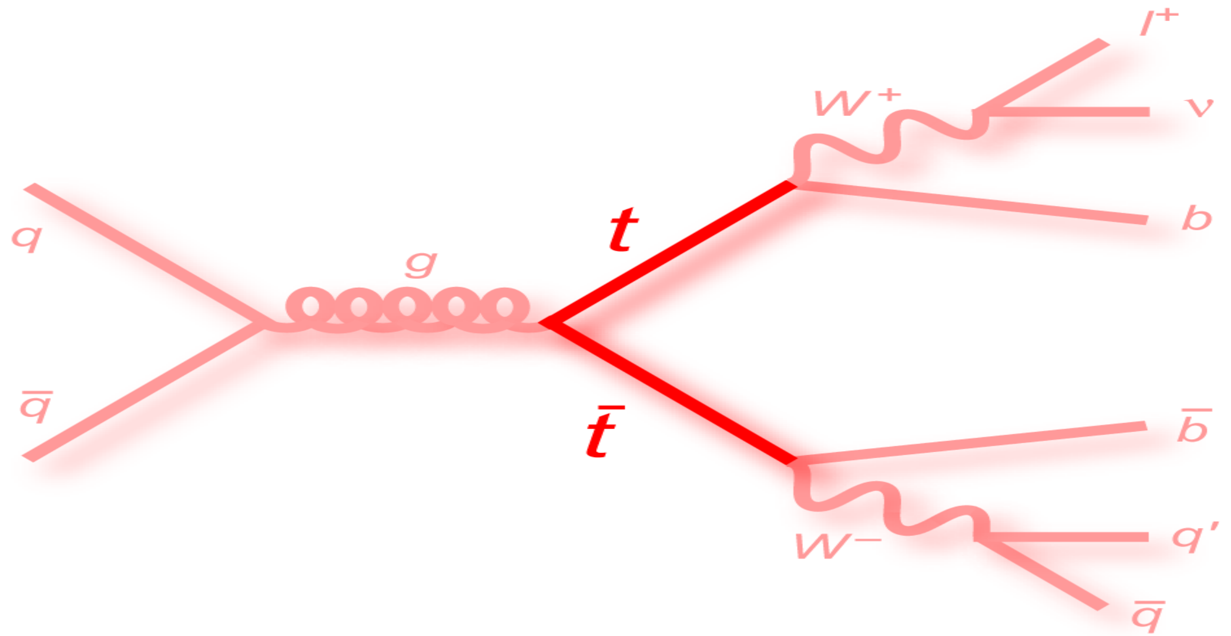
The Top Quark and search for new physics at the Tevatron.



The top-quark at the Tevatron

- Top-quark
  - At 170GeV it is the heaviest fundamental particle known (yet?).
  - Measurement of top-quark properties is an excellent test of the SM
  - The top-quark sector is sensitive to new physics like a fourth generation of quarks or BSM vector bosons etc
- Tevatron
  - High energy $p\bar{p}$ collisions at $\sqrt{s} = 1.96 TeV$
  - Discovered the top-quark in the early 90s.

The top-quark at the Tevatron

- Top-quark properties
  - Forward-backward asymmetry
  - Spin Correlation measurement
  - Boosted top measurement
  - W-boson helicity measurement
- Beyond the Standard Model Searches
  - Search for flavor changing neutral currents in top decays.
  - Fourth generation, t'
  - Exotic fourth generation with dark matter, T'

Top-quark properties

Forward-backward asymmetry.

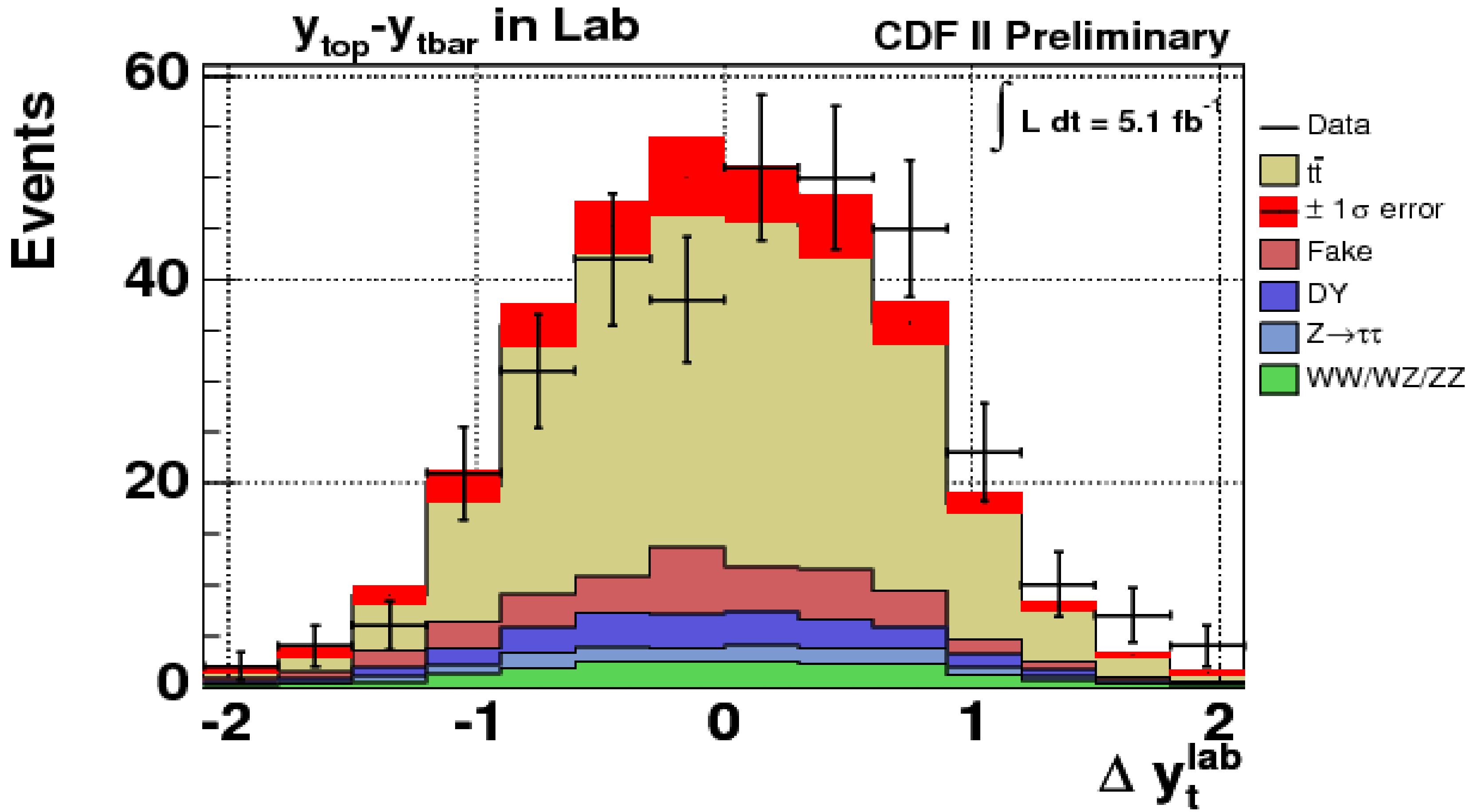
- Observed forward-backward asymmetry in top-quark pair production at the Tevatron.
- At the Tevatron, color-charge asymmetry is observable as forward-backward symmetery

$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}.$$

- Predicted by NLO QCD, but a small effect 5-10%
- Many BSM models predict such asymmetry, eg Z'

Forward-backward asymmetry: CDF

- **Analysis in dilepton channel with 5.1/fb of data.** [Conf Note:March, 2011]
- **Positive asymmetry observed: Af-b (data) = 0.14 ± 0.05(stat)**



Forward-backward asymmetry: CDF

- **Positive asymmetry observed in all dilepton channels: e-e, mu-mu and e-mu.**
- **Result(background-subtracted):**

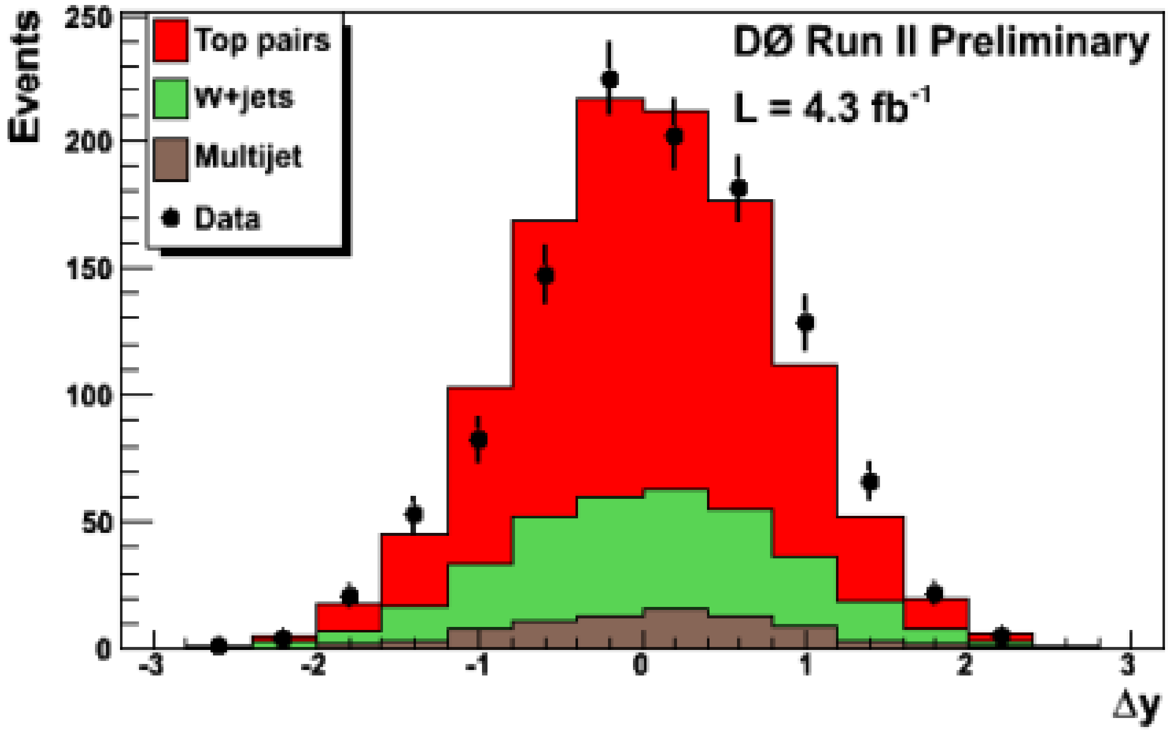
$$A_{fb} = 0.42 \pm (0.15)^{stat} \pm (0.05)^{syst}$$

2.3 sigma from SM prediction of 0.06

Forward-backward asymmetry: D0

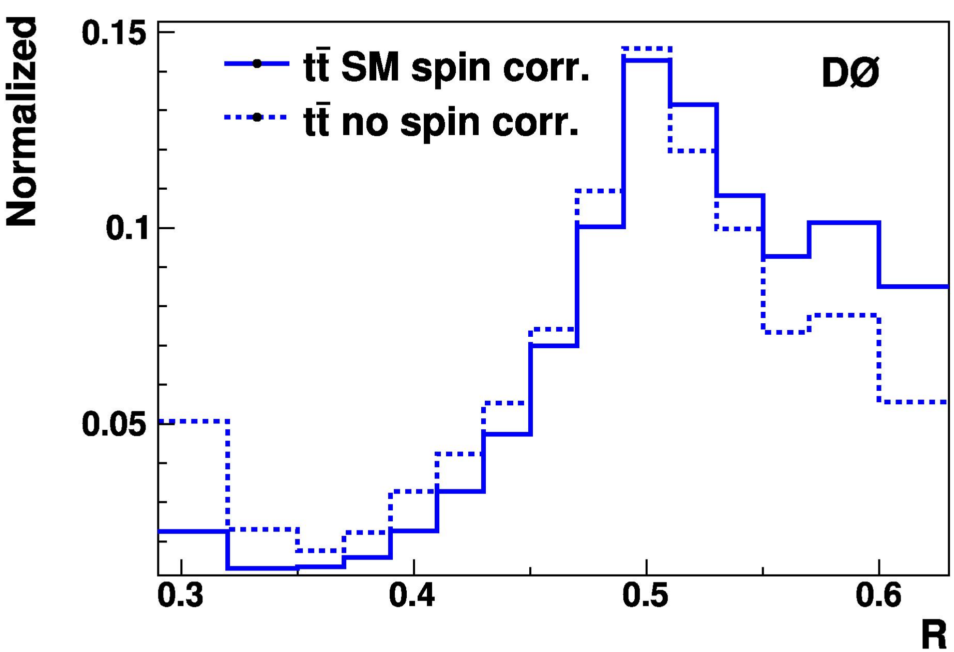
- **Lepton + jets channel and 4.3/fb of data.**
- **Report asymmetry:** $A_{fb} = (8 \pm 4\,(\mathrm{stat}) \pm 1\,(\mathrm{syst}))\,\%$

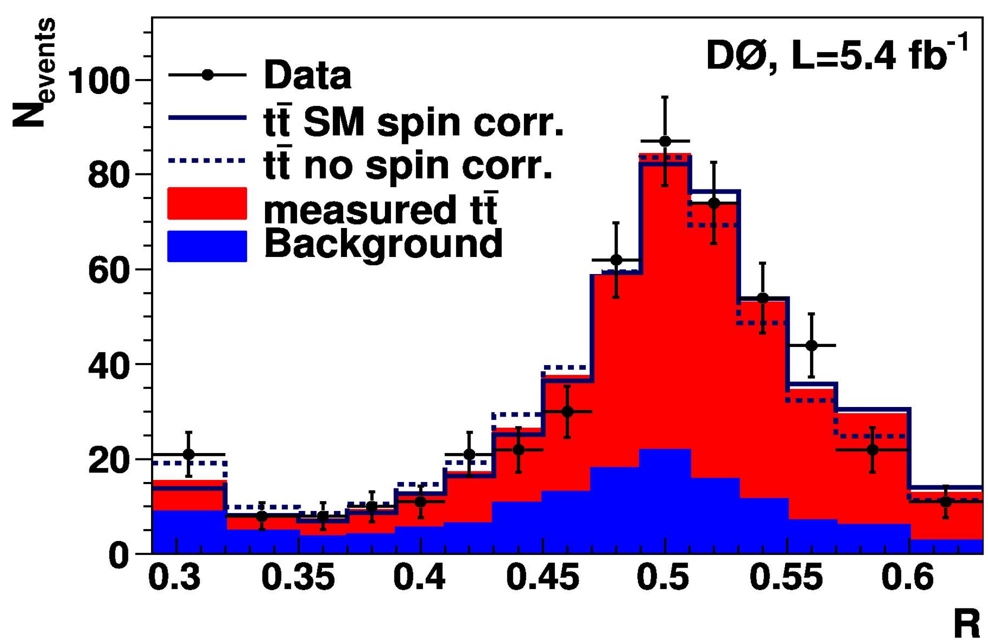
$$A_{fb}^{pred} = (1^{+2}_{-1}(\mathrm{syst}))\%.$$



Spin Correlation

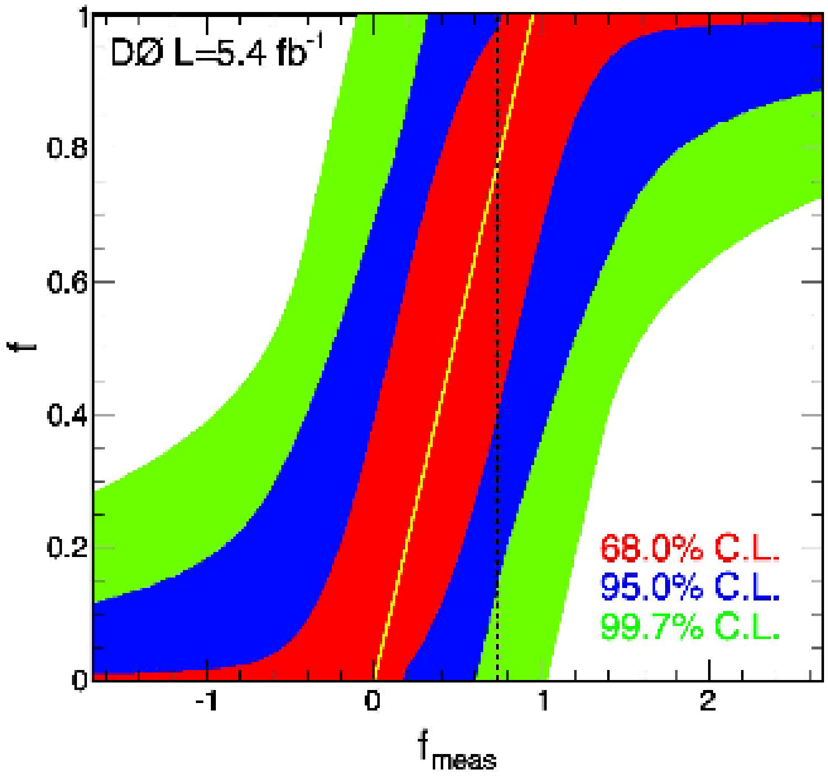
- **Measurement of spin correlation in ttbar production in dilepton channel with 5.4/fb of data**
- **Matrix-element based discriminant,** $$R = \frac{P_{\rm sgn}(H=c)}{P_{\rm sgn}(H=u) + P_{\rm sgn}(H=c)},$$





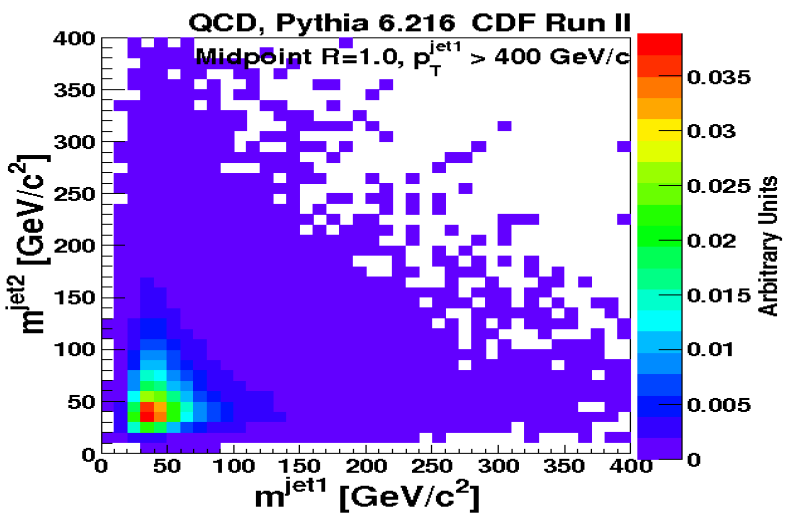
Spin Correlation

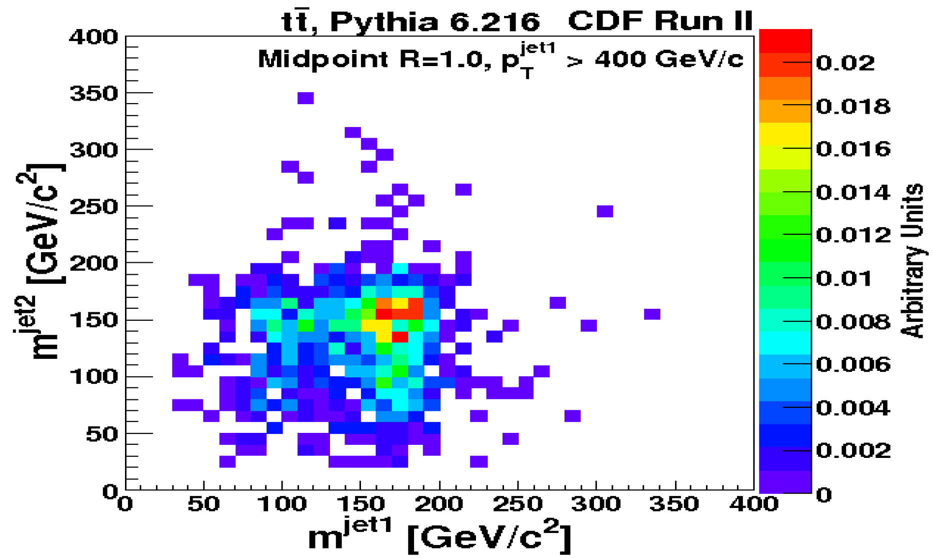
- Measure fraction of correlated events, $f_{\mathrm{meas}} = 0.74^{+0.40}_{-0.41}\,(\mathrm{stat{+}syst})$.
- Consistent with SM, exclude f=0 hypothesis at 97.7% C.L.
- Correlation strength = 0.57 ± 0.31 (stat+syst), most precise value to date.



Boosted top search.

- Motivation
  - Good cross check for the Standard Model, and validates Monte Carlo modeling.
  - Will be important to understand at the LHC, more high energy tops.
- For a high enough pT the top-quark will decay in to a single jet cone.
- Main background is massive jets from QCD.



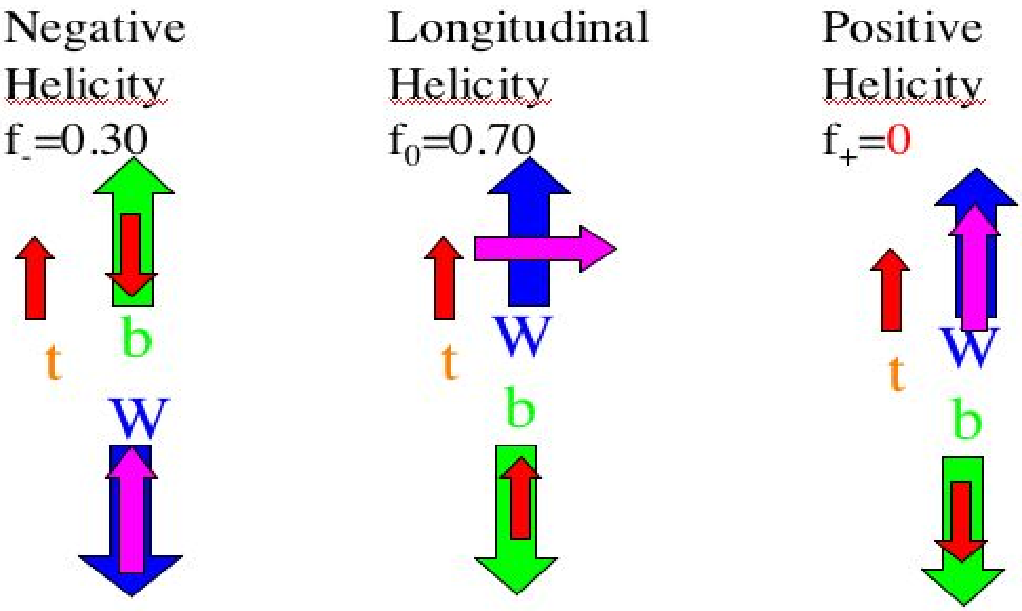


Boosted tops: Results

- Conference note posted in January 2011
- Observed 58 candidate events, estimated 44±15.4 background events and approximately 5 signal events from Standard Model top quark production.
- The data are not sufficiently significant to support a claim for observation of top quark production.
- 95% C.L. Upper limit on SM Top quark production with pT > 400 GeV at 40 fb
- 95% C.L. Upper limit on heavy object pair Production with pT > 400 GeV in Hadronic Channel at 20 fb

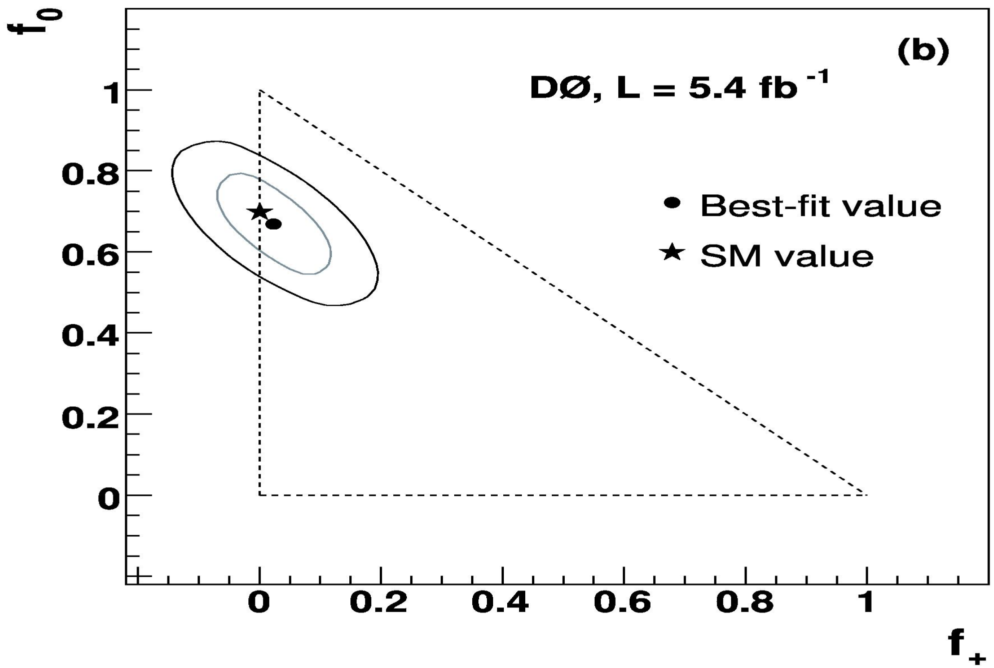
W boson helicity measurements.

- **Measurement W-boson helicity in top quark decays is a great test of the Standard Model.**
- **SM V-A tWb coupling only allows for negative or longitudinal W-boson helicity.**



W boson helicity:Results

- **Modeling: reweighted V-A and V+A coupling assumptions to yield** f_0, f_+ **from 0 to 1.0 in 0.1 increments. (Model-independent assumptions)**

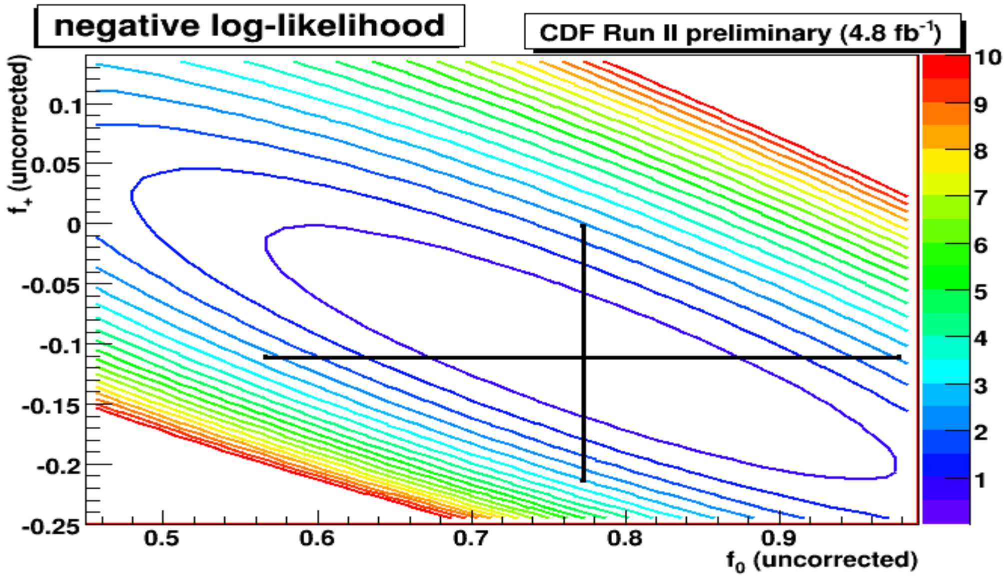


- **Results:** $f_0 = 0.669 \pm 0.102[\pm 0.078(stat) \pm 0.065(syst)]$
  $f_+ = 0.023 \pm 0.053[\pm 0.041(stat) \pm 0.034(syst)]$
- **Consistent with SM**

W boson helicity: Results

- **1D fits:**
  - **Assuming SM f+ = 0.0 →** $f_0 = 0.62 \pm 0.11(stat.) \pm 0.06(syst.)$
  - **Assuming SM f0 = 0.7 →** $f_+ = -0.07^{+0.06}_{-0.05}(stat.) \pm 0.03(syst.)$
- **Simultaneous measurement:**

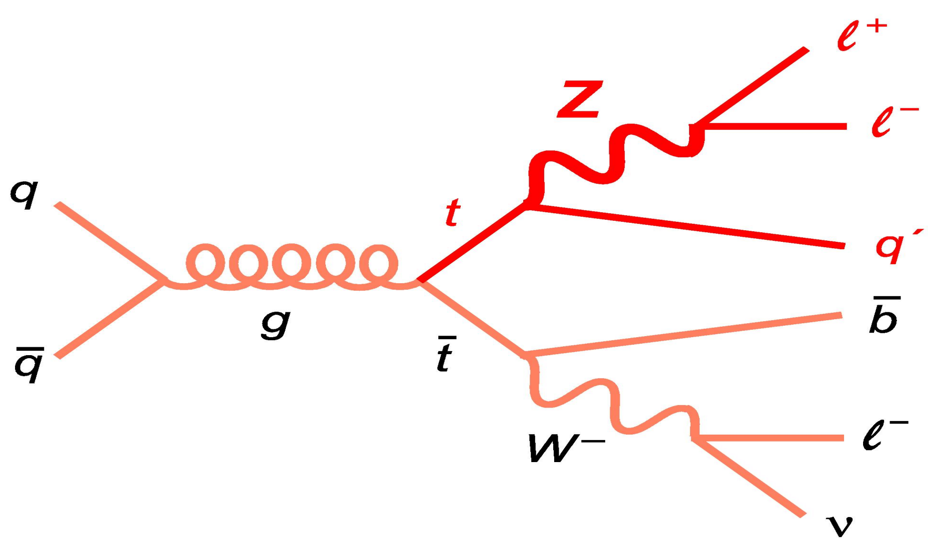
$$f_0 = 0.78^{+0.19}_{-0.20}(stat.) \pm 0.06(syst.)$$
$$f_+ = -0.12^{+0.11}_{-0.10}(stat.) \pm 0.04(syst.)$$



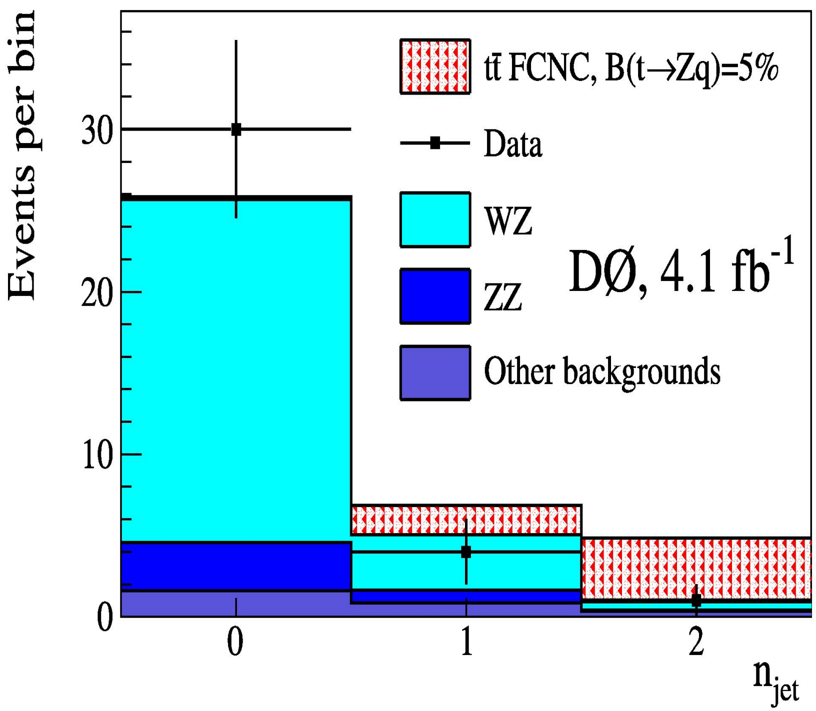
Searches for new physics

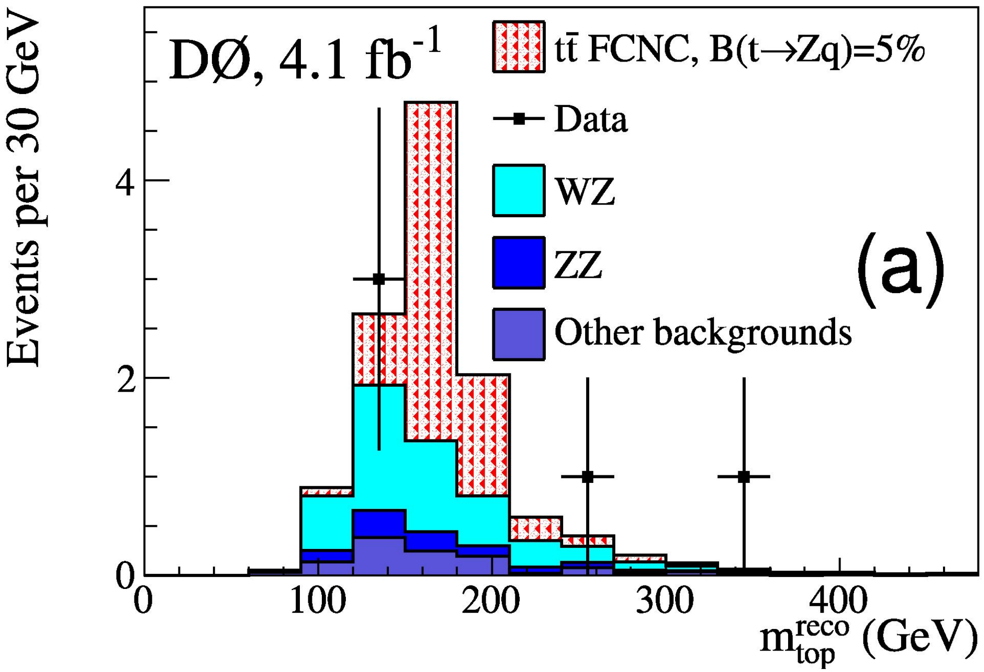
FCNC in top decays.

- Flavor changing neutral currents (FCNC) allow for transitions between quarks of different flavor but same electric charge.
- Sensitive indicators of BSM as FCNC are suppressed in the SM
- Look for $B(t \to Zq)$ (q = u or c quarks), assuming anomalous tZu, tZc couplings.



FCNC in top decays: Result

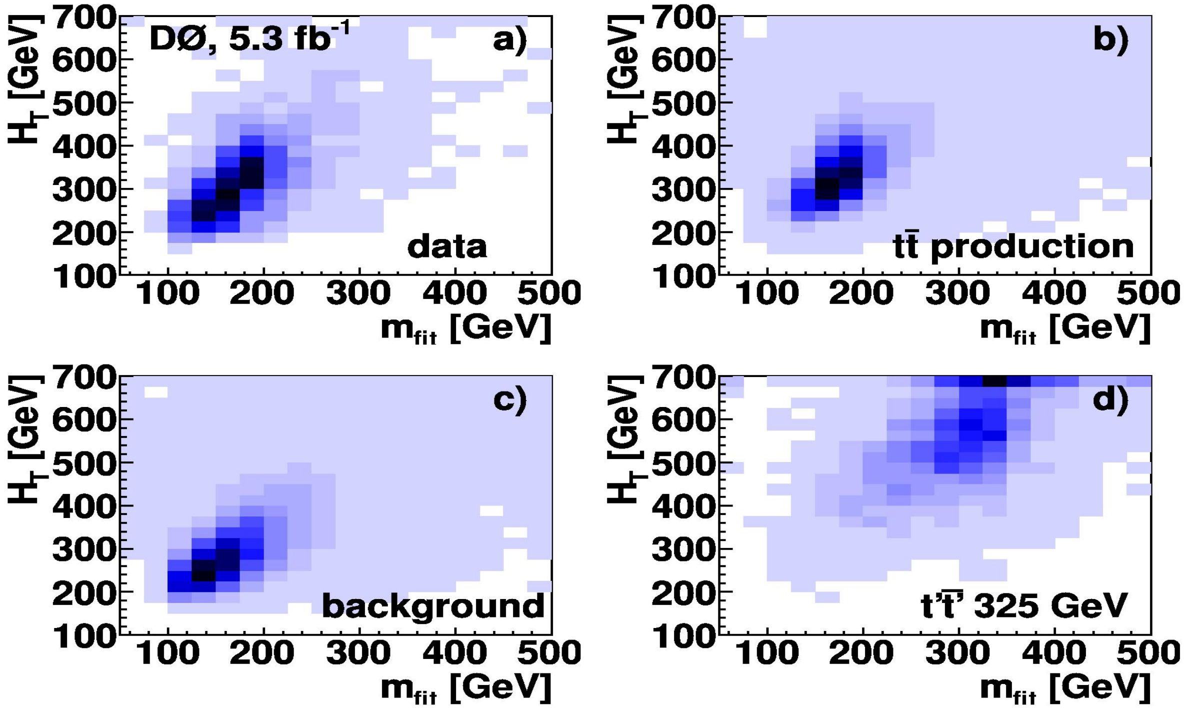




- Do not observe any sign of such anomalous coupling and set a limit of $B(t \to Zq)$ < 3.2% at 95% C.L.
- Best limits to date, submitted to PLB (March 2011).

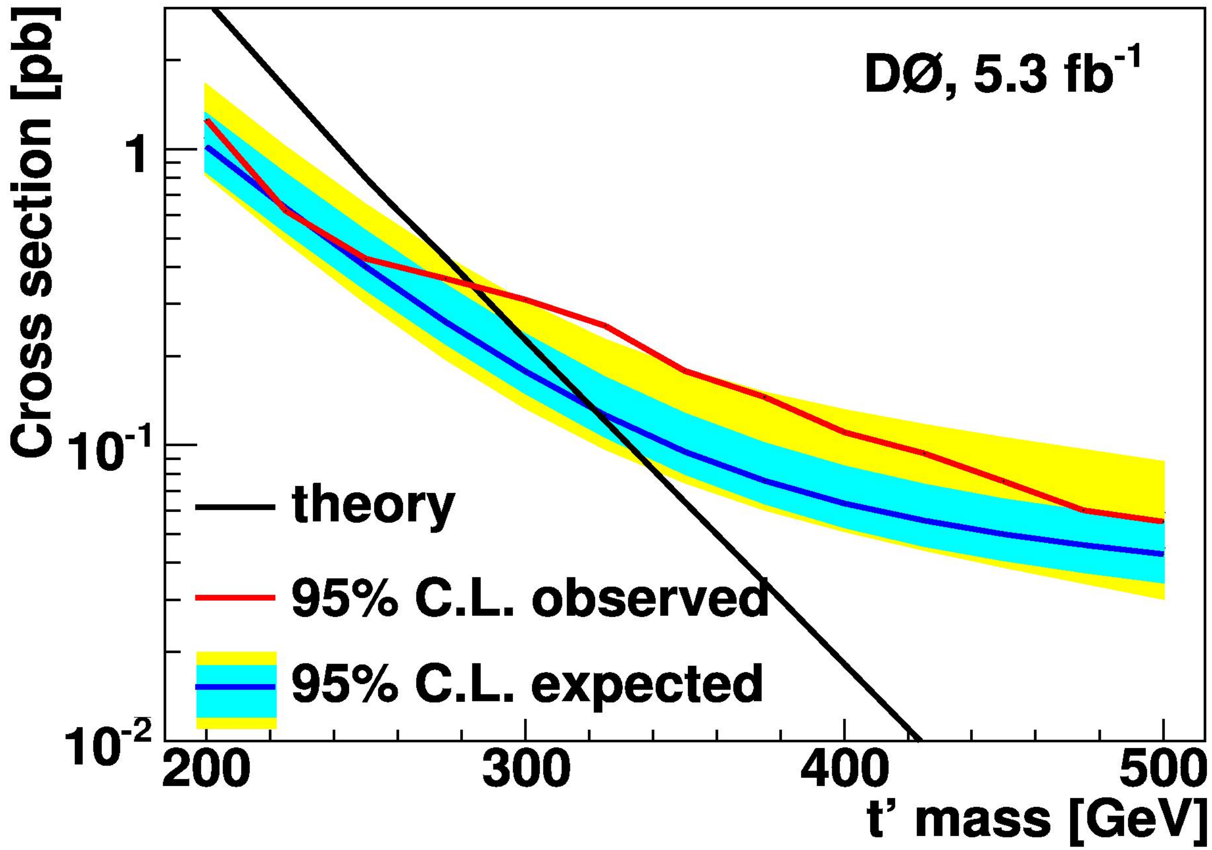
t' search.

- Lepton + jets channel with 5.3/fb of data.
- Require at least 4 jets and large missing transverse energy.
- HT = sum of jet pT and lepton pT
- Mfit = kinematic fit assuming $t\bar{t} \to l\nu bq\bar{q}'\bar{b}$



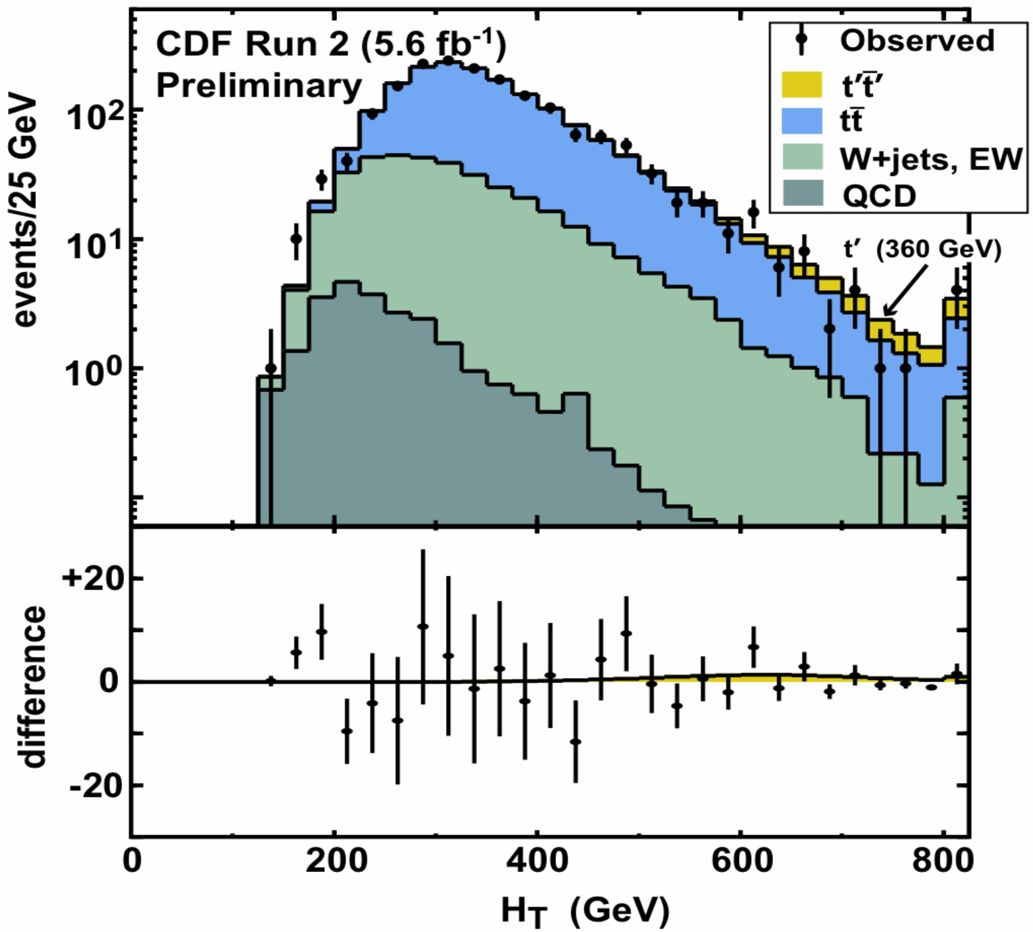
t' search: limits

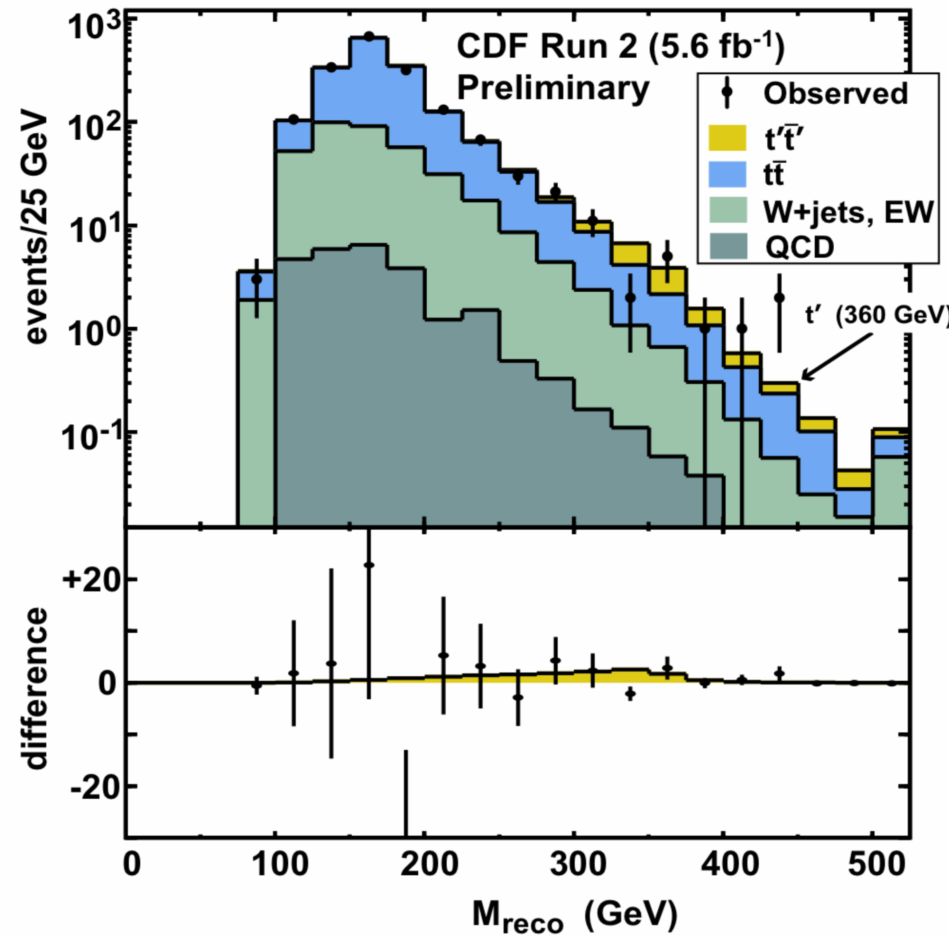
- Combined limit: t' < 285 GeV at 95% C.L.
- Submitted to PRL (April 2011), [http://arxiv.org/abs/1104.4522]



t' search

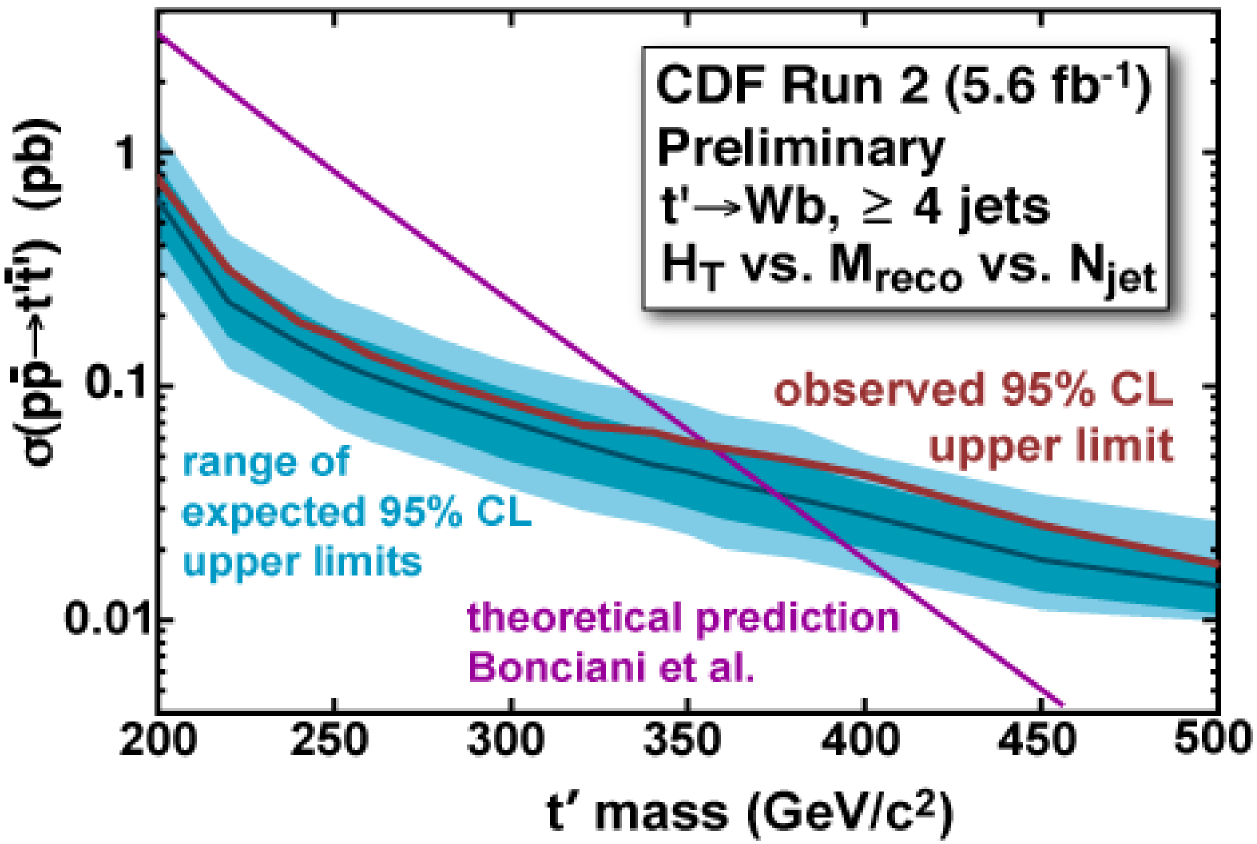
- L + jets with with 5.6/fb of data





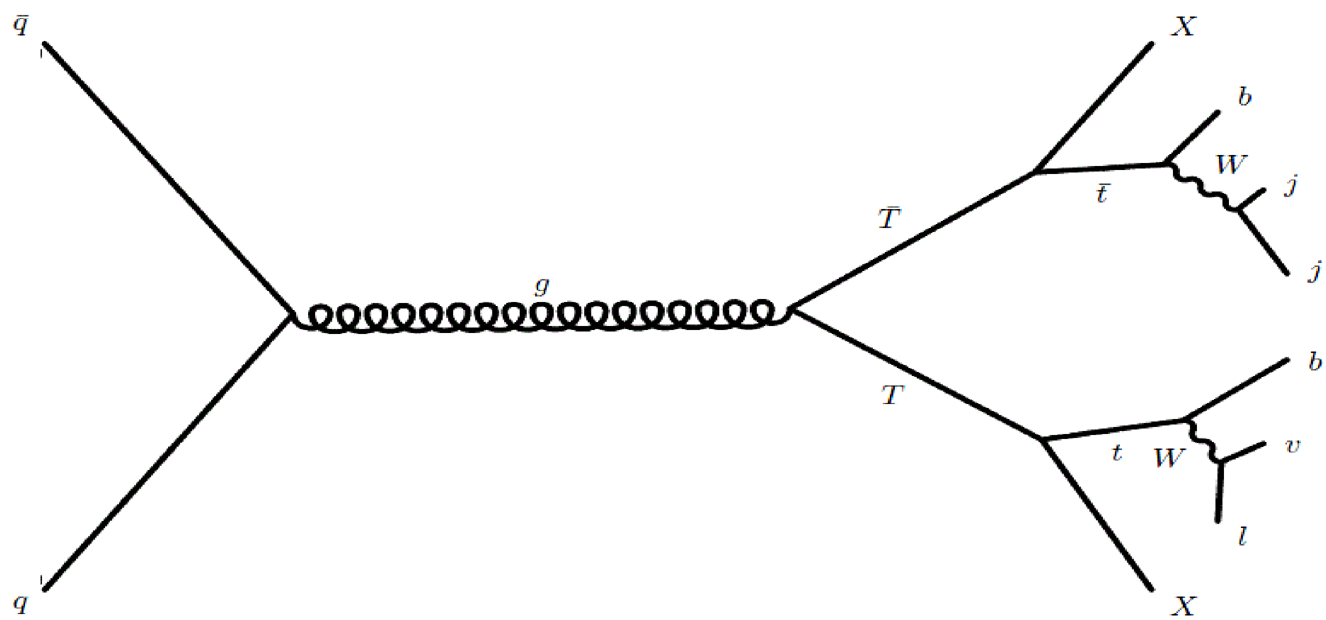
t' search: Limits

- Exclude t' < 358 GeV at 95% C.L.
- Conference note March 2011



Exotic T' search with dark matter

- 4th generation quarks T' decay via $T' \to t + X$, where t is the top quark and X is dark matter. [arXiv:1002.3366]
- T' has both SM charges and a 'dark charge' and hence couples to dark matter and SM

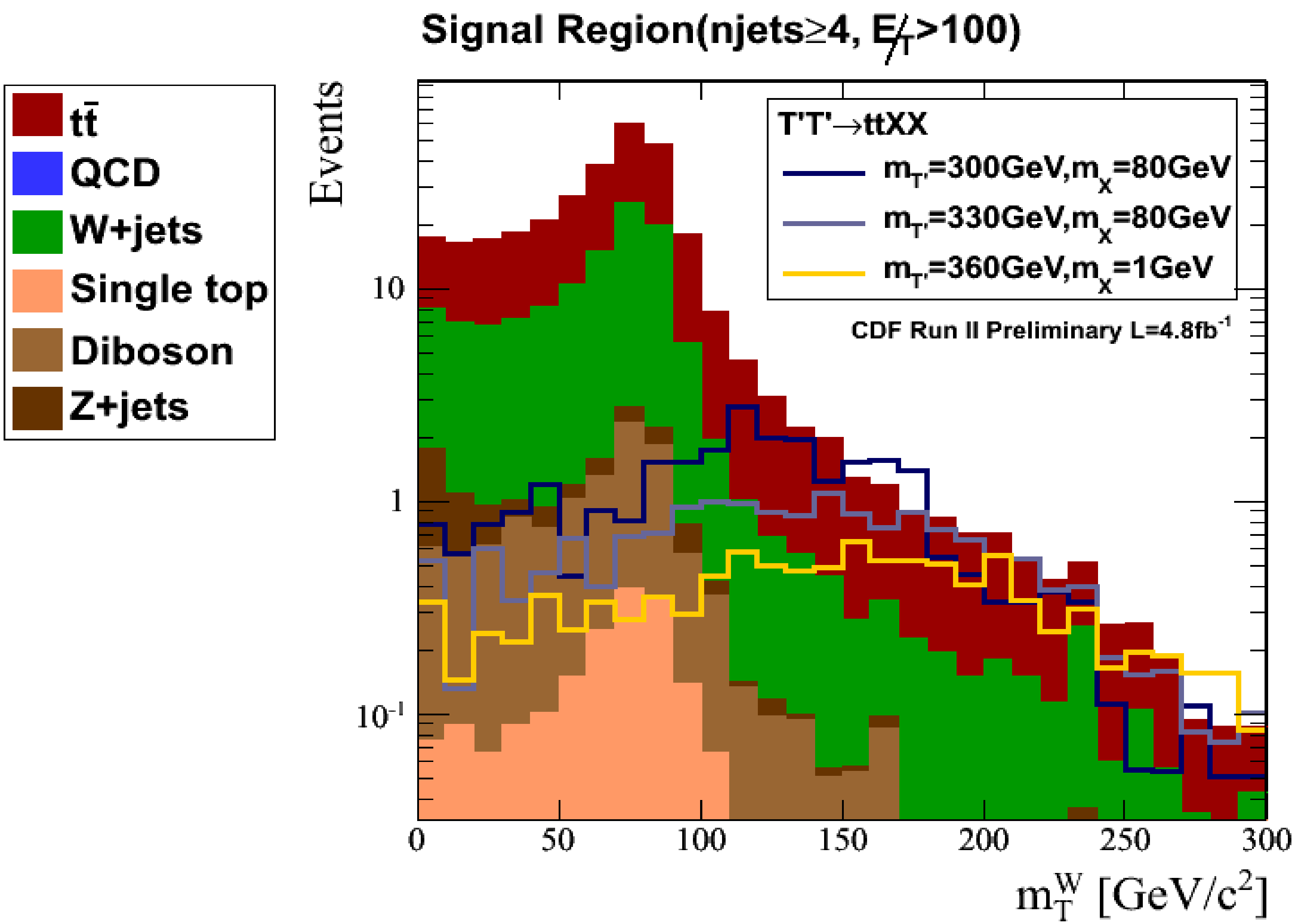


- Looks like top quark pairs plus two additional dark matter particles.

Exotic T': Analysis

- L+jets channel with 4.8/fb of data
- Our signal is characterized by two parameters: mT' and mX.
- This signal differs from SM backgrounds in two ways:
- $\not{E}_T$: T' decays are associated with an excess of missing energy coming from the two dark matter particles.
  We exploit this by requiring high missing transverse energy.
  - The amount of missing energy in the T' decays depends mT' and mX, each mass get its own optimized cut.
    The cut varies from $\not{E}_T \geq 100GeV$ to $\not{E}_T \geq 150GeV$
- m_T^W : SM processes will have a peak around the W-mass while the signal will have no such peak.
  We exploit this by fitting templates in this variable.

Exotic T': Analysis



Model independent limit setting

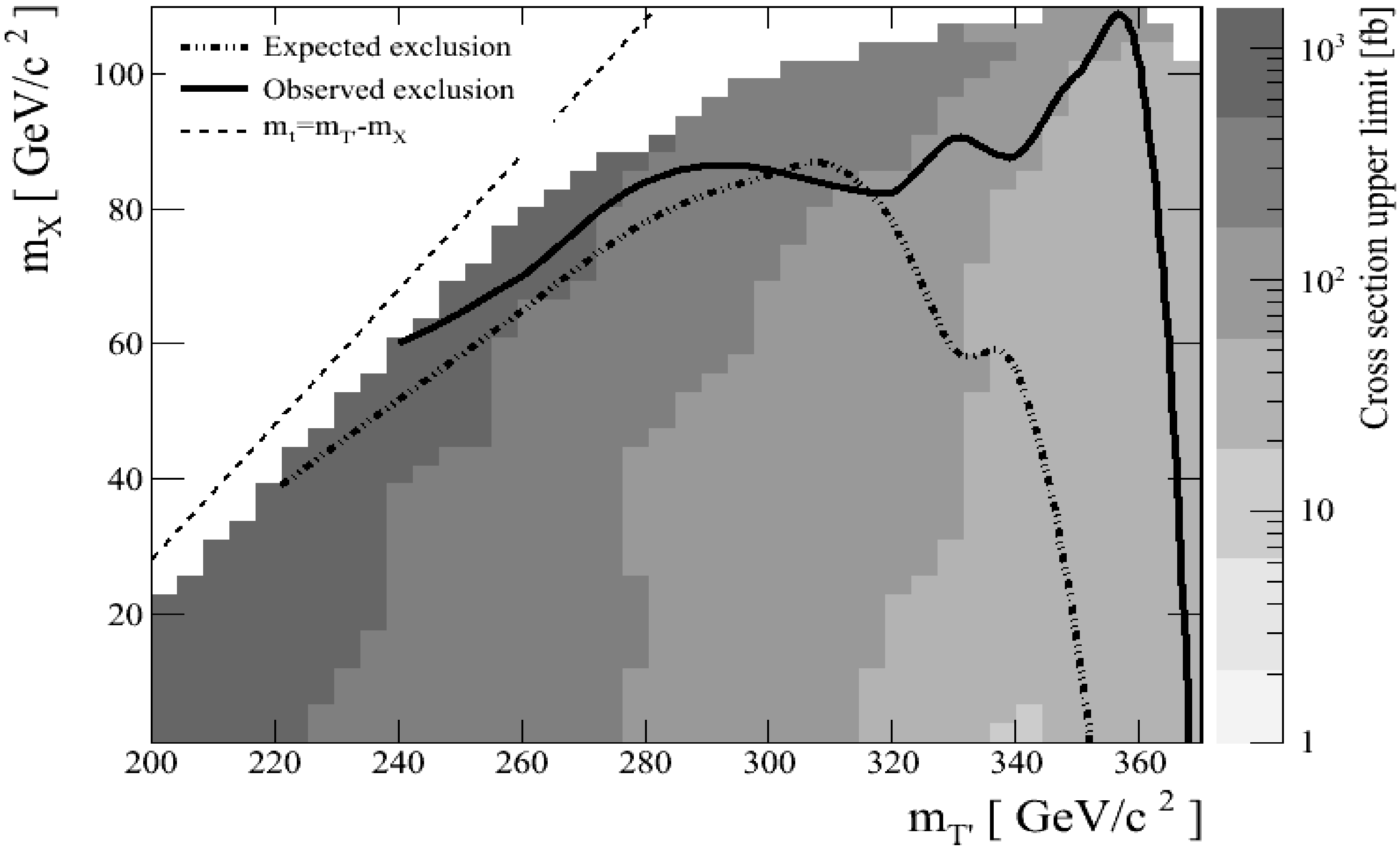
- We set limits on a model independent process; pair production of heavy particles decaying to top quark pairs and invisible particles.
- We then apply those limits to specific physics models, in particular the dark matter model.
- Our limits also apply to other relevant models
  - Supersymmetry: pair production of scalar tops and decay to top quark pairs and LSP:

$$\tilde{t} \rightarrow t + \chi$$

  - LSP : lightest supersymmetric particle, it is stable and hence acts as our invisible particle.

Results: Dark matter model mass limits.

- Best current limits, but similar search ongoing at the LHC
- Accepted to PRL, May Issue.



Summary

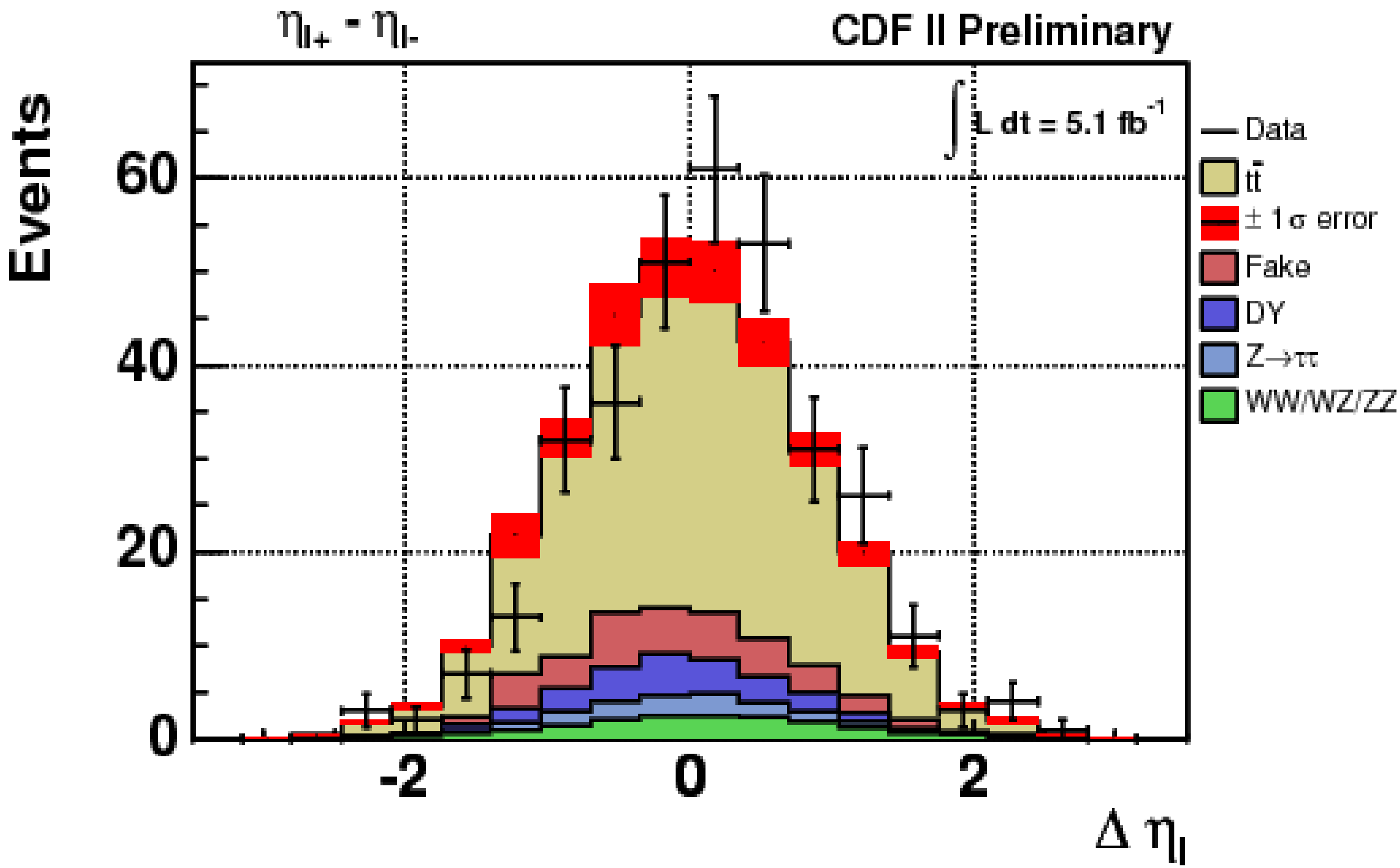
- Test of SM top-quark properties:
  - Observed forward-backward asymmetry in top-quark pair production.
  - Spin correlation in ttbar production found to be consitent with SM.
  - Boosted top search at CDF set cross section limits on high pT top-quark pair production
  - Verified SM in W-boson helicity measurements.

- BSM Searches:
  - FCNC search in top decays at D0 set limits on $B(t \to Zq)$
  - Search for fourth generation up-type quark at D0 excludes t' < 285 GeV with 5.3/fb of data, and at CDF excludes t' < 358 GeV with 5.6/fb.
  - A Search for exotic T' involving dark matter at CDF excluded such quarks at < 360 GeV

Back up slides.

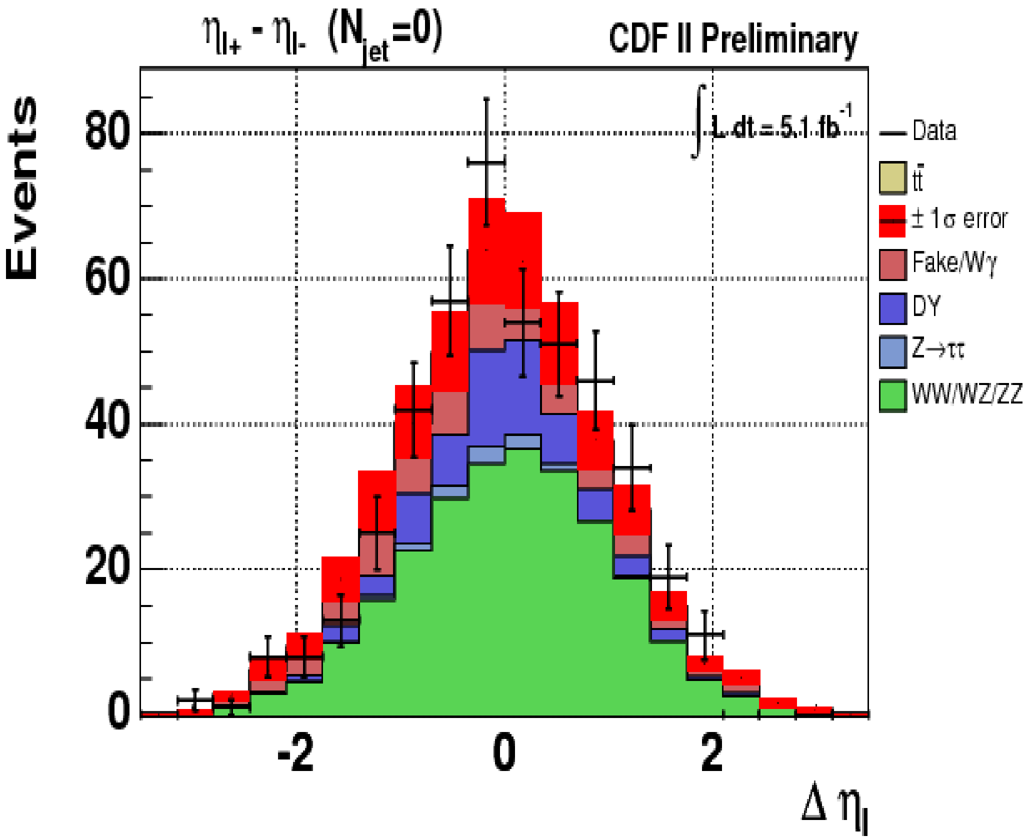
Forward-backward asymmetry: CDF

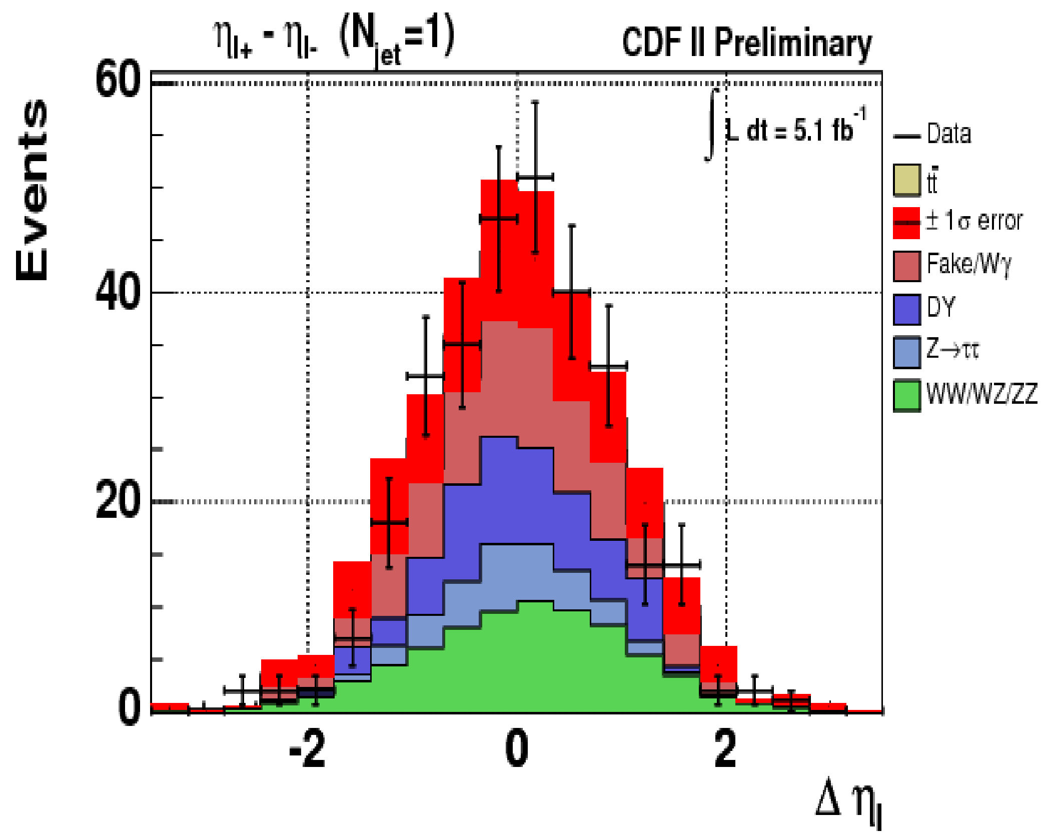
- **Asymmetry in leptons(identical to tops):**



Forward-backward asymmetry: CDF

- **Control regions: well-modeled.**

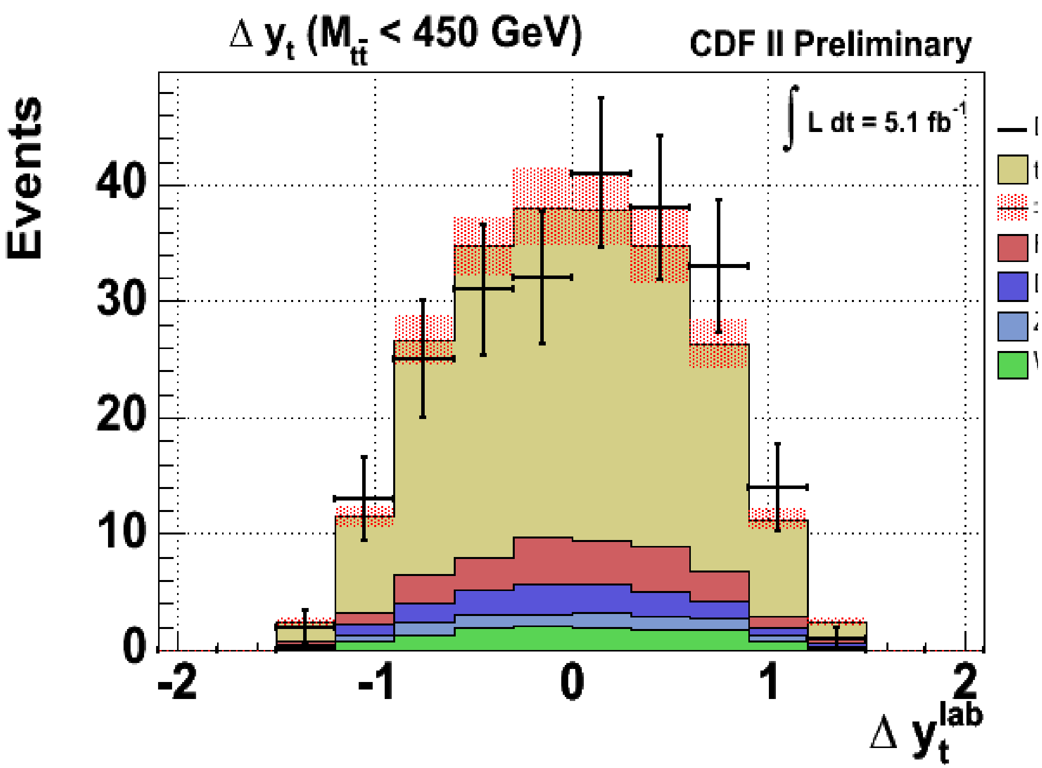


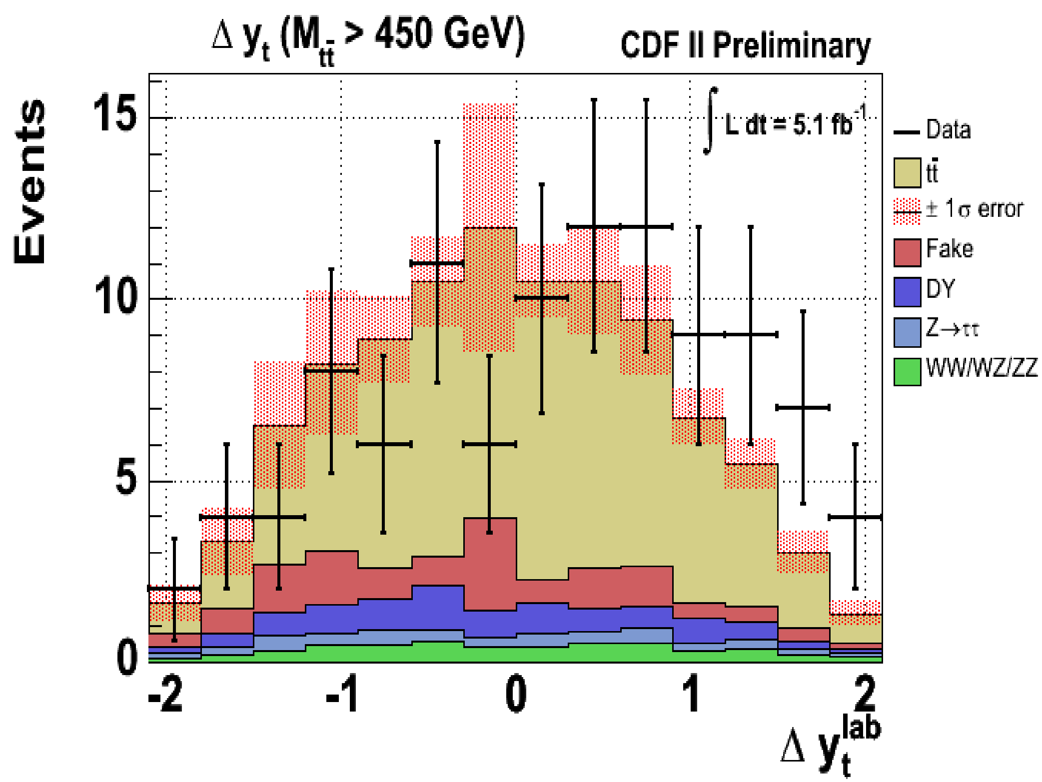


Forward-backward asymmetry: CDF

- **Asymmetry vs ttbar mass.**

$$A_{\rm obs}^{<450\ {\rm GeV}} = 0.104 \pm 0.066({\rm stat.}) \qquad ({\rm Pred.:}\ \ 0.003 \pm 0.031)$$
$$A_{\rm obs}^{>450\ {\rm GeV}} = 0.212 \pm 0.096({\rm stat.}) \qquad ({\rm Pred.:}\ \ -0.040 \pm 0.055)$$



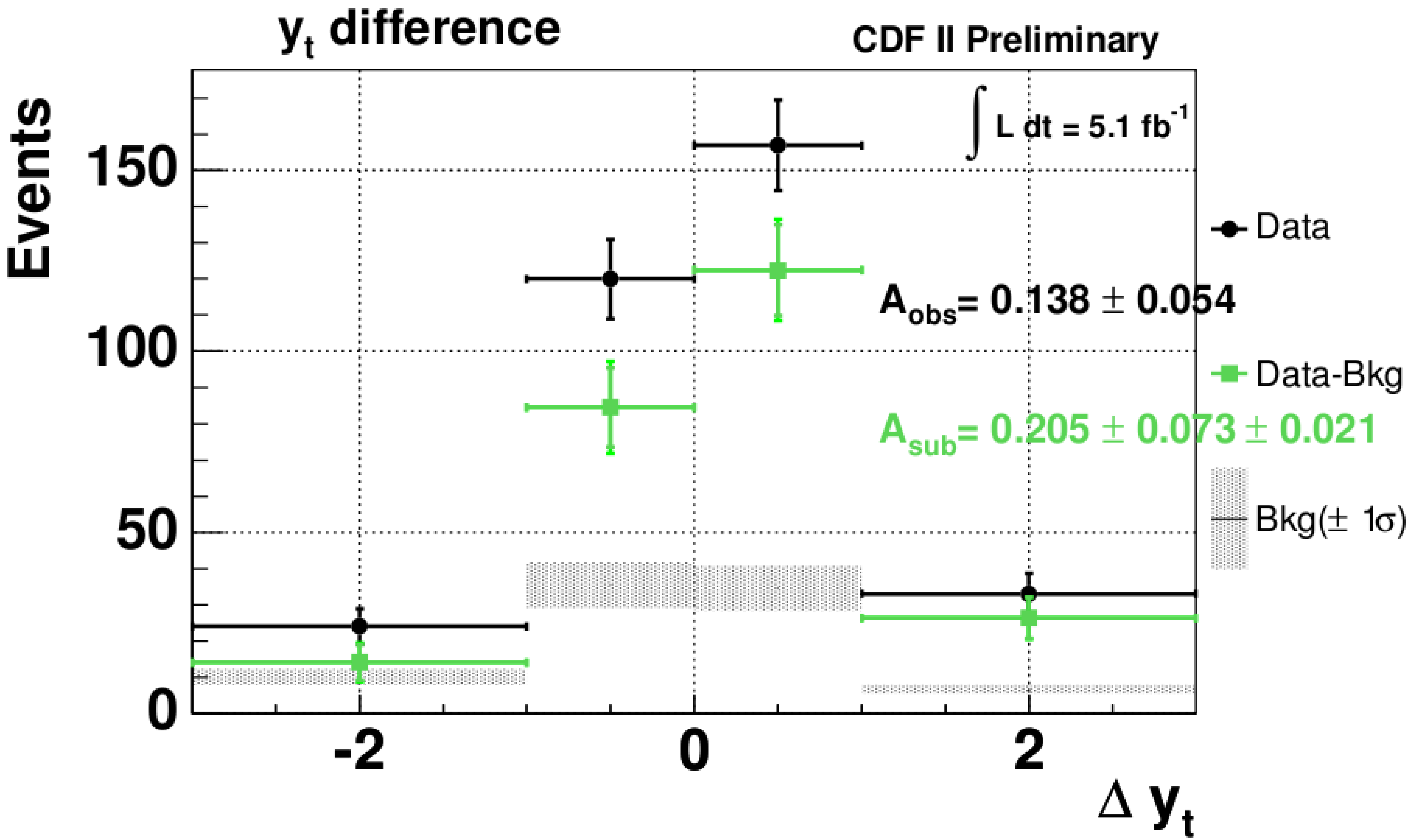


CDF AF_B

- **Reconstruction of 334 candidate events (most likely solution is chosen):**

$$
\begin{aligned}
M^2_{\ell^+\nu} &= (|\vec{p}_{\ell^+}| + |\vec{p}_\nu|)^2 - (\vec{p}_{\ell^+} + \vec{p}_\nu)^2 = M^2_W \\
M^2_{\ell^-\bar{\nu}} &= (|\vec{p}_{\ell^-}| + |\vec{p}_{\bar{\nu}}|)^2 - (\vec{p}_{\ell^-} + \vec{p}_{\bar{\nu}})^2 = M^2_W \\
M^2_{\ell^+\nu b} &= (|\vec{p}_{\ell^+}| + |\vec{p}_\nu| + |\vec{p}_b|)^2 - (\vec{p}_{\ell^+} + \vec{p}_\nu + \vec{p}_b)^2 = M^2_t \\
M^2_{\ell^-\bar{\nu}\bar{b}} &= (|\vec{p}_{\ell^-}| + |\vec{p}_{\bar{\nu}}| + |\vec{p}_{\bar{b}}|)^2 - (\vec{p}_{\ell^-} + \vec{p}_{\bar{\nu}} + \vec{p}_{\bar{b}})^2 = M^2_t \\
(\vec{p}_\nu + \vec{p}_{\bar{\nu}})_x &= (\not{E}_T\ )_x \\
(\vec{p}_\nu + \vec{p}_{\bar{\nu}})_y &= (\not{E}_T\ )_y \,.
\end{aligned}
$$

CDF AF_B



y_t difference
CDF II Preliminary
$\int L\,dt = 5.1\ fb^{-1}$
Events
150
100
50
0
-2
0
2
Δy_t
Data
A_{obs}= 0.138 ± 0.054
Data-Bkg
A_{sub}= 0.205 ± 0.073 ± 0.021
Bkg(± 1σ)

Boosted top: Analysis

- Use 6.0/fb of data
- Low statistics: NNLO calculation yields a total cross section of 8.15 pb and a cross section for pT > 400 GeV/c of 4.55fb (few in 10,000 effect)
- Selection: Look for events with one high pT (>400 GeV) jet with
  - Hadronic channel: two massive (130-210 GeV) jets
  - Leptonic channel: one massive (130-210 GeV) jet with MET significance in (4,10)

$$S_{MET} \equiv \frac{\not{E}_T}{\sqrt{\sum E_T}}$$

All Hadronic — CDF, $L_{int} = 6\ fb^{-1}$

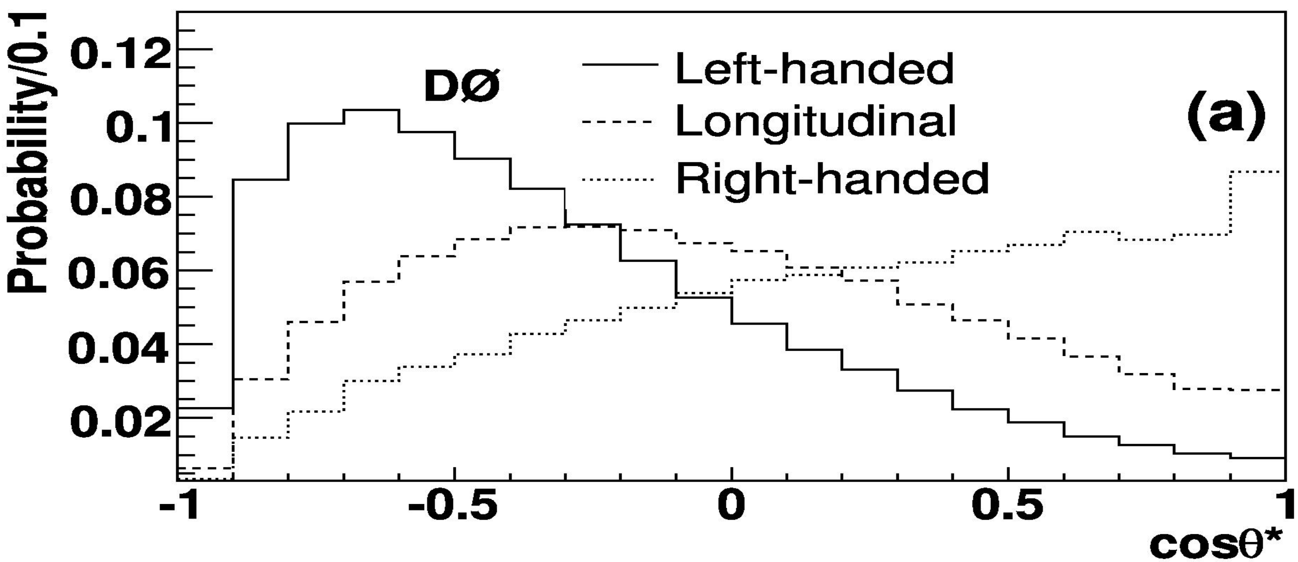
Region	m^{jet1} (GeV/c^2)	m^{jet2} (GeV/c^2)	Data (events)	ttbar MC (events)
A	(30, 50)	(30, 50)	370	0.00
B	(130, 210)	(30, 50)	47	0.08
C	(30, 50)	(130, 210)	102	0.01
D (signal)	(130, 210)	(130, 210)	32	3.03
Predicted QCD in D	13±2.4			

Semileptonic — CDF, $L_{int} = 6\ fb^{-1}$

Region	m^{jet1} (GeV/c^2)	S_{MET} ($GeV^{1/2}$)	Data (events)	ttbar MC (events)
A	(30, 50)	(2, 3)	256	0.01
B	(130, 210)	(2, 3)	42	1.07
C	(30, 50)	(4, 10)	191	0.03
D (signal)	(130, 210)	(4, 10)	26	1.90
Predicted QCD in D	31.3±8.1			

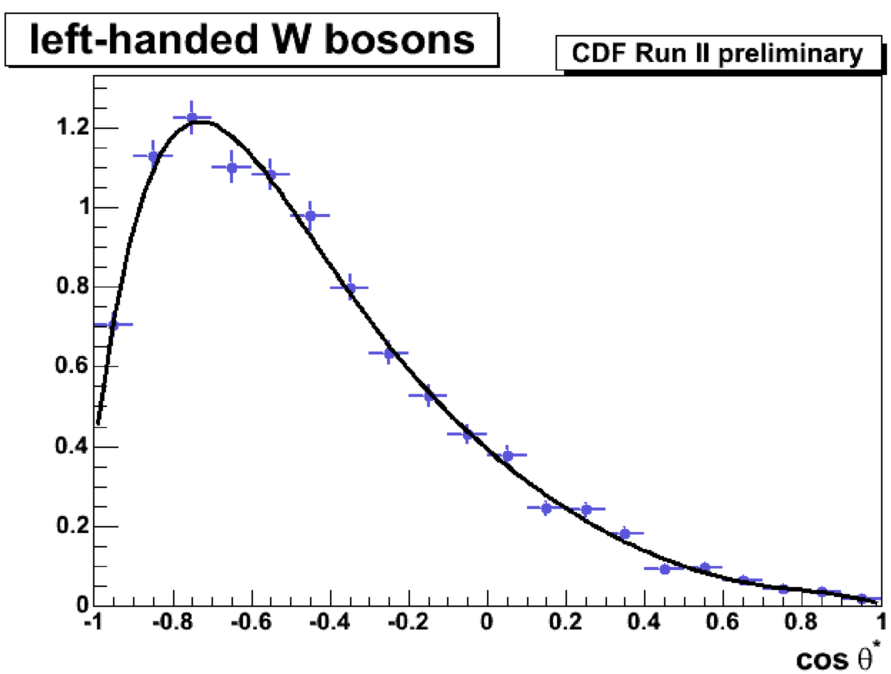
W-helicity

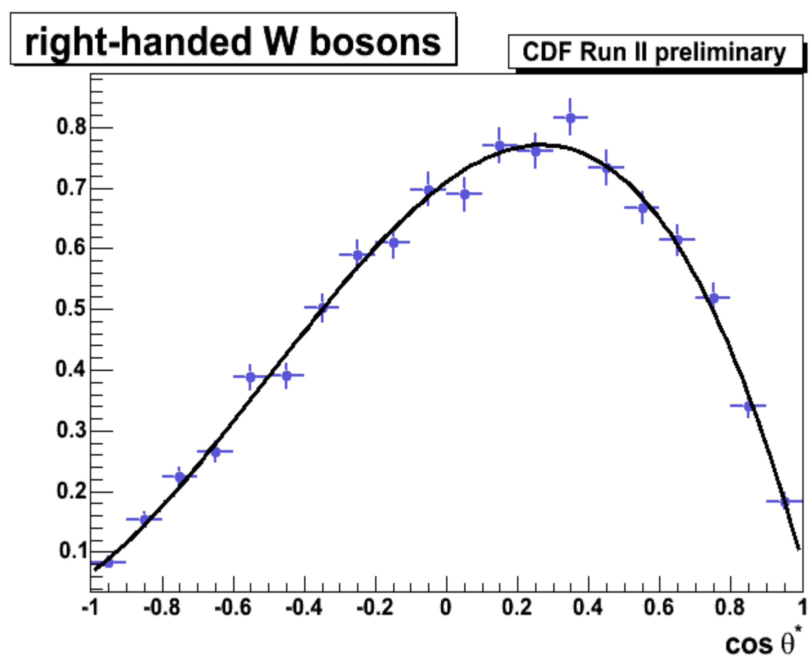
- Analysis at D0 with 5.4/fb in l+jets and dilepton channels.
- Select and reconstruct a top enriched sample:
  - L+jets: Exactly 1 lepton, 4 jets, 2 btags and missing energy
    - Eg require 2 jets/lepton+neutrino match W mass, reconstructed top = 172.5 GeV
  - Dilepton: Exactly 2 leptons, 2 btags and missing energy
- Measure θ^* : angle between the top quark and down-type fermion (charged lepton or d,s quark in W frame)



W-helicity

- Analysis at CDF with 4.8/fb in the dilepton channel.
- Selection:
  - Dilepton: Exactly 2 leptons, >=1 btags and missing energy
  - Reconstruct full ttbar event
- MC samples: purely right, left and longitudinal samples.





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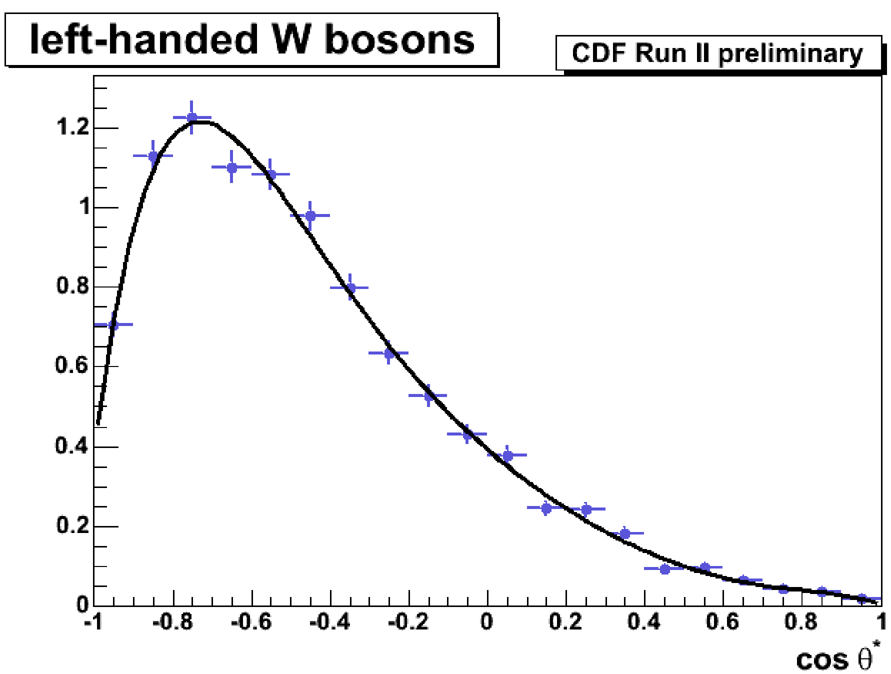
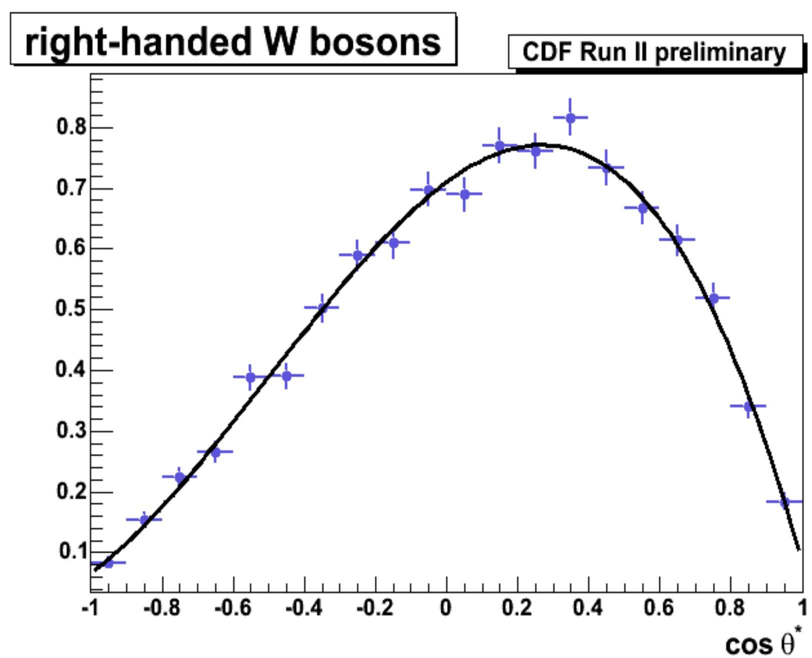


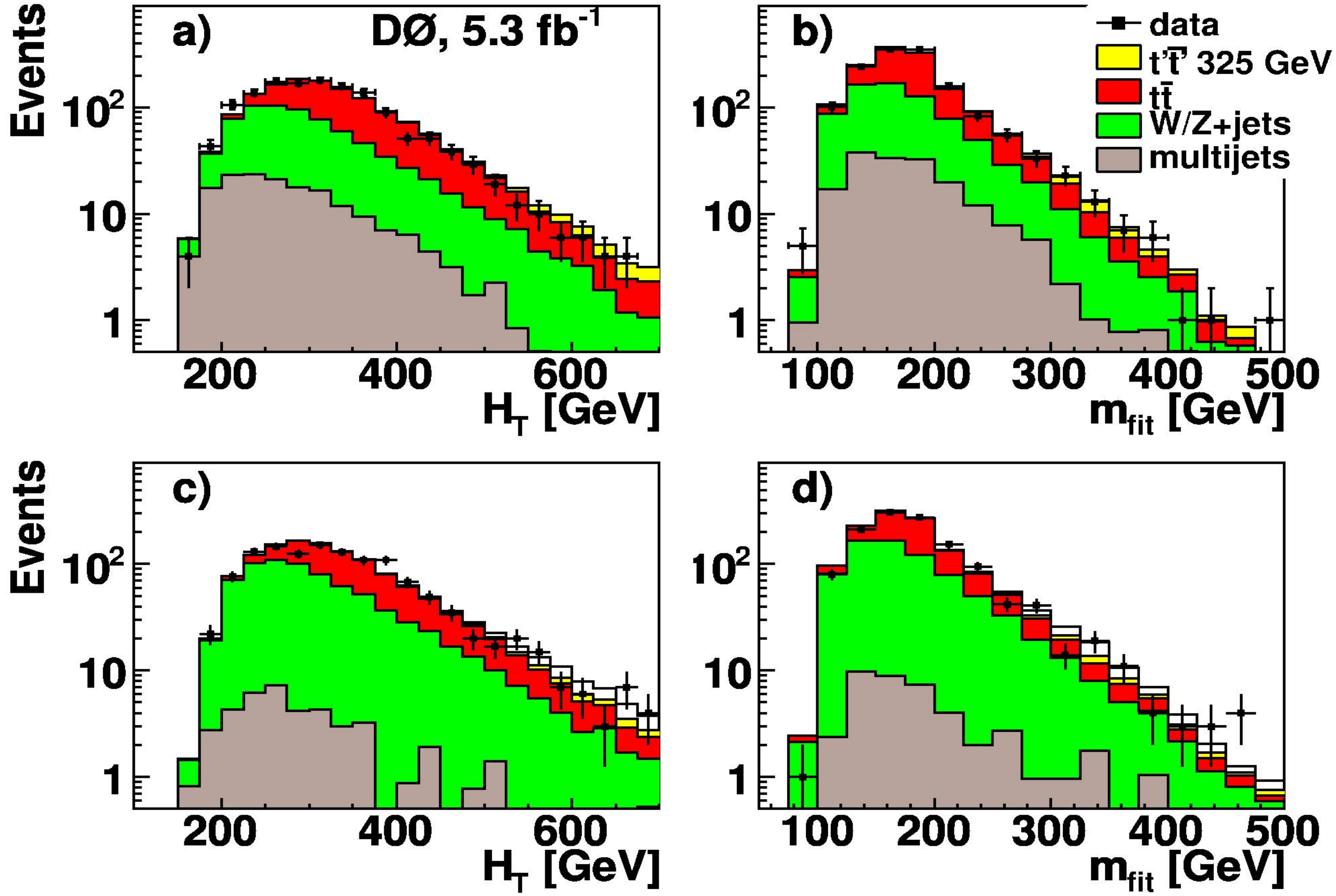


FCNC in top decays: Analysis.

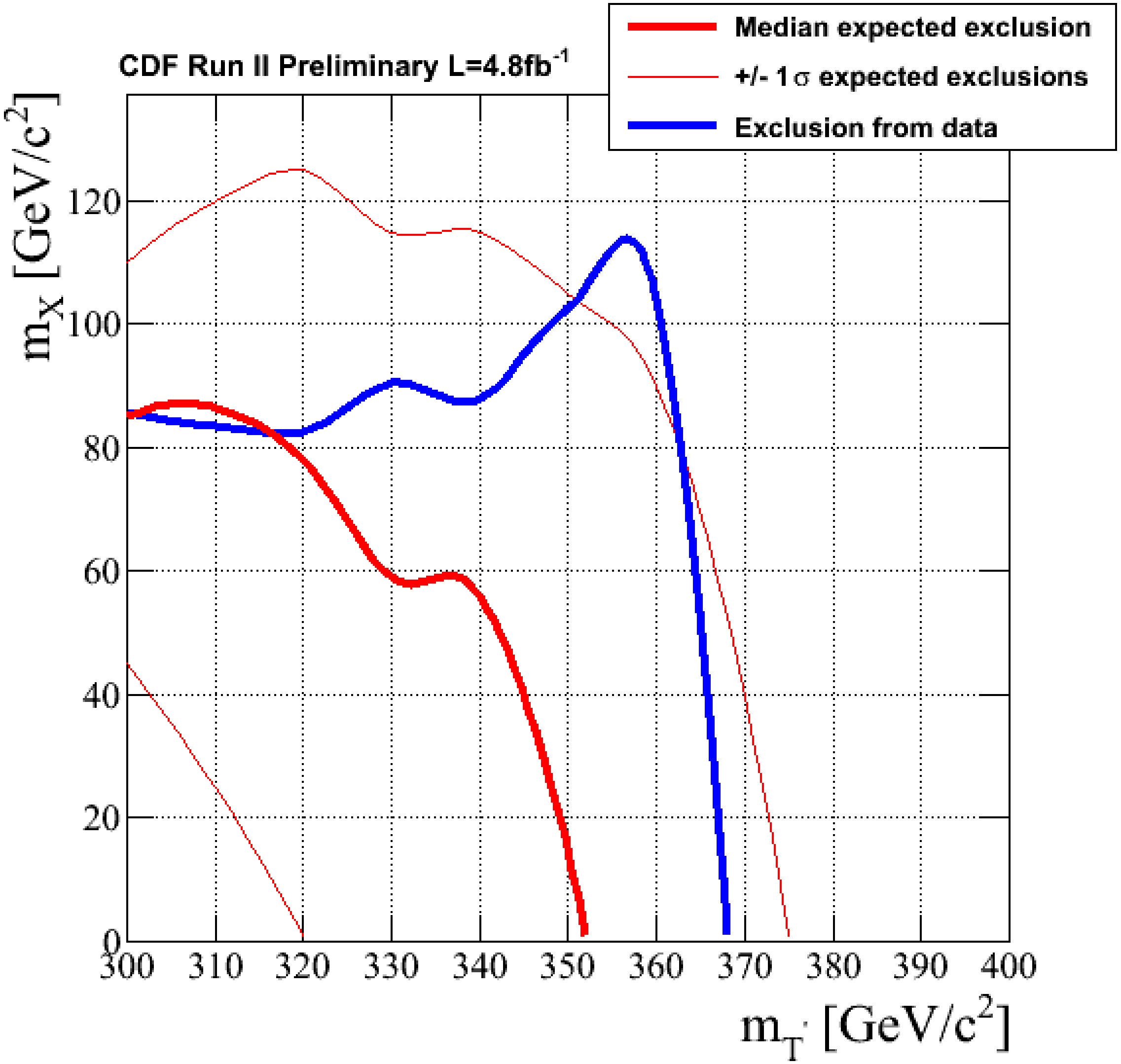
- Search in trilepton final states with 4.1/fb of data.
- Final states
  - $eee + \not{E}_T + X \quad ee\mu + \not{E}_T + X \quad \mu\mu e + \not{E}_T + X \quad \mu\mu\mu + \not{E}_T + X$
  - X – any number of jets
  - MET > 20 GeV
- Z → pair of leptons must have opposite charge and invariant mass in Z-mass window
- Main SM backgrounds are WZ and ZZ

t' search: backgrounds

- Major SM backgrounds are W+jets and $t\bar{t}$
- MC is well described in signal depleted regions.

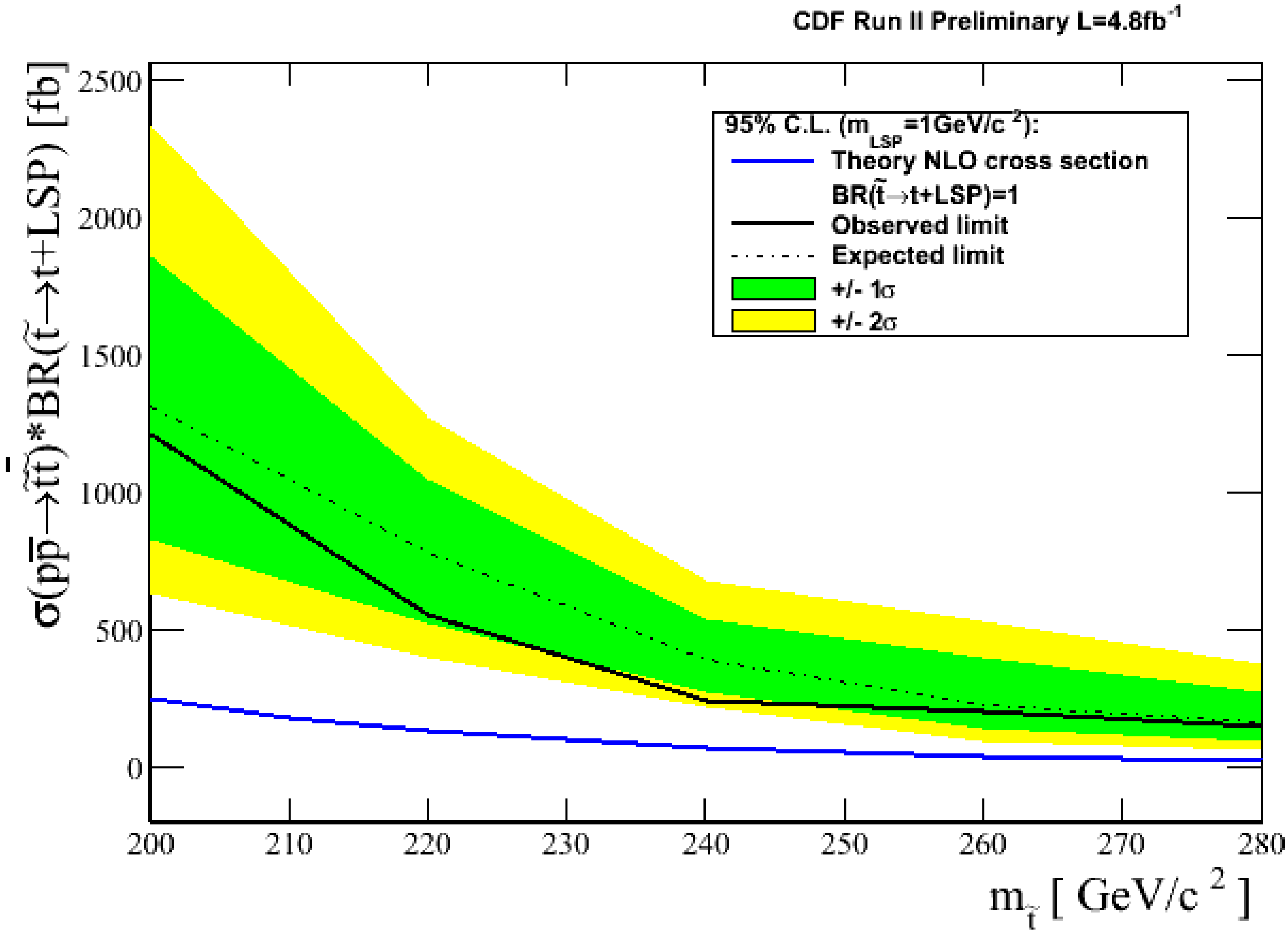


T': Exclusion.



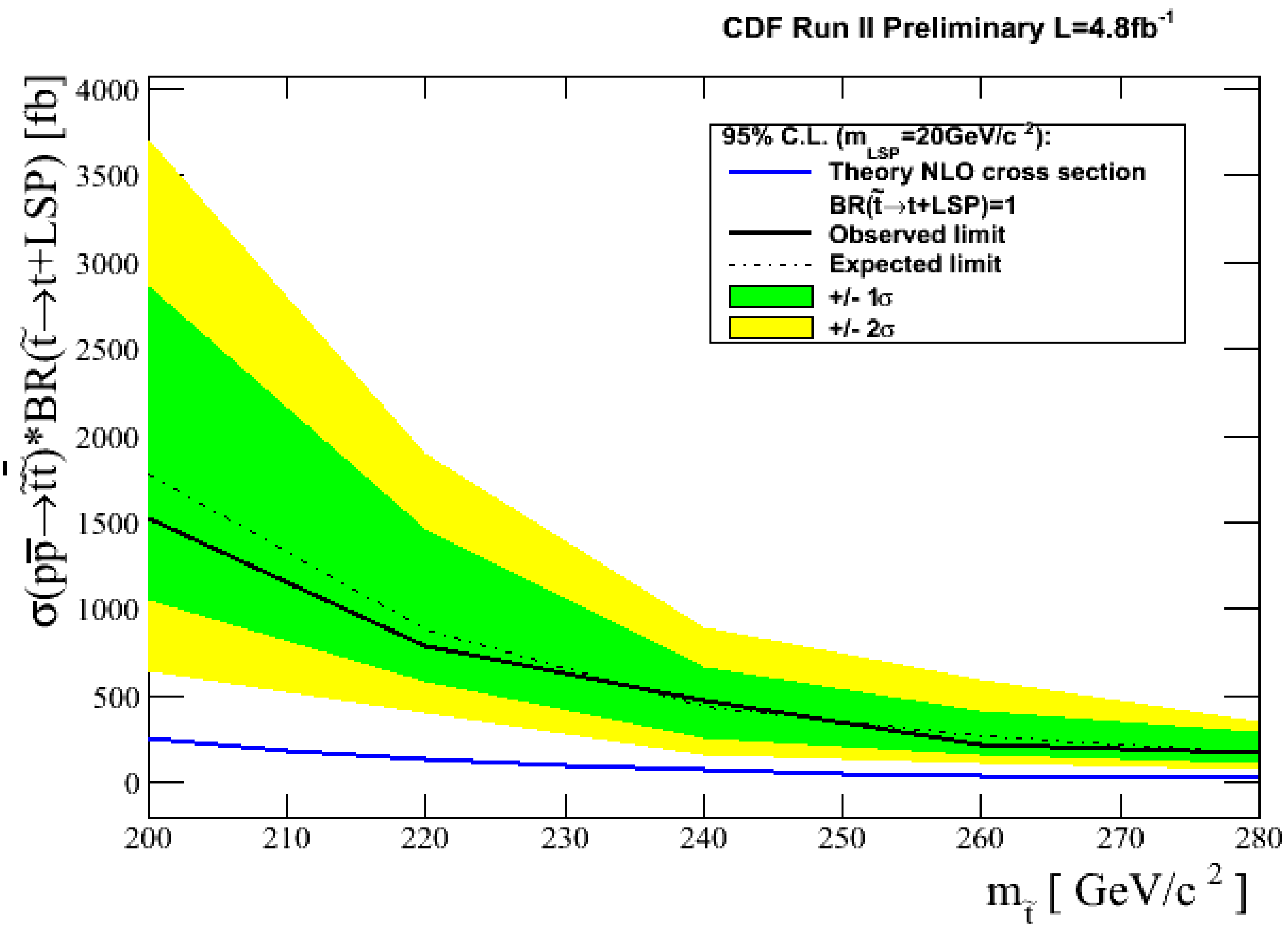
Median expected exclusion
+/- 1σ expected exclusions
Exclusion from data
CDF Run II Preliminary L=4.8fb-1
mX [GeV/c2]
120
100
80
60
40
20
0
300
310
320
330
340
350
360
370
380
390
400
mT' [GeV/c2]

Susy limits



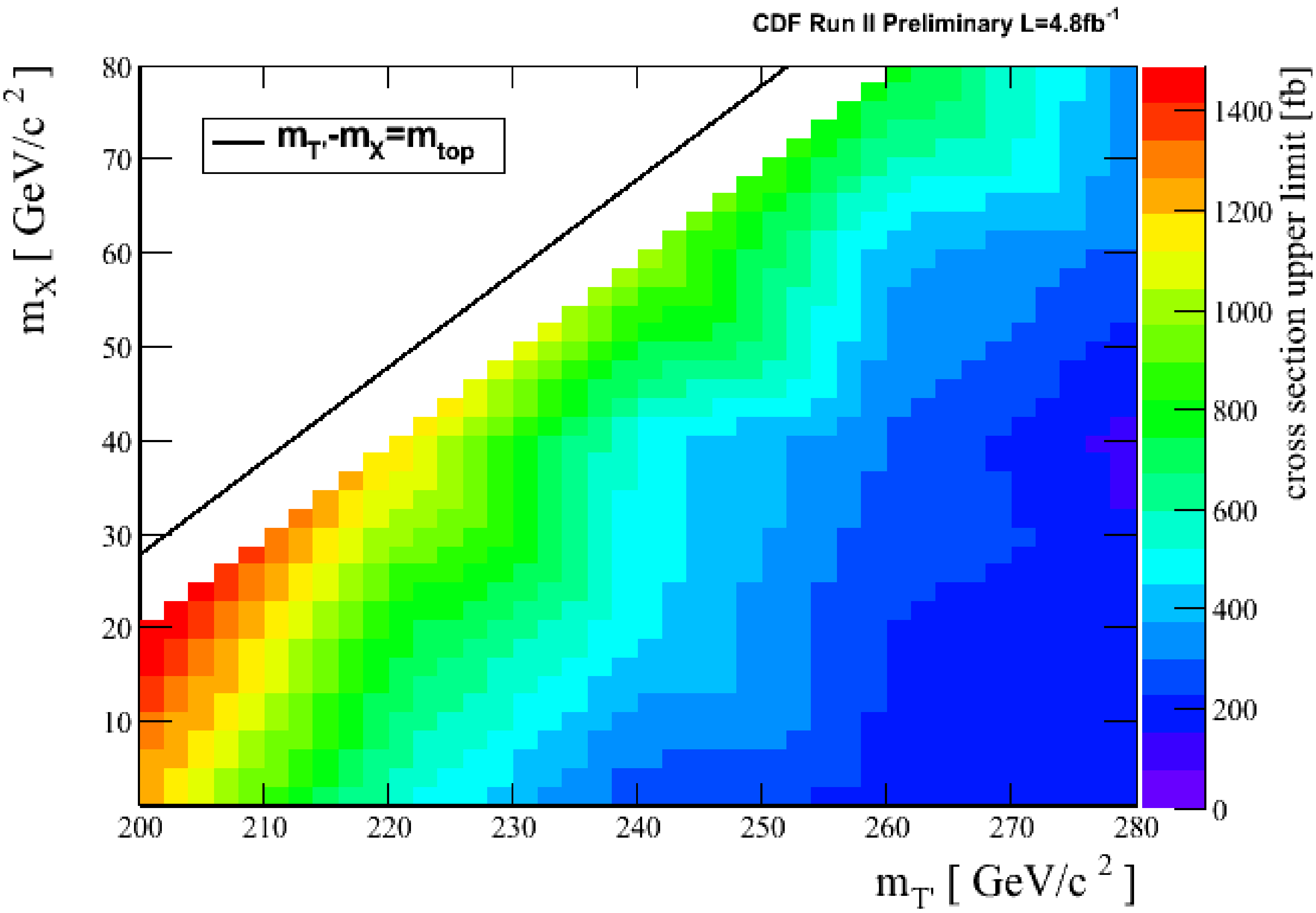
CDF Run II Preliminary L=4.8fb^{-1}
95% C.L. (m_{LSP}=1GeV/c^2):
Theory NLO cross section
BR($\tilde{t}\to$t+LSP)=1
Observed limit
Expected limit
+/- 1σ
+/- 2σ
$\sigma(p\bar{p}\to\tilde{t}\bar{\tilde{t}})$*BR($\tilde{t}\to$t+LSP) [fb]
2500
2000
1500
1000
500
0
200
210
220
230
240
250
260
270
280
$m_{\tilde{t}}$ [GeV/c^2]

Susy limits



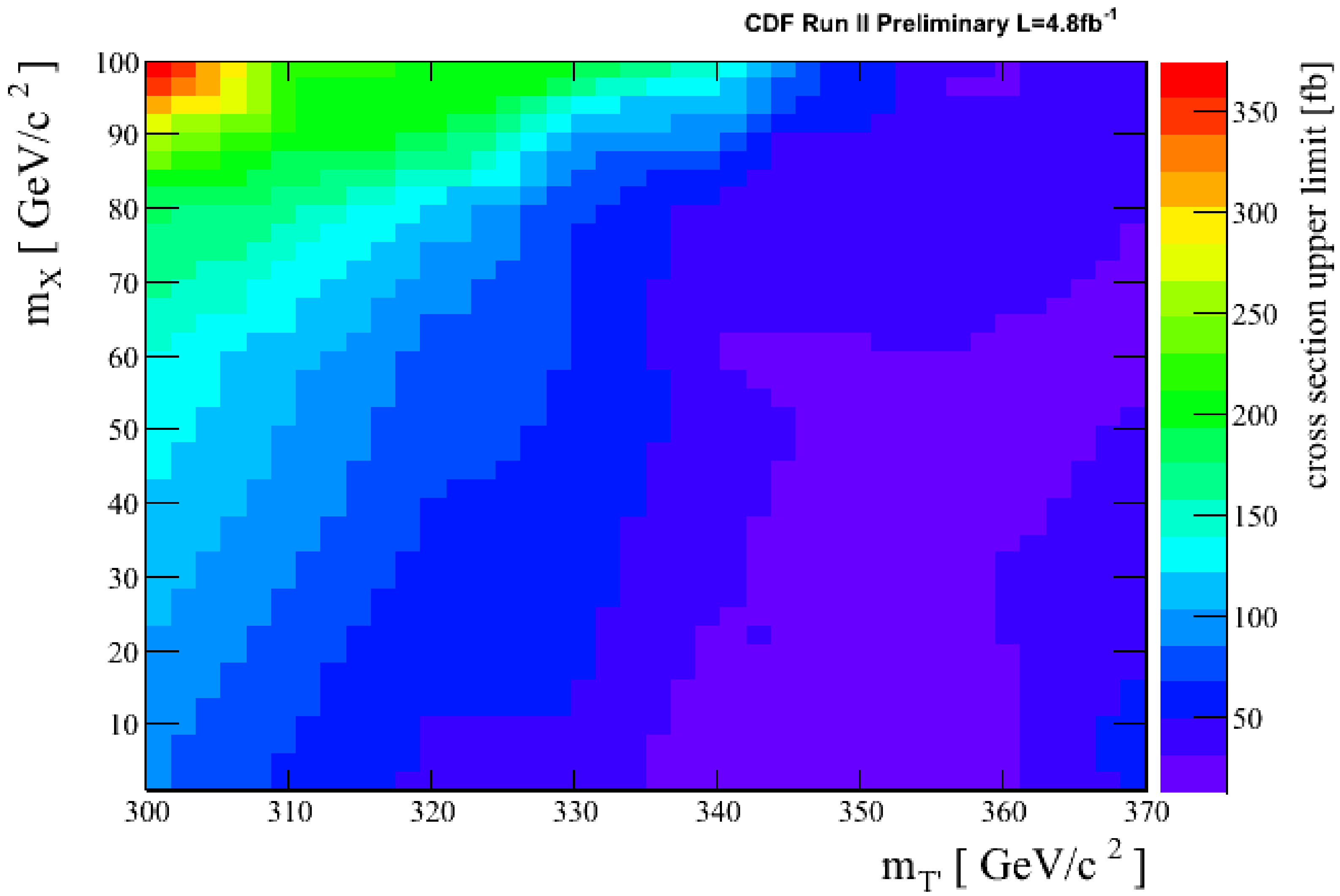
CDF Run II Preliminary L=4.8fb-1
95% C.L. (m LSP =20GeV/c 2):
Theory NLO cross section
BR(t̃→t+LSP)=1
Observed limit
Expected limit
+/- 1σ
+/- 2σ
4000
3500
3000
2500
2000
1500
1000
500
0
200
210
220
230
240
250
260
270
280
σ(pp̄→t̃t̃)*BR(t̃→t+LSP) [fb]
m t̃ [GeV/c 2]

Susy limits



CDF Run II Preliminary L=4.8fb^{-1}
$m_{T'}$-m_X=m_{top}
m_X [GeV/c ^{2}]
80
70
60
50
40
30
20
10
200
210
220
230
240
250
260
270
280
$m_{T'}$ [GeV/c ^{2}]
1400
1200
1000
800
600
400
200
0
cross section upper limit [fb]

Cross section limits



Kanishka Rao (UCI)

Cross section limits

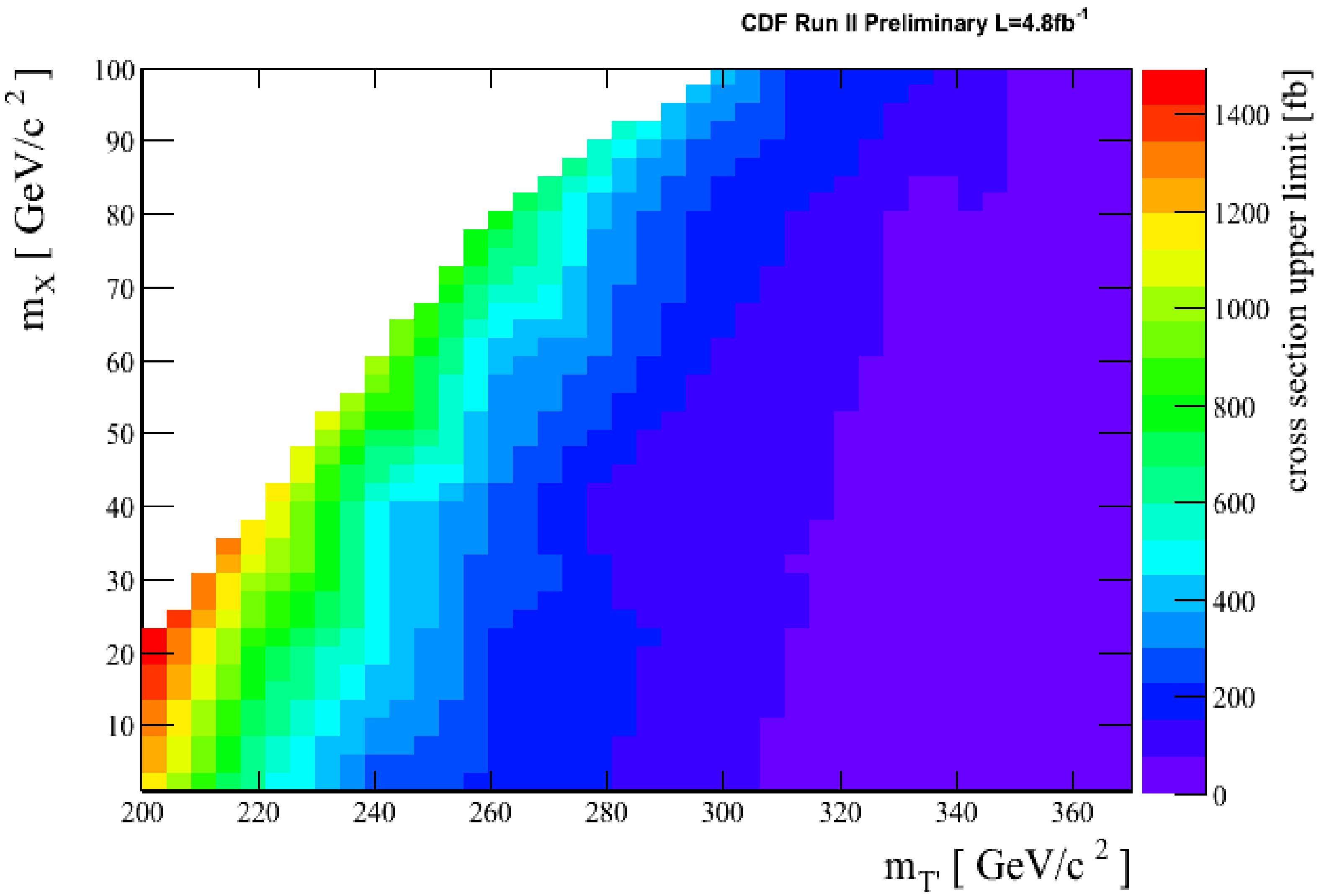


TABLE II: Expected 95% CL upper limit on $T'\bar{T}'$ production cross-section, σ_{exp}, and observed limit, σ_{obs}, for each signal point in $(m_{T'}, mX)$ tested with the $\not{E}_T$ used.

$m_{T'}$,m_X (GeV)	$\not{E}_T$ Cut (GeV)	σ_{exp} [pb]	$+\sigma$	$-\sigma$	$+2\sigma$	-2σ	σ_{obs} [pb].
200,1	94	1.31	1.86	0.83	2.34	0.63	1.21
200,20	104	1.78	2.86	1.06	3.71	0.65	1.53
220,1	96	0.78	1.05	0.53	1.28	0.40	0.55
220,20	110	0.89	1.46	0.58	1.90	0.40	0.79
220,40	95	1.40	2.17	0.93	2.94	0.69	1.20
240,1	100	0.39	0.54	0.27	0.68	0.22	0.24
240,20	112	0.44	0.67	0.26	0.89	0.15	0.47
240,40	104	0.61	0.91	0.40	1.17	0.27	0.49
240,60	96	1.39	2.06	0.90	3.92	0.63	1.02
260,1	118	0.23	0.40	0.14	0.53	0.09	0.20
260,20	126	0.27	0.42	0.16	0.59	0.11	0.22
260,40	114	0.36	0.52	0.23	0.67	0.16	0.29
260,60	98	0.49	0.66	0.34	0.83	0.28	0.40
280,1	130	0.16	0.27	0.09	0.38	0.06	0.15
280,20	126	0.18	0.29	0.11	0.36	0.07	0.17
280,40	126	0.17	0.27	0.11	0.35	0.08	0.12
280,60	122	0.27	0.41	0.16	0.58	0.11	0.28
280,80	124	0.40	0.65	0.27	1.06	0.17	0.35
300,100	110	0.34	0.51	0.24	0.82	0.17	0.39
300,90	119	0.26	0.41	0.15	0.67	0.06	0.26
300,80	119	0.20	0.31	0.13	0.42	0.08	0.18
300,70	128	0.19	0.31	0.12	0.42	0.08	0.17
300,60	126	0.16	0.25	0.10	0.34	0.06	0.14
300,30	134	0.13	0.19	0.08	0.31	0.06	0.12
300,1	136	0.11	0.18	0.06	0.28	0.03	0.09
310,100	124	0.23	0.37	0.15	0.83	0.09	0.22
310,90	125	0.19	0.29	0.11	0.46	0.08	0.21
310,80	124	0.16	0.24	0.11	0.30	0.08	0.16
310,1	138	0.10	0.17	0.06	0.27	0.03	0.06
320,90	129	0.15	0.27	0.09	0.49	0.05	0.19
320,80	130	0.15	0.24	0.08	0.44	0.06	0.12

$m_{T'}$,m_X (GeV)	$\not{E}_T$ Cut (GeV)	σ_{exp} [pb]	$+\sigma$	$-\sigma$	$+2\sigma$	-2σ	σ_{obs} [pb].
320,70	132	0.12	0.19	0.07	0.28	0.05	0.09
320,60	138	0.11	0.18	0.07	0.31	0.02	0.08
320,30	136	0.09	0.15	0.06	0.21	0.04	0.06
320,1	142	0.09	0.14	0.05	0.20	0.03	0.04
330,100	131	0.14	0.23	0.08	0.40	0.04	0.21
330,90	137	0.13	0.20	0.08	0.29	0.04	0.10
330,80	136	0.11	0.17	0.06	0.30	0.02	0.07
330,70	136	0.10	0.16	0.07	0.25	0.02	0.07
330,60	136	0.09	0.14	0.06	0.21	0.02	0.07
330,30	140	0.09	0.14	0.05	0.20	0.03	0.06
330,1	136	0.08	0.12	0.05	0.17	0.03	0.04
340,100	133	0.11	0.19	0.06	0.35	0.05	0.15
340,80	143	0.10	0.15	0.06	0.29	0.02	0.04
340,70	142	0.09	0.15	0.06	0.30	0.04	0.04
340,60	150	0.08	0.14	0.06	0.24	0.03	0.03
340,30	144	0.07	0.11	0.04	0.16	0.03	0.03
340,1	144	0.07	0.11	0.04	0.15	0.03	0.01
350,110	130	0.09	0.15	0.05	0.35	0.03	0.11
350,100	138	0.10	0.17	0.06	0.47	0.02	0.05
350,70	150	0.08	0.13	0.04	0.36	0.02	0.04
350,50	150	0.07	0.10	0.04	0.17	0.01	0.02
350,30	150	0.07	0.10	0.04	0.16	0.02	0.02
350,1	143	0.07	0.11	0.04	0.21	0.03	0.02
360,110	130	0.09	0.19	0.05	0.21	0.02	0.09
360,100	146	0.08	0.14	0.05	0.29	0.02	0.03
360,70	155	0.07	0.12	0.04	0.28	0.02	0.04
360,30	148	0.06	0.10	0.04	0.20	0.02	0.03
360,1	143	0.06	0.09	0.04	0.25	0.02	0.03
370,100	148	0.07	0.11	0.05	0.19	0.01	0.04
370,70	154	0.07	0.11	0.04	0.24	0.02	0.02
370,1	160	0.06	0.10	0.04	0.19	0.02	0.05