Search for Third Generation Squarks in the Missing Transverse Energy plus Jet Sample at CDF Run II

Miguel Vidal

CIEMAT

PhD Dissertation
March 2nd, 2010

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Outline

Standard Model of Particle Physics

The Standard Model (SM) has been really successful
during the last 30 years

However, there are still open questions that the SM cannot address

Just an example:

Dark matter is one of missing pieces of the puzzle

- Evidence from gravitational lensing
- Galaxy rotation

CHANDRA

At hadron collider experiments, we look for “New Physics” beyond the SM. The market is plenty of models waiting to be proved.

SUSY I

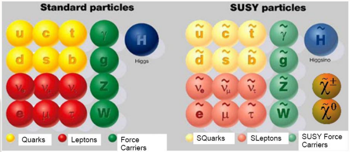
Supersymmetry (SUSY) is the most promising extension of the SM and also an elegant way to solve some of its problems.

New spin-based symmetry relating fermions and bosons:

$Q|Fermion>=|Boson>$

$Q|Boson>=|Fermion>$

Mirror spectrum of particles



R-parity

$R_P = (-1)^{2S+3B+L}$

1 for SM particles, -1 for super-partners

Under R-parity conservation ⇒

- Dark Matter candidate (LSP)
- The SUSY particles are produced in pairs

SUSY must be broken

SUSY II

- The breaking mechanism determines the phenomenology and the search strategy
- $\tilde{t}$ and $\tilde{b}$ are very good candidates for being the lightest s-quark states

The stop case:

$$m^2_{\tilde{t}_{1,2}} = \frac{1}{2}[m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} \pm \sqrt{(m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R})^2 + 4m^2_t(A_t - \mu \cot\beta)^2}]$$

Since top is so massive

- large mixing is expected in the stop sector and it could be really light ~ 150 GeV/c^2

SUSY III

The sbottom case:

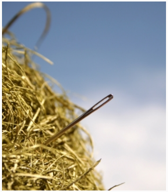
$$m^2_{\tilde{b}_{1,2}} = \frac{1}{2}[m^2_{\tilde{b}_L} + m^2_{\tilde{b}_R} \pm \sqrt{(m^2_{\tilde{b}_L} - m^2_{\tilde{b}_R})^2 + 4m^2_b(A_b - \mu \tan\beta)^2}]$$

where $\tan\beta$ is a parameter in the MSSM-like theories

Assuming large $\tan\beta$

- large mixing is expected in the sbottom sector and it could be light $\sim 250\ \mathrm{GeV/c^2}$

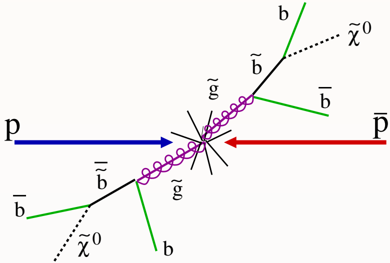
Based on these assumptions, the challenge is to set the tools to isolate these signatures (final states) from the rest of the SM processes within the data



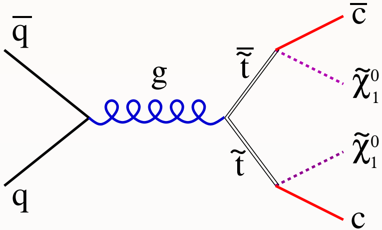
The Final States

Third generation squarks in $\not\!\!E_T$ + jets final states

Sbottom from gluino decay



Stop decaying into charm and neutralino



$\not\!\!E_T$ from the LSP ($\tilde{\chi}^0$)
Heavy flavor jets from c and b quarks

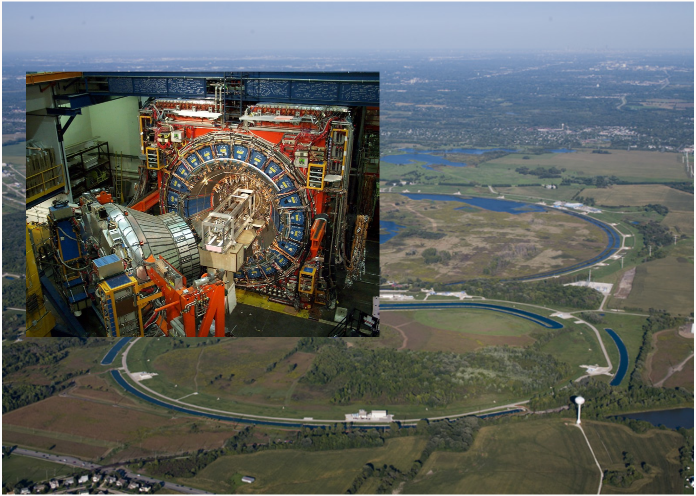
The Experimental Setup

Tevatron

Proton-antiproton collisions at 1.96 TeV center of mass energy.
Tevatron was providing the highest collision energy until last year!!!

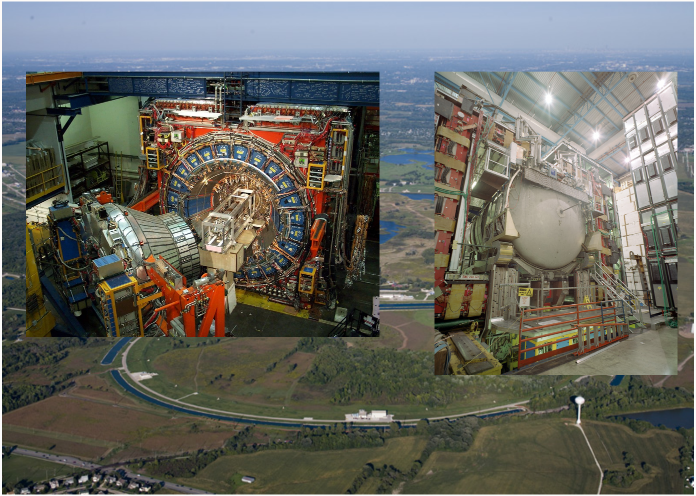
Tevatron

Proton-antiproton collisions at 1.96 TeV center of mass energy.
Tevatron was providing the highest collision energy until last year!!!



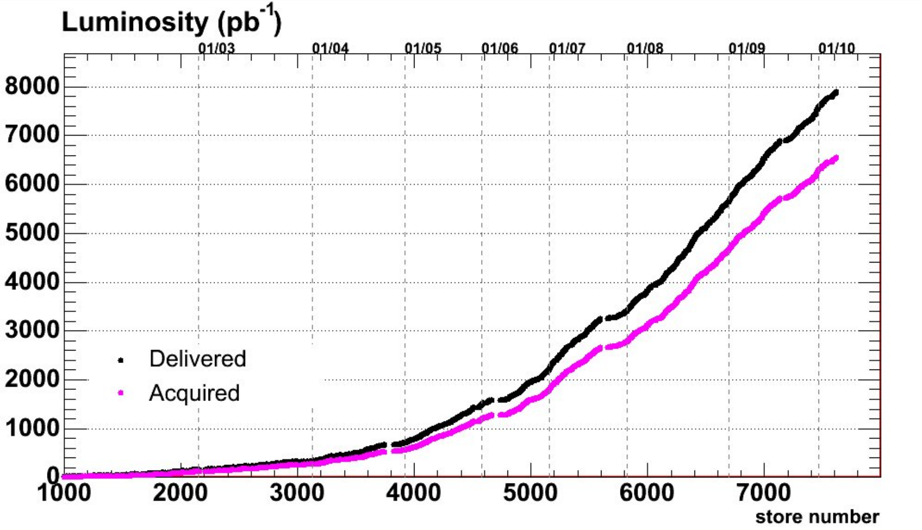
Tevatron

Proton-antiproton collisions at 1.96 TeV center of mass energy.
Tevatron was providing the highest collision energy until last year!!!



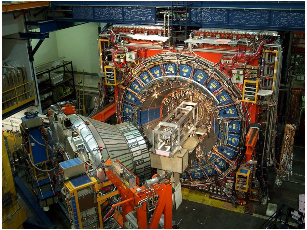
Luminosity

$$N = L \cdot \sigma_{int}$$

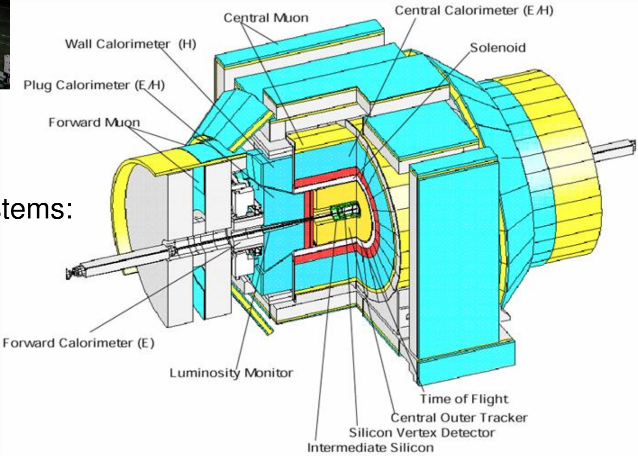


CDF integrated luminosity

CDF II Detector



Dimensions:
$10\text{m} \times 10\text{m} \times 15\text{m}$

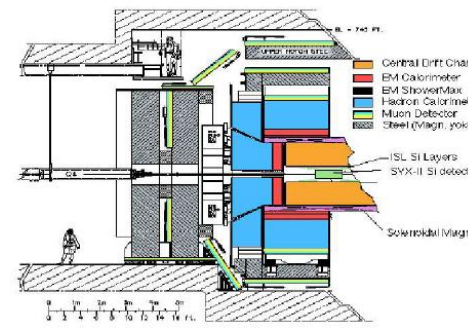


Basic detection systems:

- Tracking
- Calorimeter
- Muons

Sub-detectors

- **Silicon Detector**
  - precision vertex detection
  - heavy flavor tagging
- **Drift chamber** measures charged particle p_T up to $\eta \sim 1.5$ ($\eta = -\ln(\tan(\frac{\theta}{2}))$)
- **Sampled calorimeters**, electromagnetic and hadronic
  - $\sim 4\pi$ coverage
  - measures jets and missing transverse energy ($\not{E}_T$)
- **Muon detectors** outside calorimeter



Solenoid surrounding the tracking system. Magnetic field 1.4 T

The Recipe

SUSY at Hadron Colliders

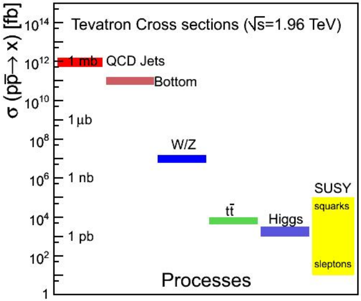
How to recognize our third generation squarks final states within the CDF data?

High $\not\!\!E_T$ and heavy flavor jets

$\not\!\!E_T$ is the missing transverse momentum due to particles not detected (i.e. neutrinos), in our case due to $\tilde{\chi}^0$ that are massive

Bad news:

- SM backgrounds orders of magnitude larger than the signal
- Mainly multijet processes (hard to simulate), as expected from a hadron collider



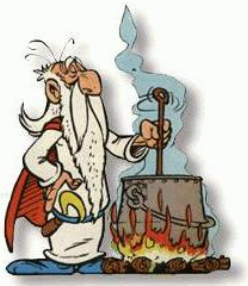
SUSY at Hadron Colliders

Good news:

- Signal topology different enough from backgrounds
- $\not\!\!E_T$ based optimization
- Dedicated samples (i.e. triggers) based on $\not\!\!E_T$ only or $\not\!\!E_T$+jets
- Multijet estimation extracted from data
- Heavy flavor tagging ⇒ one of the main tools

We got the cookbook,
let's cook something

In summary, Tevatron is an excellent place to find SUSY!!



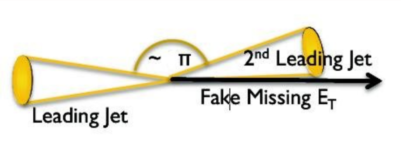
Sample and Tools

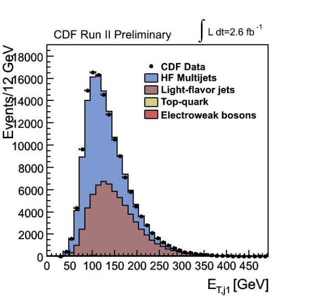
The $\not\!\!E_T$ Sample

The sample is dominated by multijet processes, some of them with real $\not\!\!E_T$: Semi-leptonic decays from heavy flavor, aligned with the jet

Fake $\not\!\!E_T$

- Mainly due to jet mis-measurements in the calorimeter
- The $\not\!\!E_T$ is aligned with the mis-measured jet
- Introduces a huge amount of multijet events in our sample



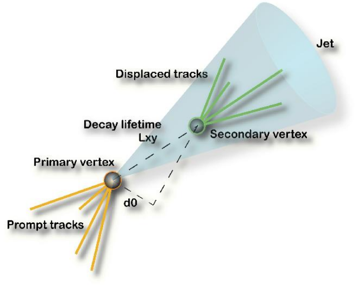


Requiring $\not\!\!E_T$ aligned with one of the jets, almost everything is multijet events

Heavy Flavour (HF) Tagging

The goal is to enhance the presence of signal in the sample by identifying HF jets in the final state

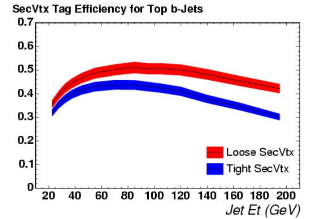
- The tagging algorithms identify vertices from long lifetime B hadrons
- The decay distance is $L_{xy} \sim 500\ \mu\text{m}$
- The algorithms are based on properties of the secondary vertex and the tracks associated to it



The algorithm allows some tuning:

In the analyses shown in this talk:

- Tight requirements for b jet tagging
- Loose requirements for c jet tagging



Background Estimation

Our background = SM processes with $\not\!\!E_T$ and jets in the final state

	Method	
Dibosons	MC Simulation	Pythia
W/Z+jets	MC Simulation	Alpgen/Pythia
Top-quark	MC Simulation	Pythia
Light-flavor jets	From Data	Matrix parameterization
HF Multijets	From Data	Matrix parameterization

Main background ⇒ HF multijet production

Due to its high cross section it is almost impossible to simulate it using MC (CPU time consuming)

Light-flavor jets (Mistags) ⇒ coming from jets falsely tagged as HF

Multijet Estimation From Data I

MUTARE Method

The **MU**ltijet **TA**g-**R**ate **E**stimator (MUTARE) is a method to estimate the HF multijet background from data as a tag rate

The naïve way:

$$R = \frac{HF\ \ tagged\ \ jets}{Taggable\ \ jets}$$

$\Rightarrow$

Where taggable is a tagging-algorithm definition for quality jets

The actual way:

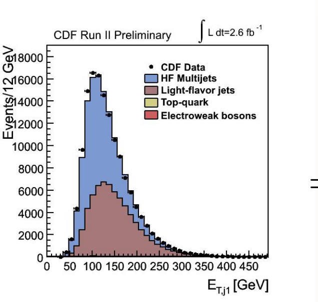
- A three-dimensional tag-rate matrix is computed
- Parameterized on E_T, $|\eta|$, and sumE_T
- Built from a multijet enhanced sample

$$R_{MUTARE} = \frac{N_{tags} - N_{mistags} - N^{MC}_{tags}}{N_{taggable} - N^{MC}_{taggable}}$$

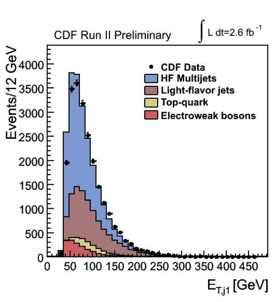
Multijet Estimation From Data II

Once the matrix is computed, the number of HF multijets events in any region is obtained as:

$$N^{HF\ multijet}_{events} = R \times (N^{data}_{taggable} - N^{MC}_{taggable})$$



$$\Rightarrow \left(R_{MUTARE} \right) \Rightarrow$$



Multijet region to build MUTARE

Multijet prediction from MUTARE

Good agreement in control regions

Basic Background Rejection

Basic Cuts

- Jets: $E_T \geq$25 GeV and $|\eta| \leq 2.4$
- Leading jet $E_T \geq$35 GeV
- At least 1 central jet $\Rightarrow |\eta| \leq 0.9$
- $\not{E}_T$ cut (analysis dependent)
- Dijet selection $\Rightarrow$ against beam-related backgrounds

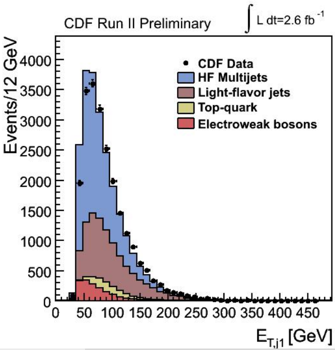
EWK Rejection

- Reject events with electrons misidentified as jets
- No leptons in the final state

Background composition in the stop analysis $\Rightarrow$

QCD Rejection

- $\Delta\phi(\not{E}_T, jets) \geq 0.7$ Remove events with mismeasured jets ($\not{E}_T$ aligned to the direction of one of the jets)

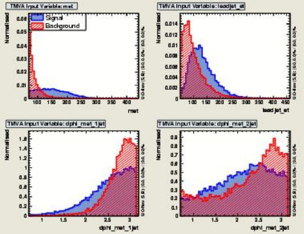


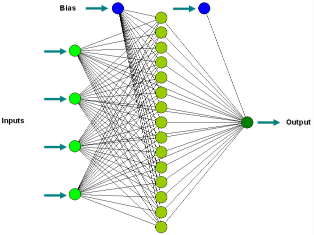
Artificial Neural Networks

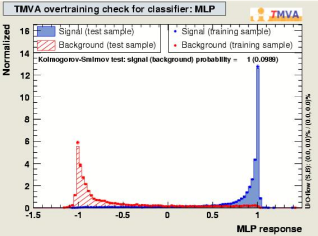
During the optimization processes, several NN are used to separate signal and background

Being careful to:

- select the appropriate set of variables
- avoid overtraining



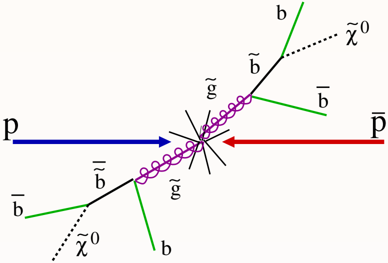




The NN takes into account correlations within variables, something really hard to do “by hand”

The Sbottom from Gluino Decay

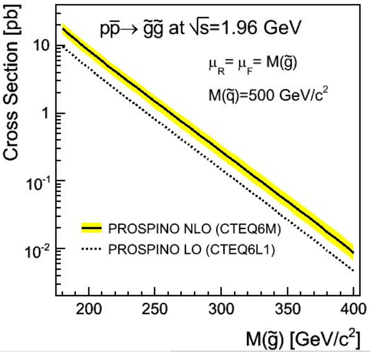
Analysis Features



Final State:

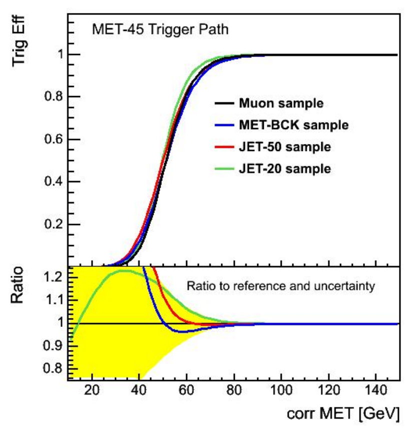
- 4 b-jets
- $\not{E}_T$ (from $\tilde{\chi}^0$)

- Process strongly dependent on the $\tilde{g}$ cross section production
- Test in the SUSY region $m_t, m_{\tilde{\chi}^+} > m_{\tilde{b}} > m_{\tilde{\chi}^0}$
- $\tilde{g} \rightarrow b\tilde{b}$, $\tilde{b} \rightarrow b\tilde{\chi}^0$ with 100% B.R.



Trigger Efficiency

$\not{E}_T \geq 45$ Trigger $\Rightarrow \mathcal{L} = 2.5\ \mathrm{fb}^{-1}$



Trigger cuts

- Level 1: $\not{E}_T \geq 25$ GeV
- Level 2: $\not{E}_T \geq 35$ GeV
- Level 3: $\not{E}_T \geq 45$ GeV

Cut in the analysis: $\not{E}_T \geq 70$ GeV

Parameterizations

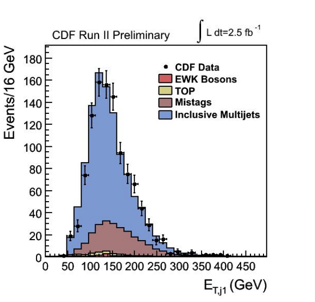
- Four different samples used to extract the trigger turn-on
- The muon sample is the central one (real $\not{E}_T$)
- The others are used to quote an uncertainty

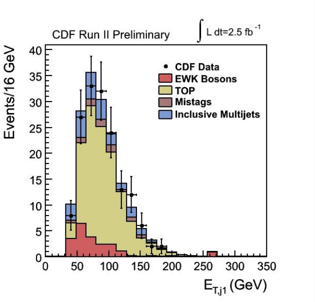
Control Regions

Three control regions defined for background validation:

- **Inclusive Multijet region:**
  $\not\!\!E_T$ aligned with the 2nd Jet
- **Lepton region:**
  At least 1 lepton required
- **Pre-optimization region:**
  Benchmark point to optimize sensitivity

	Multijet Region	Lepton Region	Pre-optimization Region
Electroweak bosons	10 ± 7	21 ± 14	33 ± 22
Top-quark	19 ± 6	111 ± 34	146 ± 45
Light-flavor jets	225 ± 49	8 ± 2	57 ± 12
HF Multijets	839 ± 419	25 ± 12	270 ± 135
Total expected	1093 ± 422	165 ± 39	506 ± 144
Observed	1069	159	451



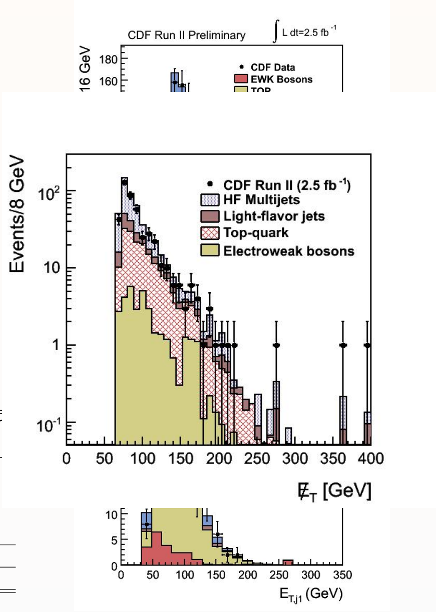


Control Regions

Three control regions defined for background validation:

- **Inclusive Multijet region:**
  $\not\!\!E_T$ aligned with the 2nd Jet
- **Lepton region:**
  At least 1 lepton required
- **Pre-optimization region:**
  Benchmark point to optimize sensitivity

	Multijet Region	Lepton Region	Pre-optimizatior Region
Electroweak bosons	10 ± 7	21 ± 14	33 ± 22
Top-quark	19 ± 6	111 ± 34	146 ± 45
Light-flavor jets	225 ± 49	8 ± 2	57 ± 12
HF Multijets	839 ± 419	25 ± 12	270 ± 135
Total expected	1093 ± 422	165 ± 39	506 ± 144
Observed	1069	159	451



Optimization I

Two different optimizations ⇒ different kinematic behavior:

m($\tilde{g}$) = 335 GeV/c^2, m($\tilde{b}$) = 260 GeV/c^2, m($\tilde{\chi}^0$) = 60 GeV/c^2 ⇒ Large Δm
m($\tilde{g}$) = 335 GeV/c^2, m($\tilde{b}$) = 315 GeV/c^2, m($\tilde{\chi}^0$) = 60 GeV/c^2 ⇒ Small Δm

- 1st- Neural Network to remove the Multijet background
- 2nd- Neural Network to remove the $t\bar{t}$ background
- We use the same set of variables for the two Neural Networks

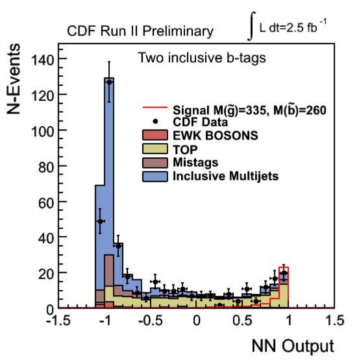
Large Δm Optimization (Njets $\geqslant$ 3):

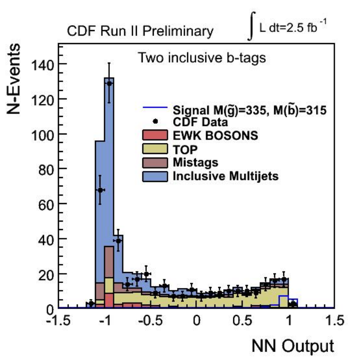
$\not{E}_T, E_{T,j1}, E_{T,j2}, E_{T,j3}, \Delta\phi(\not{E}_T, j1), \Delta\phi(\not{E}_T, j2), \Delta\phi(\not{E}_T, j3), H_T$

Small Δm Optimization (Njets $\geqslant$ 2):

$\not{E}_T, E_{T,j1}, E_{T,j2}, \Delta\phi(\not{E}_T, j1), \Delta\phi(\not{E}_T, j2), Min\Delta\phi(\not{E}_T, jets), H_T$

Optimization II





Selection cuts based on $S/\sqrt{B}$:

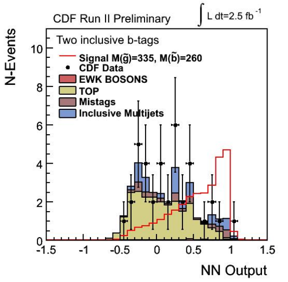
Large $\Delta m \Rightarrow$ 0.8 cut on multijet-NN output
Small $\Delta m \Rightarrow$ 0.8 cut on multijet-NN output

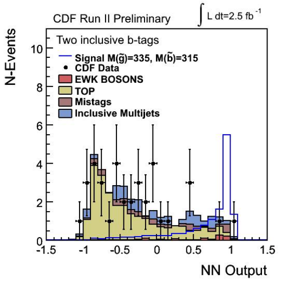
Results

Signal Region:
Large $\Delta m \Rightarrow$ 0.6 cut on top-NN output
Small $\Delta m \Rightarrow$ 0.8 cut on top-NN output

	Large Δm Optimization	Small Δm Optimization
Electroweak bosons	0.17 ± 0.05	0.5 ± 0.3
Top-quark	1.9 ± 1.0	0.6 ± 0.4
Light-flavor jets	1.0 ± 0.3	0.6 ± 0.1
HF Multijets	1.6 ± 0.8	0.7 ± 0.3
Total expected SM	4.7 ± 1.5	2.4 ± 0.8
Observed	5	2
Optimized $\tilde{g}$ signal	14.9 ± 5.0	8.5 ± 2.8

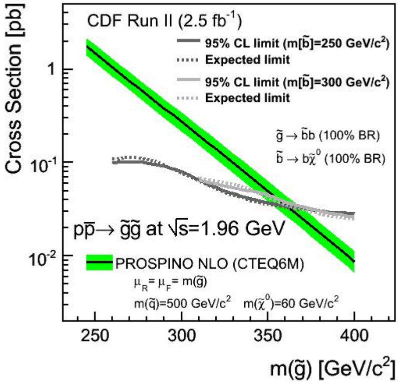
Good agreement between expected (from SM) and observed events

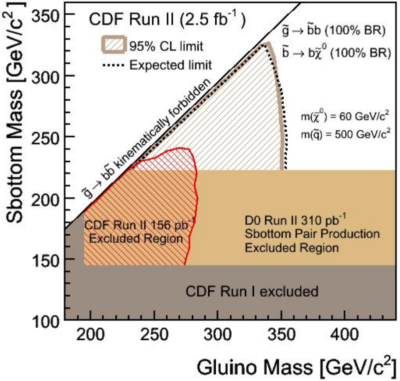




Observed Limits

95% C.L. limits on Cross Section and m($\tilde{b}$)-m($\tilde{g}$) plane





Phys. Rev. Lett 102, 221801 (2009)

The Stop Decaying into Charm and Neutralino

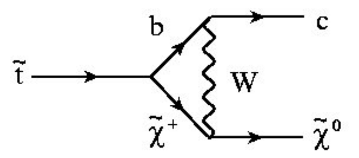
Analysis Features I

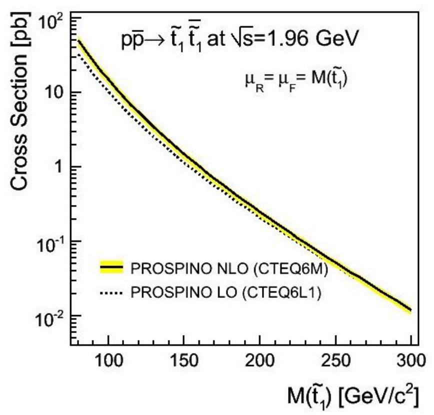
Due to the low mass, the decay to top quark is forbidden

The $\tilde{t} \rightarrow c\tilde{\chi}^0$ is well justified as dominant

Final State:

- 2 c-jets
- $\not{E}_T$ from $\tilde{\chi}^0$





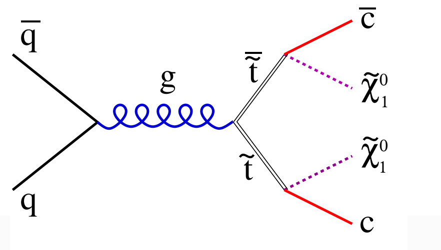
Analysis Features I

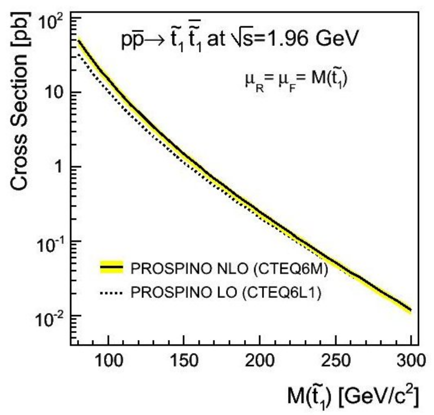
Due to the low mass, the decay to top quark is forbidden

The $\tilde{t} \rightarrow c\tilde{\chi}^0$ is well justified as dominant

Final State:

- 2 c-jets
- $\not{E}_T$ from $\tilde{\chi}^0$





Analysis Features II

The same approach as in the sbttom-gluino search:

- Similar final state, $\not{E}_T$ + jets
- Same backgrounds ⇒ In a different proportion
- Same background estimation
- Same control regions

But, it is not that easy...

Sbottom-gluino

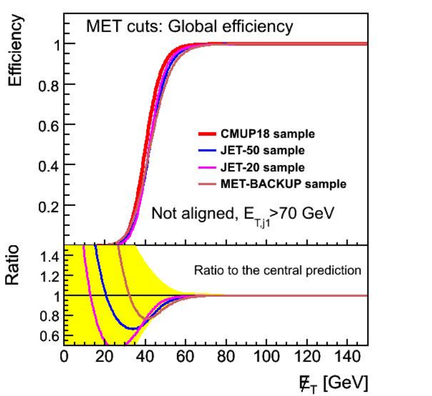
- Clean final state: 4 b-jets+$\not{E}_T$
- $t\bar{t}$ dominated ⇒ well known
- "Standard" tagging with tight requirements

Stop

- 2 c-jets+$\not{E}_T$
- W+jets dominated
- "Standard" tagging with loose requirements + c tagging

Trigger Efficiency

$\not\!\!E_T$+Jets Trigger $\Rightarrow \mathcal{L} = 2.6\ \mathrm{fb}^{-1}$



Trigger history

- Level 1: $\not\!\!E_T \geq 25$ GeV
- Level 2: requirements on jet E_T and $\not\!\!E_T$
- Level 3: $\not\!\!E_T \geq 35$ GeV

$\not\!\!E_T$ cut in the analysis: $\not\!\!E_T \geq 50$ GeV

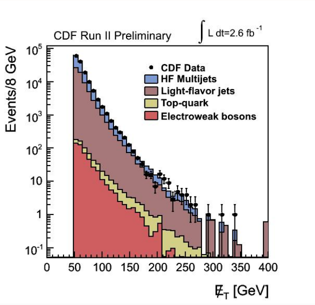
6 parameterizations

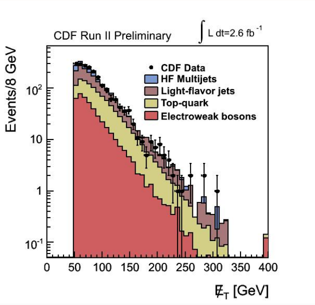
- For $\not\!\!E_T$ aligned with the second jet or not
- $E_{T,j1} < 50$ GeV
- $50 < E_{T,j1} < 70$
- $E_{T,j1} > 70$ GeV

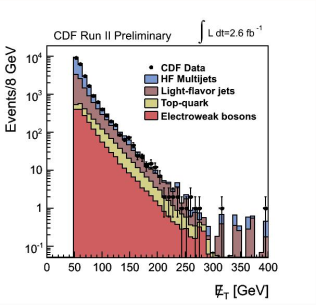
Control Regions

CDF Run II Preliminary 2.6 fb^{-1}

Regions	Multijet	Lepton	Pre-optimization
W/Z + jets production	457 ± 190	375 ± 156	1551 ± 644
Diboson production	17 ± 2	45 ± 5	118 ± 13
Top pair production	188 ± 21	547 ± 60	870 ± 96
Single top production	11 ± 2	71 ± 10	130 ± 19
HF QCD Multijets	75407 ± 23376	268 ± 83	12935 ± 4010
Light-flavour contamination	65839 ± 8427	720 ± 92	7741 ± 991
Total expected	141919 ± 24849	2026 ± 208	23345 ± 4182
Observed	143441	2026	22792



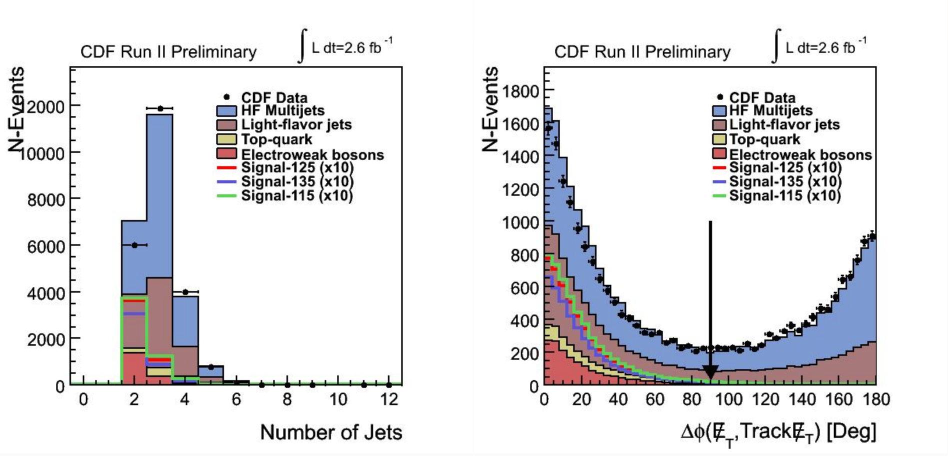




Optimization: Multijet Rejection Cuts

Two clear cuts to remove multijet background easily

- $\Delta\phi(\not\!\!E_T, track\not\!\!E_T) < 90^\circ$
- Njets = 2

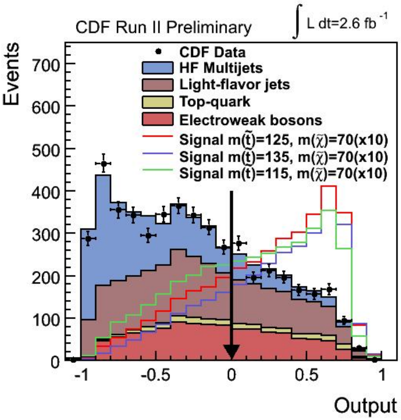


Optimization: Multijet-NN cut

Using a NN we train stop-signal vs Multijet production

- **Signal:** m($\tilde{t}$)=125 GeV/c^2, m($\tilde{\chi}^0$)=70 GeV/c^2
- **Multijet events**

- Cutting at 0 in the NN output
- Region between -1 and 0 is another control region
- Multijet normalization in the (-1,0) region ⇒ SF = 0.71
- (0,1) is the signal region
- Next step:
  apply charm-enhancing tagger to (0,1) region

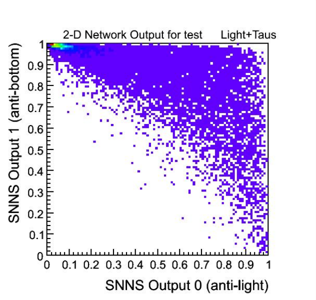


Optimization: Flavor Separator - CHAOS

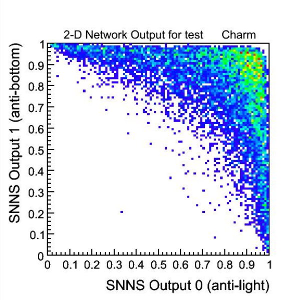
Charm **H**adron **A**nalysis **O**riented **S**eparator

How does **CHAOS** work?

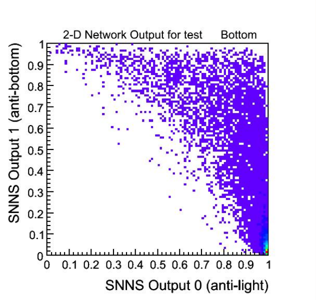
- Using a Neural Network CHAOS distinguish the flavor of a tagged jet (on top of loose “standard” tagging)
- CHAOS separates the tagged jets using a 2D output
- Three different targets: b-jets, light-jets and c-jets



light-jets+taus



c-jets

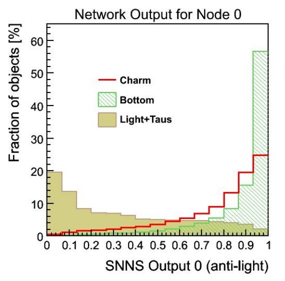


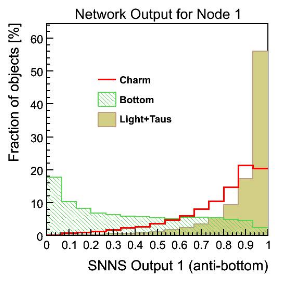
b-jets

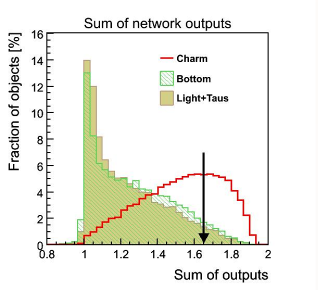
Applying CHAOS

The Neural Network is trained using a set of 22 variables:

- Related to tagging properties (vertex, quality tracks, etc)
- No dependence on kinematic (using ratios)

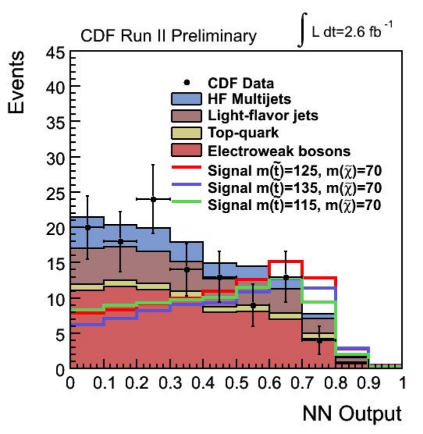






Cutting on CHAOS output to get the final region

Final Discriminant



The Multijet-NN output is the best discriminant

CDF Run II Preliminary 2.6 fb^{-1}

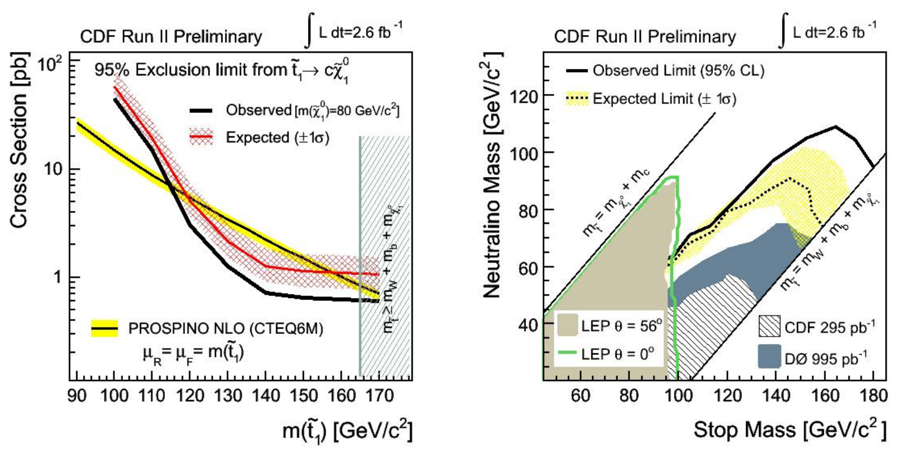
	Final Region
W/Z + jets production	60.9 ± 26.6
Diboson production	10.7 ± 1.9
Top pair production	4.6 ± 1.3
Single top production	3.2 ± 0.8
HF QCD Multijets	20.4 ± 15.2
Light-flavour contamination	32.2 ± 12.7
Total expected	132.0 ± 24.4
Observed	115
Signal m($\tilde{t}$)=125, m($\tilde{\chi}^0$)=70	90.2 ± 23.9
Signal m($\tilde{t}$)=135, m($\tilde{\chi}^0$)=70	78.0 ± 20.7
Signal m($\tilde{t}$)=115, m($\tilde{\chi}^0$)=70	82.4 ± 21.8

One more time, no hint of SUSY!!!

From this plot we extract the limit using shapes

Observed Limits

95% C.L. limits on Cross Section and $m(\tilde{\chi}^0)$-$m(\tilde{t})$ plane



Summary

- Tevatron and CDF are performing really well (also DØ, I guess..)
  - $\sim$ 8 fb^{-1} delivered
  - $\sim$ 6.5 fb^{-1} recorded
- Two SUSY searches were covered in this thesis:
  - Gluino-Mediated Sbottom **(Phys. Rev. Lett 102, 221801 (2009))**
  - Stop Decaying into Charm and Neutralino (**Presented at EPS & LP09**)
- No evidence of third generation squarks in $\sim$2.5 fb^{-1} of data
- Still good agreement with the SM
- New tools were developed for these analyses:
  - **MUTARE** method to compute HF multijet background
  - **CHAOS** flavor separator to select c-jets

Using these tools we have set world best limits in these searches and improved other CDF analysis.