Workshop Summary & Outlook

Thanks to the organizers: John Ellis, Tim Gershon, Gino Isidori, Patrick Koppenburg, Gilad Perez, Frederic Teubert, Andreas Weiler, Guy Wilkinson etc…

*Apologies if I did not mention your talk
Prime Objective

- Dictates that physics beyond the Standard Model must be found.
- “The success of the LHCb experiment has so far been a nightmare for all flavour physicists…” Gauld, Goetz and Haisch.
1 TeV Scale New Particles

Naturalness

- Higgs is most sensitive to physics of order $M=125$ GeV, has been pushed to $\sim 1$ TeV due to absence of signals. Can be pushed higher. (Soni suggests 10 TeV for KK)
- But corrections to Higgs mass go as $M^2$, so can’t push $M$ too high without getting into fine tuning problem (see Zupan’s talk)
- Need New Physics to cut off quantum corrections

Suggested NP mechanisms: SUSY, Higgs compositeness, and extra dimensions. Each predicts a rich spectrum of new states

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Flavor as a High Mass Probe

- Already excluded ranges if $c_i \sim 1$

\[ L_{\text{eff}} = L_{\text{SM}} + \frac{c_i}{2} O_i, \quad \text{take } c_i = 1 \]

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

New physics ruled out from $\Lambda_f = 0$ to somewhere in the blue boxes

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Meson Mixing

* Meson mixing’s powerful:

<table>
<thead>
<tr>
<th>Technique</th>
<th>Coupling</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$ oscillations</td>
<td>$</td>
<td>Y_{uc}</td>
</tr>
<tr>
<td>$B^0_s$ oscillations</td>
<td>$</td>
<td>Y_{ub}</td>
</tr>
<tr>
<td>$B^0_d$ oscillations</td>
<td>$</td>
<td>Y_{ub}</td>
</tr>
</tbody>
</table>

**“Natural” models are constrained!**

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Generic Analyses

- Compare measurements
- Look for discrepancies

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NP via $\Delta F=2$ processes

- $B^0_{(s)}$ mixing and CP. Parameterize NP as $h \& \sigma$

\[ M_{12} = M_{12}^{SM} \times (1 + h e^{2i\sigma}) \]

- Tree level processes are assumed not to contain NP, so measure well, especially $V_{ub} \gamma$

- From Zoltan’s talk, now and future
95% cl Limits

Current

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Future

- Belle II, LHCb Upgrade
- Assuming no NP

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Although we assumed before that there was no NP in tree level diagrams, here we revoke that criteria

What do we know about right-handed currents in $b$ decays?

CLEO result from $\sim 1/fb$
- $\cos\theta$ is $D^{*+}$ decay angle

**TABLE III.** The $\chi^2/N_{\text{DF}}$ for $N_{\text{DF}}=4$ for the fits to the $\cos\theta$ distribution and 95% C.L. limits for allowed amount of $V + A$ hadronic current.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\bar{B}^0 \rightarrow D^{*+}l^-\bar{\nu}_l$</th>
<th>$B^- \rightarrow D^{*0}l^-\bar{\nu}_l$</th>
<th>Simultaneous fit $(V + A)/(V - A)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISGW</td>
<td>1.6</td>
<td>9.0</td>
<td>&lt; 19%</td>
</tr>
<tr>
<td>KS</td>
<td>0.9</td>
<td>15.7</td>
<td>&lt; 30%</td>
</tr>
<tr>
<td>WSB</td>
<td>2.3</td>
<td>12.0</td>
<td>&lt; 24%</td>
</tr>
</tbody>
</table>

**FIG. 3.** $dN/d\cos\theta$ distribution: (a) in the decay $\bar{B}^0 \rightarrow D^{*+}l^-\bar{\nu}_l$ and (b) in the decay $B^- \rightarrow D^{*0}l^-\bar{\nu}_l$. Overlaid are the results of the fits of the ISGW model assuming pure $V - A$ or $V + A$ currents for the $b \rightarrow c$ transition.
A fix for $V_{ub}$?

- Conflicts among $V_{ub}$ measurements
- Different processes have different sensitivities to right-handed currents

| Decay               | $|V_{ub}| \times 10^4$ | add right-handed current |
|---------------------|------------------------|--------------------------|
| $B \rightarrow \pi \ell \bar{\nu}_\ell$ | $3.23 \pm 0.30$        | $(1 + \epsilon_R)$      |
| $B \rightarrow X_u \ell \bar{\nu}_\ell$ | $4.39 \pm 0.21$        | $(1 + \epsilon_R^2)$    |
| $B \rightarrow \tau \bar{\nu}_\tau$    | $4.32 \pm 0.42$        | $(1 - \epsilon_R)$      |

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- $V_{ub}$ values as functions of $\varepsilon_R$
- First done by: Crivellin, arXiv:0907.2461
- Ligeti suggests using $\rho \ell \nu$ to measure $\varepsilon_R$
LHCb does semileptonic decays

- Used to measure $f_s/f_d$, otherwise $B_s \rightarrow \mu^+\mu^-$ is only half a measurement (inclusive e.g. $D_s\mu X\nu$; also used for $A_{s_{sl}}$)

- Exclusive semileptonic can also be done using constraint of knowing $b$-decay direction (ala’ FNAL fixed target experiments)

- Projections of 2-D fit to $D_s\mu X\nu$
Shopping list

- $B_s \rightarrow K^{(*)} \mu \nu$
- $B_s \rightarrow D_s^{(*)} \mu \nu$ these & above used to provide an independent measure of $V_{ub}/V_{cb}$
- $B^0 \rightarrow \rho^0 \mu \nu$ including right-handed current measurements
- $B^0 \rightarrow D^{*-} \mu \nu$ including right-handed current measurements
- $B \rightarrow D^{**} \mu \nu$ needed to understand
- $B^0 \rightarrow D^{*-} \tau \nu$, see talk of Ciezarek
See talk of Gandini

Use clean methods only

Don’t use $B^- \rightarrow D^0 \pi^-$, due to possible contamination from $D^0$ CPV. Use $B^- \rightarrow D^0 K^-$ & eventually $D_s K$

Don’t use $B^0 \rightarrow \pi^+ \pi^-$, with $B^0 \rightarrow K^+ K^-$ assuming U-spin symmetry, but use this to measure the U-spin breaking, so we may be able to use U-spin for something else (e.g. limiting Penguins in $\phi_s$)

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Top Down Analyses

- Here we pick a model and work out its consequences in many modes
- Example

Girrbach

\[ u (2)^3 \]

\[ \epsilon_K \]

\[ \Delta M_s \leftrightarrow \Delta M_d \]

\[ S_{\psi\phi} \leftrightarrow S_{\psi\phi} \]

\[ B_s \rightarrow \mu\bar{\mu} \leftrightarrow B_d \rightarrow \mu\bar{\mu} \]

\[ K^+ \rightarrow \pi^+\bar{\nu}\nu \leftrightarrow K_L \rightarrow \pi^0\bar{\nu}\nu \]

\[ B \rightarrow K^{(*)}\bar{\nu}\nu \]

enhancement

suppression

no change

correlation ⇔

anti-correlation ⇔

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I find $K\ell^+\ell^-$ very interesting (Langenbruch talk)

(1) Isospin asymmetry at 4.4 $\sigma$ level & doesn’t look like experimental effect as not seen in $K^*\ell^+\ell^-$. No model can reproduce effect. A real hint at NP or long distance effects that we do not understand? (Zwicky talk)
(2) Resonant substructure in $\ell^+\ell^-$. Should be present in $K^{(*)}\ell^+\ell^-$. Why hasn’t it been seen?

- Are there more states?
- Need to put in $K^*$ calculations. Can affect angular distributions far from mass peaks as states are wide
K* $\ell^+ \ell^-$ déjà vu $\Delta A_{cp}$?

- 1\textsuperscript{st} $\Delta A_{cp}$ then $P_5$ in one $q^2$ bin. Theory input…
Much ado about discrepancy in one $q^2$ bin with some SM predictions

In order to see NP must see more than one effect. Need to establish a pattern

van Dyk: some difference between using all data and selected

red(all)
blue(sel)
68%, & 95%

cl intervals

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- Straub: top down model with multi-TeV $Z'$ can explain data
- PS: some disagreement in theoretical prediction uncertainty (see talks of van Dyk and Mahoudi) & relatively large errors.
Wingate: lattice QCD can help
Null Test From Charm

- Charm CPV not established. $\Delta A_{cp}$
  - HFAG = (0.33±0.12)%
  - LHCb $\pi^\pm$ tags (-0.34±0.18)%, $\mu^\pm$ tags (0.49±0.37)%
  - My view $|\Delta A_{cp}|<(1-\varepsilon)$%, where $\varepsilon\sim0.5$ (more data needed)
  - A very useful constraint on NP models

- Not a null test: Charm mixing firmly established at 1% level, likely long distance effect
  $D^0 \Rightarrow \pi\pi(KK)(...) \Rightarrow \bar{D}^0$, but $x'$ & $y'$ parameters not yet well measured

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Null Tests from B CPV

- $\phi_s: 0.01 \pm 0.07 \pm 0.01$ rad
- Potential use of all the $B_s \rightarrow J/\psi \ K^+K^-$ rate (see Van Leerdam’s talk)
- $A_{SL}^s \times 3$ statistics available
- Both important to search for NP

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Seeking NP at higher masses (Coco)

- Since Higgs couples to mass we should do what we can on top quarks especially where we can do better than ATLAS & CMS despite the factor of 10 less $\int L$
- Strassler points out other searches for new Higgs decays or new long lived particles
- Can also search for Majorana neutrinos from D, B or even W decays

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tt\bar{t} asymmetry

- Seen in CDF & D0
- (By the way getting fed up with disproving CDF/D0 results hinting at NP, e.g. $\phi_s$, $A_{sl}$)
- Because LHC is at larger $\eta$ asymmetry is larger than in ATLAS/CMS due to more $qq$ and $qg$ scattering
- Use $t\rightarrow Wb$, $W\rightarrow \mu\nu$, 
- Predictions of signal & background from Kagan, Kamenik, Perez & Stone
  arXiv:1103.3747

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Predictions for LHCb

- $t \rightarrow Wb$, $W \rightarrow \mu \nu$ signal
- $W+$light quark jet including charm scaled to ATLAS measured $\sigma$.
- Single top production
  - $W+b$ jet (not from top)
  - $b\bar{b}$ with one $b \rightarrow \mu$, reduced by jet isolation (anti-kt jet algorithm used)
- light dijet’s reduced by $b$ tagging, jet isolation & $\mu$ id
Necessary Ingredients for $t \rightarrow bW$

- $W^{\pm} \rightarrow \mu^{\pm} \nu$ detection
- Jet reconstruction and energy measurement
  - Require large efficiency for high $p_T$, and energy resolution so that $\sigma_{m(\mu\text{-jet})} \sim 20$ GeV
- Algorithm for $b$-jet tagging
  - Measurement of tagging efficiency ($\varepsilon$)
  - Measurement of light quark rejection (R)
  - Requirement is $R > 100:1$ for $\varepsilon > 50\%$

Tuesday meeting, Oct. 25, 2011
Jet energy scale determined to 1% from Z+1 jet events

For $p_T > 10$ GeV jet energy resolution is 10-15%

b-jet tagging: for 50% eff have 99.5% light quark rejection. $b\bar{b}$ asymmetry already measured

$t\bar{t}$ asymmetry measurement is ready for prime time
My view -- **Highest priority for LHCb for Long-Lived Particles:** Higgs boson decays

- We know at least one exists!
- The Higgs decays via weak couplings/loops/off-shell W/Z and is very sensitive to new particles.
- Must develop comprehensive knowledge of this particle
- Tough Target: Many final states difficult for ATLAS/CMS
- But if you can do it, many Higgs-related searches will exclude other models too

- For long-lived particles, LHCb has a niche
  - Low masses (0.1? – 100? GeV)
  - Short lifetimes (ps – 100 ps)
  - Complex final states with multiple (possibly clustered) vertices
  - Final states with 1 or 0 leptons and many hadrons

- Fortunately this is an extremely interesting niche because it is where the Higgs boson sits

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Conclusions

- Recall Prime Objective: to seek out and find new physics wherever it may be hiding
- We have a great deal to do even with current data: many areas not discussed in this workshop, e.g. CPV in $B^0$, $B_s$ etc…light meson spectroscopy: $qq$ versus tetraquark, etc..
- Much to do with jets, right-handed currents, $\gamma$, $V_{ub}$, $K^{(*)}\mu\mu$, even charm
- It will be fun!

- Much thanks to our theory friends for coming Implications workshop, Oct. 18, 2013

For Yuval
Pleasant Dreams!

- LHCb discovers New Physics
The End
Signal example

- Predicted cross-section difference between $t$ and $\bar{t}$ in the $Z'$ model of Jung et al. [arXiv:0907.4112]