Top Mass Measurements at CDF

BEACH 2004, Chicago, July 2

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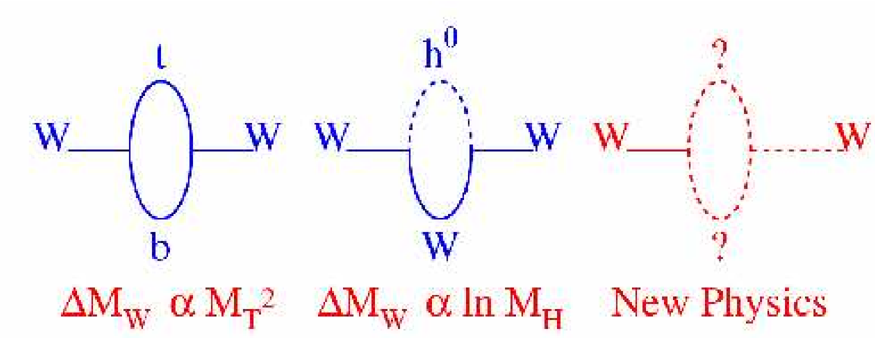
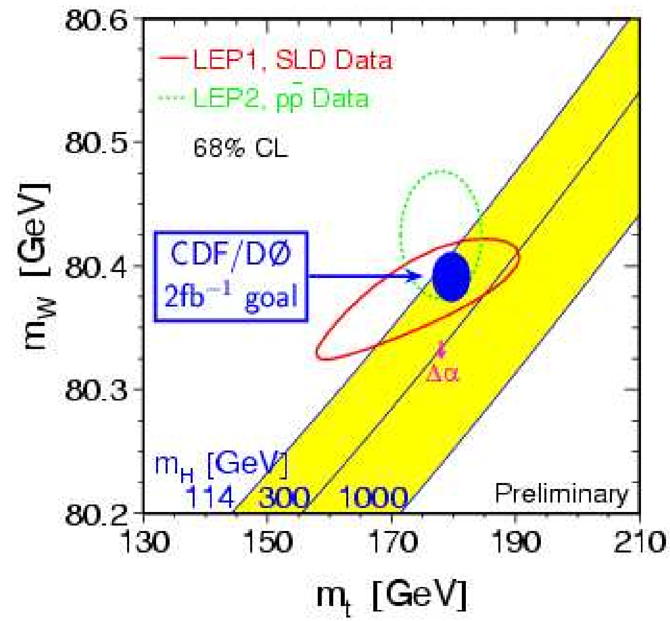
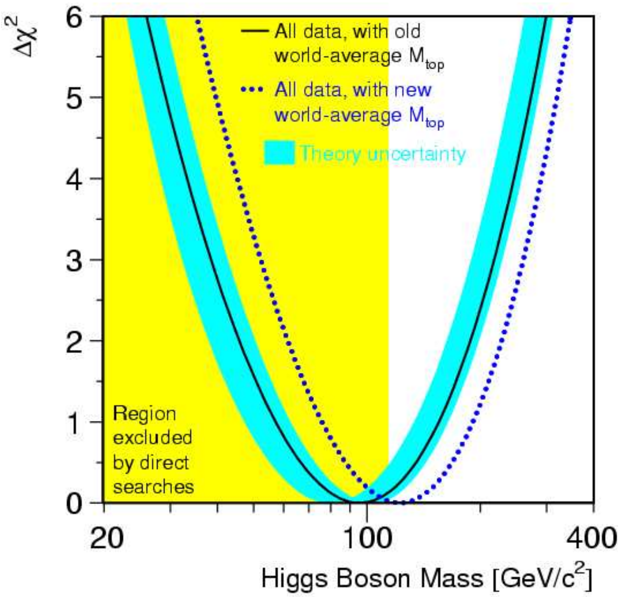
for the CDF Collaboration

Why Measure the Top Mass?

- Fundamental parameter
- Correlated to other SM parameters via electroweak corrections







Updated m_t world average:

[Nature 429 (2004) 638]

$m_t = 178.0 \pm 4.3$ GeV/c^2 (old: 174.3 ± 5.1GeV/c^2)

Updated constraint on Higgs mass:

$m_H = 113^{+62}_{-42}$GeV/c^2 (old: 96^{+60}_{-38}GeV/c^2)

$m_H < 237$GeV/c^2 (old: $m_H < 219$GeV/c^2)

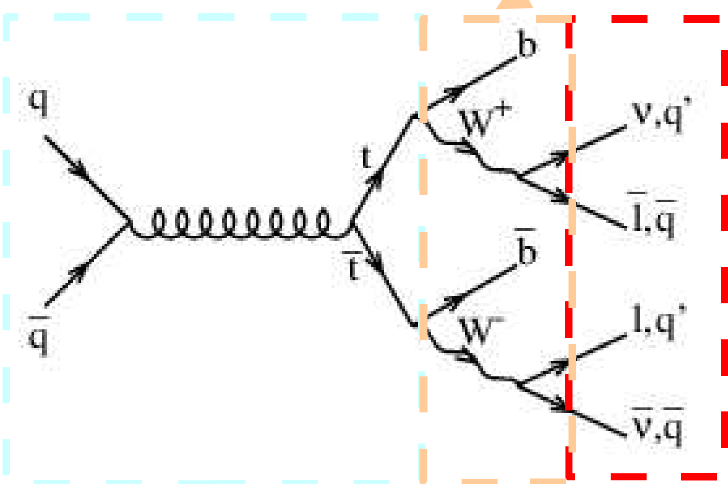
Precise measurement provides stringent SM tests

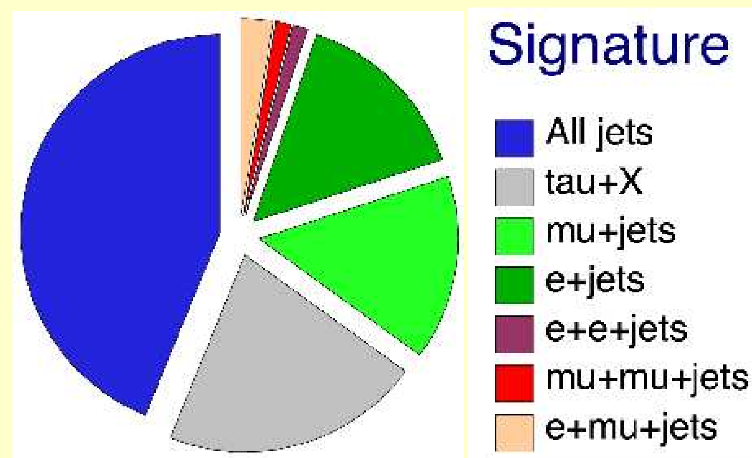
SM Top Quark Signatures

Top Production (Tevatron):
mainly in pairs via
85% $q\bar{q}$ annihilation
15% gg fusion
$\sigma_{t\bar{t}}$(1.96TeV)~6.7pb (theory)

Top Decay:
$\tau \sim 10^{-24}$sec
$t \rightarrow Wb$
BR~99.9%

W Decay:
defines top event signature
$W \rightarrow q\bar{q}'$ hadronic (BR=6/9)
$W \rightarrow l\nu$ leptonic (BR=3/9)

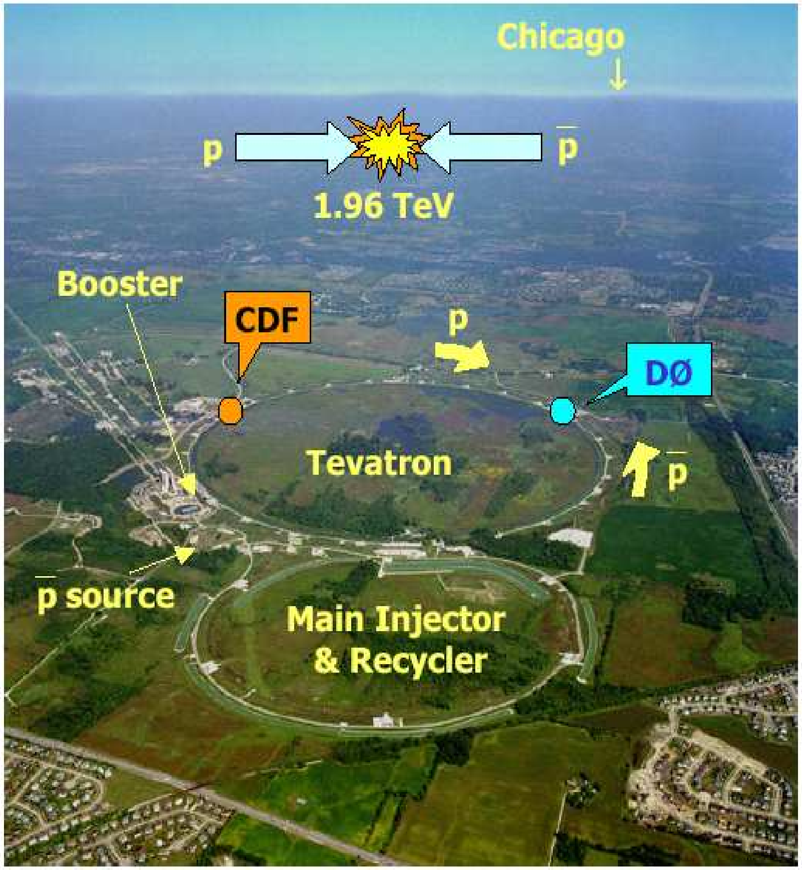




General Event Topology:
- spherical events ($t\bar{t}$ production near threshold)
- 2 b jets from top quarks (crucial for ident.)
- jets/leptons with high transverse energy E_T
- large missing E_T in leptonic decay modes

CDF II Top Mass Measurements:
Dilepton: 2 e/μ, 2 jets, large miss. E_T
(BR=5%, S/B~10)
Lepton+Jets: 1 e/μ, 4 jets, large miss. E_T
(BR=30%, S/B~1)

Tevatron Run II

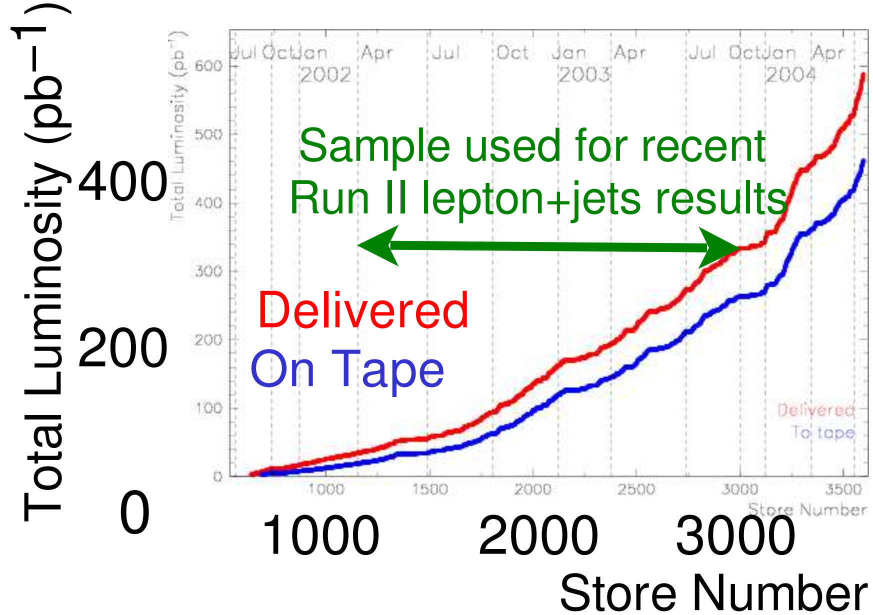


CM energy 1.96TeV (Run I: 1.8TeV)
Increase of $t\bar{t}$ cross section by ~30%

Substantial increase of luminosity:
Record: ~$8\text{x}10^{31}\text{cm}^{-2}\text{s}^{-1}$

Total on tape (now): 460 pb^{-1}
Analysis samples:
- Dileptons: 126 pb^{-1}
- Lepton+Jets: 162 pb^{-1}
  (with at least 1 SVX tag)

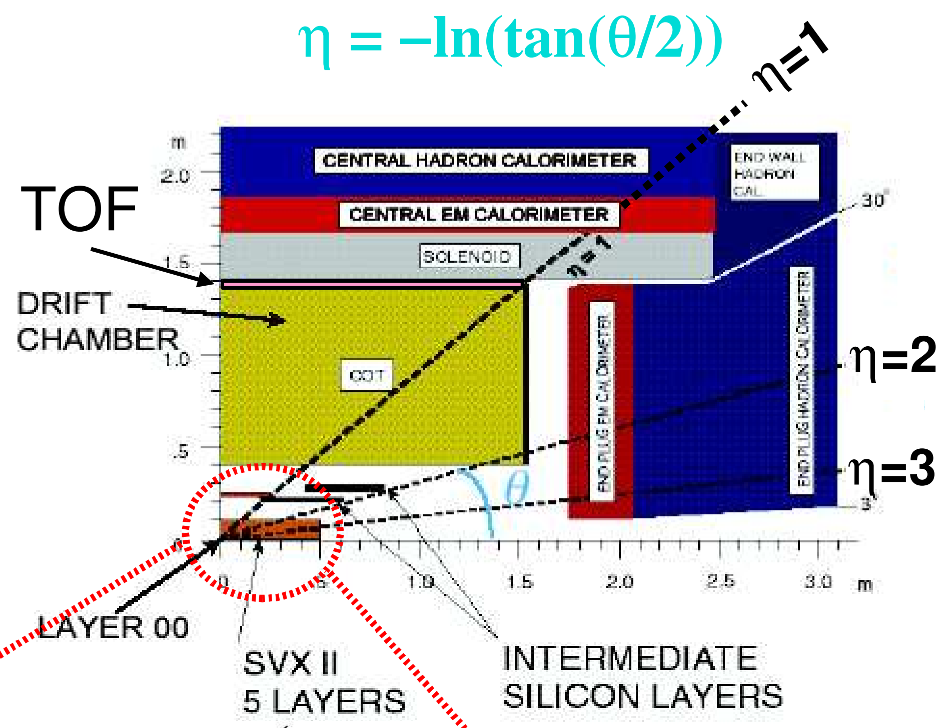
CDF II integrated luminosity



Top Event Selection (Lepton+Jets)

CDF II detector:

- Calorimeter (EM, HAD)
- Tracking system
- Vertex detector

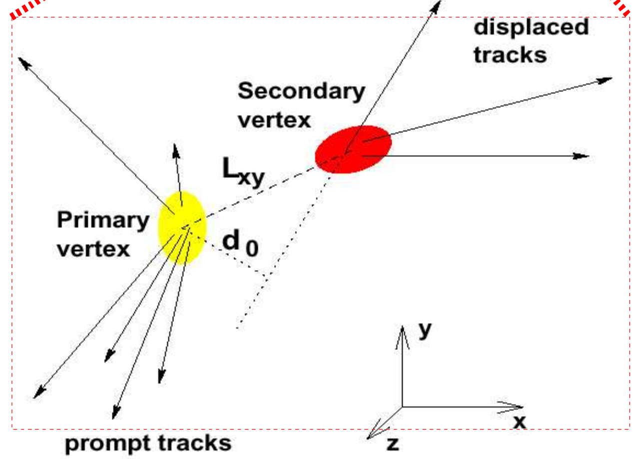


Basic kinematical cuts:

1. One lepton E_T>20 GeV
2. Missing E_T>20GeV
3. Four jets E_T>15GeV, $|\eta| < 2$ (depend on analysis)
4. At least one SVX tag

SVX b jet tagging:

Identification of **displaced decay vertices** from long–lived B–hadrons



$L_{xy}/\sigma \geq +3$ (σ~150 μm)

$t\bar{t}$ tag efficiency: 55%

$t\bar{t}$ fake rate: 0.5%

Methods

I. Template Method (**TM**) (= Run I Method):

- Kinematic fitter to reconstruct top mass
- Kinematic constraints
- Use ''best'' of 12 combinations (4 if double b tag)
  (6 jet–quark combinatorics, 2 neutrino solutions)
- 1–dimensional templates parametrized as function of top mass

II. Multivariate Template Method (**MTM**):

- Refined kinematic fitter with jet energy scale optimization
- Kinematic constraints
- Use ''best'' of 12 combinations (4 if double b tag),
  Weight according to correct permutation probability
- Multidimensional non–parametric templates

III. Dynamical Likelihood Method (**DLM**):

- Matrix element likelihood
- Use all 12 combinations (4 if double tag)
- Use calorimeter transfer functions

Template Method (TM)

Reconstruct invariant top mass for each event

- Minimize χ^2 expression, kinematic constraints
  $m_t = m_{\bar{t}}$, $M_{W^+} = M_{W^-}$, $p_{t\bar{t}}$ balance;

$$\chi^2 = \sum_{\ell,jets} \frac{\left(\hat{P}_T - P_T\right)^2}{\sigma^2_{P_T}} + \sum_{i=x,y} \frac{\left(\hat{U}_i^! - U_i^!\right)^2}{\sigma^2_{U_i^!}} + \frac{(M_{\ell\nu} - M_W)^2}{\sigma^2_{M_W}} + \frac{(M_{jj} - M_W)^2}{\sigma^2_{M_W}} + \frac{(M_{\ell\nu j} - M_t)^2}{\sigma^2_{M_t}} + \frac{(M_{jjj} - M_t)^2}{\sigma^2_{M_t}}.$$

- Combinatorial problem: 12(4) solutions for 1(2) b tags
  2 p_z neutrino solutions, 6(2) jet–parton combinations;
  (we don't distinguish between q and q' from W decay); **Use smallest χ^2 solution;**

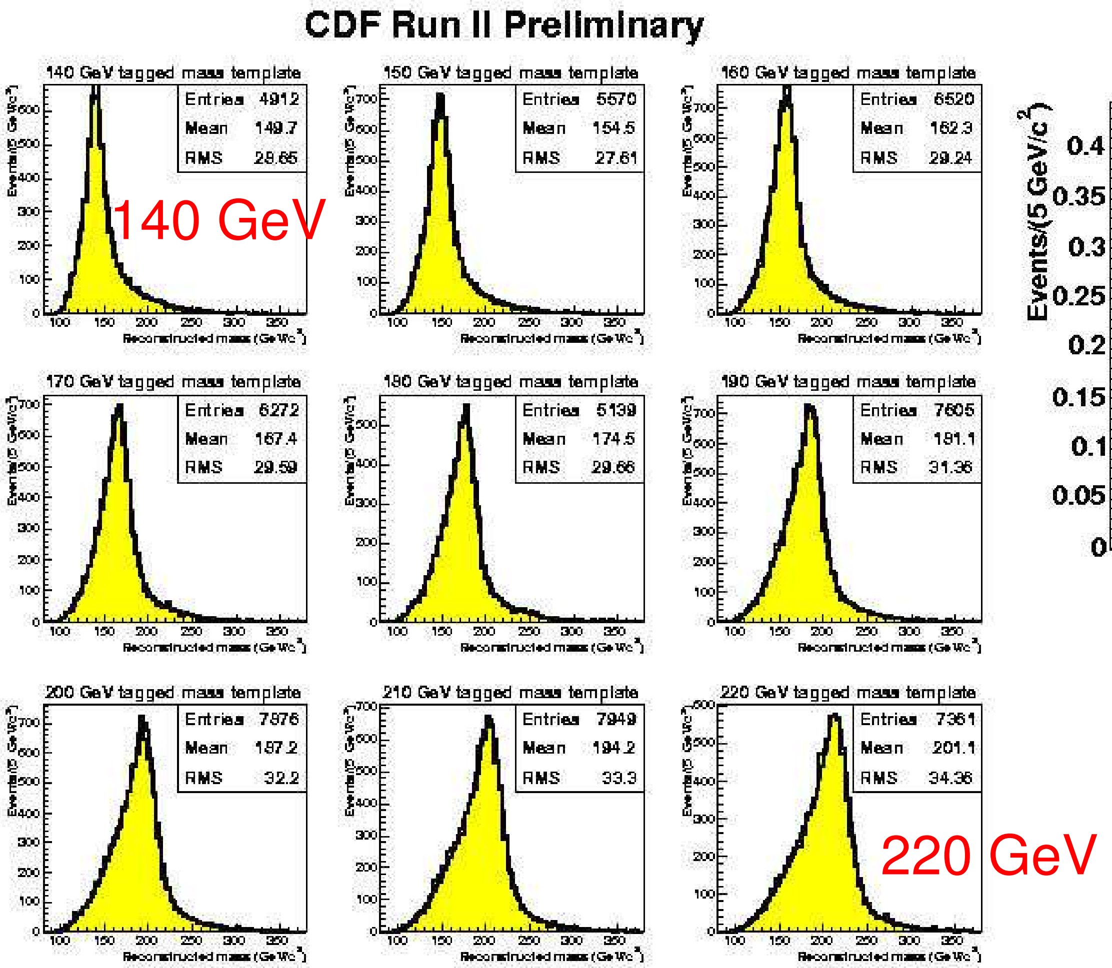
Build top mass templates from MC samples

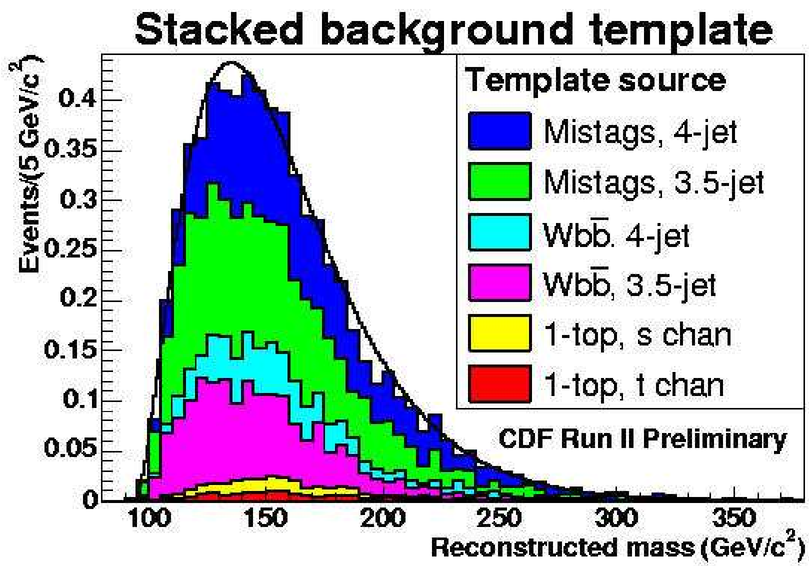
for signal process with different $\mathbf{m_t}$ and for the background processes;

Calculate top mass likelihood

- Use templates as probability densities to be compared with data in order to derive a top mass probability for each event
- Top mass is value of $\mathbf{m_t}$ which maximizes likelihood for the whole data sample = product of event–by–event top mass probabilities (**unbinned likelihood fit**)

TM Templates





Reconstructed invariant top mass

Signal:
- Herwig

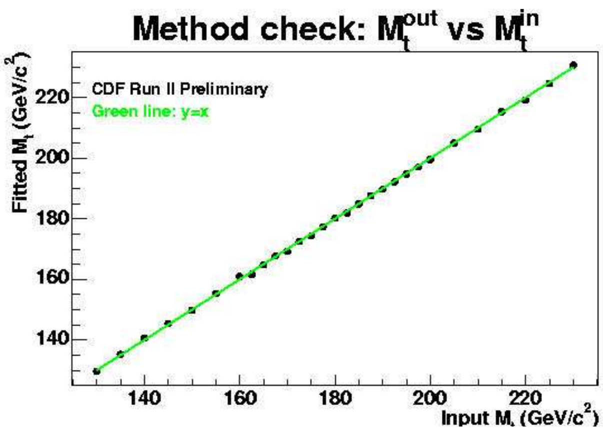
Background:
- Wbb̄ (Alpgen+Herwig)
- Single Top (Pythia)
- Mistags (W4p Alpgen+Herwig)

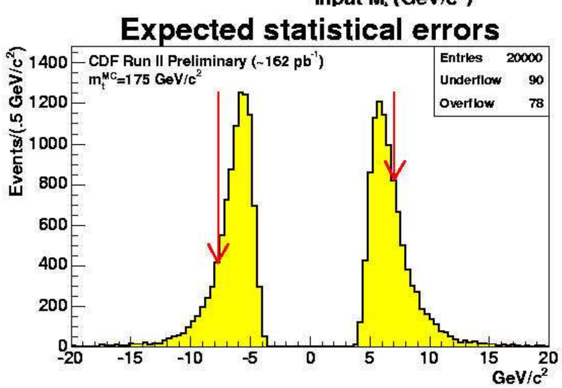
Signal templates are parametrized by continuous functions of m_t

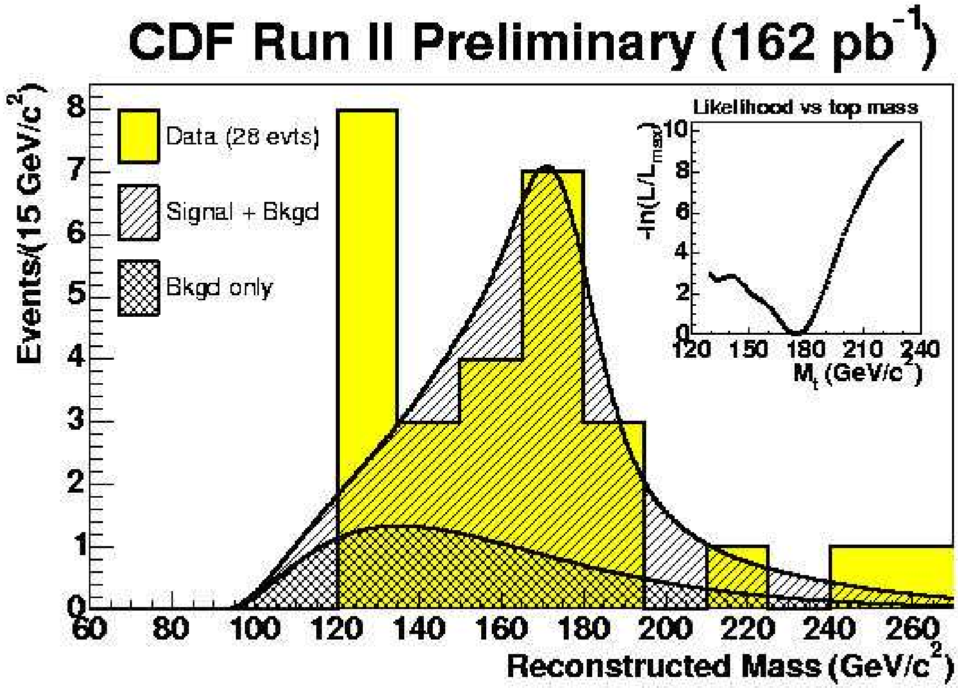
TM Results

28 $t\bar{t}$ candidate events

6.8 ± 1.2 background events
(expected value from cross section measurement)
... fixed in the fit







$$M_{top} = 174.9^{+7.1}_{-7.7}\,(\text{stat.}) \pm 6.5\,(\text{syst.})\ \text{GeV}/c^2$$

Jet energy systematic: ±6.3 GeV/c^2

Systematic Uncertainties

Jet energy systematics are by far dominant

Jet Energy Scale	6.3
Initial State Radiation	0.4
Final State Radiation	0.9
Parton Distribution Functions	0.2
Generators	0.4
Other MC Modeling	0.7
Background Shape	0.8
B-tagging	0.1
Total	6.5

Relative to Central	3.0
Central Calorimeter Response	4.6
Corrections to Hadrons (Absolute Scale)	2.2
Corrections to Partons (Out-of-Cone)	2.3
Total	6.3

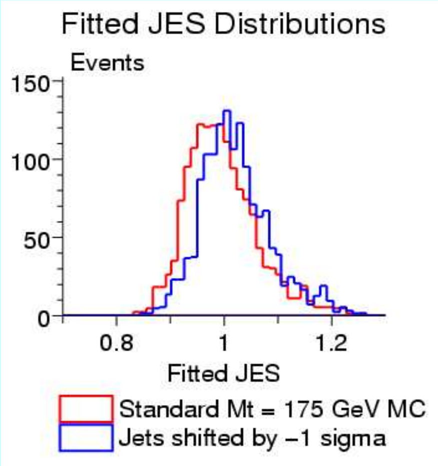
Preliminary, will be reduced soon!

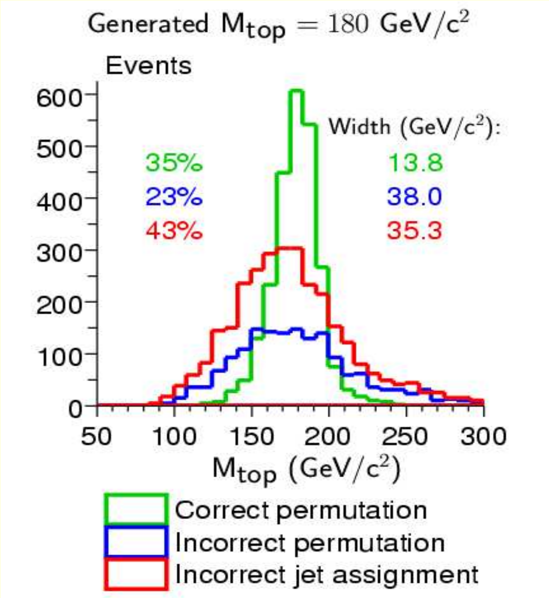
Multivariate Template Method (MTM)

1) Kinematic fitter for event reconstruction:

Includes adjustable jet energy scale factor (JES) to be calibrated in the reconstruction of the $W \rightarrow qq'$ decay by using W mass constraint; Multiply all jet energies with JES scale factor

- decrease of JES systematics
- increase of statistical error





2) Three types of signal templates:

- Correct permutation samples (**CP**)
- Incorrect permutation samples (**IP**)
- Incorrect jet assignment samples (**IJ**)

Uses information from fit and from tt production/decay dynamics to predict CP probability and to weight signal templates accordingly. Useful quantities are

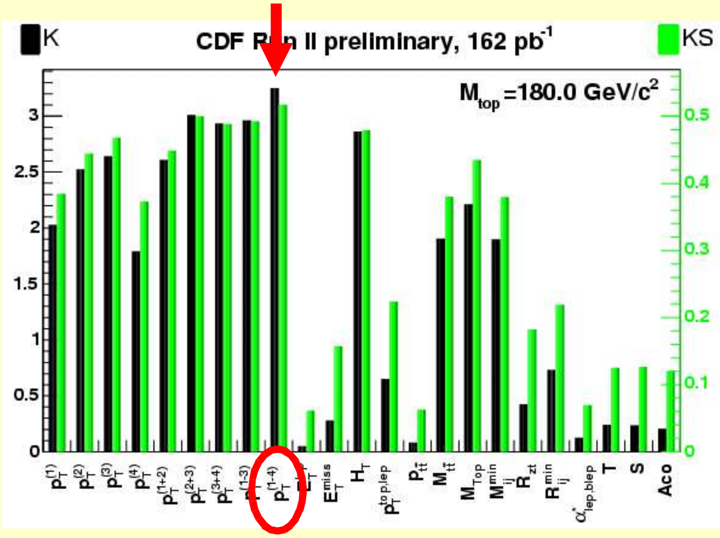
- fit χ^2(permutation i)$-\chi^2$(best permutation)
- cos∠(lepton, leptonic b) in W rest frame
- tt spin correlation term

"Knowledge" of template type improves mass resolution

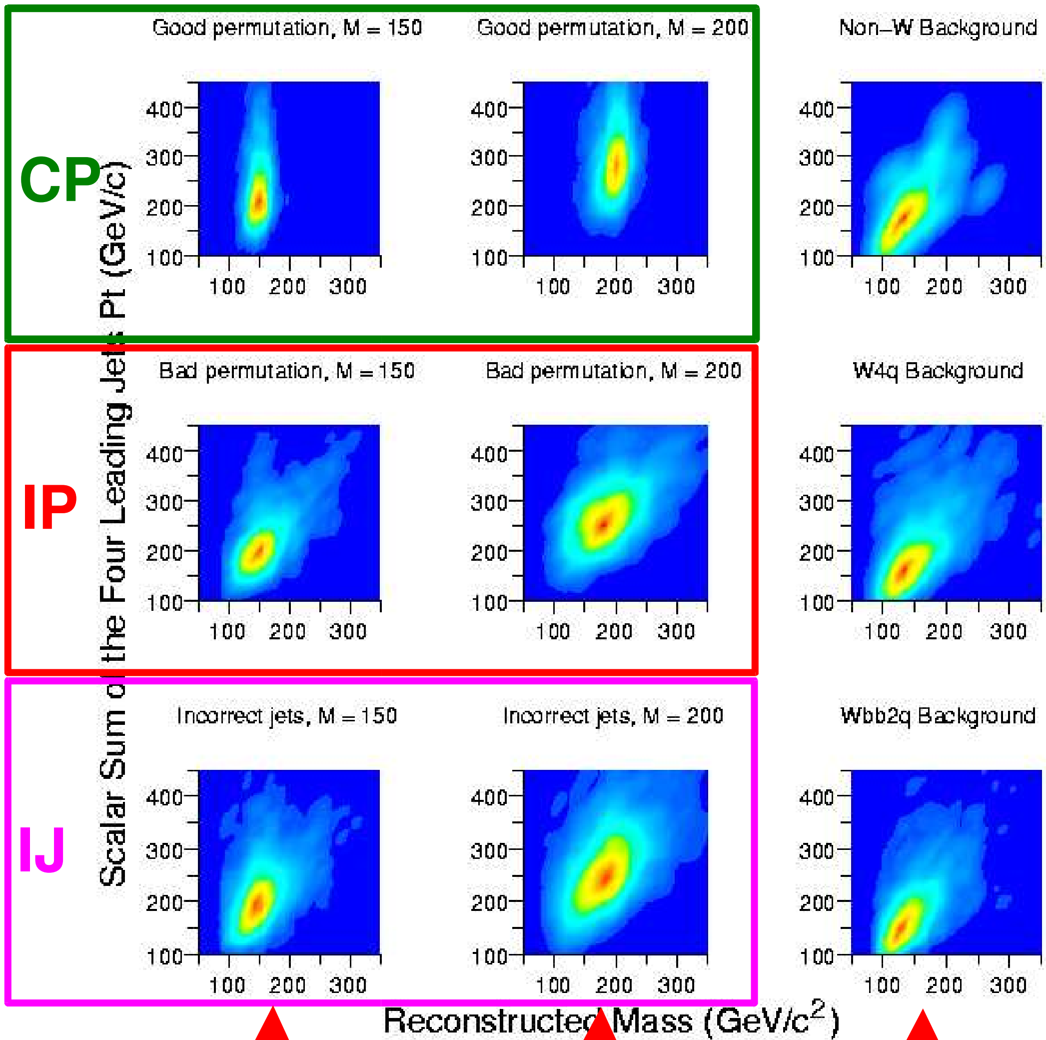
MTM Templates

3) Multivariate Templates:

- In addition to the reconstructed top variables are used to improve S/B separation (avoids hard cuts)
- Sum p_T of 4 leading jets favored by statistical divergence measures



- Kernel Density Estimation is used to create probability densities (non–parametric density reconstruction technique)

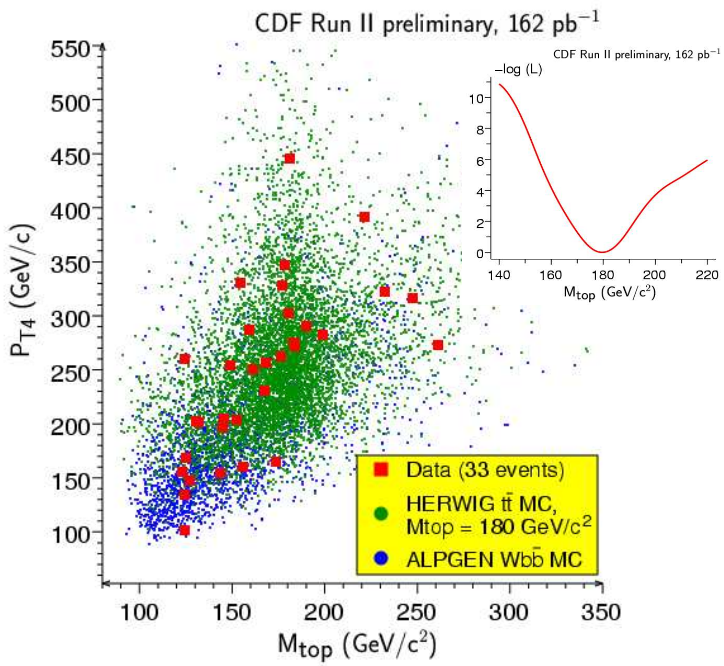


signal m_t=150 GeV

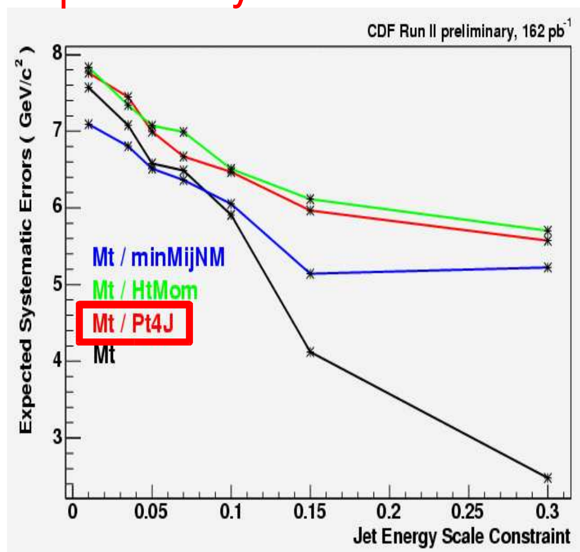
signal m_t=200 GeV

various backgrounds

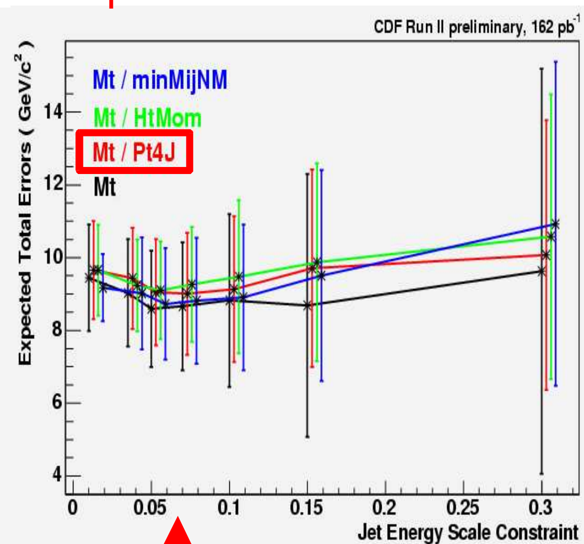
MTM Results



Expected systematic errors:



Expected total errors:



33 candidate events

$$M_{top} = 179.6^{+6.4}_{-6.3} \text{ (stat.)} \pm 6.8 \text{ (syst.) GeV/c}^2$$

Fitted background fraction:

f=0.34±0.14

- JES constraint in kinematic fit can be used to treat with systematic errors
- JES constraint optimized w.r.t. total error
- Several variable sets with similar performance; use the one with best S/B discrimination
- JES constraint more important in the future as statistical error decreases

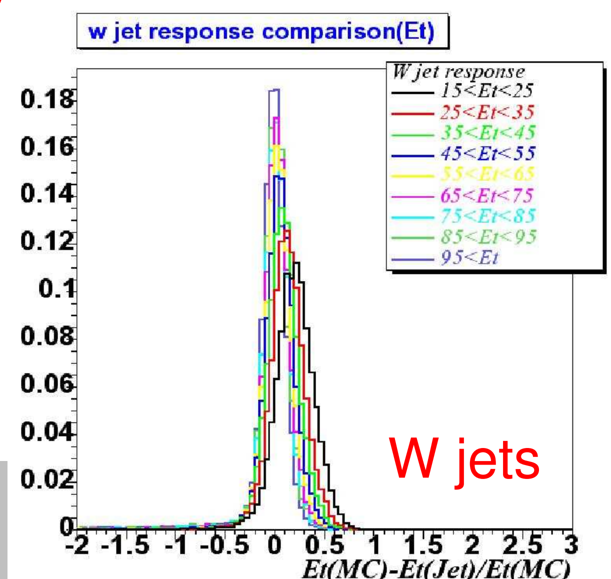
Dynamical Likelihood Method (DLM)

DLM is **original CDF method** (K. Kondo, J. Phys. Soc. 57 (1988) 4126)
It attempts to use as much amount of info on top quarks provided by SM

Top mass likelihood for i^{th} event:

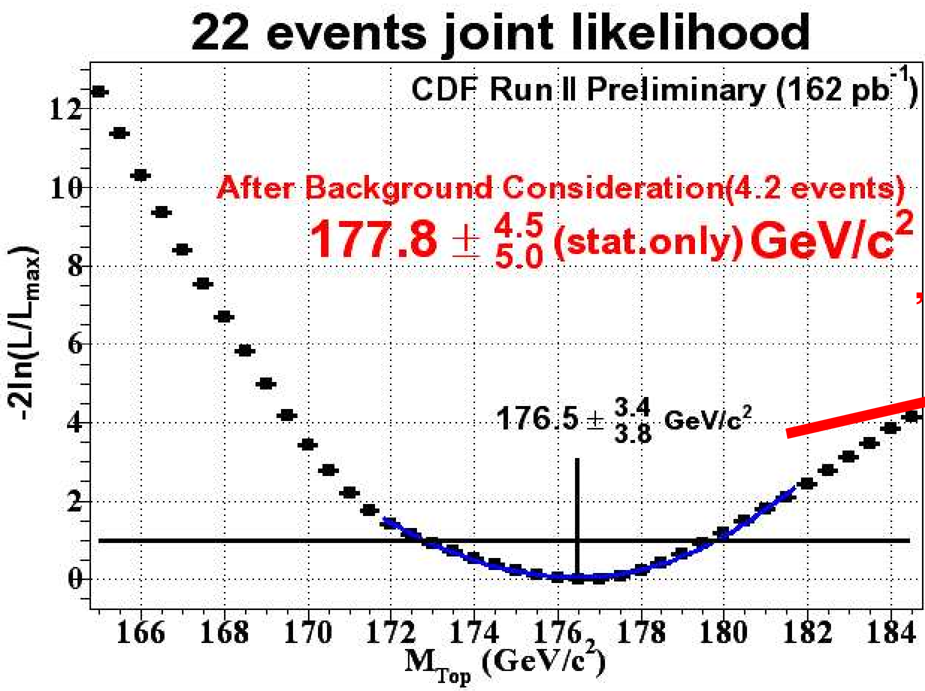
$$L^{(i)}(m_t) = \int \sum_{perm} \sum_{\nu sol.} \frac{2\pi^4}{\text{flux}} |\mathcal{M}|^2 F(z_1, z_2) f(p_t) w(\mathbf{x}, \mathbf{y}; m_t) \mathrm{d}\mathbf{x}$$

- Parton distribution function: $F(z_1, z_2)$
- Probability of p_T of tt system: $f(p_t)$
- Production/Decay Matrix Element: $|\mathcal{M}|^2$
  Signal only, no bkg M.E. ... correct for this!
- Transfer function for jet energies: $w(\mathbf{x}, \mathbf{y}; m_t)$
  Bayesian probability that *x* was generated when y was reconstructed (derived from $t\bar{t}$ MC)
  - are expressed as function of
    (E(parton)–E(jet))/ E(parton)
  - are dependend on jet type (W or b jet)
  - are parametrized in jet E_T and η bins

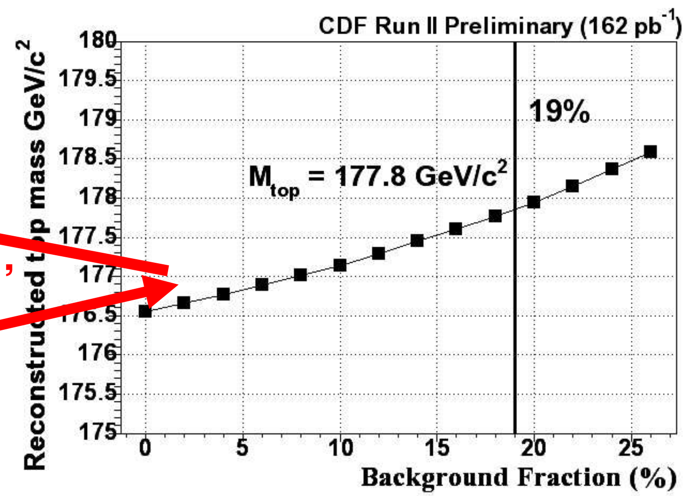


To obtain top mass, maximize $\prod_i L^{(i)}(m_t)$

DLM Results



"mapping"



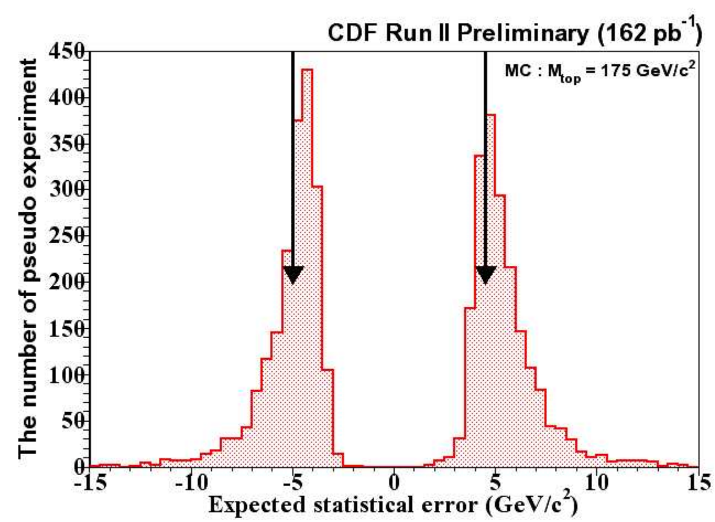
22 candidate events

Background fraction : 19%

After applying mapping function

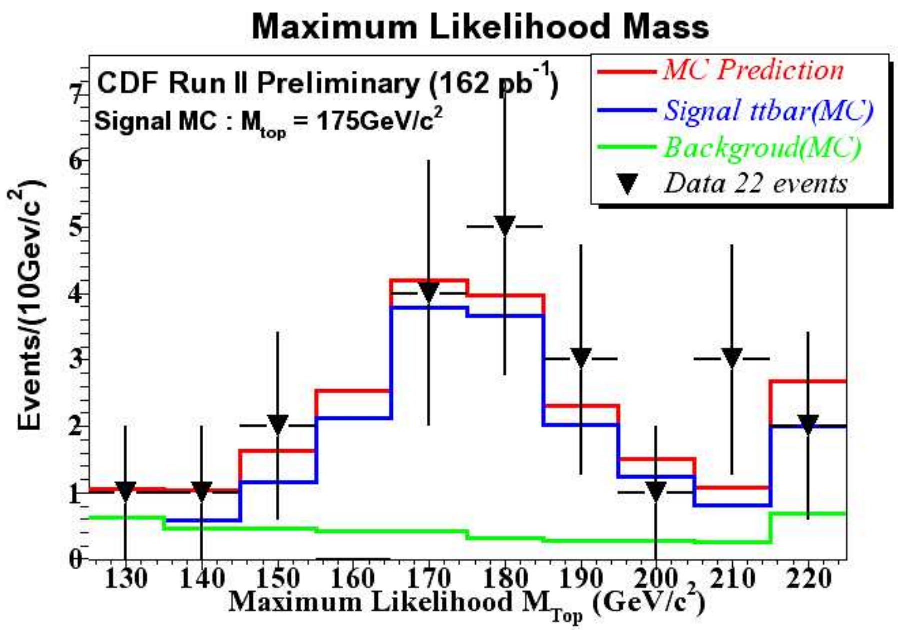
(errors scaled accordingly):

$$M_{top}=177.8^{+4.5}_{-5.0}\text{(stat.)}\pm 6.2\text{ (syst.) GeV/c}^2$$



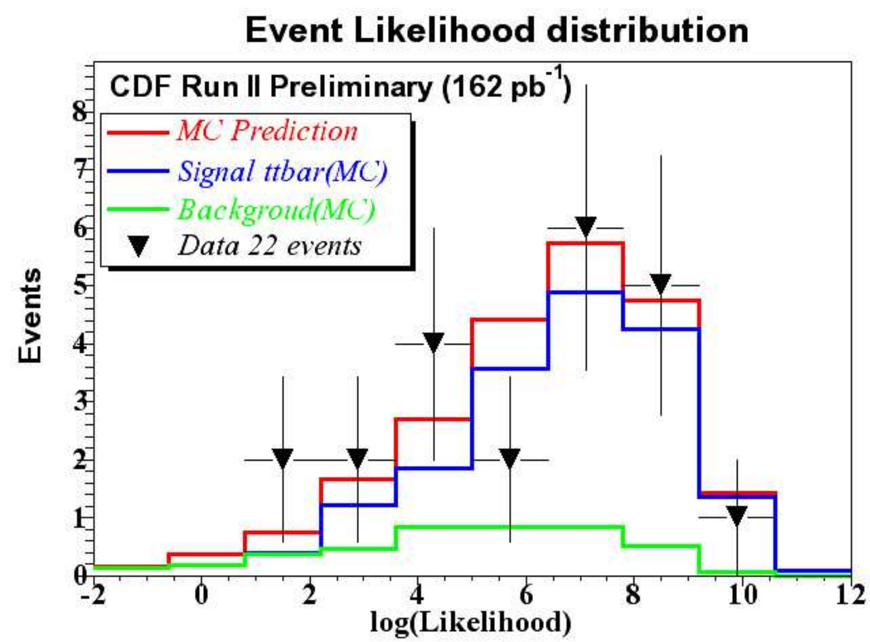
DLM Event–by–Event

Event–by–Event maximum likelihood mass



Event Likelihood

$$L^{(i)}=\int L^{(i)}(M)\mathrm{d}M$$



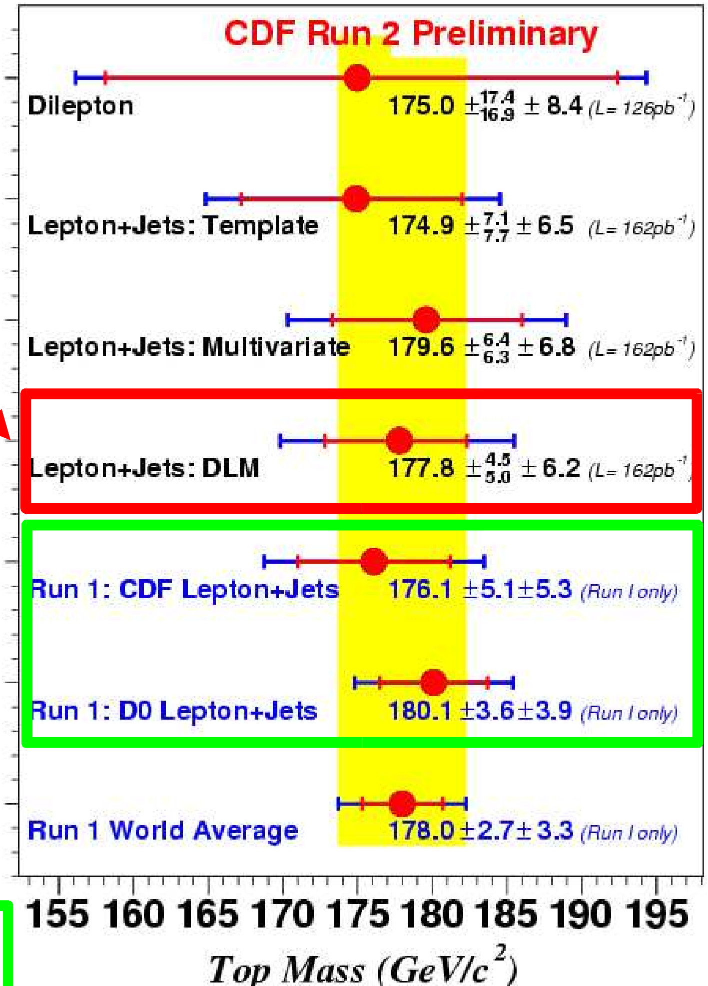
Comparison data / MC ok!

Summary and Outlook

- Three recent CDF II measurements of the top mass in the lepton+jets channel:
  DLM method provides smallest error (attempts to use max. theory information)
- Future improvements
  - **More data** (Tevatron performing well!):

160 pb^{-1}	present results
400 pb^{-1}	end 2004
1000 pb^{-1}	end 2005
4400–8500 pb^{-1}	end Run II

  - **Reduce jet energy systematics (priority!)** Expect significant improvement in calorimeter simulation!
  - **Big potential to refine/extend analysis methods**



Best single measurements from Run I lepton + jets

Precision measurement is coming ...

Backup Slides

CDF II Detector

CDF underwent substantial upgrades:

Improved geometrical acceptance:

- SVX coverage $|\eta| < 2$, 8 layers
- Expanded Muon system
- Forward calorimeter

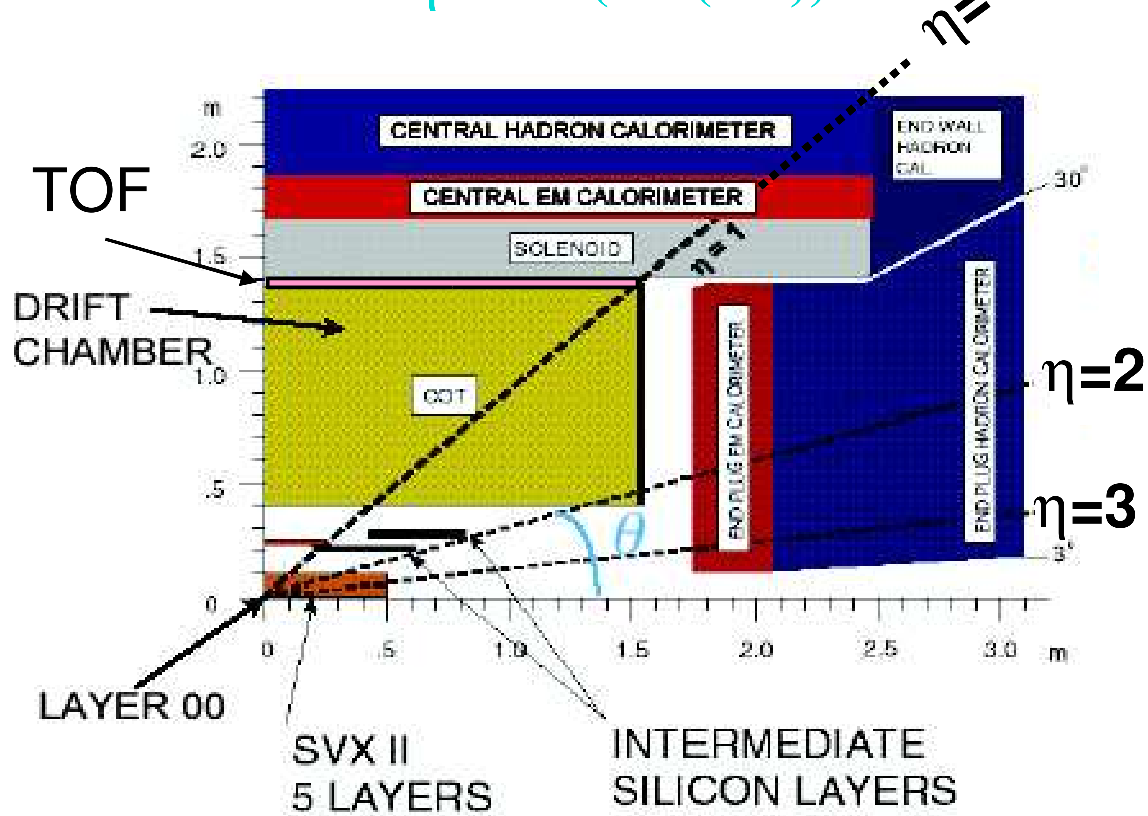
New central tracker

- 96 layers

Time of Flight

Trigger, DAQ ...

$$\eta = -\ln(\tan(\theta/2))$$



MTM Correct Permutation Probability

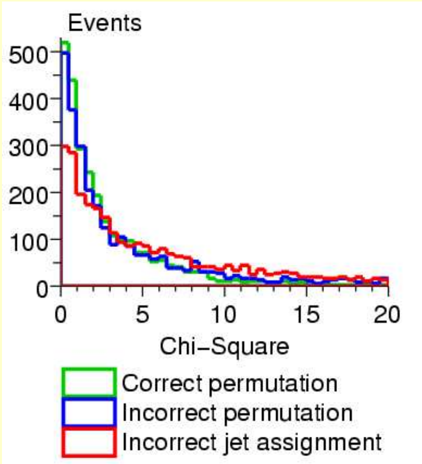
CP probability:

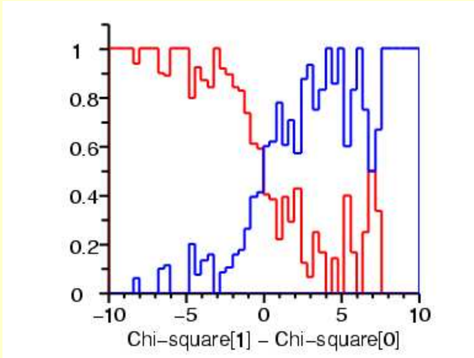
- Fit $\chi^2_{(best)}$ not useful quantity
- $\chi^2(i) - \chi^2(best)$ does better job

Use a "permutation diffusion" inspired model:

- 2 permutation case:

$p_{CP} \propto 1/\exp(\chi^2(2nd\ best) - \chi^2(best))$

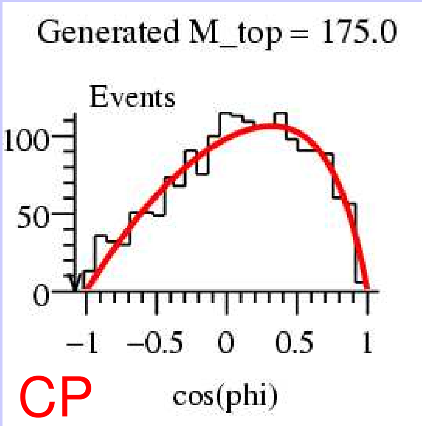


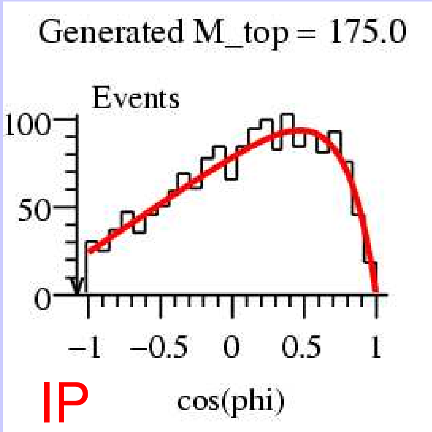


Blue: perm. 0 is correct
Red: perm. 1 is correct

Enhance approach by adding kinematic information

- cos∠(lepton, leptonic b)
- tt spin correlation term
- Define discriminator $\kappa = p_{X|CP} / p_{X|IP+IJ}$ to be calculated using MC
- Use Bayes Statistical techniques to derive the probabilities $p_{CP|X} = p(p_{CP}, \kappa)$





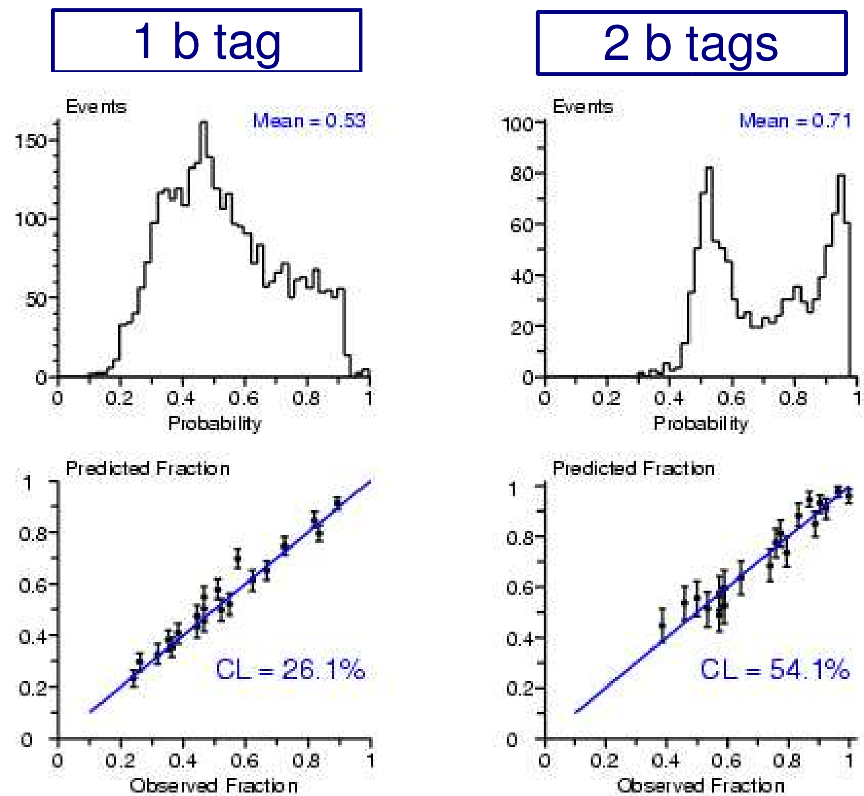
MTM Correct Permutation Probability (2)

$$p_{cp} = \frac{a_b}{\sum_{i=1}^{12} a_i \exp\left(-\frac{\chi_i^2 - \chi_b^2}{w_e(\chi_i^2 + \chi_b^2)}\right)}$$

$$w_e(y) = \exp(b_e + c_e y + d_e y^2)$$

$$p_{cp|X} = \frac{\kappa p_{cp}}{\kappa p_{cp} + (1 - p_{cp})}, \quad \kappa \sim \frac{P_{X|cp}}{P_{X|c\bar{p}}}$$

Derived from MC



MTM Likelihood

$$L(m_t) = \prod_{i=1}^{N} (f_b P_b(m_i, x_i) + (1 - f_b) P_s(m_i, x_i, m_t))$$

$$P_b(m, x) = \sum_{\text{bg types}} a_j B_j(m, x), \qquad \sum_{\text{bg types}} a_j = 1$$

$$P_s(m, x, m_t) = (p_{cp} S_{0,m_t}(m, x) + (1 - p_{cp}) S_{1,m_t}(m, x)) p_{cj} + (1 - p_{cj}) S_{2,m_t}(m, x)$$

N is the number of observed events

m_i is the top mass in the ith event. x_i symbolizes all other template variables.

P_s and P_b are the signal and background densities

f_b is the background fraction, treated as a nuisance parameter

B_j are the templates for different background types. a_j are the background composition coefficients (assumed known).

S_{0,m_t}, S_{1,m_t}, and S_{2,m_t} are the three signal templates for the given generated m_t

p_{cj}, p_{cp} are the probabilities of correct jet and permutation assignments, respectively

Systematic Uncertainties

CDF Run II Preliminary (162 pb^{-1})

Source		Uncertainty (GeV/c^2) ≥ 3.5 jets	Uncertainty (GeV/c^2) ≥ 4 jets
Statistical		+7.1 / −7.7	±6.6
Systematic	Jet Energy Scale	6.3	6.6
	Initial State Radiation	0.4	0.6
	Final State Radiation	0.9	1.0
	Parton Distribution Functions	0.2	0.2
	Generators	0.4	0.4
	Other MC Modeling	0.7	0.7
	Background Shape	0.8	0.8
	B-tagging	0.1	0.1
	Total	6.5	6.8

CDF Run II Preliminary

Source	Uncertainty (GeV/c^2) ≥ 3.5 jets	Uncertainty (GeV/c^2) ≥ 4 jets
Relative to Central	3.0	3.2
Central Calorimeter Response	4.6	4.7
Corrections to Hadrons (Absolute Scale)	2.2	2.3
Corrections to Partons (Out-of-Cone)	2.3	2.3
Total	6.3	6.6

I. Template Method

III. Dynamical Likelihood M.

Source	ΔM_{top} GeV/c^2
Jet Energy Corrections	5.3
ISR	0.5
FSR	0.5
PDFs	2.0
Generator	0.6
Spin correlation	0.4
NLO effect	0.4
Transfer Function	2.0
Background fraction(±5%)	0.5
Background modeling	0.5
Monte Carlo modeling	0.6
Total	6.2

II. Multivariate Template Method

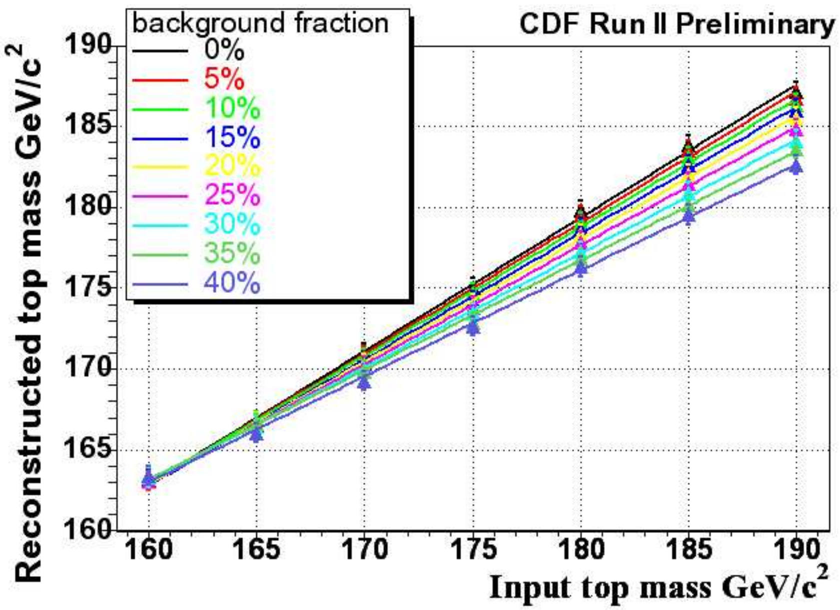
Systematic	ΔM_{top} (GeV/c^2)
Jet Energy	6.7
Generators	0.2
ISR	0.2
FSR	0.6
PDF	0.6
Background Shape	0.4
b Tagging	0.3
Fitting Procedure	0.7
Total	6.8

DLM Mapping Function

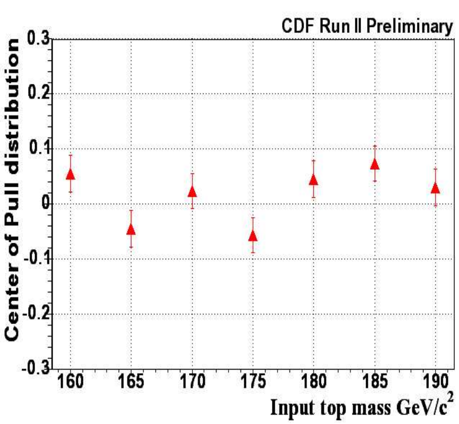
Mapping function:
reconstructed top mass
→ generated top mass

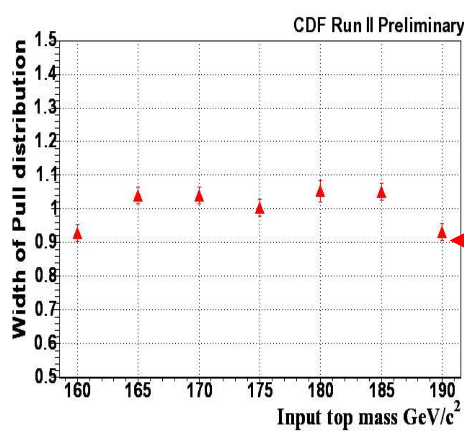
Needed to handle
- Background effects
- Top mass dependence of transfer function

Background fraction is minimized by requiring exactly 4 jets



- Slope depends on background fraction
- Expected background from cross section measurements used





Checks with pseudo experiments:
- Pulls ~ 0
- Pull widths are unit Gaussian