Results from the Tevatron - Flavor

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Anomalous CP Violation

Spectroscopy

(WS Hou)
• **Goal:**
  – Interesting and competitive results in the B factory era.

• **Requirements:**
  – Very large sample of b hadrons
  – Good detectors
    • Particularly vertexing
  – **Niche**
    • Something you can do better than the B factories
• Highest lum hadron machine + very large production cross sections = large b hadron sample

Peak lum: 
3.5 x 10^{32} cm^{-2}s^{-1}

Delivered: ~6 fb^{-1}
Expect: ~12 fb^{-1}

Micro-barn level cross sections for heavy hadrons after acceptance cuts.
Both large multi purpose detectors with excellent impact parameter resolution and muon identification

CDF advantage:
momentum resolution plus trigger bandwidth.

DØ advantage:
Muon acceptance and purity.

Common disadvantage:
Low momentum photon ID

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• Niche:
  – b hadron spectroscopy
  – $B_s$ physics
• High center of mass energy gives access to all b hadrons

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• Most can also be done at B factories running off the 4S but for now, this is our competitive niche.
Spectroscopy

The $\Omega_b$
**Importance of Spectroscopy**

- Spectroscopy is the study of how colored particles combine to form the colorless objects we observe.

\[
Q \bar{Q} \quad Q \bar{q} \quad Q q \quad Q \bar{Q} q \quad q \bar{q} q \quad q \bar{q} \quad q \bar{q} g
\]

- Has played a vital role in our understanding of the Standard Model
  - Symmetries
  - The quark model
  - Confinement
  - Lattice QCD
  - Exotic bound states

- Observables:
  - Allowed or forbidden
  - Mass, width, spin
  - Production and decay properties

- If physics beyond the Standard Model is strongly coupled, many of the tools used to understand low energy spectroscopy will be needed for high energy spectroscopy
  - Little higgs, 4th generation, dynamical symmetry breaking mechanisms…
Baryon spectroscopy at the Tevatron

- Very large data set so can afford to look in clean modes containing $J/\psi \rightarrow \mu\mu$ in the final state

- Many also contain long lived particles like $\Lambda$ which also help reduce backgrounds

- Strategy: start with $B_d \rightarrow J/\psi \ K_S$ and replace the $K_S$ with a baryon
  - $\Lambda_b \rightarrow J/\psi \ \Lambda$
  - $\Xi_b \rightarrow J/\psi \ \Xi$
  - $\Omega_b \rightarrow J/\psi \ \Omega$

\[ \sim 29 \ M \ J/\psi \text{ in } 4.2 \ fb^{-1} \]

\[ \sim 3.6 \ M \ \Lambda \]

\[ \sim 5 \ cm \]

\[ \sim 3 \ cm \]
Tracking for Very Long Lived Particles

• Complication at DØ:
  – Standard tracking is inefficient for very long lived particles (impact parameters > 2 cm)
    • Too slow to run algorithms with looser cuts on all the data
  – Can run looser tracking (imp ~ 10 cm) on events containing $J/\psi \rightarrow \mu\mu$

• CDF tracker radius is ~2x DØ’s so not really a problem.
  – CDF has results up to 4.2 fb$^{-1}$

Still complicated and only first 1.3 fb$^{-1}$ available for analysis.
Background reduction

• Difficult to use MC
  – Momentum,
  – mass,
  – lifetime unknown

• DØ:
  – Remove background by tuning on intermediate resonances

• CDF:
  – simple cuts motivated by other b hadrons + more data.
August 08

1.3 fb$^{-1}$

18 ± 5 events

5.4 $\sigma$ significance

$m = 6165 \pm 10 \pm 13$ MeV

PRL 101, 232002 (2008)
May 09
4.2 fb$^{-1}$
12 ± 4 events
5.5 $\sigma$ significance
$m = 6054.4 \pm 6.8 \pm 0.9$ MeV
arXiv:0905.3123v1 submitted to PRD
Mass measurements differ by $111 \pm 12 \pm 14$ MeV

CDF does not confirm DØ observation
**Same production rate?**

\[
\frac{f(b \rightarrow \Omega_b^-) Br(\Omega_b^- \rightarrow J/\psi \Omega^-)}{f(b \rightarrow \Xi_b^-) Br(\Xi_b^- \rightarrow J/\psi \Xi^-)} = 0.80 \pm 0.32(\text{stat})^{+0.14}_{-0.22}(\text{syst})
\]

\[
\frac{\sigma B(\Omega_b^- \rightarrow J/\psi \Omega^-)}{\sigma B(\Xi_b^- \rightarrow J/\psi \Xi^-)} = 0.27 \pm 0.12 \pm 0.01
\]

1.3 \(\sigma\) difference in production rate

1.6 \(\sigma\) stat only

\[
\frac{\sigma B(\Omega_b^- \rightarrow J/\psi \Omega^-)}{\sigma B(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = 0.045^{+0.017}_{-0.012}(\text{stat.}) \pm 0.004(\text{syst.})
\]
SAME LIFETIME?

CDF

\[ c \tau(\Omega_b) = 340^{+160}_{-120} \text{ \(\mu m\)} \]

DØ

no measurement, just comparison with 0 \(\mu m\) and 460 \(\mu m\) proper decay lengths

Both consistent with a weakly decaying particle
Both experiments demonstrate lack of peaking background with sidebands and wrong-sign combination events.
Both experiments agree on all other hadrons. Intermediate resonances also in the correct place.
Both experiments claim observation of the $\Omega_b$ but the masses differ by > 100 MeV
- CDF’s mass measurement agrees with expectations, DØ’s does not

Both results robust and seem to agree on other properties within large uncertainties

More data coming (and on tape at DØ) so hopefully this will be resolved soon
Anomalous CP Violation
In $B_s$ mixing

(WS Hou)
CP Violation

- CP Violation allows us to differentiate matter interactions from anti-matter interactions

- CP Violation is needed to explain our existence

- CP violation already seen in B and K systems is not enough

- Motivates current searches:
  - Neutrinos
  - Atomic and lepton EDMs
  - Rare decays with loops
  - Neutral meson mixing

- Today: $B_s$ system
Probing for new CP violating phases that effect $B_s$ mixing but have little or no effect on $B_d$ mixing

Good example is 4th generation models

Penalty in weak interactions for skipping a generation

$V_{t's} \gg V_{t'd}$

Recent summary:
"Four Statements about the 4th Generation" arXiv:0904.4698
Holdom, Hou, Hurth, Mangano, Sultansoy, Unel
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**Phenomenology**

- ‘**Kaon**’ type CPV:
  - $K_{\text{Short}} \neq K_{\text{even}}$, $K_{\text{Long}} \neq K_{\text{odd}}$
    - Experiment: study of decays of $K_{\text{Short}}$ and $K_{\text{Long}}$
    - $\Delta \Gamma$: lifetime difference between states

- ‘$B_d$’ type CPV:
  - interference in decays before or after mixing
    - Experiment: separate the time dependence of $B_d$ and anti-$B_d$ decaying to CP eigenstates
    - $\Delta m$: time it takes to mix

- $B_s$:
  - Interference between mixing and decay ($B_d$ type)
  - $\Delta \Gamma_s >$ experimental resolution: separate study of heavy and light decay channels (Kaon type)
    - Experiment: both
B_s → J/ψ φ: Kaon Type CPV

Pseudo scalar → Vector + Vector. Both even and odd states contribute.

Angular analysis tells if its even or odd.

Lifetime measurement tells if its long or short

Look for even states decaying with a longer lifetime ⇒ CPV
$B_s \rightarrow J/\psi \phi$: $B_D$ Type CPV

Mirror image of a double slit experiment

Need to analyze $B_s$ and $\bar{B}_s$ initial states separately

Fragmentation: $\bar{s}$ or $s$?

recoil: $\bar{b}$ or $b$?

Validate tagging performance using $B^\pm$ samples

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Results taken from a multi-parameter fit including flavor, lifetime, polarization, backgrounds, CP conserving, and CP violating interference

\[ \psi \phi \text{ RESULTS} \]

Results taken from a multi-parameter fit including flavor, lifetime, polarization, backgrounds, CP conserving, and CP violating interference

\[ \beta_s^{J/\psi} < 1.42 \text{ @ 95\% CL} \]

(2\% chance SM is still OK) (\(\beta_s \approx 0.04\))
Flavor specific lifetimes

\[ \tau_{FS} = \frac{1}{\Gamma_s} \left( \frac{1 + y^2}{1 - y^2} \right) \]

\[ y = \frac{\Delta \Gamma}{2 \Gamma} \]

Direct measurements of width difference

\[ A_{SL} = \frac{\Delta \Gamma}{\Delta m} \tan \phi \]

\[ 2B(B_s \rightarrow D_s^{(*)} D_s^{(*)}) \approx \frac{\Delta \Gamma}{\cos \phi_s} \left( \frac{1 + \cos \phi_s}{2 \Gamma + \Delta \Gamma} + \frac{1 - \cos \phi_s}{2 \Gamma - \Delta \Gamma} \right) \]

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CDF Run II Preliminary

1.3 fb⁻¹

n(\mu⁺) versus n(\mu⁻) versus time in semileptonic B_s decay

B_s \rightarrow D_s \pi

B_s \rightarrow D_s \mu \nu

Full measurements of width difference

\[ \Delta \Gamma \]

\[ \Delta m \]

\[ \tan \phi \]
**Info from other channels**

- **DØ J/ψ φ only**
- **J/ψ φ + A_{SL}(world average)**

\[ \beta_s = -\frac{\phi_s}{2} \]

- **J/ψ φ + A_{SL} + \tau_{fs}**
- **J/ψ φ + A_{SL} + \tau_{fs} + D_s(*)D_s(*)**
Anomalous CP Violation conclusions

• 45 years after the discovery of $K_L \rightarrow \pi\pi$ we still haven't found enough CP violation to explain the matter in our universe.

• There are hints in the $B_s$ system but not yet significant enough to draw conclusions

• Good news: Much more data is around the corner
  – Tevatron, 4S and 5S running, LHC