CDF note 7136

Search for Sbottom Quarks from Gluino Decays

The CDF Collaboration
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We search for sbottom quarks in events with missing energy ($\not\!\!E_T$) and b-jets collected by the CDF Run II experiment at the Tevatron using 156 pb^{-1} of data. If in reach of Tevatron energies, gluino pair production is expected to have a significant production cross section. In a scenario where the sbottom is lighter than the gluino, sbottoms could be produced through the decay of gluinos into bottom and sbottom quarks, yielding a rich signature consisting of four b-jets, and two neutralinos from the sbottom decay $\tilde{b}_1 \to b\tilde{\chi}_1^0$. We search for a final state with four b-jets and missing transverse energy from the undetected neutralinos. Several control regions are studied to check the background estimation, and are found to be in good agreement with the data. The signal region is defined by $\not\!\!E_T > 80$ GeV and vetoing the presence of leptons. It is subdivided into exclusive single and inclusive double b-tagged events. For the exclusive single tag, 21 events are observed, which is in agreement with standard model background expectations of 16.4 ± 3.7 events. Requiring inclusive double b-tag we observe 4 events, where 2.6 ± 0.7 are expected. Hence, no evidence for gluino pair production with squential decay into sbottom-bottom is observed, and a 95% C.L. exclusion limit is set on the masses of the gluino and sbottom of up to 280 and 240 GeV respectively.

Preliminary Results for Summer 2004 Conferences

I. INTRODUCTION

In the Minimal Supersymmetric extension of the Standard Model (MSSM), to every fermionic Standard Model (SM) particle a bosonic superpartner is assigned and vice versa. Therefore, the SM quark helicity states q_L and q_R have scalar MSSM superpartners, which are also the mass eigenstates (in good approximation) for the first two generations. However, for the third generation, strong mixing can appear depending on the parameters of the theory: $\tan\beta$ (the ratio of the VEV's of the two Higgs fields) and A_b (the Higgs-sbottom trilinear coupling). The masses of the two sbottom particles are given by:

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

If $\tan\beta$ is large, then there can be a large mass splitting in the sbottom sector, yielding low mass for one of the $\tilde{b}$ which could be in the reach of the Tevatron center of mass energies. Assuming R-parity conservation, SUSY particles are pair produced and the Lightest Supersymmetric Particle (LSP) must be stable. If in addition it is colorless and neutral, then it will escape from the detector undetected leaving large missing transverse energy.

The gluino pair production cross section is large compared to direct sbottom pair production of similar mass. At the Tevatron energies, gluinos are produced mainly through quark-antiquark annihilation and gluon fusion. If the sbottom is light enough, then the two body decay $\tilde{g} \to b\tilde{b}$ would be kinematically allowed.

This note describes the search for the scalar partner of the bottom quark, the sbottom ($\tilde{b}$) produced through gluino ($\tilde{g}$) decays in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with the CDF detector. We look for gluino pair production $p\bar{p} \to \tilde{g}\tilde{g}$, where the gluino decays to $\tilde{g} \to b\tilde{b}$ with the subsequent sbottom decay to a b-quark and the lightest neutralino ($\tilde{\chi}^0_1$), $\tilde{b} \to b\tilde{\chi}^0_1$. The neutralino is taken to be the LSP and R-parity conservation is assumed. Therefore, the decay signature is 4 b-jets and large missing transverse energy ($\not\!\!E_T$), as shown in Figure 1.

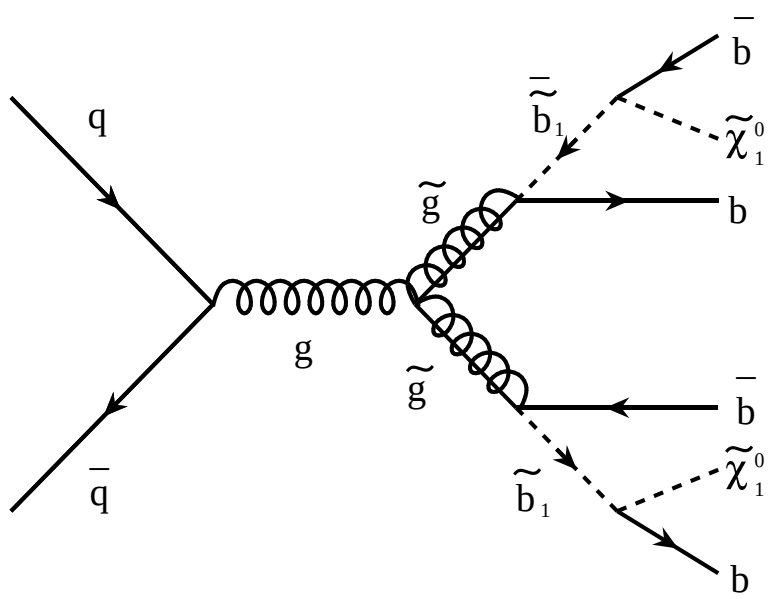

FIG. 1: Schematic representation of the sbottom production through gluino decays.

For this analysis, we take advantage of the new $\not\!\!E_T$ CDF triggers which have increased acceptance for our signature compared with previous RUN-I studies.

The signal predictions have been computed with the ISAJET [2] event generator program using the CTEQ5L parton distribution functions. The generated events have been passed through the simulation of the CDF detector, which is described in detail in [1]. The signal event characteristics depends strongly on the mass difference between the gluino and the sbottom. For small mass differences, the b-quark from the gluino has low transverse energy due to the reduced phase space, and therefore the acceptance is reduced if one requires multiple jets in the events since some of the jets will be fail the jet requirements. In the opposite case, the neutralinos from the sbottom decays are produced with a considerable boost and therefore they tend to be back to back, yielding a lower $\not\!\!E_T$ in the event.

II. DATA SAMPLE AND EVENT SELECTION

The analysis presented here is based on an integrated luminosity of 156 pb^{-1} collected with the CDF-II detector between July 2002 and September 2003. The data are collected with a missing transverse energy plus jets trigger, requiring a $\not\!\!E_T$ above 35 GeV and two jets with transverse energy (E_T) above 10 GeV.

From this data sample, events are selected offline by requiring $\not\!\!E_T > 35$ GeV and at least 3 jets with $E_T > 15$ GeV and pseudorapidity (η) smaller than 2.0. At least one of these jets is required to be in the central part of the CDF-II detector ($\eta < 1$).

This preselected three-jet sample is mostly dominated by QCD-multijet events where the $\not\!\!E_T$ arises due to mismeasurements of the jet energy for one or more of the jets. In addition, QCD heavy-flavor jets could generate $\not\!\!E_T$ if the heavy quark decays semileptonically due to the presence of neutrinos and muons in the event.

A. Secondary Vertex b-Tagging Algorithm

To reduce the presence of multijet background and light-flavor jet processes, the sample is required to contain at least one jet tagged as a *"b-jet"*. In order to do this, an algorithm identifying secondary vertices is used. This algorithm identifies tracks within the jet that are used to reconstruct a displaced vertex which is related to the decay of long-live hadrons containing a heavy-flavor quark.

After requiring one or more jets in the sample to be tagged as b-jets, the multijet background from light flavor quark and gluon jets is largely reduced. After this step, the sample is dominated by QCD production of heavy-flavor jets.

B. Isolated Lepton Identification

In order to reduce the presence of W/Z+jet(s), diboson and top-pair-production backgrounds, events are rejected if a high-p_T isolated lepton is found. Three kind of leptons are considered and identified using different approaches:

- **Electrons** are identified as small and isolated energy deposits in the electromagnetic calorimeters of the CDF-II detector. In order to avoid the identification of photons as an electron, the tracking system is used to identify the presence of tracks pointing to the deposited energy associated to the electron.
- **Muons** are identified as high-p_T tracks reconstructed with the tracking system and whose extrapolated position in the muon chambers is associated to hits in the muon chambers of the CDF-II detector. The calorimeter energy deposited by the muon is required to be consistent with the signature of a minimum ionizing particle. Additionally the muon is required to be isolated.
- **Taus** are identified as high-p_T isolated tracks in the tracking system. Isolated muons not associated to hits in the muon chambers are identified as this kind of leptons.

Isolated high-p_T leptons are expected to be produced in ElectroWeak (EWK) processes, as hard Drell-Yan production or by the decay of W and Z bosons. Other processes producing leptons (as the semileptonic decay of b-hadrons) usually result in non-isolated leptons or leptons of lower p_T.

C. Kinematic Cuts And Control Regions

In order to further reduce the multijet background, kinematic cuts are applied to the sample. In the QCD-multijet events, we expect that the jets are aligned with the direction of the $\not\!\!E_T$ in the transverse plane. By requiring that the angular distance in the transverse plane (azimuthal angle ϕ) between the first three jets and the $\not\!\!E_T$ is greater than 40°, the multijet background is mostly reduced while still keeping a large acceptance for the gluino into sbottom events.

After applying this cut in the azimuthal distance, three control regions are defined. Since in the gluino events we do not expect the presence of high-p_T isolated leptons and the $\not\!\!E_T$ is pretty large, the three control regions are defined as follows:

- **A region** *C0* for which a medium $\not\!\!E_T$ ($35 < \not\!\!E_T < 50$ GeV) and the presence of a high-p_T isolated lepton is required. This region has contributions from QCD (containing fake or real leptons), top and some weak boson plus jet(s) events.
- **A QCD-dominated region** *C1* for which we required medium $\not\!\!E_T$ ($35 < \not\!\!E_T < 50$ GeV) and no lepton identified as such. This region is completely dominated by QCD multijet events.
- **A top-dominated region** *C2* for which we require high $\not\!\!E_T$ ($\not\!\!E_T > 50$ GeV and at least one high-p_T isolated lepton. This region is dominated by top-pair production.

These control regions are defined in order to provide an independent cross-check of the background predictions. The signal region is subdivided into an exclusive single b-tag and an inclusive double b-tag bin. For both of them, we perform a counting experiment comparing the number of observed events with the number of expected background events.

III. BACKGROUNDS

As mentioned in the previous section, there are three sources of background for the analysis. Those have been treated and their contributions reduced in different ways since the signatures are slightly different. Since most of the background contribution is estimated by means of the detector simulation and MC events, the control regions are used to cross check the validity of the method and the samples used in each case.

A. Electroweak Backgrounds

The production of W and Z bosons in association with jets is one of the sources of background in the signal region. Events with high $\not\!\!E_T$ can be produced by the leptonic decay of the W or muons escaping detection. In addition to the single-boson processes, diboson production is also included as part of the EWK background.

This background is estimated by using MC samples generated with the ALPGEN program [3] and the total NLO cross section was calculated with MCFM [4]; they are summarized in Table I. For those processes not included in MCFM, the LO prediction by ALPGEN is used and scaled with a K-factor obtained for a similar process. MCFM is also used to estimate the uncertainty in the total cross section due to the renormalization and factorization scale.

B. Multijet Background

Although the QCD multijet contribution is small in the signal region, it is an important background in the control regions and it has to be well under control before checking the presence of the other backgrounds.

There are two main sources of this background: light-flavor jet production where jets could be misidentified as "b-jets" and heavy-flavor jet production. The later is the most important contribution.

The contribution of light-flavor jets which are misidentified as "b-jets" is estimated using jet data. The method uses the tagged jets in a QCD-multijet sample where the impact parameter is in the opposite direction to the tagged jet (negative impact parameter). Such "negative tags" occur due to resolution and misreconstruction effects and therefore provide an estimate for the positive fake tag rate, i.e. how often a light jet gets misidentified as a b-jet.

Process	NLO σ [pb]
$W \to l\nu_l + 2$partons	319.8
$Z \to ll + 2$partons	30.7
$Z \to \nu\nu + 2$partons	184.2
WW	11.11
WZ	3.235
ZZ	1.260

TABLE I: Cross-sections for $W/Z + 2$ partons processes computed with MCFM.

Control Region	C0	C1	C2
$\not\!\!E_T$	$35-50$ GeV	$35-50$ GeV	>50 GeV
lepton	required	vetoed	required
$Wjj \to e\nu jj$	1.38 ± 0.56	0.38 ± 0.30	2.76 ± 0.77
$Wjj \to \mu\nu jj$	1.23 ± 0.44	0.60 ± 0.31	2.95 ± 0.68
$Wjj \to \tau\nu jj$	0.26 ± 0.19	5.14 ± 0.87	1.63 ± 0.47
$Zjj \to eejj$	$0.00^{+0.02}_{-0}$	$0.00^{+0.02}_{-0}$	0.02 ± 0.02
$Zjj \to \mu\mu jj$	0.12 ± 0.04	0.05 ± 0.03	0.13 ± 0.04
$Zjj \to \tau\tau jj$	0.31 ± 0.07	0.15 ± 0.05	0.27 ± 0.07
$Zjj \to \nu\nu jj$	0.08 ± 0.08	1.04 ± 0.29	0.62 ± 0.22
$Zjj \to b\bar{b}jj$	$0.00^{+0.13}_{-0}$	2.15 ± 0.55	0.13 ± 0.13
ZZ	0.17 ± 0.03	1.11 ± 0.08	0.41 ± 0.05
WZ	0.12 ± 0.05	0.16 ± 0.06	0.22 ± 0.07
WW	0.26 ± 0.12	0.21 ± 0.11	0.48 ± 0.16
Total W/Z+jets/Diboson	3.9 ± 0.8	11.0 ± 1.2	9.6 ± 1.2
Top	11.7 ± 0.2	8.2 ± 0.1	35.2 ± 0.3
QCD-multijet	13.4 ± 2.9	105.3 ± 12.3	2.9 ± 1.1
Fake tags	5.8 ± 3.0	24.3 ± 12.1	8.0 ± 4.4
Predicted background	34.8 ± 4.2	148.8 ± 17.3	55.7 ± 4.7
Observed	36	121	63

TABLE II: Total number of expected events in the control regions. The "Fake Tags" refers to the prediction for tagging a light-flavor jet as a "b-jet", obtained from the data. The total number of predicted events is in agreement with the number of observed events in data. We quote statistical uncertainties only.

Studies with MC are used to apply a scale factor to this prediction to take into account that it is easier to tag a jet (even a light-flavor jet) as a positive tag than a negative tag.

The contribution from real "b-jets" has been estimated by using Monte Carlo QCD-multijet events generated with the PYTHIA program [5] and passed through the detector simulation. The different rate for tagging b-jets in data and in the simulation is taken into account in order to correctly predict the contribution in the different regions.

C. Top Background

This is the dominant background in the region with large $\not\!\!E_T$ and multiple b-tags, including the signal region. In this case, the PYTHIA MC program [5] was used to generate the events which where passed through the detector simulation to estimate the acceptance of the event selection to top events. The theoretical prediction for top-pair production at Tevatron is $6.7^{+0.7}_{-0.9}$ pb [6].

The predicted number of expected events from the backgrounds in the three control regions are summarized in Table II. Only events containing one or more tags are considered. The predicted values are in reasonable agreement with the number of events observed in the data. In addition, Figures 2 to 4 show the distributions in the control regions for the azimuthal angle between the $\not\!\!E_T$ and the tagged jets. It can be seen that the Standard Model predicted background describes the data distributions well.

IV. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties in this analysis arise from Monte Carlo modeling of the geometric and kinematic acceptance for the signal, knowledge and modeling of the b-tagging efficiency, energy scale, the uncertainties in the background predictions, and the luminosity. The obtained numbers for these contributions were the following:

- The calorimeter energy scale: although it has little effect on the signal acceptance, it is the largest uncertainty

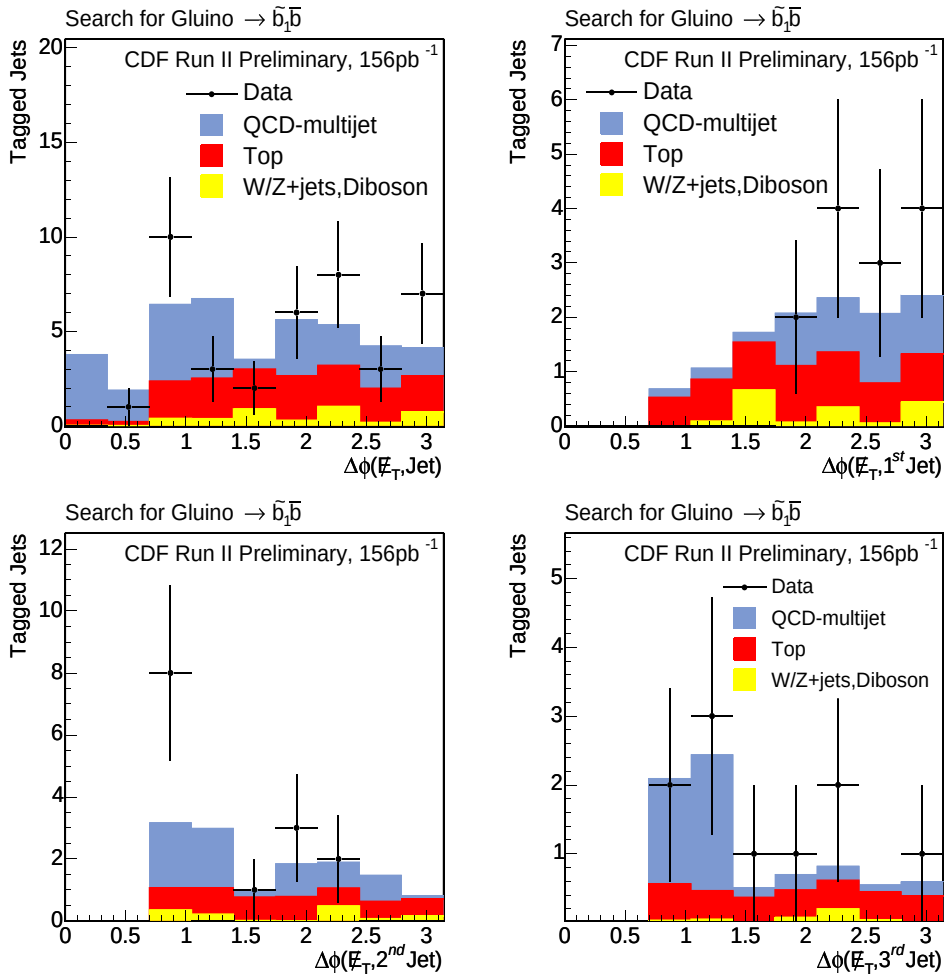

FIG. 2: $\Delta\phi$ distributions in Control Region $C0$. Top left shows $\Delta\phi(\not{E}_T, \text{anyjet})$, where any jet is any jet that passes our jet requirements and that is b-tagged. Top right shows $\Delta\phi(\not{E}_T, 1^{\text{st}}\text{jet})$, where 1st jet is the leading jet in the event, if it is tagged. Bottom left shows $\Delta\phi(\not{E}_T, 2^{\text{nd}}\text{jet})$, where 2nd jet is the second leading jet in the event, if it is tagged. Bottom right shows $\Delta\phi(\not{E}_T, 3^{\text{rd}}\text{jet})$, where 3rd jet is the third leading jet in the event, if it is tagged. The 1st jet, 2nd jet, 3rd jet apply to the highest energy, 2nd highest energy, 3rd highest transverse energy jet. For each plot the angle of the $\not{E}_T$ with respect to the b tag is shown, where the b tag is in the highest, second highest, or third highest E_T jet.

for the background predictions. It was estimated to be around 16% (14.5%) for exclusive single tag (inclusive double tag) events for top production. For EWK backgrounds, 25% uncertainty is obtained for both exclusive single tag and inclusive double tag. QCD-multijet MC shows a similar dependence on the energy scale and we found a 25% uncertainty;

- the uncertainty on the normalization of the $b\bar{b}$ multijet background was found to be 15%;
- the systematic uncertainty of tagging efficiency was taken to be the error on the scale factor taking into account the different rate for data and simulated events. This yields a 7% uncertainty in the acceptance for single tag events and 14% for double tagged events.

  In addition, we assigned a 8% systematic uncertainty per tag coming from the uncertainty in the rate of light flavor jets being misidentified as "b-jets". Also, a 11% uncertainty was included due to the uncertainty in the factor used to scale the negative tag prediction for positive tags;
- a 11.5% uncertainty related to the MCFM predictions of the cross section for W/Z+partons processes. This uncertainty was estimated by scaling by 1/2 and 2 the renormalization and factorization scale.
- the luminosity yields a 6% uncertainty in all the cross sections.

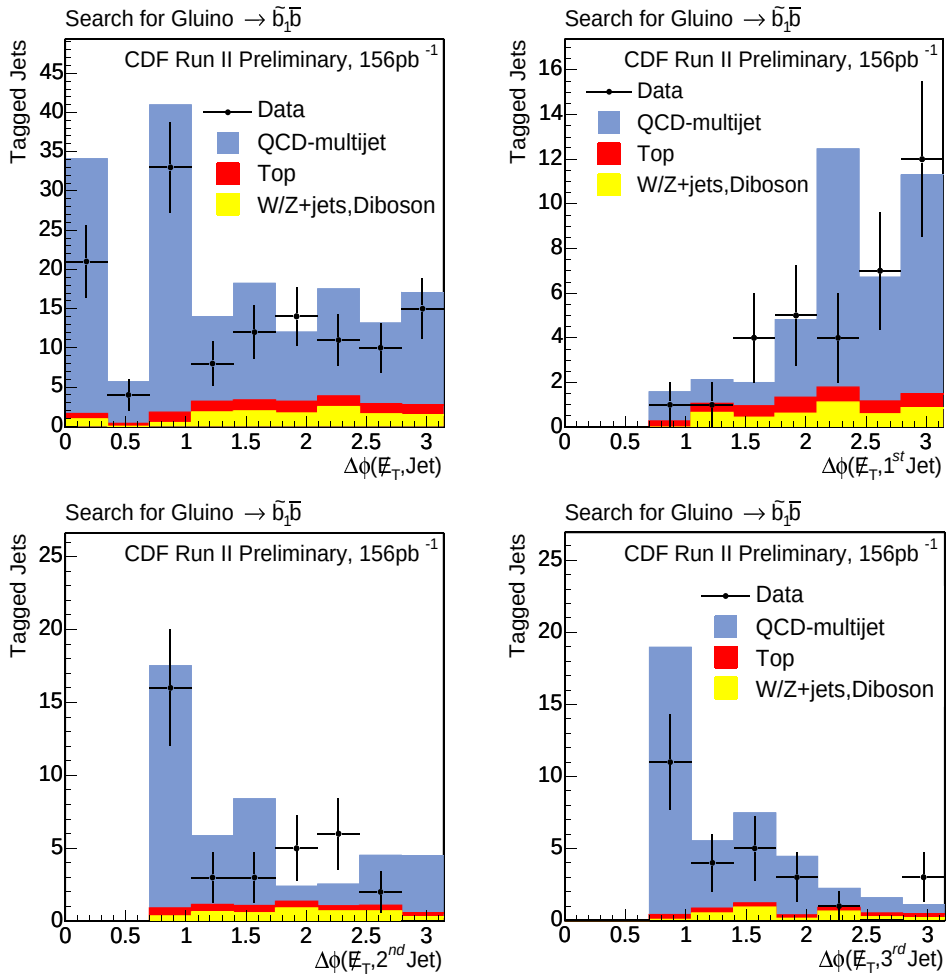

FIG. 3: $\Delta\phi$ distributions in control region $C1$. Other details are as described in the caption to Fig 2

Some smaller contributions to the total systematic uncertainty include the uncertainty in the cut on the azimuthal angle between the jets and the $\not{E}_T$ (0.5%), the uncertainty in the acceptance due to the partonic content of the proton (2%), the uncertainty in the lepton veto (2%) and the trigger efficiency (2.5%). For the signal, additional uncertainties due to the modeling of the final state in ISAJET are also computed. The uncertainty in the final and initial state radiation modeling is observed to strongly increase for small mass difference between the gluino and the sbottom. That dependence was taken into account and limits our acceptance close to the kinematic limit for gluino decaying into sbottom and b-quark. Finally, the contribution of the statistical uncertainty in the different MC samples for the signal predictions are computed by propagating the statistical uncertainty in the predictions.

The systematic uncertainties for the background and for gluino signal are summarized in Tables III and IV.

V. RESULTS

After applying all the cuts to select the events in the signal region, the $\not{E}_T$ cut was raised to 80 GeV for optimal sensitivity to the signal (with the use of exclusive single tag events). After that cut was fixed, we performed a counting experiment for events in the signal region. Results are summarized in Table V for both, the exclusive single tag and inclusive double tag bins. The number of observed events in data is around one standard deviation above the central expectations.

Figure 5 shows the distributions for the azimuthal angle between the $\not{E}_T$ and the taggged jets. As mentioned, cuts on these variables were applied to reduce the presence of multijet background.

Figures 6 and 7 show the $\not{E}_T$ spectrum, for exclusive single tagged and inclusive double tagged events, requiring

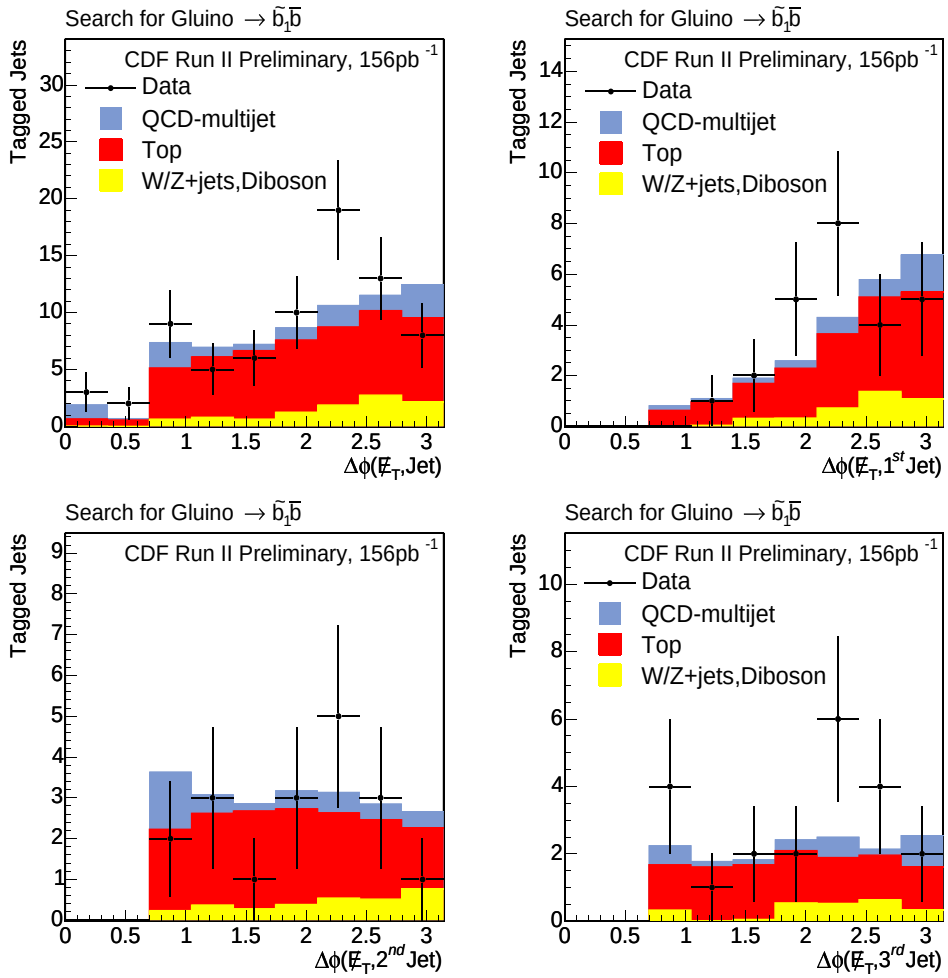

FIG. 4: $\Delta\phi$ distributions in control region $C2$. Other details are as described in the caption to Fig 2

and vetoing leptons. The observed distributions are found to be in good agreement with the predictions from the Standard Model.

Since the data is in good agreement with the expectation, we used the results to exclude gluino production at the Tevatron. Figure 8 shows the upper limit cross section at 95% C.L. from this analysis as a function of the gluino mass for a fixed mass difference between the gluino and the sbottom of 60 GeV. Figure 9 shows the excluded region at 95% C.L. in the gluino and sbottom mass plane for a fixed mass of the neutralino. The excluded cross section is convoluted with the acceptance to get the exclusion limit. Finally, Figure 10 shows the obtained upper limit cross section at 95% C.L. as a function of the sbottom mass and for a fixed gluino mass.

The sensitivity obtained in the analysis to the signal, especially for double tagged events, allows to exclude masses of the gluino up to 280 GeV for a sbottom mass of 200 GeV.

Acknowledgments

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Uncertainty	EWK		TOP		QCD	
B-Tags	$=1$	≥ 2	$=1$	≥ 2	$=1$	≥ 2
Luminosity	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
Tagging efficiency	7.0%	14.0%	7.0%	14.0%	7.0%	14.0%
Energy scale	25.0%	25.0%	16.0%	14.5%	25.0%	25.0%
Trigger efficiency	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
PDF uncertainty	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Scale factor	-	-	-	-	15.0%	15.0%
Cross-section	11.5%	11.5%	13.5%	13.5%	-	-
Lepton veto	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
$\Delta\phi$ cuts	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
Total	30.5%	31.5%	23.0%	25.0%	31.0%	33.0%

TABLE III: Summary of the systematic uncertainties for the background in the signal region.

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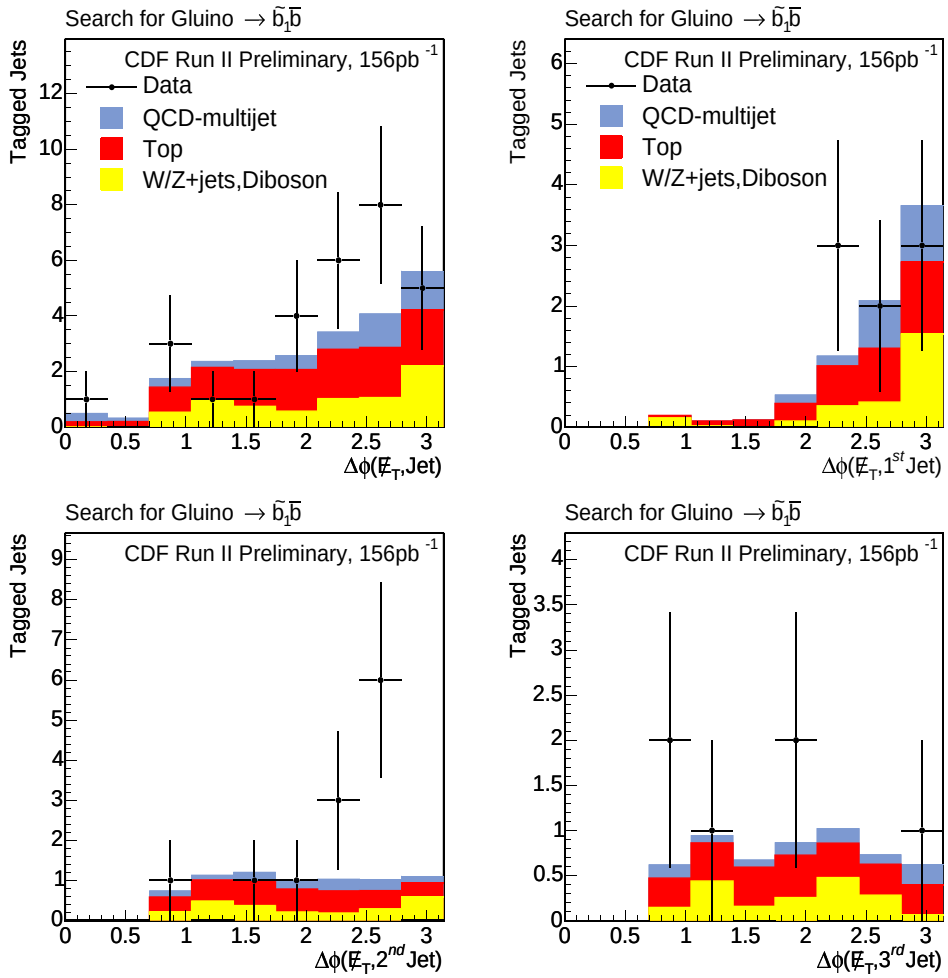

FIG. 5: $\Delta\phi$ distributions in the signal region with a $\not{E}_T$ cut of 80 GeV. Other details are as described in the caption to Fig 2

Systematic uncertainties	single tag	double tag
PDF	2.0%	2.0%
Luminosity	6.0%	6.0%
ISR/FSR	7.5%	5.0%
MC Statistics	3.0%	3.0%
Vertex Cut	0.5%	0.5%
$\Delta\phi$ Cuts	0.5%	0.5%
Lepton Veto	2.0%	2.0%
Trigger Efficiency	2.5%	2.5%
Tagging Efficiency	7.0%	14.0%
Energy Scale	10.0%	10.0%
Total correlated	14.0%	18.5%
Total uncorrelated	8.5%	6.5%
Total	16.5%	19.5%

TABLE IV: Systematic uncertainties on the signal acceptance.

Process	Exclusive Single B-Tag	Inclusive Double B-Tag
W/Z+jets/Diboson	$5.66 \pm 0.76(\text{stat}) \pm 1.72(\text{sys})$	$0.61 \pm 0.21(\text{stat}) \pm 0.19(\text{sys})$
TOP	$6.18 \pm 0.12(\text{stat}) \pm 1.42(\text{sys})$	$1.84 \pm 0.06(\text{stat}) \pm 0.46(\text{sys})$
QCD-multijet	$4.57 \pm 1.64(\text{stat}) \pm 0.57(\text{sys})$	$0.18 \pm 0.08(\text{stat}) \pm 0.05(\text{sys})$
Total Predicted	$16.41 \pm 1.81(\text{stat}) \pm 3.15(\text{sys})$	$2.63 \pm 0.23(\text{stat}) \pm 0.66(\text{sys})$
Observed	21	4

TABLE V: Number of expected and observed events in the signal region with a $\not\!\!E_T$ cut of 80 GeV .

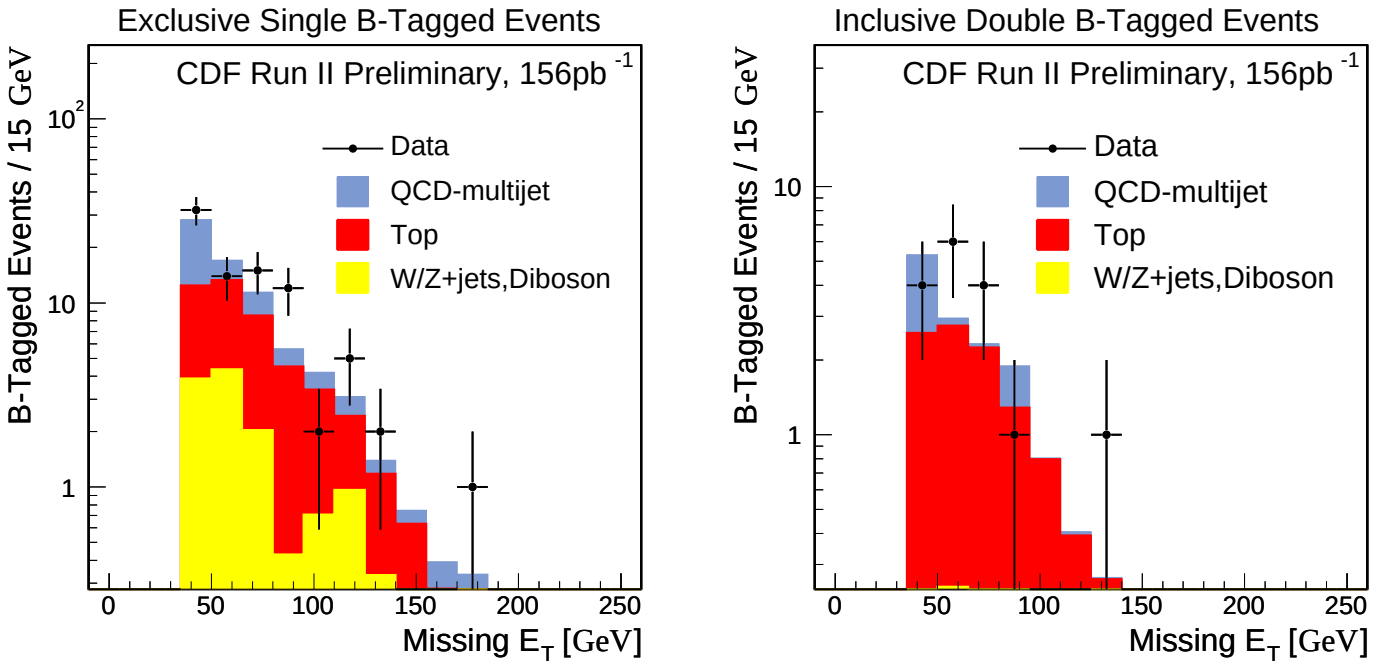

FIG. 6: $\not\!\!E_T$ spectrum, for exclusive single tagged events and inclusive double tagged events requiring leptons.

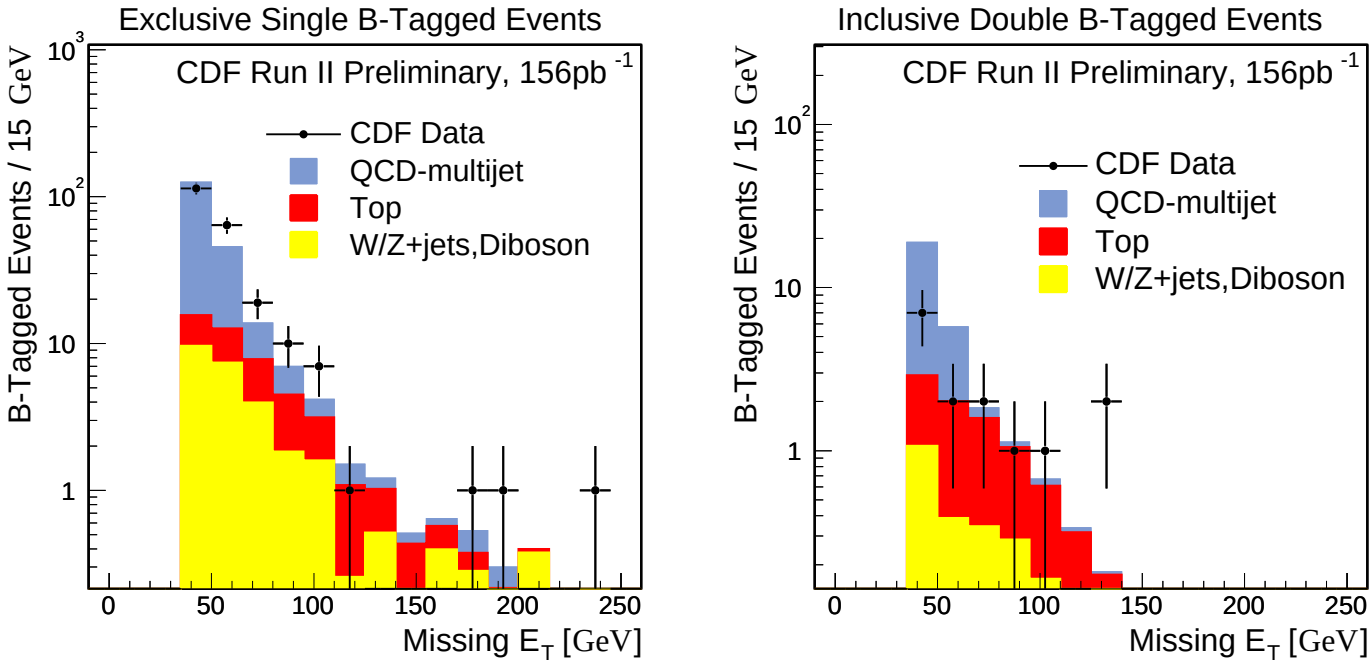

FIG. 7: $\not\!\!E_T$ spectrum, for exclusive single tagged events and inclusive double tagged events vetoing leptons. The signal region is defined to have $\not\!\!E_T > 80$GeV.

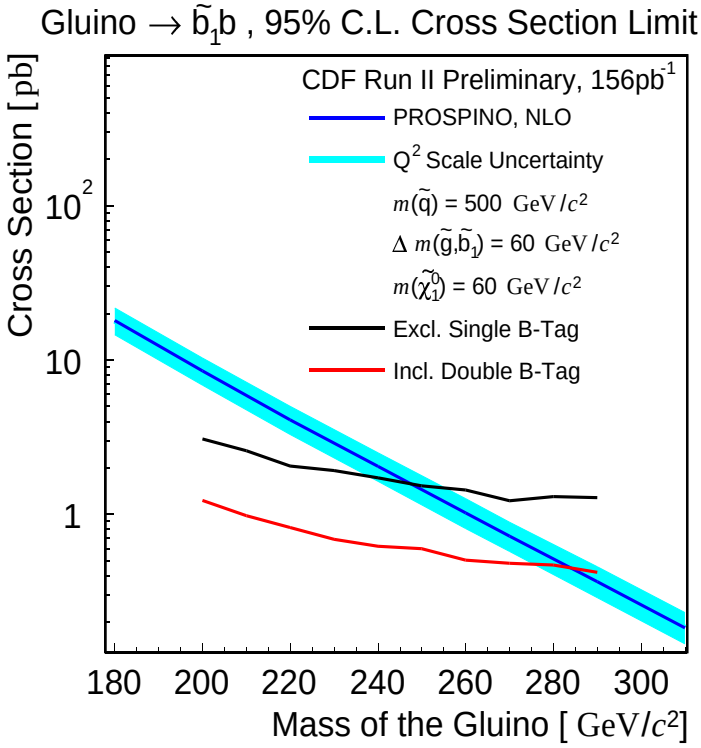

FIG. 8: 95% C.L. upper cross section limit as a function of the gluino mass and a fixed mass difference between the gluino and sbottom of 60 GeV/c^2.

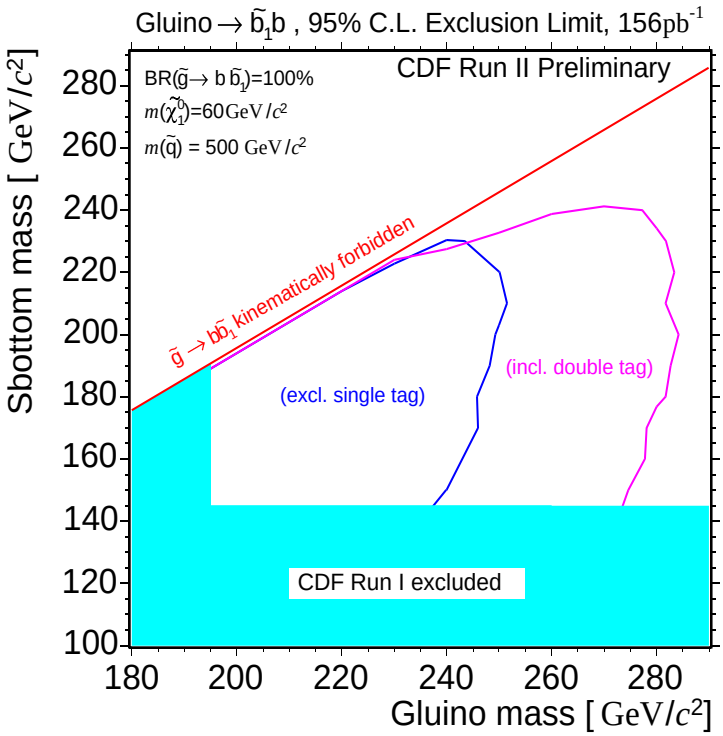

FIG. 9: 95% C.L. exclusion contours in the $m(\tilde{g})$ and $m(\tilde{b_1})$ plane.

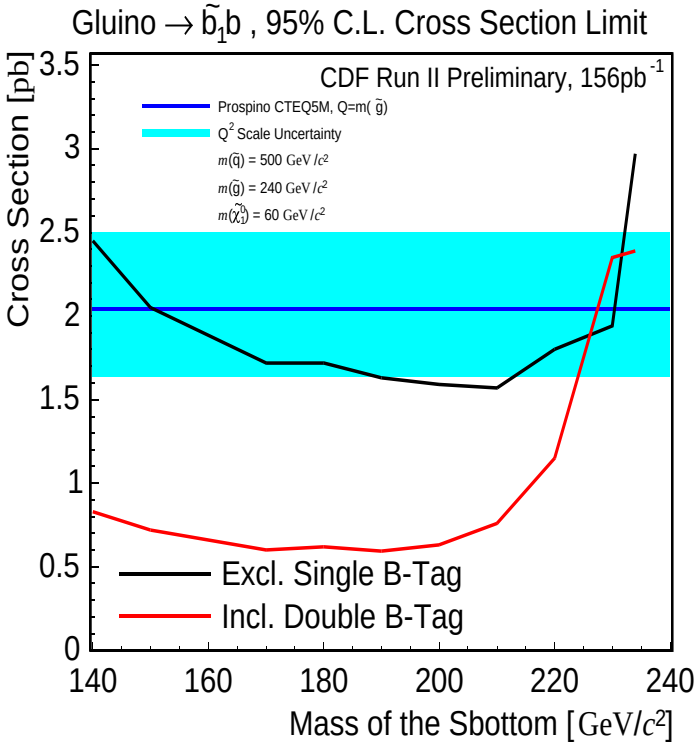

FIG. 10: 95% C.L. upper cross section limit as a function of the sbottom mass and a constant gluino mass $m(\tilde{g}) = 240$ GeV/c^2. It can be seen that for the nearly mass degenerated gluino sbottom scenario the limit obtained from exclusive single tagged events is better.