Searches for new physics using the top quark at the Tevatron

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Overview

- The top quark has inspired many searches for physics beyond the standard model
  - The large top quark mass gives the top a special role in BSM models
  - BSM models predict the top quark is special to accommodate its large mass

Overview

- Searches was not a priority in the top physics program
  - The number of publications on searches for new particles was about 15/experiment – compare with an average of 25/expt for ttbar cross section, 20/expt single top, 25/expt top quark mass

- Nevertheless, the program for searches using top quarks originated at the Tevatron

Overview

- Searches for new particles that predominately couple to the top quark
  - Charged Higgs H^+ and CP-odd Higgs boson
  - Resonances: Z' and W' bosons
  - Vector like quarks: T' and B' quarks
  - Dark matter
  - Supersymmetry: stop quark

Overview

- The Tevatron started searching for new particles associated with top in Run I

- **Charged Higgs, H^+:**
  - Phys.Rev.Lett.72,1977 (1994) - CDF
  - Phys.Rev.Lett.73,2667 (1994) - CDF
  - Phys.Rev.D54,735-742, (1996) – CDF
  - Phys.Rev.Lett.88,151803 (2002) – D0
  - Phys.Rev.Lett.82,4975-4980 (1999) –D0
- **W' boson**:
  - Phys.Rev.Lett.90, 081802 (2003) – CDF
- **Z' boson**:
  - Phys.Rev.Lett.85, 2062-2067 (2000) – CDF
  - Phys.Rev.Lett.92, 221801 (2004) – D0

Overview

- Searches at the Tevatron were done in very closely collaboration with the measurement of the ttbar and single top cross sections

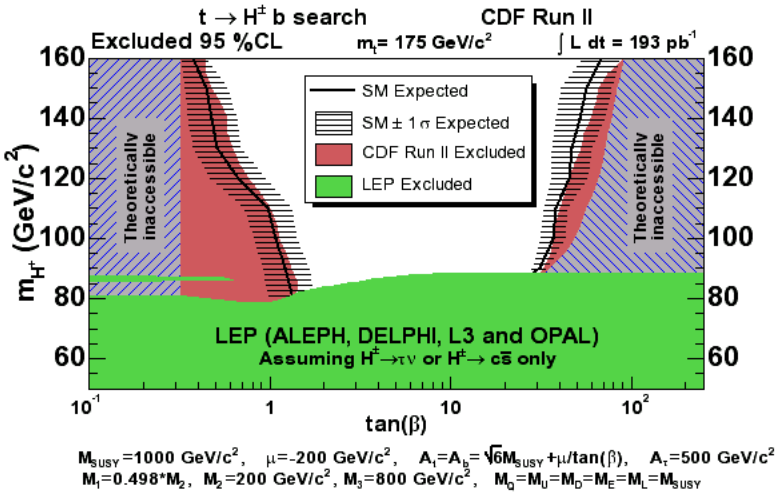
- Here I will go over the Tevatron Run II results
  - Charged Higgs H^+ and CP-odd Higgs boson
  - Resonances: Z' and W' bosons
  - Vector like quarks: T' and B' quarks
  - Dark matter
  - SuperSymmetry: stop quark

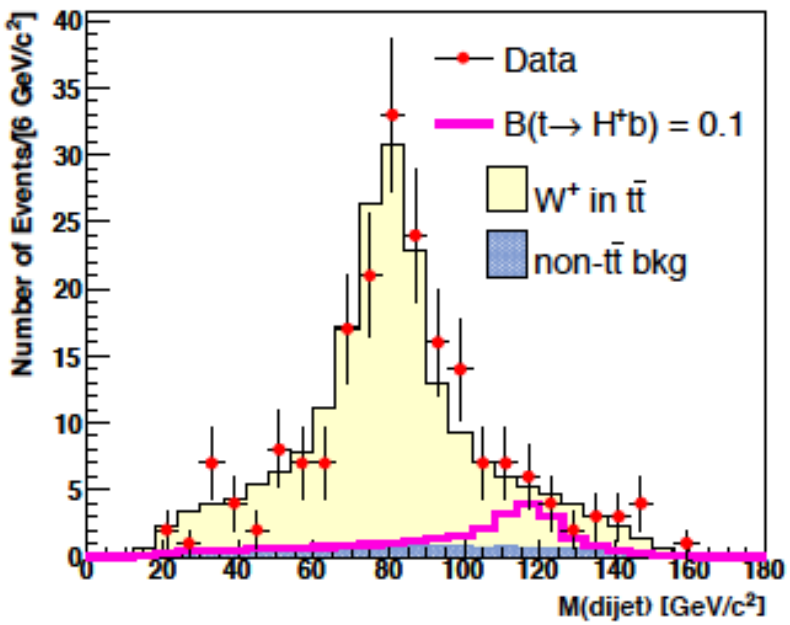
Charged Higgs, H^+

- Extended Higgs sectors proposed to explain EWSB
- The two Higgs doublet (2HDM) fields manifest themselves as
  - 2 charged Higgs bosons ($H^{\pm}$) and 3 neutral Higgs bosons (h, H, A)
- In 2HDM and MSSM, depending on the value of the H^+ mass (m_{H+}): $t \to H^+b$ or $H^+ \to tb$
  - Branching ratio is a function of m_{H+} and tanβ:
    - $B(t \to H^+b)$ also depends on extra parameters related to the masses and couplings of the other supersymmetric particles
    - At low tanβ, H^+ predominantly decays into
      - $H^+ \to cs$ for low m_{H+} (<130 GeV)
      - $H^+ \to t^*b$ for higher m_{H+}
    - At high tanβ, H^+ predominantly decays into
      - $H^+ \to \tau\nu$ almost 100% of the time

Charged Higgs, H^+

- First search with top at CDF II [Phys.Rev.Lett.96, 042003, 2006]
  - Recast of ttbar cross section in lepton + jets, dilepton, τ+lepton done with **190pb^{-1}**
  - Assumes one top decaying SM $t \to W^+b$; and the other $t \to H^+b$ with $H^+ \to \tau$bar ν, $H^+ \to$csbar, $H^+ \to t^*$bbar, $H^+ \to W^+h^0$, h^0->bbar

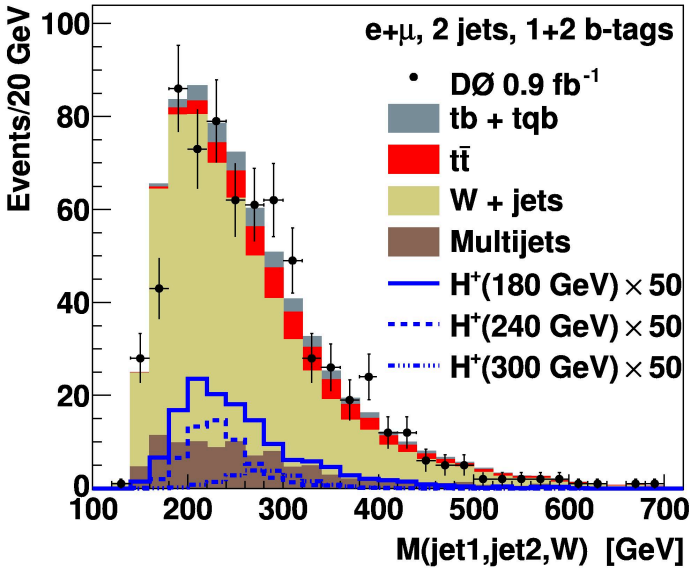




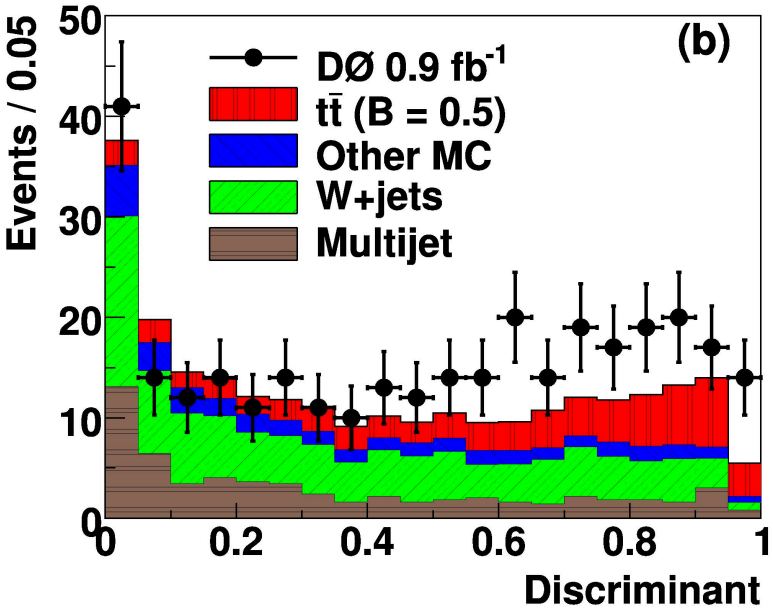
- CDF first direct search for analysis $t \to H^+b$, $H^+ \to$csbar with **2.2fb^{-1}** in lepton+ jets channel [Phys.Rev.Lett. 103, 101803, 2009]
  - Uses similar kinematic fitter to ttbar to reconstruct event
  - Fits dijet mass of non b-tagged jets

Charged Higgs, H^+

- D0 first direct search of H^+ done with **0.9fb^{-1}**
- Complementary to CDF searches since assumes $m_H > m_t$; $180<m_H<300$ GeV ppbar→H^+→tb→Wbb in lepton + jets (search done in single top s-channel search) [Phys.Rev.Lett.102:191802, 2009]

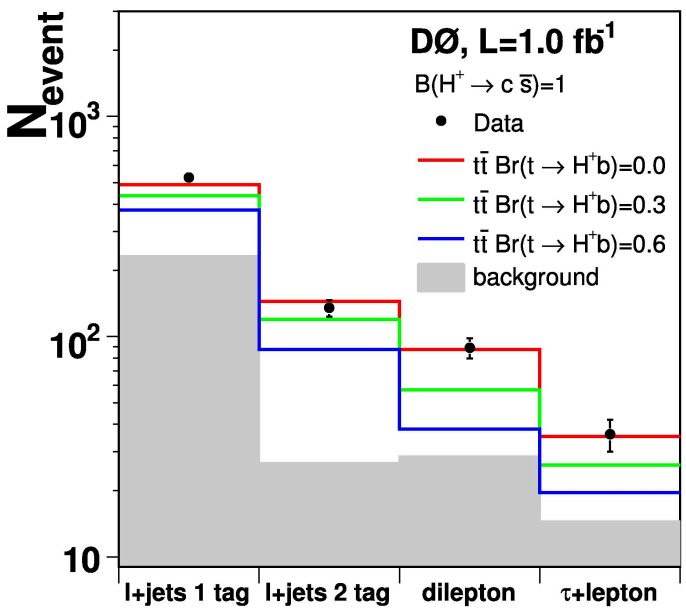


- With the ttbar sample D0 searches using **0.9 fb^{-1}** for tt→WbHb with W→lν and H→τν in lepton+jets where assumes one of the jets is from the hadronic τ decay [Phys.Rev.D80:051107,2009]

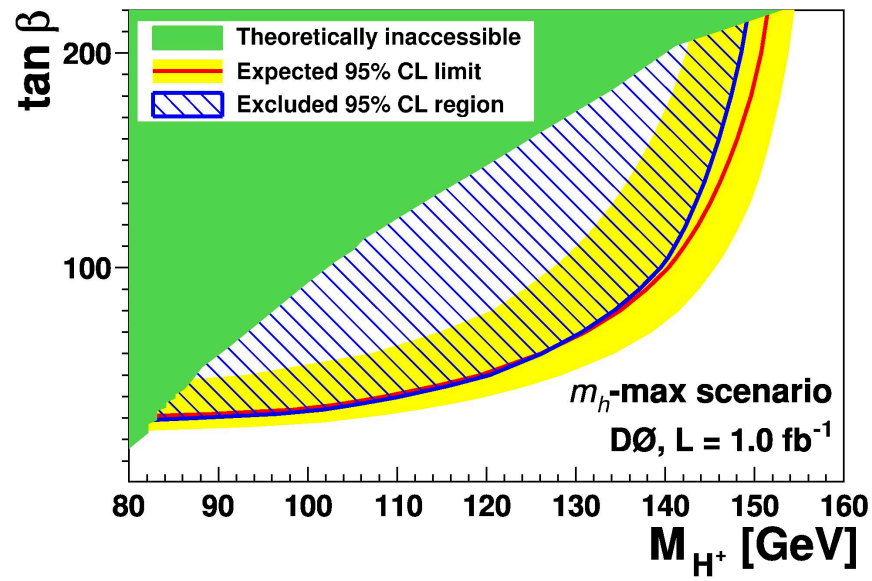


Charged Higgs, H^+

- D0 uses the measurements of the ttbar cross section in lepton+jets, dilepton, and τ +lepton done with **0.9 fb^{-1}** to search for charged Higgs $80<m_H<150$ GeV by computing [Phys.Rev.D80:071102,2009]
  - $\sigma_{\ell\ell}/\sigma_{\ell j}$ to set limits assuming B(H→cs)=1
  - $\sigma_{\tau\ell}/\sigma_{\ell\ell\text{-}\ell j}$ to set limits assuming B(H→τν)=1

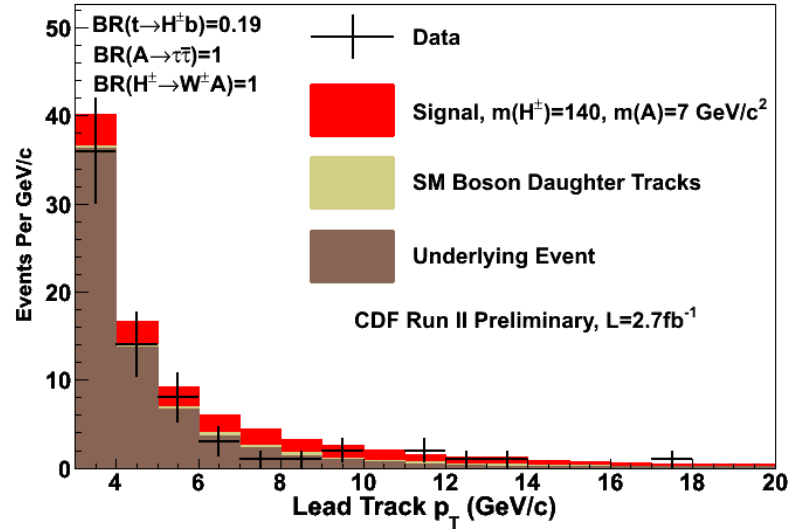


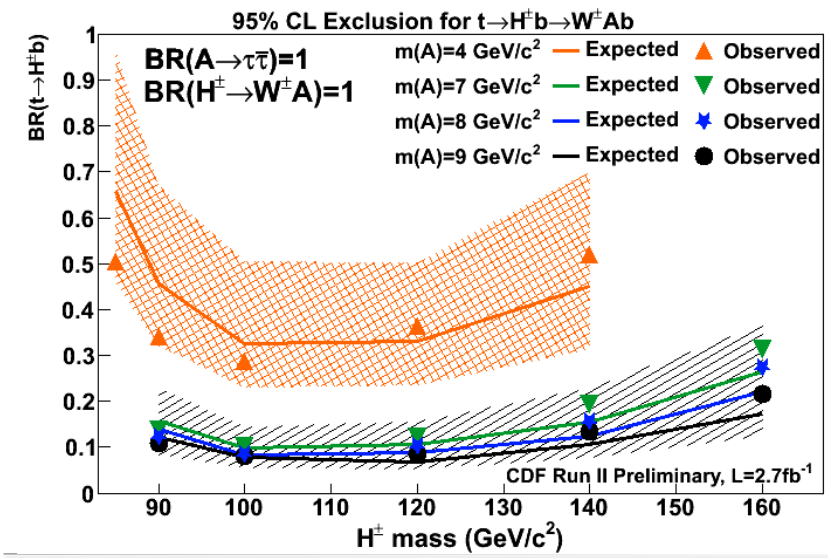
- Direct search done by D0 with **0.9 fb^{-1}** in decay channels H→cs and H→τν in ttbar lepton+jets and dilepton channels [Phys.Lett.B682:278-286,2009]
  - Divided in 14 channels, including tau decaying leptonically and hadronically, and bins of b-jets
  - Extracts limits for t→Hb by fixing tt̄ cross section or fiting it simultaneously



CP-odd Higgs

- Search for CP-odd Higgs A originating from top quark decays $t \to H^+ b \to W^+ A b$, and subsequently decaying into $A \to \tau\tau$
- Search done in the ttbar lepton+ channel with **2.7fb^{-1}** [Phys.Rev.Lett.107:031801, 2011]
  - Assumes the mass of the light pseudo-scalar Higgs boson is less than twice the b-quark mass,
  - Search for the presence of low-p_T tracks that could be attributed to τ -decay products.





New Gauge Bosons

- Searches for more gauge groups
  - New gauge groups would result in new gauge bosons

- Search for W' and Z' bosons
  - Need to make assumptions about couplings
  - Or need to do search as function of the couplings

W' boson

- W' heavy partner of the SM W boson
- Some models couple more strongly to fermions of the third generation than other generations
  - Constrains on W'→lν (currently $M_{W'} > 3.4$ TeV) assuming certain values of $M(\nu_R)$ for W' with purely right-handed couplings
- W' signal
  - W'_L bosons couple like the SM W, there is an interference between s-channel tb production via a W boson and via W'_L boson
  - W'_R can only decay leptonically if there is a right-handed neutrino ν_R such that $M(\nu_R) + M(l) < M(W'_R)$, or
  - W'_R would decay to top+b quarks if $M(\nu_R) > M(W'_R)$
- **W'→ tb search for a bump in the invariant mass tb spectrum**

	CDF 106pb^{-1}
$M(W'_L)$ (GeV)	NA
$M(W'_R)$ (GeV)	225-536
$M(W'_R)$ (GeV) only top	225-566

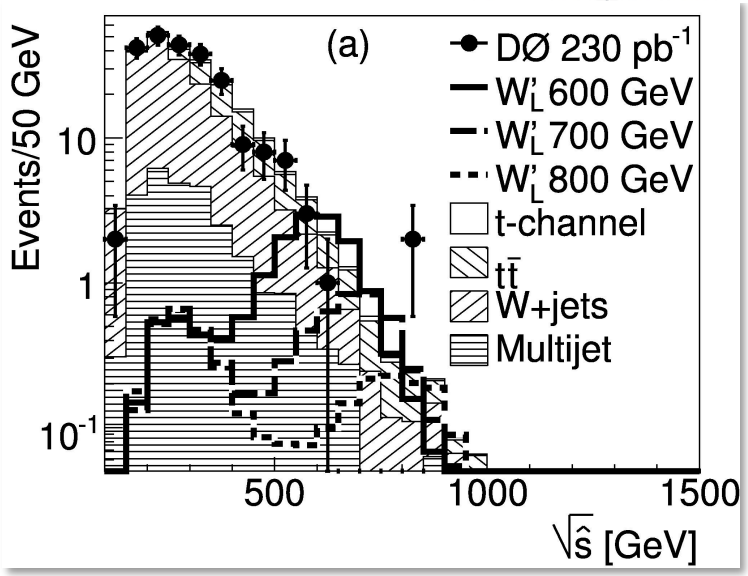
W' boson

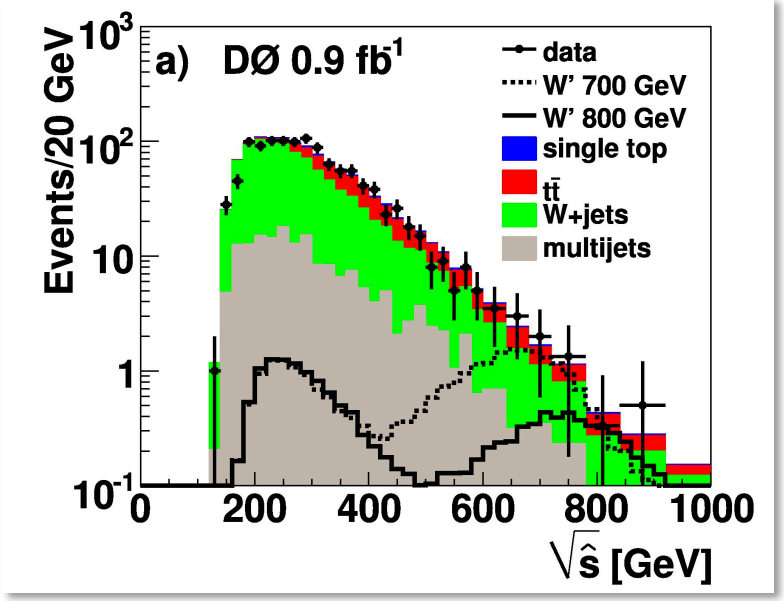
- Tevatron first search using top quarks sample (s-channel) with **230pb^{-1}**

  W'→ tb→Wbb→lvbb

- [Phys. Rev. D 72, 011104(R),2005; Phys.Lett.B641:423-431,2006]

- Followed with a result using **0.9fb^{-1}** [Phys.Rev.Lett. 100:211803,2008]

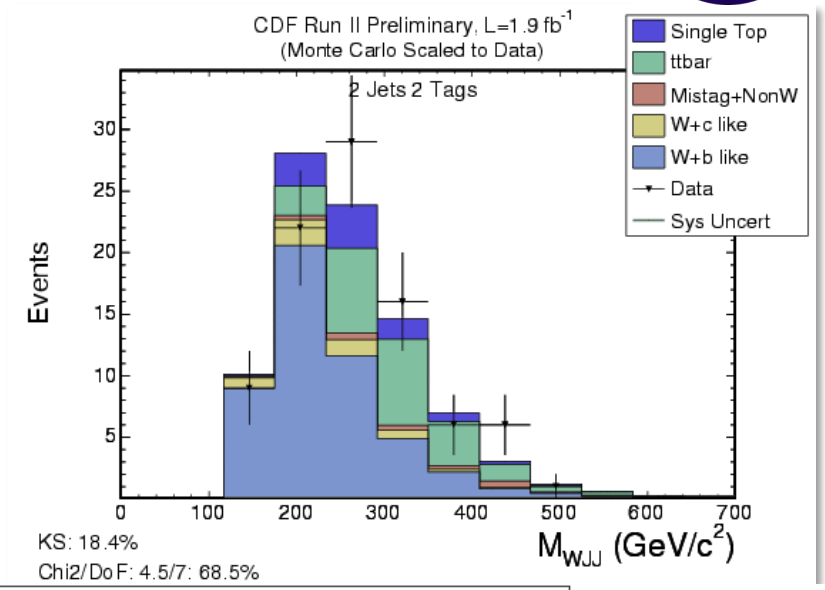


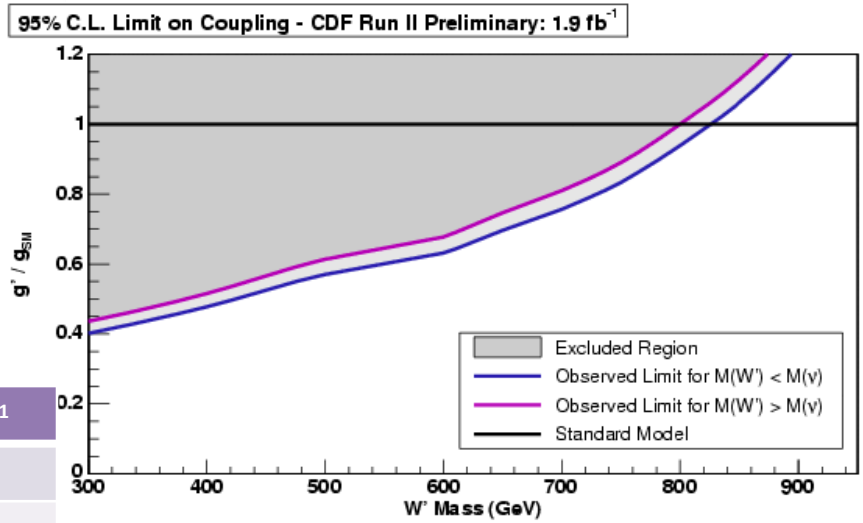


	CDF 106pb^{-1}	D0 230pb^{-1}	D0 0.9fb^{-1}
M(W'$_{L)}$ (GeV)	NA	200-610	731
M(W'$_{R)}$ (GeV)	225-536	200-630	739
M(W'$_{R)}$ (GeV) only top	225-566	200-670	768

W' boson

- CDF first W' search was with 1fb^{-1} a preliminary note followed by a result with **1.9fb^{-1}** [Phys.Rev.Lett. 103:041801,2009]
  - Divides sample in 2 and 3 jets and b-tag bins
  - Relaxes the assumption of the universal weak coupling, cross section limits can be rewritten as upper limits on $g_{W'}$ as a function of M(W')'

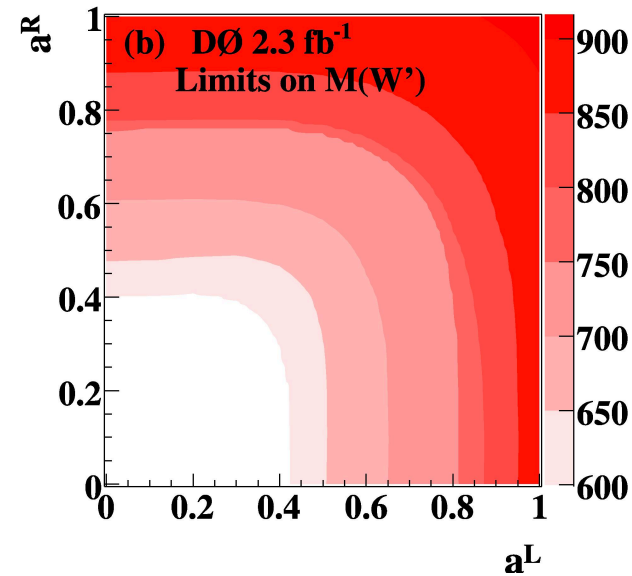


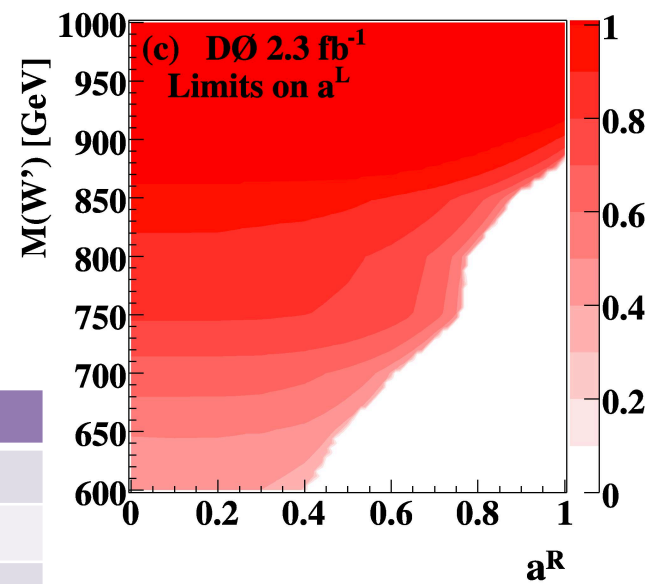


	CDF 106pb^{-1}	D0 230pb^{-1}	D0 0.9fb^{-1}	CDF 1.9fb^{-1}
M(W'$_{L)}$ (GeV)	NA	200-610	731	NA
M(W'$_{R)}$ (GeV)	225-536	200-630	739	800
M(W'$_{R)}$ (GeV) only top	225-566	200-670	768	825

W' boson

- D0 W' last search uses **2.3fb^{-1}** [Phys.Lett.B 699,145,2011]
  - Same dataset used for the single top observation
  - For left-handed W' includes interference with SM single top
- For the first time, limits are set for arbitrary combinations of left- and right-handed couplings of the W' boson to fermions
  - M(W') > 916 GeV if both couplings are present



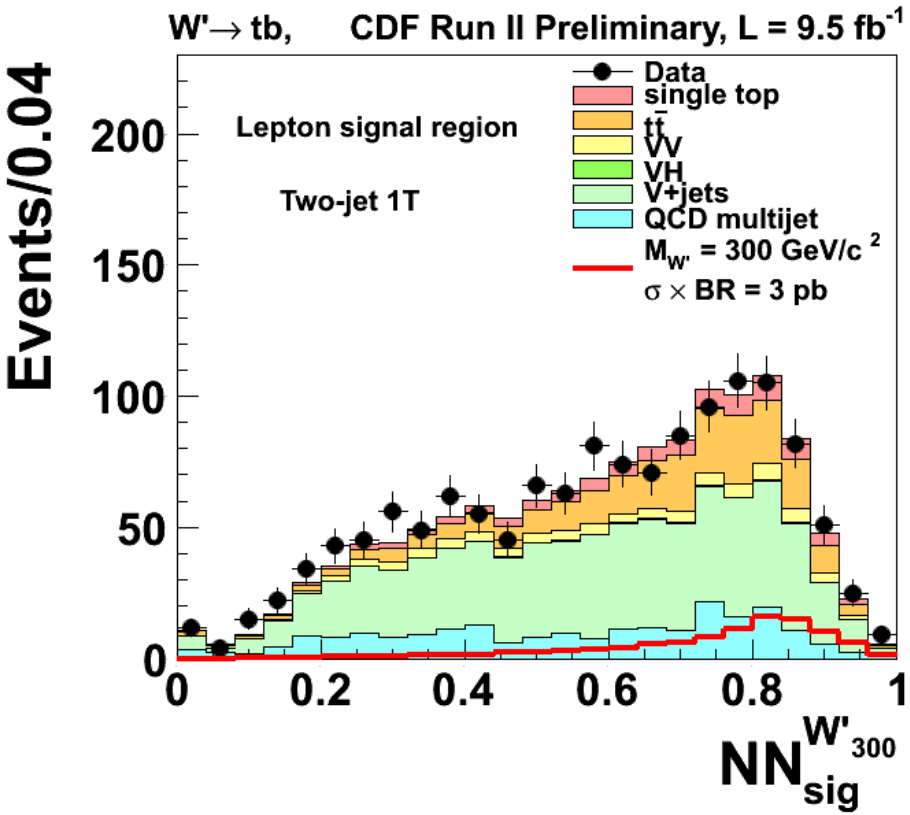


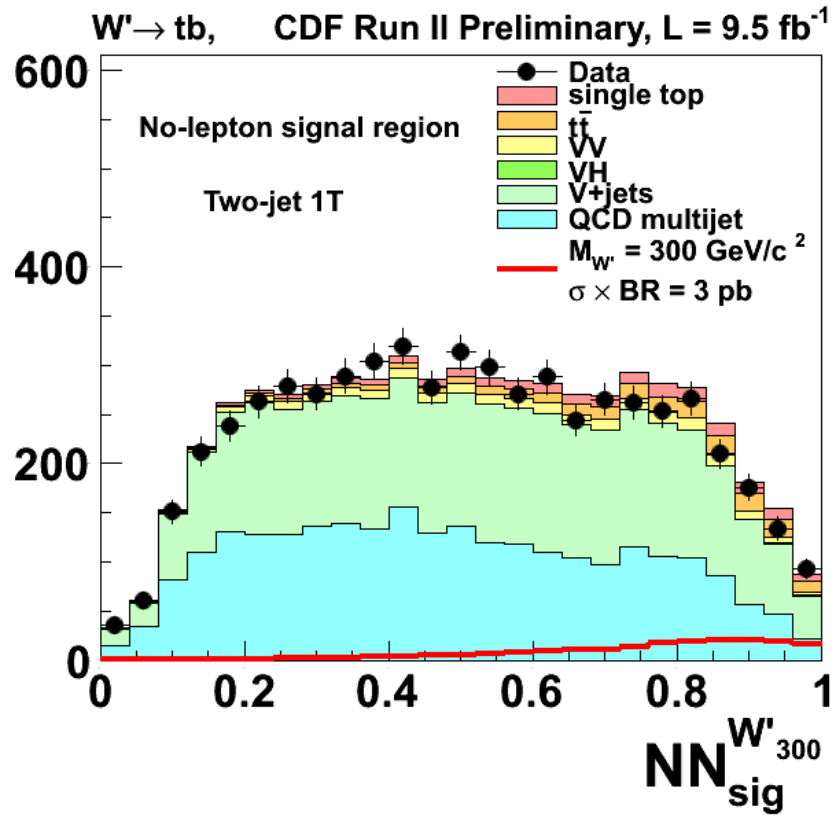
	CDF 106pb^{-1}	D0 230pb^{-1}	D0 0.9fb^{-1}	CDF 1.9fb^{-1}	D0 2.3fb^{-1}
M(W'$_{L)}$ (GeV)	NA	200-610	731		863
M(W'$_{R)}$ (GeV)	225-536	200-630	739	800	885
M(W'$_{R)}$ (GeV) only top	225-566	200-670	768	825	890

W' boson

Full Run II dataset

- Search using a MET trigger using **9.5fb^{-1}**: vetoing on leptons + including lepton
  - Includes a third jet of E_T>15 jet to increase acceptance to hadronic tau W decays
- Many NN to discriminate multijets and V+jets background and to extract signal

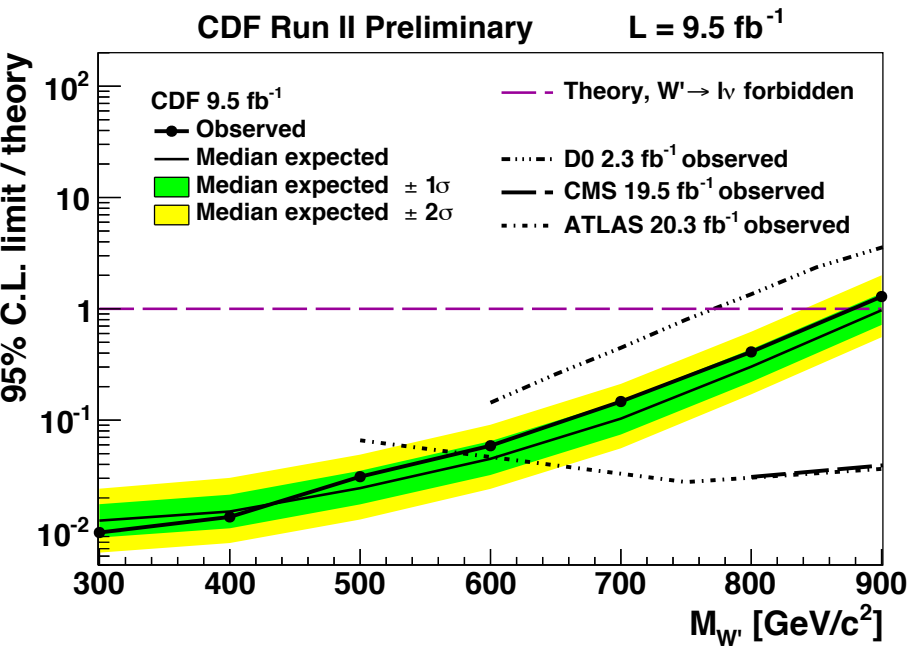


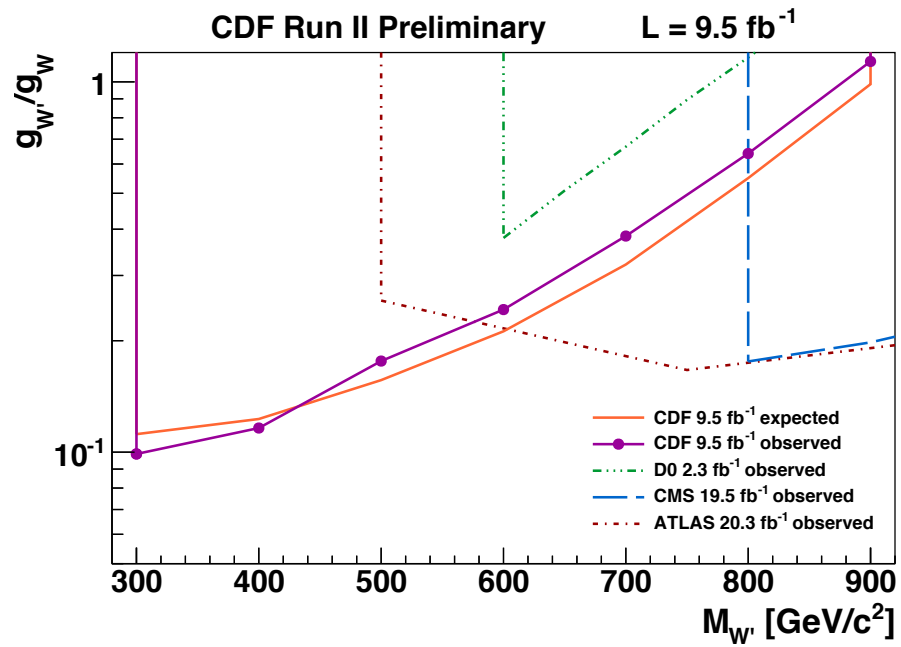


W' boson

Full Run II dataset

- Limiits on W' right handed
  - *In the lower mass region (M(W') < 700 GeV) the Tevatron experiments have competitive sensitivity due to the more favorable signal-to-background ratio in searches for particles produced in quark-initiated states, such as the W', with respect to the gluon-initiated dominant SM background processes*
- Submitted to PRL on Tuesday!





Z' boson

- Many BSM theories predict the existence of new particles that decay to ttbar
  - Topcolor, chiral color models, Randall–Sundrum models with warped extra dimensions, etc.

- At the Tevatron the most used theoretical benchmark:
  - Narrow resonance(*) (topcolor, leptophobic (Z')) with $\Gamma_{Z'}/m_{Z'}$=1.2%

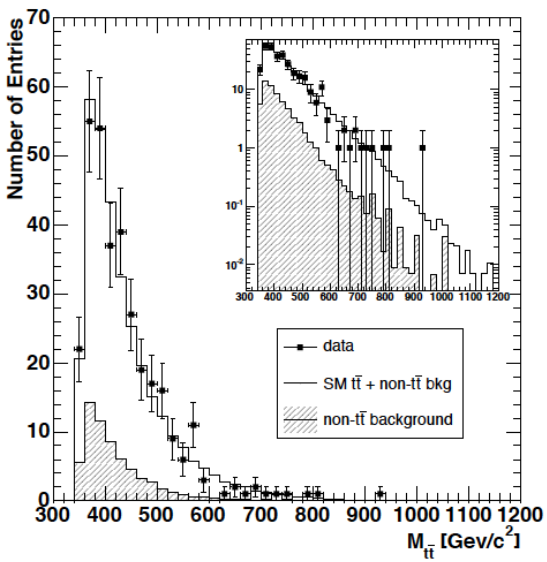
- **Search for enhancement in the invariant mass ttbar spectrum**

	CDF 106 fb^{-1}	D0 130 fb^{-1}
M(Z') (GeV)	480	560

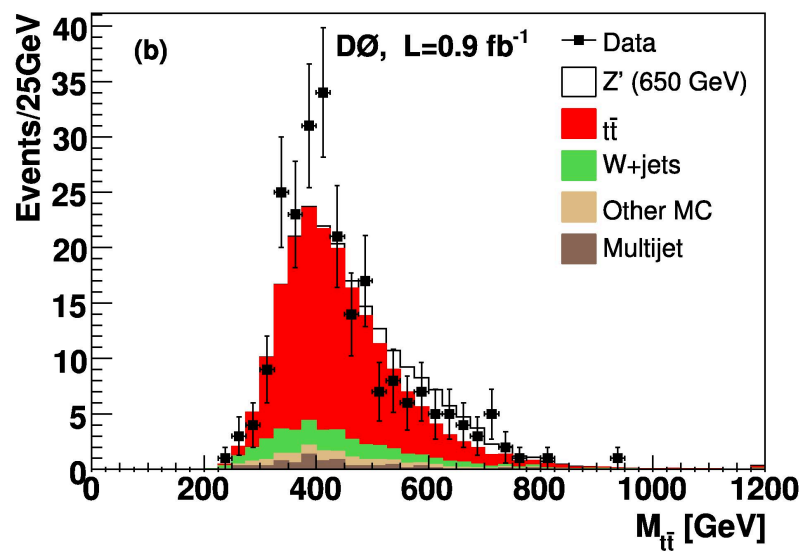
Z' boson

- First searches done used the lepton+jets sample and reconstruct ttbar using a kinematic fitter

- CDF search with **955pb^{-1}** [Phys.Rev.D77:051102,2008]



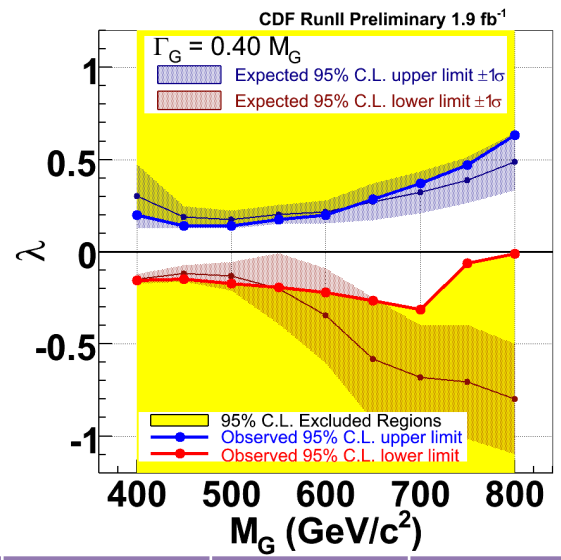
- D0 search with **0.9fb^{-1}**, [Phys.Lett.B668,98-104,2008]



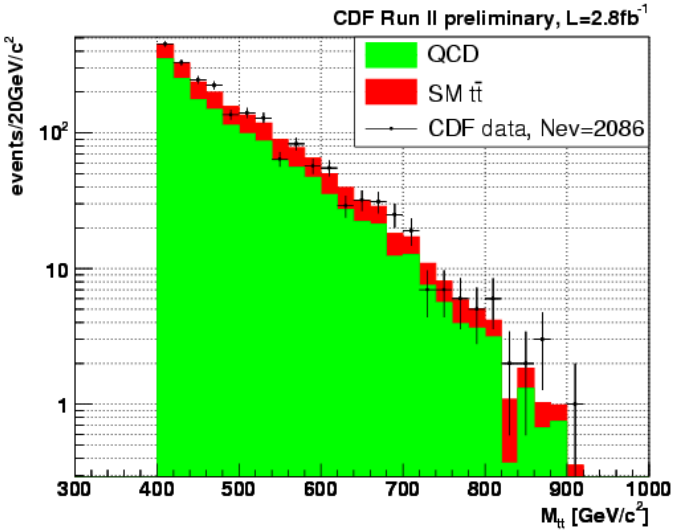
	CDF 106 fb^{-1}	D0 130 fb^{-1}	CDF 955pb^{-1}	D0 0.9fb^{-1}
M(Z') (GeV)	480	560	720	700

Z' boson

- CDF uses a matrix-element based method to reconstruct M(ttbar) with **1.9fb^{-1}** [Phys.Lett.B691:183-190,2010]
  - With the lepton+jets sample sets limits on the strength of the couplings of the massive gluon G



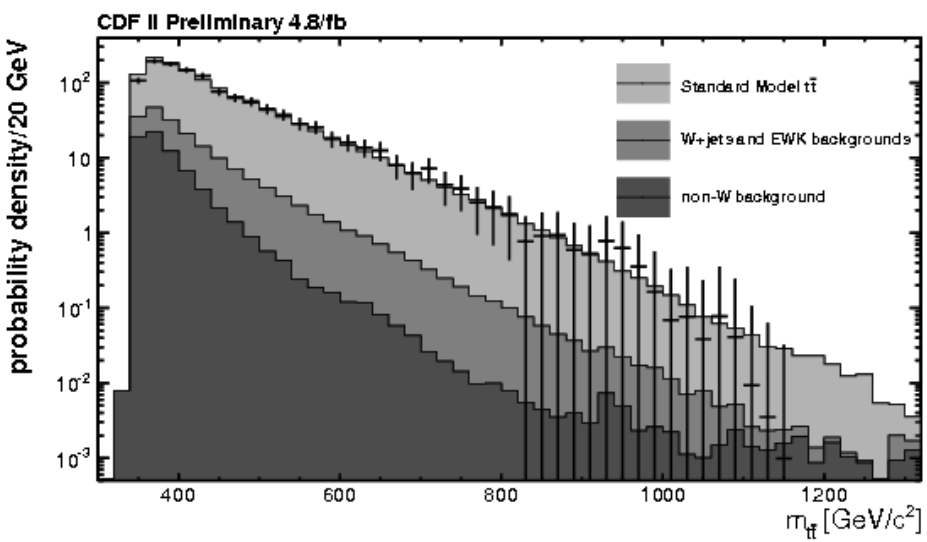
- CDF search in all hadronic channel using **2.8fb^{-1}** [Phys.Rev.D.84.072003,2011]
  - Use Matrix-Element to improve resolution adn NN to separate QCD background

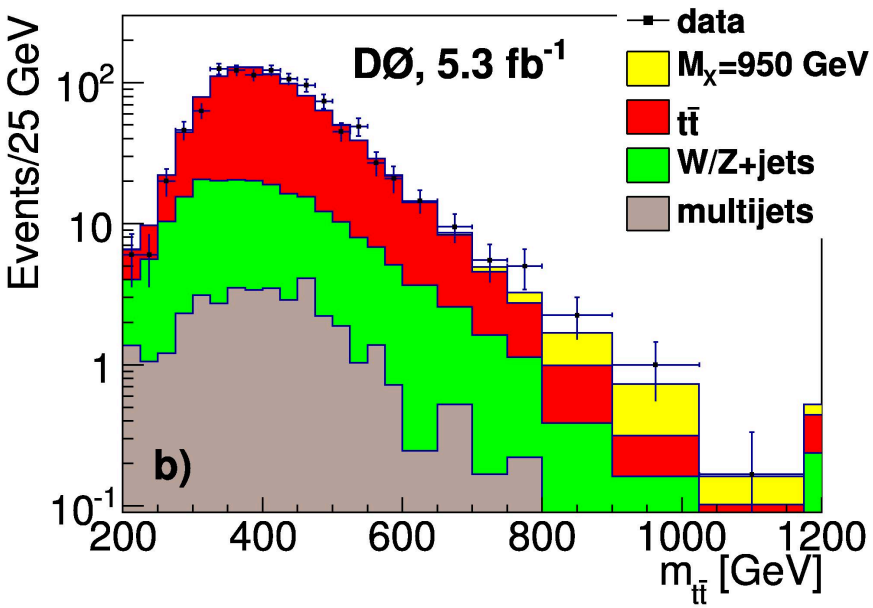


	CDF 106 fb^{-1}	D0 130 fb^{-1}	CDF 955pb^{-1}	D0 0.9fb^{-1}	CDF 1.9fb^{-1}	CDF 2.8fb^{-1}
M(Z') (GeV)	480	560	720	700	plot	805

Z' boson

- CDF lepton + jets **4.8fb^{-1}** [Phys.Rev.D84,072004,2011]
- D0 **5.3fb^{-1}** l+jets [Phys.Rev.D85,051101,2012]



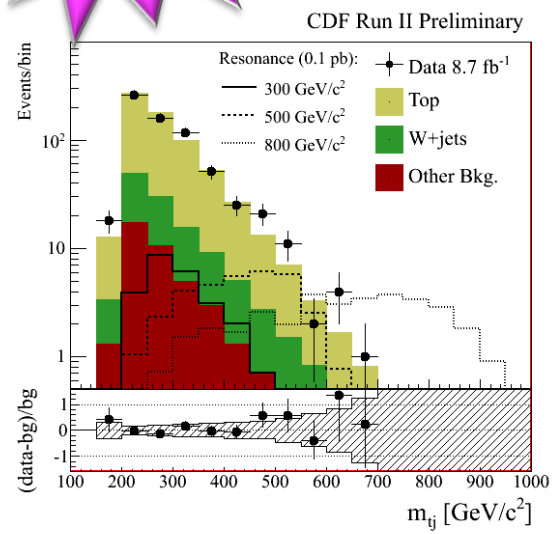


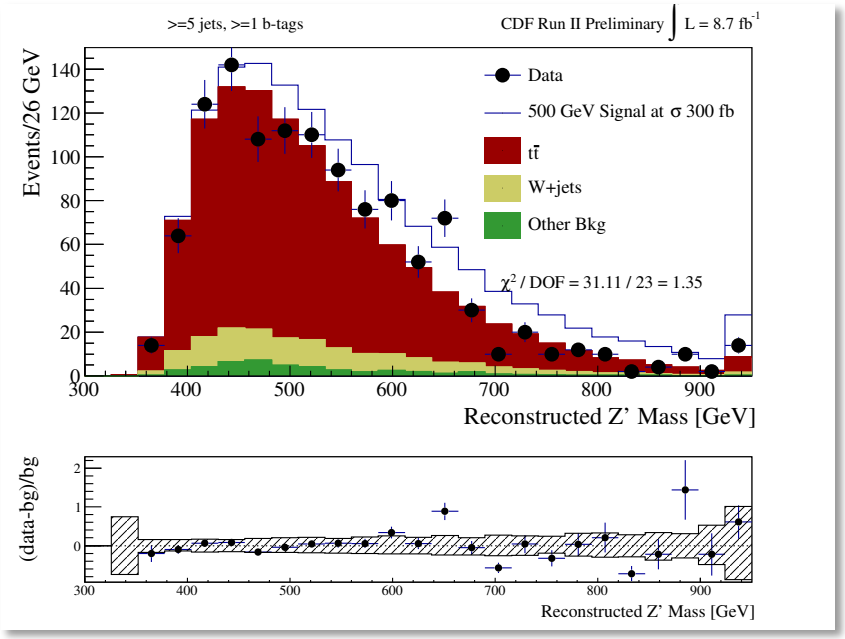
	CDF 106 fb^{-1}	D0 130 fb^{-1}	CDF 955pb^{-1}	D0 0.9fb^{-1}	CDF 1.9fb^{-1}	CDF 2.8fb^{-1}	CDF 4.8fb^{-1}	CDF 5.3fb^{-1}
M(Z') (GeV)	480	560	720	700	plot	805	900	835

Z' boson

Full Run II dataset

- Search for resonance in tt+jet produced by pp→tM with M→tq, where q stands for up quarks and down quarks. Done with **8.7fb^{-1}** [Phys.Rev.Lett. 108:211805,2012]
  - A new mediating particle M introduced to explain the Afb discrepancy seen at the time
  - Use kinematic fitter to choose tt jet pairing, all light jets remaining paired with t and tbar to reconstruct M(tj)



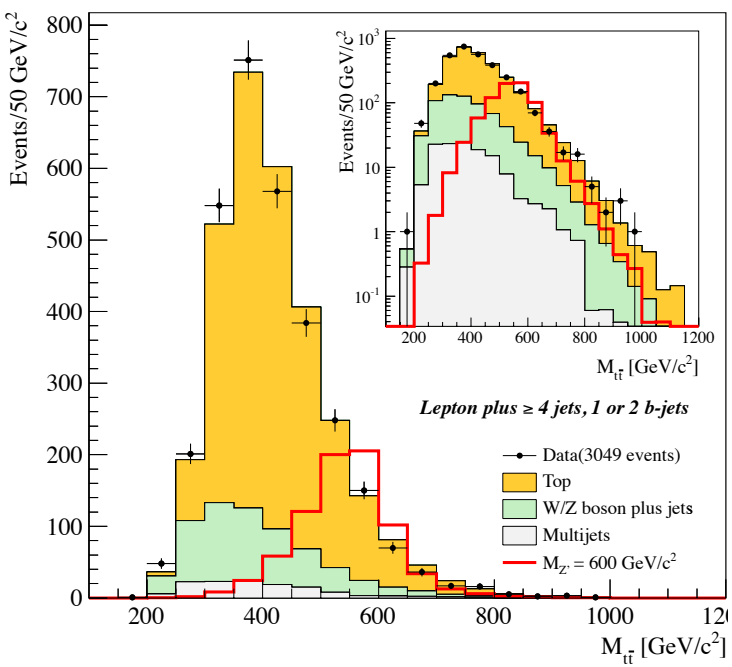


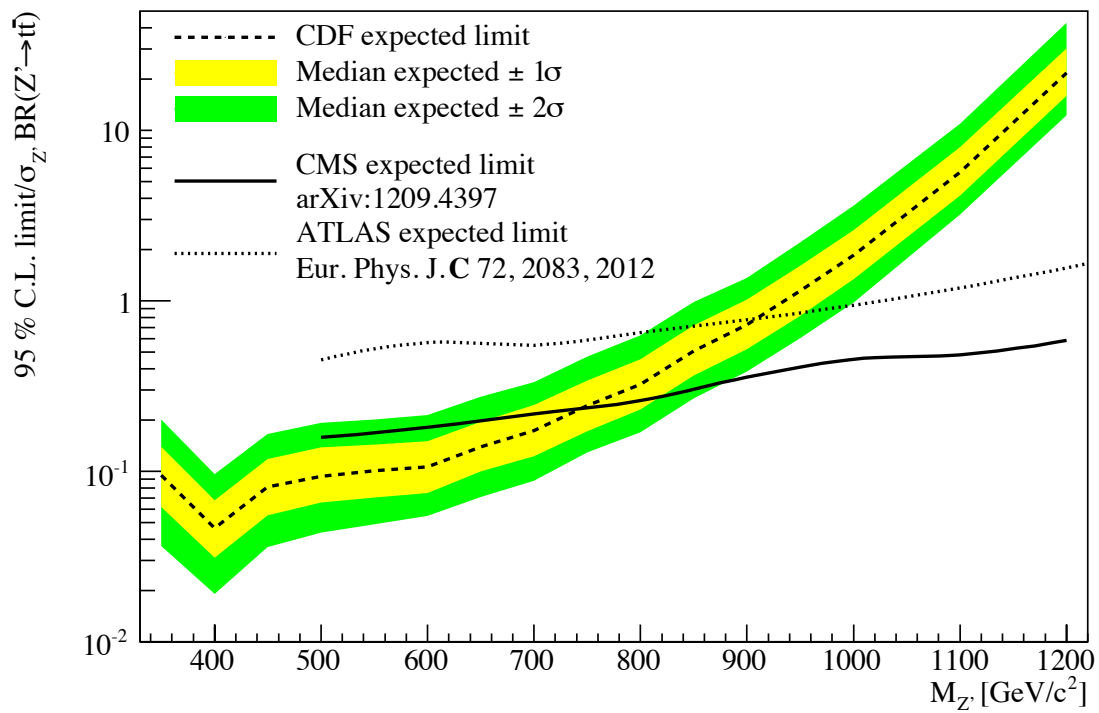
- Search for a chromophilic Z' → g*g where the off-shell gluon g*→ttg→WbWbg using **8.7fb^{-1}** of data in the lepton + jets channel [Phys.Rev.D. 86.112002, 2012]

Z' boson

Full Run II dataset

- Exclude **M(Z') < 915 GeV**
- For masses below 750 GeV it yield the most constraining limits until last year [Phys.Rev.Lett.110:121802,2013]





Vector Like Quarks

- Proposed in extensions of SM to address the naturalness problems
  - Little Higgs, Composite Higgs, etc. *natural models*

- VLQ means left and right handed components transform identically under $(SU2)_L$

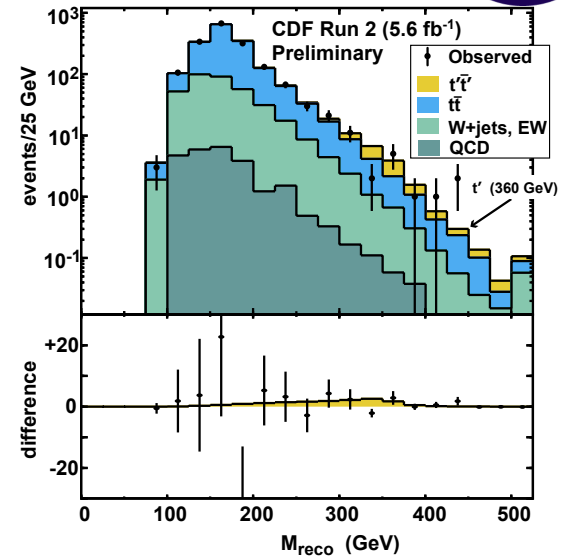
- Predominantly VLQ decay to third generation

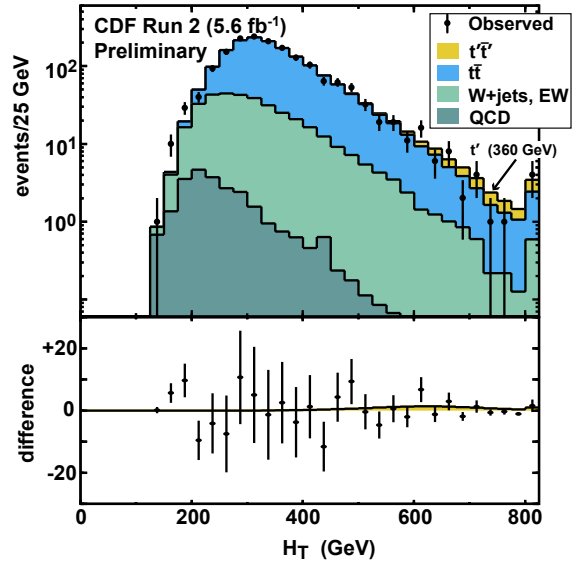
- Both charged and neutral decays can occur
  - Searches at the Tevatron only on pair production of B' ➔Wt or T' ➔Wb

T' quark

- CDF first search T'T'→WbWb→lvbqqb **760pb^{-1}** [Phys.Rev.Lett.100:161803,2008]
  - Assumes B(T'→Wq)=100%
  - No b-tagging
  - H_T calculated with lepton and jets
  - m_{fit} kinematic fit to the T'T'→lepton +jets hypothesis reconstructs the mass of the T' quark
  - **$M_{T'}$> 256 GeV**

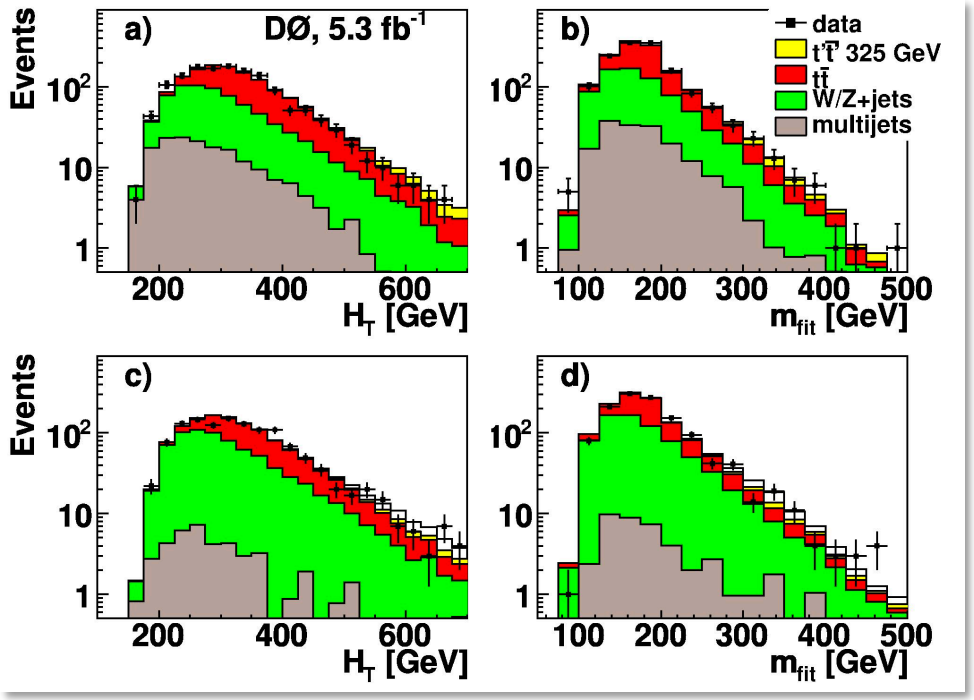
- CDF updates method with **5.6fb^{-1}** [Phys. Rev. Lett. 107, 261801,2011]
  - **$M_{T'}$> 358 GeV**
  - And with b-tagging:
  - **$M_{T'}$> 340 GeV** for B(T'→Wb)





T' quark

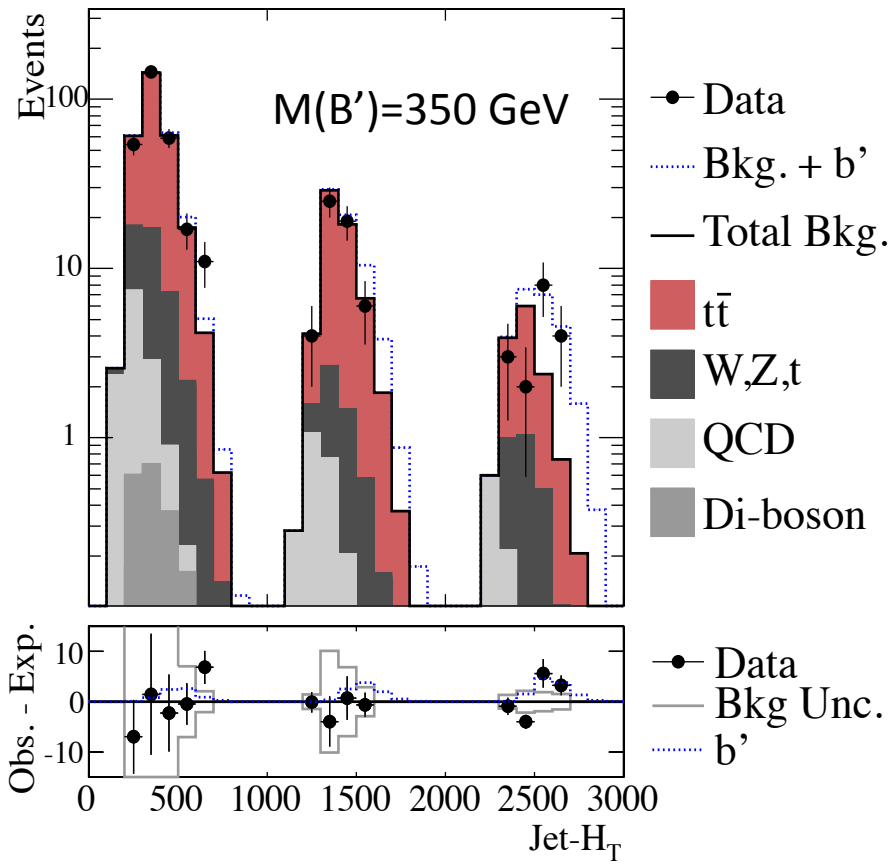
- D0 first search in search T'T'→WbWb→l+jets **5.3fb^{-1}** [Phys.Rev.Lett. 07, 082001,2011]
  - Observes a 2.5σ excess in the μ+jets channel which reduce the mass range excluded compared to the expected limit of 320 GeV in the absence of a signal
  - **$M_{T'}$> 285 GeV**



B' quark

- B'B' (or $T_{5/3}T_{5/3}$)→tWtW search using same sign dilepton with **2.7fb^{-1}** [Phys. Rev. Lett.104, 091801,2010]
  - Assume B(B'→tW)=100%
  - M(B') > M(t) + M(W)
  - **M(B') >338GeV**
  - **M($T_{5/3}$) >365GeV**

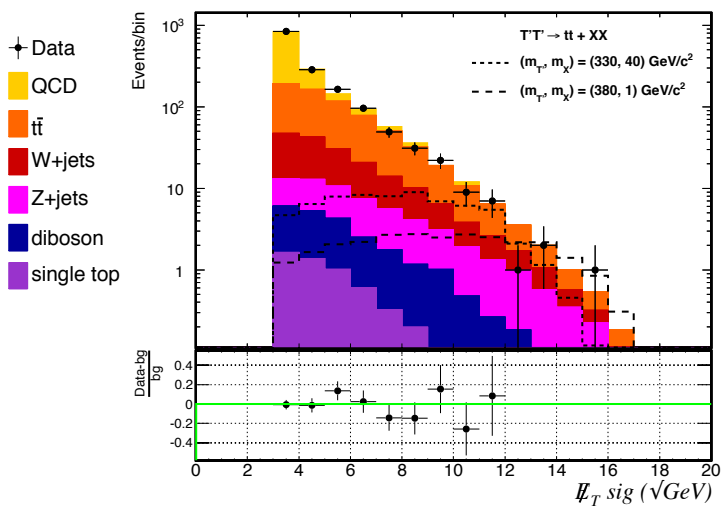
- B'B'→tWtW search done with **4.8fb^{-1}** in lepton+jets channel [Phys.Rev.Lett.106:141803,2011]
  - Introduce "Jet-H_T" variable -5 jets = H_T, 6 jets H_T+1000 GeV, 7 jets H_T+2000 GeV
  - **M(B') >372 GeV**



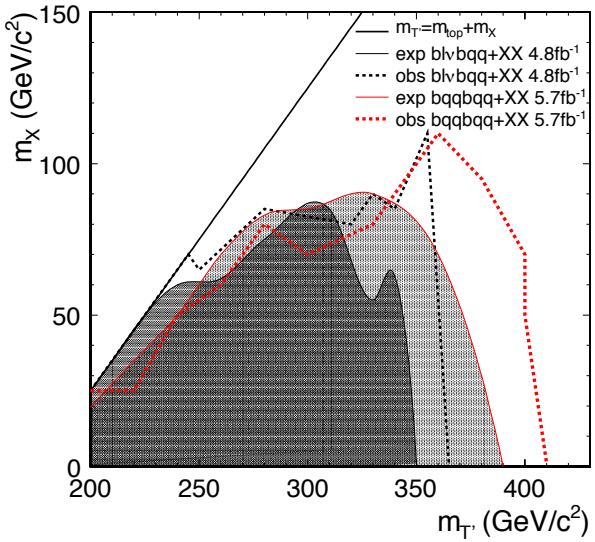
T’ / Dark matter

Search for a fourth generation up-type quark T’ which decays to a top quark and dark matter, T’ → t + X

- With **4.8fb^{-1}** in the lepton+jets channel [Phys.Rev.Lett. 106:191801,2011]
  - **$M_{T'}$>360 GeV for m_X≤100 GeV**



- Similar search done in the all hadronic channel with **5.7fb^{-1}** [Phys.Rev.Lett.107:191803,2011]
  - **$M_{T'}$ > 400 GeV for m_X ≤70 GeV**

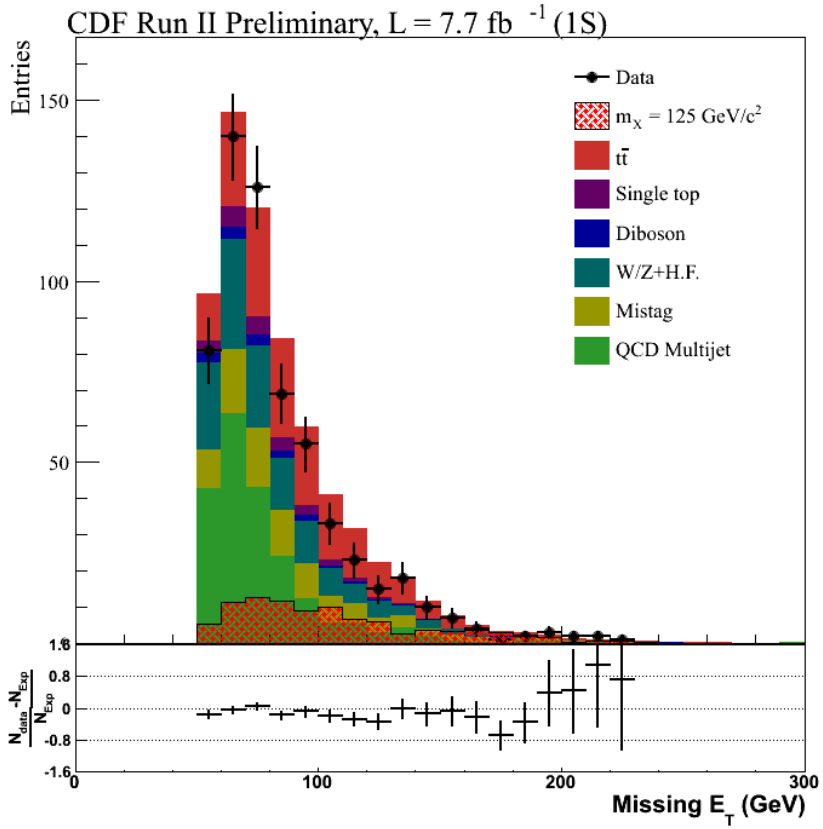


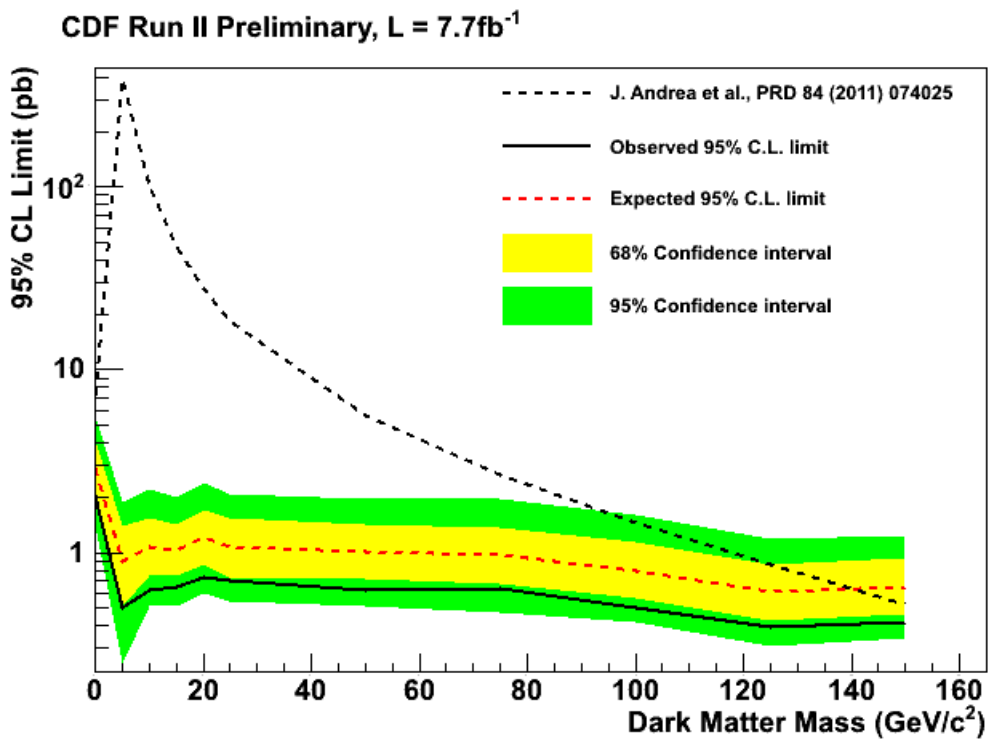
Dark matter

Full Run II dataset

- First search for dark matter associated with top quarks using CDF almost full dataset **7.7fb^{-1}**
  - Monotop + X: pp → t+X → bW + MET → bjj + MET

  [Phys. Rev. Lett.108,201802,2012]



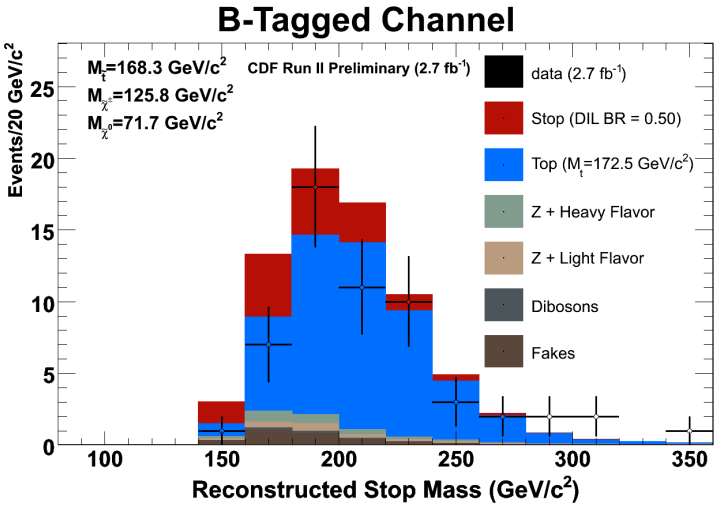


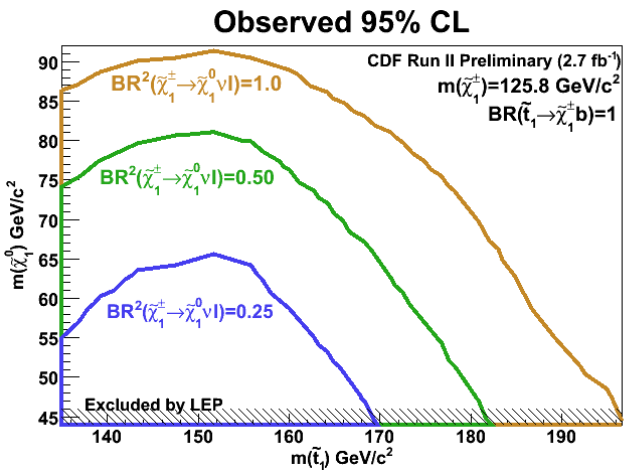
Stop

- Search for pair production stop mimicking top events signatures

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm} \rightarrow b\tilde{\chi}_1^0 W^{\pm(*)} \rightarrow b\tilde{\chi}_1^0 l\nu$$

- Premilinary result done with 1.9fb^{-1} and published with **2.7fb^{-1}** [Phys.Rev.Lett.104:251801,2010]
  - Use the dilepton sample
  - Reconstruct stops using the kinematic fitter
  - Produce limits on cross section for stop masses between 115 GeV and 197 GeV





Summary

- Tevatron pioneered the searches for new particles using top quarks
  - Most of the results shown have been superseded by LHC
- The search program using top moved to LHC where it flourished during the 7 and 8 TeV run and is expected to produce interesting results in the coming Run II