Top Mass Measurement at the Tevatron

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for CDF and D0 Collaborations

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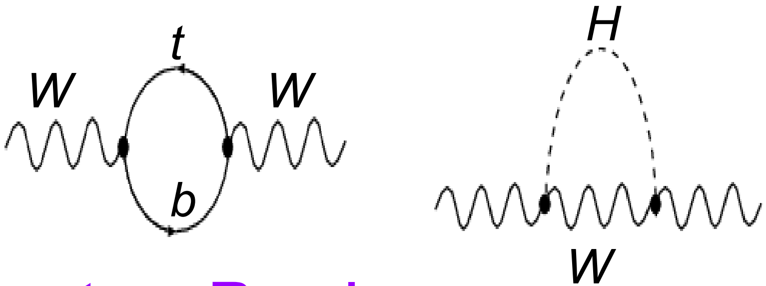
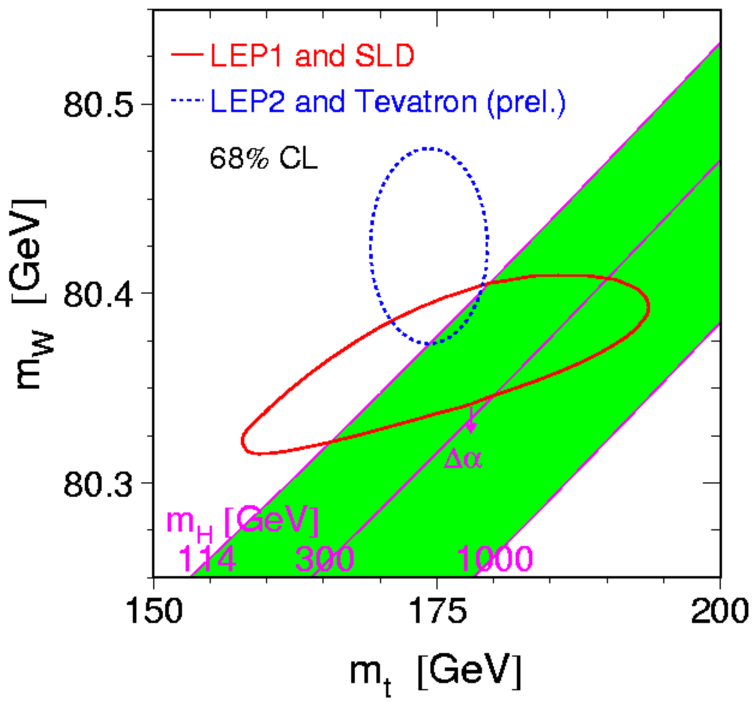
Top Quark Mass - Introduction

- Top mass is a fundamental parameter of the Standard Model.
- Mass measurements of top and W constrain the Higgs mass.



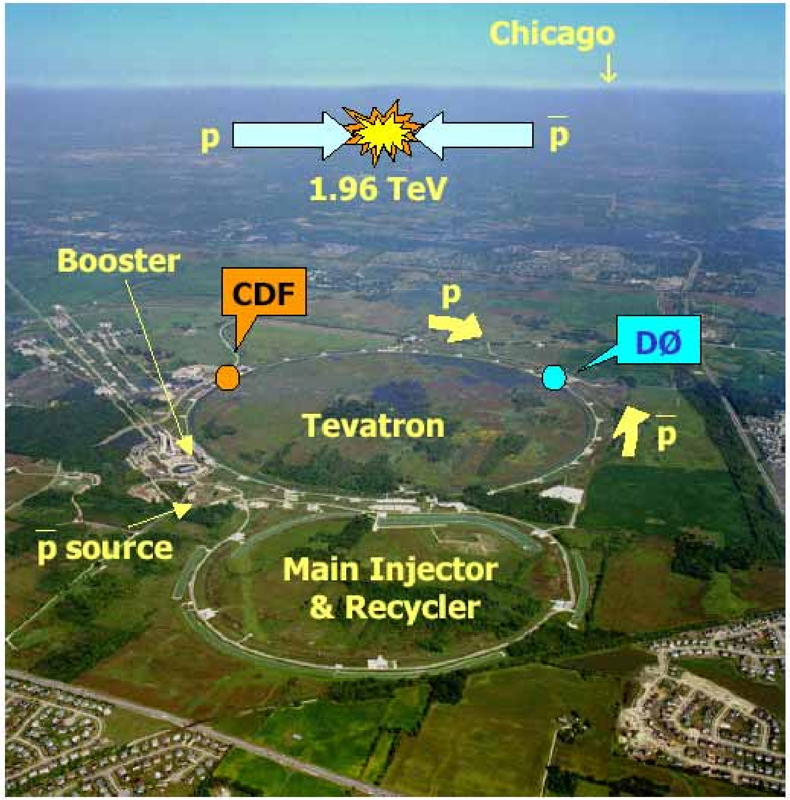


- Tevatron Run I average :
  $m_{top} = 178.0 \pm 2.7 \pm 3.0$ GeV/c^2
  $\rightarrow m_{higgs} < 260$ GeV/c^2 (95%)

- $m_{top} \sim$ EWSB scale.
  $\rightarrow$Special role of top?

Tevatron Run II

- $p - \bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV.
- Peak luminosity >~ 1.2×10^{32} cm^2 s^{-1}.
- ~900 pb^{-1} of data already acquired by CDF and D0.
- Current analyses use 300 – 400 pb^{-1}.
- Direct study on top is only possible at Tevatron!

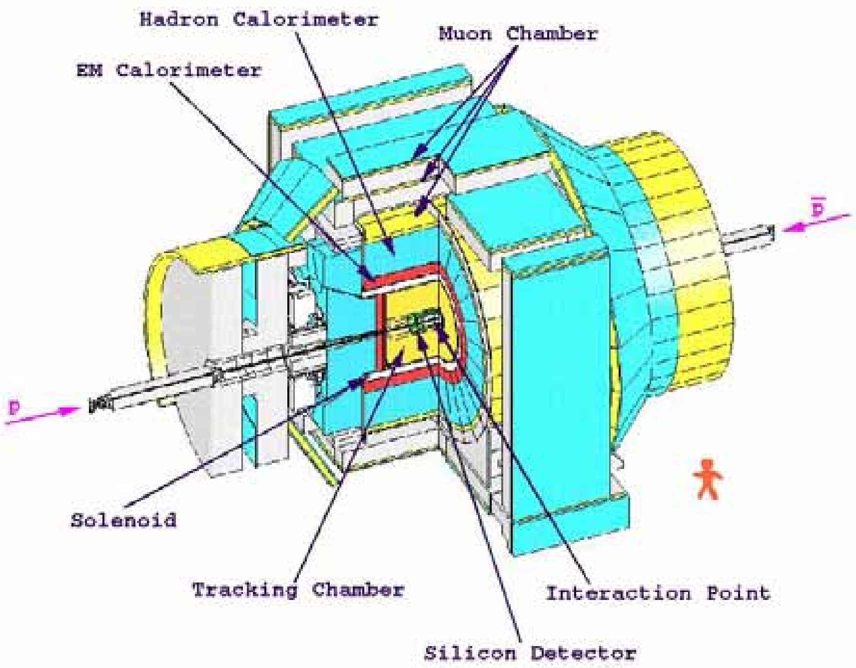


CDF and D0 Detectors

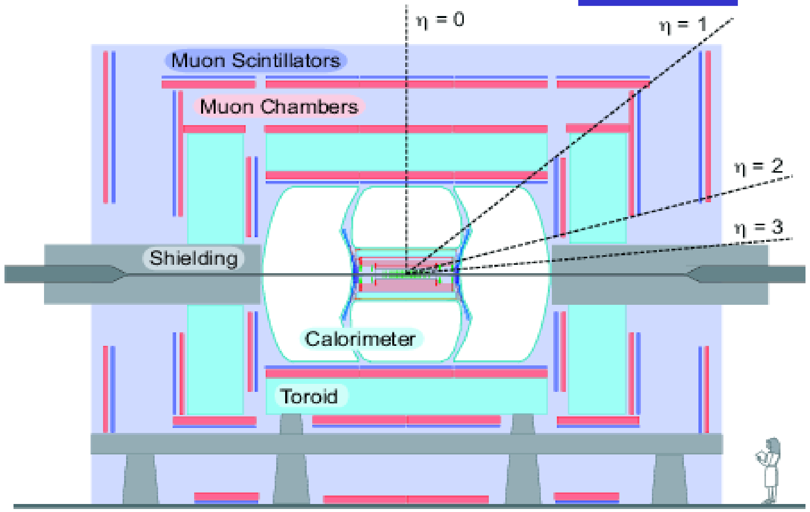
Both multi-purpose detector

with:
- Tracking in magnetic field.
- Precision tracking with silicon.
- Calorimeters.
- Muon chambers.

CDF



D0



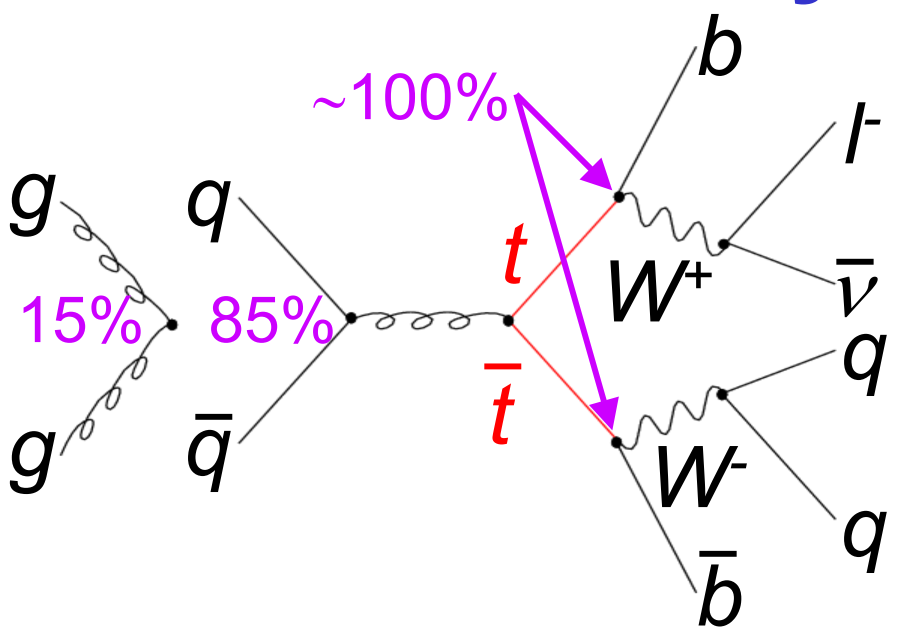
Jet $\sigma_{ET}/E_T \sim 84\%/\sqrt{E_T}$ (GeV/c^2)

Top Quark Production and Decay

- We use pair creation events to measure m_{top}.
- Top decays before hadronization.

  τ_{top}=0.4x10^{-24} s < 1/Λ_{QCD}~10^{-23} s.

  Br(t→Wb) ~ 100%.



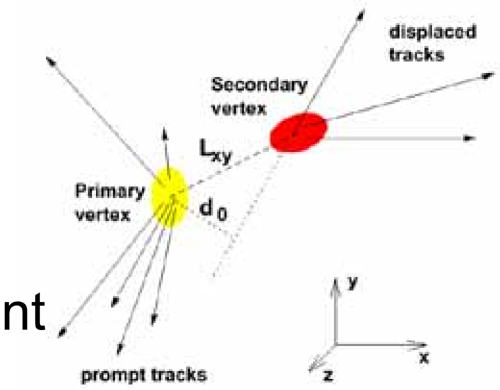
Final state :

Mode	Br.(%)	
dilepton	5%	Clean but few signal. Two ν's in final state.
lepton+jets	30%	One ν in final state. Manageable bkgd.
all hadronic	44%	Large background.
τ + X	21%	τ-ID is challenging.

Event Selection

L+jets

- 1 lepton (e/μ)
- $\not\!\!E_T$
- 4 jets (2 *b*-jets)
- Special cut on for 0tag event (CDF:hard cut on E_T^{4thjet})
- Secondary vertex *b*-tagging.



Dilepton

- 2lepton (e/μ)
- $\not\!\!E_T$
- 2 jets (2 *b*-jets)
- No *b*-tagging

Typical CDF event rate and S/B

	L+jets			Dilepton
	0tag	1tag	2tag	
Nevt (320pb^{-1})	40	82	16	33
S:B	<1:1	3:1	10:1	2:1
# Parton-jet assign.	12	6	2	2

B-tagging helps reject wrong assignments besides reduces background.

Measurement Methods

Template Method

- Reconstruct event-by-event M_{top}.
- Describe dependence of M_{top} distribution on true top mass m_{top} using MC — Templates.
- Likelihood fit looks for m_{top} that describes data M_{top} distribution best (template fit).
- Less assumptions / robust measurement.

Matrix Element Method

- Calculate likelihood (probability) for m_{top} in each event by Matrix Element calculation.
- Multiply the likelihood over the candidate events.
- m_{top} determination by the joint likelihood maximum.
- Better statistical precision expected w/ using more info.

All methods in all channels are well validated by a blind sample.

CDF L+jets Template Method (1)

Minimize χ^2 to reconstruct event-by-event top mass.

Fluctuate particle momenta according to detector resolution.

M_{top} as free param.

$$\chi^2 = \sum_{i=l,jets} \frac{(P_T^{i,fit} - P_T^{i,meas.})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(UE_j^{j,fit} - UE_j^{j,meas.})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W} + \frac{(M_{l\nu b} - M_{top})^2}{\Gamma_{top}} + \frac{(M_{jjb} - M_{top})^2}{\Gamma_{top}}$$

Constrain masses of 2 W's.

t and $\bar{t}$ have the same mass.

- 2 jets from W decay / 2 *b*-jets.
  →12 jet-parton assignments.
- *B*-tagging helps reject wrong assignments besides reduces background.

→

- Subdivide candidate events into 0, 1, 2 tag.
- Choose assignment with smallest χ^2.

CDF L+jets Template Method (2)

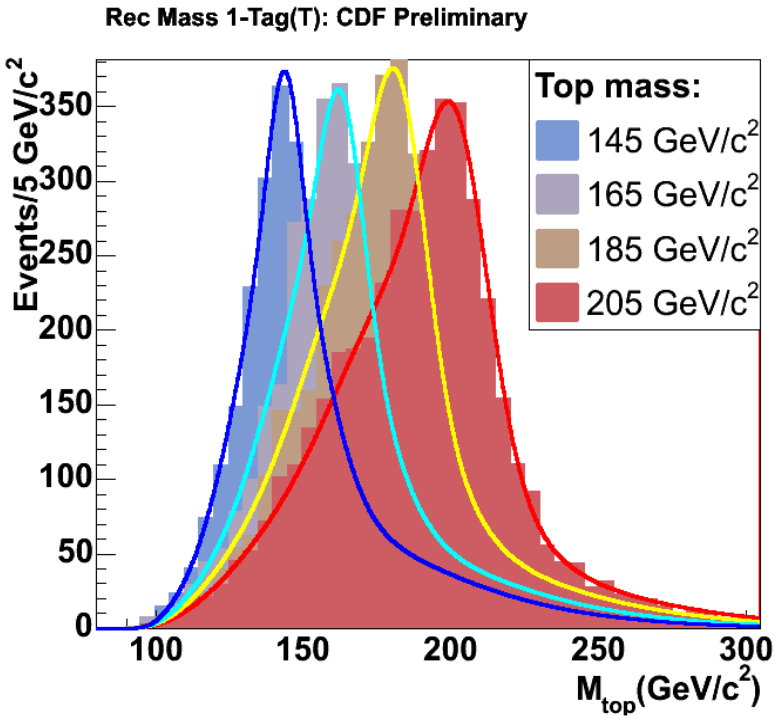
Largest uncertainty←Jet Energy Scale (JES)

- Better understanding of JES
- Minimize JES uncertainty

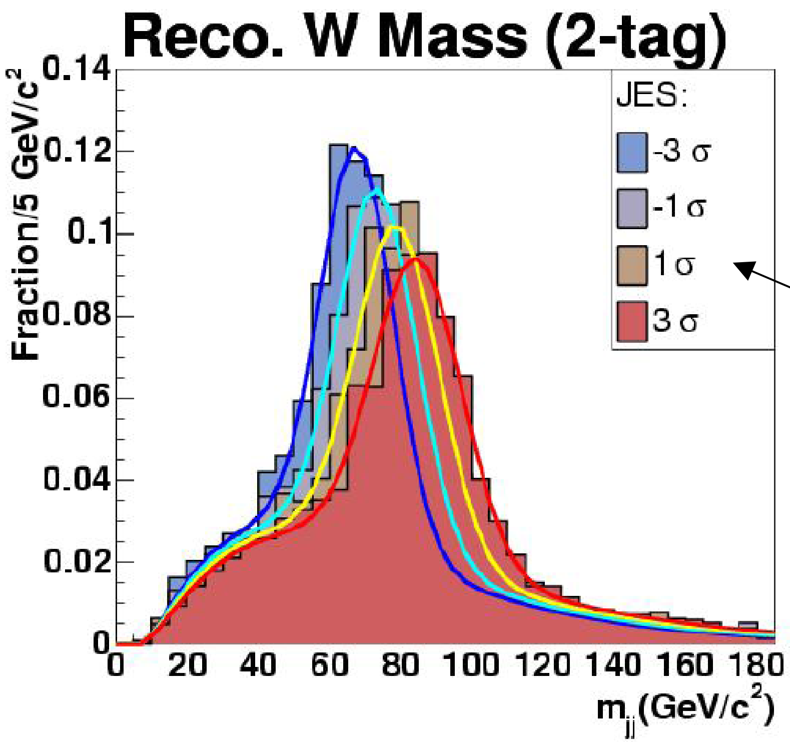
In situ JES calibration using W→jj in $t\bar{t}$ events.

M_{top} and hadronic W invariant mass distributions are parametrized as functions of true top mass and Jet Energy Scale (JES) using Monte Carlo samples.

M_{top} Template



Hadronic W mass Template



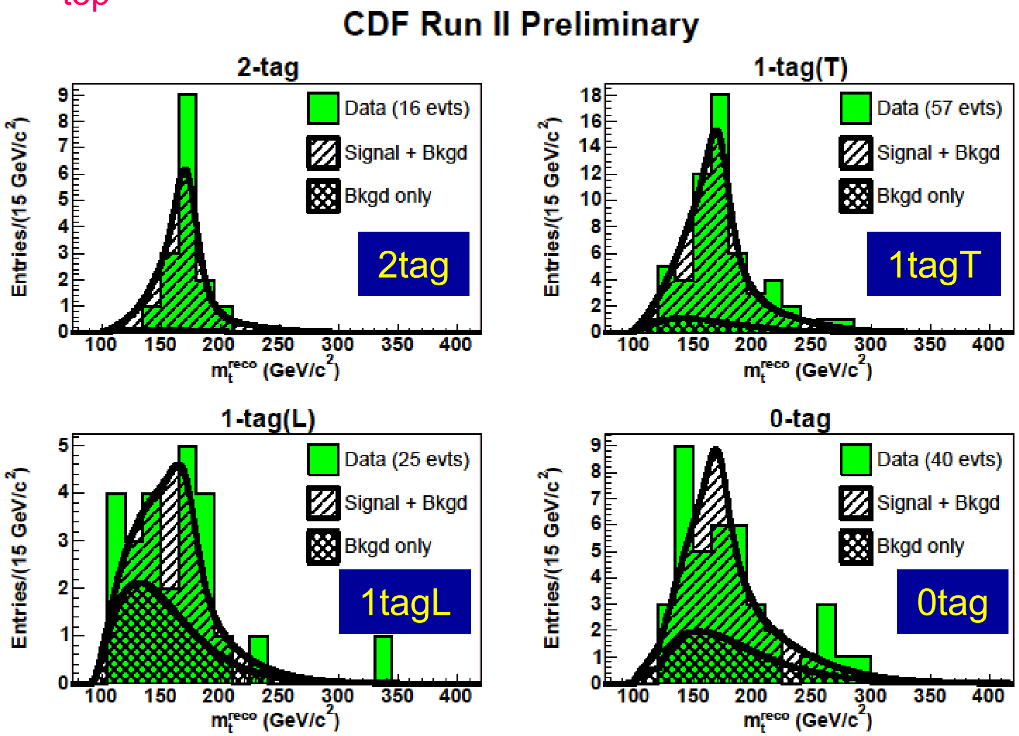
JES shifted by −3σ,-1σ,… of generic jet calibration

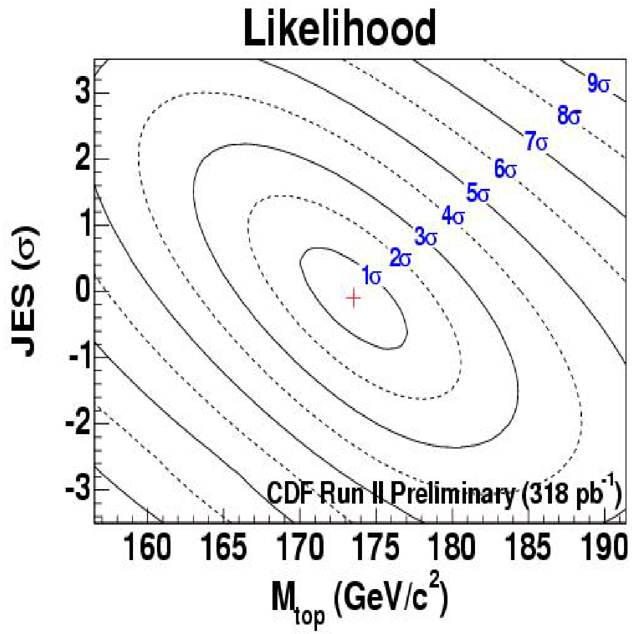
CDF L+jets Template Method (3)

Likelihood fit looks for top mass, JES and background fraction that describes the data M_{top} distribution best (template fit).

M_{top} distributions :

$\mathcal{L}$ = 318 pb^{-1}





$$m_{top} = 173.5 \; +2.7/-2.6 \; (stat) \pm 3.0 \; (syst) \; GeV/c^2$$

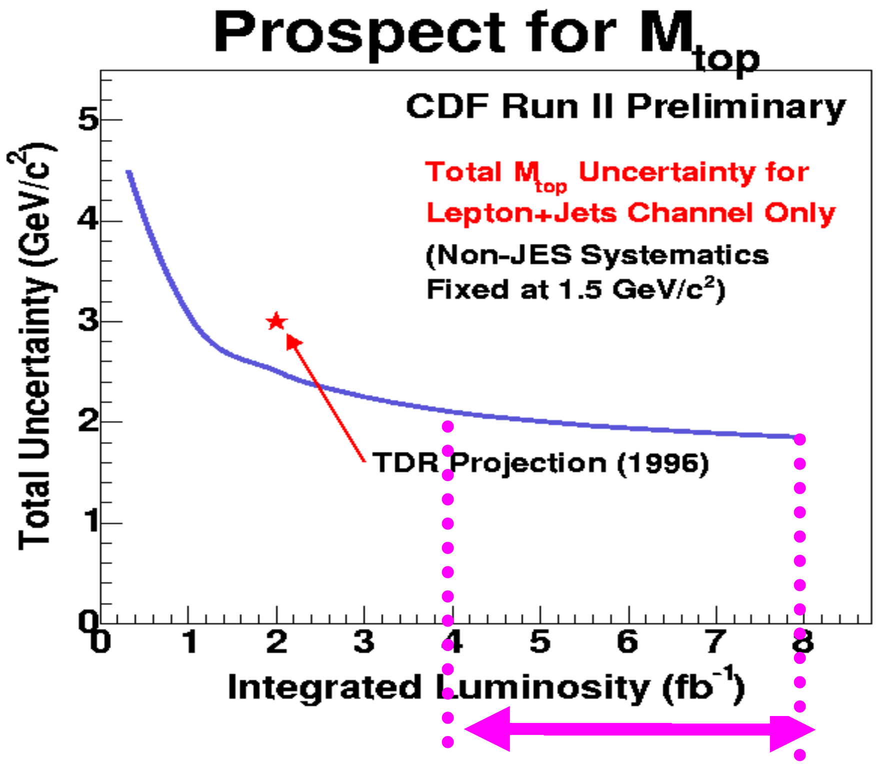
World's Best Single Measurement!!

JES syst 2.5 compared to 3.1 wo/ in situ calibration

CDF L+jets Template Method (4)

- Future Projection -

- Total uncertainty of
  $\Delta m_{top} \sim 2$ GeV/c^2
  in the end of CDF Run II.
- Conservative projection assuming only stat. and JES will improve.
  → We will do better!
  (I will discuss later).



Aimed for luminosity of Tevatron Run II.

CDF L+jets Dynamical Likelihood Method (1)

Calculate likelihood as a function of m_{top} according to Matrix Element for each event.

Sum over jet-parton combination.

Probability for $P_T(t\bar{t})$

$$L(m_{top}) = \sum \int \frac{2\pi^4}{Flux} PDF_{a/p}(z_a) \cdot PDF_{b/\bar{p}}(z_b) \cdot f(P_T)$$

$$\times \left| \mathcal{M}_{t\bar{t}}(a,b \rightarrow \mathbf{x}; m_{top}) \right|^2 \cdot w(\mathbf{x},\mathbf{y})\, d\mathbf{x}$$

Matrix Element for signal

Transfer func. (**parton $E_T \rightarrow$ jet E_T**)

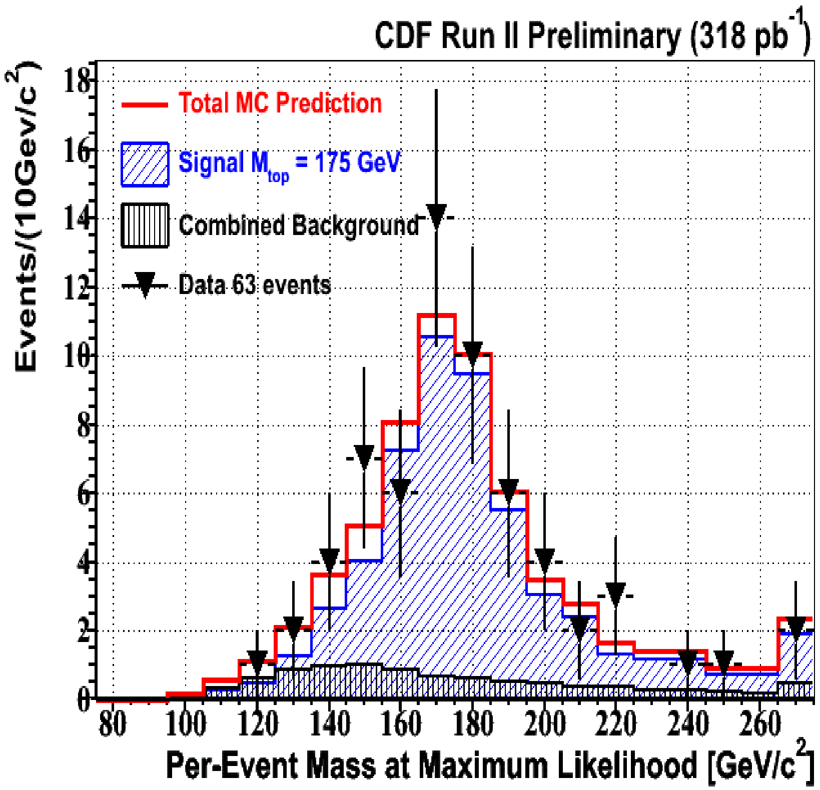
x(Parton), ***y***(Observable)

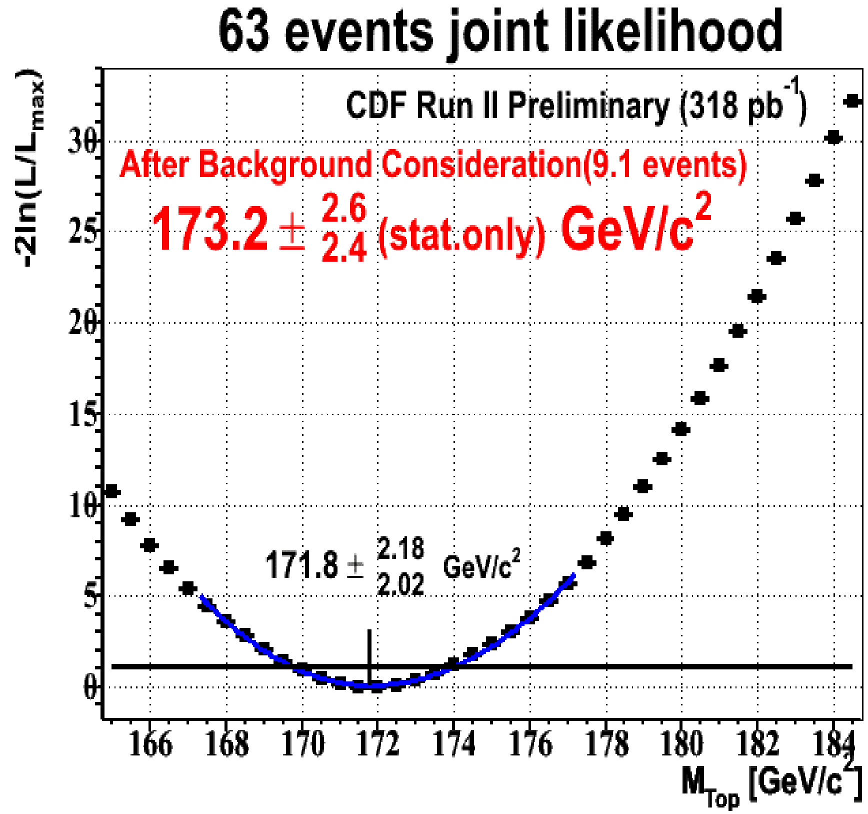
CDF L+jets Dynamical Likelihood Method (2)

$\mathcal{L}$ = 318 pb^{-1}

- 63 candidates with exact 4 jets (≥1 jet *b*-tagged).
- Signal fraction ~ 85.5%.

to reduce impact of gluon radiation events





M_{top} = 173.8 +2.6/-2.4(stat) ± 3.2(syst) GeV/c^2

D0 L+jets Matrix Element Method (1)

- Calculate probability density for m_{top}.
- Matrix Element for background included.
- In situ calibration of JES.

Probability density for m_{top}

Hadronic W mass in ME → In situ JES calib.

Signal probability for m_{top} calculated w/ Matrix Element

$$P_{evt}(m_{top}, JES) = f_{top} \cdot P_{sig}(\mathbf{y}; m_{top}, JES) + (1 - f_{top}) \cdot P_{bkgd}(\mathbf{y}; JES)$$

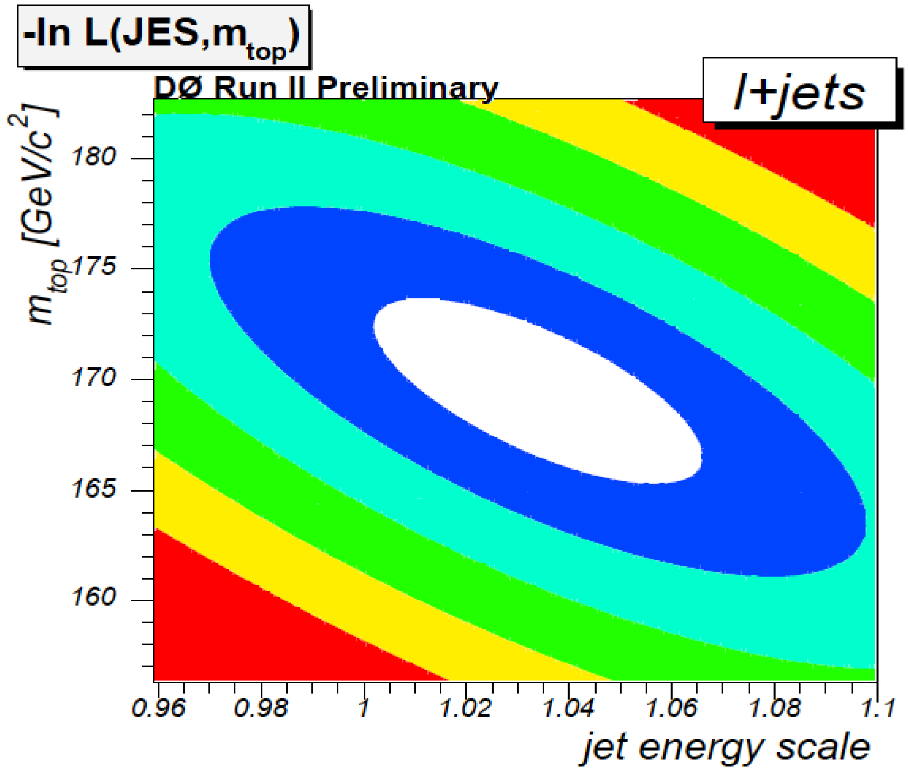
Signal fraction in measurement sample

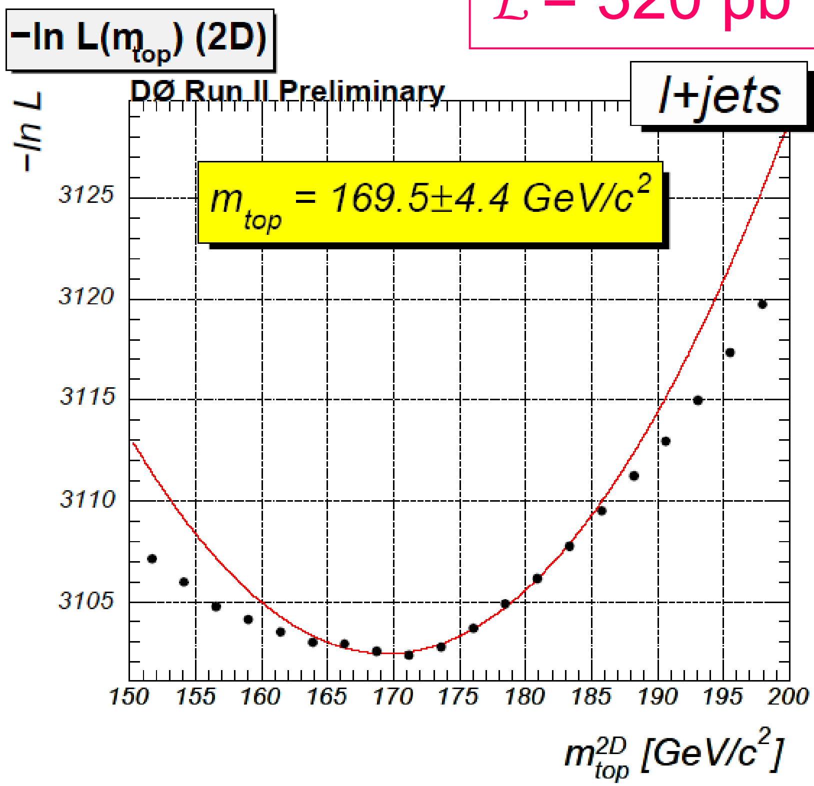
Background probability Calculated w/ ME

D0 L+jets Matrix Element Method (2)

- 150 candidates w/ exactly 4 jets (w/o b-tagging).
- Signal fraction ~ 36.4%.

$\mathcal{L}$ = 320 pb^{-1}





M_{top} = 169.5 ±4.4(stat+JES) +1.7/-1.6(syst) GeV/c^2

D0 Dilepton Matrix Weighting Method (template method)

Dilepton→2ν's
→under-constrained system
→need kinematic assumption

CDF assumes
$(\eta_{\nu1}, \eta_{\nu2}), (\phi_{\nu1}, \phi_{\nu2}), P_z(t\bar{t})$

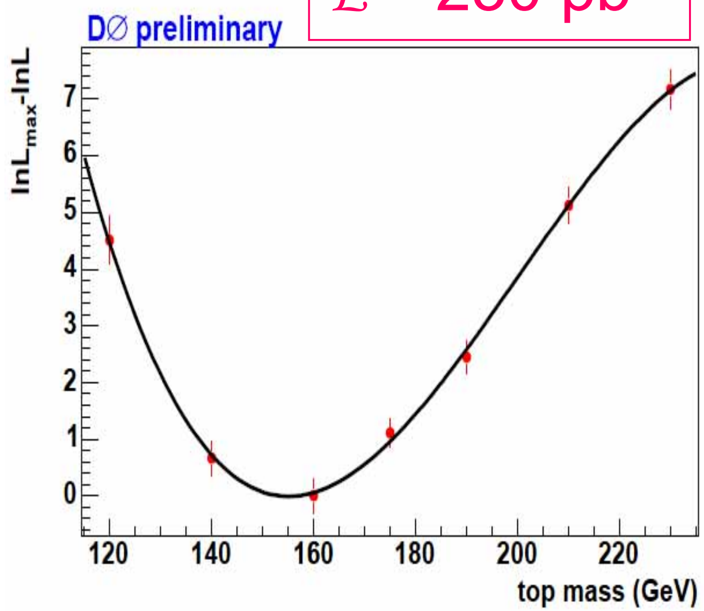
- Assume (x_1,x_2).
- Calculate weight for each event.

$$W(M_{top}) = \sum_{solution} PDF_{a/p}(x_1)\cdot PDF_{b/\bar{p}}(x_2) \times p(E_l^* | M_{top})\cdot p(E_l^* | M_{top})$$

Probability to observe E_l^* in top decay

- Scan (x_1,x_2).
- Pick M_{top} at maximum weight.
- Template fit (w/ 13 candidates).

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

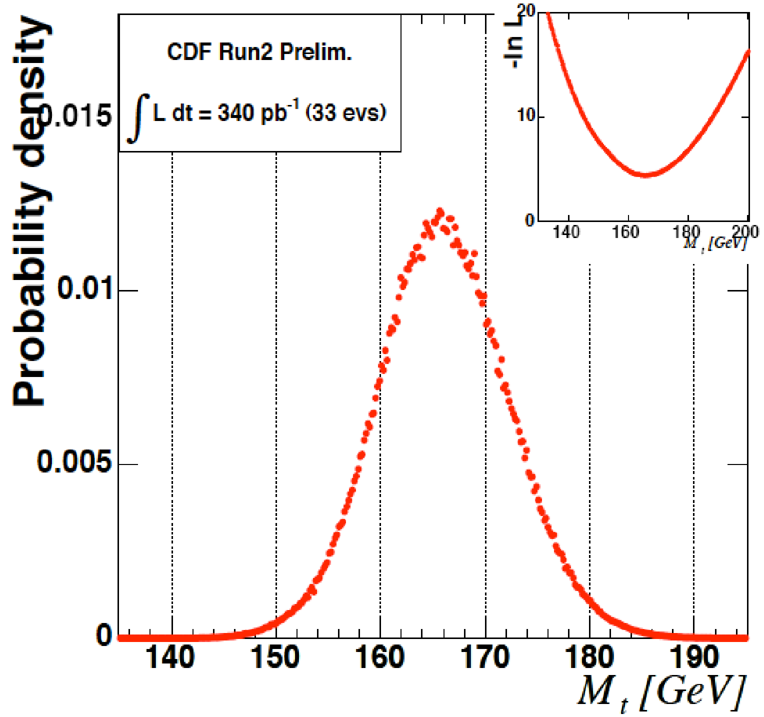


m_{top} = 155 +14/-13 (stat) ± 7 (syst) GeV/c^2

CDF Dilepton Matrix Element Method

$\mathcal{L}$ = 340 pb^{-1}

- Calculate per-event differential cross section due to LO Matrix Element.
- Background ME is also considered to reduce the impact of background contamination.
- Calculates probability vs m_{top} for each event.



M_{top} = 165.3 ± 6.3 (stat) ± 3.6 (syst) GeV/c^2

New

CDF L+jets L_{XY} Method

Boost of *b* in top rest frame : $\gamma_b \sim 0.4\ m_{top}/m_b$

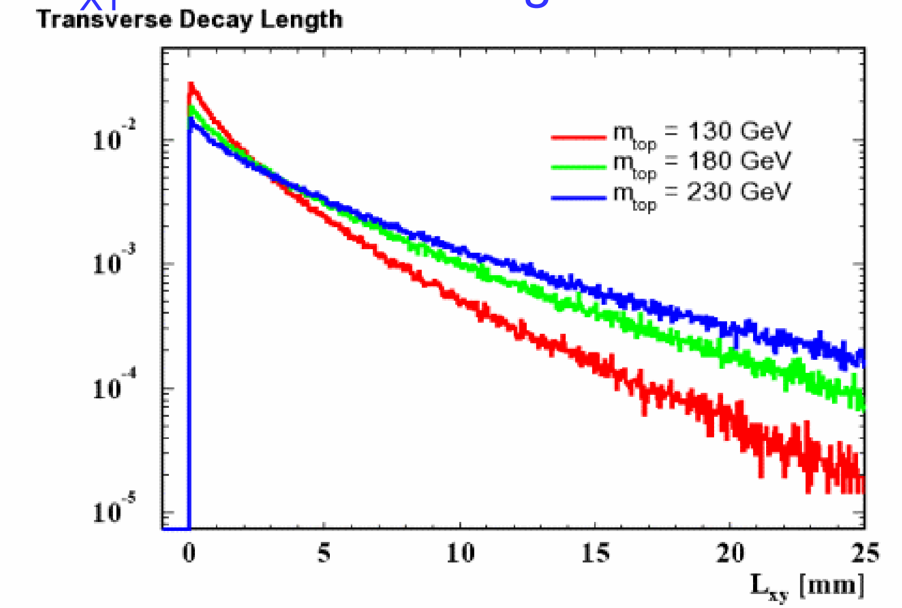
Transverse decay length L_{XY} of B depends on m_{top}

Use 216 secondary vertex b-tagged jets found in 178 events w/ ≥3 jets.

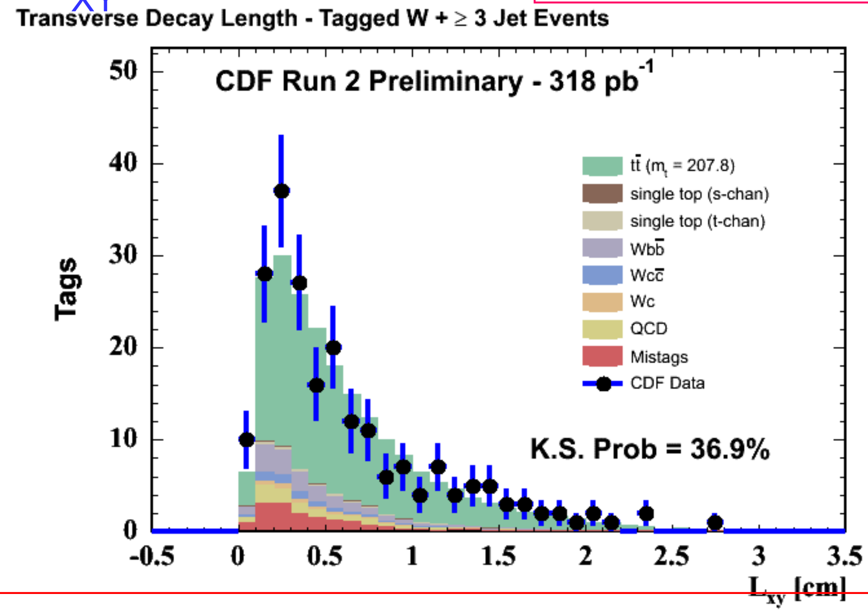
to increase efficiency

$\mathcal{L}$ = 318 pb^{-1}

L_{XY} distribution for signal



L_{XY} distribution

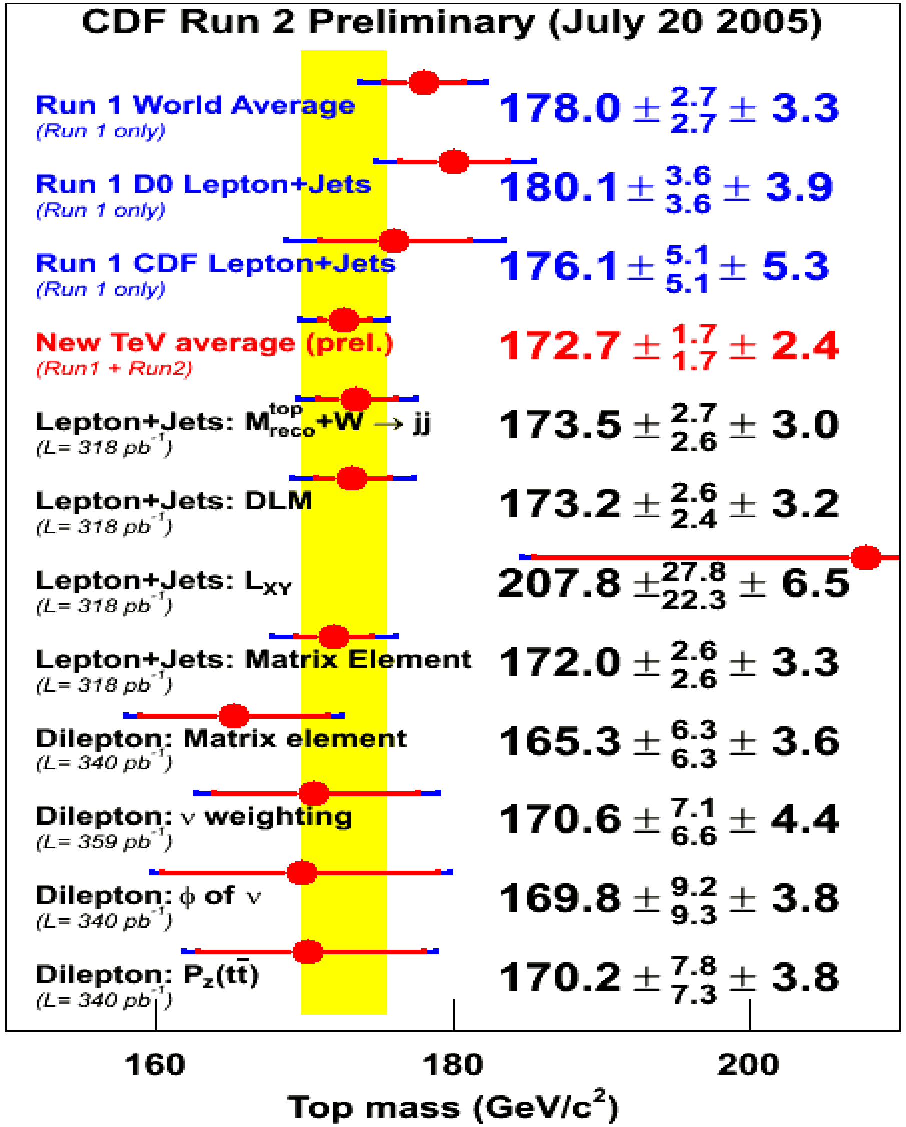


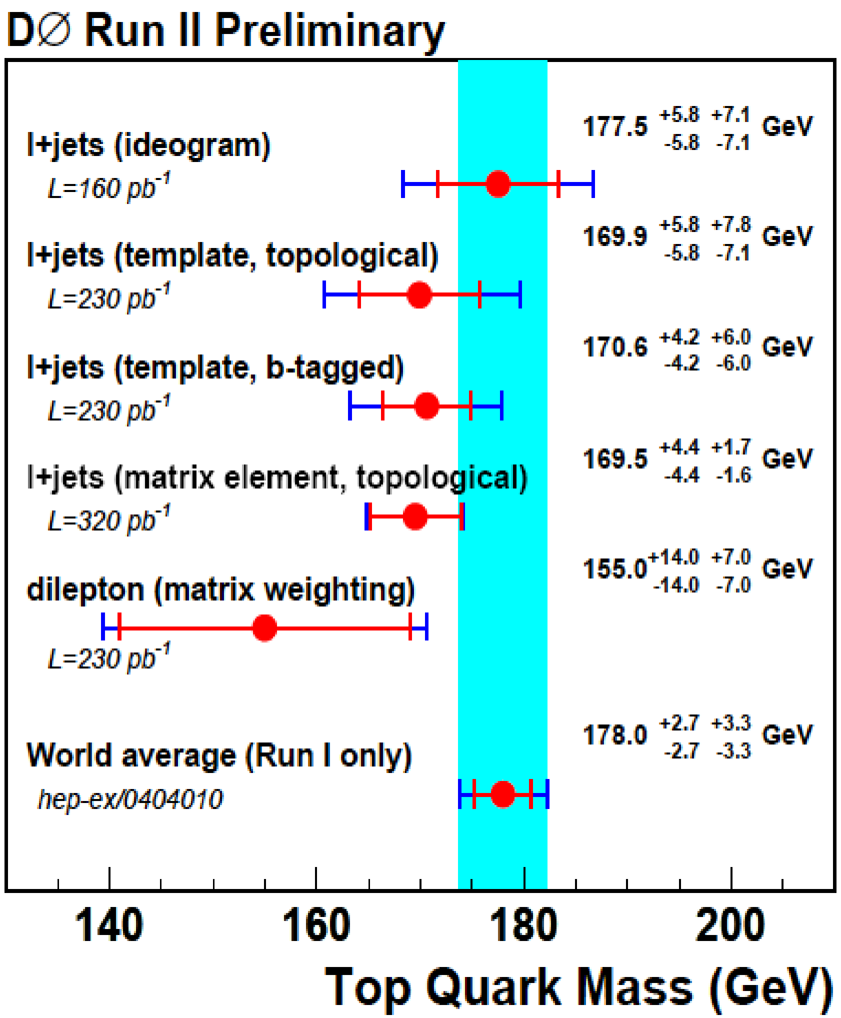
M_{top} = 207.8 +27.8/-22.3 (stat) ± 6.5 (syst) GeV/c^2

Syst. highly uncorrelated from other measurements.

- Data/MC <L_{XY}> scale factor : ±5.1 GeV/c^2
- JES : ±0.3 GeV/c^2

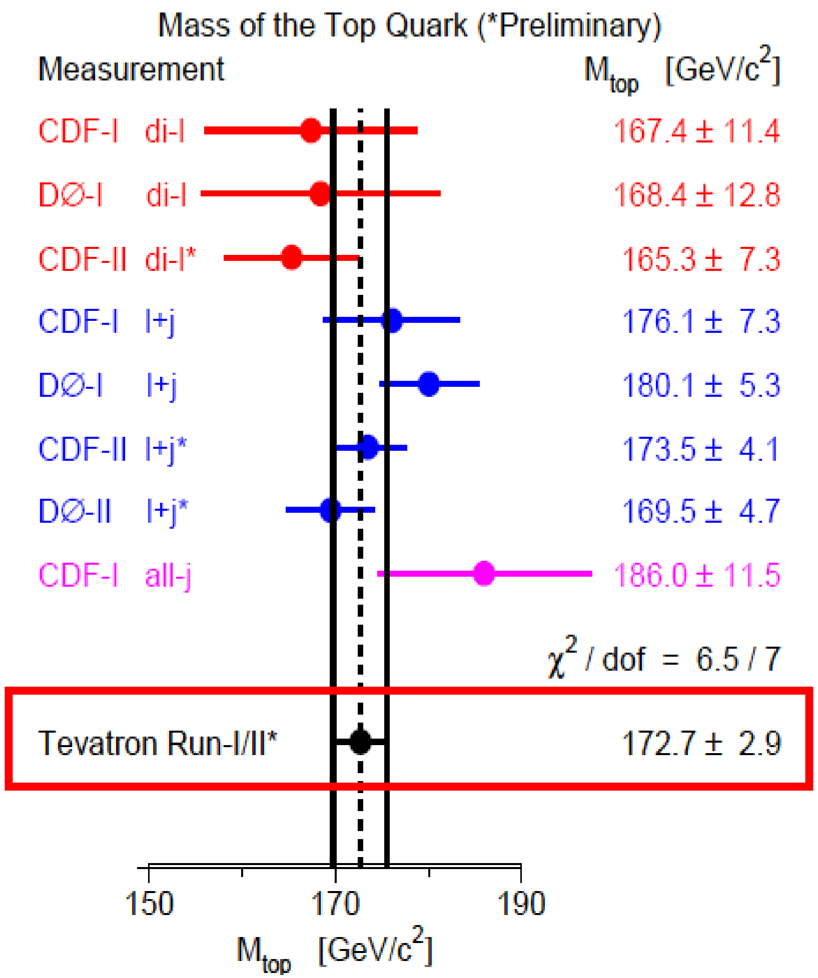
Summary of Measurements





Combination of Measurements

Only best analysis from each decay mode, each experiment.



Correlation :

- uncorrelated
  - stat.
  - fit method
  - in situ JES
- 100% w/i exp (same period)
  - JES due to calorimeter
- 100% w/i channel
  - bkgd. model
- 100% w/i all
  - JES due to fragmentation,
  - signal model
  - MC generator

Future Improvement

Combined Result:

	GeV/c^2
Result	172.7
Stat.	1.7
JES	2.0
Sig. Model	0.9
Bkgd. Model	0.9
Multi-Interaction	0.3
Fit Method	0.3
MC Generator	0.2
Total Syst.	2.4
Total Error	2.9

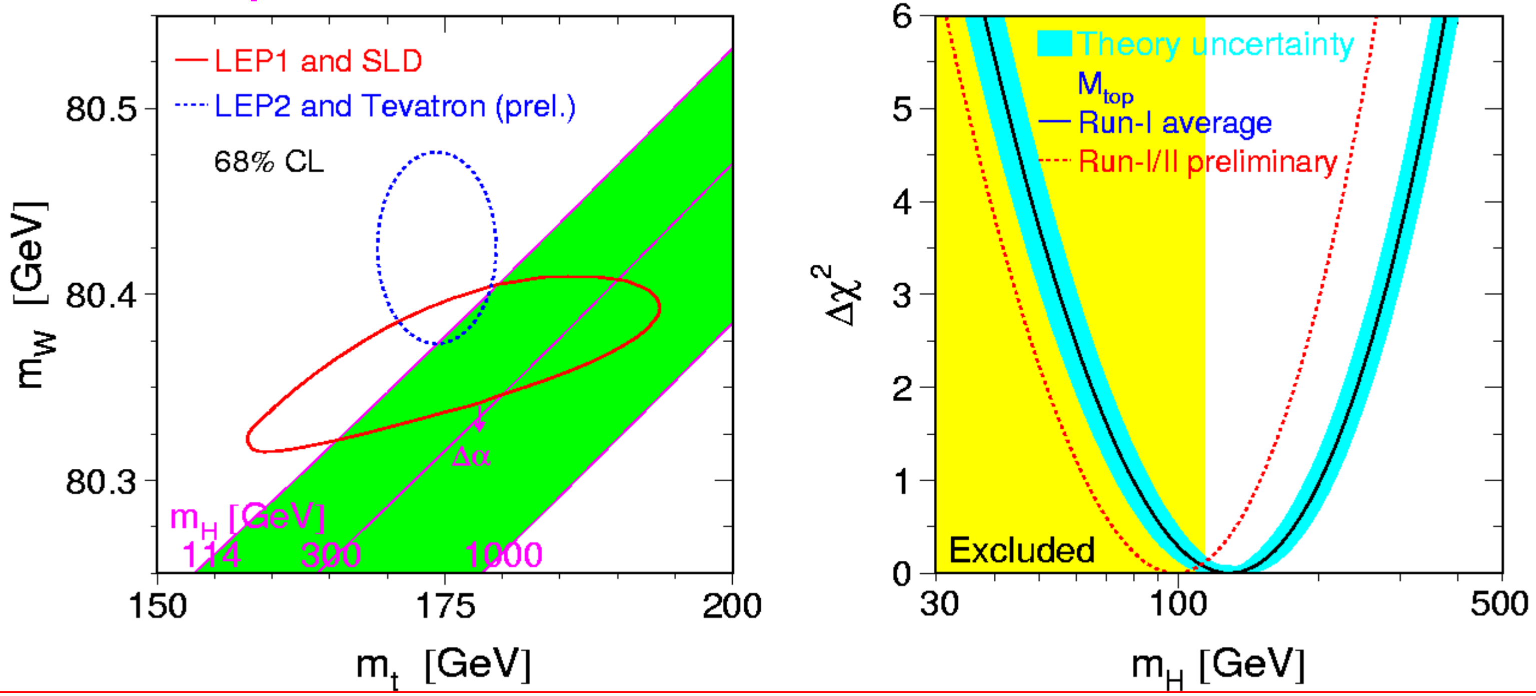
- Basic improvement by $\sim 1/\sqrt{\mathcal{L}}$
  - $\mathcal{L} \sim 1 fb^{-1}$ in next Winter.
  - Further improvement on JES by direct *b*-jet JES calibration by $Z \rightarrow bb$ events. Current *b*-jet JES taken same as generic jet + additional uncertainty according to LEP/SLD measurements.
- Sig./Bkgd. Modeling (ISR/FSR/Q^2 dependence etc.) can be improved by using our own data.
- Measurement in All Hadronic mode is coming soon.
- Syst. of L_{XY} method is highly uncorrelated w/ other analyses.

New ElectroWeak Fit

ElectroWeak fit is under update w/ new combined m_{top}.

w/ previous Preliminary CDF Run II + D0 Run I Combined :

m_{top}=174.3 ±2.0 (stat) ±2.8 (syst) GeV/c^2



m_{higgs}=98 +52/-36 GeV/c^2, m_{higgs}<206 GeV/c^2 (95%)

w/ Tevatron Run I average : 178.0 ± 2.7 ±3.3 GeV/c^2 :

m_{higgs}=114 +69/-45 GeV/c^2, m_{higgs}<260 GeV/c^2 (95%)

Summary

- CDF L+Jets Template Method is the best single measurement :

  m_{top}=173.5 +4.1/-4.0 GeV/c^2

  and will achieve Δm_{top}<~2 GeV/c^2 in Run II.
- Preliminary combination of CDF and D0 :

  m_{top}=172.7 ± 2.9 GeV/c^2 .

  (Run I average : 178.0 ± 4.3 GeV/c^2)

  From previous preliminary world ave. m_{top}=174.3 ± 3.4 GeV/c^2

  → m_{higgs}=98 +52/-36 GeV/c^2, m_{higgs}<206 GeV/c^2 (95%).

  → **This will be updated shortly!**
- Next Winter with ~1fb^{-1}.

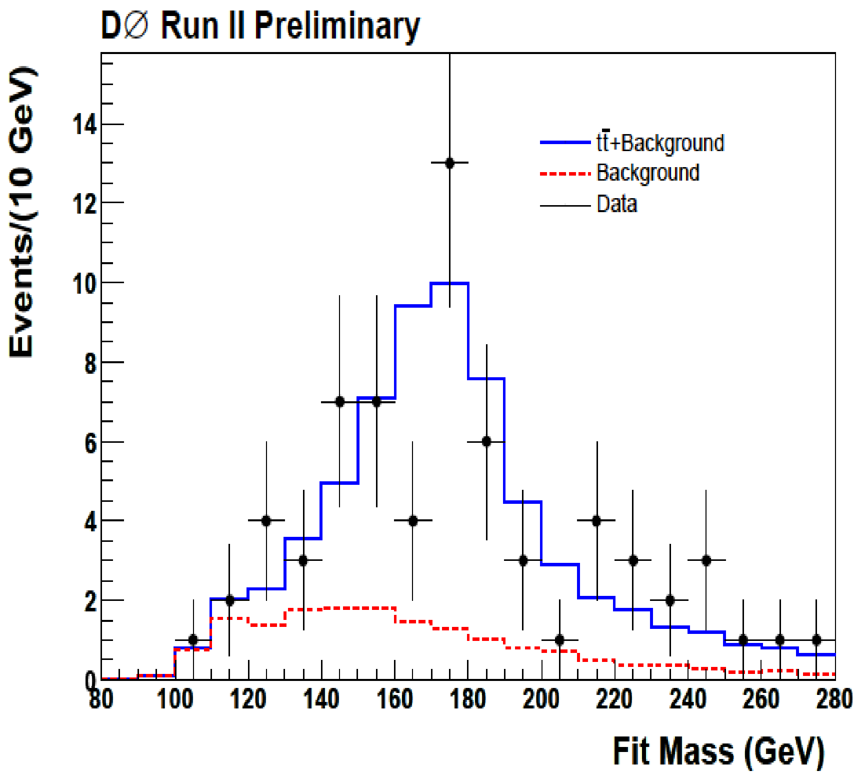
  - Improvement of dominant uncertainties better than by ~1/√L.
  - D0 Run II dilepton and All Hadronic channel from CDF/D0 will be included in combined measurement.

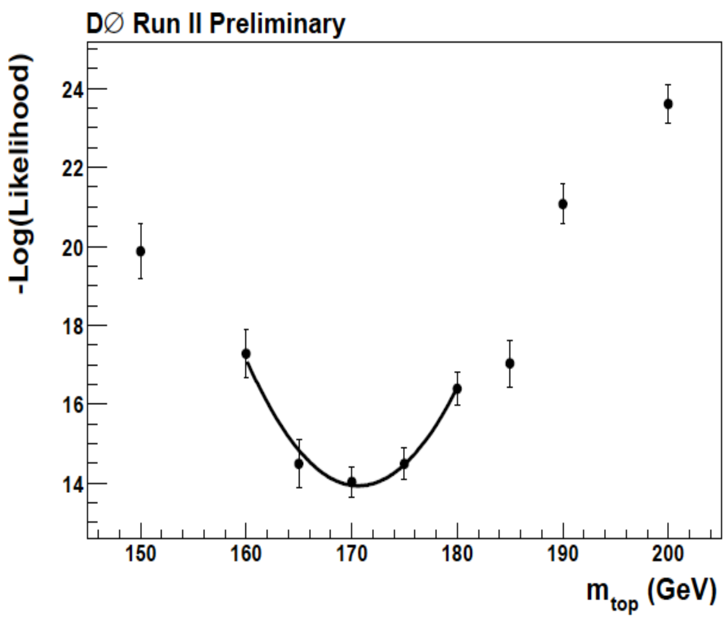
Backup

D0 L+jets Template Method

- Event-by-event M_{top} by χ^2 fit.
- Use 69 candidate events with ≥1 *b*-tagged jet.

$\mathcal{L}$ = 229 pb^{-1}





$$m_{top} = 170.6 \pm 4.2\ (\text{stat}) \pm 6.0\ (\text{syst})\ \ \text{GeV}/c^2$$

CDF L+jets Matrix Element Method (1)

Similar to D0 L+jets ME, but does not include JES in probability definition.

$$P_{t\bar{t}}(x;m_t) = \frac{1}{\sigma_{tot}} \int d\sigma_{t\bar{t}}(y;m_t) dq_1 dq_2 f(q_1) f(q_2) W(x,y)$$

x ≡ measured quantities, y ≡ parton level

$d\sigma = |\mathcal{M}|^2 d\Phi$ — LO qqbar matrix element from Mahlon & Parke

$f(q_1)f(q_2)$ — Structure functions, (q_i ≡ momentum fraction)

$W(x,y)$ — Transfer functions (Map measured quantities into parton level quantities).

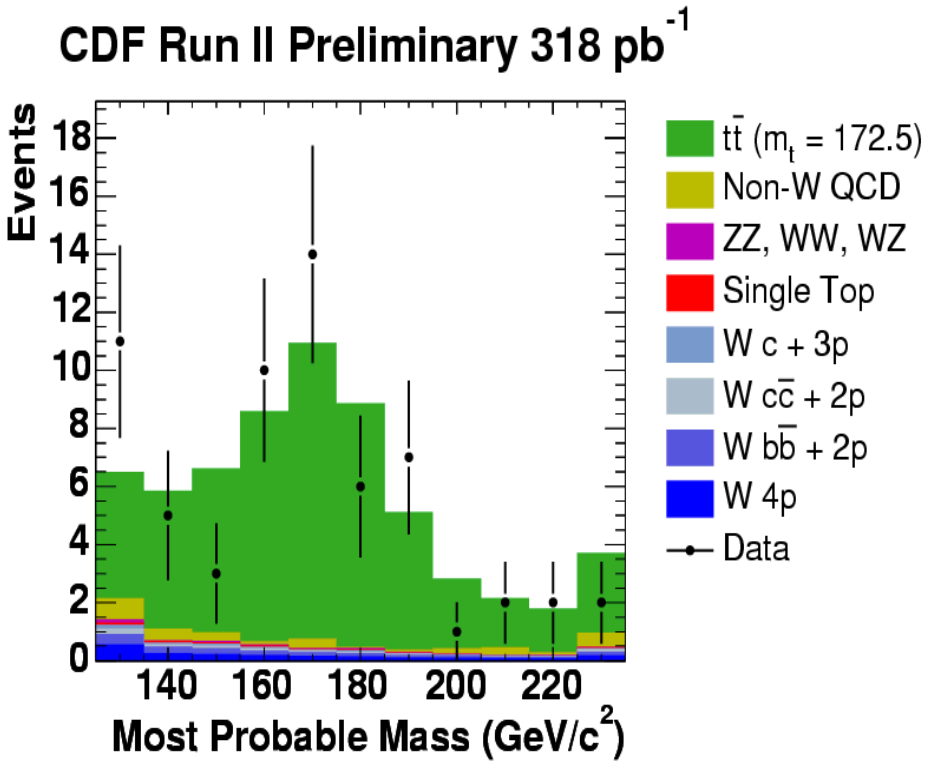
$$L(m_t) = \prod_{i=1}^{N} c_1 \frac{P_{t\bar{t}}(x_i;m_t)}{\langle Acc(x) \rangle_{t\bar{t}}(m_t)} + (1-c_1) \frac{P_{Back}(x_i)}{\langle Acc(x) \rangle_{Back}}$$

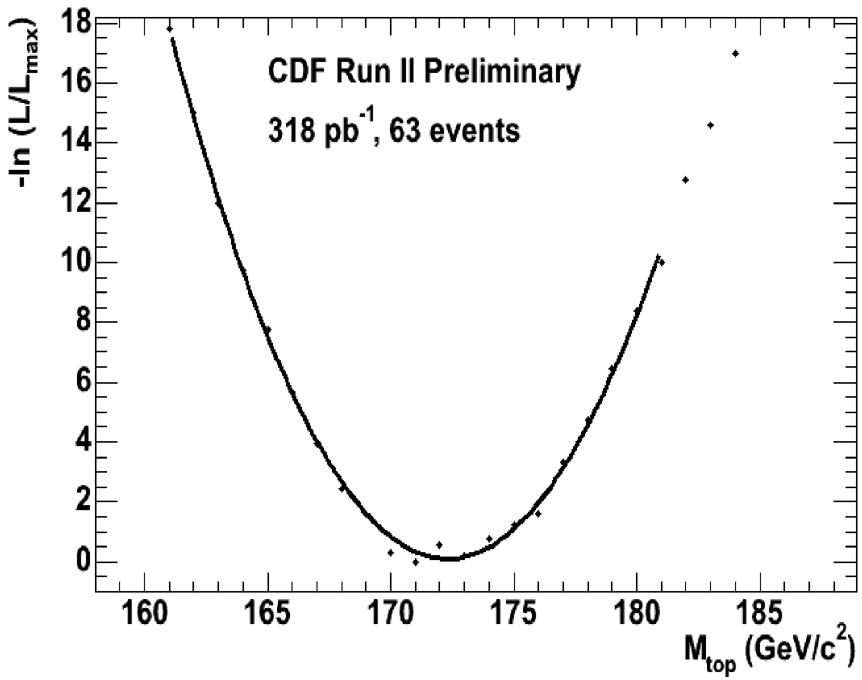
CDF L+jets Matrix Element Method (2)

$\mathcal{L}$ = 318 pb^{-1}

63 candidates with exact 4 jets (≥1 jet *b*-tagged).

to reduce impact of gluon radiation events





m_{top} = 172.0 ± 2.6 (stat) ± 3.3 (syst) GeV/c^2

Dilepton Template Methods

With 2 ν's, dilepton decay of tt is an under-constraint system even supposing pole mass of W.

- D0 matrix weighting
- CDF ν weighting
- CDF φ of ν
- CDF $P_z(tt)$

How do we measure top mass?

Make an assumption.

- (x_1, x_2), $(\eta_{\nu 1}, \eta_{\nu 2})$, $(\phi_{\nu 1}, \phi_{\nu 2})$, $P_z(tt)$, etc., ….

↓

Calculate probability for M_{top}.

Scan the assumed variable due to Monte Carlo distributions.

Calculate the most probable M_{top} for each event.

↓

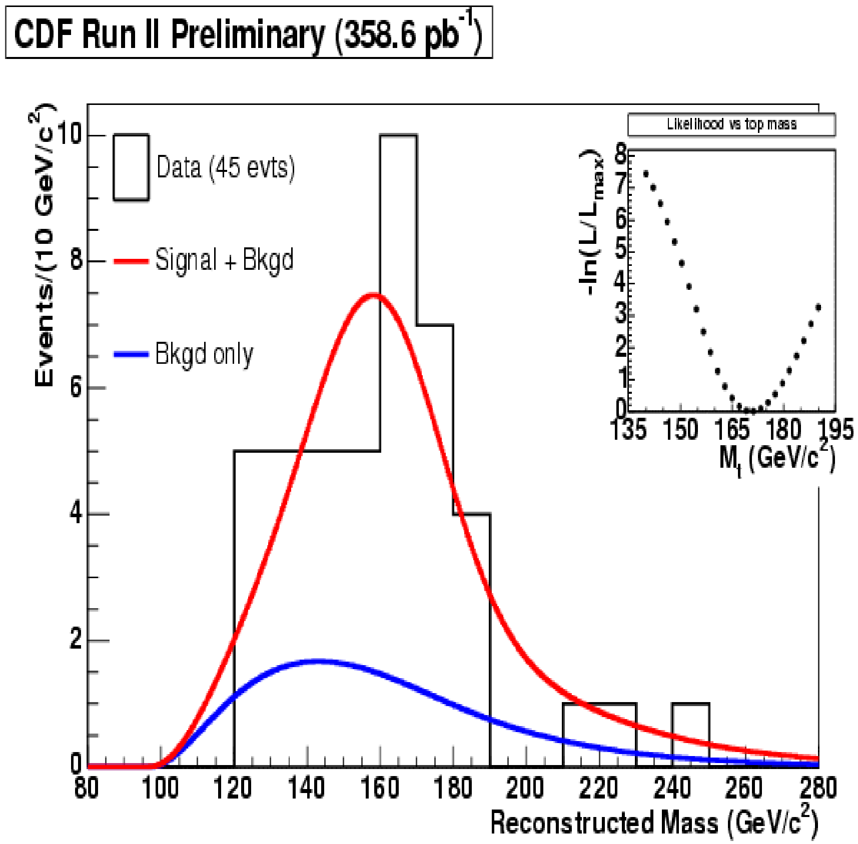
Template fit.

CDF Dilepton Neutrino Weighting Method

- Assume pseudo-rapidity of 2 ν's and M_{top}.
- Solve the 4-vector of ν's due to (E,p) conservation.
- Calculate the probability of measuring observed $\not{E}_T$.
- Scan over assumed variables.

  → probability of M_{top}.
- Pick the most probable value of M_{top} for the event.

  → Template fit.

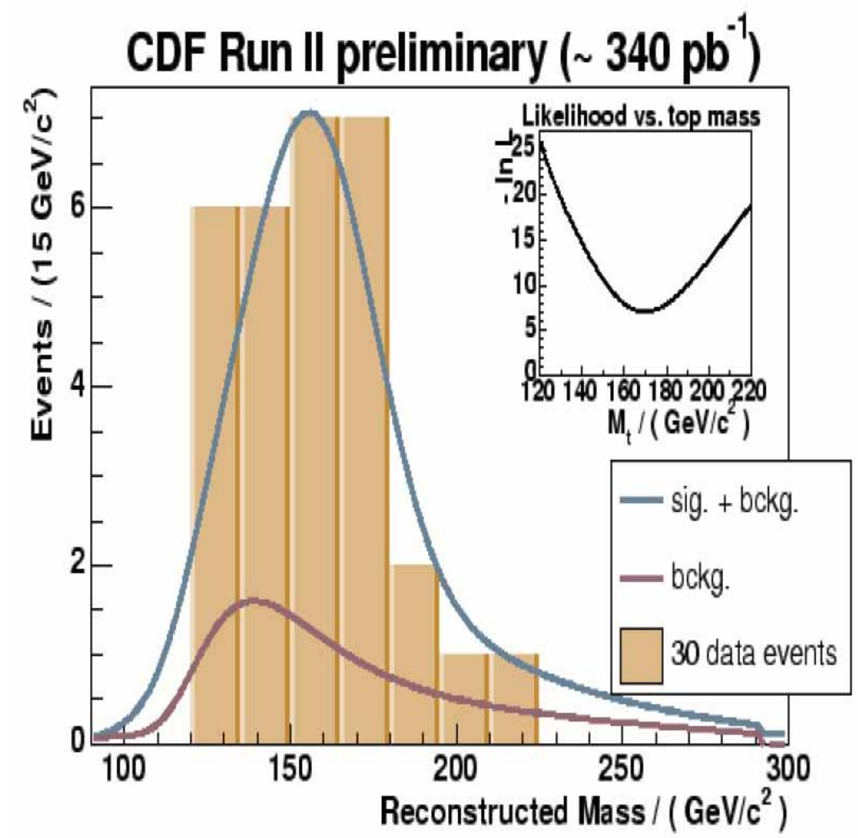


$\mathcal{L}$ = 359 pb^{-1}

m_{top} = 170.6 +7.1/-6.6 (stat) ± 4.4 (syst) GeV/c^2

CDF Dilepton $P_z(t\bar{t})$ Method

- By assuming $P_{\bar{z}}$ of tt system, momenta of the 6 final particles can be calculated from the observables.
- Calculate the invariant mass of top.
- Scan over assumed variables.
  $\rightarrow$ probability of M_{top}.
- Pick the most probable value of M_{top} for the event.
  $\rightarrow$ Template fit.



$\mathcal{L} = 340\ pb^{-1}$

m_{top} = 170.2 +7.8/-7.2 (stat) $\pm$ 3.8 (syst) GeV/c^2

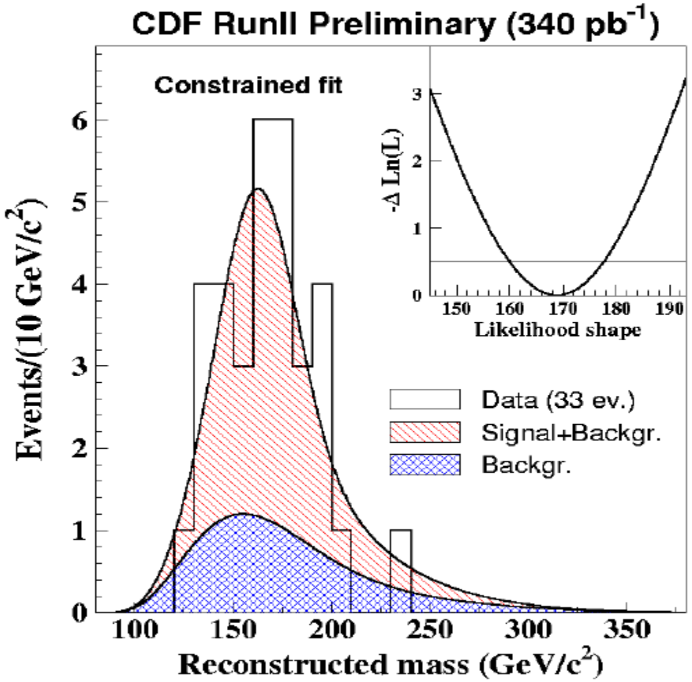
CDF Dilepton ϕ of ν Method

$$\chi^2 = \sum_{i=l,jets} \frac{(P_T^{i,fit} - P_T^{i,meas.})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(UE_j^{j,fit} - UE_j^{j,meas.})^2}{\sigma_j^2} + \frac{(M_{l_1\nu_1} - M_W)^2}{\Gamma_W} + \frac{(M_{l_2\nu_2} - M_W)^2}{\Gamma_W} + \frac{(M_{l_1\nu_1 b_1} - M_{top})^2}{\Gamma_{top}} + \frac{(M_{l_2\nu_2 b_2} - M_{top})^2}{\Gamma_{top}}$$

- Assume $(\phi_{\nu 1}, \phi_{\nu 2})$.
- Calculate M_{top} by χ^2 fit.
- Scan over assumed variables.

  $\rightarrow$ probability of M_{top}.
- Pick the most probable value of M_{top} for the event.

$\rightarrow$ Template fit.



$\mathcal{L}$ = 340 pb^{-1}

m_{top} = 169.8 +9.2/-9.3 (stat) $\pm$ 3.8 (syst) GeV/c^2

New Preliminary World Average

Combination of the best analysis from each decay mode, each experiment.

Correlation :

Split into 2 to isolate “in situ” JES systematics from other JES

		Run-I published					Run-II preliminary			
		CDF			DØ		CDF			DØ
		all-j	l+j	di-l	l+j	di-l	$(l+j)_i$	$(l+j)_e$	di-l	l+j
CDF-I	all-j	1.00								
CDF-I	l+j	0.32	1.00							
CDF-I	di-l	0.19	0.29	1.00						
DØ-I	l+j	0.14	0.26	0.15	1.00					
DØ-I	di-l	0.07	0.11	0.08	0.16	1.00				
CDF-II	$(l+j)_i$	0.04	0.12	0.06	0.10	0.03	1.00			
CDF-II	$(l+j)_e$	0.35	0.54	0.29	0.29	0.11	0.45	1.00		
CDF-II	di-l	0.19	0.28	0.18	0.17	0.10	0.06	0.30	1.00	
DØ-II	l+j	0.02	0.07	0.03	0.07	0.02	0.07	0.08	0.03	1.00

m_{top}=172.7 ±1.7 (stat) ±2.4 (syst) GeV/c^2

$Zb\bar{b}$

Trigger :

- 2 SVT track + 2 10GeV clusters.

Offline Cuts :

- N==2 jets w/ E_T>20GeV, $|\eta|$<1.5 (JetClu cone 0.7).
- Both jets are required to have secondary vertex tag.
- $\Delta\phi$(j1,j2)>3.0.
- $E_T^{3rd\text{-}jet}$<10GeV.