Aspen Winter 2009 Workshop on Physics at the LHC era (Feb 8-14, 2009)

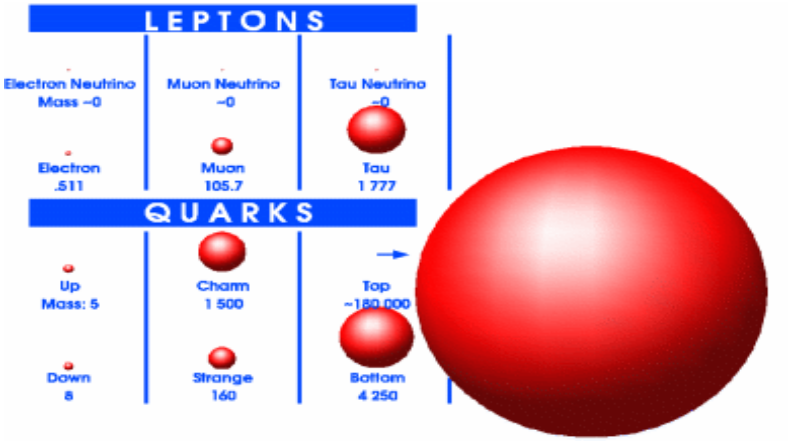
Top Quark Measurements at the Tevatron

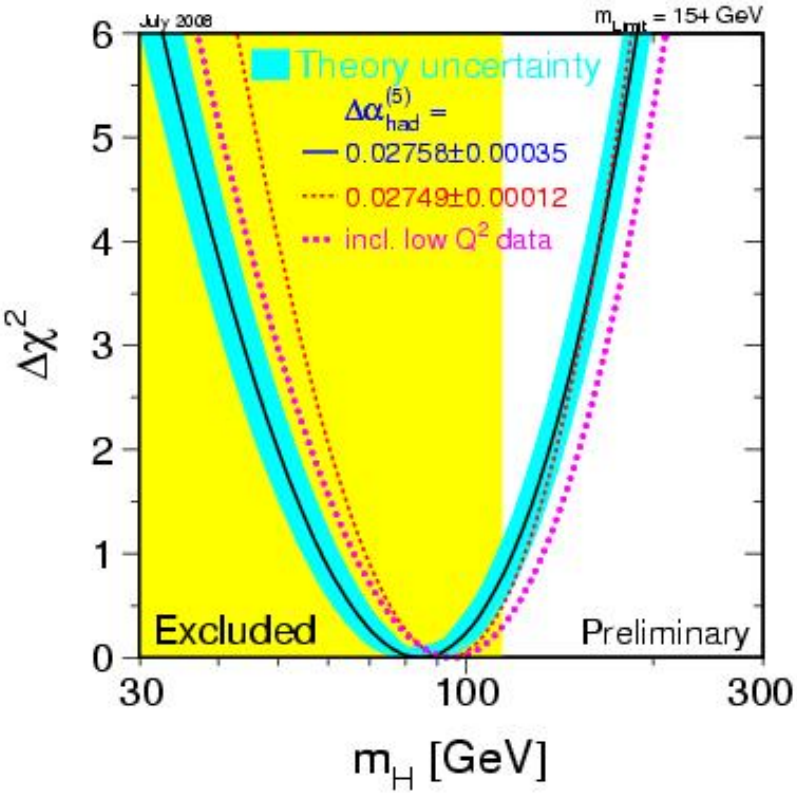
Zhenyu Ye / Fermilab

for CDF and DØ Collaborations

Why is Top Interesting?

- Discovered by CDF and DØ in 1995.
- Pair production by strong interaction. EW decay and single production.
- Top+W mass constrain SM Higgs mass.
- A major background for Higgs and NP searches.
- Most of the interests come from the potential to find NP, e.g., why is it so heavy? Is it the SM top? …





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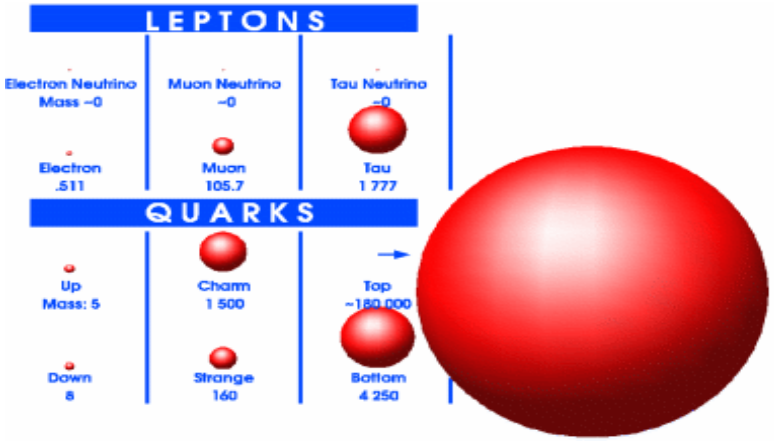
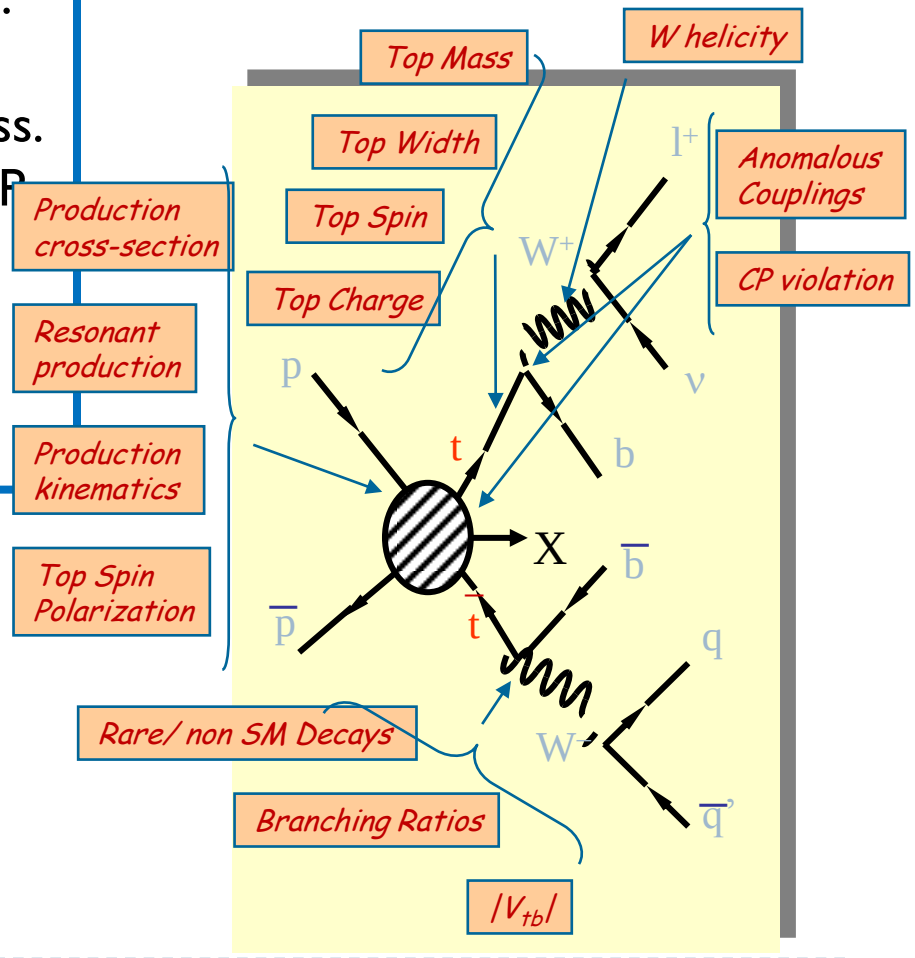


Very Rich Physics Program



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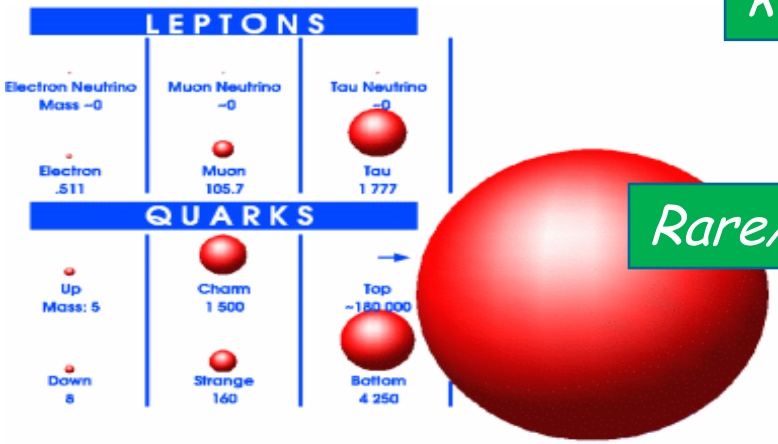
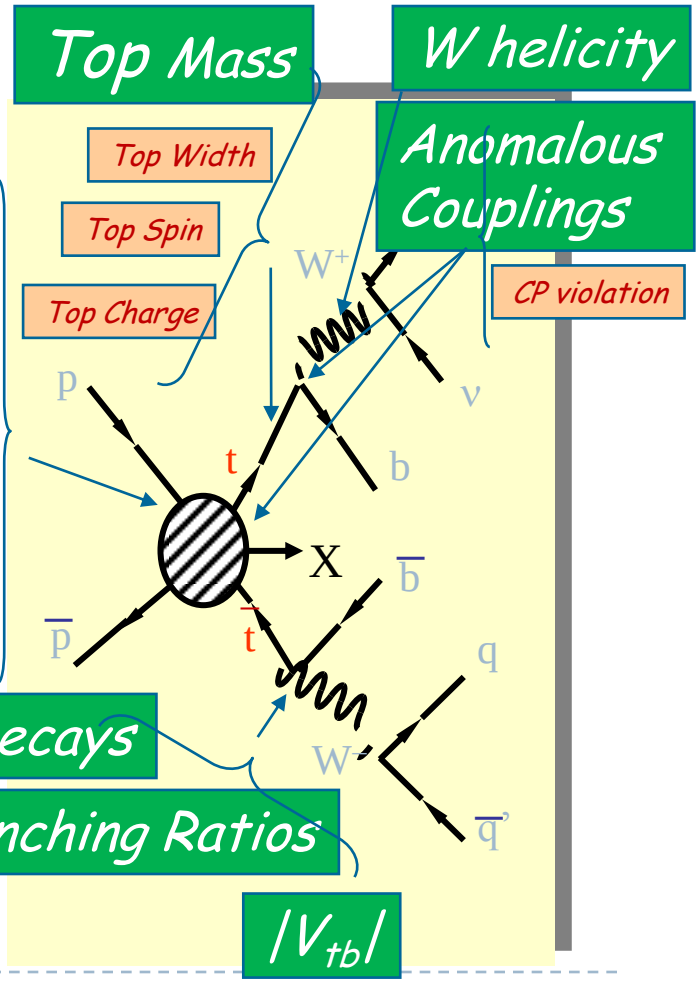
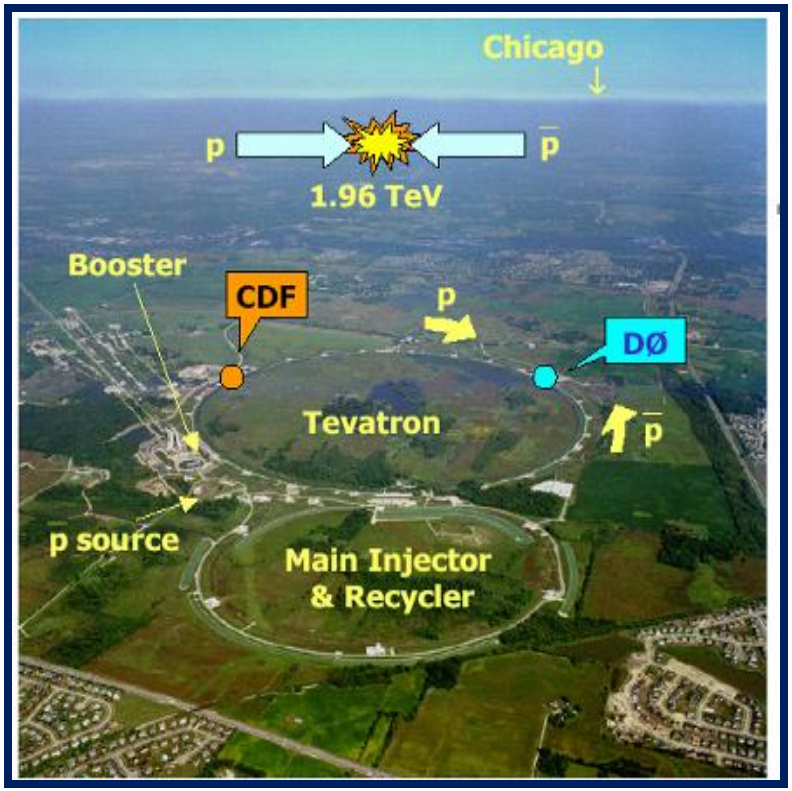
Presented Results

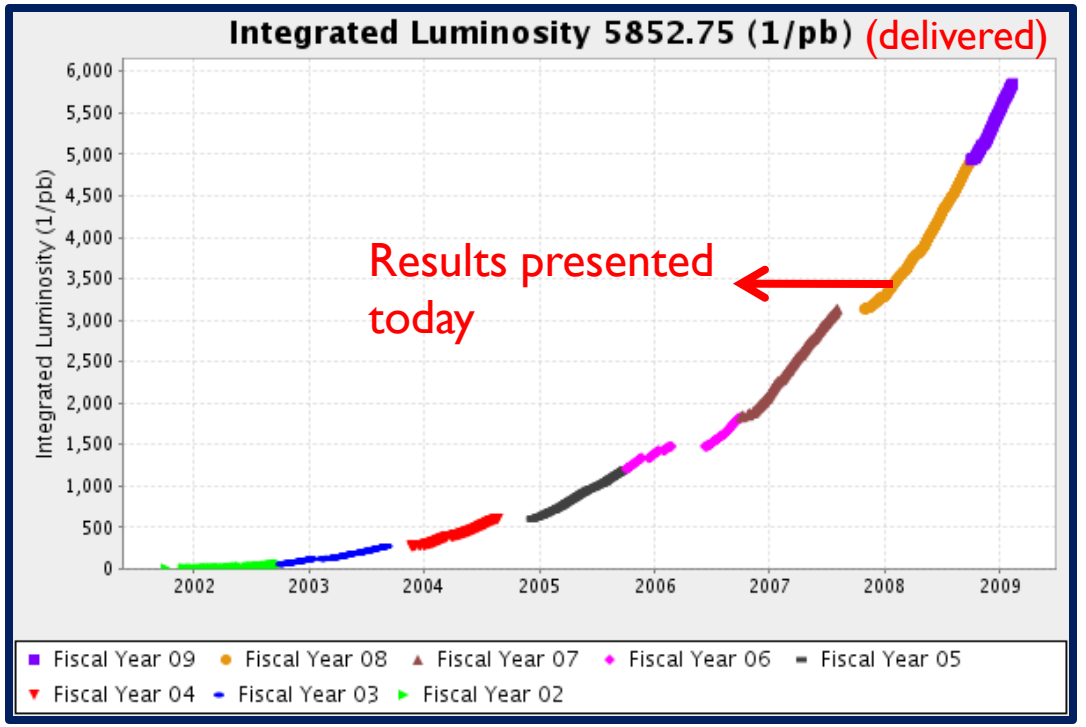
- Top Mass
- W helicity
- Production cross-section
- Top Width
- Anomalous Couplings
- Top Spin
- CP violation
- Resonant production
- Top Charge
- Production kinematics
- Top Spin Polarization
- Rare/ non SM Decays
- Branching Ratios
- $|V_{tb}|$





Tevatron At Fermilab



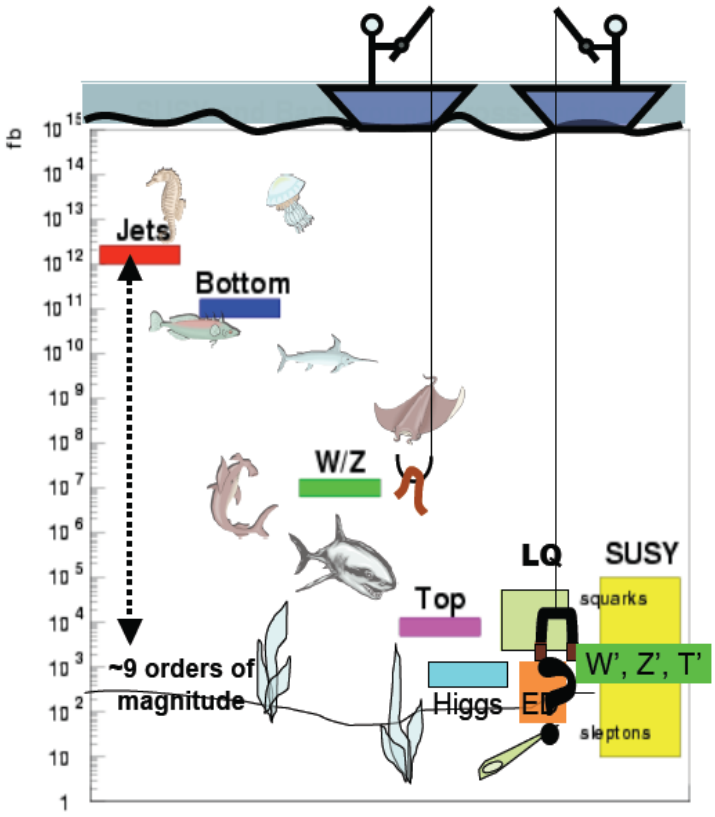


The only place that has produced top quarks!

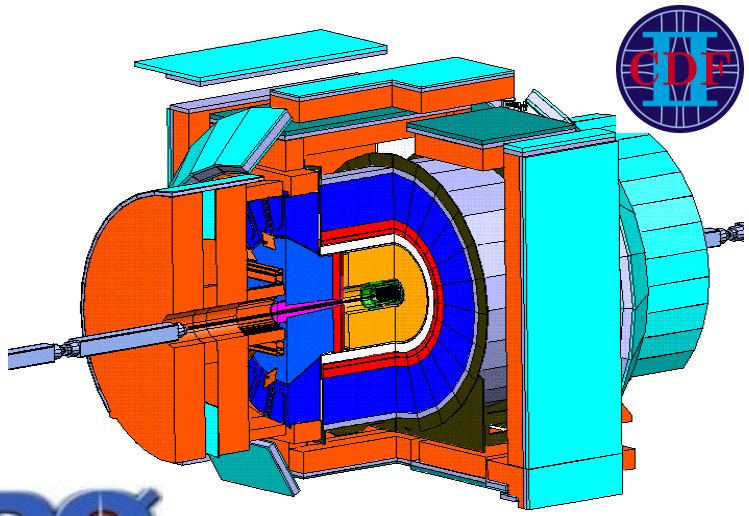
Excellent performance:

- Record instantaneous lumi.: 3.5×10^{32} cm^{-2}s^{-1}
- Total delivered ~5.8 fb^{-1}
- Results based on <3.5 fb^{-1}
- Projected ~10 fb^{-1} by end of FY10

CDF and Dzero Detectors



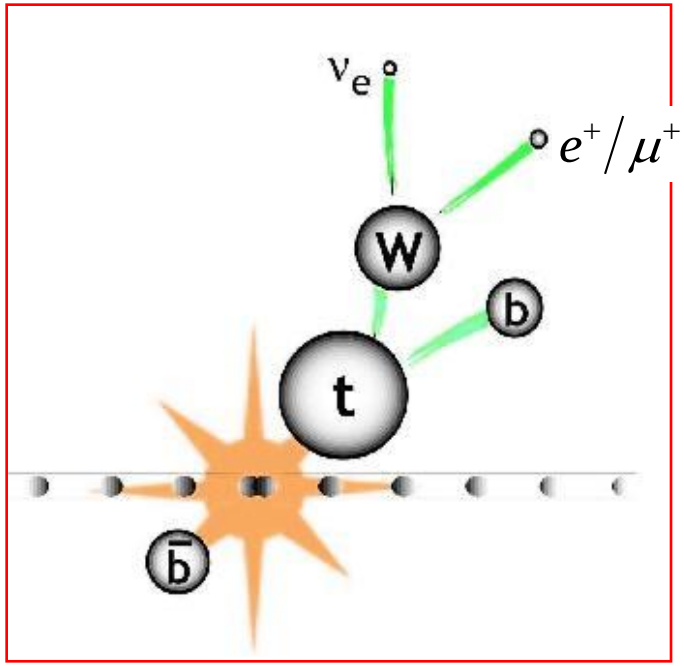
Finding Top quarks is challenging!



Selected Results

- Single top production

– cross section (|Vtb|, anomalous coupling)



- Top pair production

– cross section, M(ttbar) spectrum

– search for new physics (ttH, t')

- Top decay

– branching ratio, FCNC, rare decay

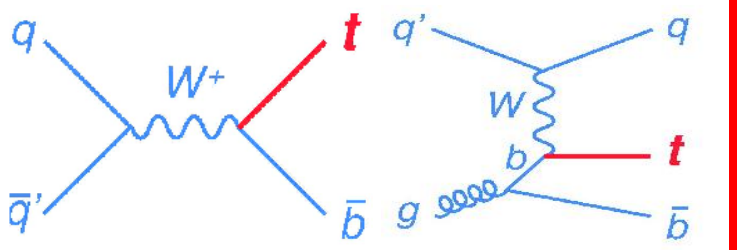
– charged Higgs search

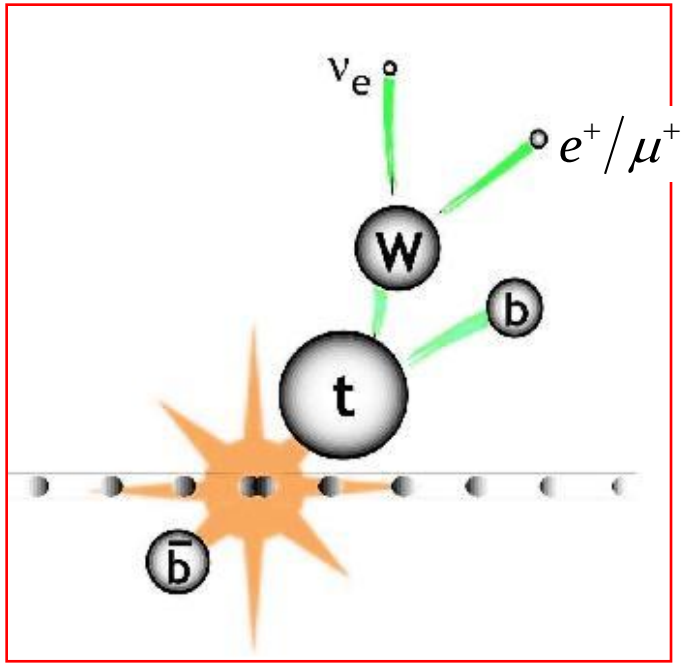
– W-helicity

- Top mass

Single Top Production

At the Tevatron:
s-channel: 0.88 pb t-channel: 1.98 pb





Direct access to the *Wtb coupling*
- overall rate and ratio between s- and t-channels are sensitive to NP
• Experimental challenge:
-cross section ~ half of the *ttbar*
-mostly done in lep+MET+jets
-large backgrounds from W+2 jets
-S/B ~1/200 before *b-tagging*
• Need multivariate techniques to extract signal.

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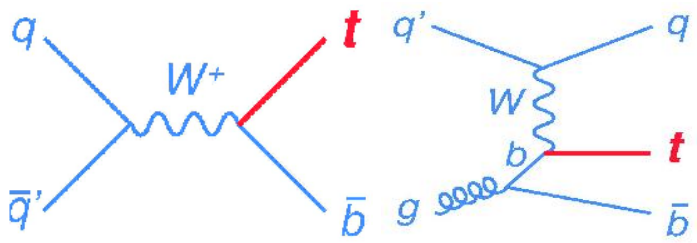

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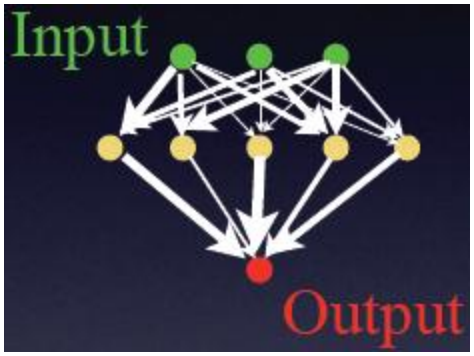
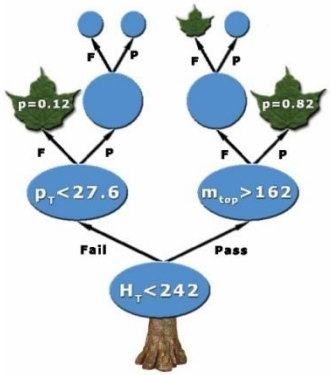


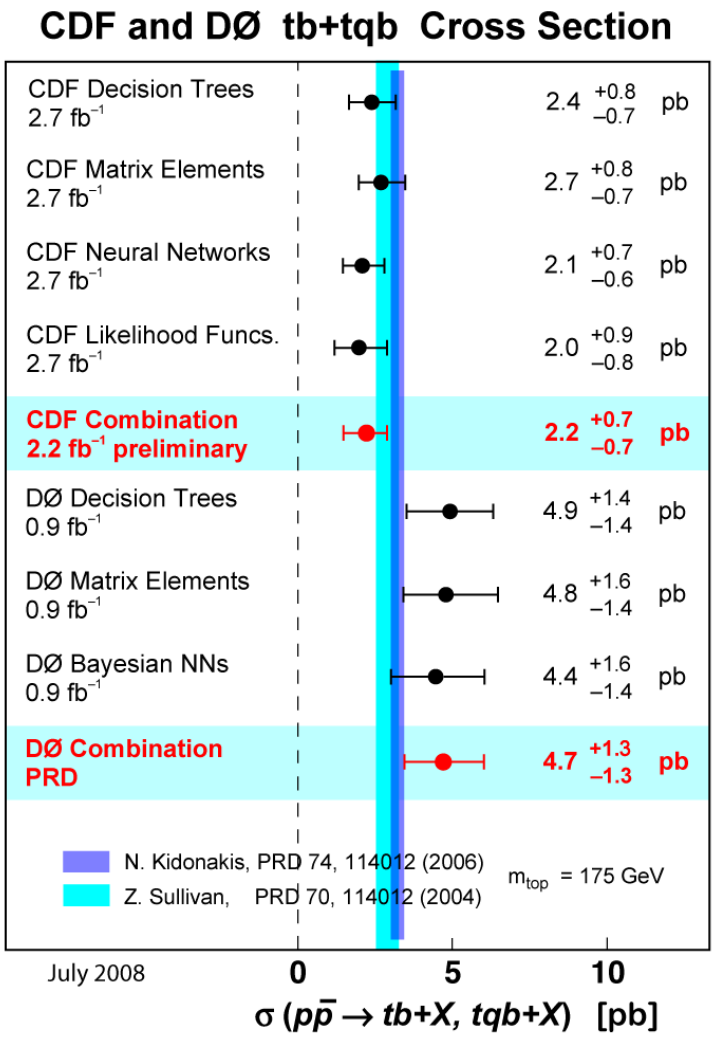
Neural Network:
Train with MC to optimize weight



Boosted Decision Trees:
Train with MC to determine the shape of the tree

Matrix Element:
Calculate signal/background probabilities from the cross section Matrix Element and detector resolutions

Single Top Production – Cross Section, V_{tb}

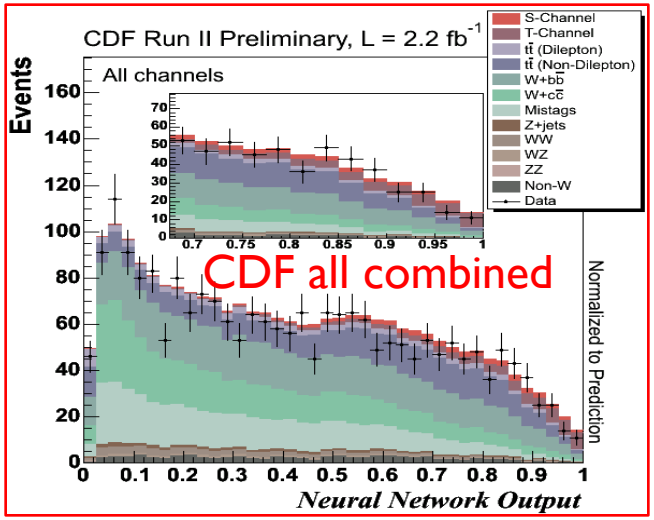


σ=2.2 ±0.7pb

5.1σ exp. significance

3.7σ obs. significance

$0.66<|V_{tb}|\leq 1$ at 95% C.L.

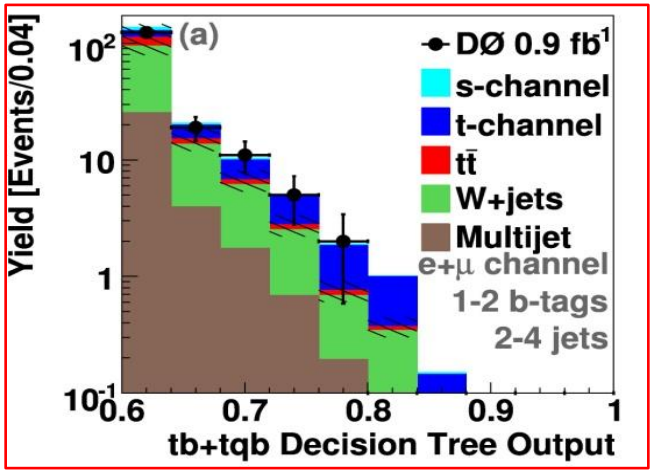


σ=4.7 ±1.3pb

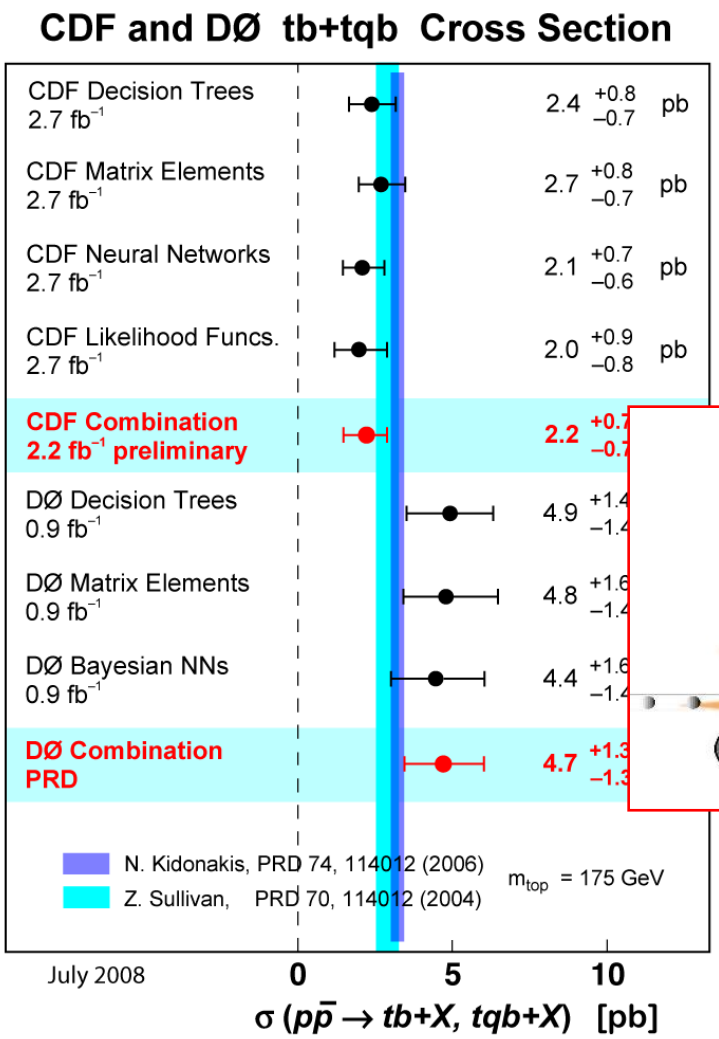
2.3σ exp. significance

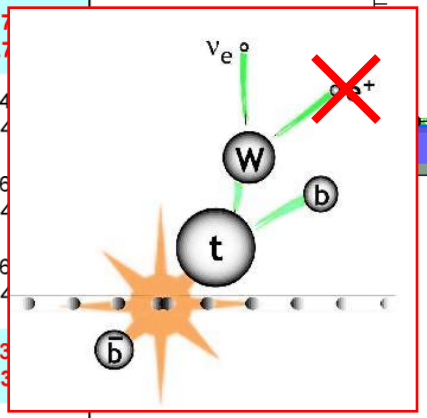
3.6σ obs. significance

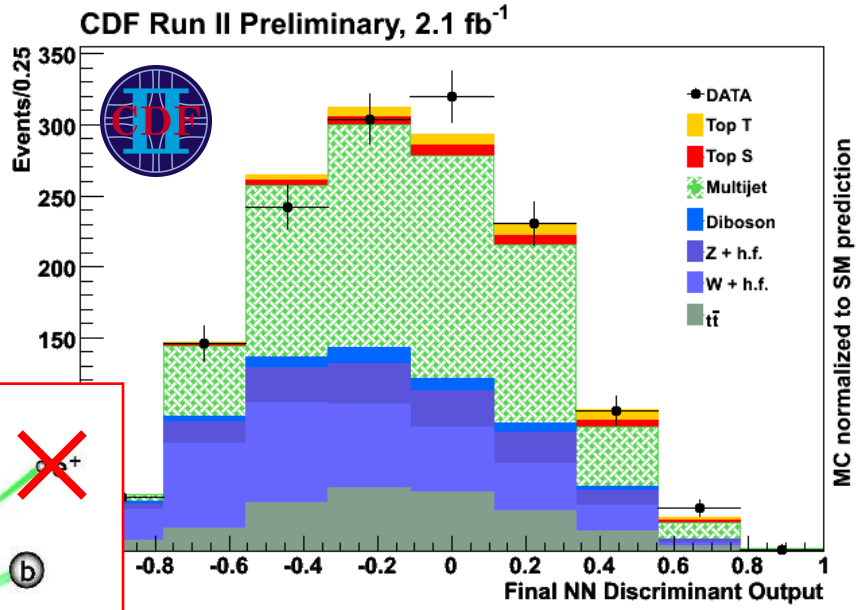
$0.68<|V_{tb}|\leq 1$ at 95% C.L.



Single Top Production – Cross Section, V_{tb}







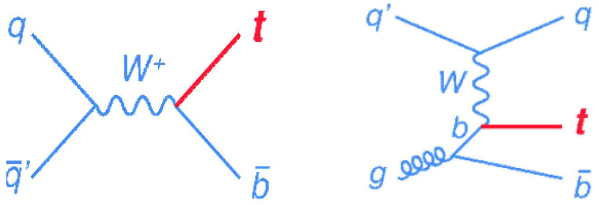
New channel explored by CDF:

MET + jets $4.9\ ^{+2.5}_{-2.2}$ pb

complement the acceptance

1.4σ (2.1σ) exp. (obs.) significance

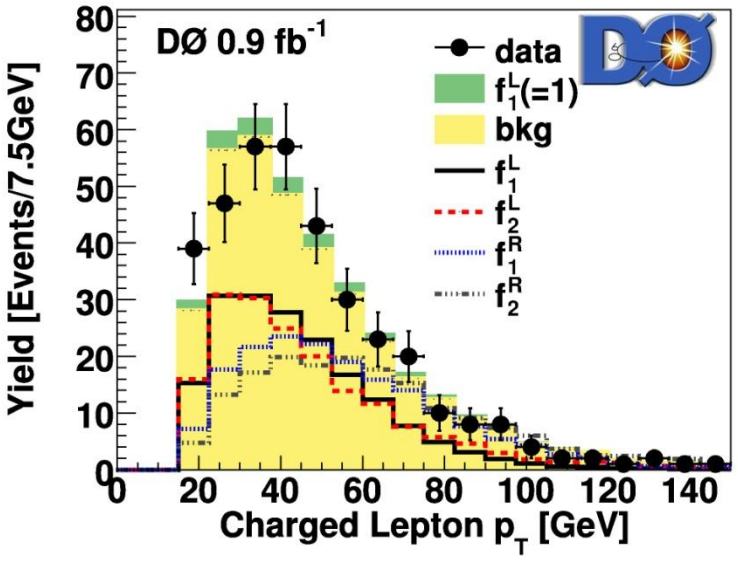
Constraints on Anomalous Couplings

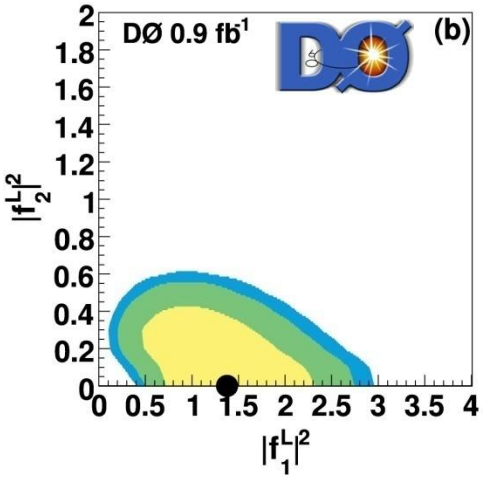


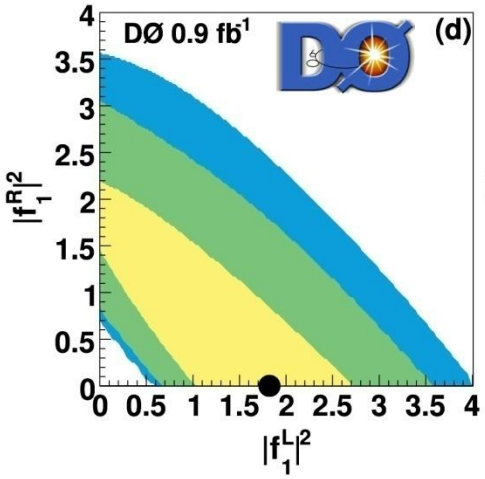
$$\mathcal{L} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t$$

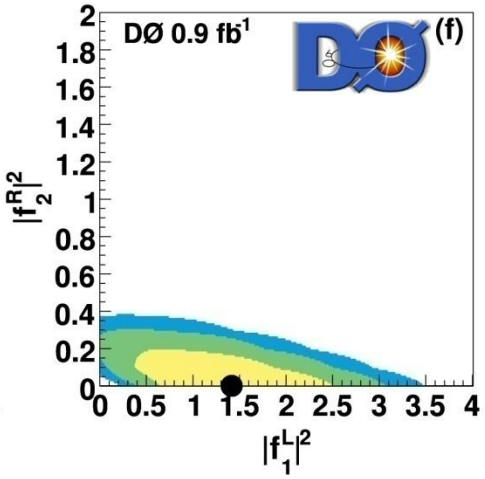
$$- \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t + h.c.$$

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









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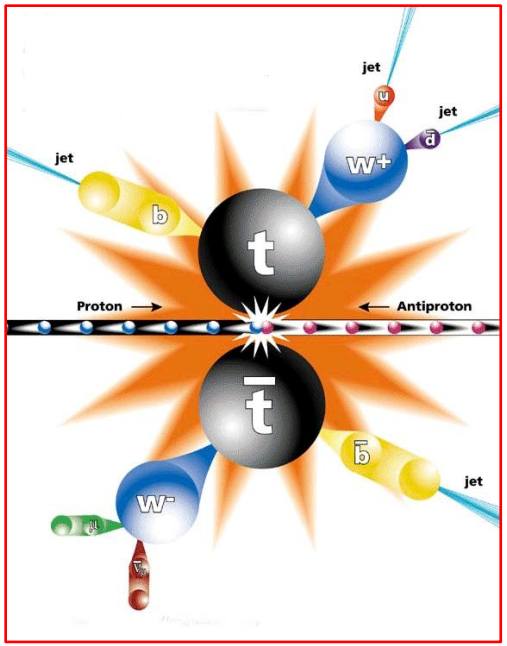
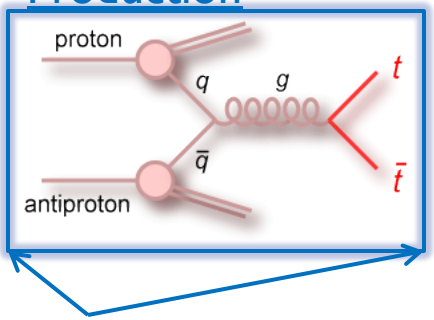
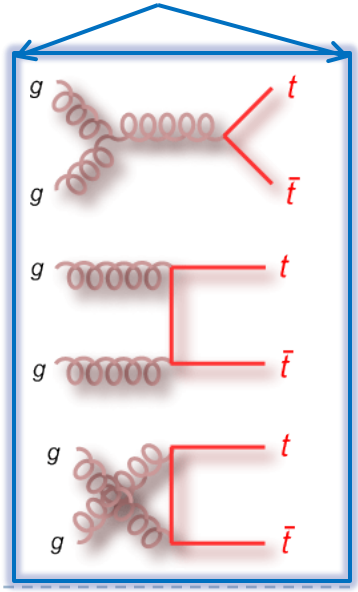


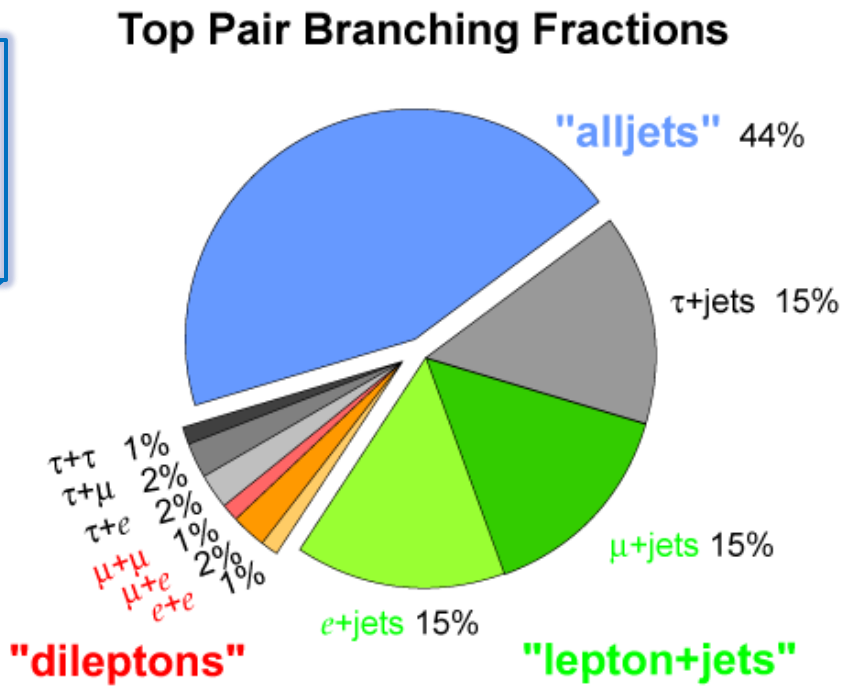
Top Pair Production

Production

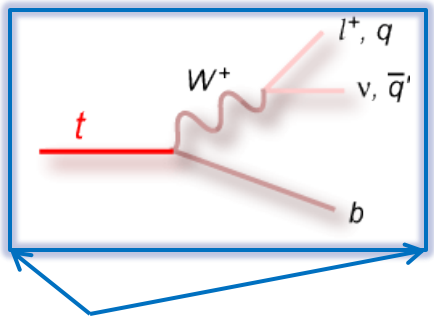


~85% qqbar
~15% gg





Decay



100% t→W+b in SM

$\Gamma^{SM} \approx 1.4$ GeV at m=175 GeV

main background:

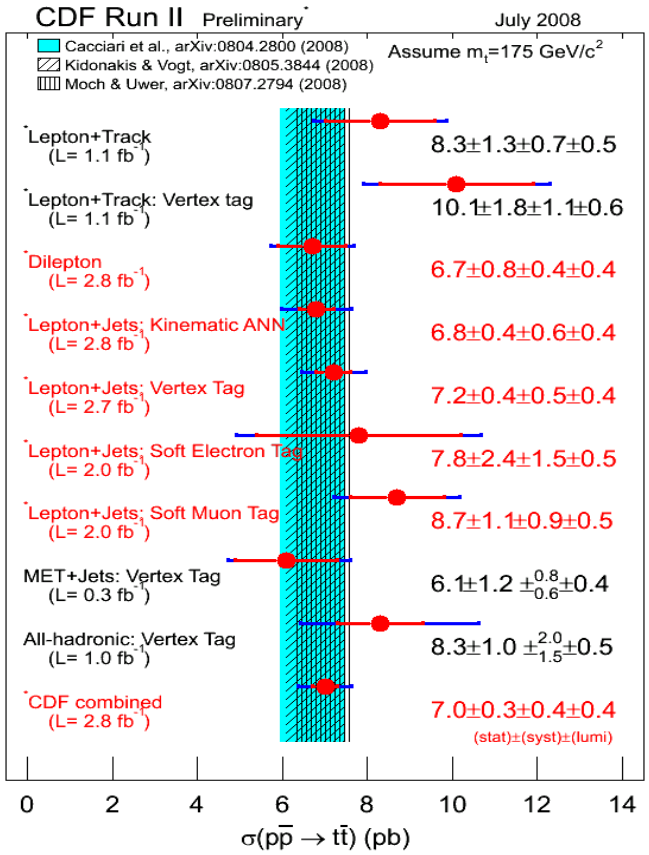
- W/Z + jets
- multi-jets

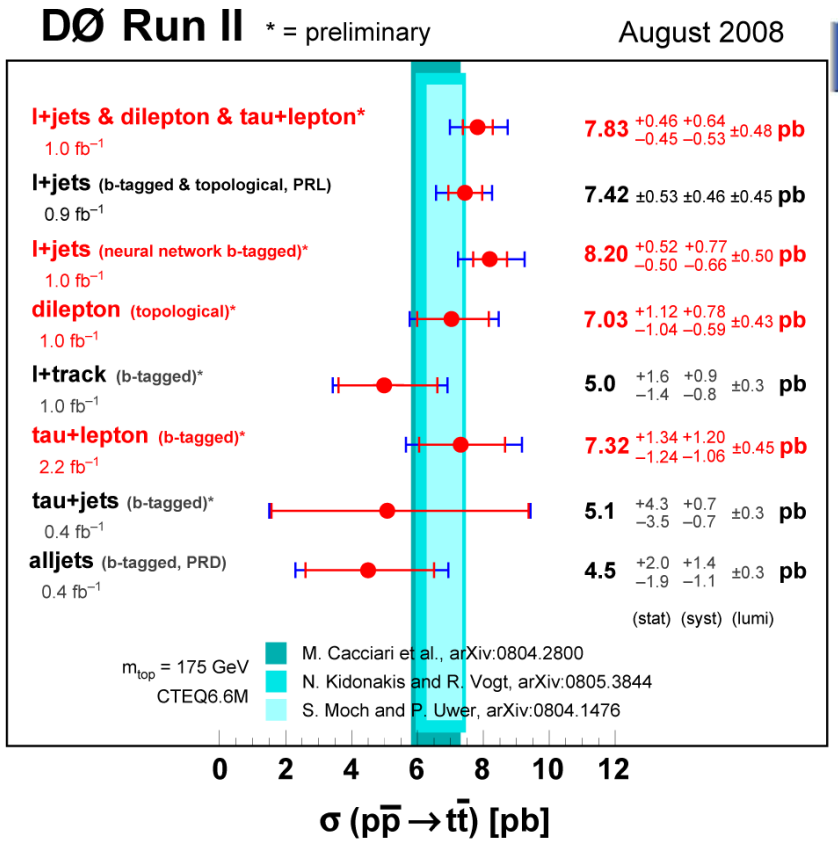
event selection by:

- event kinematics and topology
- isolated lepton (optional)
- MET (optional)
- b-jet ID (optional)

Top Pair Production - Cross Section

Measure in different final states. NP may affect differently.

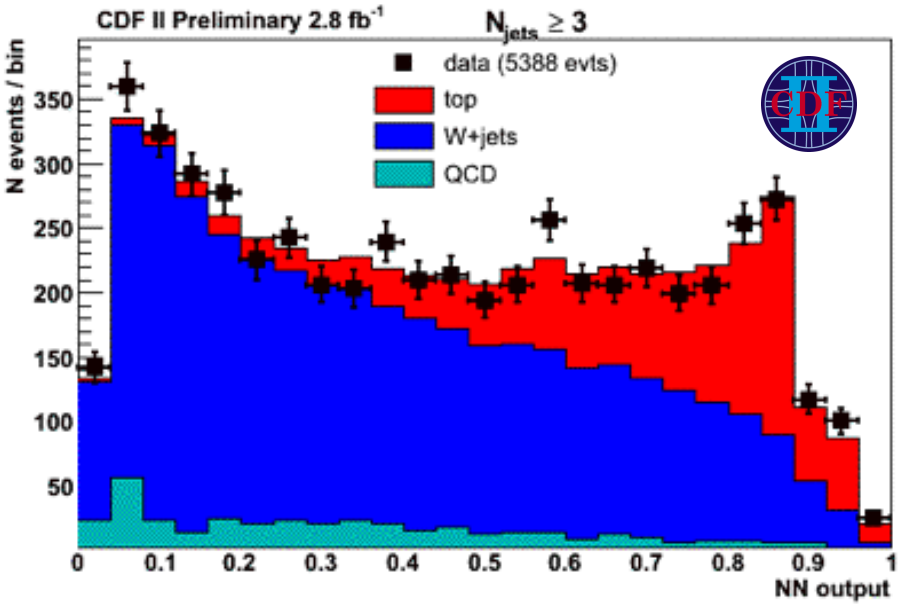


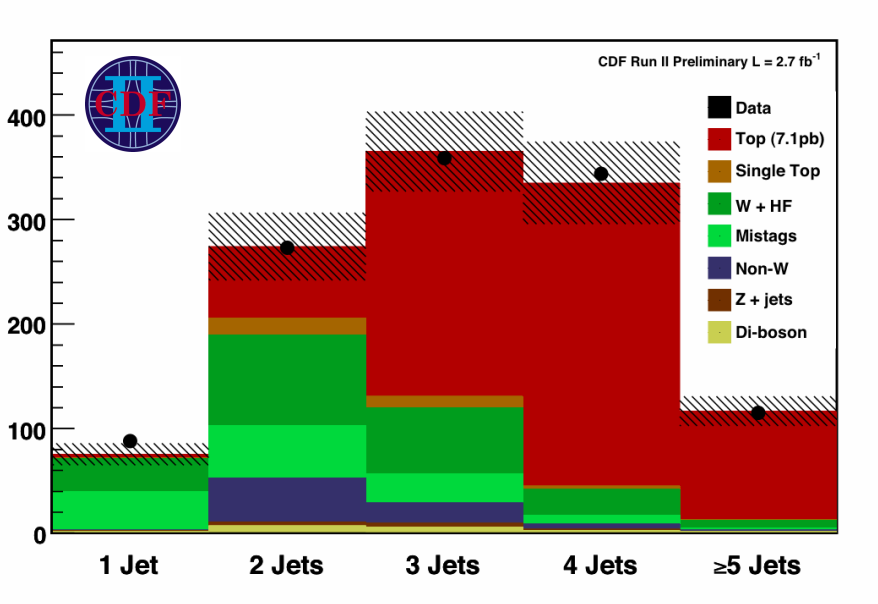


CDF combined (0.3-2.8 fb^{-1}) :
7.0±0.3(stat)±0.4(syst)±0.4(lumi) pb

DØ combined (0.4-2.2 fb^{-1}):
7.8±0.5(stat)±0.6(syst)±0.5(lumi) pb

Top Cross Section - Top/Z Ratio



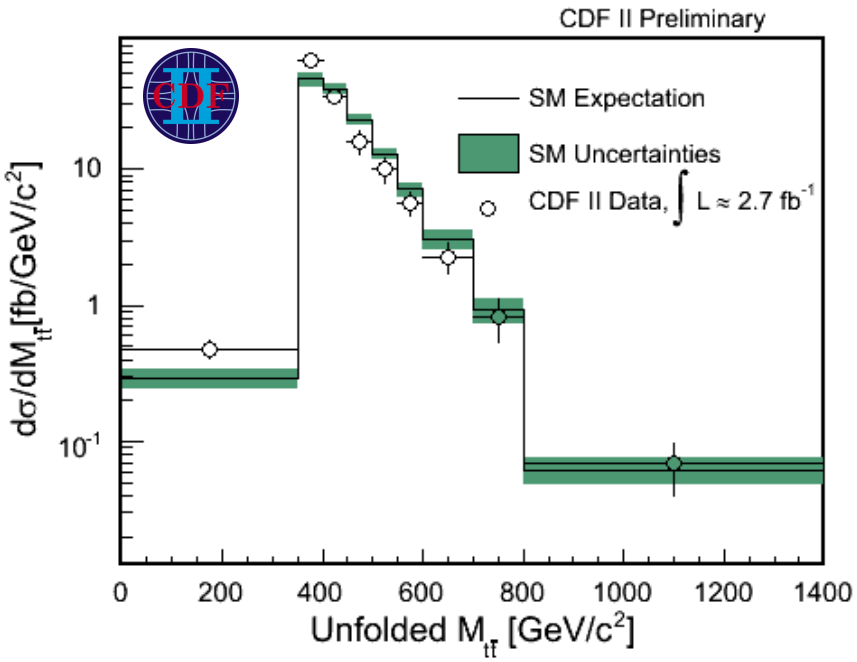


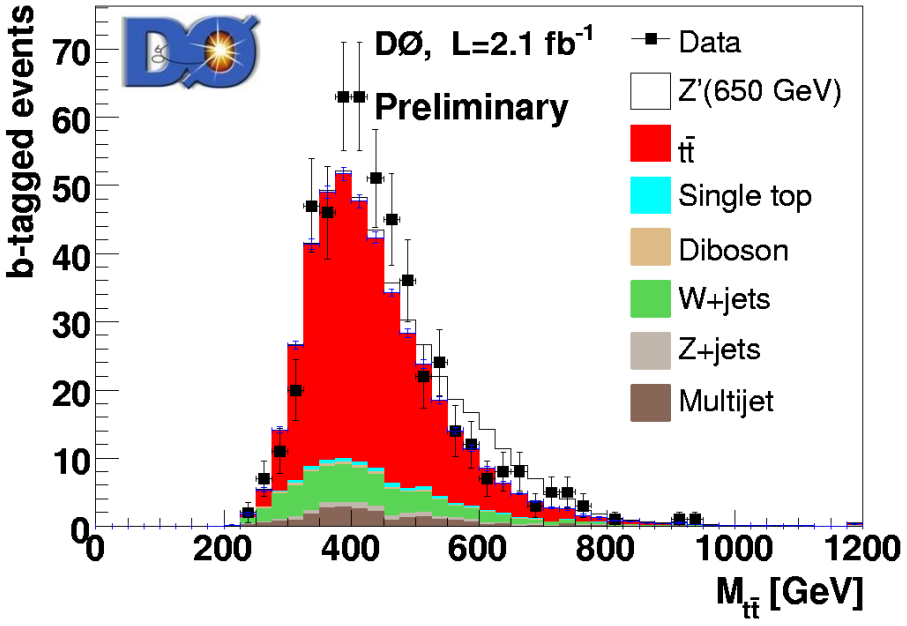
CDF NN (2.8 fb^{-1}):
6.9±0.4(stat)±0.4(syst)±0.1(theo) pb

CDF btagged (2.8 fb^{-1}):
7.0±0.4(stat)±0.6(syst)±0.1(theo)pb

CDF recently measured the Top cross section through Top/Z ratio with greatly reduced systematic uncertainty due to lumi.
The uncertainty in one single measurement is 8.2% (9.7% in direct measurement), comparable to theoretical uncertainty.

M(ttbar) Diff. Cross Section/Spectrum

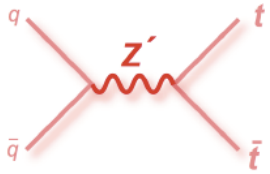




in Randull-Sandrum model

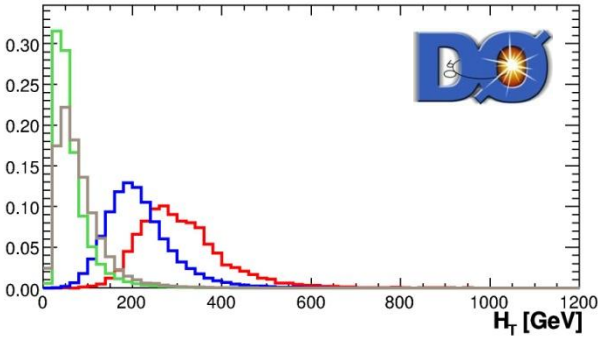
$\kappa/M^{Pl} > 0.16 @ 95\% CL$

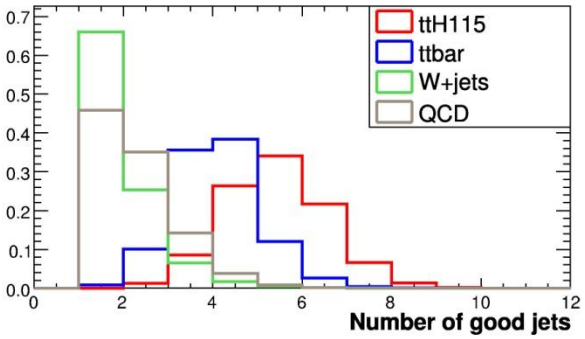
$m_{Z'} > 760\ GeV\ @\ 95\%\ CL$

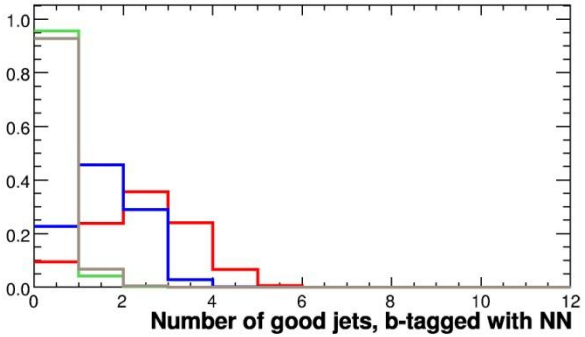


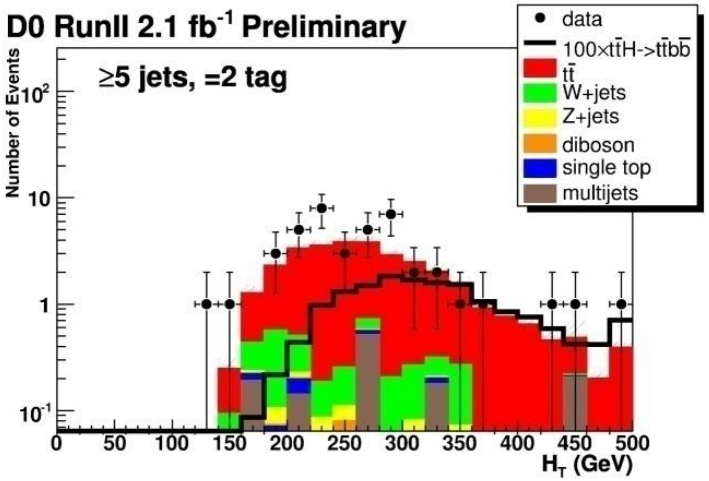
M(tt) sensitive to a broad class of NP models, e.g. peak-dip structure (MSSM), narrow resonances (Z' boson). No evidence for new physics.

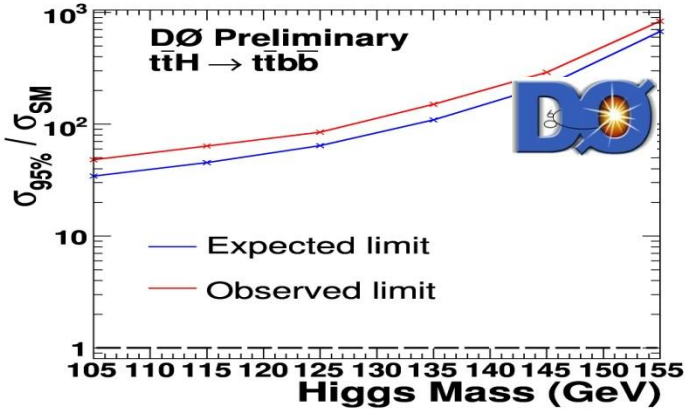
Search for New Physics – ttH(->bbar)





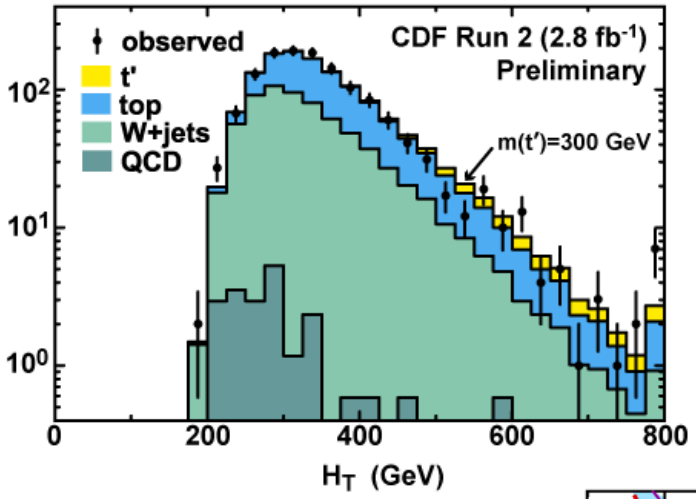


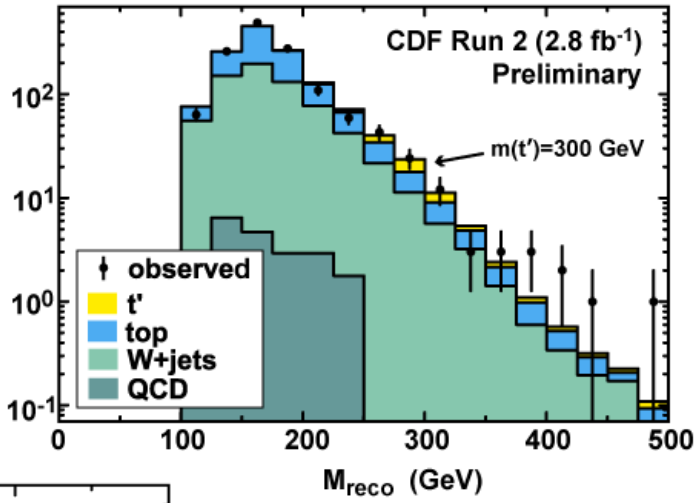




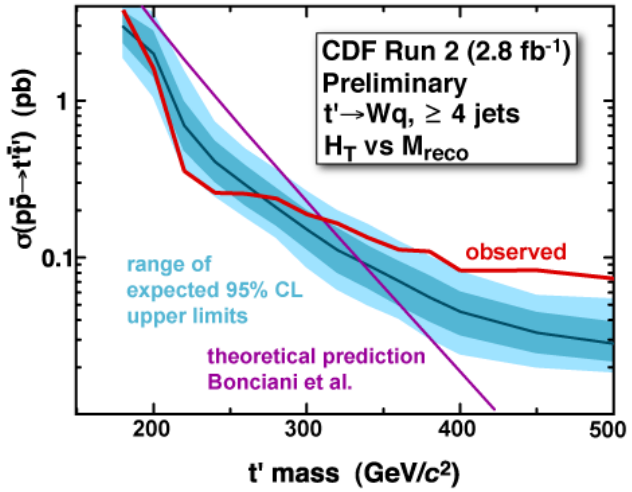
σ(ttH) < 64× SM value
for M_{Higgs} = 115 GeV

Search for New Physics – t'





Assuming t' pair-produced strongly mass larger than top decay promptly to Wq



$m_{t'} > 311 GeV @ 95\% CL$

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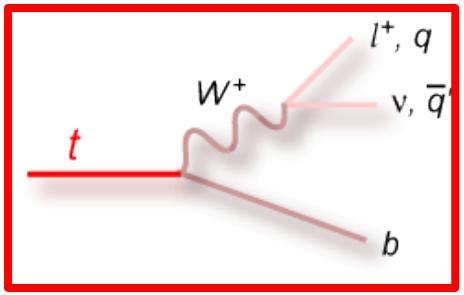
– charged Higgs search

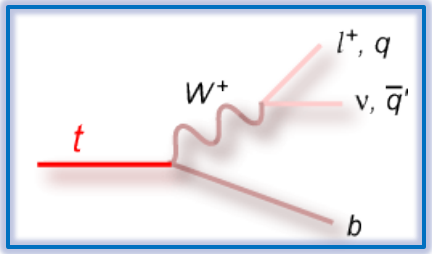
– W-helicity (anomalous coupling)



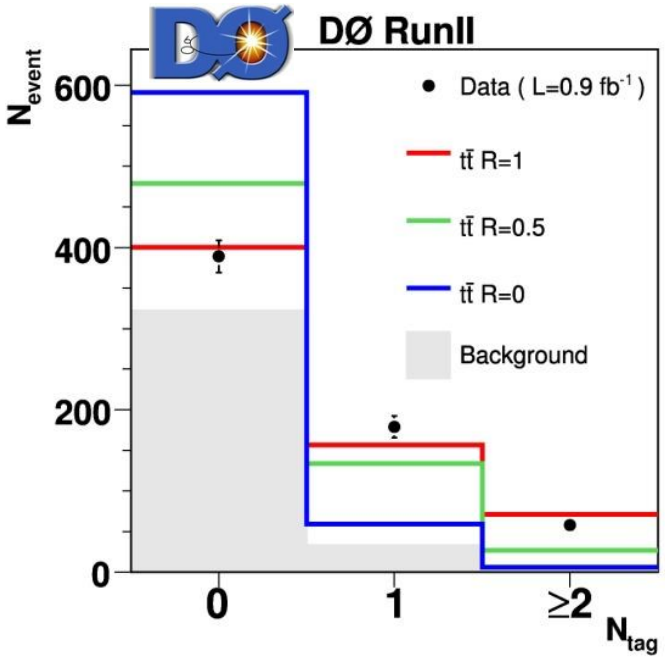
- Top mass

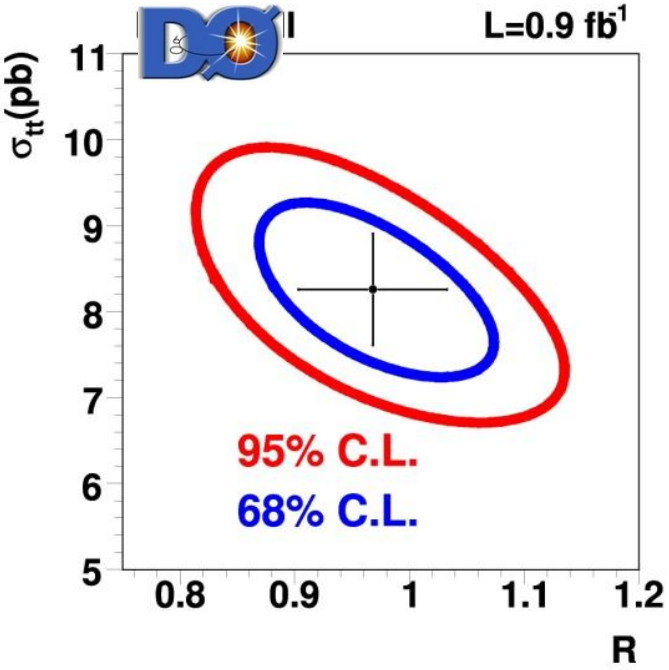
Top Decay - Branching Ratio

Decay



100% t→W+b in SM, deviations suggest NP





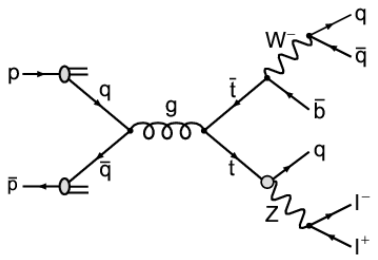
R = Br(t->Wb)/Br(t->Wq)
> 0.79 @95% C.L.

$|V_{tb}|$ > 0.89@95% C.L. (if 3x3 CKM is unitary)

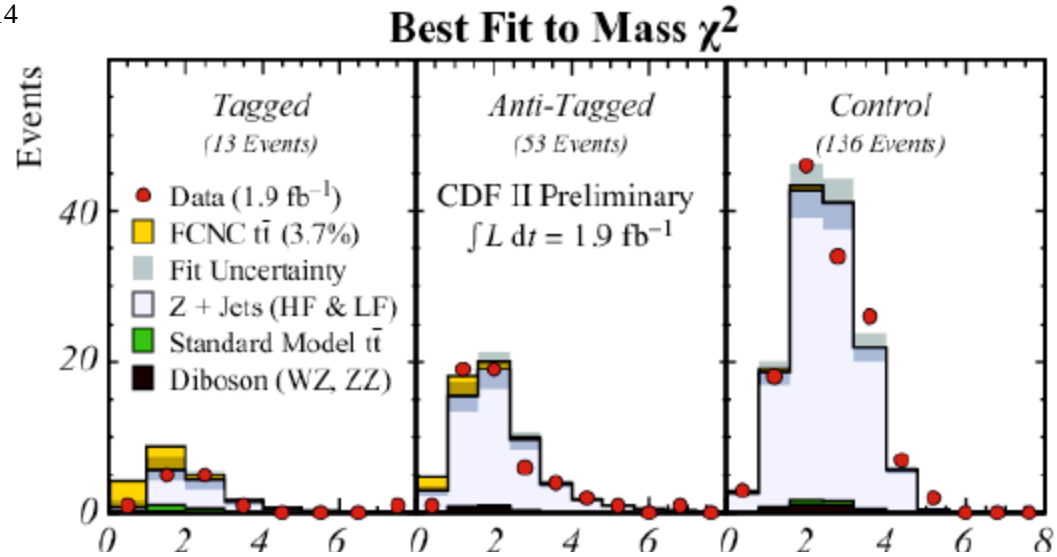
Top Decay – FCNC, Invisible Decay

SM FCNC branching ratio ~ 10^{-14}

Sensitive to NP



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



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

Invisible Decay Search:

Measure absolute rate of events with 2 btag-jets to determine Br(t->X). X is a state with different acceptance than Wb

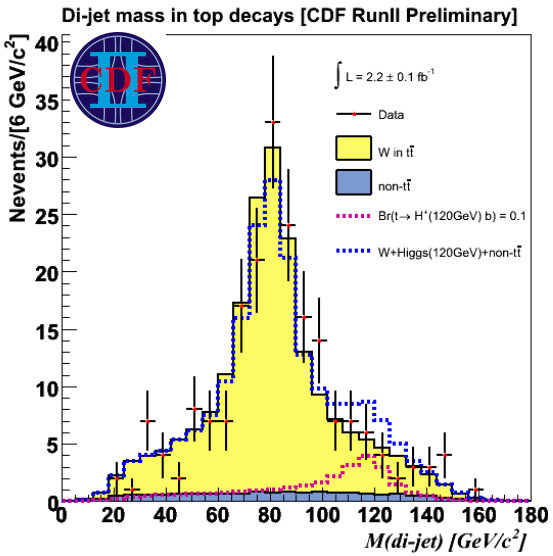
$B(t \to Zc) < 13\%$

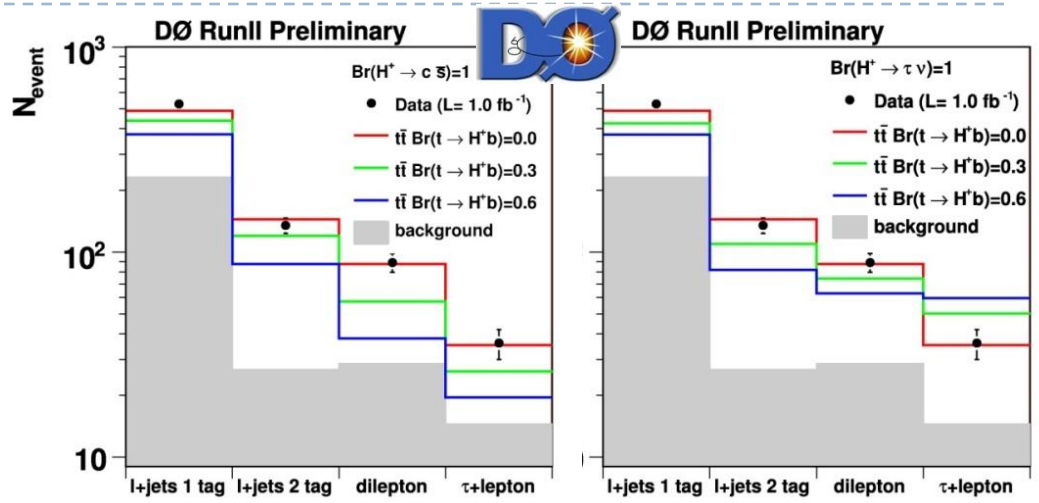
$B(t \to \text{invisible}) < 9\%$

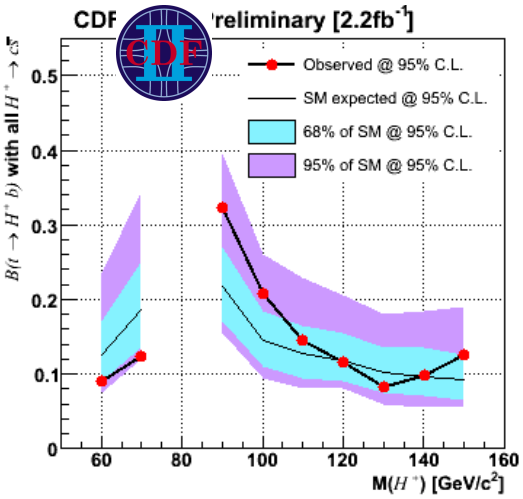
CDF Run II Preliminary 1.9 fb^{-1}

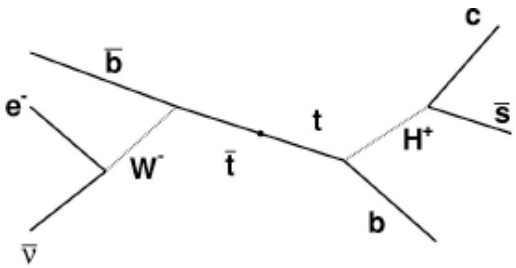
Decay	$\mathcal{R}_{wx/ww}$ (%)	Upper Limit (%) (175 GeV)	Upper Limit (%) (172.5 GeV)	Upper Limit (%) (170 GeV)
$\mathcal{B}(t \to Zc)$	32	13	15	18
$\mathcal{B}(t \to gc)$	27	12	14	17
$\mathcal{B}(t \to \gamma c)$	18	11	12	15
$\mathcal{B}(t \to \text{invisible})$	0	9	10	12

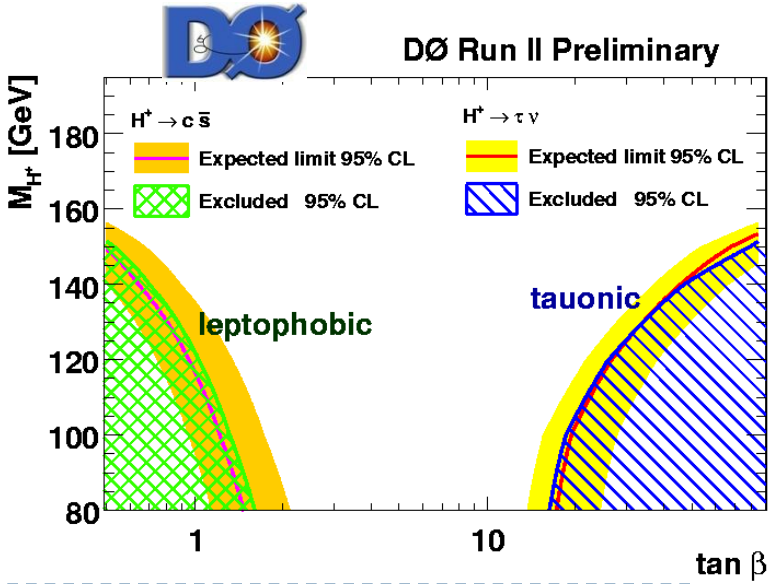
Top Decay – H+ (mH+<mt) Search



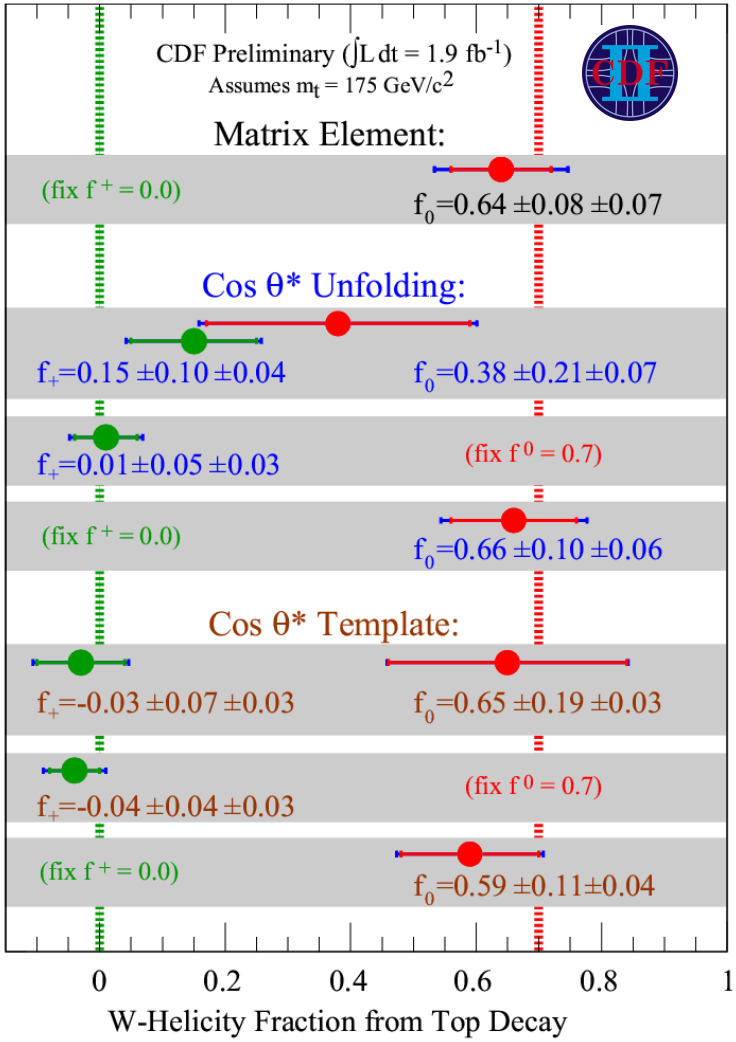




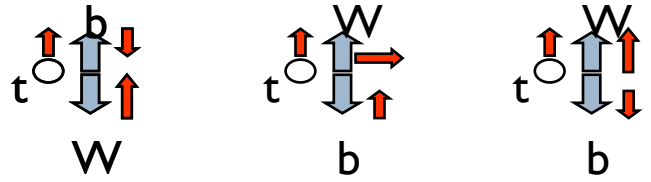




Top Decay - W-Helicity

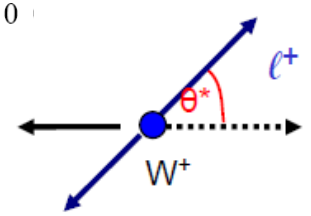


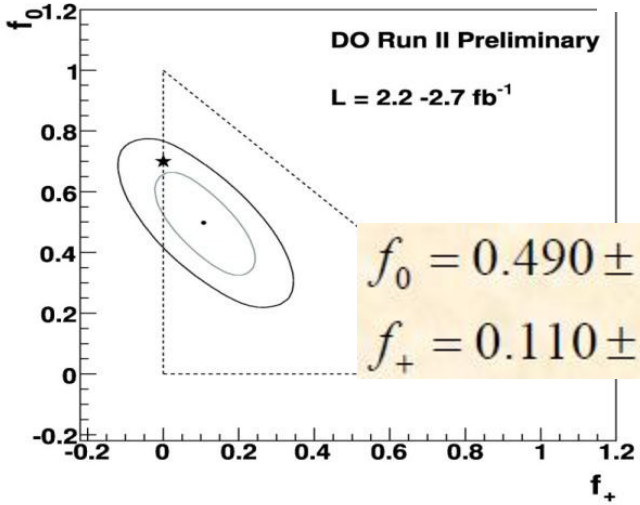
W helicity in top quark decays



$$F_- \approx \frac{2M_W^2}{m_t^2 + 2M_W^2} = 0.30 \qquad F_0 \approx \frac{m_t^2}{m_t^2 + 2M_W^2} = 0.70 \qquad F_+ = 0$$

- Reconstruct helicity angle of lepton in top quark pair event

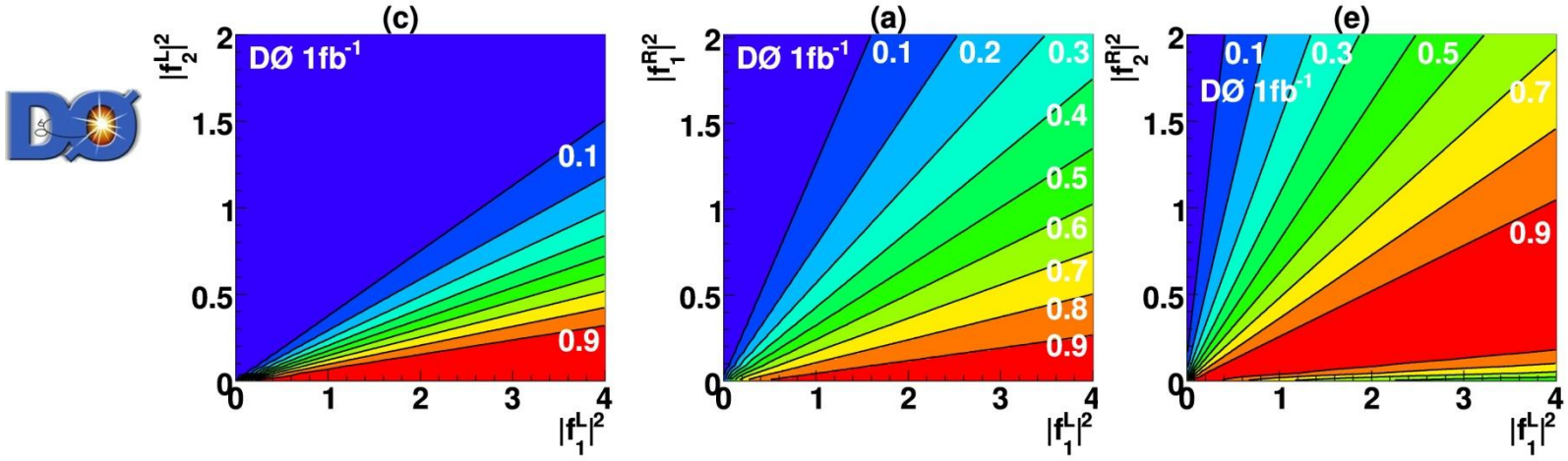




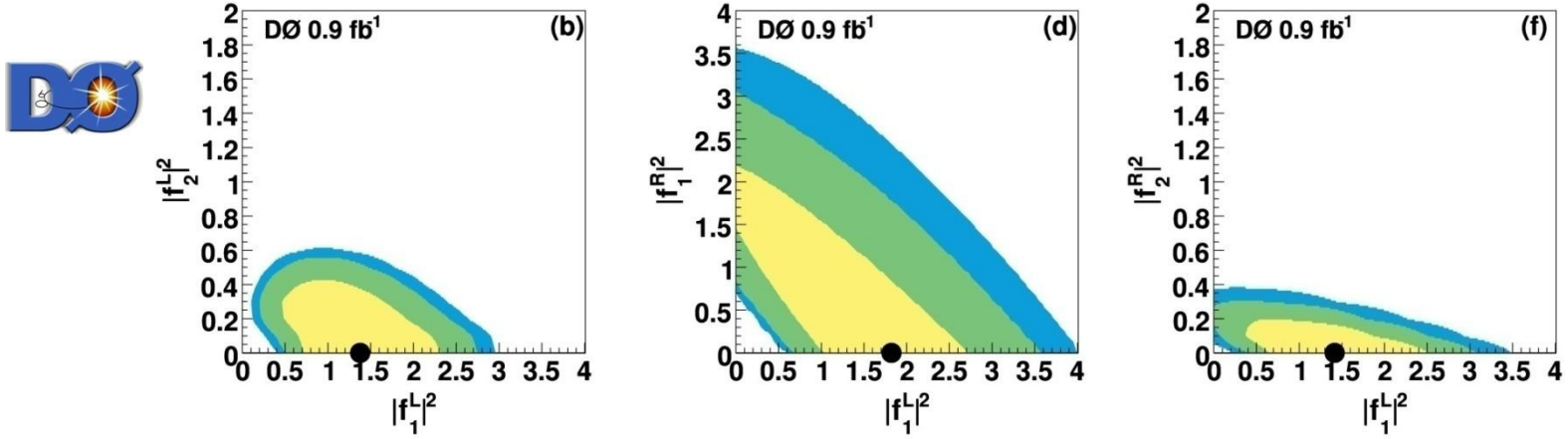
$$f_0 = 0.490 \pm 0.106 \pm 0.085$$
$$f_+ = 0.110 \pm 0.059 \pm 0.052$$

Constraints on Anomalous Couplings

Constraint from W-helicity

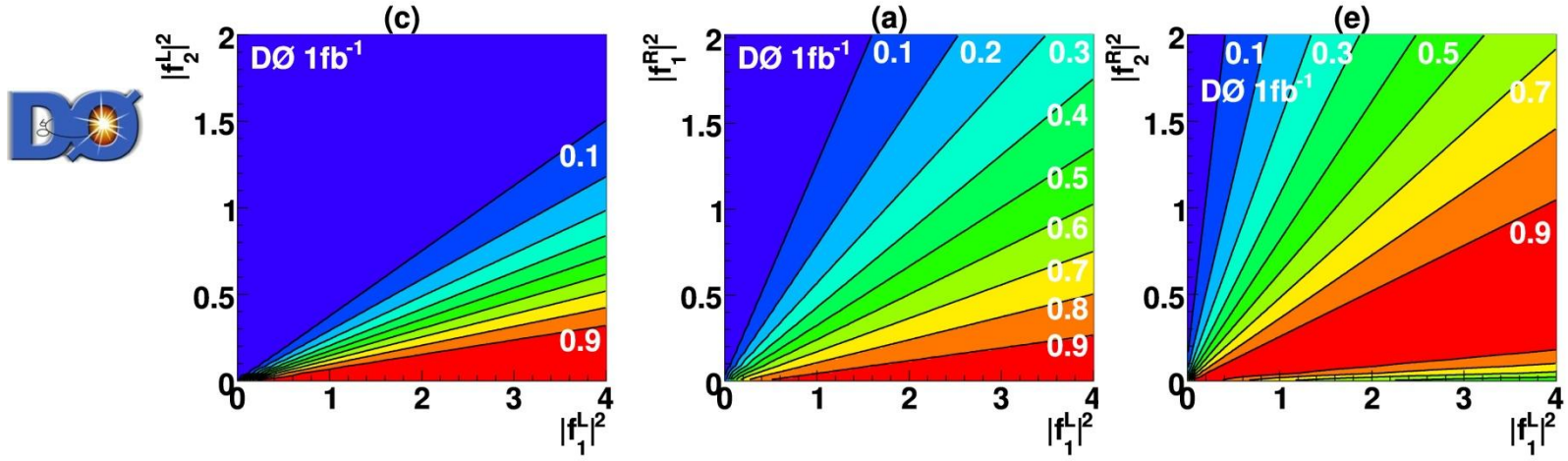


Constraint from single top

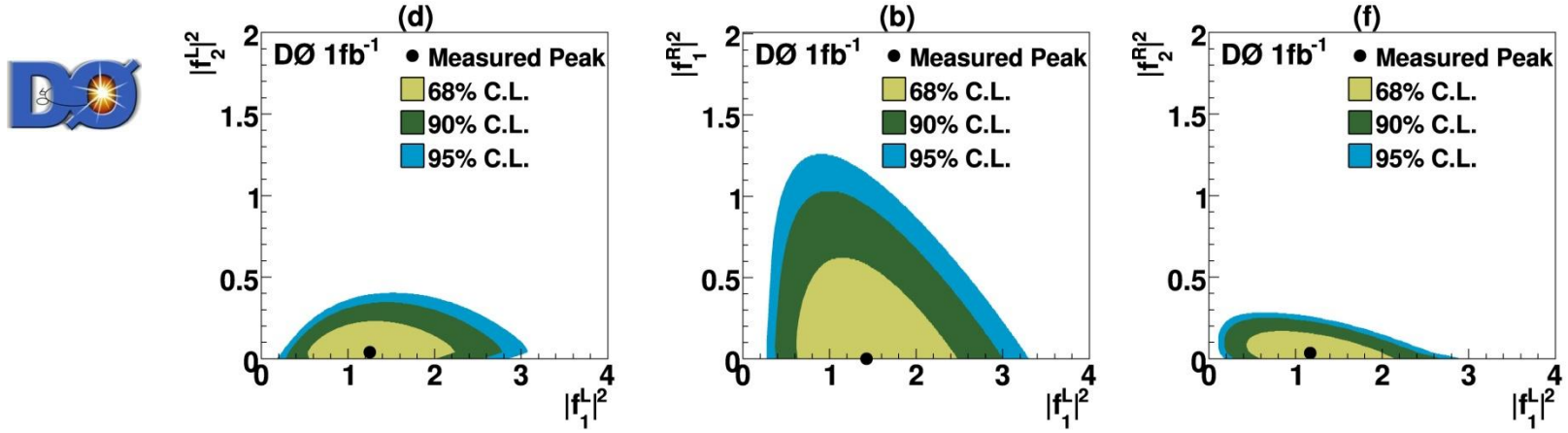


Constraints on Anomalous Couplings

Constraint from W-helicity



Combined with the constraint from single top



Selected Results

- Single top production

– search, cross section (|Vtb|, anomalous coupling)

- Top pair production

– cross section, M(ttbar) differential cross section/spectrum

– search for new physics (ttH, t')

- Top decay

– branching ratio, FCNC, rare decay

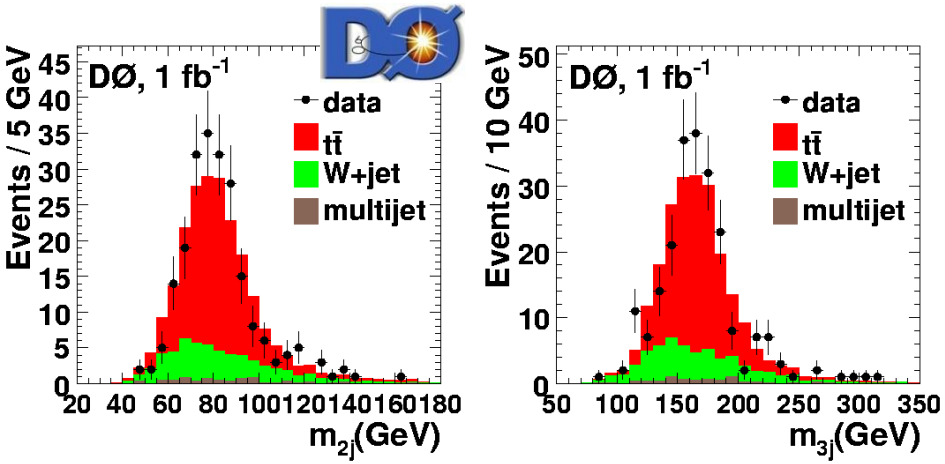
– charged Higgs search

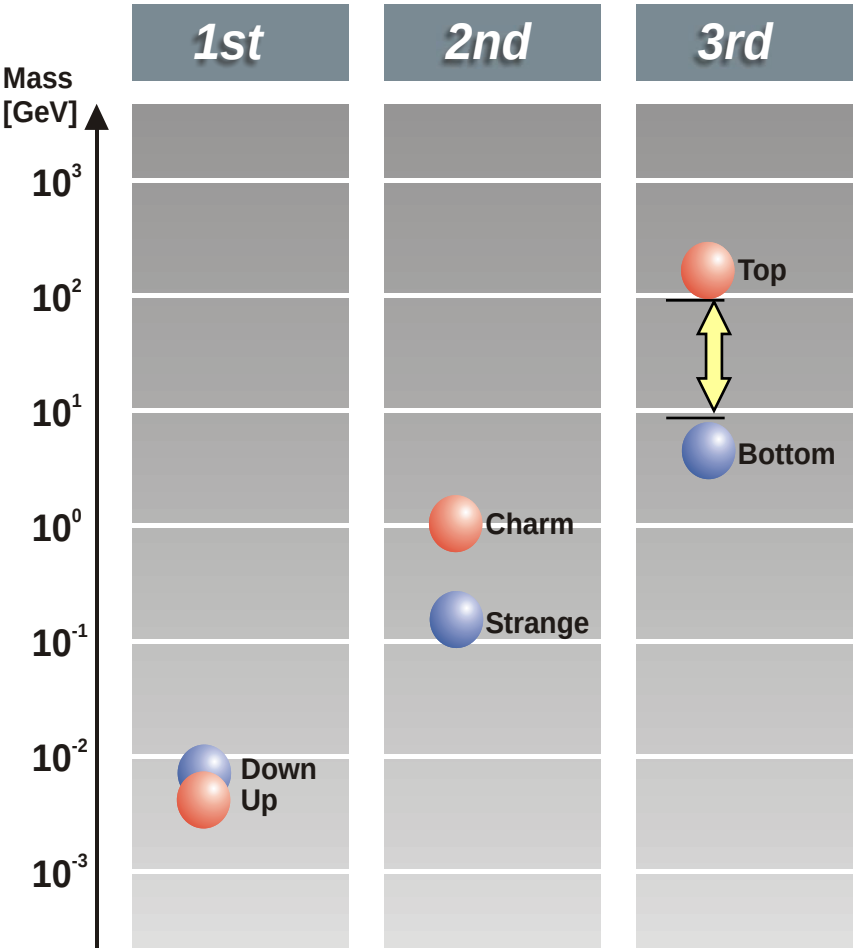
– W-helicity (anomalous coupling)

- Top mass

Top Quark Mass

- Fundamental parameter of the SM
- Important ingredient for EW precision analyses
  ⇒ incisive consistency checks
  ⇒ constrain/rule out models
- Sophisticated techniques to minimize statistical and dominant systematic uncertainties (in-situ calibration of jet energy scale correction in l+jets channel through hadronic M_W).





Top Quark Mass - Matrix Element Method

– The M.E. method is based on the calculation of event probability densities which are taken to be the sum of all contributing (and assumed to be non-interfering) processes. For example, in the case of two major processes:

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

– Probabilities are taken to be the differential cross sections for the process in question. For example, the signal probability is given by:

$$P_{sig}(x;m_{top}) = \frac{d\sigma(x;m_{top})}{\sigma_{obs}(m_{top})}$$

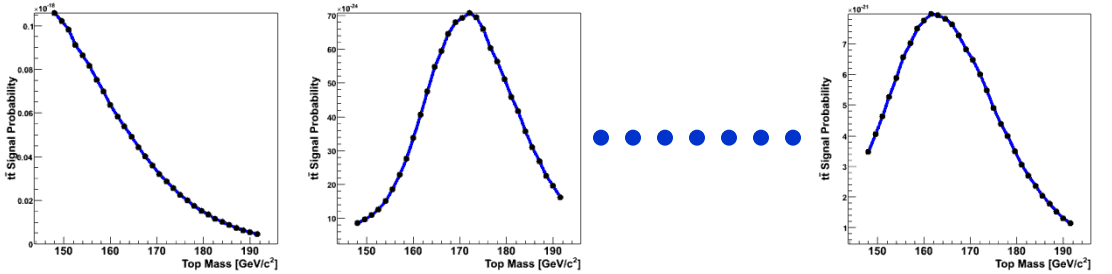
$$= \frac{1}{\sigma_{obs}(m_{top})} \times \int d\sigma(y) dq_1 dq_2 f(q_1) f(q_2) W(y,x)$$

where:

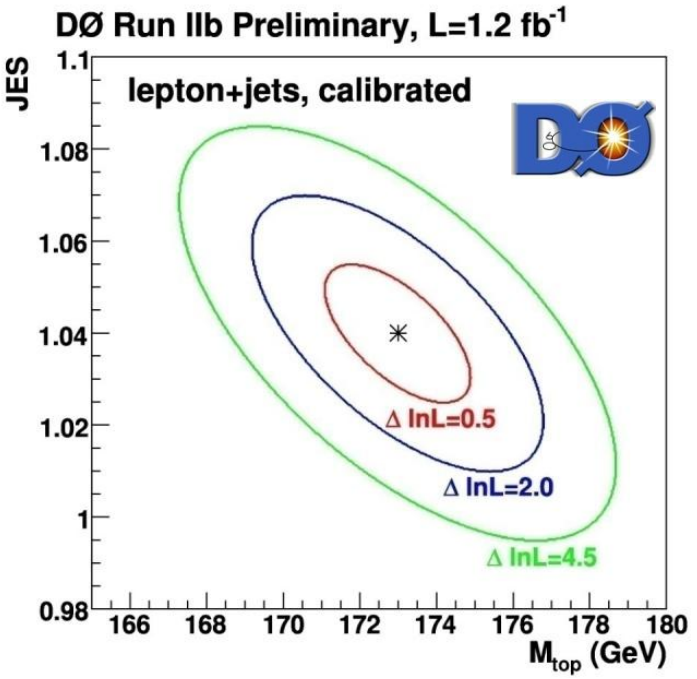
$$d\sigma = \frac{(2\pi)^4 |\mathbf{M}|^2}{4\sqrt{(q_1 \cdot q_2 - m_1 m_2}} d\Phi_6$$

Top Quark Mass - Matrix Element Method

Probabilities are calculated for each individual event as a function of m_{top} (and JES):

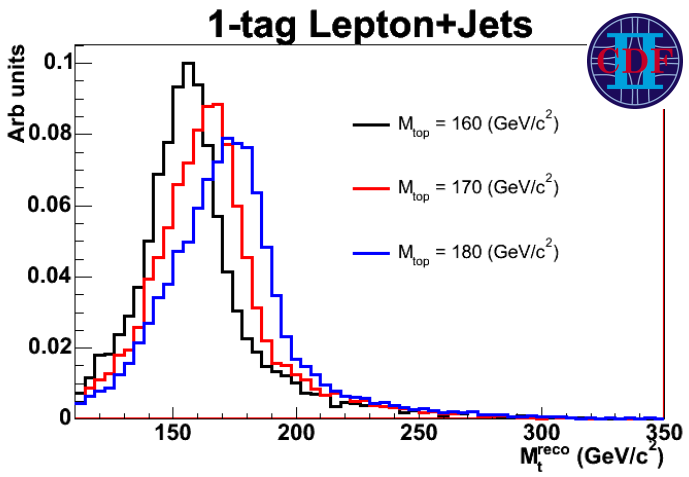


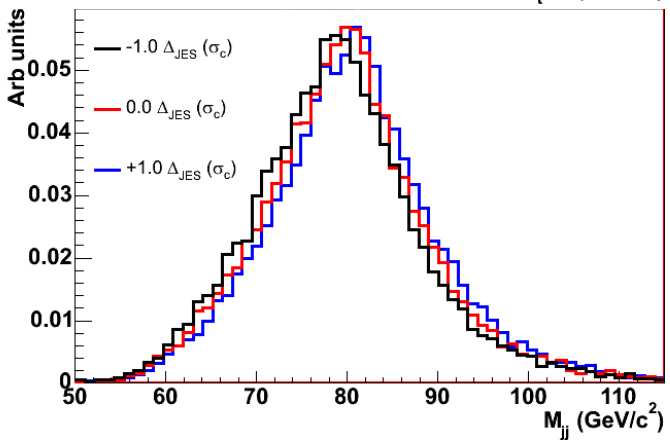
$$L\ (x_1 \ldots x_n ; m_{top}) = \prod_{i=1}^{n} P(x_i ; m_{top})$$

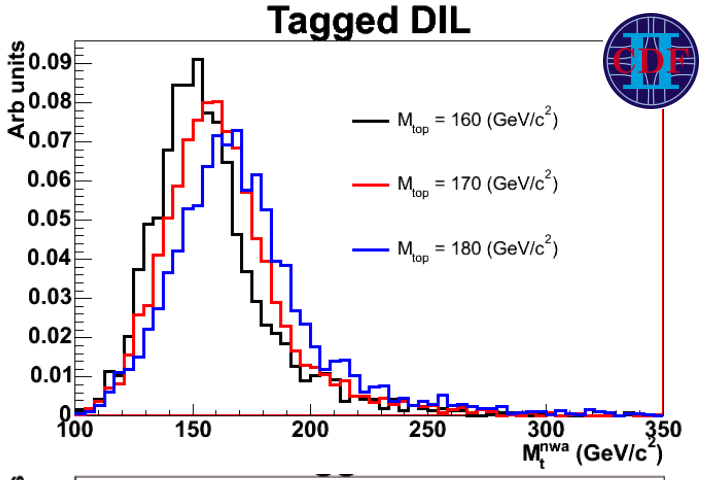


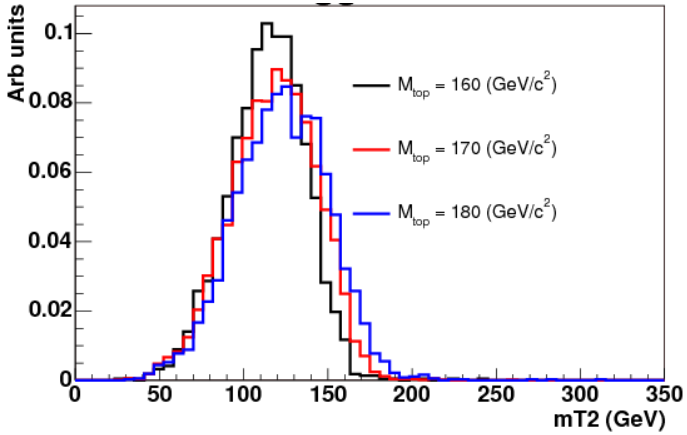
173.0±1.9(stat+JES) ±1.0(syst) GeV

Top Quark Mass – Template Method



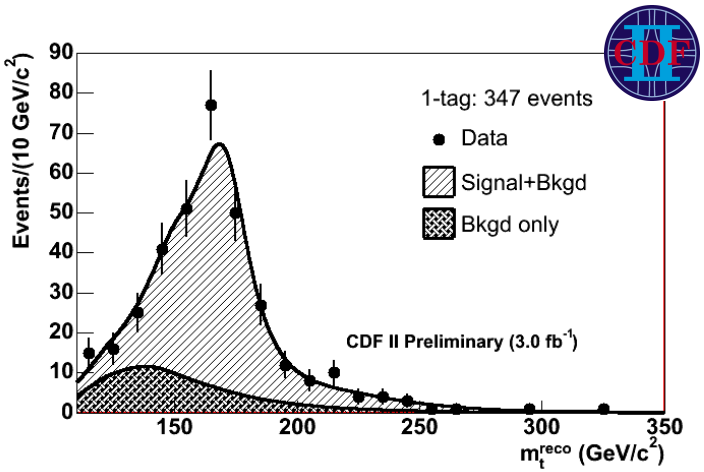


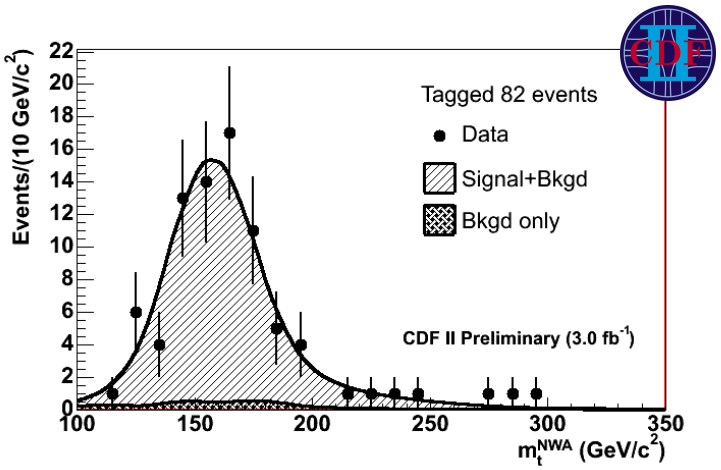


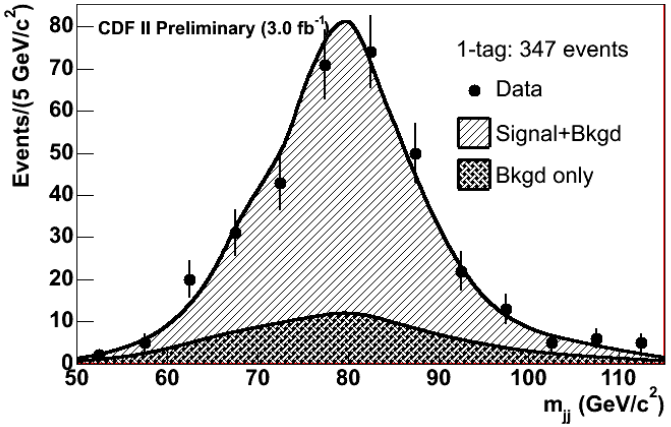


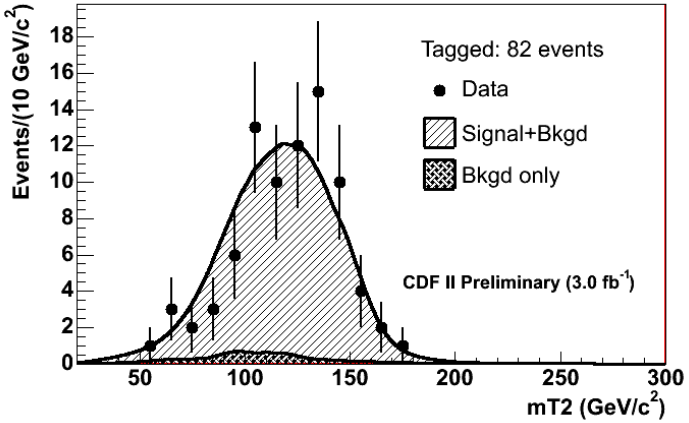
$$\mathcal{L}_k = \exp\left(-\frac{(n_b - n_b^0)^2}{2\sigma_{n_b}^2}\right) \times \prod_{i=1}^{N} \frac{n_s P_{sig}(m_i, y_i; M_{top}, \Delta_{JES}) + n_b P_{bg}(m_i, y_i)}{n_s + n_b}$$

Top Quark Mass – Template Method









172.5 ±1.6 (stat.+JES) ± 1.1 (syst) GeV/c^2

169.0 ±2.7 (stat.) ± 3.2 (syst) GeV/c^2

Combined: 171.8 ± 1.5 (stat.+JES) ± 1.1 (syst) GeV/c^2

Top Quark Mass – Direct Measurements

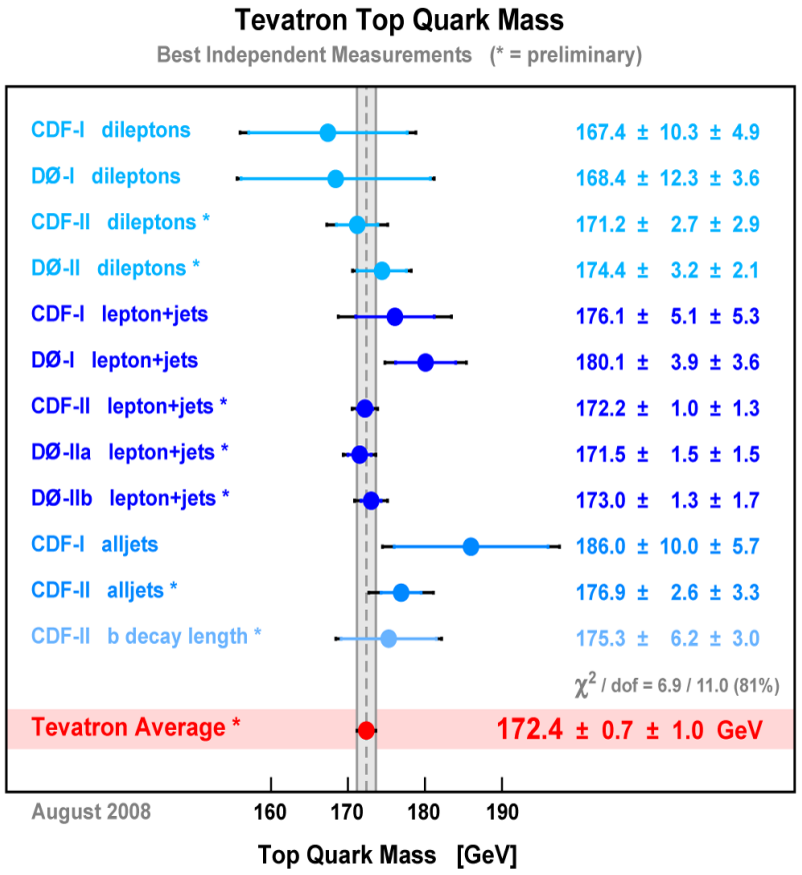
- Fundamental parameter of the SM
- Important ingredient for EW precision analyses
  $\Rightarrow$ incisive consistency checks
  $\Rightarrow$ constrain/rule out models

- Sophisticated techniques to minimize statistical and dominant systematic uncertainties.

- Current world-average (most sensitive channels use up to 2.7 fb^{-1}):

$$m_t = 172.4 \pm 0.7(stat) \pm 1.0(syst)\ GeV$$

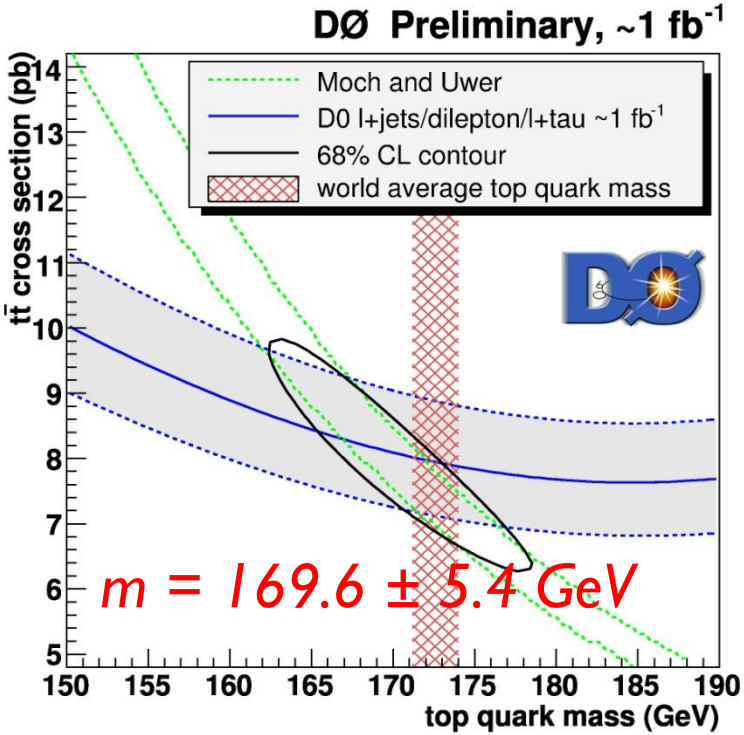
Measurements are limited by systematic uncertainties (signal modeling, b-jet response).



Top Quark Mass - From Cross Section

Assuming SM production, top mass can be extracted by comparing measured to calculated cross sections

- mass is measured in a well-defined renormalization scheme
- systematic largely uncorrelated with other methods



Summary

- A broad and exciting Top physics program on-going at the Tevatron.
- Many new results, consistent with SM.
  - More results at

    http://www-cdf.fnal.gov/physics/new/top/top.html

    http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html
- Keep trying to improve sensitivity and precision.