Top Quark Mass Measurements

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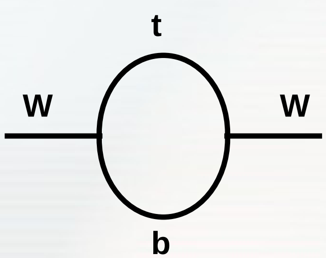
On Behalf of the CDF and D0 Collaborations

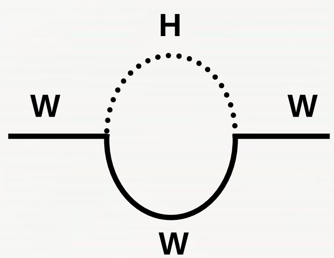
Why Measure the Top Quark Mass?

- "Because it's there"
  - George Leigh Mallory
    (when asked why climb Mt. Everest)

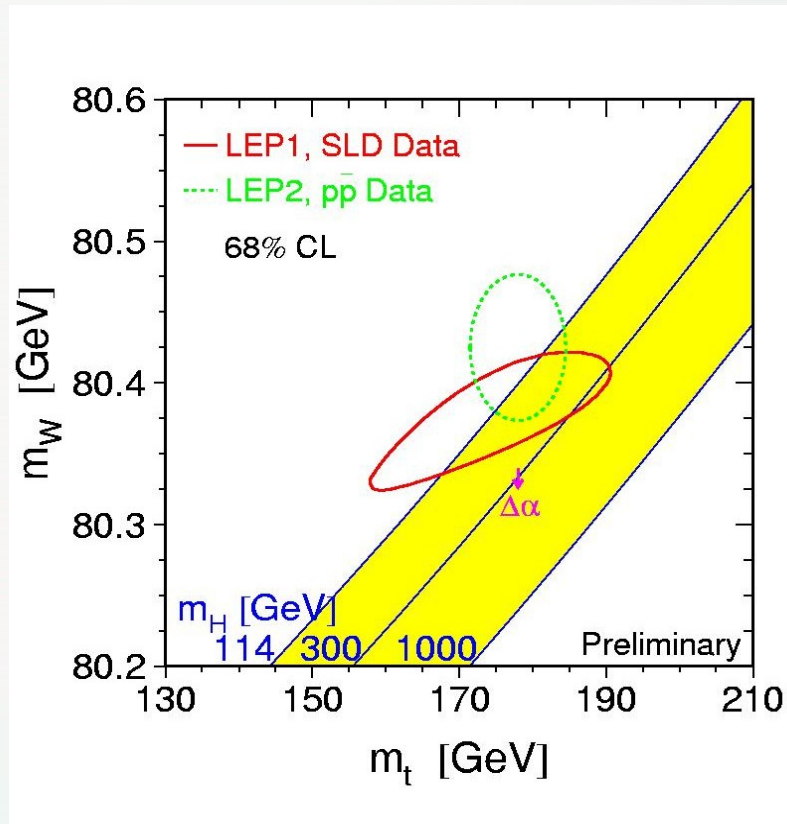
- m_{top} is a fundamental parameter of the Standard Model

- When combined with precision electroweak data, constrains the mass of the elusive Higgs Boson





$$\delta m_W^2 \propto m_t^2 \qquad \delta m_W^2 \propto \log m_H$$

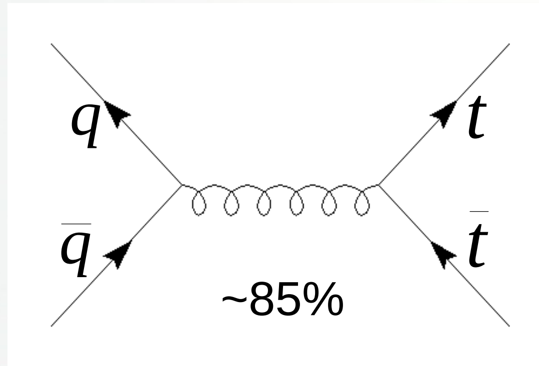


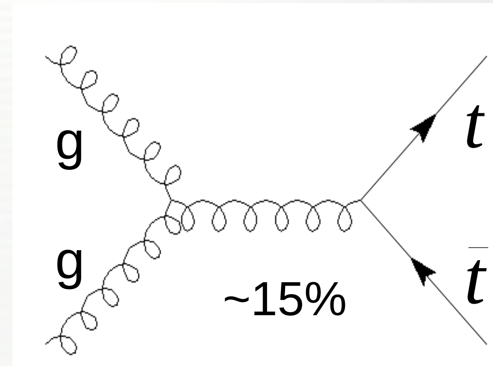
Top Production and Decay at Tevatron

- Pair Produced
  - q/anti-q annihilation
  - gluon fusion
  - At $\sqrt{s}$ = 1.96 TeV

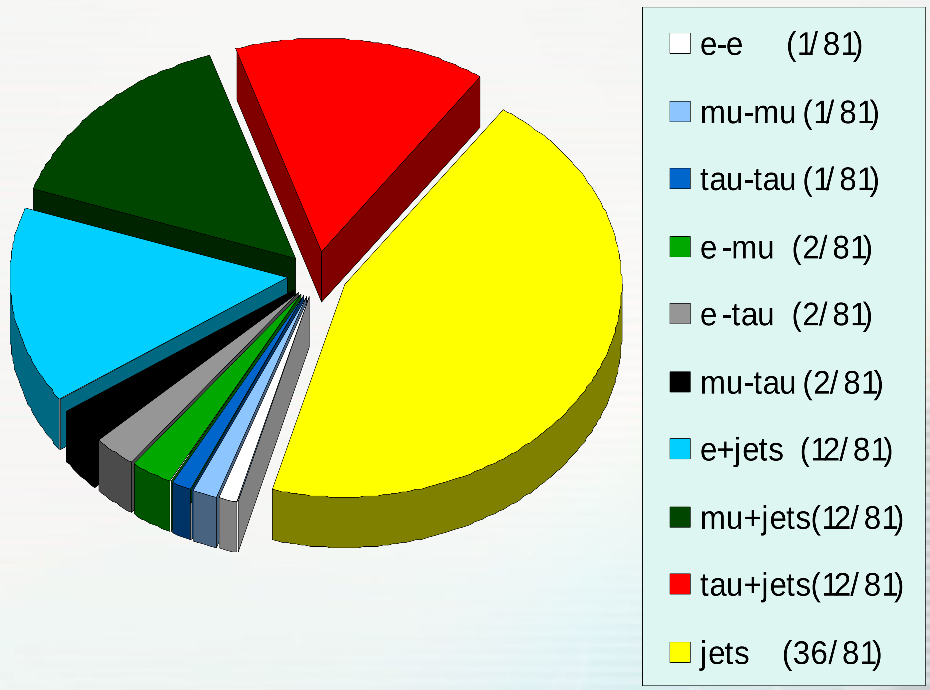
$$\sigma_{t\bar{t}} = 6.7^{+0.7}_{-0.9}\ \text{pb}$$

(for m_{top} = 175 GeV/c²)



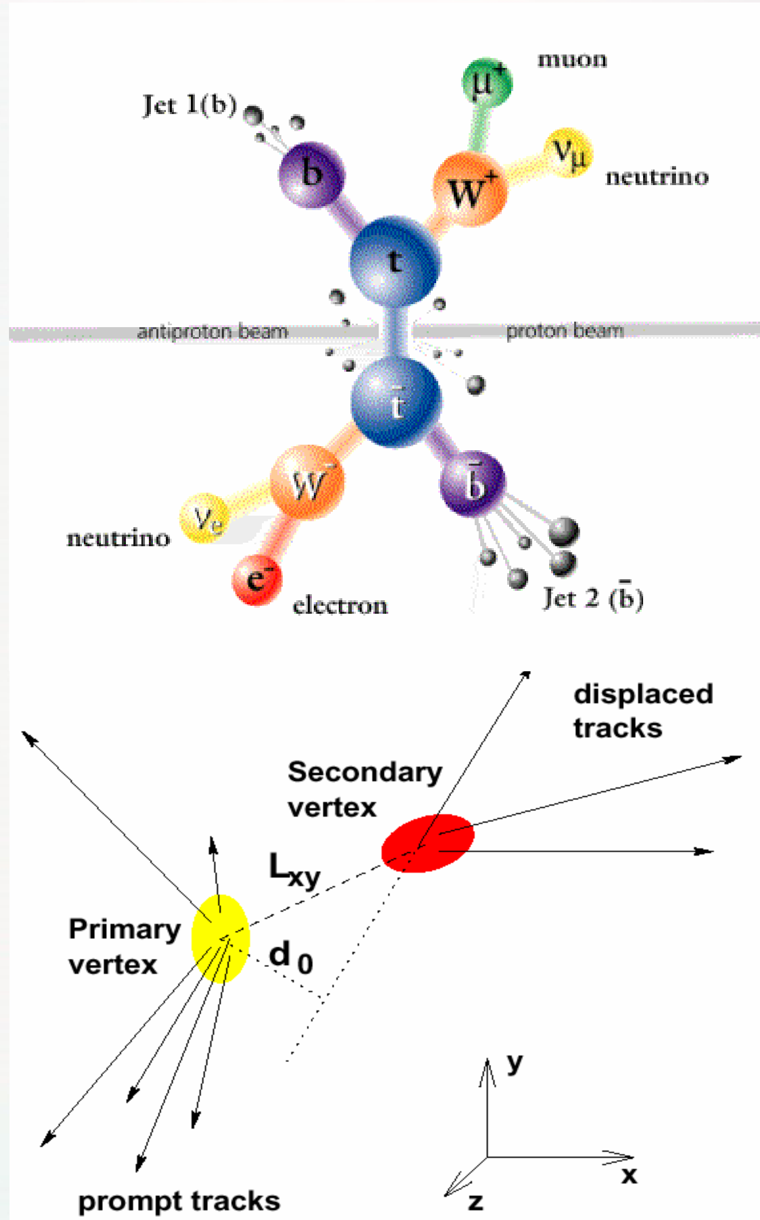


- Decays before hadronizing
  - •$t \to Wb$
- Events classified by W decay
  - "Lepton [e,μ] + jets" (30%)
    - •$tt \to bl\nu bqq'$
  - "Dilepton [e,μ] " (5%)
    - •$tt \to bl\nu bl\nu$
  - "All jets" (44%)
    - •$tt \to bqq'bqq'$
  - "Tau + X" (21%)



Experimental Signatures

- Spherical, central events
  - Decay within $|\eta| < 2.0$
- Two b quark jets with high E_T
  - Identified by displaced secondary vertex ("b-tag")
- Additional energetic light quark jets or leptons from W decay
  - Significant $\not{E}_T$ from undetected neutrino in leptonic modes
- Possible additional jets from initial or final state gluon radiation

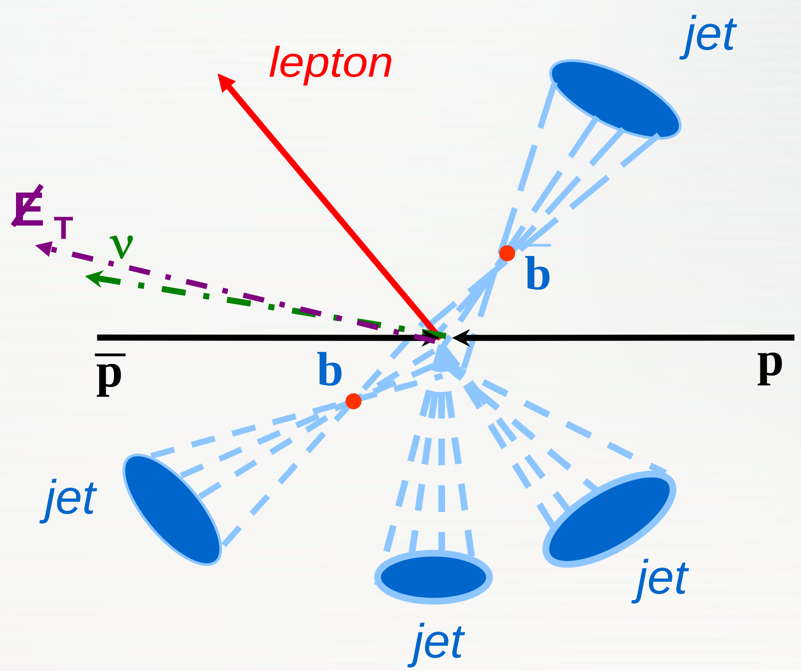


Experimental Challenges

- Mass reconstruction done at parton level but …
- We detect missing transverse energy not neutrinos
  - p_z^{ν} unknown
  - Ambiguity in m_{top}
- We measure jets not quarks
  - Measured energy has to be corrected back to parton-level
    - Limited jet energy resolution
    - Imperfect jet energy scale
  - Many possible jet-parton assignments
    - E.g. lepton+jets mode has 4 jets to be assigned to b_1, b_2, q_1, q_2

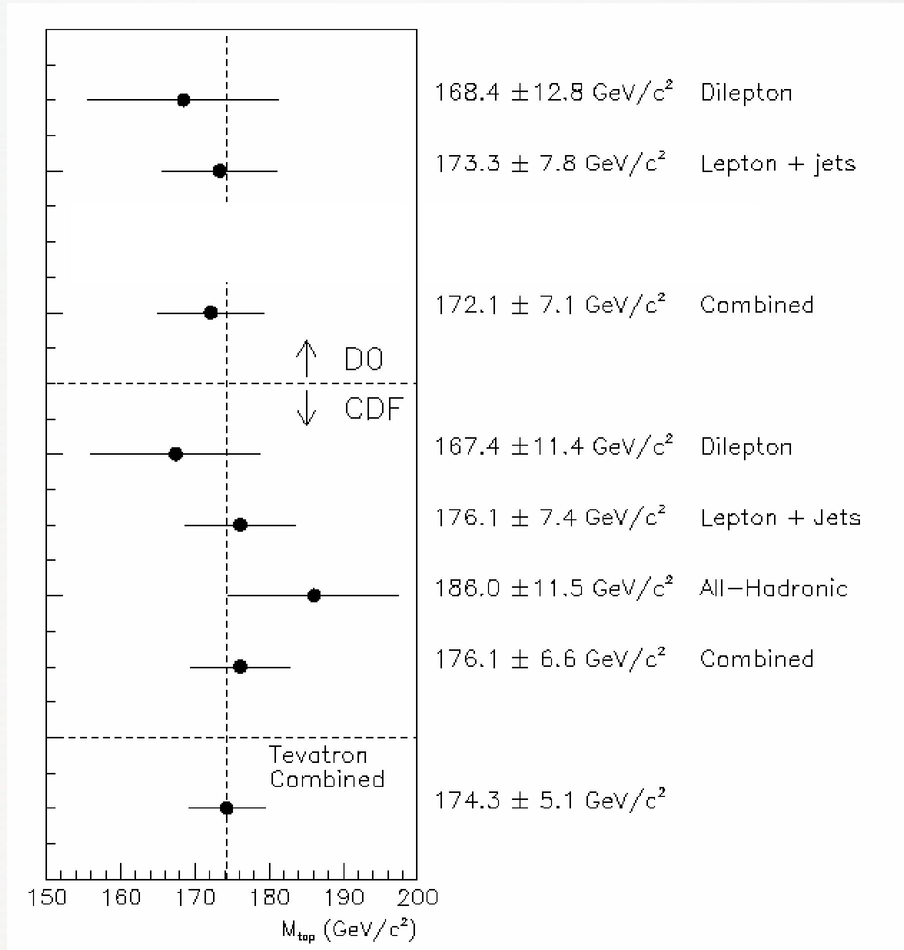
$\therefore 4! = 24$ permutations

» Can be reduced if one or more b′s are tagged



Review of Run I Measurements

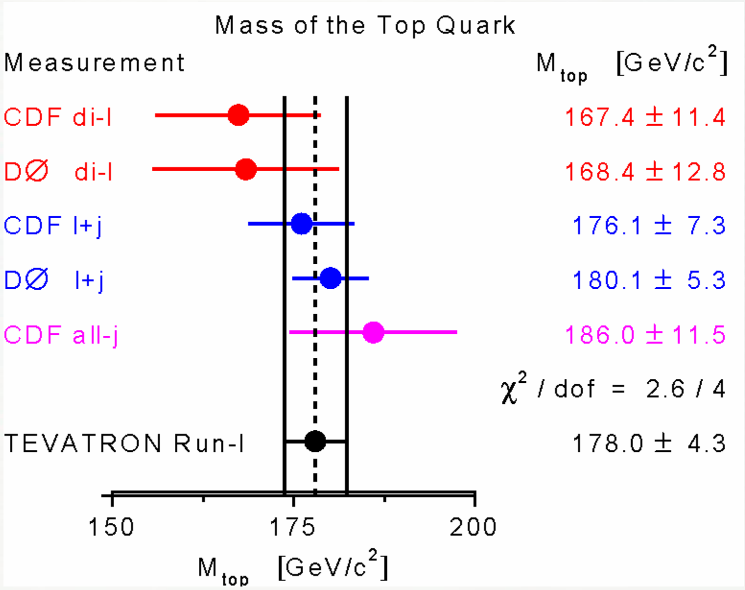
- **Measurements of top mass in all decay modes were made by CDF & D0 with data from Run I of the Tevatron**
  - **For many years world average was**
    - **m_{top} = 174.3 ± 5.1 GeV/c^2**
- **Recent, significantly more precise D0 measurement**
  - **m_{top} = 180.1 ± 5.4 GeV/ c^2**
  - Nature **429**, 638-642 **(2004)**
  - **Comparable precision to <u>all</u> previous measurements <u>combined</u>**

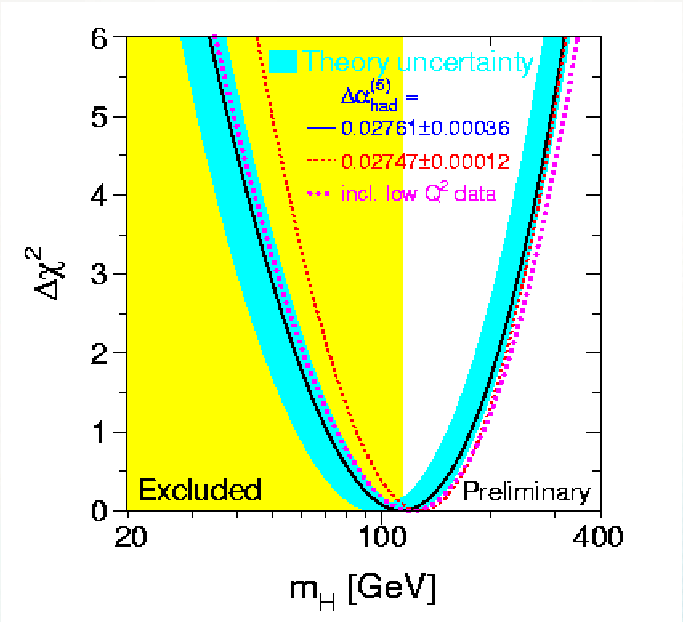


Significant Effect on Expected Higgs Mass

- New world average
  - $m_{top} = 178.0 \pm 4.3$ GeV/ c^2
  - Changes Higgs mass value favored by electroweak fits
    - $m_H \approx 113$ GeV/ c^2
    - Much less in conflict with LEP limit on SM Higgs
      - $m_H > 114.4$ GeV/c^2 @ 95% C.L.

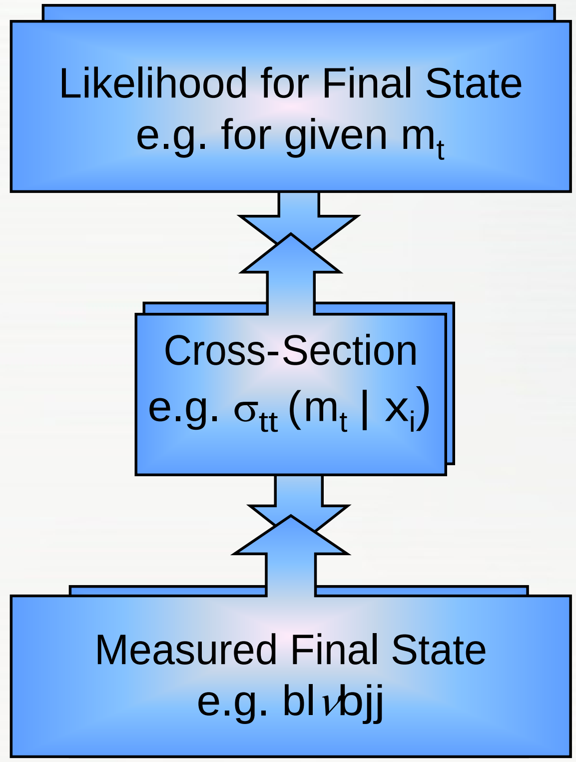
    (old value was 96 GeV/ c^2)

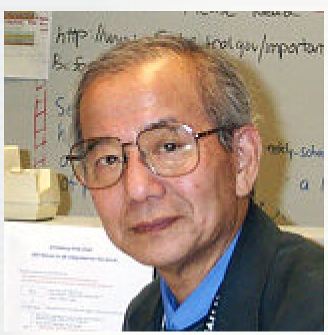




Where does improved precision come from?

- **Matrix Element ("ME") analysis technique using maximal event information**
  - **Instead of using cross-section as a** prior **probability to predict a final state**
  - **Use cross-section as a** posterior **probability for likelihood of the measured final state**





Similar to Dynamical Likelihood Method ("DLM")

- **1988 by K. Kondo (**J.Phys. Soc. **57, 4126)**

General description of DO ME technique

- To measure a parameter α from N events
  - Maximize likelihood given by $L(\alpha) = e^{-N\int \bar{p}(x;\alpha)dx} \prod_{i=1}^{N} \bar{P}(x_i;\alpha)$

where x_i is a set of measured observables and $P(x_i;\alpha)$ is obtained from the differential cross-section for the process as follows:

W(y,x) is the probability that a parton level set of variables ***y*** will be measured as a set of variables ***x***

$d^n\sigma$ is the differential cross section

$$\bar{P}(x;\alpha) = \frac{1}{\sigma}\int d^n\sigma(y;\alpha)\,dq_1\,dq_2\,f(q_1)\,f(q_2)\,W(x,y)$$

f(q) is the probability distribution than a parton will have a momentum ***q***

- Detector resolution is accounted for in the "transfer function", W(x,y)
- Detector acceptance is incorporated as $\bar{P}_{measured}(x;\alpha) = Acc(x)\bar{P}_{production}(x;\alpha)$
- Background processes ME's are explicitly included in the likelihood

For K-1 backgrounds, $\bar{P}(x;c_1,\ldots,c_K,\alpha) = \sum_{i=1}^{K} c_i \bar{P}_i(x;\alpha)$

D0 Run I Top Mass Analysis Using ME Method

- **Analysis performed in lepton (e,μ) + jets channel**
  - **22 candidate $t\bar{t}$ events with exactly 4 jets selected**
- **Signal Probability given by**

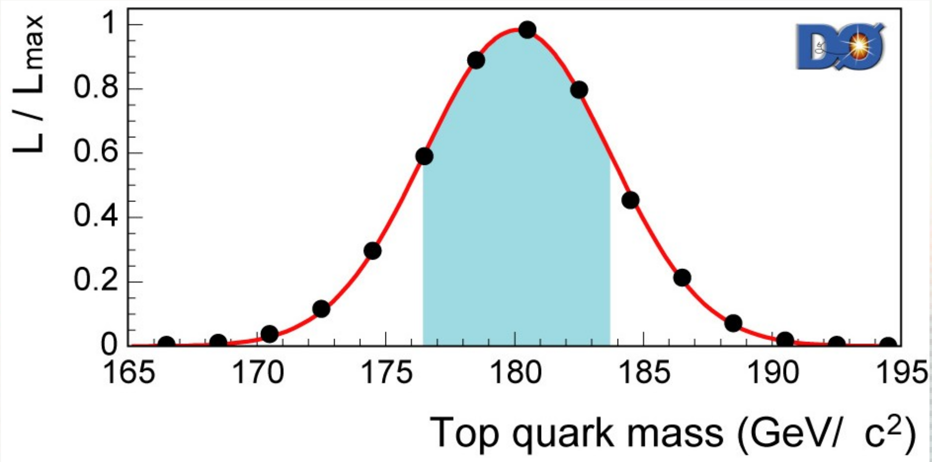
$$P_{t\bar{t}}(x, m_{top}) = \frac{1}{12\,\sigma_{t\bar{t}}} \int d^5\Omega \sum_{perm,\nu} |M_{t\bar{t}}(m_{top})|^2 \frac{f(q_1) f(q_2)}{|q_1||q_2|} \Phi_6 W(x,y)$$

- **With transfer function**

$$W(x,y) = \delta^3(p_e^y - p_e^x) \prod_{j=1}^{4} W_{jet}(E_j^y, E_j^x) \prod_{i=1}^{4} \delta^2(\Omega_i^y - \Omega_i^x)$$

  - **Electrons, angles considered well-measured**
- **Background model is VECBOS W+jets**

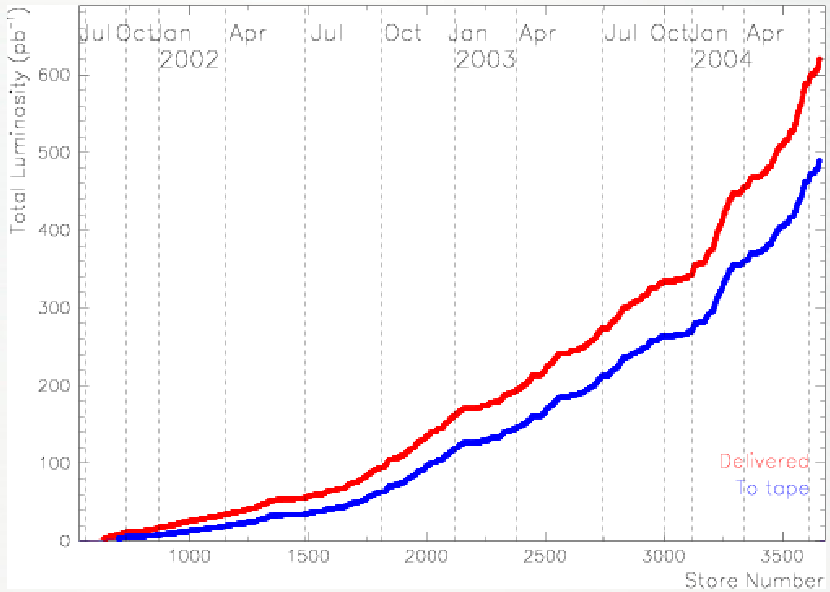
$$P_0(x; c_1, c_2, \alpha) = c_1 P_{ttbar}(x;\alpha) + c_2 P_{W+jets}(x)$$

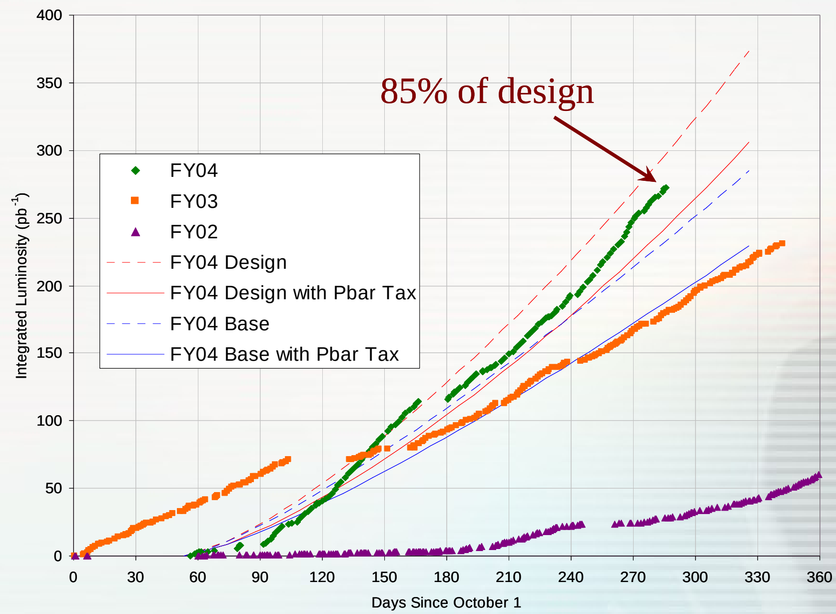


$m_{top} = 180.1 \pm 3.6(stat) \pm 3.9(syst)$ GeV/c^2

Tevatron Run II

- **CDF & D0 upgraded detectors performing well**
- **Run II Luminosity**
  - **After slow start, both experiments have recorded nearly 0.5 fb^{-1}**
  - **Results with up to 200 pb^{-1}**
  - **Expect 4.4-8.5 fb^{-1} by end of Run II**
    - **Currently 85% of "Design"**
- **Precision of Top Mass measurements will soon be limited by systematic uncertainties**
  - **Goal: $\delta m_{top} \approx$ 2-3 GeV**





CDF Run II Top Mass Analysis Using DLM Method

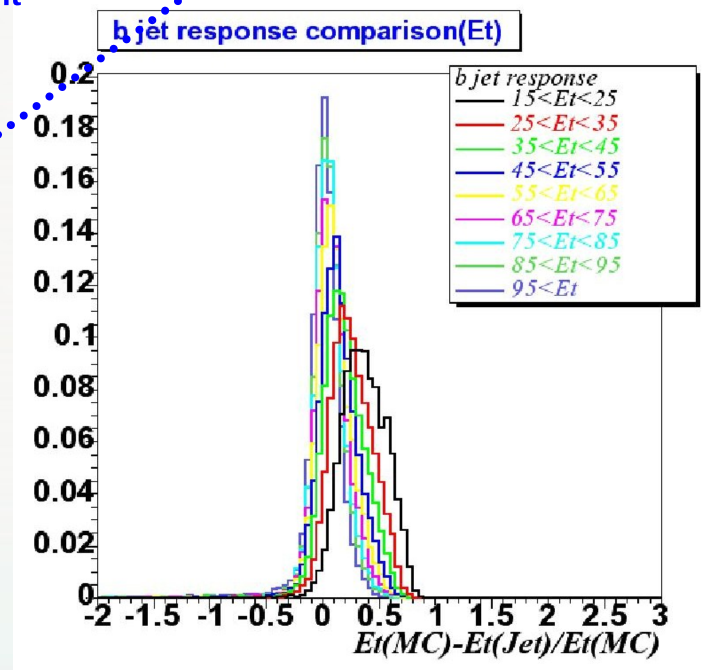
- **Analysis performed in lepton (e,μ) + jets channel**
  - **Require exactly 4 jets**
- **For i^th event, likelihood is defined as**

$$L^i(M_{top}) = \sum_{I_t}\sum_{I_s}\int \frac{2\pi^4}{Flux} F(z_a, z_b) f(p_T) |M|^2 \, w(I_t, \mathbf{x}|\mathbf{y}; M_{top}) d\mathbf{x}$$

PDFs

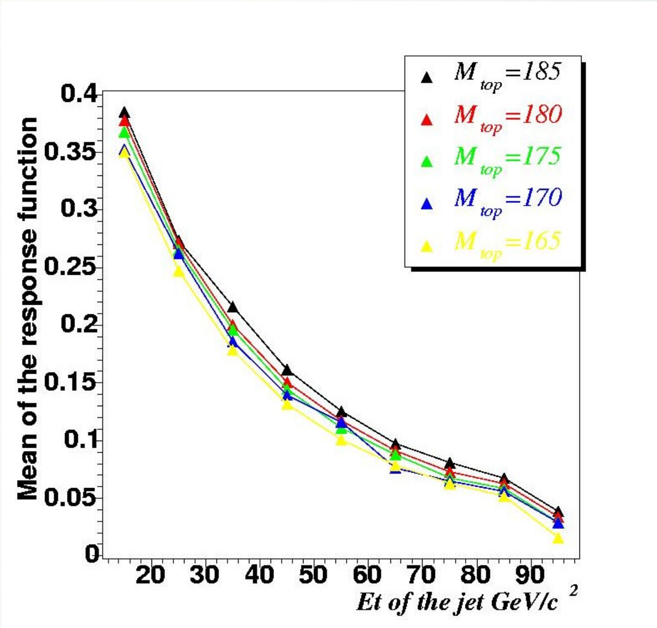
LO ttbar Matrix Element

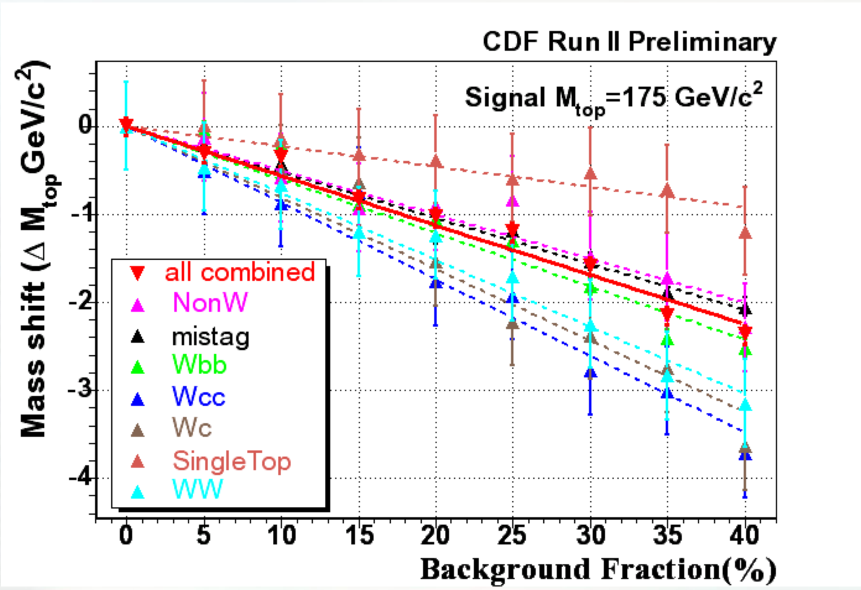
- **Two summations over**
  - **Jet-Parton Assignments (I_t)**
  - **Neutrino Solutions (I_s)**
- **Transfer Function w (x,y)**
  - **$(E_{parton}-E_{jet})/E_{jet}$**
  - **Parametrized as function of E_T and η**
  - **Computed separately for b and light quark jets**

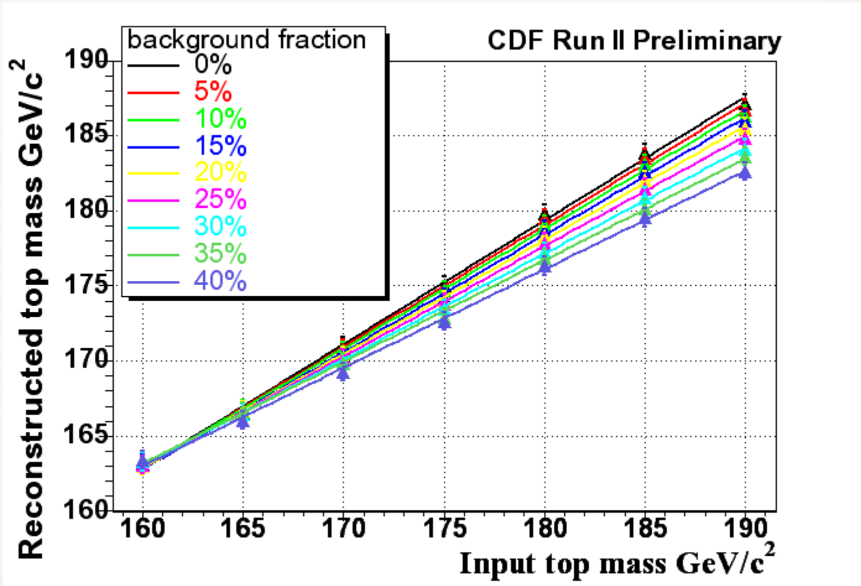


DLM Background – Mapping Function

- Background not included in likelihood
- Instead "Mapping" Function used
  - $M_{reconstructed} \rightarrow M_{generated}$
  - Effective shift on reconstructed mass due to background measured in MC as a function of background fraction
  - Also incorporates mass dependence of transfer functions



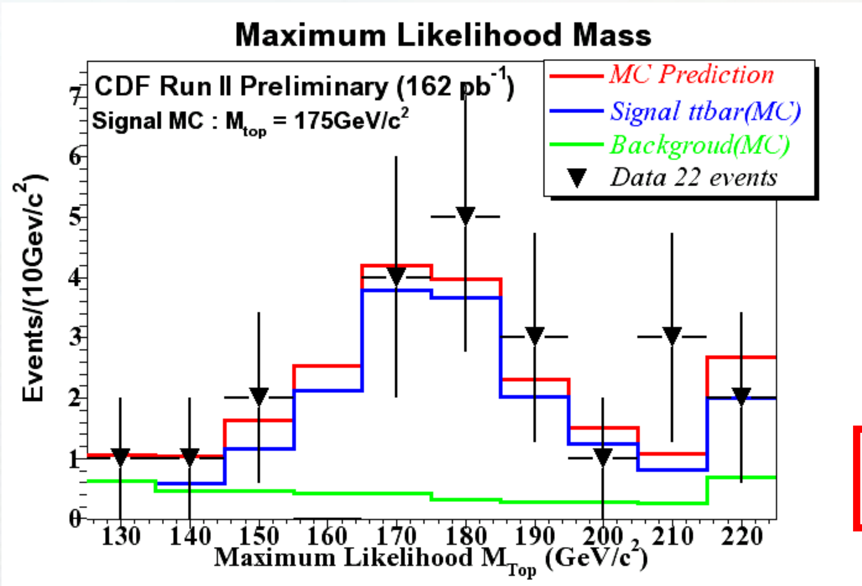




CDF Run II Top Mass - DLM Results

- 22 $t\bar{t}$ candidate events selected
  - 4.2 ± 1.2 estimated background
- Top quark mass extracted by minimizing $\Lambda(M_{top}) = -2ln\left(\prod_{event} L^i(M_{top})\right)$ and applying 19% background fraction mapping function

Systematic Uncertainties	$\Delta M_{top}(GeV/c^2)$
Jet Energy Scale	5.3
ISR	0.5
FSR	0.5
PDF	2.0
Generator	0.6
Spin correlation	0.4
NLO effect	0.4
Bkg fraction(± 5%)	0.5
Bkg Modeling	0.5
MC Modeling(jet,UE)	0.5
Transfer function	2.0
Total	6.2



$$m_t = 177.8^{+4.5}_{-5.0}(stat) \pm 6.2(syst)\ \mathrm{GeV}/c^2$$

CDF Run II Top Mass – Template Method

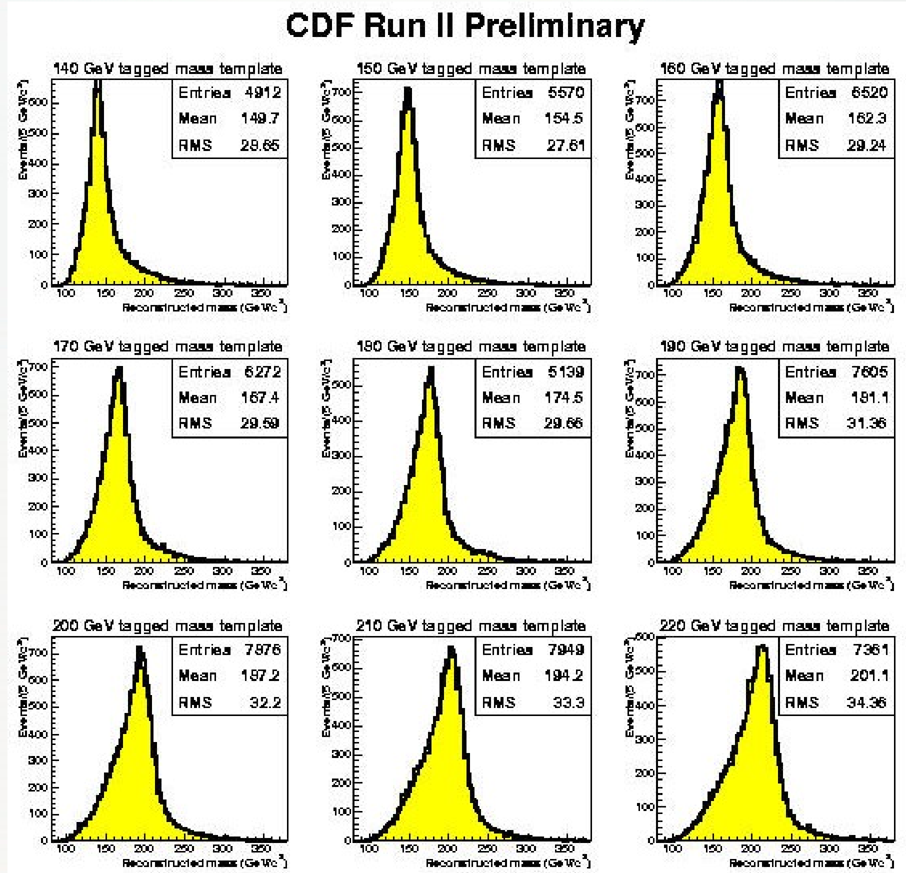
- **Lepton+Jets Event Selection**
  - **1 e, mu with p_T > 20 GeV/c**
  - **$\geq$ 3.5 jets with E_T > 15(8) GeV**
  - **$\not{E}_T$ > 20 GeV**
  - **$\geq$ 1 b-tag**

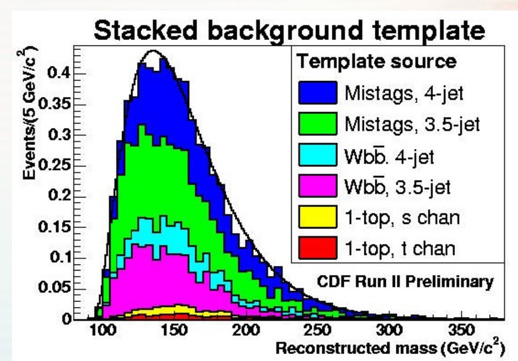
- **Reconstruct invariant mass of top in each event**
  - **Compute χ^2 as follows:**

$$\chi^2 = \sum_{l,jets} \frac{(\hat{p}_T - p_T)^2}{\sigma_{p_T}^2} + \sum_{x,y} \frac{(\hat{U}_i - U_i)^2}{\sigma_{p_T}^2} + \frac{(M_{jj} - M_w)^2}{\Gamma_w^2} + \frac{(M_{l\nu} - M_w)^2}{\Gamma_w^2} + \frac{(M_{bjj} - M_t)^2}{\Gamma_t^2} + \frac{(M_{bl\nu} - M_t)^2}{\Gamma_t^2}$$

  - **Minimize with M_t as a free parameter for all parton assignment permutations and two neutrino solutions**

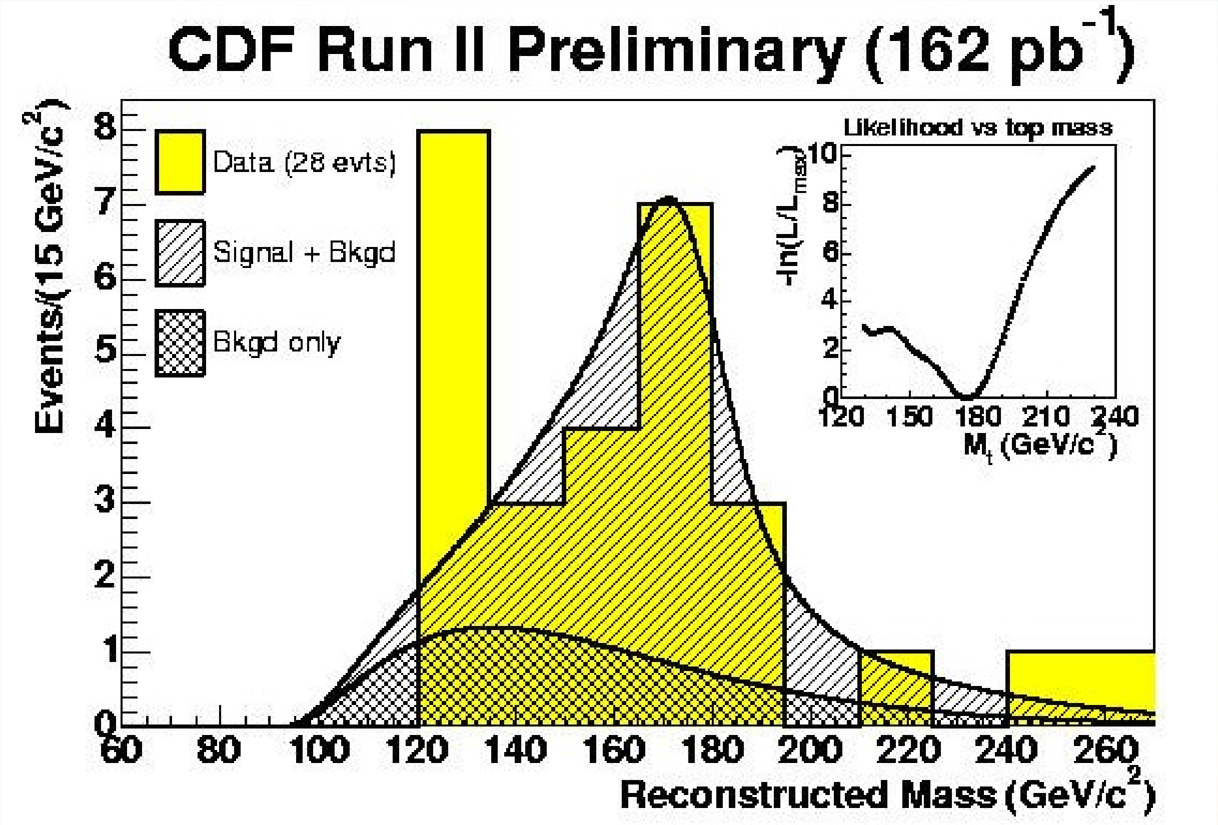
- **Histogram reconstructed mass with smallest χ^2**
  - **Build templates from MC for**
    - **Signal process with different m_{top}**
    - **Background processes**





CDF Run II Top Mass – Template Results

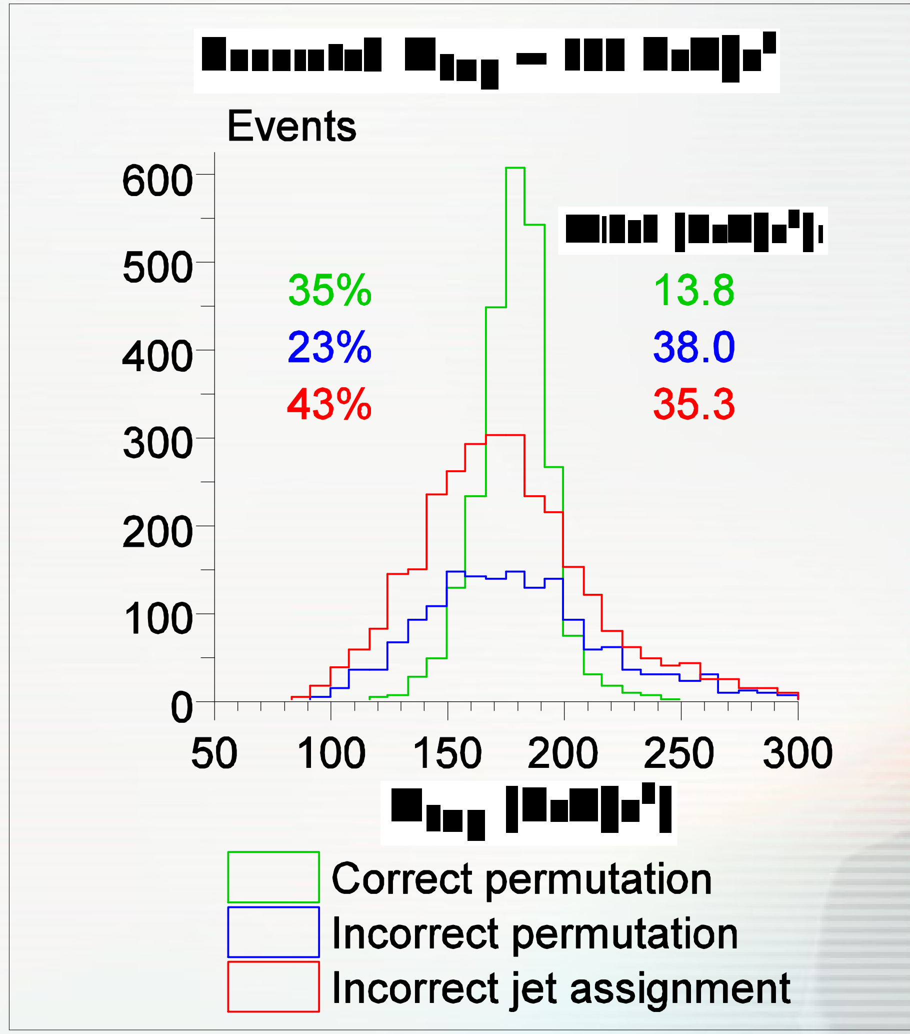
- **28 $t\bar{t}$ candidate events selected**
  - **6.8 ± 1.2 estimated background**
- **Extract top mass**
  - **Compare reconstructed mass distribution in data (yellow) to signal & background templates**
    - **Unbinned likelihood fit**



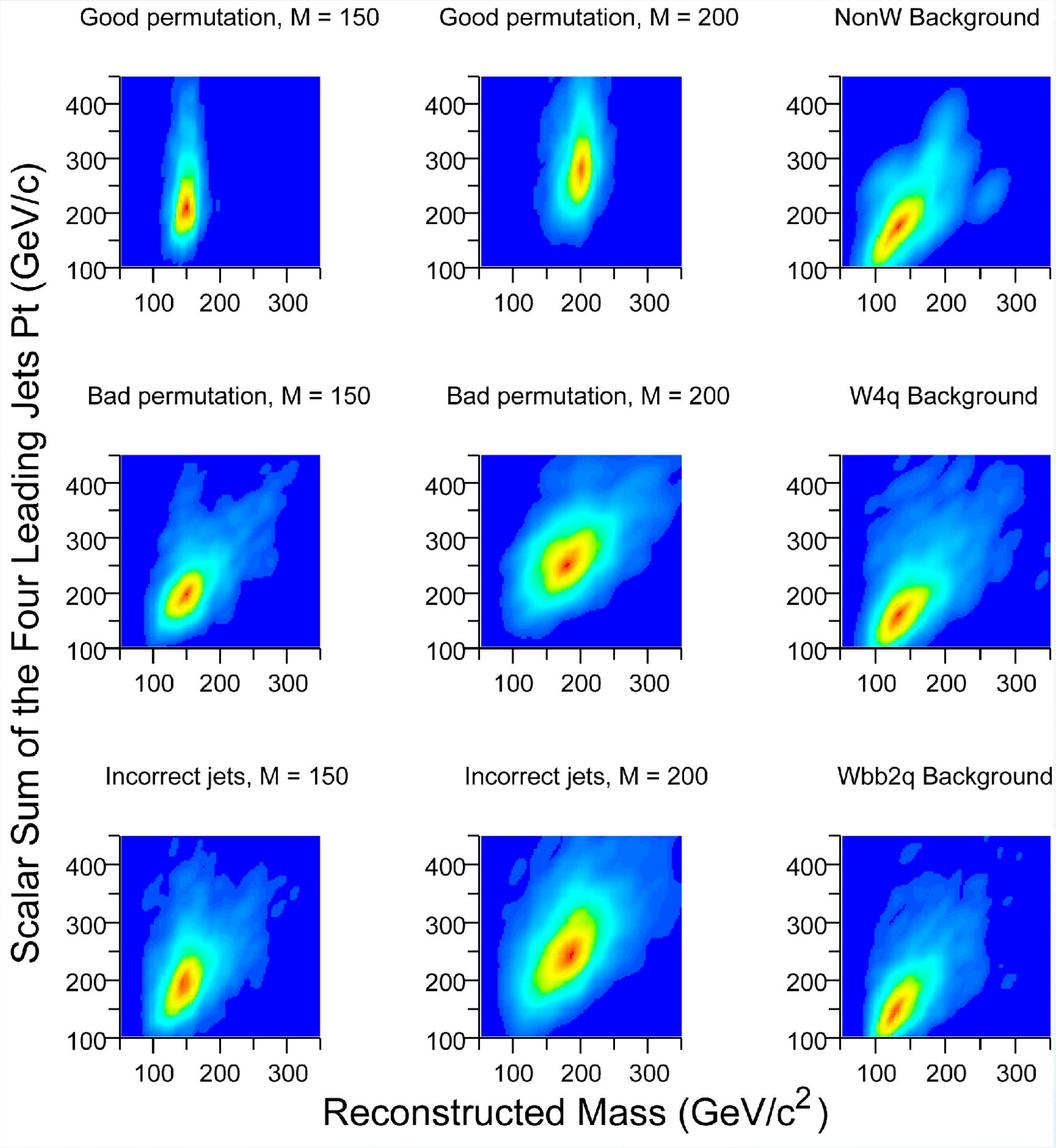
$$m_t = 174.9^{+7.1}_{-7.7}(stat) \pm 6.5(syst)\ \mathrm{GeV}/c^2$$

CDF Run II Top Mass – Multivariate Method

- **Another lepton+jets template analysis**
- **Reduces systematic uncertainty**
  - **Adjustable jet energy scale calibrated in W → qq′ decay**
- **Improves mass resolution**
  - **Uses kinematic variables to determine probability that best χ^2 results from correct jet-parton assignment**
  - **Weight signal templates accordingly**
- **Augments reconstructed top mass with kinematic information to improve signal/background separation**
  - **Σp_T of 4 leading jets**

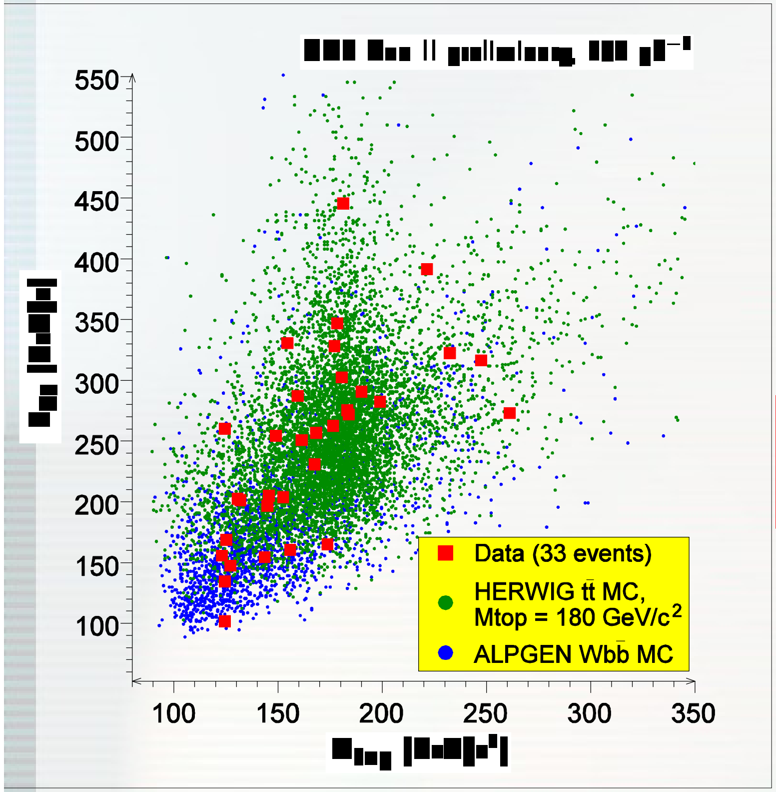


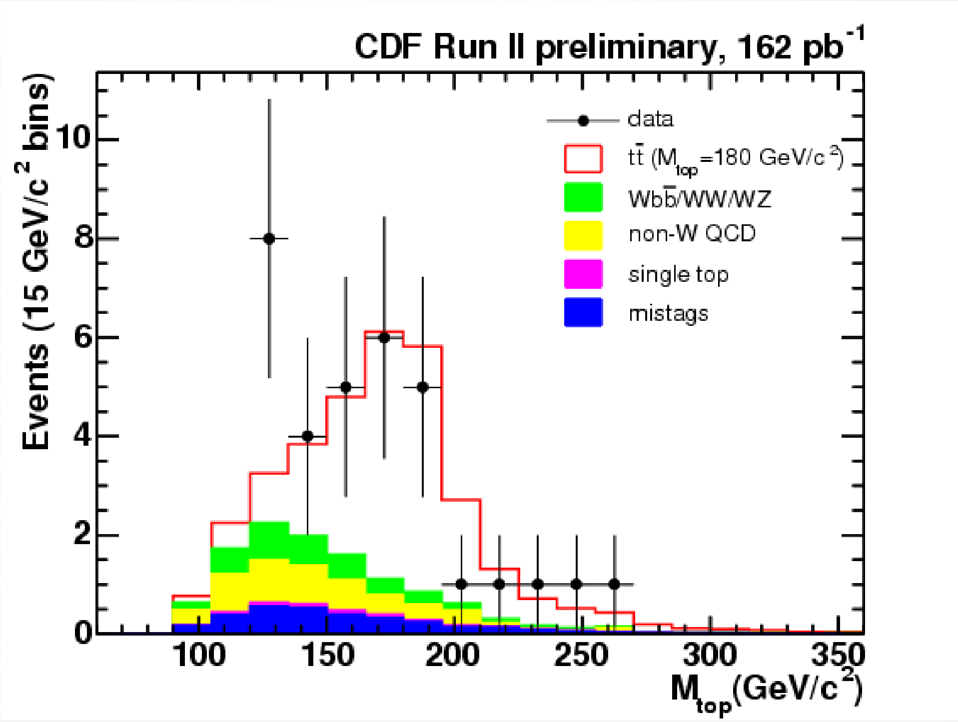
Multivariate Templates



CDF Run II Top Mass – Multivariate Results

- 33 $t\bar{t}$ candidate events selected
  - Background fraction determined by fit



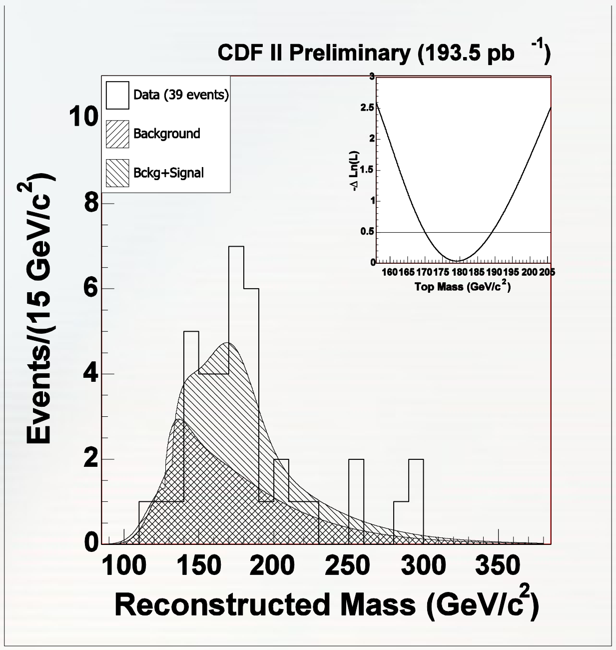


$$m_t = 179.6^{+6.4}_{-6.3}(stat) \pm 6.8(syst)\ \mathrm{GeV}/c^2$$

$$f_b = 0.34 \pm 0.14$$

Other CDF Run II Top Mass Analyses

- **Non-Tagged Mass**
  - **Lepton plus jet events without any b-tags**
    - **Exclusive complement to b-tag sample**
      - **Result will be combined with measurements from tagged sample**

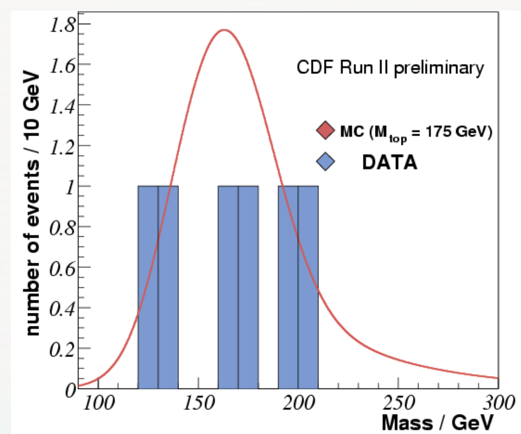


$$m_t = 179.1^{+10.5}_{-9.5}(stat) \pm 8.4(syst)\ \mathrm{GeV}/c^2$$

- **Dilepton Mass**
  - **Event Selection**
    - **2 e, μ with p_T > 20 GeV**
    - **≥ 2 jets with E_T > 15 GeV**
    - **$\not{E}_T$ > 25 GeV**
  - **Top mass is under-constrained due to two ν**
    - **Introduces the following constraint to kinematically solve the system**

$$P_z^{t\bar{t}} = P_z^t + P_z^{\bar{t}} = 0$$

  - **Analysis was performed on 126 pb^{-1}**
    - **Currently being updated to 193 pb^{-1}**



$$m_t = 175.0^{+17.4}_{-16.9}(stat) \pm 8.4(syst)\ \mathrm{GeV}/c^2$$

Summary and Future Outlook

- Substantial recent progress in m_{top} measurements
  - D0 Matrix Element technique
    - Significantly more precise Run I world average
  - CDF preliminary m_{top} results with Run II data in lepton+jets and dilepton channels
    - D0 Run II measurements in progress
  - Combined measurements soon
    - Across decay modes
    - Between experiments
- Both experiments now have ~5x Run I dataset on tape
  - <u>Precision</u> m_{top} measurements in the not too distant future
    - Challenge will be reduction of jet-energy scale systematic uncertainty