Tevatron experience in *B* physics

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"From Tevatron to LHC" forum

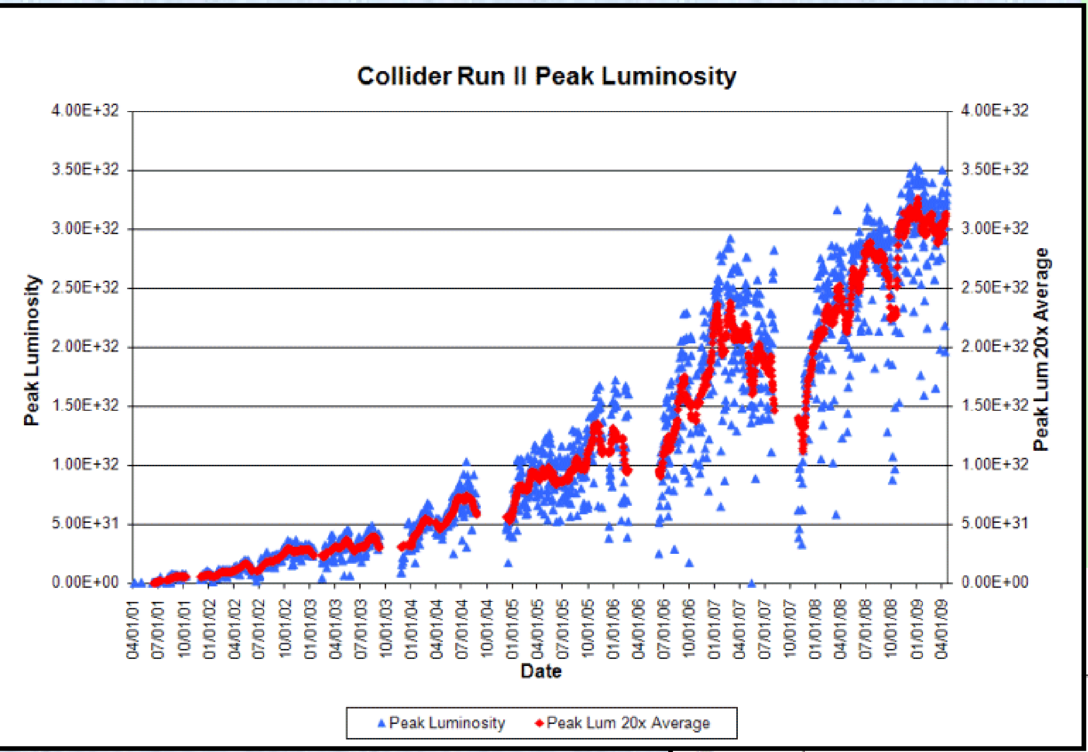
Cosener's House, Abingdon-on-Thames

7 May 2009

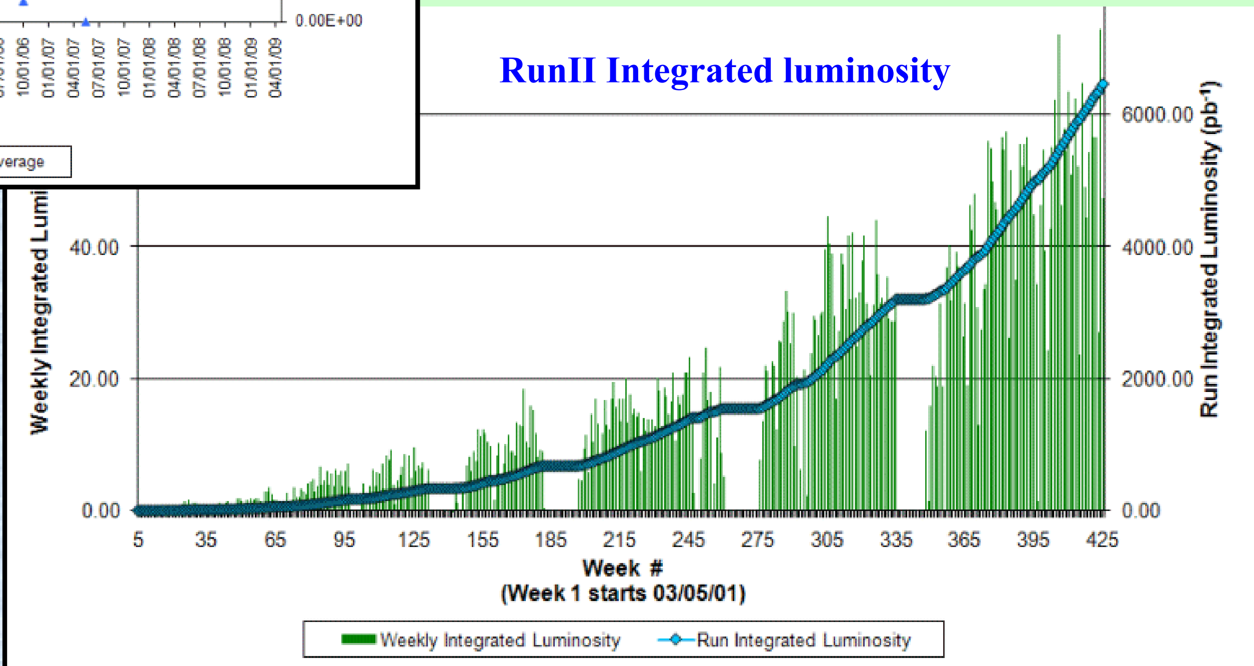
Introduction

- 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 ~3×10^{32};
- With this luminosity:
  - ~8 interactions / event;
  - ~300 tracks / event;
- >6 fb^{-1} already collected;
- Collection efficiency ~90%
  - 5.8 fb^{-1} collected in DØ;



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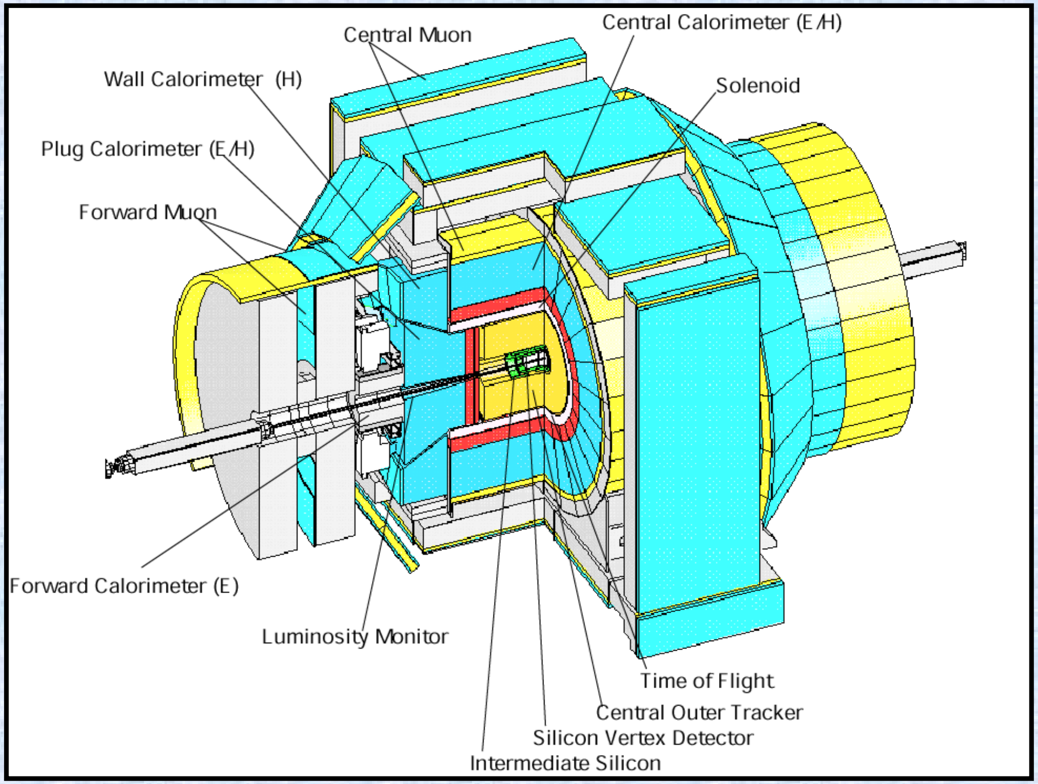
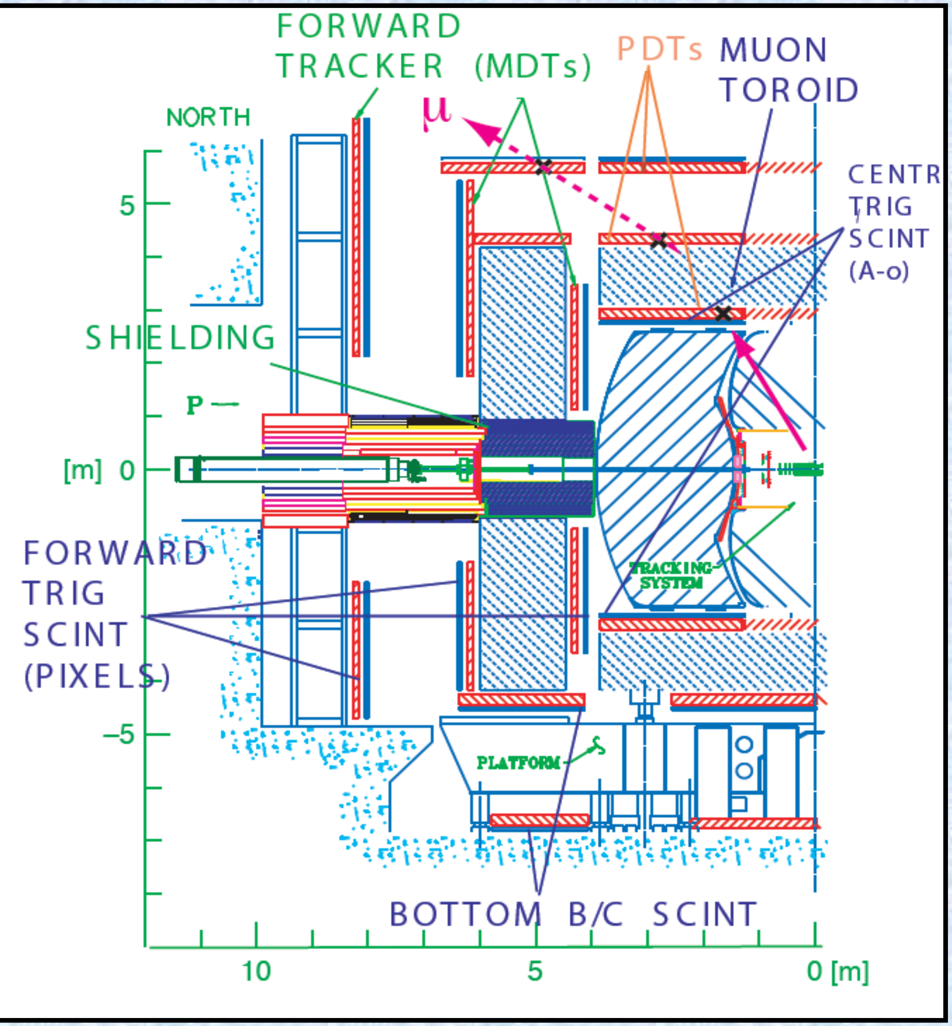
CDF detector: Parts essential for *B* physics

- Silicon detector (SVX):
  - 5 double sided layers, $|\eta|<2$;
  - Radius: from 2.5 to 10 cm;
  - L00 at r~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 $|\eta| < 1$;



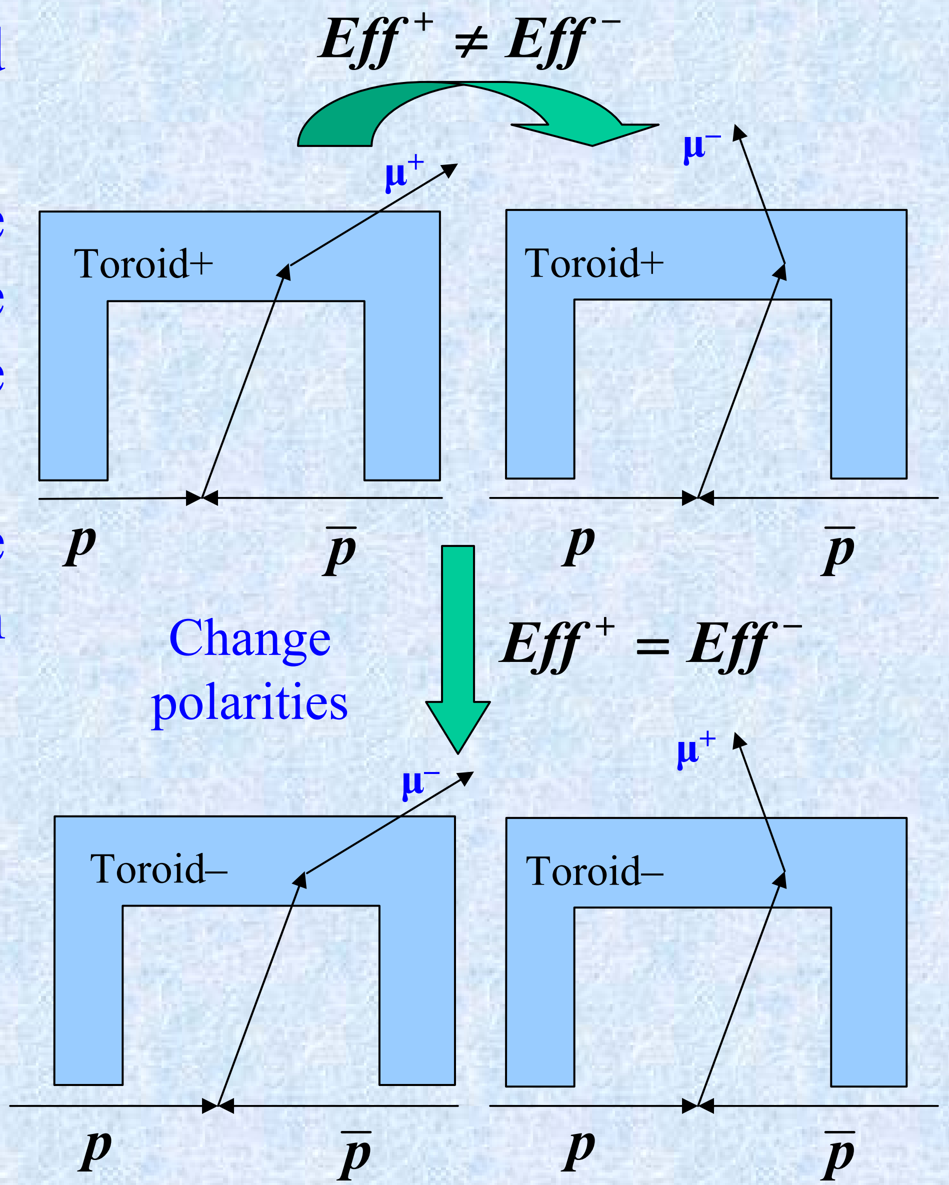
DØ detector for *B* physics



- Silicon detector (SMT):
  - 4 mainly double sided layers;
  - $|\eta| < 2$;
  - L0 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;

DØ: Reversing Magnet Polarities

- 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;



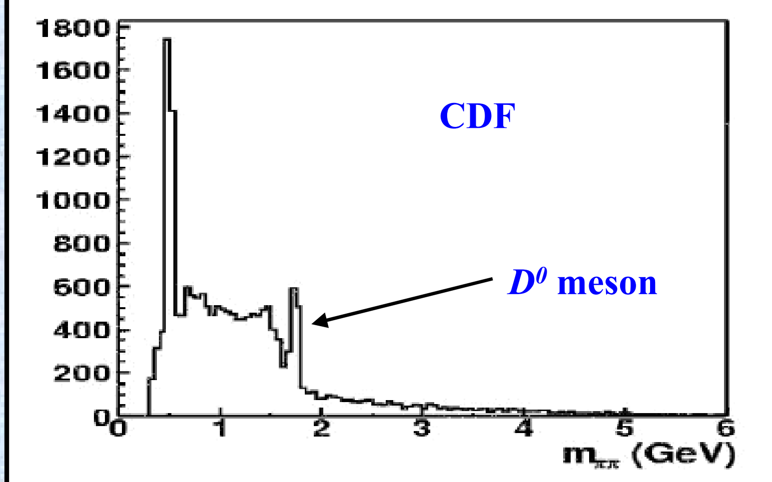
Changing Magnet polarities is an important feature of DØ detector, which reduces significantly the systematics in CP violation measurements

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;

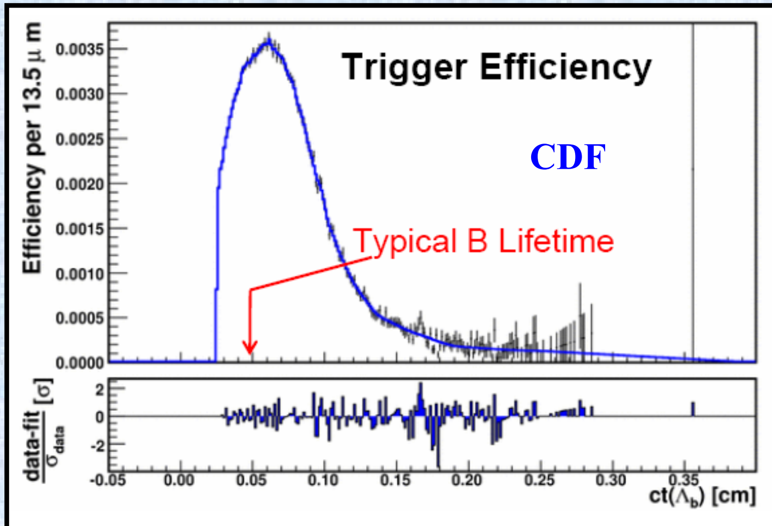
CDF Triggers for *B* physics

- 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 $B \rightarrow h^+ h^-$;
- The displaced tarcks triggers bias the lifetime efficiency;
  - Difficulty in measuring the lifetime of *B* hadrons;
  - Corrections based on MC are required;



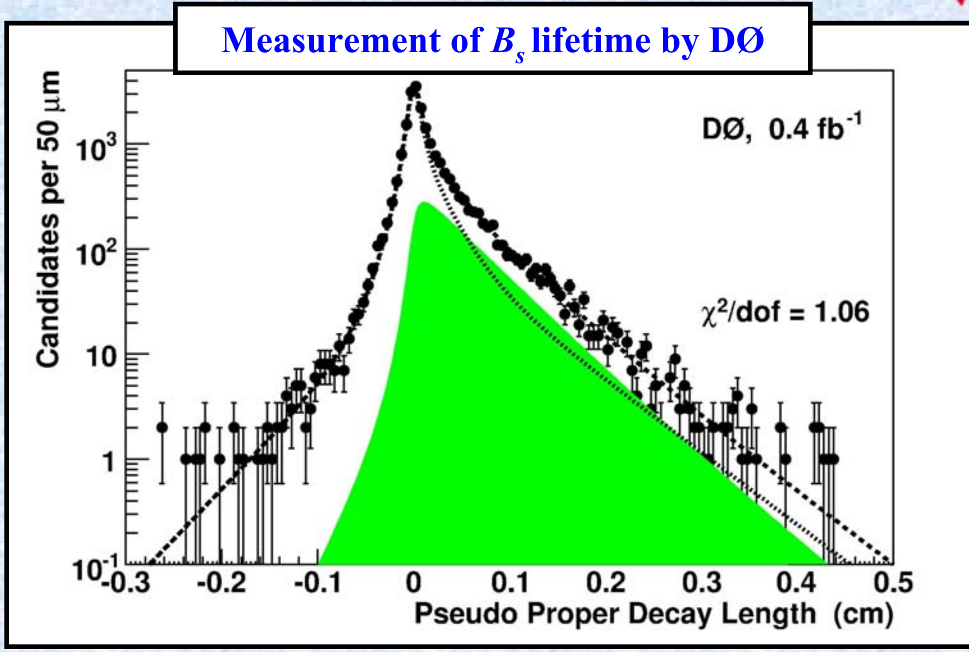
A. Annovi, Nucl. Phys. B170, 283

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;

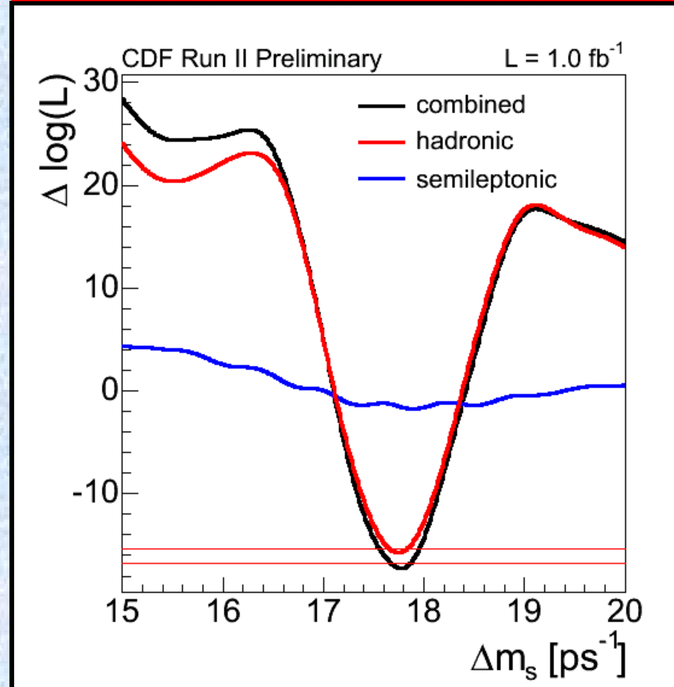
Properties of B_s meson

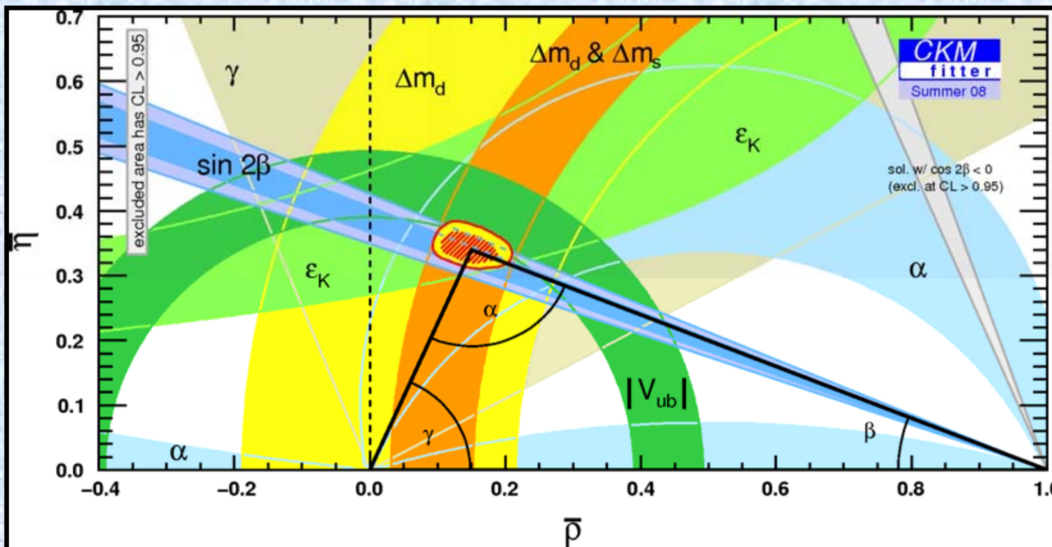
- B_s meson is a special particle with unique properties:
  - Essential information to understand the quark mixing:
    - Mass difference;
    - Width difference;
  - Probe new physics beyond the SM:
    - CP violation;
    - Rare decays;
  - Can be studied only at hadron colliders;
- B_s is actively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

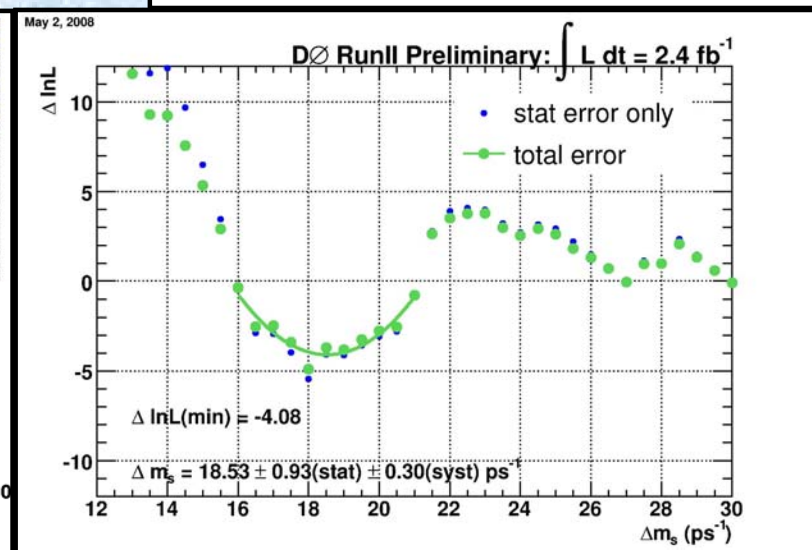
Mass difference of B_s

$$\text{CDF}: \quad \Delta M_s = 17.77 \pm 0.10 \pm 0.07\ \text{ps}^{-1}$$

- 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);

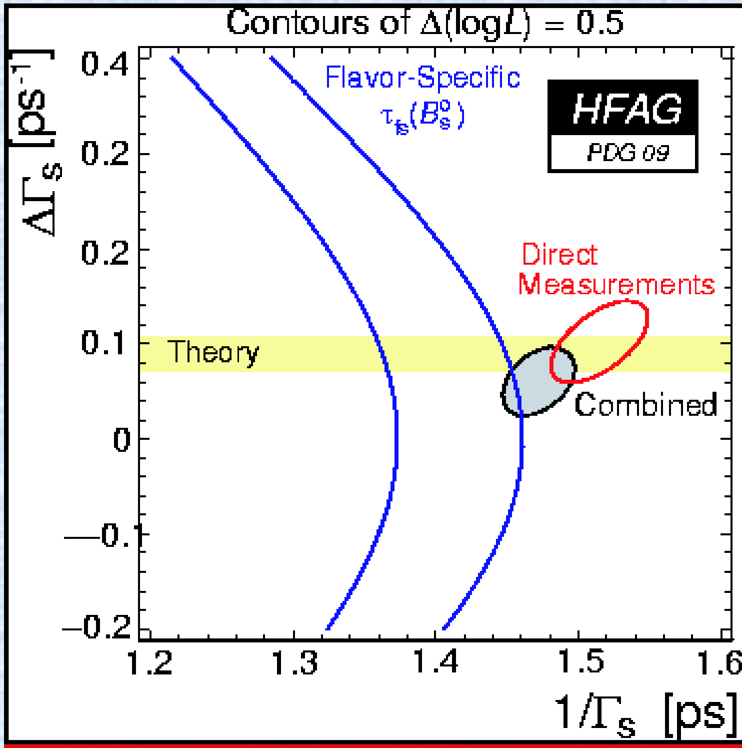






Width difference of B_s

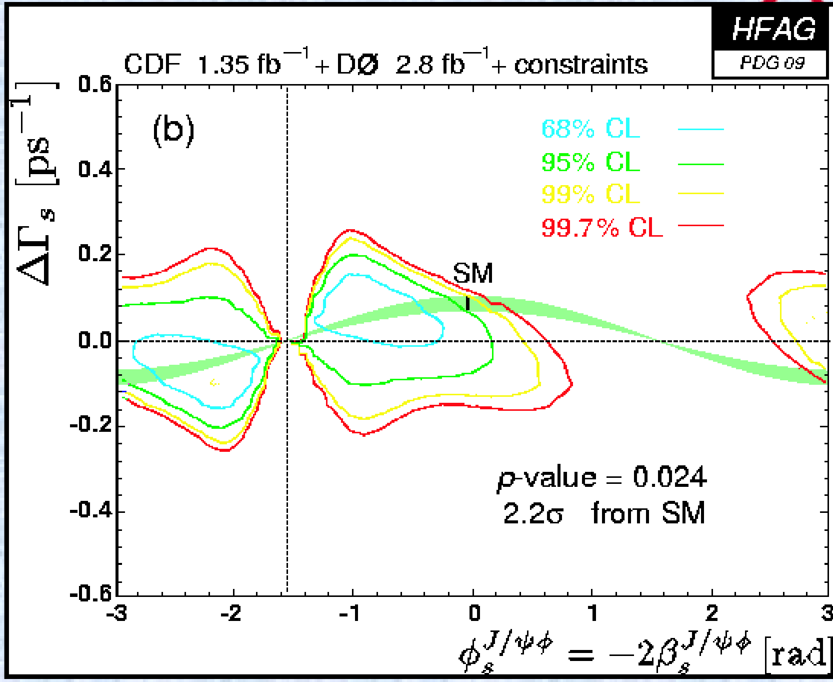
- Another important measurement performed by Tevatron;
- The value is extracted from the measurement of $B_s \rightarrow J/\psi\ \varphi$;
- Other possibilities include measurement of B_s lifetime in CP-specific decays (like $B_s \rightarrow K^+K^-$, CDF);
- Obtained precision: $\sigma(\Delta\Gamma_s)$~0.035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



$$\textbf{PDG2009:}\quad \Delta\Gamma_s = 0.062^{+0.034}_{-0.037}\ \text{ps}^{-1}$$

$$\textbf{Theory:}\quad \Delta\Gamma_s = 0.088 \pm 0.017\ \text{ps}^{-1}$$

CP violating mixing phase of B_s



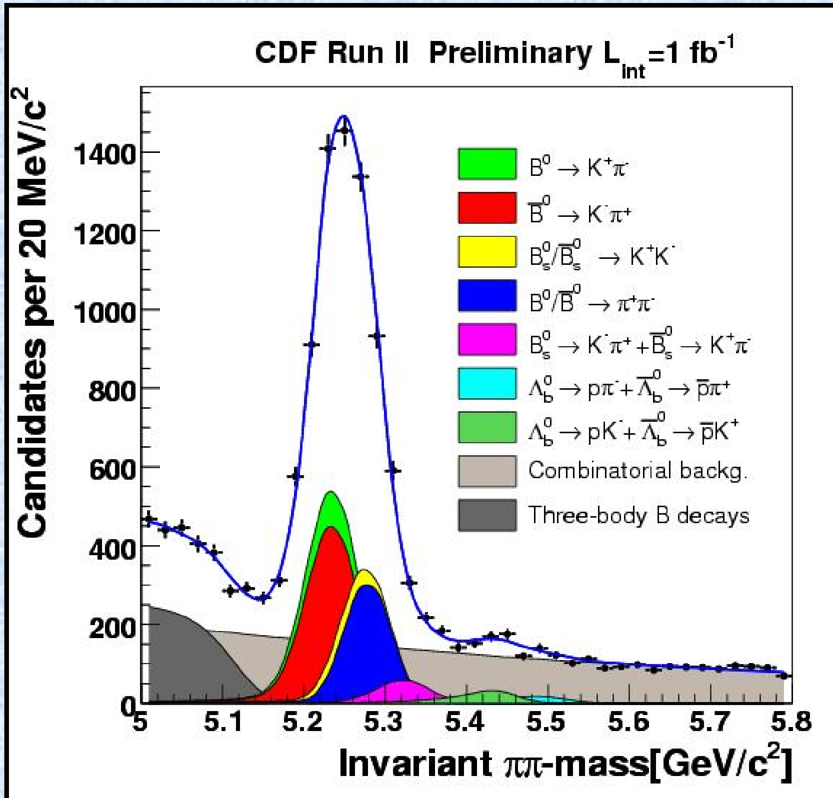
- The CP violating phase ϕ_s extracted from the $B_s \to J/\psi\ \varphi$ decay is very small in the SM:

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

- It can be considerably increased by contributions of the new physics;
- Both CDF and DØ performed measurement of this phase;
- Results shows ~2.2σ deviation from the SM: $\mathbf{PDG2009:}\ \phi_s = -0.094^{+0.43}_{-0.25}$
- Study will continue with the new statistics, ~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;

Other CP violation studies

- The most important other achievements of Tevatron:
  - dimuon same sign charge asymmetry: $\textbf{Dzero}: \quad A_{SL}^{d} + 0.7 A_{SL}^{s} = (-9.2 \pm 4.4 \pm 3.2) \times 10^{-3}$
  - Semileptonic charge asymmetry in B_s decay: $\textbf{Dzero}: \quad A_{SL}^{s} = (-1.7 \pm 9.1_{-2.3}^{+1.2}) \times 10^{-3}$
    - Both measurements are directly related with the phase ϕ_s;
  - Direct CP asymmetry in $B^+ \to J/\psi K^+$: $\textbf{Dzero}: \quad A_{CP}(B^+ \to J/\psi K^+) = +0.0075 \pm 0.0061 \pm 0.0027$
  - CP asymmetry in $B \to h^+ h^-$ decays: $\textbf{CDF}: \quad A_{CP}(B^0 \to K^+ \pi^-) = -0.086 \pm 0.023 \pm 0.009$
- These results can be improved and extended at LHC:
  - Charge asymmetry requires just muon triggers, good understanding of detector and large statistics;
  - To select $B \to h^+ h^-$ decays, special triggers are required;
  - Particle ID will be essential for $B_s \to K^+ K^-$ studies, probably can be performed only at LHCb;



Rare decays

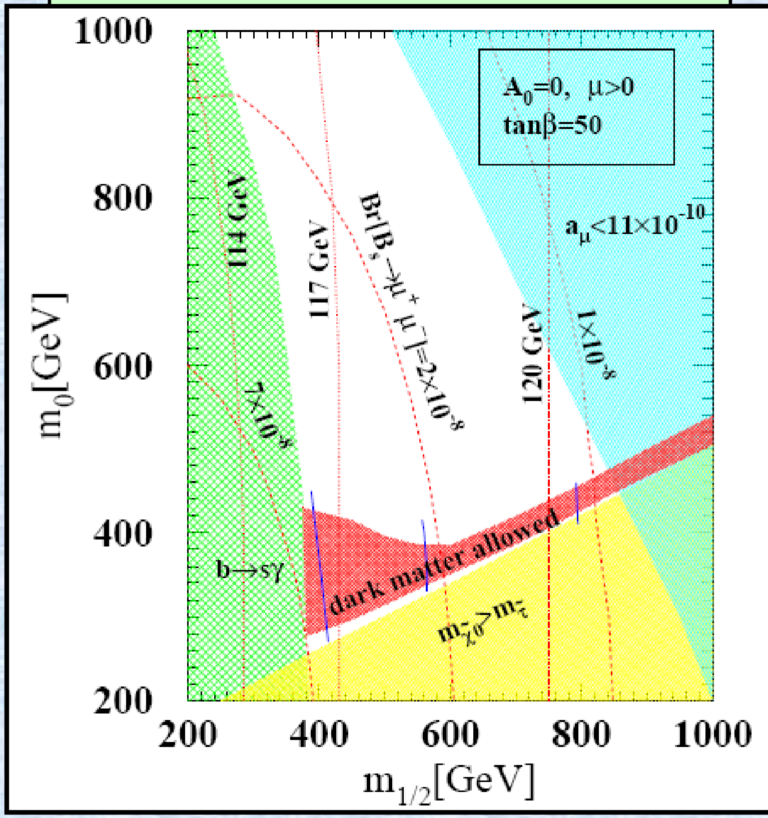
- The most interesting decay is $B_s \to \mu^+ \mu^-$;
- SM prediction: $\sim 4\times10^{-9}$;
- New physics (e.g. mSUGRA) can significantly change this decay rate;
- Recent results for 2 fb^{-1}:

$$\textbf{CDF: } \mathrm{Br}(B_s \to \mu^+\mu^-) < 5.8\times10^{-8} \text{ (95\% CL)}$$

$$\textbf{Dzero: } \mathrm{Br}(B_s \to \mu^+\mu^-) < 9.3\times10^{-8} \text{ (95\% CL)}$$

  - DØ recently updated analysis with the expected sensitivity for 5 fb^{-1}: $Br(B_s \to \mu\mu) < 5.3\times10^{-8}$ (95% CL);
- The limit expected by the end of RunII: $\sim 2\times10^{-8}$;
- The SM level is achievable at LHC, both at CMS/ATLAS and LHCb;

mSUGRA with tanβ = 50
T. Arnowitt et al. PLB 538(2002), 121



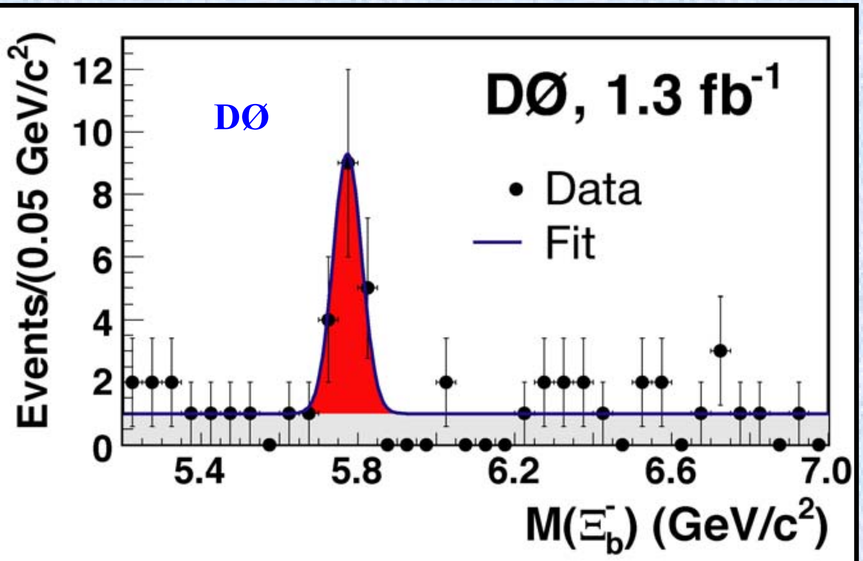
Properties of *B* hadrons

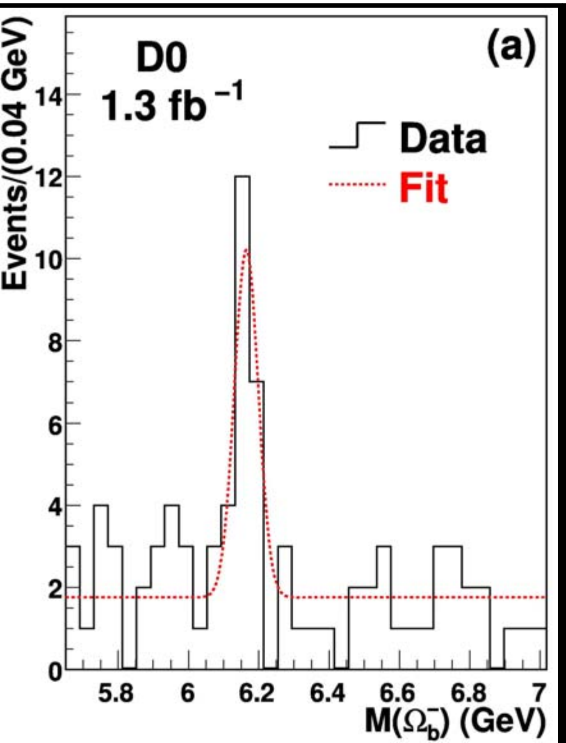
- *B* hadrons – excellent place to test the QCD and adjust theoretical models describing quark bound states:
  - predictions of theory are very precise for heavy-light quark bound system:
    - Example: ratios of lifetimes of different B hadrons are predicted to ~1-3%;
    - Masses of different *B* baryons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

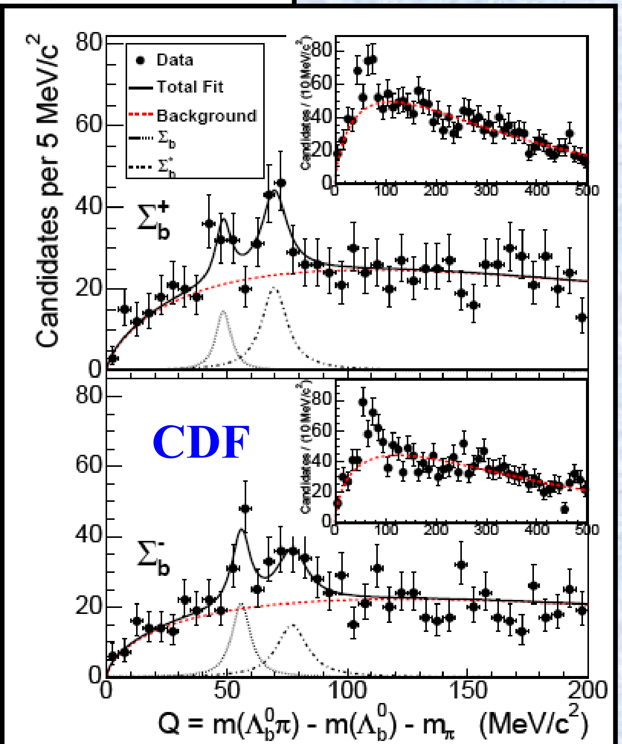
B baryon spectroscopy

- Many heavy baryons were observed at Tevatron:
  - Ξ_b (DØ and CDF); Σ_b, Σ_b^* (CDF); Ω_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

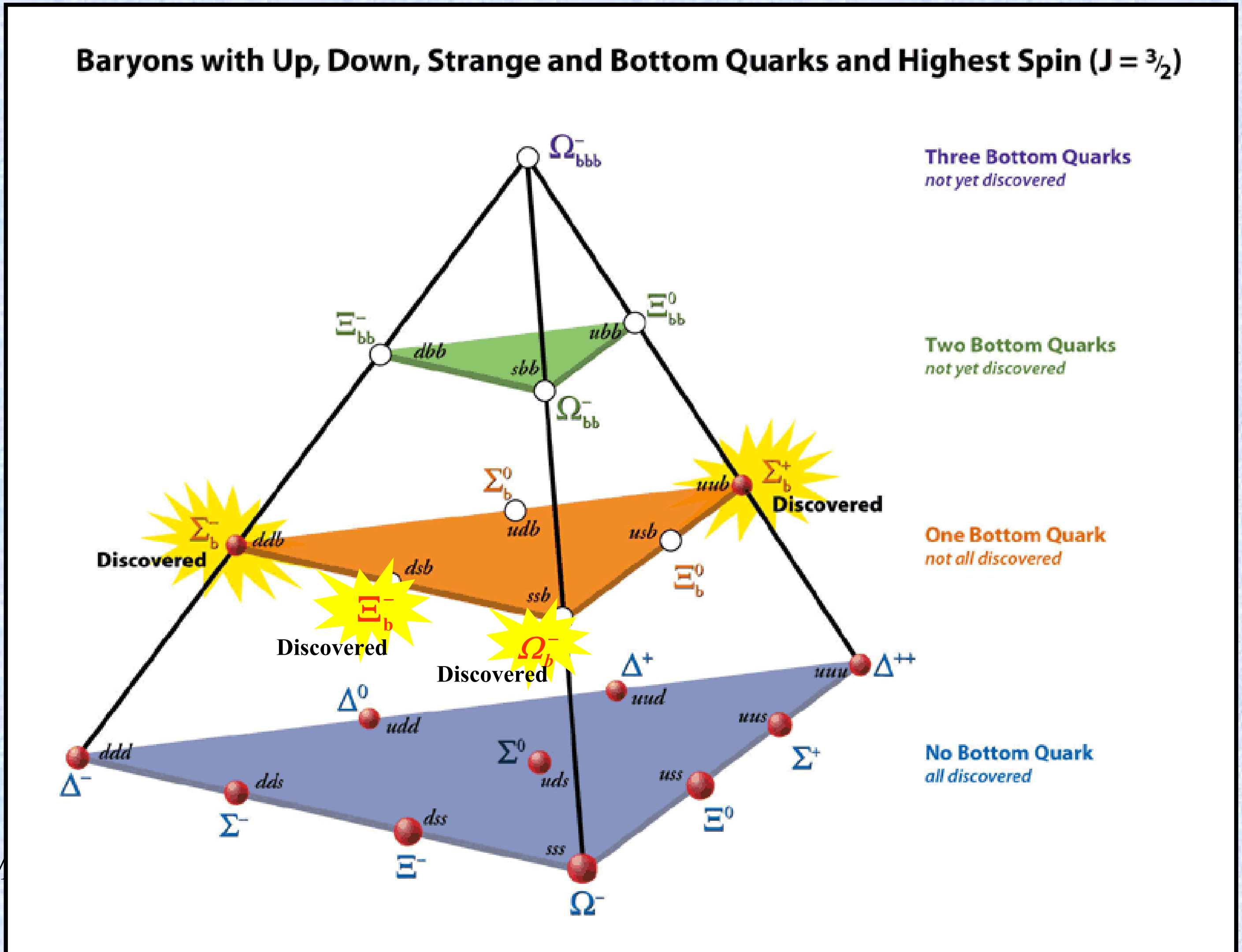
$M(\Sigma_b^-) = 5815.2 \pm 1 \pm 1.7$ MeV

$M(\Sigma_b^{*+}) = 5829^{+1.6}_{-1.8} \pm 1.7$ 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

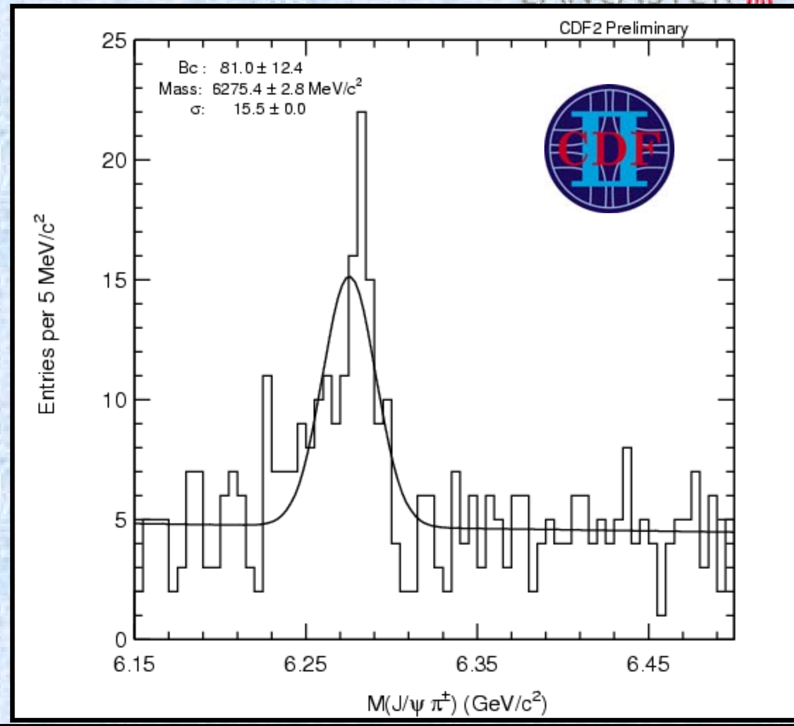
- Now measured by both CDF and DØ collaborations in $B_c \to J/\psi\ \pi$ mode;
- Consistent results are obtained:

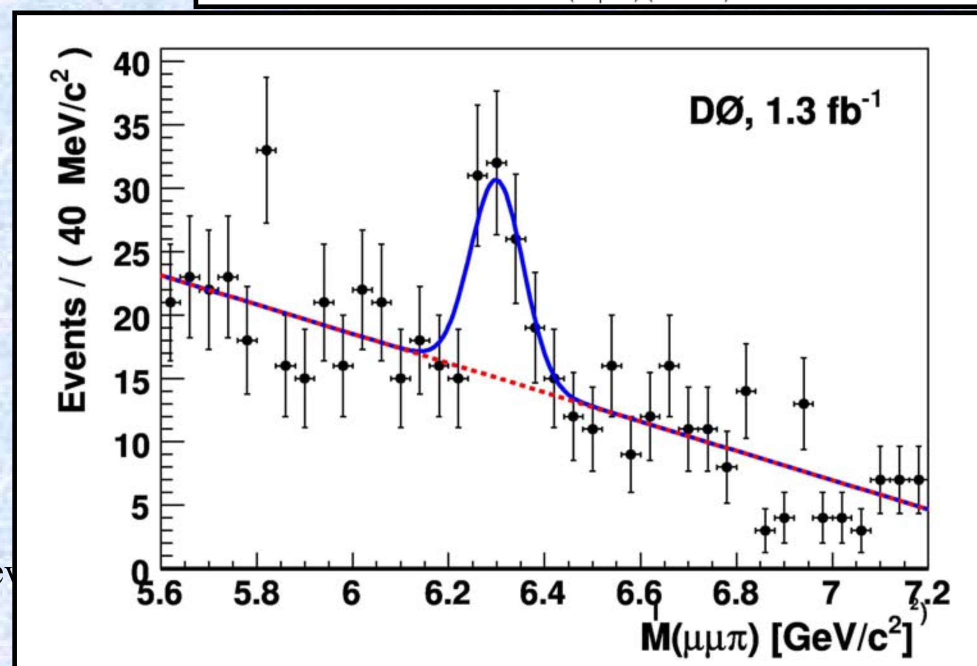
$$M(B_c) = 6275.6 \pm 2.9 \pm 2.5 \quad \text{MeV (CDF)}$$
$$M(B_c) = 6300 \pm 14 \pm 5 \quad \text{MeV (Dzero)}$$

- Agree well with theory prediction:

$$M(B_c) = 6304 \pm 12\ ^{+18}_{-0} \quad \text{MeV (Theory)}$$

  - (lattice QCD calculations, J. Allison *et al.* PRL 94, 172001 (2005)):



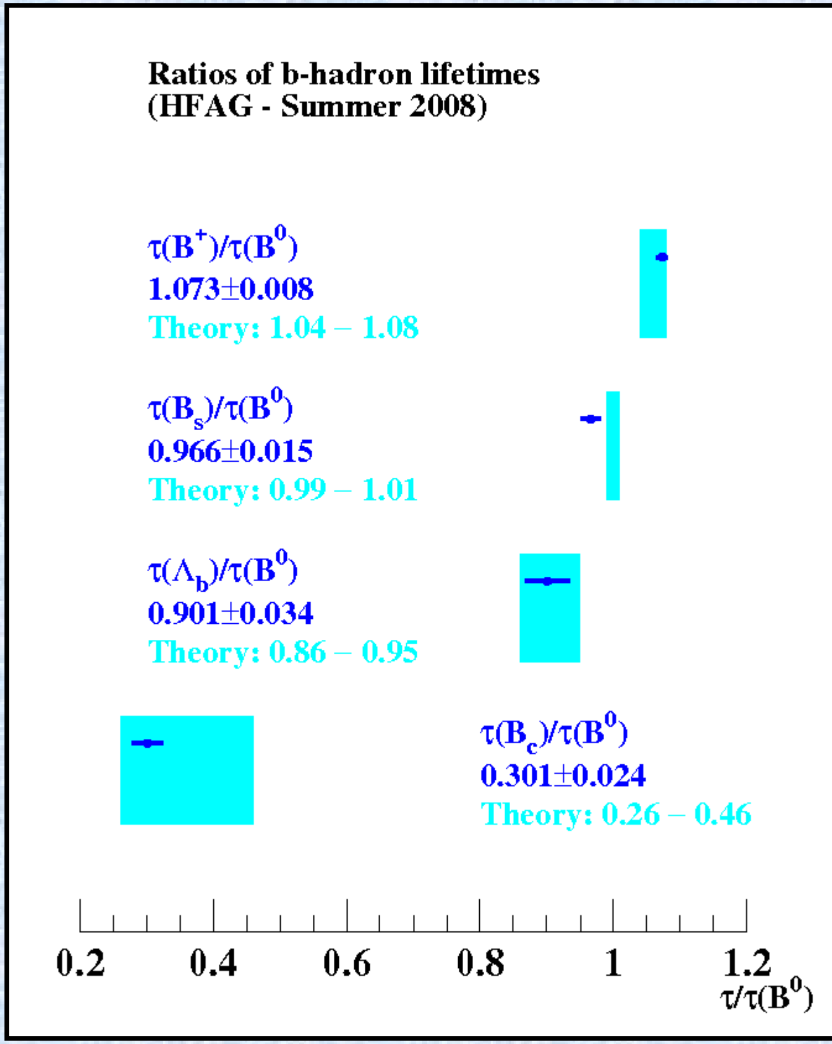


Lifetime of b hadrons

- Lifetime is another quantity which allows direct comparison between theory and experiment;
- Theory predicts the hierarchy:

$$\tau(B_c^+) << \tau(\Lambda_b^0) < \bar{\tau}(B_s^0) \approx \tau(B^0) < \tau(B^+)$$

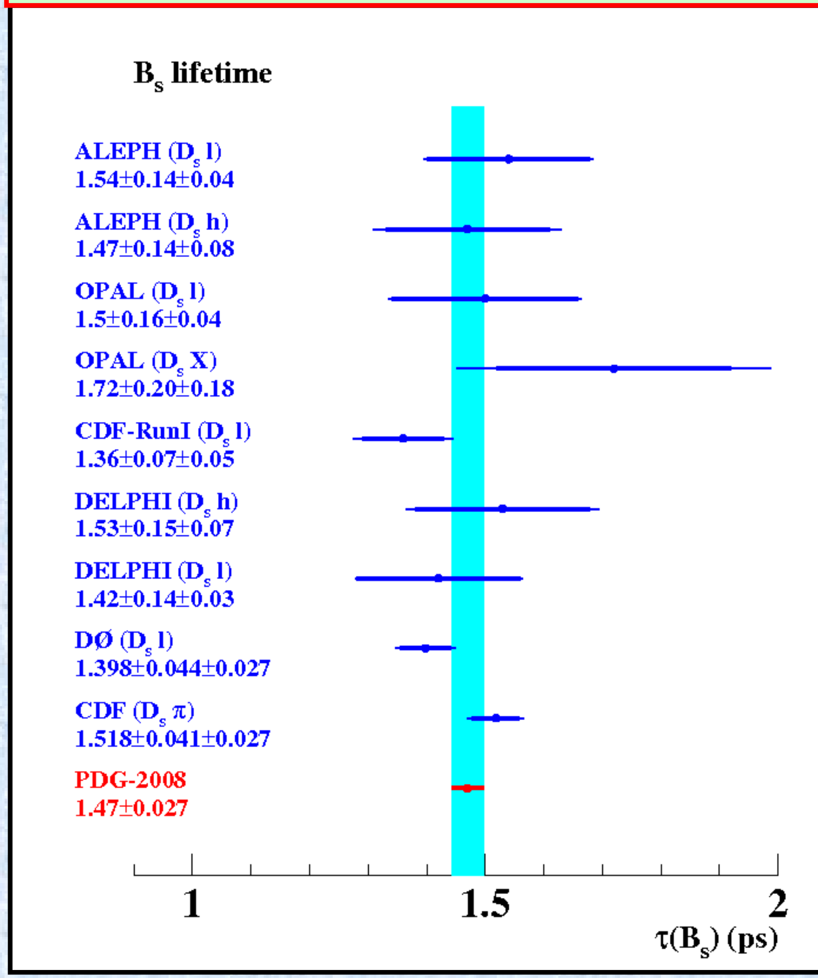
- Theory predictions are especially precise for lifetime ratios;
- Precision of Tevatron results is now determining for B_s, Λ_b and B_c lifetimes;
- It is much better than all previous measurements;



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 ~30% by the end of the Tevatron run;

$$\text{PDG2008:} \quad \bar{\tau}(B_s^0) = \frac{2}{\Gamma_L + \Gamma_H} = 1.470^{+0.027}_{-0.026} \text{ ps}$$



Λ_b Lifetime

- A lot of discussion of Λ_b lifetime recently ("Λ_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 $\Lambda_b \to J/\psi\, \Lambda$: $\tau(\Lambda_b) = 1.580 \pm 0.077 \pm 0.012\ ps$ (CDF)
  - CDF measurement in $\Lambda_b \to \Lambda_c\, \pi$ $\tau(\Lambda_b) = 1.410 \pm 0.046 \pm 0.029\ ps$ (CDF)
  - DØ measurement in $\Lambda_b \to J/\psi\, \Lambda$: $\tau(\Lambda_b) = 1.218^{+0.130}_{-0.115} \pm 0.042\ ps$ (D0)
  - DØ measurement in $\Lambda_b \to \mu\nu\Lambda_c$: $\tau(\Lambda_b) = 1.290^{+0.119}_{-0.110} \pm^{+0.087}_{-0.091}\ ps$ (D0)
    - Notice ~1.8σ difference between 2 CDF results;

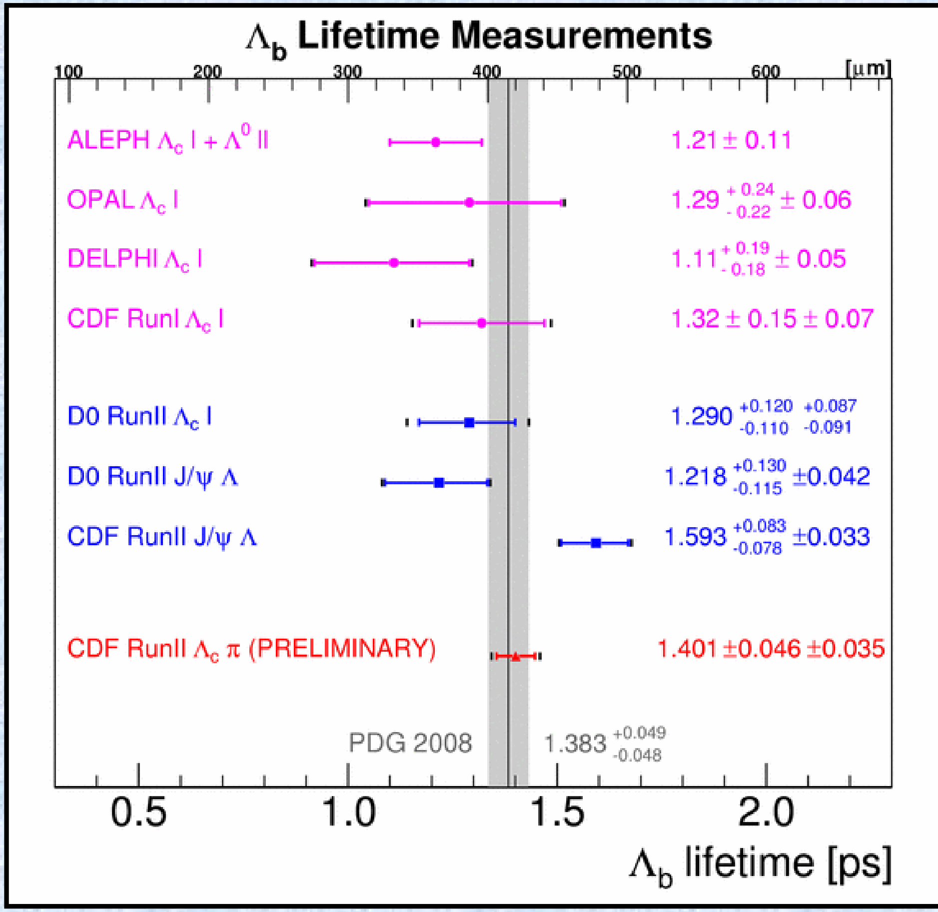
Λ_b lifetime

- New results from Tevatron now dominate in the world average precision of Λ_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 ~50%;
- Theoretical precision needs to be improved for the meaningful comparison;

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



B_c lifetime

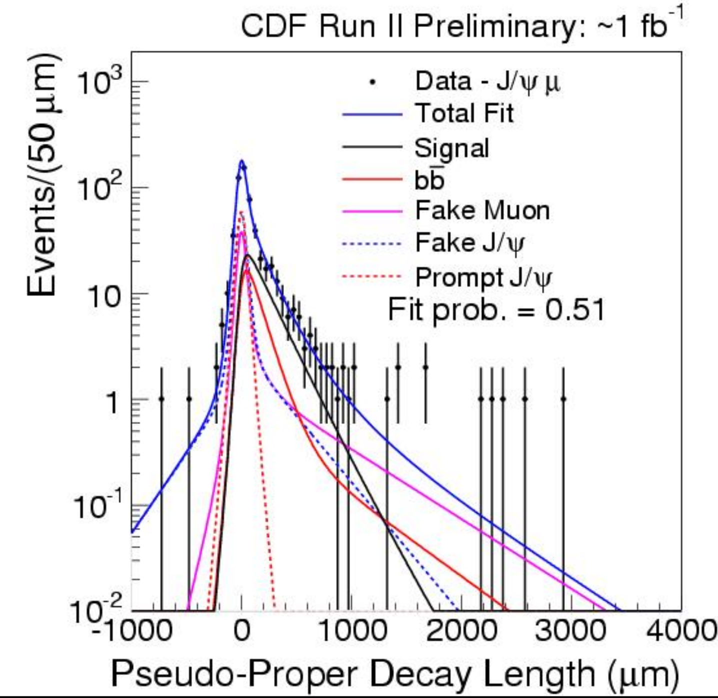
- Now measured by both CDF and DØ collaborations in $B_c \to J/\psi\ l\ \nu$ mode
  - CDF uses events with $l = \mu, e$, DØ with $l = \mu$ only;
- Results are consistent and precision is similar:

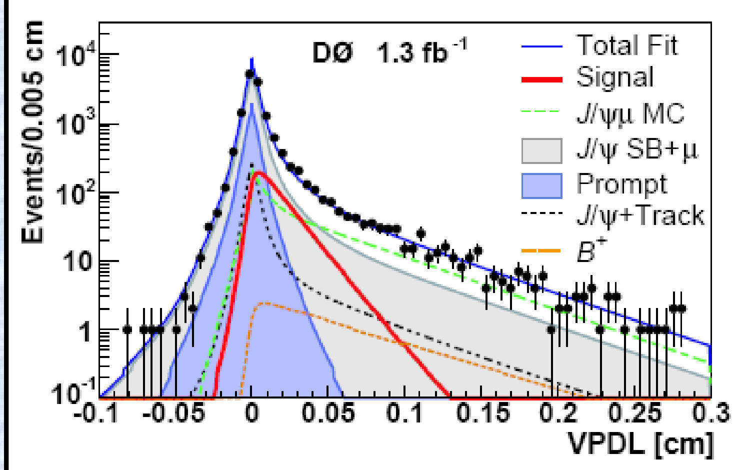
$$\tau(B_c) = 0.475^{+0.053}_{-0.049} \pm 0.018 \text{ ps (CDF)}$$
$$\tau(B_c) = 0.448^{+0.038}_{-0.036} \pm 0.032 \text{ ps (Dzero)}$$

- World average value:

$$\tau(B_c) = 0.461 \pm 0.036 \text{ ps (HFAG)}$$

- Experimental precision is now much better than the theoretical:
  - $\tau(B_c) = 0.4 - 0.7$ 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;

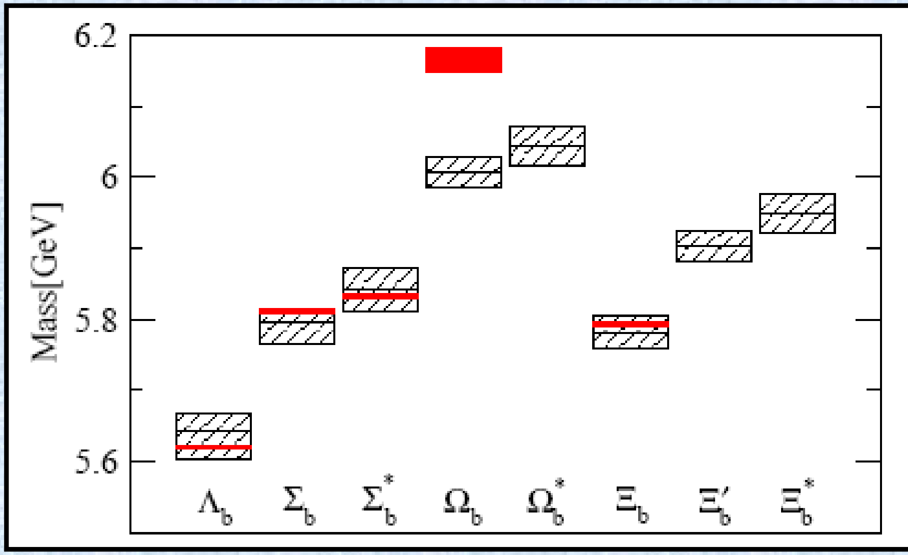
Summary (continued)

- 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 Ω_b mass:
  - 6039 ± 8 MeV
    E. Jenkins, PR D77, 034012 (2008);
  - 6052.1 ± 5.6 MeV
    M. Karliner *et al.* arXiv:0804.1575;
  - 6036 ± 81 MeV
    X. Liu *et al.* , PR D77, 014031 (2008);
  - 6006 ± 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 Ω_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:

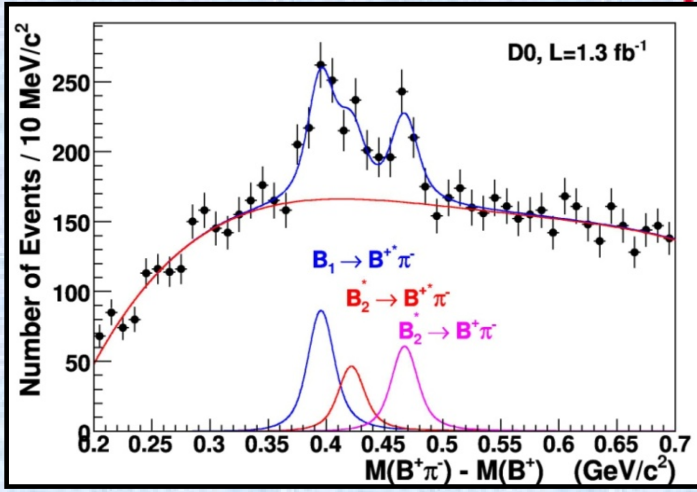
$$M(B_1) = 5720.6 \pm 2.4 \pm 1.4 \text{ MeV (Dzero)}$$

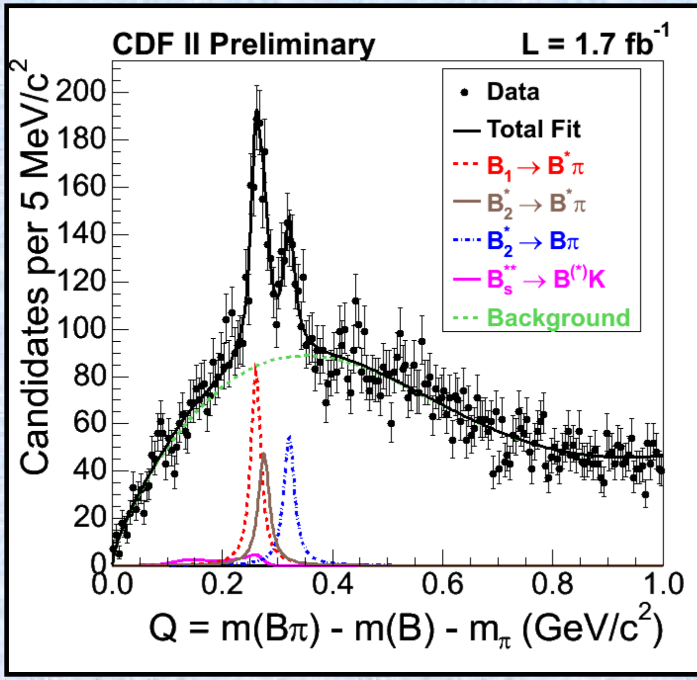
$$M(B_1) = 5725.3^{+1.6}_{-2.2}{}^{+1.4}_{-1.5} \text{ MeV (CDF)}$$

$$M(B_2^*) = 5746.8 \pm 2.4 \pm 1.7 \text{ MeV (Dzero)}$$

$$M(B_2^*) = 5740.2^{+1.7}_{-1.8}{}^{+0.9}_{-0.8} \text{ MeV (CDF)}$$

- Maximal difference between results of two collaborations is *~2σ*





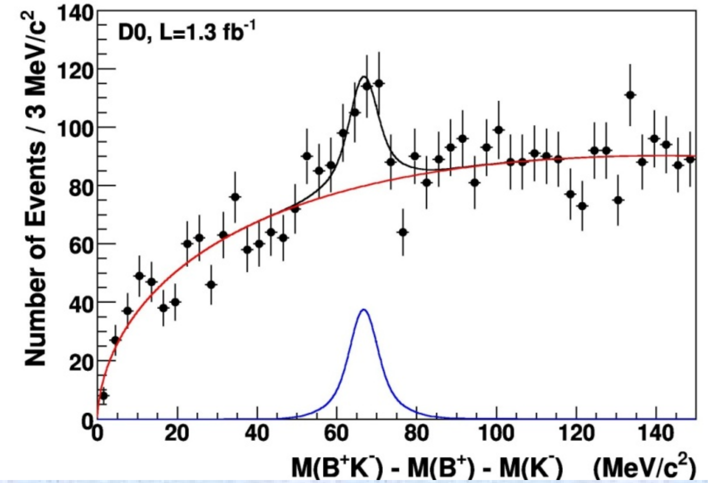
Excited B_s^{**} states

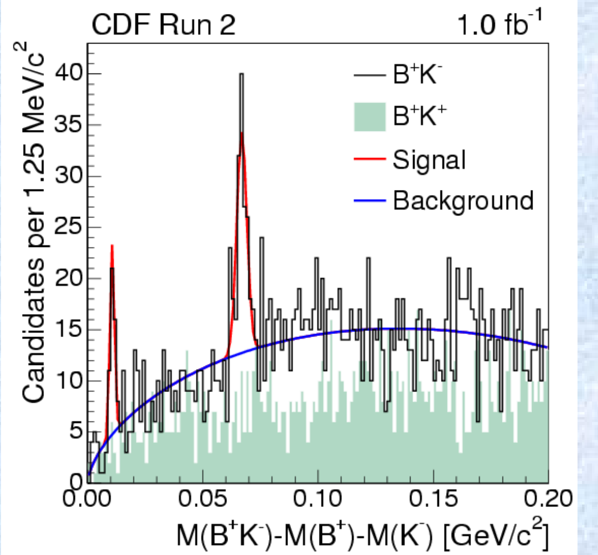
- CDF observes both B_{s2}^* and B_{s1} states, while DØ confirmed only B_{s2}^* meson:
  - Lack of statistics does not allow the DØ collaboration to either confirm or deny B_{s1};

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

$$\boxed{\begin{aligned} M(B_{s2}^*) &= 5839.6 \pm 1.1 \pm 0.7 \text{ MeV (Dzero)} \\ M(B_{s2}^*) &= 5839.6 \pm 0.7 \text{ MeV (CDF)} \end{aligned}}$$

- 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:
  - $B_s \to D_s(3\pi)$ (CDF);
  - $B_s \to K^+K^-$ (CDF);
  - $B_s \to \mu\nu D_s^{**}$ (DØ);
  - $B_s \to D_s^{(*)}D_s^{(*)}$ (DØ);
  - $B_s \to D_sD_s$ (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. $B_s \to K^+K^-$, $B_s \to D_sD_s$);
- Other B hadrons will not be studied at Tevatron;
- Good possibility for LHCb; the displaced tracks triggers are required for this study;