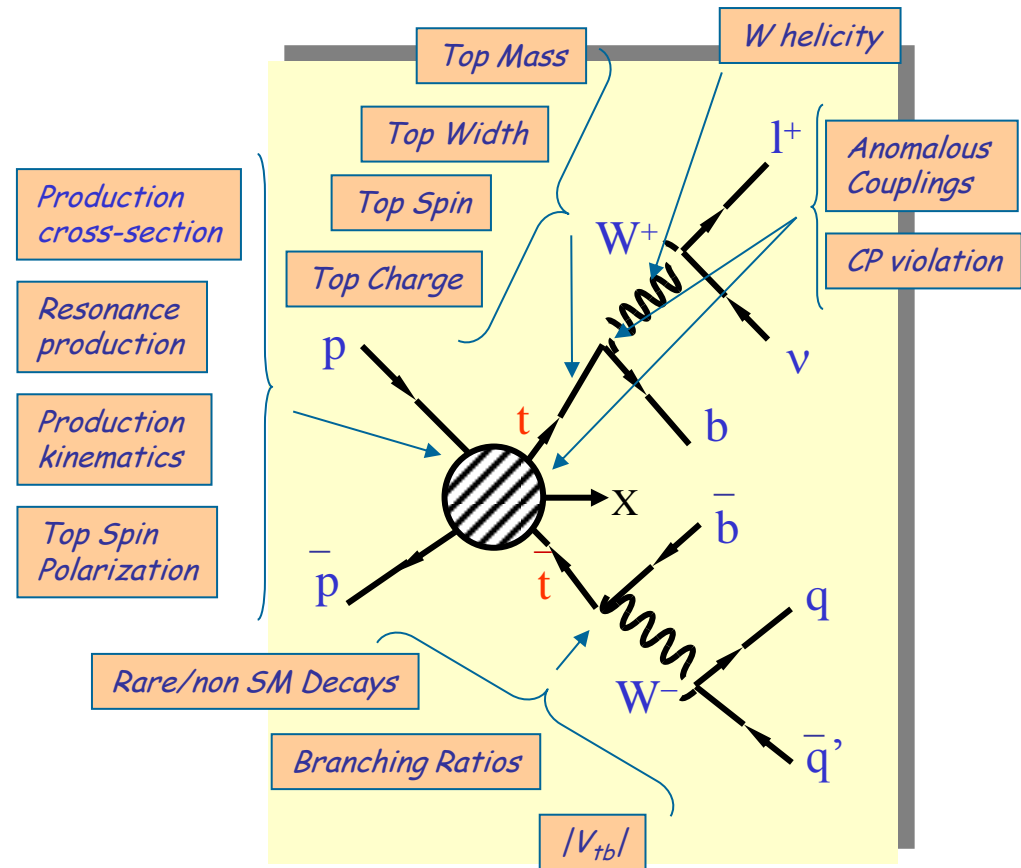




Top Quark Precision Measurements in Run II

- Pre-Run II forecasts
 - Forecasts from Snowmass 1996 and Snowmass 2001
- Core measurements
 - Cross section
 - Mass
 - V_{tb} and top width
 - couplings
- Newer ideas that came to fruition



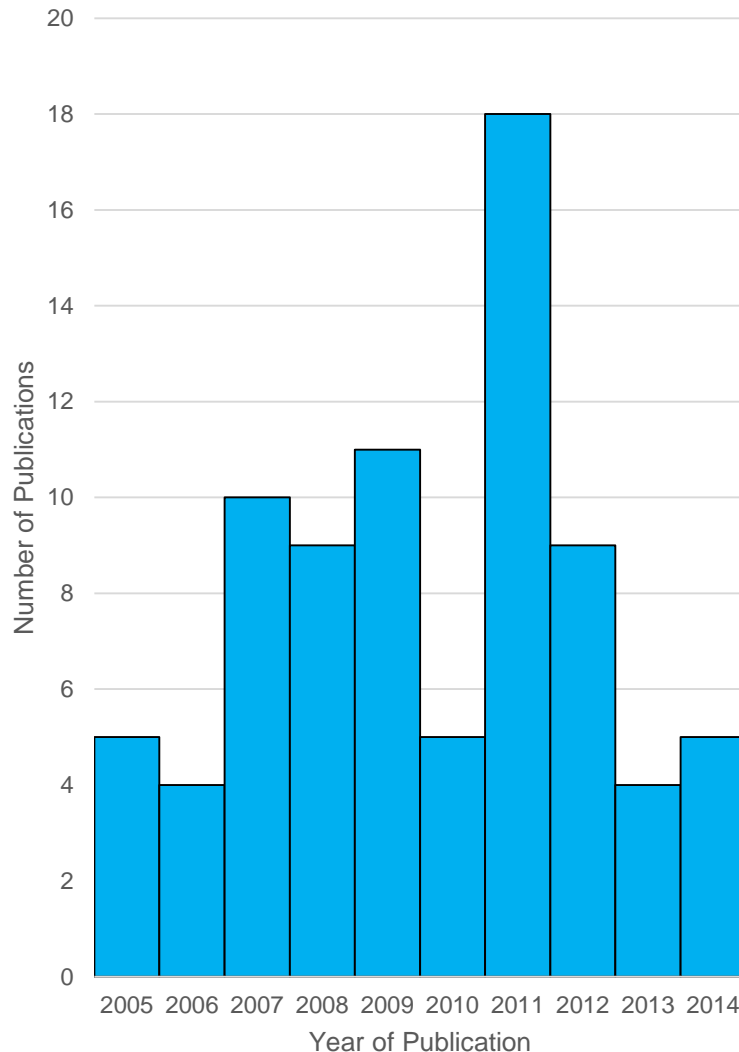
Darien Wood





A large body of work...

DZero Run II top quark publications



- 80 papers published so far by DØ on Run II top physics
- In the peak (2011) an average of more than one top paper every three weeks
- Think about all the things that are needed for top results
 - Electrons, muons
 - Jets, JES
 - B-tagging
 - Complex trigger conditions
 - ...
- A great education in particle physics



Snowmass Forecasts

- Snow mass 1996 and 2001
 - Considered Run II luminosity scenarios of 2 fb^{-1} , 3 fb^{-1} , 10 fb^{-1} , 15 fb^{-1} and a “TeV 33” scenario (30 fb^{-1}). (I interpolate where necessary)
 - Assumptions:
 - Vertex tagging efficiency for b’s: 50-60% per jet
 - Double b-tag efficiency: 40% per event

Top Quark Physics: Future Measurements

R. Frey, D. Gerdes, J. Jaros, S. Vejcek, E. Berger, R. S. Chivukula, F. Cuyper, P. Drell, M. Fero, N. Hadley, T. Han, A. Heinson, B. Knuteson, F. Larios, H. Miettinen, L. Orr, M. Peskin, R. Raja, T. Rizzo, U. Sarid, C. Schmidt, T. Stelzer, Z. Sullivan

- Measurements covered in 1996 paper
 - Top mass, top mass, W helicity in top decays, V_{tb} from single top

BNL-HET-02/5
DCPT/02/14
UB-HET-02-02
FERMILAB-Conf-02/010-T

FT2002-01
IPPP/02/07
PITHA 02/04
KA-TP-3-2002
hep-ph/0202001

Present and Future Electroweak Precision Measurements and the Indirect Determination of the Mass of the Higgs Boson[†]

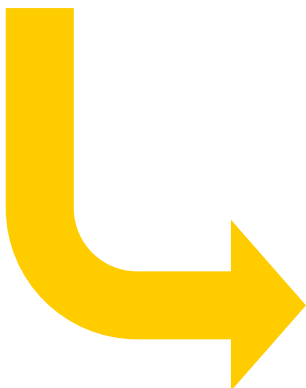
The Snowmass Working Group on Precision Electroweak Measurements
U. BAUR¹, R. CLARE^{2,*}, A. DENNER³, J.L. DIAZ CRUZ⁴, S. DITTMAIER⁵, J. ERLER^{6,*},
M. GRÜNEWALD⁷, S. HEINEMEYER^{8,*}, U. HEINTZ⁹, M. KRAEMER¹⁰, H.E. LOGAN¹¹, K. MÖNIG¹²,
M. NARAIN⁹, M. ROTH¹³, M. SCHMITT¹⁴, D. WACKEROTH¹⁵, G. WEIGLEIN¹⁶, D.R. WOOD^{17,*} AND
J. WUDKA²

- In 2001 report, mainly just updates on top quark mass predictions

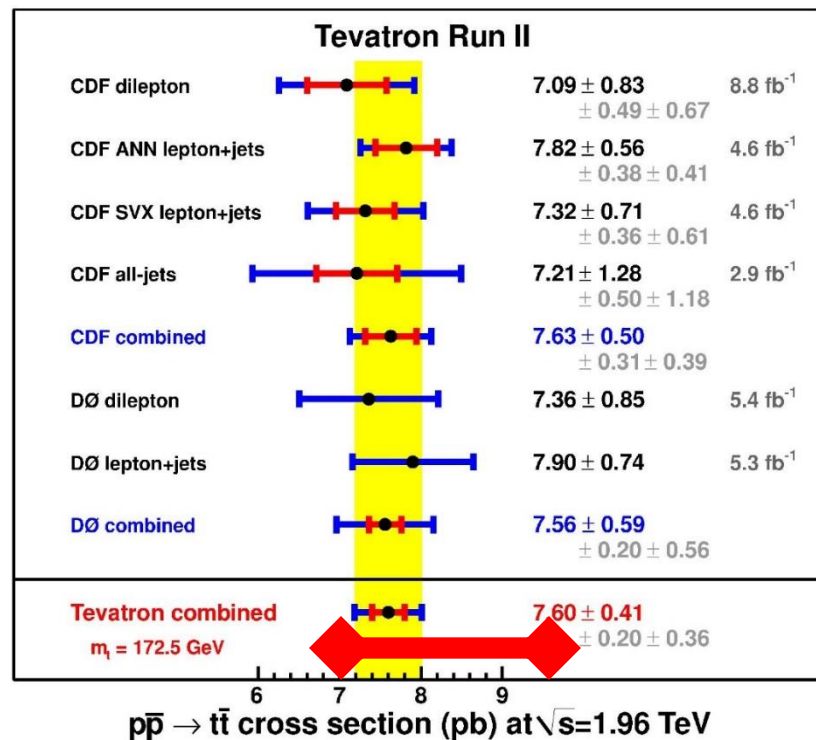


$t\bar{t}$ production cross section

- First Run II cross section measurement (lepton plus jets)
- $\sigma = 8.6_{-1.5}^{+1.6} \pm 0.6$ (lumi) pb
- with 0.23 fb^{-1} integrated lum analyzed
- 20% precision



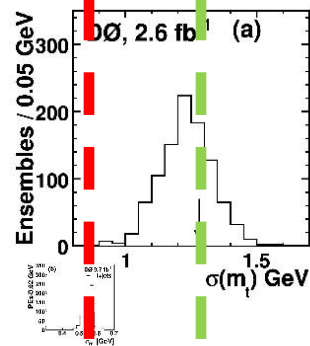
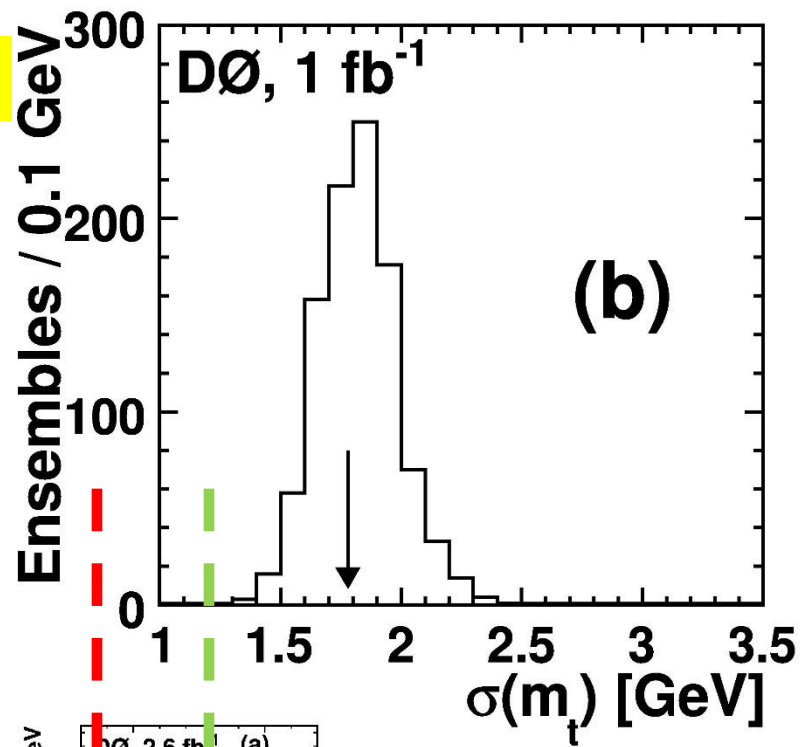
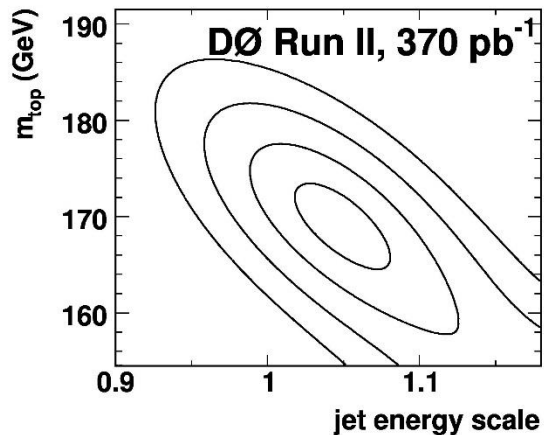
- Final D0 precision
– 7.5%





top mass – ℓ +jets

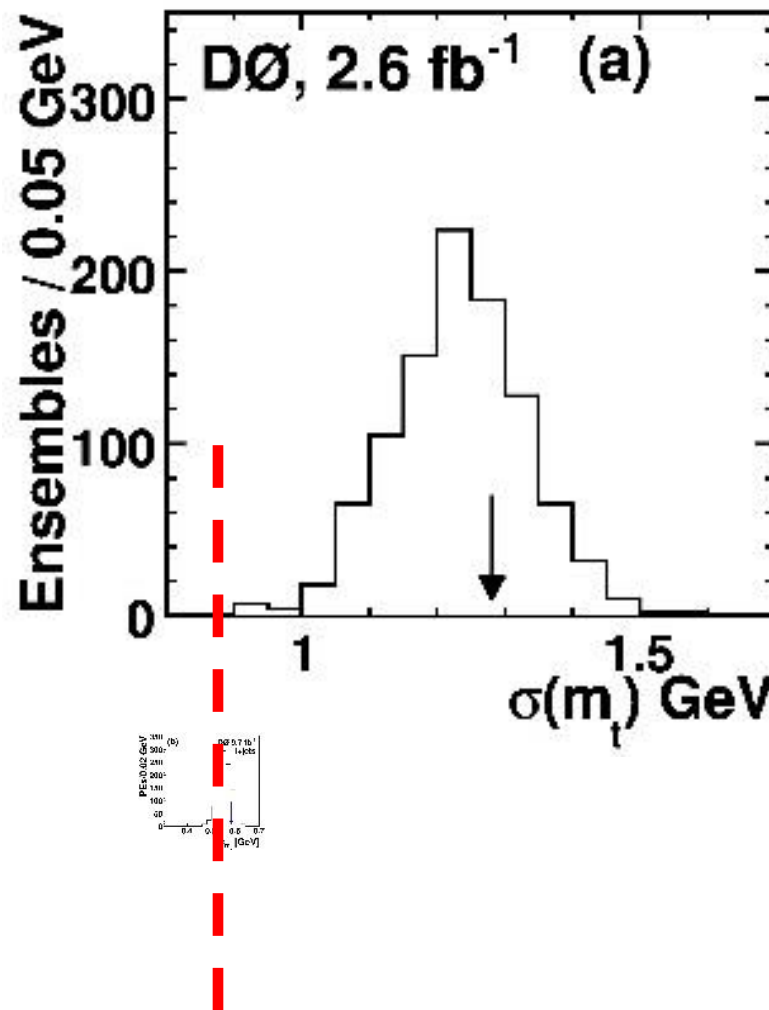
Precision increase through Run II





top mass – ℓ +jets

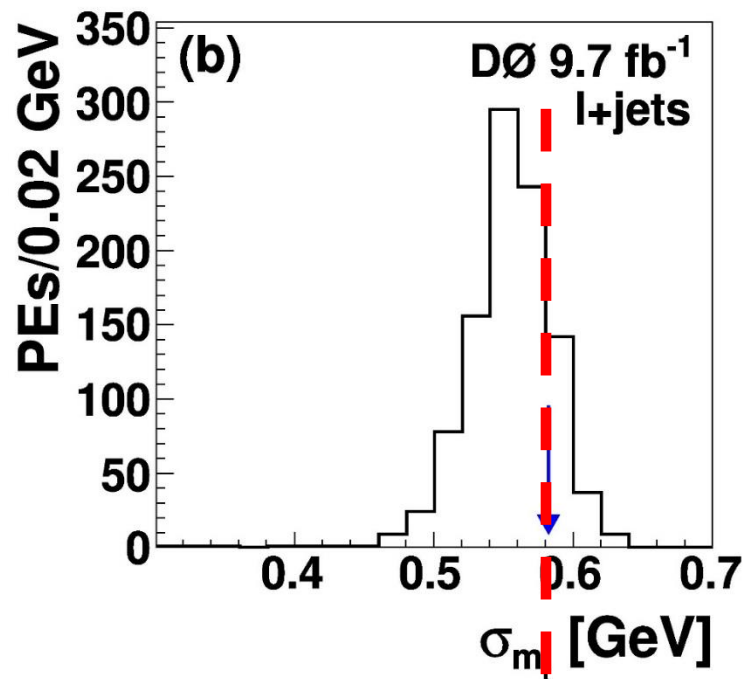
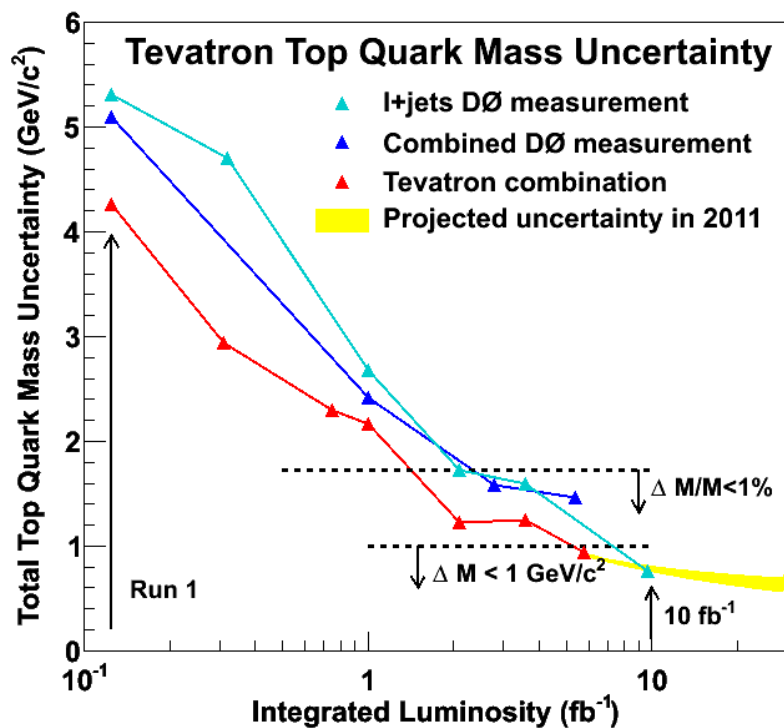
Precision increase through Run II





top mass – ℓ +jets

2011 Projections

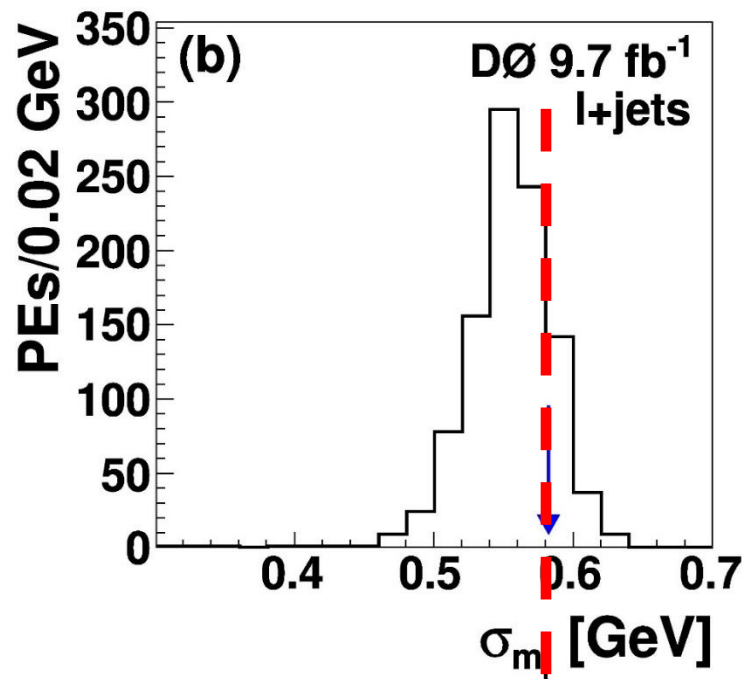
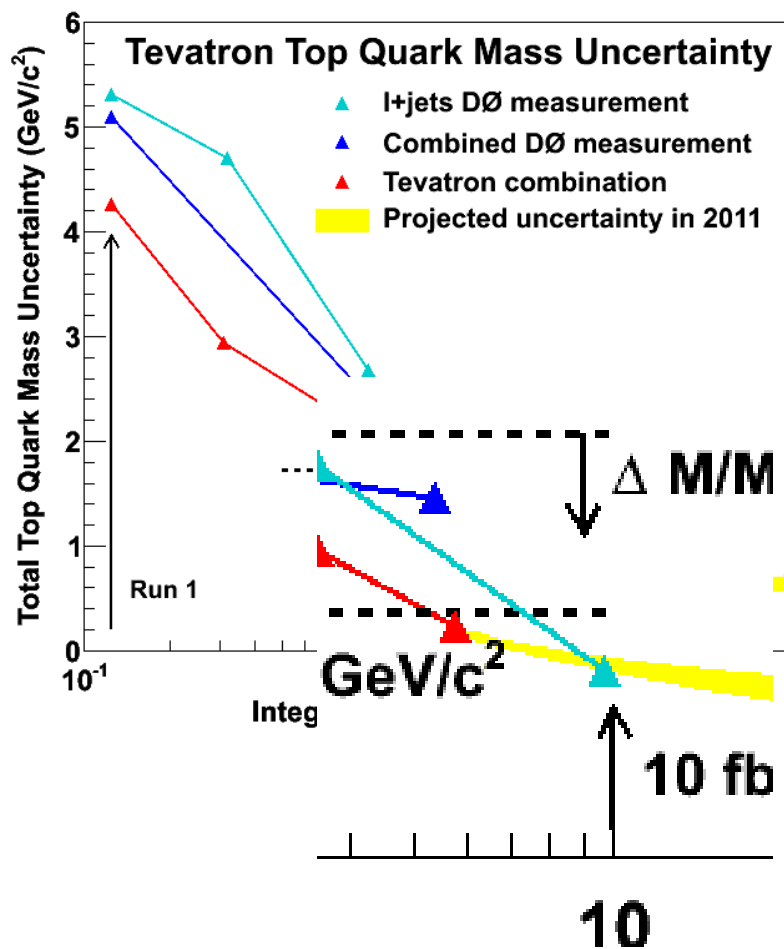


Uncertainty	Snowmass prediction (1996/2001)	Achieved
Statistical	0.14 GeV	0.41 GeV
Jet Energy Scale	0.9/0.5* GeV	0.41 GeV
Other syst.	3/1 GeV	0.49 GeV



top mass – ℓ +jets

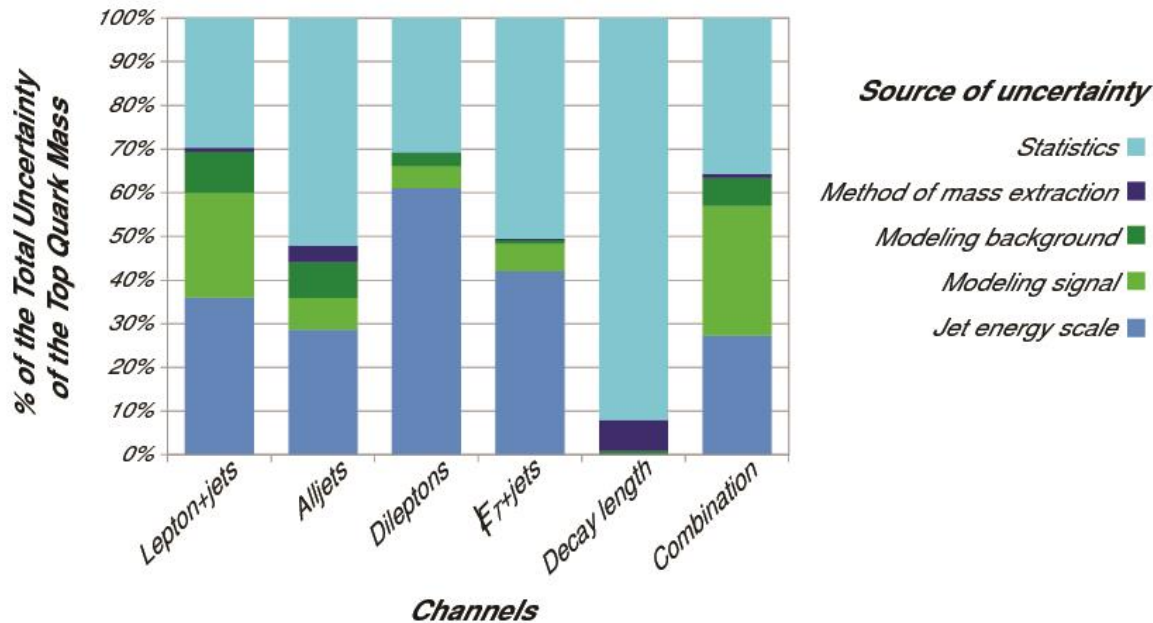
2011 Projections



Uncertainty	Snowmass prediction (1996/2001)	Achieved
Statistical	0.14 GeV	0.41 GeV
Jet Energy Scale	0.9/0.5* GeV	0.41 GeV
Other syst.	3/1 GeV	0.49 GeV

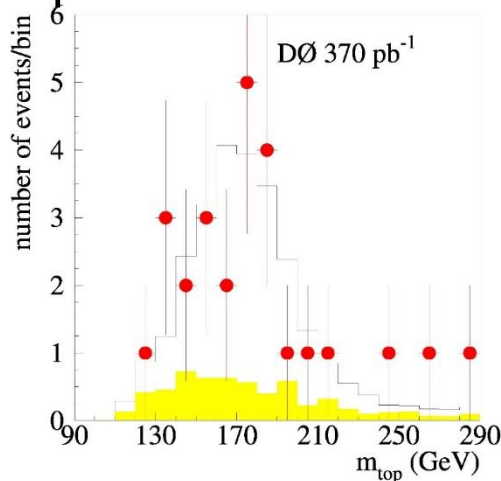


top mass – dileptons and combination

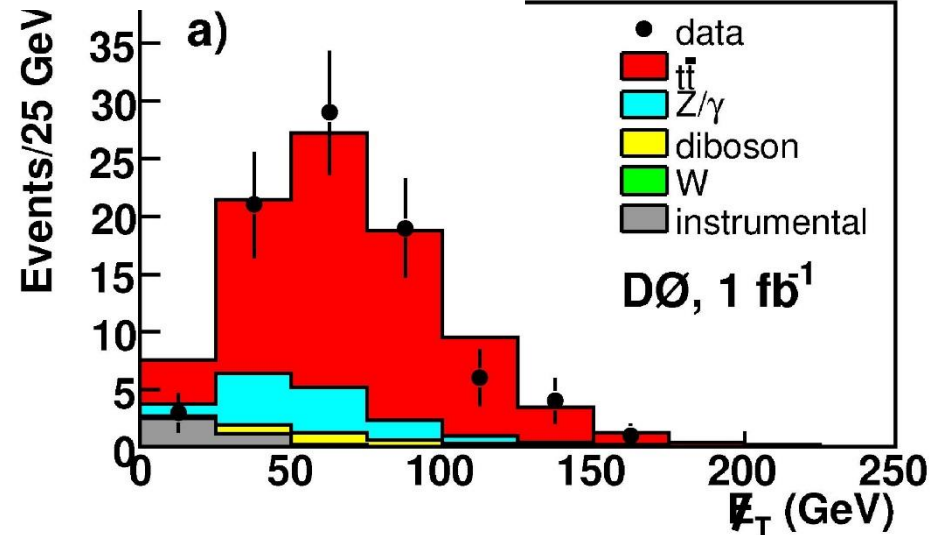


From 2012
Tevatron top mass
combination paper

Dileptons 2007

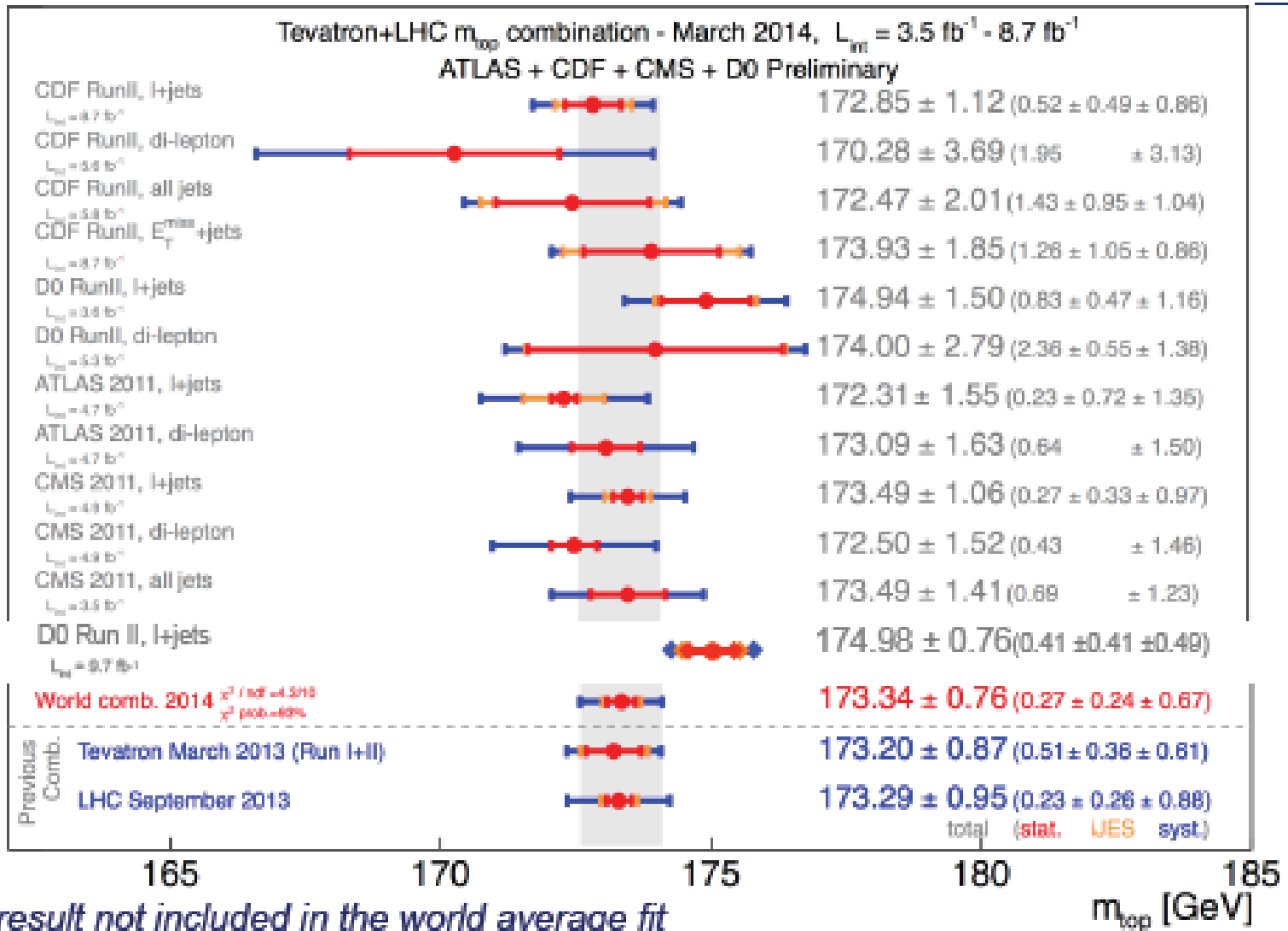


Dileptons 2009





top mass and world average

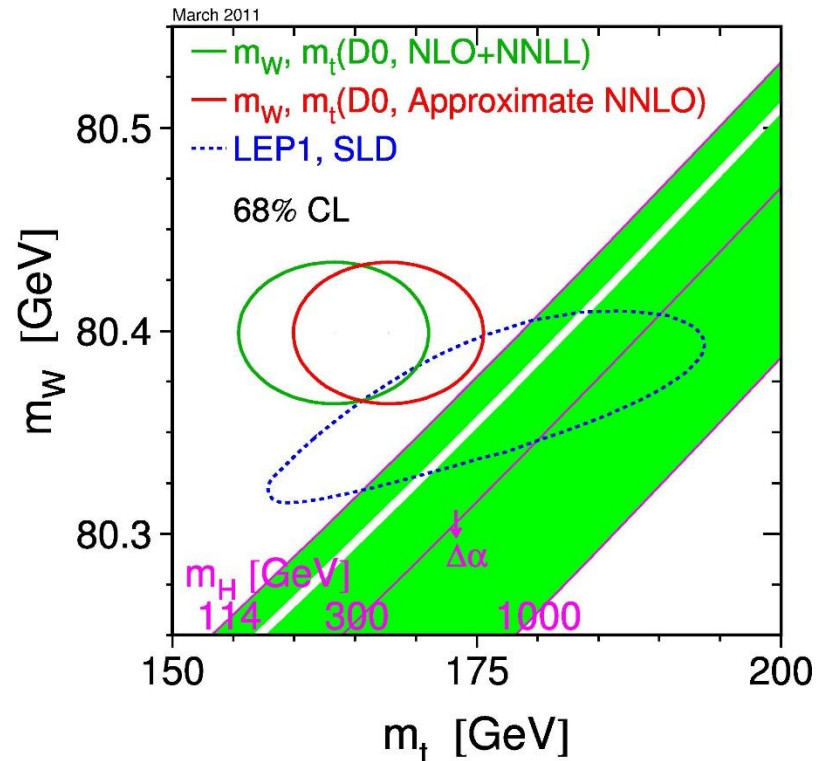
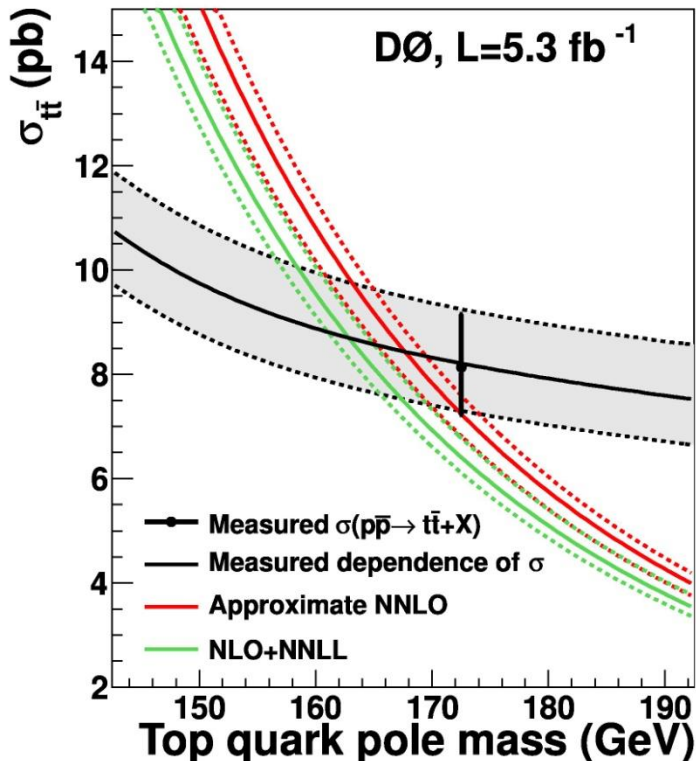




Pole mass or \overline{MS} mass

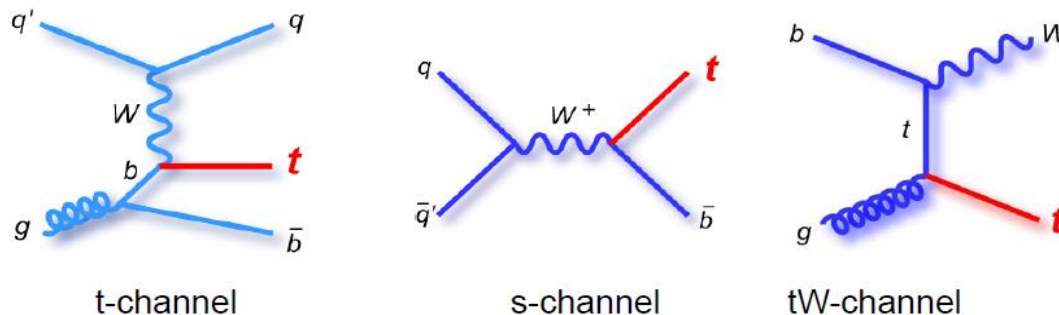
- Beyond LO QCD, the mass of the top quark is a convention-dependent parameter

- $$m_t^{\text{pole}} = m_t^{\overline{MS}}(m_t^{\overline{MS}}) \left[1 + \frac{4}{3} \frac{\overline{\alpha}_s(m_t^{\overline{MS}})}{\pi} + 8.28 \left(\frac{\overline{\alpha}_s(m_t^{\overline{MS}})}{\pi} \right)^2 + \dots \right] + \mathcal{O}(\Lambda_{\text{QCD}})$$

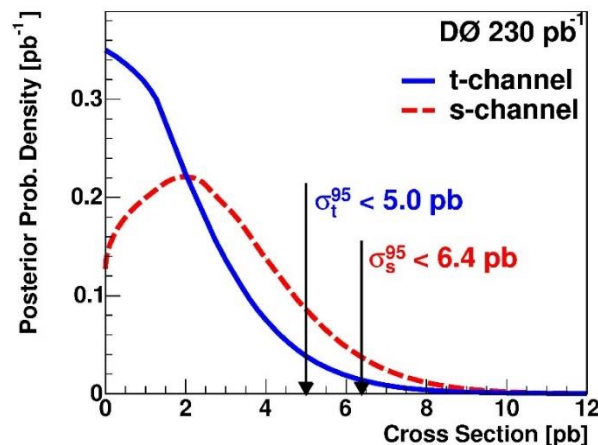
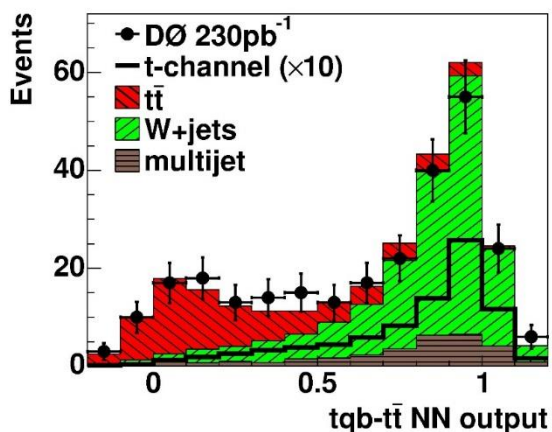




Single top and V_{tb}



- Already two Run 1 papers setting limits (~ 20 pb) on single top production
- One of the first Run II top papers was a limit on single top (6.4 pb s-channel, 5.0 pb t-channel)



Then, with a bit more data, the Golden Age of Single Top began...



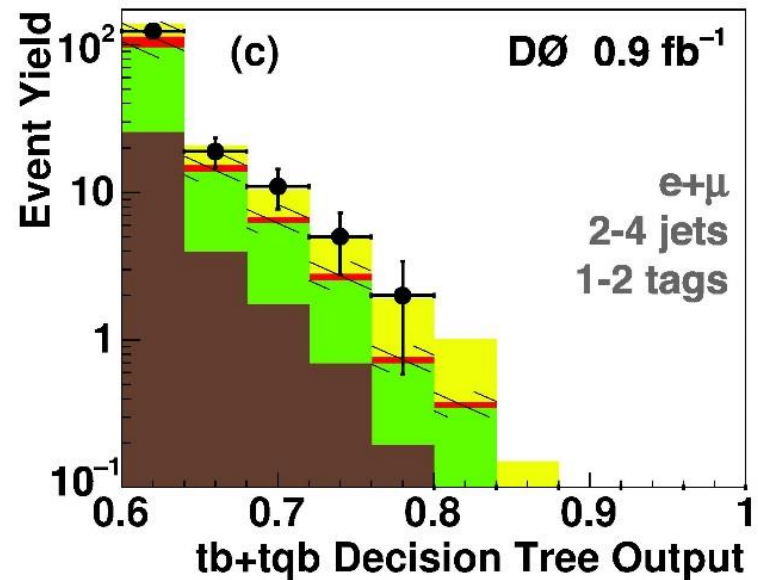
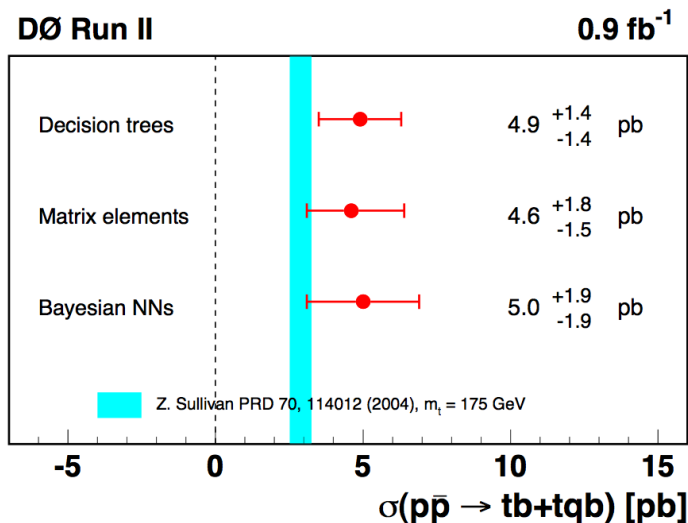
2006: Evidence for single top

December 13, 2006

Fermilab Press Release

For immediate release

DZero finds evidence of rare single top quark; Observation marks a step closer to finding Higgs boson



Why all the fuss?



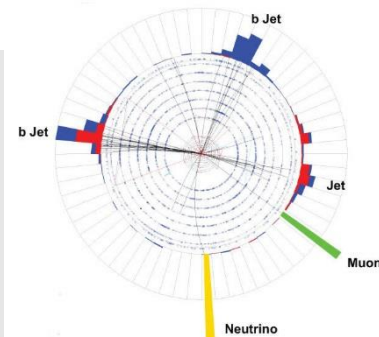
2009: single top discovery (DØ and CDF)

March 9, 2009

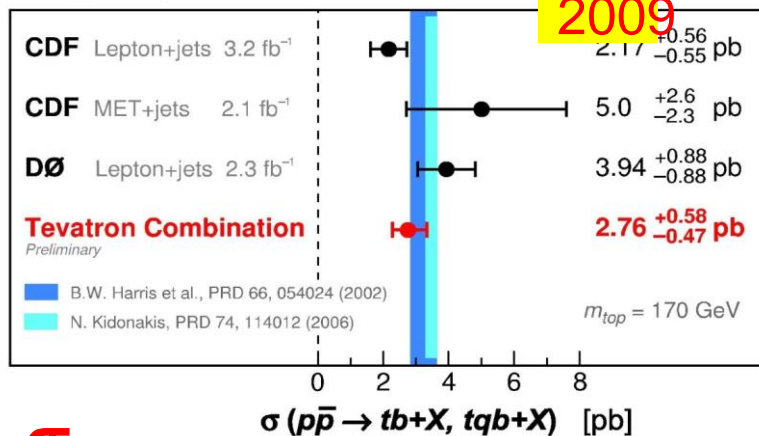
Fermilab Press Release

For immediate release

Fermilab collider experiments discover rare single top quark

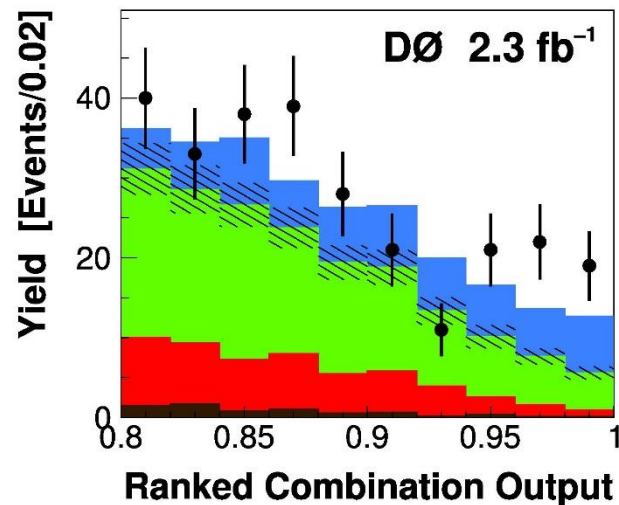


Single Top Quark Cross Section



σ_{tqb+tb}

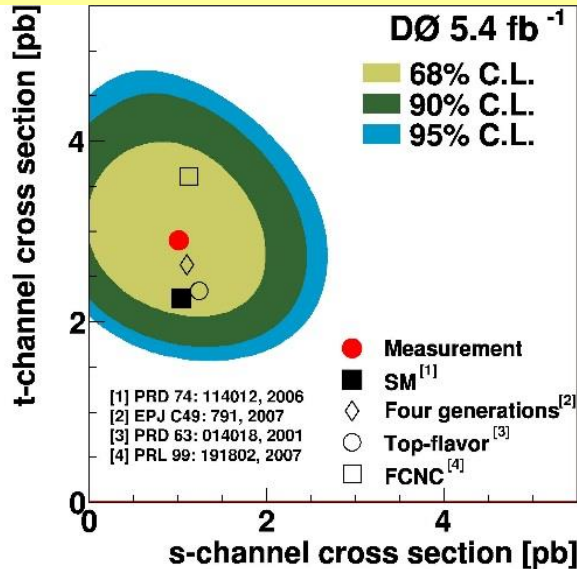
(b) Signal Region



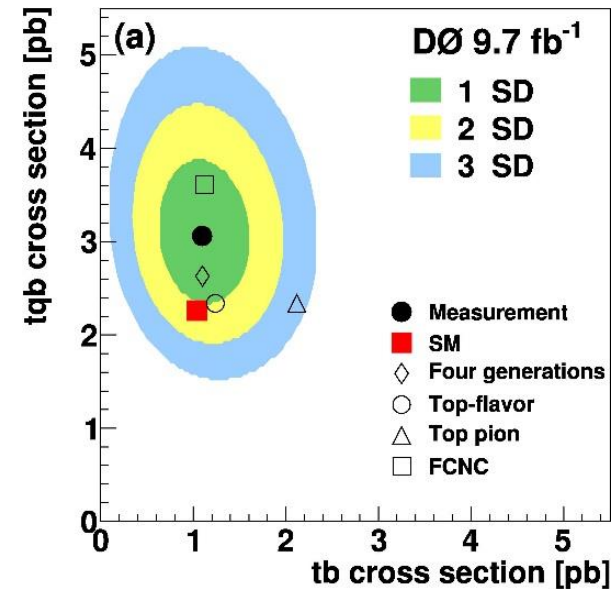


Separation of s-channel and t-channel

DØ t-channel observation 2011



DØ s-channel evidence 2013



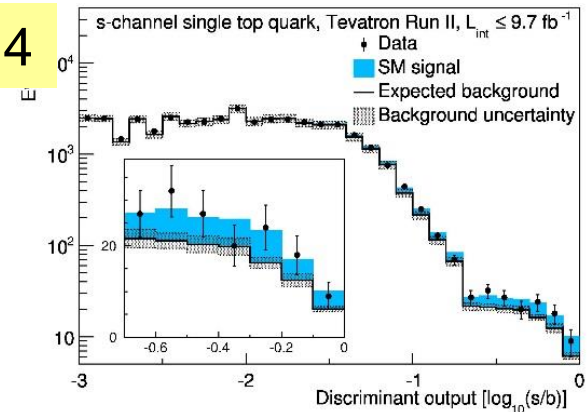
CDF+DØ s-channel observation 2014

February 24, 2014

Fermilab Press Release

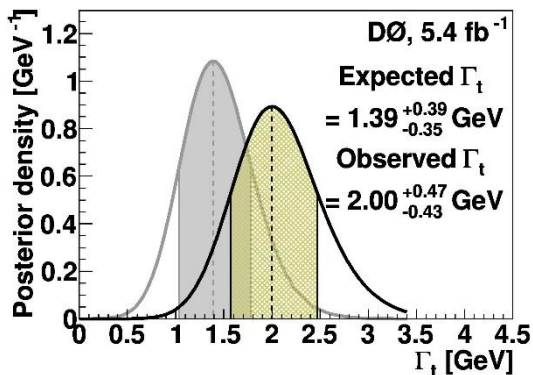
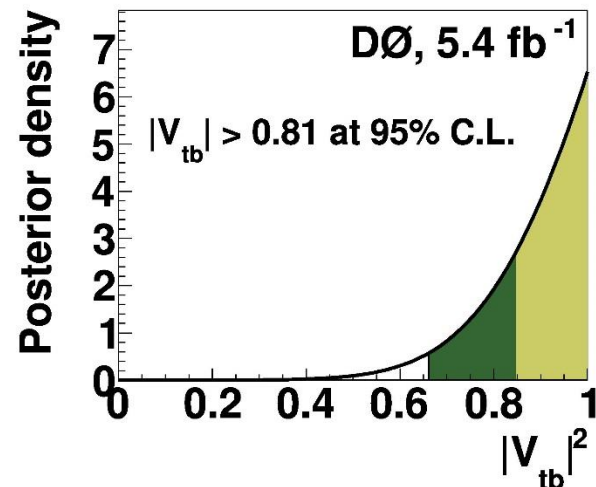
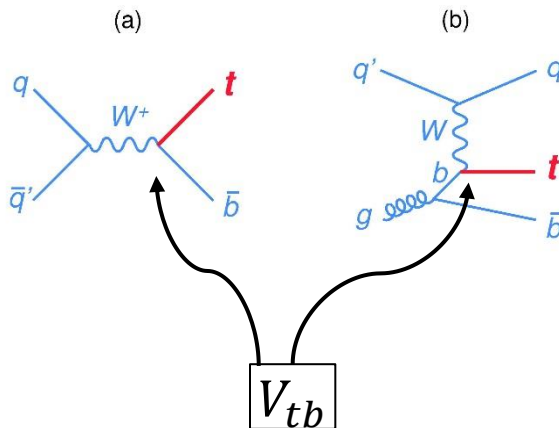
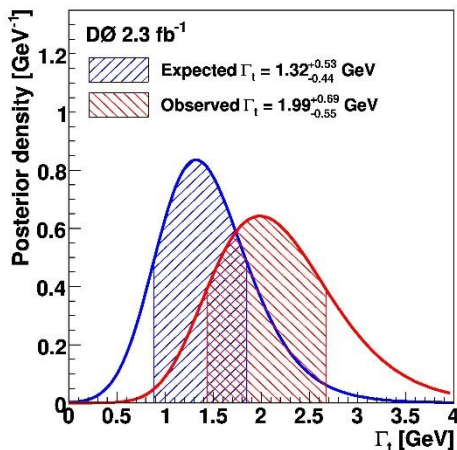
FOR IMMEDIATE RELEASE

Scientists complete the top quark puzzle





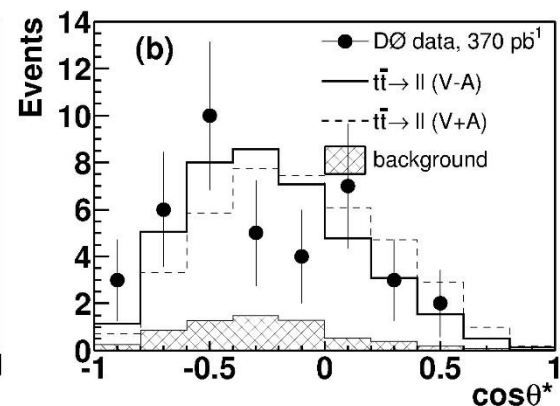
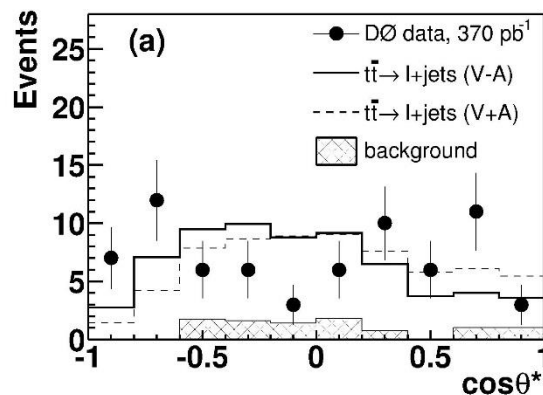
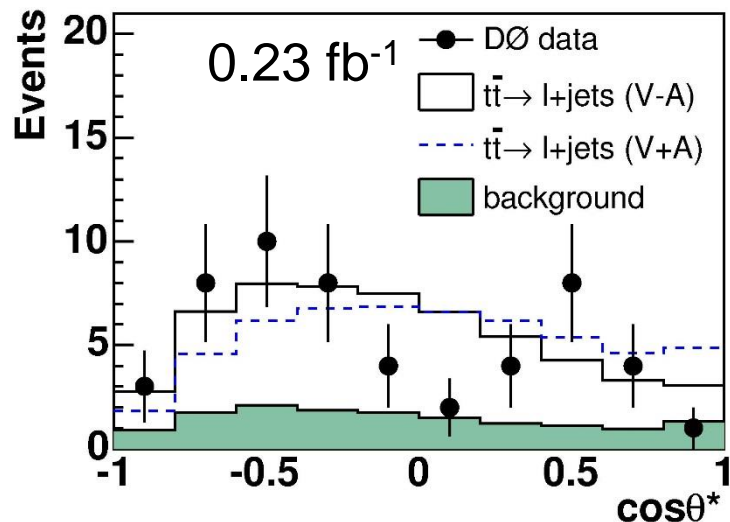
V_{tb} and the top width



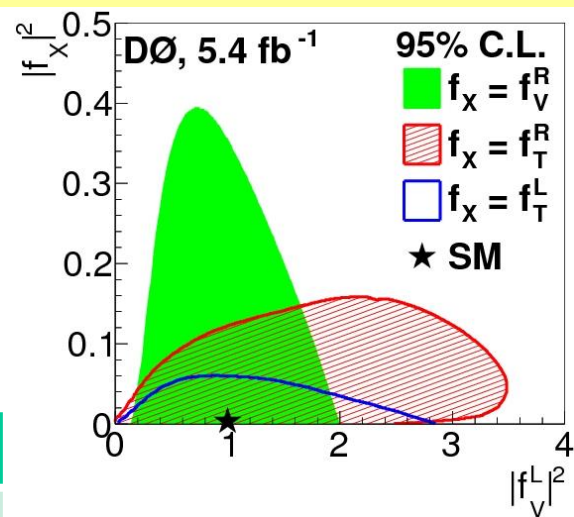
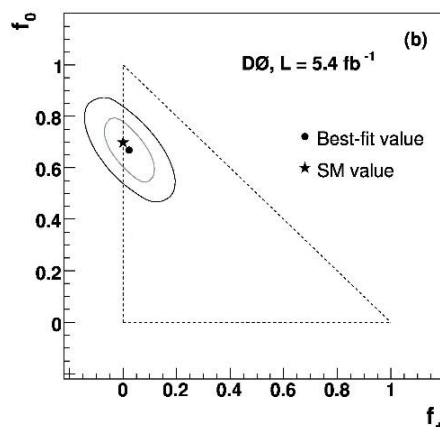
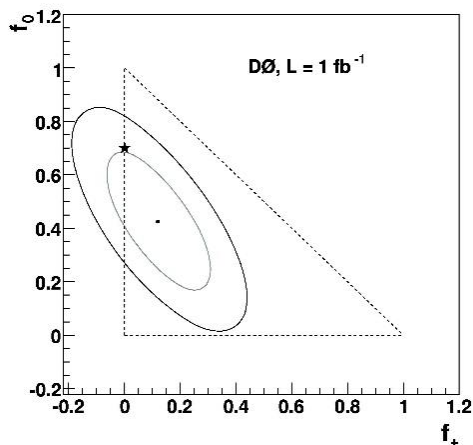
Quantity	Snowmass prediction (1996)	Achieved
95% CL on $ V_{tb} $	0.93	0.92
Uncertainty $B(t \rightarrow Wb)/B(t \rightarrow Wq)$	0.01	0.04
Uncertainty on Γ_t	21%	23%



W helicity and anomalous top couplings



W helicity combined with anomalous coupling limits from single top



Quantity

Snowmass prediction

achieved

uncertainty f_+

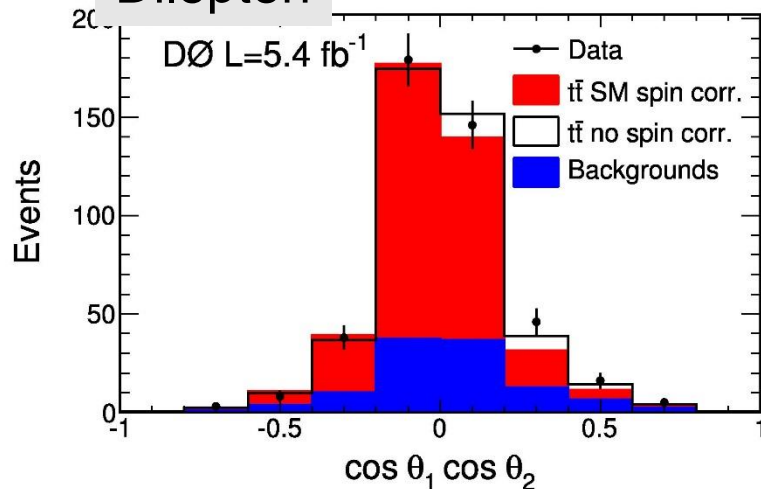
1.5%

4%

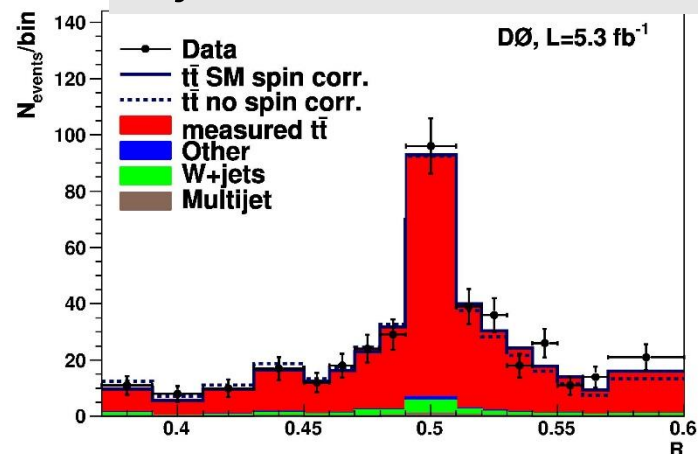


Spin correlations

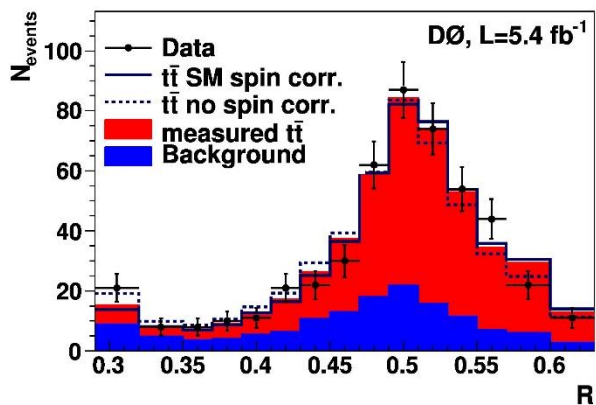
Dilepton



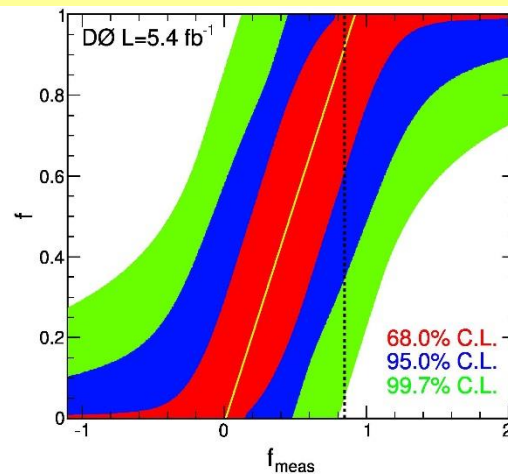
ℓ +jets with matrix element



Dilepton, with matrix element



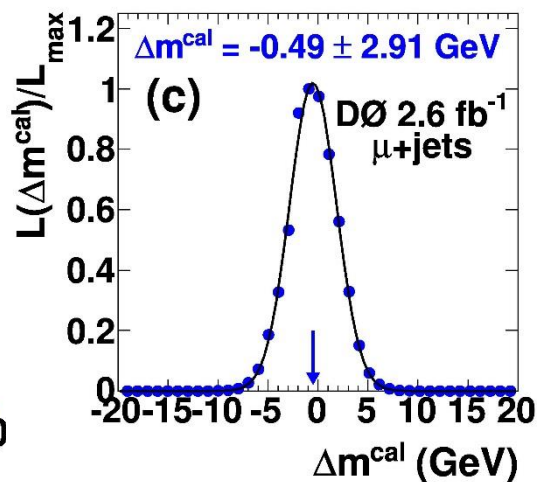
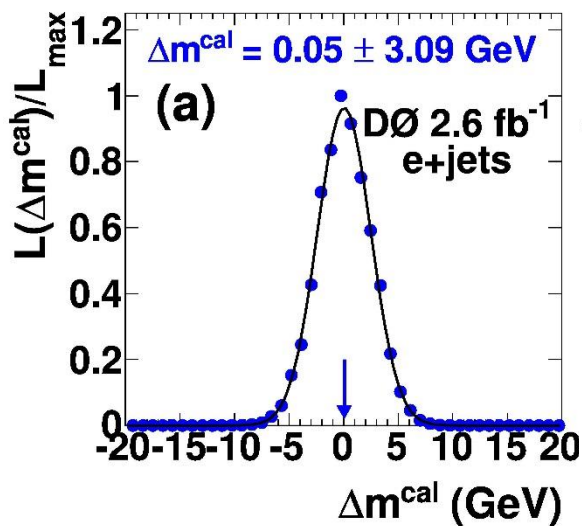
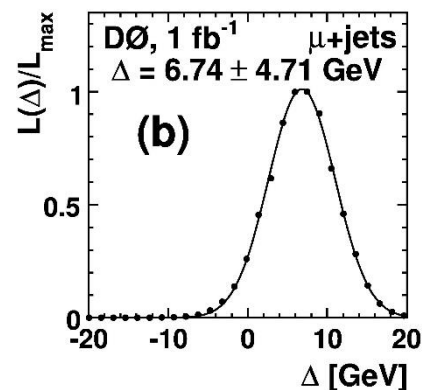
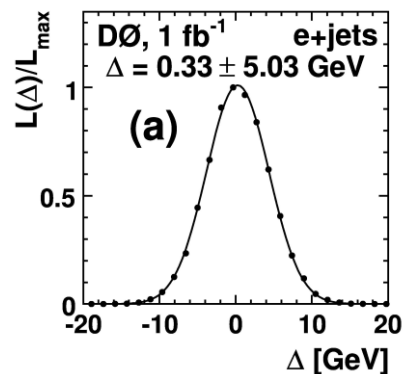
Combination: Evidence for spin correlations





$t\bar{t}$ mass difference

- New measurement in Run II

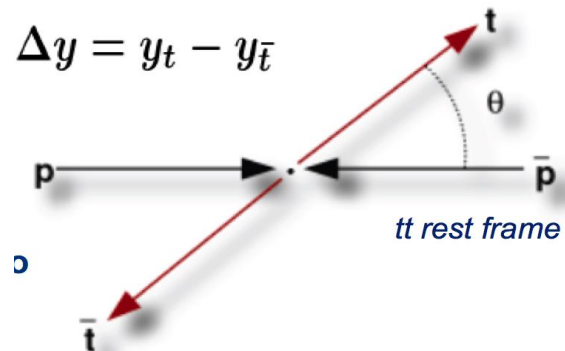
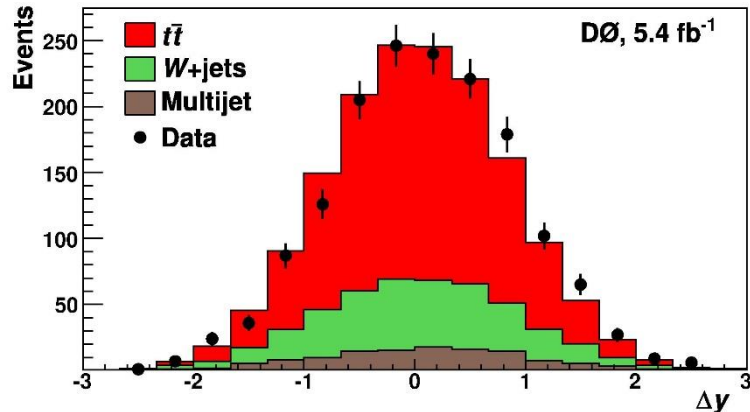
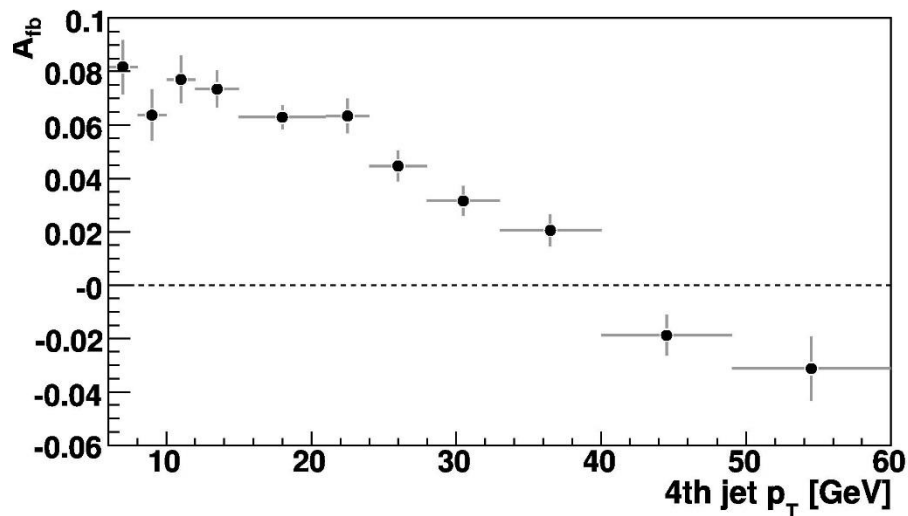


$$\Delta m = 0.8 \pm 1.8 \pm 0.5 \text{ GeV}$$

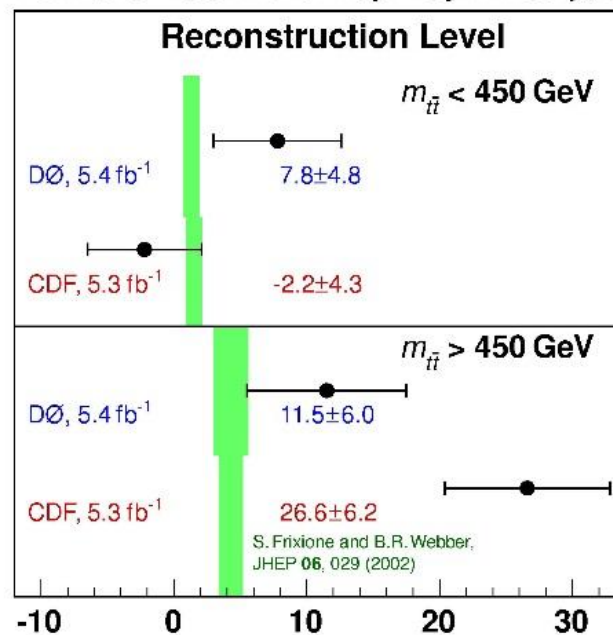


Forward-backward charge asym

- Emerged as a hot topic late in Run II

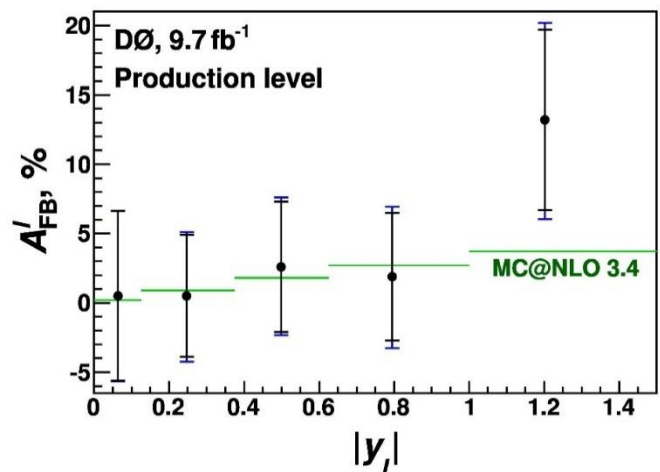
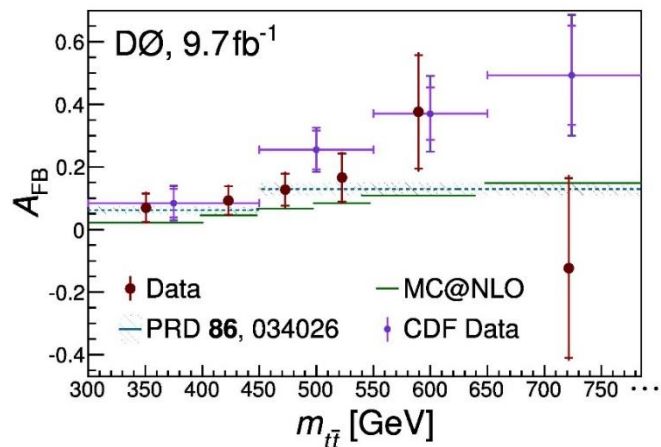


Forward-Backward Top Asymmetry, %

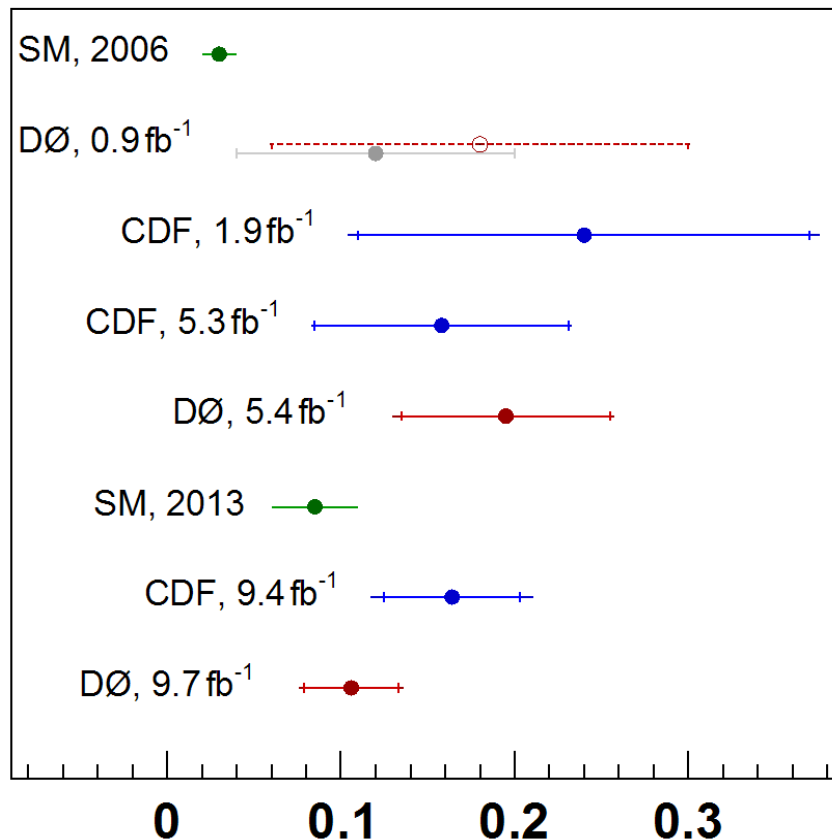




Forward-backward charge asym - latest



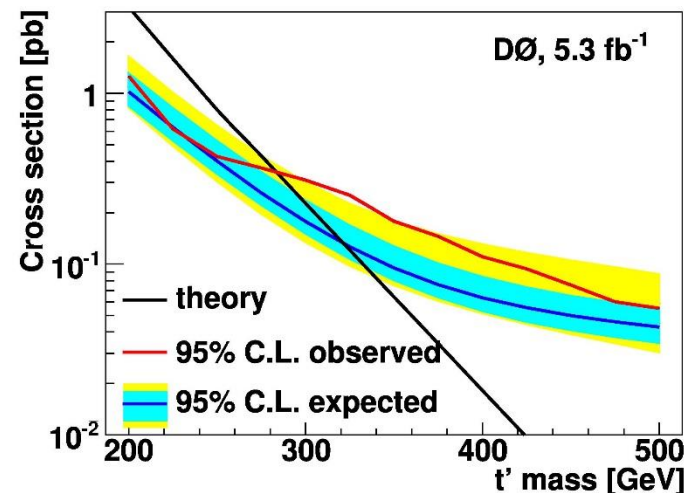
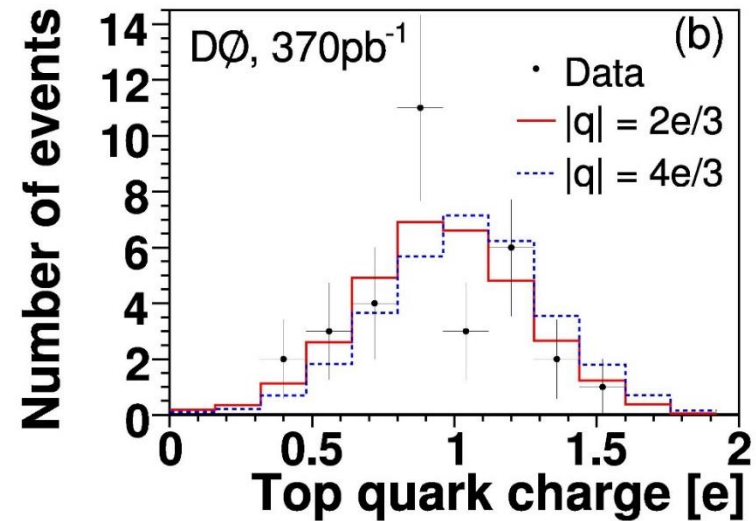
$t\bar{t}$ forward-backward asymmetry





Many other top quark analyses

- Measurement of
 - top electric charge
 - top quark polarization
 - color flow
- Searches for
 - W-prime in single top
 - t'
 - $t\bar{t}'$ admixture
 - anomalous couplings
 - charged Higgs
 - $t\bar{t}$ resonances
 - ...





Ongoing work

- A great deal accomplished
 - rich and exciting period
 - many legacy measurements already published
 - superb education for many students (and more senior physicists)
 - careers advanced
- Still some important results in the works
 - e.g. agenda from Physics Workshop:

11:05	top quark polarization (20')	Kamil Augsten (Czech Technical University in Prague)
	Slides 	
15:50	top mass dileptons, v-wgting (20')	Huanzhao Liu (Southern Methodist University)
	Slides 	
16:30	top mass all jets (20')	Gianluca Petrillo (University of Rochester)
	Slides 	
16:50	tt(bar) gluon fraction (20')	SungWoong Cho (Korea University/D0 Fermilab) Jae hoon Lim (Korea University)
	Slides 	
17:10	ttH, t' (20')	Christian Schwanenberger (University of Manchester)
	Slides 	