Use of event-level IceCube data in SUSY scans

Pat Scott

Department of Physics, McGill University

July 3, 2012

Based on: PS, Chris Savage, Joakim Edsjö and The IceCube Collaboration (esp. Matthias Danninger and Klas Hultqvist), arXiv:1207.soon

Slides available from www.physics.mcgill.ca/~patscott
Outline

1. How to find DM with neutrino telescopes
2. Neutrino telescope data → model scans
The short version:

1. Halo WIMPs crash into the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate+oscillate their way to the Earth, convert into muons in ice/water
6. Look for Čerenkov radiation from the muons in IceCube, ANTARES, etc
Introduction

The short version:

1. Halo WIMPs crash into the Sun
The short version:

1. Halo WIMPs crash into the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
Introduction

The short version:

1. Halo WIMPs crash into the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate+oscillate their way to the Earth, convert into muons in ice/water
6. Look for Čerenkov radiation from the muons in IceCube, ANTARES, etc

Use of event-level IceCube data in SUSY scans

Pat Scott – July 3 2012 – Melbourne LHC Theory WS
The short version:

1. Halo WIMPs crash into the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
The short version:

1. Halo WIMPs crash into the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate+oscillate their way to the Earth, convert into muons in ice/water
6. Look for Čerenkov radiation from the muons in IceCube, ANTARES, etc.
The short version:

1. Halo WIMPs crash into the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate+oscillate their way to the Earth, convert into muons in ice/water
6. Look for Čerenkov radiation from the muons in IceCube, ANTARES, etc
What can the muon signal tell me?

Roughly:

**Number** – how much annihilation is going on in the Sun

\[ \Rightarrow \text{info on } \sigma_{SD}, \sigma_{SI} \text{ and } \langle \sigma v \rangle \]

**Spectrum** – sensitive to WIMP mass \( m_\chi \) and branching fractions \( BF \) into different annihilation channels \( X \)

**Direction** – how likely it is that they come from the Sun

In model-independent analyses a lot of this information is either discarded or not given with final limits

**Goal:**

Use as much of this information on \( \sigma_{SD}, \sigma_{SI}, \langle \sigma v \rangle, m_\chi \) and \( BF(X) \) as possible to directly constrain specific points and regions in WIMP model parameter spaces (\(+LHC+DD+\ldots\))
What can the muon signal tell me?

The focus here is supersymmetry (SUSY) – but this talk is on a framework, applicable to any model.

Goal:
Use as much of this information on $\sigma_{SD}$, $\sigma_{SI}$, $\langle \sigma v \rangle$, $m_\chi$ and $BF(X)$ as possible to directly constrain specific points and regions in WIMP model parameter spaces (+LHC+DD+...)
What can the muon signal tell me?

The focus here is supersymmetry (SUSY) – but this talk is on a framework, applicable to any model.

All the methods discussed here are available in DarkSUSY 5.0.6: www.darksusy.org

Goal:
Use as much of this information on $\sigma_{\text{SD}}$, $\sigma_{\text{SI}}$, $\langle \sigma v \rangle$, $m_\chi$ and $BF(X)$ as possible to directly constrain specific points and regions in WIMP model parameter spaces (+LHC+DD+...)

Use of event-level IceCube data in SUSY scans

Pat Scott – July 3 2012 – Melbourne LHC Theory WS
What can the muon signal tell me?

The focus here is supersymmetry (SUSY) – but this talk is on a framework, applicable to any model.

All the methods discussed here are available in DarkSUSY 5.0.6: www.darksusy.org

All IceCube data used are available at http://icecube.wisc.edu/science/data/ic22-solar-wimp (and in DarkSUSY, for convenience)

Goal:

Use as much of this information on $\sigma_{SD}$, $\sigma_{SI}$, $\langle \sigma v \rangle$, $m_\chi$ and $BF(X)$ as possible to directly constrain specific points and regions in WIMP model parameter spaces ($\text{+LHC+DD+...}$)
Outline

1. How to find DM with neutrino telescopes
2. Neutrino telescope data → model scans
Simplest way to do anything is to make it a counting problem . . .

Compare observed number of events $n$ and predicted number $\theta$ for each model, taking into account error $\sigma_\epsilon$ on acceptance:

$$
\mathcal{L}_{\text{num}}(n|\theta_{\text{BG}} + \theta_{\text{sig}}) = \frac{1}{\sqrt{2\pi\sigma_\epsilon}} \int_0^\infty \frac{(\theta_{\text{BG}} + \epsilon\theta_{\text{sig}})^n e^{-(\theta_{\text{BG}} + \epsilon\theta_{\text{sig}})}}{n!} \frac{1}{\epsilon} \exp \left[ -\frac{1}{2} \left( \frac{\ln \epsilon}{\sigma_\epsilon} \right)^2 \right] d\epsilon.
$$

(1)

Nuisance parameter $\epsilon$ takes into account systematic errors on effective area, from theory, etc. $\sigma_\epsilon \sim 20\%$ for IceCube.
Full unbinned likelihood with number ($\mathcal{L}_{\text{num}}$), spectral ($\mathcal{L}_{\text{spec}}$) and angular ($\mathcal{L}_{\text{ang}}$) parts

$$
\mathcal{L} = \mathcal{L}_{\text{num}}(n|\theta_{\text{signal+BG}}) \prod_{i=1}^{n} \mathcal{L}_{\text{spec},i} \mathcal{L}_{\text{ang},i}
$$

with

$$
\mathcal{L}_{\text{spec},i}(N_i, \Xi) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{dN_i}(N_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \int_{0}^{\infty} E_{\text{disp}}(N_i|E_i') \frac{dP_{\text{signal}}}{dE_i'}(E_i', \Xi) dE_i'
$$

and

$$
\mathcal{L}_{\text{ang},i}(\cos \phi_i) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{d\cos \phi_i}(\cos \phi_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \text{PSF}(\cos \phi_i|1)
$$
Full unbinned likelihood with number ($L_{\text{num}}$), spectral ($L_{\text{spec}}$) and angular ($L_{\text{ang}}$) parts

$$L = L_{\text{num}}(n|\theta_{\text{signal+BG}}) \prod_{i=1}^{n} L_{\text{spec},i} L_{\text{ang},i}$$  \hspace{1cm} (2)

with

Number of lit channels (energy estimator)

$$L_{\text{spec},i}(N_i, \Xi) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{dN_i}(N_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \int_{0}^{\infty} E_{\text{disp}}(N_i|E_i') \frac{dP_{\text{signal}}}{dE_i'}(E_i', \Xi) \, dE_i'$$  \hspace{1cm} (3)

and

$$L_{\text{ang},i}(\cos \phi_i) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{d\cos \phi_i}(\cos \phi_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \text{PSF}(\cos \phi_i|1)$$  \hspace{1cm} (4)
Full unbinned likelihood with number ($L_{\text{num}}$), spectral ($L_{\text{spec}}$) and angular ($L_{\text{ang}}$) parts

$$L = L_{\text{num}}(n|\theta_{\text{signal+BG}}) \prod_{i=1}^{n} L_{\text{spec},i} L_{\text{ang},i}$$ (2)

with

**Number of lit channels (energy estimator)**

$$L_{\text{spec},i}(N_i, \Xi) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{dN_i}(N_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \int_0^\infty E_{\text{disp}}(N_i|E'_i) \frac{dP_{\text{signal}}}{dE'_i}(E'_i, \Xi) dE'_i$$ (3)

and

**SUSY parameters**

$$L_{\text{ang},i}(\cos \phi_i) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{d\cos \phi_i} (\cos \phi_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \text{PSF}(\cos \phi_i|1)$$ (4)
SUSY Scanning with IceCube – Full Likelihood

Full unbinned likelihood with number ($\mathcal{L}_{\text{num}}$), spectral ($\mathcal{L}_{\text{spec}}$) and angular ($\mathcal{L}_{\text{ang}}$) parts

$$
\mathcal{L} = \mathcal{L}_{\text{num}}(n|\theta_{\text{signal+BG}}) \prod_{i=1}^{n} \mathcal{L}_{\text{spec},i} \mathcal{L}_{\text{ang},i}
$$

(2)

with

$$
\mathcal{L}_{\text{spec},i}(N_i, \Xi) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{dN_i}(N_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \int_{0}^{\infty} E_{\text{disp}}(N_i|E_i') \frac{dP_{\text{signal}}}{dE_i'}(E_i', \Xi) dE_i'
$$

(3)

and

$$
\mathcal{L}_{\text{ang},i}(\cos \phi_i) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{d\cos \phi_i}(\cos \phi_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \text{PSF}(\cos \phi_i | 1)
$$

(4)
Full unbinned likelihood with number ($L_{num}$), spectral ($L_{spec}$) and angular ($L_{ang}$) parts

$$L = L_{num}(n | \theta_{signal+BG}) \prod_{i=1}^{n} L_{spec,i} L_{ang,i}$$

with

$$L_{spec,i}(N_i, \Xi) = \frac{\theta_{BG}}{\theta_{signal+BG}} \frac{dP_{BG}}{dN_i}(N_i) + \frac{\theta_{signal}}{\theta_{signal+BG}} \int_{0}^{\infty} E_{disp}(N_i | E'_i) \frac{dP_{signal}}{dE'_i}(E'_i, \Xi) dE'_i$$

and

$$L_{ang,i}(\cos \phi_i) = \frac{\theta_{BG}}{\theta_{signal+BG}} \frac{dP_{BG}}{d\cos \phi_i}(\cos \phi_i) + \frac{\theta_{signal}}{\theta_{signal+BG}} PSF(\cos \phi_i | 1)$$
Full unbinned likelihood with number ($L_{\text{num}}$), spectral ($L_{\text{spec}}$) and angular ($L_{\text{ang}}$) parts

$$L = L_{\text{num}}(n|\theta_{\text{signal+BG}}) \prod_{i=1}^{n} L_{\text{spec},i} L_{\text{ang},i}$$

(2)

with

$$L_{\text{spec},i}(N_i, \Xi) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{dN_i}(N_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \int_{0}^{\infty} E_{\text{disp}}(N_i|E_i') \frac{dP_{\text{signal}}}{dE_i'}(E_i', \Xi) dE_i'$$

(3)

and

$$L_{\text{ang},i}(\cos \phi_i) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{d\cos \phi_i}(\cos \phi_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \text{PSF}(\cos \phi_i|1)$$

(4)
Full unbinned likelihood with number ($\mathcal{L}_{\text{num}}$), spectral ($\mathcal{L}_{\text{spec}}$) and angular ($\mathcal{L}_{\text{ang}}$) parts

$$\mathcal{L} = \mathcal{L}_{\text{num}}(n|\theta_{\text{signal+BG}}) \prod_{i=1}^{n} \mathcal{L}_{\text{spec},i} \mathcal{L}_{\text{ang},i} \quad (2)$$

with

$$\mathcal{L}_{\text{spec},i}(N_i, \Xi) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{dN_i}(N_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \int_{0}^{\infty} E_{\text{disp}}(N_i|E_i') \frac{dP_{\text{signal}}}{dE_i'}(E_i', \Xi) dE_i' \quad (3)$$

and

$$\mathcal{L}_{\text{ang},i}(\cos \phi_i) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{d\cos \phi_i}(\cos \phi_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \text{PSF}(\cos \phi_i|1) \quad (4)$$

Event arrival angle
Full unbinned likelihood with number ($L_{\text{num}}$), spectral ($L_{\text{spec}}$) and angular ($L_{\text{ang}}$) parts

$$
L = L_{\text{num}}(n|\theta_{\text{signal+BG}}) \prod_{i=1}^{n} L_{\text{spec},i} L_{\text{ang},i}
$$

with

$$
L_{\text{spec},i}(N_i, \Xi) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{dN_i}(N_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \int_{0}^{\infty} E_{\text{disp}}(N_i|E'_i) \frac{dP_{\text{signal}}}{dE'_i}(E'_i, \Xi) dE'_i
$$

and

$$
L_{\text{ang},i}(\cos \phi_i) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{d\cos \phi_i}(\cos \phi_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \text{PSF}(\cos \phi_i|1)
$$
How to find DM with neutrino telescopes
Neutrino telescope data → model scans

**SUSY Scanning with IceCube – Full Likelihood**

Full unbinned likelihood with number ($L_{\text{num}}$), spectral ($L_{\text{spec}}$) and angular ($L_{\text{ang}}$) parts

$$L = L_{\text{num}}(n|\theta_{\text{signal+BG}}) \prod_{i=1}^{n} L_{\text{spec},i} L_{\text{ang},i}$$  \hspace{1cm} (2)

with

$$L_{\text{spec},i}(N_i, \Xi) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{dN_i}(N_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \int_0^\infty E_{\text{disp}}(N_i|E_i') \frac{dP_{\text{signal}}}{dE_i'}(E_i', \Xi) dE_i'$$  \hspace{1cm} (3)

and

Instrument response function

$$L_{\text{ang},i}(\cos \phi_i) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{d\cos \phi_i}(\cos \phi_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \text{PSF}(\cos \phi_i|1)$$  \hspace{1cm} (4)

Predicted signal direction ($\delta$ function at Sun)
Full unbinned likelihood with number ($\mathcal{L}_{\text{num}}$), spectral ($\mathcal{L}_{\text{spec}}$) and angular ($\mathcal{L}_{\text{ang}}$) parts

\[ \mathcal{L} = \mathcal{L}_{\text{num}}(n|\theta_{\text{signal+BG}}) \prod_{i=1}^{n} \mathcal{L}_{\text{spec},i} \mathcal{L}_{\text{ang},i} \]  

(2)

with

\[ \mathcal{L}_{\text{spec},i}(N_i, \Xi) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{dN_i}(N_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \int_{0}^{\infty} E_{\text{disp}}(N_i|E'_i) \frac{dP_{\text{signal}}}{dE'_i}(E'_i, \Xi) \ dE'_i \]  

(3)

and

\[ \mathcal{L}_{\text{ang},i}(\cos \phi_i) = \frac{\theta_{\text{BG}}}{\theta_{\text{signal+BG}}} \frac{dP_{\text{BG}}}{d \cos \phi_i}(\cos \phi_i) + \frac{\theta_{\text{signal}}}{\theta_{\text{signal+BG}}} \ PSF( \cos \phi_i | 1) \]  

(4)

Predicted signal direction ($\delta$ function at Sun)
Why simple IN/OUT analyses are not enough:...

- Only partial goodness of fit, no measure of convergence, no idea how to generalise to regions or whole space.
- Frequency/density of models in IN/OUT scans means essentially nothing.
- More information comes from a global statistical fit. \[ \Rightarrow \text{parameter estimation exercise} \]

Composite likelihood made up of observations from all over:

- dark matter relic density from WMAP
- precision electroweak tests at LEP
- LEP limits on sparticle masses
- $B$-factory data (rare decays, $b \rightarrow s\gamma$)
- muon anomalous magnetic moment
- LHC searches, direct detection (only roughly implemented for now)
Example: SUSY Scanning with IceCube – Global Fits

CMSSM, IceCube-22 events

$m_0-m_{1/2}$ and $m_{\chi_1^0}$–nuclear scattering cross-sections

Contours indicate 1σ and 2σ credible regions
Grey contours correspond to fit without IceCube data
Shading+contours indicate relative probability only, not overall goodness of fit
How to find DM with neutrino telescopes
Neutrino telescope data → model scans

Example: SUSY Scanning with IceCube – Global Fits

Base Observables

Scott, Danninger, Savage, Edsjö, Hultqvist & The IceCube Collab. (2012)

Use of event-level IceCube data in SUSY scans

Pat Scott – July 3 2012 – Melbourne LHC Theory WS
How to find DM with neutrino telescopes
Neutrino telescope data → model scans

Example: SUSY Scanning with IceCube – Global Fits

Base Observables + XENON-100

Grey contours correspond to Base Observables only
How to find DM with neutrino telescopes
Neutrino telescope data → model scans

Example: SUSY Scanning with IceCube – Global Fits

Base Observables + XENON-100 + CMS 5 fb⁻¹

Grey contours correspond to Base Observables only

Use of event-level IceCube data in SUSY scans

Pat Scott – July 3 2012 – Melbourne LHC Theory WS
How to find DM with neutrino telescopes
Neutrino telescope data → model scans

Example: SUSY Scanning with IceCube – Global Fits

Base Observables + XENON-100 + CMS 5 fb⁻¹ + IC22×100

Grey contours correspond to Base Observables only

CMSSM, IceCube-22 with 100× boosted effective area
(kind of like IceCube-86+DeepCore)
How to find DM with neutrino telescopes
Neutrino telescope data → model scans

Example: Model Recovery

CMSSM, IceCube-22 × 100 signal reconstruction
60 signal events, 500 GeV, $\chi\chi \rightarrow W^+ W^−$

Grey contours correspond to reconstruction without energy information
Closing remarks

- A framework for directly comparing event-level neutrino telescope data to individual points in theory parameter spaces is in place
- These ‘iclike’ extensions are available in DarkSUSY 5.0.6
- IceCube event data has been released in a form digestible by DarkSUSY 5.0.6
- Direct SUSY analyses of IC79 data are on the way
- Many models exist that only IC86 will be sensitive to
- The extensions can be used equally well for non-SUSY BSM scenarios too
Use of event-level IceCube data in SUSY scans

Pat Scott – July 3 2012 – Melbourne LHC Theory WS
If you liked any of the plots in this talk... 

**Pippi** – parse it, plot it  
[http://github.com/patscott/pippi](http://github.com/patscott/pippi)

**Generic pdfLaTeX sample parser, post-processor & plotter**
CMS 5 fb$^{-1}$ analyses

CMS Preliminary \( L_{\text{int}} = 4.98 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV} \)

\[
\begin{align*}
\tan(\beta) &= 10 \\
A_0 &= 0 \text{ GeV} \\
\mu &> 0 \\
m_1 &= 173.2 \text{ GeV}
\end{align*}
\]

- Razor
- SS Dilepton
- OS Dilepton
- MT2
- 1 Lepton
- Multi-Lepton
- Jets+MHT

Use of event-level IceCube data in SUSY scans

Pat Scott – July 3 2012 – Melbourne LHC Theory WS
XENON-100 100-day analysis

Use of event-level IceCube data in SUSY scans

Pat Scott – July 3 2012 – Melbourne LHC Theory WS