B Physics in the LHC Era

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Is the $B$ the $K$ of the 21st Century?

$K$ meson has driven particle physics:

- Strangeness
- Mixing of neutral kaons
- $\tau - \theta$ puzzle leads to parity violation
- Strangeness leads to $SU(3)$ leads to quarks
- CP violation in $K_L$ decay
- Absence of neutral weak currents leads to charm
- $\epsilon'/\epsilon$ shows direct CP violation
• Electroweak-Symmetry Breaking

• Grand Unification/Extra Dimensions

• Baryon-Antibaryon Asymmetry

• Dark Matter

• Dark Energy
$B$ Physics: Virtual Attack

- $B_d \rightarrow J/\psi K_S$
- $B_s \rightarrow J/\psi \phi$
- $B_d \rightarrow K^*\gamma, K^*\ell^+\ell^-$
- $B_d \rightarrow \phi K_S, K^+K^-K_S, \eta'K_S$

What's in the box? SUSY?, extra generations, extra dimensions?
Tomorrow

BTeV

LHCb

$10^{36}$
1. Measure: mixing angle

2. Theory problems: none

3. Experimental problems: none

4. Precision in $\sin 2\beta$

<table>
<thead>
<tr>
<th></th>
<th>BaBar</th>
<th>Belle</th>
<th>$e^+e^-$</th>
<th>BTeV/LHC-b</th>
<th>Super B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.08 ab$^{-1}$</td>
<td>0.14 ab$^{-1}$</td>
<td>0.5 ab$^{-1}$</td>
<td>10$^7$ s</td>
<td>10 ab$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>0.067 $\oplus$ 0.033</td>
<td>0.057 $\oplus$ 0.028</td>
<td>0.03</td>
<td>0.017</td>
<td>0.008</td>
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</tbody>
</table>
1. Measure: mixing angle and possible new physics

2. Theory motivation: new physics could compete

3. Experimental problems: low branching ratio

4. Precision in $\sin 2\beta$

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<th>BaBar/Belle</th>
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<th>Super B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.11 \text{ ab}^{-1}$</td>
<td>$10^7 \text{ s}$</td>
<td>$10 \text{ ab}^{-1}$</td>
</tr>
<tr>
<td>$0.5 \text{ ab}^{-1}$</td>
<td>$0.14$</td>
<td>$0.056$</td>
</tr>
<tr>
<td>$0.43 \oplus 0.07$</td>
<td>$0.23$</td>
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\( B_s \) oscillations: \( x_s \)

1. Measure: mixing in \( B_s - \overline{B_s} \) system

2. \[
\frac{x_s}{x_d} = \frac{m_{B_s} \eta_{B_s} B_{B_s} f_{B_s}^2}{m_{B_d} \eta_{B_d} B_{B_d} f_{B_d}^2} \left| \frac{V_{ts}}{V_{td}} \right|^2 \rightarrow 10\% \text{ uncertainty in } \left| \frac{V_{td}}{V_{td}} \right|
\]

3. Experimental problems: need \( B_s \)!

4. CDF/D0 should measure \( x_S \) with good precision

5. Lattice calculations needed to get full benefit of measurement
Could this be LHC Era Physics?
CDF Estimate [K. Pitts, L-P 2003]

• Currently
  – 1600 signal events / fb $^{-1}$
  – Tagging efficiency: $\epsilon D^2 = 4\%$
  – Time resolution: $\sigma = 67 \, f s$
  – Sensitivity: $2\sigma$ for $\Delta m_s = 15 \, ps^{-1}$ with $\approx 0.5 \, fb^{-1}$

• “Modest Improvements”
  – 2000 signal events / fb $^{-1}$ [better trigger, more modes]
  – Tagging efficiency: $\epsilon D^2 = 5\%$ [kaon tagging]
  – Time resolution: $\sigma = 50 \, f s$
  – Sensitivity: $5\sigma$ for $\Delta m_s = 18 \, ps^{-1}$ with $\approx 1.7 \, fb^{-1}$
  – Sensitivity: $5\sigma$ for $\Delta m_s = 24 \, ps^{-1}$ with $\approx 3.2 \, fb^{-1}$
$B_s \rightarrow J/\psi \phi, J/\psi \eta'$

1. Measure: analog of $B \rightarrow J/\psi K_S$ No asymmetry to lowest order.

2. Theory motivation: new physics with phase of $B_d - \bar{B}_d$ mixing would show up

3. Experimental problems: requires $B_s$, good spatial resolution

4. BTeV reach in $\sin 2\chi : \pm 0.024$
\[ B \rightarrow \pi\pi \]

- Measure: mixing angle (arg \( M_{12} \)) plus \( 2\gamma \), i.e. \( 2\pi - 2\alpha \)

- Theory concern: prominent penguin contribution

- Experimental problems: small branching ratio for \( \pi^0\pi^0 \)

- Penguins are \( \Delta I = 1/2 \) operators, trees \( \Delta I = 3/2, 1/2 \)

- Use isospin to isolate \( I = 2 \) final state (no penguin contribution)
Fighting Penguins in $B \rightarrow \pi \pi$

$\alpha_{eff}$ from time-dep. $B^0, \bar{B}^0 \rightarrow \pi^+ \pi^-$

$2\alpha = 2\alpha_{eff} + \phi - \phi'$

(Four-fold) Ambiguity: $\phi \rightarrow - \phi$

- Measure time-integrated $\Gamma(B^+ \rightarrow \pi^+ \pi^0) = \Gamma(B^- \rightarrow \pi^- \pi^0)$

- Separately measure time-integrated $\Gamma(B^0 \rightarrow \pi^0 \pi^0), \Gamma(\bar{B}^0 \rightarrow \pi^0 \pi^0)$

$$\cos \phi = \frac{\mathcal{B}(\pi^+ \pi^0) + \frac{1}{2} \mathcal{B}(\pi^+ \pi^-) - \mathcal{B}(\pi^0 \pi^0)}{\sqrt{2 \mathcal{B}(\pi^+ \pi^-) \mathcal{B}(\pi^+ \pi^0)}}$$
MC Study Shows Ambiguities Bite

• Toy Monte Carlo study (RNC and Roodman):

• $BR(B^0 \rightarrow \pi^0\pi^0)$ now known:
  – $(2.1 \pm 0.6 \pm 0.3) \times 10^{-6}$ [BaBar]
  – $(1.7 \pm 0.6 \pm 0.2) \times 10^{-6}$ [Belle]

Histogram of 1000 experiments: input

• Branching ratios are in units of $10^{-6}$.

• Background based on BaBar results

| $B^{\pm} \rightarrow \pi^{\pm}\pi^0$ | 4.1 |
| $B^0 \rightarrow \pi^+\pi^-$ | 4.7 |
| $B^0 \rightarrow \pi^+\pi^-$ | 4.7 |
| $B^0 \rightarrow \pi^0\pi^0$ | 2.5 |
| $\bar{B}^0 \rightarrow \pi^0\pi^0$ | 1.5 |
• Precision in $\alpha$ in $\pi \pi$ requires enormous integrated luminosity

• This seems to be a possibility only for a $10^{36} \text{ cm}^{-2} \text{ s}^{-1} e^+e^-$ machine

• Alternatives $\rho \pi$ and even $\rho \rho$ look interesting
1. Major $\gamma$ bkgd from $\pi^0$, $\eta$, etc.

2. Lowest order is one loop so new physics should be prominent

3. Need model to get full spectrum
   - To reduce background, require $E^*_\gamma > E_{\text{min}}$
   - Require lepton from other $B$ to remove continuum.
   - Need theory for spectrum, not just total rate
   - Prediction for spectrum above 2.2 GeV uncertain by about 15%
1. Measure exclusive decays and sum, excluding in $J/\psi$ etc.

2. Theory issue: probes $\gamma, Z$ and $W$ box diagrams

3. Experimental: clean for $K^*\ell\bar{\ell}$
$b \to s \ell\bar{\ell}$ Forward-Backward Asymmetry

- Comes from interference between axial ($\mathcal{O}_{10}$) and vector ($\mathcal{O}_{7,9}$)

- Need to understand various form factors evaluated at $s = m_{\ell\ell}^2$

- New Physics can enter through $\mathcal{C}_{7,9,10}$

Simulation from BTeV, 2500 events/y
Traditional goal of $B$-physics experiments

- High precision using lots of data
- Find discrepancy with Standard Model
- Ascribe difference to virtual particles in Box
- Read announcement of discovery of supersymmetry in NYT
Two approaches:

B physics:
shake the Box, listen

LHC: open the Box
Who discovered the $W$ boson?
History of Virtual Discoveries

- 1934: Enrico Fermi (or Ernest Rutherford in 1898) discovered the $W$
- 1973: Gargamelle discovered the $Z$
- 1974: Ben Lee and Mary K. Gaillard discovered charmed particles
- 1994: LEP discovered the $t$ quark

Predictions of real particles from virtual effects are astonishing. But few are convincing until the real thing appears.
Context for Next Generation B Physics Experiments
Possible scenarios at LHC

ATLAS

• Discover new spectroscopy:
  jackpot for particle physics

• Discover single, orthodox Higgs boson:
  happy for 24 hours

CMS

• Strongly interacting $W$, $Z$ (disfavored):
  life is tough

• ???
Quark Flavor Physics in LHC Era

• If there is a new spectroscopy:
  – Confirm predicted radiative corrections?
  – Discriminate between possible models?

• If there is an orthodox Higgs
  – Confirm Standard Model predictions

• Something else
  – Confirm (modified?) Standard Model predictions

• A higher standard:
  – With competition from LHC, it will not be enough to find hints of new physics. The demands on precision and clean interpretation will be much greater.
Current Unitarity Triangle

- Precise experiments
- Theory uncertainties dominate
Theory Must Become as Rigorous as Experiment

- Lattice gauge calculations needed to sharpen tests of unitarity triangle.
- Effective theories derived from QCD needed for dynamical understanding.
- An experimental result lacking statistical and systematic errors is meaningless.
- Theory must meet same standard if it is to be used to challenge standard model.
- Give consideration to increased support for lattice work, contingent on review comparable to review of proposed experiment: real schedule for attaining verifiable performance standards.
Spirit of Next Generation Flavor Physics

• Standard Model likely to have been verified to basic level:
  – Success of SM in $\sin 2\beta$ impressive
  – Had been likely target for deviation

• Only deviations that are truly convincing are likely to be interesting
  – $2\sigma$: 50 theory papers
  – $3\sigma$: 250 theory papers
  – $5\sigma$: strong sign of effect


$B$ Physics isn’t just looking for New Physics

- Standard Model is extraordinary. It deserves thorough elucidation.
- Unitarity Triangle demands verification despite LHC advantage in New Physics.
- QCD remains incompletely understood. $B$ decays provide excellent stage for examination.
- $B$ mesons are source for other phenomena
  - $B \rightarrow DD_s(2317)$
  - $B \rightarrow \psi(3870)K$
Particle Physics circa 2010

• If a new spectroscopy is found at LHC
  – Those at LHC will be ecstatic.
  – Electrophiles will have a compelling case for LC.

• If no new spectroscopy is found at LHC
  – Mood at CERN will not be good.
  – LC is very improbable.

• In either case, there will be an active $B$ physics program
  – At CERN, LHCb might be the most interesting experiment.
  – BTeV could be leading (only?) non-neutrino HEP experiment in US.
  – At SLAC and KEK, accelerators will be pushed to higher and higher luminosity.