

# MAKING PRECISION MEASUREMENTS AT HADRON COLLIDERS: TWO LECTURES

HENRY J. FRISCH

*Enrico Fermi Institute  
University of Chicago  
5640 S. Ellis Ave.  
Chicago, Il. 60637*

These two lectures are purely pedagogical. My intent is to enable non-experts to get something out of the individual presentations on collider physics that will follow- measurements of the W,Z, top, searches for SUSY, LED's, the Higgs, etc. We often forget that we are talking about instruments and the quantities they actually measure. The surprise is how precise the detectors themselves are; the challenge will be to exploit that precision in the regime where statistics is no longer a problem, and everything is dominated by the performance of the detector ('systematics'). Precision is necessary not only for measuring numbers such as masses, mixing angles, and cross-sections, but also for searches for new physics, comparing to the Standard Model.

## **Lecture I: The Electroweak Scale: Top, the W and Z, and the Higgs via $M_W$ and $M_{top}$**

### **1. Introduction and Purpose**

My intent in these pedagogical lectures is to enable non-experts to get something out of the detailed individual presentations on collider physics that will follow. We are presented with so much detail that one often forgets that we are talking about instruments and the basic quantities they actually measure. The surprise is how precise the detectors themselves are; the challenge will be to exploit that precision in the regime where statistics is no longer a problem, and everything is dominated by the performance of the detector ('systematics').

This challenge also extends to the theoretical community- to look for something new we will need to understand the non-new, i.e. the SM predictions, at an unprecedented level of precision. Some amount of this can be done with control samples- it is always best to use data rather than Monte

Carlo, but it's not always possible. The detectors are already better than the theoretical predictions.

## 2. Problems in Making Precision Measurements

The emphasis here will be more on problems to be addressed than on new results. I have used mostly CDF plots just because I know the details better- no slight to DØ or the LHC experiments is intended. The problems however are general. I have cut some corners in places and been a little provocative in others, as teachers will.

I have intentionally used older public results from CDF and DØ instead of the hot-off-the-press results generated for the 2006 'winter conferences' so as not to steal the thunder of the invited speakers who are here to present new results from CDF and D0, and so that you can recognize the evolution of the results as the integrated luminosity grows.

The two one-hour lectures included a very large number of plots; in the interest of space I have included only a small fraction here- many (updated with more luminosity) are included in the D0 and CDF invited talks in this volume.

## 3. Some History and Cultural Background

### 3.1. Luminosity History: Orders of Magnitude

A history of luminosity, starting with the *SPPS* and the discovery of the  $W$  and  $Z^0$ , followed by the race between CERN and Fermilab to discover the top, is shown in Figure 1.

Figure 2 shows the luminosity 'delivered' and 'to tape' from the current Run II, in inverse femtobarns (right), and from the 1987 run, in inverse nanobarns (left). As a reminder, the  $W^\pm \rightarrow e^\pm \nu$  cross-section times BR is about 2.2 nb at 1.8 TeV, so  $30 \text{ nb}^{-1}$  means that  $\approx 66 W^\pm \rightarrow e^\pm \nu$  decays were created in the 1987 exposure. The cross-section for a 115 GeV Higgs in  $W^\pm \rightarrow e^\pm \nu + H$  production is  $\sim 20 \text{ fb}$ , and so the right-hand plot indicates that if  $M_H = 115$ ,  $\approx 20 W^\pm \rightarrow e^\pm \nu + H$  events would have been created in the present  $1 \text{ fb}^{-1}$  at each of DØ and CDF.

### 3.2. Hubris: The 50 GeV Top Quark and No Quarkonia

Figure 3 is an historical reminder both that we should not be over-confident about what we know, and that Nature has a rich menu of surprises. The left-hand page is the 1984 discovery of something that did not exist- a top

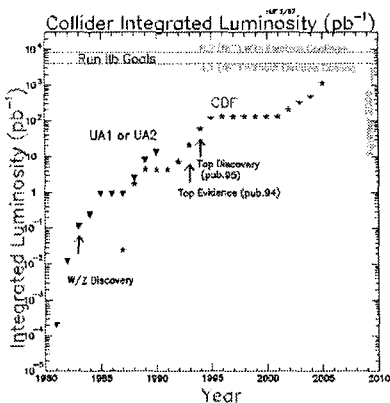


Figure 1. A history of high-energy (no ISR) hadron colliders: integrated luminosity by year.

quark with mass less than 50 GeV (it was largely W+2 jets). The right-hand page is a prediction from 1974 that there are no narrow states with masses between 3 and 10 GeV decaying into lepton pairs.

#### 4. The Tevatron and the LHC

By now everybody should know about the Tevatron and LHC. I will spare you pictures and boilerplate; the main differences that everybody, including mathematical theorists, should know are:

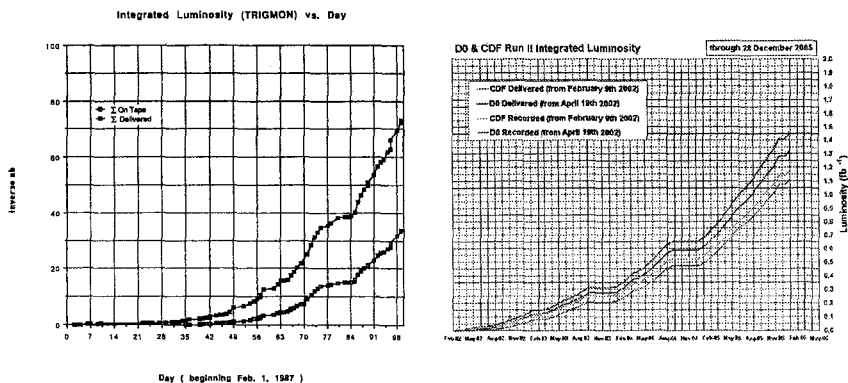


Figure 2. The integrated luminosity in the 1987 Tevatron run (Left), in Inverse Nanobarns, and in Run II (Right), in Inverse Femtobarns. Note that  $1 \text{ fb}^{-1} = 10^6 \text{ nb}^{-1}$ . Note also the efficiency to tape has improved substantially.

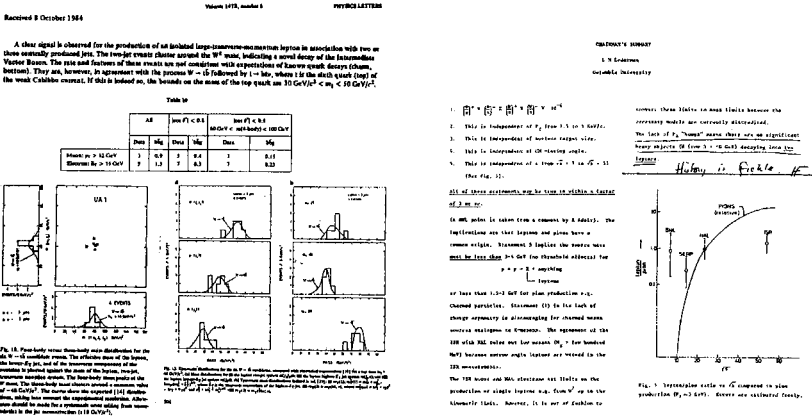


Figure 3. Left: The 1984 Top ‘discovery’; Right: The 1974 ‘no discovery’ announcement of the  $J/\psi$  and Upsilon’s.

	Tevatron	LHC
Parton Source	Antiproton-Proton	Proton-proton
Energy (TeV)	1.96 (not 2!)	14
Peak Luminosity ( $\text{cm}^{-2}\text{s}^{-1}$ )	$2 \times 10^{32}$	$1 \times 10^{34}$
Crossing Spacing (ns)	396	24.95
Peak Interactions/Crossing	5	19
Luminous Line $\sigma$ (cm)	30	$4.5^1$
Luminosity Lifetime (hours)	$3.8/23^2$	15
$\langle x \rangle$ at $M_W$	0.04	0.006
$\langle x \rangle$ at $2M_T$	0.18	0.025

An LHC upgrade to  $2 - 9 \times 10^{34}$  is planned <sup>3</sup>.

### 5. The Anatomy of Detectors at Hadron Collider: Basics

For those moving to the LHC from Cornell, SLAC, or LEP, working at a hadron collider is really different from at an  $e^+e^-$  machine— at CDF it took several years for experienced physicists who have worked only at  $e^+e^-$  machines to understand ‘whatever you ask for in your trigger will you get’ (the story of jets at ISR and Fermilab fixed-target as well).

Figure 4 shows a ‘cartoon’ of the production process for the W and Z,

which are the ‘standard candles’ along with the  $J/\psi$  and  $\Upsilon$  at the Tevatron (top will be another at the LHC).

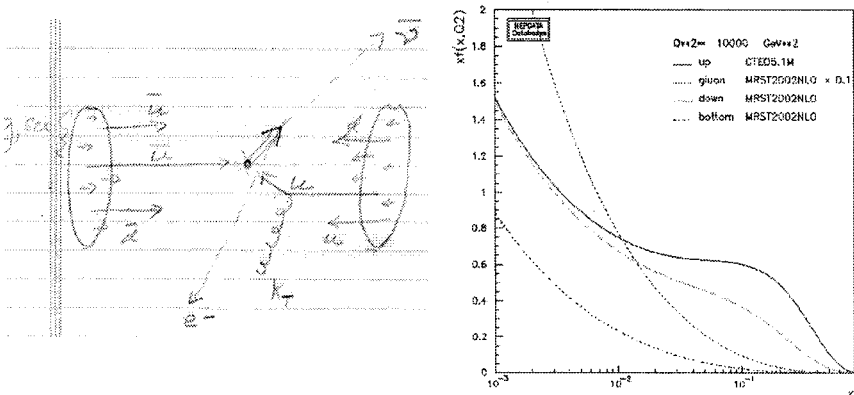


Figure 4. Left: A ‘cartoon’ of the production process for W’s and Z’s. Right: The CTEQ6.1M PDF’s at  $Q=100$  (from Joey Huston).

### 5.1. Basics: Kinematics and Coverage: $p_T$ vs $P_{||}$

The phase space for particle production at a hadron collider is usually described in cylindrical coordinates with the  $z$  axis along the beam direction, the radial direction called ‘transverse’, as in ‘Transverse Momentum’ ( $p_T$ ), and the polar angle expressed as Pseudo-rapidity  $\eta$ , where  $\eta \equiv -\ln(\tan\theta/2)$ . Pseudo-rapidity is a substitute for the Lorentz-boost variable,  $y$ , where  $y \equiv 1/2\ln(E + p_z)/(E - p_z) = \tanh^{-1}(p_z/E)$ . Since in most cases one does not know the mass of a particle produced in a hadron collision (most are light- pions, kaons, baryons,...), we use pseudo-rapidity, which assumes zero mass. (This is a common error when doing kinematics with W’s, Z’s, and top, where the mass truly matters). Note that typical particle production is 4-6 particles per unit-rapidity; in the central region one unit at CDF is about  $14 m^2$ ; the density in a min-bias event is very low. Hadron colliders are not intrinsically ‘dirty’- only complex.

Two simple equations contain much of the physics for the production of heavy states at a collider: the mass and longitudinal momentum of the heavy state (e.g. a W, Z,  $t\bar{t}$  pair, or  $WH$ ) are determined by the difference in momentum carried by the interacting partons, and the mass by the

product.

$$m^2 = x_1 * x_2 s \quad p_z = (x_1 - x_2)p_{beam} \quad (1)$$

Note that a heavy object typically has a velocity  $\beta \ll 1$ , even though the longitudinal momentum is typically not small. Note also that the transverse momentum of the system is determined by the competition of falling parton distribution functions (PDFs) as the total invariant mass of the system rises, and the increase in phase space as the momentum of the system increases. The production thus peaks with a total system energy above threshold by an amount characteristic of the slope in  $x_1 * x_2$ .

## 5.2. Basics: Particle Detection

While low-momentum- typically up to a few GeV- charged particles can be identified by processes that depend on their velocity,  $\beta$ , as a simultaneous measurement of  $p = \beta\gamma m$  and  $\beta$  allows extracting the mass, for momenta above a few GeV, pions, kaons, and protons cannot be separated. However electrons, muons, hadrons, and neutrinos interact differently, as shown in Figure 5. The measurement of their energies and/or momenta stem from their different modes of interaction.

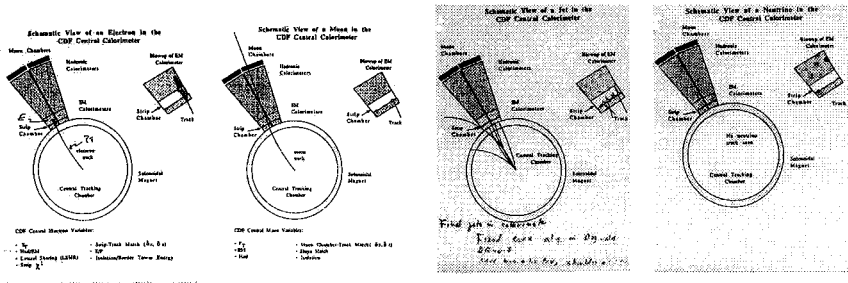


Figure 5. A ‘cartoon’ of how electrons, muons, jets, and neutrinos are identified in a solenoidal detector (by Sacha Kopp).

## 6. Calibration Techniques: CDF as an Example

### 6.1. Momentum and Energy Scales: $E/p$

In contrast to LEP, at the LHC or Tevatron the overall mass (energy) scale is not set by the beam energy- there is a continuum of c.m. energies in the parton-parton collisions. Moreover the hard scattering is not at rest either

longitudinally or transversely in the lab system- there is ‘intrinsic Kt’ as well as ‘hard’ initial-state radiation (ISR). Finally, the beam spot is a line and not a spot- the vertex point, used to calculate transverse energies, including those of missing energy and photons for which no track is observed, has to be determined from the event.

Dealing first with the issue of setting the scale for momentum, energy, and mass measurements: the current big detectors consist of a solenoidal magnetic spectrometer followed by calorimeters. The magnetic spectrometer uses a precisely measured (NMR) magnetic field and the precise geometry of the tracking chambers to measure the curvature ( $\propto 1/P_T$ ) of the tracks of charged particles. This is an absolute measurement- if perfect one has the momentum scale. One can then use particles with measured momentum as an *in situ* ‘test beam’ to calibrate the energy scale of the calorimeters.

The momentum scale can be checked by measuring the masses of some calibration ‘lines’ provided by Mother Nature- the J/Psi and  $\Upsilon$  systems, and the  $Z^0$  in its  $Z^0 \rightarrow \mu^+\mu^-$  decays ( $Z^0 \rightarrow e^+e^-$  doesn’t work for momentum calibration!).

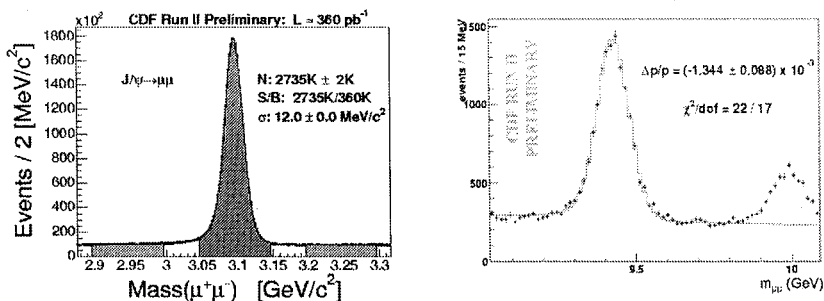


Figure 6. Left: The reconstructed  $J\Psi$  invariant mass in dimuons (CDF). Right: The similar plot for the Upsilon system.

However the momentum scale can be incorrect due to mis-alignments in the tracking chamber. The combination of a calorimeter and a magnetic spectrometer allows one to remove the 1st-order errors in both by measuring ‘E’ (calorimeter energy) over ‘p’ (spectrometer momentum). With perfect resolution, no energy loss, and no radiation, these two should be equal:  $E/p = 1.0$ .

The 1st-order error in momentum is due to a ‘false-curvature’- that is

that a straight line (0 curvature= $\infty$  momentum) is reconstructed with a finite momentum. The 1st-order error in calorimeter energy is an offset in the energy scale, and does not depend on the sign ( $\pm$ ) of the particle <sup>7</sup>. Expanding both the curvature and calorimeter energies to first order:

$$1/p = 1/p_{true} + 1/p_{false} \quad (\mu^+) \quad 1/p = 1/p_{true} - 1/p_{false} \quad (\mu^-) \quad (2)$$

$$E = E_{true} * (1 + \epsilon) \quad (e^+) \quad E = E_{true} * (1 - \epsilon) \quad (e^-) \quad (3)$$

The first-order false curvature  $p_{false}$  then is derived by measuring  $E/p$  for positive and negative electrons with the same  $E$

$$1/p_{false} = ((E/p(e^+) - E/p(e-))/2E) \quad (4)$$

The first-order calibration scale error  $\epsilon$  then is removed by setting the calorimeter scale for electrons so that  $E/p$  agrees with expectations. In CDF, this is done initially to make the calorimeter response uniform in  $\phi - \eta$ .

$$1/p_{false} = ((E/p(e^+) + E/p(e-))/2) \quad (5)$$

## 6.2. Higher-order momentum and energy corrections

The momentum and energy calibrations at this point are good enough for everything at present exposures except the W mass measurement. There are three higher-order effects that are taken care of at present:

- (1) ‘Twist’ between the two end-plates of the tracking chamber;
- (2) Systematic scale change in the z-measurements in the chamber;
- (3) Non-linearity of the calorimeter for electrons that radiate hard photons, due to  $e(E/2) + \gamma(E/2) \neq e(E)$

Figure 7 shows the use of the  $J/\Psi$  mass to correct for the first two of these effects. What is plotted is the correction to the momentum scale versus the cotan of the difference in polar (from the beam axis) angle of the two muons. There is a linear correction to the curvature of  $\delta c = 6 \times 10^{-7} \cot(\theta)$  that corrects for the twist between the endplates, and a change in the scale of the z-coordinate by 2 parts in  $10^4$ ,  $z_{scale} = 0.9998 \pm 0.0001$ . This is precision tuning of a large but exceptionally precise instrument!

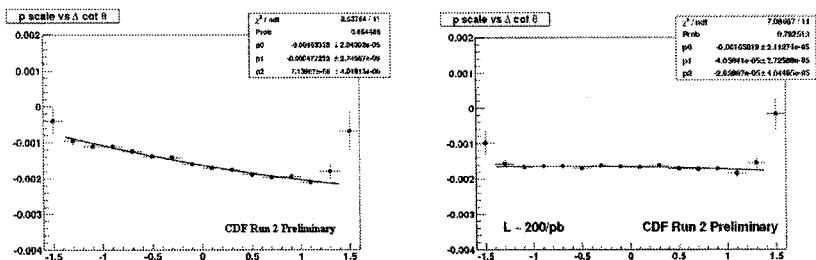


Figure 7. Left: The correction to the momentum scale versus the cotan of the difference in polar angle of the two muons in  $J/\psi$  decay before corrections: Right: The same after correcting the curvature by  $\delta c = 6 \times 10^{-7} \cot(\theta)$  the scale of the z-coordinate by 2 parts in  $10^4$ .

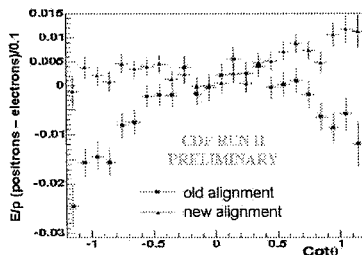


Figure 8. Measuring a higher-order correction to track curvature: the calorimeter to momentum ratio  $E/p$  versus  $\cot\theta$  for  $e^+$  and  $e^-$ , before and after the curvature and z-scale corrections.

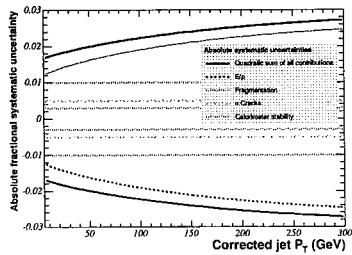
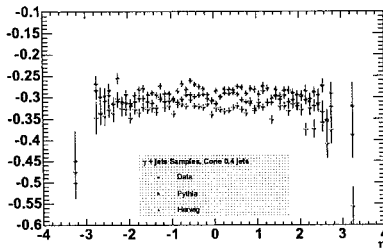
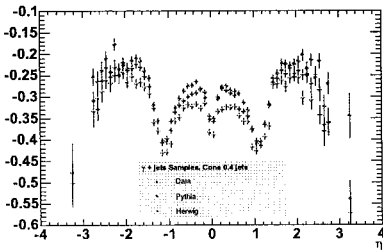
### 6.3. Calibrating the Hadron Calorimeters and the Jet Energy Scale

Much of the top mass information is encoded in its jets: the b-jets are first-generation daughters of a 2-body decay, one W decays into 2 jets, and the missing- $E_t$  of the neutrino is measured in the calorimeter.

There are a number of ways to calibrate the calorimeter response to jets:

- (1) In situ calibration by isolated hadrons ('E/p')
- (2) Test beam (for higher momenta- not easy to transport though.)
- (3) Dijet balancing (D0 uses this cleverly at large  $\eta$  for  $E_t$  reach.)
- (4)  $\gamma$ -jet balancing
- (5)  $Z^0$ -jet balancing

However with much higher statistics and the goal of precision recon-



The total (black), and individual contributions (calorimeter response in blue dashes, e.g,...) systematic uncertainty on the jet energy scale from CDF versus the measured  $p_T$  of the jet after corrections.

struction of masses in states such as the Higgs and possible SUSY states we will need a new level of sophistication. For example, we already see that fake rates for photons and taus are different for gluons and quarks, and probably for charm. The top mass analyses already use b-specific algorithms. Areas that need work are:

- (1) Energy flow algorithms
- (2) Quark/gluon-dependent corrections
- (3) Heavy-flavor dependent algorithms
- (4) Integrated QED and QCD higher-order corrections

For example, the quark/gluon/flavor content of jets in photon-jet and Z-jet balancing will be different. Another example is in W-decay to jets, where half the jets are a  $u\bar{d}$  pair and half a  $c\bar{s}$  pair.

## 7. W and Z<sup>0</sup> Production as PDF Probes

W and Z production provide a precise measure of the up and down quark parton distribution functions (PDF's).

Since we measure W's and Z's in their leptonic modes, the kinematics of the decay also matter. Consider the W's: they are polarized, as the u and d quarks are light and couple through V-A so quarks have helicity -1 and antiquarks +1. The W decays also by V-A, so the charged leptons

come out opposite to the helicity direction. However, the dominant effect, at least at the Tevatron, is that the  $W$  is moving in the rest frame, and since the (valence)  $u$  quark momentum is generally higher than the (sea)  $\bar{d}$  anti-quark;  $W^+$  go in the proton direction, and  $W^-$  in the  $\bar{p}$  direction (the LHC, being proton-proton, doesn't have this useful asymmetry).

Figure 9 shows the distribution in the difference of  $e^+$  and  $e^-$  versus  $\eta$  (pseudo-rapidity) of the electron ( $e^\pm$ ) measured by CDF. The left-hand plot shows the full range as well as the experimental uncertainty band; the right-hand plot shows a comparison with the predictions using the CTEQ6 PDF's. One can see that the PDF's do not fit well.

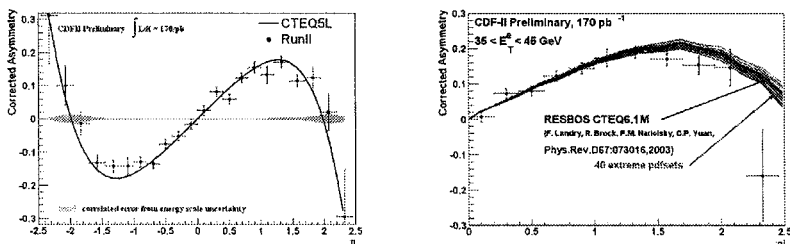


Figure 9. Left: The CDF forward-backward charge asymmetry in  $W^\pm \rightarrow e^\pm \nu$  decays plotted versus pseudo-rapidity. The black error band gives the experimental uncertainty; also shown is the prediction using the CTEQ5L parton distribution functions. Right: The same data, folded around zero in  $\eta$  (remember this is  $\bar{p}p$ ), compared to a prediction using the RESBOS MC generator and the CTEQ6.1M PDF's.

## 8. 'QCD'- Jet Production, Quark and Gluons, ISR, FSR

The dominant feature in the hadron collider landscape is the production of jets- the hard scattering of partons. Figure 10 reproduces the abstract from a seminal paper in 1971, when the idea of partons was brand new, by Berman, Bjorken, and Kogut <sup>4</sup>, pointing out that the existence of partons would lead to point-like scatterings and hence high  $p_T$  phenomena, including 'cores' (jets); the paper is amazingly prescient about high- $P_T$  phenomena, including  $W$  and  $Z$  production and hard-scattering (and there is a wonderful Peyrou plot representation of hard processes- I've omitted these pages due to space limitations.).

The precision needed for QCD measurements of jet production spectra and angular distributions is not as difficult as is needed to reconstruct final states such as top, and, we hope, the Higgs, SUSY states, etc. However

### Inclusive Processes at High Transverse Momentum\*

S. M. Berman, J. D. Bjorken, and J. B. Kogut†

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 5 August 1971)

We calculate the distribution of secondary particles  $C$  in processes  $A+B \rightarrow C + \text{anything}$  at very high energies when (1) particle  $C$  has transverse momentum  $p_T$ , far in excess of 1 GeV/c, (2) the basic reaction mechanism is presumed to be a deep-inelastic electromagnetic process, and (3) particles  $A$ ,  $B$ , and  $C$  are either leptons ( $l$ ), photons ( $\gamma$ ), or hadrons ( $h$ ). We find that such distribution functions possess a scaling behavior, as governed by dimensional analysis. Furthermore, the typical behavior even for  $A$ ,  $B$ , and  $C$  all hadrons, is a power-law decrease in yield with increasing  $p_T$ , implying measurable yields at NAL of hadrons, leptons, and photons produced in 400-GeV  $pp$  collisions even when the observed

Figure 10. The start of the seminal paper by Berman, Bjorken, and Kogut.

the counting of jets is a problem, both experimentally and theoretically. This is a case where the use of ratios, such as  $(W+n\text{jets})/(Z+n\text{jets})$ , or  $(W+n\text{jets})/(W+(n+1)\text{jets})$ , can cancel systematics.

## 9. Min Bias, Zero Bias, and the UEV: 'Soft' Physics

There is a lot of interesting physics in the large cross-section interactions. These topics are out-of-favor at the moment, but are rich and intellectually challenging. Among the topics are:

- (1) Comparison of particle production in color-singlet (e.g.  $W, Z$ ) production vs jet production.
- (2) Rapidity gaps
- (3) Multiple parton collisions
- (4) Fragmentation functions, including the  $p_T^{\text{hadron}}/p_T^{\text{parton}} = 1$  limit

In addition to their intellectual merit in their own right these topics need to be understood for high- $p_T$  physics as well. For example, the 'fake rates' for jets passing photon or tau identification criteria are measured to be different for gluon jets and quark jets. The probability for a jet to appear as an isolated  $\pi^0$  or charged track thus needs to be understood.

## 10. The $M_{Top} - M_W$ Plane and the Higgs Mass

### 10.1. Motivation

The top quark is remarkable for its physics and useful as a tool for calibration. It may also be a window into the world of heavy weakly-interacting particles (such as a Higgs of one sort or another) in that it is produced strongly in pairs, but due to its strongly-conserved flavor quantum number

(top-ness), has to decay electroweakly. Due to radiative corrections, the masses of the W, Z, Higgs, and top quark are related in the SM; precise measurements of the W and top quark masses thus predict the SM Higgs mass.

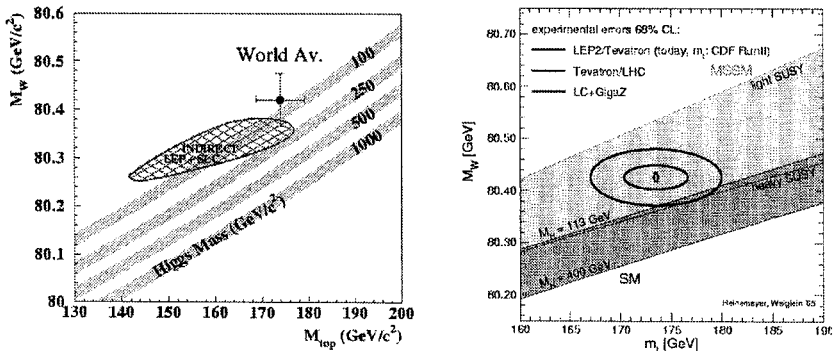


Figure 11. Left: The  $M_W$  vs  $M_T$  plane as of March 1998. Right: The  $M_W$  vs  $M_T$  plane as of the summer of 2005. Note the difference in the scales of the abscissas.

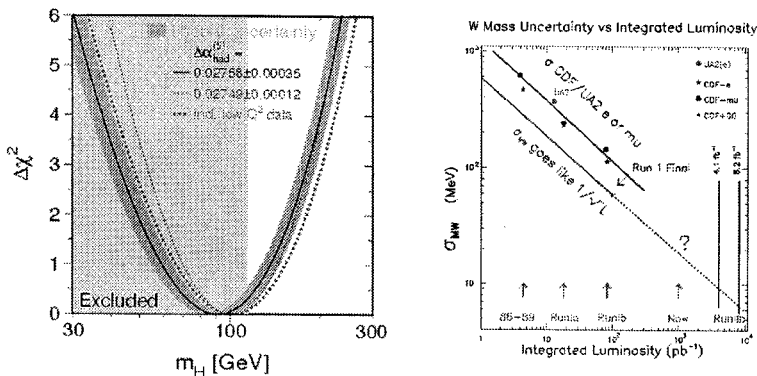


Figure 12. Left: The LEP EWKWG fit for the mass of the SM Higgs, showing the region excluded at 68% C.L.; Right: The total uncertainty on the W mass as measured at the Tevatron, versus integrated luminosity. If the control of systematic uncertainties continues to scale with statistics as the inverse root of the integrated luminosity, the Tevatron can do as well as LHC projections, and with different systematics.

## 10.2. *What limits the precision on the $W$ mass and the top mass measurements?*

Figure 12 also shows the history of the uncertainty on the  $W$  mass as a function of the square-root of luminosity. The statistical uncertainty is expected to scale inversely with the exposure. The systematic uncertainties will be discussed below when we get to the measurement of the  $W$  mass; however it is interesting to note that since the systematics are studied with data, they also seem to diminish with integrated luminosity. If the control of systematic uncertainties continues to scale with statistics as the inverse root of the integrated luminosity, the Tevatron can do as well as LHC projections, and with very different systematics. Problems include:

- (1) We need NLO QCD and QED incorporated in the same MC generator;
- (2) Recoil event modeling depends on  $W$   $p_T$  at low  $p_T$ , where the detector response is hard to measure;
- (3) The underlying event energy is typically 30 MeV/tower/interaction, which implies one has to get the detector response from data; the  $Z$  will play a critical role.
- (4) Using the  $Z$  for calibrating detector response will require Monte Carlo to treat  $W$  and  $Z$  production with NLO QED and QCD corrections in a consistent manner, and to understand any higher order differences.

## 11. Measuring the Top Quark Mass and Cross-section

I will discuss two specific measurements as pedagogic examples of some specific difficulties (challenges is the polite word) of doing precision measurements - the measurements of the top cross-section and the top mass. The idea is to make it possible for you to ask really hard questions when you see the beautiful busy plots that we all usually just let go by. First some basics.

### 11.1. *$t\bar{t}$ Production: Measuring the Top Cross-section Precisely*

The prime motivation for a precise measurement of the top cross-section is that new physics could provide an additional source for the production (leading to a larger cross-section than expected) or additional decay channels (leading to a smaller measured cross-section into  $Wb$ )<sup>9</sup>. More pro-

saically, the cross-section is a well-defined and in-principle easy-to-measure quantity that tests many aspects of QCD and the underlying universe of hadron collider physics- the PDF's, LO, NLO and NNLO calculations, and provides a calibration point for calorimeters and the energy scale. Lastly, and less defensible scientifically, is the uneasy feeling that too high a cross-section (e.g.) means that the top mass is really lighter than we measure, and so relying at  $1\text{-}\sigma$  on the crucial EWK fits and limits on the Higgs mass may be misleading us.

### 11.2. Total Cross-section for $t\bar{t}$ Production: Parsing the CDF and D0 Plots

A brief history of theoretical predictions and a summary of the D0 and CDF measurements in different channels for  $\sigma_{top}$  is tabulated in Figure 13.

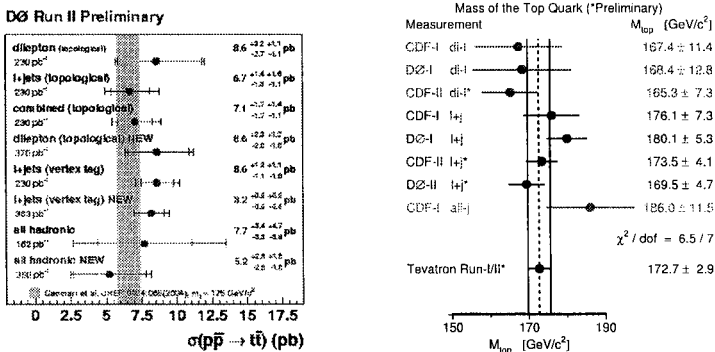


Figure 13. A summary of the CDF and D0 top cross-section measurements (left) and top mass measurements (right) as of Summer 2005.

### 11.3. Precision Measurement of the Top Mass

A summary of top mass measurements as of July 05 is given in Figure 13. Note the dilepton measurements tend to be systematically lower. Specific techniques are discussed below. (A comment- the D0 Run I measurement when analyzed by a different technique (same data, same calibration) moved from  $173.3 \pm 7.8$  to  $180.1 \pm 5.3$ . We see a somewhat similar effect in the CDF cross-section measurement shown in Fig 14; both raise the question of whether we are correctly including the systematics on data selection and algorithms in precision measurements.)

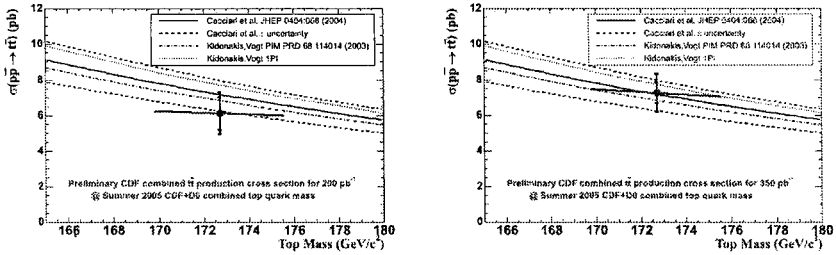


Figure 14. The measured and predicted CDF top cross-sections versus mass with approximately  $200 \text{ pb}^{-1}$ (Left) and with approximately  $350 \text{ pb}^{-1}$ (Right).

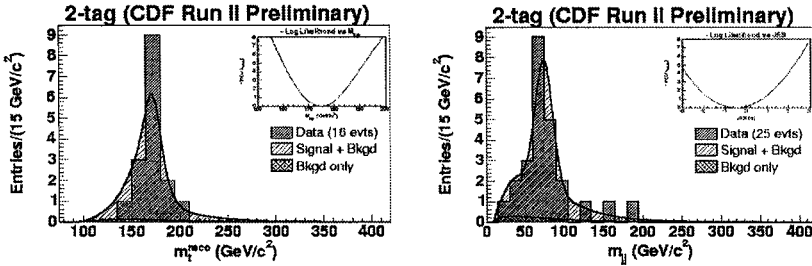


Figure 15. The fits for  $M_{top}$  and  $M_W$  in the 2-tag sample of the CDF '2D template analysis' as of summer 05.

#### 11.4. CDF Templates in $M_{top}$ and $M_{jj}$ (2D) in Lepton+Jets

Figure 15 shows the fits for  $M_{top}$  and  $M_W$  in the 2-tag sample of the CDF '2D template analysis' as of summer 05.

#### 11.5. $D\bar{O}$ Matrix Element Likelihood in $M_{top}$ and $M_{jj}$ (2D) in Lepton+Jets

Figure 16 shows the results of the  $D\bar{O}$  'matrix element' analysis of the top and W mass. However along with the extra statistical power there is a drawback from more complex methods - it is often hard to judge how good it looks. There's a net gain in precision, but one really needs simpler parallel analysis for sanity checks.

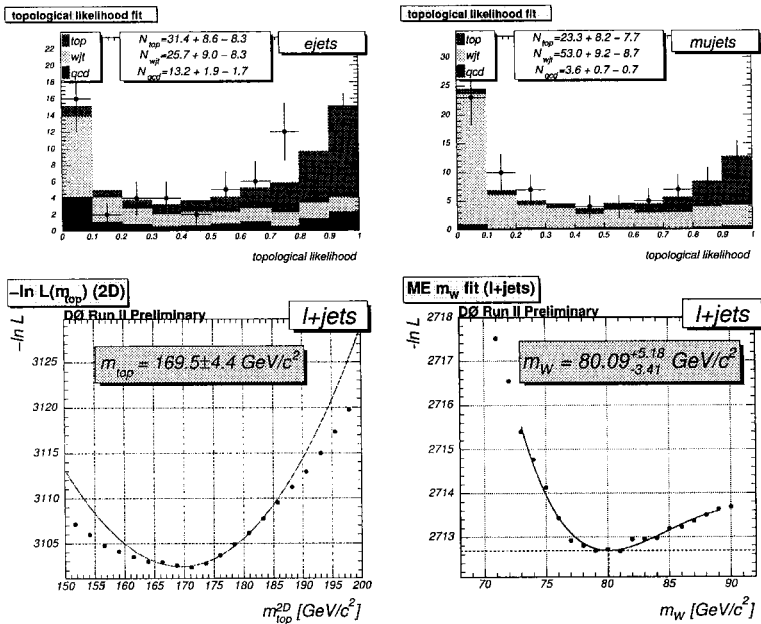


Figure 16. The D0 top and W mass fits in the 2D analysis. Closer to the dilepton number (all with 2 sigma, but...?)

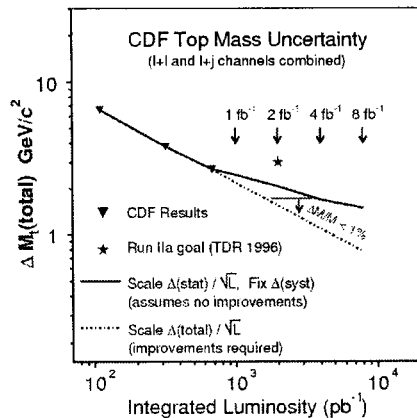


Figure 17. The CDF uncertainty on the top mass vs integrated luminosity. The red star is the projection from the Run II Technical Design Report;

## 11.6. Ultimate Precision on the Top Mass Measurement

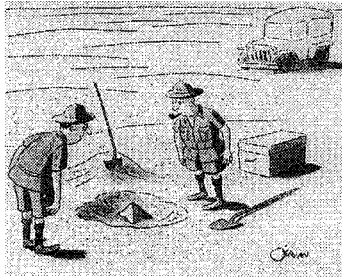
Figure 17 shows the uncertainty in the top mass as measured by CDF vs the inverse root of the luminosity. The star shows the uncertainty predicted in 1996 for  $2\text{fb}^{-1}$ ; the present uncertainty with  $0.8\text{fb}^{-1}$  is significantly better than the prediction. New techniques to measure or evade systematic uncertainties open up with more data (e.g. constraining the jet-energy scale by the  $W$  mass,  $\gamma$ -b-jet balancing,..) and so a  $1/\sqrt{\text{Luminosity}}$  scaling may be possible.

### Summary of First Lecture

- Idea was to introduce key measurements and numbers from previous data so you can look at detailed presentations with a critical eye.
- Things to watch for in the following talks on Top, and Electroweak Topics:
  - (1)  $M_{top} - M_W$  off in (upper) left-field? What is the top mass?
  - (2)  $\sigma_{top}$  and  $m_{top}$  consistent with predicted cross-section?
  - (3) Systematics- just entering an era of enough data to measure systematics better - new methods, new ideas,...
  - (4) Transparency- can we show more 'under the hood'? (less black box)
  - (5) Transparency- can CDF and  $D\emptyset$  (and soon Atlas and CMS) work harder on making comparisons- e.g. making the same plots with the same axes and scales!

## Lecture II: Searching for Physics Beyond the SM, and Some Challenges for the Audience

### High Pt Photons as New Physics Signature: (e.g. CDF Run1 $e\bar{e}\gamma\gamma$ , $\mu\bar{\mu}\gamma\gamma$ events)



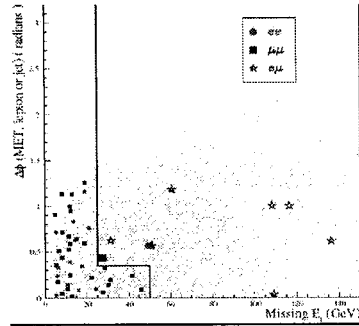
*"This could be the discovery of the century. Depending, of course, on how far down it goes."*

**Are Run 1 anomalies real? Experiments see only upward fluctuations- can estimate factor of luminosity needed to get to the mean (though huge uncert.)**

Lecture II emphasizes the problems that high statistics will bring for Beyond-the-Standard Model searches- first at the Tevatron, and then (in spades) at the LHC. Many of these problems are theoretical- in almost all cases we need precise Standard Model predictions in order to find new things (exceptions being new bumps- e.g. a Z-prime, KK excitations of the Z, etc.) Our parochial hope at the Tevatron is, of course, that we find something new before the LHC. We had hints of new things in Run I:

Some Run I oddities (none significant):

- (1) The top dilepton sample looked odd (too many e-mu events, e-mu close in  $\phi$ , a few with kinematics that didn't fit the top, and the 'trilepton' event.)
- (2) Top mass in dileptons was consistently lower than in lepton+jets.
- (3) Top mass resolution seemed too good- luck?
- (4) The  $ee\gamma\gamma\cancel{E}_t$  event and the  $2.7\sigma$  excess in  $\ell + \gamma + \cancel{E}_t$ .
- (5) High-Pt  $Z + \gamma$  event, and a  $W + 2\gamma$  event at start of Run II.



The Run-1 Dilepton events in the  $\cancel{E}_t - \Delta\Phi$  plane. The yellow dots are SM expectations for  $t\bar{t}$ .

### 11.7. Strategies: Signature-Based vs Model-Directed, Blind vs A Priori

None of the above effects was significant statistically- but made one want more data. We now have 10-times the data, and are scheduled for a factor of 4-10 beyond that. What to do? There are two major kinds of direct searches, and in each three kinds of strategies have been followed (all this categorization is arguable):

- (1) Model-Directed: Optimize sensitivity for points in theory parameter space;
- (2) Signature-Based: Look broadly under selected lamp-posts

Avoiding biases is important (see next slide)- two solid strategies:

- (1) 'A Priori'- use the same cuts as published in Run I, or in the 1st

- 1/3rd of the data; then run on rest of data without changing anything;
- (2) ‘Blind’- this is heavily used now-very useful and appropriate in some cases such as precision measurements: W mass, B lifetimes and masses, and classic well-defined searches: e.g.  $B \rightarrow \mu\mu$ .

A brief anecdote about a blind analysis around 1900:

*There was a controversy over two conflicting measurements of a line in the solar spectrum. The famous spectroscopist at Princeton asked his machinist to rule a grating at a non-standard (blind!) lines/inch, and to put the value in a sealed envelope. The Prof. then measured the line in terms of an unknown dispersion, wrote a Phys Rev with an accompanying letter that said ‘under separate cover you will receive the grating spacing from my machinist, Mr. Smith; take this number, multiply it by my number, put it in the blank space in the paper, and publish it’. Now, that’s blind.*

## 12. Theoretical Motivation and Experimental Caution

As in the search for the W and Z, there is a defining energy scale for the new physics beyond the SM. In the case of the W, Fermi’s effective field theory of a 4-fermion interaction predicted that  $\nu_e + e^- \rightarrow \nu_e + e^-$  scattering violated S-wave unitarity at a c.m. energy  $\approx 300$  GeV. For the SM, it’s more complicated (see, Gunion et al. in the Higgs Hunter’s Guide, e.g.), but the conclusion is the same- there must be something new at that scale. We experimentalists are consequently primed to find something new at the Tevatron and/or LHC. New means comparing data to precise predictions of the SM. Figure 18 shows what can happen when eagerness combines with insufficiently understood SM predictions.

### 12.1. *Lepton+Gamma+X: The $\ell\gamma\cancel{E}_t$ and $\ell\gamma$ Signatures*

One of the anomalies of Run I was the famous CDF  $ee\gamma\gamma\cancel{E}_t$  event. This spawned the advent of ‘signature-based’ searches at the Tevatron. In particular there were two follow-ups:  $\gamma\gamma + X$  (Toback) and  $\ell\gamma + X$  (Berryhill). The  $\ell\gamma + X$  search resulted in a  $2.7\sigma$  excess over SM expectations.

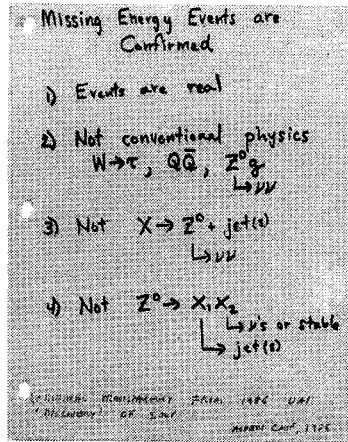
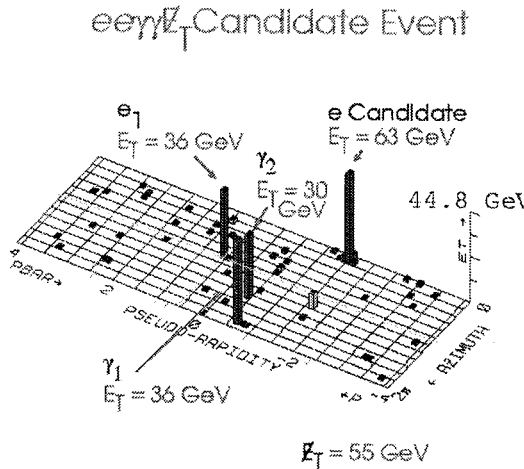
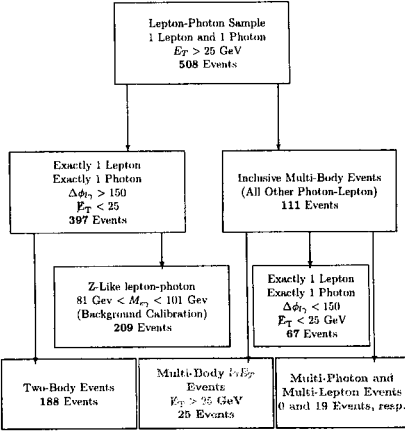


Figure 18. An example of why the careful calculation of SM predictions is so crucial: the announcement of the ‘discovery’ of SUSY at the 1986 Aspen Conference. The right explanation turned out to be a cocktail of SM processes.

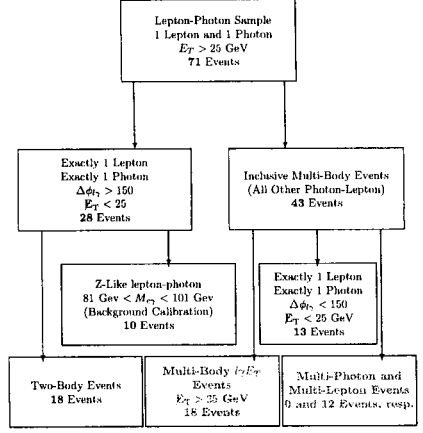


The analysis is being repeated with exactly the same kinematic cuts so this time it is a priori- (i.e. not self-selected to be interesting). Figures 19-21 show the CDF Run II results on the 2 signatures  $l\gamma E_t + X$  and  $ll\gamma + X$ . This is a repeat of the Run I search- the  $ee\gamma\gamma E_t$  event would show up in both, and so would an excess in  $l\gamma E_t$ . No more  $ll\gamma\gamma E_t$  events have been seen with  $> 3$  times the data ( $305 \text{ pb}^{-1}/86 \text{ pb}^{-1}$ ) and higher energy (30% increase in  $t\bar{t}$  crosssection, e.g.).

Photon-Electron Flow-Chart



Photon-Muon Flow-Chart

Figure 19. Left: The flow of the  $\ell+\gamma+X$  signature based search in electrons. Right: The flow in muons.

Lepton+Photon+ $E_T$ Predicted Events			
SM Source	$e\gamma E_T$	$\mu\gamma E_T$	$(e+\mu)\gamma E_T$
$W^\pm\gamma$	$11.9 \pm 2.0$	$9.0 \pm 1.4$	$20.9 \pm 2.8$
$Z^0/\gamma+\gamma$	$1.2 \pm 0.3$	$4.2 \pm 0.7$	$5.4 \pm 1.0$
$W^\pm\gamma\gamma, Z^0/\gamma+\gamma\gamma$	$0.14 \pm 0.02$	$0.18 \pm 0.02$	$0.32 \pm 0.04$
$(W^\pm\gamma \text{ or } W^\pm) \rightarrow \tau\gamma$	$0.7 \pm 0.2$	$0.3 \pm 0.1$	$1.0 \pm 0.2$
Jet faking $\gamma$	$2.8 \pm 2.8$	$1.6 \pm 1.6$	$4.4 \pm 4.4$
$Z^0/\gamma \rightarrow e^+e^-, e \rightarrow \gamma$	$2.5 \pm 0.2$	-	$2.5 \pm 0.2$
Jets faking $\ell + E_T$	$0.6 \pm 0.1$	$< 0.1$	$0.6 \pm 0.1$
<b>Total SM</b>			
<b>Prediction</b>	<b><math>19.8 \pm 3.2</math></b>	<b><math>15.3 \pm 2.2</math></b>	<b><math>35.1 \pm 5.3</math></b>
<b>Observed in Data</b>	<b>25</b>	<b>18</b>	<b>43</b>
Multi-Lepton+Photon Predicted Events			
SM Source	$ee\gamma$	$\mu e\gamma$	$ll\gamma$
$Z^0/\gamma+\gamma$	$12.5 \pm 2.3$	$7.3 \pm 1.7$	$19.8 \pm 4.0$
$Z^0/\gamma+\gamma\gamma$	$0.24 \pm 0.03$	$0.12 \pm 0.02$	$0.36 \pm 0.04$
$Z^0/\gamma+\text{Jet faking } \gamma$	$0.3 \pm 0.3$	$0.2 \pm 0.2$	$0.5 \pm 0.5$
Jets faking $\ell + E_T$	$0.5 \pm 0.1$	$< 0.1$	$0.5 \pm 0.1$
<b>Total SM</b>			
<b>Prediction</b>	<b><math>13.6 \pm 2.3</math></b>	<b><math>7.6 \pm 1.7</math></b>	<b><math>21.2 \pm 4.0</math></b>
<b>Observed in Data</b>	<b>19</b>	<b>12</b>	<b>31</b>

Figure 20. The SM predictions and observations in the CDF  $\ell\gamma E_T$  and  $ll\gamma$  signatures.

However, this has proved another educational example of MC predictions being the limiting factor. We do not have a control sample, but depend on SM predictions, largely  $W\gamma$  and  $Z\gamma$ . We have 2 MC generators-

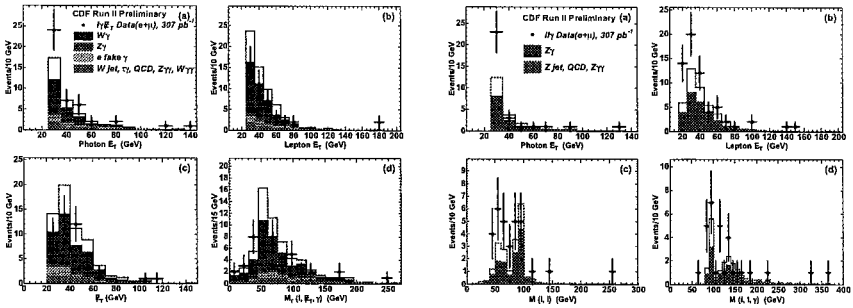


Figure 21. The distributions in photon and lepton  $E_T$ ,  $\bar{E}_T$ , and 3-body transverse mass from the CDF  $l\gamma\bar{E}_T$  search in  $305\text{ pb}^{-1}$ .

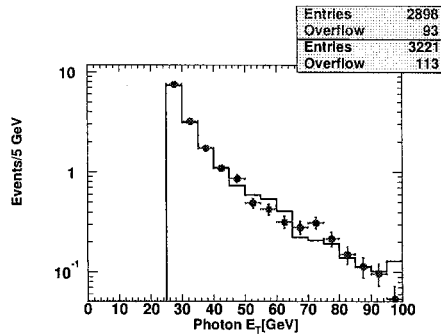


Figure 22. Comparison of the  $E_T$  spectrum of isolated photons in Drell-Yan+ $\gamma$  from MadGraph (red) and Baur (black) MC generators. There was disagreement *after* fragmentation and ISR with Pythia-now understood.

MadGraph and a program from Uli Baur. They agree beautifully. However after running them through Pythia they disagreed by 15% in yield, including a different identification efficiency for muons (!). Problems were in the interface (diagnosed by Loginov and Tsuno) for *both*- the Les Houches accord format is not precisely enough defined.

Lessons:

- (1) Always use 2 MC's- you may find both samples are flawed;
- (2) Both MC generators can be ok and you still can get it wrong;
- (3) CDF has lost huge amounts of time to the generator interfacing- needs re-examination by the theoretical community.

There is a problem coming up- we do not yet have the SM event generators with integrated higher-order QED and QCD at a precision comparable to

the coming statistics. We can normalize to data at low  $E_T^\gamma$ , but we need the next step up in prediction sophistication.

### 12.2. Inclusive High Pt W's and Z's: A Weak Boson Signature

The idea: many models of new physics- Extra Dimensions, Z-primes, Excited Top,  $t' \rightarrow Wb$ , SUSY, Right-handed Quarks- naturally give a signature of a high-Pt EWK boson- W, Z, or photon. This is natural in the strong production of pairs followed by weak decays: e.g. top.

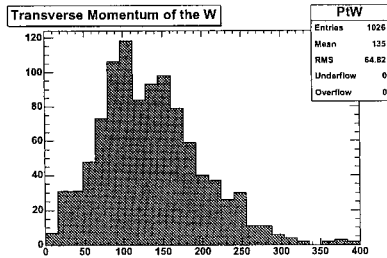


Figure 23. The  $p_T$  spectrum for Z's from the decay of a 300 GeV right-handed singlet down quark  $Q\bar{Q} \rightarrow uWdZ$  in the Bjorken-Pakvasa-Tuan model.

CDF has done a search for anomalous inclusive high-Pt Z production, as would come from the decay of new heavy particles. The analysis selects on dilepton mass  $66 < m_{\ell\ell} < 106$  and then compares the  $p_T$  spectrum with SM expectations (Figure 24). However the inclusive Z+X is dominated by SM Z+jets- we cannot yet predict this at the level needed, and at present rely on a tuning of the spectrum for  $p_T < 20$  GeV.

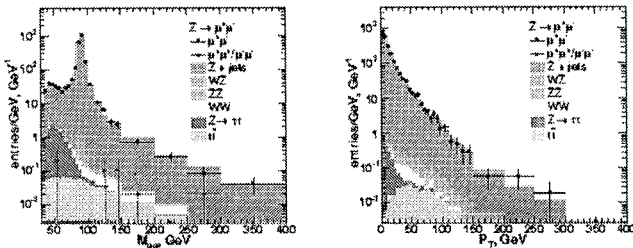
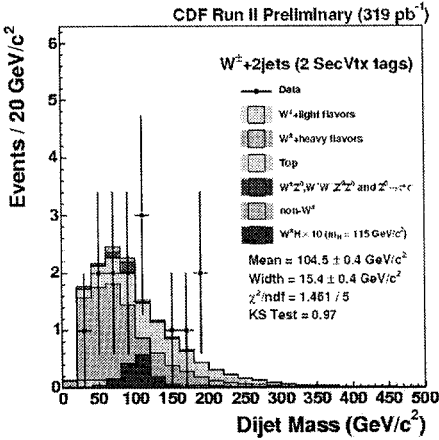


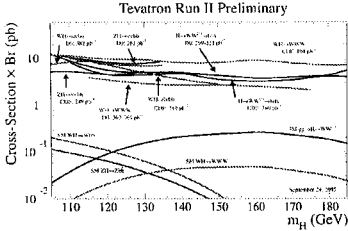
Figure 24. The inclusive search for anomalous high- $p_T$  Z+X production (CDF).



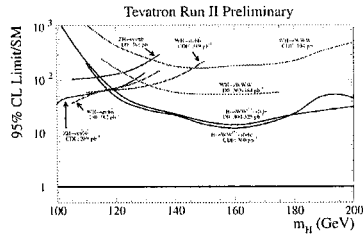
### 13. Direct Search for the Higgs



We saw in Lecture I that the EWK precision data favor a light Higgs (too light, even). Although it's not a precision measurement (my title), it is relevant to summarize the current status of direct Higgs searches. We show the dijet mass spectrum for 'W+H' channel from CDF with 319 pb<sup>-1</sup> above.



The cross-section limits from direct searches for the Higgs as of Sept., 05 from CDF and D0



The ratio of cross-section limits from direct searches to SM predictions for the Higgs as of Sept 05, from CDF and D0.

### 14. Precision Measurements in B Physics

This is an enormous topic. There are many new results in the works. I will limit myself to some thoughts on precision, illustrated by several specific results from CDF.

The measurements of masses, lifetimes, and mixing are inherently precision measurements. They differ from the other standard-bearing precision measurements at a hadron collider, the top mass, the W mass, W and Z and top cross-sections, W and Z decay asymmetries, etc., in that they are usually entirely tracking-based, rather than depending on the calorimeters. Precision thus depends on different quantities: alignment, resolution, tracking and trigger efficiencies, and tracking trigger biases. While difficult, these are more tractable than the calorimeter response to jets and the underlying event (for  $E_t$ ) in top decay, to pick an example. Consequently with much

beautiful hard work by many people in CDF and D0, these measurements are often limited by statistics.

The statistics limitation is not intrinsic: there are plenty of B's. The measured single-b cross-section at the Tevatron for  $|y| < 1$  is  $30 \mu\text{b}$ , so at  $1.8\text{E}32$  (present peak luminosity) Fermilab is making more than 5000 b's per second. Realistically one could expect more than  $10^{10}$  per year produced.

Now it seems a given that a detector at a hadron collider must have a silicon vertex detector; in 1981, however, it wasn't at all obvious that one would survive or work <sup>10</sup>. The success of the CDF SVX is a remarkable achievement, as is the subsequent SVT trigger system that allows triggering on displaced vertices.

#### 14.1. CDF measurement of the $\Lambda_b$ lifetime:

Figure 27 shows the mass peak and decay length distribution for the CDF measurement of the  $\Lambda_b$  lifetime.

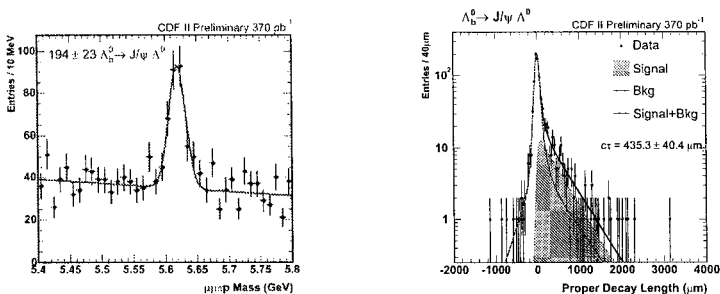


Figure 27. Left: Fully reconstructed  $p\pi\mu\mu$  mass; Right: The proper decay length distribution.

The results are:  $\tau(\Lambda_b) = 1.45_{-0.13}^{+0.14}(\text{stat}) \pm 0.02(\text{sys})$  psec and  $\tau(\Lambda_b)/\tau(B^0) = 0.944 \pm 0.089$  (CDF).

##### 14.1.1. CDF measurement of the $B_s$ lifetime:

Figure 28 shows the fully reconstructed  $B_s$  mass in  $\Phi\pi\pi$  and the distribution in  $c\tau$  in  $\Phi\pi\pi\pi\pi$  from CDF. The lifetime is measured to be  $\tau(B_s) = 1.381 \pm 0.055(\text{stat}) \pm_{0.046}^{0.052}(\text{sys})$  ps (See D. Krop's talk for the D0 number).

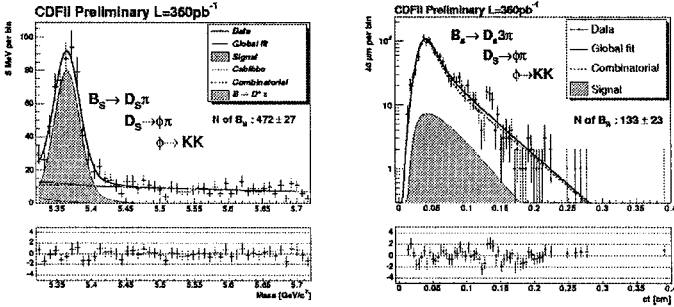


Figure 28. Left: Fully reconstructed  $B_S$  mass in  $\Phi\pi\pi$ ; Right: The distribution in  $c\tau$  in  $\Phi\pi\pi\pi\pi$ .

### 14.1.2. CDF $B_s$ Mixing:

The remarkable resolution ( $\sim 10$  microns) achievable with silicon detectors around the small beam pipe of a hadron collider allows the measurement of lifetime oscillations up to  $\sim 30$  ps<sup>-1</sup>. Both  $D\phi$  and CDF scan in frequency space for the amplitude  $A$ , where:

$$\text{Prob}(B_s^0 \rightarrow B_s^0) = 1/2\Gamma e^{-\Gamma t}(1 + A\cos(\Delta m_s t))$$

$$\text{Prob}(B_s^0 \rightarrow \bar{B}_s^0) = 1/2\Gamma e^{-\Gamma t}(1 - A\cos(\Delta m_s t))$$

Figure 29 shows the reconstructed  $\Phi\pi\pi$  mass (Left) and the amplitude scan (Right)<sup>11</sup>.

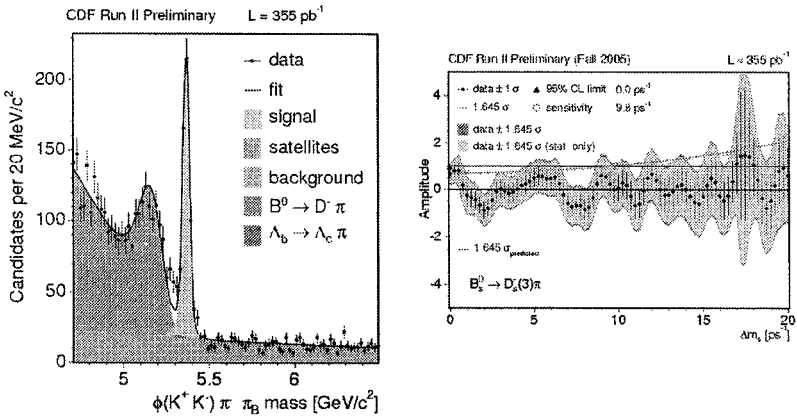


Figure 29. CDF: Exclusion (95% C.L.):  $\Delta m_s < 8.6$  ps<sup>-1</sup>

## 15. Expert Topics: Challenges for Students

I will briefly touch on an list of topics that I think lie ahead of us on the road to exploiting the higher precision inherent in our detectors.

### 15.1. *B-jet Momentum Scale: Gamma-bjet Balancing*

The response of the calorimeter to the b-quark jets from top decay is critical for the top mass; sharpening the resolution is also critical for discovering the Higgs. One source of b's of known momentum is  $Z^0 \rightarrow b\bar{b}$ ; even at the Tevatron this is very difficult as the rate of 2-jet production prohibits an unrescaled trigger threshold well below  $M_Z/2$ . At the LHC this will be hopeless, I predict. However the 'Compton' process gluon  $b \rightarrow \gamma b$  will give a photon opposite a b-jet. Figure 4 shows the flux of b-quarks versus x at  $Q = 100$  GeV (CTEQ6.1M); one can see that at  $x=0.01$  ( $p_T = 70$  GeV at the LHC) the b-quark flux is predicted to be only a factor of 3 lower than the gluon flux.

### 15.2. *Rethinking Luminosity*

To make precision measurements of cross-sections, we need both to measure the numerator and the denominator precisely, where the numerator is the number of events corrected for acceptance and efficiency, and the denominator is traditionally the proton-proton (antiproton) luminosity. However the denominator is harder to measure than the numerator. To improve the precision on crosssection measurements, it should be standard to measure the ratio to W and or Z production <sup>6</sup>. A secondary benefit would be in book-keeping- we could (should!) keep each W or Z in every file (small record)- to short-circuit the current nightmare of missing files and cockpit errors.

### 15.3. *Changing the Paradigm: W/Z ratios, Color Singlet/Color Triplet Ratios, and Other New Precision Tests*

Are there quantities that we can measure more precisely than ones we traditionally have been using? One example - instead of searching in the W+N jets and Z+ N jets for new physics, search in the ratio  $(W+N)/(Z+N)$ : The cross section corresponding to a 1-sigma uncertainty in the  $W/Z$  ratio in  $2 \text{ fb}^{-1}$ , and in  $15 \text{ fb}^{-1}$  is shown below. The bins up through  $N=4$  use the cross sections from CDF Run I; the  $N=5$  and higher bins have been

Event and W Properties		W/Z Ratio Method Reach	
N(Jets)	$\sigma_W$	$\sigma_{new} 2 fb^{-1}$	$\sigma_{new} 15 fb^{-1}$
0	1896 pb	20 pb (1.0%)	20 pb (1.0%)
1	370 pb	4.4 pb (1.2%)	3.7 pb (1.0%)
2	83 pb	1.5 pb (1.8%)	0.9 pb (1.1%)
3	15 pb	0.5 pb (3.5%)	240 fb (1.6%)
4	3.1 pb	230 fb (7.5%)	95 fb (2.9%)
5	650 fb	100 fb (16%)	40 fb (6%)
6	140 fb	50 fb (36%)	18 fb (13%)
7	28 fb	20 fb (78%)	8 fb (29%)
8	6 fb	—	4 fb (63%)

extrapolated, Using the dimuon channel one can gain approximately root-2 on these uncertainties.

#### 15.4. Particle ID: Distinguishing $W \rightarrow c\bar{s}$ from $W \rightarrow u\bar{d}$ , $b\bar{b}$ from $b$ in Top Decays

We take it for granted that we can only identify hadrons ( $\pi$ , K, and p) up to a few GeV by  $dE/dx$  and by conventional TOF. Based on simulations, 1 psec resolution may be eventually possible, extending particle ID to momenta over 10 GeV in a detector the size of CDF. A Japanese group (Ohnema et al.) has recently achieved 5 ps resolution in TOF. This would have a big impact on precision measurements- for example, same-sign tagging in  $B_s$  mixing, identifying the  $b$  and  $\bar{b}$  in the measurement of the top mass, and also separating  $c\bar{s}$  from  $u\bar{d}$  in top decays.

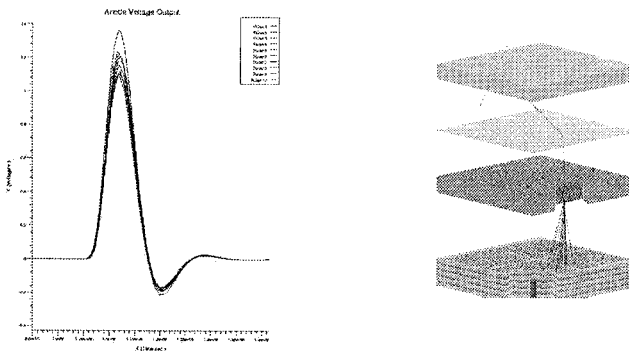


Figure 30.

## 16. Summary

- The Tevatron is just now moving into the domain where the W, Z, and top have enough statistics so that we are systematics dominated in many analyses. The LHC will turn on and immediately be in the systematics-dominated domain in almost all channels.
- In addition, the statistics is such that the theoretical SM predictions are sensitive to QED as well as QCD higher-order corrections- a new regime.
- Challenge- can we make systematics on top and W masses go down as  $1/\sqrt{\text{Luminosity}}$ ?
- $B_s$  mixing is not systematics dominated- it's a trigger problem. Challenge- can we accumulate the statistics for  $B_s$  mixing up to the inherent precision of the detector (trigger and DAQ question)?
- Watch the top mass, the W mass,  $B_s$  mixing, and for surprises out on the tails of kinematic distributions.
- These detectors are remarkable precision instruments, and are presented with a wealth of measurements. We need not only to exploit them as they are but also to support those folks working on hardware who concentrate on further developing their precision.

## 17. Acknowledgments

I thank all the CDF and DØ collaborators who have contributed to the topics I discussed. For understanding, wisdom, plots, and discussions I thank in particular: Eric Brubaker, Andrzej Czarnecki, Robin Erbacher, Rick Field, Ivan Furic, Doug Glenzinski, Chris Hays, Matt Herndon, John Hobbs, Joey Huston, Steve Levy, Andrei Loginov, Ashutosh Kotwal, Vaia Papadimitriou, Jon Rosner, Jim Strait, Evelyn Thompson, and Carlos Wagner.

Talks I have found useful and/or taken plots from: Florencia Canelli, Feb. 2005, Tev4LHC; Rick Field, XXXV Symposium on Multiparticle Dynamics, Kromericz; Kenichi Hatakeyama, Top2006, Coimbra, Jan, 2006; Aurelio Juste, Lepton-Photon, July, 2005; Cheng-Ju S. Lin, Aspen, Feb. 2006; Fabio Maltoni, HCP2005, Les Diableret, July 2005 Vaia Papadimitriou, XXXVth Multiparticle Dynamics, Kromericz; F. Ruggiero: <http://chep.knu.ac.kr/ICFA-Seminar/upload/9.29/Morning/session1/Ruggiero-ICFA-05.pdf>; Evelyn Thompson, Top2006, Coimbra, Jan, 2006; Eric Varnes, Top2006, Coimbra, Jan, 2006; Carlos Wagner, EFI Presentation, February 2006.

Lastly I would like to thank the organizers of the Winter Institute, in particular Faqir Khanna, Lee Grimard, and Roger Moore, for their unfailing hospitality and remarkable organization for what was a wonderful week.

## References

1. LHC Design Report CERN-2004-003 (June 2004), Section 2. I have taken the 7.75 cm quoted for the RMS bunch length, multiplied by the geometric luminosity reduction factor of 0.836, and divided by  $\sqrt{2}$ . I hope this is correct.
2. The initial luminosity has a lifetime of 3.8 hours, which crosses the longer lifetime after 2 hours, at which point the luminosity is half the peak.
3. See the talk by F. Ruggiero at: <http://chep.knu.ac.kr/ICFA-Seminar/upload/9.29/Morning/session1/Ruggiero-ICFA-05.pdf>
4. S.M. Berman, J.D. Bjorken, J. B. Kogut, Phys.Rev.D4:3388,1971.
5. I first learned of this method from A. Mukherjee and A. B. Wicklund, who used it in the CDF early precise (at that time) measurement of the  $Z^0$  mass.
6. H.Frisch, CDF/Phys/Top/Public/2484; Feb. 1994; M. Dittmar, F. Pauss, D. Zurcher; Phys.Rev.D56:7284-7290,1997
7. J. D. Jackson and R. McCarthy; "Z<sup>3</sup> Corrections to Energy Loss and Range", Phys. Rev. B6,4131 (1972).
8. Fabio Maltoni, *Top Physics: Theoretical Issues and Aims at the Tevatron and LHC*, HCP2005, July 8, Les Diablerets, Switz.;
9. G. L. Kane and S. Mrenna, Phys.Rev.Lett.77:3502-3505,1996.
10. Technical Design Report, CDF Collaboration; Aug. 1981
11. D0 announced the result  $17 < \Delta M_S < 21 \text{ ps}^{-1}$  at 90% C.L. at the Moriond EWK conference March 12, 2006.