Light Gravitino Search at CDF

Andrea Castro
Dipartimento di Fisica
Universitá di Padova

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- phenomenology and strategy
- sample selection
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$\boxed{\textbf{Motivation}}$

Events with large $\not{E}_T$ are interesting for searches of physics beyond the Standard Model. So far CDF has considered

- $\not{E}_T + \geq 3$ jets $\Rightarrow$ production of gluinos and squarks $\rightarrow$ neutralinos + q's
- $\not{E}_T + \geq 3$ leptons $\Rightarrow$ chargino-neutralino pair production

  - stable and undetected neutralinos are LSP's $\rightarrow \not{E}_T$

but $\not{E}_T$ can be due to other non-interacting particles like

- gravitinos considered here
- gravitons

Motivation

In SUSY models with Gauge Mediated Symmetry Breaking (GMSB):

- the goldstino is generated
- when gravitation is introduced and symmetry realized locally, the graviton, has a spin-$\frac{3}{2}$ partner, the gravitino $\tilde{G}$
- $\tilde{G}$ acquires mass absorbing the goldstino.

(see for instance:

- S. Dimopoulos, S. Thomas and J.D. Wells, Nucl. Phys. B **488**, 39 (1997)
- G.F. Giudice and R. Rattazzi, hep-ph/9801271

Phenomenology

$\sigma(\tilde{G}\tilde{G} + jet) \sim 1/m^4_{\tilde{G}}$ so if gravitino is very light ($m_{\tilde{G}} \ll 10^{-4}$ eV/c^2) we can have a sizeable production at the Tevatron:

$$q\bar{q} \to \tilde{G}\tilde{G}g, \;\; qg \to \tilde{G}\tilde{G}q, \;\; gg \to \tilde{G}\tilde{G}g$$

even if all other SUSY particles are above production threshold.

The gravitino (=LSP) goes undetected and gives rise to $\not{E}_T$. So the final states have a $\not{E}_T + jet$ topology which can be triggered on due to the presence of jets.

In this scenario the main parameter upon which these processes depend is the SUSY-breaking scale $\sqrt{F} \propto \sqrt{m_{\tilde{G}}}$.

Strategy

The strategy is simple:

1. we select events compatible with the $\not{E}_T + jet$ topology, having large $\not{E}_T$ (to reduce backgrounds)

2. we compare the events found with the expectation from SM and other backgrounds to obtain limits on $\sigma(\tilde{G}\tilde{G}j)$

3. comparing to signal simulation we derive limits on $m_{\tilde{G}}$ and $\sqrt{F}$.

Sample selection (I)

"high-E_T jet + large $\not\!\!E_T$" topology:

- $\not\!\!E_T$ trigger ($\not\!\!E_T \geq 35$ GeV, $E_T^j \geq 50$ GeV) (2.5M events)
- $\not\!\!E_T \geq 50$ GeV (to move away from trigger threshold and reduce bckgd)
- $E_T^{lead-jet} \geq 80$ GeV (to move away from trigger threshold and reduce bckgd)
- no out-of-time energy; cuts on average $EMF = E^{EM}/E^{EM+HAD}$ and charged fraction for the jets (to reduce machine-related/cosmics backgrounds)
- at least one central ($|\eta| \leq 0.7$) jet

$\Rightarrow$ 20116 events

$\boxed{\textbf{Backgrounds (I)}}$

To such topology the major contributing backgrounds are:

- instrumental, machine-related and cosmic backgrounds
- Standard Model sources:
  1. $W + jets$
  2. $Z + jets$
  3. $t\bar{t}$, WW, WZ, ZZ

Sample selection (II)

We reduce events with W's or Z's by rejecting events with:

- high-p_T electron ($\geq 10\ GeV/c$) and muon ($\geq 5\ GeV/c$)
- isolated tracks ($\sum_{trk} p_T^{trk} - p_T^{cand} < 10\ GeV/c$, $p_T^{cand} \geq 30$ GeV/c)

$\Rightarrow$ 16019 events (dominated by instrumental backgrounds)

Backgrounds evaluation

* events from a control sample (high-E_T jet trigger, $E_T \geq 50\ GeV$) to estimate instrumental, machine-related and cosmic backgrounds

- PYTHIA+CDF simulation for Standard Model sources:

  1) $W + jets$

  2) $Z + jets$

  3) $t\bar{t}$, WW, WZ, ZZ

  - need to rescale PYTHIA's cross sections for $W/Z + jets$ to reproduce CDF measurements

$\boxed{\textbf{Bckgd from machine or cosmics}}$

We infer this background from the control sample (inclusive jets), considering:

- out-of-time energy,
- average charged fraction,
- average EMF.

These backgrounds amount at most to 1% of the selected events.

Instrumental background

Large $\not\!\!E_T$ can be due to instrumental effects: fluctuations in the jet energy measurement or track multiplicity.

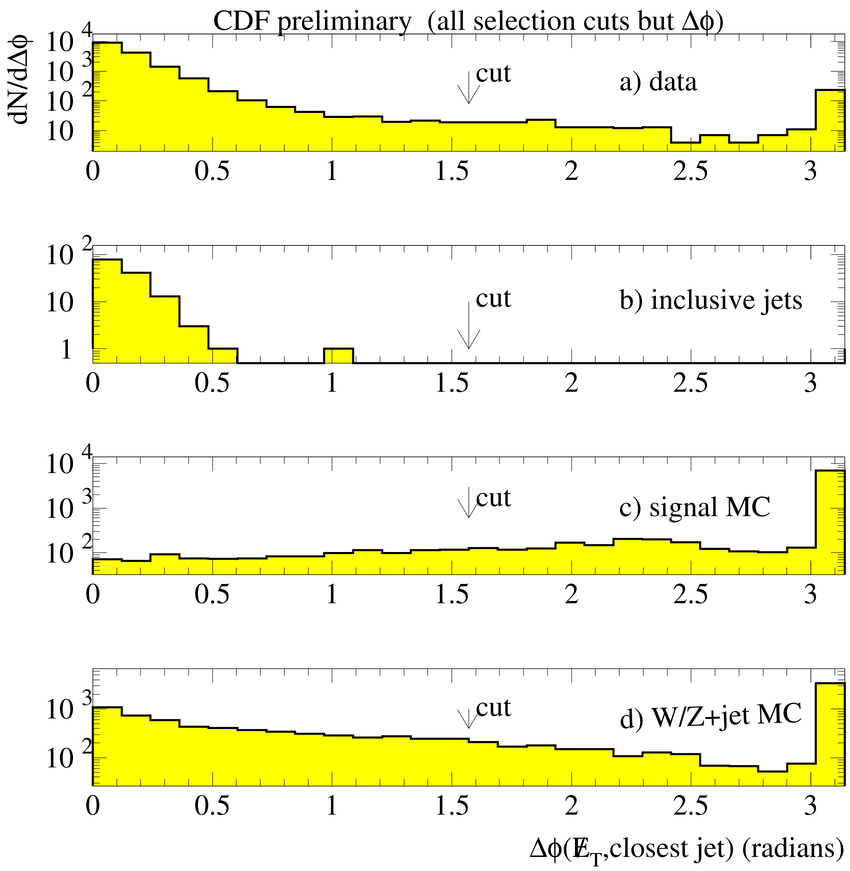
We infer this background from the data:

- use the control sample (inclusive jets) and study the $\Delta\phi(\vec{\not\!\!E_T}, \mathit{closest\ jet})$ variable

- increase statistics reducing the $\not\!\!E_T$ cut to 20 GeV

$\Rightarrow$ in the end we see this background is negligible for $\not\!\!E_T \geq 100$ GeV.

Choice of the $\Delta\phi$ cut



- $\Delta\phi \geq 90^o$ is quite efficient (88%)
- $\leq$ 14 events at 95% CL from the instrumental background.

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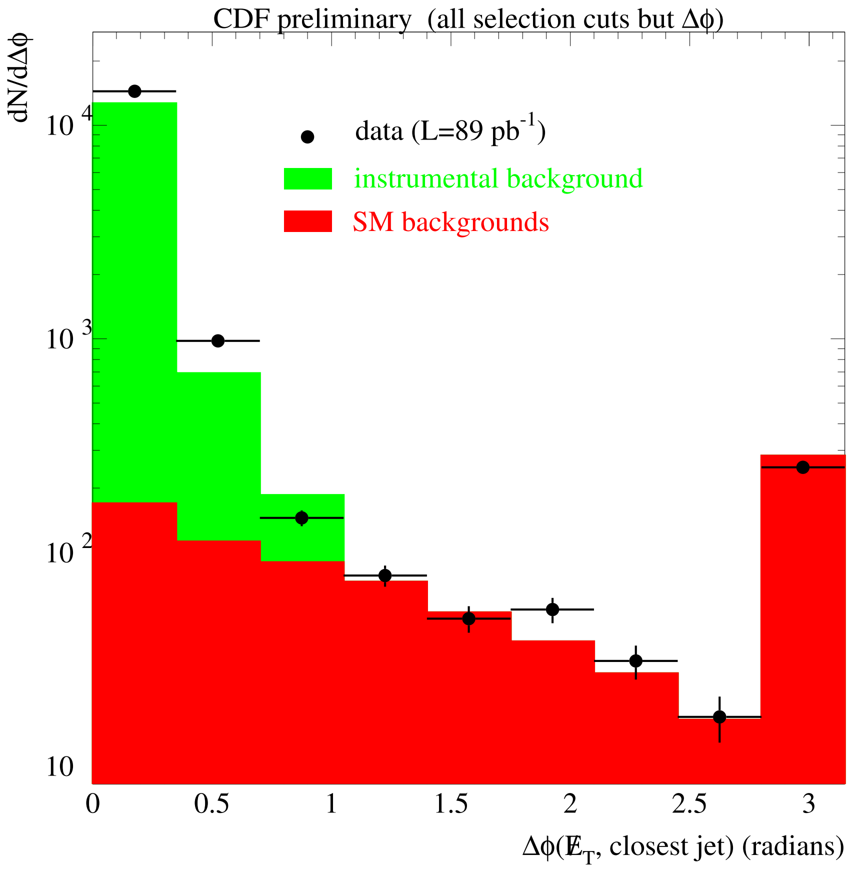
$\Delta\phi$ spectrum: data *vs* background

Before the application of the $\Delta\phi$ cut we see a good agreement between the data and the sum of Instrumental + Standard Model backgrounds:



Sample selection (III)

Finally the selection requires:

- $\Delta\phi(\vec{\not{E}}_T, closest\ jet) \geq 90°$

We are left with

$\Rightarrow$ 379 events with $\not{E}_T \geq 50$ GeV
corresponding to $\int \mathcal{L}dt = 89\ pb^{-1}$
(Run 1994/95)

Instrumental, machine-related and cosmic backgrounds are negligible.

$W/Z + jets$ Monte Carlo generation

$W/Z + jets$ events represent the majority ($\approx 45 + 54 = 99\%$) of the SM background: we study them in detail.

We use PYTHIA with a full detector simulation.

We study $W \to e\nu$, $Z \to ee$ events and compare them to experimental candidates to control

- that they reproduce relevant spectra
  - P_T^W, P_T^Z (related to radiation modeling)
  - $|\vec{\not{E}}_T + \vec{P}_T^{Z \to ee}|$ vs $\not{E}_T$ (for $Z \to \nu\bar{\nu}$)
  - $*$ these spectra are in good agreement

- their absolute normalization w.r.t. experimental cross sections
  - $B\sigma(W+\geq n\ jet, W\rightarrow e\nu)$, $B\sigma(Z+\geq n\ jet, Z\rightarrow ee)$
  * we introduce a scale factor K which depends on the jet multiplicity.

$\Rightarrow$ this factor applies to W/Z all decay channels

$W/Z + jets$: **MC** vs **experimental** σ

CDF has published results on the cross section for $W+ \geq n\ jet\ (W \to e\nu)$, $Z+ \geq n\ jet\ (Z \to ee)$, counting jets with $E_T \geq 15$ GeV, $|\eta| \leq 2.4$.

(PRL **77**, 448 (1996); **79**, 4760 (1997))

Comparing with PYTHIA's cross sections we see that we need a rescaling by

$$K = \frac{B\sigma_{data}}{B\sigma_{PYTHIA}} \approx 1.2$$

for events with ≥ 1 jet.

$W/Z + jets$: MC vs experimental cross sections

Sample	$B\sigma_{PYTHIA}$ (pb)	$B\sigma_{Data}$ (pb)	$K = B\sigma_{Data}/B\sigma_{PYTHIA}$
$W + = 0$ jets	1163 ± 3	2019 ± 177	1.74 ± 0.15
$W + = 1$ jets	313 ± 3	370 ± 76	1.18 ± 0.24
$W + \geq 2$ jets	89 ± 2	101 ± 19	1.14 ± 0.22

Sample	$B\sigma_{PYTHIA}$ (pb)	$B\sigma_{Data}$ (pb)	$K = B\sigma_{Data}/B\sigma_{PYTHIA}$
$Z + = 0$ jets	102.7 ± 0.3	185.8 ± 16.8	1.81 ± 0.16
$Z + = 1$ jets	28.8 ± 0.2	35.5 ± 7.7	1.23 ± 0.27
$Z + \geq 2$ jets	8.0 ± 0.2	9.7 ± 1.9	1.21 ± 0.24

NO (VERY FEW) Z (W) + 0 JET EVENTS PASS OUR SELECTION

SM contributions and systematics

Each SM contribution is:

$$N_i(\not{E}_T \geq \not{E}_T^{min}) = \sigma_i \cdot \epsilon_i(\not{E}_T^{min}) \cdot K_i \cdot L$$

and is affected by systematics on σ, ϵ, normalization scale K and L.

- $\delta K/K \approx 20\%$ for $W/Z + jets$
- $\delta\sigma/\sigma$:
  - $\approx 20\%$ for $\sigma_{t\bar{t}}$
  - $\approx 30\%$ for σ_{WW}, σ_{WZ}, σ_{ZZ}
- $\delta\epsilon/\epsilon \approx 25\%$ from energy scale (vary E_T by $\pm(5 \div 3)\%$)
- $\delta L/L = 7\%$

◦ so, about 33% for $W/Z + jets$, $t\bar{t}$; and about 40% for $V\bar{V}$

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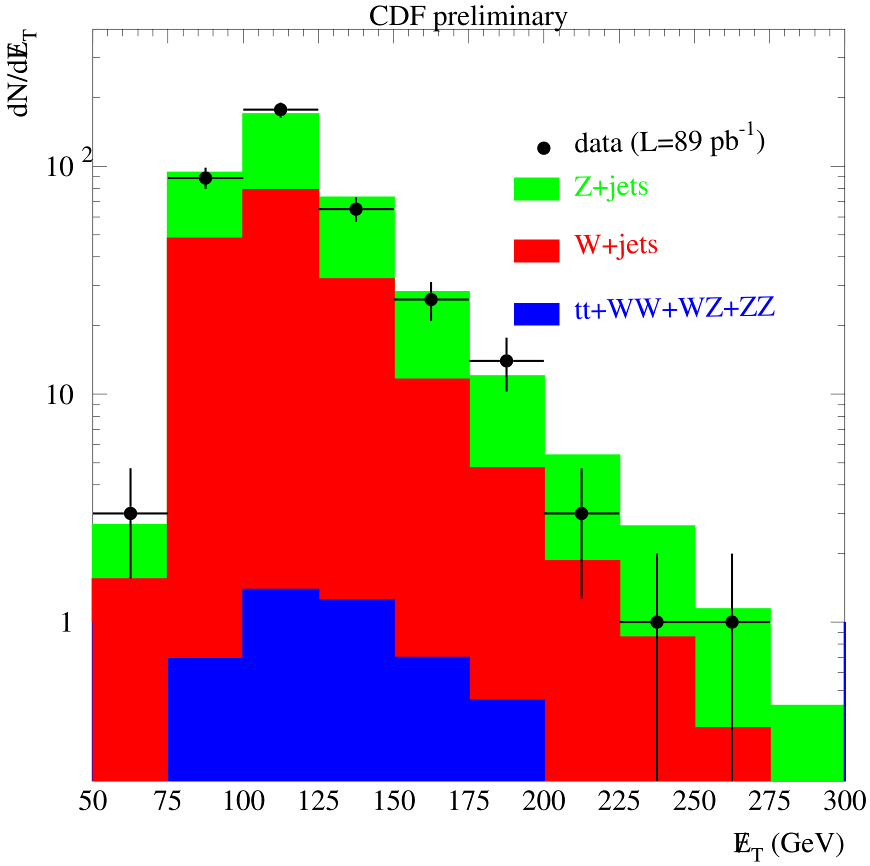
SM background expectations after the selection

Source	$N(\not\!\!E_T \geq 50$ GeV$)$	$N(\not\!\!E_T \geq 100$ GeV$)$	$N(\not\!\!E_T \geq 150$ GeV$)$
$W +$ $jets$	$174.8 \pm 3.2 \pm 57.7$	$125.8 \pm 2.7 \pm 41.5$	$18.0 \pm 0.7 \pm 5.9$
$Z +$ $jets$	$209.0 \pm 2.8 \pm 71.1$	$162.2 \pm 2.4 \pm 55.1$	$30.6 \pm 0.6 \pm 10.4$
$t\bar{t}, WW, WZ, ZZ$	$5.1 \pm 0.2 \pm 2.0$	$4.2 \pm 0.1 \pm 1.7$	$1.6 \pm 0.1 \pm 0.6$
Total	$388.9 \pm 3.9 \pm 131.7$	$292.2 \pm 3.3 \pm 99.1$	$50.2 \pm 0.9 \pm 16.9$
Data	379	287	45

SM background expectations after the selection

Source	$N(\not{E}_T \geq 200$ GeV)	$N(\not{E}_T \geq 250$ GeV)	$N(\not{E}_T \geq 300$ GeV)
$W + \ jets$	$2.8 \pm 0.2 \pm 0.9$	$0.5 \pm 0.1 \pm 0.2$	$0.1 \pm 0.1 \pm 0.1$
$Z + \ jets$	$6.8 \pm 0.2 \pm 2.3$	$1.5 \pm 0.1 \pm 0.5$	$0.5 \pm 0.1 \pm 0.2$
$t\bar{t}, WW, WZ, ZZ$	$0.5 \pm 0.1 \pm 0.2$	$0.1 \pm 0.1 \pm 0.1$	< 0.1
Total	$10.1 \pm 0.3 \pm 3.4$	$2.1 \pm 0.1 \pm 0.7$	$0.6 \pm 0.1 \pm 0.2$
Data	5	1	0

$\not\!\!E_T$ spectrum: data *vs* background



- uncertainty $\approx 33 - 40\%$ on each SM source.

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Setting an upper limit on effective σ

The 95% CL limit on the effective cross section for gravitino pair production is:

$$\sigma_{95}(\not{E}_T^{min}) = \frac{N_{95}(\not{E}_T^{min})}{A(\not{E}_T^{min}) \cdot L}$$

- we observe $n_0(\not{E}_T^{min})$ events
- we have a background $(\mu_B \pm \sigma_B)(\not{E}_T^{min})$
- $\delta L/L = 7\%$, $\delta A/A = 7\%$ (see later)
- we calculate the 95% CL limit $N_{95}(\not{E}_T^{min})$ for $\not{E}_T^{min} = 100 - 300$ GeV incorporating the uncertainties on background, A and L.

$\boxed{\textbf{Limits on } \tilde{G}\tilde{G} + jet \textbf{ production}}$

The production cross section for $\tilde{G}\tilde{G}j$ is

$$\sigma_{\tilde{G}\tilde{G}j} \propto 1/m_{\tilde{G}}^4 \propto 1/F^4$$

see Brignole, Feruglio, Mangano and Zwirner, Nucl. Phys. B **526** (1998) 136 and hep-ph 9801329 (BFMZ).

Comparing $\sigma_{\tilde{G}\tilde{G}j}$ to our upper limit we set 95% C.L. limits on

- the SUSY-breaking scale $\sqrt{F}$
- the gravitino mass $m_{\tilde{G}} = \frac{F}{\sqrt{3}\bar{M}_P}$

once we know the $\not{E}_T$ spectrum and acceptance.

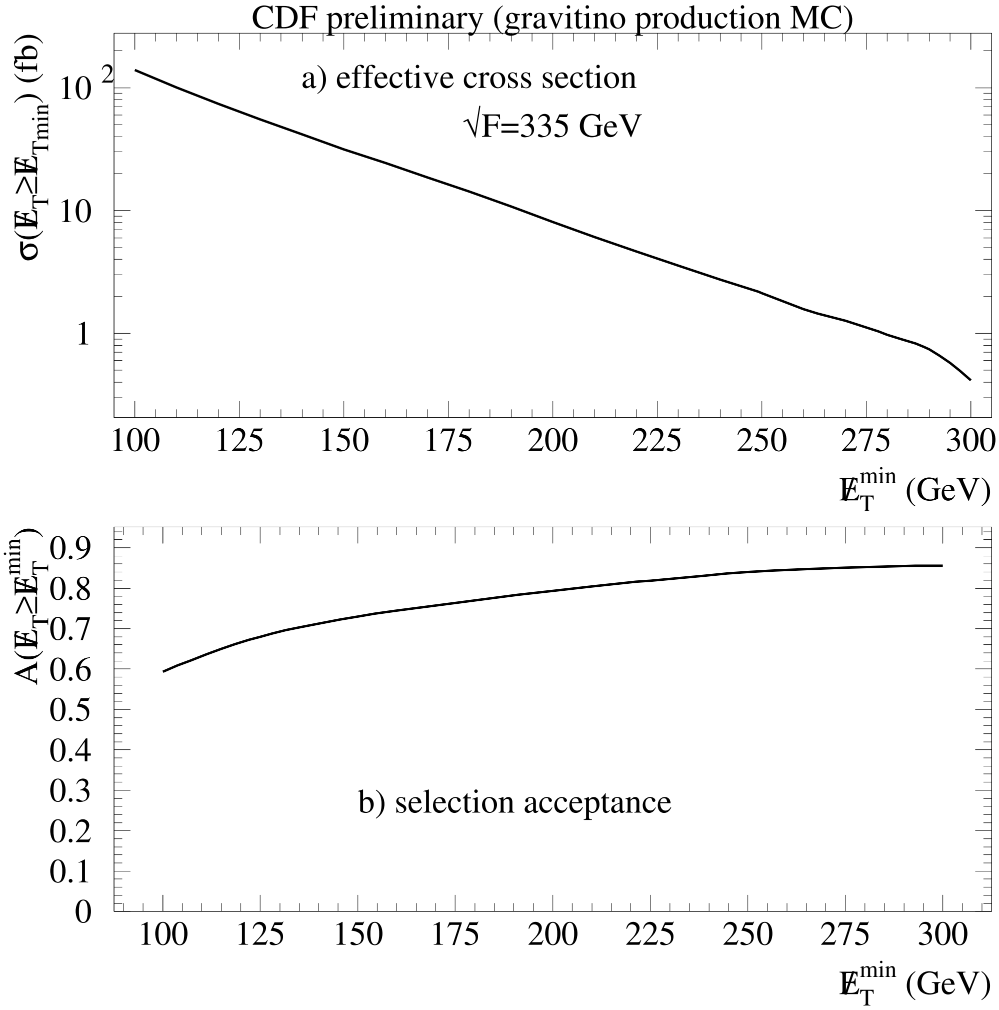
Acceptance/cross section for $\tilde{G}\tilde{G} + jet$

We evaluate $\not{E}_T$ spectrum and acceptance with a private version of HERWIG 5.6. For $\tilde{G}\tilde{G} + jet$ process we include BFMZ calculations ($\mu = E_T$, $\sqrt{F_{MC}} = 335$ GeV) and a full detector simulation.

To extract $\sqrt{F}$ we need the $\tilde{G}\tilde{G} + jet$ cross section and the acceptance as a function of $\not{E}_T^{min}$, where

$$A(selection, \not{E}_T^{min}) = \frac{N(selected, \not{E}_T \geq \not{E}_T^{min})}{N(\not{E}_T \geq \not{E}_T^{min})}$$

Cross section and acceptance *vs* $\not\!\!E_T^{min}$



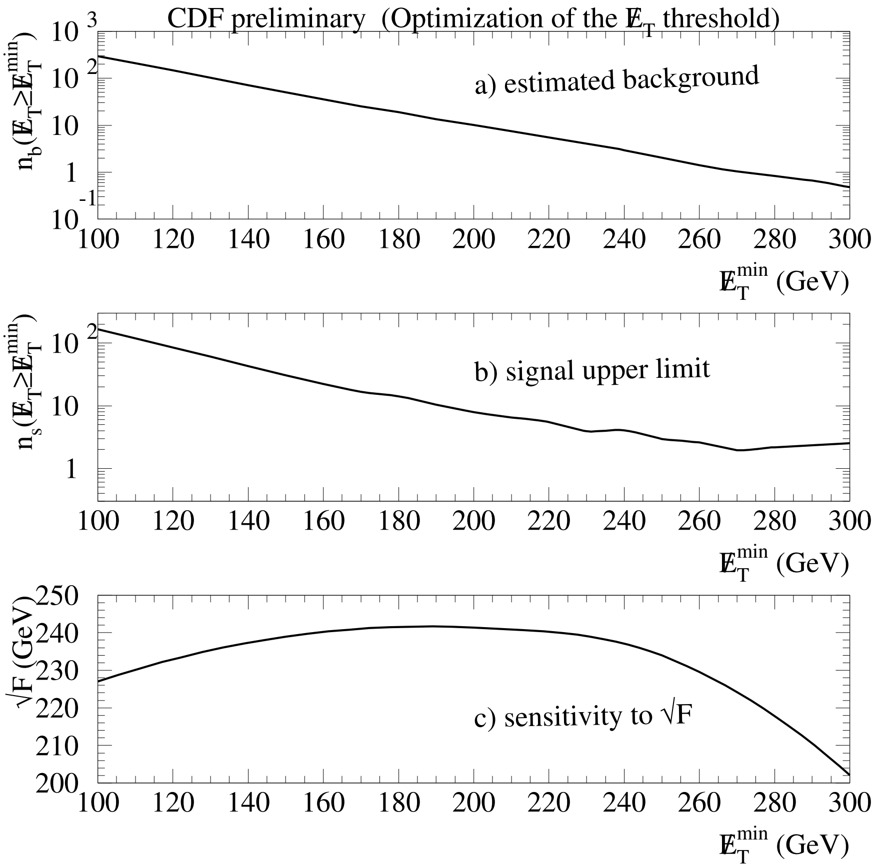
Systematic uncertainties on A

The main sources of systematic uncertainty on the acceptance are:

Source	Method	$\delta A/A$ (%)
Energy scale	$\pm(5 \div 3)\% E_T$	2
ISR/FSR	vary shower evolution	5
PDF	MRSD-$'$ vs CTEQ2M	4
μ	$2E_T$ vs $E_T/2$	2
TOTAL	$\oplus$	7

Optimization of the cut on $\not\!\!E_T$

We look at background and signal simulations: $\not\!\!E_T^{min} = 200$ provides the best sensitivity to $\sqrt{F}$:



Setting limits on $\sqrt{F}$, $m_{\tilde{G}}$

Remember that $\sigma_{\tilde{G}\tilde{G}j} \propto \frac{1}{F^4}$, so

$$\sqrt{F}_{LL}(\not{E}_T^{min}) = \sqrt{F_{MC}} \times \left(\frac{\sigma_{\tilde{G}\tilde{G}j}(\not{E}_T^{min})}{\sigma_{95}(\not{E}_T^{min})} \right)^{\frac{1}{8}}$$

We have the following major systematics on $\sigma_{\tilde{G}\tilde{G}j}(\not{E}_T^{min})$:

Source	Method	$\delta\sigma/\sigma$ (%)
μ	$2E_T$ vs $E_T/2$	29
Energy scale	$\pm(5 \div 3)\% E_T$	18
PDF	MRSD-$'$ vs CTEQ2M	11
ISR/FSR	vary shower evolution	10
TOTAL	$\oplus$	37

Setting limits on $\sqrt{F}$, $m_{\tilde{G}}$

So, considering the 37% systematic uncertainty on $\sigma_{\tilde{G}\tilde{G}j}$, we derive, by comparison to BFMZ model,

$$\sqrt{F} \geq 221\,GeV \quad \Rightarrow \quad m_{\tilde{G}} \geq 1.2\times 10^{-5}\,eV/c^2$$

(If instead we take the central value for $\sigma_{\tilde{G}\tilde{G}j}$ the limit would be $\sqrt{F} \geq 247\ GeV$ or $m_{\tilde{G}} \geq 1.5 \times 10^{-5}\ eV/c^2$).

$e^+e^-\gamma$ A. Favara's talk			
Exp	ALEPH	DELPHI	L3
$m_{\tilde{G}} \geq$ (eV/c^2)	1.1×10^{-5}	9.1×10^{-6}	8.9×10^{-6}

$\not\!\!E_T^{min}$ (GeV)	total background $\mu_B \pm \sigma_B$	data n_0	95% C.L. limits		
			N_{95}	$\sigma_{95}(\not\!\!E_T \geq \not\!\!E_T^{min})$ (fb)	$\sqrt{F}_{LL}$ (GeV)
100	292.3 ± 99.2	287	194.5	≤ 3723	≥ 199
150	50.1 ± 16.9	45	33.0	≤ 511	≥ 212
200	10.1 ± 3.4	5	6.56	≤ 92.8	≥ 221
250	2.1 ± 0.7	1	3.94	≤ 52.9	≥ 200
300	0.6 ± 0.2	0	3.02	≤ 40.5	≥ 175

values for $\not\!\!E_T \geq 200$ GeV are *optimal*

Conclusions

We have studied the $\not{E}_T$ spectra for *large-*$\not{E}_T$ + *high-*E_T *jet* events and compared them to SM expectations seeing a very good agreement.

Comparing bakground and gravitino signal simulations we derive the optimal threshold $\not{E}_T^{min} = 200$ GeV.

We have set a 95% C.L. limit on the effective σ for $\tilde{G}\tilde{G} + jet$ production.

The 95% CL limits are:

$$\boxed{\sigma(\tilde{G}\tilde{G}j, \not{E}_T \geq 200 \text{ GeV}) \leq 93 \textbf{ fb}}$$

$$\boxed{\sqrt{F} \geq 221 \textbf{ GeV}}$$

$$\boxed{m_{\tilde{G}} \geq 1.2 \times 10^{-5} \textbf{ eV/c}^2}$$