Tevatron experience in $B$ physics

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Introduction

• Both Tevatron experiments actively pursue the $B$ physics research;
• Big success of this study – many important results are obtained:
  >50% of all Tevatron papers in RunII with citation count $\geq 50$ come from
  flavour physics;
• $B$ physics will be the main research subject for LHCb;
• These studies will also be performed in ATLAS and CMS;
• Both current and future experiments will work in a similar
  (difficult) environment of hadron collider;
• Many technical parameters important for $B$ physics (e.g. mass,
  lifetime resolution) at ATLAS and CMS will be quite similar to that
  of DØ and CDF;
• LHCb, as a dedicated $B$ physics experiment, will be much superior;
• The expected statistics will be much larger;
• Learning the Tevatron experience in $B$ physics can be very useful
  for LHC;
Tevatron accelerator

• Peak luminosity $\sim 3 \times 10^{32}$;
• With this luminosity:
  – $\sim 8$ interactions / event;
  – $\sim 300$ tracks / event;
• $>6$ fb$^{-1}$ already collected;
• Collection efficiency $\sim 90%$
  – 5.8 fb$^{-1}$ collected in DØ;
CDF detector: Parts essential for $B$ physics

- **Silicon detector (SVX):**
  - 5 double sided layers, $|\eta|<2$;
  - Radius: from 2.5 to 10 cm;
  - $L_{00}$ at $r\sim 1.5$ cm;
- **Drift chambers (COT)**
  - 96 layers; $|\eta|<2$;
  - Radius from 44 to 132 cm;
- **Magnetic field 1.4 T**;
- **Muon identification**
  - trigger up to $|\eta|<1$;
• Silicon detector (SMT):
  – 4 mainly double sided layers;
  – $|\eta| < 2$;
  – $L_0$ at $r=1.6$ cm;
• Silicon Fibre Tracker (CFT):
  – 8 layers, $|\eta| < 2$;
  – Radius: 20 – 50 cm
• Muon system:
  – 3 layers + Toroid;
  – Large acceptance $|\eta| < 2.2$;
  – Scintillator layers for trigger;
  – Cosmic ray rejection;
  – Low punch-through;
  – Local measurement of muon charge and momentum;
Polarities of DØ solenoid and toroid are reversed regularly;

Trajectory of the negative particle becomes exactly the same as the trajectory of the positive particle with the reversed magnet polarity;

This cancels the difference in the reconstruction efficiency between positive and negative particles;

Changing Magnet polarities is an important feature of DØ detector, which reduces significantly the systematics in CP violation measurements.
Triggers for $B$ physics

- To a large extent the triggers determine the possibilities and goals of the $B$ physics program;
- Triggers are quite different for CDF and DØ;
- CDF exploits the possibility to select the displaced tracks using the Silicon Vertex Trigger (SVT) processor;
  - SVT is included in Level 2 and allows to find tracks with large impact parameters;
- DØ triggers for $B$ physics are based on excellent muon detector and on a powerful muon identification;
- Tevatron experience in trigger strategies can be useful for LHC experiments;
CDF Triggers for $B$ physics

• 3 types of triggers are used in CDF:
  – di-muon trigger with $p_T(\mu) > 1.5$ GeV;
  – Displaced track with IP > 120 μm and lepton with $p_T > 4$ GeV;
  – 2 tracks with $p_T > 2$ GeV and IP > 100 μm;

• Possibility to trigger on displaced tracks determines the ability to CDF to select hadronic $B$ decays and use them in the measurements:
  – $B_s$ oscillation;
  – Study of $B \to h^+ h^-$;

• The displaced tarcks triggers bias the lifetime efficiency:
  – Difficulty in measuring the lifetime of $B$ hadrons;
  – Corrections based on MC are required;

Figure 1. Online invariant two-hadron mass distribution for events collected with the two-track trigger.
DØ triggers for $B$ physics

- Two main types of triggers:
  - Single muon matched with track, $p_T > 3$ GeV;
  - Dimuon triggers with $p_T > 3$ GeV;
  - With stronger selections, the $p_T$ threshold of one muon is decreased to 1.5 GeV;

- Dimuon triggers run un-prescaled up to the highest Tevatron luminosities;

- These triggers provide the lifetime-unbiased sample of $B$ hadron decays;

- It is important especially for the lifetime-related measurements;
Review of Tevatron Results

- Physics results of Tevatron – its main legacy, and its main contribution to the LHC program;
- Review of obtained and expected results is very instructive:
  - LHC will start from the point where Tevatron finished;
  - Experimental program of LHC will be and is adjusted following the achievements of Tevatron;
  - Tevatron results provide a good guidance of precision expected in the future measurements;
Properties of $B_s$ meson

• $B_s$ meson is a special particle with unique properties:
  – Essential information to understand the quark mixing:
    • Mass difference;
    • Width difference;
  – Probe new physics beyond the SM:
    • CP violation;
    • Rare decays;
  – Can be studied only at hadron colliders;

• $B_s$ is actively studied at Tevatron;
• It is almost impossible to perform similar studies at $B$ factories;
• This exploration will be one of the most important subjects of $B$ physics at LHC;
Mass difference of $B_s$

- One of the most important achievements of Tevatron;
- Strong constraint for the Unitarity triangle;
- Obtained value is very precise, main uncertainty in translation to the CKM constraint comes from theory;
- Probably, the $B_s$ mixing at LHC will be used for calibration (e.g. flavour tagging, lifetime resolution);

CDF: $\Delta M_s = 17.77 \pm 0.10 \pm 0.07$ ps$^{-1}$
Width difference of $B_s$

- Another important measurement performed by Tevatron;
- The value is extracted from the measurement of $B_s \rightarrow J/\psi \phi$;
- Other possibilities include measurement of $B_s$ lifetime in CP-specific decays (like $B_s \rightarrow K^+K^-$, CDF);
- Obtained precision: $\sigma(\Delta \Gamma_s) \sim 0.035 \text{ ps}^{-1}$;
- Expected precision by the end of Tevatron: $\sigma(\Delta \Gamma_s) \sim 0.025 \text{ ps}^{-1}$;
- It can be improved at LHC to test the SM:

**PDG 2009**: $\Delta \Gamma_s = 0.062^{+0.034}_{-0.037} \text{ ps}^{-1}$

**Theory**: $\Delta \Gamma_s = 0.088 \pm 0.017 \text{ ps}^{-1}$
The CP violating phase $\phi_s$ extracted from the $B_s \rightarrow J/\psi \phi$ decay is very small in the SM:

$$\phi_s^{SM} = -2 \beta_s = 2 \arg \left( -\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*} \right) = -0.038 \pm 0.002$$

- It can be considerably increased by contributions of the new physics;
- Both CDF and DØ performed measurement of this phase;
- Results shows $\sim 2.2\sigma$ deviation from the SM:
- Study will continue with the new statistics, $\sim 30\%$ improvement in precision can be expected;
- The main progress will be achieved at LHC;
- It is a very promising direction in $B$ physics, both for ATLAS/CMS and LHCb;

PDG2009: $\phi_s = -0.094^{+0.43}_{-0.25}$
Other CP violation studies

• The most important other achievements of Tevatron:
  – dimuon same sign charge asymmetry:
  – Semileptonic charge asymmetry in $B_s$ decay:
    • Both measurements are directly related with the phase $\phi_s$;
  – Direct CP asymmetry in $B^+ \rightarrow J/\psi K^+$:
  – CP asymmetry in $B \rightarrow h^+ h^-$ decays:
• These results can be improved and extended at LHC:
  – Charge asymmetry requires just muon triggers, good understanding of detector and large statistics;
  – To select $B \rightarrow h^+ h^-$ decays, special triggers are required;
  – Particle ID will be essential for $B_s \rightarrow K^+ K^-$ studies, probably can be performed only at LHCb;

\[ Dzero : A_{SL}^d + 0.7 A_{SL}^s = (-9.2 \pm 4.4 \pm 3.2) \times 10^{-3} \]

\[ Dzero : A_{SL}^s = (-1.7 \pm 9.1^{+1.2}_{-2.3}) \times 10^{-3} \]

\[ \text{CDF : } A_{CP}(B^+ \rightarrow J/\psi K^+) = +0.0075 \pm 0.0061 \pm 0.0027 \]

\[ \text{CDF : } A_{CP}(B^0 \rightarrow K^+ \pi^-) = -0.086 \pm 0.023 \pm 0.009 \]
Rare decays

- The most interesting decay is $B_s \to \mu^+ \mu^-$;
- SM prediction: $\sim 4 \times 10^{-9}$;
- New physics (e.g. mSUGRA) can significantly change this decay rate;
- Recent results for 2 fb$^{-1}$:
  - CDF: $\text{Br}(B_s \to \mu^+ \mu^-) < 5.8 \times 10^{-8}$ (95% CL)
  - D$\bar{0}$: $\text{Br}(B_s \to \mu^+ \mu^-) < 9.3 \times 10^{-8}$ (95% CL)
    - D$: recently updated analysis with the expected sensitivity for 5 fb$^{-1}$:
      $\text{Br}(B_s \to \mu\mu) < 5.3 \times 10^{-8}$ (95% CL);
- The limit expected by the end of RunII: $\sim 2 \times 10^{-8}$;
- The SM level is achievable at LHC, both at CMS/ATLAS and LHCb;

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T. Arnowitt et al. PLB 538 (2002), 121
Properties of $B$ hadrons

- $B$ hadrons – excellent place to test the QCD and adjust theoretical models describing quark bound states:
  - predictions of theory are very precise for heavy-light quark bound system:
    - Example: ratios of lifetimes of different $B$ hadrons are predicted to $\sim 1-3\%$;
    - Masses of different $B$ baryons are predicted with few MeV precision;
  - Experimental input helps a lot to develop theoretical methods
    - Example: initial theoretical estimates of $\tau(Λ_b)/\tau(B^0)$ significantly improved following the discrepancy with the experimental results;

- Tevatron experiments made significant contribution in these tests ($B_s$, $B_c$, $B$ baryons);

- This study will continue in the future with both theory and LHC experiments improving the precision;
Many heavy baryons were observed at Tevatron:
- $\Xi_b$ (DØ and CDF); $\Sigma_b, \Sigma_b^*$ (CDF); $\Omega_b$ (DØ)

Measured masses can be compared with theory;
- Theoretical predictions are available for all baryons (e.g. E. Jenkins, PRD 55, R10-R12 (1997)):
  - $M(\Xi_b) = 5805.7 \pm 8.1$ MeV; $M(\Sigma_b) = 5824.2 \pm 9.0$ MeV;
  - $M(\Omega_b) = 6068.7 \pm 11.1$ MeV; $M(\Sigma_b^*) = 5840.0 \pm 8.8$ MeV;

Currently experimental precision of the mass measurement is better than the theoretical prediction;

Need to improve the theoretical models for a more quantitative comparison;
Observed $B$ baryons

$M(\Xi_b^-) = 5774 \pm 11 \pm 15$ MeV (Dzero)  
$M(\Xi_b^-) = 5792.9 \pm 2.4 \pm 1.7$ MeV (CDF)

$M(\Omega_b^-) = 6165 \pm 10 \pm 13$ MeV (Dzero)

$M(\Sigma_b^+) = 5807.8^{+2.0}_{-2.2} \pm 1.7$ MeV  
$M(\Sigma_b^-) = 5815.2 \pm 1 \pm 1.7$ MeV  
$M(\Sigma_b^{*-}) = 5829^{+1.6}_{-1.8} \pm 1.7$ MeV  
$M(\Sigma_b^{*-}) = 5836.4 \pm 2.0^{+1.8}_{-1.7}$ MeV
Expected baryons with $b$ quark

- Many heavy baryons still need to be discovered.
- Hopefully, their search will continue at LHC.
$B_c$ mass

- Now measured by both CDF and DØ collaborations in $B_c \rightarrow J/\psi \pi$ mode;
- Consistent results are obtained:
  
  $M(B_c) = 6275.6 \pm 2.9 \pm 2.5$ MeV (CDF)
  
  $M(B_c) = 6300 \pm 14 \pm 5$ MeV (Dzero)

- Agree well with theory prediction:
  
  $M(B_c) = 6304 \pm 12^{+18}_{-0}$ MeV (Theory)

- (lattice QCD calculations, J. Allison et al. PRL 94, 172001 (2005)):
Lifetime of $b$ hadrons

- Lifetime is another quantity which allows direct comparison between theory and experiment;
- Theory predicts the hierarchy:
  \[ \tau(B_c^+) \ll \tau(A_b^0) < \bar{\tau}(B_s^0) \approx \tau(B^0) < \tau(B^+) \]
- Theory predictions are especially precise for lifetime ratios;
- Precision of Tevatron results is now determining for $B_s$, $A_b$ and $B_c$ lifetimes;
- It is much better than all previous measurements;

\[ \tau(B_c^+)/\tau(B_s^0) \]
\[ 1.073 \pm 0.008 \]
\[ \text{Theory: 1.04 – 1.08} \]

\[ \tau(B_s^+)/\tau(B_s^0) \]
\[ 0.966 \pm 0.015 \]
\[ \text{Theory: 0.99 – 1.01} \]

\[ \tau(A_b^0)/\tau(B_s^0) \]
\[ 0.901 \pm 0.034 \]
\[ \text{Theory: 0.86 – 0.95} \]

\[ \tau(B_c^+)/\tau(B^0) \]
\[ 0.301 \pm 0.024 \]
\[ \text{Theory: 0.26 – 0.46} \]
**$B_s$ Lifetime**

- Lifetime of $B_s^L$ and $B_s^H$ states are different;
- Need to know the contribution of $B_s^L$ and $B_s^H$ into the final state to derive the lifetime:
  - Mainly the flavour specific decay modes ($50\% B_s^L$ and $50\% B_s^H$) are used:
    - $B_s \to \mu\nu D_s$ (*) in DØ measurement;
    - $B_s \to D_s \pi$ in CDF measurement;
- Precision of the WA value is determined by the CDF and DØ results;
- Current precision can be improved by $\sim30\%$ by the end of the Tevatron run;

**PDG 2008:**

$$\bar{\tau}(B_s^0) = \frac{2}{\Gamma_L + \Gamma_H} = 1.470^{+0.027}_{-0.026} \text{ ps}$$

![Bs lifetime graph](image-url)
$\Lambda_b$ Lifetime

- A lot of discussion of $\Lambda_b$ lifetime recently ("$\Lambda_b$ puzzle");
- Earlier theoretical calculations predicted $\tau(\Lambda_b)/\tau(B^0)$ value around 0.94, experimental values (mainly LEP measurements) were around 0.75;
- Recent calculations include higher order effects and predict a lower ratio: 0.86 – 0.95;
- Tevatron results increased the experimental value, significantly improving its precision:
  - CDF measurement in $\Lambda_b \rightarrow J/\psi \Lambda$: $\tau(\Lambda_b) = 1.580 \pm 0.077 \pm 0.012$ ps (CDF)
  - CDF measurement in $\Lambda_b \rightarrow \Lambda_c \pi$
  - DØ measurement in $\Lambda_b \rightarrow J/\psi \Lambda$: $\tau(\Lambda_b) = 1.218^{+0.130}_{-0.115} \pm 0.042$ ps (DØ)
  - DØ measurement in $\Lambda_b \rightarrow \mu \nu \Lambda_c$
    - Notice ~1.8σ difference between 2 CDF results;
$\Lambda_b$ lifetime

- New results from Tevatron now dominate in the world average precision of $\Lambda_b$ lifetime;
- World average is now consistent with the theoretical prediction:
  \[
  \tau(\Lambda_b)/\tau(B_0) = 0.901 \pm 0.034 \text{ (Experiment)}
  \]
  \[
  \tau(\Lambda_b)/\tau(B_0) = 0.905 \pm 0.045 \text{ (Theory)}
  \]
- Final Tevatron precision can be improved by \(\sim 50\%\);
- Theoretical precision needs to be improved for the meaningful comparison;

PDG 2008: \(\tau(\Lambda_b) = 1.383^{+0.049}_{-0.048} \text{ ps}\)
**$B_c$ lifetime**

- Now measured by both CDF and DØ collaborations in $B_c \rightarrow J/\psi \ell \nu$ mode
  - CDF uses events with $\ell = \mu, e$, DØ with $\ell = \mu$ only;
- Results are consistent and precision is similar:
  \[
  \tau(B_c) = 0.475^{+0.053}_{-0.049} \pm 0.018 \text{ ps (CDF)}
  \]
  \[
  \tau(B_c) = 0.448^{+0.038}_{-0.036} \pm 0.032 \text{ ps (Dzero)}
  \]
- World average value:
  \[
  \tau(B_c) = 0.461 \pm 0.036 \text{ ps (HFAG)}
  \]
- Experimental precision is now much better than the theoretical:
  - $\tau(B_c) = 0.4 - 0.7 \text{ ps (Theory)}$
  - Need to improve the theoretical prediction;
Summary

• Most important message from Tevatron to LHC:

Exploring B hadrons at hadron colliders is possible. It is a rewarding experience which produces unique and important results, not available from elsewhere.

• Experience of Tevatron clearly showed that $B$ physics can be successfully explored in a difficult environment of hadron collisions:
  – high background from QCD;
  – high track multiplicity;
  – pile-up of many background interactions;
Summary (continued)

- Excellent performance of muon identification is crucial for the success of the $B$ physics program:
  - Reversal of magnet polarities provides an additional bonus for the CP violation measurements;
- Trigger is an essential part of the $B$ physics research:
  - Muon based triggers are sufficient for many interesting measurements (DØ experience);
  - The triggers based on displaced tracks are essential for a full exploration of $B$ hadrons (CDF experience);
  - However the lifetime bias could provide additional difficulties;
Backup
Comparison with theory

- In general, theory predicts a lower $\Omega_b$ mass:
  - $6039 \pm 8$ MeV
    E. Jenkins, PR D77, 034012 (2008);
  - $6052.1 \pm 5.6$ MeV
    M. Karliner et al. arXiv:0804.1575;
  - $6036 \pm 81$ MeV
    X. Liu et al., PR D77, 014031 (2008);
  - $6006 \pm 22$ MeV
    R. Lewis, R.M. Woloshyn, PR D79, 014502 (2009);

Comparison of theoretical prediction (boxes) and experimental results (red lines). Taken from: R. Lewis, R.M. Woloshyn, PR D79, 014502 (2009);

Additional experimental and theoretical studies are required to resolve this new $\Omega_b$ puzzle.
Excited B** mesons

- Tevatron is currently the main source of information on excited (L=1) states with $b$ quark;
- Decay mode $B^{**} \rightarrow B^+ \pi^-$ is used;
- Both CDF and DØ observe $B_1$ and $B_2^*$ states:

\[
M(B_1) = 5720.6 \pm 2.4 \pm 1.4 \text{ MeV (Dzero)}
\]
\[
M(B_1) = 5725.3^{+1.6+1.4}_{-2.2-1.5} \text{ MeV (CDF)}
\]
\[
M(B_2^*) = 5746.8 \pm 2.4 \pm 1.7 \text{ MeV (Dzero)}
\]
\[
M(B_2^*) = 5740.2^{+1.7+0.9}_{-1.8-0.8} \text{ MeV (CDF)}
\]

- Maximal difference between results of two collaborations is $\sim 2\sigma$
Excited $B_s^{**}$ states

- CDF observes both $B_{s2}^*$ and $B_{s1}^*$ states, while DØ confirmed only $B_{s2}^*$ meson:
  - Lack of statistics does not allow the DØ collaboration to either confirm or deny $B_{s1}^*$;

$$M(B_{s1}) = 5829.4 \pm 0.7 \text{ MeV (CDF)}$$

$$M(B_{s2}^*) = 5839.6 \pm 1.1 \pm 0.7 \text{ MeV (Dzero)}$$

$$M(B_{s2}^*) = 5839.6 \pm 0.7 \text{ MeV (CDF)}$$

- Measured masses of $B^{**}$ states can be compared with theoretical predictions;
Decays of B hadrons

- Very limited number of results from Tevatron;
- Some highlights of measured branching rates:
  - \( B_s \rightarrow D_s (3\pi) \) (CDF);
  - \( B_s \rightarrow K^+K^- \) (CDF);
  - \( B_s \rightarrow \mu\nu D_s ** \) (DØ);
  - \( B_s \rightarrow D_s (*) D_s (*) \) (DØ);
  - \( B_s \rightarrow D_s D_s \) (CDF);
- Mainly results for \( B_s \);
- Some of these channels are very promising for the study of the CP violation in \( B_s \) system (e.g. \( B_s \rightarrow K^+K^- \), \( B_s \rightarrow D_s D_s \));
- Other \( B \) hadrons will not be studied at Tevatron;
- Good possibility for LHCb; the displaced tracks triggers are required for this study;