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CDF/PUB/CDF/PUBLIC/7276
October 26, 2004

Electroweak, Top and Bottom Physics at the Tevatron

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representing the CDF and D0 collaborations

ABSTRACT

The Tevatron Run-II program has been in progress since 2001, and the CDF and D0 experiments have been operational with upgraded detectors. Coupled with recent improvements in the Tevatron accelerator performance, the experiments have started producing important physics results and measurements. We report these measurements as well as prospects in the near future.

Plenary talk presented at

SUSY 2004
The 12th International Conference
on Supersymmetry
and Unification of Fundamental Interactions

June 17 - 23, 2004

Epochal Tsukuba, Tsukuba, Ibaraki, Japan.

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ABSTRACT

The Tevatron Run-II program has been in progress since 2001, and the CDF and D0 experiments have been operational with upgraded detectors. Coupled with recent improvements in the Tevatron accelerator performance, the experiments have started producing important physics results and measurements. We report these measurements as well as prospects in the near future.

1. Introduction

The Tevatron Run-II program officially started in March 2001 after the previous run (Run I) ended in 1996. Between these years, the Tevatron accelerator and the CDF and D0 detectors have undergone vast upgrades. The accelerator complex has added the Main Injector, replacing the old Main Ring, to inject higher intensity beams to the Tevatron and to produce more anti-protons to be used for collisions. Also the Tevatron beam energy has been increased and it resulted in a center-of-mass energy of 1.96 TeV. The instantaneous luminosity has improved steadily since the beginning of Run II, and at the time of the Conference a record value was 8.3×10^{31} cm^{-2} s^{-1}. This is about 5 times higher than the Run-I record value, and almost matches the Run-IIa goal of 8.6×10^{31}. The integrated luminosity delivered to each experiment has exceeded 500 pb^{-1}, and with about 80% of them recorded by the detector.

Both the CDF and D0 experiments have broad physics program being carried out with the data. In the remainder of this manuscript we summarize those in the areas of electroweak physics, top quark physics and bottom quark physics. Exotic physics including higgs and susy searches is covered by another speaker [1].

2. Electroweak Physics

2.1. Production of single gauge bosons

Since the termination of the operation of the LEP2 collider, Tevatron is the only accelerator capable of producing $W^{\pm}$ and Z^0 bosons. CDF and D0 collaborations have performed studies of various aspects of the weak boson properties. They are cleanly identified with their decays to leptons (electrons or muons). Figure 1 shows invariant mass spectra of di-lepton candidates from CDF and D0. The production cross sections

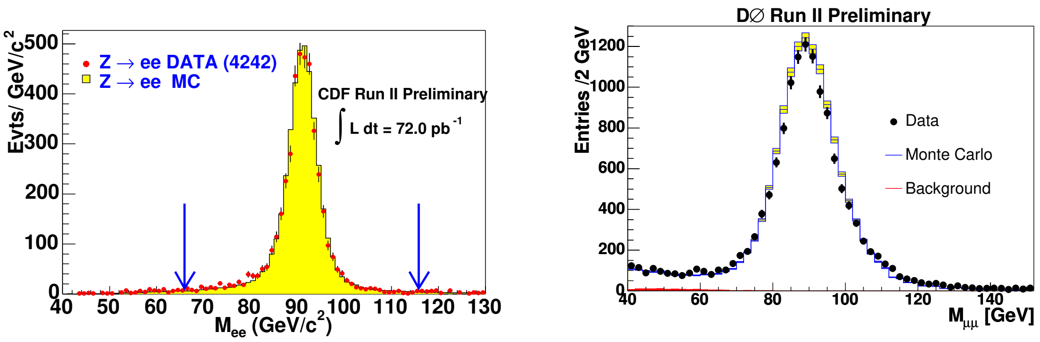


Figure 1: Invariant mass distributions of lepton pairs for $Z^0 \to e^+e^-$ (left, CDF) and $Z^0 \to \mu^+\mu^-$ (right, D0) candidates.

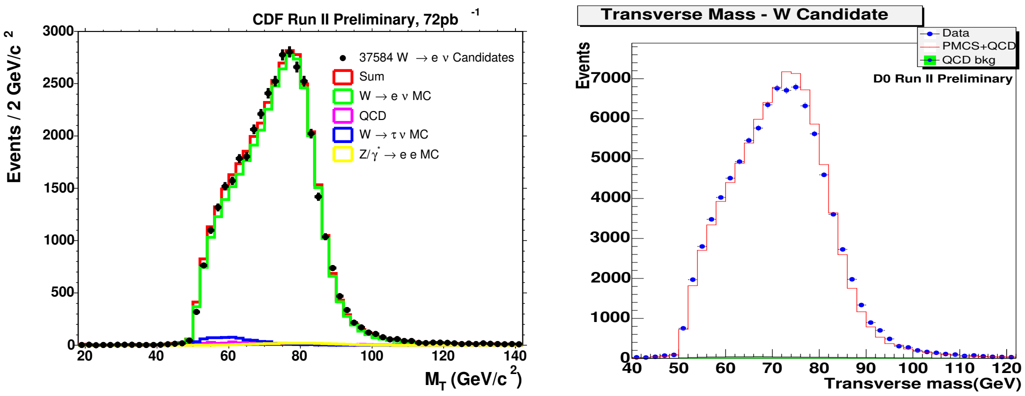


Figure 2: Transverse mass distributions of lepton and missing E_T system for $W \to e\nu$ candidates (left: CDF, right: D0).

are measured to be [2]

$$\begin{aligned}\sigma(\bar{p}p \to Z^0 \to \ell^+\ell^-) &= 254.3 \pm 3.3 \pm 4.3 \pm 15.3 \text{ pb (CDF)} \\ &= 291.3 \pm 3.0 \pm 6.9 \pm 18.9 \text{ pb (D0)},\end{aligned}$$

in good agreement with a theory prediction of 250.5 ± 3.8 pb (NNLO, MRST) [3].

W boson decays are identified with an energetic lepton and a large missing transverse energy. Figure 2 shows transverse mass distributions. The production cross sections are measured to be [2,4]

$$\begin{aligned}\sigma(\bar{p}p \to W \to \ell\nu) &= 2777 \pm 10 \pm \ \ 52 \pm 167 \text{ pb} \quad \text{(CDF)} \\ &= 2865.2 \pm 8.3 \pm 62.8 \pm 40.4 \pm 186.2 \text{ pb} \quad (\text{D0 } e) \\ &= 3226 \pm 128 \pm 100 \pm 322 \text{ pb} \quad (\text{D0 } \ \mu),\end{aligned}$$

again in good agreement with theory, 2687 ± 40 pb (NNLO, MRST) [3].

Figure 3 (left) shows a summary of those measurements, along with earlier measurements at the CERN collider, as a function of the collision center-of-mass energy.

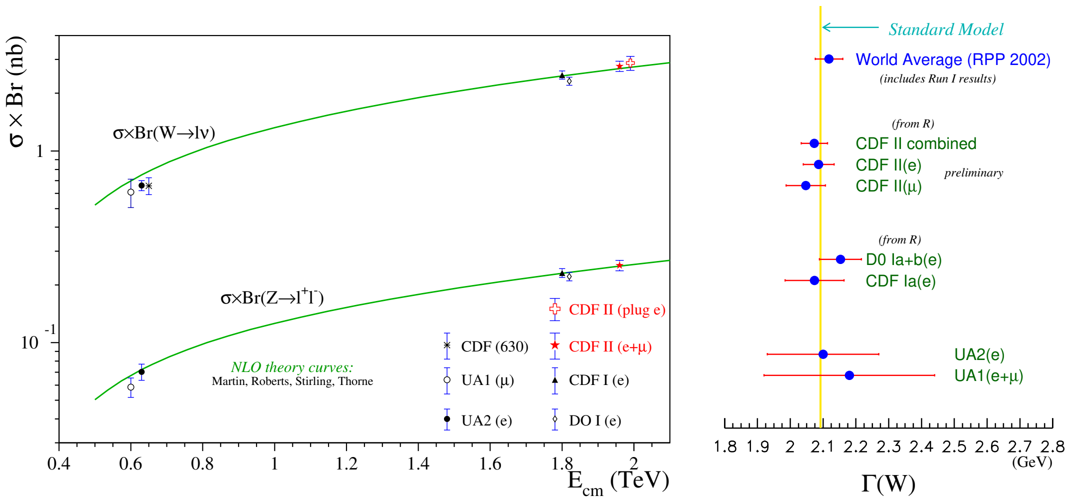


Figure 3: Left: Production cross section of weak vector bosons as a function of collision center-of-mass energy. Right: W boson width measurements.

The ratio R of the W and Z boson production rates, defined by

$$R \equiv \frac{\sigma(\bar{p}p \to W^{\pm}) \cdot \mathcal{B}(W^{\pm} \to \ell\nu)}{\sigma(\bar{p}p \to Z^{0}) \cdot \mathcal{B}(Z^{0} \to \ell^{+}\ell^{-})},$$

includes the branching fraction of the W boson. Using a theory prediction for the ratio of production cross sections and measurements of $\mathcal{B}(Z \to \ell^{+}\ell^{-})$, one can extract $\mathcal{B}(W^{+} \to \ell^{+}\nu)$, or the total width assuming the leptonic partial width. The extracted numbers are $\Gamma_W = 2.071 \pm 0.040$ GeV (CDF) and 2.187 ± 0.128 GeV (D0). They are shown in Figure 3 (right).

2.2. Pair production of gauge bosons

The unified electroweak theory has a non-Abelian gauge structure and results in self-couplings of gauge bosons. CDF has observed the production of $W^{+}W^{-}$ pairs for the first time in hadron colliders. The leptonic decay channel of the W bosons is used, resulting in two energetic leptons and a large missing E_T, and no extra jet activities. The production cross section has been measured to be [5]

$$\sigma(\bar{p}p \to W^{+}W^{-}) = 14.3\,^{+5.6}_{-4.9} \pm 1.6 \pm 0.9 \text{ pb},$$

to be compared with a theory prediction of 12.5 ± 0.9 pb [6].

Associated production of a W or Z boson with a photon is also studied. Photons are identified in the transverse momentum ranges above 7 GeV and 8 GeV in CDF and D0, respectively. Figure 4 shows transverse momentum spectra of photons in $W\gamma$ candidate events. Production cross section is measured to be [7]

$$\begin{aligned} & \sigma(\bar{p}p \to W\gamma) \cdot \mathcal{B}(W \to \ell\nu) \\ = \;& 19.7 \pm 1.7 \pm 2.0 \pm 1.1 \text{ pb} \quad \text{(CDF) vs. } 19.3 \pm 1.4 \text{ pb} \quad \text{(theory)} \\ = \;& 19.3 \pm 2.7 \pm 6.1 \pm 1.2 \text{ pb} \quad \text{(D0)} \quad \text{vs. } 16.4 \pm 0.4 \text{ pb} \quad \text{(theory)}, \end{aligned}$$

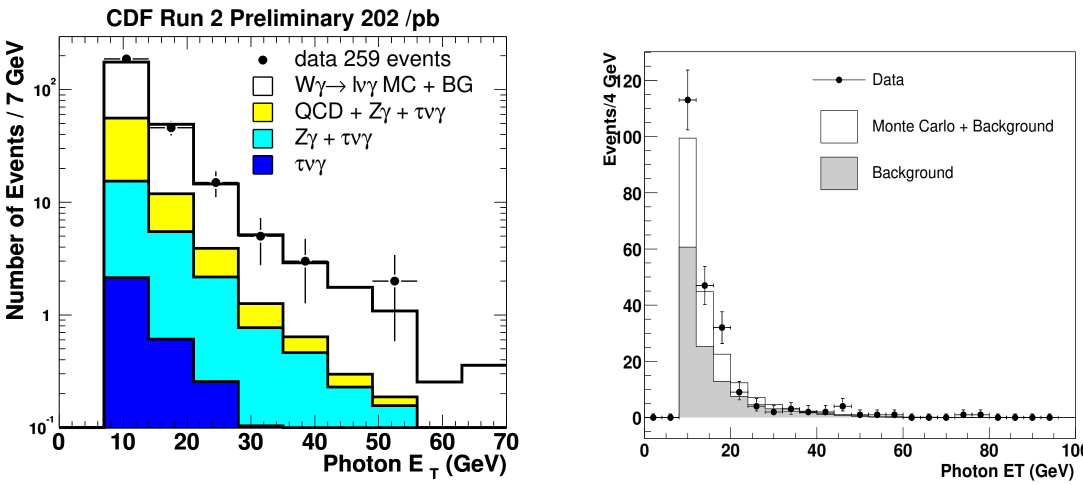


Figure 4: Transverse momentum distribution of photons produced in association with the W boson. Left: CDF, right: D0.

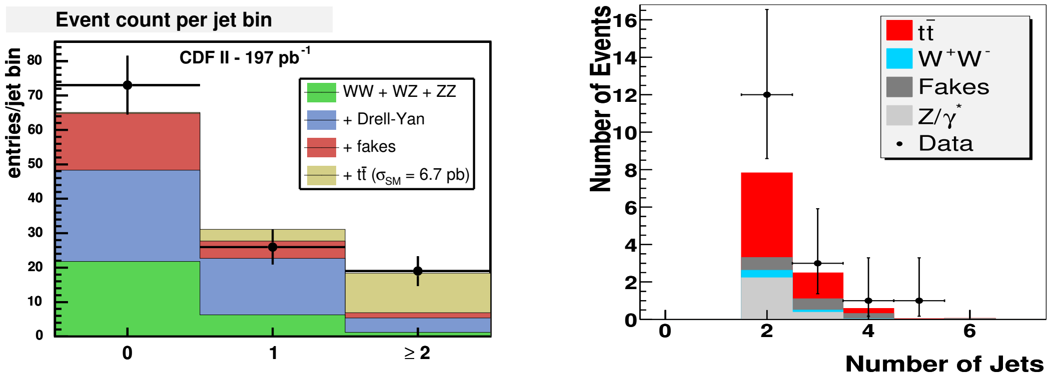


Figure 5: Jet multiplicity distributions of top candidate events in the di-lepton channel. Left: CDF, right: D0.

where the difference reflects the different kinematic requirements. A more direct test of the gauge couplings can be performed if photon angular distributions of those events are studied and radiation amplitude zero is looked for directly.

3. Top Quark Physics

The top quark was discovered by CDF and D0 in Tevatron Run-I data of about 100 pb^{-1}. Tens of events were reconstructed then, and therefore all measurements were statistically limited. The expected 20-fold increase in the amount of data in Run II should allow more detailed studies of top quark properties. They include production cross section, mass, production kinematics, $t\bar{t}$ spin correlations, helicity of W bosons produced in top decays, branching fractions of various decay modes and searches for rare decays including those beyond the standard model.

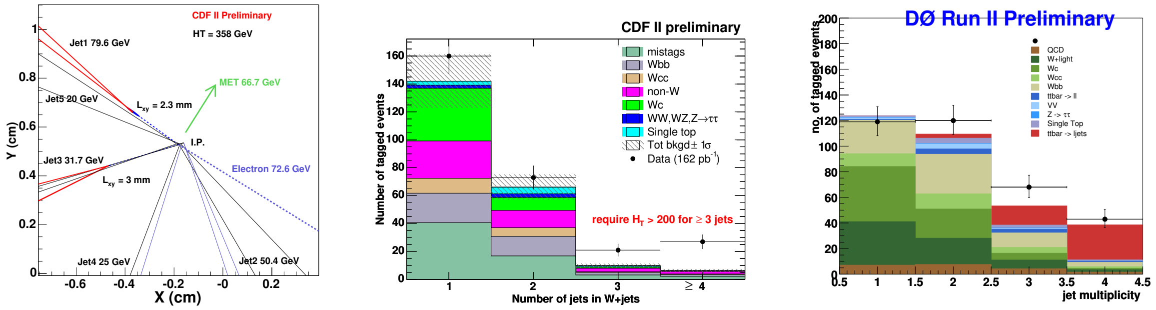


Figure 6: Left: Example of b-tagged top candidate event. Middle and right: Jet multiplicity distributions of top candidate events in the lepton plus jet channel from CDF and D0. The signal region is $N_{\rm jet} \geq 3$.

3.1. Production cross sections

The signature of top quark pair production and decays is two W bosons and two b quark jets. Depending on the W decay modes, the final states can be two leptons and two jets, one lepton and four jets, or six jets. The two b quark jets can be identified by secondary vertices (reflecting detectable B-hadron lifetimes) or "soft" leptons from semileptonic decays.

The di-lepton channel is particularly clean and does not usually require that the b-hjets be identified. Figure 5 shows the jet multiplicity distributions of the candidate events in this channel. The production cross section is measured to be [8]

$$\begin{aligned} \sigma(\bar{p}p \to t\bar{t}X) &= 7.0\,^{+2.7}_{-2.3}\,^{+1.5}_{-1.3} \pm 0.4 \text{ pb} \quad (\text{CDF } 197 \text{ pb}^{-1}) \\ &= 14.3\,^{+5.1}_{-4.3}\,^{+2.6}_{-1.9} \pm 0.9 \text{ pb} \quad (\text{D0} \quad 150 \text{ pb}^{-1}). \end{aligned}$$

The lepton plus jet final state is less pure, and it is required that one or both of b-quark jets be identified. An example event with secondary vertex tags is shown in Figure 6 (left). The jet multiplicity distributions of these candidate events are also shown in Figure 6. The excess of events in the bins $N_{\rm jet} \geq 3$ bins is nicely described after the inclusion of top contributions. The production cross section is measured to be [9]

$$\begin{aligned} \sigma(\bar{p}p \to t\bar{t}X) &= 5.6\,^{+1.2}_{-1.0}\,^{+1.0}_{-0.7} \text{ pb} \quad (\text{CDF } 162 \text{ pb}^{-1}) \\ &= 8.2 \pm 1.3\,^{+1.9}_{-1.6} \pm 0.5 \text{ pb} \quad (\text{D0} \quad 160 \text{ pb}^{-1}). \end{aligned}$$

There exit many other measurements of the quantity using various different techniques [10].

3.2. Top quark mass

The mass of the top quark is an important quantity to measure, not just for its own right, but also from other physics perspectives. When combined with the W boson mass, it can provide indirect information on the Higgs boson mass. Figure 7 shows this relation,

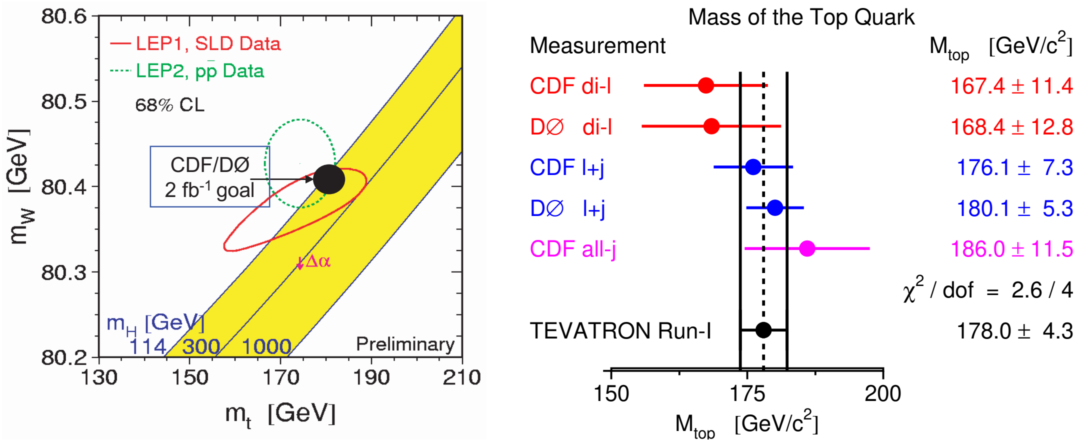


Figure 7: Left: Top quark and W boson mass measurements and their relation to the Higgs boson mass. Right: Summary of top quark mass measurements from Run I.

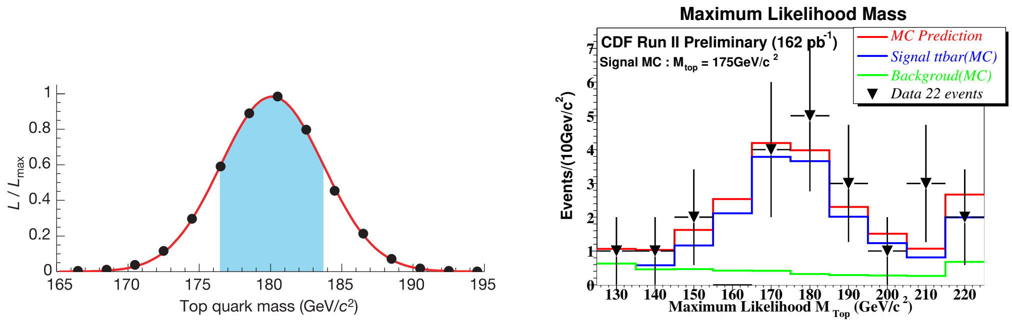


Figure 8: Left: Top quark mass likelihood distribution from D0 in re-analysis of Run-I data. Right: Distribution of top quark mass reconstructed with DLM at CDF.

together with an expected precision in the measurements of the W boson and top quark masses in Tevatron Run II [11]. The figure also summarizes Run-I measurements of the top quark mass.

The D0 collaboration has re-analyzed Run-I data using a new technique of determining the top quark mass, utilizing maximal information from the events, including matrix elements for $t\bar{t}$ production and decay and parton distributions [12]. The extracted top quark mass is

$$m_t = 180.1 \pm 3.6 \pm 4.0 \text{ GeV}/c^2.$$

The CDF Collaboration has applied a method called Dynamical Likelihood Method, originally developed in the '80s [13], to measure the top quark mass. Figure 8 shows the reconstructed top mass distribution. The extracted mass value is [14]

$$m_t = 174.9\,^{+4.5}_{-5.0} \pm 6.2 \text{ GeV}/c^2.$$

There exit many other measurements using various techniques, including those made public since the time of this Conference. However, we will not describe them in this

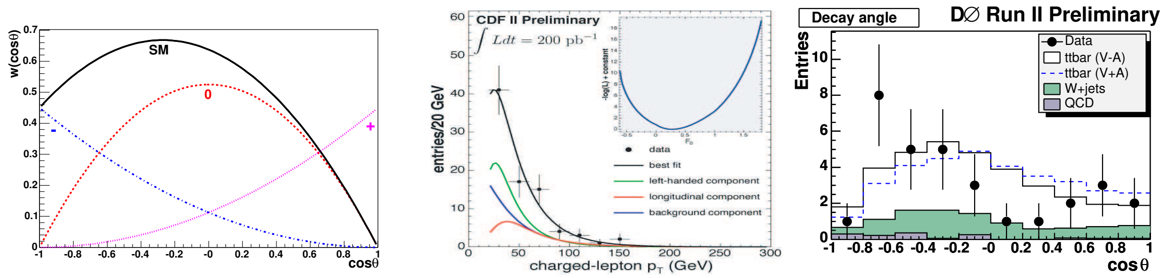


Figure 9: Left: Lepton angular distributions in the rest frame of the W boson with respect to the top quark direction in the cases of longitudinal (0) and left-handed ($-$) W bosons. Middle: Transverse momentum distribution of leptons in top candidate events (CDF). Right: Lepton angular distribution in lepton+jet top candidate events (D0).

report. We refer the reader to Ref. [10].

3.3. W helicity in top decays

The W^- boson produced in the top quark decay can be either left-handed or longitudinally polarized. Their mixture is predicted reliably by the standard model and is

$$
\begin{aligned}
f_0 &\equiv \frac{\Gamma(t \to b\,W_0)}{\Gamma(t \to b\,W_0) + \Gamma(t \to b\,W_L)} = \frac{m_t^2}{m_t^2 + 2\,m_W^2} \\
&= 0.70 \quad \text{for} \quad m_t = 175 \quad \text{GeV}/c^2,
\end{aligned}
$$

where f_0 is the fraction of the longitudinal component. Two different methods have been used to extract the fraction. The first examines the lepton momentum spectrum. The different W polarization states give different lepton angular distributions in the top quark decay. This is shown in Figure 9. The angle θ^* is the angle of the lepton momentum direction in the rest frame of the W boson with respect to the top quark momentum direction. The left-handed W boson produces leptons peaked toward the backward direction, while for the longitudinal W boson the distribution is symmetric. The right-handed W boson would give forward-peaked leptons, which is absent in the standard model.

The lepton momentum in the laboratory frame reflects these angular distributions, and is harder for the leptons from longitudinal W and softer for those from the left-handed W. The lepton spectrum from CDF is shown in Figure 9 (middle). The extracted longitudinal fraction f_0, under the assumption that the right-handed component is absent, is [15]

$$
f_0 = 0.27\,^{+0.35}_{-0.24},
$$

not inconsistent with the standard model prediction. D0 reconstructs the angle θ^* and examines its distribution. It is shown in Figure 9 (right). The fraction of the (non-SM) right-handed polarization (f_+) is fitted for, with the longitudinal fraction f_0 fixed to the standard model value, and is determined to be [15]

$$
f_+ = -0.13 \pm 0.23, \quad \text{or} \quad f_+ < 0.244 \quad (90\%\ \text{CL}).
$$

4. Bottom Quark Physics

Since the confirmation of large CP violation in some of B hadron decay modes a few years ago, the thrust of B physics is now in testing the Kobayashi-Maskawa picture of CP violation and in particular the consistency of the unitarity triangle, and in searches for possible effects of new physics such as supersymmetry. A lot of excitement has emerged since the summer of 2003, when the Belle Collaboration announced a possible hint of new physics in a measurement of CP asymmetry in the $B^0 \to \phi K^0_S$ decay. Within the standard model, the CP asymmetry measured in this decay mode should be identical to that measured in the (well-established) $B^0 \to J/\psi K^0_S$ decay mode. In both cases CP asymmetry arises, in the standard model, from the complex phase of $B^0\bar{B}^0$ mixing and is $\sin 2\beta$. However, if a new phase exists in their decays, the asymmetries in the two modes can be different. The $B^0 \to \phi K^0_S$ decay proceeds via a quark-level transition $b \to s\bar{s}s$, which is a loop process in the standard model and is suppressed relative to tree-level processes. The asymmetry in the $B^0 \to \phi K^0_S$ mode as of summer 2003 was -0.96 ± 0.51 [16][a], which is about 3.5 σ away from $+0.731 \pm 0.056$ measured with $b \to c\bar{c}s$ modes. Therefore, if new physics exists, it is in the $b \to s$ transitions.

The CDF and D0 experiments can provide unique tests of some of the $b \to s$ processes, taking advantage of decays of the B^0_s meson, which cannot be produced at the $\Upsilon(4S)$ resonance. They are :

- $B^0_s \bar{B}^0_s$ oscillations.
- Search for CP violation in $B^0_s \to J/\psi\,\phi$.
- Measurement of CP asymmetries in $B^0_d \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ modes.
- Search for rare decays $B^0_{s,d} \to \mu^+\mu^-$.

We discuss each of them in some detail below. Before doing that, however, we describe a benchmark B physics measurement from D0, which concerns the ratio of the charged and neutral B mesons, B^- and $\bar{B}^0$.

The lifetimes of different B-hadron species are of interest, because they offer probes into B-hadron decay mechanisms beyond the simple spectator model picture. One way to measure their lifetimes separately is to use signals of fully reconstructed decays. Another way is to use semileptonic decays, which can be written as $\bar{B} \to \ell^-\bar{\nu}\mathbf{D}$, where $\mathbf{D}$ is a charm hadron system whose charge is correlated with the parent B hadron charge. To be more specific, the $\ell^- D^{*+}$ final state is dominated by the $\bar{B}^0$ meson decays, and the $\ell^- D^0$ final state is dominated by the B^- meson decays (provided that those coming from D^{*+} decays are excluded), allowing us to extract the two lifetimes. The D0 signal of the $\bar{B} \to \mu^-\bar{\nu}D^{*+}X$ decay is shown in Figure 10 (left). D0 examines the lifetime dependence

[a] As of ICHEP 2004, the new value of CP asymmetry in the ϕK^0 mode from Belle is $+0.06 \pm 0.33 \pm 0.09$ (hep-ex/0409049).

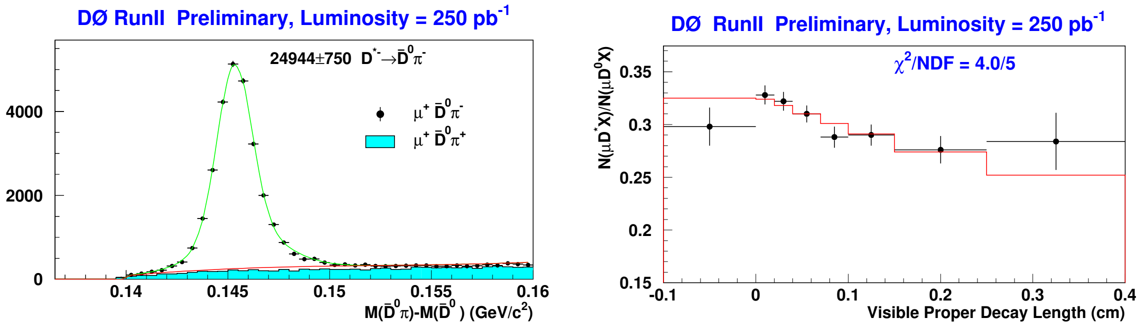


Figure 10: Left: Signal of $\bar{B} \to \mu^- \bar{\nu} D^{*+} X$ decays reconstructed in D0 data. Right: Ratio of $\mu^- D^{*+}$ and $\mu^- D^0$ yields as a function of their estimated proper decay time.

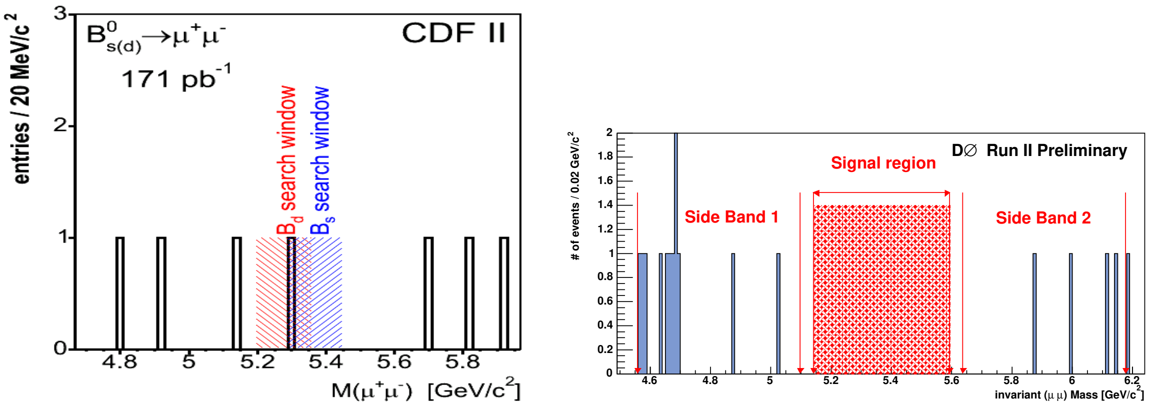


Figure 11: Dimuon invariant mass distributions near the B meson mass. Left from CDF and right from D0.

of the ratio of the rates of the two final states, $\mu^- D^{*+}$ and $\mu^- D^0$. If the lifetimes of the two parent B meson states are different, the ratio should change as a function of the decay time. Figure 10 (right) shows this dependence, and the ratio clearly deceases with an increasing decay time, meaning that the $\bar{B}^0$ meson has a shorter lifetime than the B^- meson. The extracted number is [17]

$$\tau(B^-)/\tau(\bar{B}^0) = 1.093 \pm 0.021 \pm 0.022,$$

consistent with recent measurements at the B factory and other experiments.

Now we discuss $b \to s$ flavor-changing processes and related topics that can be studied at the Tevatron.

4.1. Search for rare decays $B^0_{s,d} \to \mu^+\mu^-$

In the standard model these decays can proceed via higher-order, box and loop, diagrams with weak bosons in the intermediate states. They are also suppressed by CKM factors, $|V_{ts}|^2$ for the B^0_s meson and $|V_{td}|^2$ for the B^0_d meson. Furthermore, the initial state is spin zero, so they are suppressed by helicity conservation. The standard model

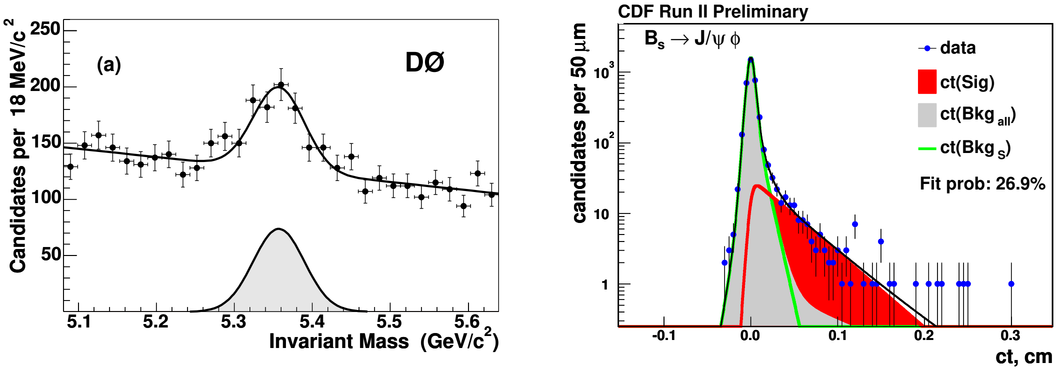


Figure 12: $B_s^0 \to J/\psi\phi$ decays reconstructed (left, D0) and the decay time distribution (right, CDF).

predictions for the branching fractions are [18]

$$\begin{aligned}\mathcal{B}(B_s^0 \to \mu^+\mu^-) &= (3.4 \pm 0.5) \times 10^{-9} \\ \mathcal{B}(B_d^0 \to \mu^+\mu^-) &= (1.00 \pm 0.14) \times 10^{-10}.\end{aligned}$$

The values for the corresponding electron modes are five orders of magnitude smaller. They are extremely small values, and so the decay is a good place to look for effects of new physics.

Both the CDF and D0 experiments have performed the search. Figure 11 (left) shows an invariant mass spectrum of CDF dimuon candidate events near the B meson mass. The shaded regions show the search windows. One candidate event is found in the overlap region of B_d^0 and B_s^0 mesons in a data sample of 171 pb^{-1}, while the expected number of background events is 1.1 ± 0.3. The following upper limits (95% CL) have been placed [19]

$$\begin{aligned}\mathcal{B}(B_s^0 \to \mu^+\mu^-) &< 7.5 \times 10^{-7} \\ \mathcal{B}(B_d^0 \to \mu^+\mu^-) &< 1.9 \times 10^{-7},\end{aligned}$$

which improves the previous CDF limits by a factor of three. The mass distribution from D0 is also shown in the figure. At the time of the Conference they had completed a sensitivity study but had not opened the signal region data box yet. The estimated sensitivity with 180 pb^{-1} of data was $\mathcal{B}(B_s^0 \to \mu^+\mu^-) \sim 10.1 \times 10^{-7}$ at the 95% CL. After the Conference D0 has improved the sensitivity further and obtained a 95% CL upper limit of [19]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.6 \times 10^{-7}.$$

4.2. Studies of $B_s^0 \to J/\psi\,\phi$ decays

The decay mode $B_s^0 \to J/\psi\,\phi$ is attractive experimentally because it provides distinctive signatures. The reconstruction can be done with relative ease. Figure 12 (left) shows the signal from the D0 experiment in 220 pb^{-1} of data. The lifetime of the B_s^0 meson is measured to be [20]

$$\tau(B_s^0) = 1.473\,^{+0.052}_{-0.050} \pm 0.023 \text{ ps}.$$

CDF reconstructs a similar signal (not shown), whose decay time distribution is shown in Figure12 (right). CDF extracts [21]

$$\begin{aligned} m(B_s^0) &= 5366.01 \pm 0.73 \pm 0.33 \text{ MeV}/c^2 \\ \tau(B_s^0) &= 1.369 \pm 0.100 \pm 0.010 \text{ ps} \end{aligned}$$

using a data sample of 240 pb^{-1}.

Theory predicts that the lifetime of the B_s^0 meson should be the same as that of the B_d^0 meson within 1%. However, a sizable width difference, $\Delta\Gamma_s/\Gamma_s$ of order 10% [22], can exist between the two mass eigenstates of the $B_s^0\bar{B}_s^0$ system. The decay mode currently in discussion has been measured to be dominated by a CP-even state, which should correspond roughly to the shorter lifetime mass eigenstate of the two [23]. Therefore, the lifetime measured with this mode can be shorter if it is compared to other measurements of the B_s^0 meson lifetime, which come mostly from flavor-specific final states, or if it is compared to the B_d^0 meson lifetime.

As for the CP content of the decay mode, CDF has measured the polarizations in the decay as well as in the $B^0 \to J/\psi K^{*0}$ mode. The fraction of the transverse helicity state (CP odd) is measured to be [24]

$$\begin{aligned} \Gamma_\perp/\Gamma &= 0.183 \pm 0.051 \pm 0.054 \quad (B_d^0 \to J/\psi\, K^{*0}) \\ &= 0.232 \pm 0.100 \pm 0.013 \quad (B_s^0 \to J/\psi\, \phi). \end{aligned}$$

After the Conference, CDF released [24] a result of an attempt to measure $\Delta\Gamma_s$, which gives a value of

$$\Delta\Gamma_s/\Gamma_s = 0.65\,^{+0.25}_{-0.33} \pm 0.01,$$

though it is not significant yet. A sizable $\Delta\Gamma$ is important also because it may allow CP studies of B_s^0 meson decays without the necessity of flavor tagging.

In the future, this decay mode will be used to search for mixing-induced CP violation. The mode is a B_s^0 equivalent of the $B_d^0 \to J/\psi K_S^0$ mode, except that the B_s^0 mode is not a pure CP eigenstate. If the phase of particle-antiparticle oscillations is non-zero, it can lead to CP asymmetry in time-dependent decay rates modulated with the oscillation frequency Δm. In the standard model, $B_s^0\bar{B}_s^0$ mixing receives very little complex phase because it is $\arg(V_{ts})$. Therefore, if CP violation is found to be sizable, it will be an unambiguous signal of new physics.

4.3. $B_s^0\bar{B}_s^0$ oscillations

To study the consistency of the unitarity triangle of the KM matrix, the information on the lengths of the sides of the triangle and their precise determination are crucial. In particular the determination of $|V_{td}|$ from the oscillation frequency Δm_d of $B_d^0\bar{B}_d^0$ mixing currently suffers from a relatively large theoretical uncertainty, typically of order 20%. Unquenched lattice calculations of B meson decay constants have become available in recent years, and they should help reduce the uncertainty. From the experimental side,

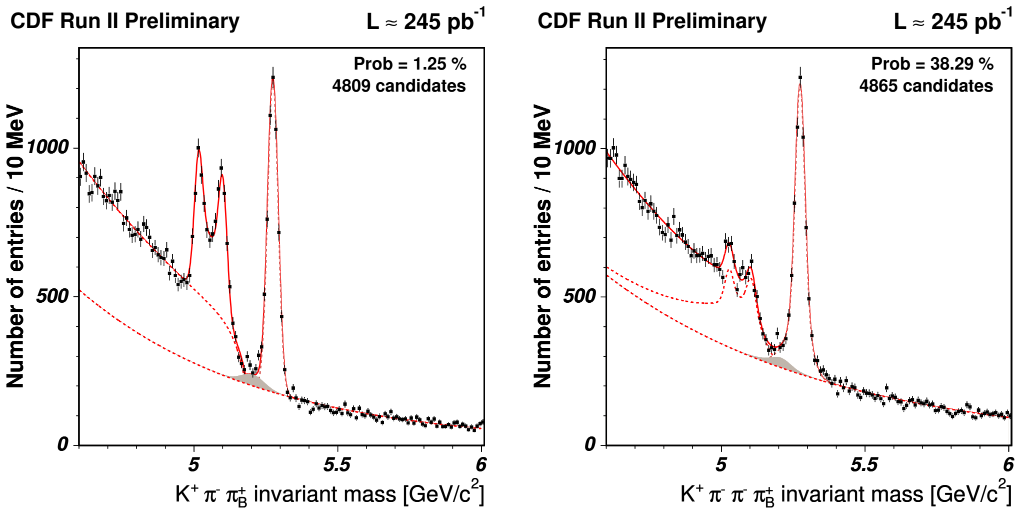


Figure 13: Example of fully reconstructed B meson signals among CDF data triggered with SVT. Left: $B^- \to D^0\pi^- \to (K^-\pi^+)\pi^-$. Right: $\bar{B}^0 \to D^+\pi^- \to (K^-\pi^+\pi^+)\pi^-$.

the theory uncertainty can in principle be reduced once we observe the $B_s^0\bar{B}_s^0$ oscillations and use the ratio $\Delta m_s/\Delta m_d$ to extract $|V_{ts}/V_{td}|$. For example, Ref. [25] calculates the ratio ξ, of the B_s^0 and B_d^0 decay constants times the bag parameters, to be $\xi \equiv (f_{B_s}\sqrt{B_{B_s}})/(f_{B_d}\sqrt{B_{B_d}}) = 1.14 \pm 0.03\,^{+0.13}_{-0.02}$, which involves a smaller uncertainty than when trying to extract V_{td} using only Δm_d. However, the expected very high value of Δm_s poses a challenge to experiments.

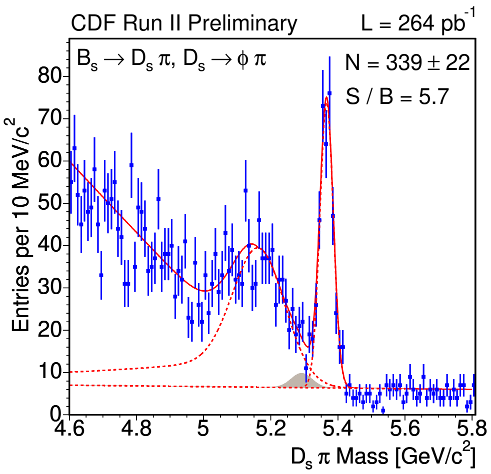
In order to measure particle-antiparticle oscillations with a very high frequency, it is necessary, or at least desirable, to have precise vertex determinations and a good proper time resolution. The former can be achieved by having a good detector very close to the B meson production point, and the latter requires measuring B meson momentum on an event-by-event basis. The latter can be achieved if decays are reconstructed fully. Such reconstruction of all-hadronic final states has become possible in CDF Run-II, by using silicon detector information at the second level of the trigger (SVT triggers). Figure 13 shows an example of such signals. They will be used as calibration modes, for understanding flavor tagging and proper time resolution.

The B_s^0 meson signals are also reconstructed by CDF with the SVT trigger. Figure 14 shows the signal, of about 340 events in 265 pb^{-1} of data. The study can in principle be made using the partially reconstructed semileptonic decay $\bar{B}_s^0 \to \ell^-\bar{\nu}D_s^+X$. Figure 14 (right) shows such a signal from the D0 experiment, which takes advantage of a large acceptance of the muon detector.

Attempts will be made using these signals to look for the oscillations and possibly set a lower limit on Δm_s toward winter 2005.

4.4. Studies of $B_{d,s}^0 \to PP$ decays

The decay mode $B_d^0 \to \pi^+\pi^-$, if it proceeds only through a $b \to u$ "tree" transition, receives the phase of V_{ub} in the decay (which is angle γ) and the phase of V_{td} in



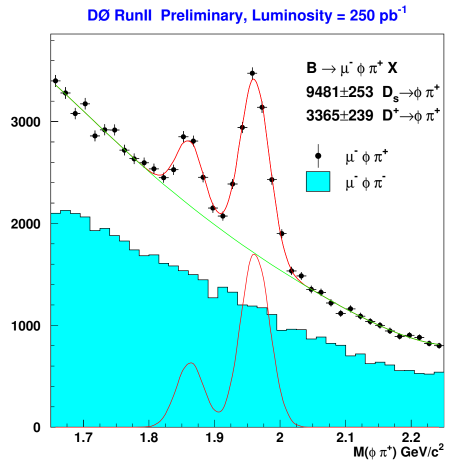


Figure 14: Example of reconstructed B_s^0 meson signals. Left: $\bar{B}_s^0 \to D_s^+ \pi^- \to (\phi\pi^+)\pi^-$ (CDF). Right: $\bar{B}_s^0 \to \mu^- \bar{\nu} D_s^+ X$ (D0).

$B_d^0 \bar{B}_d^0$ mixing (which is β). Therefore, its CP asymmetry should allow a determination of $\sin 2(\beta + \gamma)$, which should be identical to $\sin 2\alpha$ if the triangle closes ($\alpha + \beta + \gamma = \pi$). However, the existence of the $b \to s$ "penguin" amplitude complicates the matter, making it less straightforward to extract angle α from experimentally observed CP asymmetry. Various strategies have been proposed to solve this, but they are not necessarily easy experimentally.

One proposed by Fleischer [26] is unique in that it measures CP asymmetries in the $B_s^0 \to K^+K^-$ mode in conjunction with the $B_d^0 \to \pi^+\pi^-$ mode, and extract angle γ as well as tree and penguin decay amplitudes, taking advantage of the penguin pollution. It is by no means easy experimentally, because it involves extraction of CP asymmetries modulated with Δm_s.

The first step toward those measurements will be to see the signals of two-body decays of the B mesons. CDF uses a data sample triggered using SVT. Figure 15 shows the invariant mass spectrum of two-track pairs, where the pion mass is assumed for both charged particles. A clear signal of 900 events is observed near the B meson mass. The peak is actually expected to be a mixture of four decay modes, $B_d^0 \to K^+\pi^-$ and $\to \pi^+\pi^-$, and $B_s^0 \to K^+K^-$ and $\to K^-\pi^+$. A Monte Carlo calculation of the mass spectra of these decay modes is shown in Figure 15 (right). Specific ionization measurements (dE/dx) in the main tracking chamber are used to separate kaons and pions statistically and, together with the mass distributions, to estimate the mixture of the four decay modes. The approximate yields are 509 for $B_d^0 \to K^+\pi^-$, 134 for $B_d^0 \to \pi^+\pi^-$, and 232 for $B_s^0 \to K^+K^-$.

This represents the first observation of the decay $B_s^0 \to K^+K^-$. The ratio of the production fractions times the branching fractions is measured to be [27]

$$\frac{f(\bar{b} \to B_s^0) \cdot \mathcal{B}(B_s^0 \to K^+K^-)}{f(\bar{b} \to B_d^0) \cdot \mathcal{B}(B_d^0 \to K^+\pi^-)} = 0.48 \pm 0.12 \pm 0.07.$$

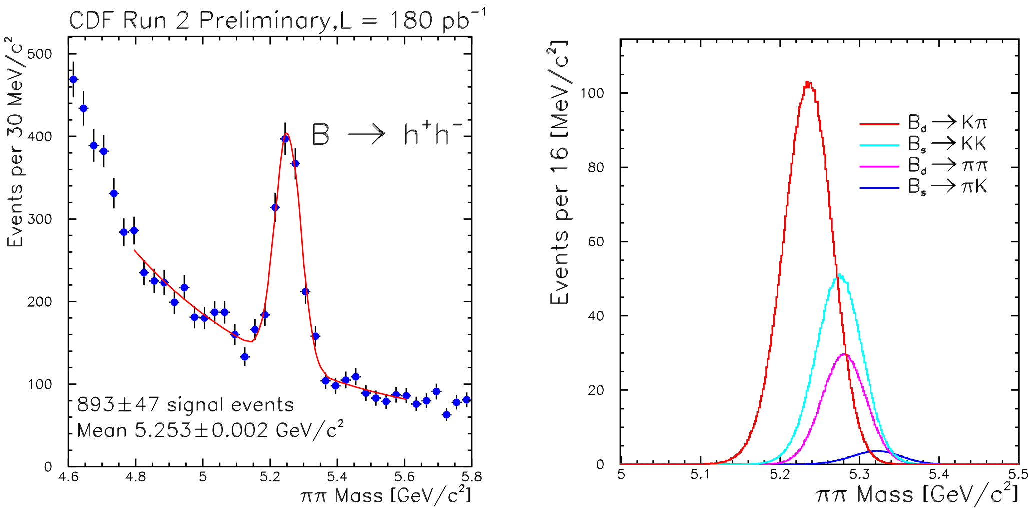


Figure 15: Left: Invariant mass spectrum of two charged particles near the B meson mass by CDF. Pion masses are assigned to each particle. Right: Monte Carlo simulation of the mass spectra for four decay modes considered.

Also the ratio of the branching fractions for the B_d^0 meson is extracted to be

$$\frac{\mathcal{B}(B_d^0 \to \pi^+\pi^-)}{\mathcal{B}(B_d^0 \to K^+\pi^-)} = 0.26 \pm 0.11 \pm 0.06,$$

as well as direct CP asymmetry in the $B_d^0 \to K^+\pi^-$ decay

$$\mathcal{A}_{\rm CP}(B^0 \to K^+\pi^-) \equiv \frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)} = -0.04 \pm 0.08 \pm 0.01.$$

The latter is becoming competitive in precision with the Belle and BaBar results. In a longer term we hope to measure angle γ with the Fleischer method.

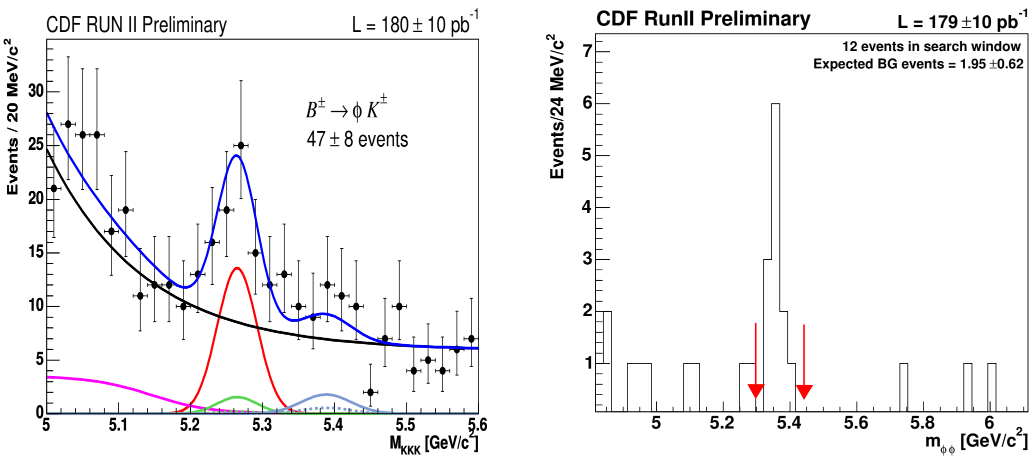


Figure 16: Reconstructed CDF signals of $B^+ \to \phi K^+$ (left) and $B_s^0 \to \phi\phi$ (right).

4.5. Direct check with $B \to \phi K$ decays

CDF reconstructs the $B^+ \to \phi K^+$ decays using the SVT trigger. Figure 16 shows the signal of about 50 events. The ratio of branching fractions is measured to be

$$\frac{\mathcal{B}(B^+ \to \phi K^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = (0.72 \pm 0.13 \pm 0.07) \times 10^{-2}.$$

The decay proceeds through the same quark level transition $b \to s\bar{s}s$ as the $B^0 \to \phi K^0_S$ mode. Therefore if new physics phase exists it should show up in this mode as well. Direct CP asymmetry is measured to be

$$\mathcal{A}_{\mathrm{CP}} = -0.07 \pm 0.17\,^{+0.06}_{-0.05},$$

which does not seem to show a large deviation from zero, and again achieves a precision comparable to B factory measurements.

Another $b \to s\bar{s}s$ transition mode has been seen at CDF. It is the $B^0_s \to \phi\phi$ decay mode, whose signal is shown in Figure 16 as well.

5. Conclusion

The Tevatron Run-II program is in progress since 2001. Both CDF and D0 experiments have accumulated roughly five times more data than in Run I, with much improved detectors. Many physics results have been produced and more are expected in the near future. They could be summarized as follows.

- Electroweak physics

  Production of weak vector bosons has been measured at a new center of mass energy, and has provided opportunities to study electroweak phenomena very precisely. Pairs of gauge bosons are now being produced in reasonably high statistics, and interactions among gauge bosons will be studied in detail. Measurements of the W boson mass is a high priority in the near term future.

- Top quark physics

  Top quark pair production has been confirmed in Run II data. New precision in measurements of production cross sections and mass is expected and in some cases is already achieved. Many new different measurements will be performed, taking advantage of expected 20-fold increase in the data sample and 30% increase in the production cross section. Combined with W boson mass measurements, top quark mass measurements will provide indirect information on the Higgs boson mass.

- Bottom quark physics

  CDF has vastly improved its B physics capability by introducing a displaced track trigger, enabling to collect B decays into final states consisting only of hadrons. D0 is also commissioning a trigger under the same philosophy.

CDF and D0 could provide useful and unique measurements of $b \to s$ transitions, including $B_s^0 \bar{B}_s^0$ oscillations, searches for $B_s^0 \to \mu^+\mu^-$ decays and non-zero width difference $\Delta\Gamma_s$, and studies of decays $B_s^0 \to J/\psi\phi$, $B_s^0 \to K^+K^-$, and $B \to \phi K$.

In the near future, each of the CDF and D0 experiments is expected to collect about 2 fb^{-1} of integrated luminosity. We hope to see some exciting measurements come out of the data.

6. Acknowledgements

I would like to thank the organizers of the Conference, in particular Professor Kaoru Hagiwara and Dr. Nobuchika Okada, for their help, and also patiently waiting for my writing this Proceedings contribution. Many members of the CDF and D0 Collaborations helped me during the preparation of my talk and this manuscript. They include Evelyn Thompson, Marco Verzocchi, Arnulf Quadt, Aurelio Juste.

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