Precision Measurements of the Top Quark Mass in the Dilepton Channel

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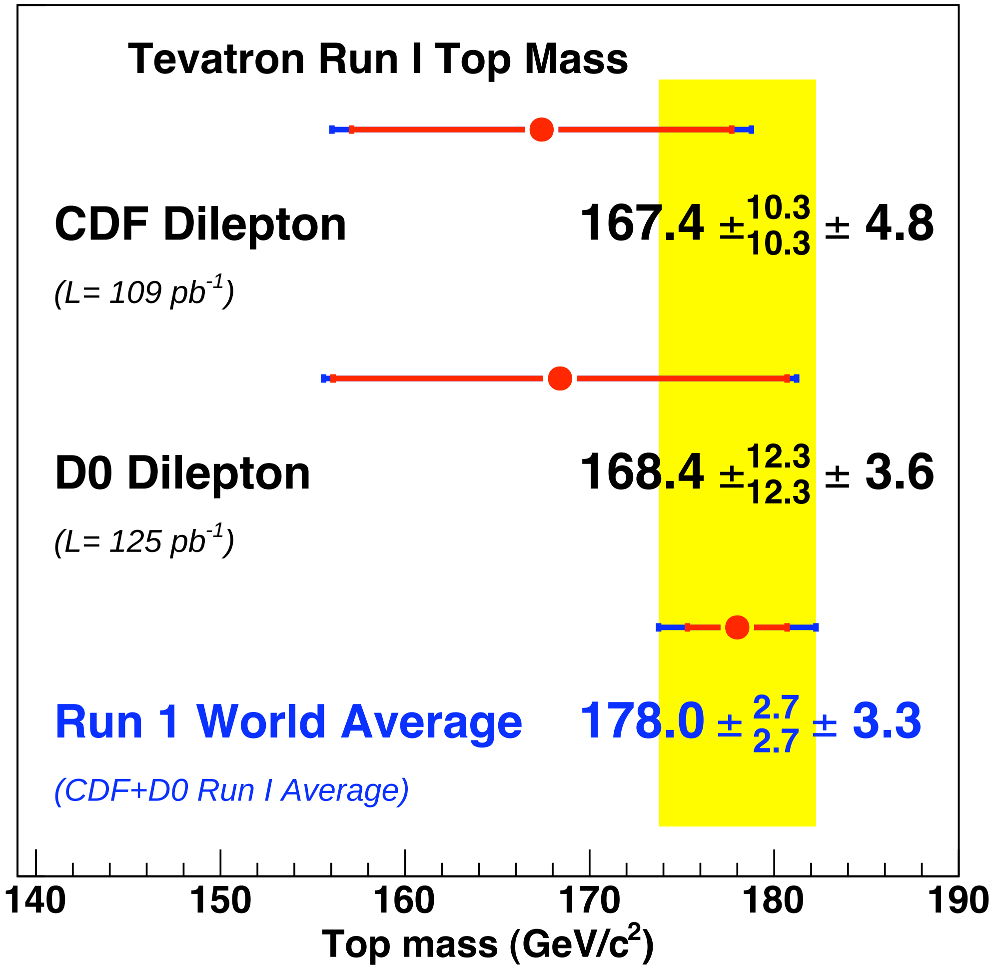
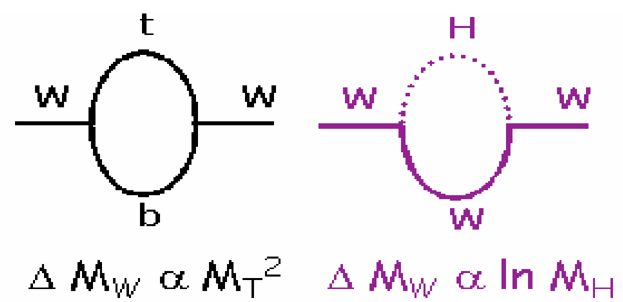
Outline

- Why measure the top mass?
  - Why the dilepton channel in particular?
- The dilepton channel and data sets
- Methods to measure the top mass
- Measurements
  - CDF template measurement
  - DØ template measurement
  - CDF matrix element measurement
  - CDF combination
- Conclusion and outlook

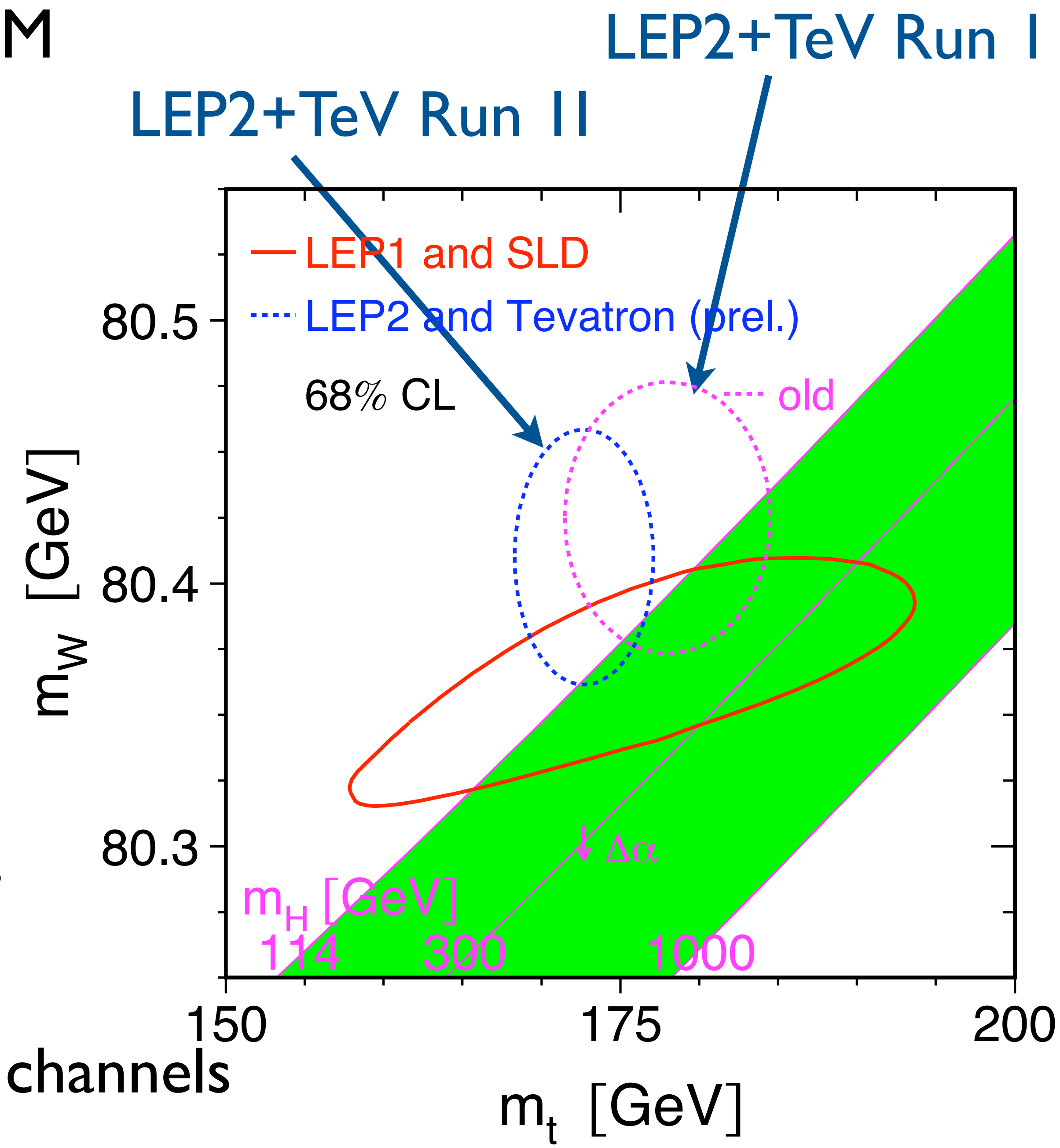


Why Measure the Top Mass

- Top mass is a fundamental parameter in SM
  - Important in radiative corrections



- Why so massive?
  - Only fermion with mass near EW scale
  - Yukawa coupling of ~1
- Constrains SM Higgs mass and SUSY models

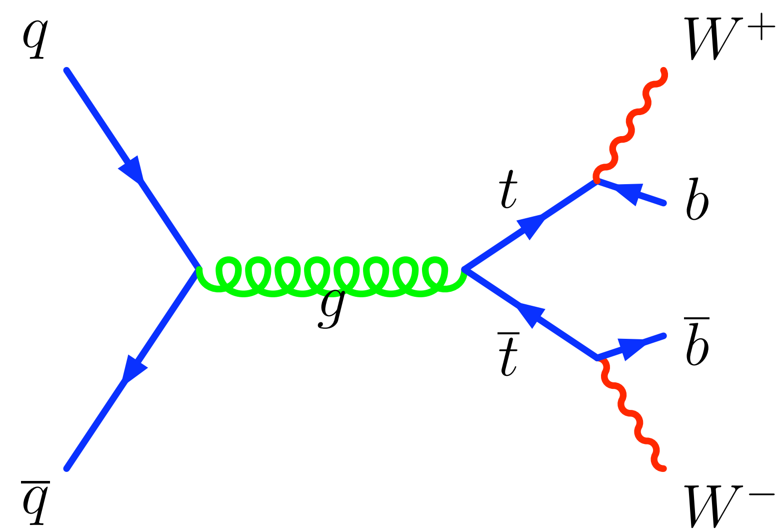


Dilepton Channel

- Important to check consistency between channels (is it SM top?)
- Discrepancy could indicate new physics

Top Decay: The Dilepton Channel

- Top quarks are primarily pair produced
  - Decay channel is defined by *W* decay modes
- Both *W*s decay leptonically in ~5% of all decays
  - 2 leptons (e or μ), 2 jets (from *b*-quarks), large $\not\!\!E_T$ from νs

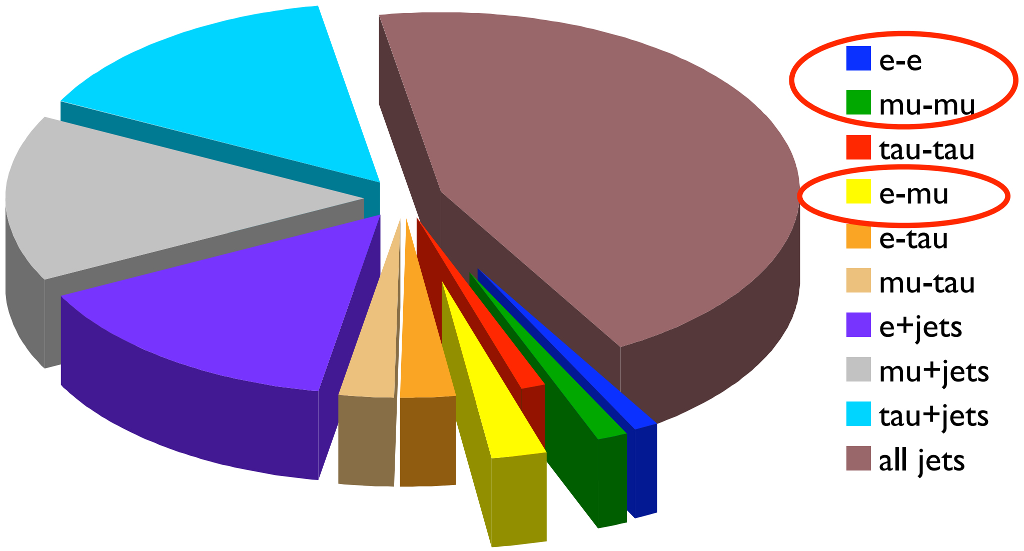


Advantages

- Clean: little background without need for *b*-tagging
- Least jets of any channel (less reliant on JES, less ambiguity in jets)

Disadvantages

- Low statistics
- 2 νs escape undetected– underconstrained system



Backgrounds

- Drell-Yan + jets
- Diboson + jets
- Mis-ID leptons ("fakes")

Data Samples

- DØ: 230 pb^{-1}, 13 candidate events in data
- CDF: Two complementary selection methods*
  - DIL: Lower acceptance, higher *S:B*
    - 340 pb^{-1}, 33 candidate events in data
  - LTRK: Higher acceptance, lower *S:B*
    - 359 pb^{-1}, 46 candidate events in data

Source	*CDF(DIL)*	*CDF(LTRK)*	*DØ*
tt (M_t=175 GeV/c^2)	17.2±1.4	19.4±1.35	7.1±0.67
Drell-Yan	4.7±1.2	8.71±3.31	0.61±0.09
Fakes	3.5±1.4	3.96±1.21	0.27±0.07
WW/WZ	1.6±0.22	1.96±0.37	0.54±0.22
$Z\to\tau\tau$	0.8±0.2	**	0.53±0.13
Total	27.7±2.3	34.1±3.89	9.00±0.67
Data	*33*	*46*	*13*

** $Z\to\tau\tau$ Included in Drell-Yan estimate

DØ

- 2 leptons with p_T >15 GeV/*c*
- 2 jets with p_T >20 GeV/*c*, $|\eta|<2.5$
- $\not{E}_T$ >25 GeV, 40 GeV for same flavor leptons
- H_T >140 GeV
- 80 GeV/c^2< m_{ll} < 100 GeV/c^2 for same flavor leptons

CDF(DIL)

- 2 leptons with p_T >20 GeV/*c*
- 2 jets with E_T >15 GeV/*c*, $|\eta|<2.5$
- $\not{E}_T$ >25 GeV
- H_T >200 GeV
- Higher $\not{E}_T$ requirement for 76 GeV/c^2<m_{ll}<106 GeV/c^2

CDF(LTRK)

- 1 lepton with p_T >20 GeV/*c*
- 1 isolated, well-measured track with p_T >20 GeV/*c*
- 2 jets with E_T >20 GeV, $|\eta|<2$
- $\not{E}_T$ >25 GeV

* PRL **93**, 142001 (2004)

Measuring the Top Mass

1. Template-based

Reconstruct mass for each event → Form "templates" for signal (varying M_{top}) and background using simulated events → Perform maximum likelihood fit to extract measured M_{top}

Advantages: Takes all (simulated) detector effects into account, (relatively) computationally simple

Disadvantages: Only single number (recon. mass) per event in final Likelihood, all events have equal weight

2. Matrix Element-based

Form per-event probability using matrix element → Integrate over unmeasured quantities → Form ensemble probability and calibrate using simulated events

Advantages: More statistical power, probability curve rather than single mass per event, events weighted naturally

Disadvantages: Complex numerical integration (much CPU)→machinery does not account for all detector effects

CDF: Template Methods

- Since dilepton channel is under-constrained by 1 d.o.f., template methods must make assumption about one variable
  - Assumed variable is then integrated over
  - Most probable mass selected for each event
- Resulting mass distribution is fitted to templates
- Signal and background templates are formed using simulated events

Method	Assumed Variable	Dataset
Neutrino Weighting (NWA)	η of two neutrinos	LTRK (46 events)
Full Kinematic (KIN)	p_z of $t\bar{t}$ system	DIL (30 events)*
Neutrino-ϕ Weighting (PHI)	ϕ of two neutrinos	DIL (33 events)

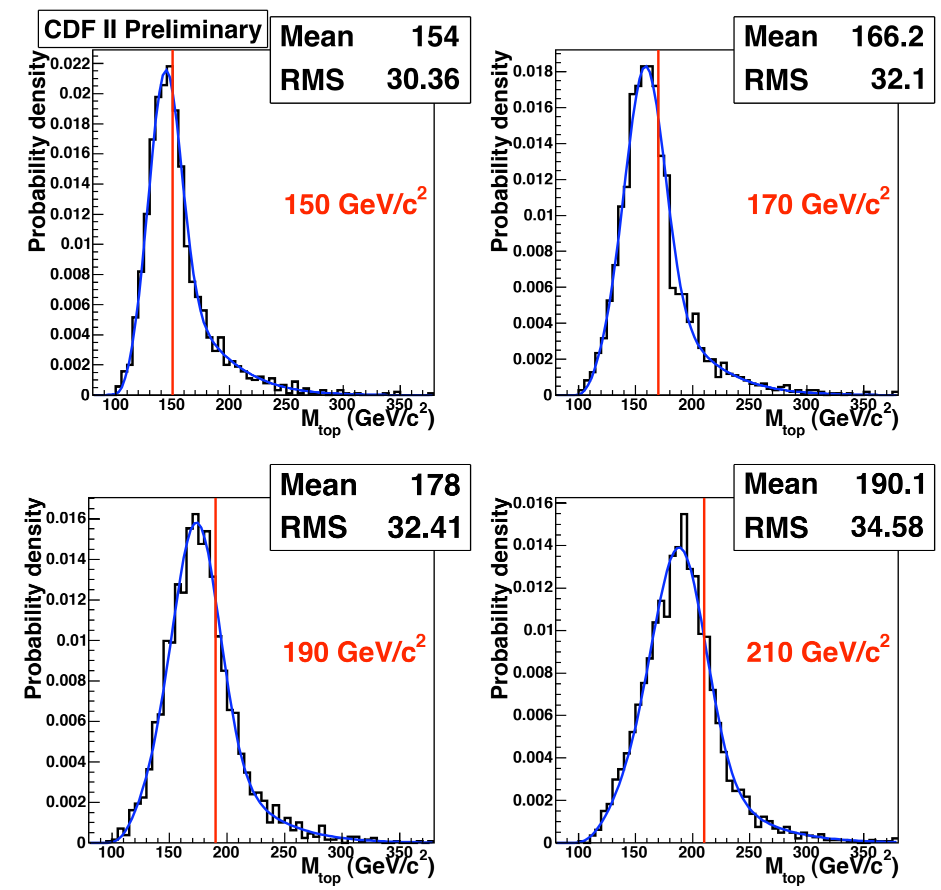
CDF: Template (NWA)

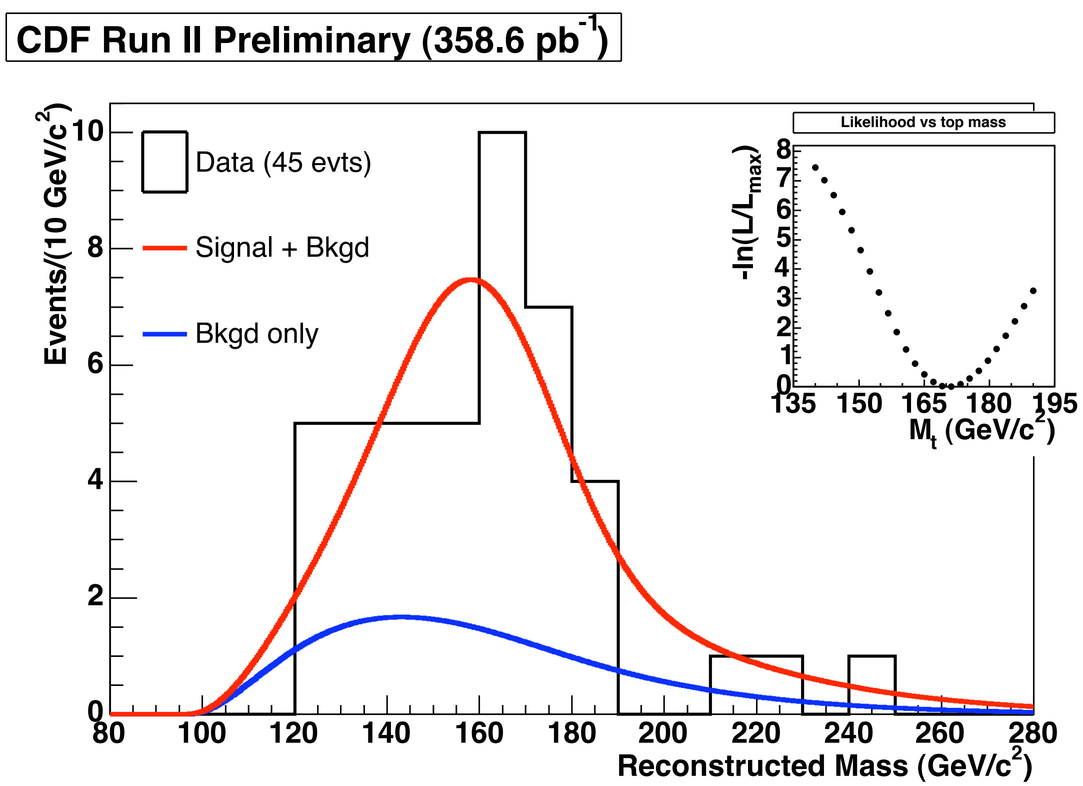
- Form kinematic solutions for events by assuming η_1, η_2 and m_t
  - Each solution assigned weight based on measured $\not{E}_T$ and $\not{E}_T$ resolution

$$w_i = \exp\Big(-\frac{(\not{E}_{Tx} - p_x^{\nu} - p_x^{\overline{\nu}})^2}{2\sigma_x^2}\Big)\cdot\Big(-\frac{(\not{E}_{Ty} - p_y^{\nu} - p_y^{\overline{\nu}})^2}{2\sigma_y^2}\Big)$$

- Calculate probability by integrating over unknowns (ν ηs, lepton-jet pairings)
- Pick m_t that maximizes prob. for each event
- Fit to signal+background templates
  - "Standard" template machinery from this step

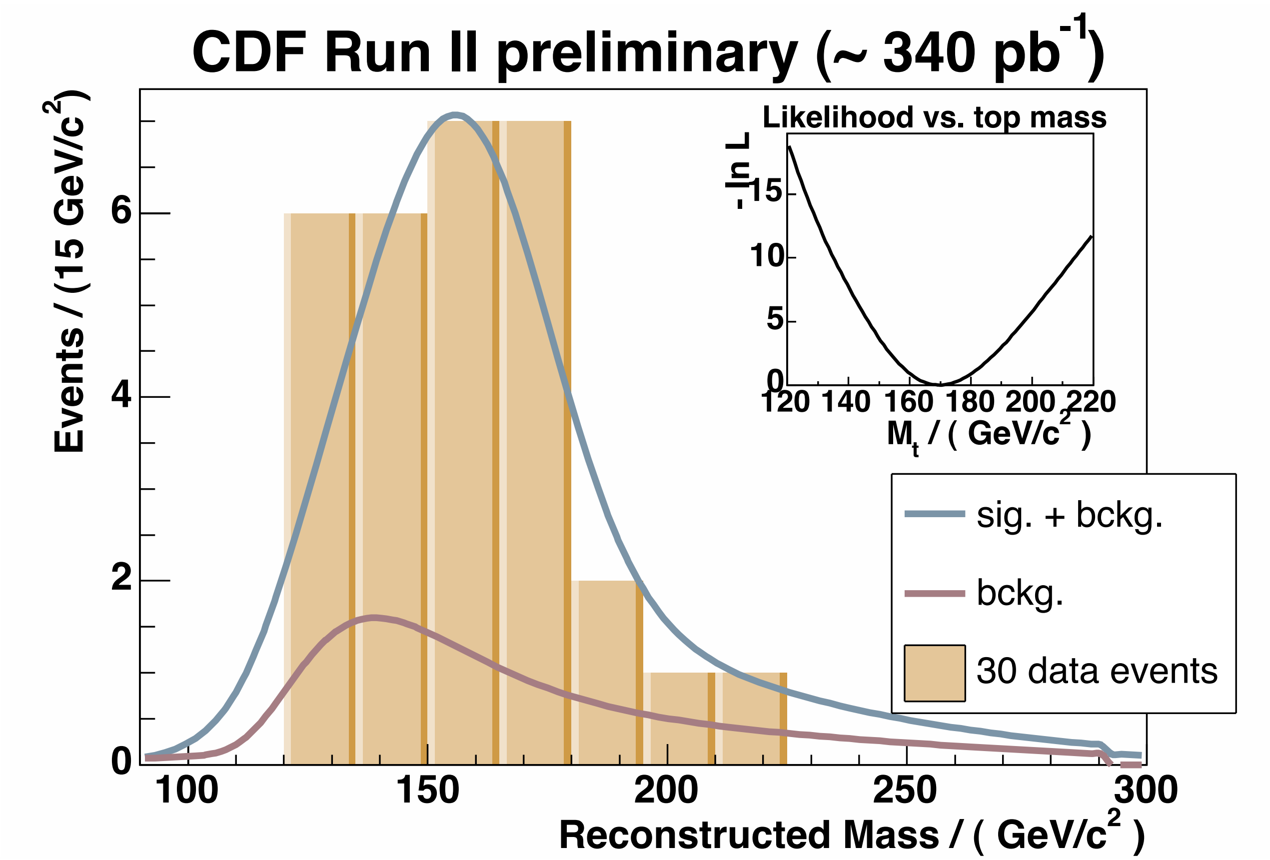
$M_{top} = 170.7^{+6.9}_{-6.5}(\text{stat.}) \pm 4.6(\text{syst.})\,\text{GeV}/c^2$





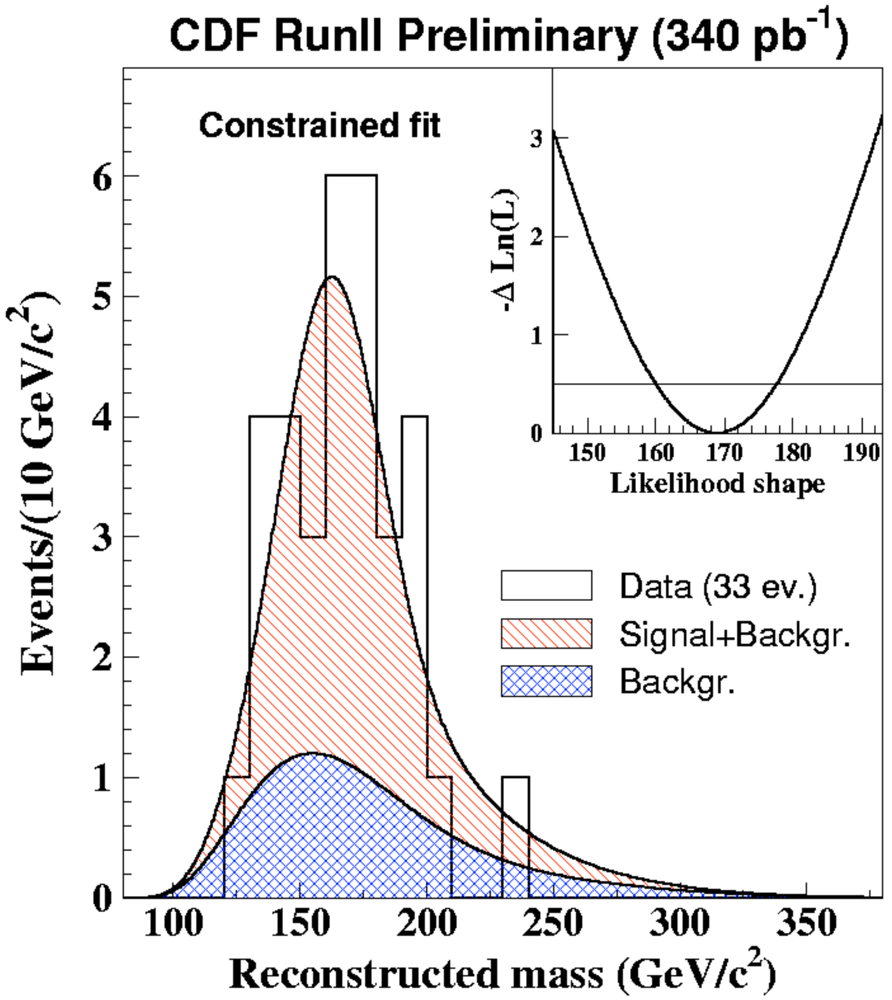
CDF: Template (KIN and PHI)

KIN



$M_{top} = 169.9^{+7.7}_{-7.2}(\text{stat.}) \pm 4.0(\text{syst.}) \text{GeV}/c^2$

PHI



$M_{top} = 169.7^{+8.9}_{-9.0}(\text{stat.}) \pm 4.0(\text{syst.}) \text{GeV}/c^2$

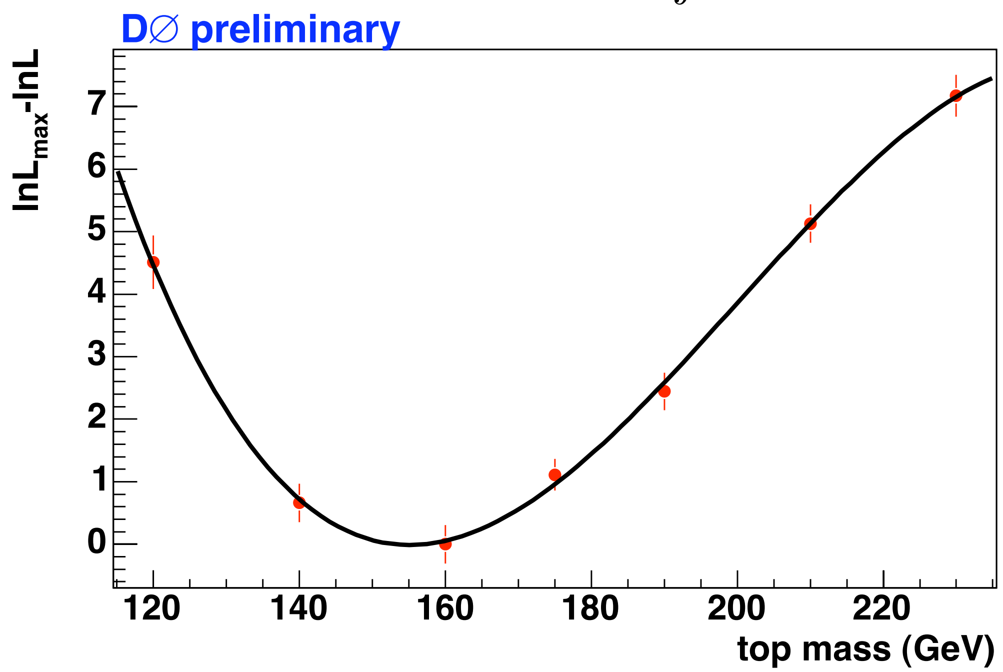
DØ : Template

- Weight assigned for each solution

$$W_0(m_t) = \sum_{\text{solutions}} \sum_{\text{jets}} f_{PDF}(x) f_{PDF}(\overline{x}) p(E^*_\ell | m_t) p(E^*_{\overline{\ell}} | m_t)$$

  - $p(E_l|m_t)$ derived from matrix element
- Most likely mass chosen for each event
- Mass distribution fit to S+B templates
- Final mass extracted by maximum likelihood

$$\int \mathcal{L}dt = 230\text{pb}^{-1}$$

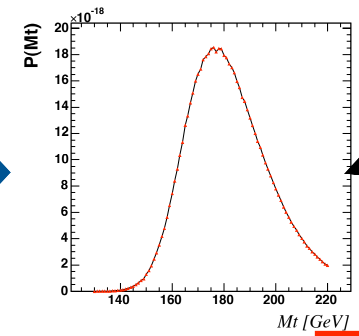


$M_{top} = 155^{+14}_{-13}(\text{stat.}) \pm 7(\text{syst.})\text{GeV}/c^2$

CDF: Matrix Element

- Use differential cross-section to calculate probability of event coming from M_{top}

$$\frac{1}{\sigma(M_t)}\frac{d\sigma(M_t)}{d\mathbf{x}} \Rightarrow$$



Probability curve rather than single mass per event

- Formulate differential cross-section using LO matrix element and transfer functions

$$\frac{d\sigma(M_t)}{d\mathbf{x}} = \frac{1}{N}\int d\Phi_6 |\mathcal{M}_{t\bar{t}}(p_i;M_t)|^2 \prod W(p_i,\mathbf{x}) f_{PDF}(q_1) f_{PDF}(q_2)$$

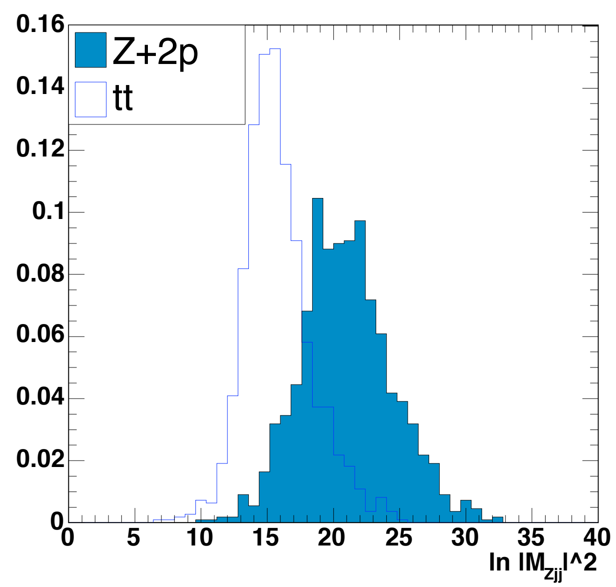
  - Transfer functions link measured quantities **x** to parton-level ones, p_i
  - Perform integrals over unknown quantities (6)
- Simplifying assumptions made for tractability
  - p_T of system ~0
  - Lepton momenta and jet angles well measured
  - Leading jets in events are from *b*-decay
- Use similar differential cross-sections for background processes

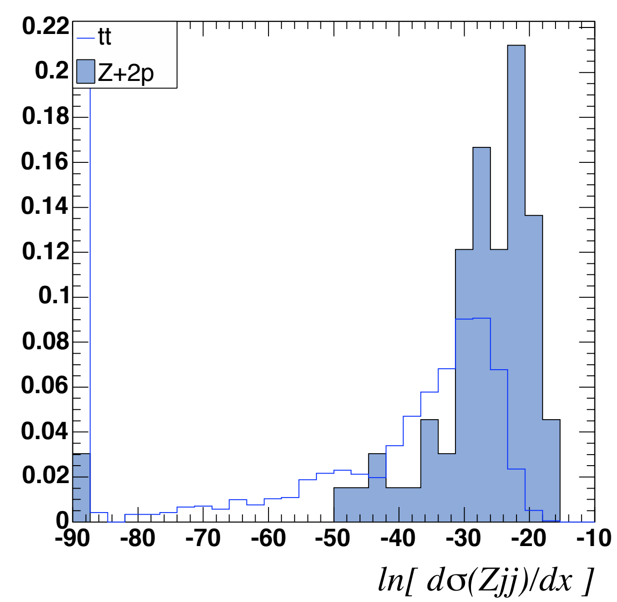
CDF: Matrix Element (Backgrounds)

- Final event probability is weighted sum of signal and background probabilities

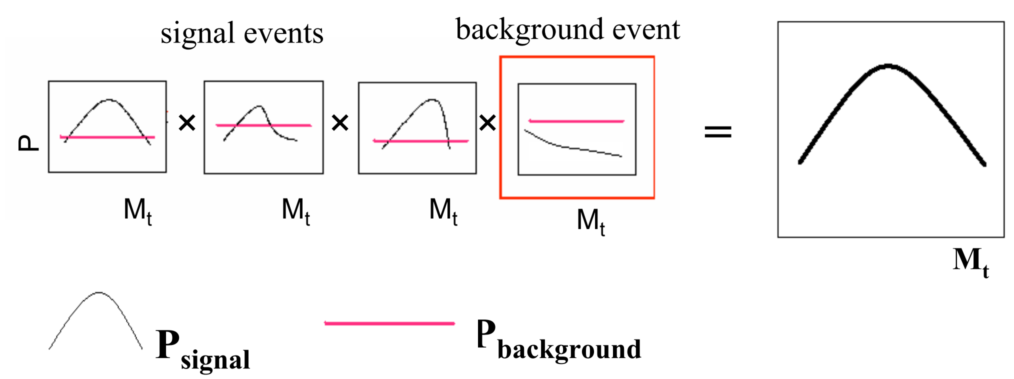
$$P(\mathbf{x}|M_t) = P_s(\mathbf{x}|M_t)p_s + P_{bg_1}(\mathbf{x})p_{bg_1} + P_{bg_2}(\mathbf{x})p_{bg_2} + \cdots$$

- Weights are determined from expected fractional contribution of each source
- Form differential cross-sections as in signal for each modeled background process
  - Difficult to determined closed-form expression for backgrounds: use ME-based generators instead (*e.g.* ALPGEN)
- Example: DY+2 jets





- Modeled backgrounds
  - DY+jets
  - WW+jets
  - W+3 jets (for fakes)
- Product of per-event prob. densities give likelihood for sample



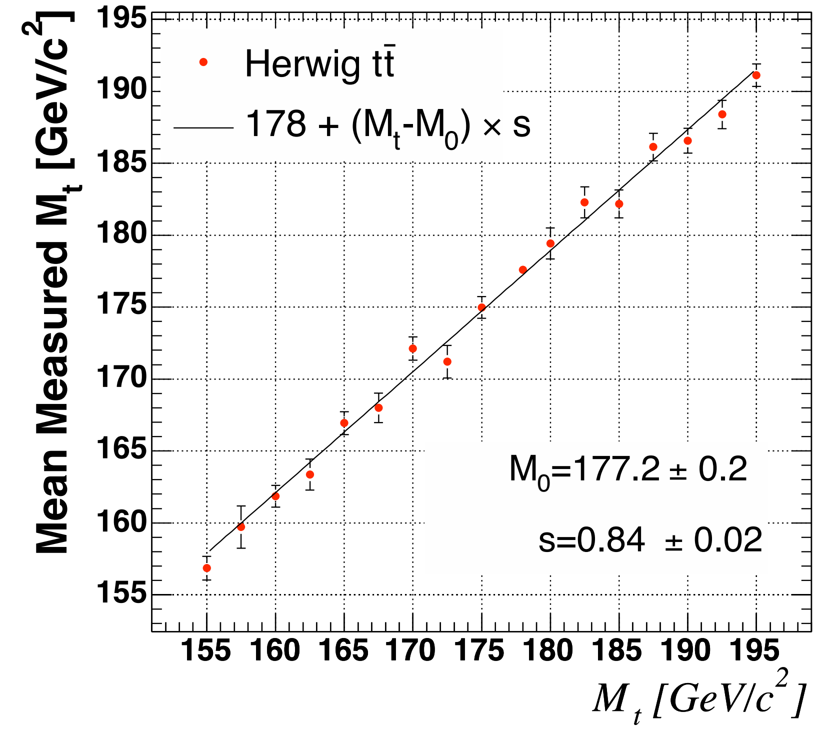
CDF: Matrix Element (Result)

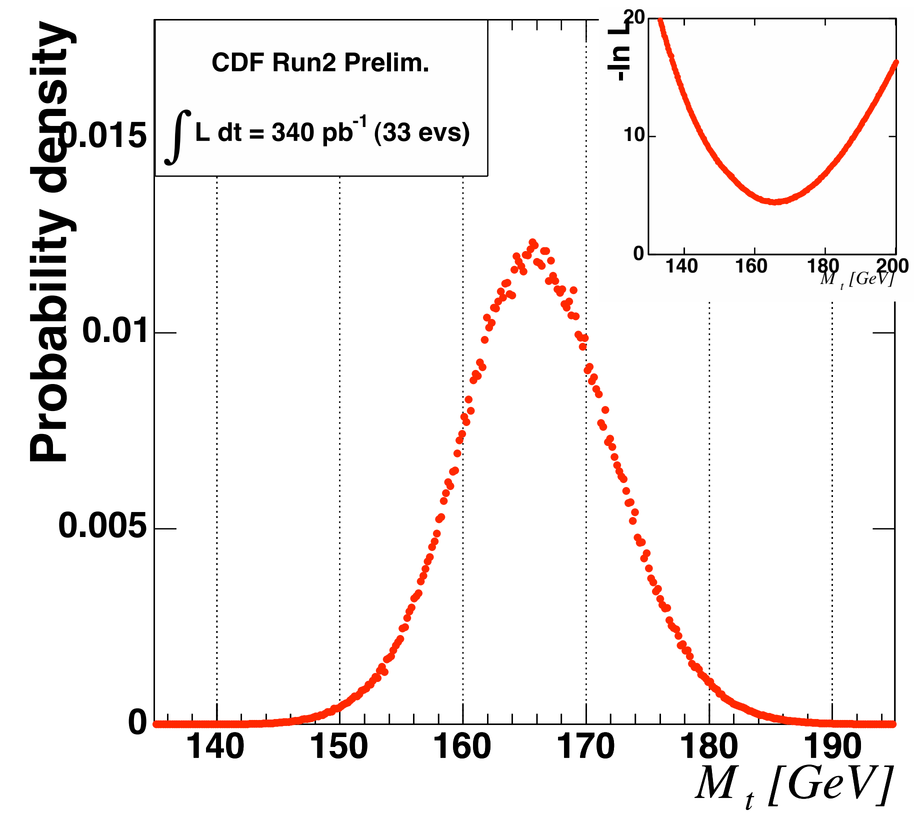
- Calibrated using simulated events. Accounts for:
  - Detector effects resulting in violation of assumptions
  - Presence of energetic jets resulting from ISR
  - Presence of unmodeled backgrounds
- Method has best *a priori* sensitivity of CDF dilepton top mass measurements
  - Inclusion of background likelihoods improves resolution (stat. uncertainty) by 15%
- Measured result:

$$M_{top} = 165.2 \pm 6.1(\text{stat.}) \pm 3.4(\text{syst.})\,\text{GeV}/c^2$$

Single most precise dilepton top mass measurement to-date

hep-ex/0512070, Submitted to PRL





Systematic Uncertainties

Source	CDF (ME) GeV/c^2	CDF (NWA) GeV/c^2	DØ (Template) GeV/c^2
Jet Energy Scale	2.6	3.5	5.6
MC Statistics	1.2	1.3	1.0
PDFs	1.1	0.5	0.9
Generator	0.8	0.5	3.0
Background Shape	0.8	2.6	1.0
ISR/FSR	0.7	0.8	*
Method	0.4	N/A	1.1
Sample Composition	0.3	N/A	N/A
Total	**3.4**	**4.6**	**6.7**

* ISR/FSR included in generator uncertainties

Improves with better methods and/or more data

Improves with more CPU

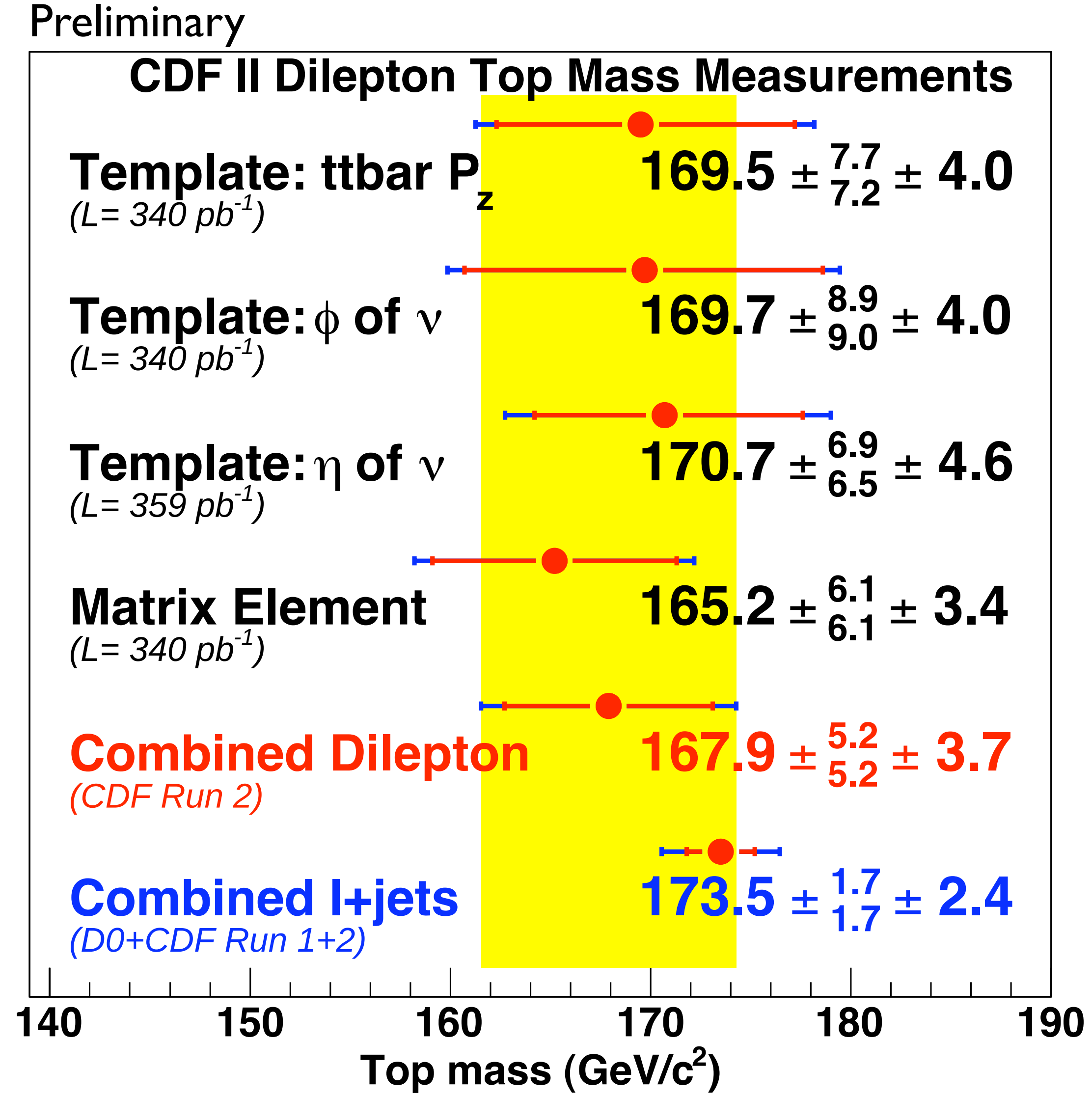
- JES is dominant systematic in all measurements
  - Can't incorporate *in-situ* JES calibration in the same way as in l+jets (only *b*-jets)
  - Work being done on possibly incorporating $Z \to b\bar{b}$ to calibrate *b*-jet energy scale
- Note: DØ measurement JES systematic using older algorithm

CDF: Combination

- Combination performed on 4 CDF measurements
  - Uses BLUE method (also used for world ave. top mass)
- Statistical correlations extracted from common pseudo-experiments
- Systematics assumed 100% correlated except method-specific systematics
- Resulting combination gives 15% greater precision than single-best measurement

M_{top} = 167.9±5.2(stat.)±3.7(syst.)GeV/c^2

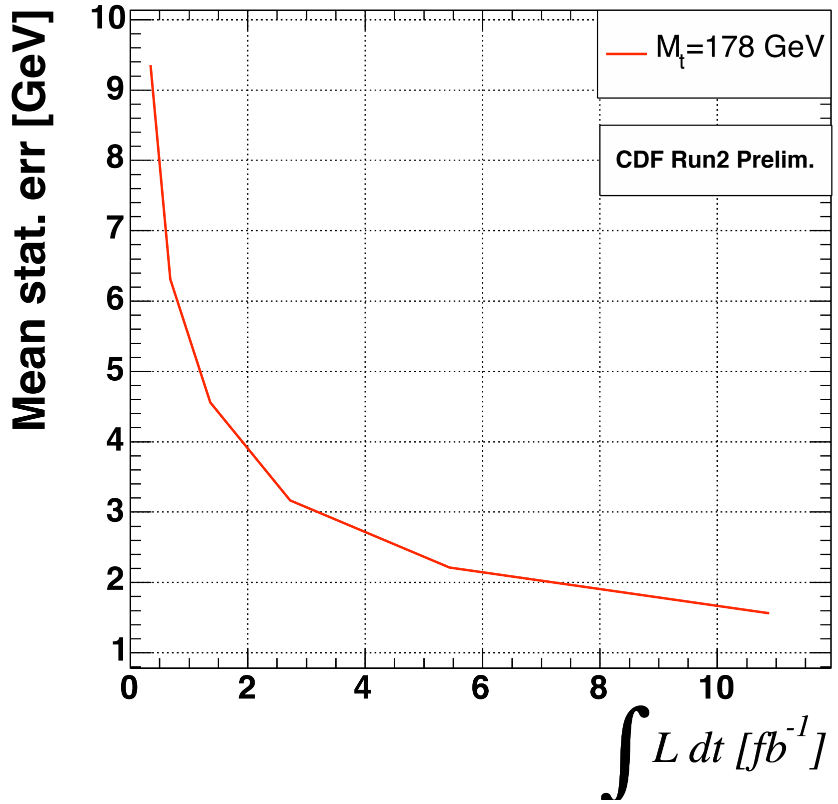
hep-ex/0512070, Submitted to PRL

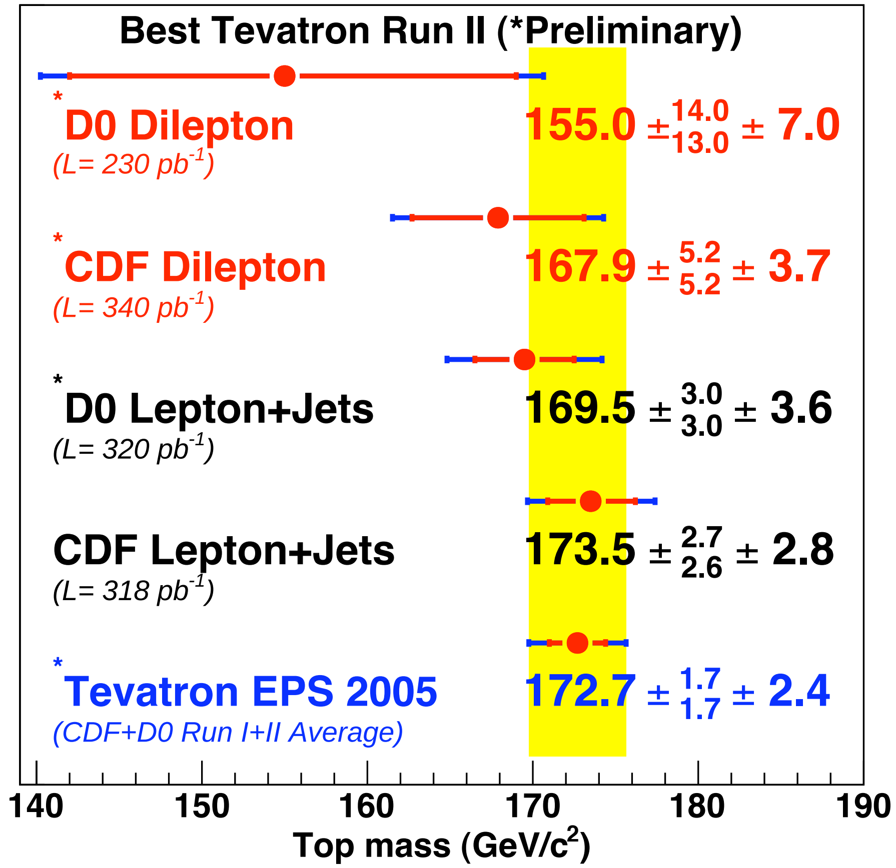


Method	Correlation Matrix				Weight
ME	1				0.47
NWA	0.12	1			0.36
KIN	0.40	0.14	1		0.18
PHI	0.43	0.25	0.35	1	0.00

Conclusion and Outlook

- Dilepton top mass precision from 11.4 GeV/c^2 (in Run 1) to 6.4 GeV/c^2 (CDF combined)
  - CDF ME measurement ~8% weight in world average top mass (hep-ex/0507091)
- With 2.5 fb^{-1} of data, statistical error and systematic error become comparable (with no method improvements)
  - Dilepton top mass becomes a precision measurement
  - l+jets and dilepton top mass will have comparable overall errors with 8 fb^{-1}
- Many further improvements expected: the best is yet to come!

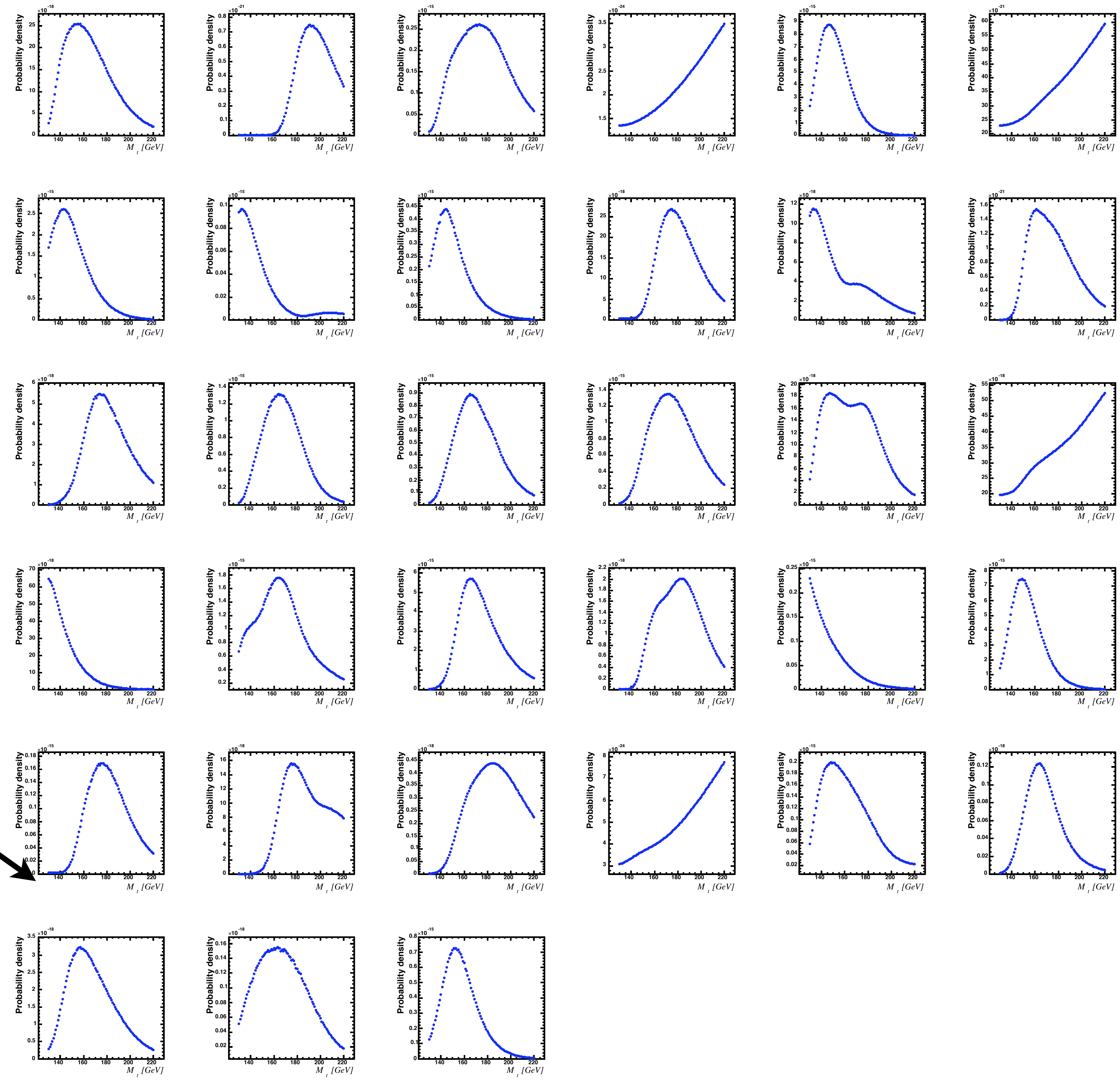




Backup Slides

Matrix Element Data Events

- 33 candidate events in data
  - Int. Lum of 340 pb^{-1}
- Each curve is sig+bg likelihood
- *x*-axes are 130-220 GeV/c^2



Effects of SUSY Events on Dilepton Mass

Chargino/Neutralino
Decaying to *lll*+2 jets or *ll*+2*q*

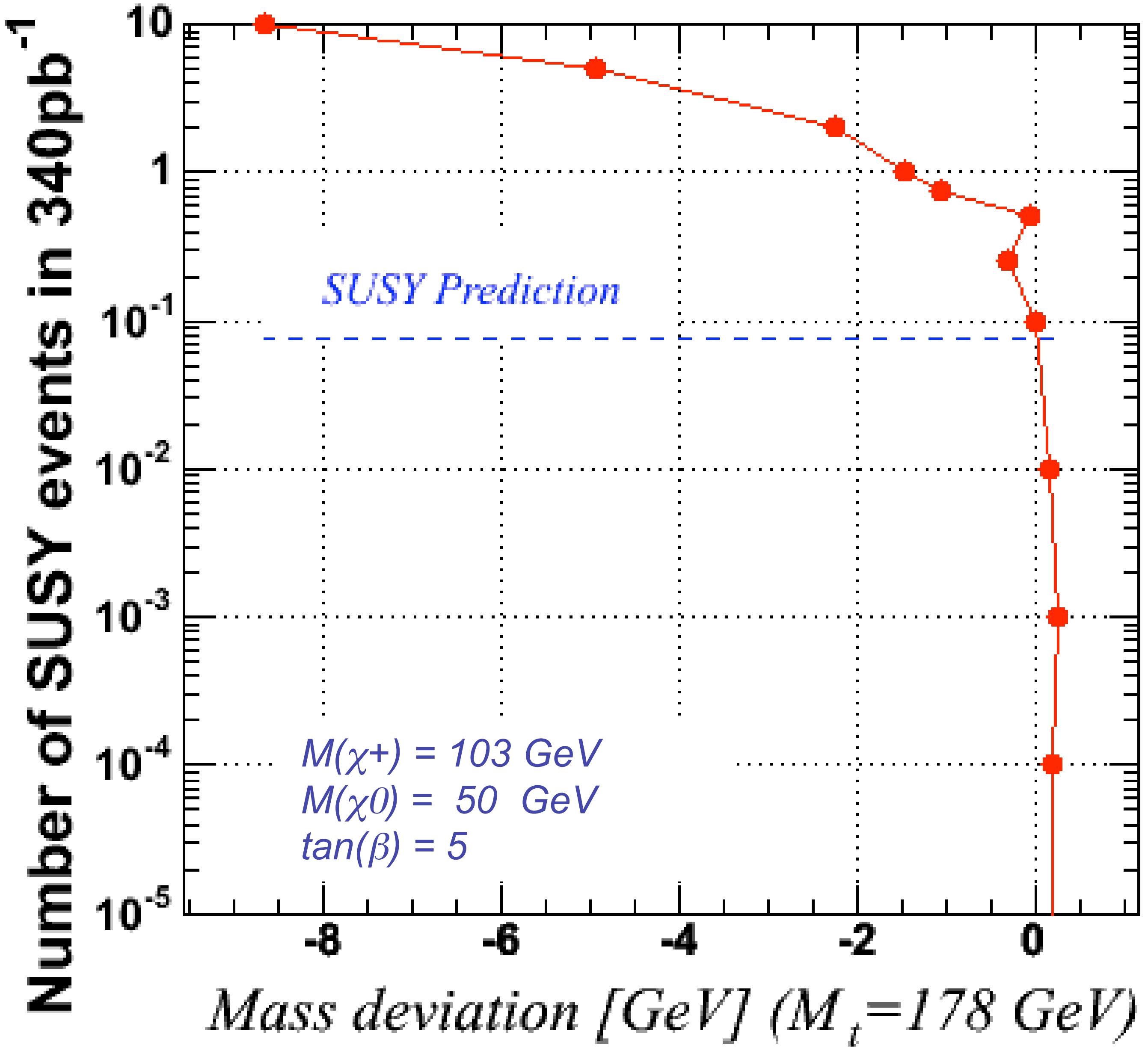
$M_{\chi+}$ = 103 GeV/*c*

$M_{\chi 0}$ = 50 GeV/*c*

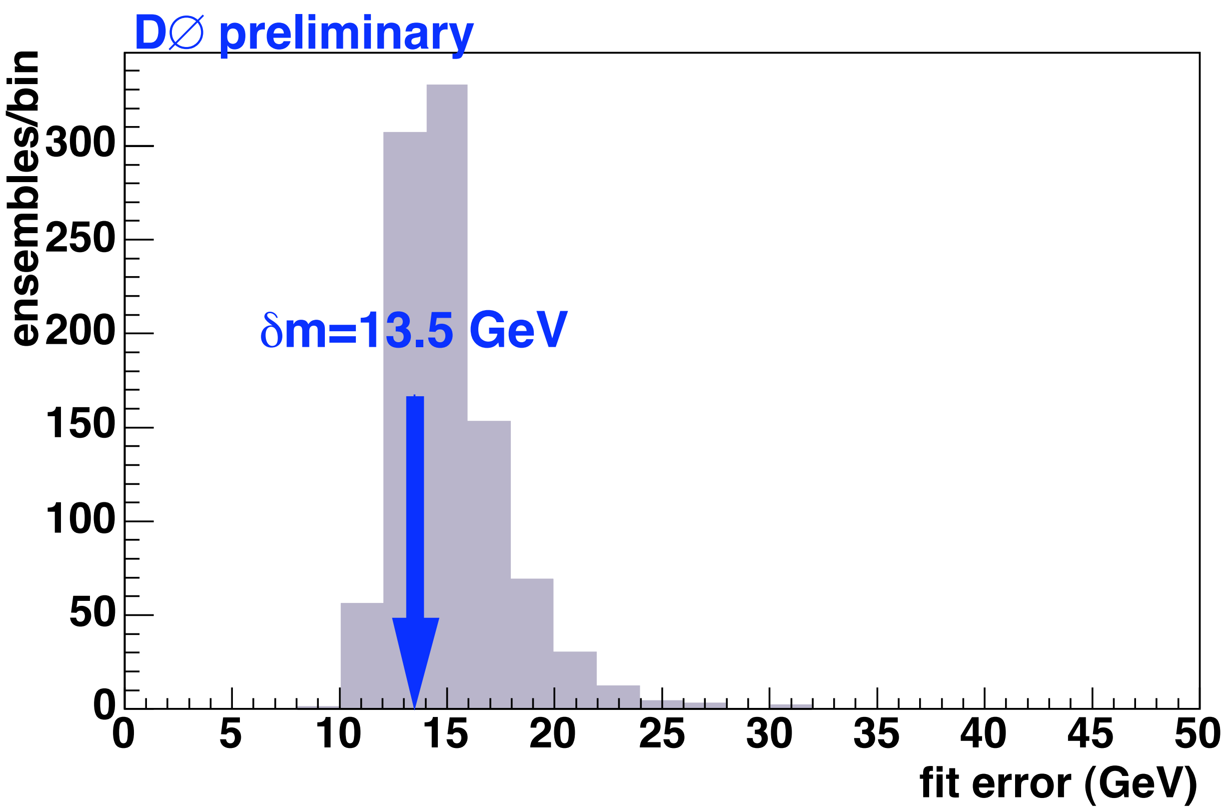
tanβ = 5

σ · BR = 150 fb

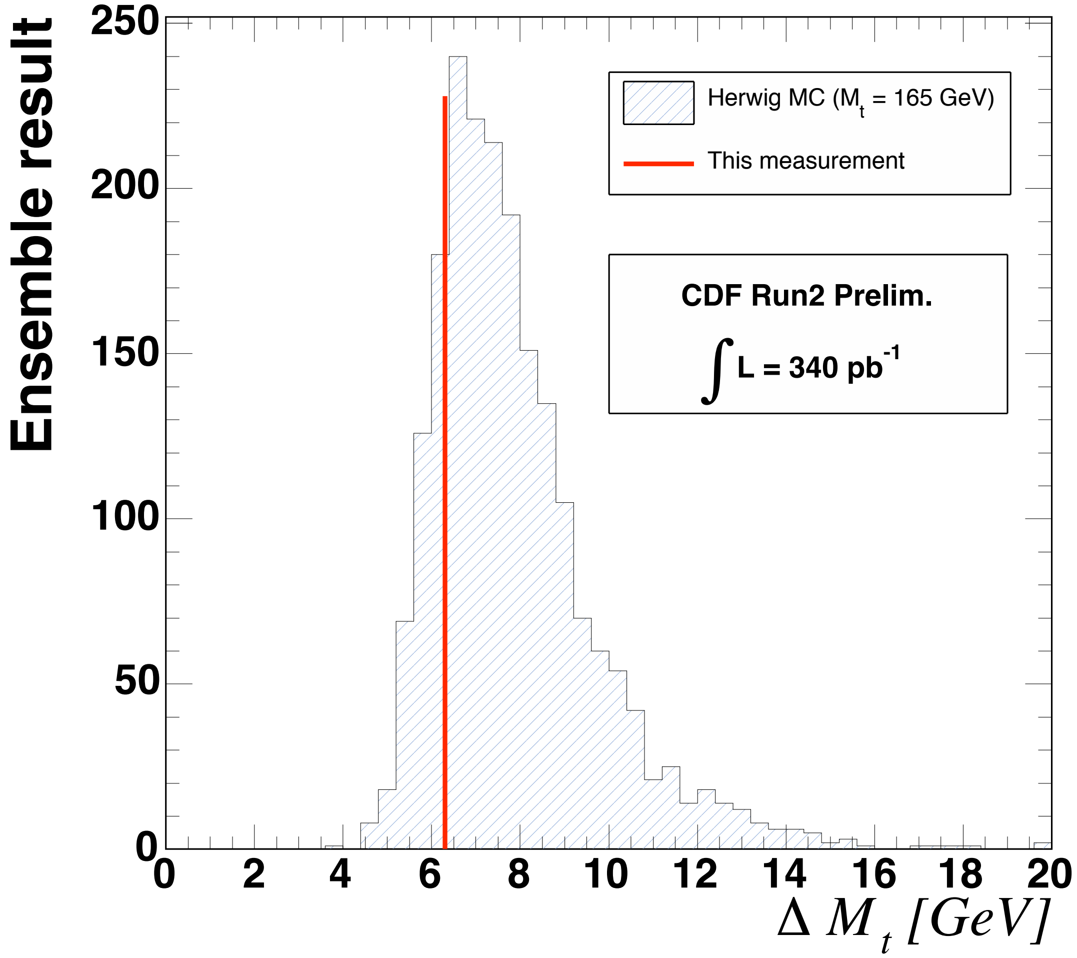
Acc = 0.15%



Expected Stat. Uncertainties

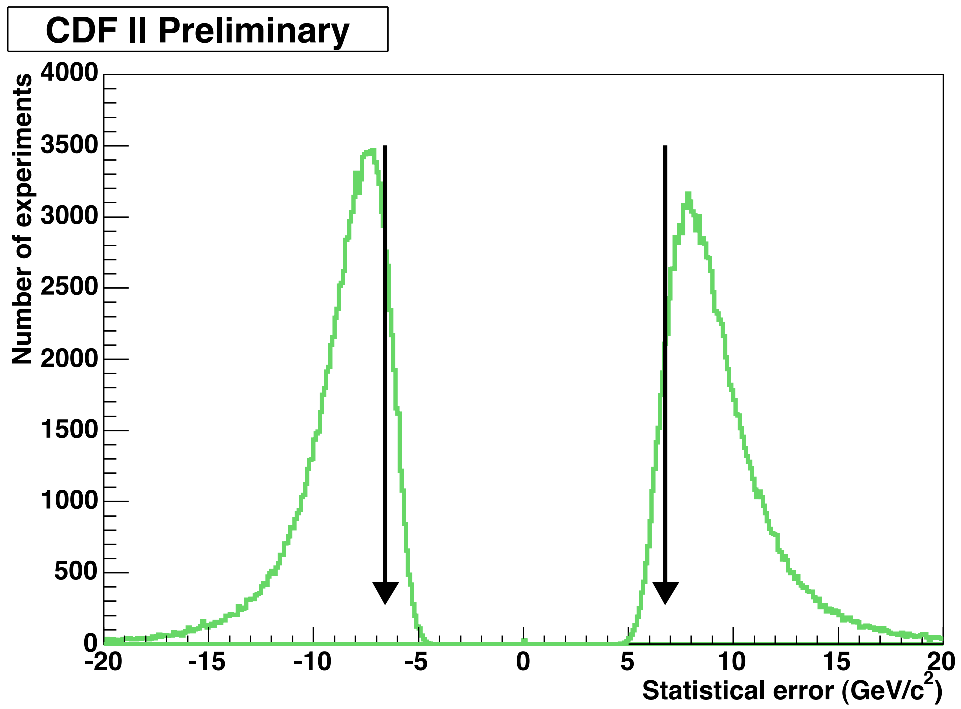


DØ: Template (sim. events for M_t = 175 GeV/c^2)

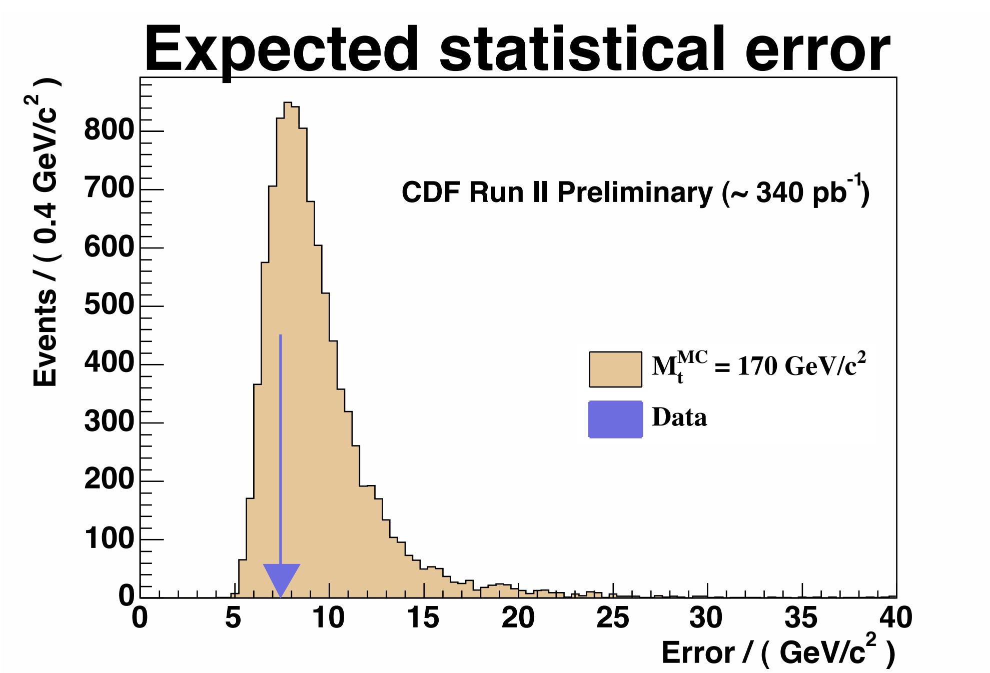


CDF: ME (sim. events for M_t = 165 GeV/c^2)

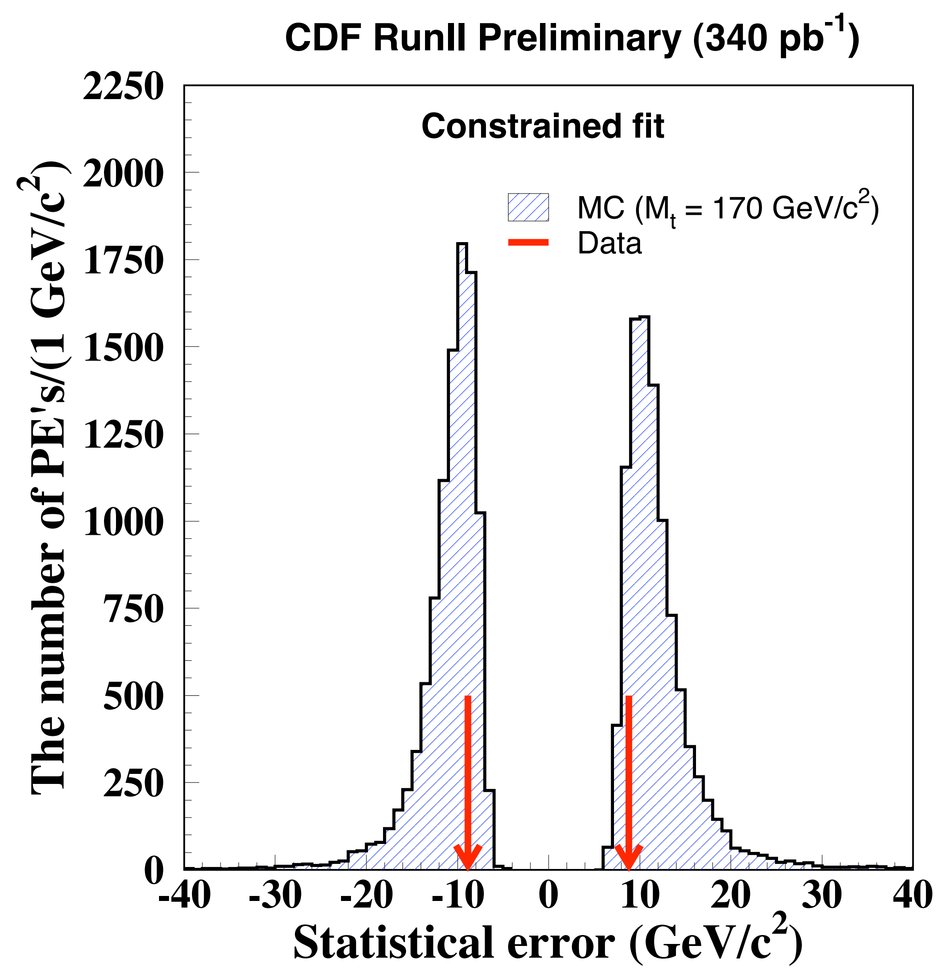
Expected Stat. Uncertainties (cont.)



CDF: NWA (sim. events for M_t = 170 GeV/c^2)



CDF: KIN (sim. events for M_t = 170 GeV/c^2)



CDF: PHI (sim. events for M_t = 170 GeV/c^2)

CDF: KIN and PHI Systematics

	KIN (GeV/c^2)	PHI (GeV/c^2)
Jet Energy Scale	3.2	3.5
Generator	0.6	1.0
PDFs	0.5	1.0
ISR/FSR	0.7	1.1
Background Shape	1.5	0.7
Background Amount	0.3	--
Background Statistics	0.8	--
Total	4.0	4.0

World Average

- hep-ex/0507091
- Dominated by Run II l+jets from CDF (36%) and D0 (33.3%)
  - D0 Run I l+jets: 18.8%
  - CDF Run II dilepton: 8.0%
- Mass of top quark known to precision of 1.7%