Top quark mass results at Tevatron

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On behalf of CDF and D0 collaborations

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Outline

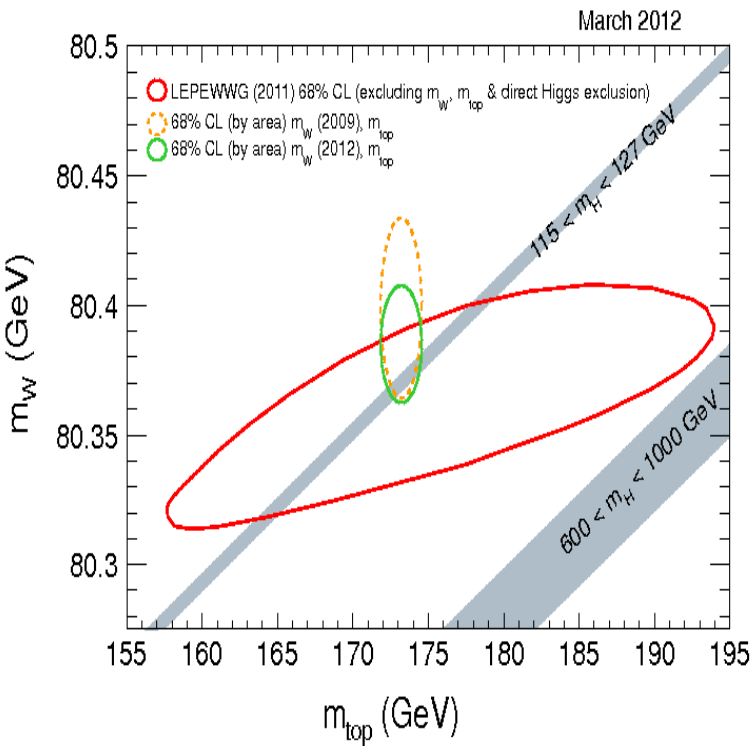
- Motivation
- Top quark production and decay
- b-tagging methods
- Methods used for top quark mass measurements
- Previously presented results
- New results

Motivation

- Top quark mass value is close to the scale of electroweak symmetry breaking (EWSB)
  → does ***t*** quark have more fundamental role in EWSB?
- Huge mass gives importance to QCD corrections for ***t*** quark
  … precise ***t*** quark mass measurement leads to better constrain the Higgs mass window.

27

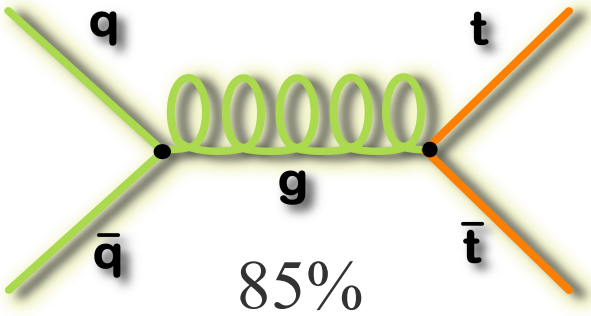
$$\left(\frac{m_W}{m_Z}\right)^2 = (1-\sin^2\theta_W)\cdot(1+\Delta\rho(m_t^2;\ln m_H))$$

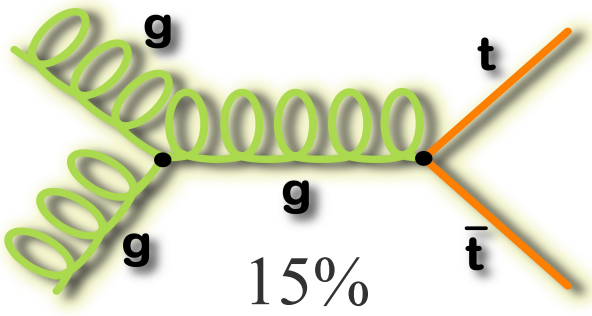


- The top sector is expected to be sensitive to a new physics

Top quark production and decays

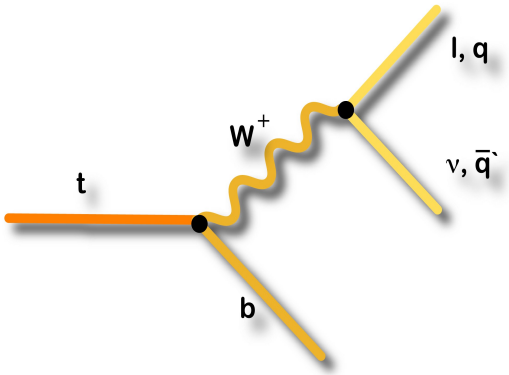
Top quark at Tevatron is mainly produced in $t\,\bar{t}$ pairs:

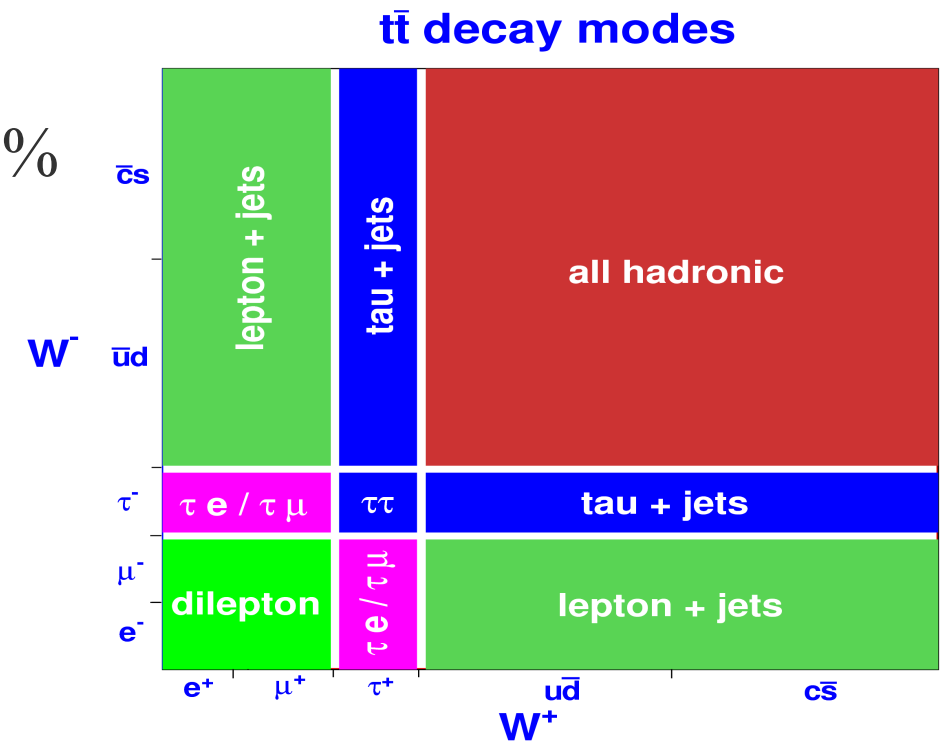




According to SM:

$\Gamma(t \to Wb) \sim 100\%$





Channels:

→ **LJ ~30 %**

→ **DIL ~5 %**

→ All Had ~44 %

* lepton = ***e*** or ***μ***

**MET+jet channel

Jet b - tagging

→ helps to decrease background fraction

→ several methods are developed to assign the jet originated from ***b*** quark as b-jet:

- ✔ Soft lepton tagging

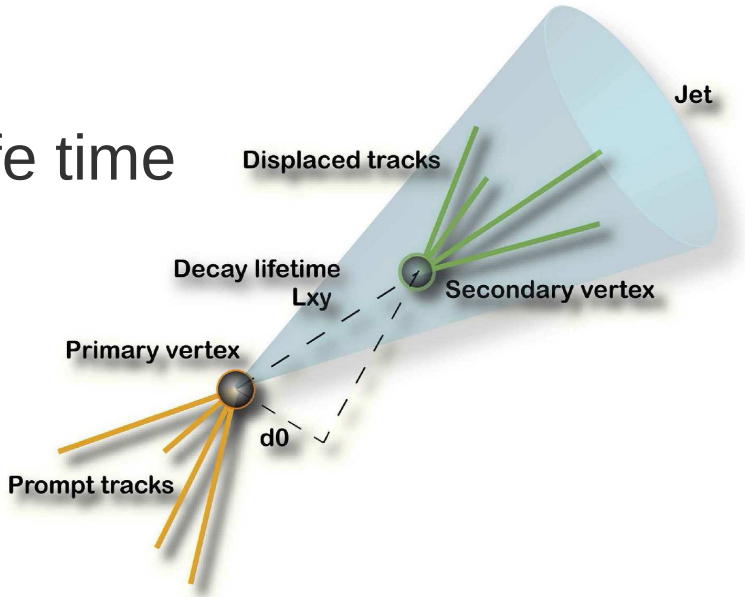
  → lepton comes from semileptonical decay of ***b*** quark

- ✔ Secondary vertex tagging

  → B hadrons have relatively long life time

  => their decay is displaced from primary vertex

- ✔ Neural network



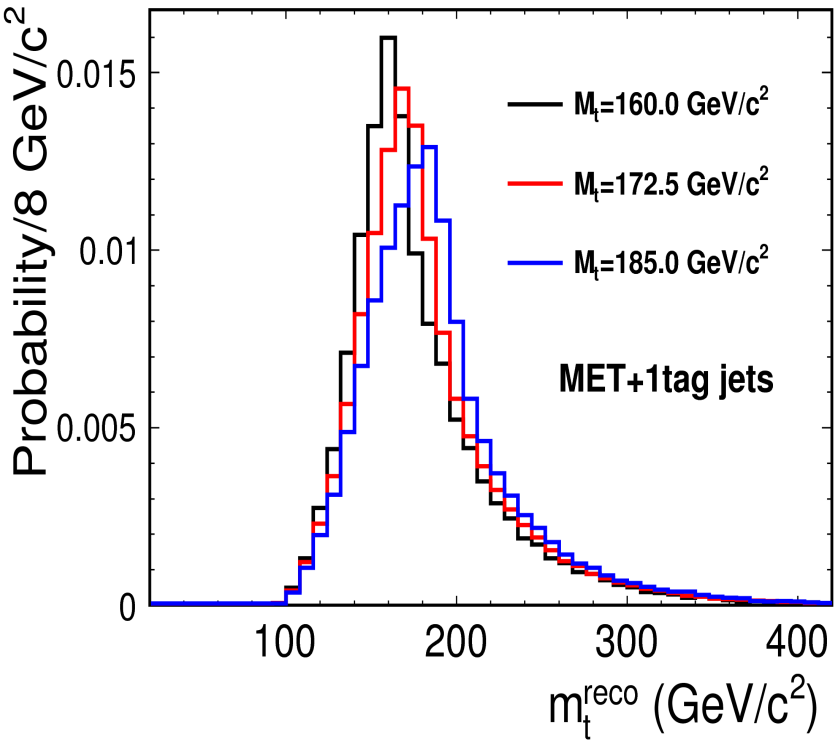
Methods – Template method

→ uses variable sensitive to ***t*** quark mass – e.g. top quark mass reconstructed from its decay products

→ obtain templates by reconstruction of the variable using MC samples generated with different ***t*** quark mass

→ comparing reconstructed sensitive variable obtained from templates with one from data leads to the result.

→ fast but statistical uncertainty is worse then in other methods



Methods – Matrix element method

→ Compute event probability density, P_E :

$$P_E(x; m_t, f_{t\bar{t}}) = f_{t\bar{t}} \cdot P_{t\bar{t}}(x; m_t) + (1 - f_{t\bar{t}}) \cdot P_b$$

… probability that the event with certain input ***t*** quark mass will lead to measured variables as we see them in the detector

… probability that events represent $t\bar{t}$:

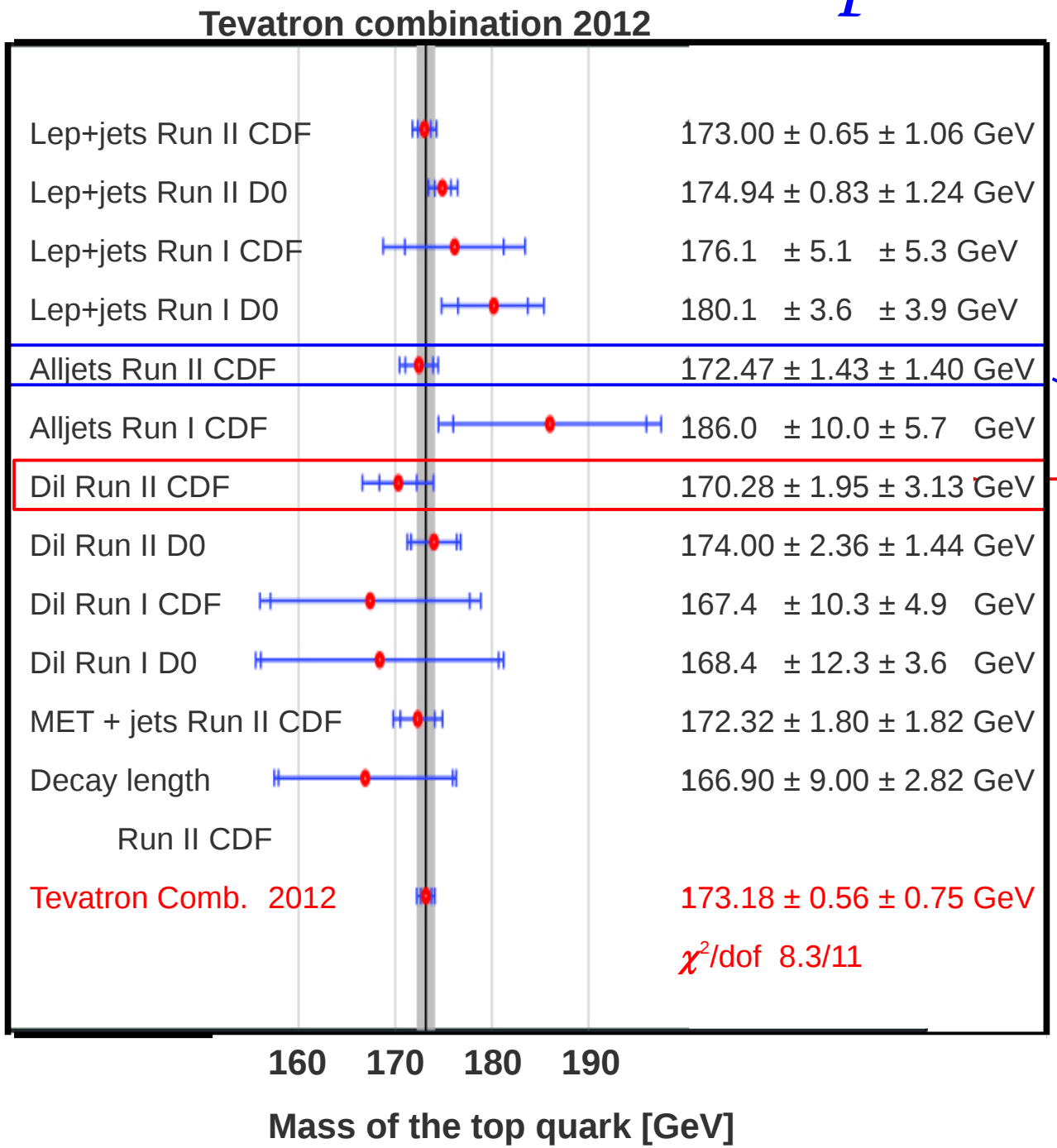
$$P_{t\bar{t}} = \frac{1}{\sigma_{t\bar{t}}(m_t)} \sum_{j-p} \int \sum_{flavors} dq_1 dq_2 \frac{d\sigma(p\bar{p} \to t\bar{t} \to y)}{dy} \cdot f(q_1) f(q_2) \cdot W(x; y) \cdot dy$$

Matrix element **PDFs** **resolution**

→ mass is exctracted from sample likelihood $L = \prod P_E$

→ uses full event information and event-by event differences

Presented on Top 2011 workshop



Tevatron combination:

$$m_t = 173.2 \pm 0.6\,(\text{stat}) \pm 0.8\,(\text{syst})$$
$$= 173.2 \pm 0.9\,\text{GeV}/c^2$$

Uncertainty below 1 GeV/c^2!

arXiv:1207.1069, accepted by PRD

Preliminary → public

Updated

Measurements are limited by syst. uncertainty!

… JES* is dominated syst.

* Jet energy scale

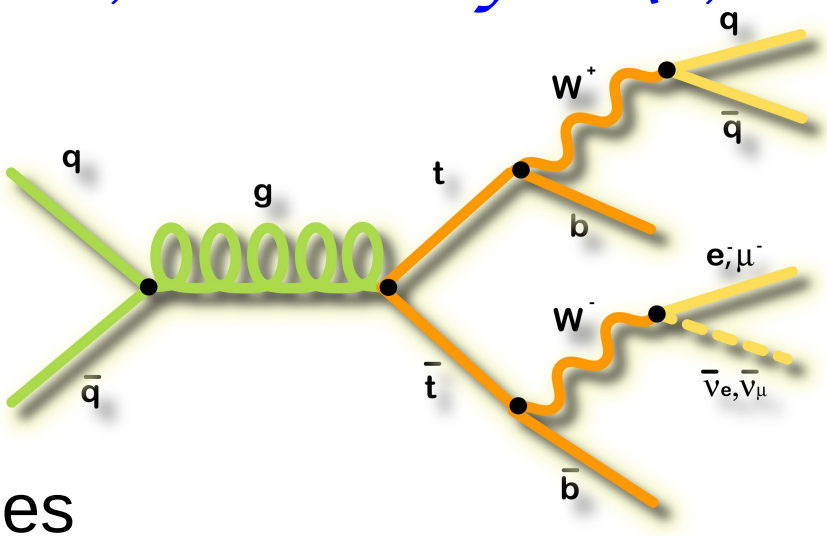
In following slides:

1) new measurements:
   2 from CDF, 1 from D0
2) update of Δm_t measurement

Lepton + jets channel (CDF) $\mathcal{L} = 8.7\ fb^{-1}$ (I)

→ template based measurement

… templates obtained from MC samples generated with 76 different m_{top} and 29 possible shifts in JES



→ event selection: … 5 subsamples

$$H_T = MET + \sum_{i=l,\,jets} E_T^i$$

QCD veto: minimum $\Delta\phi_i(jet, MET)$

	0-tag	1-tag	2-tag
b-tag	=0	=1	=2
Leading 3 jets E_T (GeV)	> 20		
Leading 3 jets $\lvert\eta\rvert$	< 2.0		
Missing E_T (GeV)	> 20		
4th jet E_T (GeV)	> 20	> 12	
4th jet $\lvert\eta\rvert$	< 2.0	< 2.4	
Extra jets E_T (GeV)	< 20	Any	
H_T (GeV)	< 250		Any
QCD veto	yes		no
χ^2	< 3	< 9	

Lepton + jets channel (CDF) $\mathcal{L}$ = 8.7 fb^{-1} (II)

5 subsamples:

→ 0-tag – no b-tagged jets, 4 tight jets (E_T>20 GeV, $|\eta|$<2.0)

→ 1-tagT (2-tagT) – 1 (2) b-tagged jet(s), 4 tight jets

→ 1-tagL (2-tagL) – 1 (2) b-tagged jets(s), > 4 tight jets or 3 tight+1 loose jet*

*(E_T>12 GeV, $|\eta|$<2.4)

→ top mass reconstruction: kinematic fitter

$$\chi^2 = \sum_{i=l,\,jets} \frac{(p_T^{i,\,fit} - p_T^{i,\,meas})^2}{\sigma_i^2} + \sum_{j=x,\,y} \frac{(UE_j^{fit} - UE_j^{meas})^2}{\sigma_j^2}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - m_t^{reco})^2}{\Gamma_t^2} + \frac{(M_{bl\nu} - m_t^{reco})^2}{\Gamma_t^2}$$

UE – unclustered energy (not associated with jets, nor lepton)

M_W = 80.42 GeV/c^2, Γ_W = 2.12 GeV/c^2, Γ_t = 1.5 GeV/c^2

Lepton + jets channel (CDF) $\mathcal{L}$ = 8.7 fb^{-1} (III)

→ Background predictions:

… obtained using MC samples and cross-section, QCD – data driven method

CDF II Preliminary 8.7 fb^{-1}

	0-tag	1-tagL	1-tagT	2-tagL	2-tagT
$Wb\bar{b}$	37.6±15.9	54.4±22.6	34.0±14.3	8.5±3.6	6.1±2.6
$Wc\bar{c}$	117.8±46.2	35.7±13.6	22.3±9.0	1.4±0.7	1.2±0.5
Wc	54.2±25.1	19.1±10.0	10.4±5.1	0.8±0.3	0.5±0.2
W+light jets	493.6±111.5	60.5±13.5	35.4±9.0	0.9±0.3	0.6±0.2
Z+jets	52.3±4.4	8.9±1.1	5.9±0.7	0.8±0.1	0.5±0.1
single top	4.9±0.5	10.5±0.9	6.8±0.6	2.2±0.3	1.7±0.2
Diboson	60.3±5.6	11.1±1.4	8.5±1.1	1.0±0.2	0.8±0.1
QCD	143.0±114.4	34.5±12.6	20.7±16.6	4.4±2.5	2.5±2.4
Total	963.5±229.3	234.7±61.1	144.0±40.9	19.9±5.5	13.8±4.2
$t\bar{t}$	644.8±86.3	695.0±86.7	867.3±107.6	192.3±29.7	303.7±46.6
Expected Events	1608.4±245.0	929.8±106.1	1011.3±115.1	212.2±30.2	317.6±46.8
Observed Events	1627	882	997	208	275

Lepton + jets channel (CDF) $\mathcal{L} = 8.7\ fb^{-1}$ (IV)

→ three m_t sensitive variables:

… reconstructed mass from two smallest χ^2 comb.: m_t^{reco}, $m_t^{reco(2)}$

… dijet mass m_{jj} – dijet mass obtained from non-b tagged jets, which is closest to M_W.

→ Kernel Density Estimate

– non-parametric method used to derive more dimensional probability density functions (3 dimensional in this case)

→ Likelihood fit:

Gaussian constrain of background part

$$L_{subsample} = \boxed{\exp\left(-\frac{(n_b - n_b^0)^2}{2\sigma^2_{n_b^0}}\right)} \times \prod_{i=1}^{N} \frac{n_s . P_s + n_b . P_b}{n_s + n_b}$$

N – number of events in subsample

n_b^0 – expected # of bckg events

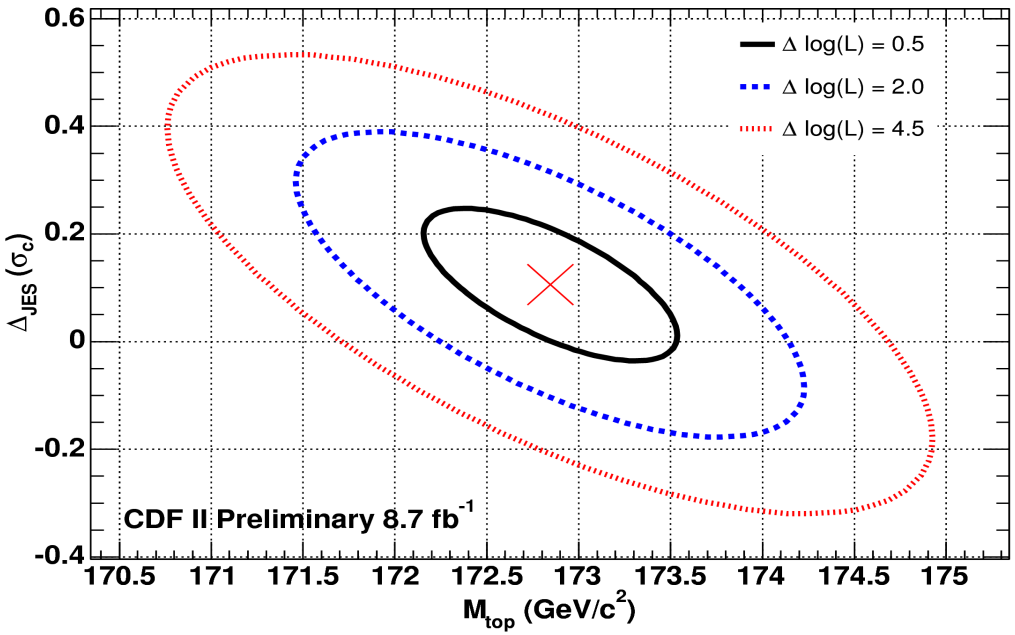
$n_{s(b)}$ – free parameter, corresponds to # of signal (bckg) events

$P_{s\,(b)}$ – signal (bckg) probability density functions:

$$\boxed{P_s = P_s(m_t^{reco}, m_{jj}, m_t^{reco(2)}; M_{top}, \Delta_{JES}) \qquad P_b = P_b(m_t^{reco}, m_{jj}, m_t^{reco(2)}; \Delta_{JES})}$$

Lepton + jets channel (CDF) $L = 8.7\ fb^{-1}$ (V)

Result: **(Conf. Note 10761)**



CDF II Preliminary 8.7 fb^{-1}

Systematic	GeV/c^2
Residual JES	0.52
Generator	0.56
Next Leading Order	0.09
PDFs	0.08
b jet energy	0.10
b tagging efficiency	0.03
Background shape	0.20
gg fraction	0.03
Radiation	0.06
MC statistics	0.05
Lepton energy	0.03
MHI	0.07
Color Reconnection	0.21
Total systematic	0.84

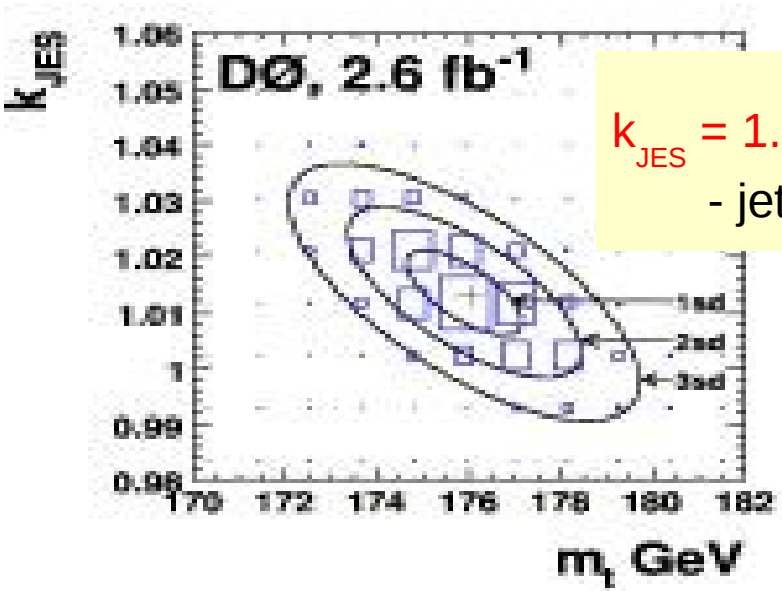
m_t = 172.85 ± 0.71 (stat.) ± 0.84 (syst.)

= 172.85 ± 1.10 GeV/c^2

Lepton + jets channel (D0) $L = 3.6\ fb^{-1}$

Most precise measurement of D0

→ matrix element method



k_{JES} = 1.013 ± 0.008 (stat.)
- jet energy scale factor

Phys. Rev. D 84 032004 (2011)

Combination with another independent sample (=> L = 3.6 fb^{-1}):

m_t = 172.94 ± 0.83 (stat.)
± 0.78 (JES)
± 0.96 (syst.)

m_t = 172.94 ± 1.49 GeV/c^2

Table IV. Summary of systematic uncertainties.

Source	Uncertainty (GeV)
Modeling of production:	
Modeling of signal:	
Higher-order effects	±0.25
ISR/FSR	±0.26
Hadronization and UE	±0.58
Color reconnection	±0.28
Multiple $p\bar{p}$ interactions	±0.07
Modeling of background	±0.16
W+jets heavy-flavor scale factor	±0.07
Modeling of b jets	±0.09
Choice of PDF	±0.24
Modeling of detector:	
Residual jet energy scale	±0.21
Data-MC jet response difference	±0.28
b-tagging efficiency	±0.08
Trigger efficiency	±0.01
Lepton momentum scale	±0.17
Jet energy resolution	±0.32
Jet ID efficiency	±0.26
Method:	
Multijet contamination	±0.14
Signal fraction	±0.10
MC calibration	±0.20
Total	±1.02

MET + jets channel (CDF) $\mathcal{L}$ = 8.7 fb^{-1} (I)

→ template based measurement

→ event selection:

... large contribution of events with W decaying to τ

… use multijet trigger

→ 4 – 6 jets with E_T > 15 GeV and $|\eta|$ < 2.0

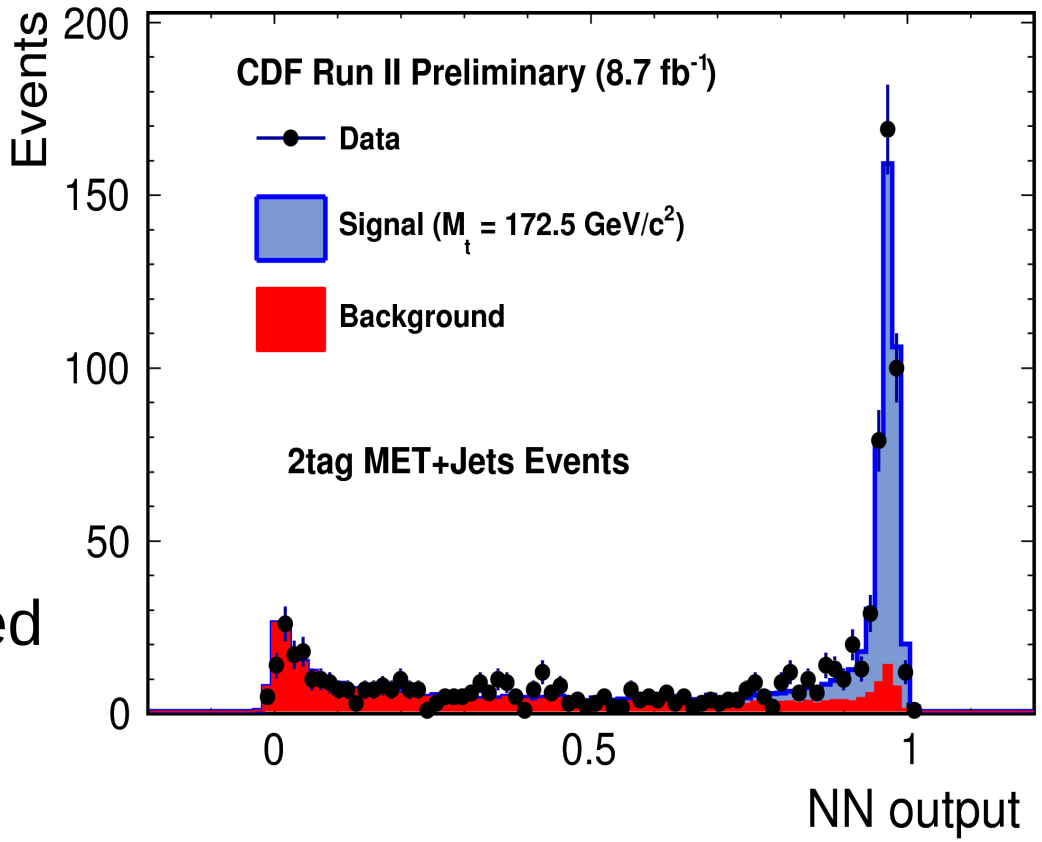
→ missing E_T significance:

$$MET/\sqrt{\sum E_T} < 3\,GeV^{1/2}$$

→ no leptons

→ at least 1 b-tagged jet (SecVtx algorithm)

→ Neural Network output > 0.9 (0.8) for 1 (2) b-tagged events



MET + jets channel (CDF) $\mathcal{L} = 8.7\ fb^{-1}$ (II)

→ top mass reconstruction:

$$\chi^2 = \sum_{i=l,\,jets} \frac{(p_T^{i,\,fit} - p_T^{i,\,meas})^2}{\sigma_i^2} + \sum_{j=x,\,y} \frac{(UE_j^{fit} - UE_j^{meas})^2}{\sigma_j^2} + \boxed{\frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{b,\,MET} - m_t^{reco})^2}{\Gamma_t^2}} + \frac{(M_{bjj} - m_t^{reco})^2}{\Gamma_t^2}$$

UE – unclustered energy (not associated with jets, nor lepton)

M_W = 80.42 GeV/c^2, Γ_W = 2.12 GeV/c^2, Γ_t = 1.5 GeV/c^2

→ background contributions:

Data driven method:

→ per jet b-tag rate obtained from 3 jet tt-signal-neglectible data sample

→ b-tag rate depends on E_T, num. of tracks MET projection along jet direction.

→ bckg rate is estimated by applying b-tag rate matrix to events with high jet multiplicity.

MET + jets channel (CDF) $\mathcal{L} = 8.7\ fb^{-1}$ (III)

→ three m_t sensitive variables:

… reconstructed mass from two smallest χ^2 comb.: m_t^{reco}, $m_t^{reco(2)}$

… dijet mass m_{jj} – dijet mass obtained from non-b tagged jets, which is closest to M_W.

→ Kernel Density Estimate

– non-parametric method used to derive more dimensional probability density functions (3 dimensional in this case)

→ Likelihood fit:

Gaussian constrain of background part

$$L_{subsample} = \boxed{\exp\left(-\frac{(n_b - n_b^0)^2}{2\sigma^2_{n_b^0}}\right)} \times \prod_{i=1}^{N} \frac{n_s . P_s + n_b . P_b}{n_s + n_b}$$

N – number of events in subsample

n_b^0 – expected # of bckg events

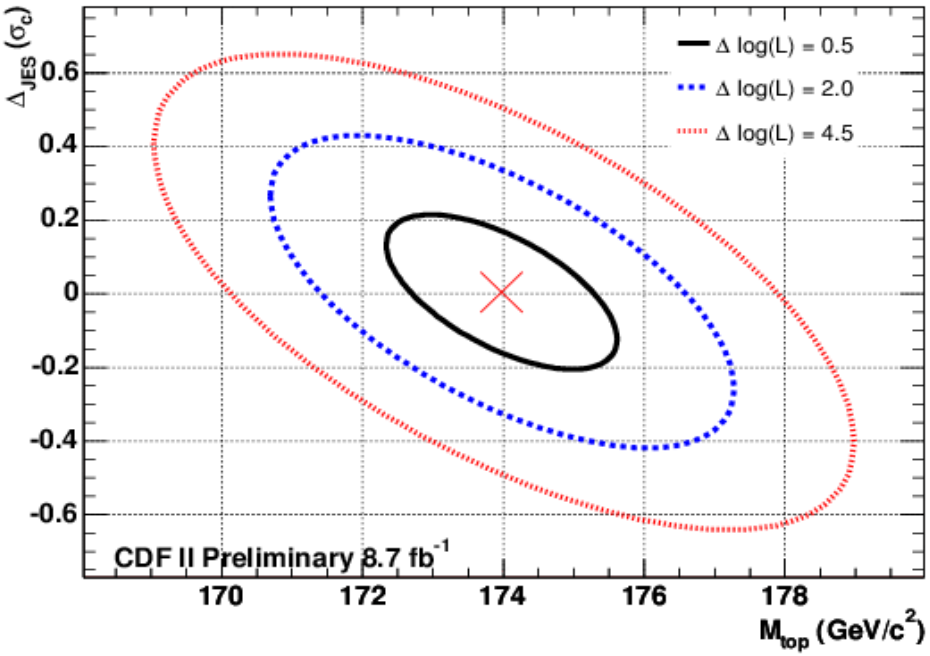
$n_{s(b)}$ – free parameter, corresponds to # of signal (bckg) events

$P_{s\,(b)}$ – signal (bckg) probability density functions:

$$P_s = P_s(m_t^{reco}, m_{jj}, m_t^{reco(2)}; M_{top}, \Delta_{JES}) \qquad P_b = P_b(m_t^{reco}, m_{jj}, m_t^{reco(2)}; \Delta_{JES})$$

MET + jets channel (CDF) $\mathcal{L} = 8.7\ fb^{-1}$ (IV)

→ result: **(Conf. Note 10810)**



CDF II Preliminary 8.7 fb^{-1}

Systematic	ΔM_{top} (GeV/c^2)
Residual JES	0.4
Generator	0.4
PDFs	0.2
b jet energy	0.2
Background	0.2
gg fraction	0.3
Radiation	0.3
Trigger simulation	0.1
Multiple Hadron Interaction	0.2
Color Reconnection	0.3
Calibration	0.2
Total Effect	0.9

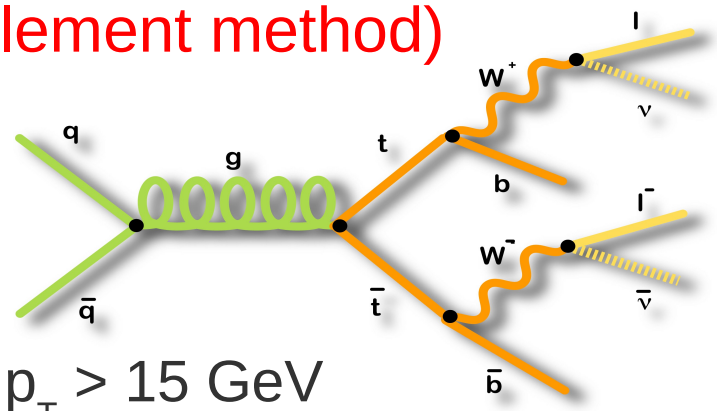
m_t = 173.9 ± 1.6 (stat.+JES) ± 0.9 (syst.) GeV/c^2

m_t = 173.9 ± 1.9 GeV/c^2

Events with 2 leptons (D0) $\mathcal{L}$ = 5.3 fb^{-1} (I)

→ neutrino weighting technique (matrix element method)

… MC samples generated for
$140 < M_{top} < 200$ GeV/c^2



→ event selection:

… 2 isolated leptons (electron or μ) with p_T > 15 GeV

… ele (muon) $|\eta| < 2.5$ (2.0)

… at least 2 jets with E_T > 20 GeV and $|\eta| < 2.5$

→ have 3 subsamples: ee, eμ, $\mu\mu$.

… in $\mu\mu$ – MET > 40 GeV

… in eμ – H_T > 120 GeV

$$H_T = \text{leading lepton } p_T + \sum_{i=jets} p_T^i$$

… in ee and $\mu\mu$ – MET significantly different from Z events distr.

→ background:

… Z/γ* and Diboson - MC simulations

…

Events with 2 leptons (D0) $\mathcal{L}$ = 5.3 fb^{-1} (II)

→ reduction of JES systematics:

… jet calibration is improved by using the energy scale derived from in D0 lepton+jets measurements:

$$k_{JES} = 1.013 \pm 0.008 \text{ (stat.)}$$

→ neutrino weighting technique:

… consequence of two neutrinos – underconstrained kinematic

… simplification of matrix element method

… probability density function depends on $\boldsymbol{\eta}$ of neutrinos (strictly said it's weight, no probability after simplification)

$$\mathcal{W} \propto \int \boxed{\mathcal{P}\left(\eta_1 | m_t\right) \mathcal{P}\left(\eta_2 | m_t\right)} \boxed{\rho_{\eta 1} \rho_{\eta 2}} d\eta_1 d\eta_2$$

evaluated from MC $t\bar{t}$ samples

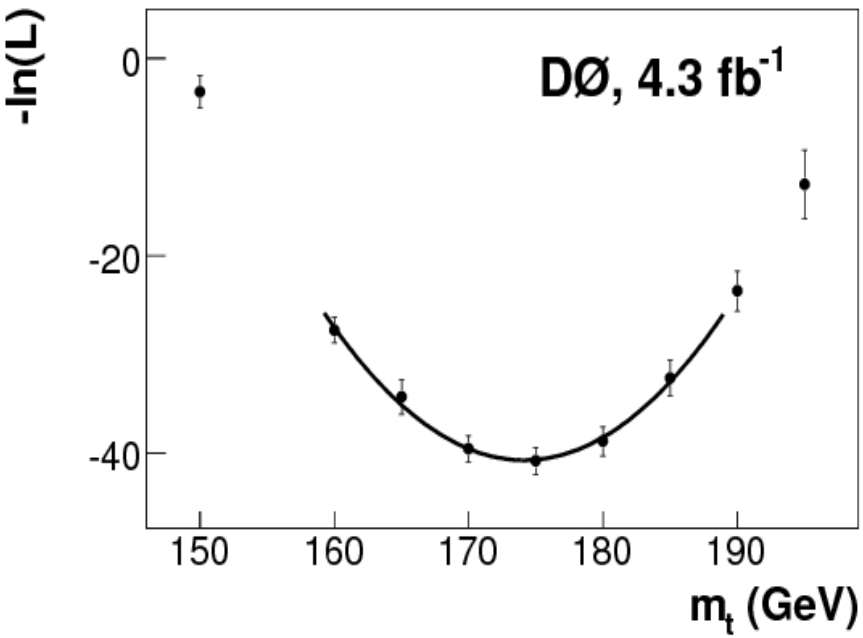
Solution of resolution factor does not take so much time

… *weight* depends on m_t and is evaluated for some range of assumed top quark masses

… binned maximum likelihood fit is used for final decision.

Events with 2 leptons (D0) $\mathcal{L}$ = 5.3 fb^{-1} (III)

→ result:



→ combination with other 1fb^{-1} dataset: (total L = 5.3 fb^{-1}):

arXiv:1201.5172, accepted by Phys. Rev. D

m_t = 174.0 ± 2.4 (stat.) ± 1.4 (syst.)
m_t = 174.0 ± 2.8 GeV/c^2

Source	Uncertainty (GeV)
Jet energy calibration	
Overall scale	0.9
Flavor dependence	0.5
Residual scale	0.3
Signal modeling	
ISR/FSR	0.4
Color reconnection	0.5
Higher order effects	0.6
b quark fragmentation	0.1
PDF uncertainty	0.5
Object reconstruction	
Muon p_T resolution	0.2
Electron energy scale	0.2
Muon p_T scale	0.2
Jet resolution	0.3
Jet identification	0.3
Method	
Calibration	0.1
Template statistics	0.5
Signal fraction	0.2
Total systematic uncertainty	1.5

Top-antiTop mass difference (CDF) $\mathcal{L}$ = 8.7 fb^{-1}

→ template based measurement

… 20 MC samples generated with different Δm_t

→ event selection

… use lepton + jets events

$$H_T = MET + \sum_{i=l,\,jets} E_T^i$$

	0-tag	1-tag	2-tag
b-tag	=0	=1	=2
Leading 3 jets E_T (GeV)	> 20		
Leading 3 jets $\lvert\eta\rvert$	< 2.0		
Missing E_T (GeV)	> 20		
4th jet E_T (GeV)	> 20	> 12	
4th jet $\lvert\eta\rvert$	< 2.0	< 2.4	
Extra jets E_T (GeV)	< 20	Any	
H_T (GeV)	< 250		Any
χ^2	< 3	< 9	

→ kinematic fitter ($\overline{M}_t$ = 172.5 GeV/c^2 is used)

$$\chi^2 = \sum_{i=l,\,jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,\,y} \frac{(UE_j^{fit} - UE_j^{meas})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2}$$
$$+ \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{\{M_{bjj} - \boxed{(\overline{M}_{top} + dm_{reco}/2)}\}^2}{\Gamma_t^2} + \frac{\{M_{bl\nu} - \boxed{(\overline{M}_{top} - dm_{reco}/2)}\}^2}{\Gamma_t^2}$$

Top-antiTop mass difference (CDF) $\mathcal{L} = 8.7\ fb^{-1}$

→ Δm_t sensitive variables:

$$\Delta m_{reco} = -Q_{lepton} \times dm_{reco}^{min}\ , \qquad \Delta m_{reco(2)} = -Q_{lepton} \times dm_{reco}^{2^{nd}\,min}$$

where dm_{reco}^{min} - is the dm_{reco} from the minimal χ^2 combination

→ result: **(Conf. Note 10777)**

… obtained by unbinned maximum likelihood fit, which is defined by 2 dimensional probability density functions obtained by KDE method.

ΔM_{top} = -1.95 ± 1.11 (stat.) ± 0.59 (syst.) GeV/c^2

ΔM_{top} = -1.95 ± 1.26 GeV/c^2

Summary

- *New measurements from CDF and D0 were presented*
- *CDF comes with measurements using the full dataset*
- *D0 measurement improved the treatment of JES systematic (the main source of systematic error)*
- *The most precise measurement is still the Tevatron combination results – top quark mass is measured with uncertainty less then 1 GeV*
- *Measurements of top antitop mass difference using full CDF dataset was presented*

Thank you!

Back up slides

Kernel Density Estimate

non-parametric method used to derive more dimensional probability density functions:

$$\hat{f}(x,y,z)=\frac{1}{n}\sum_{i=1}^{n}\frac{1}{h_{x,i}h_{y,i}h_{z,i}}[K(\frac{x-x_i}{h_{x,i}})\times K(\frac{y-y_i}{h_{y,i}})\times K(\frac{z-z_i}{h_{z,i}})]$$

$x,\ y,\ z$ - observed variables in data ($x\sim m_t^{reco},\quad y\sim m_{jj},\quad z\sim m_t^{reco(2)}$)

$x_i,\ y_i,\ z_i$ - observed variables in i^{th} event of MC with n entries

h_x, h_y, h_z - smoothing parameters