Top quark mass: Latest CDF results, Tevatron combination and electroweak implications

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on behalf of the CDF Collaboration

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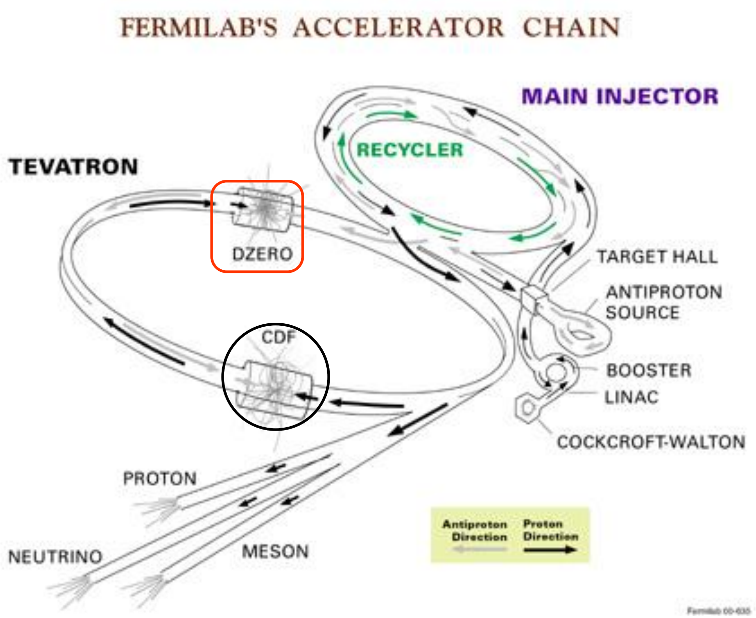
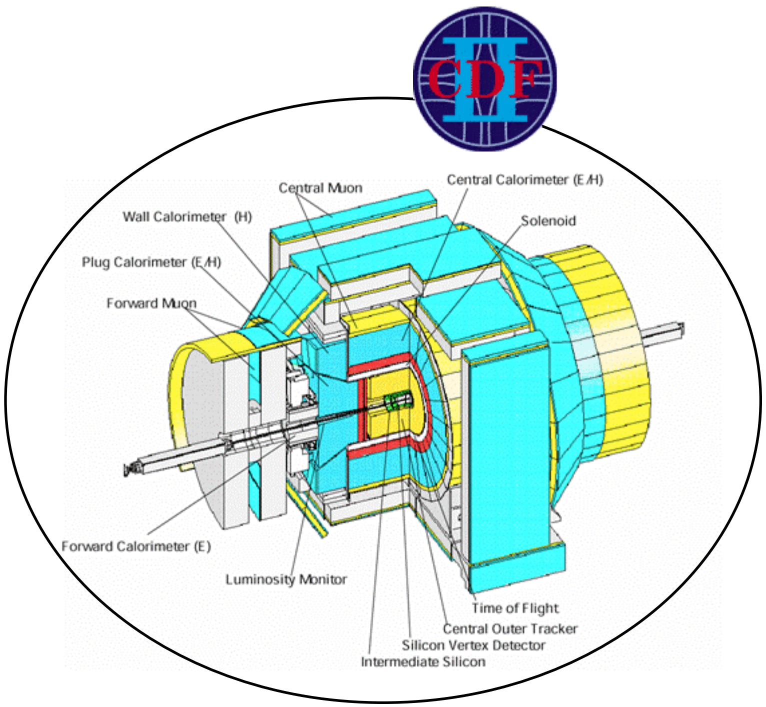
Experimental Environment: Fermilab Tevatron



- ❑ So far the only place where top has been produced
- ❑ ppbar collisions at 1.96 TeV (since 2001)
- ❑ About 6 fb^{-1} delivered, about 5 fb^{-1} on tape for both experiments



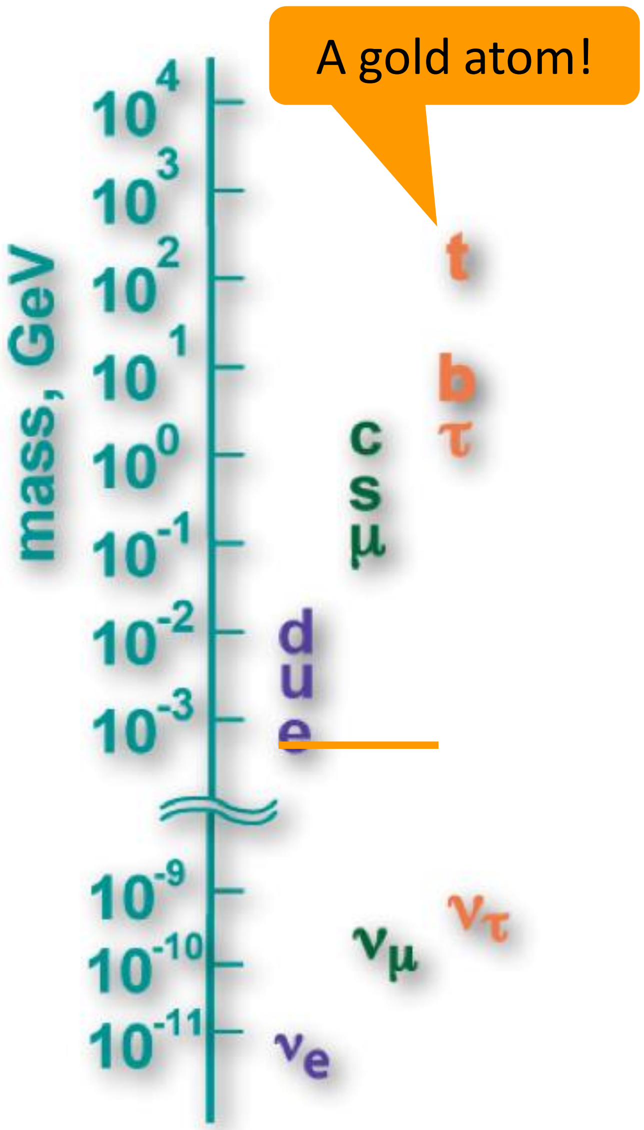
❑ *Two multi-purpose detectors*

→ Accurate tracking system with Si

→ Calorimeters to measure e, γ, jet energy

→ Muon detection system

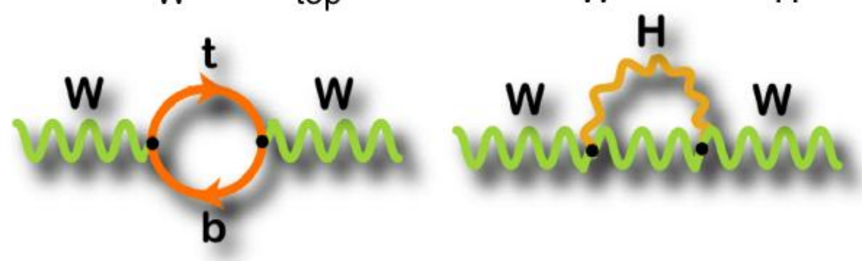
The top quark



Last discovered quark!

- **Top mass is a fundamental parameter in the SM → must be measured accurately**
  - **Yukawa coupling ~1: hint of special role of the top quark?**
  - **M_{top} enters in radiative corrections allowing constraint on Higgs mass**

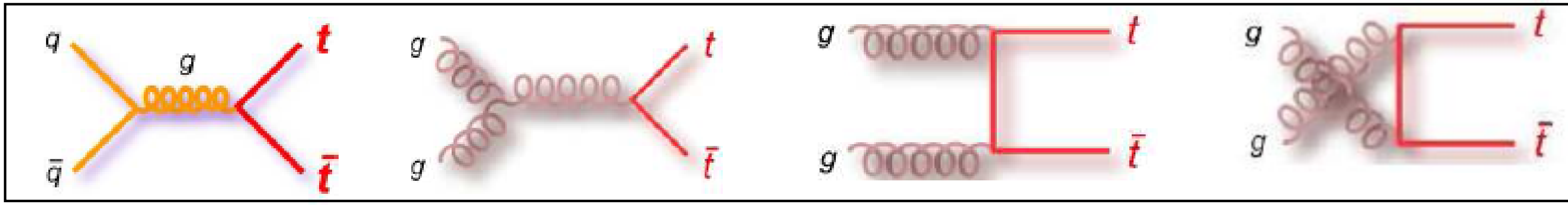
$\Delta M_W \propto M_{top}^2$ $\Delta M_W \propto \ln M_H$



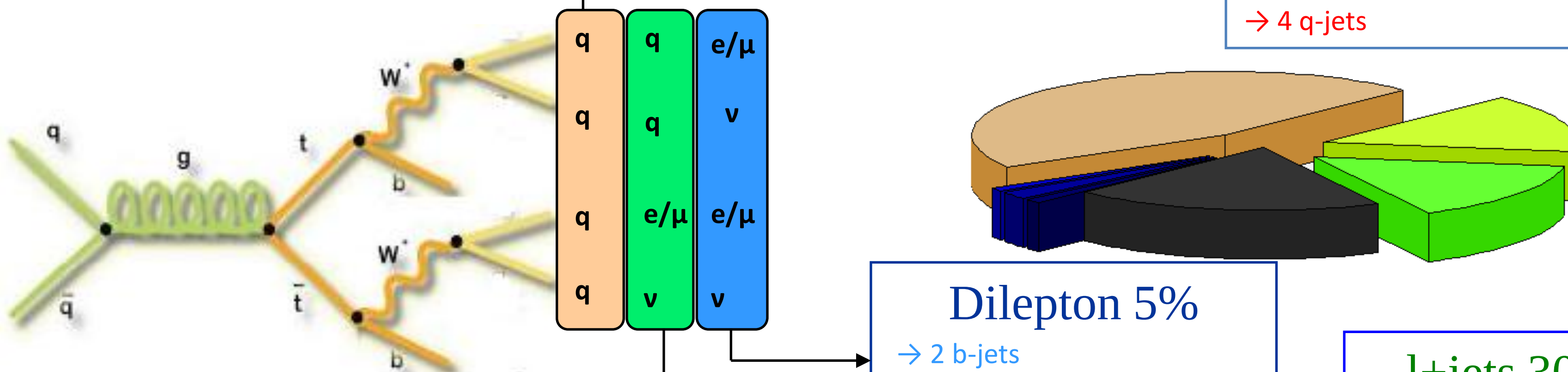
- **Top cross section at 1.96 TeV is O(pb) → tens of thousands produced so far!**
  - **Tevatron is a (small) top factory**

Top Production and Signature

Produced in pairs mainly via strong interactions → ~7 pb



Decaying in Wb ~100 % of the times → 3 possible signatures depending on W's products



all hadronic 65%
- → 2 b-jets
- → 4 q-jets

Dilepton 5%
- → 2 b-jets
- → 2 high P_T e/ μ
- → large missing transverse energy (MET)

l+jets 30%
- → 2 b-jets, 2 q-jets
- → high P_T e/ μ
- → large MET

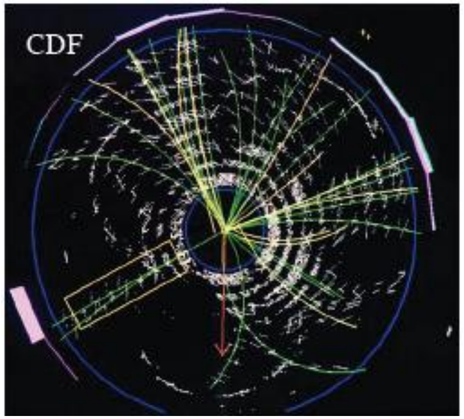
Top Mass Challenges

❖ A needle in the haystack: $\sigma_{tt}/\sigma_{inel} = 10^{-10}$

→ Dedicated top triggers

→ Sophisticated event selections

l+jets event



❖ Neutrino(s) escape the detector

→ Indirect measurement of ν energy: MET

→ Hypotheses needed to constrain the kinematics (dilepton channel)

❖ Jets of particles instead of quarks are measured

→ Several jet-to-partons ("j2p") possible assignments

→ Procedure to report jet energy back to partons: "Jet energy scale" (JES)

→ Not all jets originate from top/W : gluon radiation

Jets in top mass analyses

- JES corrections account for:

→ Detector effects (non-linearity, non-compensation, multiple ppbar interactions, ...)

→ Physics effects (underlying event, energy out of the jet cone)

- JES calibration "in situ":

→ Invariant mass of dijets from W needs to match W mass

→ Possible in l+jets and all-hadronic channels

→ Calibration returns a JES shift "Δ_{JES}"

Tevatron Combined M_{top} Errors	
Source	Error (GeV)
iJES	0.48
aJES	0.33
bJES	0.23
cJES	0.19
dJES	0.30
rJES	0.13
lepPt	0.11
Signal	0.30
MC	0.49
UN/MI	0.03
BG	0.26
Fit	0.16
CR	0.41
MHI	0.07
Syst.	1.07
Stat.	0.65
Total	1.25

0.73 GeV

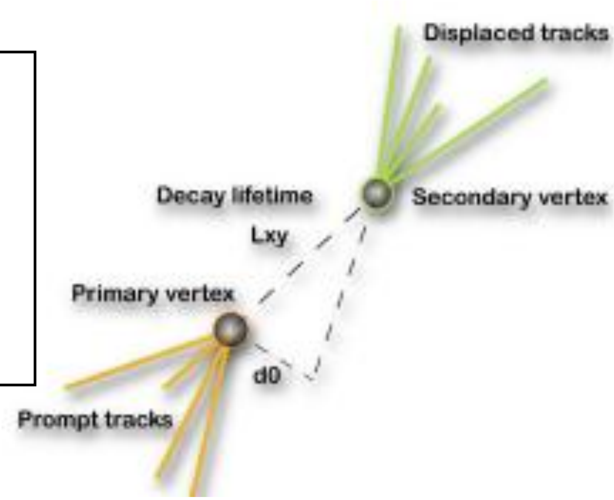
0.78 GeV

- Flavour tagging

→ Vertex displacement hints to long-lifetime hadrons from b's ("b-tagging")

→ Decreases j2p possible assignments

→ Increases signal to background ratio



Top mass analysis techniques

Matrix Element (ME) method: uses an event-by-event probability

$$P_{ev}(\vec{x} \mid m_t, \Delta_{JES}) = N \sum_{j2p} \int d\Phi_6 \frac{|M(q\bar{q} \to \ldots \to \vec{y})|^2}{FF} dz_1 dz_2 f_{PDF}(z_1) f_{PDF}(z_2) \, TF(\vec{x} \mid \vec{y}, \Delta_{JES})$$

$\vec{x}$: Event observables $(P_\mu^{lep}, P_\mu^{jet})$

N : normalization factor

M : ME for signal or bg process

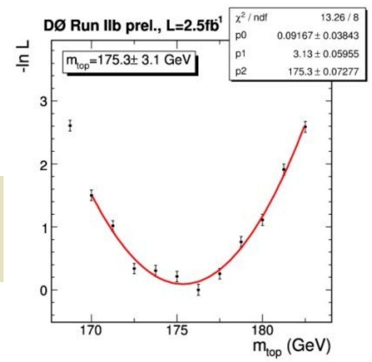
$\vec{y}$ = parton momenta

FF = flux factor

PDF for incoming partons

Jet calorimeter response given a parton momentum $\vec{y}$

$$L = \prod_{events} P_{ev}$$

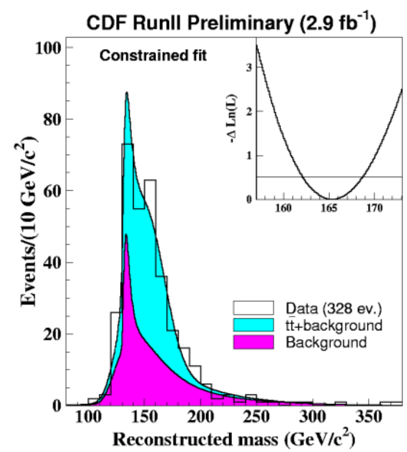


Template Method (TM):

1) Choose a m_t estimator (typically event-by-event reconstructed m_t)

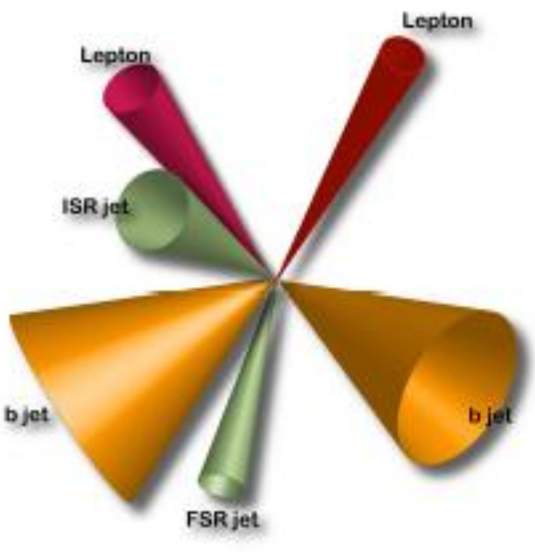
2) Build distributions ("templates") of simulated events

3) Fit the data to a combination of a mass-dependent signal template and of a background template



Dilepton channel

High S:B (2:1) , low statistics



Event selection algorithm

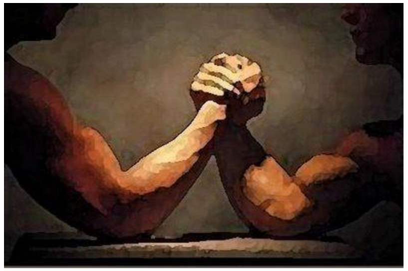
- ✓ Two leptons (P_T >2 GeV)
- ✓ Large MET (>25 GeV)
- ✓ At least two jets (E_T >20 GeV)
- ✓ Other topological cuts to reject background

Main backgrounds

- ✓ W+jets (fake lepton), Drell-Yan, dibosons

Main Challenge

No "in situ" JES calibration possible



Mass measurements in the dilepton channel

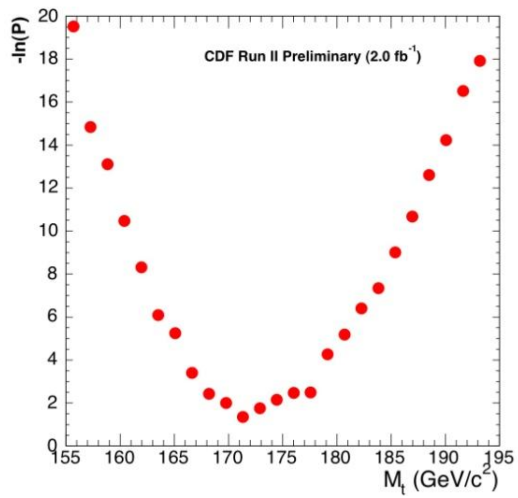
dilepton Tevatron best

ME - ∫Ldt = 2.9/fb

PRL 102 152001

- Evolutionary NN for event selection
  - Optimized on mass resolution
  - 20% improvement despite of lower S:B

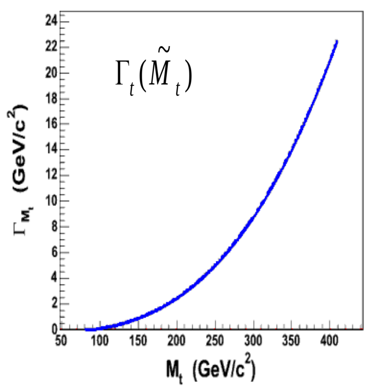
$$M_{top} = 171.2 \pm 2.7\,(stat.) \pm 2.9\,(syst.)\ \text{GeV}$$
$$(\delta M_{top} / M_{top} = 2.3\%)$$



Neutrino ϕ Weighting (TM , lepton+isolated track) - ∫Ldt = 2.8/fb

PRL 96 152002

PRD 73 112006



- Integrate over neutrino ϕ's to constrain kinematics
- Reconstruct an event-by-event m_t via χ^2 minimization

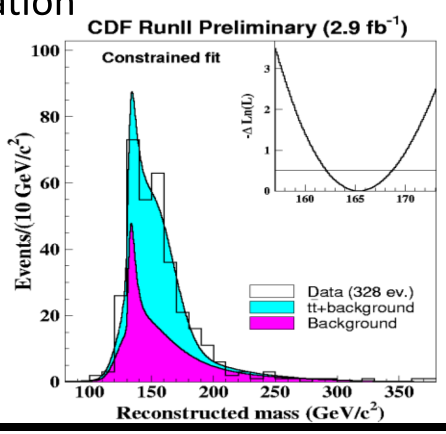
→ *use of a) Breit-Wigner distributions instead of Gaussians*

b) and $\Gamma_t = \Gamma_t(m_t)$ as in the SM

leads to 20% improvement

- Build templates and fit to data

$$M_{top} = 165.1 \pm^{3.3}_{3.2}\,(stat.) \pm 3.1\,(syst.)\ \text{GeV}$$
$$(\delta M_{top} / M_{top} = 2.8\%)$$



Lepton+jets channel

Reasonable S:B (1:2), high statistics: the golden channel!

Top quark discovery in 1995

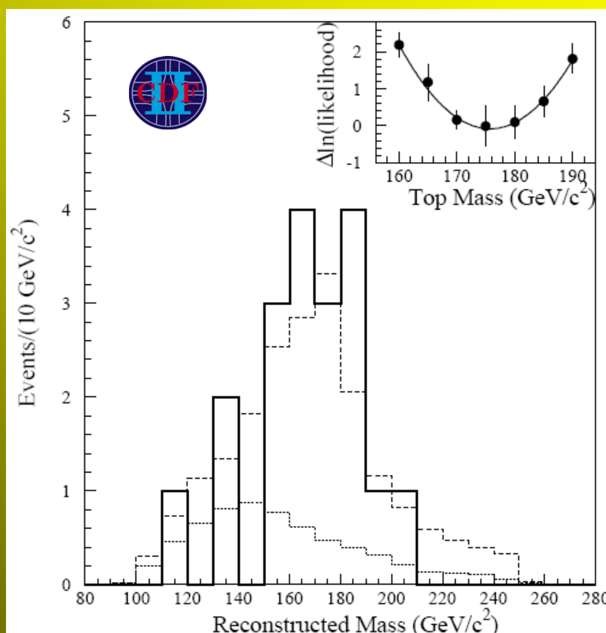


Figure 3: Reconstructed mass distribution for the b-tagged W + ≥ 4-jet events (solid). Also shown are the background shape (dotted) and the sum of background plus $t\bar{t}$ Monte Carlo for M_{top} = 175 GeV/c^2 (dashed), with the background constrained to the calculated value, $6.9^{+2.5}_{-1.9}$ events. The inset shows the likelihood fit used to determine the top mass.

Event selection algorithm

- ✓ 1 lepton (P_T > 20 GeV)
- ✓ Large MET (> 20 GeV)
- ✓ At least 4 jets (>20 GeV)
- ✓ 1 b-tag → S:B = 4:1

Main backgrounds

W+HF (HF=b,c), W+jets (fake b-tag), QCD multi-jets (fake lepton)

Problem

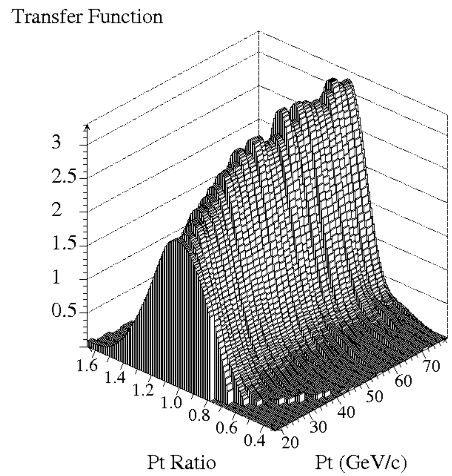
j2p possible assignments: 12 (0 b-tags), 6 (1 b-tag)

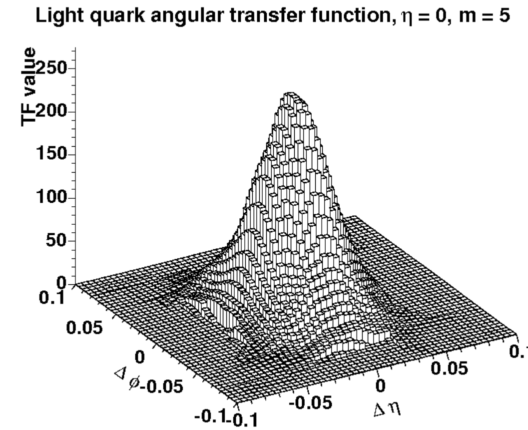
Mass measurements in the lepton+jets channel

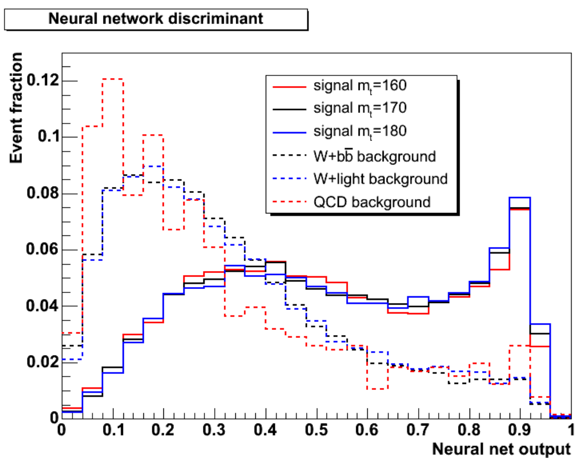
Tevatron best

ME, ∫Ldt = 3.2/fb

- Parametrizations of angular and energetic calorimeter response





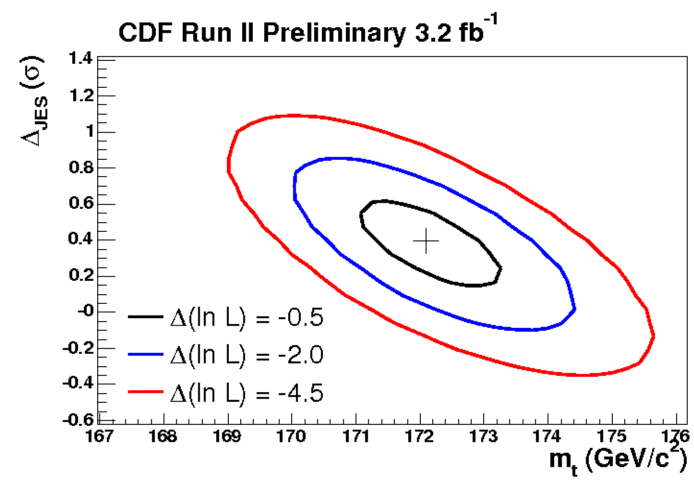


- NN for a better signal from background separation

→ Returns the per-event expected background fraction f_{bg}

→ Different f_{bg} evaluated for "bad signal" (ttbar with gluon jets, dilepton, etc.) and non-ttbar background

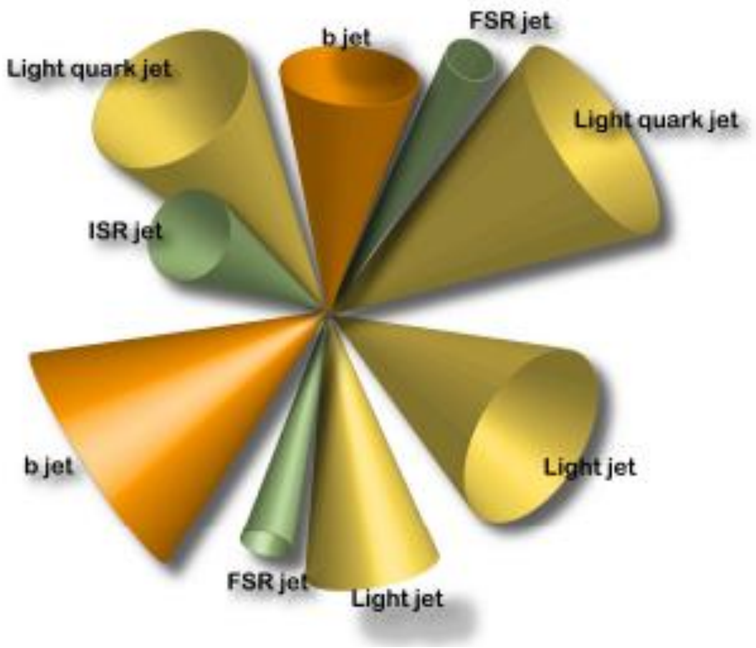
- Weight j2p assignments with b-tag probability
- JES calibrated "in situ"
- Mass estimated from likelihood profile along m_t and Δ_{JES} axes



$$M_{top} = 172.1 \pm 1.1(stat.+JES) \pm 1.1\ (syst.)\ \text{GeV}$$
$$(\delta M_{top} / M_{top} = 0.9\%)$$

All-hadronic channel

Very tiny S:B (1:400), high statistics



Event selection algorithm

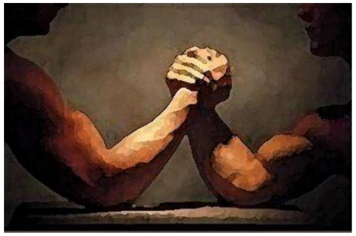
- ✓ 6 to 8 central jets (P_T >15 GeV)
- ✓ At least 1 b-tag

Main background

- ✓ QCD multi-jets

Main Challenges

- ✓ Huge background
- ✓ Many j2p assignments



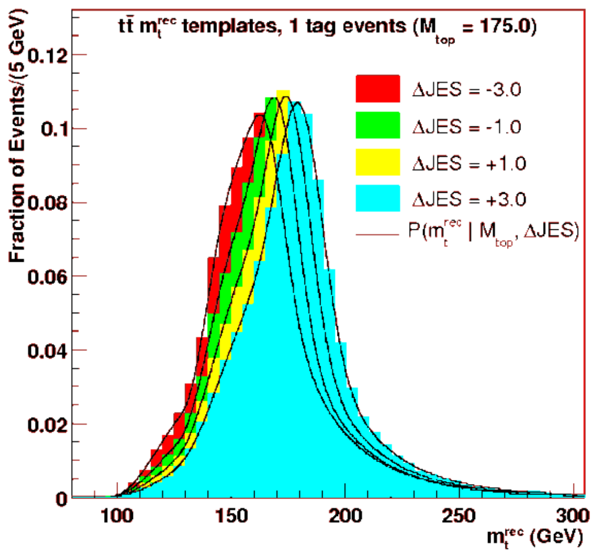
Mass measurements in the all-hadronic channel

All-jets best

TM, ∫Ldt =2.9/fb

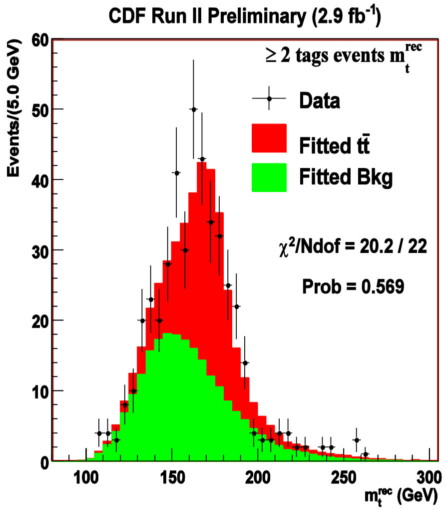
- NN employed to select events

→ Jet-shape variables recently added to distinguish between gluon jets (background) and light-quark jets (signal)
→ Increases S:B up to 1:4 (1:1 if 2-tags)
→ NN different threshold for 1-tag and 2-tag sample



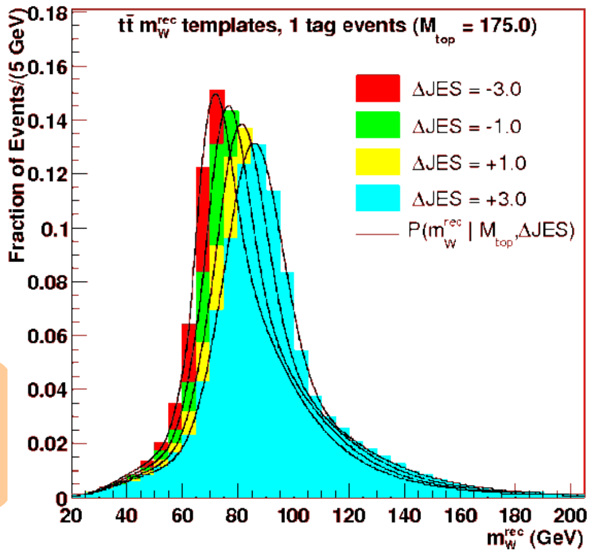
- Event-by-event we reconstruct (via χ2 minimization)

→ Top mass (m_t)
→ W mass → allows a m_t-independent JES calibration



- Fit templates to data:

$$M_{top} = 174.8 \pm 2.4(stat. + JES) \pm^{1.2}_{1.0} (syst.) \text{ GeV}$$
$$(\delta M_{top} / M_{top} = 1.5\%)$$



Mass measurements with minimal dependence on JES

- **Leptons are independent of JES**

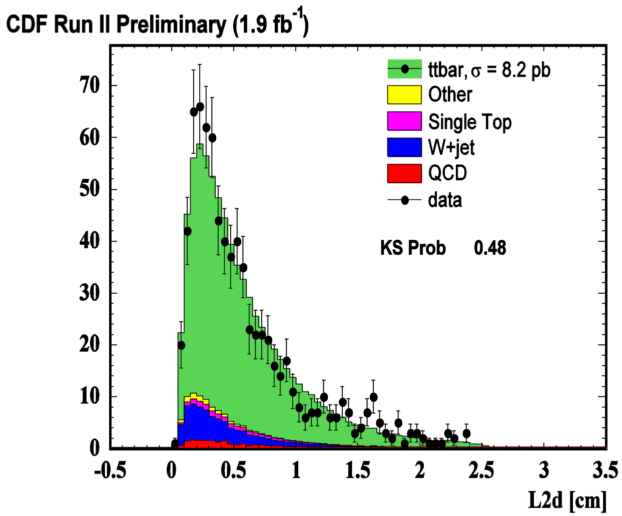
→ Select a lepton kinematic variable (P_T) and use MC to determine the relation of its distribution with M_{top}

→ Fit the MC signal & background lepton P_T distributions to the data to measure M_{top}

- **The SecVtx transverse decay length L2d (or L_{xy}) of b-tagged jets is minimally dependent on bJES**

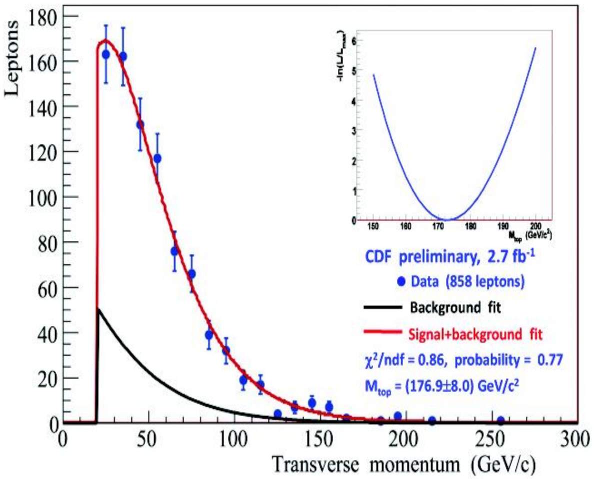
→ Use MC to determine the relation of ⟨L2d⟩ with M_{top}

→ Solve the MC-established relation of the measured ⟨L2d⟩ with M_{top} to measure M_{top}

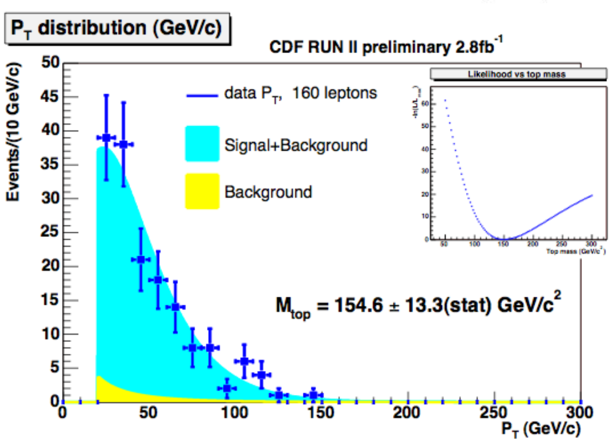


$$M_{top} = 175.3 \pm 6.2(stat.) \pm 3.0(syst.)\ \text{GeV}$$

$\int Ldt = 1.9/fb$ $\quad (\delta M_{top} / M_{top} = 3.9\%)$



Two TM-like, track-based, fast and accurate methods for LHC, where statistics will not limit the precision

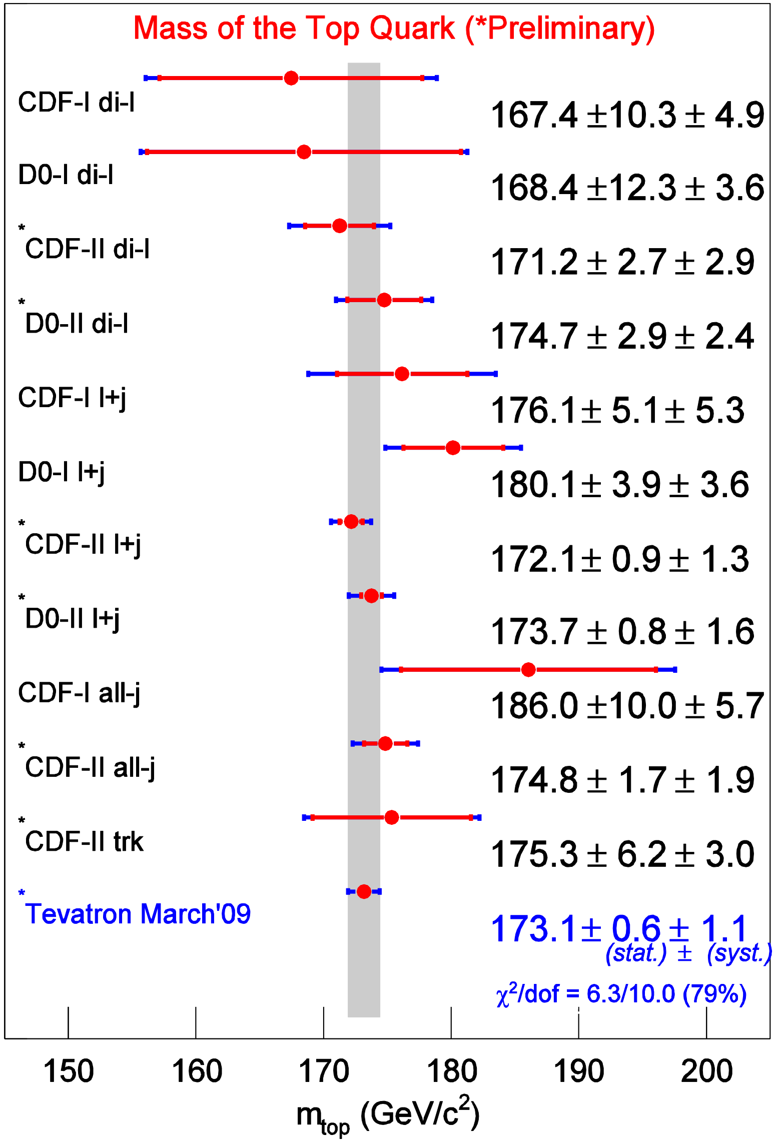


$$M_{top} = 176.9 \pm 8.0(stat.) \pm 2.7(syst.)\ \text{GeV} \quad (l + \text{jets})$$

$$M_{top} = 154.6 \pm 13.3(stat.) \pm 2.3(syst.)\ \text{GeV} \quad (\text{dil})$$

$\int Ldt = 2.8/fb$ $\quad (\delta M_{top} / M_{top} = 4.4\%)$

Combination of most accurate analyses

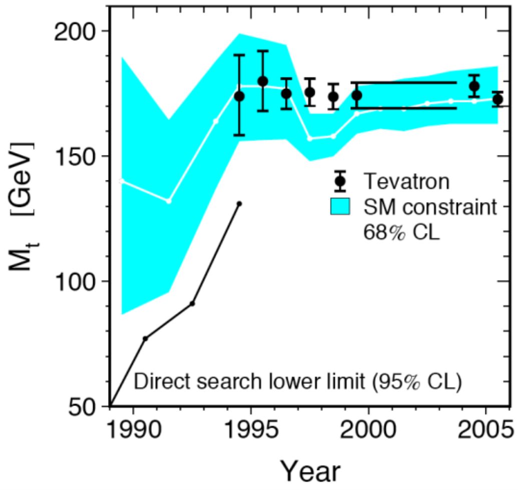


Tevatron world average (March '09)

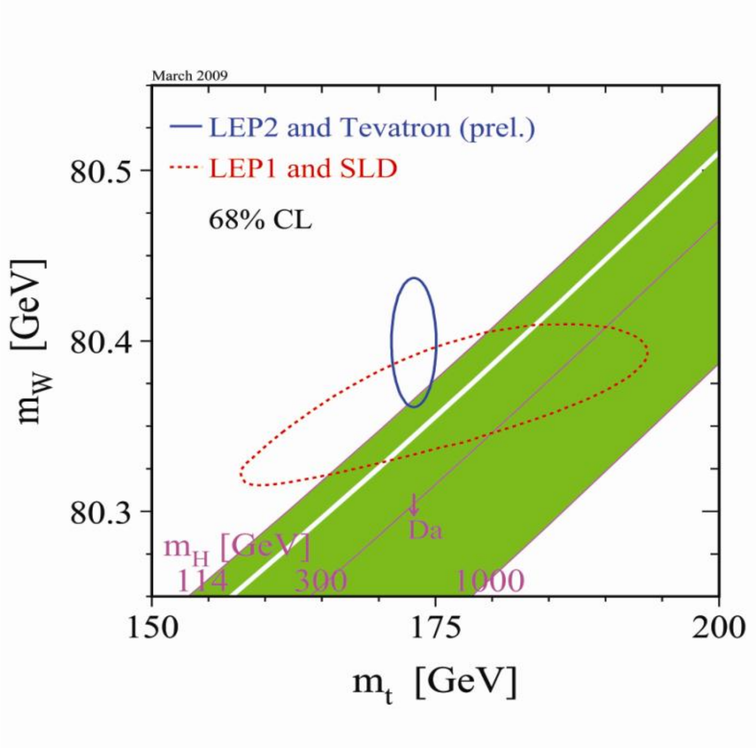
$$M_{top} = 173.1 \pm 0.6\,(stat.) \pm 1.1\,(syst.)\ GeV$$

$$(\delta M_{top} / M_{top} = 0.75\%)$$

How does it fit in the big picture (SM)



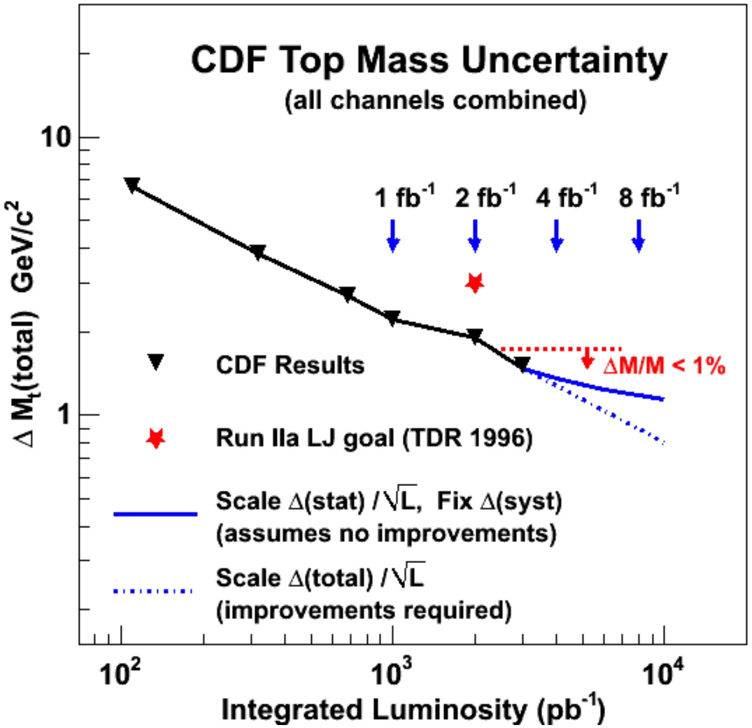
- EWK predictions were verified in the top quark mass - good agreement with SM
  - Will it happen for the Higgs (if it exists)?



- Running traditional EWK fits, updated using latest Tevatron W boson (2007) and top quark mass (2009)

Conclusions & plans for the future

Both CDF and DØ reached <1% precision in their combined measurements



- ❑ Already beyond Run II goal (δMtop ~3 GeV)

→ but still more data coming

- ❑ Precision now dominated by systematic uncertainties

→ In order to push it down we are planning to:

i. Understand better physics models
   - ISR/FSR with the increased Drell-Yan samples
   - Improved color reconnection models

ii. Disentagle correlations among different uncertainties, e.g. residual JES vs. MC generator

More info available at

➢ http://www-cdf.fnal.gov/physics/new/top/public_mass.html