Measurement of the $t\bar{t}$ Production Cross Section and Top Quark Mass at DØ

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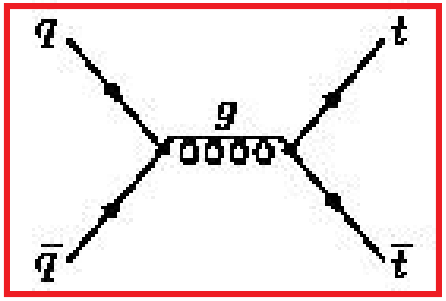
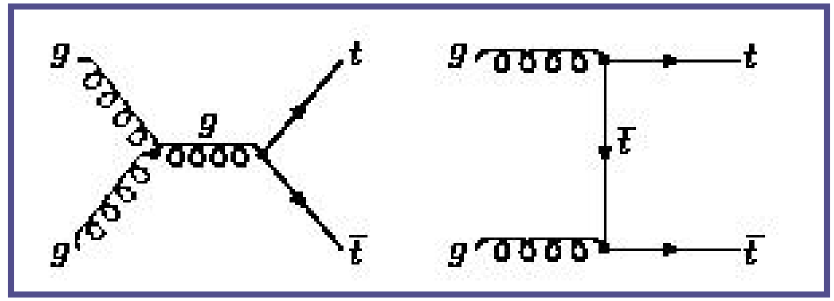
Introduction

- Improving our understanding of the top quark is one of the primary goals for RunII of the Tevatron
- The $t\bar{t}$ production cross section is predicted by perturbative QCD
- Measurement is sensitive to anomalous top quark couplings
  - Non-Standard Model production diagrams
  - Top quark decay non-Standard particles (H^+b, for example)
- Precise top quark mass measurement, combined with precise *W* mass measurement, constrains the SM Higgs mass

$t\bar{t}$ Production and Decay

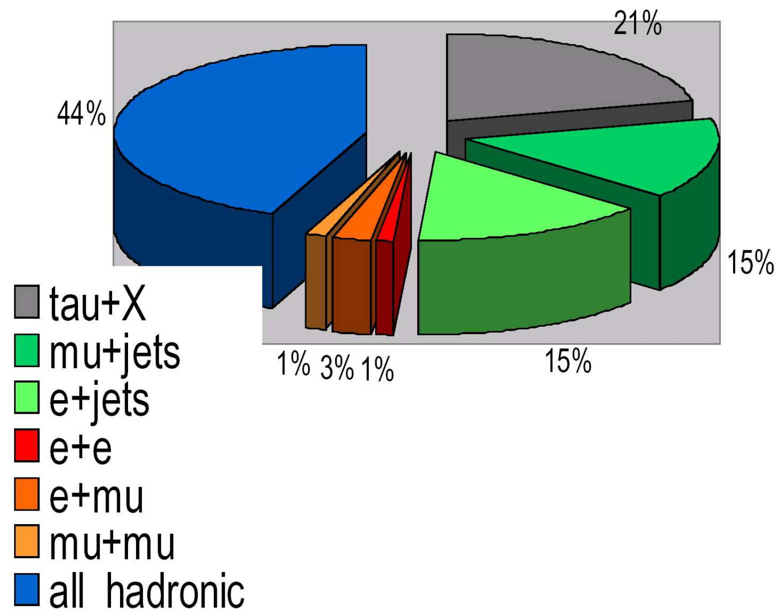
- Top quark pairs produced via $q\bar{q}$ annihilation (85%) or gluon fusion





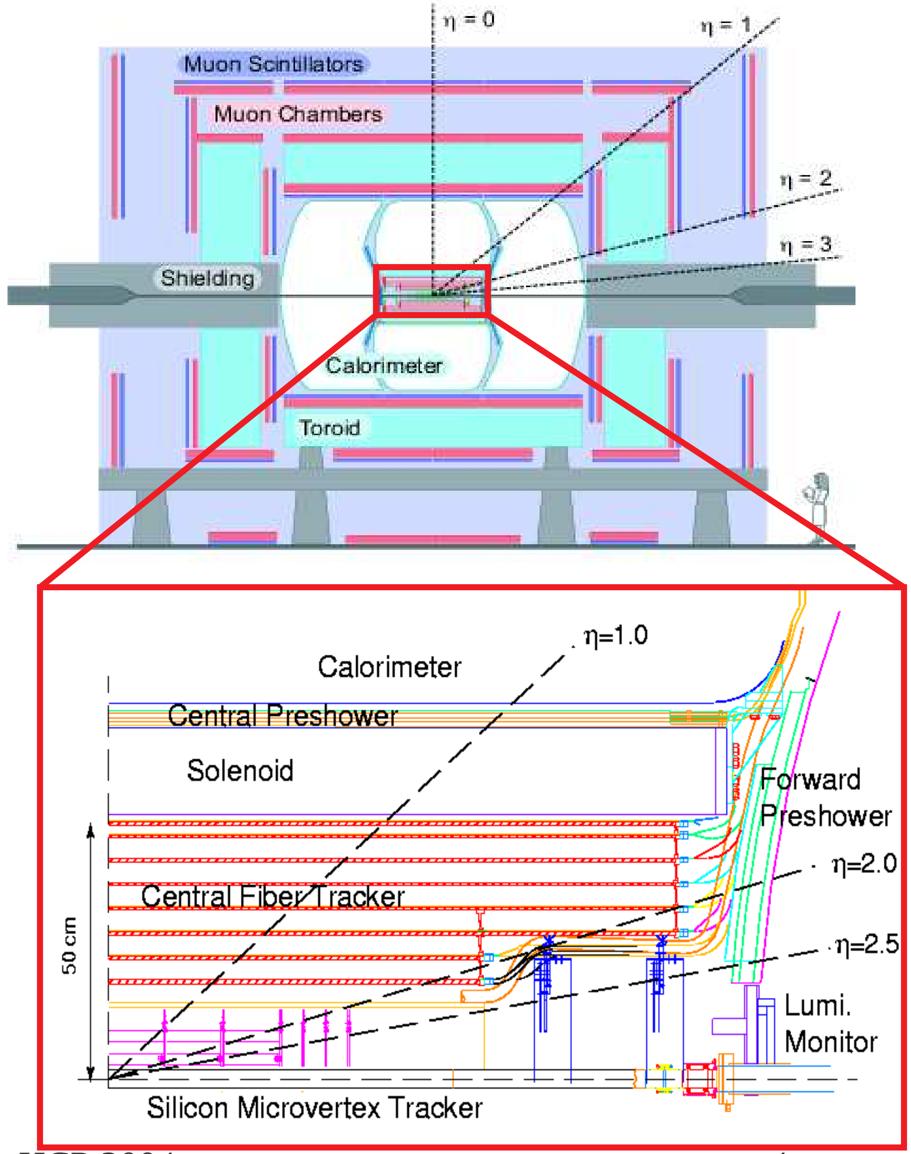
- In the SM, top can decay only via the weak interaction
  - And the CKM element $|V_{tb}|$ is nearly unity

  $\rightarrow$ top decays almost always to *Wb*
- Decay channels differ due to *W* final states
  - Results from all non-τ channels will be presented



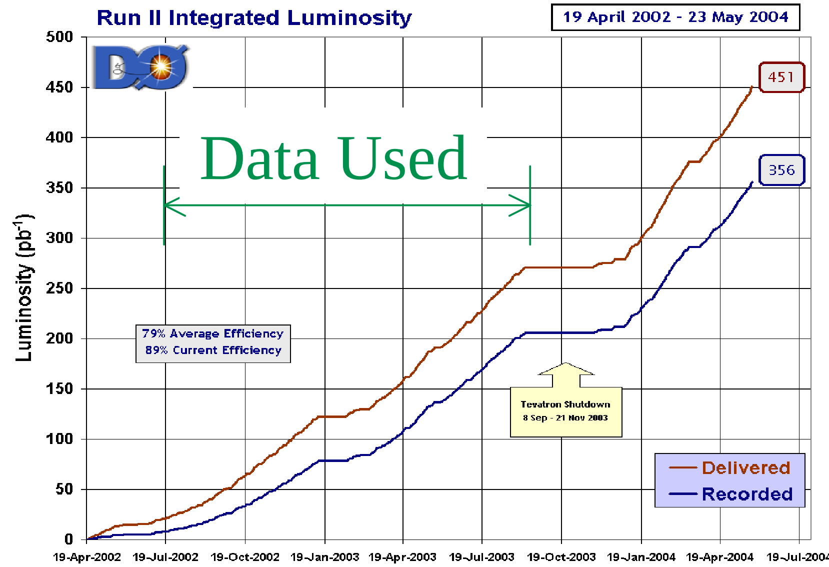
DØ Detector

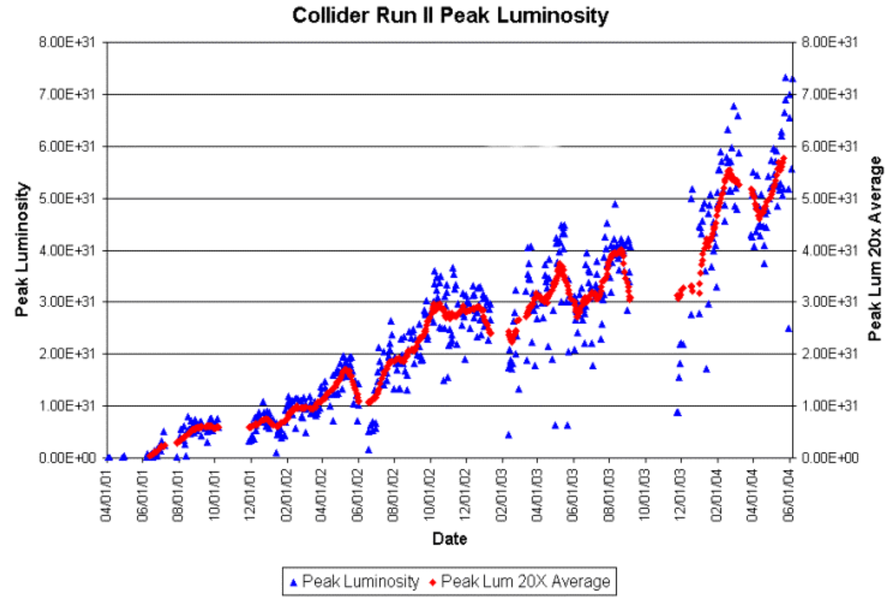
- DØ has undergone a significant upgrade for RunII
- Increased trigger and DAQ capacity
- Muons:
  - New forward system, scintillators added
- Calorimeters:
  - Faster electronics
- Tracking system is all-new
  - 2T solenoid
  - Scintillating fiber and silicon microstrip detectors
- *b* lifetime tagging now available



Data Sample

- Physics data-taking began in April 2002
  - DØ fully instrumented
- Results presented here use data taken up to Nov. 2003
  - Analysis of subsequent data is in progress
- Total of ~160pb^{-1} of good data
  - About 1.5x the RunI sample
- In addition, c.m. energy increased to 1960 GeV
  - $t\bar{t}$ cross section ~30% higher





Object Identification

- Extraction of top quark signal requires identification of jets, electrons, muons, and neutrinos

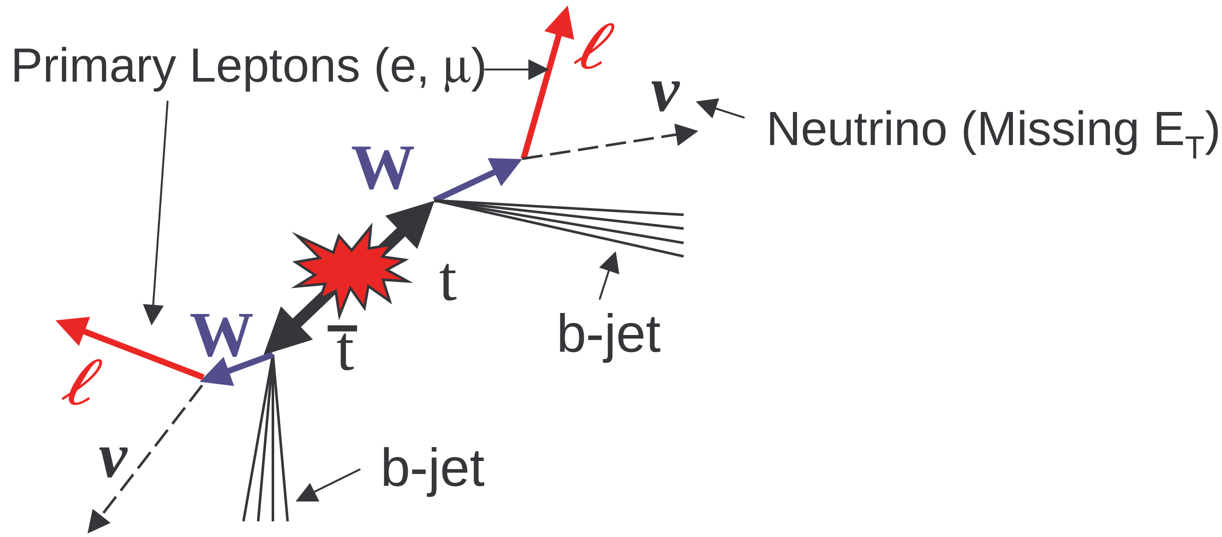
Jets:
- Calorimeter energy clusters in $R = 0.5$ cone
- 5 to 95% of energy in EM layers
- Inconsistent with noisy/hot cells

Electrons:
- Isolated energy cluster
- > 90% of energy in EM layers
- Shower shape consistency with EM
- Matching central track
- E/p ratio

Muons:
- In-time hits in all three layers
- Good track fit in muon system
- Matching central track, pointing to event vertex

Neutrinos:
- Inferred from imbalance in event E_T ($\not{E}_T$)
- Calorimeter and muon energies used in calculation

Cross Section in Dilepton Channel



- Main backgrounds are:
  - $Z/\gamma^* \rightarrow \ell\ell$, $Z \rightarrow \tau\tau \rightarrow \ell\ell'$
  - QCD multijets
  - WW
- $e\mu$ channel has lowest background and highest branching fraction

$Z/\gamma^* \rightarrow \ell\ell$ does not contribute to $e\mu$ channel

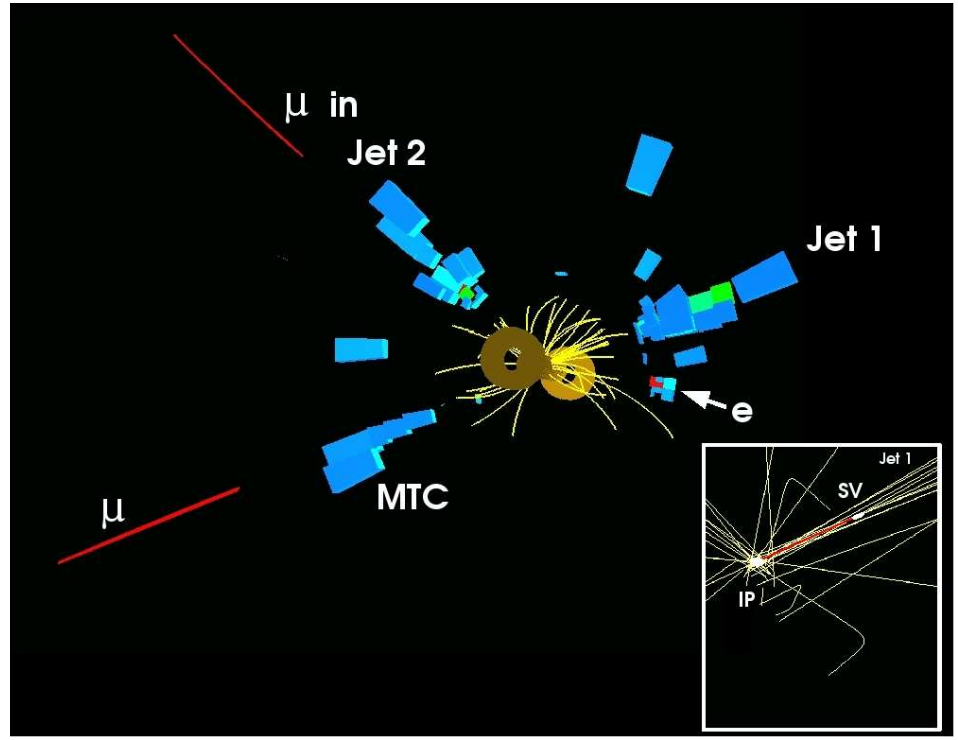
$\ell\ell$ Event Selection

- Initial selection in all three channels requires well-reconstructed primary vertex, two identified leptons, two jets with p_T > 20 GeV
- Additional topological criteria then applied to reduce backgrounds:

ee channel:
- $\not\!\!E_T > 35$ GeV
- $M_{ee} < 70$ GeV or > 110 GeV

$e\mu$ channel:
- $\not\!\!E_T > 25$ GeV
- $H_T^{\ell} > 140$ GeV

$e\mu$ candidate event



$\mu\mu$ channel:
- $\not\!\!E_T > 35$ GeV
- $M_{\mu\mu} < 70$ GeV or > 110 GeV
- $H_T^{\ell} > 120$ GeV
- $\Delta\phi\left(\not\!\!E_T, \mu_{\text{leading}}\right) < 165^{\circ}$

Dilepton $t\bar{t}$ Yield

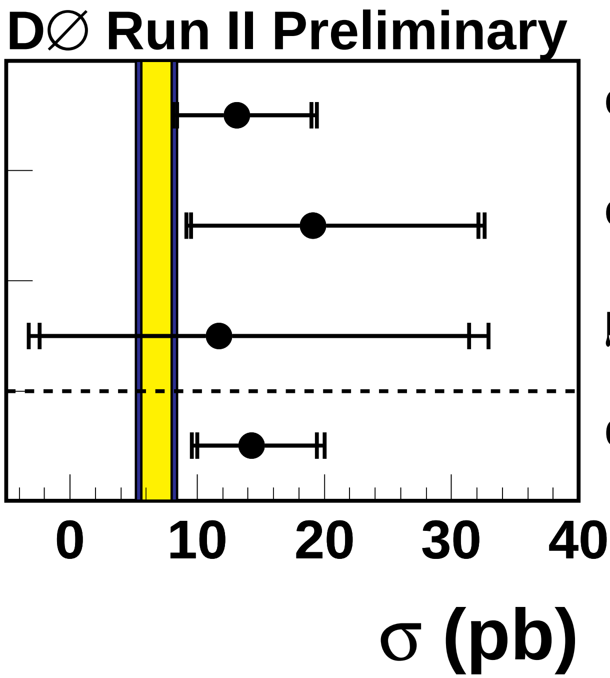
- Backgrounds rates for sources requiring fake $\not{E}_T$ and/or leptons estimated from data control samples, or from MC smeared to match data resolutions
- Other background sources estimated from MC
- Results:

	ee	$e\mu$	$\mu\mu$	$\ell\ell$
Z/γ^*	0.15 ± 0.10	0.47 ± 0.17	2.04± 0.49	2.66 ± 0.53
WW	0.14 ± 0.08	0.29 ± 0.06	0.10 ± 0.04	0.53 ± 0.11
Fakes	0.91 ± 0.30	0.19 ± 0.06	0.46 ± 0.20	1.56 ± 0.36
Total bkg.	1.20 ± 0.33	0.95 ± 0.19	2.61 ± 0.53	4.76 ± 0.65
Observed	5	8	4	17

Excess above background observed in all three channels

Dilepton Cross Sections

- Based on observed yields, expected background, and signal efficiency, we (preliminarily!) measure the following $t\bar{t}$ production cross sections:



eμ $13.1^{+5.9}_{-4.7}$ (stat.) $^{+2.2}_{-1.7}$ (syst.) ± 0.9 (lumi.) pb

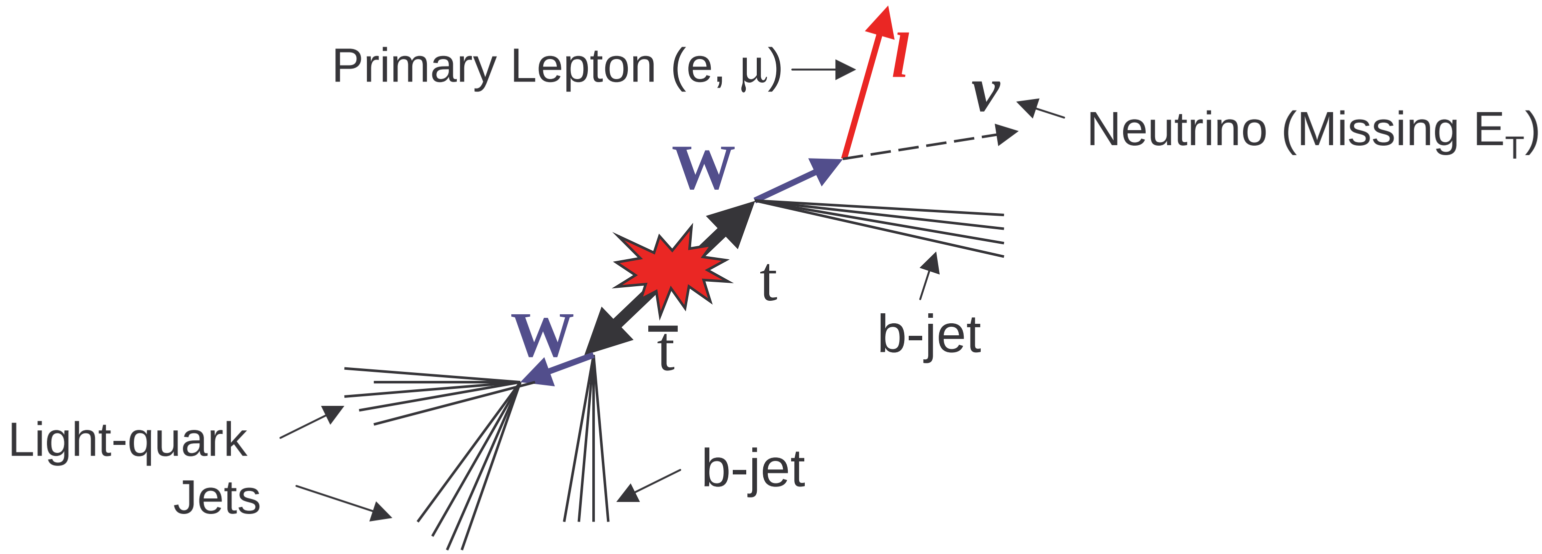
ee $19.1^{+13.0}_{-9.6}$ (stat.) $^{+3.7}_{-2.6}$ (syst.) ± 1.2 (lumi.) pb

μμ $11.7^{+19.7}_{-14.1}$ (stat.) $^{+7.9}_{-5.2}$ (syst.) ± 0.8 (lumi.) pb

dilepton $14.3^{+5.1}_{-4.3}$ (stat.) $^{+2.6}_{-1.9}$ (syst.) ± 0.9 (lumi.) pb

- Leading systematic effects:
  - Jet energy scale, jet selection efficiency, top quark mass

Cross section in ℓ+jets Channel



- Primary backgrounds are *W* + jets and QCD multijets
  - For latter, one jet fluctuates to mimic lepton, $\not{E}_T$ arises from mismeasured jet energies

Extracting $t\bar{t}$ Yield

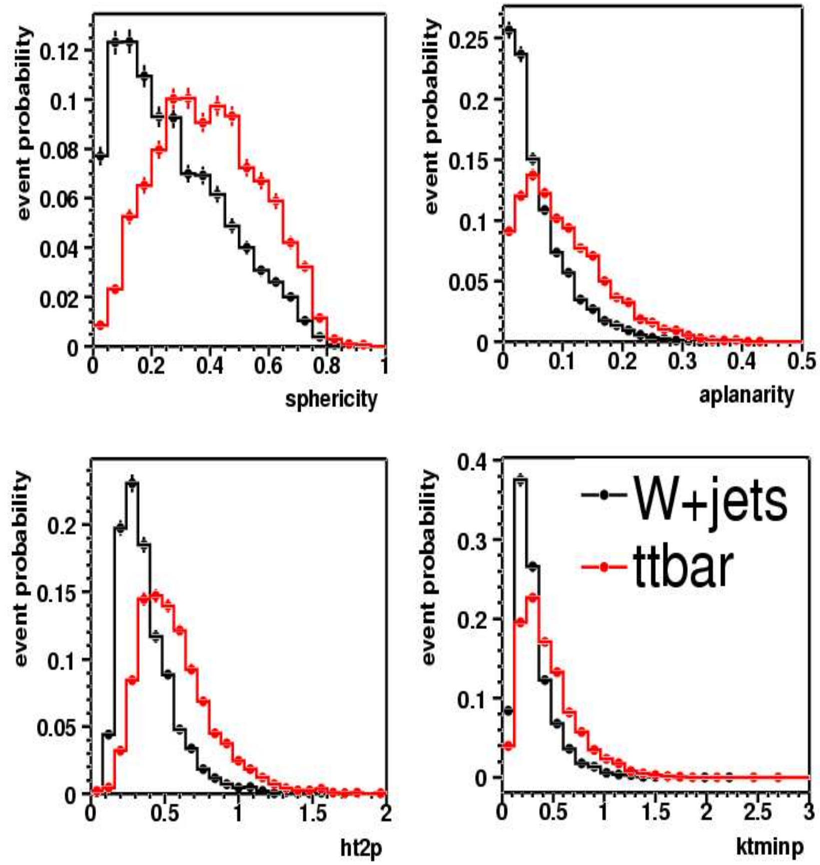
- "Loose" selection requires loosely-identified lepton, well-reconstructed event vertex, at least 4 high-p_T jets, and significant $\not{E}_T$
  - Sample consists of mixture of $t\bar{t}$, W+jets, and QCD events
- "Tight" selection starts from loose sample, and applies more stringent lepton identification criteria
  - Efficiency for real lepton to pass measured in $Z \to \ell\ell$ control sample
  - Efficiency for QCD event to pass measured in low-$\not{E}_T$ control sample
- With these known efficiencies, can determine N_{QCD} and $N_{t\bar{t}+W}$ in tight sample:

	e + jets	μ + jets
$N_{t\bar{t}+W}$	122 ± 10	93 ± 10
N_{QCD}	14 ± 1	7 ± 1

Last step is to disentangle $t\bar{t}$, W contributions

Extracting $t\bar{t}$ Yield

- Four topological variables that distinguish top from *W* are used:
  - Event shape variables: aplanarity and sphericity
  - Variable sensitive to jets from radiation
- We use these variables because they are:
  - Insensitive to jet energy scale
  - Modeled well in Monte Carlo
  - Nearly uncorrelated with each other
- The four variables are combined into a single topological discriminant L_T
  - Formed from product of top and *W*+jets p.d.f. for each variable

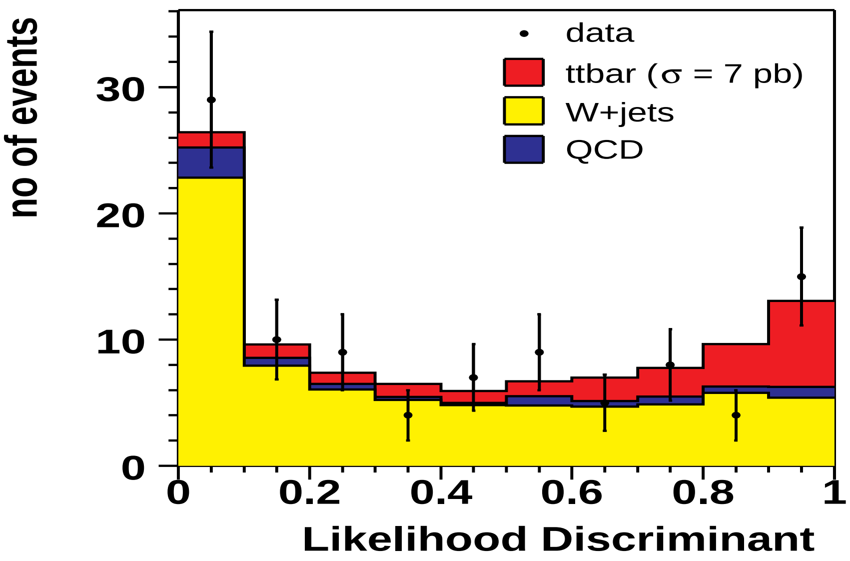


Observed ℓ+jets events

- Tight sample is fit to expected distribution for signal and background to extract $t\bar{t}$ yield:

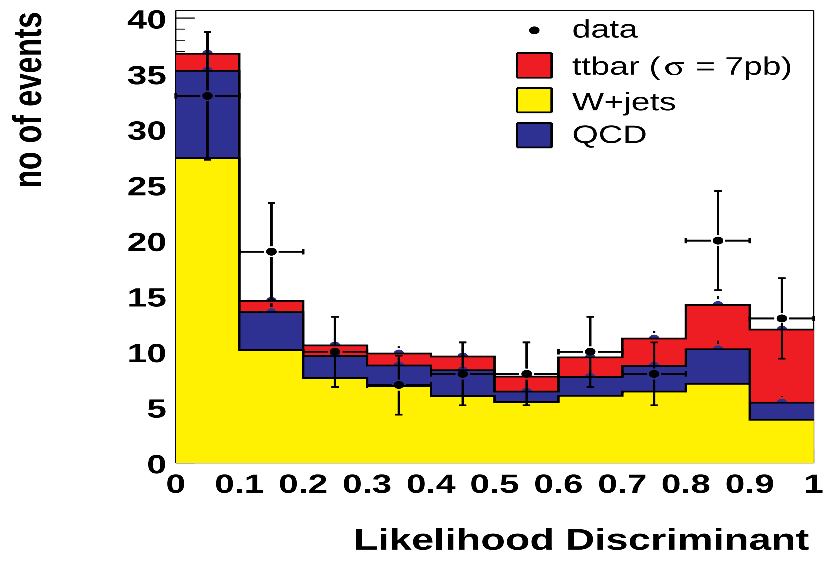
μ + jets

$$N_{t\bar{t}} = 17.8^{+9.8}_{-8.7}\ \text{(stat.)}$$



e + jets

$$N_{t\bar{t}} = 27.5^{+12.7}_{-11.7}\ \text{(stat.)}$$



ℓ+jets cross section

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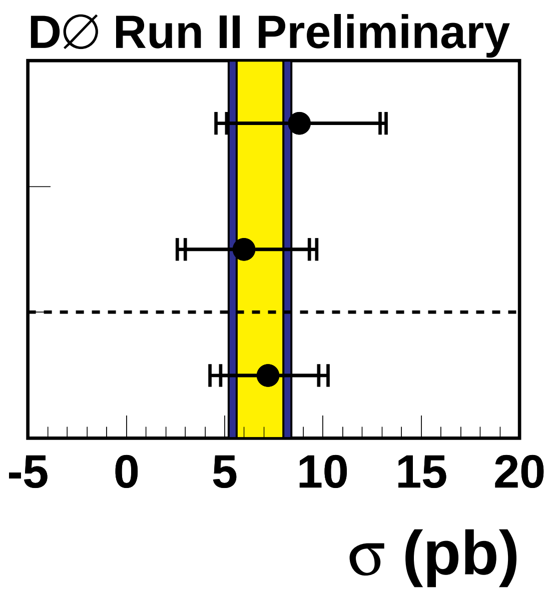


e+jets (topological) $8.8^{+4.1}_{-3.7}$ (stat.) $^{+2.1}_{-1.6}$ (syst.) ± 0.6 (lumi.) pb

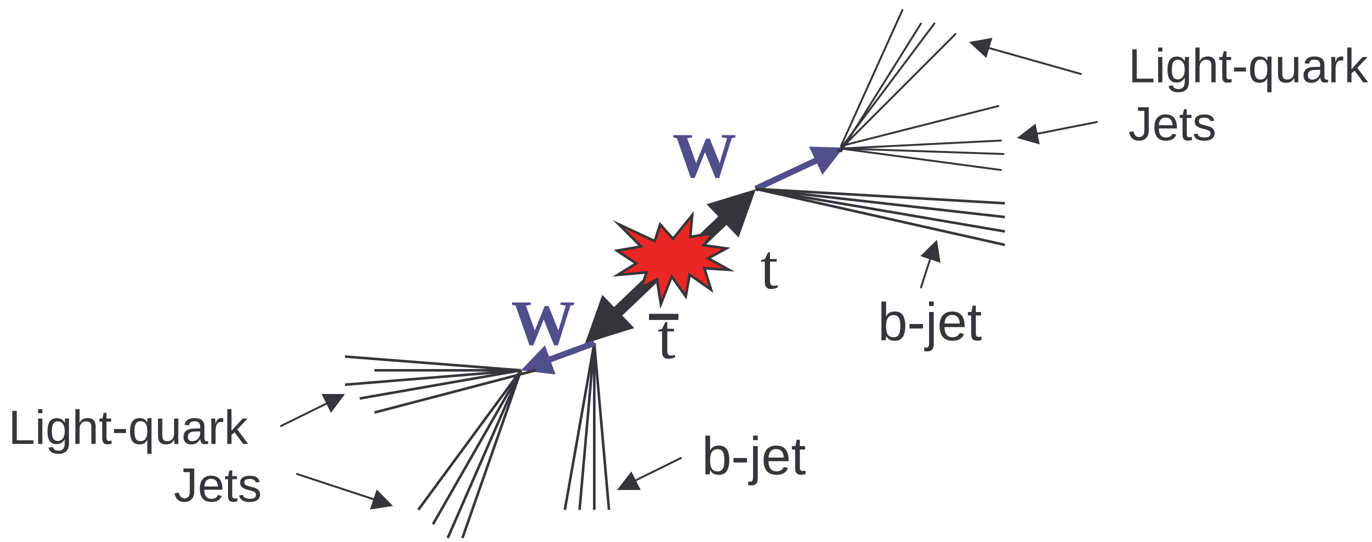
μ+jets (topological) $6.0^{+3.4}_{-3.0}$ (stat.) ± 1.6 (syst.) ± 0.4 (lumi.) pb

lepton+jets (topological)

$7.2^{+2.6}_{-2.4}$ (stat.) $^{+1.6}_{-1.7}$ (syst.) ± 0.5 (lumi.) pb

- Leading systematics are jet energy scale, jet selection efficiency

Cross Section in All-Hadronic Channel



- The all-hadronic channel has the largest branching fraction (46%)
  - But the QCD multijet background is ~10^3 larger
- Signal observed via combination of topological and *b*-tagging criteria
- Initial selection requires six or more jets with $p_T > 15$ GeV and $|\eta| < 2.5$
  - Events with isolated leptons or poorly-reconstructed vertex are vetoed
- Displaced vertex *b*-tagging efficiency measured using this sample (which is nearly all background)

Topological Selection

- Kinematic variables used are sensitive to:
  - Energy scale: H_T and $\sqrt{\hat{s}}$
  - Soft jets from gluon radiation: p_T-weighted multiplicity, sum of all jet p_T's except leading two, geometric mean of 5th and 6th p_T's
  - Event shape: aplanarity and sphericity
  - Rapidity distribution: p_T-weighted variance in η, ratio of transverse to total energy
  - Typical top properties: W and top mass χ^2, WW and tt masses, minimal dijet masses

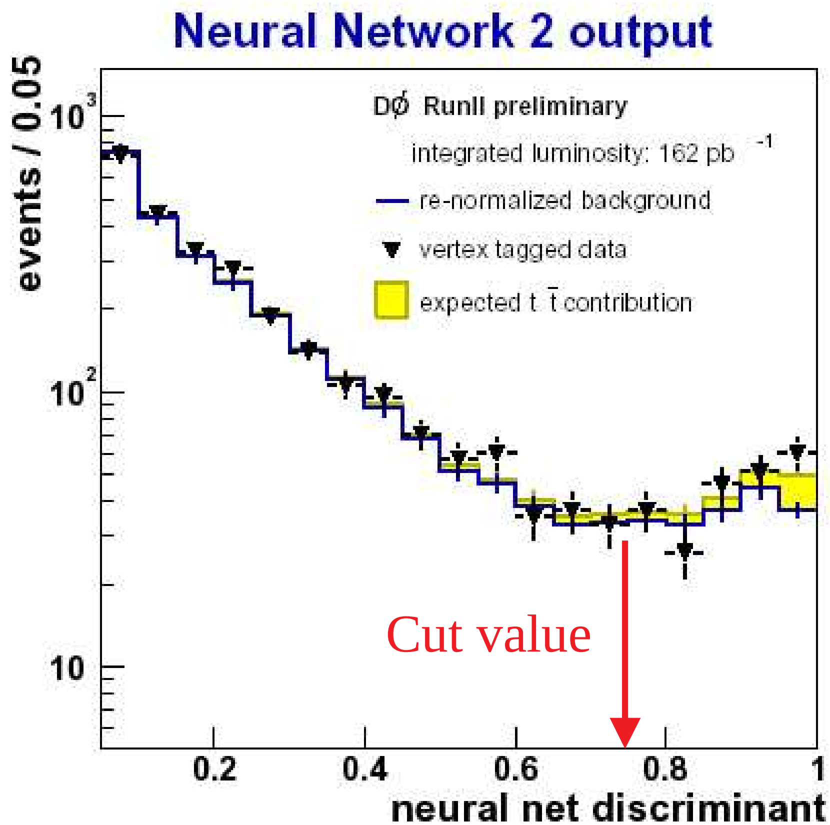
Used in NN1

Used in NN2

- Variables are combined in a chain of neural networks
  - Initial network (NN0) designed to eliminate obvious background, be highly efficient for signal
  - Events that pass go to second network (NN1)
  - Output of NN1 is one input to final network (NN2)
  - Trained on non-b tagged events (for background) and $t\bar{t}$ MC

All Hadronic $t\bar{t}$ Cross Section

- Neural network is applied to events with a single *b*-tagged jet
- Optimal cut (from MC studies) of 0.75 applied
  - Background level of 185 5 (stat.) expected from measured background *b*-tag rate
  - 220 events observed
- Jet energy scale is dominant systematic effect
- Preliminary result:



$$\sigma_{t\bar{t}} = 7.7^{+3.4}_{-3.3}\ \text{(stat.)}\ ^{+4.7}_{-3.7}\ \text{(syst.)}\ \pm 0.5\ \text{(lumi.) pb}$$

Top Quark Mass Measurement

- Measurements of m_t using RunII data are in progress
- The RunI data has been re-analyzed using a novel technique that dramatically improves the sensitivity
- Rather than a kinematic fit, the probability for a top (or background) event to give rise to the observed jets, leptons, and $\not{E}_T$ is computed
- If we define the set of measured quantities as *x*, this probability is:

Produced partons

Incoming quark momenta

$$P(x,m_t) = \frac{1}{\sigma(m_t)} \int d\sigma(y,m_t)\, dq_1 dq_2\, f(q_1)\, f(q_2)\, W(y,x)$$

Differential cross section

Structure functions

Detector resolution function

Method, cont.

- Can also define a background probability for each event
  - Use background cross section rather than $t\bar{t}$
  - Events required to have background probability < 10^{-11}
- Top quark mass measured by maximizing Poisson likelihood for entire event sample
- Advantages:
  - All jet permutations contribute
  - Additional kinematic information used
  - Event-by-event resolutions considered
  - Non-Gaussian detector response accounted for
- Compromises:
  - Only leading-order $t\bar{t}$ cross section is used
    - Means that only events with exactly four jets can be analyzed
  - Gluon fusion diagrams neglected
  - Only background process computed is W + jets

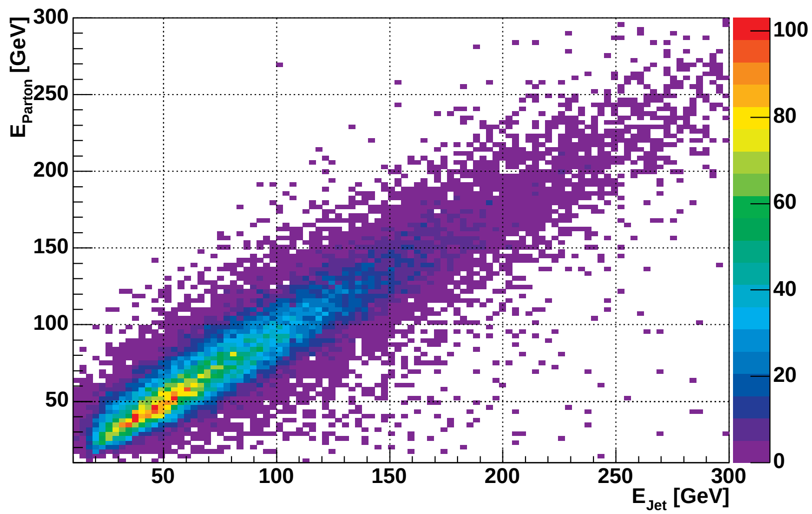
Detector Resolution

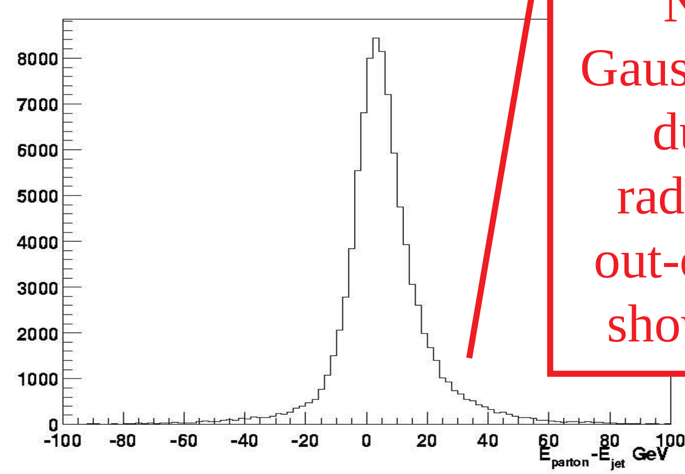
- The "transfer function" that gives the probability for *x* to be measured when *y* was produced is approximated as:

$$W(x,y)=\delta^3(p_e^y-p_e^x)\prod_{i=1}^{4}\delta^2(\Omega_i^y-\Omega_i^x)\prod_{j=1}^{4}W_{jet}(E_j^y,E_j^x)$$

Electron energies and all angles are considered well-measured

- W_{jet} in Monte Carlo:





Non-Gaussian tail due to radiation, out-of-cone showering

Expected Uncertainty

- Using a set of simulated experiments, we compare the expected precision of the new measurement to our previously published method:

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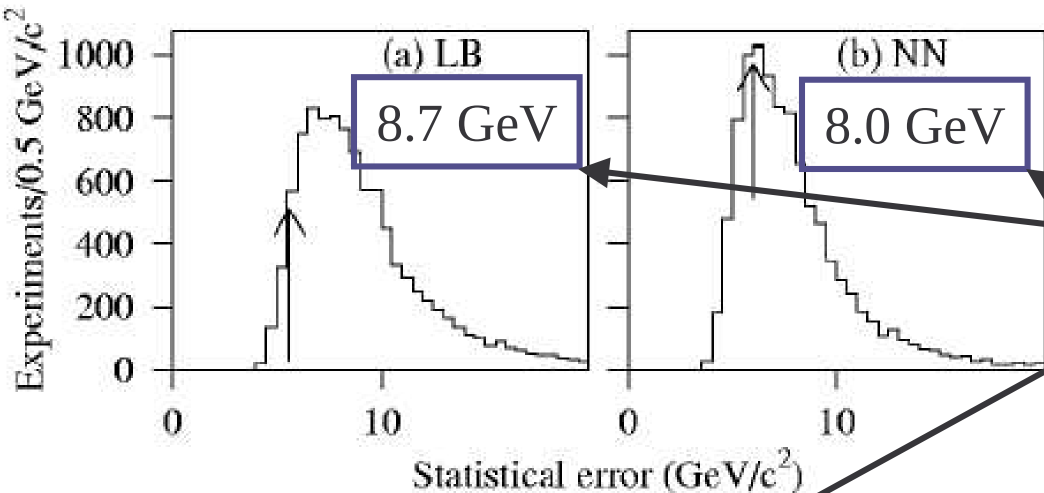
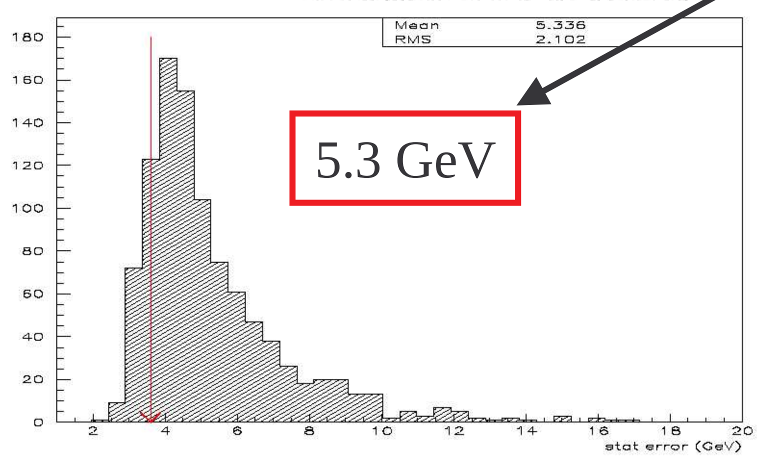


Avg. $\sigma(m_t)$

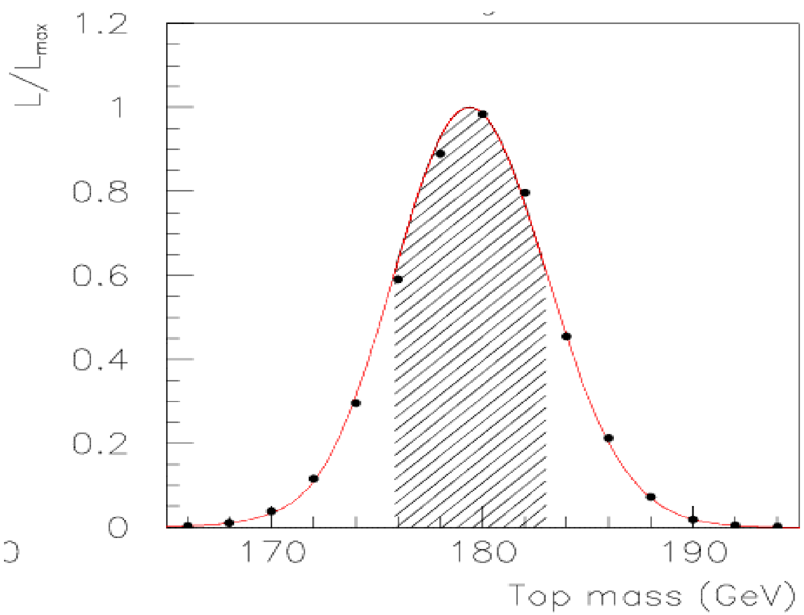
New method



Improvement equivalent to more than factor of two in data sample

Preliminary Result

- We observe the following likelihood distribution for the RunI sample
  - 22 events, of which 12 are estimated to be signal



Systematics:

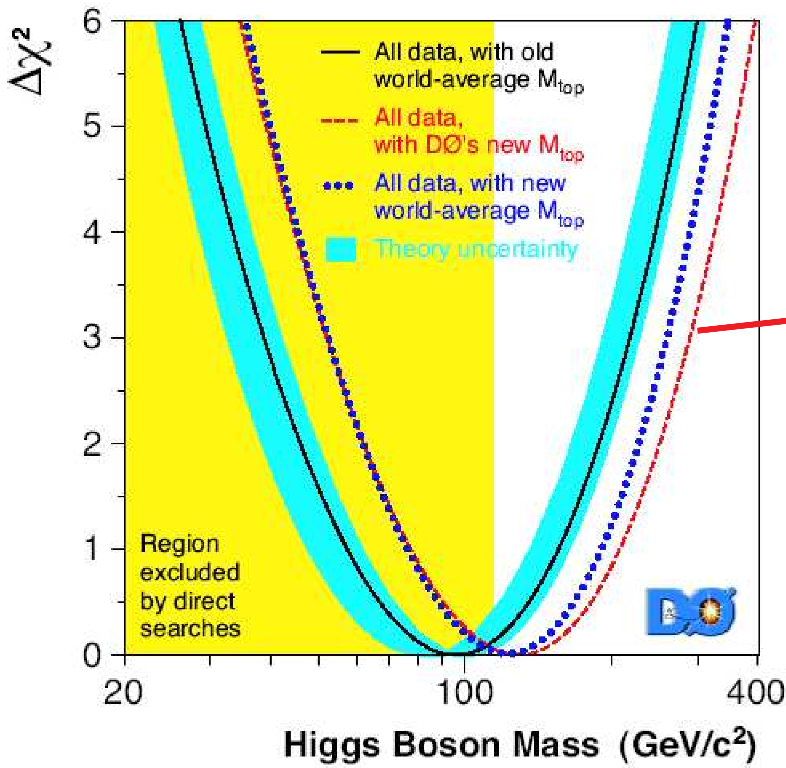
Jet energy scale	3.3 GeV
Parton dist. func.	0.2 GeV
Acceptance corr.	0.5 GeV
Signal model	1.5 GeV
Background model	1.0 GeV
Noise, mult. int.	1.3 GeV
Total	4.0 GeV

$$m_t = 180.1 \pm 3.6\,(\text{stat.}) \pm 4.0\,(\text{syst.})\ \text{GeV}$$

Precision comparable to previous world average!

Implications for the Higgs

- This new measurement, combined with other top quark mass measurements, yields the following constraint on the Higgs mass:



Most likely m_H is 123 GeV
m_H < 277 Gev @ 95% CL

Most likely value no longer excluded by searches!

Summary

- The RunII top quark physics program is off to a strong start
- The $t\bar{t}$ cross section has been measured at $\sqrt{s} = 1960$ GeV
- Preliminary results:
  - Dilepton: $14.3^{+5.1}_{-4.3}$ (stat.) $^{+2.6}_{-1.9}$ (syst.) ± 0.9 (lumi.) pb
  - ℓ+jets: $7.2^{+2.6}_{-2.4}$ (stat.) $^{+1.6}_{-1.7}$ (syst.) ± 0.5 (lumi.) pb
  - All-hadronic: $7.7^{+3.4}_{-3.3}$ (stat.) $^{+4.7}_{-3.7}$ (syst.) ± 0.5 (lumi.) pb
- Results are consistent with pQCD prediction
- New technique used to measure top quark mass with RunI data
  - Preliminary result:

$$m_t = 180.1 \pm 3.6 \text{ (stat.)} \pm 4.0 \text{ (syst.) GeV}$$

  - Improvement in statistical precision equivalent to factor of 2.4 in data sample
- More data is arriving rapidly

Updated results will be available soon!