Feasibility of solar neutrino measurement with the CYGNO/INITIUM experiment

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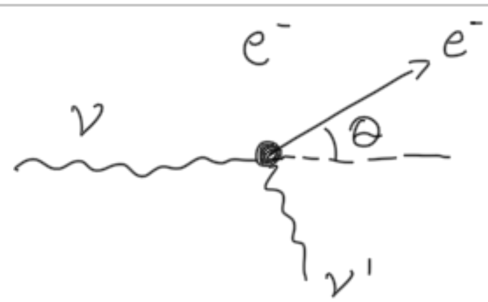
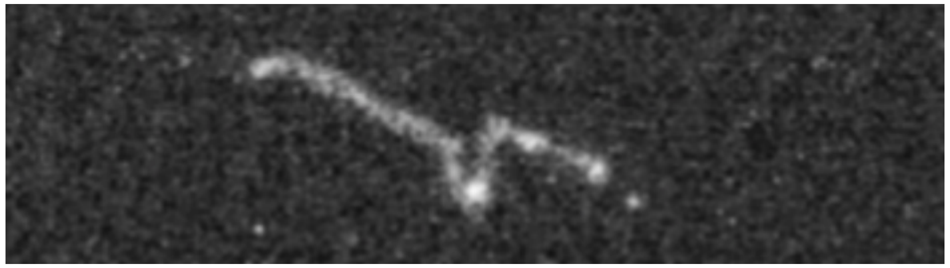
CYGNO Meeting - 21/11/2021

Solar neutrino with CYGNO/INITIUM



- Neutrino from the sun can be object of study with large TPC through $\nu - e^-$ scattering as proposed in '90:
  Seguinot, Jacques & Ypsilantis, Thomas & Zichichi, Antonino. (1992). A high rate solar neutrino detector with energy determination.



Electron track detected with CYGNO/INITIUM sCMOS

- Directional detection→ capability of discriminating particles from different sources through directionality

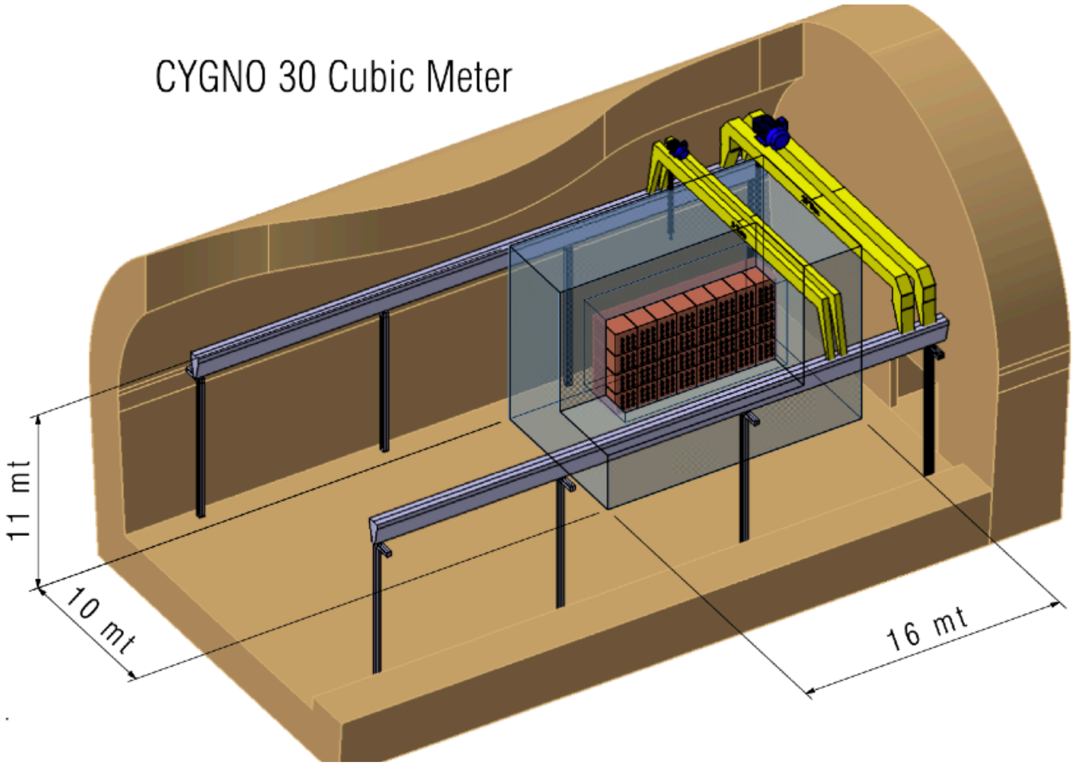
- Fixed kinematic relationship between the neutrino energy, recoil energy, and scattering angle: a directional measurement allows the event-by-event reconstruction of the initial neutrino Energy

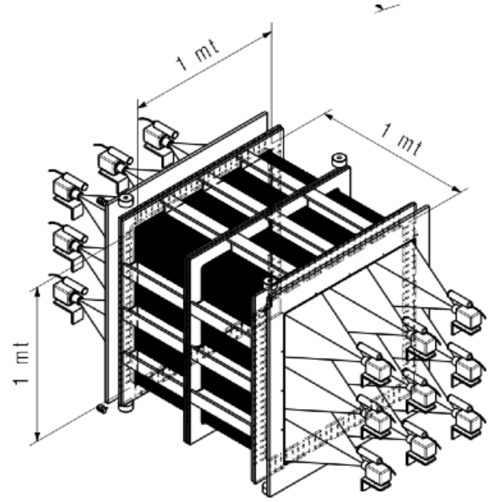
- Expected rate @ 1 atm: $R = N_e \sum_i \varphi(E_i)(P_{ee}\sigma_{\nu_e}(E_{\nu,i}) + P_{e\mu}\sigma_{\nu_\mu}(E_{\nu,i}))\Delta E = 2.9 \cdot 10^{-8} \frac{events}{s \cdot m^3} = \boxed{0.9 \frac{events}{y \cdot m^3}}$

- With a CYGNO PHASE 2 detector of $30\ m^3$ active volume we expect: ~ 90 events in $3\ y$

- The goal of my research is to establish the exposure needed to claim detection of solar neutrino with a CYGNO PHASE 2 detector, and therefore demonstrate the feasibility of solar neutrino spectroscopy with this TPC technology

CYGNO 30 Cubic Meter





CYGNO 1 Cubic Meter

Evaluation of expected angular distribution

1. Random neutrino energy from the flux extracted, with random $\cos\theta$ value according to the differential cross section

$$T'_e(\theta) = \frac{2E_\nu^2 m_e cos^2(\theta)}{(E_\nu + m_e)^2 - E_\nu^2 cos^2(\theta)}$$

2. Calculation of the e^- kinetic energy given E_ν and $\cos(\theta)$ $\rightarrow$ kinematic closed

3. Smearing of energy and angle according to the resolutions:

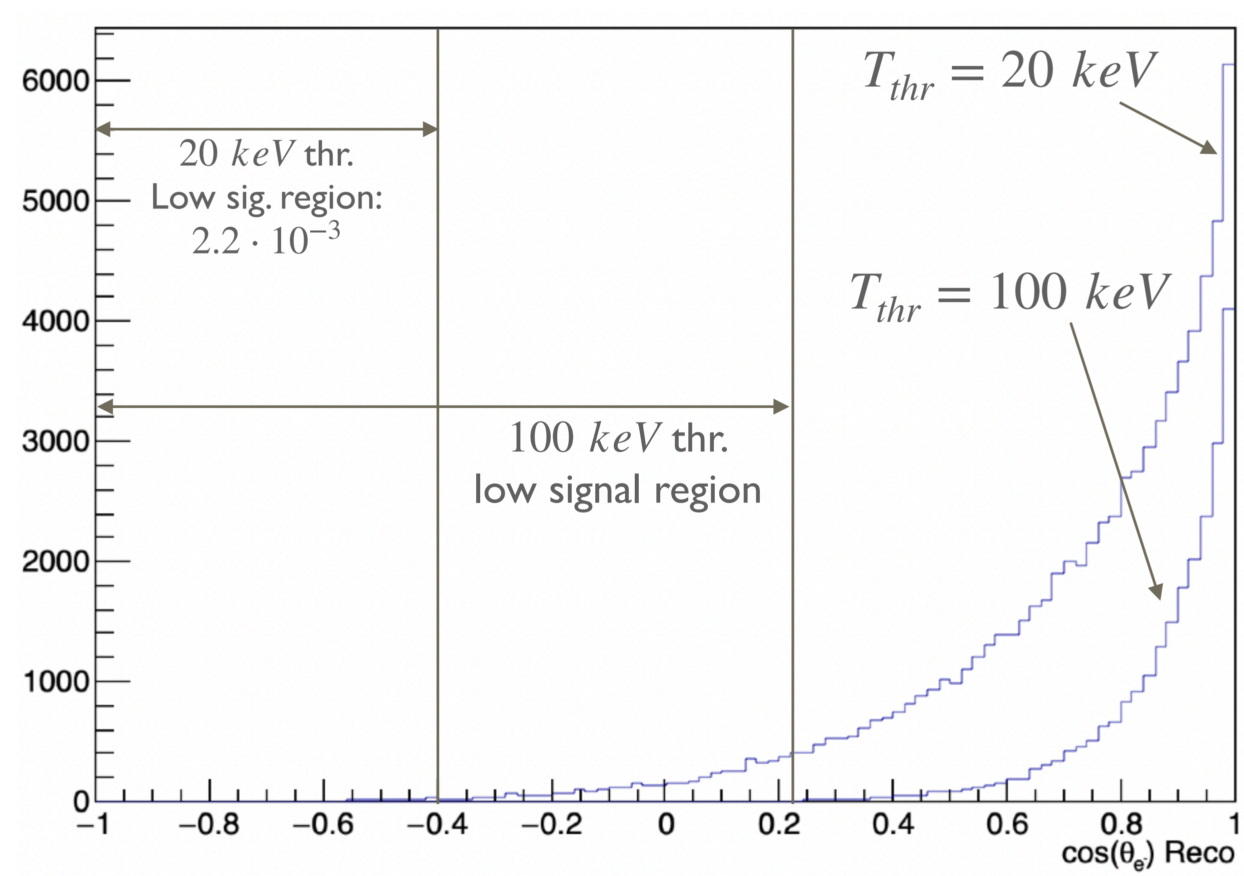
$$\frac{\sigma_E}{E} = \sqrt{4.33 + \frac{1890}{E}} \qquad \sigma_\theta = 0.3490 = 20^\circ$$

(Realistic resolutions for gas detector)

4. Reconstruct the energy of the neutrino with E_{e^-} and $\cos\theta$ smeared

$$E_{\nu,Reco} = \frac{-m_e T_e - \sqrt{T_e^2 m_e^2 \cos(\theta)^2 + 2T_e m_e^3 \cos(\theta)^2}}{(T_e - T_e\cos(\theta)^2 - 2m_e\cos(\theta)^2)}$$

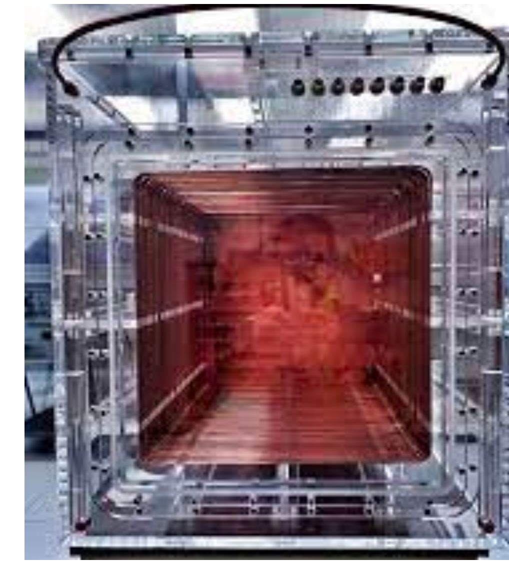
- $\cos(\theta)$ distribution for two different threshold: $20 - 100\ keV$ (E_ν 80-220 keV)
- Very low signal regions available for background characterisation
- With 100 keV threshold sharper peak but $R \sim 0.3\ ev/(m^3 \cdot y)$



Study of low-energy electron directionality performances

Track images production

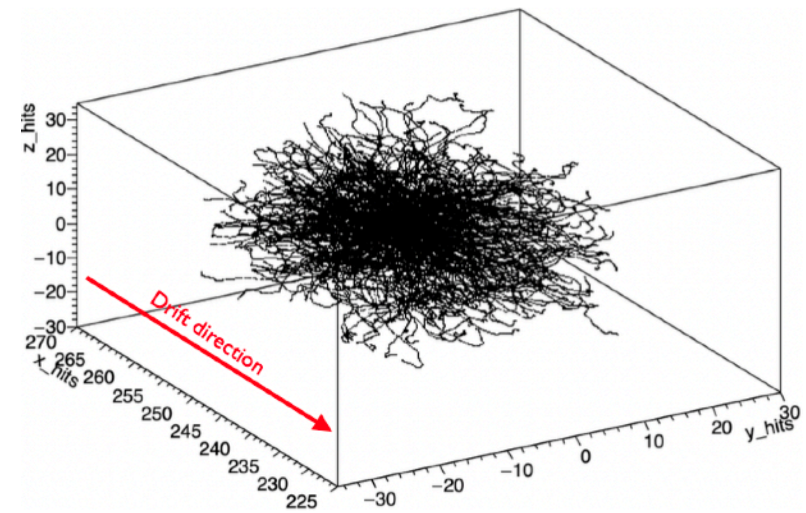
LIME



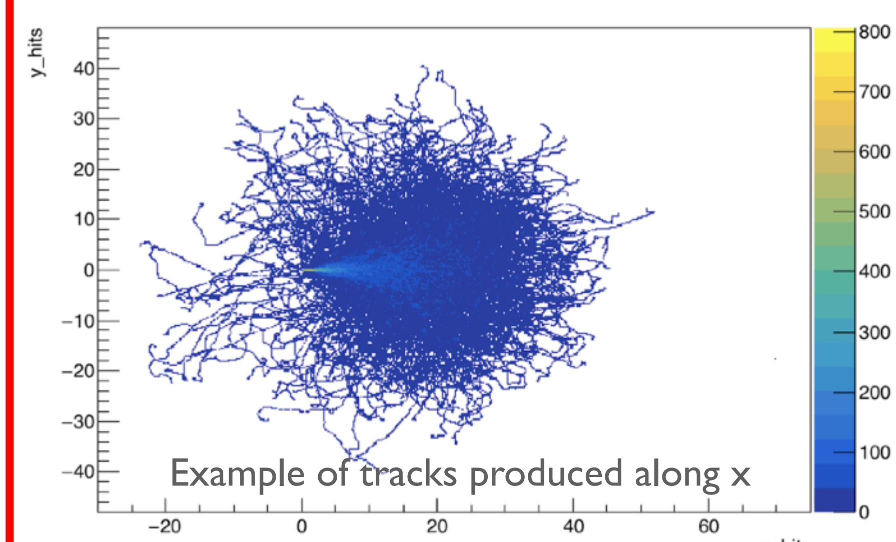
- Tracks imaged are produced as they would appear in the CYGNO PHASE I and PHASE II with module:
  - 50 cm drift length
  - 33x33 cm^2 readout area
  - Triple GEM amplification
  - Light collected by sCMOS + 4 PMTs

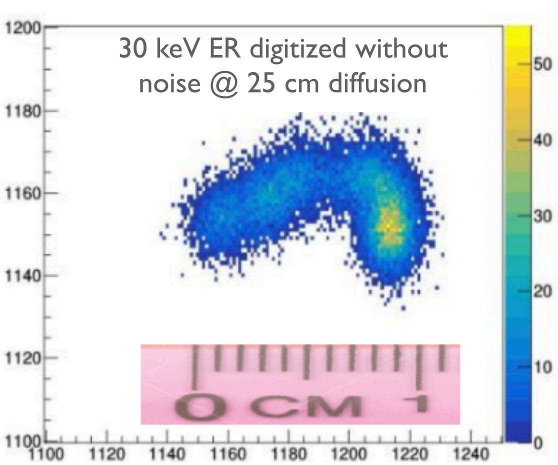
- Electron tracks produced using GEANT4 at the center of the detector in He:CF_4 60:40 at 1 atm

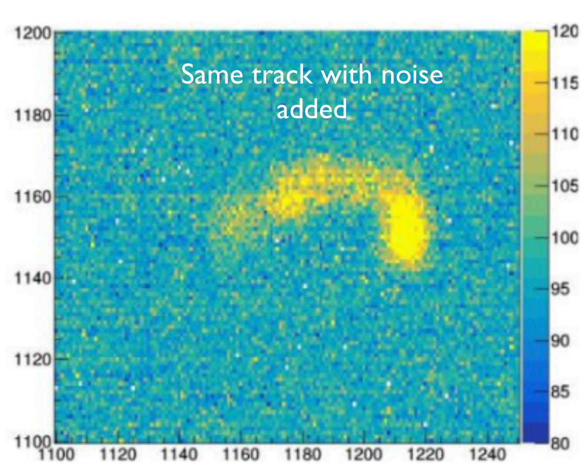
- Tracks are then digitized in images simulating
  - Fluctuation in primary ionization
  - GEM gain and light production variation
  - sCMOS granularity and solid angle
  - Carriers diffusion (at random Z for each track)
- Noise from real pedestal is superimposed



Tracks backscatter, not trivial to determine the direction

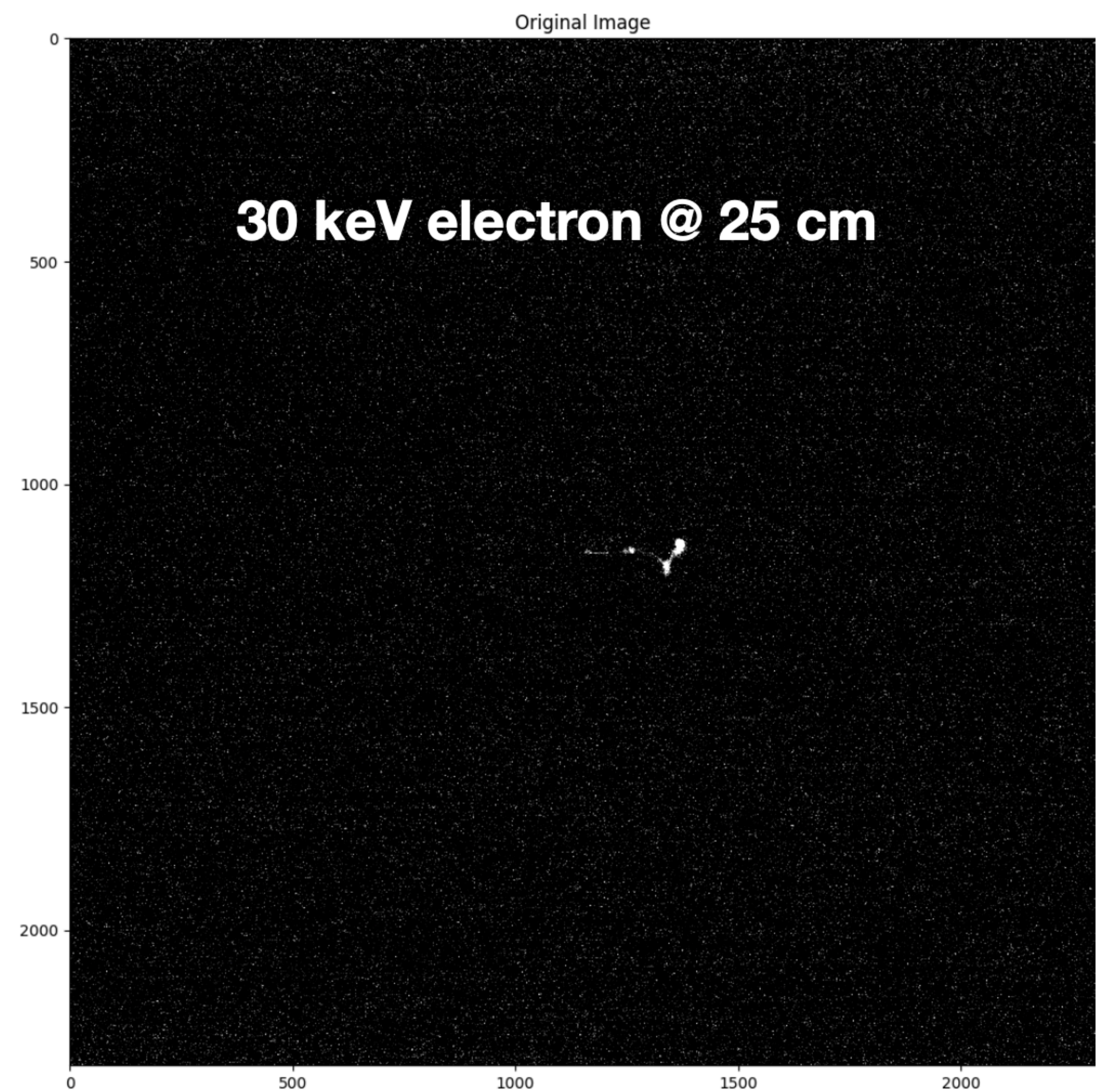






Dataset

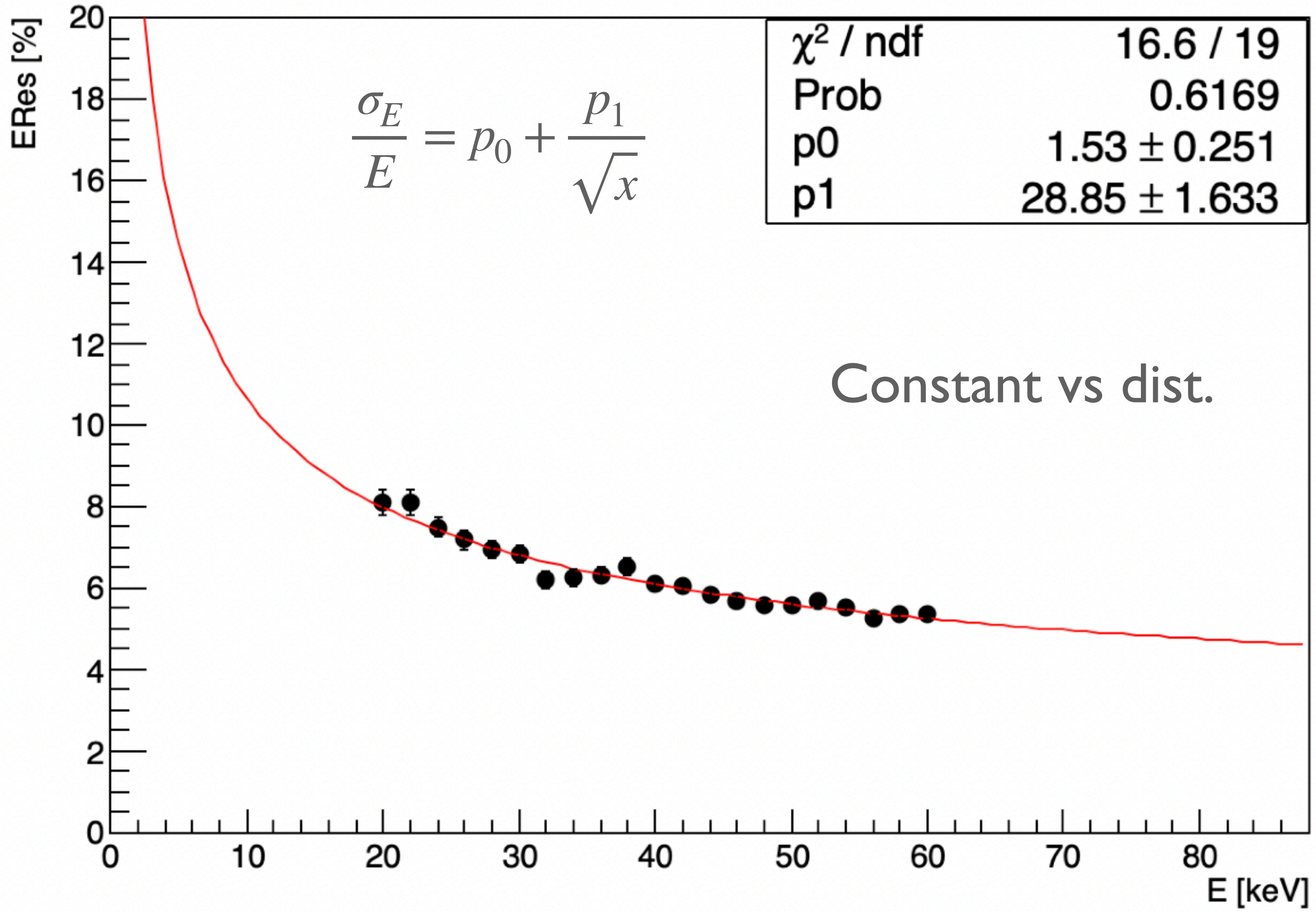
- Electrons generated at the center of the detector
- 1 track per event
- Angular distribution isotropic on theta and phi, with original information saved
- Electron energies simulated in range [20-60] keV with step of 2 keV
- Diffusion simulated uniform in 5-45 cm



- All tracks reconstructed with lime2021 (Chan-Vese version) using same reconstruction algorithm parameters for all energies

Reconstruction efficiency and energy resolution

- Reconstruction efficiency @ E>20 keV =100%
- Capability of reconstructing the whole track >99% below 50 keV, 95% and 90% at 50 and 60 keV

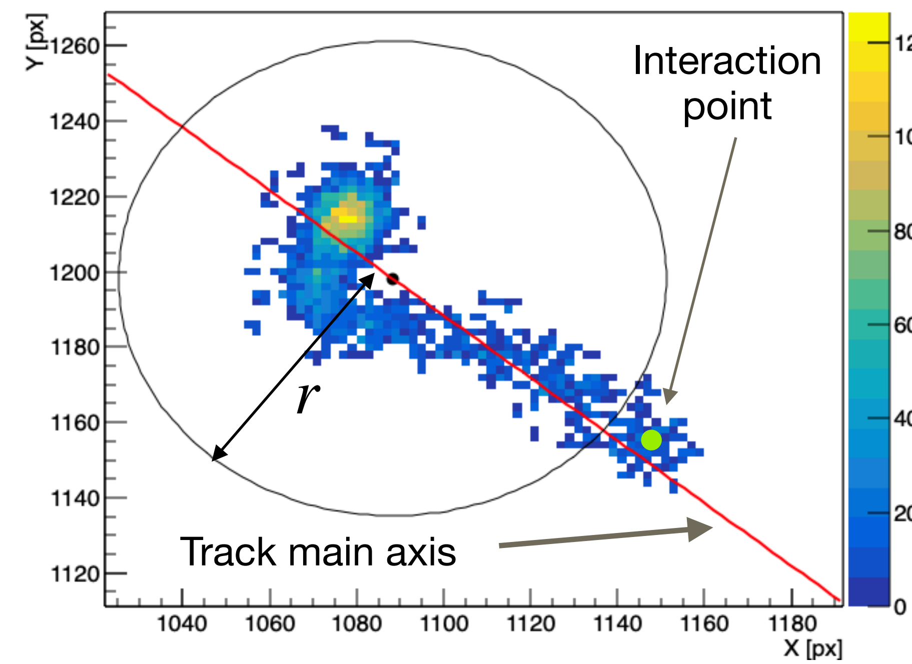


- Data-Montecarlo comparison in progress with tracks from different radioactive sources
- Once track energy is known the directionality algorithm parameters can be optimised for the energy

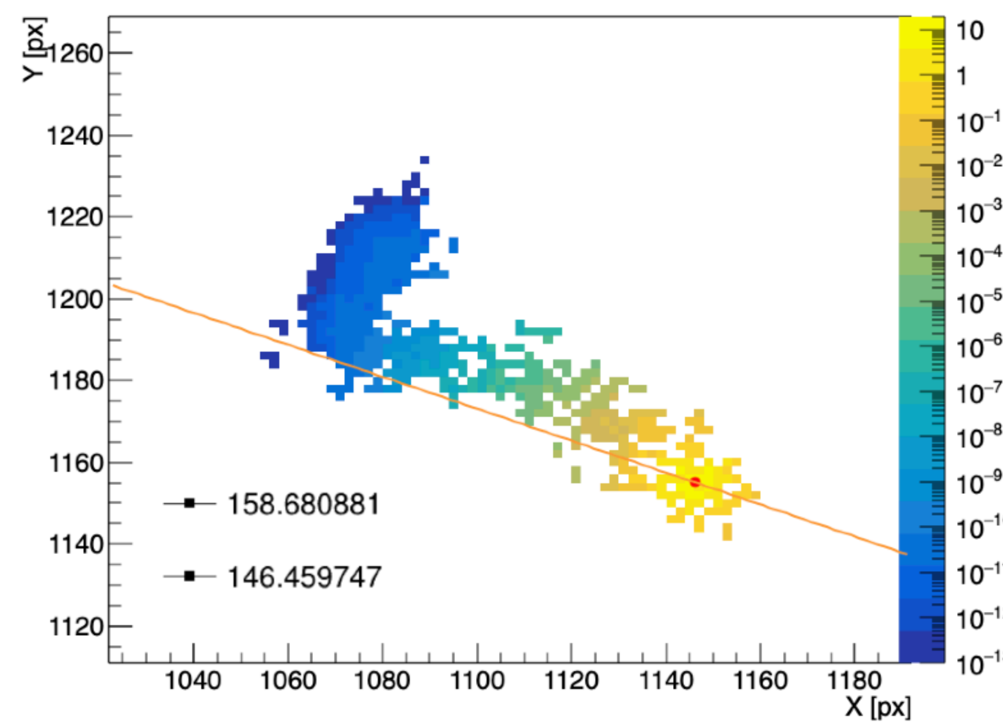
The directionality algorithm in a nutshell

- Algorithm adapted from X-ray polarimetry:

"Measurement of the position resolution of the Gas Pixel Detector"
Nuclear Instruments and Methods in Physics Research Section A, Volume 700, 1 February 2013, Pages 99-105



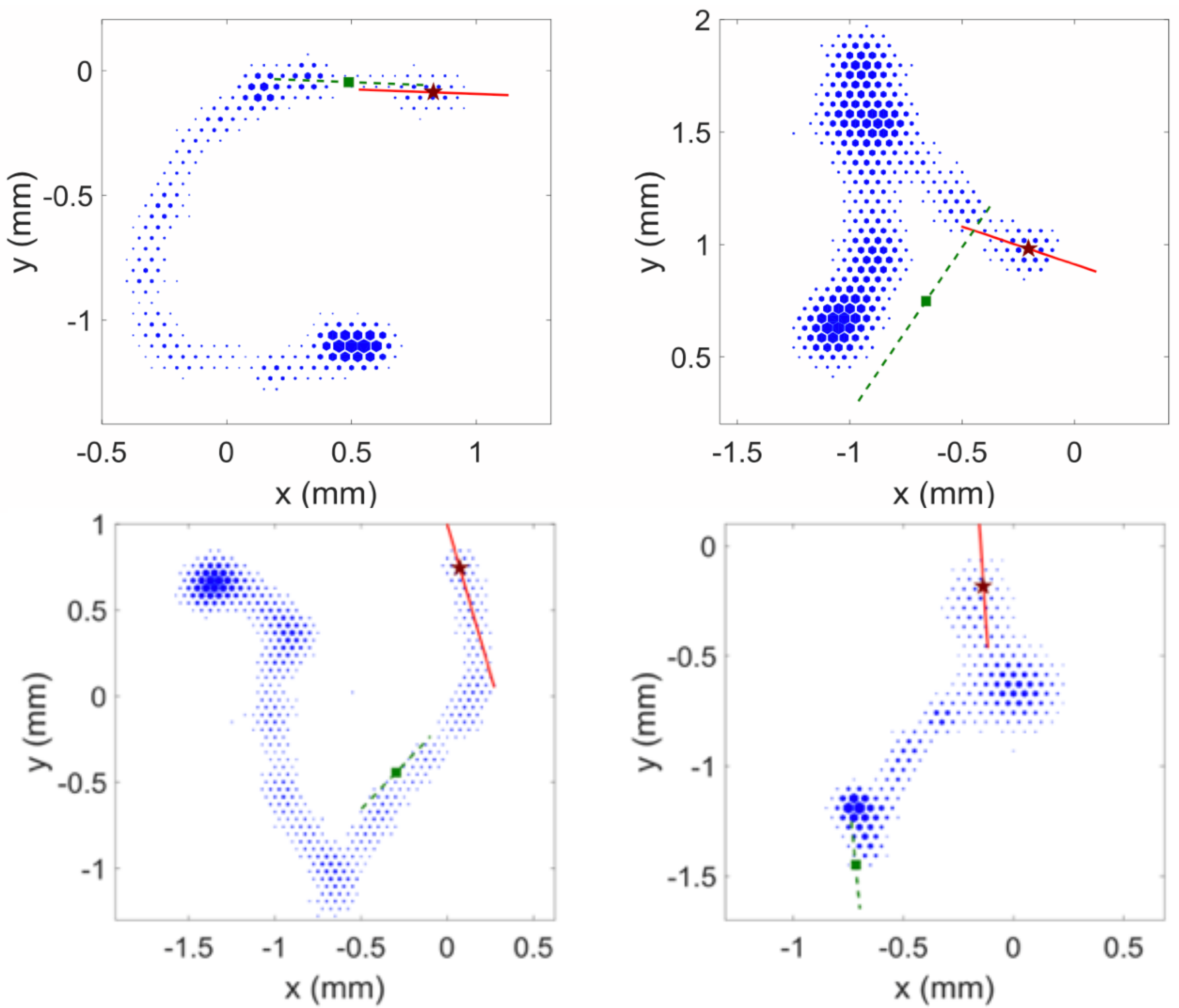
- First part of the algorithm: searching for the beginning of the track with:
  - Skewness
  - Distance of pixels from barycenter (farthest pixels)
  - Selection of a region with fixed number of points N_{pt}



- Second part of the algorithm aims to find the direction:
  - Track point intensity rescaled with the distance from the interaction point: $W(d_{ip}) = exp(-d_{ip}/w)$
  - Direction taken as the main axis of the rescaled track passing from the interaction Point
  - Orientation given following the light in the Pixels

When the algorithm fails

★ Real interaction point
Calculated interaction point



+

Cases in which the track is parallel to the GEM for lack of 3Dness

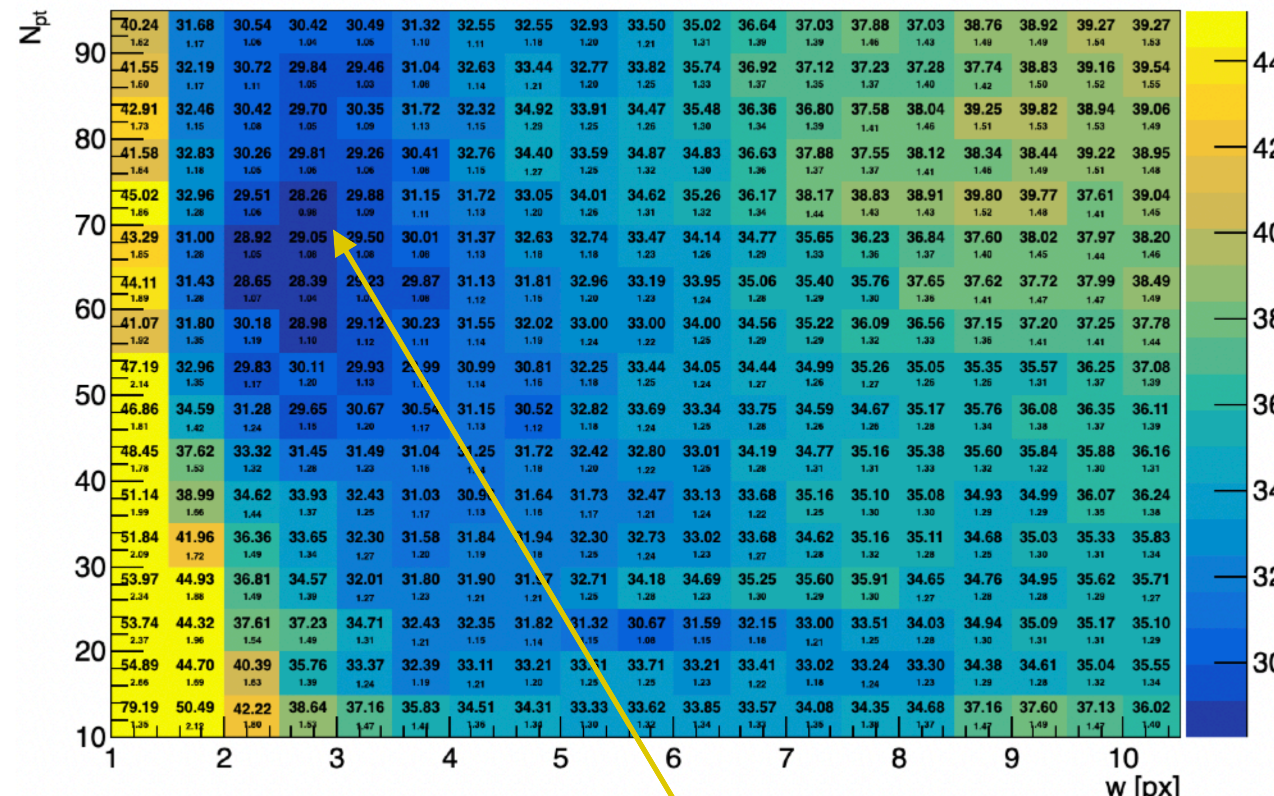
- Cases on the left can be solved with an algorithm that follows the sense of the track

Parameter scan

- The parameters of the algorithm (N_{Pt} and w) for each energy are not known a priori

- Scan parameters have been done for 20 30 40 50 60 keV, to find the ones which minimize the angular resolution

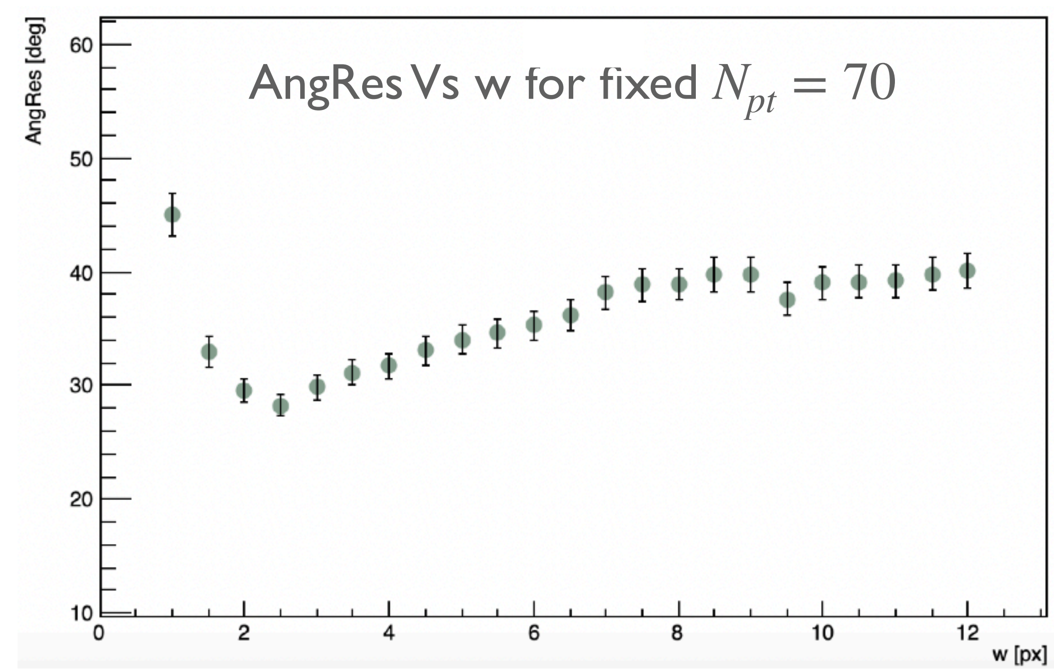
Ang. resolution vs parameters at 30 keV



Best value $N_{Pt} = 70 \quad w = 2.5$

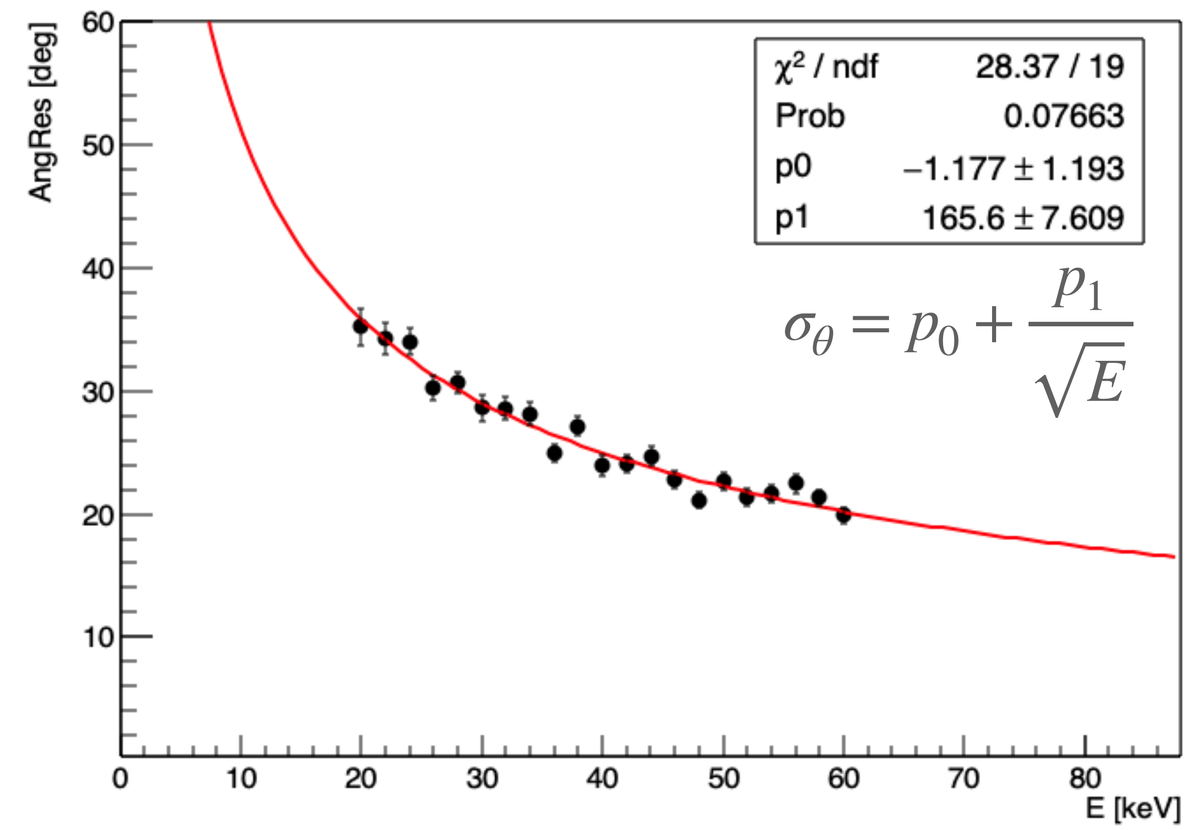
Scan results:

	20keV	30keV	40keV	50keV	60keV
w	2.5	2.5	3.5	3.5	5
N_{Pt}	65	70	75	80	85

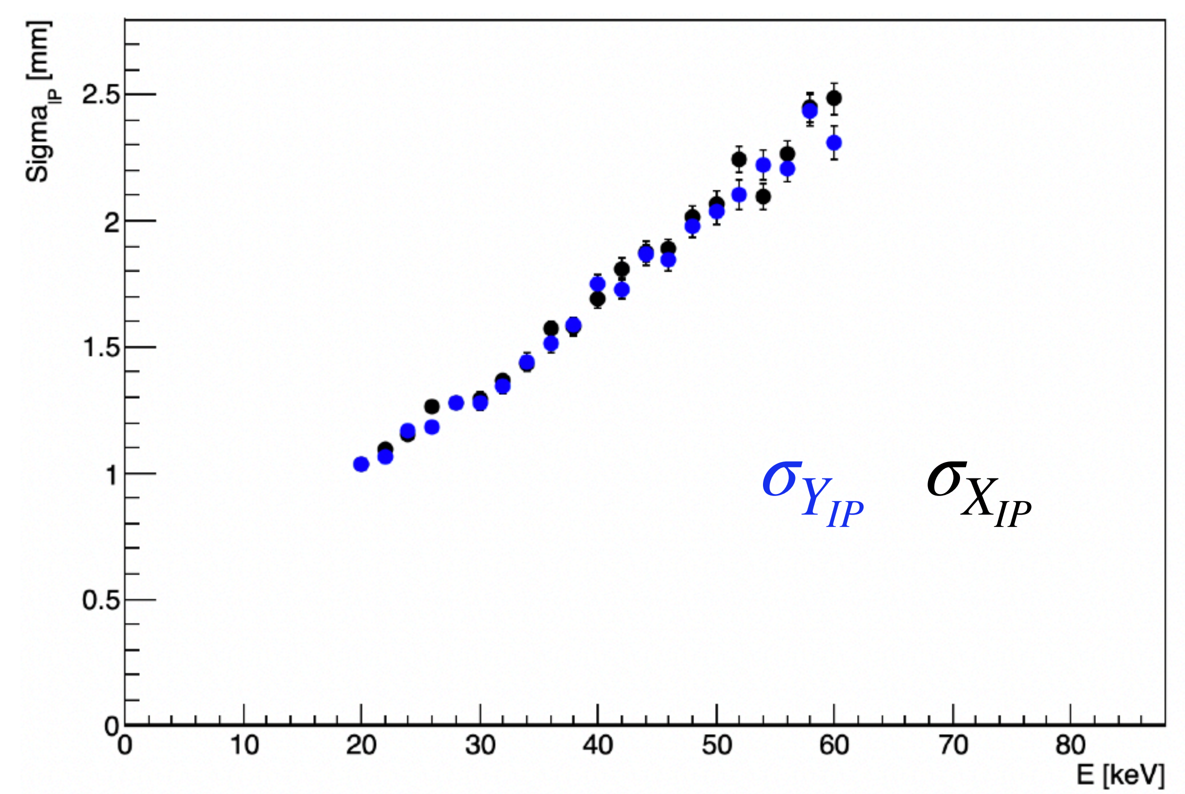


Directionality performances

- Sigma of the distributions as a function of the energy
- Parameter tuned on 20 30 40 50 60 keV
- For intermediate energy the parameters coming form point interpolation are used

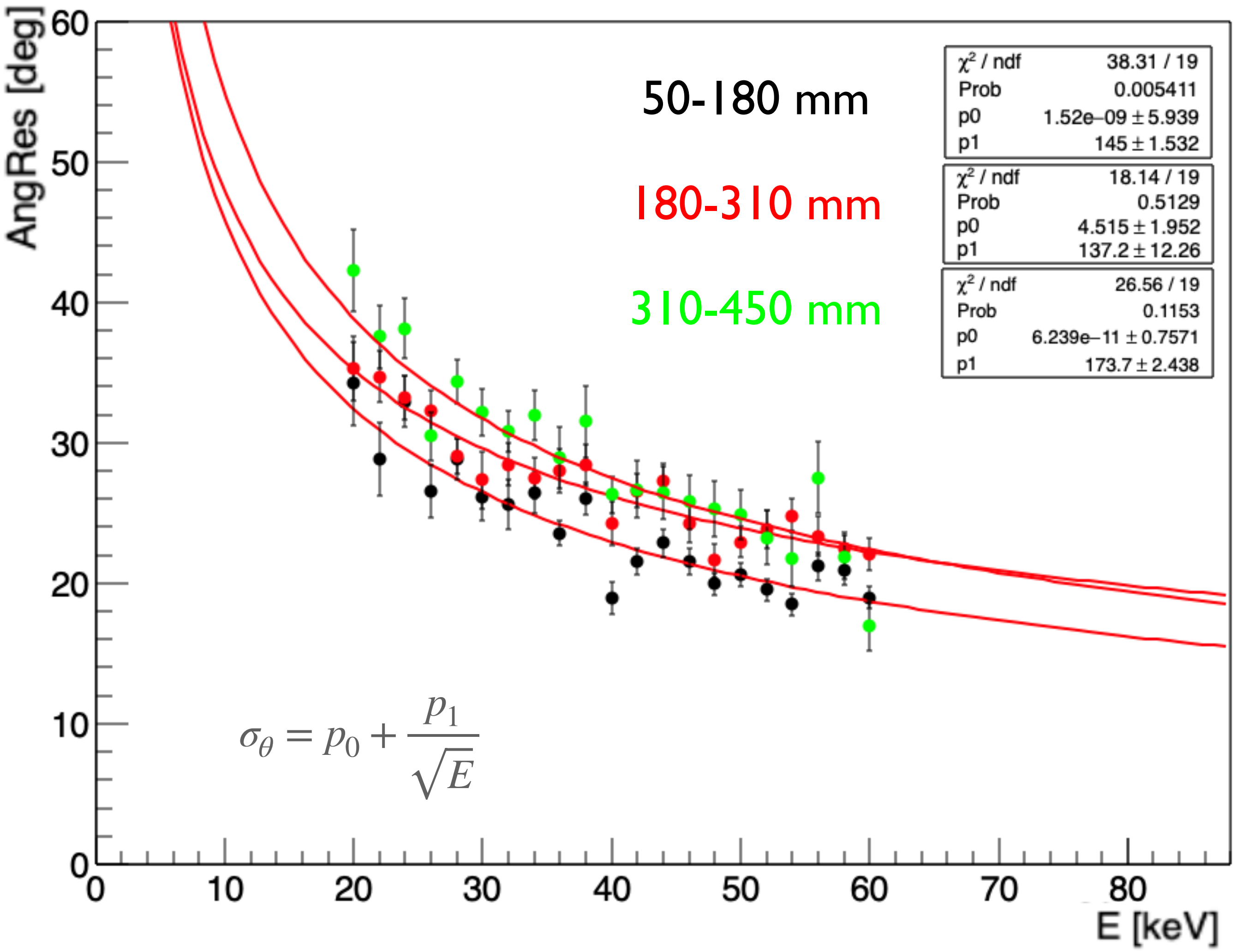


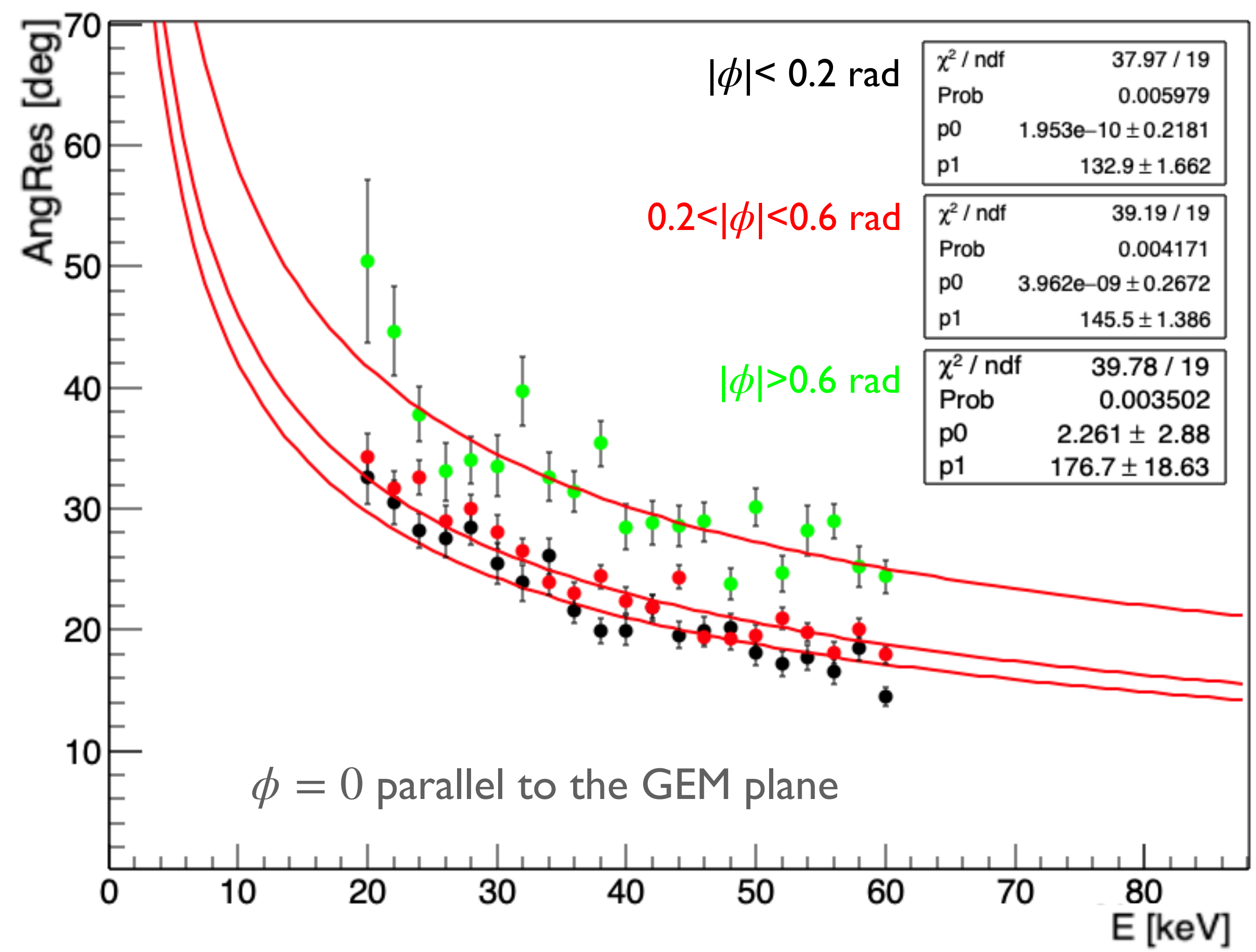
- Impact point resolution worsen with energy due to track variability at higher energy
- It can be improved exploiting the z information



Deeper studies on Directionality performances

- Directionality studied for different drift distances and angles with respect to the GEM plane



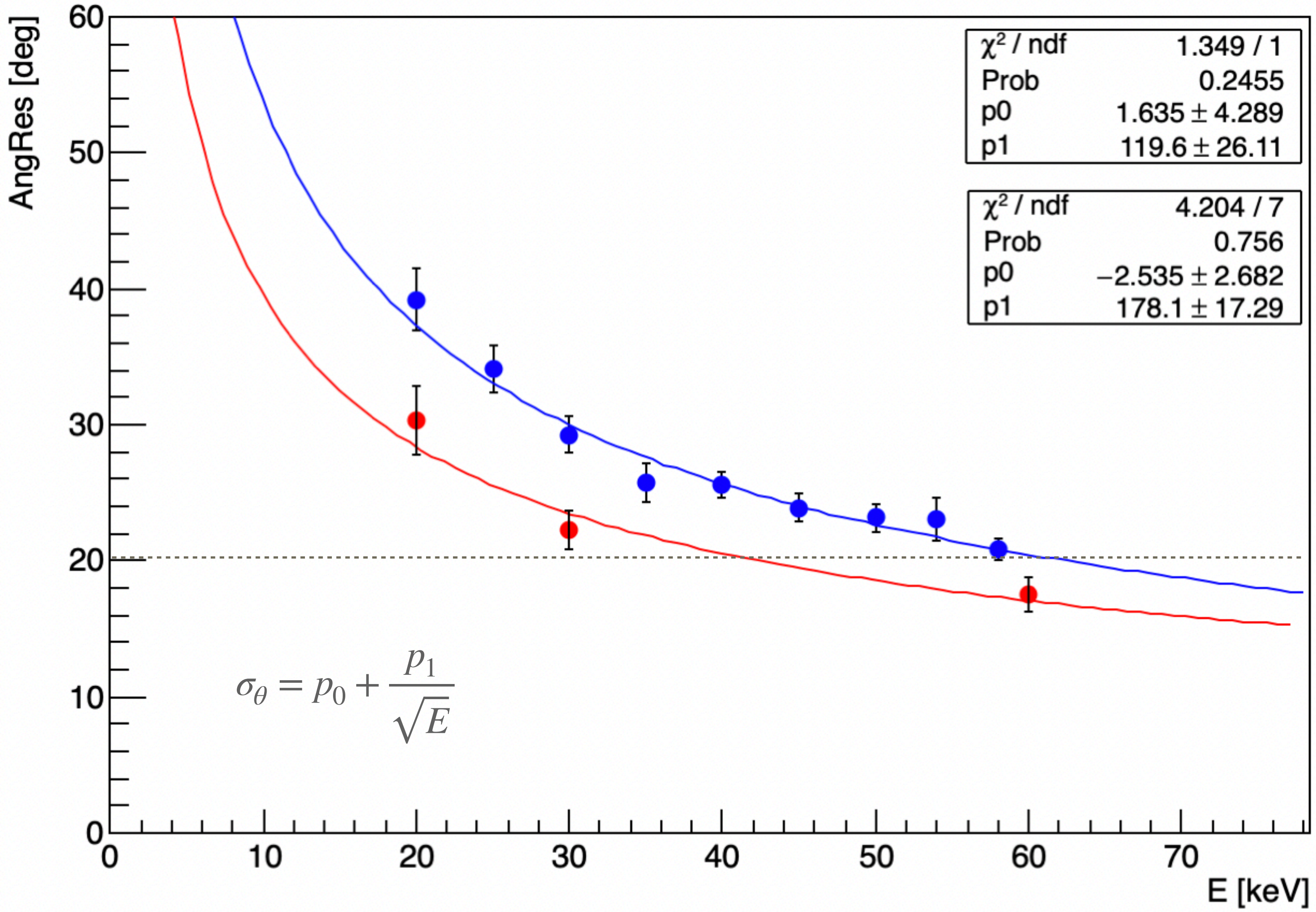


- Diffusion weights less on higher energies
- Angular resolution converges at higher energies for different distances

- Worsening with tracks parallel to the GEM plane
- Difference constant even at higher energies

Scenarios comparison on directionality capability

- Worst case scenario: Isotropic tracks at random diffusion



- Ideal inclination scenario: Tracks produced along the positive direction of x axis @ 25 cm diffusion

- In the best case scenario the resolution is comparable to the one hypothesised before

Considerations on directionality application

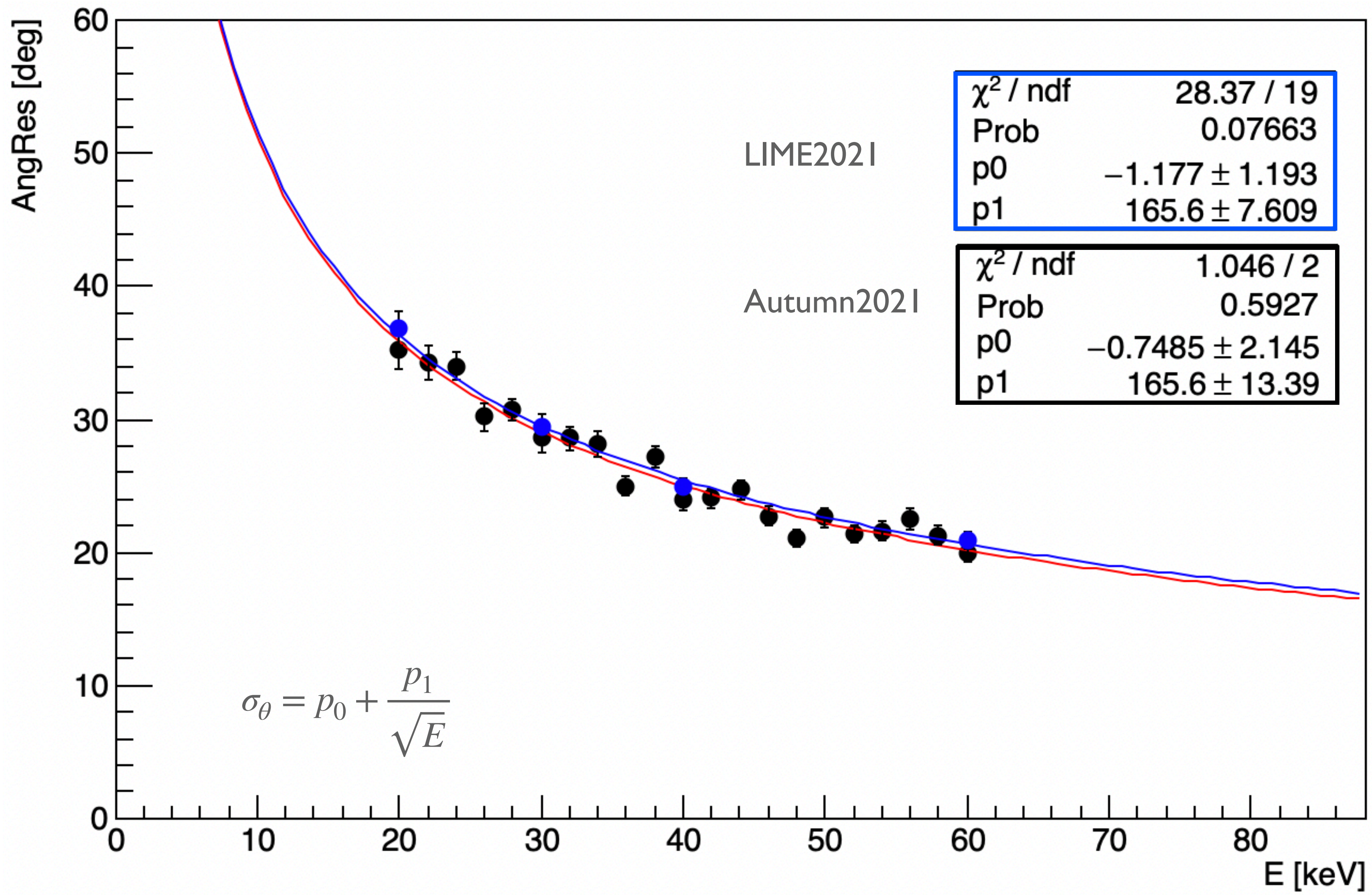
- At the moment we don’t have a PMT simulation for 3D tracking
- Angular resolution studied on sCMOS images (2D detector)
- This will be used in the sensitivity evaluation in two ways:

1. PMT doesn’t help at all with 3D reconstruction: use the distribution obtained with 2D and I study the feasibility in 2D
2. PMT resolution comparable with the sCMOS one: feasibility study in 3D with the same angular resolution on θ and ϕ

Truth will be in the middle

Final considerations

- 20 30 40 60 keV reconstructed with Autumn21 giving compatible results



- Test on saturated tracks at 20 30 60 keV on going, not big differences expected

- Montecarlo comparison with X-Ray data from LIME is on going

Conclusions & outlook

- The TPC approach can be very powerfull for solar neutrino study exploiting the feature of the directionality
- CYGNO PHASE2 could be the first experiment to demonstrate the possibility of performing neutrino spectroscopy with event by event energy determination, exploring lower neutrino energies than the one reached by Borexino.
- Preliminary studies on the expected interaction rate of solar neutrino from the pp-cycle in our gas mixture at atmospheric pressure, and on the kinematic of the process with slightly optimistic angular and energy resolution have been performed
- The algoritm for low energy electron directionality is ready
- The next step will be to verify the bounties of the simulation with a data mc comparison, and to develop a first estimation of the exposure needed to claim detection of solar neutrino from the pp-flux
- We are thinking about some application in the polarimetry field

Backup slides

Expected rate for pp-flux neutrino on 60:40 He/CF_4 gas mixture @ 1atm

$$\sigma_{\nu_e}(E_\nu) = \frac{G_F^2 m_e}{2\pi}\Bigg\{(g_V + g_A + 2)^2\left[\frac{2E_\nu^2}{(m_e + 2E_\nu)} - T'_{e,Thr}\right] + \\ -(g_V - g_A)^2\frac{E_\nu}{3}\left[\left(1 - \frac{2E_\nu}{m_e + 2E_\nu}\right)^3 - \left(1 - \frac{T'_{e,Thr}}{E_\nu}\right)^3\right] + \\ -(g_V - g_A)(g_V + g_A + 2)\frac{m_e}{2}\left[\frac{4E_\nu^2}{(m_e + 2E_\nu)^2} - \frac{T'^{\,2}_{e,Thr}}{E_\nu^2}\right]\Bigg\}$$

Cross section I obtained as a function of E_ν with fixed threshold on e^- energy

$$E_{\nu,Reco} = \frac{-m_e T_e - \sqrt{T_e^2 m_e^2 \cos(\theta)^2 + 2T_e m_e^3 \cos(\theta)^2}}{(T_e - T_e\cos(\theta)^2 - 2m_e\cos(\theta)^2)}$$

θ : angle of e^- recoil respect to sun direction

- Average oscillation probability considered in the calculation

$$P(\nu_e \to \nu_\mu) = P_{e\mu} = \frac{1}{2}\sin^2(2\theta_{12})$$

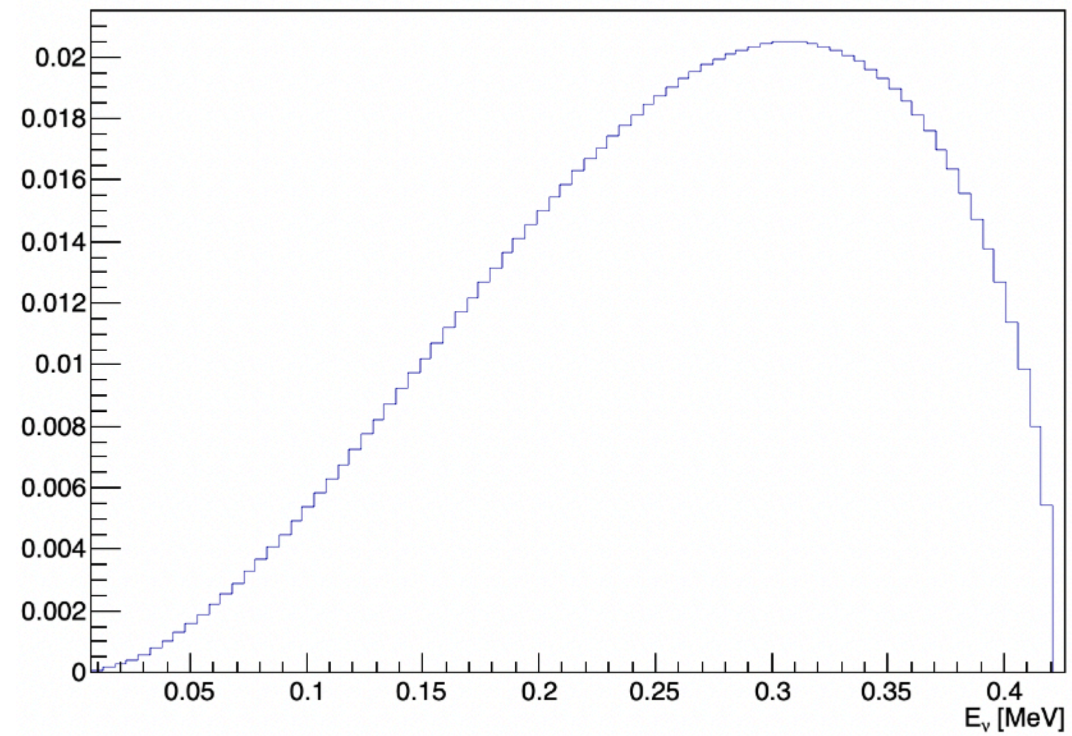
$$P(\nu_e \to \nu_e) = P_{ee} = 1 - \frac{1}{2}\sin^2(2\theta_{12})$$

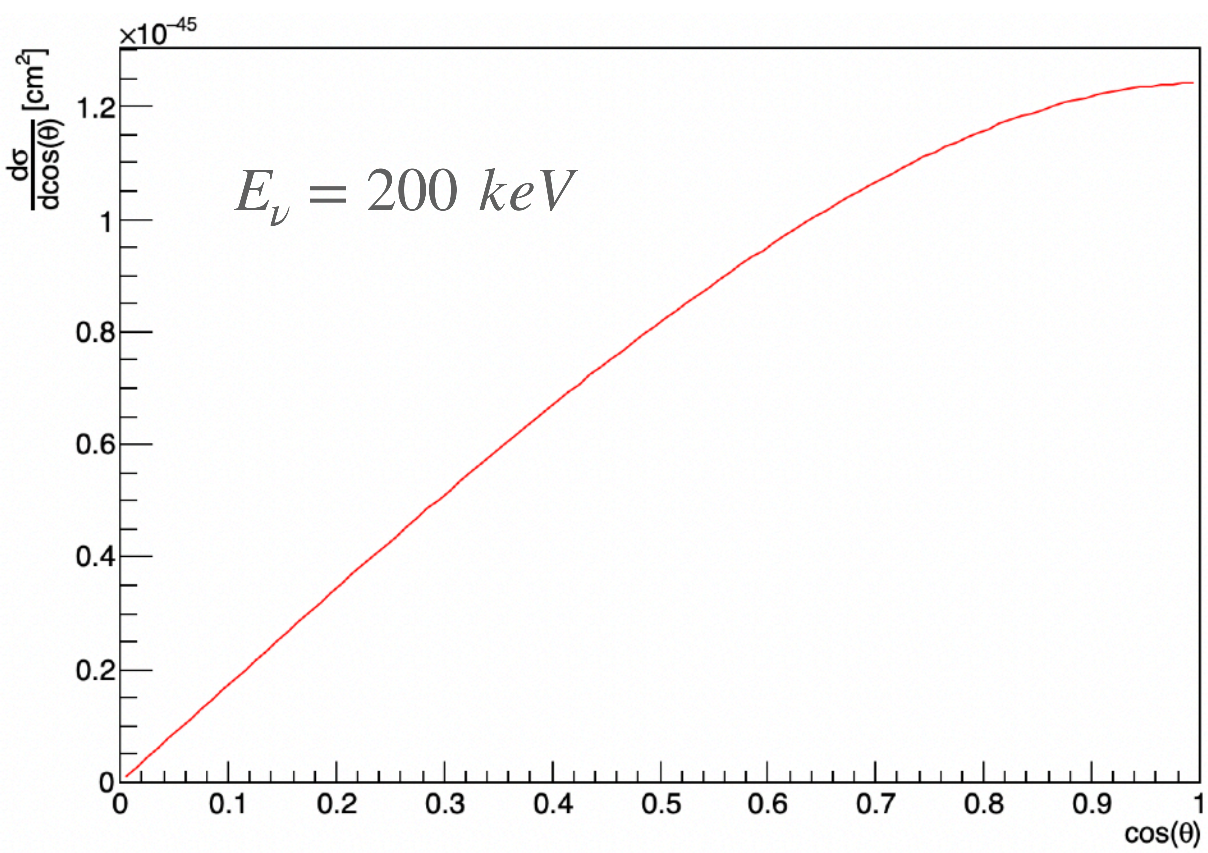
- Solar pp flux tabulated from Bahcall:

q [MeV]	P(q)	q [MeV]	P(q)	q [MeV]
0.00504	0.0035	0.11089	1.2477	0.21675
0.01008	0.0138	0.11593	1.3417	0.22179
0.01512	0.0307	0.12097	1.4370	0.22683
0.02016	0.0538	0.12601	1.5335	0.23187
0.02520	0.0830	0.13106	1.6310	0.23691
0.03024	0.1179	0.13610	1.7291	0.24195
0.03528	0.1582	0.14114	1.8278	0.24699
0.04032	0.2038	0.14618	1.9267	0.25203
0.04537	0.2543	0.15122	2.0258	0.25707

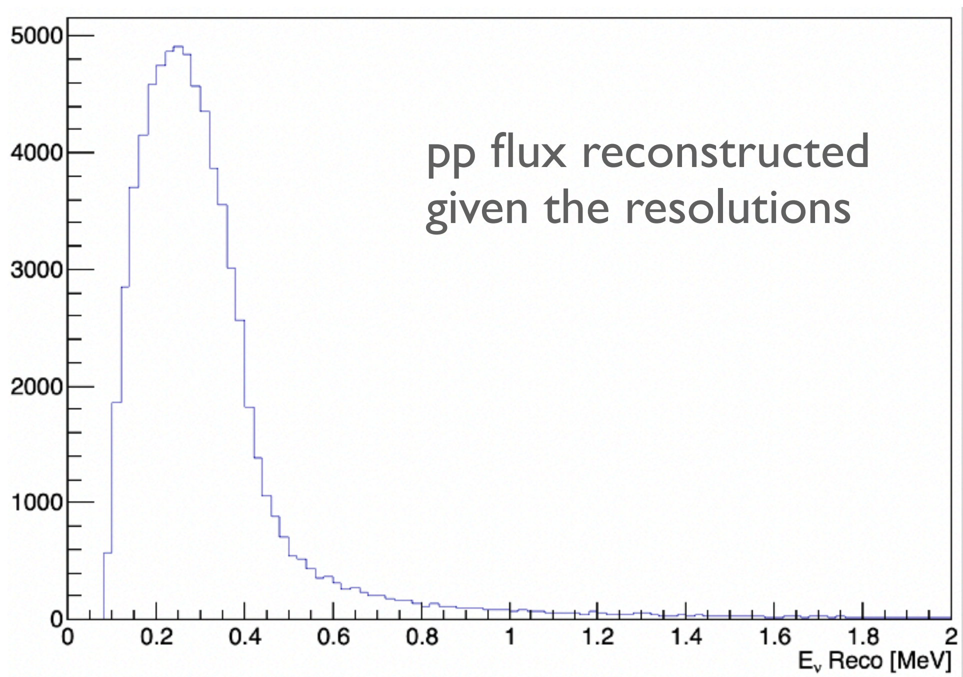
- Expected rate: $R = N_e \sum_i \varphi(E_i)(P_{ee}\sigma_{\nu_e}(E_{\nu,i}) + P_{e\mu}\sigma_{\nu_\mu}(E_{\nu,i})))\Delta E = 2.9 \cdot 10^{-8}\,\frac{events}{s \cdot m^3} = \boxed{0.9\,\frac{events}{y \cdot m^3}}$

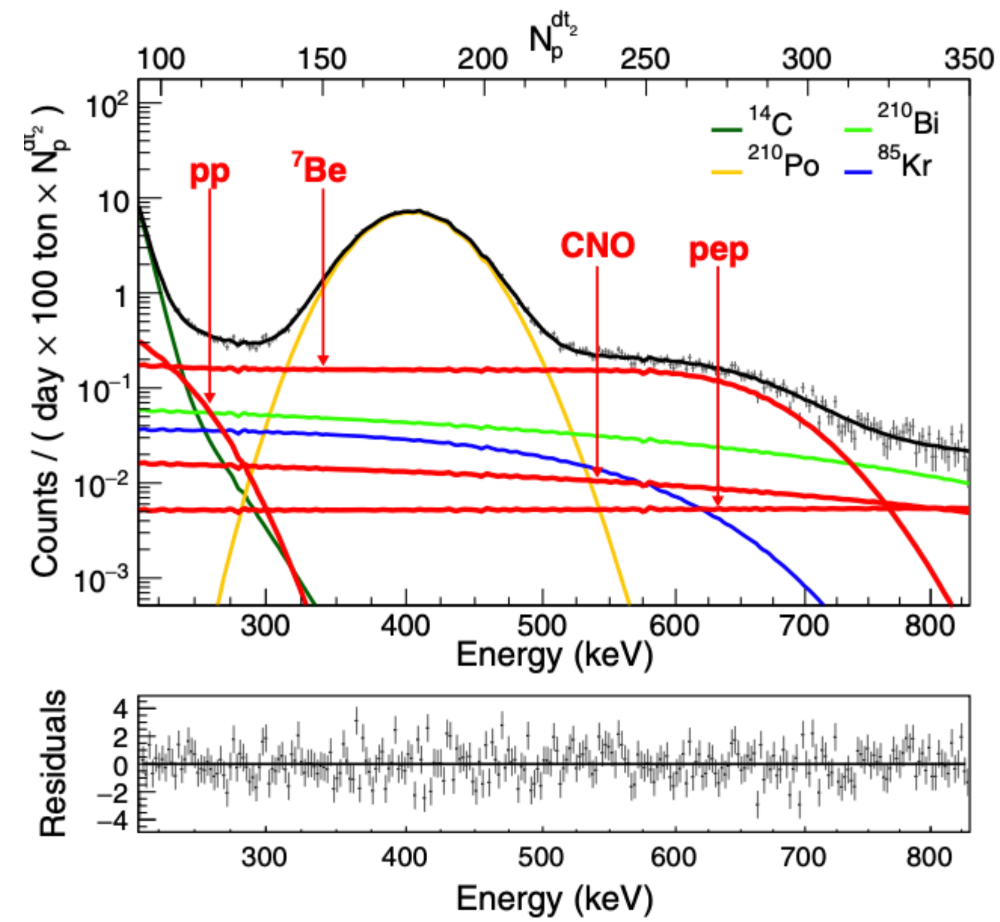
1. Random neutrino energy from the flux extracted, with random $\cos\theta$ value according to the differential cross section

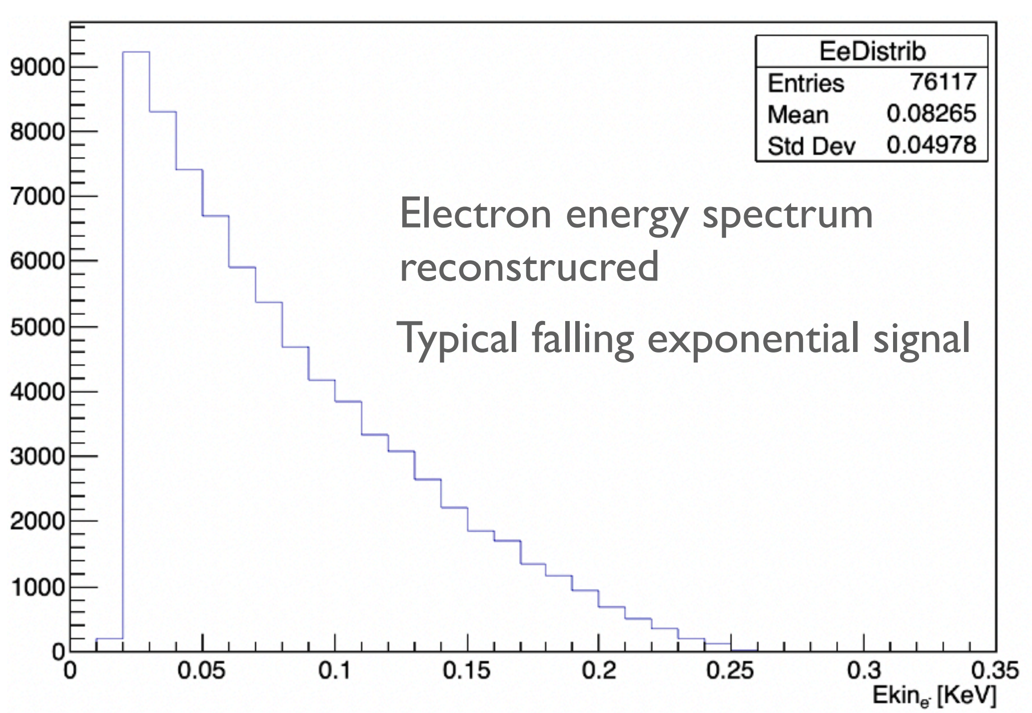


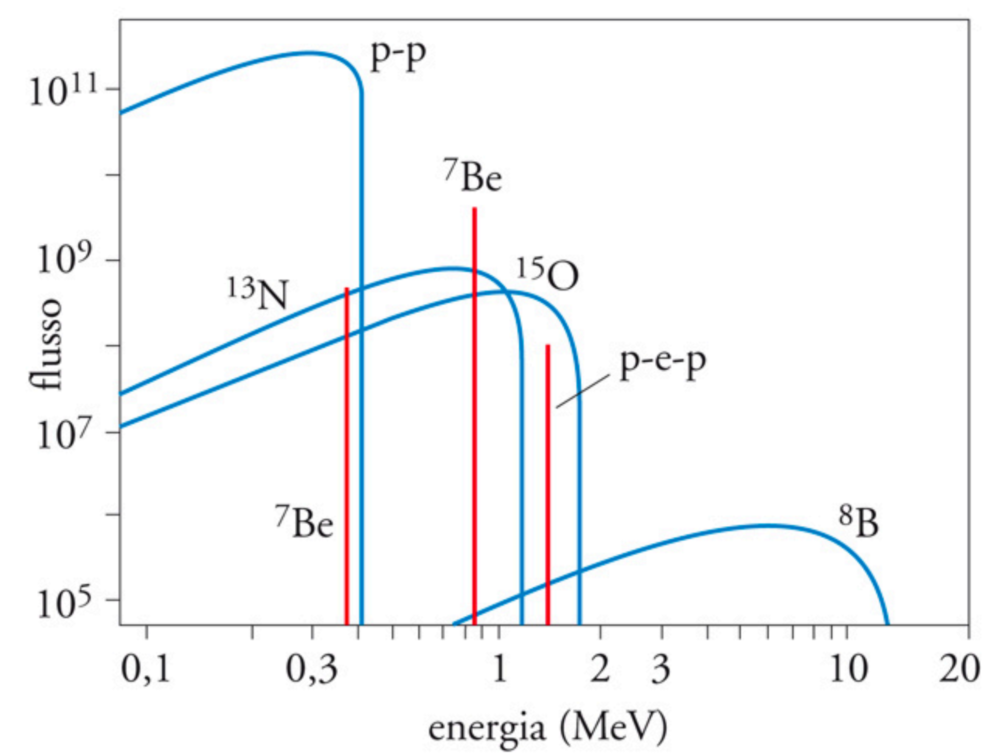


2. Random $\cos\theta$ value according to the differential cross section for extracted neutrino energy


pp flux reconstructed
given the resolutions
E_ν Reco [MeV]


N_p^dt2
pp
7Be
CNO
pep
14C
210Bi
210Po
85Kr
Counts / (day × 100 ton × N_p^dt2)
Energy (keV)
Residuals
Energy (keV)


EeDistrib
Entries 76117
Mean 0.08265
Std Dev 0.04978
Electron energy spectrum
reconstrucred
Typical falling exponential signal
Ekin_e- [KeV]


p-p
7Be
13N
15O
p-e-p
7Be
8B
flusso
energia (MeV)