Top Quark Measurements at Tevatron Run II

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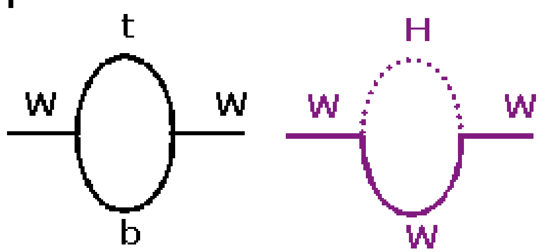
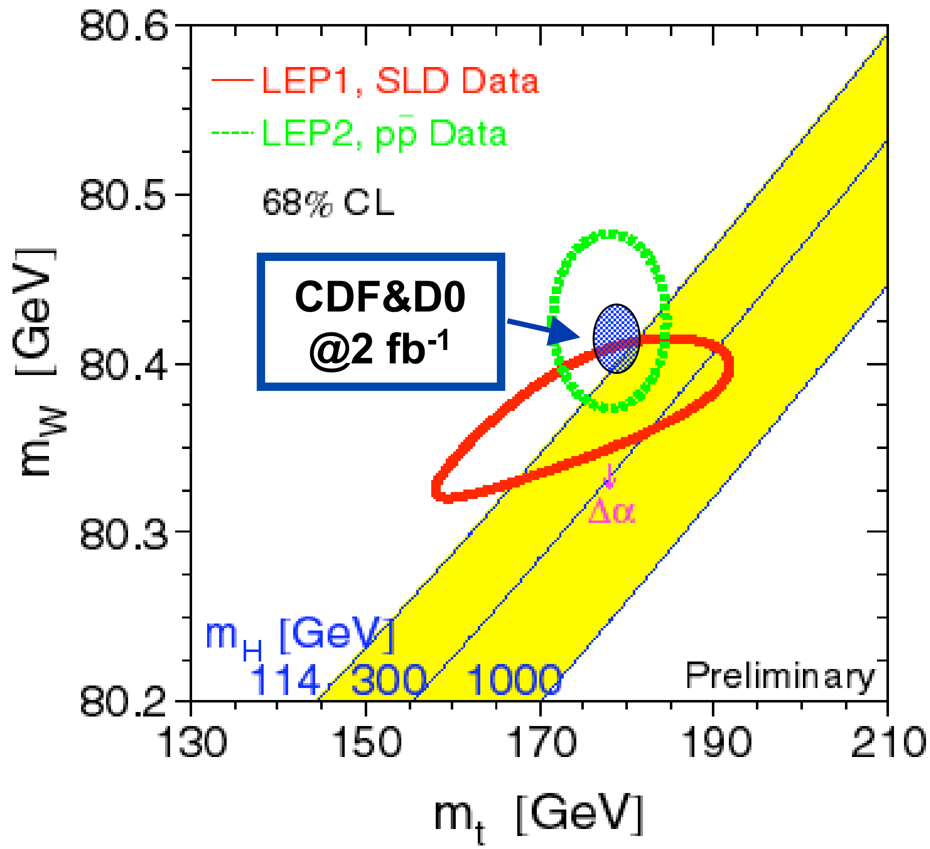
Motivation

- The top quark mass is a fundamental parameter of SM
- Top and W mass measurements constrain the mass of the Higgs Boson



$\Delta M_W \propto M_T^2$ $\Delta M_W \propto \ln M_H$

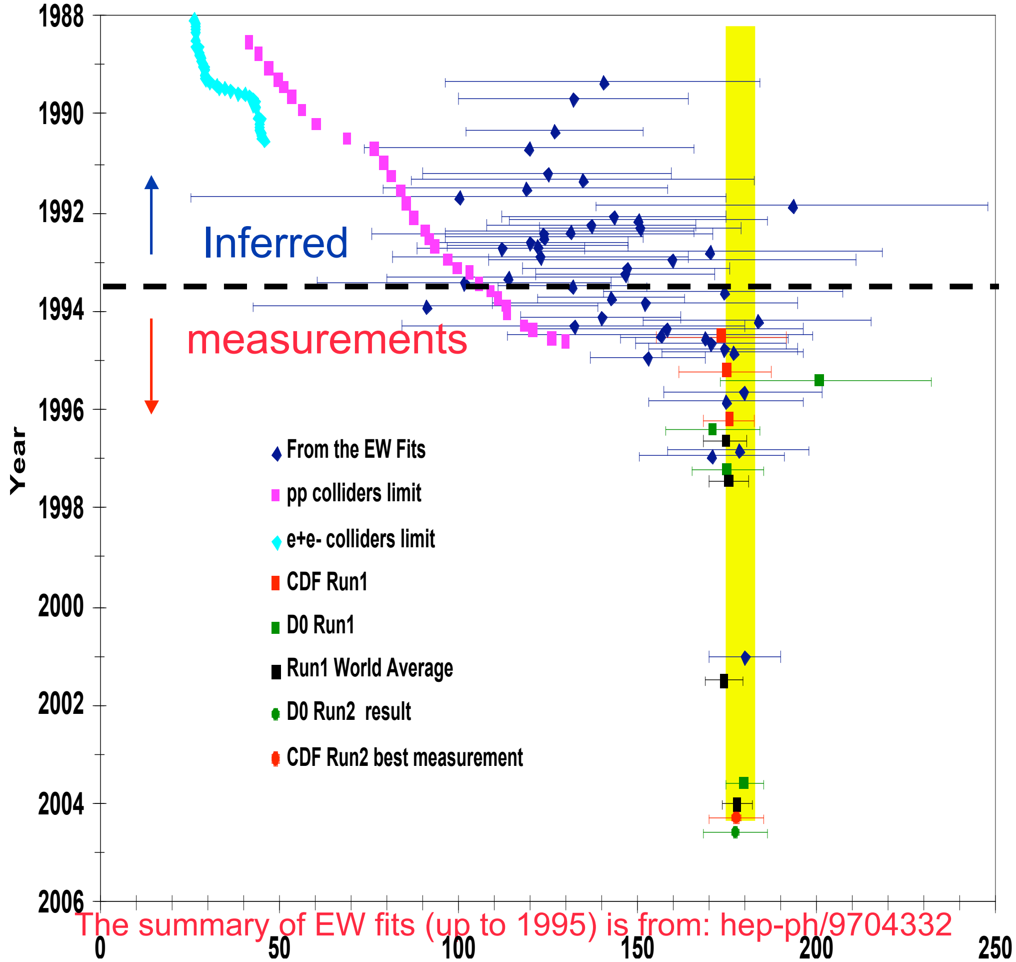
- Top is the only fermion with a mass of the order of EW symmetry breaking scale
  - M_{top} ~ VEV of the Higgs field – special role of the top quark?



hep-ph/0410177

Top mass measurement

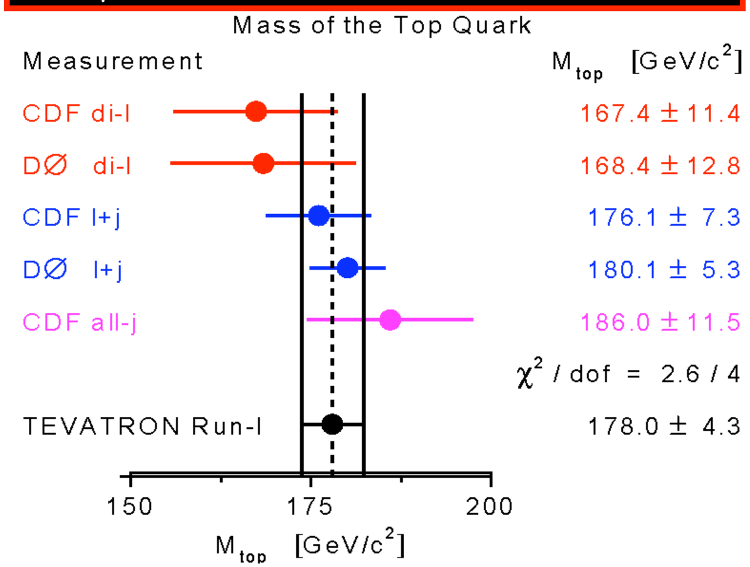
Top mass history



New Run1 analysis on the sample of ~125 pb^{-1} collected by D0 in 1994 - 1996

- Lepton + jets sample
- Matrix Element type analysis technique ***Nature*** 429, **638-642** (2004)

M_{top} = 180.1 ± 3.6 (stat) ± 3.9 (sys)



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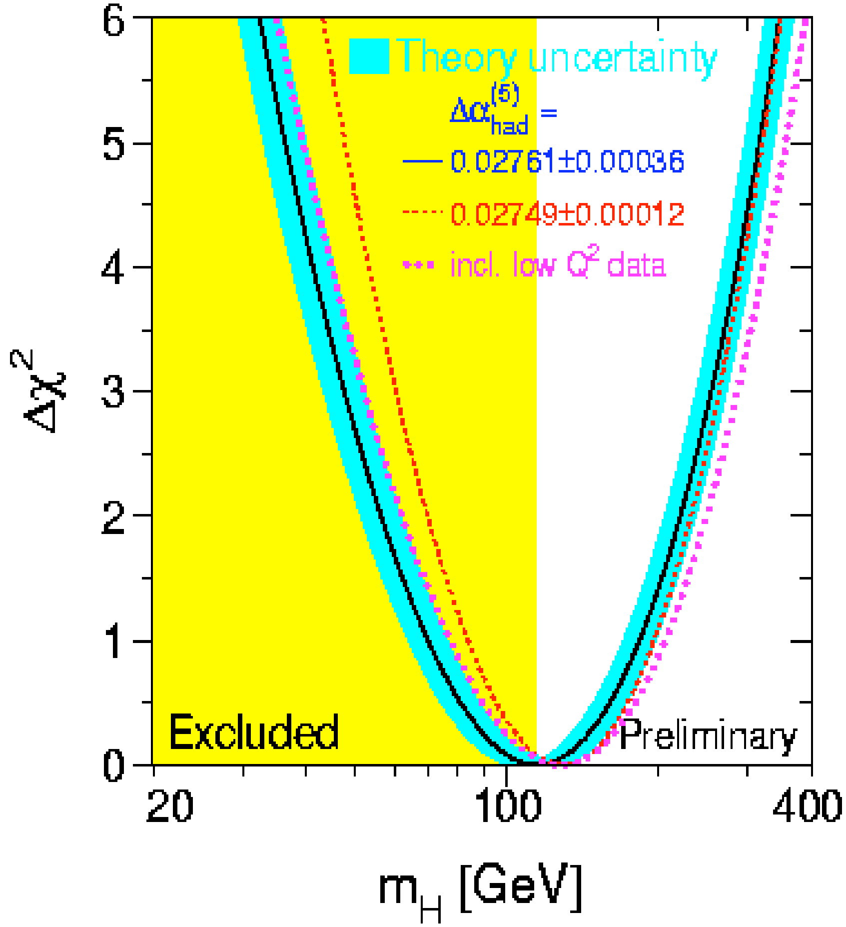
New Run1 result and Higgs limit



New world average

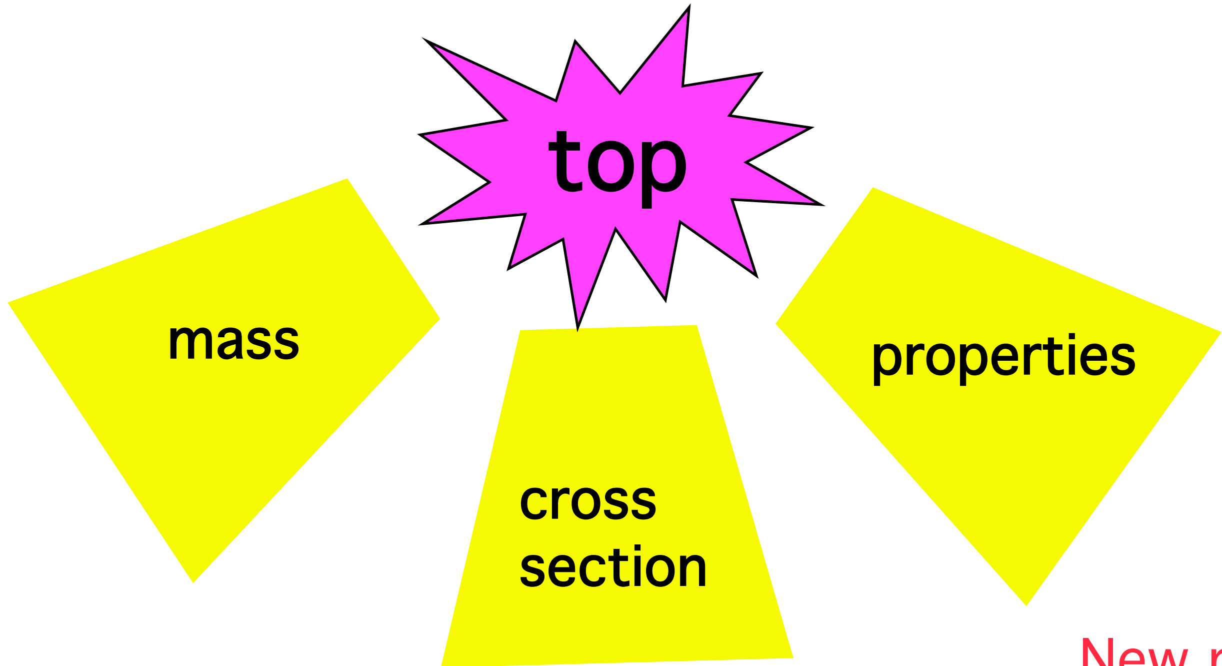
m_t = 178.0 ± 4.3 GeV/c^2

m_{top} = 174.3 ± 5.1 GeV/c^2
m_H = 96^{+60}_{-38} GeV
m_H < 219 GeV @ 95% C.L.

Δm_{top} = 2% ⬇ Δm_H = 19%

m_{top} = 178.0 ± 4.3 GeV/c^2
m_H = 114^{+69}_{-45} GeV
m_H < 260 GeV @ 95%C.L.

Current experimental focus



Improve precision
- Reduce systematics
- New tecniques

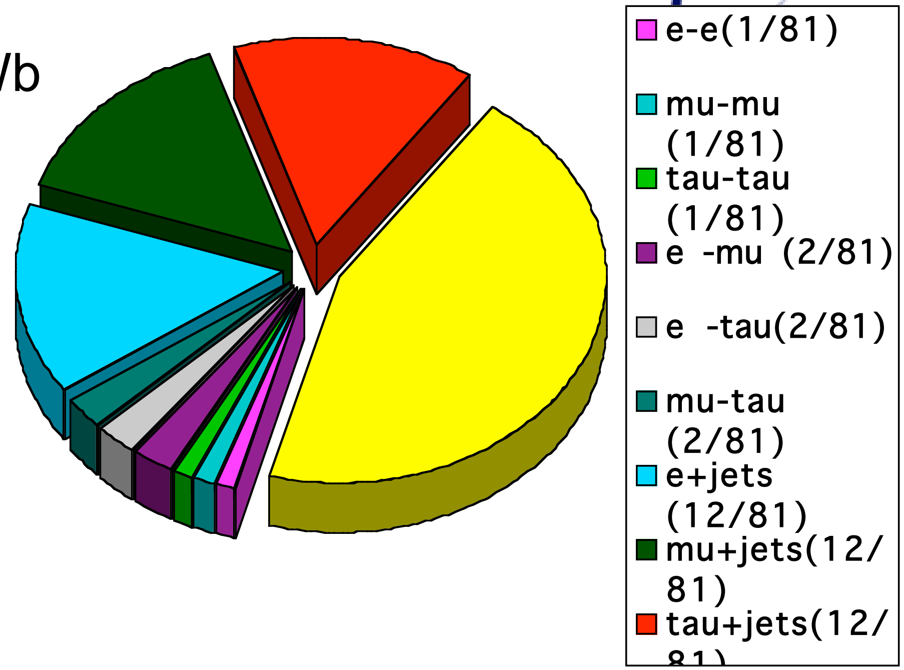
All the channels
- Exploit b-tagging
- Exploit kinematics
- Add tau+jets

New measurements
- Better statistical significance
- New methods

Top Quark Decay and Event Signatures

Assume top hadronizes before decay to Wb

Top event signatures (from W bosons)



Expect 2 b jets from top pair production

Channel	Typical S/B
dilepton	1 - 3
Lepton + jets	0.2
all jets	4×10^{-4}
(Had)Tau+jets	1×10^{-4}

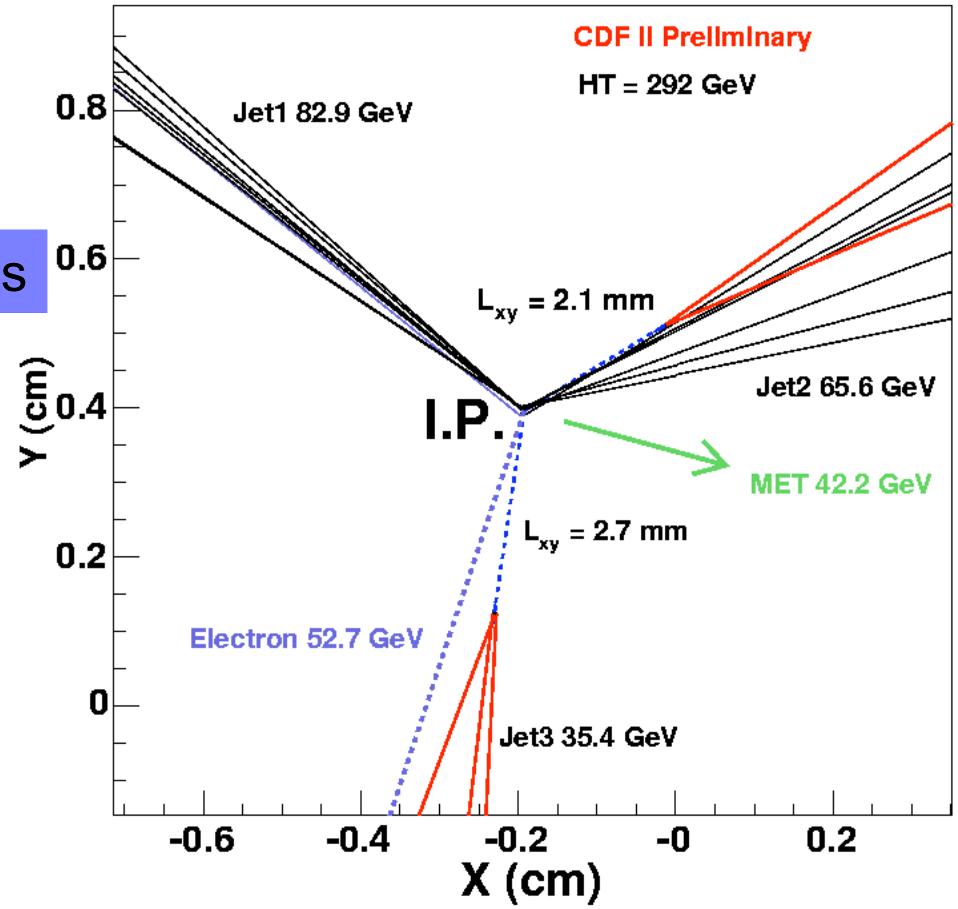
Need special techniques to flag top signal here

Lepton + Jets Channel

High-pT electron, muon with missing ET and ≥4 jets (2 are b-jets)

Large sample for other measurements
- mass, other top properties, W helicity
- single top and BSM searches

W+jets physics background dominates



Typically 500 events in 160 pb^{-1}
(includes 3-jet events, too)

↓

B-tagged sample of 50 -120 events

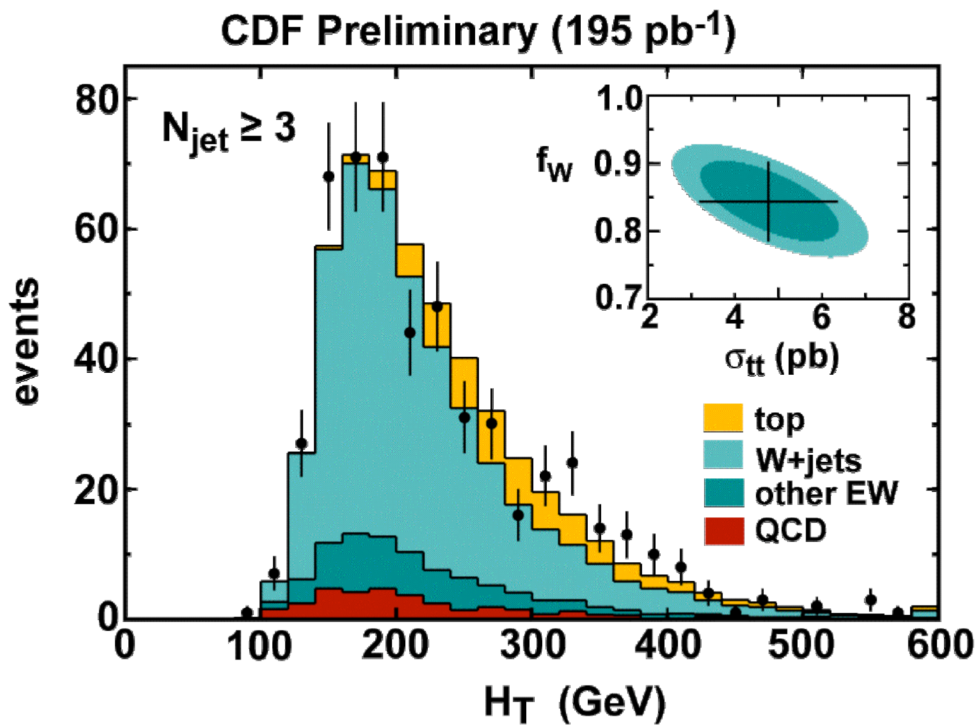
Double-tagging can improve S/B
- tight tagging (8 events): S/B=8
- loose tagging (19 events): S/B=4

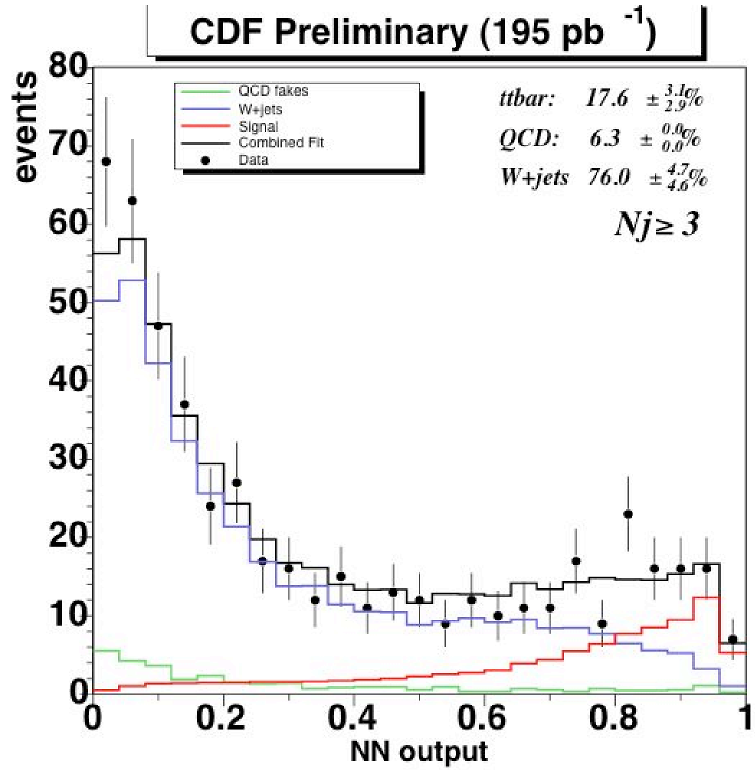
Largest uncertainty is on b-tagging efficiency measurement

L+jets Topological cross section (CDF)

Use jet energy and event shape info to discriminate top pairs from W + jets

(Trade off S/B for increased number of top signal events)

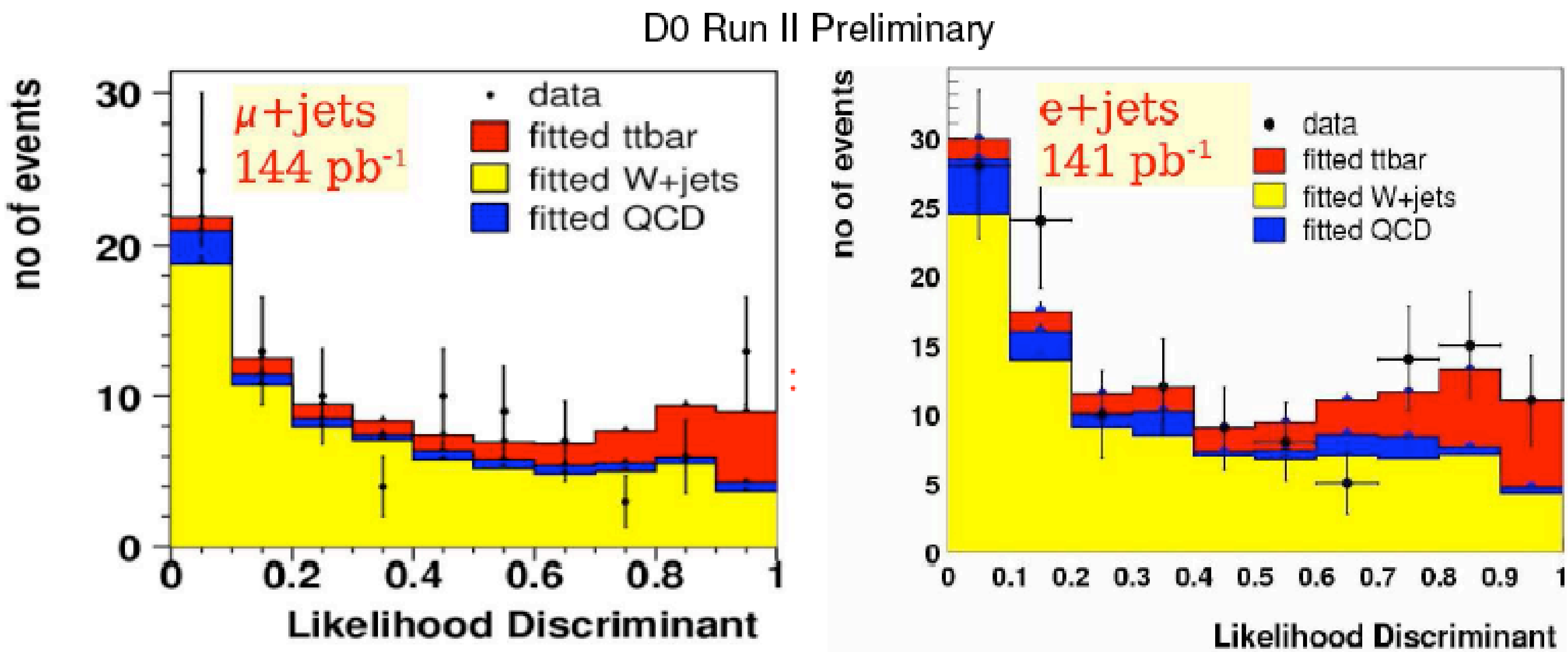




Fit to data distribution to extract top pair signal fraction (15-20%)

- Large uncertainty for energy scale when fitting jet energies
- In future, can apply b-tagging before performing fit

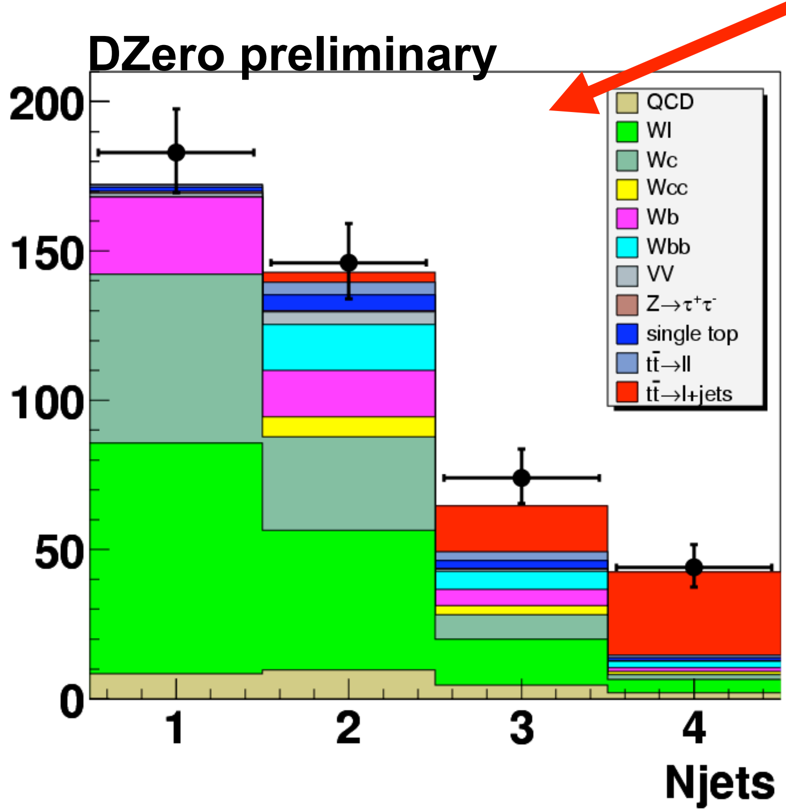
L+jets topological cross section (D0)

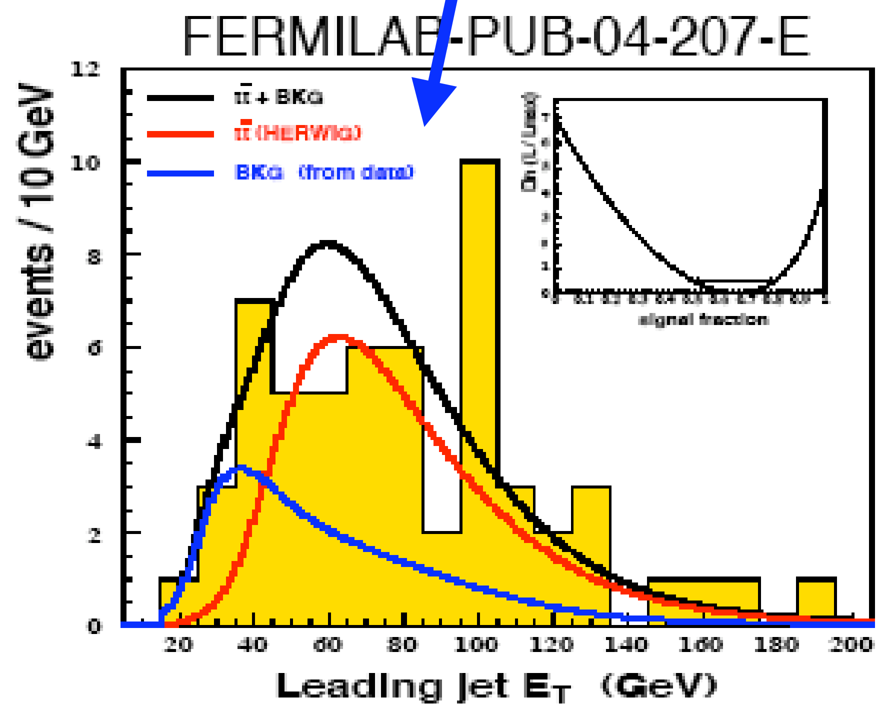


Combined $\sigma_{tt} = 7.2\ ^{+2.6}_{-2.4}$ (stat.) $^{+1.6}_{-1.7}$ (syst.) $\pm$ 0.5 (lum.) pb

Cross Section Results using B-Tagging

SVT tag in 3+4 jet bins: counting experiments or fit leading jet Et





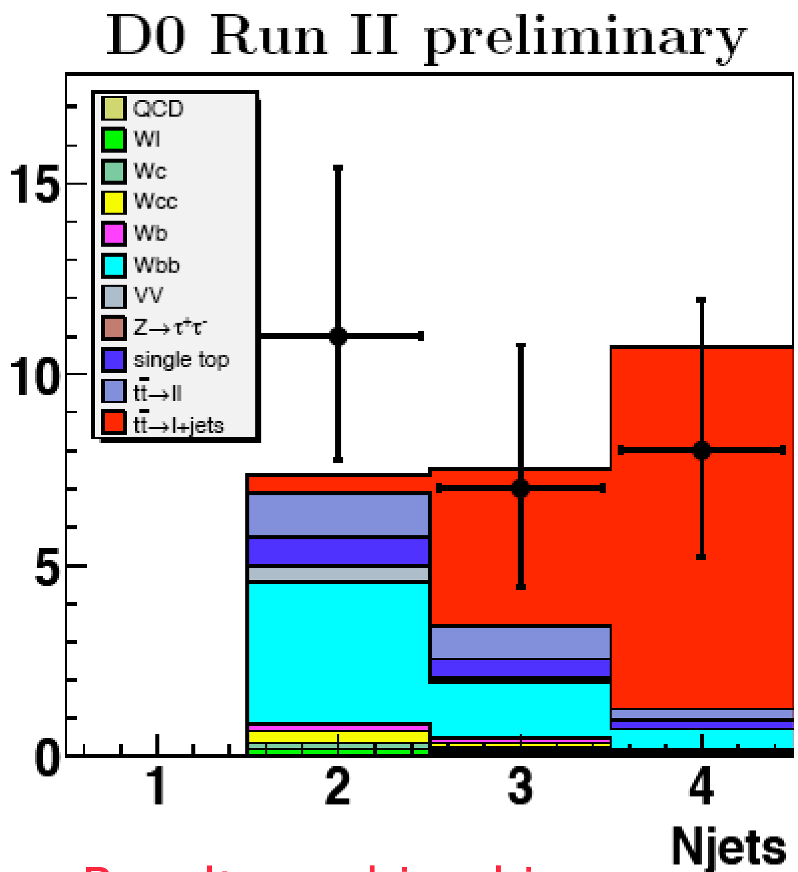
Estimate backgrounds in the lepton + jets sample from first principles:

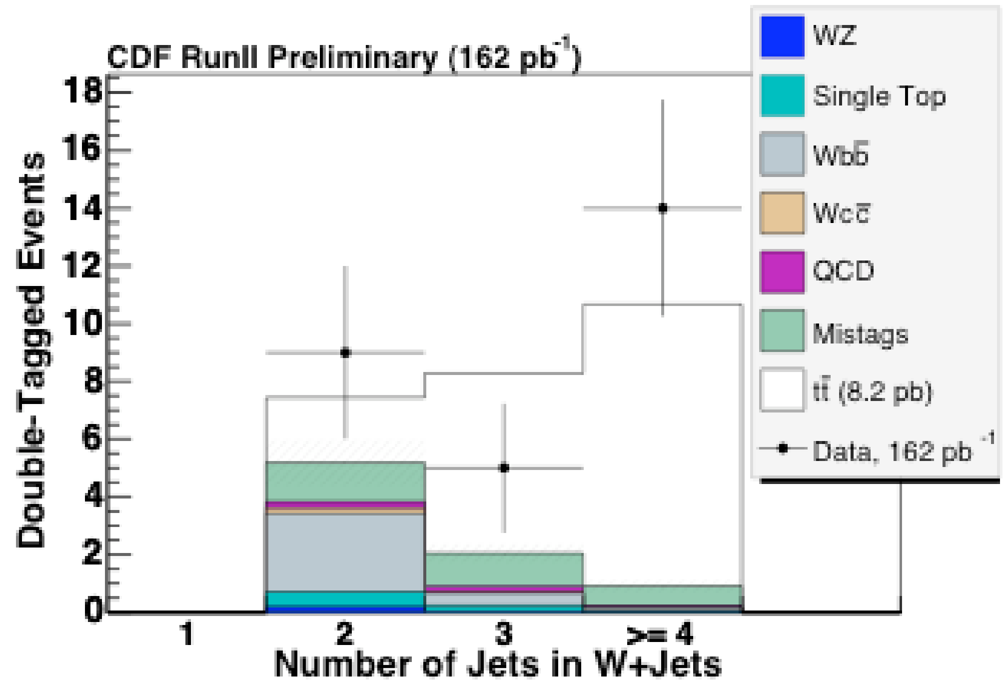
- Using data as much as possible (fake W bosons, fake b-tags)
- Some MC calculations for diboson and W + heavy flavor backgrounds

Most precise measurements at Run 2 are in b-tagged lep+jets sample

Cross section using double b-tag

Larger statistics and eff(b-tag) allow first double-b-tag measurements!



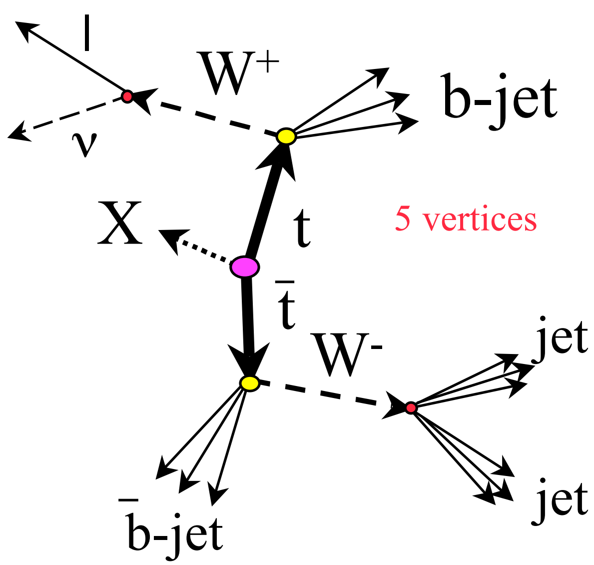


Result combined in SVT cross section

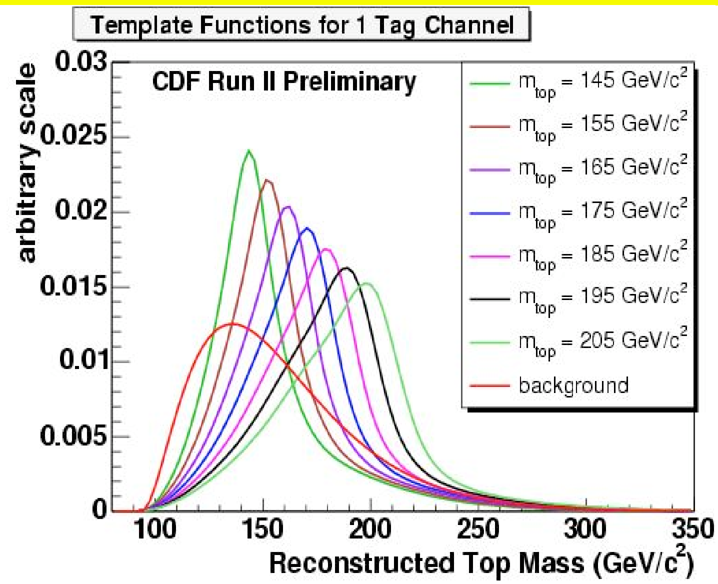
$$\sigma(\mathrm{CDF}) = 5.0^{+2.4\ +1.1}_{-1.9\ -0.8}\ \mathrm{pb}$$

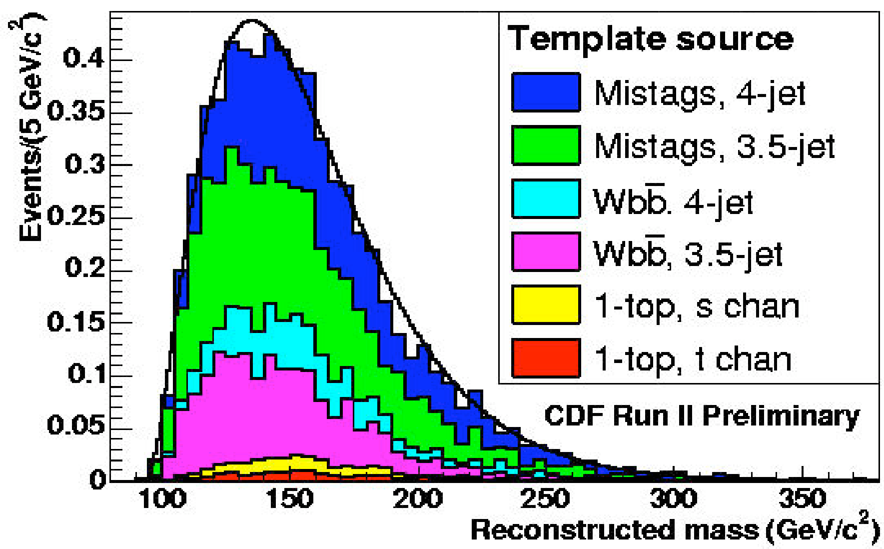
Top Mass - Template Method

Template method: data are compared with signal and background MCs

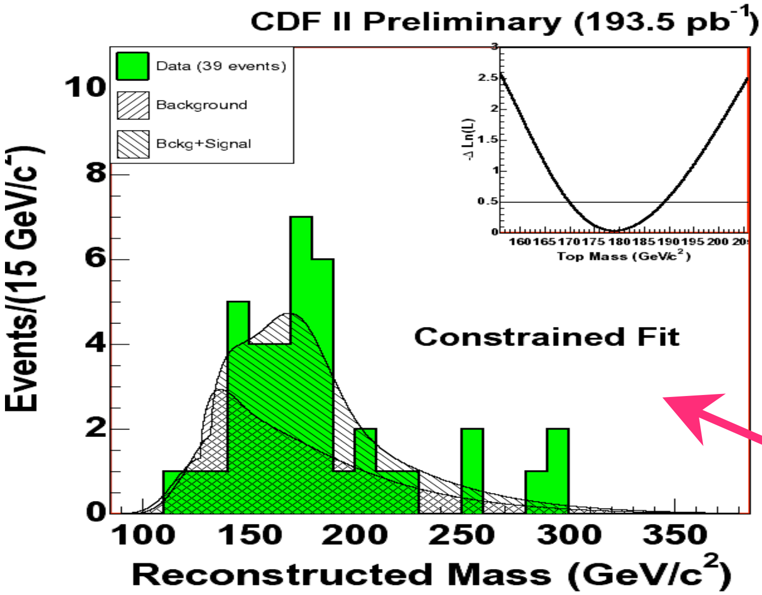


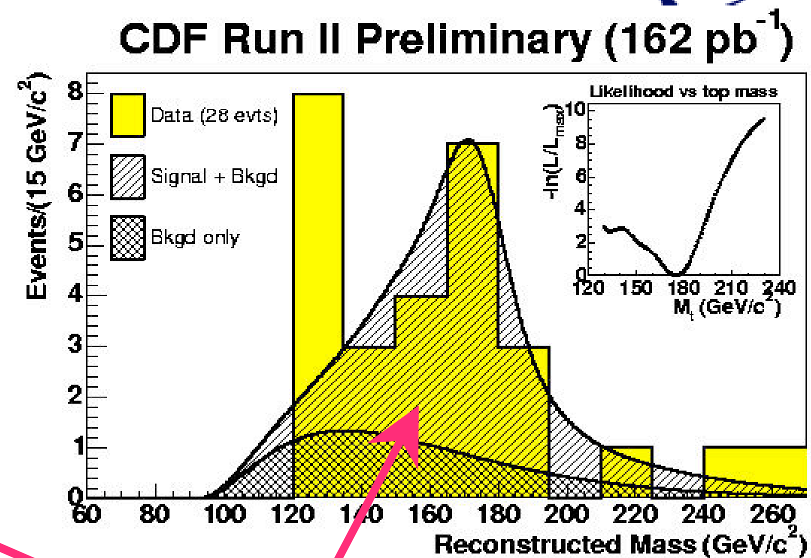
Particles	Unknowns
t's	7
X	2
W's	6
b's	0
q's	0
l	0
ν	3
Total	18

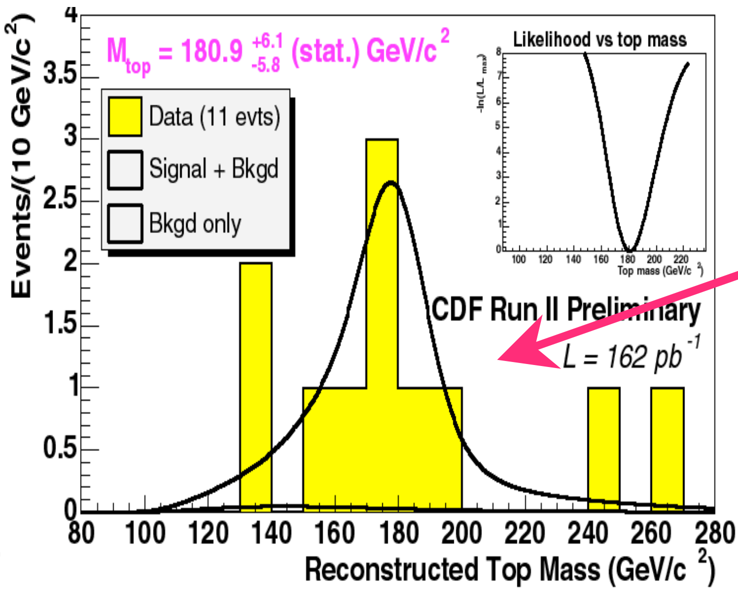




CDF l+jets Template Mass







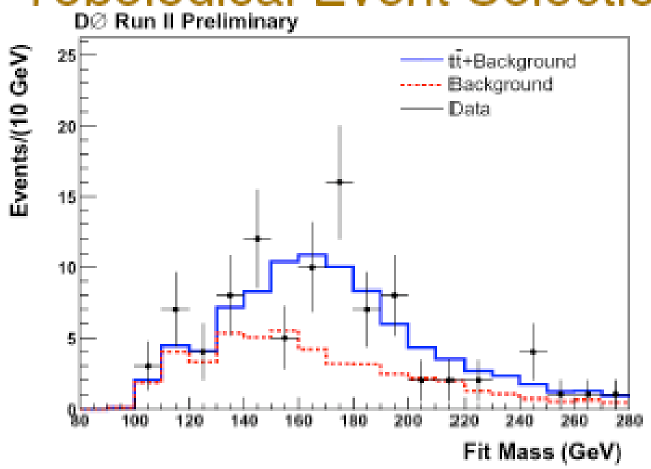
0 tag
1 tag
2 tags
combine!

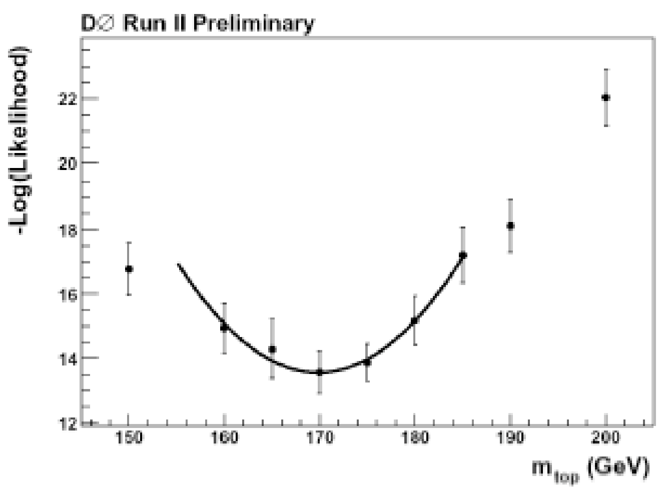
(JES is 85% of syst)

$M_{top} = 177.2^{+4.9}_{-4.7}$ (stat) ± 6.6 (sys) GeV/c^2

D0 l+jets Template Mass

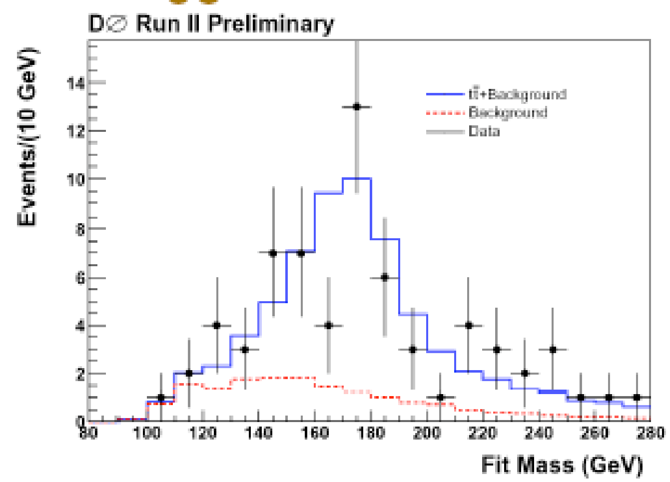
Topological Event Selection

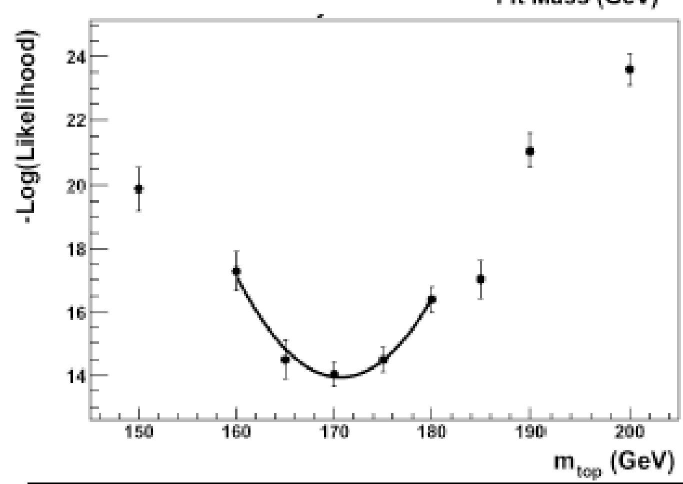




$m_t = 169.9 \pm 5.8\,^{+7.8}_{-7.1}$ GeV/c^2

B-tagged Event Selection





$m_t = 170.6 \pm 4.2 \pm 6.0$ GeV/c^2

D0 l+jets Template Mass

Source	Topological (GeV/c²)	b-tagged (GeV/c²)
Statistical	±5.8	±4.2
Jet Energy Scale	+6.8 −6.5	+4.7 −5.3
Jet Resolution	±0.9	±0.9
Gluon Radiation	±2.6	±2.4
Signal Model	+2.3	+2.3
Background Model	+0.7	±0.8
b-tagging		±0.7
Calibration (fitting bias)	±0.5	±0.5
Trigger	±0.5	±0.5
MC Statistics	±0.5	±0.5
Total Systematic	+7.8 −7.1	±6.0

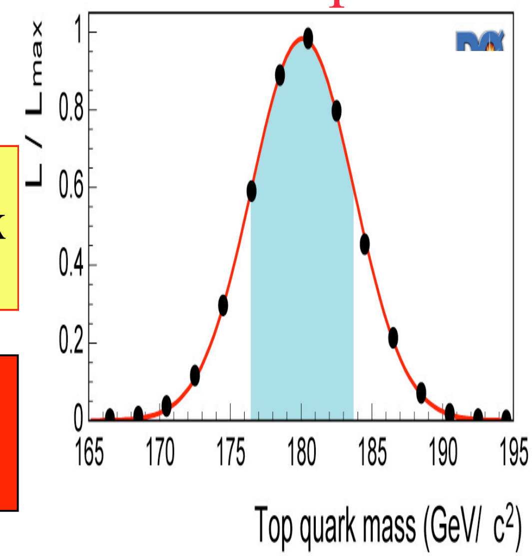
Top Mass: DLM, ME Methods

- Calculate the probability per an event
- Examples: DØ ME, CDF DLM analyses
  - using maximal event information, e.g. takes into account event-by-event resolution effects

Dalitz, R. H. & Goldstein, G. R., Proc. R. Soc. *Lond. A* **445**, 2803 (1999)

K. Kondo, *J.Phys. Soc.* **57**, 4126 (1988) (Dynamical Likelihood Method)

Example



Probability density per event

$$L^i(M_{top}) = \sum_{I_t}\sum_{I_s}\int \frac{2\pi^4}{Flux} F(z_a, z_b) f(p_T) |M|^2 \, w(I_t, \mathbf{x} | \mathbf{y}; M_{top}) dx$$

PDFs

LO ttbar matrix element

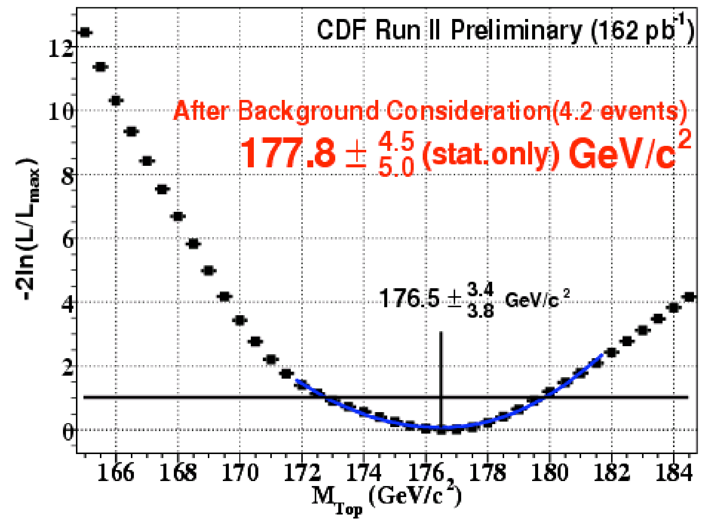
Sum over all possible parton states

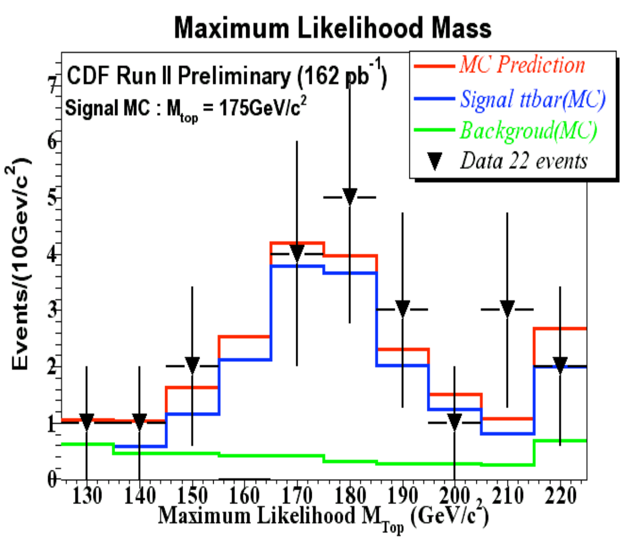
Transfer function: the probability for a measured variable **x** to arise from a parton level variables **y** ***(energy resolution, etc…)***

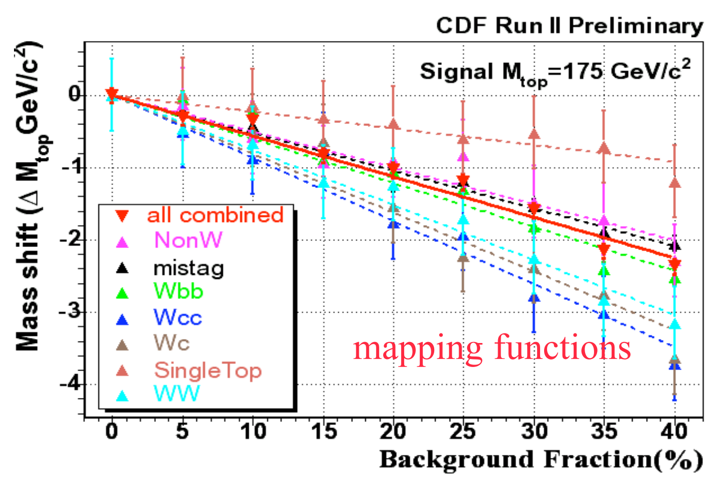
- Sum over all 12 permutations of jets and neutrino solutions
- Background process ME are (or not) explicitly included in the likelihood
- Top mass: maximize $\Pi_i P^i(M_{top})$

lepton+jets (CDF): DLM

- Lepton + jets channel w/ b-tag
- 19% background fraction (mapping function)







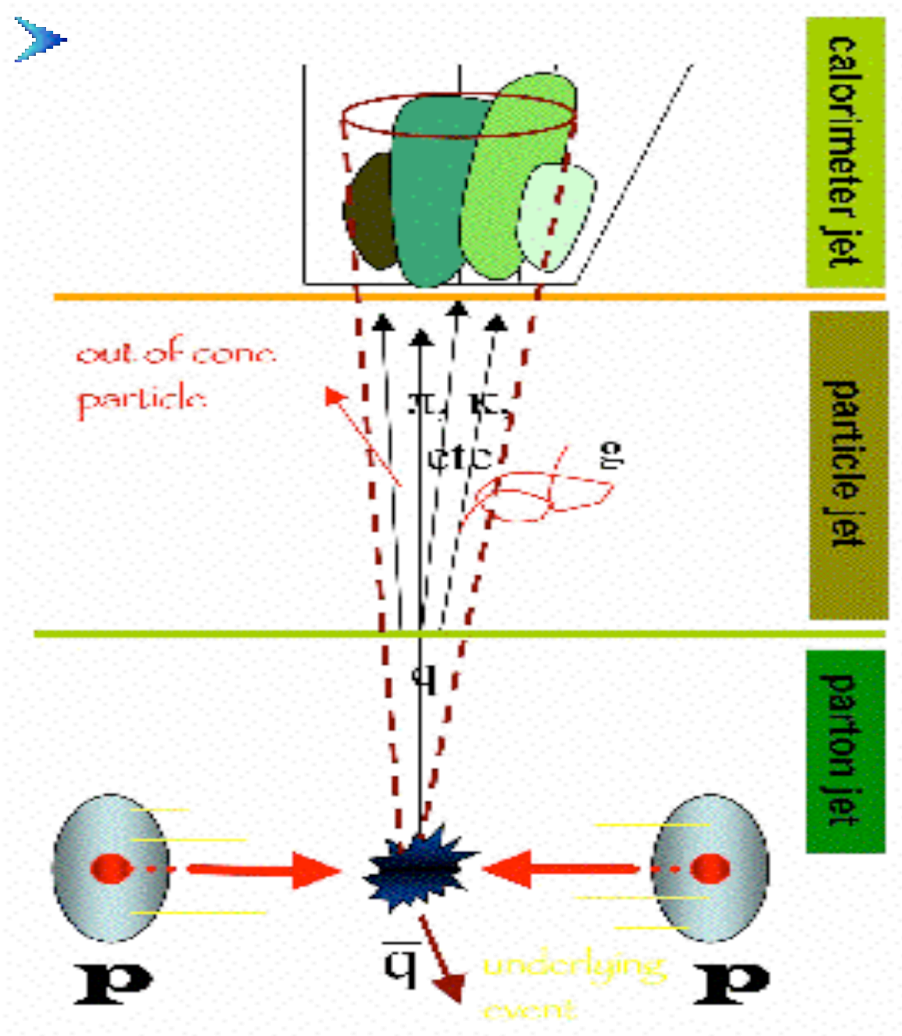
Systematic Uncertainties	ΔM_{top} (GeV/c²)
Jet Energy Scale	5.3
Transfer function	2.0
ISR	0.5
FSR	0.5
PDF	2.0
Generator	0.6
Spin correlation	0.4
NLO effect	0.4
Bkg fraction	0.5
Bkg Modeling	0.5
MC Modeling	0.5
Total	6.2

$m_{top} = 177.8^{+4.5}_{-5.0}$ (stat) ± 6.2 (sys) GeV/c²

Jet Energy Corrections

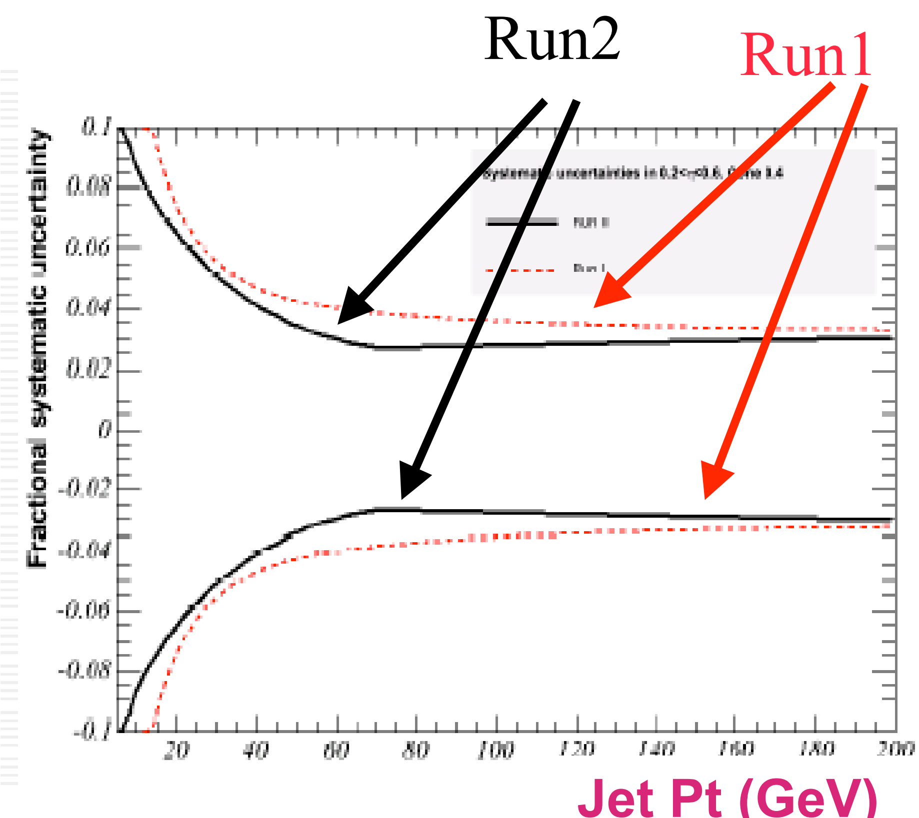
Determine true "particle", "parton" jet E from measured jet E

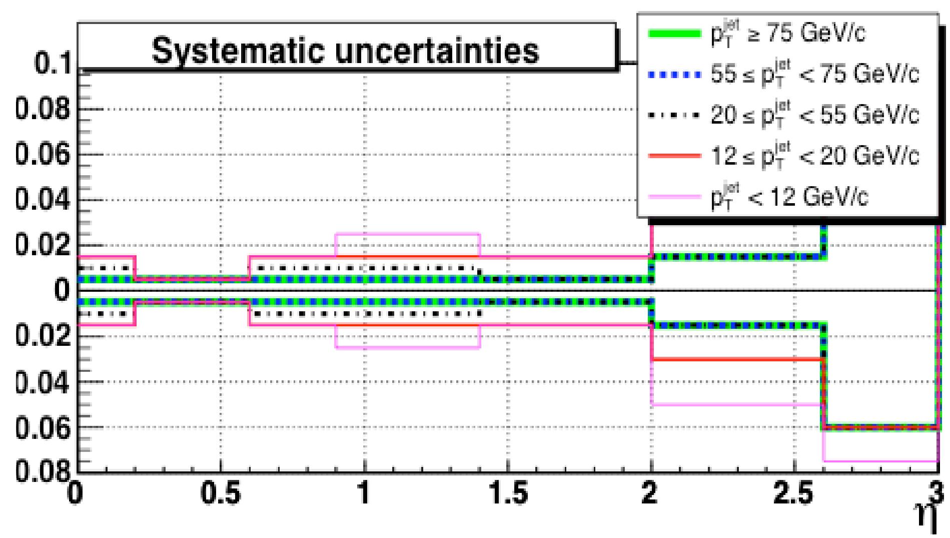
- Non-linear response
- Uninstrumented regions
- Response to different particles
- Out of cone E-loss
- Spectator interactions
- Underlying event



Jet Energy Scale

- Both experiment working toward reducing the systematics from jet energy scale
  - D0 still quoting a 5% for jets with $E_T \geq 30$ GeV (was 2.5% in Run I)
  - New Run2 CDF systematic uncertainties are now same or better than Run1





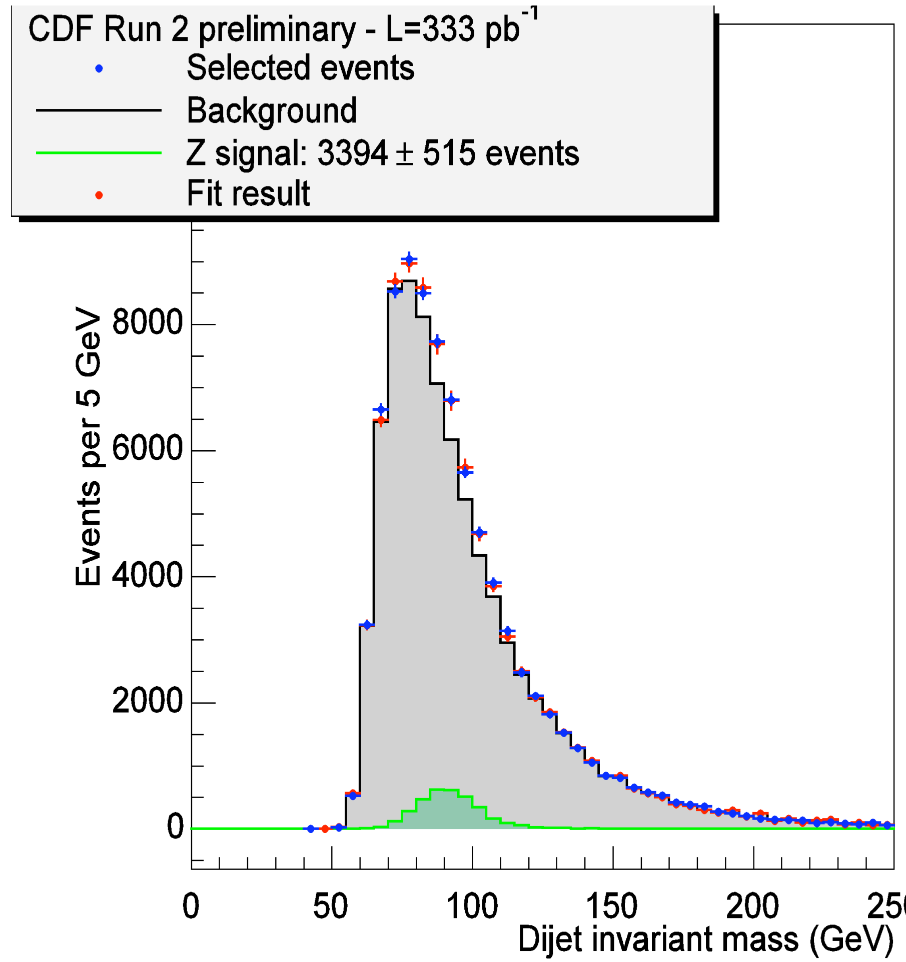
CDF NEW!

Improving the Top Mass Measurement

- Determine the b-quark energy scale from Z->bb
- ...but first we have to see the Z→bb decay in our data.
  - The S/N is not higher than 1/5 at the most in the signal region

Double b-tagged events with no extra jets and a back-to-back topology are the signal-enriched sample: $E_t^3<10$ GeV, $\Delta\Phi_{12}>3$

Among 85,784 selected events CDF finds
3400±500 Z→bb decays
- signal size ok
- resolution as expected
- jet energy scale ok!



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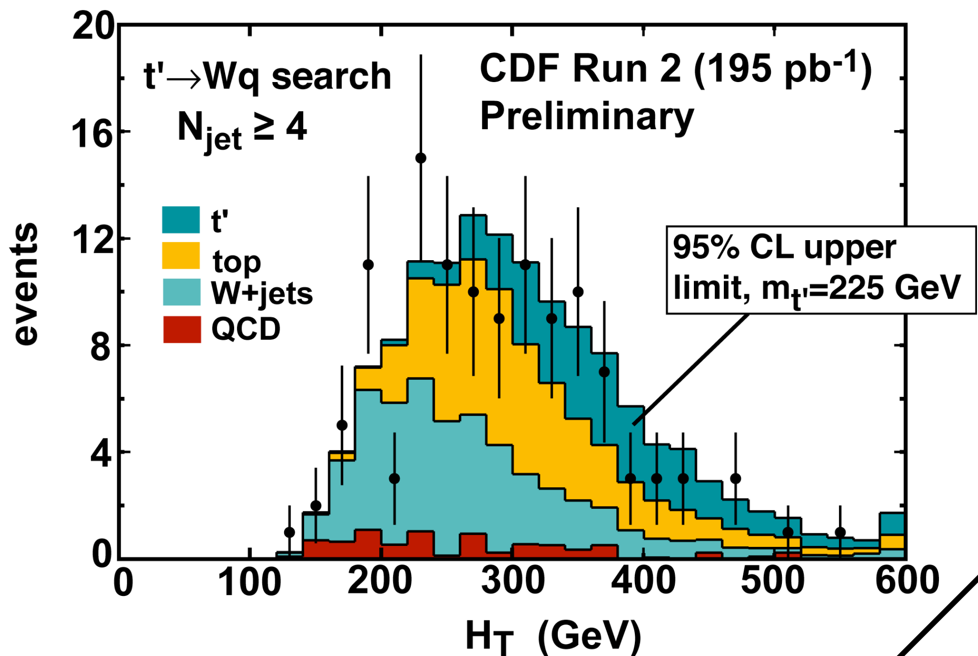
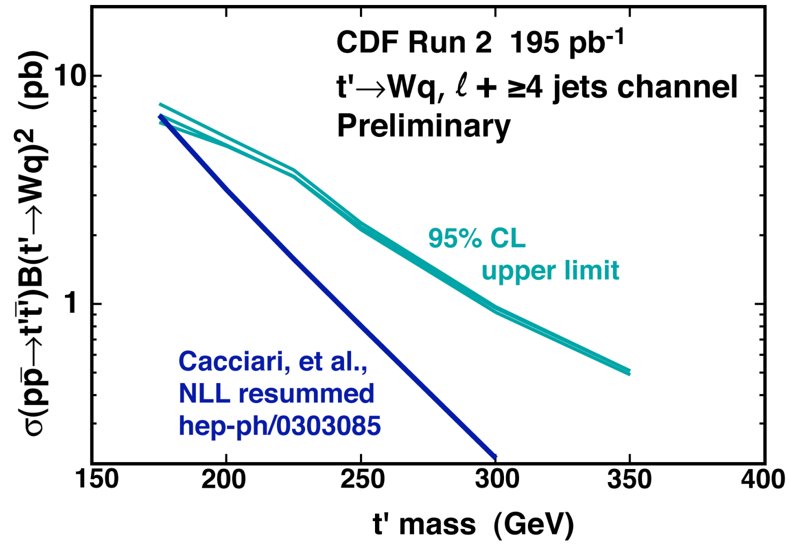
Search for 4th generation t'

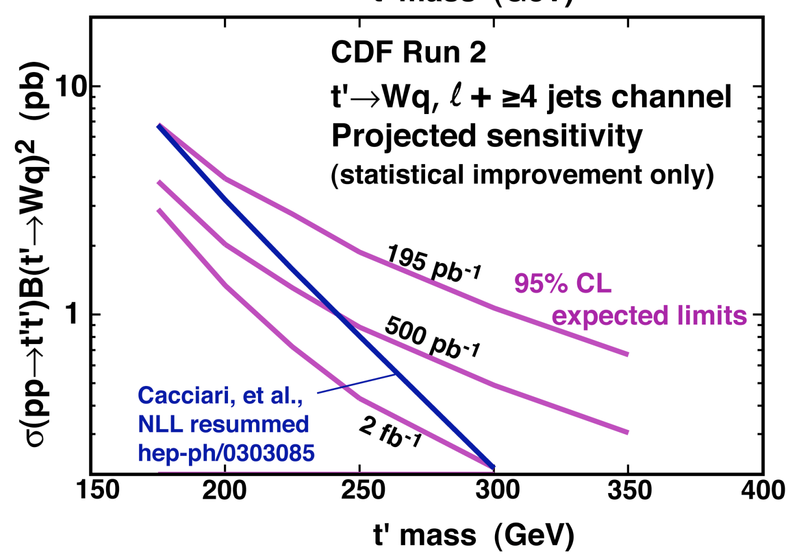
Using l+jets sample for searches beyond SM

- Same selection as kinematic top xs
- Fit Ht to t',t,W+jets and QCD
- Likelihood for different Mt'



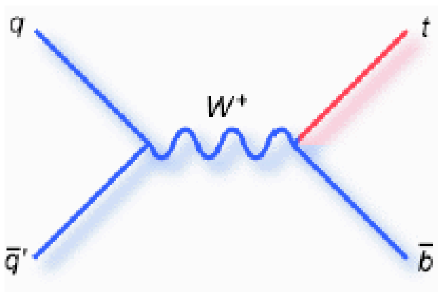
(one such plot for each point)





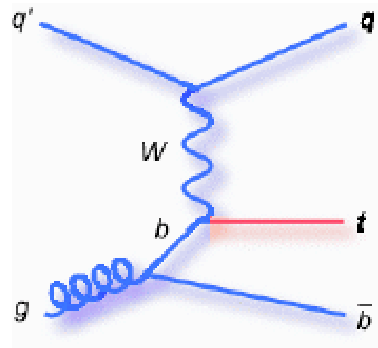
Single Top Search

Use l+jets sample in lower jet multiplicities for SM search



s-channel

$\sigma \sim 0.9$ pb



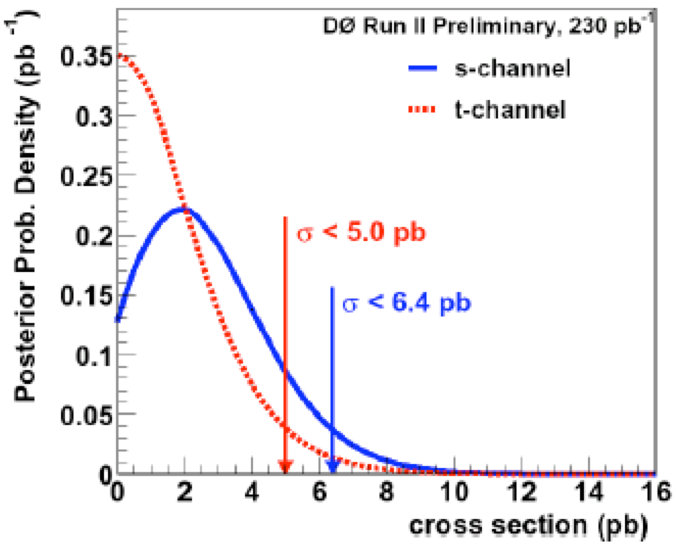
t-channel

$\sigma \sim 2.0$ pb

- Single top quarks produced by weak interaction are a direct probe of top quark weak couplings.
  - Measure $|V_{tb}|$ without assuming three-generation unitarity.
- Cross section is close to top quark pair production cross section (2.9 pb vs. 6.7 pb), but background is much larger because there are fewer jets.

New D0 Limits!

Limit from 2D binned likelihood (NN vs. NN)



s-channel: $\sigma < 6.4$ pb (95% CL)
(expected limit: 4.5 pb)

t-channel: $\sigma < 5.0$ pb (95% CL)
(expected limit: 5.8 pb)

Previous Limits (95% CL)

- s-channel

σ < 17 pb (D0 Run I)
σ < 18 pb (CDF Run I)
σ < 13.6 pb (CDF Run II)

- t-channel

σ < 22 pb (D0 Run I)
σ < 13 pb (CDF Run I)
σ < 10.1 pb (CDF Run II)

- s+t combined

σ < 14 pb (CDF Run I)
σ < 17.8 pb (CDF Run II)

Di-lepton Datasets

2 lepton + ≥2 jets + missing E_T sample is small but very clean for top signal

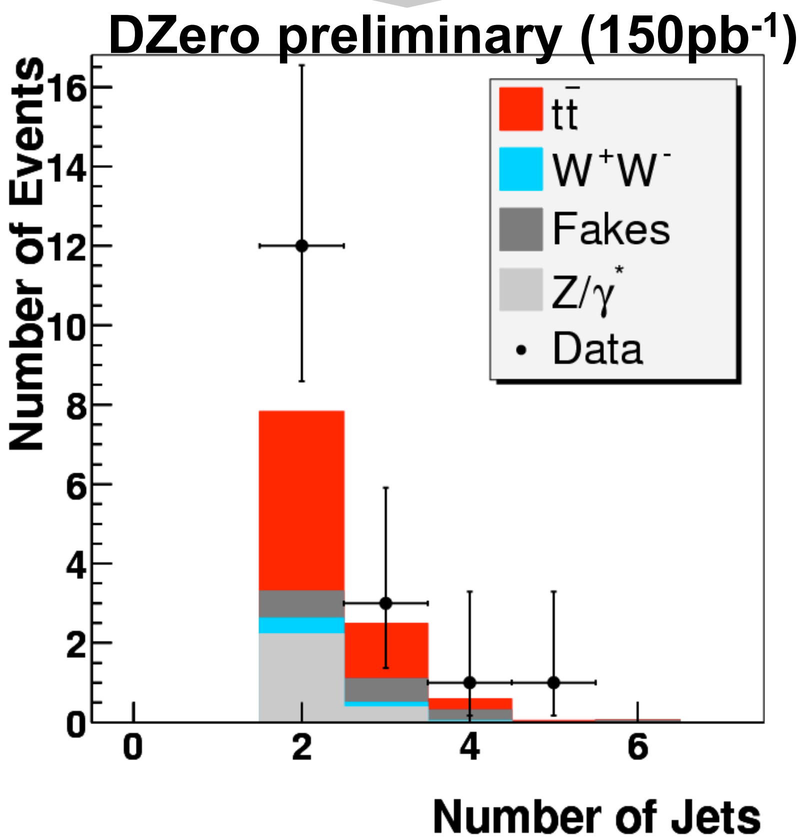
- Event Selection
  - one isolated and well identified lepton (e, μ)
  - second oppositely charged lepton (e, μ): tight or loose identification (isolated track)
  - Significant missing transverse energy from the two ν's
  - N(jets) ≥ 2 to account for the b's
  - Additional topological or kinematic selection

Physics backgrounds:
- Z-->$\tau\tau$, WW

Instrumental backgrounds:
- Fake isolated leptons
- Fake missing E_T

Dilepton cross section (D0)

First without b-tagging .... then require a b-tag



DZero Preliminary (158 pb^{-1})

Expected Sample	$N_{jets}\geq 2$	After tagging
Top	4.58±0.09	2.70±0.09
WW	0.46±0.03	0.008±0.002
Z_ττ	0.6±0.1	0.017±0.007
Z _μμ	0.10±0.04	<0.005
QCD, W+j	0.33±0.04	0.011±0.002
Total	6.1±0.2	2.74±0.09

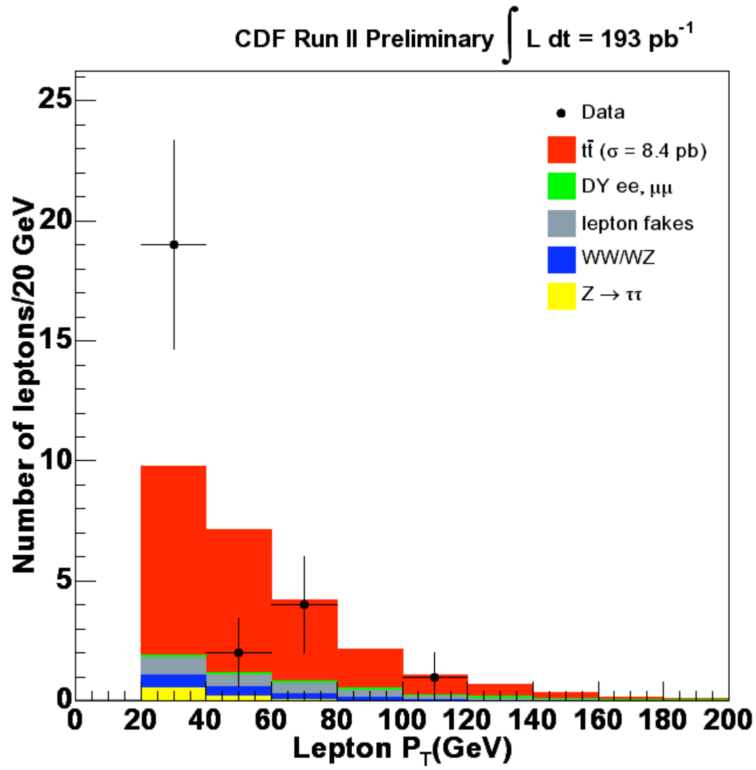
Reduce background in eμ channel with b-tagging!

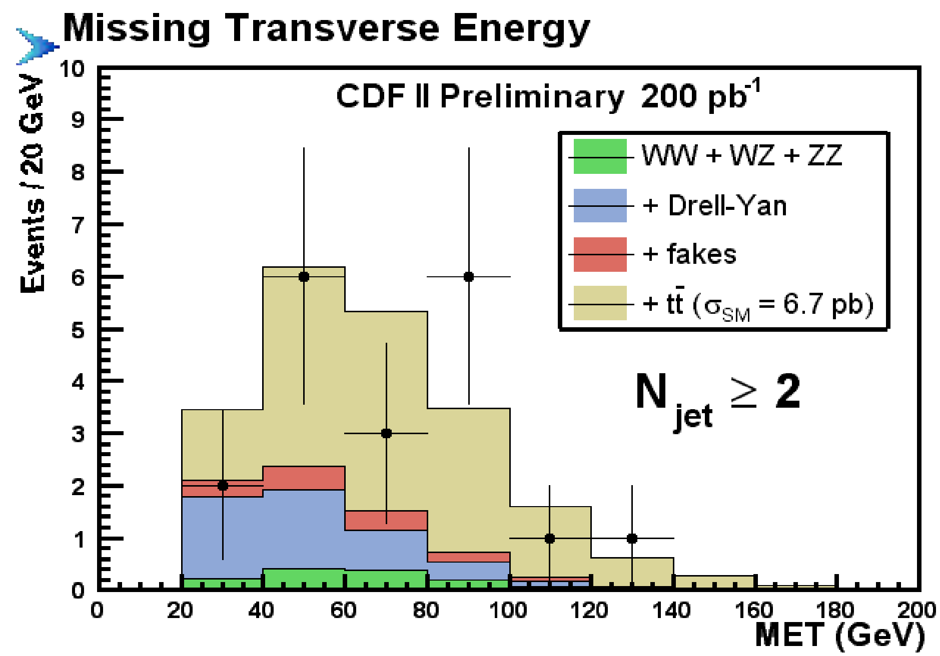
5 observed events with negl bkgd

$$\sigma = 11.1^{+5.8}_{-4.3} \pm 1.4 \pm 1.7(\text{lumi})\,\text{pb}$$

Dilepton Cross section (CDF)

Tight-tight sample ...or... tight-loose sample

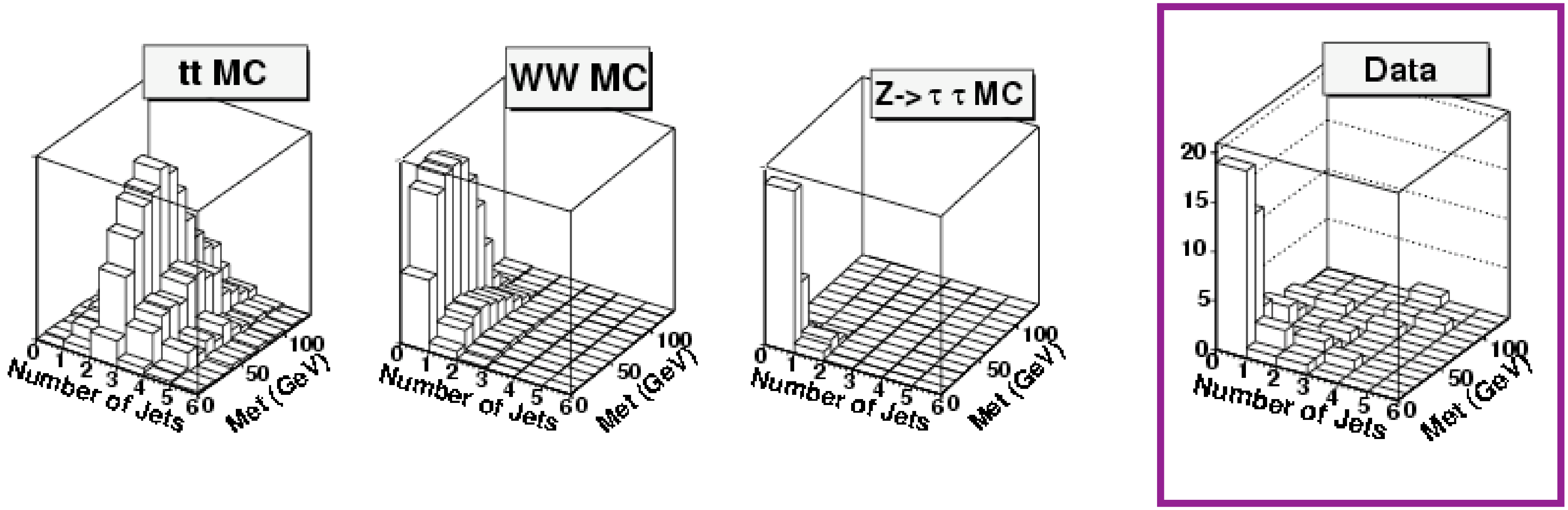




- Cross section requires careful study of background contributions
- Ready for comparison of kinematic distributions in the sample

Inclusive Dilepton Sample (CDF)

…or even looser cuts to increase number of signal events…



Fit distributions for all physics backgrounds and find 10 top dilepton events in ee,eμ,μμ

CDF Preliminary 200 pb^{-1}

$$\sigma = 8.6^{+2.5}_{-2.4} \pm 1.1 \, \text{pb}$$

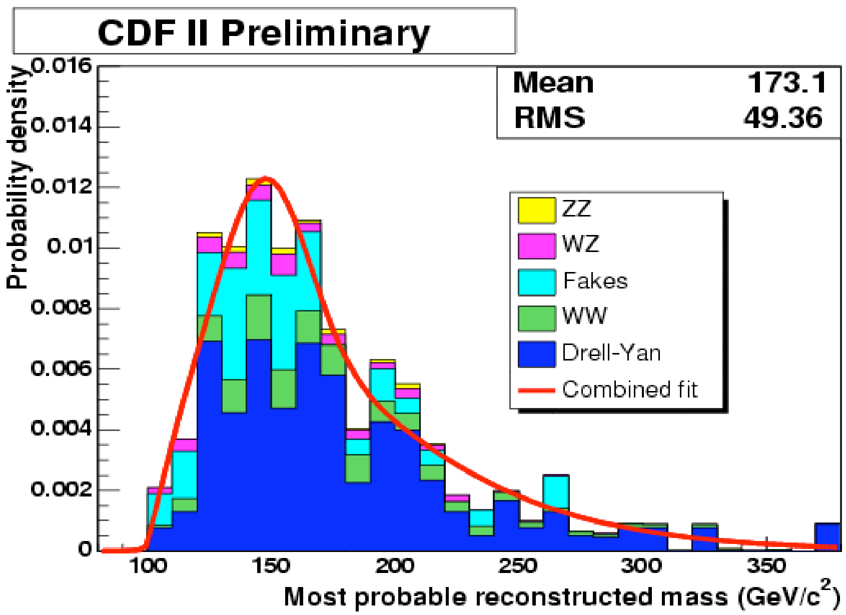
CDF: Dilepton mass analyses

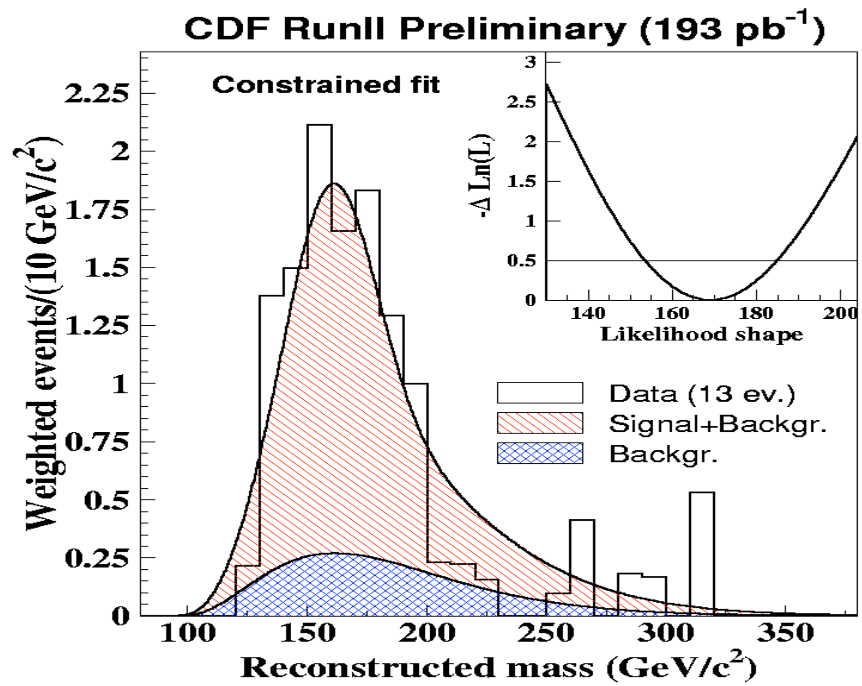
- The final state is under-constrained: how do the analyses solve the problem of under-constrain kinematics?
  - introduces one constraint: $P_z^{tt} = P_z^{t} + P_z^{t} = 0$
  - scan $\eta_{\nu 1}$ and $\eta_{\nu 2}$, assume m_t and M_w, calculate the maximum of the event probability vs m_t (DØ Run1)
  - scan the $\phi_{\nu 1}$ and $\phi_{\nu 2}$

Three independent mass analyses in two experiments with consistent results!

Dilepton mass (CDF)

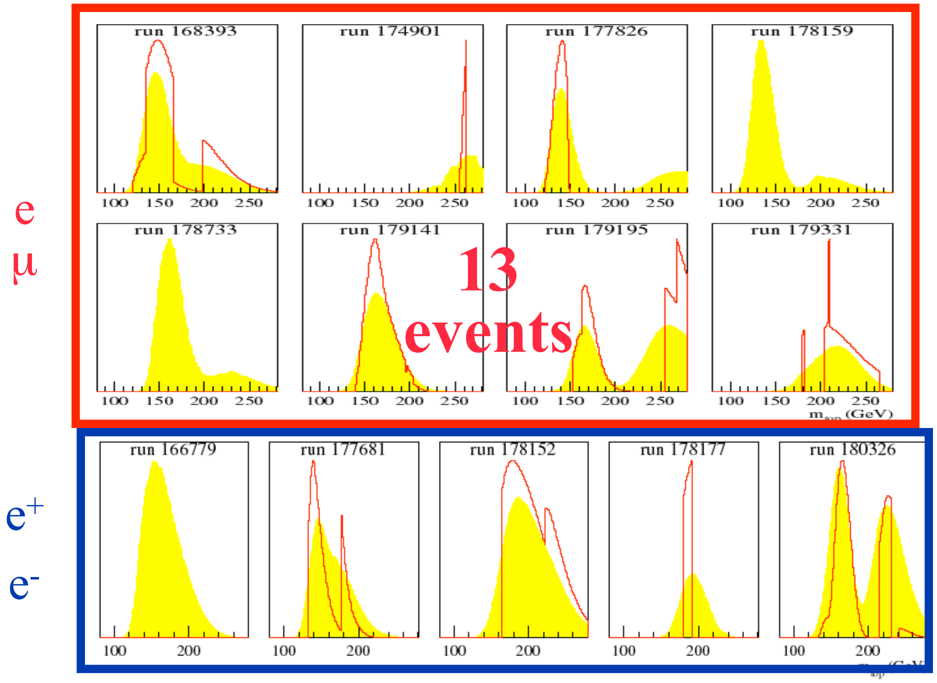
- Dominant Backgrounds
  - Di-boson, W+jets with a jet faking a lepton, Drell-Yan ($Z/\gamma \rightarrow ee, \mu\mu, \tau\tau$)



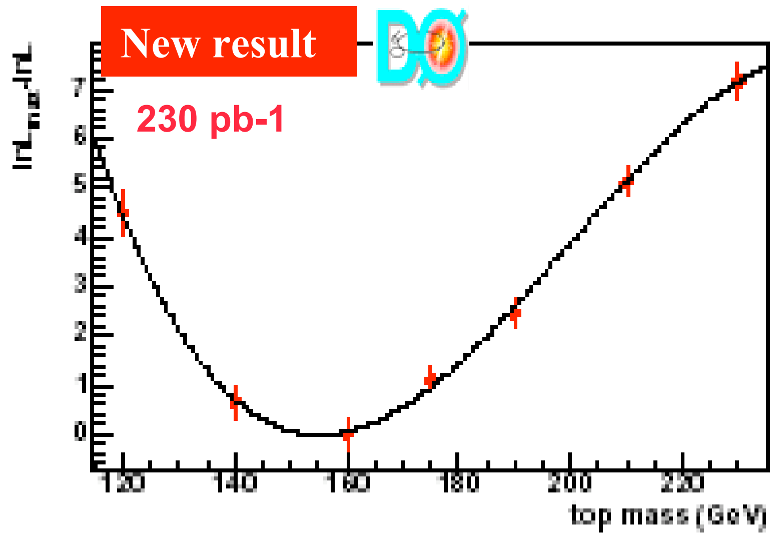


m_{top} = 168.1 ± 10. (stat) ± 8.6 (sys) GeV/c^2

Dilepton mass (D0)



- A weight for every event is calculated and sampled over the detector resolution



$$W = \sum_{solutions} \sum_{jets} f(x) f(\bar{x}) p(E_l^* \mid m_t) p(E_{\Gamma}^* \mid m_t)$$

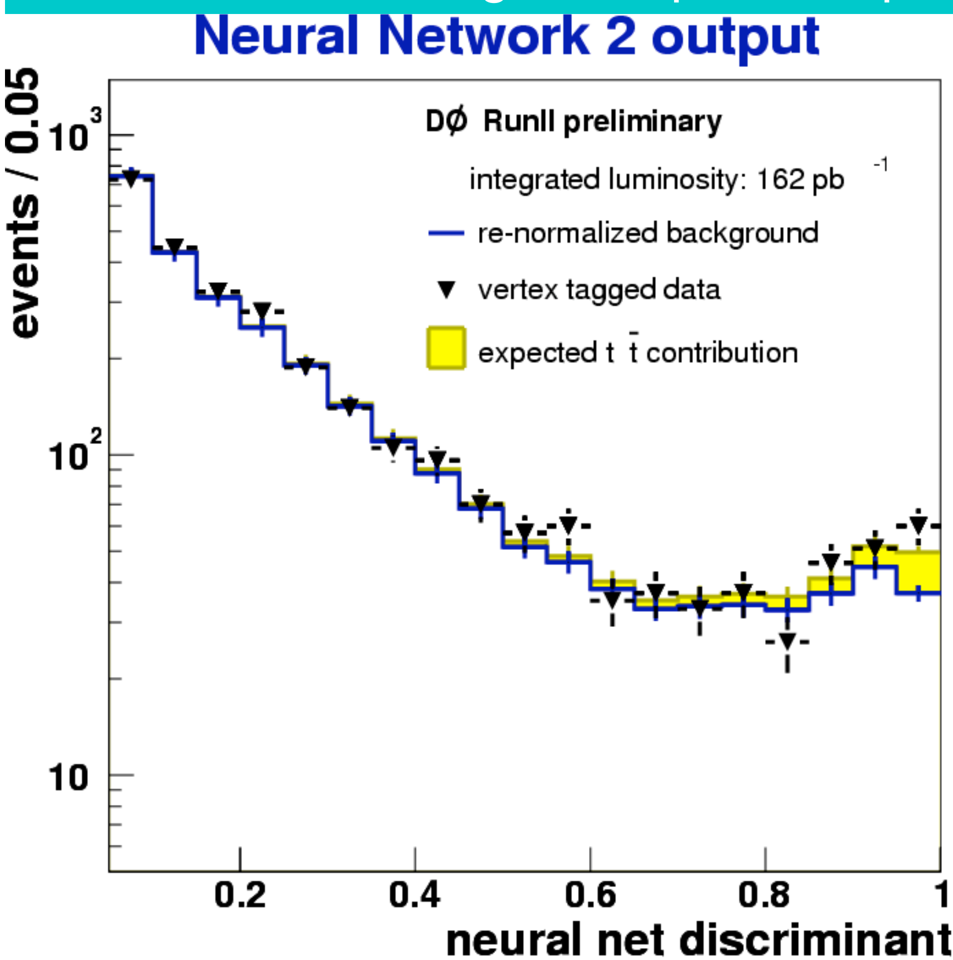
Parton distribution functions

Probability that the observed energy of lepton ℓ is coming from top quark with mass m_t

$m_{top} = 155\ ^{+14.0}_{-13.0}$ (stat) ± 7.0 (sys) GeV/c^2

All-Jets Channel (D0)

Challenge to separate top from QCD multijet production



Kinematic neural network
- total transverse energy H_T
- aplanarity, sphericity
- rough cut on tagged events

Final Neural Network variables are sensitive to high mass objects:
- output from first neural network
- dijet masses, top pair mass

Fit for 220 evts, estimate 186 are bkgd (large error from jet energy scale)

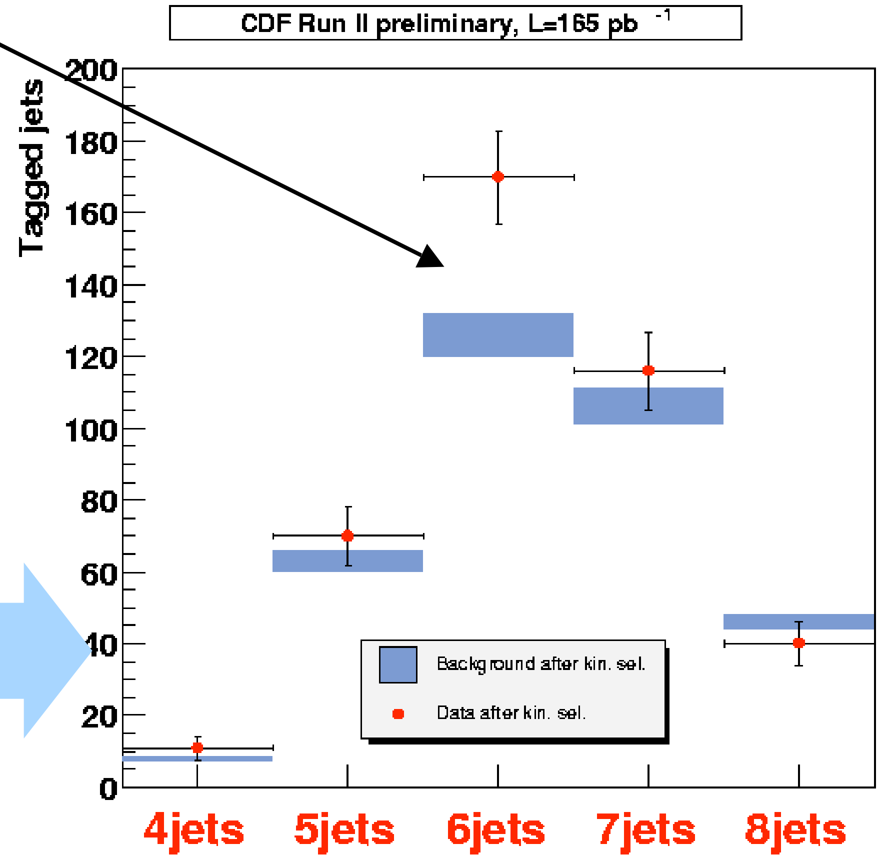
$$\sigma = 7.7^{+3.4}_{-3.3}(\text{stat})^{+4.7}_{-3.8}(\text{syst}) \pm 0.5(\text{lumi})\ \text{pb}$$

All-Hadronic Channel (CDF)

Expect ≥6 jets when W decay hadronically

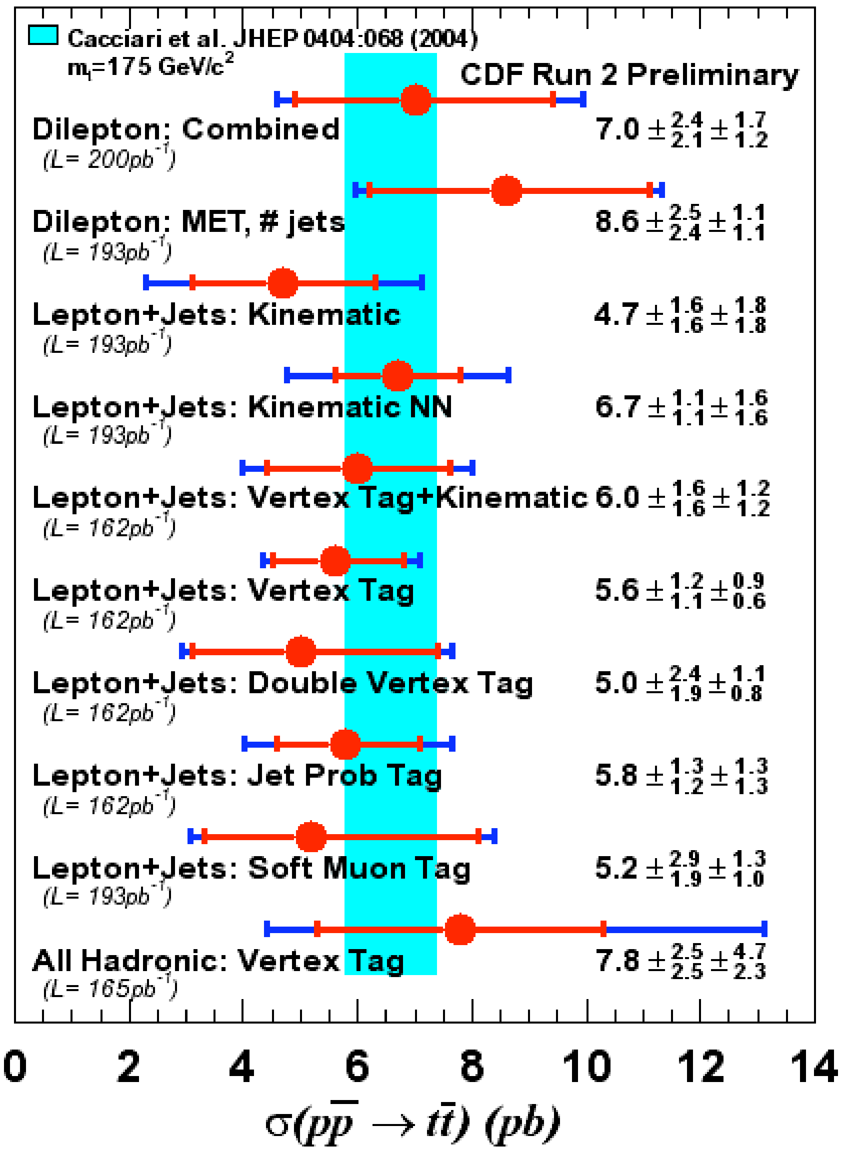
Special multijet trigger:
- 4 high E_T jets (≥15 GeV)
- large missing E_T (>125 GeV)
- optimized for hadronic top events

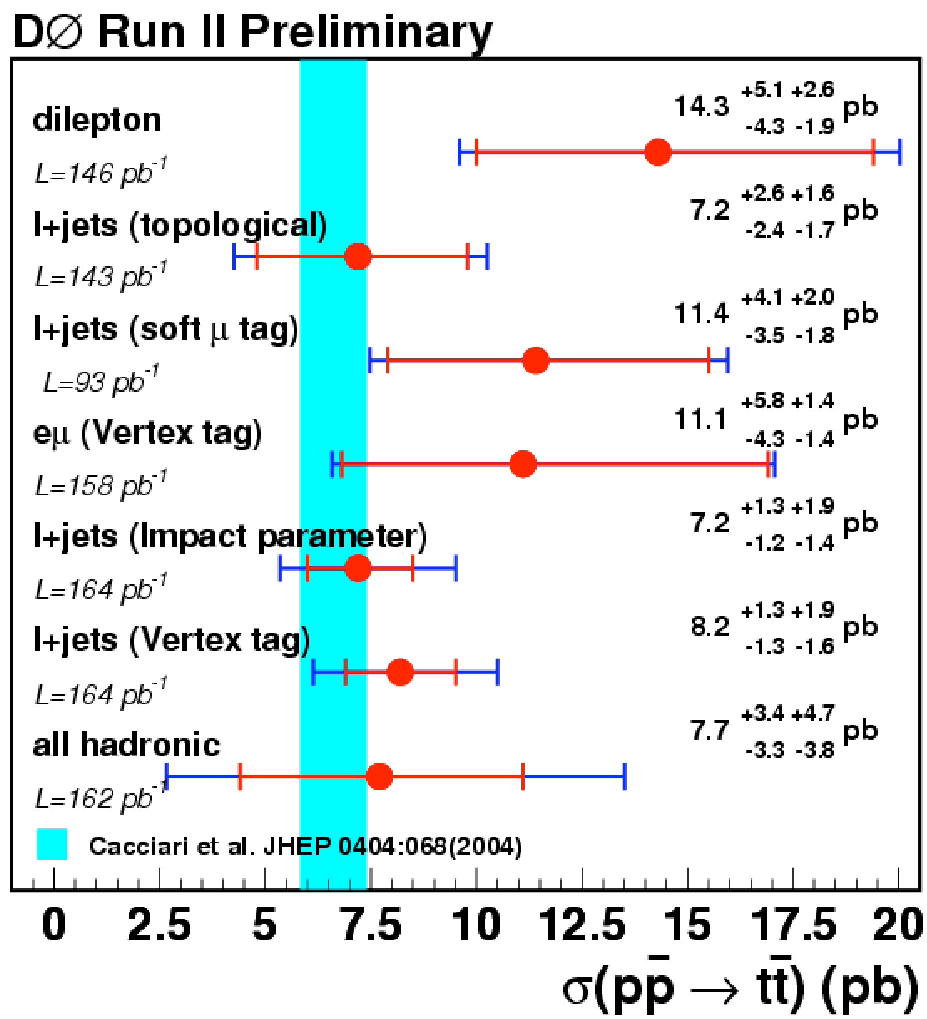
1. Estimate background tags expected from data with little top contribution
2. Require high E_T spherical events: S/B = 0.03 - 0.3
3. Cross section from event counting



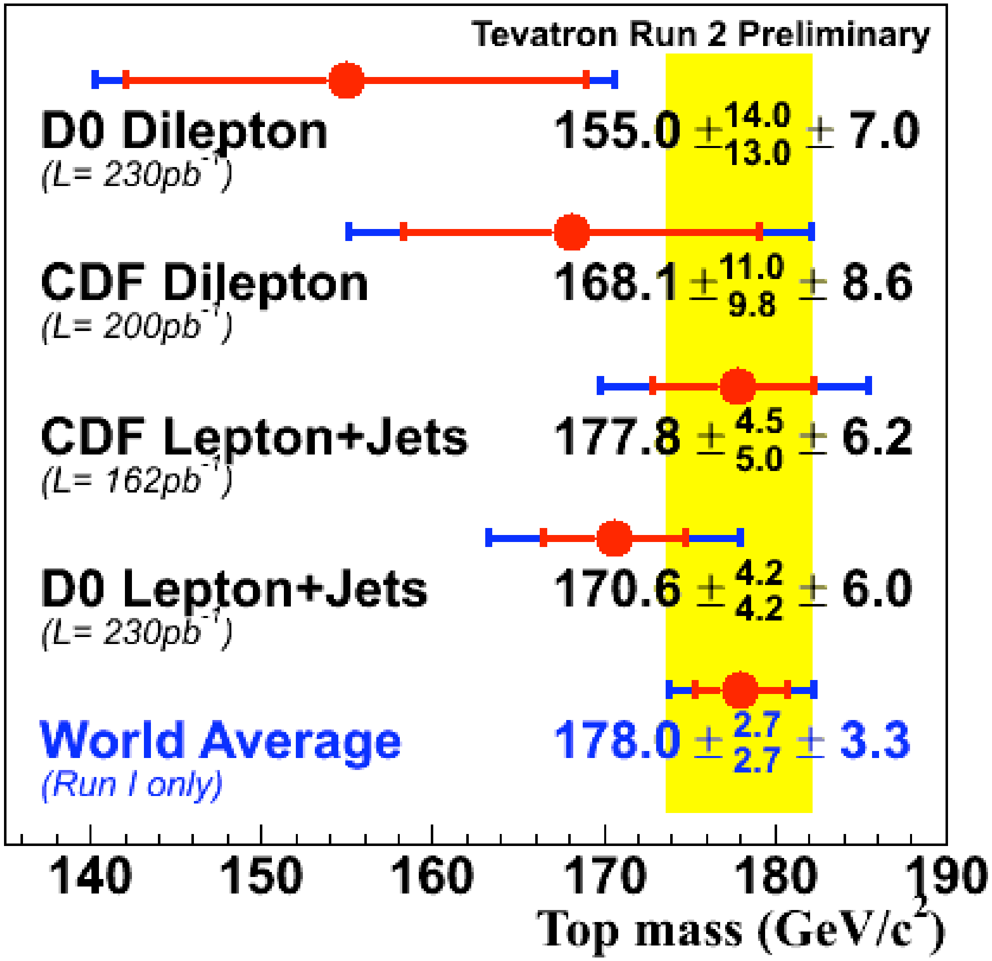
$\sigma = 7.8 \pm 2.5\,(\text{stat.})\,^{+4.7}_{-2.3}\,(\text{syst.})\,\text{pb}$ competitive with neural network

Summary of tt Cross Sections





Summary of Mass measurements



error bars: red=stat, blue=total

- Current results: systematic uncertainty largely dominated by jet energy scale (CDF & D0)
- New corrections and systematics available for CDF
- New mass measurements with Run I-like or better JES uncertainties SOON!

Conclusions

- Measurements status:
  - Cross Section in lepton+jets already systematics limited:
    - Jet Energy Scale
    - B-tagging efficiency
  - Mass measurements also need improved JES

New results with higher statistics and better systematics coming soon!

- New things to expect:
  - Add new channels
  - More significant measurement of the top properties
- Tevatron performing well: experiment very busy in staying after the data and using all of them!
  - Lots of work on triggers at high luminosity
  - D0 will upgrade the vertex detector at the end of the year