Feasibility Study For Measurement of $\sigma_{Z \to b\bar{b}}$ in CDF Run II

Oral Qualifier Exam

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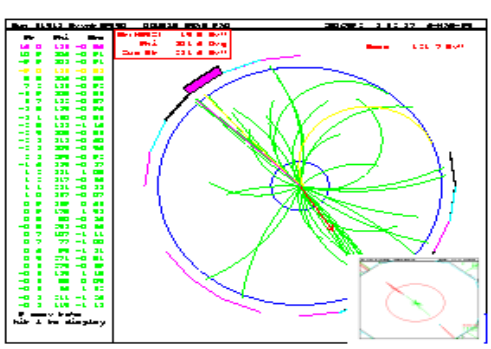
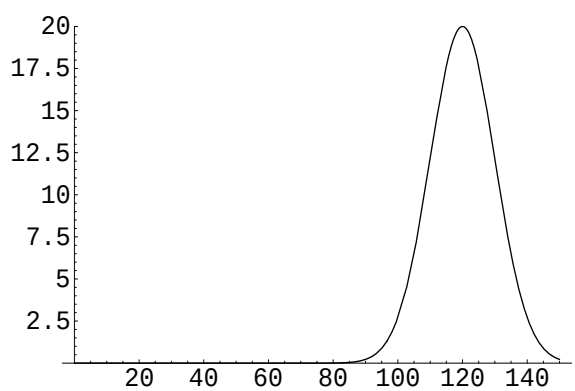
Why $Z \to b\bar{b}$?

- Outstanding question in particle physics:**The Origin of Electroweak Symmetry Breaking.**
- Most Famous: Higgs mechanism. So the search is on . . .
  - Know $m_H > 115\ GeV$ (95% C.L.) from LEP searches in $e^+e^- \to WH \to l\nu b\bar{b}$ and other channels

  $\Rightarrow$ Need high energy ($p\bar{p}$) collider
- Accessible decay mode at the Tevatron: $H \to b\bar{b}$ (Above $2M_W$, $H \to W^+W^-$ is dominant)

$\Rightarrow$ Should examine $b\bar{b}$ spectra at colliders to find resonances:



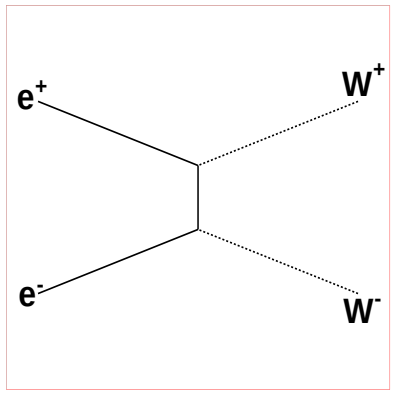


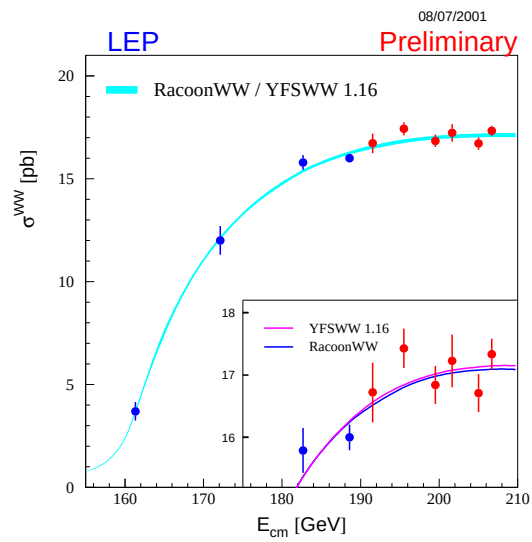
- Opportunity to study $Z \to b\bar{b}$ as a training ground.
  - b-jet energy calibration
  - Resolution of di-bjet invariant mass

Unitarity Violation In The Standard Model

- Let $s =$ CM Energy squared, $t =$ momentum tranfer squared
- Can show $l = 0$ partial wave unitarity requires

$$\int_0^s d|t| \left[\frac{1}{4\pi}\frac{d\sigma}{dt}\right]^{\frac{1}{2}} < 1$$

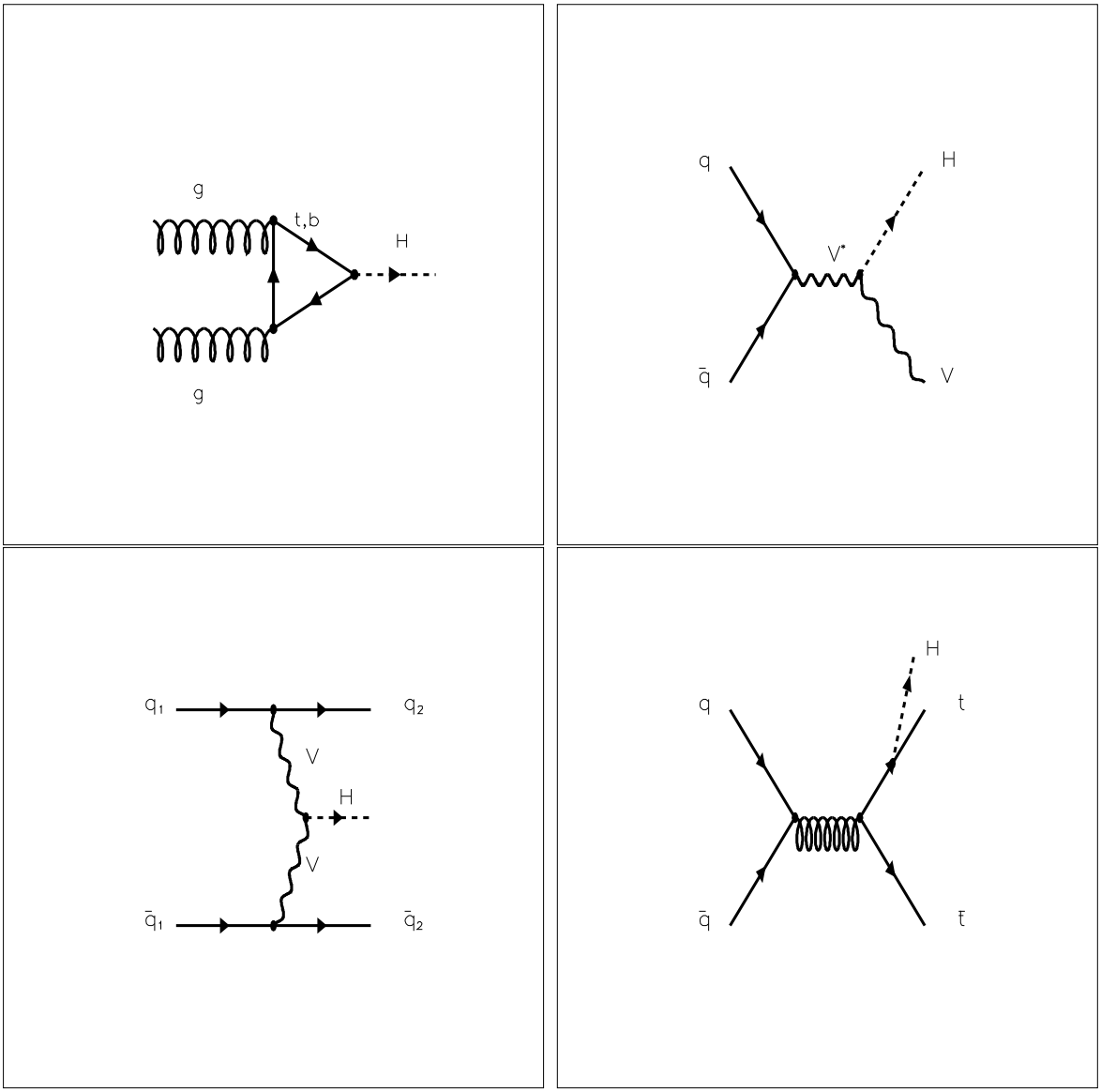




- Violated if $\frac{d\sigma}{dt} \rightarrow 0$ slower than $\frac{1}{s^2}$
- $\frac{d\sigma}{dt} \sim \frac{\alpha^2}{s^2}$ (For 2→2 scattering with dimensionless coupling)
- For $e^+e^- \rightarrow W^+W^-$, $\frac{d\sigma}{dt} \sim \frac{m_e^2}{M_W^2}\frac{s}{M_W^2}\frac{1}{s^2}$
- Need spin-0 object to take up $1/s$ divergence
- Higgs Boson cancels divergence

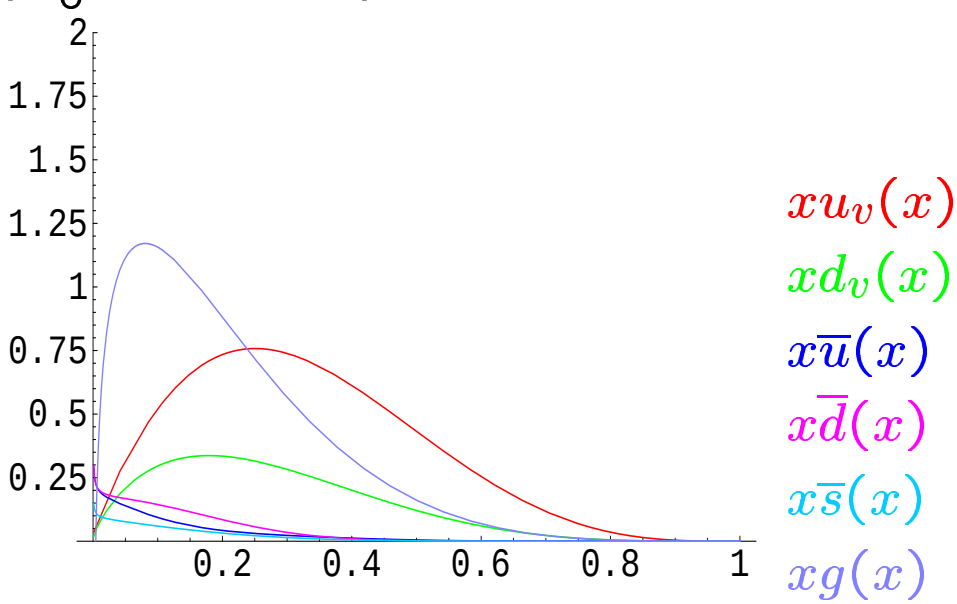
Higgs Production Modes

- Primary production modes for the Fermilab Tevatron are:



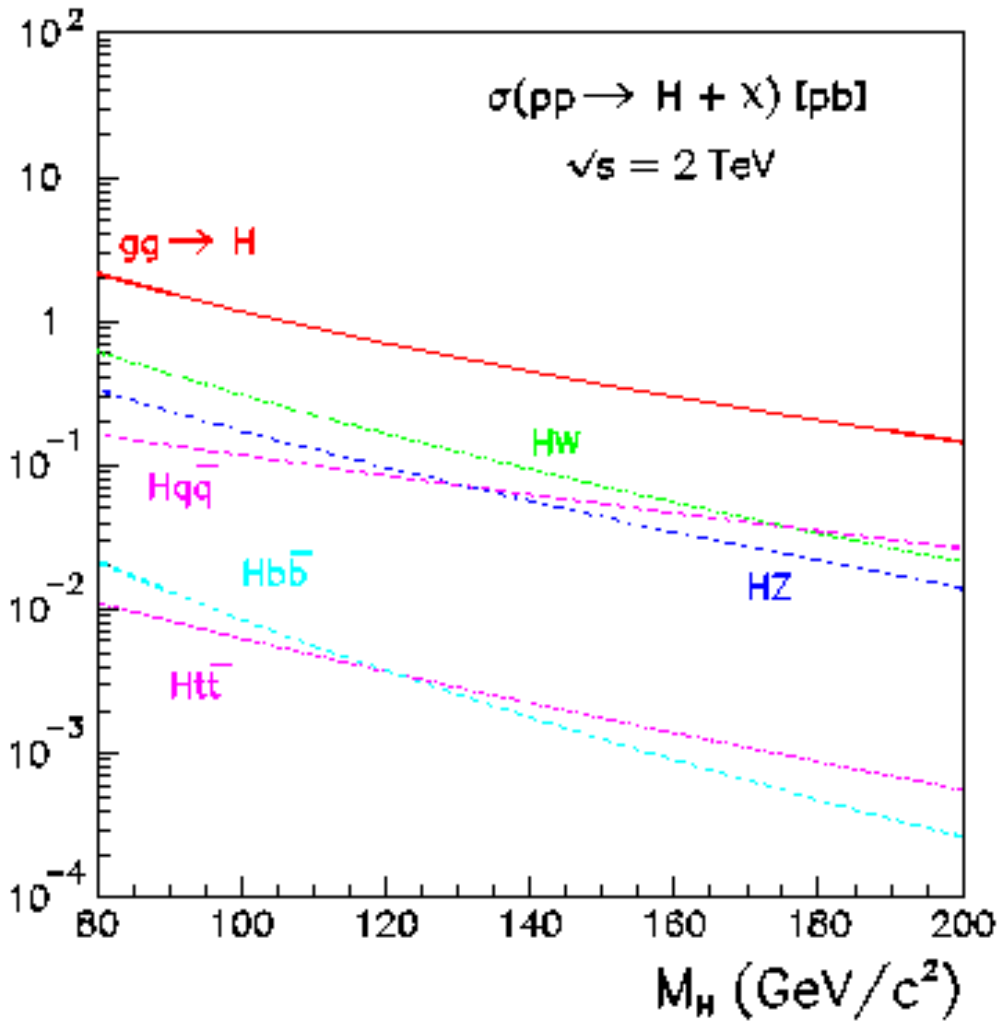
$p\overline{p}$ Colliders

- Protons carry valence quarks, sea quarks, and gluons.
- Let x_a be the fraction of the proton's momentum carried by a parton of type a (quarks, antiquarks, or gluons).
- Let $q(x)$ be the probability that a parton of type q has momentum fraction x.
- MRST2001 Parton Distribution Functions are ($Q_0^2 = 1\ GeV^2$):



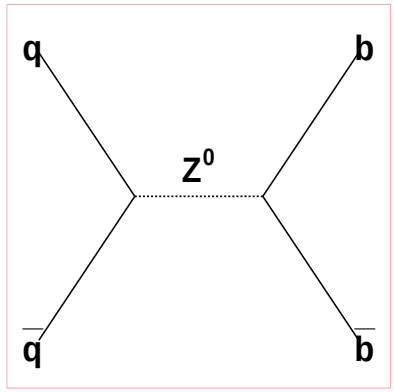
- To calculate σ's, need to account for these distribution functions

Higgs Production Cross Section



- With 2 fb^{-1} of data at the Tevatron, will produce about 1600 Higgs in $gg \to H$, and about 400 Higgs in WH production.

$p\overline{p} \to Z \to b\overline{b}$ Cross Section



- Differential cross section in rapidity is

$$\frac{d\sigma}{dy}(p\overline{p} \to ZX) = K\frac{8\pi}{3}\frac{G_F}{\sqrt{2}}\int dx_a dx_b \sum_q \left[(g_V^q)^2 + (g_A^q)^2\right] \times x_a\, x_b\, q(x_a)\, \overline{q}(x_b)$$

Numerically, $C_V \approx -0.35$, $C_A = -0.5$

- At the Tevatron, $\sigma(p\overline{p} \to Z) \approx 6.7\ nb$.

- Decay width is

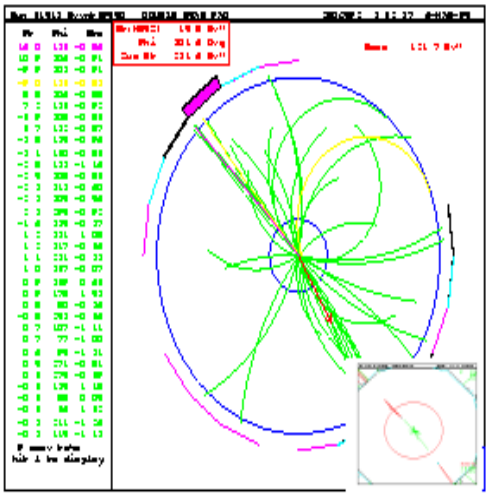
$$\Gamma(Z \to b\overline{b}) = \frac{G_F M_Z^3}{12\pi\sqrt{2}} 24(g_V^2 + g_A^2)$$

- Best known value for $BR(Z \to b\overline{b})$ is measured by LEP, $(15.13 \pm 0.05)\%$

- $\sigma(p\overline{p} \to Z) \times BR(Z \to b\overline{b}) \approx 1\ nb$.

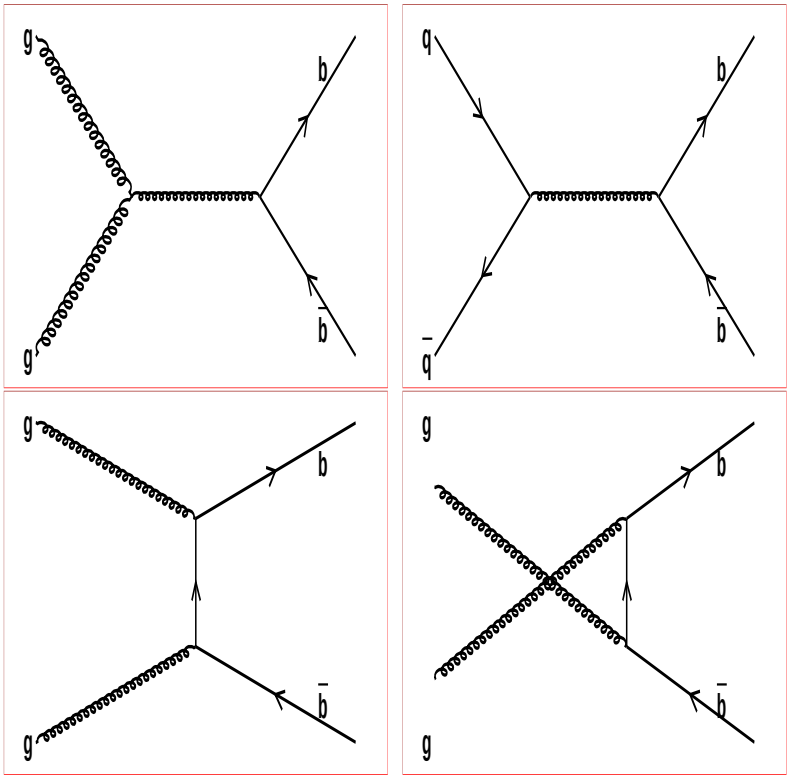
$\Rightarrow$ Expect about 120k Z decays to $b\overline{b}$.

The QCD Di-bjet Background



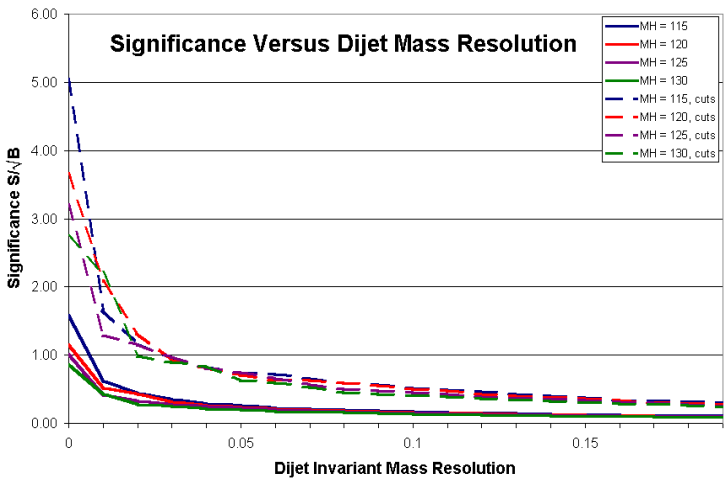
- Background is the same signature:
  - 2 jets
  - Both b's

$\Rightarrow$ Irreducible



QCD Di-bjet Background $\Rightarrow$ No $gg \to H$

- $gg \to H \to b\bar{b}$: Can we see it?
- Performed Monte Carlo study with
  - ≥ 2 bjets ("Divine" b-tagging - ΔR to b-quarks)
  - $|\eta|_{bjet} < 2$
  - $p_T > 15, 10\ GeV$ for first, second bjet
- Resolution $= \frac{\Delta M}{M}$, significance $= \frac{S}{\sqrt{S+B}}$



- For 3σ discovery, resolution is 0.8%
- Resolution obtained in Run I was 15%

$\Rightarrow$ Best channel is $p\bar{p} \to WH \to l\nu b\bar{b}$ (*Associated production*)

$\Rightarrow$ Use Tevatron at Fermilab and CDF

Experimental Prescription

- Even in associated production, $b\bar{b}$ invariant mass is signal plot for Higgs

- Experimentally, want a calibration peak

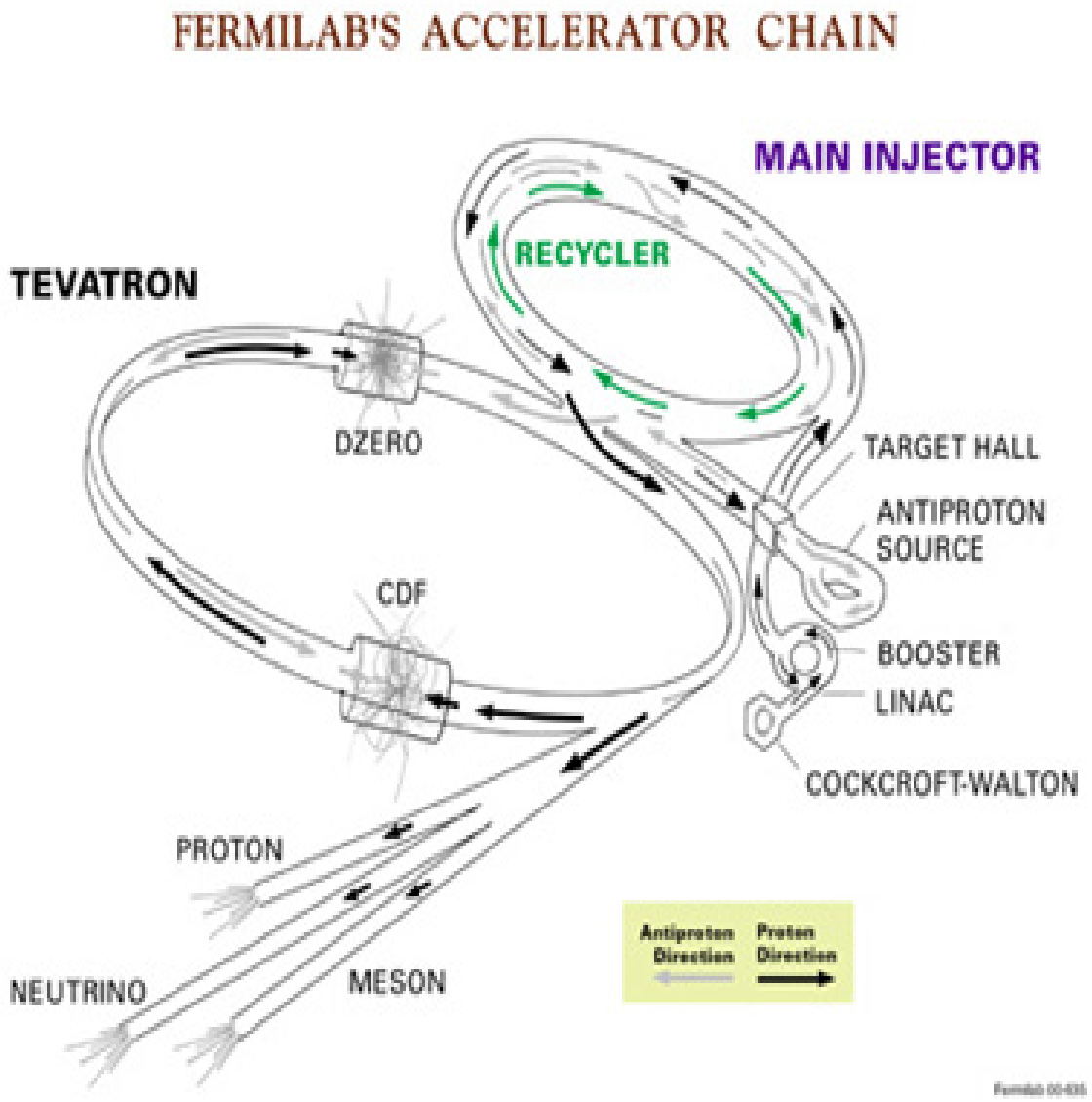
$\Rightarrow$ Examine $Z \to b\bar{b}$ at CDF

- Experimental problems:
  - Find Z bump in $b\bar{b}$ spectrum
  - Measure m_Z
  - Maximize significance of Z
  - Measure σ_Z

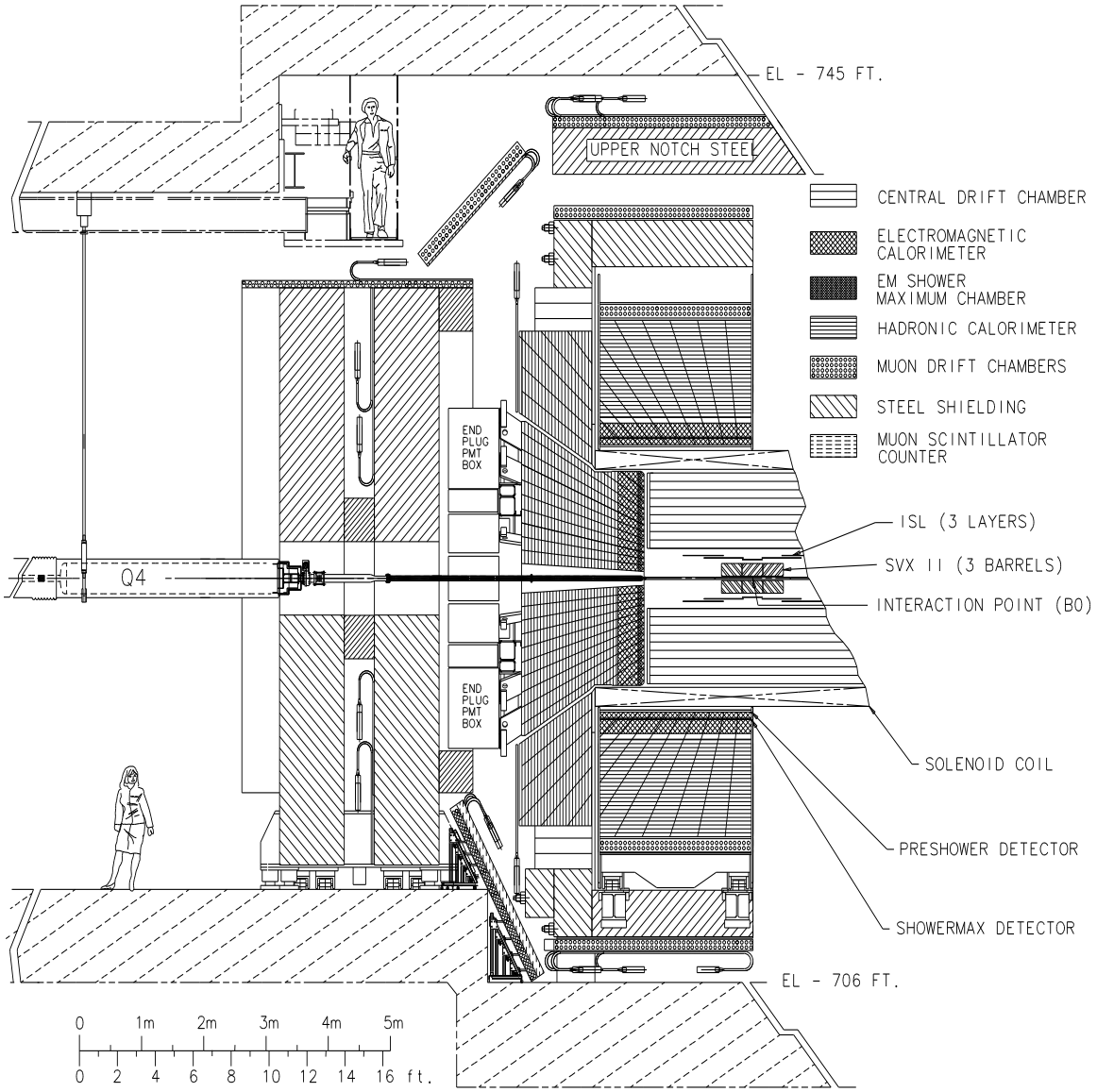
- Examine Run I measurement

- Examine prospects for Run II

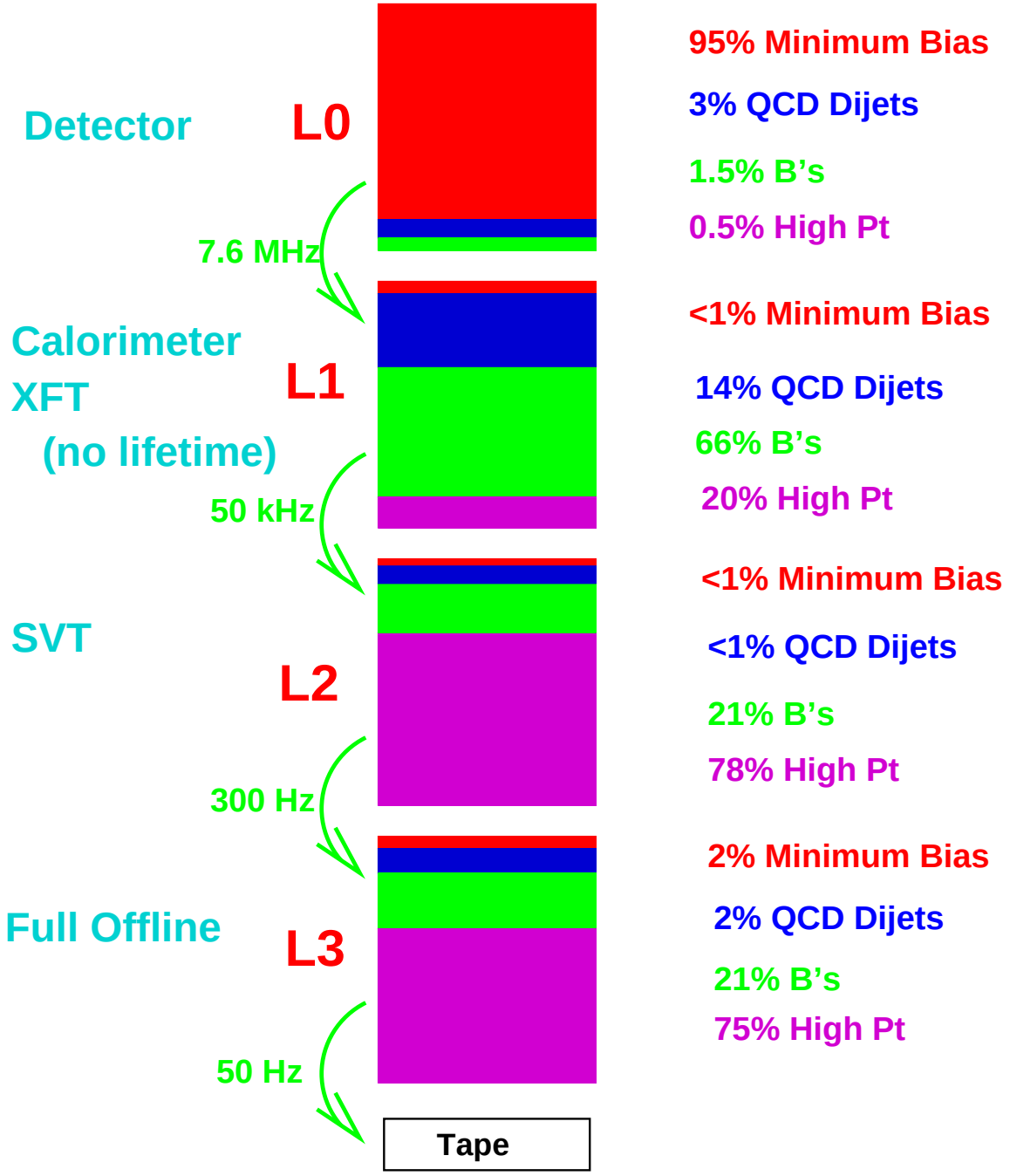
Tevatron


FERMILAB'S ACCELERATOR CHAIN
MAIN INJECTOR
RECYCLER
TEVATRON
DZERO
TARGET HALL
ANTIPROTON SOURCE
CDF
BOOSTER
LINAC
COCKCROFT-WALTON
PROTON
NEUTRINO
MESON
Antiproton Direction
Proton Direction

CDF

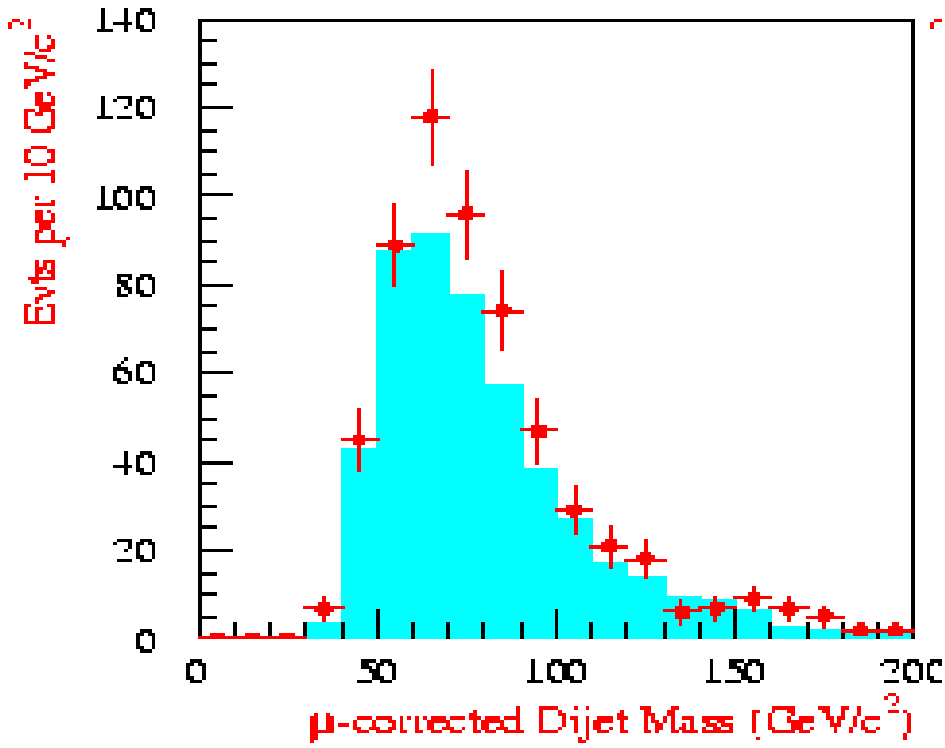

EL - 745 FT.
UPPER NOTCH STEEL
CENTRAL DRIFT CHAMBER
ELECTROMAGNETIC CALORIMETER
EM SHOWER MAXIMUM CHAMBER
HADRONIC CALORIMETER
MUON DRIFT CHAMBERS
STEEL SHIELDING
MUON SCINTILLATOR COUNTER
END PLUG PMT BOX
END PLUG PMT BOX
Q4
ISL (3 LAYERS)
SVX II (3 BARRELS)
INTERACTION POINT (B0)
SOLENOID COIL
PRESHOWER DETECTOR
SHOWERMAX DETECTOR
EL - 706 FT.
0 1m 2m 3m 4m 5m
0 2 4 6 8 10 12 14 16 ft.

Triggering System At CDF



Use $Z \to b\bar{b}$ As Training Ground For Higgs

- Know there is a bump in $m_{b\bar{b}}$ spectrum from $Z \to b\bar{b}$
- Has been measured at CDF in Run I by T. Dorigo:

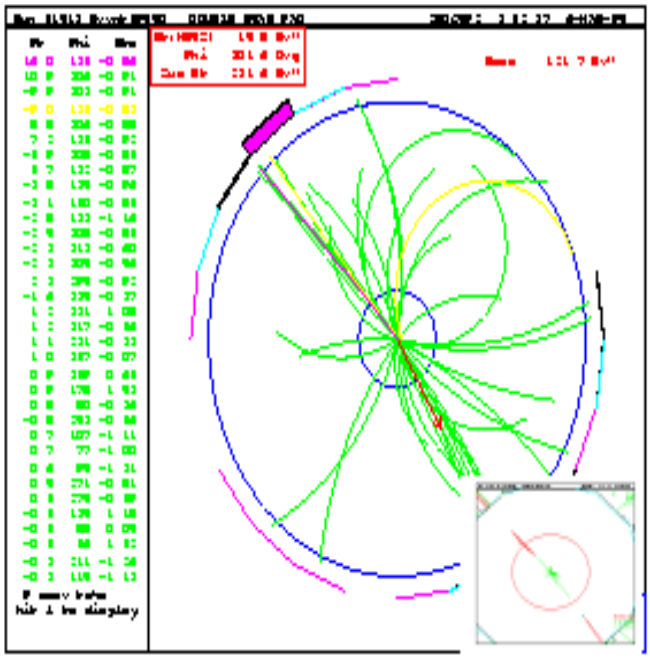


- Note background is mostly QCD $gg \to b\bar{b}$ ($Z \to b\bar{b} \not< gg \to b\bar{b}$)
- Require $m_{b\bar{b}} > 10\ GeV$

Process	$\sigma \times$ BR (nb) $\times$ Gen. Weight
$f\bar{f} \to b\bar{b}$	90
$gg \to b\bar{b}$	1500
$p\bar{p} \to Z^0 \to b\bar{b}X$	1
$p\bar{p} \to H^0 Z^0 \to b\bar{b}X$	$8.5 \times 10^{-4\dagger}$

- Expect $\sim$ 120k $Z \to b\bar{b}$

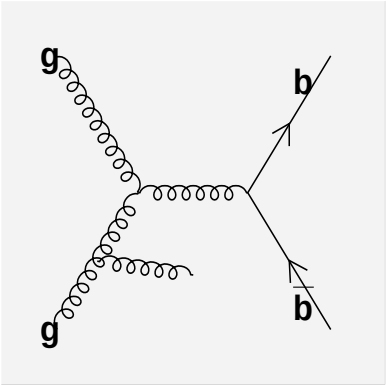
$Z \to b\bar{b}$ in CDF Run I



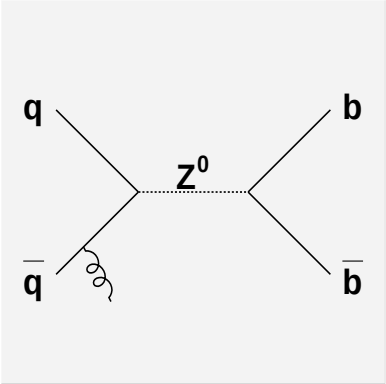
- No lifetime trigger in Run I, so looked in the muon dataset ($b \to \mu\nu c$).
- Use vertex-based b-tag
- $Br(b \to \mu\nu c) \sim 10\% \Rightarrow$ Single Jet Trigger Efficiency $\sim$ 20%
- Purity is very small for this sample ($\frac{S}{B} \approx$ 1/6).
- What discriminates background from signal? Gluon Radiation

Radiation Considerations

- QCD:
  - Initial and final state color multiplet
  - $\Rightarrow$ Color connection between inital and final state
  - Gluon initial states $\Rightarrow$ more ISR



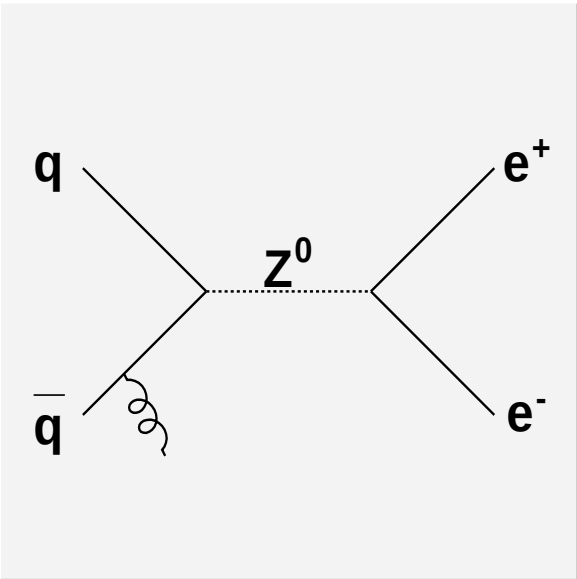
- Electroweak:
  - Initial and final state color singlets
  - No color connection
  - Quark initial state $\Rightarrow$ less ISR

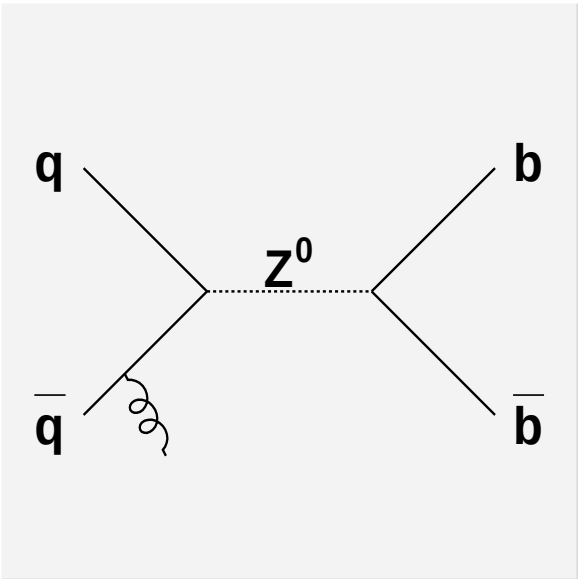


$\Rightarrow$ Expect more radiation from QCD, and in different patterns

Radiation Considerations - cont'd

- As background, used single-tagged sample (one displaced vertex)
- Used $Z \to e^+e^-$ data to determine effects of extra radiation:

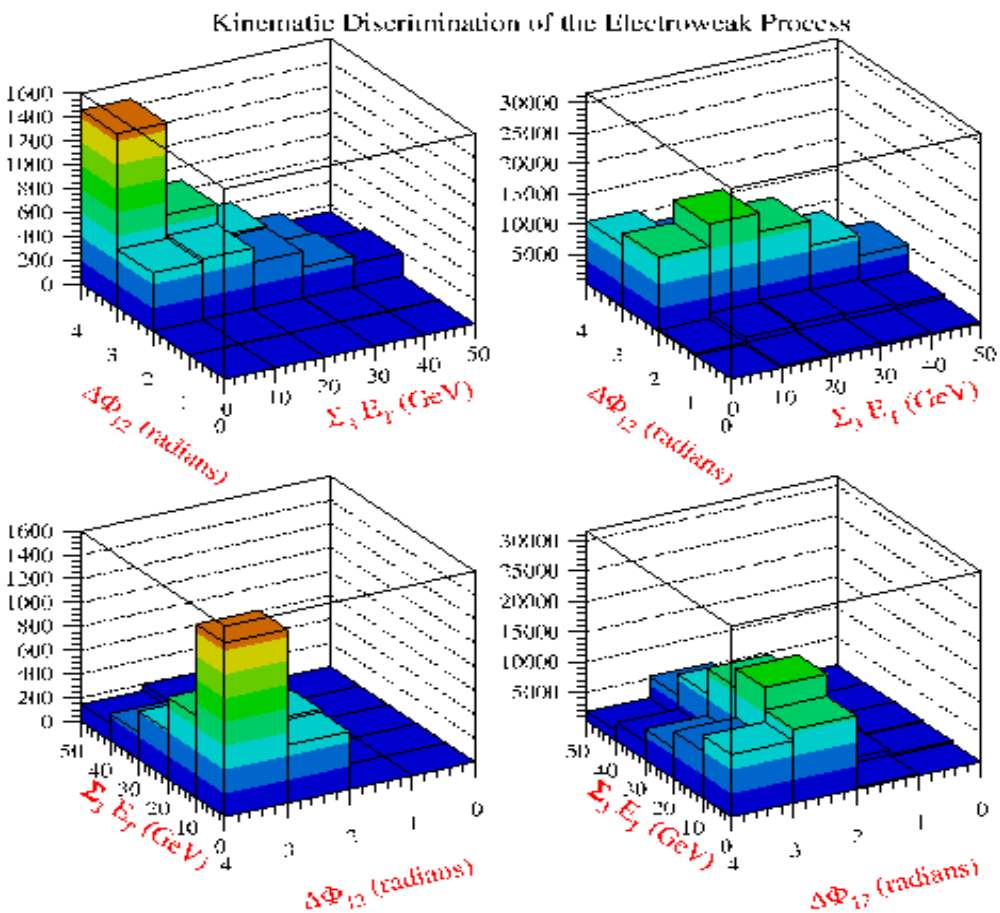




- Since final state quarks are in a color singlet, final state radiation is suppressed, so radiation patterns are similar in $Z \to e^+e^-$ and $Z \to b\bar{b}$
  - No discrimination from radiation pattern
  - Discrimination from total amount of radiation.

Selection Criteria

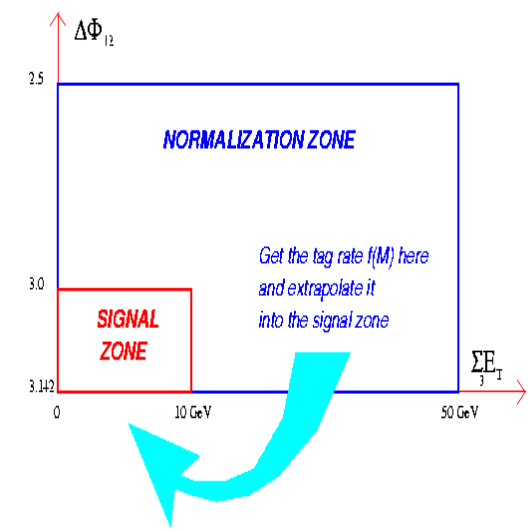
- $\Delta\phi_{12} > 3.0$ rad - signal has more back-to-back jets in ϕ
- $\sum_3 E_T (\equiv \sum_{cluster} E_T^{cluster} - E_T^{jet\ 1} - E_T^{jet\ 2}) < 10$ GeV - signal has less energy outside leading jets



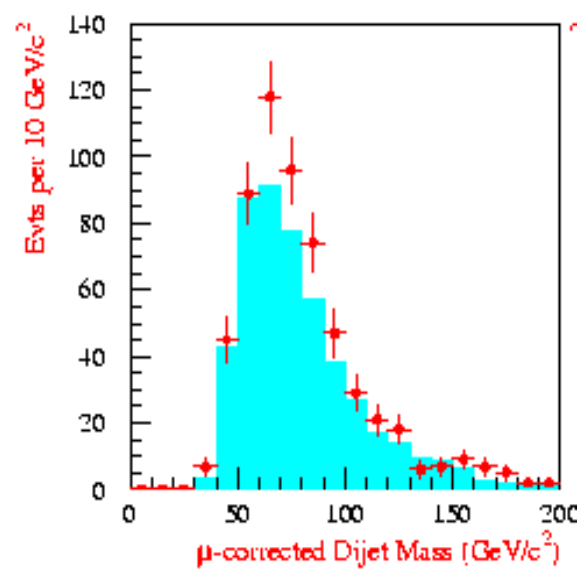
Background Normalization

- Background is single-tag (one displaced vertex) sample that passes kinematic cuts (N_{pass}^{+0})
- Signal is double-tag (two displaced vertices) sample that passes kinematic cuts (N_{pass}^{++})
- Use events that don't pass kinematic cuts to normalize expected background on a bin-by-bin basis:

$$\frac{N_{pass}^{++}(M_{jj})}{N_{pass}^{+0}(M_{jj})} = \frac{N_{fail}^{++}(M_{jj})}{N_{fail}^{+0}(M_{jj})}$$

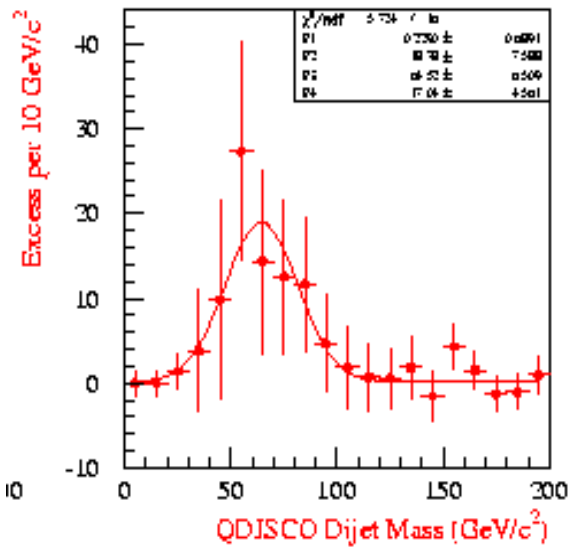


- Assuming kinematics of QCD $b\bar{b}$ same as kinematics of QCD dijets
- Calculate events expected from background, look at excess as signal



$b\bar{b}$ Invariant Mass Spectrum

- Measured invariant mass of $b\bar{b}$ pair. Excess over QCD background:



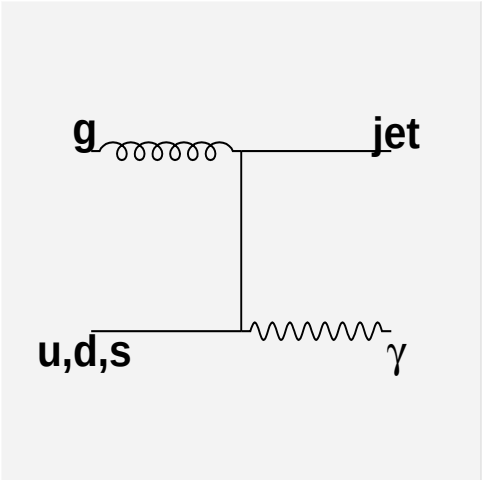
- Apply "standard" jet corrections

$\Rightarrow$ $m_Z = 64.5 \pm 6.5$ GeV, $\sigma_{jj} = 17.0 \pm 4.6$ GeV

- Why?

- Jet Energy Scale for b's different than jet energy for generic QCD

How To Set The Jet Energy Scale?



- Fragmentation models and measurements using photons set correct energy scale

- Large fluctuations in particle content $\Rightarrow$ large variations in the deposited energy

$\Rightarrow$ Large Measurement uncertainties (100%/$\sqrt{E}$ hadronic, as opposed to 15% / $\sqrt{E}$ electromagnetic)

- For b-jets, the mix of particles is different $\Rightarrow$ standard corrections give biased answer for b-jets - μ,ν in every event

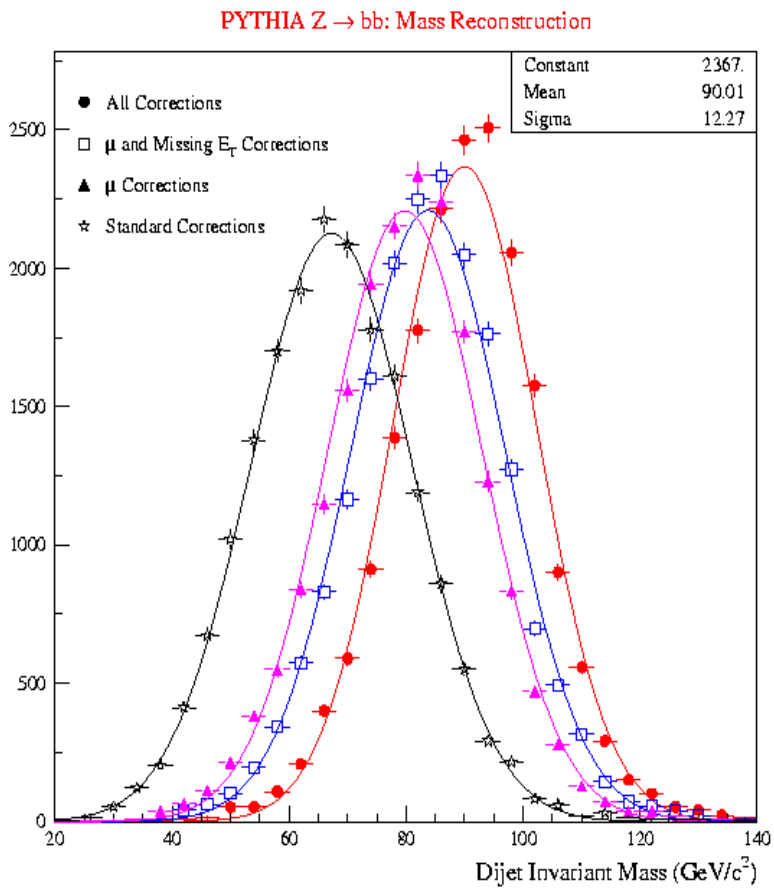
- If we can get the Z, we can set the jet energy scale for b-jets.

- Dominant systematic in m_t (4.4 GeV).

- If tracking information used, jet resolution of calorimeter reduces to 85%/$\sqrt{E}$.

Jet Corrections

- Examined biases in Monte Carlo study (where you know the b)



- Muon correction
- Charge fraction correciton

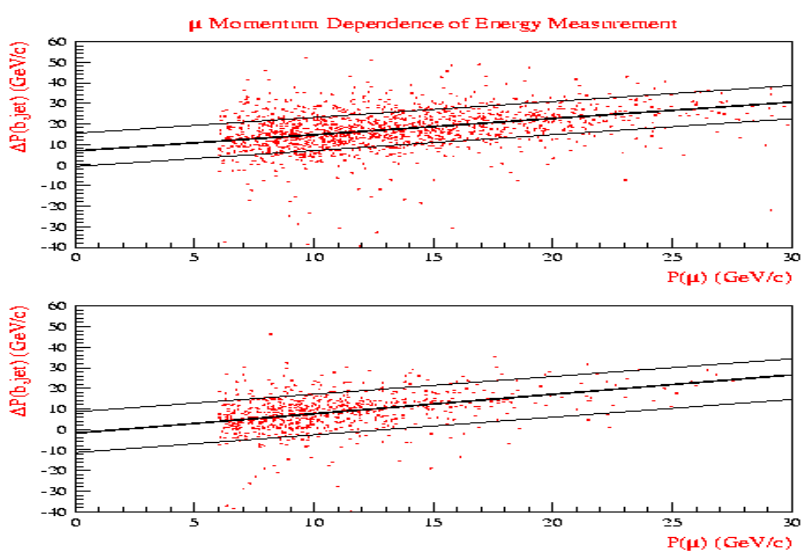
⇒ Jet by jet correction

Muon Jet Correction

- Dorigo found strong correlation between muon momentum and jet momentum
- Assumed $\vec{P}_b - \vec{P}_{jet} = \alpha\vec{P}_\mu + \beta\vec{E}_{tower}$ (checked that $\vec{P}_\mu$ and $\vec{E}_{tower}$ were uncorrelated)
- Found $\beta = 0$, $\alpha = 1.0$ was best parameterization

$\Rightarrow$ Lost momentum is mostly in the muon.

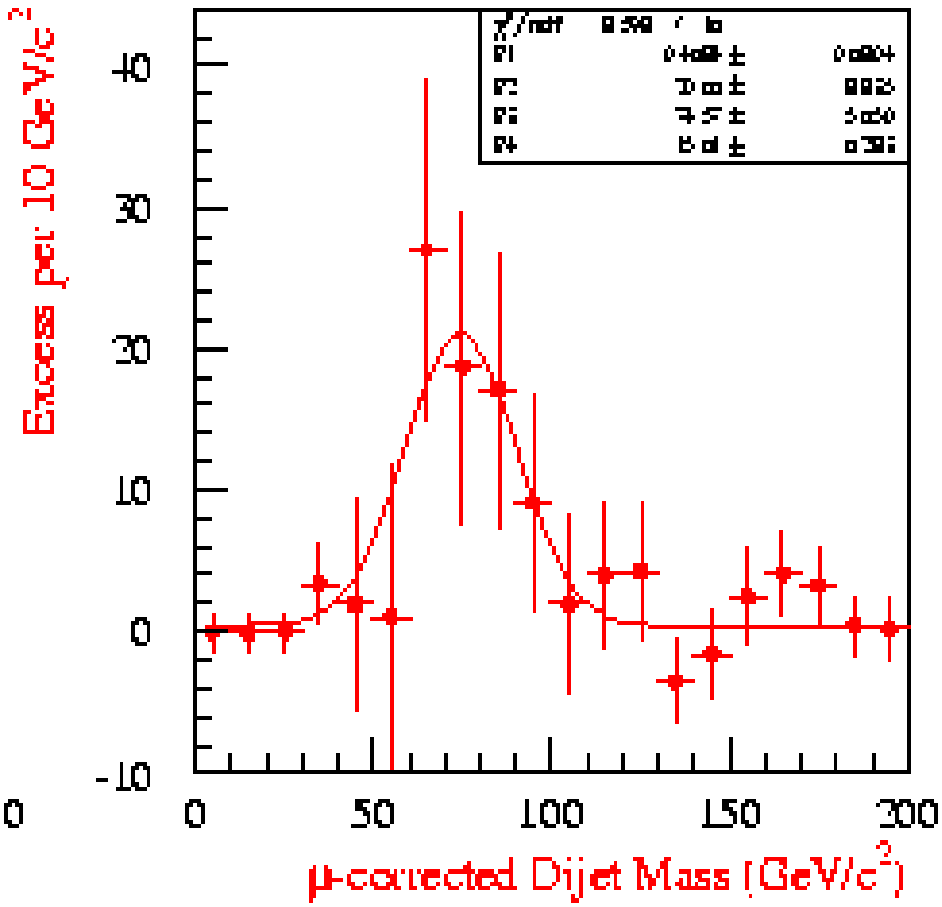
- Assumed $\Delta P = P_b - P_{jet} = mP_\mu + q$
- Fit to plot, discarding points more than 2σ away, and find correlation



$\Rightarrow$ Can correct events with muon in jet on a jet-by-jet basis

Jet Corrections - cont'd

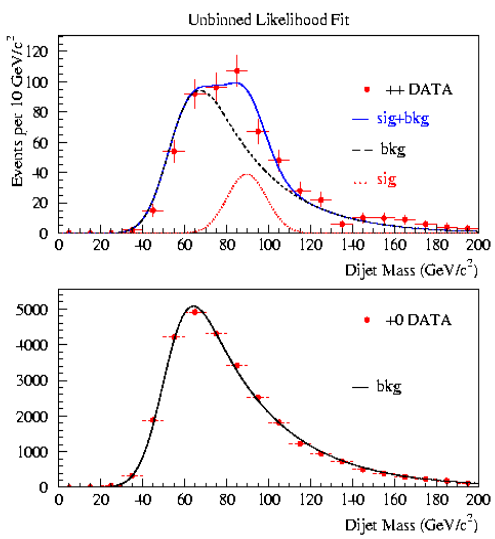
- With new corrections (not taken from this data):



Quantity	Standard jet corrections	B-jet corrections
m_Z	64.5 ± 6.5 GeV	88.5 ± 4.9 GeV
σ_Z	17.0 ± 4.6 GeV	13.6 ± 4.8 GeV
$\frac{\Delta M}{M}$	0.264	0.154
N_Z	93.5 ± 27	

Likelihood Fit

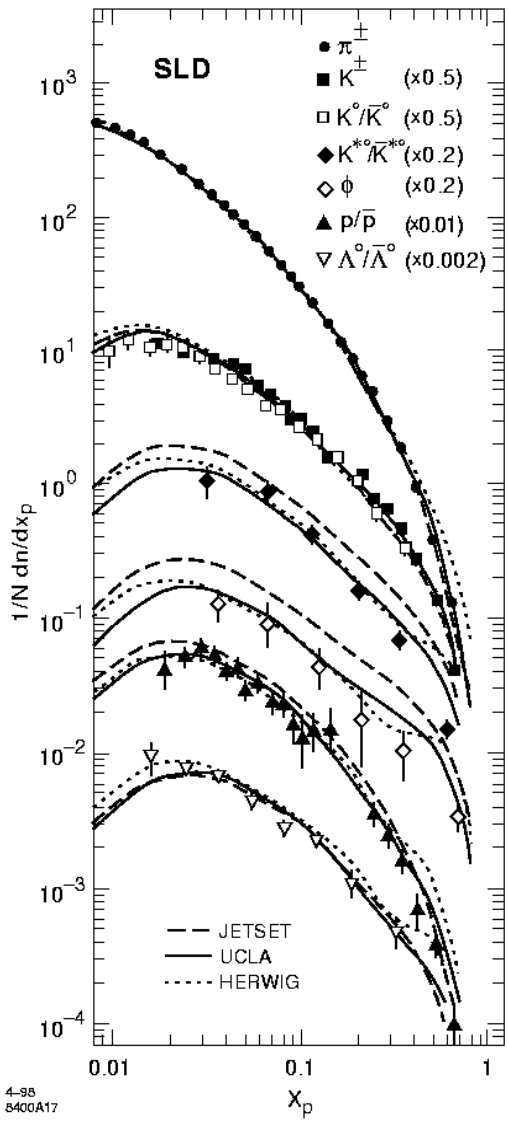
- Performed unbinned likelihood fit
- Single tagged (one displaced vertex) sample was taken as pure background
- Performed likelihood fit to background for expected background shape only

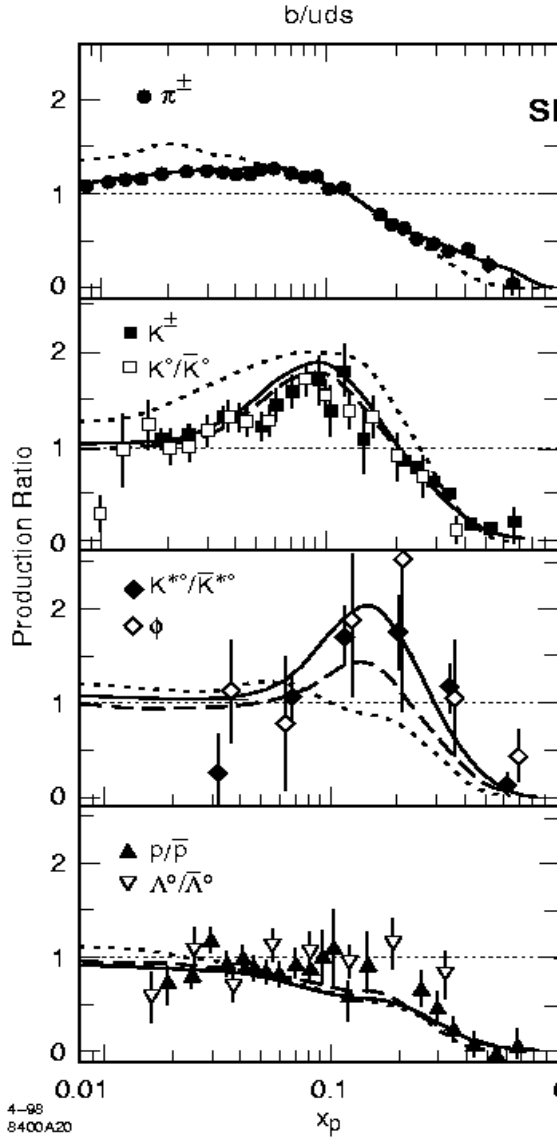


- Floated M_Z, σ_Z, number of signal, and number of background
- Signal was assumed to be a gaussian
- Finds $M_Z = 90.0 \pm 2.4$ GeV, $\sigma_Z = 9.4 \pm 3.5$ GeV, $N_Z = 91 \pm 30 \pm 15$

Particle Mix In Bjets From SLD

- SLD has measured particle mix in hadronic jets of different flavors (udsg, c, b) from Z decays





⇒ As a group, we should obtain a new set of jet corrections using this information

Run II Prescription

- Examine new lifetime trigger (Silicon Vertex Tracker - SVT) dataset

  $\Rightarrow$ More data per pb^{-1}

- Require 2 displaced vertices

  – Improved silicon coverage

  $\Rightarrow$ More data per pb^{-1}

- Require $\Delta\phi_{12} > 3.0$ rad, $\sum_3 E_T < 10$ GeV

- Calculate invariant mass of $b\bar{b}$ pair

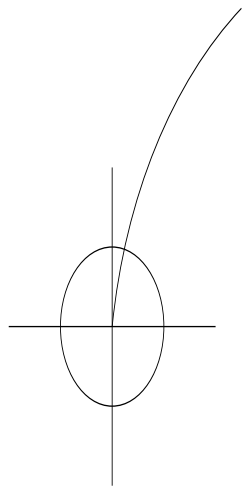
  – Possible improvement in b identification

  – Minimize mass resolution

  $\Rightarrow$ More data per pb^{-1}

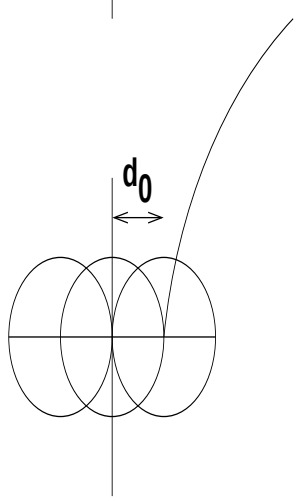
The SVT

- Level 2 trigger
- Has track information from XFT (eXtremely Fast Tracker):
  - 2-d information (p_T, ϕ, charge sign)
  - COT only
  - No Lifetime information
- Requires two displaced tracks
- No z information $\Rightarrow$ if misaligned, tracks from beam will appear to have large impact parameters
- SVT specs on alignment are:
  - Barrel-to-barrel offsets $< 50\ \mu m$
  - Barrel-to-barrel slopes $< 200\ \mu rad$
  - Overall alignment of SVX to COT $< 100\ \mu rad$
- Examine internal aligment



Proper Internal Aligment:

From Beam Spot

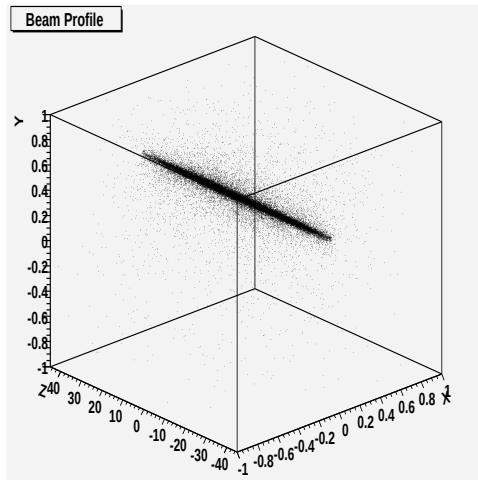


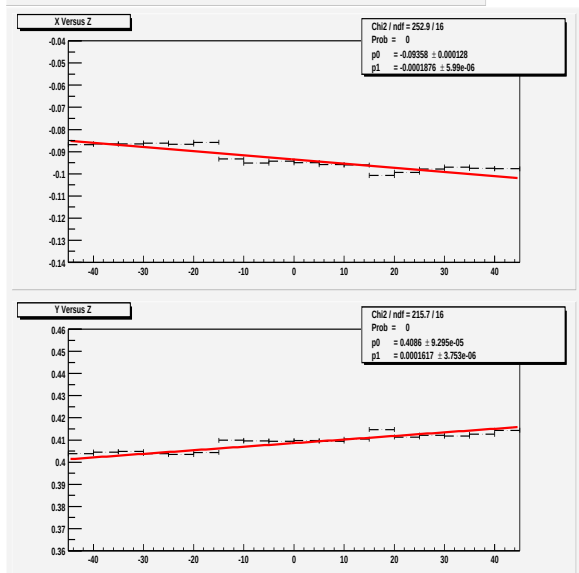
Improper Internal Alignment

High Impact Parameter

Estimation of Barrel-To-Barrel and Overall Alignments of SVX

- Examined alignment using offline software last summer:

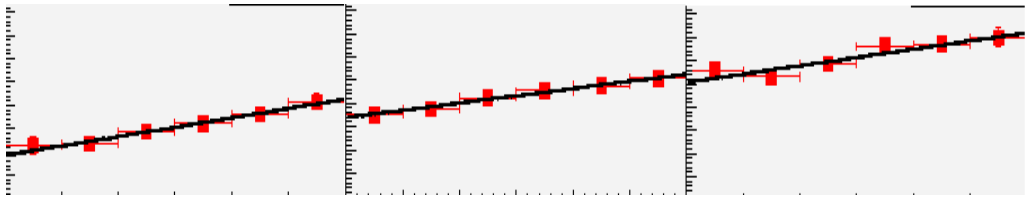




1. Vertexed highest two p_T tracks
2. Form beam profile for run
3. Calculate beam spot as function of z
4. Fit projections of x and y to gaussians, record means and widths

- Mechanically adjusted SVX to have overall alignment with COT

Alignment



Results (after alignment to SVT):

Barrel	$\Delta\overline{x}$	$\sigma_{\Delta\overline{x}}$	$\Delta x'$	$\sigma_{\Delta x'}$	$\Delta\overline{y}$	$\sigma_{\Delta\overline{y}}$	$\Delta y'$	$\sigma_{\Delta y'}$
0-1	75.6	12.2	106.1	41.4	-60.1	10.6	-44.5	36.7
1-2	37.2	16.7	-210.4	50.2	-26.9	14.1	41.1	48.3

$\Rightarrow$ All within spec

Estimate of ϵ_{SVT}

- Used J/ψ data with silicon information (trigger on muons)

- Procedure:

  1. Take muon candidates in muon chambers with trigger
  2. Select "good" displaced J/ψ events and perform simulation of SVT
  3. Match "good SVT " tracks with muon candidates
  4. Take ratio of tracks found by SVT to total tracks in J/ψ sample

$\Rightarrow$ Found single-track efficiency is $\epsilon_{\mathrm{SVT}} \approx 71.7 \pm 2.2\%$

- Compare 49% (two track efficiency) to $\sim 15 - 20\%$ for soft lepton trigger

Increased Silicon Coverage

- SVX twice as long

Possible Tracking Efficiency In Run II

- Combined effect of new tracking subsystems (COT , SVX II, ISL):

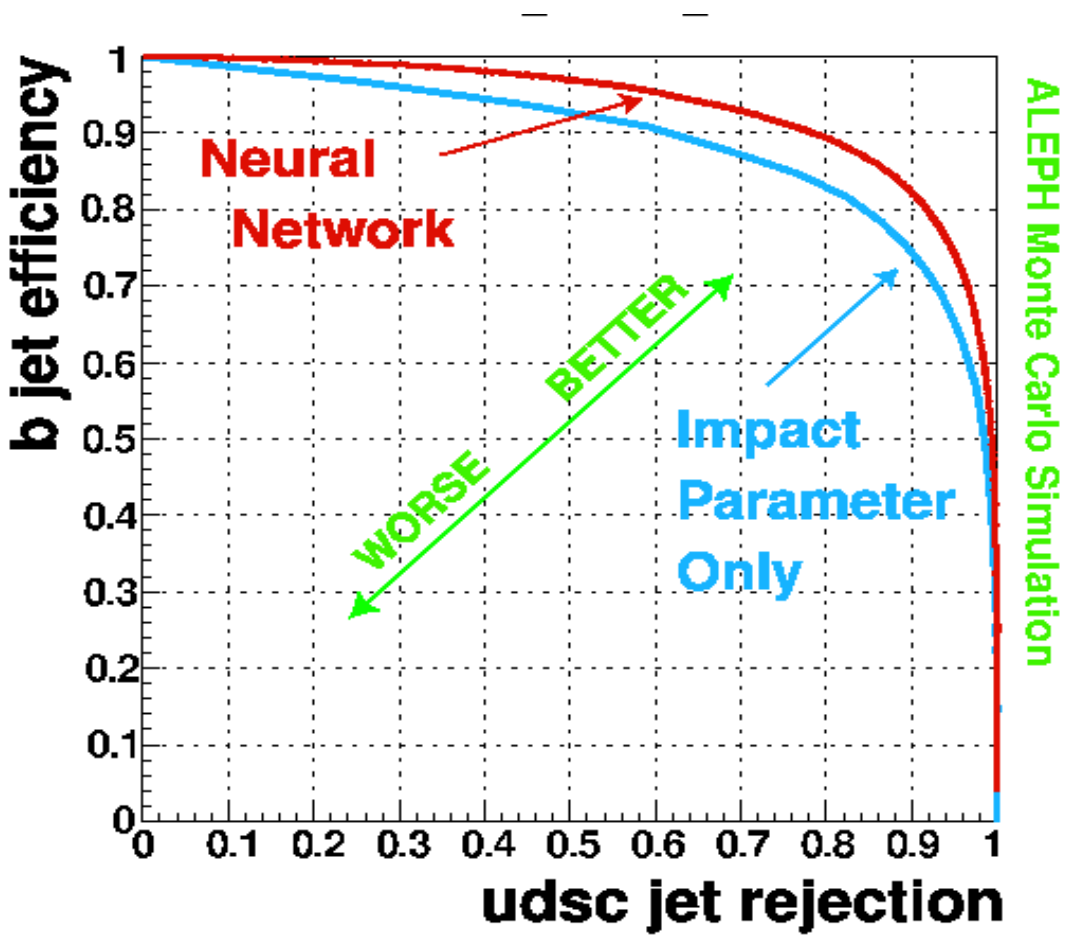
Detector Configuration	Single Tag ϵ (%)	Double Tag ϵ (%)
SVX' + CTC	37.6$\pm$1.0	6.9$\pm$0.5
SVX II + COT	46.7$\pm$1.1	8.7$\pm$0.6
SVX II + COT+ISL	60.1$\pm$1.0	15.1$\pm$0.8

- Taken from CDF Technical Design Report, MC parametric study

- Used displaced vertex b-tagger

- Can we do better? Neural nets

Neural Nets At LEP - Success Story



at 90% rejection, neural network has

≈ 8% better b-jet efficiency

Mass Resolution Corrections

- Dorigo et. al. had a muon and neutrino in every event

$\Rightarrow$ Corrected for jet p_T using muon p_T

- SVT has more than semileptonic decays

$\Rightarrow$ Goal should be to come up with jet corrections for b-jets without semileptonic decays as good as those with semileptonic decays.

What Is The Effect of These Three Improvements?

- Significance of signal increases
- Lower errors on Jet Energy Scale
- Discovery Potential

Significance Increase In Run II

- Purity will not change, significance will
- Know $N_{events} = \epsilon_{tag}\epsilon_{trig}\sigma \int dt\mathcal{L}$
- Significance is

$$\mathcal{S} = \frac{S}{\sqrt{S+B}} = \sqrt{\epsilon_{tag}\epsilon_{trig}\int dt\mathcal{L}}\frac{\sigma_S}{\sqrt{\sigma_S+\sigma_B}}$$

- Run I
  - $\epsilon_{tag} = 7\%$ (from SECVTX)
  - $\epsilon_{trig} \sim 2\%$ (from soft lepton trigger)
  - $\int dt\mathcal{L} = 100\ pb^{-1}$.
  - Dorigo measured:

$$\begin{aligned} \mathcal{S}_{\mathrm{I}} = 3.3 &= \sqrt{0.07 \cdot 0.02 \cdot 100}\frac{\sigma_S}{\sqrt{\sigma_S+\sigma_B}} \\ \Rightarrow \frac{\sigma_S}{\sqrt{\sigma_S+\sigma_B}} &= 8.9\ pb^{-\frac{1}{2}} \end{aligned}$$

  - 8.9 pb$^{-\frac{1}{2}}$ is the significance per pb^{-1} for a perfect detector

Significance Increase In Run II

- Run II
  - Assume σ's are the same (slightly changed $\sqrt{s}$)
  - Same mass resolution as Dorigo's jet corrections.
  - $\epsilon_{tag} = 15\%$ (from enhanced coverage of silicon)
  - $\epsilon_{trig} \sim 20\%$ (from J/ψ study)
  - $\int dt\mathcal{L} = 2\ fb^{-1} = 2000\ pb^{-1}$

$$\begin{aligned} \mathcal{S}_{\rm II} &= (8.9)\sqrt{0.15 \cdot 0.20}\sqrt{2000\ pb^{-1}} \\ &= 68.9 \end{aligned}$$

- If we do 8% better with a neural net,

$$\begin{aligned} \mathcal{S}_{\rm II} &= (8.9)\sqrt{0.17 \cdot 0.2}\sqrt{2000\ pb^{-1}} \\ &= 74.2 \end{aligned}$$

Run I Versus Run II

Quantity	Run I	Run II
ϵ_{tag} (%)	7	15 (17)
ϵ_{trig} (%)	10	20
$\int dt\mathcal{L}$ (pb^{-1}	100	2000
Significance	3.3	30 (33)

Using This: Jet Energy Scale Errors

- To get jet energy scale errors from mass errors:

$$\begin{aligned} E^2 &= m^2 + p^2 \\ \frac{\Delta E}{E} &= \frac{\Delta m}{m(1+\frac{p^2}{m^2})} \approx \frac{\Delta m}{m} \end{aligned}$$

- Run I (100 pb^{-1}):
  - Measured $N_Z = 91 \pm 30 \pm 19$, with dijet mass error $\frac{\delta m_{jj}}{m_{jj}} = 2.4\%$

$\Rightarrow$ Jet energy scale error is 2.4%

- Run II (2000 pb^{-1}):
  - Using MC simulation of signal after cuts, expect $N_{signal} \approx 4000$, so estimate for Run II is:

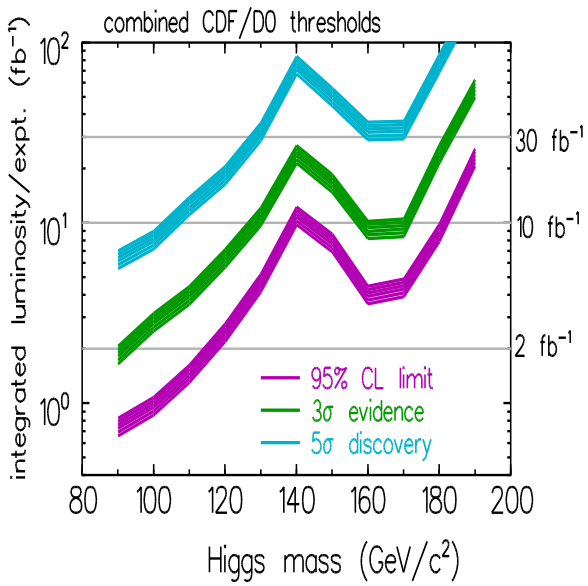
$$\frac{\delta m_{\mathrm{II}}}{m} = \frac{\sigma_{jj}}{\sqrt{N}} \frac{1}{m_Z} = \frac{14}{\sqrt{4000}} \frac{1}{90} \approx 0.2\% \ (stat)$$

$\Rightarrow$ Systematically dominated in Run II (background parameterization and neglecting signal in bg region)

  - Monte Carlo study shows $\frac{\delta m_{jj}}{m_{jj}} \approx 1.7\%$ (syst)

$\Rightarrow$ Jet energy scale error is 1.7%, systematically dominated (must get systematics down!)

Discovery Potential



- Assumed dijet mass resolution for SUSY-Higgs workshop study was 15%

- Dorigo obtained 15% mass resolution

- Can expect to exclude Higgs masses up to about $120\ GeV$

Conclusions

- Will increase significance of $Z \to b\bar{b}$ tenfold

- Will measure b-jet energy scale for better top quark mass measurement

- Will maximize discovery potential in $b\bar{b}$ channels

- Crucial steps for Run II:

  1. Find new jet corrections since those that Dorigo applied were only for semileptonic decays

  2. Cut down systematics on background normalization procedure

  3. Maximize b-tagging capabilities as much as possible