Precision Measurement of the Top Quark Mass in the Lepton+Jets Channel

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On behalf of the CDF and DØ collaborations

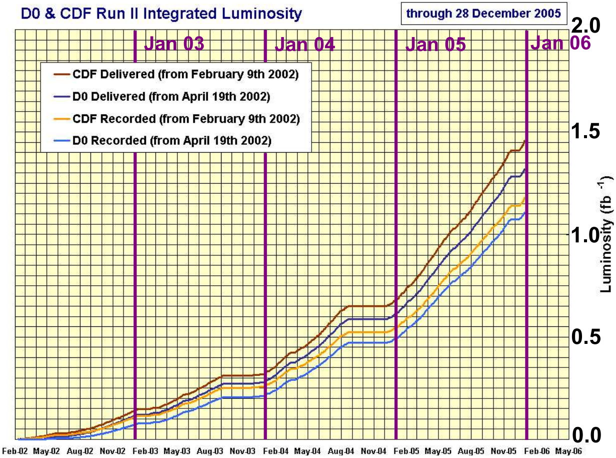
01/12/06

- Tevatron, CDF, and DØ
- CDF: Template, DLM, Decay Length
- DØ: Template, Ideogram, Matrix Element
- Jet energy scale issues
- Summary + Outlook

UNIVERSITY OF ROCHESTER

Alexander von Humboldt Stiftung/Foundation

Accumulated luminosity



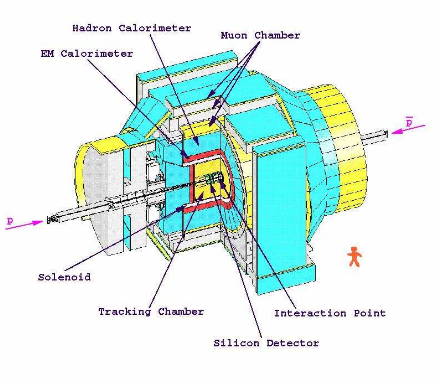
Data sets used in presented analyses

Method	$\int \mathcal{L} dt$ (pb^{-1})
CDF Template	318
CDF DLH	318
CDF Decay length	318
DØ Template	230
DØ Matrix Element	320
DØ Ideogram	160

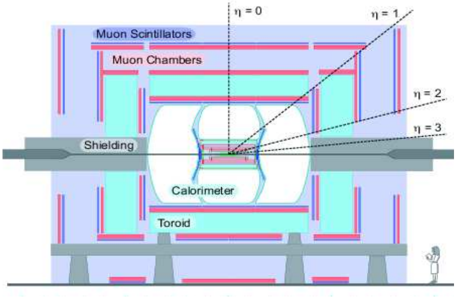
More than 1 fb^{-1} on tape!

CDF and DØ

CDF



DØ



- Precise tracking and vertexing
  new/bigger silicon/fiber tracker, new drift chamber, TOF
- Upgraded calorimeter and muon systems
- Upgraded DAQ/trigger

Decays of the top quark

dilepton channel

- BR ∼5%:
  2 jets, 2 charged leptons, missing energy from 2 ν's
- cleanest channel

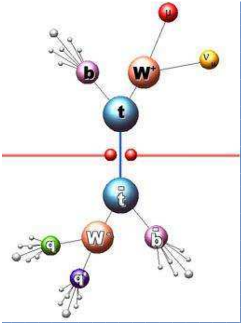
lepton+jets channel

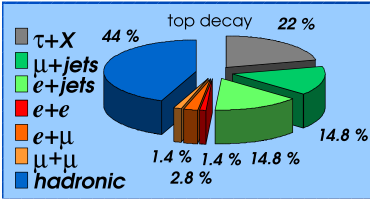
- BR ∼30%:
  4 jets, 1 charged leptons, missing energy from 1 ν's
- compromise between statistics and background

all-jets channel

- BR ∼45%:
  6 jets 2 ν's
- large backgrounds

All channels include 2 b-jets





General procedure

1. Select signal-like events
   (isolated lepton, missing energy, $\geq$ 4 jets)

2. Reduce background (mainly W+jets and QCD):
   - additional cuts
   - b-tagging

3. Reconstruct the final state (e.g., χ^2 fit).
   (Calculate masses m_{qqb} and $m_{\ell\nu\mathrm{b}}$.)

4. Extract top-quark mass.
   Templates, likelihoods, . . .

Important step in recent measurements:
Use in-situ m_W constraint for jet energy scale calibration.

CDF: Template Method, 318 pb^{-1}

Uses in-situ m_W constraint to get jet energy scale (JES).

Event selection:

- 1 e or μ with $p_T > 20$ GeV
- $E_T^{miss} > 20$ GeV
- ≥ 3 jets $E_T > 15$ GeV
  4th jet with $E_T > 8$ GeV
- 0, 1 or 2 b-tags

165 candidates subdivided into 4 sets:

- 0 b-tag: 4 jets $E_T > 21$ GeV
  high combinatorics; larger background
- 1 b-tag (tight): 4 jets $E_T > 15$ GeV
- 1 b-tag (loose): 3 jets $E_T > 15$ GeV, 4th jet
  8 GeV $< E_T <$ 15 GeV
- 2 b-tags: 3 jets $E_T > 15$ GeV, 4th jet
  $E_T > 8$ GeV
  reduces combinatorics; best mass resolution; low background

Category	2-tag	1-tag(T)	1-tag(L)	0-tag
expected S:B	10.6:1	3.7:1	1.1:1	N/A
No. events	25	63	33	44

Background estimates

Source	Expected bkg.		
	2-tag	1-tag(T)	1-tag(L)
Non-W(QCD)	0.31±0.08	2.32±0.50	2.04±0.54
$Wb\bar{b} + Wc\bar{c} + Wc$	1.12±0.43	3.91±1.23	6.81±1.85
W+light jets	0.40±0.08	3.22±0.41	4.14±0.53
WW/WZ	0.05±0.01	0.45±0.10	0.71±0.13
Single top	0.008±0.002	0.49±0.09	0.60±0.11
Total	1.89±0.52	10.4±1.72	14.3±2.45

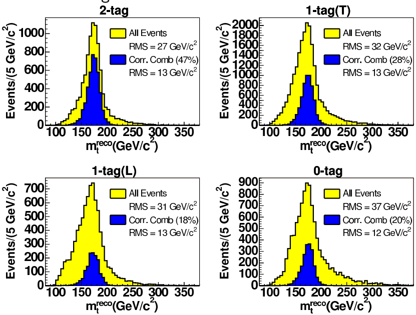
CDF: Template Method, 318 pb^{-1}

Mass reconstruction: Event-by-event χ^2 fit for each combination.

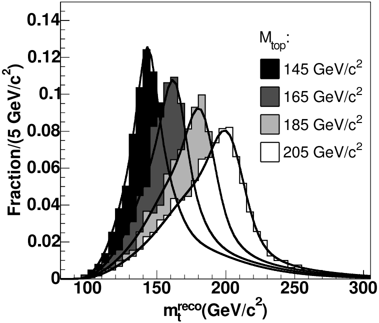
$$\chi^2 = \sum_{i=\ell,4\text{jets}} \frac{\left(\hat{p}_T^i - p_T^i\right)^2}{\sigma_i^2} + \sum_{j=x,y} \frac{\left(\hat{p}_j^{UE} - p_j^{UE}\right)^2}{\sigma_j^2}$$
$$+ \frac{\left(m_{jj} - m_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{\ell\nu} - m_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{bjj} - m_t^{reco}\right)^2}{\Gamma_t^2} + \frac{\left(m_{b\ell\nu} - m_t^{reco}\right)^2}{\Gamma_t^2}$$

Select jet-quark combination and neutrino solution that gives smallest $\chi^2 < 9$.
m_t is fit parameter:

$t\bar{t}$ Herwig MC



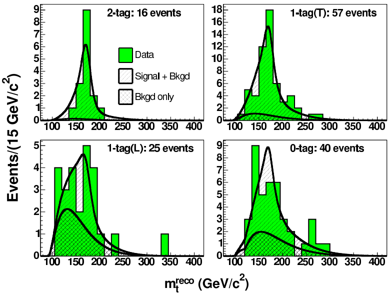
templates $\longrightarrow$



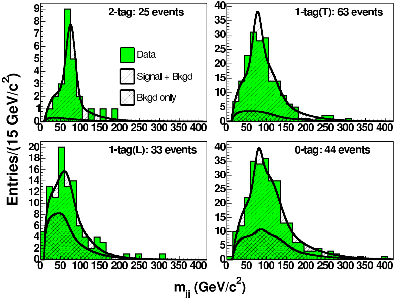
CDF: Template Method, 318 pb^{-1}

Background shape obtained in similar way.

Template fits to data



JES from fit to m_W



Likelihood fit for m_t

$$\mathcal{L}_{\text{sample}} = \mathcal{L}_{\text{shape}}^{m_t^{\text{reco}}} \times \mathcal{L}_{\text{shape}}^{m_{jj}} \times \mathcal{L}_{\text{nev}} \times \mathcal{L}_{\text{bg}}$$

(for details see hep-ex/0510048)

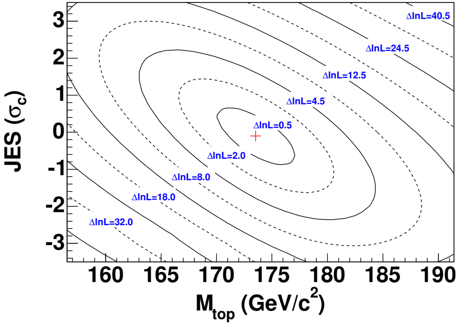
Combined likelihood

$$\mathcal{L}_{\text{total}}(m_t, JES) = \mathcal{L}_{\text{2-tag}} \times \mathcal{L}_{\text{1-tag(T)}} \times \mathcal{L}_{\text{1-tag(L)}} \times \mathcal{L}_{\text{0-tag}} \times \mathcal{L}_{\text{JES}}$$

CDF: Template Method, 318 pb^{-1}

Don't need to use external JES (with all its uncertainties). Can fit JES in-situ!

Combined likelihood JES vs. m_t



Systematic uncertainties

Source	Δm_t (GeV)	ΔJES (σ)
b-JES	0.6	0.25
Method	0.5	0.02
ISR	0.4	0.08
FSR	0.6	0.06
PDFs	0.3	0.04
Generators	0.2	0.15
Bkg. shape	0.5	0.08
b-tagging	0.1	0.01
MC stats	0.3	0.05
total	1.3	0.33

$$m_t = 173.5^{+3.7}_{-3.6}(\text{stat.} + \text{JES}) \pm 1.3(\text{syst.})\ \text{GeV}$$

$$(\Delta m_t(JES) = 3\ \text{GeV})$$

Dynamic Likeihood Method (DLM)

Event selection:

- 1 e or μ with $p_T > 20$ GeV
- exactly 4 jets $E_T > 15$ GeV
- $E_T^{\text{miss}} > 20$ GeV
- ≥ 1 b-tag (SecVtx)

Then, calculate event-by-event likelihood

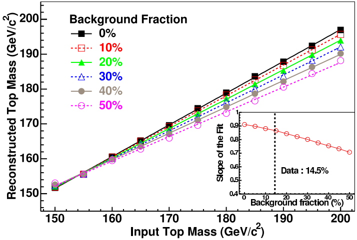
$$L^i(m_t) =$$

$$\int \sum_{\text{jet comb}} \sum_{\nu\text{sol.}} \frac{2\pi^4}{\text{flux}} |M^2| F(z_1, z_2) f(p_T) w(x, y_t; m_t) dx$$

- M: LO matrix element for $t\bar{t}$ process
- $F(z_1, z_2)$: parton distribution function
- $f(p_T)$: p_T distribution of $t\bar{t}$ system
- $w(x, y; m_t)$: transfer function (detector resolution)

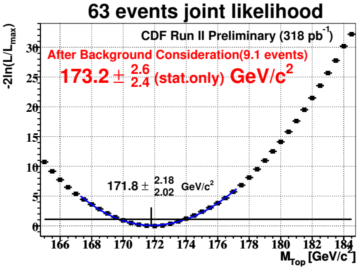
- No bkg. probability term
- b-tagging to reduce background.
- Combine all events: $\prod_{\text{events}} L^i$.

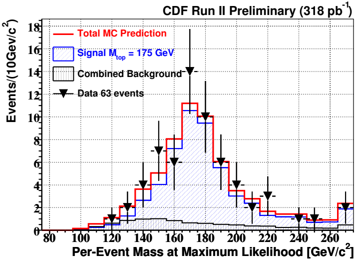
Reconstructed m_t vs. input m_t

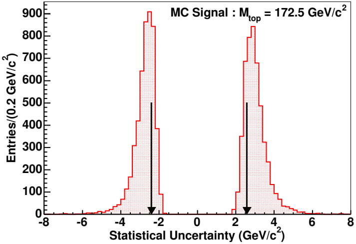


Background fraction from data fit: 14.5%

CDF: Dynamic Likelihood Method, 318 pb^{-1}







Systematic uncertainties:

Source	Δm_t (GeV)
JES	3.0
Transfer function	0.2
ISR	0.4
FSR	0.5
PDFs	0.5
Generator	0.3
Bkg. fraction	0.2
Bkg. modeling	0.4
b jet energy modeling	0.6
b-tagging	0.2
total	3.2

$$m_t = 173.2^{+2.6}_{-2.4}(\text{stat.}) \pm 3.2(\text{syst.})\ \text{GeV}$$

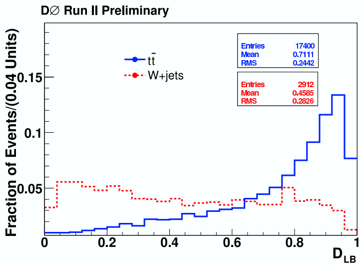
Event selection:

- e or μ with $p_T > 20$ GeV
- ≥ 4 jets with $p_T > 20$ GeV
- no b-tag
- kinematic fit; use combination with lowest $\chi^2 < 10$

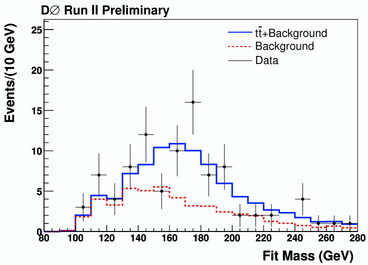
- Low bias discriminant D_{LB} from 4 topological input variables. $D_{LB} > 0.4$
- 94 $t\bar{t}$ candidates, S/B $\sim 1/1$
- Compare data to MC templates with various m_t $\rightarrow$ likelihood fit

$$m_t = 169.9 \pm 5.8(\text{stat.})^{+7.8}_{-7.1}(\text{syst.})\ \text{GeV}$$

Low bias discriminant



Reconstructed top mass

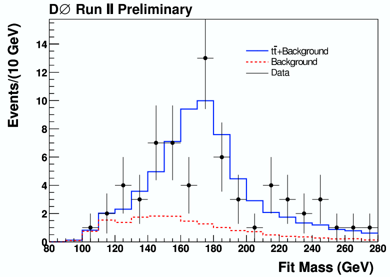


DØ: Template method (b-tag), 230 pb^{-1}

Uses 'SVT' secondary vertex tagger

- similar l+jets selection
- $\geq$ 1 b-tagged jet(s)
- $\geq$ 4 jets with $p_T > 15$ GeV
- No cut on low bias discriminant D_{LB}
- 69 $t\bar{t}$ candidates, S/B $\sim$ 3/1

Reconstructed top mass



Systematic uncertainties

Source	Δm_t (GeV)
JES	-5.3 / $+4.7$
gluon radiation	2.4
signal modelling	2.3
jet energy resolution	0.9
calibration	0.5
bkg modelling	0.8
b-tagging	0.7
trigger bias	0.5
MC statistics	0.5
total	6.0

Topological analysis:
$\Delta m_t(\text{JES}) = -6.5/+6.8$ GeV.

$m_t = 170.6 \pm 4.2(\text{stat.}) \pm 6.0(\text{syst.})$ GeV

DØ: Ideogram method, 160 pb^{-1}

Based on same kinematic fit as template method, using same low-bias discriminant D_{LB}. Improves statistics by

- using all jet/neutrino solutions for fitted mass m_i, σ_{m_i}, χ^2
- calculating event-by-event likelihood using all jet/neutrino solutions and probab. of event to be background (using D_{LB})

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

$$w_i = \exp(-\chi_i^2/2) \quad \text{(best permutation gets highest weight)}$$

$$S(m_i, \sigma_i, m_t) = \int dm' \, G(m', m_i, \sigma_i) \cdot BW(m', m_t, \Gamma_{\text{top}})$$

Signal likelihood based on Gaussian resolution and Breit-Wigner.

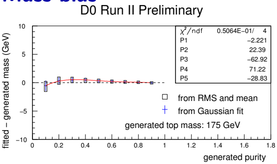
BG shape from Monte Carlo simulation.

Event selection (no b-tagging):

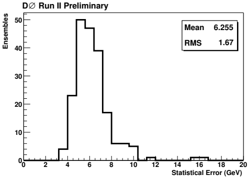
- e or μ with $p_T > 20$ GeV
- ≥ 3 jets with $p_T > 20$ GeV
  ≥ 4 jets with $p_T > 15$ GeV
- lowest $\chi^2 < 10$, no cut on D_{LB}

191 $t\bar{t}$ candidates, S/B $\sim 1/2$

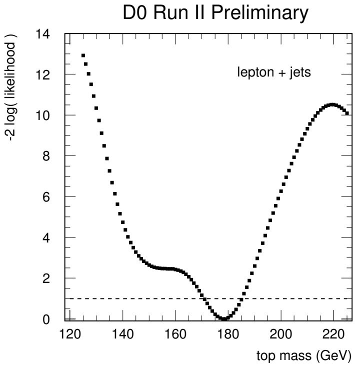
Mass bias



Expected stat. error



Likelihood



$$m_t = 177.5 \pm 5.8(\text{stat.}) \pm 7.1(\text{syst.})\ \text{GeV}$$

New results with 320 pb^{-1}, b-tag and in-situ JES calibration expected very soon!

DØ: Matrix element method, 320 pb^{-1}

Uses in-situ m_W constraint to calibrate jet energy.

- Make maximal use of information in event by calculating probability for event to be signal or background from the matrix element
  - $P(x; M_{top}) = \frac{1}{\sigma} \int d^n\sigma(y; M_{top}) dq_1 dq_2 f(q_1) f(q_2) W(x, y)$
  - LO matrix element differential cross section
  - f(q) probability distribution of initial parton having momentum q
  - probability of parton level variable y to be measured as variable x
- Input: 4-vectors of final-state particles, acceptance, resolution of detector
- $P_{\text{evt}}(x; m_t, JES) = f_{\text{top}} \cdot P_{\text{sgn}}(x; m_t, JES) + (1 - f_{\text{top}}) \cdot P_{\text{bkg}}(x; JES)$
- Combine all events into likelihood:

$$-\ln L(x_1, \ldots, x_n; m_t, JES) = -\sum_{i=1}^{n} \ln \left(P_{\text{evt}}(x_i; m_t, JES) \right).$$

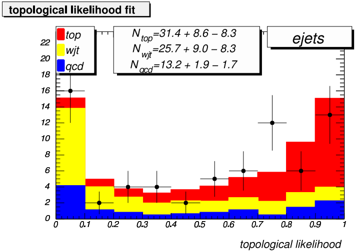
- Maximize likelihood L as a function of m_{top} and JES.

Event selection

- e or μ with $p_T > 20$ GeV
- exactly 4 jets with $p_T > 20$ GeV, (veto on 5th jet), no b-tag
- $E_T^{miss} > 20$ GeV
- $\Delta\phi$ cut between ℓ and E_T^{miss}

$\rightarrow$ 150 candidate events

Likelihood technique to estimate signal and bkg. fractions

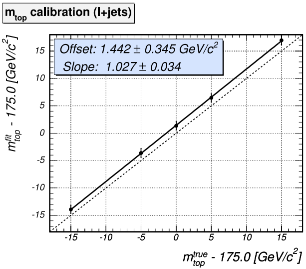


N_{evt}	f_{top}	N_{top}	f_{QCD}
150	$36.4^{+11.3}_{-10.7}$ %	54.7	$11.2^{+1.8}_{-1.6}$ %

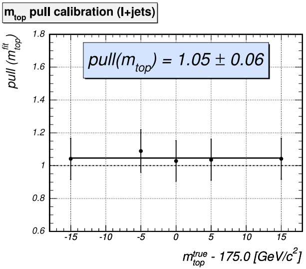
This value of f_{top} only used for calibration.

Ensemble tests with MC events

Mass calibration



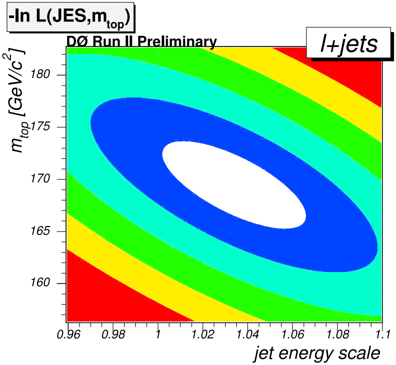
Pull distribution



DØ: Matrix Element method, 320 pb^{-1}

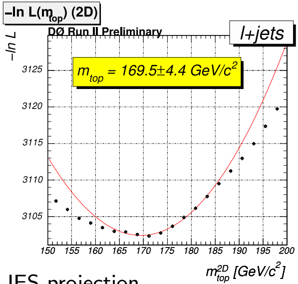
Simultaneous fit of m_t, JES (from m_W constraint) and f_{top}.

$$P_{\rm evt}(x; m_t, JES) =$$
$$f_{\rm top} \cdot P_{\rm sgn}(x; m_t, JES)$$
$$+(1 - f_{\rm top}) \cdot P_{\rm bkg}(x; JES)$$

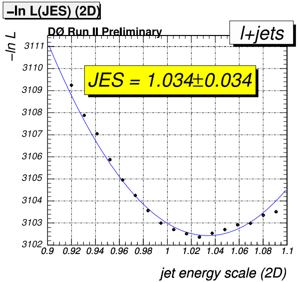


$f_{top} = 31.6^{+4.9}_{-5.5}\%$

m_t projection

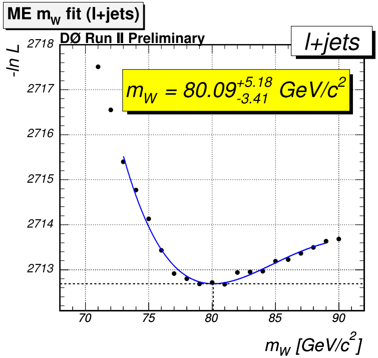


JES projection

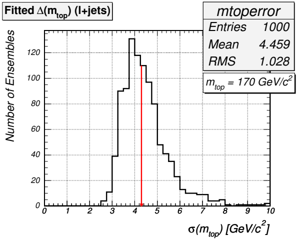


Cross check on W mass

- scale jets by fitted JES factor
- adjust E_T^{miss} accordingly
- refit with m_W as parameter



Expected stat. error



Systematics

Source	Δm_t (GeV)
JES	0.7
B response (h/e)	0.8
B fragmentation	0.7
Signal modelling	0.3
Bkg. modelling	0.3
Signal fraction	+0.5 / −0.2
QCD contamination	0.7
MC calibration	0.4
Trigger	0.1
PDFs	0.3
total	+1.7 / −1.6

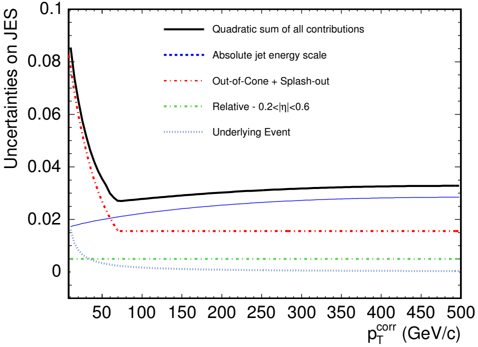
Dominated by jet energy scale.

$$\mathbf{m_t = 169.5 \pm 4.4(\text{stat.} + \text{JES})^{+1.7}_{-1.6}(\text{syst.})\ \text{GeV}, \qquad \Delta m_t(\text{JES}) = 3.2\ \text{GeV}}$$

Issues with Jet Energy Scale

- JES corrections account for offset (noise, underlying event, . . .), out-of-cone showering, and detector response.
- JES is largest single uncertainty.
- CDF: New Run II systematics better than Run I.
- DØ: Systematics in presented analyses > than Run I, but new analyses using reprocessed data will benefit from much improved JES.
- Often, the *relative* data/MC JES agreement is important for top-mass measurements.
- In-situ m_W calibration helps to improve light-jet JES.
- Nothing equivalent for b-JES yet. In the future: b-JES from $Z \to b\bar{b}$?

CDF JES uncertainties



for a jet with $0.2 < |\eta| < 0.6$

For more information about Jet Energy Scale, see talk by K. Hatakeyama, Friday 9:55.

CDF: Decay length method, 318 pb^{-1}

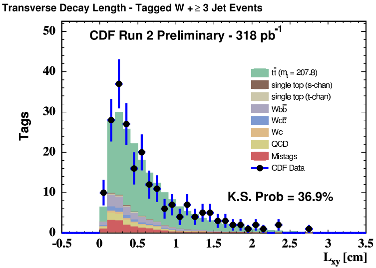
- New method: extract m_t from transverse decay length of b-hadrons from top decays.
- Relies on tracking; minimized JES uncertainties. Uncorrelated to all other methods.
- boost of b-quarks:

$$\gamma_b = \frac{m_t^2 + m_b^2 - m_W^2}{2 m_t m_b} \approx 0.4 \frac{m_t}{m_b}$$

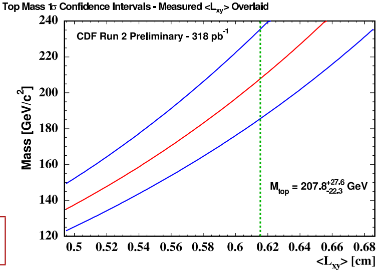
- experimentally, measure average transverse decay length $\langle L_{xy} \rangle$
- ℓ with $p_T > 18$ GeV, $E_T^{miss} > 20$ GeV, ≥ 3 jets with $E_T > 15$ GeV. At least one jet SecVtx tagged.
- 216 positive tags in 178 events.
- $\langle L_{xy} \rangle = 0.6153 \pm 0.0356$ cm.

$m_t = 207.8^{+27.6}_{-22.3}$(stat.) $\pm$ 6.5(syst.) GeV

Decay length distributions

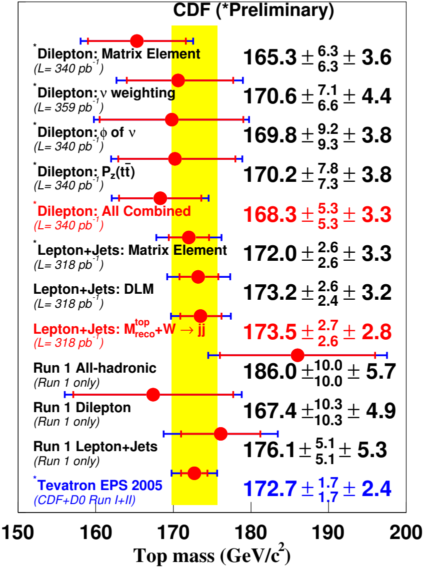


Calibration curve from ensemble testing

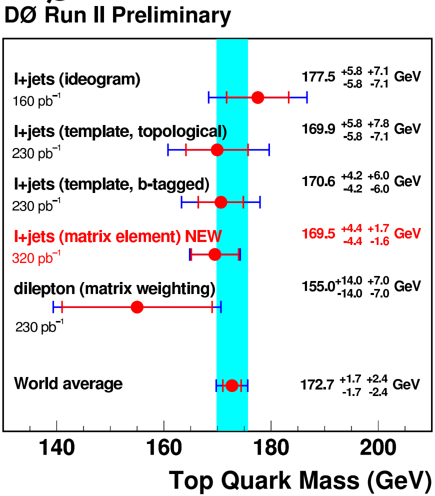


Summary of measurements

CDF

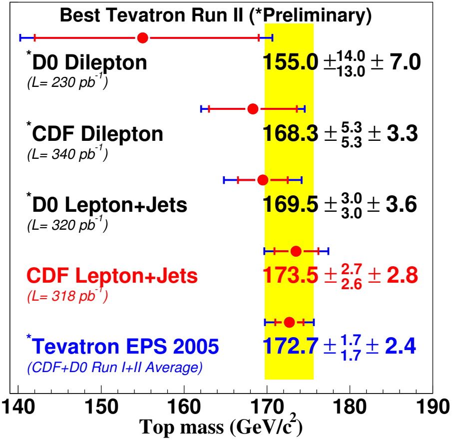


DØ



Summary and Outlook

CDF and DØ



- Lepton+Jets channels provide the most precise top-mass measurements.
- Important new step is to use in-situ JES calibration from m_W constraint.
- Results with smaller statistical error and increasing use of b-tagging expected soon.

BACKUP

From hep-ex/0507091

Global correlations

		Run-I published					Run-II preliminary			
		CDF			DØ		CDF			DØ
		all-j	l+j	di-l	l+j	di-l	$(l+j)_i$	$(l+j)_e$	di-l	l+j
CDF-I	all-j	1.00								
CDF-I	l+j	0.32	1.00							
CDF-I	di-l	0.19	0.29	1.00						
DØ-I	l+j	0.14	0.26	0.15	1.00					
DØ-I	di-l	0.07	0.11	0.08	0.16	1.00				
CDF-II	$(l+j)_i$	0.04	0.12	0.06	0.10	0.03	1.00			
CDF-II	$(l+j)_e$	0.35	0.54	0.29	0.29	0.11	0.45	1.00		
CDF-II	di-l	0.19	0.28	0.18	0.17	0.10	0.06	0.30	1.00	
DØ-II	l+j	0.02	0.07	0.03	0.07	0.02	0.07	0.08	0.03	1.00

Pull and weight

	Run-I published					Run-II preliminary			
	CDF			DØ		CDF			DØ
	all-j	l+j	di-l	l+j	di-l	$(l+j)_i$	$(l+j)_e$	di-l	l+j
Pull	+1.19	+0.51	−0.48	+1.67	−0.34	+0.18	+0.24	−1.11	−0.86
Weight [%]	+1.0	−0.2	+1.1	+18.8	+2.1	+18.6	+17.4	+8.0	+33.3

Summary of combination

Parameter	Value	Correlations		
$M_{\mathrm{top}}^{\mathrm{all-j}}$ [GeV/c^2]	185.0 ± 10.9	1.00		
$M_{\mathrm{top}}^{\mathrm{l+j}}$ [GeV/c^2]	173.5 ± 3.0	0.22	1.00	
$M_{\mathrm{top}}^{\mathrm{di-l}}$ [GeV/c^2]	165.0 ± 5.8	0.15	0.31	1.00