Top Quark Mass at D0

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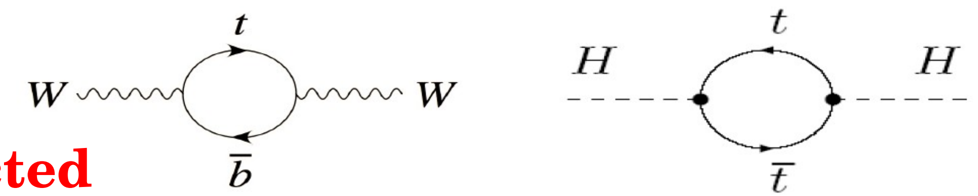
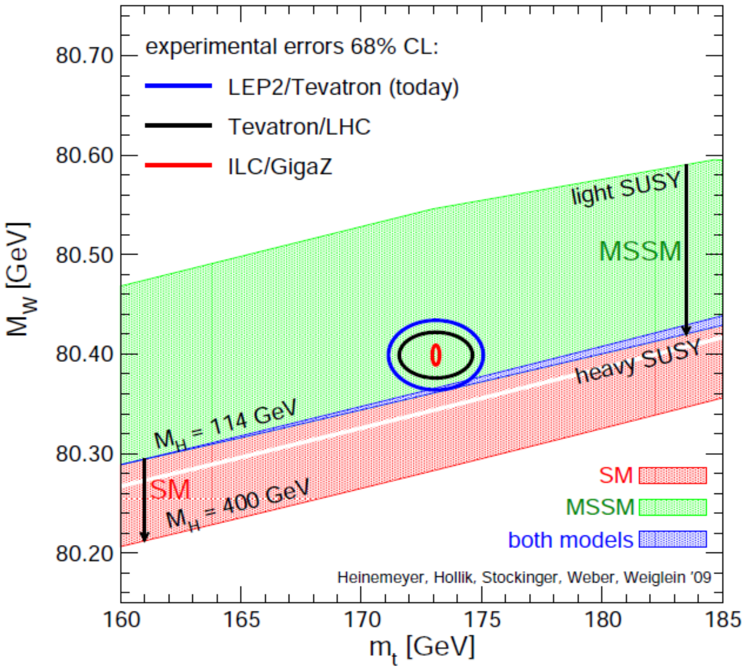
Motivation

why measure the top quark mass:

- the top quark mass is **not predicted** by the Standard Model (SM)
- the top quark and W boson masses **constrain** the **mass** of the yet unobserved **Higgs boson**





why using different channels:

- very important **consistency** check
- different final states are differently affected by **new physics**, e.g stop pair production affects the dilepton channel more than lepton+jets

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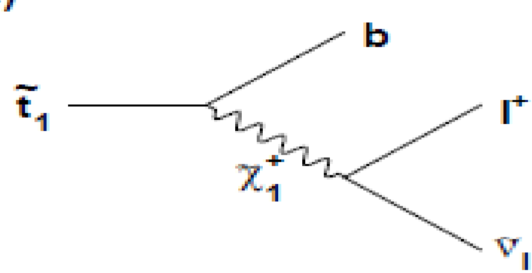


Top Mass Measurements at D0

Top Mass over Time

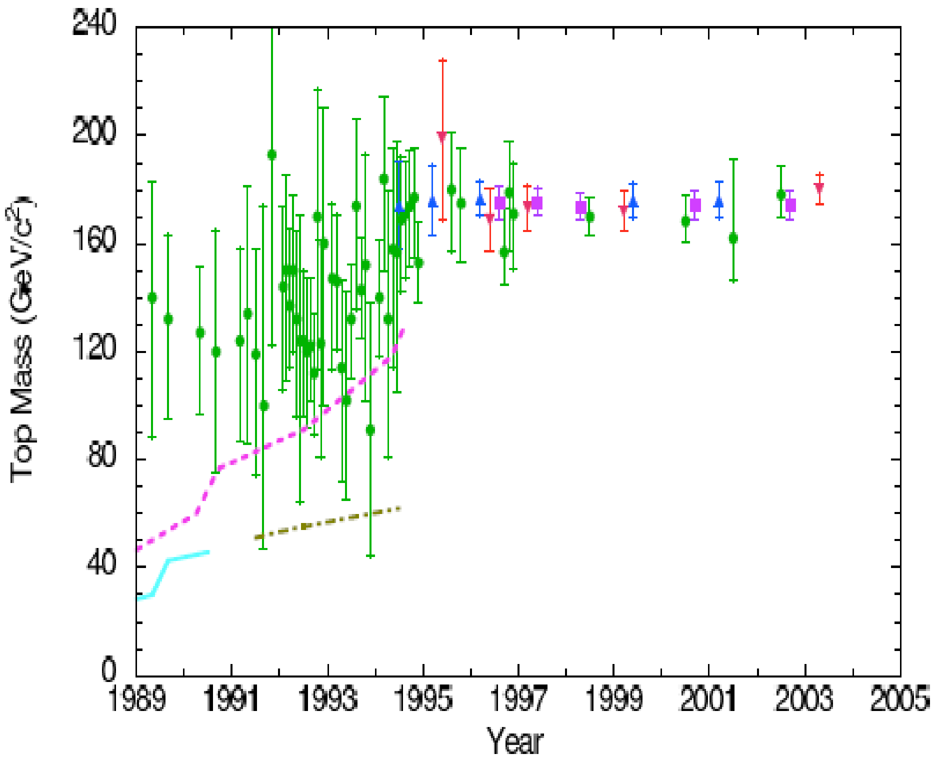


Figure 1.2: Evolution of the indirect prediction and direct measurement of the top quark mass with time [21]. (●) Indirect bounds on the top-quark mass from precision electroweak data. (■) World-average direct measurement of the top-quark mass; (▲) CDF and (▼) D0 measurements. Lower bounds from direct searches of $p\bar{p}$ (dashed) and e^+e^- (solid) colliders.

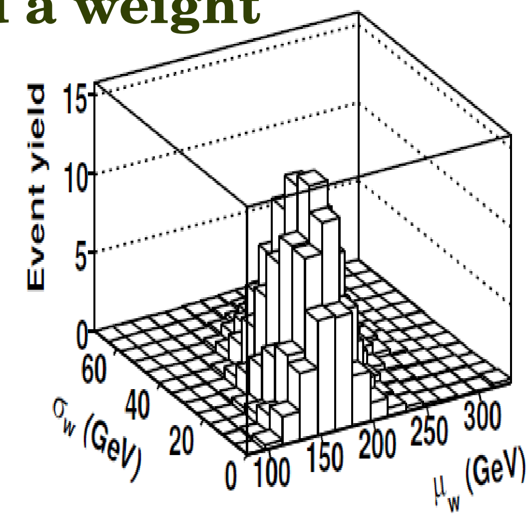
- **lepton+jets channel:**
  - **Ideogram method**
  - **Matrix Element method**
- **dilepton channel:**
  - **Nu-Weighting**
  - **Matrix Element method**
- **all-jets channel**
  - **"Iterative Jet Weighting" (under construction)**
- **indirect from cross section**

Neutrino Weighting (Dilepton)

- template based approach in dilepton events
- comparing the measured **missing tranverse energy** to the calculated **neutrino momenta**, each event can be assigned a weight

$$w(m_{top}) = \frac{1}{n_{sol}} \sum_{i=0}^{n_{sol}} \exp\left(\frac{-(\vec{\not{E}}_T - \vec{p}_T^{\,\nu_1}(m_{top}) - \vec{p}_T^{\,\nu_2}(m_{top}))^2}{2\sigma^2_{\not{E}_T}} \right)$$

- using the mean μ_W and rms σ_W of each event weight distribution, **templates** for signal and background can be formed
- extract mass from a **maximum likelihood fit**



m_{top} = 176.2 ± 4.8 (stat) ± 2.1 (syst) GeV (L=1.0 fb^{-1}, dilepton)

m_{top} = 172.7 ± 2.8 (stat) ± 2.1 (syst) GeV (L=4.3 fb^{-1}, emu)

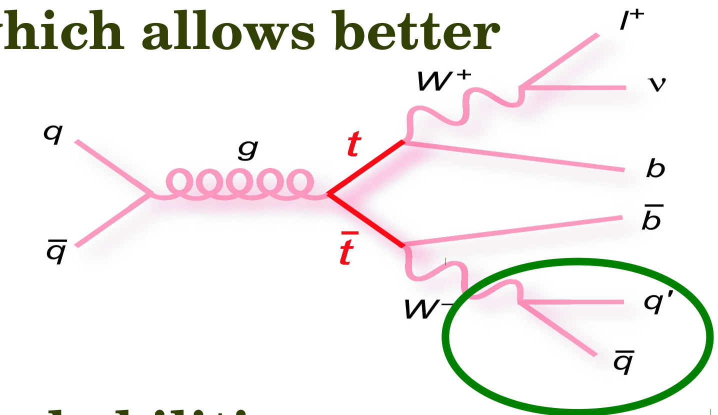
- main systematic uncertainty of **1.6 GeV** due to **jet** energy **uncertainties**

Current Status

- measurement currently in group review using the full 5.4 fb^{-1} dilepton data:
  - sample dependent jet correction derived by Zhenyu to reduce the systematic uncertainty from b jets (more details later)
  - to avoid large JES uncertainty, analysis makes use of the in-situ JES from lepton+jets
- as in-situ JES was derived on 2.6 fb^{-1} of lepton+jets data, possible differences need to be well studied:
  - dependency on number of primary vertices
  - "aging" response (0.7% uncertainty)
  - ICD corrections
- currently estimating new systematic uncertainties
- statistical uncertainty: 2.4 GeV

Ideogram Method (Lepton+Jets)

- ideogram method offers both the **fast turn**-around of a template based method and an **event-by-event evaluation** which allows better measured events to contribute more
- **simultaneously** to the mass an additional jet energy scale factor **JES** is measured using the hadronic W decay



- analysis based on **signal** and **background** probabilities:

$f^{ntag}_{correct}$: rel. prob. to look at the right comb.

BW: Breit Wigner to account for top width

$$P_{\rm sig}\left(x_{i=1,24}^{\rm fit};\, m_t\right) \equiv \sum_{i=1}^{24} w_i \left[f_{\rm correct}^{\rm ntag} \cdot \int_{m_{\rm min}}^{m_{\rm max}} {\rm G}(m_i, m', \sigma_i) \cdot {\rm BW}(m', m_t) dm' + (1 - f_{\rm correct}^{\rm ntag}) \cdot S_{\rm wrong}^{\rm ntag}(m_i, m_t) \right]$$

wi: chi² weight of cur. combi &b-tagging

$$w_i = \exp(-\frac{1}{2}\chi_i^2) \cdot w_{{\rm btag},i}$$

G: Gaussian to account for experimental resolution of top mass

S^{ntag}_{wrong}: top quark mass distribution for wrong combination

$$P_{\rm bg}\left(x_{i=1,24}^{\rm fit}\right) \equiv \sum_{i=1}^{24} w_i \cdot BG(m_i)$$

Performance of Ideogram Method

- up to now, method only applied once to 0.4 fb^{-1} (new result hopefully soon):

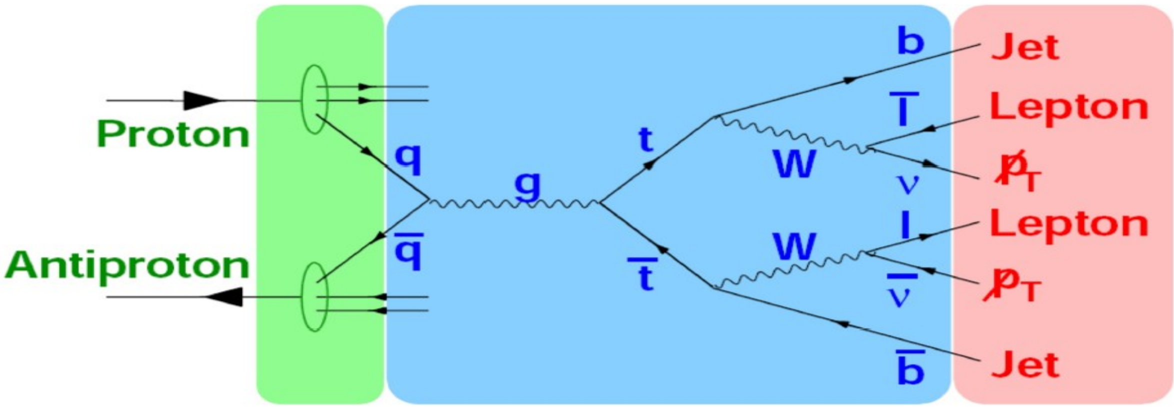
$$m_{top} = 173.7 \pm 4.4\ (stat) \pm 2.1\ (syst)\ GeV\ \ (L=0.4\ fb^{-}, lepton+jets)$$

- would expect an uncertainty of 1.2 GeV using 5.4 fb^{-1} of lepton+jets and achieving no improvements
- some technical improvements still possible
- advantages
  - very fast turn-around
  - event-by-event: the more signal-like an event is the more it will contribute

The Matrix Element Method

- matrix element method is based on full LO calculation of top pair production and includes detector effects
- for each event, the probability to be produced under the assumption of a certain top mass via signal process is given by

$$P_{sgn}(x, m_{top}) = \frac{1}{\sigma^{obs}_{ttbar}} \int_{q1q2y} \sum_{flavor} \boxed{dq_1 dq_2 f_{PDF}(q_1) f_{PDF}(q_2)} \boxed{\frac{(2\pi)^4 |M_{ttbar}(y)|^2}{q_1 q_2 s}} \boxed{d\phi_6 w(x, y)}$$



parton distribution functions $f_{PDF}(q)$

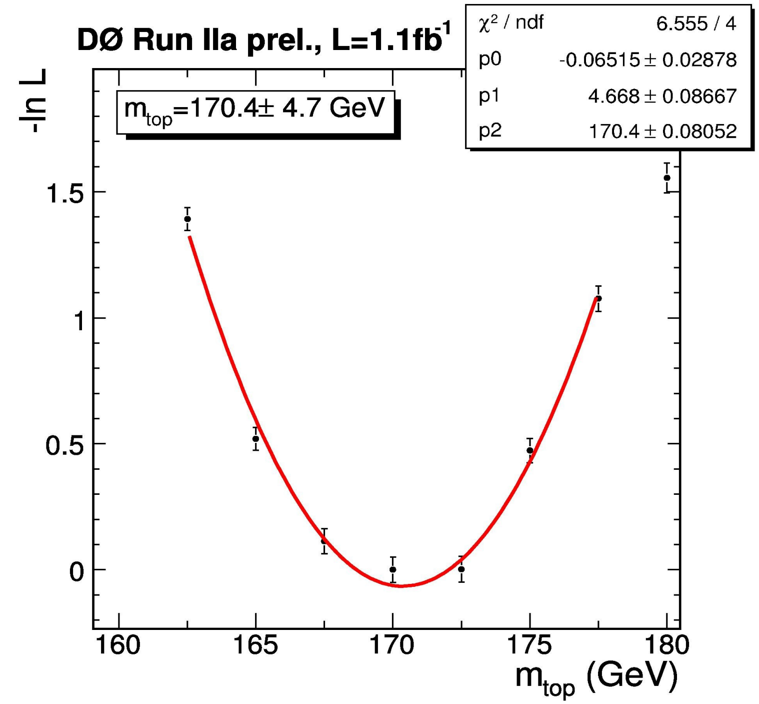
leading order matrix element $|M_{ttbar}(y)|^2$

transfer functions W(x,y): mapping from parton y to measured object x

The Matrix Element Method (Dilepton)

- calculate main background probabilities (Z+jj) in a similar way
- build event probabilities by adding up the normalized signal and background probabilities

$$P_{evt}(x, m_{top}) = f_{sgn} P_{sgn}(x, m_{top}) + (1 - f_{sgn}) P_{bkg}(x)$$



- determine the top quark mass from a likelihood fit to the event probabilities

m_{top} = 174.0 ± 1.8 (stat) ± 2.4 (syst) GeV (L=5.4 fb^{-1}, dilepton)

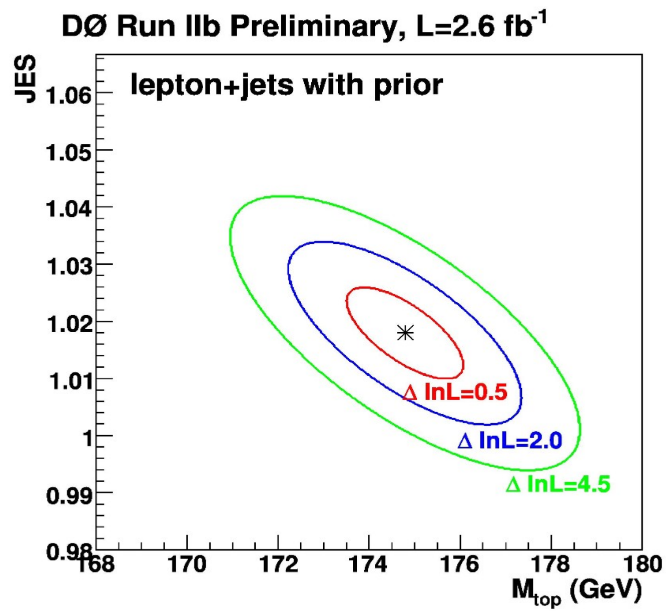
- main systematic uncertainty due to jet uncertainties: 2.2 GeV
- paper submitted to PRL

MEM in Lepton+Jets

- as in the case of the Ideogram method, both the top mass and an overall JES are simultaneously measured in the lepton+jets channel
- to do so the **matrix element** from the previous page is **extended** by a second free parameter **JES**

$$P_{sig}(x, m_{top}) \rightarrow P_{sig}(x, m_{top}, JES)$$

- for both QCD and W+jets the W+4jets ME is included as background ME
- a 2-dim fit is performed and the mass is measured to be



m_{top} = 174.9 ± 0.8 (stat) ± 1.2 (syst+JES) GeV (L=3.6 fb^{-1}, lepton+jets)

- paper in sign-off

Sample Dependent JES

- data and MC show **different responses** for b and light quark jets as well as quark and gluon jets
- need to account for possible differences by systematic uncertainties or correct for the differences
- use particle-jets matched to reco-level jets to estimate the **correction factor**

$$F^{corr} = \frac{\sum_i E_i^{truth}(\text{particle}) \cdot R_i^{data}}{\sum_i E_i^{truth}(\text{particle}) \cdot R_i^{MC}}$$

where the index i runs over all particles in the jets, R is the single particle response in data and MC (as a function of particle type, particle energy and eta)

- when applying sample dependent JES:
  - top mass increases by **1.26 GeV**
  - uncertainty on the data/MC corrections need to be propagated to the mass: **0.28 GeV**

Systematic Uncertainties (Lepton+Jets)

signal modeling: 0.85 GeV

remaining jet uncertainties: 0.54 GeV (previously 1.0 GeV)

Source	Uncertainty (GeV)
Physics modeling:	
Signal modeling:	
higher order effects	± 0.25
ISR/FSR	± 0.26
hadronization and UE	± 0.58
color reconnection	± 0.50
multiple hadron interactions	± 0.07
Background modeling	± 0.03
W+jets heavy flavor scale factor	± 0.07
b-modeling	± 0.09
PDF uncertainty	± 0.24
Detector Modeling:	
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 ID efficiency	± 0.26
Jet energy resolution	± 0.32
Method:	
Multijet contamination	± 0.14
Signal fraction	± 0.10
MC calibration	± 0.20
Total	± 1.02

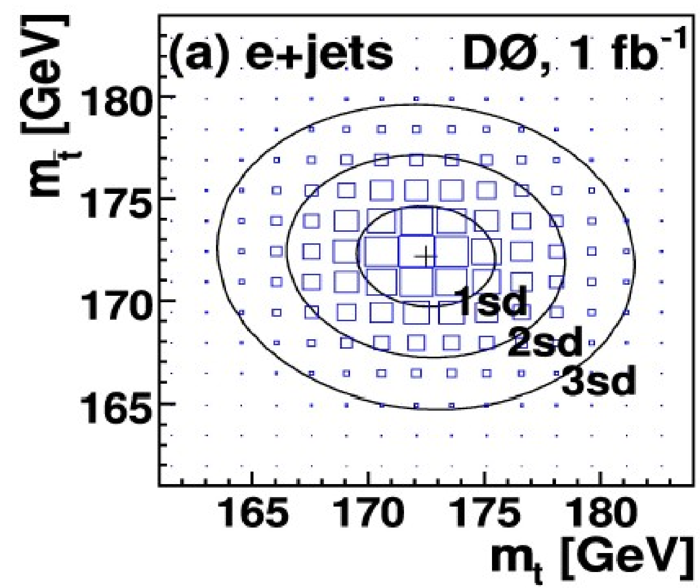
Top Quark Mass Difference (Lepton+Jets)

- all mass measurements assume top and anti-top quark to have the same mass
- any difference would imply CPT violation
- Matrix Element approach can be used with

$$P_{sig}(x, m_{top}, JES) \rightarrow P_{sig}(x, m_{top}, m_{topbar})$$

- first measurement of bare quark anti-quark mass difference

$$\boxed{m_{top} - m_{topbar} = 3.8 \pm 3.7 \text{ (stat+syst) GeV}}$$



- measurement in good agreement with SM expectation
- published in PRL 103/132001 (2009), featured in Nature Vol. 461 October 2009

Top Quark Mass Difference

- mass difference was updated this summer and currently in sign-off

$$m_{top} - m_{topbar} = 0.8 \pm 1.8\ (\mathrm{stat}) \pm 0.5\ (\mathrm{syst})\ \mathrm{GeV}$$

- analysis method basically unchanged compared to first result
- systematic effects that are not expected to effect top and anti-top in a different way are only evaluated as cross-check
- measurement still dominated by statistics

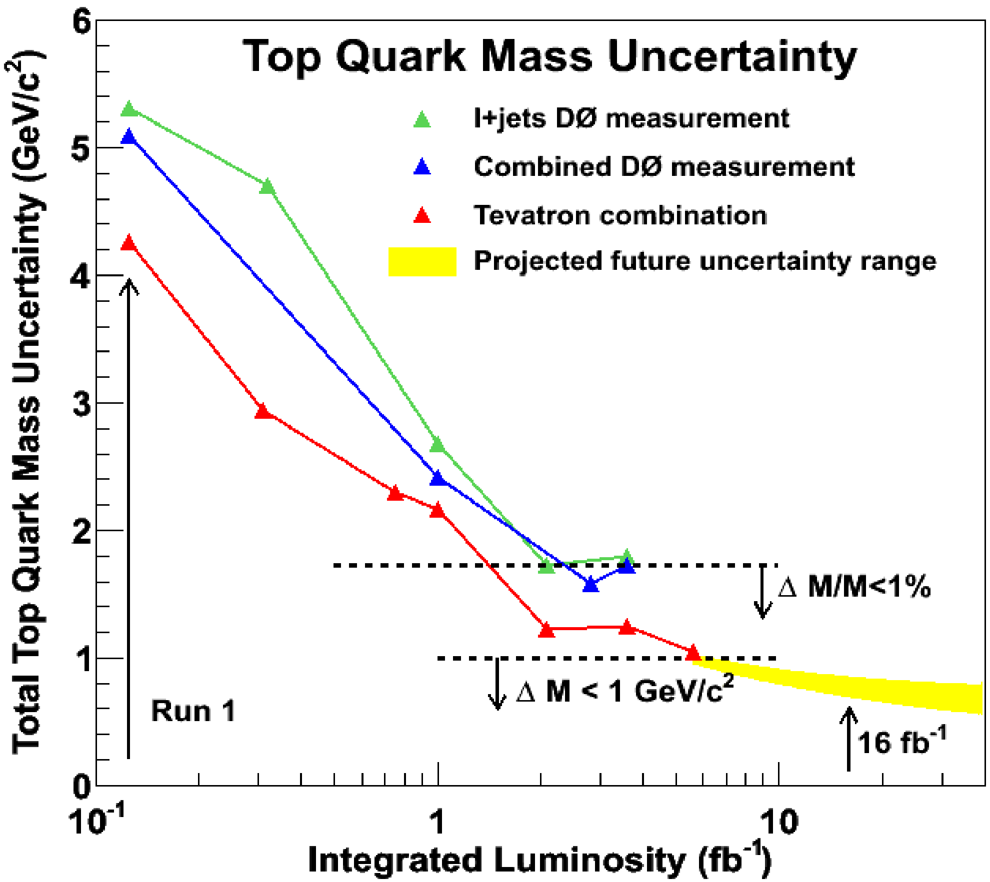
Source	Uncertainty on Δm (GeV)
Modeling of detector:	
Jet energy scale	0.15
Remaining jet energy scale	0.05
Response to b and light quarks	0.09
Response to b and $\bar{b}$ quarks	0.23
Response to c and $\bar{c}$ quarks	0.11
Jet identification efficiency	0.03
Jet energy resolution	0.30
Determination of lepton charge	0.01
ME method:	
Signal fraction	0.04
Background from multijet events	0.04
Calibration of the ME method	0.18
Total	0.47

Update of the Dilepton ME Mass

- as spin-off from dilepton ME mass, studied the impact of stop events
  - best case:
    1.5 GeV increased offset for high stop and low sneutrino masses
  - with the current precision of 1.8 GeV (stat) not possible
- plan to update the measurement with 8.4 fb^{-1} of dilepton events
  - for the first time use of b-tagging for ee and mumu (especially important for mumu with ~50% background)
  - will apply sample dependent jet correction from Zhenyu and in-situ JES to reduce the main systematic uncertainties
  - improved integration method
    - 30% faster than previously
    - parton-level tests show good agreement between old and new integration scheme
  - started integration for default sample

Outlook

- top mass measurements are one of the legacy measurements of Tevatron
- sample dependent JES and in-situ JES will help to reduce main jet systematics in dilepton
- group wide effort to identify possible systematic improvements
- all method well established and tested
- expect soon first results from lepton+jets Ideogram and a first all-jets result



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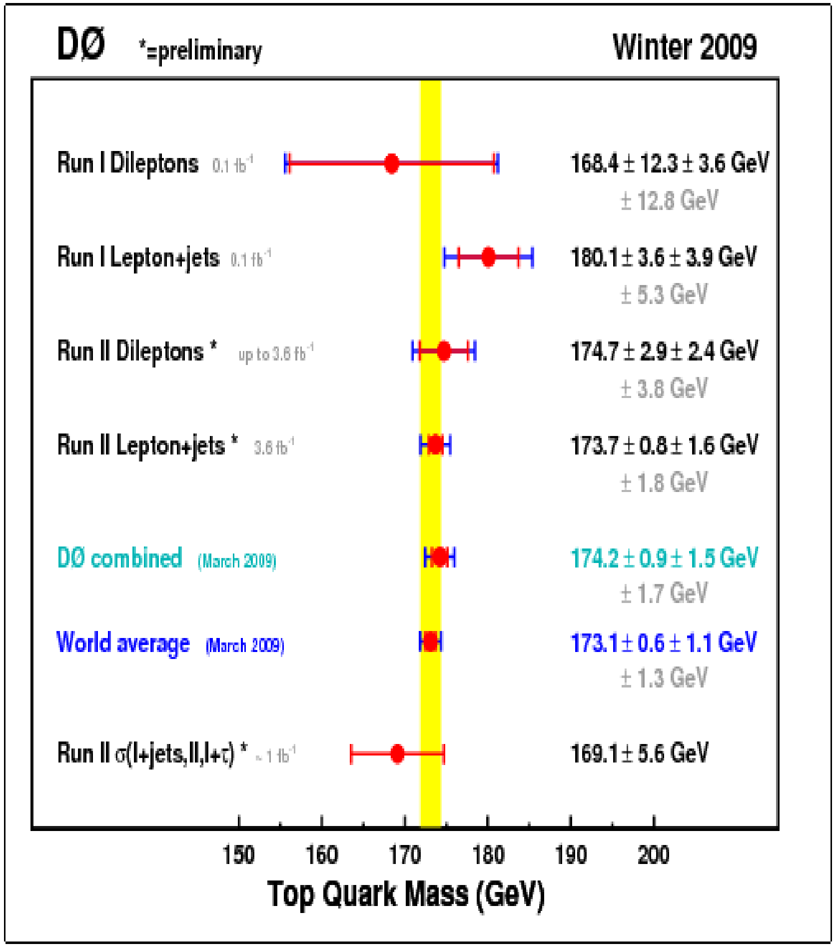
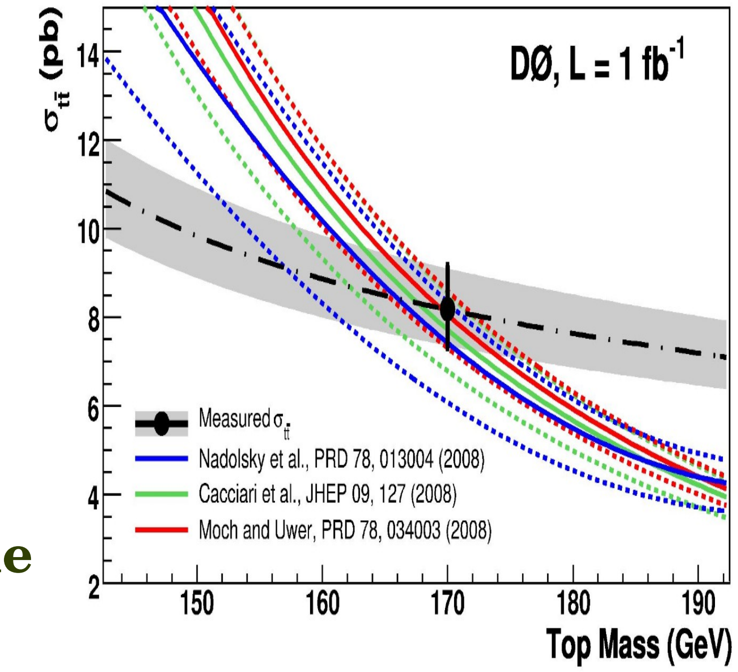
Top Quark Mass Summary

- all **direct** top quark mass **measurements** are in **excellent agreement** with each other
- top mass limited by **systematic** uncertainties on **jets** and **signal** modeling
- extraction of mass **from production cross section** yields a consistent result
- measurement of top quark **mass difference** still limited by statistics:
  no deviation from SM observed so far



Top Quark Mass From Cross Section

- definition of top quark mass convention-dependent
- implementation in Monte Carlo only close to pole mass
- extraction of top quark mass from top pair production cross section allows for an unambiguous interpretation in the pole mass scheme



- comparison of the measured cross section to the theoretical NNLO$_{approx}$ prediction yields:

$$m_{top}^{pole} = 169.1 + 5.9 - 5.2 \text{ (stat+syst) GeV}$$

- result consistent with all direct measurements