Lecture 1: b quarks at Hadron Colliders

CTEQ Summer School
Rhodes, Greece - July 2006
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Discovery of b quark

- E288/CFS experiment at Fermilab
  - Search of lepton pairs
    - $p+Nucleus \rightarrow \mu^+\mu^- + X$
  - 1977: narrow resonance in $\mu$ pair mass spectrum


  - In analogy with the J/$\psi$ case this new particle, $\Upsilon$, can be interpreted as a $b\bar{b}$ bound state
b-production around the world

Active experiment
- Year ’73-79
- Year ’80-88
- Year ’89-today
- Near future
B-production at e+e- production on \( \gamma(4s) \) resonance

- \( \sigma \sim 1.1 \text{ nb} \)
- \( \text{S/N} \sim 1/5 \)
- B’s are at rest or have small \( \beta \gamma \) in asymmetric B factories (~ 0.6)
- Produce only Bu or Bd in coherent QM state
  - Don’t know which is which until decay

(Z resonance production: LEP)

- \( \sigma \sim 6.5 \text{ nb} \)
- \( \text{S/N} \sim 1/5 \)
- B’s have large boost and are monochromatic
- Produce all kinds of B’s

\[ M(B \bar{B}) = M(Bs \bar{B}s) = 10.74 \]
B-production in e+e-

- Typical event properties
  - Low charged multiplicity
    \(~11\)
  - Collisions/crossing <1

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B-production at hadronic machines

- Tevatron $\rightarrow p\bar{p} @ \sim 1.96$ TeV CM energy
  - $\sigma \sim 100 \mu b$
  - $S/N \sim 1/1000$
  - B’s are boosted $\beta\gamma \sim 1-4$
  - Each B’s produced in flavor specific state
  - Produce all kind of B’s

Production

Flavor creation (annihilation)

Flavor creation (gluon fusion)

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B-production at hadronic machines

- Typical Tevatron event
  - Large charged multiplicity
    ~ 40
  - Multiple interactions per crossing ~ 1-10
  - Very demanding trigger to exploit efficiently the large sample potentially available
Tevatron for Run II

- New Main Injector:
  - Improve p-bar production
- Recycler ring:
  - Additional storage and cooling of p-bars

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### Tevatron Run II 2001-2009

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Run I</th>
<th>Run II (low)</th>
<th>Run II (high)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/beam</td>
<td>900 GeV</td>
<td>980 GeV</td>
<td>980 GeV</td>
</tr>
<tr>
<td>Peak Luminosity</td>
<td>$1.6 \times 10^{31}$</td>
<td>$1.6 \times 10^{32}$</td>
<td>$2.9 \times 10^{32}$</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>6</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>3500 nsec</td>
<td>396 nsec</td>
<td>396 nsec</td>
</tr>
<tr>
<td>Interactions/crossing</td>
<td>2.8</td>
<td>5</td>
<td>8.5</td>
</tr>
<tr>
<td>Run period</td>
<td>1992-96</td>
<td>2001-06</td>
<td>2007-09</td>
</tr>
<tr>
<td>Integral Luminosity</td>
<td>118 pb$^{-1}$</td>
<td>2 fb$^{-1}$</td>
<td>8 fb$^{-1}$</td>
</tr>
</tbody>
</table>

- $10^{32}$ cm$^{-2}$s$^{-1} = 10^{-4}$ pb$^{-1}$s$^{-1}$
Tevatron delivered more than 1.5 fb\(^{-1}\) up to Feb 2006

- Recorded 1.4 fb\(^{-1}\) (CDF) / 1.2 fb\(^{-1}\) (D\(\emptyset\))
- Now ~ 1.0 fb\(^{-1}\) reconstructed and under analysis

Expect 4 – 8 fb\(^{-1}\) by Oct. 2009
Tevatron Detectors

CDF
- Excellent mass and impact parameter measurement
- Good ability of lepton identification
- Limited PID capability

DØ
- Extended tracking and muon coverage
- Good electron/mu identification

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D0: side view

- Tracker: Silicon, Fiber, 2T Solenoid Preshower
- Front End Electronics
- Triggers / DAQ (pipeline)
- Online & Offline Software
- Calorimeters
- Forward Muon System
- Central Muon System
- p
- p-bar
- Partially New
- New
- Old

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Key detector features for b physics

- Electron/muon identification
  - Identify semi-leptonic B decays or decays involving $\psi \rightarrow \mu^+ \mu^-$

- Secondary vertices
  - Identify decay vertex
    - Requires high resolution tracking (silicon vertex detector)

- Powerful tracker
  - Find all decay tracks with high efficiency

- Trigger:
  - Identify leptons and detached tracks in times $\sim 5 - 20 \mu$s
  - Only way to collect large samples of hadronic B decays
    - Currently implemented only at CDF
L2 SVT trigger

Secondary Vertex L2 trigger

- Online fit of primary Vtx
- Beam tilt aligned
- Observed D resolution
  - 48 μm (33 μm beam spot transverse size)

8 VME crates
Find tracks in Si in 20 μs with offline accuracy

Online track impact param.

σ = 48 μm

Efficiency

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Example of $b$ production event

CDF:
$J/\psi ~ K^*$
Run 42565 Event 72426
11 Dec 92

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b quark interest

- b is only 3rd generation particle being produced in abundance
  - fundamental probe of SM
    - CKM in particular (see later)
    - Couplings to $\gamma$ and $Z$ extensively studied at LEP
    - Strong coupling to SM Higgs
- $M_b \gg \Lambda_{QCD}$ improves accuracy of many theory predictions
  - No time to explore all of them!
- This lecture:
  - Production $x$-section/correlations
    - Test QCD
  - $B^0$ mixing, $\Delta \Gamma$, CPV in mixing
    - Many new recent results
B production

- Big gluon x-section/flux → large NLO contribution
- Large b-mass provides natural cut-off, but introduces additional scale (and potential divergences) in calculations (see Carlo’s lectures)
B production

- From $J/\psi$ sample (low pt)
  - Sensitivity up $p_t=0$
  - B-fractions from lifetime analysis
  - Find consistency with FONLL ($=\text{NLO} + \text{NLL}$) after reanalysis of fragmentation

- From $b$-tagged jets (hi pt)
  - Compatible also with QCD
B production correlations

- Double b-tagged semileptonic sample
  - Consistent with significant higher order production

![Graph showing B production correlations](image)

CDF preliminary 1994-1995 (90^{-1}pb)

- Fraction with $\Delta\phi < 90^\circ$:
  - $28.8 \pm 1.0$ (stat.) $\pm 3.1$ (syst)\%  

Trigger B: $p_T > 14$ GeV/c, $|\eta| < 1$
Other B: $p_T > 7.5$ GeV/c, $|\eta| < 1$

- Error Bars Statistical
- Correlated Systematic Error

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CKM matrix (1)

- CKM matrix describes flavor mixing in weak charged current transitions
  - All up-type quarks (u, c, t) can couple with any down-type quarks with a strength modulated by the elements of the CKM matrix

CKM matrix =

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

- CKM matrix must be unitary if there are only 3 generations

- Only 2 elements are complex*

- \[V_{ub} = |V_{ub}| e^{-i\gamma}\]

- \[V_{td} = |V_{td}| e^{-i\beta}\]

- \[V_{ts} = |V_{ts}| e^{-i\beta_s}\]

* Only 1 phase needed, the two phases are related

\[\beta_s \text{ very small}\]
CKM matrix (2)

- CKM can be expressed in powers of
  \( V_{us} = \lambda = \sin(\theta_{\text{Cabibbo}}) \approx 0.22 \)
  - Wolfenstein representation

\[
\begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^2(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2(1 + i\lambda^2\eta) & 1
\end{pmatrix}
\]

Measurement of CKM elements allows test of unitarity \( \rightarrow \) triangle is closed
1st, 3rd col.: \( V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \)
Other triangles less interesting
Let: \( V_{ud} = 1, V_{cd} = -\lambda, V_{tb} = 1 \)
\( V_{ub}^* + V_{td} = \lambda V_{cb}^* \quad O (3\%) \)
Divide by \( A\lambda^3 = \lambda V_{cb}^* = -\lambda V_{ts} \)

Angles: CP violation

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Basic Theory (1)

1 state effective theory:

\[ H = m - \frac{i\gamma}{2} \]

\[ i \frac{d|B(t)>}{dt} = H|B(t)> \]

\[ |B(t)> = e^{-imt}e^{-\gamma t/2} |B(0)> \]

\[ <B(0)|B(t)>^2 = e^{-\gamma t} \]

2 state effective theory:

- M, \( \Gamma \) hermitian
  - CPT invariance: \( M_{11} = M_{22}, \Gamma_{11} = \Gamma_{22} \)
- Solution reduces to 1 state case after diagonalization of \( H \)

\[ M = \begin{pmatrix} m & m_{12} \\ m_{12}^* & m \end{pmatrix} \]

\[ \Gamma = \begin{pmatrix} \gamma & \gamma_{12} \\ \gamma_{12}^* & \gamma \end{pmatrix} \]

Eigenvalues:

\[ \lambda_{\pm} = (m \pm \Delta m) - \frac{i}{2} (\gamma \pm \Delta \gamma) \]

\[ = m - \frac{i}{2} \gamma \pm \sqrt{(m_{12} - \frac{i}{2} \gamma_{12})(m_{12}^* - \frac{i}{2} \gamma_{12}^*)} \]

Eigenstates:

\[ |B_{\pm}> = \frac{1}{|p|^2 + |q|^2} (p|B> \pm q|\bar{B}> \) \]
Box diagrams

- $m_{12}$ from box diagram
  - Top quark dominant
  - $m_{12} \propto V_{td(s)}^2 \propto e^{-2i\beta(s)}$

- New particles can run in loops besides $W$ and quarks

- Assuming $m_{12} \gg \Gamma_{21}$:
  - $2|m_{12}| = \Delta m_{s(d)} = [G_F^2 m_t^2 \eta \ F(m_t^2/m_W^2)/6\pi^2] \ m_{Bs(d)} f_{Bs(d)} B_{Bs(d)} |V_{ts(d)}|^2 \ V^*_{tb}|^2$
  - Oscill. Freq. Known factors
  - From lattice
  - O(30 %) error

Neutral B’s can turn into their antiparticle

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Basic Theory (2)

- Time evolution of $|B(0)>$ and $|\bar{B}(0)>$
- Assume $\Gamma_{12} \ll m_{12}$

$$
|B(t)> = e^{-i m t} e^{-\frac{\Gamma_{12} t}{2}} \left[ \cos \left( \frac{\Delta m t}{2} \right) |B(0)> - \frac{i q}{p} \sin \left( \frac{\Delta m t}{2} \right) |\bar{B}(0)> \right]
$$

$$
|\bar{B}(t)> = e^{-i m t} e^{-\frac{\Gamma_{12} t}{2}} \left[ \cos \left( \frac{\Delta m t}{2} \right) |\bar{B}(0)> + \frac{i p}{q} \sin \left( \frac{\Delta m t}{2} \right) |B(0)> \right]
$$

$$
\frac{p}{q} \approx \frac{m_{12} - \frac{i}{2} \Gamma_{12}}{|m_{12}|} \approx \frac{m_{12}}{|m_{12}|} = e^{-2i \beta_{(s)}}
$$

$$
\left| \frac{p}{q} \right|^2 \approx 1 + \text{Im} \left( \frac{\Gamma_{12}}{m_{12}} \right) \approx 1 + \mathcal{O}(10^{-3} - 10^{-5})
$$

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Mixing theory

- Neutral mesons time evolution with mixing can be easily derived from the equations of previous slide:

\[ P_{B \to B}(t) = |<B|B(t)>|^2 = e^{-\Gamma t} \left[ \cos^2 \left( \frac{\Delta m t}{2} \right) \right] = \frac{e^{-\Gamma t}}{2} (1 + \cos \Delta m t) \]

\[ P_{B \to B}(t) = |<\bar{B}|B(t)>|^2 = e^{-\Gamma t} \left[ \sin^2 \left( \frac{\Delta m t}{2} \right) \right] = \frac{e^{-\Gamma t}}{2} (1 - \cos \Delta m t) \]

- **Bd mixing well established** $\Delta m_d = 0.507 \pm 0.004$ ps\(^{-1}\)
  - Measurements from LEP, Tevatron and B-Factories
    - Accuracy dominated by BaBar and Belle

- **Bs mixing much harder**
  - Less signal and much faster ($\sim x 1/\lambda^2$) oscillation
  - Tevatron has first results NOW!
Mixing measurements

- **Steps needed to measure mixing:**
  - Select signal in flavor specific final states
  - Identify B type at production: FLAVOR TAG
  - Measure proper decay time and its resolution
  - Parameterize background contributions
  - **Fit time dependence**

$$\#\sigma \text{ significance of oscillation} = \sqrt{\frac{N_S}{N_S + N_B}} \sqrt{\frac{N_S e^{D^2/2}}{2}} e^{-\frac{\Delta m^2}{2}}$$

**Significance from Fourier like analysis**

- #signal
- #background
- Tagging power
- cτ resolution
CDF Signal Sample for $\Delta m_s$

**Semileptonic Modes**

<table>
<thead>
<tr>
<th>$D_s$ Reaction</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell D_s: D_s \to \phi\pi$</td>
<td>32 K</td>
</tr>
<tr>
<td>$\ell D_s: D_s \to K*K$</td>
<td>11 K</td>
</tr>
<tr>
<td>$\ell D_s: D_s \to \pi\pi\pi$</td>
<td>10 K</td>
</tr>
</tbody>
</table>

~53 K events

**Hadronic Modes**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \to D_s \pi (\phi\pi)$</td>
<td>1600</td>
</tr>
<tr>
<td>$B_s \to D_s \pi (K^* K)$</td>
<td>800</td>
</tr>
<tr>
<td>$B_s \to D_s \pi (3\pi)$</td>
<td>600</td>
</tr>
<tr>
<td>$B_s \to D_s 3\pi (\phi \pi)$</td>
<td>500</td>
</tr>
<tr>
<td>$B_s \to D_s 3\pi (K^*K)$</td>
<td>200</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3700</strong></td>
</tr>
</tbody>
</table>

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Huge Control Signals

- **Hadronic decays:**
  - $B^+ (J/\psi K^+, D^0\pi, D^03\pi)$: ~ 50 k events
  - $B^0 (J/\psi K^*, D^-\pi, D^-3\pi, D^*-3\pi)$: ~ 60 k events

- **Semileptonic decays:**
  - $lD^0 (D^0 \rightarrow K\pi)$: ~ 540 k events
  - $lD^{*-} (D^{*-} \rightarrow D^0\pi)$: ~ 74 k events
  - $lD^- (D^- \rightarrow K\pi\pi)$: ~ 300 k events
Flavor tagging

Use combined same side and opposite side tags

- Opposite side: electrons, muons, jet charge
- Same Side: tag with selected track (kaon) close to reconstructed (signal) B

Taggers characterized by:
- Efficiency ($\varepsilon$)
- Dilution ($D$) = 1 - 2w
  $w = \text{prob. wrong tag}$

Observed time evolution

\[ P_{B\to B}(t) = \frac{e^{-\Gamma t}}{2} \left( 1 + D \cos \Delta m t \right) \]
\[ P_{\bar{B}\to \bar{B}}(t) = \frac{e^{-\Gamma t}}{2} \left( 1 - D \cos \Delta m t \right) \]
OST tagger calibration

❖ Dilution calibration
  ➢ Use the large control samples of B+ and B0
  ➢ Works only for OST
    ▢ SST different for every B type.
    Must use MC

❖ Bd mixing by-product and cross-check

hadronic: \[ \Delta m_d = 0.536 \pm 0.028 \text{ (stat)} \pm 0.006 \text{ (syst)} \text{ ps}^{-1} \]
semileptonic: \[ \Delta m_d = 0.509 \pm 0.010 \text{ (stat)} \pm 0.016 \text{ (syst)} \text{ ps}^{-1} \]
world average: \[ \Delta m_d = 0.507 \pm 0.004 \text{ ps}^{-1} \]
Particles closer to B in fragmentation carry information on B type at production
Bs likely to have a K
Use TOF/dE/dx for K/π separation
Tune MC:
- Reproduce B+, Bd
- Determine systematics
- Apply to Bs
## Flavor tag summary

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon D^2$ Hadronic (%)</th>
<th>$\varepsilon D^2$ Semileptonic (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon</td>
<td>0.48 ± 0.06 (stat)</td>
<td>0.62 ± 0.03 (stat)</td>
</tr>
<tr>
<td>Electron</td>
<td>0.09 ± 0.03 (stat)</td>
<td>0.10 ± 0.01 (stat)</td>
</tr>
<tr>
<td>JQ/Vertex</td>
<td>0.30 ± 0.04 (stat)</td>
<td>0.27 ± 0.02 (stat)</td>
</tr>
<tr>
<td>JQ/Prob.</td>
<td>0.46 ± 0.05 (stat)</td>
<td>0.34 ± 0.02 (stat)</td>
</tr>
<tr>
<td>JQ/High $p_T$</td>
<td>0.14 ± 0.03 (stat)</td>
<td>0.11 ± 0.01 (stat)</td>
</tr>
<tr>
<td>Total OST</td>
<td>1.47 ± 0.10 (stat)</td>
<td>1.44 ± 0.04 (stat)</td>
</tr>
<tr>
<td>SSKT</td>
<td>3.42 ± 0.06 (stat)</td>
<td>4.00 ± 0.04 (stat)</td>
</tr>
</tbody>
</table>

- **Opposite side:** use combination of tags
- **Same side/OST combination assumes independent tagging information**

Total $\varepsilon D^2 \sim 5\%$
Measuring proper time

\[ c\tau = \frac{L}{\gamma \beta} = \frac{L_{xy} M_B}{p_T} \]

\[ \sigma_{ct} = \sigma_{ct}^0 \oplus ct \times \frac{\sigma_p}{p} \]

- For fully reconstructed (hadronic) modes
  \[ \sigma_{ct} \sim O(30 \mu) \quad \text{(c.f. } ct \sim 450 \mu) \]

- For semileptonic modes, missing neutrino causes
  \[ \frac{\sigma_p}{p} \sim O(15\%) \]

\[ \Rightarrow \text{Resolution poor at large decay time} \]

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Bs proper time resolution

- Average $\sigma_t \sim 87$ fs
- Good sensitivity for $\Delta m_s \sim 20$ ps$^{-1}$
Putting all together

- Amplitude scan
  - Fit $e^{-t/\tau}(1 \pm A(\omega) \cos \omega t) \otimes G(t)$ for various values of $\omega$
  - $A(\omega) = 1$ for $\omega = \Delta m$
  - Similar to a Fourier transform

- Test amplitude scan on $B_d$
  - $A=1$ at the correct value
  - Shape consistent with model expectations

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CDF Bs result

CDF Run II Preliminary

L = 1.0 fb^{-1}

- data ± 1σ
- 95% CL limit 16.7 ps^{-1}
- 1.645 σ
- sensitivity 25.8 ps^{-1}

- data ± 1.645 σ
- data ± 1.645 σ (stat. only)

A/σ_A (17.31 ps^{-1}) = 3.7

B_s^0 \rightarrow l^+ D_s^- X, B_s^0 \rightarrow D_s^- \pi^+, B_s^0 \rightarrow D_s^- \pi^+ \pi^- \pi^-

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CDF Bs result

\[ \Delta m_s = 17.31 + 0.33 - 0.18 \text{(stat)} \pm 0.07 \text{(sys)} \]

- D0 consistent but lower sensitivity

Resolution dominated by hadronic decays

Probability of background fluctuation $= 0.2\% \sim 3\sigma$
\[ \Gamma_{12} \]

- \( \Gamma_{12} \) from common final states

\[ \Gamma_{12} = \sum_f <B|f> \rho_f <f|\bar{B}> \]

- B\(_d\) dominated by D\(^+\)D\(^-\), \(\pi^+\pi^-\), \ldots , \(\Gamma_{12} \sim O(\lambda^4), \Delta \Gamma/\Gamma \sim 3 \times 10^{-3}\)

- B\(_s\) dominated by D\(_s^+\)D\(_s^-\)

\(\Delta \Gamma = 2 \text{Re}\{\Gamma_{12}/m_{12}\} |m_{12}| = 2 |\Gamma_{12}| \cos \phi\)

| \(\Gamma_{12}/m_{12}\) | \(\sim 5 \times 10^{-3}\) in SM

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Measurements of $\Delta \Gamma / \Gamma$

- $\Delta \Gamma_d$ very hard
  - Limits from LEP and B-factories consistent with SM value

- $\Delta \Gamma_s$ feasible at Tevatron with several techniques:
  - Combined lifetime/transversity (angular) analysis of $B_s \rightarrow \psi \phi$ decay
    - Found to be $\sim 19\%$ CP-odd
  - Measurement of $BR(B_s \rightarrow D_s^{(*)} D_s^{(*)})$
    - Mostly CP-even (theory expectations > 95%)
  - Combination of flavor specific and CP specific lifetime measurements (e.g. $B_s \rightarrow l\nu D_s$ and $B_s \rightarrow K+K-$)
DØ transversity analysis

- Update of published analysis with 800 pb\(^{-1}\)

\[
\bar{\tau}_{B_s} = 1.53 \pm 0.08^{+0.01}_{-0.03} \text{ ps}
\]

\[
\Delta \Gamma_s = 0.15 \pm 0.10^{+0.03}_{-0.04} \text{ ps}^{-1}
\]
Combined $\Delta \Gamma_s$ Results

- **Theoretical prediction (Nierste)**
  \[ \Delta \Gamma_s = 0.10 \pm 0.03 \text{ ps}^{-1} \left( \frac{f_B}{250 \text{ MeV}} \right)^2 \]

- **Unofficial world average**
  \[ \Delta \Gamma_s = 0.097^{+0.041}_{-0.042} \text{ ps}^{-1} \]
  \[ \bar{\tau}_s = \frac{1}{\Gamma_s} = 1.461 \pm 0.030 \text{ ps} \]
CPV in mixing

- $|p/q| \neq 1 \rightarrow$ CPV
- Measure asymmetry: $A = \frac{N(BB) - N(\bar{B}\bar{B})}{N(BB) + N(\bar{B}\bar{B})} = \frac{N(l^+l^+) - N(l^-l^-)}{N(l^+l^+) + N(l^-l^-)}$
- Expect:
  
  $N(BB) = N(B \rightarrow B)(\bar{B} \rightarrow B) = \left( e^{-\Gamma t} \cos^2 \left( \frac{\Delta m t}{2} \right) \right) \left( \frac{p}{q} \right)^2 e^{-\Gamma' t} \sin^2 \left( \frac{\Delta m' t}{2} \right)$

  $N(\bar{B}\bar{B}) = N(\bar{B} \rightarrow \bar{B})(B \rightarrow \bar{B}) = \left( e^{-\Gamma t} \cos^2 \left( \frac{\Delta m t}{2} \right) \right) \left( \frac{q}{p} \right)^2 e^{-\Gamma' t} \sin^2 \left( \frac{\Delta m' t}{2} \right)$

  $A = \frac{1 - \left| \frac{q}{p} \right|^4}{1 + \left| \frac{q}{p} \right|^4} \approx \Im \left( \frac{\Gamma_{12}}{m_{12}} \right)$

- SM prediction: $B_d: 9 \times 10^{-4}$, $B_s: 1 \times 10^{-5}$
- $B_d$ avg: $-0.0030 \pm 0.0078$ (LEP, CLEO, Belle, BaBar)
- $B_s$ avg: $0.0013 \pm 0.0014$ (D0 2006)

$|p/q| = 1 \rightarrow$ Mass eigenstates = CP eigenstates
Summary of lecture 1

- B-quark hadrons have been studied for about 30 years
- e+e- storage rings and hadronic machines have complemented each other
  - Now B-factories and Tevatron
- b-hadron production and their basic properties are now known with an unprecedented level of detail
  - Their study has helped develop and test QCD, even in non-perturbative regimes
- Detailed measurements of neutral B meson mixing have become recently available for both species
  - Find overall consistency with Standard Model
  - In conjunction with CP violation measurements (next lecture) further confirm SM and limit possible new physics

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