GRAN SASSO SCIENCE INSTITUTE
CENTER FOR ADVANCED STUDIES INFN

Second Year Report:

Directional rare events searches with the CYGNO detector

Candidate: **G. Dho**

Advisor: **E. Baracchini**

Summary

- Introduction
- Analysis & Simulation (A&S)
  - Discrimination of DM Models
  - Sensitivity CYGNO/INITIUM
- Experimental studies (ES)

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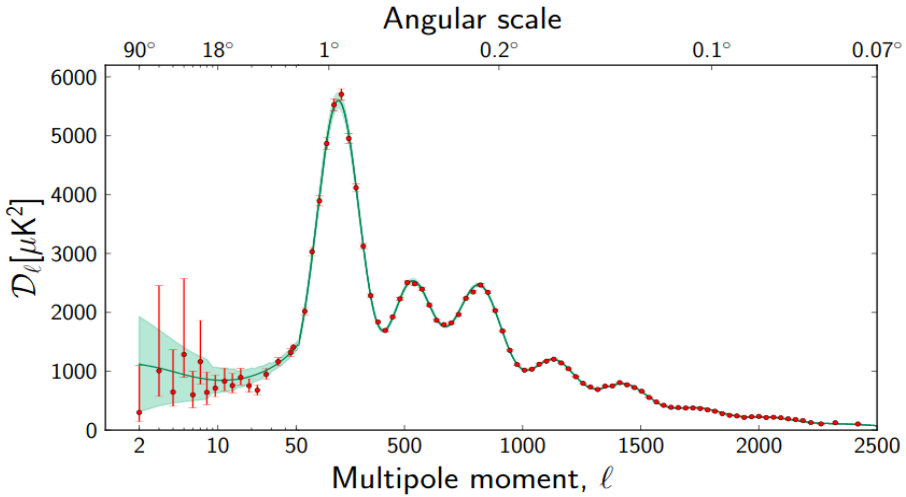
Dark Matter

- Well established theoretical paradigm of modern Physics

- The most supported hypotheses predict the existance of at least one new particle



Taken from Planck coll., https://doi.org/10.1051/0004-6361/201321529

- The Galaxy resides in a halo of these particles and Earth motion makes it more likely for these particles to interact with regular matter on our planet

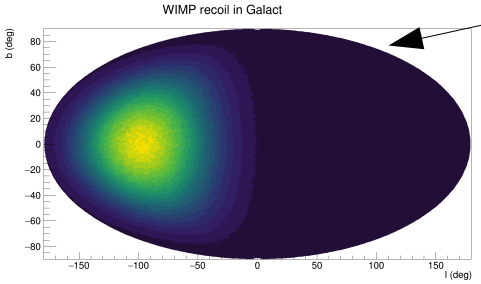
↓

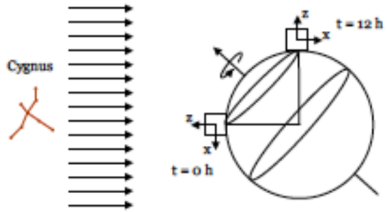
Direct Detection Experiments

Directionality Relevance

- Typical signal measured is the energy of the recoils in the detector, but the Earth motion in the Galaxy and around its axis imprints a directional dependence on the recoils

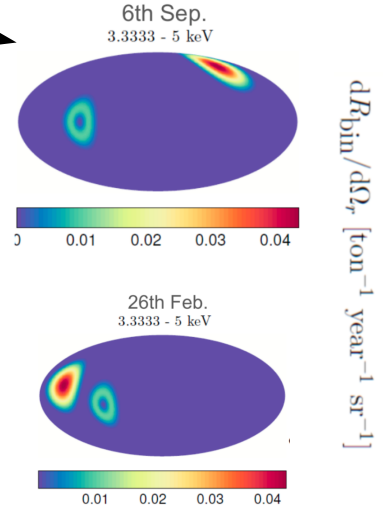
F recoil due to WIMP





The signal of the recoil is highly unikely to be reproduced by background

Recoils from coming from Solar neutrinos will not overlap with DM ones

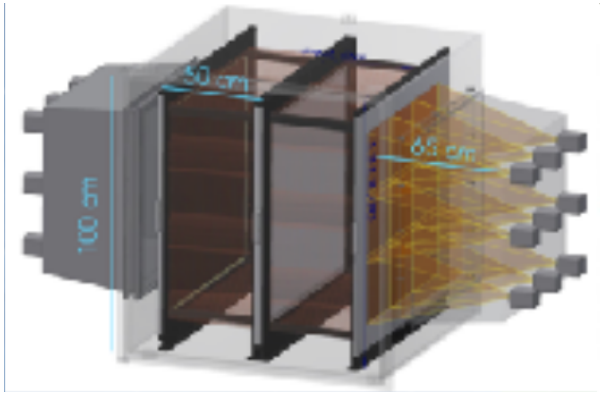


High potential for positive discovery and astronomy

What is now considered background can become signal

CYGNO/INITIUM Experiment

- CYGNO/INITIUM is the project of a directional detector, whose main goal is the direct detection of Dark Matter (DM)



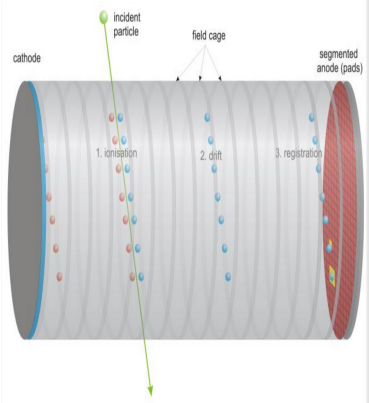
1 m^3 operated at:

room temperature

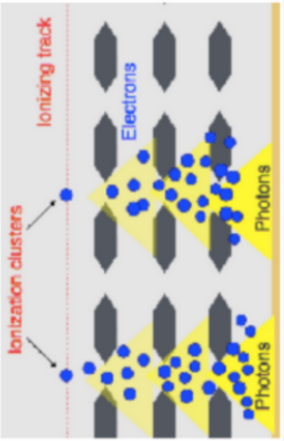
atmospheric pressure

He:CF_4 gas mixture

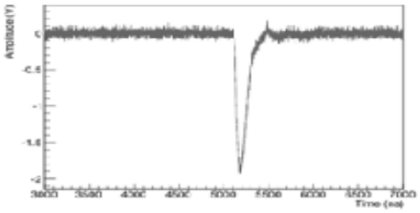
Time Projection Chamber



GEM apmlification stage



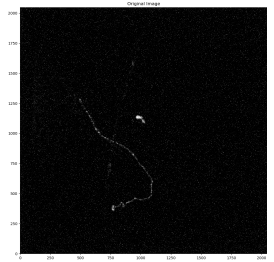
Optical readout



PMT

Signal temporal distribution

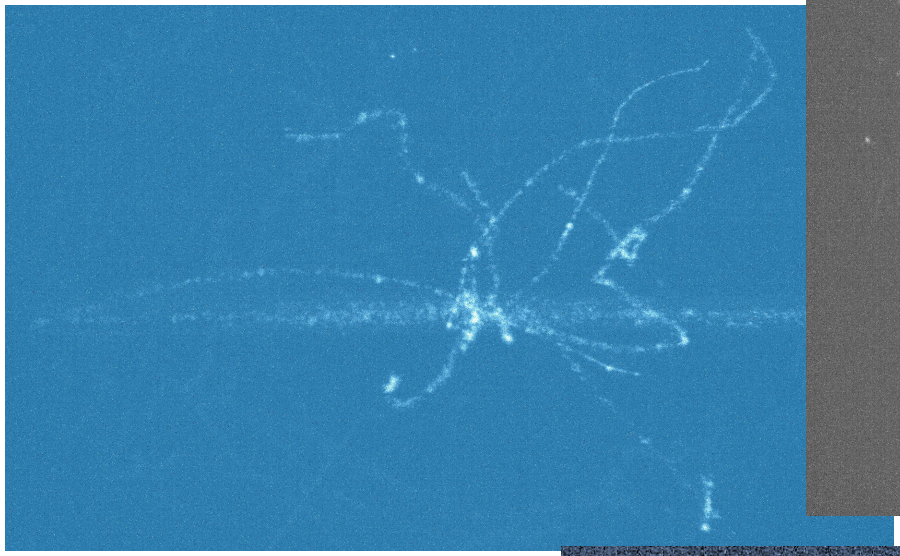
Energy

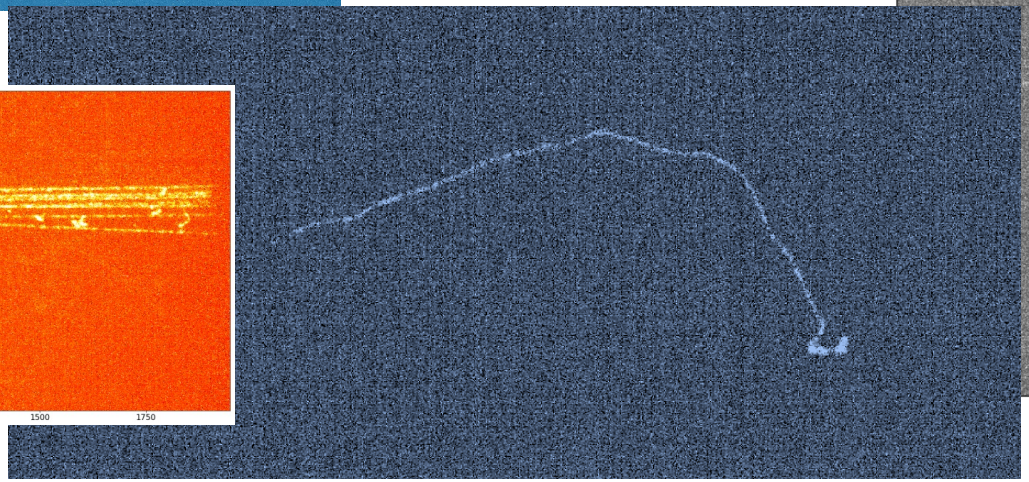


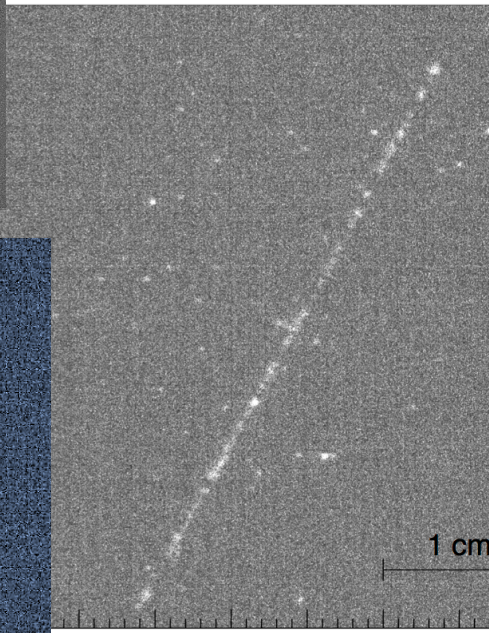
SCMOS camera

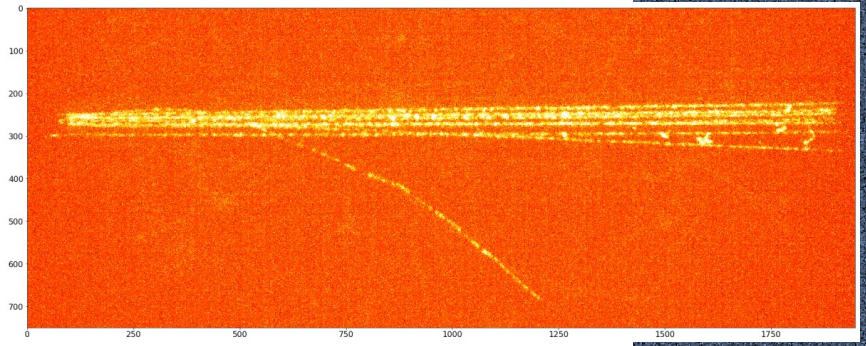
x–y signal distribution

Energy






1 cm


0
100
200
300
400
500
600
700
0
250
500
750
1000
1250
1500
1750

Work Done

- The work can be split in two branches

Analisys and simulation (A&S)

Studies on the importance and relevance of directionality in the field of DM:

- Discrimination of different models of DM
- Sensitivity limits of the CYGNO/INITIUM experiment

Experimental studies (ES)

Characterization of detector parameters with laboratory measurements:

- Studies on electro-luminescence of He:CF_4

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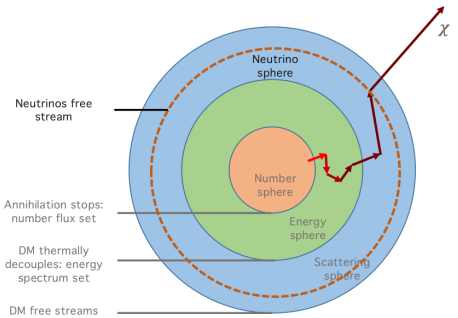
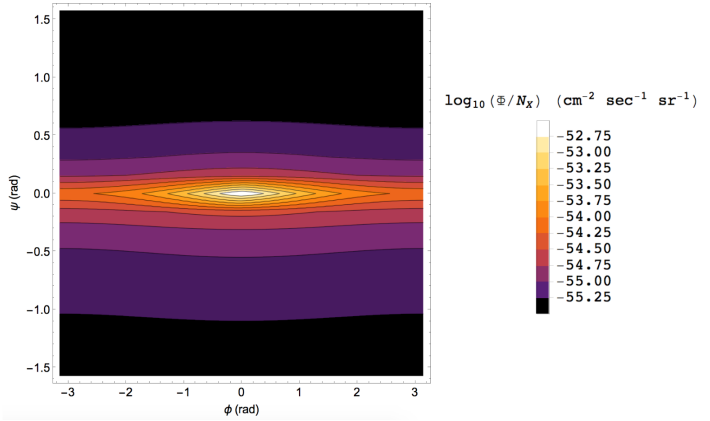
A&S: SuperNovae Dark Matter (SNDM) Model

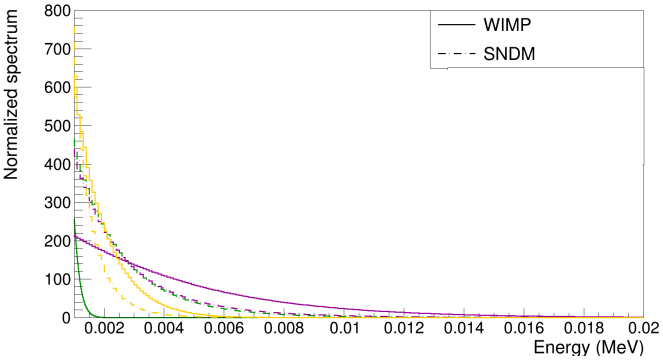
- Collaboration with Stanford PhD W. DeRocco [1]



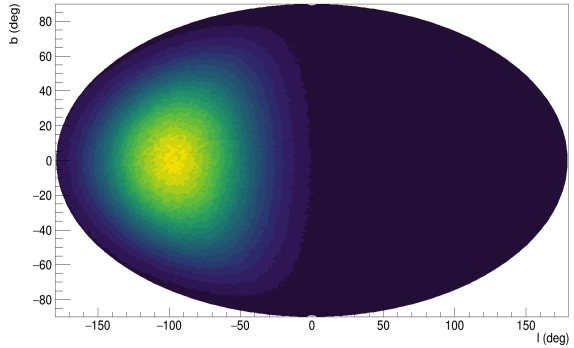
MeV scale particles at semirelativistic velocities could stream from SN explosions



- While the energy spectrum should be similar to WIMP induced one, the angular should not

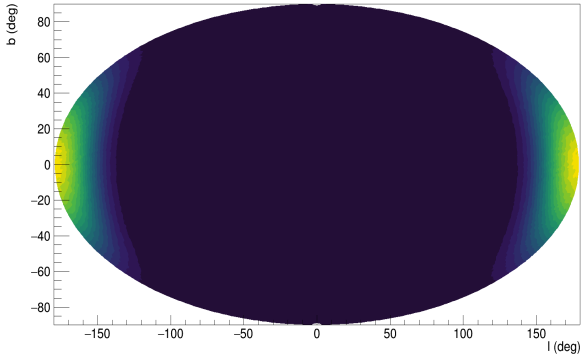


WIMP



F recoil

SNDM



A&S: Setup of the Analysis

- We wanted to know **how many events we needed to distinguish the two models**

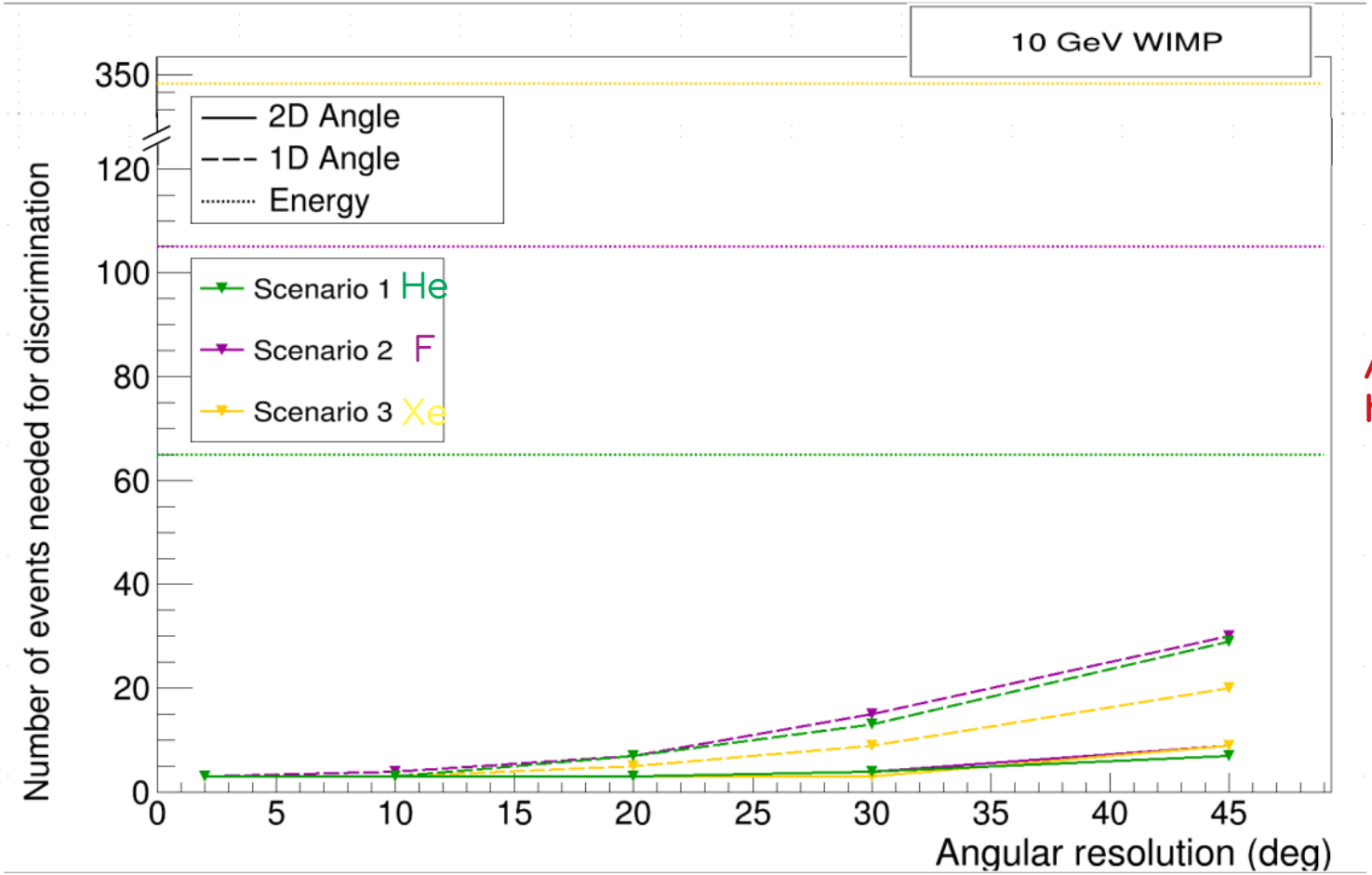
calculated theoretical spectra

simulated fake experiments

profile likelihood ratio test

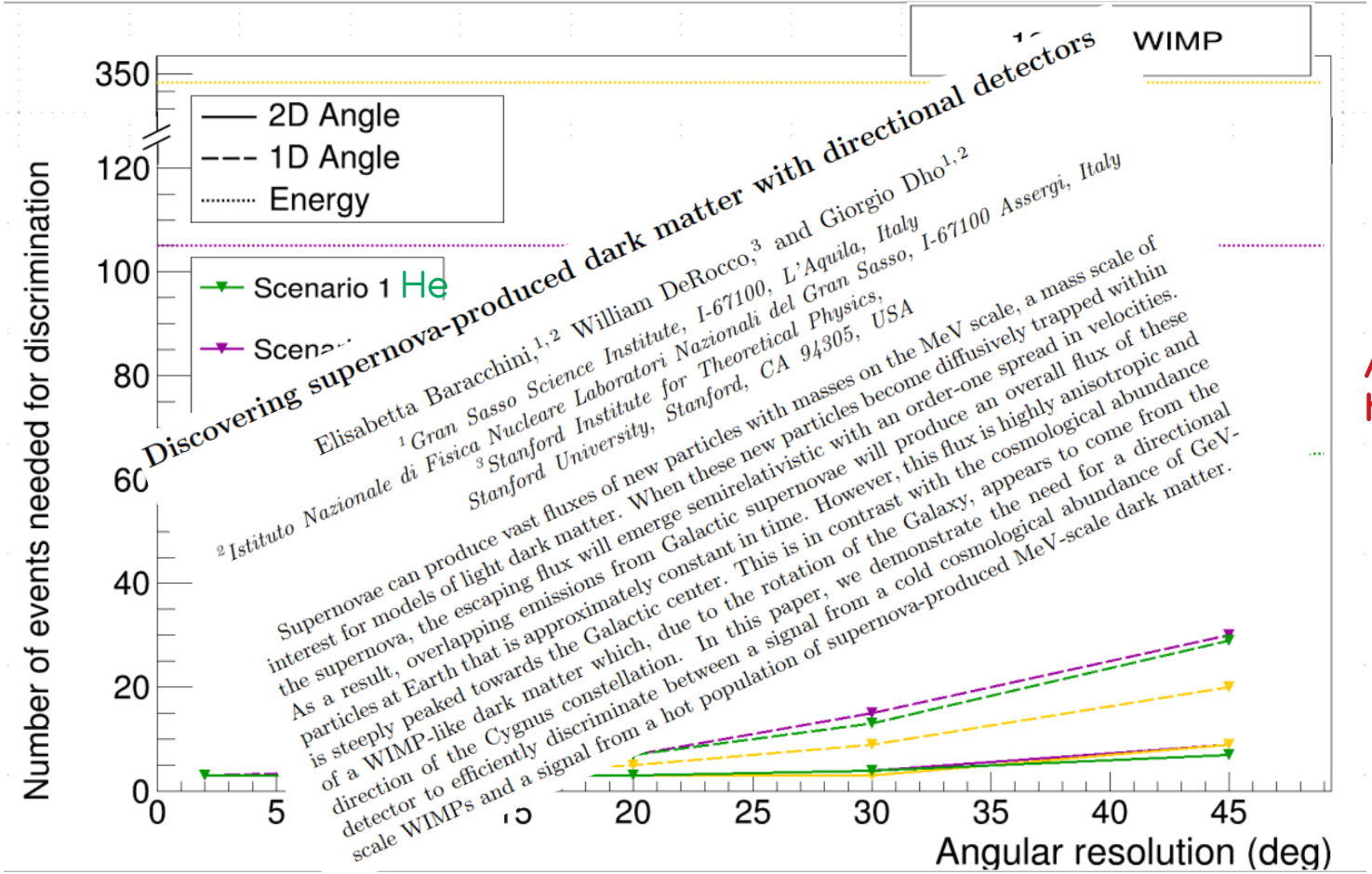
- In the analysis we considered
  - Different elements for heavier and lighter targets (He, F, Xe)
  - Heavier and lighter WIMP masses and corresponding SNDM with **no background assumption**
  - Energy resolution and energetic region of interest taken from measurement [2][3][4]
  - Diverse angular resolutions

A&S: Results



Angular information helps discriminating better than energy

A&S: Results



Discovering supernova-produced dark matter with directional detectors

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[3] *Stanford Institute for Theoretical Physics, Stanford University, Stanford, CA 94305, USA*

Supernovae can produce vast fluxes of new particles with masses on the MeV scale, a mass scale of interest for models of light dark matter. When these new particles become diffusively trapped within the supernova, the escaping flux will emerge semirelativistic with an order-one spread in velocities. As a result, overlapping emissions from Galactic supernovae will produce an overall flux of these particles at Earth that is approximately constant in time. However, this flux is highly anisotropic and is steeply peaked towards the Galactic center. This is in contrast with the cosmological abundance of a WIMP-like dark matter which, due to the rotation of the Galaxy, appears to come from the direction of the Cygnus constellation. In this paper, we demonstrate the need for a directional detector to efficiently discriminate between a signal from a cold cosmological abundance of GeV-scale WIMPs and a signal from a hot population of supernova-produced MeV-scale dark matter.

Angular information helps discriminating better than energy

arXiv:2009.08836v1

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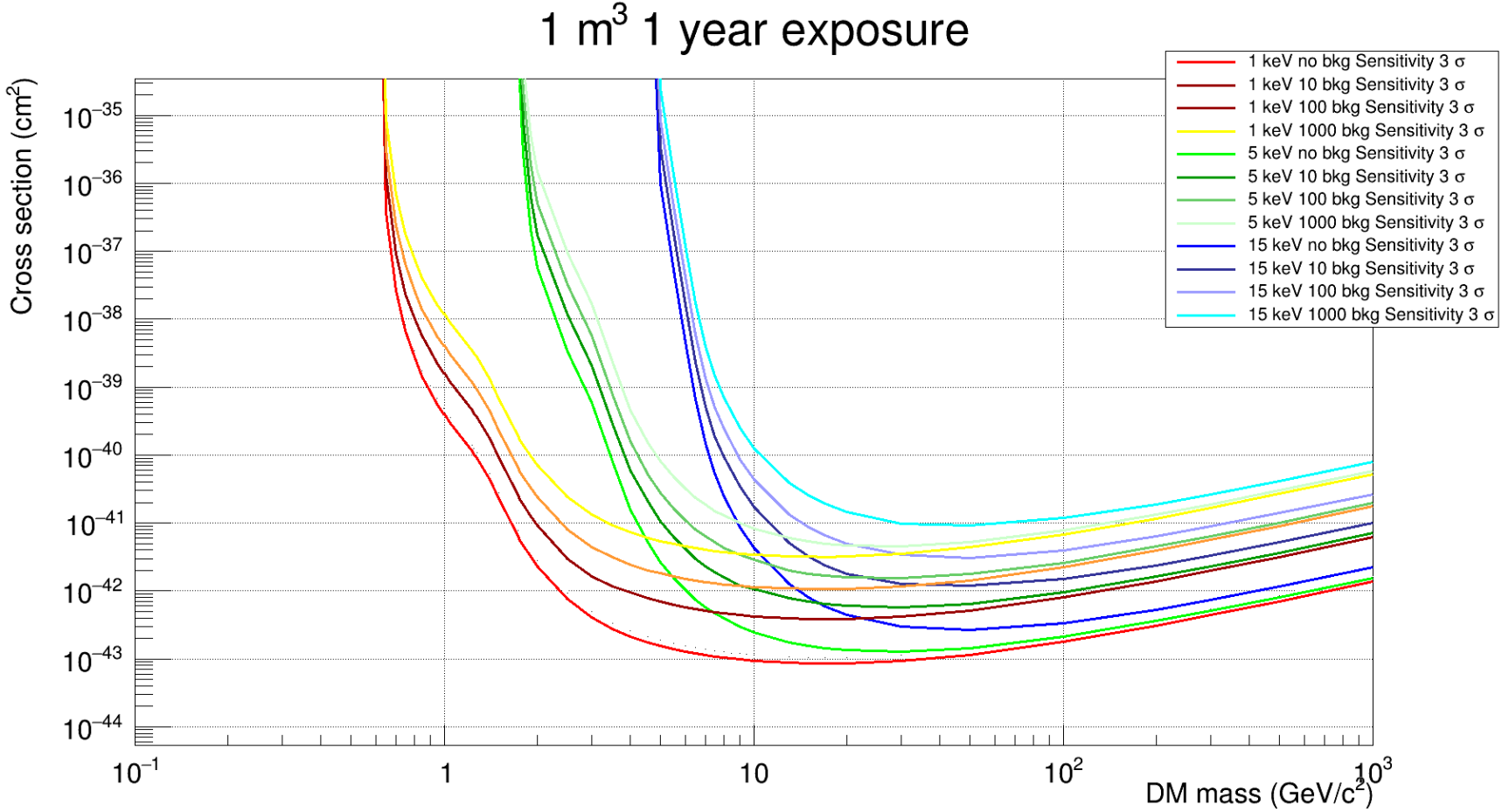
A&S: Sensitivity for CYGNO/INITIUM

- A similar work can be performed trying to discriminate WIMP signal from background
- The background is expected to be isotropic in angle at the first order approximation
- The gas mixture is He:CF_4 at 60/40 at atmosferic pressure
- The likelihood has to be slightly adapted, considering the background of μ_b and of WIMP signal of μ_s

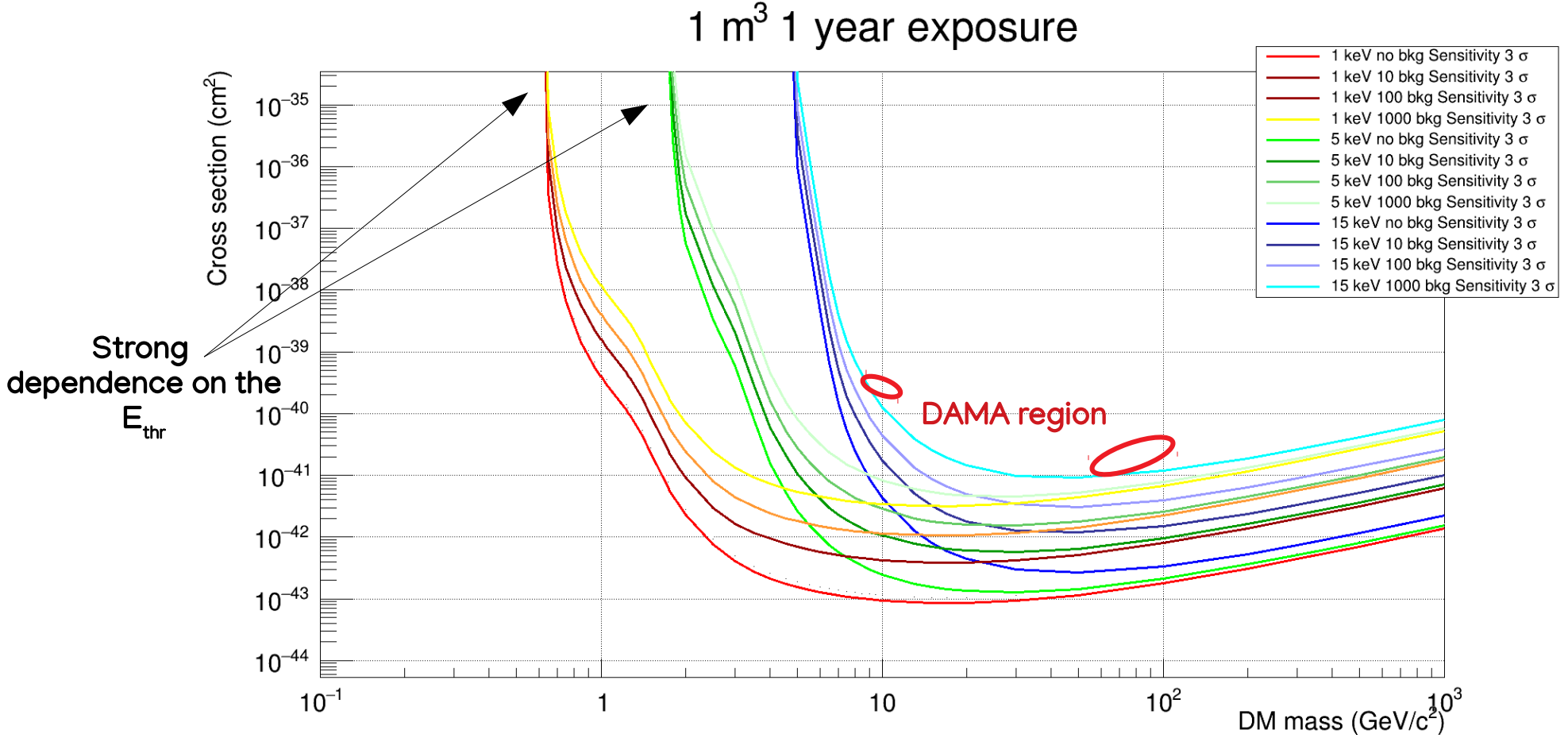
$$L_{b+s} = \frac{(\mu_s + \mu_b)^{N_{evt}}}{N_{evt}!} e^{-(\mu_s+\mu_b)} \times N_{evt}! \times \prod_{i=1}^{N_{bin}} \left[\left(\frac{\mu_s}{\mu_s+\mu_b} P_{si} + \frac{\mu_b}{\mu_s+\mu_b} P_{bi} \right)^{n_i} \frac{1}{n_i!} \right]$$

- The criterion for the sensitivity is adapted to have the 3 sigma sensitivity curve

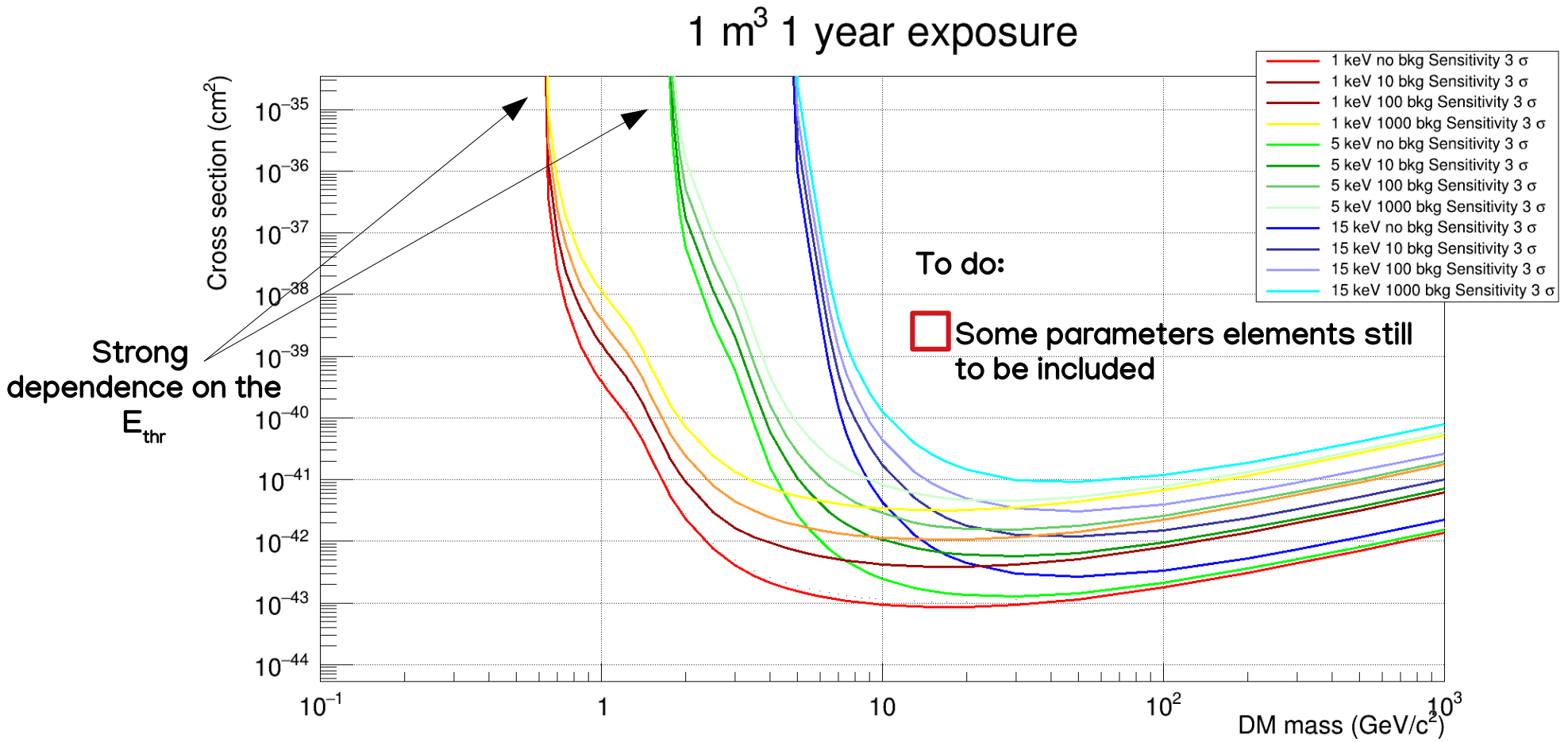
A&S: Sensitivity 3 σ Level



A&S: Sensitivity 3 σ Level



A&S: Sensitivity 3 σ Level



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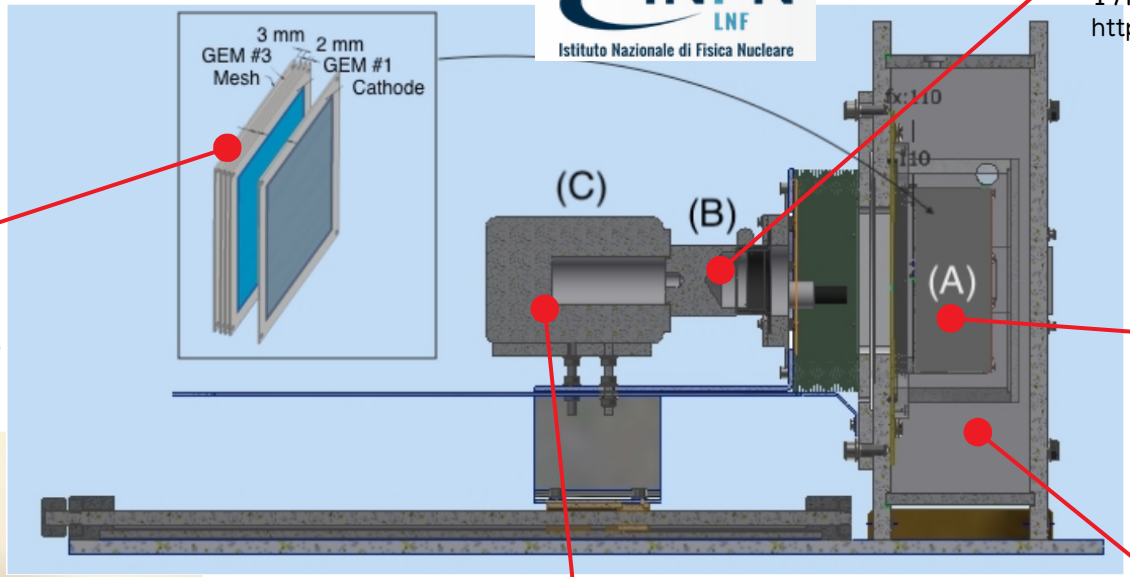
ES: MANGO Prototype

A Multipurpose Apparatus for Negative ion studies with GEM Optically readout



Lenses

17mm FL, f/0.95 Fast C Mount
https://www.schneideroptics.com

3 GEMs:
50 um thick

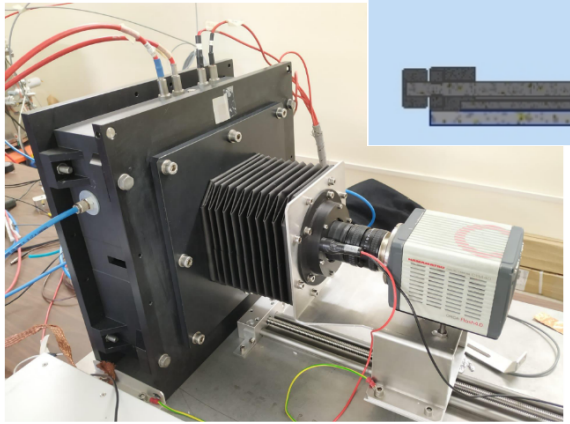
140 um pitch

70 um holes diametre

TPC volume:
Max volume 500 cm^3
(10x10 cm^2) area

He:CF_4 mixture 60/40

1 atm



sCMOS Camera
Orca flash 4.0.

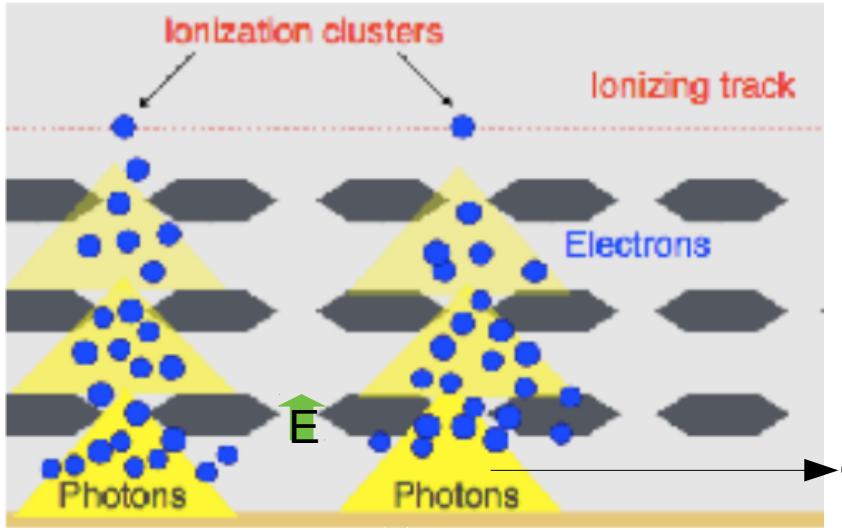
2048x2048 pixels

noise <2 ph/pixel

www.hamamatsu.com.

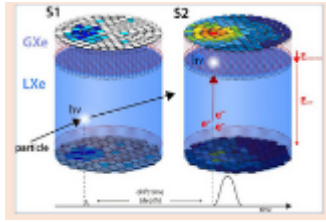
Plastic gas-tight box

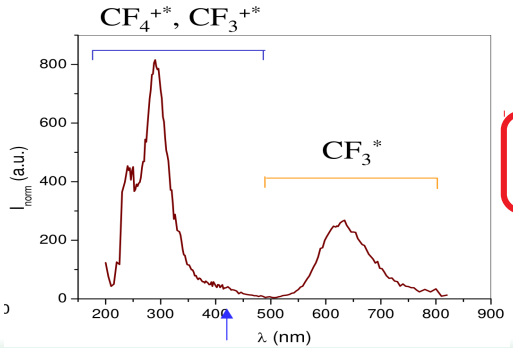
ES: ELECTRO-LUMINESCENCE



- During the ionization process also neutral fragment of CF_4 are produce with consequent emission of light
- Increasing the amount of light would improve the performance of the detector
- It could be useful to generate more photons without any ionizing the gas:

Electro-luminescence



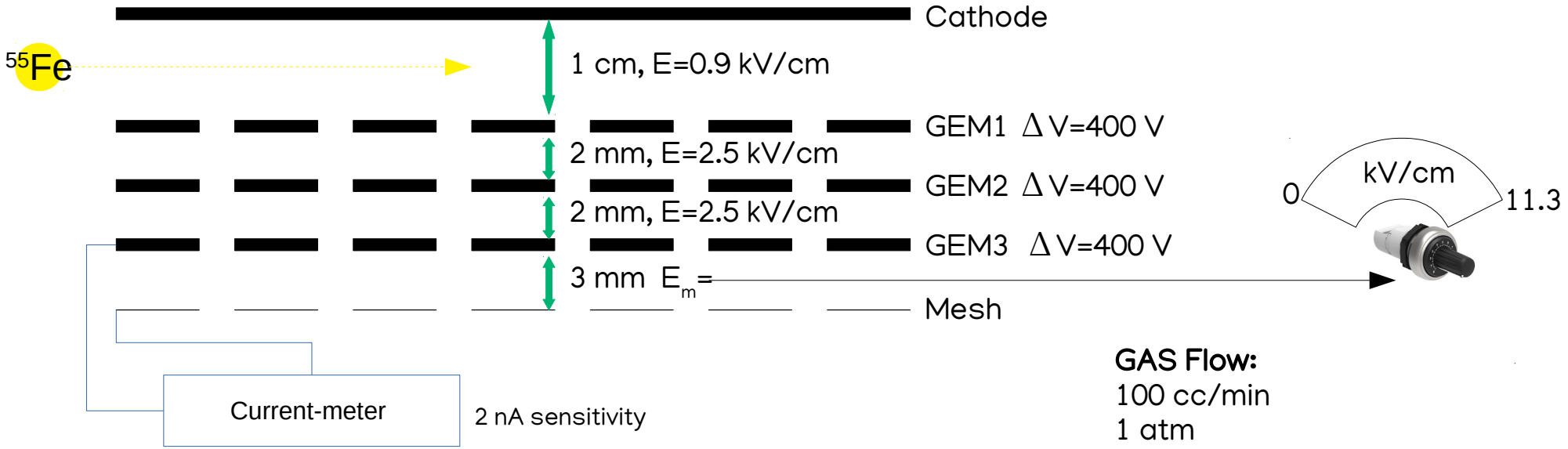


Electronic excitation (dissociation into neutral fragments)†	12.5 (10)	12.5 (10)
Dissociative ionization†	15.9	15.9

Taken from [5]

Should be possible

ES: Data Taking



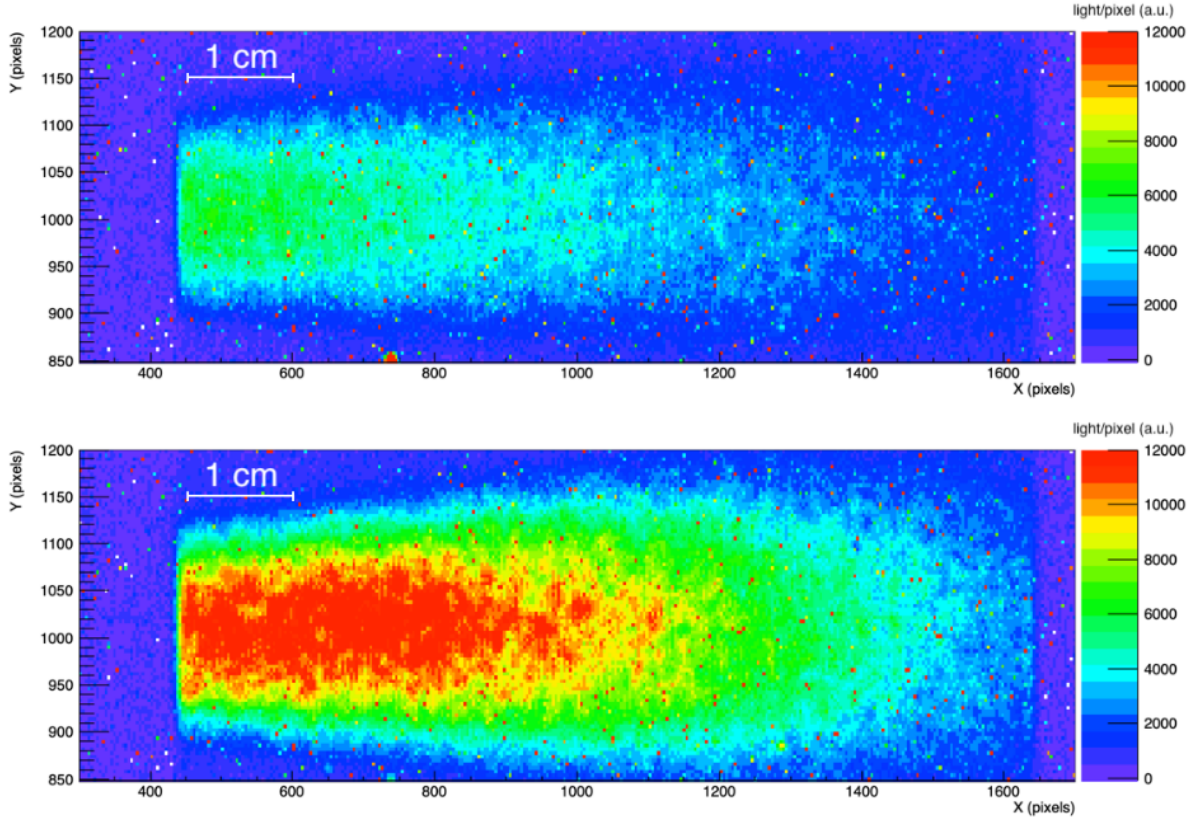
GAS Flow:
100 cc/min
1 atm
He:CF_4 60/40

- Typical signal to look for are iron spots

ES: Light Measurements

- Do we see more light?

Visible light output increase



E_m 0 kV/cm

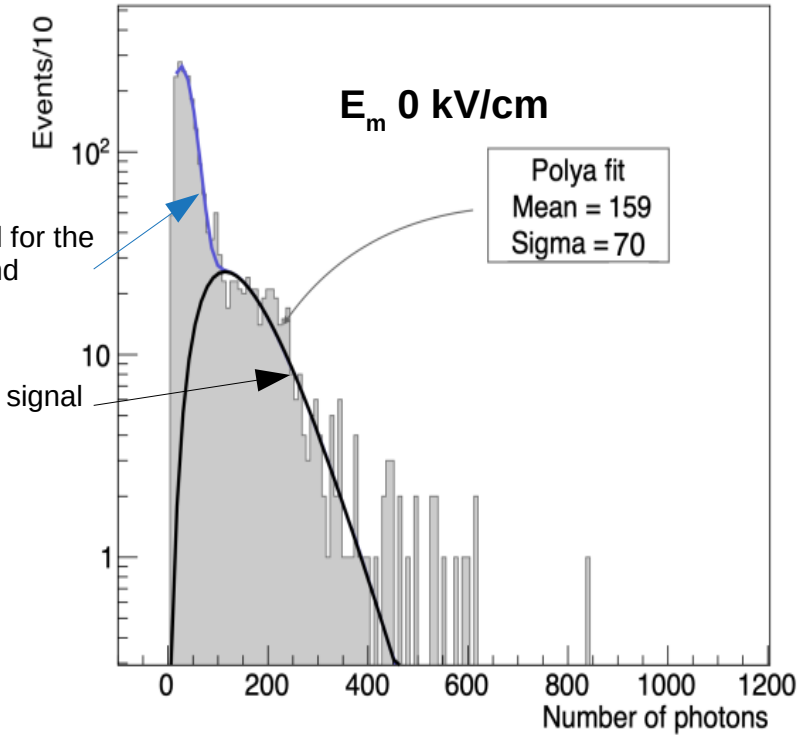
E_m 11.3 kV/cm

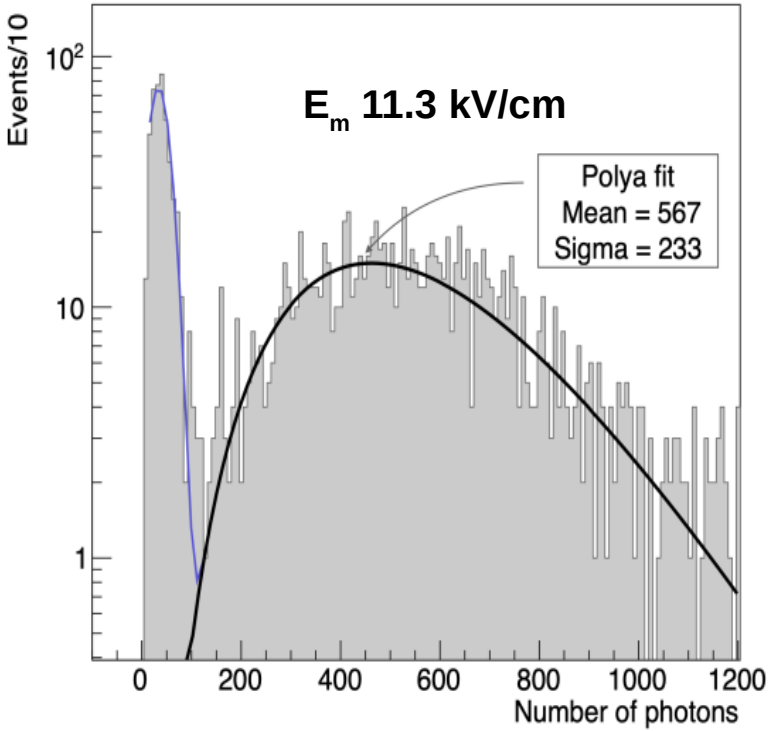
ES: Light Measurements

- With short exposure (500 ms), an algorithm to find round spots was used
- 200 pictures combined were utilized to have more statistics

Gaussian model for the background

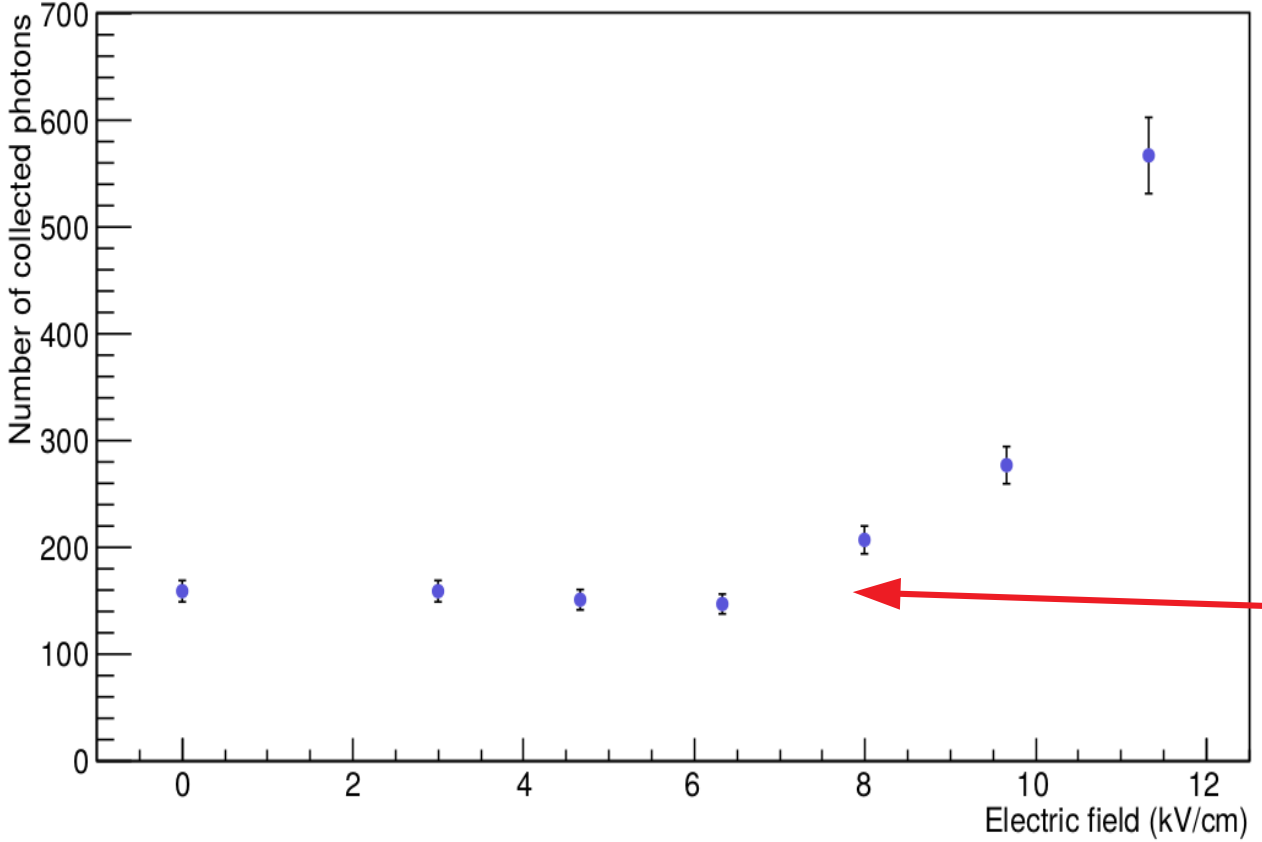
Polya fit for the signal





ES: Light Measurements

- Analysing the various electric fields applied it is visible a clear influence on the photon yield



Consistent with a threshold effect

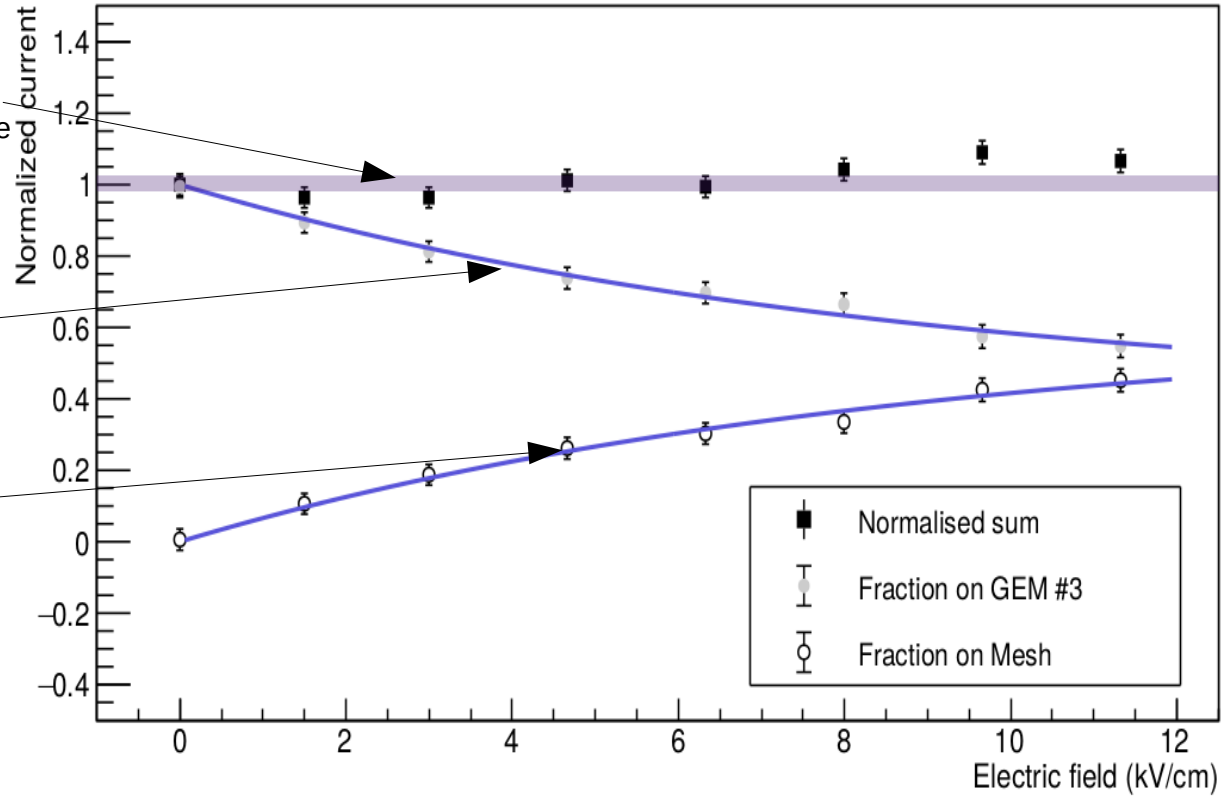
ES: Charge Measurements

$I_{tot} = I_{GEM\,3} + I_{Mesh}$

Normalized to initial value

$\frac{I_{GEM\,3}}{I_{tot}}$

$\frac{I_{Mesh}}{I_{tot}}$



No significant increase in charge total charge collection

No increase of charge with increase of light output suggests pure electro-luminescence is happening

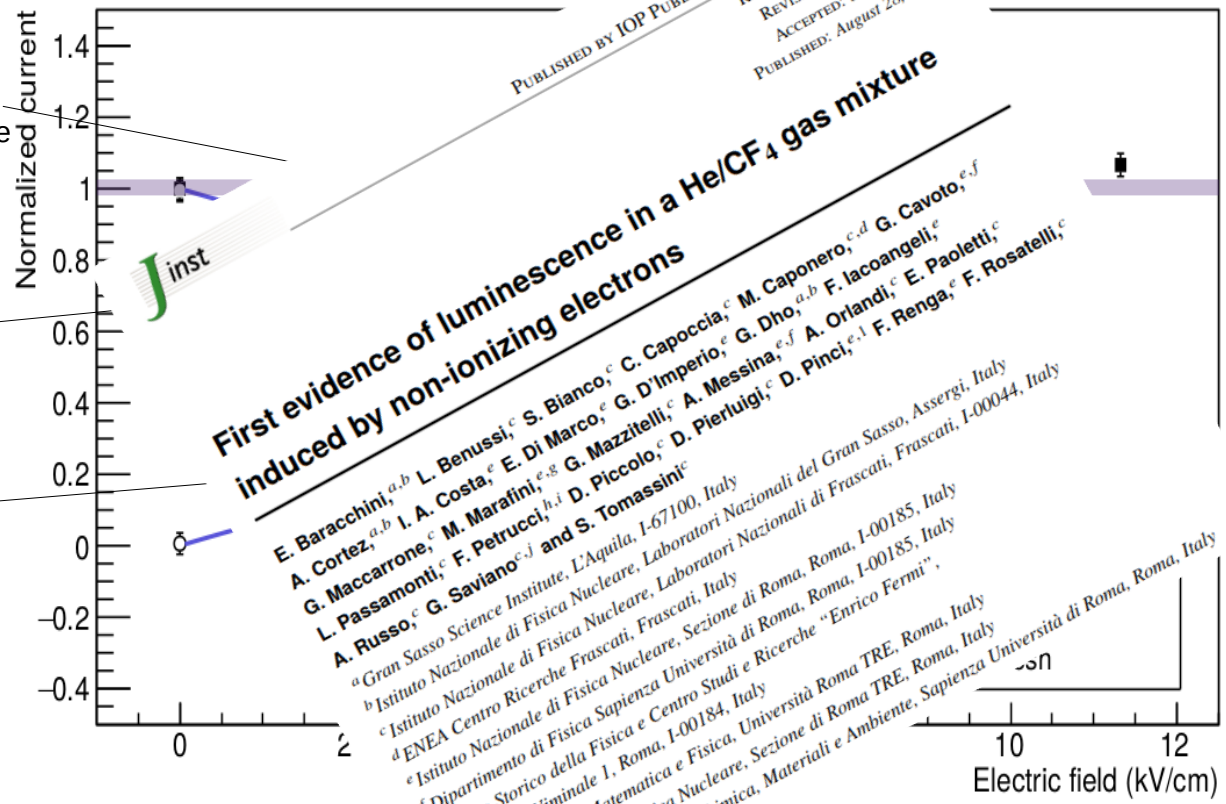
ES: Charge Measurements

$I_{tot} = I_{GEM\,3} + I_{Mesh}$

Normalized to initial value

$\frac{I_{GEM\,3}}{I_{tot}}$

$\frac{I_{Mesh}}{I_{tot}}$



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First evidence of luminescence in a He/CF_4 gas mixture induced by non-ionizing electrons

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No significant increase in charge total charge collection

↓

No increase of charge with increase of light output suggests pure electro-luminescence is happening

Conclusions and Plans

- In the context of the CYGNO/INITIUM experiment I have worked both on experimental and analysis studies
- I developed a simple simulation and statistical analysis tool to inspect more in depth the directionality approach for discrimination of different DM models and of the expected WIMP signal from the background
- I also performed experimental studies on the possibility of exploiting electro-luminescence in our gas mixure

WHAT IS NEXT

- I will continue the study of the sensitivity and limits plots of the experiment adding more experimental and practical details
- MANGO is at LNGS, so I can continue the study of the phenomenon of electro-luminescence and try to optimize it for the purposes of the experiment

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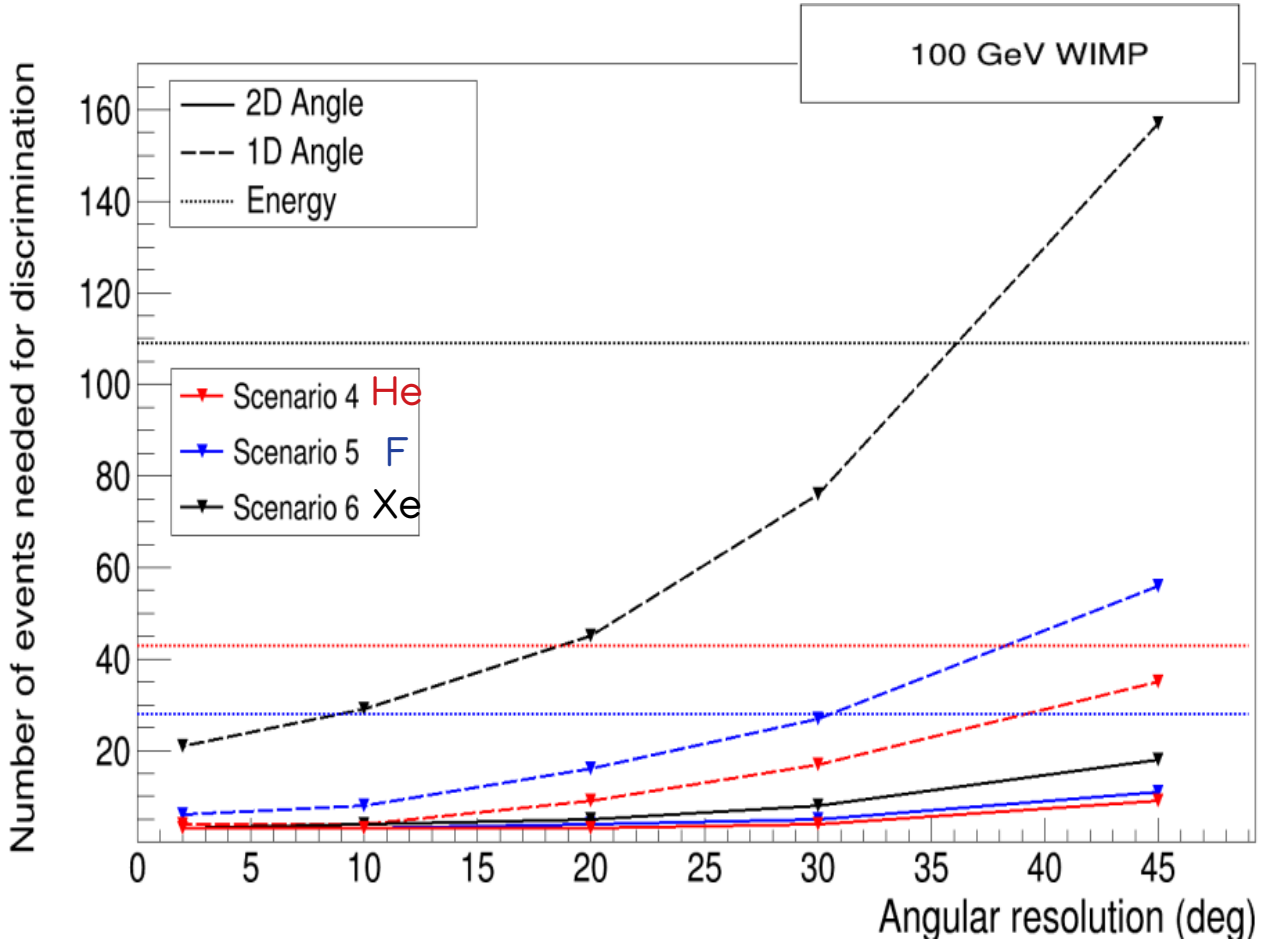
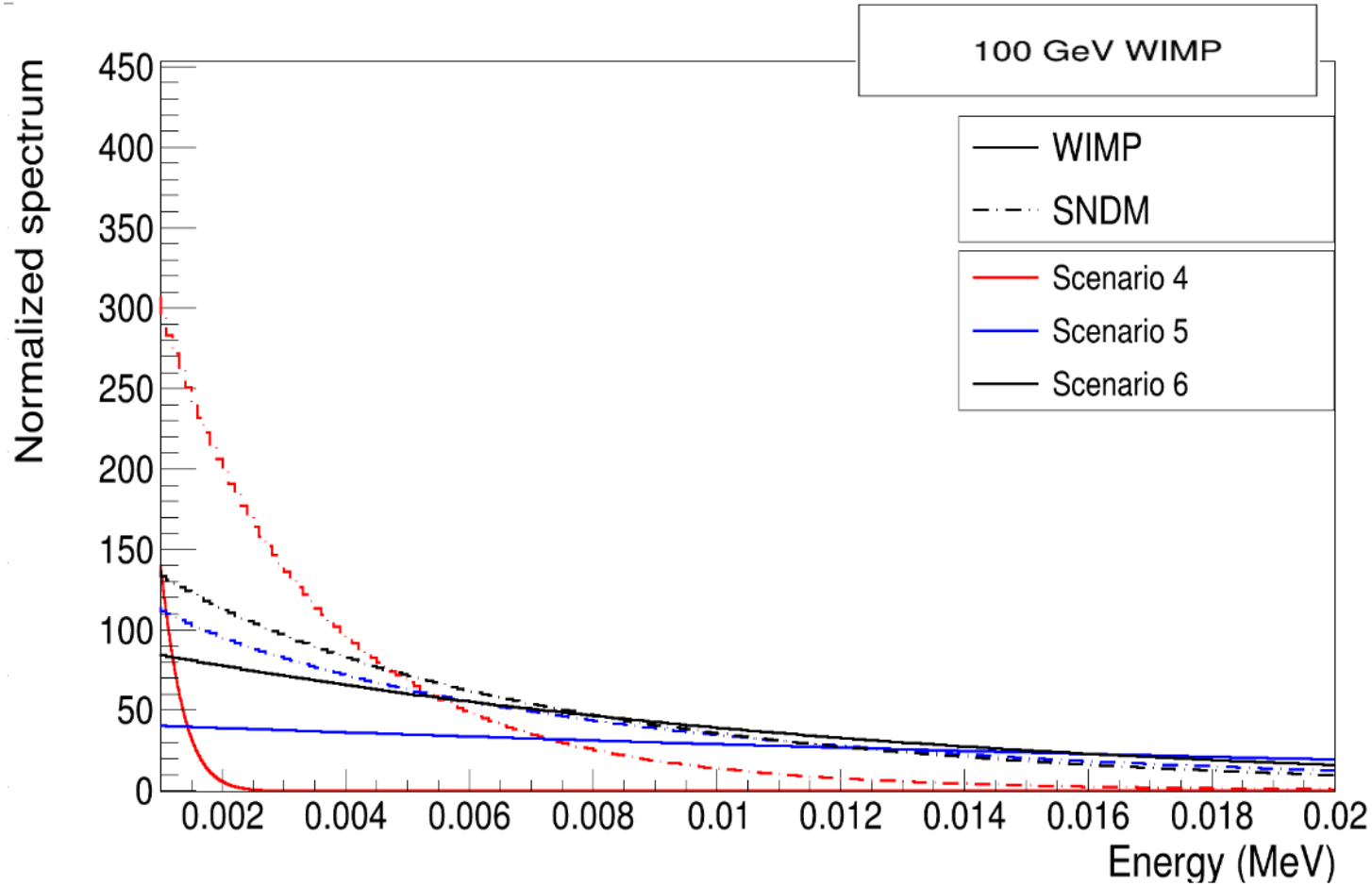
BACKUP

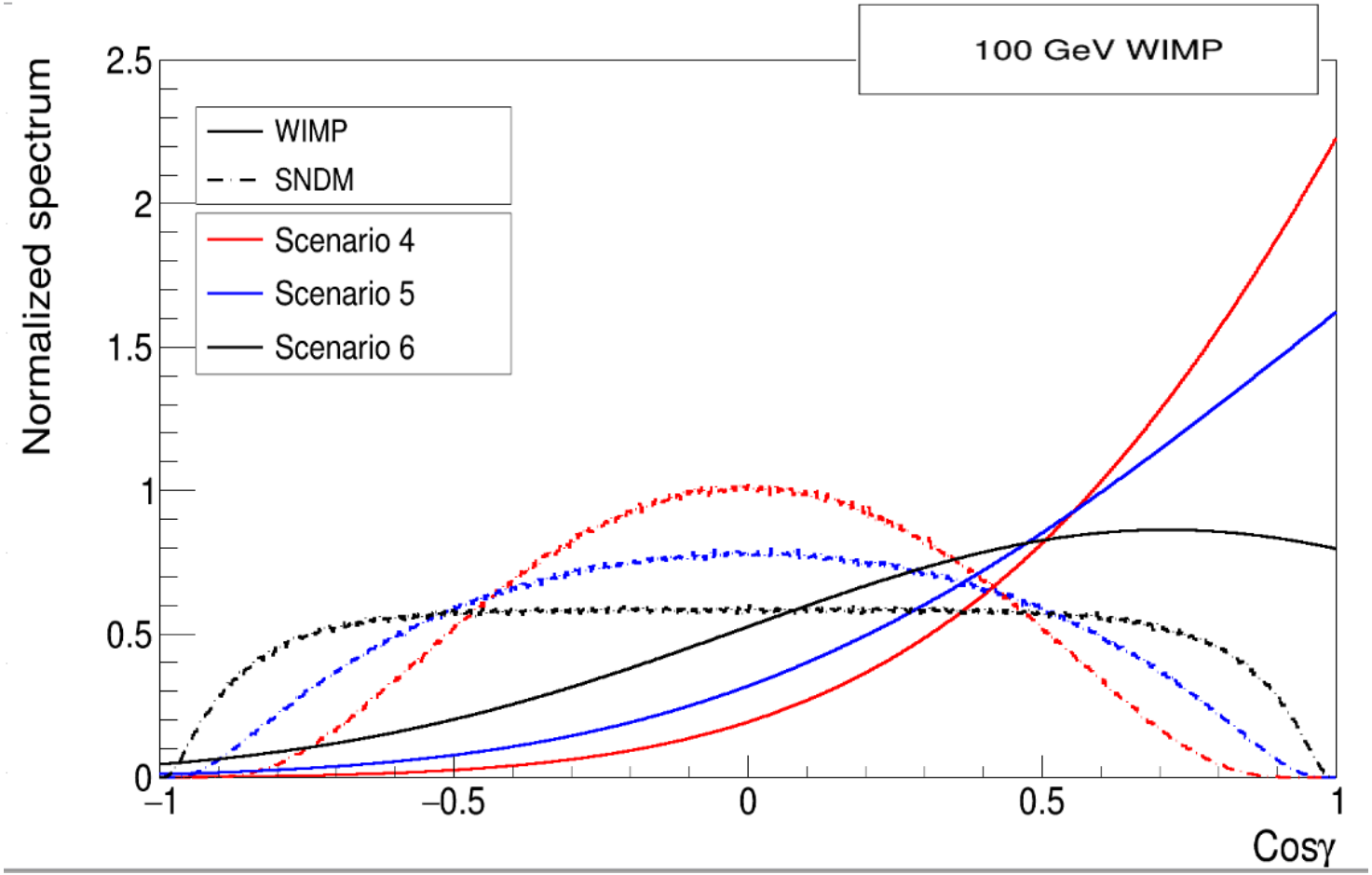
A&S: Results


100 GeV WIMP
2D Angle
1D Angle
Energy
Scenario 4 He
Scenario 5 F
Scenario 6 Xe
Number of events needed for discrimination
Angular resolution (deg)
0
5
10
15
20
25
30
35
40
45
20
40
60
80
100
120
140
160

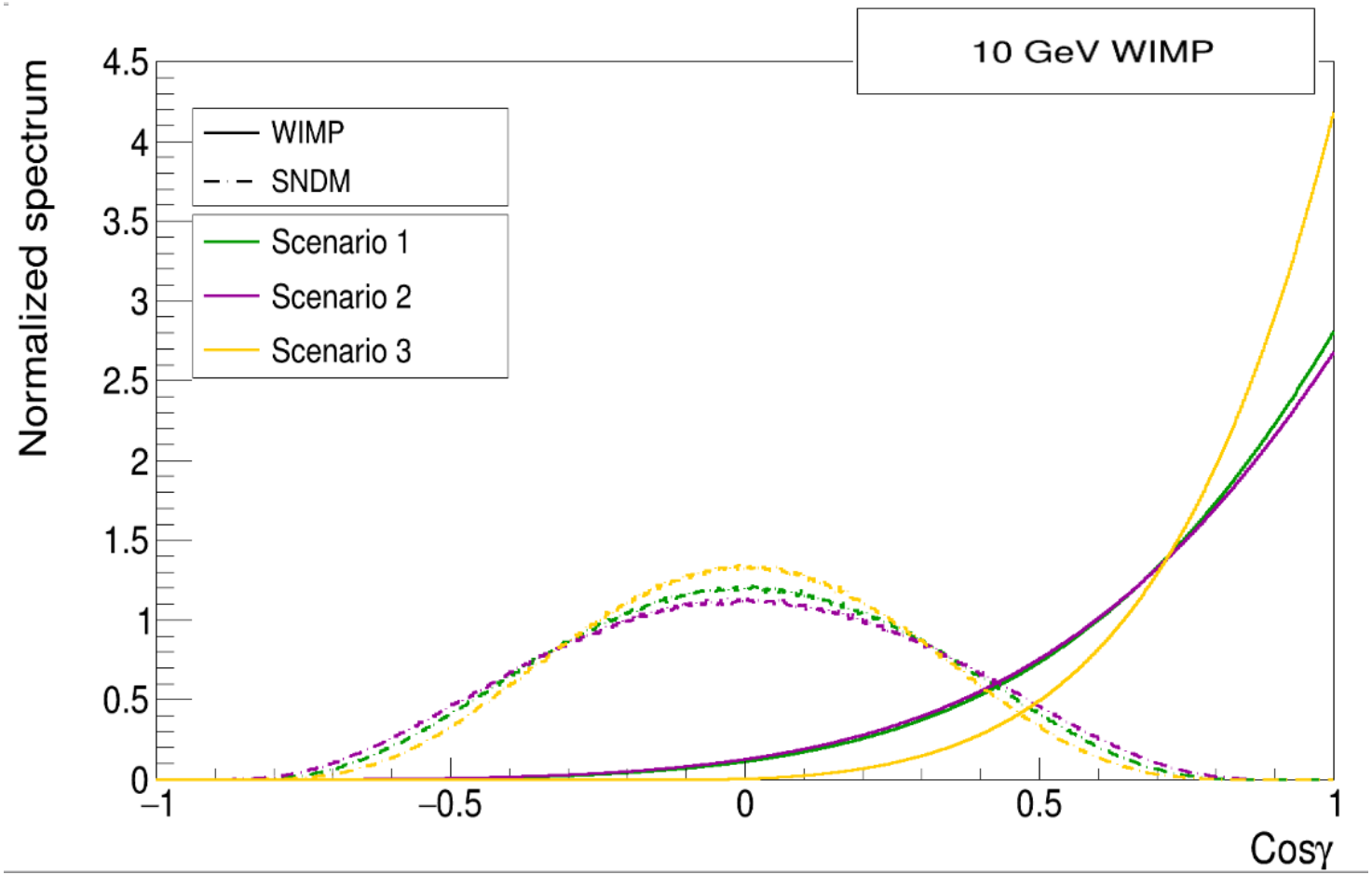
A&S: Results


100 GeV WIMP
WIMP
SNDM
Scenario 4
Scenario 5
Scenario 6
Normalized spectrum
450
400
350
300
250
200
150
100
50
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
Energy (MeV)

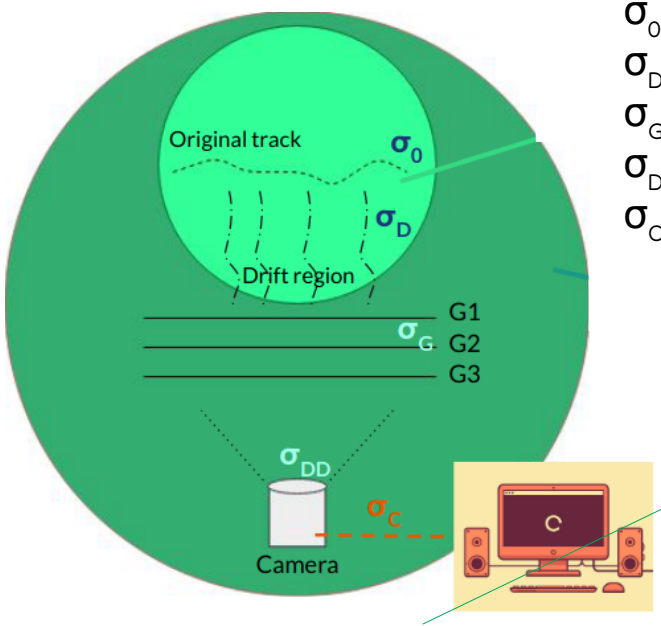
A&S: Results


100 GeV WIMP
WIMP
SNDM
Scenario 4
Scenario 5
Scenario 6
Normalized spectrum
2.5
2
1.5
1
0.5
0
−1
−0.5
0
0.5
1
Cosγ

A&S: Results

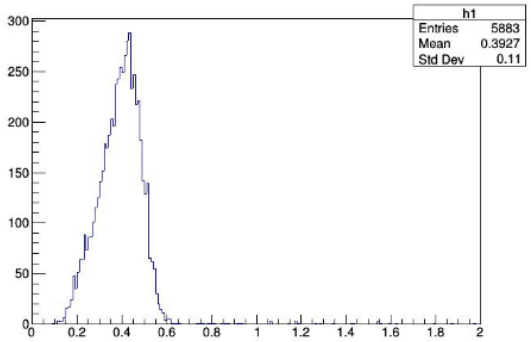

10 GeV WIMP
WIMP
SNDM
Scenario 1
Scenario 2
Scenario 3
Normalized spectrum
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
−1
−0.5
0
0.5
1
Cosγ

ES: Contribution of Diffusion of GEMs



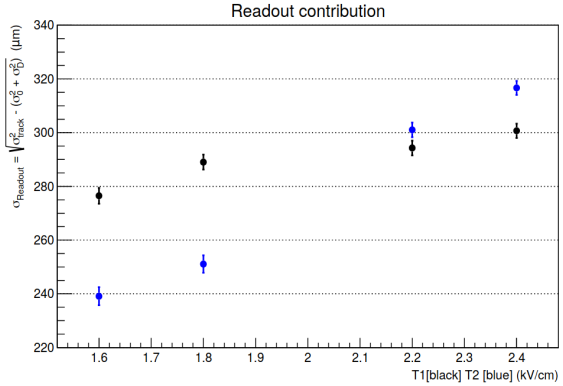
σ_0 original dispersion
σ_D Diffusion contribution
σ_G GEM contribution
σ_{DD} Light translation contribution
σ_C Clustering contribution

Simulated by Garfield++



$$\sigma_{track} = \sqrt{\sigma_0^2 + \sigma_D^2 + \sigma_G^2 + \sigma_{DD}^2 + \sigma_C^2}$$

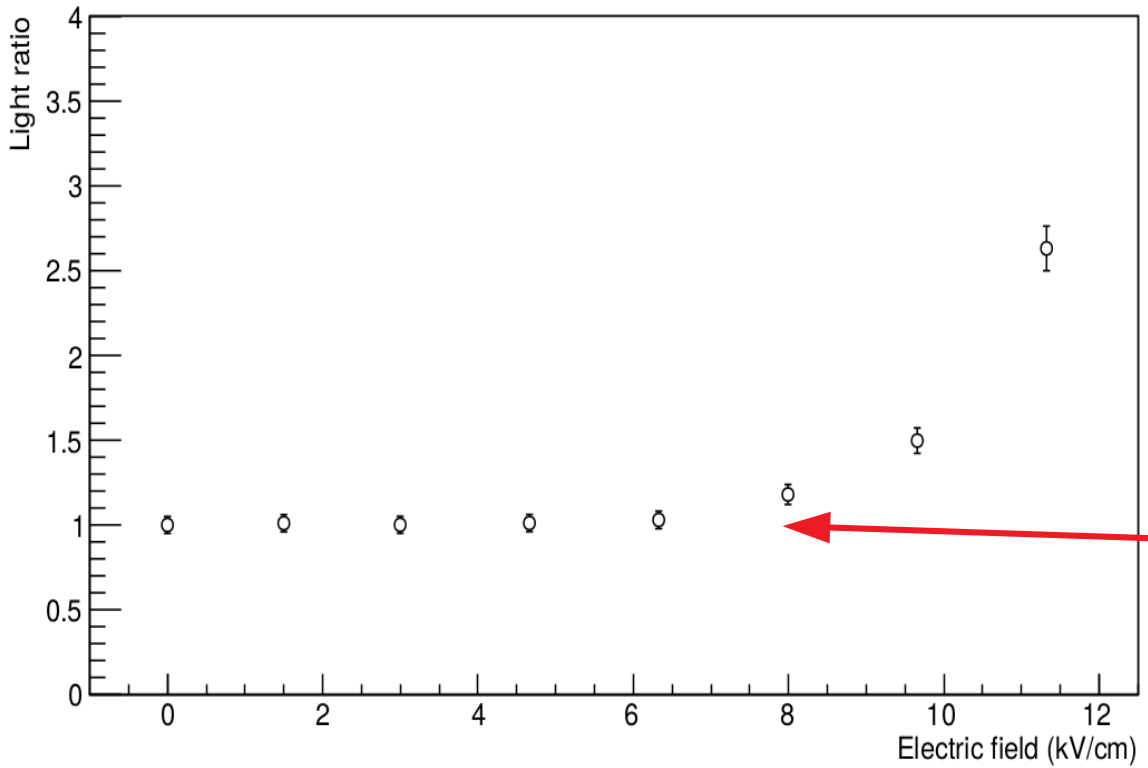
Data varying transfer field



The average peaks
At **300 µm**

ES: Light Measurements

- Analysing the various electric fields applied it is visible a clear influence on the photon yield



Increase in light appears around the same E

A&S: Statistical Framework

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$$L_{x,H_i} = \mu! \times \prod_{j=1}^{N_{bin}} \left[P_{j,H_i}^{n_j} \frac{1}{n_j!} \right] \qquad \lambda_x = \frac{L_{x,H_1}}{L_{x,H_0}}$$

ln(λ)

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  - The discrimination criterion is applied to the distributions of λ

Error type I and II both at 5% or less