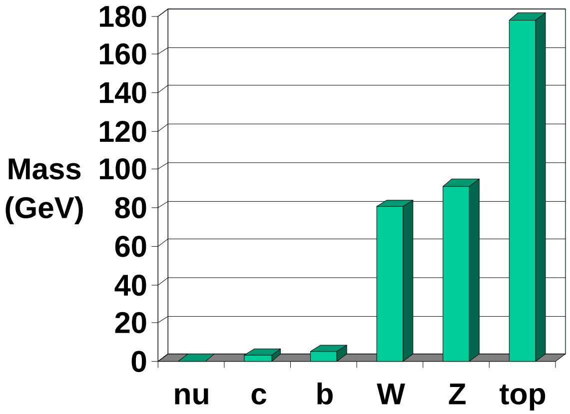
Measuring the Top Quark Mass at the TeVatron



WIN '05

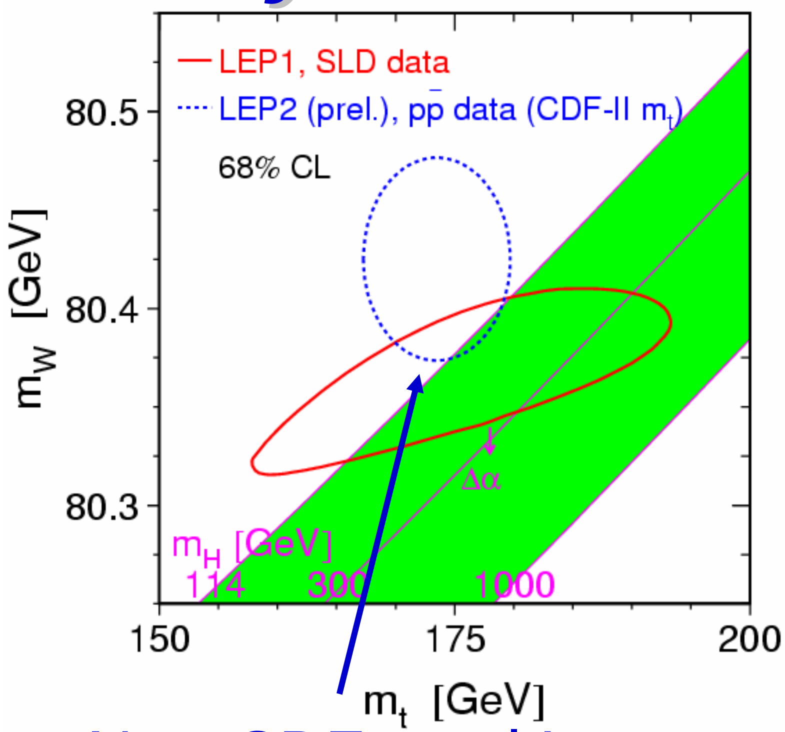
June 6-11, 2005

Eva Halkiadakis

University of Rochester

For the CDF and D0 Collaborations

Why Measure m_t?

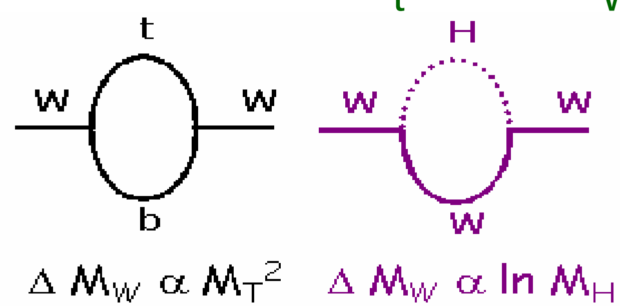


Direct measurements of m_t:

- tests SM predictions
- constrains SM Higgs mass
- key to EWSB

Higgs is "*giver*" of mass.

Its mass is tied to m_t and m_W.



New CDF result! (only used above)

$$m_t(\mathrm{CDF}) = 173.5^{+4.1}_{-4.0}\,\mathrm{GeV/c^2}$$

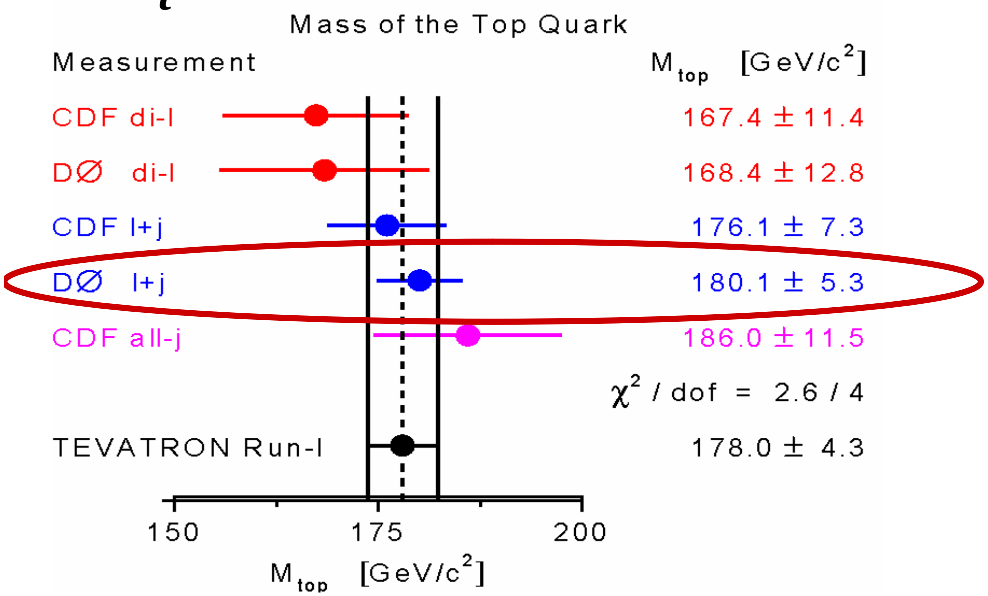
l + jets channel with 318 pb^{-1}

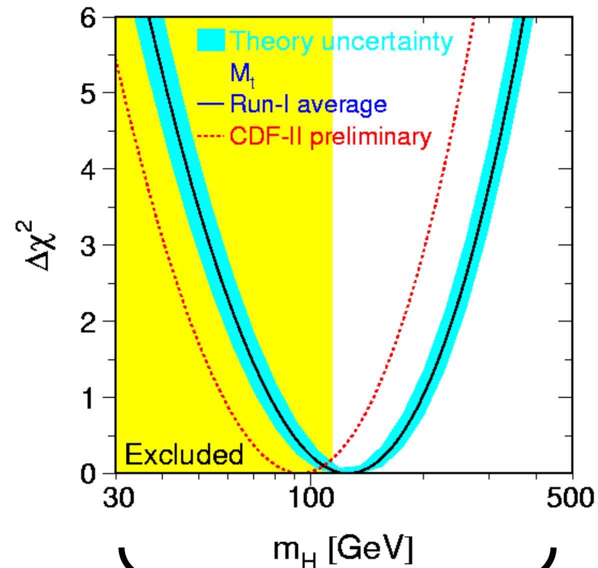
Better than World Average! (Run I) $m_t(\mathrm{WA}) = 178.0^{+4.3}_{-4.3}\,\mathrm{GeV/c^2}$

m_t Tevatron Run I vs. New Run II Results

Run I World Average(~110pb^{-1})

$$m_t = 178.0 \pm 4.3 \text{GeV/c}^2$$





This result only used above

$$m_t(\text{CDF RunII}) = 173.5^{+4.1}_{-4.0} \text{GeV/c}^2$$

$$m_H = 114^{+69}_{-45} \text{ GeV/c}^2 \quad \Longrightarrow \quad m_H = 94^{+54}_{-35} \text{ GeV/c}^2$$

$$m_H < 260 \text{ GeV/c}^2 \text{ @ } 95\% \text{C.L.} \qquad m_H < 208 \text{ GeV/c}^2 \text{ @ } 95\% \text{C.L.}$$

(Thanks to M. Grunewald)

The TeVatron

The world's only top factory!

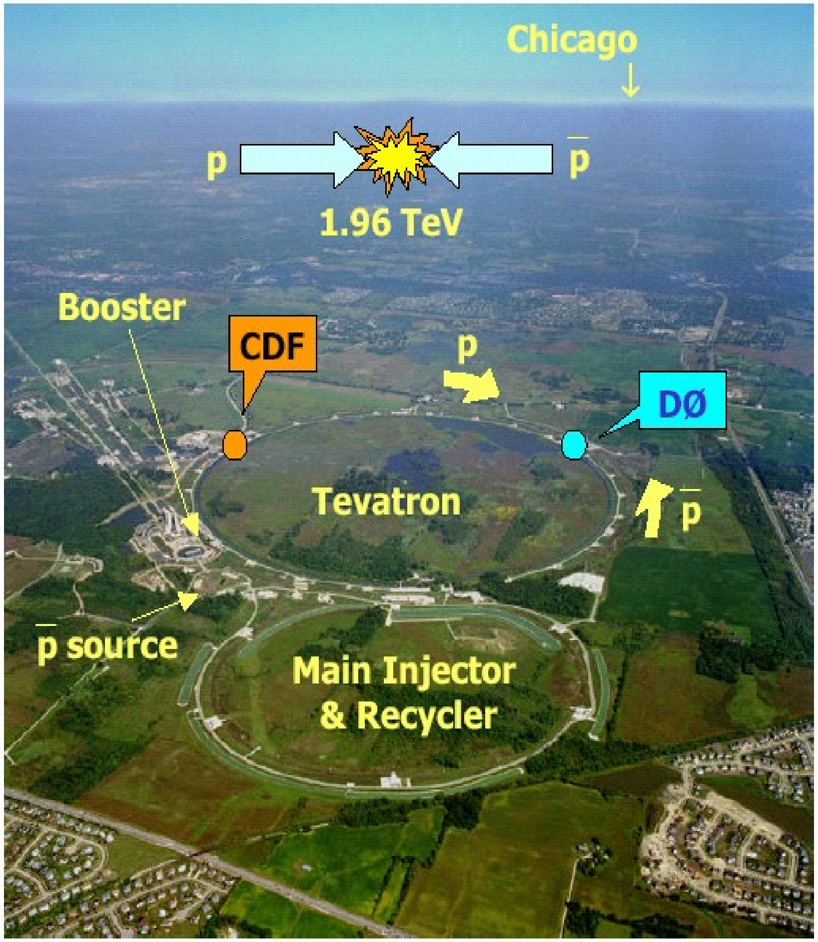
$>700pb^{-1}$ per experiment on tape

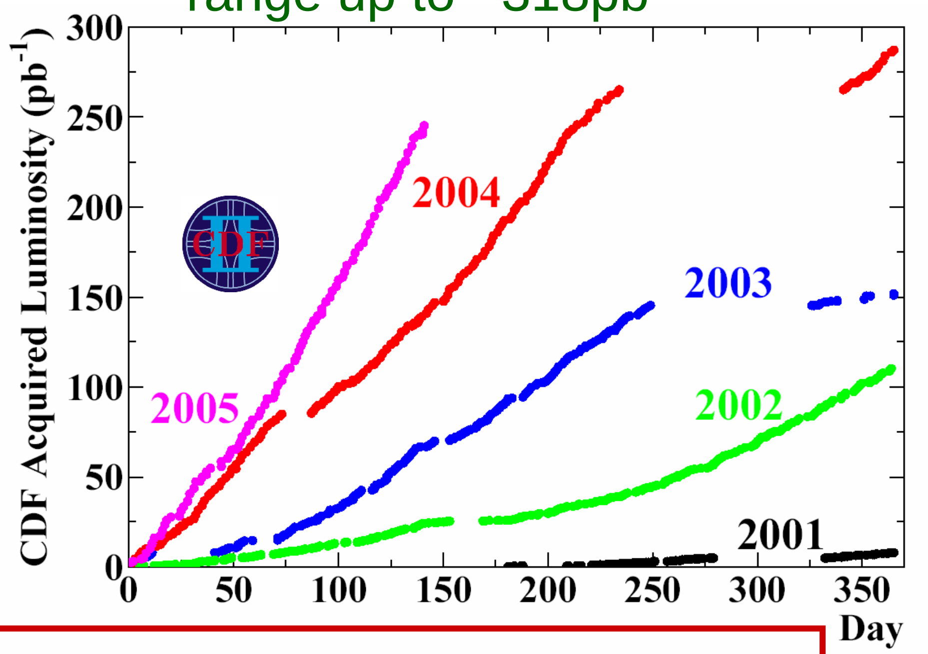
$>1fb^{-1}$ delivered luminosity!

Peak luminosity > $10^{32}cm^{-2}s^{-1}$

Analyses presented today:

range up to $\sim318pb^{-1}$





TeVatron Run II goal: $\int Ldt \approx 4-9\,\text{fb}^{-1}$ $\delta m_t \approx 2\text{GeV/c}^2$

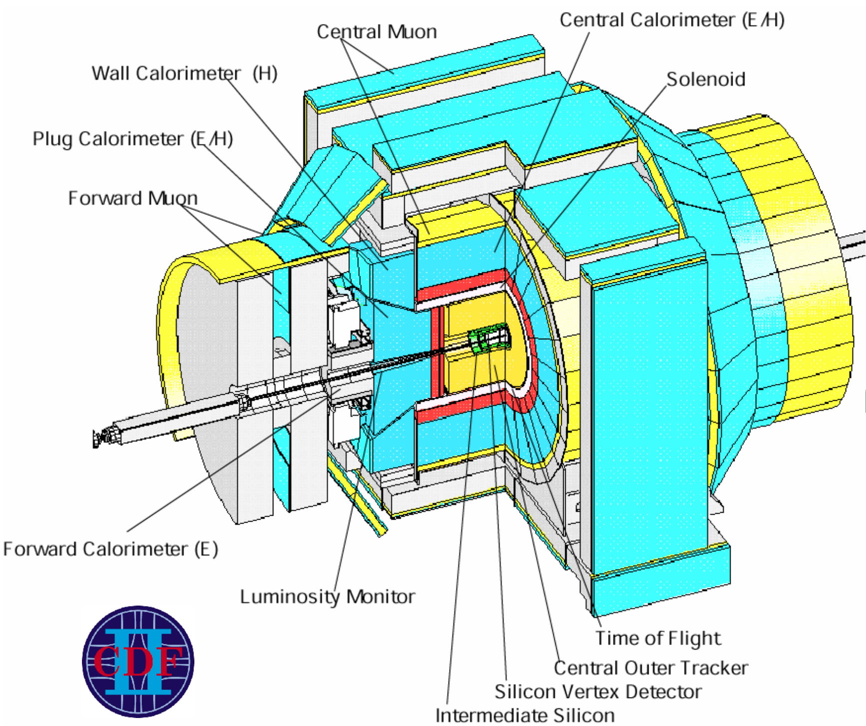
The Run II Detectors

Both experiments:

- New tracking systems
- Upgraded electronics, trigger, DAQ

Excellent tracking

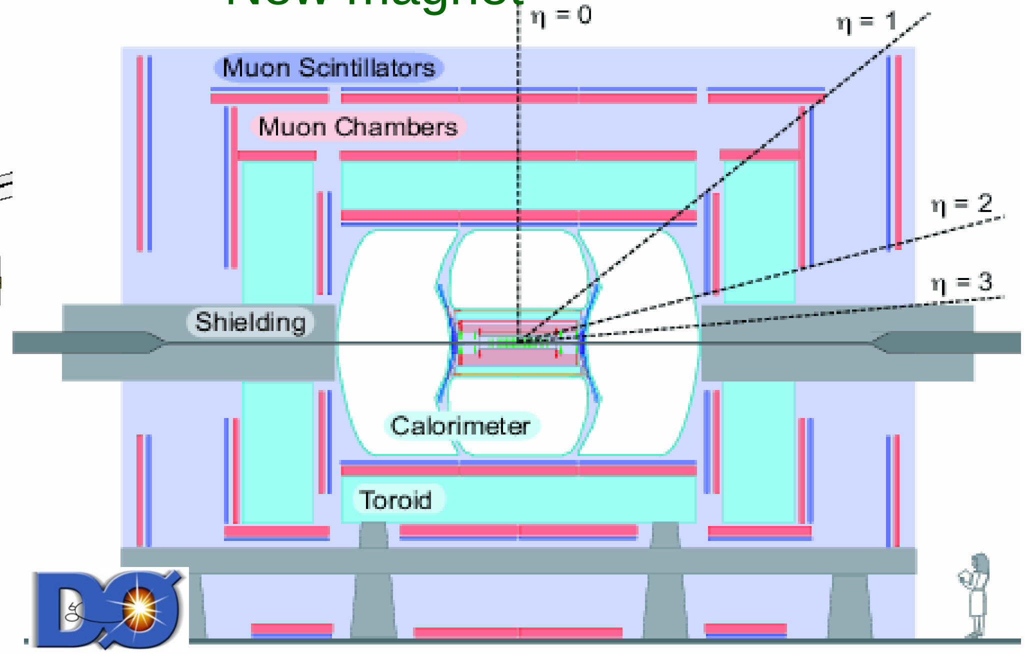
New forward calorimeters



Excellent coverage

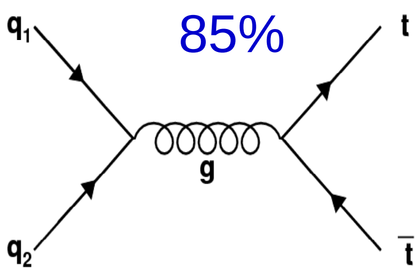
New pre-shower detectors

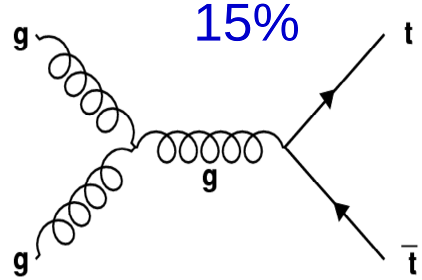
New magnet



Top Quark Production at the TeVatron

Top quarks are primarily produced in pairs:





$$\sigma(\bar{p}p \to t\bar{t} \,@\, m_t = 175\text{GeV}) \approx 6.7 \text{ pb}$$
$$\sigma(\bar{p}p \to t\bar{t} \,@\, m_t = 178\text{GeV}) \approx 6.1 \text{ pb}$$
$$\sigma(\bar{p}p \to t\bar{t} \,@\, m_t = 180\text{GeV}) \approx 5.7 \text{ pb}$$

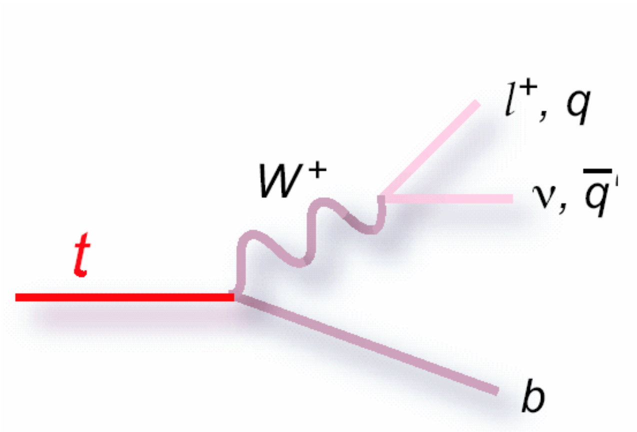
@ √s=1.96TeV

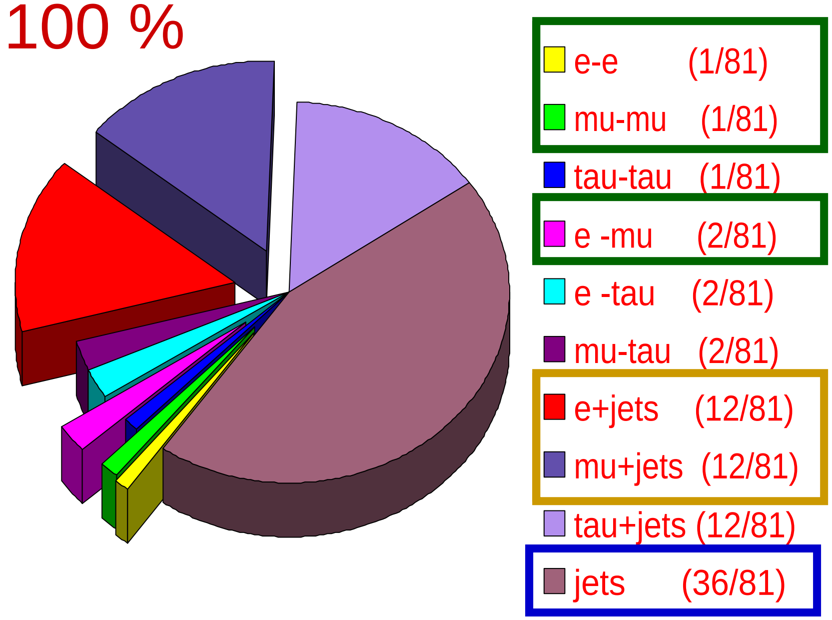
$$\sigma(\bar{p}p \to t\bar{t} \,@\, \sqrt{s} = 1.96\text{TeV}) \approx 1.30 \times \sigma(\bar{p}p \to t\bar{t} \,@\, \sqrt{s} = 1.8\text{TeV})$$

~ one top event every 10 BILLION inelastic collisions

Top Quark Decay Modes

BR(t→Wb) ~ 100 %





Experimental signatures

Dilepton (5%, small backgrounds – QCD *fakes*, Drell Yan, Diboson)

2 high-p_T leptons(e/μ), 2 b jets, large missing E_T

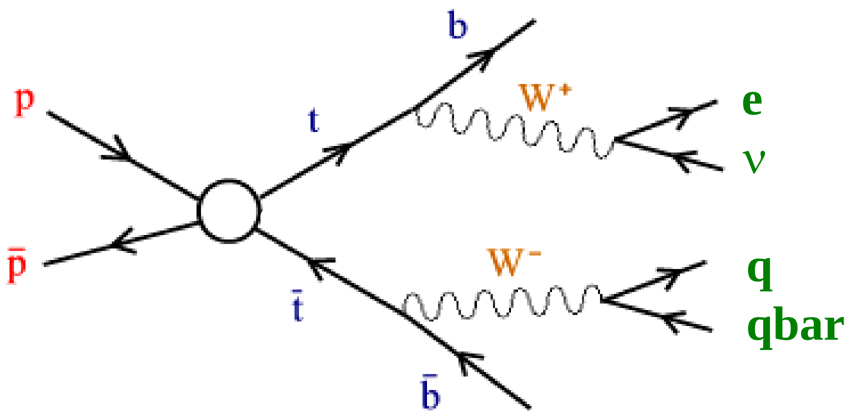
golden channel ⇒ Lepton+Jets (30%, manageable backgrounds – W+jets, QCD *fakes*)

1 high-p_T lepton(e/μ), 4 jets (2 b jets), large missing E_T

All-hadronic (44%, large backgrounds - QCD)

6 jets

Measuring m_t is Challenging!



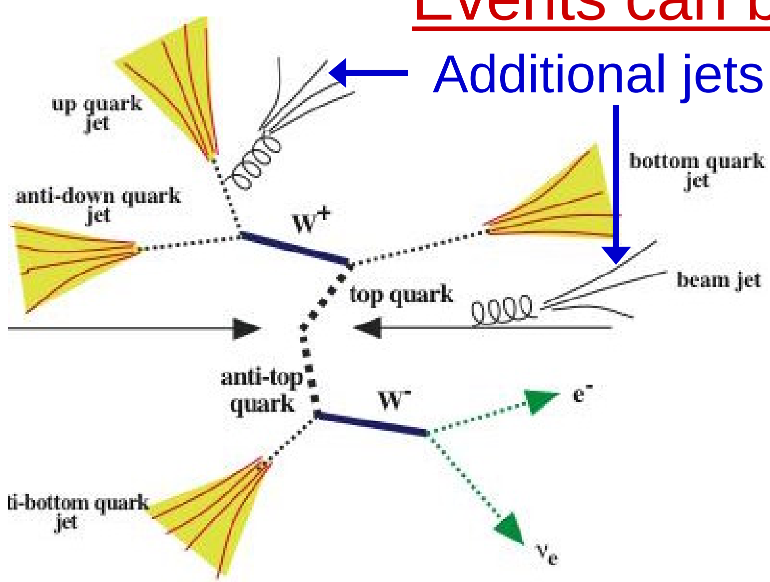
Experimental observations are not as *pretty* as Feynman diagrams!

Which jets go with which quarks?

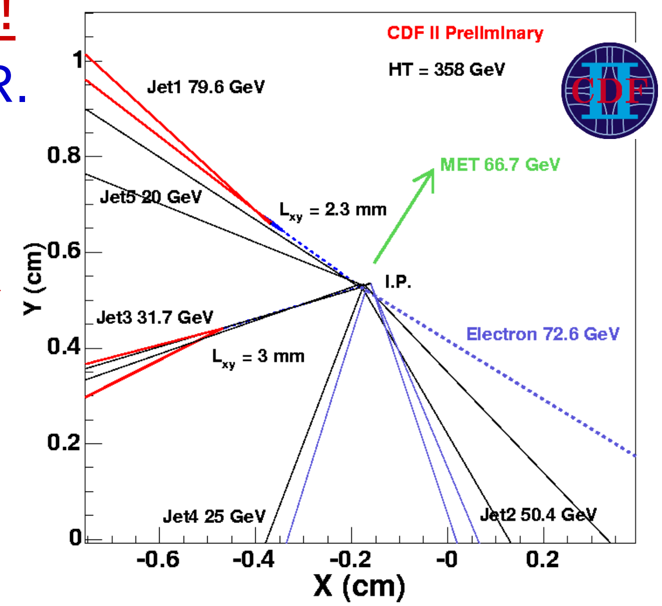
Dileptons:
2 neutrinos ⇨ 1 missing E_T measurement.

Events can be very busy!

Additional jets from ISR, FSR.



Ideal!



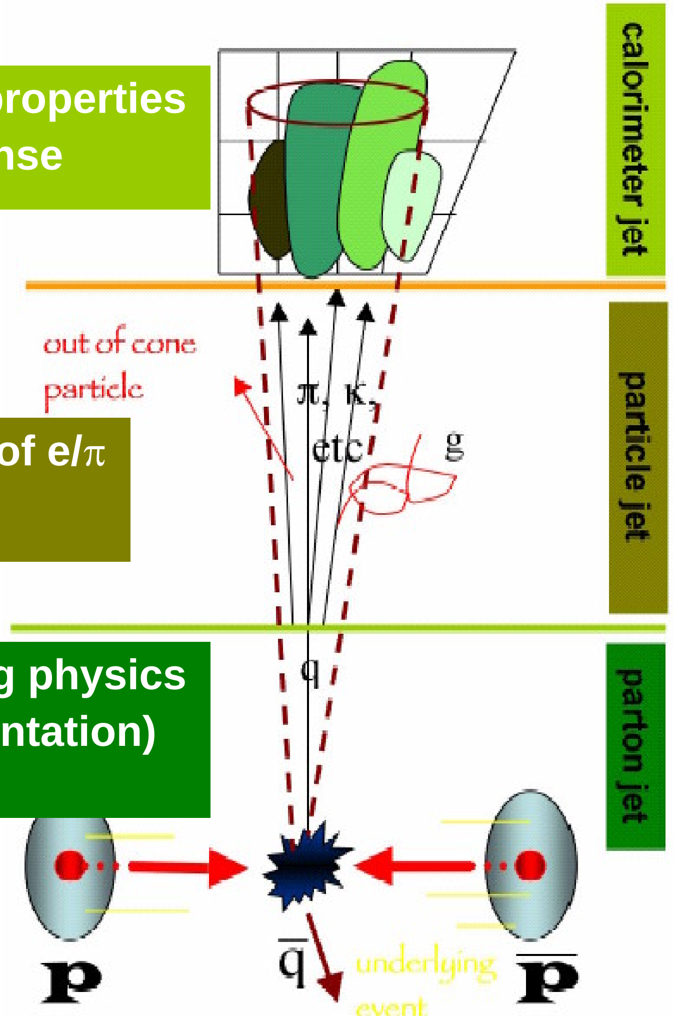
Jet Energy Scale (JES)

Determine true "parton" energy from measured jet energy in a cone

Complex detector properties
Non-uniform response

Different response of e/π
Non-linearity

Complex underlying physics (showering, fragmentation)
Analysis specific



JES is dominant systematic for m_t measurements.

Current m_t world average uncertainty is ±4.3GeV/c^2 .

⇨ 2.6 GeV/c^2 JES

⇨ 2.7 GeV/c^2 stat.

Correct for detector, algorithm and physics effects to obtain the true energy of the jet.

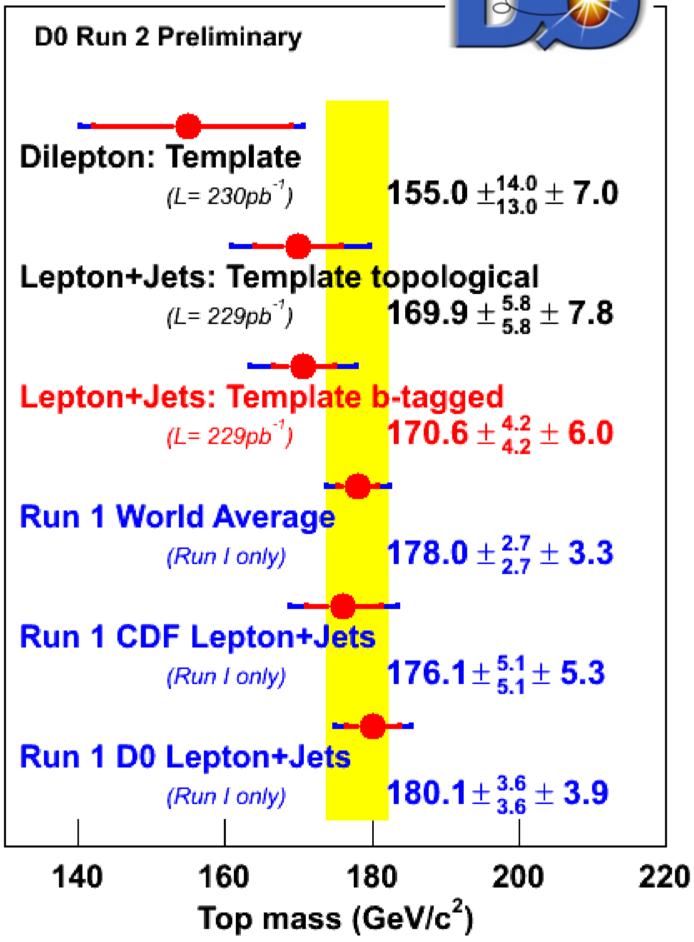
Uncertainty in modeling the behavior of jets (particle's response, fragmentation).

Measuring m_t

Run II goal: m_t error ≈ 2 GeV

Measure m_t in all experimental signatures

Combine methods/channels



Two different techniques

Template	**Matrix Element weighting**
Pick a test statistic (e.g. reconstructed mass).	Build likelihood from *matrix element*(s), PDFs and transfer functions (connect quarks and jets).
↓	↓
Create "*templates*" using events simulated with different m_t values (+ background).	Integrate over unmeasured quantities (e.g. quark energies).
↓	↓
Perform maximum likelihood fit to extract measured m_t.	Calibrate measured m_t and uncertainty using simulation.

Template Method: l+jets CDF

Each event has 2 top quarks

$$L_{sub-sample} = L_{shape} \times L_{bkg}$$

For jet-parton assignment impose constraints:
$m_t = m_{tbar}$, $m_{jj} = m_{l\nu} = m_W$

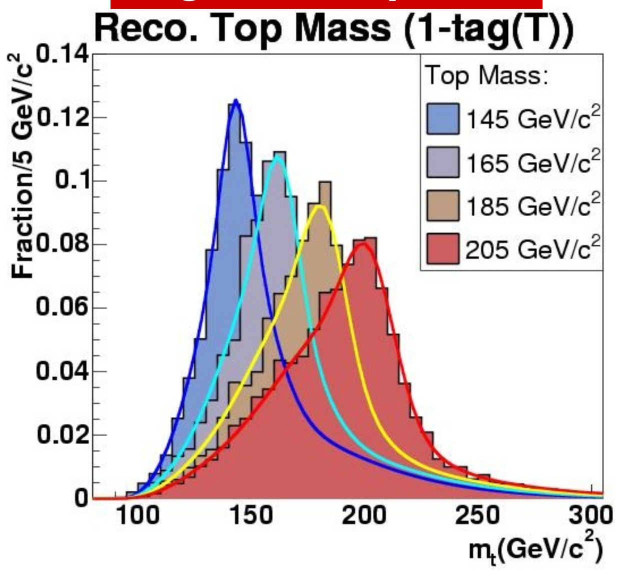
Combinations	b-tags
24	None
12	1
4	2

Choose combination with lowest χ^2

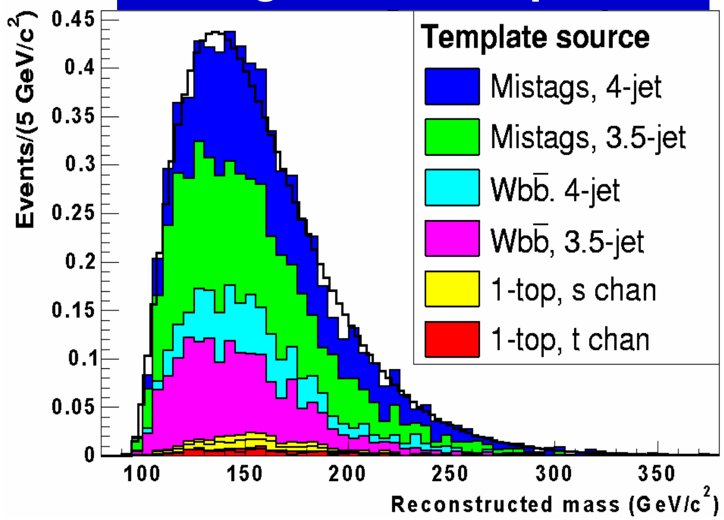
$\int L$ = 318pb^{-1}

leading 4 jets

Signal Template

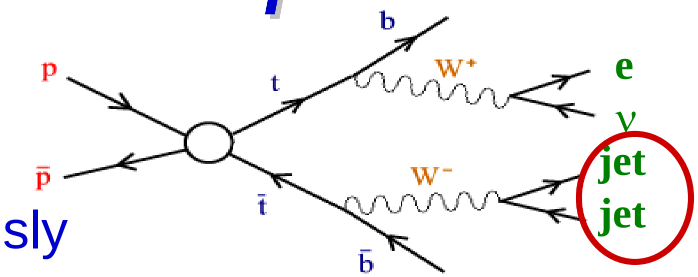


Background Template



Sample	Jet E_T cut [GeV]	S/B	Events
2 b-tags	3 jets Et>15, 4th jet Et > 8	18:1	16
1 b-tag	(T) 4 jets E_T > 15	4:1	57
1 b-tag	(L) 3 jets E_T > 15, 4th jet 8 < E_T <15	1:1	25
0 b-tags	4 jets E_T > 21	1:1	40

Improving the Template Method



$m_{jj}(W)$

Extend 1-D template:

- m_t and JES fit simultaneously
- ⇨ use shapes of m^{reco}_t and m^{reco}_{jj}
- ⇨ account for correlations

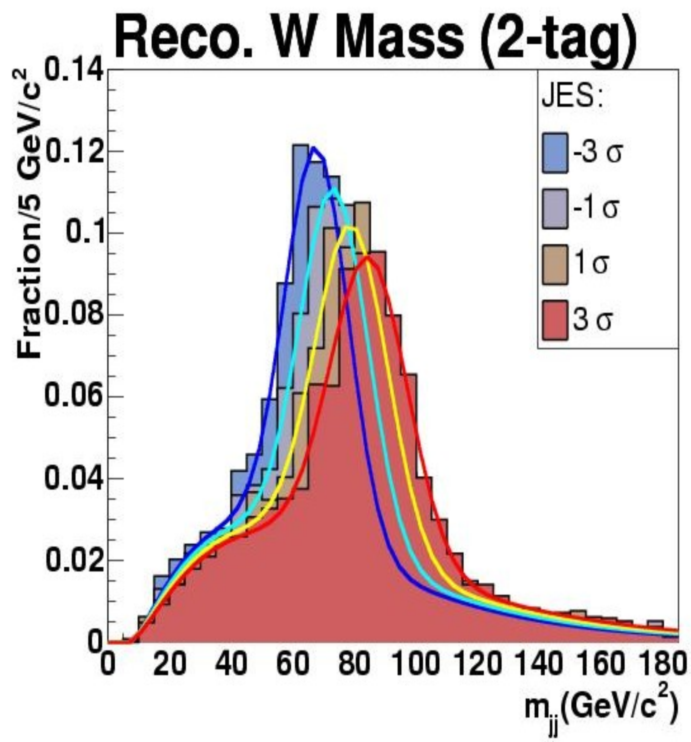
$$L_{subsample} = L^{m_t}{}_{shape} \times L^{m_{jj}}{}_{shape} \times L_{bkg}$$

2-D templates:

$P(m^{reco}_t; m_t, JES)$ and $P(m^{reco}_{jj}; m_t, JES)$

Use *a priori* CDF information on JES

$$L_{JES} = \exp\left(-\frac{(JES - JES_{STD})^2}{2\sigma^2_{JES_{STD}}}\right)$$



Advantages:

Improve uncertainty on JES (dominant systematic)

With this method, JES uncertainty improves with statistics!

Results - Template Method: l+jets CDF

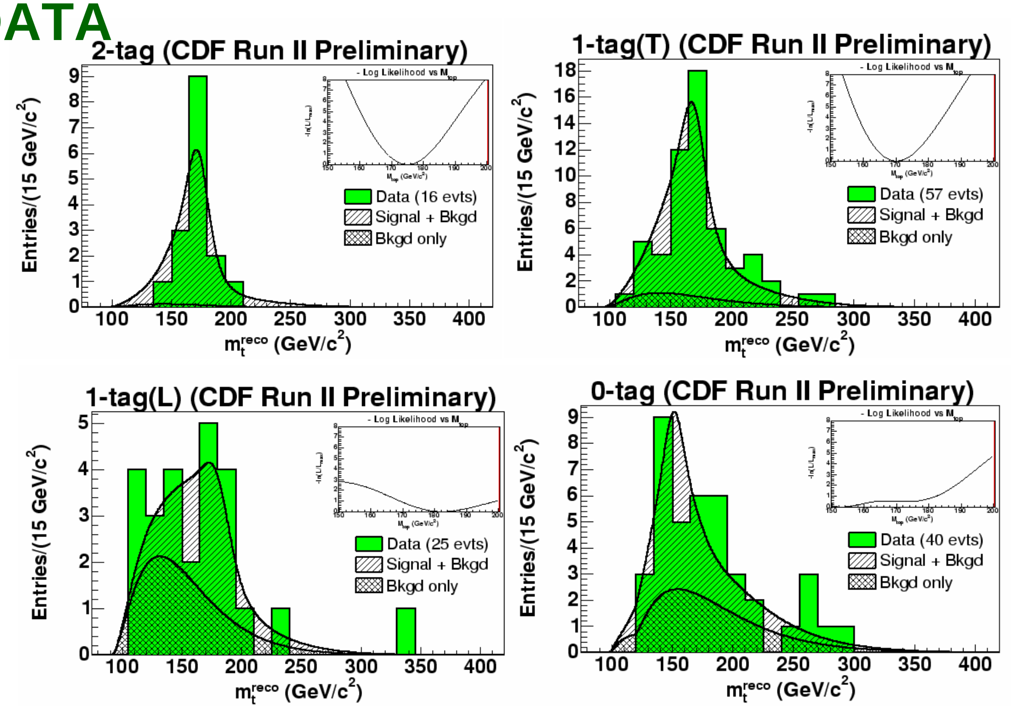
$$m_{top} = 173.5^{+2.7}_{-2.6}\,(\text{stat.}) \pm 2.5(\text{JES}) \pm 1.7\ (\text{syst.})\ \text{GeV/c}^2$$

Best single top mass measurement in the world!

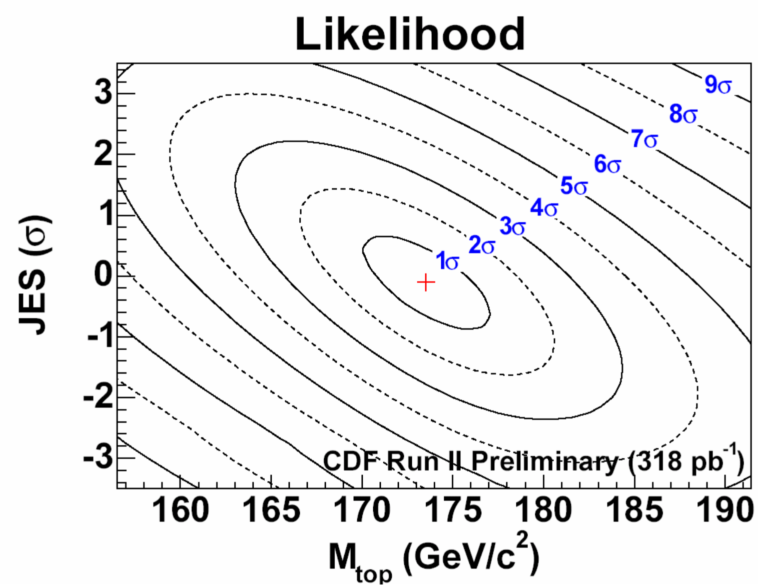
Result without using W→jj (1-D):

$$m_{top} = 173.2^{+2.9}_{-2.8}(\text{stat.}) \pm 3.1(\text{JES}) \pm 1.5(\text{syst.})\text{GeV/c}^2$$

DATA



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

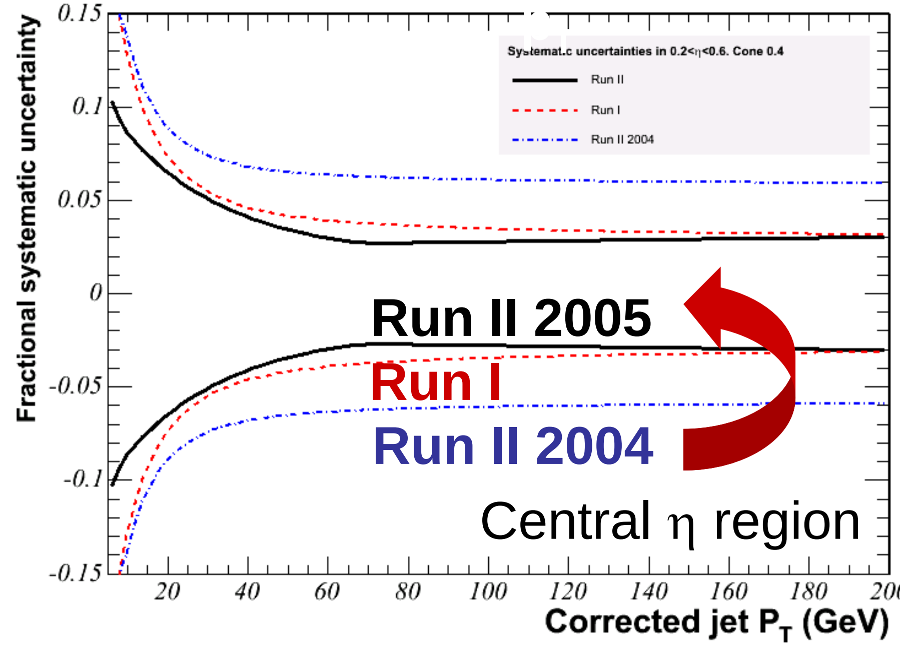


Template Method Systematics

Systematic Source	2-D fit Δm_t (GeV)	1-D fit Δm_t (GeV)
JES	2.5	3.1
b-jet modeling	0.6	0.6
ISR	0.4	0.4
FSR	0.6	0.4
PDFs	0.3	0.4
Generators	0.2	0.3
Bkg shape	1.1	1.0
b-tagging	0.1	0.2
MC statistics	0.3	0.4
Method	0.5	-
TOTAL	**3.0 = $2.5\oplus1.7$**	**3.4 = $3.1\oplus1.5$**

~3% jet p_T uncertainty in top events

JES Frac. Syst. uncert. vs jet



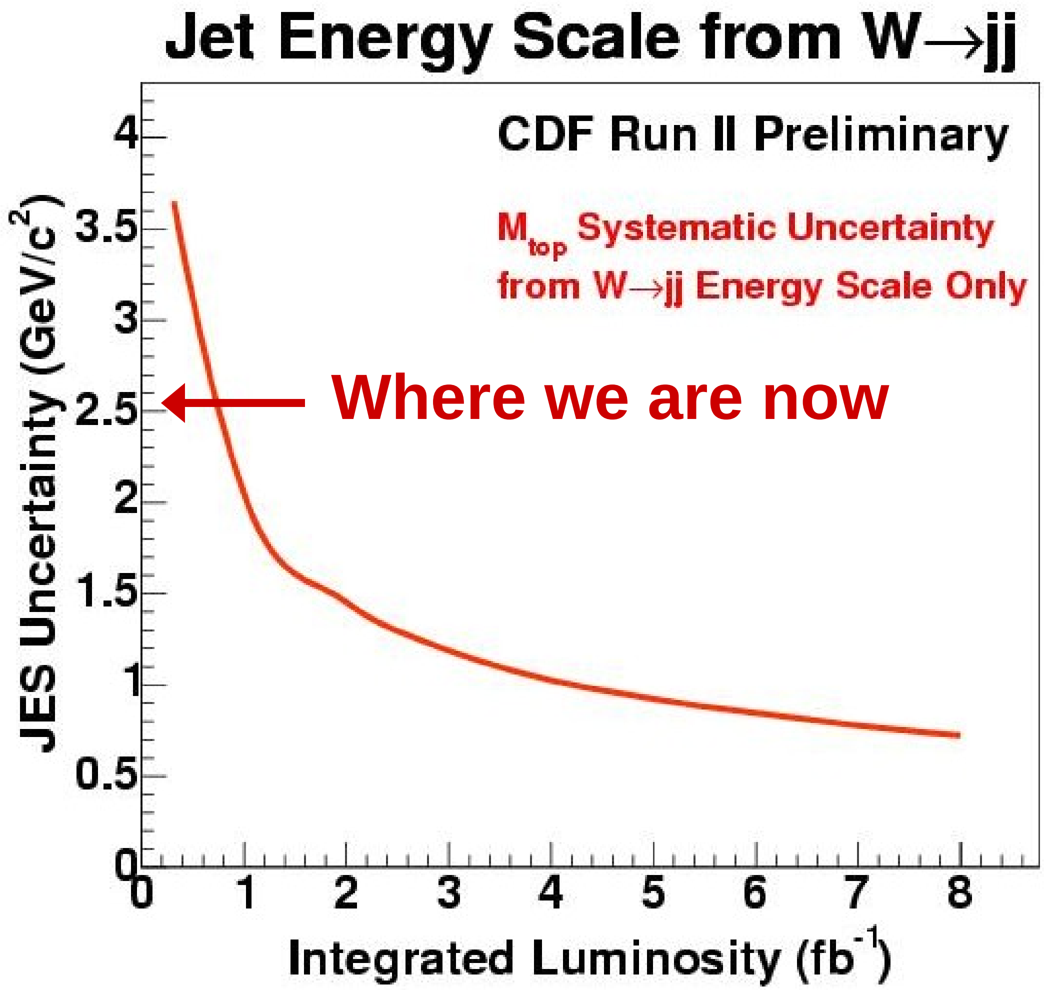
~factor of 2 decrease!

Future of the CDF Analysis with W→jj

Advantage:
statistical and JES systematic uncertainties will improve with $\int L$.

Expect to reach JES uncertainty below 1 GeV/c^2 for m_t in the future of CDF.

Total m_t uncertainty can reach 2 GeV/c^2!



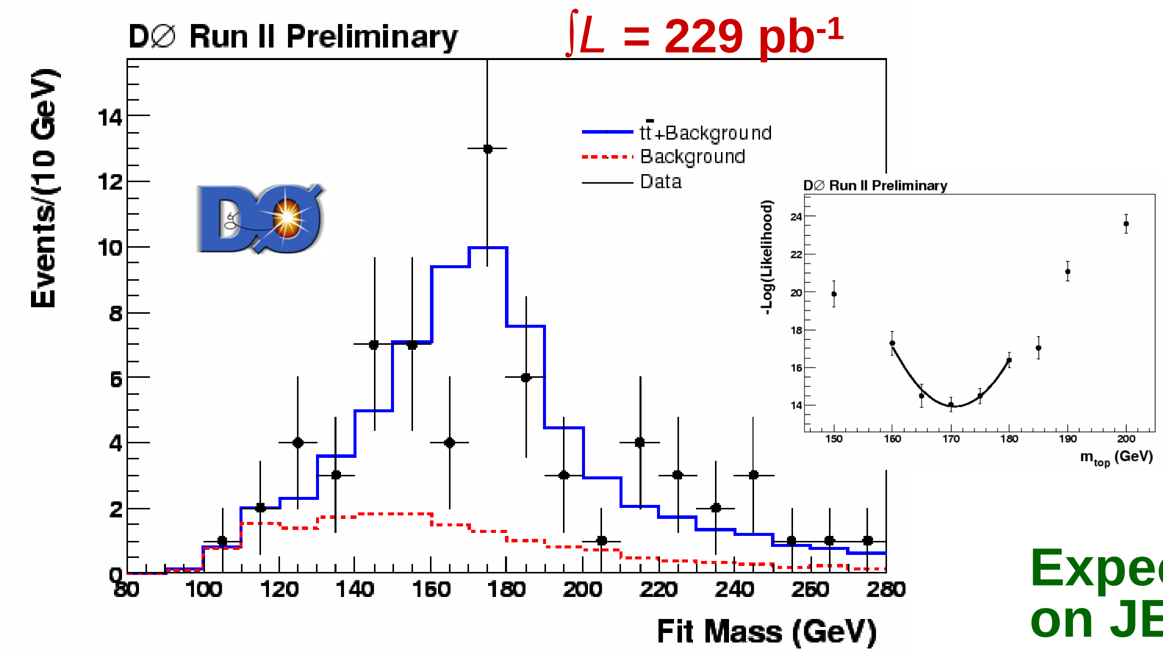
Template Method: l+jets + b-tagging D0

At least one b-tagged jet

69 events, S/B ~ 3/1

First m_t measurement with b-tagging at D0!

$$m_t = 170.6 \pm 4.2(\text{stat})^{+4.7}_{-5.3}(\text{JES}) \pm 3.7(\text{syst})\,\text{GeV}/c^2$$

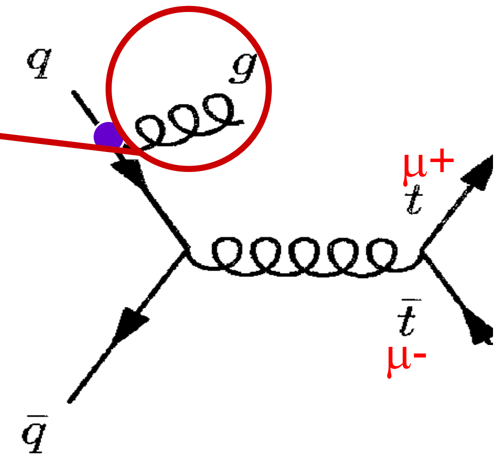


Systematic source	b-tagged Analysis (GeV)
JES	+4.7/-5.3
Jet Res.	0.9
Gluon Rad.	2.4
Signal Model	2.3
Bkg Model	0.8
b-tagging	0.7
Calibration	0.5
Trigger Bias	0.5
MC Stat.	0.5
Total	**6.0**

Expect significant improvements on JES from D0 soon!

Gluon Radiation Systematic Uncertainty

ISR/FSR gluons misidentified as quark jets



Estimate Δm_t for events with and without gluon jets

Δm_t ~2.5GeV/c^2 in l+jets events

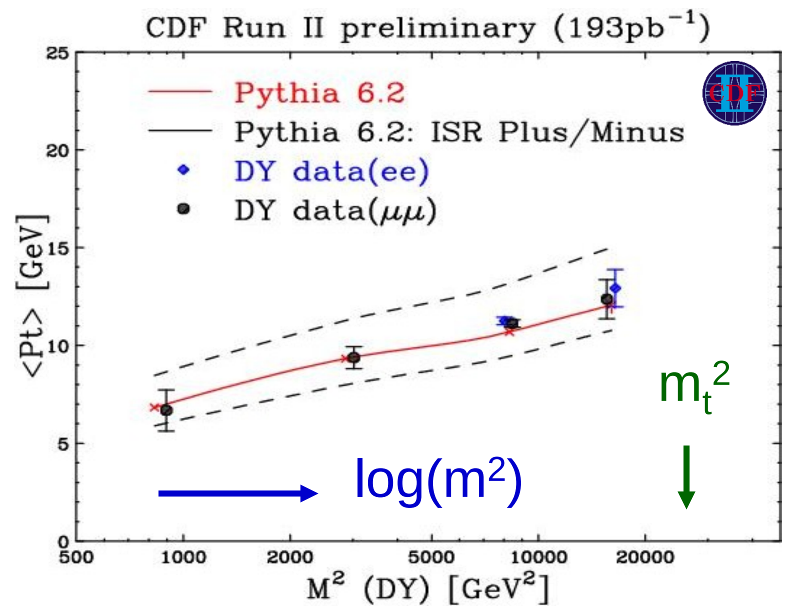
Take full difference as uncertainty

Study ISR in Drell-Yan events

Extrapolate uncertainties to m_t energies

FSR same variations as ISR

ISR/FSR Δm_t=0.7GeV/c^2



Matrix Element Method: l+jets D0 Run I

Using all the variables in the event, integrate over all unknowns

Sum over all permutations of jets and ν solutions

Background process probabilities explicitly included in likelihood

Maximize $L = \Pi_i P^i(x;m_t)$

$d^n\sigma$: cross section (LO Matrix element)

W(y,x): probability parton variables ***y*** measured as variables ***x***

$$P(x;m_t) = \frac{1}{\sigma}\int d^n\sigma(y;m_t)dq_1dq_2 f(q_1)f(q_2)W(x,y)$$

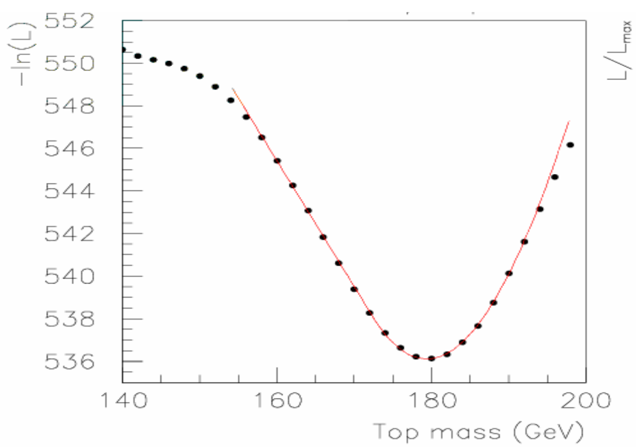
f(q) : probability distribution that parton has momentum ***q***

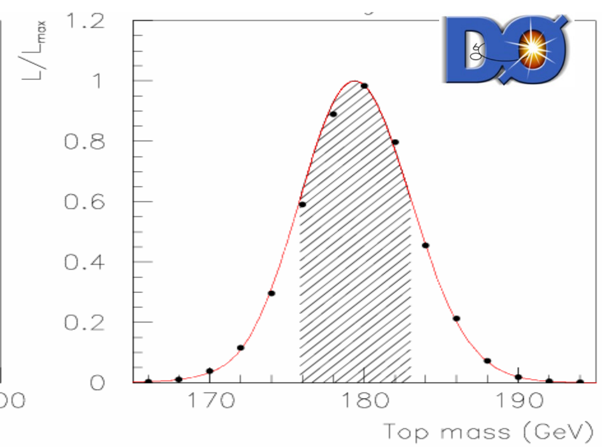
$$m_t = 180.1 \pm 3.6(\text{stat.}) \pm 3.3(\text{JES}) \pm 2.1(\text{syst.})\text{GeV/c}^2$$

Nature Vol 429, Page 640

Run I results: June 2004

125pb^{-1}, 91 events





Dynamical Likelihood Method l+jets CDF

DLM: K. Kondo J. Phys. Soc. 57 4126 (1988)

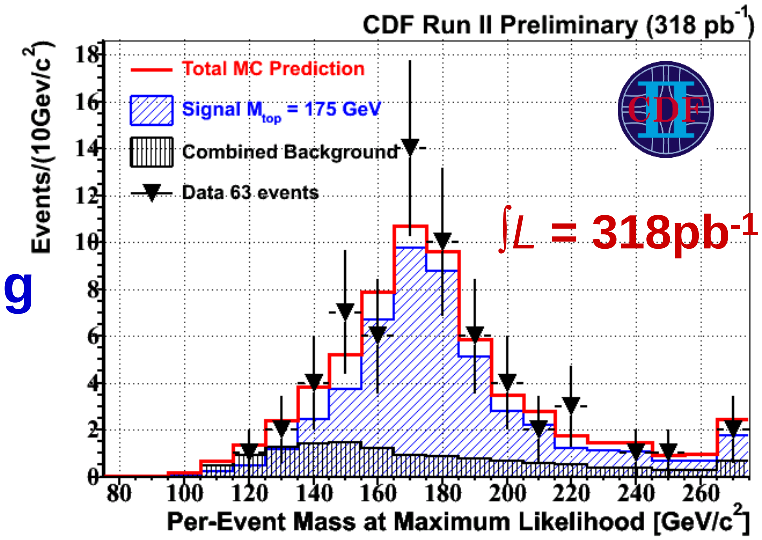
Exactly 4 jets, at least 1 b-tagged

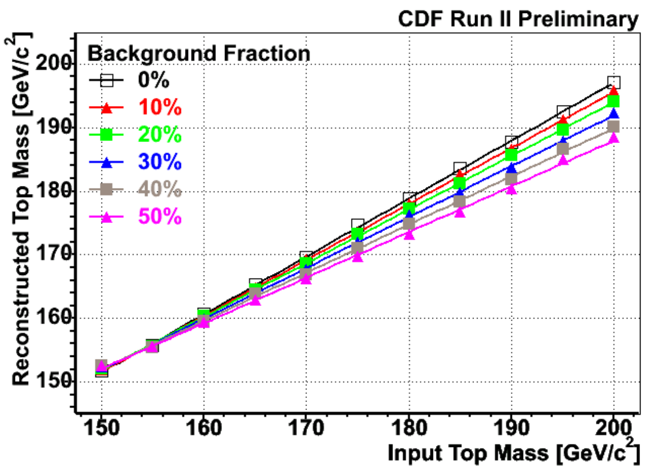
63 events, 13.1 expected background

No background probability term

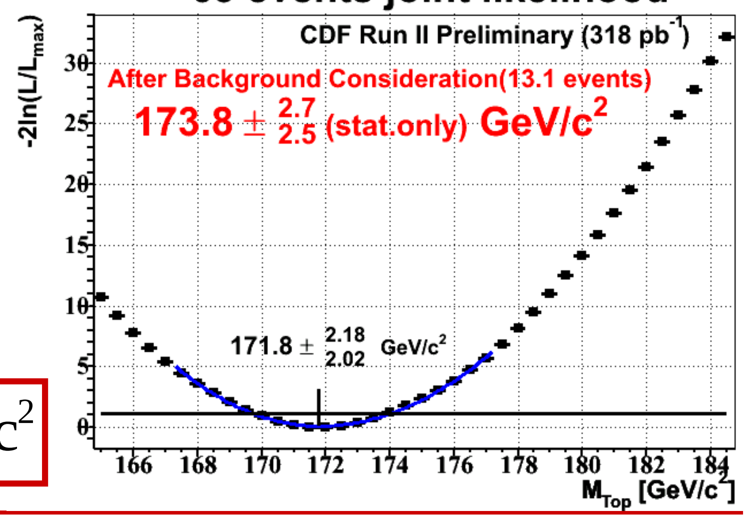
m_t extracted after background mapping function (measured →true mass)

Uncertainties also scale





63 events joint likelihood



$$m_t = 173.8^{+2.7}_{-2.5}(\text{stat.}) \pm 3.0(\text{JES}) \pm 1.4(\text{syst.})\,\text{GeV/c}^2$$

DLM Systematic Uncertainties

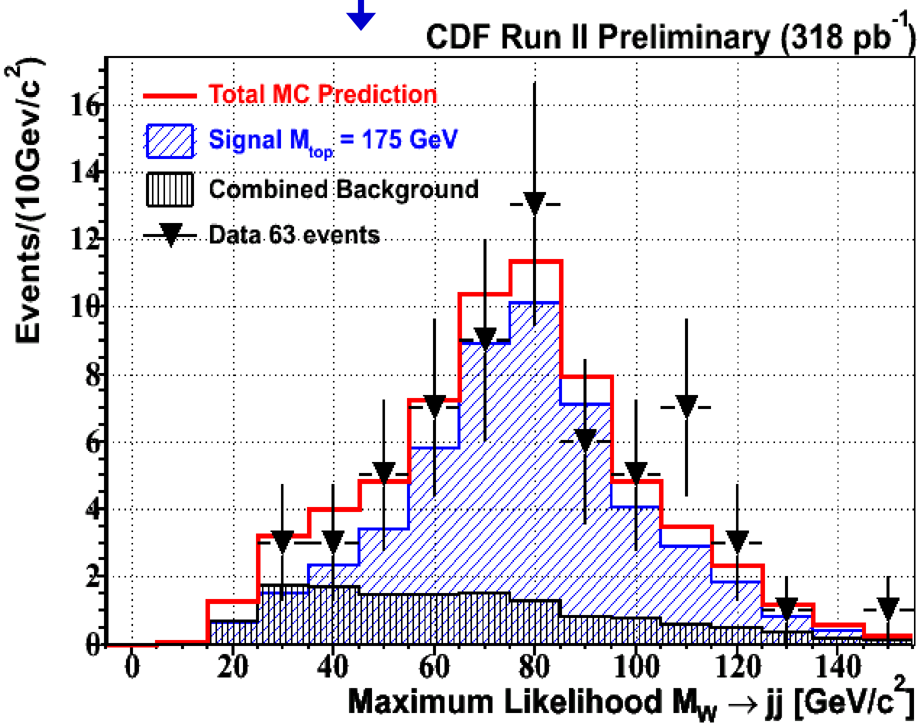
Systematic Source	Δm_t (GeV)
JES	3.0
Transfer Functions	0.2
ISR	0.4
FSR	0.5
PDFs	0.5
Generators	0.3
Bkg fraction	0.6
bkg Modeling	0.6
b-tagging	0.2
b-jet Modeling	0.6
Total	**3.3**

JES dominant systematic

<u>Future improvements:</u>

Add background probability to likelihood

Use $W \rightarrow jj$ information for JES



m_t results with Dileptons D0 & CDF

Under-constrained kinematics:

2 ν's, 1 missing E_T observable

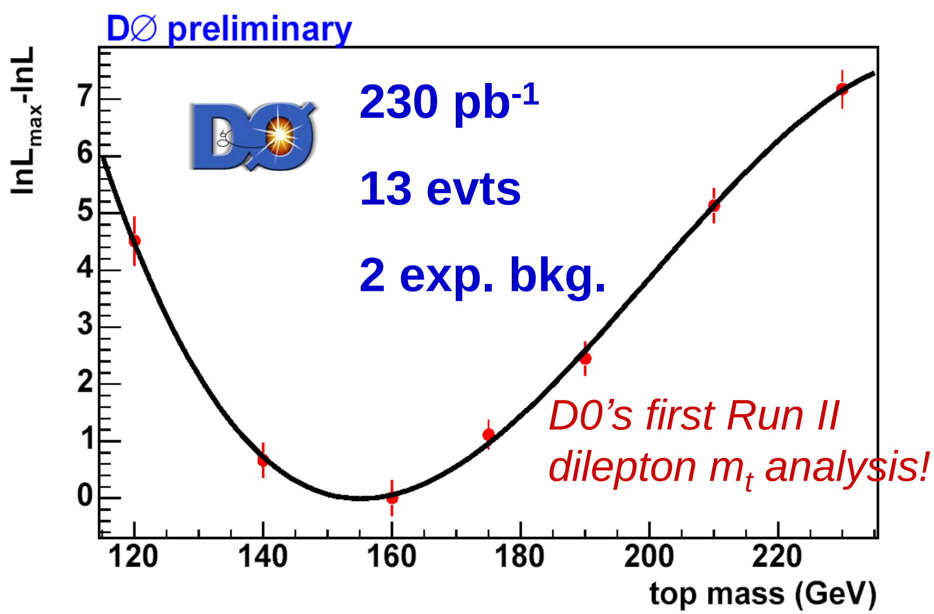
❶ Assume some kinematic quantities are known (ex: η or φ of ν's, P_z^{ttbar}, E_{lepton})

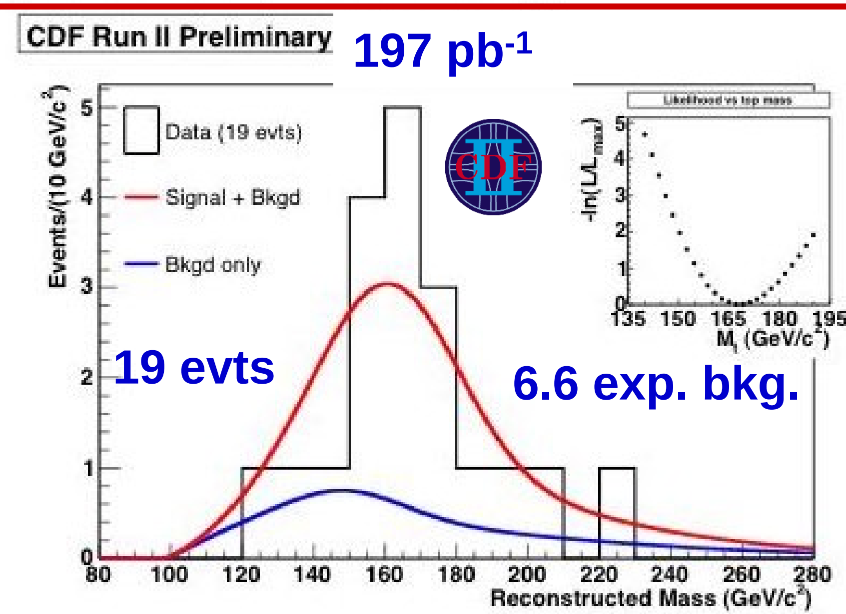
❷ Calculate weight : assumed quantity explains the observed event given a true m_t

❸ Follow template procedure

$$m_t = 155^{+14}_{-13}(\text{stat.}) \pm 5.6(\text{JES}) \pm 3.6(\text{syst.})\,\text{GeV/c}^2$$

$$m_t = 168.1^{+11.0}_{-9.8}(\text{stat.}) \pm 7.4(\text{JES}) \pm 4.3(\text{syst.})\,\text{GeV/c}^2$$





Expectation with 320pb^{-1} $\delta m_t \sim 9$ GeV !

Summary

Tevatron is performing very well
Delivered luminosity >1 fb^{-1}

Several new m_t measurements available in different decay channels

⇨*CDF dilepton results soon with reduced systematics*

⇨*D0 results soon with reduced systematics*

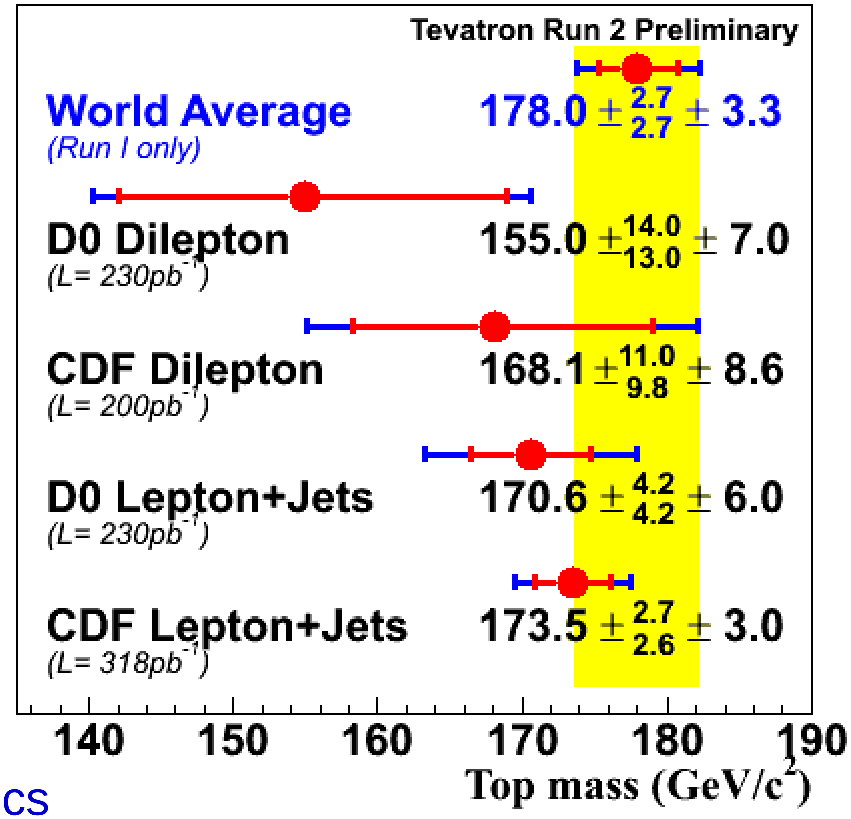
⇨ongoing efforts to combine

New techniques developed

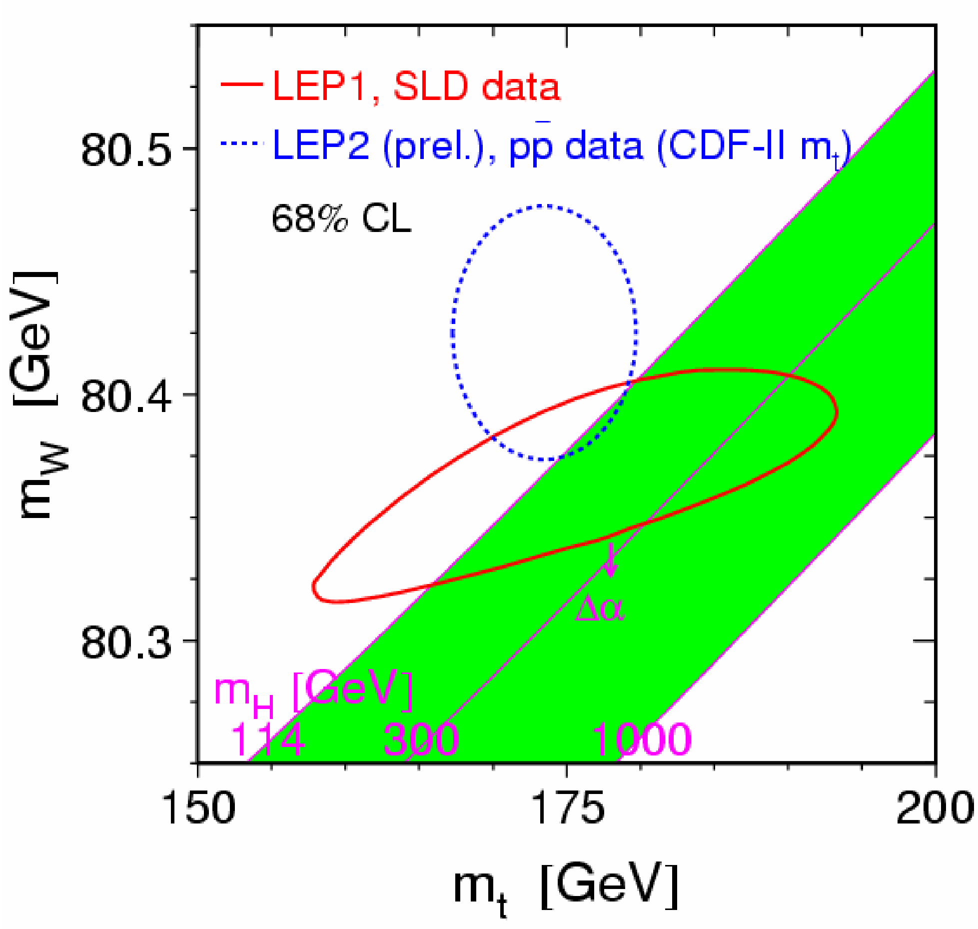
Precision will be limited by systematics

A lot of work *already* to reduce systematics
⇨ especially JES

Will reach goal of measuring m_t to ~ 2 GeV in Run II!

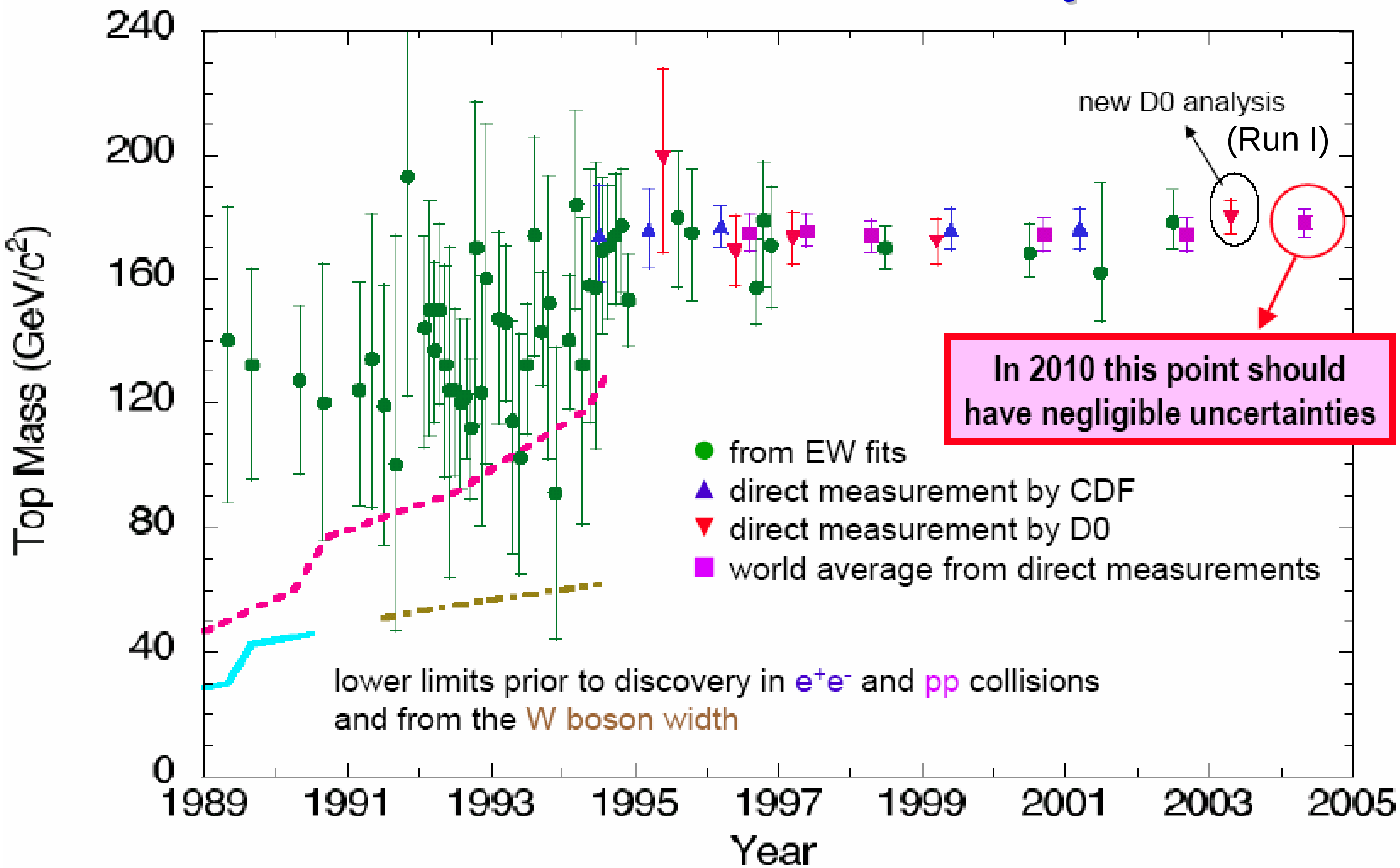


More to come ….


LEP1, SLD data
LEP2 (prel.), p$\bar{p}$ data (CDF-II m_t)
68% CL
$\Delta\alpha$
m_H [GeV]
114
300
1000
80.5
80.4
80.3
150
175
200
m_W [GeV]
m_t [GeV]

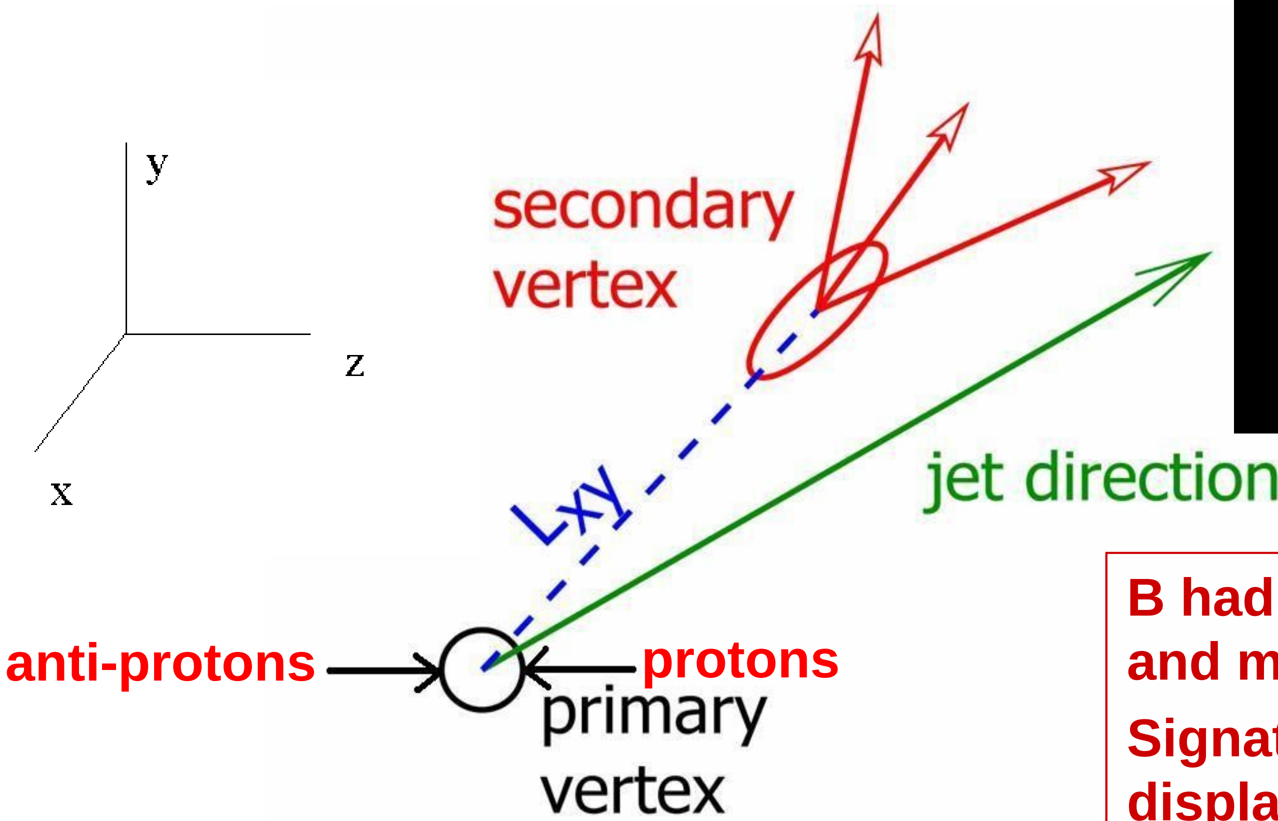
Backup

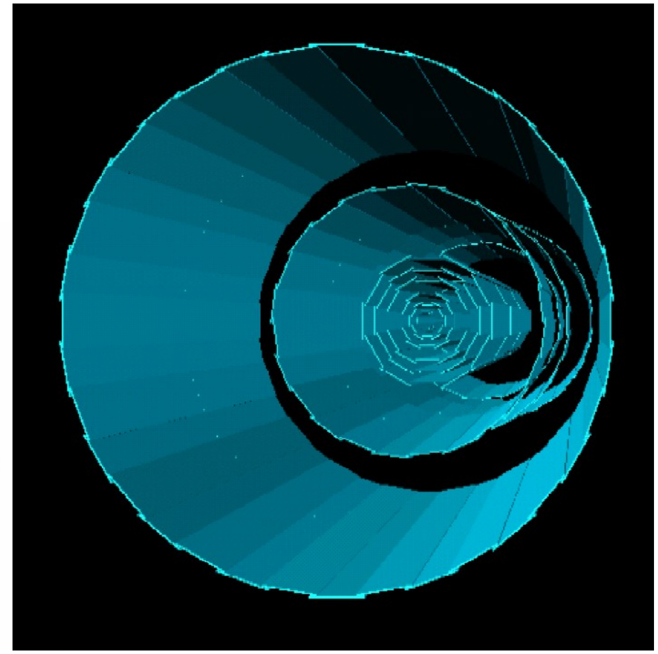
History of Measuring m_t



TeVatron Run II goal: $\int Ldt \approx 4-9\,\mathrm{fb}^{-1}$ $\delta m_t \approx 2\mathrm{GeV/c}^2$

Tagging the b quark





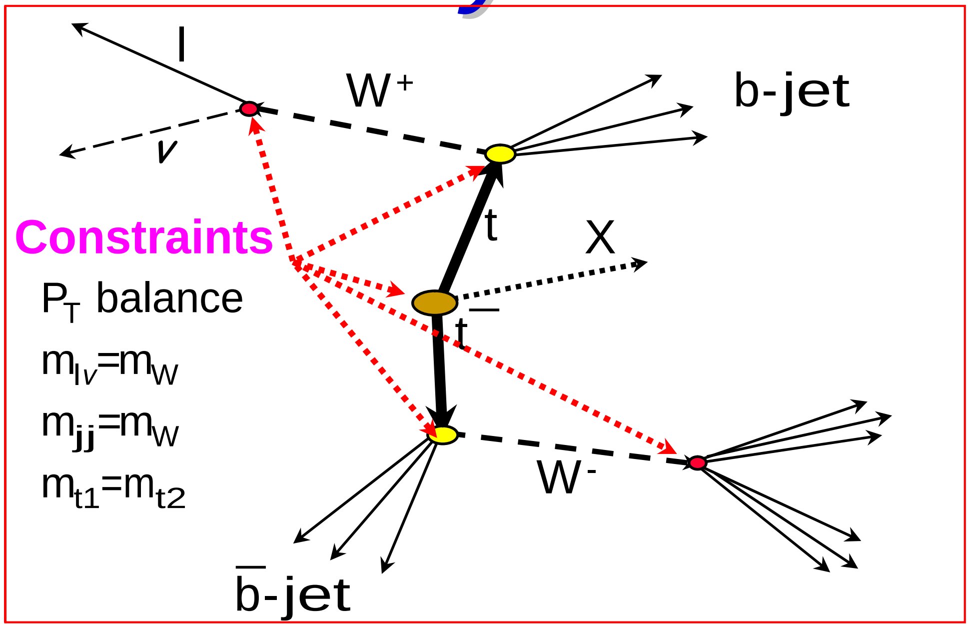
B hadrons are long-lived and massive.

Signature of a b decay: displaced vertex.

Top event b-tag efficiency: ~55%

False tag rate (QCD light quark jets): ~0.5%

Event-by-Event Mass Fitter

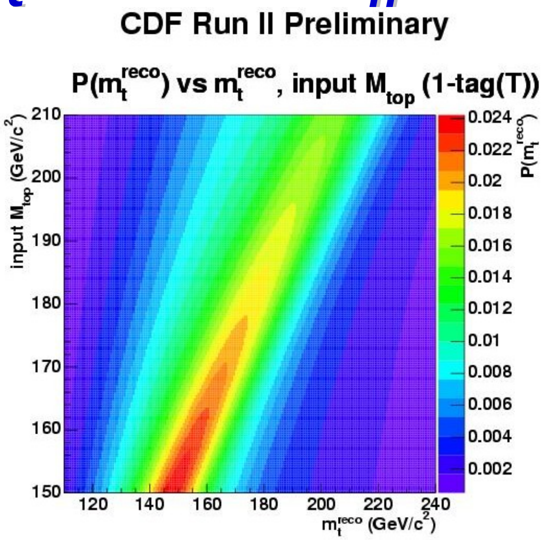


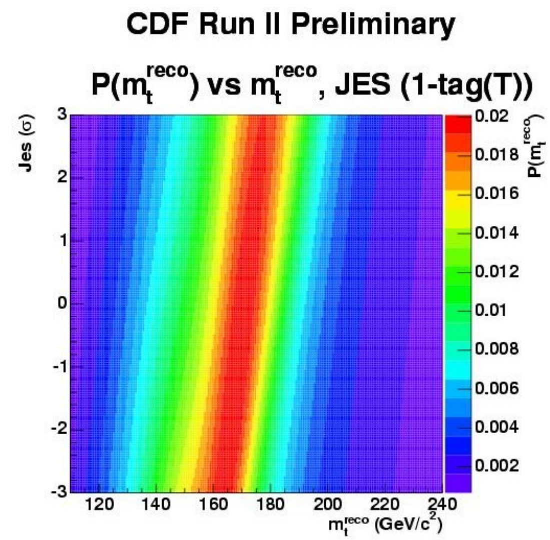
- Distill all event information into one number (called reconstructed mass).
- Select most probable jet-parton assgnmt based on χ^2, after requiring b-tagged jets assigned to b partons.

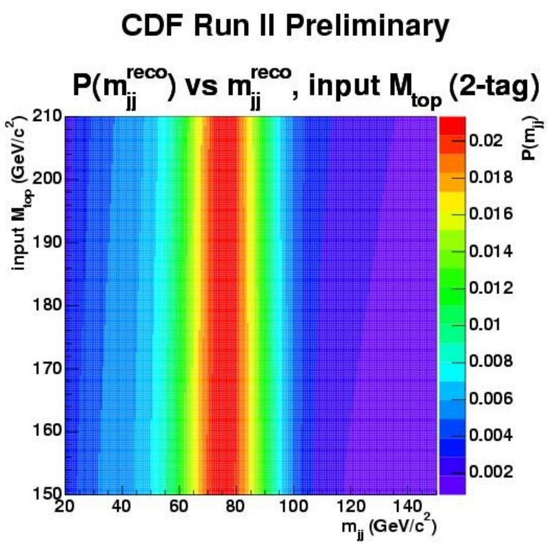
Reconstructed top mass is free parameter

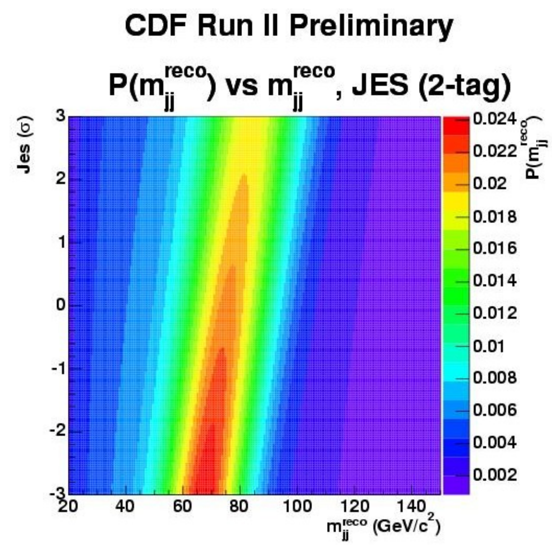
$$\chi^2 = \sum_{i=\ell,4\text{ jets}} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_t)^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - M_t)^2}{\Gamma_t^2}$$

m_t and m_{jj} templates









Template Method: l+jets D0

Uses unique topology of ttbar events

Discriminant using *topological* variables (D_{LB})

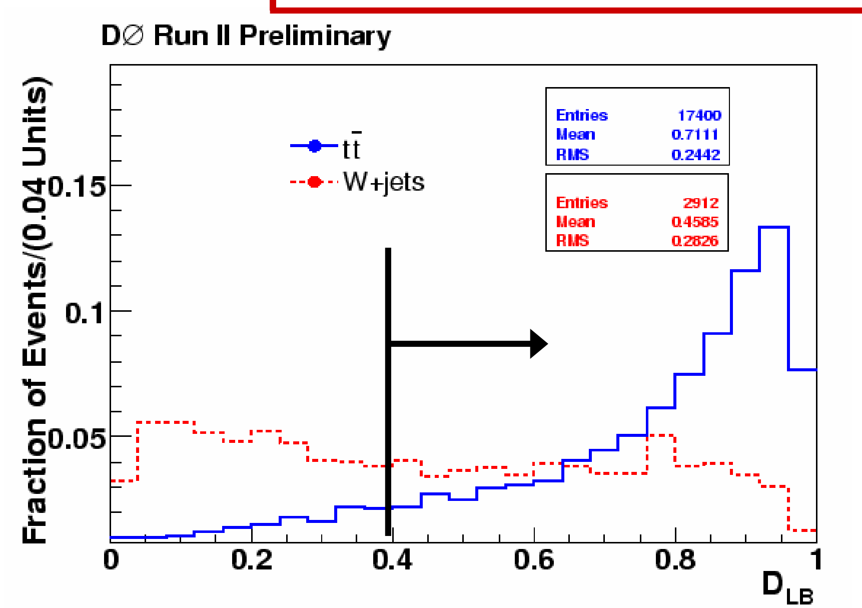
Distinguish signal and background

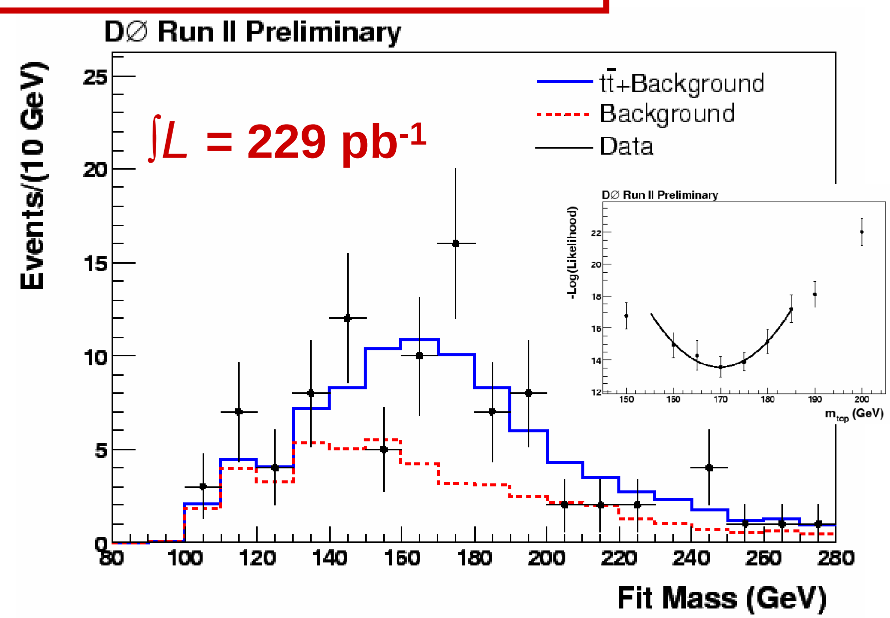
1 lepton (e,μ)
large missing E_T
at least 4 jets
cut on D_{LB}

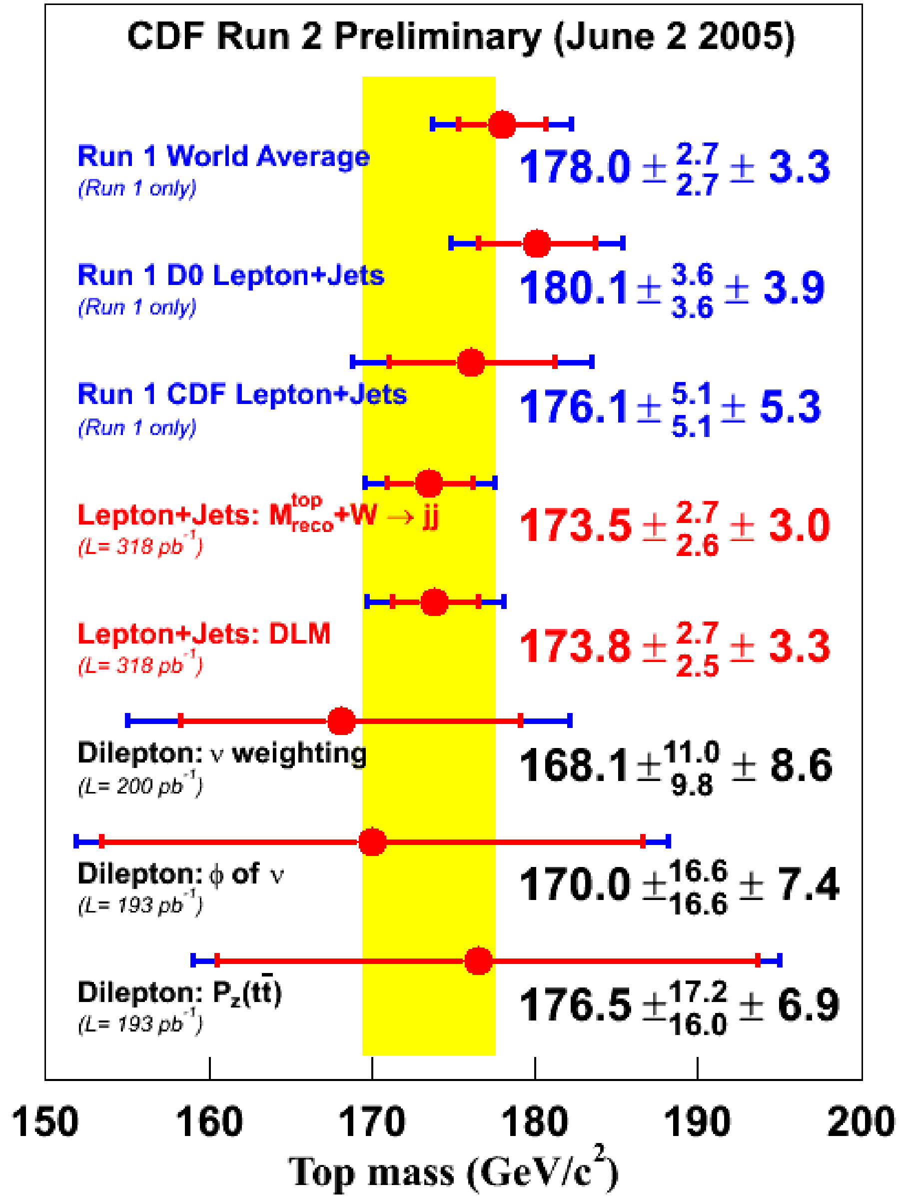
Fit to signal+bkg templates

94 events, S/B ~ 1

$$m_t = 169.9 \pm 5.8(stat.)^{+7.8}_{-7.1}(syst.) GeV/c^2$$






CDF Run 2 Preliminary (June 2 2005)
Run 1 World Average
(Run 1 only)
178.0 ± 2.7 2.7 ± 3.3
Run 1 D0 Lepton+Jets
(Run 1 only)
180.1 ± 3.6 3.6 ± 3.9
Run 1 CDF Lepton+Jets
(Run 1 only)
176.1 ± 5.1 5.1 ± 5.3
Lepton+Jets: M_{reco}^{top}+W → jj
(L= 318 pb^{-1})
173.5 ± 2.7 2.6 ± 3.0
Lepton+Jets: DLM
(L= 318 pb^{-1})
173.8 ± 2.7 2.5 ± 3.3
Dilepton: ν weighting
(L= 200 pb^{-1})
168.1 ± 11.0 9.8 ± 8.6
Dilepton: ϕ of ν
(L= 193 pb^{-1})
170.0 ± 16.6 16.6 ± 7.4
Dilepton: $P_z(t\bar{t})$
(L= 193 pb^{-1})
176.5 ± 17.2 16.0 ± 6.9
150
160
170
180
190
200
Top mass (GeV/c^2)