TOP QUARK PHYSICS AT THE TEVATRON
results and prospects

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TOP QUARK

- Top quark was expected in the Standard Model (SM) of electroweak interactions as a partner of b-quark in SU(2) doublet of weak isospin in the third family of quarks
- First published evidence for top quark by CDF in 1994

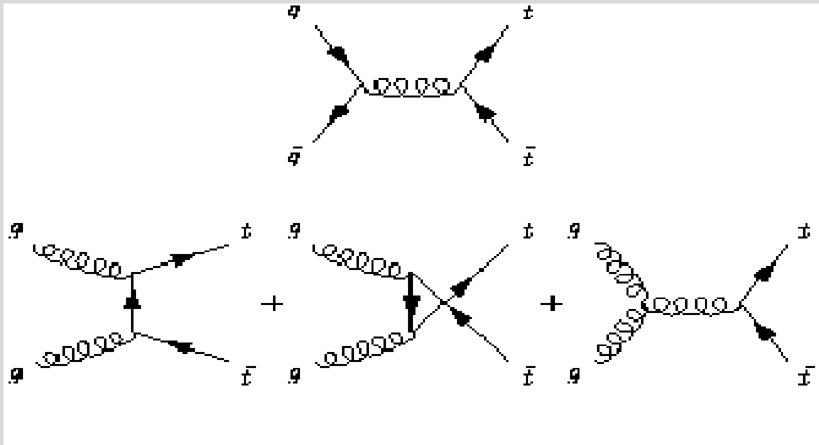
  CDF : F. Abe *et al.* Phys. Rev. Lett. **73** (1994) 225
- Observation (discovery) by CDF and D0 in 1995

  CDF : F. Abe *et al.* Phys. Rev. Lett. **74** (1995) 2626

  D0 : S. Abachi *et al.* Phys. Rev. Lett. **74** (1995) 2632
- With all data from Run-0 and Run-I analysed (~110 pb^{-1}) a summary of results and a perspective view on the status quo of top physics is given
- In anticipation of much increased statistics in Run-IIa (2 fb^{-1}) the fact that top quark physics is one of the best windows to the new physics beyond the SM is emphasised; prospects are discussed

TOP QUARK PRODUCTION

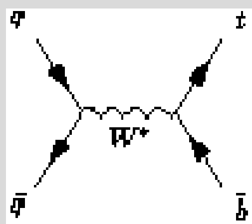
- production of top-antitop quark pairs



$q\bar{q} \rightarrow t\bar{t}$

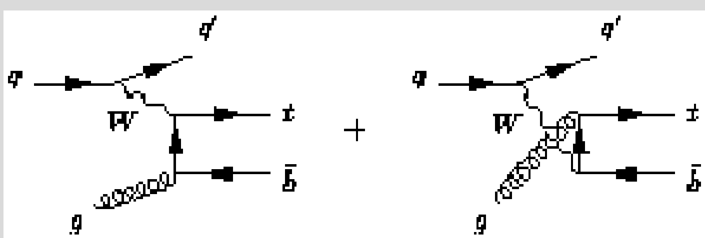
$gg \rightarrow t\bar{t}$

- single top quark production



$q\bar{q} \rightarrow t\bar{b}$

(Drell-Yan)



$qg \rightarrow q' t\bar{b}$

(W-gluon fusion)

TOP MASS AND CROSS SECTION - methodology

MEASUREMENT OF CROSS SECTION (CDF and D0)

i. search for events with top signature

ii. calculate expected SM background

iii. count events above backgrounds

iv. apply corrections for acceptance and reconstruction inefficiencies and biases

⇛ tt pair-production cross section

⇛ single top production cross section

TOP MASS AND CROSS SECTION - methodology

MEASUREMENT OF CROSS SECTION (CDF and D0)

One should remember two important details:

It is *assumed* that the selected sample of events contains just the *tt events* and the *SM background*. This is the simplest and the most natural hypothesis since top quark is *expected* in the SM.

Some of the acceptance corrections are strongly varying functions of top quark mass, M_t. The measured cross section depend on the adopted value of M_t, which has to be determined independently.

TOP MASS AND CROSS SECTION - methodology

DIRECT MEASUREMENT OF TOP MASS (CDF and D0)

All mass measurement techniques assume that each selected event contains a pair of massive objects of the same mass (top and anti-top quarks) which subsequently decay as predicted in SM. A variety of fitting techniques use information about the event kinematics. A one-to-one mapping between the observed leptons and jets and the fitted partons is assumed.

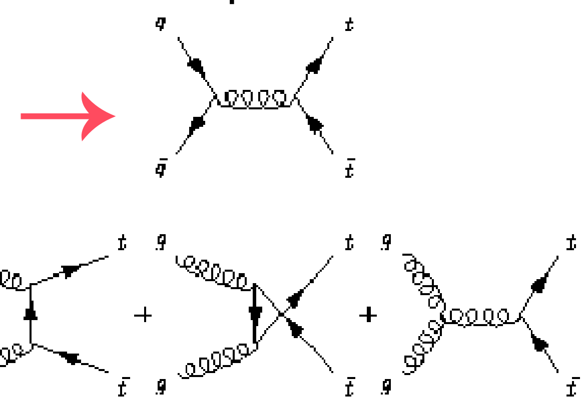
Two things to remember:

It is *assumed* that the selected sample of events contains just the *tt events* and the *SM background*. This is the simplest and the most natural hypothesis since top quark is *expected* in the SM.

The combinatorics, i.e. the problem that only one out of a large number of jets-lepton(s) combinations is correct, adds to the complexity of the problem.

TOP MASS AND CROSS SECTION - methodology

Production of tt pairs via strong interactions from qq or gg initial state is the dominant production mechanism at s=1.8 TeV; for top quark masses above M_t □ 120 GeV the qq fusion process dominates and the SM top quarks are expected to decay into real W and b quarks.



Assuming SM, there will be three classes of final states, all with 2 b-quark jets:

di-leptons, when both W decay leptonically, with 2 jets and missing transverse energy (MET): BF□ 4/81 for e,□ (~5%)

lepton+jets, when one W decays leptonically and the other into quarks, with 4 jets and MET: BF□ 24/81 for e,□ (~30%)

all-hadronic, when both W decay into quarks, with 6 jets and no MET:
BF□ 36/81 (~45%)

TOP MASS AND CROSS SECTION DIRECT SEARCHES - methodology

- All CDF and D0 searches impose stringent identification, selection and transverse energy, E_t, cuts on leptons and jets to minimize background
- Except for the di-lepton sample, where backgrounds are expected to be small, various techniques of b-tagging are employed. “Soft-lepton” tagging is used by both CDF and D0, and the secondary vertex tagging using a silicon vertex detector (SVX) by CDF
- D0, not equipped with a SVX makes greater use of various kinematic variables to reduce backgrounds
- The largest SM background is QCD W+jets production. Both CDF and D0 use VECBOS calculations to estimate the shapes of background distributions due to this process
- Presently available samples of top candidates are small, and the measurements of the cross section and the top quark mass is still dominated by statistical errors. THIS WILL NO LONGER BE TRUE IN RUN-II

TOP MASS AND CROSS SECTION

results of D0 and CDF searches : Run-I (~110 pb^{-1})

Channel	D0 sample	D0 background	CDF sample	CDF background
di-leptons	5	1.4 ± 0.4	9	2.4 ± 0.5
lepton+jets SVX tagged			34	9.2 ± 1.5
lepton+jets soft-lepton tagged	11	2.4 ± 0.5	40	22.6 ± 2.8
lepton+jets topological cuts	19	8.7 ± 1.7		
all-jets	41	24.8 ± 2.4	187	144 ± 12
e[illegible]	4	1.2 ± 0.4		
e[illegible], [illegible]			4	[illegible]2

References:

CDF: F. Abe et al. Phys. Rev. Lett. 80 (1998) 2773

F. Abe et al. Phys. Rev. Lett. 79 (1997) 3585

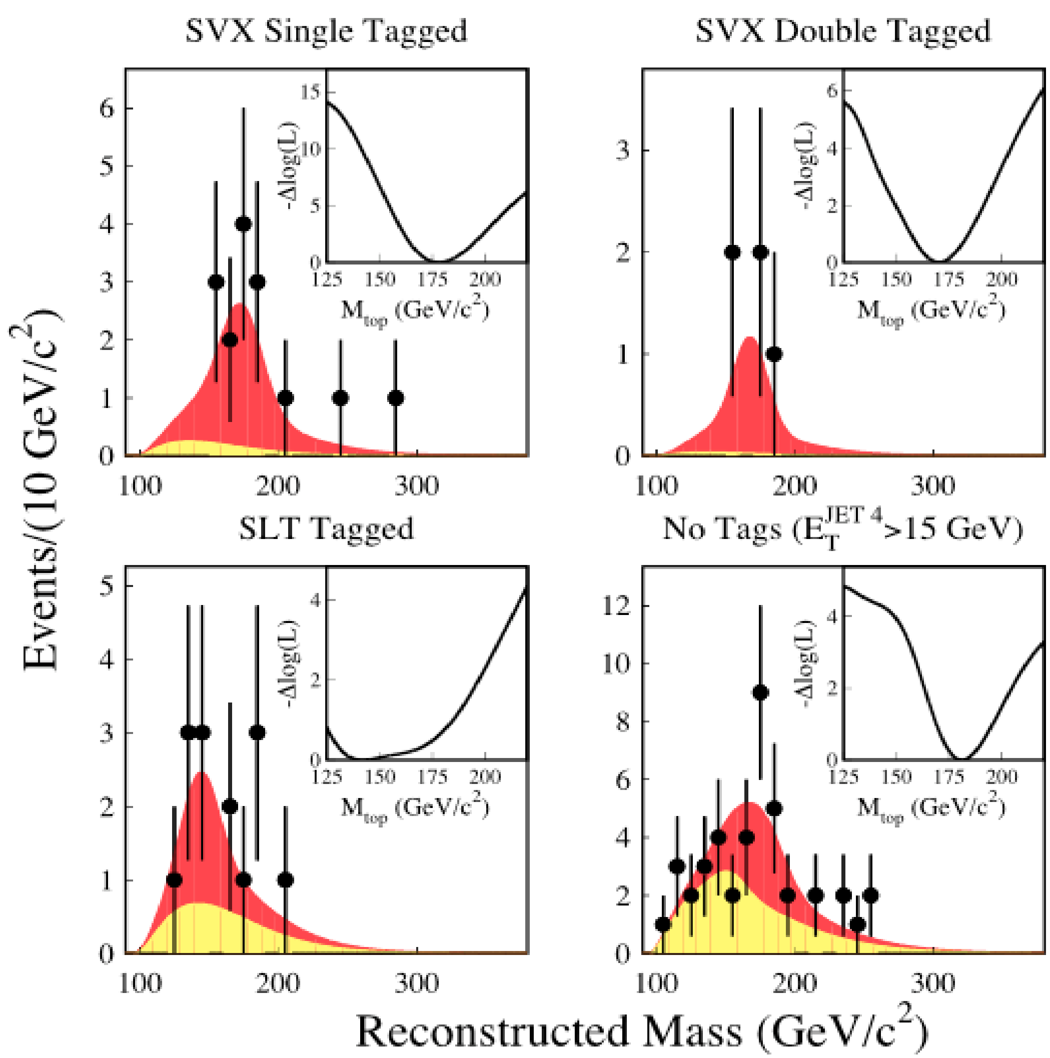
D0: S. Abachi et al. Phys. Rev. Lett. 79 (1997) 1203

S. Abachi et al. Phys. Rev. D 58 (1998) 052001

TOP MASS MEASUREMENT IN LEPTON+JETS CHANNEL

- In the lepton+jets and all-jets final states there is enough kinematical constraints to perform a genuine fit
- Four-momenta of the measured lepton and jets are treated as the corresponding input lepton and quarks' four-momenta in the kinematical fitting procedures.
- Leptons are measured best, jets not as well (in Run-I better in D0 than in CDF), while the missing transverse energy (MET) has the largest uncertainty
- In the lepton+jets final state one may, or may not, use MET as the starting point for the transverse energy of the missing neutrino. In their published analyses CDF and D0 make use of MET.
- D0 use two multivariate discriminant analyses to select their top enriched and background samples of events that are basis of their top mass and cross section analyses.

CDF Top Mass in lepton+jets channel



CDF Top Mass in lepton+jets channel

Dominant systematic uncertainties (in GeV/c^2)

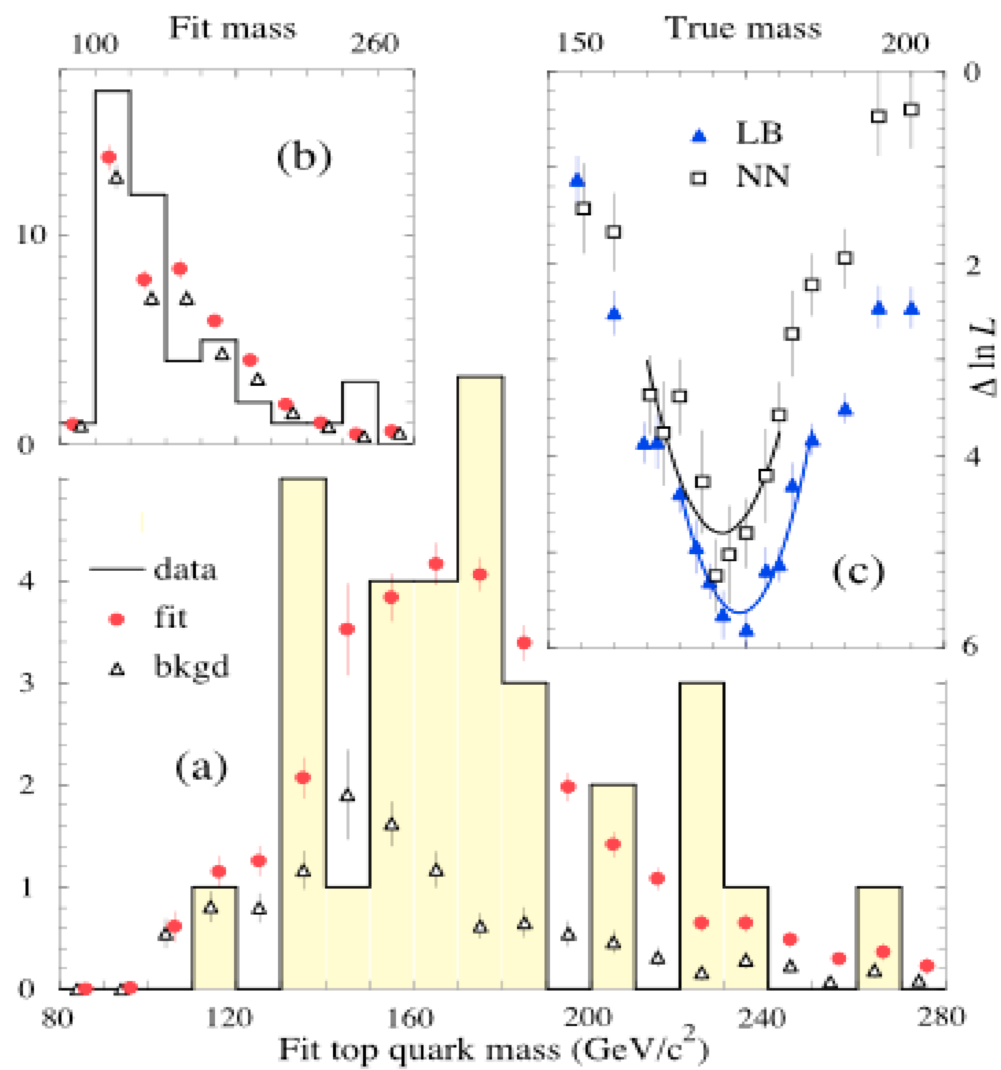
jet energy measurement	4.4
final state radiation	2.2
initial state radiation	1.8
shape of background spectrum	1.3
b-tag bias	0.4
parton distribution functions	0.3
Total	5.3

Subsample	N	Expected background fraction (%)	Measured M_t (GeV/c^2)
SVX double tagged	5	5 ± 3	170.1 ± 9.3
SVX single tagged	15	13 ± 3	178.1 ± 7.9
SLT tag (no SVX tag)	14	40 ± 9	142 + 33 - 14
no tag (all jets E_t > 15 GeV)	42	56 ± 15	181 ± 9

Combined CDF result:

175.9 ± 4.8 (stat) ± 5.3 (syst)

D0 Top Mass in lepton+jets channel



D0 Top Mass in lepton+jets channel

Dominant systematic uncertainties (in GeV/c^2)

jet energy measurement	4.0
background model	2.5
signal model	1.9
fitting technique	1.5
calorimeter noise	1.3
total	5.5

D0 result combining two methods, LB-“low bias” and NN-“neural network”, each using four variables to construct the top quark likelihood discriminant. Correlation between methods (88 ± 4)% were taken into account.

$$173.3 \pm 5.6\ (\text{stat}) \pm 5.5\ (\text{syst})$$

TOP MASS MEASUREMENT IN DI-LEPTON CHANNEL

- In the di-lepton mode situation is much more complicated, as the problem is underconstrained (two missing neutrinos). Several techniques were developed. All obtain a probability density distribution as a function of M_t whose shape allows identifying the most likely mass which satisfies the hypothesis that a pair of top quarks were produced in an event and that their decay products correspond to a given combination of leptons and jets.

- MET may, or may not, be used.

- D0 developed two methods, the Neutrino Phase Space weighting technique (□WT) and the Average Matrix Element technique (MWT), a modified form of Dalitz-Goldstein and Kondo methods

- Three measurements of top quark mass have been “blessed” in CDF. Two use MET (□WT and “Minuit” fitting); one does not (a modified Dalitz-Goldstein, which instead includes information about parton distribution functions, transverse energy of the tt system and angular correlations among top decay products in the definition of likelihood - in the Bayesian way)

CDF Top Mass in di-lepton channel

- Neutrino-weighting (essentially D0 □WT method)

  This result has been available in summer 1998, and was used in CDF and CDF/D0 combined mass analyses.

  167.4 + 10.7 – 9.8 (stat) ± 4.8 (syst) GeV/c^2

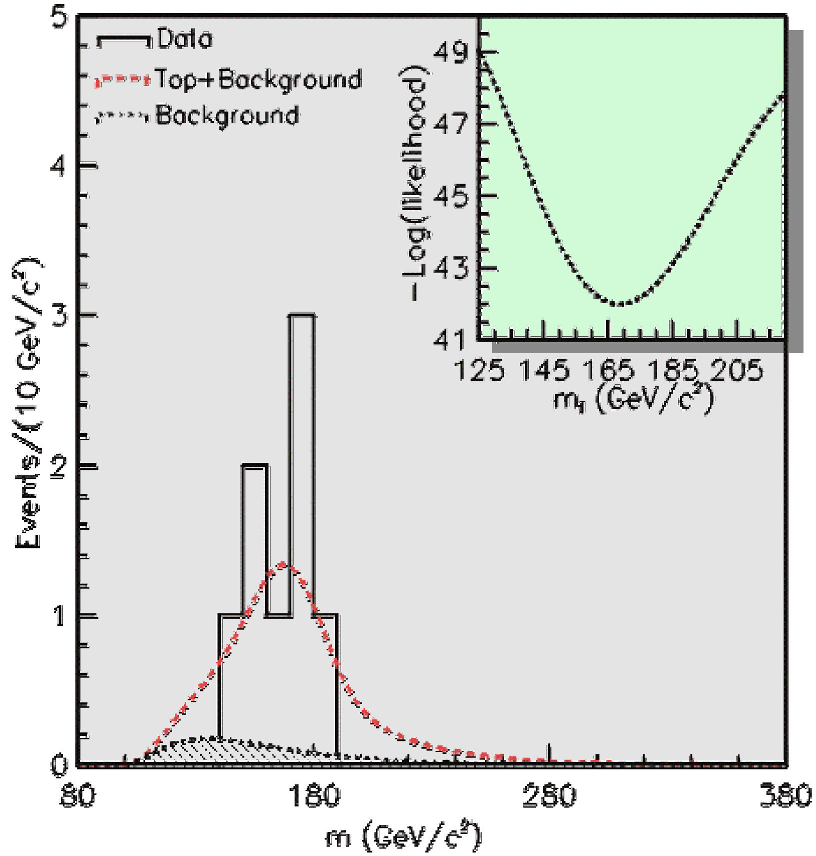
- "MINUIT" fitting method

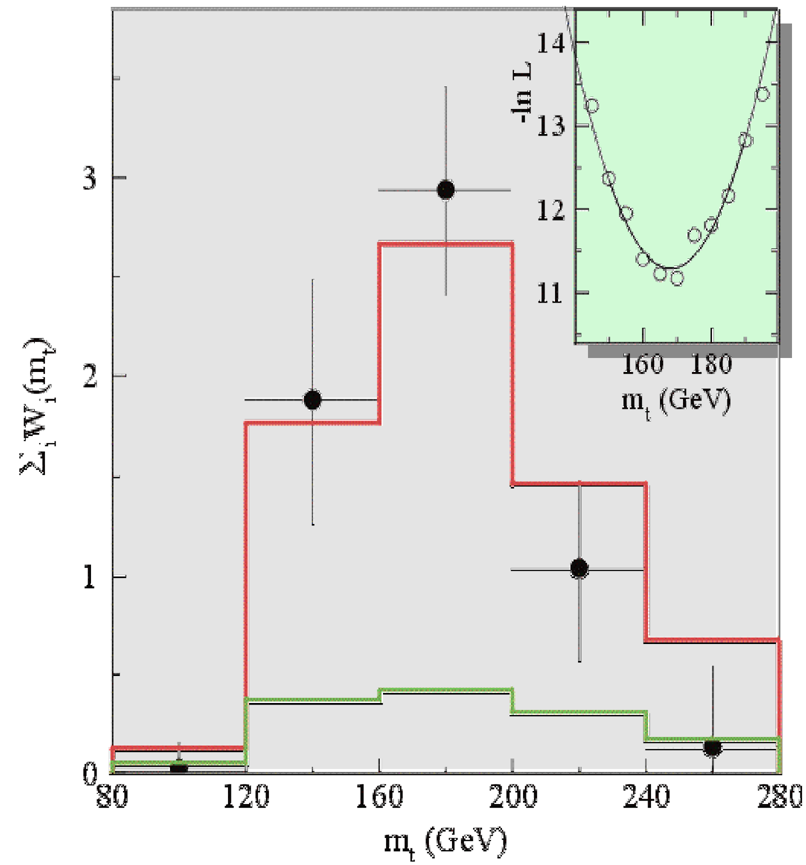
  170.7 ± 10.6 (stat) ± 4.6 (syst) GeV/c^2

- Dalitz-Goldstein method (finds a single, "best", combination of leptons+jets in an event)

  157.1 ± 10.9 (stat) + 4.4 – 3.7 (syst) GeV/c^2

CDF/D0 Top Mass in di-lepton channel

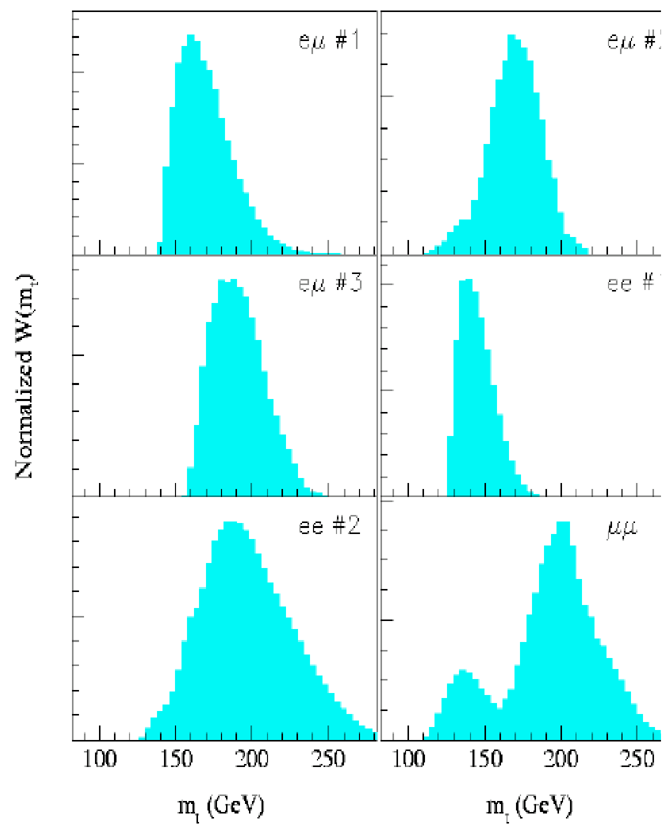


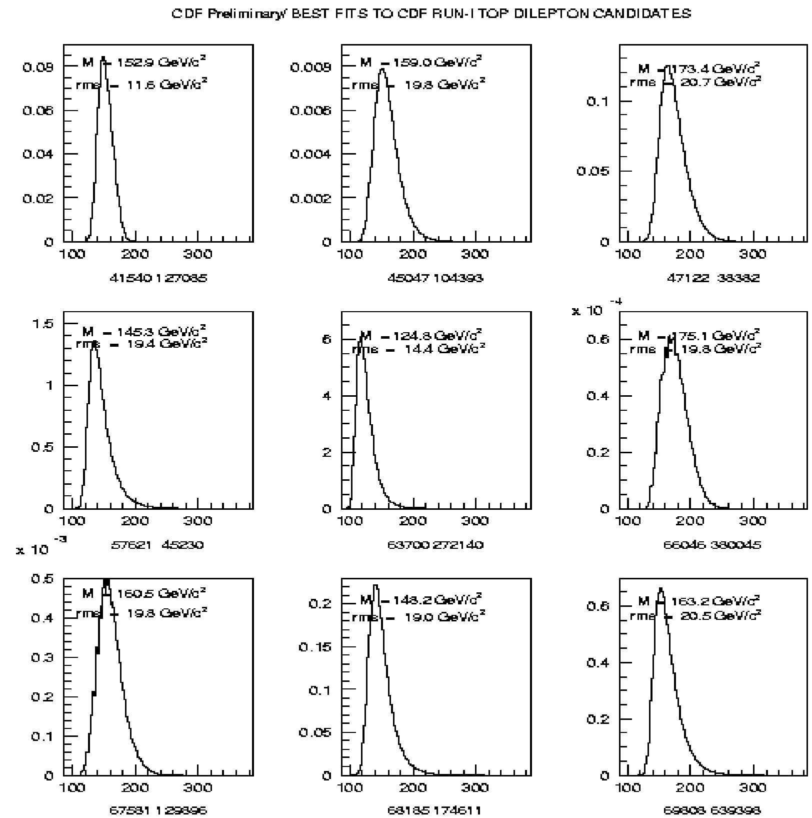


CDF: 167.4±10.3±4.8 GeV/c^2

D0: 168.4±12.3±43.6 GeV/c^2

CDF/D0 Top Mass in di-lepton channel





Likelihood distributions for individual D0 (left) and CDF (right) events

CDF and D0 systematic errors in di-lepton channel

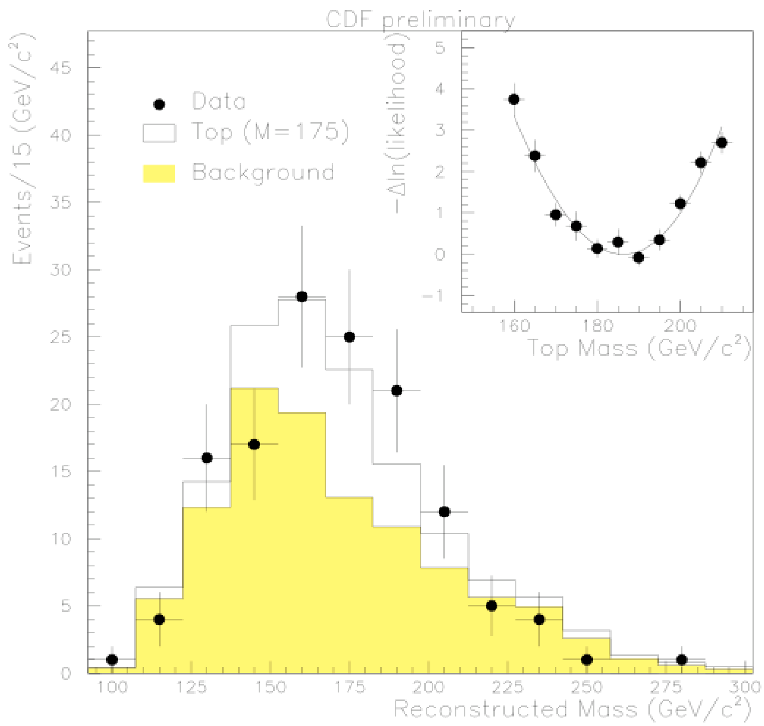
Dominant uncertainties (in GeV/c^2)

Uncertainty	CDF	D0
jet energy scale	3.8	2.4
signal model (ISR,FSR)	2.8	1.8
Monte Carlo generators	0.6	0.0
Background model	0.3	1.1
fitting technique	0.7	1.5
Calorimeter noise	0.0	1.3
Total	4.8	3.6

CDF Top Mass in all-jets channel

There is enough kinematical contraints for a 3C fit. Huge backgrounds from QCD multi-jet production. B-quark tagging required.

M_t = 186±10.0(stat)±5.7(syst) GeV/c^2



Systematic errors in all-jets channel (GeV/c^2)

jet energy scale	5.0
final state radiation	1.8
Background models	1.7
Monte Carlo generators	0.8
Monte Carlo statistics	0.6
initial state radiation	0.1
Total	5.7

COMBINED TOP MASS MEASUREMENTS

Summary of results used in combined CDF, D0 and joint CDF+D0 measurements of top quark mass (all results in GeV/c^2)

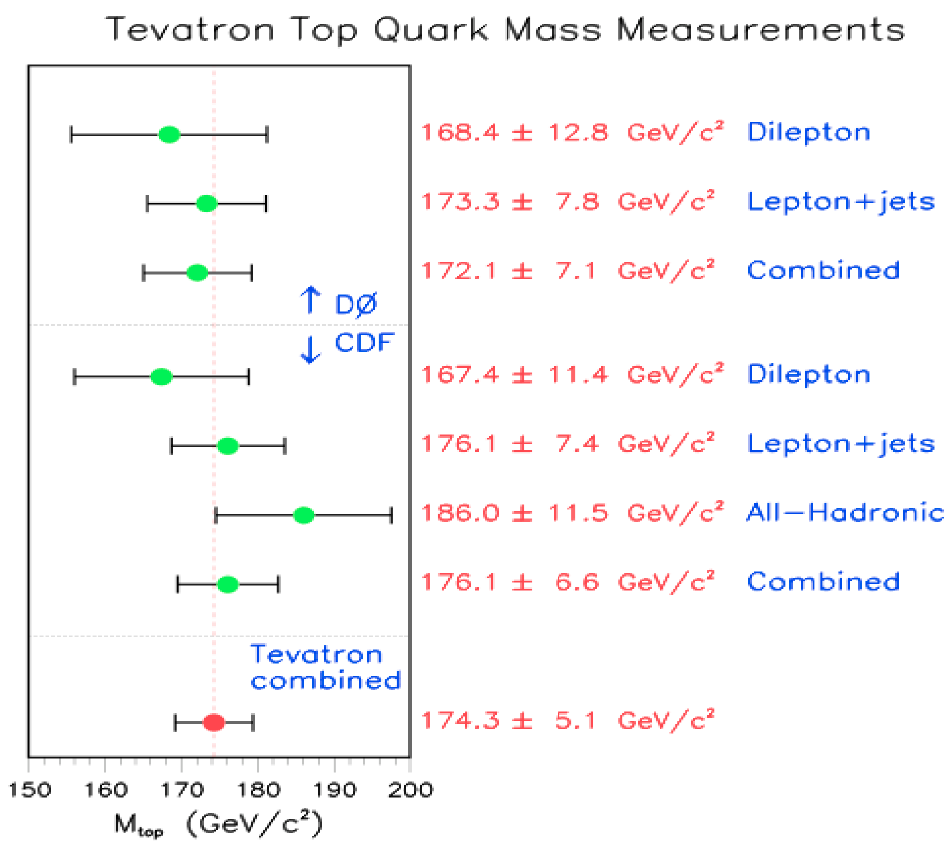
Channel	CDF	D0
di-leptons	167.4 ± 10.3 ± 4.8	168.4 ± 12.3 ± 3.6
Lepton+jets	175.9 ± 4.8 ± 5.3	173.3 ± 5.6 ± 5.5
all-jets	186.0 ± 10.0 ± 5.7	-
Combined	176. 0 ± 4.0 ± 5.1	172.1 ± 5.2 ± 4.9

combined CDF and D0 result from Run-I:

The Tevatron average was obtained by combining five CDF and D0 results in a similar manner as done separately for CDF and D0 averages. The systematic errors that did not depend directly on MC (jet energy scale, backgrounds…) were taken as uncorrelated between the experiments, while the MC model systematic errors (ISR, FSR, PDF dependence…) were treated as 100% correlated between the experiments since both rely on identical Monte Carlo models.

$$M_t = 174.3 \pm 3.2 \text{ (stat)} \pm 4.0 \text{ (syst)} \;\; GeV/c^2$$

CDF AND D0 TOP MASS MEASUREMENTS



TOP PAIR PRODUCTION CROSS SECTION

CDF measurements in individual channels

	lepton+jets	lepton+jets	di-leptons	all-jets	all-jets
tag	SVX	SLT	-	SVX	2 SVX
$\square_{tag}$	0.505±0.051	0.157±0.016	-	0.544±0.057	0.17±0.05
geo•kin	.078±0.01	.078±0.01	.0074±.0008	.099±.016	.263±.045
trigger	0.90±.07	0.90±.07	0.98±.01	$.998\pm^{.002}_{.009}$	$.998\pm^{.002}_{.009}$
acc.total	.035±.005	.011±.002	.0074±.0008	.054±.01	.045±.015
events	29	25	9	187	157
backg.	6.7±1.0	13.22±1.22	2.4±0.5	144±12	120±18
$\square_{tt}$ (in pb)	5.1+1.6-1.4	9.2+4.8-3.9	8.2+4.4-3.4	7.4+3.8-3.1	7.8+5.2-4.6

CDF combined the above cross sections using a likelihood technique that takes into account correlations in the uncertainties (at top mass of 175 GeV/c^2)

CDF combined $\square_{tt}$ = 6.5 + 1.6 – 1.4 pb

TOP PAIR PRODUCTION CROSS SECTION

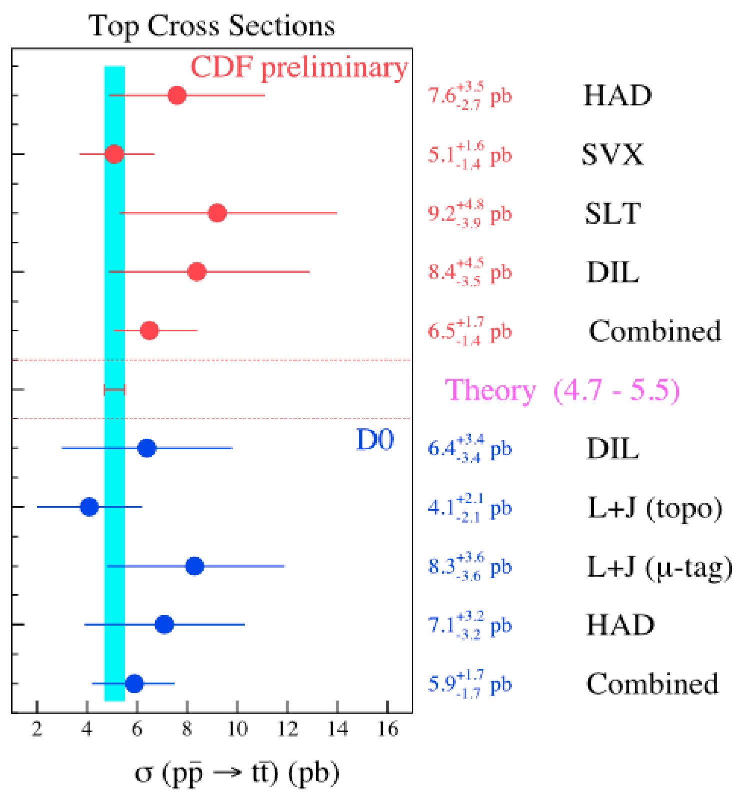
D0 measures tt cross section in 4 modes (at 172.1 GeV/c^2)

di-lepton + e□	(9 events)	6.4 ± 3.3 pb
l+jets (topological)	(19 events)	4.1 ± 2.1 pb
l+jets (□-tagged)	(11 events)	8.3 ± 3.5 pb
all-jets	(41 events)	7.1 ± 3.2 pb

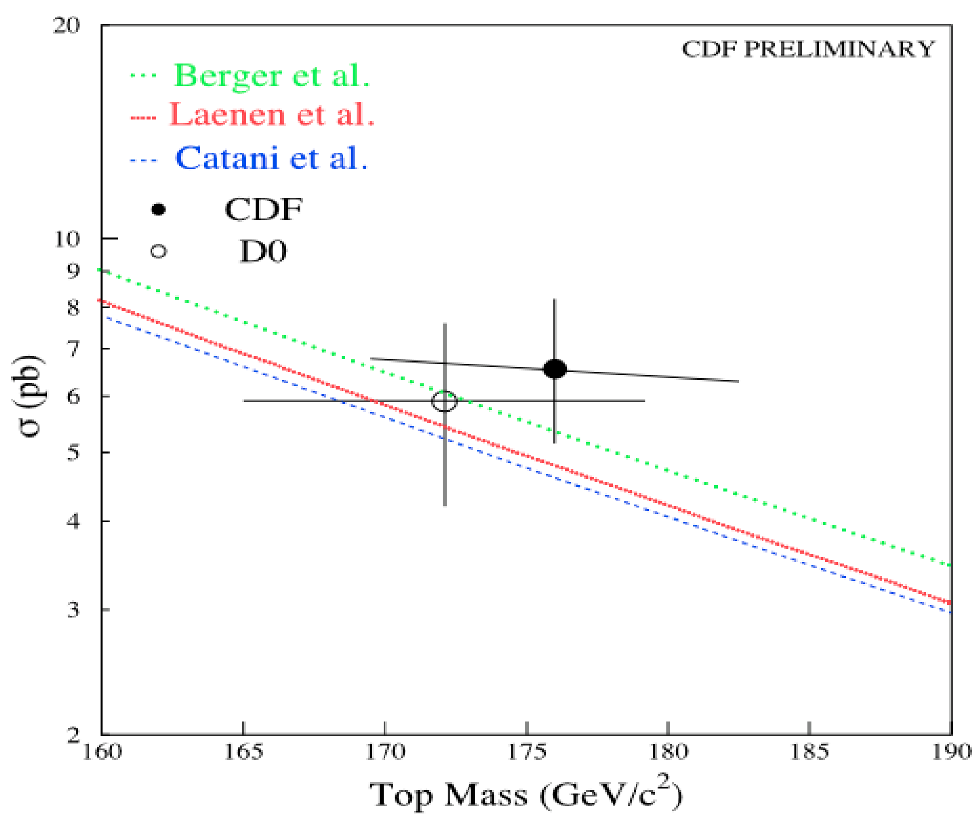
combined (at top mass of 172.1 GeV/c^2)

D0 combined $\square_{tt}$ = 5.9 ± 1.7 pb

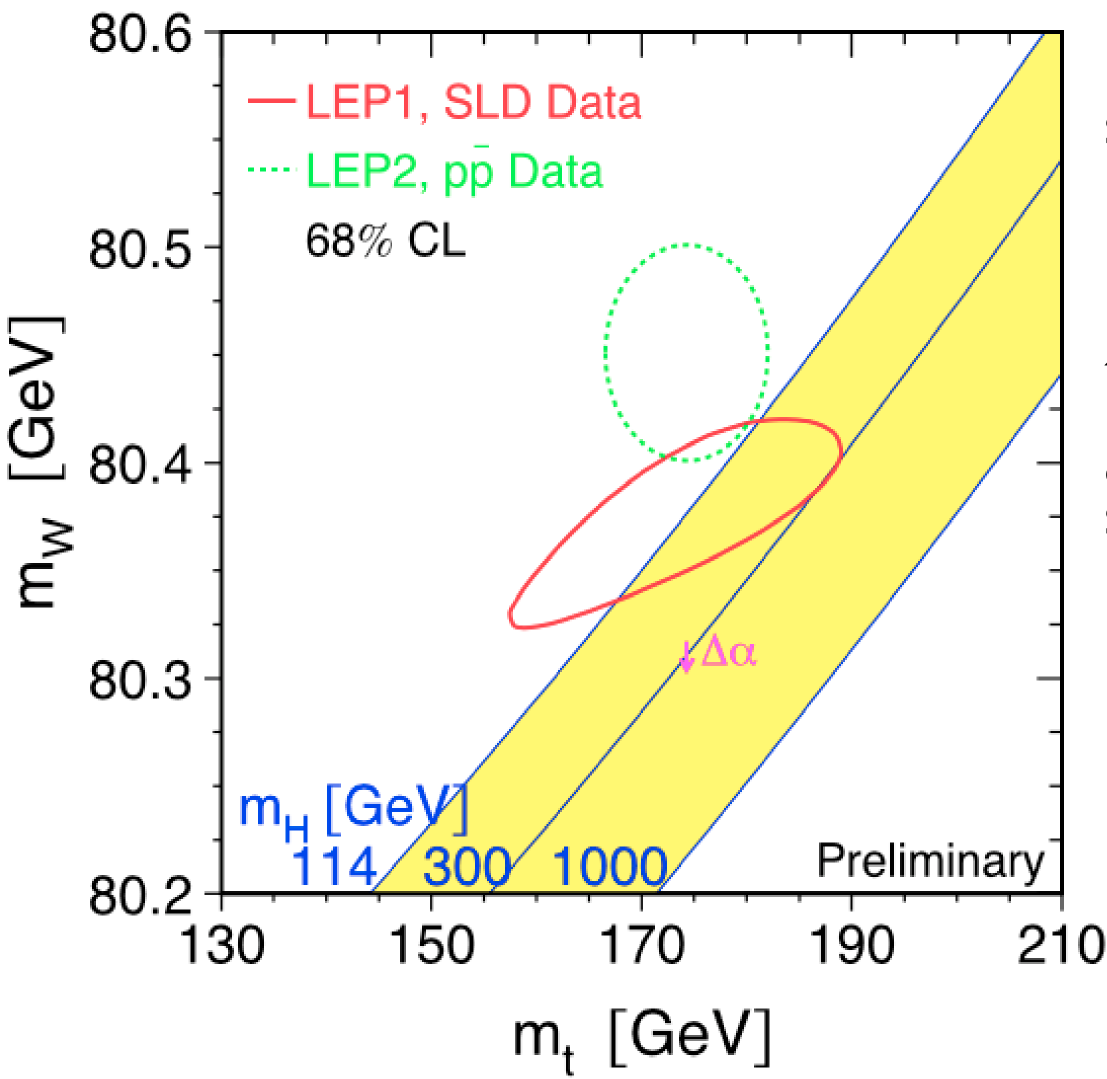
TOP PAIR PRODUCTION CROSS SECTION



TOP PAIR PRODUCTION CROSS SECTION



SM consistency checks: W mass vs M_{top}



Results of LEP EWWG SM consistency fits (Spring 2002)

Measurements of W and top mass constrain Higgs mass. Fundamental consistency tests of Standard Model

SUMMARY OF TEVATRON RUN-I RESULTS

TOP MASS AND CROSS SECTION

combined CDF results from Run-I:

$M_t = 176.0 \pm 6.5$ GeV/c^2

$\sigma_{tt} = 6.5{+}1.7{-}1.4$ pb (for M_t=175 GeV/c^2)

combined D0 results from Run-I:

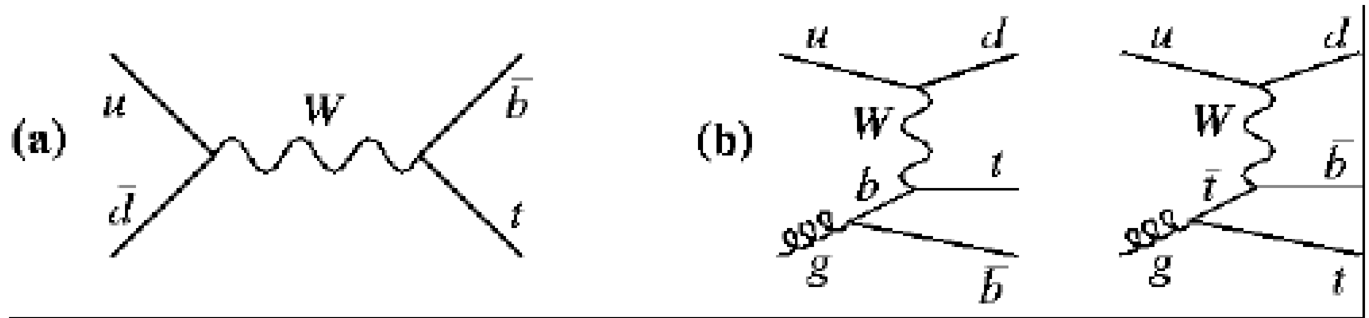
$M_t = 172.1 \pm 7.1$ GeV/c^2

$\sigma_{tt} = 5.9 \pm 1.7$ pb (for M_t=172.1 GeV/c^2)

combined CDF and D0 result from Run-I:

$M_t = 174.3 \pm 5.1$ GeV/c^2

SINGLE TOP PRODUCTION



Electroweak process. Standard Model cross sections:

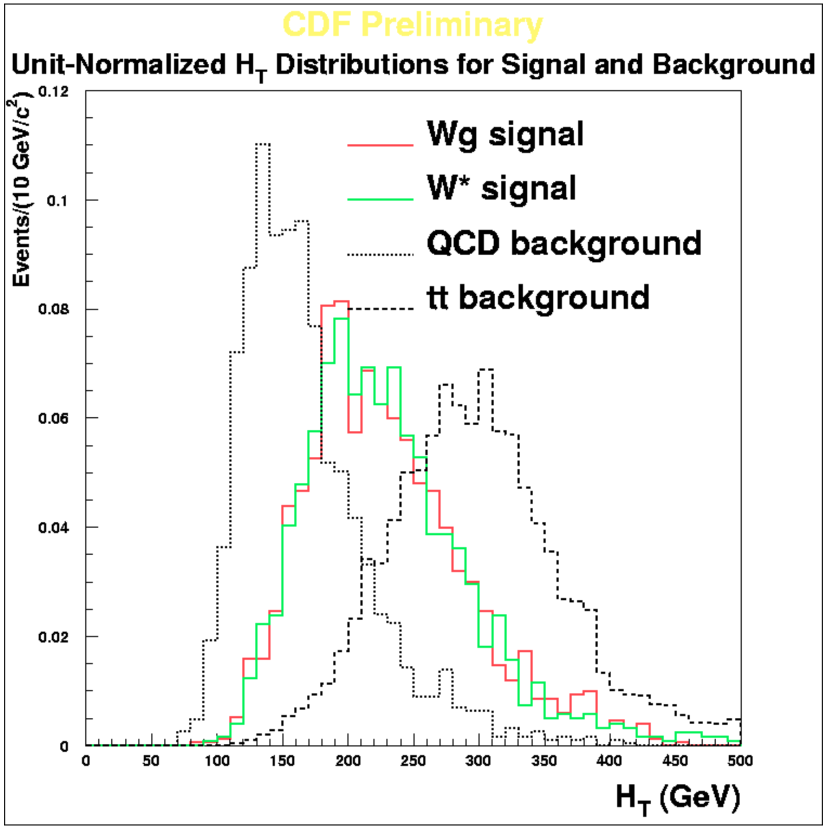
□(pp□ Wg□ t+X) = 1.70±0.20 pb (Stelzer at al)

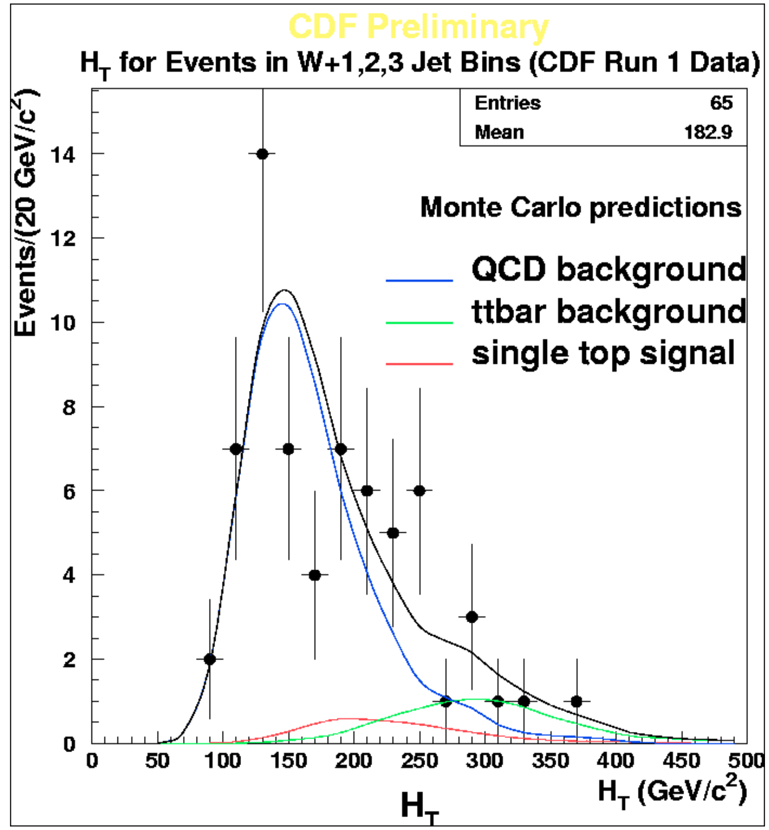
□(pp□ W*□ t+X) = 0.72±0.04 pb (Smith at al)

Direct access to Wtb vertex, one could determine the $|V_{tb}|$ element of Cabibbo-Kobayashi-Maskawa matrix

Search for anomalous couplings - large production rates or anomalous angular distributions

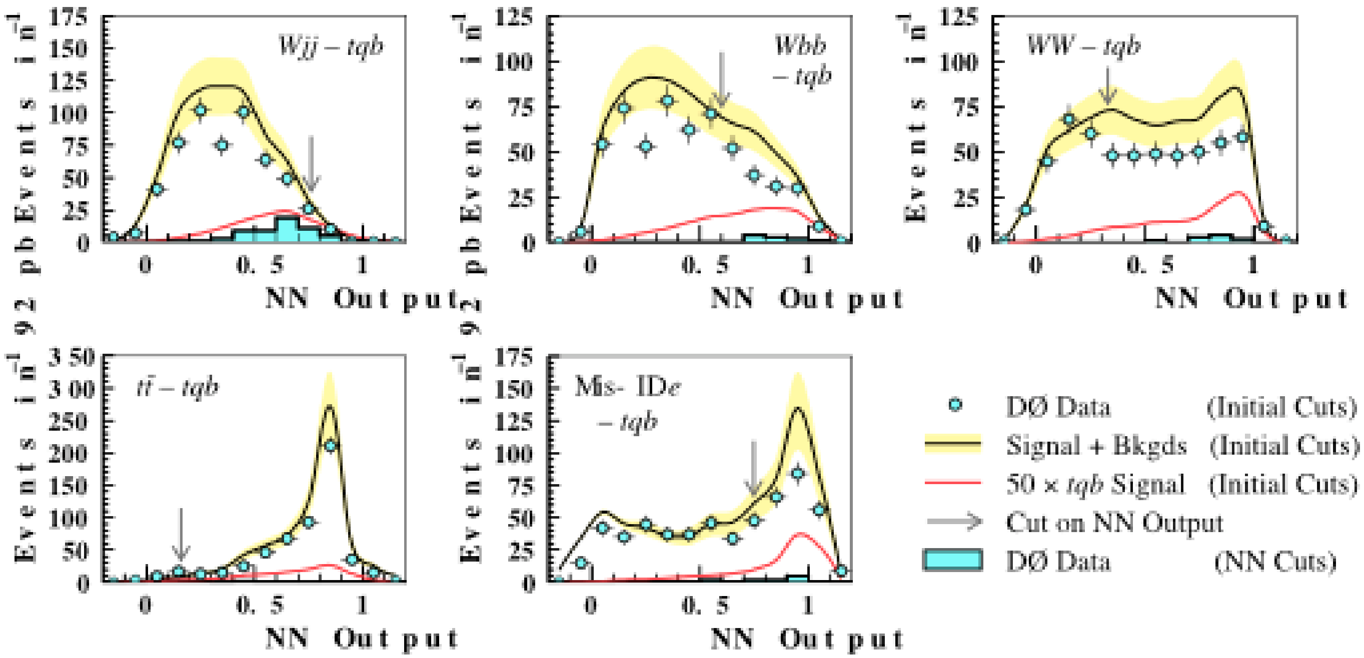
SINGLE TOP PRODUCTION





CDF: □ < 13.5 pb at 95% CL

SINGLE TOP PRODUCTION



Using an array of neural nets:

D0 : s-channel σ < 17 pb at 95% CL

t-channel σ < 22 pb at 95% CL

RUN-II AT TEVATRON
2001-?

New Main Injector □ CM energy (s) increased from
1800 GeV to 1960 GeV (tt cross section increases by ~35%)

Different beam crossing time (396 ns and 132 ns later, instead of 3.5 □s in Run-I) - fewer multiple interactions

Significant upgrades to both detectors:

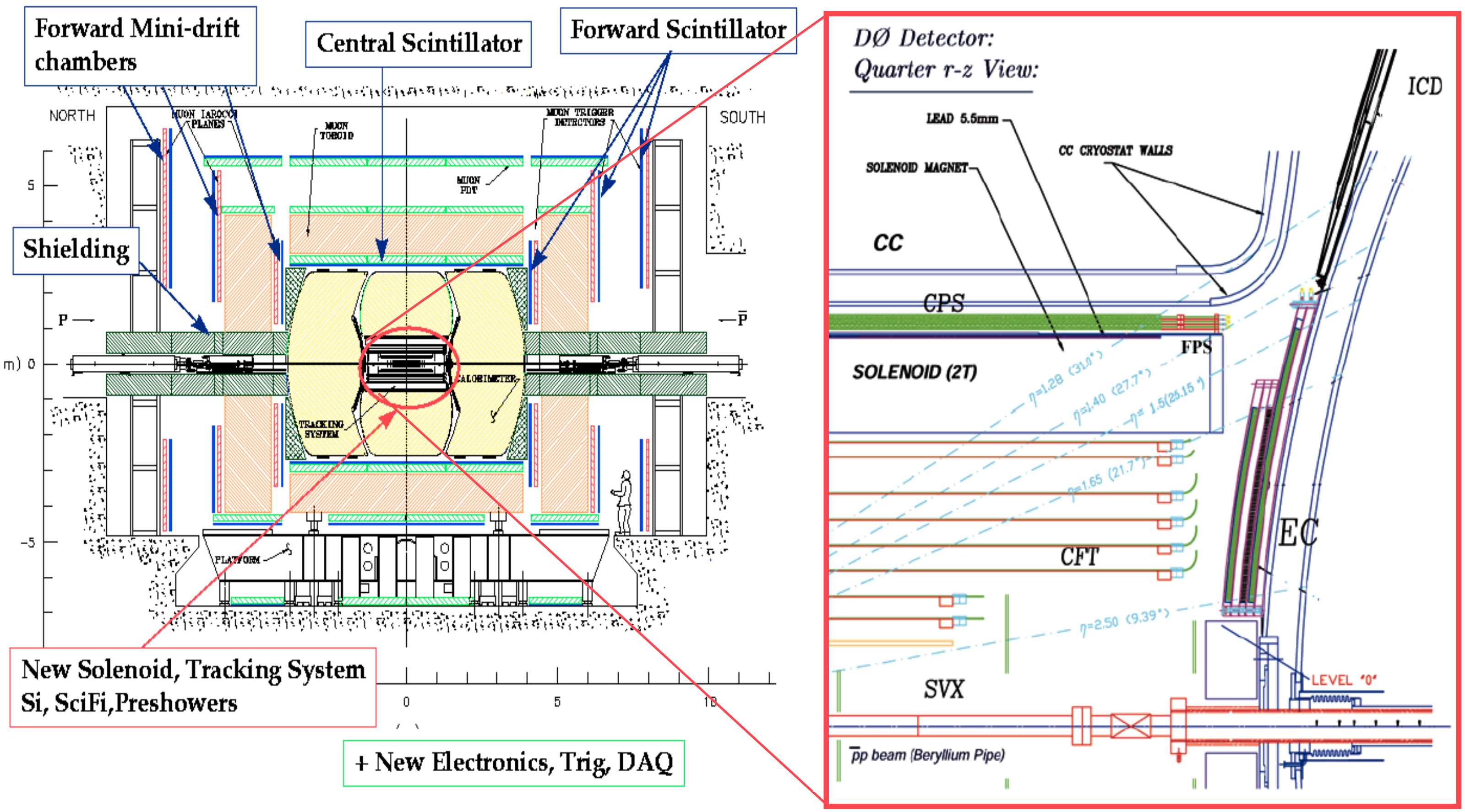
D0 : addition of SVX to allow better b-tagging
addition of a solenoid to allow track momentum reconstruction

CDF : new calorimeter for 1.1< |□|<3.5 (much better energy resolution)
new (longer) SVX with double the Run-I tagging efficiency

RUN-II AT TEVATRON 2001 - ?

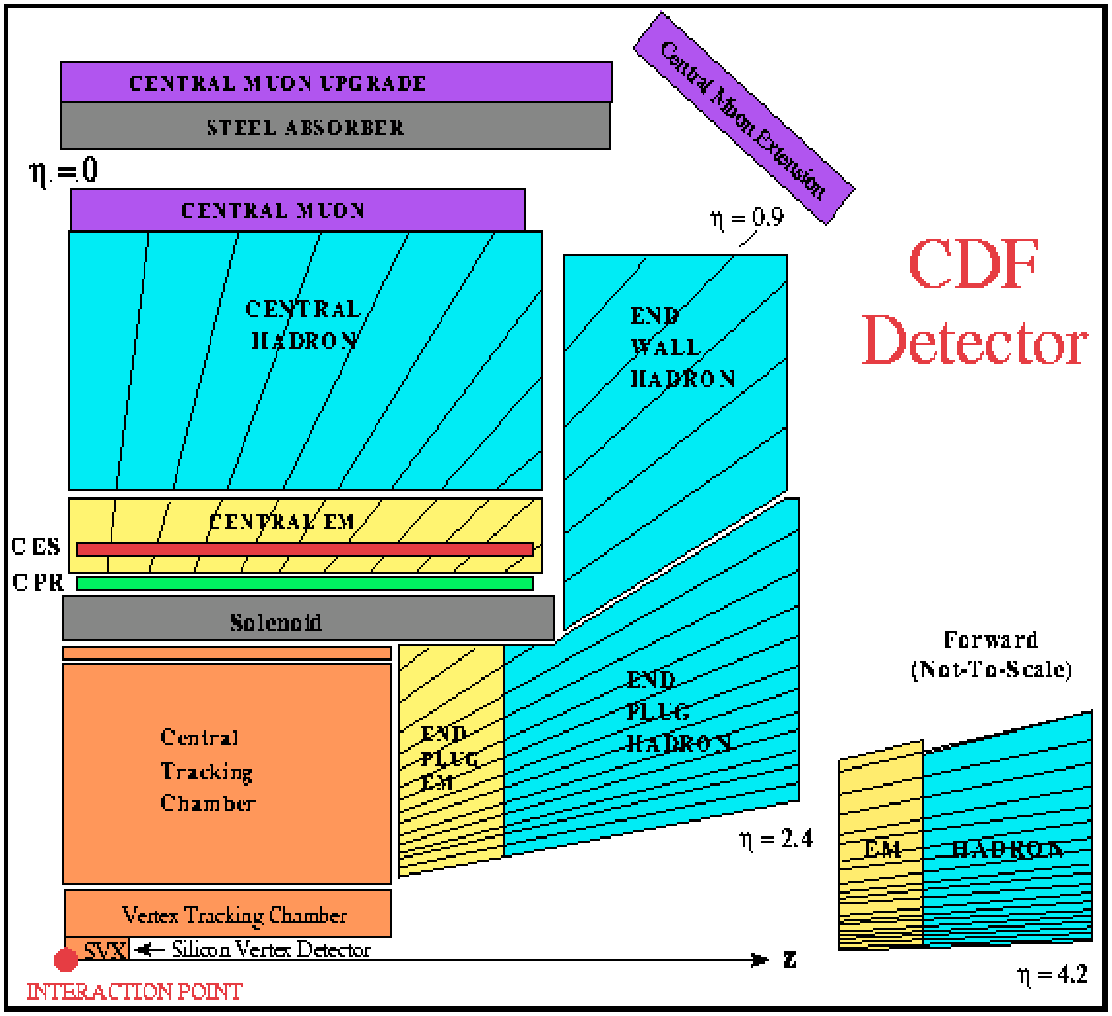
Aerial view of Fermi National Accelerator Laboratory

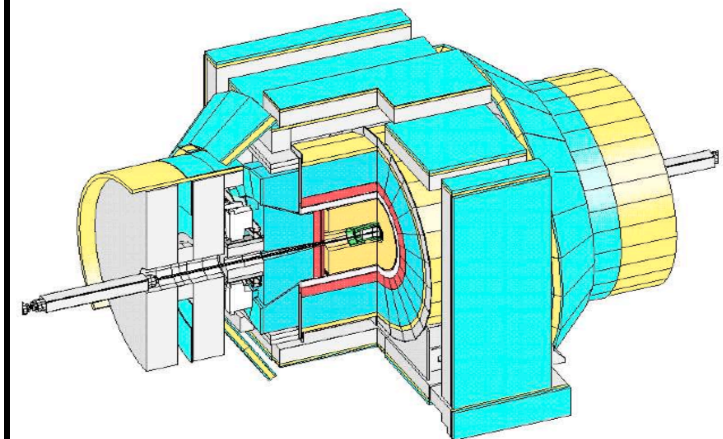
RUN-II AT TEVATRON 2001 - ?



D0 detector in its current configuration

RUN-II AT TEVATRON 2001 - ?





CDF detector in its current configuration

PROSPECTS FOR RUN-II

	RUN-I	RUN-IIa CDF	Run-IIa D0
"typical" L($cm^{-2}s^{-1}$)	$1.6x10^{30}$	$8.6x10^{31}$	$8.6x10^{31}$
integrated luminosity	~110 pb^{-1}	2 fb^{-1}	2 fb^{-1}
dilepton events	~10/exp	140	200
lepton+≥4jets	~20/exp	1500	1800
lepton+≥3jets+≥ 1b tag	~30/exp	1400	1400
lepton+≥4jets+2 b tags	~5	610	450
ΔM_{top}	7 GeV/c^2	2-3 GeV/c^2	2-3 GeV/c^2
$\Delta\sigma(tt)$	~30%	~8%	~8%

Run-II a: 2001-2005

Run-II b: >2005 ($\int L\,dt$ =15 fb^{-1},"typical" L=$5.2x10^{32}$ $cm^{-2}s^{-1}$)

IS IT ONLY TOP ?

The large top mass makes the selected samples coincident with samples one would select when looking for physics processes beyond SM (SUSY, Technicolor…) TOP IS THE BACKGROUND TO ANY NEW PHYSICS

Measured cross section values depend on mass measurement, which has been obtained in CDF and D0 using various kinematical fitting techniques assuming that events are tt and SM background.

If the sample is not purely top+SM background (as it had been assumed), the mass measurement may be incorrect. The number of events seen may not agree with the calculations. Presence of additional processes will most likely increase the number of observed events.

It is thus imperative to compare various distributions of the reconstructed top quarks, and especially those of the t-tbar system, with the predictions for top production. Discrepancies could indicate new physics.

Both CDF and D0 made numerous comparisons. No significant disagreements were found, as perhaps should be expected given the still limited statistics of the data.

IS IT ONLY TOP ?

With increased integrated luminosity (20x), combined with improvements to CDF and D0 detectors, the number of observed top events will increase by about a factor of 40.

List of things to watch when Run-IIa yields more statistics in 2003, as they may be offering us glimpses of new physics:

- cross section: CDF value seem a little high compared to theoretical predictions, however, they agree within quite large errors;
- mass: it has been suggested there is a hint of increase of the top mass with a number of jets; values agree within errors
- tagged jet multiplicity: there seem to be a bit too many W+2jet events with jets SVX and SLT tagged in CDF data (2-3 □ discrepancy in kinematical distributions – Phys. Rev. D65 (2002) 052007)
- two (out of 9) CDF di-lepton events have unexpectedly large MET+□E_t^{lepton}, (both give very poor "fits" to tt hypothesis); one such event exists in D0 sample. (Flagged by Hall and Barnett as candidates for SUSY events in their DPF 96' paper).
- mass of tt system, both CDF and D0 plots seem to deviate a little from expected distributions; but both agree well within errors

IS IT ONLY TOP ?

- transverse momentum of tt system: the spectrum based on 32 CDF tagged events, which are the basis of the CDF top mass measurement, seems to be a little harder than that expected from MC calculations; it is a difficult variable to measure because of possible fitter biases.

- Rapidity of tt system: probes directly the fitted longitudinal component of the neutrino momenta, verifying the goodness of the fits.

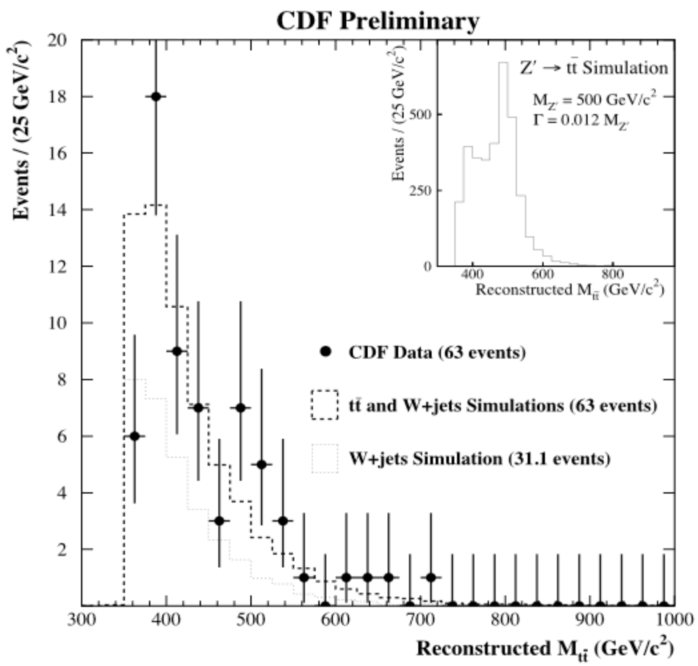
  It is perhaps more sensitive than others to the original assumption, and as such should be watched in Run-II.

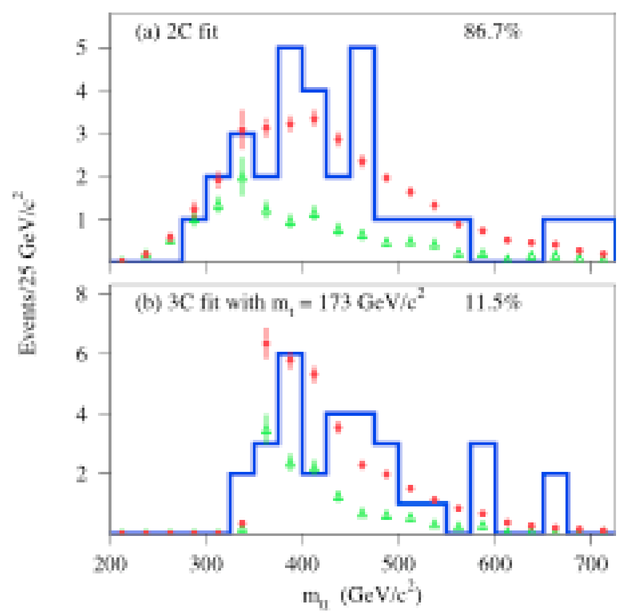
  CDF plot based on 32 tagged events has a strikingly different shape than one would expect from MC simulations.

  However, an analogous distribution based on D0 events is in much better agreement with the one expected for tt events, which may simply mean that the CDF distribution is a result of an unlikely fluctuation.

- mass of the two non-b jets (from hadronic W decay, requires removing one of the constraints)

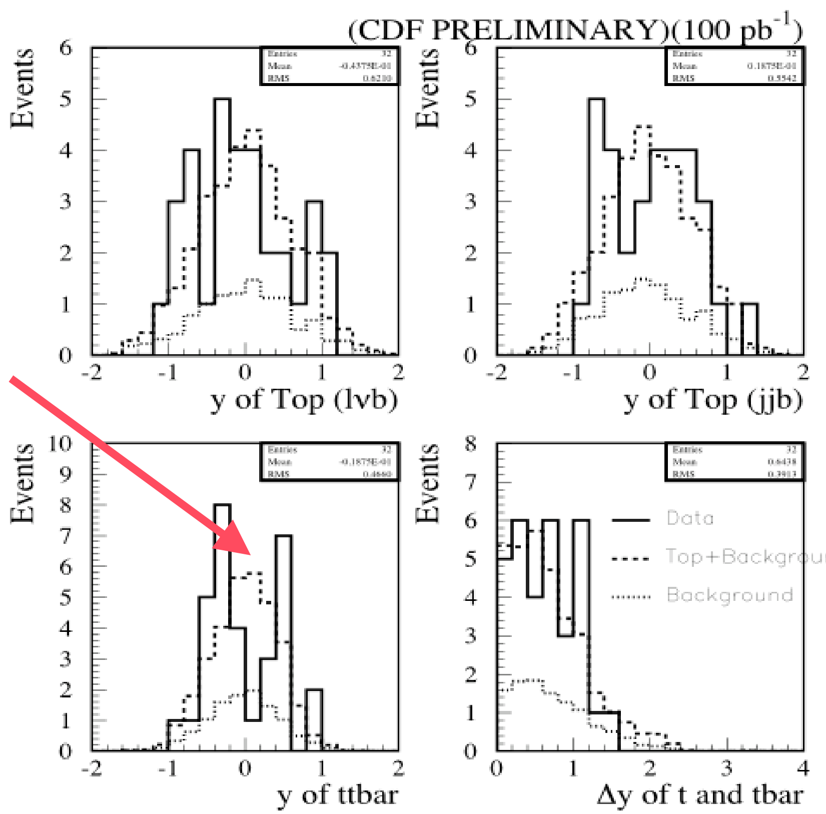
IS IT ONLY TOP ?

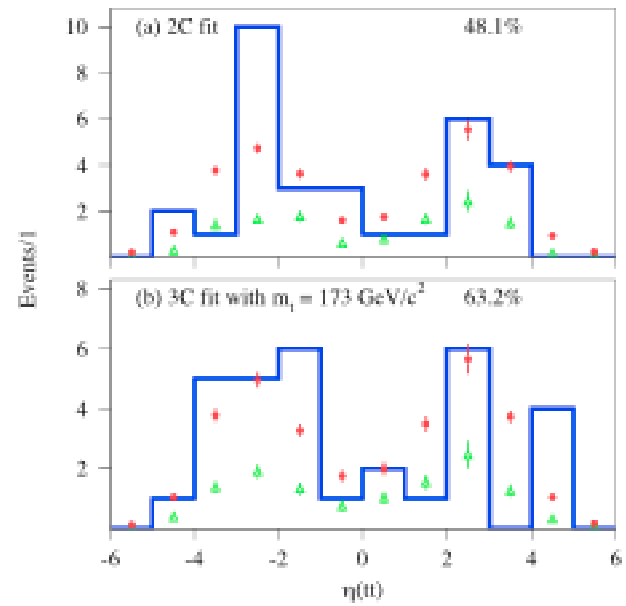




CDF and D0 distributions of mass of the tt system

IS IT ONLY TOP ?





Rapidity (CDF) and pseudorapidity (D0) distributions of tt system

PHYSICS WITH LARGE STATISTICS TOP SAMPLES

top quark mass measurements (within 2-3 GeV/c^2)

tt pair production cross section (within 8%)

single top production cross section

top-antitop spin correlations, studies of top polarization

rapidity of tt system

mass of tt system

W helicity in top decays

$|V_{tb}|$

NEW PHYSICS ?

any anomalies in the above studies

rare decays….

CAN'T WAIT FOR MORE DATA IN 2003 !!

IS IT ONLY TOP ?

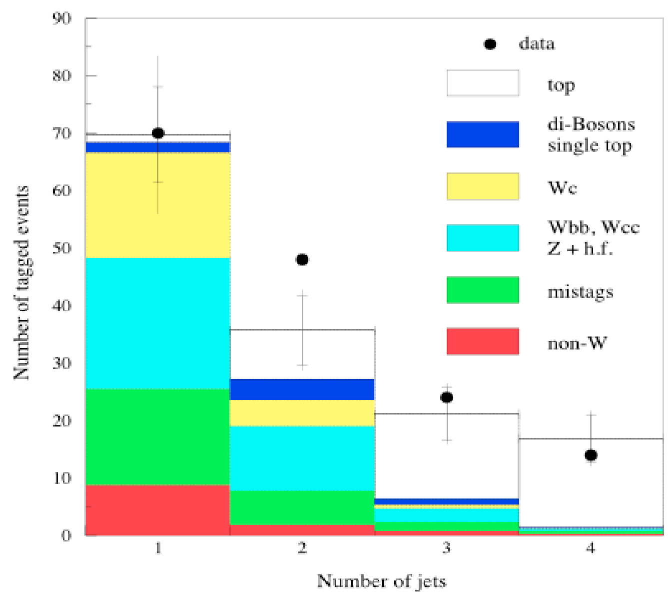


Figure 5: Observed and expected number of tagged events when using standard C jet counting. The vertical bars represent the overall uncertainty on the expected nu ber of tags discussed in the text, the horizontal ticks on the bars mark the contribut from the statistical uncertainty.

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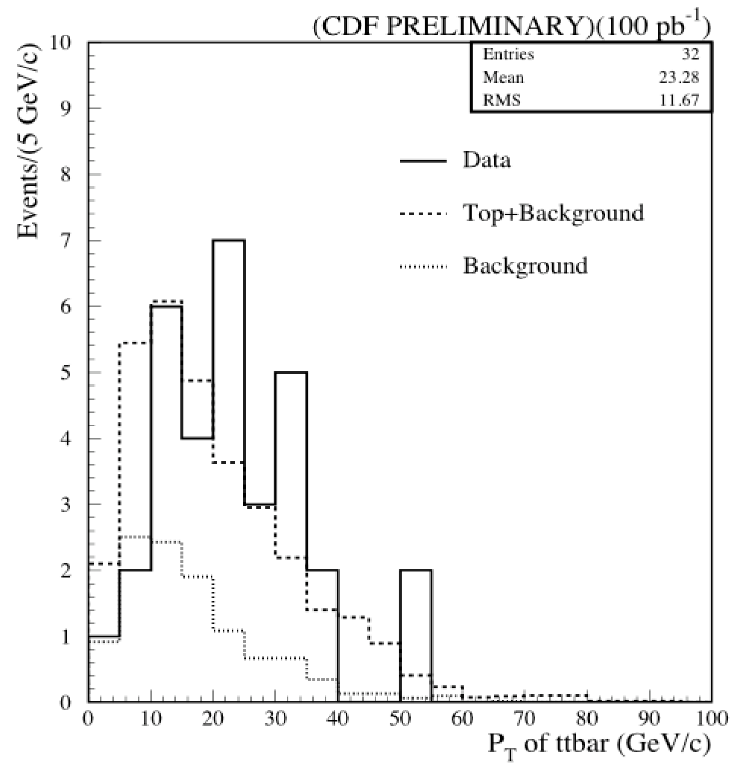

IS IT ONLY TOP ?

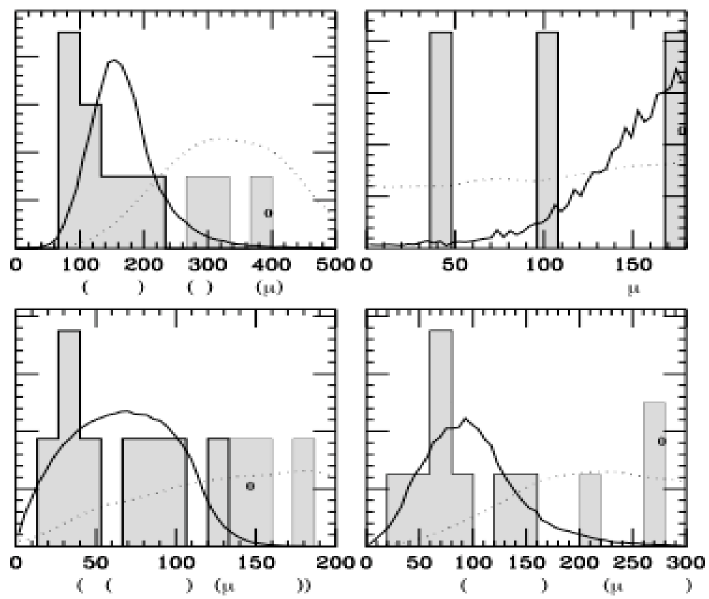

Figure 1: Expected distributions for (a) $E_T = E_T^{\ell_1} + E_T^{\ell_2} + \not{E}_T$, (b) $\delta\phi$ between the two leptons for $E_T > 250$ GeV, (c) the product of the transverse masses of $\ell_1 + \not{E}_T$ and $\ell_2 + \not{E}_T$, and (d) the maximum of the two transverse masses in (c). The solid curves are for $t\bar{t}$ production. The dotted curve has both leptons from $\tilde{\ell} \to \ell\tilde{\chi}_1^0$ decays. The histograms show the CDF data. The three events mentioned in the text are labelled A, B, and D0.

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