Advanced Reconstruction in Large Volume Liquid Scintillator Detectors

Applied to LENA

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

Overview

- **Tracking at high energies (GeV)**
  - Basic algorithm
  - Performance

- **Application to low energies (MeV)**
  - New techniques to improve robustness
  - Positron discrimination

Motivation: Tracking at High Energies

ν_e appearance experiments:

NC-background

→ Is it possible to identify the π_0?

Reactor experiments

Short-lived cosmogenics (^{9}Li/^{8}He) dangerous background

Full veto produces too much deadtime

→ Identify places of high energy deposition

(showers induced by muon)

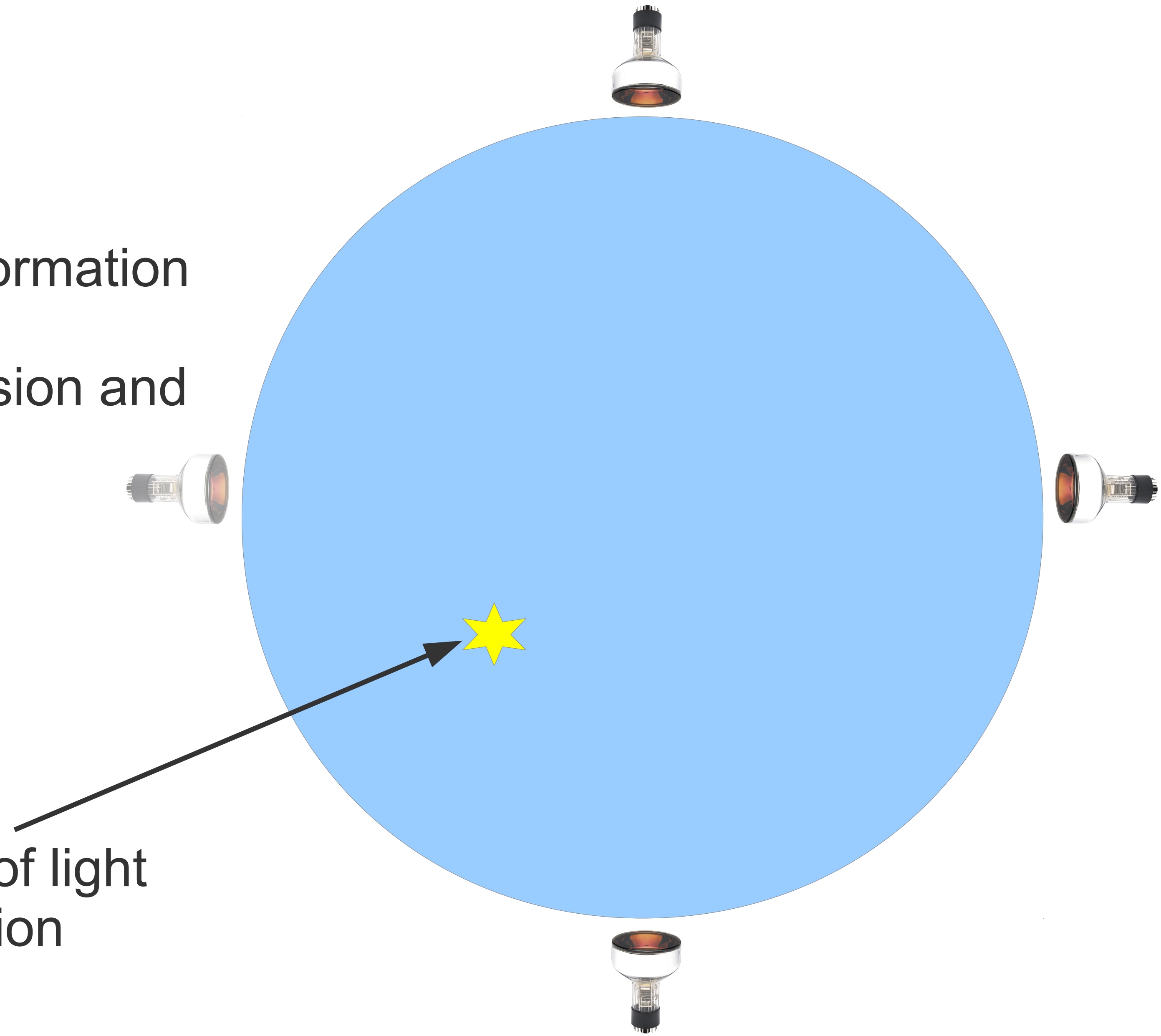
Why no 3D Tracking (so far)?

Point-like event:

Light emitted in 4π
→ no directional information

Time between emission and detection = distance

→ Circles



Point of light emission

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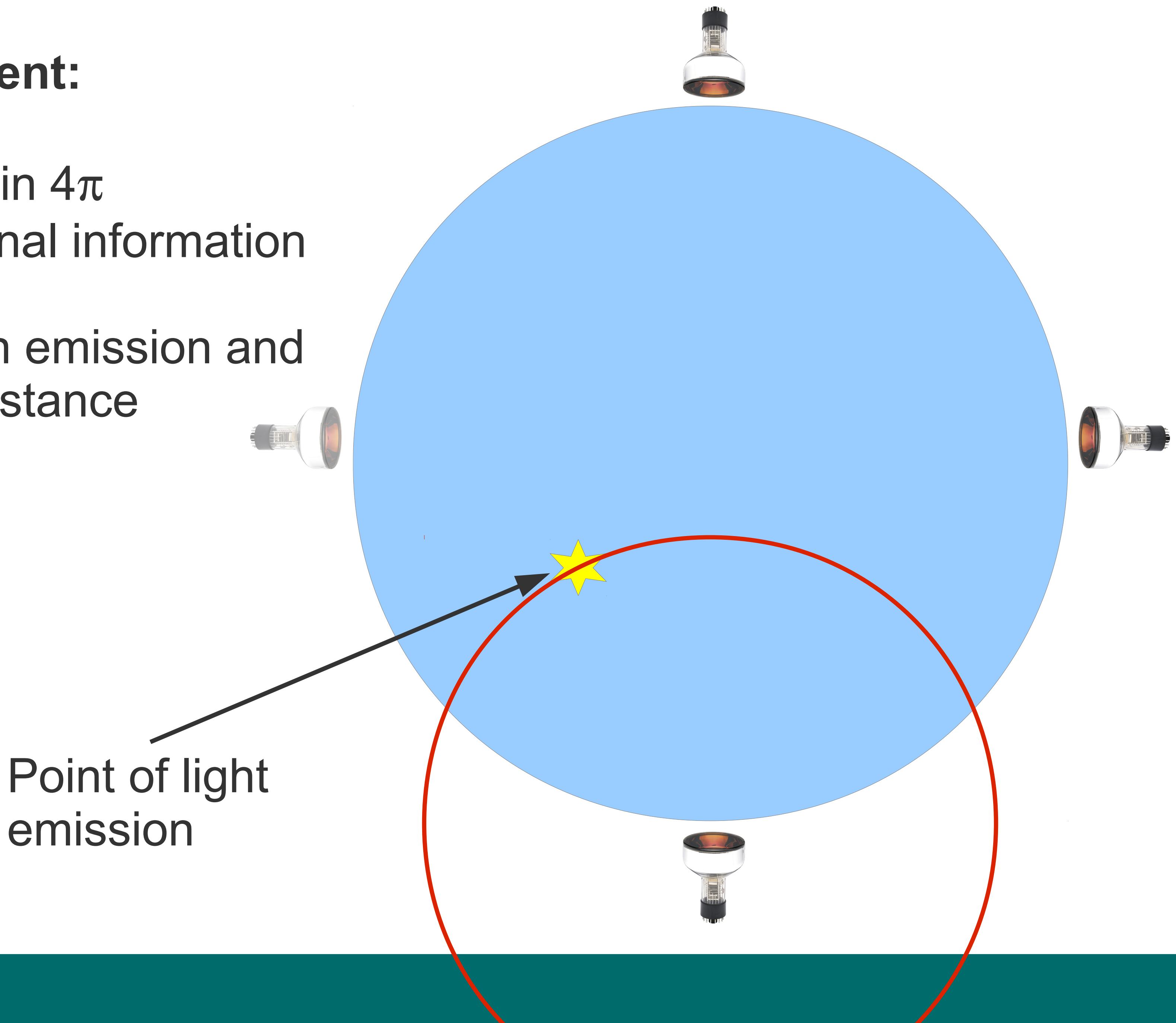
$\rightarrow$ Circles



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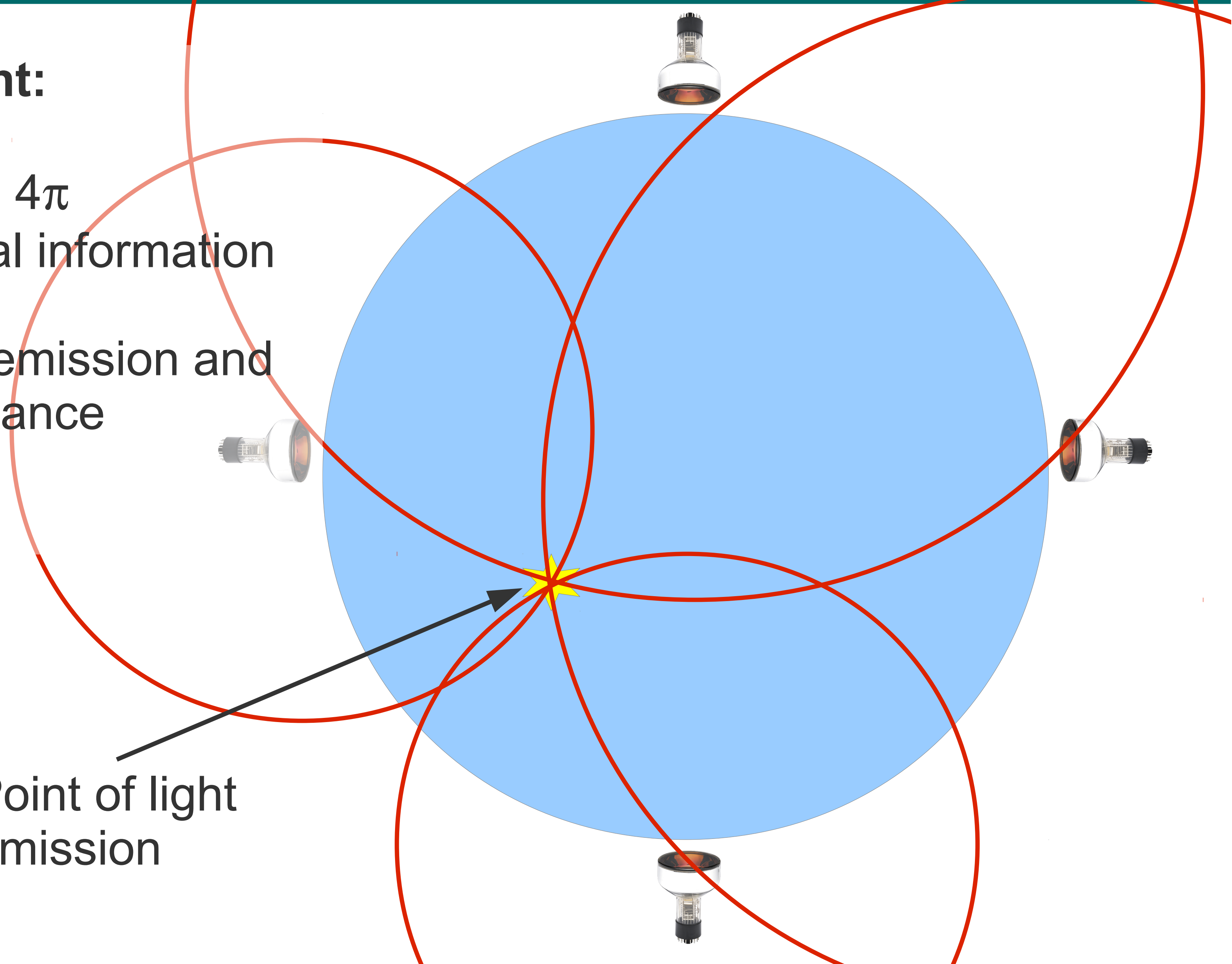
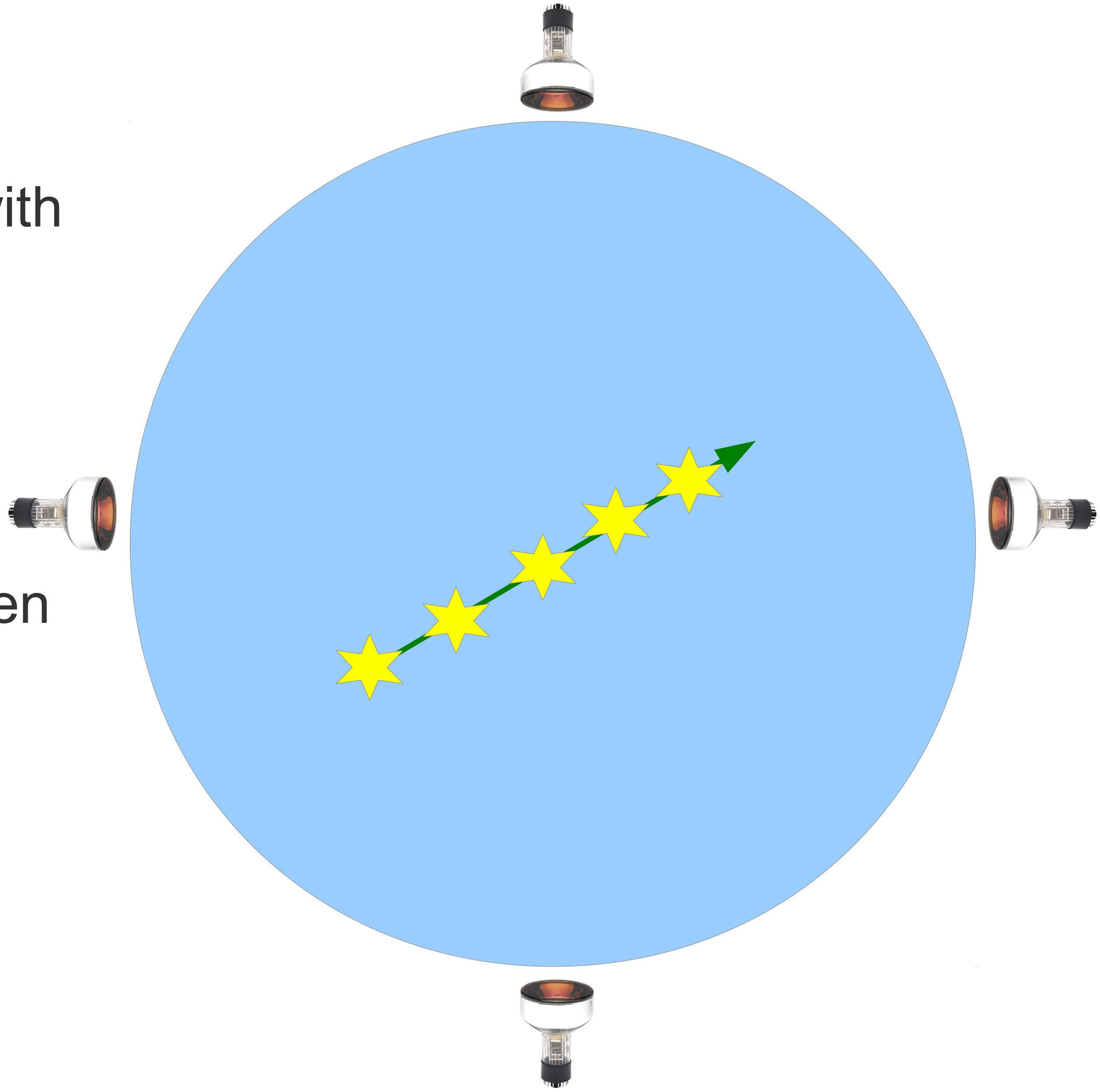


Why no 3D Tracking (so far)?

Track:

Lots of emission points with different emissions times

→ No association between signal and emission time



My Basic Idea

Assumption:

- One known reference-point (in space & time)
- Almost straight tracks
- Particle has speed of light

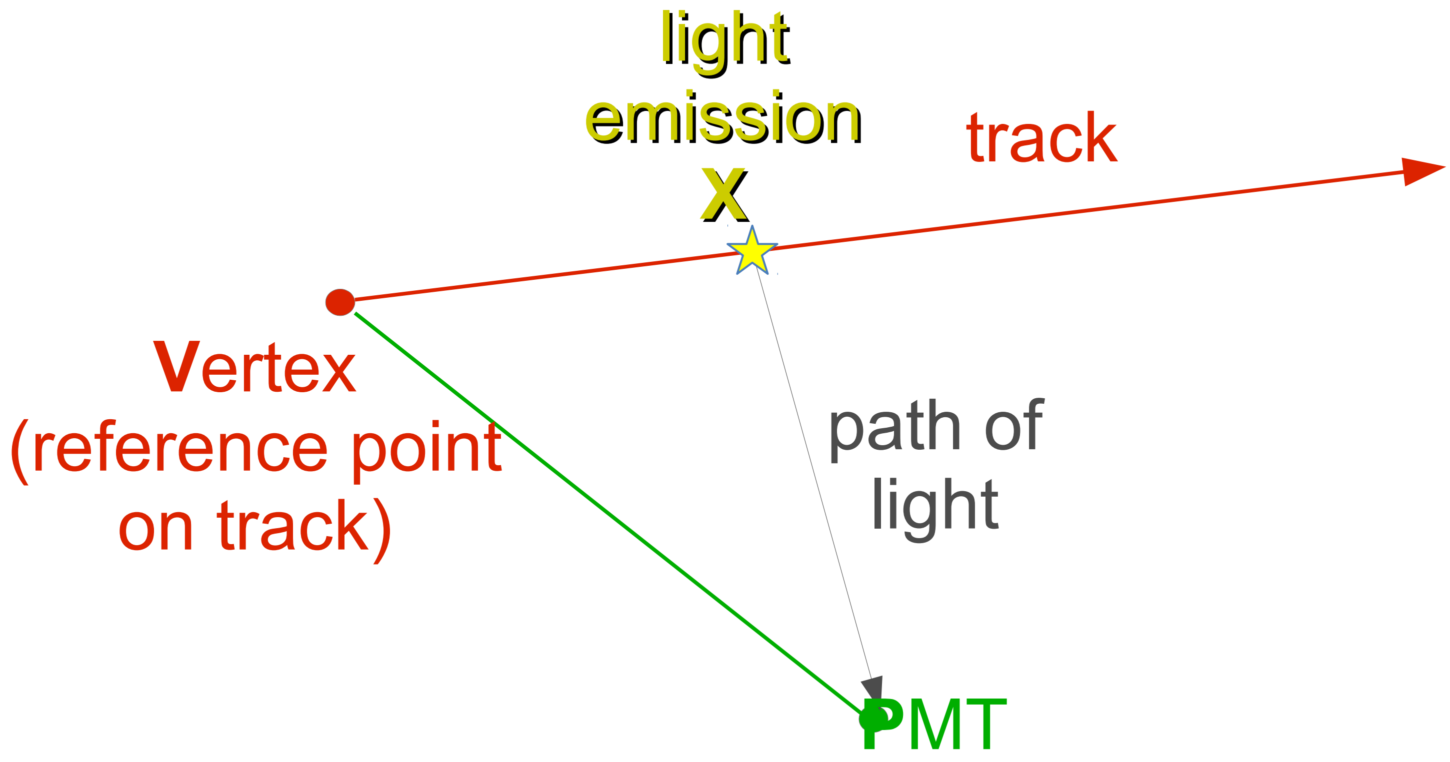
Concept:

- Take this point as reference for all signal times

The Drop-like Shape

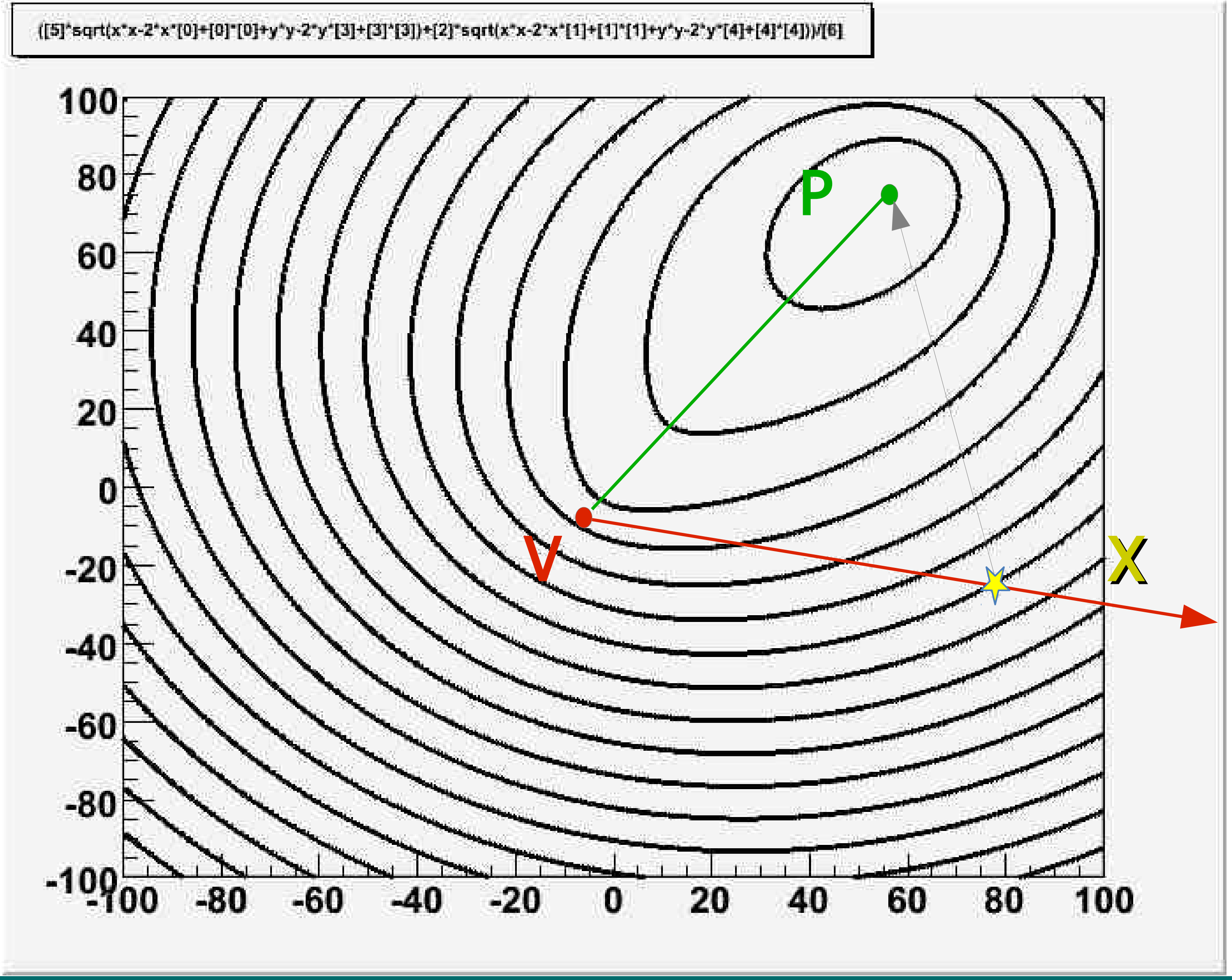
Signal time = particle tof + photon tof

→ ct = |VX| + n*|XP|



The Drop-like Shape

ct = |VX| + n*|XP| → drop-like form



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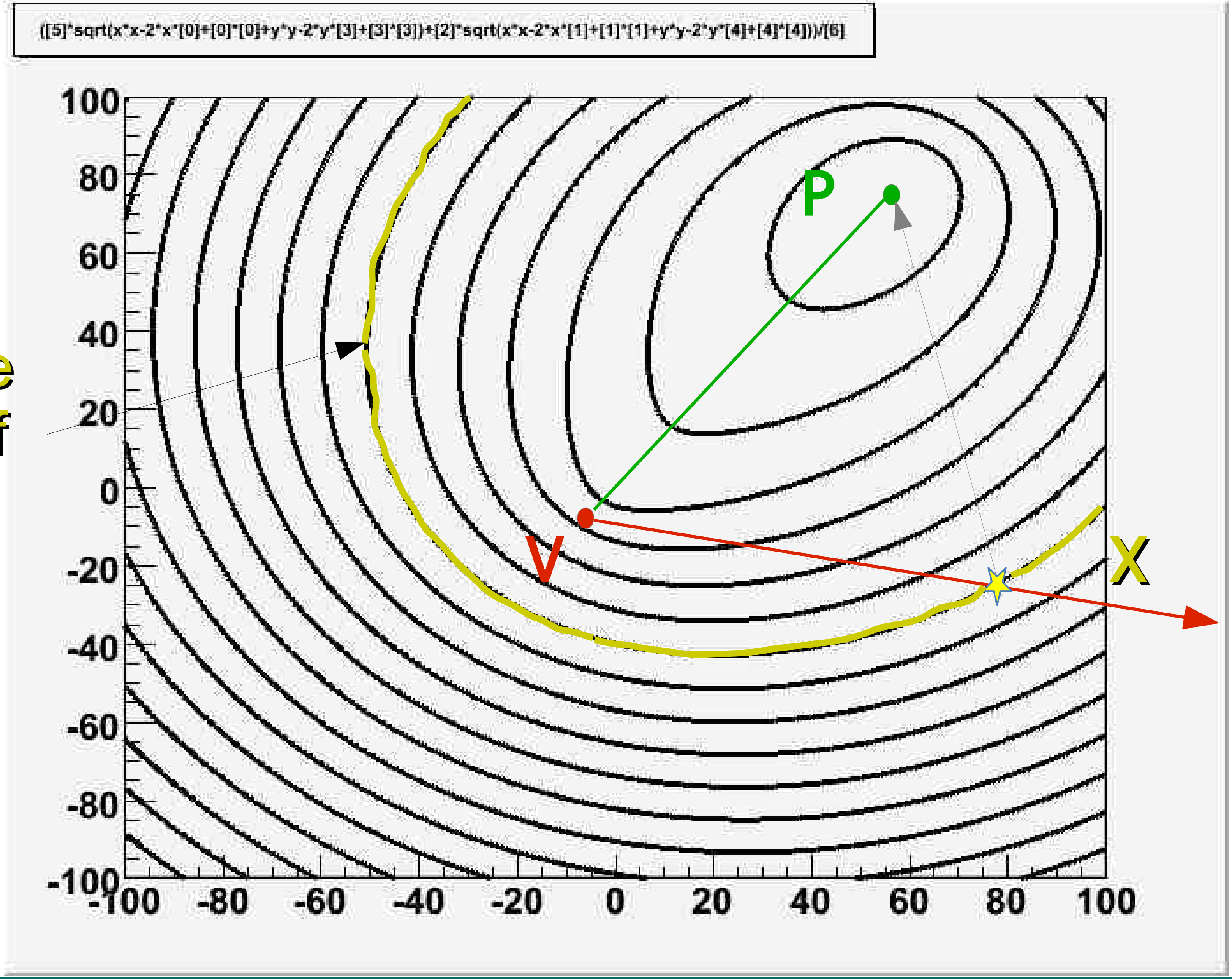
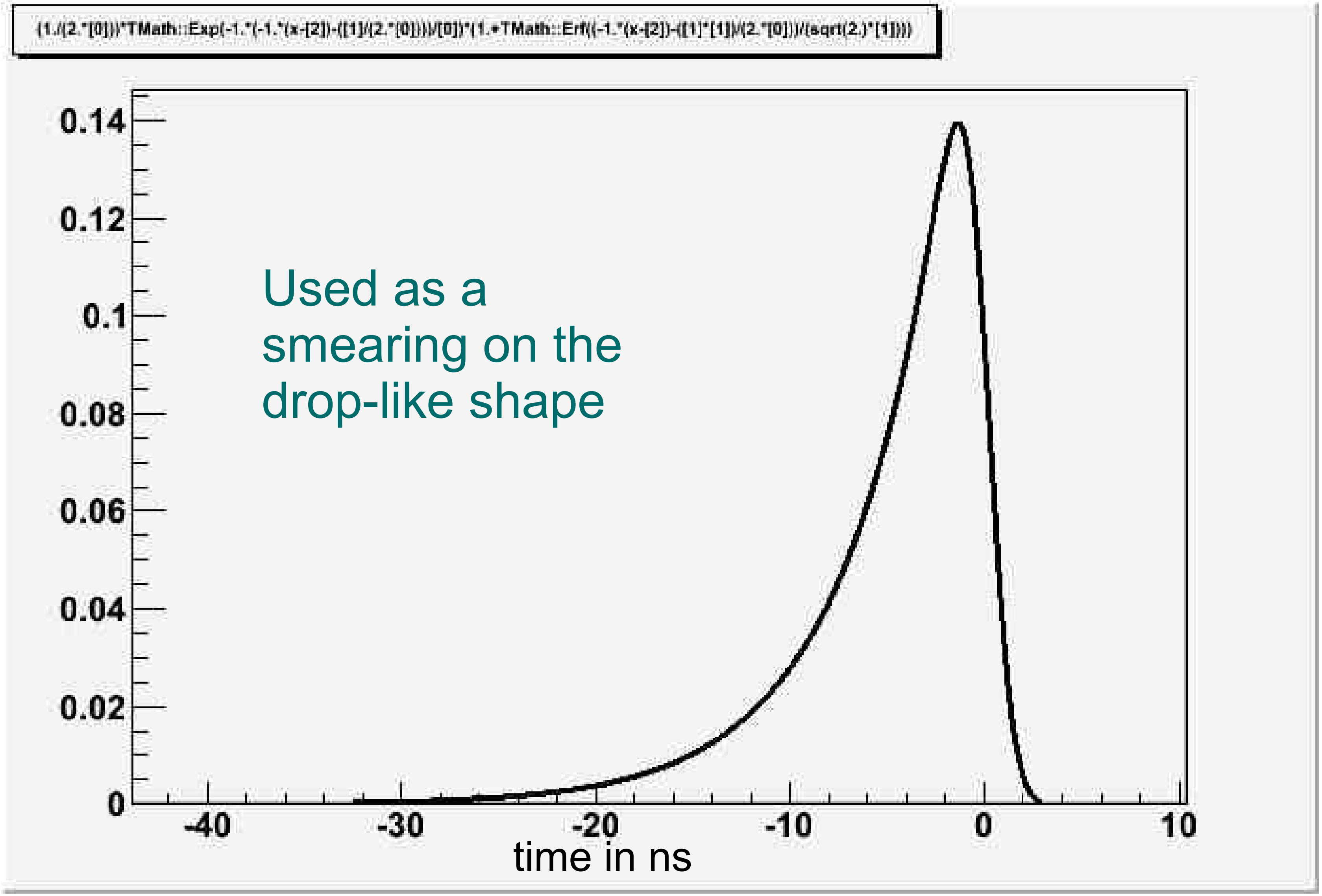


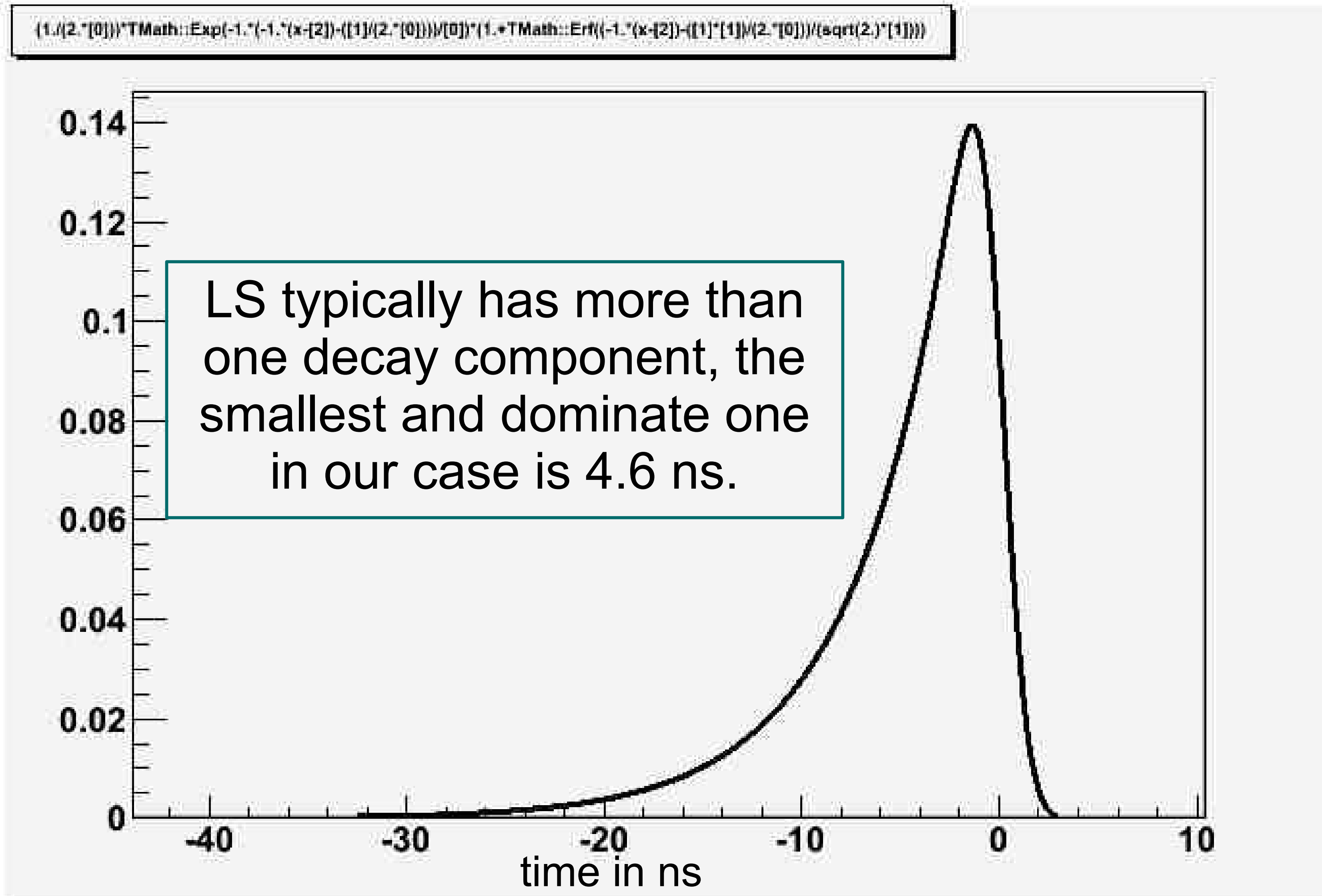
Possible origin of light

Time Distribution



Convolution of Gaus and Exponential-Function

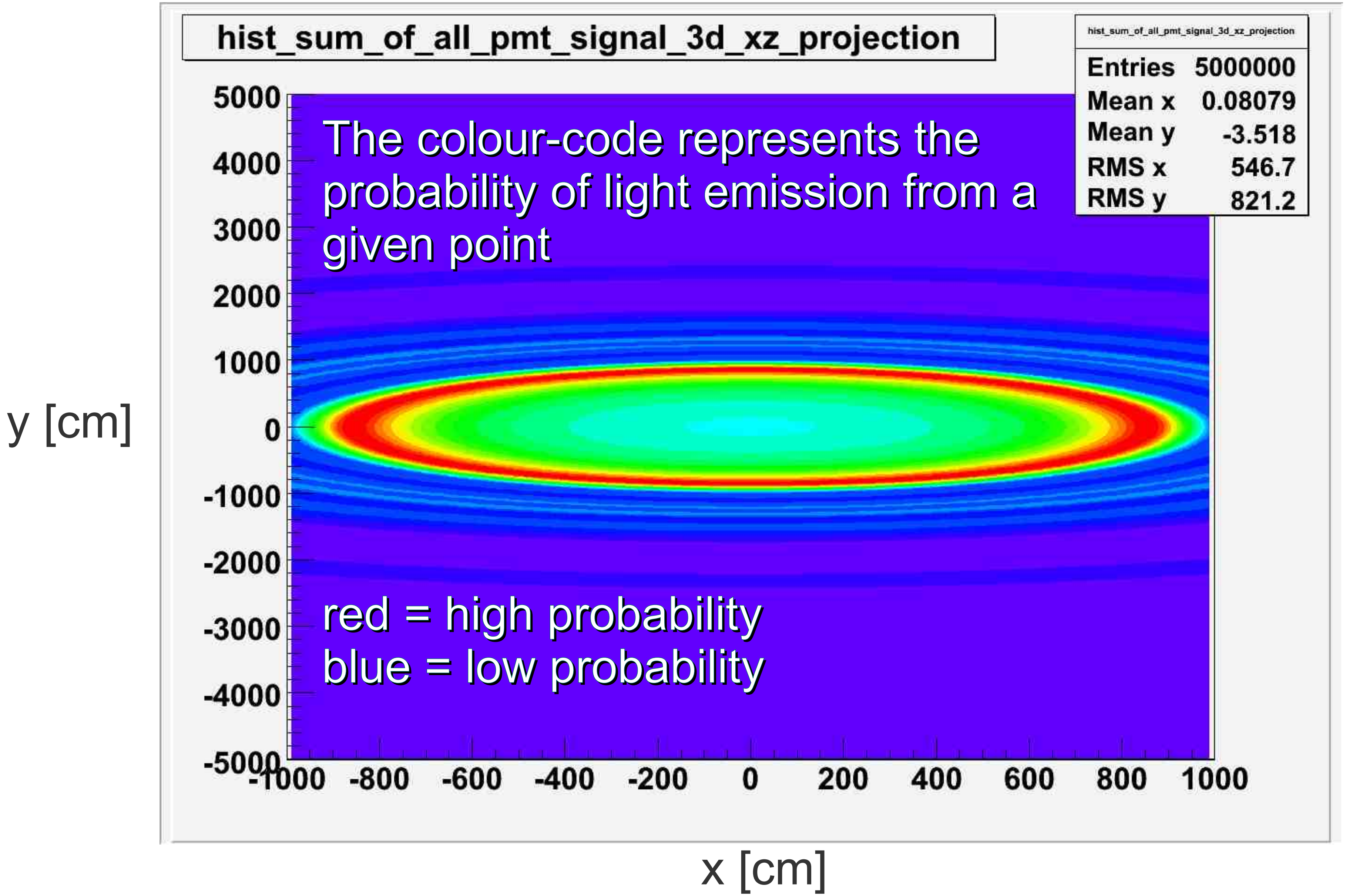
Time Distribution



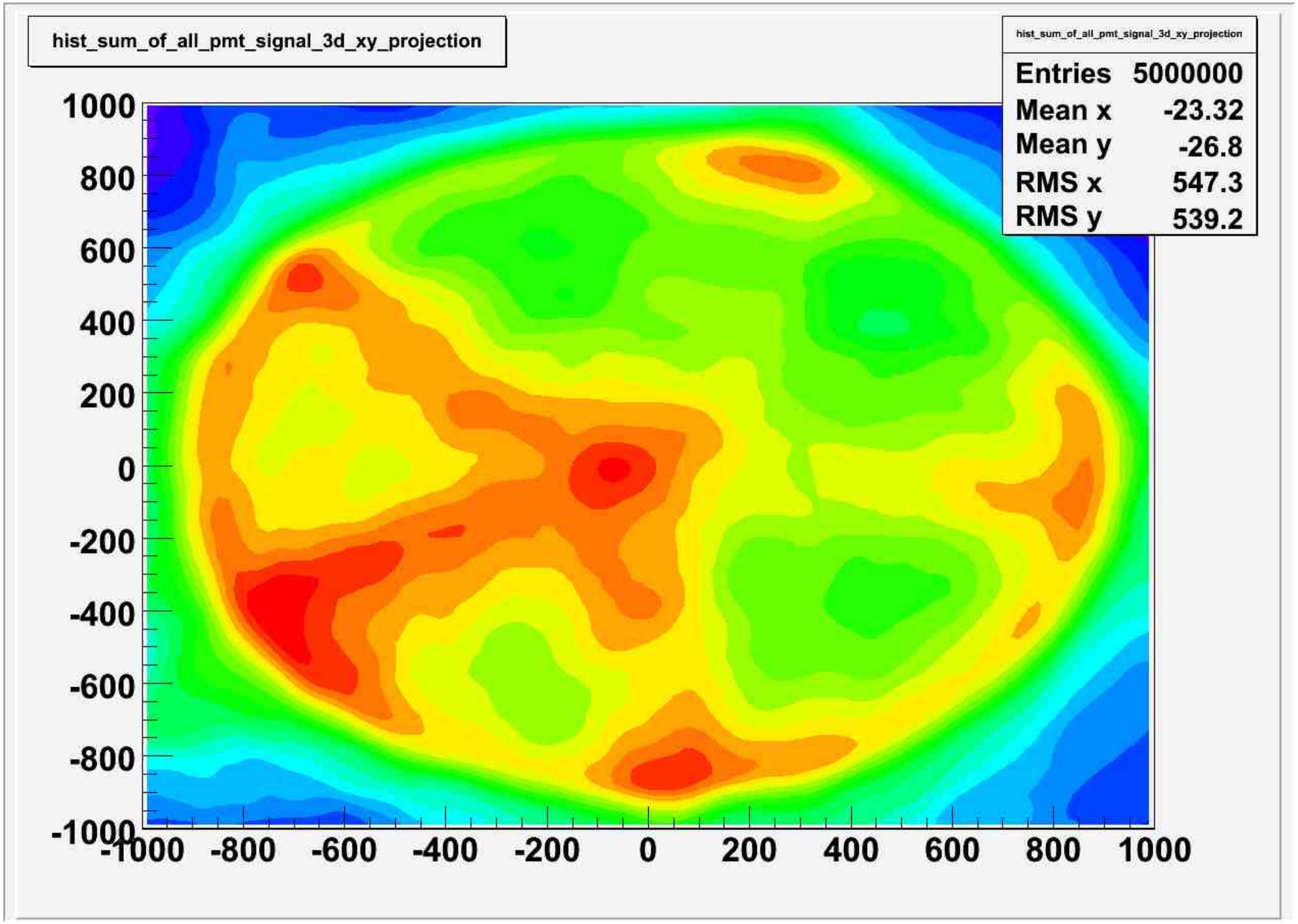
LS typically has more than one decay component, the smallest and dominate one in our case is 4.6 ns.

Convolution of Gaus and Exponential-Function

Result 1 PMT


hist_sum_of_all_pmt_signal_3d_xz_projection
Entries 5000000
Mean x 0.08079
Mean y -3.518
RMS x 546.7
RMS y 821.2
The colour-code represents the probability of light emission from a given point
red = high probability
blue = low probability
y [cm]
x [cm]
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-1000
-800
-600
-400
-200
200
400
600
800
1000

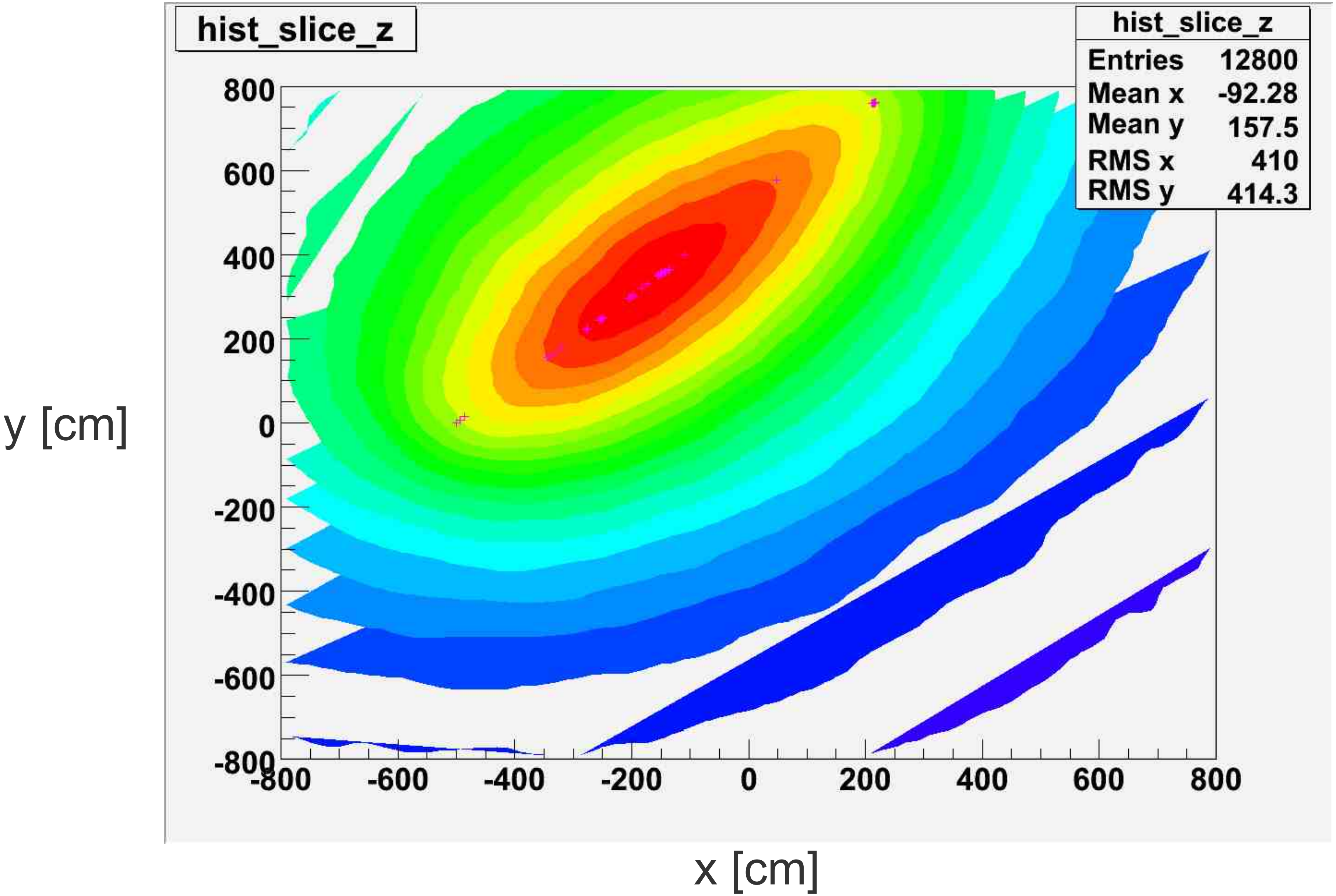
Result a Few PMTs



y [cm]

x [cm]

Result 266 PMTs



Light Distribution (LD) Effects

Some parts of each drop-like shape are more likely the origin of light, because:

- they are closer
- directly in front of the PMT

→ Need to consider:

- solid angle of PMT area
- attenuation
- angular acceptance

Light Distribution (LD) Effects

Some parts of each drop-like shape are more likely the origin of light, because:

- they are closer
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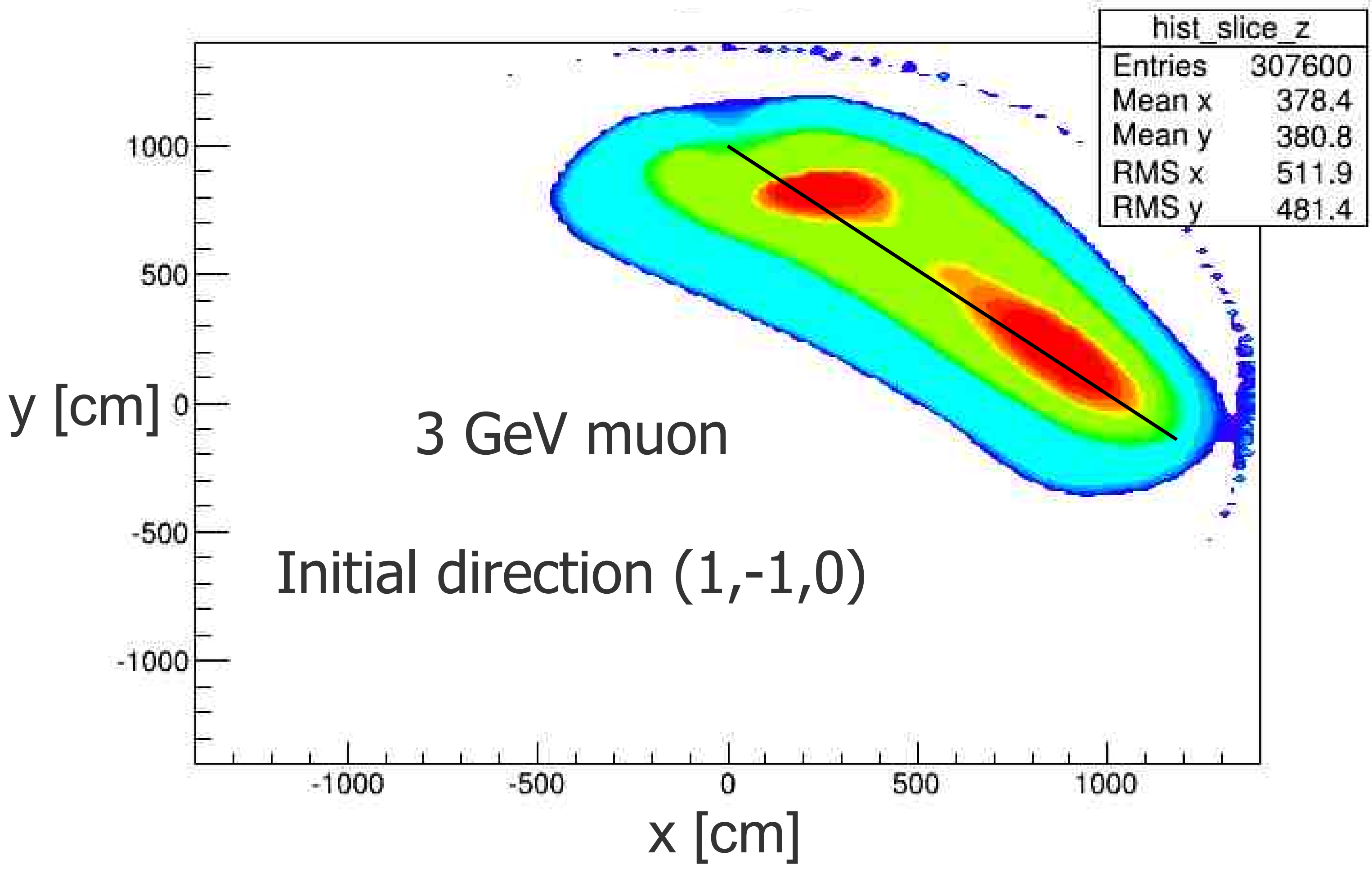
→ Need to consider:

- solid angle of PMT area
- attenuation
- angular acceptance

Finally I have to normalise the resulting pdf !

Result all PMTs



Probability Mask

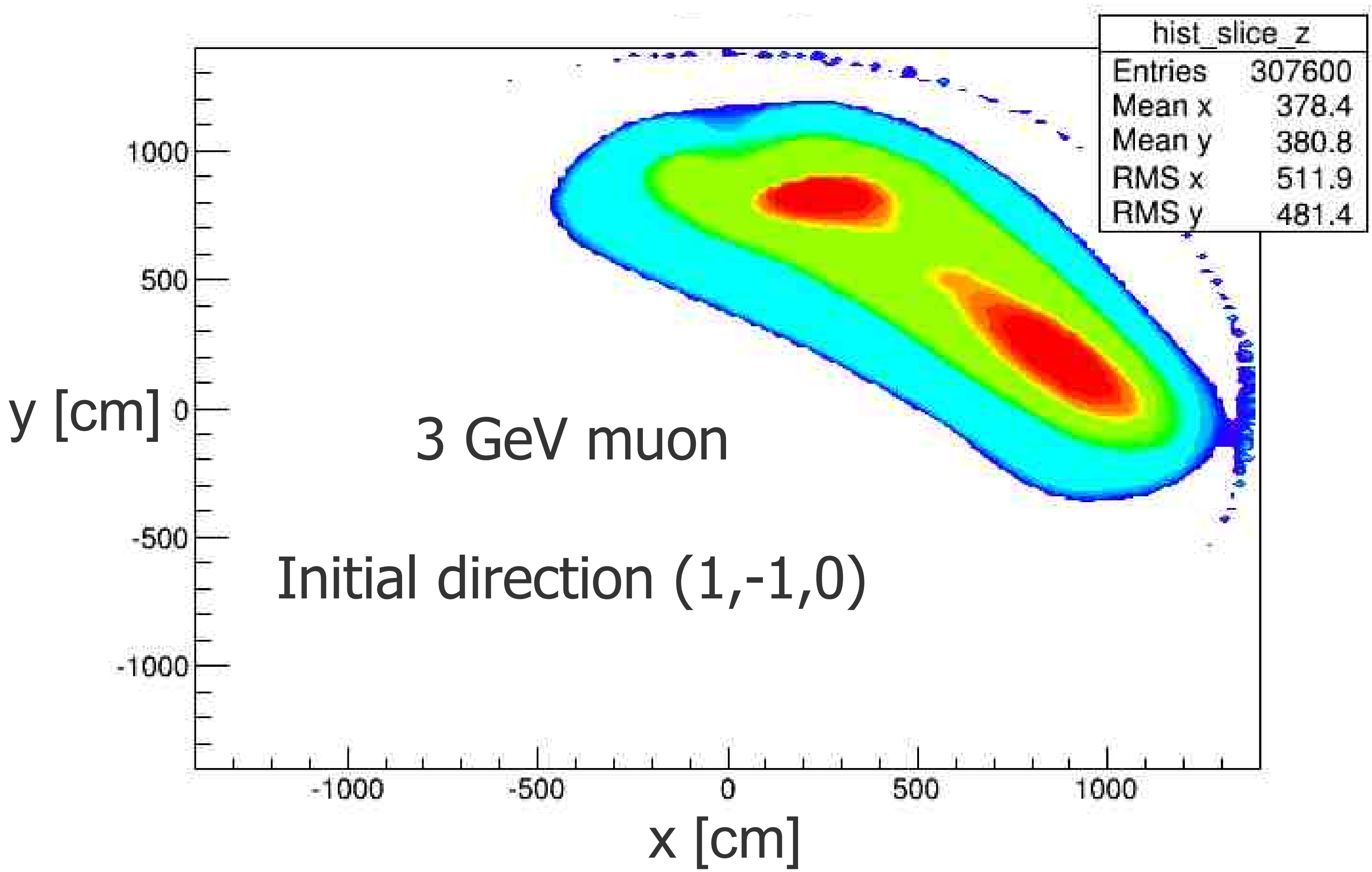
So far probabilities have been added!
→ correct for **independent information**

However:

Light signals are **not completely independent** from each other, because they belong to the same track.

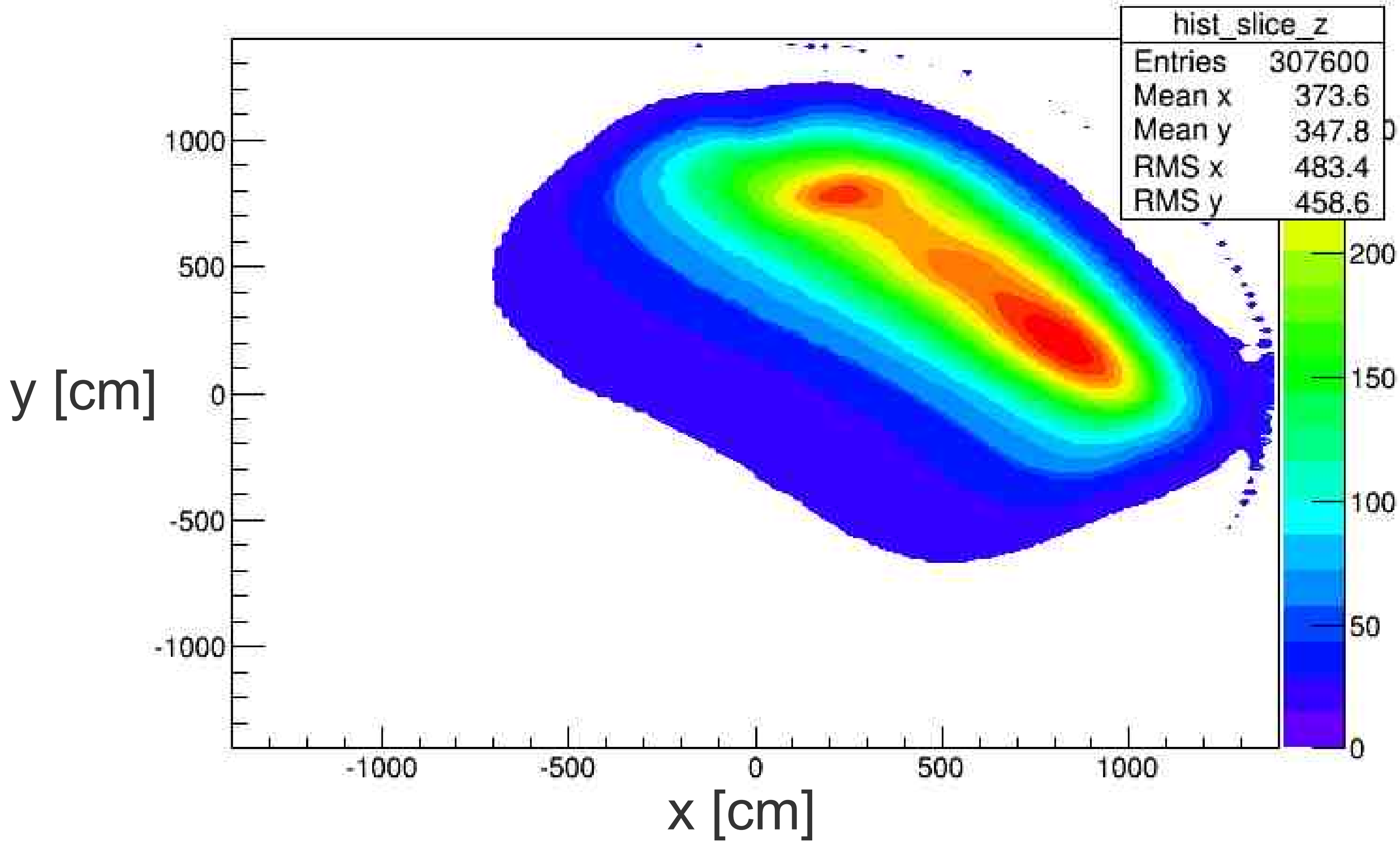
→ Use “Result I” to **weight** all the single light contribution **and re-normalise** each of them!

Result I

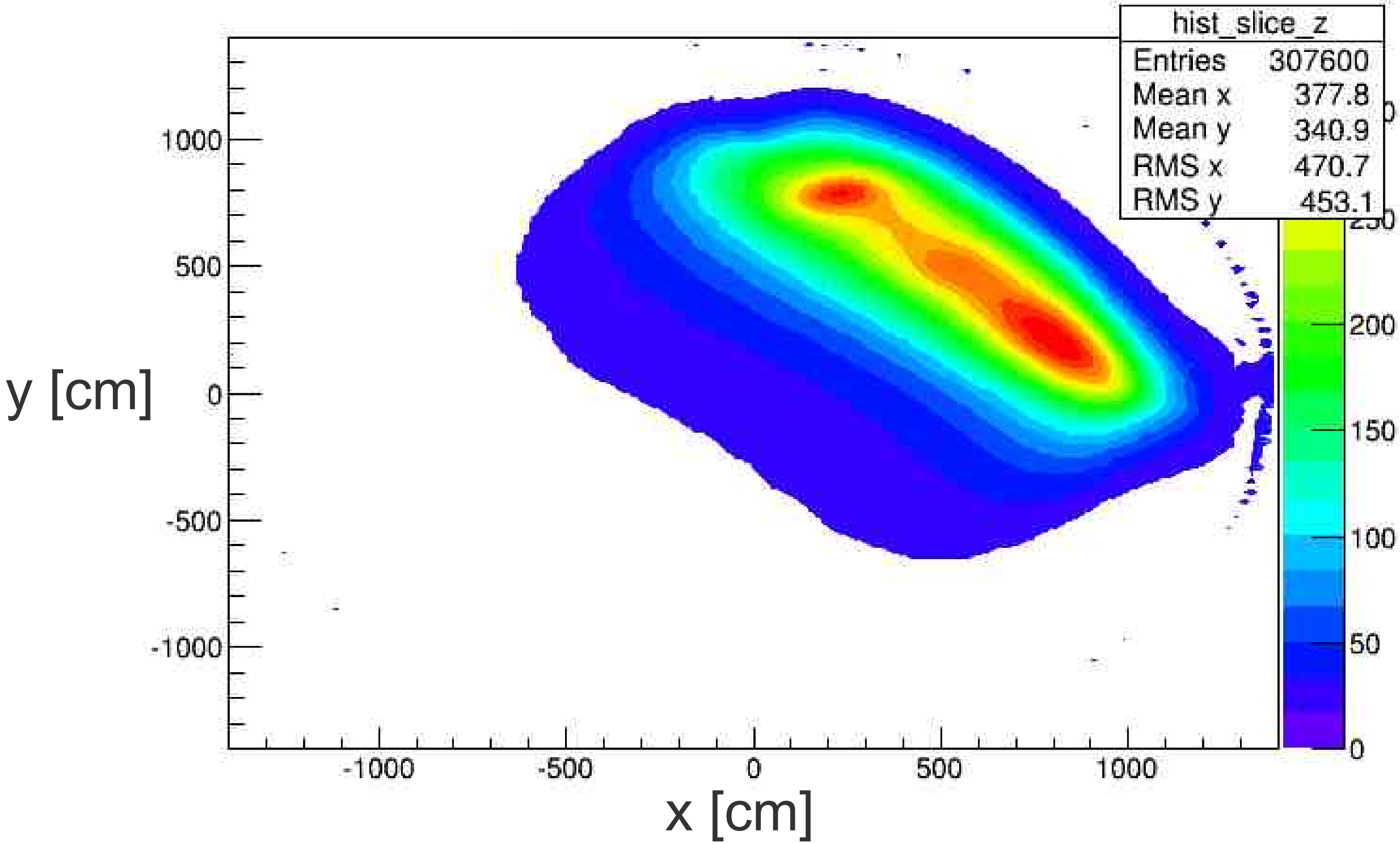


hist_slice_z
Entries 307600
Mean x 378.4
Mean y 380.8
RMS x 511.9
RMS y 481.4
1000
500
0
-500
-1000
y [cm]
3 GeV muon
Initial direction (1,-1,0)
-1000
-500
0
500
1000
x [cm]

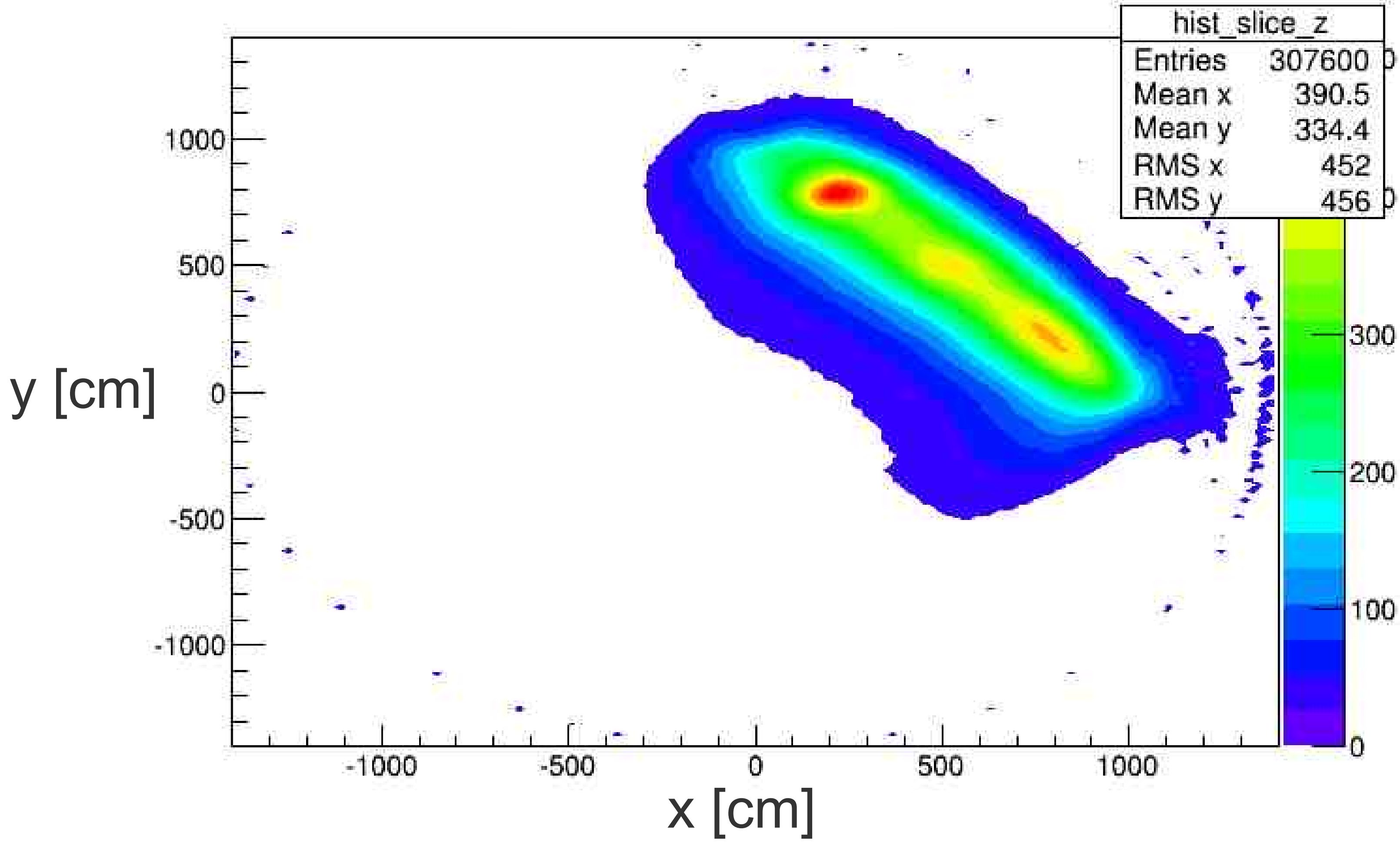
Result 2nd Iteration



Result 3rd Iteration

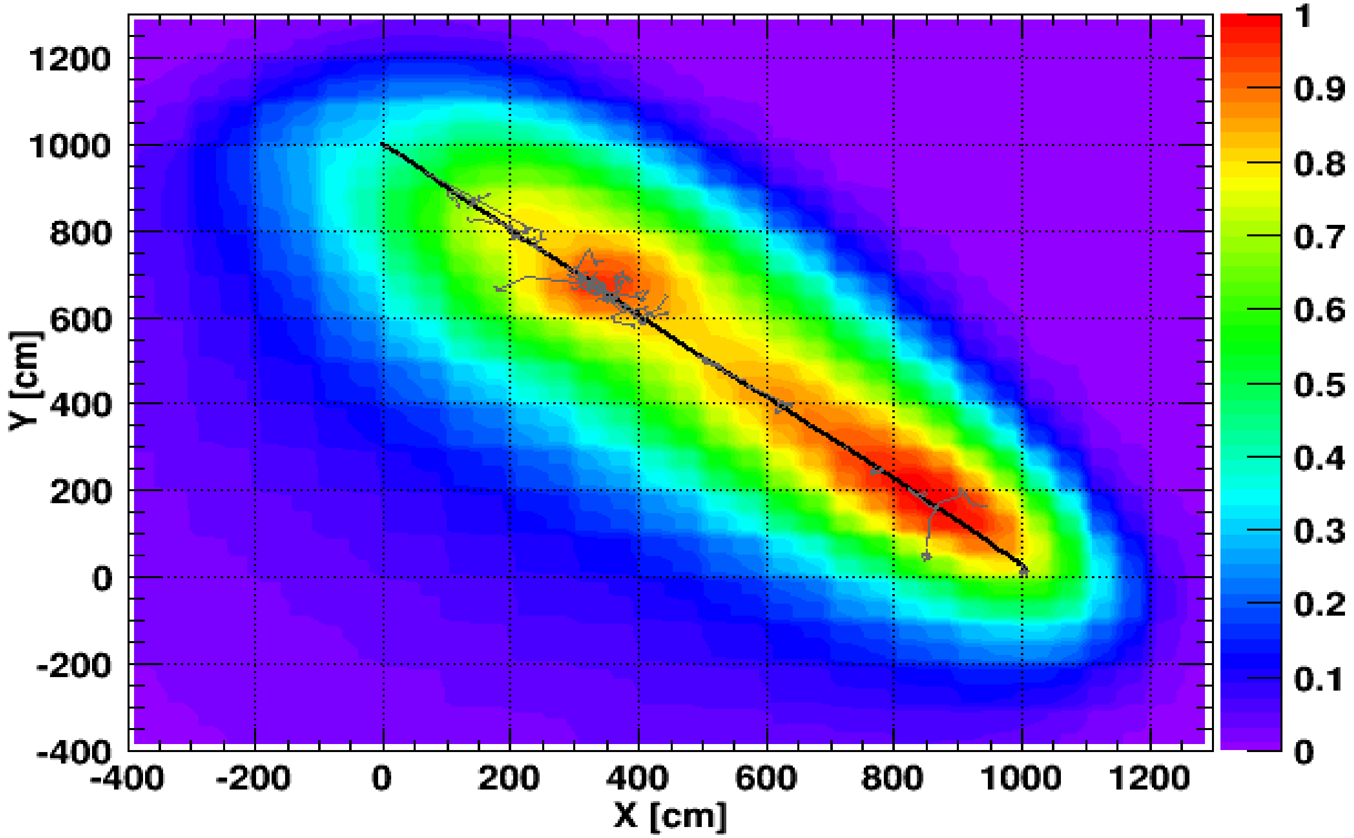


Result 9th Iteration



3D Topology

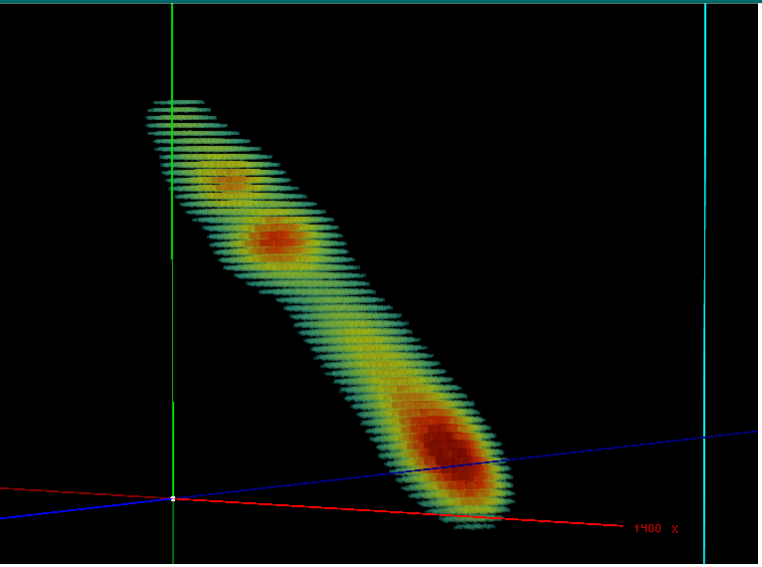
Probability distribution projected into the xy plane

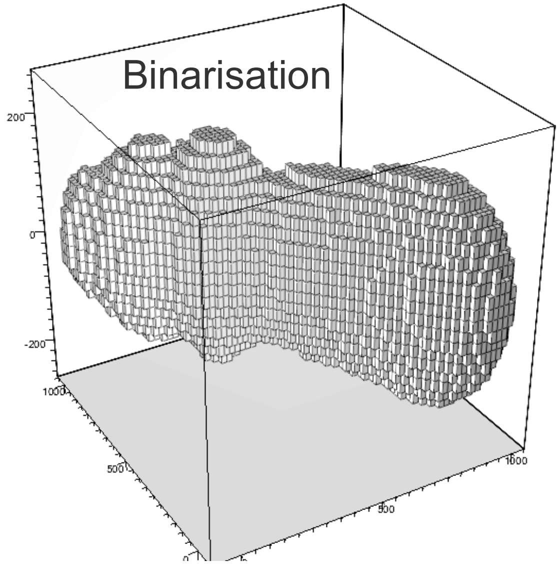


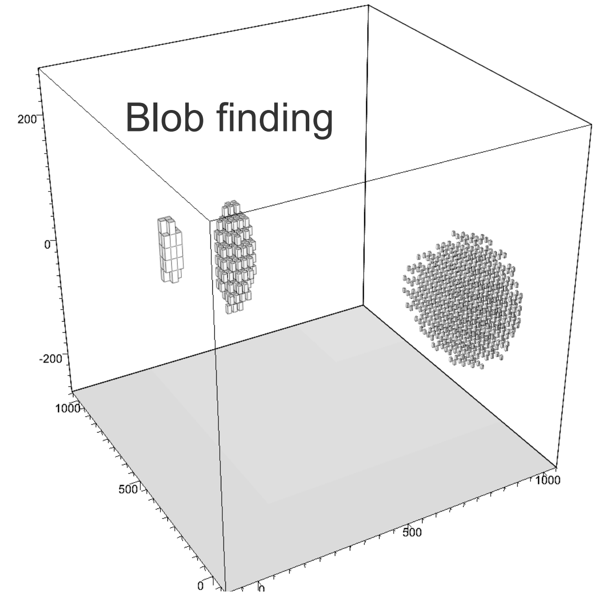
Color: Total photon emission probability in arbitrary units

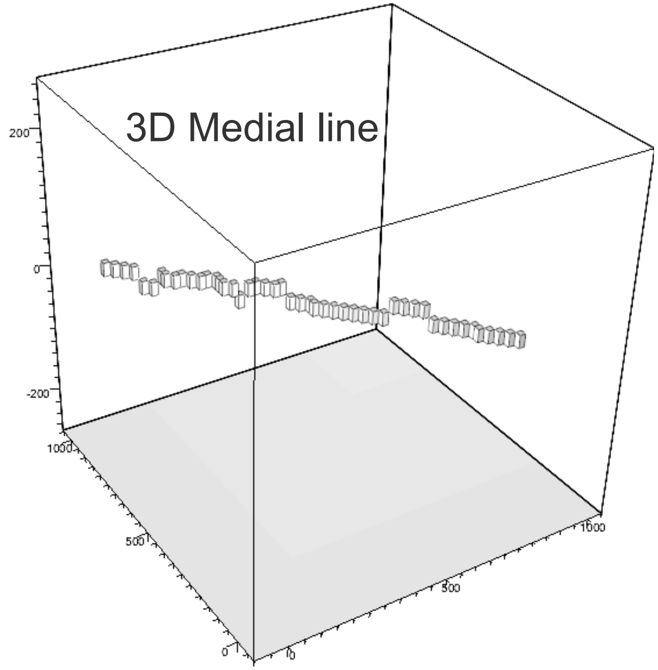
→ dE/dx seems accessible

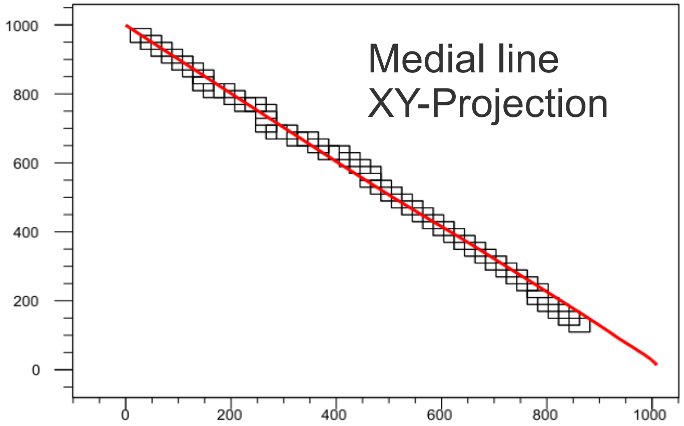
Image Processing

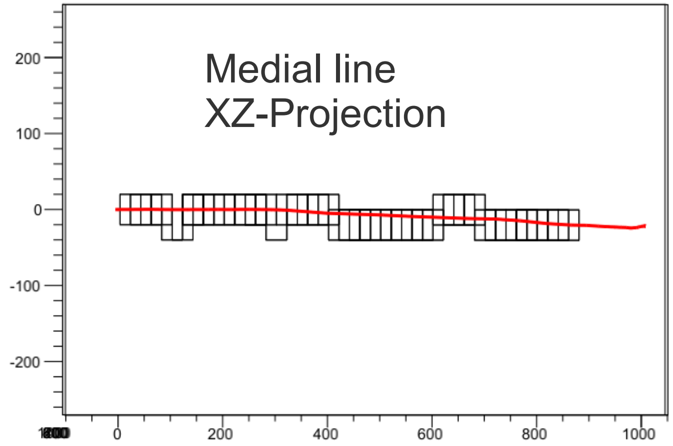












Ph. D. student Sebastian Lorenz

Resolution < 20 cm

Computing

One 3 GeV event, 20 cm bins, full light, 22 iterations in LENA
→ **several hours** (despite usage of adaptive mesh refinement)

However:

- I'd like to go to 2 cm bins
  - because there should be enough light for this resolution

- In principle many more iterations are allowed

But algorithm highly parallisable
→ GPUs, etc.

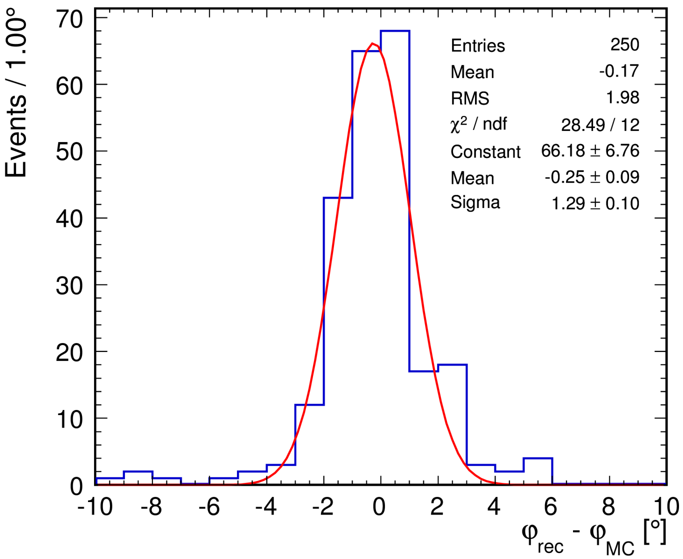
Current Status

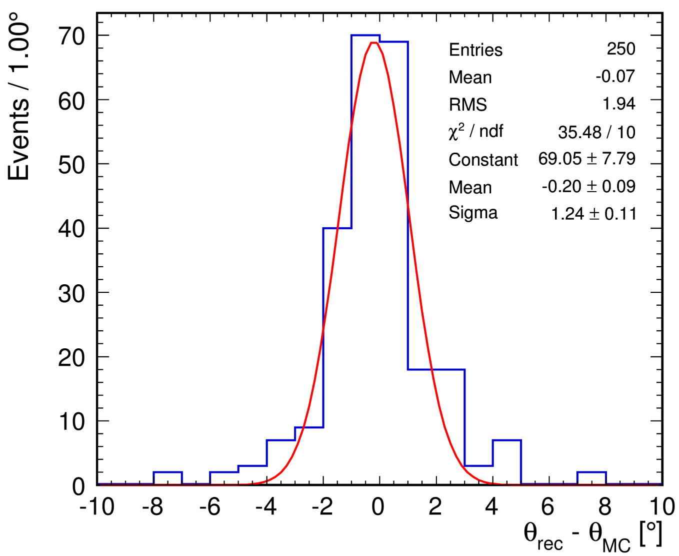
Large reconstruction campaign ongoing!

Muons with 1-5 GeV: (first results)

- Robustness → okay
- Angular resolution: ~1.5°

Preliminary





Electron events under production

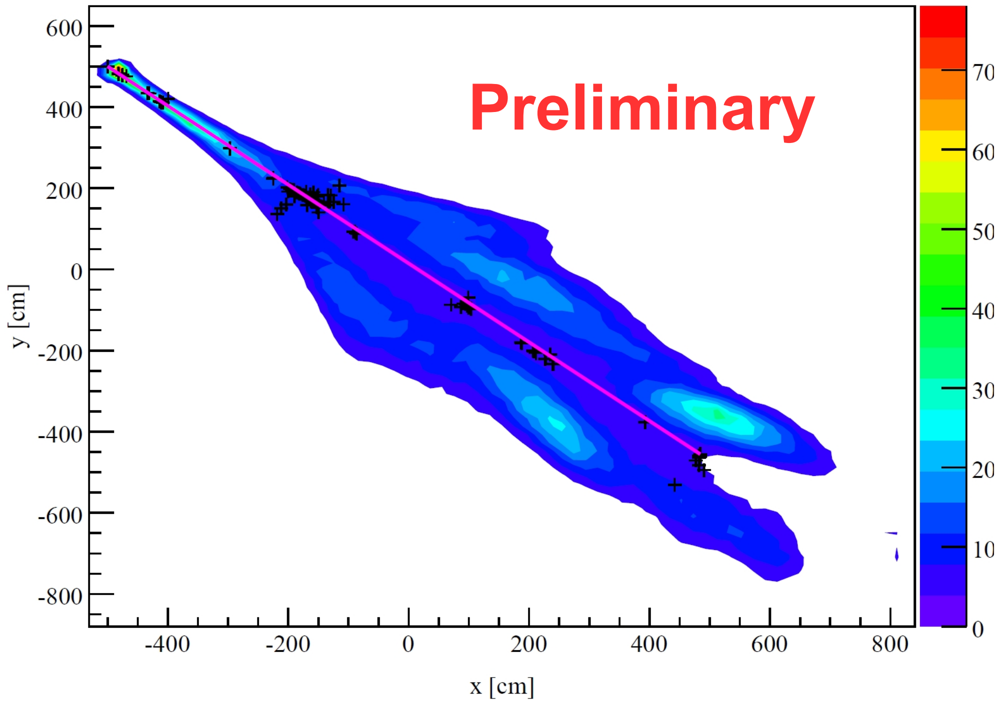
Other event classes still to be studied

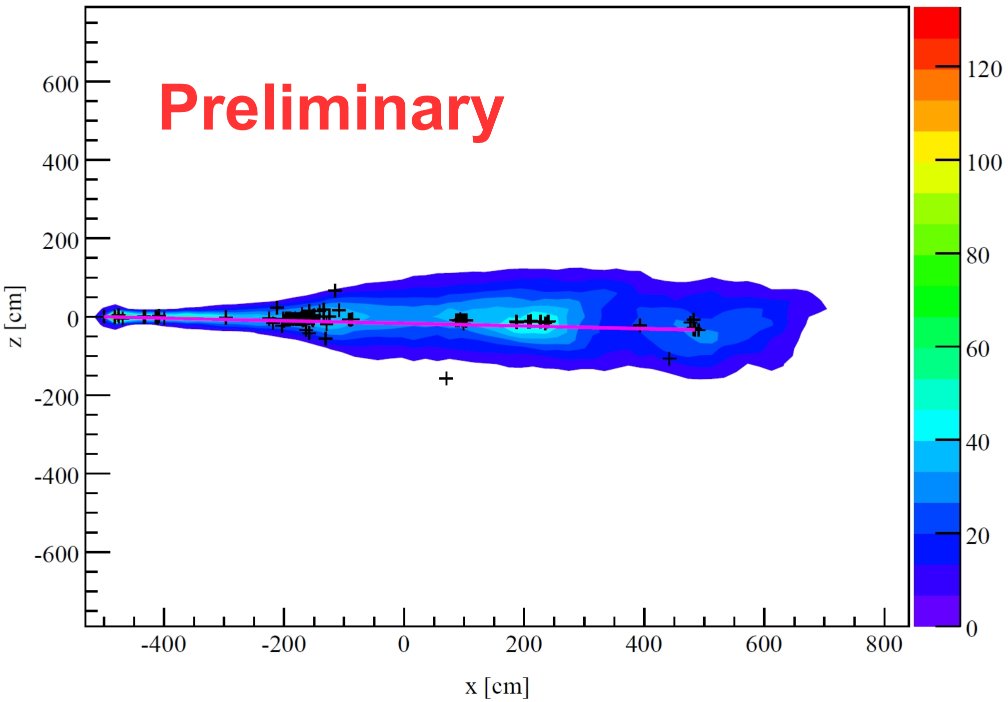
Paper under preparation!

Ph. D. student Sebastian Lorenz

Can also do it with Cherenkov Light

3 GeV muon, initial direction (1,-1,0)





Bachelor student David Meyhöfer

A few % of light in liquid Scintillator is Cherenkov light

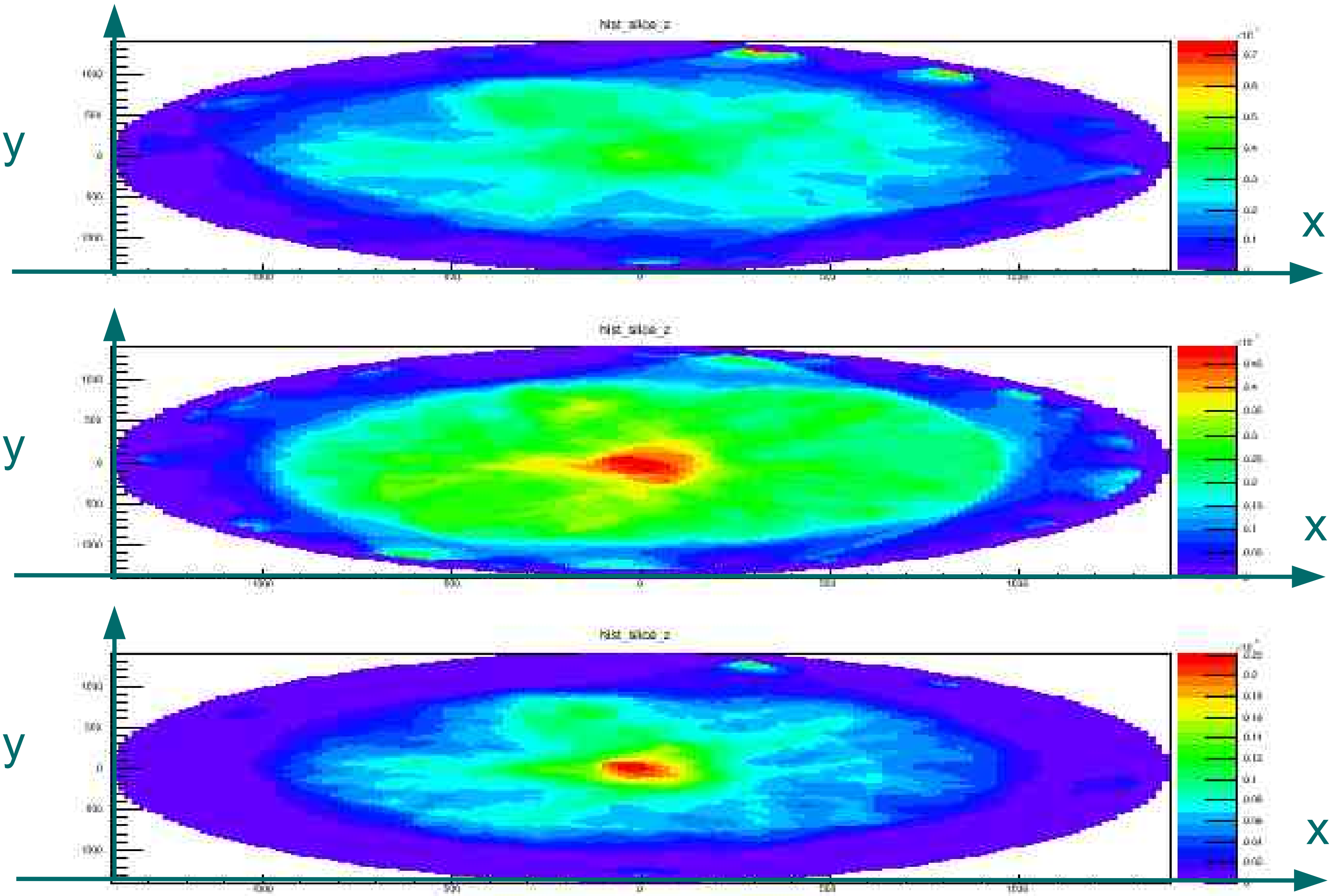
→ using both could help pattern and partical identification

Also suitable for water Cherenkov detectors!   Perfect for WbLS!

Tracking at Low Energies

(a few MeV)

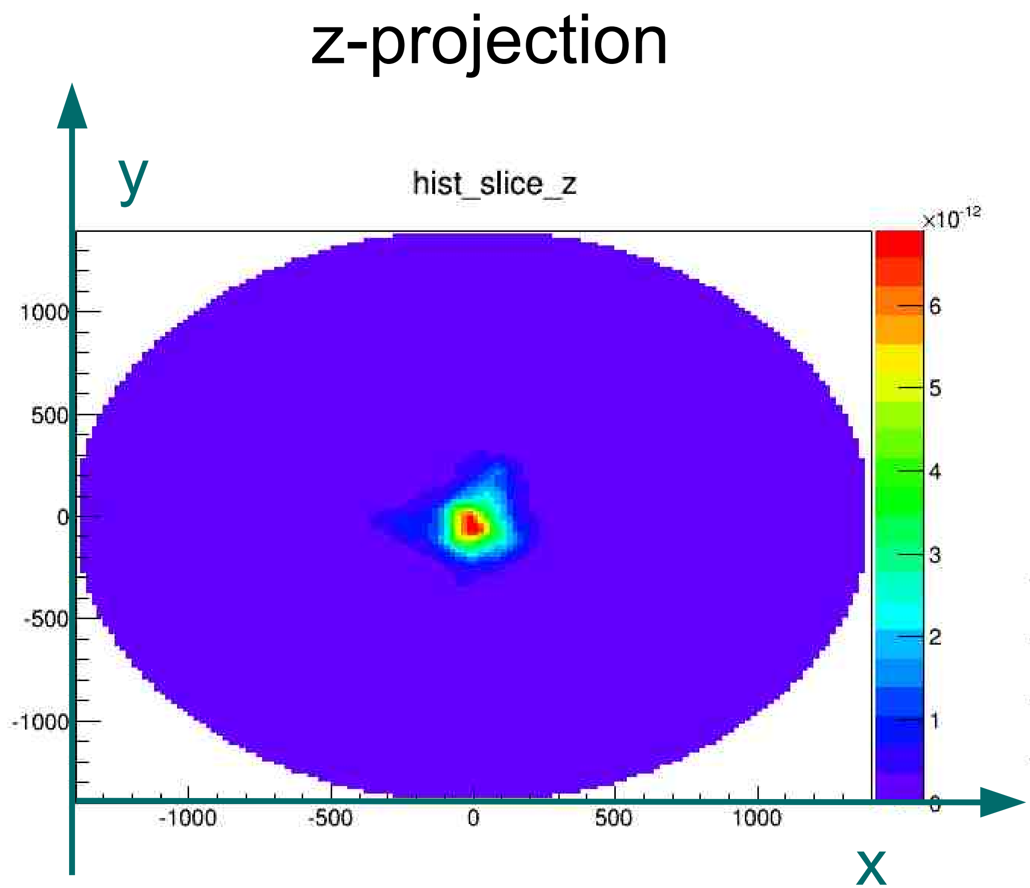
Robust Iterations!?

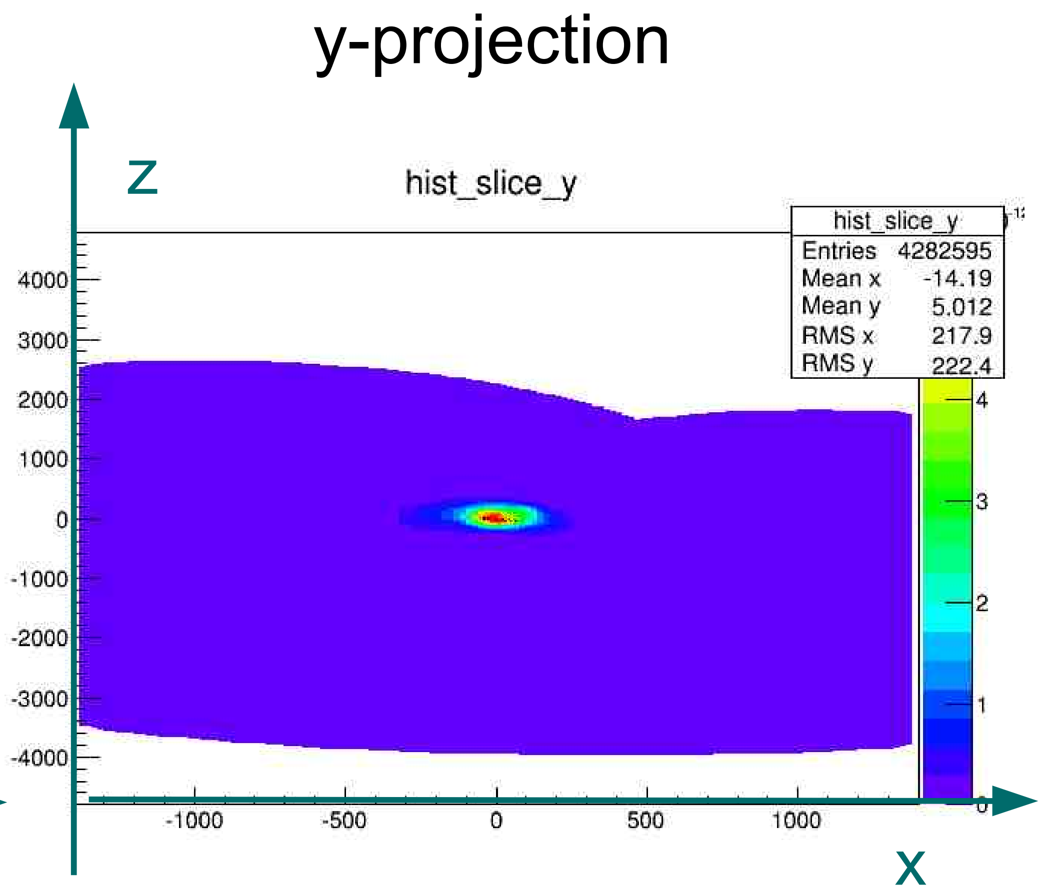


New Procedure

- **Divide detector in different parts**
- **Do reconstruction for each part**
- **Multiply results**
- **Use this as Probability Mask**
- **Go back to first step**

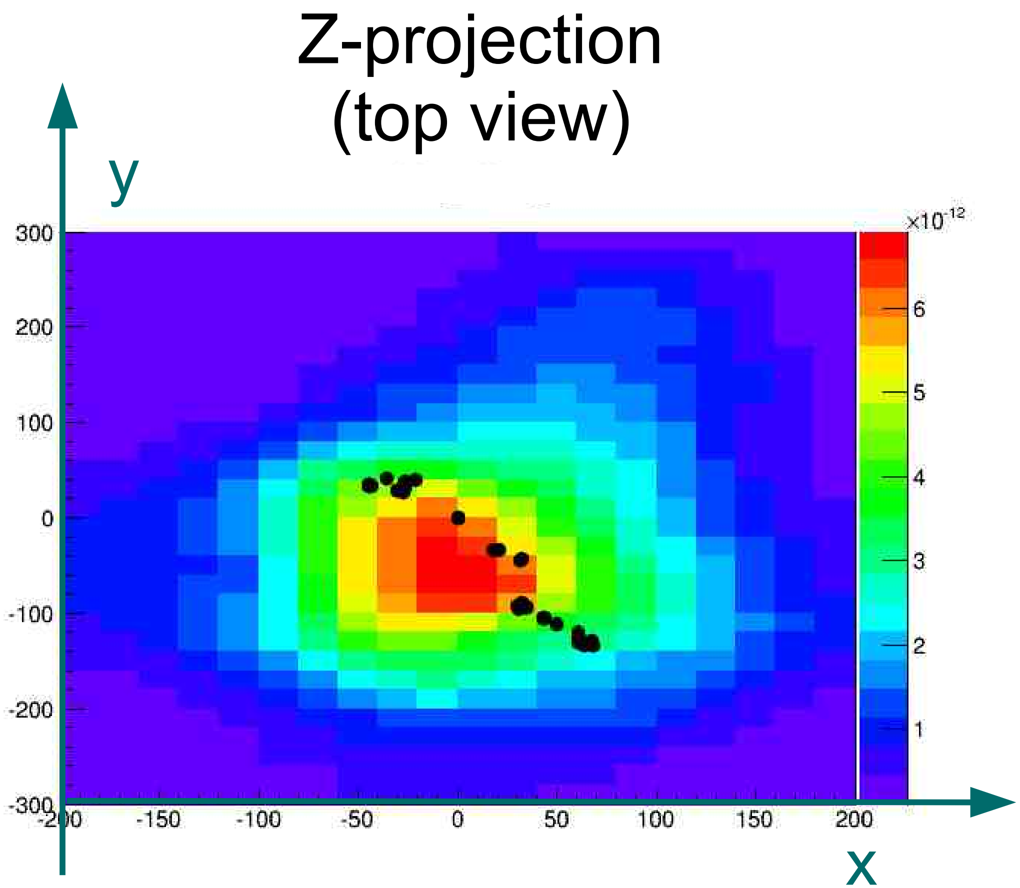
Result 2nd Iteration

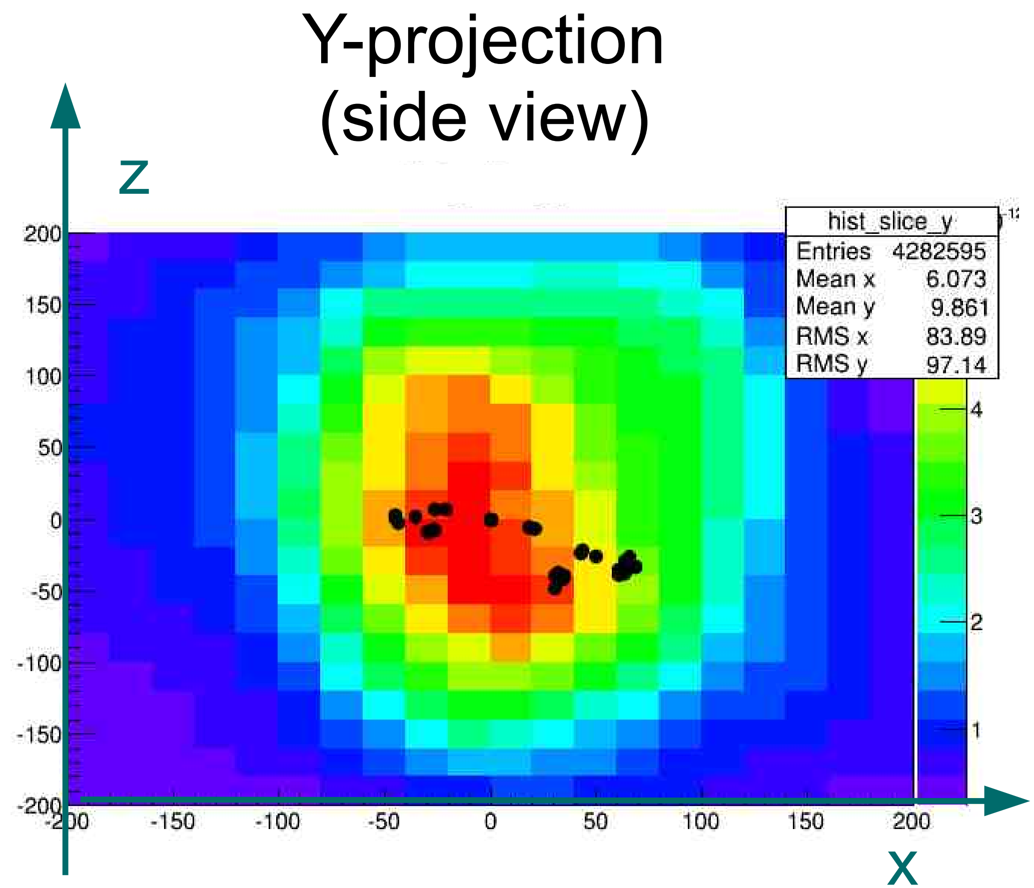




1MeV positron at center

Result 2nd Iteration (Zoom)

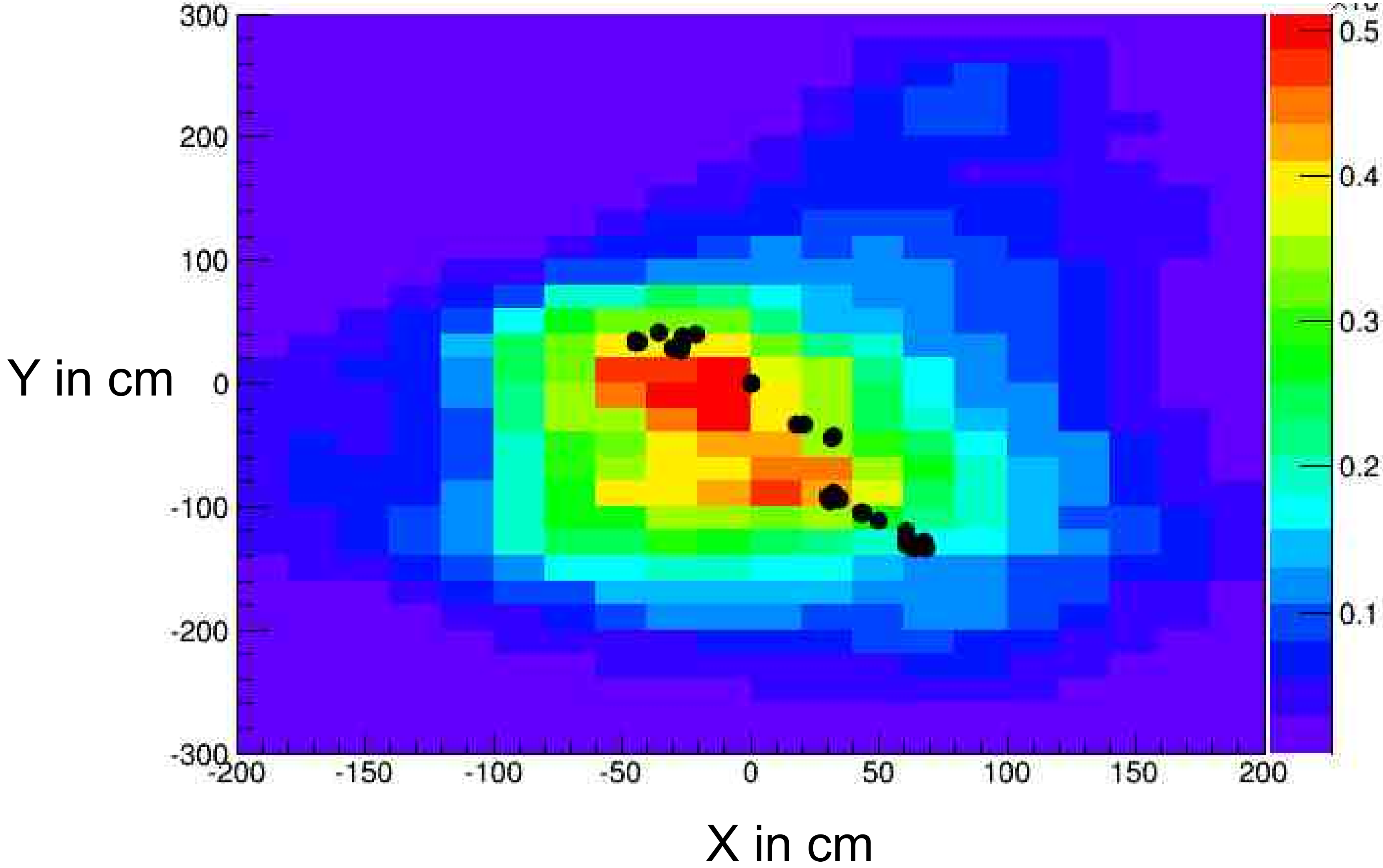




1MeV positron at center

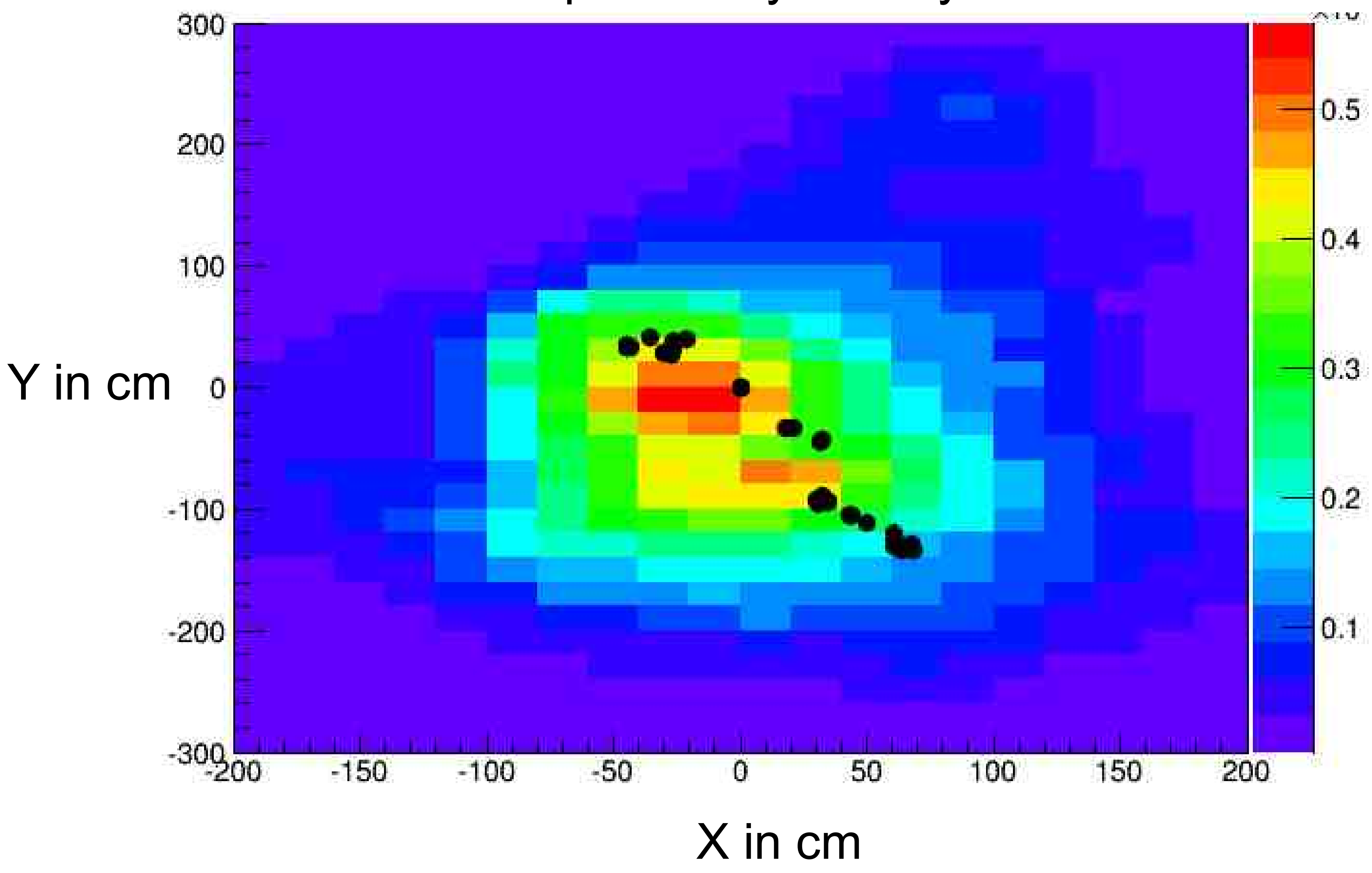
Result 2nd Iteration Slice 241

XY-slice of 3d probability density distribution

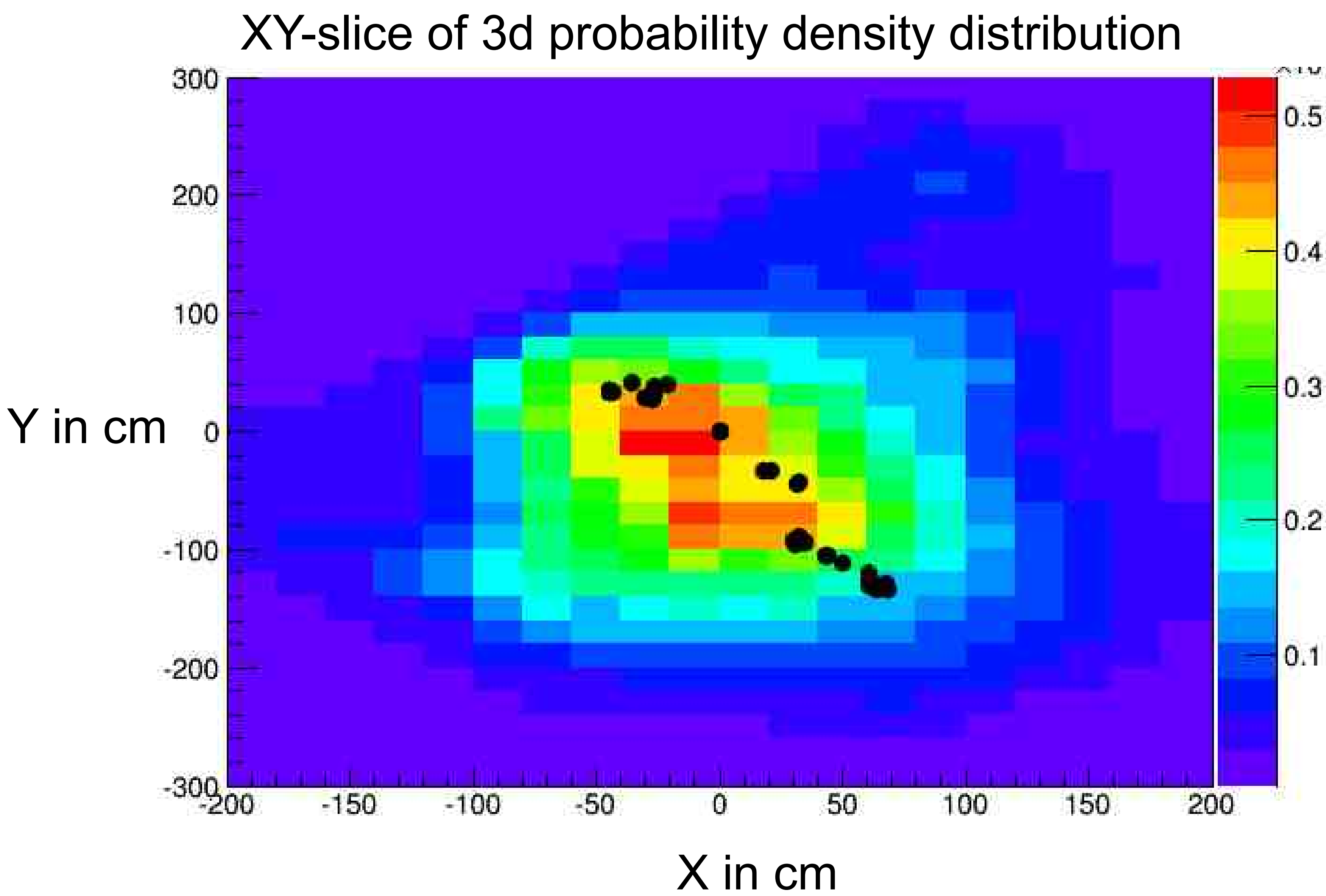


Result 2nd Iteration Slice 240

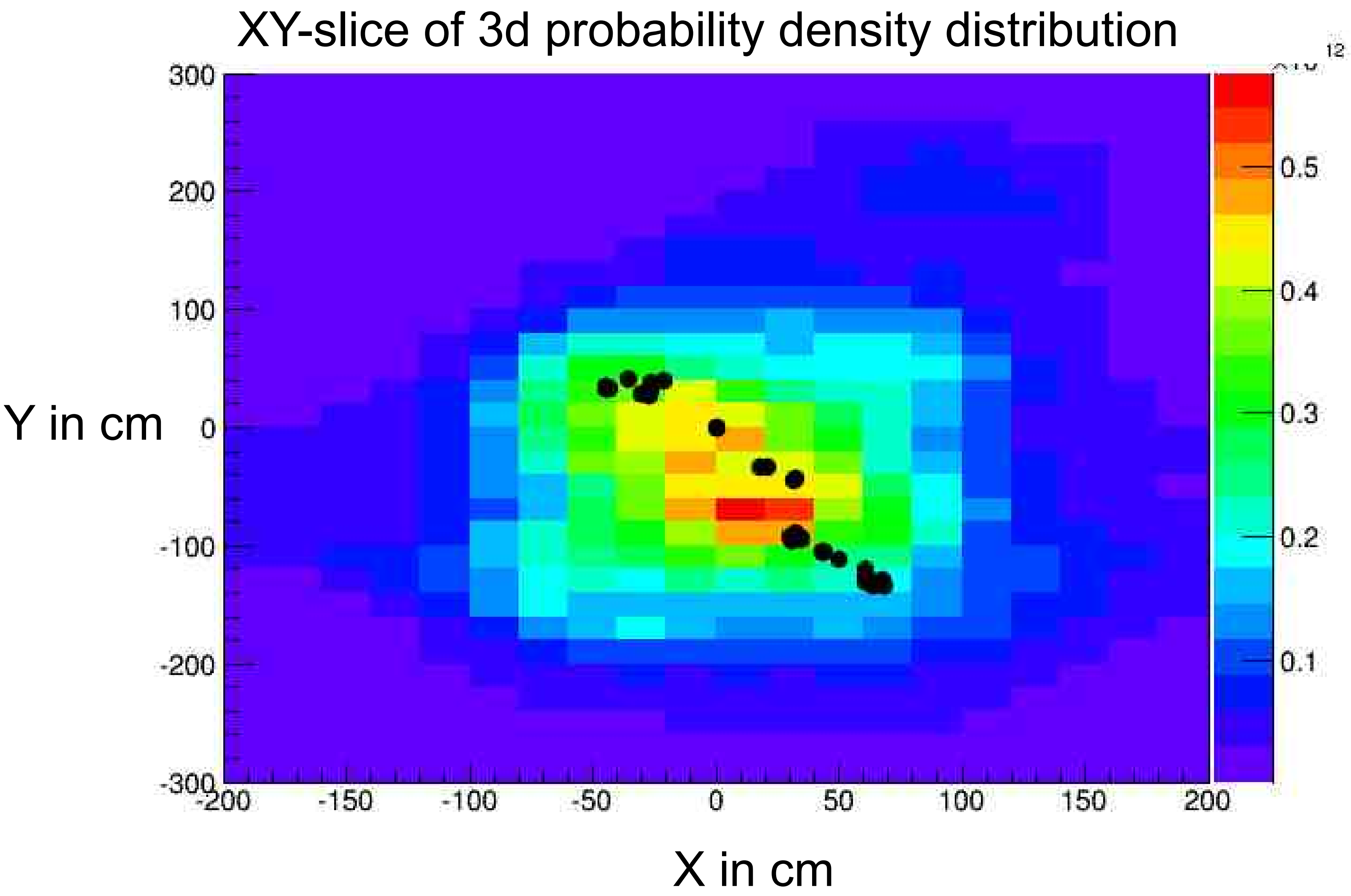
XY-slice of 3d probability density distribution



Result 2nd Iteration Slice 239

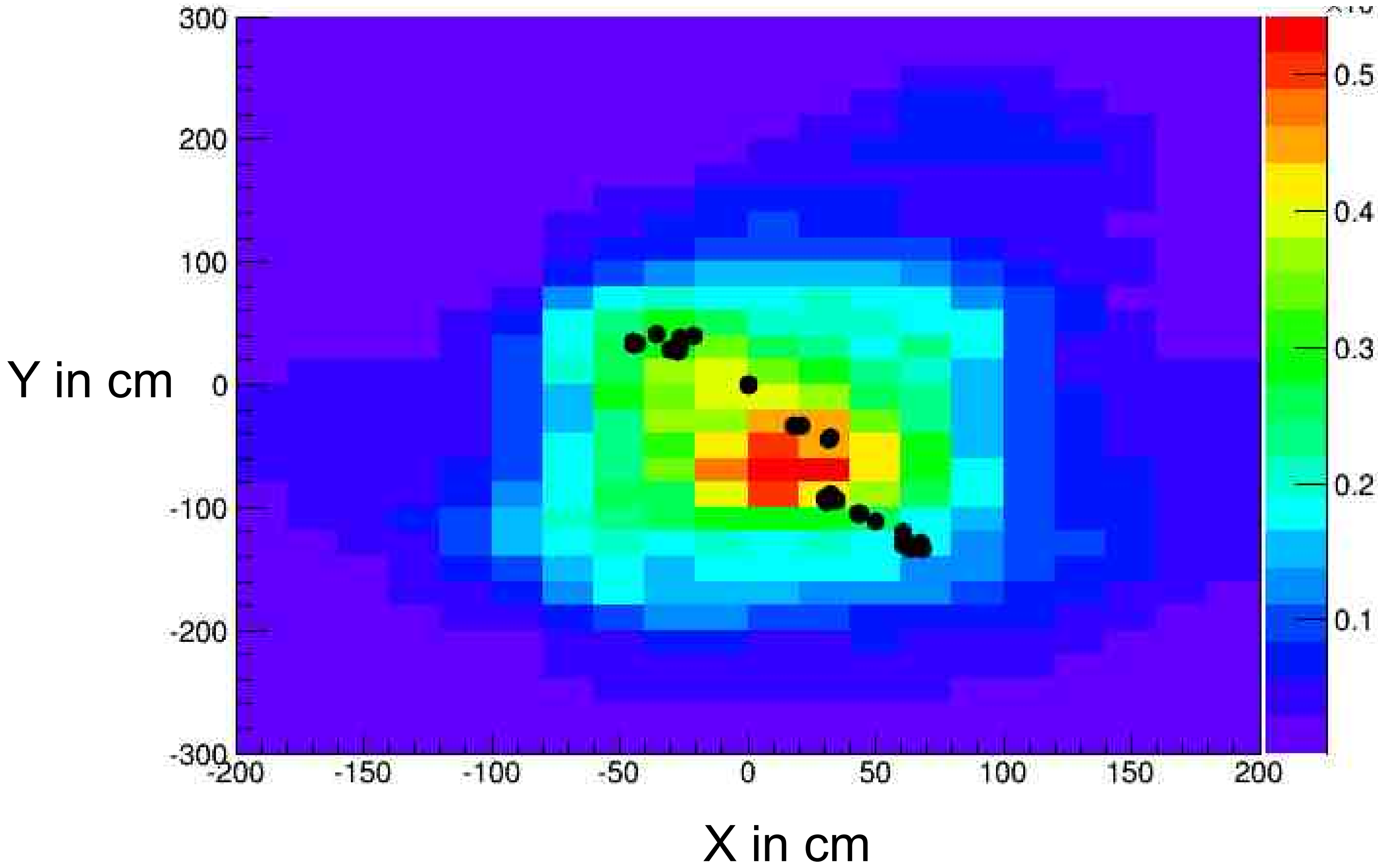


Result 2nd Iteration Slice 238



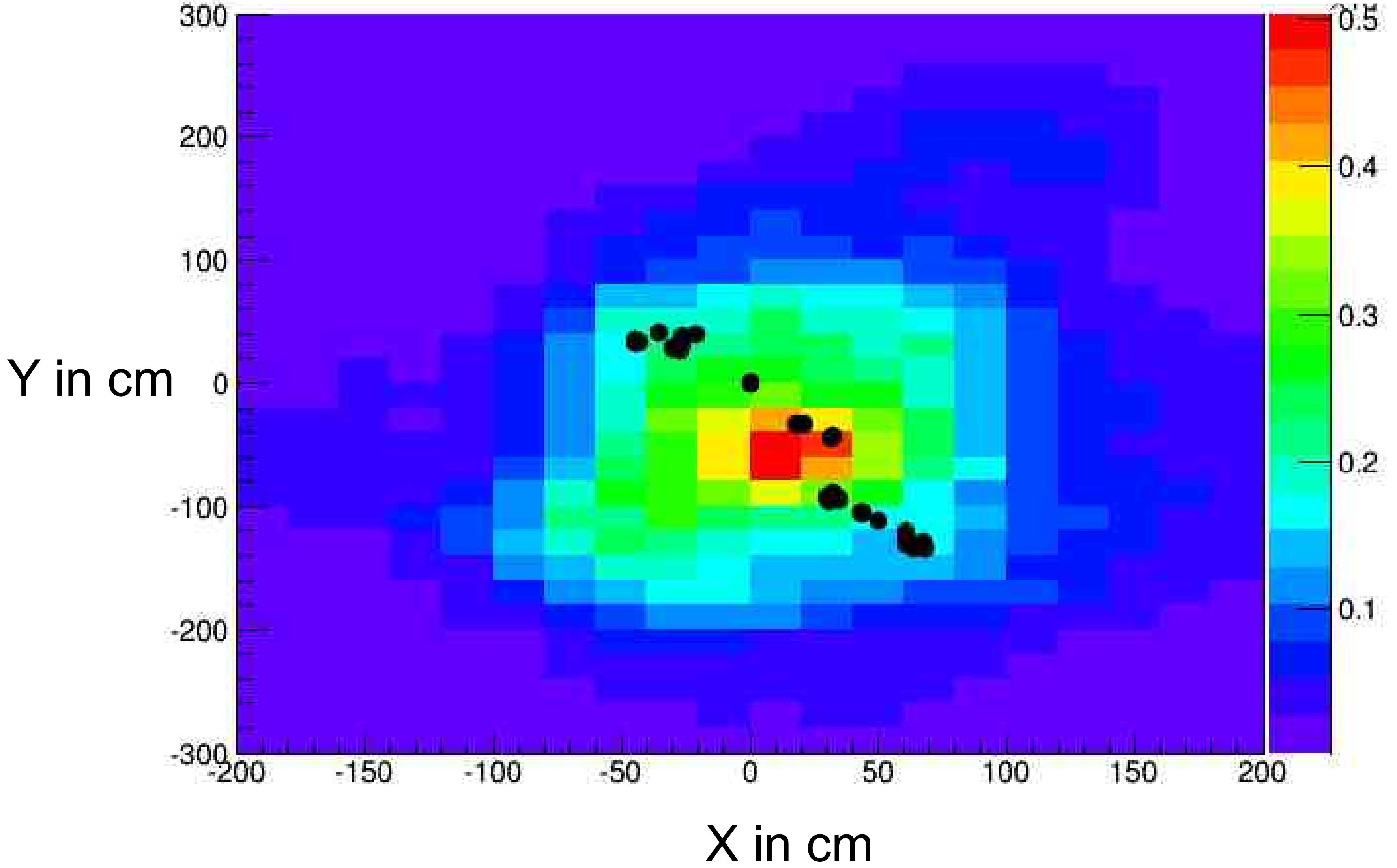
Result 2nd Iteration Slice 237

XY-slice of 3d probability density distribution



Result 2nd Iteration Slice 236

XY-slice of 3d probability density distribution

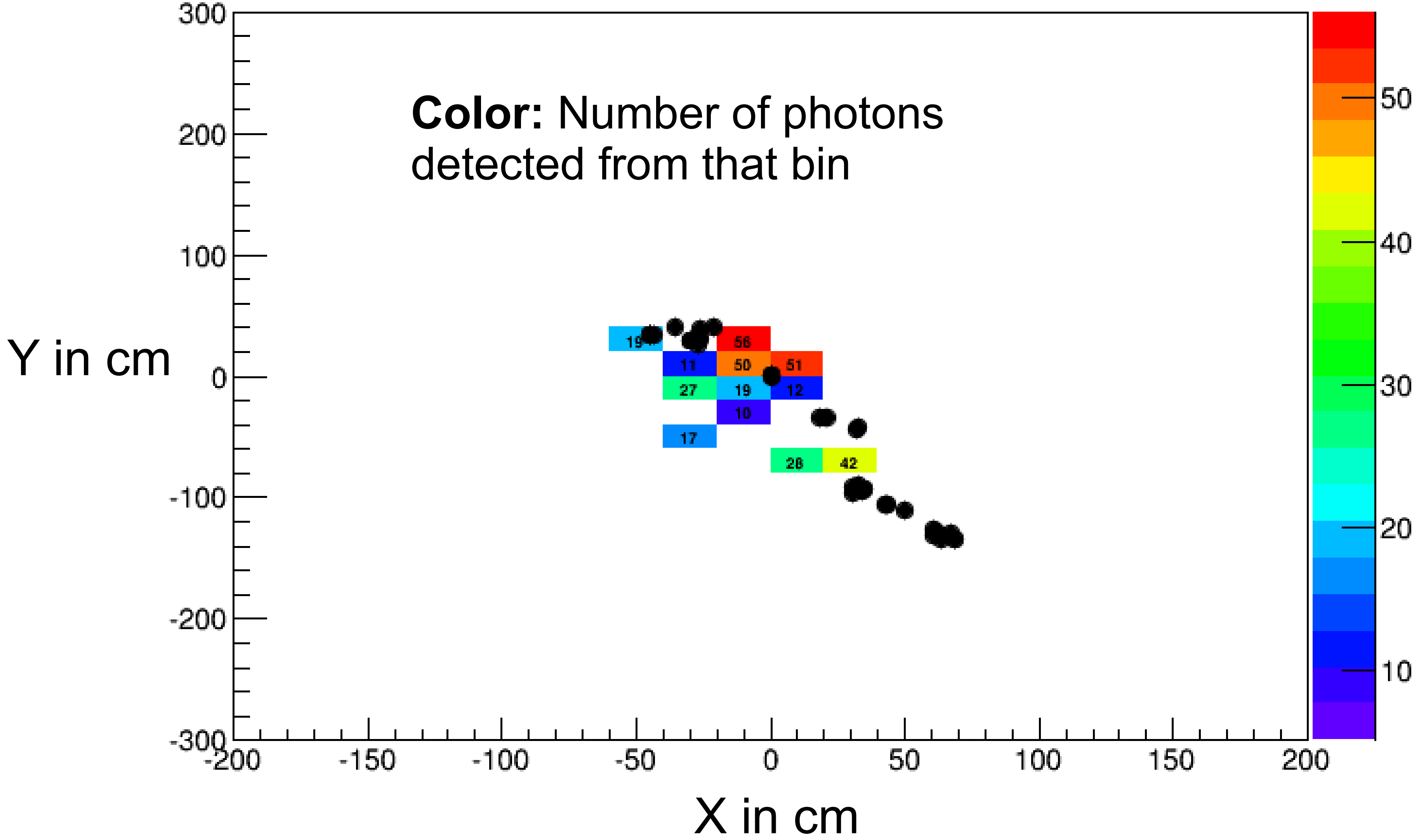


Crystalisation of the Result

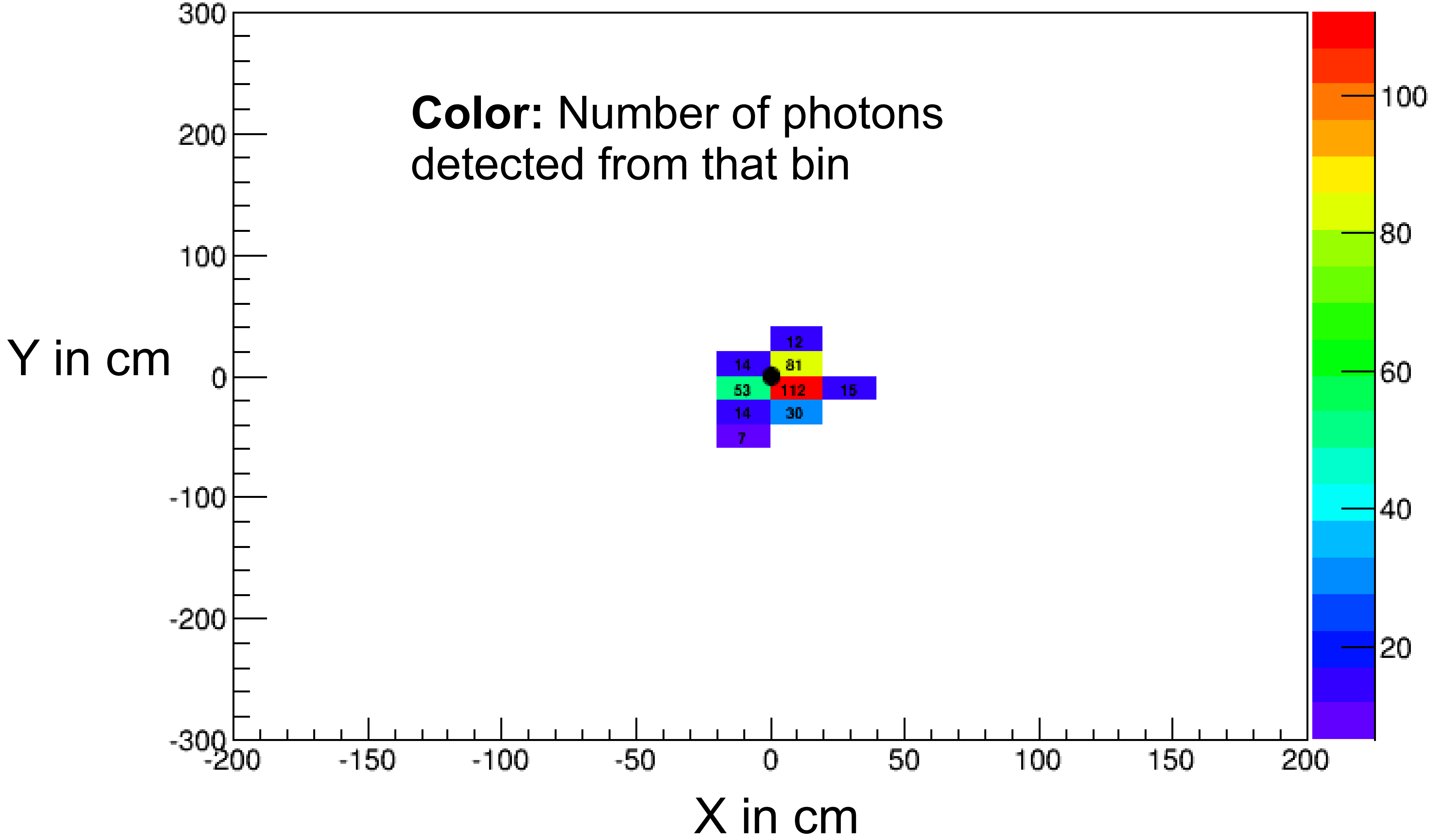
- Use well defined probability mask
- Do reconstruction for each photon
- Identify bin with highest probability
- Associate photon with this bin

  $\rightarrow$ number of photons from that bin

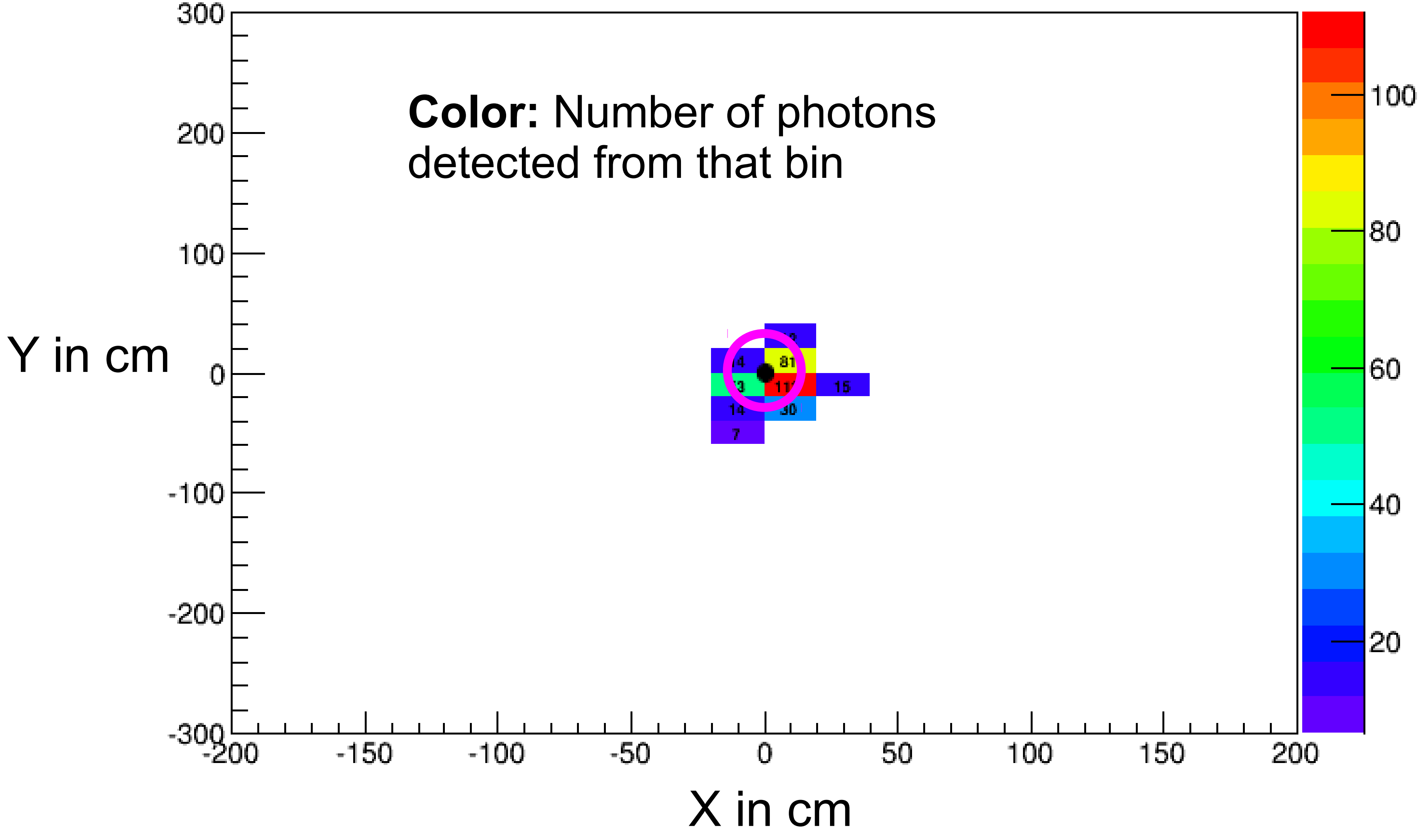
Crystalisation: 1 MeV Positron



Crystalisation: 2 MeV Electron

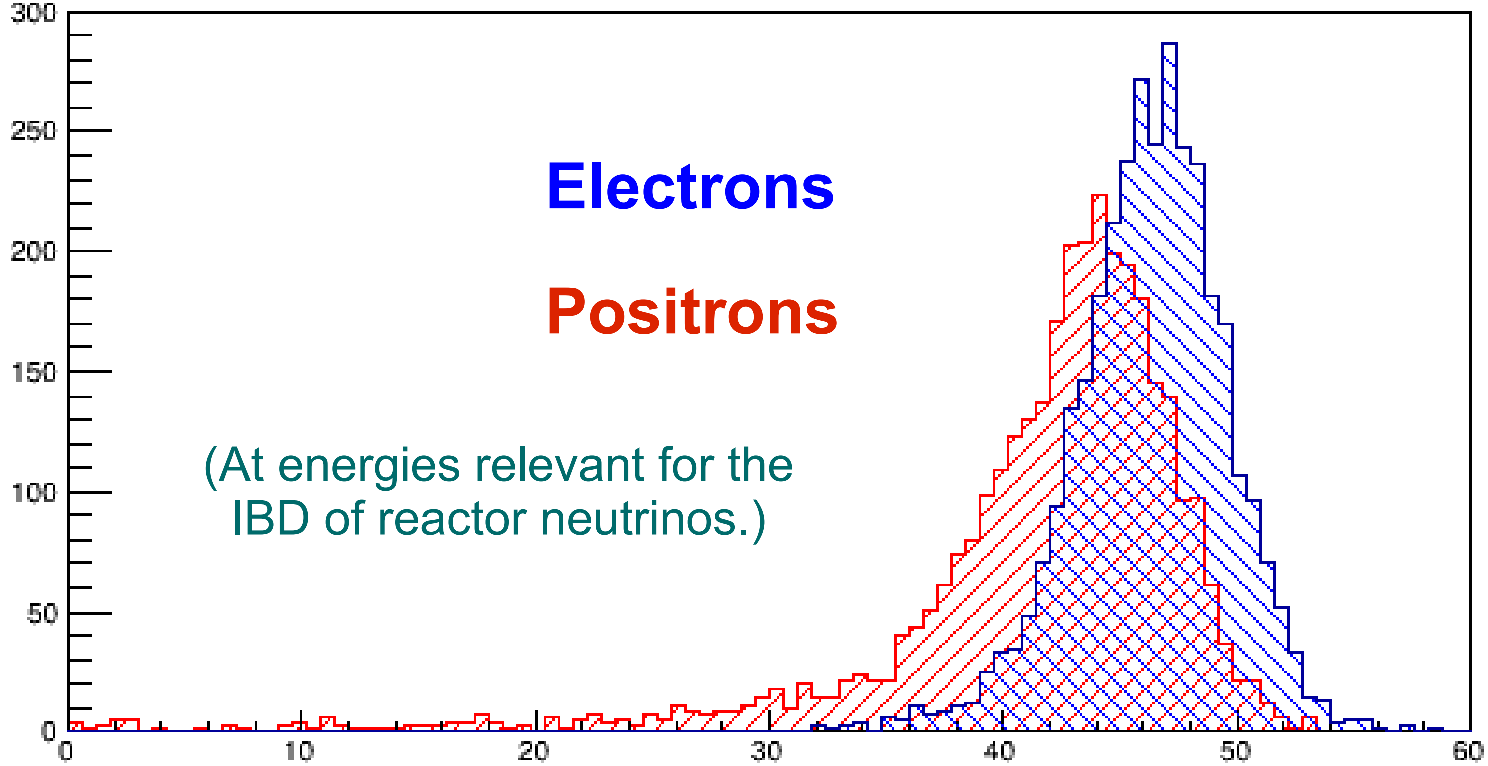


Crystalisation: 2 MeV Electron



Electron vs. Positron Discrimination: First Try Results I

Ratio R of light reconstructed near vertex
vs. total light



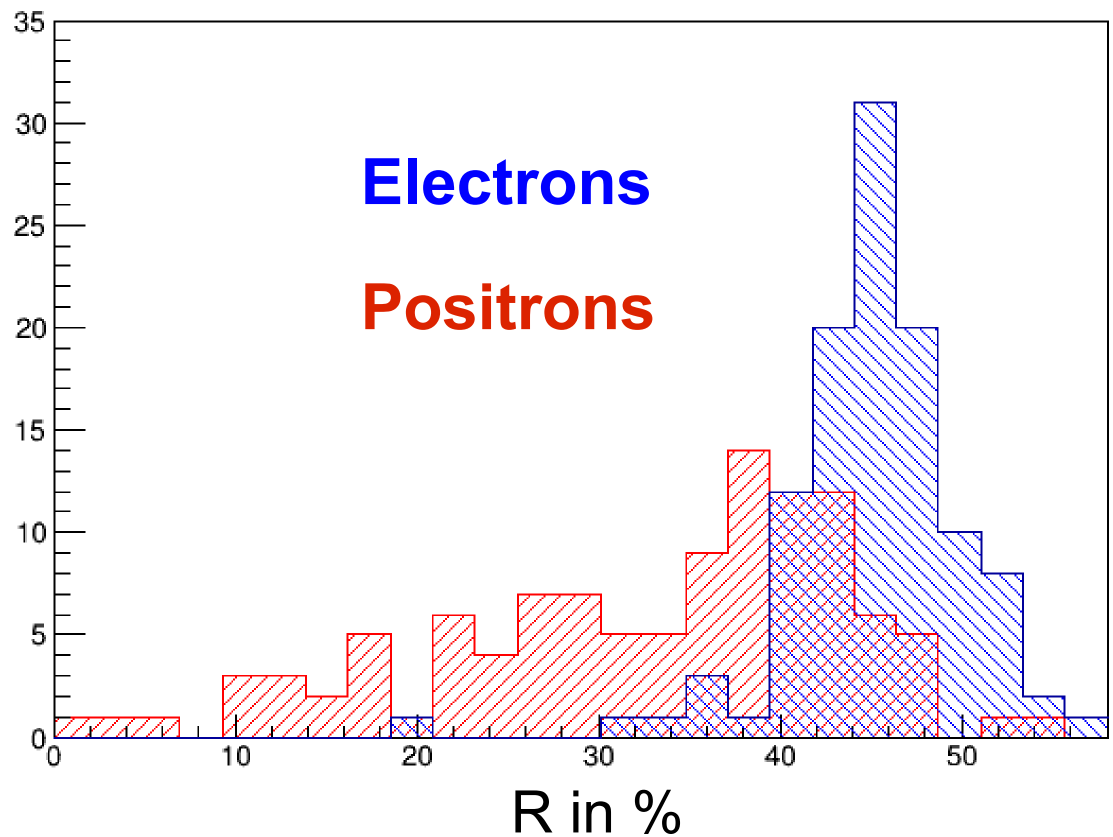
R in %

- 3343 events of electron and positron events each
- Visible energy 1 – 5.5 MeV
- At the center of the detector → worst place
- LENA-MC → 250 photons per MeV

Notice: Used perfect vertex position for this analysis

Electron vs. Positron Discrimination: At C-11 Energy Region

Ratio R of light reconstructed near vertex vs. total light



- 111 events of electron and positron events each
- Visible energy 1 – 2 MeV
- At the center of the detector → worst place
- LENA-MC → 250 photons per MeV

Notice: Used perfect vertex position for this analysis

Remarks on Potential

- **Possible improvements:**
  - So far only 250 p.e/ MeV
    $\rightarrow$ Borexino: 500 p.e/ MeV, JUNO: 1200 p.e/ MeV
  - Remove scattered light statistically
  - Faster scintillator
  - Multivariate analysis

- **Other ideas:**
  - Use time as 4th dimension
  - Gradient information (Sobel-Filter)

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Eliminating Influence of Scattered Light

- **Idea:** Use probability mask and lookup tables to calculate for each signal the probability to be scattered

  → reweigh signals after each iteration

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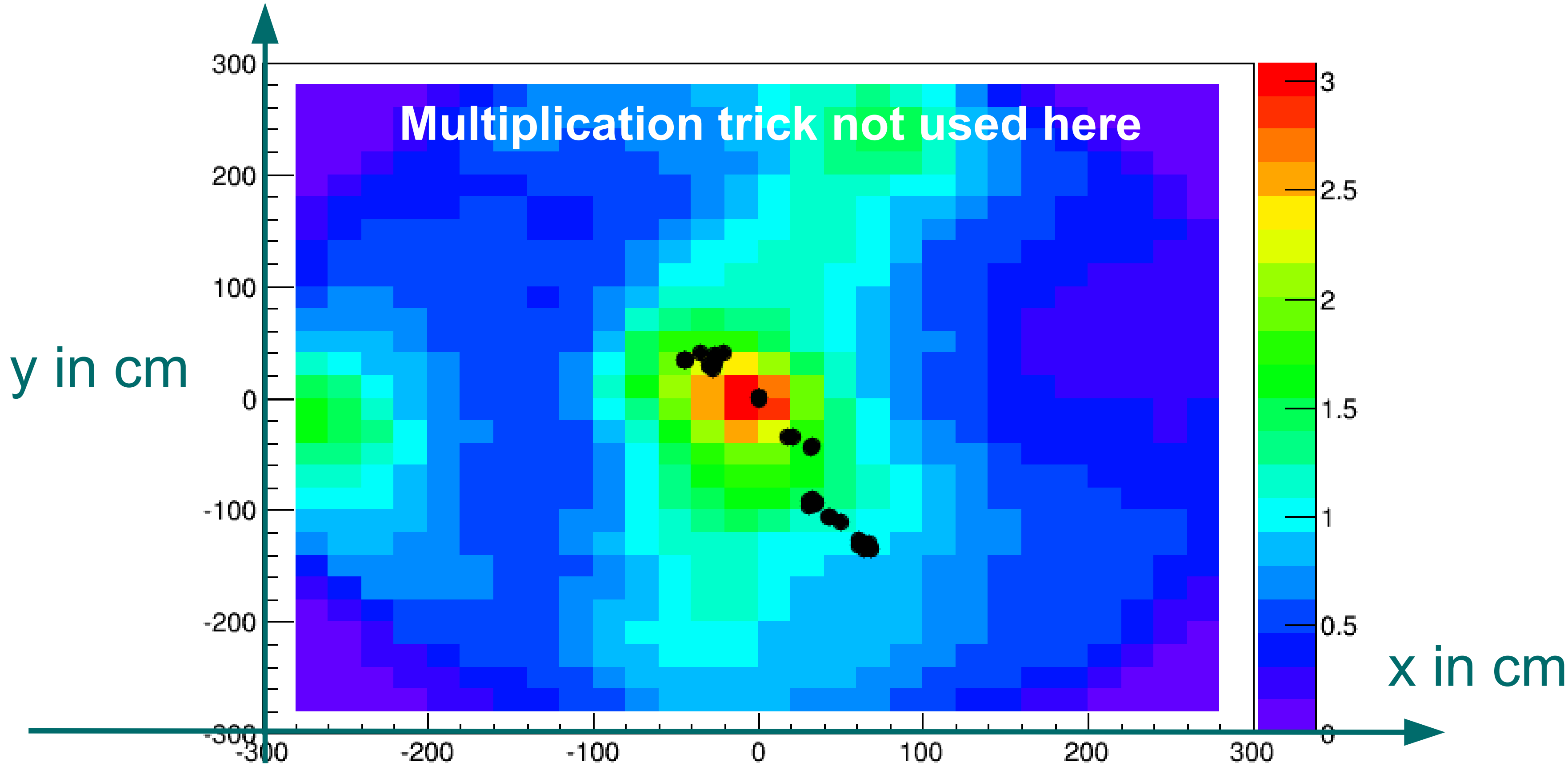

Result **before** removal of scattered light!

Eliminating Influence of Scattered Light

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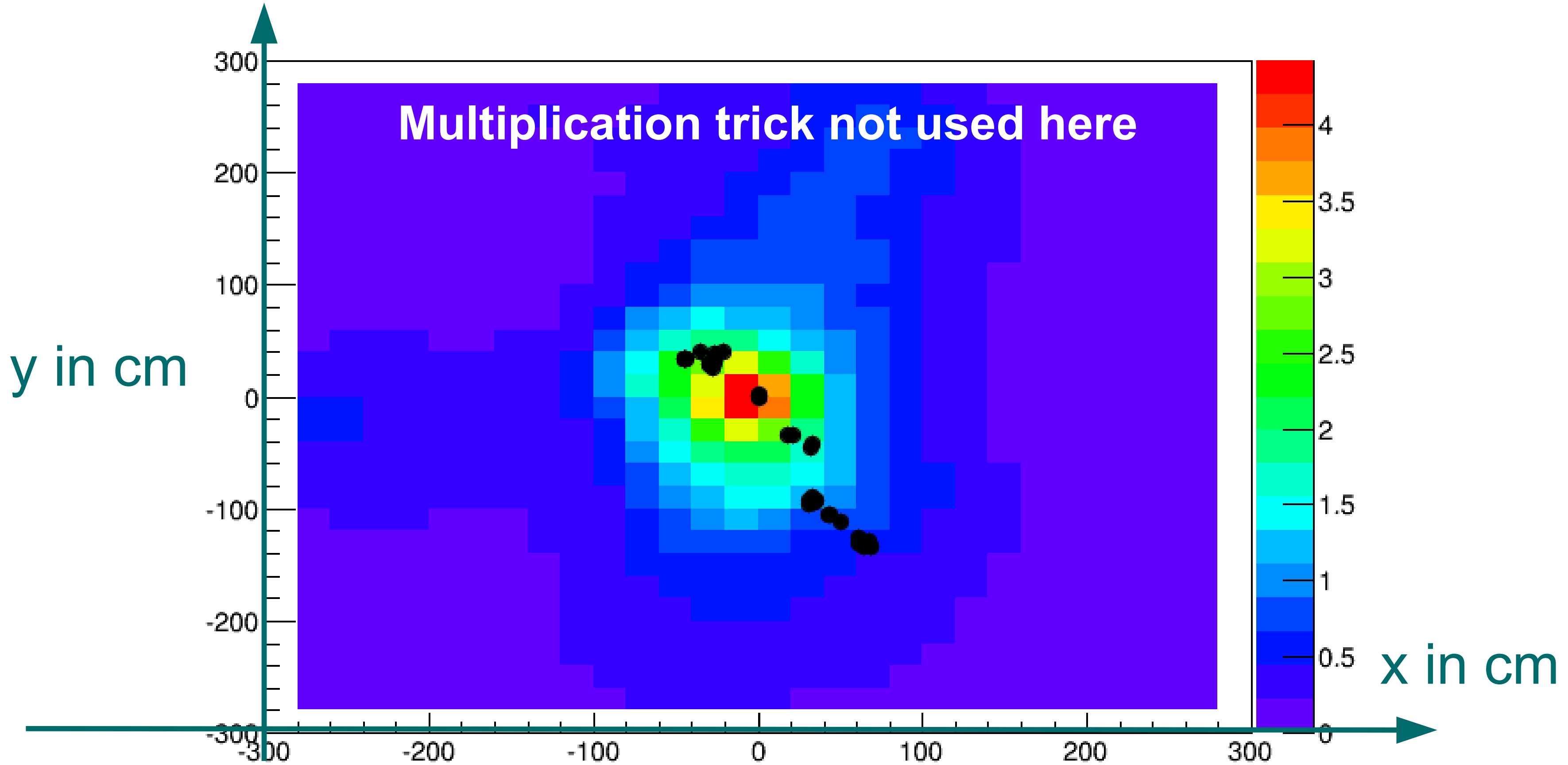
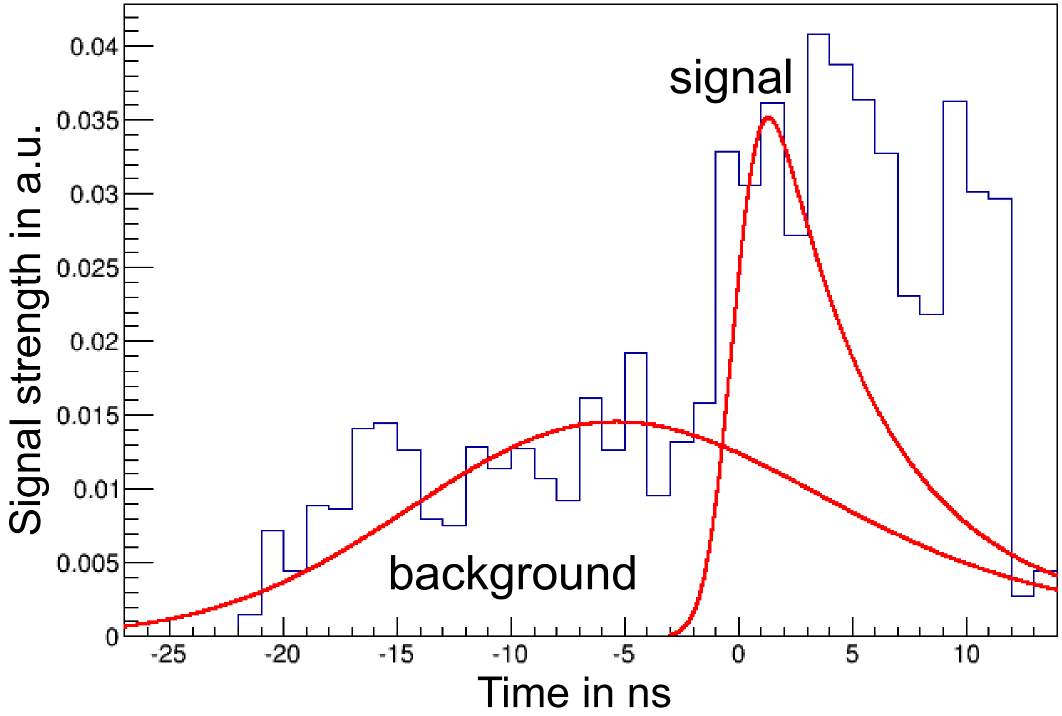
  → reweigh signals after each iteration



Result **after** removal of scattered light!

Using the 4th Dimension

- **Observation:**
  - Contrast limited by influence of neighbour bins
- **Idea:**
  - Use time distribution at each point
  - Fit signal-function + background from neighbours



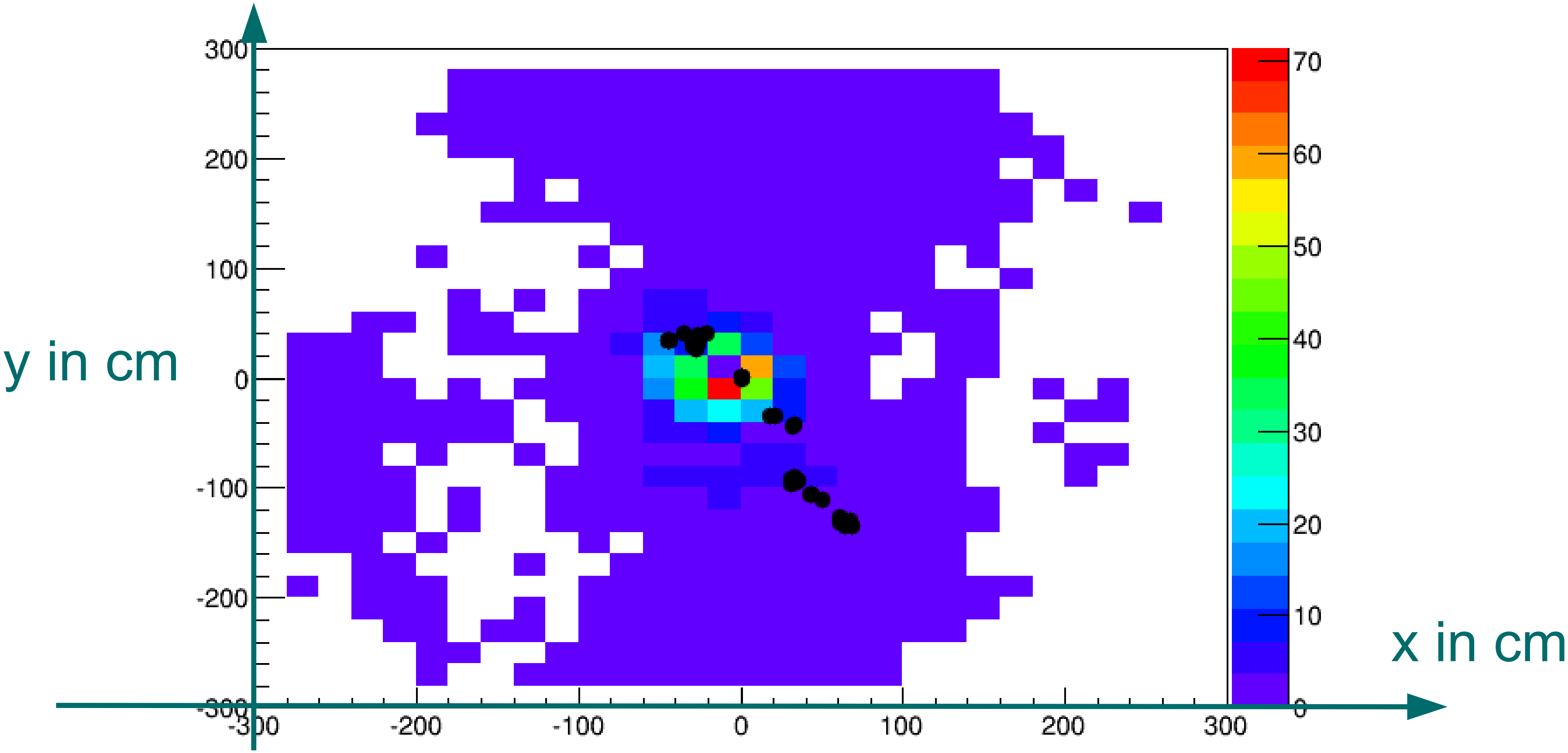
Example of a bad bin with a lot of noise!

Scattered light not removed!

Using the 4th Dimension: Result

First result:

- Very preliminary!



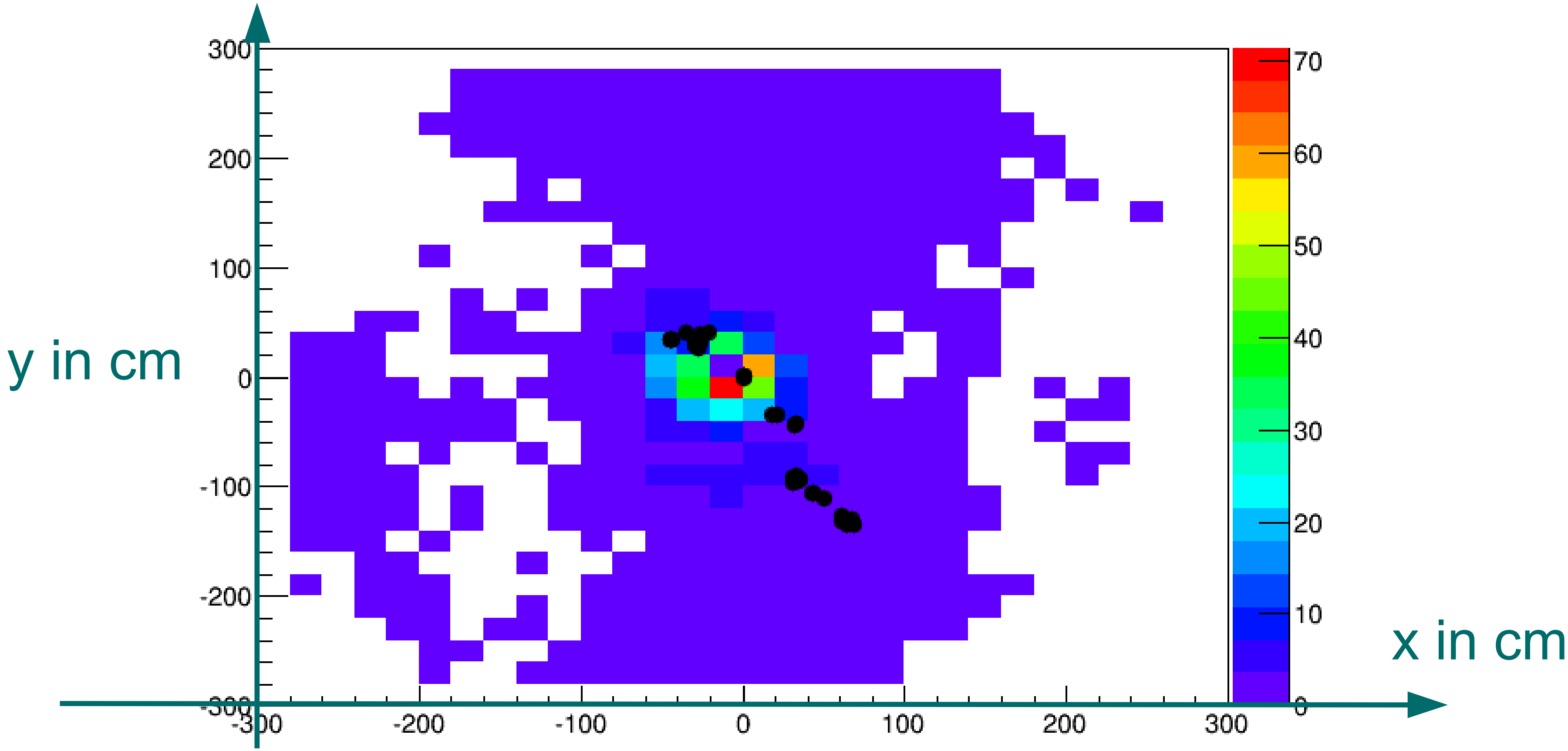
This now respresents a real dE/dx!

Using the 4th Dimension: Result

First result:

- Very preliminary!

- Background estimate must be more robust
- One possibility is to use probability mask to calculate background from neighbour bins



This now respresents a real dE/dx!

Other Possible Applications

- **Improvement of:**
  - Position reconstruction
  - Energy reconstruction

Influence on non-stochastic term of energy resolution

- **IBD directional information**

Supernova neutrinos

- **Gamma identification**

^{8}B neutrinos
(^{208}Tl background at 2.6 MeV)

- **Charge of stopping muons**

Atmospheric neutrinos

- **Background reduction for $0\nu\beta\beta$-experiments**

γ-cacade vs. point-like

(e.g. ^{110m}Ag in KamLAND-Zen)

Conclusion I

- **My Tracking:**
  - Powerful new tool to increase physics potential
  - At both high and low energies
  - Wide range of applications

    Liquid Scintillator, Water Cherenkov, Water based Liquid Scintillator, even Liquid Argon

- **Performance:**
  - Spatial resolution of less than 20cm
  - dE/dx accessible
  - Angular resolution for 1-5 GeV muon tracks ~1.5°

Used realistic vertex information

→ As expected from backtracking algorithm

Conclusion II

- **Positron-Discrimination:**
  - Promising first results
  - Separation seems possible at low energies

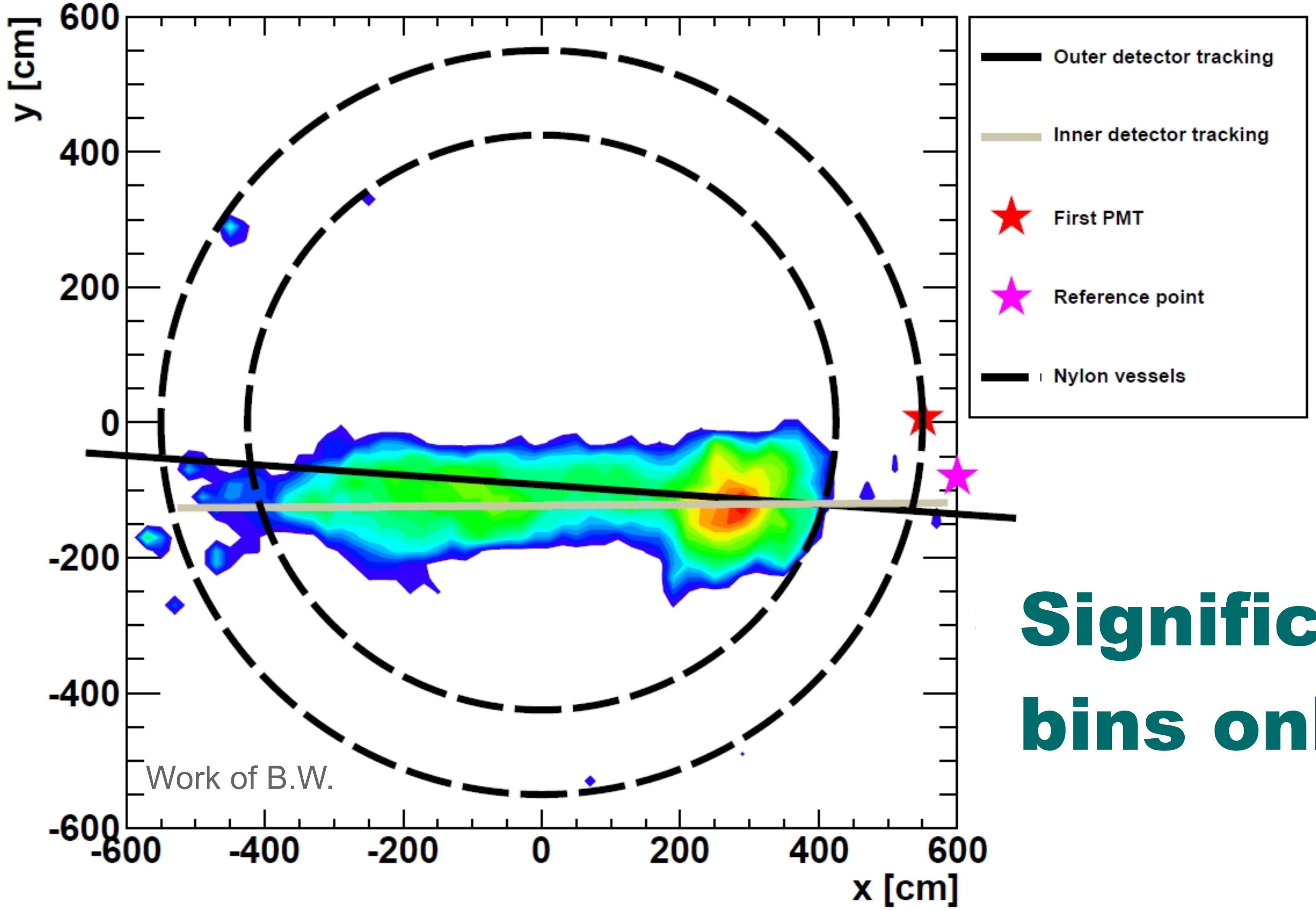
- **Tracking at low energies:**
  - Topological dE/dx will be challenging
  - Many possible applications

Used perfect vertex information so far

→ Need to use existing vertex finding algorithms

Backup slides

Example: Real Borexino Data



Significant bins only

Comment on Ortho-Positronium

- **Longer lifetime**

  → Additional time-offset

  → Annihilation photons not (or badly) reconstructable

  - **But:**

    - Better separation in inside vs. outside analysis expected

    - Residual asymmetry expected

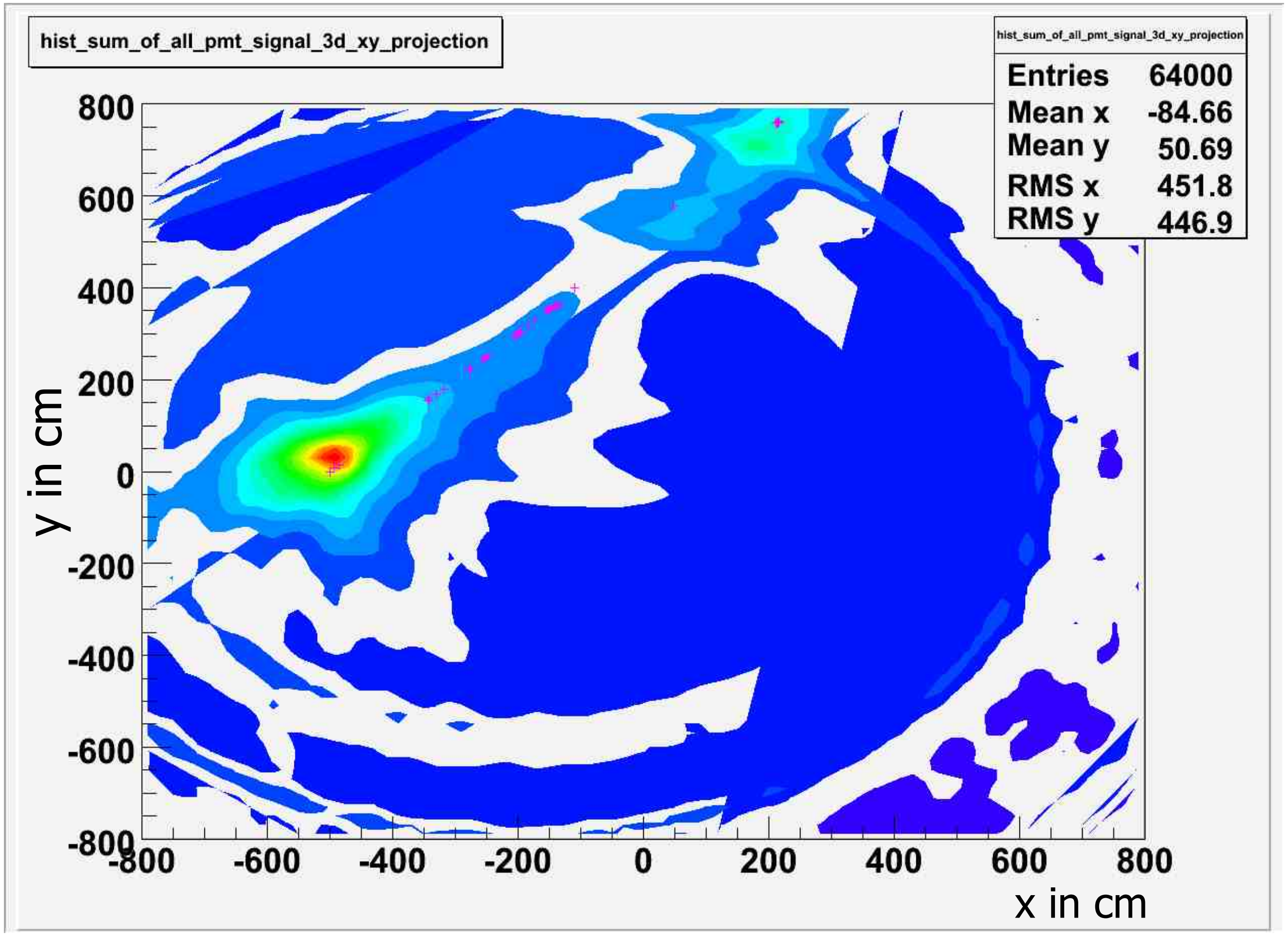
    (deviation from spherical symmetry)

But what about the reference point?

Answer: Any point on track can be used if I know the time the particle passing!

2GeV Muon, First Hit Information

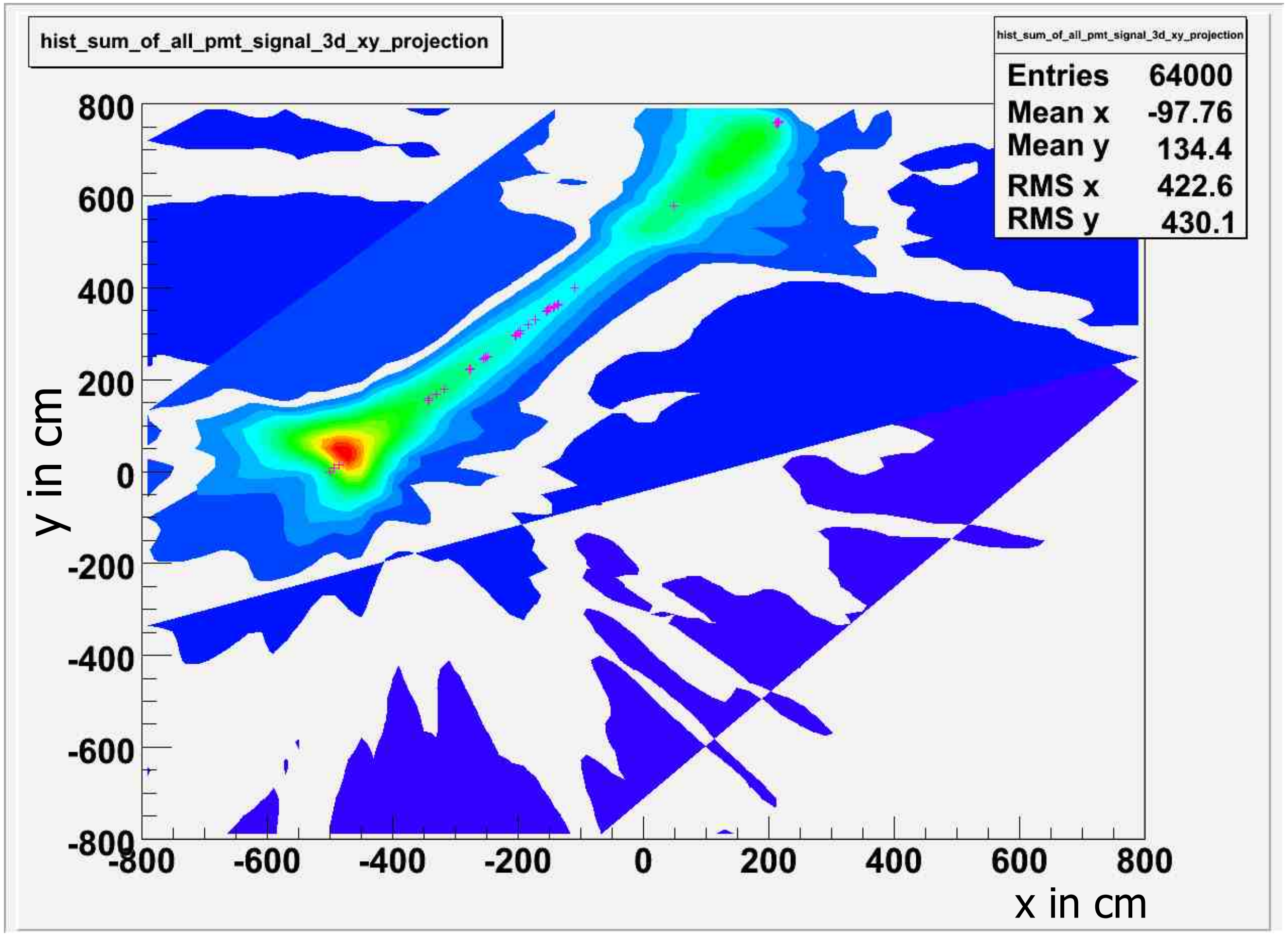
- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**



10% of PMTs at +-500 cm in z with respect to vertex

2GeV Muon, First Hit, Backwards

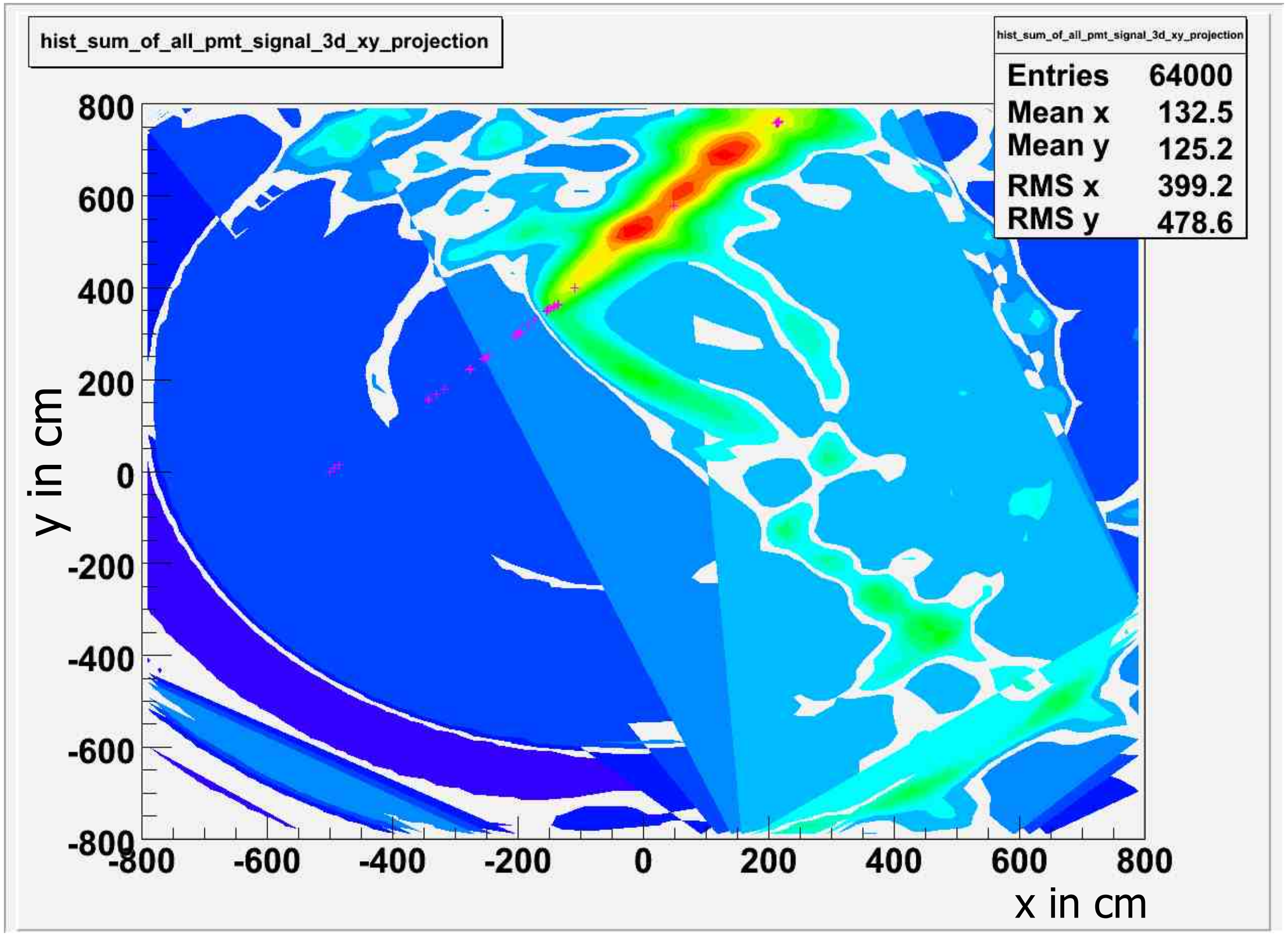
- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**



10% of PMTs at +-500 cm in z with respect to vertex

2GeV Muon, First Hit, from Middle

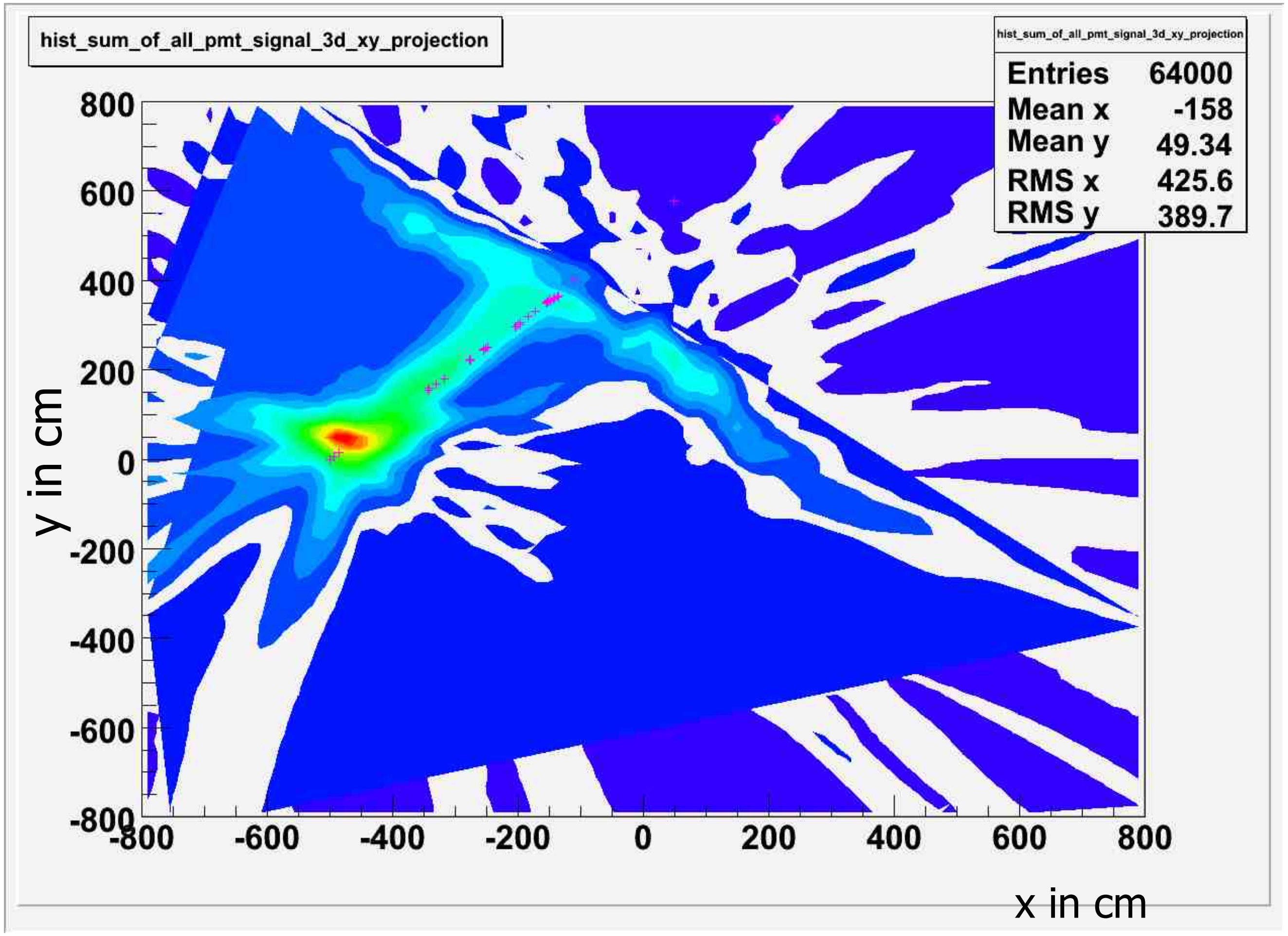
- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**



10% of PMTs at +-500 cm in z with respect to vertex

2GeV Muon, First Hit, Back from Middle

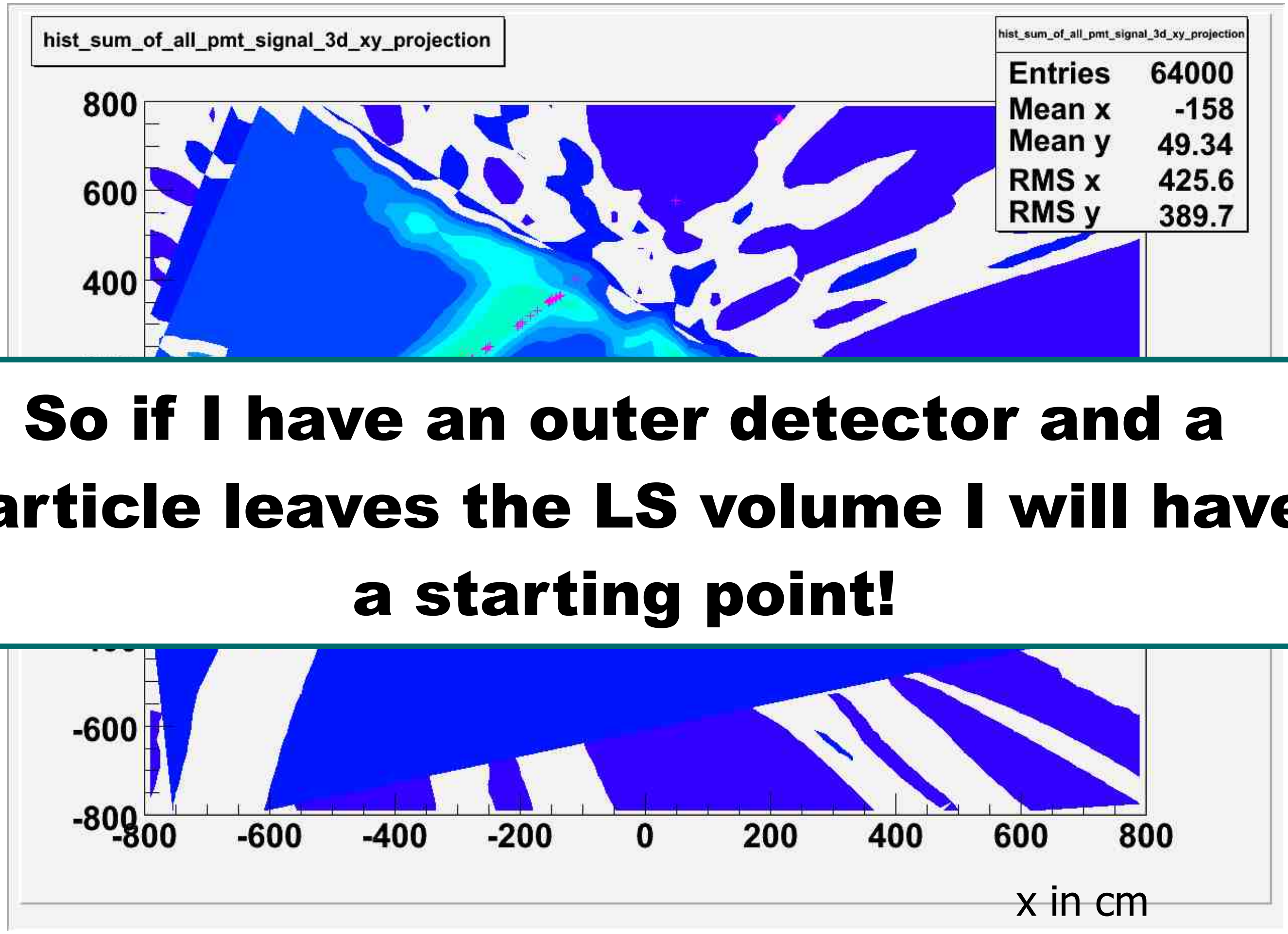
- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**



10% of PMTs at +-500 cm in z with respect to vertex

2GeV Muon, First Hit, Back from Middle

- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**



So if I have an outer detector and a particle leaves the LS volume I will have a starting point!

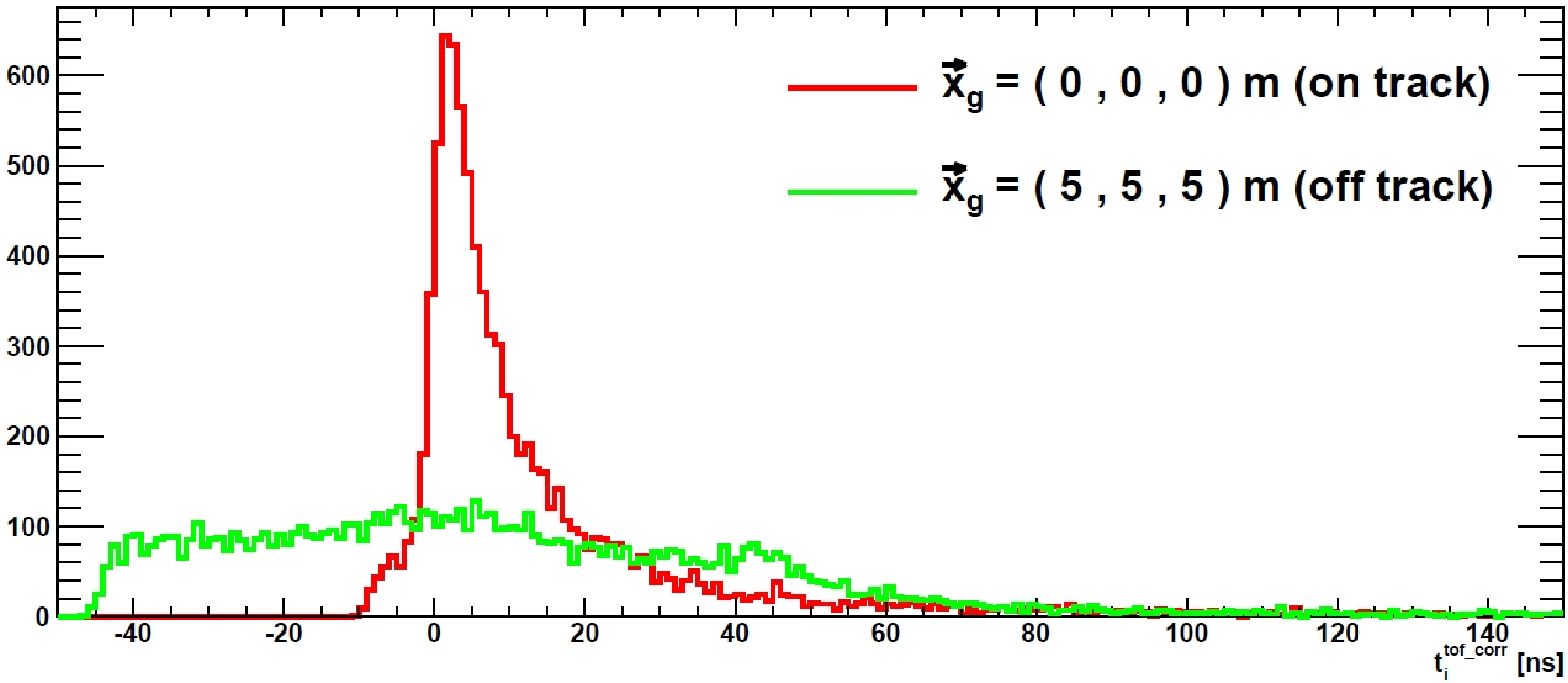
10% of PMTs at +-500 cm in z with respect to vertex

Vertex Finding/Backtracking

Basic idea:

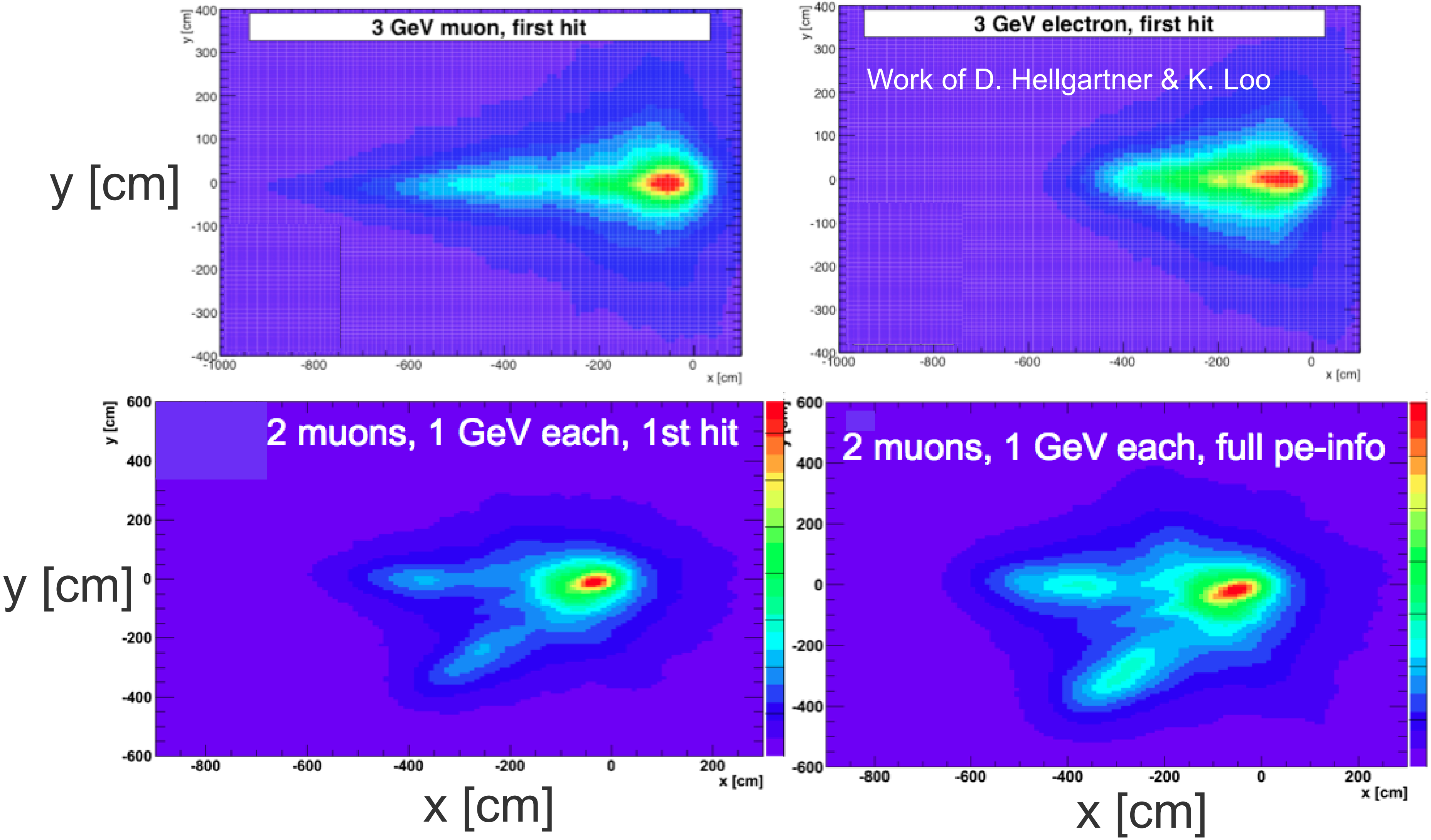
from Domenikus Hellgartner

- Calculate at every point the time correction needed for each first hit signal to match the flight time to that point
- Then look for peaks in this time distribution



Vertex Reconstruction I

Uses first hit time of each PMT and gaussian time distribution

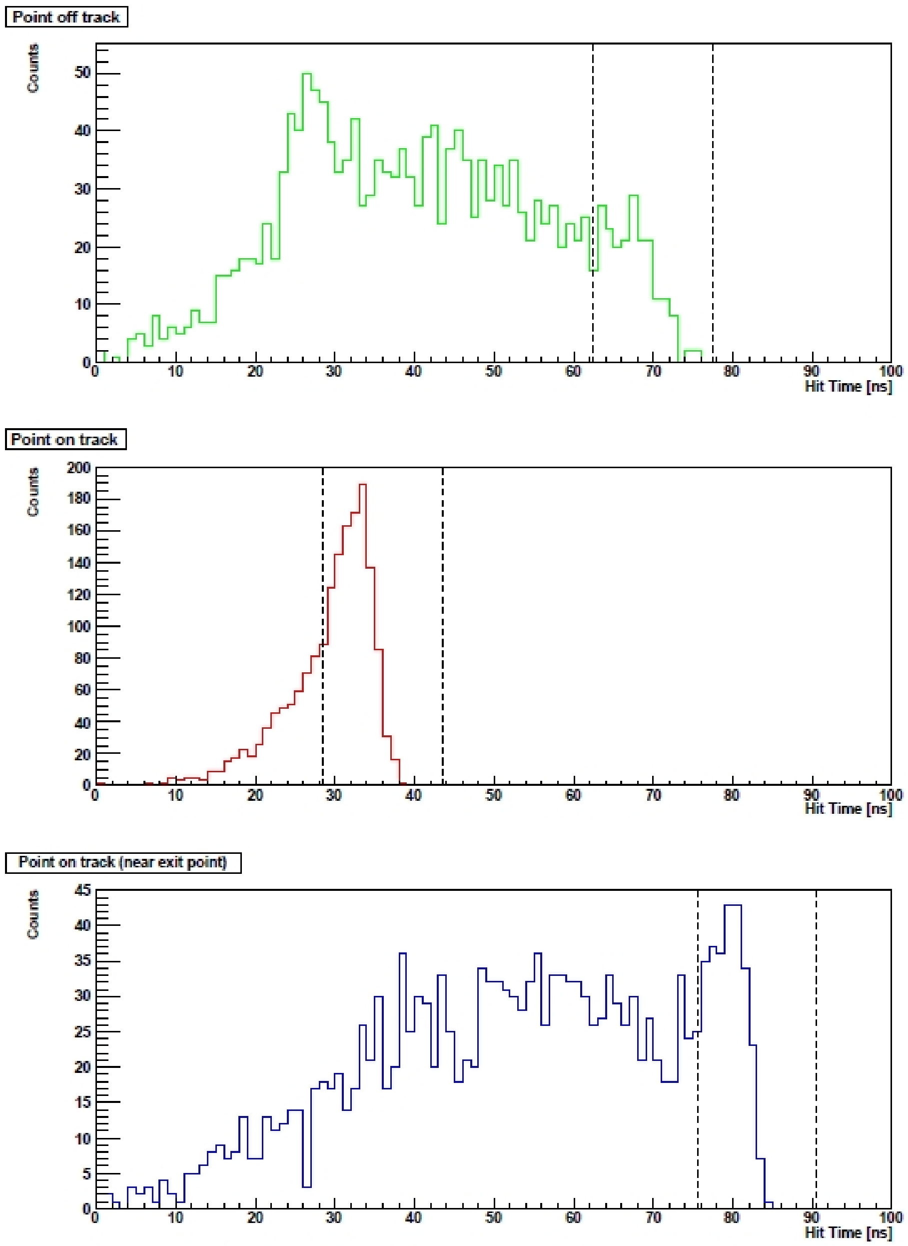


How to improve Backtracking

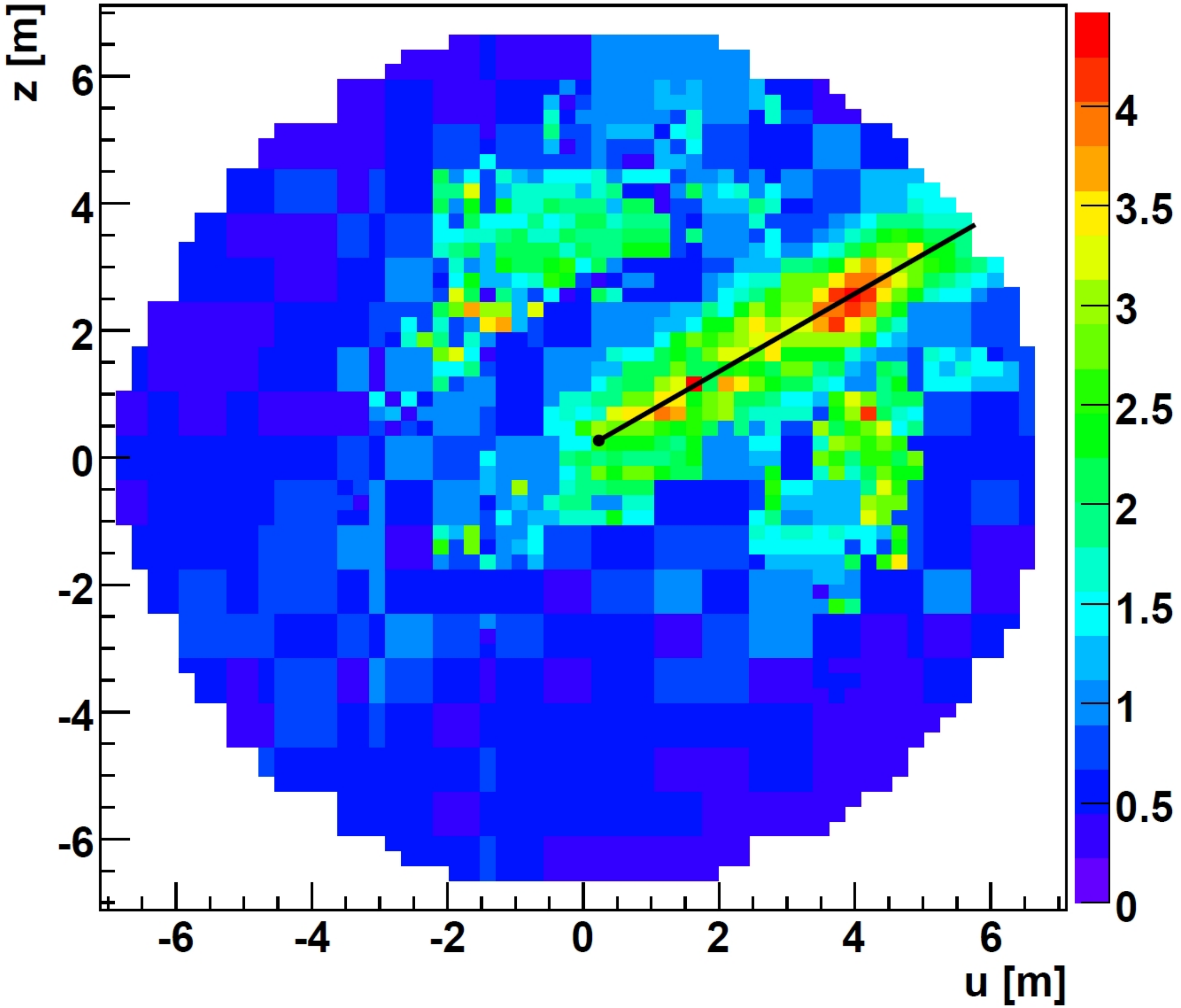
Some regions on track do not produce many 'first hits'

→ Need to look more closely at timing patter (tof corrected)

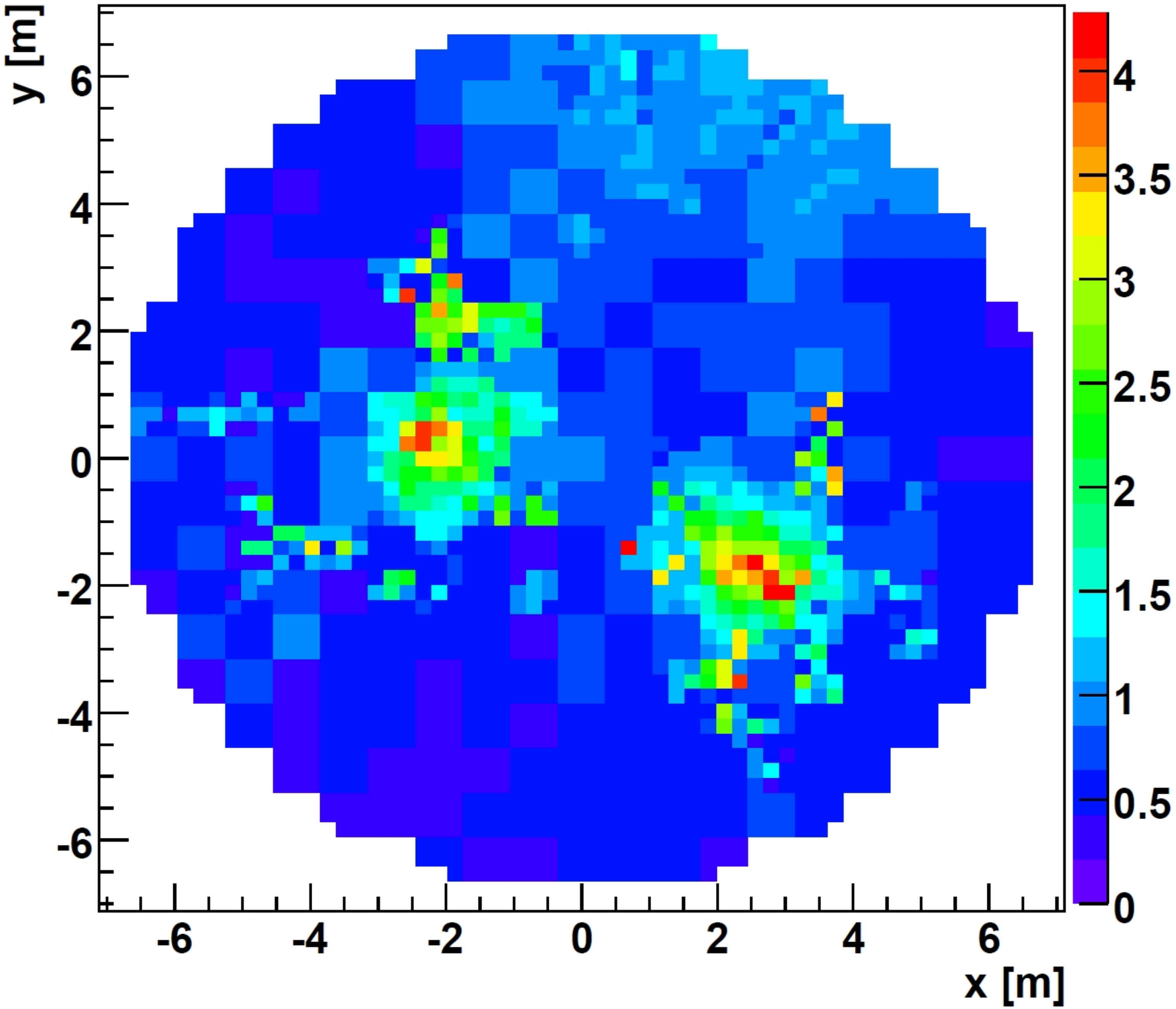
→ **whole track**



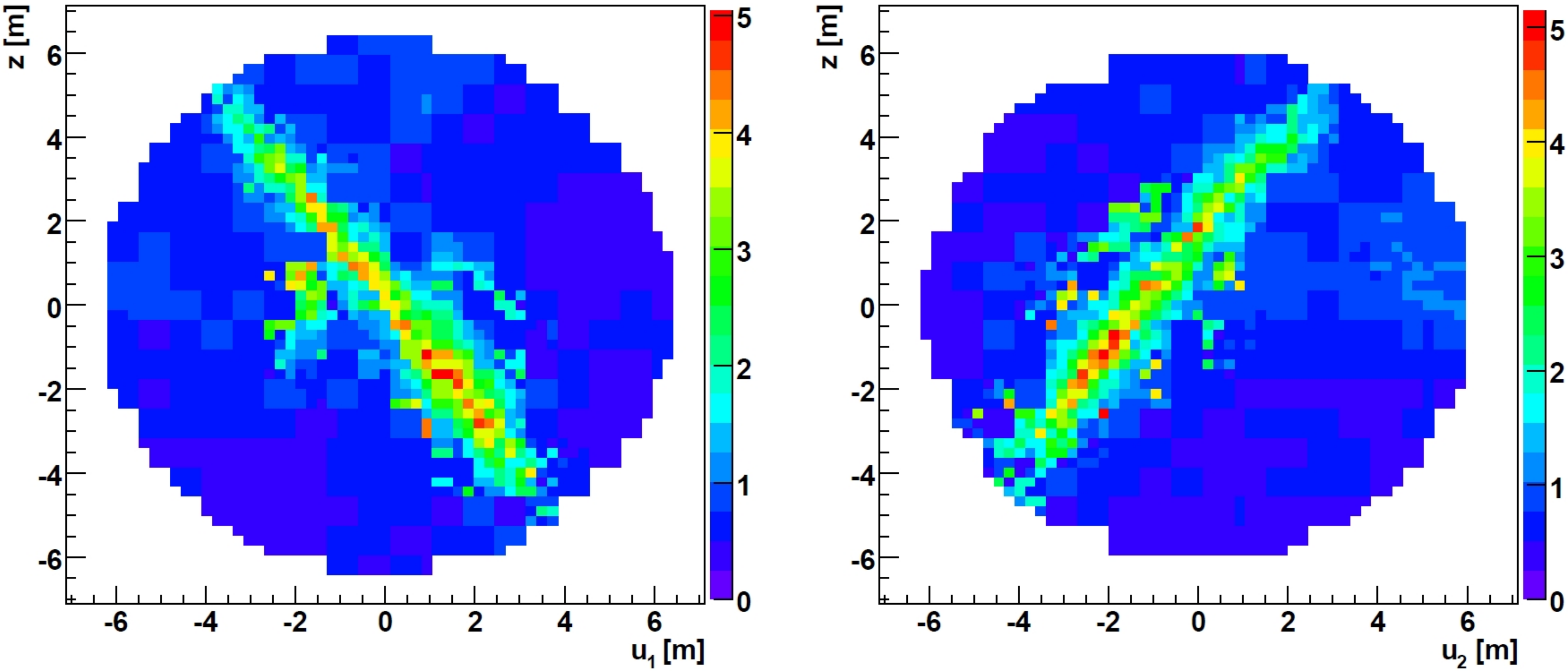
Stopped Muon in Borexino



Double Muon Event in Borexino



Double Muon Event in Borexino

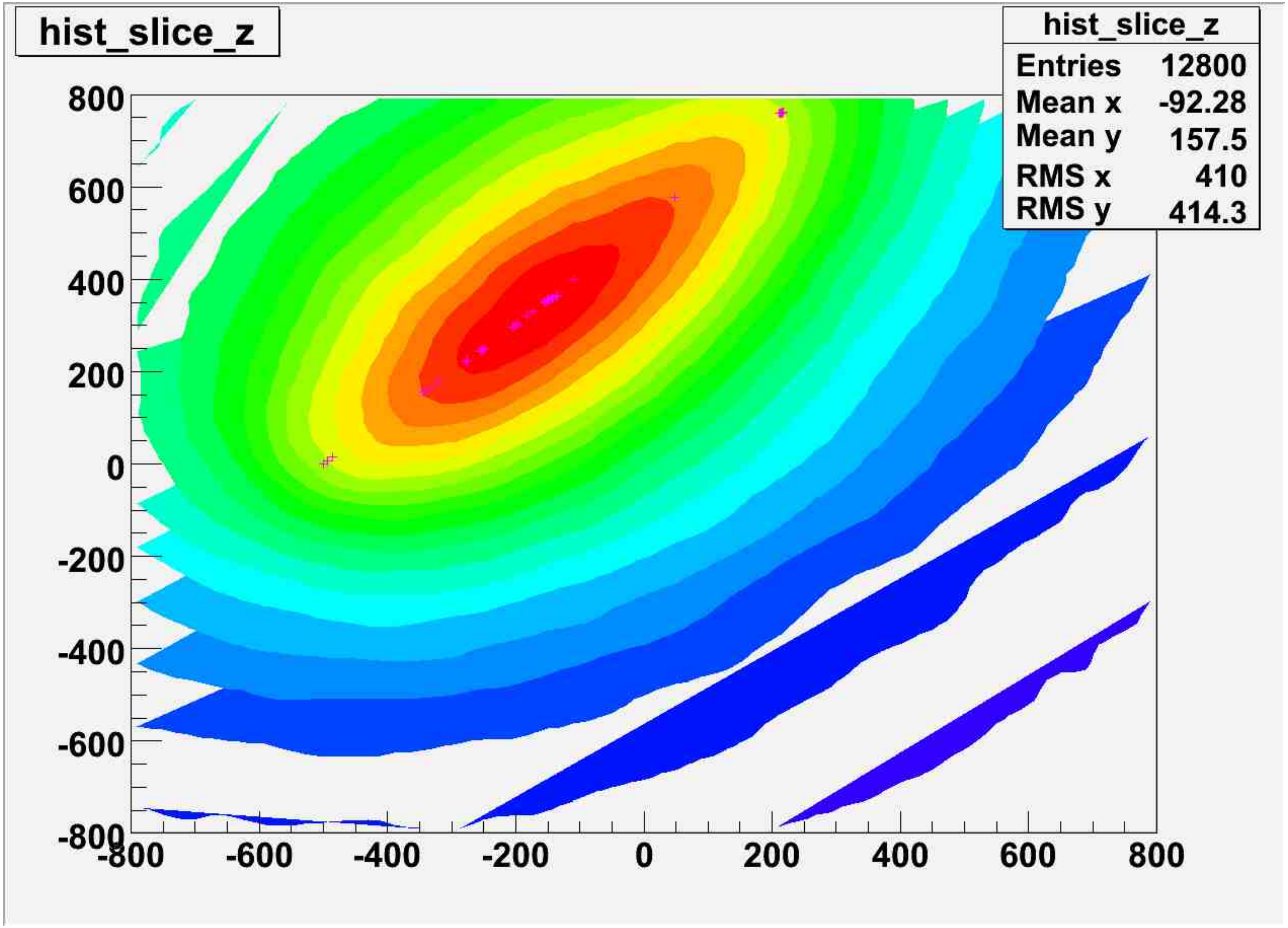


Both tracks cut out!

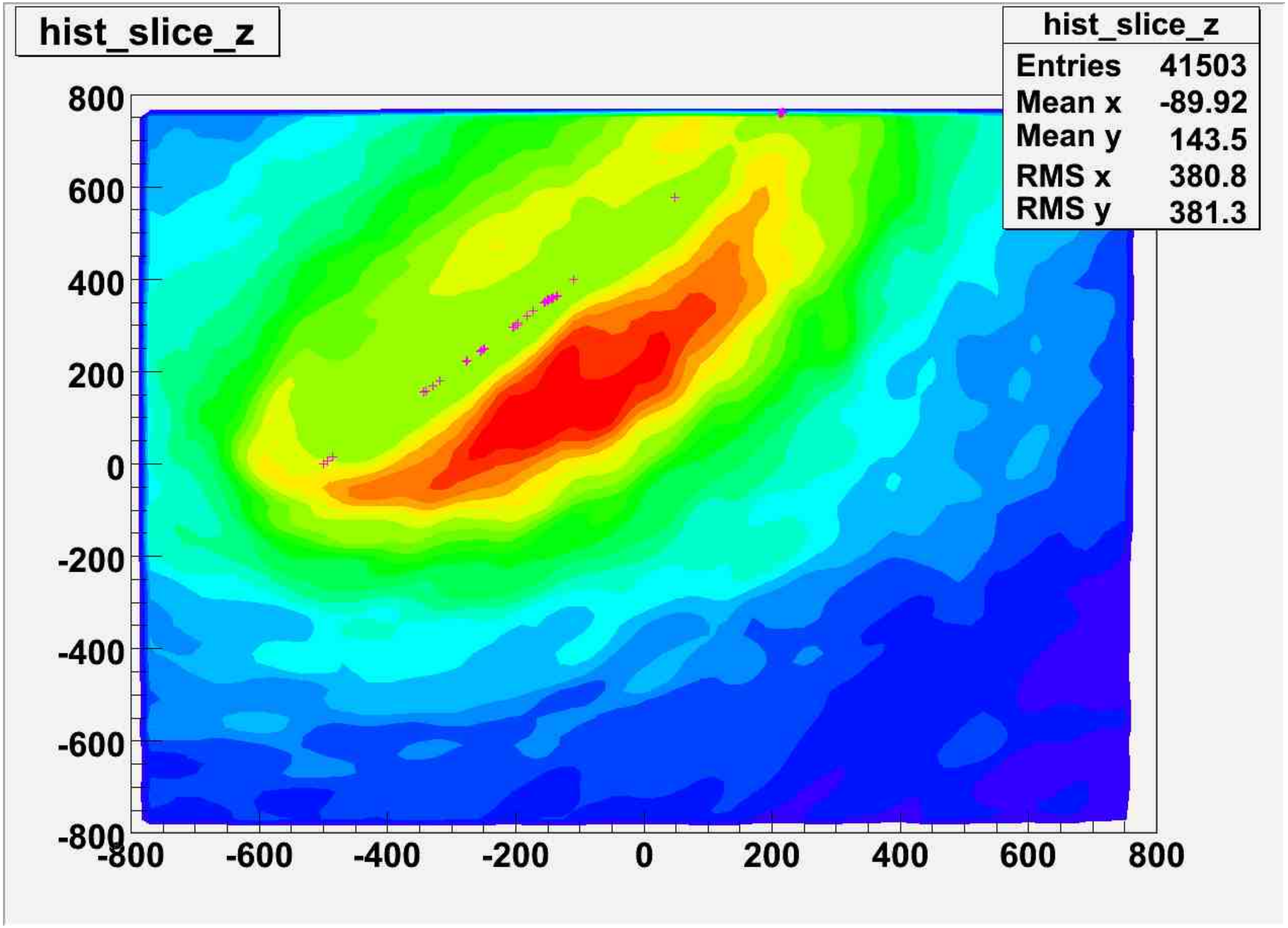
The power of the 4th dimension

4d Canny Algorithm

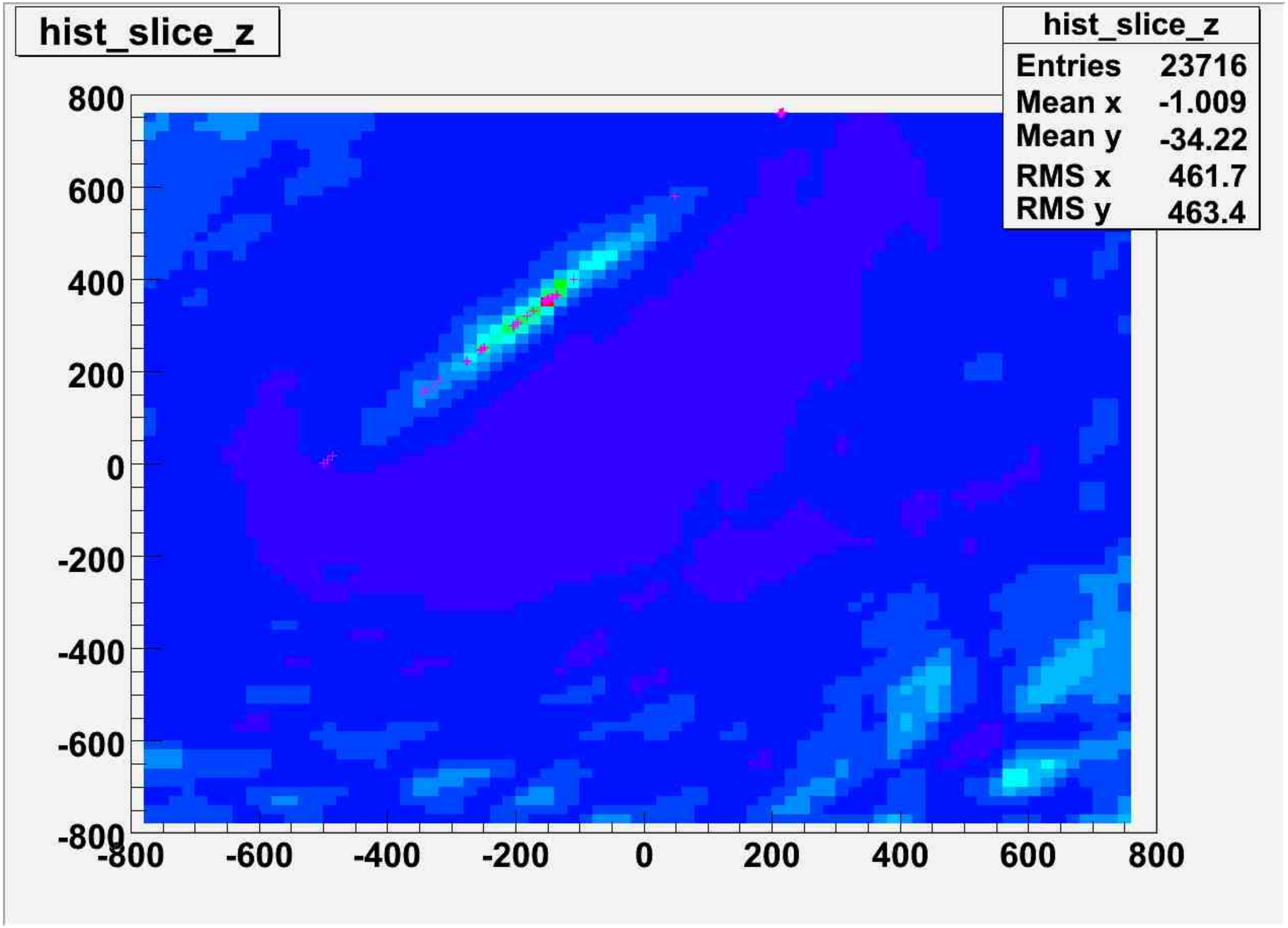
The Reco Result (266 PMTs)



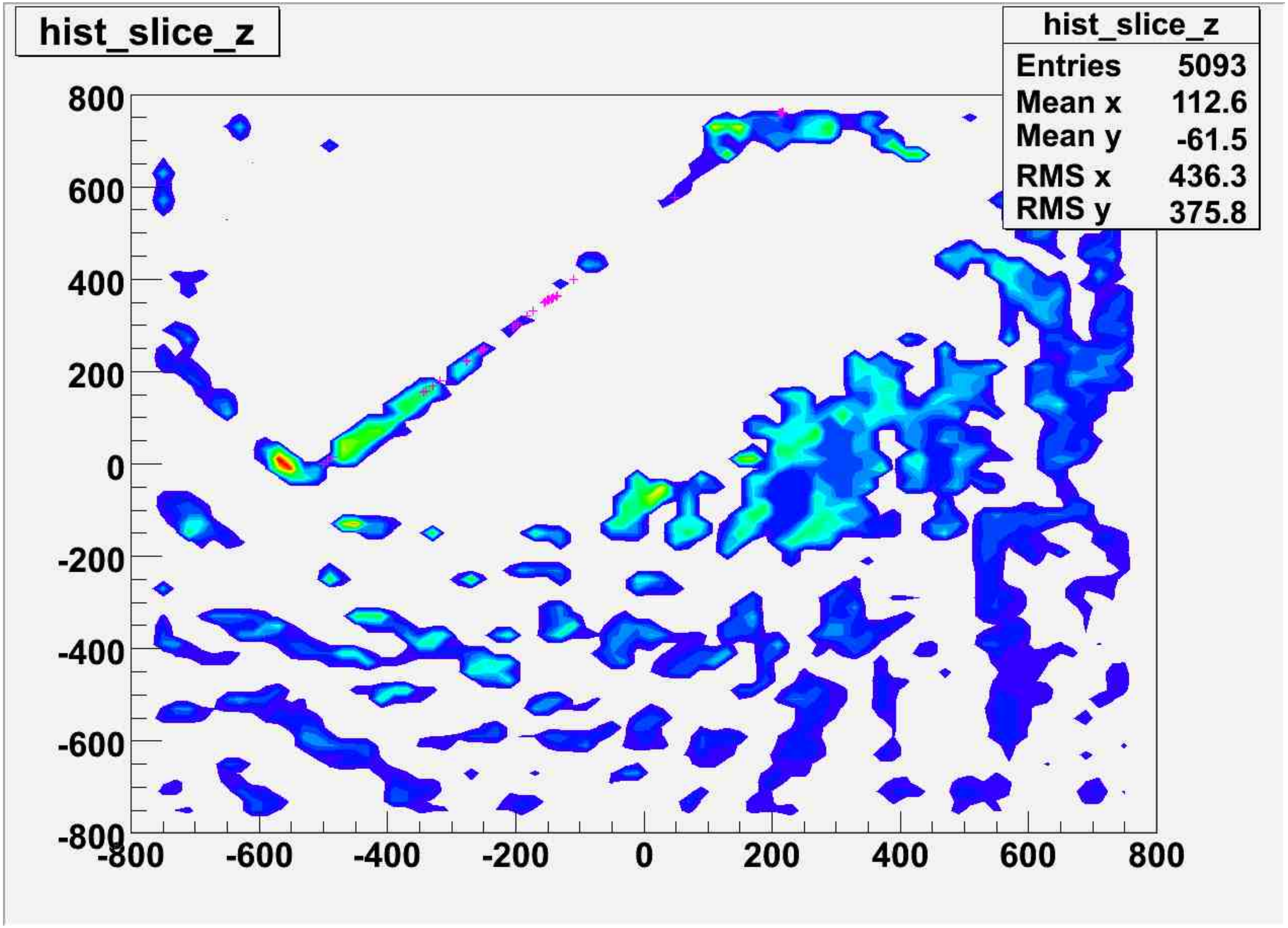
4d-Sobel Result



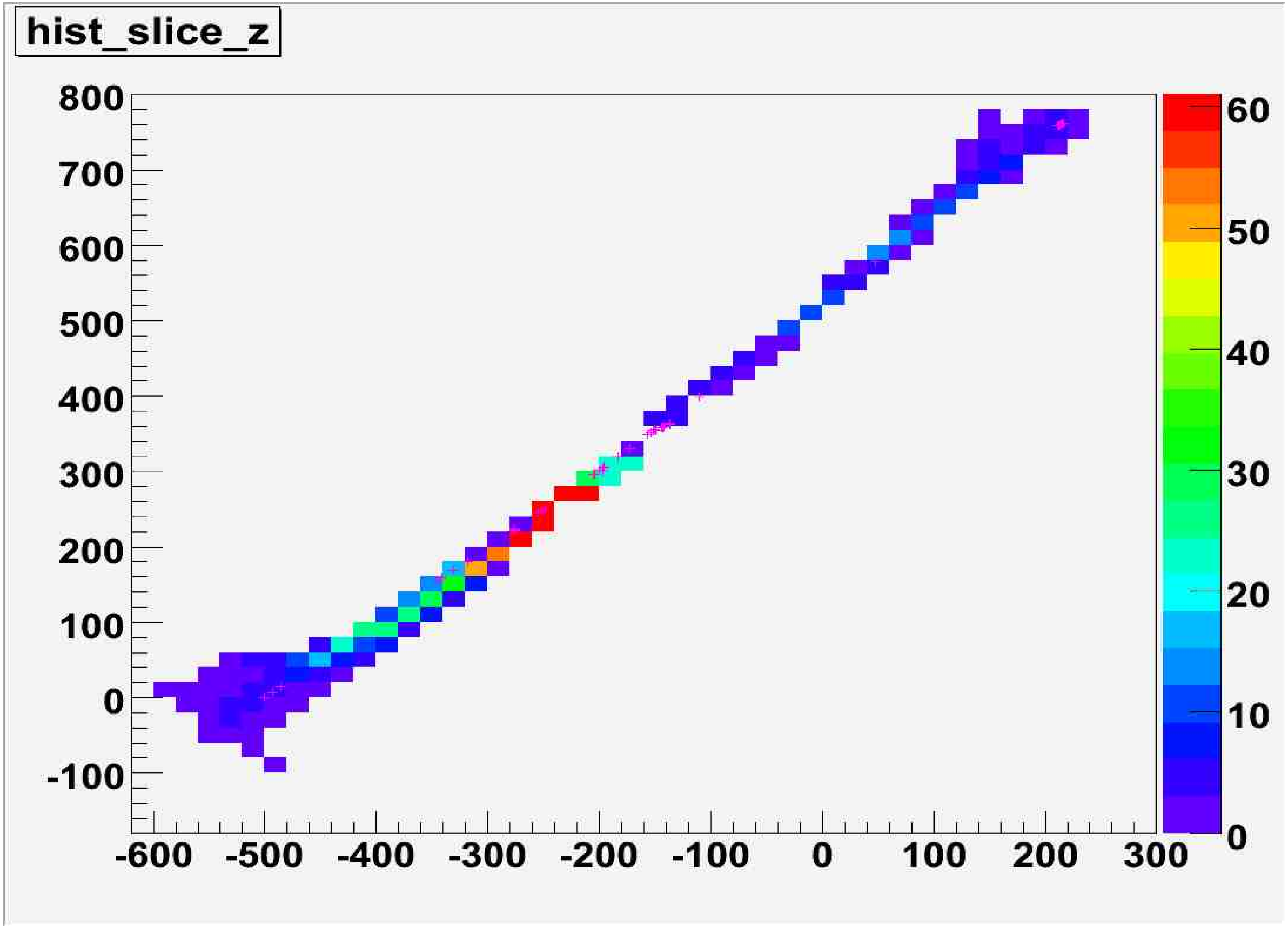
Reco Result divided by 4d-Sobel



Minima of 4d-Sobel



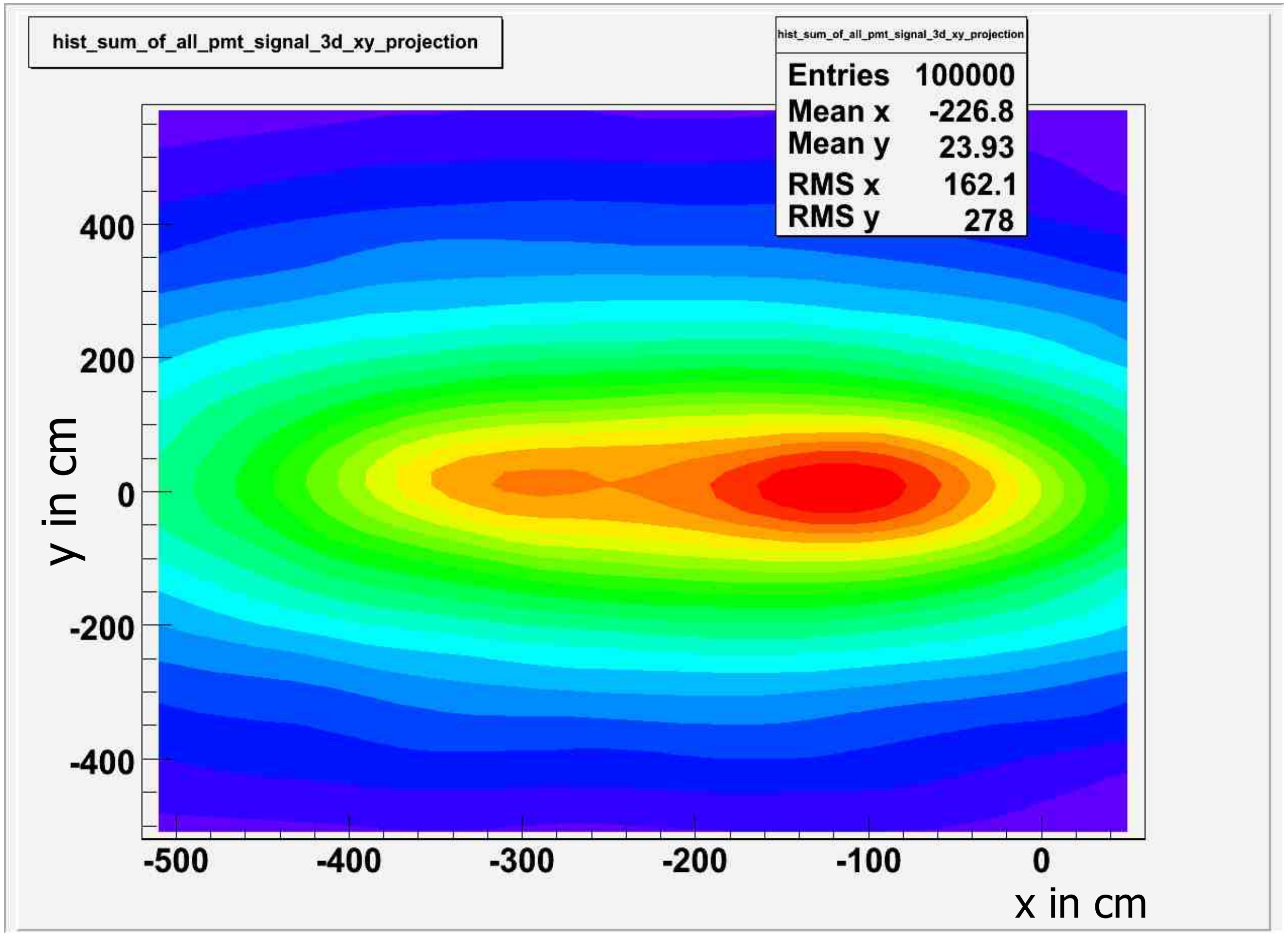
Result after Follow-up



Some early examples with different particles

465 MeV π_0

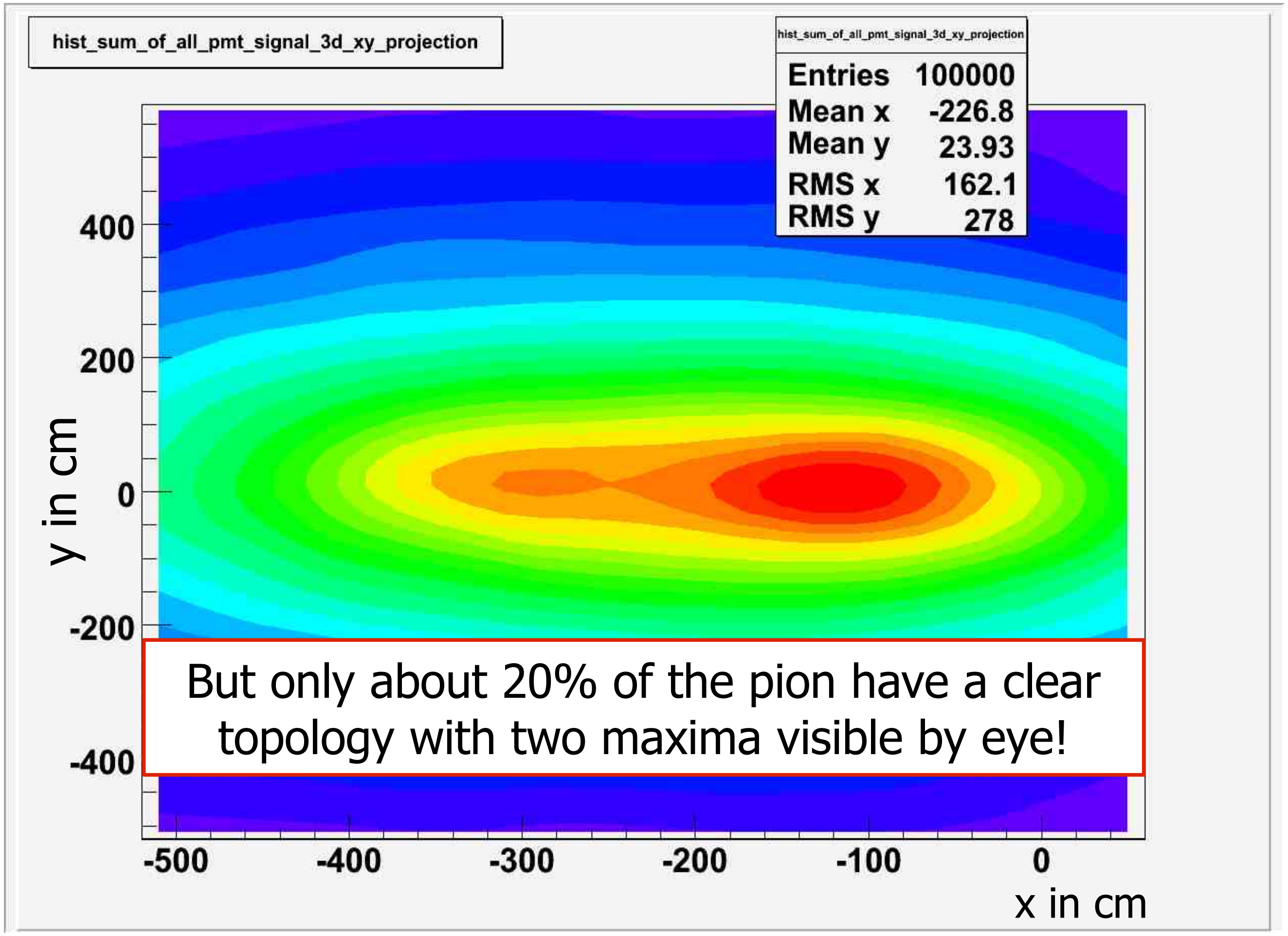
- **Vertex (0.,0.,0.), Orientation (-1.,0.,0.)**



10% of PMTs at +-500 cm in z with respect to vertex

465 MeV π_0

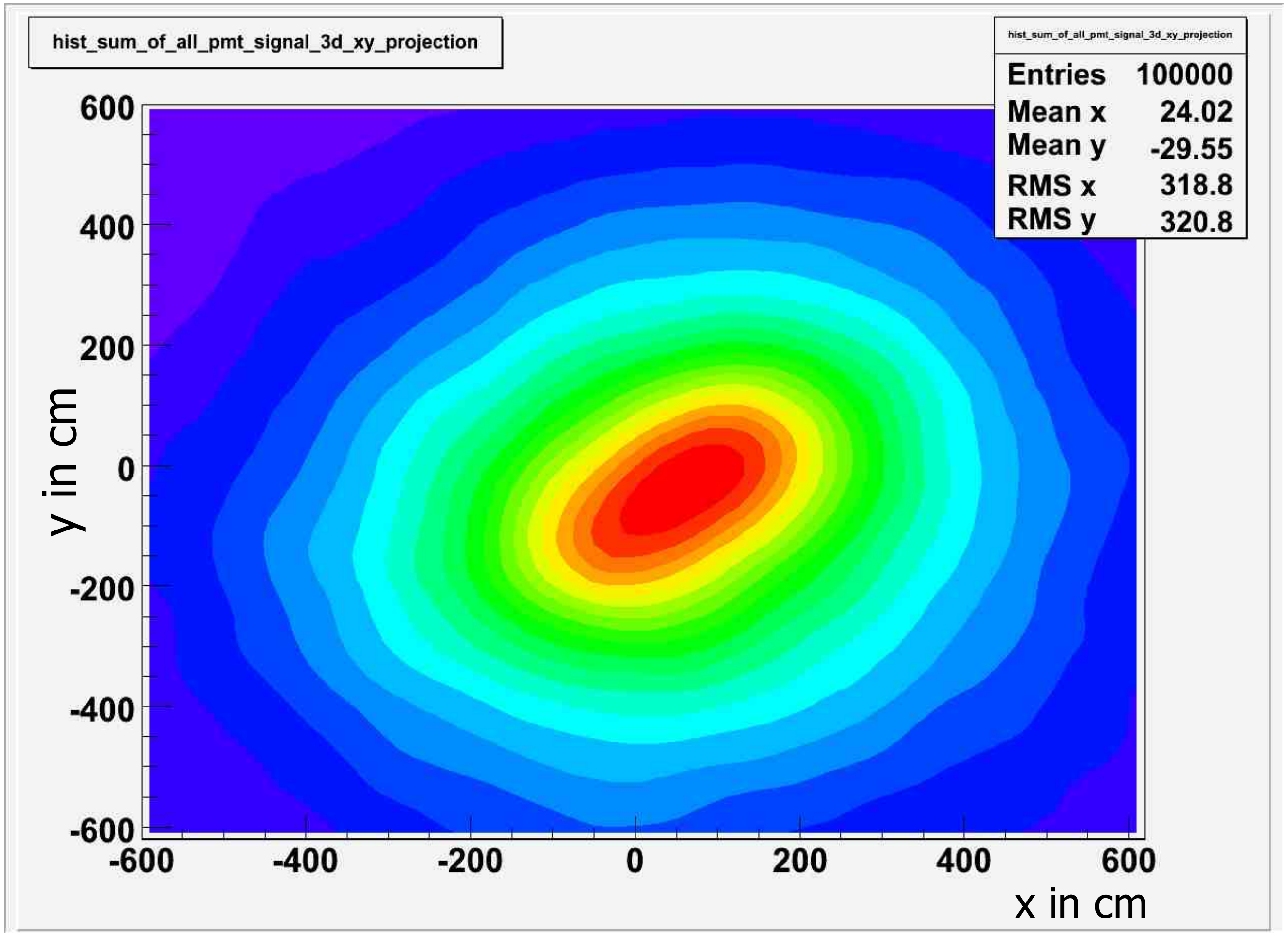
- **Vertex (0.,0.,0.), Orientation (-1.,0.,0.)**



10% of PMTs at +-500 cm in z with respect to vertex

Muon 800 MeV

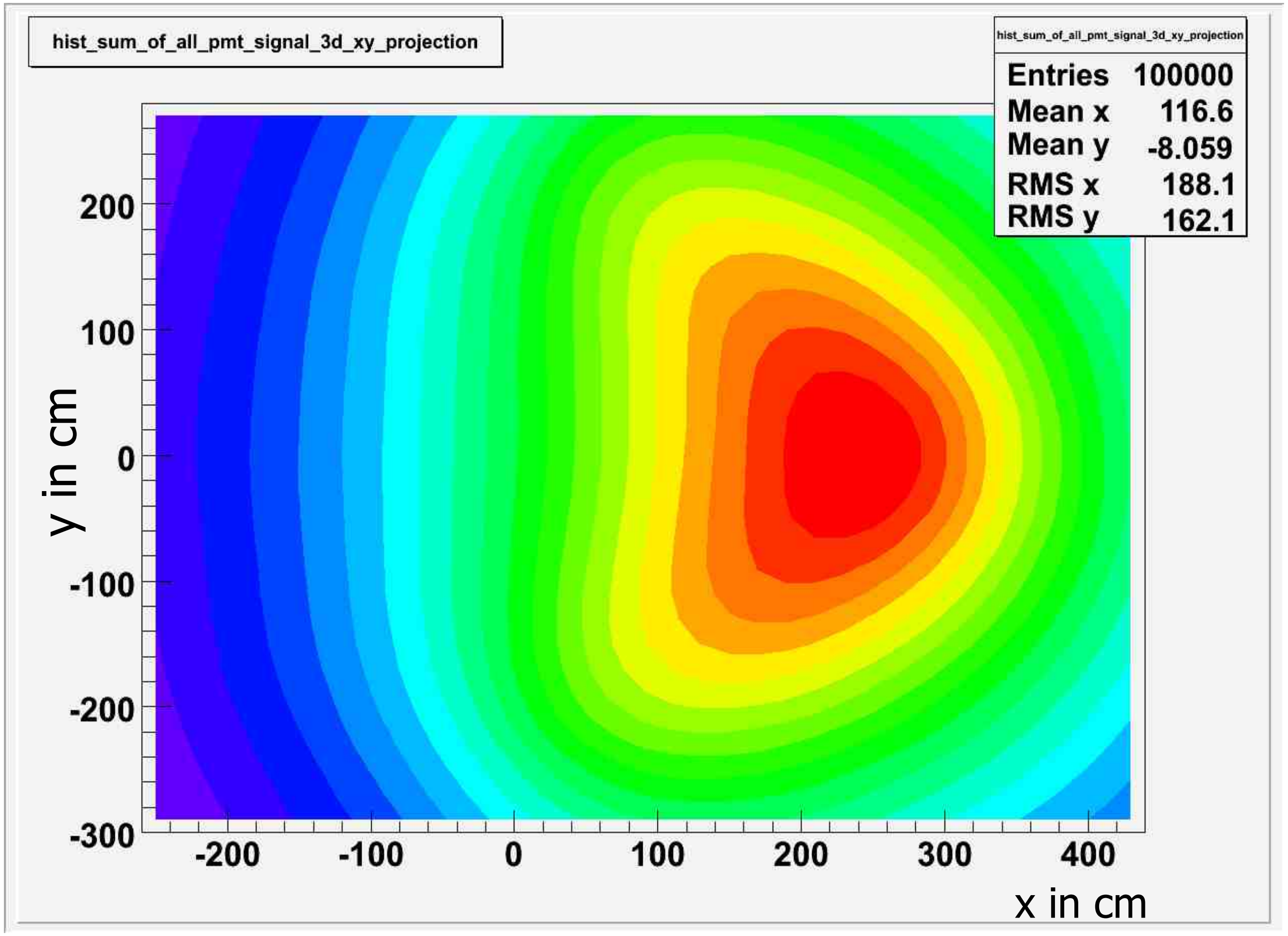
- **Vertex (200.,100.,0.), Orientation (-1.,-1.,0.)**



10% of PMTs at +-500 cm in z with respect to vertex

2 Muons with 750 MeV each

- **Vertex (300.,0.,0.), Orientation +-45°**



10% of PMTs at +-500 cm in z with respect to vertex

Ridge-Line Analysis

- **Remark:**
  - The pictures seem to give only rough spatial information
  - This is only because the single photon resolution is poor
- **But we have a lot of light**

  → mean value should be very accurate

  → Need method to increase contrast/use the picture to find the track position

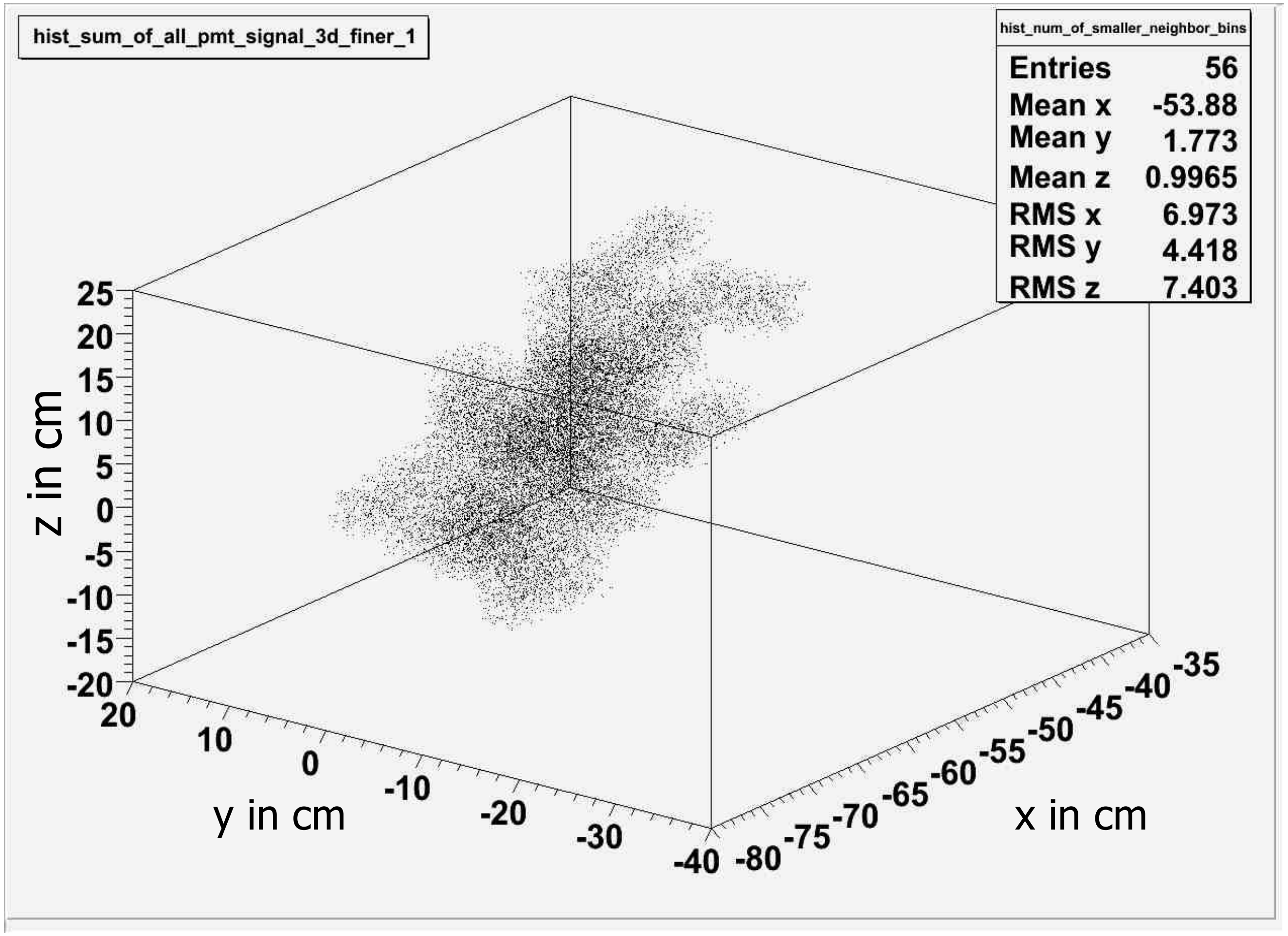
Ridge-Line Analysis

- **Idea: Track should be a kind of ridge (in 3d)**

  → Take only bins, with more than 17 smaller neighbour bins

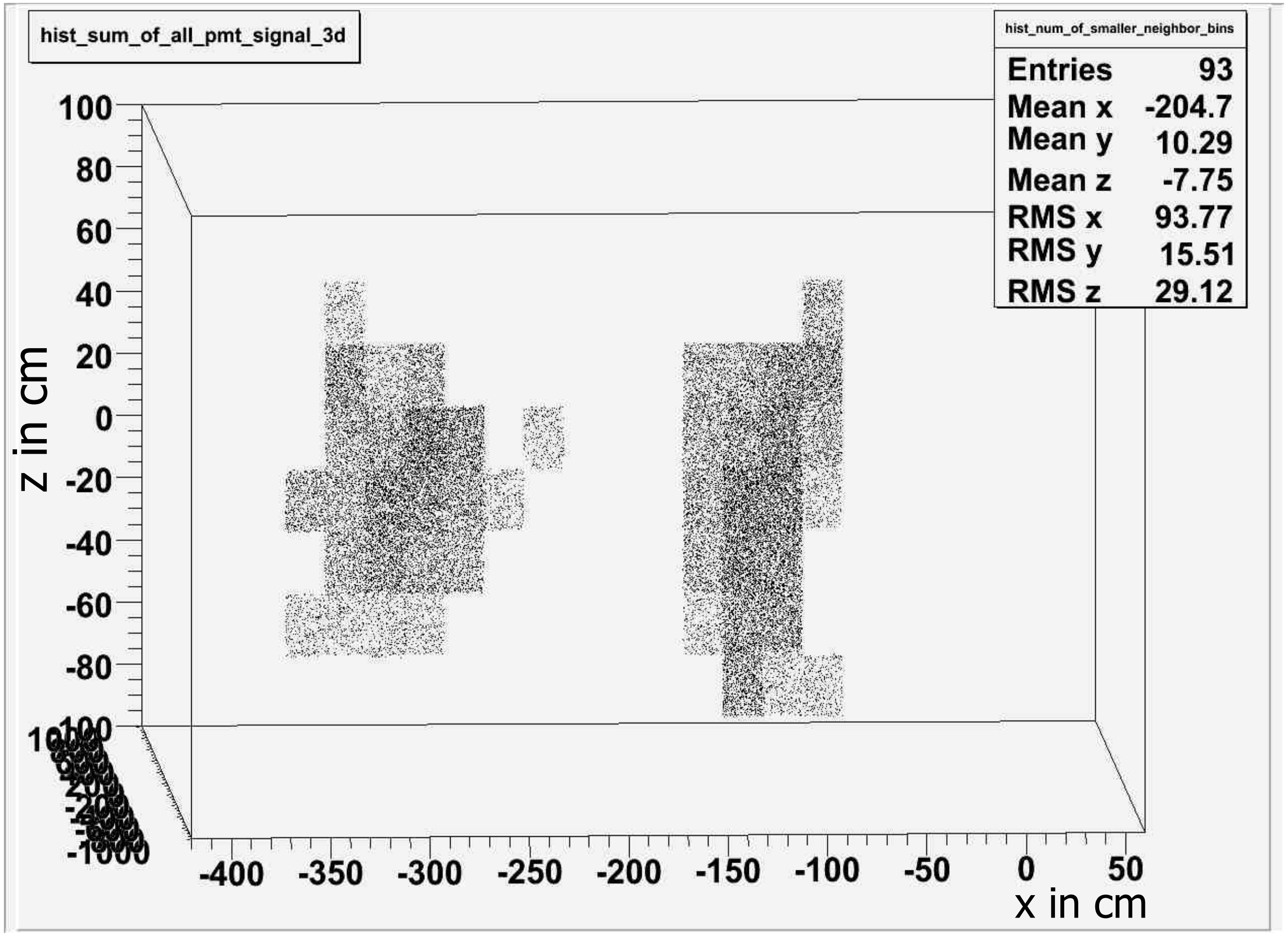
Resultat: 500 MeV Electron

- **Vertex (0.,0.,0.), Orientation (-1.,0.,0.)**



465 MeV π_0

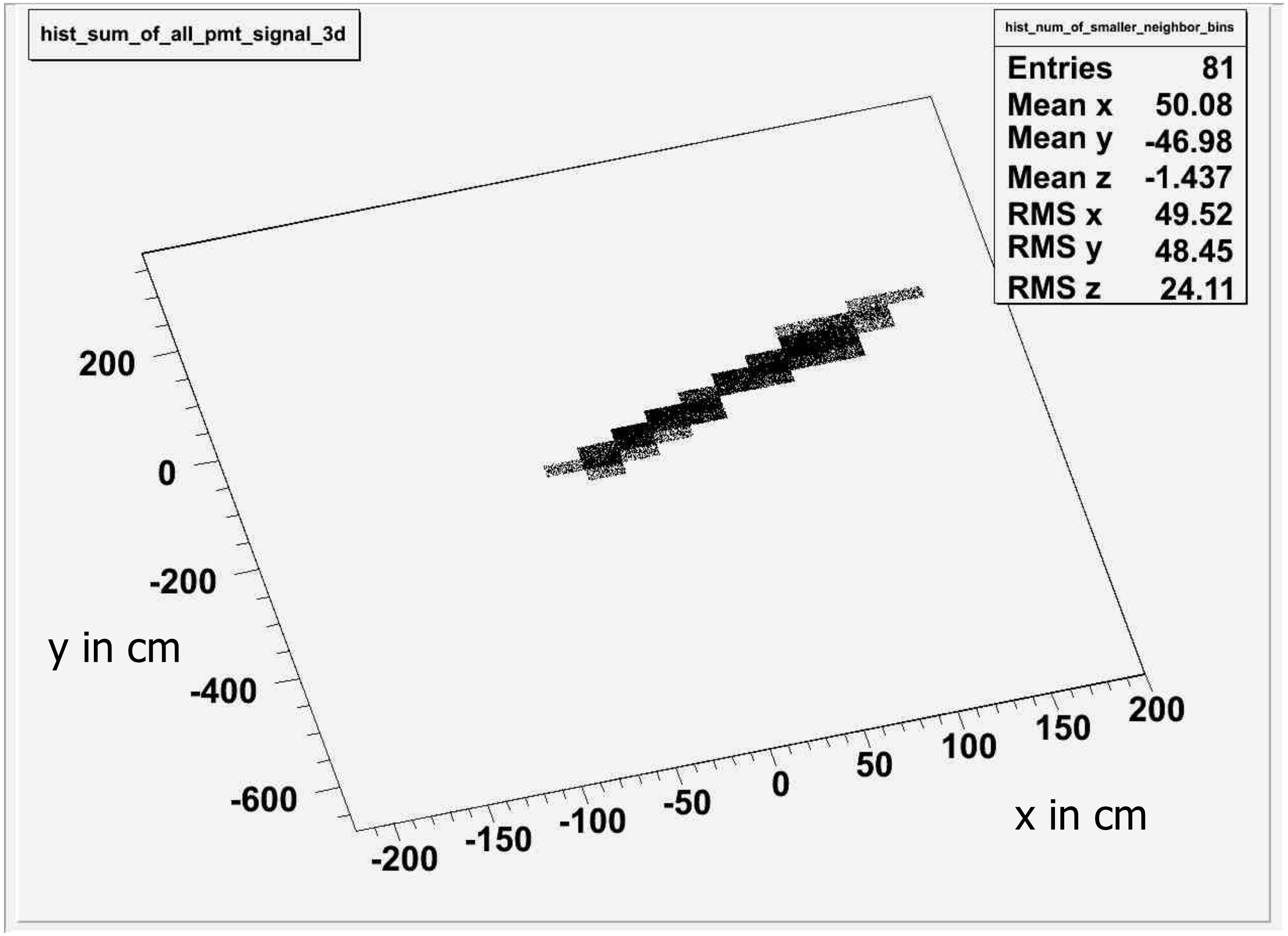
- **Vertex (0.,0.,0.), Orientation (-1.,0.,0.)**



10% of PMTs

Muon 800 MeV

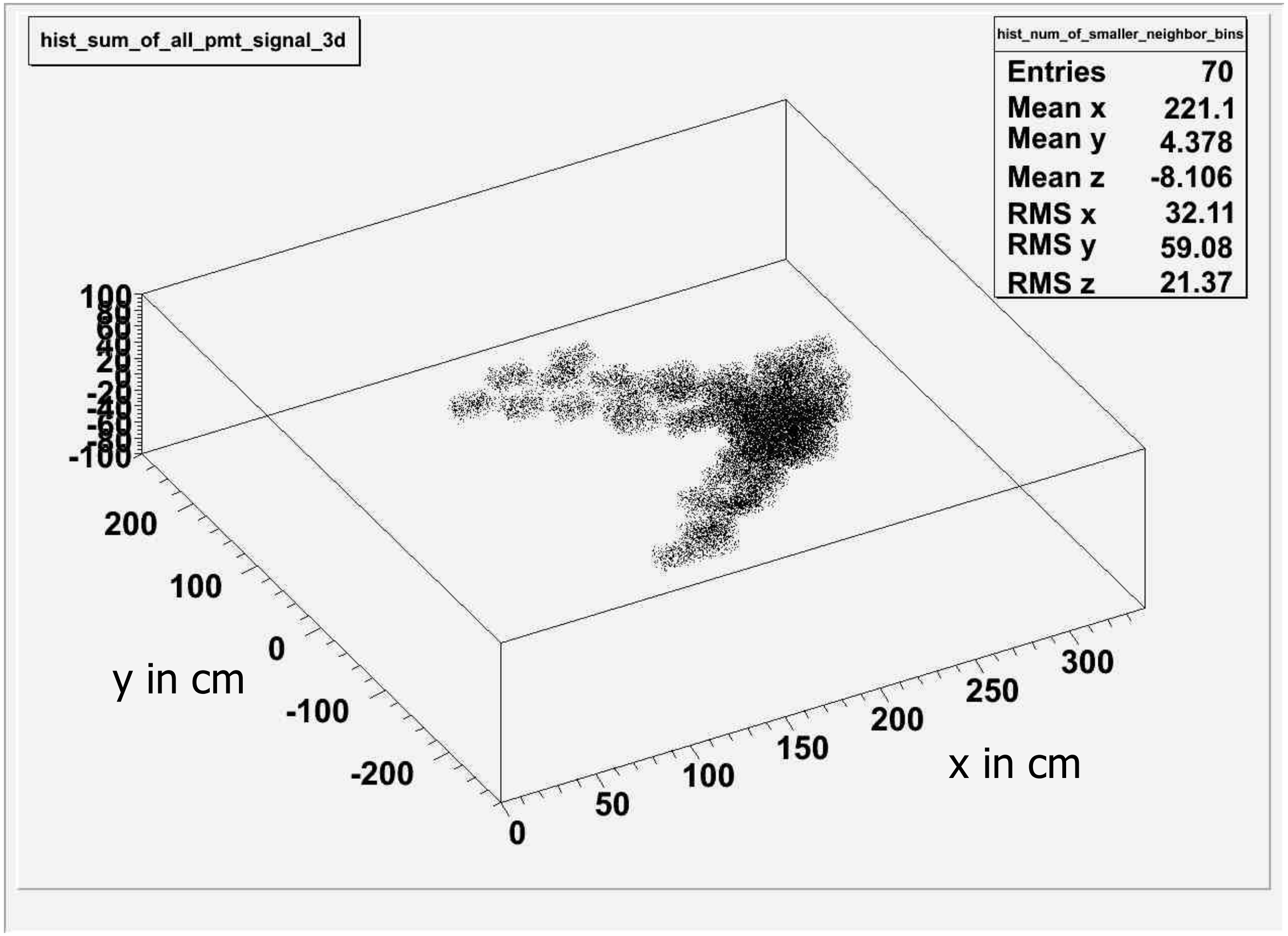
- **Vertex (200.,100.,0.), Orientation (-1.,-1.,0.)**



10% of PMTs at +-500 cm in z with respect to vertex

2 Muons with 750 MeV each

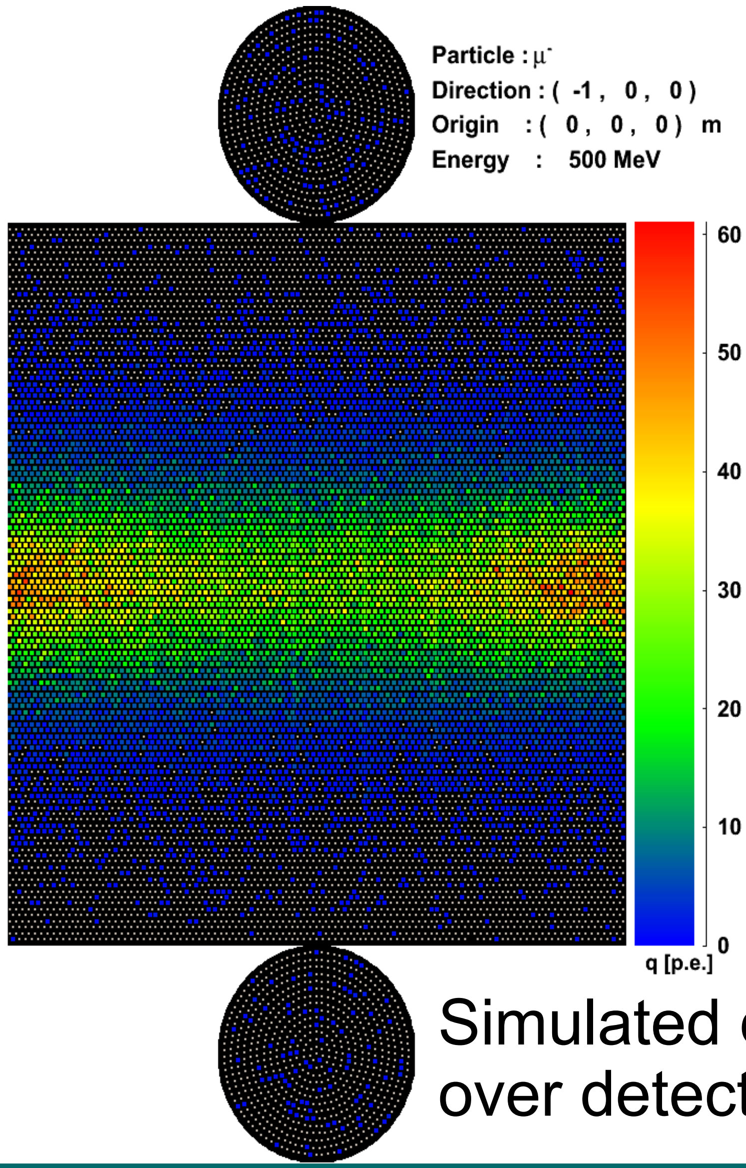
- **Vertex (300.,0.,0.), Orientation +-45°**



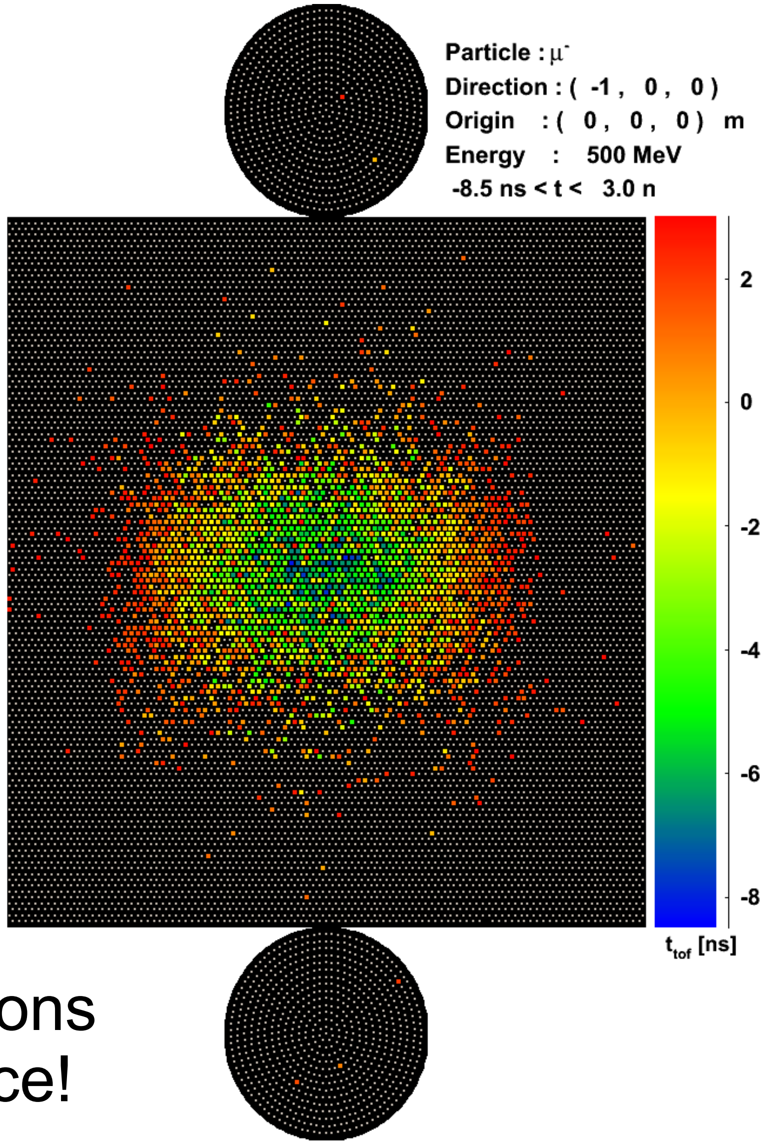
10% of PMTs at +-500 cm in z with respect to vertex

Event Signature for Tracking

Charge



(First) Hit time



Simulated distributions over detector surface!