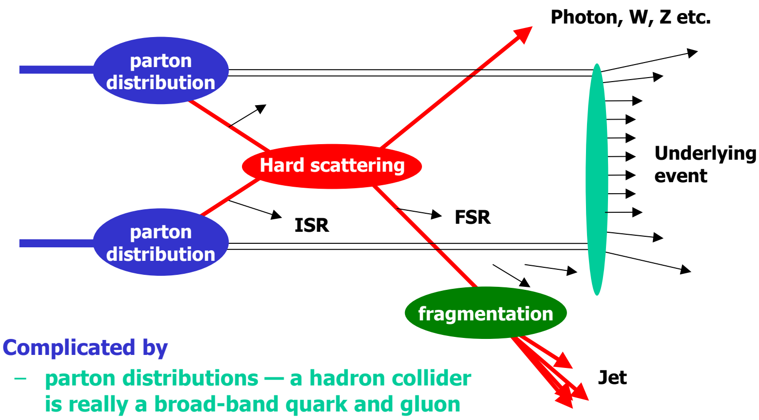
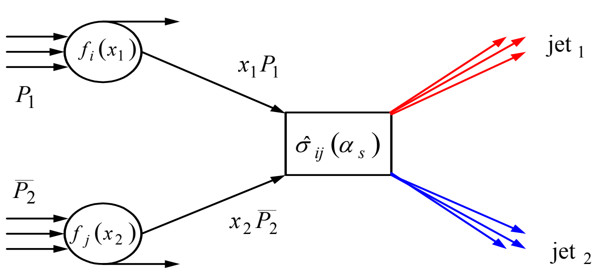
Hadron-hadron collisions



- Complicated by
  - parton distributions — a hadron collider is really a broad-band quark and gluon collider
  - both the initial and final states can be colored and can radiate gluons
  - underlying event from proton remnants



$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i\left(x_1, \mu_F^2\right) f_j\left(x_2, \mu_F^2\right) \hat{\sigma}_{ij}\left(\alpha_s^m\left(\mu_R^2\right), x_1 P_1, x_2 P_2, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

Sum over initial states

Parton Distributions

Factorization Scale

Point Cross Section

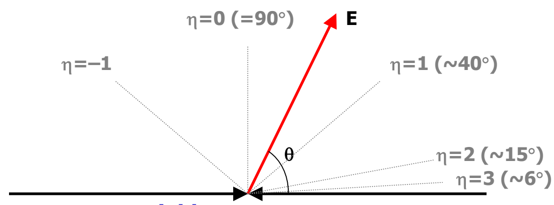
Order α_s^m

Renormalization Scale

John Womersley

Hadron Collider variables

- The incoming parton momenta x_1 and x_2 are unknown, and usually the beam particle remnants escape down the beam pipe
  - longitudinal motion of the centre of mass cannot be reconstructed



- Focus on transverse variables
  - Transverse Energy $E_T = E \sin\theta$ (= p_T if mass = 0)
- and longitudinally boost-invariant quantities
  - Pseudorapidity $\eta = -\log(\tan\theta/2)$ (= rapidity y if mass = 0)
  - particle production typically scales per unit rapidity

John Womersley

Quantum Chromodynamics

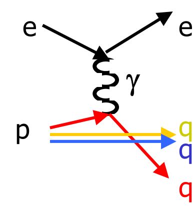
- Gauge theory (like electromagnetism) describing fermions (quarks) which carry an SU(3) charge (color) and interact through the exchange of vector bosons (gluons)
- Interesting features:
  - gluons are themselves colored
  - interactions are strong
  - coupling constant runs rapidly
    - becomes weak at momentum transfers above a few GeV

$$\alpha_s(q^2) = \frac{12\pi}{(33 - 2n_f)\ln q^2/\Lambda^2}$$

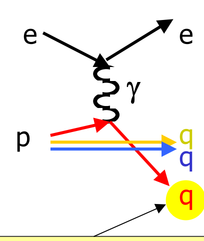
John Womersley

Quarks

- These features lead to a picture where quarks and gluons are bound inside hadrons if left to themselves, but behave like "free" particles if probed at high momentum transfer
  - this is exactly what was seen in deep inelastic scattering experiments at SLAC in the late 1960's which led to the genesis of QCD
  - electron beam scattered off nucleons in a target
    - electron scattered from pointlike constituents inside the nucleon
    - ~ $1/\sin^4(\theta/2)$ behavior like Rutherford scattering
    - other (spectator) quarks do not participate



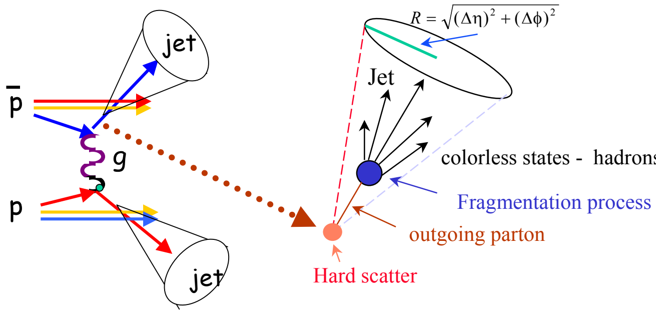
Fragmentation



So what happens to this quark that was knocked out of the proton?

- α_s is large
  - lots of gluon radiation and pair production of quarks in the color field between the outgoing quark and the colored remnant of the nucleon
- these quarks and gluons produced in the "wake" of the outgoing quark recombine to form a "spray" of roughly collinear, colorless hadrons: a jet
  - "fragmentation" or "hadronization"

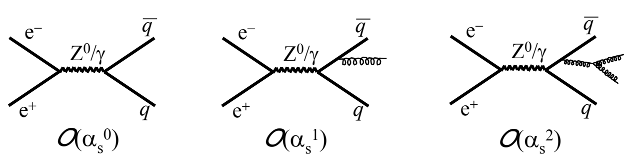
What are jets?



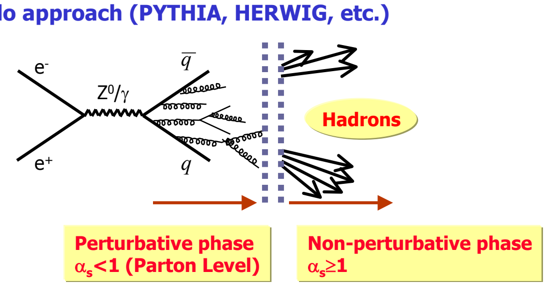
- **The hadrons in a jet have small transverse momentum relative to the parent parton's direction and the sum of their longitudinal momenta is roughly the parent parton momentum**
- **Jets are the experimental signatures of quarks and gluons and manifest themselves as localized clusters of energy**

e^+e^- annihilation

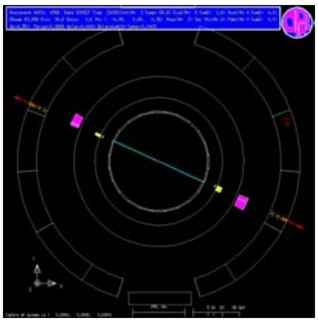
- **Fixed order QCD calculation of $e^+e^- \rightarrow (Z^0/\gamma)^* \rightarrow$ hadrons :**



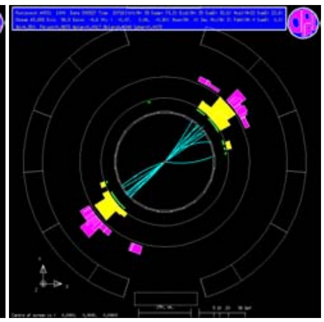
- **Monte Carlo approach (PYTHIA, HERWIG, etc.)**



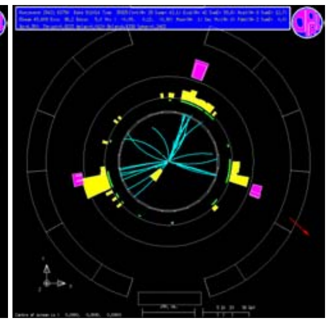
$e^+e^- \rightarrow \mu^+\mu^-$



$e^+e^- \rightarrow \bar{q}q$



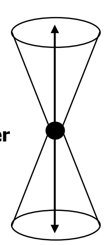
$e^+e^- \rightarrow \bar{q}qg$

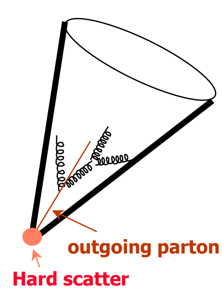


Jet Algorithms

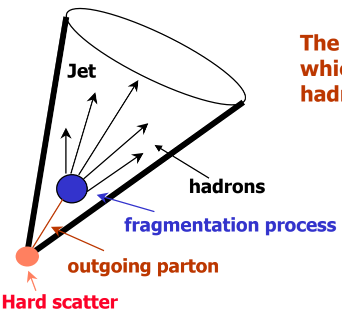
- **The goal is to be able to apply the "same" jet clustering algorithm to data and theoretical calculations without ambiguities.**
- **Jets at the "Parton Level"**
  - **i.e., before hadronization**
  - **Fixed order QCD or (Next-to-) leading logarithmic summations to all orders**

Leading Order



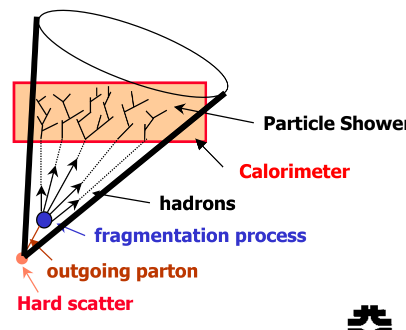


- Jets at the particle (hadron) level



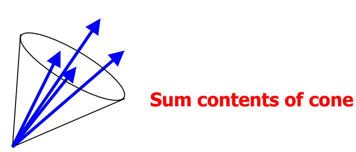
The idea is to come up with a jet algorithm which minimizes the non-perturbative hadronization effects

- Jets at the "detector level"

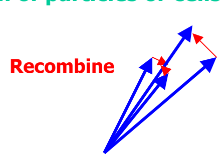


Jet Algorithms

- Traditional Choice at hadron colliders: cone algorithms
  - Jet = sum of energy within $\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$

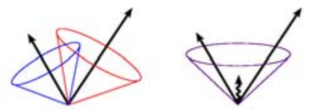


- Traditional choice in e^+e^-: successive recombination algorithms
  - Jet = sum of particles or cells close in relative k_T

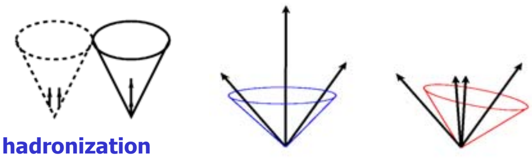


Theoretical requirements

- **Infrared safety**
  - **insensitive to "soft" radiation**



- **Collinear safety**

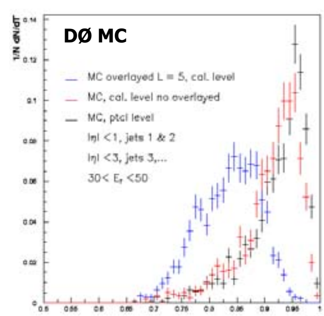


- **Low sensitivity to hadronization**
- **Invariance under boosts**
  - **Same jets solutions independent of boost**
- **Boundary stability**
  - **maximum $E_T = \sqrt{s}/2$**
- **Order independence**
  - **Same jets at parton/particle/detector levels**
- **Straightforward implementation**

Experimental requirements

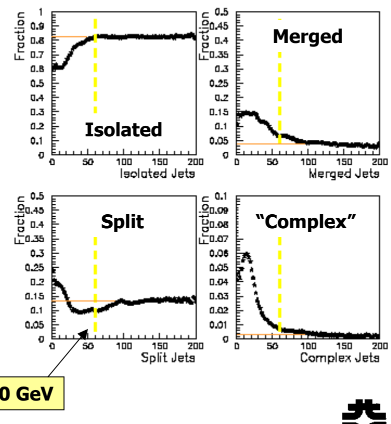
- **Detector independence**
  - **can everybody implement this?**
- **Best resolution and smallest biases in jet energy and direction**
- **Stability**
  - **as luminosity increases**
  - **insensitive to noise, pileup and small negative energies**
- **Computational efficiency**
- **Maximal reconstruction efficiency**
- **Ease of calibration**
- **…**

Effect of pileup on Thrust
k_T algorithm jets, E_T > 30 GeV



Splitting and Merging of Cone Jets

- **Jets spread out in the calorimeter, and cannot be perfectly resolved. Some compromise is necessary**
- **Overlapping cone jets lead to ambiguous jet definitions:**
  - **which clusters belong in the jet?**
  - **do I have one or two jets?**
- **Need to define split/merge rules: e.g. DØ choices**
  - **overlapping jets are merged if they share > 50% of the lower E_T jet**
  - **otherwise they are split: each cell is assigned to the closer jet**
  - **but the process can get very involved when three or more jets overlap**



R_{sep}

- **Ad hoc parameter introduced to mock up experimental jet separation effects in NLO theoretical calculations**

Phenomenological parameter introduced to accommodate difference in NLO cone algorithm and calorimeter algorithm

Rsep = 1.3 R determined from jet merging studies in data, in essence jets within a distance of 1.3 R are merged, farther jets are split.

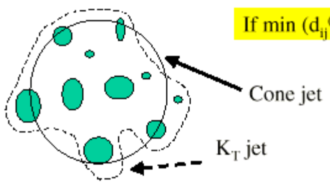
k_T algorithm

Define jets, not by geometric cones, but by more "organic" standards:

Cal. towers clustered into singles: $d_i^{(n)} = E_{Ti}^2$

pairs: $d_{ij}^{(n)} = \min(E_{Ti}^2, E_{Tj}^2) \times \Delta R_{ij}^2 / D$

If $\min(d_{ij}^{(n)}, d_i^{(n)}) = d_{ij}^{(n)}$ merge clusters, else keep separate



Repeat iterations until only separate objects remain

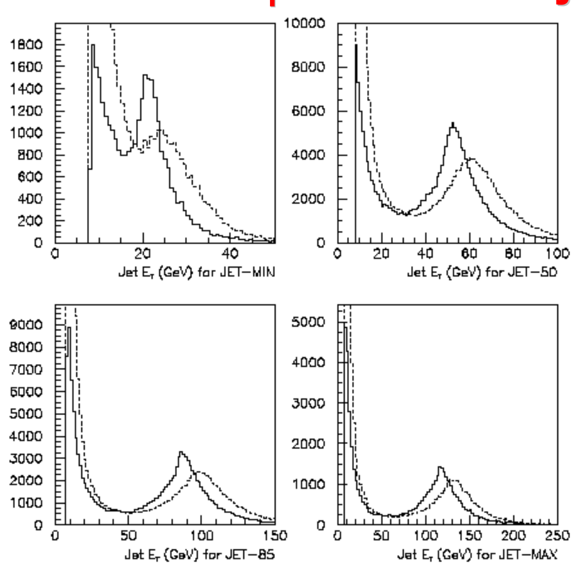
$E_T < f \times E_T^{max}$ - 'f' cut to drop low E_T/beam jets

Conceptually:
- All clusters w/in radius, D, are merged (like cone algorithm)
- Clusters >>D can be merged if ΔE_T>>0

Shapes are more natural
- no arbitrary spl/mer param @ calorim.
- no Rsep param @ parton level

same algorithm @ all levels

Does k_T find the same jets?



Cone jets (solid)

K_T jets (dashed)

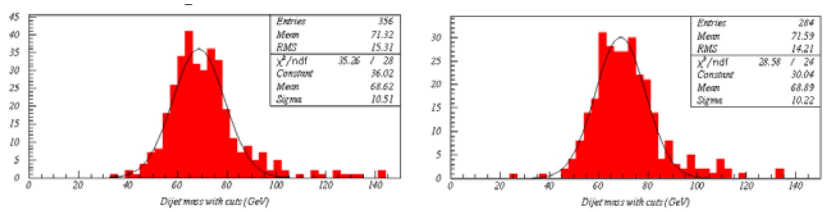
'seedless' K_T algorithm finds many more low E_T jets

scale difference from 0.7 cone jets even at large E_T

k_T vs. cone jets

- It has been suggested that k_T would give improved invariant mass reconstruction for $X \rightarrow$ multijet states
- Not clear that this is true in practice:
  - 1000 $Z \rightarrow \bar{b}b$ events from DØ GEANT simulation reconstructed with C++ offline clustering and jet reconstruction

R=0.7 cone jet-finder **k_T jet-finder**



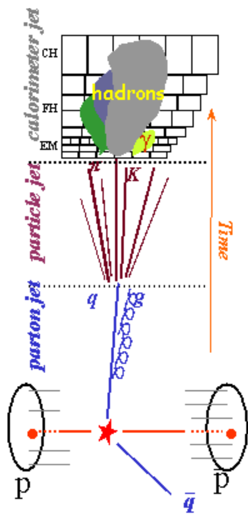
Invariant mass of leading two jets (E_T > 20, $|\eta|<2$)
Jet response corrections included

Jet Energy Calibration

1. Establish calorimeter stability and uniformity
   - pulsers, light sources
   - azimuthal symmetry of energy flow in collisions
   - muons
2. Establish the overall energy scale of the calorimeter
   - Testbeam data
   - Set E/p = 1 for isolated tracks
     - momentum measured using central tracker
   - EM resonances ($\pi^0 \rightarrow \gamma\gamma$, J/ψ, Υ and $Z \rightarrow e^+e^-$)
     - adjust calibration to obtain the known mass
3. Relate EM energy scale to jet energy scale
   - Monte Carlo modelling of jet fragmentation + testbeam hadrons
     - CDF
   - E_T balance in jet + photon events
     - DØ

Cone Jet Energy Scale

NIM A424 352-392 (1999) (hep-ex/9805009)



Calorimeter jet

↓

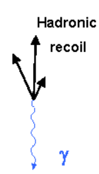
Particle jet

$$E^{ptcl}_{jet} = \frac{E^{meas}_{jet} - O}{R_{jet}\ S_{cone}}$$

- **Offset (O):** Ur noise, pileup, underlying event (ue)
- **Response (Rjet):** E_{meas} / E_{true} (using transverse energy balance in γ-jet events)
- **Showering ($1/S_{cone}$):** out-of-cone showering loss

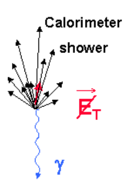
John Womersley

Response Correction



Use p_T balance in γ + jet events

- photon calibrated using $Z \to e^+e^-$ events
- assume missing p_T component parallel to jet is due to jet miscalibration

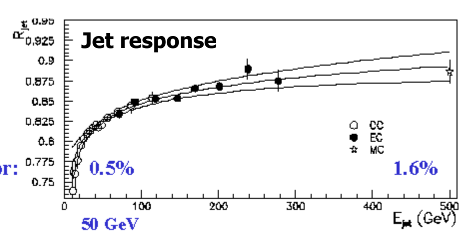


Missing E_T: $\vec{\not{E}}_T = -\sum_{i=1}^{n} \vec{P}_{Ti}$

due to hadronic response < 1

$$R_{had} = 1 + \frac{\vec{\not{E}}_T \cdot \hat{n}_\gamma}{E_{T\gamma}} = 1 + MPF$$

Fit error:

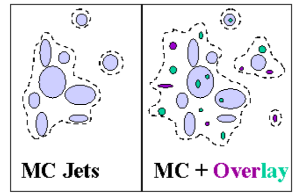


0.5% (50 GeV) 1.6% (450 GeV)

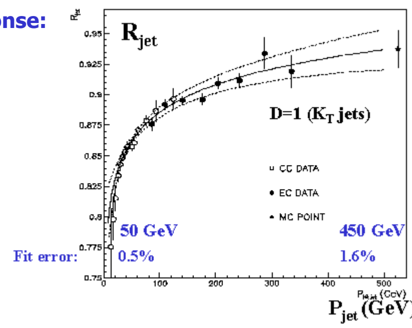
John Womersley

k_T jet energy scale

- **Similar procedure, but:**
  - no out-of-cone showering losses
  - can't just use energy in a cone for the underlying event and noise, so derive this correction from Monte Carlo jets with overlaid crossings

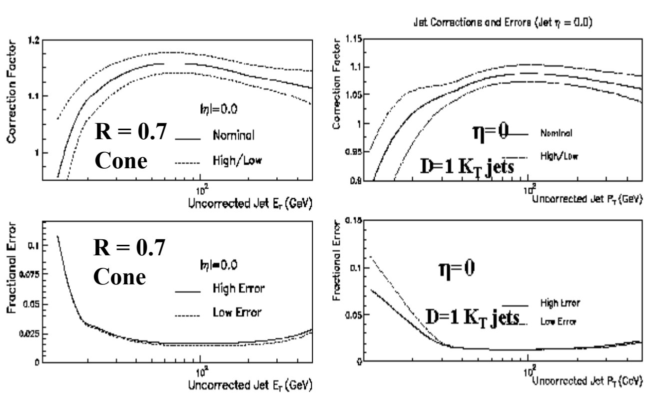


- **Response:**



John Womersley

Overall Energy scale correction



E_T (GeV)	CorrFac
R=0.7 cone jets	
20	1.08 ± 0.030
100	1.15 ± 0.017
450	1.12 ± 0.025

E_T (GeV)	CorrFac
D=1 K_T jets	
30	1.05 ± 0.022
100	1.09 ± 0.015
450	1.06 ± 0.023

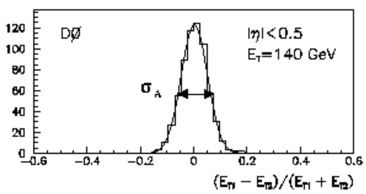
John Womersley

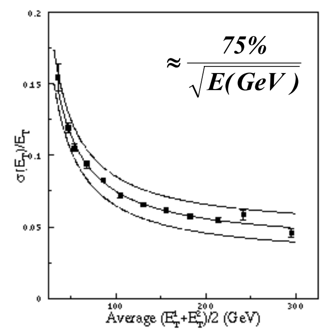
Jet Resolutions

- Determined from collider data using dijet E_T balance

$$A = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \Rightarrow \frac{\sigma_{ET}}{E_T} = \sqrt{2}\sigma_A$$

In the limit of no soft radiation



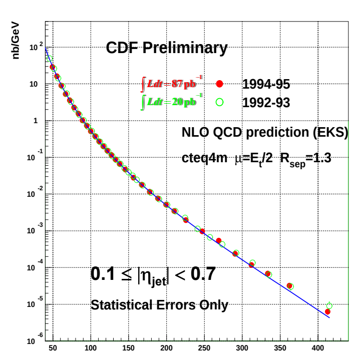


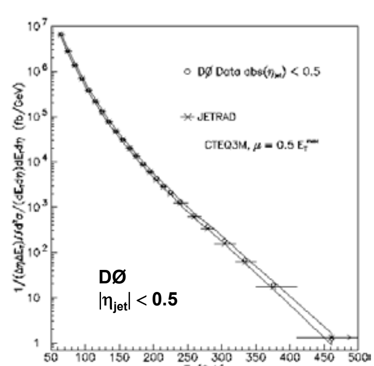
ET :	50 GeV	100 GeV	450 GeV
σ_{ET} /ET:	0.105	0.075	0.035

Jet cross sections at √s = 1.8 TeV

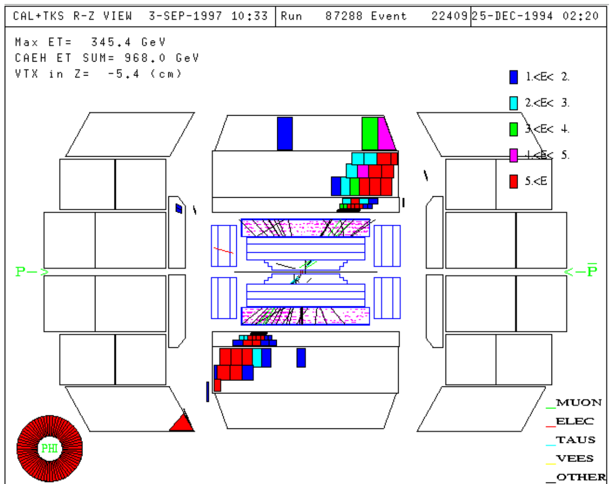
R = 0.7 cone jets

- Cross section falls by seven orders of magnitude from 50 to 450 GeV
- Pretty good agreement with NLO QCD over the whole range





Highest E_T jet event in DØ

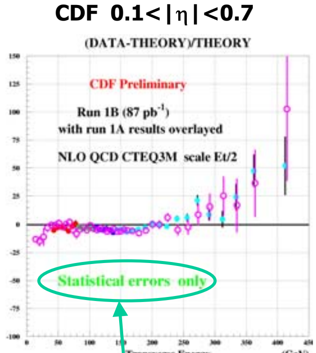


E_{T1} = 475 GeV, η_1 = -0.69, x_1=0.66
E_{T2} = 472 GeV, η_2 = 0.69, x_2=0.66

M_{JJ} = 1.2 TeV
$Q^2 = 2.2\text{x}10^5$ GeV^2

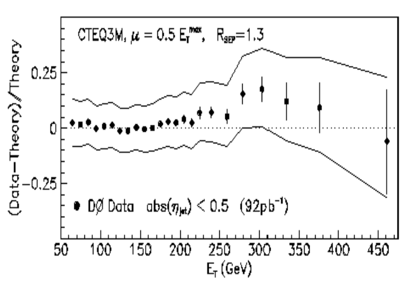
What's happening at high E_T?

CDF 0.1<|η|<0.7



NB Systematic errors not plotted

DØ |η|<0.5

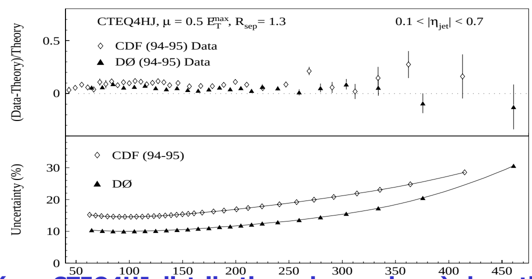


- So much has been said about the high-E_T behaviour of the cross section that it is hard to know what can usefully be added:

Figure 1: *"The horse is dead"*

The DØ and CDF data agree

- **DØ analyzed 0.1 < | η | < 0.7 to compare with CDF**
  - **Blazey and Flaugher, hep-ex/9903058 Ann. Rev. article**



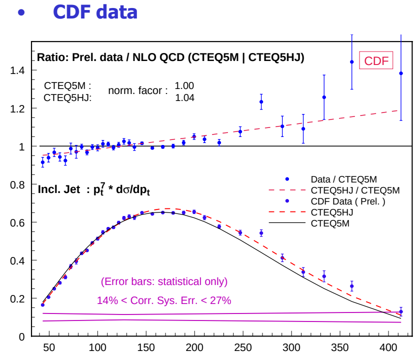
- **Studies (e.g. CTEQ4HJ distributions shown above) show that one can boost the gluon distribution at high-x without violating experimental constraints*; results are more compatible with CDF data points**

  *except maybe fixed-target photons, which require big k_T corrections before they can be made to agree with QCD (see later)

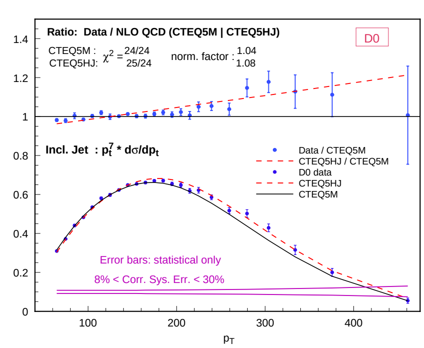
John Womersley

Jet data with latest CTEQ5 PDF's

- **CDF data**



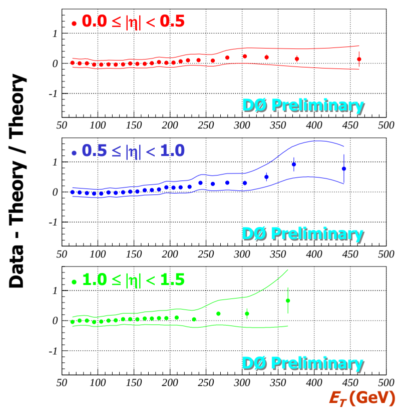
- **DØ data**

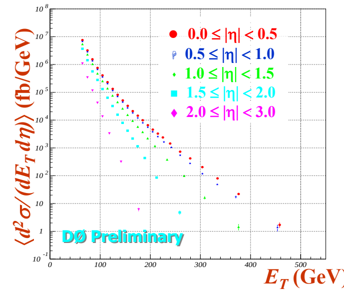


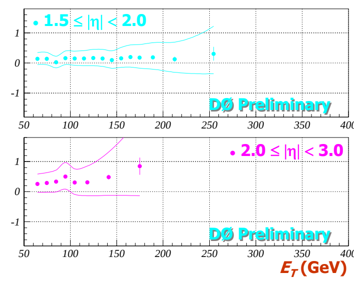
John Womersley

Forward Jets

- DØ inclusive cross sections up to |η| = 3.0
- Comparison with JETRAD using CTEQ3M, $\mu = E_T^{max}/2$

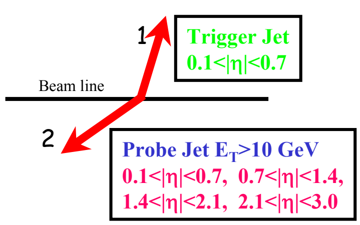




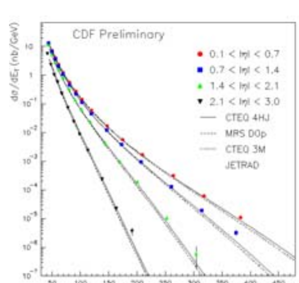


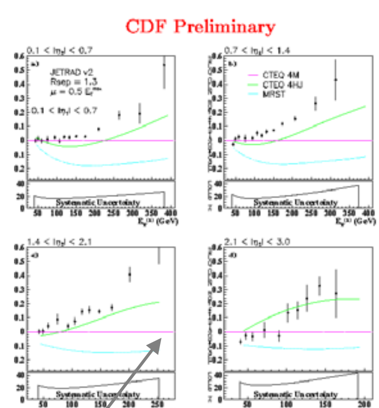
John Womersley

Triple differential dijet cross section $\frac{d^3\sigma}{dE_1^T d\eta_1 d\eta_2}$



Can be used to extract or constrain PDF's

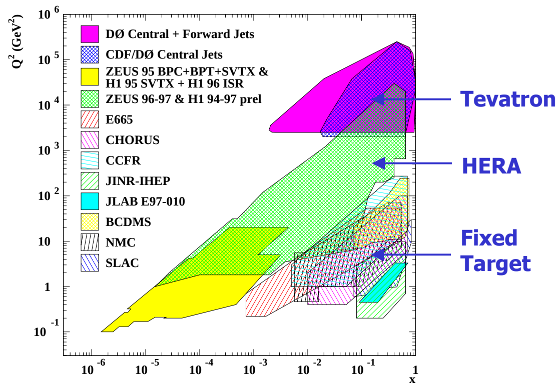




At high E_T, the same behaviour as the inclusive cross section, presumably because largely the same events

John Womersley

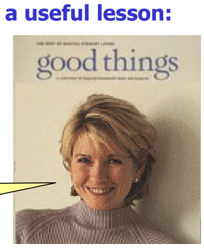
Tevatron jet data can constrain PDF's



- **For dijets:** $$x_{1(2)} = \sum_{i=1}^{2} +(-)\frac{E_{T,i}}{\sqrt{s}} exp(\eta_i) \quad and \quad Q^2 = E_{T,1}E_{T,2}$$

What have we learned from all this?

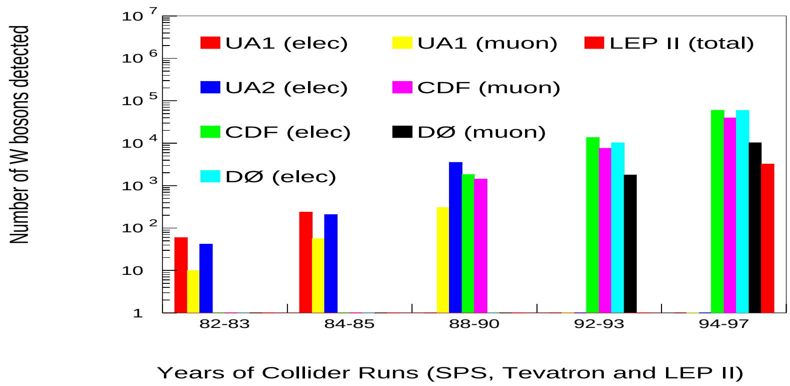
- **Whether nature has actually exploited the "freedom" to enhance gluon distributions at large x will only be clear with the addition of more data**
  - **with 2fb^{-1} the reach in E_T will increase by ~70 GeV and should make the asymptotic behaviour clearer**
- **whatever the Run II data show, this has been a useful lesson:**
  - **parton distributions have uncertainties, whether made explicit or not**
  - **we should aim for a full understanding of experimental systematics and their correlations**



It's a good thing

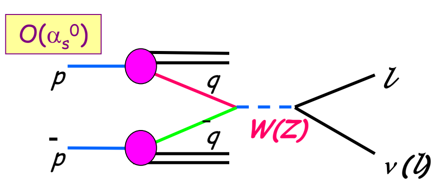
- **We can then use the jet data to reduce these uncertainties on the parton distributions**

W samples



John Womersley

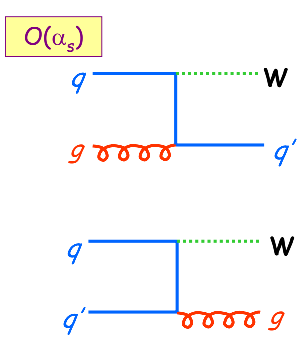
W and Z production at hadron colliders



Production dominated by $\bar{q}q$ annihilation (~60% valence-sea, ~20% sea-sea)

Due to very large pp → jj production, need to use leptonic decays

BR ~ 11% (W), ~3% (Z) per mode



Higher order QCD corrections:

- **Boson produced with mean p_T ~ 10 GeV**
- **Boson + jet events (W+jet ~ 7%, E_T^{jet} > 25 GeV)**
- **Inclusive cross sections larger**
- **Boson decay angular distribution modified**

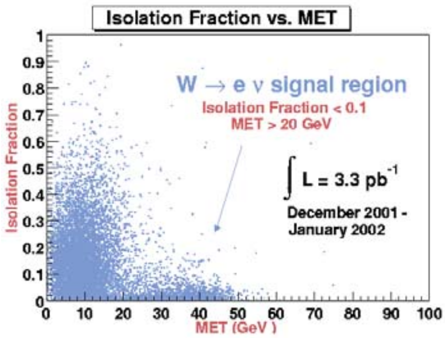
Benefits of studying QCD with W&Z Bosons:

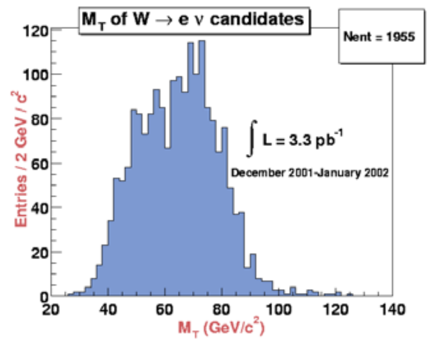
- **Distinctive event signatures**
- **Low backgrounds**
- **Large Q^2 (Q^2 ~ $Mass^2$ ~ 6500 GeV^2)**
- **Well understood Electroweak Vertex**

John Womersley

W identification

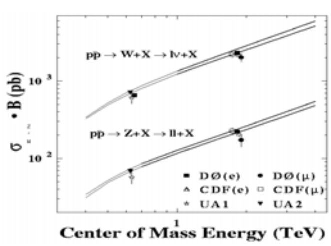
- **Isolated lepton + missing E_T**



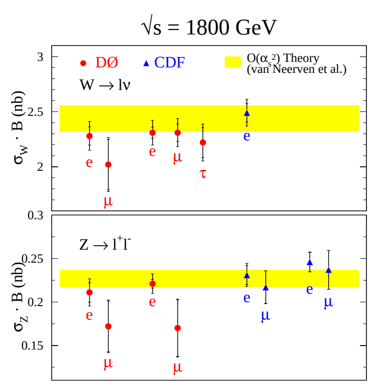


$$\textit{Transverse mass} \quad m_T = \sqrt{2p_T(e)p_T(\nu)(1 - \cos\Delta\phi)}$$

Cross section measurements



- **Test $O(\alpha^2)$ QCD predictions for W/Z production**
  - $\sigma(p\bar{p} \to W + X)\ B(W \to \lambda\nu)$
  - $\sigma(p\bar{p} \to Z + X)\ B(Z \to \lambda\lambda)$
- **QCD in excellent agreement with data**
  - so much so that it has been seriously suggested to use σ_W as the absolute luminosity normalization in future



Note: CDF luminosity normalization is 6.2% higher than DØ (divide CDF cross sections by 1.062 to compare with DØ)

W mass measurement

- One of the major goals of the Tevatron program: together with m_t, provides strong constraints on the SM and m_H
- Simplest method:
  - fit transverse mass distribution
- Recent method:
  - also fit p_T(lepton) and missing E_T and combine the three
- It's all in the systematics
  - must constantly fight to keep beating them down as the statistical power of the data demands more precision
  - Use the Z to constrain many effects
    - Energy scale
    - p_T distribution
    - etc etc.

- DO 1999 measurement

TABLE II. Uncertainties in the combined m_T, $p_T(e)$, and $p_T(\nu)$ W boson mass measurement in MeV, for the forward sample (first column), and the combined central and forward 1994–1995 sample (second column).

Source	Forward	Forward + Central
W boson statistics	108	61
Z boson statistics	181	59
Calorimeter linearity	52	25
Calorimeter uniformity	⋯	8
Electron resolution	42	19
Electron angle calibration	20	10
Recoil response	17	25
Recoil resolution	42	25
Electron removal	4	12
Trigger and selection bias	5	3
Backgrounds	20	9
Parton distribution functions	17	7
Parton luminosity	2	4
$p_T(W)$ spectrum	25	15
W boson width	10	10
Radiative decays	1	12

95 MeV total

- Summer 2002 m_W measurements:
  - Hadron colliders 80.454 (59)
  - LEP 80.450 (39)
- Anticipated
  - With 2fb^{-1}, $\Delta m_W \sim 27$ MeV per experiment
  - With 15fb^{-1}, $\Delta m_W \sim 17$ MeV per experiment

W and Z p_T

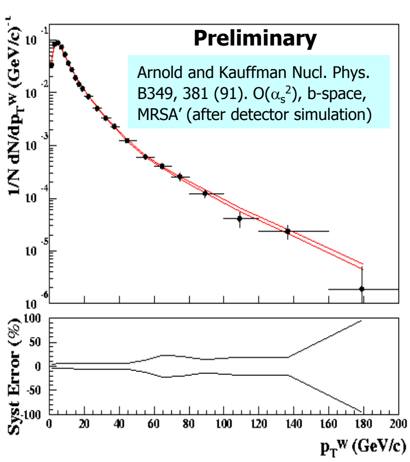
- Large p_T (> 30 GeV)
  - use pQCD, $O(\alpha_s^2)$ calculations exist

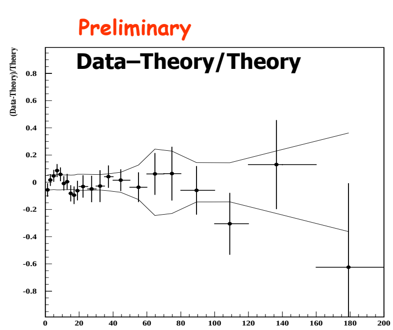
- Small p_T (< 10 GeV)
  - resum large logarithms of M_W^2/p_T^2

$$\frac{d\sigma}{dp_T^2} \sim \frac{\alpha_s}{p_T^2} \ln(\frac{M_W^2}{p_T^2}) \left[v_1 + v_2 \alpha_s \ln^2(\frac{M_W^2}{p_T^2}) \right]$$

- Match the two regions and include non-perturbative parameters extracted from data to describe $p_T \sim \Lambda_{QCD}$

DØ p_T^W measurement





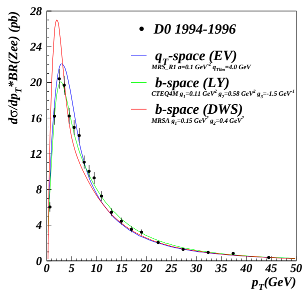
χ^2/dof=7/19 (p_T^W<120 GeV/c)

χ^2 /dof=10/21 (p_T^W<200GeV/c)

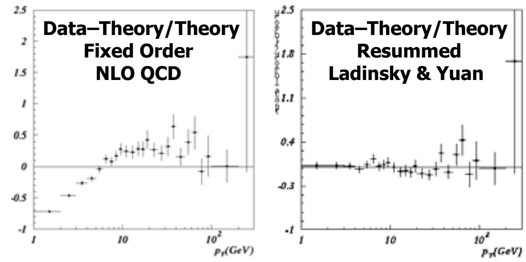
- Resolution effects dominate at low p_T
- High p_T dominated by statistics and backgrounds

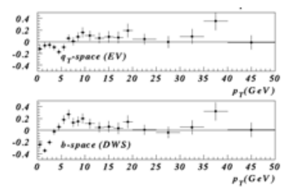
DØ p_T^Z measurement

- New DØ results hep-ex/9907009



Data





Ellis & Veseli and Davies, Webber & Stirling (Resummed)

not quite as good a description of the data

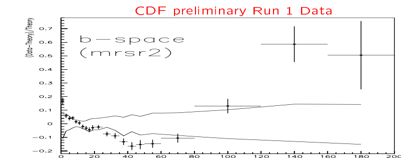
John Womersley

CDF p_T^W and p_T^Z

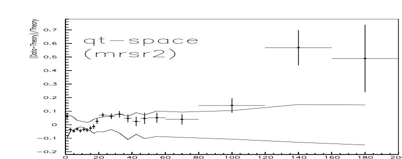
Ellis, Ross, Veseli, NP B503, 309 (97). $O(\alpha_s)$, q_T space, after detector simulation.

$\frac{(Data-Theory)}{Theory}$

CDF preliminary Run 1 Data

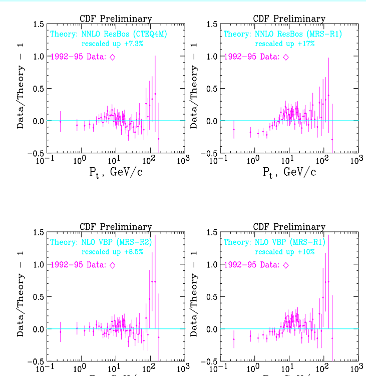


$\chi^2/d.o.f. = 1.85$ ($P_T^W < 120$ GeV/c), 2.49 (< 200 GeV/c)



$\chi^2/d.o.f. = 1.05$ ($P_T^W < 120$ GeV/c), 1.71 (< 200 GeV/c)

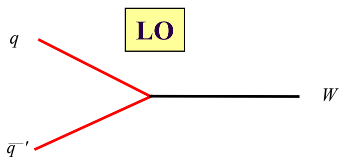
ResBos: Balasz, Yuan, PRD 56, 5558 (1997), $O(\alpha_s^2)$, b-space
VBP: Ellis, Veseli, NP B511,649 (1998), $O(\alpha_s)$, qT-space

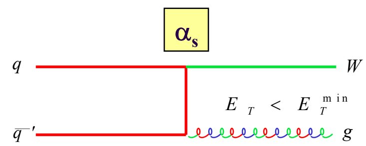


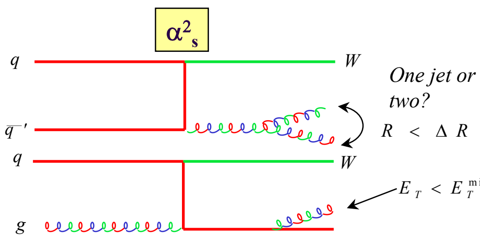
John Womersley

W + jet production

- **A test of higher order corrections:**







$$R^{10}(E_T^{min}, R) = \frac{\sigma(W+1Jet)}{\sigma(W+0Jets)}$$

$$\sigma(W+0Jets) = A_0 + \alpha_s B_0(E_T^{min})$$

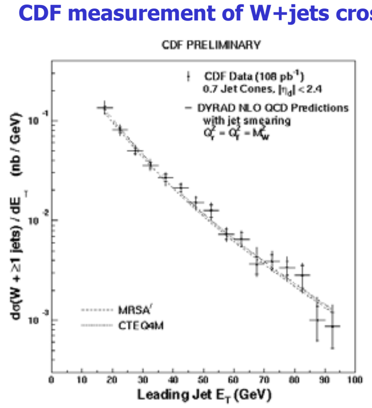
$$\sigma(W+1Jet) = \alpha_s A_1(E_T^{min}) + \alpha_s^2 B_1(E_T^{min}, R)$$

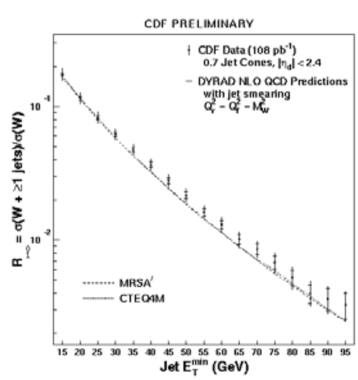
- **Calculations from DYRAD (Giele, Glover, Kosower)**

W + jet measurements

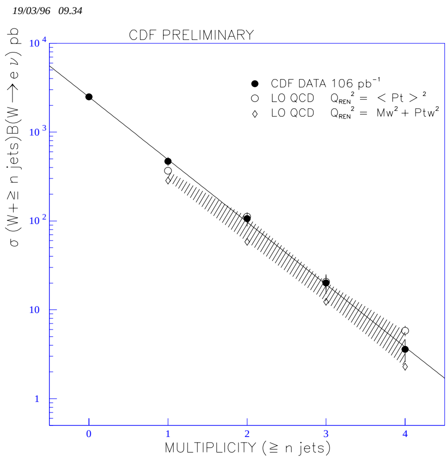
- **DØ used to show a W+1jet/W+0jet ratio badly in disagreement with QCD. This is no longer shown (the data were basically correct, but there was a bug in the DØ version of the DYRAD theory program).**

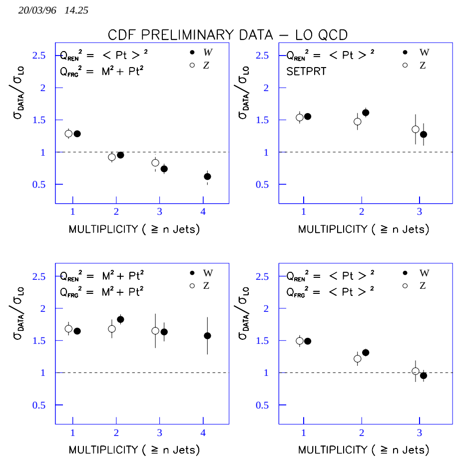
- **CDF measurement of W+jets cross section agrees well with QCD:**





CDF W/Z + n jets



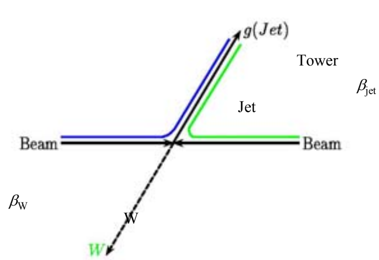


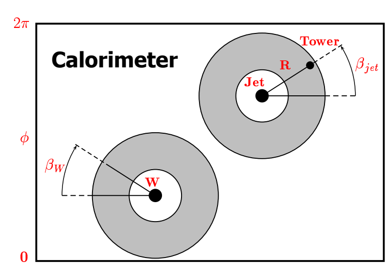
- **Data vs. tree-level predictions for various scale choices**
- **These processes are of interest as the background to top, Higgs, etc.**

John Womersley

Colour coherence in W + jet events

Compare pattern of soft particle flow around jet to that around the *W*



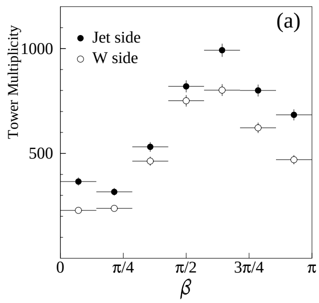


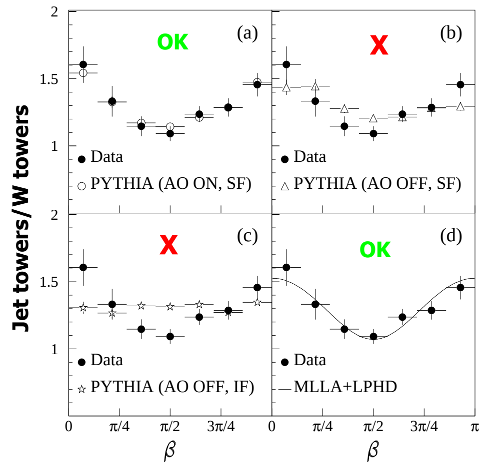
In each annular region, measure number of calorimeter towers with E_T > 250 MeV

Plot ratio of jet-side to W-side as a function of angle β (β = 0 is "near beam", β = π is "far beam")

John Womersley

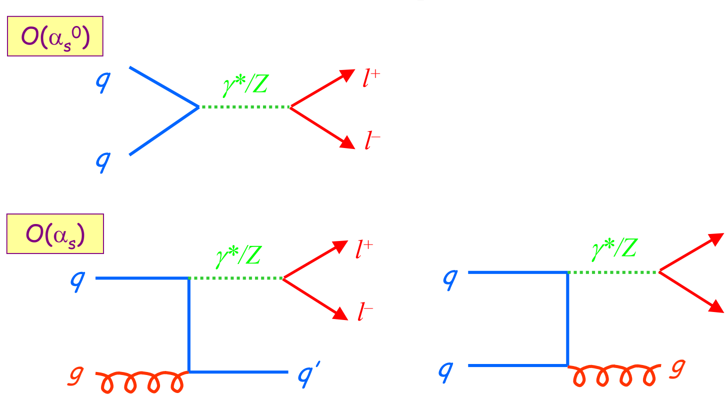
Colour coherence in W + jet events





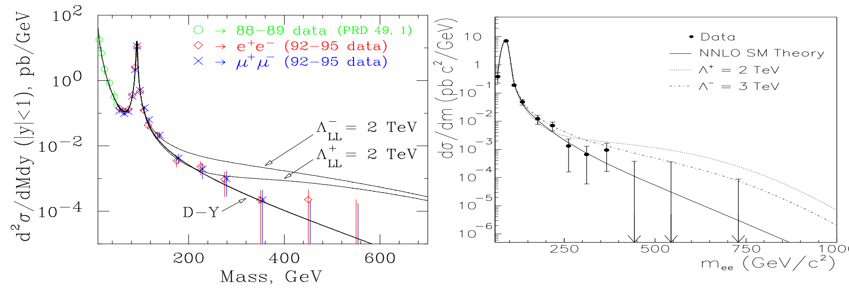
Data agree with PYTHIA and MLLA+LPHD;
Do not agree with models without coherence

Drell-Yan process



- **Measure $d\sigma/d_M$ for $\bar{p}p \rightarrow l^+l^- + X$**
- **Because leptons can be measured well, and the process is well understood, this is a sensitive test for new physics (Z′, compositeness)**

Drell-Yan data from CDF and DØ



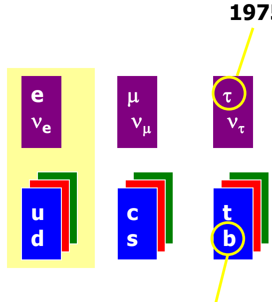
- **Compositeness limits: 3 – 6 TeV**
  Assuming quarks & leptons share common constituents
  (Limits depend on assumed form of coupling)

John Womersley

3 generations of fundamental fermions

1975, Perl et al. PRL 35, 1489 (1975)

- **leptons q = 1**
  q = 0
- **quarks q = $^2/_3$**
  q = $-^1/_3$



1977, Herb et al. PRL 39, 252 (1977)
No flavor changing neutral currents:
b must have a weak isospin partner = top

- **The top quark was discovered at Fermilab in 1995**
  (and the tau neutrino was directly observed for the first time in 2000)

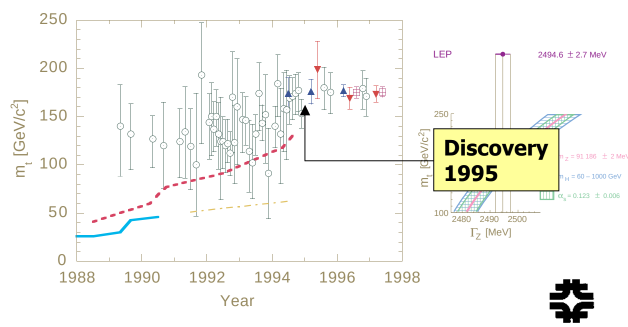
John Womersley

Searches for top

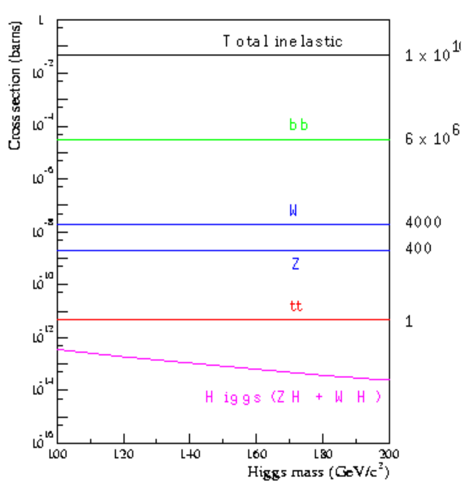
- **Direct searches**

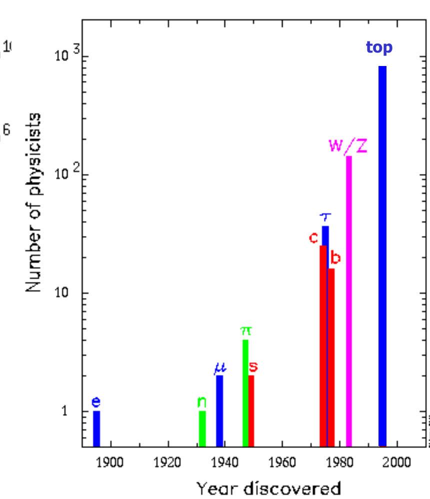
1979-84	PETRA (DESY)	e^+e^-	m_{top}>23.3 GeV
1987-90	TRISTAN (KEK)	e^+e^-	m_{top}>30.2 GeV
1989-90	SLC (SLAC) LEP (CERN)	e^+e^-	m_{top}>45.8 GeV
1990	SppS (CERN)	pp	m_{top}>69 GeV
1991	Tevatron (FNAL)	pp	m_{top}>77 GeV
1992	Tevatron (FNAL)	pp	m_{top}>91 GeV
1994	Tevatron (FNAL)	pp	m_{top}>131 GeV

- **Indirect mass determinations as a function of time**



John Womersley

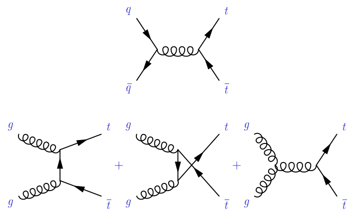




John Womersley

Top quark production

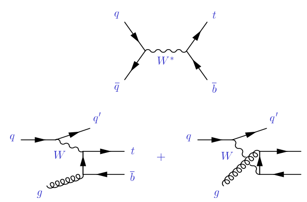
- **Top-antitop quark pair production**



$q\bar{q} \rightarrow t\bar{t}$

$gg \rightarrow t\bar{t}$

- **Single top quark production**



$q\bar{q} \rightarrow t\bar{b}$

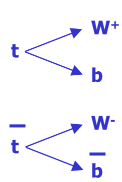
(Drell-Yan)

$qg \rightarrow q' t\bar{b}$

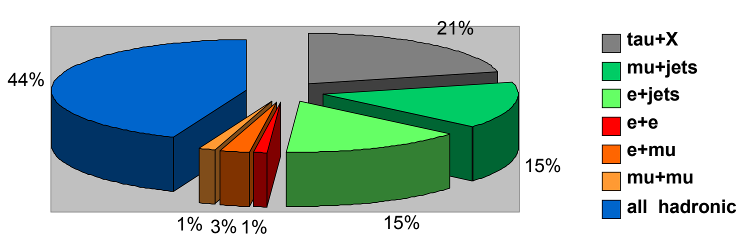
(W-gluon fusion)

Top quark decays

- **Standard Model (with $m_t > m_W + m_b$)**
  - expect $t \rightarrow Wb$ to dominate



$l^+\nu$	$q\bar{q}$	$l^+\nu$	$q\bar{q}$
b	b	b	b
$l^-\bar{\nu}$	$l^-\bar{\nu}$	$q\bar{q}$	$q\bar{q}$
$\bar{b}$	$\bar{b}$	$\bar{b}$	$\bar{b}$



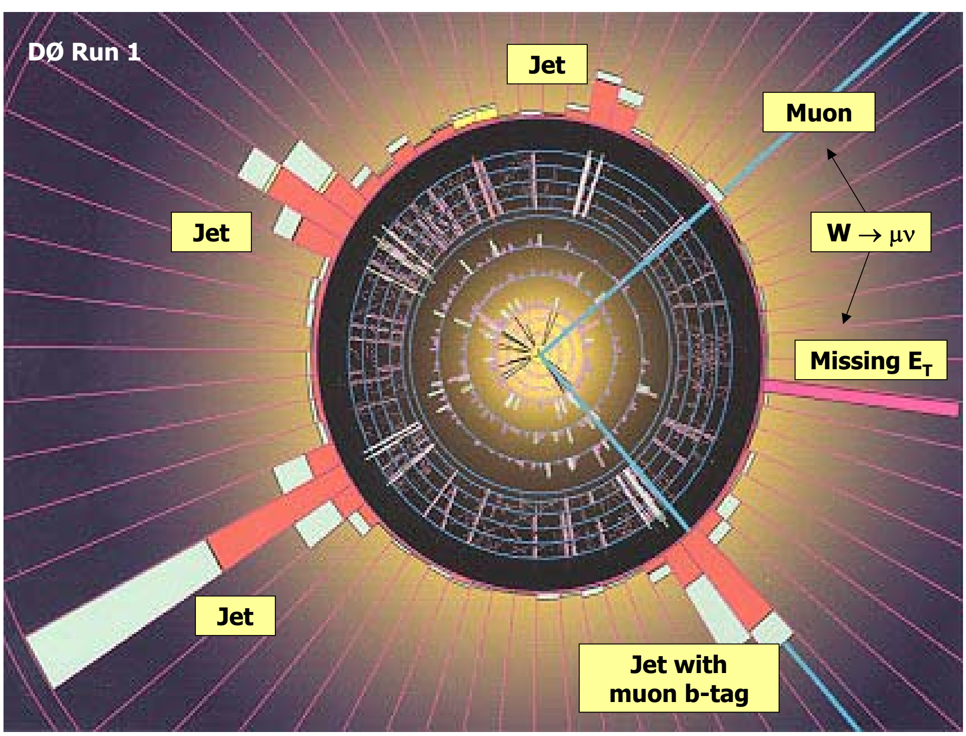
Event selection

- **Requirements:**
  - High p_T Leptons (leptonic W decay)
  - Large Missing E_T (neutrinos)
  - 3 or more Jets with large E_T
  - Jets from b-quarks
    - Soft lepton tagged b-jets (CDF, DØ)
    - Jet tagged in the SVX (CDF)
- **Run 1**
  - ~ 120 pb^{-1}= handful of $t\bar{t}$ events (~100/ experiment)
- **Run 2a : 2 fb^{-1}**

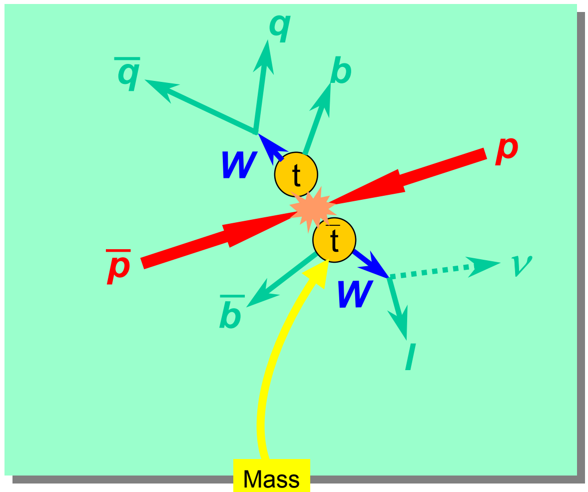
dilepton	200 events
lepton+≥4jets	1800 events
lepton+ ≥3jets/b-tag	1400 events
lepton+ ≥4jets/2 b-tags	450 events

- **Run 2b : 15 fb^{-1}**

John Womersley

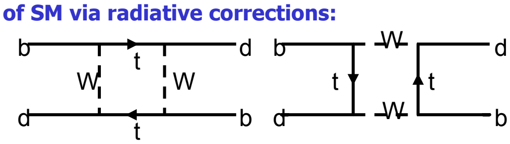


Top quark properties



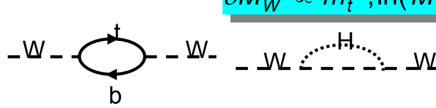
Top Quark Mass

- Fundamental parameter of Standard Model (SM)
- Affects predictions of SM via radiative corrections:
  - BB mixing



  - W and Z mass

$$\delta M_W \propto m_t^2, \ln(M_H)$$

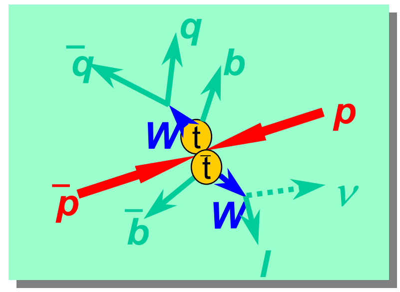


  - measurements of M_W, m_t constrain M_H
- Large mass of top quark
  - Yukawa coupling ≈ 1
  - may provide clues about electroweak symmetry breaking

Lepton + Jets Channel

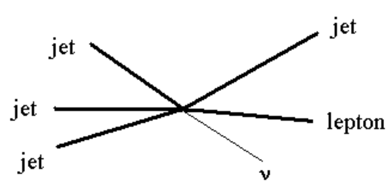
- 1 unknown (p_z^{ν})
- 3 constraints
  - $m(l\nu) = m(qq) = m_W$
  - $m(l\nu b) = m(qqb)$
- 2-constraint kinematic fit
- up to 24-fold combinatoric ambiguity
- compare to MC to measure m_t

$$t\bar{t} \to l\nu b\, q\bar{q}\bar{b}$$



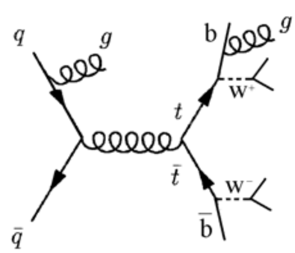
Complications

- Combinatorics:



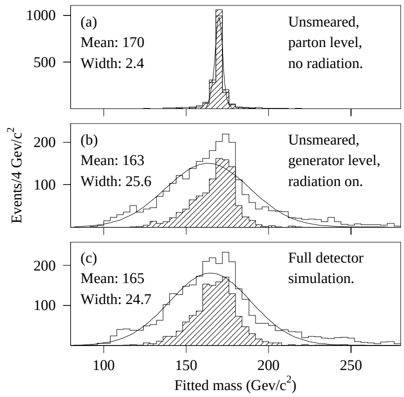
- 4 possible jlν pairings
- there are 12 possible assignments of the 4 jets to the 4 quarks (bbqq)
  - only 6 if one of the jets is b-tagged
  - only 2 for events with double b-tagged jets

- Gluon radiation can add extra jets



Combinatorics

- **Monte Carlo tests:**
  - shaded plots show correct combinations (Herwig MC, m_t = 175 GeV)



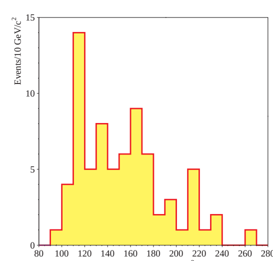
The width and shape of the fitted mass distribution is due primarily to
- jet combinatorics
- QCD radiation
  - Double b-tag helps... but, too few events in RunI

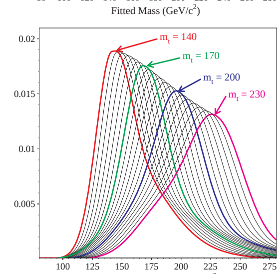
John Womersley

Basic Procedure

- **In a sample of tt candidate events**
  - For each candidate make a measurement of X = f(m_t), where X is a suitable estimator for the top mass
    - e.g. result of the kinematic fit
  - This distribution contains signal and background.

- **From MC determine shape of X as a function of m_t**
  - Determine shape of X for background (MC & data).
  - Add these together and compare with data



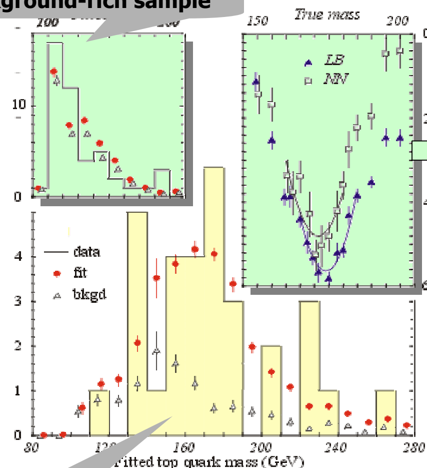


likelihood fit for m_t.

John Womersley

Lepton + Jets channel (DØ)

Background-rich sample



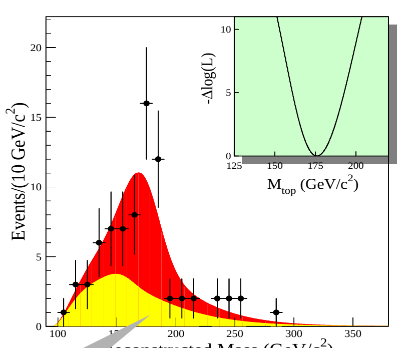
Signal-rich sample

m_t = 173.3±5.6±5.5 GeV

largest systematics	
jet energy	4.0 GeV
MC generator	3.1 GeV
noise/pile-up	1.3 GeV

dominated by
jet energy scale and
gluon radiation

Lepton + Jets channel (CDF)



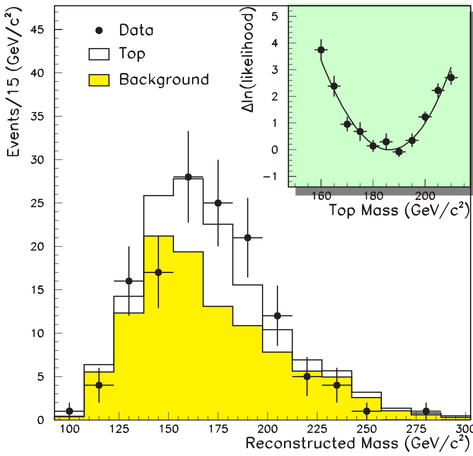
Signal-rich sample

176.1±5.1±5.3 GeV

largest systematics	
jet energy	4.4 GeV
MC generator	2.6 GeV
background	1.3 GeV

All-hadronic channel (CDF)

- Large background
- 3-constraint kinematic fit

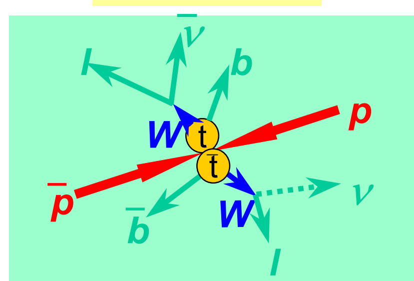


m_t = 186.0±10.0±5.7 GeV

largest systematics	
jet energy	4.4 GeV
MC generator	1.8 GeV
background	1.3 GeV

Dilepton Channel

$$t\bar{t} \to l^- \bar{\nu} b\, l^+ \nu \bar{b}$$



- dilepton channel:
  - 6 particles in the final state
  - We measure 14 quantities:
    - 2 charged leptons
    - 2jets
    - $p_x(\nu)+p_x(\nu)$
    - $p_y(\nu)+p_y(\nu)$
  - 4 unknowns
    - only Σp_T^{ν} known
  - 3 constraints

$$m(l^-\bar{\nu}) = m(l^+\nu) = m_W$$
$$m(l^-\bar{\nu}b) = m(l^+\nu\bar{b})$$

⇨ underconstrained
⇨ dynamical likelihood analysis

Dilepton channel

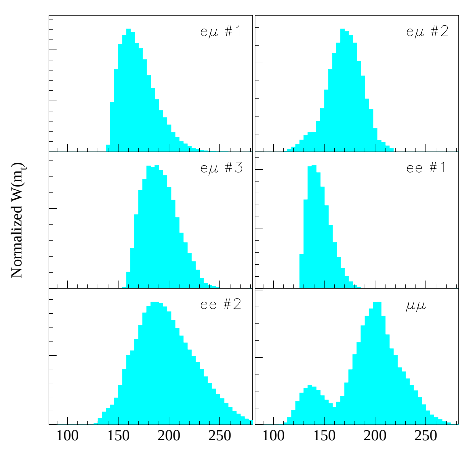
- Two different strategies …
- Find a kinematic variable with a strong mass dependence, OR, calculate a weight as a function of m_t
  - Assume m_t
    - 18 degrees of freedom,
    - 14 known quantities + 4 constraints
  - t and t momenta can be determined
  - Assign a weight
    - using parton distribution functions and lepton p_T's (an extension of ideas proposed by Kondo and Dalitz & Goldstein)
    - Characterizes how likely this event originates from a top quark of mass m_t

→ Weight curve is determined for each assumed value of m_t for a given event

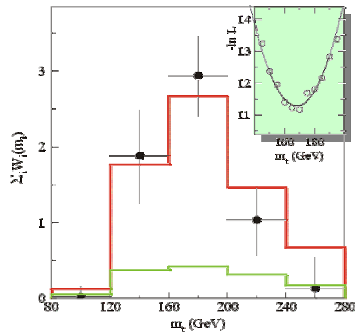
K. Kondo, J. Phys. Soc. Jpn. 57, 4126 (1988) and 60, 836 (1991).
R.H. Dalitz and G.R. Goldstein, Phys. Rev. D 51, 4763 (1995).

DØ dilepton sample weight curves

- For each event:
  - Assume a value of m_t
  - Reconstruct event
  - Calculate weight
  - Repeat for all m_t
- Combine events
- Fit the resulting distribution to MC samples as before



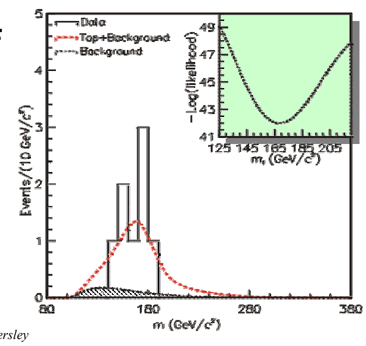
DØ



m_t =168.4±12.3±3.6 GeV

largest systematics	
jet energy	2.4 GeV
MC generator	1.8 GeV
noise/pile-up	1.3 GeV

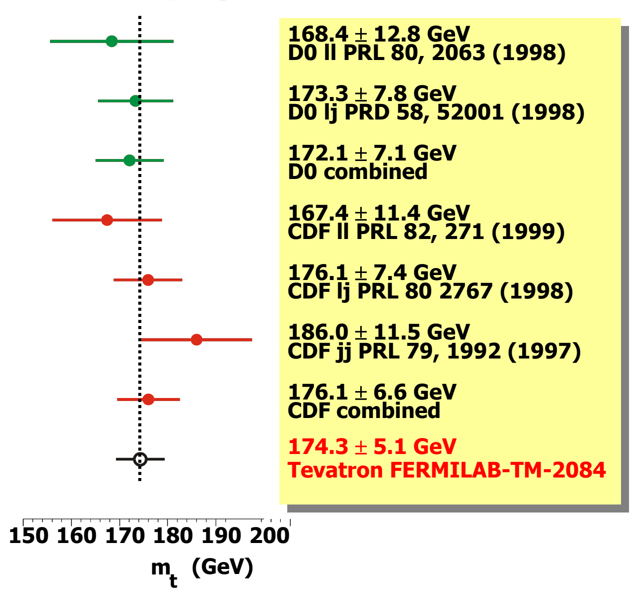
CDF



m_t = 167.4±10.3±4.8 GeV

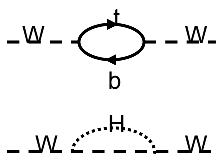
largest systematics	
jet energy	3.8 GeV
gluon radiation	2.7 GeV

Top Quark mass

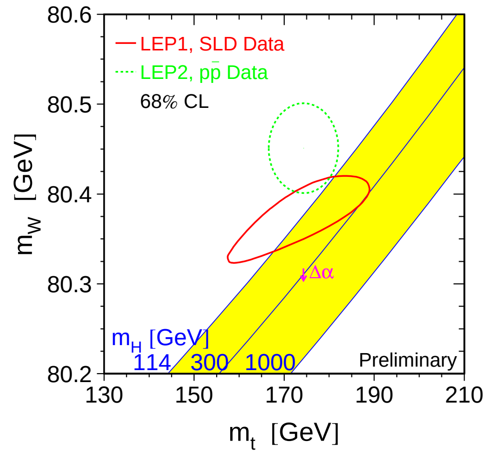


Constraints on the Higgs Mass

- m_W = 80.451±0.033 GeV (LEP EWWG, Winter 2002)



$$\delta M_W \propto m_t^2, \ln(M_H)$$



John Womersley

Mass: future prospects

- Lepton+jets channel:

	Run I (DØ)	Run IIa (2 fb^{-1})	w/ Z→bb
statistics	5.6 GeV	1.3 GeV	
jet p_T scale	4.0 GeV	2.2 GeV	0.5 GeV
MC generator	3.1 GeV	0.7 GeV	
MC model	1.6 GeV	0.4 GeV	
fit procedure	1.3 GeV	0.3 GeV	
Total syst	5.5 GeV	2.3 GeV	1.0 GeV
Total	7.8 GeV	2.7 GeV	1.6 GeV

- Combine with dilepton channel (smaller systematics)
- Improvements:
  - calibrate jet p_T scale using data
    - Z+jet, γ+jet, W→jj, Z→bb
  - constrain gluon radiation effects in MC with data
  - Maybe use stringent cuts to reduce effects of hard gluon radiation…
  - double b-tag ⇒ reduce combinatorics
- Total uncertainty ≈ 2-3 GeV (per experiment)
- combined with W mass uncertainty ≈ 30 MeV

John Womersley

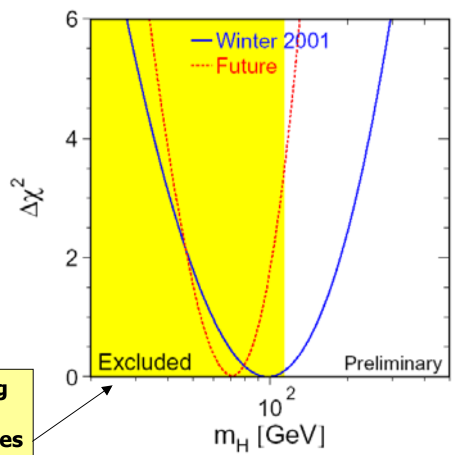
Indirect Constraints on Higgs Mass

- **Future Tevatron W and top mass measurements, per experiment**

	Δm_W
2 fb^{-1}	**±27 MeV**
15 fb^{-1}	**±15 MeV**

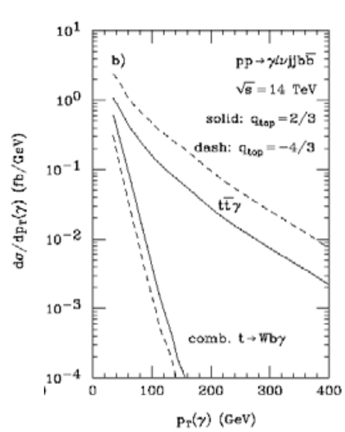
	Δm_t
2 fb^{-1}	**±2.7 GeV**
15 fb^{-1}	**±1.3 GeV**

Impact on Higgs mass fit using Δm_W = 20 MeV, Δm_W = 1 GeV, $\Delta\alpha = 10^{-4}$, current central values
M. Grünewald et al., hep-ph/0111217



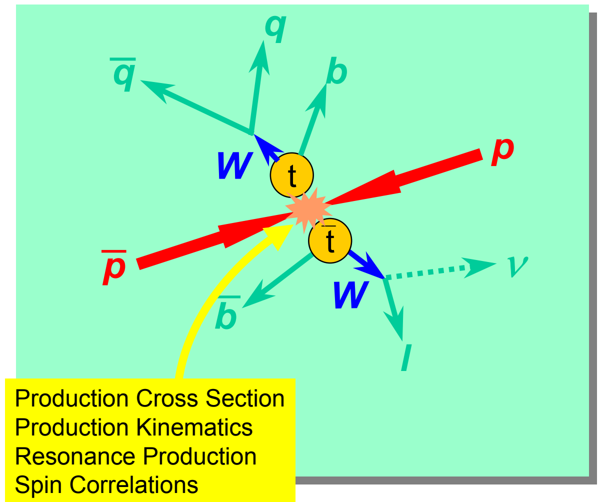
An idea for the future

- **Use $t\bar{t}\gamma$ events to measure the electric charge of the top quark**
  - **How do we know it's not 4/3?**
    - **Baur et al., hep-ph/0106341**



John Womersley

Top quark production properties



Cross Section

- **Why?**
  - **test of QCD predictions**
  - **Any discrepancy indicates possible new physics:**
    - **production via a high mass intermediate state**
    - **Non Wb decay models**
- **How?**
  - **Measurement performed using various final states**
  - **Dilepton channels**
    - **ee, eμ, $\mu\mu$ and eν final states**
  - **Lepton + jets channels**
    - **e+jets, μ+jets**
      - topological analysis
      - b-tagging (using soft leptons from semileptonic decays of the b)
  - **All-jets channel**
    - **Use topological variables**
    - **exploit b-tagging using soft leptons**
      - Combine them using a Neural network technique

Cross Section Event Samples

- **Dilepton channel: ee, eμ, μμ + 2 jets + missing p_T**

	DØ	CDF	
	ee,eμ,μμ	ee,eμ,μμ	eτ,μτ
data	9	9	4
background	2.6±0.6	2.4± 0.5	2.0±0.4

- **Lepton + jets channels: e, μ + 3 or 4 jets + missing p_T**

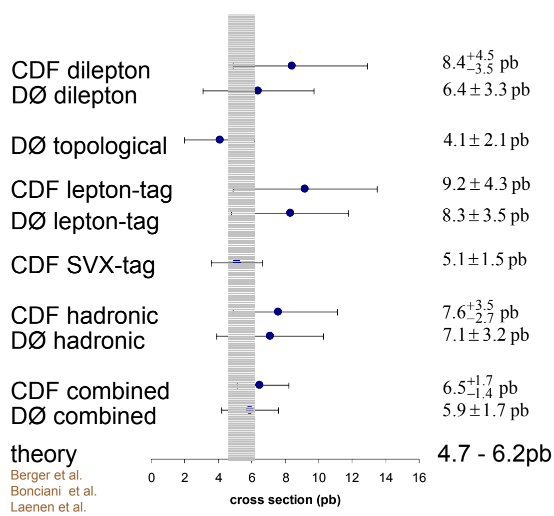
	DØ		CDF	
	topological	lepton-tag	SVX-tag	lepton-tag
data	19	11	29	25
background	8.7±1.7	2.4± 0.5	8.0±1.0	13.2±1.2

11 events in common

- **All jets: 5 or 6 jets, b-tag, neural networks**

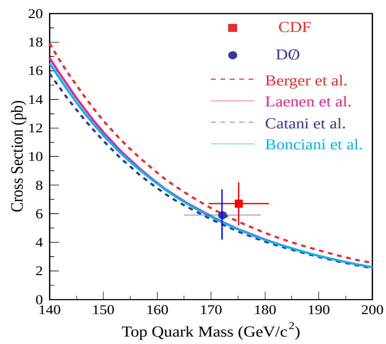
	DØ	CDF
data	41	187
background	24±2.4	151±10

Results



DØ: PRL 79 1203 (1997); CDF: PRL 80 2773 (1998)(+updates)

Cross section vs. m_t



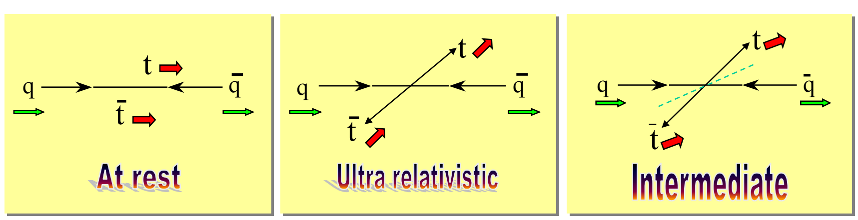
Prospects for Run 2a (2 fb^{-1})

- **Precision on top cross section ~8%**
  - **Statistical Error : 4%**
  - **Systematic errors assumed to scale with statistics**
    - **errors from backgrounds: decrease with increased statistics of control samples (2%)**
    - **jet energy scale (2%)**
    - **Radiation :**
      - » Initial state (2%),
      - » Final state (1%)
  - **Limiting Factors ?**
    - **error on geometric and kinematic acceptances depend on differences between generators (Pythia, Herwig, Isajet) (4%)**
    - **luminosity error (4%)**

$\bar{t}t$ spin correlations

- **Standard Model predicts:**
  - **90% of top quark pairs produced at $\sqrt{s}$=1.8 TeV come from $\bar{q}q$ annihilation via spin-1 gluon ☞ source of spin correlation**
  - **width $\Gamma_t = \Gamma(t \to bW) \approx 1.55$ GeV**
  - **lifetime $\tau \approx 4 \times 10^{-25}$ s**
  - **QCD time scale $1/\Lambda_{QCD} \approx$ few $\times 10^{-24}$ s**
  - **Top quark decays before losing the spin information at production**
    - ☞ **spin can be reconstructed, as decay products carry spin information.**
- **Motivation**
  - **Experimental proof that top-quark lifetime is shorter than spin-decorrelation time scale**
  - **Lower bound on Γ_t and $|V_{tb}|$**
  - **Direct probing of the properties of quark, free of QCD long-distance effects**
  - **Probe for non-standard interactions, both in production and decay**

Spin Configurations



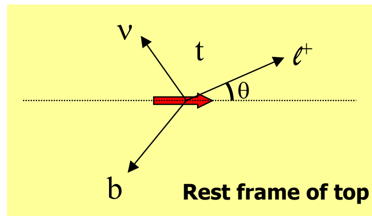
- **Optimal spin quantization basis is off-diagonal**
- **Basis is determined once the velocity and scattering angle is known**
  - **Only like-spin combinations are produced in this optimized basis**
    - G. Mahlon and S. Parke, PLB 411, 173 (1997)

Decay of polarized top quark

- **Differential decay rate of top quark with spin fully aligned:**

$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_i)} = \frac{1+\alpha_i\cos\theta_i}{2}$$

Particle$_i$	α_i
l^+ or d	1
ν or u	-0.31
W^+	0.41
b	-0.41



- **To find the direction of spin:**
  - **measure angle between the off-diagonal basis and the lepton flight direction in rest frame of the top θ_-, θ_+**
  - **Spin correlation → correlation in θ_+ vs. θ_- space**

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta_+)d(\cos\theta_-)} = \frac{1+\kappa\cos\theta_+\cos\theta_-}{4}$$

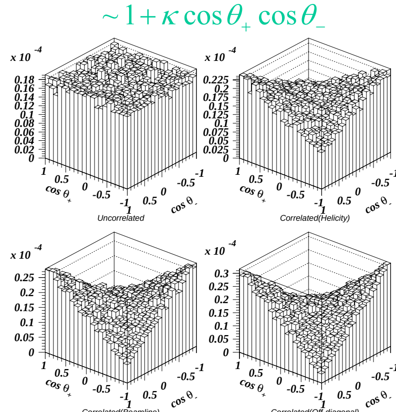
correlation parameter SM value ≈ 0.9

Angular correlations

$$\sim 1+\kappa\cos\theta_+\cos\theta_-$$

No spin correlation $\kappa=0$

Helicity basis $\kappa=0.40$



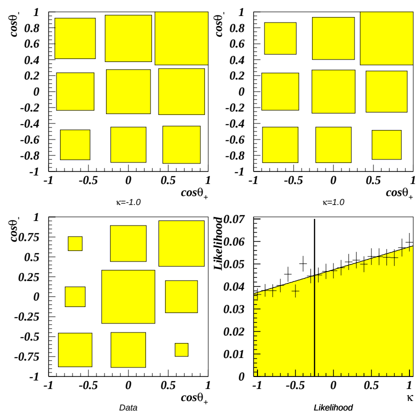
Beamline basis $\kappa=0.68$

Off-diagonal basis $\kappa=0.87$

$$\kappa = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}}$$

DØ spin correlation analysis

- 6 dilepton events (that's all we have!); use binned 2D likelihood fit



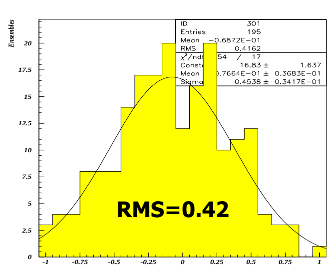
$\kappa > -0.25$ @ 68% CL

Fermilab-Pub-00/046-E

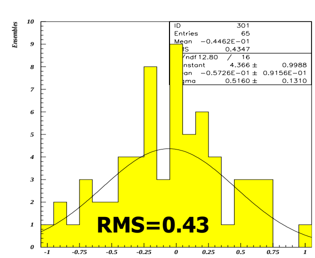
Prospects for Run 2

- Based on ensemble tests of 150 dilepton events (1.5 fb^{-1})

likelihood



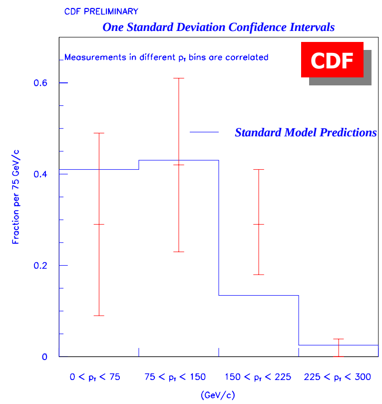
probability density estimator



- One can distinguish κ=0 from κ=1 at greater than 2σ

Top Quark Transverse Momentum

- **Another tool for investigating non-standard production mechanisms**
- **Good agreement with QCD prediction**



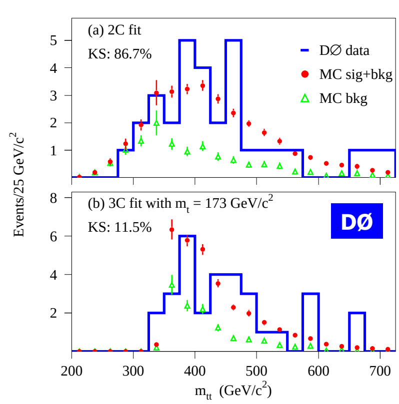
p_T Bin	Measured Fraction of Top Quarks
$0 < p_T < 75$ GeV/c	$R_1 = 0.29^{+0.18}_{-0.18}$(stat)$^{+0.08}_{-0.08}$(syst)
$75 < p_T < 150$ GeV/c	$R_2 = 0.42^{+0.18}_{-0.18}$(stat)$^{+0.05}_{-0.07}$(syst)
$150 < p_T < 225$ GeV/c	$R_3 = 0.29^{+0.12}_{-0.10}$(stat)$^{+0.06}_{-0.05}$(syst)
$225 < p_T < 300$ GeV/c	$R_4 = 0.000^{+0.035}_{-0.000}$(stat)$^{+0.019}_{-0.000}$(syst)

John Womersley

$t\bar{t}$ resonances

- **A general search for heavy objects decaying to top pairs**
- **Predicted (for example) in dynamical models of Electroweak Symmetry Breaking where the "Higgs" is a bound state**
  - color octet resonances → $t\bar{t}$
  - mass ≈ several hundred GeV
  - Technicolor
    - $gg \rightarrow \eta_T \rightarrow (tt, gg)$
  - Topcolor
    - $qq \rightarrow V_8 \rightarrow (tt, bb)$

⇒ **peak in $t\bar{t}$ invariant mass**



DØ limits on σ·B for Z′ → tt → eν4j

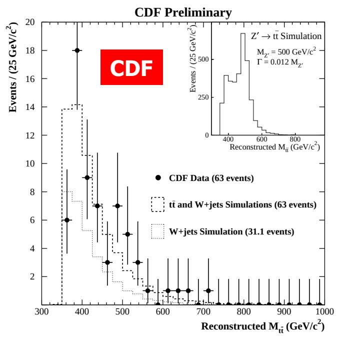
Note: multiply limits ×9 to remove B(W → eν)

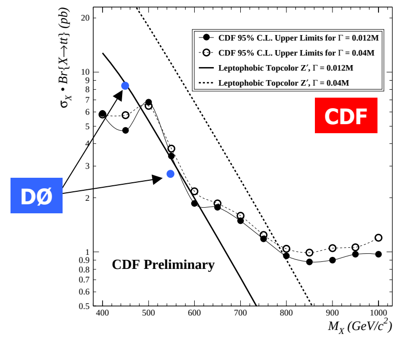
Z′ Mass	σ · B (95% CL)
350 GeV	1.1 pb
450 GeV	0.9 pb
550 GeV	0.3 pb

John Womersley

$t\bar{t}$ resonances

- Use W+ ≥ 4jet events
- No evidence for a deviation from expectation (KS prob ~20%)

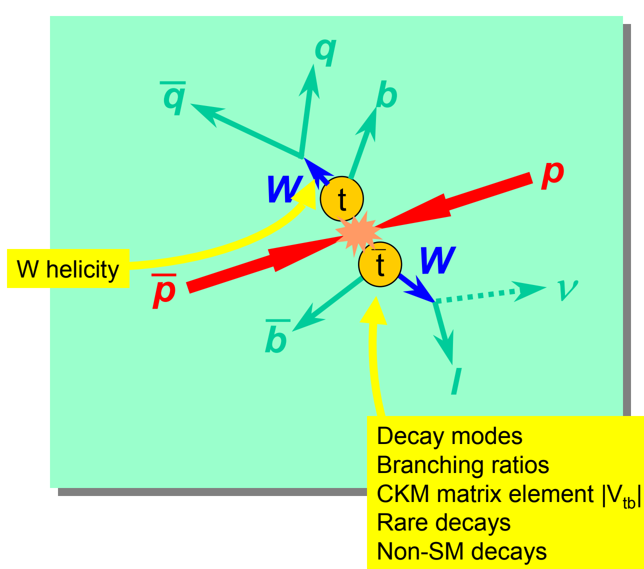




- Use tt invariant mass spectrum to set limits on narrow Z′ resonances in topcolor models
- With 2fb^{-1}, can probe Z′ resonances up to 1 TeV.

John Womersley

Top Quark Decay Properties



John Womersley

W helicity in top decays

- Top quarks decay before they hadronize
- polarization of W : $$\frac{W_{long}}{W_{left}} = 0.5 \left(\frac{m_t}{m_W} \right)^2$$
  - non-standard top couplings may result in different W polarization

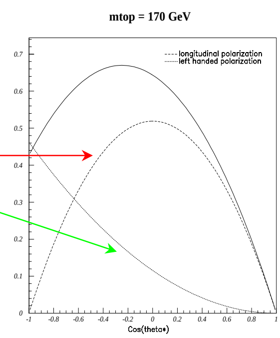
Charged lepton p_T & angular distribution

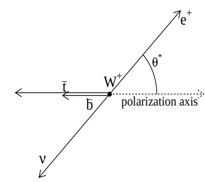
↓

Longitudinal W vs.

Left Handed W's

$\delta B(t \to bW_{long}) \approx 5\%$





W helicity in top decays

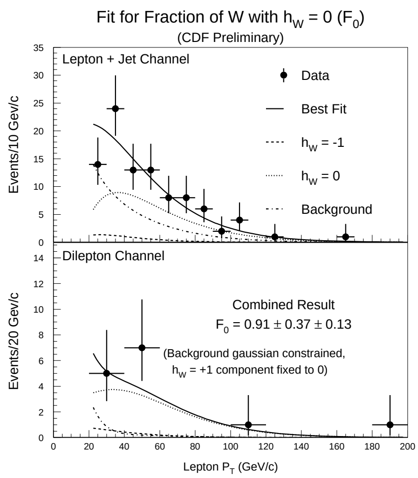
- SM top (spin ½, V-A coupling)
  - top quark decays to longitudinal (h_W=0) or left-handed (h_W=-1) W bosons

$$\frac{\mathrm{BR}(t \to bW_0)}{\mathrm{BR}(t \to bW_{-1})} = \frac{1}{2}\left(\frac{m_t}{m_W}\right)^2 = \frac{0.70}{0.30}$$

- Lepton p_T distribution in $t \to bl\nu$ distinguishes the two helicity states.
  - h_W= 0: hard p_T
  - h_W=-1: soft p_T
- Check for V+A component
  - F_{+1} determined by repeating fit with F_0 constrained to SM value
  - should be zero in SM

CDF analysis in Run 1

- **Use dilepton and lepton+jets tt samples:**



F_0= 0.91 ± 0.37 (stat) ± 0.12 (sys)
F_{+1}= 0.11 ± 0.15 (stat) ± 0.06 (sys)
CDF, PRL 84, 216 (2000)

$|V_{tb}|$

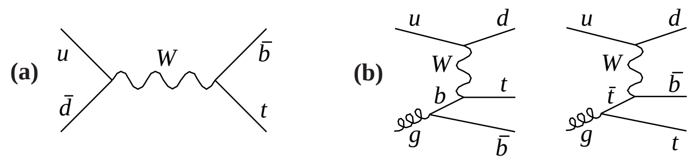
- **$|V_{tb}|$ expected to be close to 1 ($\geq$0.998), assuming 3 generations**
  - **if 4th generation exists $\Rightarrow$ no constraints**
- **Any departure of $|V_{tb}|$ from 1 → indication of non standard physics**
  - **Extract from**

$$R = \frac{B(t \to W + b)}{B(t \to W + q)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

- **Measure R using b-tagging in $t\bar{t}$ decays**
  - **Count events with zero, single and double tags in in l+jets and dilepton events.**
  - **CDF (RunI): measure R = 0.94 +0.31/-0.24**
    - **$|V_{tb}|$ = 0.97+0.16/-0.12 or $|V_{tb}|$ > 0.75 at 95% C.L.**
      - Assuming 3 generations
    - **$|V_{tb}|$ > 0.046 at 95% CL**
      - Without the 3 generation hypothesis
- **Run II projections: $\delta V_{tb} \approx$ 2% (with 2 fb^{-1})**
  benefits from improvements in b-tagging efficiency and reduced systematic errors

Single top production

- **Electroweak process:**

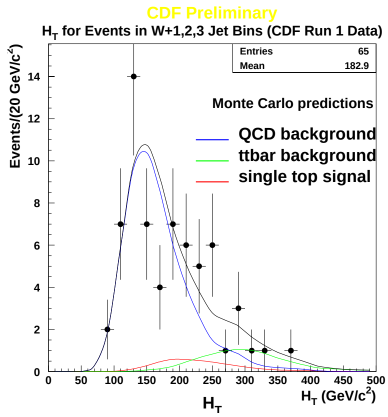


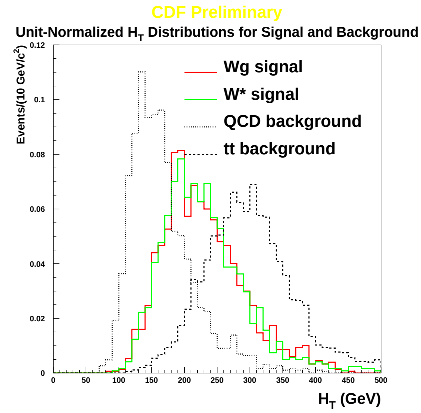
- **SM cross sections**
  - **$\sigma(\bar{p}p \to Wg \to t+X) = 1.7\pm0.2$ pb** **(Stelzer et al.)**
  - **$\sigma(\bar{p}p \to W^* \to t+X) = 0.72\pm0.04$ pb** **(Smith et al.)**
- **direct access to Wtb vertex: measure top quark width and $|V_{tb}|$**
  - **$\sigma(qq \to tb) \propto \Gamma(t \to W+b) \propto |V_{tb}|^2$**
    - **Measure CKM element $|V_{tb}|$ without any assumptions on number of generations**
- **probe of anomalous couplings**
  - **large production rates**
  - **anomalous angular distributions**

Single top production

- **Event topology**
    - **W decay products (lepton+neutrino) plus:**
  - **for the s-channel (W*) process:**
    - **Two high P_T, central b-jets**
  - **or for the t-channel (Wg) process:**
    - **One high P_T central b-jet (from top)**
    - **One soft, central b-jet**
    - **One high P_T, forward light quark jet**
- **Backgrounds:**
  - **Top pair production, W+jets, multijets**
- **Ability to extract signal depends on**
  - **b-tagging efficiency**
  - **fake lepton and fake b-quark jet reconstruction rates**
- **Desirable to separately measure the two processes**
  - **different systematic errors for V_{tb}**
  - **different sensitivities to new physics**
  - **measure W and top helicities**
    - **sensitivity to V+A, anomalous couplings, CP violation etc**

CDF Run 1 search

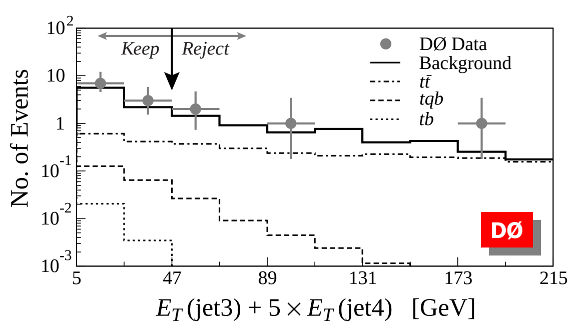




Cross section σ < 13.5 pb at 95% CL

"Standard" DØ Run 1 search

- Search using 92 pb^{-1} data from Run I for s and t channel production of single top quarks
- Optimize $S/\sqrt{B}$ for best significance



s channel: σ < 39 pb at 95% CL
t channel: σ < 58 pb at 95% CL

Neural Network search

- DØ Run 1 analysis repeated with increased efficiency and purity by using Neural Networks to discriminate between signal and background
  - Different backgrounds have very different kinematic properties.
  - Train 20 networks, to discriminate each signal type
    - e and μ with and without a tag muon
  - from each of the 5 major backgrounds
    - Wjj
    - Wbb
    - WW
    - tt
    - Misidentified leptons
- This is a lot of work, but the results are about a factor of two better:

s channel: σ < 17 pb at 95% CL
t channel: σ < 22 pb at 95% CL

Single top prospects

- Production Cross section too low to see single top in Run 1
- In Run 2:
  - Using 2 fb^{-1}, expect to see a clear signal
  - Use it to measure
    - $\sigma(qq \rightarrow tb)$ to ~ 20%
    - Γ $(t \rightarrow W+b)$ to ~ 25%
    - V_{tb} to ~12%
  - Note single top will be a background for Higgs searches and many new physics signatures

Rare decays: SM and beyond

- **Within the Standard Model**
  - $t \to Wb + g/\gamma$
  - $t \to Wb + Z$ — Near kinematic threshold
  - $t \to Wb + H^0$ — Beyond threshold
  - $t \to W + s/d$ — Measure CKM matrix element
- **Beyond the SM** — Run II sensitivity
  - $t \to c/u + g/\gamma$ (FCNC) — < 1.4% / 0.3%
  - $t \to c/u + Z$ (FCNC) — < 2%
  - $t \to c/u + H^0$ (FCNC)

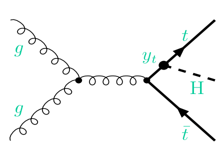
  SM predictions for FCNC decays ~ 10^{-10}
  Observation of these decays would signal new physics

  - $t \to H^+ + b$ (SUSY) — < 11%
- Current limits on rare decays (CDF)
  - BR($t \to Zq$) < 33% @ 95% CL
  - BR($t \to \gamma q$) < 3.2% @ 95% CL
- Search for $t \to H^+ b$ (DØ)

Top Quark Yukawa Coupling

- In the SM, fermions acquire mass via Yukawa couplings to Higgs field (free parameters in the SM but set proportional to the fermion mass)
  - for the top quark $$y_t = \sqrt{2}\frac{m_t}{vev} \approx 1$$
- Large value of m_t has generated proposals for alternate mechanisms (e.g. topcolor) in which top plays a role in EW symmetry breaking

  A direct measurement of y_t is of extreme interest!
- Measure y_t via associated Higgs production (ttH):

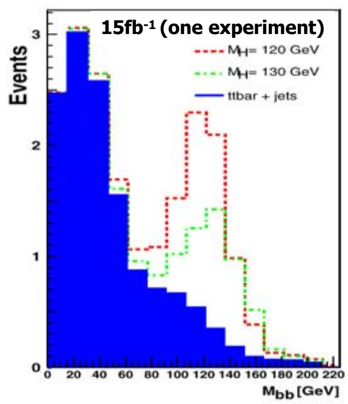


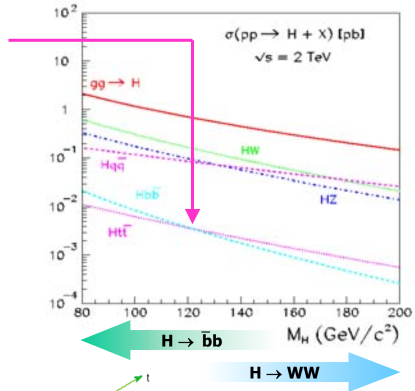
- for m_H < 130 GeV, $H \to \bar{b}b$ is the dominant decay
  - ➔ look for events with $W(\to l\nu)W(\to jj)$+4b-jets
  - ➔ A recent feasibility study finds it may be possible to carry out this measurement at the Tevatron with large data samples in RunII

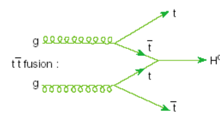
    Goldstein et al., hep-ph/0006311

Associated production $\bar{t}t$ + Higgs

- **Cross section very low (few fb) but signal:background good**
- **Major background is $\bar{t}t$ + jets**
- **Signal at the few event level:**







Tests top quark Yukawa coupling