Test of EGRET hypothesis and indirect measurement of relic density at the LHC

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Outline

- Introduction - Short summary of EGRET analysis
- Supersymmetric interpretation of the excess
- Testing the EGRET hypothesis at the LHC
- Indirect measurement of relic density at LHC
- Summary
Excess above 1 GeV is compatible with DM annihilation of WIMPs

Depending on Galactic bg model: \( m_{WIMP} < 60 \ldots 130 \) GeV

de Boer et al., A & A 444 (2005) 51

\( \gamma \) rays from the Galactic center:

\[
\chi^2 / d.o.f. \text{ and probability:}
\]
Extragalactic Background

- Residual isotropic EGB shows bump at a few GeV
- Fit of new EGB with double power law and DMA signal ($\chi^2/d.o.f. = 5.7/4 \Rightarrow 22.4\%$)
- Fit with single power law ($\chi^2/d.o.f. = 11.7/6 \Rightarrow 6.9\%$)

de Boer et al., A & A 470 (2007) 61

Elsaesser et al., astro-ph/0405235
Supersymmetric Interpretation
Testing the EGRET hypothesis at LHC
Indirect Measurement of Relic Density at LHC

Supersymmetry

LSP (often Neutralino) is perfect CDM candidate

**SUSY is broken, e.g. mSUGRA → 5 new Parameters**

- \( m_0 \): unified mass of the fermion partners
- \( m_{1/2} \): unified mass of the gauge boson partners
- \( \tan \beta \): ratio of the VEVs of the 2 Higgs doublets
- unified trilinear coupling \( A_0 \), \( \text{sign}(\mu) \)

**Constraints on the Parameter Space**

- Higgs mass \( m_h > 114.4 \text{ GeV} \) \( \text{SuSpect, hep-ph/0211331} \)
- \( Br(b \rightarrow X_s\gamma) = (3.43 \pm 0.36) \times 10^{-4} \) \( \text{micrOMEGAs, hep-ph/0112278} \)
- \( \Delta a_\mu = (27 \pm 10) \times 10^{-10} \) \( \text{micrOMEGAs} \)
- \( \Omega_{DM} = 0.113 \pm 0.008 \) \( \text{micrOMEGAs or DarkSusy, astro-ph/0406204} \)
- SUSY mass limit, EWSB, LSP neutral \( \ldots \) \( \text{SuSpect, hep-ph/0211331} \)
- \( m_{WIMP} < 60 \ldots 130 \text{ GeV} \)
Allowed Parameter Space

- Scan over $m_0$-$m_{1/2}$-plane for fixed values of $\tan \beta = 52.2$ and $A_0 = 0$ GeV
- $2\sigma$-contours for allowed region + consistency of the models (LSP neutral, EWSB ok)
- with EGRET-excess only a small region is left over: $m_0: \sim 1500$ GeV \ldots \sim 2000$ GeV $m_{1/2}: \sim 100$ GeV \ldots \sim 250$ GeV
Top mass $m_t$ dependence, other parameters fixed:

with $m_b$, $\alpha_s$ and mSUGRA parameters $m_0$, $m_{1/2}$, $A_0$:

Large uncertainty, in particular for large $\tan \beta$
Allowed Parameter Space version 2

Scatterplot of $m_0$, $m_{1/2}$ and $\tan \beta$; only parameter sets with correct $\Omega h^2$ are plotted.

At large $\tan \beta$ mSUGRA parameter space not constrained by $\Omega h^2$.

wo. exp. constraints: w. exp. constraints:
Representative low mass benchmark point **LM9**: 
\[ m_0 = 1450 \text{ GeV}, \quad m_{1/2} = 175 \text{ GeV} \]
\[ \tan \beta = 50, \quad A_0 = 0 \text{ GeV}, \quad \text{sign} \mu = + \]

Channel: \( qq \to \chi_2^0 \chi_1^\pm, \quad \sigma \propto \frac{1}{m_{1/2}^4} \)

at LM9: \( \sigma \chi_2^0 \chi_1^\pm \to \chi + 3l \approx 10^{-2} \text{ pb} \)

Signature: 3 leptons with at least one OSSF combination, no jets, small MET

If \( m_{1/2} \) is small \( \to \) mass difference between \( \chi_2^0 \) and \( \chi_1^0 \) smaller than \( M_Z \) \( \to \) 3-body decay trough virtual particle: \( M_{\parallel}^{\text{max}} = m_{\chi_2^0} - m_{\chi_1^0} \)
Background

- **WZ** (suppressed by cut on reconstructed Z mass)
- Other backgrounds: $t\bar{t}$, DY, Z+jets and W+jets (with fake leptons)

leptons faked by …

- **$e$**
  - $K$, $\pi$ decay
  - electromagnetic jet
  - photon conversion

- **$\mu$**
  - hadronic punch through
  - jet containing $\mu$
reconstructed invariant dilepton mass at LM9

5 $\sigma$ can be achieved at $L_{\text{int}} = 30$ fb$^{-1}$ for $m_{1/2} < 180$ GeV

Detailed analysis can be found in CMS NOTE-2006/113
Another Channel: Gluino-Gluino Production

- Larger cross section (strong interaction)
- General SUSY signatures
  - Multiple jets and/or leptons
  - Large amount of missing energy
- Signature at small $m_{1/2}$: mass edge in invariant OSSF lepton mass
- LHC discovery reach: $M_{\tilde{g}}, M_{\tilde{q}} \leq 2.5$ TeV/c$^2$
Gluino Production at LM9

Total cross section $\sigma \tilde{g}\tilde{g} \approx 40$ pb

Branching Ratios:

- $\tilde{g} \rightarrow \chi_2^0 + q/g \rightarrow \chi_1^0 + l^+l^- + q/g : 1.7\%$
- $\tilde{g} \rightarrow \chi_2^\pm + q/g \rightarrow \chi_2^0 + W^\pm + q/g \rightarrow \chi_1^0 + l^+l^- + l^\pm + q/g : 0.4\%$
- $\tilde{g} \rightarrow \chi_3^0 + q/g \rightarrow \chi_1^0 + Z^0 + q/g \rightarrow \chi_1^0 + l^+l^- + q/g : 0.5\%$
- $\tilde{g} \rightarrow \chi_4^0 + q/g \rightarrow \chi_1^\pm + W^\mp + q/g \rightarrow \chi_1^0 + l^\pm + l^\mp + q/g : 0.4\%$
- Other contributions from heavy neutralinos/charginos

Larger cross section $\sigma \tilde{g}\tilde{g}\rightarrow X + 3l \approx 1$ pb $= \mathcal{O}(2) \cdot \sigma \chi_2^0\chi_1^\pm \rightarrow X + 3l$
But signature less clear due to at least 2 additional jets
Reconstructed invariant dilepton mass at LM9 (study by B. Mura)

\[ L_{int} = 1 \text{ fb}^{-1} \]  
(full detector simulation)

\[ L_{int} = 20 \text{ fb}^{-1} \]  
(fast detector simulation)
Dependence on SM Parameters

Ratio or absence of $Z$-peak + position of mass edge gives handle on SM parameters, mainly because of $\chi_{3,4}^0$ and $\chi_{2}^{\pm}$ mass dependence on $m_t$ (study by N. Mohr)

Strong dependence on used RGE code!

C. Sander

EGRET, SUSY and the LHC
Coannihilation: ATLAS Results

If mass difference of $\chi^0_1$ and $\tilde{\tau}$ is small, $\chi^0_1 \tilde{\tau} \rightarrow \tau Z / \gamma$ contribute to $\Omega h^2$
eq m_0 = 70 \text{ GeV}, m_{1/2} = 350 \text{ GeV}, A_0 = 0, \tan \beta = 10$ and $\mu > 0$

G. Comune et al., ATL-PHYS-CONF-2005-003

Decays of $\chi^0_2$ to both $\tilde{l}_L$ and $\tilde{l}_R$ kinematically allowed → double dilepton invariant mass edge structure

$\tilde{\tau}$ channels enhanced (large $\tan \beta$ → soft tau signatures → one edge expected but less clear due to poor tau visible energy resolution
Indirect Determination of $\Omega h^2$: ATLAS Results

Extraction of Dark Matter properties from LHC measurements

Nojiri et al., hep-ph/0512204

parameters for this study: $m_0 = 70$ GeV, $m_{1/2} = 250$ GeV, $A_0 = -300$ GeV, $\tan \beta = 10$ and $\mu > 0$

<table>
<thead>
<tr>
<th>Sparticle</th>
<th>mass (GeV)</th>
<th>Sparticle</th>
<th>mass (GeV)</th>
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<tr>
<td>$\tilde{\chi}_1^0$</td>
<td>97.2</td>
<td>$\tilde{\chi}_2^0$</td>
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<td>$\tilde{\chi}_3^0$</td>
<td>398.4</td>
<td>$\tilde{\chi}_4^0$</td>
<td>413.8</td>
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<tr>
<td>$\ell_L^-$</td>
<td>189.4</td>
<td>$\ell_R^-$</td>
<td>124.1</td>
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<tr>
<td>$\tilde{\tau}_1^-$</td>
<td>107.7</td>
<td>$\tilde{\tau}_2^-$</td>
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<td>$\tilde{t}_1$</td>
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<td>$\tilde{t}_2$</td>
<td>562.3</td>
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<td>$\tilde{u}_L^+$</td>
<td>533.3</td>
<td>$\tilde{g}$</td>
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<td>$h$</td>
<td>116.8</td>
<td>$A$</td>
<td>424.6</td>
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Process | Fraction |
<table>
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<tbody>
<tr>
<td>$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \ell^+ \ell^-$</td>
<td>40%</td>
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<tr>
<td>$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \tau^+ \tau^-$</td>
<td>28%</td>
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<tr>
<td>$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \nu \bar{\nu}$</td>
<td>3%</td>
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<tr>
<td>$\tilde{\chi}_1^0 \tilde{\tau}_1^-$</td>
<td>4%</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 \tilde{\tau}_1^-$</td>
<td>18%</td>
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<tr>
<td>$\tilde{\tau}_1^+ \tilde{\tau}_1^-</td>
<td>2%</td>
</tr>
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mass spectrum calculated with ISAJET 7.71

contributing annihilation channels
Measured Quantities and Uncertainties

Only kinematic end points of invariant masses can be measured; ATLAS expectations for assumed int. luminosity of 300 $fb^{-1}$:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value (GeV)</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\tilde{e}}^{max}$</td>
<td>81.2</td>
<td>Stat+Sys (GeV)</td>
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<tr>
<td>$m_{\tilde{\ell}}^{max}$</td>
<td>425.3</td>
<td>0.03</td>
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<td>$m_{\tilde{\ell} q}^{low}$</td>
<td>266.9</td>
<td>1.4</td>
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<td>$m_{\tilde{\ell} q}^{high}$</td>
<td>365.9</td>
<td>0.9</td>
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<td>$m_{\tilde{\ell} q}^{min}$</td>
<td>207.0</td>
<td>1.0</td>
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<tr>
<td>$m_{\tilde{\ell} q}^{max}$</td>
<td>315.8</td>
<td>2.3</td>
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<tr>
<td>$m_{\tilde{\tau}}^{max}$</td>
<td>62.2</td>
<td>5.0</td>
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Method: Determine the best fitting SUSY parameters for a large number (e.g. 10000) of sets of independent measurements, each corresponding to 300 $fb^{-1}$ → calculate $\Omega h^2$ for each parameter set
Result

Distribution of calculated $\Omega h^2$ corresponding to the best fitting parameter sets of each measurement:

Strong dependence on the error of the $\tau\tau$ edge (left: 5 GeV, right 0.5 GeV), coannihilation channels are quite sensitive on the $\tilde{\tau}$ mass.
Uncertainty of $\Omega h^2$

- Assume a less constrained SUSY scenario than mSUGRA
- Measurements of the Higgs sector parameters important
- At LHC, Higgs sector only accessible for some parameter sets

\[ \Omega h^2 \]

uncertainty on $m_A$

\[ \Omega h^2 \]

uncertainty on $\tan \beta$

worse at large $\tan \beta \rightarrow$ EGRET
EGRET data are compatible with DM consisting of supersymmetric neutralinos ⇒ together with constraints from EWSB, Higgs mass, $Br(b \rightarrow X_s \gamma)$, $a_\mu$ only a small region of mSUGRA-SUSY parameter space is left over.

Particle masses are in the discovery range of the LHC, in particular mass difference of $\chi^0_2$ and $\chi^0_1$ in dilepton invariant mass edge.

LHC has possibility to make an indirect measurement on $\Omega h^2$, but in case of large tan $\beta$ (e.g. EGRET hypothesis) sensitivity to model parameters is too large.