

Indirect searches of Dark Matter from gamma-ray line signatures with the H.E.S.S. experiment

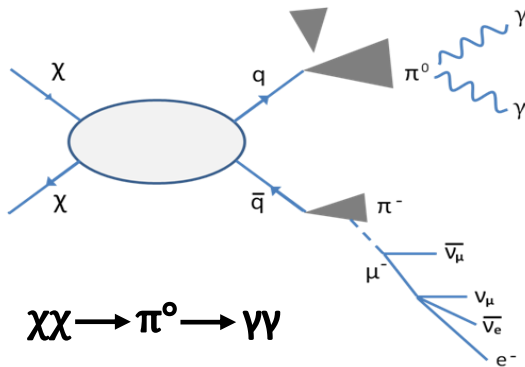
Matthieu Kieffer LPNHE - Paris , Humboldt University Berlin
On behalf of the H.E.S.S. Collaboration

TeVPA/IDM Conference - Amsterdam
25/06/2014

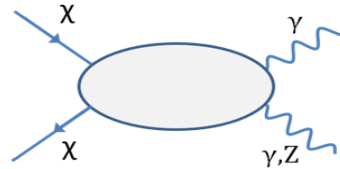
Gamma rays as messengers from Dark Matter annihilation

Annihilation of neutralinos to gamma-rays → Predicted by SUSY models

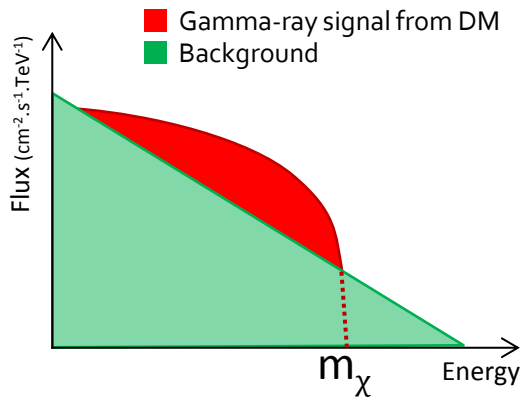
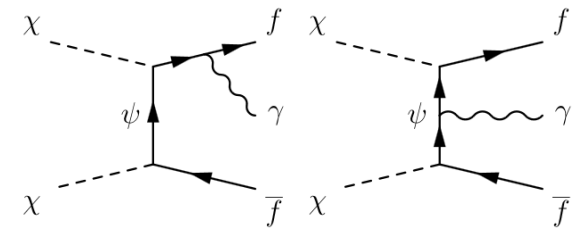
Secondary photons



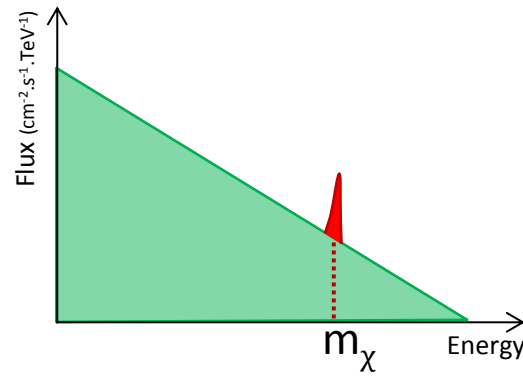
$\gamma\gamma$ or γZ



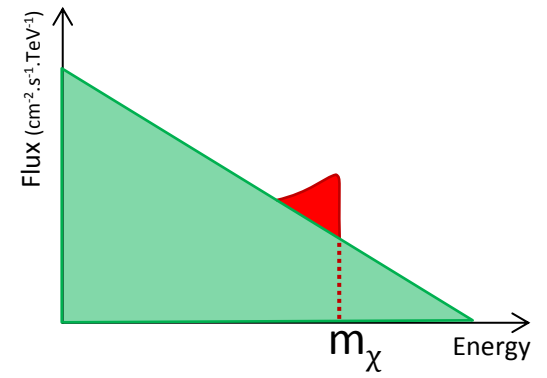
Internal Bremsstrahlung



Continuous spectrum



Monochromatic line



Extended spectral features

Dark Matter gamma-ray flux

$$\text{Flux} = \frac{d\Phi}{dE_\gamma}(E_\gamma, \Delta\Omega) = \boxed{\Phi^{\text{ASTRO}}(\Delta\Omega)} \cdot \boxed{\frac{d\Phi^{\text{PP}}}{dE_\gamma}(E_\gamma)} \quad (\text{cm}^{-2}.\text{s}^{-1}.\text{TeV}^{-1})$$

Astrophysical factor

$$\Phi^{\text{ASTRO}}(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{l.d.v.} dl \underbrace{\rho^2(r(l))}_{\text{Halo profile}}$$

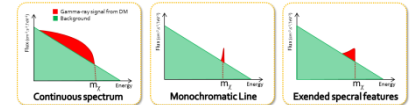


Regions of interest

- Galactic Center
- Central Galactic Halo
- Extragalactic sources (AGN, Galaxy clusters)
- Dwarf Galaxies

Particle Physics factor

$$\frac{d\Phi^{\text{PP}}}{dE_\gamma}(E_\gamma) = \frac{\langle\sigma_{\text{ann}}v\rangle}{8\pi m_\chi^2} \cdot \underbrace{\frac{dN_\gamma}{dE_\gamma}(E_\gamma)}_{\text{DM energy spectrum}}$$



$\langle\sigma_{\text{ann}}v\rangle$ is related to DM density
 → Relic Density : $\langle\sigma_{\text{ann}}v\rangle_{\text{min}} = 3.10^{-26} \text{ cm}^3.\text{s}^{-1}$

Monochromatic line searches with Fermi

Fermi papers



- “Fermi LAT Search for Dark Matter in Gamma-ray Lines and the Inclusive Photon Spectrum”

Fermi Collaboration, *arXiv:1205.2739v1* [May 2012](#)

→ Line scan [7 GeV ; 200 GeV], ROI = most of the sky → no detection (flux limits)

- “A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope” C. Weniger, *arXiv:1204.2797v2* [April 2012](#)

→ Line scan [20 GeV ; 300 GeV], ROI = Different profiles around GC

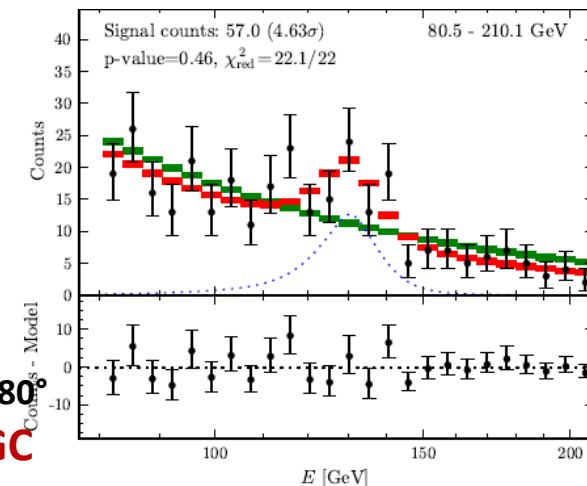
→ **3.2 σ signal, line at 130 GeV**

- “Strong Evidence for Gamma-ray Line Emission from the Inner Galaxy”

D. Finkbeiner, *arXiv:1206.1616v2* [June 2012](#)

→ Line scan [80 GeV ; 200 GeV], ROI = Galactic halo region $|b| > 1^\circ$, $|l| < 180^\circ$

→ **5 σ detection, line at 129 GeV, best fit at -1.5° latitude from GC**



- “Search for Gamma-ray Spectral Lines with the Fermi Large Area Telescope and Dark Matter Implications”

Fermi Collaboration, *arXiv:1305.5597v3* [May 2013](#)

→ Line scan [5 GeV ; 300 GeV], ROI = $\theta < 3^\circ$ around GC

→ **1.5 σ spectral feature** (local significance = 3.3 σ), **line at 133 GeV**

The H.E.S.S. Experiment



Imaging Atmospheric Cherenkov Telescopes
Location : Namibia, Khomas Highland

H.E.S.S. phase 1

- 4 telescopes (CT1234, \varnothing 12 m) - Functional since 2003
- Energy range : **100 GeV – 100 TeV** (VHE γ -rays)

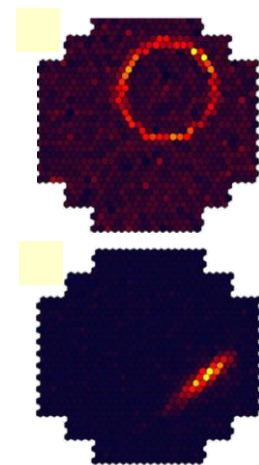
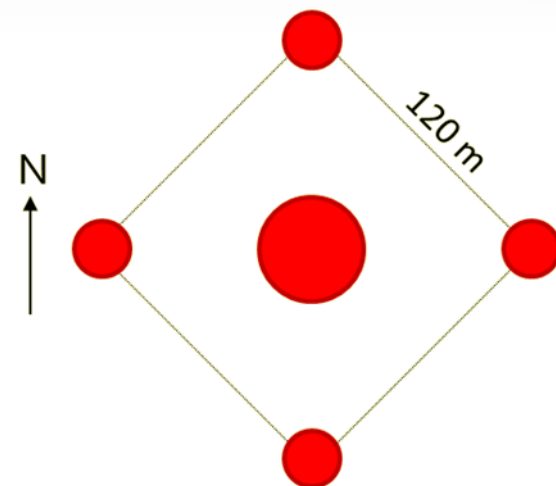
H.E.S.S. phase 2

- 5th telescope installed in 2012 (CT5, \varnothing 28 m)
- Increases sensitivity to lower energy γ -ray flux
- Expected energy threshold : **30 GeV**

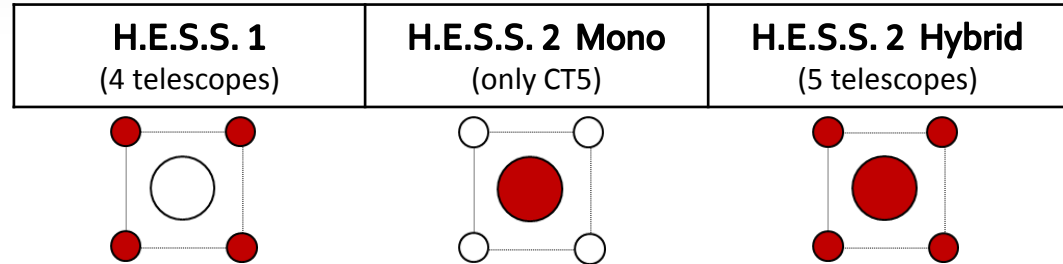


Energy range complementary with Fermi-LAT

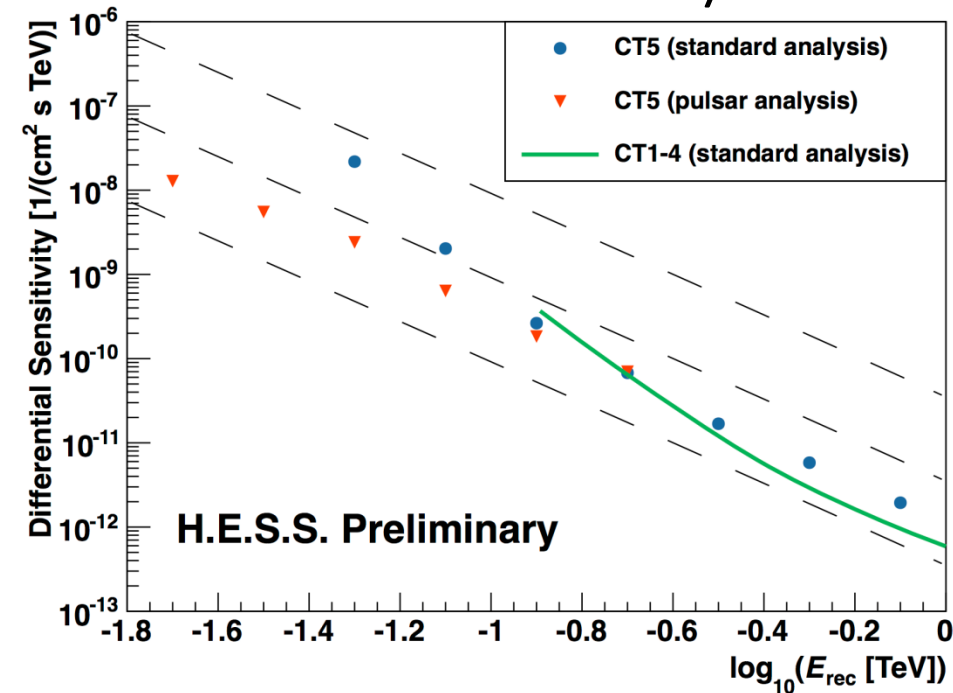
Possibility to detect a line-like signal at 130 GeV with H.E.S.S. 2



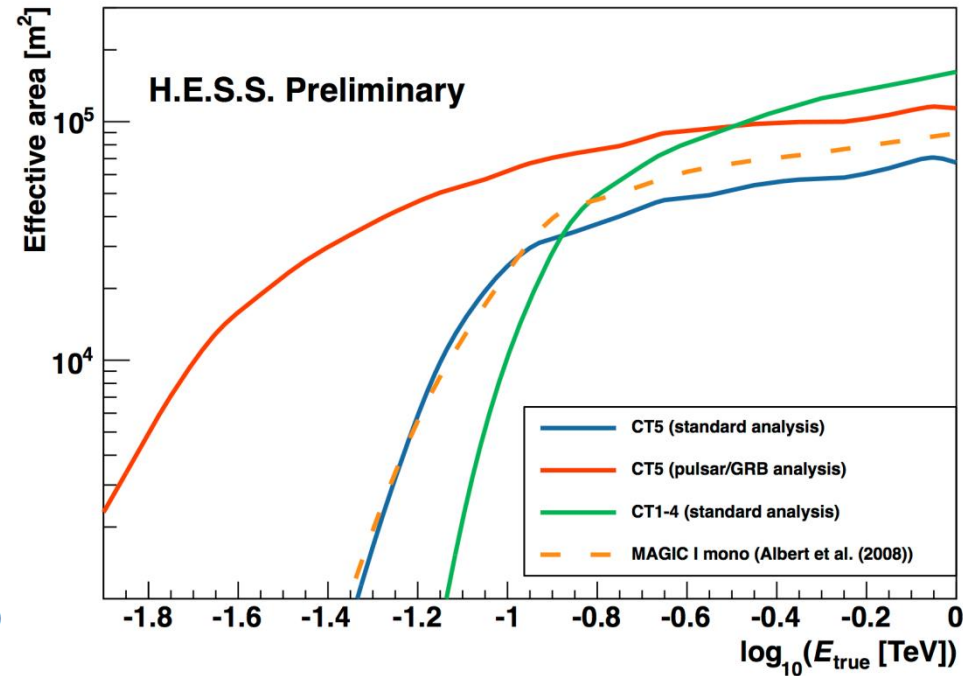
H.E.S.S. Response Functions



Differential sensitivity



Effective area



H.E.S.S. 2 Mono reconstruction will be considered for first line studies

Line search with H.E.S.S. 1

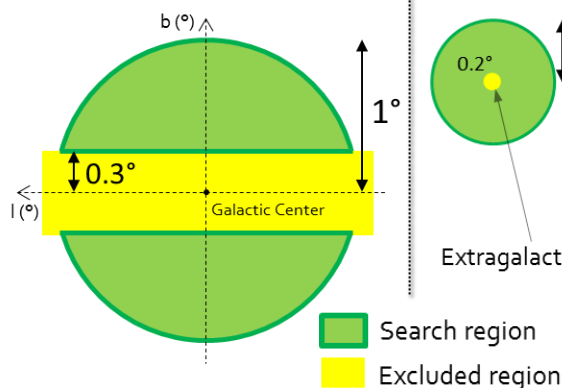
Search for photon line-like signatures from Dark Matter annihilations with H.E.S.S.
H.E.S.S. Collaboration, *arXiv:1301.1173v1* December 2012

Goals and data samples

- Goals :**
- Search for line-like features :
 - In **Central Galactic Halo (CGH)**
 - Around **extragalactic sources** (AGN, Galaxy clusters)
 - Scan in line energies ranging from **500 GeV to 25 TeV**
 - Also investigates Internal Bremsstrahlung spectral features
- **Compute flux limits and limits on DM annihilation cross-section**

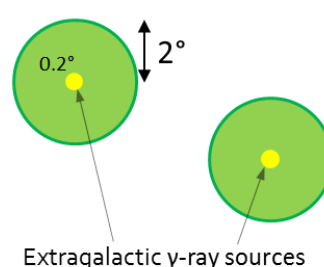
Central Galactic halo data sample

- **112 h** data (2004-2008)
- Pointing at Galactic Center
- Excludes Galactic plane



Extragalactic data sample

- **1153 h** data (2004-2007)
- Pointing many Extr. Sources
- Excludes the sources



+ H.E.S.S. 1 Standard Cuts + Trigger with all 4 telescopes
(keeps 15 % of the total events, but 50 % better sensitivity to gamma)

Line search method

Both CGH and Extragalactic background spectra can be modeled by :

$$\frac{dN}{dE_\gamma} = a_0 \left(\frac{E_\gamma}{1 \text{ TeV}} \right)^{-2.7} [P(x) + \beta G(x)]$$

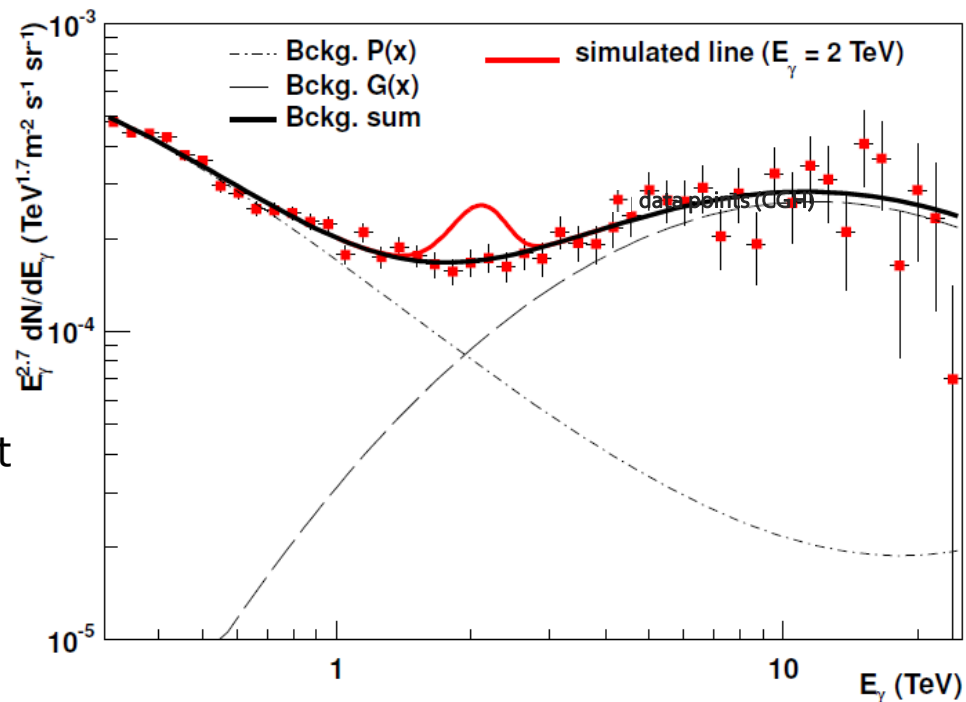
$\exp(a_1 x + a_2 x^2 + a_3 x^3)$ Gaussian(μ_x, σ_x)
 $x = \log_{10}(E_\gamma / 1 \text{ TeV})$

- **Step 1:** Add a line at a fixed energy to the above parametrization (convoluted with I.R.F.s)
- **Step 2:** Fit all the above parameters ($a_0 \dots a_3, \beta, \mu_x, \sigma_x$) + **amplitude of the line** together on real data using a binned Likelihood approach :

$$\ln \mathcal{L} = \sum_{i=1}^{N_{bins}} n_i \ln \lambda_i - \lambda_i$$

n_i → Number of reconstructed counts in bin i
 λ_i → Expected number of counts in bin i

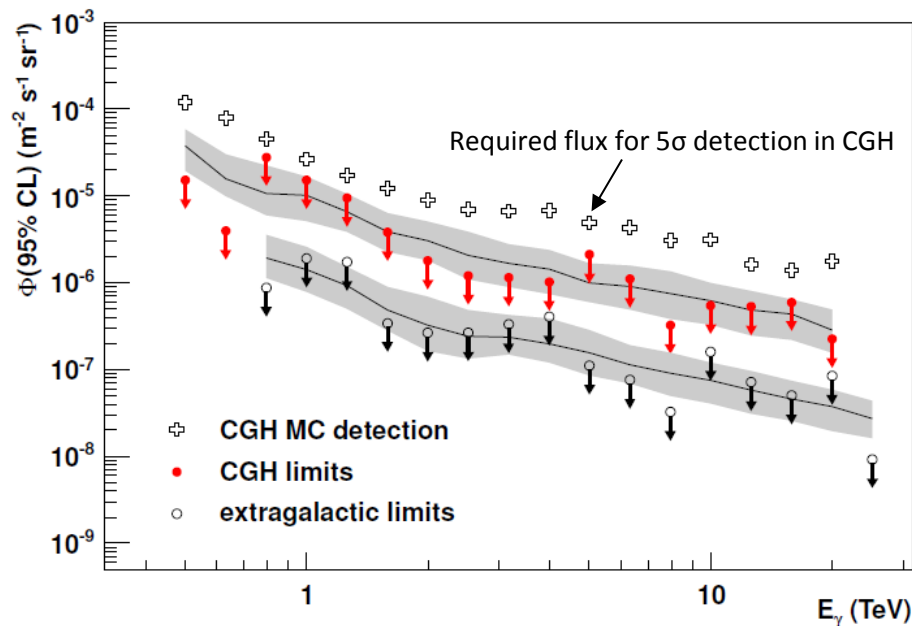
+ repeating the procedure for lines at different energies between [500 GeV ; 25 TeV]



Results - γ -ray Line Flux limits

No significant γ -ray line flux detected in both samples \rightarrow γ -ray line Flux limits

Flux limits for DM Monochromatic line

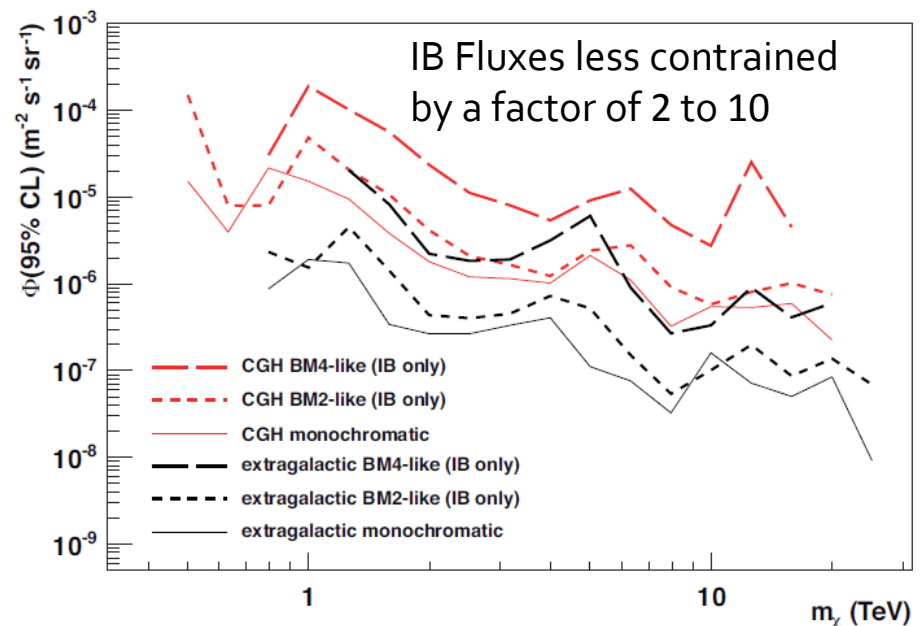


Flux at 1 TeV : CGH $\sim 2.10^{-5} \text{ m}^2 \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$

Extragalactic $\sim 2.10^{-6} \text{ m}^2 \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$

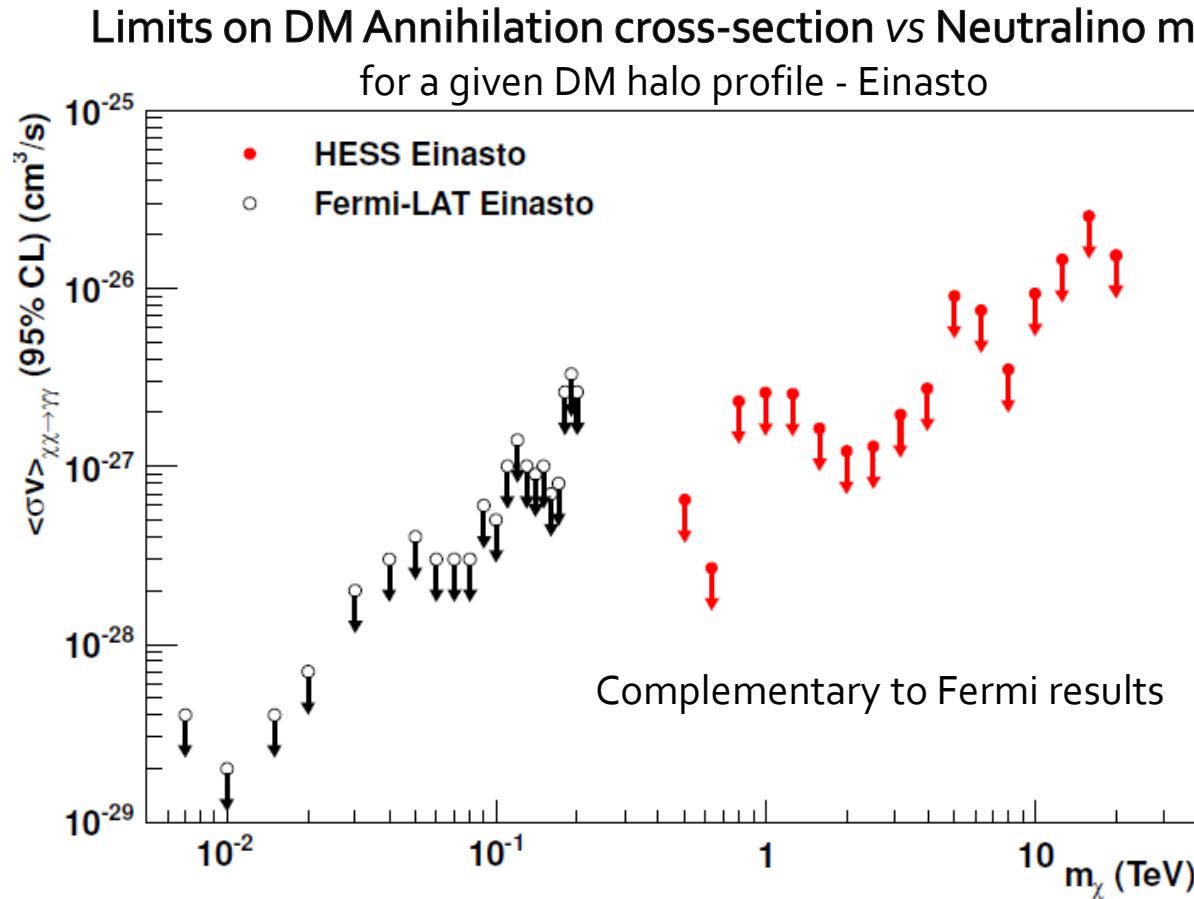
Total systematic error on flux = 50 %

Flux limits for IB Models



Results - Dark Matter models

Constraints on γ -ray line flux \rightarrow Constraints on Dark Matter models



$$\langle\sigma_{\text{ann}}\cdot v\rangle|_{1\text{TeV}} \leq 10^{-27} \text{ cm}^3\cdot\text{s}^{-1}$$

Prospects with H.E.S.S. 2

Expected data and strategy

H.E.S.S.2 data for line search (2013-2014)

~60 h pointing at **Galactic Center**

~10 h scan towards the **Fermi Line best fit region** until now

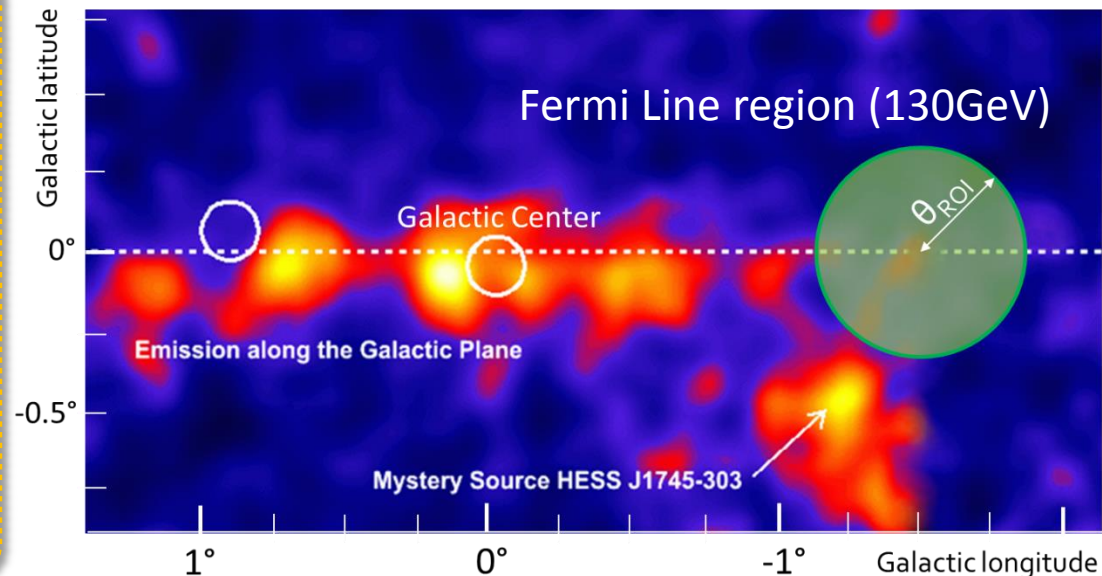
+ **Control sample** :

Point like calibration sources for tests, optimisations and background studies

H.E.S.S. 2 energy threshold allows for **130 GeV line study**

Strategy :

- Analyse both GC and Fermi Line regions
- Optimisation of Regions Of Interest and excluded regions
- Background shape from Monte-Carlo simulations
- "Profile Likelihood" analysis**
→ **potential Line signal search**
Range for this analysis [80 GeV ; 1 TeV]



Method developments

Idea : Identify a line-like signal from H.E.S.S.2 data in the presence of
2 different types of background

- **Hadrons** (profile known from control sample or MC)
- **Diffuse gamma ray emission** in the galactic plane (profile from MC)

Expected signal

- Gaussian line (smeared by response functions), 130GeV expected

■ Profile Likelihood approach:

$$\mathcal{L}(N_{EST}, M(\theta) | N_{OBS}, E_1, \dots, E_{N_{OBS}}) = \frac{N_{EST}^{N_{OBS}}}{N_{OBS}!} e^{-N_{EST}} \times \prod_{i=1}^{N_{OBS}} \mathcal{P}(E_i; M(\theta))$$

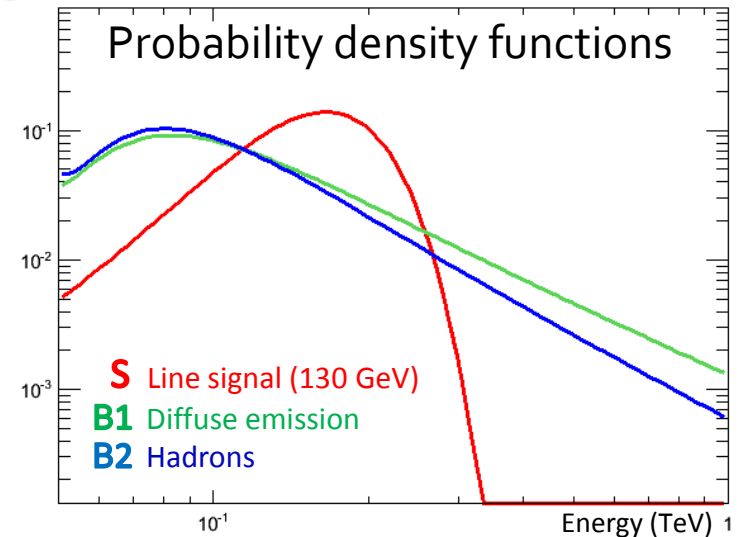
Sum over data events in the energy range [80GeV ; 1TeV]

■ Unbinned approach, based on spectral shapes

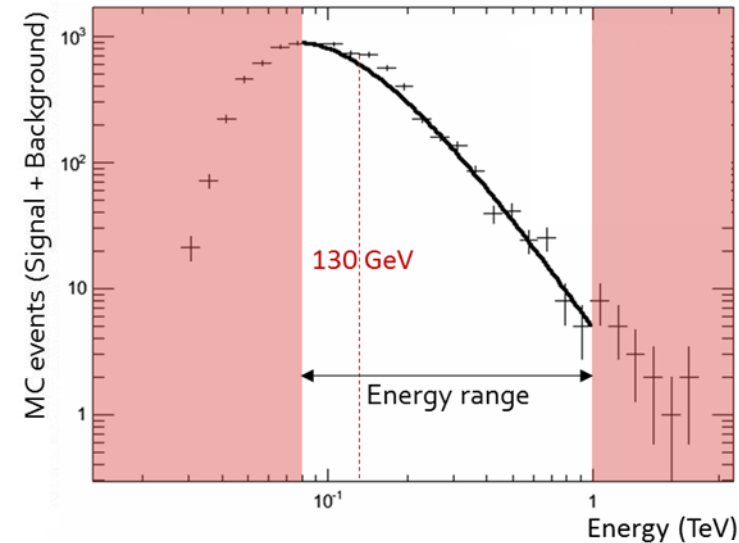
■ Minimization of the $-2\ln(L)$ function

→ **Reconstruction of the Line energy and Line rate η**
(+ fit of background components foreseen)

■ Use of test statistic estimator TS



Preliminary results with Monte-Carlo



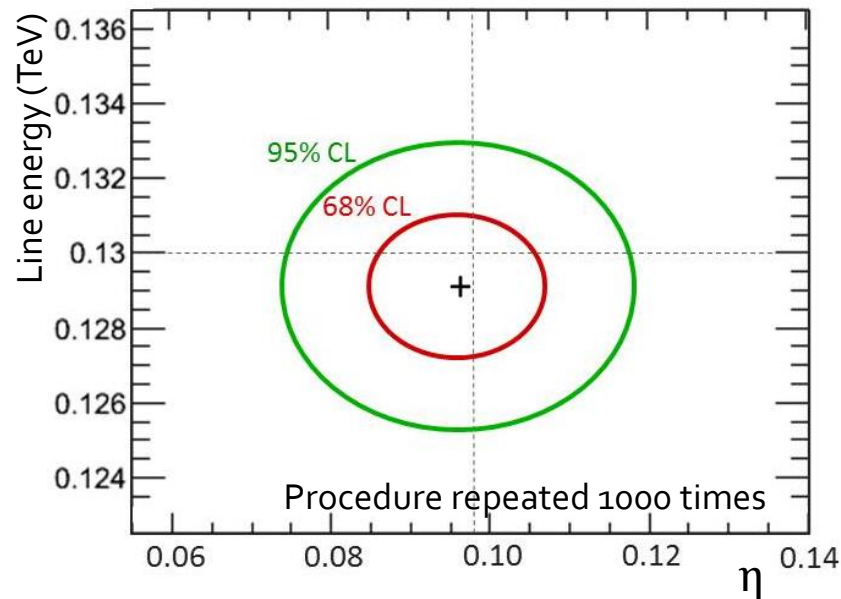
R.O.I. : Fermi Line region ($l = -1.5^\circ$), $\theta_{\text{ROI}} = 0.25^\circ$
Observation time : 50 h

MC events :

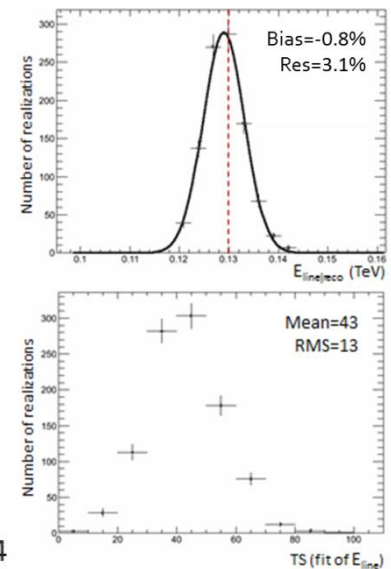
- Number of line events derived from Fermi 130GeV line flux (C. Weniger, $\langle \sigma_{\text{ann}} v \rangle = 2.3 \cdot 10^{-27} \text{ cm}^3 \cdot \text{s}^{-1}$)
- Line rate to reconstruct: $\eta = S/(S+B) \sim \mathbf{10\%}$
 \rightarrow According to H.E.S.S. 2 Mono reconstruction (*preliminary*)

- **Reconstruction works well**
(few % errors, $\langle \text{TS} \rangle \sim 40$)
- **Line reconstruction possible for rates $> 2\%$**
on [80 GeV ; 100 GeV]
- **Detection (5σ) for rates $> 7\%$**

2D reconstruction of Line energy & rate



Reconstruction of Line energy



Conclusions on H.E.S.S.2 future Line analysis

- Aim : extend the work done in H.E.S.S. 1 paper to lower energies
→ **Line study between 80 GeV and 1 TeV,**
possibility to X-check Fermi 130 GeV line feature
 - Final analysis strategy under discussion (ROI, Reconstruction model...)
 - High level analysis :
Development of the profile Likelihood procedure
Discrimination with 3 components – Line, Hadrons (Cosmic rays), Diffuse (Galactic plane)
Tests of the method with MC → Ok, sensitive to low rates > 2%
Huge efforts on **background studies with control samples**
Systematics under study
- Method looks promising for Line search!