

# Standard Model Higgs and Top Mass Measurements at the Tevatron

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A summary of the present Standard Model Higgs search and measurement of top quark mass at the Tevatron are presented. The sensitivity of the present Higgs search at the Tevatron is limited by statistics to a cross section approximately two orders of magnitude higher than the predicted cross section for standard model Higgs production. With  $30 \text{ fb}^{-1}$  of integrated luminosity, the Tevatron offers an unique potential discovery window for the Standard Model Higgs mass up to  $130 \text{ GeV}/c^2$  before LHC era. The study of top at the Tevatron has moved from discovery phase to one of characterizing its properties. The combined result of top quark mass is  $174.3 \pm 5.1 \text{ GeV}/c^2$  ( $\delta m_t/m_t < 3\%$ ).

## I. SEARCH FOR STANDARD MODEL HIGGS AT TEVATRON

For several decades, the standard model has been remarkably successful in explaining and predicting experimental data. However, the mechanism of electroweak symmetry breaking is still not known. The most popular mechanism to induce spontaneous symmetry breaking of a gauge theory, resulting in the gauge bosons and fermions acquiring masses, is the Higgs mechanism [1], which predicts the existence of a Higgs particle with unknown mass. The current direct search limit [2] for Standard Model Higgs Boson at LEP-2 is  $m_h \geq 96 \text{ GeV}/c^2$  at 95% C.L. LEP-2 will continue their run until the end of year 2000, which will allow them to either exclude the Higgs mass up to  $110 \text{ GeV}/c^2$  or have a  $5 \sigma$  Higgs discovery for Higgs mass below  $106 \text{ GeV}/c^2$ . The indirect search via electroweak precision tests through radiative correction yields  $m_h \leq 260 \text{ GeV}/c^2$  at 95% C.L.

At the Tevatron, one of the Higgs production processes more likely to be observed is an associated production  $V + h$  for  $m_h \leq 130 \text{ GeV}/c^2$ , where  $V=W, Z$  and  $h \rightarrow b\bar{b}$ . For the Higgs mass above  $130 \text{ GeV}/c^2$ , different search strategies need to be developed since the dominant decay mode is no longer  $b\bar{b}$ , but  $WW^*$  [3].

### A. Search for $Wh \rightarrow l\nu b\bar{b}$

The experimental signature considered is  $Wh$  with  $W \rightarrow e\nu$  or  $\mu\nu$ , and  $h \rightarrow b\bar{b}$ , giving final states with one high- $P_T$  lepton, large missing transverse energy ( $\cancel{E}_T$ ) due to the undetected neutrino and two  $b$  jets. The ability to tag  $b$  jets with high efficiency and a low mistag rate is vital for searching for the decay of  $h \rightarrow b\bar{b}$ . CDF uses the secondary vertex (SECVTX) and soft-lepton (SLT)  $b$ -tagging algorithms developed for the top quark discovery, while D0 uses a soft-muon  $b$ -tagging only. Both CDF and D0 select the  $b$ -tagged  $W + 2$  jet events since it is expected to contain most of the signal, while  $b$ -tagged  $W + \geq 3$  jet events are dominated by  $t\bar{t}$  decays.

In a data sample of  $109 \pm 9 \text{ pb}^{-1}$ , CDF observed 36 events with single SVX  $b$ -tag and 6 events with two  $b$ -tagged jets (SVX-SLT and SVX-SVX) [4]. The expected backgrounds are  $30 \pm 5$  for single and  $3.0 \pm 0.6$  for double tagged events, which are predominately from  $Wb\bar{b}$ ,  $Wc\bar{c}$ , mistags and  $t\bar{t}$  decays. The probability that the background fluctuated upward to the number of observed events is found to correspond to one standard deviation. The dijet mass distribution for the single and double tagged events are shown in Figure 1, along with the background expectation. The single-tag data show a slight excess of events at higher two-jet mass but there is no mass peak as would be expected from the two-body decay of a new particle. Likelihood fits to the mass distributions yield a 95% C.L. limit on the production cross section times branching ratio, shown in Figure 2, as a function of Higgs mass.

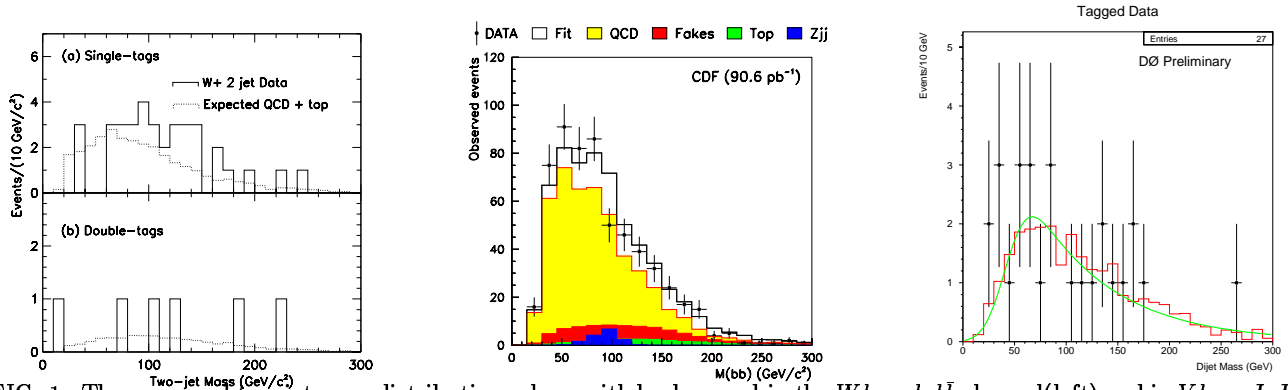


FIG. 1. The measured two-jet mass distributions along with background in the  $Wh \rightarrow l\nu b\bar{b}$  channel(left) and in  $Vh \rightarrow J_1 J_2 b\bar{b}$  (center) for the CDF(left) and D0(right).

D0 also performed similar search in their  $100 \text{ pb}^{-1}$  lepton + jets data [5]. They observed 27 events with at least one  $b$ -tag, which are in good agreement with the background expectation of  $25.5 \pm 3.3$  events. The observed dijet mass distribution and corresponding 95% C.L. limit on the production cross section times branching ratio are shown in Figure 1 and 2.

### B. Search for $Vh \rightarrow j_1 j_2 b\bar{b}$

CDF also searches for Higgs in the four-jets channel of  $Vh$  process, where  $V=W,Z$  decays into two jets [6]. The events are required to have at least two SVX  $b$ -tagged jets and the  $P_T$  of two  $b$ -jets greater than  $50 \text{ GeV}/c^2$  in order to reduce the large QCD background. In a multi-jet trigger sample of  $91 \pm 7 \text{ pb}^{-1}$ , CDF observed 589 candidate events. The invariant mass of two  $b$ -tagged jets is shown in Figure 1, along with the main backgrounds from QCD, fake tags and  $t\bar{t}$  decay. A likelihood fit is then applied to the shape of signal plus background, with the normalization of signal and QCD free, which yields total 600 background events and consistent with zero signal events. The corresponding 95% C.L. limits on the production cross section times branching ratio is shown in Figure 2. It also shows the CDF combined limit obtained from both all-hadronic and lepton +jets channels.

### C. Search for $Zh \rightarrow (l^+ l^-, \nu\bar{\nu}) b\bar{b}$

Several studies [7] in past have indicated that there is significant potential of observing associated production of Higgs and  $Z^0$  boson with  $Z^0 h \rightarrow (l^+ l^-, \nu\bar{\nu}) b\bar{b}$ , because of large branching ratios of  $Br(Z^0 \rightarrow \nu\bar{\nu}) = 19.2\%$ . The signature of such decay is relative clean, a resonance of two  $b$  tagged jets, plus either large missing  $E_T$  ( $E_T > 40 \text{ GeV}$ ) or dilepton pair mass near the  $Z^0$  mass, which were triggered experimentally by either  $E_T > 35$  or leptons in the event.

The  $E_T$  in the background sample is predominately due to mismeasured jets resulting in the  $E_T$  direction being aligned along with the jet direction while the  $\delta\phi_{min}(E_T, jet)$  in the signal sample is flat. By requiring large missing  $E_T$  ( $E_T > 40 \text{ GeV}$ ) and  $\delta\phi_{min}(E_T, jet) > 1.0$ , the QCD background can be reduced to minimum, which results in a Higgs reach sensitivity similar to the one in  $Wh \rightarrow l\nu b\bar{b}$  channel.

The analysis of CDF search in Run1 is in progress. D0 has searched for  $ZH \rightarrow \nu\bar{\nu} b\bar{b}$  in their Run1 data. They observed 2 events in the data, in good agreement with the expected background of  $2.0 \pm 0.7$  events. The corresponding 95% C.L. limits on the production cross section times branching ratio is shown in Figure 2.

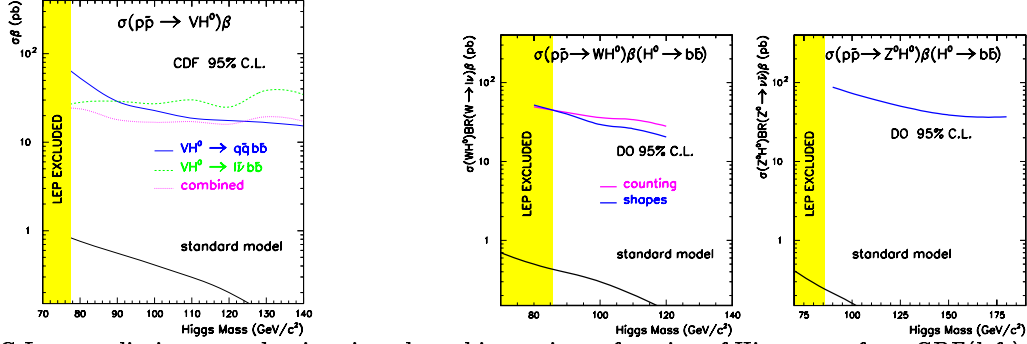


FIG. 2. 95% C.L. upper limits on production times branching ratios as function of Higgs mass from CDF(left) and D0 (right).

#### D. The Prospects of Standard Model Higgs Search at Tevatron

During Feb.- Nov. 1998, there was a joint CDF/D0/Theory working group to study Higgs searches at Run-II or beyond at the Tevatron using more realistic CDF/D0 detector simulation for the signal and background estimation (see <http://fnth37.fnal.gov/higgs.html> for more details). Since the Tevatron would be the only chance to discover the Higgs before LHC, it would be important to establish the realistic Higgs discovery potential beyond LEP-2. Great progress has been made in terms of extending the depth and breadth of previous studies on the Higgs reach [8]. There is no single, golden discovery channel at the Tevatron. Combining all the channels and data from both experiment data is crucial. The preliminary results indicate that the Tevatron should be able to exclude the Higgs mass up to  $130 \text{ GeV}/c^2$  at the 95% C.L. with  $2 \text{ fb}^{-1}$  data, or have a  $5 \sigma$  discovery of the Higgs mass up to  $130 \text{ GeV}/c^2$  with  $30 \text{ fb}^{-1}$  data [9].

## II. TOP MASS MEASUREMENTS

A precise measurement of the top quark mass is an important ingredient in testing the consistency of the standard model with experimental data. In addition, precise  $W$  and top mass measurements can provide information on the mass of the Higgs boson, which is a remnant of the mechanism that gives rise to spontaneous electroweak symmetry breaking.

Within the framework of the Standard Model the top quark decays almost exclusively into a real  $W$  boson and a  $b$  quark. The observed event topology is then determined by the decay modes of the two  $W$  bosons, which can be classified into three decay channels. The Dilepton Channel has about 5% of the cases, with both  $W$  bosons decay to  $e\nu$  or  $\mu\nu$ . The Lepton + Jets Channel has 30% of the cases, one  $W$  boson decays to  $e\nu$  or  $\mu\nu$ , and the other to a  $q\bar{q}'$  pair. The All-Hadronic Channel has 44% of the cases, involving the hadronic decay of both  $W$  bosons.

TABLE I. The observed number of events and expected backgrounds for the top decay by the CDF and D0 experiments.

Channels	CDF Events	BG	D0 Events	BG
Dilepton	9	$2.4 \pm 0.5$	5	$1.4 \pm 0.4$
Lep+Jets(SVX)	34	$9.2 \pm 1.5$	-	-
Lep+Jets(SLT)	41	$24.8 \pm 2.4$	11	$2.5 \pm 0.5$
Lep+Jets (topological)	-	-	19	$8.7 \pm 1.7$
Alljets	187	$142 \pm 12$	44	$25.3 \pm 3.1$
$e\nu$			4	$1.2 \pm 0.4$
$(e, \mu)\tau$	4	$\approx 2$	-	-

Table I. shows that CDF and D0 observe a clear excess of events over the expected background in the dilepton, lepton + jets, and all-hadronic channels. The two experiments taking slightly different approaches in defining their events samples, with CDF taking advantage of their silicon vertex detector (SVX) and D0 making greater use of kinematic variables to reduce backgrounds. The present sample of top candidates are consistent with Standard Model decays. One of CDF and D0 physics goals in Run1 is to determine the top mass as accurately as possible using many different channels and techniques. As a result, the uncertainty on the top quark mass has improved from  $M_{top} = 174 \pm 16 \text{ GeV}/c^2$  [10], first published in 1994 to the present  $M_{top} = 174.3 \pm 5.1 \text{ GeV}/c^2$ .

### A. Lepton + jets Channel

The advantage of measuring a top quark mass in the Lepton + Jets channel is its relatively larger branching ratio and the ability to full reconstruct the top mass on an event-to-event basis. Both CDF and D0 select events containing a high  $E_T$  ( $P_T$ ) single isolated electron (muon) in the central region, large missing transverse energy and at least four jets.

Measurement of the top quark mass begins by fitting each event in the sample to the hypotheses of  $t\bar{t}$  production followed by decay in the lepton + jets channel ( $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow (l^+\nu b)(q\bar{q}'\bar{b})$ ). There are twelve distinct ways of assigning the four leading jets to the four partons  $b, \bar{b}, q$  and  $\bar{q}'$ . In addition, there is a quadratic ambiguity in the determination of the longitudinal component of the neutrino momentum. This yields up to twenty-four different configurations for reconstructing an event according to the  $t\bar{t}$  hypothesis with no  $b$ -tag, 12 configurations for events with a single  $b$ -tag, and 4 configurations for events with double  $b$ -tags. Both CDF and D0 choose the jet configuration with the lowest  $\chi^2$ .

The precision of the top quark mass measurement is expected to increase with the number of observed events, the signal-over-background ratio, and the narrowness of the reconstructed-mass distribution. In CDF lepton + jets mass analysis [11], Monte Carlo studies show that an optimum way to partition the sample consists of subdividing the events into the four statistically independent subsamples: SVX single  $b$ -tag, SVX double  $b$ -tag, SLT  $b$ -tag and untagged events.

The reconstructed-mass distributions of the four subsample is plotted in Figure 3, from which CDF measures  $m_t = 175.9 \pm 4.8(stat.) \pm 5.3(syst.) \text{ GeV}/c^2$ .

The D0 lepton + jets mass analysis uses four kinematic variables weakly correlated with top mass to separate the top signal from the background processes [12]. They were combined into two different multivariate discriminant: a weighted likelihood that minimizes correlation with the reconstructed mass (LB or “Low Bias”) and a Neural Network output (NN). The data are binned according to the discriminant value to create top-rich and background-rich subsamples. The subsamples are simultaneously fit to obtain the top quark mass  $m_t = 173.3 \pm 5.6(stat.) \pm 5.5(syst.) \text{ GeV}/c^2$ , shown in Figure 3.

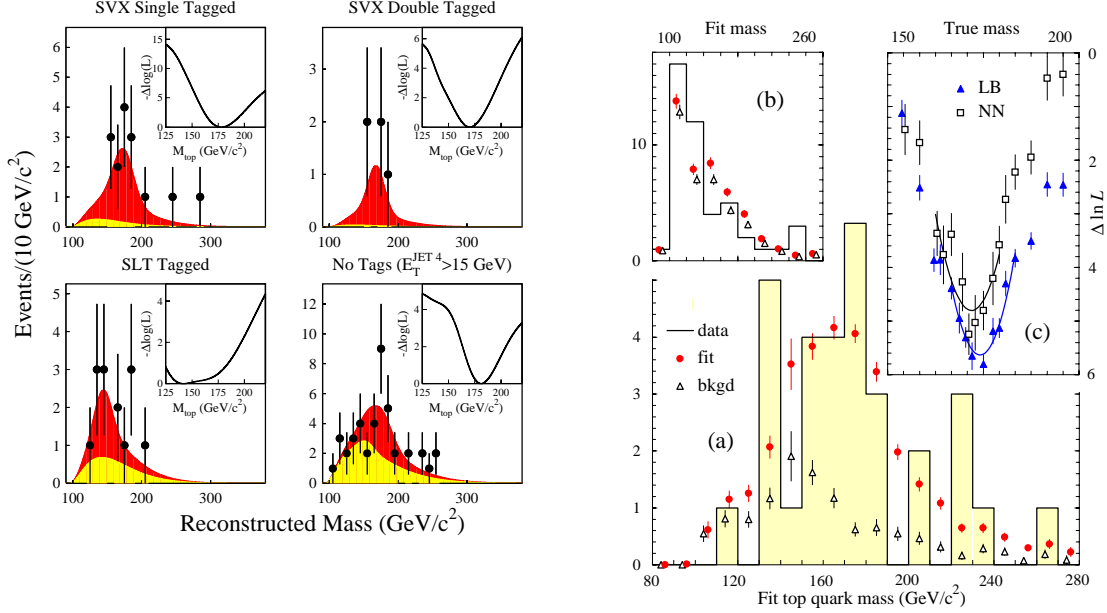


FIG. 3. Left: CDF Lepton + jets mass fits in the SVX single  $b$ -tag, SVX double  $b$ -tag, SLT  $b$ -tag and untagged sub-samples, along with the background(light shaded) and the fitted top (dark shaded). Right: D0 Lepton + jets mass fit for (a) the signal-rich LB sample and (b) the background-rich LB sample and (c) the dependence of the likelihoods on  $m_t$ .

## B. Dilepton Channel

CDF recently reported an improved measurement of the top quark mass using dilepton events [13] originating predominantly from  $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow (l^+\nu b)(l^-\bar{\nu}\bar{b})$ , where  $l = e$  or  $\mu$ . This measurement supersedes their previously reported result in the dilepton channel [14], which was obtained by comparing data with Monte Carlo simulation of  $t\bar{t}$  events for two kinematic variables, the  $b$ -jet energies and the invariant masses of the lepton and  $b$ -jet systems.

Since the dilepton system is under-constrained due to the two missing neutrinos in the final state, the CDF and D0 dilepton mass analyses [15] proceed by hypothesizing a top mass ( $m_t$ ) and solving event kinematics up to four-fold ambiguity for each of the two lepton-jet pairings. Two different weighting techniques have been developed.

- Neutrino weighting technique assigns a weight to each solution by comparing the predicted and measured missing transverse energy (CDF and D0) [15].
- Matrix Element weighting technique assigns a weight to each solution by the parton distribution functions and the matrix element for  $W$  boson decay (D0) [16].

For both weighting methods, the weights are summed over each lepton-jet pairing, and over the detector resolution for jets and leptons by sampling (*i.e.* fluctuating) the measured quantities many times according to their detector resolutions. The resulting weight functions for each CDF and D0 dilepton events, normalized to unity, are shown in Figure 4.

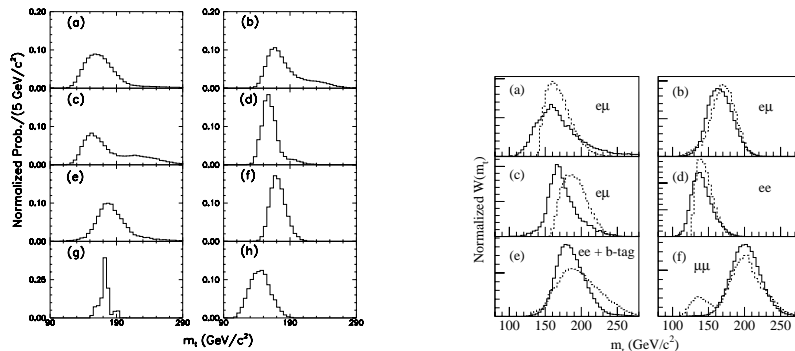


FIG. 4. The normalized weight function for each dilepton candidate event CDF(left) and D0(right).

CDF assign each event a mass by averaging the two mass values corresponding to the weight closest to and greater than the half maximum weight on either side. Figure 5 shows the distribution of these masses, together with the Monte Carlo expectation for background and fitted top, from which CDF determines a top quark mass value of  $167.4 \pm 10.3(stat.) \pm 4.8(syst.) \text{ GeV}/c^2$ .

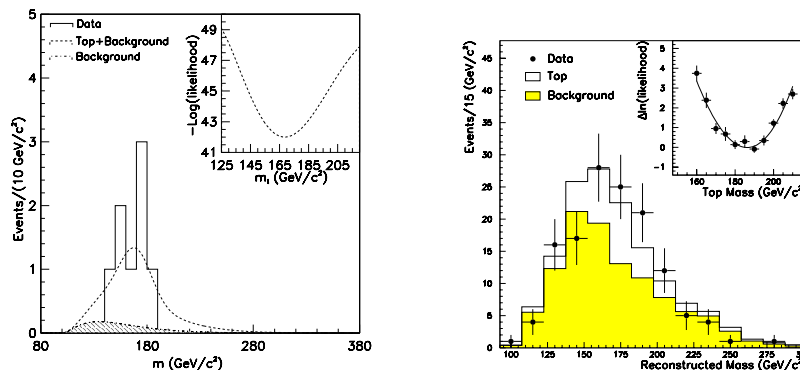


FIG. 5. Left: CDF reconstructed top mass for the eight dilepton events (solid) with background(shaded) and fitted top(dashed). Right: CDF reconstructed top mass in all hadronic events (point) with background(shaded) and fitted top (solid). The inset shows the dependence of the likelihood on  $m_t$ .

D0 accounts for the shape of the weight function by integrating the weights in five equally spaced mass bins and forming a four-dimensional vector from the normalized weights. The top quark mass is extracted by comparing the distribution of observed events in this four-dimensional vector space with the predicted densities for top signal and background. The results of these fits give a top quark mass value of  $168.4 \pm 12.3(stat.) \pm 3.6(syst.) \text{ GeV}/c^2$ .

### C. All-hadronic Channel

In this analysis [17] CDF selects  $t\bar{t}$  events in which both  $W$  bosons decay into quark-antiquark pairs, leading to an all hadronic final state. The study of this channel, with a branching ratio of about 4/9, complements the leptonic modes, and the mass measurement takes advantage of fully reconstructed final state, but suffers a very large QCD multijet background. To reduce this background, events with at least one identified SVX  $b$ -jet are required to pass strict kinematic criteria that favor  $t\bar{t}$  production and decay.

The data sample consist of 136 events, of which  $108 \pm 9$  events are expected to come from background. Events are then reconstructed to the  $t\bar{t} \rightarrow W^+ b W^- \bar{b}$  hypothesis, where both  $W$  bosons decay into a quark pair, with each quark associated to one of the six highest  $E_T$  jets. All the combinations are tried and the combination with lowest  $\chi^2 < 10$  is chosen. The reconstructed 3-jet mass distribution is shown in Figure 5, from which CDF measures a top quark mass of  $186.0 \pm 10.0(stat.) \pm 5.7(syst.) \text{ GeV}/c^2$ . The overall systematic error has been revised from 12.0 to 5.7

GeV/c<sup>2</sup> [13].

#### D. A Combined Top Mass from CDF and D0

The individual results from both CDF and D0 are combined according to a procedure developed by a joint CDF-D0 working group. The combined top mass from the Tevatron is  $174.3 \pm 3.2(stat) \pm 4.0(sys)$  GeV/c<sup>2</sup>. The good agreement among the measurements is reflected by a  $\chi^2$  probability of 75% of the mass average. Combining the statistical and systematic errors in quadrature, we find  $m_t = 174.3 \pm 5.1$  GeV/c<sup>2</sup>, which gives the best measured quark mass ( $\delta m_t/m_t < 3\%$ ).

#### E. Future Improvements at Run II

In Run-II with 2 or more fb<sup>-1</sup> of integrated luminosity and the increased capabilities of the upgraded CDF and D0 detectors, we expect more than 1000 single tagged and about 600 double tagged  $t\bar{t}$  events for each experiment. It will allow us to measure  $m_t$  down to statistical error of 0.5 GeV/c<sup>2</sup> by scaling the present results. The dominant systematic errors are expected to be the uncertainties in modeling gluon radiation and the jet energy scale of the detectors, which hopefully can be reduced to 2 GeV/c<sup>2</sup> by studying  $W \rightarrow j_1 j_2$  in the double tagged  $t\bar{t}$  events and  $32K Z \rightarrow b\bar{b}$  events from secondary vertex trigger.

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