Top Quark Mass Measurements at the Tevatron

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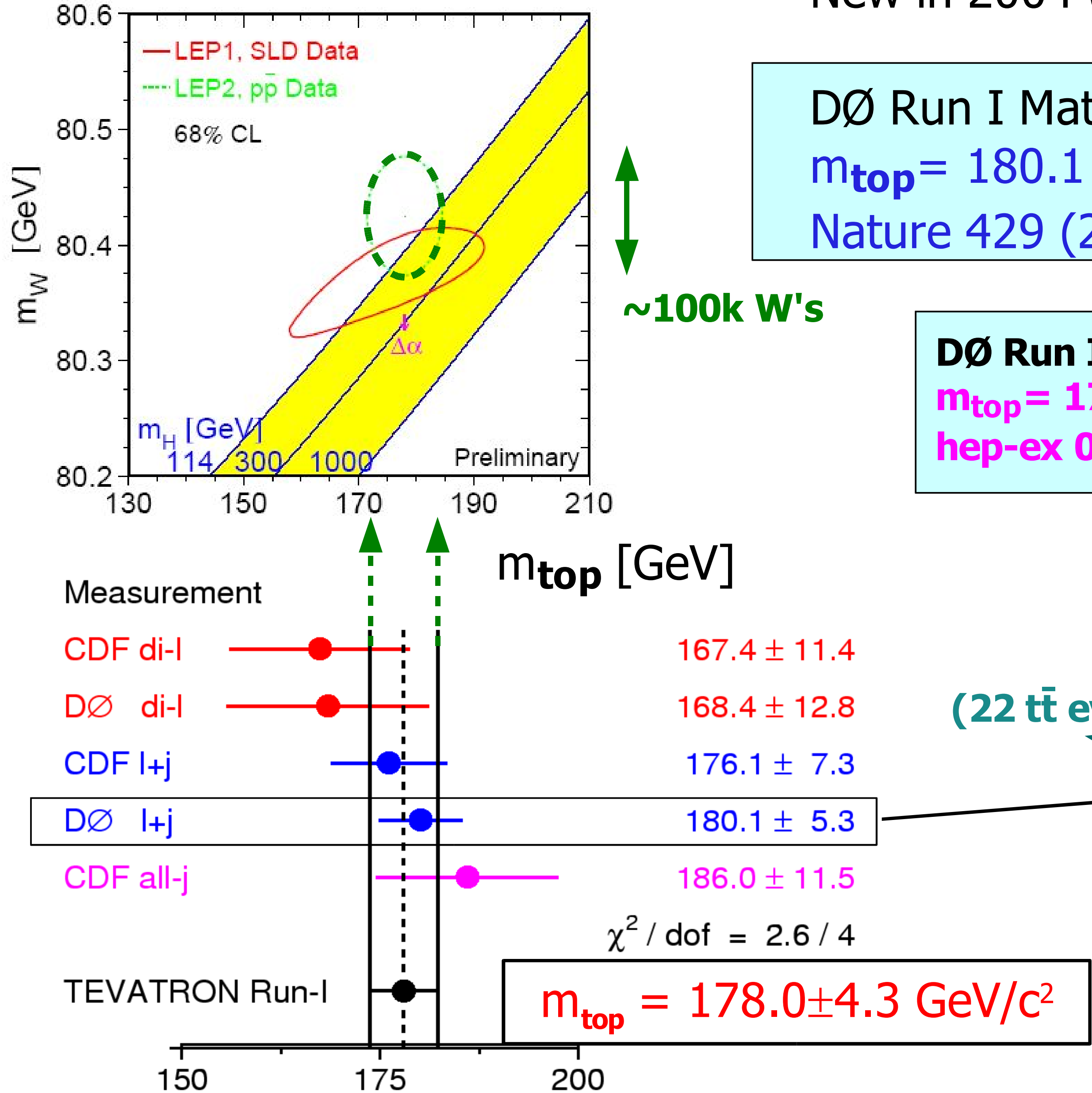
on behalf of the CDF and DØ collaborations

All RunII results in this talk are preliminary

XXXXth Rencontres de Moriond (QCD), March 12-19, 2005

The Top Quark Mass

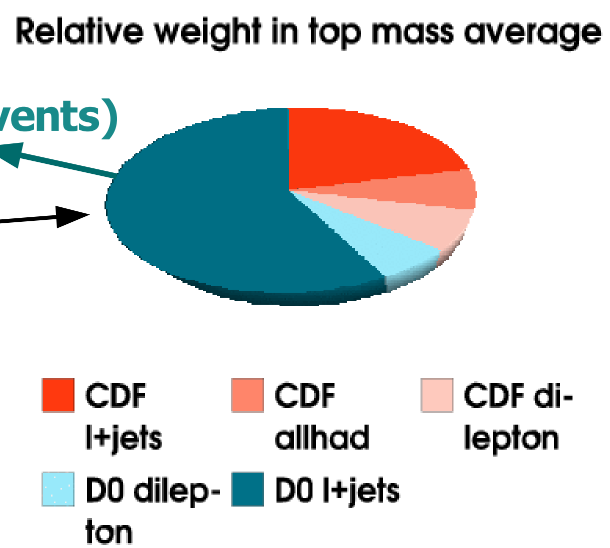


New in 2004 (Run I data):

DØ Run I Matrix Element method l+jets:
m_{top}= 180.1 ± 3.6 (stat) ± 3.9 (sys) GeV
Nature 429 (2004) p638

DØ Run I all-jets:
m_{top}= 178.5 ± 13.7 (stat) ± 7.7 (sys) GeV
hep-ex 0410086, accepted by Phys.Lett.B

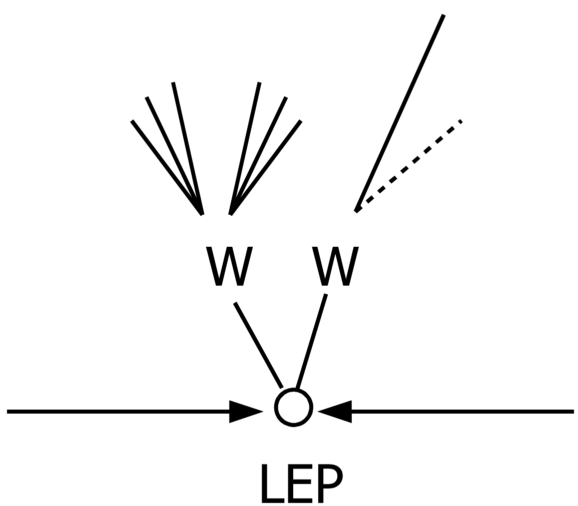
(22 tt̄ events)



Event kinematics

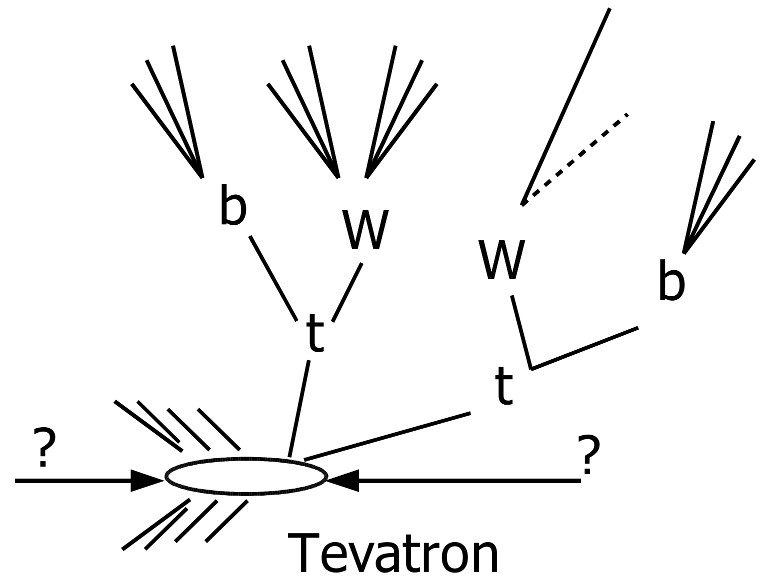
Similarities with direct measurement W mass using W pair events at LEP:

- Use invariant mass of decay products to measure mass
- Decay determined by W's (tau hardly contributes)
  - BR~10% di-lepton: small background 2 ν 's: under-constrained
  - BR~45% lepton+jets: 'moderate' backgrounds 1 ν: over-constrained
  - BR~45% all jets: overwhelming backgrounds (not used so far in RunII)
- But $t\bar{t}$, Tevatron: more jet combinations, (much) more backgrounds, trigger
- Harder to reconstruct jets (underlying hadronic activity!) + Jet Energy Scale less constrained



5 typical constraints:

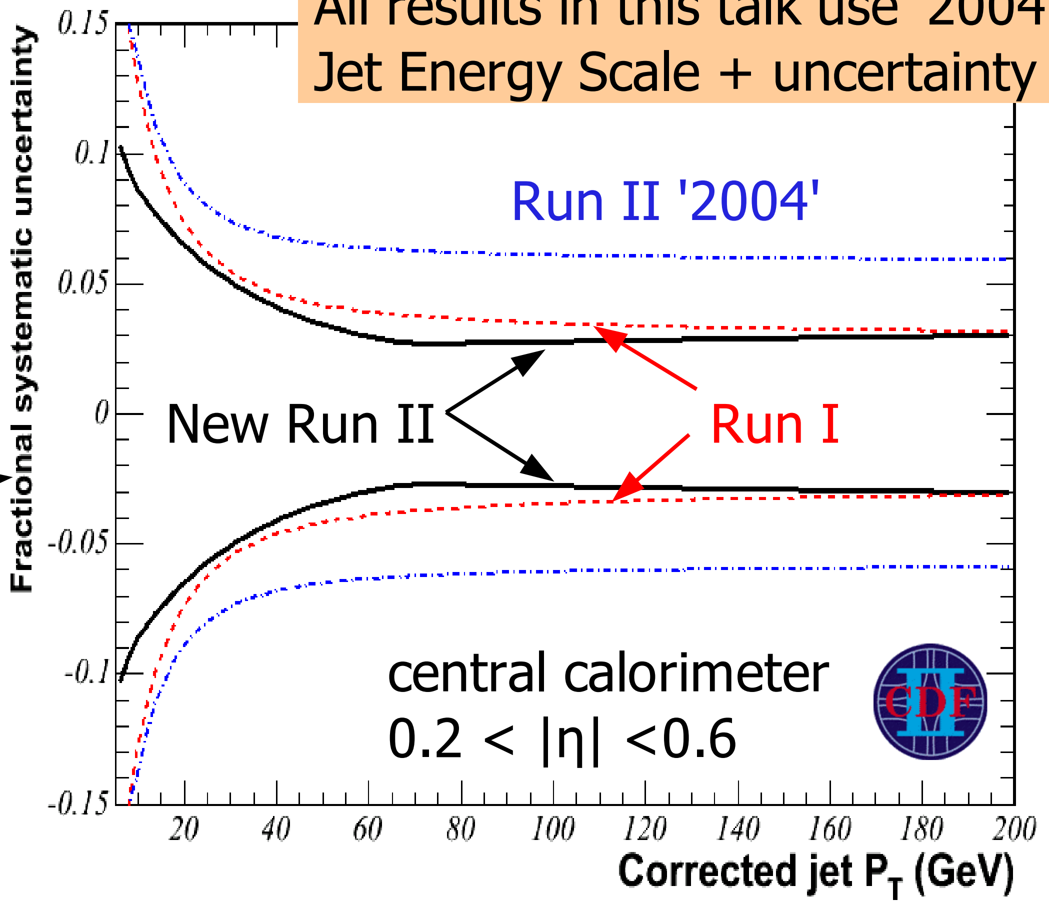
Σ px=0	Σ px=0
Σ py=0	Σ py=0
Σ pz=0	mW=80.4
Σ E =$\sqrt{s}$	mW'=80.4
mW=mW'	mt = mt'



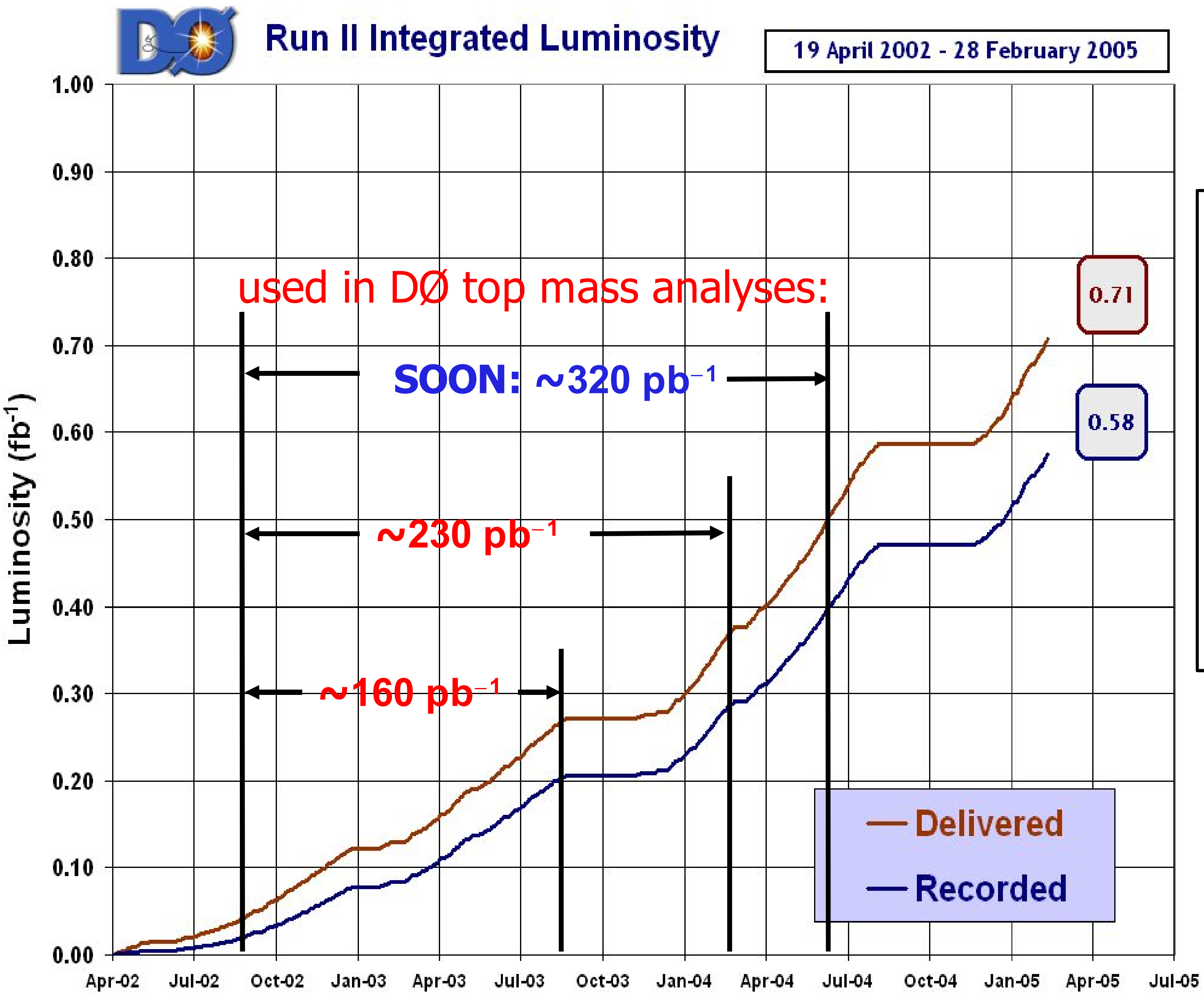
Jet Energy Scale

- Correct jet energy as well as possible for calorimeter effects (offset / non-linearity) underlying hadronic activity and out-of-cone showering
- Events samples used for checks/calibration: γ + jet, di-jet (data and MC)
- Relative calibration uncertainty data/MC is what counts for Top mass
- Dominant systematic uncertainty on Top mass
- A lot of work done to better understand the jet energy scale in Run II
- CDF: New Run II systematic uncertainty improved ~ factor 2 (!) Now comparable to Run I
- Also expect significant improvements in DØ Jet Energy Scale uncertainty

All results in this talk use '2004' Jet Energy Scale + uncertainty



Run II



Used in CDF analyses:

- 160 pb^{-1} with b-tagging
- 193-197 pb^{-1} without b-tagging
- SOON: 325 pb^{-1}

both CDF and DØ ~0.6 fb^{-1} on tape

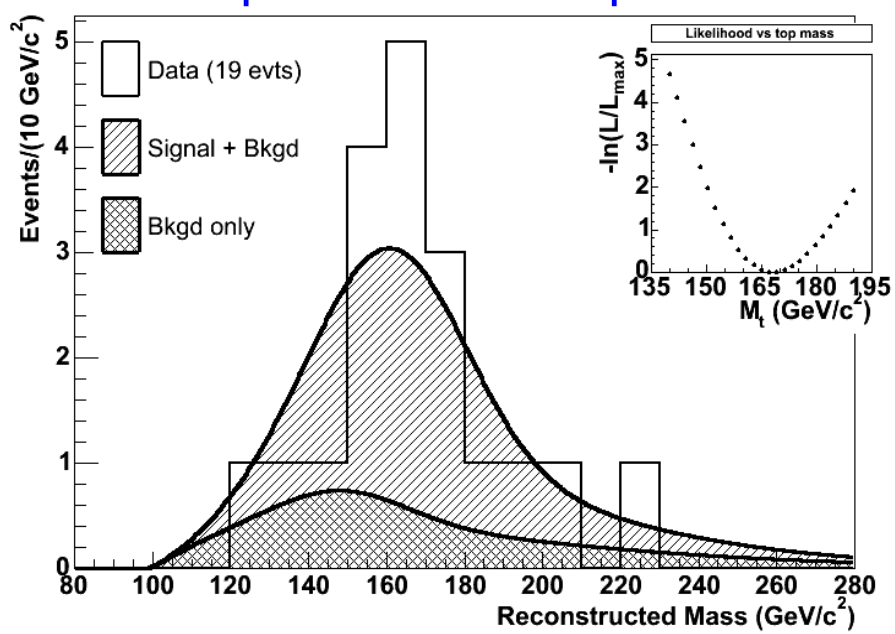
Di-lepton channel: CDF result

- Di-lepton event selection:
  - 1 isolated e or μ with p_T>20 GeV/c
  - 2nd oppositely charged lepton (e,μ) or isolated track with p_T>20 GeV/c
  - ≥ 2 jets with E_T>15 GeV
  - significant missing energy from two ν's (at least E_T>25 GeV)
- Good signal-to-background ratio ~ 4/1
- Low statistics (13 – 19 evts. @ 192 pb^{-1})
- Kinematics under-constrained
- Three different methods to add extra constraint give consistent results
- Best result with ν Weighting:

Assume rapidities of both neutrino's, scan all possible values and calculate likelihood of observed missing E_T:

$$W_x \sim \exp\left((p_x^{\nu 1+\nu 2} - E_x^{obs})^2 / 2\sigma_{Ex}^2 \right)$$

plot m_t which maximizes Wx·Wy, and compare to MC templates:



$$M_{top} = 168.1^{11.0}_{-9.8}(stat) \pm 8.6(sys)\, GeV/c^2$$

Di-lepton channel: DØ result

- Calculate weight as function of m_t for each event using Dalitz and Goldstein method. Also sample detector resolution:

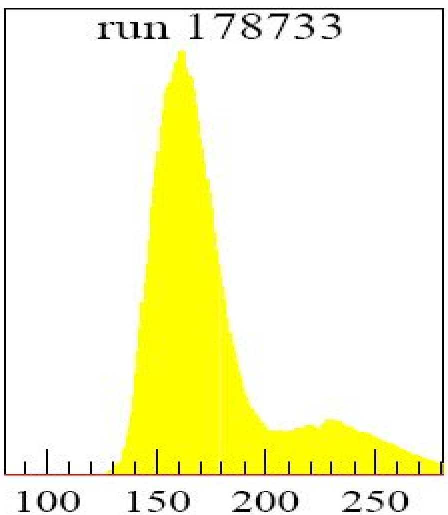
$$W = \sum_{solutions} \sum_{jets} f(x) f(\bar{x}) p(E_\ell^* | m_t) p(E_{\bar{\ell}}^* | m_t)$$

Parton distribution functions

Probability that the observed energy of lepton ℓ is coming from top quark with mass m_t

R.H. Dalitz and G.R. Goldstein, Phys.Rev. D45, 1531 (1992)

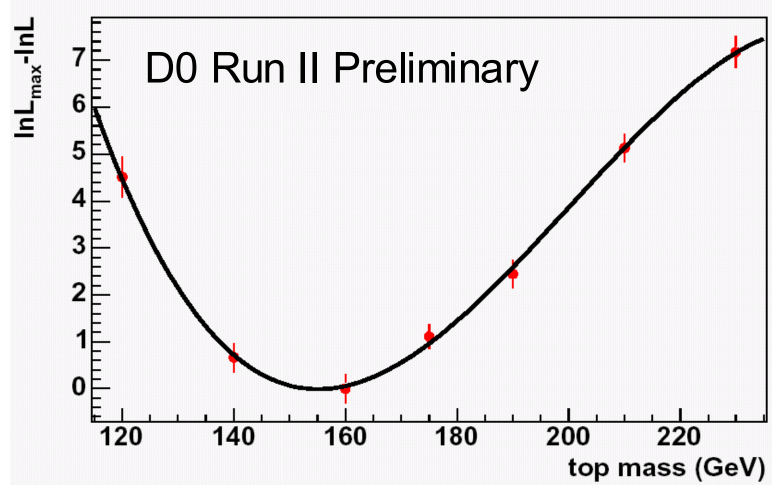
Example of one eμ event:



Take value of m_t with max. likelihood, fit data histogram with binned MC Templates

- Same selection as di-lepton cross-section analysis
- Event sample: 13 events
- Expected background: 3.3 events

$$M_{top} = 155^{+14}_{-13}(stat) \pm 7(sys)\ GeV/c^2$$

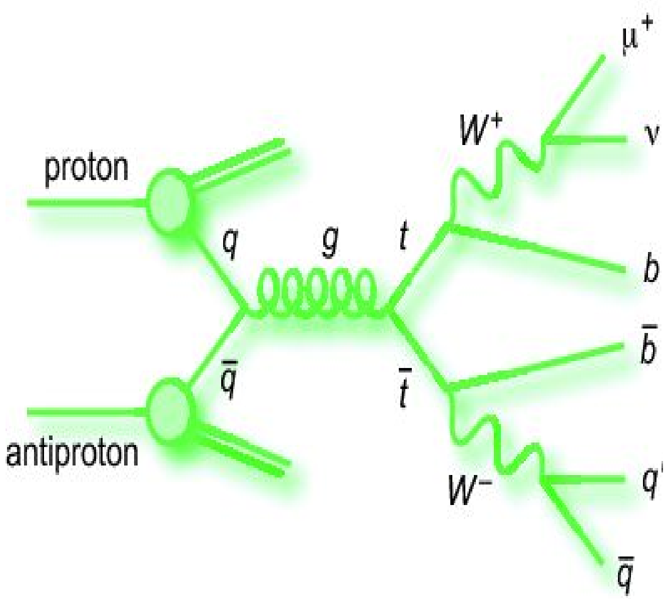


NEW

~230 pb^{-1}

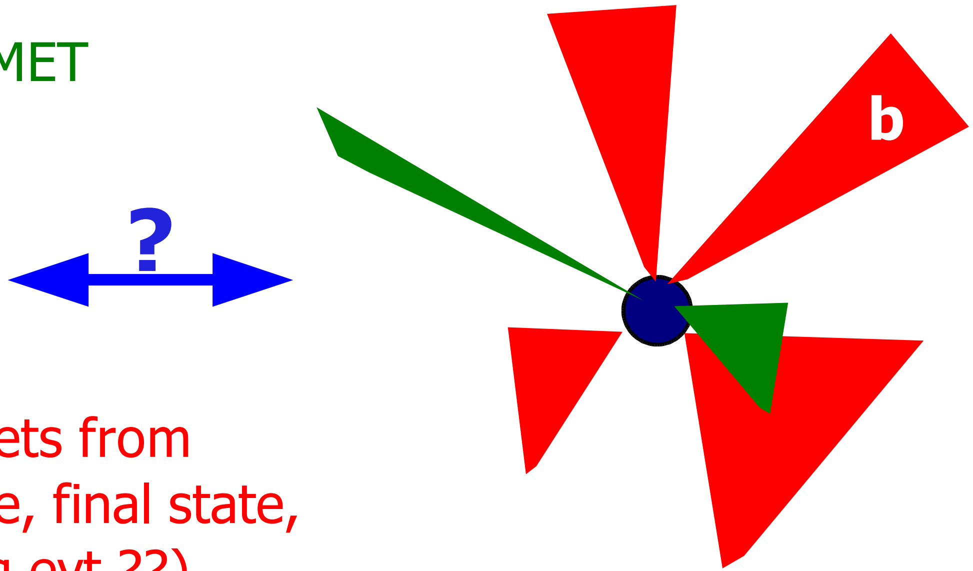
8% CL with respect to 175 GeV/c^2

Top mass in lepton + jets channel



lepton + MET

4 jets
(+ extra jets from
initial state, final state,
underlying evt ??)



Two-fold advantage of b-tagging for Top mass measurement:

1 Reduce main backgrounds:

W+jets

multi-jet events (QCD)

→ **improve S/B**

2 Reduce no. of possible jet permutations:

0 tag: 12 ways to assign 4 jets to partons

1 tag: 6

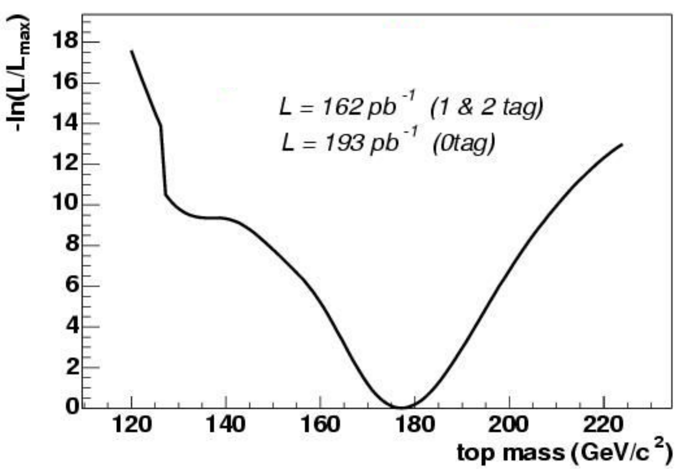
2 tags: 2

~60 % of $t\bar{t}$ events have 1 or more b-tagged jets (see talk by J.Nielsen)

Lepton+jets: CDF Template Method

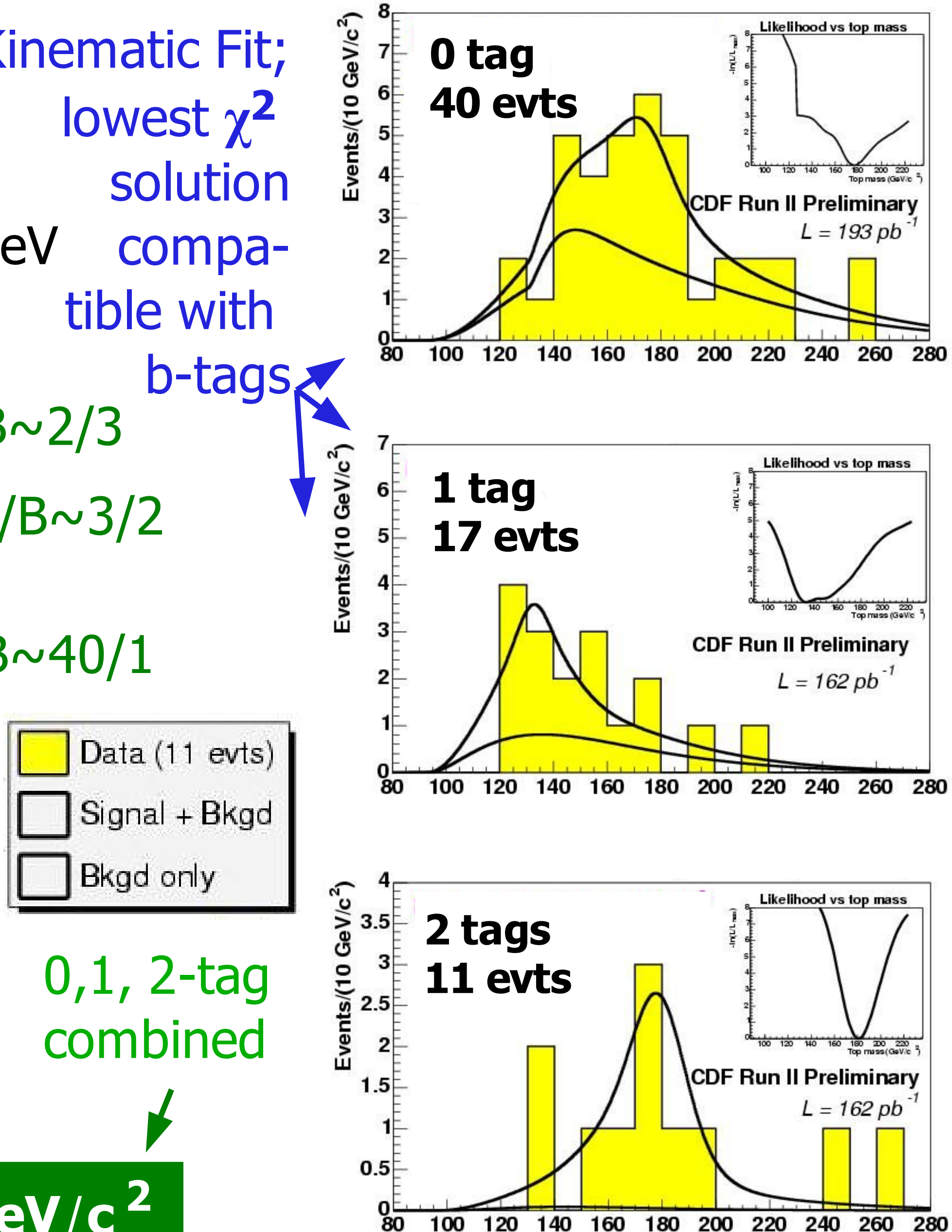
- Lepton +jets selection:
  - One e or μ with p_T>20 GeV/c
  - 3 jets with E_T>15 GeV, 4th jet E_T>8 GeV
  - missing E_T>20 GeV
- 0 tag sample: 4th jet E_T > 21 GeV →S/B~2/3
- 1 tag sample: One jet with SVX tag →S/B~3/2
- 2 tag sample: Use more efficient Jet Probability algorithm for 2nd b-tag →S/B~40/1

Kinematic Fit; lowest χ^2 solution compatible with b-tags



0,1, 2-tag combined

$$M_{top} = 177.2^{+4.9}_{-4.7}(stat) \pm 6.6(sys)\, GeV/c^2$$



CDF Multivariate Template Method

Doing more with Templates:

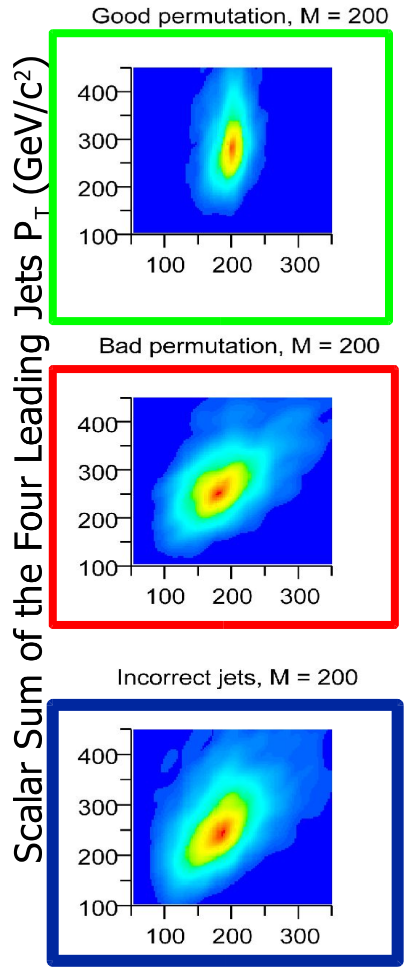
- ≥1 btag lepton+jets
- 2D Templates, mass vs H_T
- Use lowest χ^2 solution
- 3 types of signal templates; use kinematic variables to determine probability that best χ^2 solution is correct; weight signal templates accordingly
- Jet energy scale fitted event-by-event, using reconstructed mass of $W \to q\bar{q}$

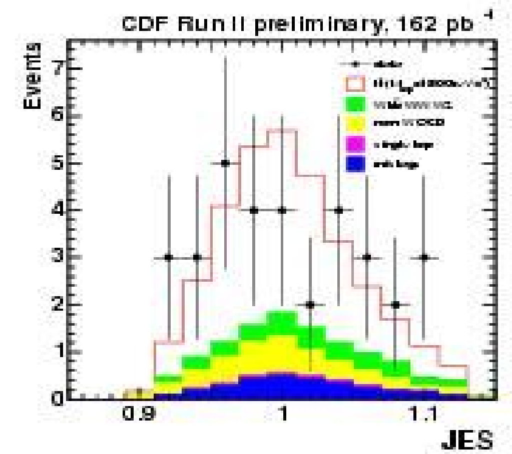
Multivariate Templates

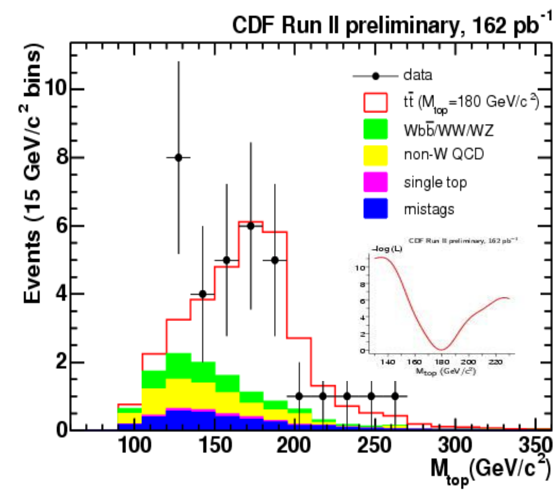
correct jet-to-parton assign ment

wrong jet-to-parton assign ment

jets from non-top decay assigned to top partons





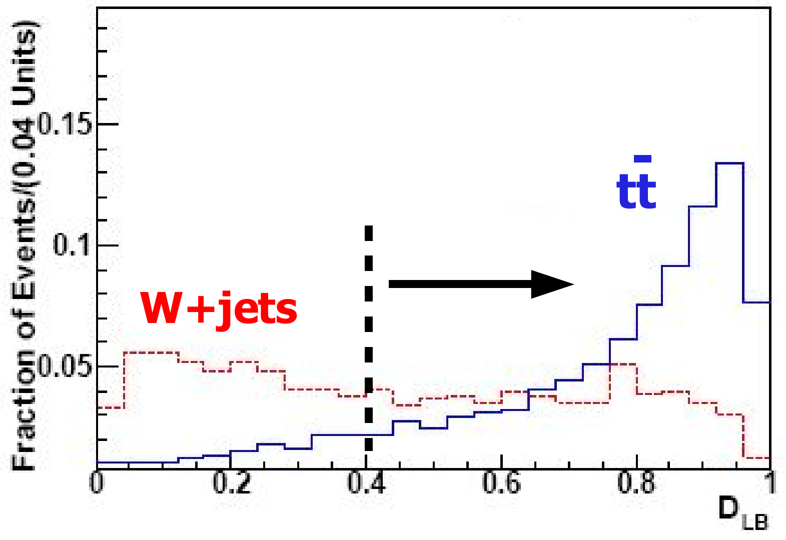


Reconstructed Top Mass (GeV/c²)

$$M_{top} = 179.6^{+6.4}_{-6.3}(\text{stat}) \pm 6.8(\text{sys})\ \text{GeV}/c^2$$

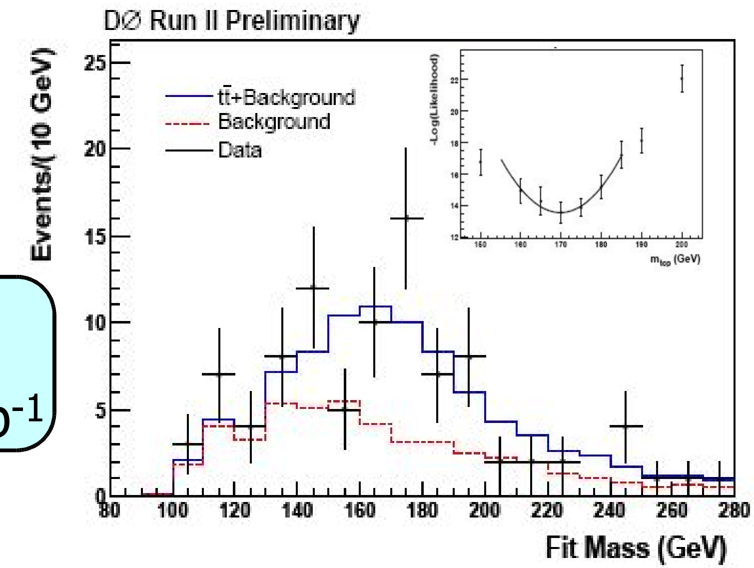
Lepton+jets: DØ Template Method

- Lepton + jets channel without b-tag
  - e or μ with p_T>20 GeV/c
  - ≥ 4 jets with p_T>20 GeV
  - No b-tag requirement
  - Kinematic fit, require lowest χ^2<10
- Low bias discriminant (D_{LB}) using topological variables
  - require D_{LB}>0.4
- Plot lowest χ^2 solution from fit, compare data to binned MC templates
- 94 $t\bar{t}$ candidates selected, S/B ~ 1/1



NEW

~230 pb^{-1}

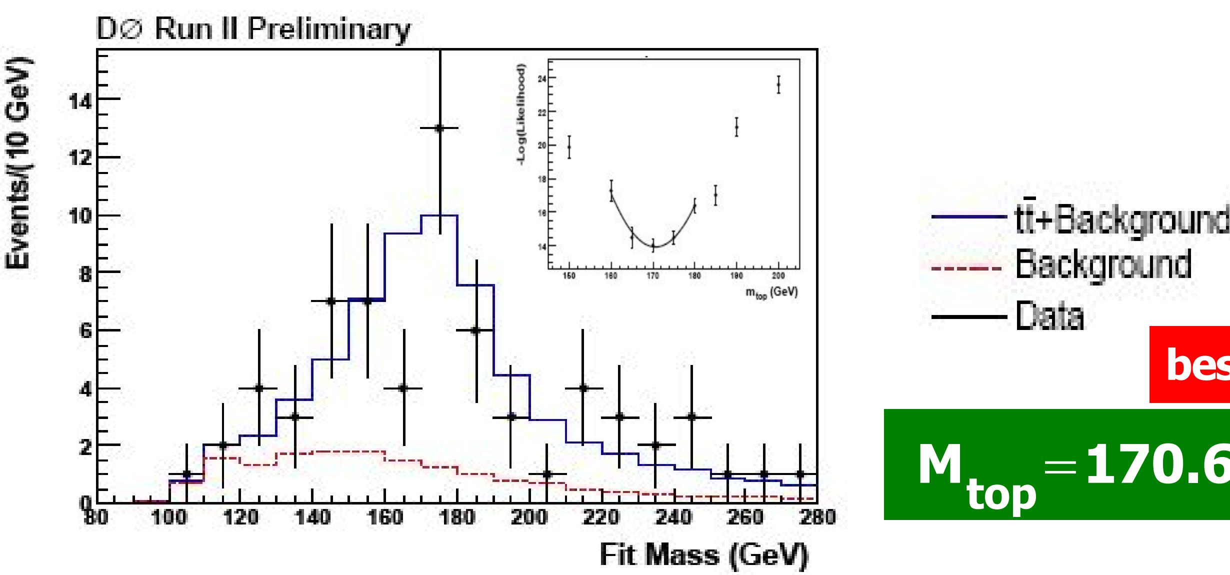


$$M_{top} = 169.9 \pm 5.8(stat)^{+7.8}_{-7.1}(sys)\, GeV/c^2$$

Lepton+jets: DØ Template Method

- Lepton + jets channel with b-tag using 'SVT' secondary vertex tagger
  - similar selection
  - one or more b-tagged jets
  - $\geq$ 4 jets with p_T>15 GeV
  - No cut on low bias discriminant D_{LB}
- 60 $t\bar{t}$ candidates selected, S/B ~ 3/1

Systematic Uncertainties	Δmtop (GeV/c2)
Jet Energy Scale	-5.3/+4.7
Gluon Radiation	2 .4
Signal Model	2 .3
Jet Energy Resolution	0.9
Calibration	0.5
Background Model	0.8
b-tagging	0.7
Trigger Bias	0.5
Limited MC Statistics	0.5
Total	**6.0**



NEW

~230 pb^{-1}

best preliminary RunII top mass result

$$M_{top} = 170.6 \pm 4.2(stat) \pm 6.0(sys)\ GeV/c^2$$

Lepton+jets: DØ Ideogram Method

Based on same kinematic fit as Template method and using same low-bias discriminant D_{LB} but improves statistical sensitivity, by

- Using all jet/neutrino solutions for the fitted mass m_i, error σ_i, and χ^2_i
- Calculating event-by-event likelihood taking into account all jet/neutrino solutions and the probability that the event is background (estimated with D_{LB})

Uses all possible jet/neutrino combinations, best permutation has most weight:

$$w_i = \exp(-\chi_i^2/2)$$

Gives relative weight to signal and background term according to estimated event purity $P_{evt}(D_{LB}, P_{sample})$ so that the events that are most likely top count the most

$$L(m_{top}, P_{sample}) = \sum_i w_i \left[P_{evt} \cdot S(m_i, \sigma_i, m_t) + (1 - P_{evt}) \cdot BG(m_i) \right]$$

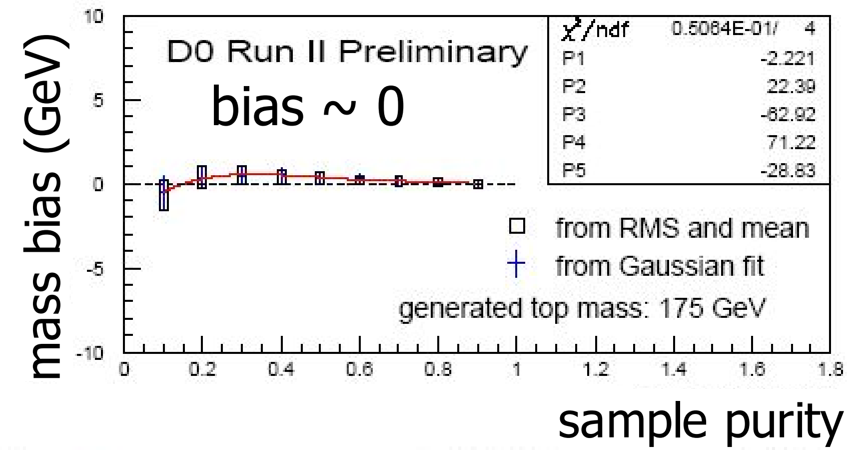
$$\int dm' \, G(m', m_i, \sigma_i) \, BW(m', m_{top}, \Gamma_{top})$$

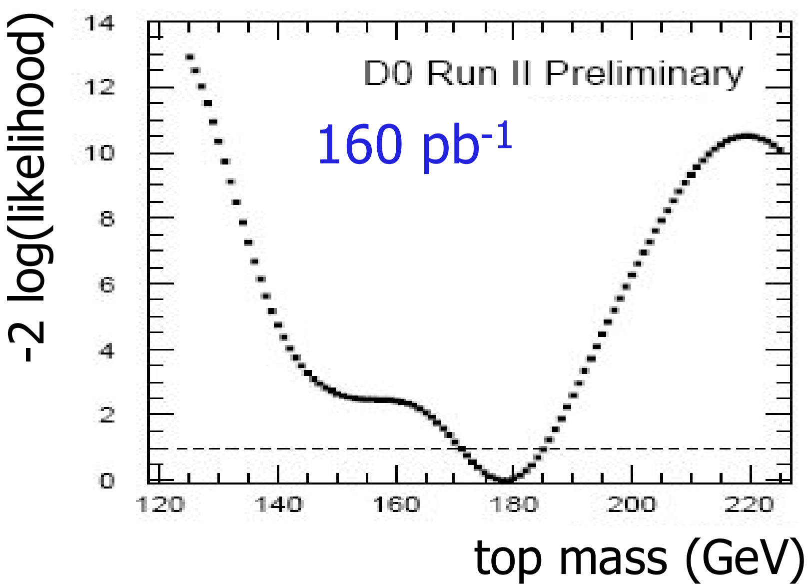
Signal likelihood based on Gaussian resolution and Breit-Wigner

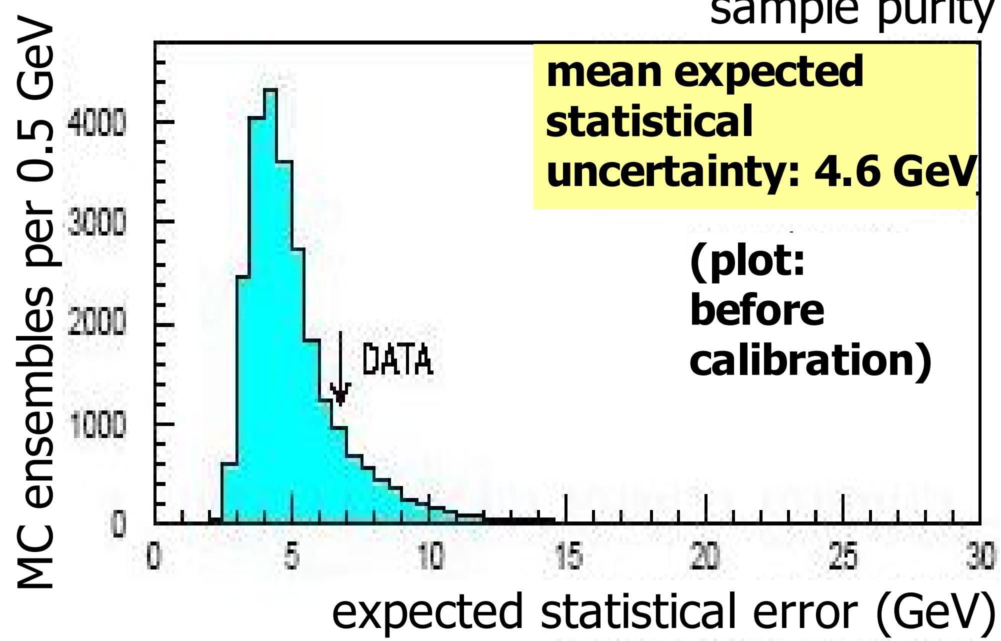
BG shape from MC

Lepton+jets: DØ Ideogram Method

- Lepton + jets selection without b-tagging
  - e or **μ** with p_T>20 GeV/c
  - ≥3 jets with p_T>20 GeV,
    ≥4 jets with p_T>15 GeV
  - lowest χ^2<10, no cut on D_{LB}
- 191 tt̄ candidate events, S/B ~ 1/2







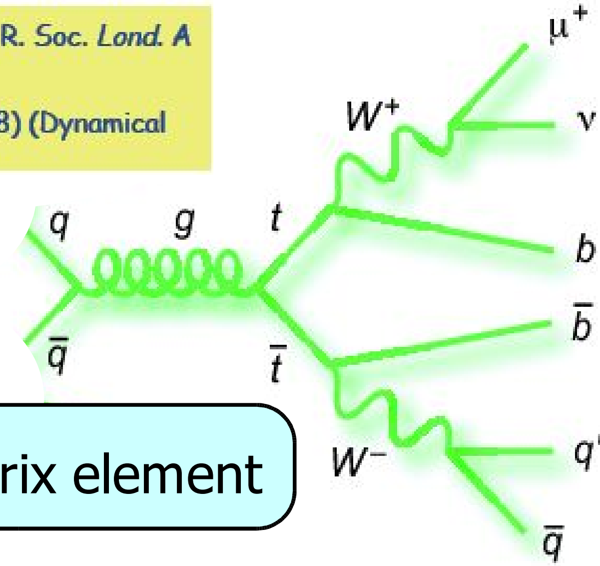
$$M_{top} = 177.5 \pm 5.8(\text{stat}) \pm 7.1(\text{sys})\ \text{GeV}/c^2$$

DØ RunI Matrix Element:
expected stat. unc.: 5.4 GeV
estimated in data : 3.6 GeV

Lepton+jets: CDF DLM Method

- Dynamical Likelihood Method
  - 1 e or μ with $p_T > 20$ GeV/c
  - Exactly 4 jets with $E_T > 15$ GeV – LO ME
  - missing $E_T > 20$ GeV
  - ≥1 btag
  - Calculate event-by-event likelihood:

Dalitz, R. H. & Goldstein, G. R., Proc. R. Soc. Lond. A **445**, 2803 (1999)
K. Kondo, J.Phys. Soc. **57**, 4126 (1988) (Dynamical Likelihood Method)



LO $t\bar{t}$ matrix element

$$L(m_{top}) = \sum_i \iiint \frac{2\pi^4}{Flux} F(z_a, z_b) f(p_t) |M^2| w_i(x|y; m_{top}) dx$$

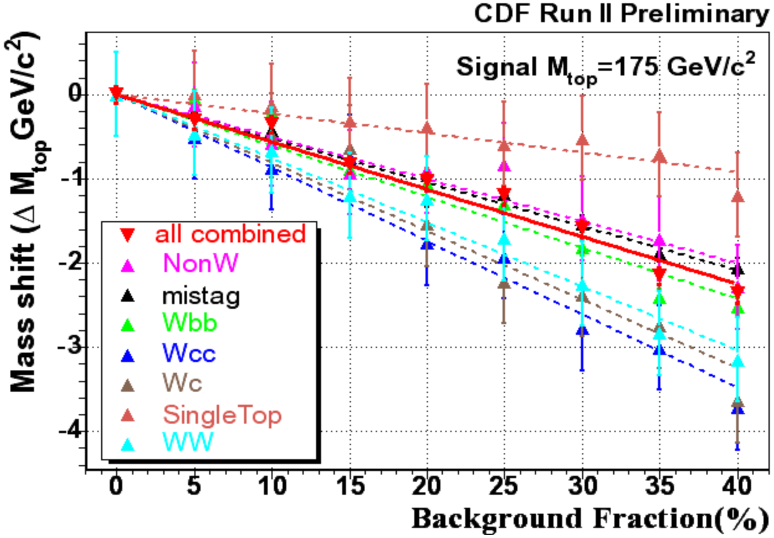
sum over all jet, neutrino solutions and integration over phase space

Transfer function describes jet resolution (from MC), computed separately for b- and light quark jets

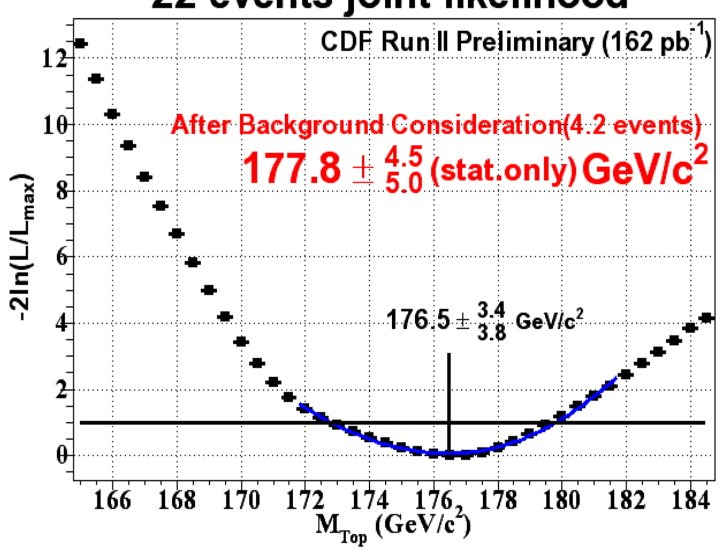
- Very similar to DØ Run I Matrix Element analysis, but without background probability term (background reduced thanks to b-tag)

Lepton+jets: CDF DLM Method

- Correct mass for estimated 19% background:



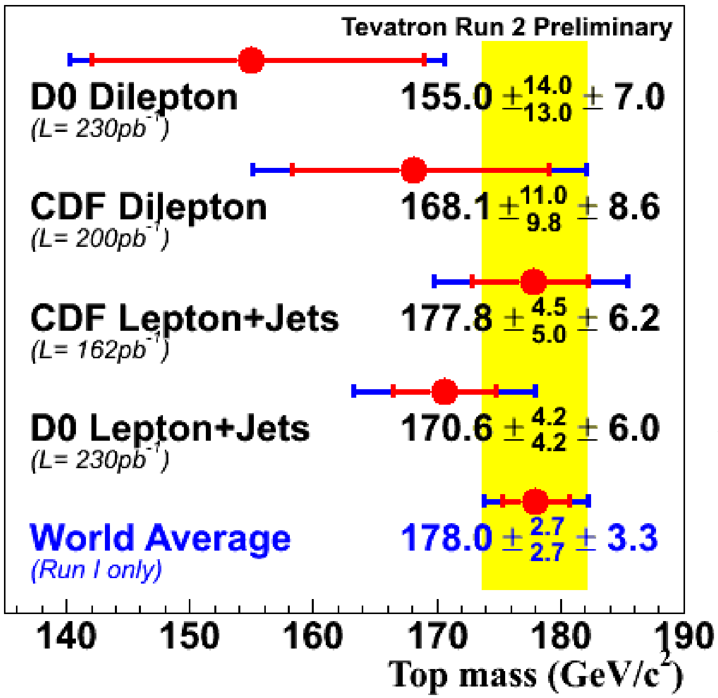
22 events joint likelihood



Systematic Uncertainties	Δmtop (GeV/c2)
Jet Energy Scale	5 .3
Transfer function	2 .0
ISR	0 .5
FSR	0 .5
PDF	2 .0
Generator	0 .6
Spin correlation	0 .4
NLO effect	0 .4
Background fraction	0 .5
Background Model	0 .5
MC Model	0 .4
Total	**6.2**

$$M_{top} = 177.8^{+4.5}_{-5.0}(stat) \pm 6.2(sys)\, GeV/c^2$$

Summary and Outlook



← Dynamical Likelihood Method, b-tag

← Template analysis, b-tag

Goal for 2005:

Top mass measurement competitive with current World Average, for each Tevatron experiment

Very soon expect:

- New results with ~325 pb-1
- Reduced Jet Energy Scale systematics (~ factor 2 !)
- Run II version of DØ Matrix Element analysis

Run II Top Mass References

- CDF preliminary top results webpage, with method descriptions, plots and conference notes:

  (general) http://www-cdf.fnal.gov/physics/new/top/top.html

  (Jet Energy Scale) http://www-cdf.fnal.gov/physics/new/top/public/jets/cdfpublic.html

  (b-tagging algorithms) http://www-cdf.fnal.gov/physics/new/top/public/btag/

- DØ preliminary top results webpage, with links to plots and conferences notes:

  (general) http://www-d0.fnal.gov/Run2Physics/WWW/results/top.htm

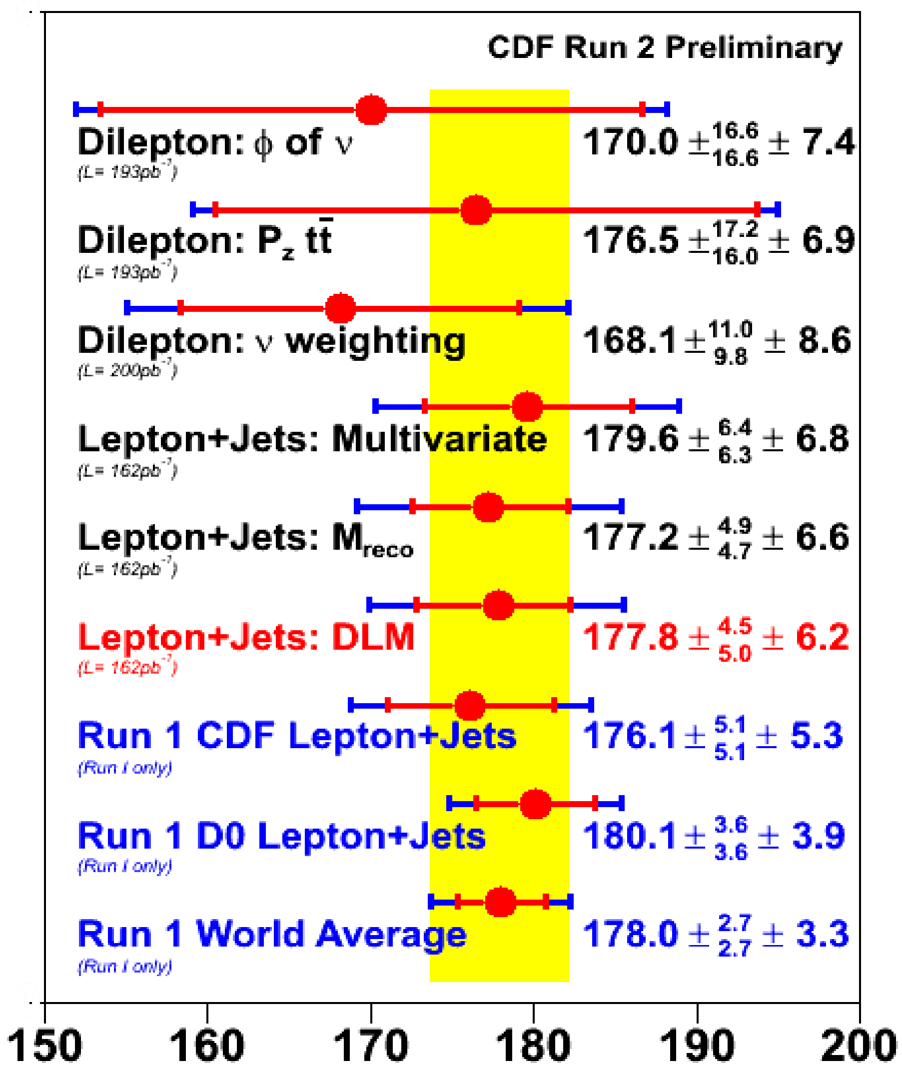
  (di-lepton) http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/TOP/T11/T11.pdf

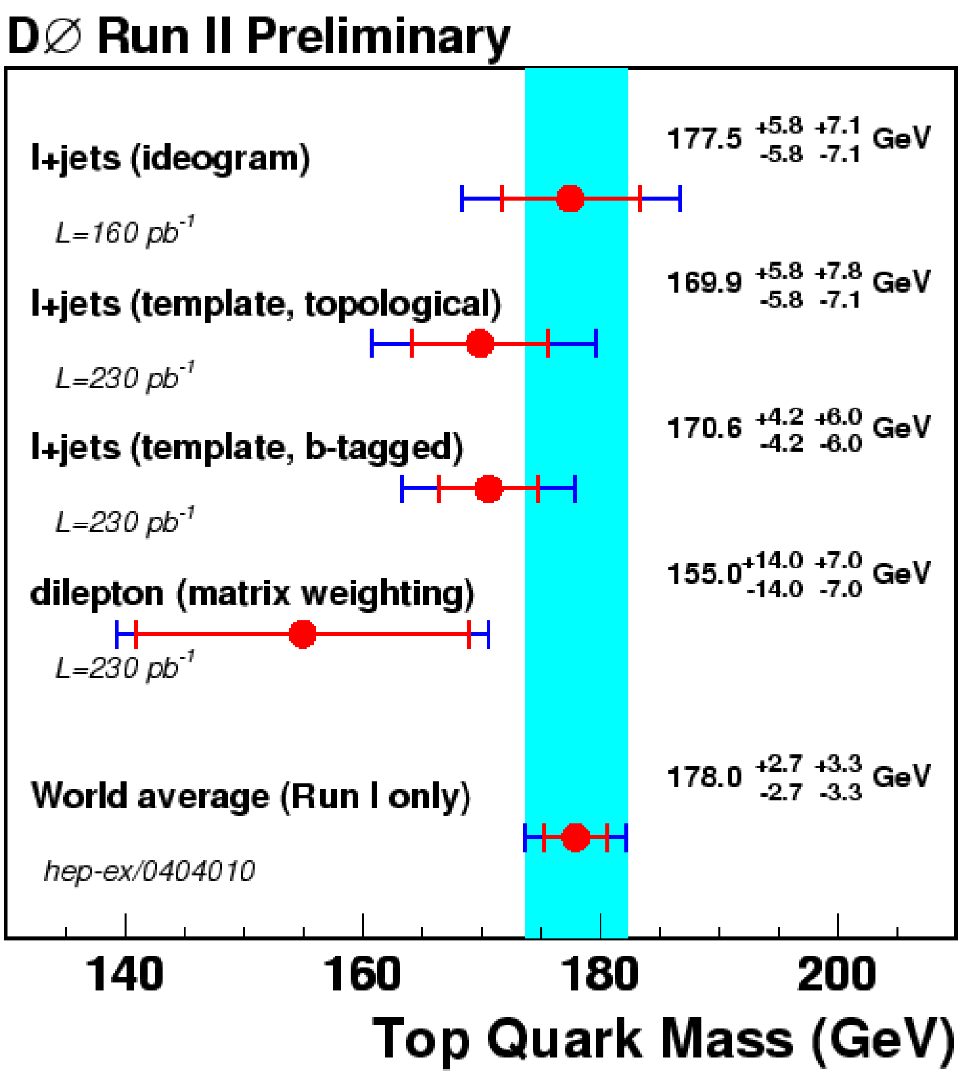
  (Template) http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/TOP/T12/T12.pdf

  (Ideograms) http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/TOP/T08/T08.pdf

Backup Slides

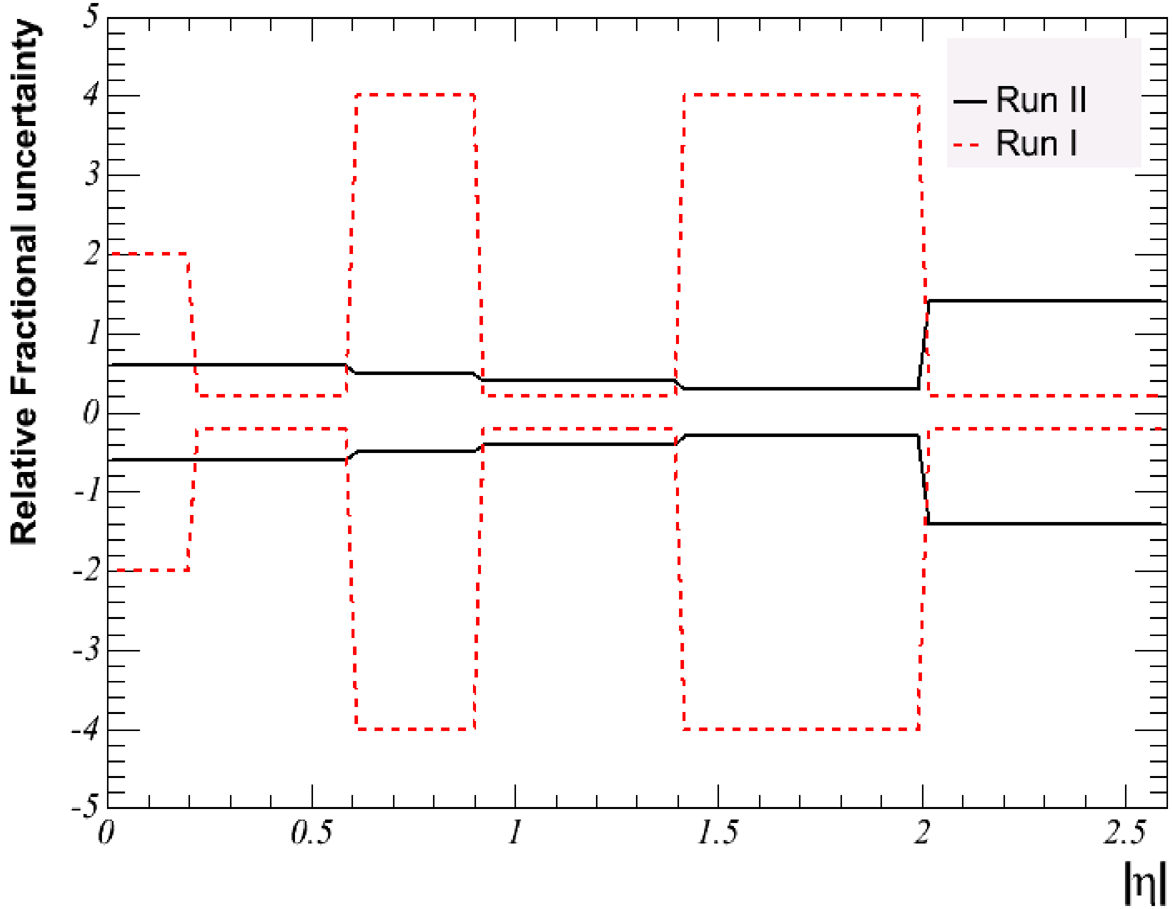
Overview prel. RunII results:





Jet Energy Scale (CDF)

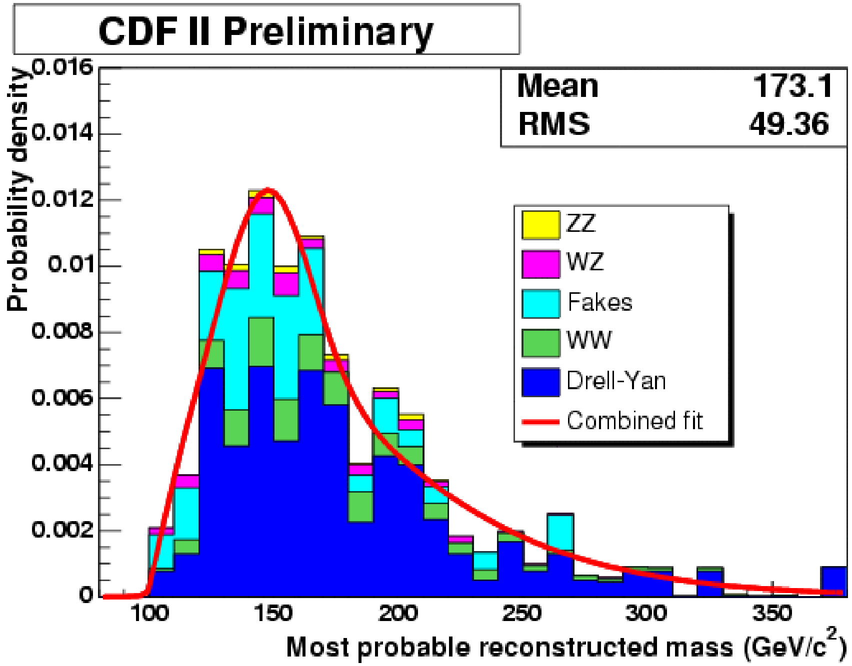
- From http://www-cdf.fnal.gov/physics/new/top/public/jets/cdfpublic.html
- For non-central jets, the total uncertainty is obtained adding in quadrature the relative (eta-dependent) and the central uncertainties. The central uncertainties (0.2<|eta|<0.6) are of the same order than Run I. The CDF simulation has greatly improved since Run I, therefore in the non-central regions the Run II uncertainties are smaller even by a factor of 4 in some regions. At low PT, the main contribution is from the out-of-cone uncertainty, while at high PT is from the absolute jet energy scale. Reducing the uncertainty at low PT requires a better understanding of the differences between data and Monte Carlo in samples like photon+jet. A better CDF simulation and larger statistics to determine the uncertainties should reduce the uncertainties at high PT.
  We improved the CDF simulation and now understand part of the origin of the differences between data and Monte Carlo. As consequence, comparing to the jet energy scale from 2004, the error decreased in about a factor of 2 in the central region and by more than 5 in other regions.

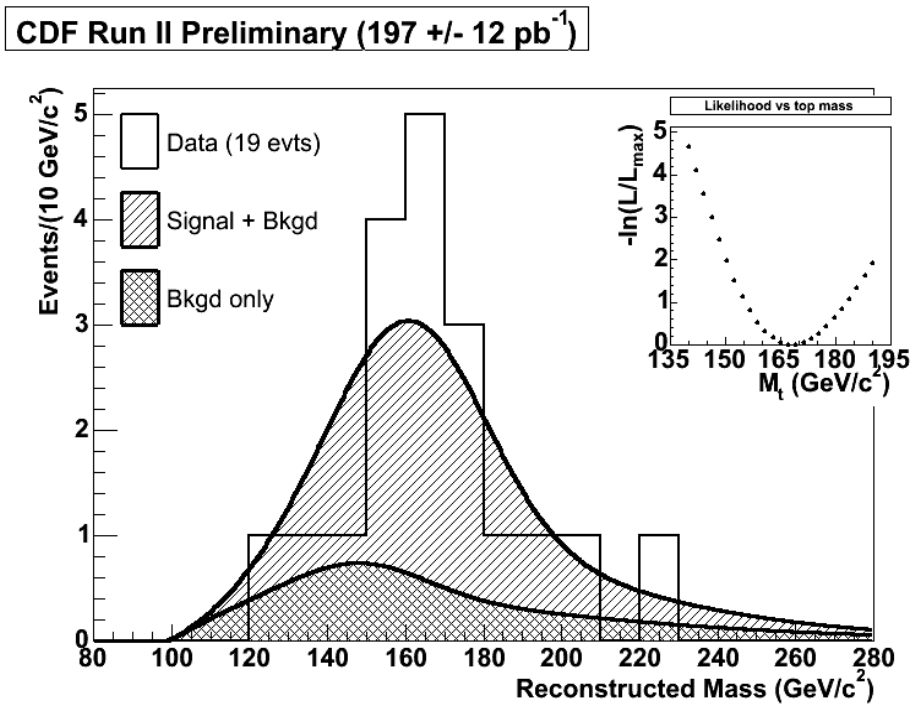


Di-lepton: CDF results

- Compare most probable mt from each event with MC Templates
- Dominant Backgrounds:
  - Di-boson, W+jets with a jet faking a lepton, Drell-Yan (Z/gamma→ee, μμ, ττ)
- All 3 analyses give consistent results
- Most precise result with neutrino weighting and loose lepton track selection (→19 events):

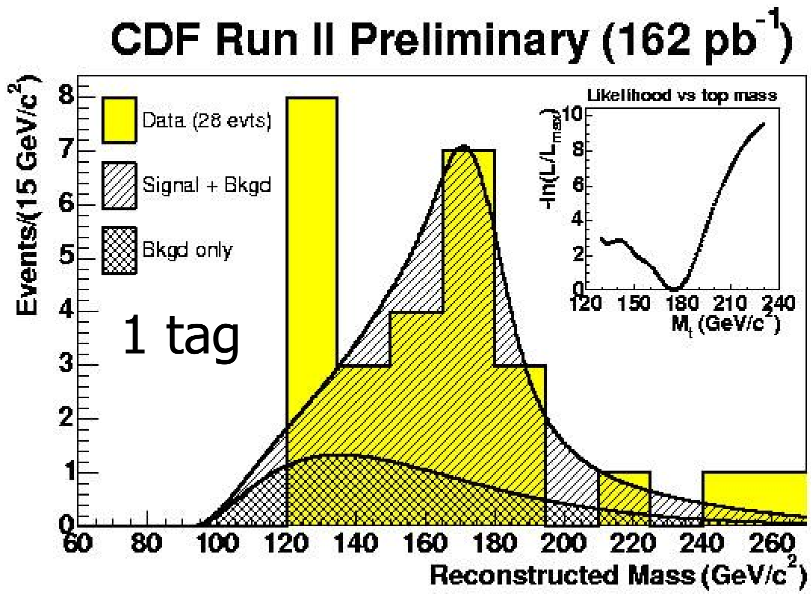
$$M_{top} = 168.1^{11.0}_{-9.8}(stat) \pm 8.6(sys)\,GeV/c^2$$

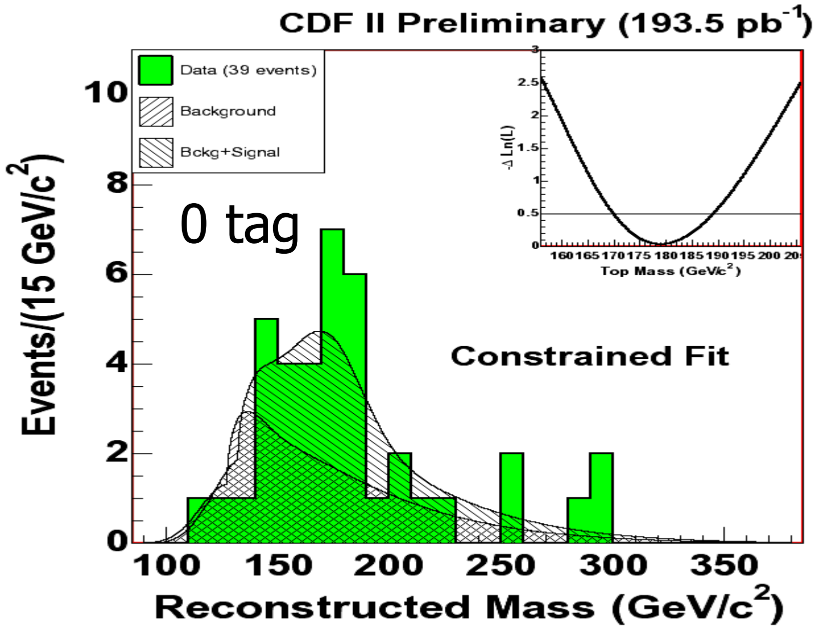




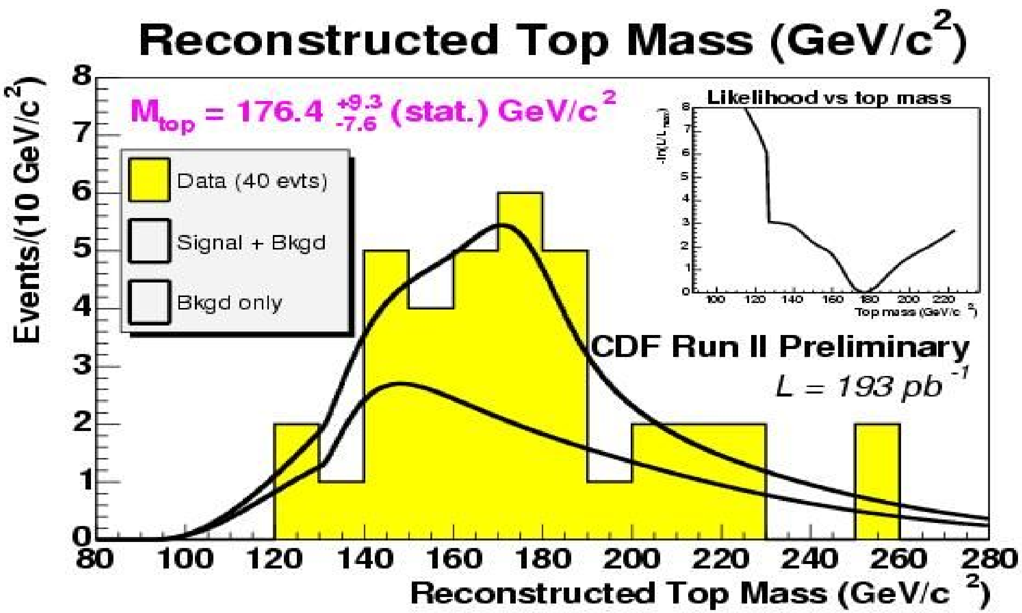
Lepton+jets: Templates in CDF

- Lepton +jets selection
  - one e or μ with pt>20 GeV/c
  - 3 jets with Et>15 GeV, 4th jet with Et>8 GeV
  - missing Et>20 GeV
- ≥ 1 SVX tag
  - 28 $t\bar{t}$ candidates (6.8+-1.2 estimated background)
- New: 0 tag
  - extra cut on 4th jet Et > 21 GeV
  - improves S/B ~ 1/1
  - 39 events selected
- Kinematic (2C) fit → plot lowest-chi2 mass solution and compare to (unbinned) MC Templates

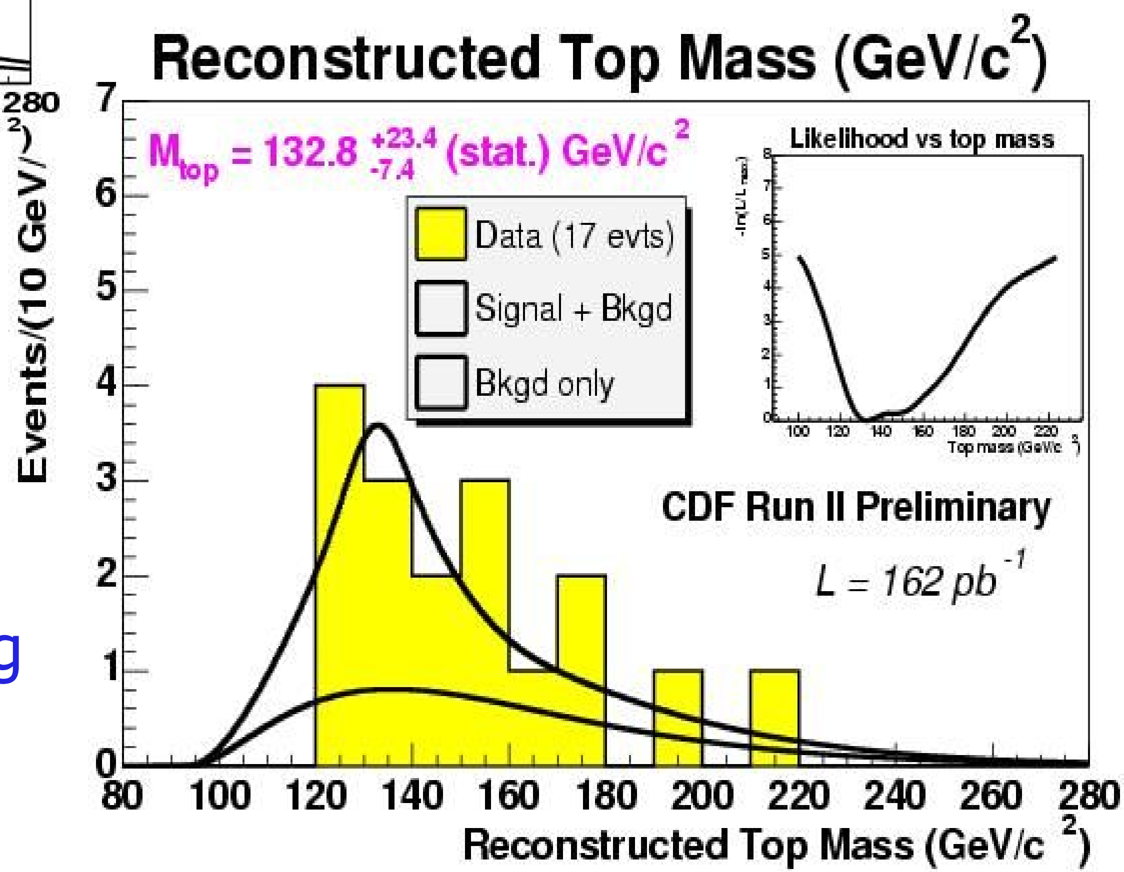




CDF: 0, 1-tag



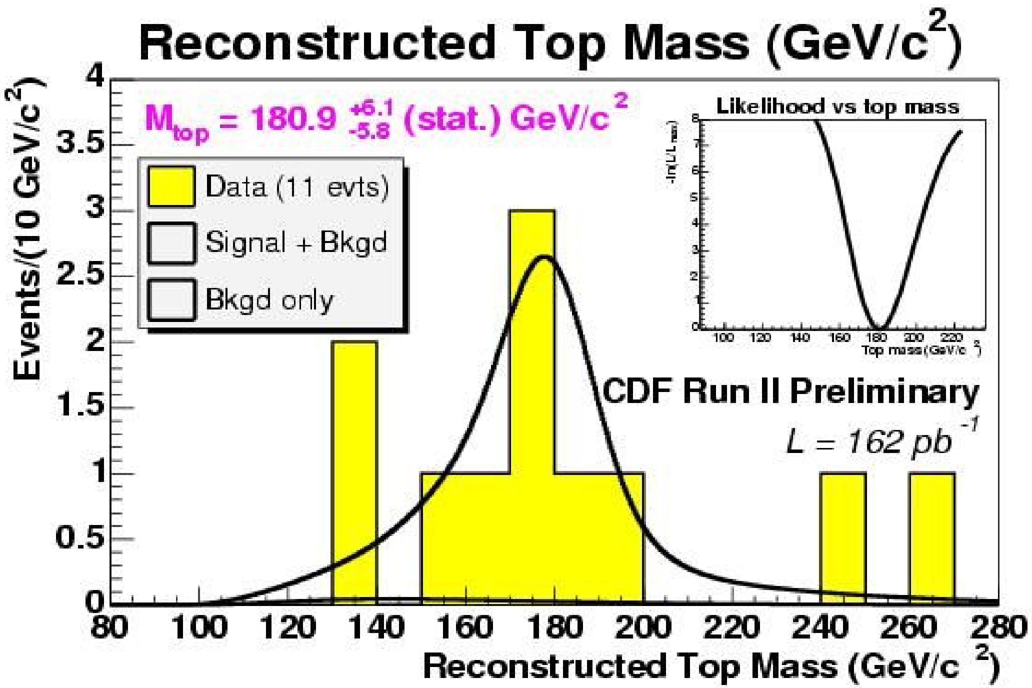
0 tag



1 tag

CDF: 2-tag

2 tag

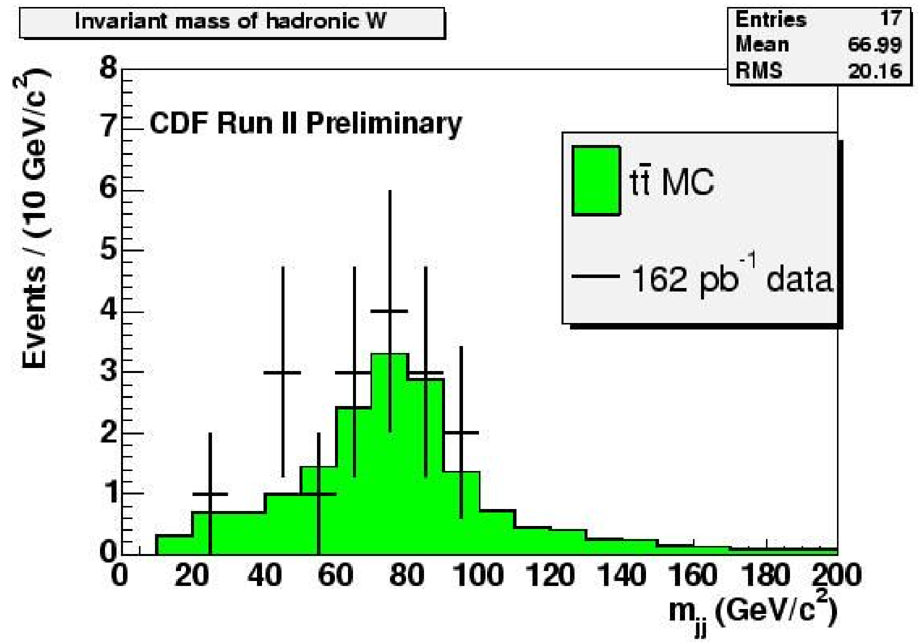


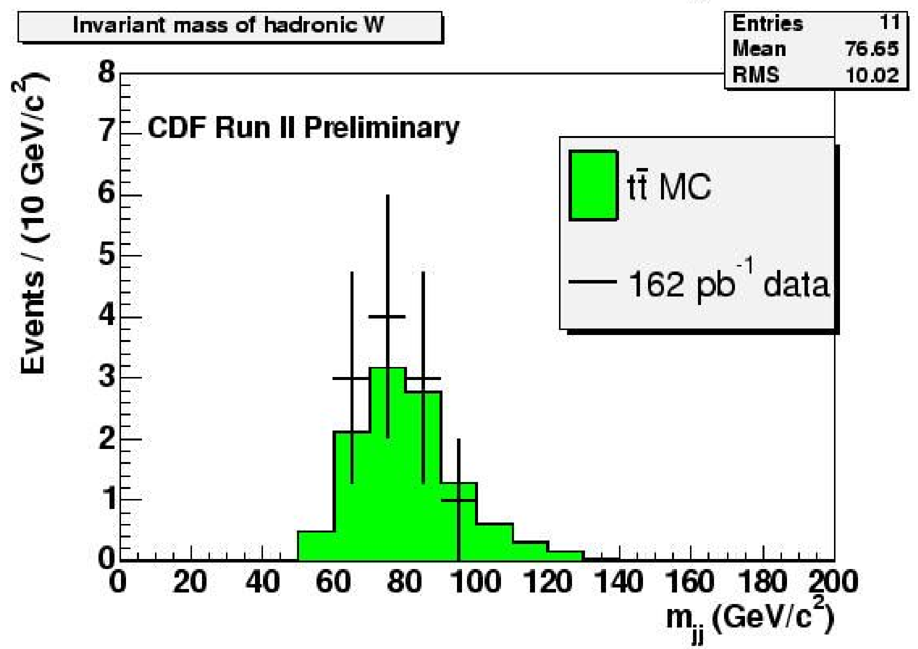
CDF Run II Preliminary

		input	2tag sample fit	combined sample fit
constraint	Best fit (GeV/c^2)	–	$180.9^{+6.1}_{-5.8} \pm 5.8$	$177.2^{+4.8}_{-4.6} \pm 6.6$
	0tag bkgd fraction	0.61 ± 0.18	–	0.57 ± 0.16
	1tag bkgd fraction	0.38 ± 0.07	–	0.41 ± 0.07
	2tag bkgd fraction	0.025 ± 0.015	0.031 ± 0.015	0.026 ± 0.005
unconstraint	Best fit (GeV/c^2)	–	$181.9^{+7.1}_{-6.4} \pm 5.8$	$179.4^{+5.4}_{-5.0} \pm 6.6$
	0tag bkgd fraction	–	–	0.42 ± 0.32
	1tag bkgd fraction	–	–	1 - at limit
	2tag bkgd fraction	–	0.27 ± 0.30	0.26 ± 0.30

lepton+jets: JES W mass cross-check

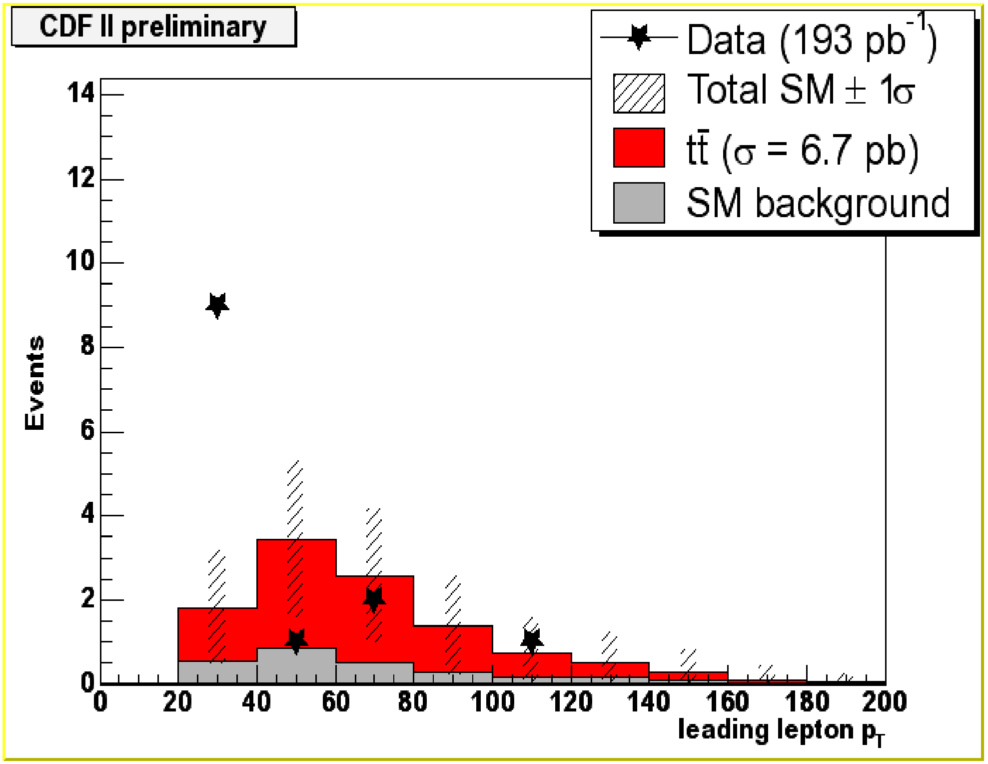
- For 4-jet events with 2 b-tags, the two untagged jets are supposed to be the decay products of the hadronically decaying W
- In these plots the invariant mass of the light-quark jets is shown for data compared to ttbar simulation
- The top plot all events are shown that pass the kinematic event cuts. The bottom plot contains events that pass the full event selection, including the lowest χ^2 <9 requirement





Di-lepton lepton pt spectrum

Search for Anomalous Kinematics in Dilepton Events at CDF II submitted to Phys.Rev.Lett 12/10/2004 FERMILAB-PUB-04-396-E



DØ RunII Preliminary
~230 pb^{-1}

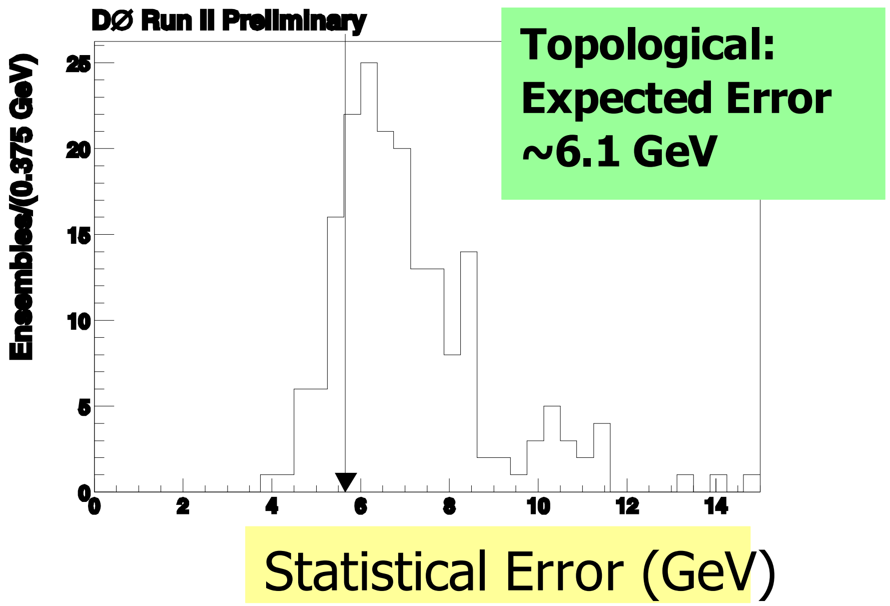
2 entries per event per 25 GeV

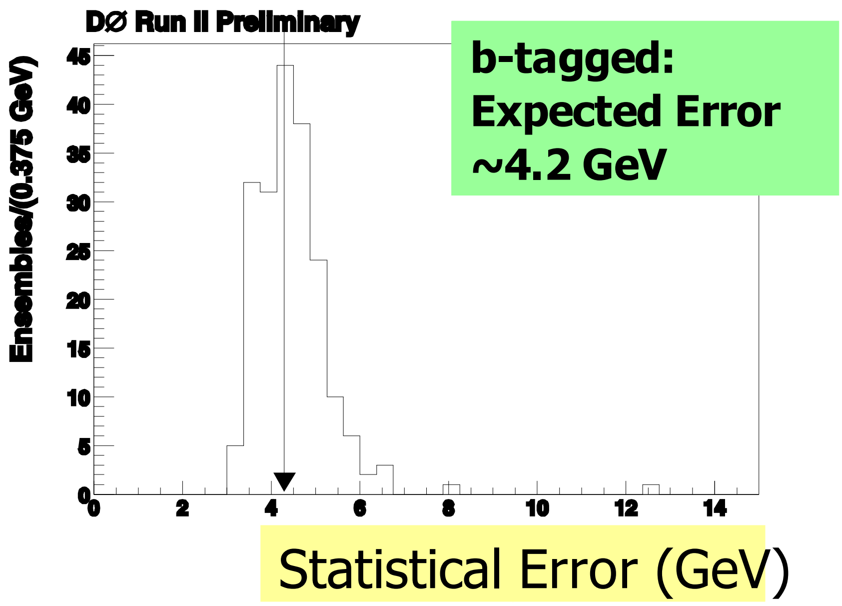
ile:///Documents%20and%20Settings/Martijn/Desktop/lepton.tif

Lepton pT (GeV)

DØ Template expected uncertainty

- Expected statistical uncertainty for the DØ Template analysis in the lepton+jets channel without (left) and with (right) use of b-tagging
- Pseudo-experiments were generated using the expected sample size and composition for an integrated luminosity of ~230 pb^{-1}





Top Turned 10

FERMILAB
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NEWS RELEASE

Top Turned Ten
March 2nd, 2005

News Release - March 2, 1995

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PHYSICISTS DISCOVER TOP QUARK

Batavia, IL--Physicists at the Department of Energy's Fermi National Accelerator Laboratory today (March 2) announced the discovery of the subatomic particle called the top quark, the last undiscovered quark of the six predicted by current scientific theory. Scientists worldwide had sought the top quark since the discovery of the bottom quark at Fermilab in 1977. The discovery provides strong support for the quark theory of the structure of matter.

Two research papers, submitted on Friday, February 24, to Physical Review Letters by the CDF and DZero experiment collaborations respectively, describe the observation of top quarks produced in high-energy collisions between protons and antiprotons, their antimatter counterparts. The two experiments operate simultaneously using particle beams from Fermilab's Tevatron, world's highest energy particle accelerator. The collaborations, each with about 450 members, presented their results at seminars held at Fermilab on March 2.

"Last April, CDF announced the first direct experimental evidence for the top quark," said William Carithers, Jr., cospokesman, with Giorgio Bellettini, for the CDF experiment, "but at that time we stopped short of claiming a discovery. Now, the analysis of about three times as much data confirms our previous evidence and establishes the discovery of the top quark."

The DZero collaboration has discovered the top quark in an independent investigation. "The DZero observation of the top quark depends primarily on the number of events we have seen, but also on their characteristics," said Paul Grannis, who serves, with Hugh Montgomery, as DZero cospokesman. "Last year, we just did not have enough events to make a statement about the top quark's existence, but now, with a larger data sample, the signal is clear."

Physicists identify top quarks by the characteristic electronic signals they produce. However, other phenomena can sometimes mimic top quark signals. To claim a discovery, experimenters must observe enough top quark events to rule out any other source of the signals.

"This discovery serves as a powerful validation of federal support for science," said Secretary of Energy Hazel R. O'Leary. "Using one of the world's most powerful research tools, scientists at Fermilab have made yet another major contribution to human understanding of the fundamentals of the universe."

The Department of Energy, the primary steward of U.S. high-energy physics, provided the majority of funding for the research. The Italian Institute for Nuclear Physics and the Japanese Ministry of Education, Science and Culture made major contributions to CDF. Support for DZero came from Russia, France, India, and Brazil. The National Science Foundation contributed to both collaborations. Collaborators include scientists from Brazil, Canada, Colombia, France, India, Italy, Japan, Korea, Mexico, Poland, Russia, Taiwan, and the U.S.

"The discovery of the top quark is a great achievement for the collaborations," said Fermilab Director John Peoples, "and also for the men and women of Fermilab who imagined, then built, and now operate the Tevatron accelerator. We have much to learn about the top quark, and more of nature's best-kept secrets to explore. We look forward to beginning a new era of research with the Tevatron, making the best use of the world's highest-energy collider."

Fermilab, 30 miles west of Chicago, is a high-energy physics laboratory operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy.