CYGNUS Studies of Angular Resolution of Electron Recoils in Gas

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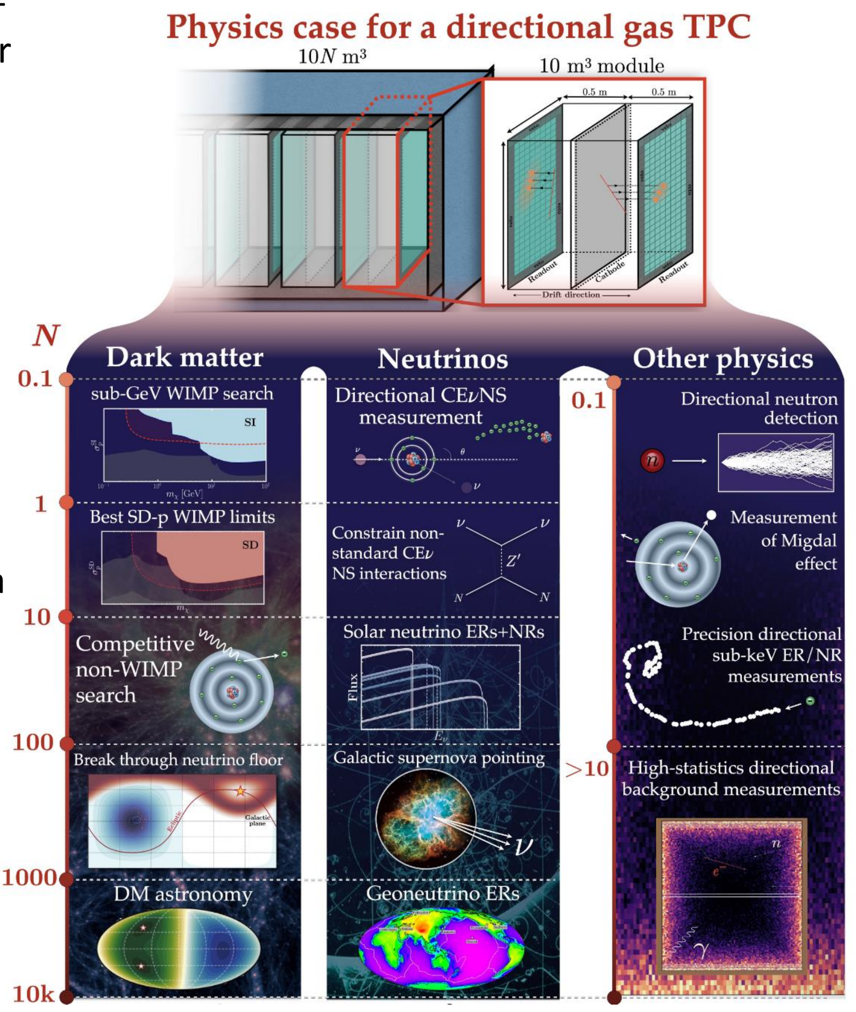
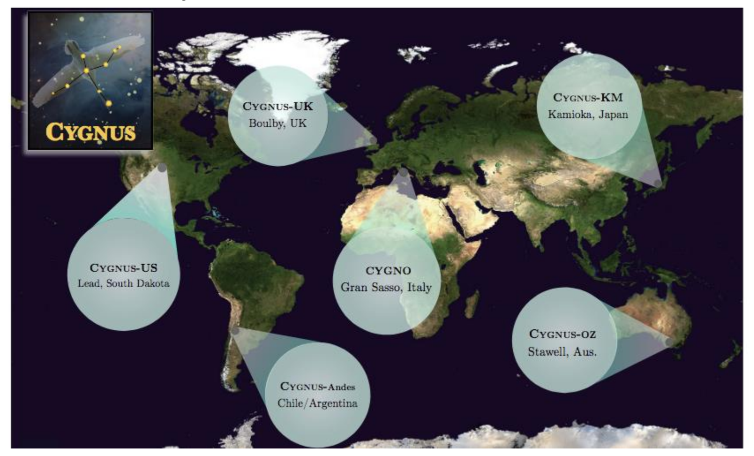
The CYGNUS Collaboration and Directional Recoil Detection

- The CYGNUS Collaboration aims to construct a ton-scale directional dark matter and neutrino detector
- Gas time projection chambers are capable of reconstructing the topology and direction of low-energy nuclear and electron recoils
- A modular, multi-site observatory is envisioned to reach ton-scale target mass with gas
- A rich, long-term physics program is foreseen
- 55 members from US, UK, Japan, Italy, Spain, China
- 6 US faculty members are involved.

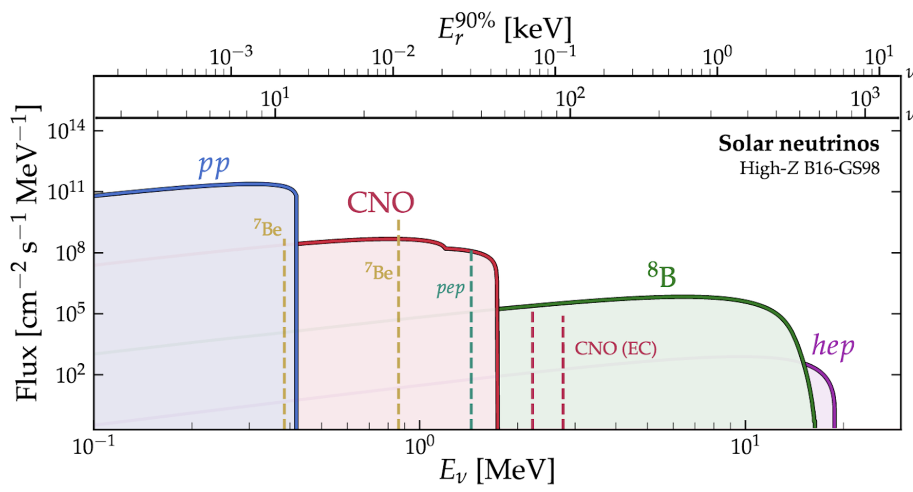




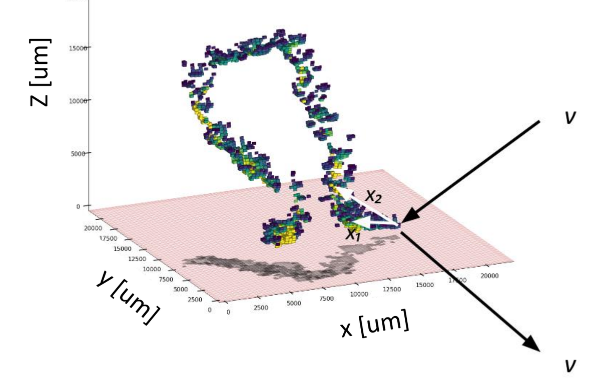
S. E. Vahsen et al., *Directional Recoil Detection*, Annu. Rev. Nucl. Part. Sci.

Solar Neutrinos and Electron Recoils

- A firm measurement of the **CNO** flux can resolve a disagreement between two models for the Sun's heavy element content
- The **electron recoil** channel is particularly promising because the kinematics result in higher recoil energies at a given neutrino energy
- Knowing the sun's position, alongside a measurement of **recoil energy and direction**, event-by-event reconstruction of the neutrino energy spectrum is possible
- Evaluating and optimizing the CYGNUS sensitivity to neutrinos requires a good understanding of the **detector's energy resolution** and the angular resolution of electron recoils.
- We know the **recoil energy** if the recoil track is fully contained. We want to know how well the **initial direction** can be determined
- Two main factors are **multiple scattering** and **point resolution**



Source: Ciaran A.J. O'Hare



(left) One of ten BEAST TPCs constructed by U. Hawaii (right) 3D ionization density distribution of an electron recoil event, measured with a BEAST TPC

I. Jaegle et al., *Compact, directional neutron detectors capable of high-resolution nuclear recoil imaging*, Nucl. Instrum. Methods A (2019)

Multiple Scattering: History

PDG Review of Particle Physics "Passage of Particles Through Matter"

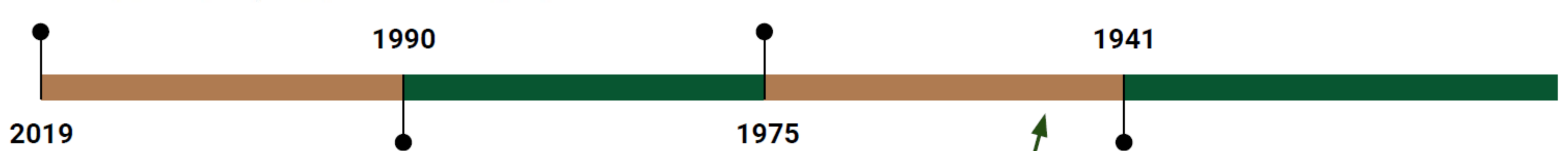
Multiple scattering through small angles

$$\sigma_\psi^{\text{plane}} = \frac{z}{\sqrt{3}}\frac{13.6\text{MeV}}{\beta cp}\sqrt{\frac{x}{X_o}}\left[1+0.038 ln(\frac{xz^2}{X_o\beta^2})\right]$$

Highland "Some Practical Remarks on Multiple Scattering"

Added a correction term and fit Rossi and Greisen's equation to approximations of Moliere Theory.

$$\sigma_\psi^{\text{plane}} = \frac{1}{\sqrt{3}}\frac{13.9\text{MeV}}{\beta cp}\sqrt{\frac{x}{X_o}}\left[1+0.048\ln(\frac{x}{X_o\beta^2})\right]$$



Lynch and Dahl "Approximations to multiple Coulomb Scattering"

Noted Highland didn't use Bethe's prescription of Moliere Theory. Refit the Highland's equation, specifying the fit is for heavy particles.

$$\sigma_\psi^{\text{plane}} = \frac{z}{\sqrt{3}}\frac{13.6\text{MeV}}{\beta cp}\sqrt{\frac{x}{X_o}}\left[1+0.038 ln(\frac{xz^2}{X_o\beta^2})\right]$$

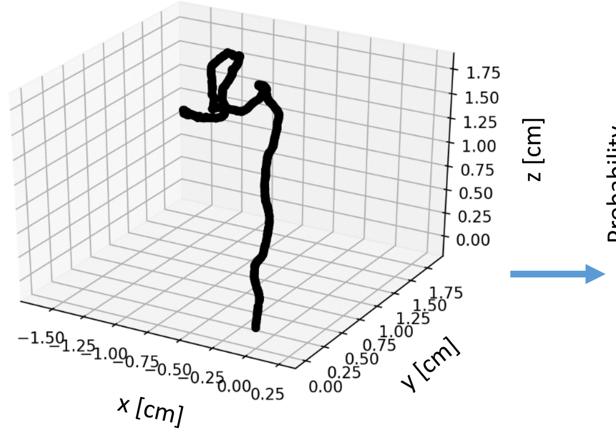
Moliere Theory: Moliere (1947) Bethe (1953)

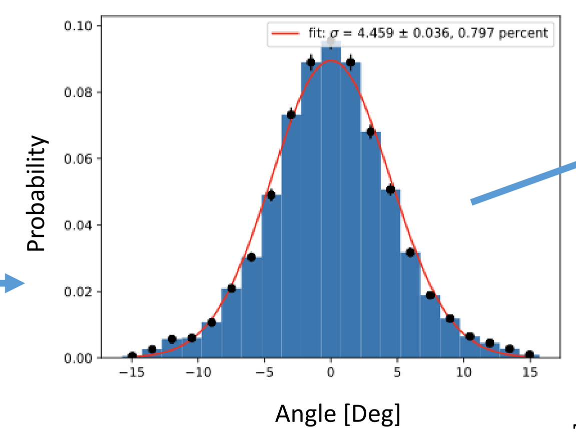
Rossi and Greisen "Cosmic-Ray Theory"

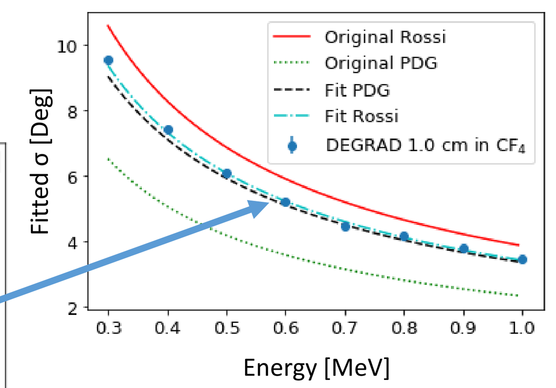
Derived first simple gaussian approximation of multiple scatter via statistical methods.

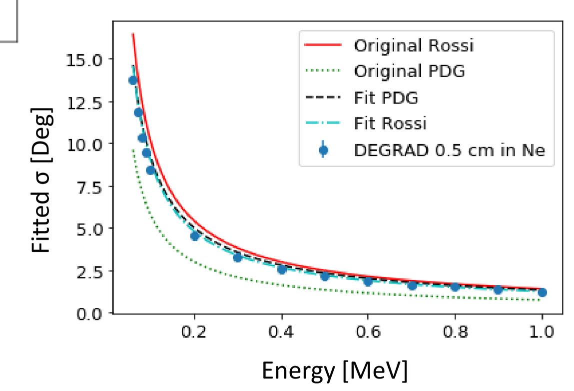
$$\sigma_\psi^{\text{plane}}(x) = \frac{1}{\sqrt{3}}\frac{14.8\text{MeV}}{\beta cp}\sqrt{\frac{x}{X_o}}$$

Multiple Scattering: Fitting the models









Electron recoil simulations

Gases: CF_4, CO_2, CH_4, C_2H_6, Ne, Ar, Xe

Energies: 100 - 1000 keV

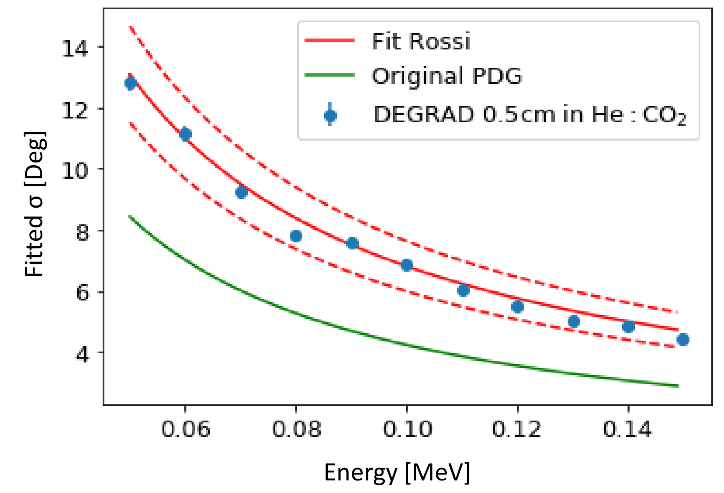
Length: 0.5 – 2.0 cm

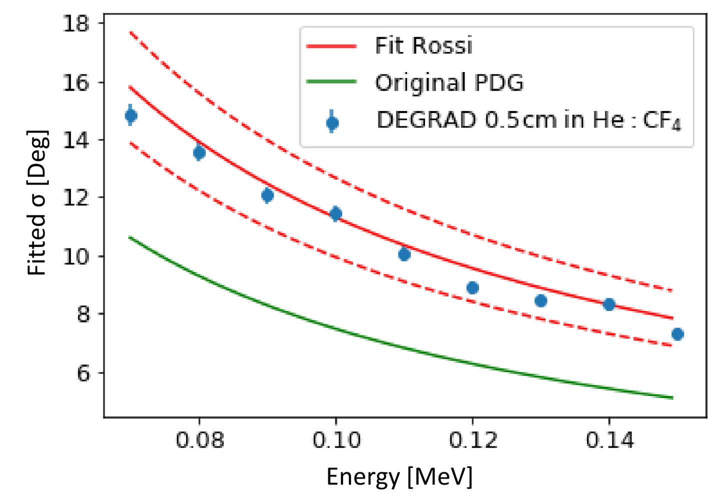
Multiple Scattering: Testing Fit on new Mixtures

Gas Mixture	Pressure	Rad. Length
60% He 40% CF_4	760 torr	220 m
70% He 30% CO_2	760 torr	606 m

The Lynch and Dahl equation quoted in the PDG is not accurate for electron recoils in gas

$$\sigma_\Psi^{\text{plane}}(x) = \frac{1}{\sqrt{3}}\frac{13.1\text{MeV}}{\beta cp}\sqrt{\frac{x}{X_o}}$$





Point Resolution

- We also need to include the effect of detector point resolution on electron recoil angular resolution.
- This is give by: $$\sigma_\phi^{\text{plane}} = \frac{\sqrt{12}\sigma_{x/y/z}}{L\sqrt{N}}$$

S.E. Vahsen et al., *3-D tracking in a miniature time projection chamber*, Nucl. Instrum. Methods A (2014)

- We combine point resolution and multiple scattering effects in quadrature

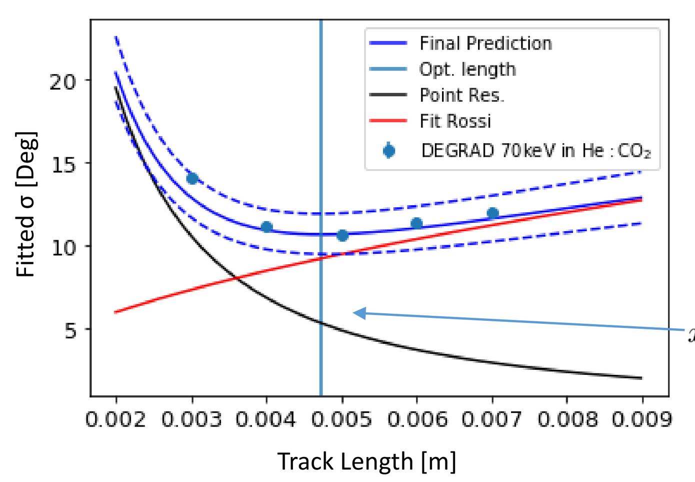
Results

$$\sigma_\Psi^{\text{plane}}(x) = \sqrt{a^2x + b^2x^{-3}}$$

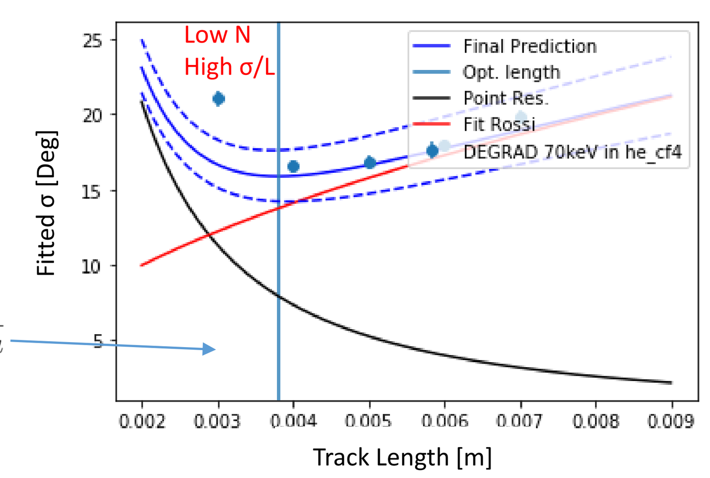
$$a \equiv \frac{1}{\sqrt{3}}\frac{13.1\text{MeV}}{\beta cp\sqrt{X_o}} \qquad b \equiv \sigma_{x/y/z}\sqrt{\frac{12W}{dE/dx}}$$

- Our formula estimate the angular resolution of electron recoils given the recoil energy and gas properties (W, X_o, dE/dx, $\sigma_{x/y/z}$)
- The optimal track and the angular resolution near the optimal length are well predicted

70 keV electron recoils in 70% He 30% CO_2



70 keV electron recoils in 60% He 40% CF_4



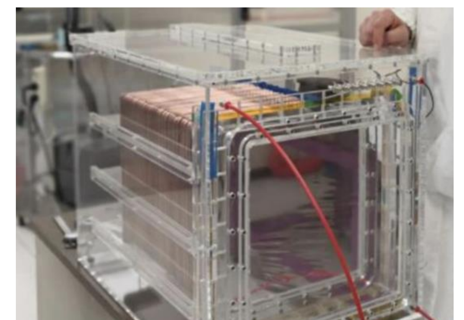
$x_o = 3^{\frac{1}{4}}\sqrt{b/a}$

Outlook

- We are currently recording high-resolution 3D electron recoil data with the BEAST TPCs to validate our findings
- Our methodology will then be used to evaluate the CYGNUS physics reach with electron recoils
- This will include optimizing the detector segmentation and gas mixture specifically for detection of electron recoils.

Complementary Results from CYGNO

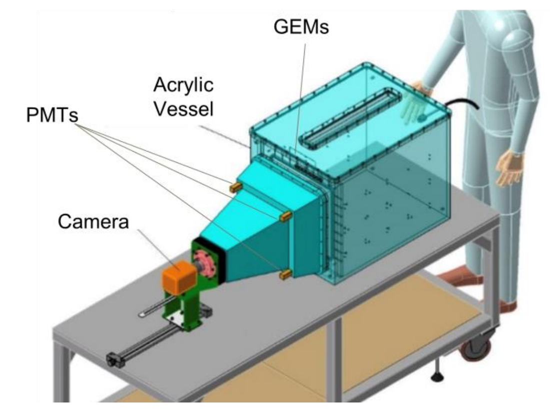
The CYGNO collaboration has independently developed full simulations and alternative analysis techniques for their optical-readout TPCs. Their findings can be used to cross-check our results, and there seems to be good agreement. Qualitatively their results appear consistent with our formulae. Detailed quantitative comparison are ongoing.



F. D. Amaro et al., *The CYGNO Experiment*, Instruments (2022)

The Lime Prototype

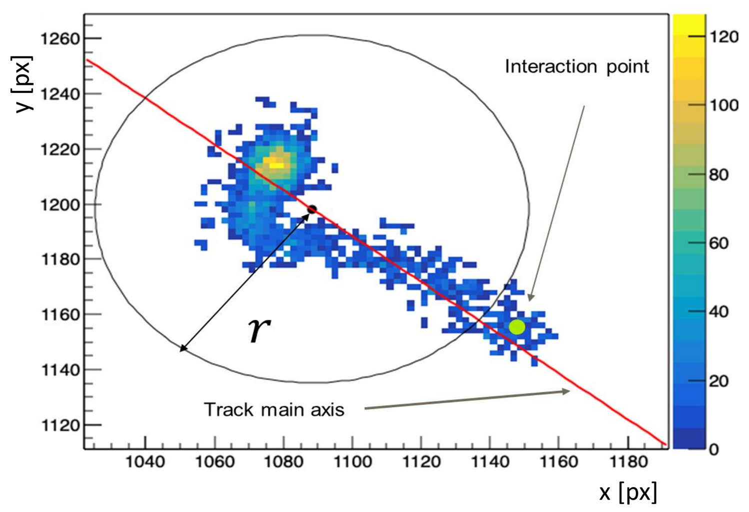
- CYGNO PHASE_1 O(1) m3 demonstrator (funded) will be based on readout modules having the LIME dimensions and layout
- Installed at underground Laboratori Nazionali del Gran Sasso in March 2022, under commissioning
- 50 cm drift length, 33 x 33 cm^2 triple thin GEMS, 50 L sensitive volume
- 60:40 He:CF4 at atmospheric pressure
- sCMOS Camera (Hamamtsu ORCA Fusion), 4 PMTs
- 2304 x 2304 pixel images with 151 x 151 um^3 granularity



Directionality fitting algorithm on Simulation

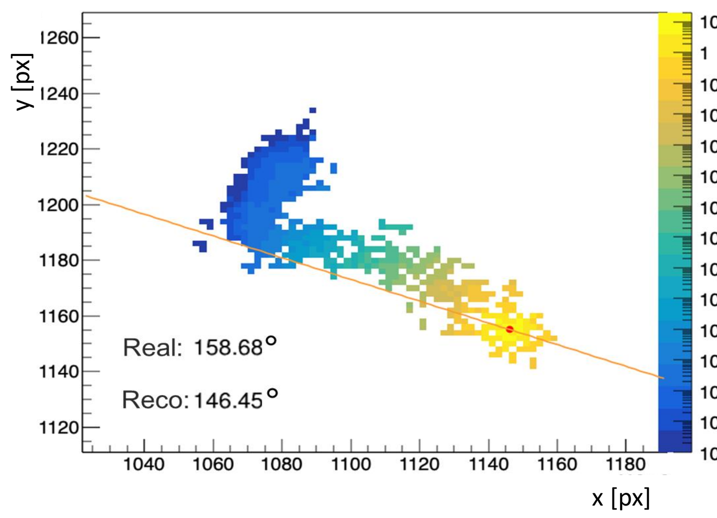
Simulations:

- Electron recoils simulated in GEANT4
- Angular resolution evaluated on MC simulated sCMOS images that take into account GEM gain fluctuations, photon production, sensor calibration and diffusion during drift as evaluated on LIME. PMT waveforms information can further improve this scenario (on going work)

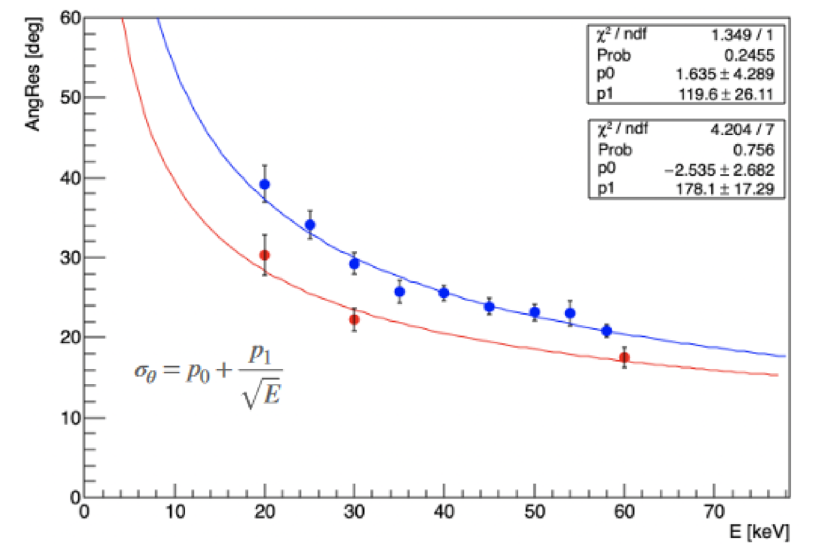


Fitting Algorithm:

1. Determine beginning of track
   - Find barycenter
   - Determine r s.t. $\mathbf{N_{pt}}$ points are contained
   - Remaining region in the interaction region
   - Interaction point is the barycenter of the interaction region
2. Determine direction
   - Point weights are rescaled w.r.t. distance from interaction point: W = exp(-d_{ip} / **w**)
   - Direction is principle axis of the reweighted track



- Worst case scenario: Isotropic tracks at random diffusion
- Averaged ideal scenario: Tracks produced long positive x direction with 25 cm diffusion



Acknowledgements

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