Top Mass Measurement at DØ

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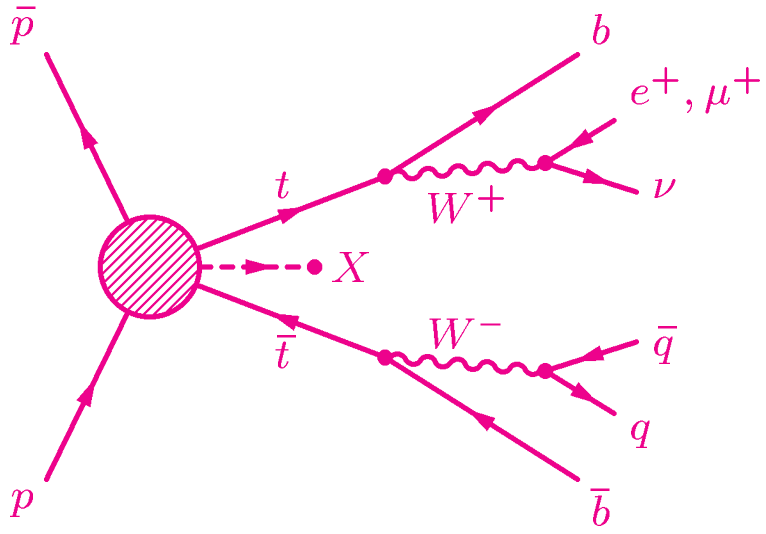
Outline

- I. Mass analysis of lepton + jets events.
- II. Mass analysis of dilepton events.
- III. Summary.

I. Lepton + Jets Mass Analysis

Event Selection



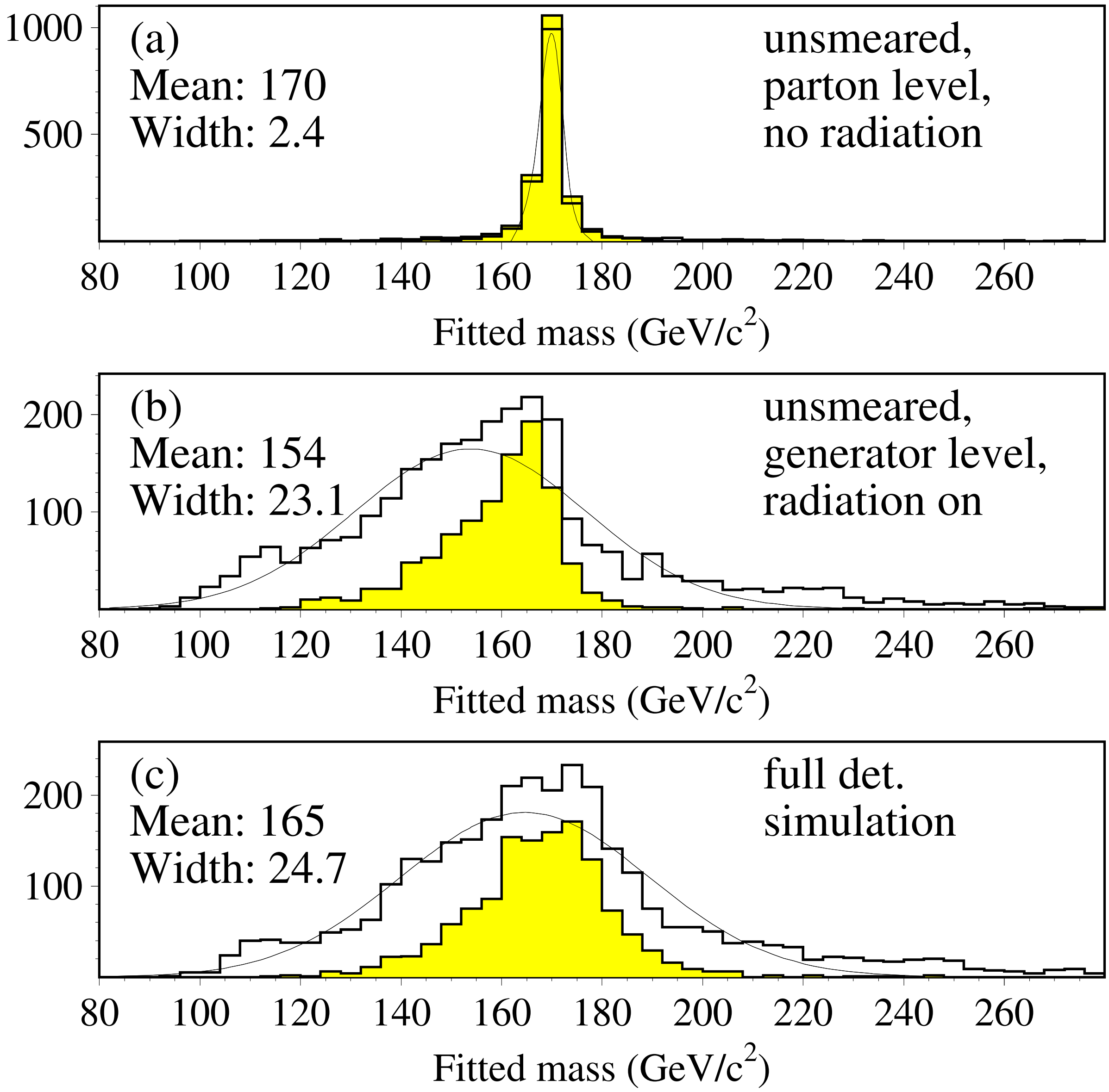
- Lepton, $\not\!\!E_T$, and jet cuts identical to untagged lepton + jets channels from cross section analysis.
  - High-p_T lepton (e or μ).
  - Large $\not\!\!E_T$.
  - ≥ 4 jets with $E_T > 15\,\text{GeV}$ and $|\eta| < 2$.
- Further require either:
  - $E_T^L = E_T^{lep} + \not\!\!E_T > 60\,\text{GeV}$ and $|\eta_W| < 2.0$.
  - OR: b-tag muon.
- 91 events selected.
  - 7 with b-tag.

Lepton + Jets Method

- Use leading four jets, corrected back to parton level.
- 2C kinematic fit to $t\bar{t} \to (l\nu b)(q\bar{q}\bar{b})$.
  - One unknown: $p_z(\nu)$.
  - Three constraints:
    - $m(l\nu) = M_W$.
    - $m(jj) = M_W$.
    - $m(l\nu j) = m(jjj)$.
  - 2C fit $\to m_{\text{fit}}$, χ^2.
  - 12 ways of assigning 4 jets to $b\bar{b}jj$ (6 if event is tagged). Try all possibilities.
  - Require $\chi^2 < 10$ and pick m_{fit} corresponding to smallest χ^2.
- Yields 77 events with 5 b-tags.
- Signal and background models:
  - Signal: Herwig (v5.7).
  - $W +$jets background: Vecbos (v3.0).
  - Multijet background: data.

Monte Carlo Tests

For $m_t = 170\,\mathrm{GeV}/c^2$ Herwig top.
Shaded plot shows correct permutation.



Multivariate Discriminants

- Want to distinguish top signal from background while avoiding any large correlations with top mass.

- Variables:

$$x_1 = \not{E}_T \qquad (\text{Missing } E_T)$$

$$x_2 = \mathcal{A} \qquad (\text{Aplanarity})$$

$$x_3 = \frac{H_{T2} \equiv H_T - E_T^{\text{jet1}}}{|p_z(l)| + |p_z(\nu)| + \sum_j |p_z(j)|}$$

$$x_4 = \frac{\Delta R_{jj}^{\text{min}} E_T^{\text{min}}}{E_T^L}$$

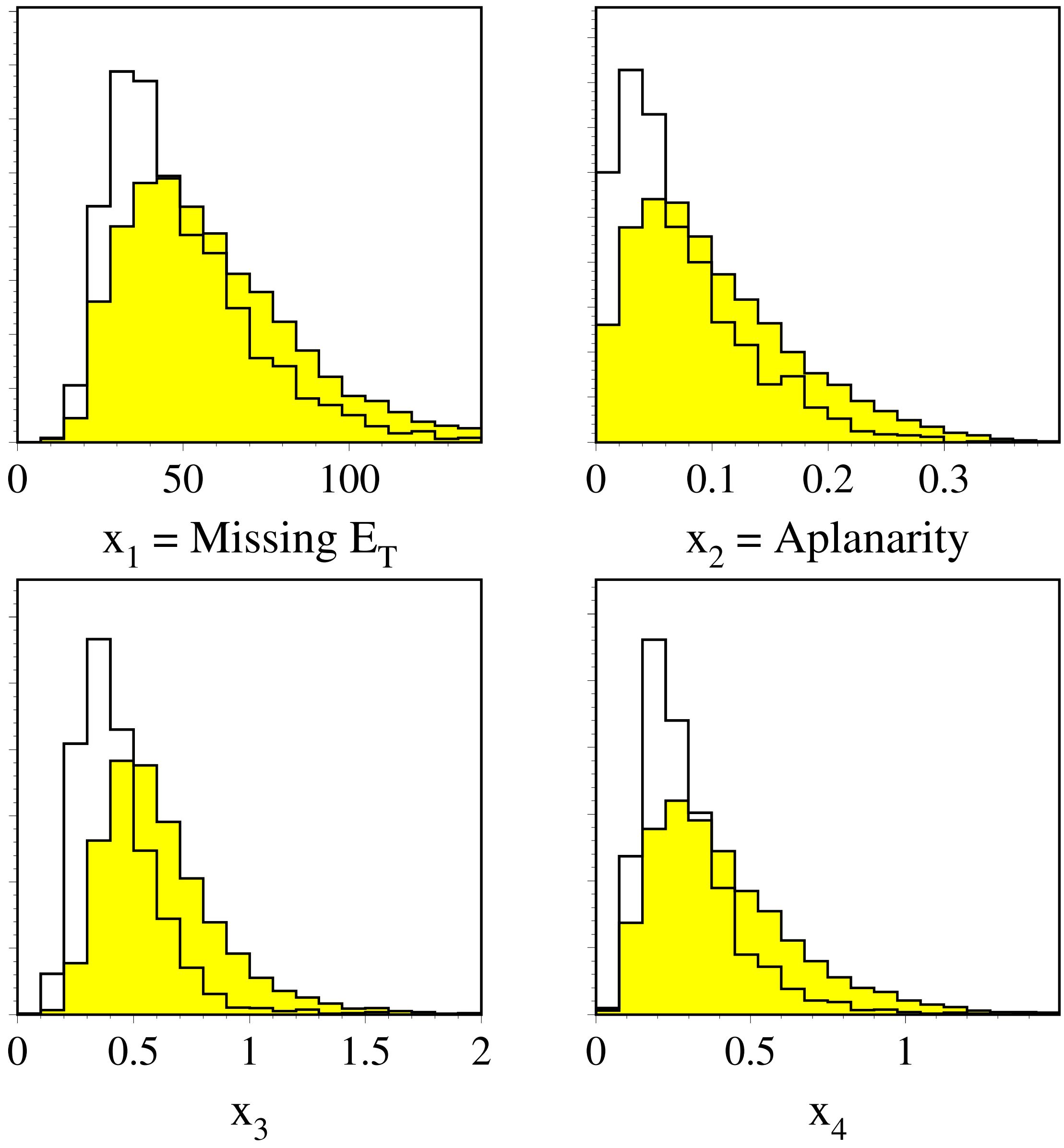
- x_3 measures the event centrality.

- x_4 measures the extent to which jets are clustered together.

- Combine these four variables into a multivariate discriminant $0 \le \mathcal{D} \le 1$.

Discriminant Variables

For Background and $m_t = 175\,\mathrm{GeV}/c^2$ Herwig top.

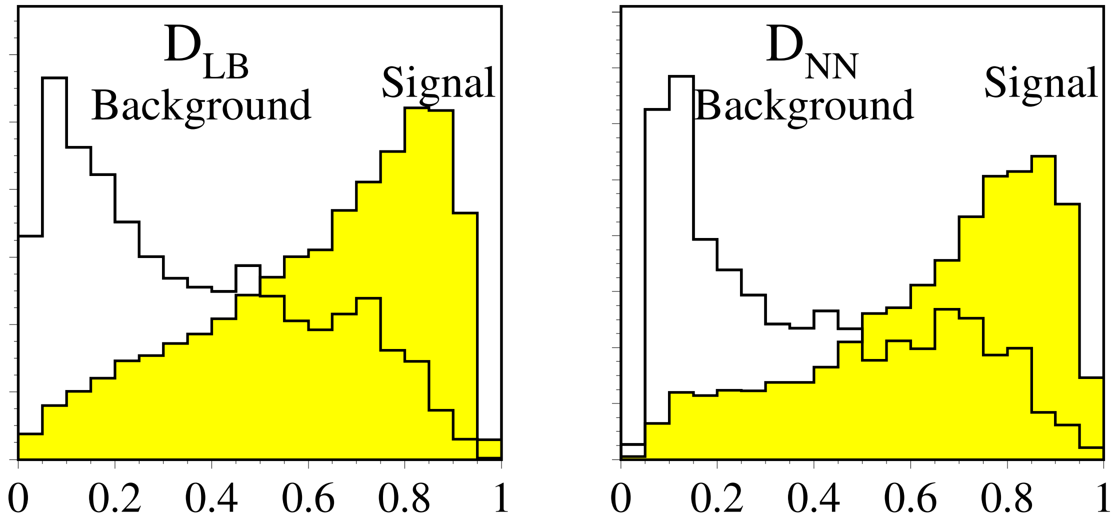


Multivariate Discriminants

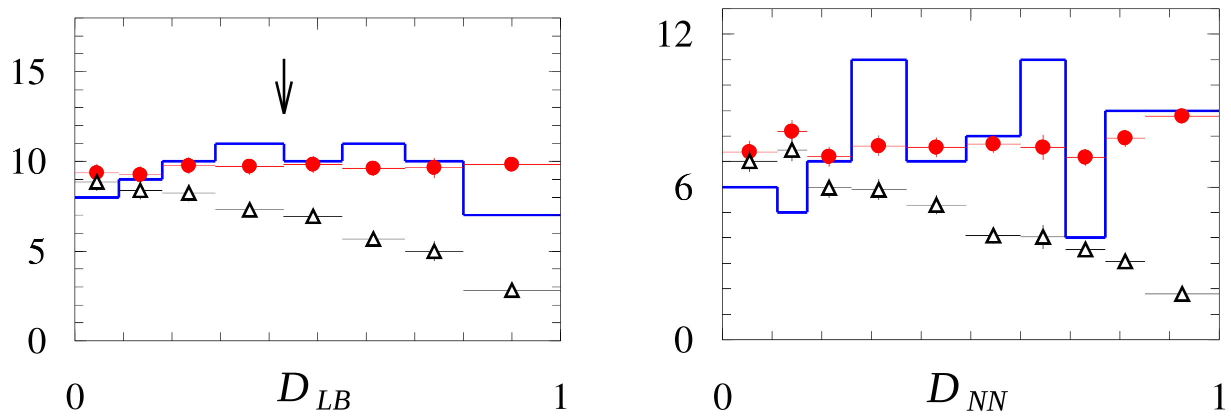
- Likelihood Discriminant:
  - Parameterize $L_i(x_i) = \frac{s_i(x_i)}{b_i(x_i)}$.
  - Form $\ln \mathcal{L} = \sum_i w_i \ln L_i$ for each event.
  - Adjust w_i to minimize correlation of $\mathcal{L}$ with m_{fit}.
  - $\mathcal{D}_{LB} = \frac{\mathcal{L}}{1+\mathcal{L}}$.
- Neural Network Discriminant:
  - Sensitive to multivariate densities.
  - Train on samples of top and background.
  - $\mathcal{D}_{NN}$ approximates signal probability directly.

The Discriminants

For Background and $m_t = 175\,\text{GeV}/c^2$ Herwig top.



Comparison with Data

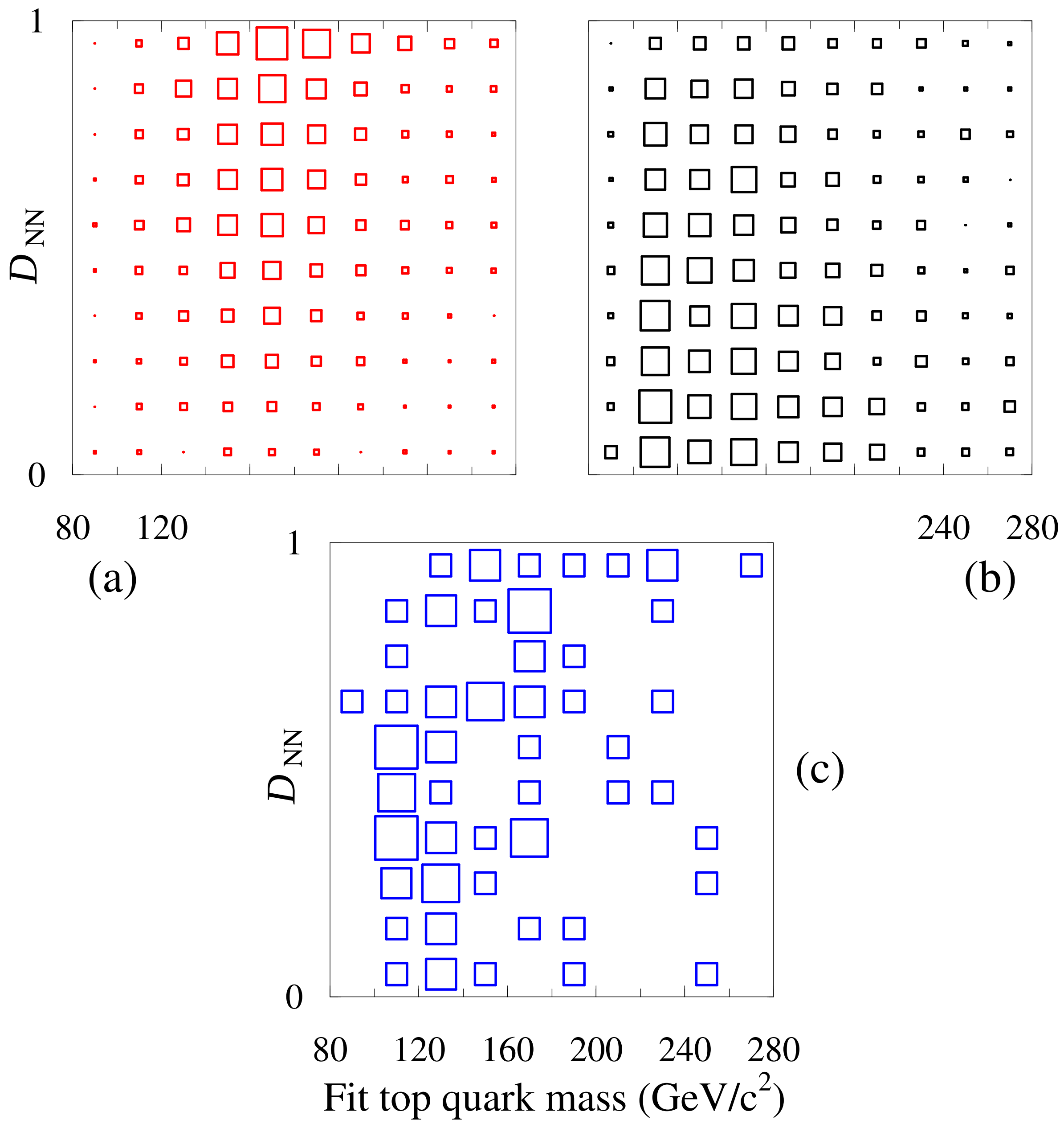


Likelihood Fitting

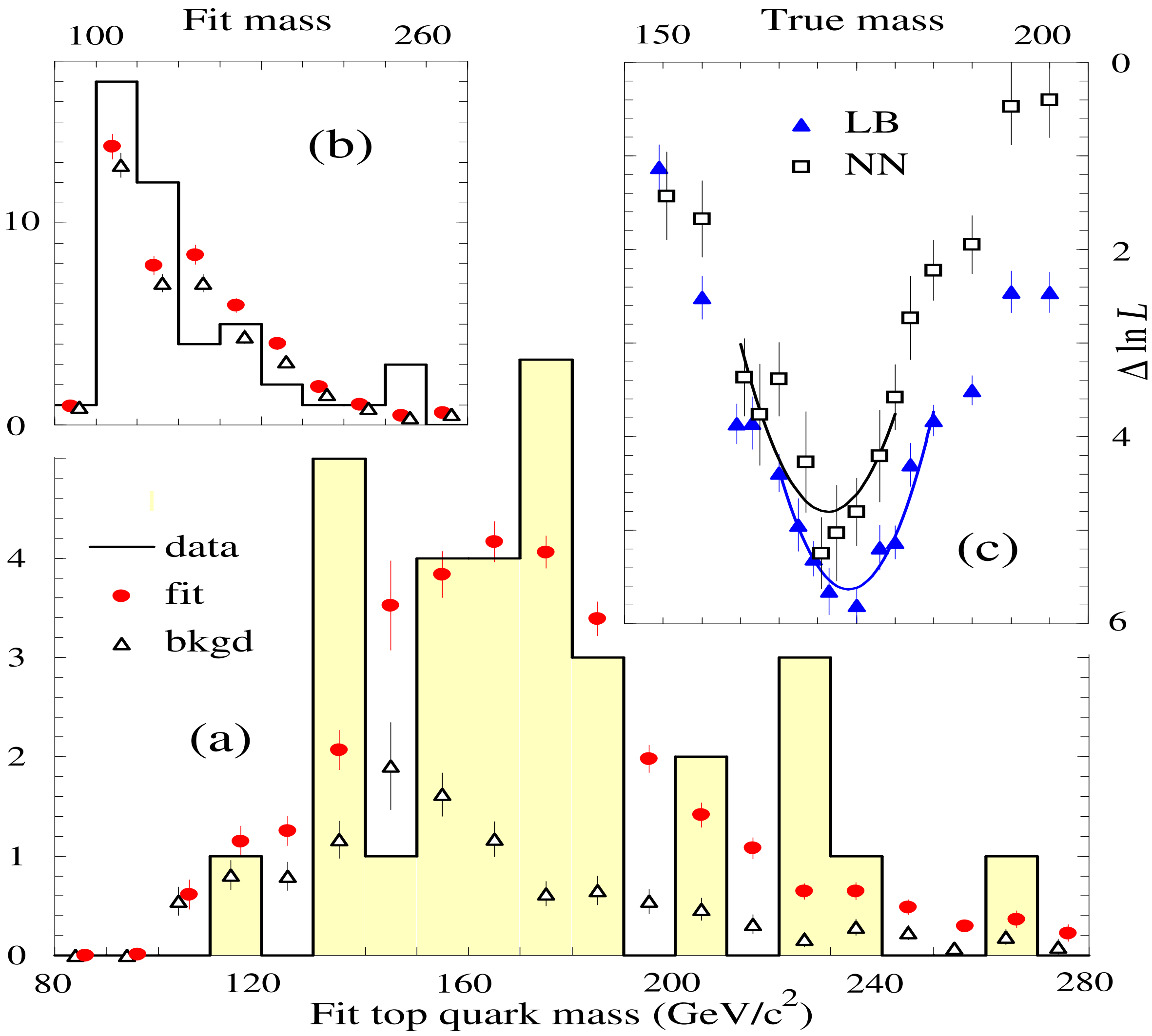
- Bin the data, signal, and background samples in the ($\mathcal{D}$, m_{fit}) plane.
  - $\mathcal{D}$: 0–1.
  - m_{fit}: $80 - 280\,\text{GeV}/c^2$.
- LB Analysis.
  - 2 bins in $\mathcal{D}$, 20 in m_{fit}.
  - LB cut:
    - $\mathcal{D}_{LB} > 0.43$ and $H_{T2} > 90\,\text{GeV}$.
    - OR event has a b-tag.
- NN Analysis.
  - 10 bins in $\mathcal{D}_{NN}$, 20 in m_{fit}.
- For each MC top mass m_t:
  - Fit data to signal + background models.
    - Use binned Poisson-statistics likelihood technique.

  $\rightarrow L(m_t)$.
- Quadratic fit to $-\ln L$ to extract m_t and σ_m.

$\mathcal{D}_{NN}$ vs. m_{fit}



Fit Results



	m_t	n_s	n_b
LB	174.0 ± 5.6 GeV/c^2	$23.8^{+8.3}_{-7.8}$	$53.2^{+10.7}_{-9.3}$
NN	171.3 ± 6.0 GeV/c^2	$28.8^{+8.4}_{-9.1}$	$48.2^{+11.4}_{-8.7}$

- Combined: $m_t = 173.3 \pm 5.6$ GeV/c^2. (88% correlation.)

Lepton + Jets Result

- Systematic errors:

Jet energy scale	4.0 GeV/c^2
(Per-jet error: 2.5% + 0.5 GeV)	
Generator	
Signal generator	3.3 GeV/c^2
Vecbos models	2.6 GeV/c^2
Multiple interactions	1.2 GeV/c^2
MC Statistics	0.8 GeV/c^2
LB/NN Difference	1.4 GeV/c^2
Likelihood fit	1.0 GeV/c^2
Total	6.2 GeV/c^2

- Lepton + jets result:

$$\boxed{m_t = 173.3 \pm 5.6(\text{stat.}) \pm 6.2(\text{syst.})\ \text{GeV}/c^2}$$

II. Dilepton Mass Analysis

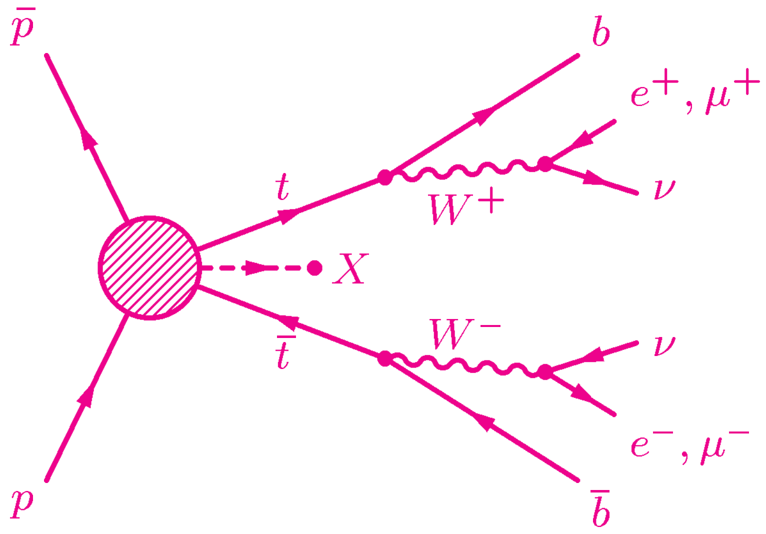
- Dilepton events: $t\bar{t} \to (bl\nu) + (bl\nu)$.

- Event selection almost the same as cross section analysis:
  - Two high-p_T leptons (e or μ).
  - Large $\not{E}_T$.
  - ≥ 2 jets with $E_T > 20\,\mathrm{GeV}$ and $|\eta| < 2.5$.
  - H_T cut.

- Selection results (from $\approx 125\,\mathrm{pb}^{-1}$):

Channel	Observed	Background
ee	2	0.47 ± 0.09
$e\mu$	3	0.21 ± 0.16
$\mu\mu$	1	0.73 ± 0.25

Dilepton Analysis Method



- Two neutrinos in final state.
  - Not enough information in measured event to define top kinematics (-1C):
    - 18 variables.
    - 14 measured quantities.
    - 3 constraints.
- If m_t is assumed, the kinematics of the event can be calculated (up to a possible 4-fold ambiguity in the neutrino solutions).
- But not all such solutions are equally likely.
  - Define a likelihood as a function of top mass.
- Extract final mass with a maximum likelihood fit.

Solution Likelihood

- Analytic solution likelihood:

$$p(m_t|\{o\}) \propto \int |\mathcal{M}\{v\}|^2 \rho(\{o\}|\{v\})\delta^4(m_i - M_i)\, d\{v\}$$

  $|\mathcal{M}|^2$ is the matrix element, $\{v\}$ is a convenient set of variables, ρ represents the detector resolution, and the δ-functions enforce the mass constraints.

- Too expensive to evaluate on large MC samples.

- DØ uses two different approximations.

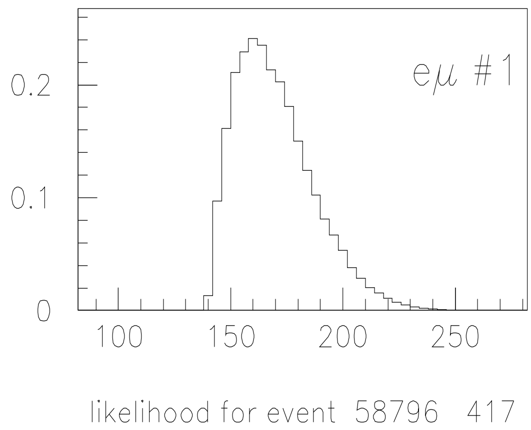
- Effects of making this approximation are small compared to effects of detector resolution and jet combinatorics.

Matrix-Element Weighting (MWT)

- Extension of ideas proposed by Kondo and Dalitz and Goldstein.
- Use the weight

$$\mathcal{W}(m_t) = \mathcal{A}(m_t)\, f(x) f(\bar{x})\, p(E^*(l)|m_t)\, p(E^*(\bar{l})|m_t),$$

  - $f(x) \equiv$ Structure function for valence quarks.
  - $p(E^*(l)|m_t) \equiv$ Probability distribution for the energy of the charged lepton in the top rest frame.
  - $\mathcal{A}(m_t) \equiv$ Normalization factor.
- Account for detector resolution:
  - Smear the event many times.
  - Sum the resulting likelihoods.
- Also sum over both possible pairings of b-jets with leptons.
- Example: an $e\mu$ event.



Method 2: Neutrino Weighting (νWT)

- Assume a top mass (m_t) and a rapidity for each neutrino (η_1, η_2).

- The event can then be solved without using the measured $\not\!\!E_T$ (up to a possible 4-fold ambiguity).

- Assign a weight based on the agreement between the calculated neutrino p_T ($\vec{p}_T(\nu\nu)$) and the measured $\vec{\not\!\!E}_T$:

$$\mathcal{W}(m_t, \eta_1, \eta_2) = \sum_{\text{solutions}} \prod_{k=x,y} \exp\left[-\frac{\left(\not\!\!E_k - p_k(\nu_1\nu_2)\right)^2}{2\sigma(\not\!\!E_k)^2} \right]$$

- Integrate over the neutrino rapidity phase space:

$$\mathcal{W}(m_t) = \int d\eta_1\, d\eta_2\, p(\eta_1|m_t)\, p(\eta_2|m_t)\, \mathcal{W}(m_t, \eta_1, \eta_2)$$

  Approximate prior probabilities $p(\eta|m_t)$ by gaussians with widths taken from $t\bar{t}$ Monte Carlo.

- Event smearing and jet combinatorics handled as in MWT method.

Dilepton Jet Combinatorics

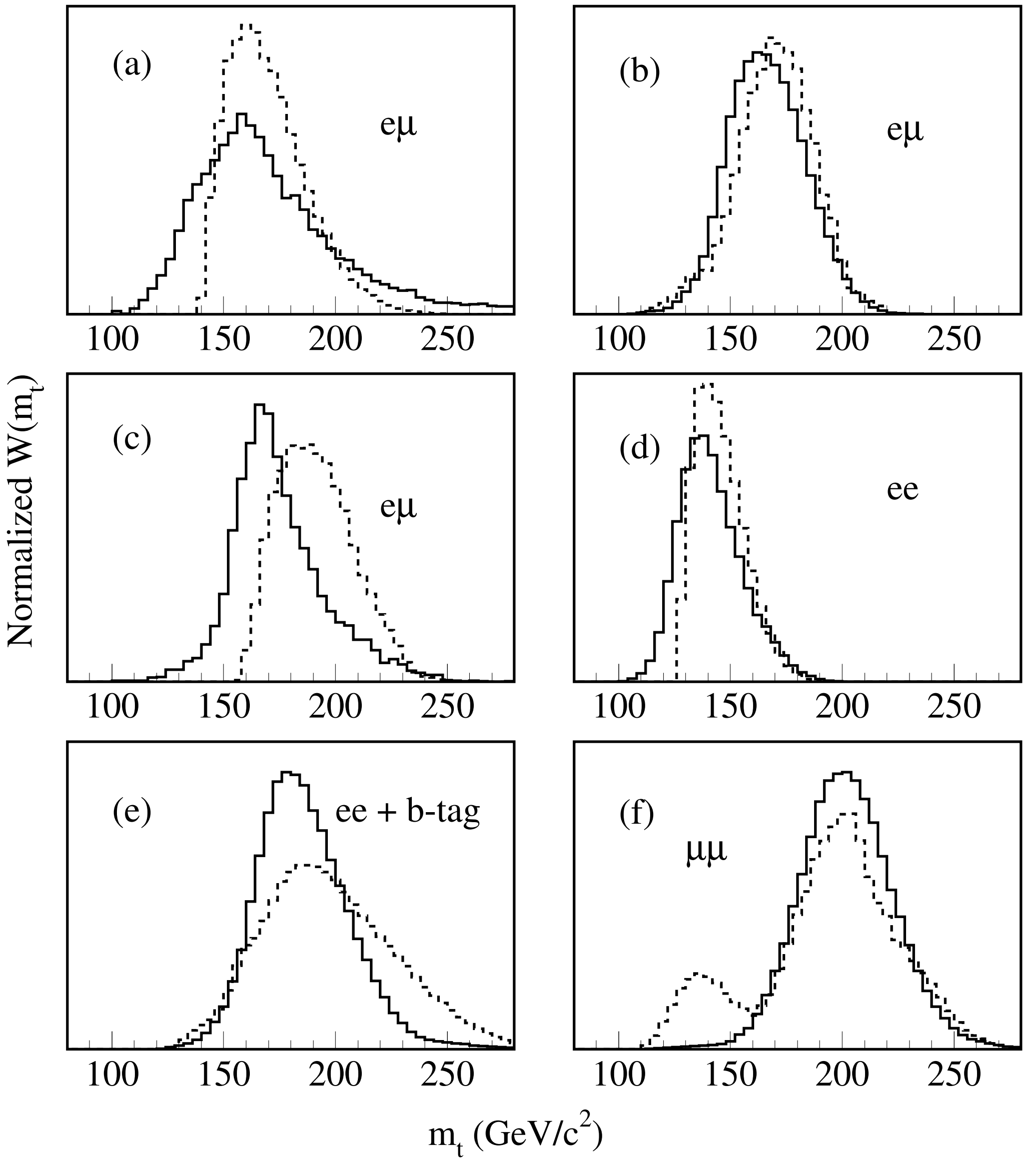
- Gluon radiation may produce additional jets.
- With three jets there are two possibilities:
  - Ignore one jet (initial state radiation, ISR).
  - Merge two jets together.
- Six possible ways of doing this:

b_1	b_2	ISR
j_1	j_2	j_3
j_1	j_3	j_2
j_2	j_3	j_1
$j_1 + j_2$	j_3	
$j_2 + j_3$	j_1	
$j_3 + j_1$	j_2	

- Assign a weight to each such permutation:
  - ISR jet: $\propto \exp\left(-0.04\, p_T \sin\theta\right)$.
  - Two jets merged: $\propto \exp\left(-0.05\, m_{jj}\right)$.
- For each three-jet event, multiply each of the six event likelihood curves by the weight and sum them to form a single likelihood curve.

Dilepton Candidate Sample

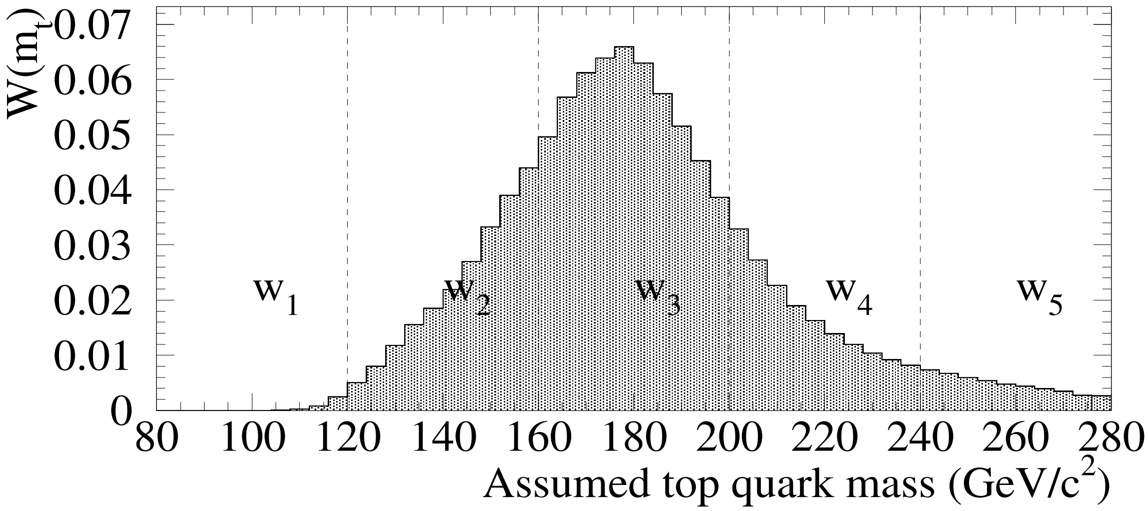
- Solid: νWT. Dashed: MWT.



Maximum Likelihood Fit

- Find the top quark mass most consistent with the entire data sample.

- Divide normalized $\mathcal{W}(m_t)$ into 5 bins.



- Describe events by 4 independent quantities $\mathrm{w} \equiv w_1 \ldots w_4$. Sum over all data.

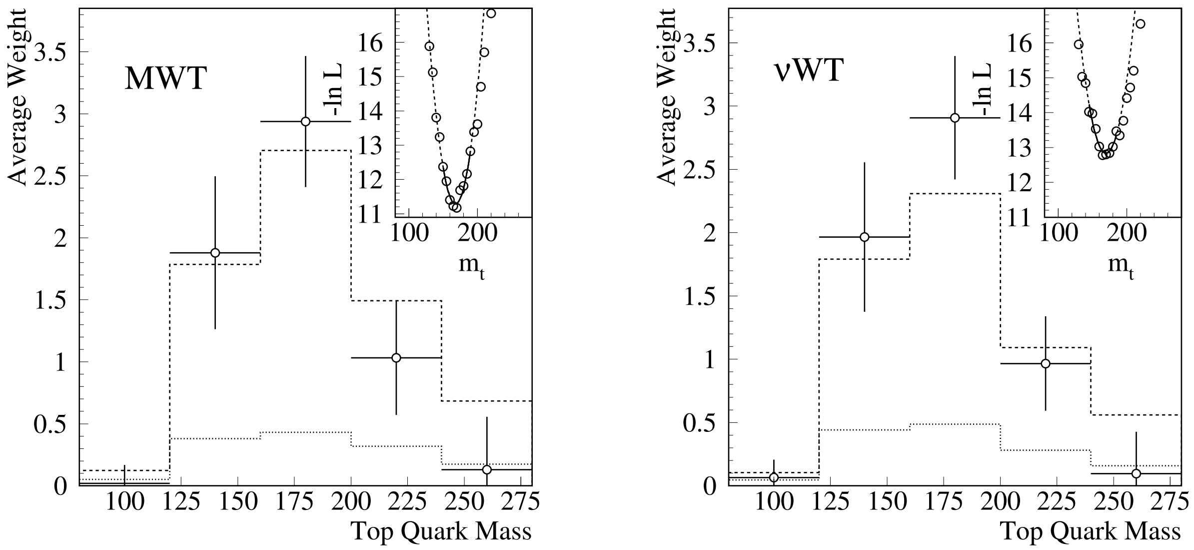
- Do a ML fit for n_s, n_b using

$$L(m_t) = g(n_b)p(n_s + n_b)\frac{n_s f_s(\mathrm{w}|m_t) + n_b f_b(\mathrm{w})}{n_s + n_b}.$$

- Approximate f_s and f_b using MC.

- Plot $-\ln L$ versus m_t and fit a quadratic to the 9 points nearest the minimum.

Dilepton Results



- MWT: $m_t = 168.1 \pm 12.4(\text{stat.})$ GeV/c^2.
- νWT: $m_t = 169.9 \pm 14.8(\text{stat.})$ GeV/c^2.
- Systematic errors:

Jet Scale	2.5
Signal Generator	1.7
BG Shape	1.2
Mult. Int.	1.3
Likelihood fit	1.3
Total	3.7

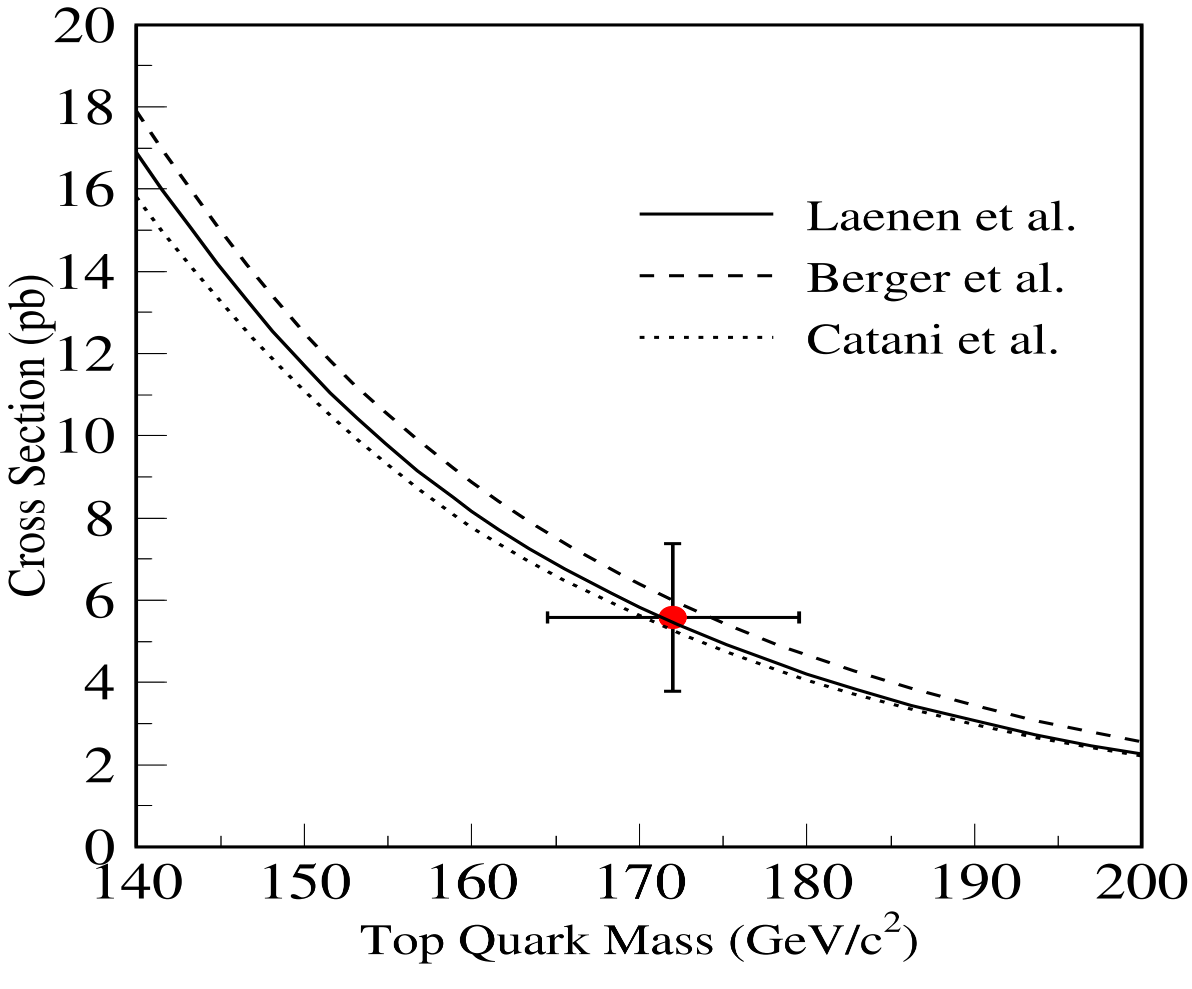
- Combined:

$$\boxed{m_t = 168.4 \pm 12.3(\text{stat.}) \pm 3.7(\text{syst.})\ \text{GeV}/c^2}$$

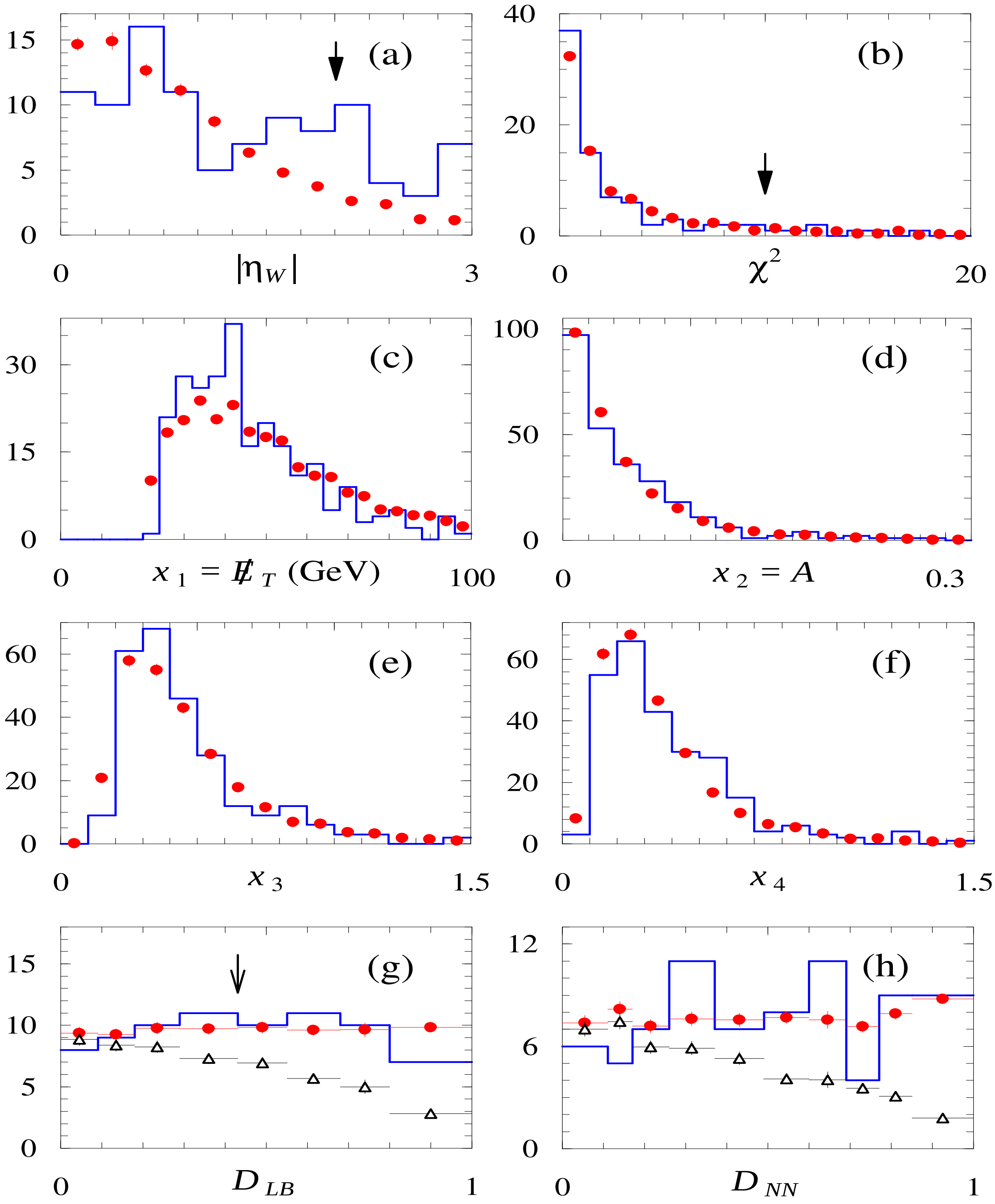
III. Summary

- lj: $m_t = 173.3 \pm 5.6(\text{stat.}) \pm 6.2(\text{syst.})\ \text{GeV}/c^2$.
- ll: $m_t = 168.4 \pm 12.3(\text{stat.}) \pm 3.7(\text{syst.})\ \text{GeV}/c^2$.
- Combined:

$$\boxed{m_t = 172.0 \pm 5.1(\textbf{stat.}) \pm 5.5(\textbf{syst.})\ \textbf{GeV}/c^2}$$

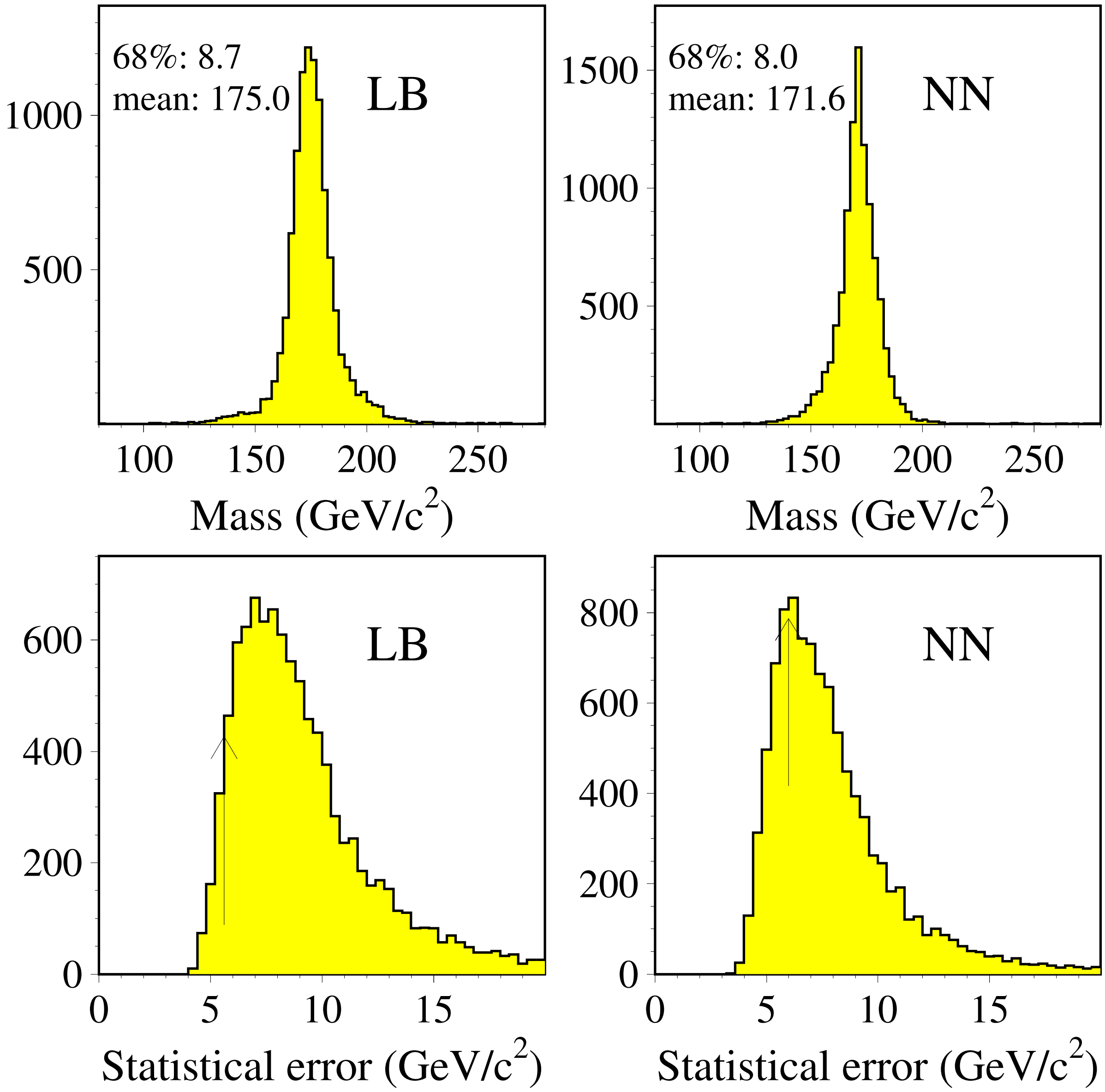


Comparison of Data and Predictions



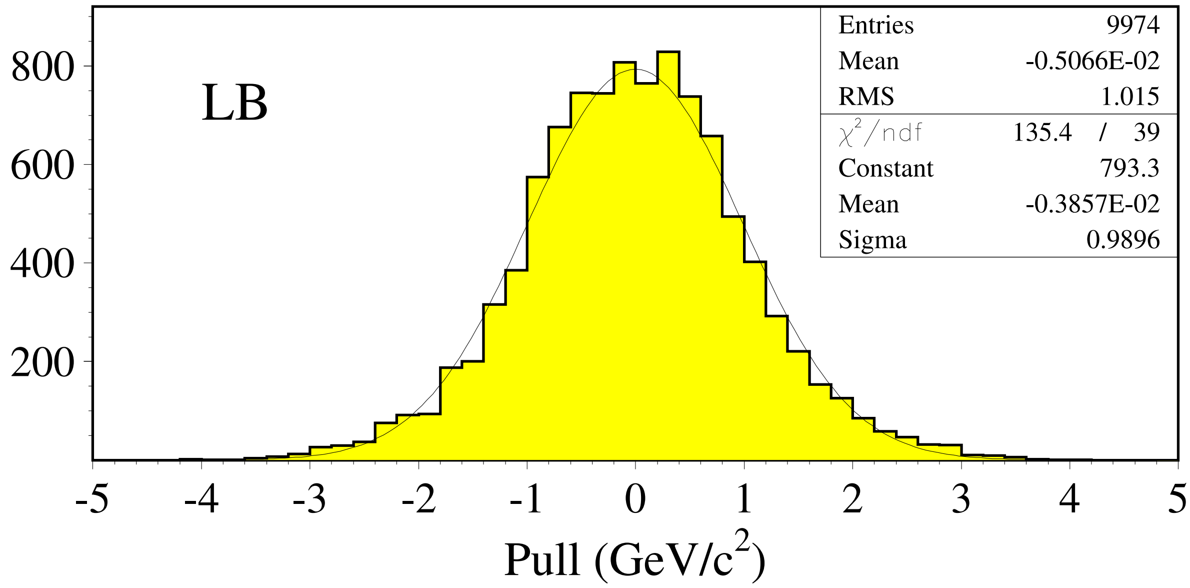
Monte Carlo Checks

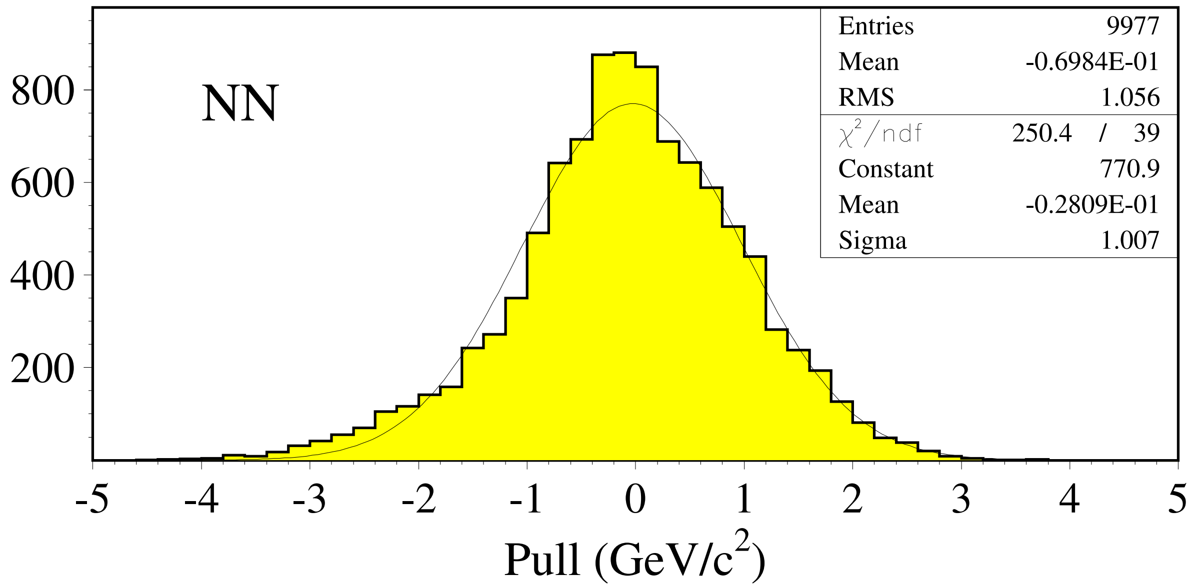
- Inputs:
  - LB: $m_t = 175\,\mathrm{GeV}/c^2$, $\langle n_s \rangle = 24$, $\langle n_b \rangle = 53$.
  - NN: $m_t = 172\,\mathrm{GeV}/c^2$, $\langle n_s \rangle = 29$, $\langle n_b \rangle = 48$.



Monte Carlo Checks

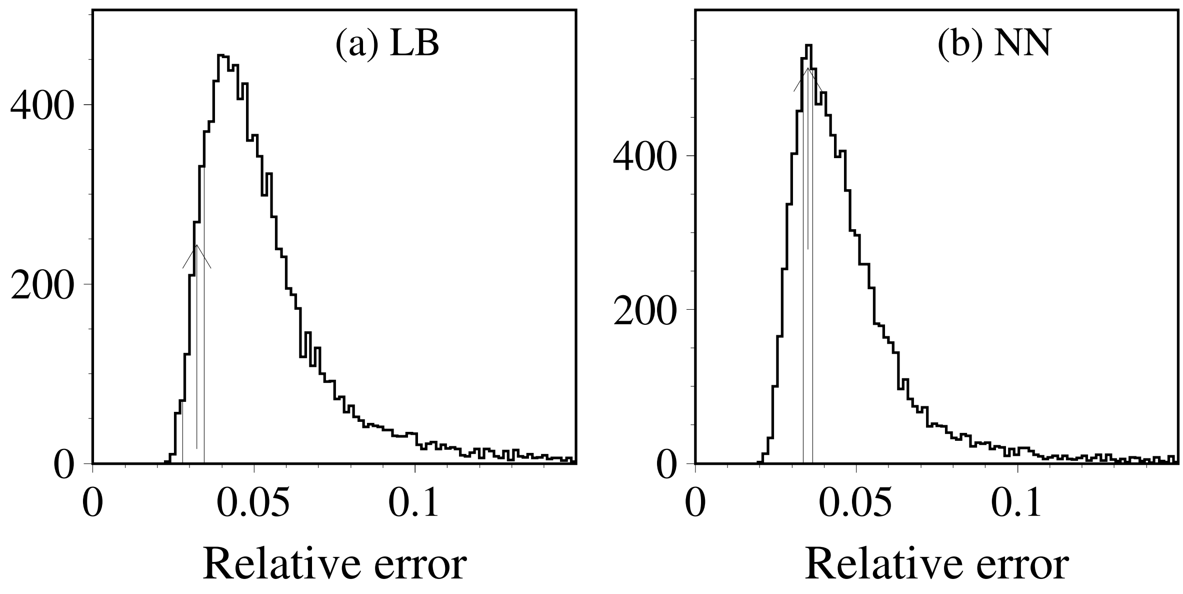
- Pulls: $m - m_{\text{true}}/\sigma_m$.



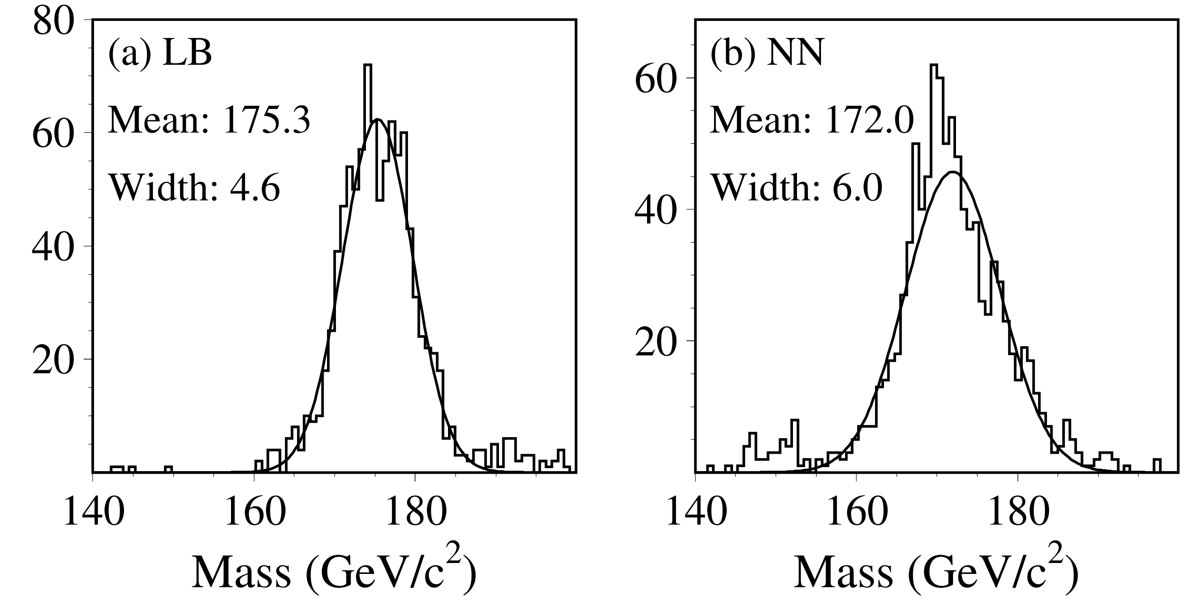


Ensemble Subsets

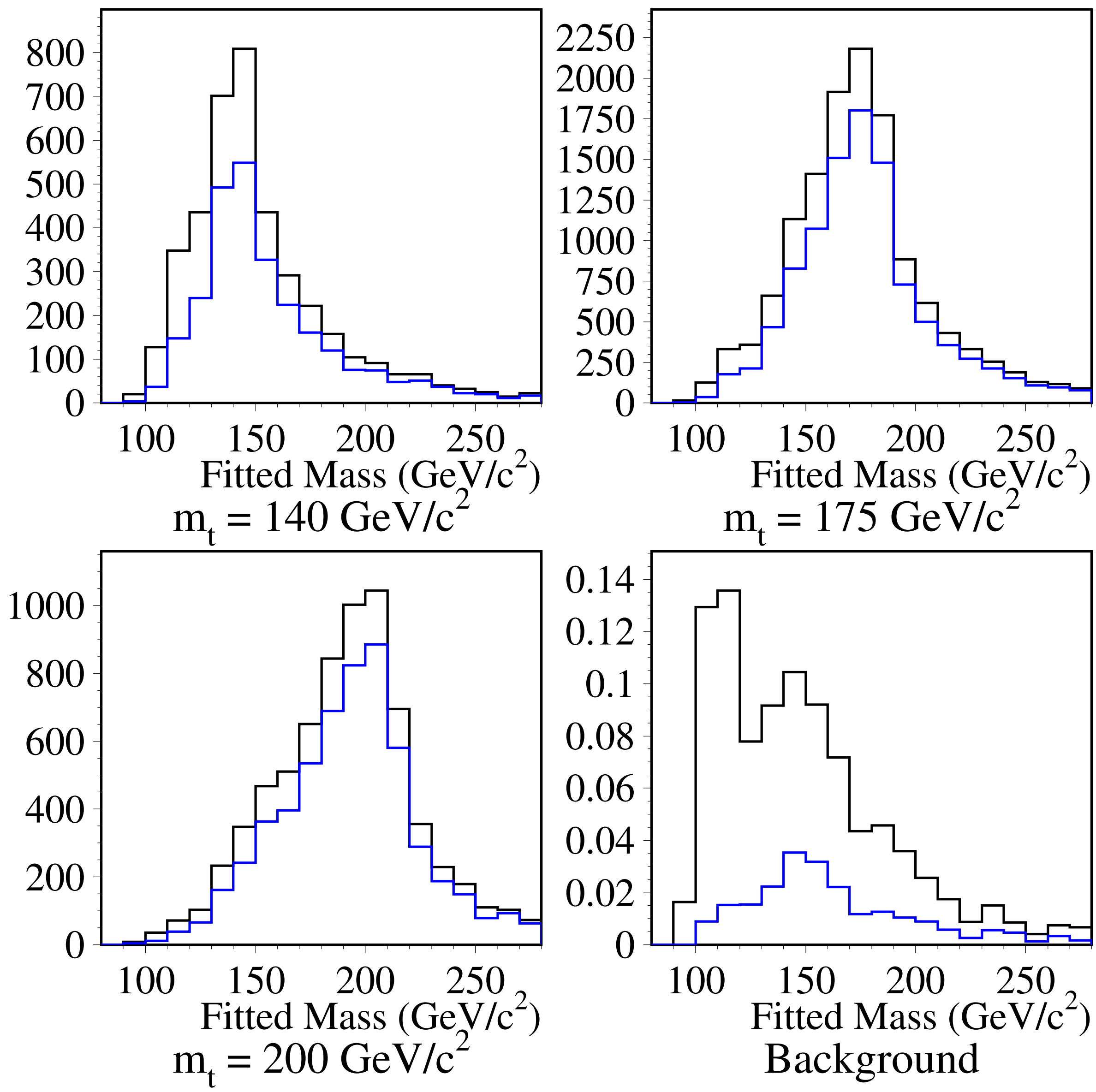
- Define subsets using relative error distributions.



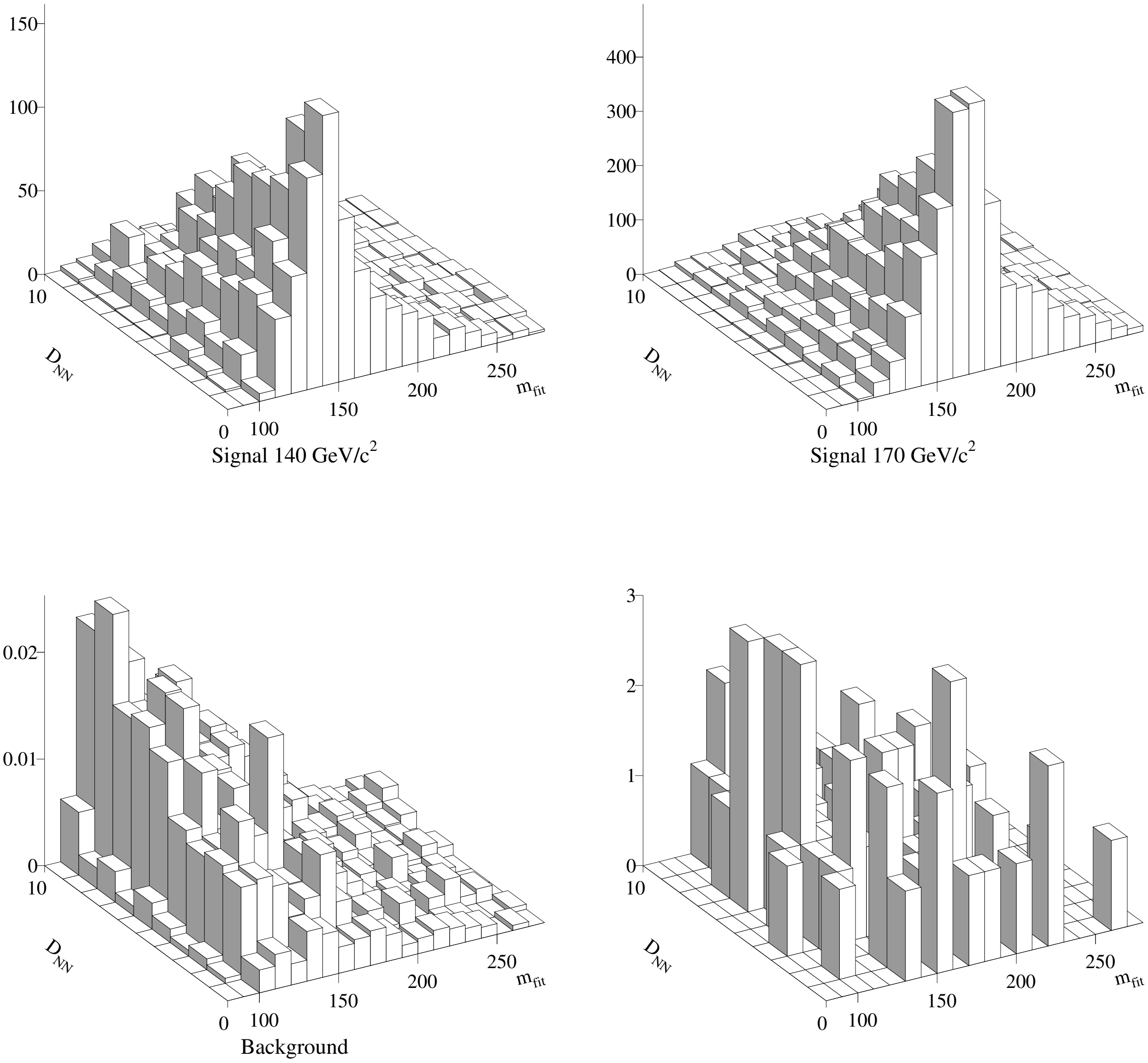
- Subset mass distributions.



Resolution Histograms



Resolution Histograms



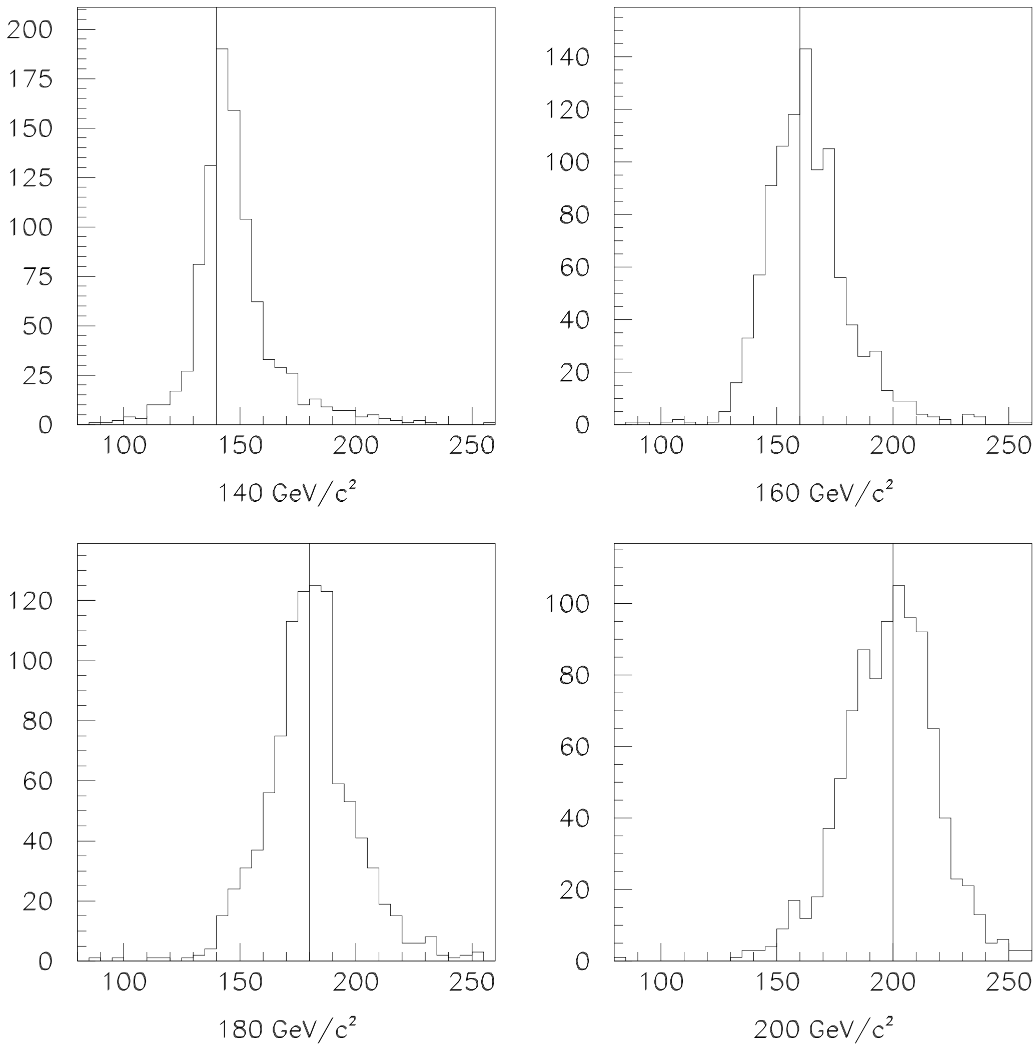
Dilepton Subsample Results

Channels Fit	MWT	νWT
$ee + e\mu + \mu\mu$	168.1 ± 12.4 GeV/c^2	169.9 ± 14.8 GeV/c^2
$ee + e\mu$	167.9 ± 12.6 GeV/c^2	173.2 ± 14.0 GeV/c^2
$e\mu$	173.1 ± 13.3 GeV/c^2	170.1 ± 14.5 GeV/c^2

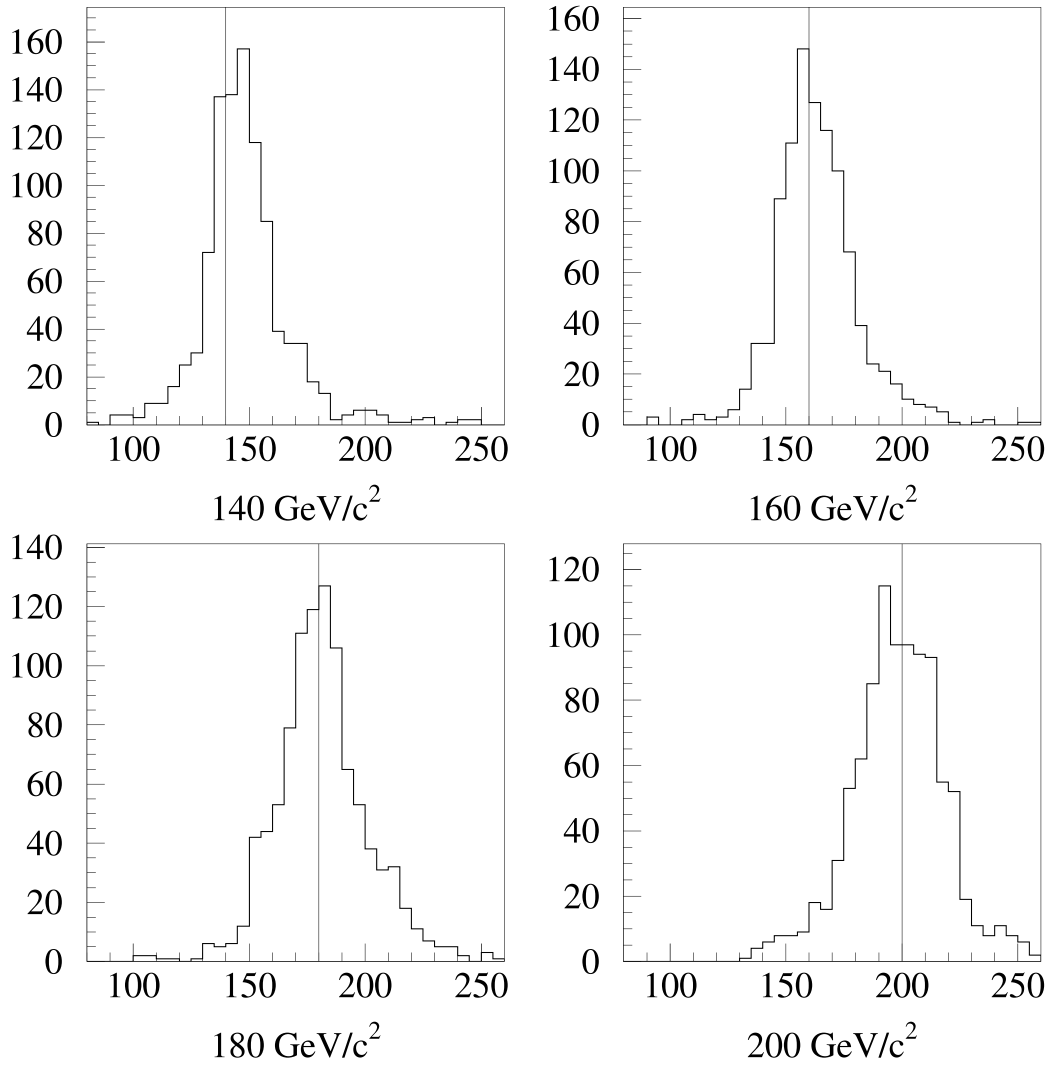
Dilepton Ensemble Results

	MWT		νWT	
MC Mass	Median	Width	Median	Width
140	144.6	12.7	145.9	13.9
150	151.6	12.8	151.9	13.6
160	161.6	15.8	161.5	14.4
170	172.2	16.7	172.2	16.2
180	180.5	17.3	180.5	18.1
190	189.5	17.8	188.7	17.7
200	200.3	19.5	198.8	18.9

MWT Ensemble Distributions

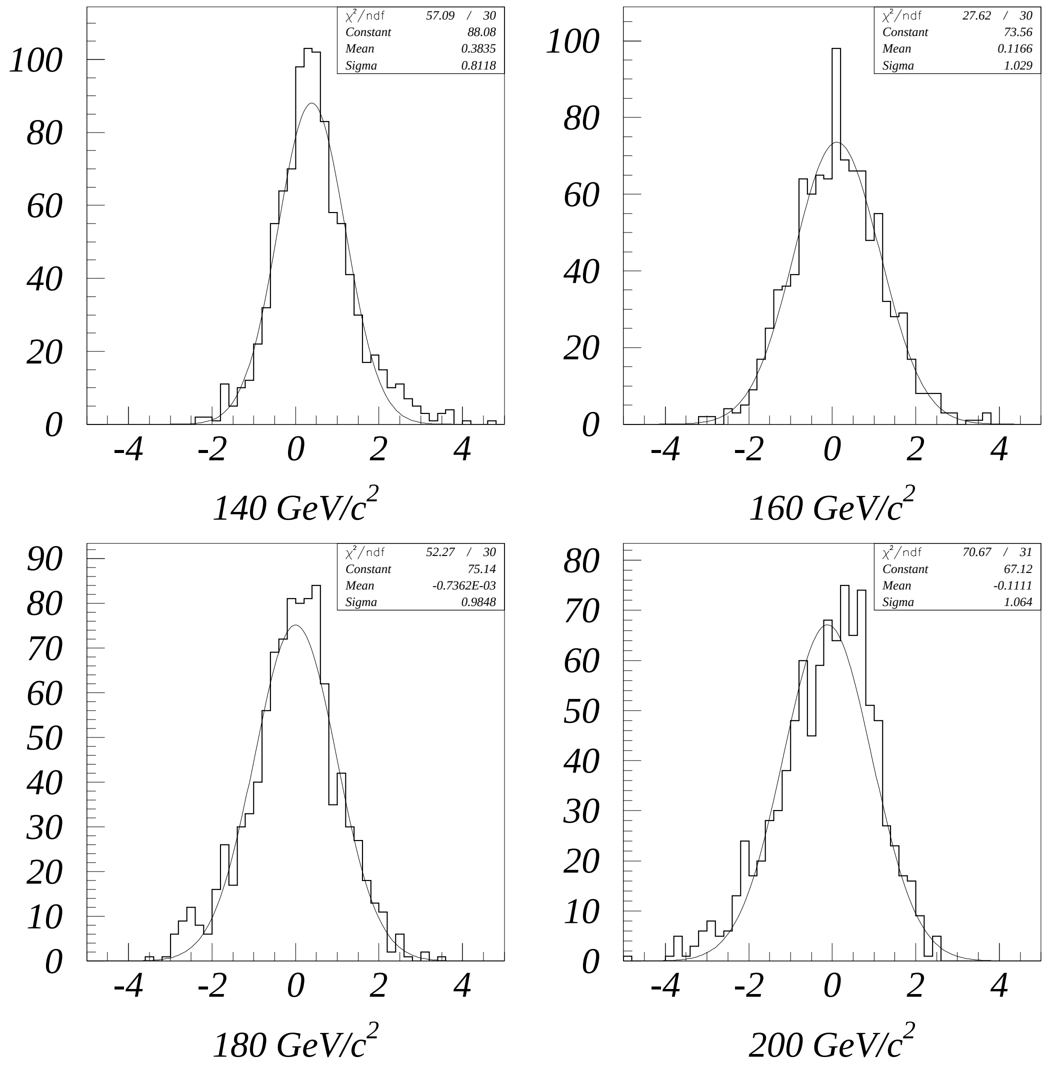


νWT Ensemble Distributions

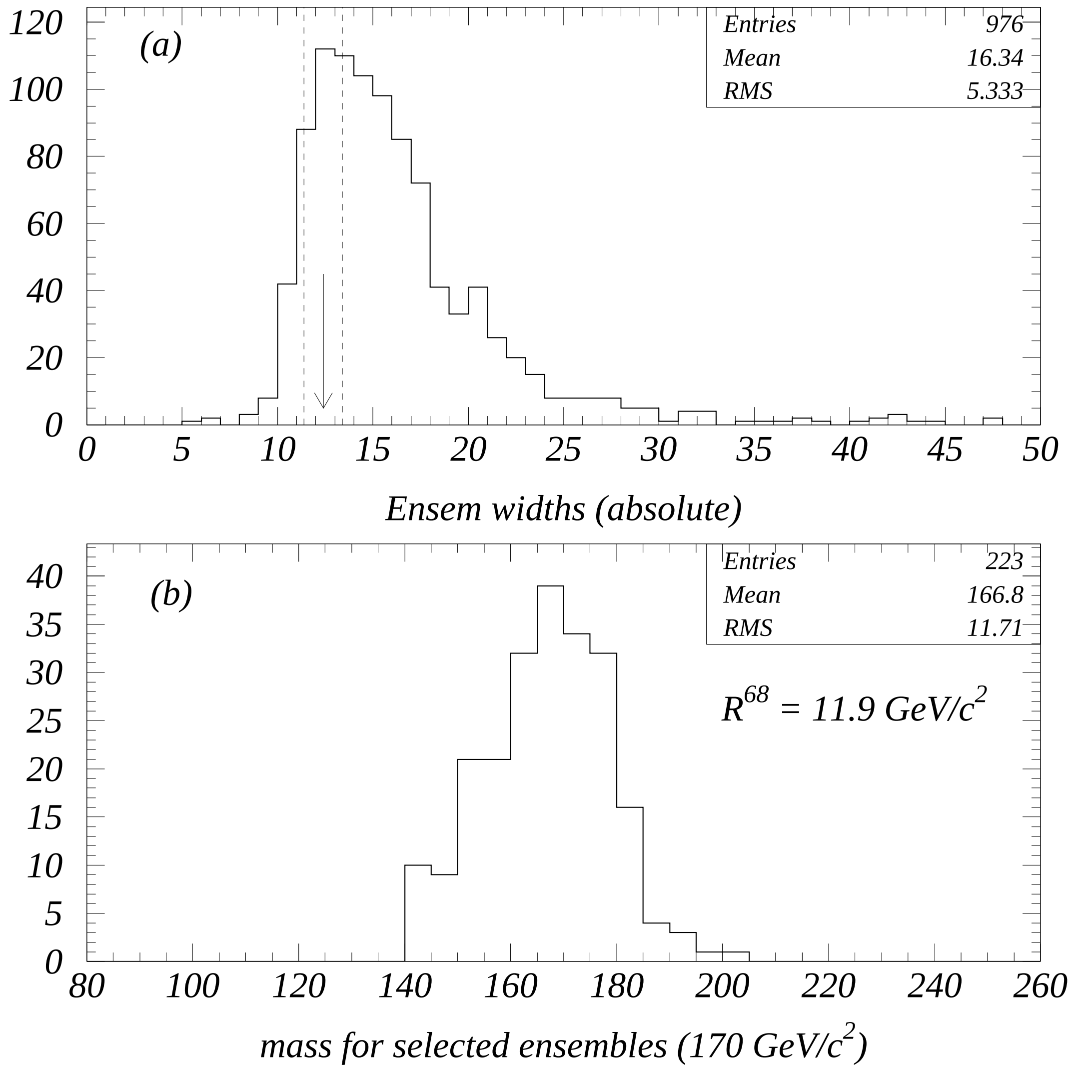


Dilepton Pull Distributions

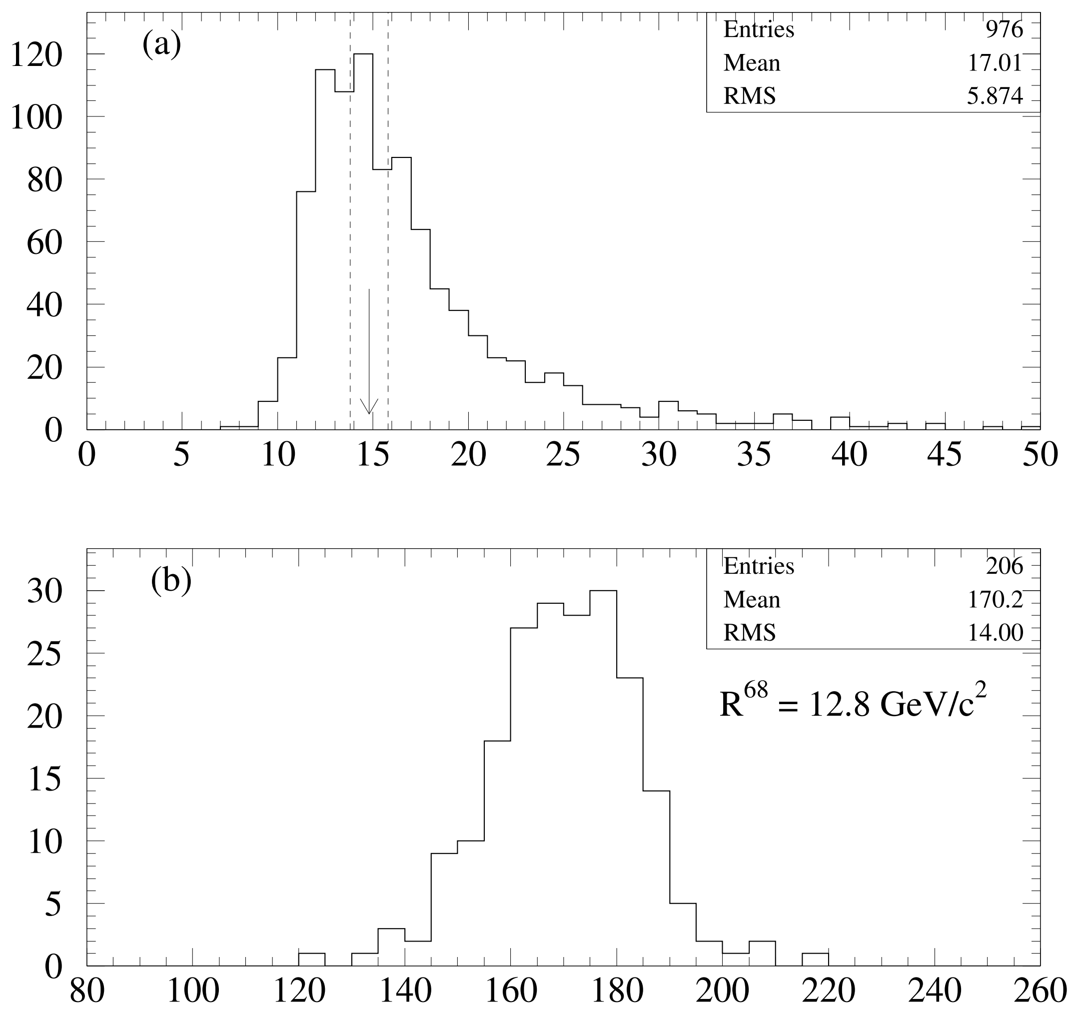
- For MWT analysis.



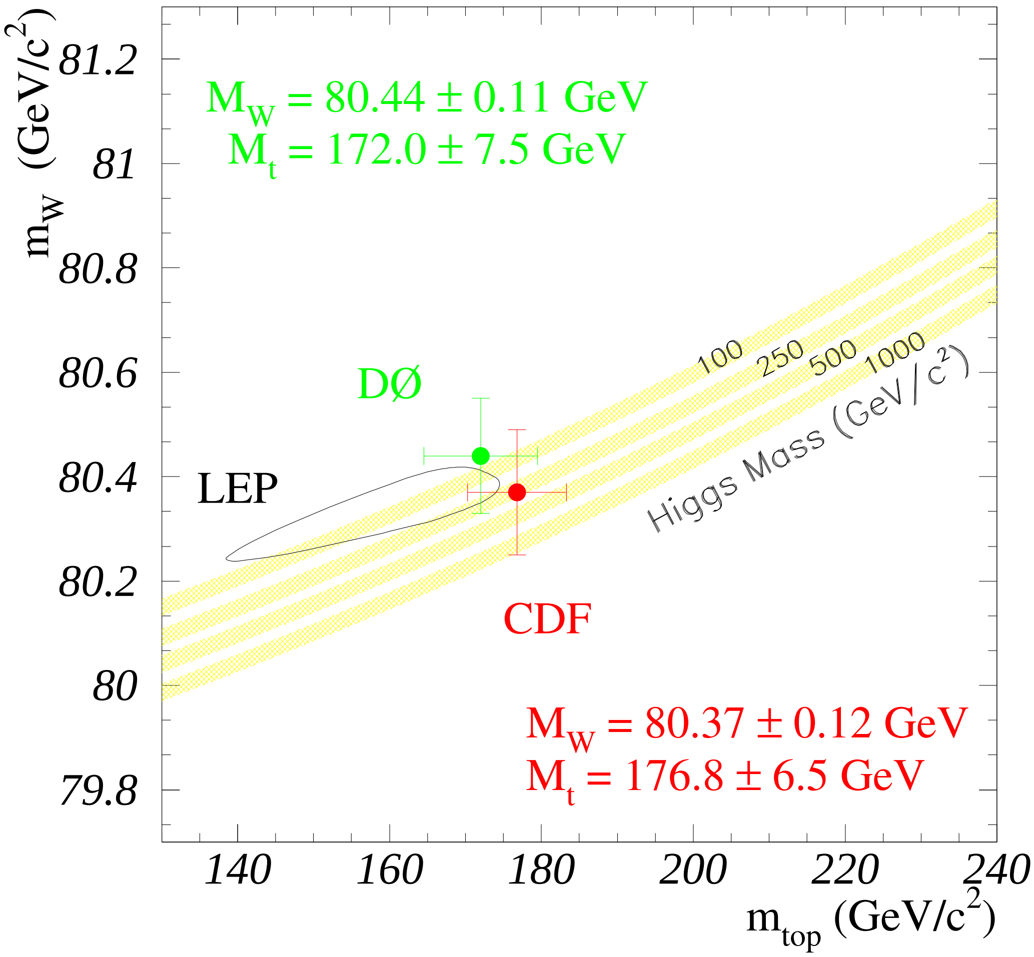
MWT Ensemble Errors



νWT Ensemble Errors



M_W versus m_t



M_W = 80.44 ± 0.11 GeV
M_t = 172.0 ± 7.5 GeV
DØ
LEP
CDF
M_W = 80.37 ± 0.12 GeV
M_t = 176.8 ± 6.5 GeV
100
250
500
1000
Higgs Mass (GeV/c²)
m_W (GeV/c²)
81.2
81
80.8
80.6
80.4
80.2
80
79.8
140
160
180
200
220
240
m_{top} (GeV/c²)