Track reconstruction with MIMAC

Julien Billard

With Frédéric Mayet and Daniel Santos

Laboratoire de Physique Subatomique et de Cosmologie
Grenoble - France

Outline

1. Track measurement with MIMAC

2. Study of the systematics and track simulation

3. A likelihood analysis of the MIMAC events

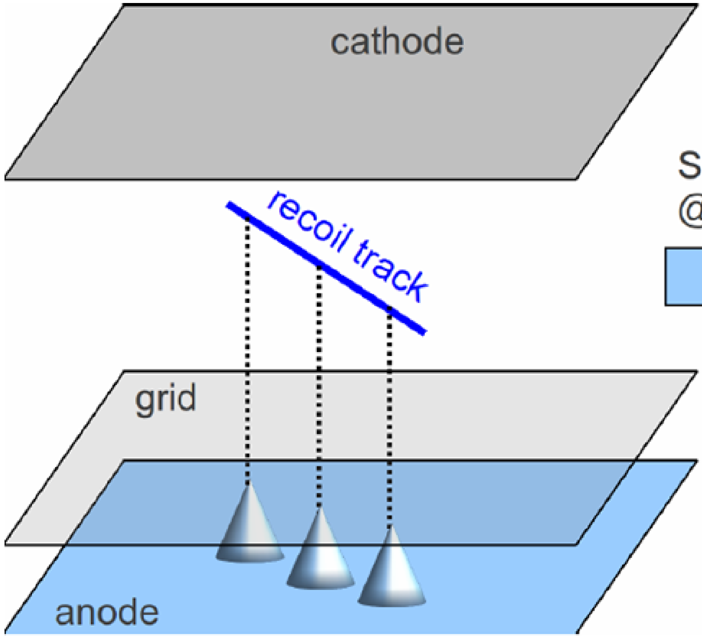
4. Estimation of the expected resolutions: spatial and angular

5. Toward a Head-Tail discrimination?

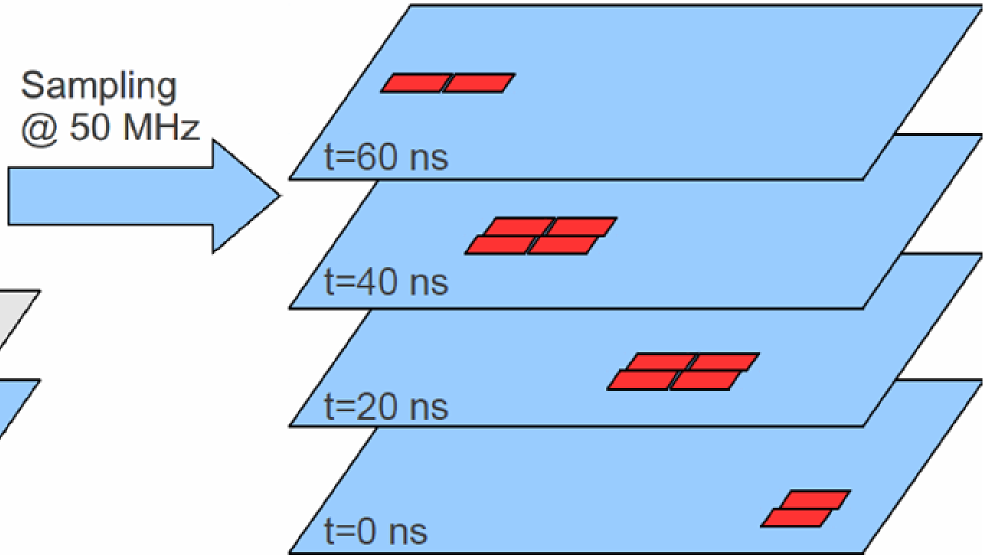
Conclusions & discussion

Track measurement with the MIMAC detector

Track measurement with MIMAC



Representation of a MIMAC µTPC

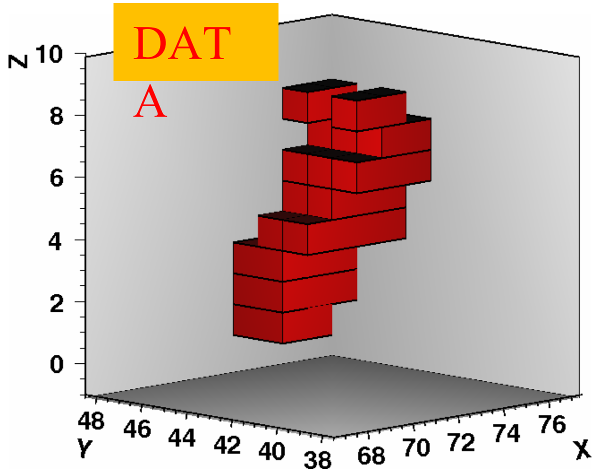


Evolution in time of the collected charges on the anode

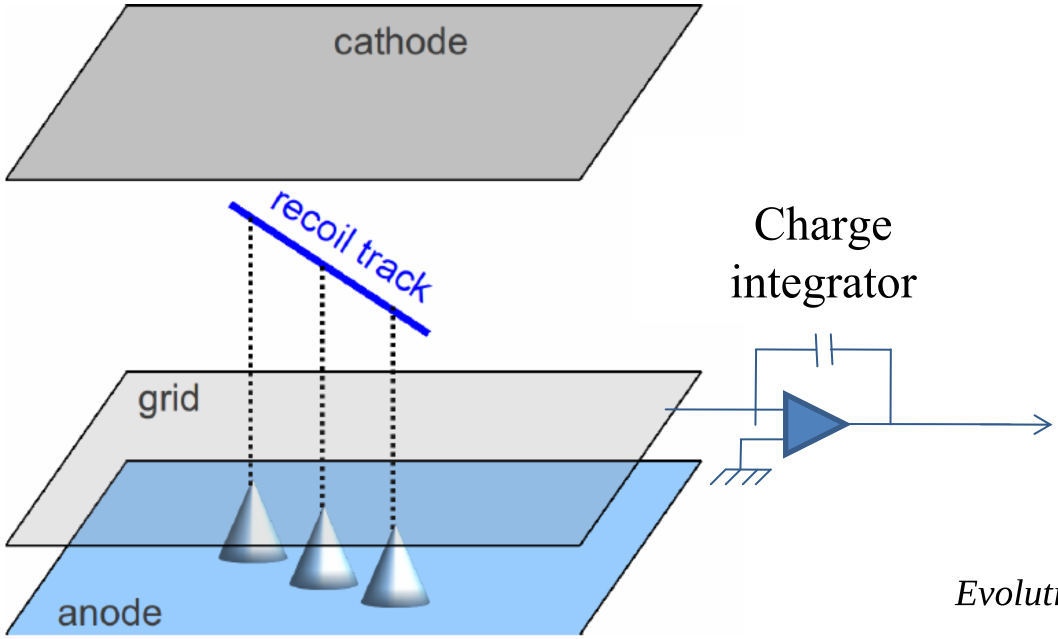
70 % CF_4 + 30% CHF_3

55 mbar,
170 V/cm

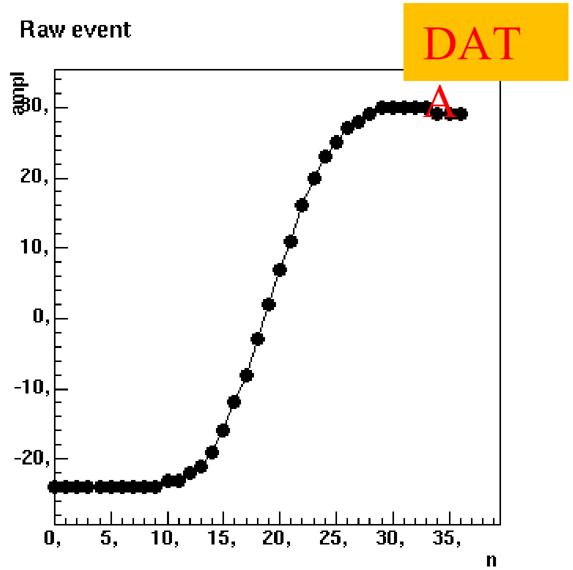
Fluorine candidate
@ 50 keV ionization



Energy and dE/dX measurement with MIMAC



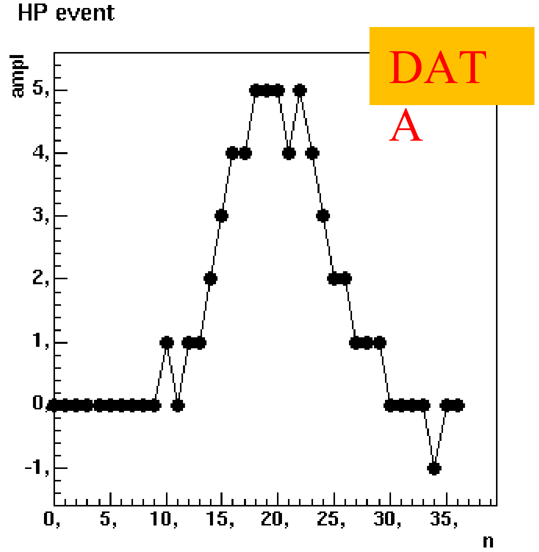
Representation of a MIMAC μTPC



Evolution in time of the charge integrator signal

Profile of the collected charges:

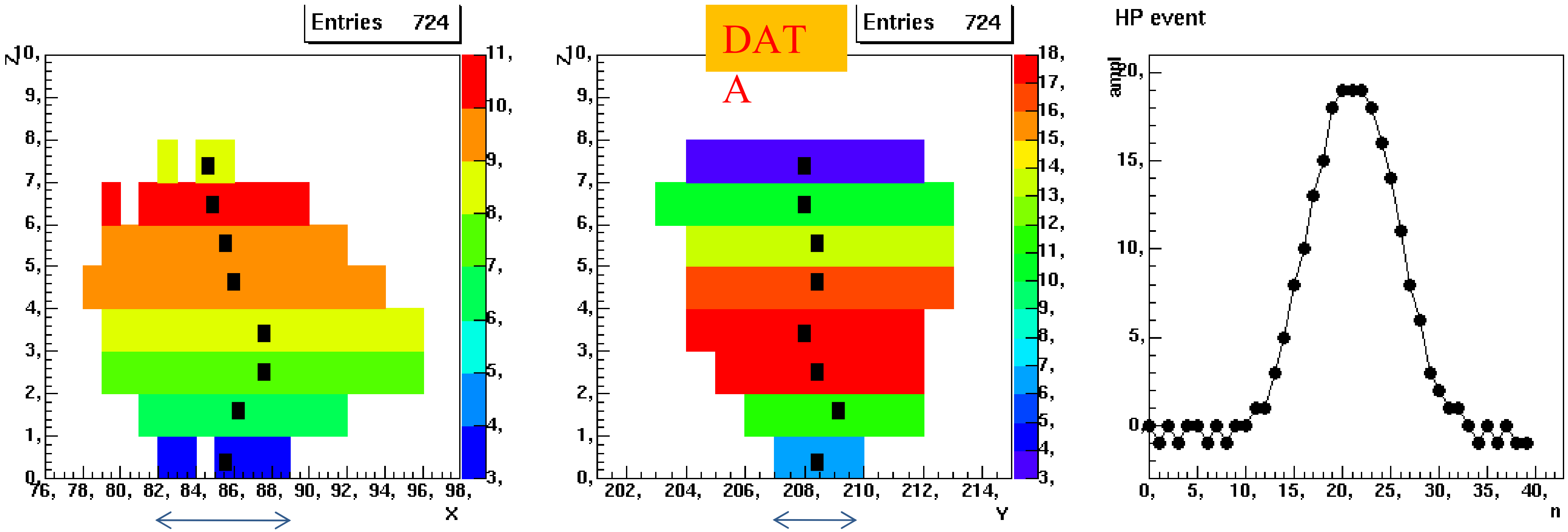
dE/dx



Need charge integrator characterization (ongoing…)

Derivative of the charge integrator signal

MIMAC observables



- The number of slices N_{slice}
- Center of Gravity (X^{bary},Y^{bary}) of each slice
- Width (ΔX, Δ Y) of each slice
- The energy collected in each slice E

(assuming a perfect knowledge of the charge integrator response)

$$N_{obs} = 1 + 5*N_{Slice}$$

What are the characteristics of the measured track {X,Y,Z,θ,φ} ?

↓

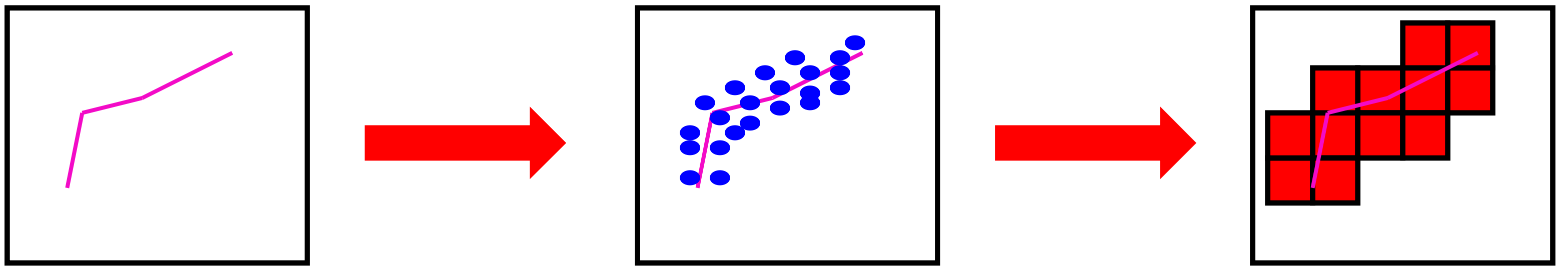
Likelihood analysis

↓

Requires track simulation to propagate the systematics

Systematics of nuclear recoil measurements

SRIM + **Magboltz** + **MIMAC DAQ**



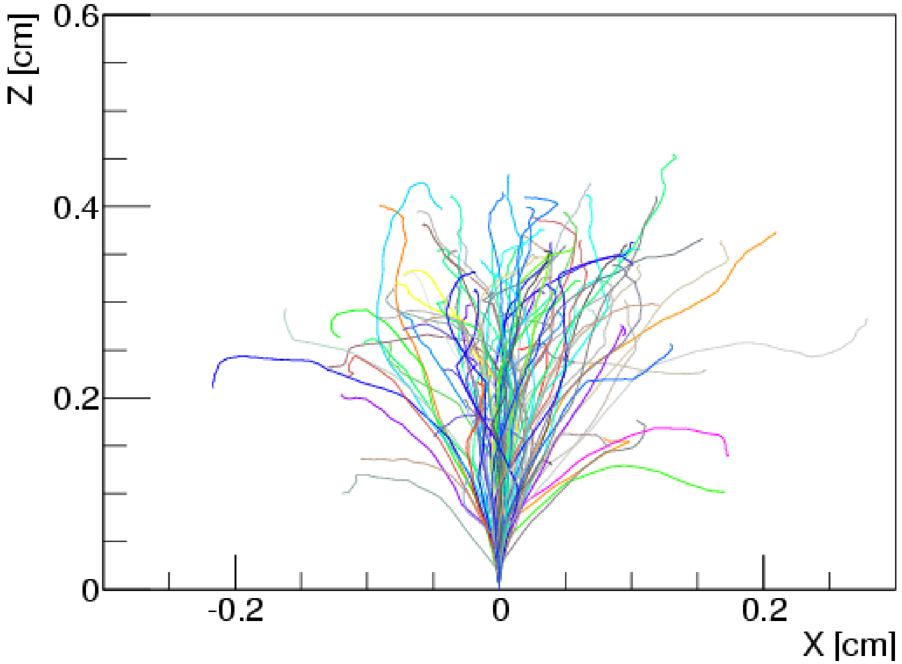
Track properties — *Electron drift* — *MIMAC electronic response*

Systematics of nuclear recoils: simulation

SRIM: The **S**topping and **R**ange of **I**ons in **M**atter [J. F. Ziegler et *al.*]

- For a given gas mixture and pressure it can simulate any kind of recoils at any energy

*Fluorine recoil of 100 keV (recoil) in **70% CF4 + 30% CHF3 @ 50 mbar***



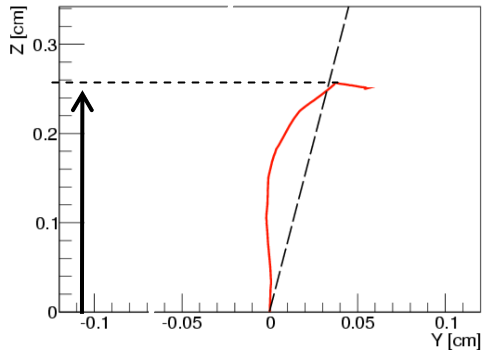
Spatial straggling is very important for Fluorine recoils… ***effects?***

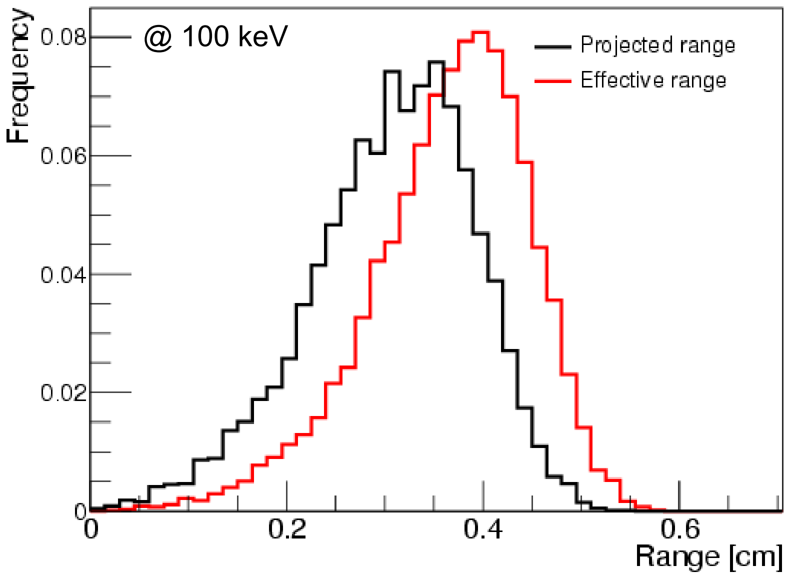
Systematics of nuclear recoils: range distribution

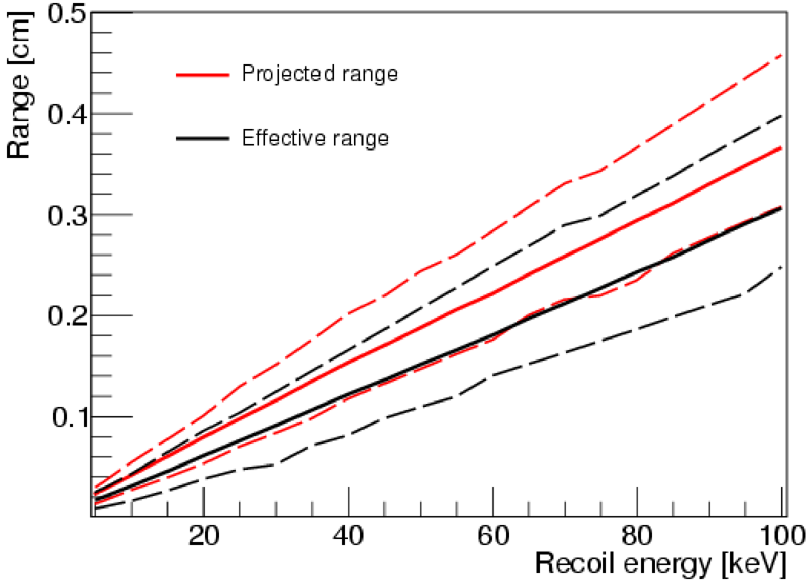
First effect:

Two definitions of the range can be used:

- **Projected range:** projection along the Z axis
- **Effective range:** sum of all the segments



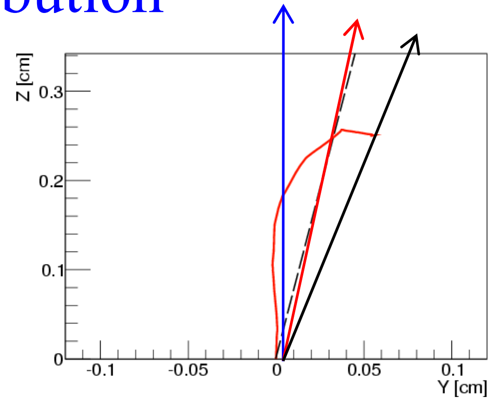




- Dispersion in the range is important ~ 30% at 100 keV
- Range are between 200 and 3500 μm for a recoil energy between 10 and 100 keV

Need for high spatial resolution readout…

Systematics of nuclear recoils: angular distribution

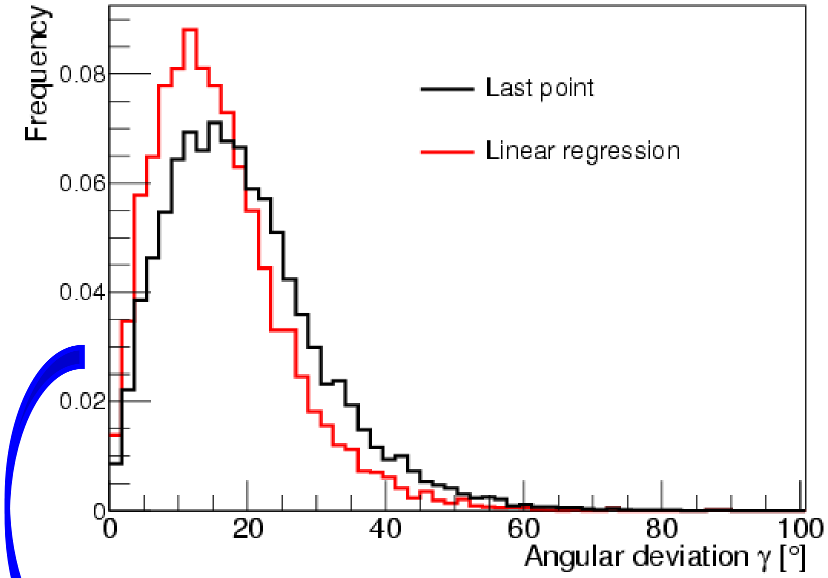


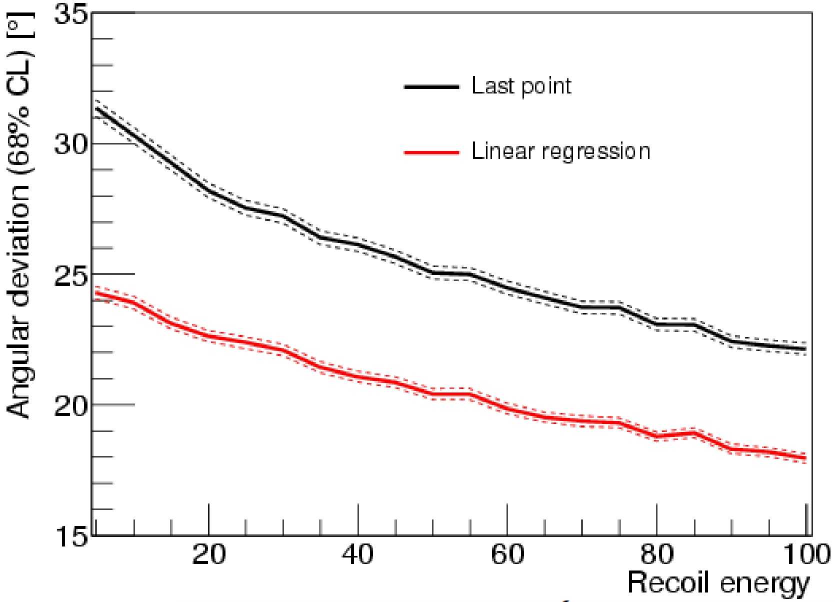
Second effect:

Two definitions of the angular deviation γ:

- Direction between the first and last point

- Linear regression





In the case of a gaussian angular resolution, we have: $f(\gamma) \propto \sin\gamma \exp\left\{-\frac{1}{2}\left(\frac{\gamma}{\Delta\gamma}\right)^2\right\}$

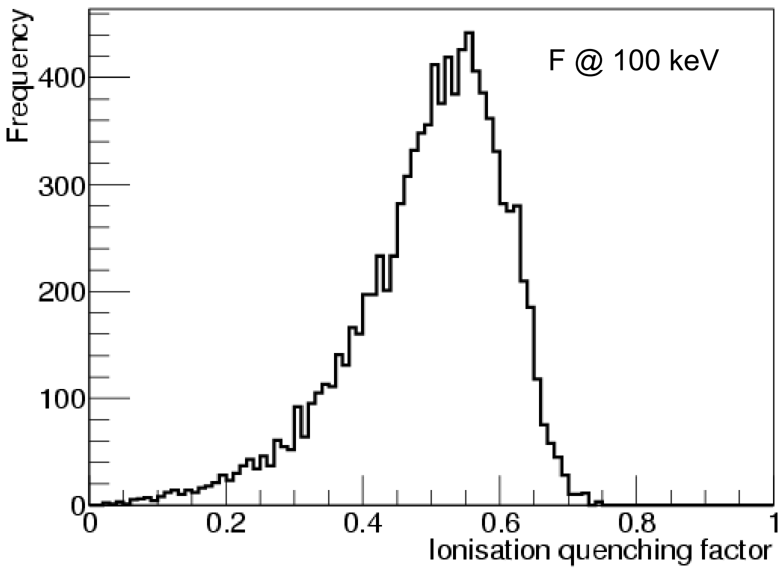
Angular deviation is between 25° and 18° for E_R between 10 and 100 keV

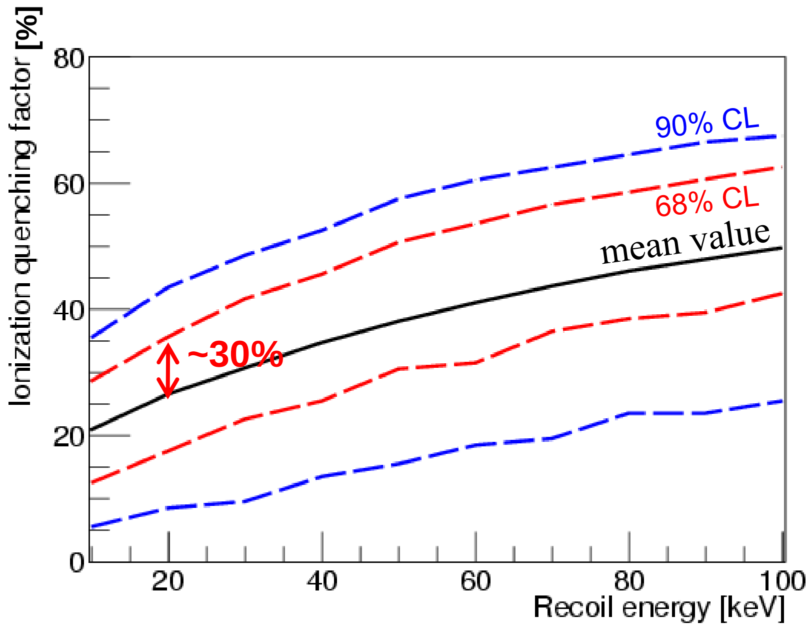
Systematics of nuclear recoils: Quenching factor

The Ionization Quenching Factor is a key issue for direct detection:

$$Q_{ion} = \frac{E_{ion}}{E_{Recoil}}$$

Necessary to estimate the recoil energy E_R => **Need to be measured**
[ref. talk O. Guillaudin]





- **Limitations on the energy resolution of the detector**
- **Energy resolution is different for electronic and nuclear recoils!!**

Systematics of nuclear recoils: number of primary electrons

The number of primary electrons generated follows the following statistics

$$N_{elec} \propto f\left(\bar{N}_{elec}, \sigma_{N_{elec}}\right)$$

With:

$$\bar{N}_{elec} = Q \times \frac{E_{recoil}}{W}$$ Mean number of primary electrons

W: the mean energy to produce an electron-ion pair

$$\sigma_{N_{elec}} = \sqrt{F \times \bar{N}_{elec}}$$ Dispersion of the number of primary electrons

F: The Fano's factor taken equal to one (conservative approach)

Fluctuation in the number of primary electrons generated will highly contribute to the energy and spatial resolution

Systematics of nuclear recoils: drift of primary electrons

Due to the electric field ~ 200 V/cm, drift of the primary electrons toward the anode

According to MagBoltz,

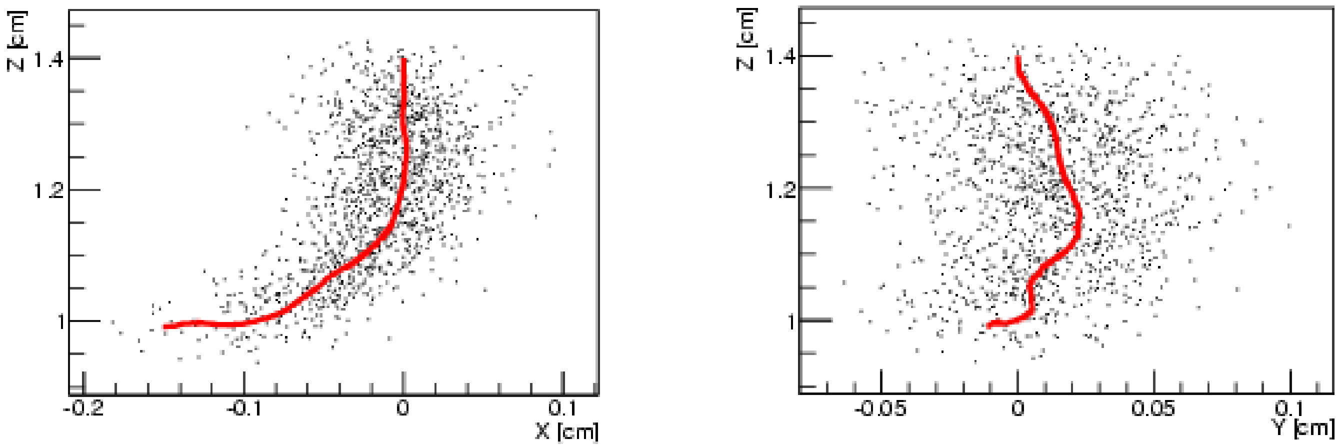
-Drift velocity: $V = 21.4\ \mu m/ns$

-Transverse Diffusion: $D_t = 246.0\ \mu m/(cm)^{1/2}$

-Longitudinal Diffusion: $D_l = 278.4\ \mu m/(cm)^{1/2}$

σ ~ 1 mm @ Z = 16 cm

Need to be precisely measured (ongoing…)



Representation, in co-mobile coordinates, of a Fluorine recoil @ 100 keV

Drift characteristics will mainly contribute to:

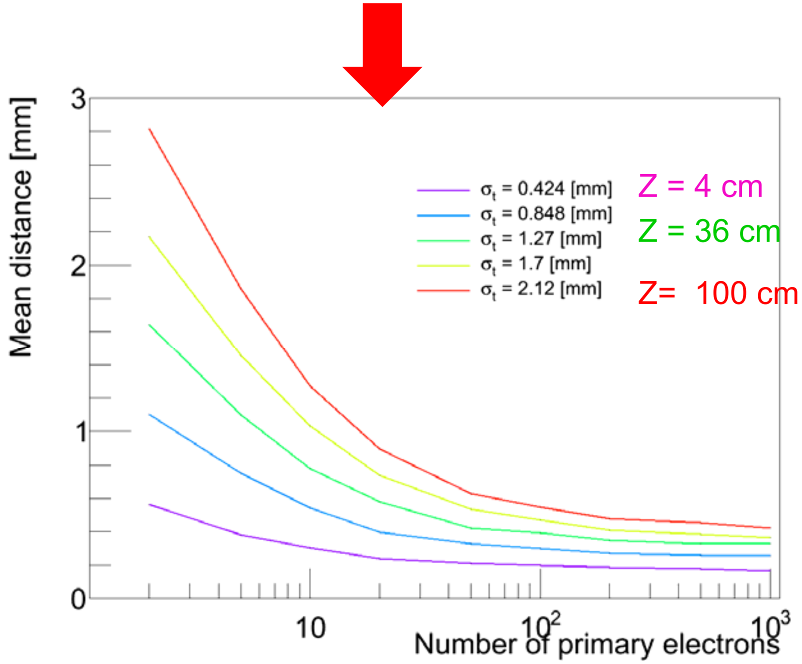
- Spatial and angular resolution

- The profile of the charge integrator

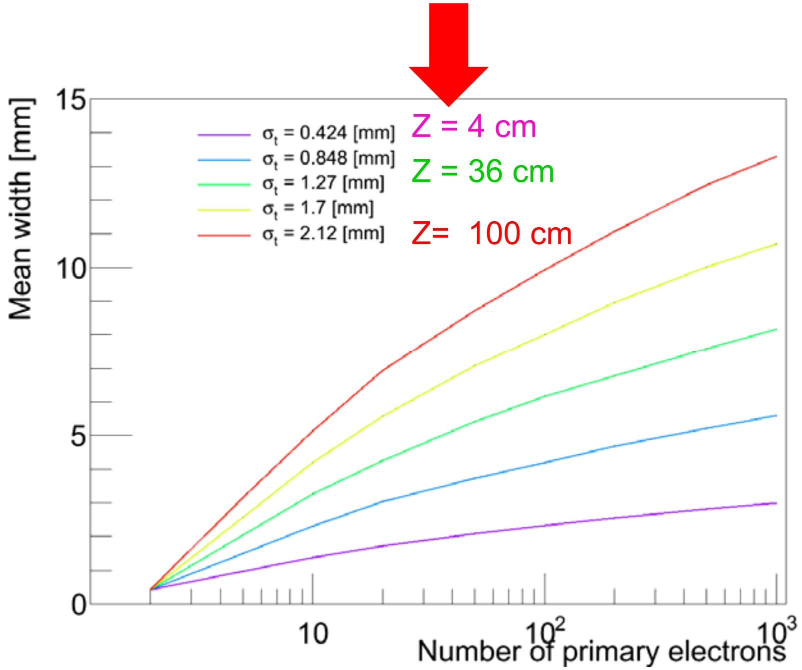
Systematics of nuclear recoils: MIMAC aquisition (DAQ)

Considering the MIMAC track aquisition system [ref. talk O. Bourrion] some systematic uncertainties will remain:

On the exact location of the **center of gravity** of a single time slice



On the **width (X,Y)** of a time slice



Both depend on the transverse diffusion (σ_t) and the number of collected electrons per slice

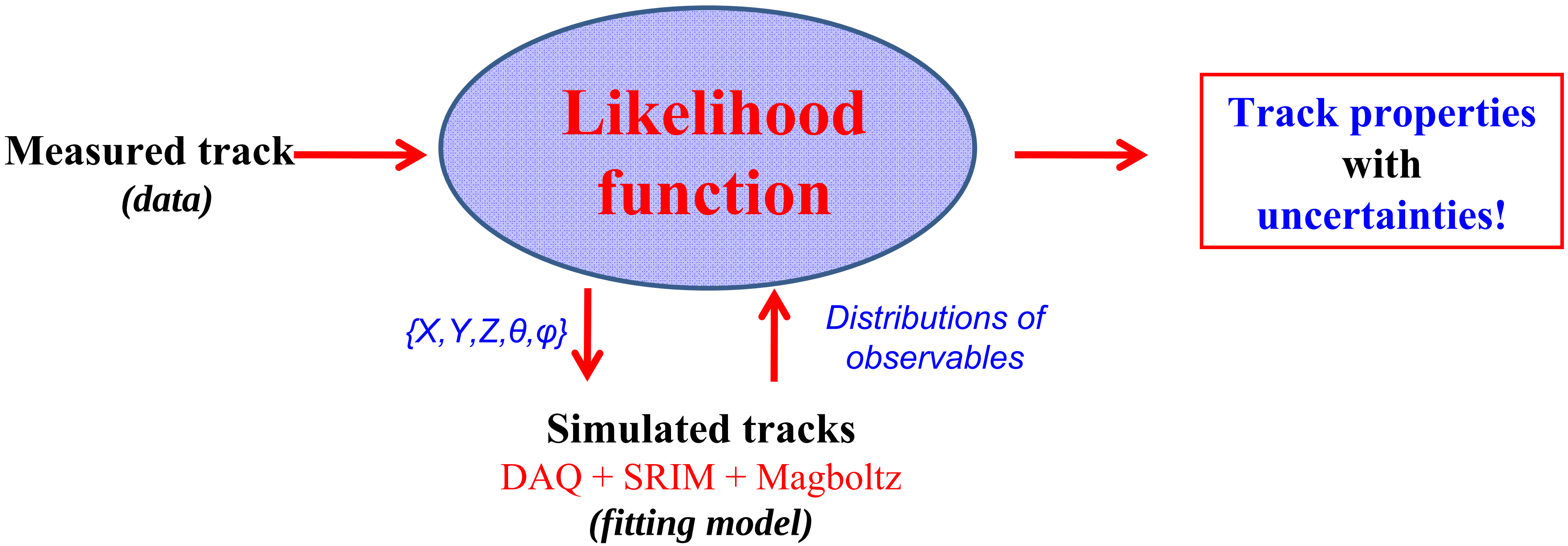
A likelihood analysis of MIMAC events

J. Billard et al., in preparation

… Because a simple linear fit doesn't work!!

II.c Likelihood definition

Main idea: Compare real track to simulated ones



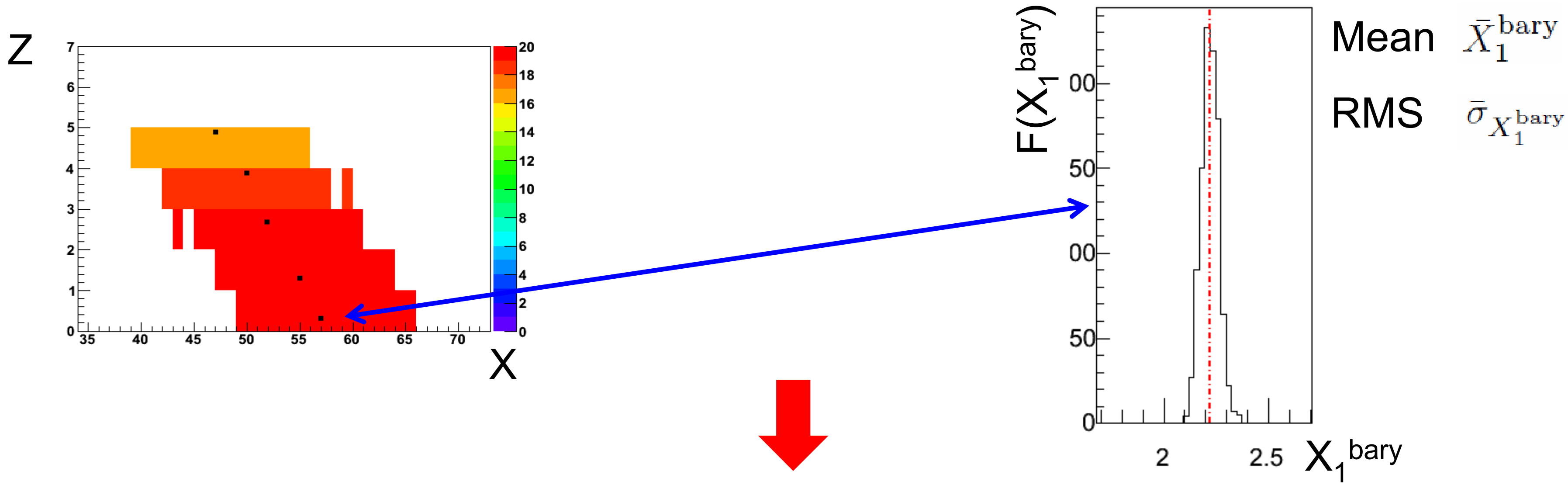
The recipe:

- Simulate a large number (1000) of tracks for a given set of parameters {X,Y,Z,θ,φ}
- Look at the distribution of the different observables (Mean value and RMS)
- Compare them with the measured one

Simulated pseudo data will be used to estimate the different expected resolutions…

II.c Likelihood function

From the distributions of the different observable, the likelihood function can be evaluated:



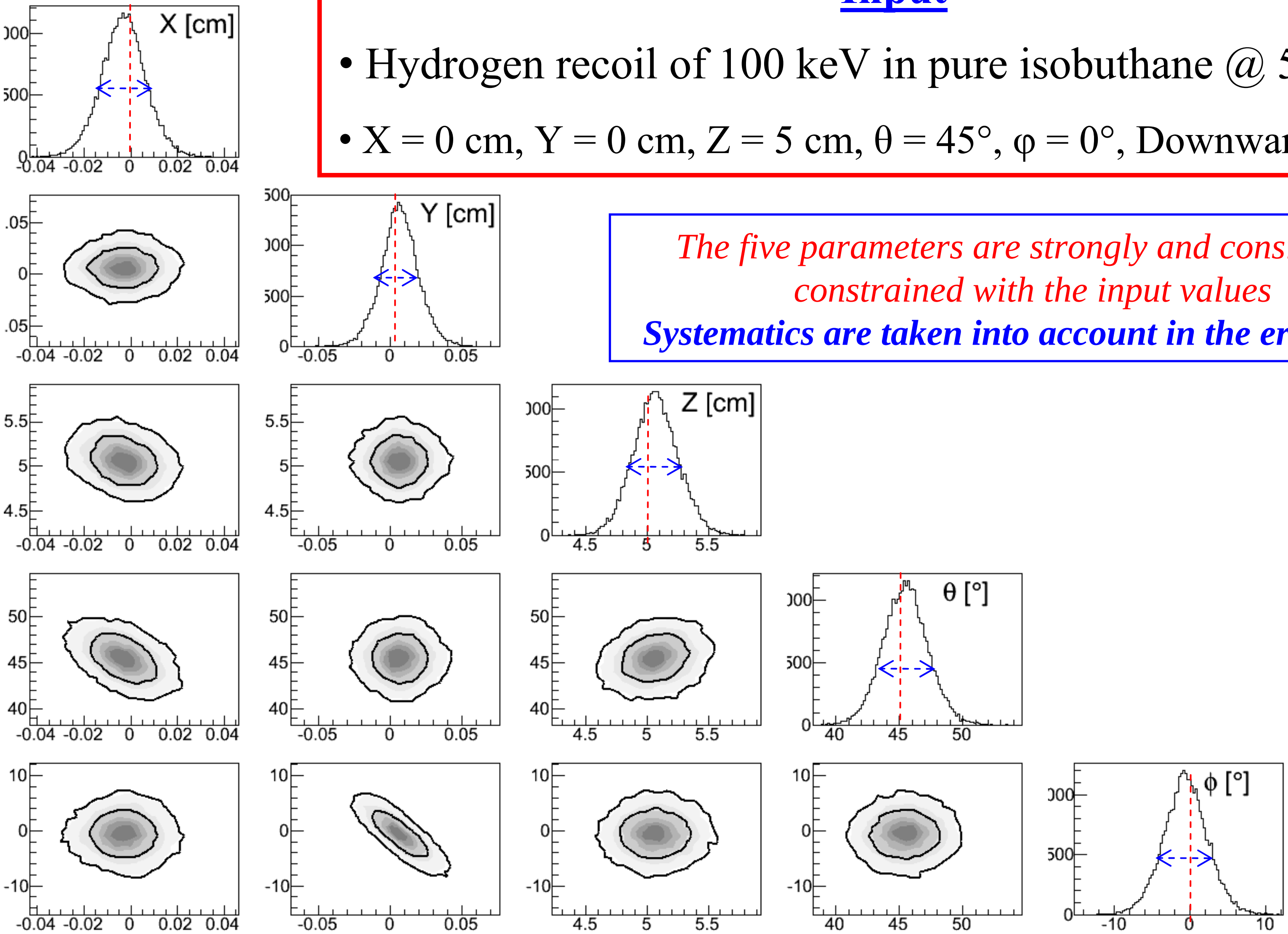
Calculation of the likelihood for $X_1^{\rm bary}$:

$$P(X_1^{\rm bary}) = \exp\left\{-\frac{1}{2}\left(\frac{X_1^{\rm bary} - \bar{X}_1^{\rm bary})}{\bar{\sigma}_{X_1^{\rm bary}}}\right)^2\right\}$$

Then, the likelihood function is given by:

$$\mathscr{L}(X, Y, Z, \theta, \phi) = P(N_{\rm slice}) \prod_{n=1}^{N_{\rm slice}} P(X_n^{\rm bary})P(Y_n^{\rm bary})P(\Delta X_n)P(\Delta Y_n)P(N_{{\rm elec}_n})$$

II.d MCMC sampling of likelihood function



Input

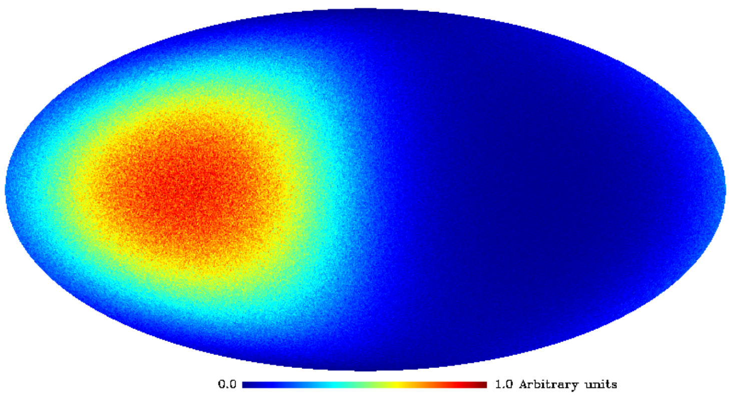
- Hydrogen recoil of 100 keV in pure isobuthane @ 50 mbar
- X = 0 cm, Y = 0 cm, Z = 5 cm, θ = 45°, φ = 0°, Downward

The five parameters are strongly and consistently constrained with the input values

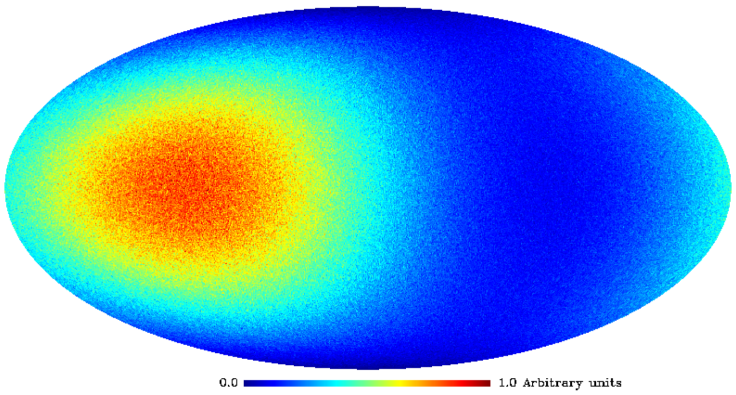
Systematics are taken into account in the error bars!

Estimation of the different resolutions

J. Billard et al., in preparation



WIMP event distribution with an ***angular resolution of 15°***



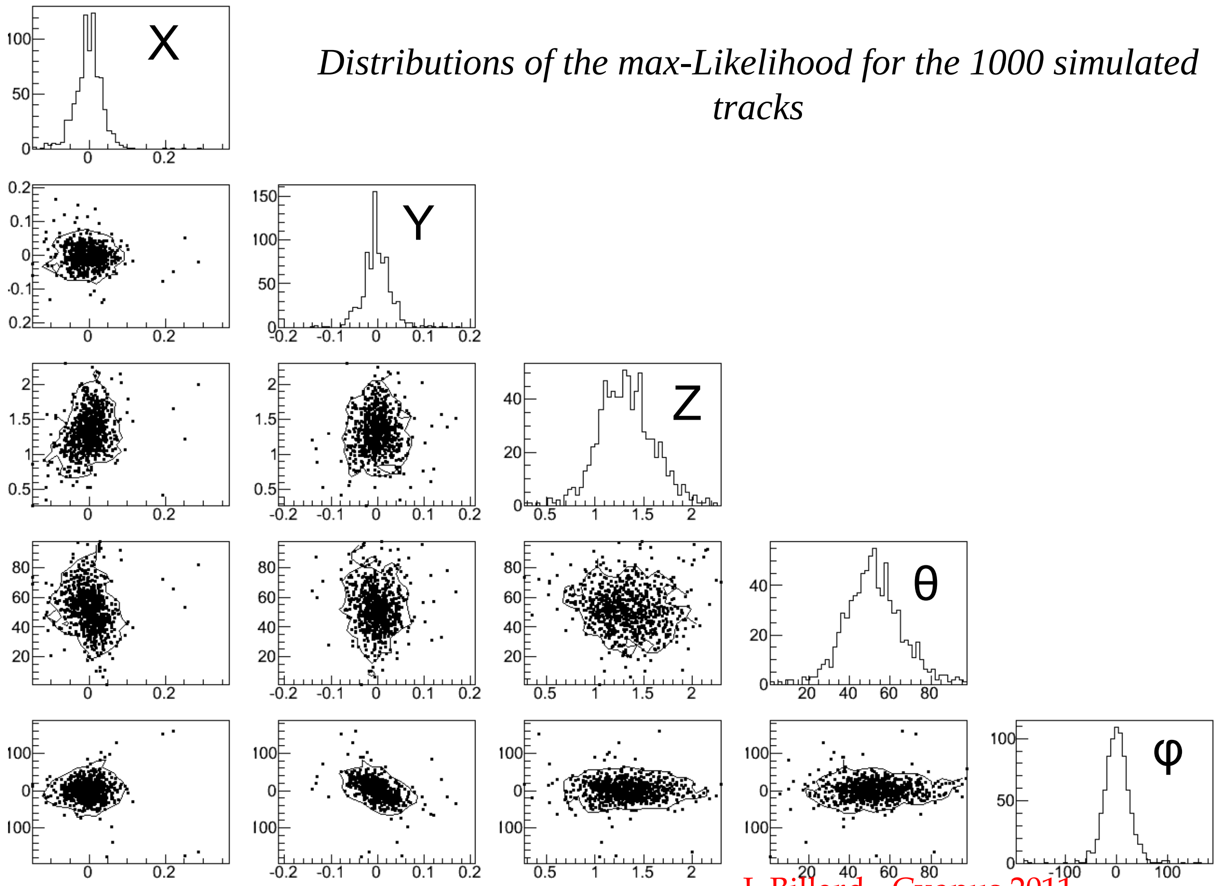
WIMP event distribution with an ***angular resolution of 45°***

III.d) Estimation of the different resolutions

Estimation of the different resolutions using Monte Carlo simulations => **Max-Likelihood**

Input

X = 0 cm, Y = 0 cm, Z = 1.3 cm, θ = 45°, φ = 0°, Sense = **down**



Distributions of the max-Likelihood for the 1000 simulated tracks

Resolution in the (X,Y) plan

$$\sigma_{x,y} = 314 \pm 10 \ \mu\text{m}$$

Z resolution

$$\sigma_z = 2.7 \pm 0.1 \ \text{mm}$$

Angular resolution

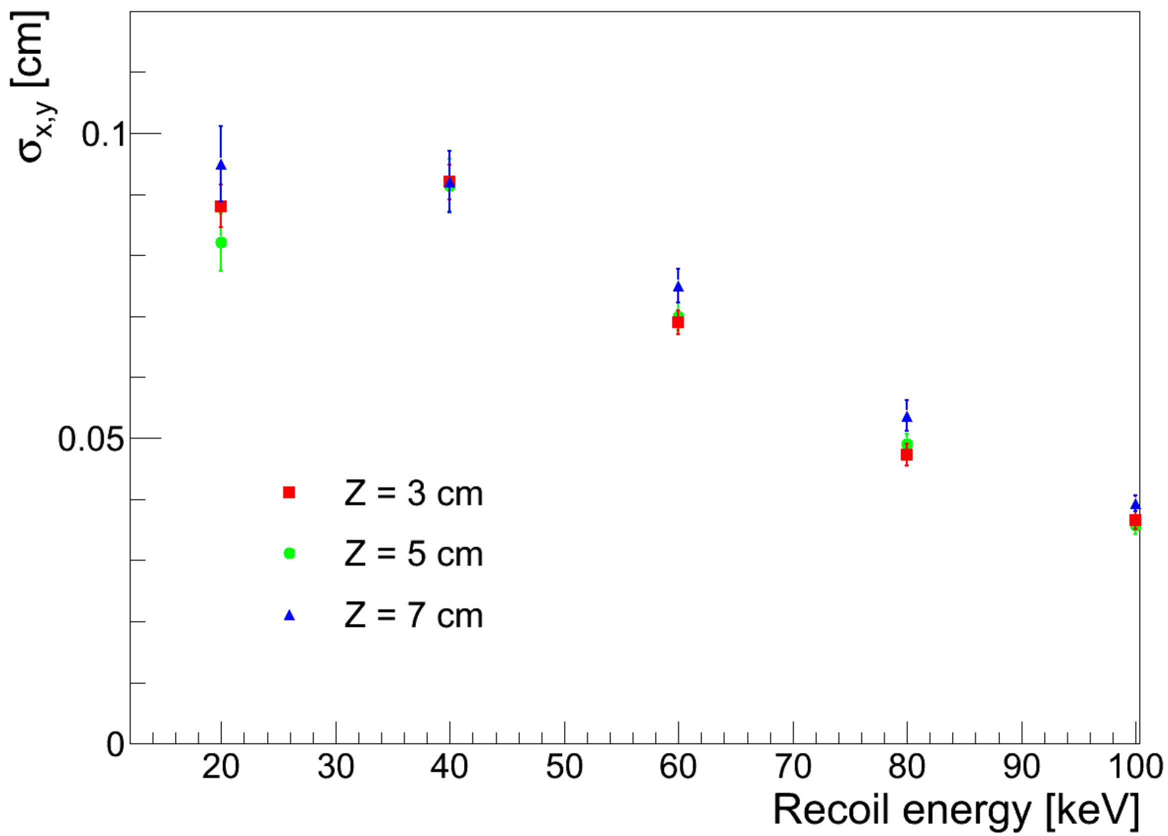
$$\sigma_\gamma = 23.7 \pm 0.6^\circ$$

(With an intrinsic opening angle of 18°)

III.d) Resolution in the (X,Y) plan

For each recoil energy simulate 1000 tracks

Tracks are generated isotropically in the lower half sphere (downward)



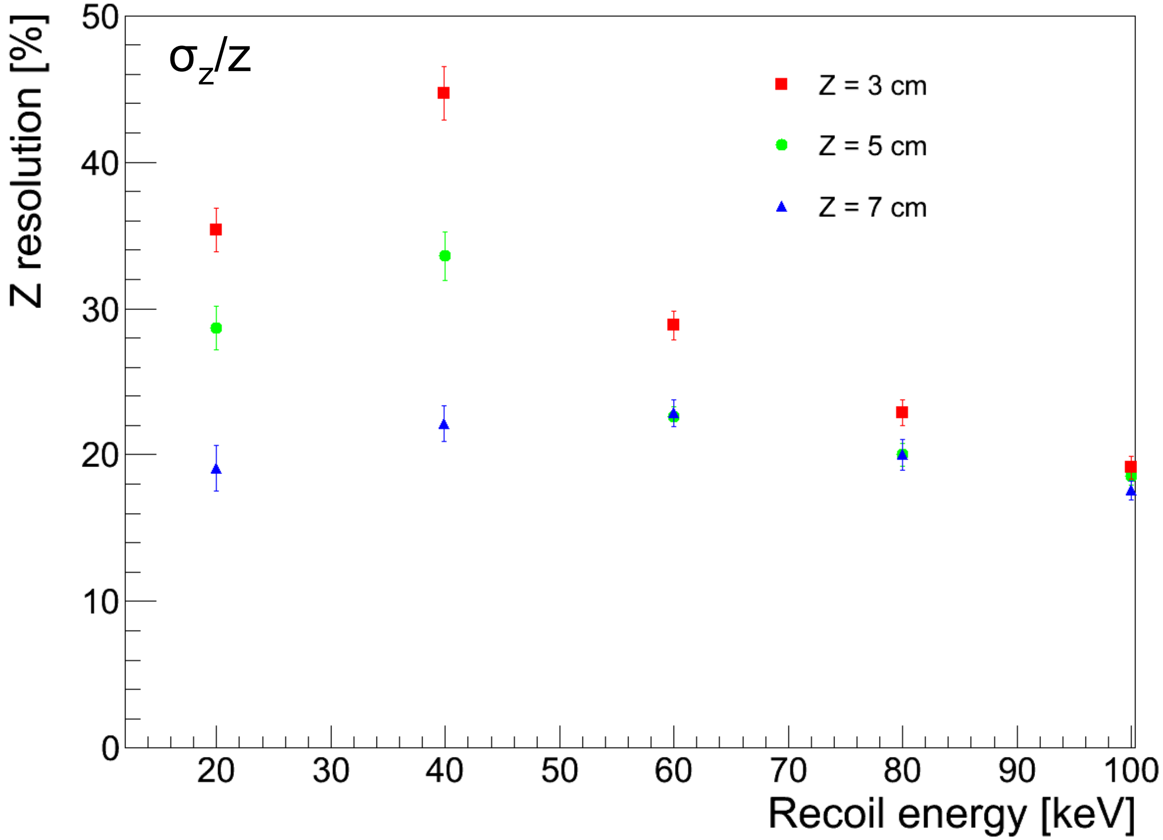
Resolution on the (X,Y) plan is from ~1mm at 20 keV to 0.4 mm at 100 keV

Depends on the energy but not on Z

III.d) Resolution in the Z axis

For each recoil energy simulate 1000 tracks

Tracks are generated isotropically in the lower half sphere (downward)



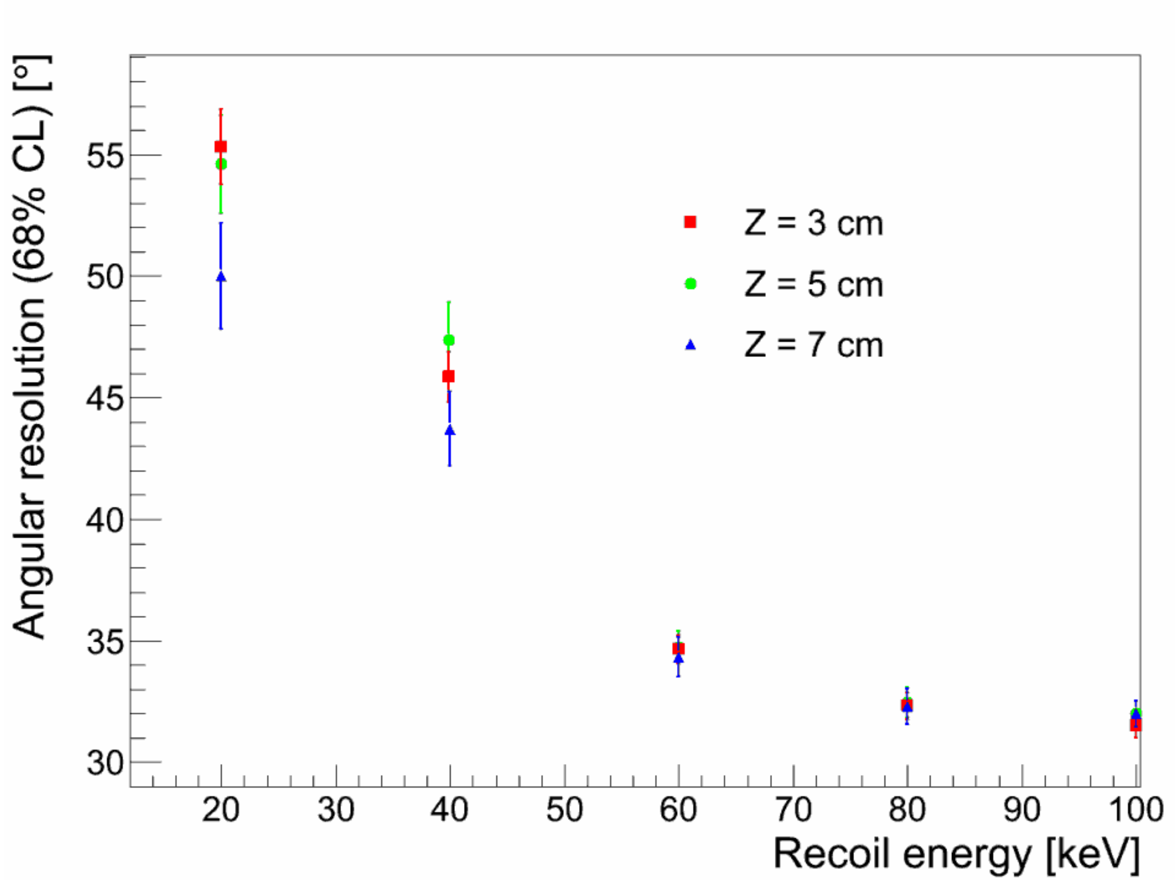
Resolution in the Z axis is from ~1.5 mm at 40 keV to 1 mm at 100 keV

Depends mildly on energy but strongly on Z

III.d) Angular resolution

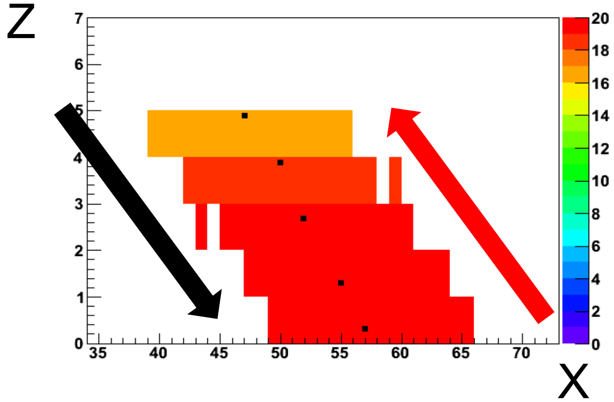
For each recoil energy simulate 1000 tracks

Tracks are generated isotropically in the lower half sphere (downward)



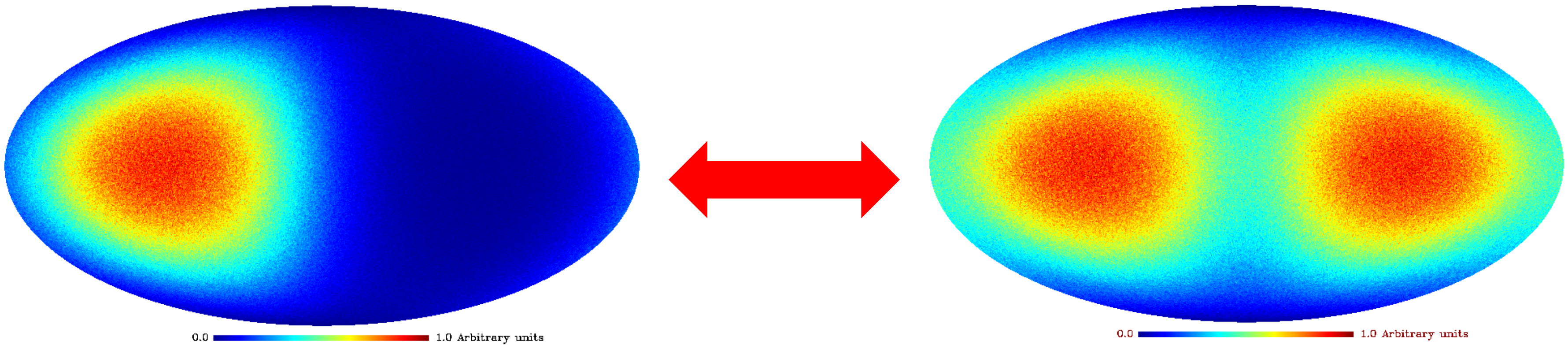
Angular resolution is from ~ 50-55° at 20 keV to 32° at 100 keV

Depends on the energy but not on Z



Toward a head-tail discrimination?

J. Billard et al., in preparation

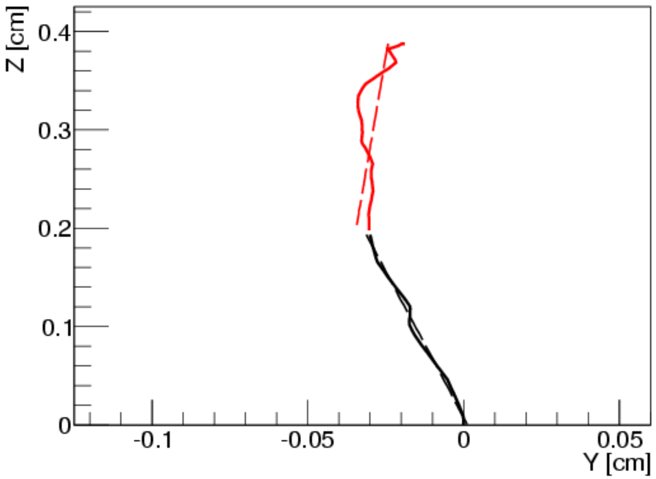


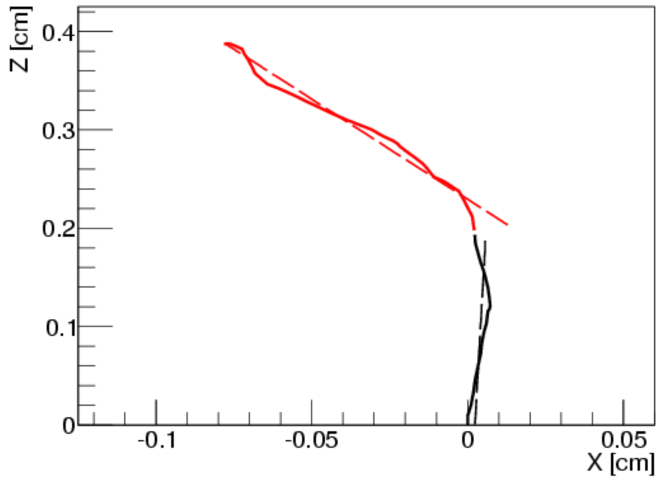
WIMP event distribution with Head-Tail

WIMP event distribution without Head-Tail
Tends to isotropy

III.d) Spatial asymmetry

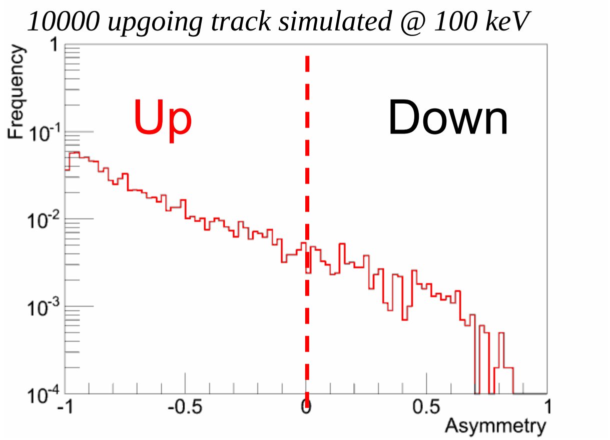
From SRIM simulations, we found an asymmetry due to spatial straggling:





The begining of the track should be more linear than its end

Asymmetry factor which is negative/positive for upgoing/downgoing tracks



More than 92% of the tracks present a negative asymmetry in favor of upgoing tracks!

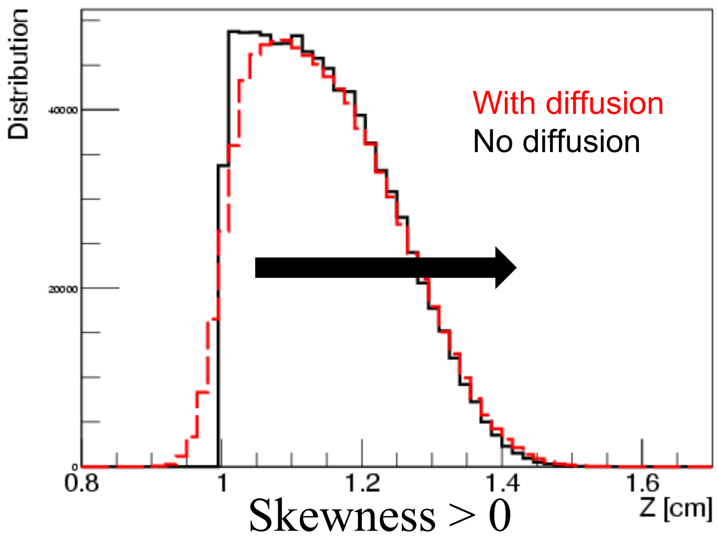
III.d) Charge collection asymetry

The Bethe-Bloch model of the dE/dx is uncertain for recoiling nucleus @ O(100) keV

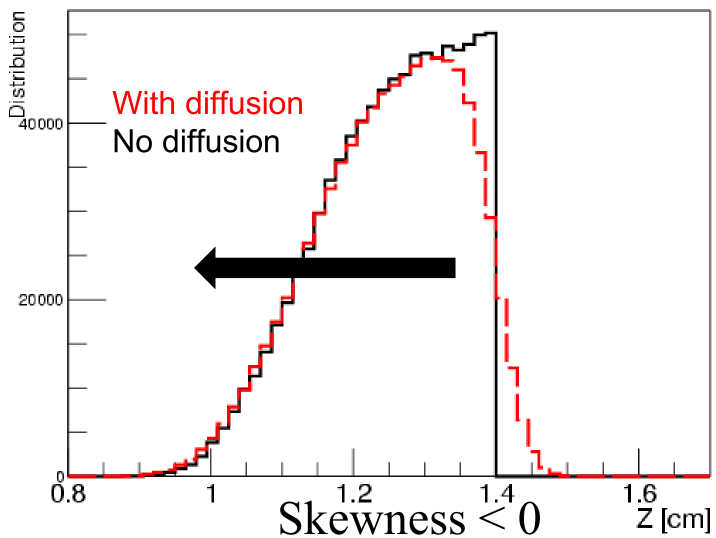
⇒ Lindhard theory predicts a decreasing dE/dx with energy

⇒ More primary electrons should be generated at the begining of the tracks

Charge profile as a function of Z for ***upgoing*** *tracks (10000 tracks)*



Charge profile as a function of Z for ***downgoing*** *track (10000 tracks)*



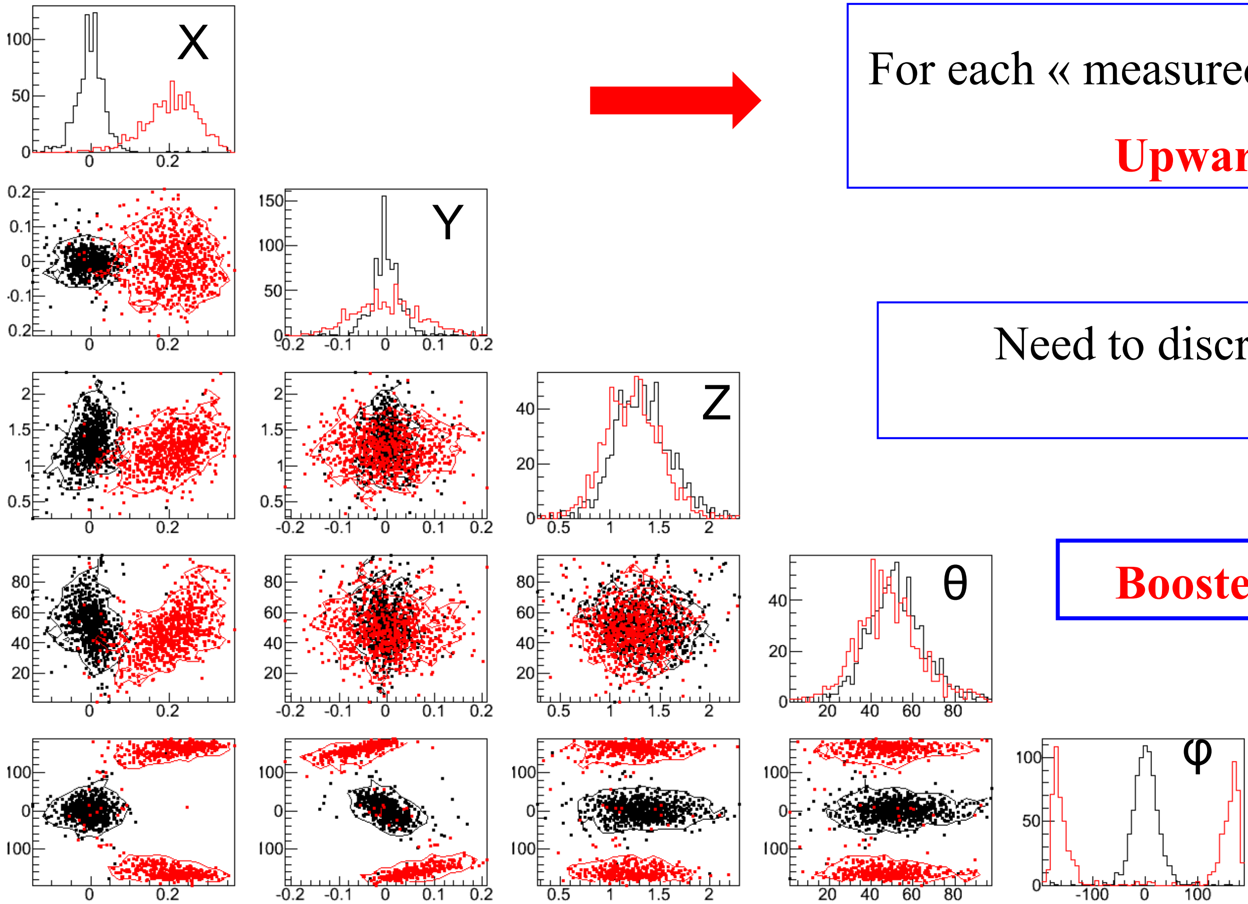
An asymmetry between upgoing and downgoing tracks is expected!

III.d) The two hypothesis: max-Likelihood

Estimation of the maximum likelihood for the two hypothesis: **Upward** and **Downward**

Input

X = 0 cm, Y = 0 cm, Z = 1.3 cm, θ = 45°, φ = 0°, **Downward** @ 100 keV



For each « measured track » two hypothesis:

Upward and **Downward**

Need to discriminate between the two hypothesis

Boosted Decision Tree

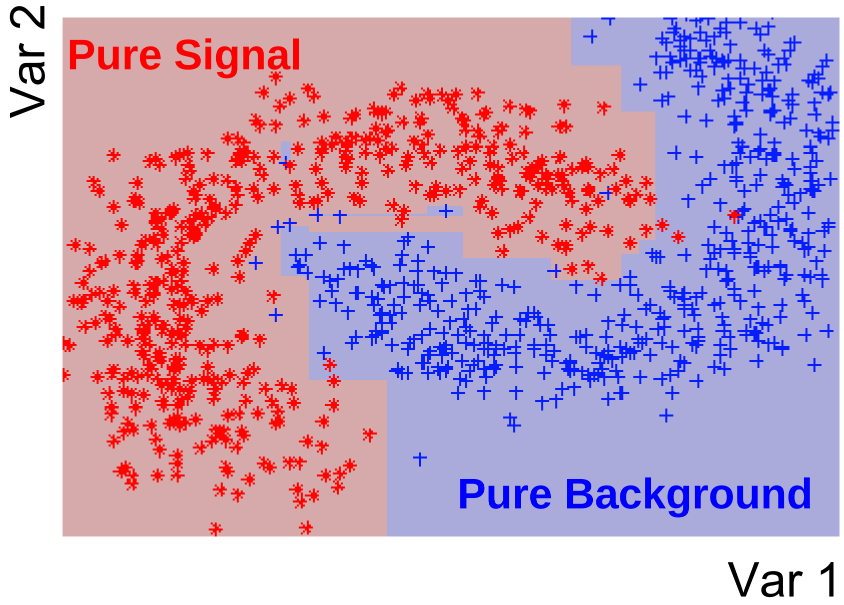
Multivariate analysis: Boosted Decision Tree (BDT)

The Boosted Decision Tree can be considered as a classifier (signal/background)

Optimisation of linear cuts on the different observable/variable

$(X_1^{bary}, Y_1^{bary}, \Delta X_1, \Delta Y_1, Nelec_1, \ldots, X_N^{bary}, Y_N^{bary}, \Delta X_N, \Delta Y_N, Nelec_N)$

Illustration of a boosted decision tree with two variables



• Defines contour regions to discriminate Background and Signal (Up/Down)

• Can easily manage a high number of observables/variables

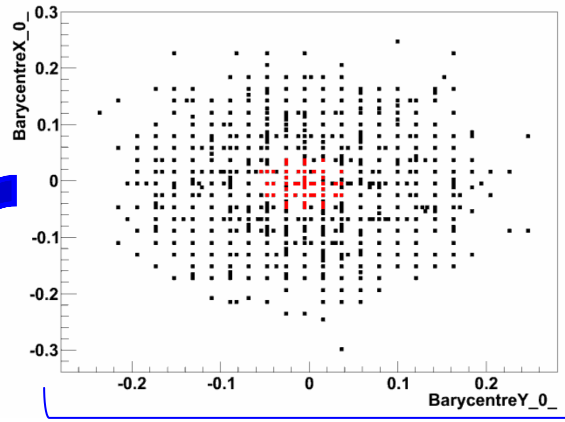
• It requires a very little calculation time

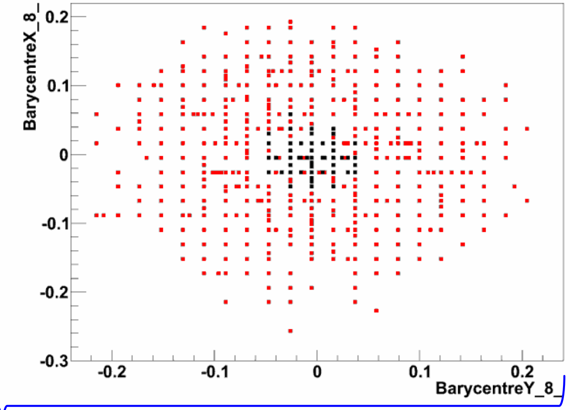
Well suited for Head-Tail discrimination

Multivariate analysis: Boosted Decision Tree (BDT)

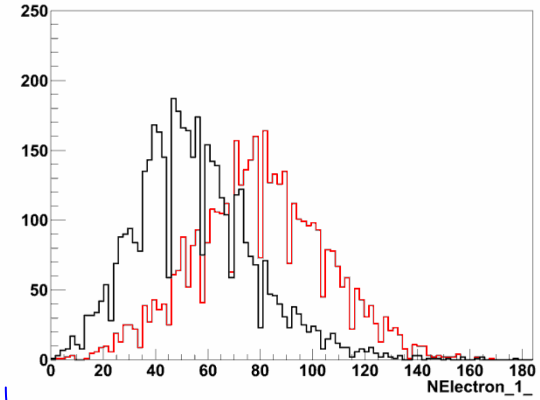
The recipe:

- Generate a large sample of tracks (10000) for the two hypothesis
- Use a fraction of it to train your Boosted Decision Tree
- Check for overtraining





Spatial discrimination



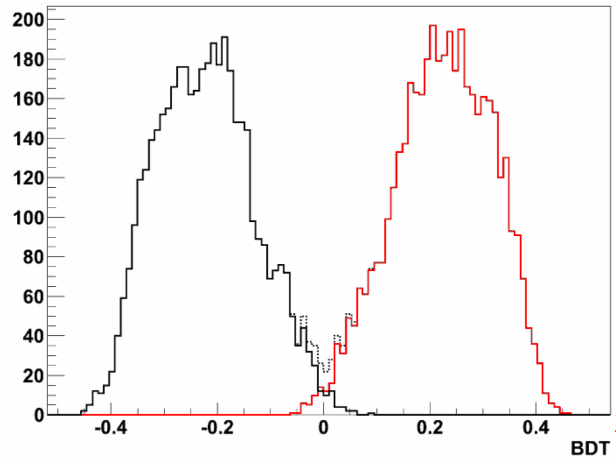
Charge discrimination

It returns a function defined as:

BDT = f(X)

if Upward track: BDT > 0

if Downward track : BDT < 0



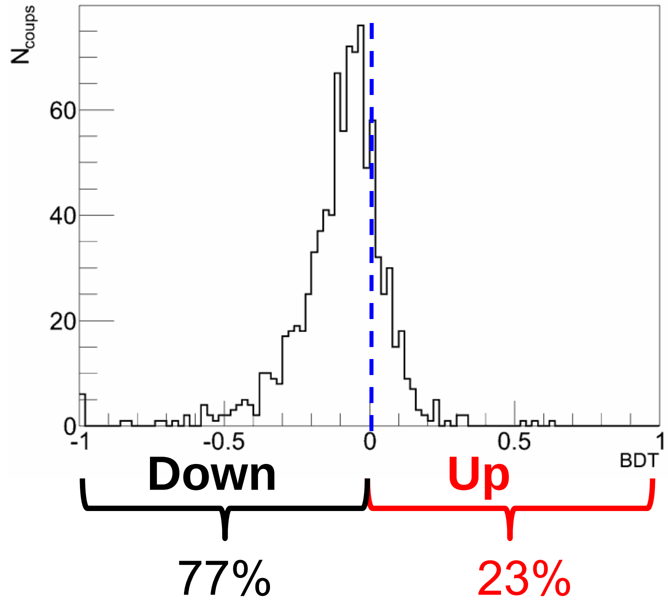
A discrimination power of 99%!

III.e) Sense recognition: Head-tail effect

Once the Boosted Decision Tree is set up, use it to estimate the BDT value of the pseudo track:

Input

X = 0 cm, Y = 0 cm, Z = 1.3 cm, θ = 45°, φ = 0°, **Downward** @ 100 keV



How to take a decision?

- if BDT > 0 Upward track
- if BDT < 0 Downward track

The sense recognition efficiency is about 77% in these conditions

… or to not take a decision?

Just consider the probability to be Up/Down and propagate it into your prefered Dark Matter run analysis

To be confirmed with experimental data!!

Conclusion

Track analysis *(likelihood + Boosted Decision Tree method)*: ***(J. Billard et al., in preparation)***

We developed a likelihood approach for track reconstruction

⇒ Optimisation of the reconstruction: expected resolutions are encouraging

⇒ For each track we can quantify the degree of belief of the reconstruction

⇒ All the systematic uncertainties are taking into account

⇒ Can be taken into account in future Dark Matter interpretation (*profile likelihood,…*)

Combined with a Boosted Decision Tree

⇒ Optimisation of the sense recognition by taking every observable into account

⇒ Evaluate the probability for both hypothesis (Up/Down) to take a decision (or not!)

⇒ In the future we could also use it to discriminate between H, C, F and electronic recoils

Need to be confirmed with experimental data, ongoing…