The State of the Top Quark:
Recent Results from CDF

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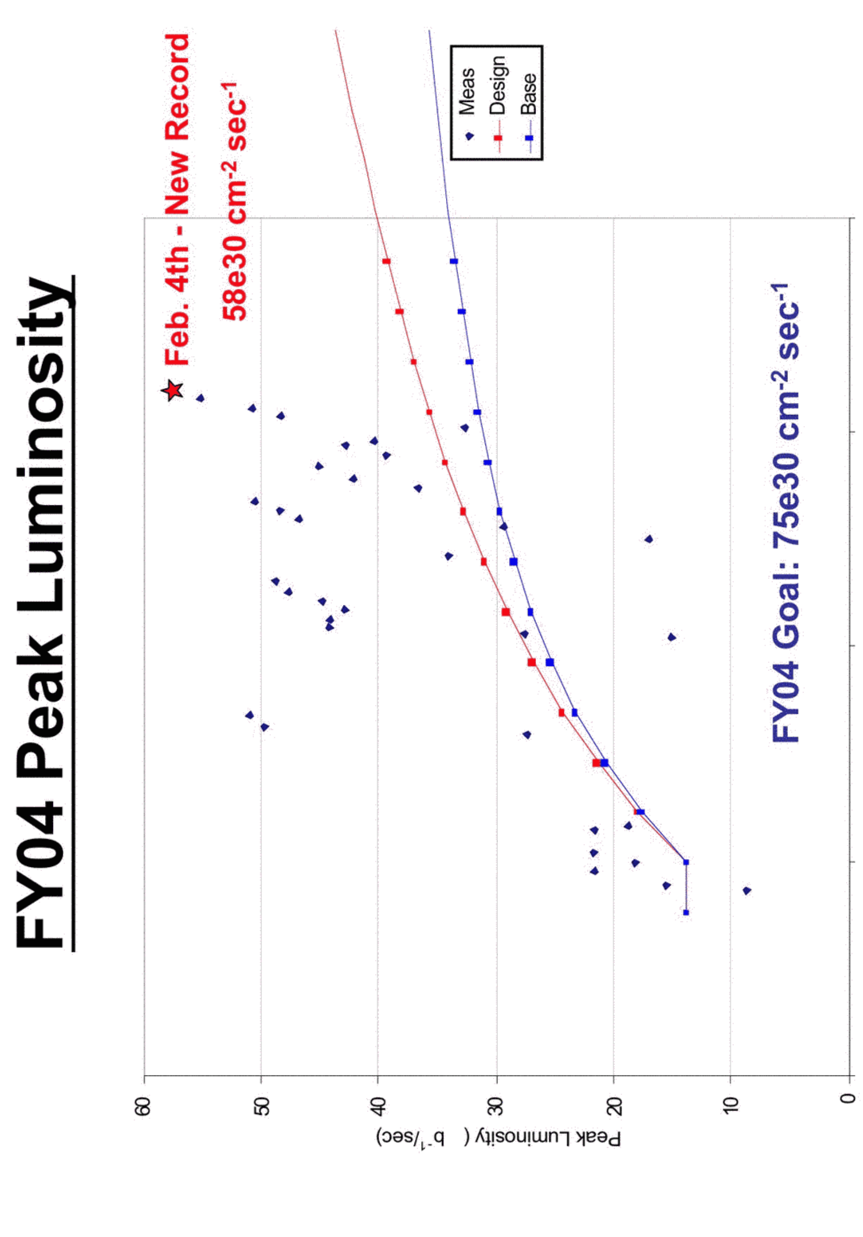
KITP seminar

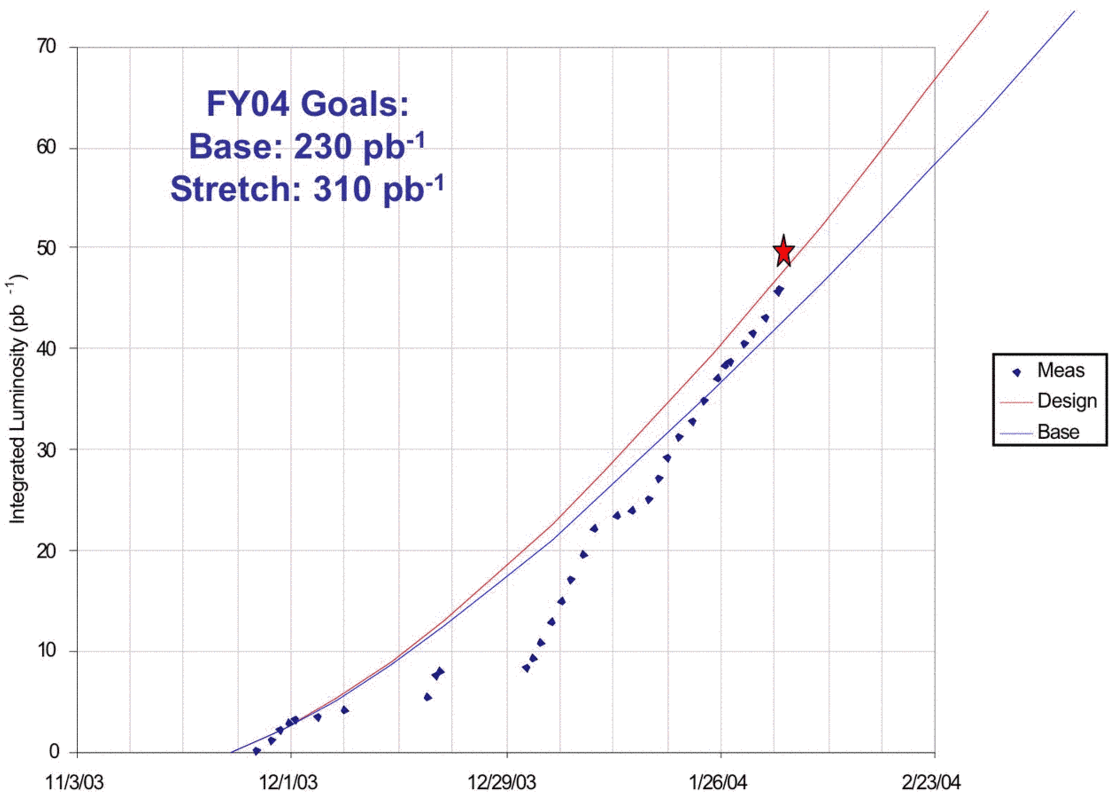
- Status of Accelerator and CDF
- Top at the Tevatron
- Top cross-section measurements
- Search for Single Top production
- Top quark mass
- Improvements

An Experimentalist's Motivation


Run I vs. Run II
Run I → Run II
E_CM = 1.8 → 1.96 TeV
T_bunch = 3500 → 396 ns
Chicago
DØ
CDF
Tevatron
Main Injector
(new)
Booster
p̄ source


FY04 Peak Luminosity
Feb. 4th - New Record
58e30 cm-2 sec-1
FY04 Goal: 75e30 cm-2 sec-1
Meas
Design
Base
Peak Luminosity (b-1/sec)
0
10
20
30
40
50
60
10/31/03
11/30/03
12/30/03
1/29/04
2/28/04

FY04 Integrated Luminosity



Accelerator Long Term Goal

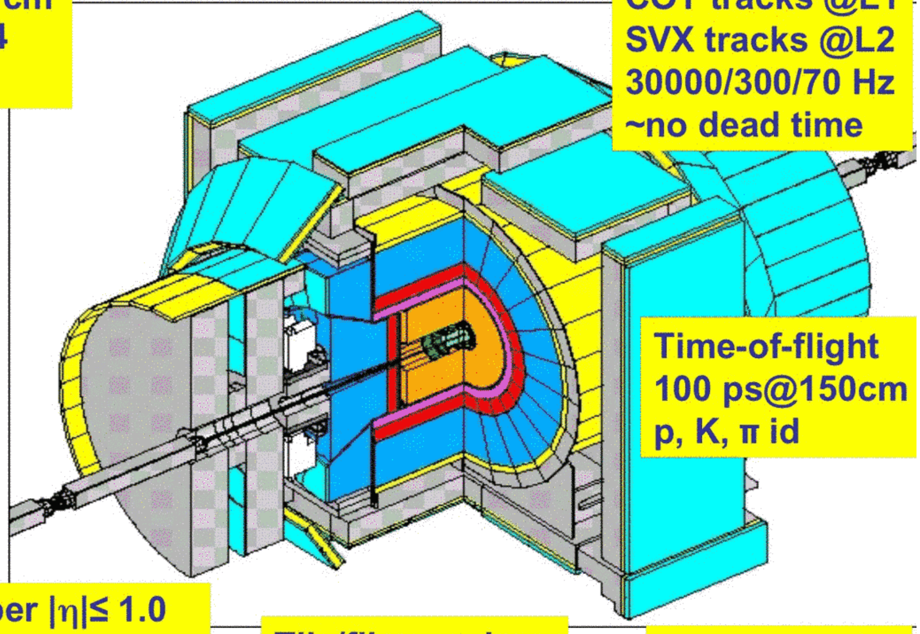
- Oct.-Nov. 2003 - shutdown to work on recycler, magnet alignment and vacuum
  - Instantanteous luminosity improved
  - Integrated luminosity > $8pb^{-1}$/week
- Last week ran using pbars from recycler
- End of 2004 expect ~500 pb-1 of data
- Sept-Dec 04 shutdown to work on electron cooling
- End of 2009 expect integrated luminosity of
  - 4.4 fb-1 (no electron cooling)
  - If electron cooling in the Recycler expect 8.5 fb-1
    - will give 40% increase in integrated luminosity per week
    - Commissioned by June 2005

CDF Detector Upgrades

1.4 T magnetic field
Lever arm 132 cm

7-8 silicon layers
1.6<r<28 cm, |z|<45 cm
|η| ≤ 2.0, cosθ=0.964
σ(hit) ~ 14 μm

132 ns front end
COT tracks @L1
SVX tracks @L2
30000/300/70 Hz
~no dead time



Some resolutions:
p_T ~ (0.7 ⊕ 0.1 p_T)%
J/ψ mass ~15 MeV
EM E ~ 16%/√E
Had E ~ 100%/√E
d_0 ~ 6+22/p_T μm
Primary vtx ~10 μm
Secondary vtx
r-φ ~ 14 μm
r-z ~ 50 μm

Time-of-flight
100 ps@150cm
p, K, π id

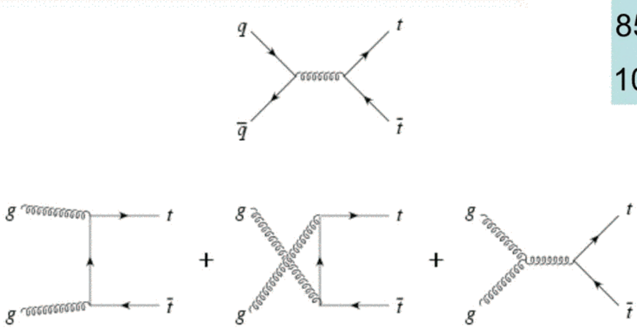
96 layer drift chamber |η|≤ 1.0
44<r<132 cm, 30k channels
σ(hit) ~ 150 mm
dE/dx for p, K, π id

Tile/fiber endcap
calorimeter
1.1<|η|<3.5

μ coverage to
|η|≤1.5
80% in phi

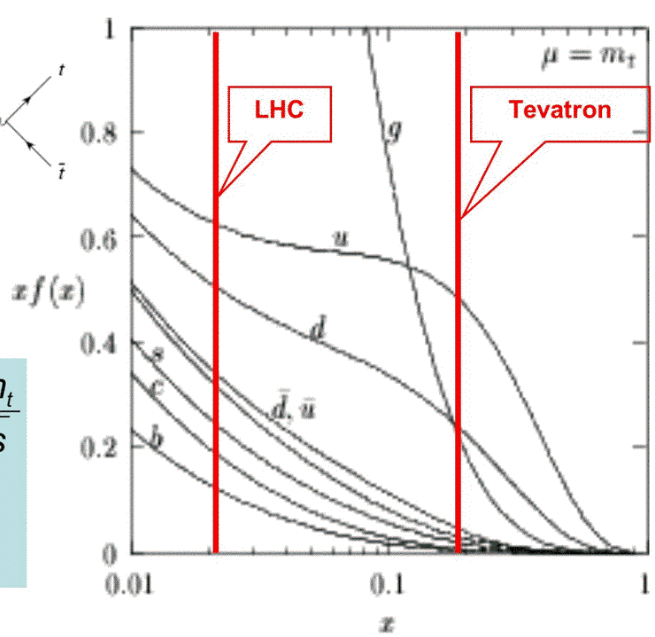
Top Quark Production

Top pairs via strong interaction:



90% $q\bar{q}$ 10% gg at Tevatron $\sqrt{s} = 1.8\ TeV$
85% $q\bar{q}$ 15% gg at Tevatron $\sqrt{s} = 1.96\ TeV$
10% $q\bar{q}$ 90% gg at LHC $\sqrt{s} = 14\ TeV$

Parton density function of proton

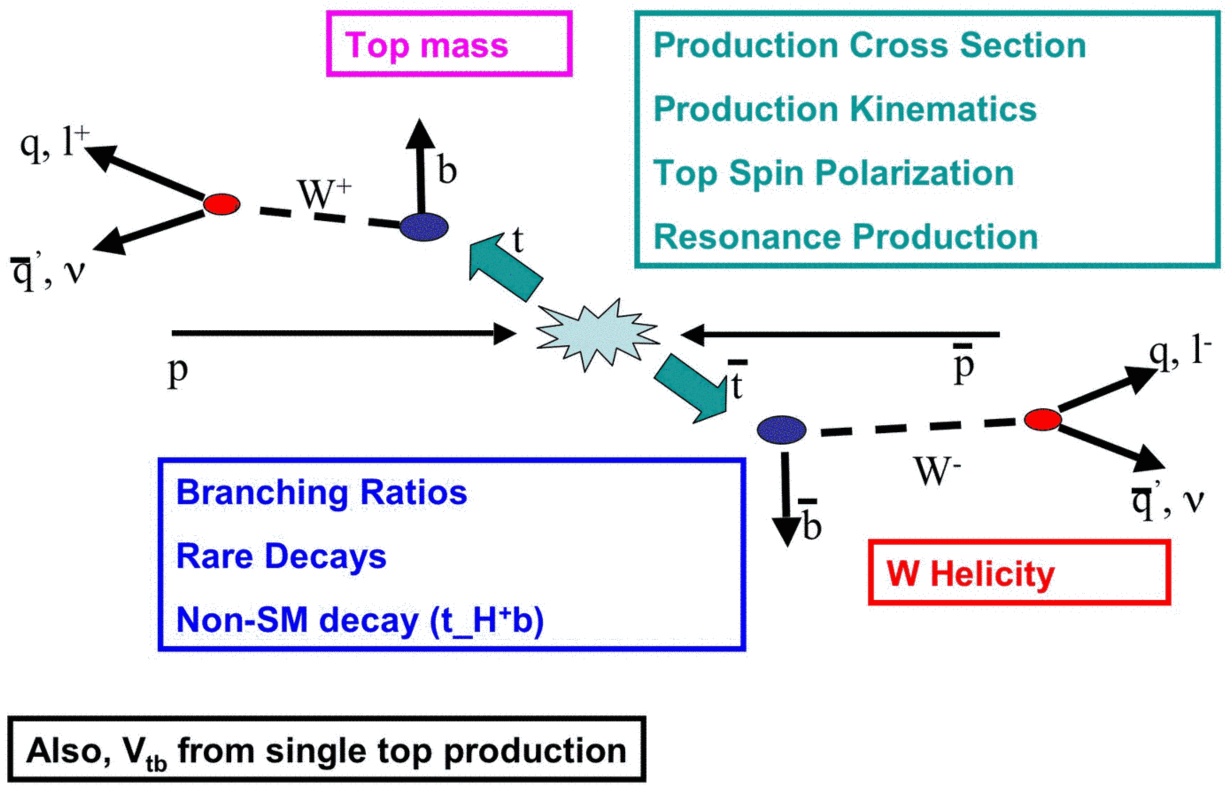


$$x_1 x_2 = \frac{\hat{s}}{s} \geq \frac{4m_t^2}{s} \quad so \quad x_1 \approx x_2 \approx \frac{2m_t}{\sqrt{s}}$$

$$Tevatron\ \sqrt{s} = 1.96\ TeV \quad x \approx 0.18$$

$$LHC\ \sqrt{s} = 14\ TeV \quad x \approx 0.02$$

Top Properties



Top Quark Decay

Top quark decays to Wb almost 100% in Standard Model

– $\Gamma(t \rightarrow Wb) \sim 1.5$ GeV means $\tau_t \sim 4 \times 10^{-25}$ s
  - Too short for hadronization
  - No top spectroscopy!
  - Spin observable in decay products

3 characteristic event signatures from WW decay

Dilepton: BR small but pure

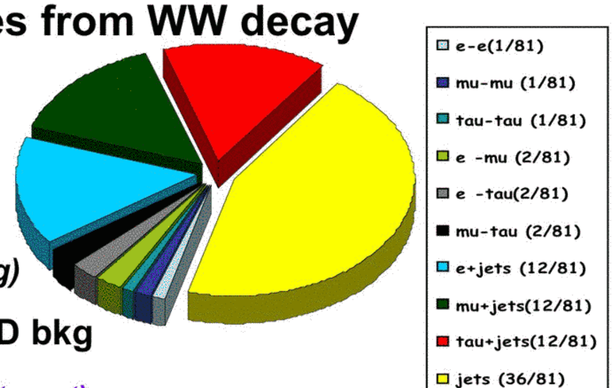
2 high p_T leptons, high MET, ≥2 jets

Lepton+Jets: BR larger but less pure

1 high p_T lepton, high MET, ≥4 jets (1 b-tag)

All-hadronic: BR largest but huge QCD bkg

≥ 6 jets (2 b-tags) *(No all-hadronic results yet)*



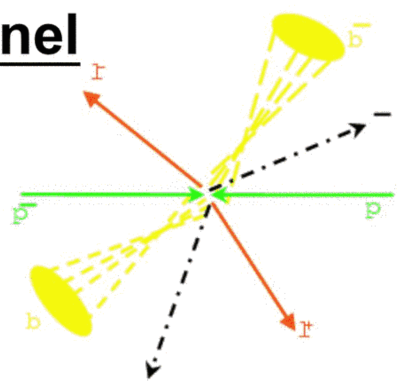
Top Pair Production Cross-Section

$$\sigma(t\bar{t}) = \frac{N_{obs} - N_{bkg}}{A\int L}$$

4 pieces:
- Estimate acceptance from top Monte Carlo
- Estimate number of background events
- Measure integrated luminosity to ± 6%
- Observe number of candidates in data

2 channels:
- Dilepton – 2 measurements
- Lepton+Jets – 4 measurements (so far)

Cross-section: Dilepton Channel



Two similar analyses:
- – Two identified leptons
  - Run I style analysis
- – One identified lepton + one isolated track $|\eta|<1.0$
  - Increase acceptance in future
    - » Add forward leptons and tracks $|\eta|<2.0$
- – Both analyses require:
  - Electron/muon with $E_T/P_T>20$ GeV
  - High MET>20 GeV or 25 GeV
  - ≥ 2 high E_T jets (JETCLU cone 0.4)

Cross Sections in Dilepton Events

Lepton + Track Analysis:

- Observe 19 candidates in 200 pb^{-1} of data
- Background estimate 7.0 ± 1.0 events

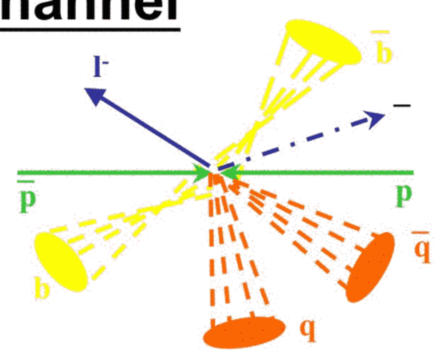
$$\sigma_{tt} = 6.9^{+2.7}_{-2.4}\ (stat) \pm 1.2\ (sys) \pm 0.4\ (lum)\ pb$$

Two Identified Leptons:

- Observe 10 candidates in 126 pb^{-1} of data
- Background estimate 2.9 ± 0.9 events

$$\sigma_{tt} = 7.6 \pm 3.4\ (stat) \pm 1.5\ (sys)\ pb$$

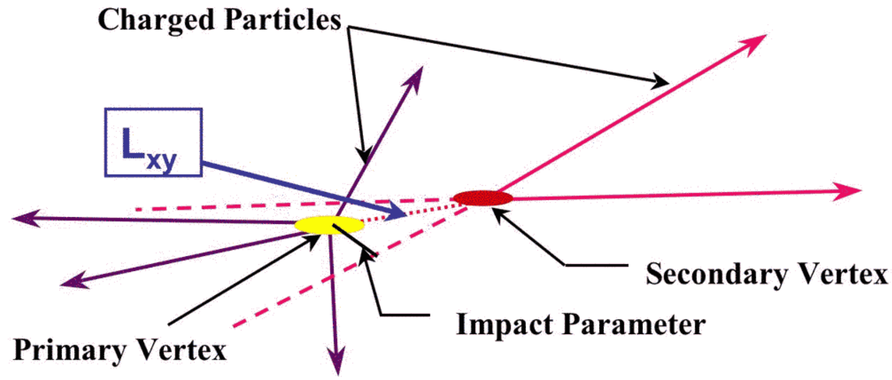
Cross-section: Lepton+Jets Channel



Four different analyses:

- Three use b-tagging
  - Displaced Vertex Tagging (SVX)
    - Run I style analysis
    - Fit to kinematic variables (New for Run II)
  - Soft Lepton Tagging (SLT)
    - New result - uses muons only
- One uses no b-tagging
    - Fit to discriminating kinematic variables (New for Run II)
- All have common event selection
  - 1 identified high E_T>20 GeV electron or muon
  - High MET > 20 GeV
  - ≥ 3 high E_T>15 GeV jets (JETCLU cone 0.4)

Silicon B-tagging in Run 2



b-quark lifetime
$c\tau \sim 450\mu m$

→ b hadrons travel $L_{xy} \sim 3$ mm before decay

SECVTX: *Secondary Vertex Tagger*

Jet is tagged if $L_{xy}/\sigma_{xy} > 3$ (typical $\sigma_{xy} \sim 150\mu m$)

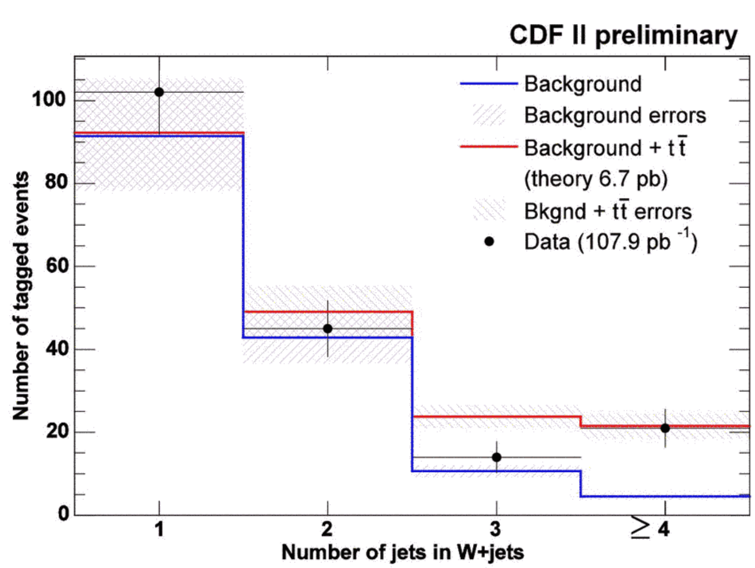
¬ Efficiency to tag a ttbar event:

→ ε (event tag) ~ 55 %

Run I Style - SVX b-tag

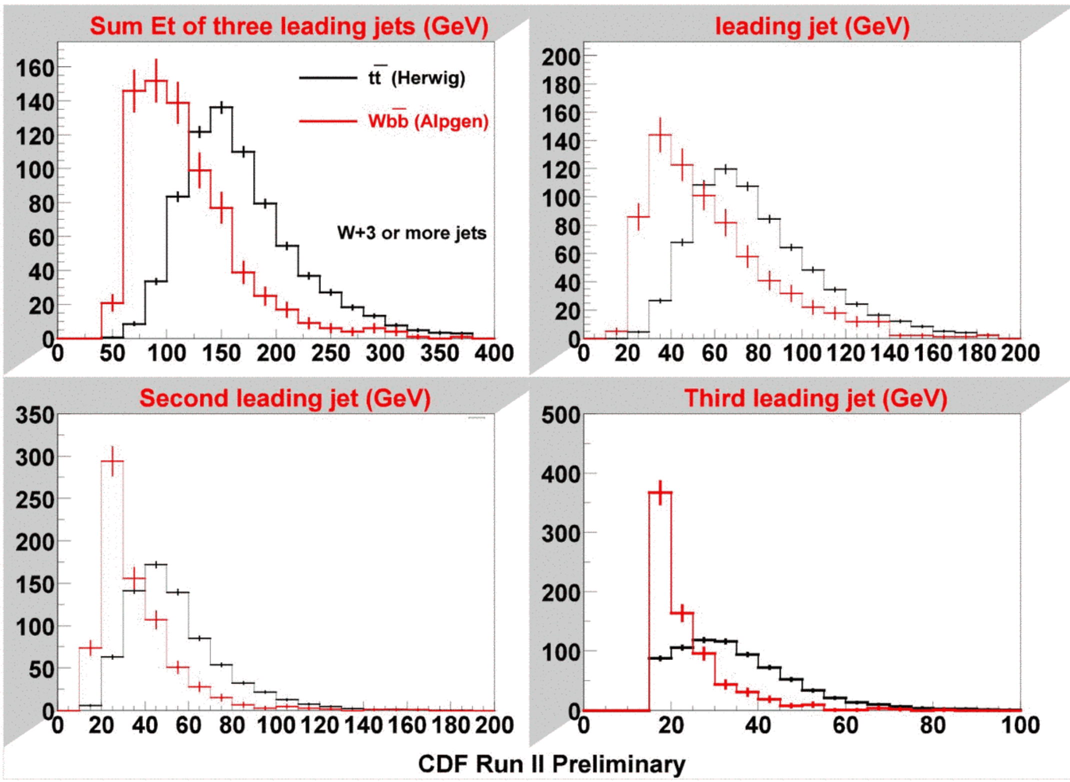
- Observe 35 candidates in 108 ± 6 pb^{-1} of data
- Background estimate 15.1 ± 2.0 events

$$\sigma_{tt} = 4.5 \pm 1.4\ (stat) \pm 0.8\ (sys)\ pb$$



Systematic Source	Uncertainty (pb)
Background	0.46
Acceptance	0.26
b-tag efficiency	0.36
Luminosity	0.27

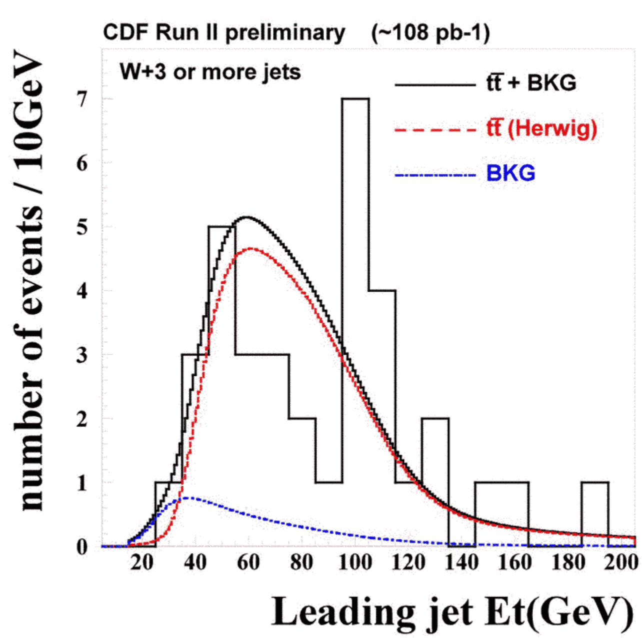
Use fits to kinematics instead?



Jet E_T Shape plus SVX b-tag

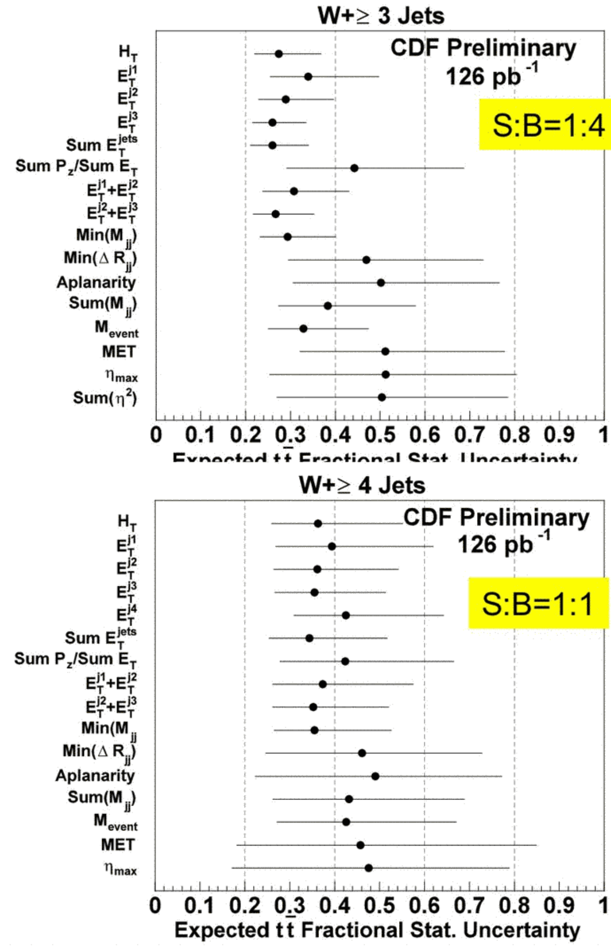
- Same 35 events as previous analysis in 108 pb^{-1}

$$\sigma_{tt} = 6.9\ ^{+1.6}_{-1.8}\ (\text{stat}) \pm 0.9\ (\text{sys})\ \text{pb}$$

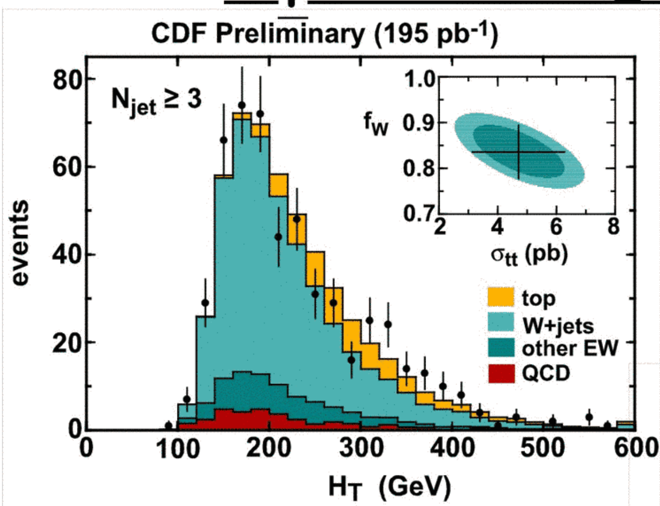


Kinematic Fit without a b-tag

- 2x data
- Cross-check of b-tag result
- But higher backgrounc
  - W+jets, Z+jets, WW, WZ from MC
  - Non-EWK from data non-isolated lepton:
- Choose H_T as discriminating variable based on expected statistical sensitivity



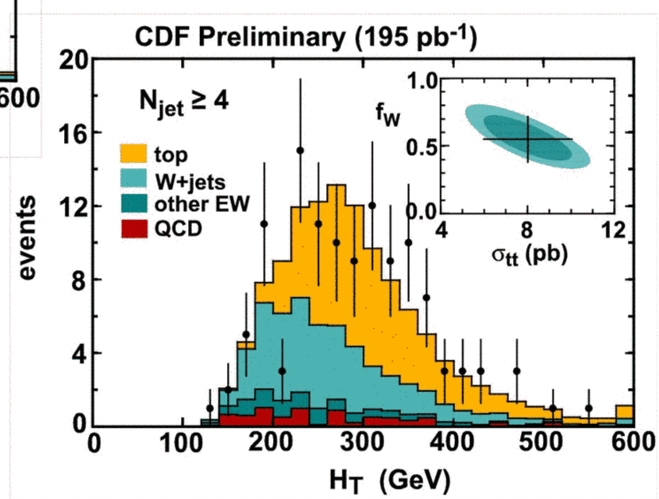
H_T Fit to Signal Region



W+≥3 Jets

Top Fraction:

12.5 ± 4.2%



W+≥4 Jets

Top Fraction:

51.2 ± 12.9 %

Systematic Effects W+≥3 Jets

Effect	Shape	Acceptance	Total
Energy Scale	28%	5.1%	30%
Generator	0.60%	---	0.6%
Q^2 Choice	14%	---	14%
PDF	3.3%	5.3% (from lepton ID)	8.6%
ISR (Pythia)	0.56%	0.78%	1.3%
Luminosity			5.9%
Background model	16%	1.7% (normalization)	16%
Total			38.3%

Top Pair Production cross-section
Summary of results (pb)

Channel	Analysis	Int. Lum	σ_{tt}	Stat	Syst	Lum
Dilepton	Lepton+Track	200 pb-1	6.9	2.6	1.2	0.4
	Two Lepton	126 pb-1	7.6	3.4	1.5	
Lepton+Jets	SVX b-tag	108 pb-1	4.5	1.4	0.8	
	Lead Jet E_T + SVX	108 pb-1	6.9	1.7	0.9	
	SLT muons	126 pb-1	4.1	3.5	2.2	
	H_T kin fit (W≥3 jets)	195 pb-1	4.7	1.6	1.8	
	H_T kin fit (W≥4 jets)	195 pb-1	8.0	2.0	3.0	

Theoretical cross sections

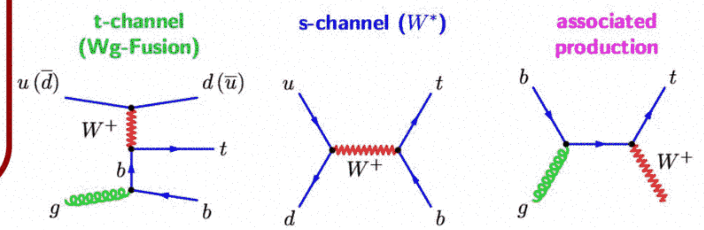
Tevatron $\sqrt{s} = 1.96\ TeV$ hep-ph/0303085

m_t (GeV)	Min _ (pb)	Ref _ (pb)	Max _ (pb)
170	6.79	7.83	8.69
175	5.82	6.70	7.41
180	5.00	5.75	6.34

Search for Single Top

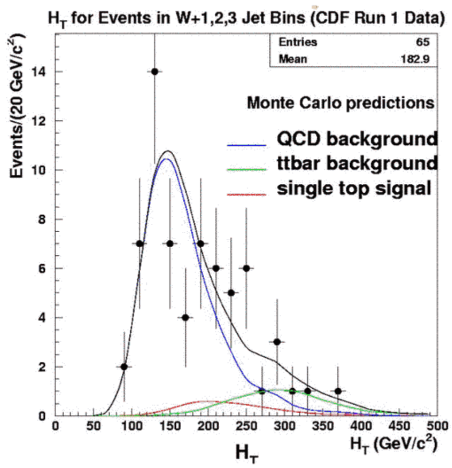
- CDF and D0 have performed searches for s and t channels separately in Run 1.
- CDF has also searched for combined process: $\sigma(t) < 14$ pb at 95% C.L.

Electroweak Wtb Vertex



1.98 ± 0.15 pb   0.88 ± 0.12 pb   σ<0.1 pb

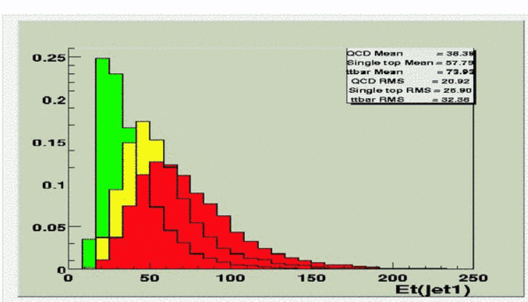
Tevatron $\sqrt{s} = 1.96$ *TeV*   hep-ph/0207055



- Expect about 100-150 events in 2 fb^{-1}
- If SM is correct, observation in Run 2a
- Measure $|V_{tb}|$ with 10-15% precision

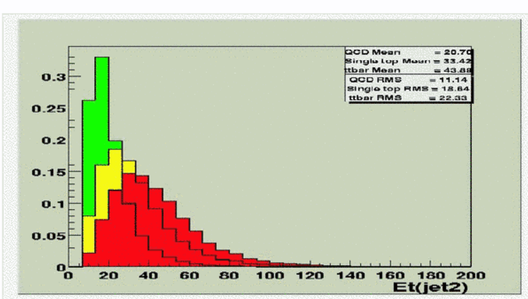
What makes single top so difficult?

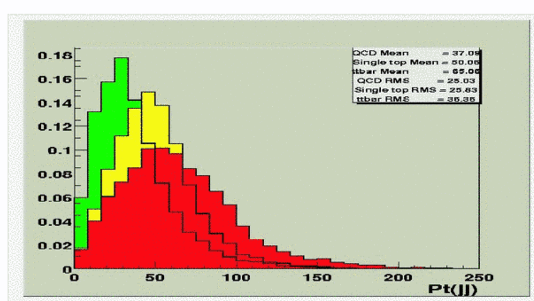
- Challenge: discriminate signal from background in W+2jet region
  - Top pair production is now a background!
  - Multivariate methods will be important



non-top
tt
signal

All normalized to unit area for shape comparison



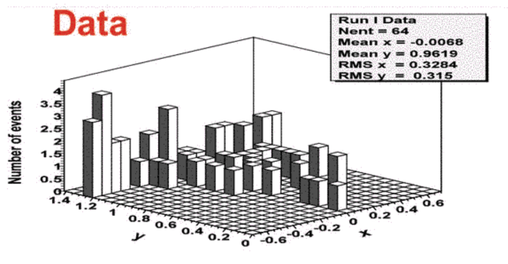


Single Top Search in Run I

All Run I searches saw excess of events in data

Recent artificial Neural Net search 22% more sensitive

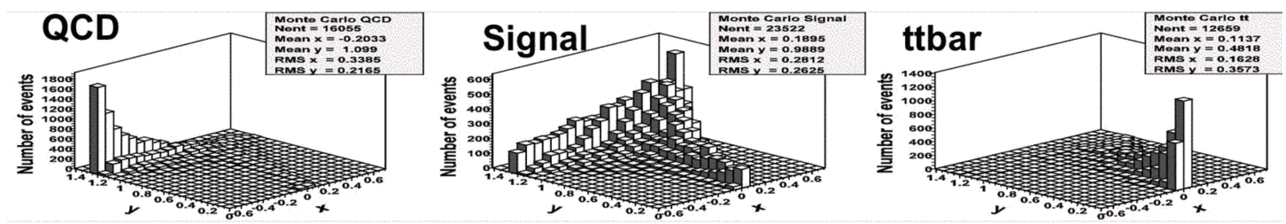
- a priori limit $\sigma < 9.6$ pb @ 95% CL
- Observed limit $\sigma < 24.4$ pb @ 95% CL



7 input variables are

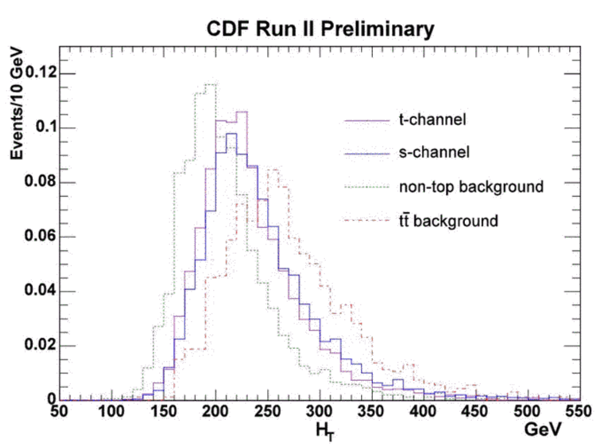
E_T of lepton and jets, MET, H_T, dijet P_T, $Q\eta$

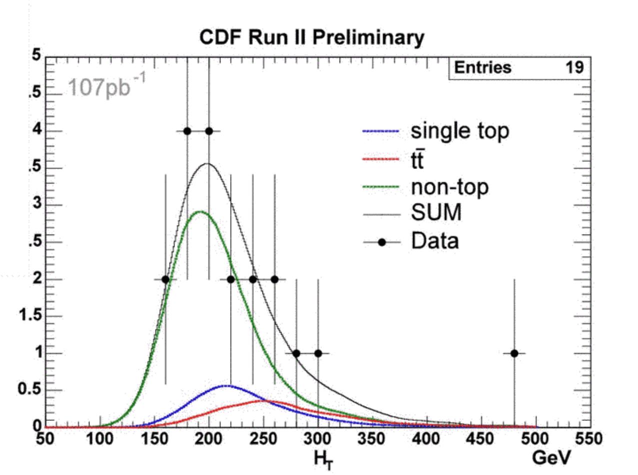
3 outputs to classify ttbar, QCD, Signal



Single Top Combined Search in Run II

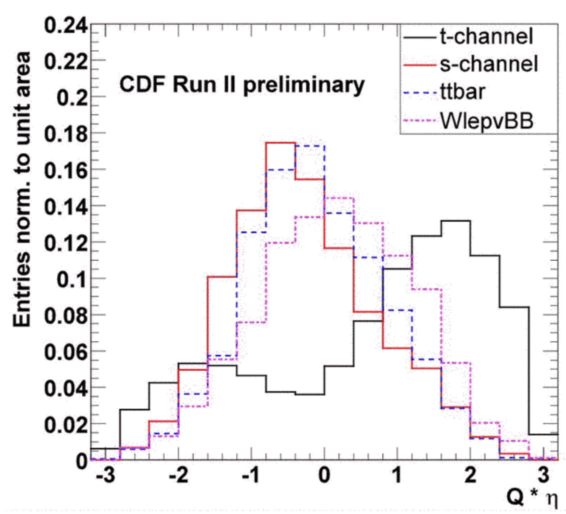
- No excesses yet in Run II…
- ~~Observed limit $\sigma < 17.5$ pb @ 95% CL~~
- Observed limit $\sigma < 13.7$ pb @ 95% CL using 162 pb-1

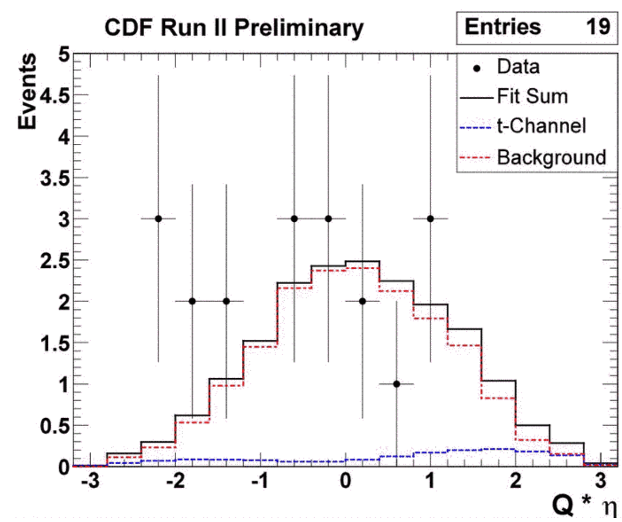




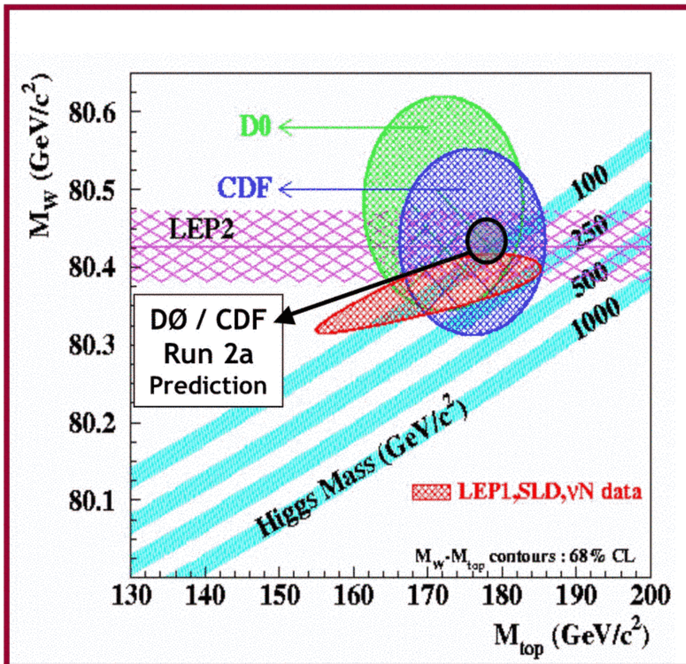
Single Top t-channel Search

- Distinguish t- from s-channel using $Q \times \eta$
  - Disadvantage t-channel only 2/3 of single top
- ~~Observed limit $\sigma < 15.4$ pb @ 95% CL~~
- Observed limit $\sigma < 8.5$ pb @ 95% CL with 162 pb^{-1}





EWSB Constraints

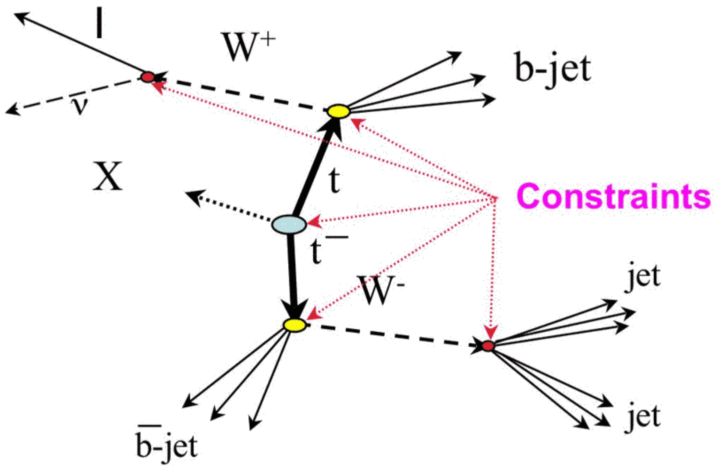


Precision measurements of top and W masses constrain the mass of the Standard Model Higgs

- M_W : CDF ⊕ DØ
  $\sigma_M \sim 30$ MeV (2 fb^{-1})
- M_t : CDF or DØ
  $\sigma_M < 3$ GeV (2 fb^{-1})

Precision top mass measurement crucial!
5 GeV shift in m_t implies 37% shift in m_H

Top Mass in Lepton + Jets



Use constrained fit technique with 2 dof

$M_{l\_}=M_W$, $M_{jj}=M_W$, $M_{t1}=M_{t2}$, p_T balance

4 jets = 12 possible jet-parton combinations
x 2 solutions for neutrino p_z
!!!Use b-tagging to reduce permutations!!!

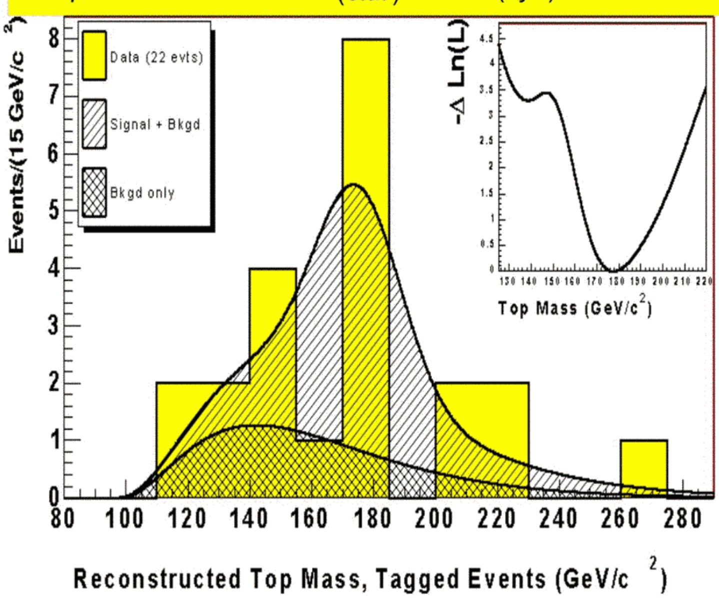
Choose combination with lowest χ^2

Run II Top Mass: Lepton + Jets

1 high p_T lepton, high MET, ≥3 jets, 1 b-tag
4^{th} jet E_T>8 GeV (usually 15 GeV)
22 events, expect 6.5 ± 2.0 from bkg

CDF Run II preliminary 108 pb^{-1}

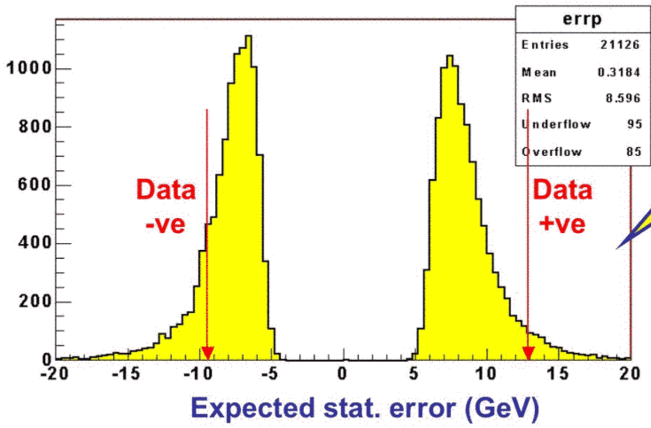
$$m_{top} = 177.5 \pm ^{12.7}_{9.4}\,_{(stat)} \pm 7.1_{(sys)}\ GeV/c^2$$



Same technique as Run I
- **All events carry same weight**
- **Fit to shapes from MC**

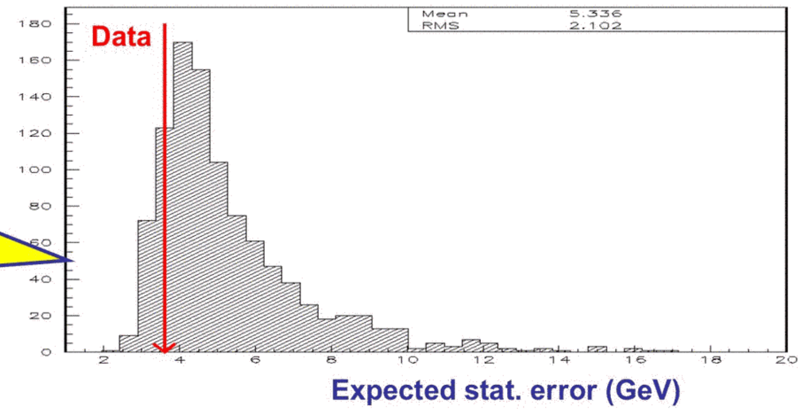
Source	Systematic (GeV/c^2)
Jets	6.2
ISR/FSR	2.6
PDF	2.0
Other MC modeling	1.0
Generators	0.6
Bkgd shape	0.5
b-tag	0.1
Total	7.1 GeV

Top Mass – Expected Statistical Errors



CDF Run II (108 pb^{-1})
Preliminary
Expected 8.8 GeV
Observed +12.7, -9.4 GeV

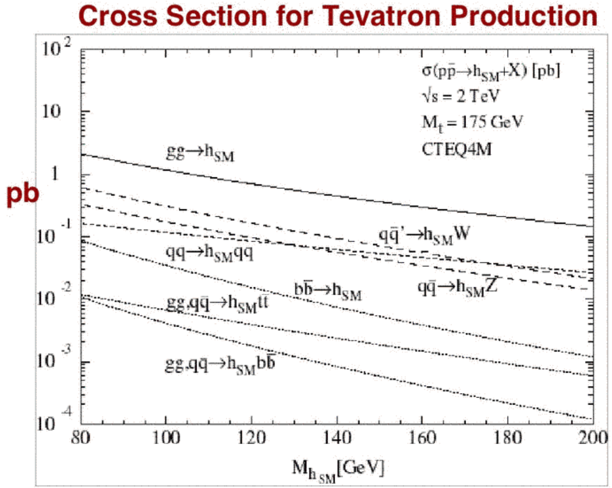
Observed errors consistent with expectations



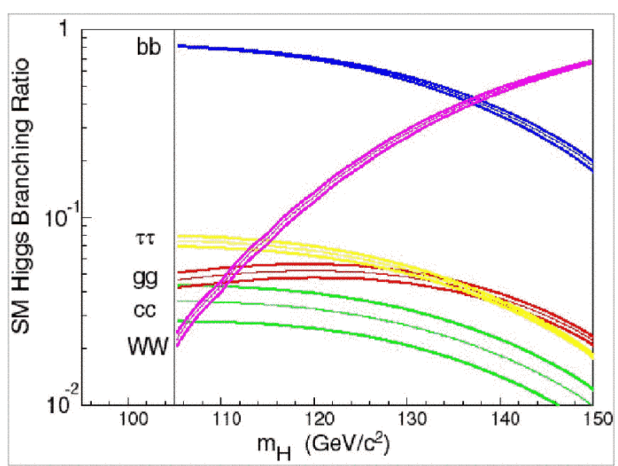
D0 Run I (125 pb^{-1})
Preliminary
Expected 5.4 GeV
Observed 3.6 GeV

The Standard Model Higgs

Cross Section for Tevatron Production



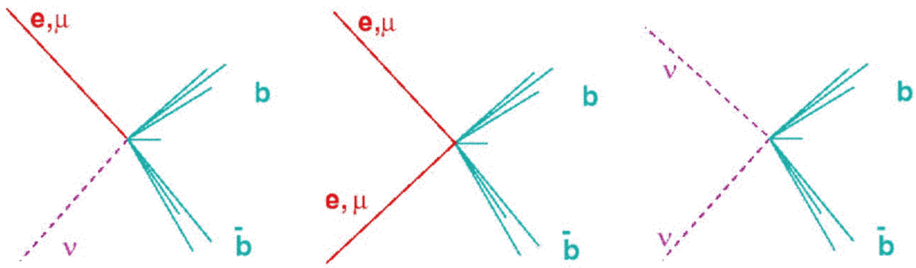
- gg → H rate large but too much bb dijet background
  - bb background ~6μb
- Main modes: WH, ZH



- Best search channels:

M_H<135GeV	M_H>135GeV
lνbb	llνν
ννbb	lljj
llbb	

Main Higgs Channels



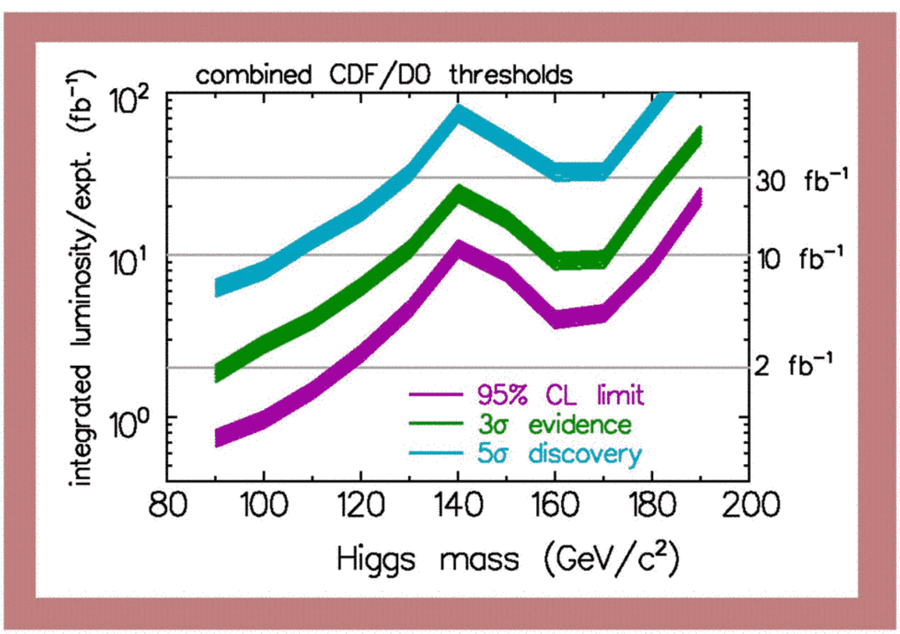
lνbb

- lepton trigger (e,μ)
- $E_T(l) > 20$ GeV
- missing $E_T > 20$ GeV
- 2 jets (E_T >15, 10 GeV)
- b tag (tight/loose)
- cosΔφ (jet-MET) …
- reconstruct bb mass

ννbb

- missing E_T trigger
- 2 jets ($E_T > 20$, 15 GeV)
- b tag (tight/loose)
- p_T(bb), …
- reconstruct bb mass

SM Higgs Reach



CDF+D0 combined integrated luminosity thresholds assuming 10% mass resolution, NN selection, nominal systematics

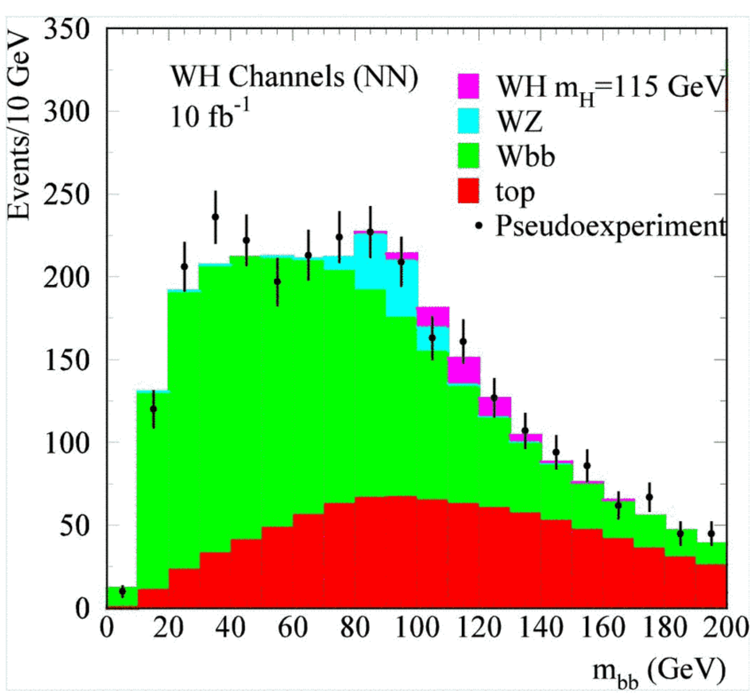
Higgs Discovery Potential

- SM Higgs
  - With 2 fb-1 and no signal exclude Mass > 120 GeV
  - Need 5 fb-1 for 3σ discovery
- MSSM Higgs
  - Better exclusion reach with 5fb-1 than SM

Top as a Background

Examples:

- WH with H→bb
  - Need excellent understanding of top kinematics to set limits
  - Remember m_H<120GeV is the most difficult mass range at LHC
- $H \rightarrow ZZ^* \rightarrow 4l$
- H→WW
- SUSY searches



Improvements

- Improve SVX b-tagging by adding
  - Forward tracking with ISL
  - 3D tracking
  - Innermost layer of silicon (L00)
- New detector simulation and reconstruction code
  - Better jet corrections
  - Greatly improved detector simulation
  - Above improvements for b-tagging
- Need time to understand detector
- Adding new analysis techniques
  - So far focused repeating Run I analysis

Conclusions

- We see top!
  - Several cross section measurements + mass
- Have twice as much data as Run I
  - Expect new results with larger data sample for winter 04
- New analysis techniques starting
- Expect publications this summer with 200pb-1
- Stilled limited by systematic uncertainties
  - Need time to understand detector
  - Summer 2004 new top mass result with better precision than Run I