi$ is not a CP eigenstate, as it’s a vector-vector final state, so must do an angular analysis to separate the CP+ and CP- components

$\phi_s^{SM} \equiv -2\beta_s = -2 \arg \left( -\frac{V_{ts} V_{*}^{*}}{V_{cs} V_{*}^{*}} \right) = -0.04 \text{ rad}$
phi_s from J/psi pi^+ pi^-

- Reconstructed pi^+ pi^- mass spectrum
- In region between arrows, measured to be >97.7%
- CP-odd @95% cl

- a[f(t)] ~ 2sin(phi_s) sin(ΔMt)

- φ_s = -0.019^{+0.173+0.004}_{-0.174-0.003} rad

- See || talk of G. Cowan
\[ \frac{d^4 \Gamma(B_s^0 \rightarrow J/\psi \phi)}{dt \ d \cos \theta \ d \varphi \ d \cos \psi} \equiv \frac{d^4 \Gamma}{dt \ d \Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega) \]

<table>
<thead>
<tr>
<th>(k)</th>
<th>(h_k(t))</th>
<th>(f_k(\theta, \psi, \varphi))</th>
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<tbody>
<tr>
<td>1</td>
<td>(</td>
<td>A_0</td>
</tr>
<tr>
<td>2</td>
<td>(</td>
<td>A_\parallel(t)</td>
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<tr>
<td>3</td>
<td>(</td>
<td>A_\perp(t)</td>
</tr>
<tr>
<td>4</td>
<td>(\Im(A_\parallel(t) A_\perp(t)))</td>
<td>(\sin^2 \psi \sin 2 \theta \sin \phi)</td>
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<tr>
<td>5</td>
<td>(\Re(A_0(t) A_\parallel(t)))</td>
<td>(\frac{\sqrt{2}}{2} \sin 2 \psi \sin^2 \theta \sin 2 \phi)</td>
</tr>
<tr>
<td>6</td>
<td>(\Im(A_0(t) A_\perp(t)))</td>
<td>(\frac{\sqrt{2}}{2} \sin 2 \psi \sin 2 \theta \cos \phi)</td>
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<tr>
<td>7</td>
<td>(</td>
<td>A_s(t)</td>
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<tr>
<td>8</td>
<td>(\Re(A_\ast_s(t) A_\parallel(t)))</td>
<td>(\frac{\sqrt{6}}{3} \sin \psi \sin^2 \theta \sin 2 \phi)</td>
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<tr>
<td>9</td>
<td>(\Im(A_\ast_s(t) A_\perp(t)))</td>
<td>(\frac{\sqrt{6}}{3} \sin \psi \sin 2 \theta \cos \phi)</td>
</tr>
<tr>
<td>10</td>
<td>(\Re(A_\ast_s(t) A_0(t)))</td>
<td>(\frac{4}{3} \sqrt{3} \cos \psi \left(1 - \sin^2 \theta \cos^2 \phi\right))</td>
</tr>
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for S-wave under \(\phi\) predicted by Stone & Zhang PRD 79, 074024 (2009)
Transversity II

\[ |A_0|^2(t) = |A_0|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) - \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) + \sin \phi_s \sin(\Delta mt) \right], \]

\[ |A_{\parallel}(t)|^2 = |A_{\parallel}|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) - \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) + \sin \phi_s \sin(\Delta mt) \right], \]

\[ |A_{\perp}(t)|^2 = |A_{\perp}|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) + \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \sin \phi_s \sin(\Delta mt) \right], \]

\[ \Im(A_{\parallel}(t)A_{\perp}(t)) = |A_{\parallel}| |A_{\perp}| e^{-\Gamma_s t} \left[ - \cos(\delta_{\parallel} - \delta_{\perp}) \sin \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) \right. \]
\[ - \cos(\delta_{\parallel} - \delta_{\parallel}) \cos \phi_s \sin(\Delta mt) + \sin(\delta_{\parallel} - \delta_{\perp}) \cos(\Delta mt) \left. \right], \]

\[ \Re(A_0(t)A_{\parallel}(t)) = |A_0| |A_{\parallel}| e^{-\Gamma_s t} \left[ \cos(\delta_{\perp} - \delta_0) \sin \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) \right. \]
\[ + \sin \phi_s \sin(\Delta mt) \left. \right], \]

\[ \Im(A_0(t)A_{\perp}(t)) = |A_0| |A_{\perp}| e^{-\Gamma_s t} \left[ - \cos(\delta_{\parallel} - \delta_0) \sin \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) \right. \]
\[ - \cos(\delta_{\parallel} - \delta_0) \cos \phi_s \sin(\Delta mt) + \sin(\delta_{\parallel} - \delta_0) \cos(\Delta mt) \left. \right], \]

\[ |A_s(t)|^2 = |A_s|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) + \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \sin \phi_s \sin(\Delta mt) \right], \]

\[ \Re(A_s^*(t)A_{\parallel}(t)) = |A_s| |A_{\parallel}| e^{-\Gamma_s t} \left[ - \sin(\delta_{\parallel} - \delta_s) \sin \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) \right. \]
\[ - \sin(\delta_{\parallel} - \delta_s) \cos \phi_s \sin(\Delta mt) \left. \right] + \cos(\delta_{\parallel} - \delta_s) \cos(\Delta mt) \right], \]

\[ \Im(A_s^*(t)A_{\perp}(t)) = |A_s| |A_{\perp}| e^{-\Gamma_s t} \left[ \sin(\delta_{\perp} - \delta_s) \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) \right. \]
\[ - \sin \phi_s \sin(\Delta mt) \left. \right], \]

\[ \Re(A_s^*(t)A_0(t)) = |A_s| |A_0| e^{-\Gamma_s t} \left[ - \sin(\delta_0 - \delta_s) \sin \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) \right. \]
\[ - \sin(\delta_0 - \delta_s) \cos \phi_s \sin(\Delta mt) + \cos(\delta_0 - \delta_s) \cos(\Delta mt) \left. \right]. \]
Combining LHCb results: $\phi_s = -0.002 \pm 0.083 \pm 0.027$ rad
\( \Gamma_s \) & \( \Delta \Gamma_s \)

- **B_s** lifetime measurements using fully reconstructed decays
- For \( K^+K^- \) \( A_{\Delta \Gamma} = -1 \)
- Ovals show 39% cl, while bands 68% cl
- \( \tau_s = 1.509 \pm 0.010 \) ps, \( \Delta \Gamma_s = 0.092 \pm 0.011 \) ps\(^{-1} \), \( y_s = \Delta \Gamma_s / 2 \Gamma_s = 0.07 \pm 0.01 \) (from Anna Phan)

*Only full reconstructed B\(_s\) decays used*
By definition

\[ a_{sl} = \frac{\Gamma(\bar{M} \to f) - \Gamma(M \to \bar{f})}{\Gamma(\bar{M} \to f) + \Gamma(M \to \bar{f})} \]

at \( t=0 \) \( \bar{M} \to f \) is zero as is \( M \to \bar{f} \)

Here \( f \) is by construction flavor specific, \( f \neq \bar{f} \)

Can measure eg. \( \bar{B}_s \to D^+_s \mu^- \nu \), versus \( B_s \to D^-_s \mu^+ \nu \),

Or can consider that muons from two B decays can be like-sign when one mixes and the other decays, so look at \( \mu^+ \mu^+ \) vs \( \mu^- \mu^- \)

\( a_{sl} \) is expected to be very small in the SM,

\[ a_{sl} = (\Delta \Gamma/\Delta M) \tan \phi_{12} \]

where \( \tan \phi_{12} = \text{Arg}(-\Gamma_{12}/M_{12}) \)

In SM \( (B^o) \) \( a_{sl}^d = -4.1 \times 10^{-4} \), \( (B_s) \) \( a_{sl}^s = +1.9 \times 10^{-5} \)
Using dimuons (3.9σ)

\[ A_{sl}^b = (-0.787 \pm 0.172 \pm 0.093)\% \]

Indication from D0 that its \( B_s \)

Separate dimuons into \( B_d \) and \( B_s \) samples using muon impact parameter

Find \( a_{sl}^d = (-0.12 \pm 0.52)\% \)
\( a_{sl}^s = (-1.81 \pm 1.06)\% \)
New D0 Analysis

- Measure $a_{sI}^s$ using $D_s \mu^- \nu$ events, $D_s \rightarrow \phi \pi^\pm$
- Detect a $\mu$ associated with a $D_s$ decay
- Find $a_{sI}^s = (-1.08 \pm 0.72 \pm 0.17)\%$
- Also measure $a_{sI}^d$ using $D^+ \mu^- \nu$, $D^+ \rightarrow K\pi^+\pi^+$
  $a_{sI}^d = (0.93 \pm 0.45 \pm 0.14)\%$

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\( a_{sl} \) according to D0

- \( a_{sl}^s = (-1.81 \pm 0.56)\% \)
- \( a_{sl}^d = (-0.22 \pm 0.30)\% \)
- 3\( \sigma \) from SM

(see || talk of Bertram)

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LHCb measurement

- Use $D_s \mu^- \nu$, $D_s \rightarrow \phi \pi^\pm$, magnet is periodically reversed. For magnet down:

- Effect of $B_s$ production asymmetry is reduced to negligible level by rapid mixing oscillations
- Calibration samples ($J/\psi$, $D^{*+}$) used to measure detector trigger, track & muon ID biases
LHCb finds

\[ a_{sl}^s = (-0.24 \pm 0.54 \pm 0.33)\% \]

B-factory

\[ a_{sl}^d = (-0.05 \pm 0.56)\% \]

Results consistent with SM

Expect \( \phi_s \) to grow as 
\[ \sin[2|\beta_s| + \text{arg}(M_{12}^s)] \] for finite \( a_{sl} \).
CPV in Charm


- Define: \[ A_{CP}(D \to f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} \], if \( f \) is a CP eigenstate then \( f = \bar{f} \)

- Current data mainly from LHCb, CDF & Belle show

\[ \Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.74 \pm 0.15)\% \]

- A 4.9 \( \sigma \) effect

- Both SM & NP explanations are prolific

- Choose to treat this as a limit on NP: \( 1\% > -\Delta A_{CP} > 0\% \)
$B \rightarrow K^{(*)}\ell^+\ell^-$

- Similar to $K^\ast \gamma$, but more decay paths

- Several variables can be examined, e.g. muon forward-backward asymmetry, $A_{FB}$ is well predicted in SM

+ new particles in loops
B^0 \rightarrow K^{*0} \ell^+ \ell^-

Conforms to SM prediction

LHCb preliminary
CDF
BELLE
BaBar

J/\psi
\psi'

Theory

LHCb ||
Gallas Torreira,
BaBar ||
Eigen,
CDF ||
Miyake,
Belle
PRL 103, 171801 (2009)

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Forward-Backward asymmetry

\[ A_{FB} \]

- LHCb preliminary
- J/\psi
- \( \psi' \)
- Sign of \( C_7 \) reversed
- Sign of \( C_9 C_{10} \) reversed
- Signs of \( C_7 \) & \( C_9 C_{10} \) reversed

Standard Model
NP models

No evidence of deviation from SM so far
Isospin asymmetry

$$\frac{\Gamma(B^0 \to K(\ast)^0 \mu^+ \mu^-) - \Gamma(B^+ \to K(\ast)^+ \mu^+)}{\Gamma(B^0 \to K(\ast)^0 \mu^+ \mu^-) + \Gamma(B^+ \to K(\ast)^+ \mu^+)}$$

Not SM, but no NP model yet. Annihilation diagram only for $B^-$, but why the difference for $K^*$ & $K$?
Other Processes

- Other processes probe different operators
  - Time dependent CPV in $B^0 \rightarrow K^*\gamma$, $K^* \rightarrow K_s\pi^0$, is given by
    \[
    \frac{\Gamma(\bar{B}^0(t) \rightarrow \bar{K}^{*0}\gamma) - \Gamma(B^0(t) \rightarrow K^{*0}\gamma)}{\Gamma(\bar{B}^0(t) \rightarrow \bar{K}^{*0}\gamma) + \Gamma(B^0(t) \rightarrow K^{*0}\gamma)} = S_{K^*\gamma} \sin(\Delta M_d t) - C_{K^*\gamma} \cos(\Delta M_d t)
    \]
    where $S_{K^*\gamma} = -2.3\%$ in SM
  - For Generic NP
    \[
    S_{K^*\gamma} \approx \frac{2}{|C_7|^2 + |C_7'|^2} \text{Im}(e^{-2i\beta}C_7C_7')
    \]
  - Data, BaBar & Belle (-16±22)%, still useful even with the large error
Rare Decays - Generic

\[ H_{\text{eff}} = -\frac{4 G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.} \]

- \( C_i O_i \) for SM, \( C_i' O_i' \) are for NP. Operators are for \( P_{R,L} = (1 \pm \gamma_5)/2 \)

\[ O_7 = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}, \quad O_8 = \frac{g m_b}{e^2} (\bar{s}\sigma_{\mu\nu} T^a P_R b) G^{\mu\nu a}, \]

\[ O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^{\mu}\ell), \quad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^{\mu} \gamma_5 \ell), \]

\[ O_S = m_b (\bar{s} P_R b)(\bar{\ell}\ell), \quad O_P = m_b (\bar{s} P_R b)(\bar{\ell}\gamma_5 \ell), \]

- \( O' = O \) with \( P_{R,L} \rightarrow P_{L,R} \)
- Each process depends on a unique combination
Common Analysis


Many more such generic constraints

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**$B_s \rightarrow \mu^+ \mu^-$**

- SM branching ratio is $(3.2 \pm 0.2) \times 10^{-9}$ [Buras arXiv: 1012.1447], NP can make large contributions.

Note, K. De Brun arXive:1204.1737 show that B theory needs to be raised by $1/(1-y_s)$

- Many NP models possible, not just Super-Sym
Discrimination

- LHCb & CDF use $B \rightarrow h^+ h^-$ to tune cuts. They use a multivariate analysis.
- Other variables to discriminate against bkgrd: B impact parameter, B lifetime, $B p_t$, B isolation, muon isolation, minimum impact parameter of muons, …
- CMS & ATLAS use $f_s/f_d$ from LHCb

See || talk of M. Perrin-Terrin
CLs for bkgrnd only, dashed line is the expectation, blue curve show the measurement, red the 95% cl limit

- LHCb data show slight excess consistent with SM
- Also

\[ \varepsilon(B_d \rightarrow \mu^+\mu^-) < 8.1 \times 10^{-10} \]

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$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) \times 10^{-9}$

95% confidence level limits

- LHC
- CMS
- LHCb
- ATLAS
- CDF
- D0

SM

$< 4.2 \times 10^{-9}$
Implications

- "LHC" limit
  - <4.2x10^-9 @95% CL
  - This is 1.2 times SM value

- Set serious limits in NUHM1 SUSY model

- Other LHCb results
  \[ \mathcal{B}(B_s \rightarrow \mu^+\mu^-\mu^+\mu^-) < 1.3x10^{-8} \]
  \[ \mathcal{B}(B_d \rightarrow \mu^+\mu^-\mu^+\mu^-) < 5.4x10^{-9} \]

Predicted via “portals”

see arXiv:0911.4938

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The 125 GeV Higgs observations kills off 4th generation models as the production cross-section would be 9x larger & decays to $\gamma\gamma$ suppressed
B$^-$→τ$^-$ν problem?

- B$^-$→τ$^-$ν, tree process:
  
  - sin2β, CPV in e.g. B$^0$→J/$\psi$ K$_S$: Box diagram
  
  - Measurement not in good agreement with SM prediction based on CKM fit (Yook $|$ talk)

Discrepancy may be resolved; what caused the change?

Can be new particles instead of W$^-$ but why not also in D$^{+}_{(s)}$→ℓ$^+$ν?
Peaking Backgrounds

- Since $e^+e^- \rightarrow B^+B^-$, analysis uses reconstruction of $B^+$, detection of $\tau^- \rightarrow$ one track & small extra E
Also, tree level – new BaBar result

Similar to $B^- \rightarrow \tau^- \nu$ analysis: fully reconstruct one $B$, keep events with an additional $D^{(*)}$ plus an $e^-$ or $\mu^-$. 

Signal is wide, background, especially $D^{**} \ell \nu$, needs careful estimation
BaBar results

- Results given in terms of ratio to $B \rightarrow D(*)\ell\nu$

<table>
<thead>
<tr>
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<th>SM Theory</th>
<th>BaBar value</th>
<th>Diff.</th>
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<tbody>
<tr>
<td>$R(D)$</td>
<td>$0.297 \pm 0.017$</td>
<td>$0.440 \pm 0.058 \pm 0.042$</td>
<td>$+2.0\sigma$</td>
</tr>
<tr>
<td>$R(D^*)$</td>
<td>$0.252 \pm 0.003$</td>
<td>$0.332 \pm 0.024 \pm 0.018$</td>
<td>$+2.7\sigma$</td>
</tr>
</tbody>
</table>

- Sum is $3.4\sigma$ above SM
- Also inconsistent with type II 2HDM
  (see De Nardo || talk)
Belle Results

Two types of analysis, hadronic tags (arXiv: 0910.4301) similar to BaBar and also “inclusive tags” (A. Matyja et. al, PRL 99,191807 (2007)).

• Belle data currently support BaBar indication of larger than expected rates
• Belle should be able to reduce uncertainties to the BaBar level
• Will be interesting to see results of 2D fits
The Dark Sector

Could it be that there are 3 classes of matter?
- SM particles with charges $[SU(3) \times SU(2) \times U(1)]$
- Dark matter particles with “dark” charges
- Some matter having both (“mediators”)

Searches for “dark photons”
- A mediator, couples to $b$-quarks (see arXiv:056151 hep/ph)
- BaBar $\varepsilon(Y(1S) \rightarrow \text{invisible}) < 3 \times 10^{-4} @ 90\% \text{ cl}$
- Other experiments
Search Summary

- Parameterize by mixing $\varepsilon$
- Dark photon mass $m_A'$

Needed to explain $g-2$

From B. Echenard arXiv:1205.3505
Dark Higgs

- BaBar search for $e^+e^-\rightarrow h'A', h'\rightarrow A'A'$
- $A'$ is looked for in $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ & hadrons
- Limits parameterized in terms of mixing $\varepsilon$ & dark matter coupling $\alpha_D$

- Nothing found, upper limits set at 90% cl:
Several ways of looking for presence of heavy \( \nu \)'s (N) in heavy quark decays if they are Majorana (their own anti-particles) and couple to “ordinary” \( \nu \)'s

Modes analogous to \( \nu \)-less nuclear \( \beta \) decay

Simplest Channels:

\[ B^- \rightarrow D^+ e^- e'^- \quad \& \quad B^- \rightarrow D^{**} e^- e'^- \]

\( e^- \) & \( e'^- \) can be \( e^- \), \( \mu^- \) or \( \tau^- \).
## Limits on $D^{(*)+} e^- e'^-$

- Upper limits in $e^- e^-$ mode not competitive with nuclear $\beta$ decay
- Others unique since measure coupling of Majorana $\nu$ to $\mu^-$

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<tr>
<th>Mode</th>
<th>Exp.</th>
<th>u. l. x $10^{-6}$</th>
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<tbody>
<tr>
<td>$B^- \rightarrow D^+ e^- e^-$</td>
<td>Belle</td>
<td>&lt; 2.6</td>
</tr>
<tr>
<td>$B^- \rightarrow D^+ e^- \mu^-$</td>
<td>Belle</td>
<td>&lt; 1.8</td>
</tr>
<tr>
<td>$B^- \rightarrow D^+ \mu^- \mu^-$</td>
<td>Belle</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>$B^- \rightarrow D^+ \mu^- \mu^-$</td>
<td>LHCb</td>
<td>&lt; 0.69</td>
</tr>
<tr>
<td>$B^- \rightarrow D^{*+} \mu^- \mu^-$</td>
<td>LHCb</td>
<td>&lt; 3.6</td>
</tr>
</tbody>
</table>

Belle [arXiv:1107.064]
On-Shell $\nu$

- Can also look for Majorana $\nu (N)$, where $N \rightarrow W^+ \mu^-$
- Several ways
  - A. Atre, T. Han, S. Pascoli, & B. Zhang [arXiv:0901.3589]
LHCb searches

Nothing yet

Aaij, PRD 85, 112004 (2012)
Conclusions

- Although there is no compelling evidence yet for NP, Heavy Flavor physics is very sensitive to potential effects at high mass scales. All NP theories must satisfy stringent experimental constraints.

- Experiments have been very effective at dispelling effects with marginal statistical significance, although a few remain. Will some stand when precision improves?

- Improving measurements such as $B_s \rightarrow \mu^+\mu^-$, $B \rightarrow K\mu^+\mu^-$, CPV: $\phi_s$, etc., may show NP effects, & need to be aggressively pursued.

- We are looking forward to new flavor physics discoveries from the LHC & its upgrades, BESIII, and Super B factories.

- We are looking forward to defining the next theory beyond the SM.
Theory conquers
Thanks!

- To my scientific secretary Antonio Limosani
- Conference organizers:
  - Geoffrey TAYLOR
  - Raymond VOLKAS
  - Paul HOGAN
- Apologies for all the interesting results, I left out

ICHEP, Melbourne, July 9, 2012
The End