Top Properties and Cross-section

Daniel Wicke
(Bergische Universität Wuppertal)
for the CDF and DØ collaborations

Outline

- Introduction
- Cross-section
- Properties

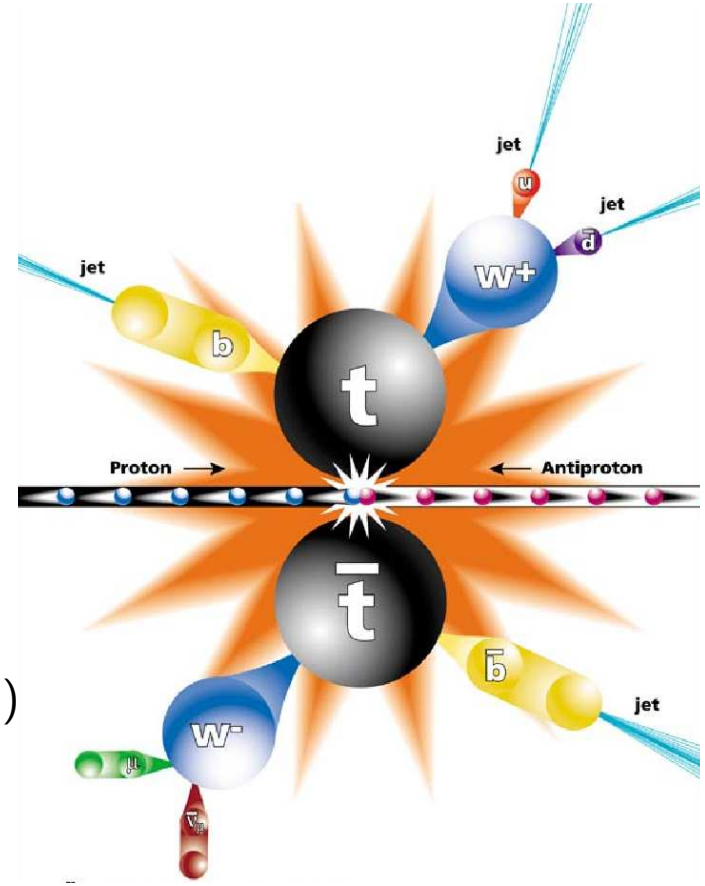
Introduction

The Top Quark

- Discovered by CDF and DØ in 1995.

- Completes set of quarks in SM.
- Quantum numbers as for up-type quarks.
- Production and decay properties fully determined within SM.

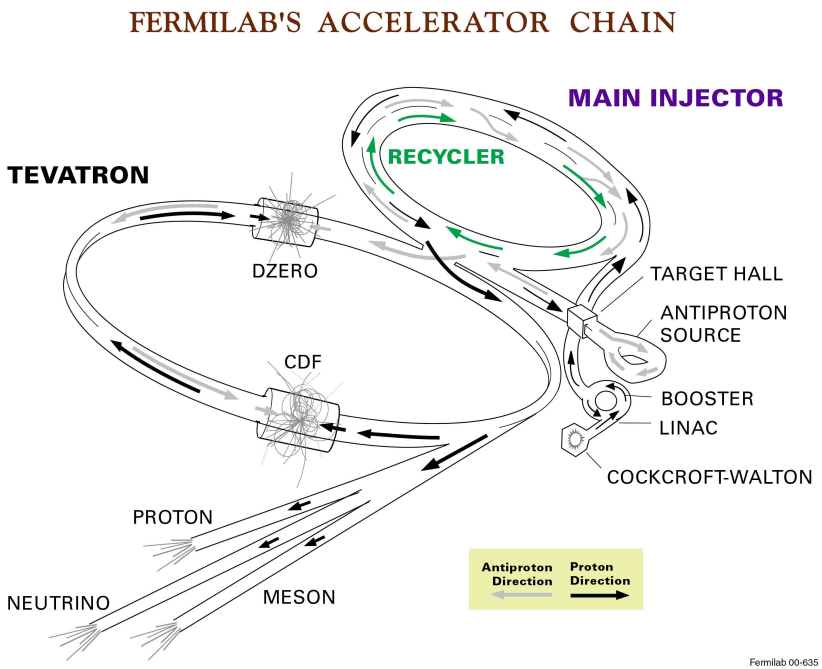
- Mass is the only free parameter (see L. Brigliadori)



Proving these properties establishes the SM top quark;
Disproving them yields new phyiscs

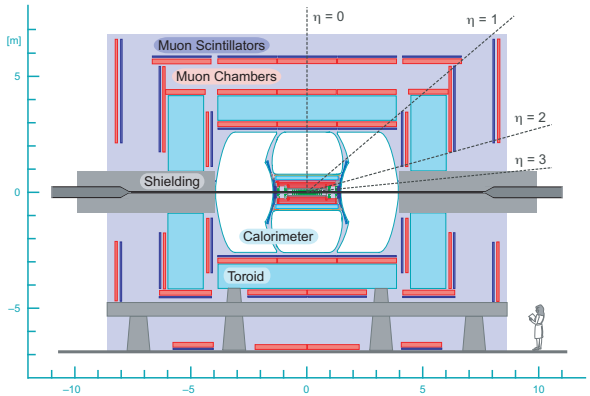
The $p\bar{p}$ Accelerator Tevatron

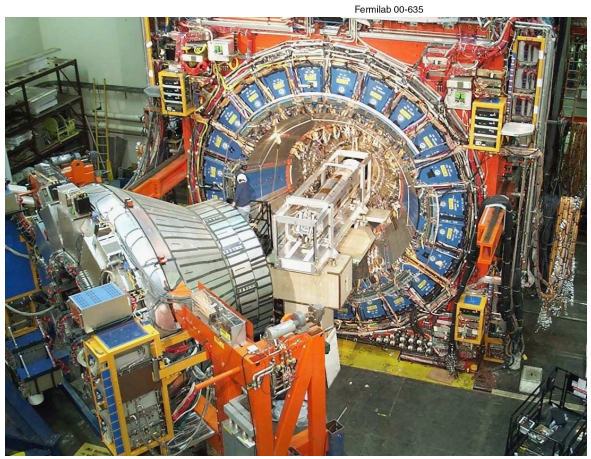
- Circumfence 7 km.
- $p\bar{p}$ collisions
- Run I (1987-1995)
- Run II (since 2001)
  Collision energy $2\,\text{TeV}$



- 2 experiments,
  CDF and DØ,
  record events.

$\mathcal{L} > 5\,\text{fb}^{-1}$ on tape.
Today: upto $\sim 3\,\text{fb}^{-1}$

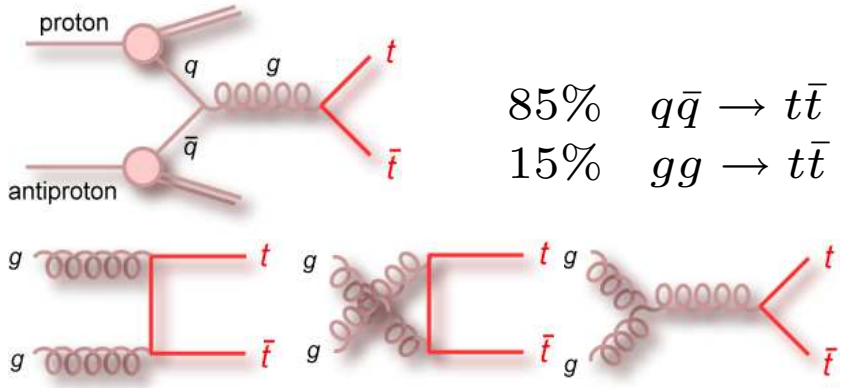




Standard Model Top Production & Decay Channels

Strong production mechanism.

Electroweak production (single top) covered by G. Otero



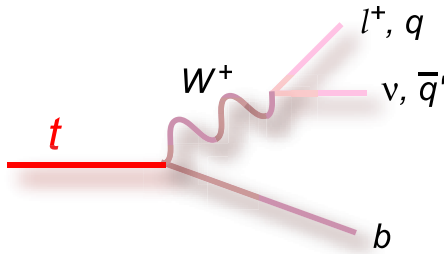
85% $q\bar{q} \to t\bar{t}$

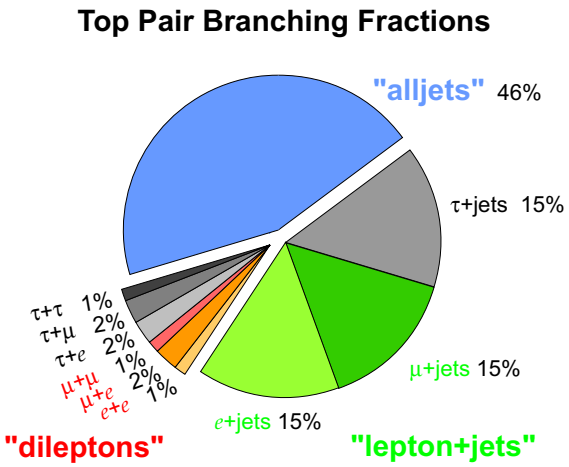
15% $gg \to t\bar{t}$

- Top quarks produced in pairs
- In SM top quark decays to bW ($\sim 100\%$).
- Decay modes are defined by W-decays:
  - Dilepton $(2b + 2\ell + 2\nu)$
  - Lepton+jets $(2b + 2q + \ell\nu)$
  - Alljets $(2b + 4q)$

  Taus always treated separately, often $\ell = e, \mu$

  Cleanest channel: Dilepton.
  Golden channel: Lepton+jets.



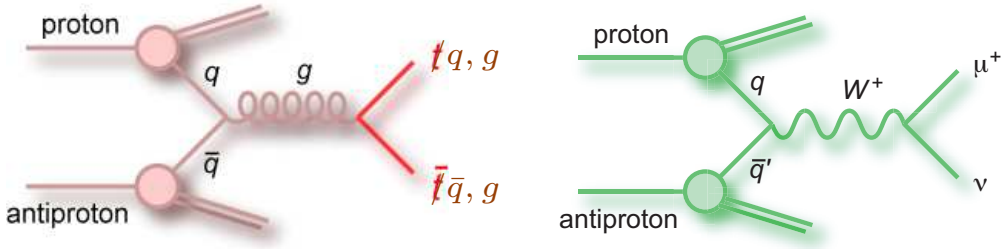


Can these be verified? Does it show expected properties?

Top Pair Production Cross-section

Dominant backgrounds

Same signature / jets faking ℓ or $\not{E}_T$

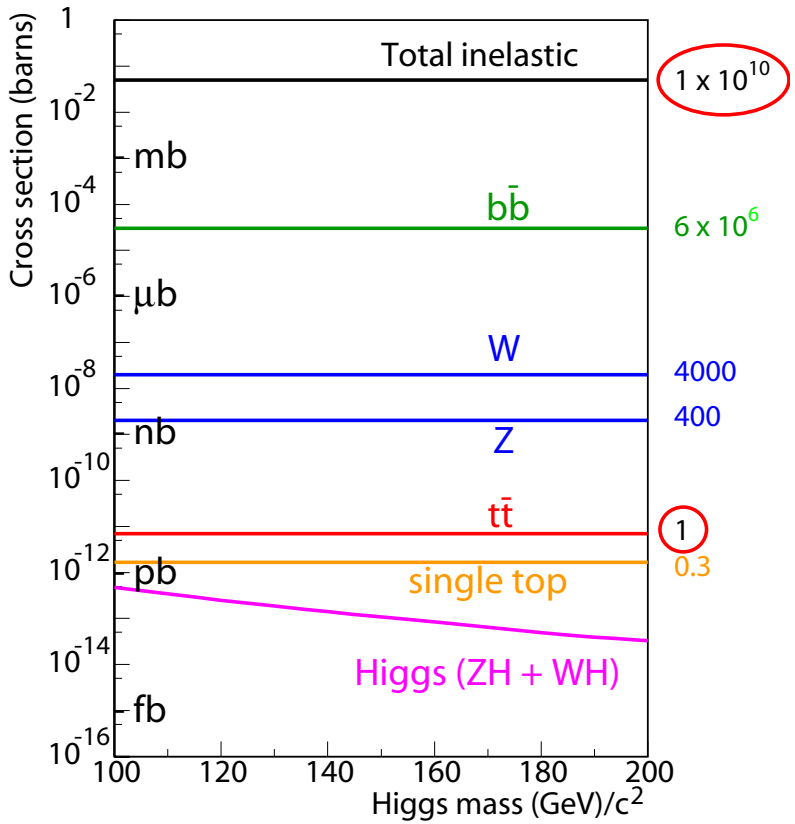


- Multijet events
  ($q\bar{q}$ or gg + gluon radiation)
- W+jets
- Z+jets

the "+jets" helps suppression.

Simulation of multijet events
and of fake rates difficult/unprecise

$\Rightarrow$ Estimation from data.

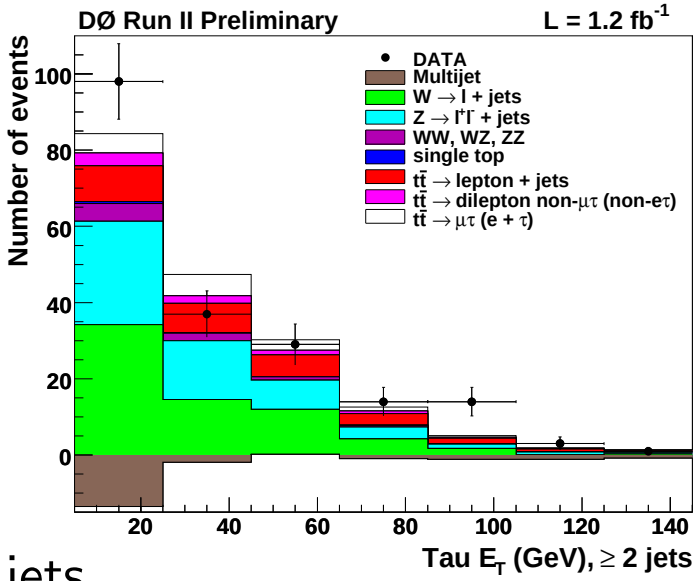


Tau plus other Lepton Channel (DØ: $2.2\,\mathrm{fb}^{-1}$)

- Identify hadronic tau with neural networks

  a) $\tau \longrightarrow \pi^{\pm} + \nu_{\tau}$
  b) $\tau \longrightarrow \pi^{\pm} + n\pi^{0} + \nu_{\tau}$
  c) $\tau \longrightarrow 3\pi^{\pm} + n\pi^{0} + \nu_{\tau}$

- Based on track quantities, calorimeter energies and shower shapes



Further require isolated e or μ, $\not{E}_T$ and at least 2 jets

- W+jets background from data before b-tagging
- Multijet background from same sign leptons before b-tagging
- From sample with opposite sign leptons and ≥ 1 b-tagged jets:

$$\sigma_{t\bar{t}} = 7.32^{+1.34}_{-1.24\ (\mathrm{stat})}{}^{+1.20}_{-1.06\ (\mathrm{syst})} \pm 0.45_{(\mathrm{lumi})}\,\mathrm{pb}$$

Dominant systematics: Background / MC statistics

Top Cross-section over Z Cross-section (CDF: $2.7/2.8\,\mathrm{fb}^{-1}$)

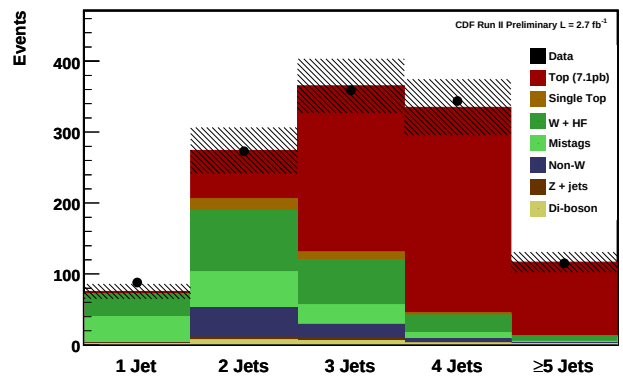
In ℓ+jets channel luminosity uncertainty dominating $\Rightarrow$ measure ratios.

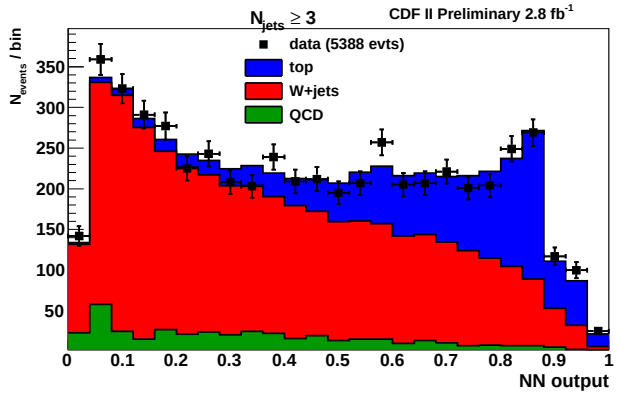
Top Pair

Isolated e or μ, $\not\!\!E_T$ and ≥ 3 jets

a) with identified b-jet:
Backgrounds from data before tagging

b) with topological neural net:
Backgrounds from fit to neural net shapes





Z Boson

- Dilepton events with $66\,\mathrm{GeV} < m_{\ell\ell} < 116\,\mathrm{GeV}$

Results

Use theory $Z \to \ell\ell$ cross-section

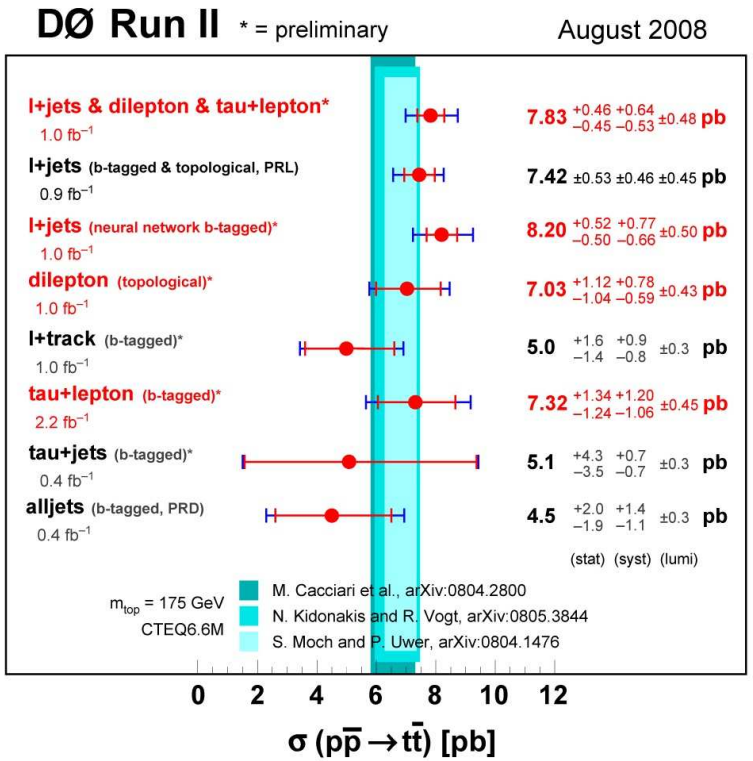
a) $\sigma_{Z\to\ell\ell}/\sigma_{t\bar{t}} = 35.7 \pm 3.8 \quad \Rightarrow \quad \sigma_{t\bar{t}} = 7.0 \pm 0.4_{(\mathrm{stat})} \pm 0.6_{(\mathrm{syst})} \pm 0.1_{(\mathrm{theory})}\,\mathrm{pb}$

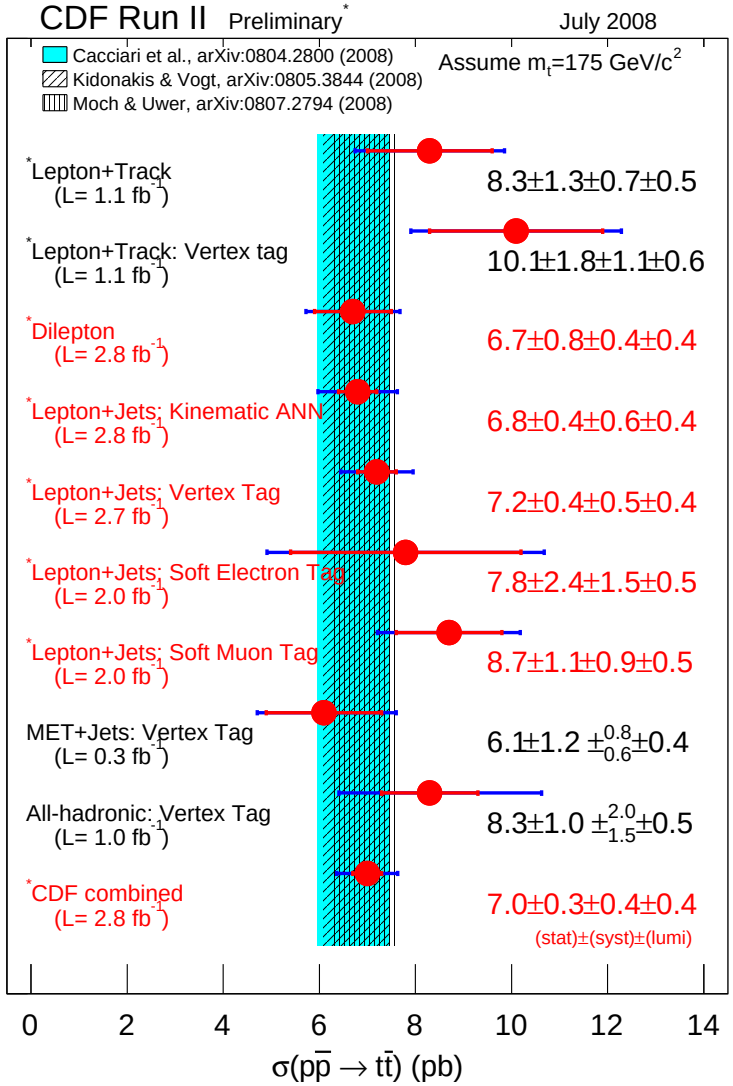
b) $\sigma_{Z\to\ell\ell}/\sigma_{t\bar{t}} = 36.5 \pm 2.9 \quad \Rightarrow \quad \sigma_{t\bar{t}} = 6.9 \pm 0.4_{(\mathrm{stat})} \pm 0.4_{(\mathrm{syst})} \pm 0.14_{(\mathrm{theory})}\,\mathrm{pb}$

No luminosity uncertainty; 8% total uncertainty

Overview of Cross-section Results

- Efficiencies depend on top mass
- Results given for $m_t = 175\,\text{GeV}$
- Good agreement between channels

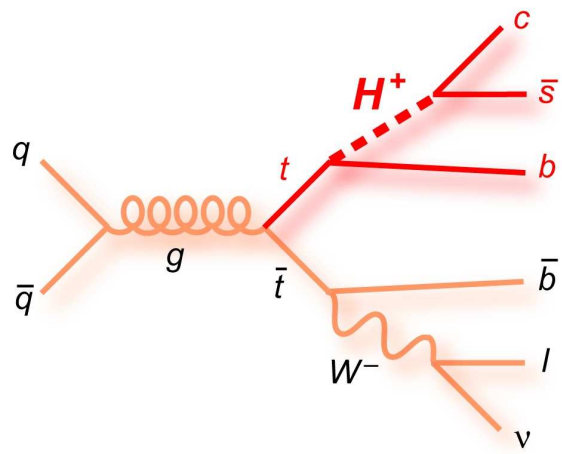




Non-standard decay mode

New particles in the final state alter deduced $\sigma_{t\bar{t}}$ depending on decay channel

$\mathrm{Ch} = \ell$+jets, Dilepton, τ+lepton

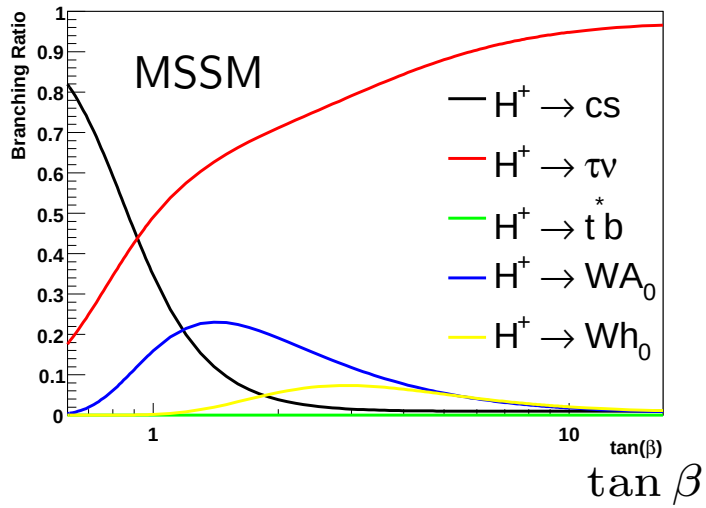


$$\sigma_{t\bar{t}}^{\mathrm{Ch}} = \sigma_{t\bar{t}} \cdot \frac{B^{\mathrm{BSM}}(t\bar{t} \to \mathrm{Ch})}{B^{\mathrm{SM}}(t\bar{t} \to \mathrm{Ch})}$$

- Check cross-section ratios

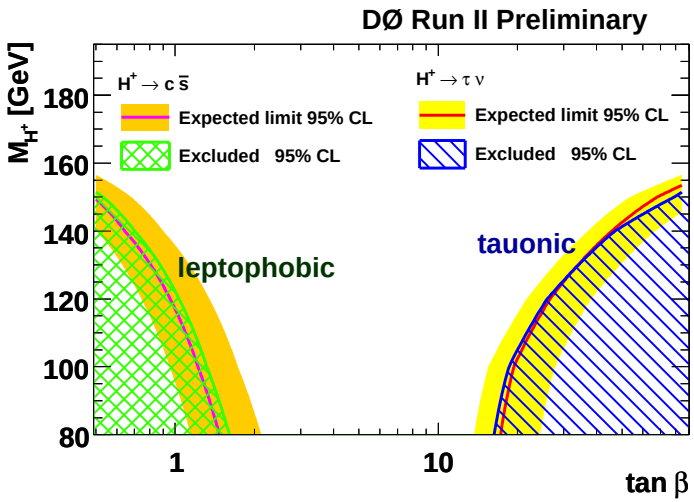
$$\sigma_{t\bar{t}}^{\ell+\mathrm{jets}} / \sigma_{t\bar{t}}^{\mathrm{Dilepton}} / \sigma_{t\bar{t}}^{\tau+\ell}$$

Within MSSM $H^{\pm} \to cs$ or $\tau\nu$ dominating depending on $\tan\beta$ and charged Higgs mass



Limits on Charged Higgs

DØ: From cross-section ratios ($1\,\mathrm{fb}^{-1}$)

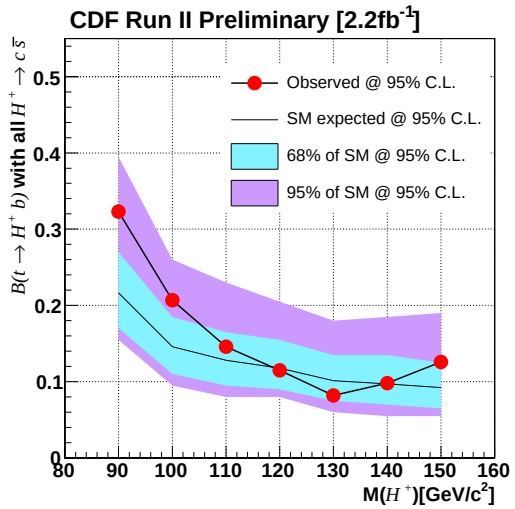


- Combine number of events in ℓ+jets, dilepton and τ+lepton (lepton=e, μ)
- Correlations of systematics taken into account.
- Limits $\sigma_{t\bar{t}}\mathcal{B}(t \to H^+)$ for leptophobic and tauonic decay and in MSSM plane ↑

CDF: Using kinematic differences ($2.2\,\mathrm{fb}^{-1}$)

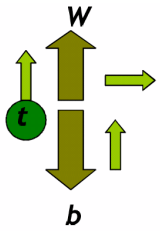
ℓ+jets events

- Compare dijet mass distribution to templates
- Here: assuming leptophobic decay: $H^\pm \to cs$
- Sensitivity improved at high $m_H^\pm$; reduced near m_W

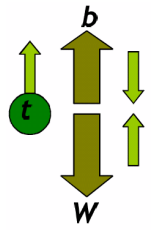


W-Helicity in Top Decays

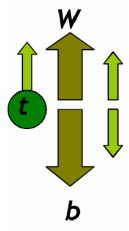
Does the top decay show the expected spin structure?
SM: only lefthanded particles couple to Ws ($V-A$ coupling),
W is lefthanded or longitudinal.



Longitudinal W
SM: $f_0 = 70\%$



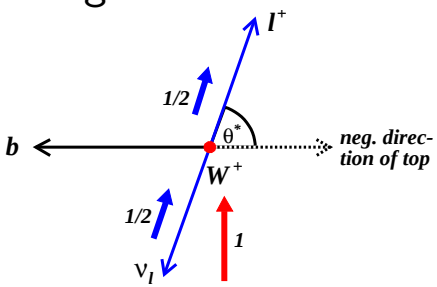
Left-handed W
SM: $f_- = 30\%$



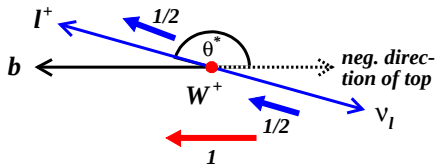
Right-handed W
SM: suppressed ($f_+ \simeq 0$)

In W-restframe lepton from W stays (preferably)

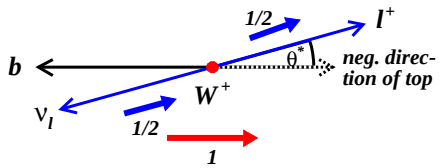
orthogonal to b



along b-direction

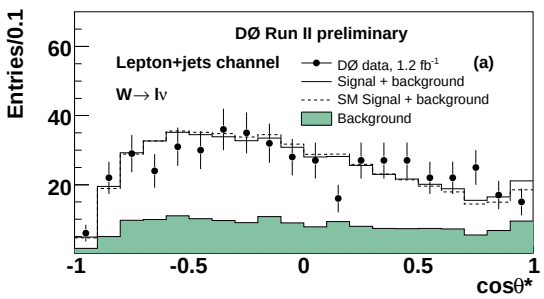


opposite to b-direction

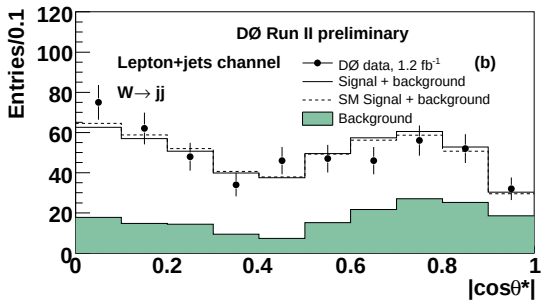


One possible observable: decay angle between b and ℓ; $\cos\theta^*$

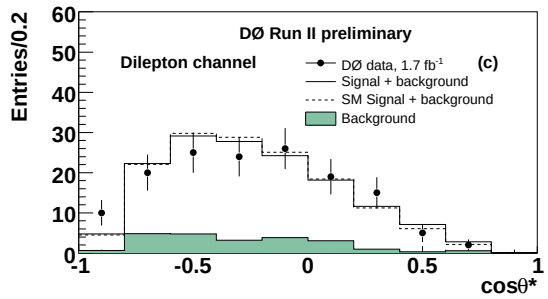
Results from decay angle $\cos\theta^*$ (CDF & DØ: $1.9 - 2.7\,\text{fb}^{-1}$)



ℓ+jets from $\ell\nu$

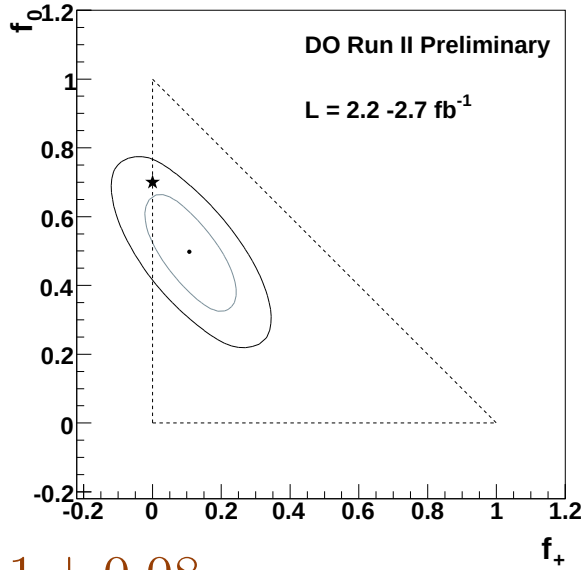


ℓ+jets from qq'



dilepton

- CDF uses ℓ+jets; DØ uses ℓ+jets and dilepton
- Compare to templates for left, right handed and longitudinal polarisation
- Fit polarisation fractions: f_0, f_+



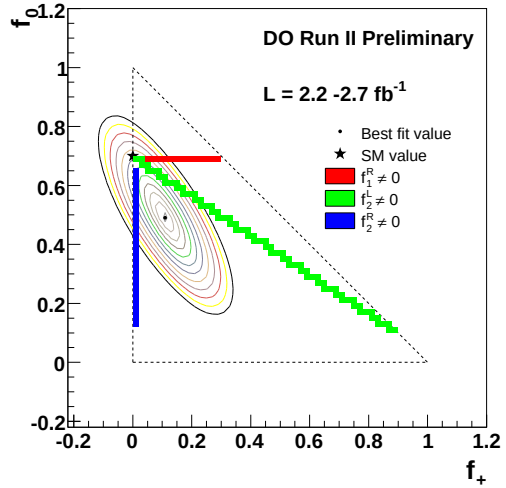
D0 $(2.2 - 2.7\,\text{fb}^{-1})$: $f_0 = 0.49 \pm 0.14$ and $f_+ = +0.11 \pm 0.08$

CDF $(1.9\,\text{fb}^{-1})$: $f_0 = 0.66 \pm 0.16$ and $f_+ = -0.03 \pm 0.07$

SM: $f_0 = 0.7$ $f_+ \simeq 0$

Anomalous Couplings

- Wtb vertex may have left/right vector, $f_1^{L/R}$, and tensor, $f_2^{L/R}$, couplings
- Combine information from Single Top and W Helicity
- Two couplings at a time (others assumed small)



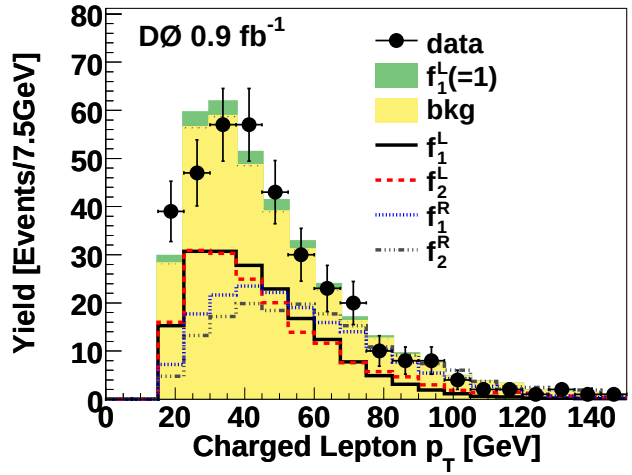
W Helicity

- from above

Single Top Sample (DØ)

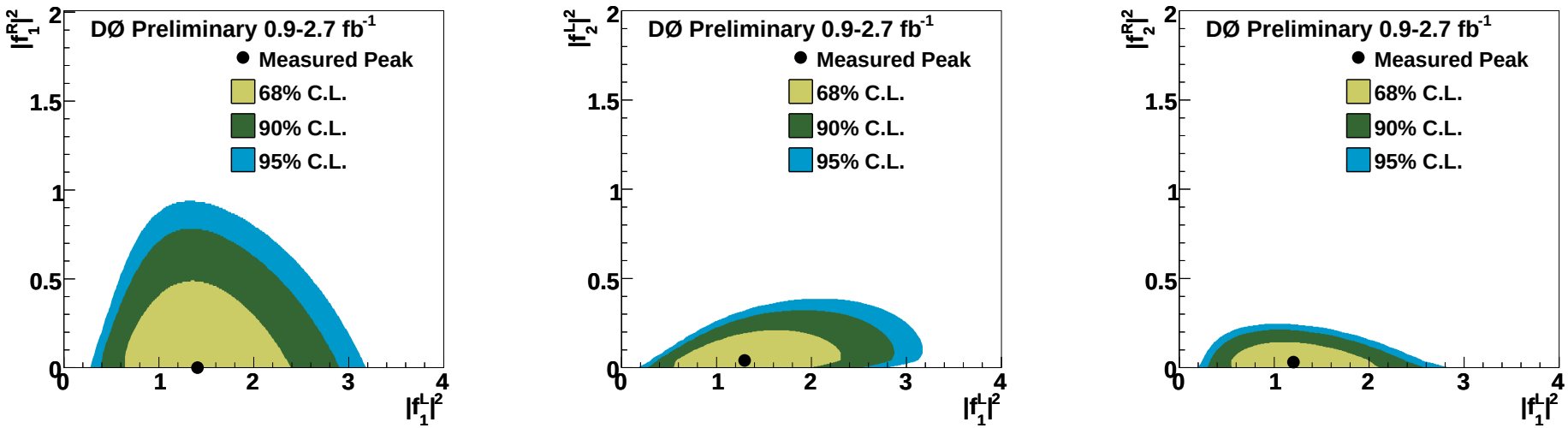
Based on $0.9\,\mathrm{fb}^{-1}$ DT (see G. Otero for details)

- Anomalous coup. change single top kinematics
- Example: p_T^ℓ for pure anomalous couplings:
- Boosted Decision Trees trained separately for three anomalous scenarios



Combined Anomalous Coupling Result (DØ: $0.9 - 2.7\,\mathrm{fb}^{-1}$)

- Inputs: Decision Tree output (Single Top) and $\cos\theta^*$ distributions (Top Pairs)
- Simultaneous comparison to templates for anomalous coupling scenarios
- Bayesian statistics is used to set combined limits



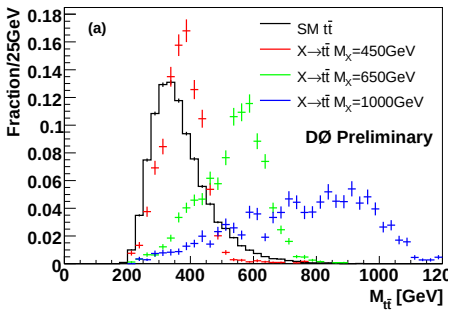
All in good agreement with SM expectation of $f_1^L = 1$ and others $= 0$

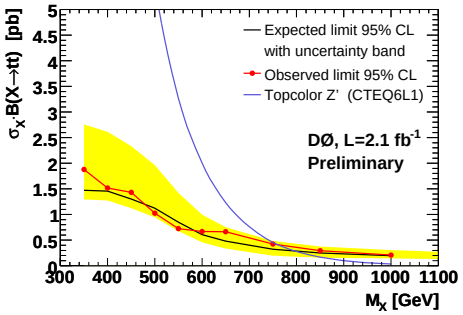
Resonant Top Pairproduction

No resonant top production in SM

Some models contain heavy resonances with decay to $t\bar{t}$

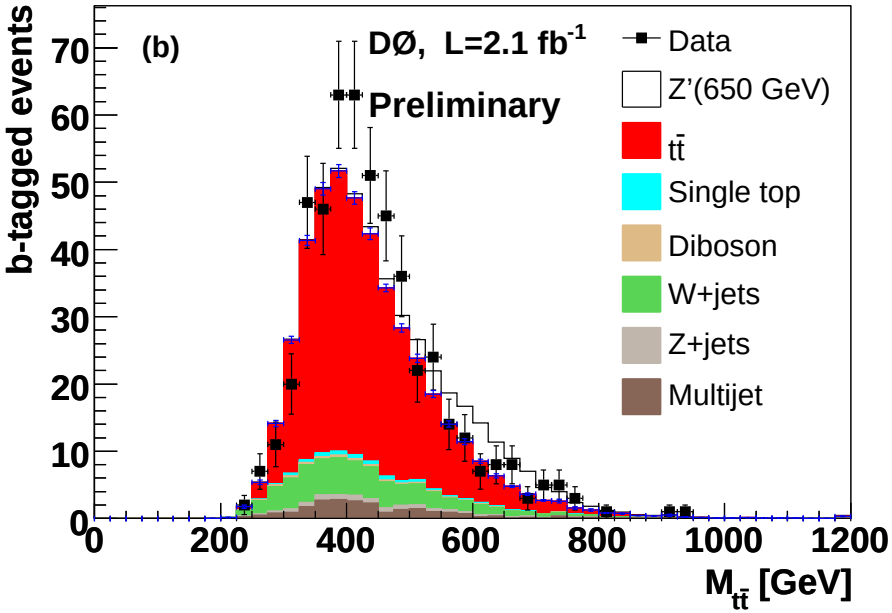
Visible in invariant mass $\frac{\mathrm{d}\sigma}{\mathrm{d}m_{t\bar{t}}}$





Search for narrow resonances

- DØ: $M_{t\bar{t}}$ from direct reconstruction
- No significant deviations.
- Limits on $\sigma_X \mathcal{B}(X \to t\bar{t})$.



E.g. topcolor-assisted technicolor:

DØ: $M_{Z'} > 760\,\mathrm{GeV}$ (expected 795 GeV)

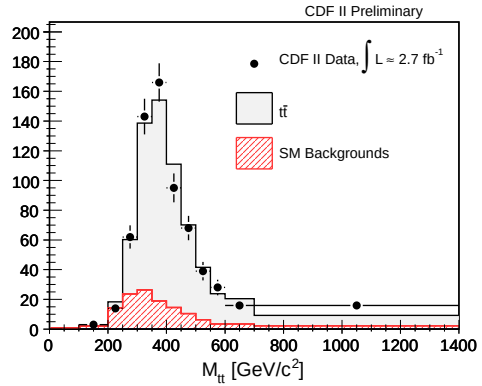
(DØ: $L = 2.1\,\mathrm{fb}^{-1}$; Last CDF: $M_{Z'} > 720\,\mathrm{GeV}$ from $0.9\,\mathrm{fb}^{-1}$)

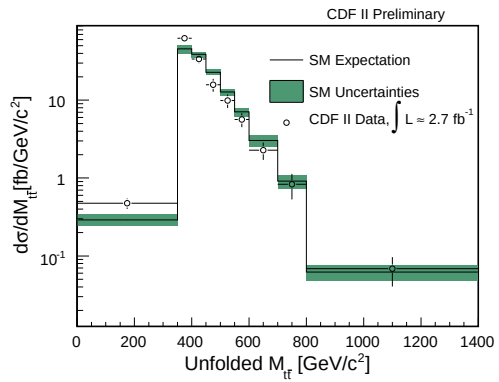
Unfolded Differential Cross-section (CDF: $2.7\,\mathrm{fb}^{-1}$)

Analysis flow

- $M_{t\bar{t}}$ from direct reconstruction
- Background subtracted
- Detector effects unfolded

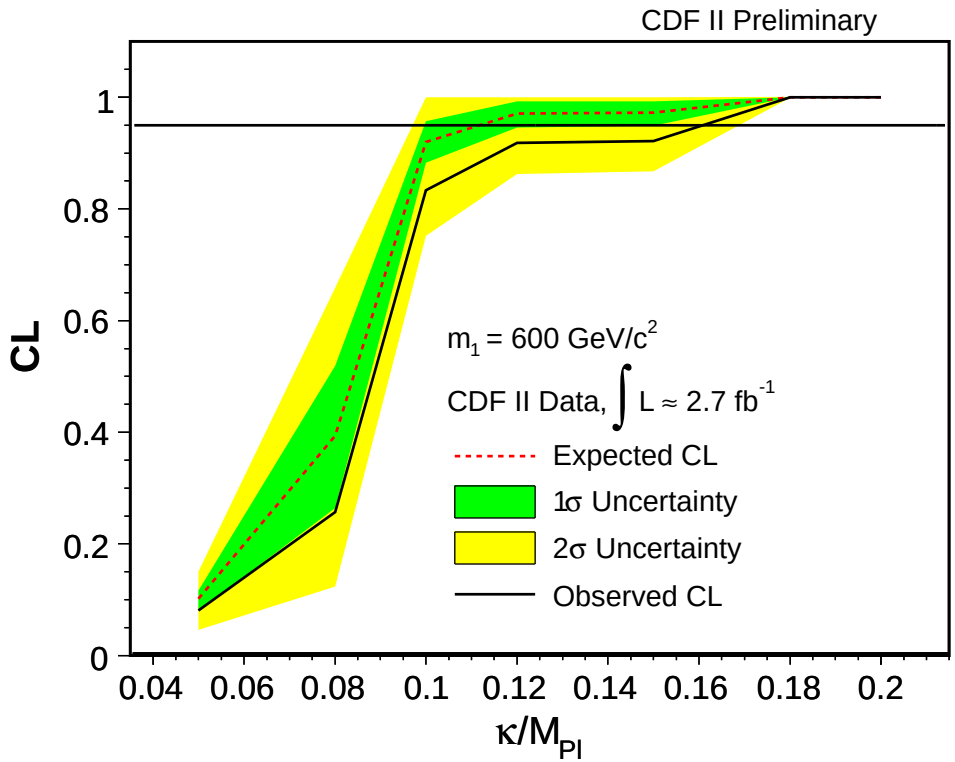
Good agreement with SM:
Only 28% of pseudo experiments show larger deviation





BSM results

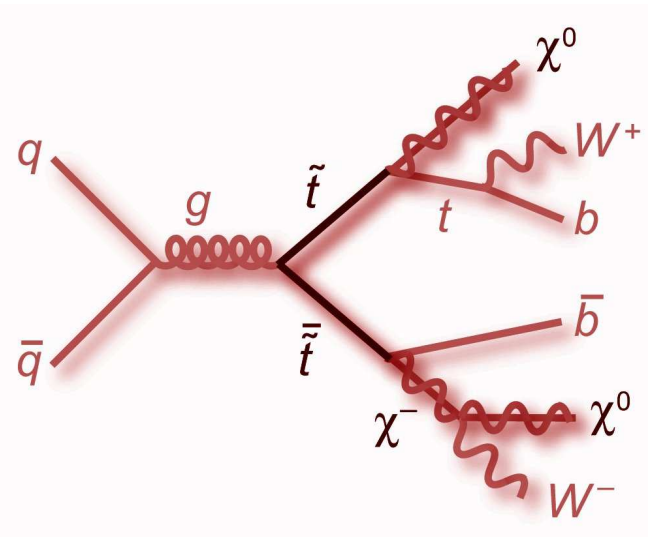
- Limits on Randall-Sundrum model
- $\kappa/M_{\mathrm{Pl}} > 0.16$ at 95%C.L. ($m_1 = 600\,\mathrm{GeV}$)

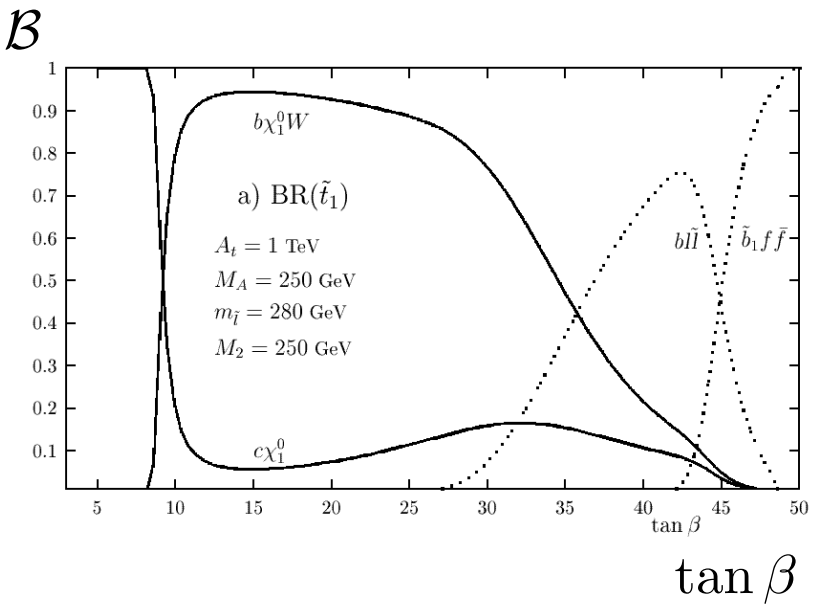


Stop Pair Production

Are we really looking at top quarks only?

- An admixture of particles with similar signature might have gone unnoticed
- Stop, $\tilde{t}$, is such a candidate
- Decays: $\tilde{t}_1 \to \tilde{\chi}_1^0 t \to \chi_1^0 bW$
  $\tilde{t}_1 \to \tilde{\chi}_1^+ b \to \chi_1^0 bW$
- Signature as top pair, but extra $\not{E}_T$
- Decays similar to top-quarks can dominate over a large range of $\tan\beta$



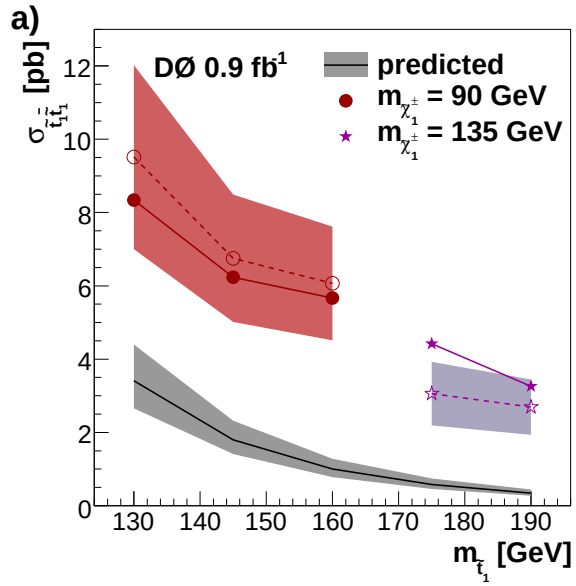


$\tan\beta$

DØ Results ($1\,\mathrm{fb}^{-1}$)

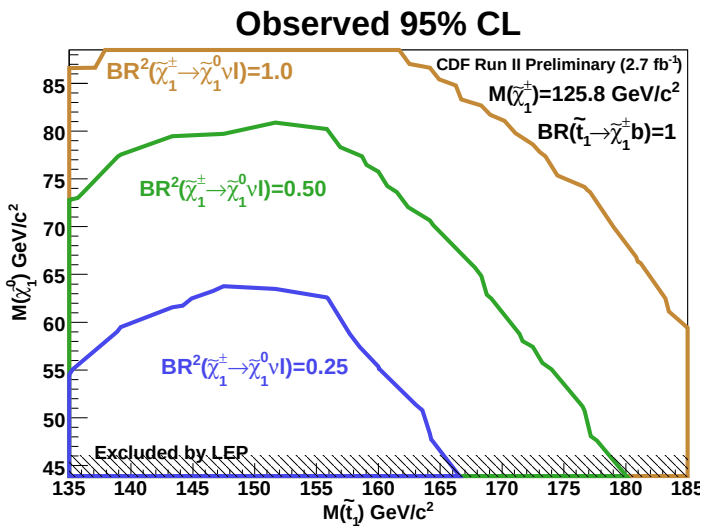
- ℓ+jets channel
- Distinguish stop from top:
  likelihood discriminant from simulation
- m_t from fit sensitive

Limits on cross-section for various $m_{\tilde{t}}$,$m_{\chi^\pm}$
MSSM prediction not reached, yet.



CDF Results ($2.7\,\mathrm{fb}^{-1}$)

- Dilepton channel
- Determine stop mass (à la ν weighting)
- Limits in stop vs. neutralino mass plane
  - very few assumptions.

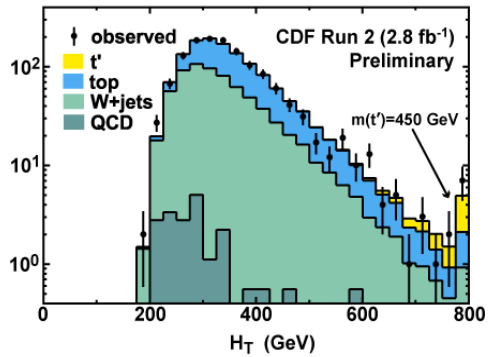


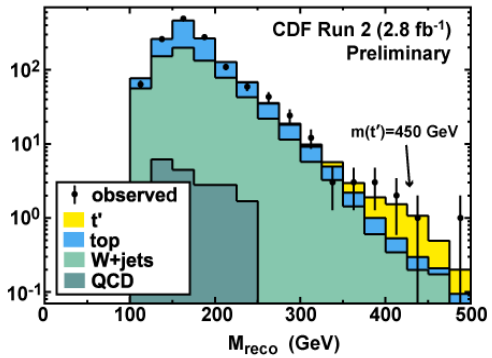
Fourth Generation u-type Quark: t' (CDF: $2.8\,\mathrm{fb}^{-1}$)

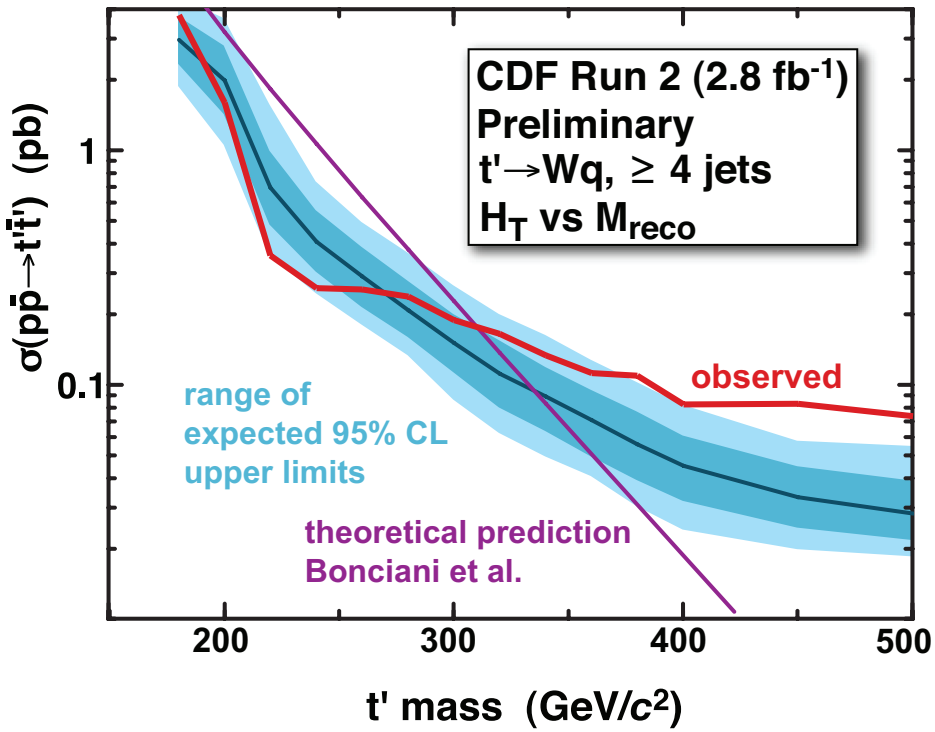
The 'top' samples could contain a fourth generation quark, t'

- ℓ+jets
- t' vs t separation:
  - Scalar sum of transverse momenta, H_T
  - $t^{(\prime)}$ mass from kin. fit.
- Observed cross-section limits fall behind expected ones for $m_{t'} > 300\,\mathrm{GeV}$

t' mass $> 311\,\mathrm{GeV}$ @ 95%C.L.







Summary

- Top cross-section and properties results are available with improved precision
- Tevatron experiments CDF and DØ check all aspects of the top quark:

Production Properties

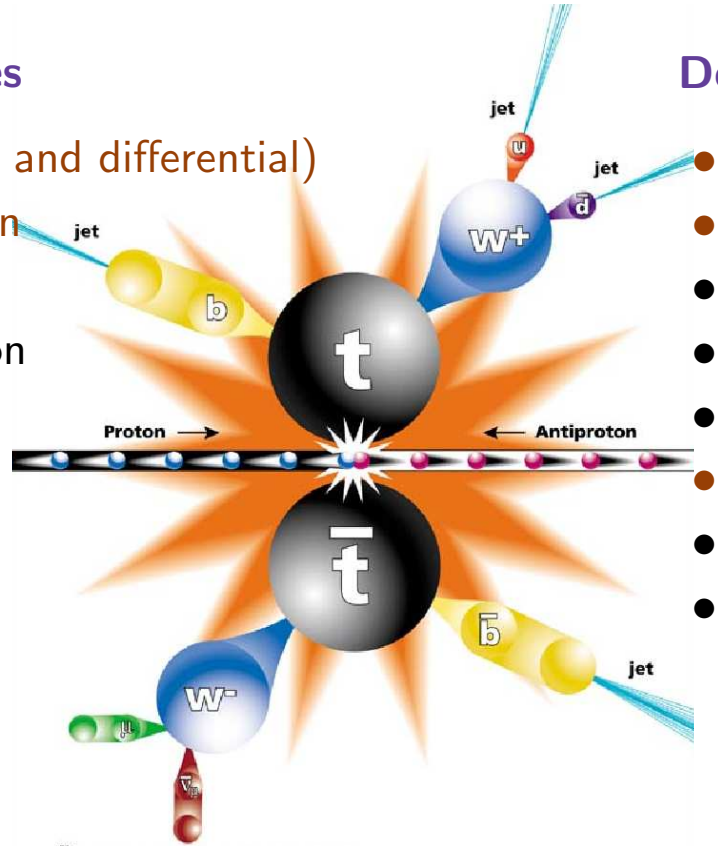
- Cross-section (total and differential)
- Resonant production
- Charge asymmetry
- Gluon fusion fraction

  ...

Inherent properties

- Top charge
- Width; lifetime
- sTop or Top′

  ...



Decay Properties

- W Helicity
- Wtb anomalous couplings
- Branching fraction; V_{tb}
- FCNC
- Invisible decay
- Charged Higgs
- ttH
- W'

  ...

- *No evidence for new physics, yet.*