

# Top Results from the Tevatron

**Andrew Ivanov**

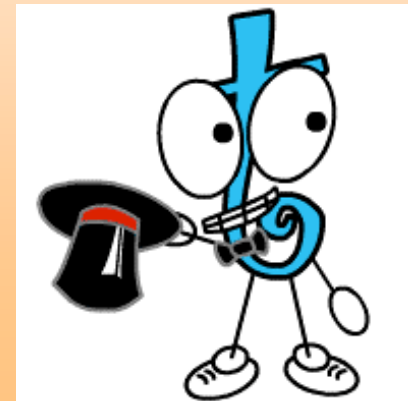
University of California, Davis  
for the CDF and D0 Collaborations



**Aspen Winter Conference**  
**February 13, 2006**

# Top Quark

- Discovered in 1995 at Tevatron
- Youngest member of the quark family
- “Last brick” to the Standard Model



- Not a surprising discovery: b-quark requires isospin partner, however ...

# Why is the top quark so special ...

LEPTONS			
Charge			
0	Electron neutrino Mass: 0?	Muon neutrino 0?	Tau neutrino 0?
-1	Electron .511	Muon 105.7	Tau 1,777
QUARKS			
Charge			
+2/3	Up Mass: 5	Charm 1,500	Top ~180,000
-1/3	Down 8	Strange 160	Bottom 4,250

Mass in millions of electron volts

**TOP**  
**~175 GeV**

- Unexpectedly huge mass
- Comparable to gold nucleus

$$y_t = \frac{\sqrt{2}m_t}{v} \approx 1$$

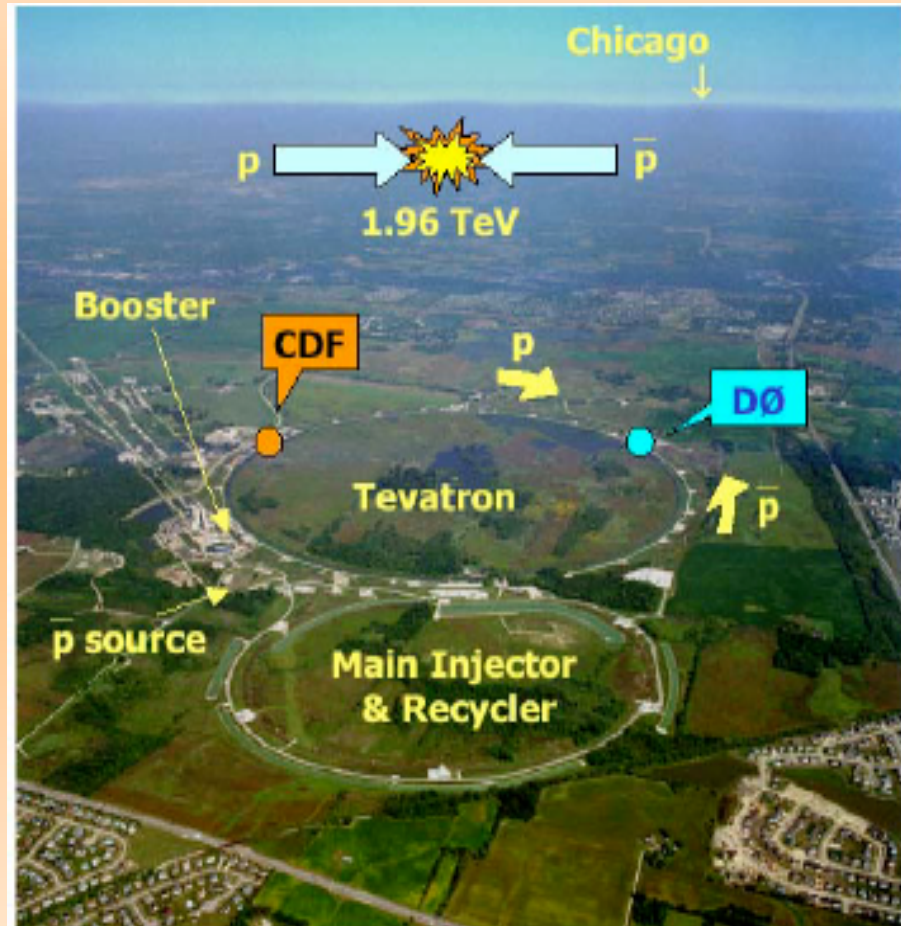
- Special role in the dynamics of EWSB ?
- Serves as a probe of BSM physics

$$\tau_{\text{top}} \sim 10^{-24} \text{ s}, \quad \Gamma^{-1} \approx (1.5 \text{ GeV})^{-1} \ll \Lambda_{\text{QCD}}^{-1} \sim (200 \text{ MeV})^{-1}$$

- Decays before hadronizing
- Passes momentum and spin info to its decay products

# Tevatron Collider

- Currently the world's only top quark production machine
- Operating at world's highest particle energy collisions
- Two multi-purpose detectors
- Run I (1992-1996)
  - $\sqrt{s} = 1.8 \text{ TeV}$
  - Integrated Lum  $\sim 110 \text{ pb}^{-1}$
  - Top Discovery!
- Run II (2001-present)
  - $\sqrt{s} = 1.96 \text{ TeV}$
  - 30% higher  $t\bar{t}$  cross section



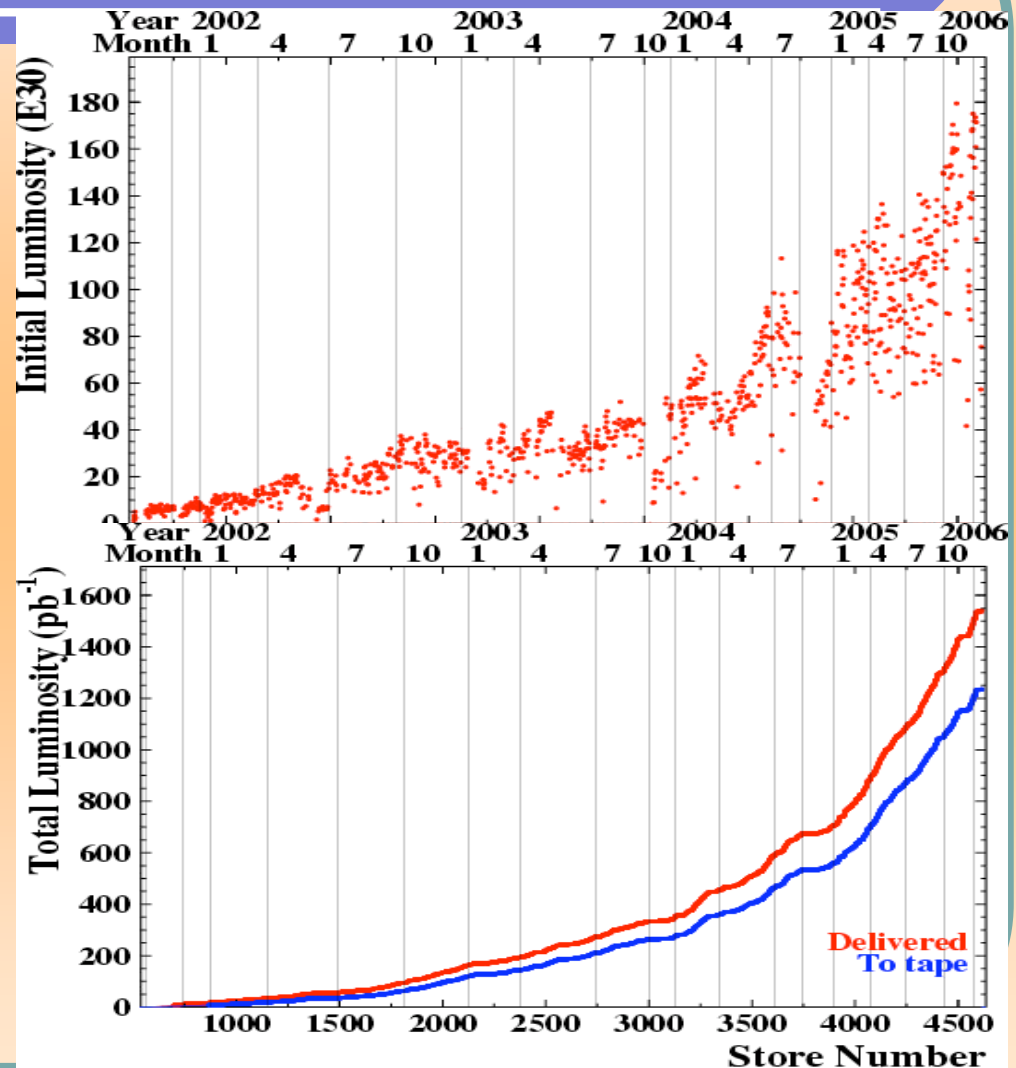
# Luminosity in Run 2

Record initial Luminosity  
 $1.8 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$   
(11/10/2005)

Expect  $2.5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  next  
year

On tape  $\sim 1.2 \text{ fb}^{-1}$

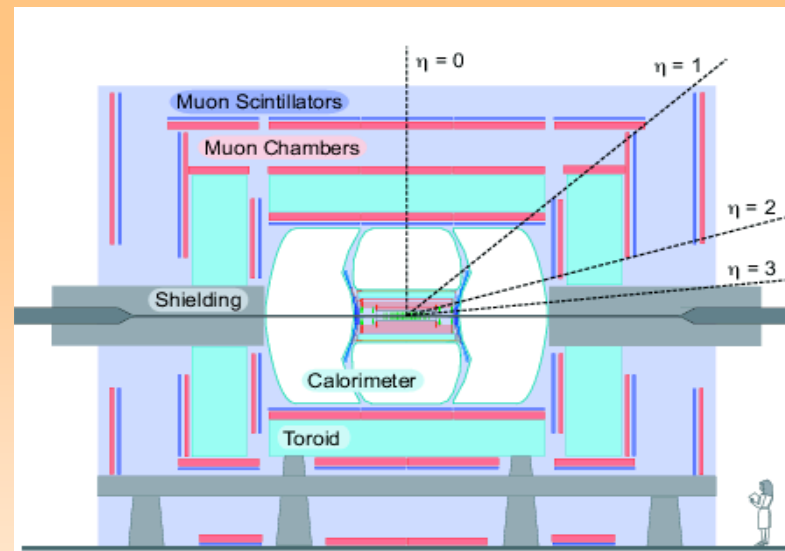
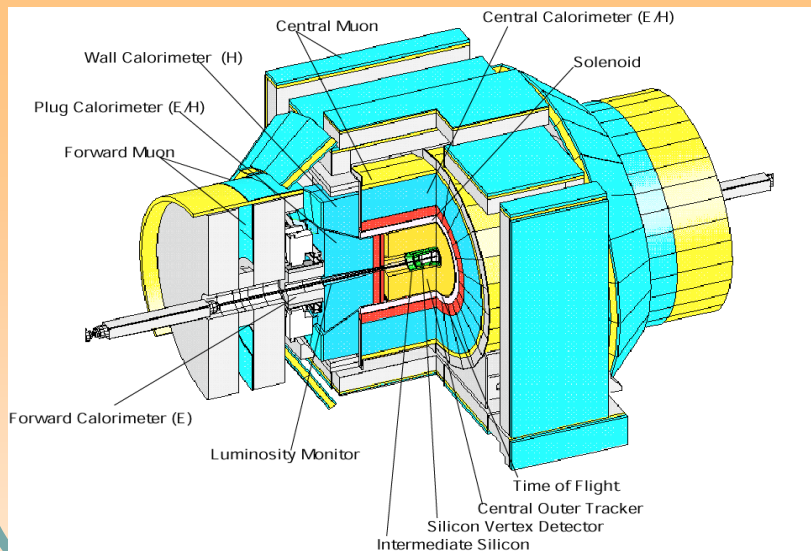
- New results with up to  
Sep 2005 (  $\sim 760 \text{ pb}^{-1}$  )  
x7 of Run I !
- Some of analyses  
presented here use up to  
Sep 2004 (  $\sim 360 \text{ pb}^{-1}$  )



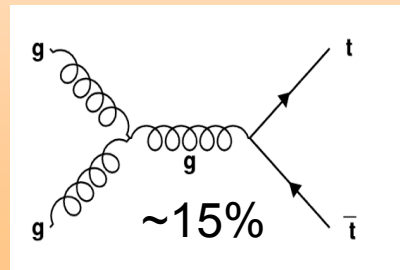
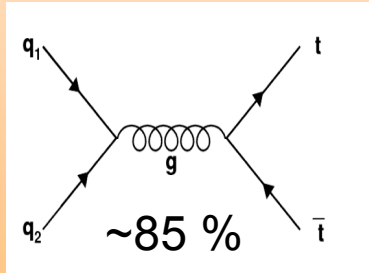
# Tevatron Detectors

- Inner Silicon Precision Tracking
- Tracking Chambers
- Solenoid
- EM and HAD calorimeters
- Muon Detectors

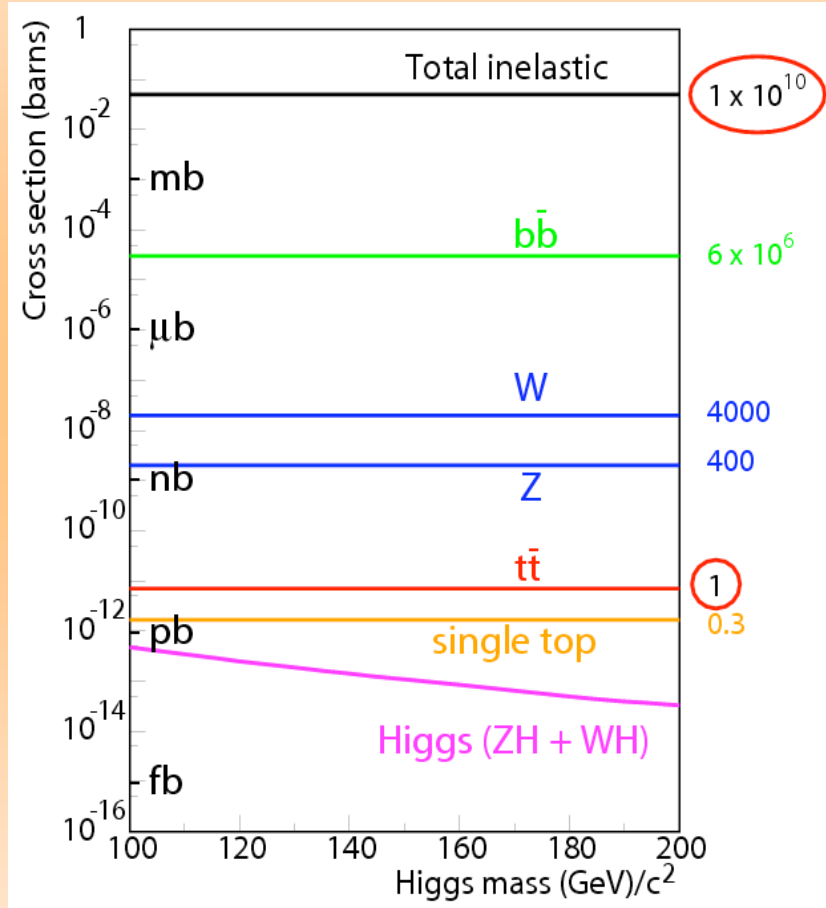
All crucial  
for top physics!



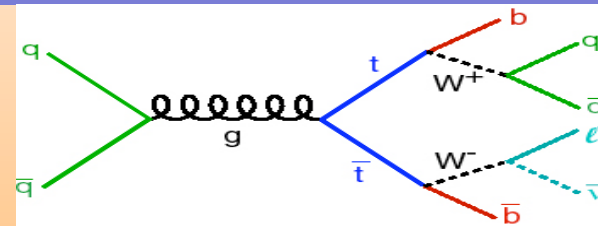
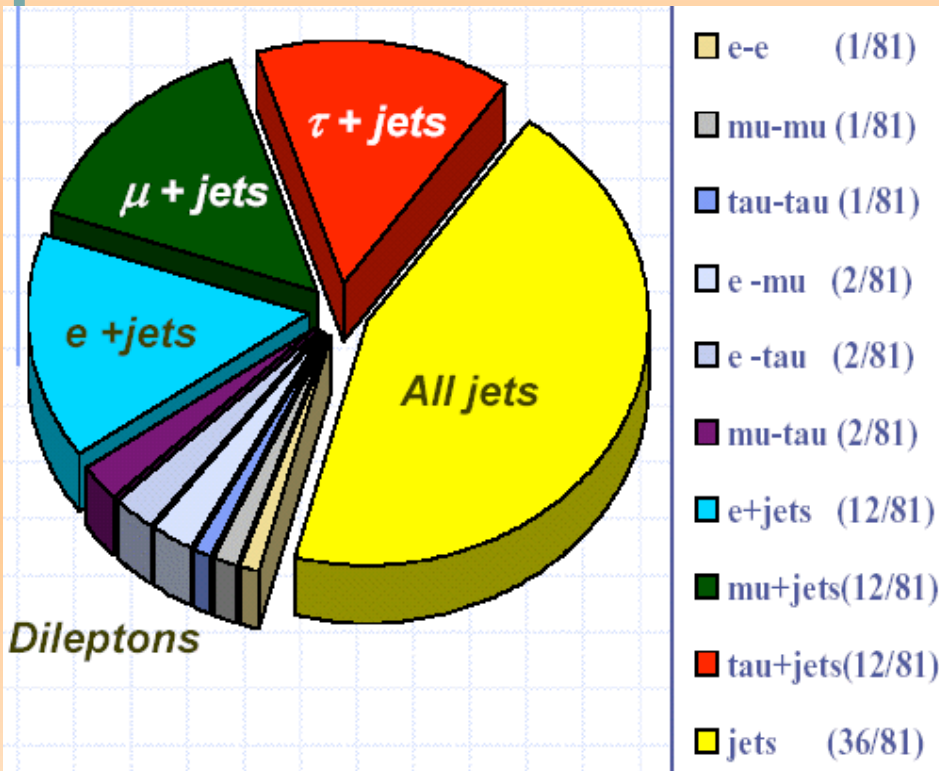
# Top Quark Production



- Within SM
- $\sigma_{tt} = 6.7 \pm_{0.9}^{0.7} \text{ pb} @ m_{\text{top}} = 175 \text{ GeV}$   
Cacciari et al. JHEP 0404:068(2004)  
Kidonakis, Vogt PRD 68 114014(2003)
- One top pair every  $10^{10}$  inelastic collisions
- Produced  $\sim 15000$  top pairs so far



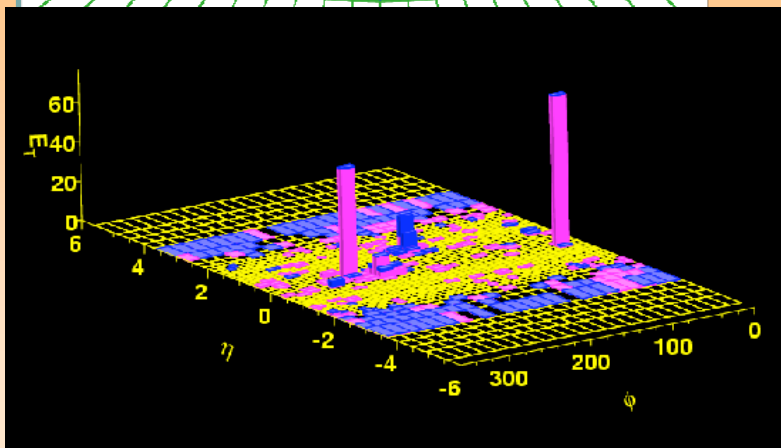
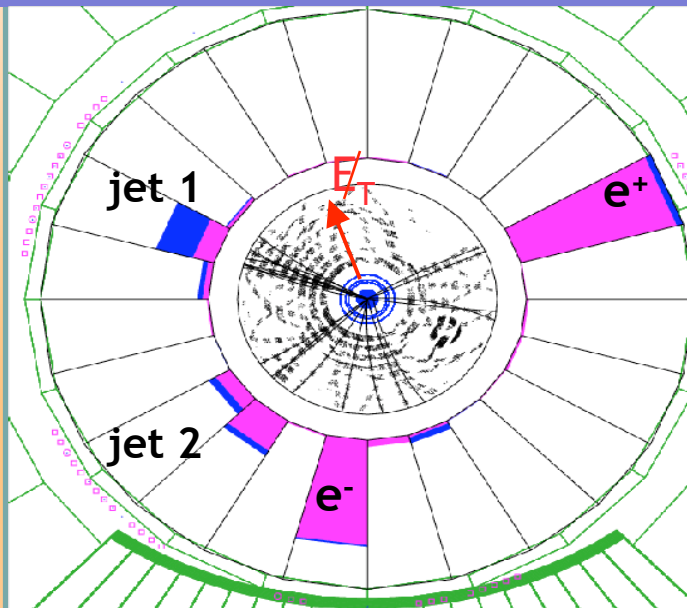
# Top Quark Decay



- $t \rightarrow Wb$
- Events classified by  $W$  decay
  - “Lepton  $[e, \mu] + jets$ ” (30%)
    - $tt \rightarrow bl\nu bqq'$
  - “Dilepton  $[e, \mu]$ ” (5%)
    - $tt \rightarrow bl\nu bl\nu$
  - “All jets” (44%)
    - $tt \rightarrow bqq'bqq'$
  - “Tau + X” (21%)



# Detecting the Top



- Signal:
  - Triggering on lepton
  - High missing transverse energy ( $E_T$ )
  - High  $E_T$  jets, central and spherical
  - Two b-jets (displaced vertex)
- Background:
  - W+jets:
    - dominant in leptonic modes
    - fakes the second lepton
  - Drell-Yan(dileptons): no  $E_T$
  - QCD: huge in HAD mode

# Production Cross Section Measurements

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\epsilon_{t\bar{t}} \cdot \int L dt}$$

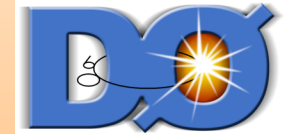
- Testing non-standard model top production mechanisms
- Top sample might contain an admixture of exotic processes

# Cross Section in Dilepton channel

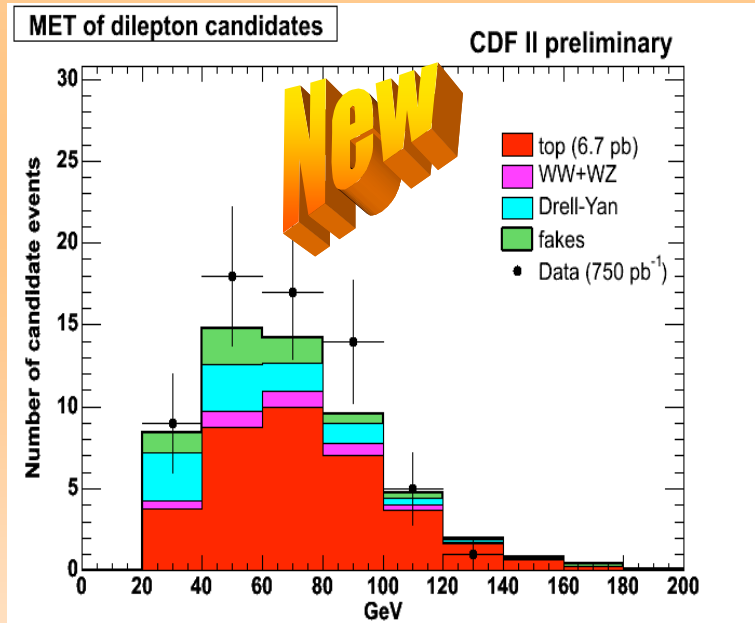


$L = 750 \text{ pb}^{-1}$

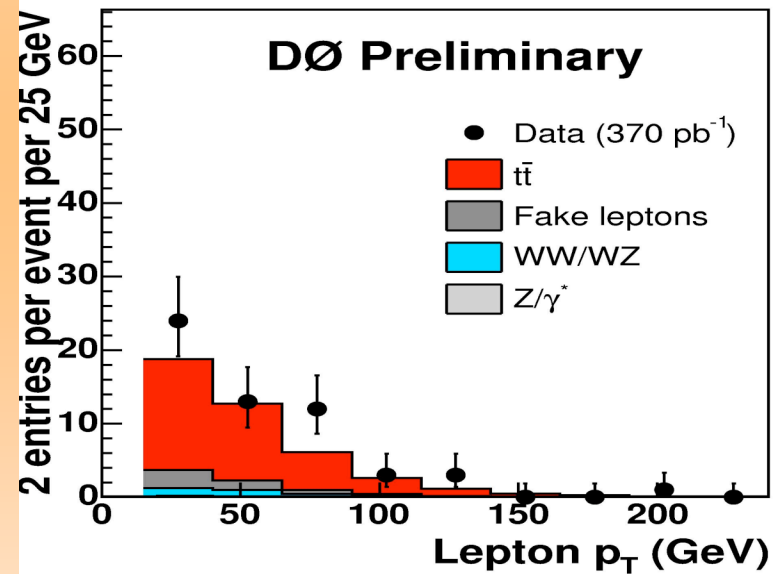
	obs	expected
ee	12	$14.3 \pm 2.2$
$\mu\mu$	24	$16.1 \pm 2.4$
$e\mu$	28	$25.0 \pm 1.5$



	obs	expected
ee	5	$4.5 \pm 0.5$
$\mu\mu$	2	$3.8 \pm 0.5$
$e\mu$	21	$15.8 \pm 2.8$



$\sigma(tt) = 8.3 \pm 1.5 \text{ (stat)}$   
 $\pm 1.0 \text{ (syst)} \pm 0.5 \text{ (lumi)} \text{ pb}$



$\sigma(tt) = 8.6 \pm 2.3 \text{ (stat)}$   
 $\pm 1.1 \text{ (syst)} \pm 0.6 \text{ (lumi)} \text{ pb}$

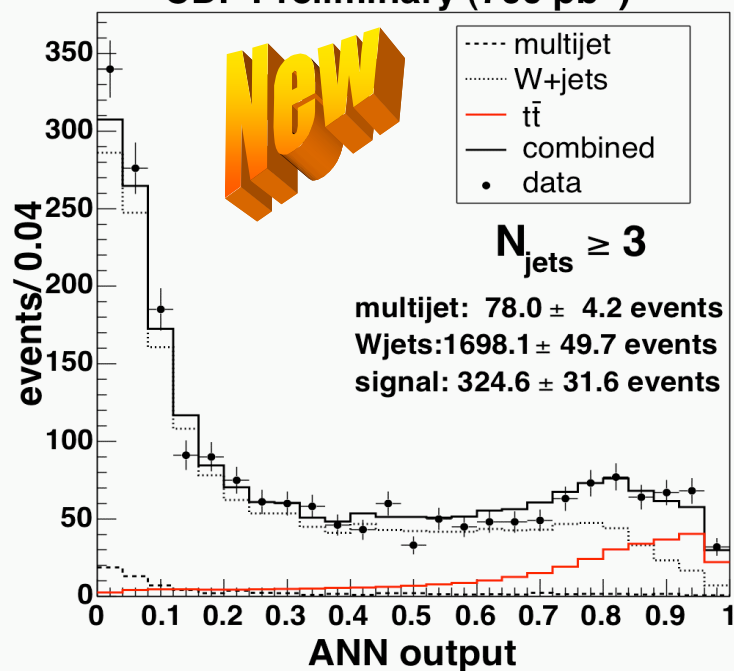
# Lepton+jets cross section



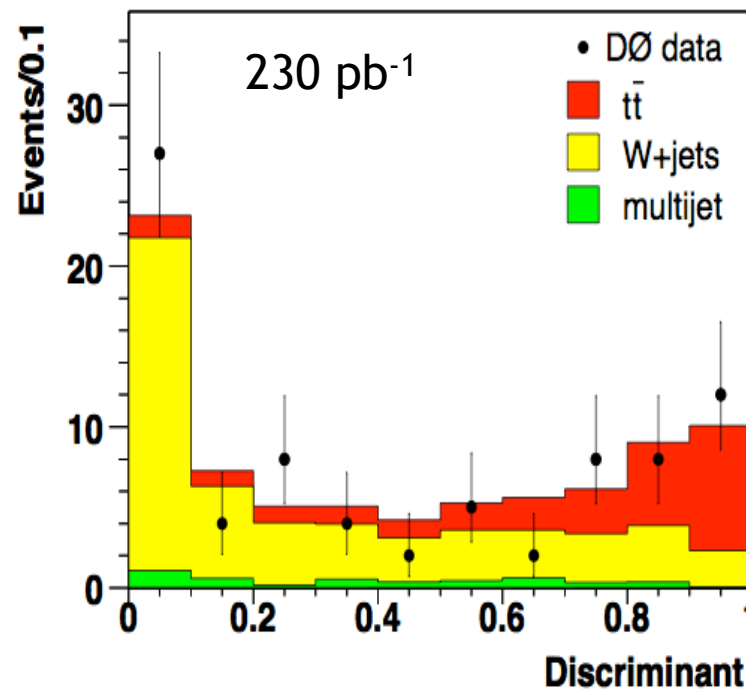
- Topological/kinematical analyses:
- Neural Network (CDF) / Likelihood Discriminant(D0)



CDF Preliminary (760 pb<sup>-1</sup>)

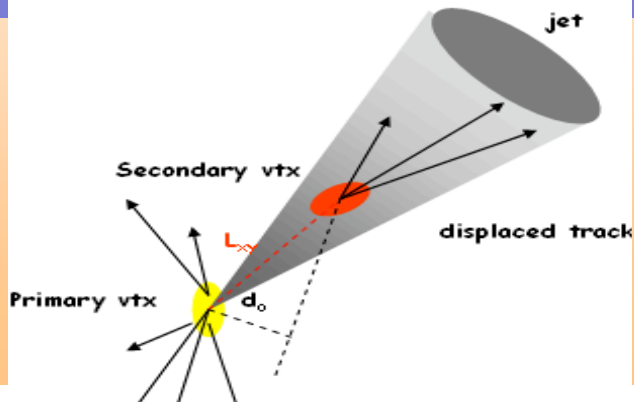
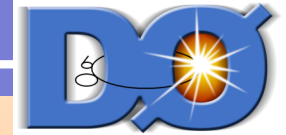


$\sigma(t\bar{t}) = 6.0 \pm 0.6$  (stat)  $\pm 0.9$  (syst) pb



$\sigma(t\bar{t}) = 6.7 \pm 1.4$  (stat)  $\pm 1.4$  (syst) pb

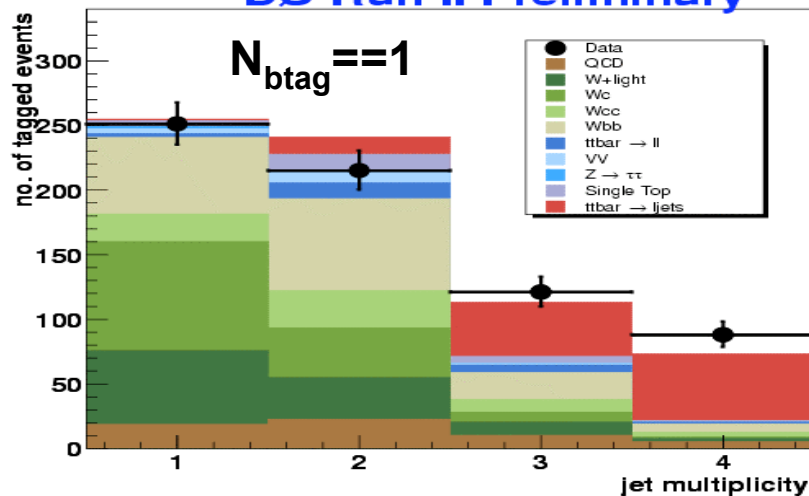
# Lepton + Jets with b-tagging



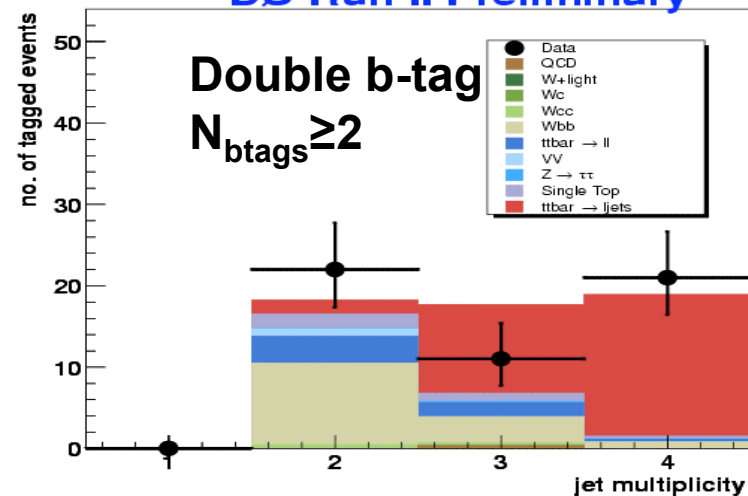
- B-jets are tagged by finding displaced vertex within a jet
- B-quark lifetime  $c\tau \sim 450 \mu\text{m}$
- Reduces backgrounds, increases purity of  $t\bar{t}$

$$L = 365 \text{ pb}^{-1}$$

DØ Run II Preliminary

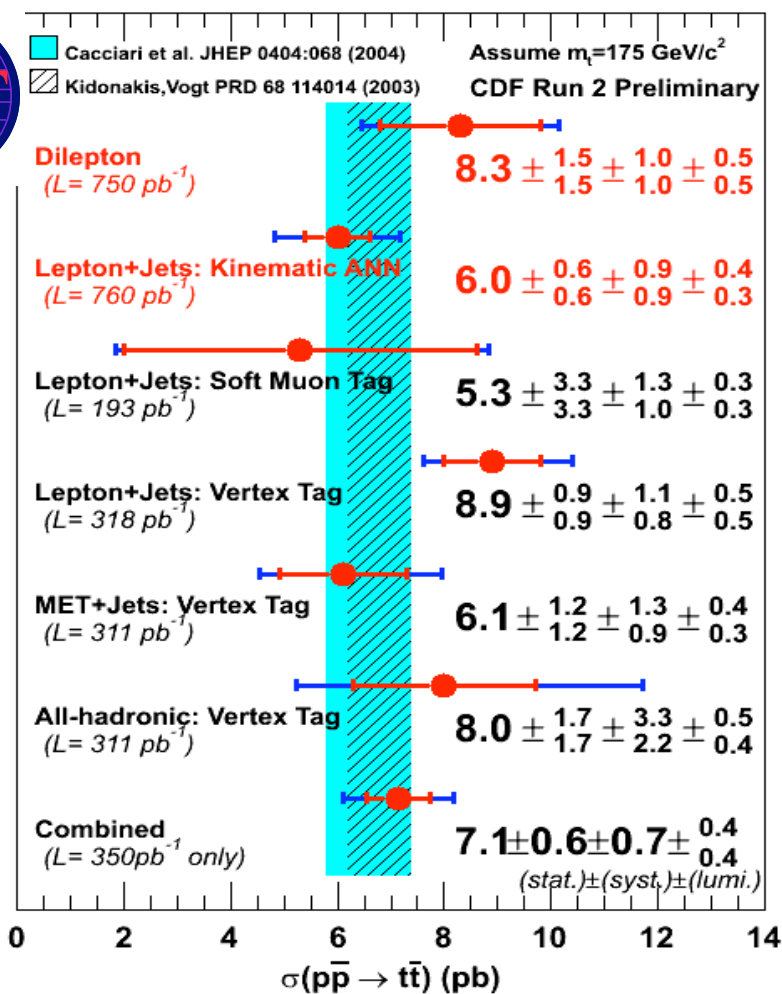


DØ Run II Preliminary

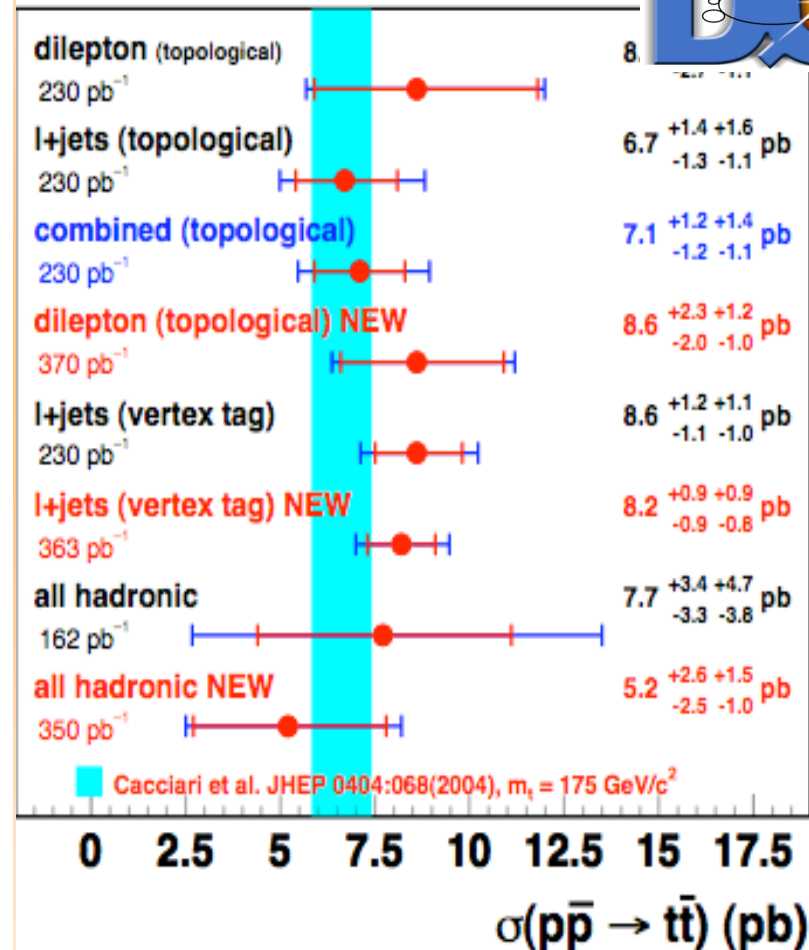


$$\sigma(t\bar{t}) = 8.1 \pm 0.9(\text{stat}) \pm_{0.8}^{0.9}(\text{syst}) \pm 0.5(\text{lumi}) \text{ pb}$$

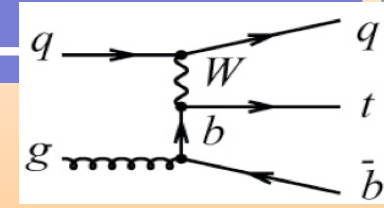
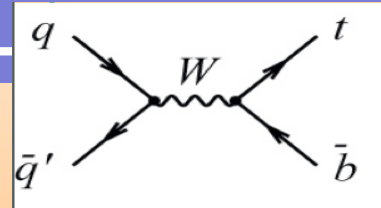
# Top Quark Pair Production: Summary



## DØ Run II Preliminary

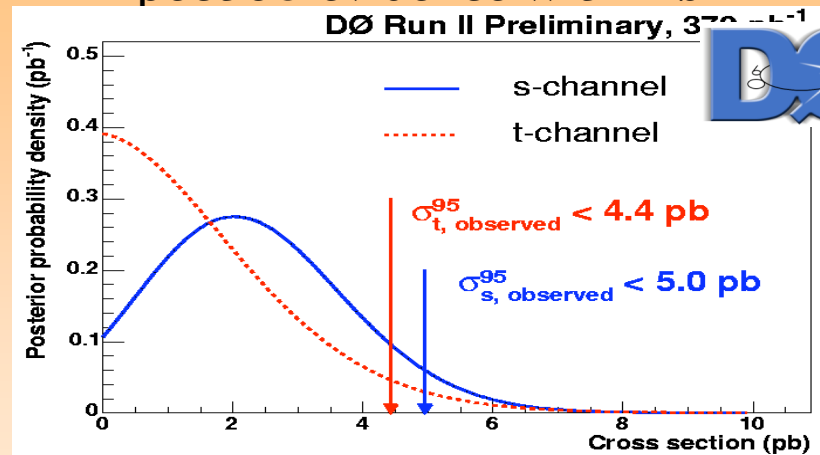
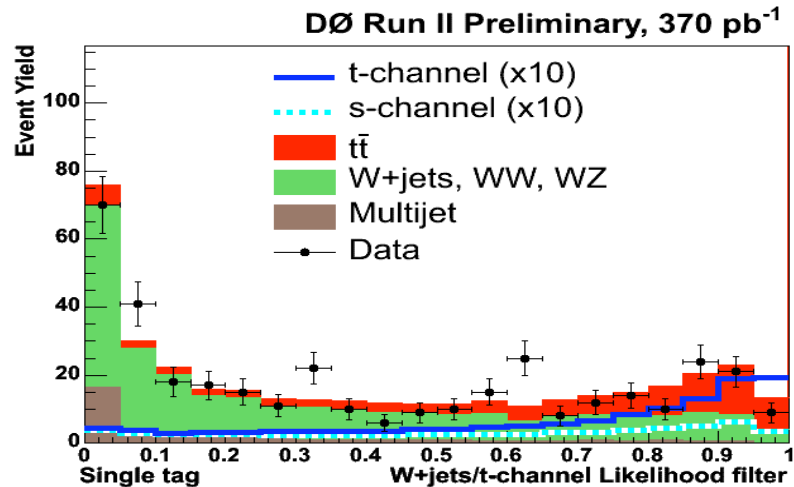
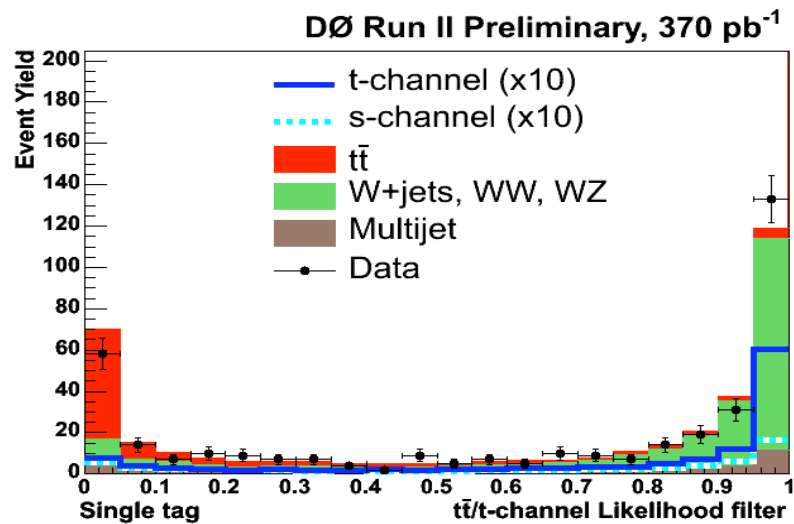


# Single Top Search



$\sigma_s = 0.88 \text{ pb}; \sigma_t = 1.98 \text{ pb}; (\sim |V_{tb}|)$   
 Harris et al PRD 66 054024(2002)

- Lepton + jets,  $\geq 1$  b-tag
- Overwhelming W+jets backgrounds
- Dedicated 2D Likelihood fitter
- Best world's upper limits so far
- Expect  $3\sigma$  evidence with  $2\text{fb}^{-1}$



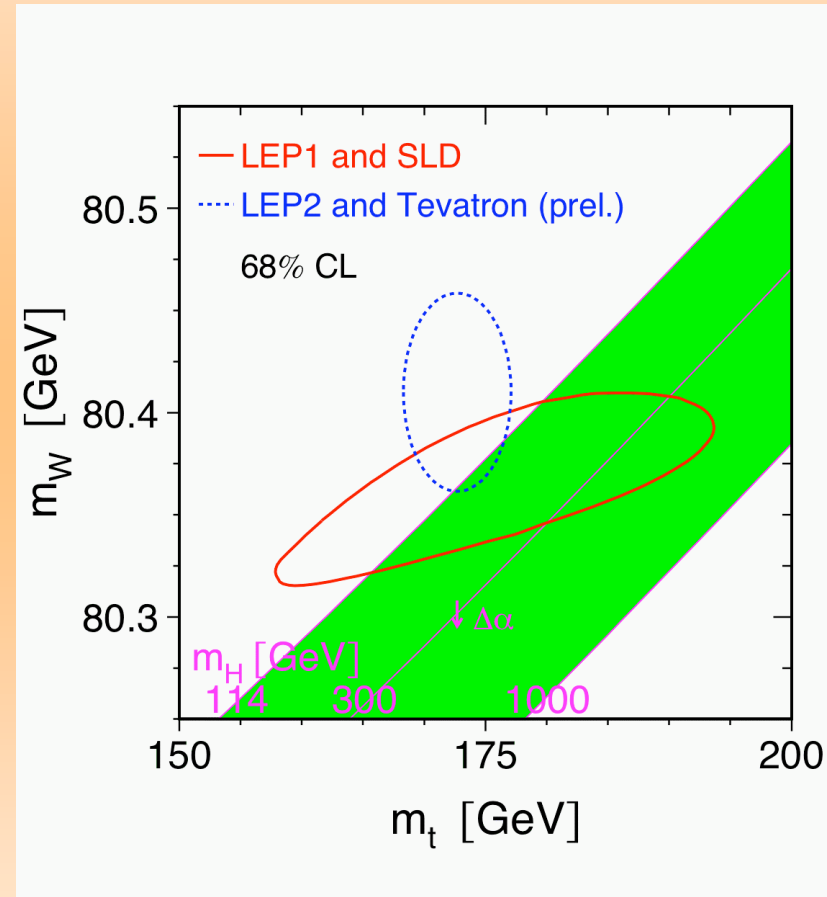
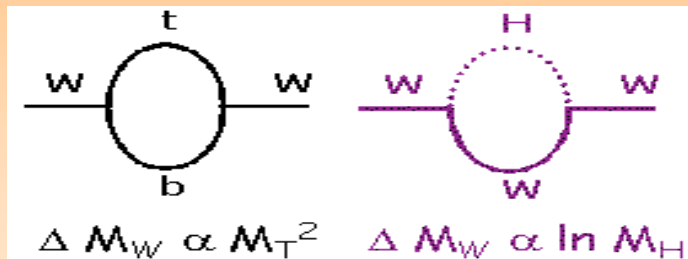
# Top Mass Measurements



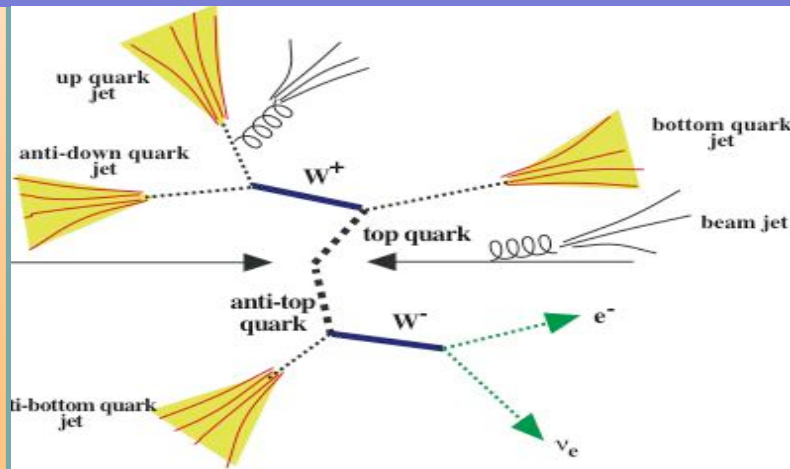


# Top mass relation to Higgs

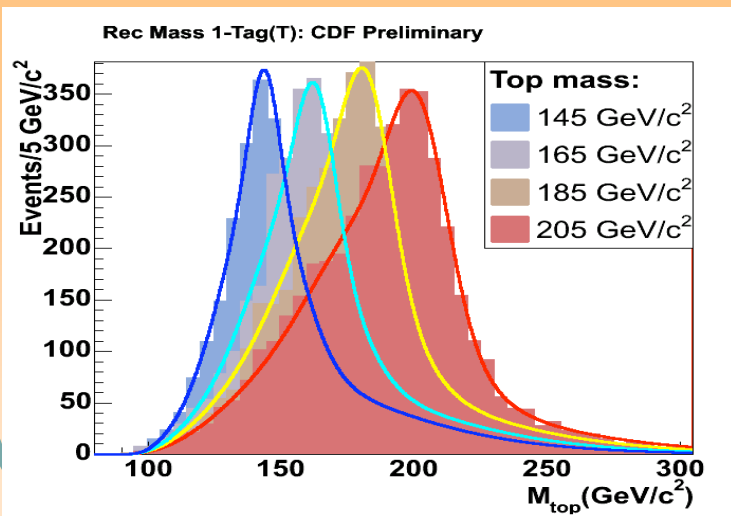
- Top quark mass is a fundamental parameter of SM
- Radiative corrections to SM predictions dominated by top mass
- Together with W mass places a constraint on Higgs mass



# CDF Lepton+jets



- Constrain  $m(jj) = m_W$ ,  $m(\ell\nu) = m_W$  and  $m(\ell\nu b) = m(jj b)$ 
  - 24 possibilities for 0 b-tags
  - 12 possibilities for 1 b-tag
  - 4 possibilities for 2 b-tags
- Select configuration with best  $\chi^2$  fit -> obtain  $M_{reco}$

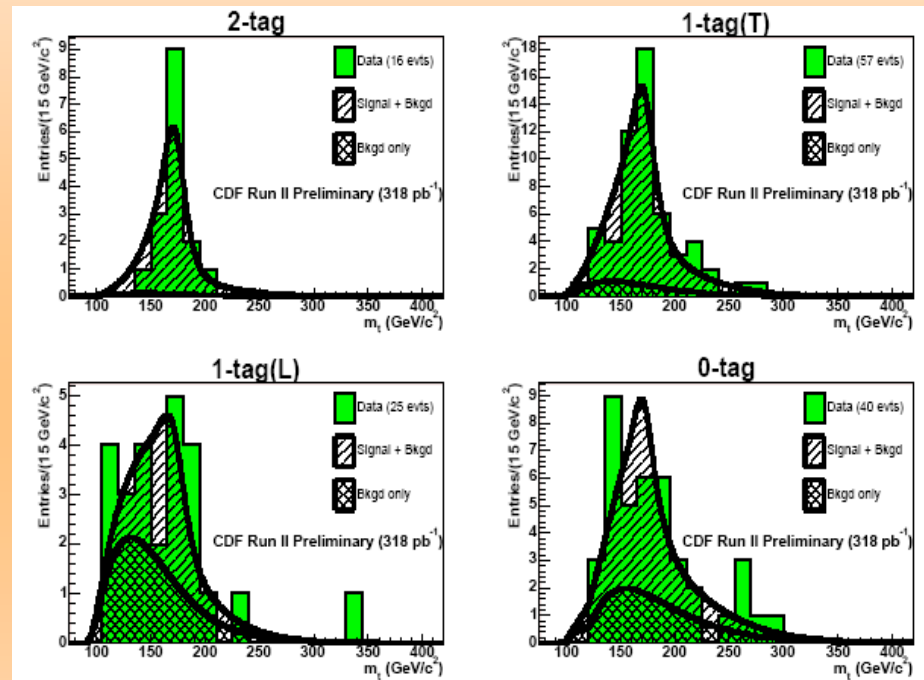


- 2005 New: Jet Energy Calibration in situ
- Simultaneous fit to invariant mass of  $W \rightarrow jj$
- Global factor used to correct energies of jet
- Reduces systematic uncertainty

# CDF $M_{\text{top}}$ Measurement in Lepton+Jets



- Up to date the best single measurement in the world!
- Better than Tevatron Run I average
- Will be shortly updated with  $\sim 750 \text{ pb}^{-1}$



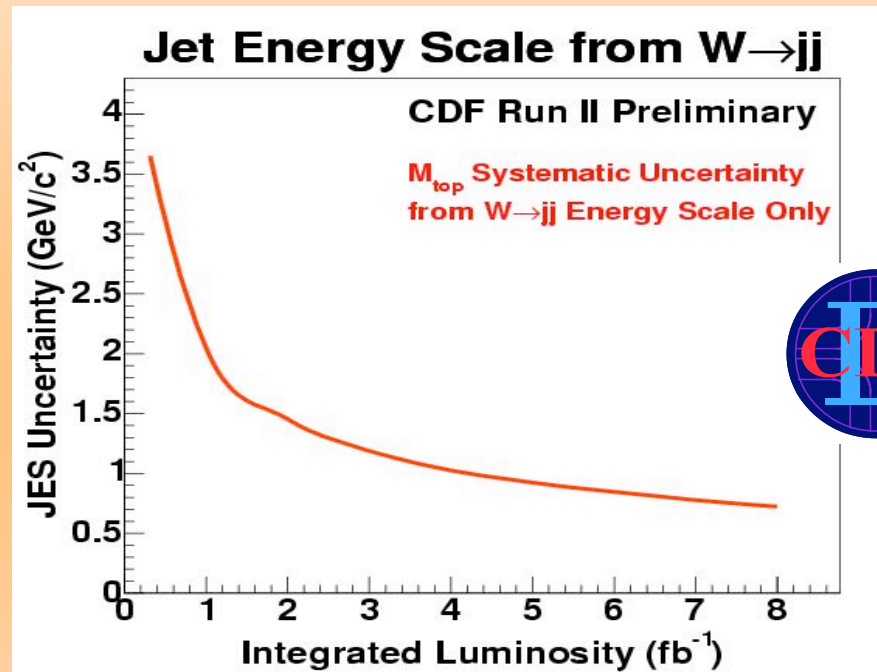
$$m_{\text{top}} = 173.5 \pm_{2.6}^{2.7} \text{ (stat)} \pm 2.5 \text{ (JES)} \pm 1.3 \text{ (syst)} \text{ GeV} / c^2$$

$$\Delta \text{JES} = -0.10 \pm_{0.80}^{0.78} \sigma \text{ (a priori)}$$

*PRD: hep-ex/0510048*  
*PRL: hep-ex/0510049*  
*(accepted)*

# Future Projection

Systematic Source	Uncertainty (GeV/c <sup>2</sup> )
Radiation	0.7
Model	0.7
b-jet	0.6
Method	0.6
PDF	0.3
Total	1.3
Jet Energy	2.5



- Expect significant reduction in JES uncertainty with more data
- Turning JES systematic into a statistical uncertainty

# D0 Matrix Element Technique

Made best single measurement in Run I

- Form probability for each event:

$$P(x; M_{top}) = \frac{1}{\sigma} \int d^n \sigma(y; M_{top}) dq_1 dq_2 f(q_1) f(q_2) W(x, y)$$

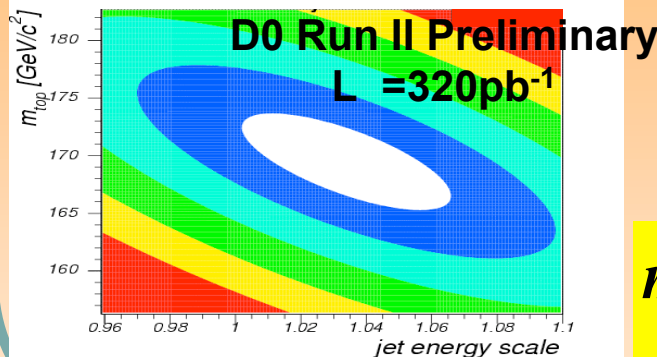
*f(q): parton density functions*

- Consider all permutations

*d<sup>n</sup>σ : LO Matrix element*

*W(x,y): transfer function between jet and parton momenta*

- Maximize Likelihood:  $\prod_i P^i(x; M_{top})$



- Use LO ME for ttbar and W+jets
- Run II Improvements: W->jj energy calibration
- No a priori energy determination

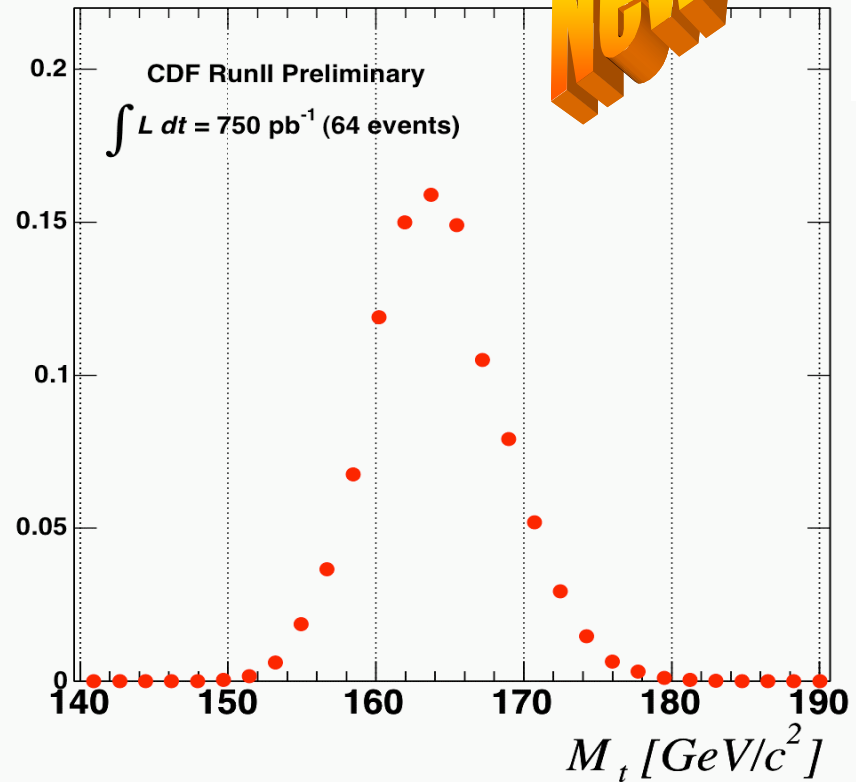
$$m_{top} = 169.5 \pm 3.0_{(stat)} \pm 3.2_{(JES)} \pm 1.7_{(syst)} \text{ GeV} / c^2$$

$$JES = 1.034 \pm 0.034$$

# CDF Dilepton Matrix Element $M_{top}$ Measurement ( $750 \text{ pb}^{-1}$ )

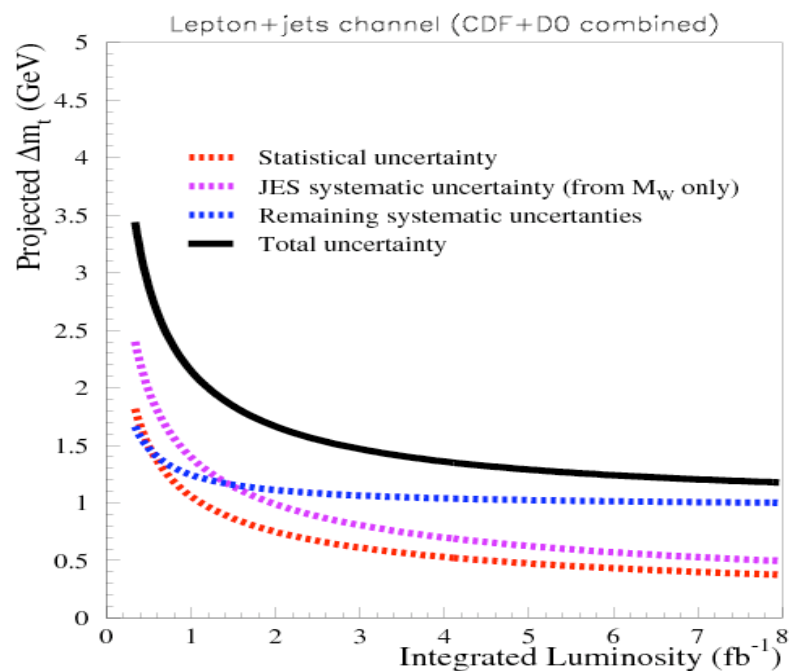
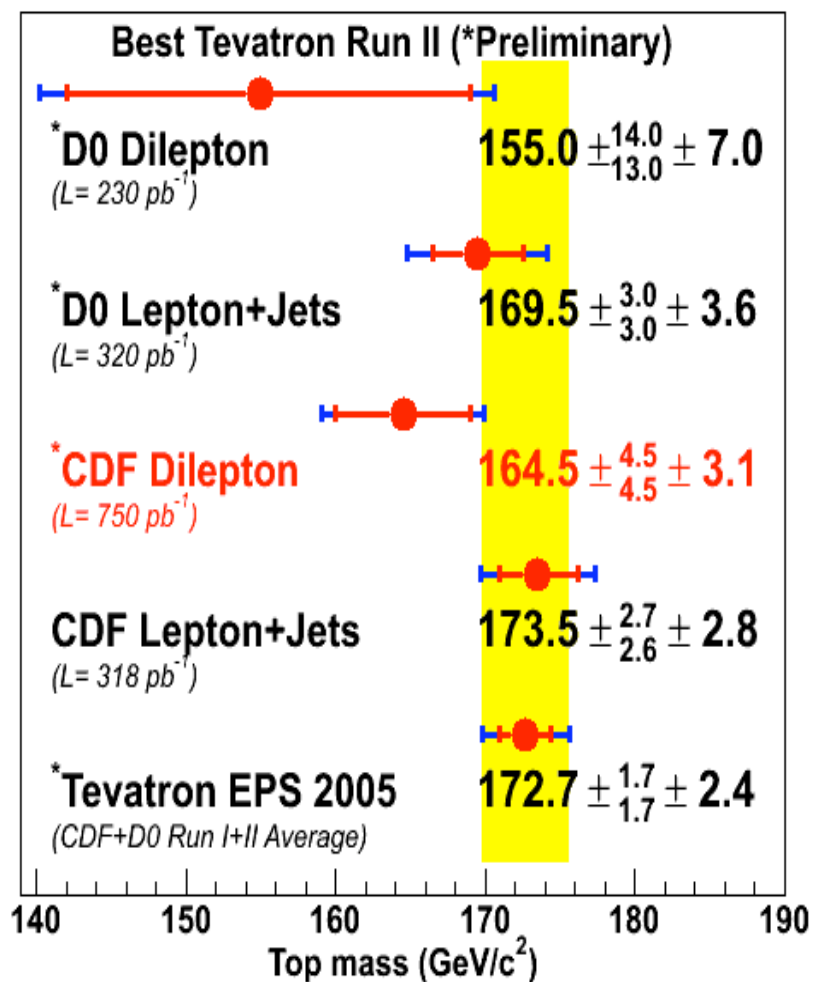
- DIL mode:
  - Reduced combinatorics
  - Only two possible parton-jet assignments
  - Unconstrained kinematics: two neutrinos in the final state
- Background LO Matrix Element treatment
- Best single measurement in Dilepton channel!

Joint Probability Density



$$m_{top} = 164.5 \pm 4.5 \text{ (stat)} \pm 3.1 \text{ (syst)} \text{ GeV} / c^2$$

# Top Mass: Summary



● Expect to get down to 1.5 GeV total uncertainty on top mass

# Searches for $t\bar{t}$ Resonances

$$p\bar{p} \rightarrow X^0 \rightarrow t\bar{t}$$

- Various exotic models predict the existence of particles decaying to  $t\bar{t}$ : **Topcolor-Assisted Technicolor**  
(Hill, Phys Lett. B345, 483 (1995); Hill and Parke Phys. Rev. D49, 4454 (1994))
- Extends technicolor models and attempts to explain EWSB by introducing a new strong interaction
- Predicts new massive bosons “topgluons” and a topcolor Z’



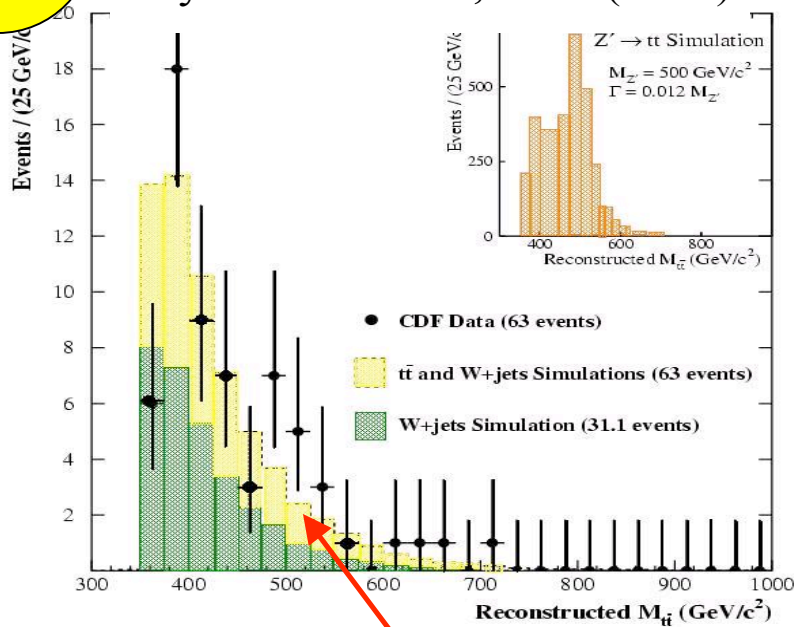
# History: Previous Measurements



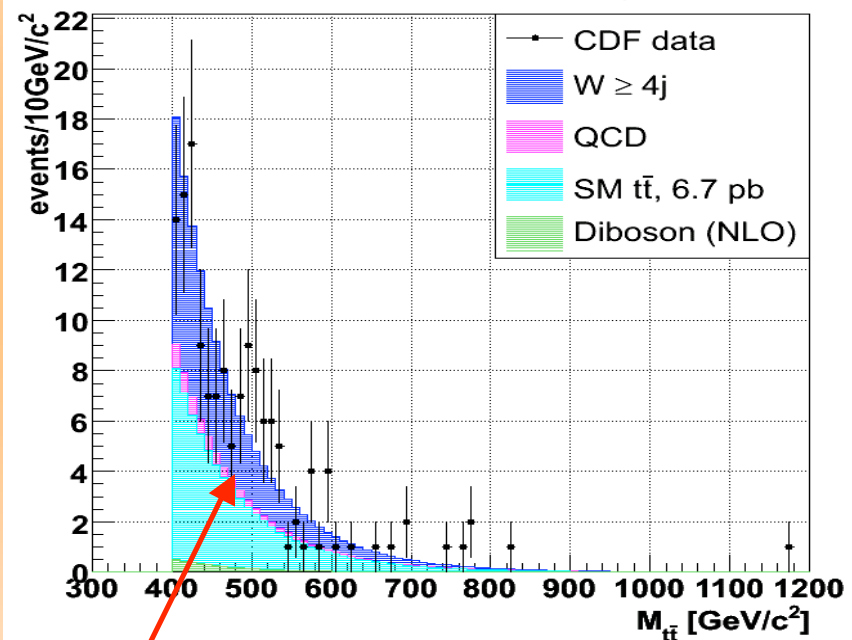
CDF Run 1

- Lepton + jets:

Phys.Rev.Lett. 85, 2062 (2000)

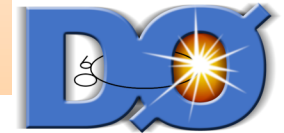


CDF Run 2 preliminary, L=319pb<sup>-1</sup>



- Observed quite intriguing excess around 500 GeV
- Had a similar although smaller excess in Run 1

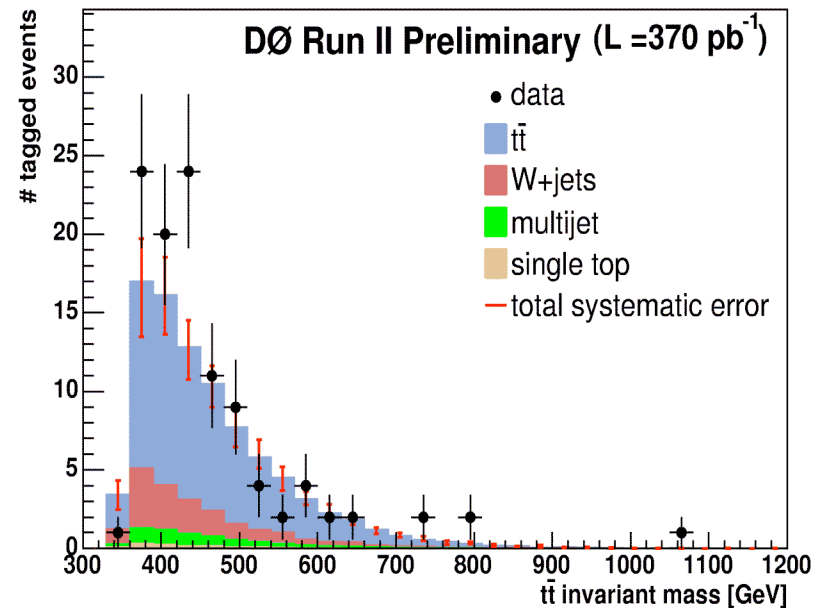
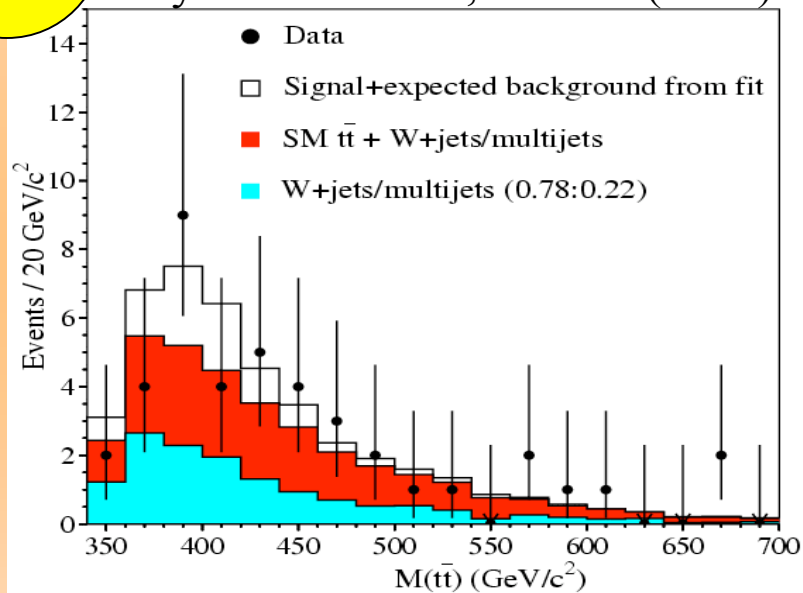
# D0 searches



D0  
Run 1

● Lepton + jets:

Phys.Rev.Lett. 92, 221804 (2004)



● No similar anomaly seen in D0 data

**Excluded with 95%CL**

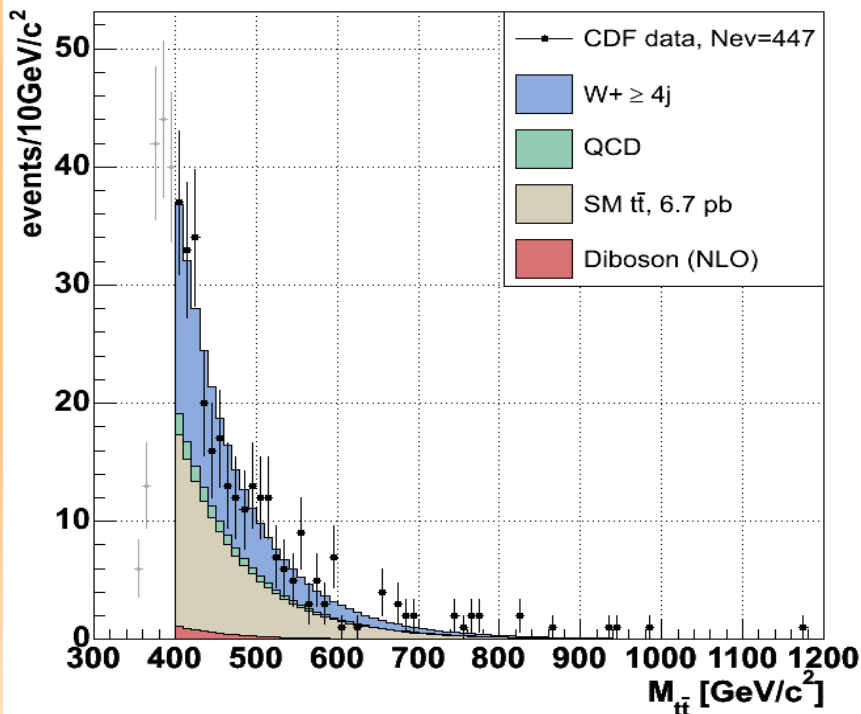
**$M_{Z'} < 680 \text{ GeV}$   
 $(\Gamma_{Z'} = 0.012 M_{Z'})$**

# Latest CDF measurement (682pb<sup>-1</sup>)

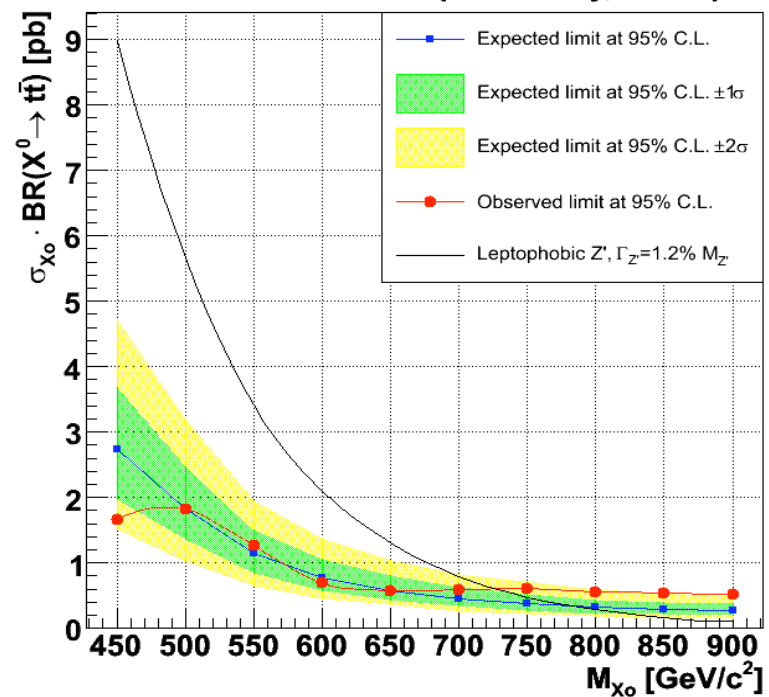


**New**

CDF Run 2 preliminary, L=682pb<sup>-1</sup>



CDF Run 2 preliminary, L=682pb<sup>-1</sup>



● Alas! With about twice more data the excess has washed out!

# Top Quark Properties

- I will cover only the latest measurements:
  - Top Charge
  - Top lifetime
  - New heavy top in the top sample?

# Top Charge

- Is it the Standard Model top ?
- W.-F. Chang et al., Phys. Rev. D 59, 091503 (1999), (hep-ph/9810531) proposes an exotic doublet of quarks  $(Q1, Q4)_R$  with charges  $(-1/3, -4/3)$  and  $M \sim 175$  GeV
- Right-handed b quark mixes with the isospin  $+1/2$  component
- while  $M_{\text{top}} \sim 274$  GeV escaped detection
- $q = -4/3$  is consistent with EW data, new b-couplings improve the EW fit (E. Ma et al. , hep-ph/9909537)

# Top Quark Charge Measurement

Lepton+jets, double b-tag events

Determine:

- charge of W (lepton)
- pairing between W and b ( $\chi^2$  fit)
- flavor of b-jet

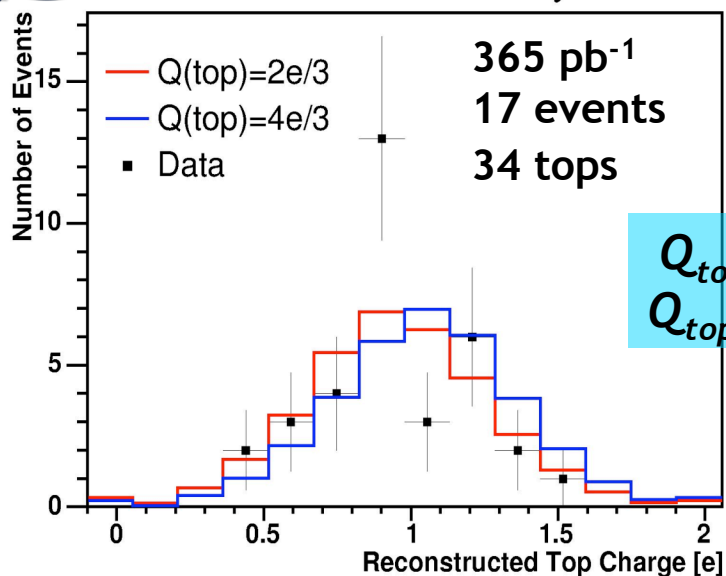
**Jet Charge:**

$$Q_{jet} = \frac{\sum q_i p_{Ti}^{0.6}}{\sum p_{Ti}^{0.6}}$$

(sum over tracks within a jet)



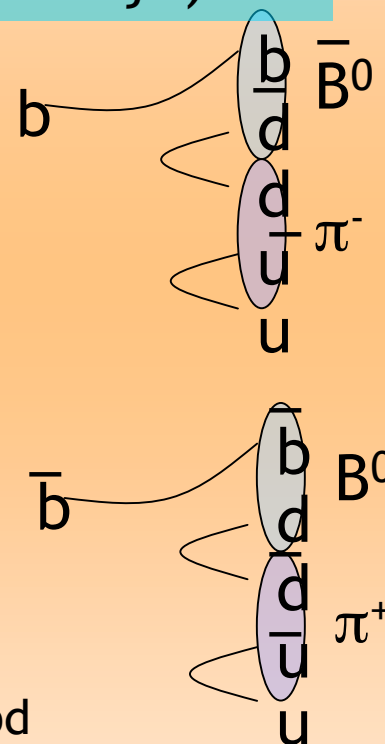
DØ Run II Preliminary



$$Q_{top,1} = |q_l + q_{b(l)}|$$

$$Q_{top,2} = |-q_l + q_{b(j)}|$$

Perform likelihood ratio test



# Top Quark Charge Measurement

Lepton+jets, double b-tag events

Determine:

- charge of W (lepton)
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- flavor of b-jet

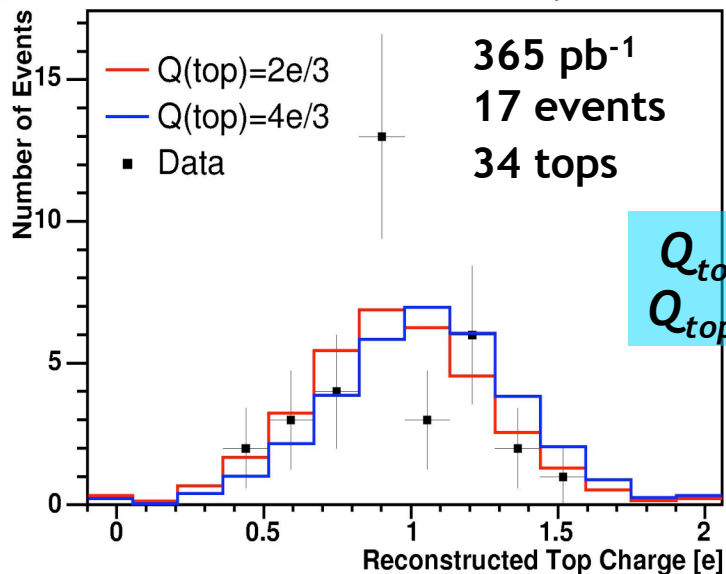
**Jet Charge:**

$$Q_{jet} = \frac{\sum q_i p_{Ti}^{0.6}}{\sum p_{Ti}^{0.6}}$$

(sum over tracks within a jet)

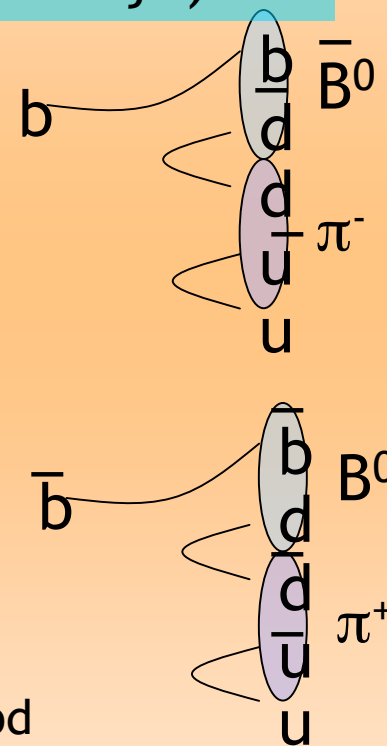


DØ Run II Preliminary



$$Q_{top,1} = |q_l + q_{b(l)}|$$

$$Q_{top,2} = |-q_l + q_{b(j)}|$$

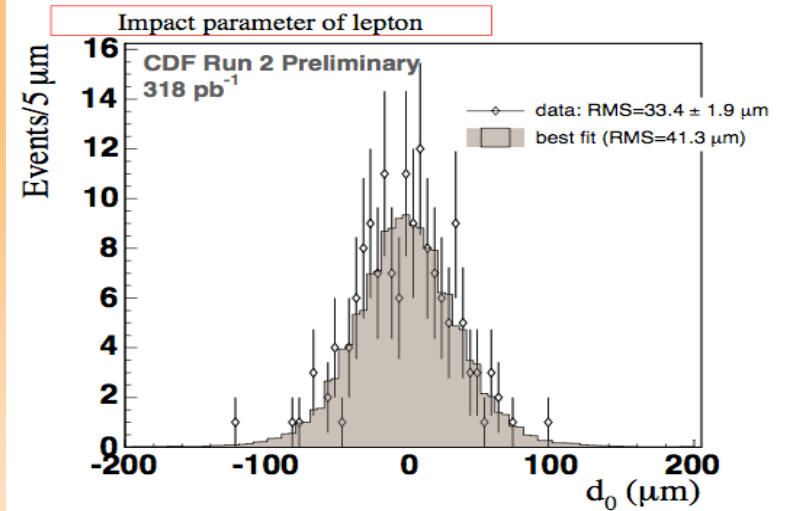


Perform likelihood ratio test:

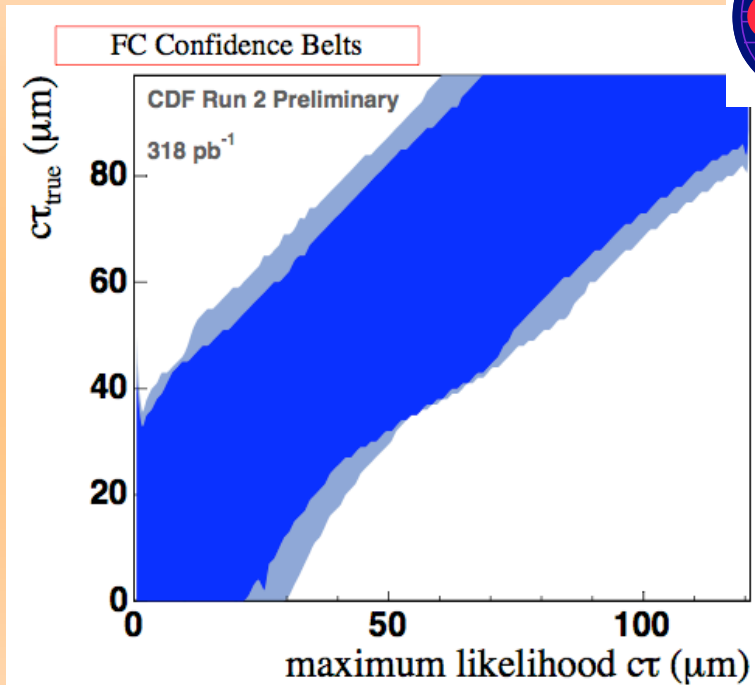
**Excluded  $Q=4/3$  with 94%CL**

# Top Lifetime

- Within the SM  $\tau_{\text{top}} \sim 10^{-24}$  s
- Long-lived top?
- Use  $d_0$ -lepton impact parameter with respect to beamline
- Determine detector resolution from  $Z^0/\gamma \rightarrow e^+e^-/\mu^+\mu^-$



Fit combination of signal/BG templates to the data: lepton+jets with  $\geq 1$  b-tag



$c\tau < 52.5 \mu\text{m}$  with 95% CL

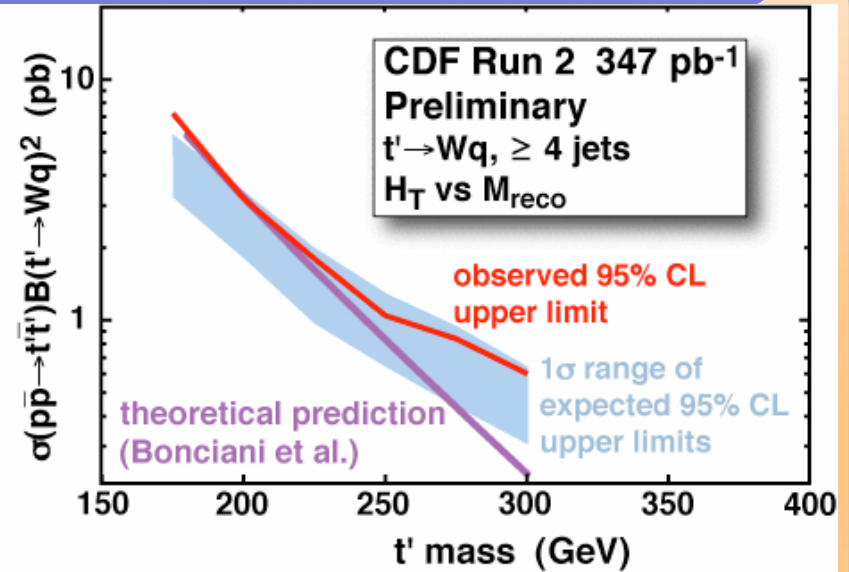
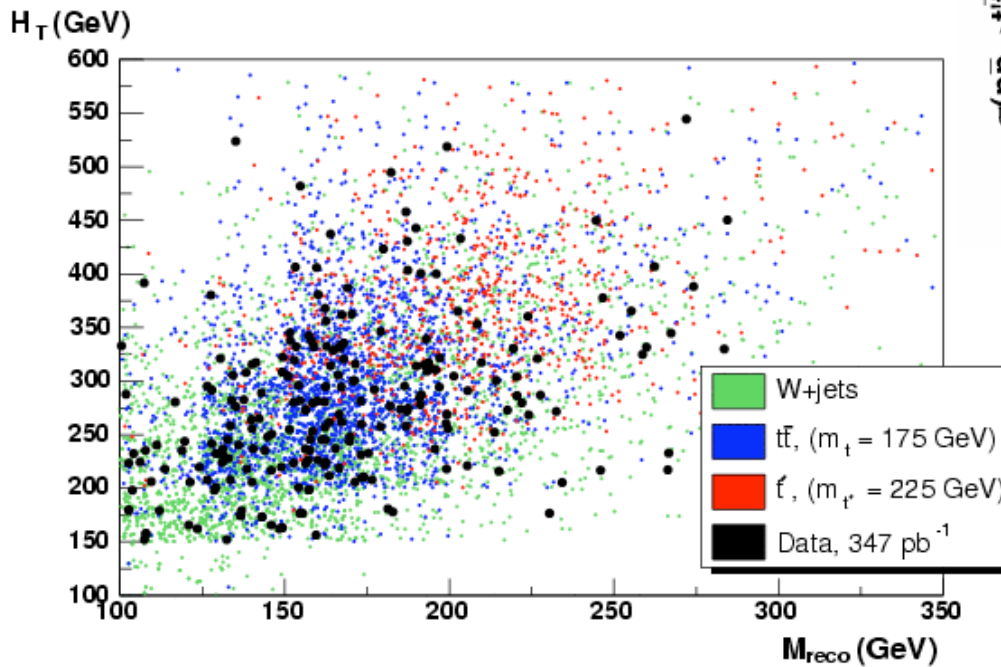




# New Heavy Particles Decaying to $Wq$ ?

- Can be a fourth generation up-type quark  
He/Polonsky/Su (hep-ph/0102144)  
a generic 4th chiral generation is consistent with EWK data;  
accommodates a heavy Higgs (500 GeV) without any other new physics
- “Beautiful Mirrors” model  
Wagner et al (hep-ph/ 0109097)  
predicts a new heavy up-type quark decaying to  $Wb$ ; naturally  
accommodates the LEP  $b$  forward-backward asymmetry results
- From the precision EWK data the mass splitting between a  $t'$  and a  
 $b'$  quark is relatively small. Therefore if  $M_{t'} < M_{b'} + M_W$ :  $t' \rightarrow W$   
 $b(q)$  (promptly)
- CDF Search in Lepton + jets channel: 2D-fit with
  - $H_T$  = sum of transverse momenta of all objects in the event
  - $M_{\text{reco}}$  from  $\chi^2$ -fit

# Search for $t' \rightarrow Wq$



- Set a limit on 4th generation up-type quark pair production
- Data did not cooperate well

Excluded  $t'$   
 $196 < m_{t'} < 207 \text{ GeV}$

# Conclusions

- Future is now! We are taking and analyzing Tevatron data
- Many other analyses utilizing datasets of integrated luminosity  $\sim 700 \text{ pb}^{-1}$  are being finalized
- Results will be presented at the forthcoming Winter conferences
- Stay tuned for  $1 \text{ fb}^{-1}$  results at the Summer conferences (x10 of Run I)
- No evidence for the top quark being non-Standard Model so far
- More precise measurements of the top mass ( $\sim 1.5 \text{ GeV}$  uncertainty) and other quantities coming soon