Cornell University
Floyd R. Newman Laboratory for
Elementary-Particle Physics

Top Physics at the Tevatron

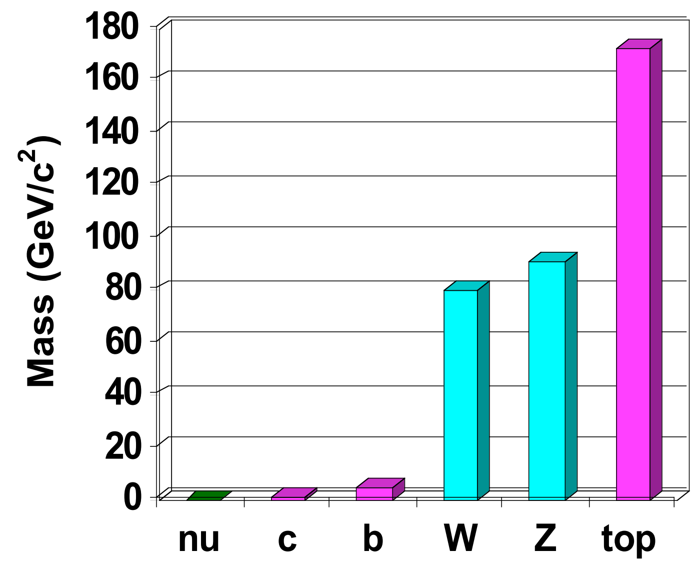
Physics at the LHC, 2010
Hamburg, 6/10/2010
Julia Thom, Cornell University

Top Quark Physics

Most massive elementary particle

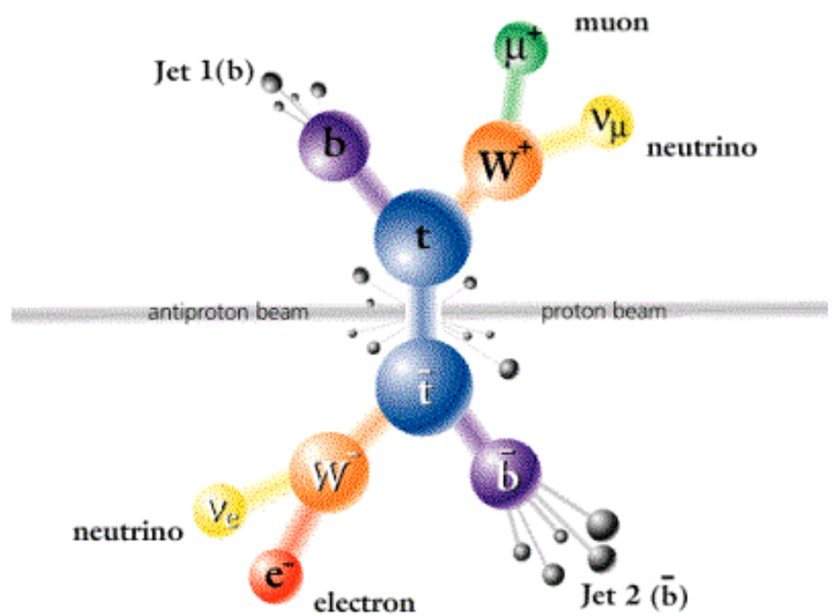
–Discovered in 1995, only few dozen candidates in 0.1 fb^{-1}

- Any effects from new physics?
  - Studies with 2-5 fb^{-1} for this talk
- Top quark mass is a fundamental parameter in the Standard Model and beyond
  - Induces significant radiative corrections to W boson mass
  - Reduced uncertainty on top quark mass imposes tighter constraints on unknowns, like Standard Model Higgs boson or SUSY
- Significant background to many searches for new physics at LHC



Outline

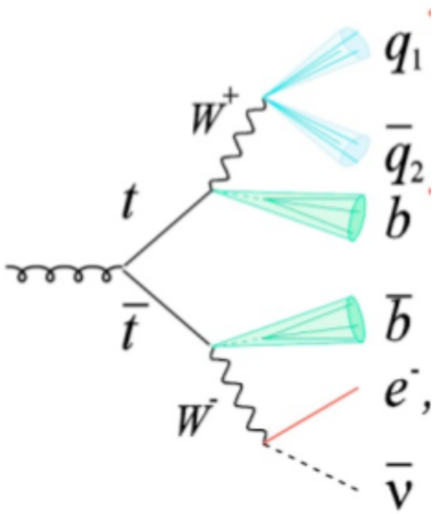
- The top signature and how to separate signal from background
- Top Quark Production
  - Top pairs, mass
  - Searches for anomalous production
  - Single top
- Tests of Top Quark Decay
  - W boson helicity in top decays
  - Probe the W-t-b vertex



Identifying top events

Events classified by decays of the two W bosons:

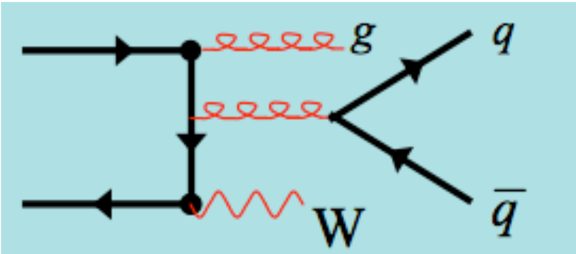
- "lepton+jets": 4 jets (2 from b) and missing E_T from ν
  - BF=24/81, but significant background from W+jet production

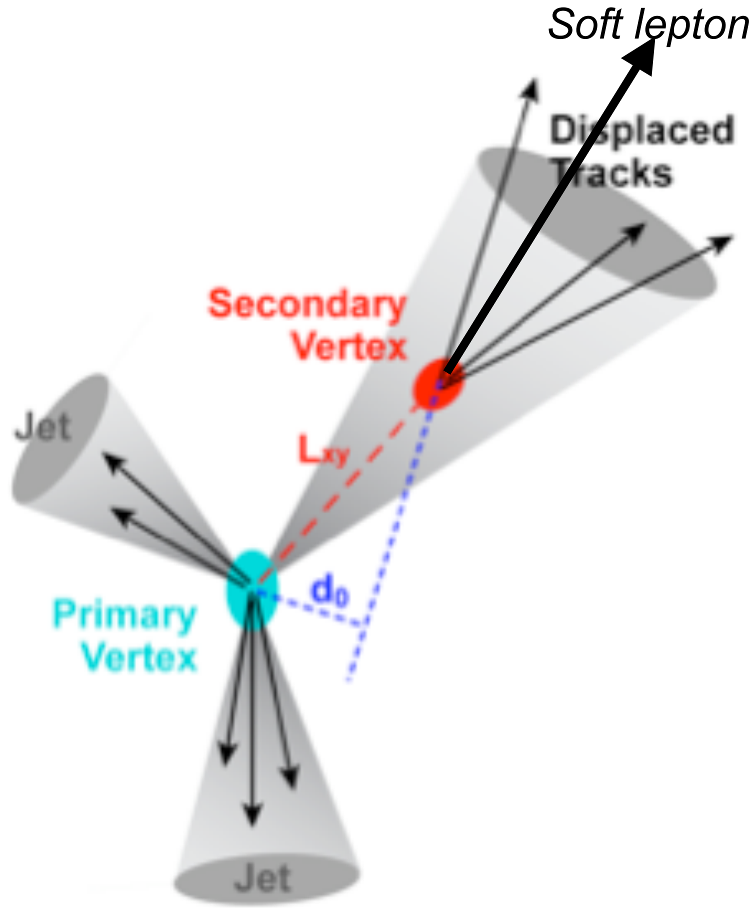


- "dilepton": 2 jets and missing E_T from ν
  - Clean, but low stat. BF=4/81
- "hadronic": 6 or more jets
  - BF=36/81, but large QCD multijet background
  - Jet energy scale uncertainty, combinatorics

"l+jets" events, background suppression

- Key is identification of at least 1 b-jet. Background reduced to Wbb (few % of W+jets background)



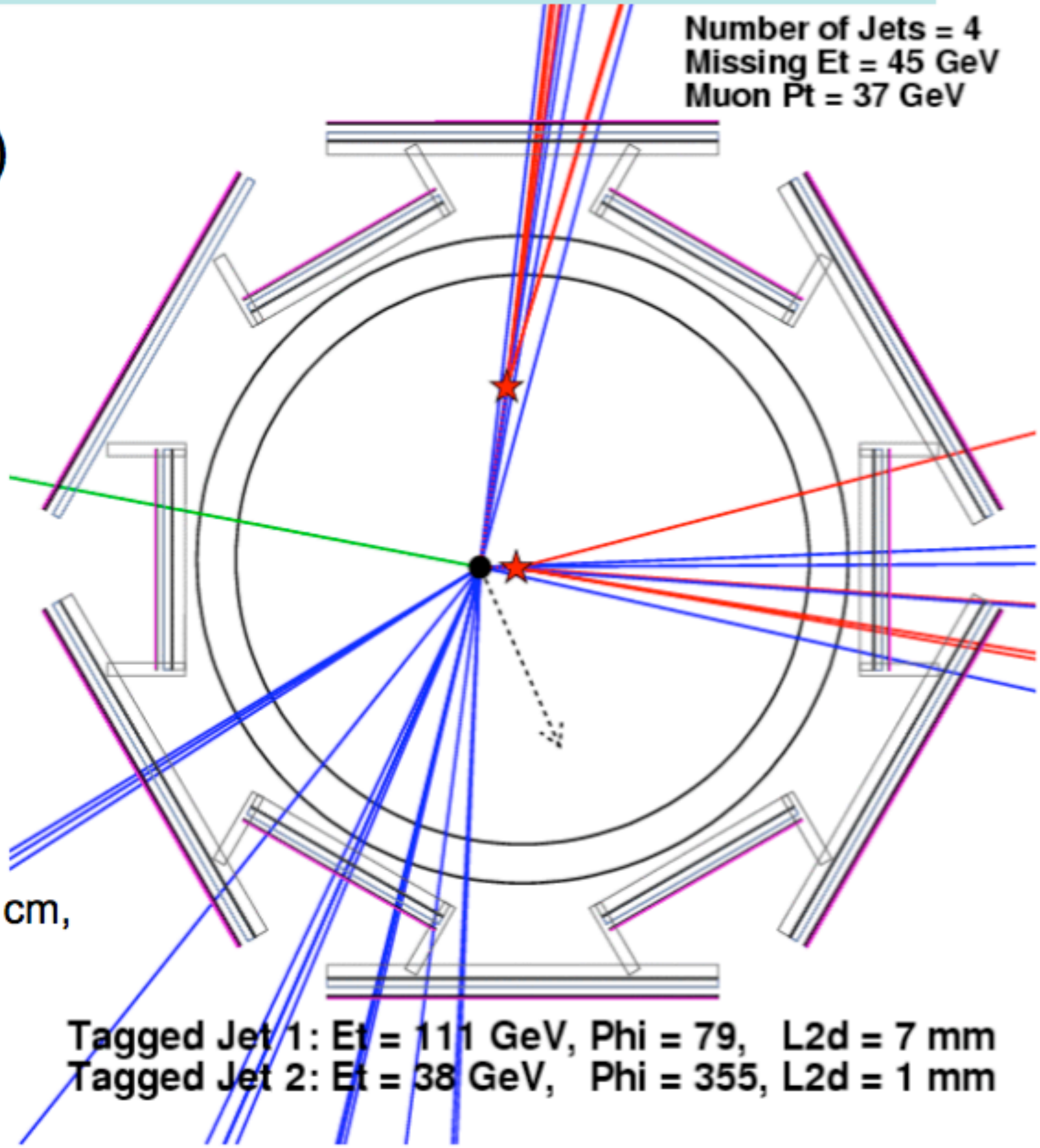


- 2 techniques:
  - Secondary vertex tag: find decay vertex of long-lived hadron in jet.
  - Soft lepton tag: lepton in jet from semileptonic decay of B
- Typically at least one b-tag required for a top l+jet candidate

Secondary vertex tag

Efficiency per b-jet: ~50% (top)

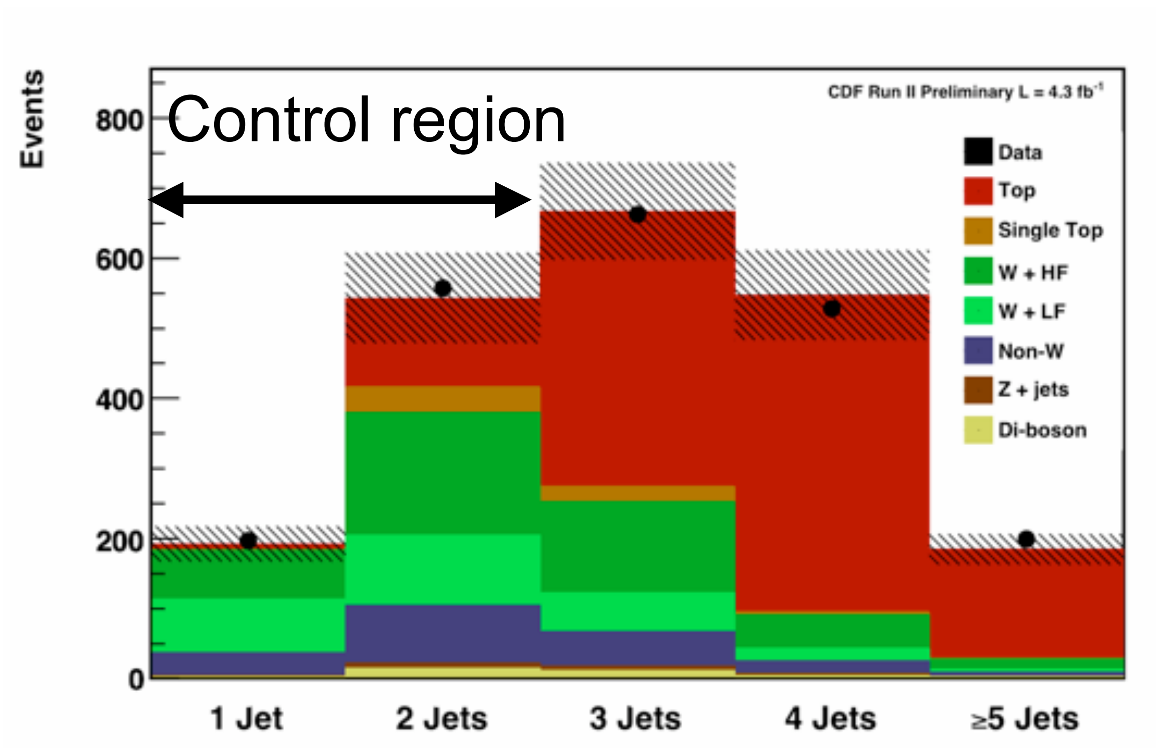
False positive rate:~1%



CDF beampipe, r=1.26 cm, and first layer of silicon microstrip detector

l+jets+btag analysis, limiting factors

- Dominant background is W+bb,cc ("W+HF"), and predicting it leads to one of the dominant systematics
- Important to understand W+HF normalization in exclusive jet bins (single top, Higgs discovery,..)



W+HF backgrounds

- Normalize ALPGEN W+jets (pretag) to data:

$$N^{pretag}_{W+jets} = N^{pretag}_{data} - N^{pretag}_{QCD} - N^{pretag}_{EWK} - N^{pretag}_{top}$$

- determine heavy flavor fraction in ALPGEN W+jets
- Measure correction factor K to heavy flavor fraction

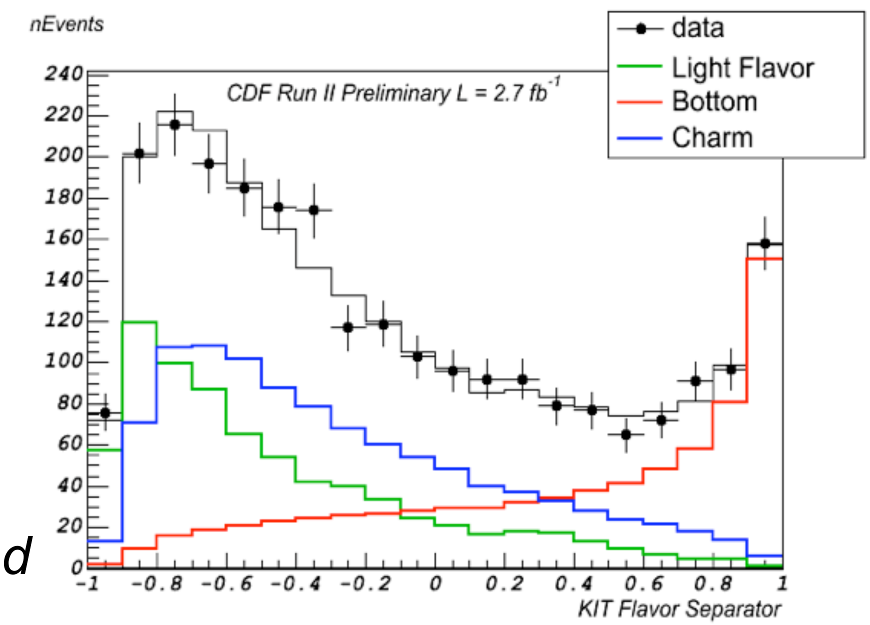
  W+HF = normalized W+jets × K × heavy flavor fraction

- at CDF, K extracted in W+1 jet control region:

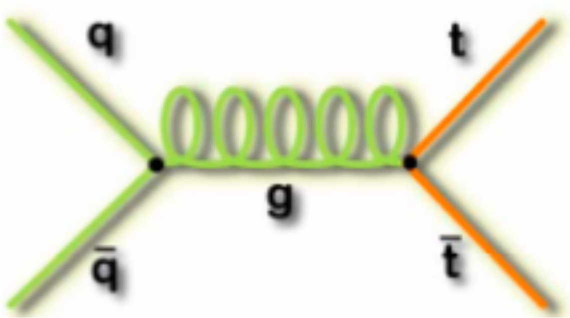
$K_{CDF} = 1.4 \pm 0.4$

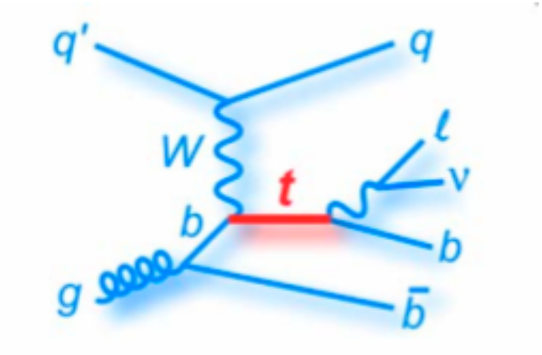
$K_{D0} = 1.5 \pm 0.45$

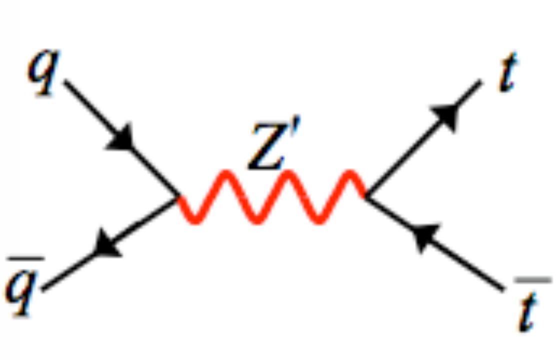
Kin.observables: top decay products are more central and more energetic than background



- **Top quark production**
  - Top pairs, mass
  - Searches for anomalous production
  - Single top
- Top quark decay
  - *W boson helicity in top decays*
  - *Probe the W-t-b vertex*



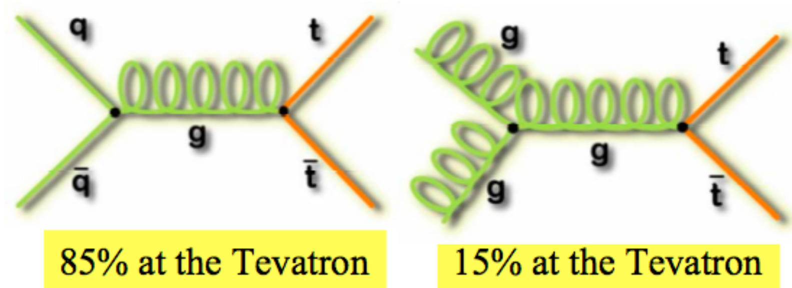




pair production cross section

Produce top in pairs via strong interaction. At m_t=170 GeV/c^2 σ=7.8±1pb

Cacciari et al. JHEP 0404:068 (2004)
Kidonakis, Vogt, PRD 68 114014 (2003)



$$\sigma_{tt} = \frac{N_{data} - N_{bkg}}{A \cdot \varepsilon \cdot L}$$

candidate events

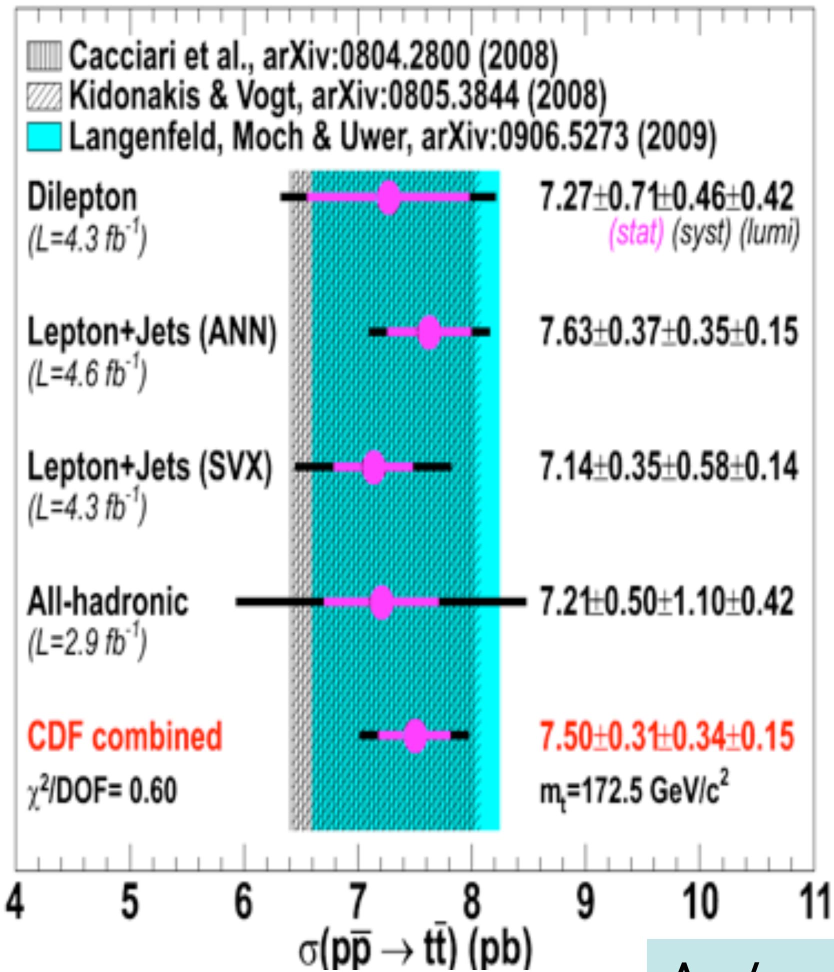
backgrounds from MC and data

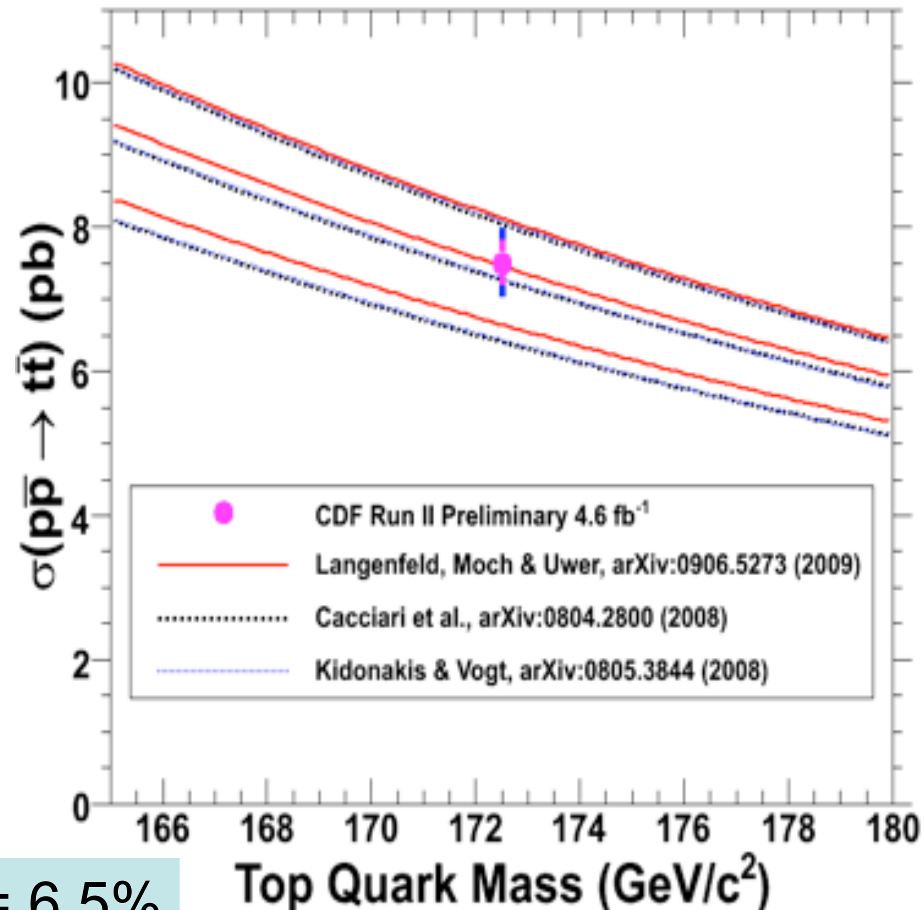
geometric acceptance and efficiencies from MC (mostly)

integrated luminosity

Cross section results 1

2.9-4.6 fb^{-1}



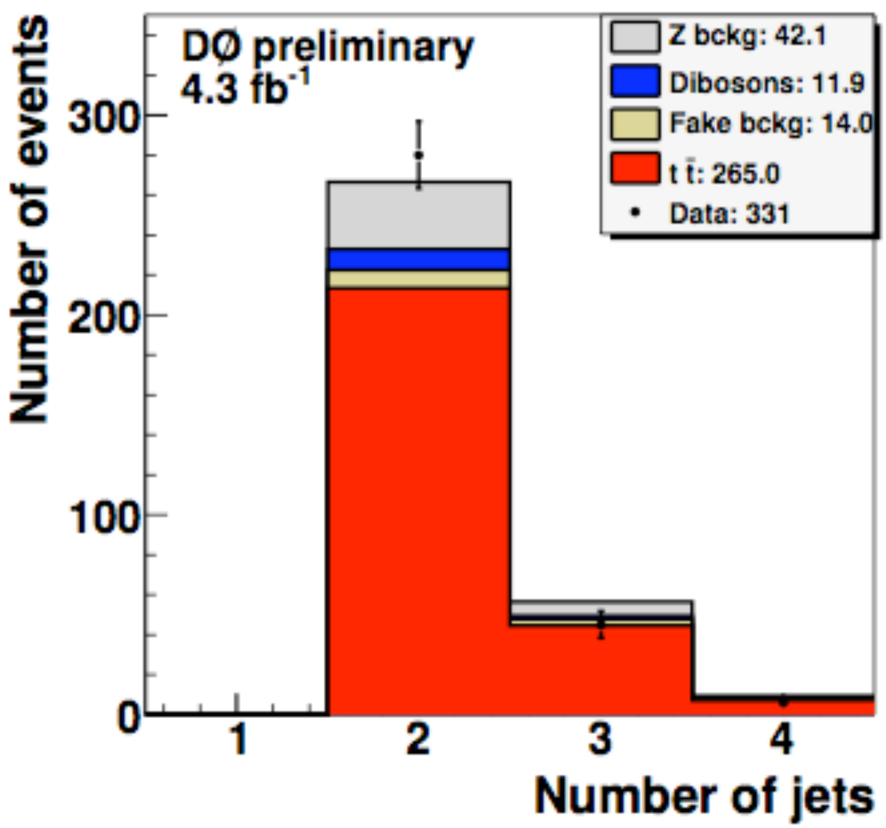


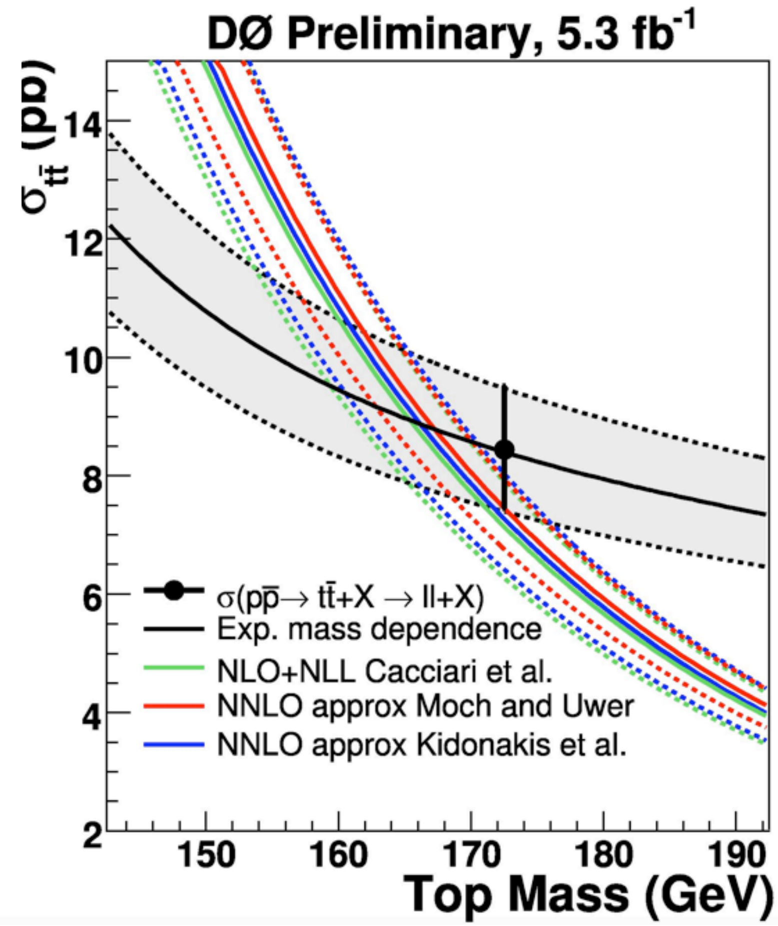
$\Delta\sigma/\sigma = 6.5\%$

$\sigma_{tt} = 7.50 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{Lumi})$ pb

Cross section results 2

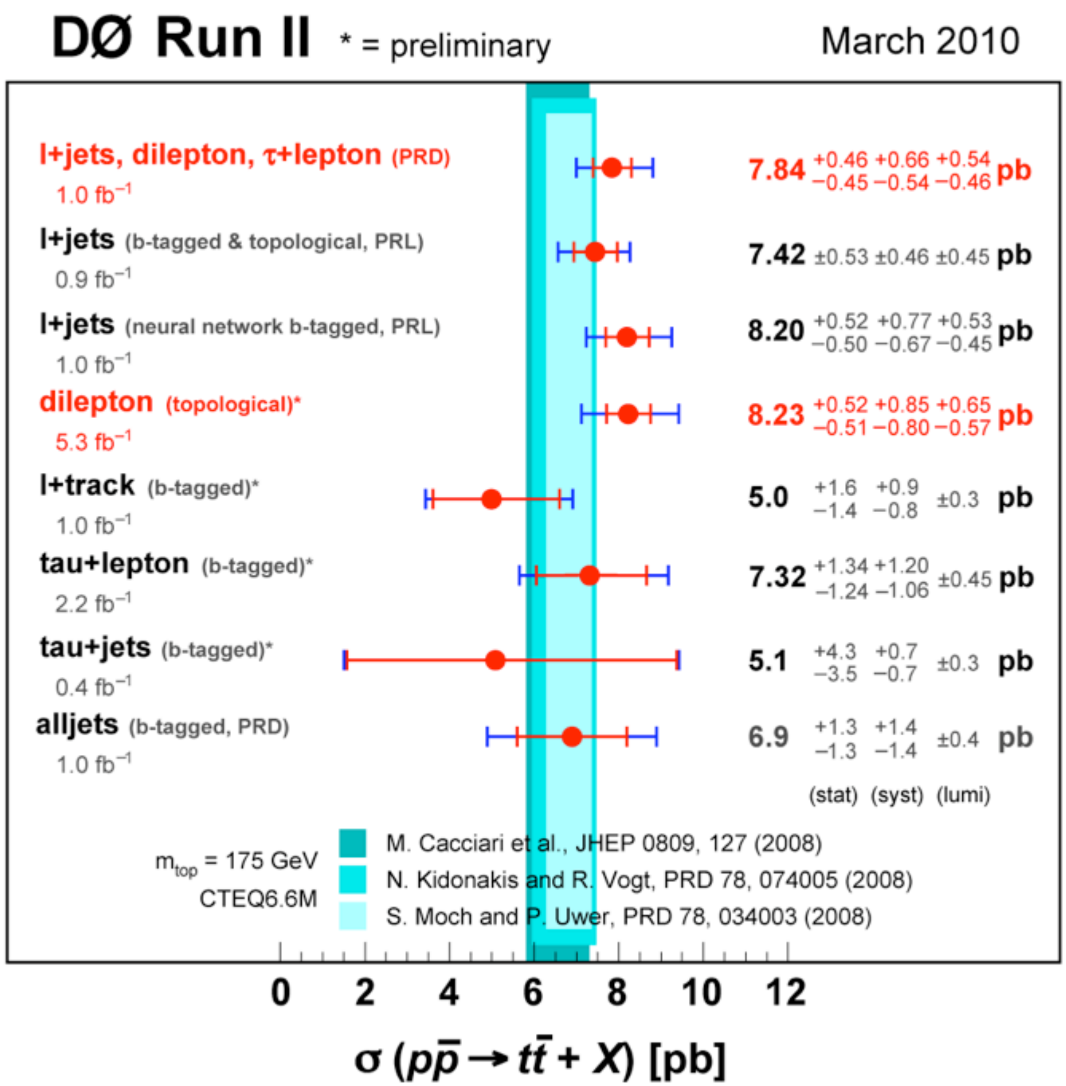
dilepton channel:





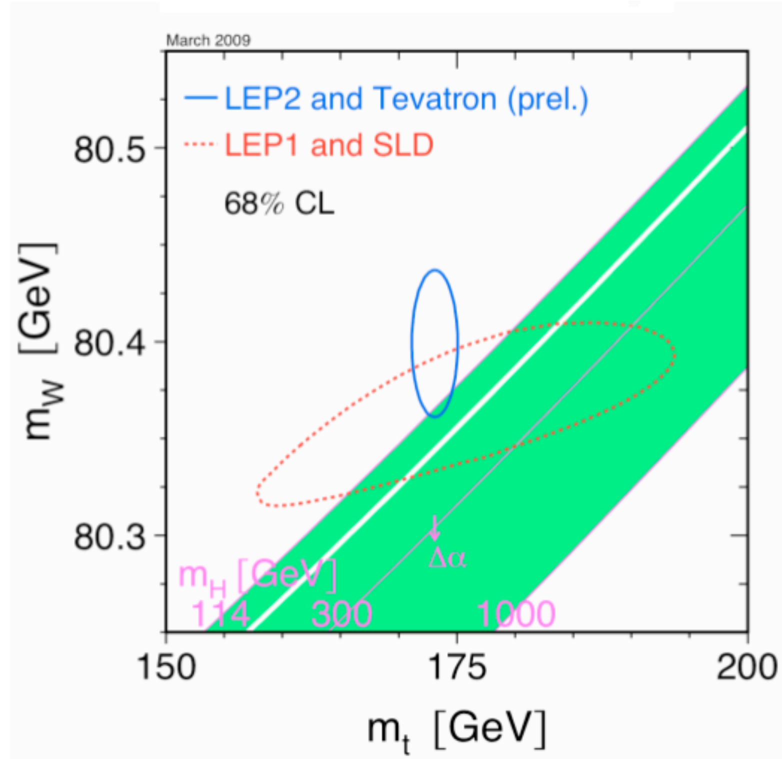
σ_{tt} = 8.4 ± 0.5(stat) ± 0.9(syst)±0.6(Lumi) pb

Cross section results 2



Top Mass

- Challenge: associate measured objects to initial state quarks and leptons (incl.neutrino), extract best possible 4-vector for each
  - E.g. Matrix element method: determine probability density for each combination



- Major systematic: Jet Energy Scale
  - Run II: constrain JES uncertainty using reconstructed hadronic W ("in-situ calibration"), fit for both JES and top mass

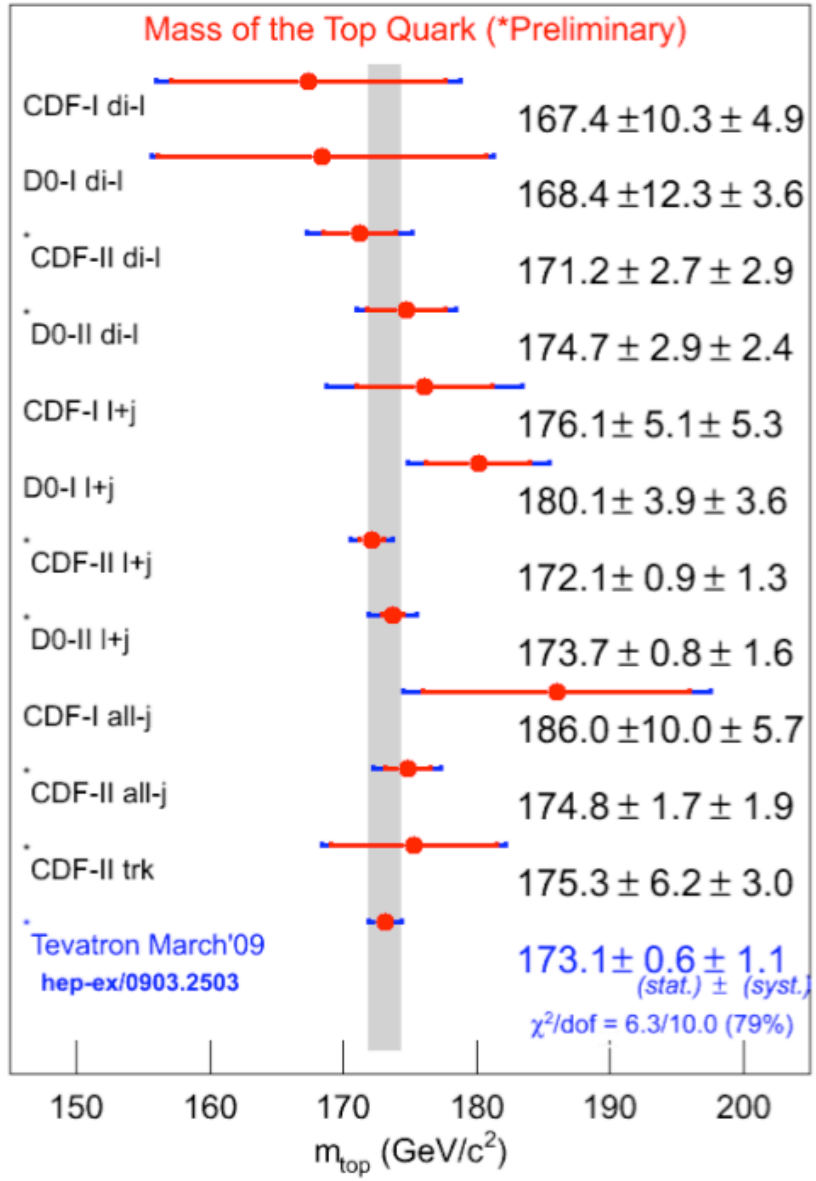
Tevatron Combination

March 2009 Tevatron combination:

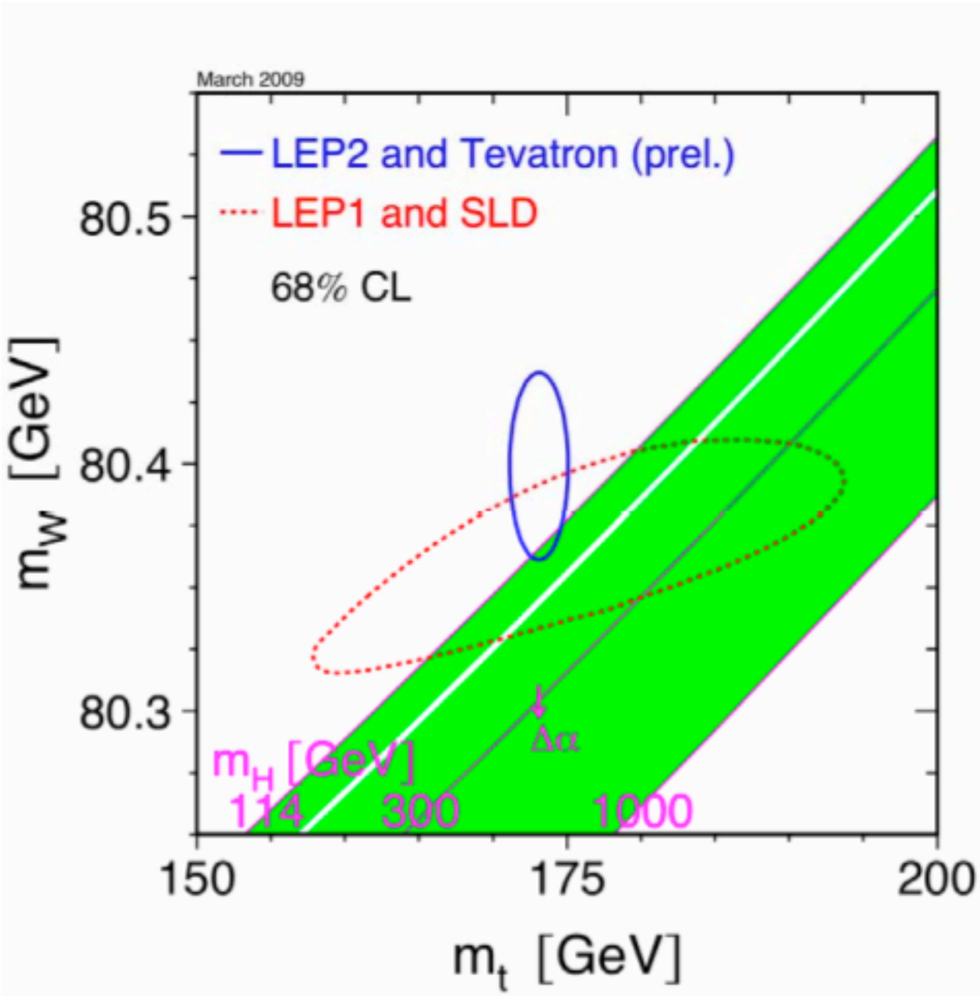
m_{top} = 173.1±0.6(stat) ±1.1(syst)GeV/c^2

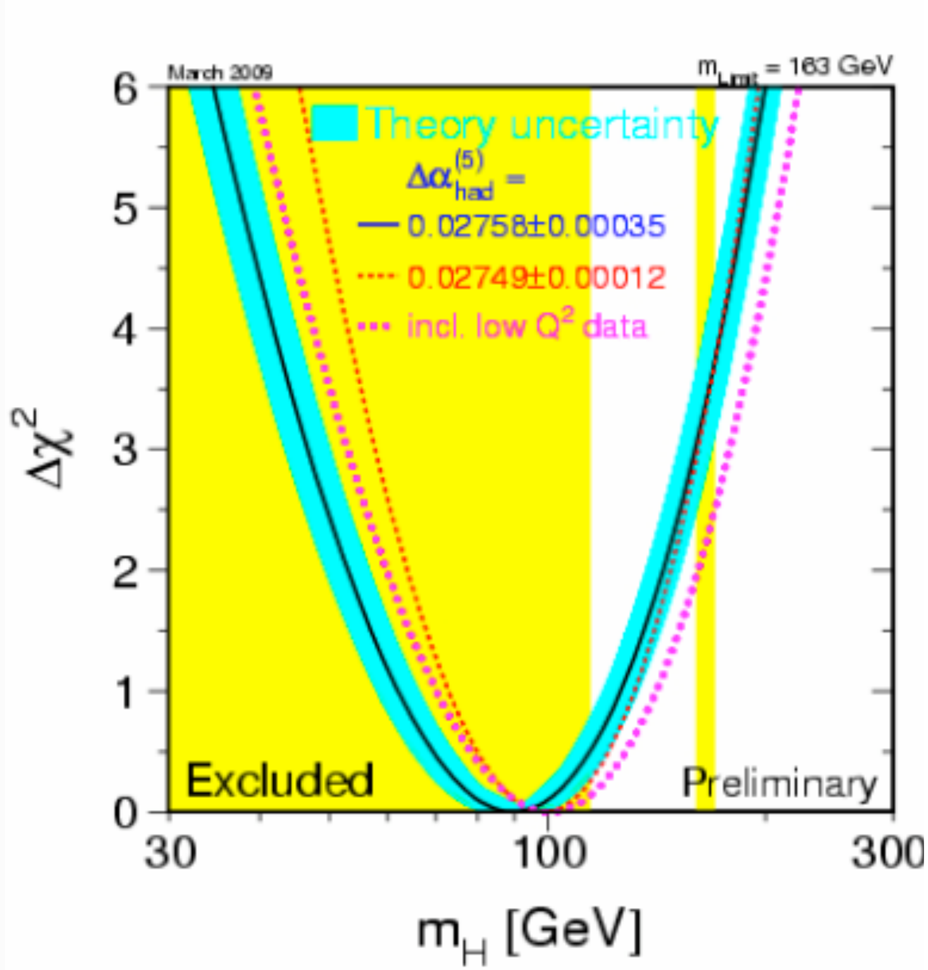
Precision now systematics limited,
(but JES scaling with statistics)

	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



Tevatron Combination (March 2009)

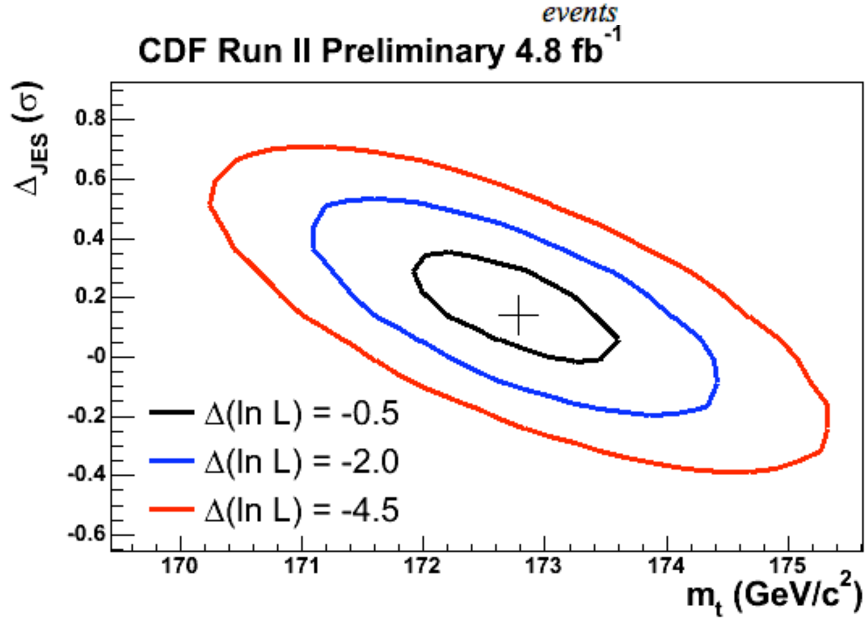


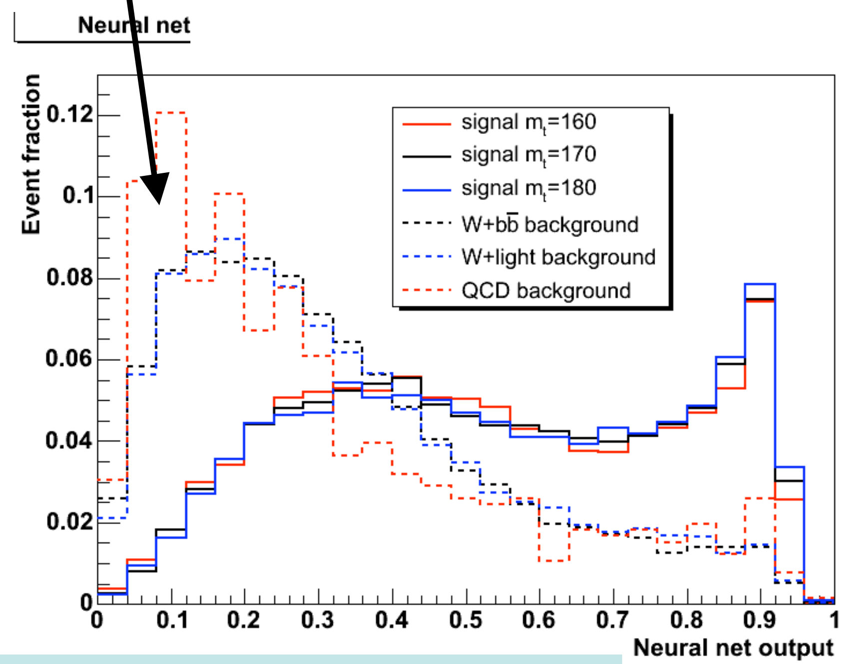


New CDF measurement: 4.6 fb^{-1}

- Most precise single measurement, l+jets channel
- As before, likelihood per event is calculated by integration over the matrix element. Assume all events are signal
- Neural Network distinguishes background, accounted for as a correction in the Likelihood

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

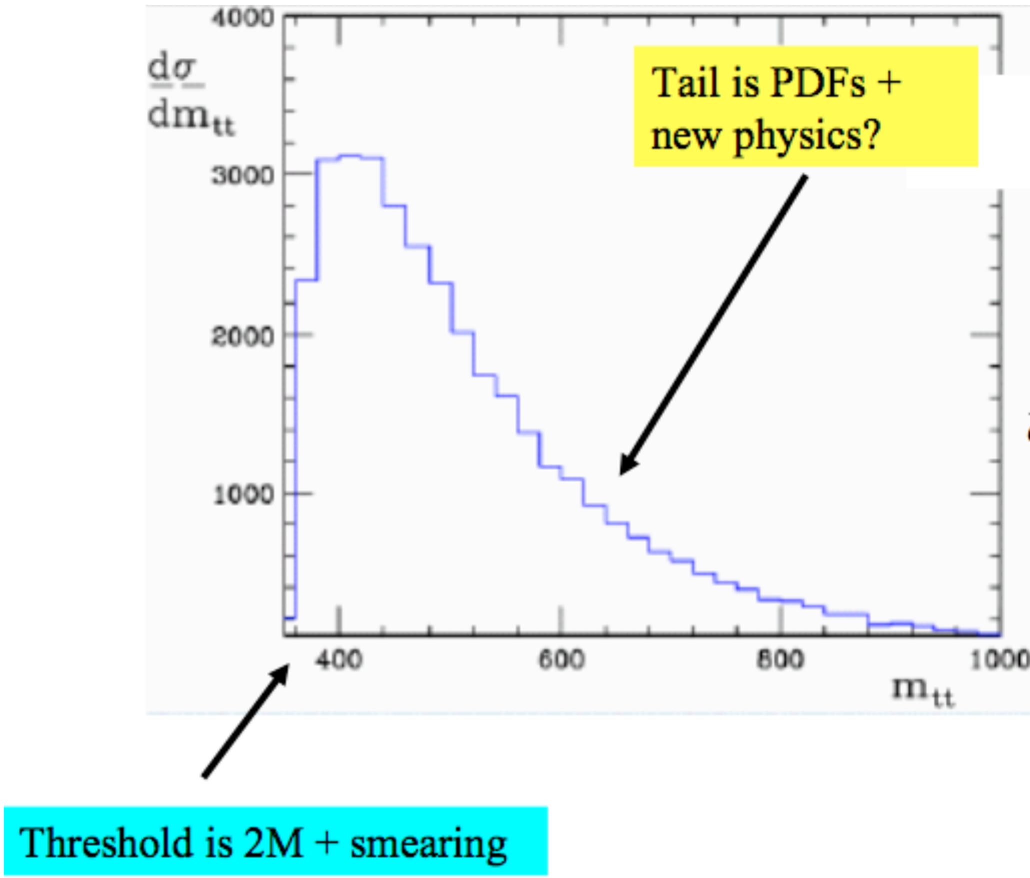


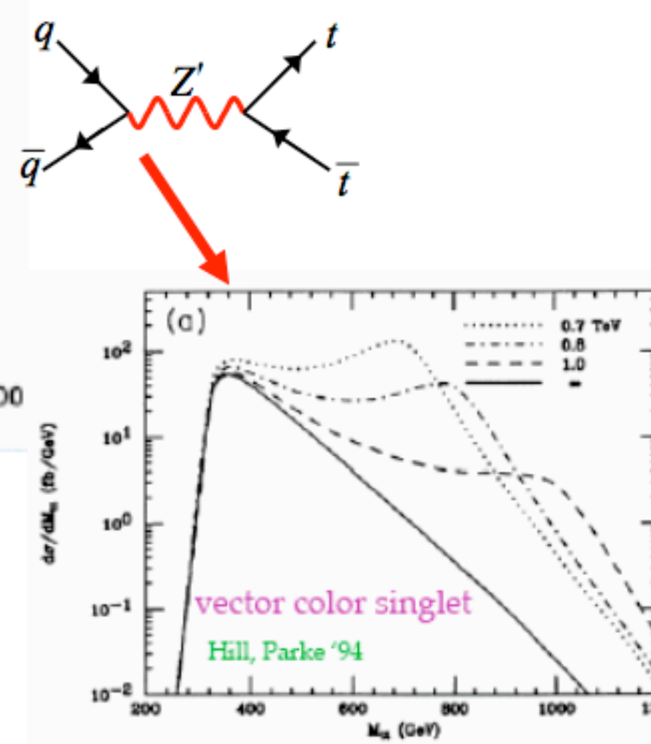


m_t = 172.8±0.7(stat)±0.6 (JES)±0.8 (syst) GeV/c^2

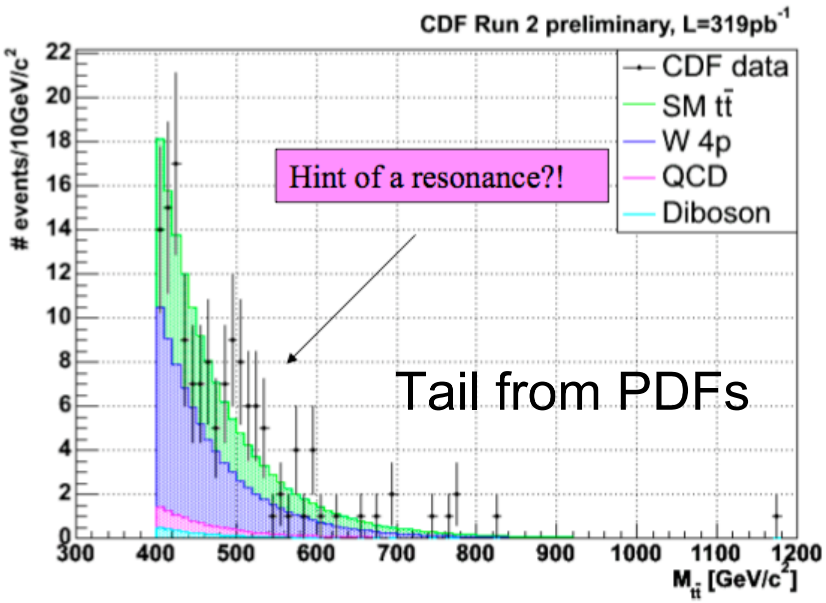
Searches for Anomalous Production of $t\bar{t}$

Expect no resonance production in SM, but NP models predict $t\bar{t}$ bound states. Reconstruct invariant mass of the $t\bar{t}$ system:

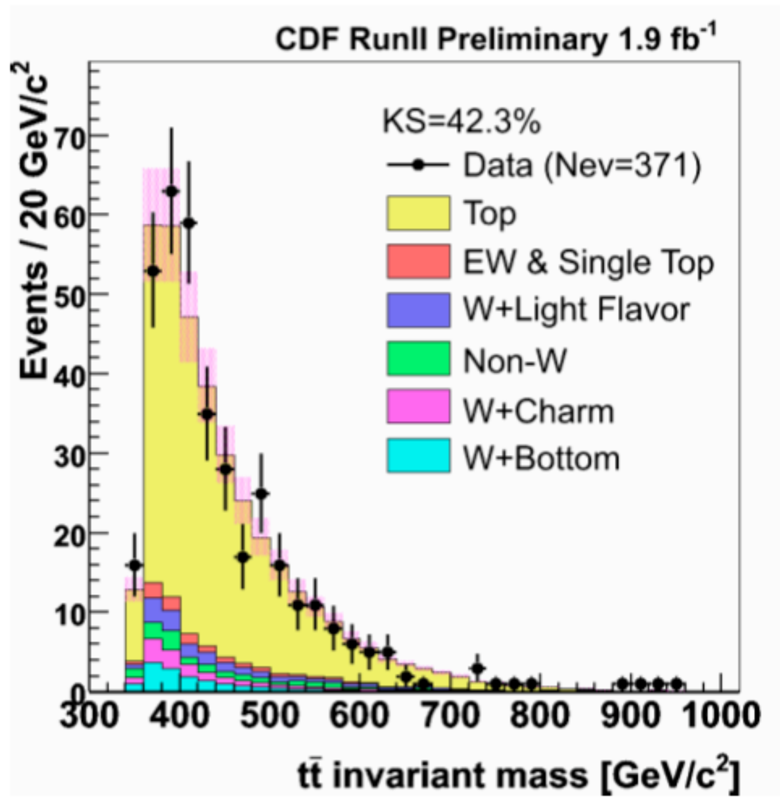




Searches for massive $X \to t\bar{t}$



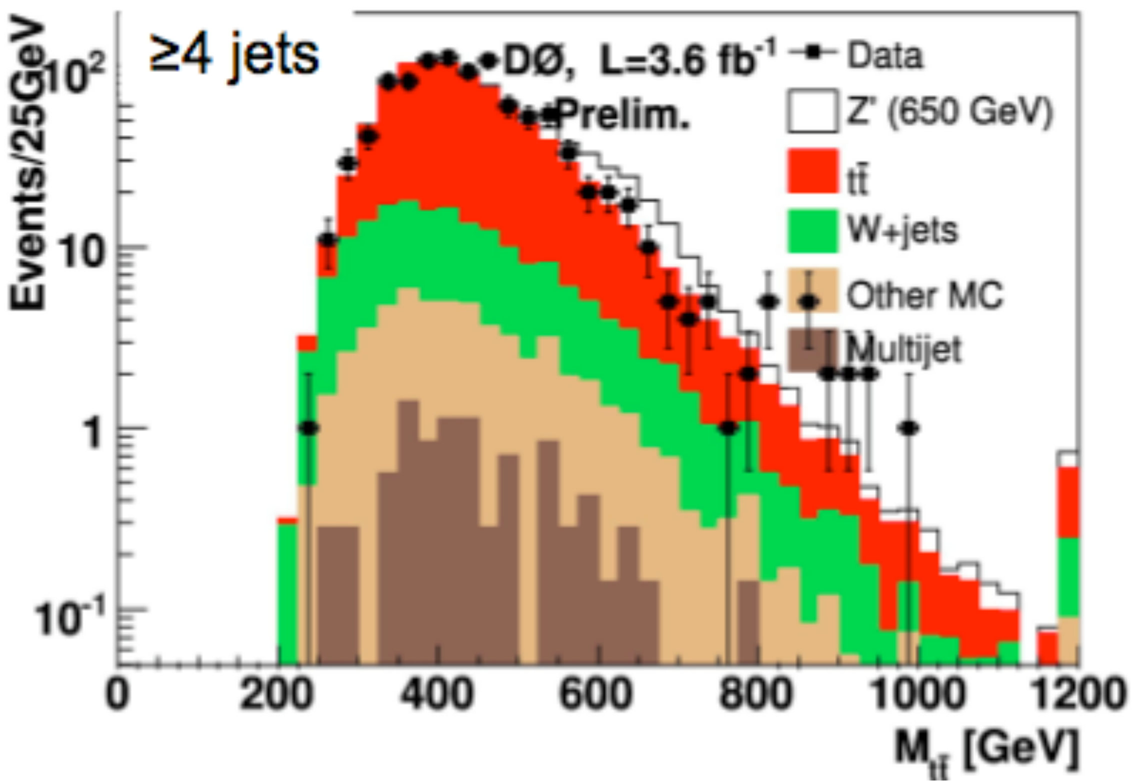
Threshold: 2 m_t (+ smearing)



..but disappears with more data.

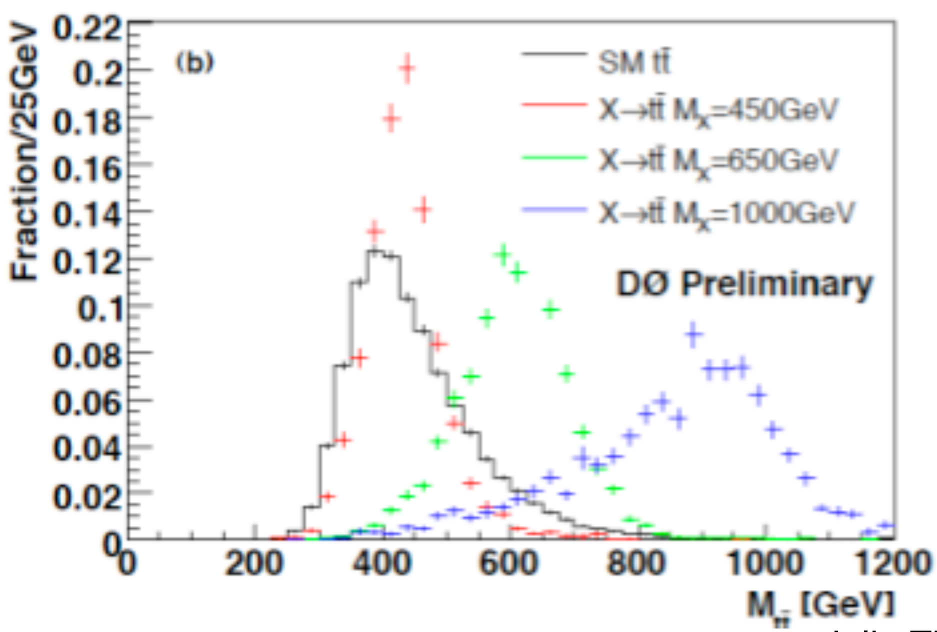
Massive $X \to t\bar{t}$ search

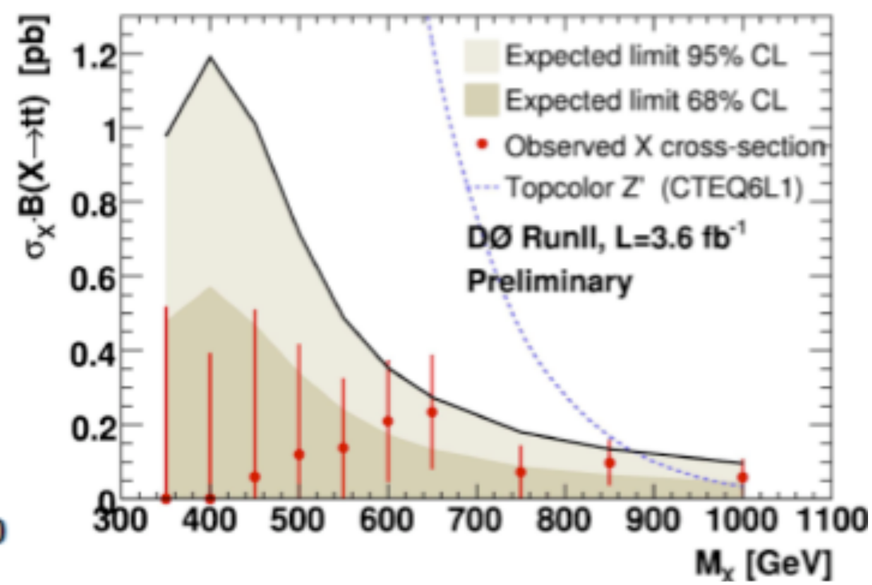
- L+jets channel, at least 1 b tag



Massive $X \to t\bar{t}$ search

- Extract Poisson probability for signal consistency using simulation of resonance processes
- Largest excess less than 2 sigma at X mass ~650 GeV
- Place limit on leptophobic Z': $M_{Z'}>820$ GeV/c^2





Search for Anomalous Production: Forward Backward Asymmetry

- Z' can change top "charge asymmetry": compare number of top and anti-top produced with momentum in a given direction
- interpret as forward backward asymmetry (top moving for or against given direction), in $p\bar{p}$ lab frame

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

- Choosing Θ between top momentum and proton beam direction:

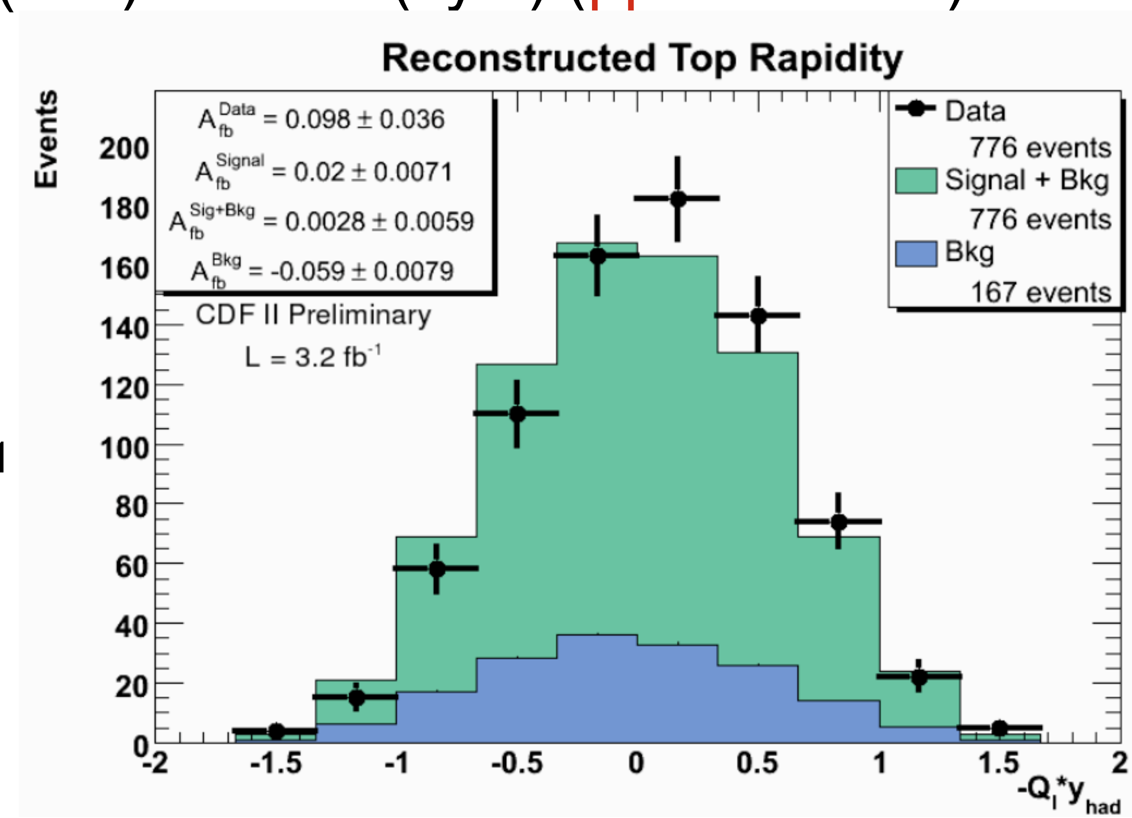
$$A_{fb} = \frac{N_t(\cos(\theta) > 0) - N_t(\cos(\theta) < 0)}{N_t(\cos(\theta) > 0) + N_t(\cos(\theta) < 0)}$$

- In l+jets+btag channel: tag t vs $\bar{t}$ with lepton charge, use hadronic side to measure top rapidity

Results, A_{FB}

- χ^2 based kinematic fitter, correct for experimental effects
- small pp lab frame charge asymmetry expected in QCD at NLO, A_{fb} = 0.05±0.015 (interference ISR and FSR diagrams)
- Using 3.2 fb^{-1}:

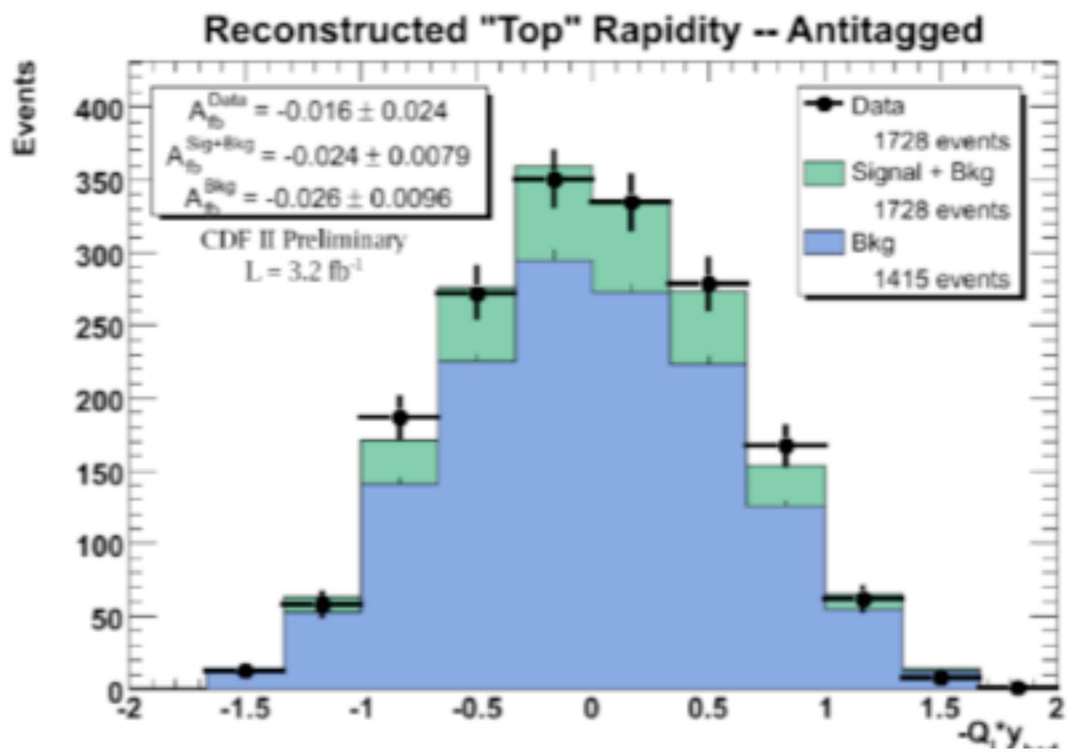
  A_{fb}= 0.193 ± 0.065 (stat) ± 0.024 (syst) ($p\bar{p}$ lab frame)



consistent with 0.9 fb^{-1} published D0 result A_{fb}= 0.12 ± 0.08 (stat) ± 0.01 (syst)

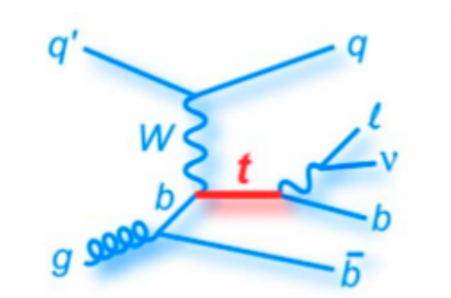
Results, A_{FB}

- Check modeling of background in sample with no btags



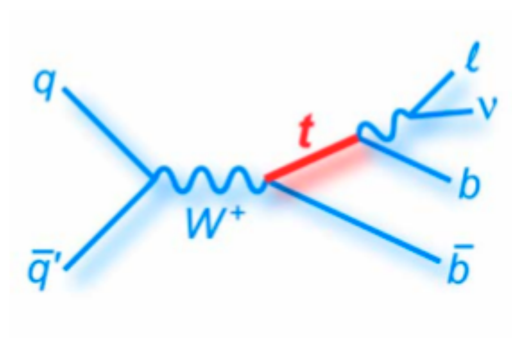
Single Top

- Observation in 2009 (2.3-3.2 fb^{-1})
- Charged EWK production only, direct probe of top weak coupling
  - Measure V_{tb} $\sigma\left(q\bar{q}', qg \to tb\right) \propto \left|V_{tb}\right|^2$
- Important background to Higgs searches
- NP (e.g. FCNC) can alter rates



"t-channel"

2pb

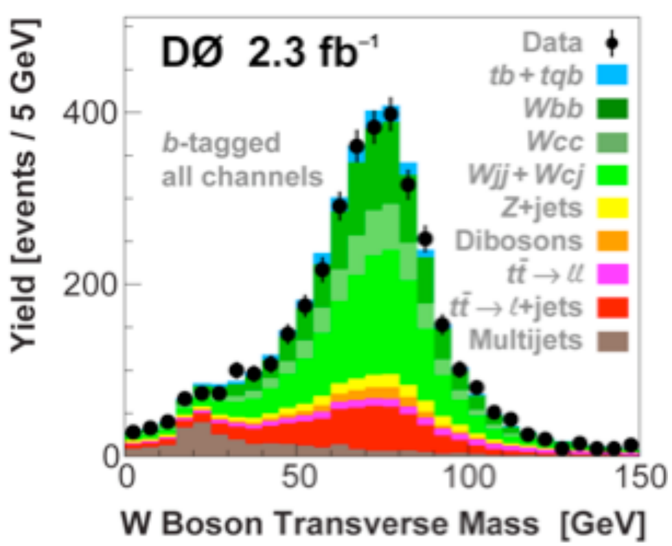


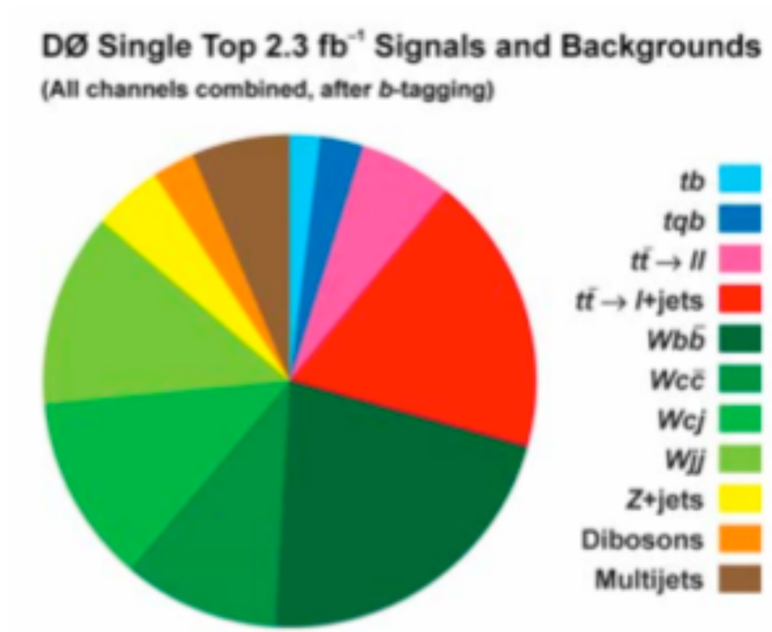
"s-channel"

0.9pb

Single Top production

- Same selection as top pairs, but signal is in W+2j
- Difficult due to large W+2j background. S/B=1/20
- Expected signal yield is smaller than background uncertainties! Not a counting experiment..





Single Top analysis strategy

full selected data set

W + 2 jets → **1 tag**, **≥ 2 tags**

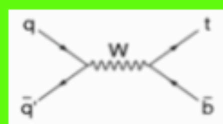
W + 3 jets → **1 tag**, **≥ 2 tags**

W + 4 jets → **1 tag**, **≥ 2 tags**

split in subsets of different purity

neural networks

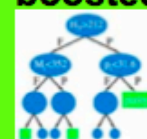
matrix elements



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

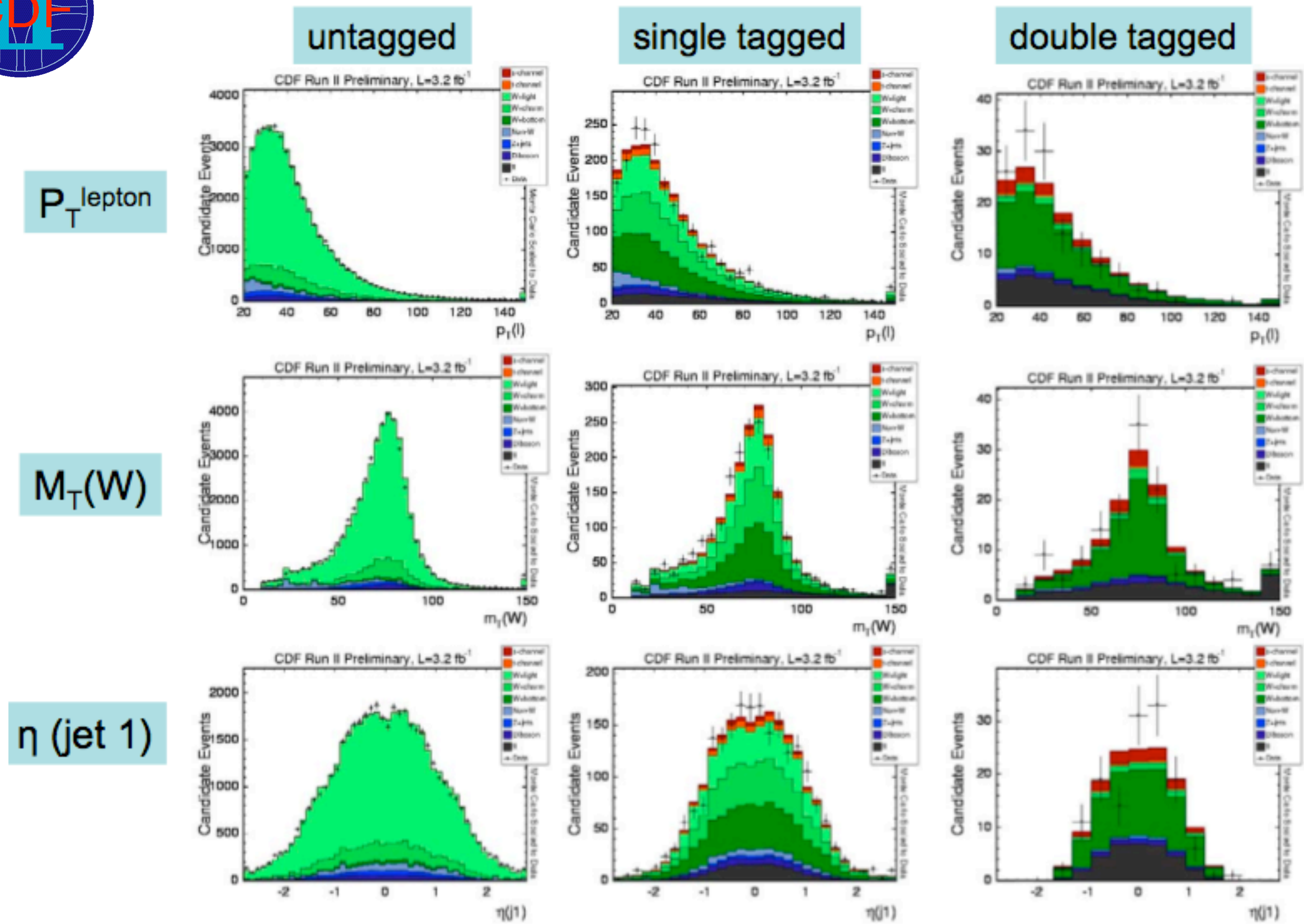
statistical analysis

D0 only

CDF only

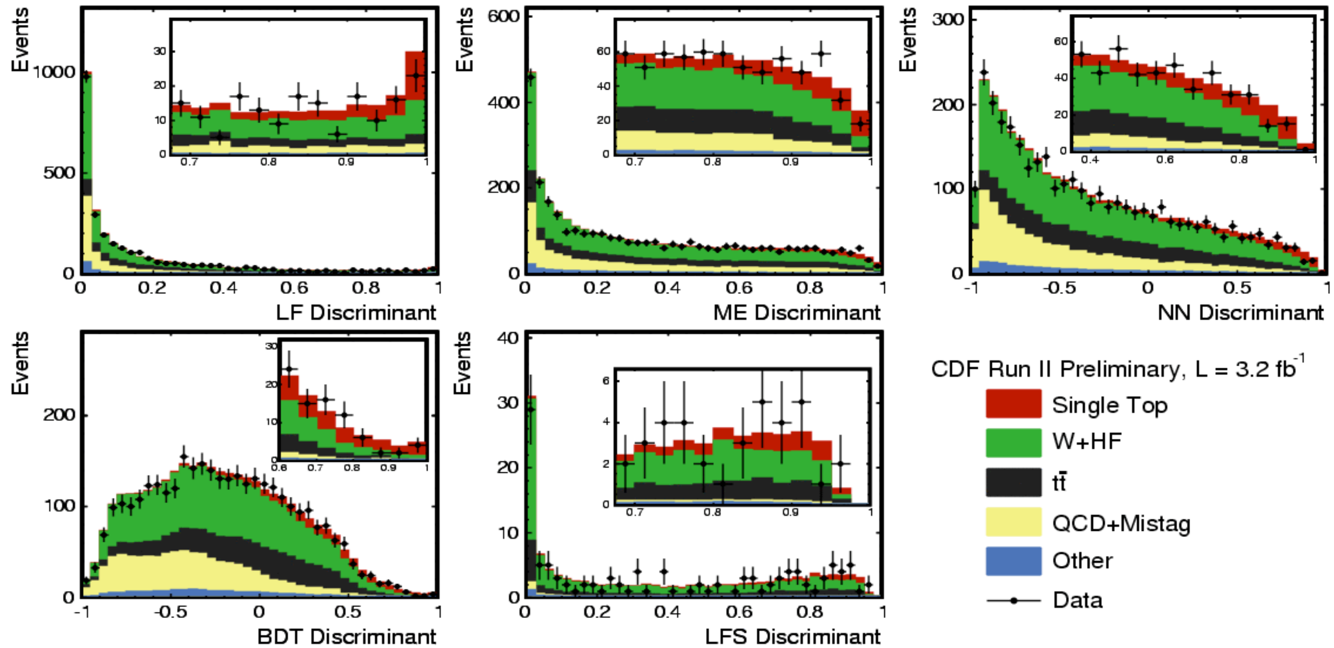
Thanks to Wolfgang Wagner

Kinematic modeling of input variables

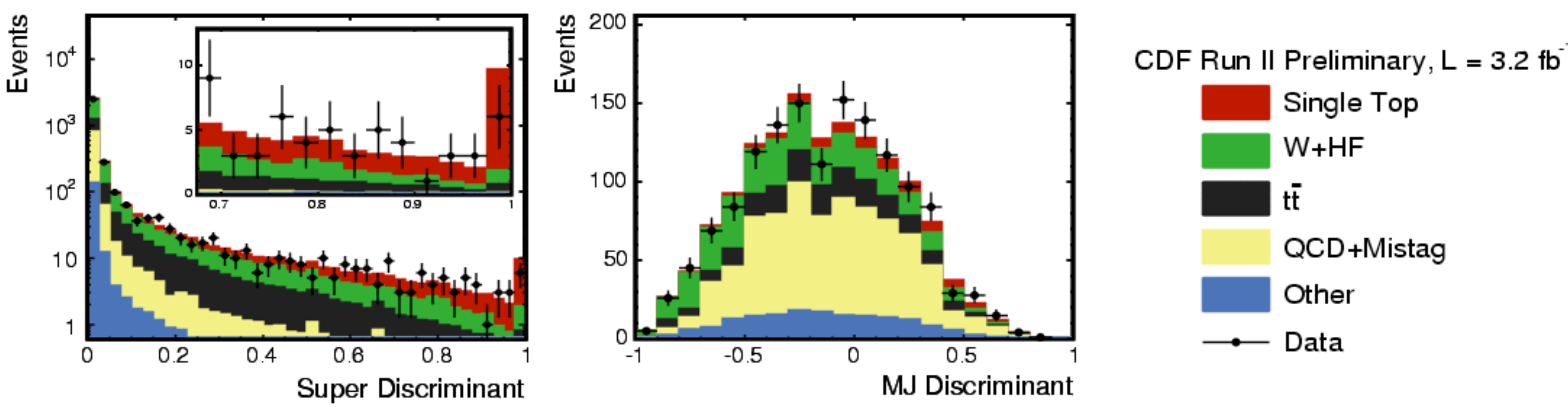


Single top results CDF

8 different l+jet+ET analyses combined….



..into single "Super Discriminant"

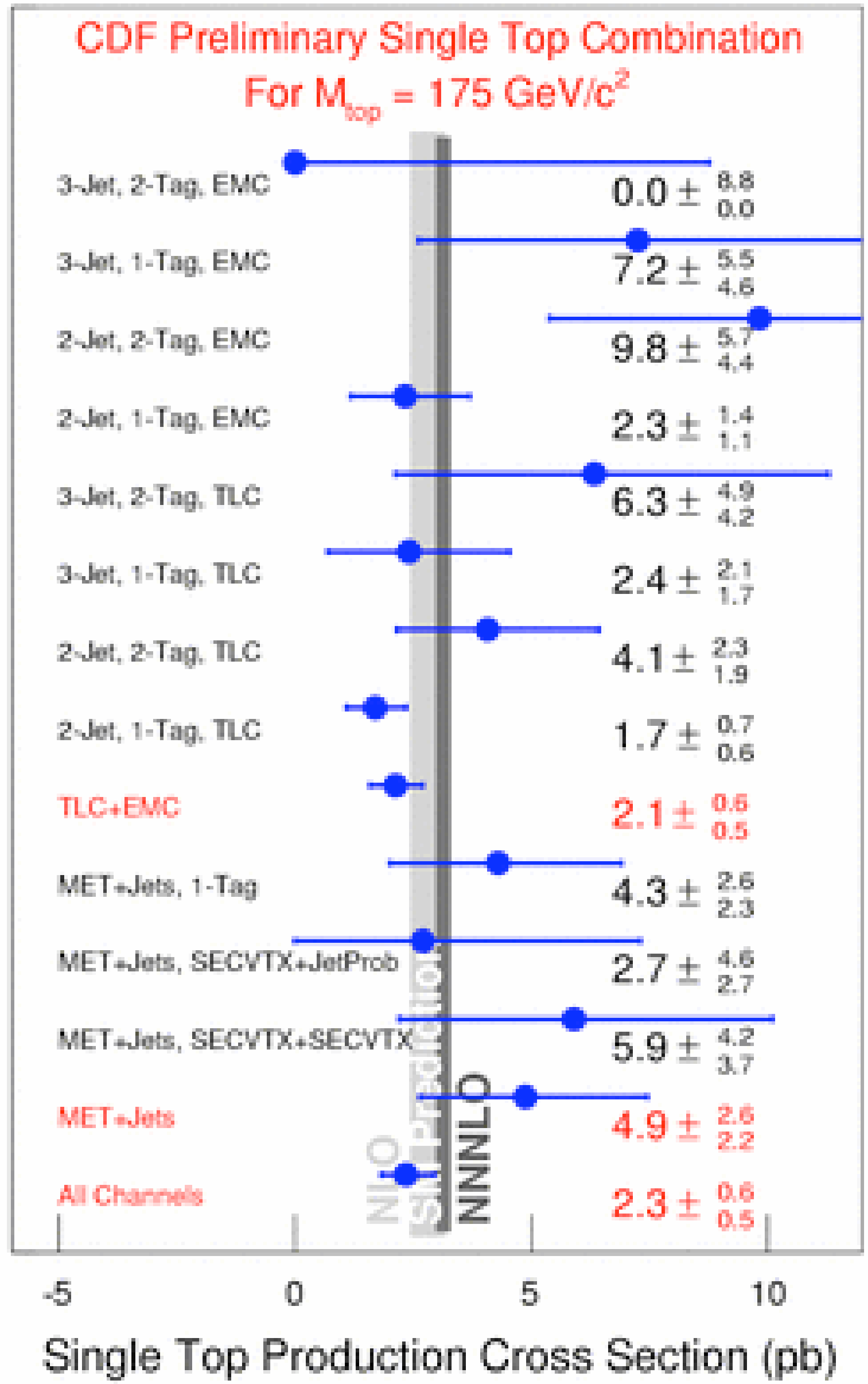


CDF results

8 l+jet+Et and
3 MET+jets analyses:

$|V_{tb}|$ = 0.91 ±0.11(exp.) ±0.07 (theory)

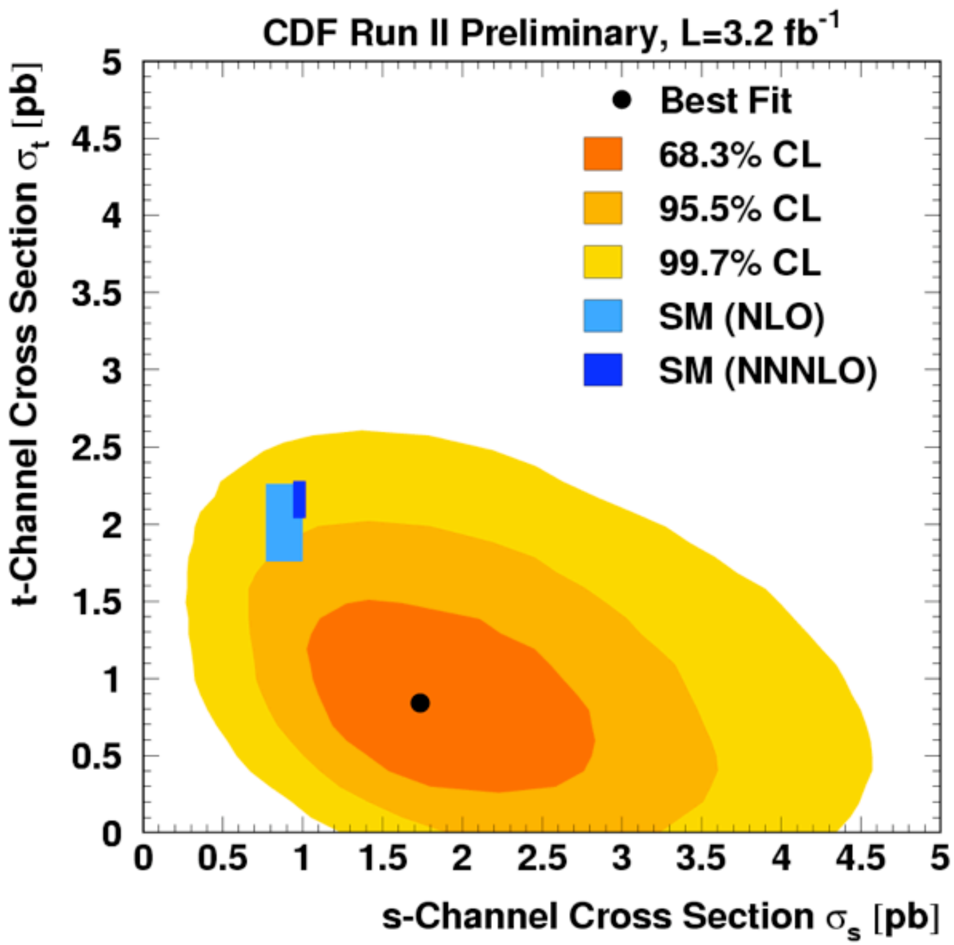
σ = 2.3+0.6-0.5 pb



2D fit for σ_s and σ_t

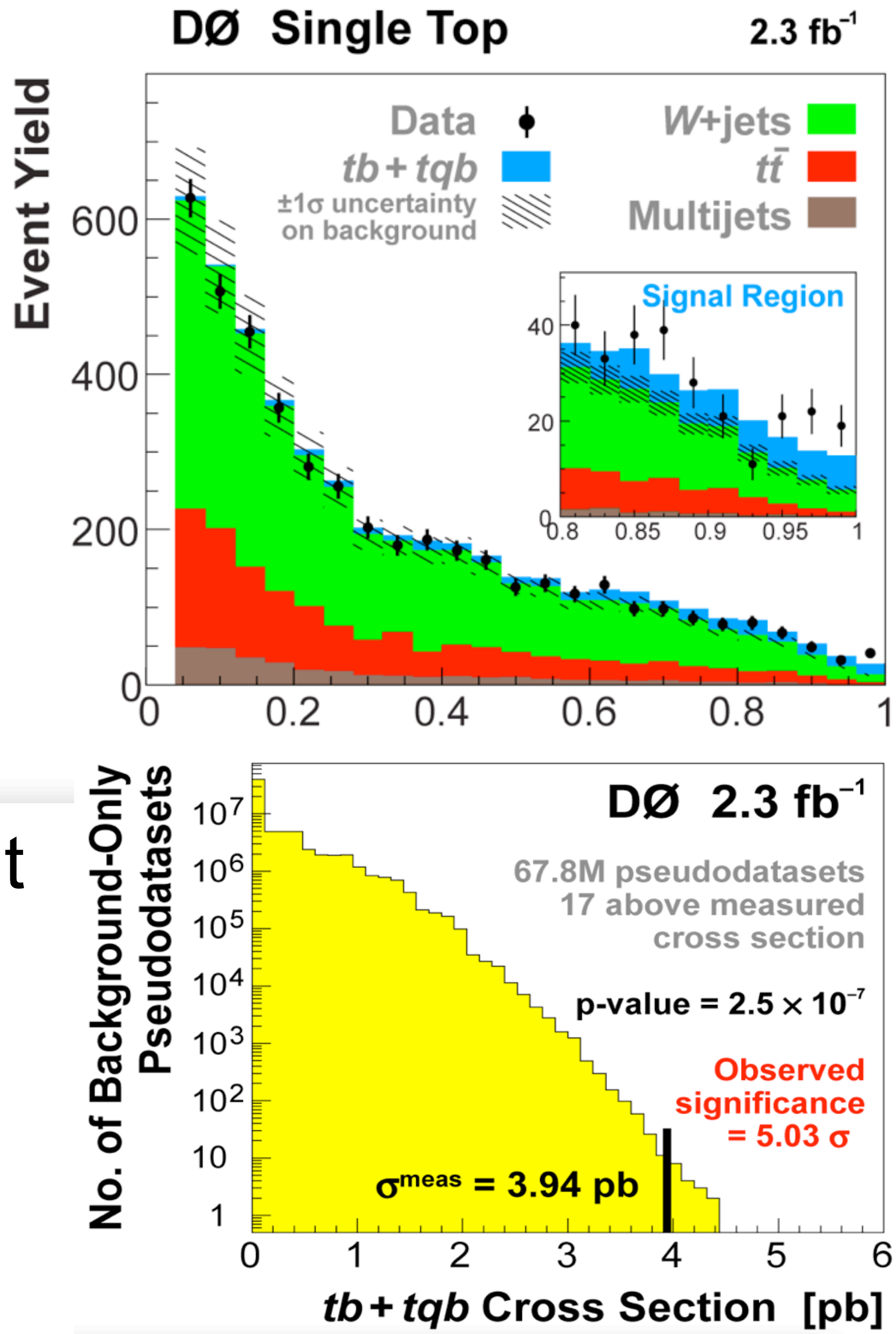
Fitting σ_s and σ_t separately: σ_t=0.8 ± 0.4 pb

And σ_s=1.8+0.7-0.5 pb

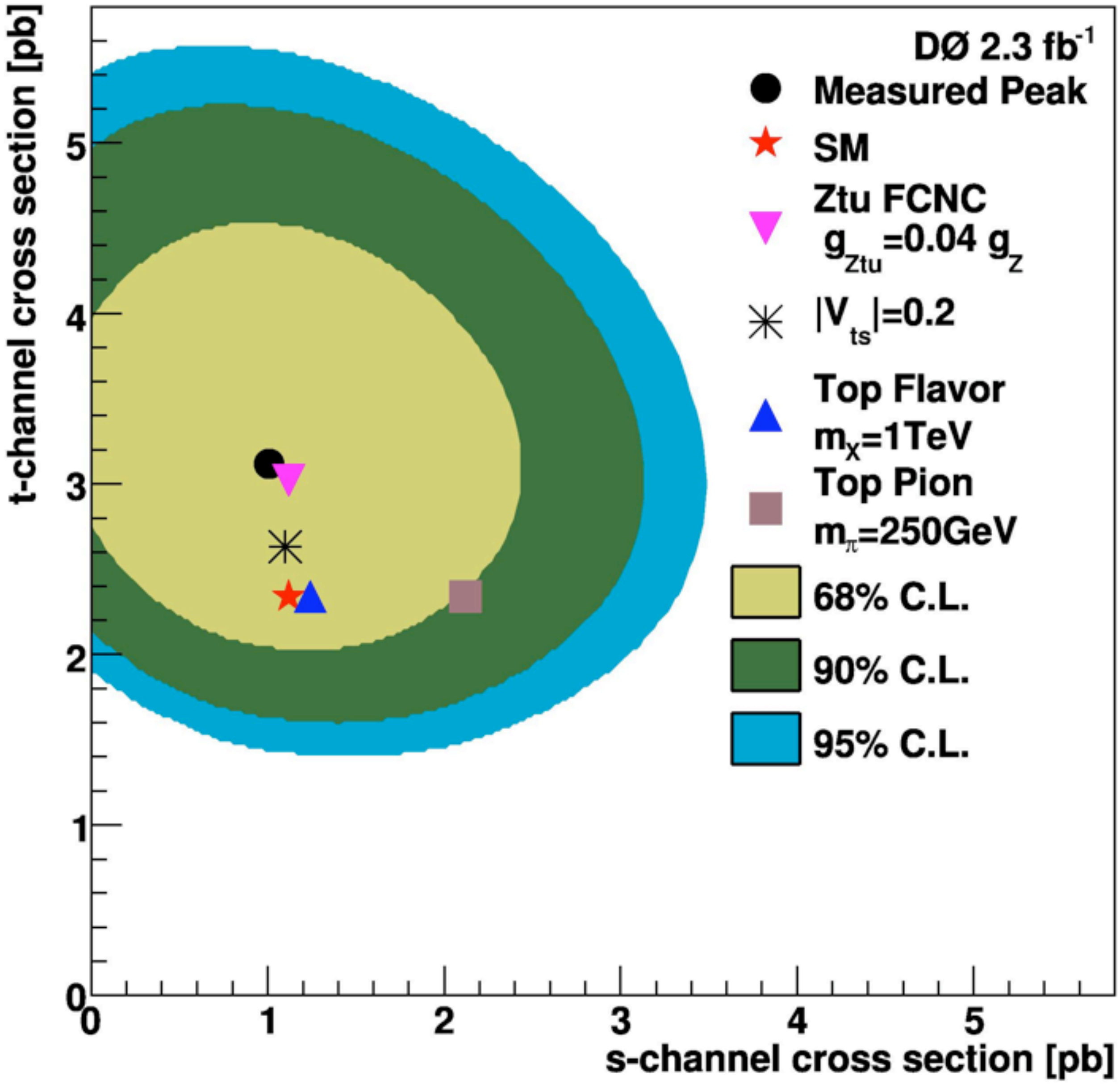


D0 results

- s, t channel fit together, assuming SM ratio
- 2,3,4 jets, 1,2 b-tagged, 1 lepton, missing E_t
- 4519 events, 223±30 expected from ST
- Multivariate discriminant

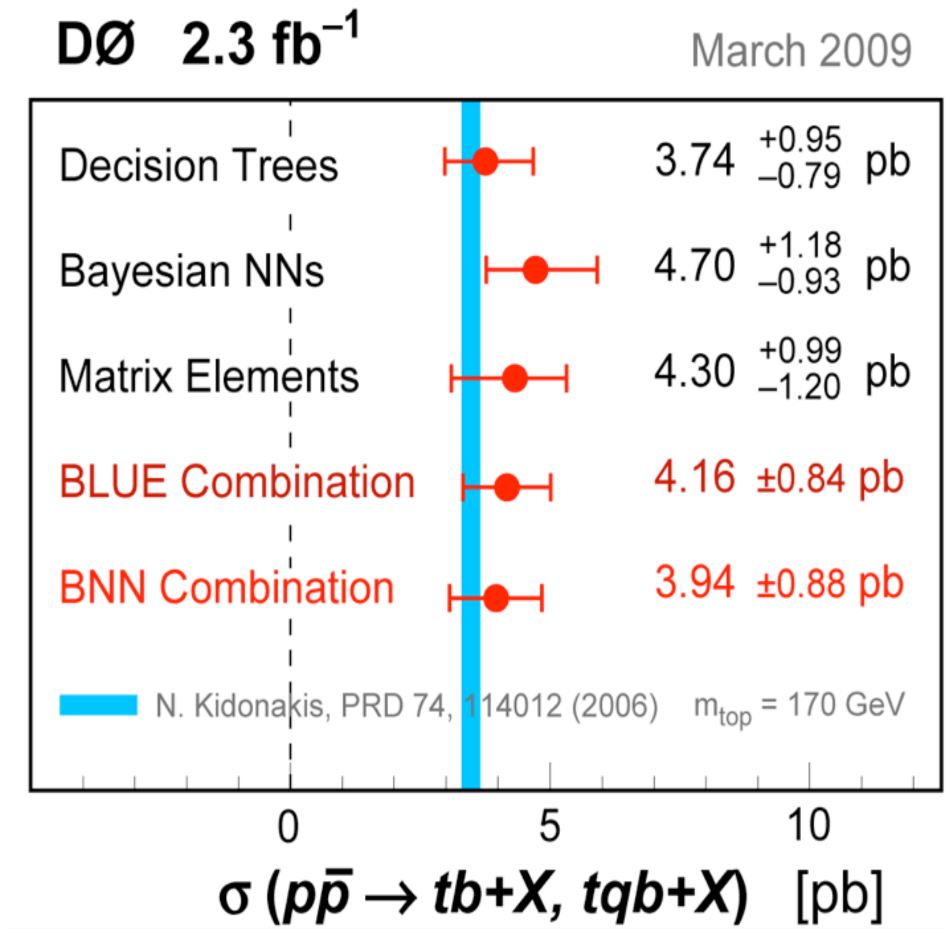


D0 t-channel result



$|V_{tb}| > 0.78$ @ 95% CL

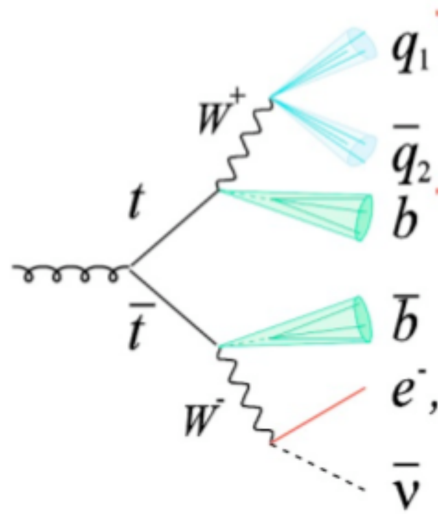
$\sigma = 3.49 \pm 0.88$ pb



combination

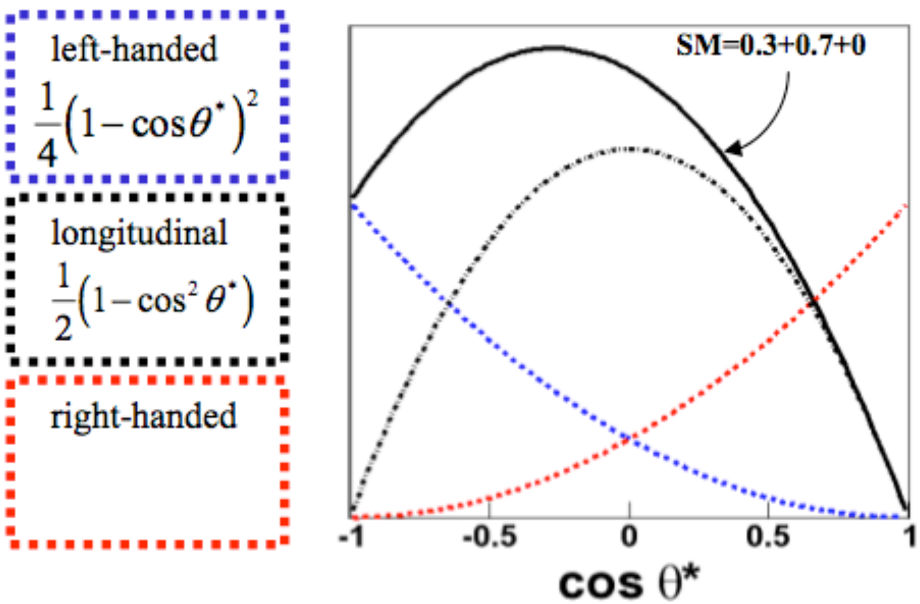
Single Top Cross Section	Signal Significance		CKM Matrix Element V_{tb}
	Expected	Observed	
DØ (2.3 fb^{-1})	**March 2009**	PRL **103**, 092001 (2009)	(m_{top} = 170 GeV)
3.94 ± 0.88 pb	4.5 σ	5.0 σ	$\left\|V_{tb} f_1^L\right\| = 1.07 \pm 0.12$ $\left\|V_{tb}\right\| > 0.78$ at 95% CL
CDF (3.2, 2.1 fb^{-1})	**March 2009**	PRL **103**, 092002 (2009)	(m_{top} = 175 GeV)
$2.3\ ^{+0.6}_{-0.5}$ pb	>5.9 σ	5.0 σ	$\left\|V_{tb} f_1^L\right\| = 0.91 \pm 0.13$ $\left\|V_{tb}\right\| > 0.71$ at 95% CL
DØ & CDF combined	**August 2009**	FERMILAB-TM-2440-E	(m_{top} = 170 GeV)
$2.76\ ^{+0.58}_{-0.47}$ pb			$\left\|V_{tb} f_1^L\right\| = 0.88 \pm 0.07$ $\left\|V_{tb}\right\| > 0.77$ at 95% CL

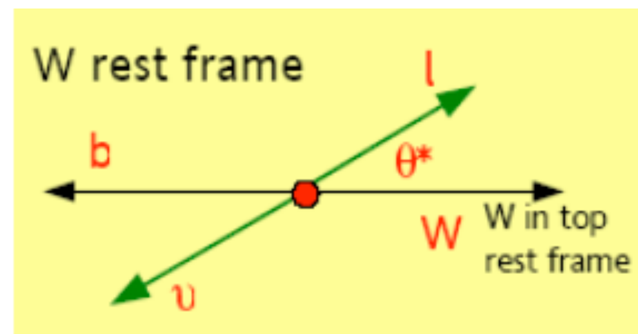
- Top quark production and properties
  - Top pairs, mass
  - Anomalous production
  - Single top
- **Top quark decay**
  - **W boson helicity in top decays**
  - **Probe the W-t-b vertex**



W helicity fractions in t->Wb decay

- fraction of longitudinally (f0) and right-handed (f+) polarized W bosons from top-quark decay
- SM at tWb vertex predicts 70% longitudinal W
- Measure via angular distribution:



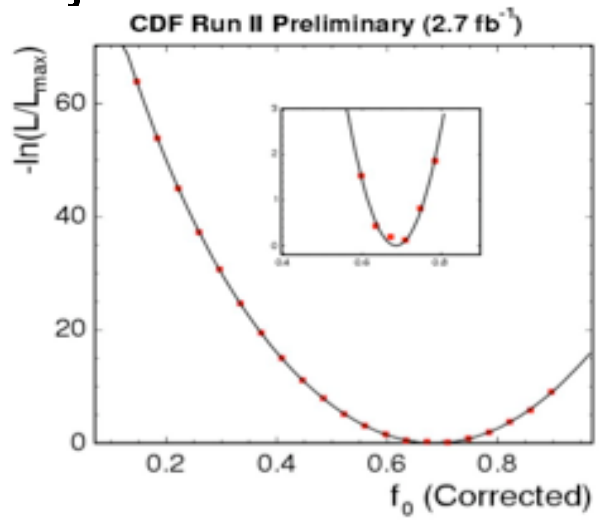


W helicity results,
2D model independent fit (f0,f+)

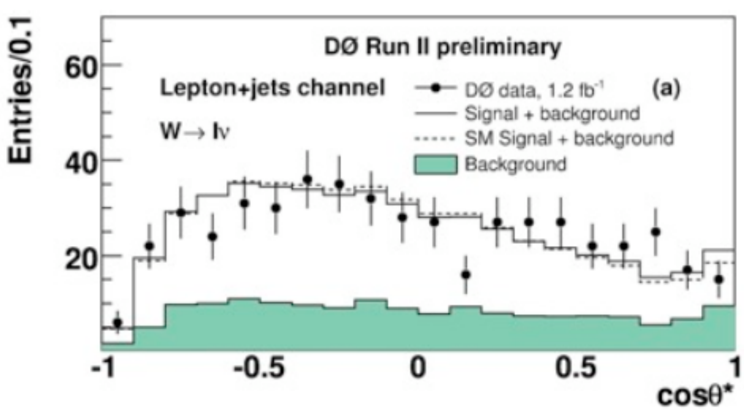
CDF: matrix element analysis in lepton+jets channel.

f0 = 0.88 ± 0.11 (stat) ± 0.06 (syst)

f+ = -0.15 ± 0.07 (stat) ± 0.06 (syst)



D0: template analysis in dilepton and l+jets channels.



f0 = 0.490 ± 0.106 (stat) ± 0.085 (syst)

f+ = 0.110 ± 0.059 (stat) ± 0.052 (syst)

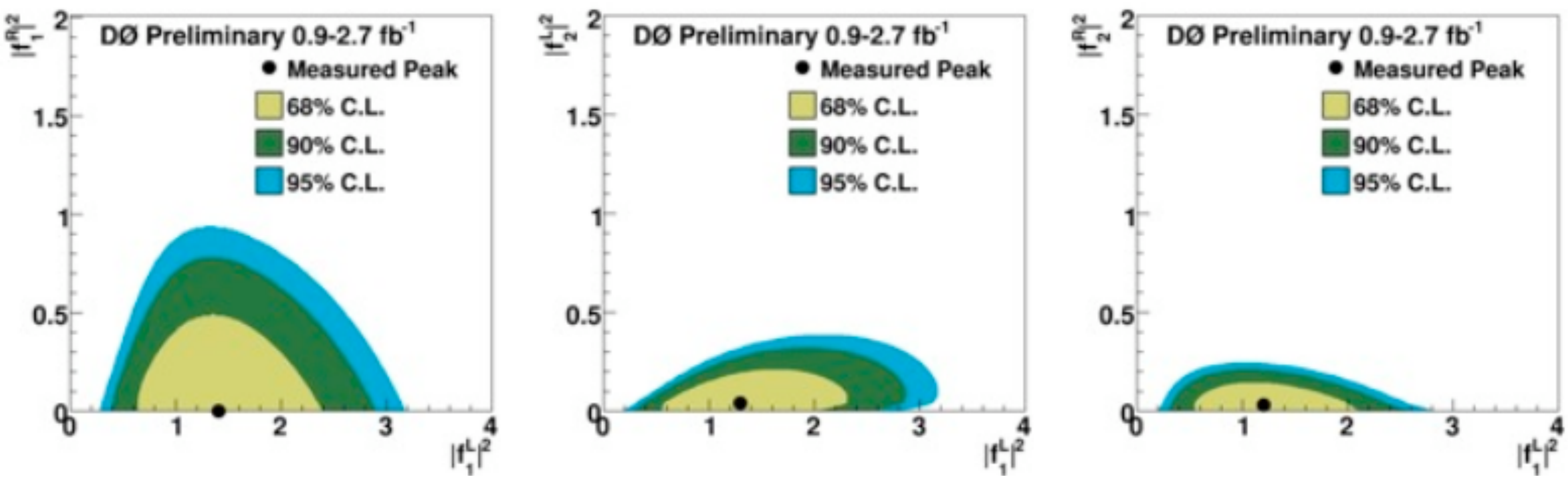
Anomalous couplings

SM lagrangian with form factors $f_1^L=1$, $f_1^R=f_2^L=f_2^R=0$

$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t$$

C.R. Chen, F. Larios and C.P Yuan, Phys.Lett.B631:126

D0 combines measurements of W helicity, single top kinematics into analysis of tWb vertex, investigating pairs of form factors

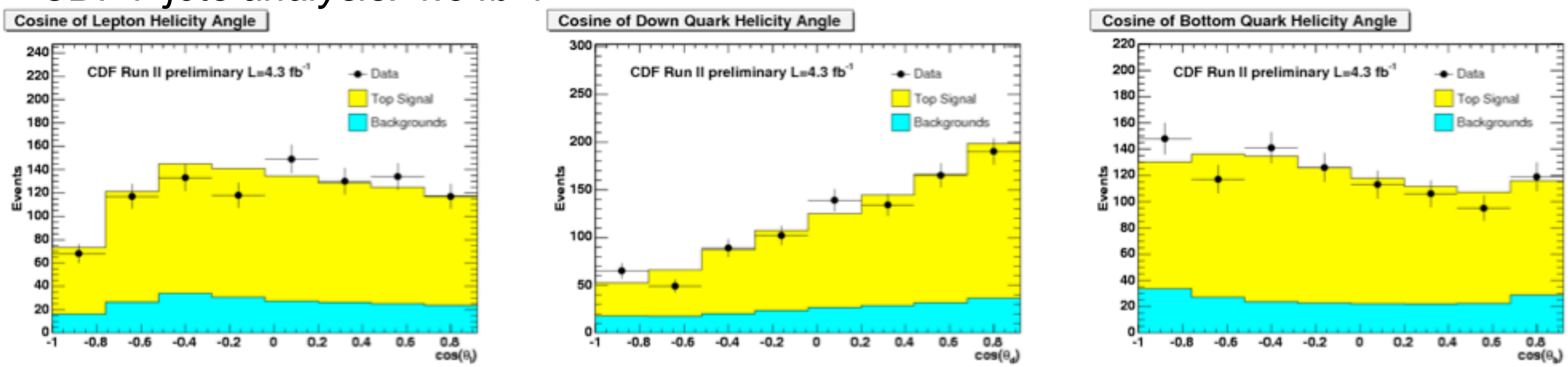


find 95%CL if $f_1^L=1$ $|f_1^R|^2<0.72$ $|f_2^L|^2<0.19$ $|f_2^R|^2<0.20$

Top Spin

- Top anti-top spins are correlated only if top lifetime is short enough. Can observe correlation in top decay products
- Measure angle of decay products (leptons, jets) in top rest frame with respect to a chosen quantization axis, e.g. top helicity axis

CDF l+jets analysis: 4.3 fb-1



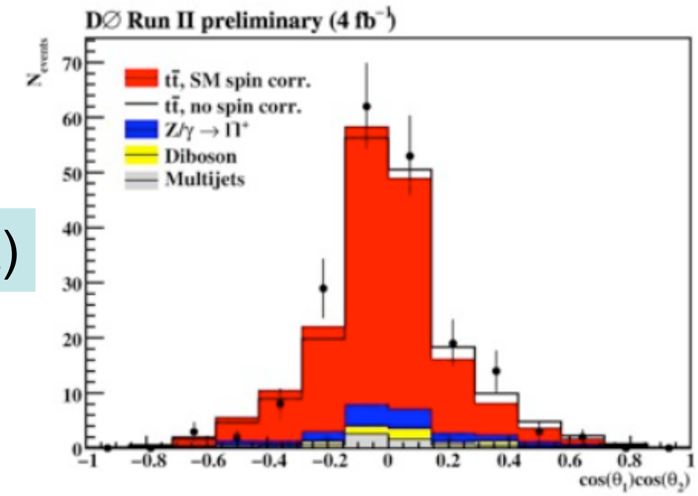
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2} = \frac{1}{4}\left(1 - C\cos\theta_1\cos\theta_2\right)$$

- Spin correlation parameter $C = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\uparrow\downarrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\uparrow\downarrow)}$

Top Spin results

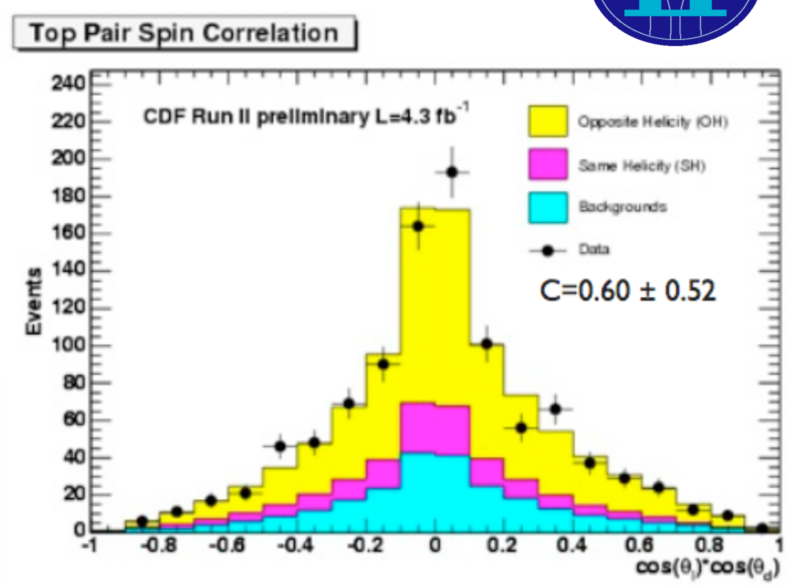
D0: dilepton sample, measure angles with respect to beam axis.
SM expectation NLO C= 0.78

C = - 0.17 + 0.64 - 0.53 (stat+syst)



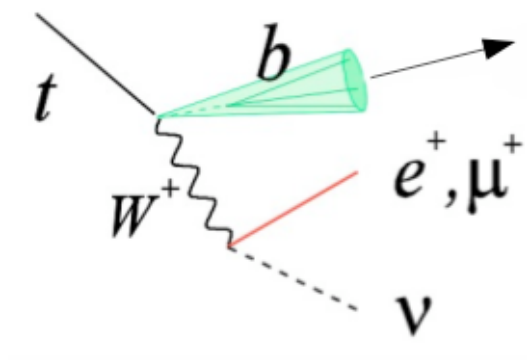
CDF: l+jet sample, template analysis, 2D fit to angular distribution of quark to lepton. Using helicity basis. SM: C = 0.4 (NLO)

C= 0.60 ± 0.50 (stat) ± 0.16 (syst)



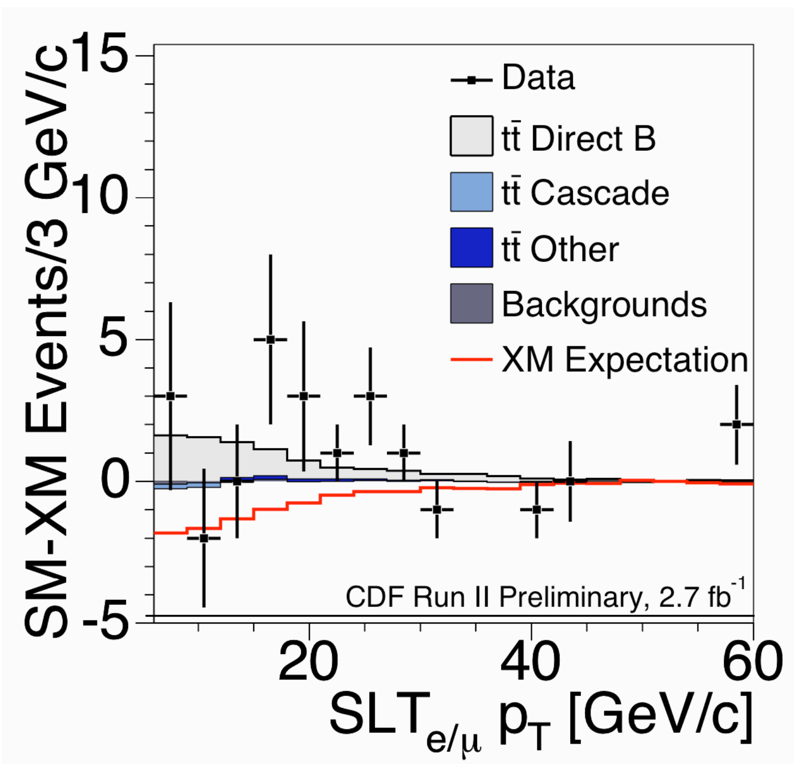
Top Charge

- Test hypothesis: top quark is an exotic particle with q_t=-4/3 ("XM")? *D.Chang et al., PRD 59 (1999) 091503*
- L+jets events with 2 tags
- Kinematic fitter associates b jets to had/lept. W decay



Soft e,m in b jet

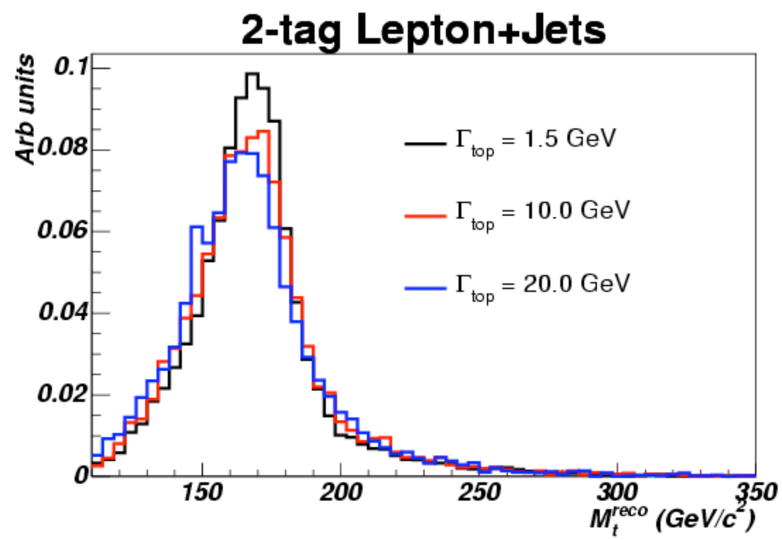
OS :SM
SS :XM

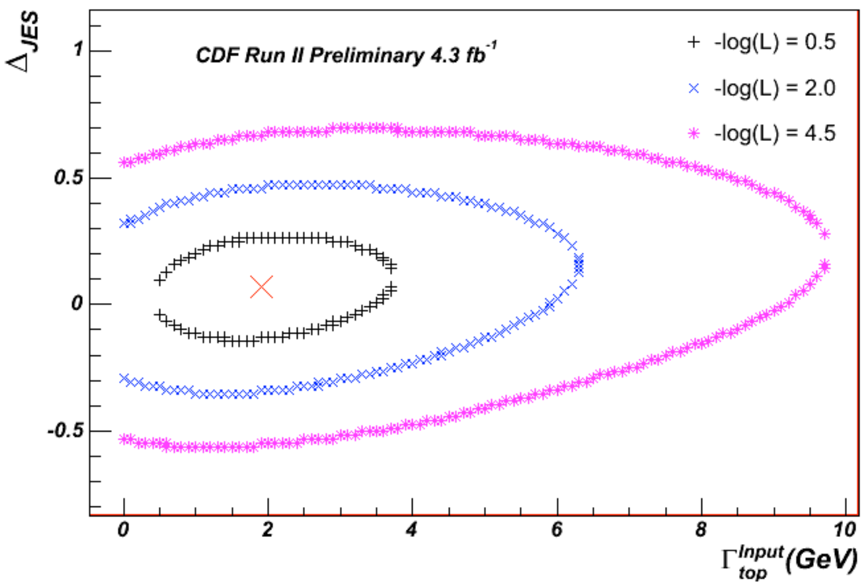


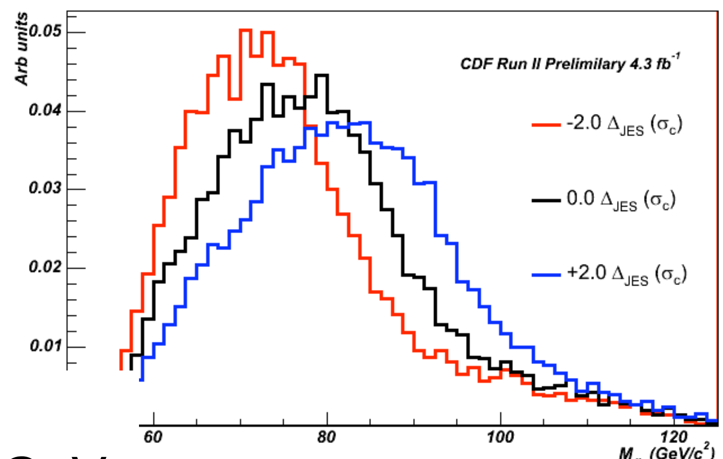
in 2.7 fb^{-1}: 29 events consistent with SM and 16 events consistent with a q=-4/3 top quark.
Result: 95% exclusion of the -4/3 charge hypothesis

Top width

- SM prediction ~1.5 GeV at m_t=175 GeV/c^2
- l+jet channel ≥1 btag, ≥4 jets
- Minimize χ^2 function for m_t
- 2D template fit (m_t, m_{jj}) to data to extract top width







95% Confidence Level: Γ_{top} < 7.5 GeV

68% Confidence Level: 0.4 GeV < Γ_{top} < 4.4 GeV

Summary

- Broad program of measurements of top quark properties ongoing at the Tevatron
- RunII dataset is beginning to provide sensitive searches for NP in top production and decay
  - SM agreement (so far)
  - results using up to 4.7fb^{-1} of data
  - Have ~7fb^{-1} on tape, expect >10fb^{-1} until end of RunII
- Uncertainty on the top mass (individual measurements) is <1%!
- Work provides guidance and focus for LHC top program and beyond

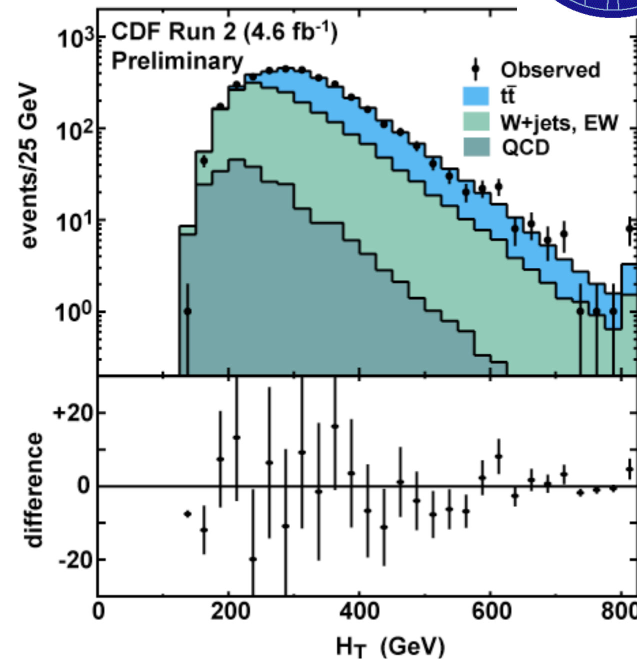
Backup Slides

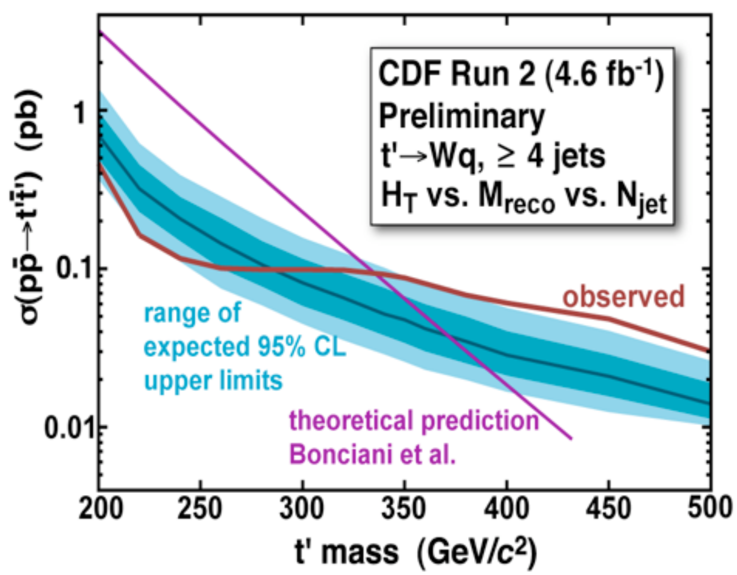
Search for Heavy Top t'→Wq

Search for heavy top decay to Wq final states (e.g.LHT)

- l+jets (no b-tag requirement)
- Template method for top reconstruction
- Use observed H_T and mass distribution to fit signal t' and background (top, W,..) distributions

- exclude a standard model fourth-generation t' quark with mass below 335 GeV at 95% CL.





Julia Thom, CU

New CDF measurement: 4.6fb-1

- As before, signal likelihood calculated by integration over the matrix element (x: parton level, y: measured quantities)
- Gives probability that we observe an event with kinematic variables y as a fct of true top mass and JES shift parameter "JES"

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

Normalization

Parton assignments

PDFs

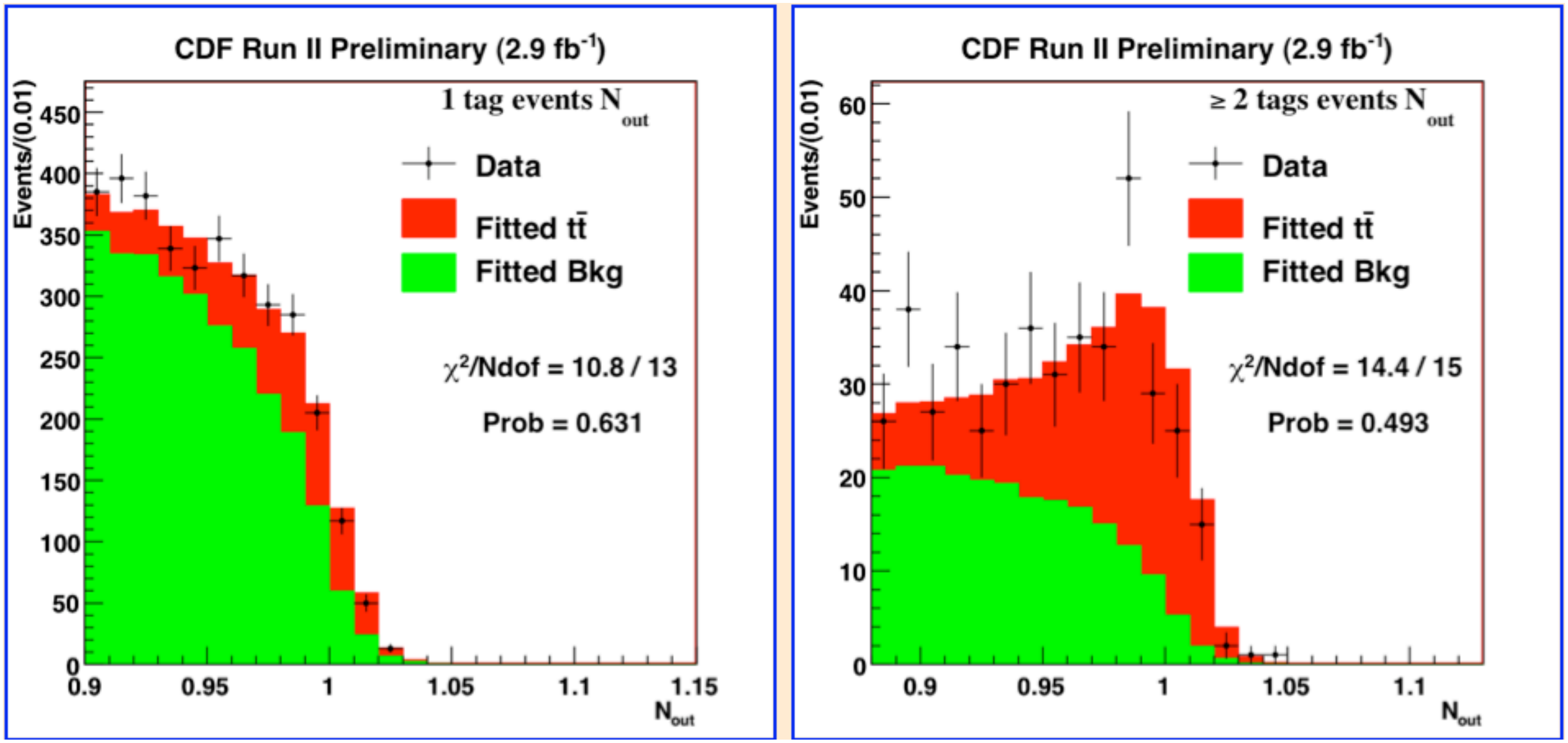
produced→measured transfer function

Matrix element

Phase space

Top mass in all hadronic channel

- Event selection in 6-8 jets (no MET) via NN:

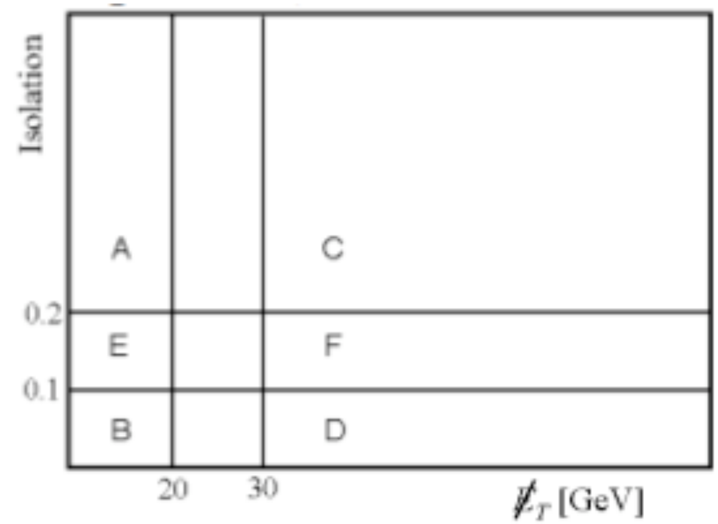


- Result $m_t = 174.8 \pm 1.7(\text{stat.}) \pm 1.9(\text{syst.})\ \text{GeV}/c^2$

QCD background estimation

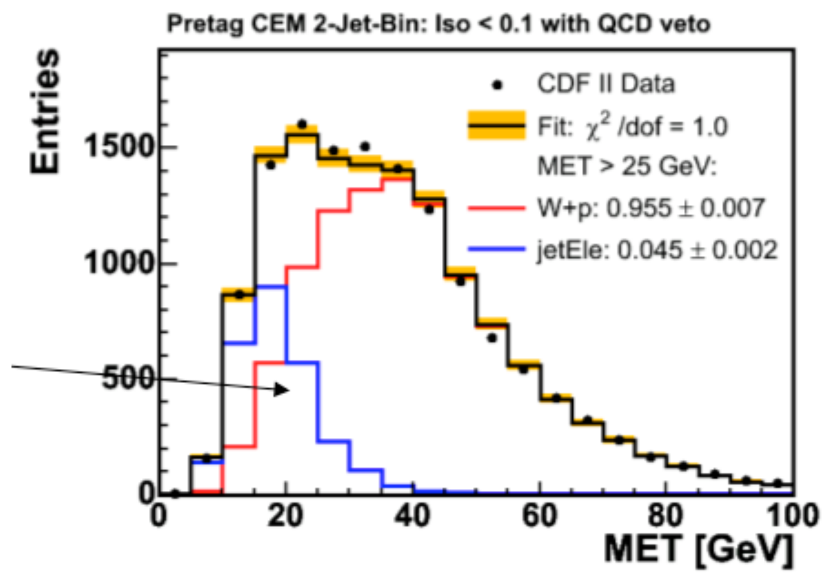
3 techniques to evaluate QCD

- Met vs iso
- Matrix technique
- Anti-electron/jet technique



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

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

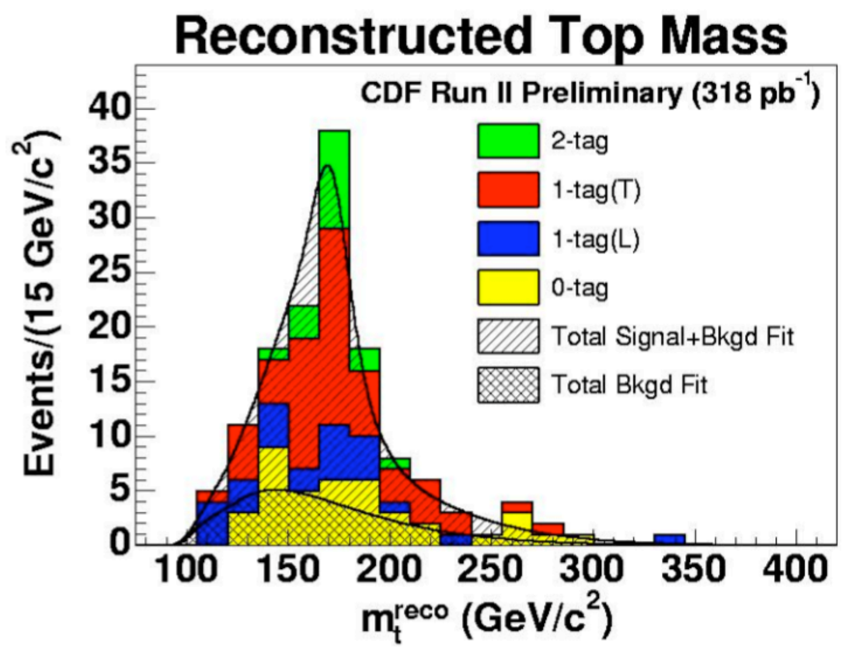


classic top mass measurement

- Step 1: Associate measured objects with initial state using best match (χ^2) to 3 constraints:
  - $M_{jj}=M_W$
  - $M_{l\nu}=M_W$
  - $M_{l\nu b}=M_{qqb}$
- Step 2: jet energy correction according to species
  - E scale for light jets tuned to match M_W
  - E scale for b jets adjusted via tuned MC

- Step 3: one invariant mass per event
  - –Final mass comes from best fit to MC template vs. M_{top}

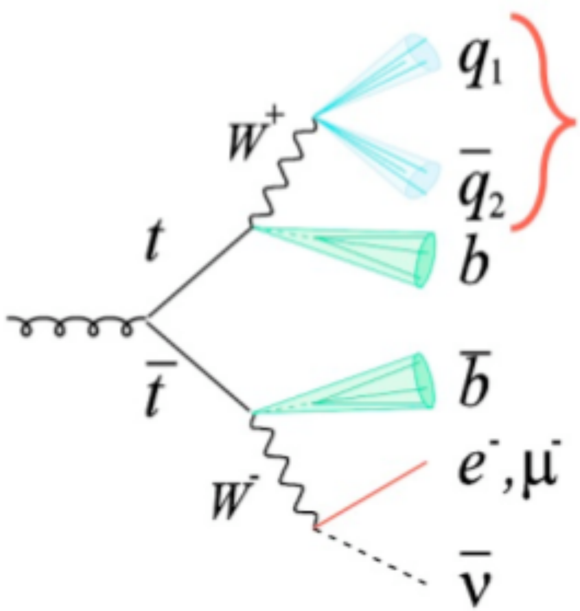
3-4 years ago:

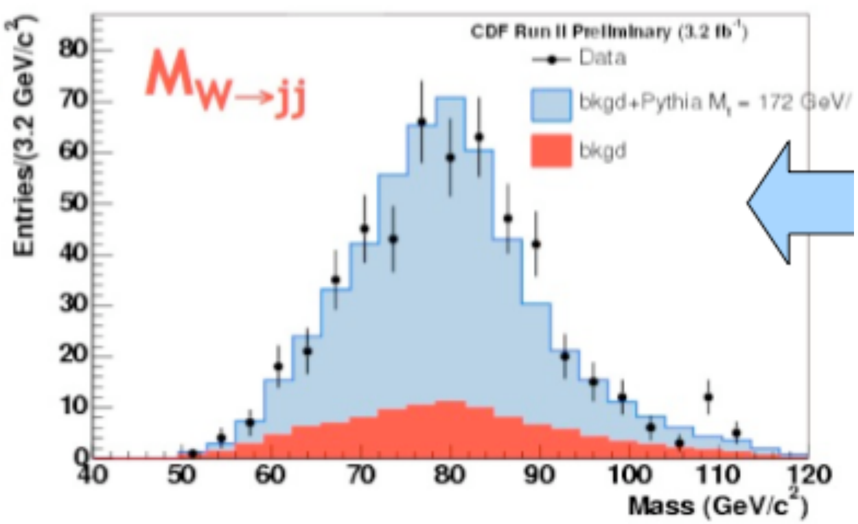


Julia Th

controlling the JES uncertainty

- Dominant contribution to δm_t from Jet Energy Scale uncertainty
- σ_{JES}/JES between 3 and 6%
- RunII: constrain JES uncertainty using reconstructed hadronic W ("in-situ calibration")
  - JES uncertainty scales with statistics





constrain inv.mass of non-tagged jets to be 80.4 GeV

Matrix Element Method

Matrix Element Method: define probability P_{evt} that the observed kinematics arise from possible signal or background kinematics at parton level, then maximize $L = \prod P_{evt}(M_{top}, JES)$

$$P_{evt}(\vec{x}) = f_{top} \cdot P_{sig}(\vec{x}, m_t, JES) + (1 - f_{top}) P_{bkg}(\vec{x}, JES)$$

$$P_{sig}(\vec{x}) = \frac{1}{\sigma(m_t, JES)} \int f(q_1) dq_1 f(q_2) dq_2 \times |M(\vec{y})|^2 \phi(\vec{y}) dy \times W(\vec{x}, \vec{y}; JES)$$

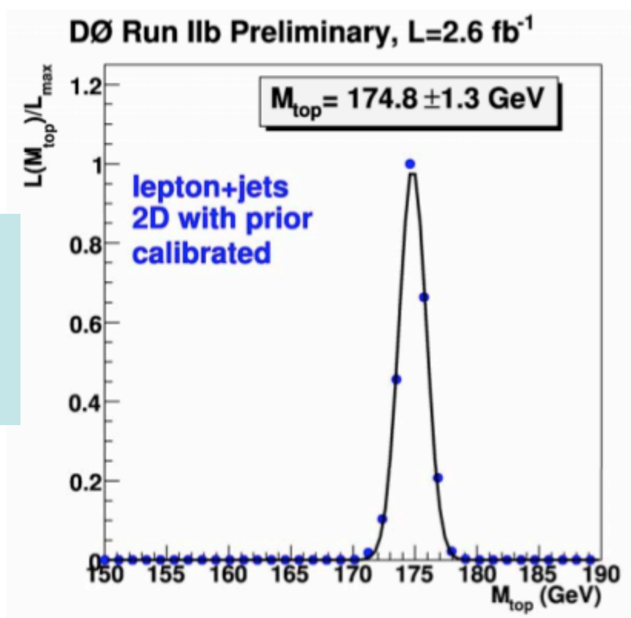
Parton distribution functions

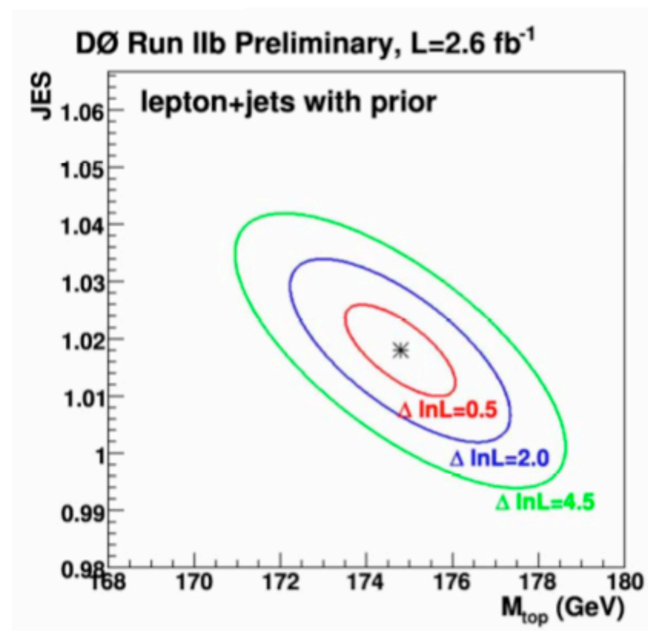
Differential cross section (LO ME)

Transfer Function: maps parton level (y) to reconstructed variables (x)

D0 3.6 fb^{-1}, l+jets

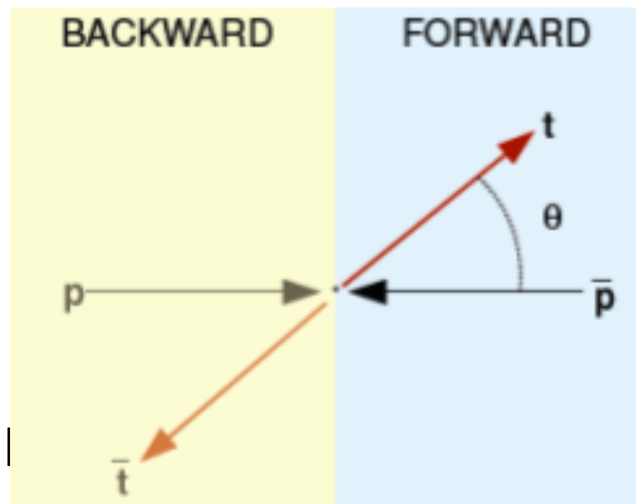
$m_t = 173.7 \pm 0.8(stat)$
$\pm 0.8(JES)$
$\pm 1.4(syst)\ GeV/c^2$





Search for Anomalous Production: Forward Backward Asymmetry

- Z' can change top "charge asymmetry": compare number of top and anti-top produced with momentum in a given direction
- interpret as forward backward asymmetry (top moving for or against given direction), in pp rest frame



- $$A_{fb} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})}$$ t with … side to