Progress in Top Quark Physics

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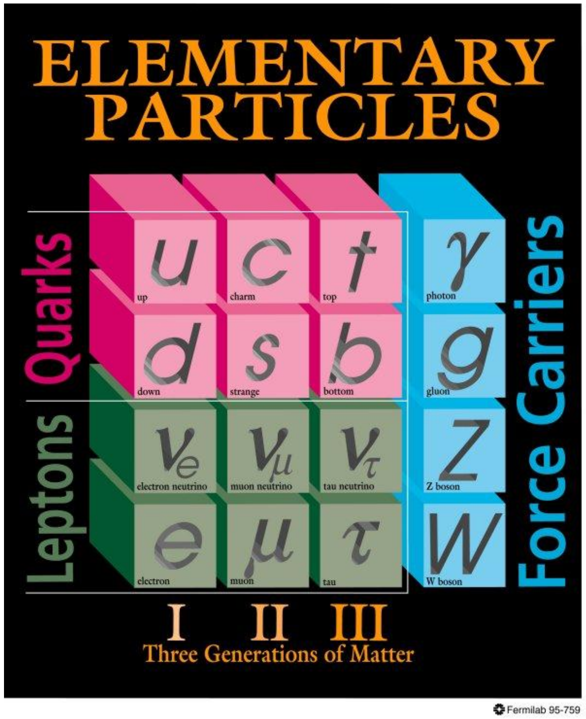
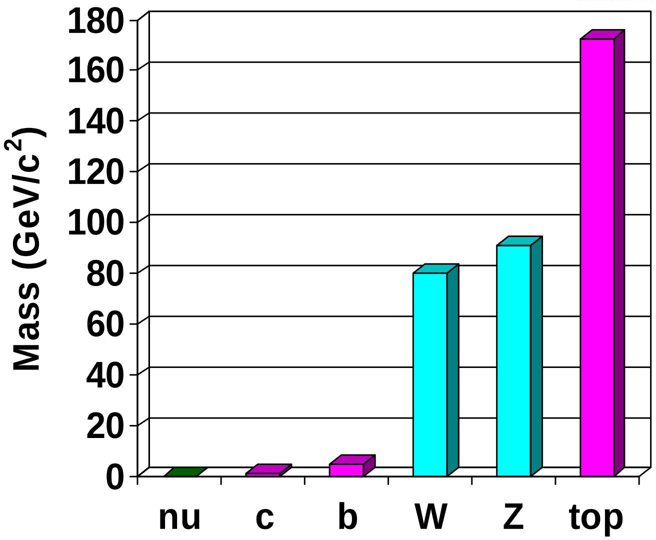
XVII Particles and Nuclei International Conference
Plenary session 28 October 2005

CDF+D0 parallel session talks:
V.4 Peter Renkel *"Top Quark Mass Measurement in Lepton+Jets Channel"*
V.4 Tuula Maki *"Top Quark Mass Measurement in Dilepton Channel"*
V.4 Robert Kehoe *"Top Quark Pair Production Cross Section Measurement"*
V.4 Charles Plager *"Measurements of Top Quark Decay Properties"*
V.4 Valentin Necula *"Search for Resonances in Top Quark Pair Production"*
V.4 Yurii Maravin *"Search for Single Top Quark Production"*
VI.2 Ben Kilminster *"Search for SM and MSSM Higgs Bosons"*

Motivation

- **Most massive elementary particle**
  - Discovered in 1995 by CDF and D0
  - Only few dozen candidates in 0.1 fb^{-1}
- **Is it really Standard Model top? Any effects from new physics?**
  - Only CDF and D0 can study top until LHC
  - Large 1 fb^{-1} data sample for Winter 2006
- **Top quark mass is a fundamental parameter in the Standard Model and beyond…**
  - Huge top quark mass induces significant radiative corrections to W boson mass
  - Reduced uncertainty on top quark mass imposes tighter constraints on unknowns, like Standard Model Higgs boson or SUSY
- **Significant background to many searches for new physics at LHC**



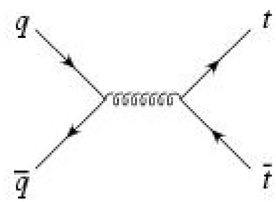


Top Quark Production & Decay

Produce in pairs via strong interaction

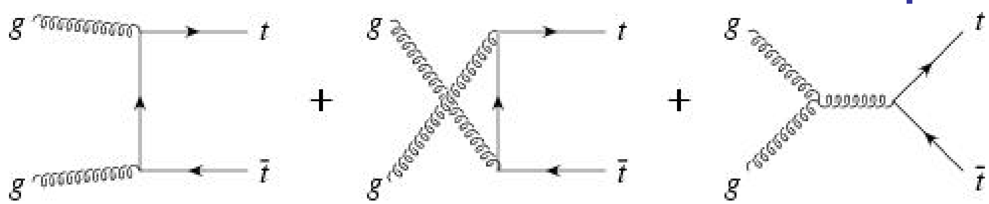
Cacciari et al. JHEP 0404:068 (2004)
Kidonakis & Vogt PRD 68 114014 (2003)

At $\sqrt{s}$=1.96 TeV:
85% qq
15% gg



m_t (GeV/c^2)	σ(pb) Min	Central	Max
170	6.8	7.8	8.7
175	5.8	6.7	7.4

At $\sqrt{s}$=14 TeV:
10% qq
90% gg
σ = 833 ± 100 pb

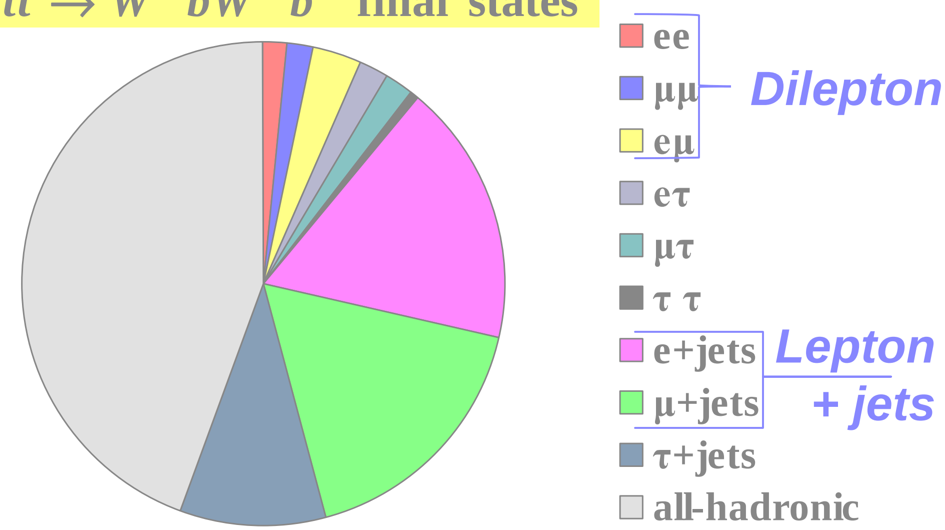


Decay singly via electroweak interaction t→W⁺b

$t\bar{t} \rightarrow W^+ bW^- \bar{b}$ final states

t→Wb has ~100% branching ratio
Width ~1.5 GeV so lifetime 10^{-25}s
No top mesons or baryons!

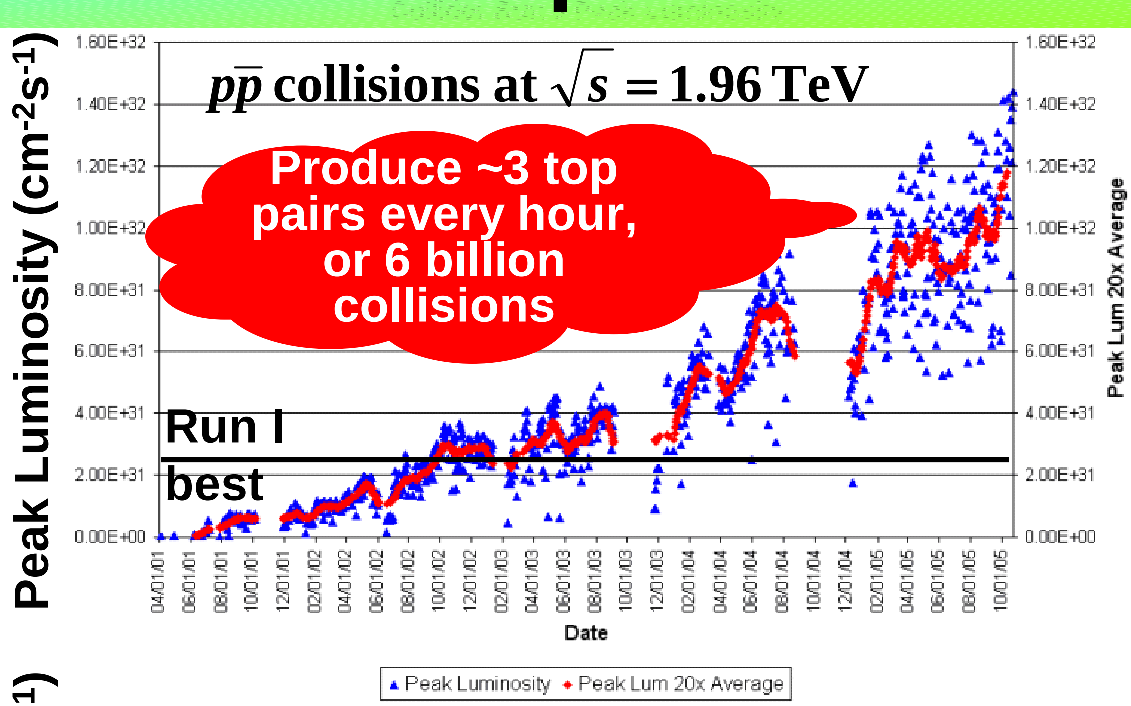
Final state characterized by number and type of charged leptons from decay of W^+ and W^- bosons

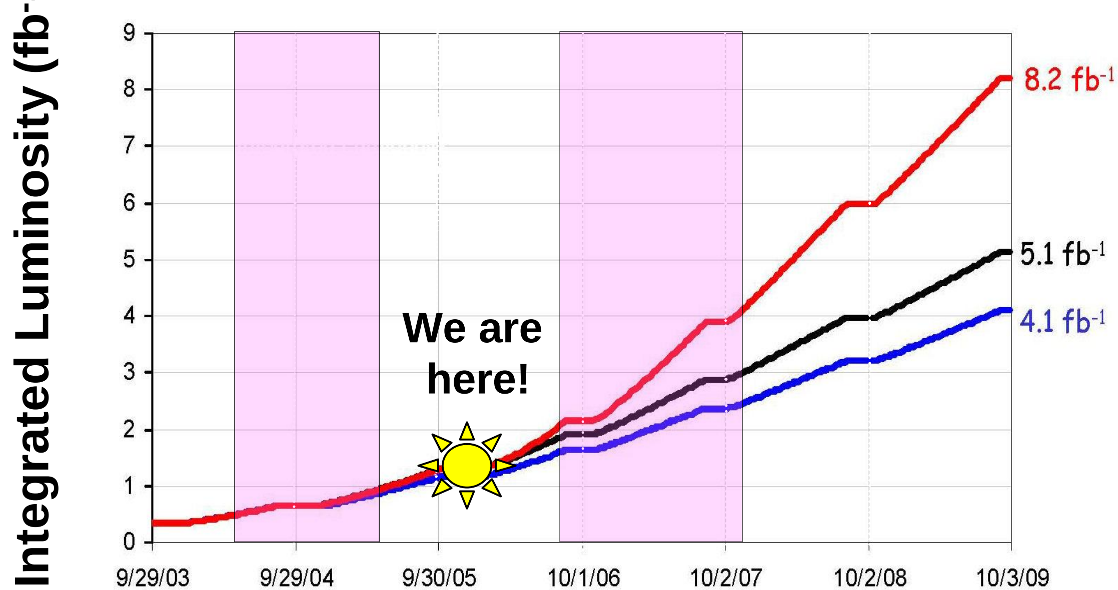


(Note e includes $\tau \rightarrow e\bar{\nu}_e\nu_\tau$ and μ includes $\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$)

Snapshot of Tevatron Operation

- World Record Peak Luminosity yesterday!
  - $1.58 \times 10^{+32} cm^{-2}s^{-1}$
- Deliver 8 fb^{-1} if all upgrades succeed
  - Note electron cooling upgrade making good progress!
- Deliver 4 fb^{-1} even if no further improvements
- Already delivered over 1fb^{-1} to experiments





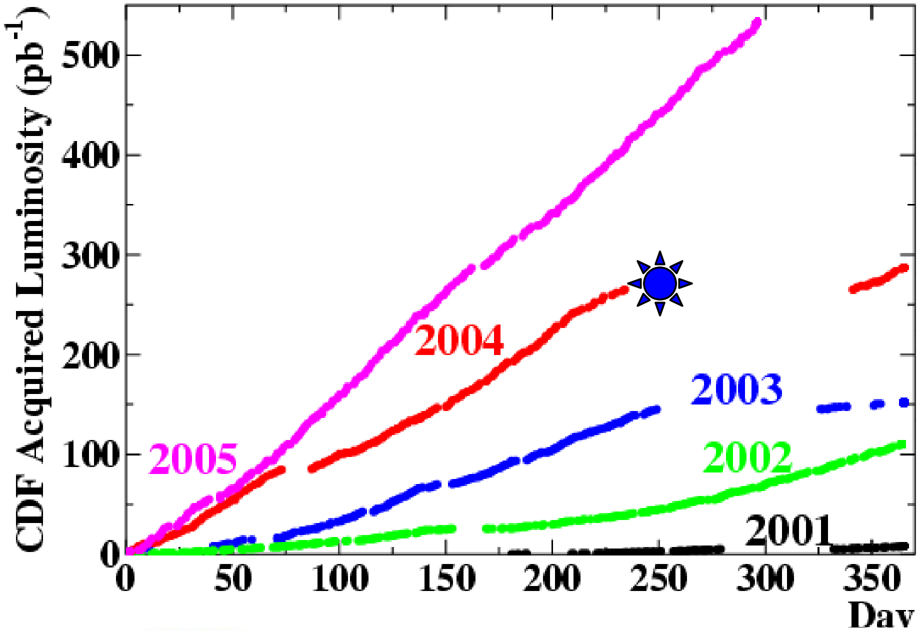
Snapshot of CDF & DO Data

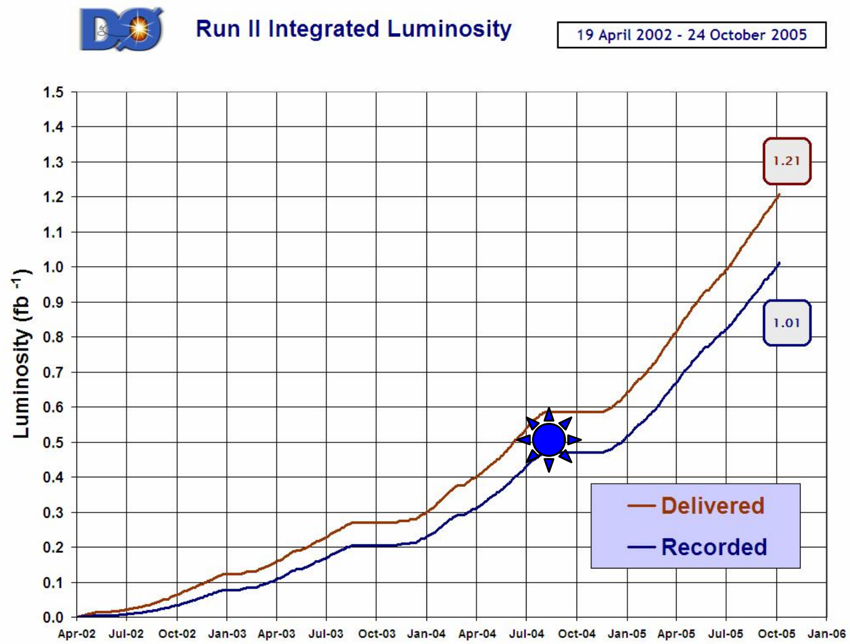
- Current top quark physics results from ~350 pb^{-1} of data up to September 2004

- 2005 excellent year for CDF and D0!

- Both experiments have collected over 1 fb^{-1} of data at $\sqrt{s}$=1.96 TeV

- Watch out for top results with 1 fb^{-1} at Moriond 2006





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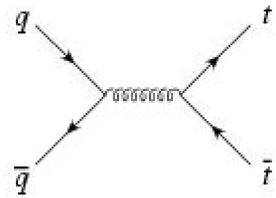

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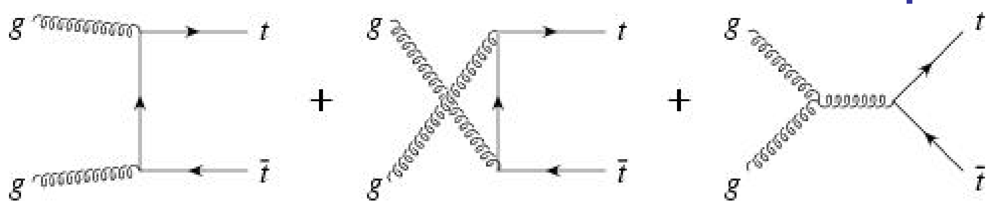

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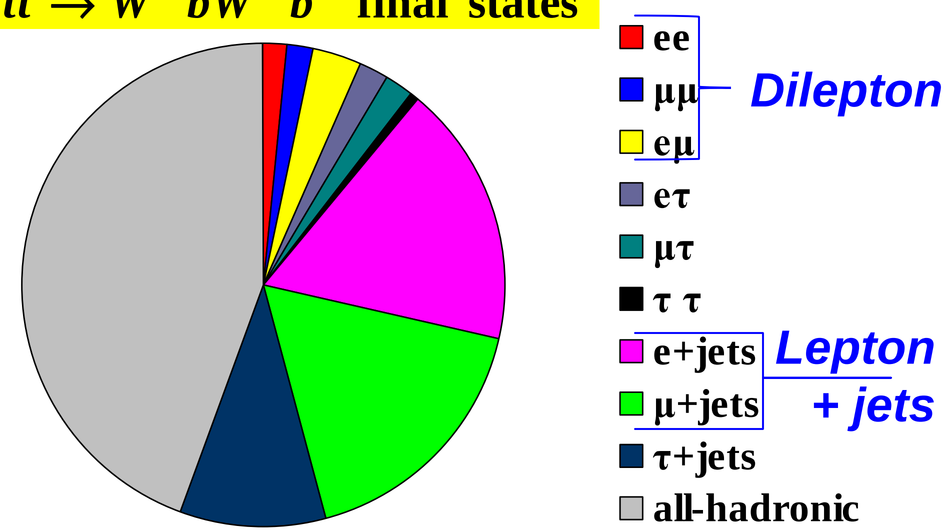


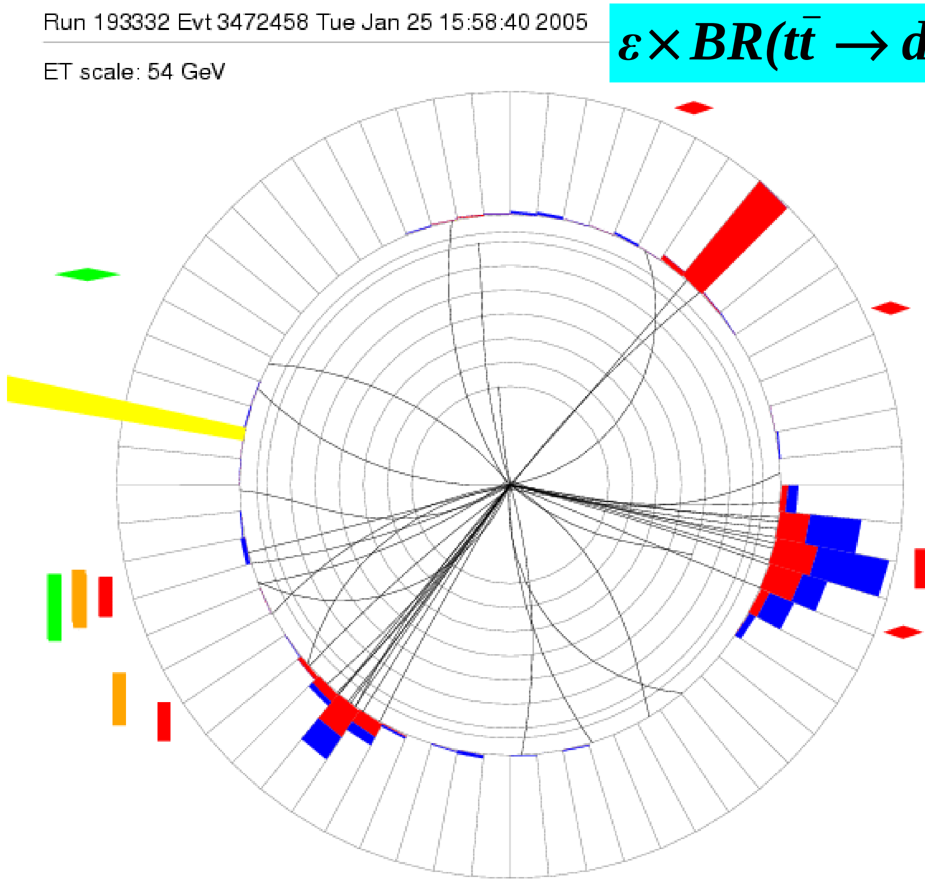
(Note e includes $\tau \rightarrow e\bar{\nu}_e\nu_\tau$ and μ includes $\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$)

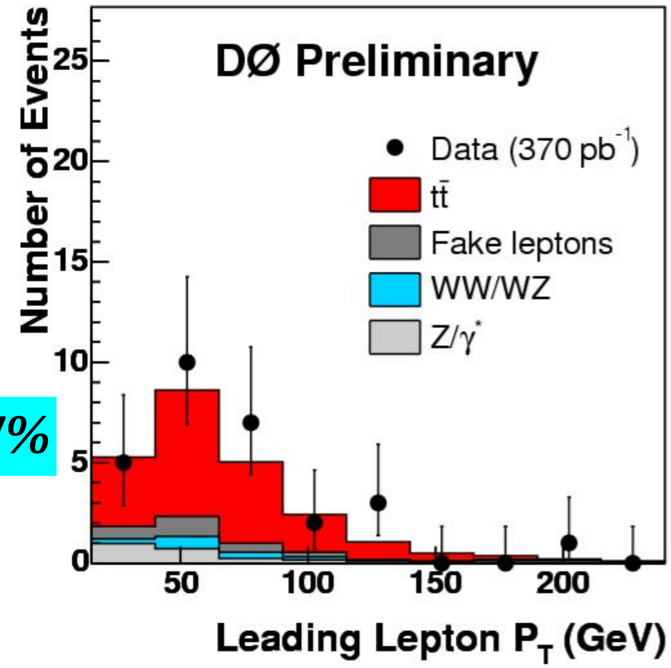
Dilepton

$\sigma(t\bar{t}) = 8.6 \pm^{2.3}_{2.0} \text{(stat)} \pm^{1.2}_{1.0} \text{(syst)} \pm 0.6 \text{(lumi) pb}$

Events	ee	μμ	eμ	Total
Bkg	1.0±0.3	1.3±0.4	4.5±2.2	6.8±2.2
Data	5	2	21	28

$\varepsilon \times BR(t\bar{t} \rightarrow dilepton) \approx 0.7\%$





2 isolated electrons/muons p_T>15 GeV/*c*

At least 2 jets p_T>20 GeV/*c*

Reduce backgrounds:

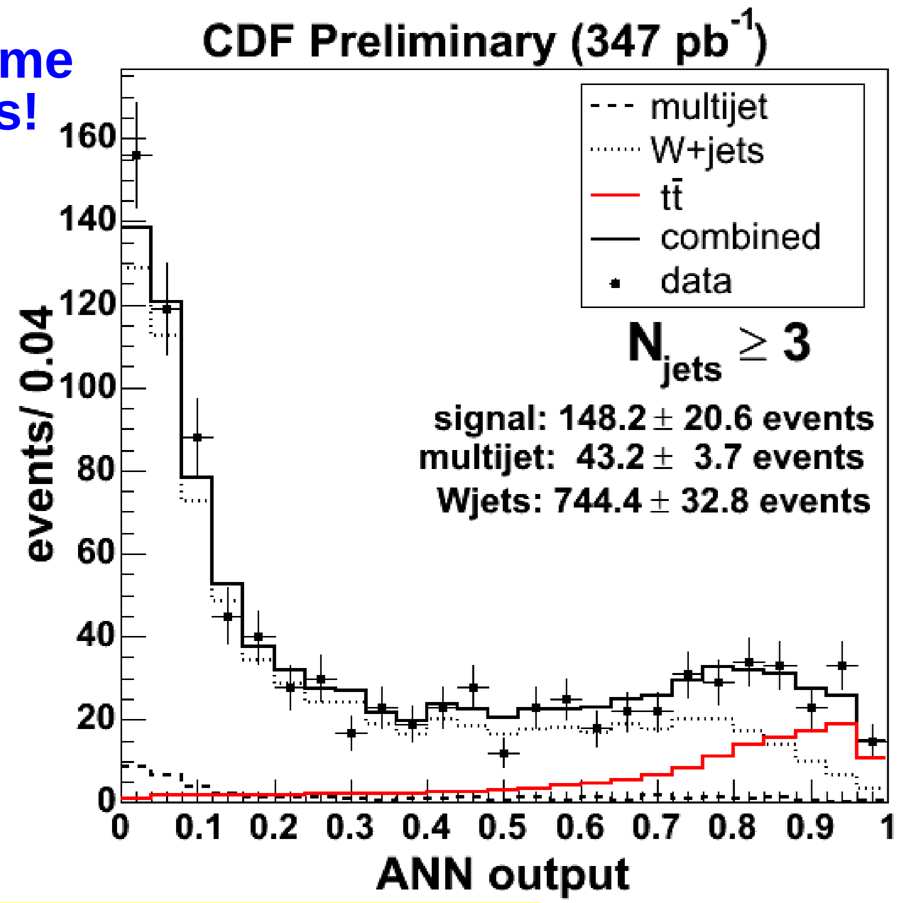
- ***Z/γ*→ee* with MET and sphericity**
- ***Z/γ*→μμ* with MET and χ^2 consistency with Z mass**
- ***Z/γ*→ττ→$e\upsilon_e\upsilon_\tau\mu\upsilon_\mu\upsilon_\tau$* with Σp_T of jets and leading lepton**
- **Instrumental with multivariate likelihood electron id in ee channel**

Lepton+Jets

1 isolated electron/muon p_T>20 GeV/c
At least 3 jets p_T>15 GeV/c
MET>20 GeV

$\varepsilon \times BR(t\bar{t} \rightarrow {}^{a} + jets) \approx 7\%$

Need more discrimination against same final state from W+jets processes!



Kinematic event observables

ØDecay products of massive top quarks more energetic and central than W+jets

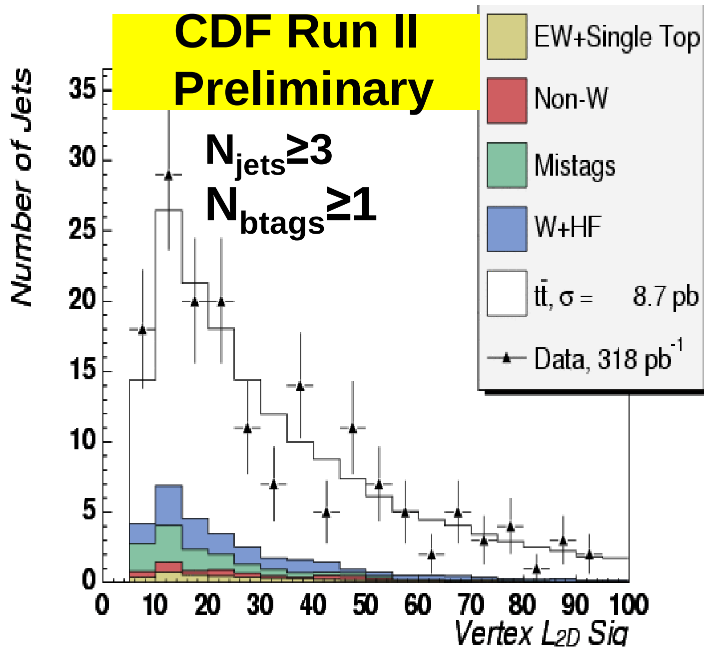
ØCombine several kinematic observables in optimal artificial neural network

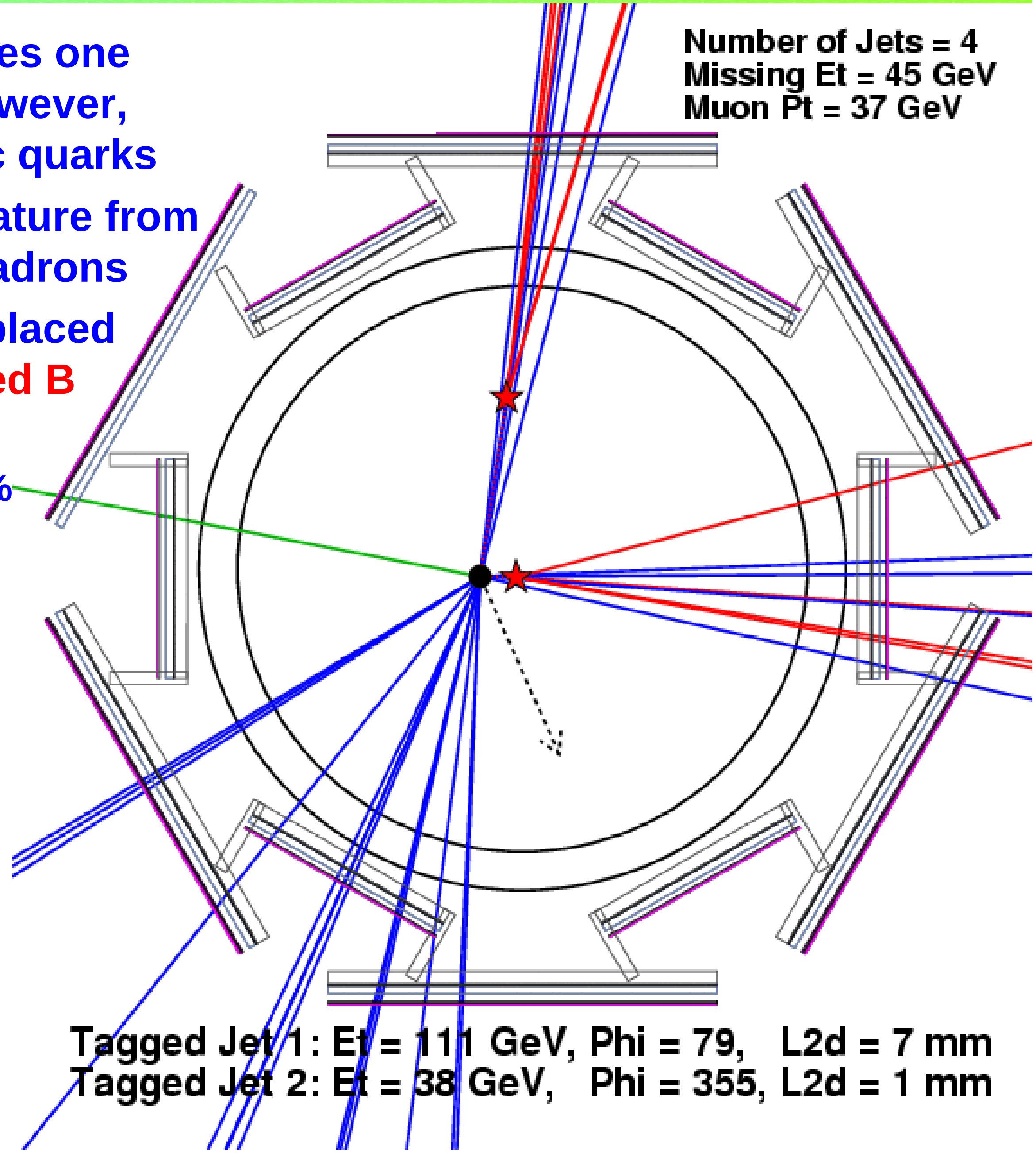
ØFit observed data to expected distributions from signal and backgrounds

$$\sigma(t\bar{t}) = 6.3 \pm 0.8(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 0.4(\mathrm{lumi})\,\mathrm{pb}$$

Lepton+Jets with b-tagging

- Each top quark decay produces one energetic central b-quark, however, only few % W+jets have b or c quarks
- Distinctive experimental signature from long lifetimes of massive B hadrons
- Reconstruct significantly displaced secondary vertex from charged B decay products inside jet
  - Efficiency per b-jet about 50%
  - False positive rate about 1%





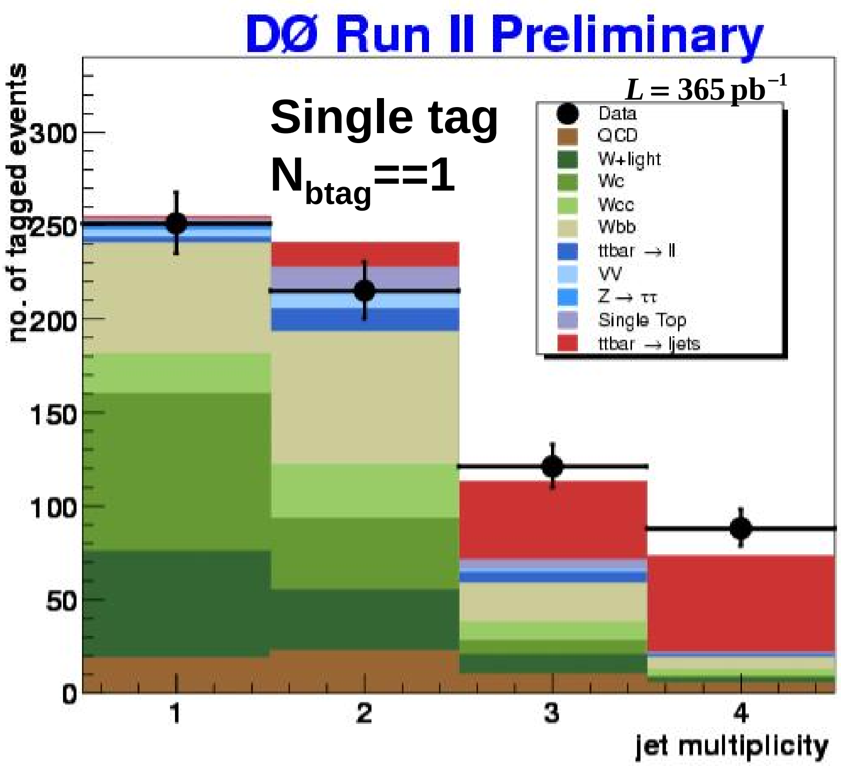
Lepton+Jets with b-tagging

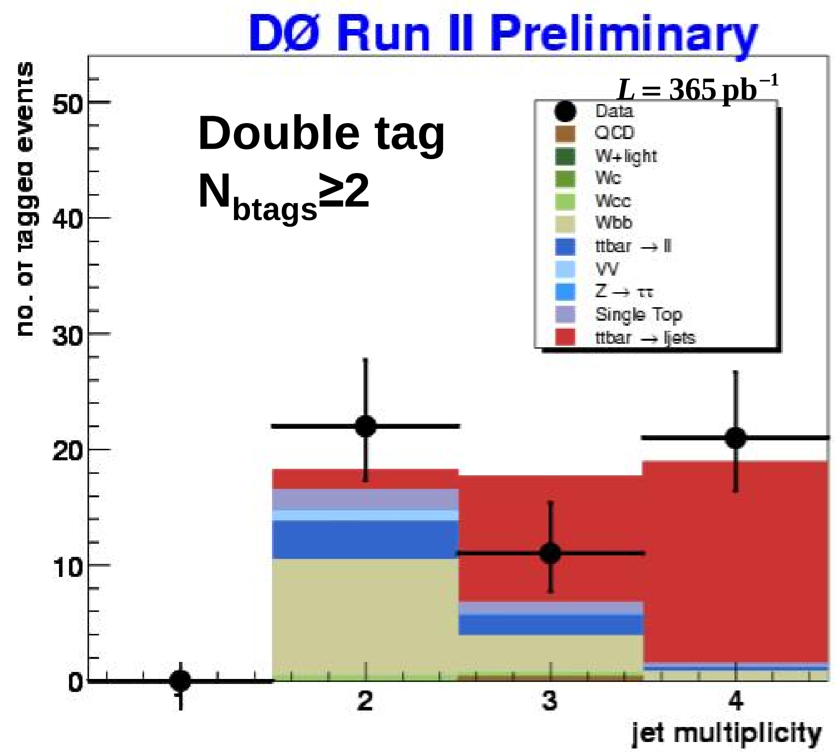
$\varepsilon \times BR(t\bar{t} \to {}^{a} + jets) \approx 4\%$

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

Events	Control region		Signal region	
N_{btag}=1	W+1 jet	W+2 jets	W+3 jets	W+≥4 jets
Bkg	254±38	228±31	71±9	22±2
Data	251	215	121	88

Events	Control	Signal region	
N_{btags}≥2	W+2 jets	W+3 jets	W+≥4 jets
Bkg	17±3	7±1	1.9±0.3
Data	22	11	21





$e\tau_h$ and $\mu\tau_h$

$$\varepsilon \times BR(t\bar{t} \to e\tau_h, \mu\tau_h) \approx 0.08\%$$

1 isolated electron/muon p_T>20 GeV/c

- 1 isolated $\tau \to \upsilon_\tau$+*hadrons* p_T>15 GeV/c
- MET>20 GeV
- At least 2 jets p_T>20 GeV/c

Reduce backgrounds

- Total transverse energy >205 GeV
- Not compatible with $Z \to \tau\tau$

Events (195 pb^{-1})	$e\tau_h$	$\mu\tau_h$
Bkg	0.8±0.1	0.5±0.1
Data	2	0

CDF set limit on anomalous decay rate

$$\frac{\Gamma(t \to \tau\upsilon_\tau q)}{\Gamma_{SM}(t \to \tau\upsilon_\tau q)} < 5.2 \text{ @ } 95\% \text{ C.L.}$$

Neutrino+jets

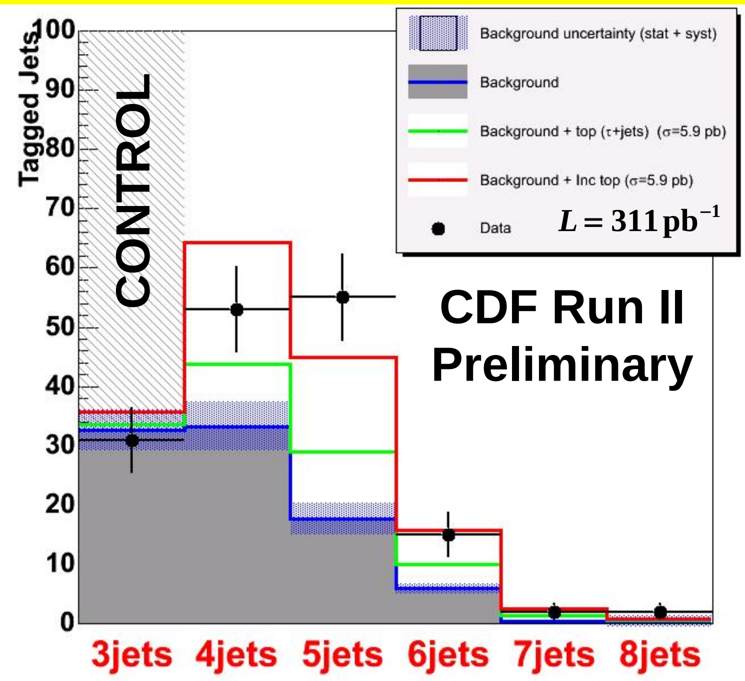
$$\varepsilon \times BR(t\bar{t} \to \nu + jets) \approx 4\%$$

Zero isolated electrons/muons!

- At least 4 jets p_T>15 GeV/c
- MET significance > 4 GeV$^{1/2}$
- MET not collinear with jets
- At least 1 b-tag

In future: explicit tau identification!

$$\sigma(t\bar{t}) = 6.1 \pm 1.2(\text{stat}) \pm^{1.3}_{0.9} (\text{syst}) \pm 0.4(\text{lumi}) \text{pb}$$



All-hadronic

- At least 6 jets with p_T>15 GeV/c

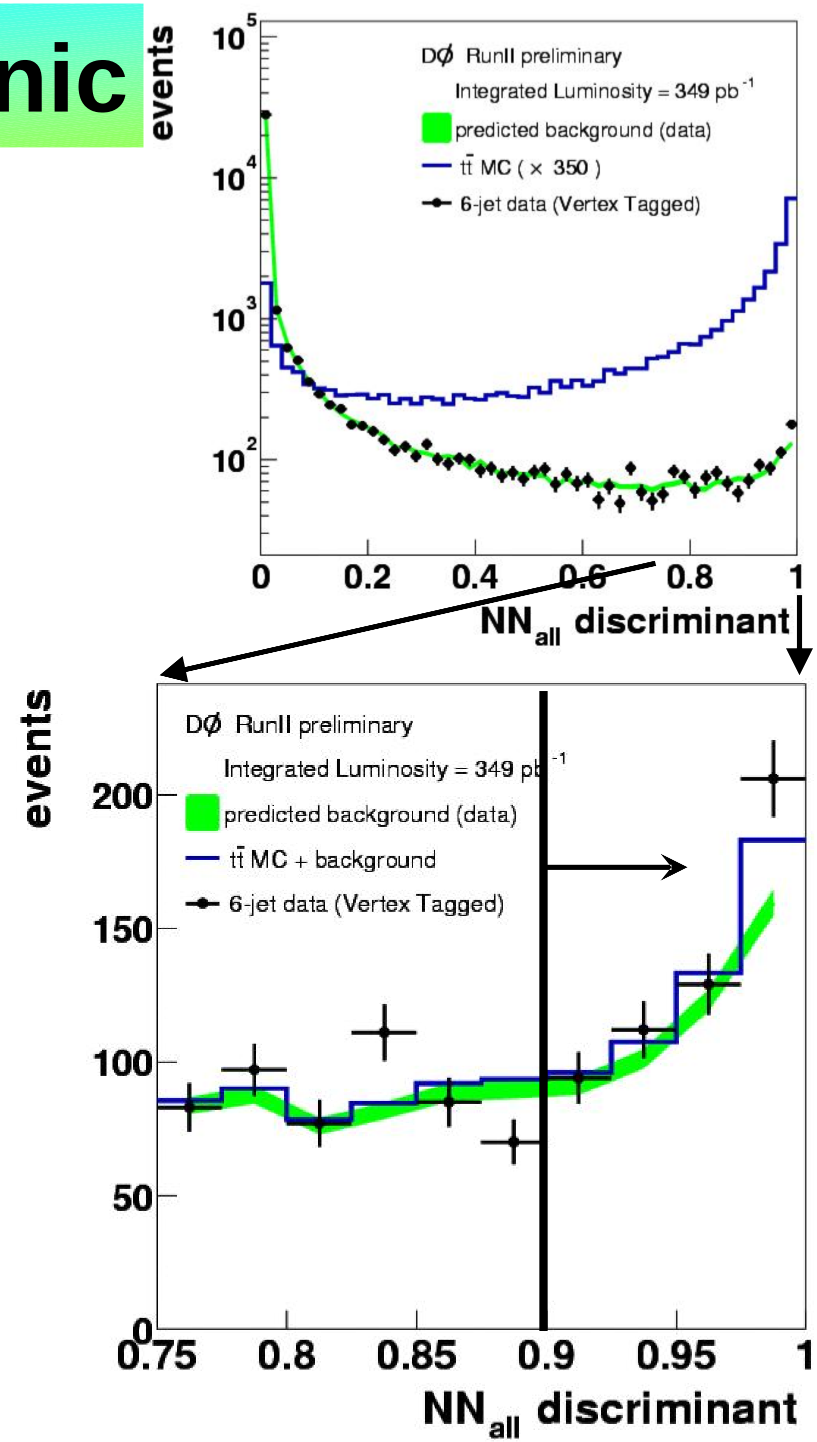
Reduce huge background from QCD processes at a hadron collider!

- At least one b-tag
- Combine kinematic observables in artificial neural network
- Require NN>0.9

$$\varepsilon \times BR(t\bar{t} \rightarrow \text{all} - \text{hadronic}) \approx 3\%$$

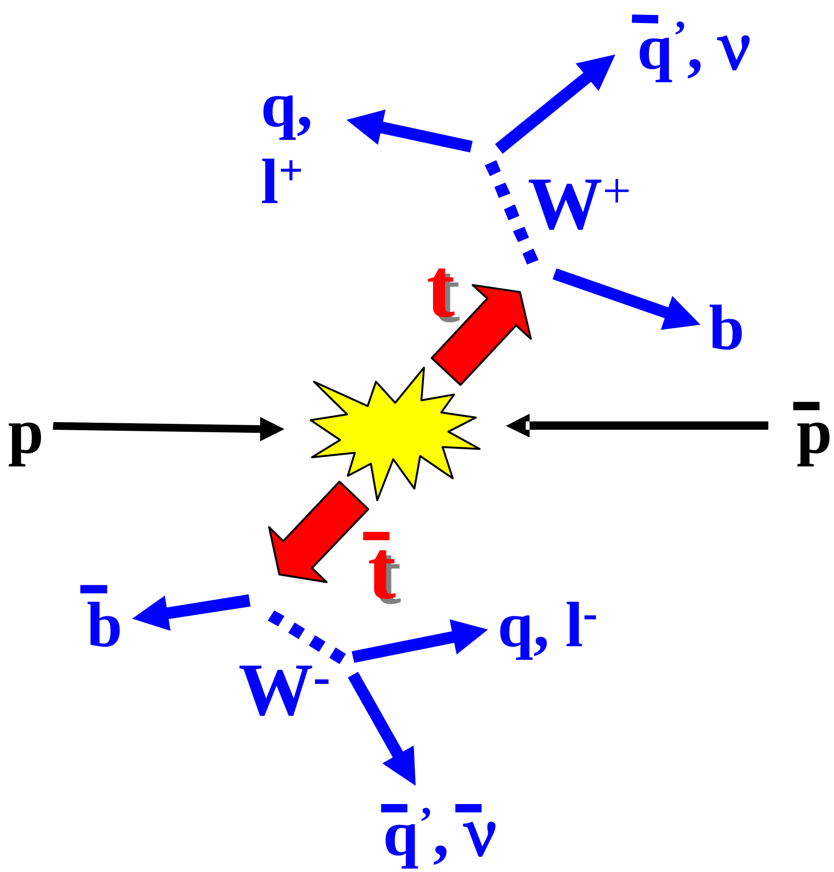
Events	All-hadronic
Raw Bkg	494±5
Corrected Bkg	482±5
Data	541

$$\sigma(t\bar{t}) = 5.2 \pm^{2.6}_{2.5} (\text{stat}) \pm^{1.5}_{1.0} (\text{syst}) \pm 0.3 (\text{lumi}) \text{pb}$$



Is this the standard model Top Quark?

Observe Top Quark Pair Production
in all final states



Search for Single Top Quark Production

Test Top Quark Decay

- Top always decays to W^+b?
- Any Charged Higgs from $t \rightarrow H^+b$?
- Top electric charge is +2/3?
- W helicity "right'?
- Anomalous FCNC $t \rightarrow Zc$, gc, γcb?

Test Top Quark Pair Production

- Pair Production Rate
- New massive resonance $X \rightarrow tt$?
- Top spin
- Tests of NLO kinematics

Precision measurement of top quark mass: 30% improvement this year!

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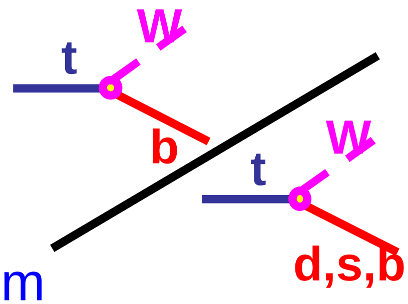
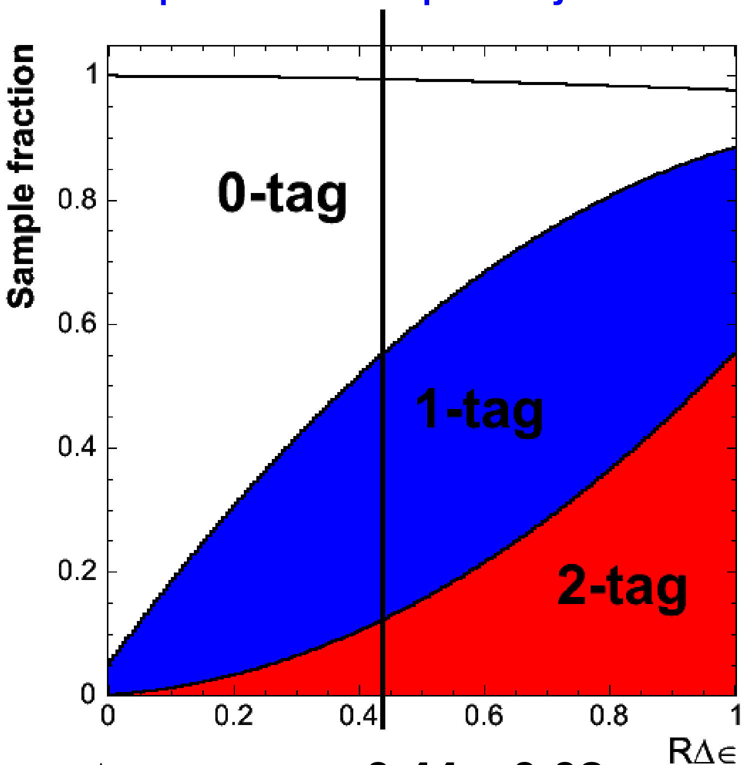
Does top always decay to W⁺b? Part (b)

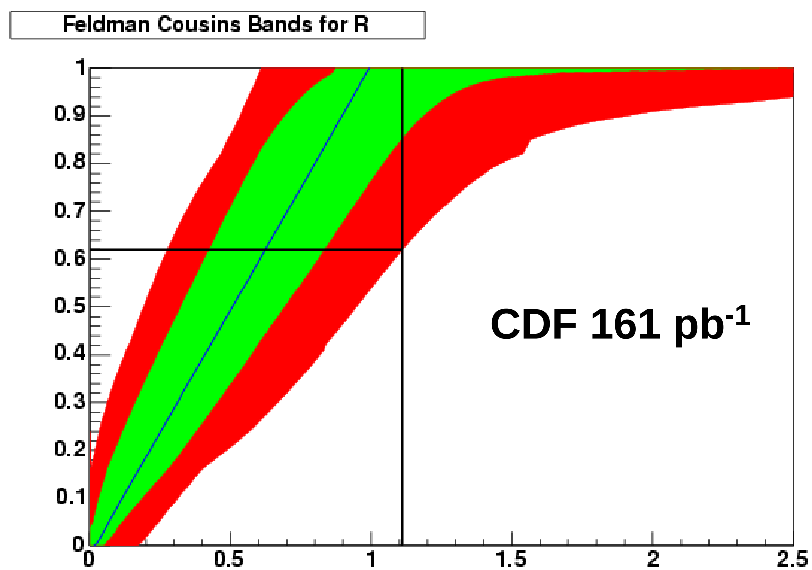
- If BR(t→Wb) is lower than SM prediction of ~100%, or if b-tag efficiency is lower than estimated value
  - observe fewer double b-tag events
  - observe more events without any b-tags
- Fit R=BR(t→Wb) / BR(t→Wq) times b-tag efficiency from observed number and estimated composition of 0,1,2-tag dilepton and lepton+jets events





$\Delta\varepsilon = \varepsilon_b - \varepsilon_{light}$ = 0.44 ± 0.03
from independent estimate

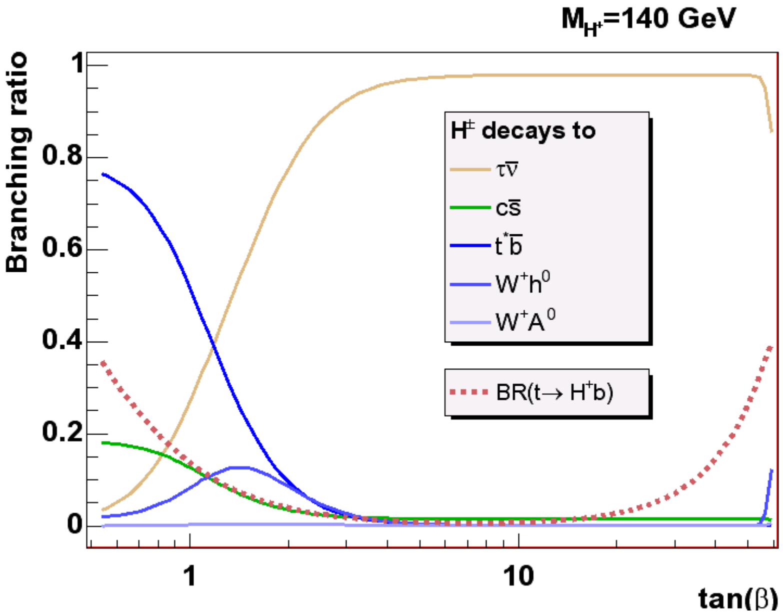
Best fit $R = 1.11 \pm^{0.21}_{0.26}$

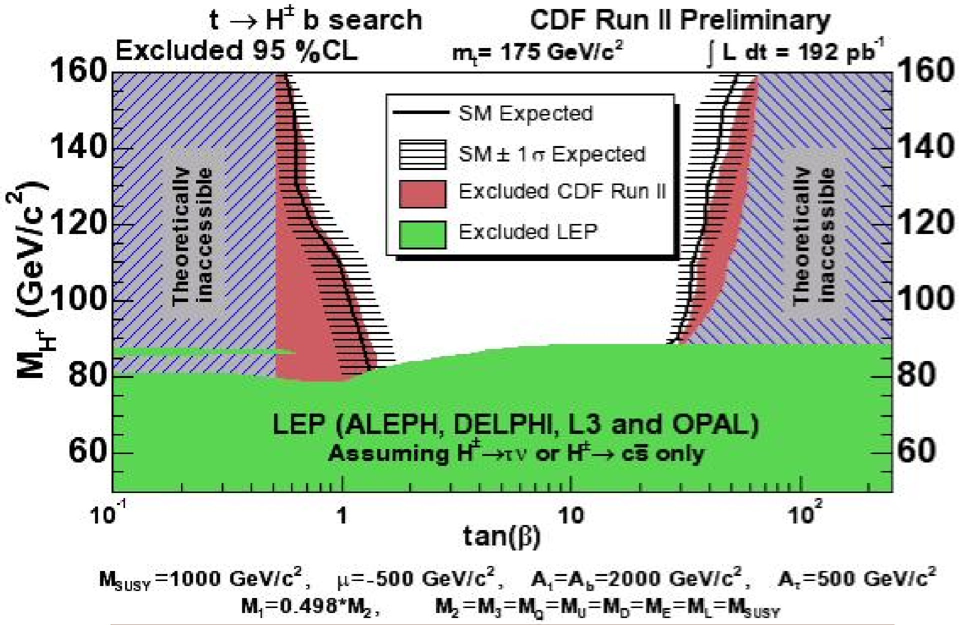


R>0.62 @ 95% C.L.

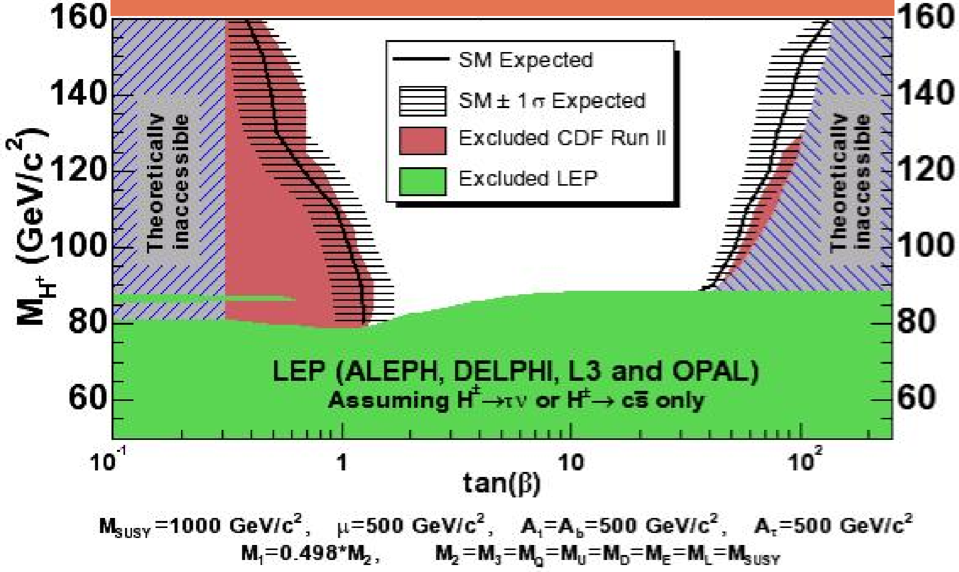
Does top always decay to W^+b? Part (W)

- Branching ratio for $t \rightarrow H^+b$ significant (>10%) for small and large $\tan\beta$
- H^+ decays differently than W^+
  - Ø $H^+ \rightarrow \tau^+ \upsilon_\tau$ enhanced if high $\tan\beta$: observe more taus!
  - Ø $H^+ \rightarrow t^* b \rightarrow W^+ bb$ for high m(H^+) if low $\tan\beta$: mimics SM signature but observe more b-tags
- Compare number of observed events in 4 final states: dilepton, $e\tau_h + \mu\tau_h$, lepton+jets with single b-tag, and lepton+jets with double b-tags





Set limits in several MSSM scenarios with NLO corrections



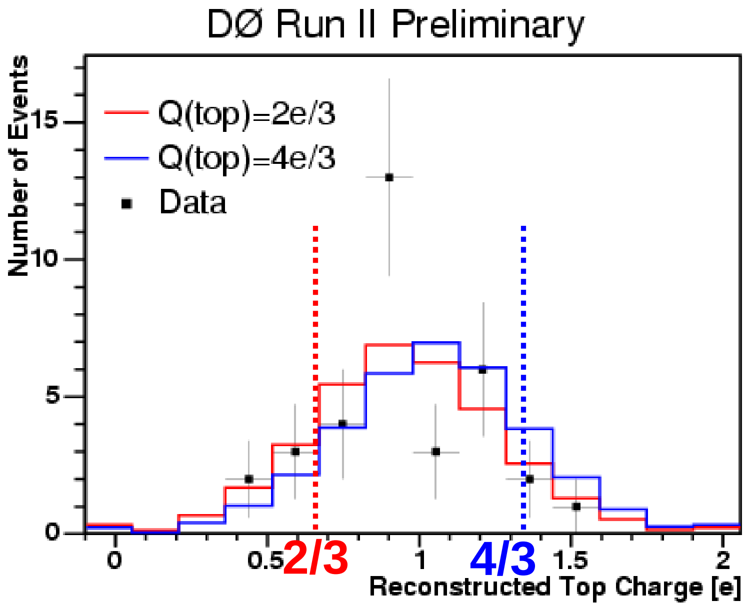
Does top always decay to W^+b? Part (W^+)

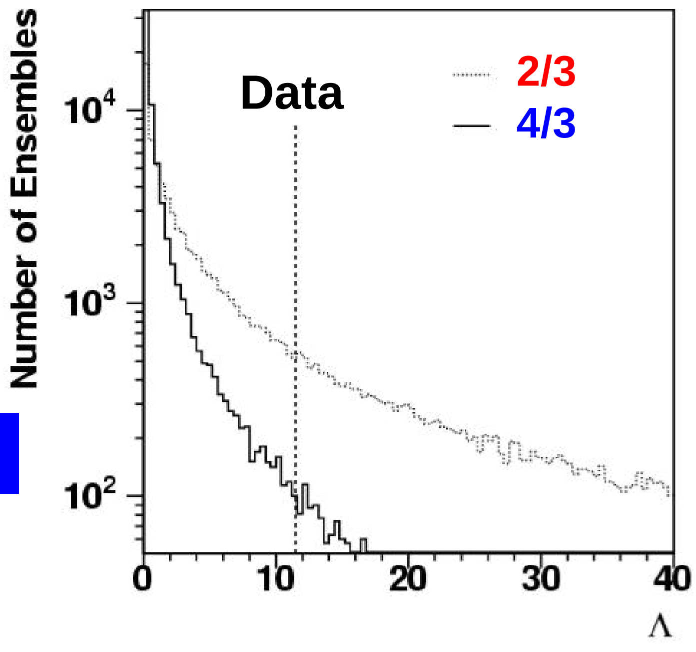
Electric charge of +2/3 implies $t \rightarrow W^+b$
Electric charge of -4/3 implies $t \rightarrow W^-b$
How to tell the difference experimentally?

- **Select 21 double b-tag lepton+≥4 jets**
  - **Very pure sample with only 5% bkg**
  - **Statistical estimate b charge from jet-charge**
- **Pick best lepton and b-jet combination with kinematic fit for fixed m_{top}=175 GeV/c^2 hypothesis**
  - **17 double b-tag events pass**
  - **Correct assignment 79±2%**
- **Calculate magnitude of "top" charges**
  - **Q_1=| lepton charge + b_1-jet charge|**
  - **Q_2=|-lepton charge + b_2-jet charge|**
- **Define Λ as ratio of unbinned likelihoods for SM (Q=+2/3) and Exotic (Q=-4/3) hypotheses**

Measure Λ=11.5
Exclude Q= -4/3 @ 94% C.L.

First result!





Decay consistent with standard model so far!

Observe Top Quark Pair Production in all final states

Test Top Quark Decay

- **Top always decays to *W^+b?***
- **Any Charged Higgs from *$t \rightarrow H^+b$?***
- **Top electric charge is +2/3?**
- **W helicity "right'?**
- **Anomalous FCNC *$t \rightarrow Zc, gc, \gamma cb$?***

Test Top Quark Pair Production

- **Pair Production Rate**
- **New massive resonance *$X \rightarrow tt$?***
- **Top spin**
- **Tests of NLO kinematics**

Search for Single Top Quark Production

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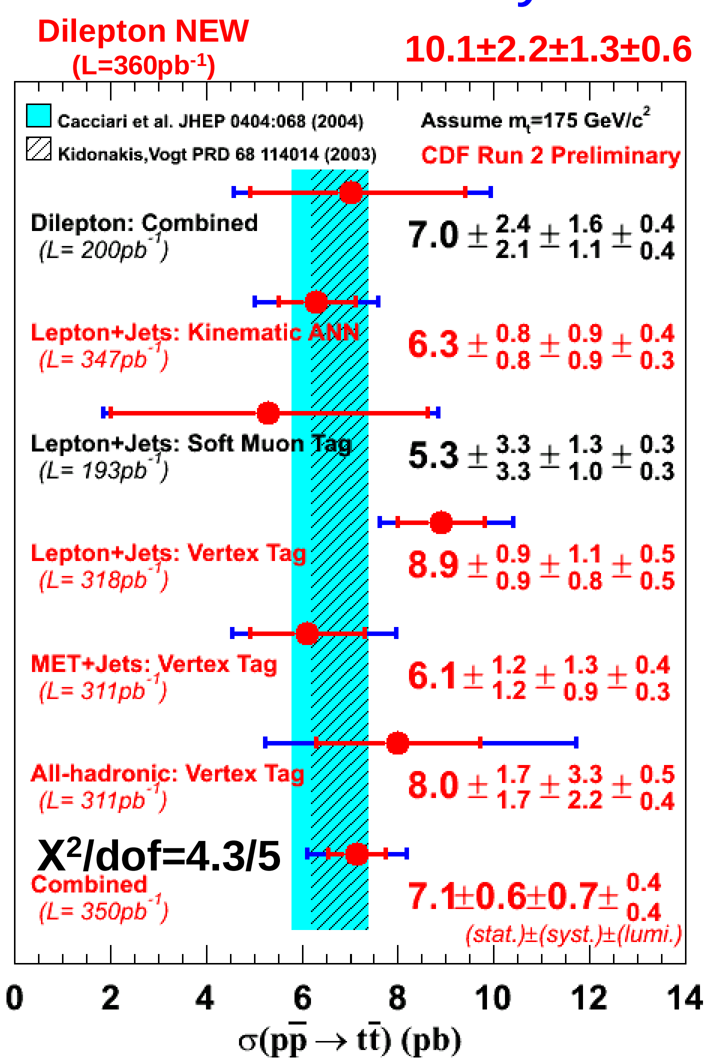
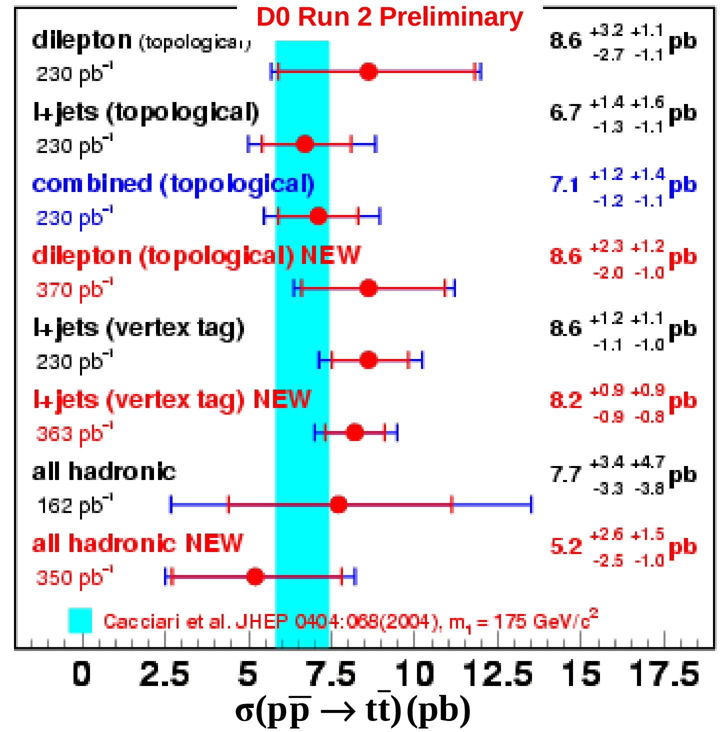
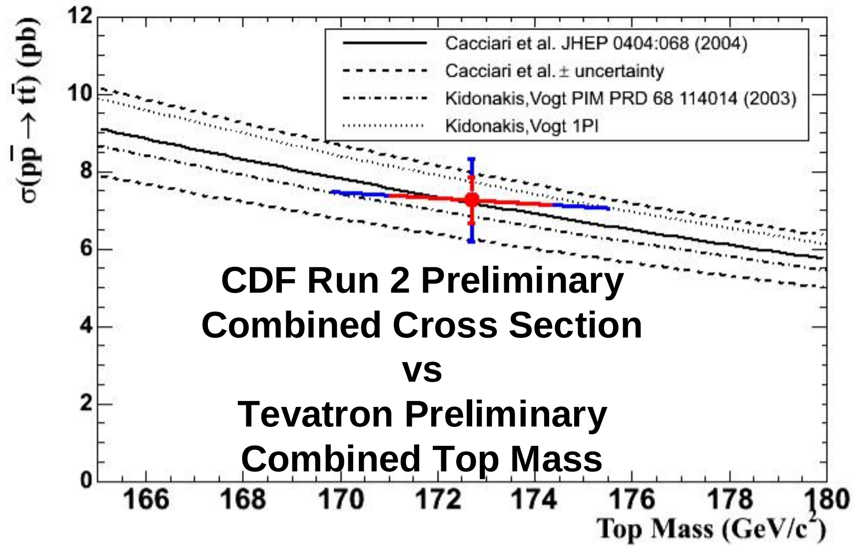
Top Pair Production Rate

- Are measurements in different final states consistent with each other and with theory?



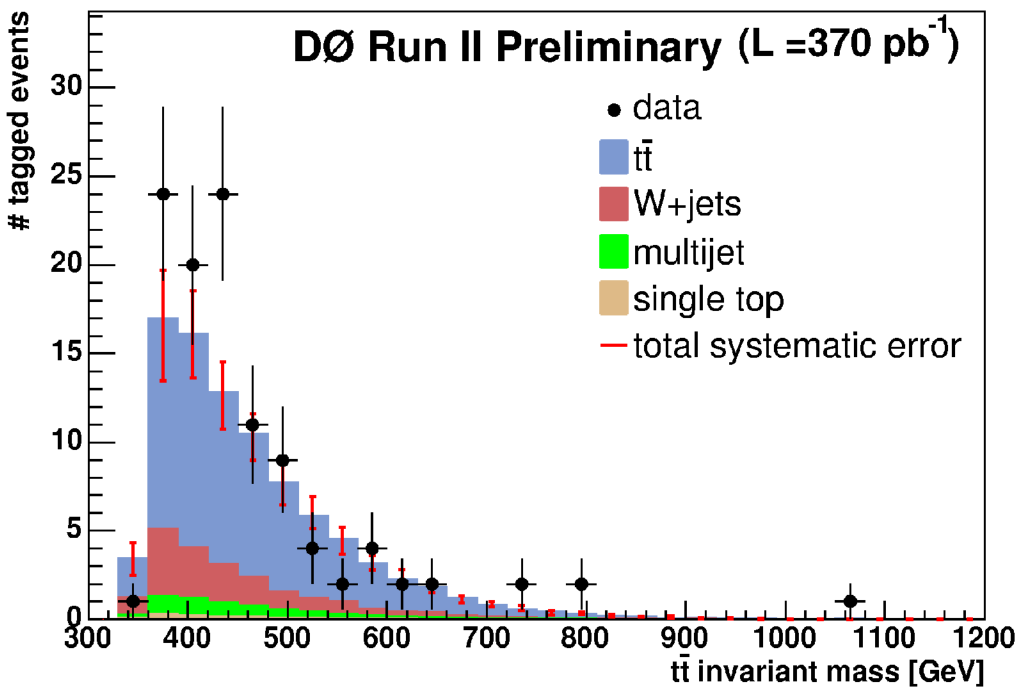


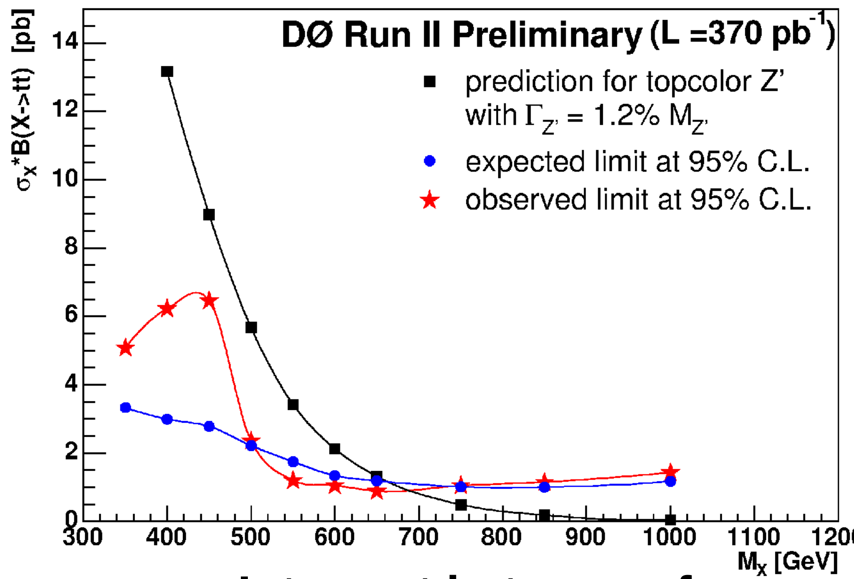


Does something new produce ttbar?

- Search for new massive resonance decaying to top pairs
  - Lepton+≥4 jets with ≥ 1 b-tags
  - Kinematic fit to ttbar hypothesis to improve experimental resolution on invariant mass of ttbar system
- Fix SM backgrounds to expected rate
  - Use theory prediction of 6.7pb for SM top pair production

Derive limit on $\sigma_X \times BR(X \rightarrow t\bar{t})$

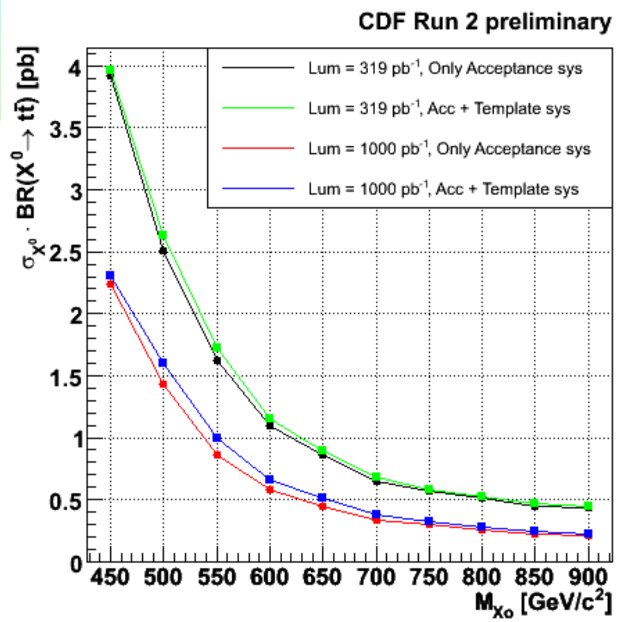


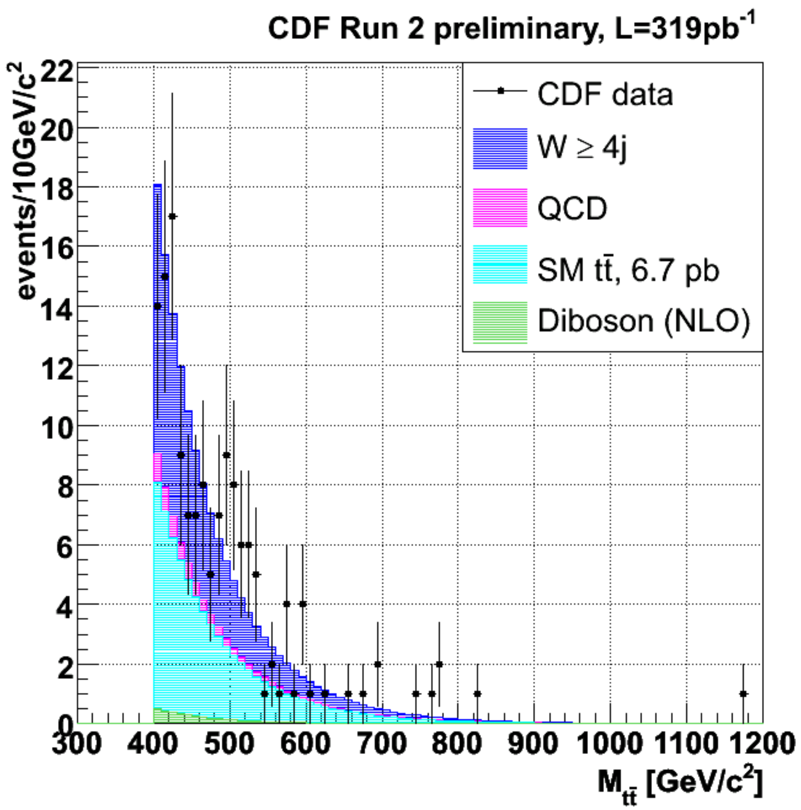


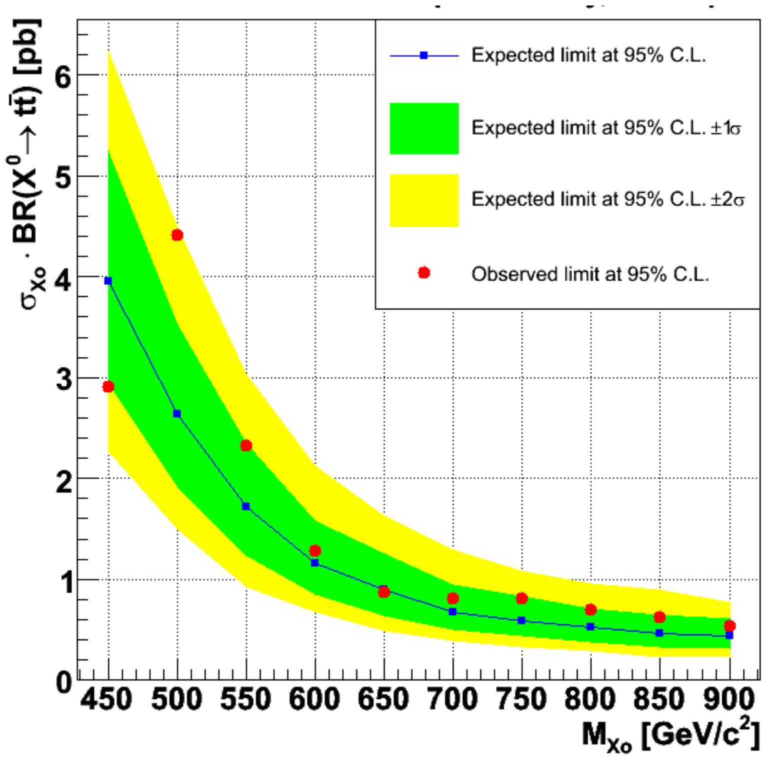
Interpret in terms of one of many possible models: topcolor assisted technicolor Z'

What does CDF observe?

- Lepton+≥4 jets (no b-tagging)
  - Matrix element technique to increase sensitivity
- Fix top pair, diboson, QCD to expected rates
  - Assume everything else is W+jets
- Also see excess around 500 GeV/c^2
  - Only 2 std. dev. now…could be interesting result with 3xdata for Moriond 2006



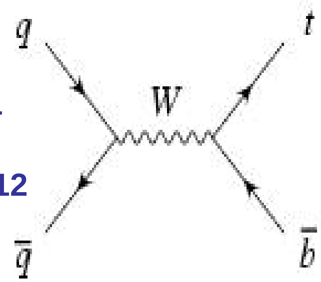


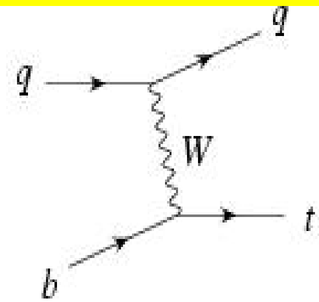


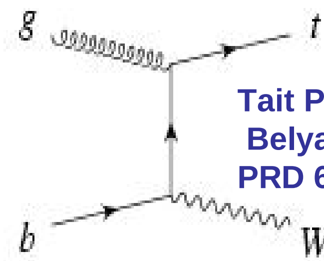
Does something new produce Single Top Quarks?

Single top quark production via electroweak interaction
Cross section proportional to $|V_{tb}|^2$

Harris et al PRD 66 (02) 054024
Cao et al hep-ph/0409040
Campbell et al PRD 70 (04) 094012







Tait PRD 61 (00) 034001
Belyaev, Boos
PRD 63 (01) 034012

0.88 ± 0.11 pb **1.98 ± 0.25 pb** **<0.1 pb**

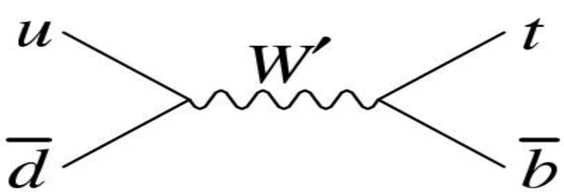
Trigger on lepton from t→Wb→ℓυb

2 b-jets for s-channel **1 b-jet and 1 light jet for t-channel**

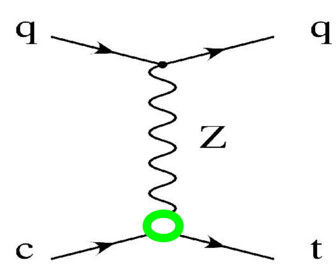
Interesting to measure both channels – sensitive to different physics

See Tait, Yuan
PRD63, 014018 (2001)

s-channel
Sensitive to new resonances



t-channel
Sensitive to FCNCs

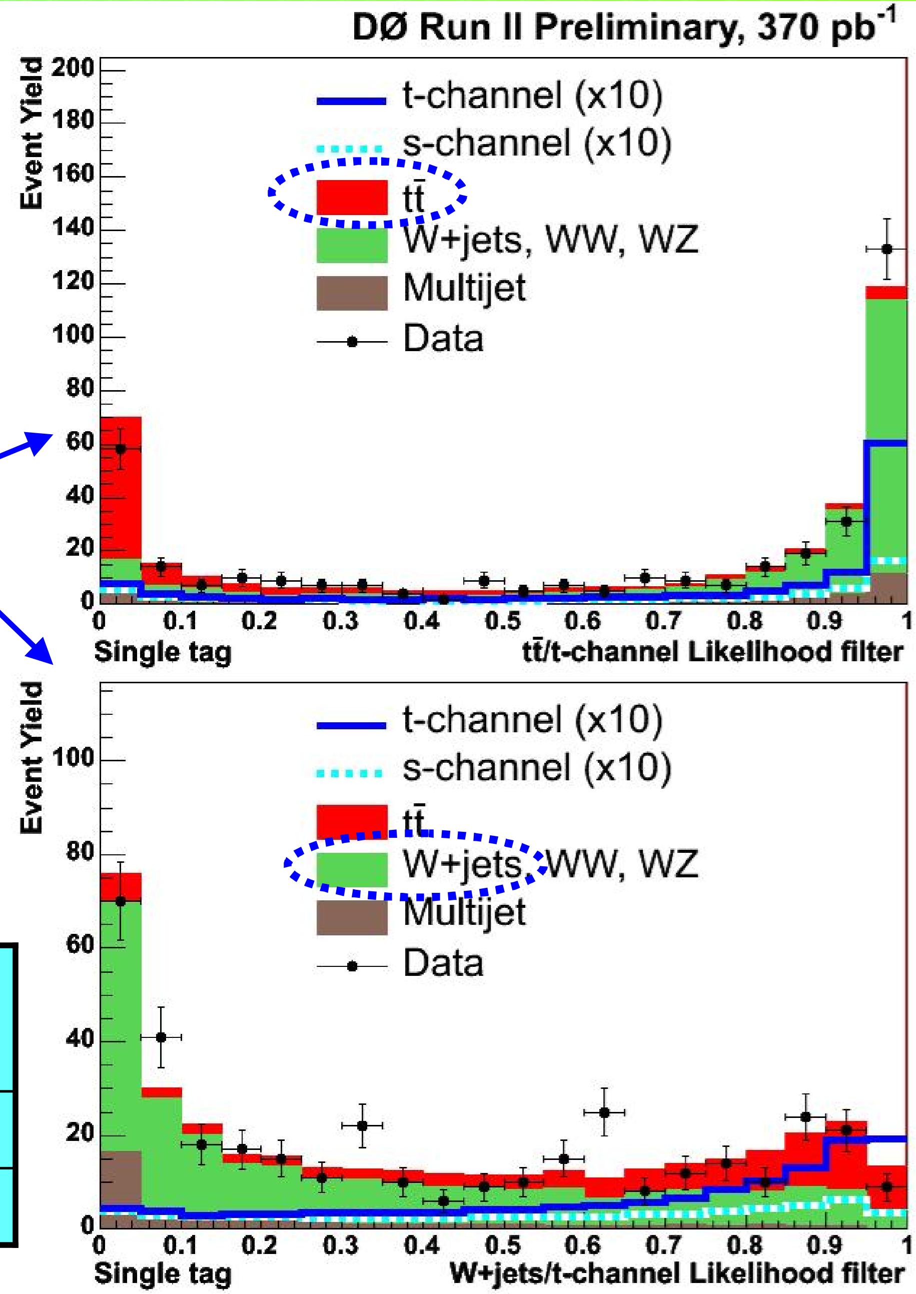


Search for Single Top Quark Production

- Why is it difficult?
  - Signal swamped by W+jets
  - Signal sandwiched between W+jets and top pair production
- Dedicated likelihood to discriminate between each signal and each background
  - Kinematic observables
  - Show likelihoods for t-channel
- Rely on good MC modeling of W+jets background composition and kinematics
  - Big challenge for discovery!
  - 3σ evidence expected with <2 fb^{-1}

D0 Preliminary: World's best limits!
Factor of 2-3 away from standard model

D0 370 pb^{-1}	Expected 95% C.L. (pb)	Observed 95% C.L. (pb)
s-channel	3.3	5.0
t-channel	4.3	4.4



Production & Decay consistent with standard model

Observe Top Quark Pair Production in all final states

Test Top Quark Decay

- Top always decays to W^+b?
- Any Charged Higgs from $t \rightarrow H^+b$?
- Top electric charge is +2/3?
- W helicity "right'?
- Anomalous FCNC $t \rightarrow Zc, gc, \gamma cb$?

Test Top Quark Pair Production

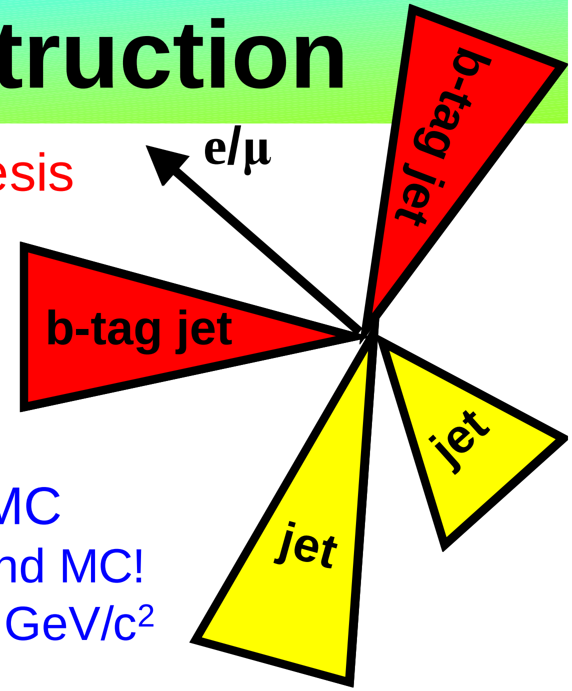
- Pair Production Rate
- New massive resonance $X \rightarrow tt$?
- Top spin
- Tests of NLO kinematics

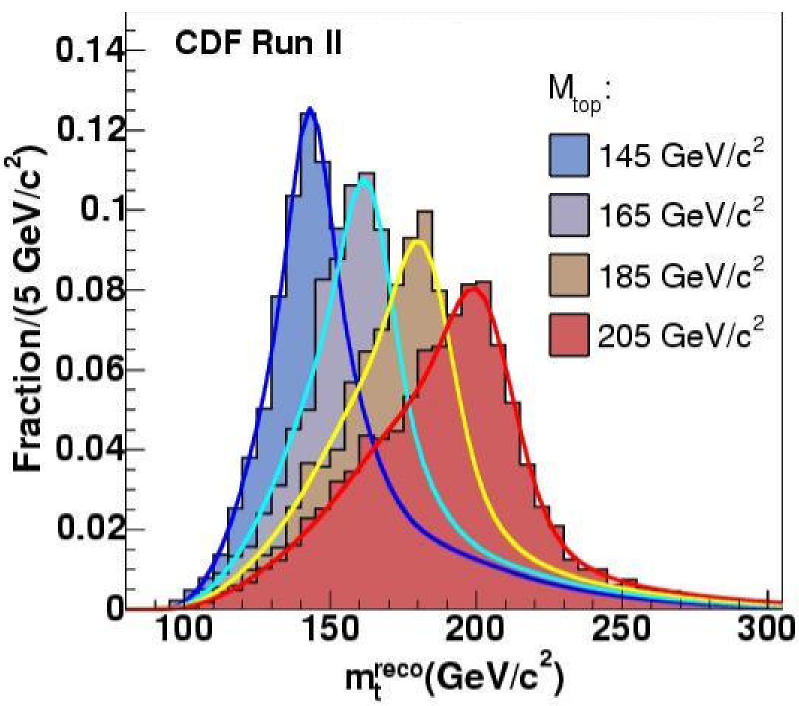
Precision measurement of top quark mass: 30% improvement this year!

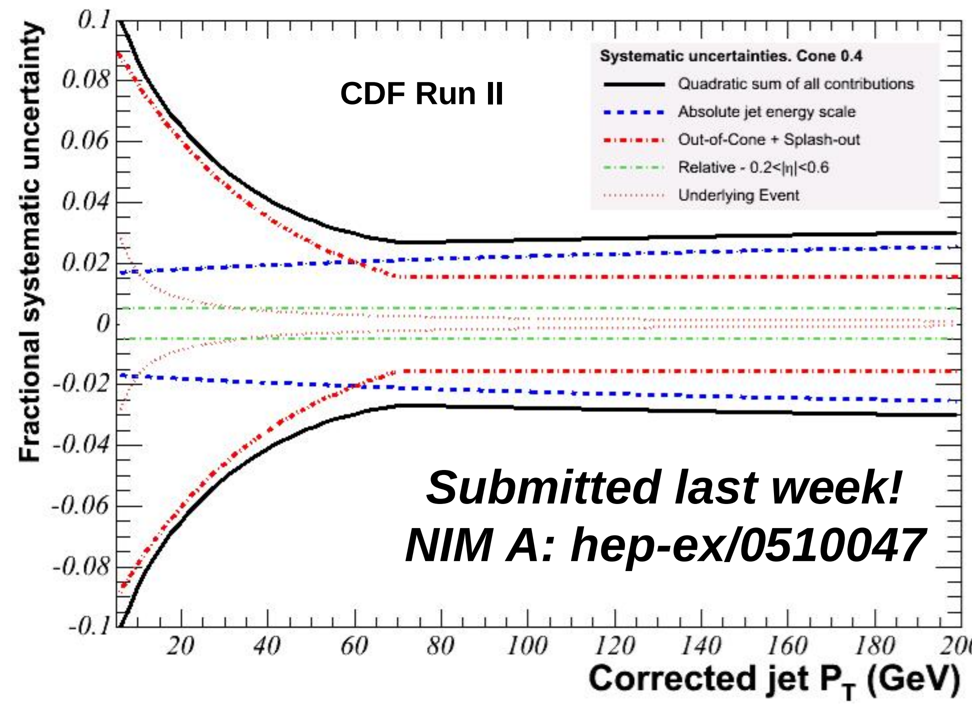
Search for Single Top Quark Production

Top Quark Mass:Reconstruction

- Kinematic fit to top pair production and decay hypothesis
  - Obtain improved resolution on reconstructed top mass
  - Choose most consistent solution for $t \rightarrow jjb$ and $t \rightarrow \ell \upsilon b$
    - 24 possibilities for 0 b-tags
    - 12 possibilities for 1 b-tag
    - 4 possibilities for 2 b-tags
- Fit data to reconstructed top mass distributions from MC
  - Need excellent calibration of jet energy between data and MC!
  - 3% systematic uncertainty on jet energy scale gives ~3 GeV/c^2 systematic uncertainty on top quark mass

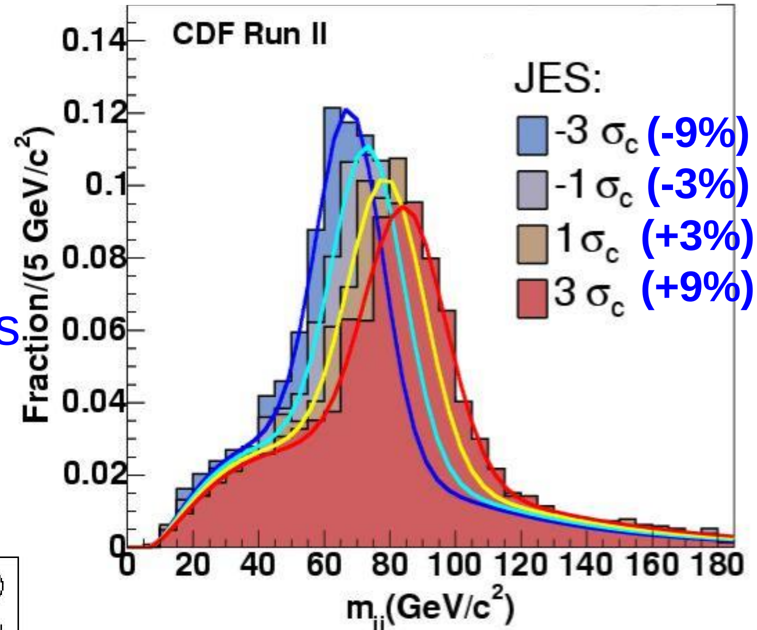


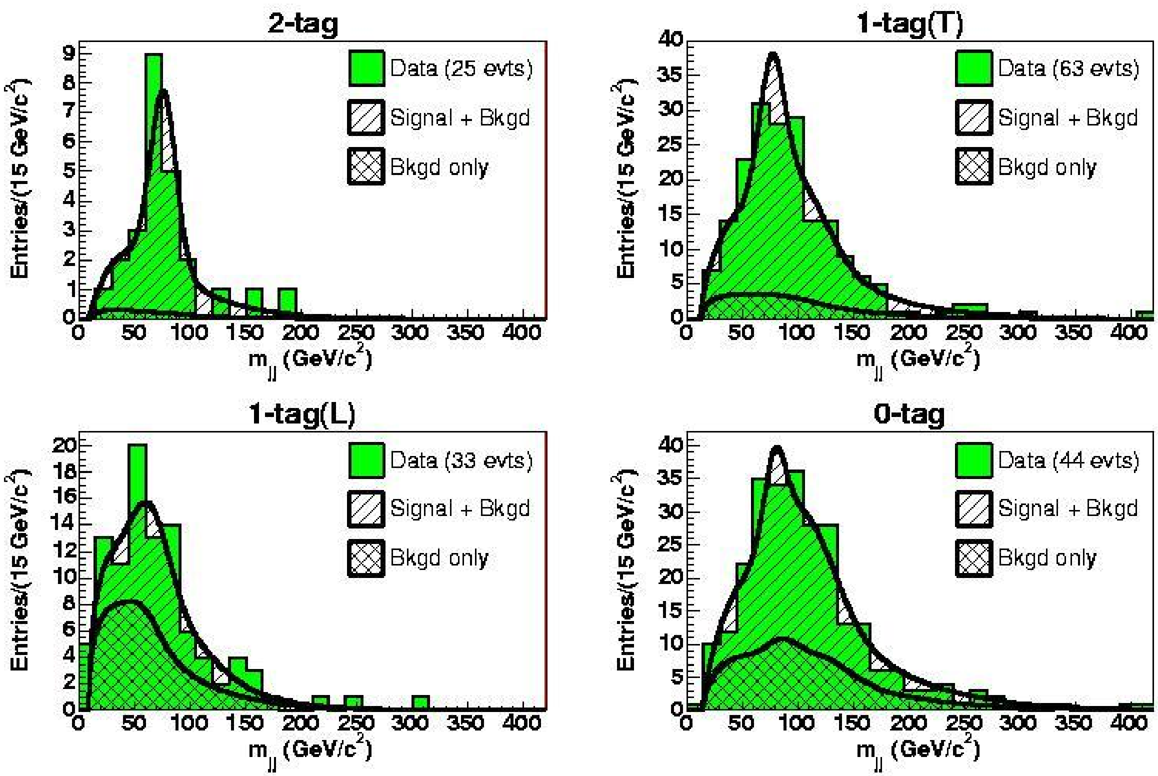


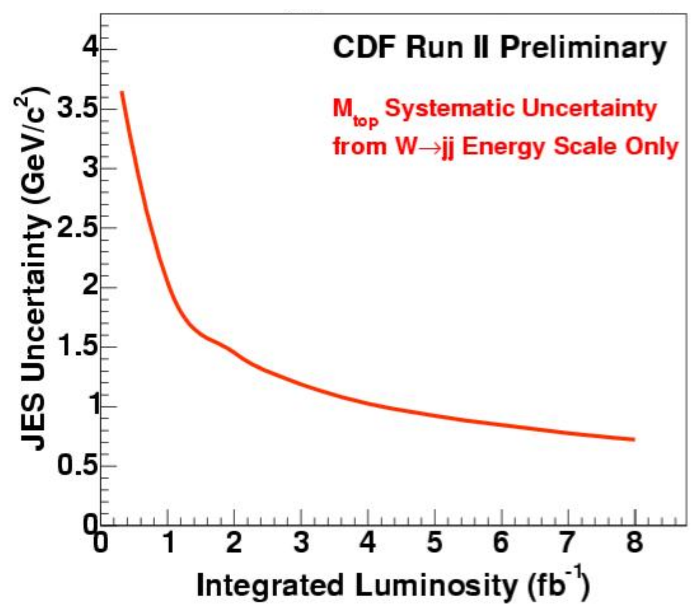


Top Quark Mass: *in situ* jet energy calibration

- New for 2005! Simultaneous fit of invariant mass of jets from $W \to jj$ *in lepton+jets data*
  – Determine global jet energy correction factor
  – Use to correct energy of all jets
- Uncertainty dominated by data $W \to jj$ statistics
  – Will decrease <1 GeV/c^2 with more data!

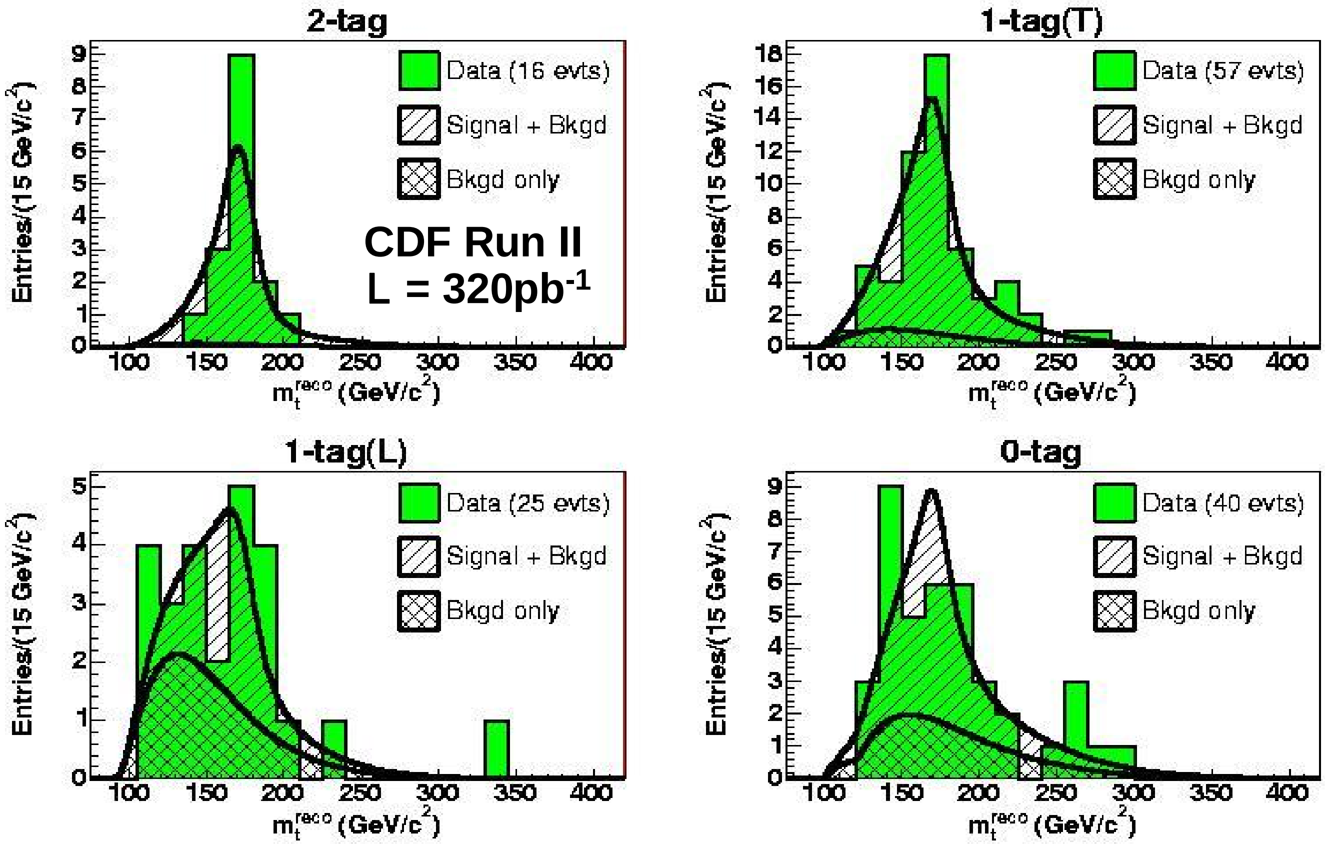






CDF Top Mass Measurement: Lepton+Jets

- Simultaneous fit of reconstructed top mass and W→jj mass
  - Include Gaussian constraint on jet energy scale from *a priori* determination
- Best single measurement! Better than previous Run I CDF+D0 average!



Submitted last week!
PRD: hep-ex/0510048
PRL: hep-ex/0510049

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

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

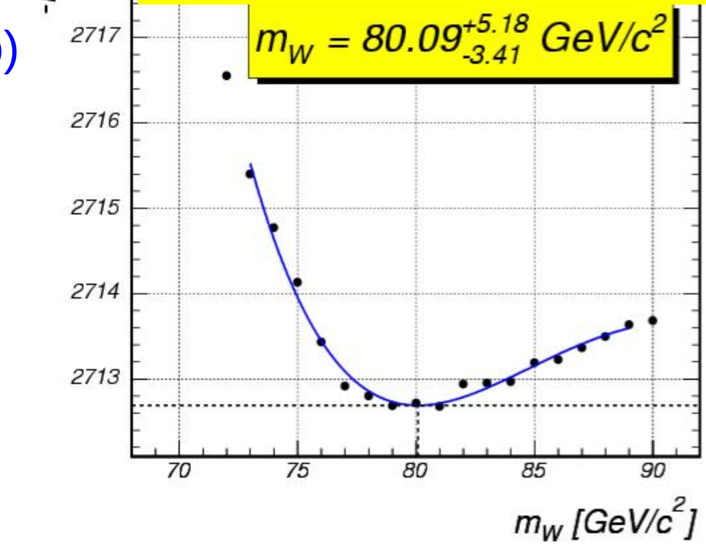
ü **Correction approx. -0.3%**
ü **Uncertainty 20% smaller**

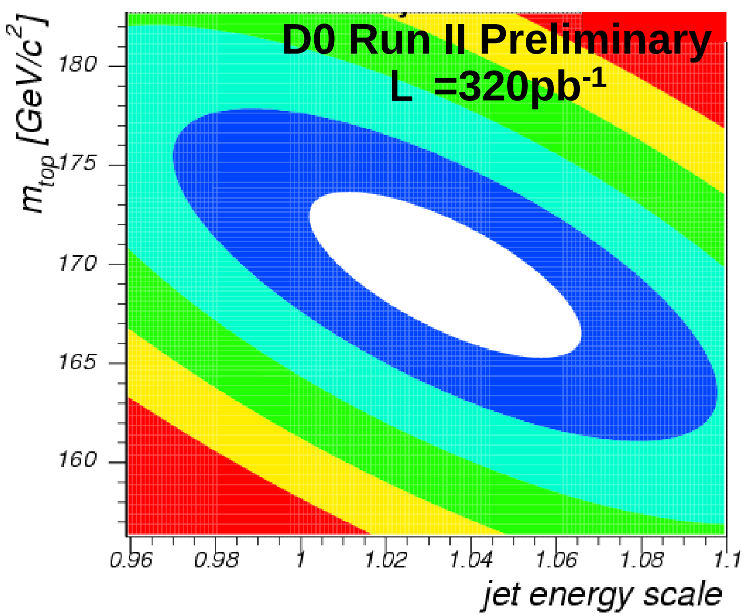
Systematic Source	Uncertainty (GeV/c^2)
ISR/FSR	0.7
Model	0.7
b-jet	0.6
Method	0.6
PDF	0.3
Total	1.3
Jet Energy	2.5

D0 Top Mass Measurement: Lepton+Jets

- LO Matrix element technique of Run I
  - Exactly 4 observed jets (150 events, 32±5% top)
  - Use LO Matrix element for ttbar and W+jets
  - Weight all 24 possible solutions (no b-tagging)
- New for 2005: W→jj jet energy calibration
  - Fit jet energy scale as well as top mass
  - No *a priori* jet energy determination

Check: apply JES and fit





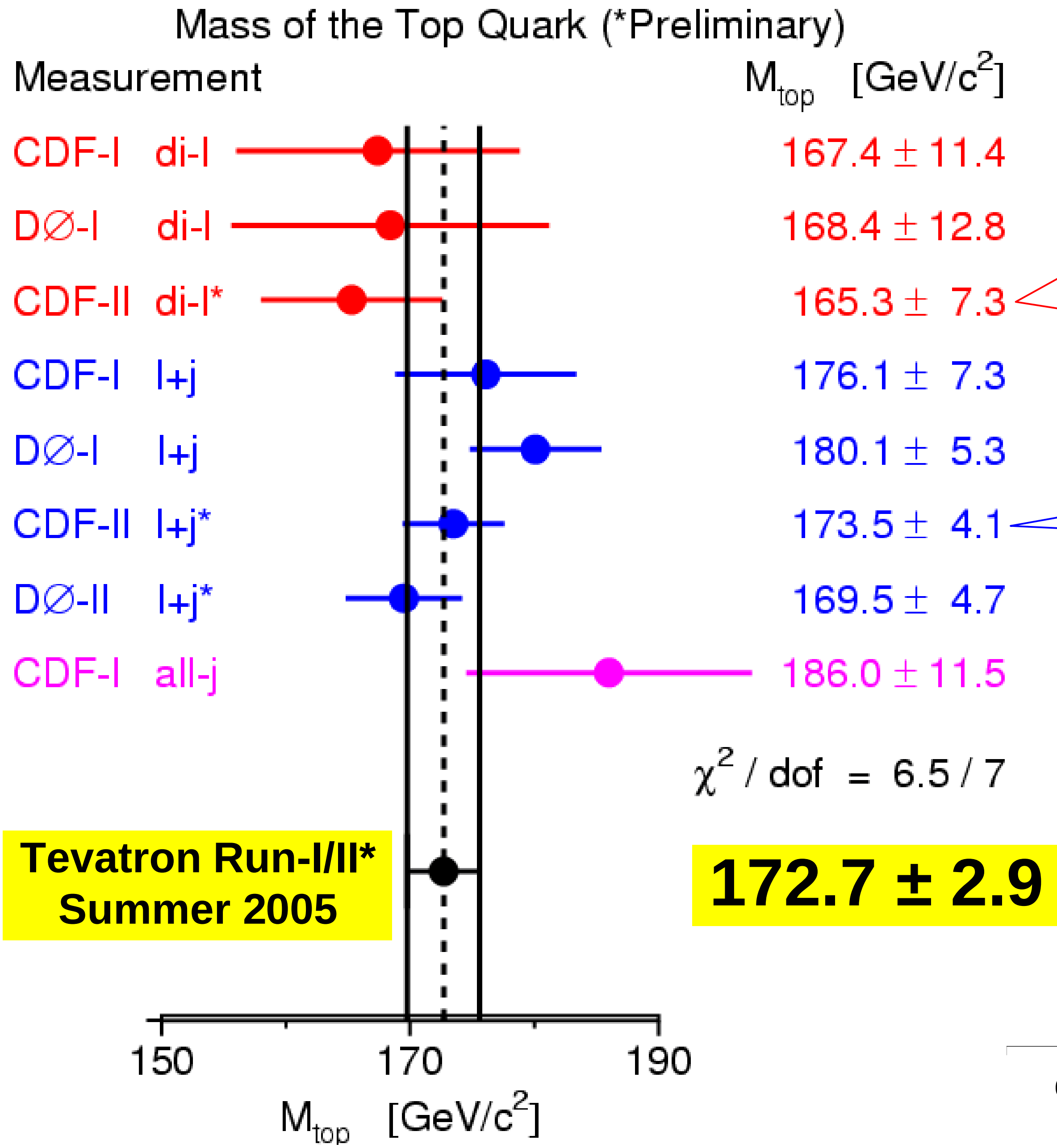
Systematic Source	Uncertainty (GeV/c^2)
ISR/FSR	0.3
Model	0.7
b-jet	1.1
Method	0.9
PDF	0.1
Total	1.7
Jet Energy	3.2

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

$$\mathrm{JES} = 1.034 \pm 0.034$$

ü**Correction +3.4%**
ü**Uncertainty ±3.4%**

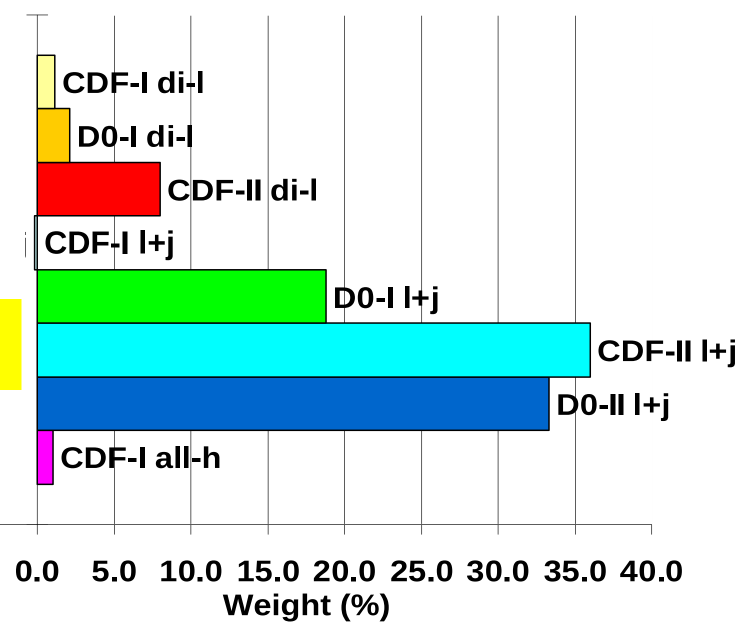
Tevatron Top Quark Mass



First application of matrix element technique to dilepton channel:

20% improvement over previous techniques!

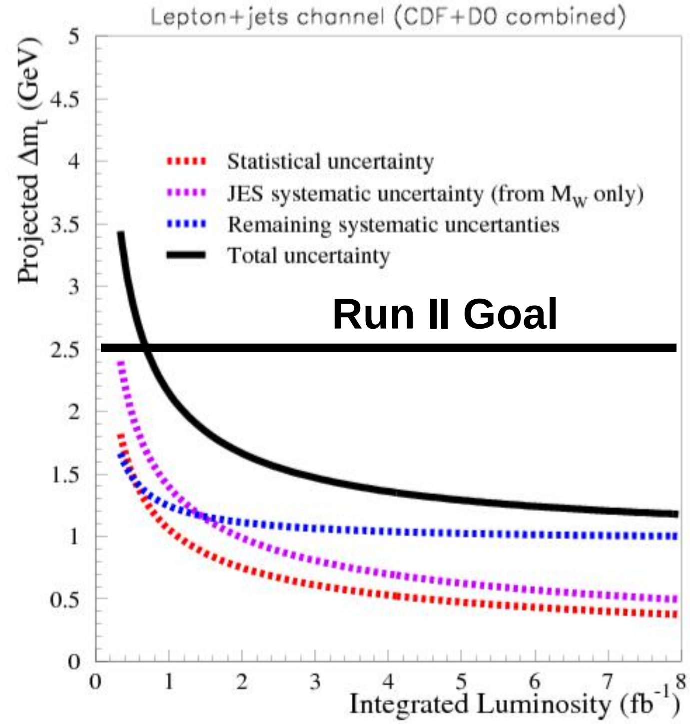
Now final: 173.5 ± 3.9

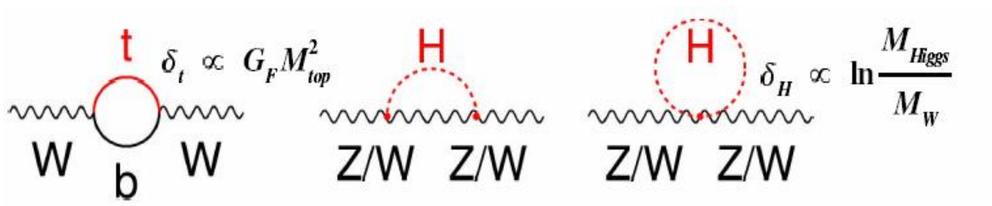


Bright Future with Inverse Femtobarns!

CDF+D0 will achieve ±2.5 GeV/c² in 2006!
Will reach ±1.5 GeV/c with 4 fb⁻¹ base!

- **Shown is only lepton+jets channel with W→jj jet energy calibration**
- **Conservative estimate of other systematics, will get smarter with more data!**





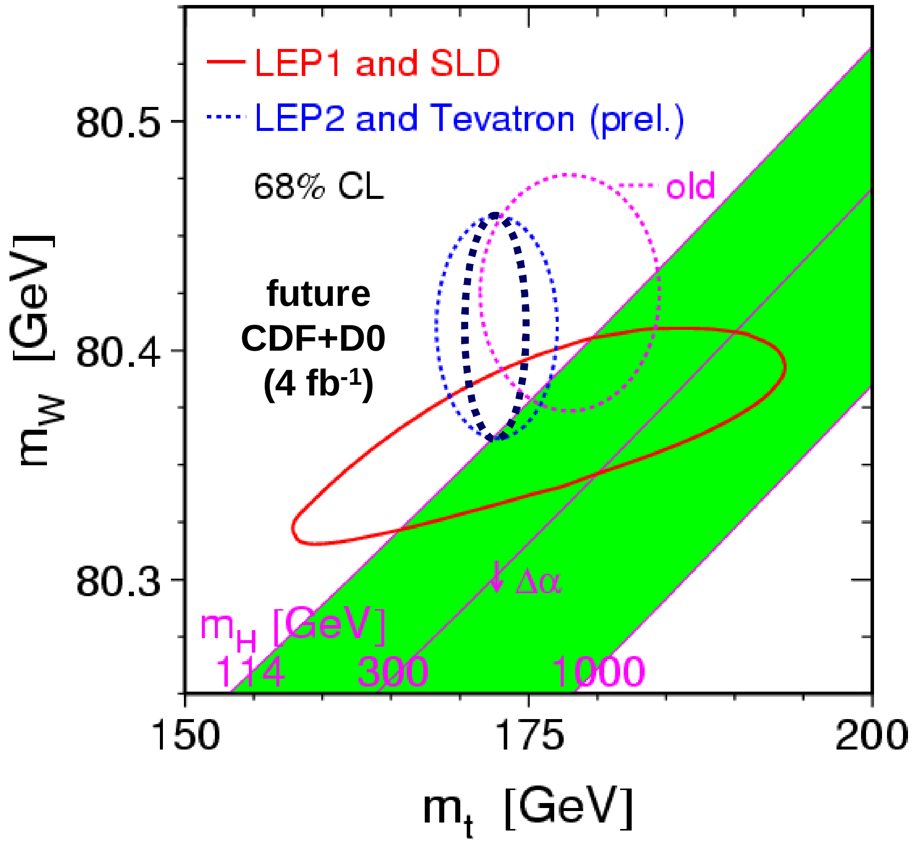
Quantum loops make W mass sensitive to top and Higgs mass

- **Recent theoretical calculation of full two-loop electroweak corrections**
- **Precise prediction of W mass in standard model limited by uncertainty on experimental measurement of top mass**

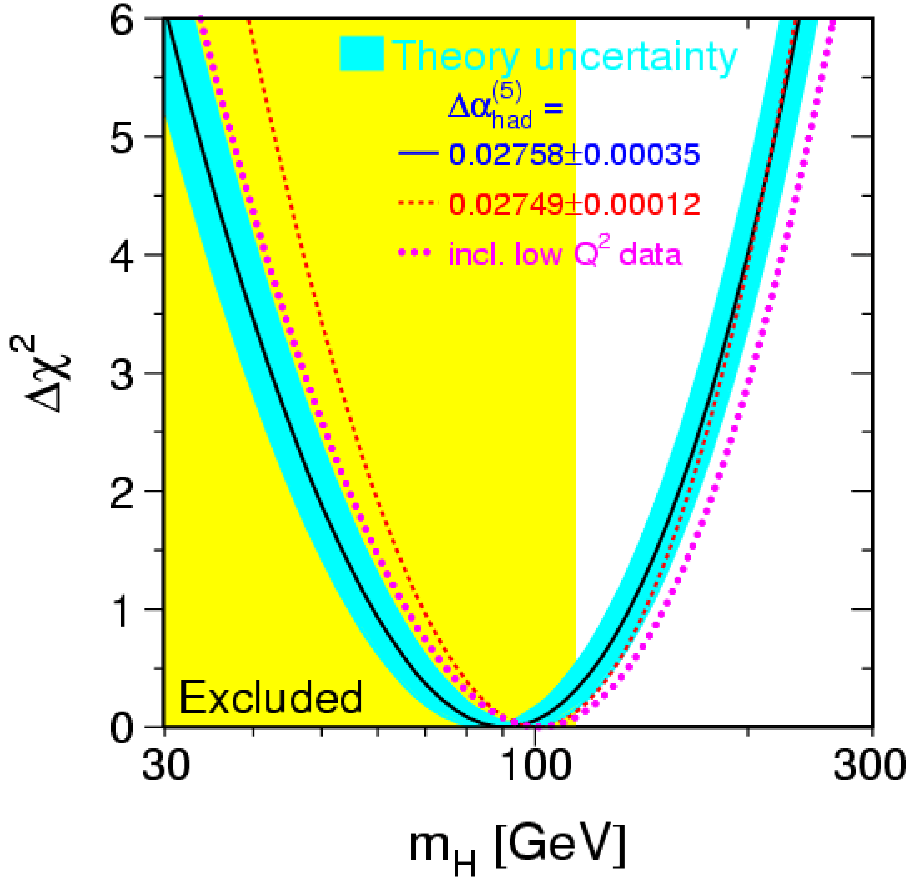
Adapted from A. Freitas *et al* hep/ph-0311148	Experiment δM_{top} (GeV/c²)	Prediction δM_W (MeV/c²)
CDF+D0 Run I	4.3	26
CDF+D0 2005	2.9	18
CDF+D0 1 fb⁻¹	2.0	12
CDF+D0 4 fb⁻¹	1.5	9
LHC	1.3	8

Test of Standard Model

Impact of CDF+D0 Top Quark Mass = 172.7 ± 2.9 GeV



Good agreement between
direct measurements
and
indirect SM prediction



$= 91 \pm^{45}_{32}$ **GeV**

$<$ **186 GeV @ 95% C.L.**

<219 GeV with LEP Excluded

Conclusions

Observed top quark consistent
with standard model
so far

Achieved
1.7% precision
top quark mass measurement

Future is bright!
Excellent performance of Tevatron & CDF & D0
delivering high statistics samples of top quarks

Watch out for interesting results with 1 fb^{-1}
at Moriond 2006!