Search for New Physics Using the Top Quark at the Tevatron

1. Introduction
2. Tevatron Status and Run II Data Collection
3. New Physics Opportunities with Top
4. Top Decays
5. Top Production
6. Conclusions

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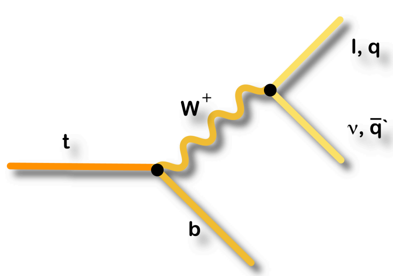
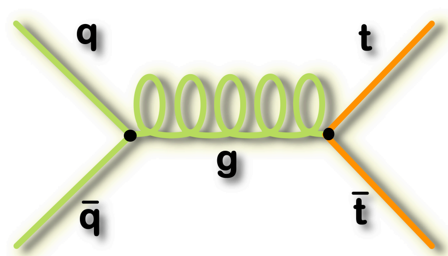
Representing the DØ and CDF Collaborations

The Top Quark and New Physics

- **The top quark provides a virtual lab to search for new phenomena**
  - **Heaviest fermion in the Standard Model, so already unique**
    - Most obvious, Higgs coupling
  - **As a bare quark, decays before hadronizing**
    - Simple couplings in SM
      - >99% decays to W^+b
  - **Simple production model**
    - **Pair production dominates**
    - **Provides tools to separate SM from "anomalous" production**





- **A large number of models predict "new physics" in top sector**
  - **Range from simple phenomenological models to new symmetries**
- **But present significant experimental challenges**
  - **Top quark signature is difficult to reconstruct efficiently**
    - Many-body final state
    - Large backgrounds
  - Production rate in SM is low
    - Predicted to be

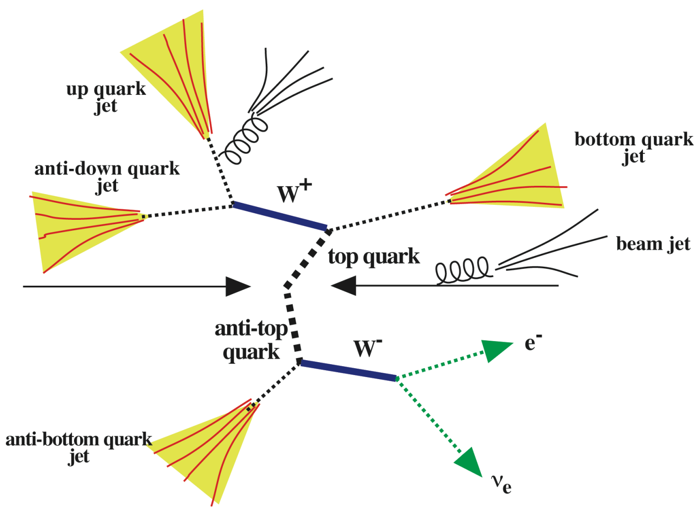
$$\sigma_{t\bar{t}} = 7.45^{+0.72}_{-0.63}\,\mathrm{pb}$$

    - Constrains possible models
    - Searches are harder

S. Moch and P. Uwer, Nucl. Phys. Proc. Suppl. 183, 75

General Strategies for Searches

1. **Top quark coupling to lower mass objects**
   - **Look at final state properties**
   - **Identify possible daughters and/or anomalous decay properties**
   - **Top quark pair production typically dominates**
     - End up with 6 parton final state
     - With additional jets

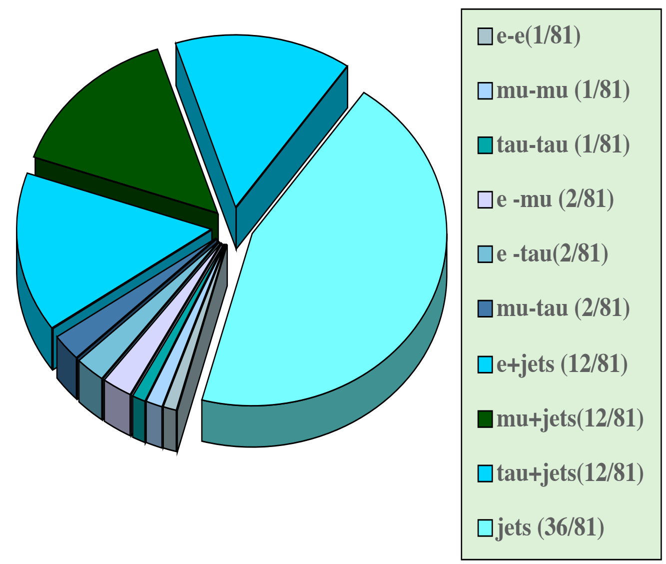


2. **For heavier objects, use kinematics of top quark pair as signature**
   - **Select "normal" ttbar events, e.g. lepton+jets mode**
     - Charged lepton + neutrino
     - 2 jets from 2nd W decay
     - 2 more jets from b quarks
   - **Look at other properties of final state**

- **In most cases, measure every accessible decay mode**
  - **Employ different techniques to test assumptions**
  - **Backgrounds vary significantly depending on selection**

Top Quark Event Selection

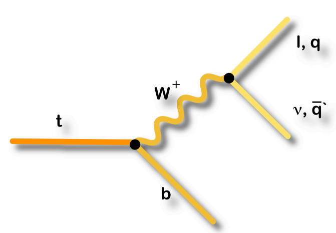
- **Goal is to efficiently identify each event topology**
  - **Dileptons (~4-6%)**
    - 2 leptons (e,μ) $P_T > 20$ GeV/c
    - Missing $E_T > 20$ GeV
    - 2 or more jets
      - **P_T>20 GeV/c and |η|<2**
    - S/B ~ 4-6 (without trying hard)
  - **Lepton + jets (~30%)**
    - 1 lepton (e,μ) $P_T > 20$ GeV/c
    - Missing $E_T > 20$ GeV
    - 2 or more jets
      - **P_T>20 GeV/c and |η|<2**
    - S/B ~ 1-4 (except double tags)
  - **All Hadronic (~44%)**
    - 6 or more jets
      - **P_T>15 GeV/c and |η|<2**
    - Kinematic cuts + neural nets
    - S/B ~ 0.3



- **Variations on the theme depending on analysis**
  - **Techniques and selection optimized to reduce systematics**
  - **Much innovation over last five years**
- **Host of studies that optimize and extend these**

Two Categories of Searches

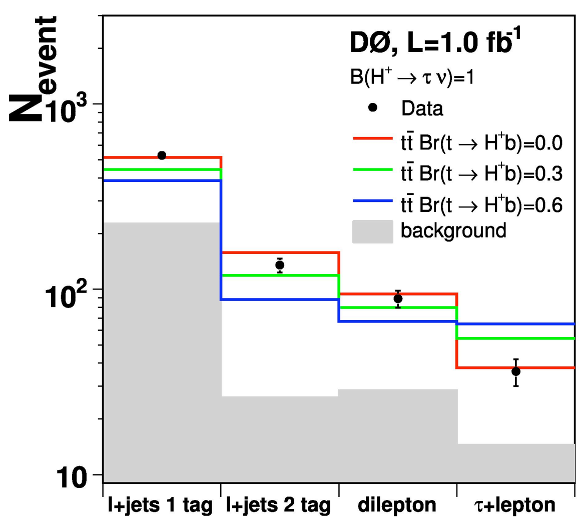
- In first category, look at what top decays/couples to:
  - Charged Higgs decays in MSSM
    - D0 has performed several separate searches with 1.0 fb^{-1}
    - CDF has searches with 2.8 fb^{-1}
  - Top decaying to H^+ in NMSSM model
  - ttbar + Higgs
    - CDF performed initial search with 0.3 fb^{-1}
    - D0 has recent study – 2.1 fb^{-1}
  - Top decaying to Zc, Zg
    - Won't have time to talk about these



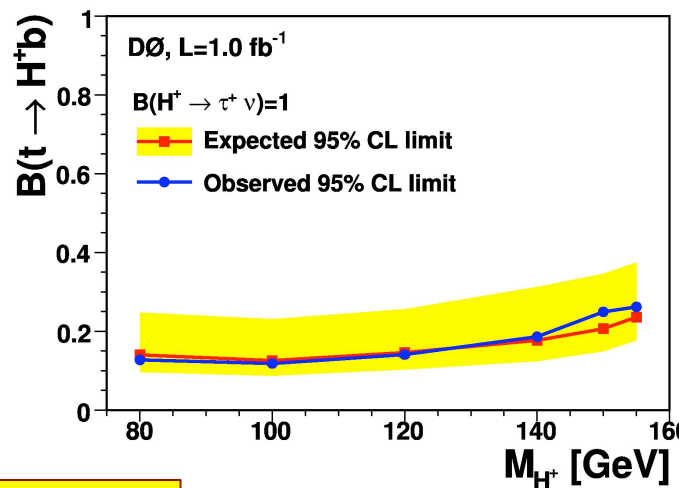
- In second, look for objects that decay to ttbar or t-bbar:
  - Resonances decaying to ttbar (CDF & DØ)
    - Significant sensitivity to high mass states
    - Top pair final state seen as a unique probe in many models
  - W' -> tbbar search (CDF & DØ)
  - t' searches (CDF)
  - Stop search
- Important to note that limits usually expressed in context of specific model
  - Should appreciate the sensitivity
    - Seeing fb observed rates
  - Especially as one compares with future studies at LHC

DØ Charged Higgs Search

- **Perform a broad multi-channel search**
  - **Use lepton+jets and dileptons**
  - **H^+ decays into either c-sbar or $\tau^+\nu_\tau$**
  - **Search for excess in 14 channels**
  - **Take into account σ_{tt} by simultaneous measurement**
    - $\sigma_{tt} = 8.18 \pm 1.0$ pb



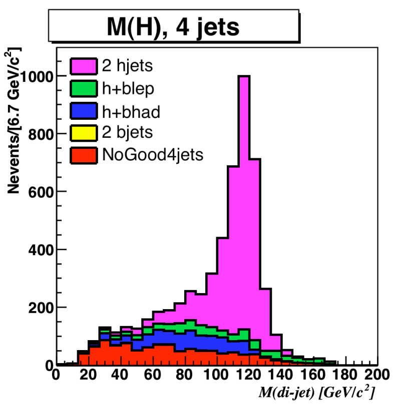
- **DØ searched in 1.0 fb^{-1}**
  - **Used a likelihood approach to combine candidate event rates**
    - See no evidence for excess
    - Place upper limits on BR and m_{H+}
  - **Analyze 3 specific H^+ models**
    - Leptophobic H^+ -- decays hadronically
    - CPX model with generation heirarchy
    - No-mixing scenario

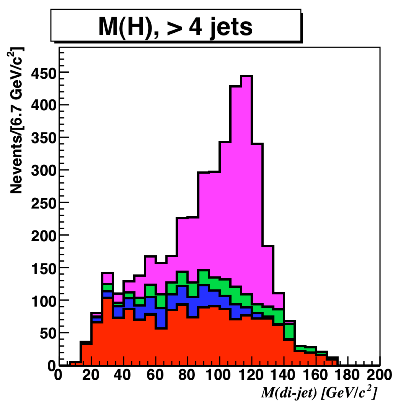


arXiv:/0908.1811 [hep-ex]

CDF Charged Higgs Search

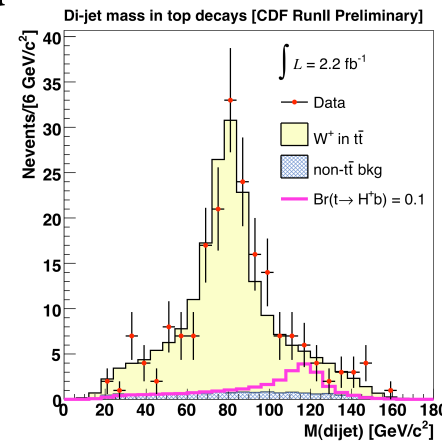
- **CDF searched for $H^+ \rightarrow$ c-sbar**
  - **Looking for dijet final state in 2.2 fb^{-1}**
  - **Work to reduce combinatorial confusion**
    - 4 jets + 5 jets with 1 jet assumed to come from FSR
    - Observed 200 events with 7% background

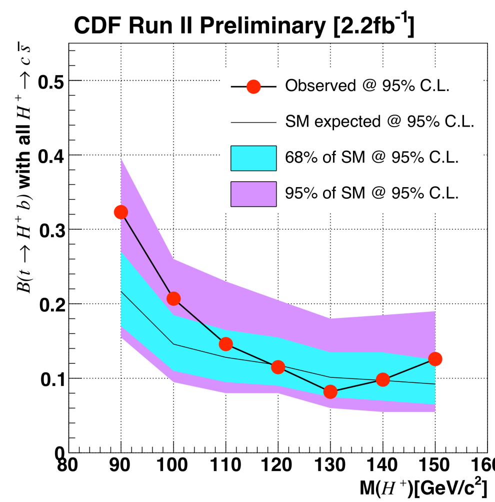




  - **Perform binned likelihood fit to look for $W^+ + H^+$ decays**

- **Don't find evidence for H^+ decay**
  - **Set limits based on fit**
  - **Shows that one can fully reconstruct final states**
  - **Limited by presence of W**

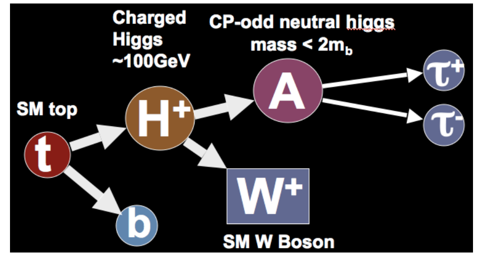




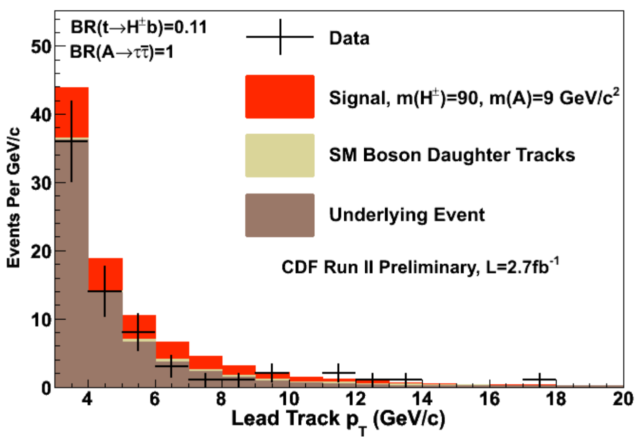
Phys. Rev. Lett. 103, 101803 (2009)

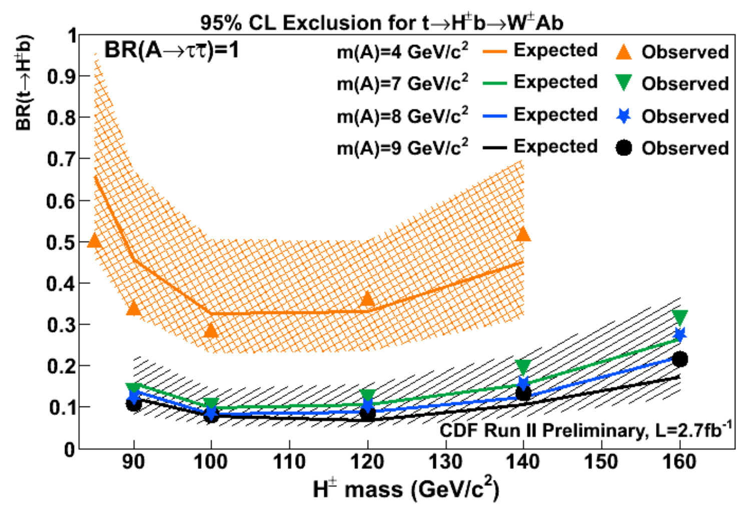
Search for H⁺ Decays in NMSSM

- CDF has also performed recent search for H⁺
  - Assume next-to-minimal SUSY model
    - Introduces another set of Higgs bosons
    - Search for evidence of lower mass A
      - Decays to ττ final state
- CDF has studied 2.7 fb^{-1}
  - Focused on lepton+jets
  - Identify τ candidates
    - Single isolated charged track
    - Underlying event model important



- Set limits based on expected BR vs charge Higgs mass
  - Exclusion depends sensitively on mass

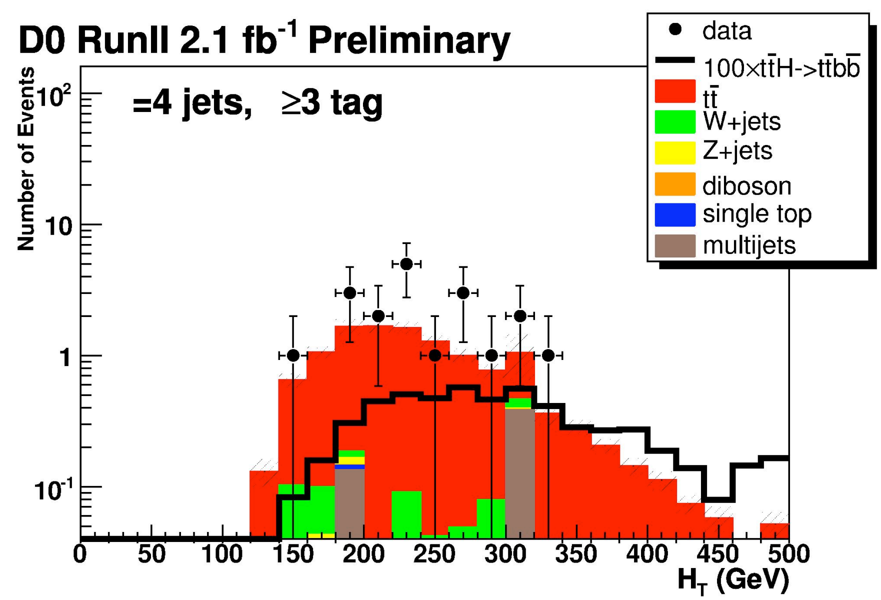




CDF Conf Note 10104 (Jan 2010)

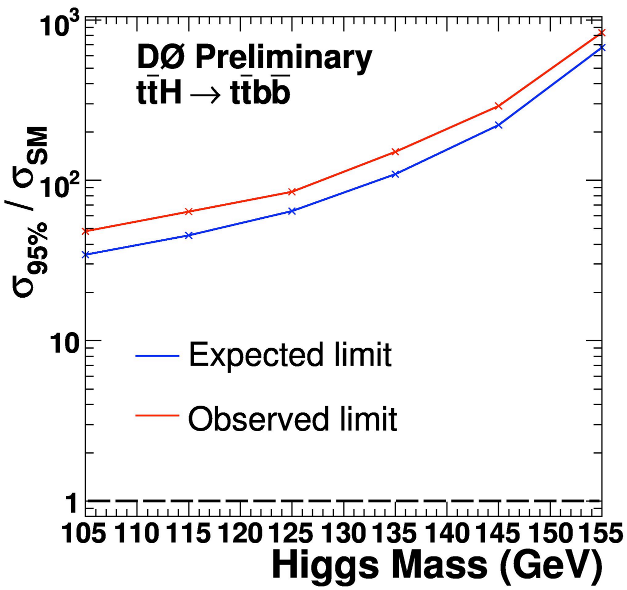
DØ Search for ttH

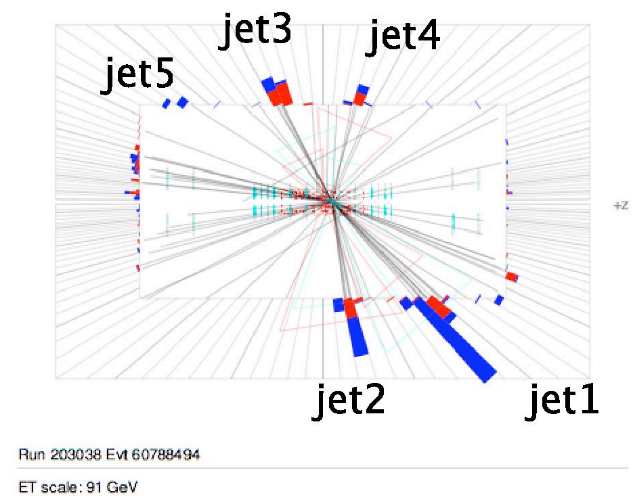
- Identified as "golden channel" for H, H-> bbar
  - Tevatron rate tiny
  - But spectacular final state
    - W+W- and 4 b's
  - CDF did search in 0.3 fb^{-1}
    - Found 2 events, x100 above SM
- DØ completed search using 2.6 fb^{-1}
  - Looked in l+jets mode
  - Divided into 12 sub-samples
    - 4 or ≥ 5 jets
    - 1, 2 or ≥ 3 b-tags
  - Use H_T as further background rejection against SM ttbar
- Analyzed S/N in each sub-sample
  - Observed 526 events
    - Expected 400 from ttbar, 173 other background
    - Best signal to noise in 5 jets, 3 tags
      - But only 0.6 ttbar+H events expected for $M_H = 105\ GeV/c^2$
      - Expected 3.8 background events
      - Observe 5 events

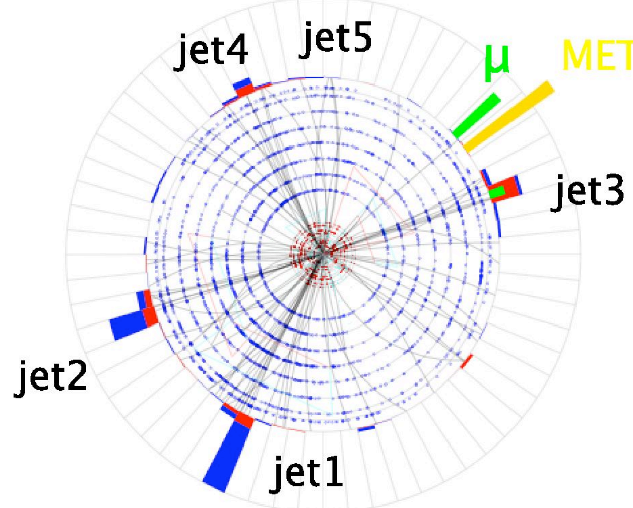


DØ ttH Results

- **Set cross section limits**
  - **About x 40 above SM prediction**
    - Small contribution, but complementary to other searches and part of Tevatron limit
  - **Background limited given the sensitivity**
    - Mistag rates are manageable
    - Intrinsic background from SM is challenge



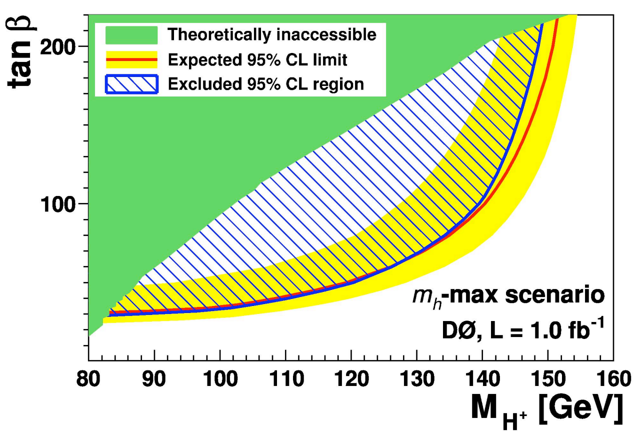




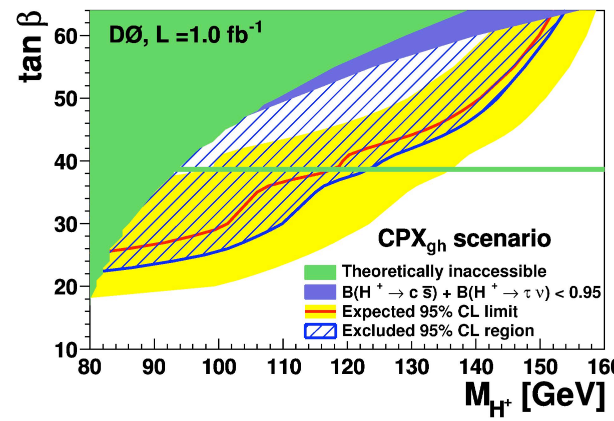
DZero note 5739-CONF (2009)

Implications of Higgs Searches

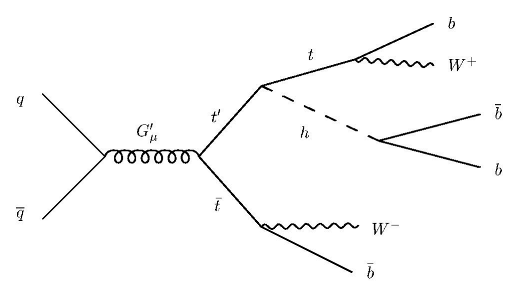
- **CDF and DØ have taken these results to further constrain MSSM**
  - **For tan β around 35, implications for Higgs sector**
    - “strangephilic” , so t and bottom modes suppressed
    - Searches employing heavy fermions would miss these
    - Picked up in searches looking at hadronic modes

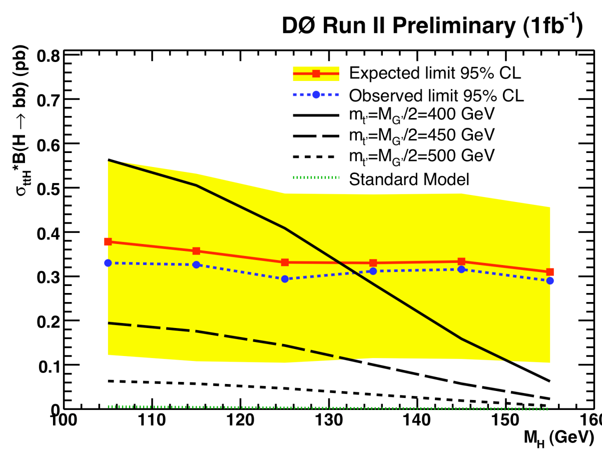


- **Model specific results from DØ:**



- **Can also place limits on stop**

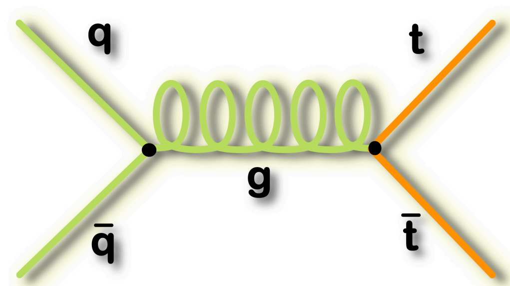




Search for Massive X → ttbar

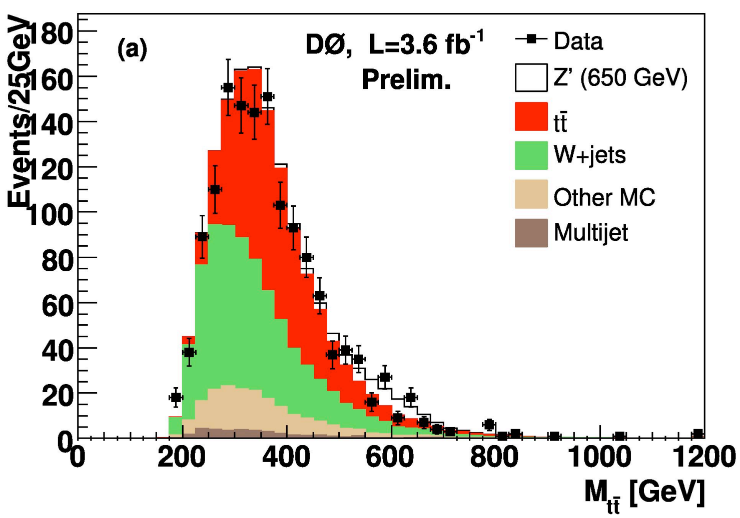
- Many models predict new massive objects that couple to top pair final state
- Search for massive objects coupling to top
  - Need to reconstruct high p_T top quarks
    - $p_T \sim 300$ GeV/c
  - Challenge is statistics and techniques
    - Pushing limits of detector understanding
- Background is now SM top quark pair production

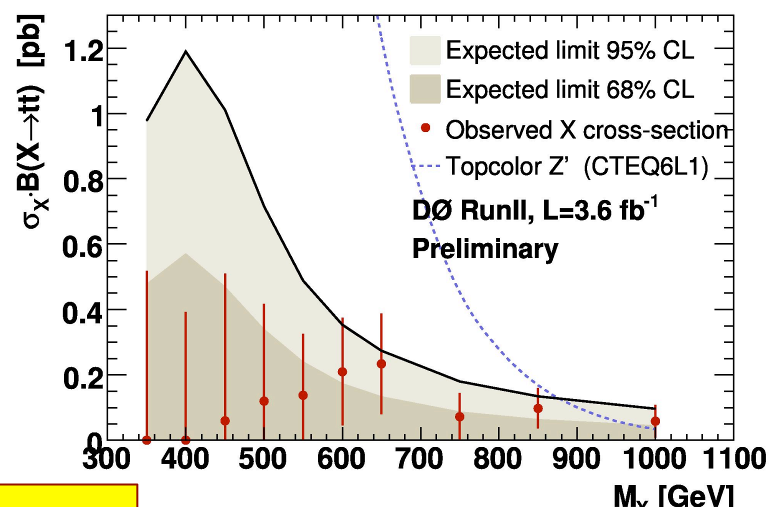
- Host of models that motivate these sorts of studies, e.g.
  - Topcolor
  - Topcolor assisted technicolor
  - String theory motivated models
    - KK excitations
    - Gravitons
- Key point is that many of these models have ttbar as preferred decay mode



DØ Search for Massive Objects

- DØ uses a standard l+jets ttbar selection
  - e/μ candidate + MET
  - ≥3 jets, one b-tagged with NN
  - Analyze 3.6 fb^{-1}
- Observe 2345 events
  - Expect 1345 coming from ttbar
    - W+jets next largest contribution at 721 events
- Form M_{ttbar} and look for resonance signal
  - Assume narrow resonance (width $0.012M_{Z'}$)
  - Take into account SM + backgrounds
  - Limit on topcolour-assisted TC model $M_{Z'}$ > 820 GeV/c^2 at 95% CL

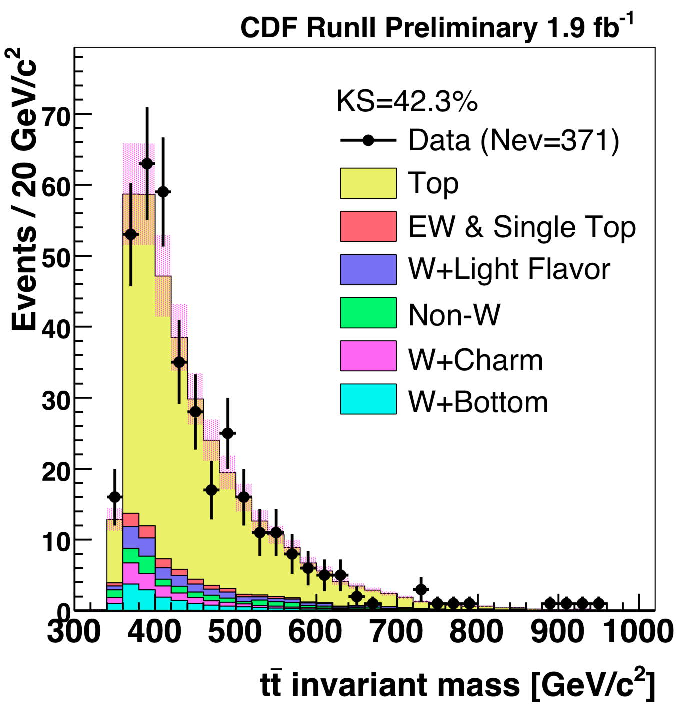




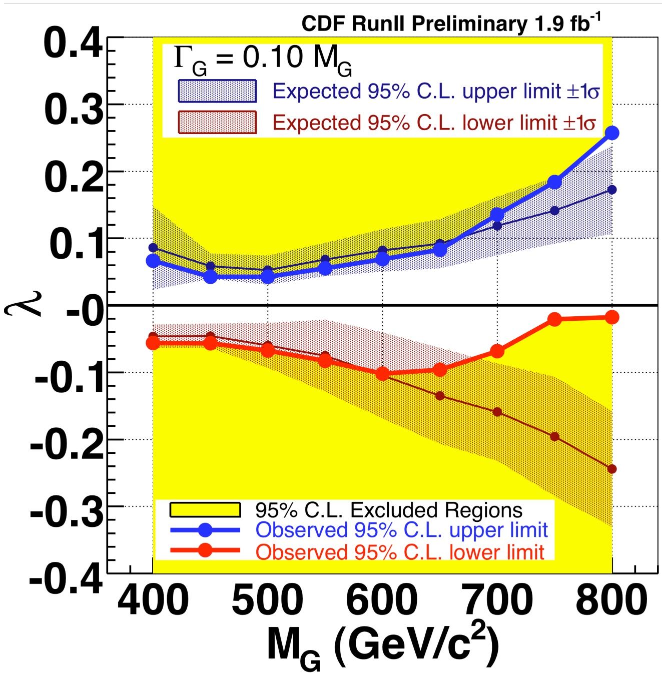
Dzero Note 5882-CONF (2009)

CDF Lepton+Jets Search

- CDF has published search looking for "massive gluon"
  - Used a "standard" l+jets selection
  - Require at least one b-tagged jet
  - Use 1.9 fb^{-1} of data



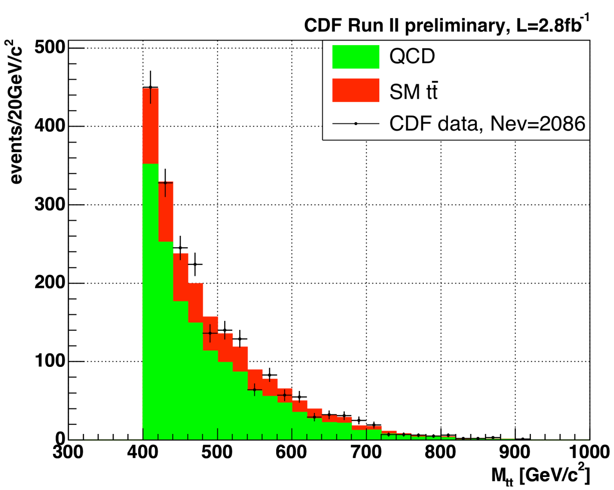
- Results given for various masses and widths
  - Model doesn't define mass-width relationship
  - Get contours of coupling strength λ



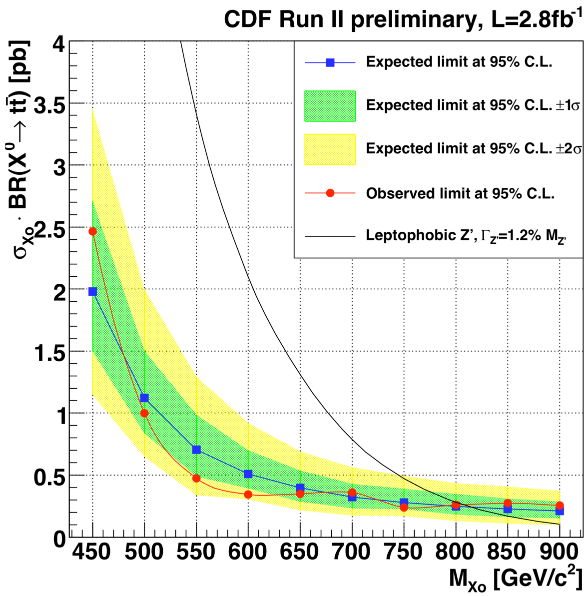
PRD 77, 051102 (2008)

CDF All-Hadronic Search

- CDF has used all-hadronic channel
  - Require 6 or 7 jets
    - ET>15 GeV and |η|<2.0
    - ≥ 1 b-tag
  - Used matrix-element to reconstruct signal
    - Shown that this works well
    - Employ various control regions
  - Analysis uses 2.8 fb^{-1} of data



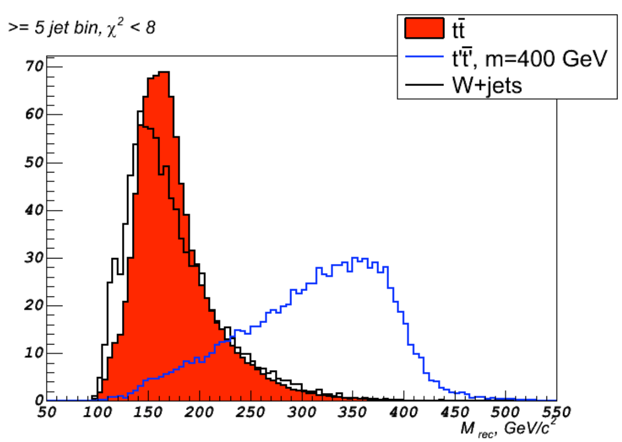
- Challenging analysis because of poor S/N
  - Observe 2086 events with M_{tt}>400 GeV/c^2
    - QCD background determined by b-tag fake rate
  - Sets limit on "leptophobic" Z' of M_Z>805 GeV/c^2 at 95% CL



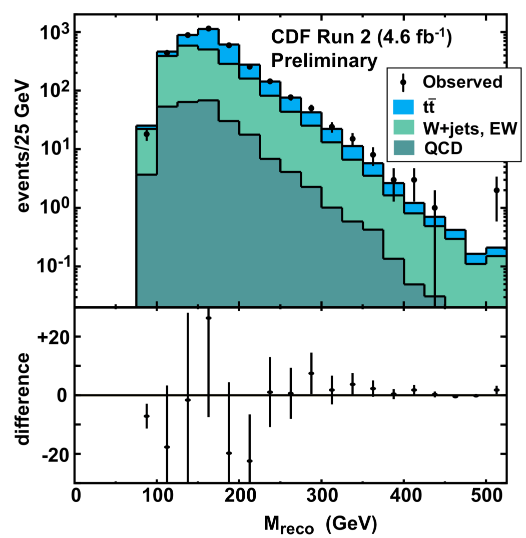
Conference Note 9844 (2009)

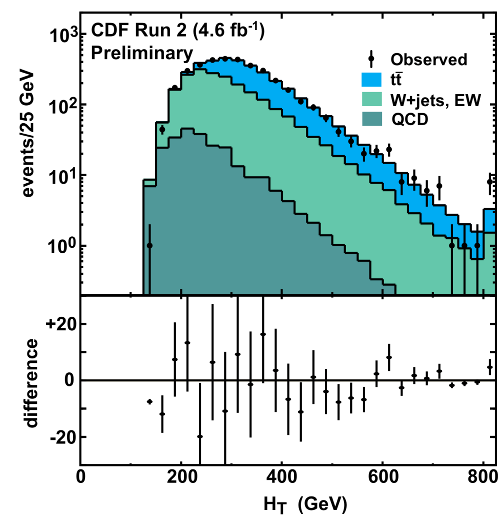
Searches for 4 Generation

- **CDF has searched for 4th generation t'**
  - **Decays to W^+q**
    - Essentially a massive top quark
    - Another spectacular signal
  - **Challenge is to manage backgrounds at high mass**
    - SM ttbar production now a problem
    - QCD backgrounds large (and uncertain)
  - **Used 4.6 fb^{-1} of data**



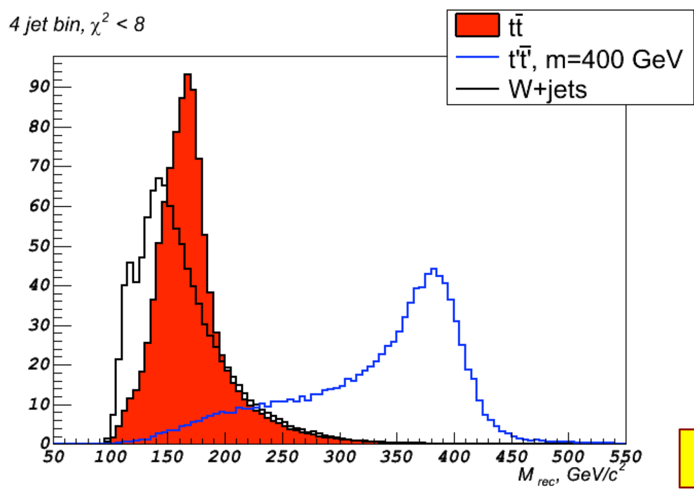
- **Need strategy to manage S/N**
  - **Reconstruct lepton, MET + ≥ 4 jets**
  - **Pick best solution**
    - Observe 3648 events
    - Expect 3664±1570
      - **Background about half ttbar and half QCD**
      - **Uncertainty comes from QCD**



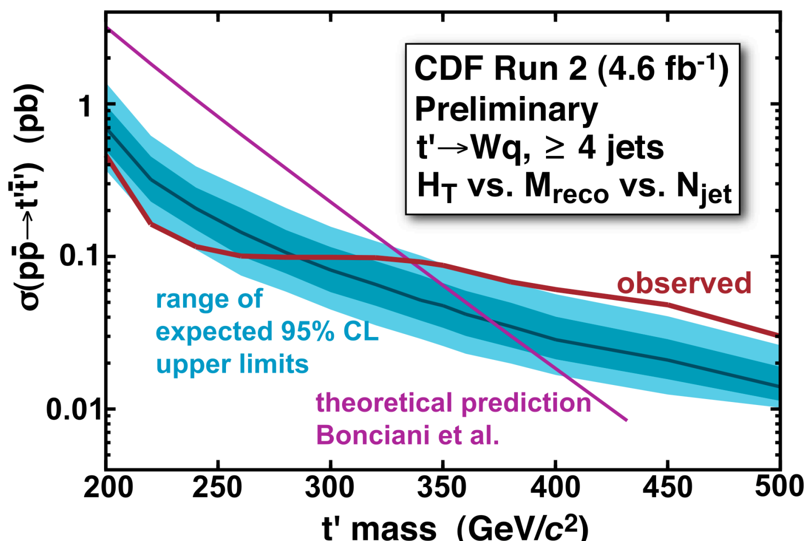


Searches for 4 Generation

- Used results to place limit on possible t'
  - Divide data into four regions
    - 4 and ≥ 5 jets
    - Good or bad kinematic fit
      - (χ^2<8 and χ^2≥8)
  - Use M_{rec} and H_T and fit data to templates 2-D templates
- Use max likelihood fit to cross section using templates



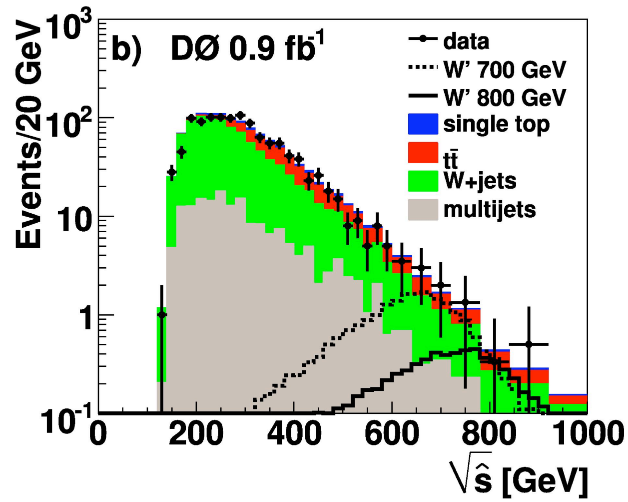
- Results show that there is significant sensitivity
  - Data consistent with backgrounds
  - Exclude t' with mass < 335 GeV/c^2 at 95% CL
    - Assumes strong couplings and decay always to W^+q
    - No b-tagging required



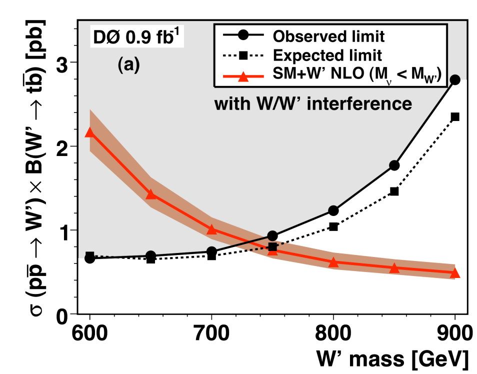
Conference Note 10110 (2010)

DØ Search for W’

- W’ searches traditionally done in l ν_l final states
  - q-qbar’ background dominated
  - W’ → t bbar is a “clean” final state
- An initial search was performed by CDF using Run I data (0.1 fb^{-1})
  - CDF set limit $M_{W'}$ > 536 GeV/c^2 at 95% CL
- DØ has now analyzed 0.9 fb^{-1}
  - Selecting lepton+jets, MET
    - Only keep 2 or 3 jet events
    - Require one to be b-tagged
    - Divide into 8 channels (e/μ), (2-3 jets), (1-2 b-tags)
  - Select 182 events
    - Expect 59 ttbar and 127 background
- No evidence of signal



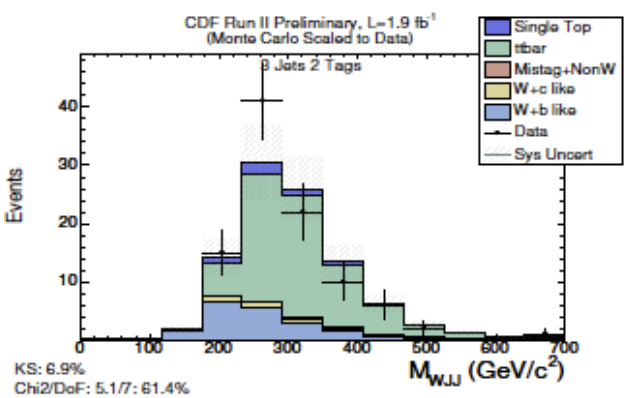
- Set limit of $M_{W'}$ > 731 GeV/c^2 at 95% CL



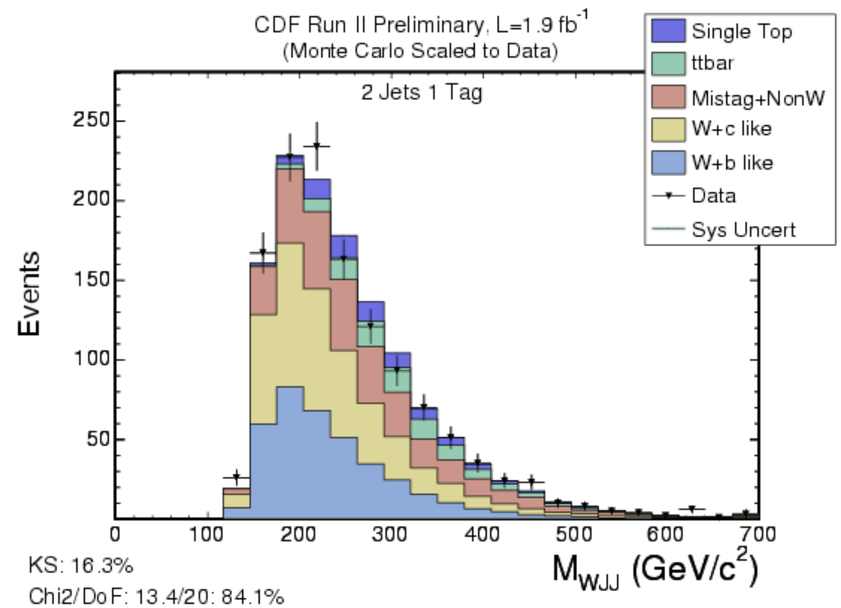
Phys. Rev. Lett. 101, 211803 (2008)

CDF Search for W'

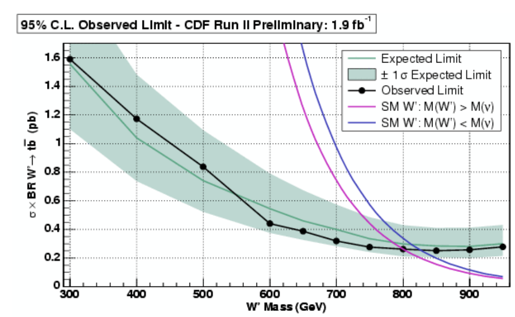
- CDF has repeated its earlier analysis with Run II data
  - Similar strategy to that of DØ
  - Select events with lepton+MET
  - Require only 2 or 3 jets in final state
    - And 1 or 2 b-tagged jets
- Analyzed 1.9 fb^{-1}
  - Have modeled the backgrounds and signals for each subsample
  - Combined them using CLs



- Also see no evidence of signal



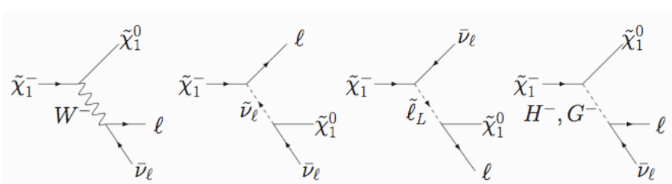
- Set limit of $M_{W'} > 800$ GeV/c^2 at 95% CL
  - Limit rises to 825 GeV/c^2 if $M_{W'} < M_{\nu R}$



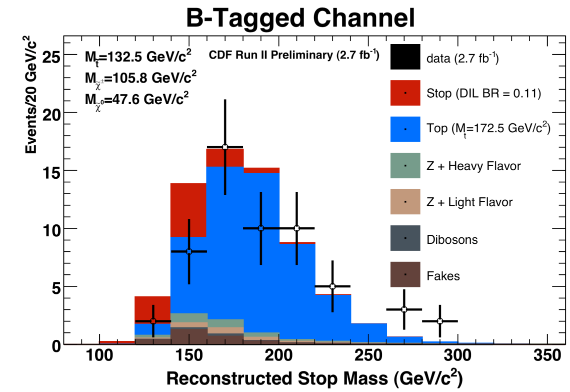
Phys. Rev. Lett. 103, 041801 (2009)

CDF Search for Stop

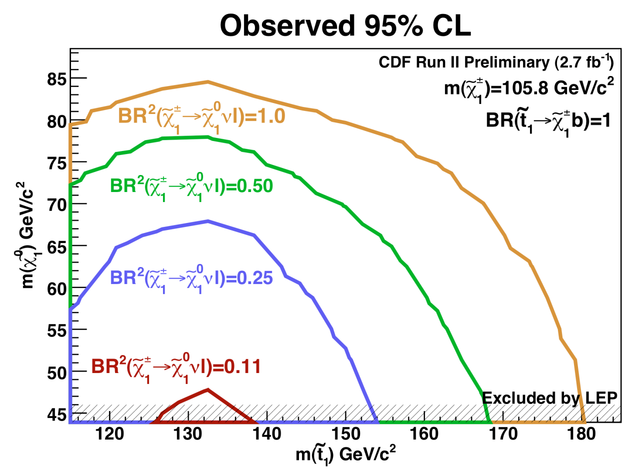
- CDF has searched for stop pair production decaying to dileptons
  - Specific model
    - LSP is neutralino
    - Lightest stop < m_{top}
    - Chargino mass < m_{top} - m_b
  - Same topology as ttbar
  - Begin with standard dilepton cuts
    - Search for combination of further cuts to maximize sensitivity
- Analyzed 2.7 fb^{-1}
  - Consider b-tagged and non b-tagged samples
    - important element



- No evidence of signal, e.g.



- Set limits depending on various masses and BRs



Conference Note 9439 (2009)

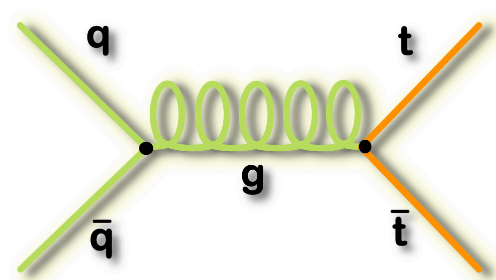
Topics Not Covered

- Many topics not covered
  - Rare top quark decays
    - $t \rightarrow Zc, gc, \gamma c$
    - $t \rightarrow Wq$, where $q \neq b$
  - Anomalous kinematics
  - Anomalous couplings
  - Earlier searches with lower sensitivity
- Some of these have been covered in other talks
  - Apologize for the others!
- What I hope to be the take-home message
  - Tevatron has significant "reach" using top quarks as laboratory
  - Now probing mass scales > 800 GeV/c^2
  - Continuing to developing new tools for these searches
- Not ready to hand over reins to LHC searches!
  - Analyses are using only half the collected data
    - That will change as we validate and calibrate latest data
  - More new analyses underway

Summary

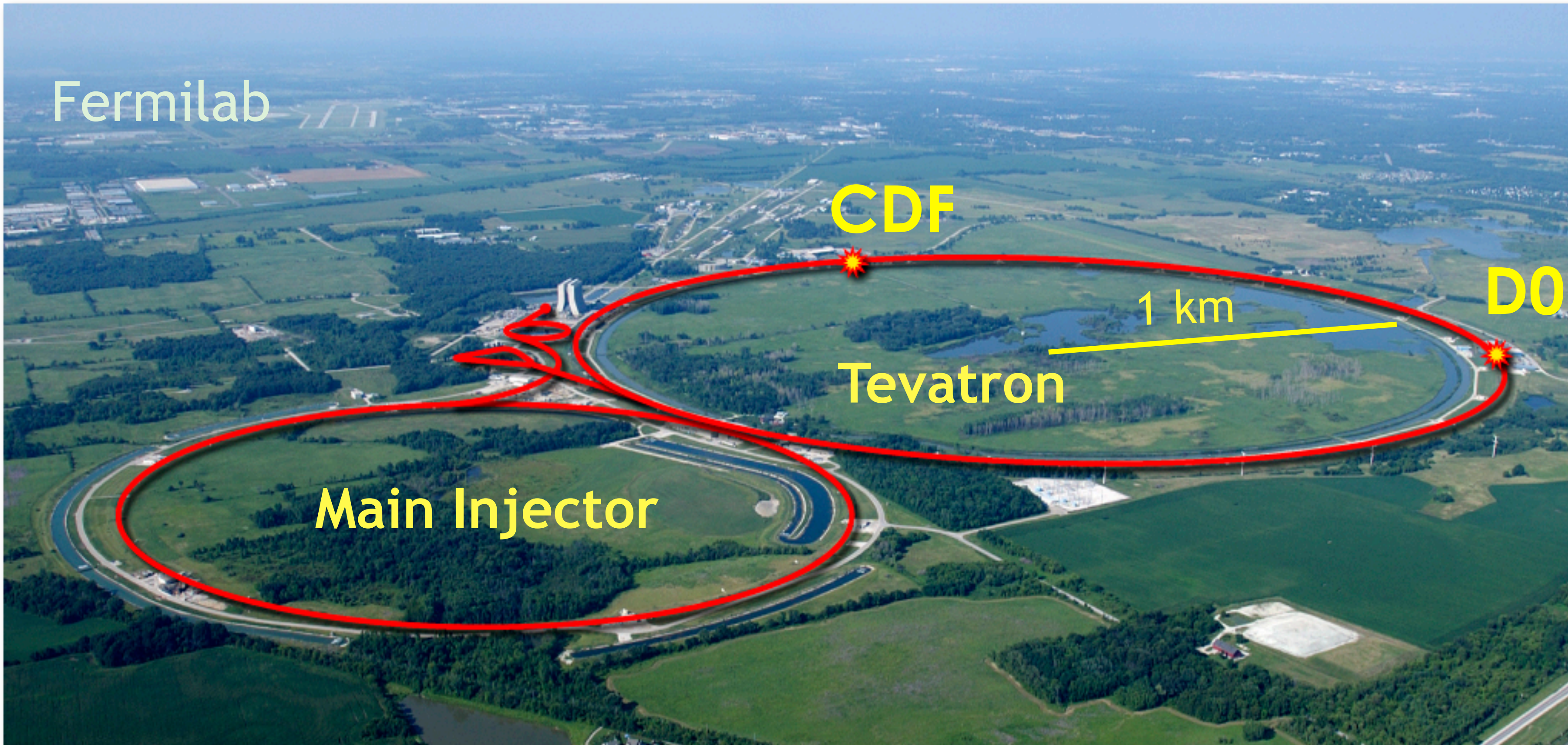
- Top provides unique access to new physics
  - Extensive searches for H+
  - Now setting limits on BR ~ 0.1 for Higgs masses 100-150 GeV/c2
  - Moving to more sophisticated models
- No evidence for high mass objects coupling to top
  - Limits on t-tbar final state
    - $M_X > 820$ GeV/c^2 at 95% CL
  - Limits on t-bbar final state
    - $M_{W'} > 731$GeV/c^2 at 95% CL
- Searches for 4th generation
  - Limited by backgrounds
    - $M_{t'} > 335$GeV/c^2 at 95% CL
- Stop search

- Most of these analyses are based on 2-3 fb^{-1}
  - Analyses are starting to appear with 4-5 fb^{-1}
  - And have > 7 fb^{-1} on "tape"
- Most of these are background-limited by top production and/or SM processes
  - Working to develop "next generation" studies



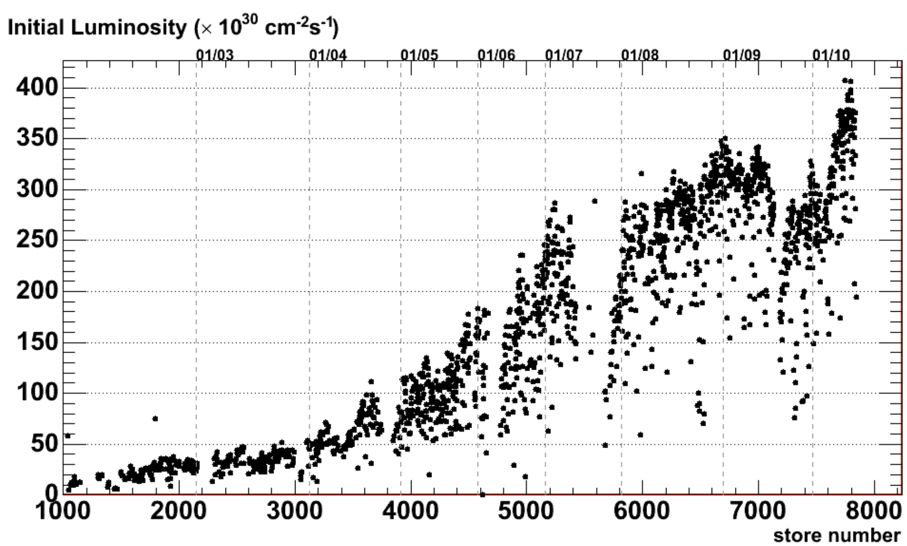
Backup Slides

Fermilab Tevatron

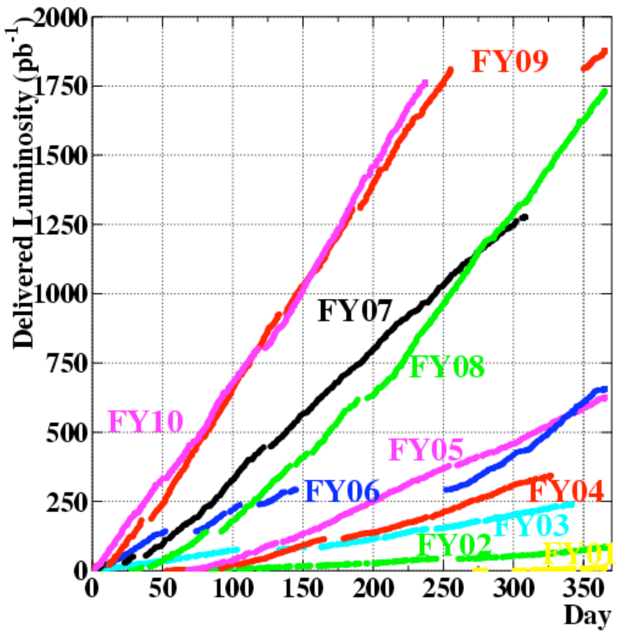


Tevatron Run II Performance

- Tevatron running very well!
  - Overcame a slow start in 2002-03
  - Exceeded goals over last three years
    - Record luminosity of 4.0×10^{32} $cm^{-2}s^{-1}$
    - $\langle N_{coll} \rangle \sim 12$ collisions/crossing!
  - Have almost 9 fb^{-1} delivered
    - 7.2 fb^{-1} recorded by both experiments
    - Now accumulating ~2 fb^{-1}/year

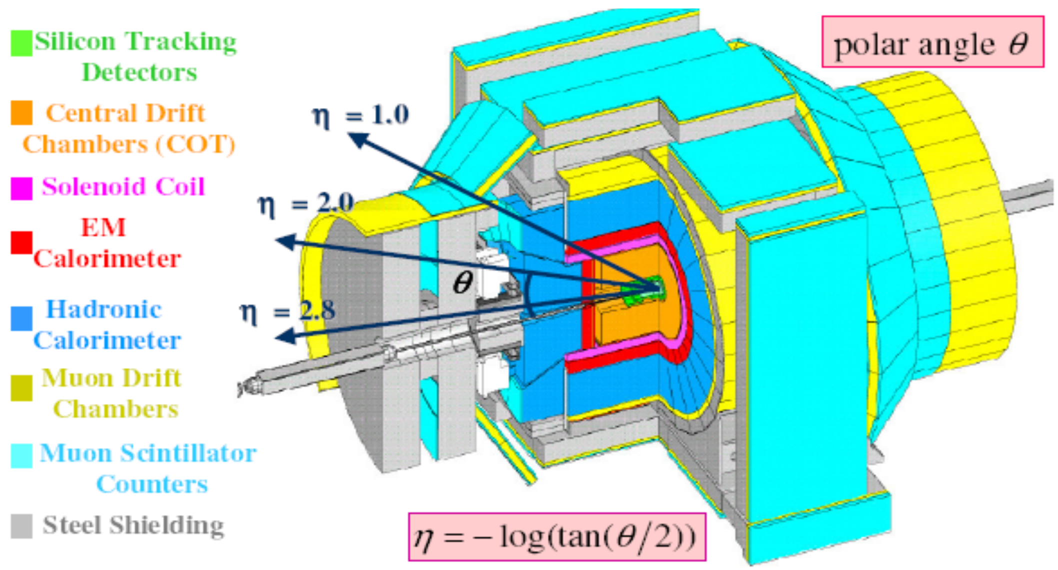


- This has led to some changes in plan
  - Originally Tevatron was to shut down by Sep 2009
  - Now running through Sep 2011 is certain given recent budget decision
  - Discussions underway about running further



CDF Detector

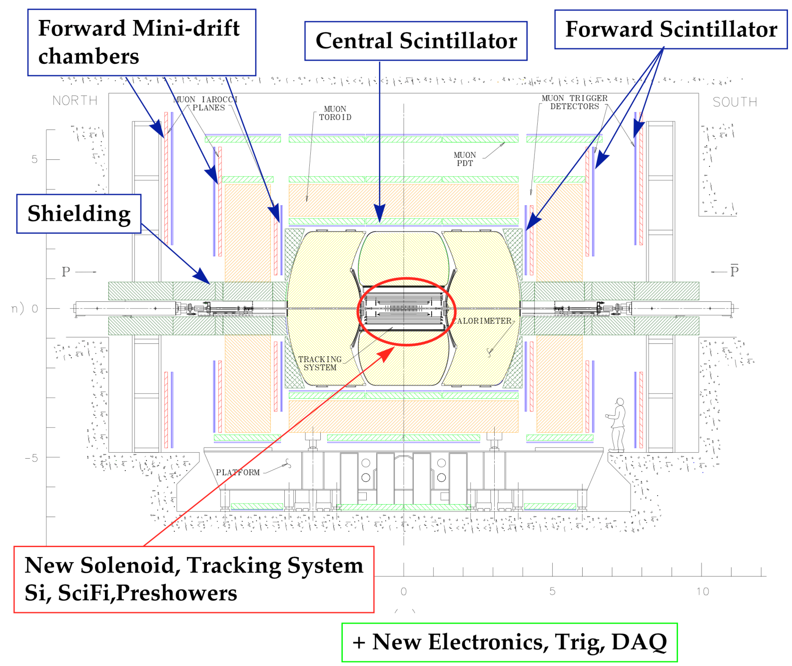
- **Collider Detector at Fermilab**
  - **Excellent charged particle tracking**
    - Large 1.4 T solenoid for particle momentum measurement
  - **Calorimeters measure jet energies and missing energy**
  - **Muon detectors outside of calorimeter**
- **Trigger & DAQ system designed to**
  - **Examine each beam crossing (2.4 MHz rate)**
  - **Select “interesting” events**
  - **Record data at rate of 100 Hz**



- **B tagging provided by 7-layer silicon tracking system**
  - **For top quarks, tagging efficiency is ~45%**
  - **Essential tool to reduce backgrounds in mass analyses**

DØ Detector

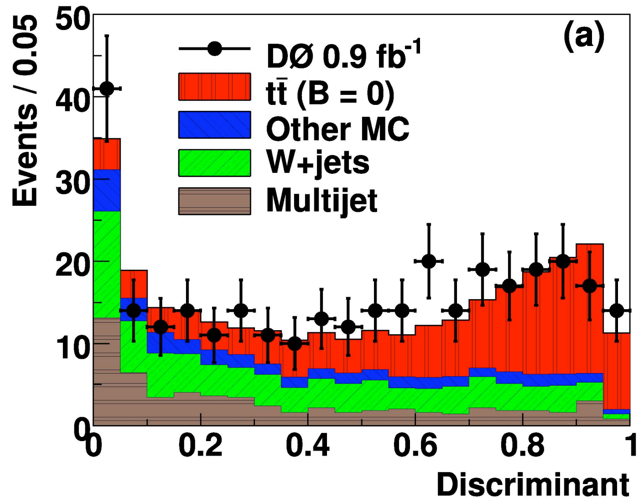
- **Dzero Detector was significar⁴ˡ⁻⁻ upgrade for Run II**
  - **State-of-the-art magnetic spectrometer**
    - 2 T Solenoid
    - SciFi tracking system
  - **New Silicon tracking**
  - **Scintillators for preshower detectors**
- **Trigger & DAQ system also upgraded**
  - **Examine each beam crossing (2.4 MHz rate)**
  - **Select "interesting" events**
  - **Record data at rate of 100 Hz**
- **Original strengths retained**
  - **Excellent muon identification**
  - **Largely hermetic calorimetry**



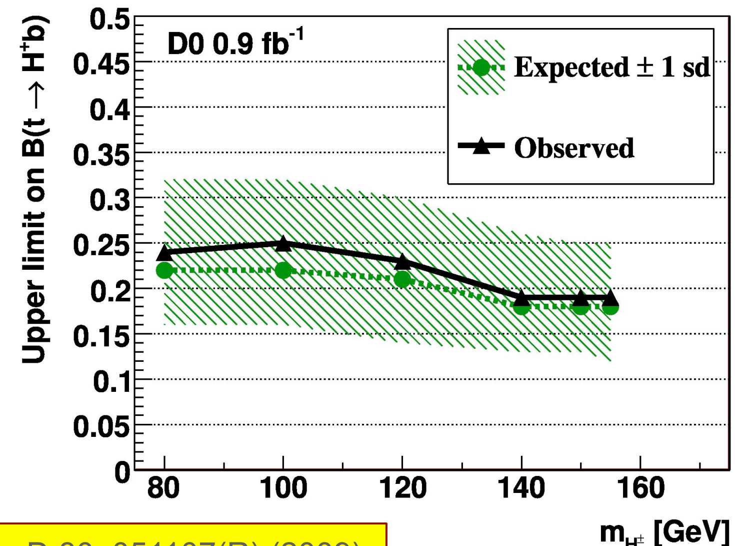
- **B tagging provided by 4-layer silicon tracking system with disks**
  - **Essential tool to reduce backgrounds in mass analyses**

DØ Charged Higgs Search I

- Top → H^+b is a favourite search channel
  - Charged Higgs comes in the simplest SUSY extension
  - H^+ decays preferentially into c-sbar and $\tau^+\nu_\tau$
  - First search, look for evidence of excess τ^+ decays
    - Use discriminant based on probabilities



- DØ searched in lepton+jets channel with 0.9 fb^{-1}
  - Look for τ lepton excess in 2386 candidate events
  - Lepton+jet & dileptons channels
  - Place upper limits on BR and m_{H+}
    - BR < 0.25 at 95% CL
    - for 80 < m_{H+} < 155 GeV/c^2



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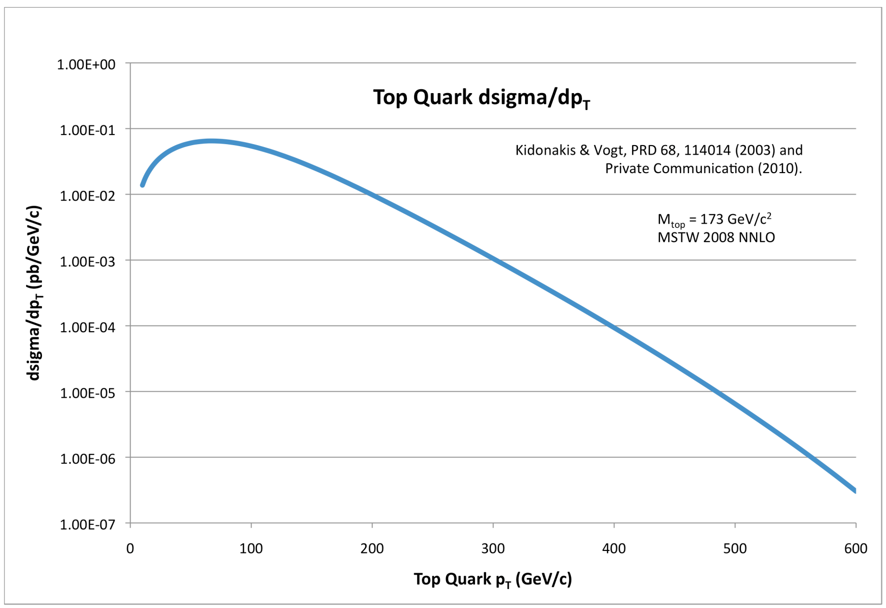
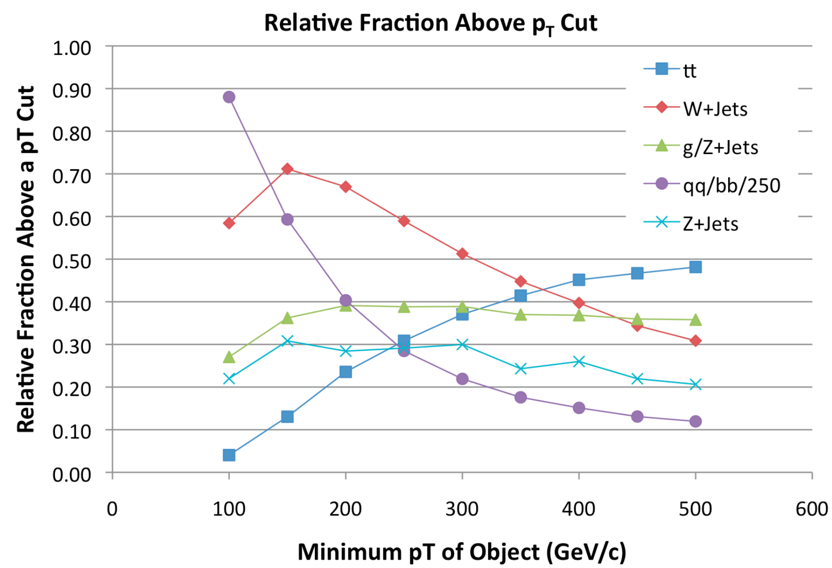
Top Production Issues

- **Helpful to keep in mind two issues**
  - **Top is produced largely at low p_T**
  - **Have large backgrounds!**





- **Need to worry about S/N**
  - **But "life" does get easier at higher p_T and mass**

Courtesy, N. Kidonakis and R. Vogt, (2010)