Top Physics at the Tevatron

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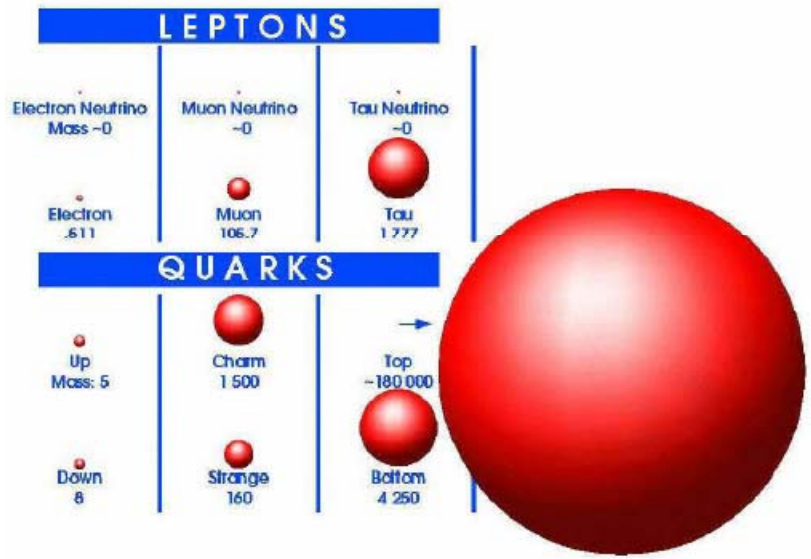
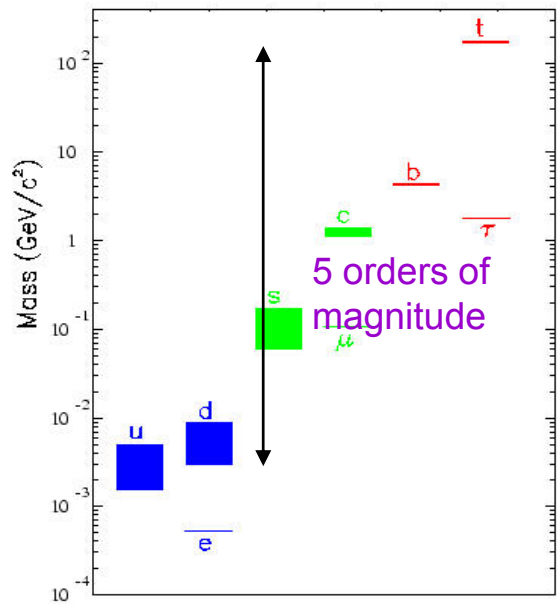
Outline

- Motivation
- Introduction to top production and decay
- Studies of Top quark pair production and decay properties
  - Is the SM correct?
  - Model-dependent searches
- Studies of single top production
- Conclusions and Outlook

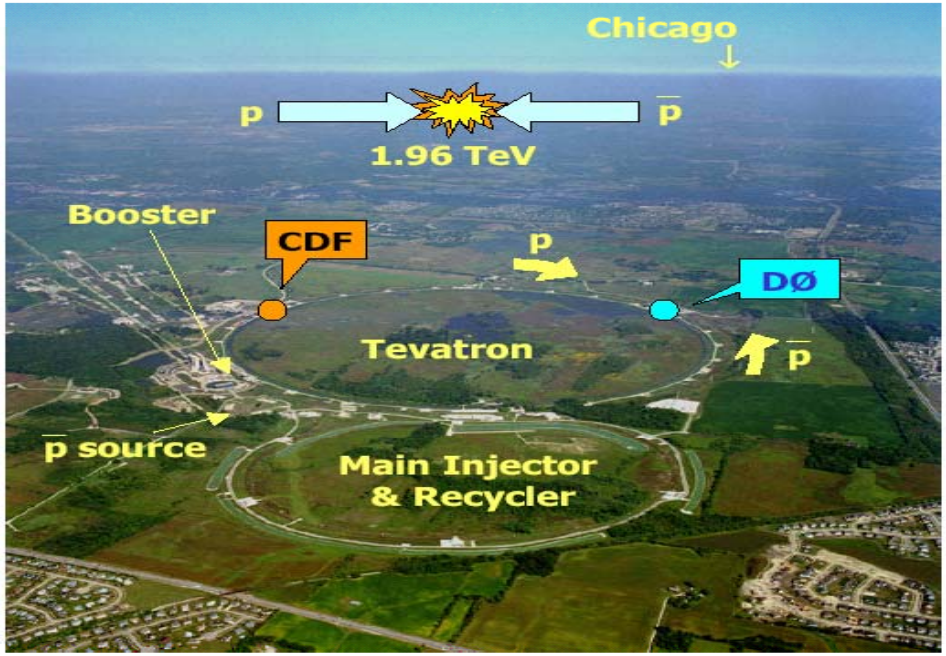
Why study the Top Quark?

- Predicted by the SM and Discovered in 1995 by CDF and DØ
  - $m_t \sim 170$ GeV vs $m_b \sim 5$ GeV
- Top-Higgs Yukawa coupling ≈ 1
  - may help identify the mechanism of EWSB and mass generation.
  - may serve as a window to new physics that might couple preferentially to top.
- Until Tevatron Run II, we knew very little about top
  - Indirect constraints from low energy data, or statistically limited direct measurements from Tevatron Run I
    - Plenty of room for new Physics
  - Run II has opened the era of precision top measurements & stringent tests of the SM.



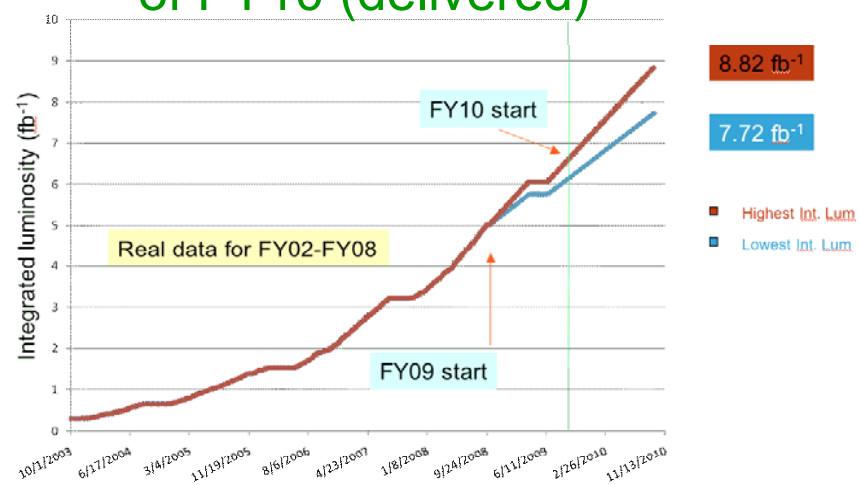


The Fermilab Tevatron



- Highest-energy accelerator currently in operation
  - only place where Top quarks have been produced
- Data delivered ~5fb^{-1}
  - expect to reach 6.5 fb^{-1} by the end of FY09, 9 fb^{-1} by the end of FY10 (delivered)

	Run I	Run IIa	**Run IIb**
Bunches in Turn	6 × 6	36 × 36	**36 ×36**
√s (TeV)	1.8	1.96	**1.96**
Peak L (cm^{-2}s^{-1})	1.6 ×10^{30}	9 ×10^{31}	**3 ×10^{32}**
∫ Ldt (pb^{-1}/week)	3	17	**50**
Bunch crossing (ns)	3500	396	**396**
Interactions/ crossing	2.5	2.3	**8**

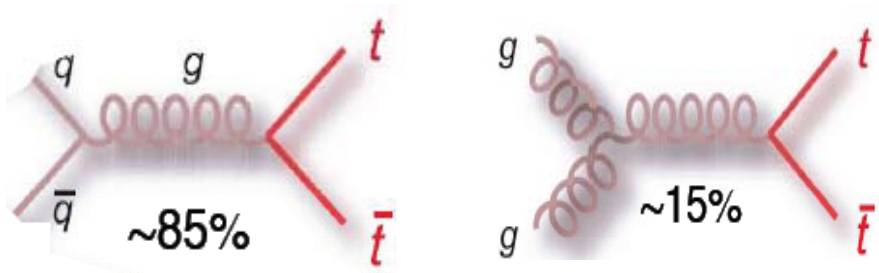


Results based on ~3fb^{-1}

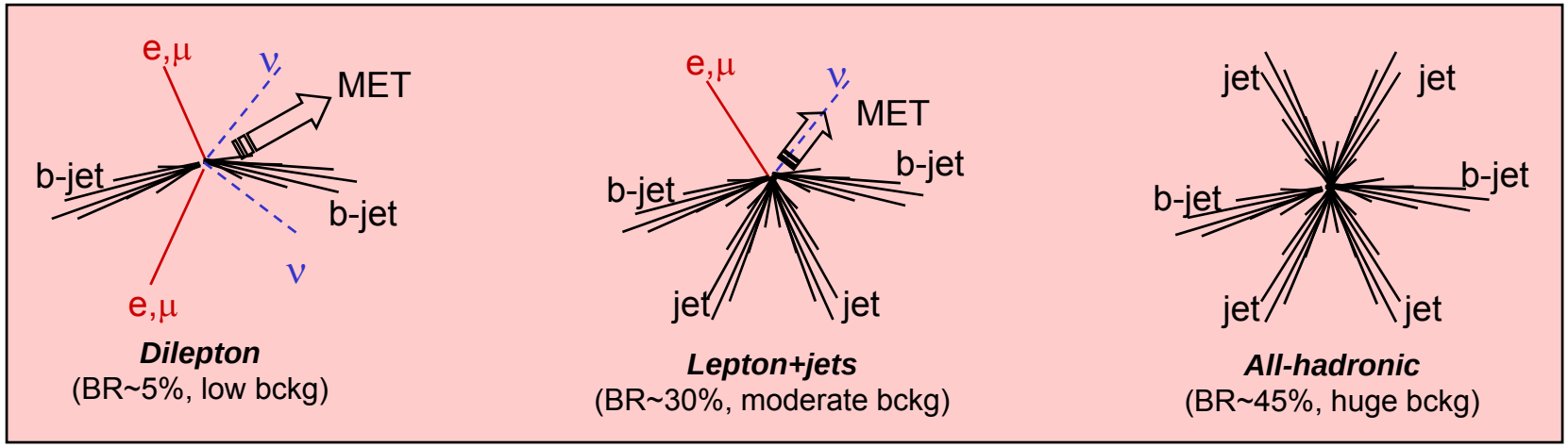
Top quark Pair Production & Decay

- Top quarks are mainly produced in pairs, via the strong interaction

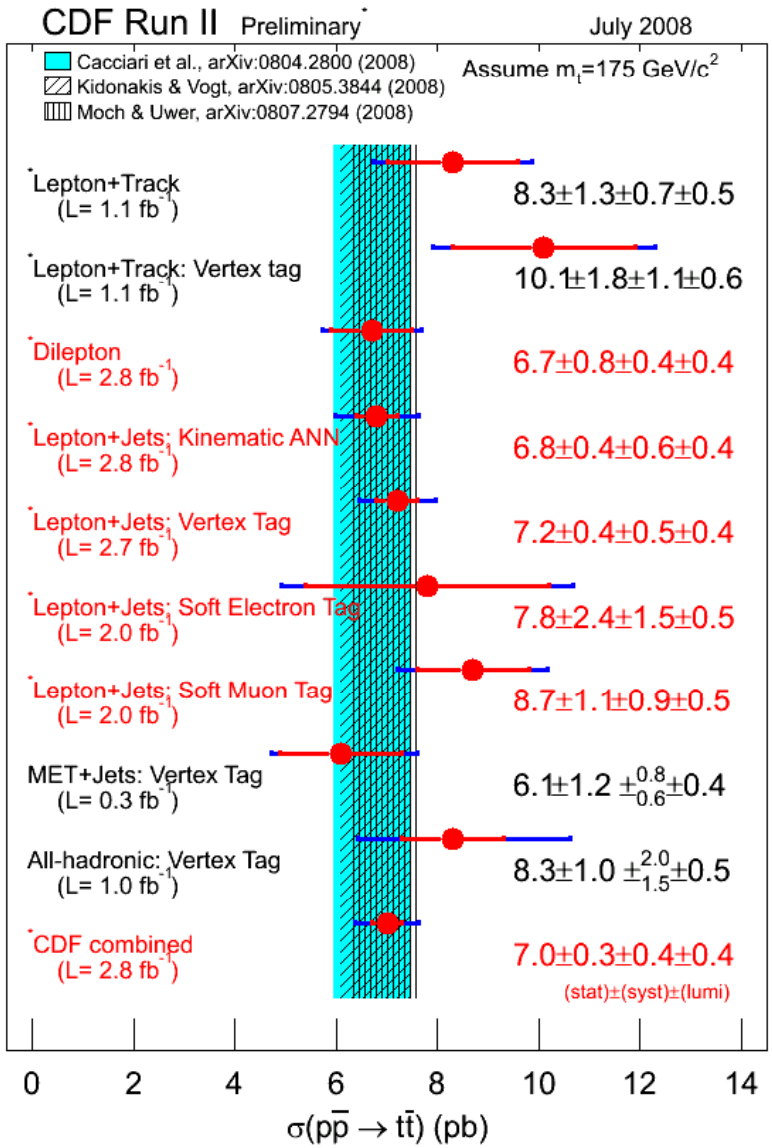
σ_{tt}=6.8±0.6 pb (Kidonakis, Vogt)
σ_{tt}=6.7+0.7-0.9 pb (Cacciari et al.)

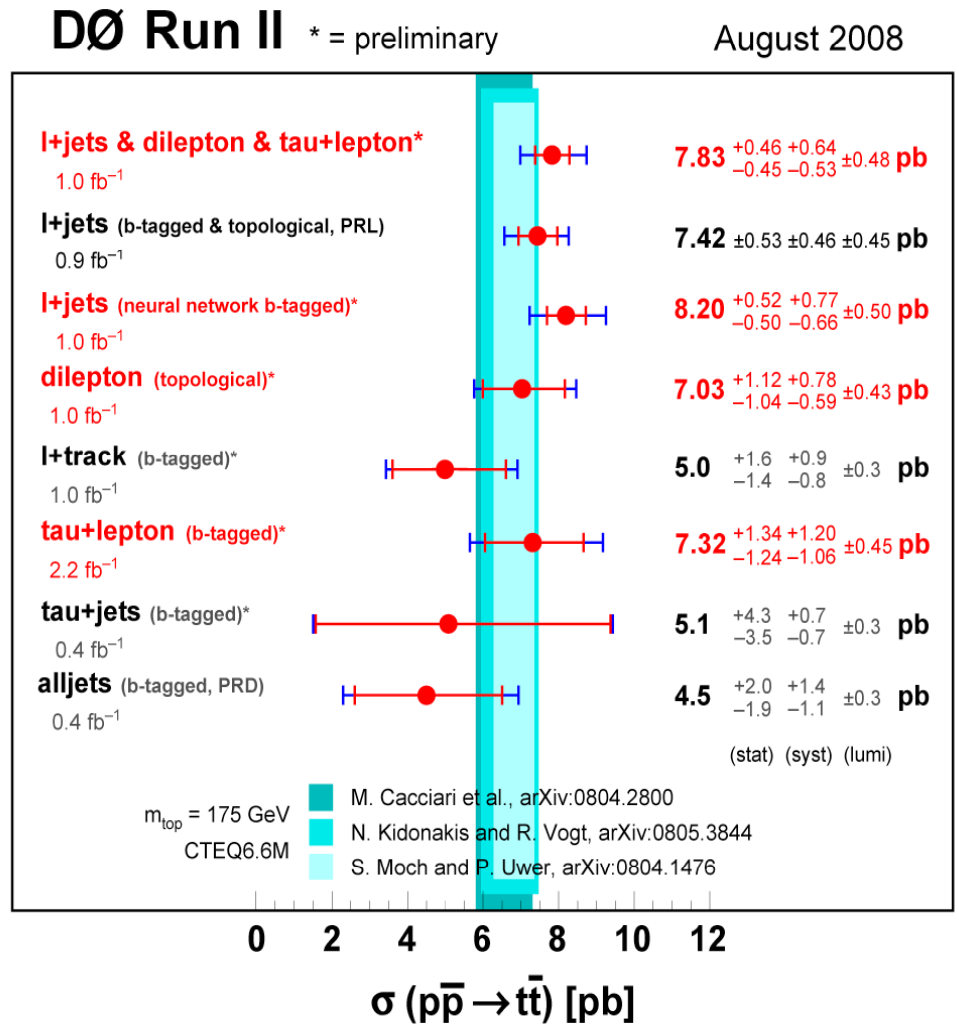


- $m_t > m_W + m_b \Rightarrow$ dominant 2-body decay $t \rightarrow Wb$
- $\Gamma_t^{SM} \approx 1.4$ GeV at $m_t = 175$ GeV
  - Top decays before top-flavored hadrons or **tt**-quarkonium bound states can form
  - Top spin and kinematics is transferred to the final state



Top pair Prod. x-section

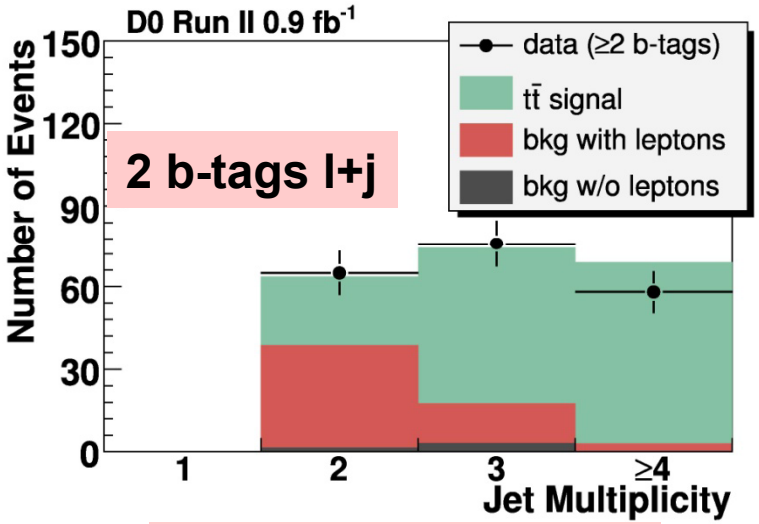


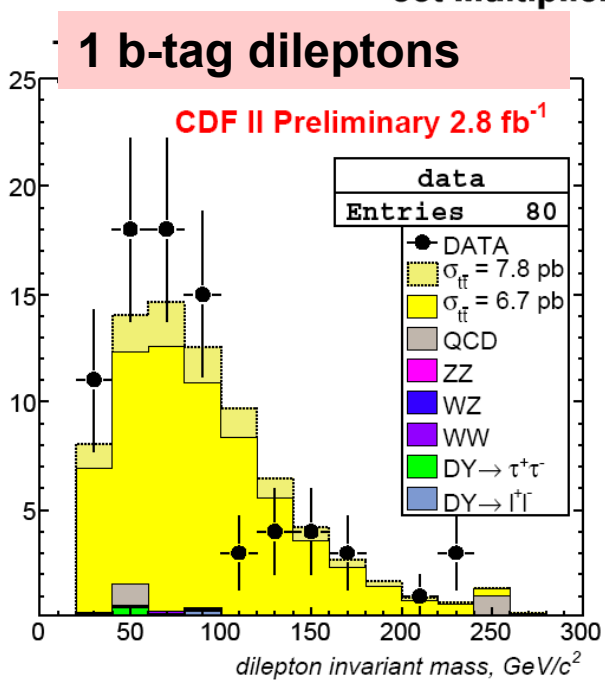


Test of pQCD at high Q^2

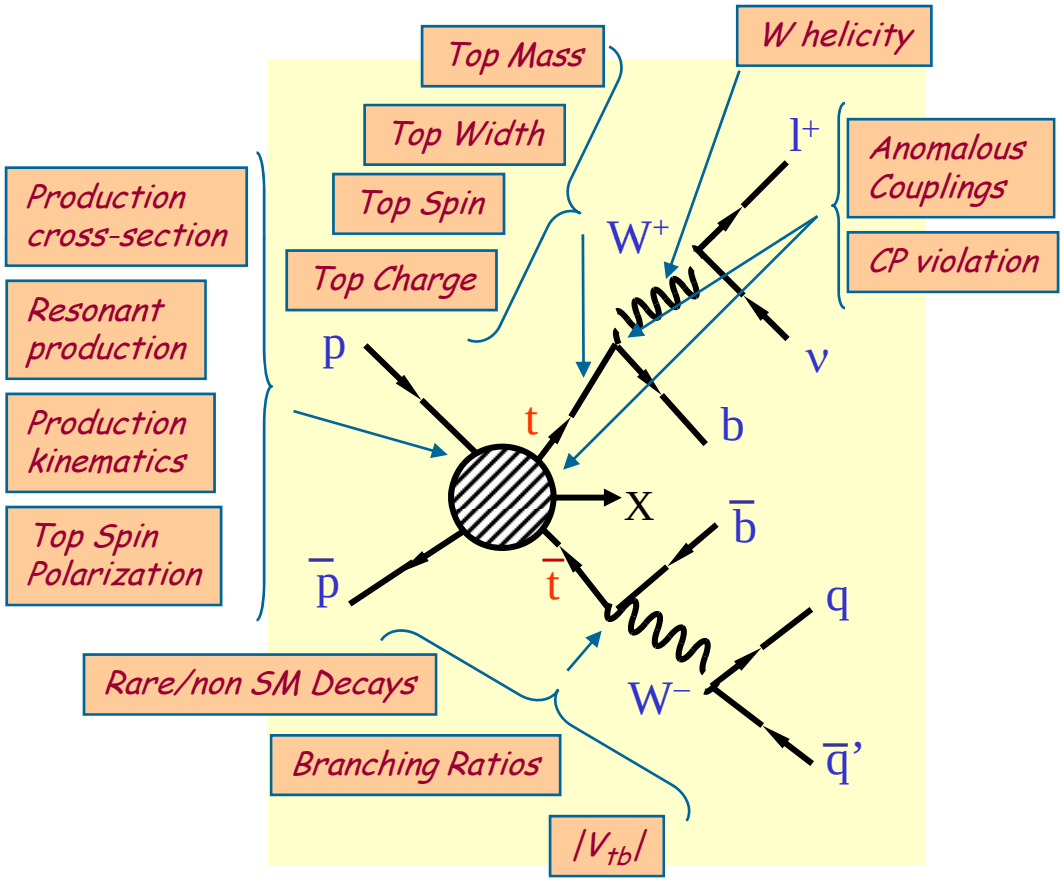
Experimental uncertainties reaching precision in theoretical prediction.

Top quark Properties

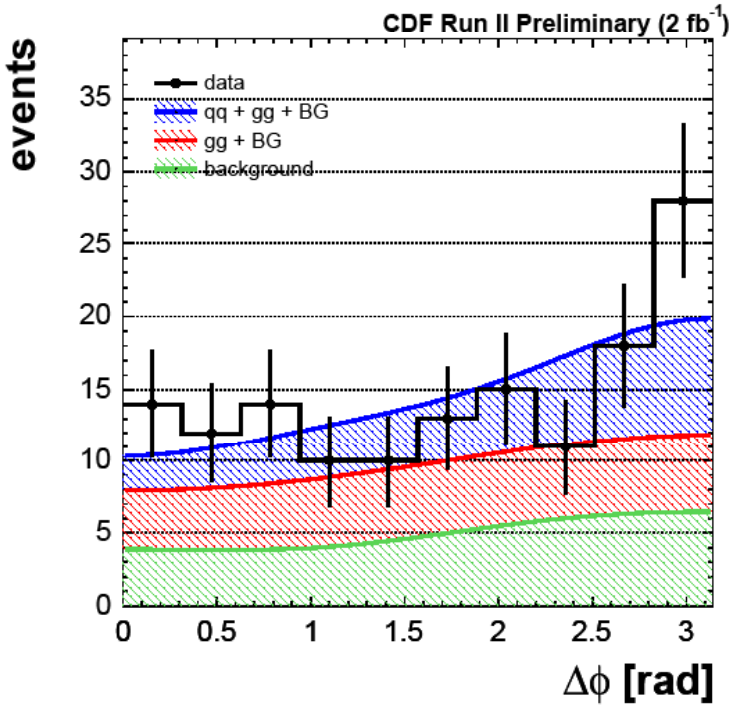




b-tagging provides pure sample of top quarks for properties measurements



Top Quark Pair Production Mechanisms



Gluon Fusion Fraction

Extracted from a fit to the azimuthal correlation between leptons (dilepton events)

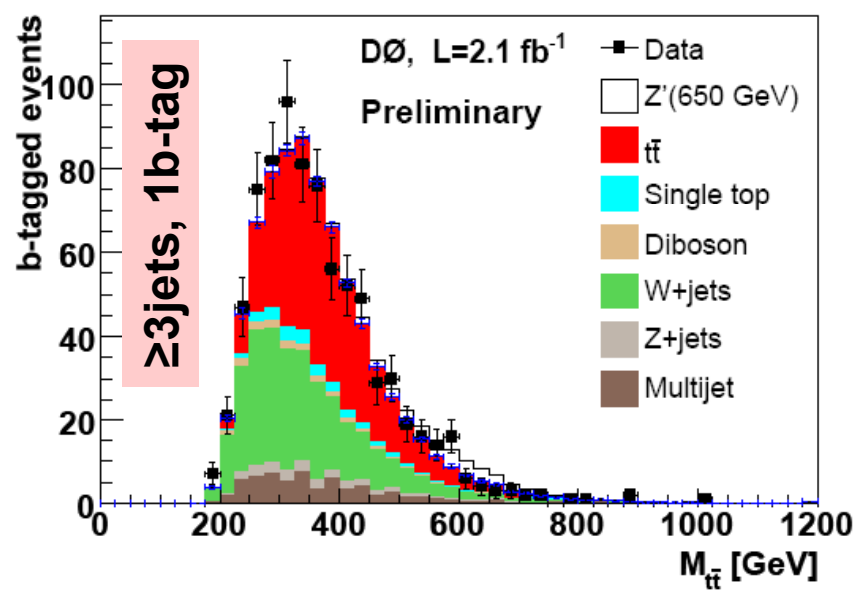
$Fgg = 0.53 \pm^{0.36}_{0.38}$ $SM(pred) = 0.15 \pm 0.05$

Uncertainty dominated by statistics

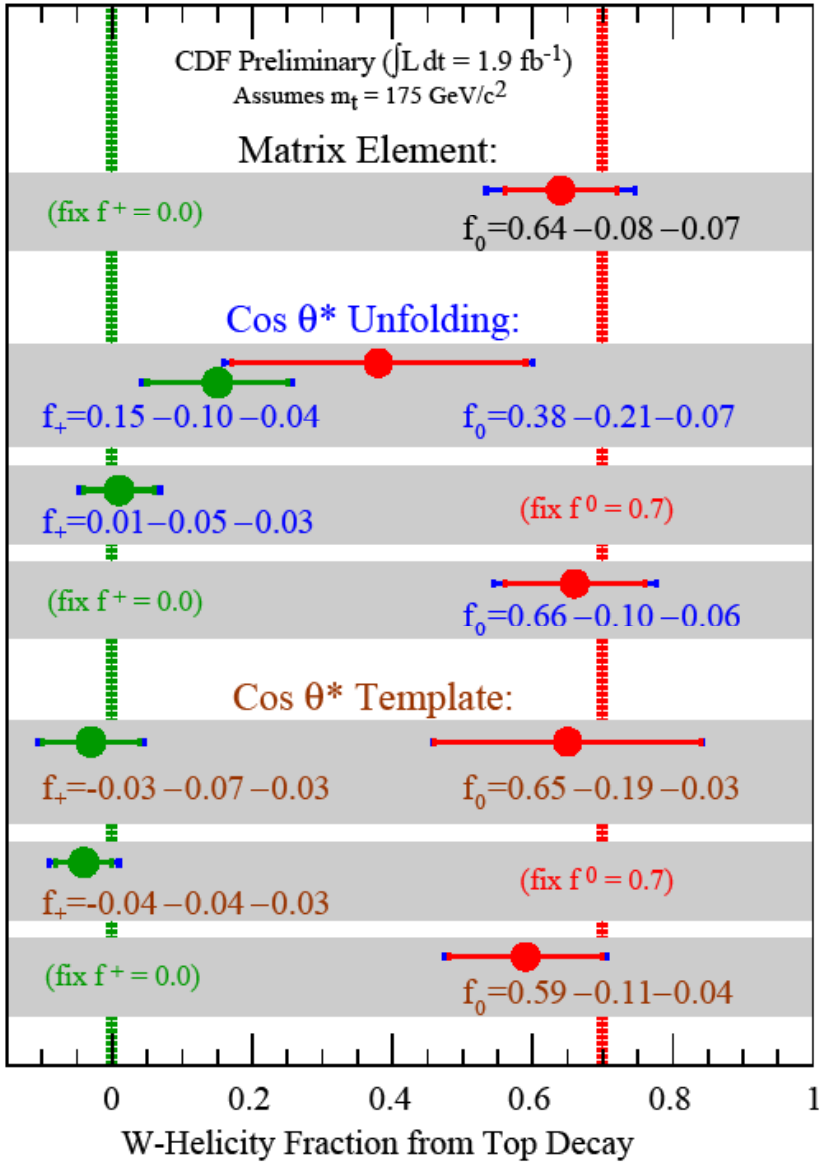
Search for ttbar resonances

Study invariant mass spectrum of l+j events

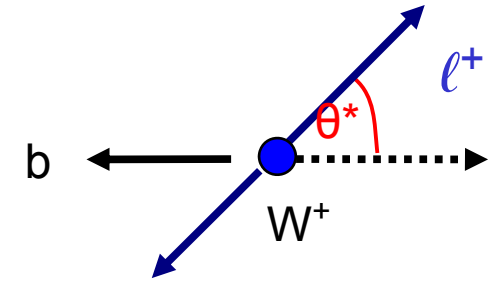
No evidence for narrow resonance decaying into ttbar



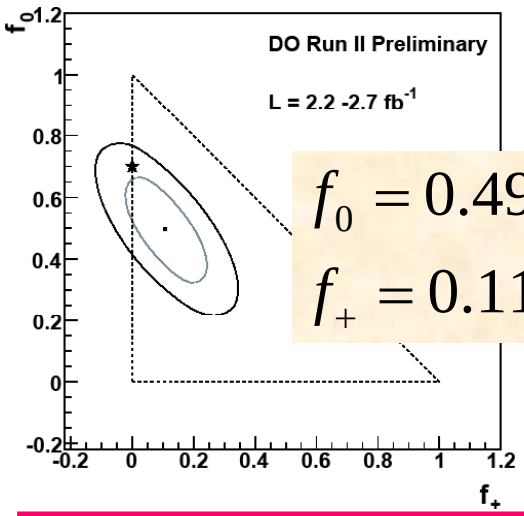
Decay Properties: W Helicity



cosθ* used as sensitive observable



2-parameter fit for fraction of longitudinal (f_0) and right-handed (f_+) polarized W bosons in top decays



$$f_0 = 0.490 \pm 0.106 \pm 0.085$$

$$f_+ = 0.110 \pm 0.059 \pm 0.052$$

Statistically limited: consistent at the 23% level with the SM prediction.

Search for non SM Decays

- Measure absolute rate of l+j events with 2 b-tagged jets and compare to theory
- Can set upper limits to non-SM decay modes B(t→X), with X any state with different acceptance than W.

Top Cross Section: Double Loose SECVTX Tag ($\int \mathscr{L} dt = 1.9\,\mathrm{fb}^{-1}$)				
Sample	**2 Jets**	**3 Jets**	**4 Jets**	**≥ 5 Jets**
WW	0.5±0.1	0.5±0.1	0.2±0.0	0.1±0.0
WZ	2.6±0.3	0.8±0.1	0.2±0.0	0.0±0.0
ZZ	0.1±0.0	0.0±0.0	0.0±0.0	0.0±0.0
Single Top (s)	8.4±1.2	2.8±0.4	0.7±0.1	0.1±0.0
Single Top (t)	2.0±0.3	1.8±0.2	0.5±0.1	0.1±0.0
Z+LF	1.1±0.2	0.7±0.1	0.2±0.0	0.1±0.0
$Wb\bar{b}$	33.9±13.3	10.6±4.3	2.0±0.9	0.5±0.2
$Wc\bar{c}/Wc$	6.1±2.5	2.7±1.1	0.7±0.3	0.2±0.1
Mistags	4.3±1.0	2.6±0.7	0.7±0.2	0.2±0.1
Non-W	2.7±1.9	0.8±1.5	0.5±1.5	0.2±1.5
Total Background	61.6±16.6	23.4±7.3	5.7±3.3	1.4±1.7
SM $t\bar{t}$ (8.8 pb)	32.9±5.2	90.2±14.1	113.7±17.6	41.1±6.3
Total Prediction	94.5±17.4	113.6±15.9	119.4±17.9	42.5±6.5
Observed	107.0	118.0	115.0	44.0

CDF Run II Preliminary

Br(t→Zc)<13%

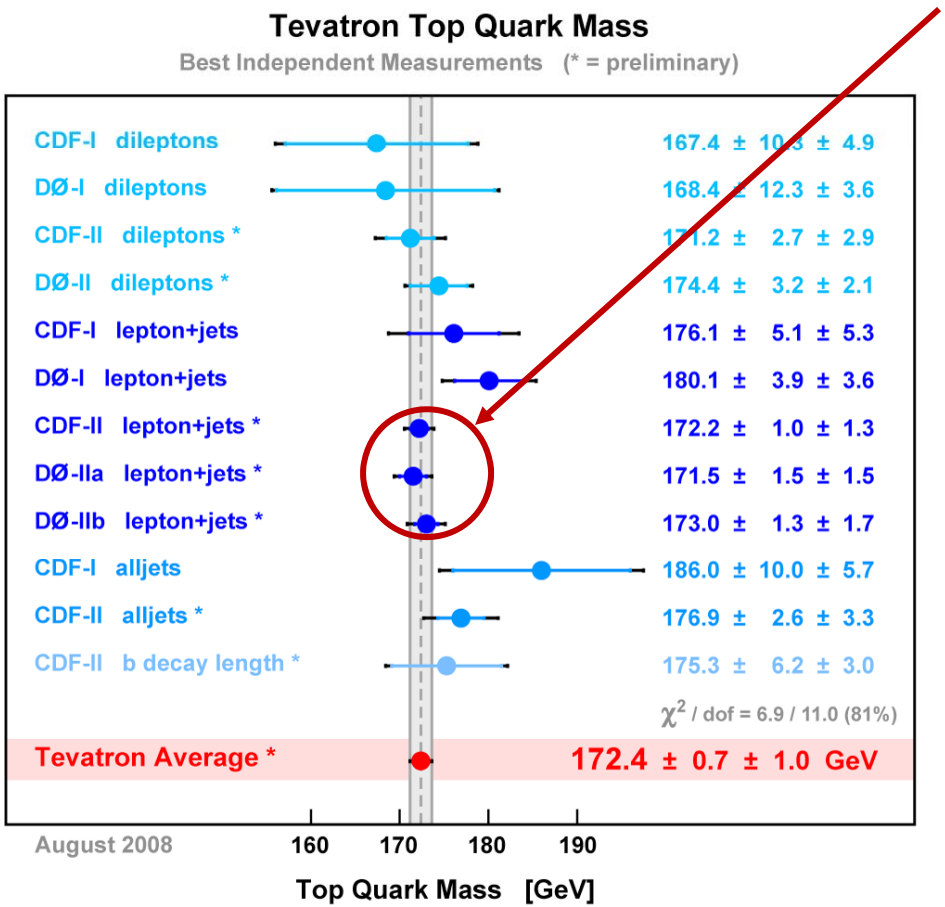
Br(t→gc)<12%

Br(t→γc)<11%

Br(t→invisible)<9%

(M(top)=175GeV)

Top quark Mass



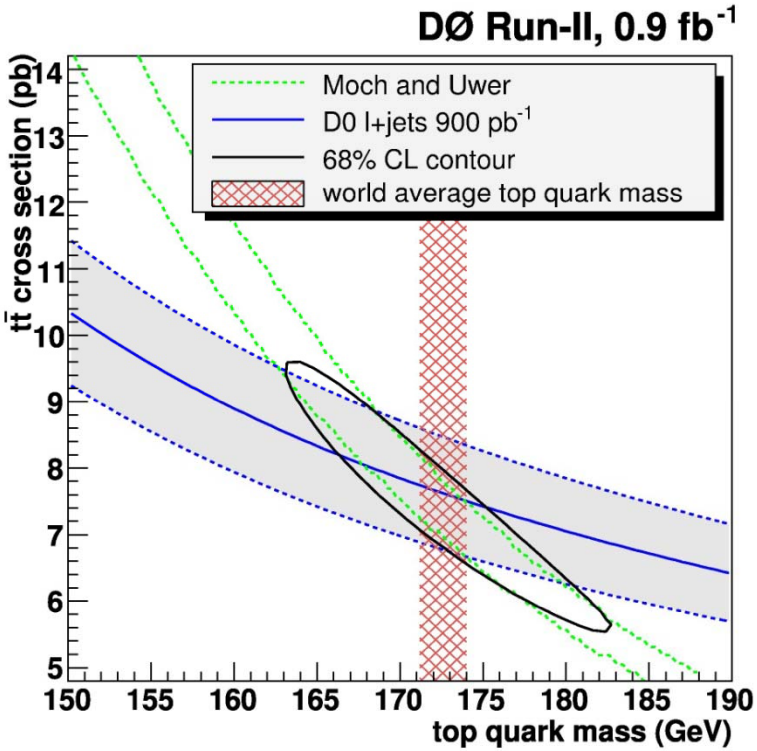
Best results (errors ~ 1%) obtained by ME Method:

- Event by event weight calculated according to quality of agreement with SM top and background differential cross-sections
- Product of all event probabilities gives the most likely mass
- JES constrained in-situ by the hadronic decay of the W→jj

Dominated by systematics

M(top)=172.4±0.7±1.0 GeV

Top Mass from x-section



M(top)=169.1±6.5 GeV

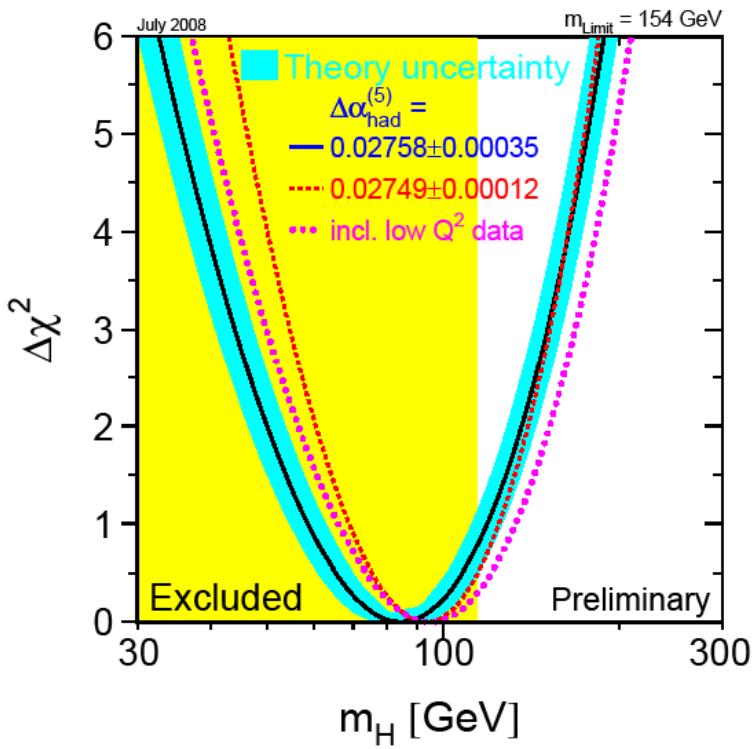
Moch & Uwer NNLO (2008)

Assuming that production is governed by the SM, Top quark mass can be extracted comparing the measured x-sec with theory

Measurement has different experimental and theoretical uncertainties than direct measurements.

Results between two methods are in agreement

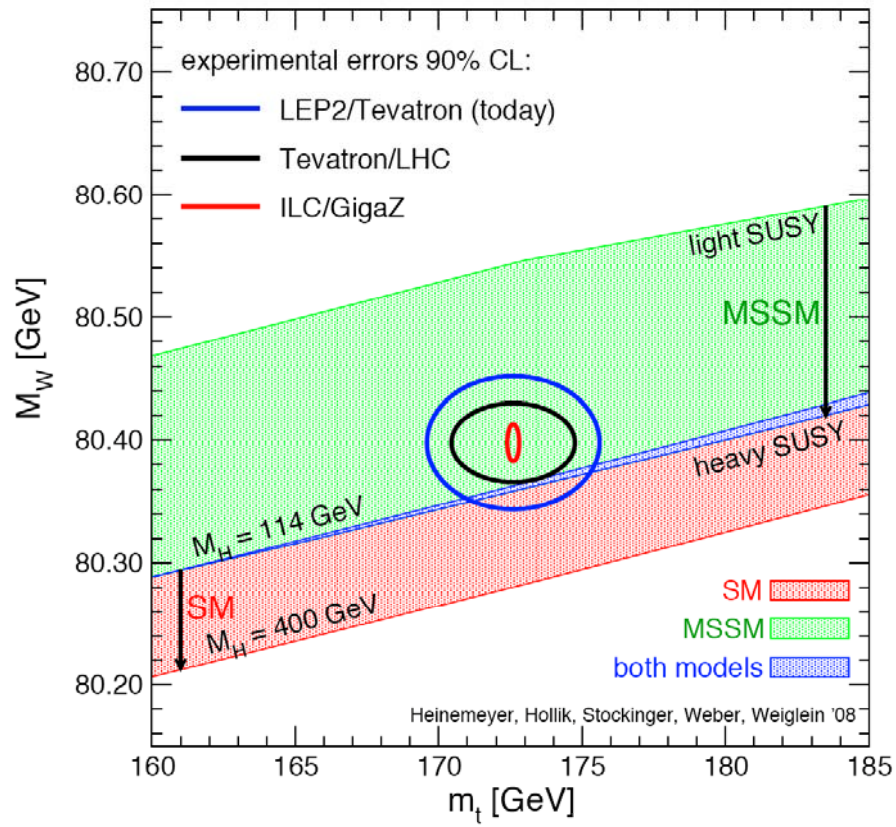
SM Constraints on the Higgs



$$m_H = 84 \pm^{34}_{26}\ GeV$$

$$m_H < 154\ GeV\ @\ 95\%C.L.$$

$$m_H > 114\ GeV(direct)$$

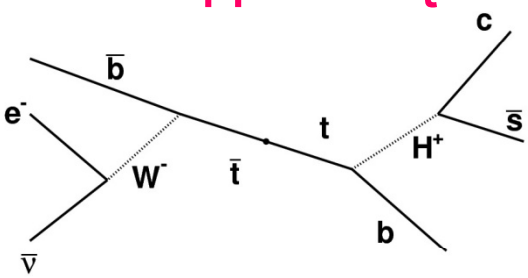


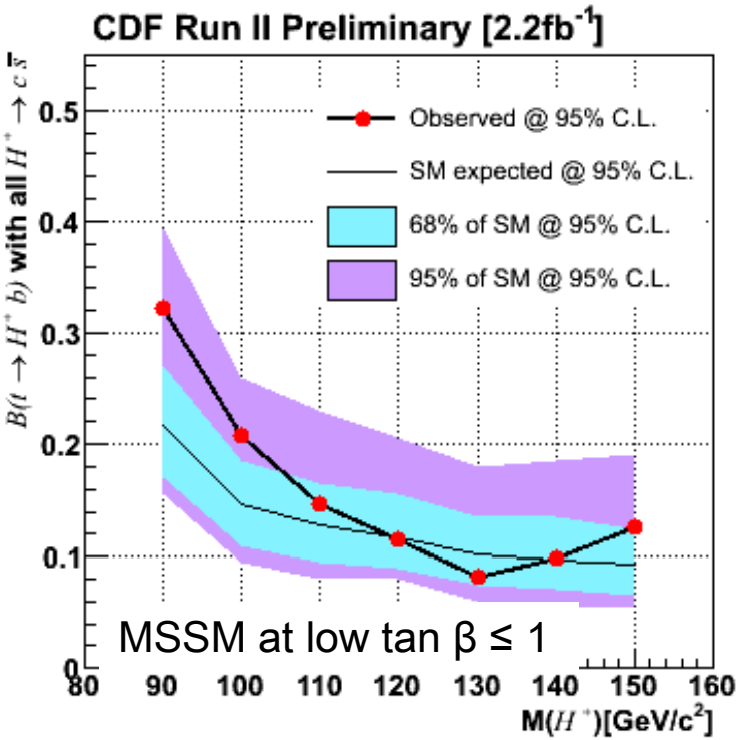
Light Higgs preferred by the SM with latest top and W mass

Plots from LEP/TEV EW working group

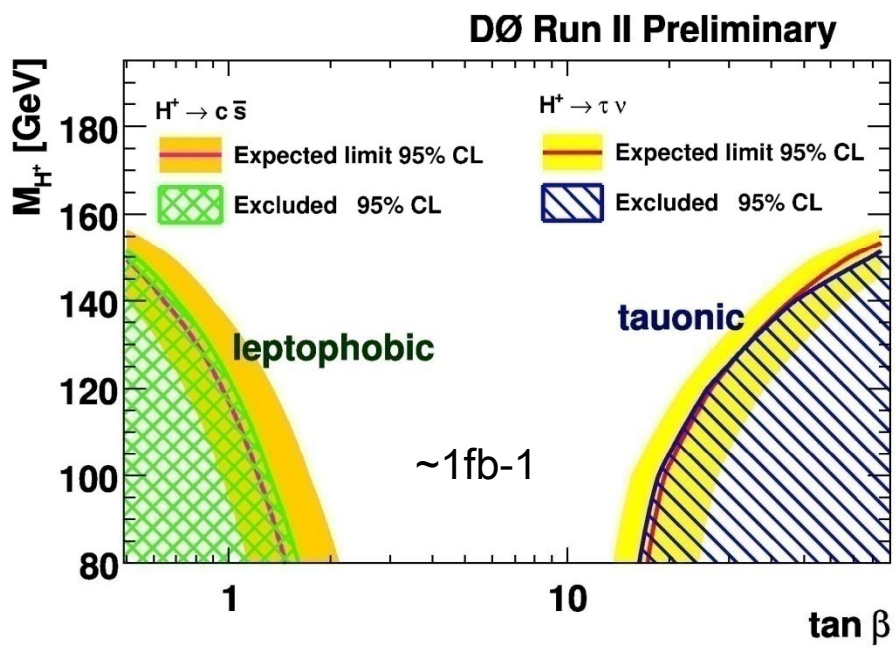
Search for H^+ with $M_{H^+}<M_t$

- l+j events with 2 b- jets
- Use kinematic fit to select the H^+ candidate jets & plot jet pair mass





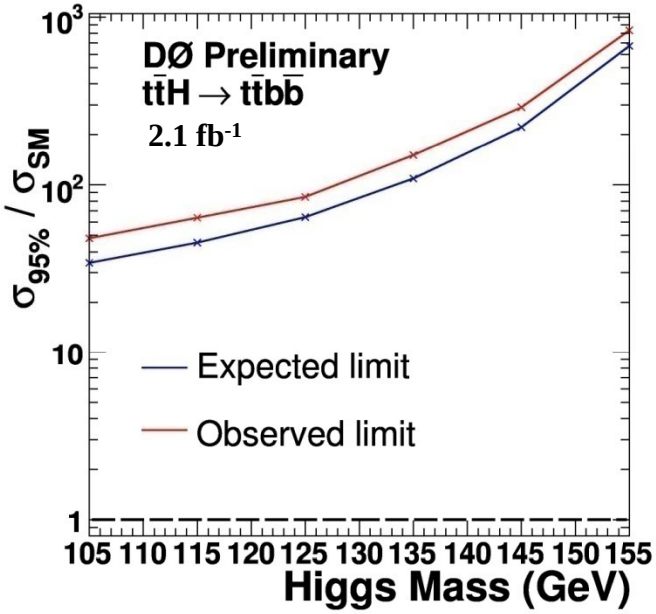
- Measure tt rates in different channels
- H+ production would result in enhancements in the Tauonic and Hadronic channels



No evidence for charged Higgs

ttH→ttbb

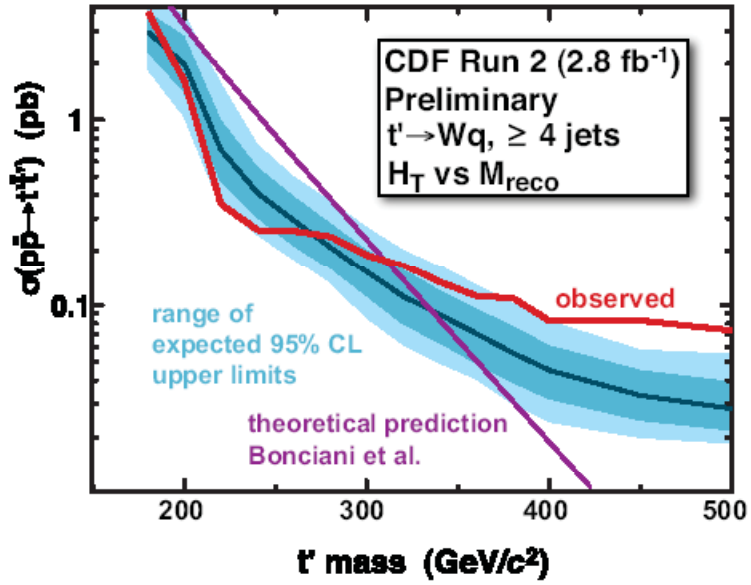
l+≥4j (≥3 b-tags)
Study H_T vs exclusive jet and b-jet multiplicities



No Hint of associated Higgs production or any other BSM process was found

Heavy t'→Wq in l+j events (no b-tag)

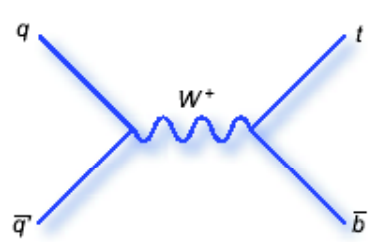
Fit reconstructed top mass and total transverse energy to t'+backgrounds (t, W, qcd)

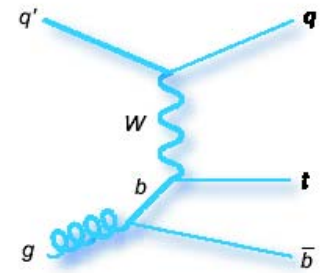


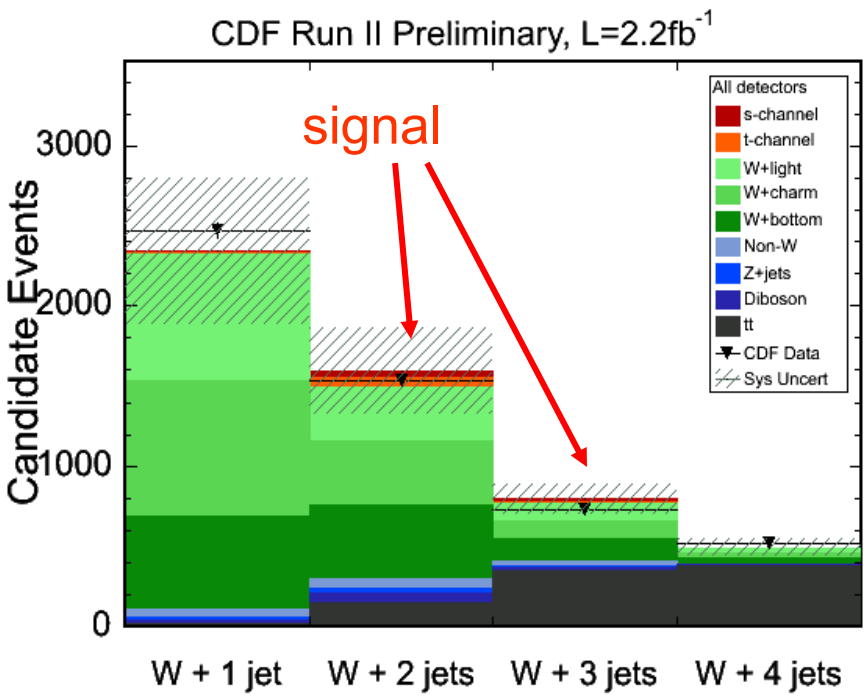
M(t')>311 GeV @ 95%CL

Single Top Production

- Experimentally challenging due to large W+jets background in lower jet multiplicities than pair production





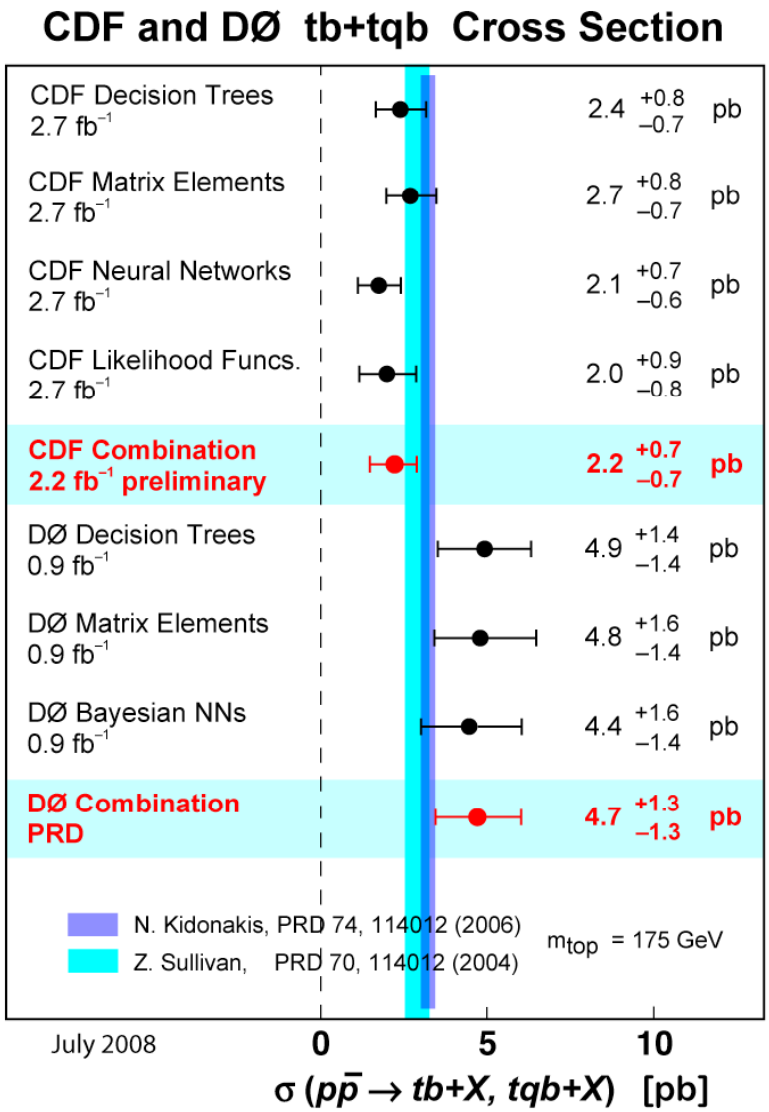


***s*-channel**	***t*-channel**
$\sigma = 0.88 \pm 0.11$ pb	$\sigma = 1.98 \pm 0.25$ pb

- Simple counting experiment cannot extract the signal from the overwhelming background
  - Need advanced techniques
  - Multiple methods per experiment
    - Serve as cross check
    - Combination adds power

Evidence for single top production

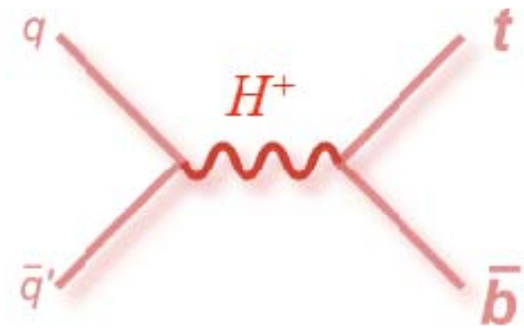
Signal Significance		Cross Section
Expected	Observed	Measured
DØ (0.9 fb^{-1}) PRL 98, 181802 (2007)		
2.3σ	3.6σ	4.7±1.3 pb
|Vtb| = 1.31 + 0.25 - 0.21		
CDF (2.2 fb^{-1}) submitted to PRL		
4.9σ	3.7σ	2.2 ± 0.7 pb
|Vtb| = 0.88 ± 0.12± 0.07		

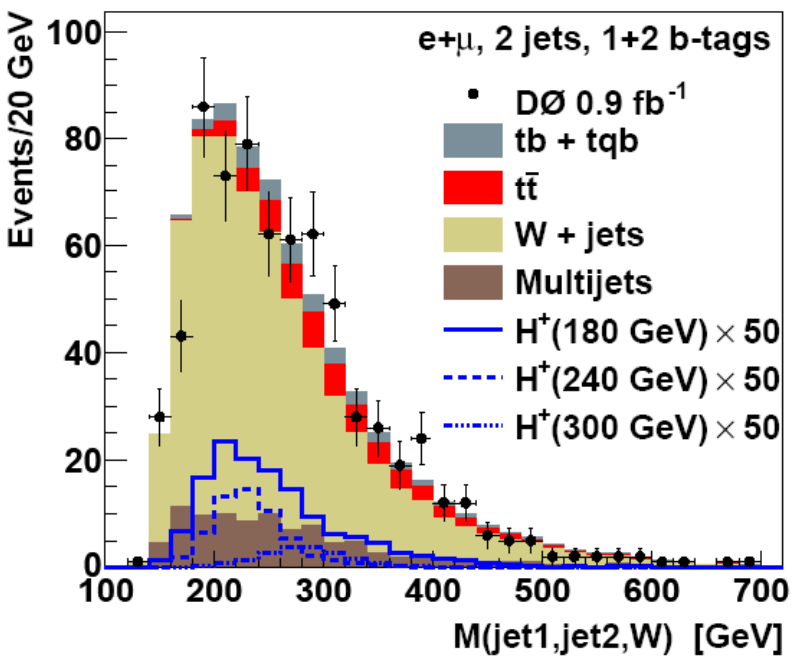


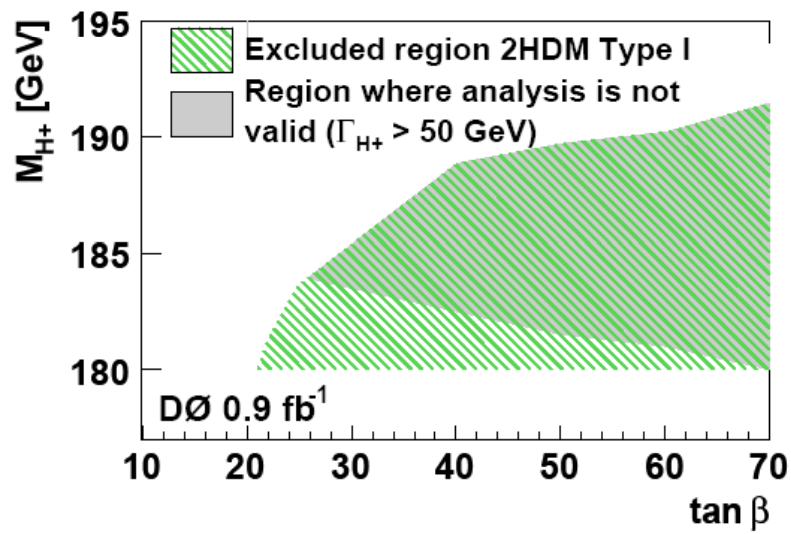
Same final state as WH

Search for H+ with $M_{H^+}>M_t$

$H^+ \rightarrow tb$ same final state as s-channel single top but with enhanced rate and resonance in M(Wjj)





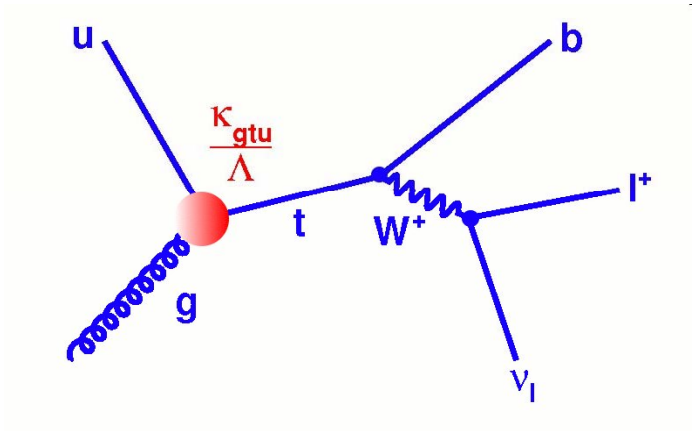


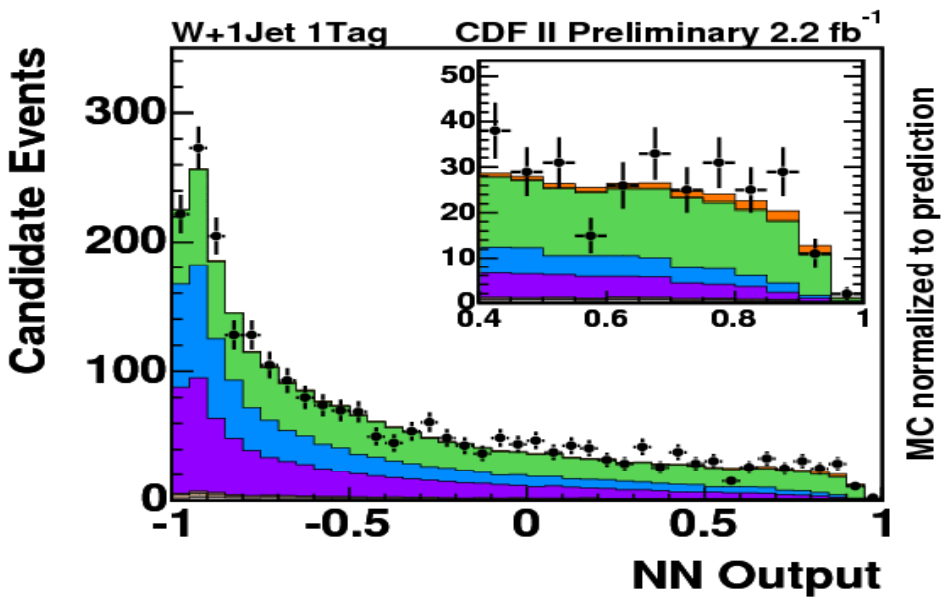
No evidence for charged Higgs production

FCNC in single top production

Model-independent search: effective theory contains FC operators in the Lagrangian

NN distinguishes between anomalous single-top-quark and background events





Observe no significant excess in collision data.

Set upper limits on the anomalous coupling parameters:

$K_{gtu}/\Lambda<0.018\text{TeV}^{-1}$

$K_{gtc}/\Lambda<0.069\text{TeV}^{-1}$

Constraints on Wtb Couplings

- Anomalous couplings can change angular distributions and event kinematics in single top events.

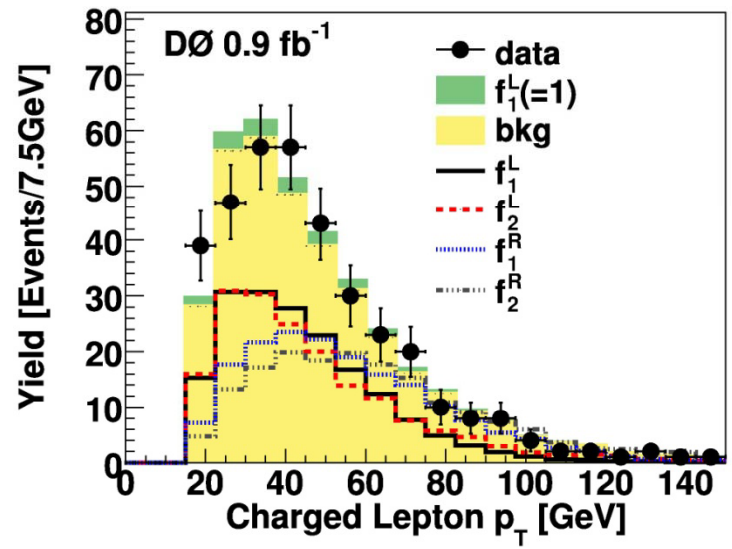
- Most general, lowest dimension, CP conserving Lagrangian for the Wtb vertex

$$\mathcal{L} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t$$

$$- \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t + h.c.$$

In SM: $f_1^L = |V_{tb}| \approx 1, f_1^R = f_2^L = f_2^R = 0$

- Look at two couplings at the time, assuming the other two are negligible



Scenario	Cross Section	Coupling
(L_1, L_2)	$4.4^{+2.3}_{-2.5}$ pb	$\lvert f_1^L \rvert^2 = 1.4^{+0.6}_{-0.5}$
		$\lvert f_2^L \rvert^2 < 0.5$ at 95% C.L.
(L_1, R_1)	$5.2^{+2.6}_{-3.5}$ pb	$\lvert f_1^L \rvert^2 = 1.8^{+1.0}_{-1.3}$
		$\lvert f_1^R \rvert^2 < 2.5$ at 95% C.L.
(L_1, R_2)	$4.5^{+2.2}_{-2.2}$ pb	$\lvert f_1^L \rvert^2 = 1.4^{+0.9}_{-0.8}$
		$\lvert f_2^R \rvert^2 < 0.3$ at 95% C.L.

Data favor the left-handed vector hypothesis.

Conclusions

- DØ and CDF are running better than ever
  - Data taking efficiencies ~ 90%
  - Fast turn-around from data-taking to physics results
  - Rate of publications consistently growing
- Precision and variety of top quark properties measurements keep increasing
  - No evidence of non-SM phenomena so far
- We are enthusiastic about the physics through the end of the decade (and beyond!)

For the latest measurements and discoveries

CDF - http://www-cdf.fnal.gov/physics/W08CDFResults.html

DØ - http://www-d0.fnal.gov/Run2Physics/WWW/results.htm