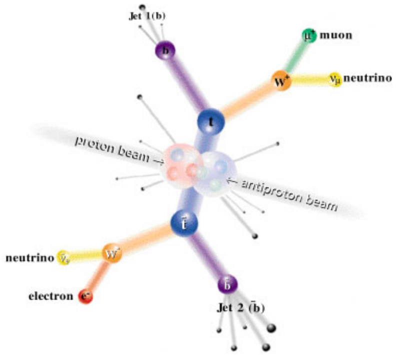
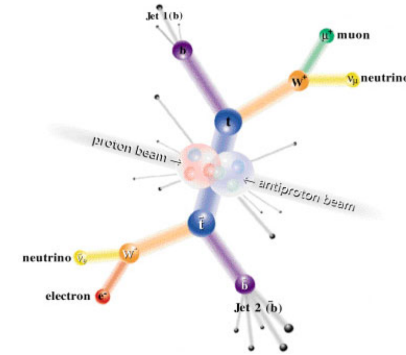
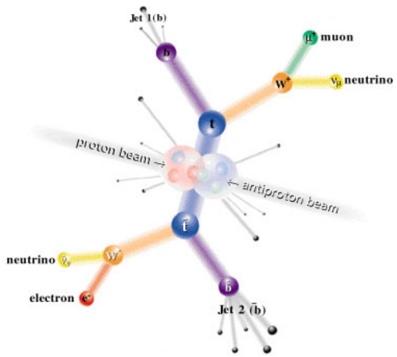
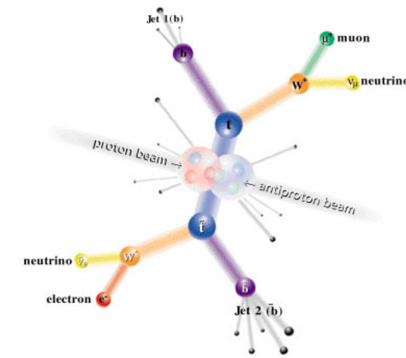




Top Physics at the Tevatron

Recent Results

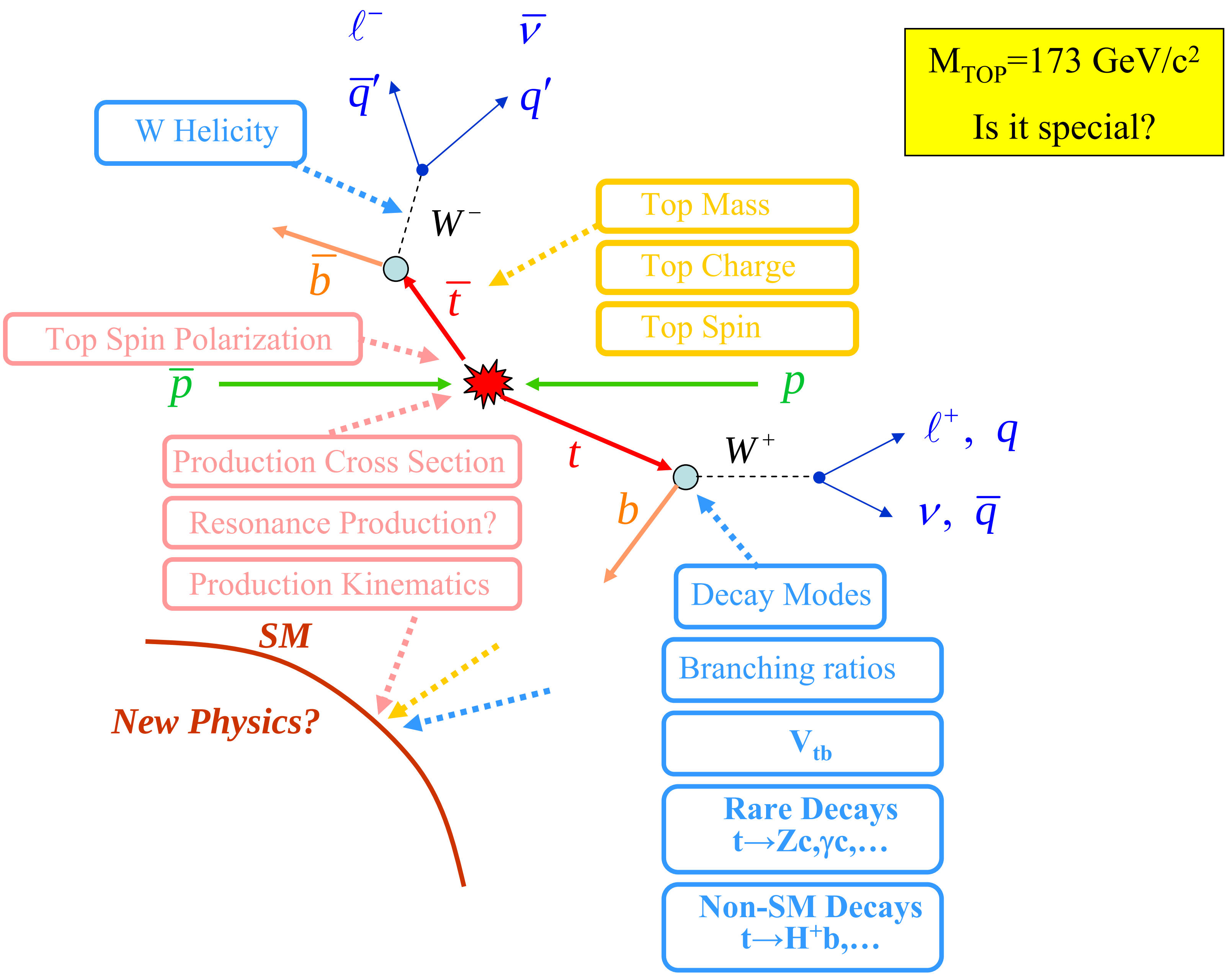




Tony Liss

CERN Top Theory Institute May 22, 2009

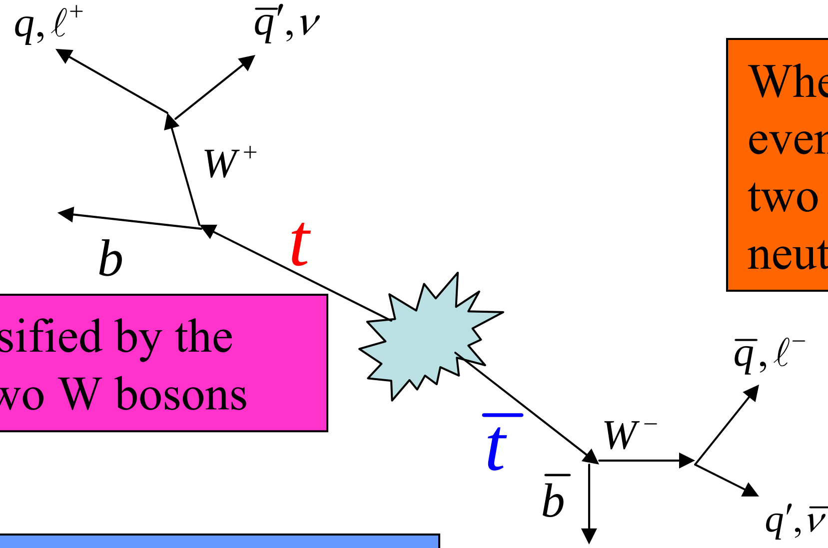
Why Study Top?



Outline

- Top Signature
  - Separating signal from background
- $t\bar{t}$ Production Cross Section
  - Testing QCD, looking for anomalies
- Measuring the top mass
  - EWK radiative corrections, M_W & M_{Higgs}
- $M_{t\bar{t}}$
  - Searches for anomalous production mechanisms
- V_{tb} and Single Top Production
- Tests of Top Quark Decay
  - W Helicity
  - Rare decays
- Forward-Backward Asymmetry
- Conclusions

Identifying Top Events



When both Ws decay to e or μ the event is a "dilepton" event and has two b-jets and missing E_T from the neutrinos.

Events are classified by the decays of the two W bosons

When one W decays to e or μ the event is a "lepton+jets" event and has four jets and missing E_T from the neutrino.

Most analyses use the cleanest channels: Dilepton and Lepton+jets.

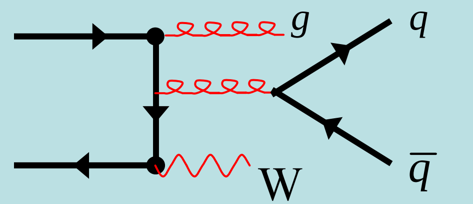
Dilepton → Cleanest, but fewest events (BF=4/81)

Lepton+jets → BF=24/81, **but significant background from W+jet production.**

Lepton+jets Events: Background Suppression

The key to background suppression in lepton+jets events is identifying at least one b-jet (reduces all of W+jets background to just Wbb)

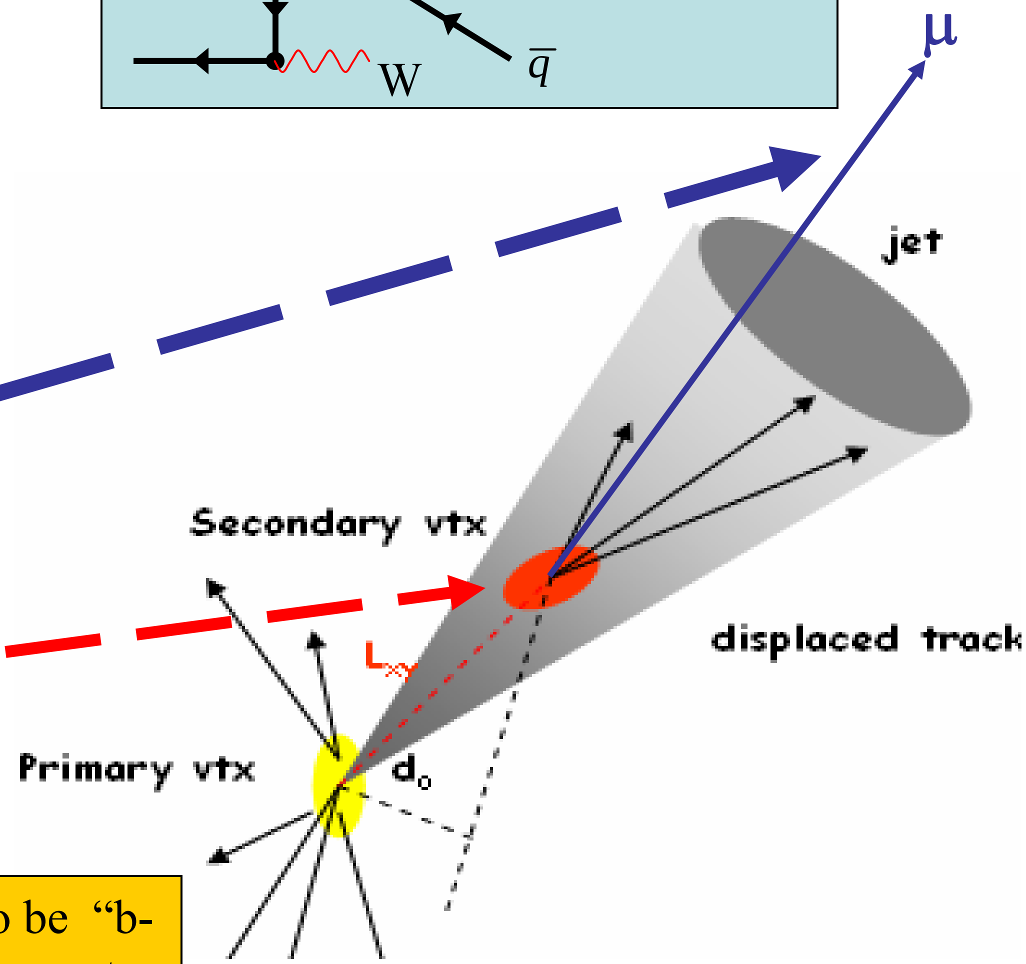
W+multijet background (example):



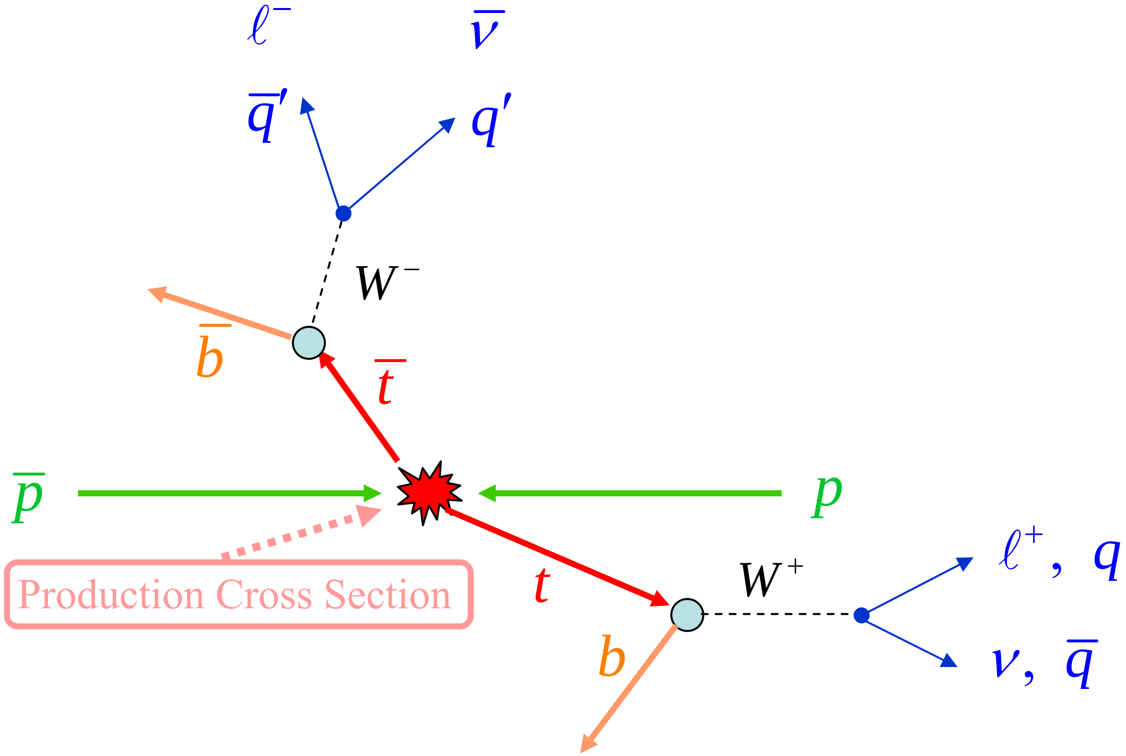
Two techniques:

1) “Soft muon tagging” identifies a muon in the jet from a semileptonic decay of a B hadron

2) “Secondary vertex tagging” finds the decay vertex of the long-lived B hadron in the jet

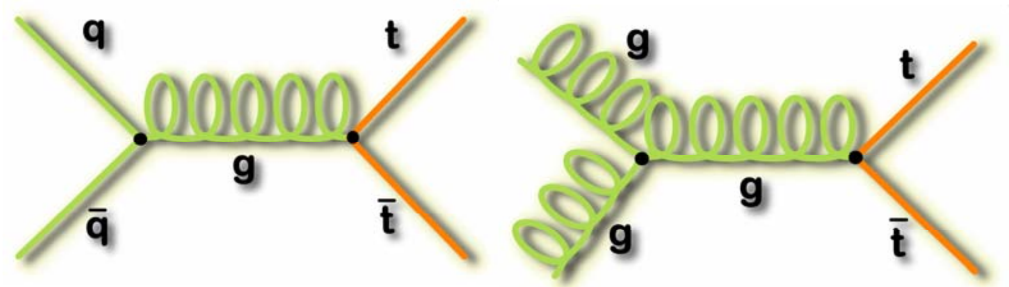


Typically we require at least one jet to be “b-tagged” in a top lepton+jets candidate event



ℓ^-
$\bar{\nu}$
$\bar{q}'$
q'
W^-
$\bar{b}$
$\bar{t}$
$\bar{p}$
p
Production Cross Section
t
W^+
ℓ^+, q
b
ν, $\bar{q}$

$t\bar{t}$ Production Cross Section



85% at the Tevatron

15% at the Tevatron

$$\sigma = \frac{N - B}{A_{geom} \bullet \varepsilon \bullet \int L dt}$$

Candidate events

Backgrounds (from data and Monte Carlo

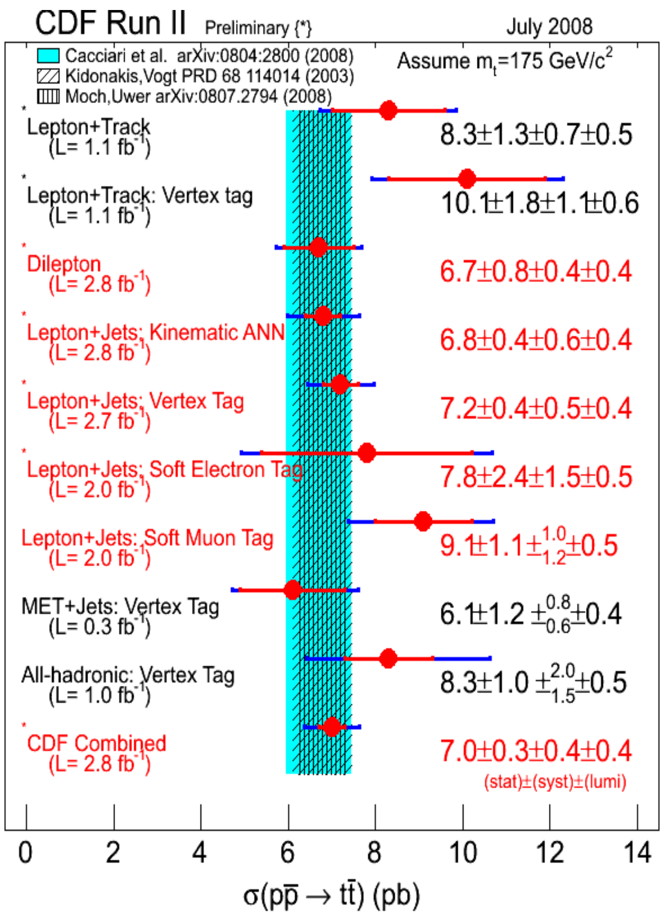
Acceptance and efficiencies from Monte Carlo (mostly)

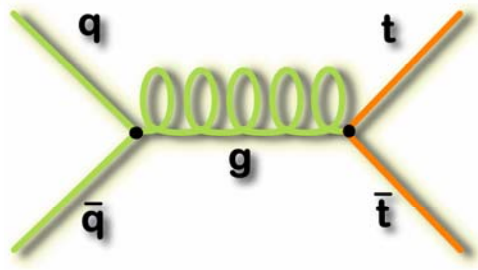
Integrated Luminosity

$t\bar{t}$ Production Cross Section

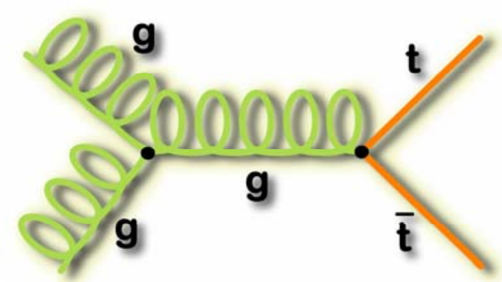
Establishes understanding of signal and background

Provides datasets for other analyses

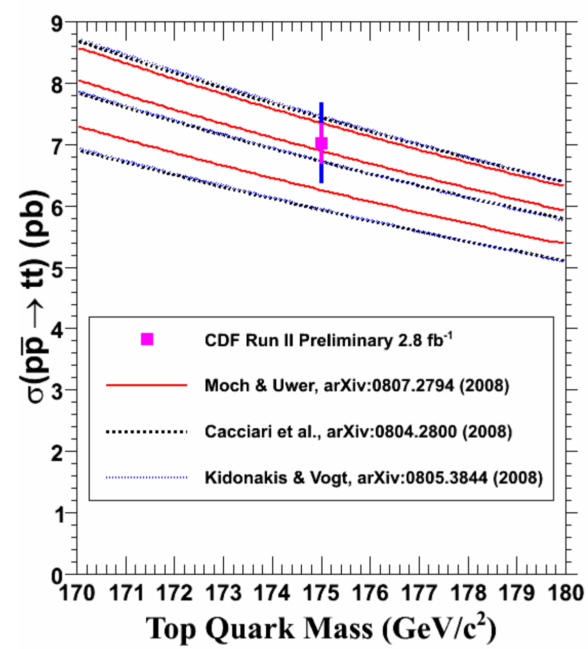




85% at the Tevatron

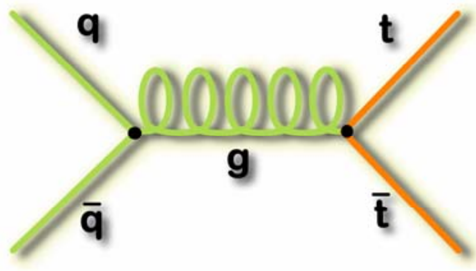


15% at the Tevatron

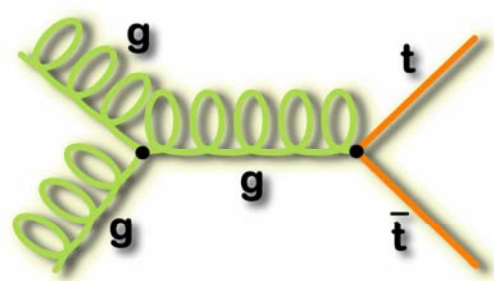


$$\sigma\left(p\bar{p} \to t\bar{t}\right) = 7.0 \pm 0.3 \pm 0.6 \; pb$$

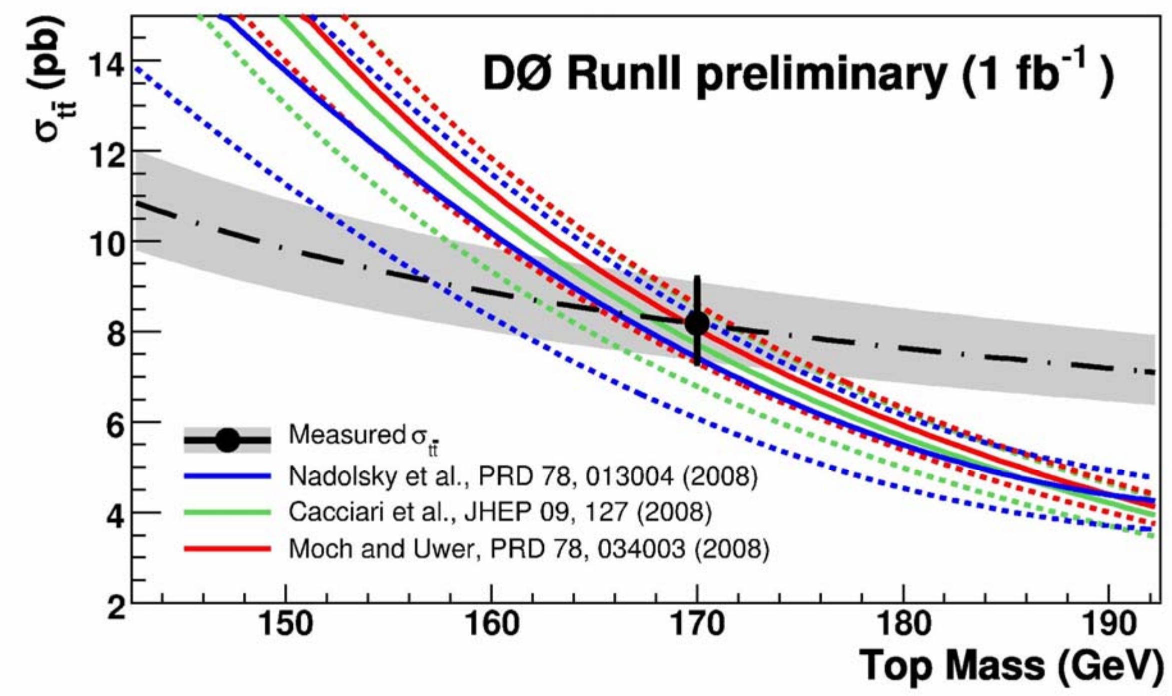
$t\bar{t}$ Production Cross Section



85% at the Tevatron



15% at the Tevatron



$$\sigma\left(p\bar{p} \rightarrow tt\right) = 8.18^{+0.98}_{-0.87} \text{ pb}$$

$t\bar{t}$ Production Cross Section

CDF Run II Preliminary $\mathcal{L} = 2.7\ fb^{-1}$

Process	3jets	4jets	5jets
Pre-tag Data	1988	1030	318
$Wb\bar{b}$	42.5 ± 13.1	16.8 ± 5.8	5.4 ± 2.0
$Wc\bar{c}$	20.7 ± 6.5	9.0 ± 3.1	3.0 ± 1.1
Wc	12.6 ± 4.0	4.1 ± 1.4	1.1 ± 0.4
Mistags	33.5 ± 5.5	10.2 ± 3.2	2.7 ± 1.3
Non-W	20.1 ± 6.8	5.6 ± 4.8	2.0 ± 2.3
Z+jets	4.3 ± 0.5	1.8 ± 0.2	0.6 ± 0.1
WW	5.1 ± 0.6	2.2 ± 0.3	0.8 ± 0.1
WZ	1.5 ± 0.2	0.7 ± 0.1	0.2 ± 0.0
ZZ	0.3 ± 0.0	0.2 ± 0.0	0.1 ± 0.0
Single Top (s-channel)	6.4 ± 0.6	2.1 ± 0.2	0.5 ± 0.1
Single Top (t-channel)	6.1 ± 0.5	2.0 ± 0.2	0.4 ± 0.0
$t\bar{t}$ (7.2pb)	271.5 ± 35.8	337.1 ± 44.3	120.5 ± 15.8
Total Prediction	424.6 ± 44.4	391.8 ± 46.1	137.3 ± 16.5
Observed	418	396	138

Limiting Factors

- The dominant background is $Wb\bar{b}$ and predicting it leads to one of the dominant systematics.

This table is for the CDF lepton+jets with vertex tag measurement in 2.7 pb^{-1}.

SYSTEMATIC	$\Delta\ \sigma$ pb	$\Delta\ \sigma/\sigma$ %
JET ENERGY SCALE	0.16	2.2
BOTTOM TAGGING	0.38	5.2
CHARM TAGGING	0.08	1.1
MIS-TAGS	0.15	2.1
HEAVY FLAVOR CORRECTION	0.23	3.2
LUMINOSITY	0.42	5.8
QCD FRACTION	0.02	0.2
PARTON SHOWER MODELING	0.13	1.8
INITIAL/FINAL STATE RADIATION	0.04	0.6
TRIGGER EFFICIENCY	0.05	0.6
PDF	0.06	1.0
TOTAL	0.67	9.3

CDF Run II Preliminary L=2.7 fb^{-1}

W+Heavy Flavor Backgrounds

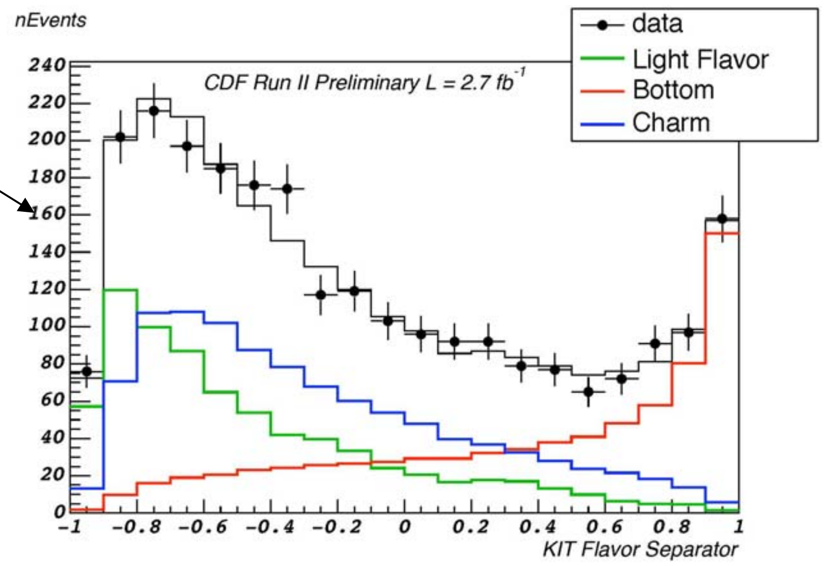
W+HF backgrounds come from ALPGEN(+ Pythia) & data.

- ❖ Normalize ALPGEN W+jets ("pretag") to data
- ❖Measure "K factor" for ALPGEN HF
    - ❖CDF: vs. data in control region of W+1 jet
    - ❖D0 From MCFM-NLO
- ❖ W+HF = Normalized W+jets * ALPGEN fraction * K

$$N^{pretag}_{W+jets} = N^{pretag}\left(1 - F^{pretag}_{QCD}\right) - N^{pretag}_{ewk} - N^{pretag}_{top}$$

$$K_{CDF} = 1.4 \pm 0.4$$

$$K_{D0} = 1.5 \pm 0.45$$

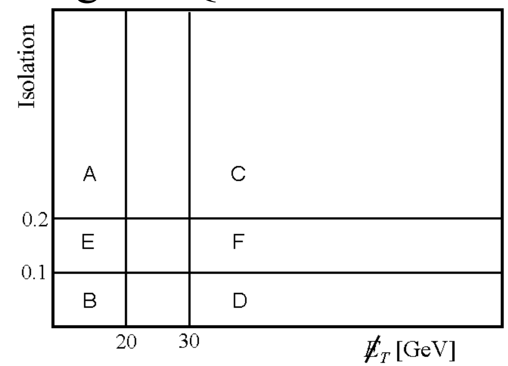


NN finds HF composition of W+1 jet data.

F_{QCD}

CDF & D0 employ 3 techniques for evaluating the QCD fraction.

Legacy technique: MET vs. ISO



$$\frac{N_A^{QCD}}{N_B^{QCD}} = \frac{N_C^{QCD}}{N_D^{QCD}}$$

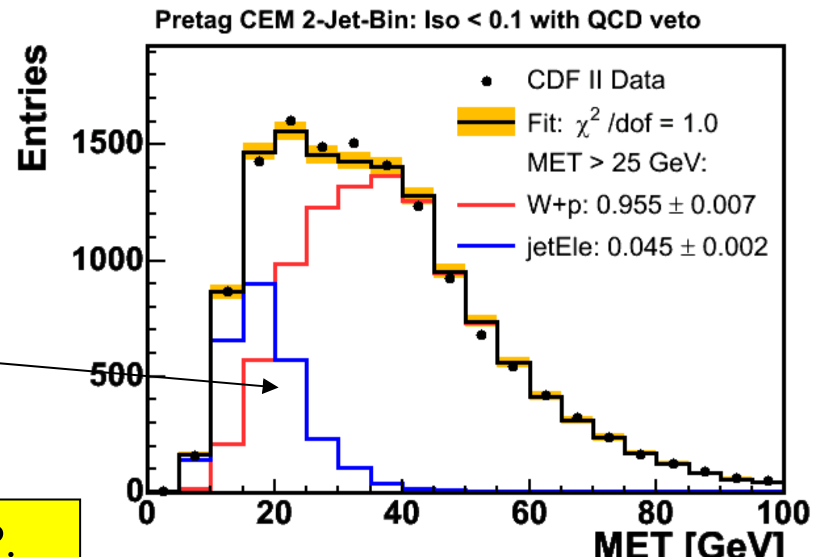
Matrix technique

$$N_{loose} = N_{loose}^{fake-\ell} + N_{loose}^{real-\ell}$$

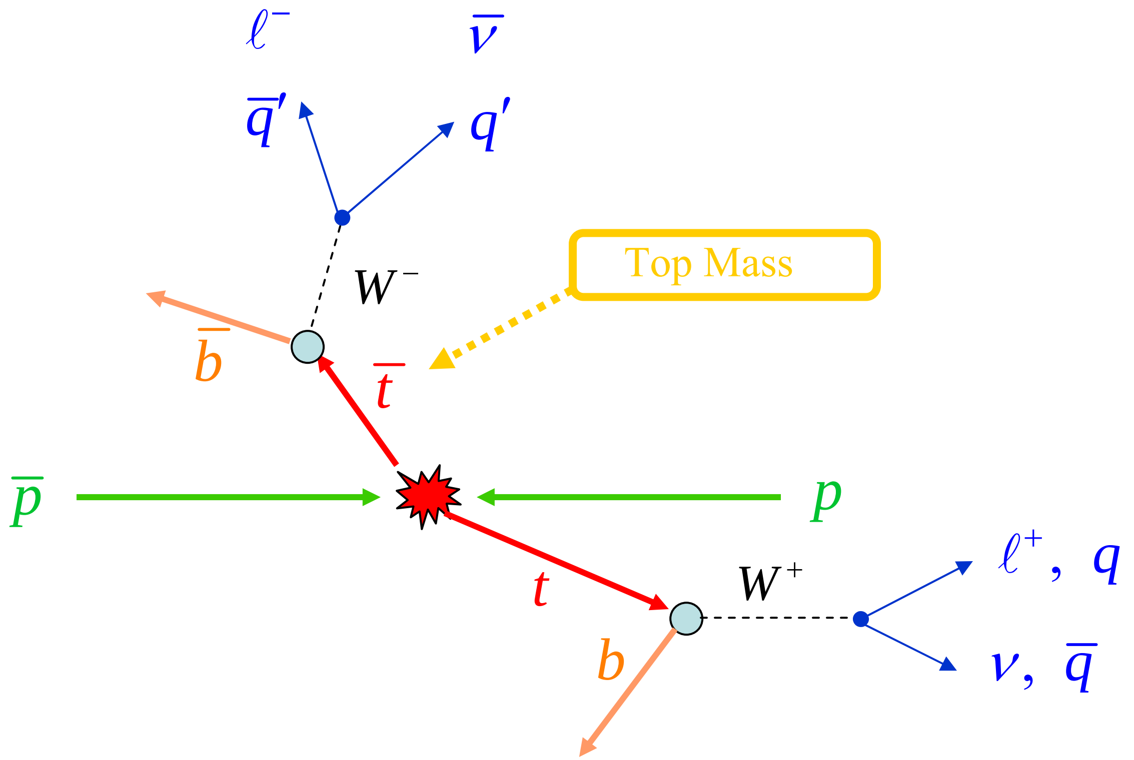
$$N_{tight} = \varepsilon_{fake-\ell} N_{loose}^{fake-\ell} + \varepsilon_{real-\ell} N_{loose}^{real-\ell}$$

Anti-electron/jet-electron technique

Fit missing E_T in data to MC W+jet template + Anti/jet – electron template from data



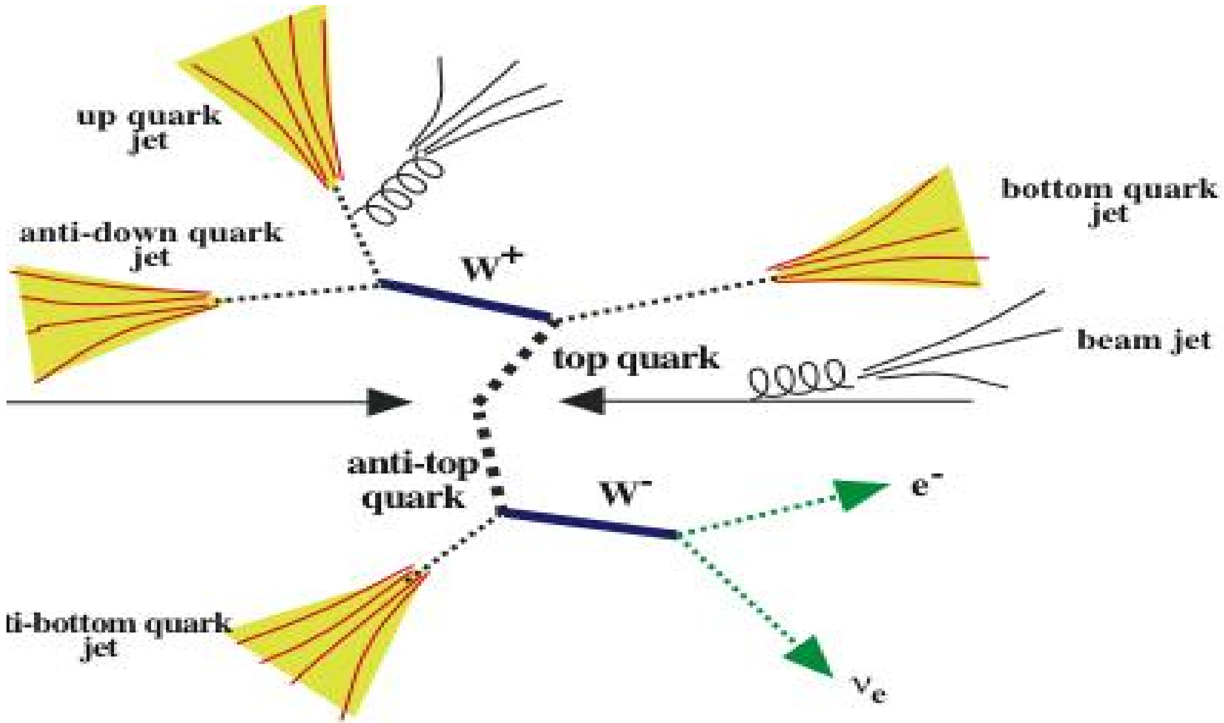
The real key is to reduce QCD background AMAP.



ℓ^-
$\bar{\nu}$
$\bar{q}'$
q'
W^-
Top Mass
$\bar{b}$
$\bar{t}$
$\bar{p}$
p
W^+
ℓ^+, q
t
b
ν, $\bar{q}$

To Measure theTop Mass

$t\bar{t}$ Production and Decay



Challenge is to:

a) Properly associate measured objects to initial state quarks and leptons (including neutrino)

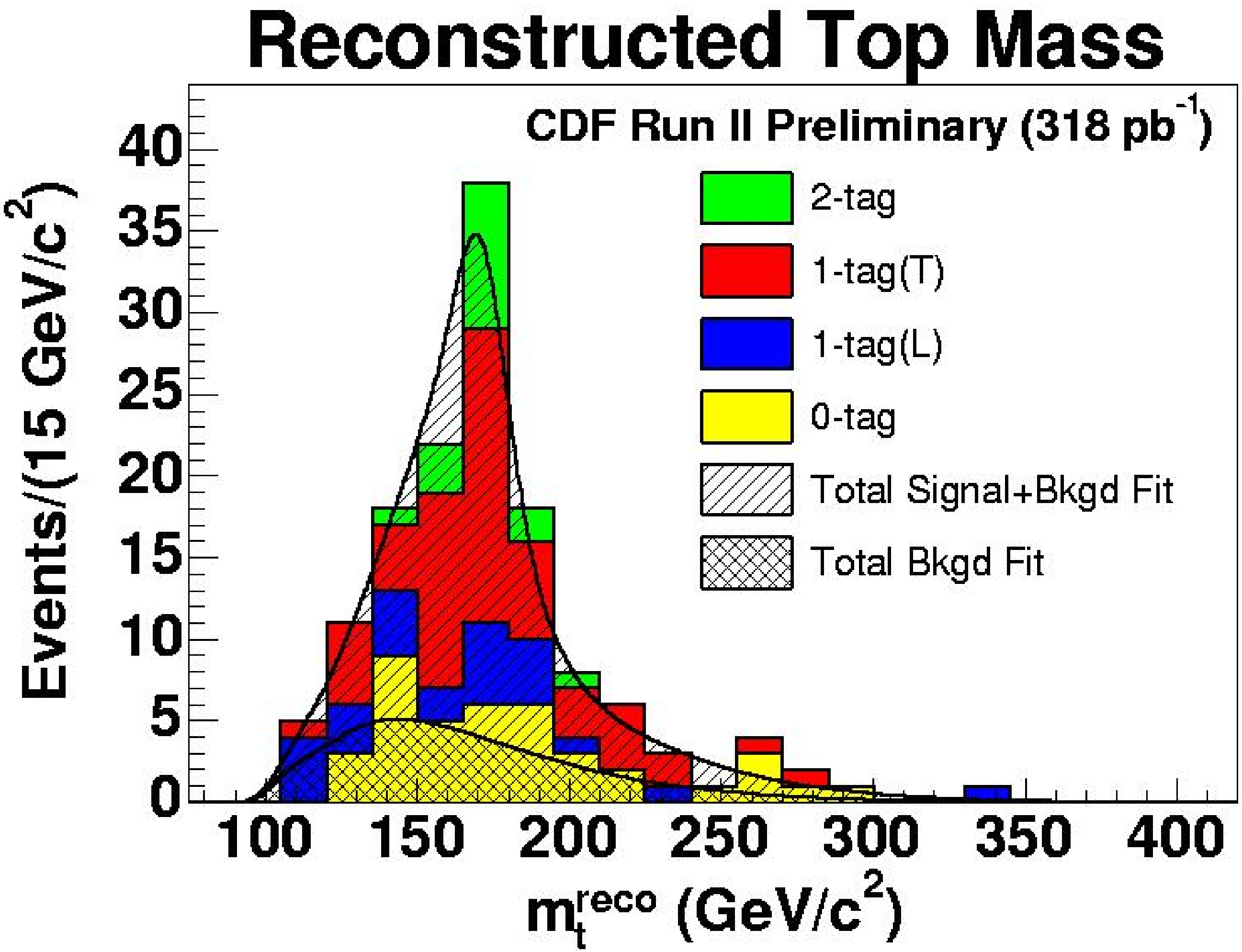
b) Extract best possible four-vector for each (energy resolution)

To Measure the Top Mass

HISTORICALLY....

- Step a): Associate measured with initial-state objects using best match (χ^2) to 3 constraints:
  - $M_{jj}=M_W$
  - $M_{\ell\nu}=M_W$
  - $M_{\ell\nu b}=M_{qqb}$
- Step b): Jet energy corrections according to species
  - E scale for light quark jets tuned to match M_W
  - E scale for b jets adjusted via tuned MC.
- After a) & b) it's just an invariant mass per event.
  - Final mass comes from best fit to MC template vs. M_{top}

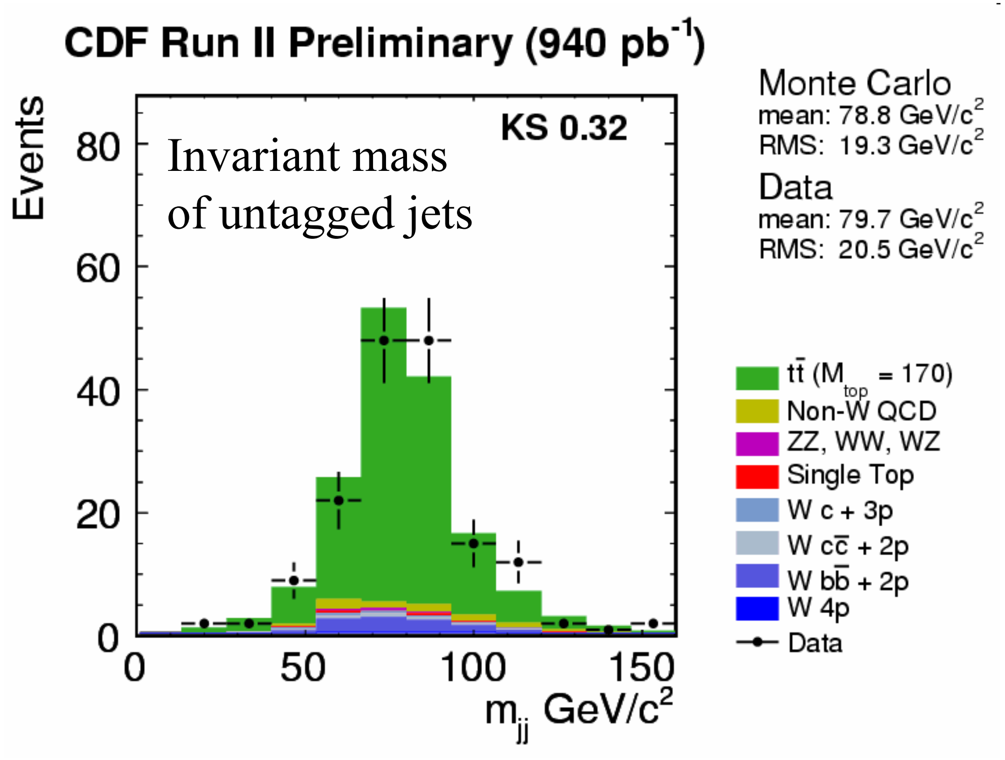
Results



~3-4 yrs ago…

Controlling the JES Uncertainty

The major advance in Run 2 has been constraining the JES uncertainty using the reconstructed hadronic W



Top Mass – The Modern Era

$$L = \frac{1}{N(m_t)} \frac{1}{A(m_t, JES)} \sum_{i=1}^{24} w_i \int \frac{f(z_1) f(z_2)}{FF} TF(\vec{y} \cdot \mathrm{JES} \mid \vec{x}) \left| M_{eff}(m_t, \vec{x}) \right|^2 d\Phi(\vec{x})$$

Normalization

Parton assignments

PDFs

produced→measured transfer function

Matrix element

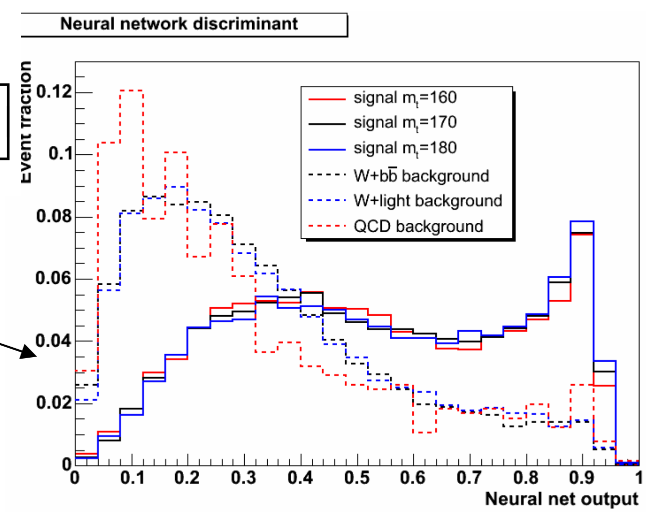
Phase space

$\vec{y}$ are the measured quantities, $\vec{x}$ the parton-level quantities.

Background is handled with a correction:

$$\log L_{sig}(m_t, JES) =$$

$$\sum_{events} \left[\log L_i(m_t, JES) - f_{bg}(q_i) \log L_{avg}(m_t, JES \mid bkg) \right]$$



Top Mass – The Modern Era II

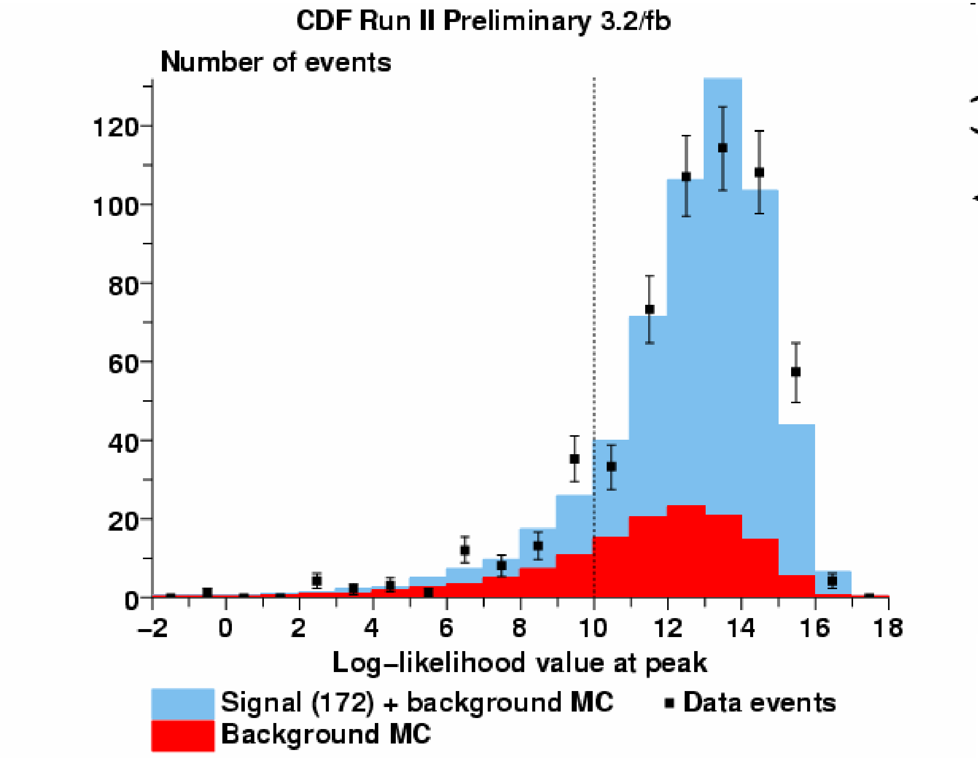
Alternatively, one can include matrix elements for the background

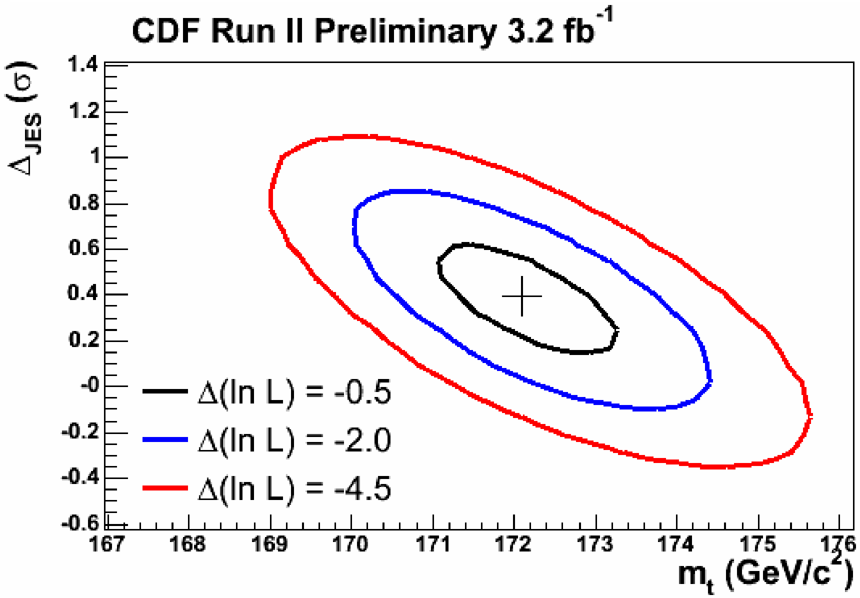
$$P_{evt}\left(y;m_t,JES,f_{top}\right)=f_{top}\bullet P_{sig}\left(y;m_t,JES\right)+\left(1-f_{top}\right)\bullet P_{bkg}\left(y;JES\right)$$

Then a likelihood function is built from P_{evt}:

$$L\left(y_1,\ldots,y_n;m_t,JES,f_{top}\right)=\prod_{i=1}^{n}P_{evt}\left(y_i;m_t,JES,f_{top}\right)$$

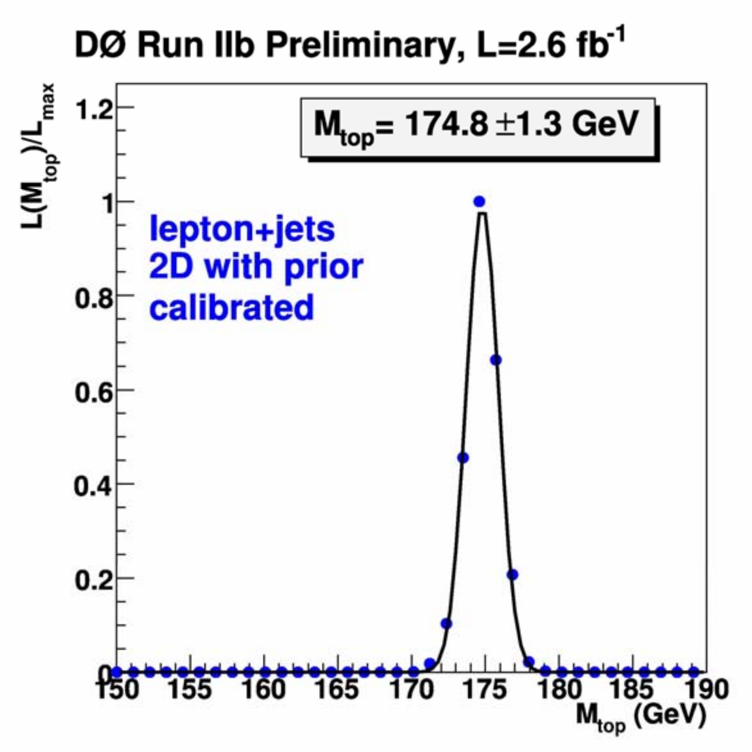
Top Mass via Likelihood - CDF Results

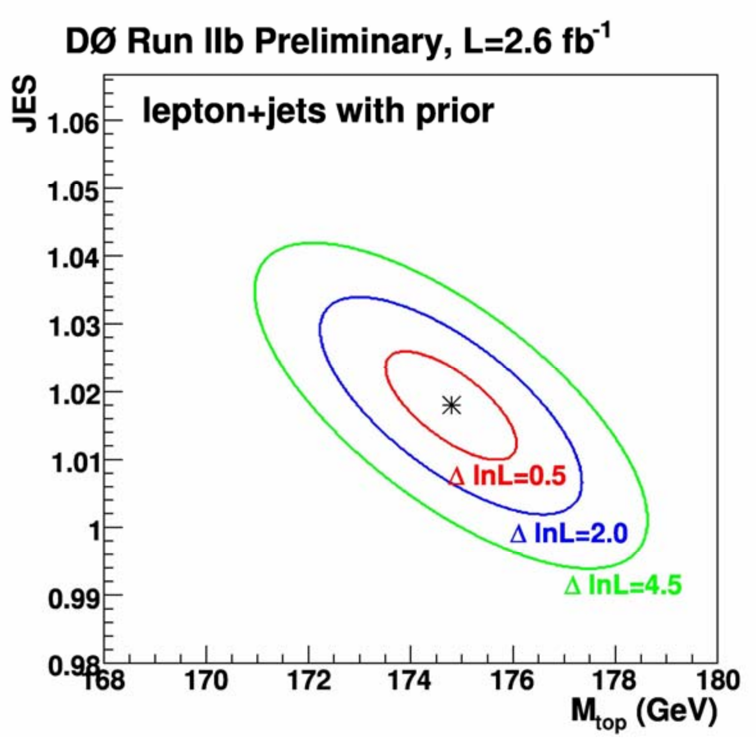




$$m_t = 172.1 \pm 0.9 \pm 0.7\,(\mathrm{JES}) \pm 1.1\,\mathrm{GeV}/c^2 = 172.1 \pm 1.6\,\mathrm{GeV}/c^2$$

Top Mass via Matrix Element – D0 Results



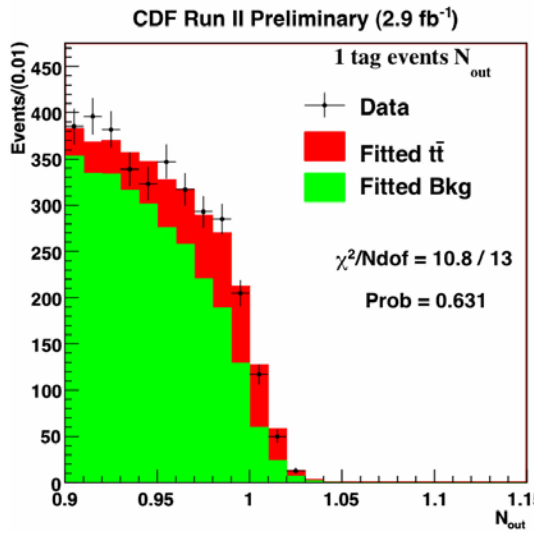


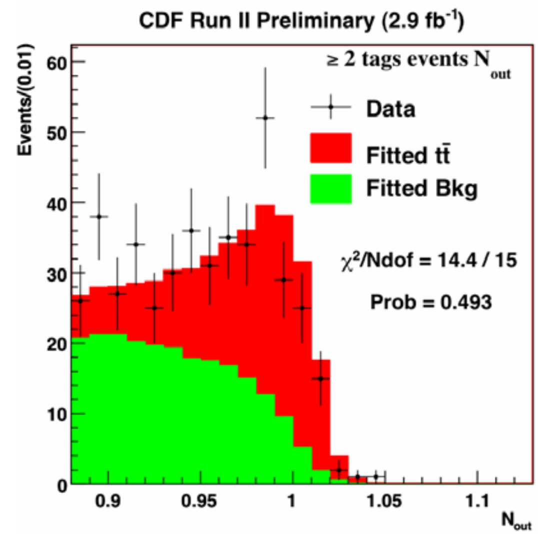
For 3.6 pb^{-1} dataset:

$$m_t = 173.7 \pm 0.8 \pm 1.6\ \mathrm{GeV}/c^2 = 173.7 \pm 1.8\ \mathrm{GeV}/c^2$$

Top Mass in the All-Hadronic Channel

Event selection in 6-8 jet events (no MET) via Neural Net:

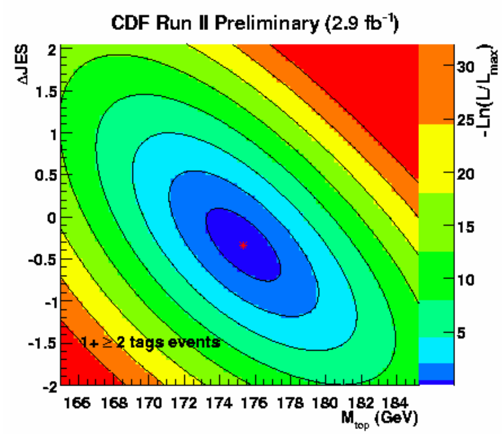




M_t from kinematic fitter:

$$\chi^2 = \frac{\left(m_{jj}^{(1)} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jj}^{(2)} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jjb}^{(1)} - m_t^{rec}\right)^2}{\Gamma_t^2} + \frac{\left(m_{jjb}^{(2)} - m_t^{rec}\right)^2}{\Gamma_t^2} + \sum_{i=1}^{6} \frac{\left(p_{T,i}^{fit} - p_{T,i}^{meas}\right)^2}{\sigma_i^2}$$

2d Likelihood fit w/ JES constraint:

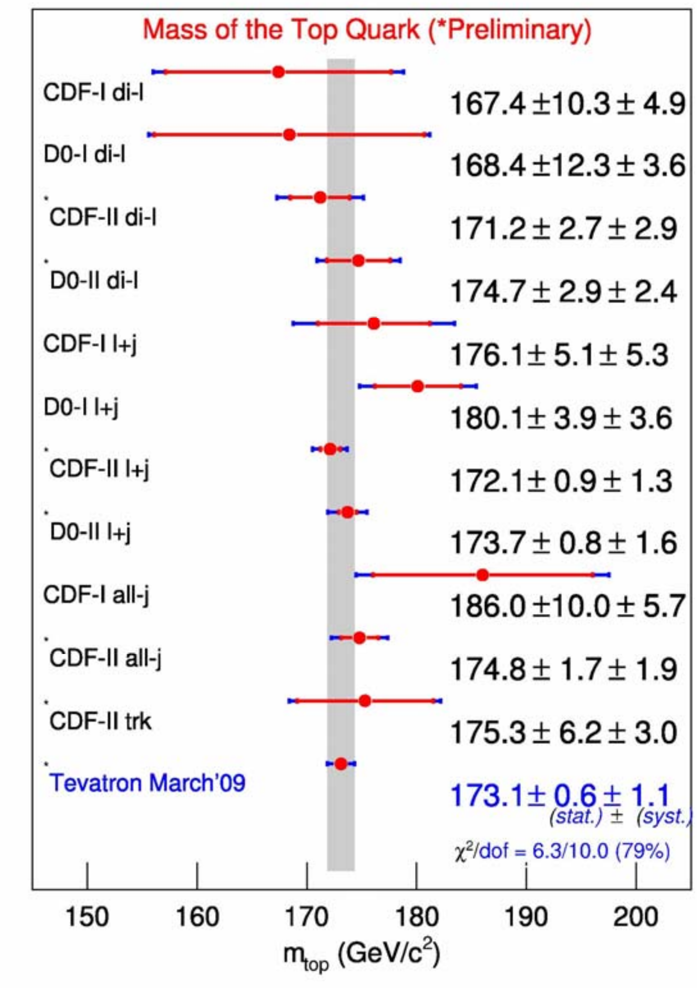


$$m_t = 174.8 \pm 1.7\,(\text{stat}) \pm 1.6\,(\text{JES})^{+1.2}_{-1.0}\,(\text{sys})\ \ \text{GeV}/c^2$$

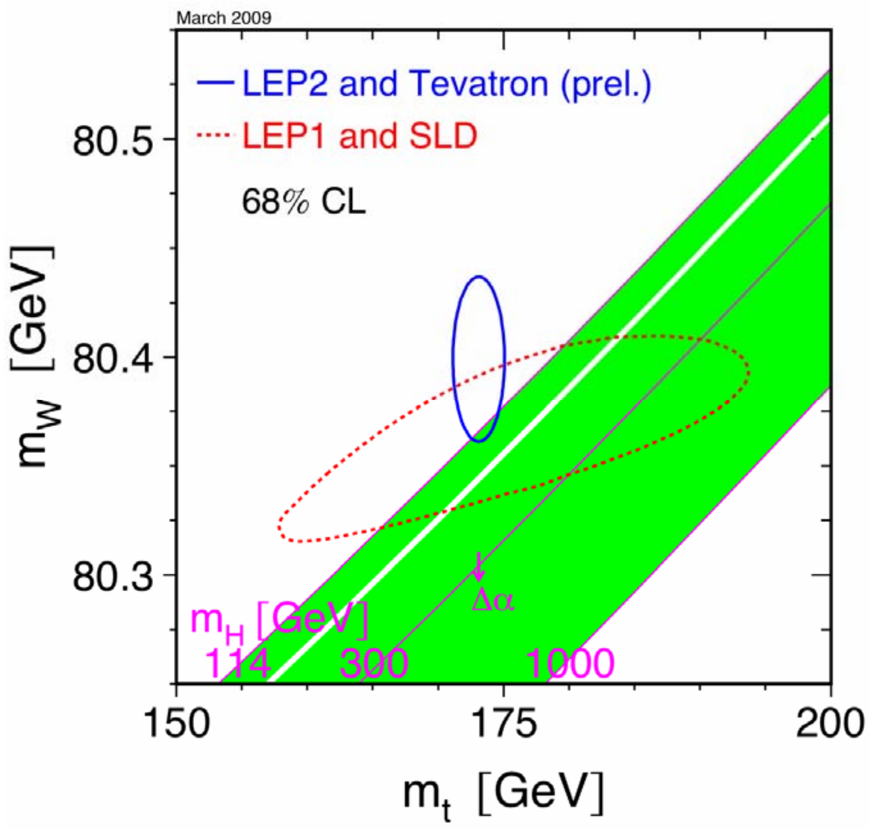
Systematic Uncertainties

	D0 + CDF
Jet Energy Scale	0.73
Lepton P_T scale	0.11
Signal modeling (ISR/FSR, PDFs)	0.30
MC modeling (Pythia vs. Herwig)	0.49
Multiple interactions (D0)	0.03
Background modeling	0.26
Fitting procedure	0.16
Color reconnection	0.41
Multiple hadron interactions	0.07
Total Systematic Uncertainty	1.07
Statistical Uncertainty	0.65

D0+CDF

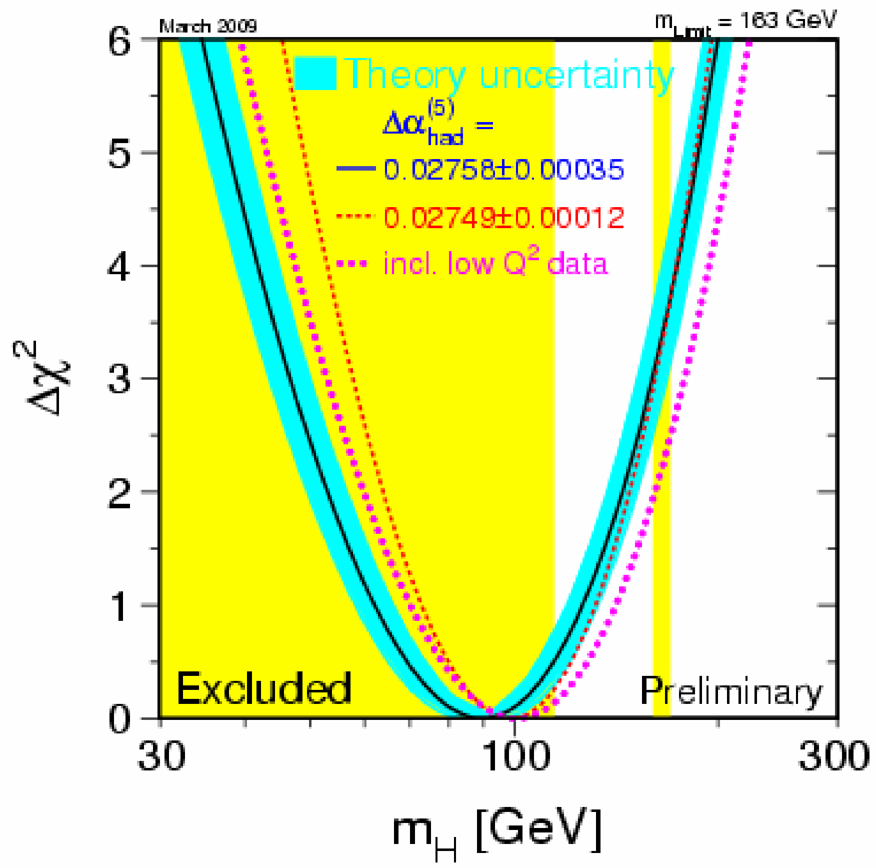


Mass of the Top Quark (*Preliminary)
CDF-I di-l
167.4 ±10.3 ± 4.9
D0-I di-l
168.4 ±12.3 ± 3.6
CDF-II di-l
171.2 ± 2.7 ± 2.9
D0-II di-l
174.7 ± 2.9 ± 2.4
CDF-I l+j
176.1 ± 5.1 ± 5.3
D0-I l+j
180.1 ± 3.9 ± 3.6
CDF-II l+j
172.1 ± 0.9 ± 1.3
D0-II l+j
173.7 ± 0.8 ± 1.6
CDF-I all-j
186.0 ±10.0 ± 5.7
CDF-II all-j
174.8 ± 1.7 ± 1.9
CDF-II trk
175.3 ± 6.2 ± 3.0
Tevatron March'09
173.1 ± 0.6 ± 1.1
(stat.) ± (syst.)
χ²/dof = 6.3/10.0 (79%)
150
160
170
180
190
200
m_top (GeV/c²)



March 2009
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
Δα
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]

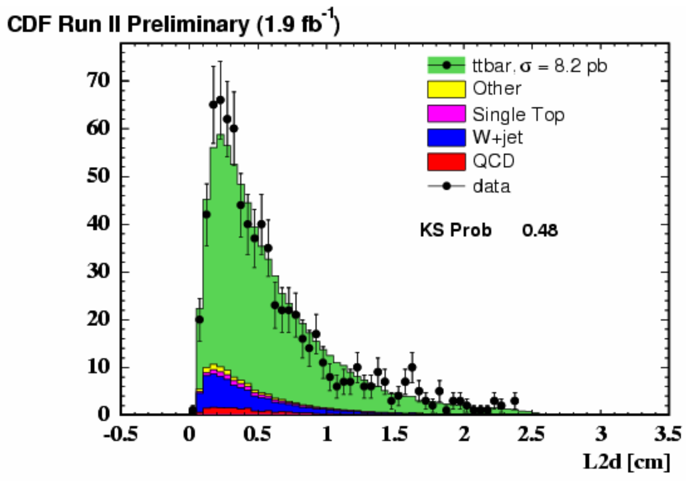
D0+CDF

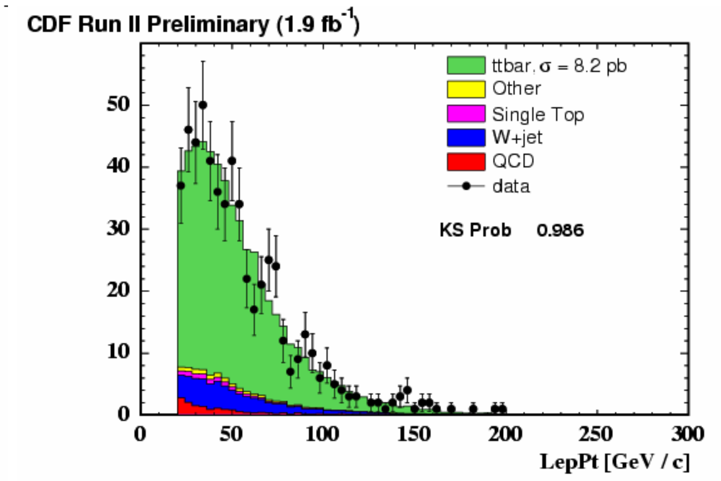


March 2009
m_{Limit} = 163 GeV
Theory uncertainty
$\Delta\alpha_{had}^{(5)}$ =
0.02758±0.00035
0.02749±0.00012
incl. low Q² data
Excluded
Preliminary
$\Delta\chi^2$
m_H [GeV]

Some New Techniques

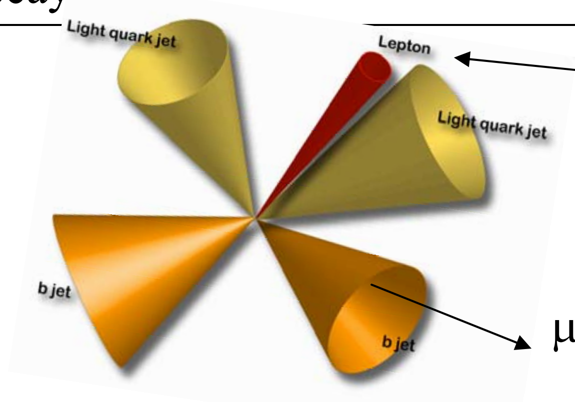
M_{top} from 2d decay length of B hadron + lepton P_T





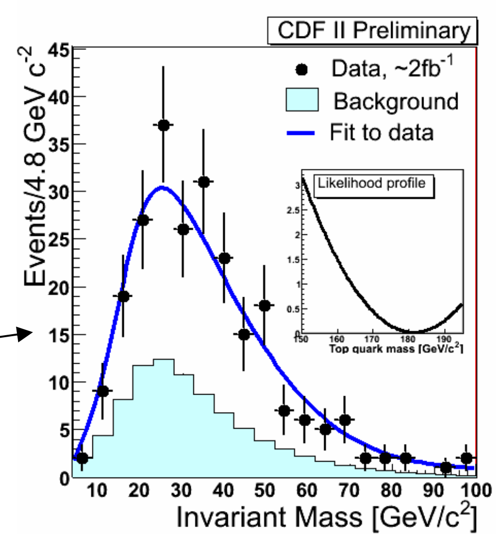
$$M_t = 175.3 \pm 6.2 \pm 3.0 \text{ GeV/c}^2$$

M_{top} from invariant mass of e/μ from W boson decay together with "soft muon" from B hadron decay

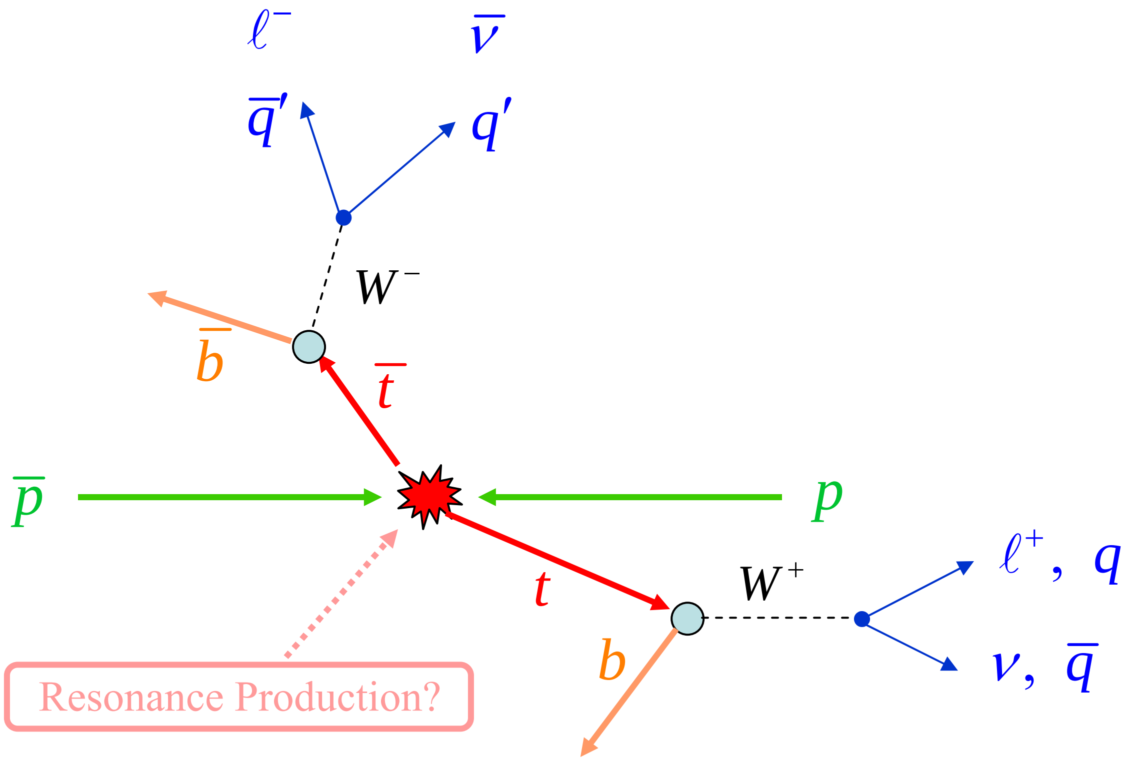


$M_{\ell\mu}$

μ



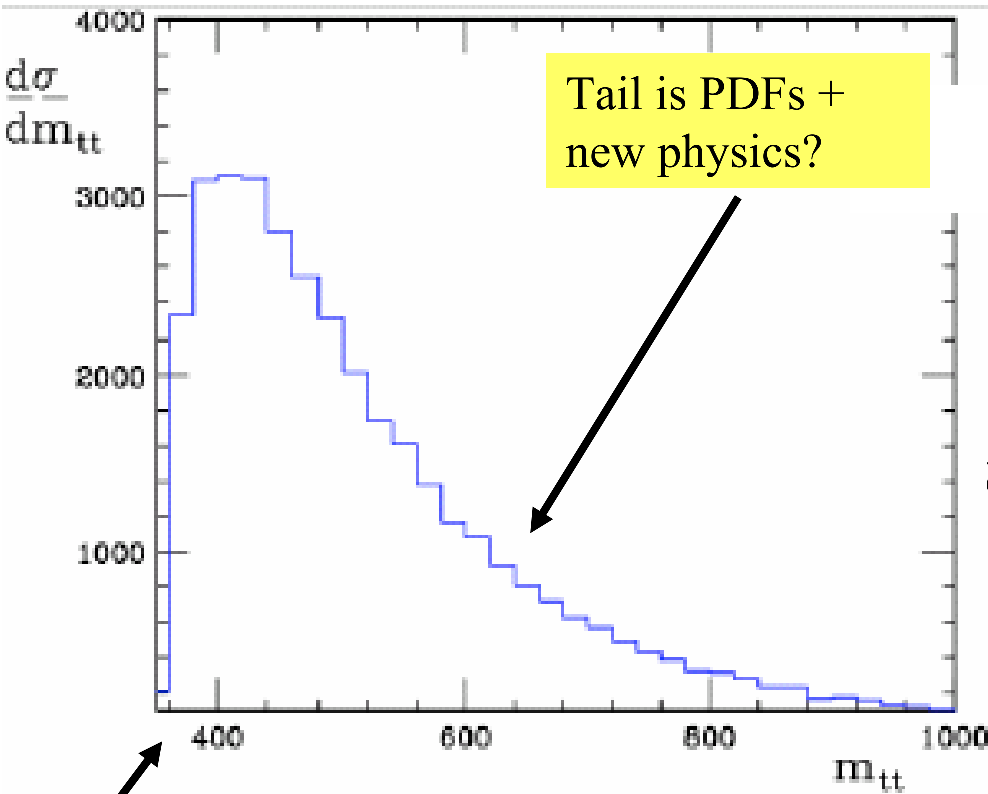
$$M_t = 181.3 \pm 12.4 \pm 3.5 \text{ GeV/c}^2$$



ℓ^-
$\bar{\nu}$
$\bar{q}'$
q'
W^-
$\bar{b}$
$\bar{t}$
$\bar{p}$
p
ℓ^+, q
W^+
t
b
ν, $\bar{q}$
Resonance Production?

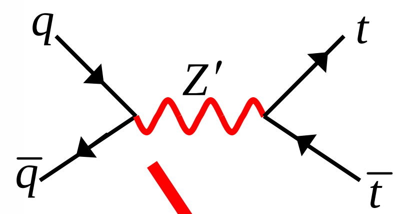
$M_{t\text{-}tbar}$

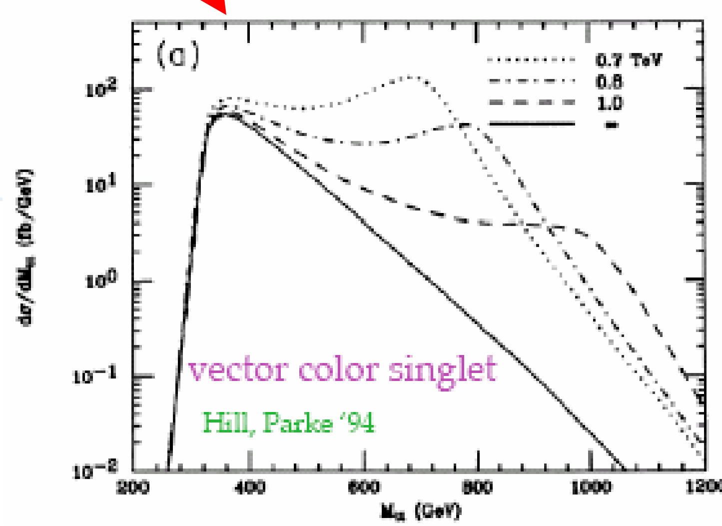
Is top produced as we think?



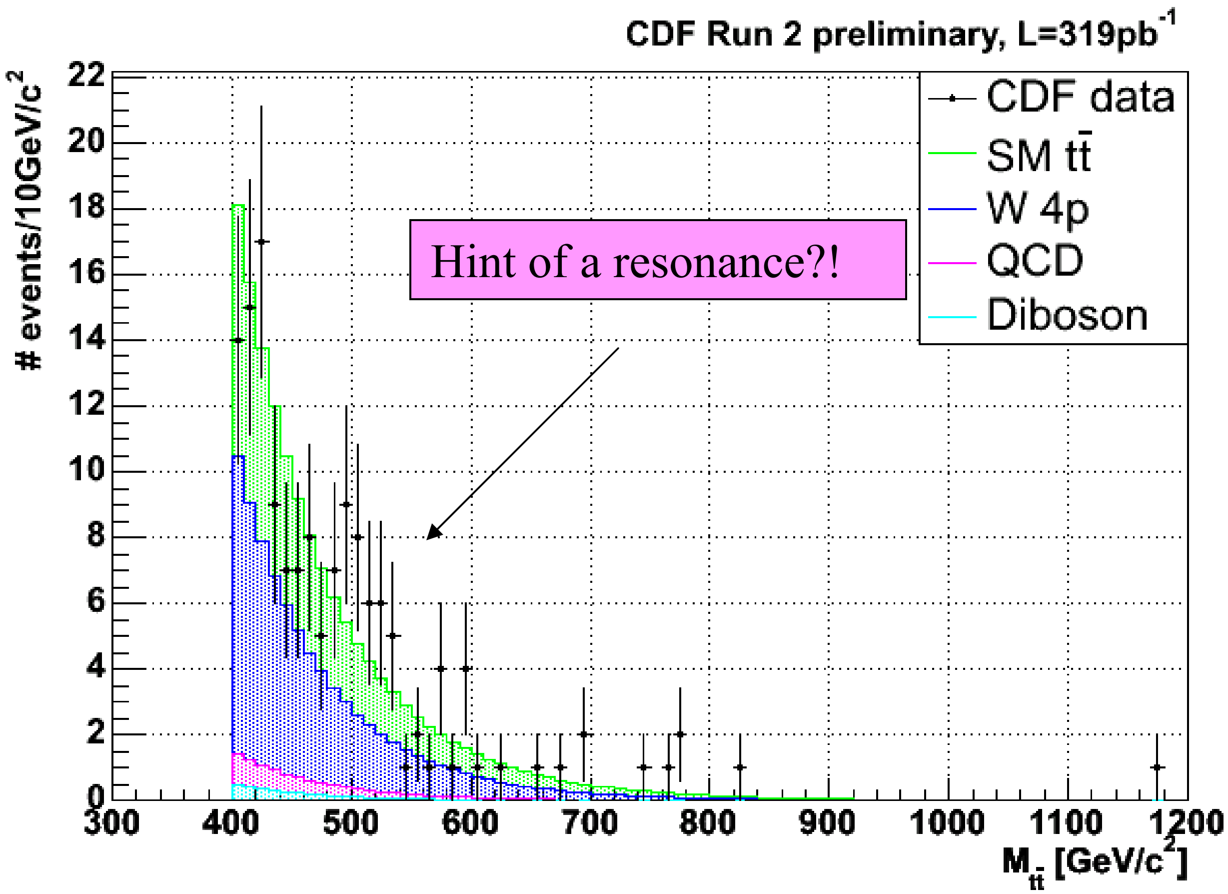
Tail is PDFs + new physics?

Threshold is 2M + smearing

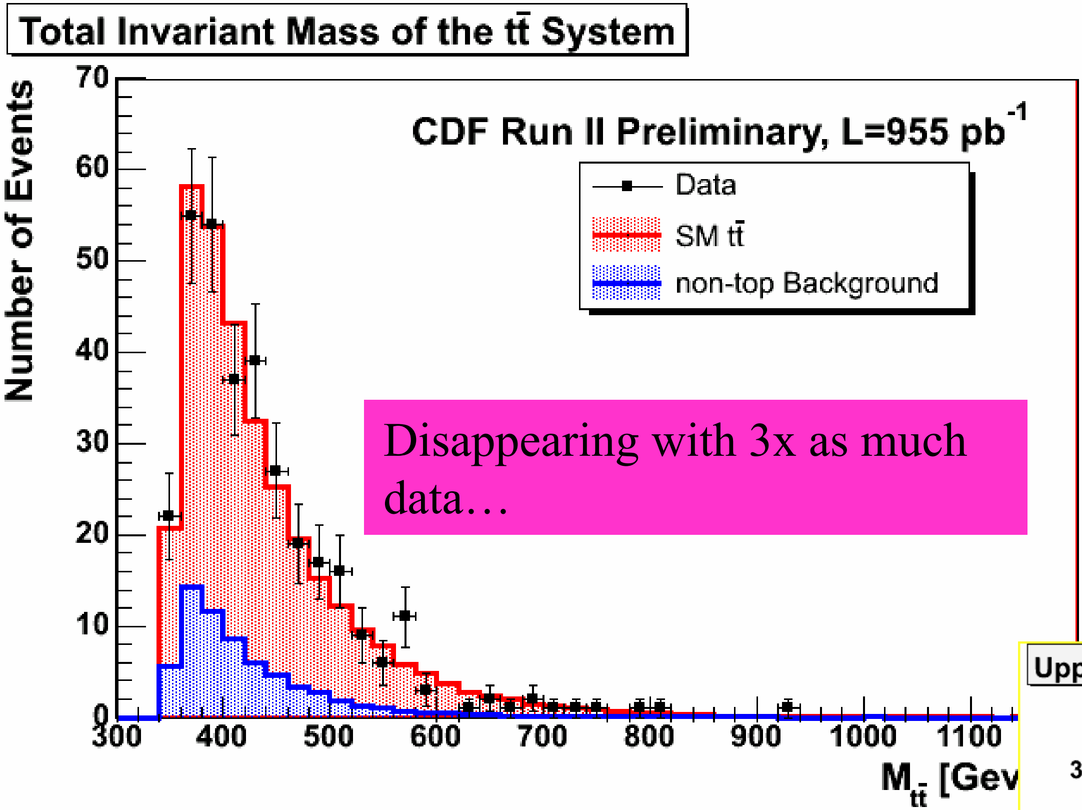




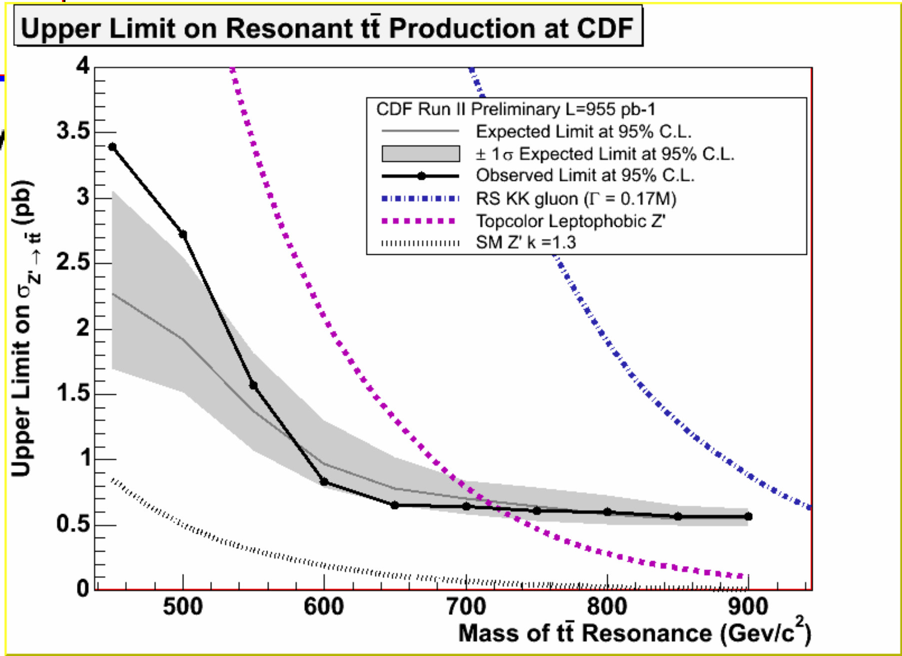
The Data


CDF Run 2 preliminary, L=319pb-1
events/10GeV/c2
22
20
18
16
14
12
10
8
6
4
2
0
300
400
500
600
700
800
900
1000
1100
1200
Mtt̄ [GeV/c2]
CDF data
SM tt̄
W 4p
QCD
Diboson
Hint of a resonance?!

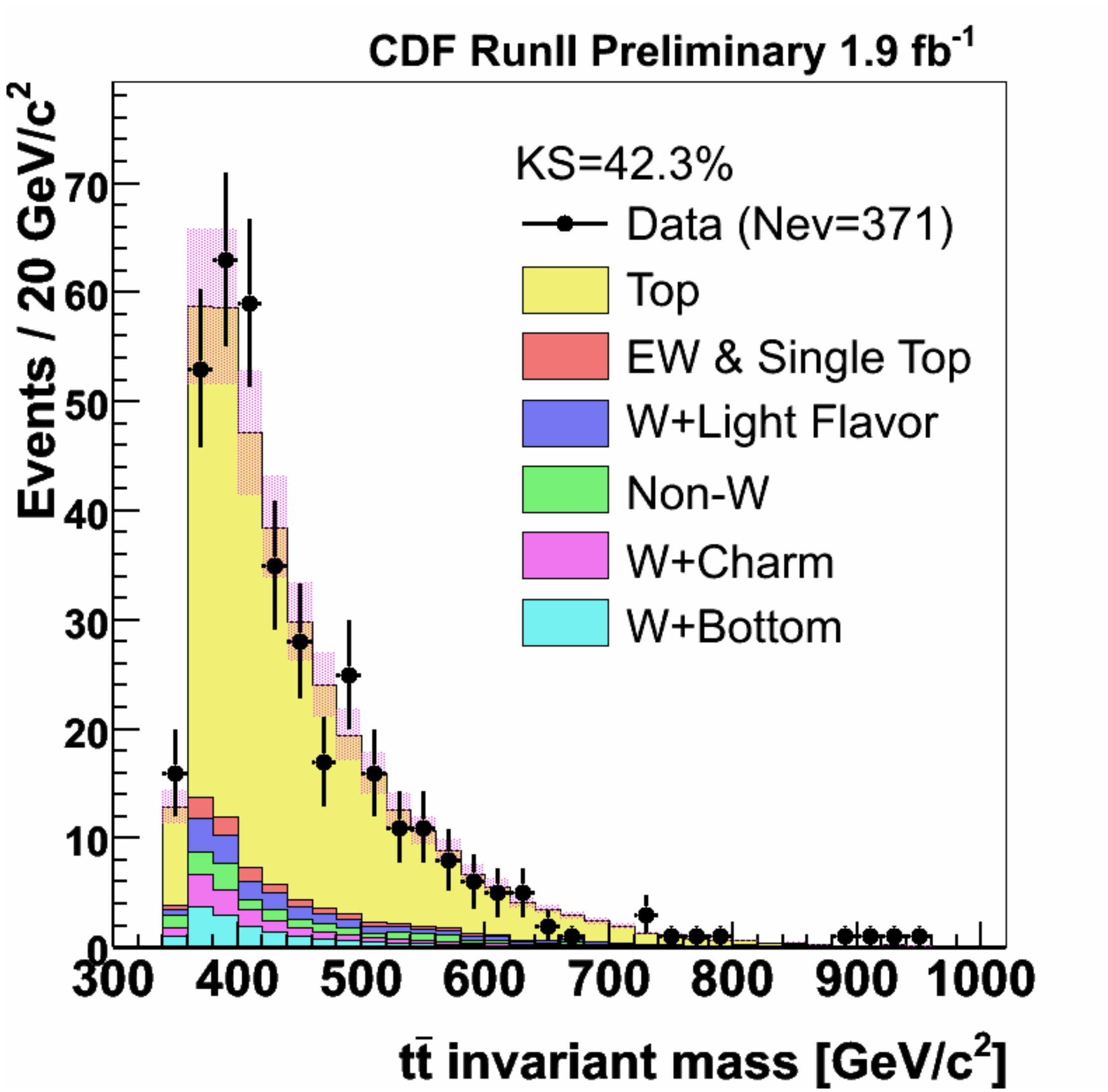
The Data



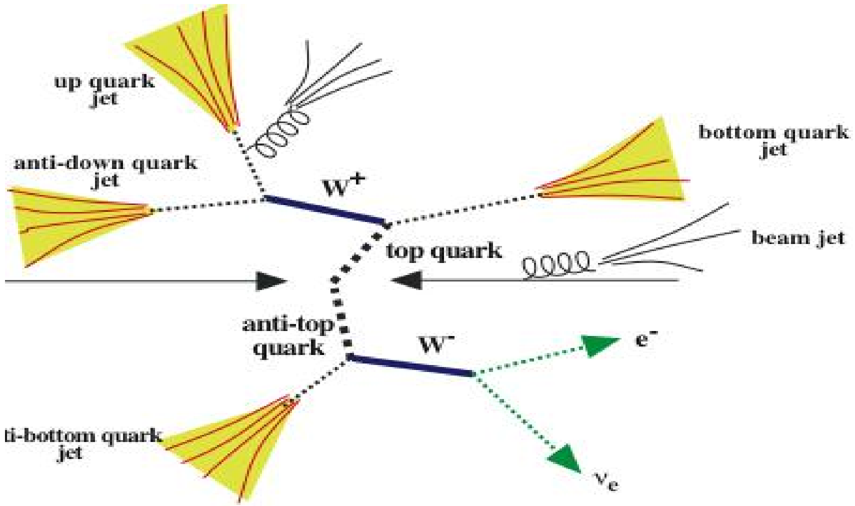
Disappearing with 3x as much data…



The Data

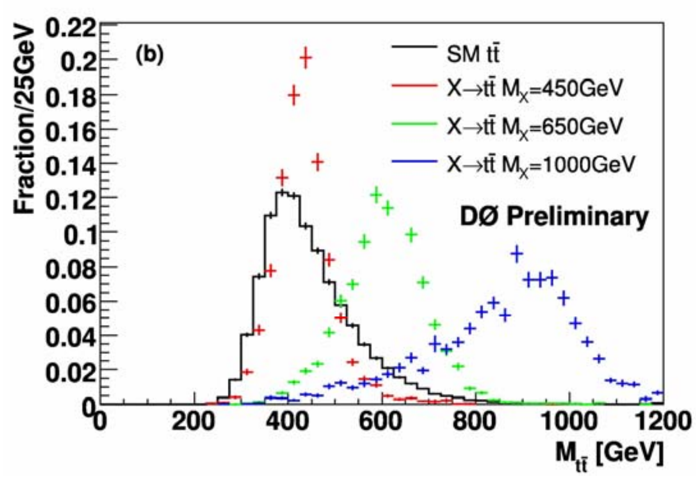

CDF RunII Preliminary 1.9 fb-1
KS=42.3%
Data (Nev=371)
Top
EW & Single Top
W+Light Flavor
Non-W
W+Charm
W+Bottom
Events / 20 GeV/c2
tt̄ invariant mass [GeV/c2]
0
10
20
30
40
50
60
70
300
400
500
600
700
800
900
1000

Narrow Resonance Search

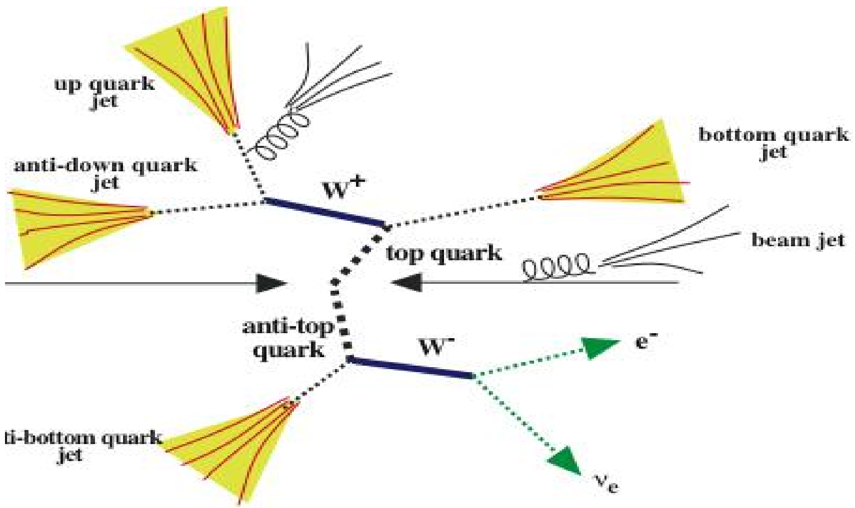


D0 reconstructs M_{ttbar} from leading 3,4 jets, e/μ and (solved) neutrino.

"Better than kinematic fitter for high mass resonance"



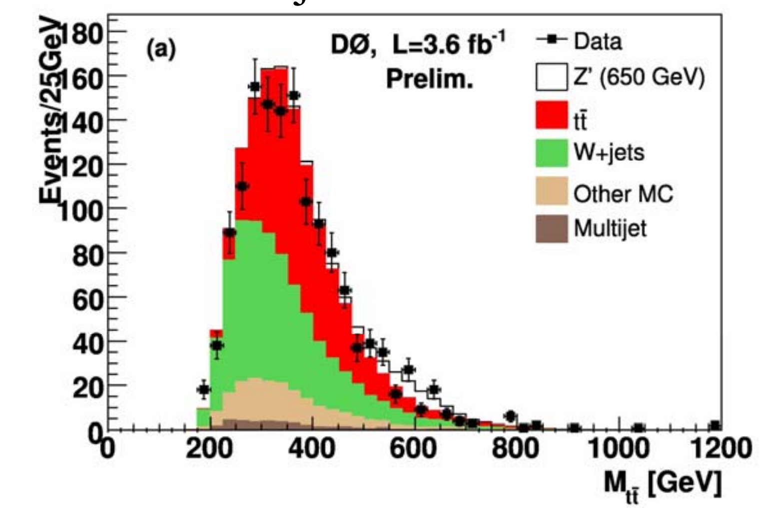
Narrow Resonance Search



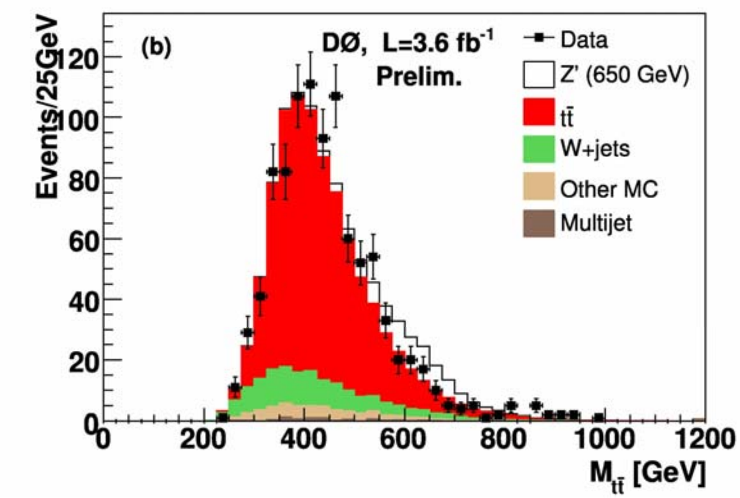
D0 reconstructs M_{ttbar} from leading 3,4 jets, e/μ and (solved) neutrino.

"Better than kinematic fitter for high mass resonance"

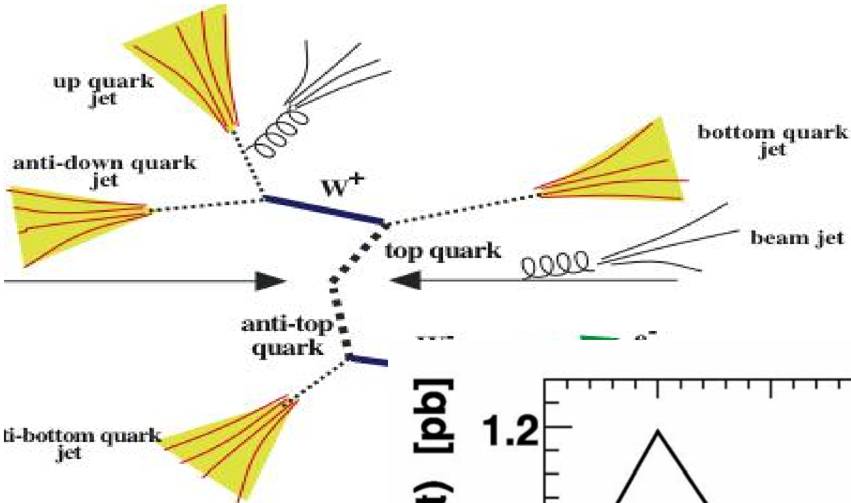
3 jet events



≥4 jet events

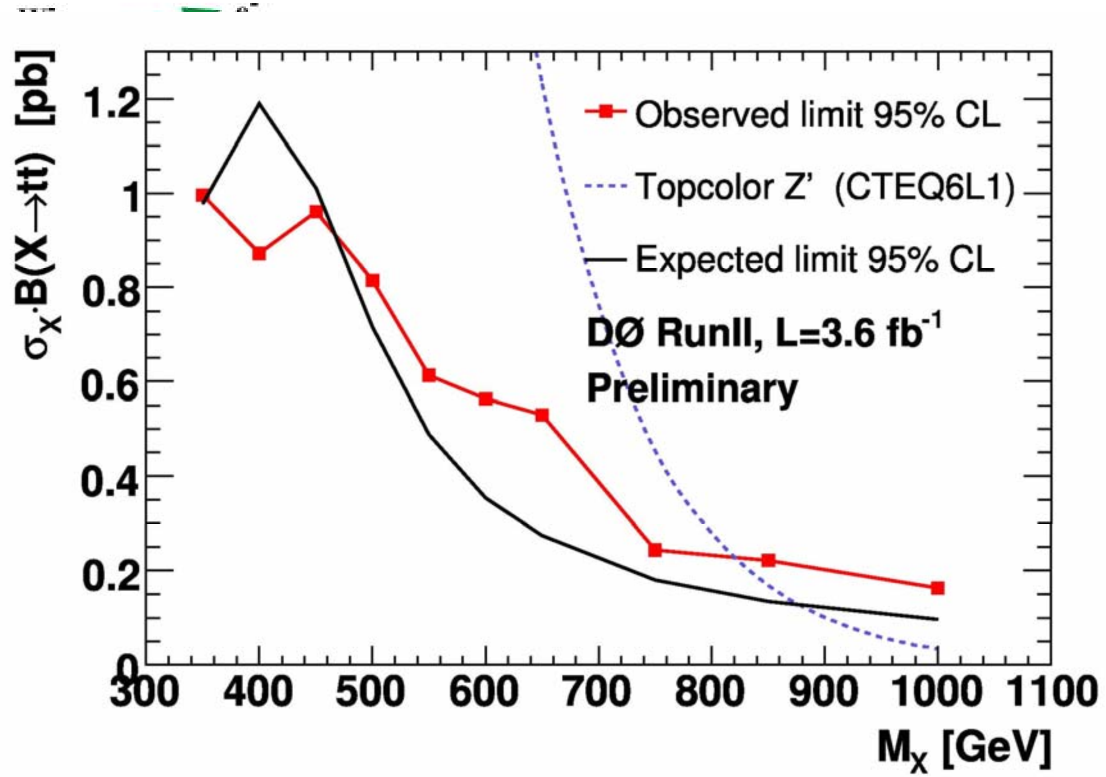


Narrow Resonance Search



D0 reconstructs M_{ttbar} from leading 3,4 jets, e/μ and (solved) neutrino.

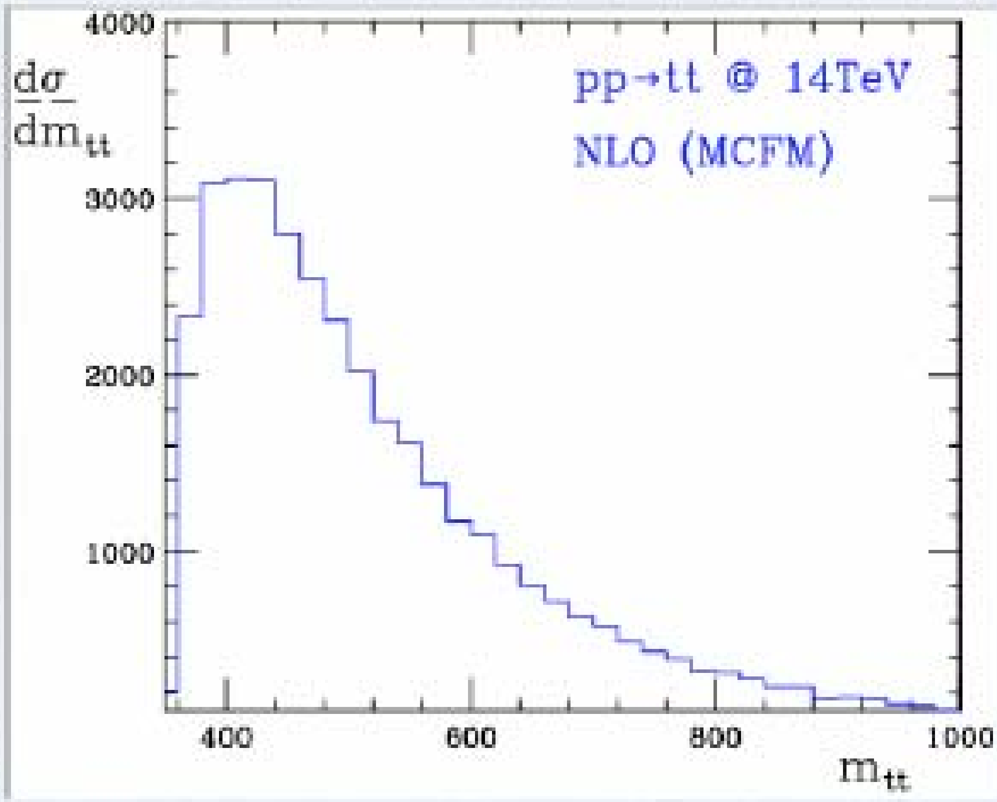
"Better than kinematic fitter for high mass resonance"

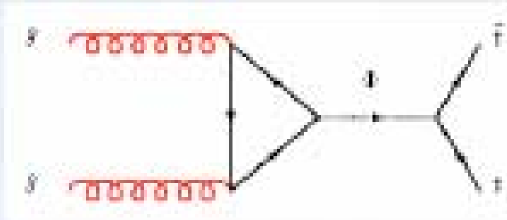


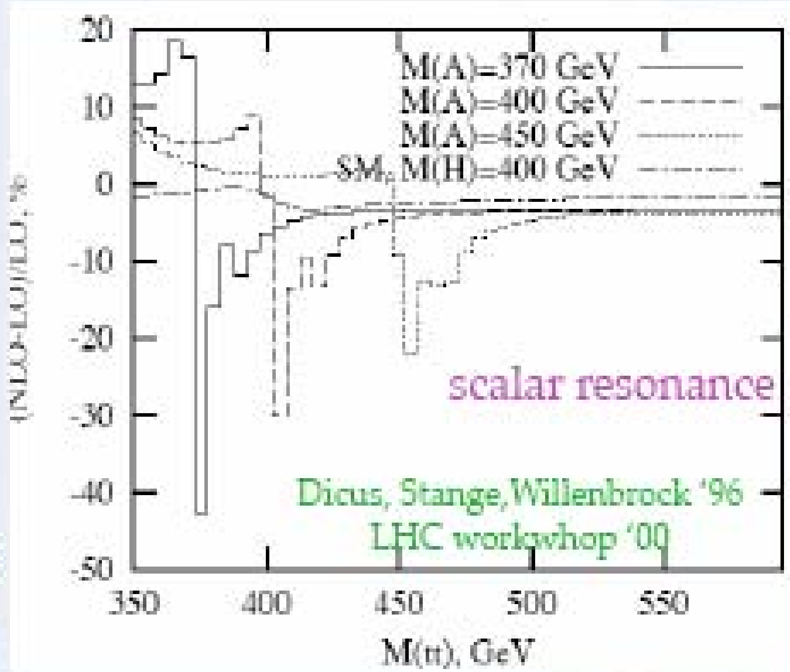
$M_{Z'}$<820 GeV/c^2 w/Γ=0.012M excluded

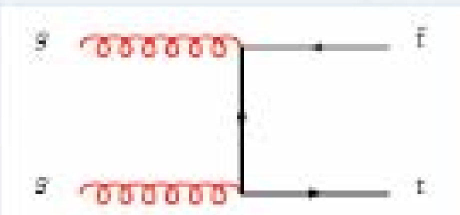
Beyond Narrow Resonances

Maltoni HCP 2005:



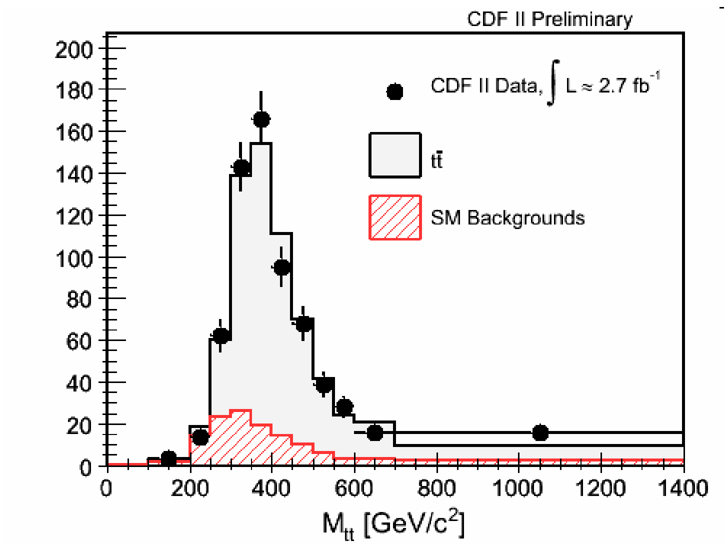


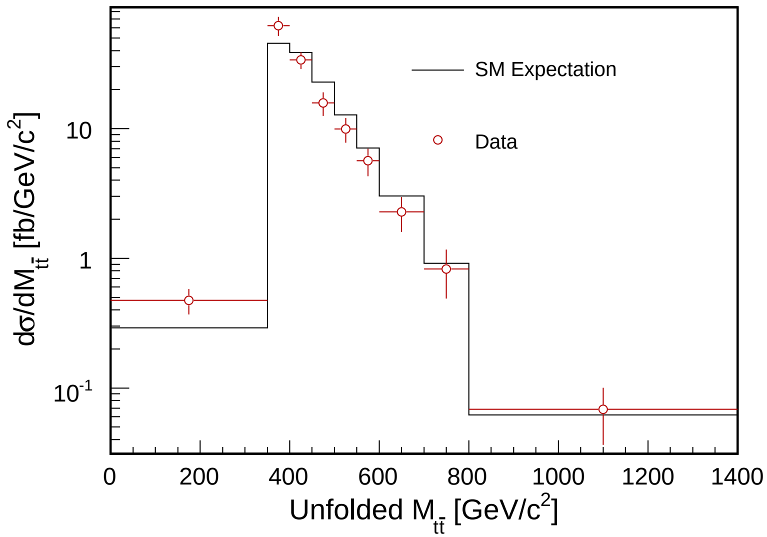




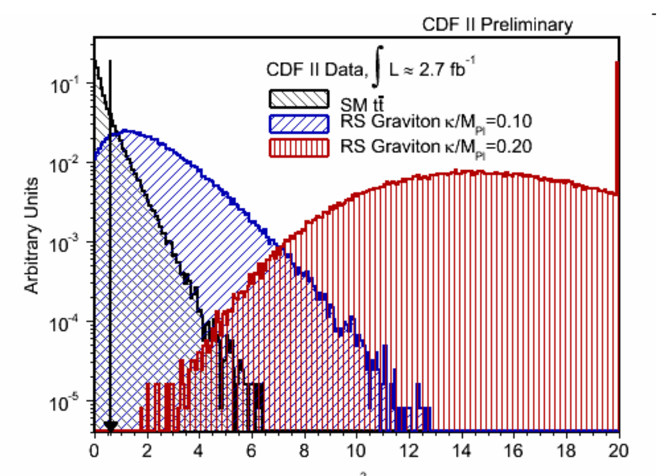
Non-trivial behavior (peak-dip) due to the interference between the signal and the background.

$d\sigma/dM_{t\bar{t}}$

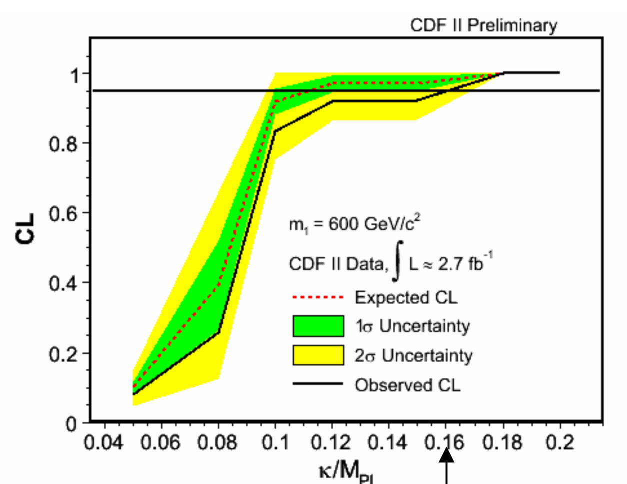




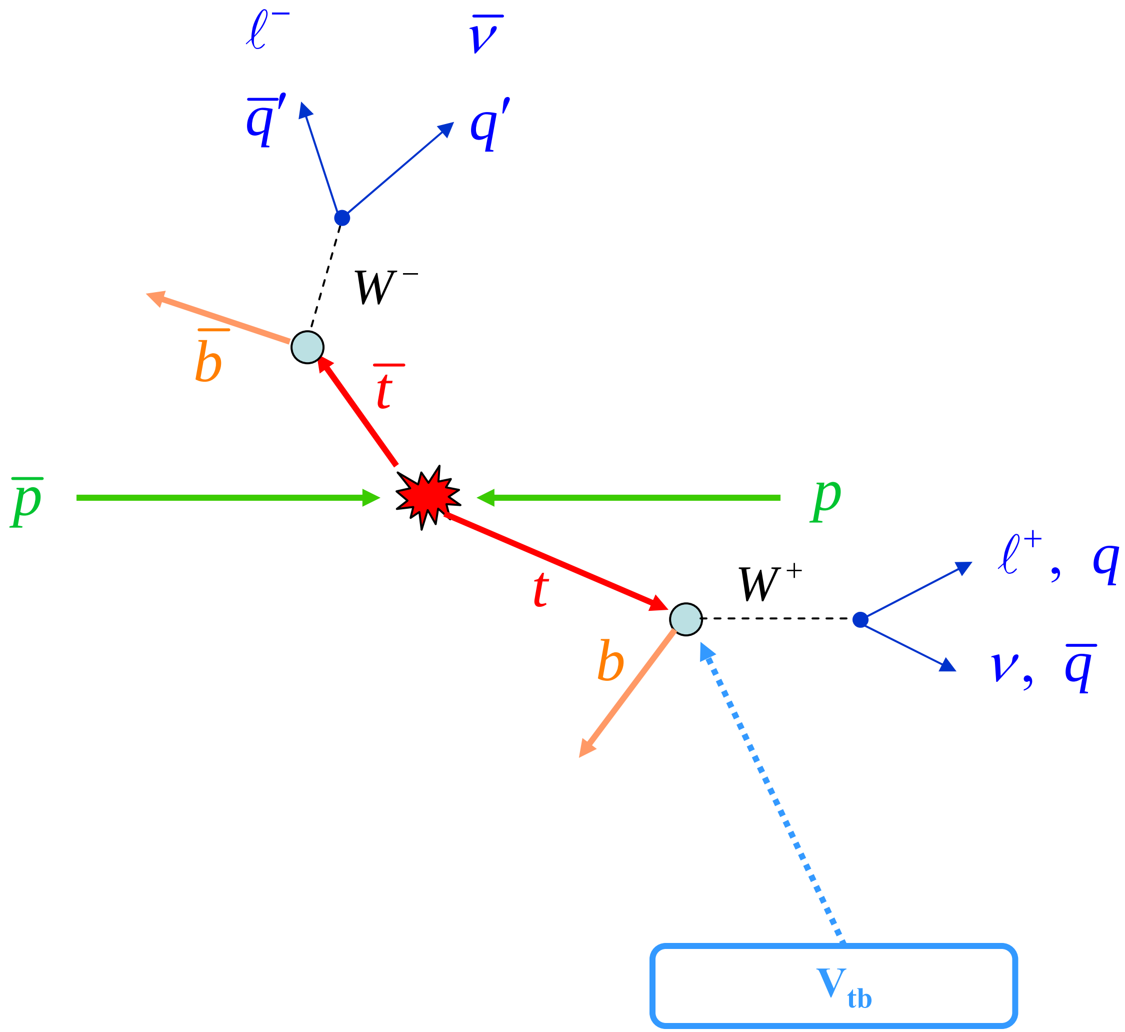
Measured → unfolding → Cross section vs. *true* Mttbar



P-value for consistency w/SM = 28%



$\kappa/M_{pl}>0.16$ excluded at 95% CL



ℓ^-
$\bar{\nu}$
$\bar{q}'$
q'
W^-
$\bar{b}$
$\bar{t}$
$\bar{p}$
p
t
W^+
ℓ^+, q
b
ν, $\bar{q}$
V_{tb}

V_{tb}

- We have measured:

$$R \equiv B(t \to Wq)/B(t \to Wb)$$

$$= 0.97^{+0.09}_{-0.08} \quad \text{(D0)}$$

$$= 1.12^{+0.27}_{-0.23} \quad \text{(CDF)}$$

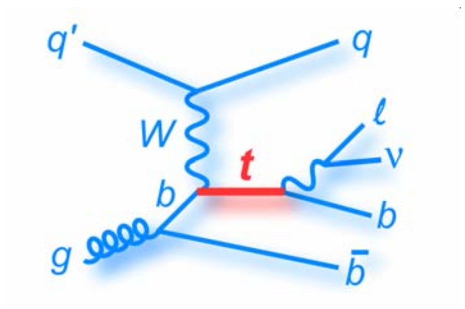
From the ratio of $t\bar{t}$ events with 0,1,2 b-tags

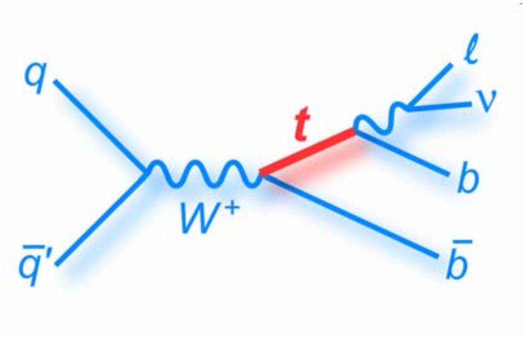
$$R = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

An interesting measurement, but not much sensitivity to V_{tb}

To REALLY measure V_{tb}...

Single Top Production





"t-channel"

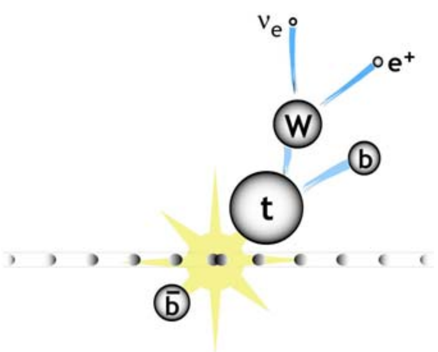
2pb

"s-channel"

0.9pb

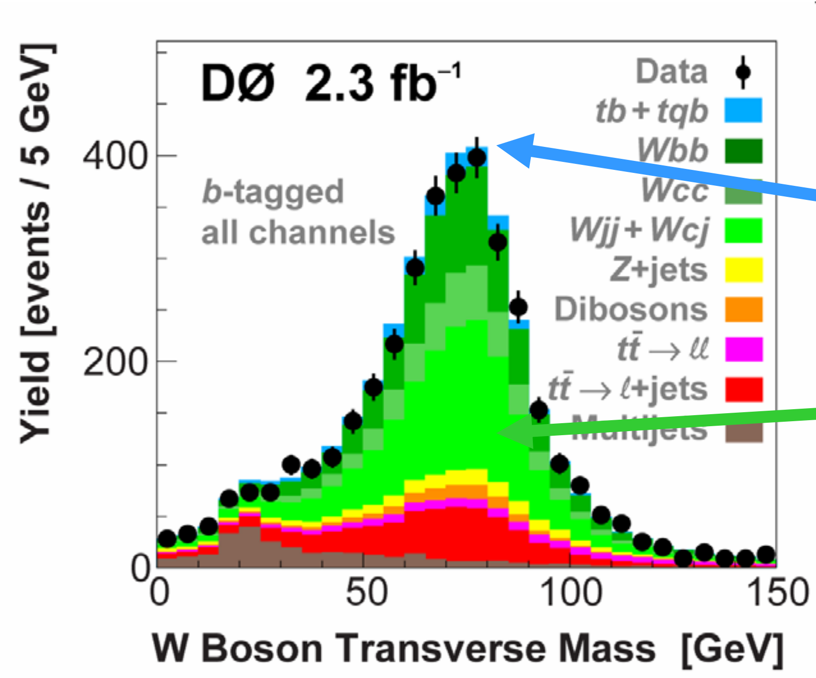
Same data selection as $t\bar{t}$ but signal is in W+2 jets sample

$$\sigma\left(q\bar{q}', qg \to tb\right) \propto \left|V_{tb}\right|^2$$



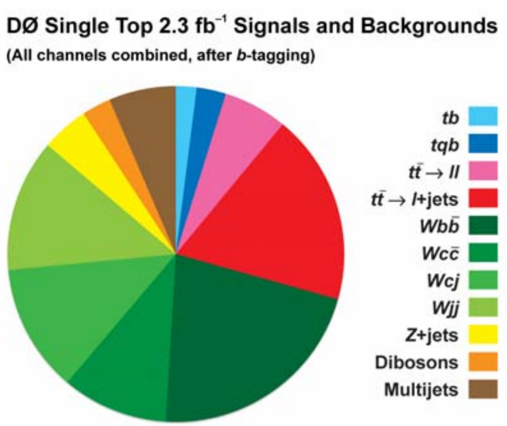
Difficult due to less distinct signature and very large *W*+2 jets background

S vs. B in Single Top



Here is the expected signal

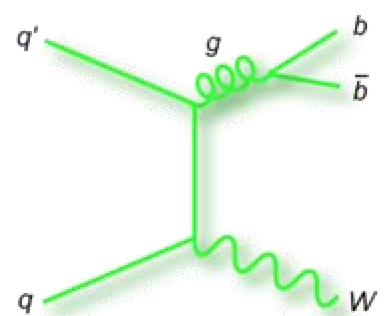
On top of a substantial background…

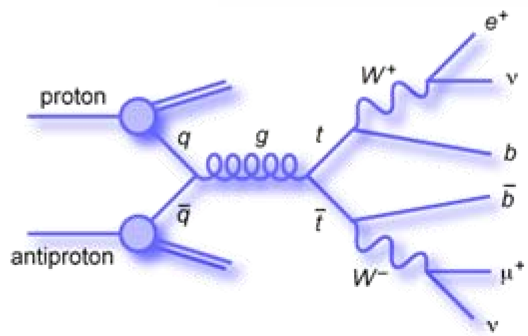


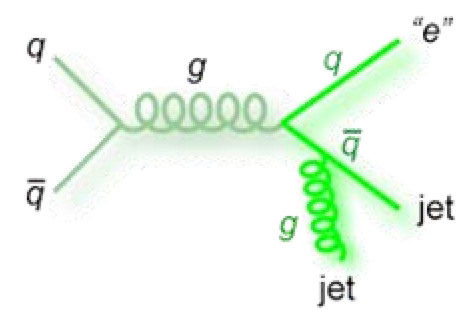
W+HF backgrounds know only to ~30%

A simple counting experiment will not do.

The culprits:







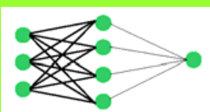
Single-Top Analysis Strategy

full selected data set

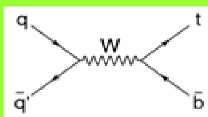
W + 2 jets		W + 3 jets		W + 4 jets	
1 tag	≥ 2 tags	1 tag	≥ 2 tags	1 tag	≥ 2 tags

split in subsets of different purity

neural networks



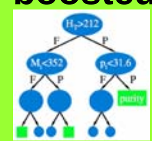
matrix elements



likelihood discriminants

$$L^j(\vec{x}) = \frac{\prod_{i=1}^{n_{var}} p_i^j(x_i)}{\sum_{k=1}^{5} \prod_{i=1}^{n_{var}} p_i^k(x_i)}$$

boosted decision trees



multivariate methods

combined search

t-channel + s-channel = one single-top signal
cross section ratio is fixed to SM value.
important for „discovery“ and test $|V_{tb}| << 1$

separate search

regard t-channel and s-channel as separate processes
important to be sensitive to new physics processes

cross section measurement
Bayesian treament

hypotheses test
modified Frequentist approach

statistical analysis

D0 only | CDF only

Thanks to Wolfgang Wagner

Search Methods

Likelihood

"Solve" each event kinematically

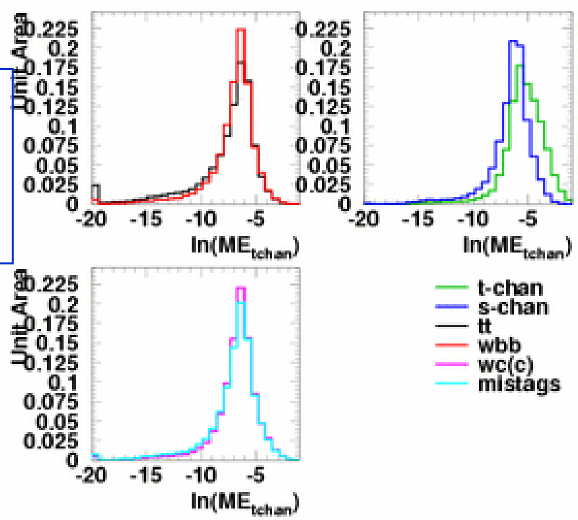
$$\chi^2 = \frac{(M_{\ell\nu b} - 175)^2}{\sigma^2_{m_t}} + \frac{(E_b^{solved} - E_b^{meas})^2}{\sigma_b^2} + \frac{(\Delta \not{E}_T)^2}{\sigma^2_{\not{E}_T}}$$

Compute a likelihood for each event based on a set of kinematic variables.

$$p_{ik} = \frac{f_{ij,k}}{\sum_{m=1}^{5} f_{ij,m}} \qquad L_k(\{x_i\}) = \frac{\prod_{i=1}^{n_{\text{var}}} p_{ik}}{\sum_{m=1}^{5} \prod_{i=1}^{n_{\text{var}}} p_{ik}}$$

k runs over S & B samples, ***i*** identifies the kin variable, and ***j*** is the bin in which it falls.

eg. L for ***MADEVENT*** matrix element

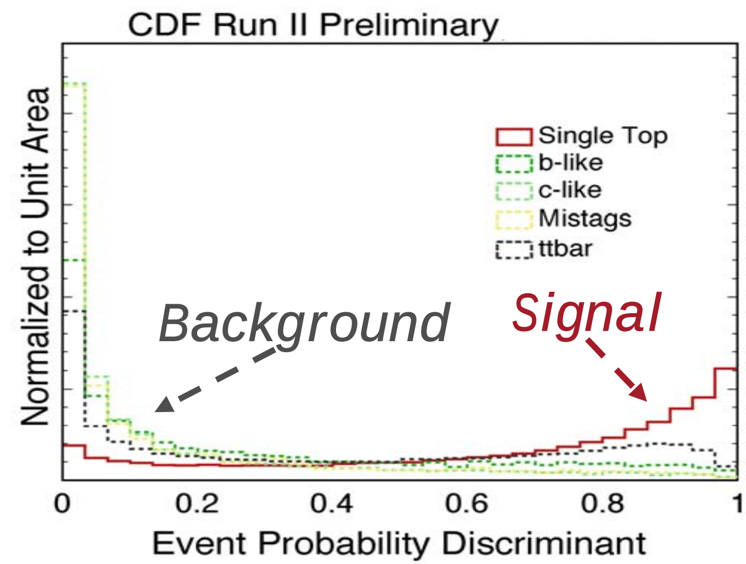


Matrix Element

$$P(x) = \frac{1}{\sigma} \int d\sigma(y)\, dq_1 dq_2\, f(x_1)\, f(x_2)\, W(y,x)$$

Parton-level xsec from ***MADEVENT*** (CDF) or ***SINGLETOP*** (D0) matrix element calc.

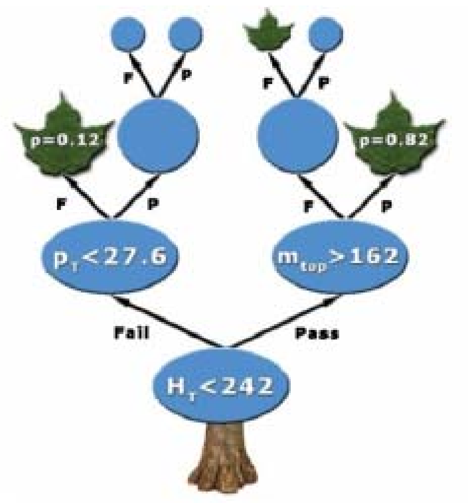
PDFs Transfer fcn



$$EPD = \frac{b \cdot P_{\text{singletop}}}{b \cdot P_{\text{singletop}} + b \cdot P_{Wbb} + (1-b) \cdot P_{Wcc} + (1-b) \cdot P_{Wcj}}$$

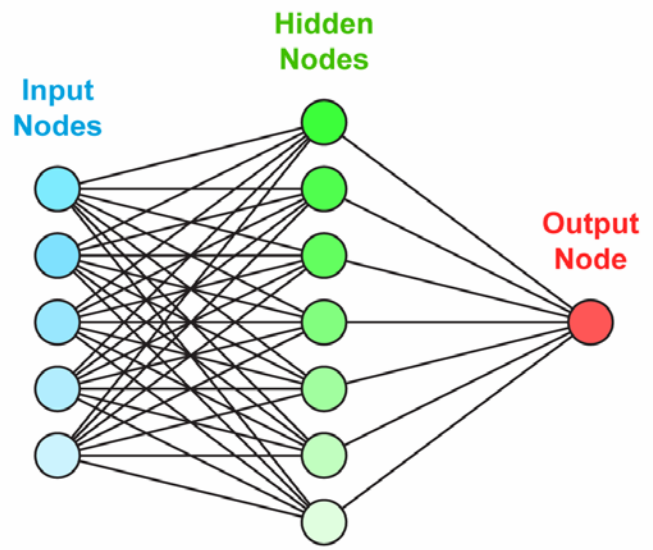
Search Methods (2)

BDT



- Events classified based on cumulative set of cuts defining disjoint subsets of events with different signal purities.
- Each cut defines two branches – Pass and Fail
- Terminal nodes (leaves) are reached when no further S/B separation is found
- Each event ends on a leaf with a defined purity.

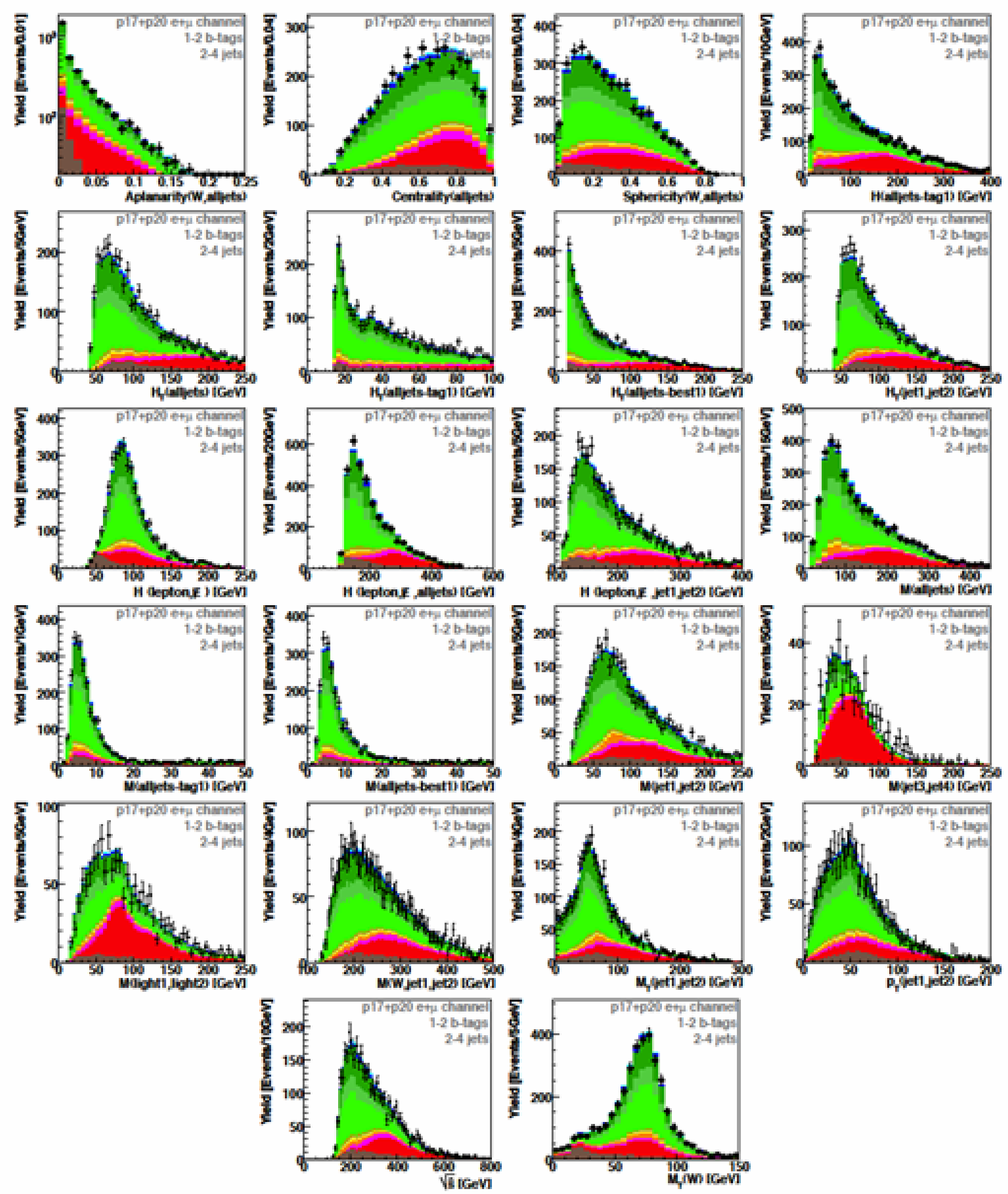
BNN



- Trained on S & B producing one, continuous output discriminant
- Bayesian NN averages over many networks
- Uses highest ranked (best discriminating power) variables.

Kinematic Modeling

EVENT KINEMATICS



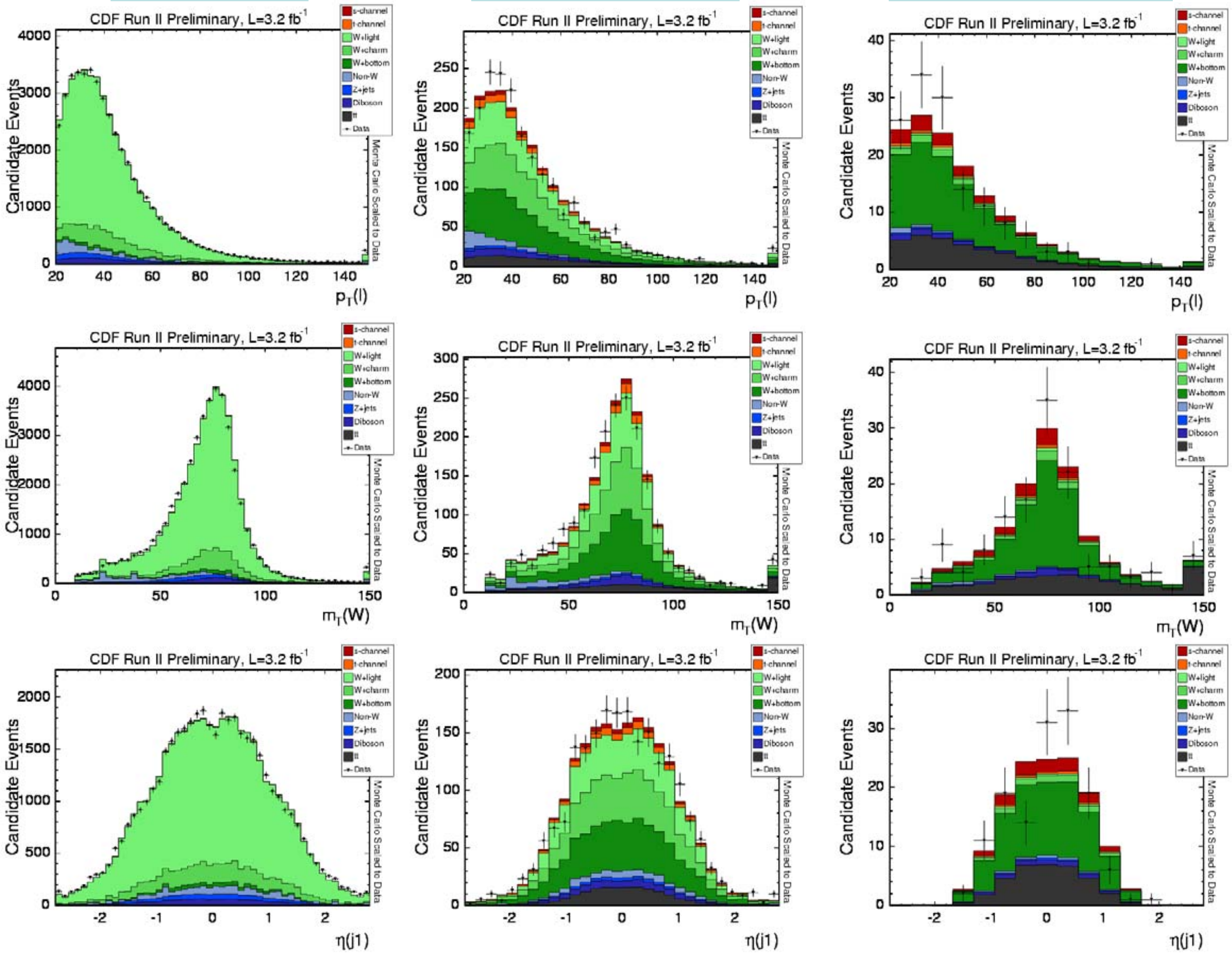
Kinematic Modeling

untagged | single tagged | double tagged

P_T^{lepton}

$M_T(W)$

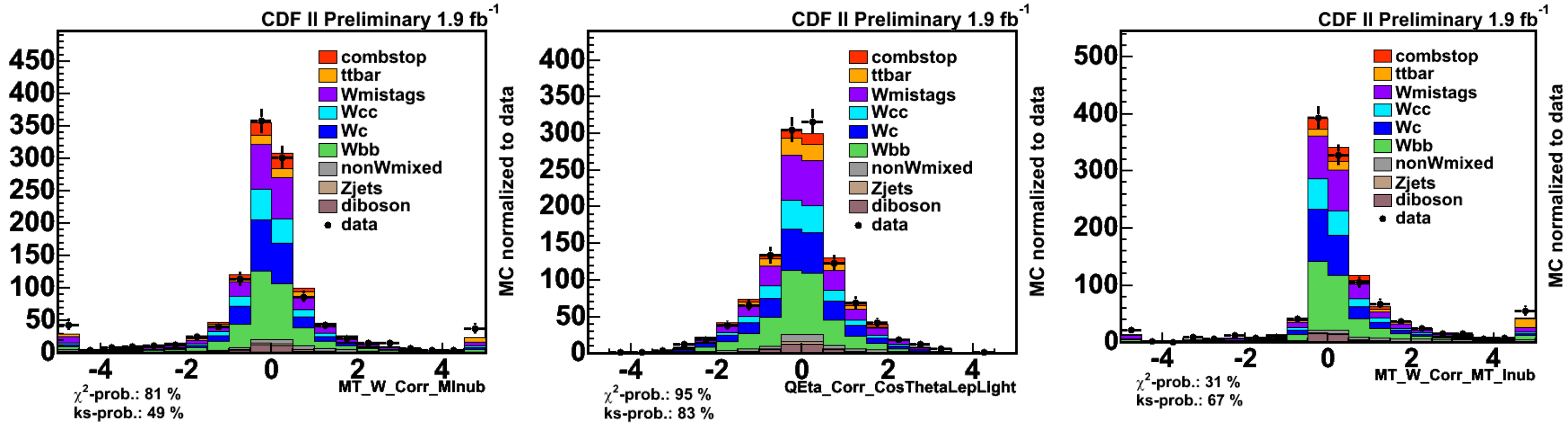
η (jet 1)



Kinematic Modeling

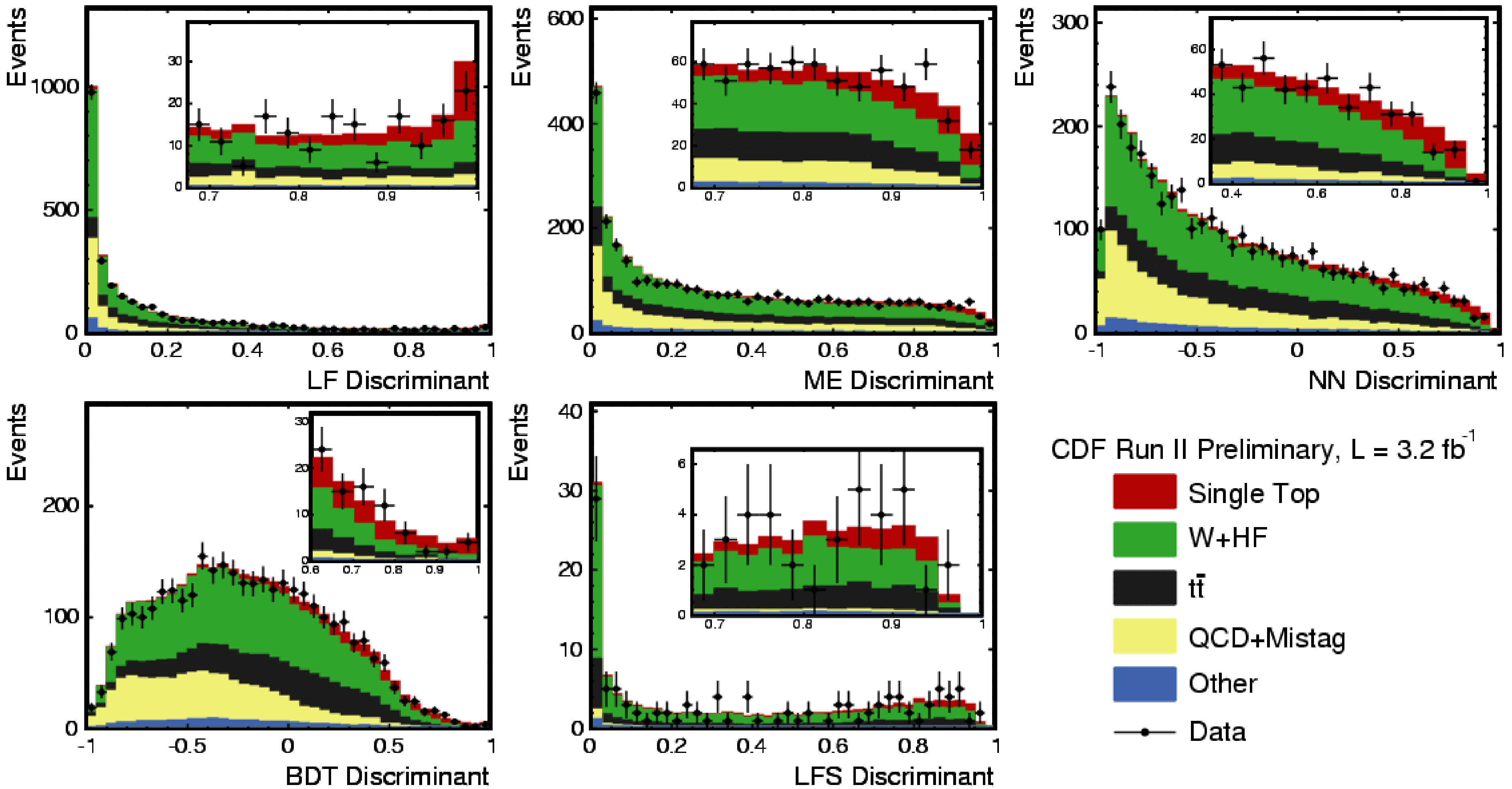
Correlations too!

$$\kappa_{ij} = \frac{x_i - \bar{x}_i}{\sigma_{x_i}} \cdot \frac{x_j - \bar{x}_j}{\sigma_{x_j}}$$

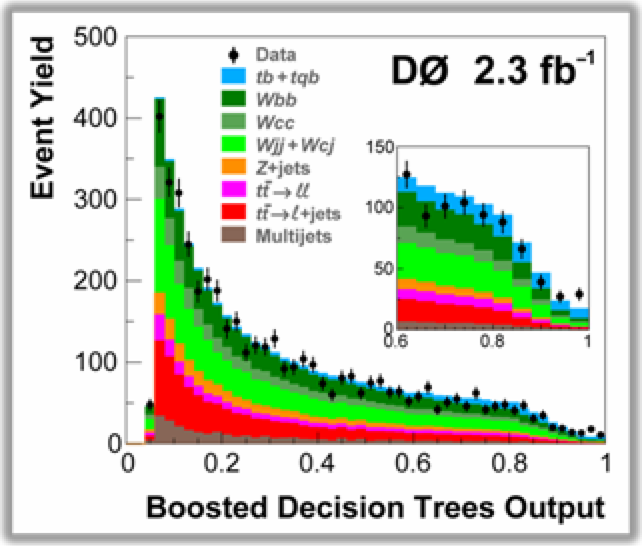


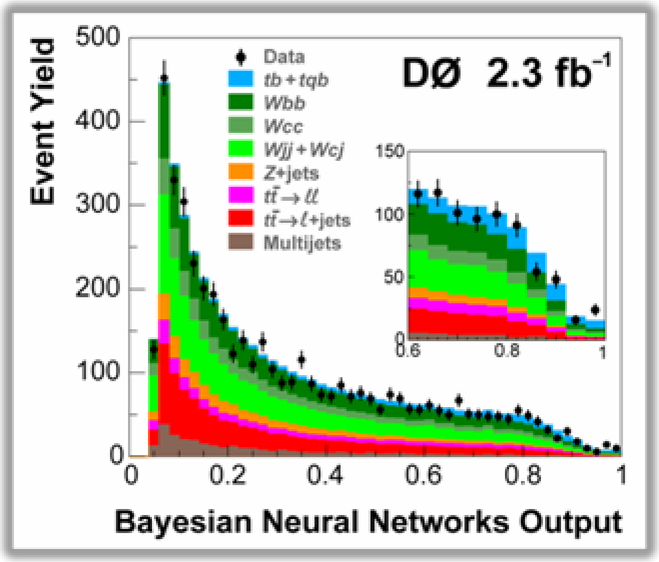
Single Top Results - CDF

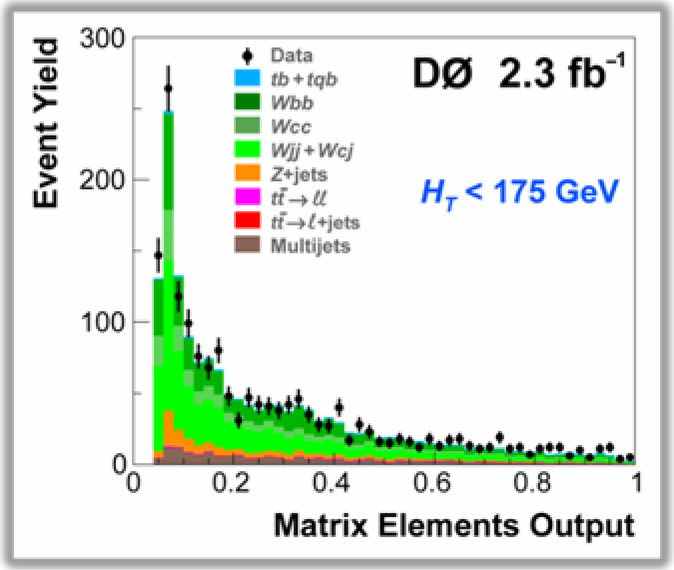
… compared to simulated events normalized to the SM expectation

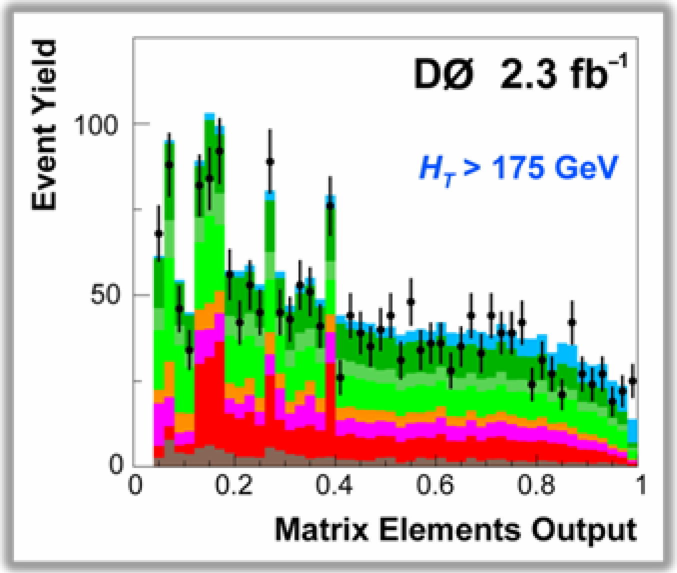


Single Top Results – D0









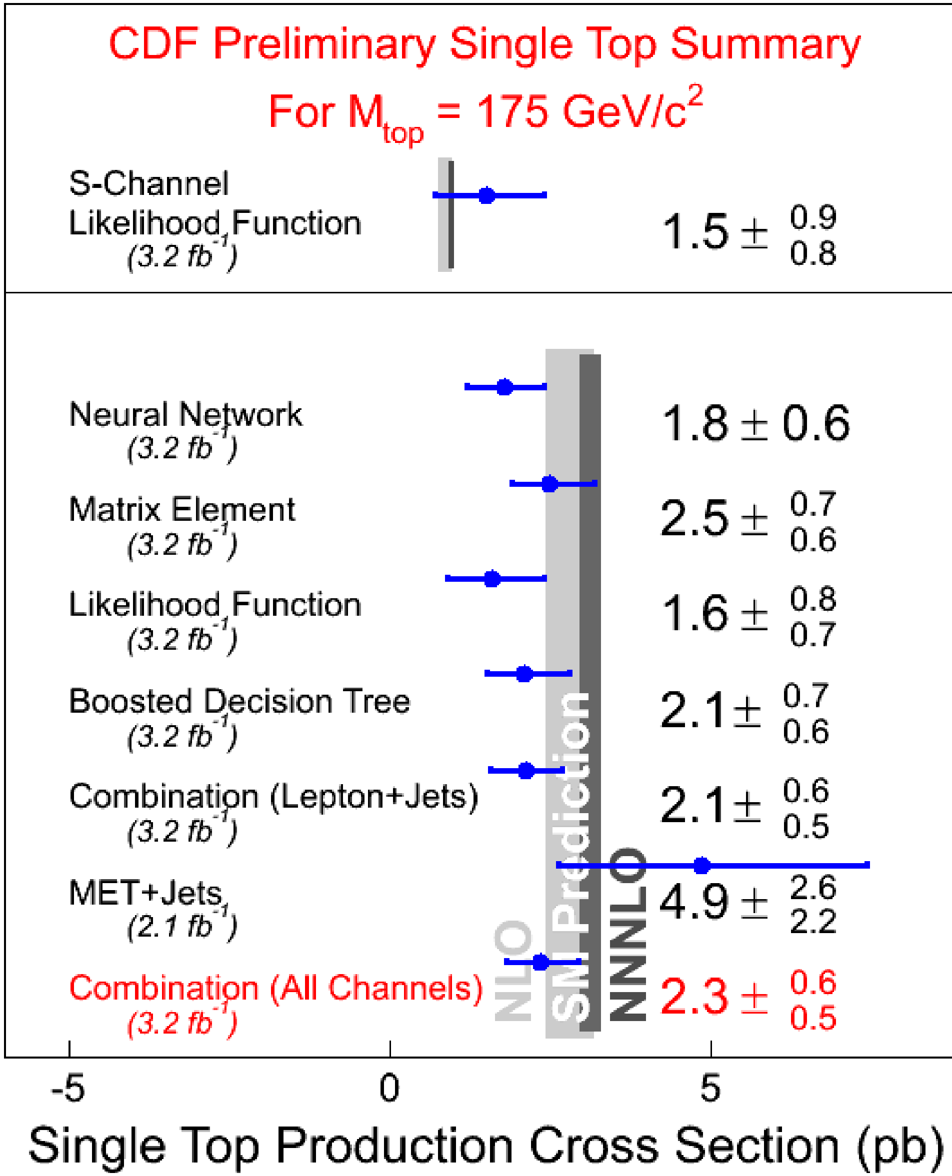
D0 Systematics

TABLE XI: Summary of the relative systematic uncertainties. The ranges shown represent the different samples and channels.

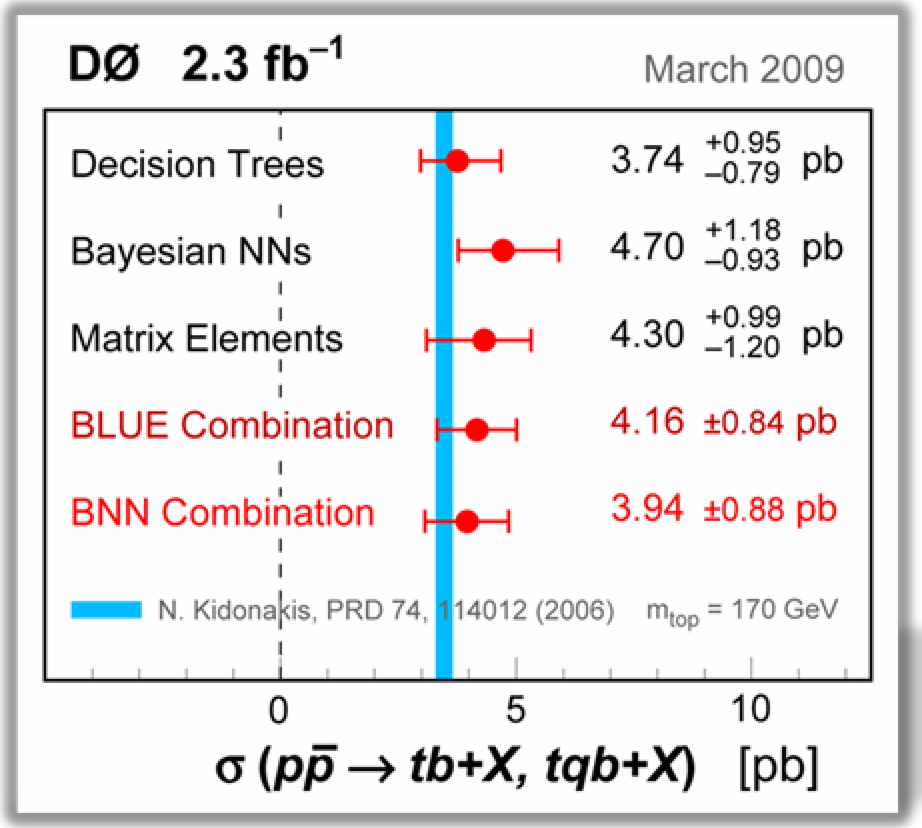
Relative Systematic Uncertainties	
Integrated luminosity	6%
$t\bar{t}$ cross section	18%
Electron trigger	3%
Muon trigger	6%
Primary vertex	3%
Electron reconstruction & identification	2%
Electron track match & likelihood	5%
Muon reconstruction & identification	7%
Muon track match & isolation	2%
Jet fragmentation	(5–7)%
Jet reconstruction and identification	2%
Jet energy scale	(1–20)%
Tag-rate functions	(2–16)%
Matrix-method normalization	(17–28)%
Heavy flavor ratio	30%
$\varepsilon_{\text{real-}e}$	2%
$\varepsilon_{\text{real-}\mu}$	2%
$\varepsilon_{\text{fake-}e}$	(3–40)%
$\varepsilon_{\text{fake-}\mu}$	(2–15)%

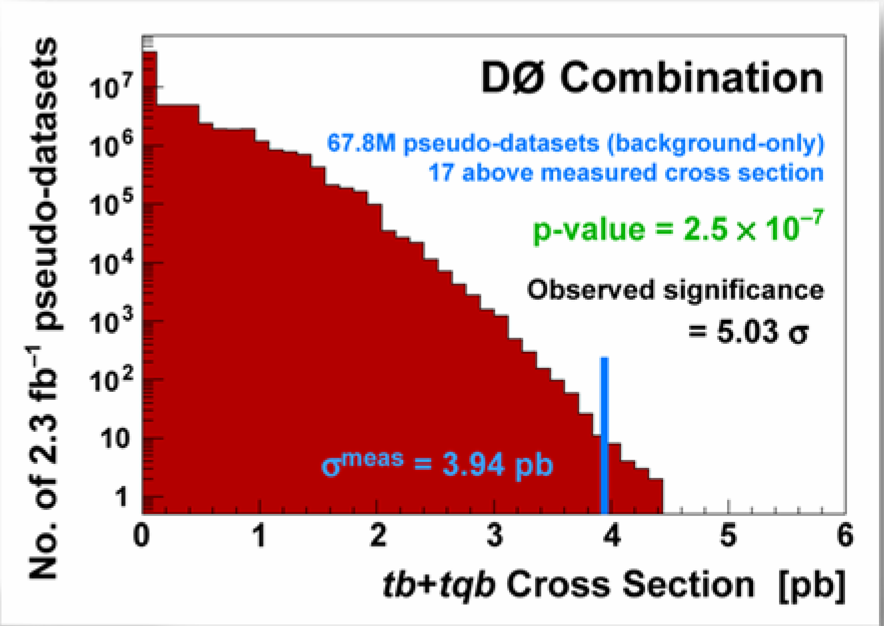
CDF Observation!

Analysis	Significance Std.Dev. (σ)	Sensitivity Std.Dev. (σ)
NN	3.5	5.2
ME	4.3	4.9
LF	2.4	4.0
LFS	2.0	1.1
BDT	3.5	5.2
SD	4.8	>5.9
MJ	2.1	1.4
Combined	5.0	>5.9



D0 Observation!





V_{tb}

$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$

CDF

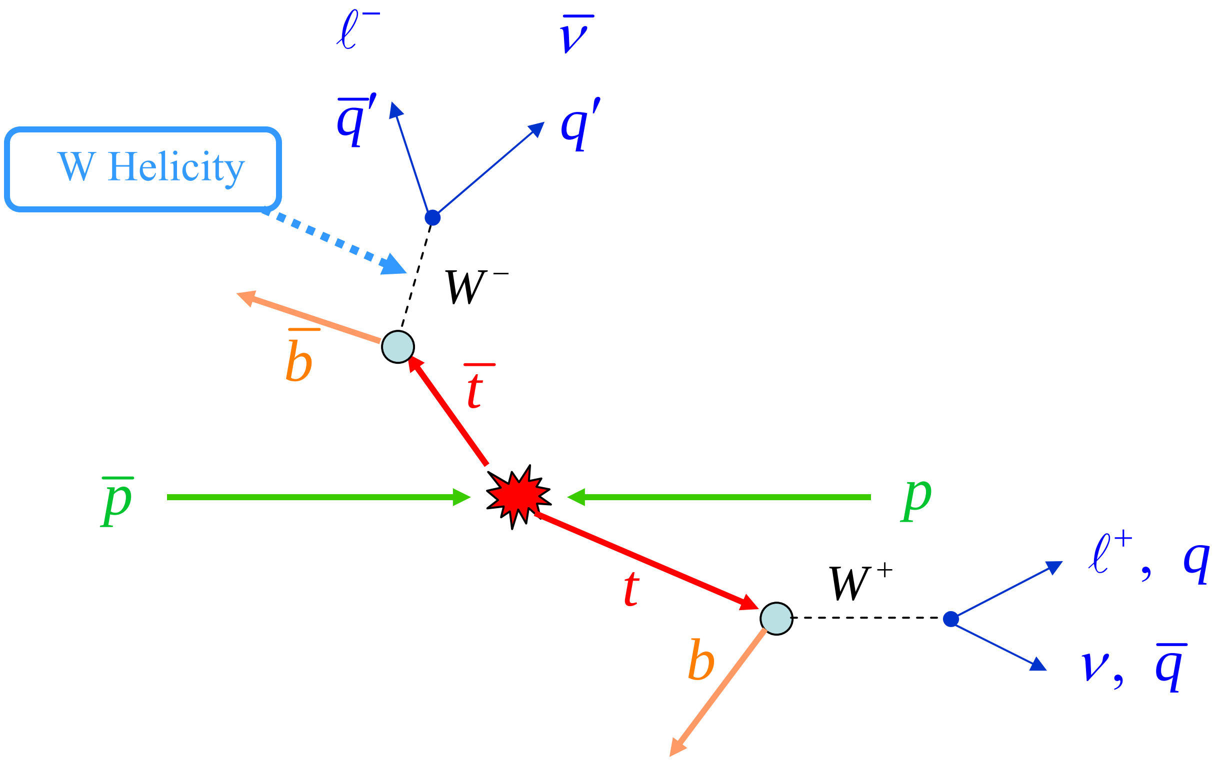
$|V_{tb}|= 0.91 \pm 0.11$ (stat+syst) ± 0.07 (theory)

$|Vtb|>0.71$ at 95% C.L.

D0:

$|V_{tb}\, f_1^L| = 1.07 \pm 0.12$

$0.78 < |V_{tb}| < 1$ @ 95% CL



ℓ^-
$\bar{\nu}$
$\bar{q}'$
q'
W Helicity
W^-
$\bar{b}$
$\bar{t}$
$\bar{p}$
p
ℓ^+, q
W^+
t
b
ν, $\bar{q}$

Does the Top Quark Decay as Expected?

Standard Model at the tWb vertex gives

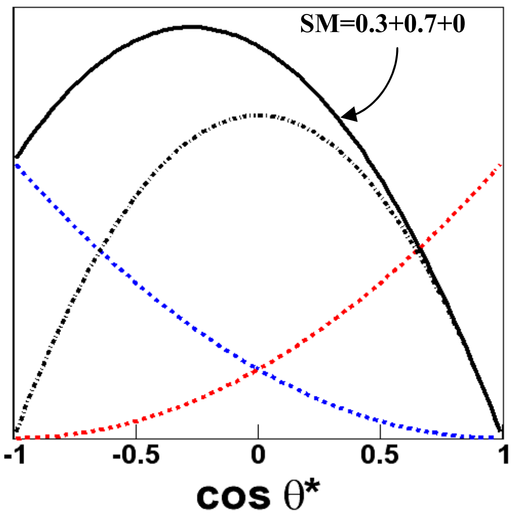
$$F_0 = \left(1 + 2\left(\frac{M_W}{M_t}\right)^2\right)^{-1} = 70\%\ \text{Longitudinal Ws}$$

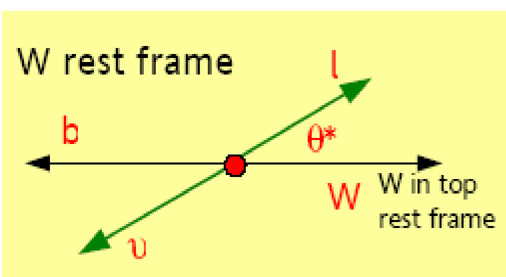
Measure via angular distribution:

left-handed $\frac{1}{4}\left(1-\cos\theta^*\right)^2$

longitudinal $\frac{1}{2}\left(1-\cos^2\theta^*\right)$

right-handed





Or: Matrix element technique

$$L(f_0, C_s) = \prod_{i=1}^{N}\left[C_s P_{t\bar{t}}(\vec{x}_i; f_0) + (1 - C_s) P_{W+jets}(\vec{x}_i)\right]$$

$$P(\vec{x}) = \frac{1}{\sigma_{obs}} \int \frac{d\sigma(\vec{y})}{d\vec{y}} f(q_1) f(q_2) W(\vec{x}, \vec{y})\, dq_1 dq_2 dp^y_{t\bar{t}} dp^x_{t\bar{t}} d\vec{y}$$

V-A → no right handed W bosons

W Helicity - Matrix Element

$$L\left(f_0, C_s\right) = \prod_{i=1}^{N}\left[C_s P_{t\bar{t}}\left(\vec{x}_i; f_0\right) + \left(1 - C_s\right) P_{W+jets}\left(\vec{x}_i\right)\right]$$

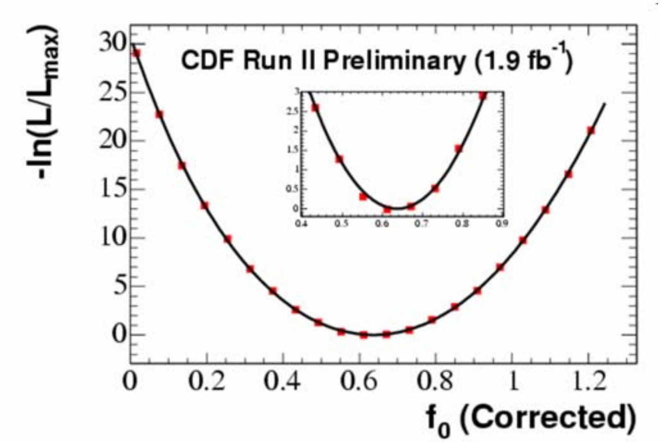
C_s = signal fraction

$$P\left(\vec{x}\right) = \frac{1}{\sigma_{obs}} \int \frac{d\sigma\left(\vec{y}\right)}{d\vec{y}} f\left(q_1\right) f\left(q_2\right) W\left(\vec{x}, \vec{y}\right) dq_1 dq_2 dp_{t\bar{t}}^{y} dp_{t\bar{t}}^{x} d\vec{y}$$

Differential xsec including helicity

PDFs

Transfer fcn from measured *x* to true *y*



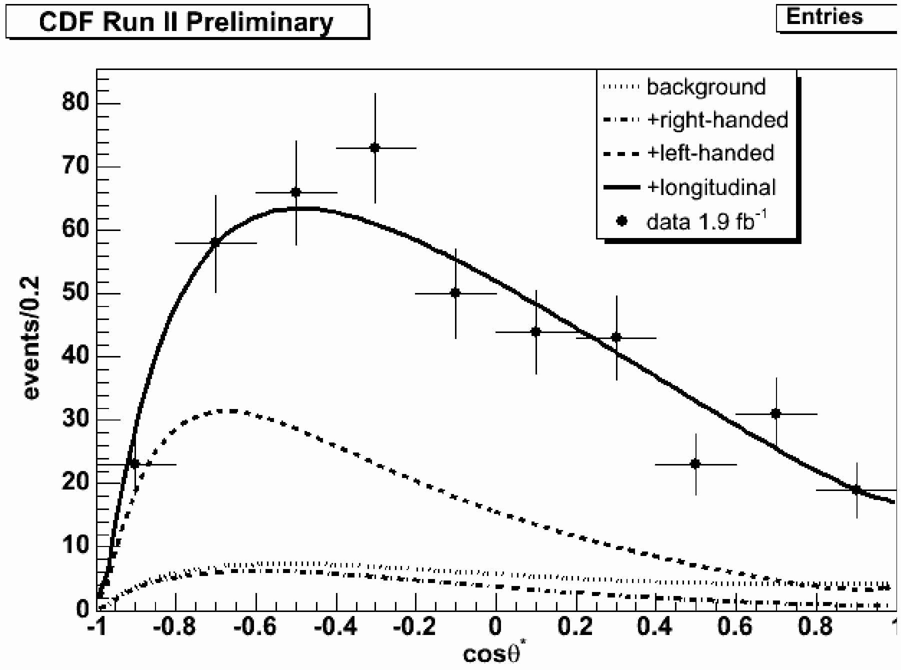
$f_0 = 0.64 \pm 0.08(\text{stat}) \pm 0.07(\text{sys})$

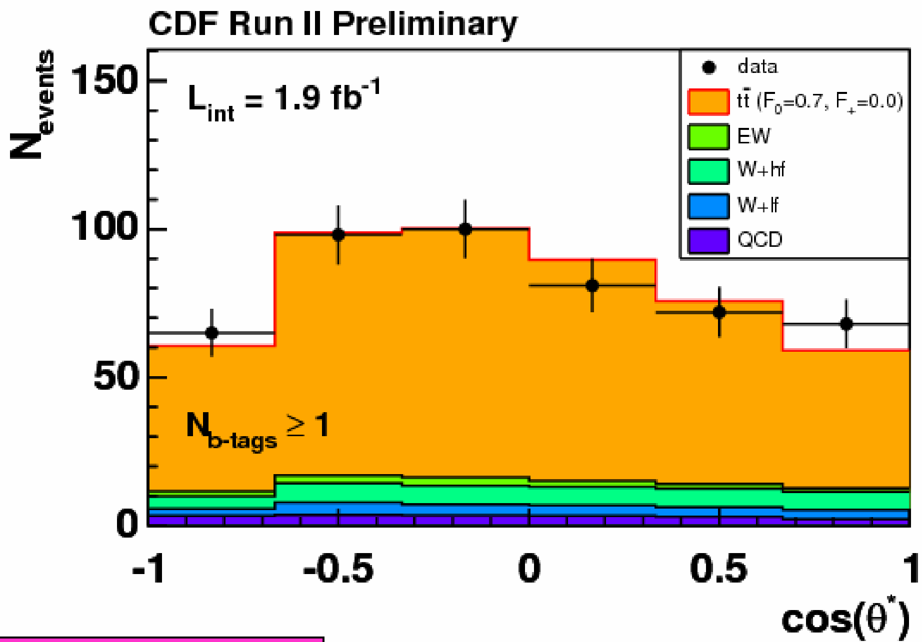
$f_+ \equiv 0$

Systematics here are dominated by MC modeling (f_0 measured $\rightarrow$ f_0 corrected)

W Helicity – cosθ*

Two reconstruction techniques used





$f_0 = 0.62 \pm 0.11$ w/ f_+ fixed

$f_+ = -0.04 \pm 0.05$ w/ f_0 fixed

$f_0 = 0.66 \pm 0.16$

2 parameter fit

$f_+ = -0.03 \pm 0.07$

Dominant systematics are background normalization & shape, and JES.

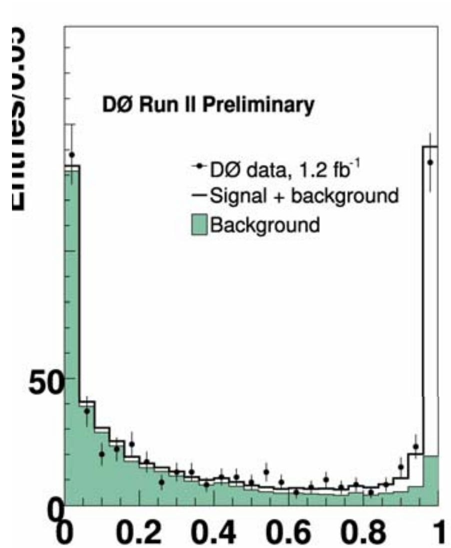
W Helicity – cosθ*

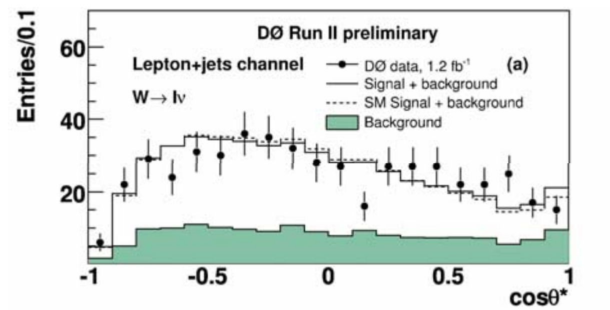
D0's latest uses lep+jets & dilep, & hadronic *W* decays

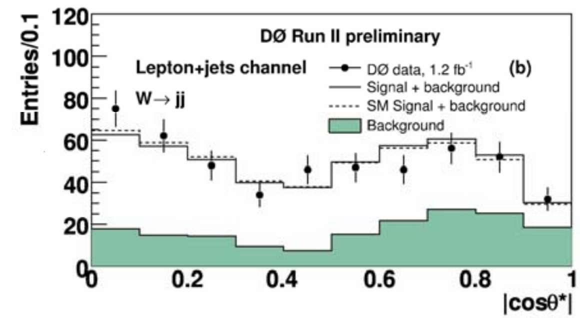
A kinematic discriminant provides extra S-B separation

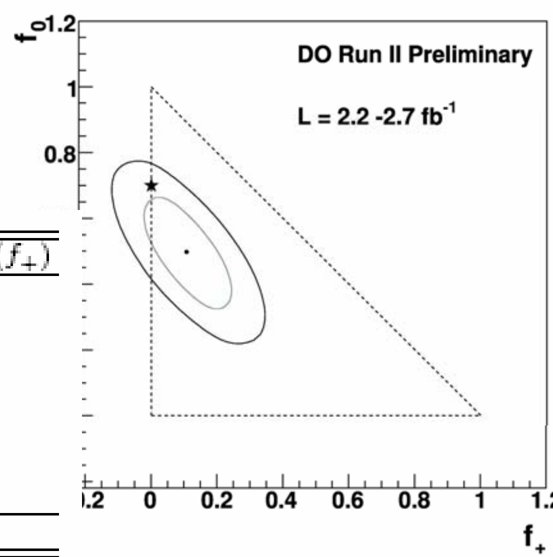
f_0 =0.490±0.106(stat)±0.085 (sys)

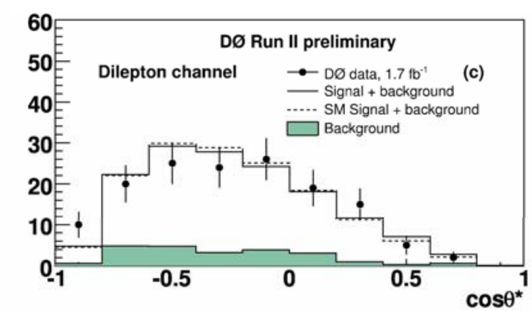
f_+ =0.110±0.059(stat)±0.052 (sys)











Source	Uncertainty (f_0)	Uncertainty (f_+)
Top mass	0.009	0.016
Jet reconstruction eff.	0.018	0.009
Jet energy calibration	0.029	0.019
Jet energy resolution	0.023	0.008
$t\bar{t}$ model	0.055	0.028
Background model	0.039	0.026
Template statistics	0.028	0.014
Total	0.085	0.052

Anomalous Couplings

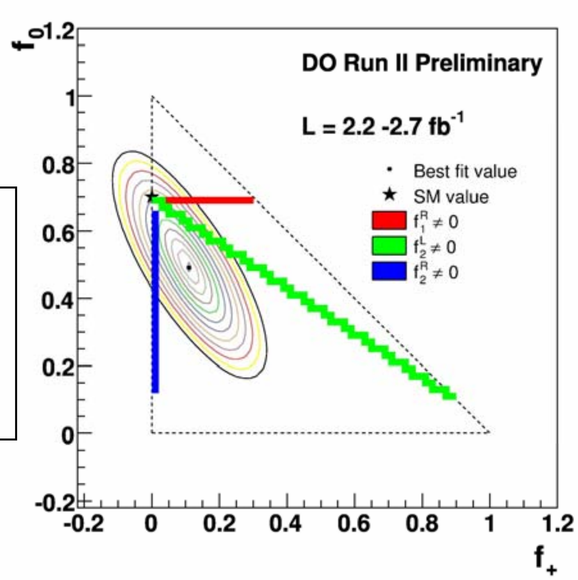
D0 combines the single-top result and W helicity measurements to set limits on anomalous couplings.

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_1^L P_- + f_1^R P_+\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{-i\sigma^{\mu\nu}q_{\nu}V_{tb}}{M_W}\left(f_2^L P_- + f_2^R P_+\right)tW_{\mu}^{-} + h.c.$$

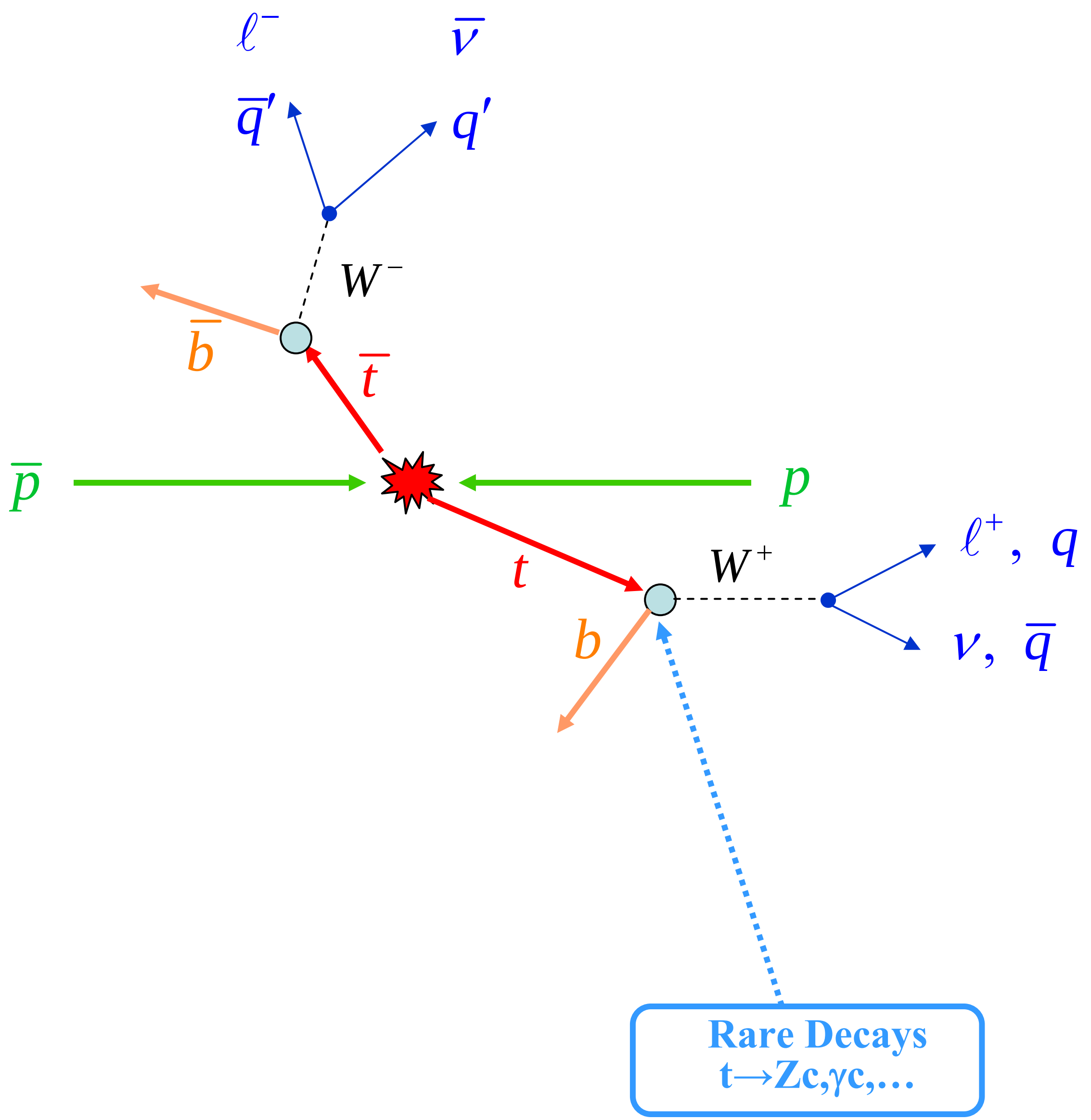
$$P_{\pm} = \left(1 \pm \gamma_5\right)/2$$

≡0 in S.M.

Non-zero values would change W helicities and kinematics and rate of single-top production.



Scenario	Coupling	Coupling limit if $f_1^L = 1$
(f_1^L, f_1^R)	$\lvert f_1^L\rvert^2 = 1.36^{+0.56}_{-0.46}$	
	$\lvert f_1^R\rvert^2 < 0.72$	$\lvert f_1^R\rvert^2 < 0.72$
(f_1^L, f_2^L)	$\lvert f_1^L\rvert^2 = 1.44^{+0.65}_{-0.51}$	
	$\lvert f_2^L\rvert^2 < 0.30$	$\lvert f_2^L\rvert^2 < 0.19$
(f_1^L, f_2^R)	$\lvert f_1^L\rvert^2 = 1.16^{+0.51}_{-0.44}$	
	$\lvert f_2^R\rvert^2 < 0.19$	$\lvert f_2^R\rvert^2 < 0.20$

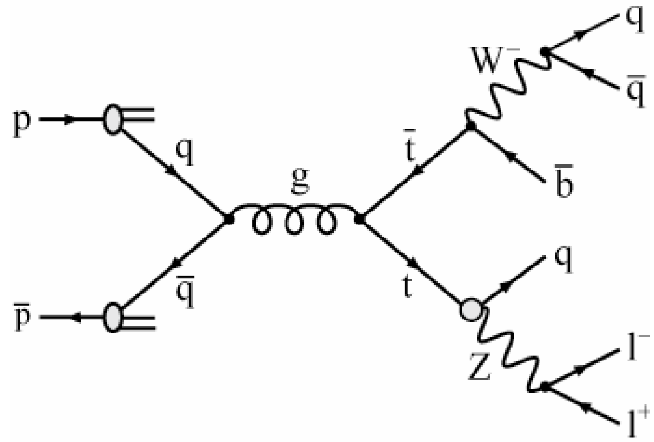


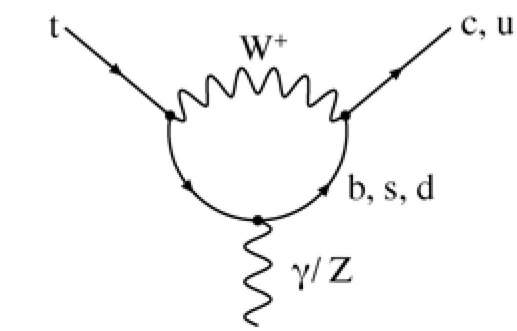
ℓ^-
$\bar{\nu}$
$\bar{q}'$
q'
W^-
$\bar{b}$
$\bar{t}$
$\bar{p}$
p
t
W^+
$\ell^+, \ q$
$\nu, \ \bar{q}$
b
Rare Decays
t→Zc,γc,…

FCNC Search

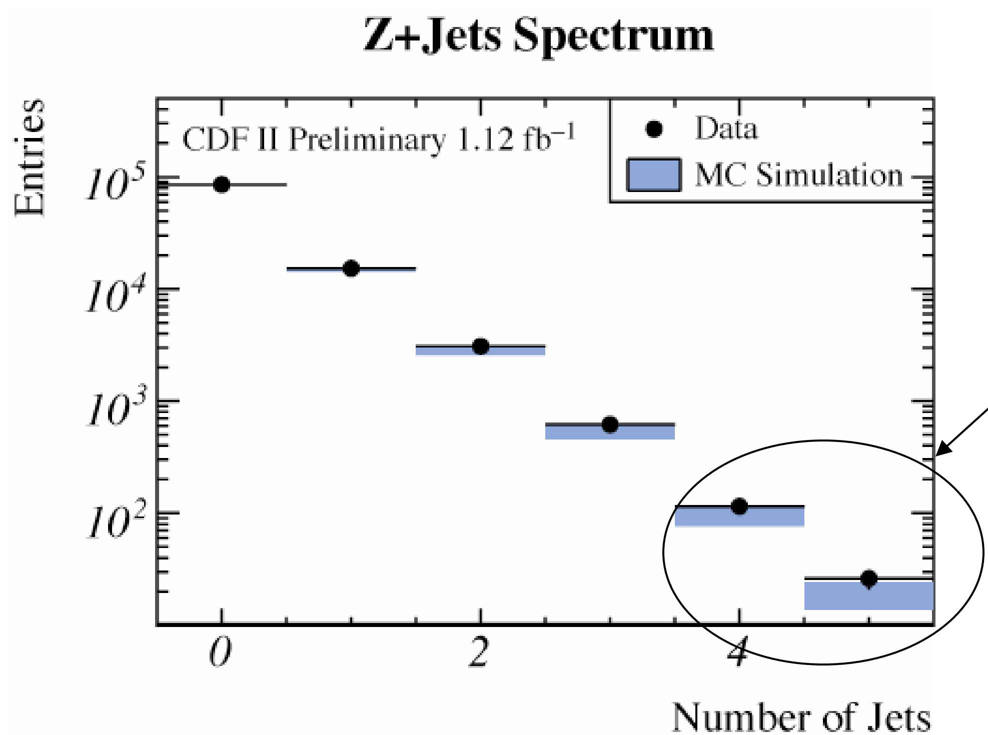
$t \rightarrow Zq$

BR ~ 10^{-14} in SM ⇒ Any observation is PBSM!





Search in Z→ee,μμ + 4 or more jets

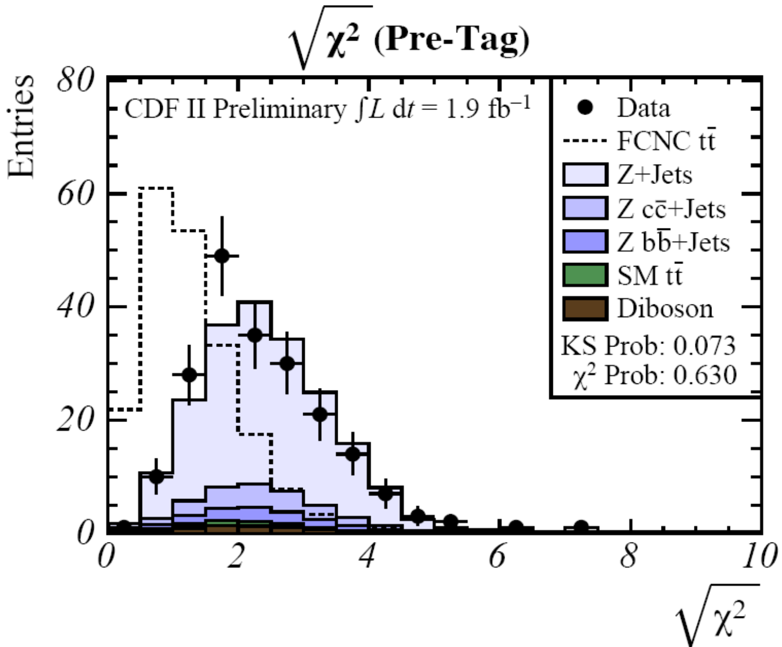


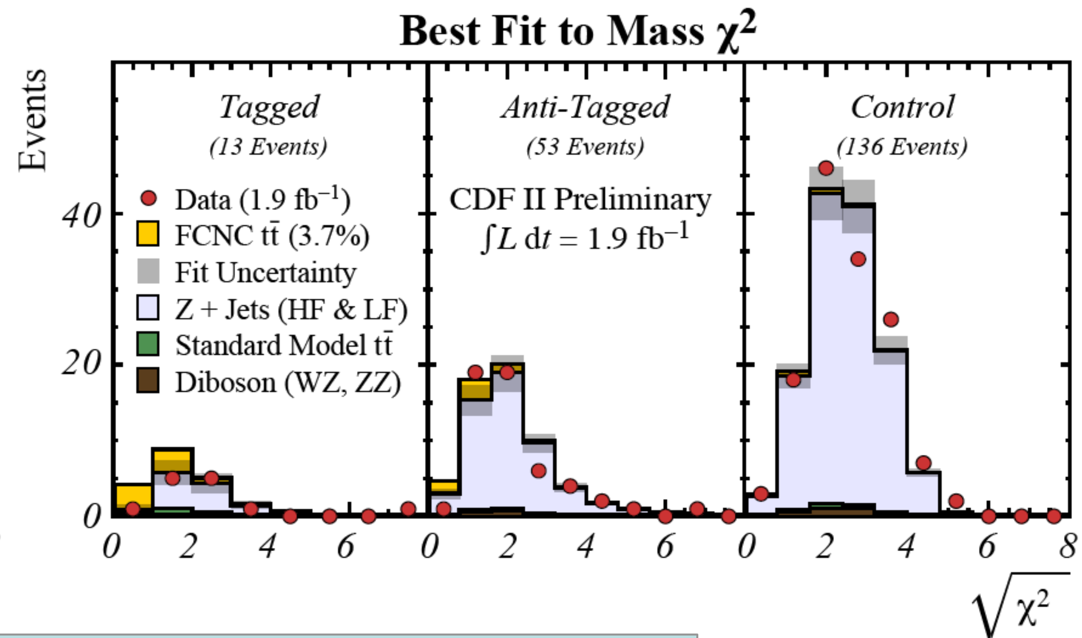
FCNC Results

Dominant backgrounds are Z+4 jets, WW, WZ.
Background suppression is achieved via a mass χ^2 variable:

$$\chi^2 = \left(\frac{m_{W,\mathrm{rec}} - m_{W,\mathrm{PDG}}}{\sigma_{W,rec}}\right)^2 + \left(\frac{m_{t\to Wb,\mathrm{rec}} - m_{t,\mathrm{PDG}}}{\sigma_{t\to Wb}}\right)^2 + \left(\frac{m_{t\to Zq,\mathrm{rec}} - m_{t,\mathrm{PDG}}}{\sigma_{t\to Zq}}\right)^2$$

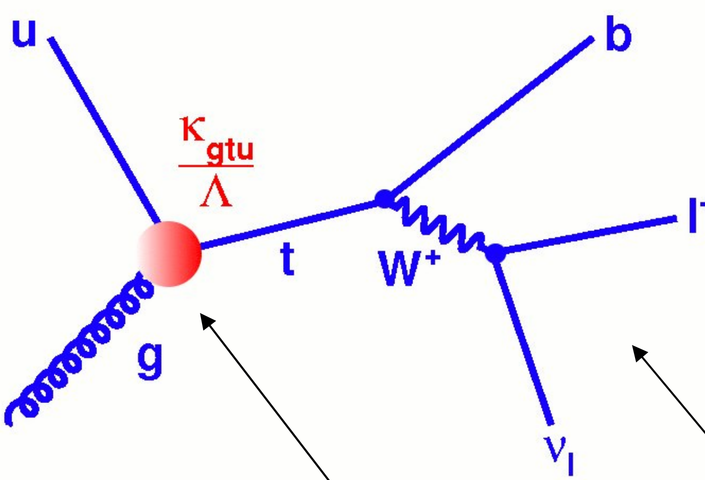
Note: final state is neutrino-free.





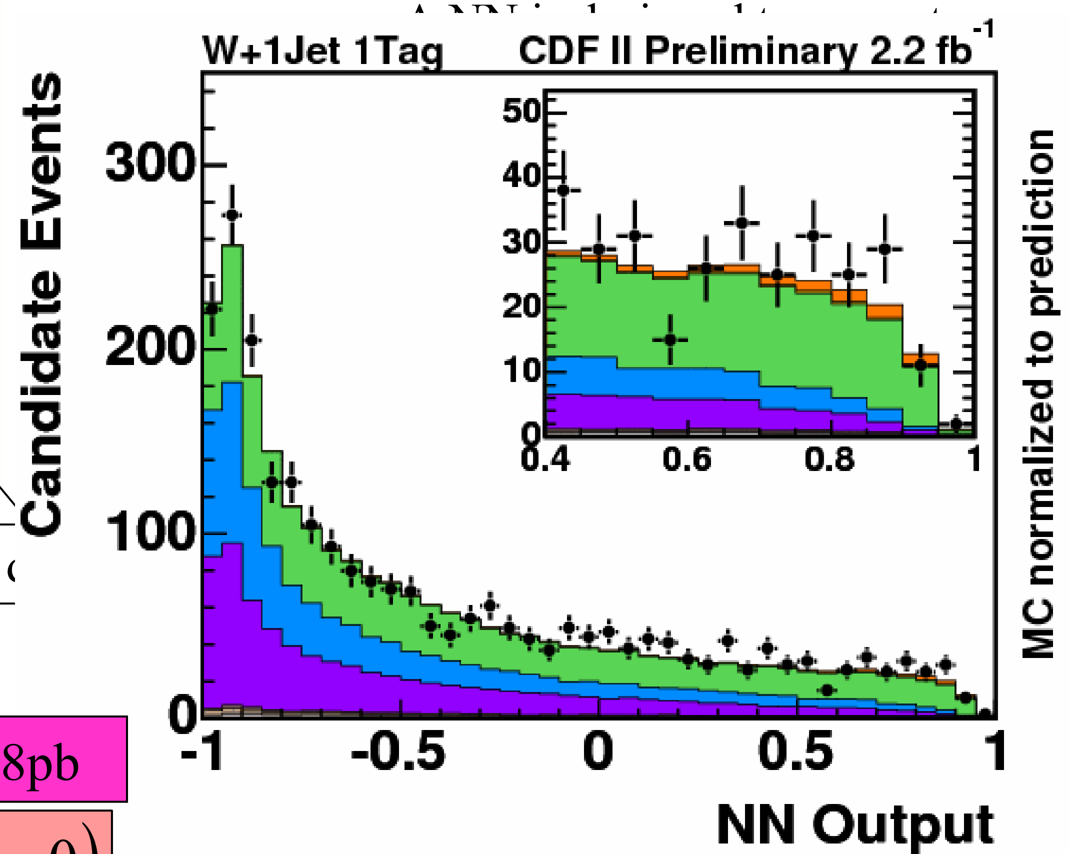
$$B(t \to Zq) < 3.7\% \text{ @ } 95\% \text{ C.L.}$$

FCNC in Single Top Production



Anomalous production

..but SM (



Very hard to distinguish SM from FCNC!

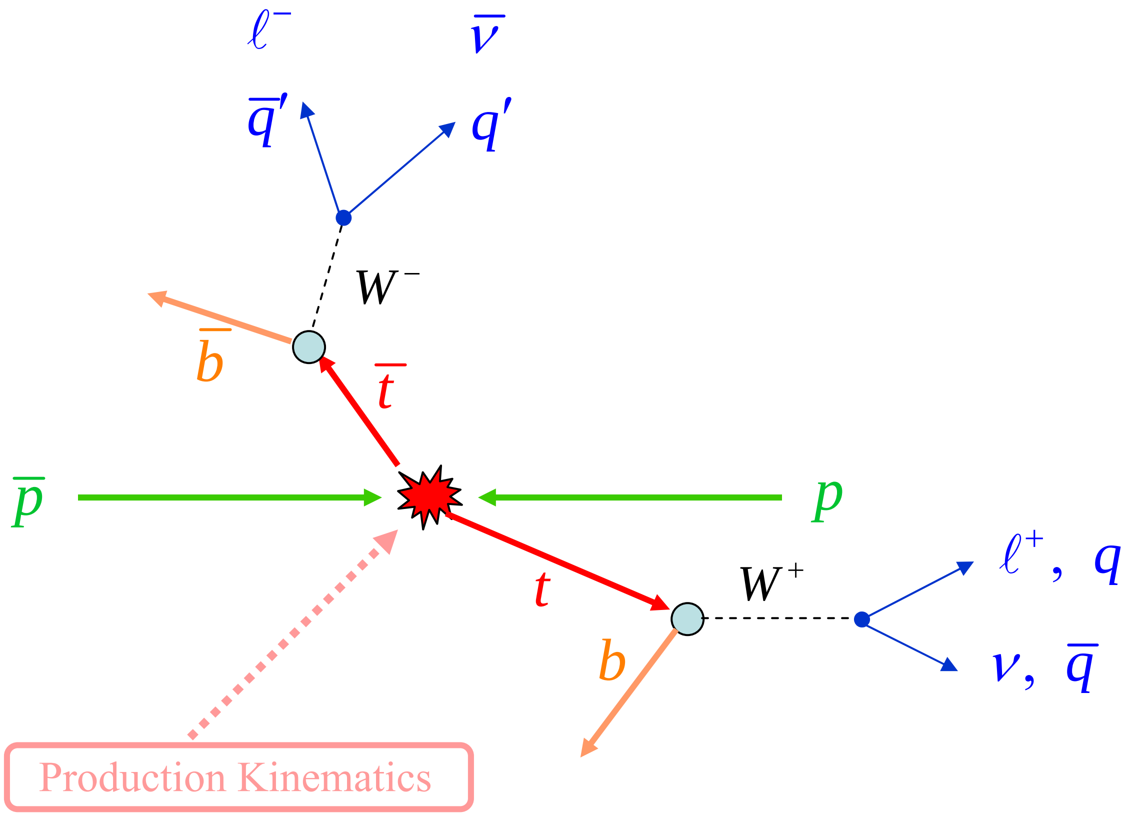
No signal observed ⇒ $\sigma_{FCNC} < 1.8$pb

$$\kappa_{tug}/\Lambda < 0.018\ \text{TeV}^{-1} \quad \left(\kappa_{tcg} \equiv 0\right)$$

$$\kappa_{tcg}/\Lambda < 0.069\ \text{TeV}^{-1} \quad \left(\kappa_{tug} \equiv 0\right)$$

$$B\left(t \rightarrow u + g\right) < 3.9 \times 10^{-4}$$

$$B\left(t \rightarrow c + g\right) < 5.7 \times 10^{-3}$$

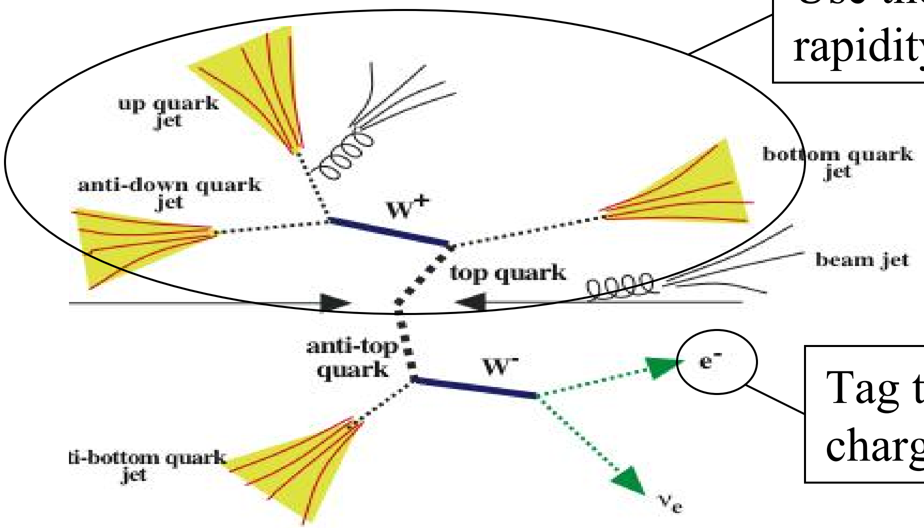


ℓ^-
$\bar{\nu}$
$\bar{q}'$
q'
W^-
$\bar{b}$
$\bar{t}$
$\bar{p}$
p
t
W^+
$\ell^+, \; q$
b
$\nu, \; \bar{q}$
Production Kinematics

Forward-Backward Asymmetry

$$A_{fb} = \frac{N_t(p) - N_t(\overline{p})}{N_t(p) + N_t(\overline{p})}$$

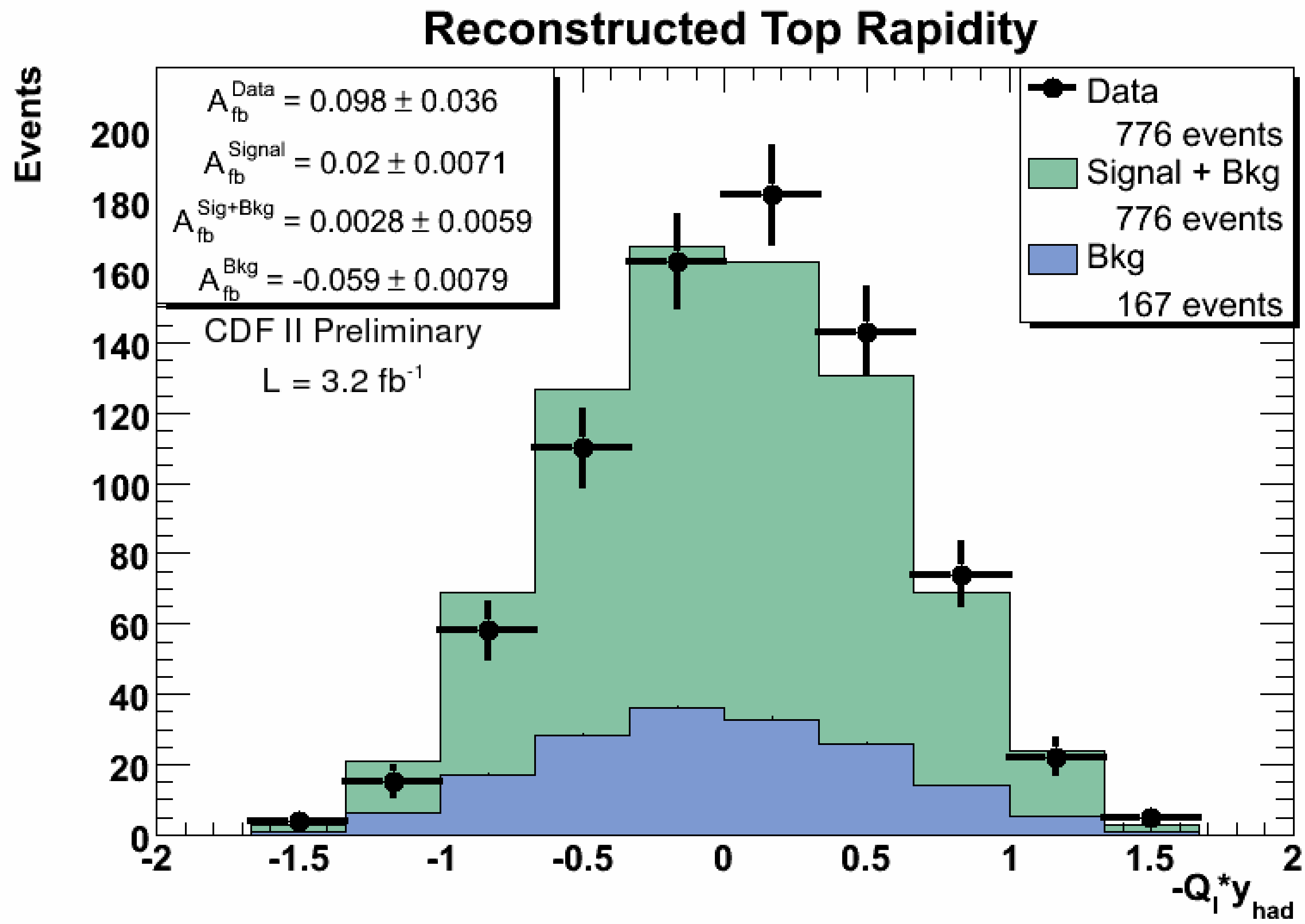
Use the hadronic side to measure top rapidity.



Tag t vs tbar with lepton charge.

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

A_{fb}



$$A_{fb}^{corrected} = 0.193 \pm 0.065 \pm 0.024$$

Conclusions

- A broad program of measurements of the properties of the top quark is underway at the Tevatron.
- Single top has (finally) been observed!
- The Run 2 dataset (CDF+D0) is beginning to provide sensitive searches for PBSM in top production and decay.
- The uncertainty on the top mass, *individually*, from CDF and D0 is <1% (!!!)
  - The Higgs appears to be light…
- These measurements will focus the work to be done at the top factory called the LHC.