Physics at the LHC

Perugia, June 9, 2011

Top quark physics at the Tevatron

- Tevatron top program
- Production cross section
- Top quark mass measurements
- Top quark properties
- Single top: separate t-channel observation
- Searches
- Conclusions

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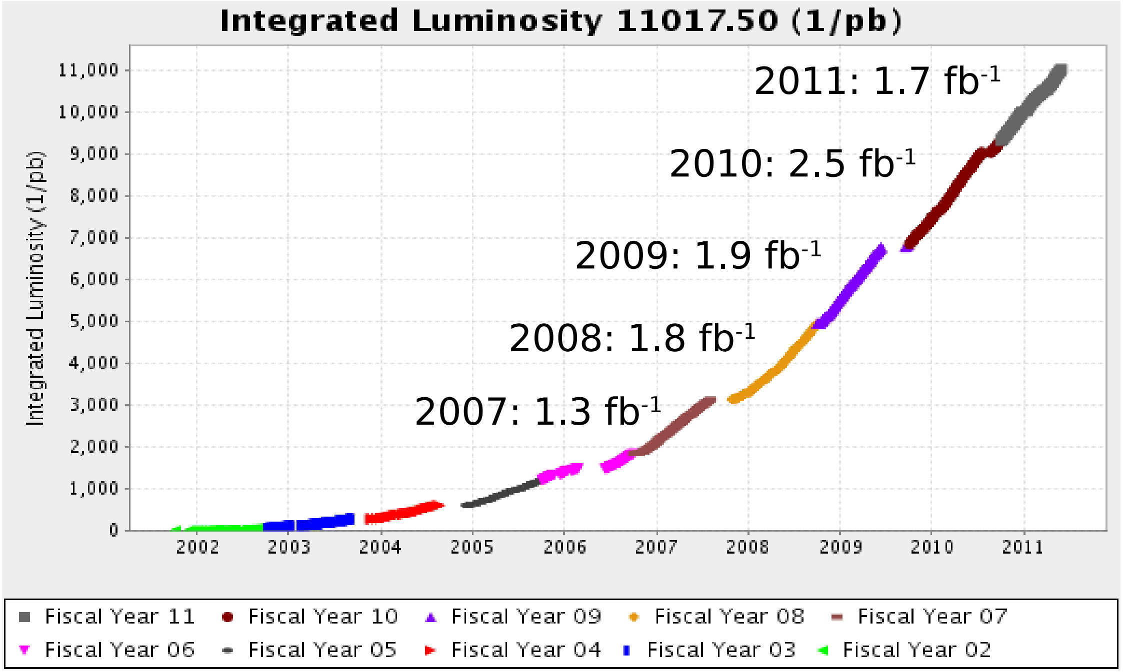
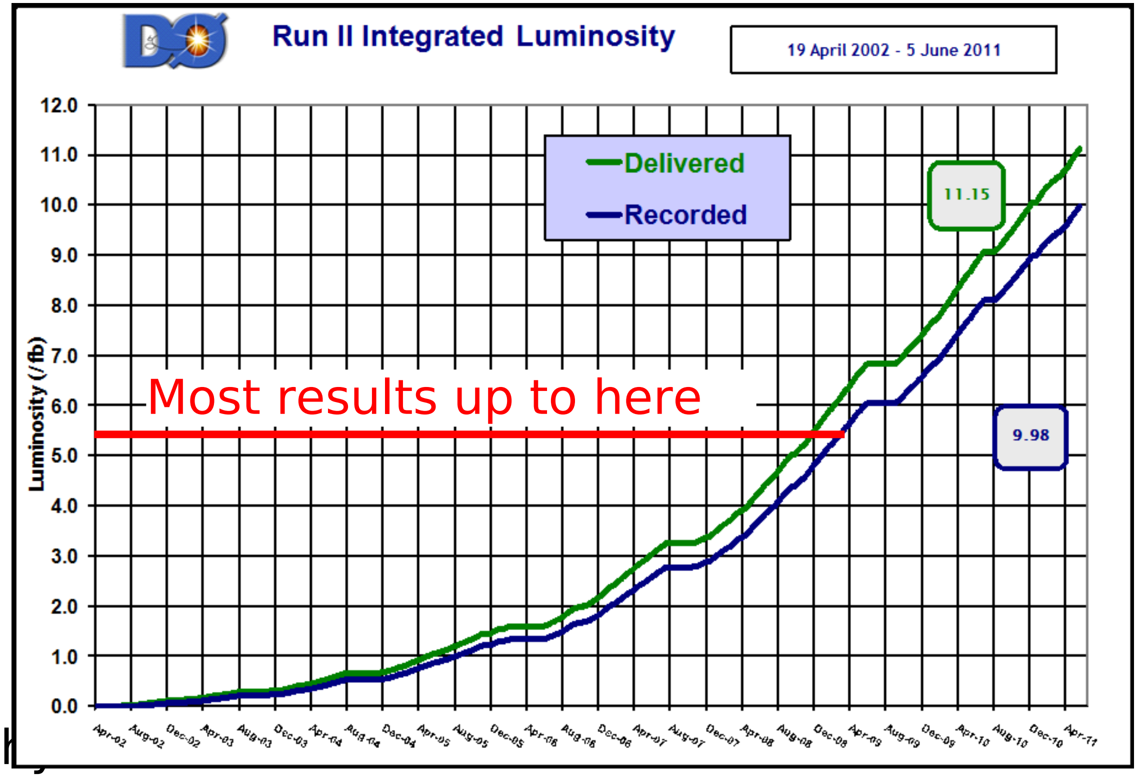
On behalf of CDF and DØ

The Tevatron

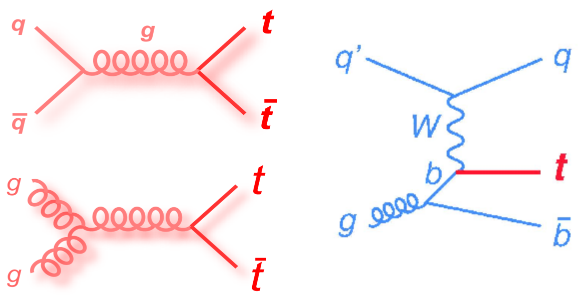
- 6.3 km $p\bar{p}$ collider @ $\sqrt{s}$=1.96 TeV
  - 25 year old!
  - 36x36 bunches
  - 10^{11} $\bar{p}$ per bunch
  - 396 ns bunch spacing
  - 1.8 M crossings/s
  - $4.3 \cdot 10^{32}$ $cm^2 s^{-1}$ peak lumi
- 11 fb^{-1} delivered
- 10 fb^{-1} recorded
- Expect ~12 fb^{-1} by October
- Detectors working well
  - ~90% data taking efficiency





Top quark Tevatron program

How is it produced



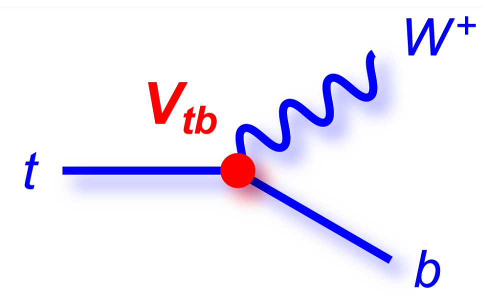
Strong force:

σ_{tt} ~ 7 pb

Electroweak force:

σ_{s+t} ~ 3 pb

How does it decay



V_{tb} ~ 1

V-A coupling:

F_0~0.7

F_+~0

What are its intrinsic properties

Mass

Width: Γ_t ~ 1.3 GeV

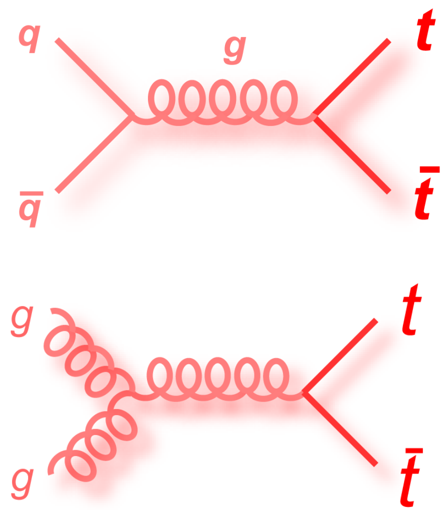
Charge: +2/3

Spin: 1/2

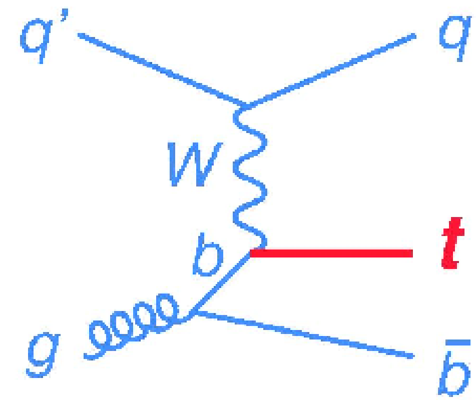
Are there signs of new physics anywhere

t', W', Z', H^+, resonances, FCNC, anomalous charge...

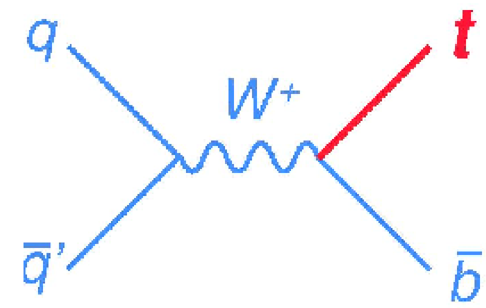
Production



t-channel



s-channel



		t-channel	s-channel
TeV:	**7.1±0.4 pb**	**2.1±0.1 pb**	**1.1±0.1 pb**
LHC7:	**163±11 pb**	**64±2 pb**	**4.6±0.2 pb**
LHC14:	**920±60 pb**	**243±6 pb**	**11.9±0.4 pb**

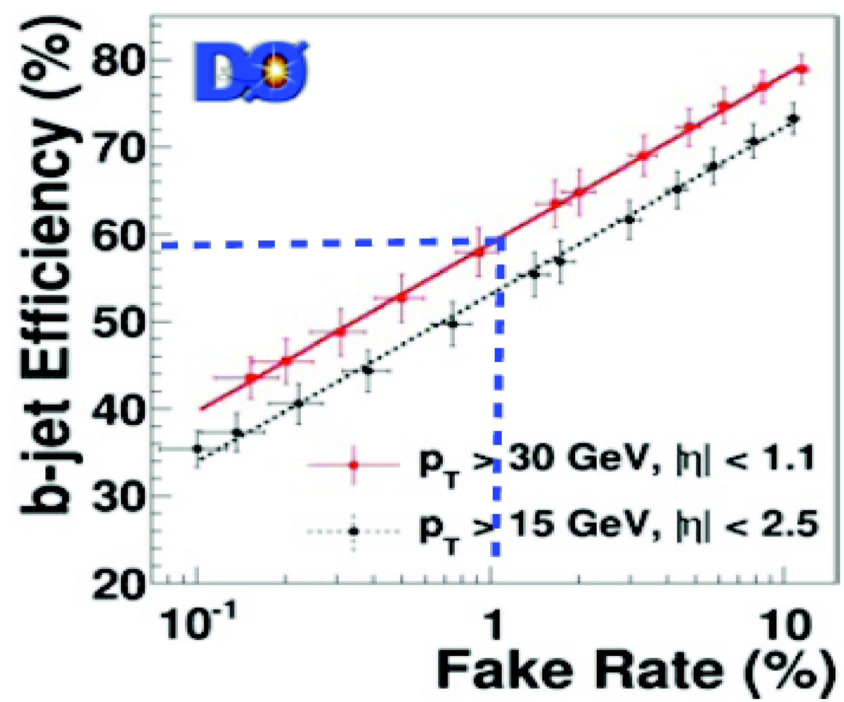
Kidonakis NNLL m_t = 173 GeV with MSTW 2008 PDFs

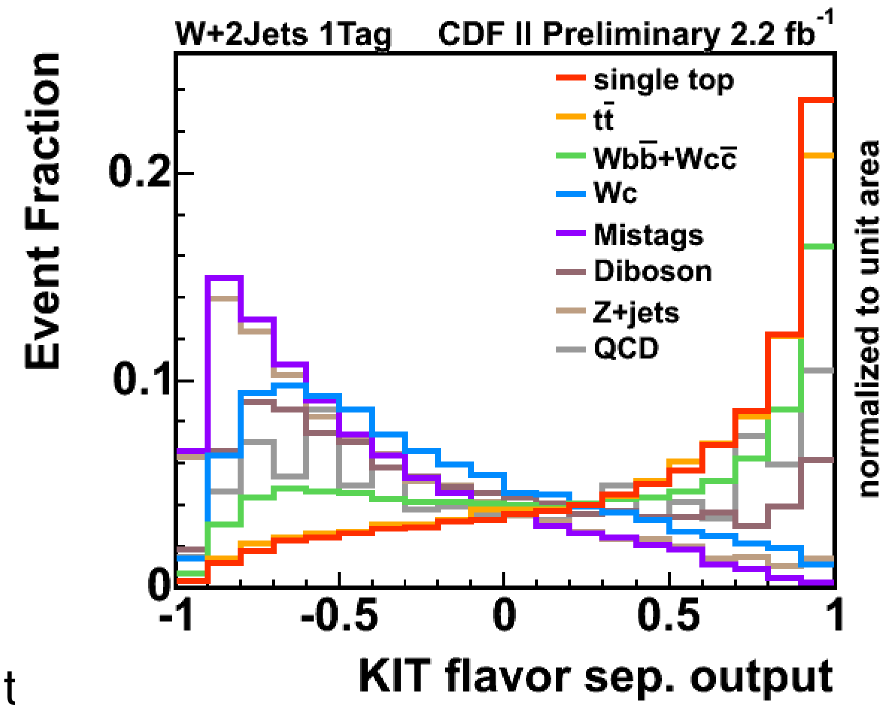
- Pair production x20 at LHC7: 250 pb^{-1} @ LHC7 ~ 5 fb^{-1} @ Tevatron
  - $q\bar{q}$ dominates at the TeV, gg at the LHC
- Single top production: CP symmetric at TeV
  - 86% more t than $\bar{t}$ at LHC7
- Third mode for EW production: gb→Wt, negligible at the Tevatron

Tools: b-tagging

- Algorithms based on jet lifetimes, track counting, μ in jet, and SVX
- Improved performance by combining variables from different taggers
- DØ: NN tagger
  - 7 input variables
  - Moving to BDT with c-separation
- CDF: NN heavy flavor separator applied after SVX tagger
  - Separates b from c and lights
  - 25 input variables
- Developed techniques to measure b-tag efficiency in data

NIM, A620, 400 (2010)





Top pair cross section: ℓ+jets

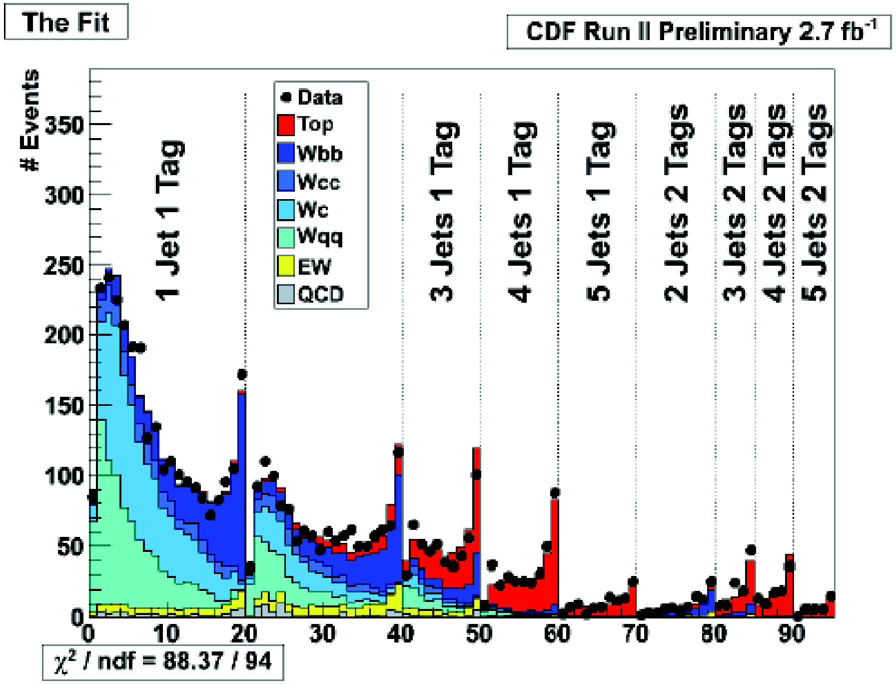
- First step to understand top quark sample
- Test QCD predictions
  - Limited by systematics: Luminosity ~6%

$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{bkg}}{A \cdot L}$$

Background modeling tools:

- Developed techniques to obtain QCD and W+jets backgrounds normalization from data
- Simultaneous measurement of $\sigma_{t\bar{t}}$ and background normalization
  - Use NN flavor separator and Njets
  - Improves by 9% stat. and 15% syst. uncertainties
  - Measures k-factors for W+jets

$$K_{W_{b\bar{b}}} = 1.57 \pm 0.25 \quad K_{W_{q\bar{q}}} = 1.10 \pm 0.29$$
$$K_{W_{c\bar{c}}} = 0.94 \pm 0.79 \quad K_{W_c} = 1.90 \pm 0.29$$



Top pair cross section: ℓ+jets

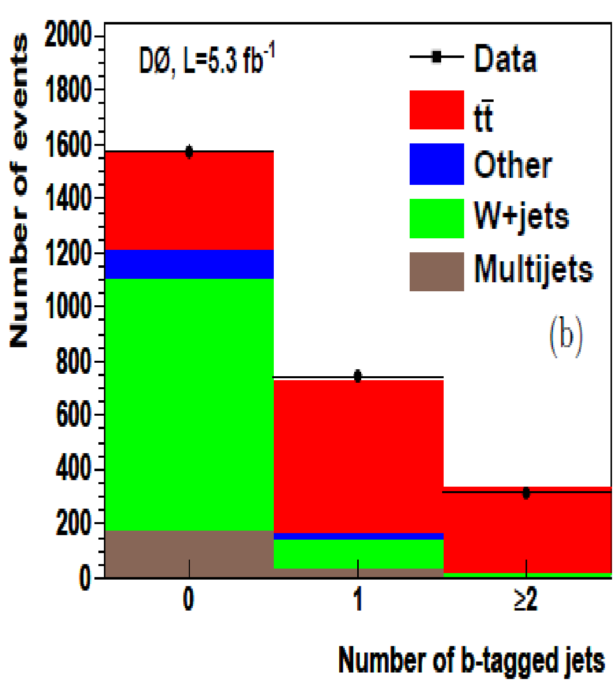
Selection D0 5.3 fb^{-1} m_t=172.5

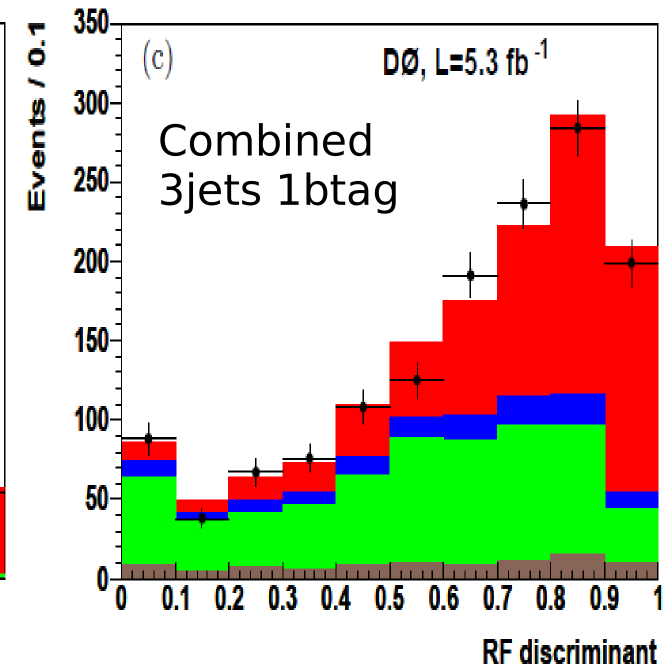
- Lead jet p_T>40 GeV, $|\eta|$<2.5
- Isolated e: p_T>20, μ: p_T>25 GeV
- MET>20 or 25 GeV (μ+jets)
- QCD cleanup cuts
- At least one tight b-tag jet

Three measurements:

- Kinematic information discriminant
- Counting using b-tagged sample
- Combined: b-tag and Random Forest

e+mu, ≥4 jets, ≥1 b-tag	
W+jets	131 ± 13
Multijet	31 ± 4
Z+jets	12 ± 2
Other	19 ± 1
$t\bar{t}$	877 ± 45
Total	1066 ± 38
Observed	1060





$\sigma_{\ell j}=7.78^{+0.77}_{-0.64}$(stat+sys) pb

8-10% relative uncertainty

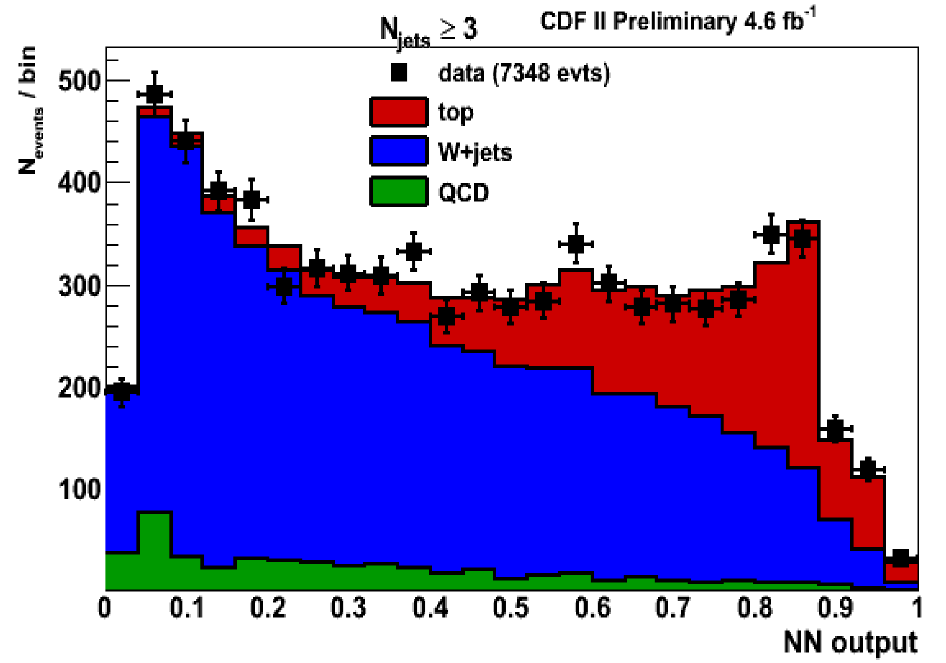
Top pair cross section: ℓ+jets

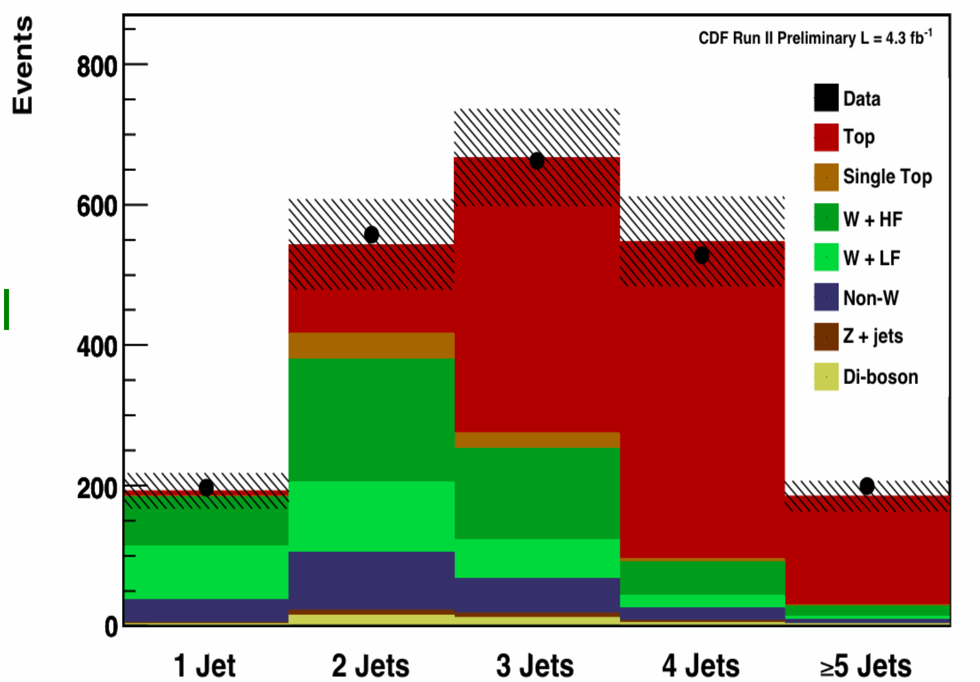
CDF 4.3-4.6 fb^{-1} m_t=172.5 GeV

- Measure ratio of cross sections to cancel out luminosity uncertainty

$$\sigma_{t\bar{t}} = \frac{\sigma_{t\bar{t}}}{\sigma_Z} \cdot \sigma_Z^{theory}$$

- Measure Z cross section on same triggers and same data sample
- (almost) Replace 6% uncertainty in luminosity with 2% uncertainty on σ_Z^{theory}
- Combine $\sigma_{t\bar{t}}$ from
  - NN discriminant with 7 topological variables before b-tag
  - SVX b-tagged sample

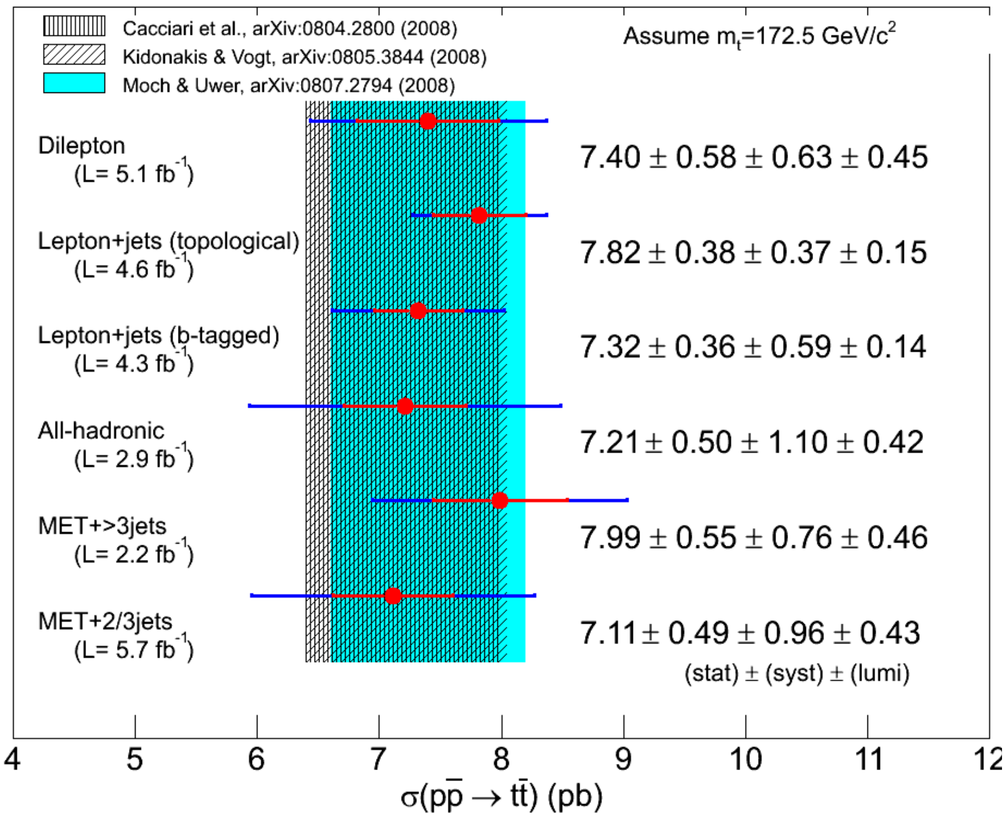


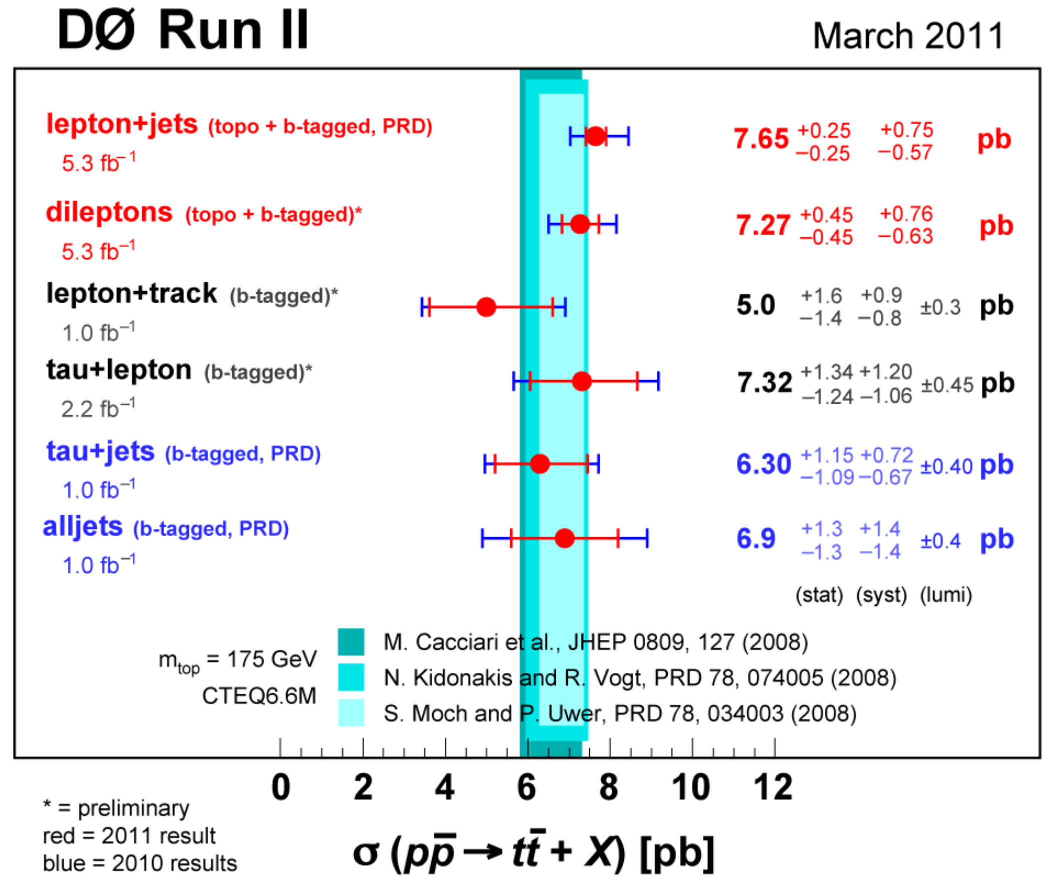


$\sigma_{\ell j}$=7.70±0.52(stat+sys) pb

7% relative uncertainty

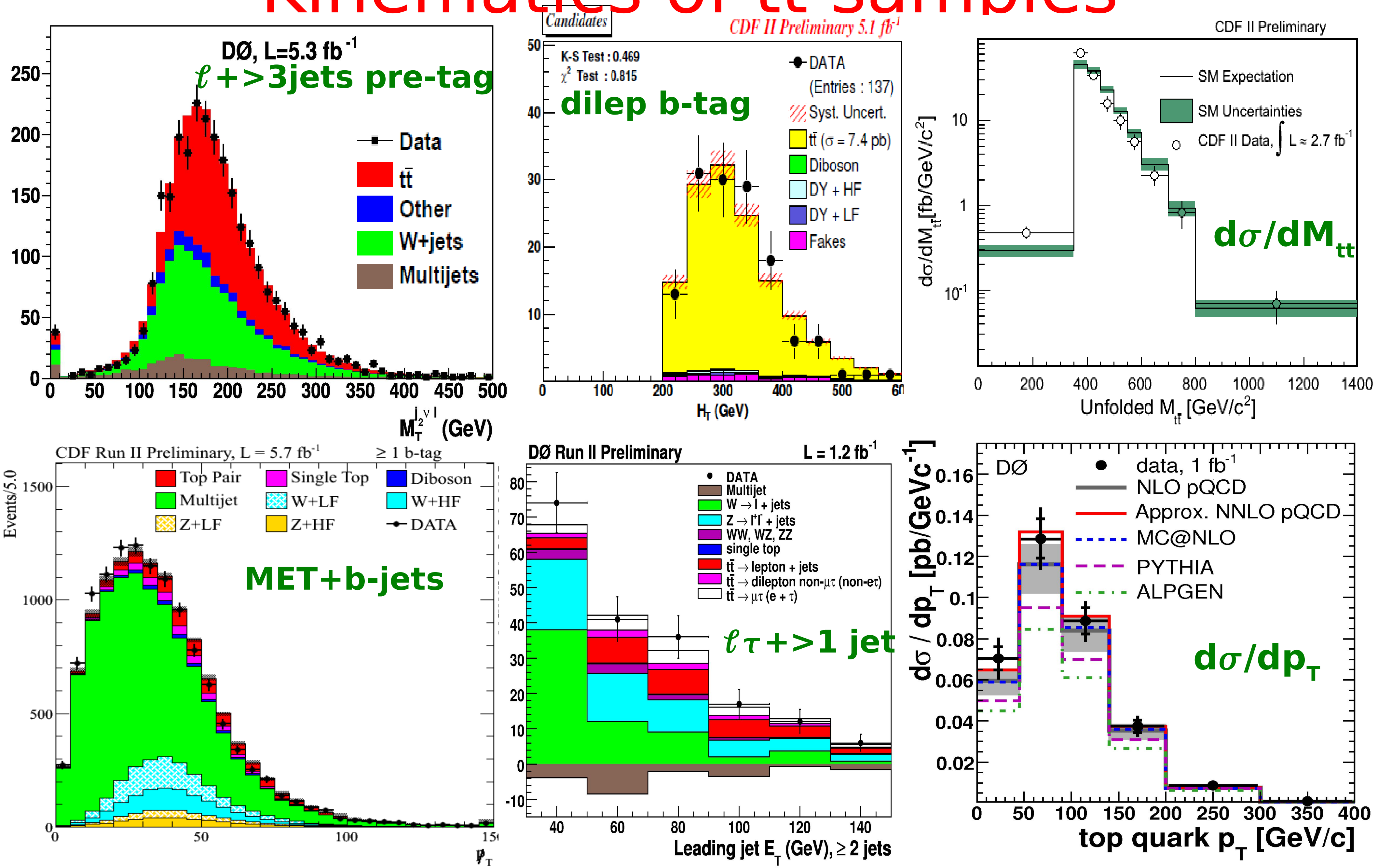
Cross sections combinations





- Tested many other channels: all hadronic, tau+lepton, tau+jets, MET+jets... all compatible results
- Best single measurement has 7% relative uncertainty: similar to theoretical uncertainty
- Most sensitive measurements limited by systematics

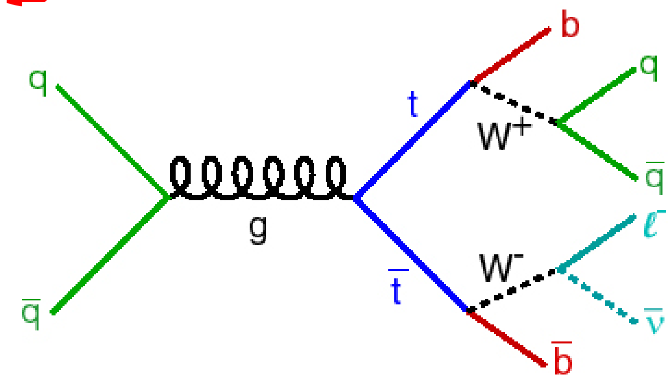
Kinematics of $t\bar{t}$ samples



Selected samples in l+jets, tau+jets, and dilepton are well modeled

Top quark mass

- Best known top quark property!
- Combinatorics: how to assign jets to partons
- Need to calibrate jet energies to particle level (JES)
  - In-situ determination with m_W



Extraction methods

Matrix Element:

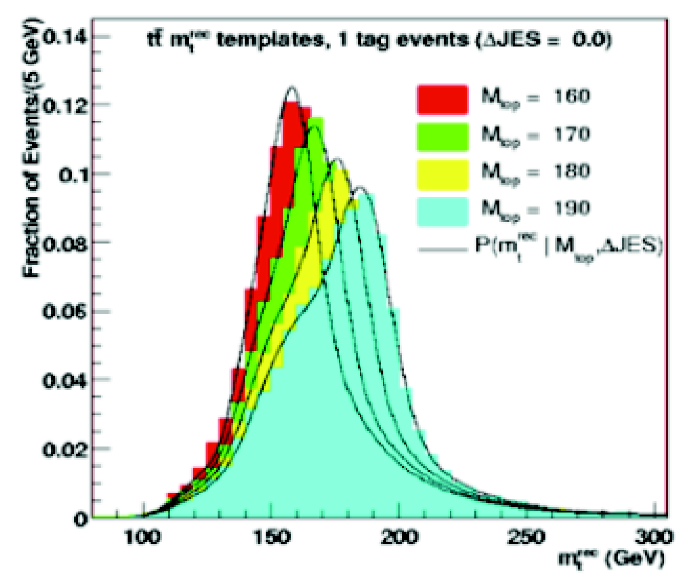
- Event probability based on parton physics
- Integrate over:
  - Incoming parton PDFs
  - Differential cross section (M)
  - Need transfer functions (reco↔parton)
- Maximizes statistical power by using full event information

$$P_{sig}(\vec{x}) = \frac{1}{\sigma(m_t, JES)} \int \text{PDFs} \, \frac{d\sigma(\vec{y})}{d\vec{y}} \, W(\vec{x},\vec{y};JES)$$

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

Templates:

- Compare data to MC with different mass hypothesis



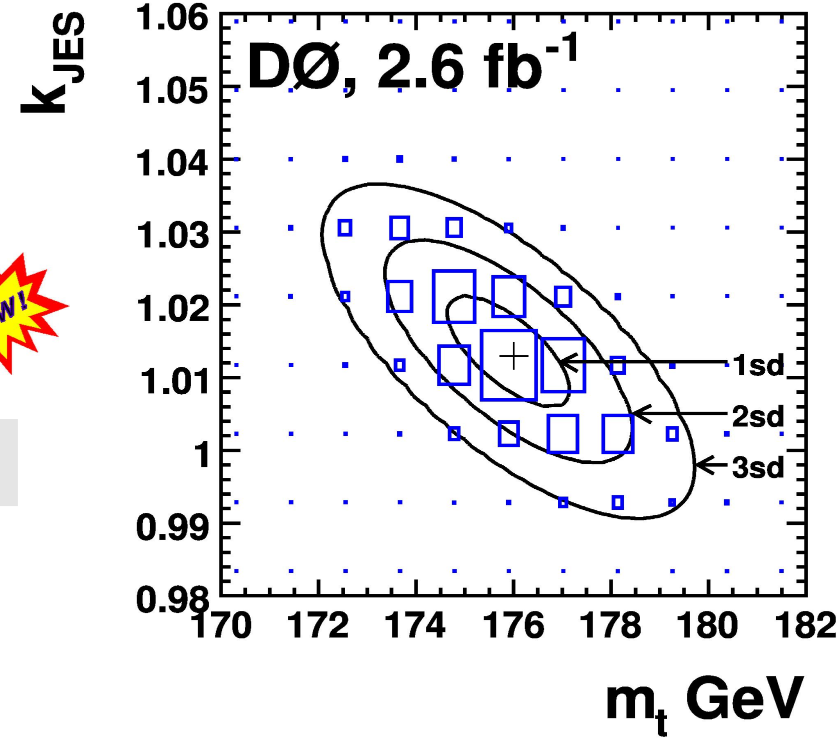
Latest m_t measurements

D0 Matrix Element (3.6 fb^{-1}) in ℓ+jets

- Detailed study of b/light jet response
  - Used γ+jets Data/MC corrections
  - Up to 1 GeV shift if corrected

m_t=174.9±0.8(stat)±1.3(sys) GeV

0.9% relative uncertainty

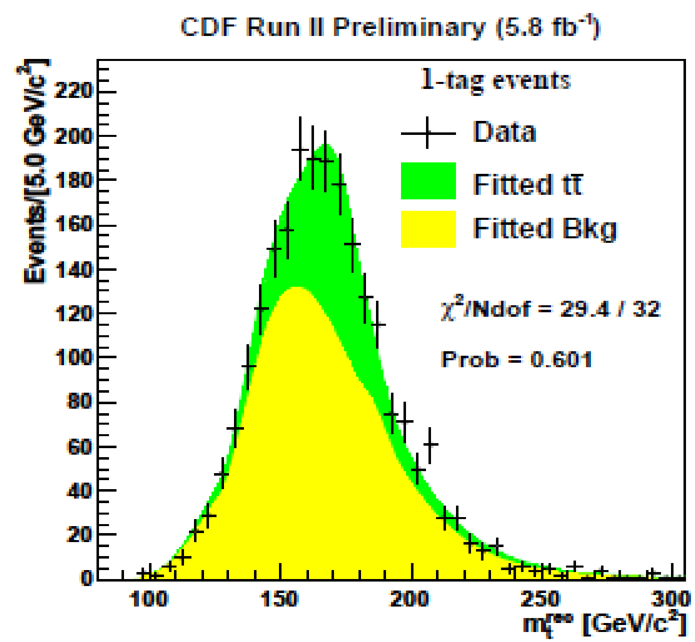


CDF templates (5.8 fb^{-1}) in all hadronic

- Derive background from data
- Cut on NN discriminant to separate QCD
- Divide sample in 1 or >1 tagged jets
- χ^2 fit with m_W and m_t templates

m_t=172.5±1.4(stat)±1.0(JES)±1.2(sys) GeV

1.2% relative uncertainty

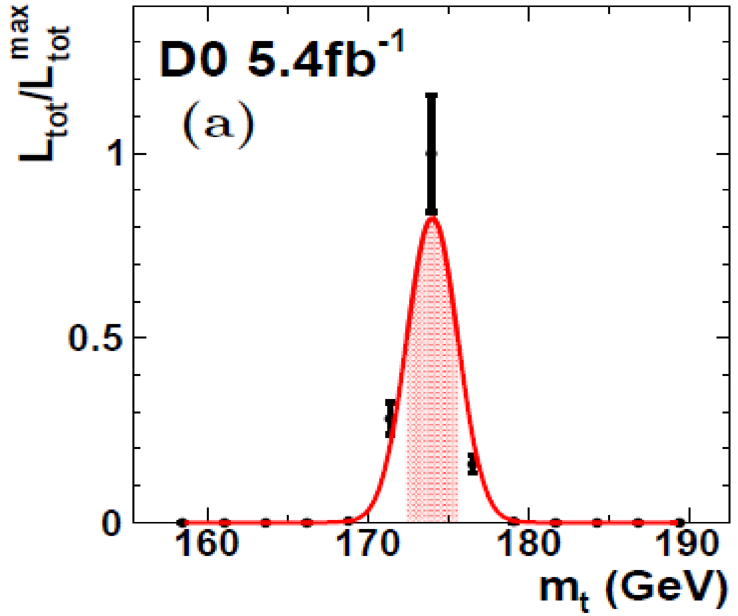


More m_t measurements

D0 Matrix Element (5.4 fb^{-1}) in dilepton

- Selects 479 events, 85% $t\bar{t}$
- Two missing neutrinos:
  - ME integrates over 8 variables
- One background ME: Z+2jets

NEW!

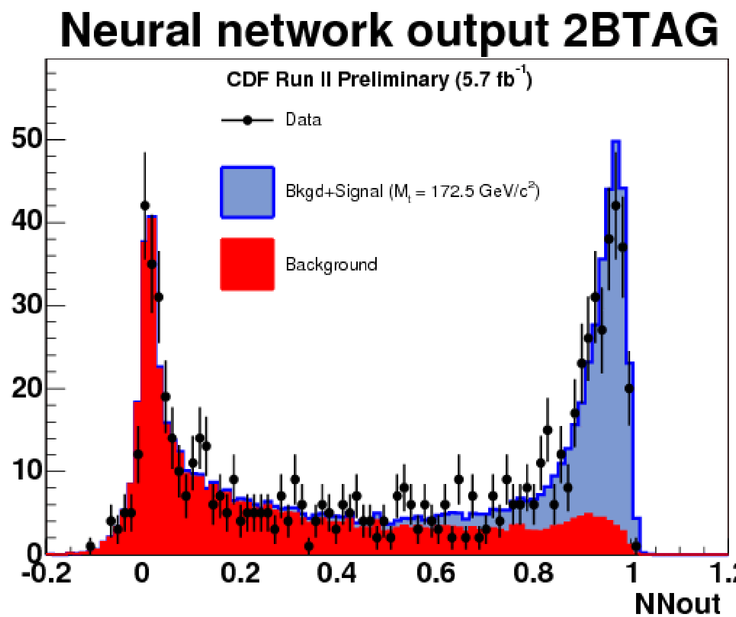


m_t=174.0±1.8(stat)±2.4(sys) GeV

1.8% relative uncertainty

CDF templates (5.7 fb^{-1}) in MET+jets

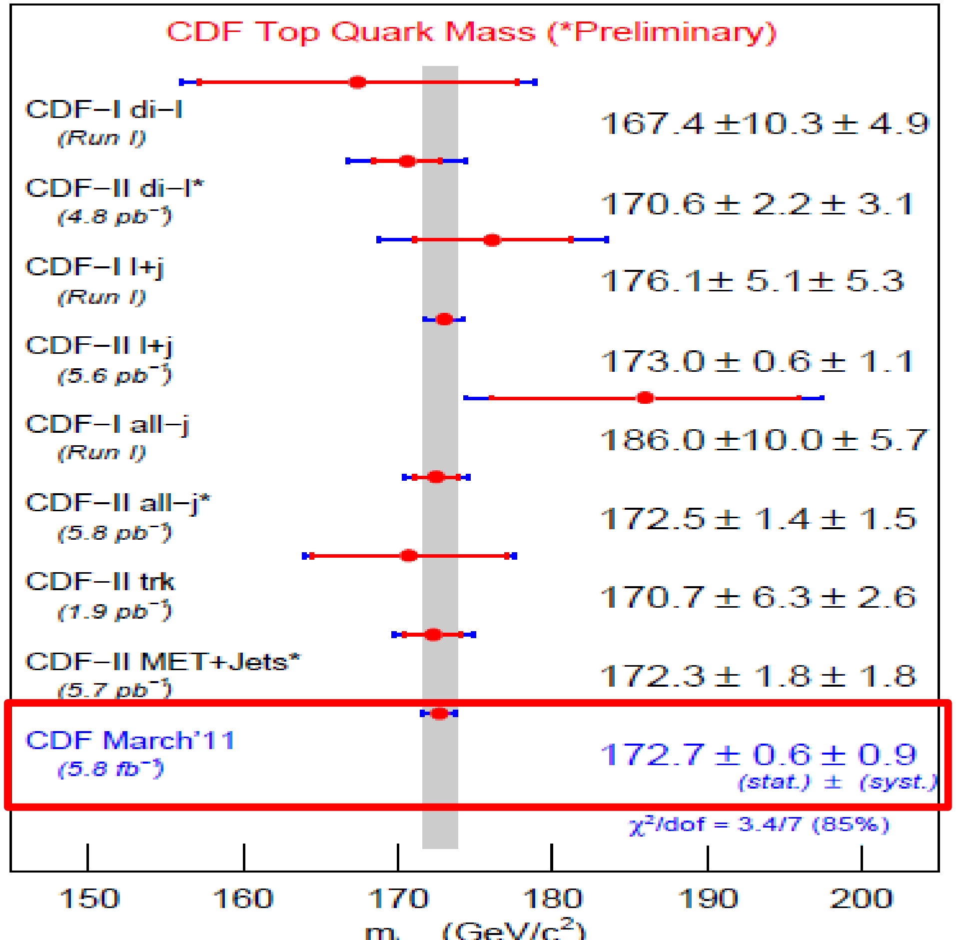
- MET+⩾4jets, 1 or 2 b-tags
- Use NN>0.8 to remove background
- Use M3, M3' and m_{jj} variables to fit likelihood, each sampled over different m_t and JES

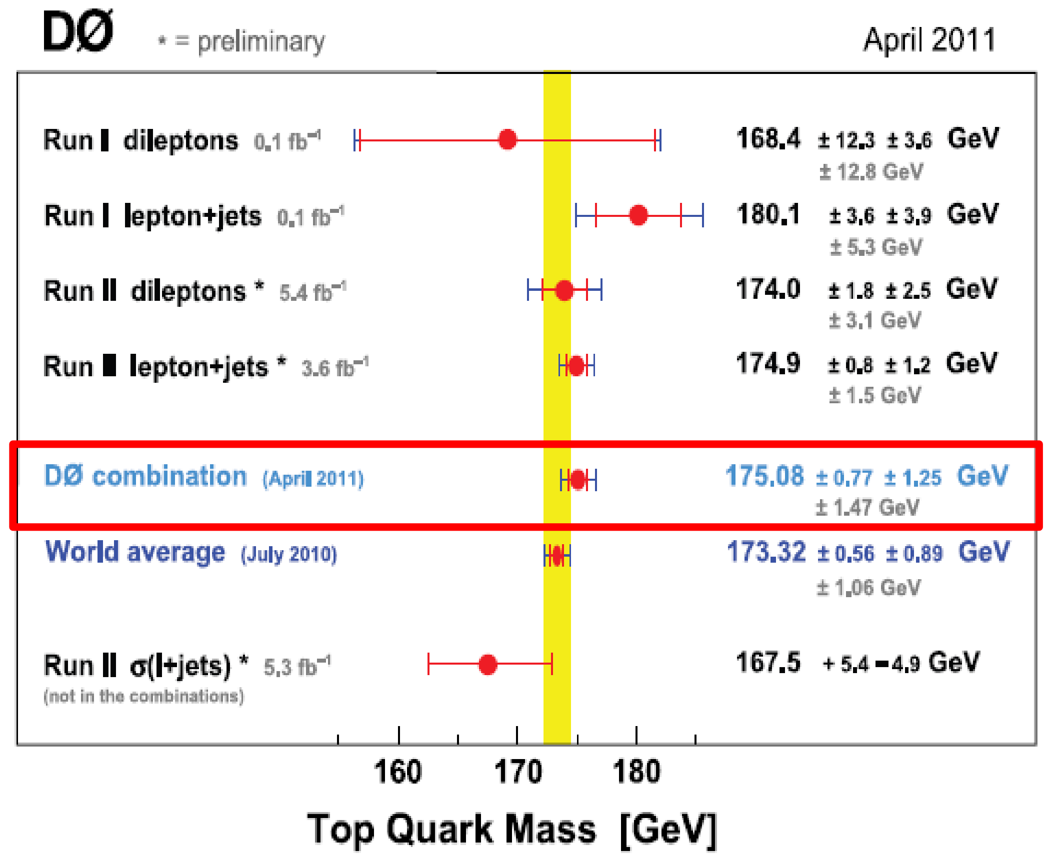


m_t=172.3±2.4(stat+JES)±1.0(sys) GeV

1.5% relative uncertainty

Combined mass results





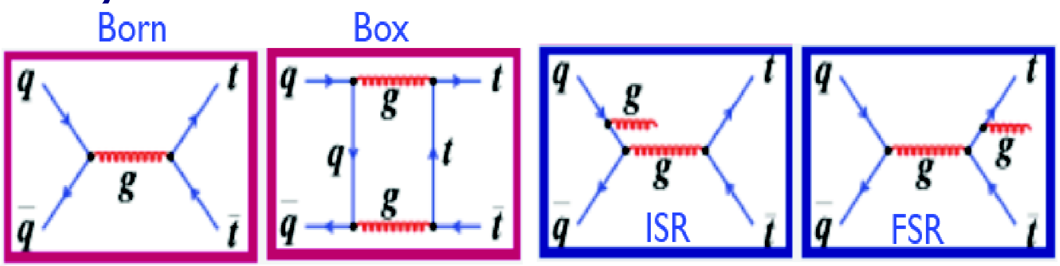
m_t=173.3±0.6(stat)±0.9(sys) GeV

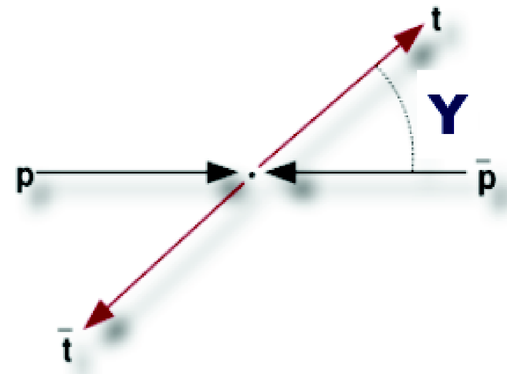
July 2010: 0.6% relative uncertainty

- Different methods produce consistent results
- Different channels are consistent with each other
- Latest CDF and D0 combinations already close to 0.6%

Color charge asymmetry

- LO: top quark production angle is symmetric wrt beam direction

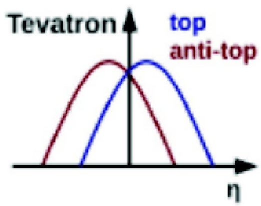




$\Delta y = y_t - y_{\bar{t}}$

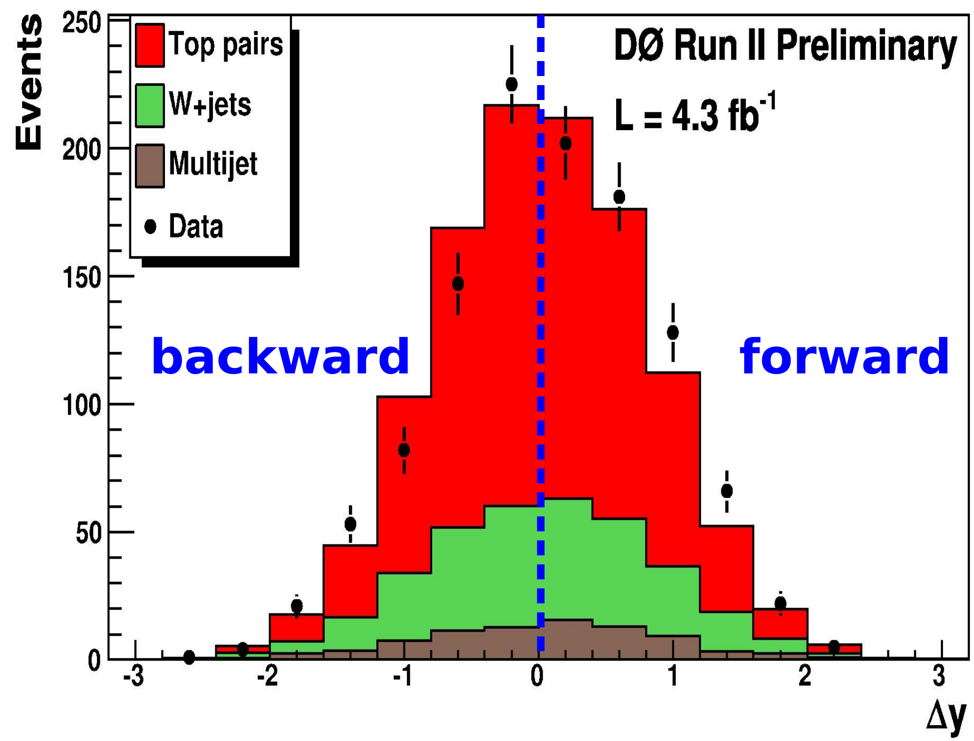
- NLO: forward-backward asymmetry A_{fb}~5% due to interference effects

$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$



D0 analysis in ℓ+jets 4.3 fb^{-1}

- ℓ+jets sample with b-tagged jets
- Kinematic fitter to reconstruct $t\bar{t}$ pair
- Extract A_{fb} from 4 templates fit: fwd and bwd tt, multijets, and W+jets
- Result is raw asymmetry (uncorrected for detector effects)



A_{fb} = 8±4 % **A_{fb}^{SM} = 1±2 %**

~2 sigma discrepancy

Color charge asymmetry

CDF ℓ+jets sample 5.3 fb^{-1}

- Unfold result to parton level
- Largest discrepancy for high Δy and large M_{tt}
- Soft QCD effect, new physics?
- Double the dataset to look at!

CDF dilepton sample 5.1 fb^{-1}

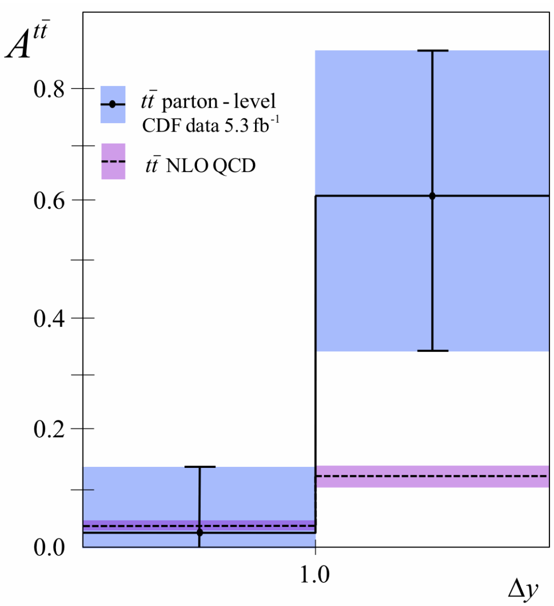
- Independent sample
- Lepton direction correlated with top direction
- Different $t\bar{t}$ reconstruction
- Raw result (not unfolded)

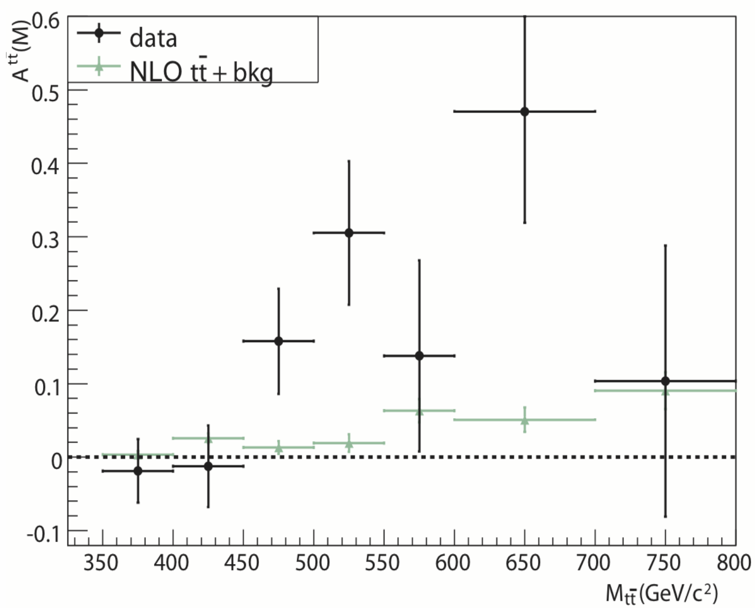
A_{fb}^{lj} = 16±7 % A_{fb}^{SM} = 6±1 %

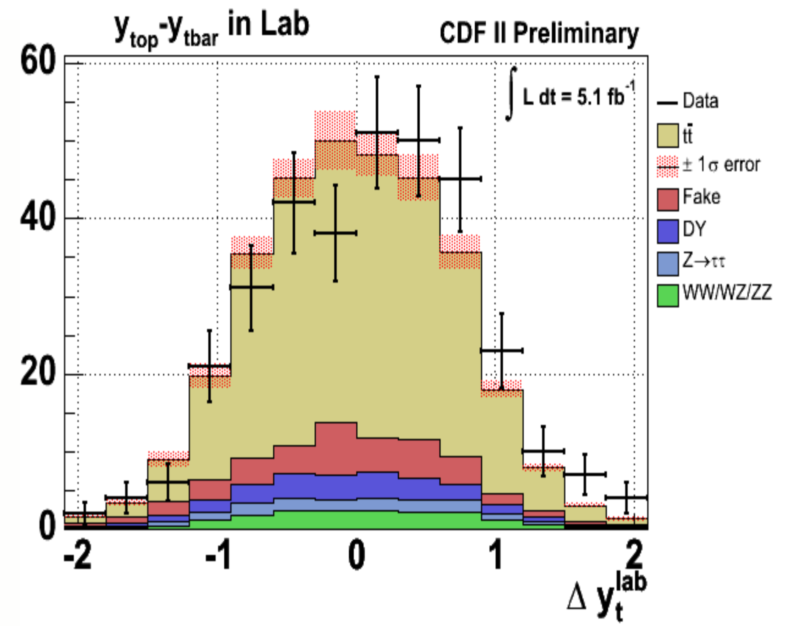
~2 sigma discrepancy

A_{fb}^{ll} = 42±16 % A_{fb}^{SM} = 6±1 %

~2.3 sigma discrepancy



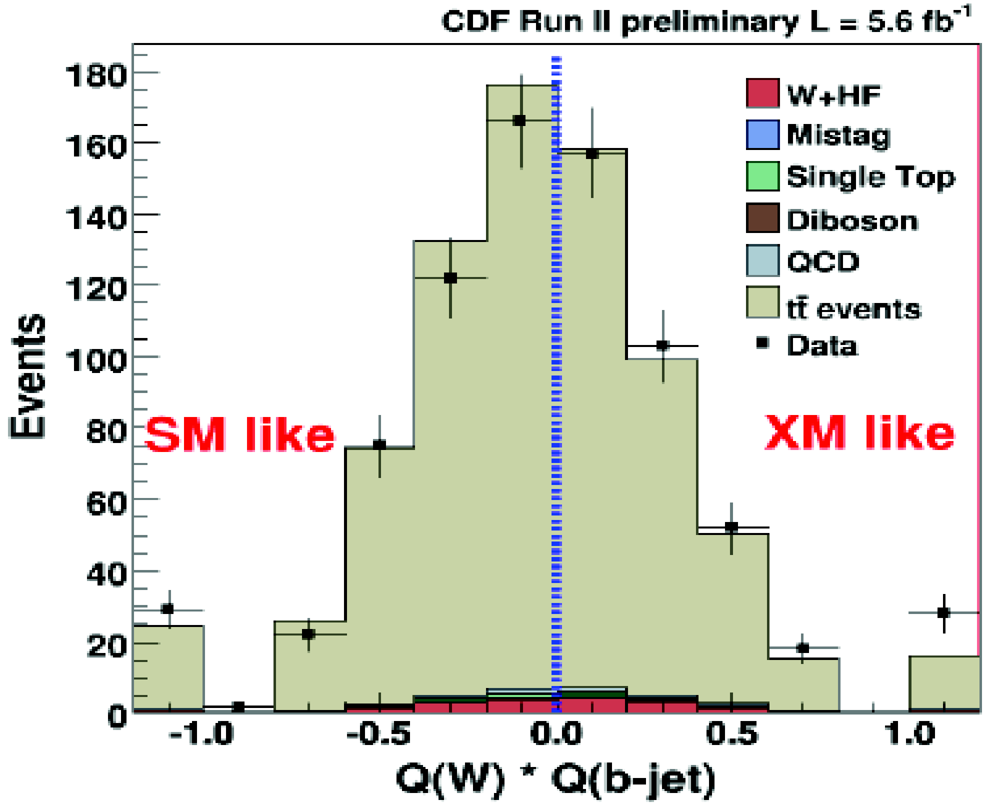




Top charge

CDF 5.6 fb^{-1} in ℓ+jets

- Possible exotic model with -4/3e
- Fit pairs W's and b's for best m_t
- Use lepton to get W charge
- Determine b charge based on tracks charges
  - Purity = 68%
  - Efficiency = 98%
- Use $Q_w x Q_b$ to build likelihood



Exclude -4/3e at 95% CL

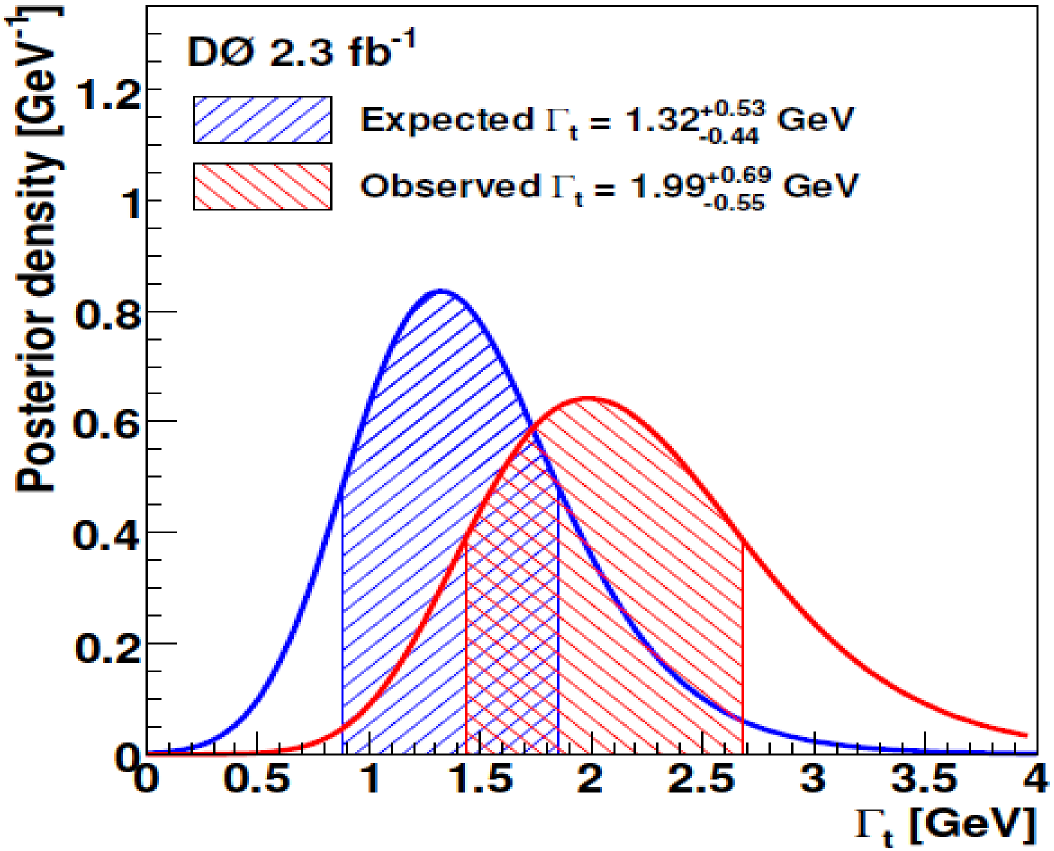
Top width

D0 singletop+B (2.3 fb^{-1})

- Direct measurement on m_t distribution is limited by detector resolution
- Indirect measurement from
  - t-channel single top σ
  - $B(t \rightarrow Wb)$ from $t\bar{t}$ decays

$$\Gamma_t = \frac{\Gamma(t \rightarrow Wb)}{B(t \rightarrow Wb)}$$

- Assumes coupling in production and decay is the same
- NLO: Γ_t=1.3 GeV for m_t=170 GeV



Γ_t = 2.0±0.7 GeV

Spin correlations

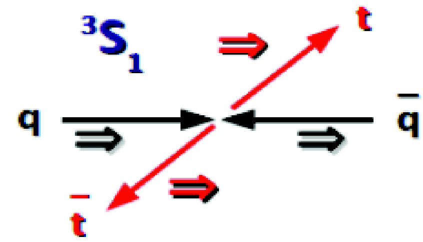
NEW!

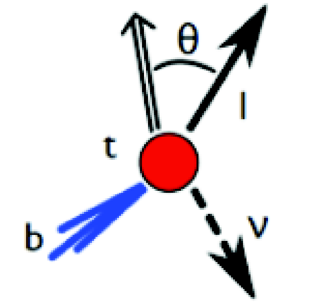
D0 5.4 fb^{-1} in dilepton

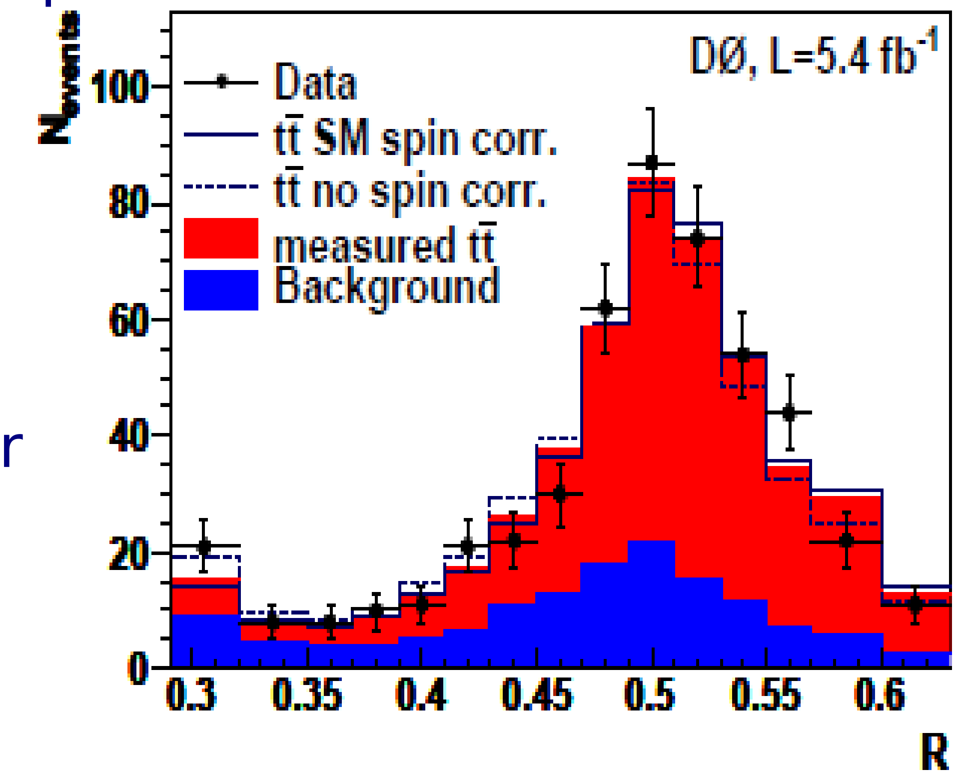
- Pair production: top quarks are unpolarized, but spins are correlated
- Flight directions of top decay products carry information about top polarization
- Matrix Element analysis (30% improvement over single variable)

$$R = \frac{P_{\rm sgn}(H=c)}{P_{\rm sgn}(H=u) + P_{\rm sgn}(H=c)}$$

- Test hypothesis of correlated (c) or uncorrelated (u) t and $\bar{t}$ spins
- Excludes uncorrelated case at 97.7%CL
- $C_{NLO} = 0.78^{+0.03}_{-0.04}$







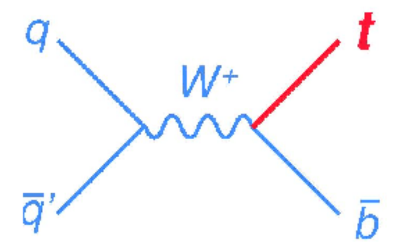
C_{obs} = 0.57±0.31

Most precise value of correlation strength

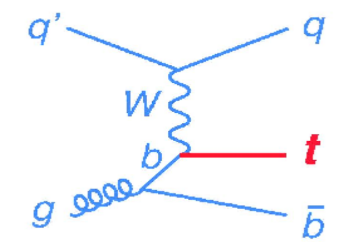
Single top physics

Electroweak production: tb and tqb

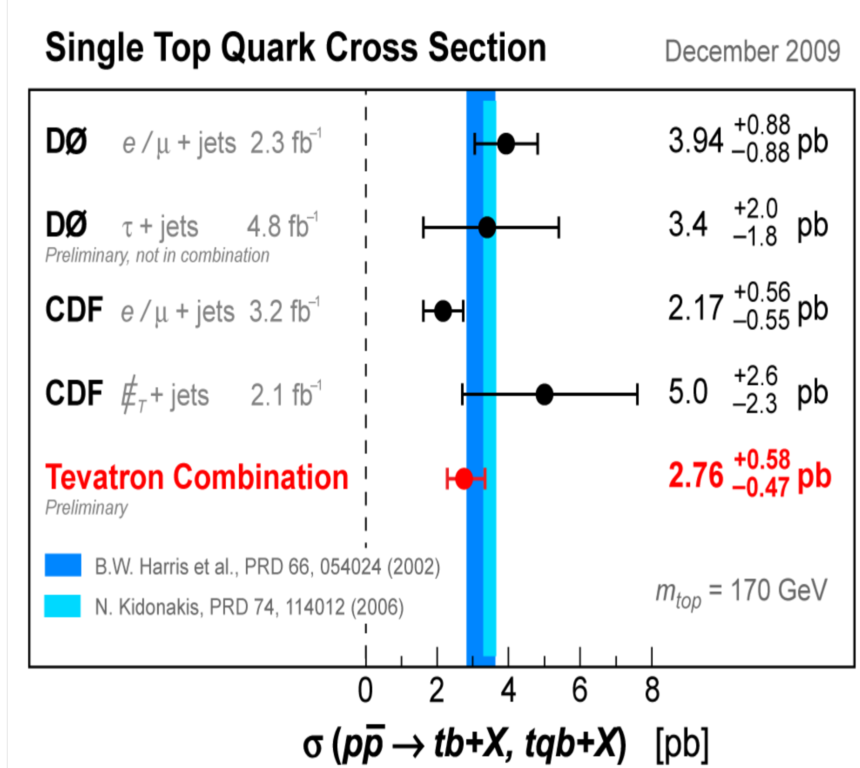
- Access directly W-t-b coupling (CKM)
- New physics:
  - s-channel sensitive to resonances
  - t-channel sensitive to anomalous couplings, FCNCs
- Extract small signal out of a large background: need MVA techniques
- Careful study of W+hf backgrounds

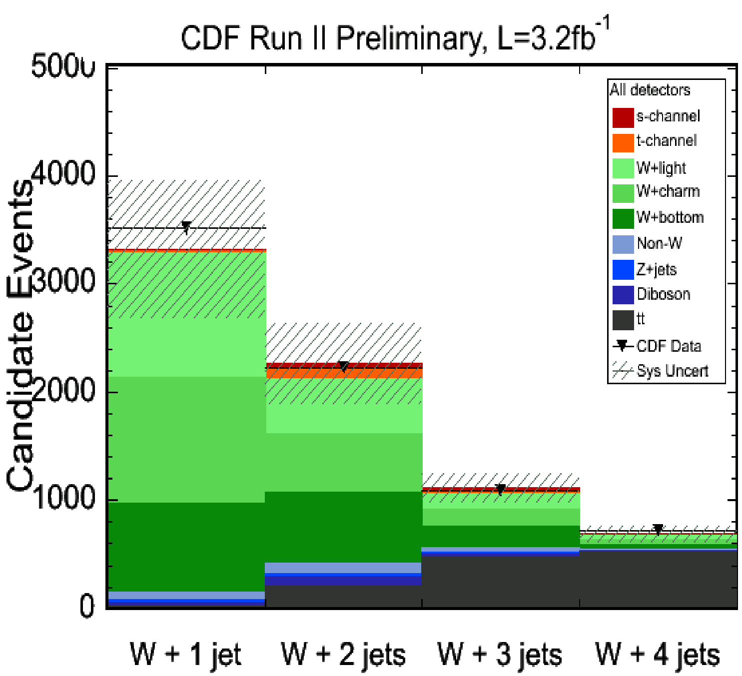


s-channel
σ(tb)=1.1pb



t-channel
σ(tqb)=2.1pb





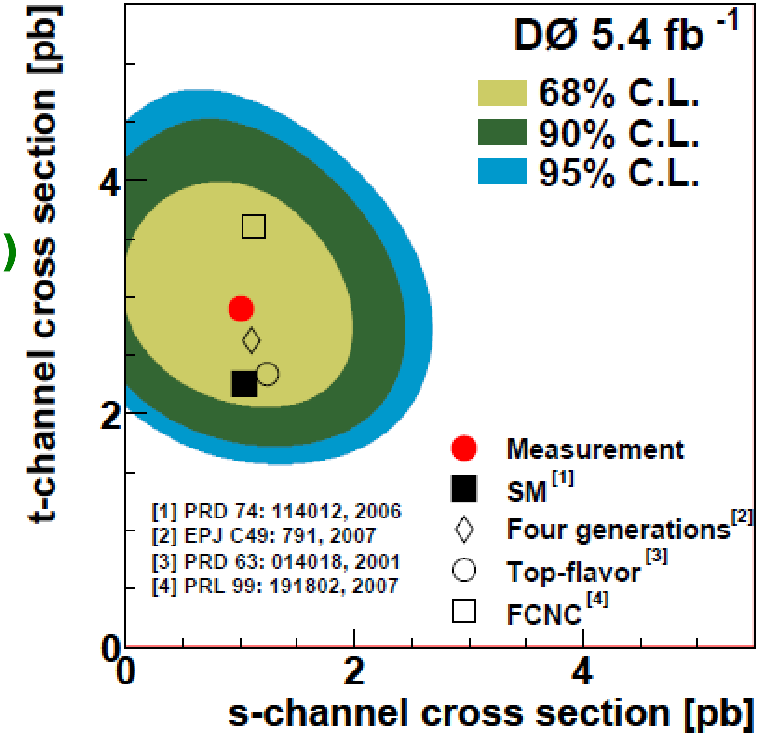
Took 14 years to observe after top discovery!

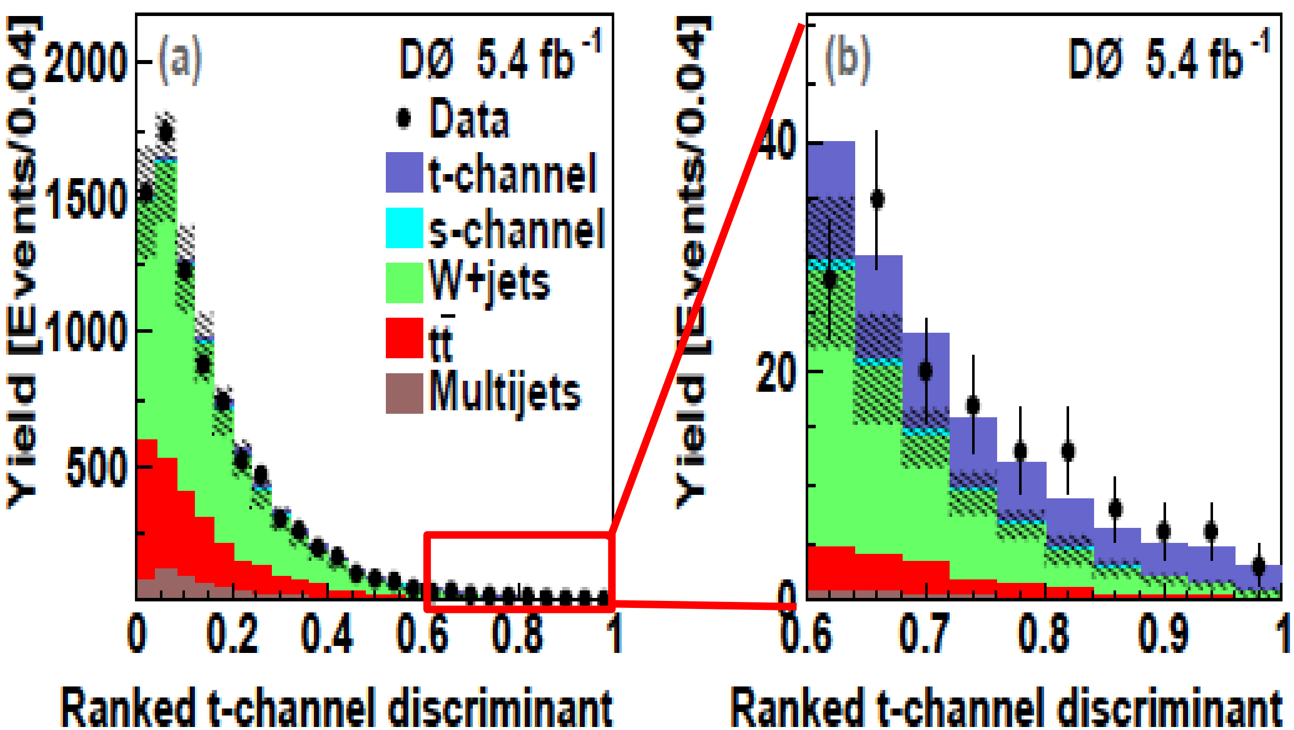
$|V_{tb}|$ = 0.88±0.07

8% relative uncertainty

Observation of t-channel

- Use three MVA techniques
  - **Boosted Decision Trees**
  - **Bayesian Neural Network (BNN)**
  - **Neuroevolution of Augmented Topologies (NEAT)**
- Combined into an additional BNN (BNNComb)
  - Only ~70% correlated with each other
- Fit simultaneously s- and t-channel cross sections: without SM assumption





σ(tb) =0.98±0.64 pb

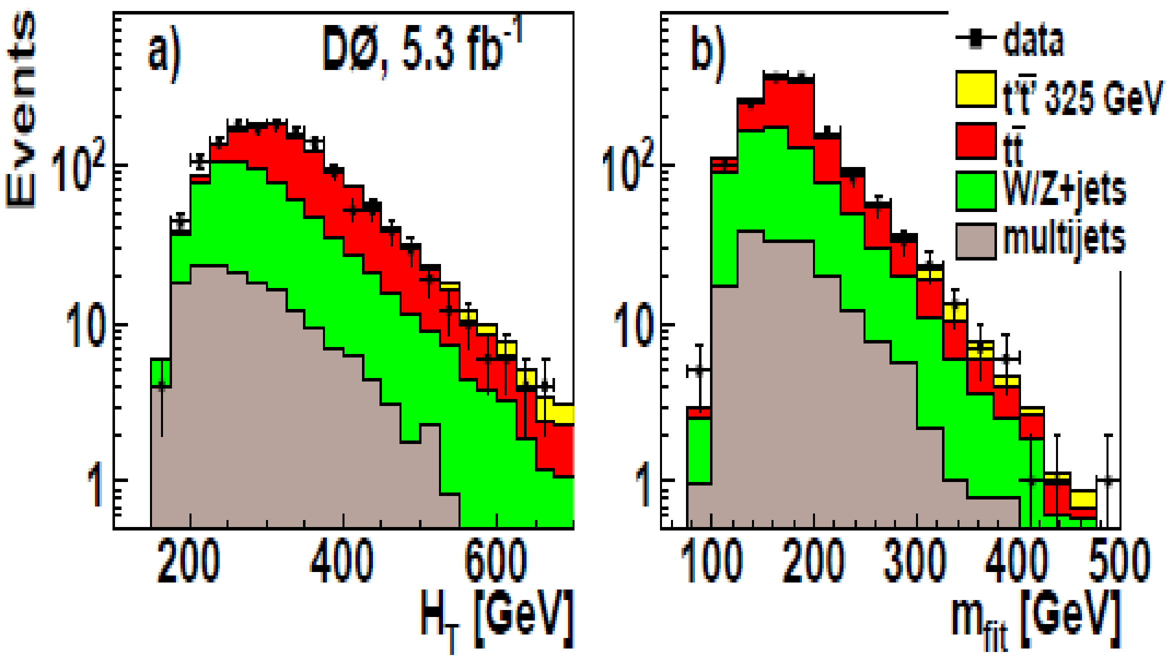
σ(tqb)=2.90±0.59 pb

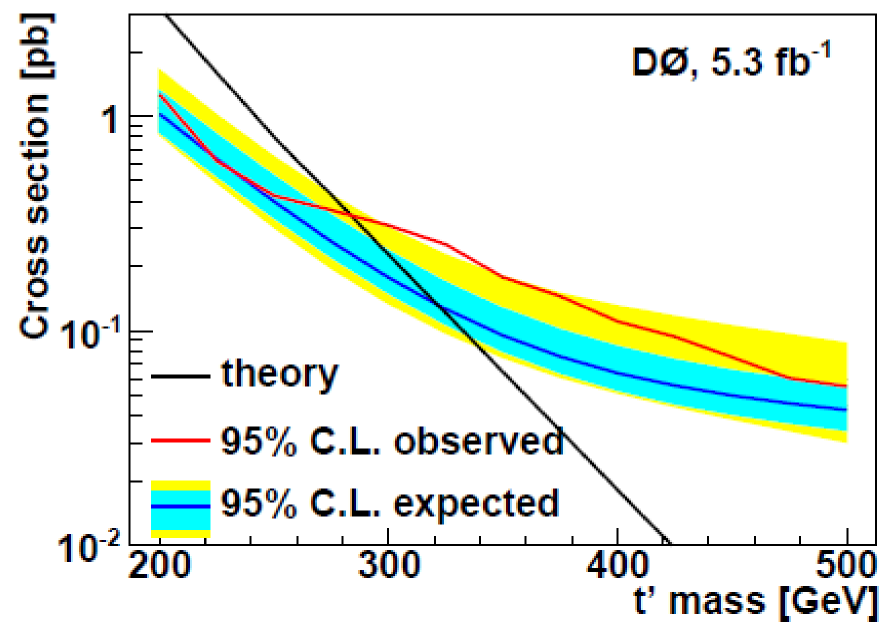
tqb: 5.5σ (4.6σ exp.)

20%-60% rel. unc.

Search for t'

- Fourth family t' not excluded if $m_{t'}-m_{b'}<m_W$
- Analyses look for $t'\bar{t}'$ production and $t'\rightarrow Wq$
- Use ℓ+jets channel without b-tagging
- 2D fit to data in H_T and $m_{t'}$ from kinematic fit



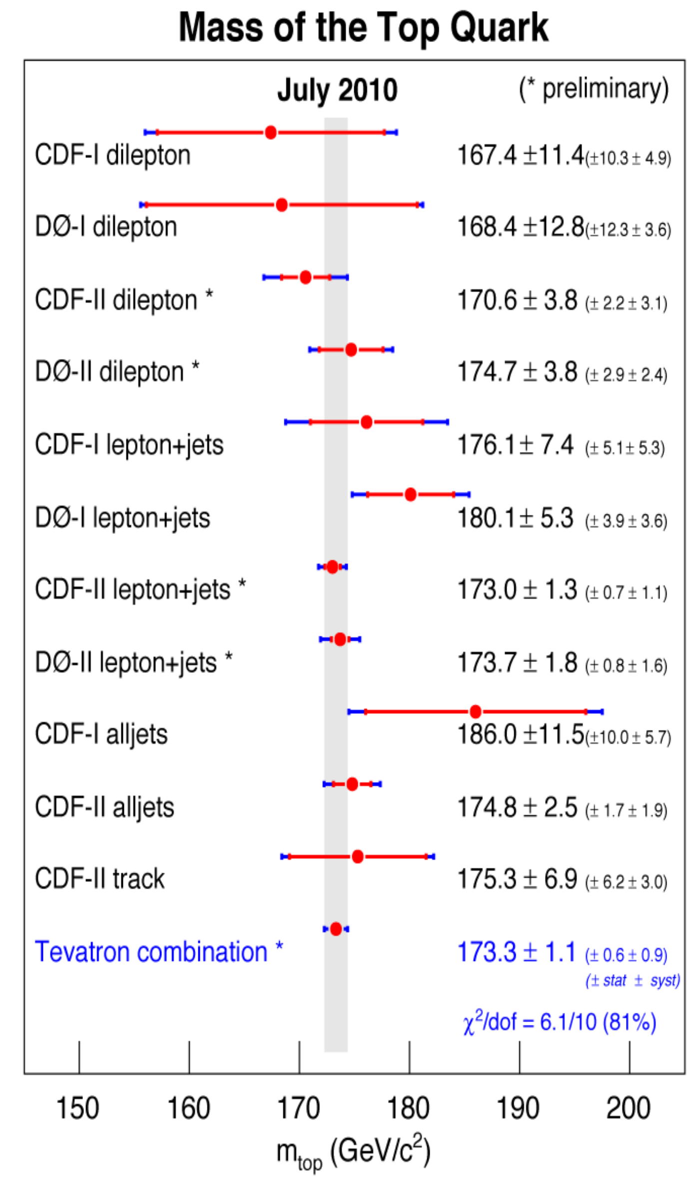


$m_{t'}$>285 GeV @ 95%CL

$m_{t'}$>358 GeV @ 95%CL

After 16 years of studies

- Impressive list of measurements
- We know:
  - m_t = 173.3±1.1 GeV
  - $\Delta m = m_t - m_{\bar{t}}$ = 3.8±3.7 GeV
  - σ(tt) = 7.0±0.6 pb
  - σ(t) = 2.7 ± 0.6 pb
  - $|V_{tb}|$ = 0.88±0.07
  - Longitudinally polarized W: f_0=0.67±0.08(stat)±0.07(sys) [f_0(SM)=0.7]
  - Charge: exclude -4/3e @ 95% CL
  - Γ_t = 2.0±0.7 GeV [Γ_t(SM) = 1.3 GeV]
  - Spins in $t\bar{t}$ are correlated: C=0.57±0.31
  - $c\tau$ < 52.2 μm @ 95% CL
  - … and many limits on new physics



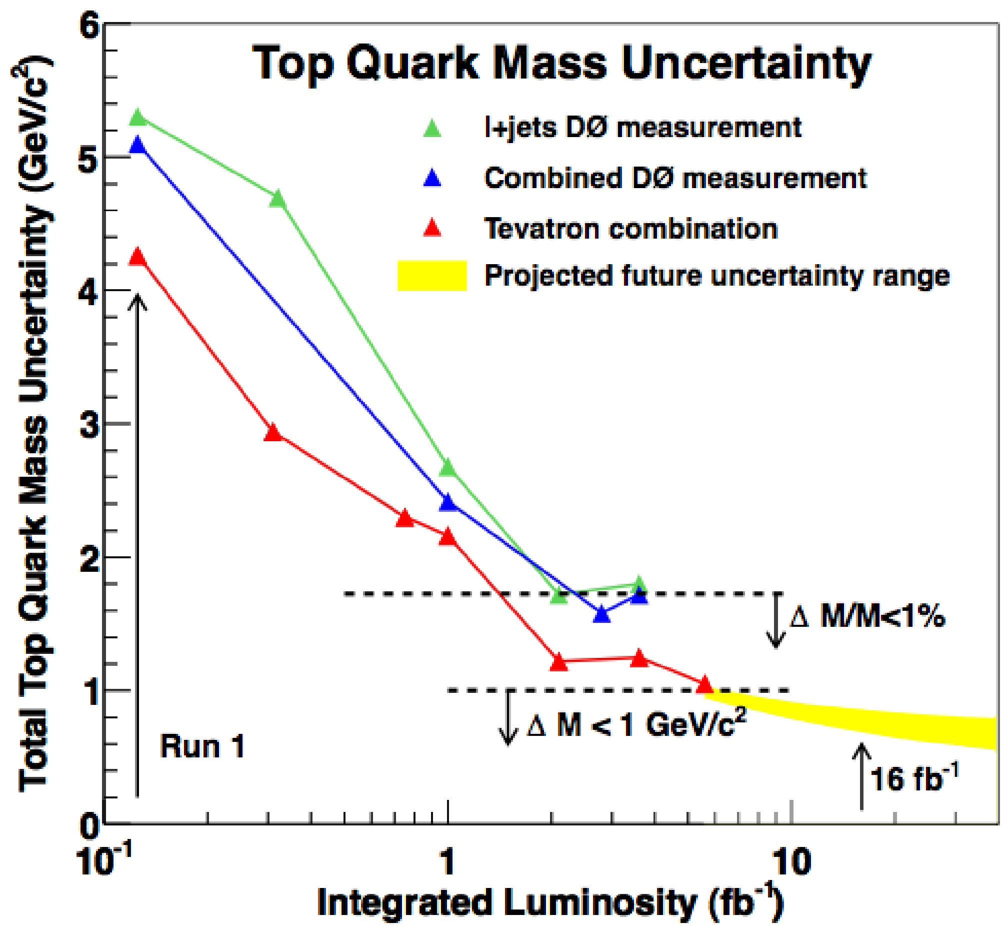
http://www-cdf.fnal.gov/physics/new/top/top.html
http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

Conclusions

- Tevatron has surpassed expectations on top mass and cross section uncertainties
  - $\Delta\sigma/\sigma \sim$ 7%, close to theoretical uncertainty
  - Δm/m=0.6% and will improve: below 1 GeV with more data
    - True legacy measurement: will be hard to surpass
- Many properties have been studied
  - No significant deviation from SM so far
  - Exciting discrepancy in color charge asymmetry: keep an eye on this
- Broad program of searches in top sector
  - Will soon be improved by LHC reach
- Single top observed (s+t and t) and continues to be studied

  - LHC at current lumis produces ten times more top quarks per minute than Tevatron!
  - Will still work on complementary searches: boosted tops, A_{fb}, s-channel, spin correlations...
  - Now 10 fb^{-1} on tape: double the data presented here

Extras


Top Quark Mass Uncertainty
l+jets DØ measurement
Combined DØ measurement
Tevatron combination
Projected future uncertainty range
Total Top Quark Mass Uncertainty (GeV/c²)
Integrated Luminosity (fb⁻¹)
Δ M/M<1%
Δ M < 1 GeV/c²
16 fb⁻¹
Run 1
0
1
2
3
4
5
6
10⁻¹
1
10

Dilepton cross section

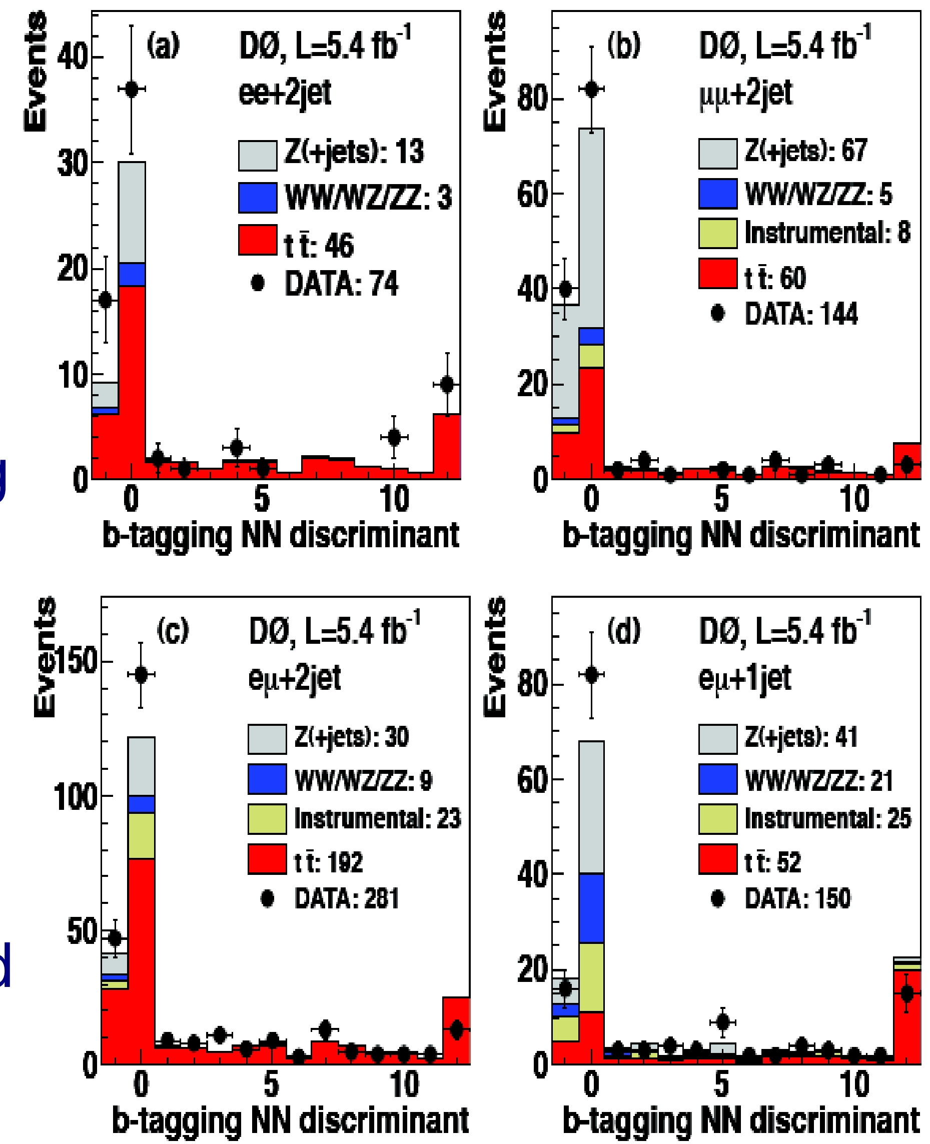
CDF 5.1 fb^{-1} m_t=172.5 GeV

- Two isolated leptons p_T>20 GeV
- Two or more jets p_T>15 GeV $|\eta|$<2.5
- MET>25 GeV, H_T>200 GeV
- In b-tagged analysis: ≥1 b-tag
- 343 (137) events before (after) b-tag

D0 5.4 fb^{-1} m_t=172.5 GeV

NEW!

- Simultaneous fit in 4 regions
- Use smallest NN b-tag output of the two leading jets
- Systematics as Gaussian constrained nuisance parameters
- Luminosity is the largest unertainty



$\sigma_{t\bar{t}}$=**7.25**±0.66(stat)±0.47(sys) **pb**

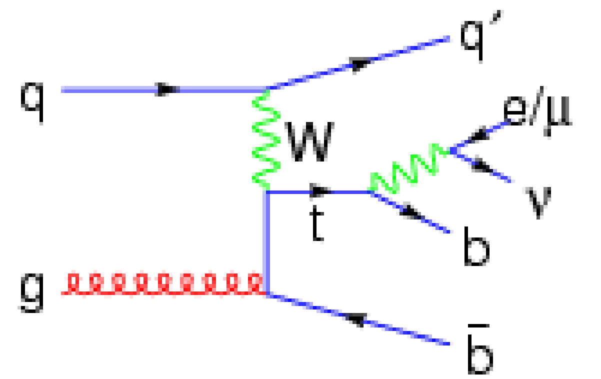
13% relative uncertainty

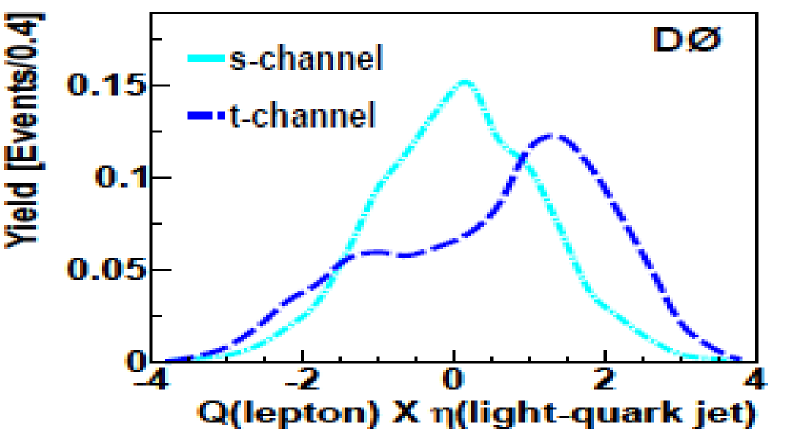
$\sigma_{t\bar{t}}$=**7.36$^{+0.90}_{-0.79}$**(stat+sys) **pb**

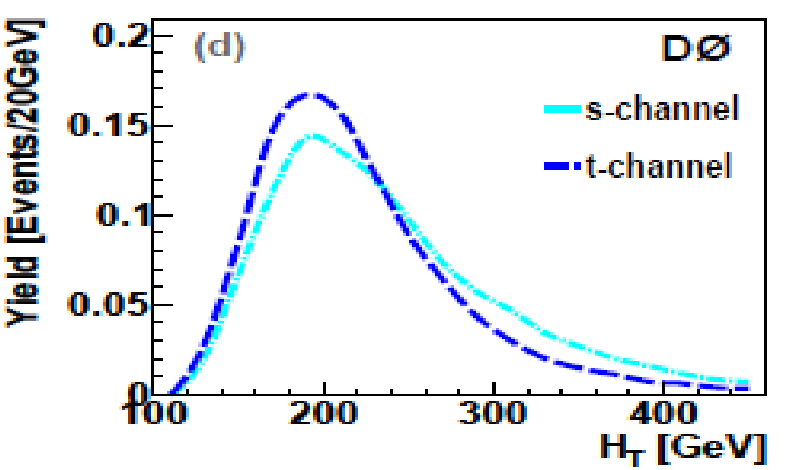
11% relative uncertainty

Signal selection

- Selection designed to be as open as possible: describe backgrounds well
  - Only one isolated ℓ; 2, 3 (4) jets; 1,2 b-tags; MET
- S/B~1/200 before b-tagging
- Best S/B~1/10 after b-tagging
- Dominated by W+jets backgrounds
- Uncertainty on background larger than expected signal yield







Source	2 jets	3 jets	4 jets
tb	104 ± 16	44 ± 7.8	13 ± 3.5
tqb	140 ± 13	72 ± 9.4	26 ± 6.4
$t\bar{t}$	433 ± 87	830 ± 133	860 ± 163
W+jets	$3{,}560 \pm 354$	$1{,}099 \pm 169$	284 ± 76
Z+jets & dibosons	400 ± 55	142 ± 41	35 ± 18
Multijets	277 ± 34	130 ± 17	43 ± 5.2
Total prediction	$4{,}914 \pm 558$	$2{,}317 \pm 377$	$1{,}261 \pm 272$
Data	4,881	2,307	1,283