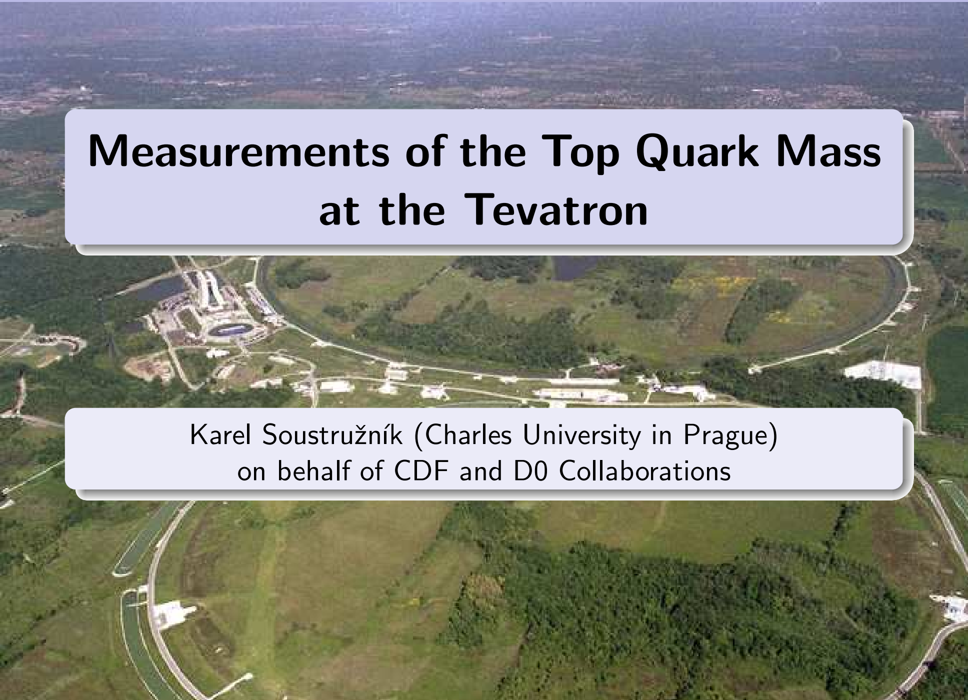
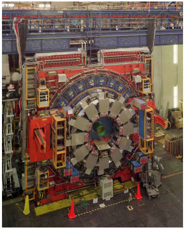
Measurements of the Top Quark Mass at the Tevatron

Karel Soustružník (Charles University in Prague)
on behalf of CDF and D0 Collaborations



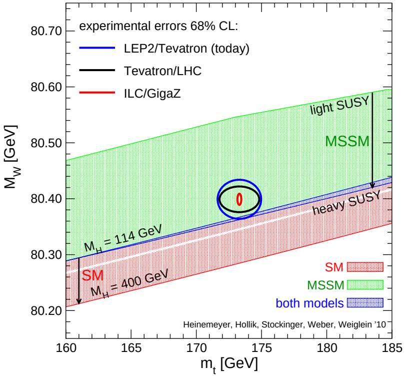
Contents



- Introduction
- Direct Measurements
  - Methods and results
- Top Quark Mass from Production Cross Section
- Top-Antitop Mass Difference
- Summary

Top Quark

- Heaviest known fundamental particle
- Top (together with W) mass constrains Higgs mass
- Window into new physics ? Couples to new physics ?
- Same properties in different final states ?



Need to precisely measure top mass

Top Quark

- Decay channels

  Dilepton : $t\bar{t} \rightarrow l\bar{l}\nu\bar{\nu}b\bar{b}$

  Lepton + jets : $t\bar{t} \rightarrow l\nu qqb\bar{b}$

  All-jets : $t\bar{t} \rightarrow qqqqb\bar{b}$

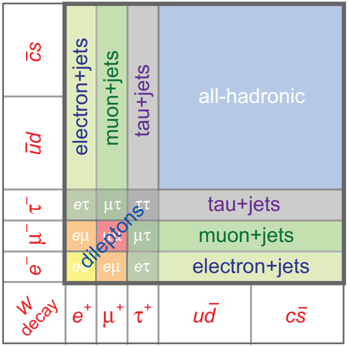
- Event selection

  kinematics, topology, b-jet ID

- Dominant background

  W/Z+jets, multi-jets, diboson

Top Pair Decay Channels



Matrix Element Method

- Matrix element method is based on the calculation of event probability densities estimated from differential cross section and detector resolutions

$$P_{evt} = f_{sig} P_{sig} + (1 - f_{sig}) P_{bkg}$$

$$P_{sig}(x; m_{top}, JES) = \frac{1}{\sigma_{obs}(m_{top})} \times \int dq_1 dq_2 f(q_1) f(q_2) \frac{(2\pi)^4 |M(y, m_{top})|^2}{4\sqrt{q_1 \cdot q_2 - m_1 m_2}} d\Phi \times W(y, x, JES)$$

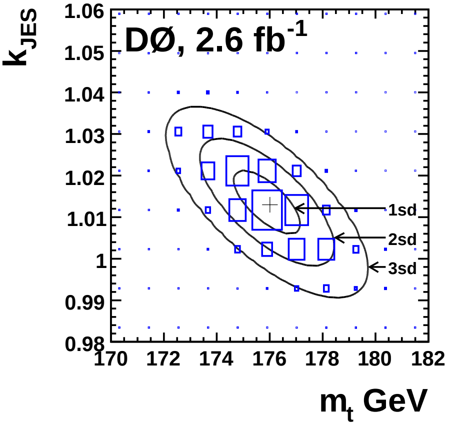
Parton densities — LO matrix element — Transfer function

$$P_{bkg}(x; JES) \sim M_{bkg}(y)$$

- *JES* - jet energy scale, global multiplicative factor for jet energies
- Transfer function contains detector resolution and provides a map from parton level y to measured set of variables x

Matrix Element in Lepton+Jets Channel

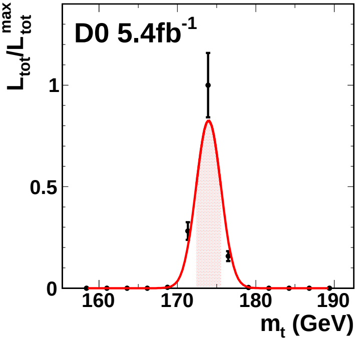
- High p_t e, μ + 4 jets
- Missing p_t, $\Delta\phi(l, \not{p}_t)$, ≥ 1 b-tagged jet
- Likelihood fit to derive top mass
- $3.6\,\mathrm{fb}^{-1}$ $(2.6 + 1.0\,\mathrm{fb}^{-1})$
- **most precise D0 measurement**



$$m_t(3.6\mathrm{fb}^{-1}) = 174.9 \pm 0.8(\mathrm{stat}) \pm 1.3(\mathrm{syst+JES})\ \mathrm{GeV}$$

Matrix Element in Dilepton Channel

- 2 OS high p_t isolated leptons
- $\geq$ 2 jets, large $\not{p}_t$ or $\not{p}_t$ significance
- Likelihood fit to obtain top mass
- 5.4 fb^{-1} sample
- **most precise measurement in dilepton channel**



$$\mathbf{m_t = 174.0 \pm 1.8(stat) \pm 2.4(syst)\ GeV}$$

arXiv:1105.0320

Recent Results from Matrix Element Method

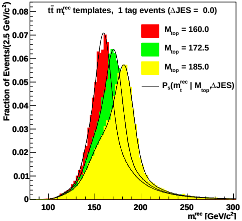
new since summer 2010

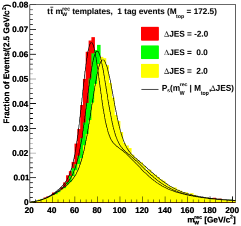
channel		Top quark mass [GeV]	luminosity
l+jets	In-situ JES with NN selection	$173.0 \pm 0.9(\text{stat+JES}) \pm 0.9(\text{syst})$	$5.6\ \text{fb}^{-1}$
l+jets	In-situ JES	$172.4 \pm 1.4(\text{stat+JES}) \pm 1.3(\text{syst})$	$3.2\ \text{fb}^{-1}$
dilepton	NN selection	$171.2 \pm 2.7(\text{stat}) \pm 2.9(\text{syst})$	$1.9\ \text{fb}^{-1}$

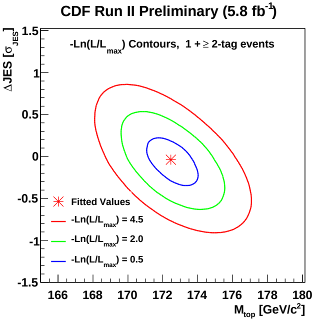
channel		Top quark mass [GeV]	luminosity
l+jets	In-situ JES	$174.9 \pm 0.8(\text{stat}) \pm 1.3(\text{syst+JES})$	$3.6\ \text{fb}^{-1}$
dilepton		$174.0 \pm 1.8(\text{stat}) \pm 2.4(\text{syst})$	$5.4\ \text{fb}^{-1}$

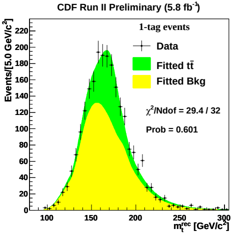
Template Fitting in All Hadronic Channel

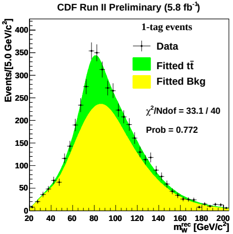
- Build MC templates for variables sensitive to top quark mass and JES
- Fit data to MC templates with different generated top masses and JES











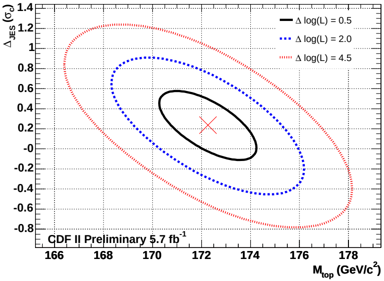
$m_t = 172.5 \pm 1.4(stat) \pm 1.5(syst)$

CDF Public Note 10456

Template Fitting in MET+Jets Channel

- Event selection : MET, $\geq$ 4 jets
- NN to enhance signal to background ratio

- 3D template fit
  M3, $\mathrm{m_{jj}}$ (hadronic top decay)
- $\mathrm{m_{jj}}$ - provides in situ improvement of jet energy scale (JES)
- 1 btag, 2 btags events
- Log-likelihood fit to obtain top mass



$\mathbf{m_t}$=172.3±2.4(stat+JES)±1.0(syst) GeV

CDF Public Note 10433

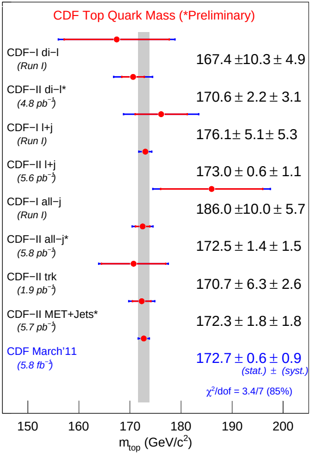
Recent Results from Template Fitting Method

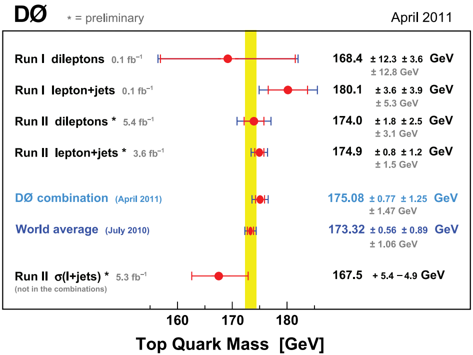
new since summer 2010

channel		Top quark mass [GeV]	luminosity
l+jets/dilepton	m_t^{reco} with in-situ JES	$172.1 \pm 1.1(\text{stat}) \pm 1.0(\text{syst})$	$4.8\,\text{fb}^{-1}$
l+jets/dilepton	lepton p_t	$172.8 \pm 7.2(\text{stat}) \pm 2.3(\text{syst})$	$2.8\,\text{fb}^{-1}$
l+jets	L_{xy} of b-jets and lepton p_t	$170.7 \pm 6.3(\text{stat}) \pm 2.6(\text{syst})$	$1.9\,\text{fb}^{-1}$
all hadronic	m_t^{reco} with in-situ JES	$172.5 \pm 1.4(\text{stat}) \pm 1.5(\text{syst})$	$5.8\,\text{fb}^{-1}$
MET+jets	m_t^{reco} with in-situ JES	$172.3 \pm 1.8(\text{stat}) \pm 1.8(\text{syst})$	$5.7\,\text{fb}^{-1}$

channel		Top quark mass [GeV]	luminosity
electron+muon	$w(m_t)$ with ν weighting	$173.3 \pm 2.4(\text{stat}) \pm 2.1(\text{syst})$	$5.3\,\text{fb}^{-1}$
dilepton/l+track	ν and matrix weighting	$174.7 \pm 4.4(\text{stat}) \pm 2.0(\text{syst})$	$1.0\,\text{fb}^{-1}$

Latest CDF and D0 Top Mass Results





Tevatron combination July 2010

$$m_t = 173.3 \pm 0.6(\text{stat}) \pm 0.9(\text{syst})\ \text{GeV}$$

Top Mass Systematics

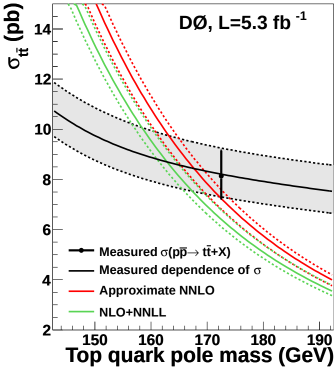
ll ME   l+jets ME   alljets TF   MET+jets TF

- **Physics modeling**
  higher order effects, ISR/FSR, color reconnection, showering, **hadronization**, **underlying** event, multiple proton interactions, PDF, b fragmentation, **background modeling**
- **Detector modeling**
  JES/resi**dual** JES, trigger, lepton ID, lepton energy scale and resolution, (b)jet ID, jet energy resolution, **b/light** jet response
- **Method**
  signal fraction, MC calibration

Top Quark Mass from Cross Section

- Top quark mass depends on the renormalization scheme.
- Direct measurements use LO MC with parton shower to extract the mass from data. The renormalization scheme is not well defined.
- It is believed that the mass from direct measurements is close to pole mass.

Top Quark Mass from Cross Section



arXiv:1104.2887

Theoretical prediction	m_t^{pole}(GeV)	
MC mass assumption	$m_t^{MC} = m_t^{pole}$	$\Delta(m_t^{MC} = m_t^{\overline{MS}})$
NLO	$164.8^{+5.7}_{-5.4}$	-3.0
NLO+NLL	$166.5^{+5.5}_{-4.8}$	-2.7
NLO+NNLL	$163.0^{+5.1}_{-4.6}$	-3.3
Approximate NNLO[1]	$167.5^{+5.2}_{-4.7}$	-2.7
Approximate NNLO[2]	$166.7^{+5.2}_{-4.5}$	-2.8

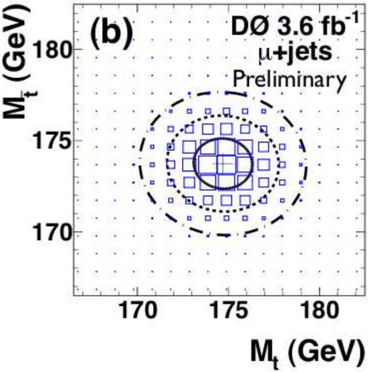
- What is the theoretical interpretation of the measured parameter ?
- Extract m_t from cross section measurement assuming pole or $\overline{\mathrm{MS}}$ mass.
- The world average is more compatible with pole mass.

Top-Antitop Quark Mass Difference

- Top (and antitop) has very short life time and decays before it hadronizes.
- This allows direct measurements of top and antitop masses and to examine the CPT invariance theorem.
- The first result from D0 ($1\,\mathrm{fb}^{-1}$) in 2009 :
  $\Delta \mathrm{m_t} = 3.8 \pm 3.4(\mathrm{stat}) \pm 1.2(\mathrm{syst})$ GeV PRL 103, 132001 (2009)
- The first result from CDF ($5.6\,\mathrm{fb}^{-1}$) in 2010 :
  $\Delta \mathrm{m_t} = -3.3 \pm 1.4(\mathrm{stat}) \pm 1.0(\mathrm{syst})$ GeV PRL 106, 152001 (2011)
  $\sim 2\sigma$ effect

Mass Difference from ME Method

- 1 isolated high p_t e or μ
  4 jets, $\not{p}_t$, $\Delta\phi(l, \not{p}_t)$
  ≥ 1 b-tag (NN based)
- $P_{evt} \sim P_{sig}, P_{bkg}$ by ME method
- Likelihood fit to extract m_t and Δm_t
- $3.6\,\mathrm{fb}^{-1}$ sample

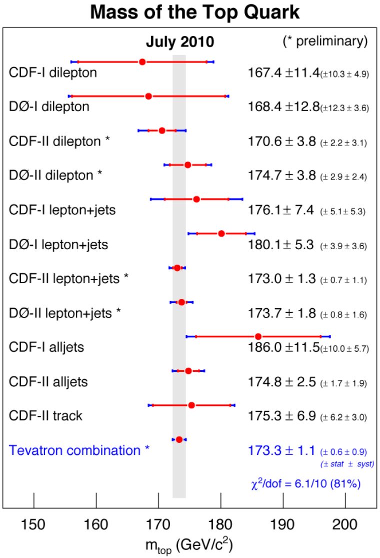


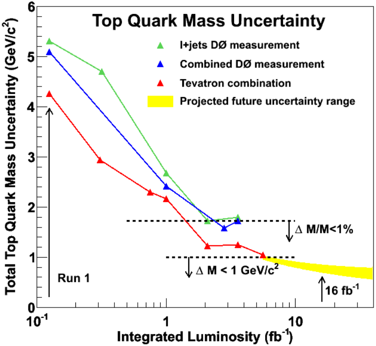
$$\Delta m_t = 0.8 \pm 1.8(\mathrm{stat}) \pm 0.8(\mathrm{syst})\ \mathrm{GeV}$$

Summary

- Thanks to well-developed analysis methods, well-understood detectors and largest top quark samples, top quark mass from Tevatron is currently better than 0.6 % and is dominated by systematics.
- Results are consistent among different final states and between CDF and D0.
- With the final data sample of 2-3 times the statistics shown here and improved systematics could be the expected uncertainty from the Tevatron below 1 GeV.

Summary


Mass of the Top Quark
July 2010
(* preliminary)
CDF-I dilepton 167.4 ±11.4 (±10.3 ± 4.9)
DØ-I dilepton 168.4 ±12.8 (±12.3 ± 3.6)
CDF-II dilepton * 170.6 ± 3.8 (± 2.2 ± 3.1)
DØ-II dilepton * 174.7 ± 3.8 (± 2.9 ± 2.4)
CDF-I lepton+jets 176.1 ± 7.4 (± 5.1 ± 5.3)
DØ-I lepton+jets 180.1 ± 5.3 (± 3.9 ± 3.6)
CDF-II lepton+jets * 173.0 ± 1.3 (± 0.7 ± 1.1)
DØ-II lepton+jets * 173.7 ± 1.8 (± 0.8 ± 1.6)
CDF-I alljets 186.0 ±11.5 (±10.0 ± 5.7)
CDF-II alljets 174.8 ± 2.5 (± 1.7 ± 1.9)
CDF-II track 175.3 ± 6.9 (± 6.2 ± 3.0)
Tevatron combination * 173.3 ± 1.1 (± 0.6 ± 0.9)
(± stat ± syst)
χ^2/dof = 6.1/10 (81%)
150 160 170 180 190 200
m_{top} (GeV/c^2)


Top Quark Mass Uncertainty
l+jets DØ measurement
Combined DØ measurement
Tevatron combination
Projected future uncertainty range
Total Top Quark Mass Uncertainty (GeV/c^2)
Δ M/M<1%
Δ M < 1 GeV/c^2
Run 1
16 fb^{-1}
10^{-1} 1 10
Integrated Luminosity (fb^{-1})