# Tracking in large Volume Liquid Scintillator Detectors

## Applied to LENA

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

# LENA Detector Layout

**Liquid Scintillator:**
~69 kton LAB

**Concrete tank:**
r=16 m, h=100 m

**32000 12'' PMTs**
light concentrators
→ 30% optical coverage

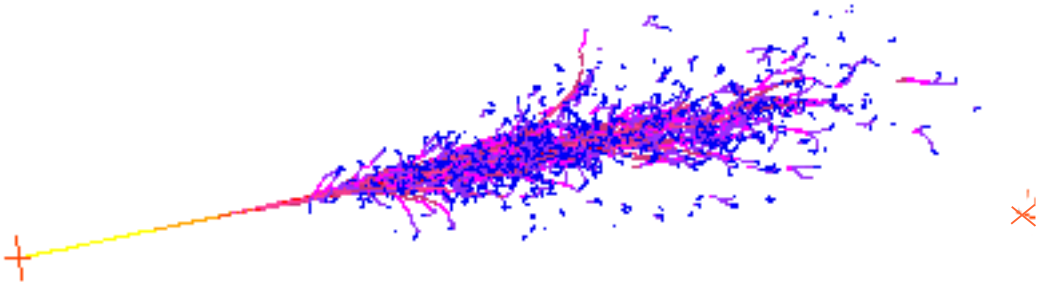
**Active volume:** ~50 kton

# Motivation for Tracking

**High energy:**

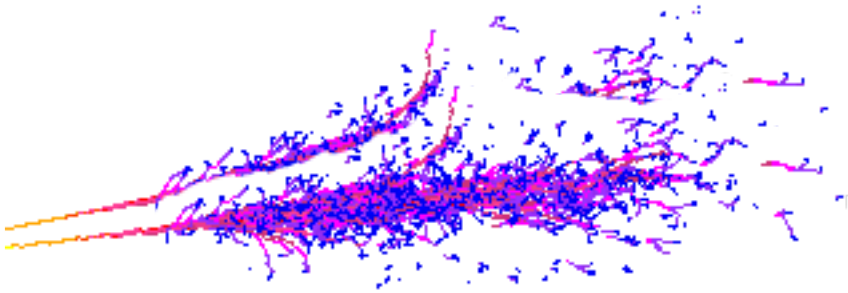
NC-background in $\nu_e$ appearance experiments

→ Is it possible to identify the $\pi_0$?



Produced by $\nu_e$-CC

Electron shower



Produced by $\nu$-NC (all-flavors)

$\pi_0 \rightarrow \gamma\gamma \rightarrow$ 2 showers

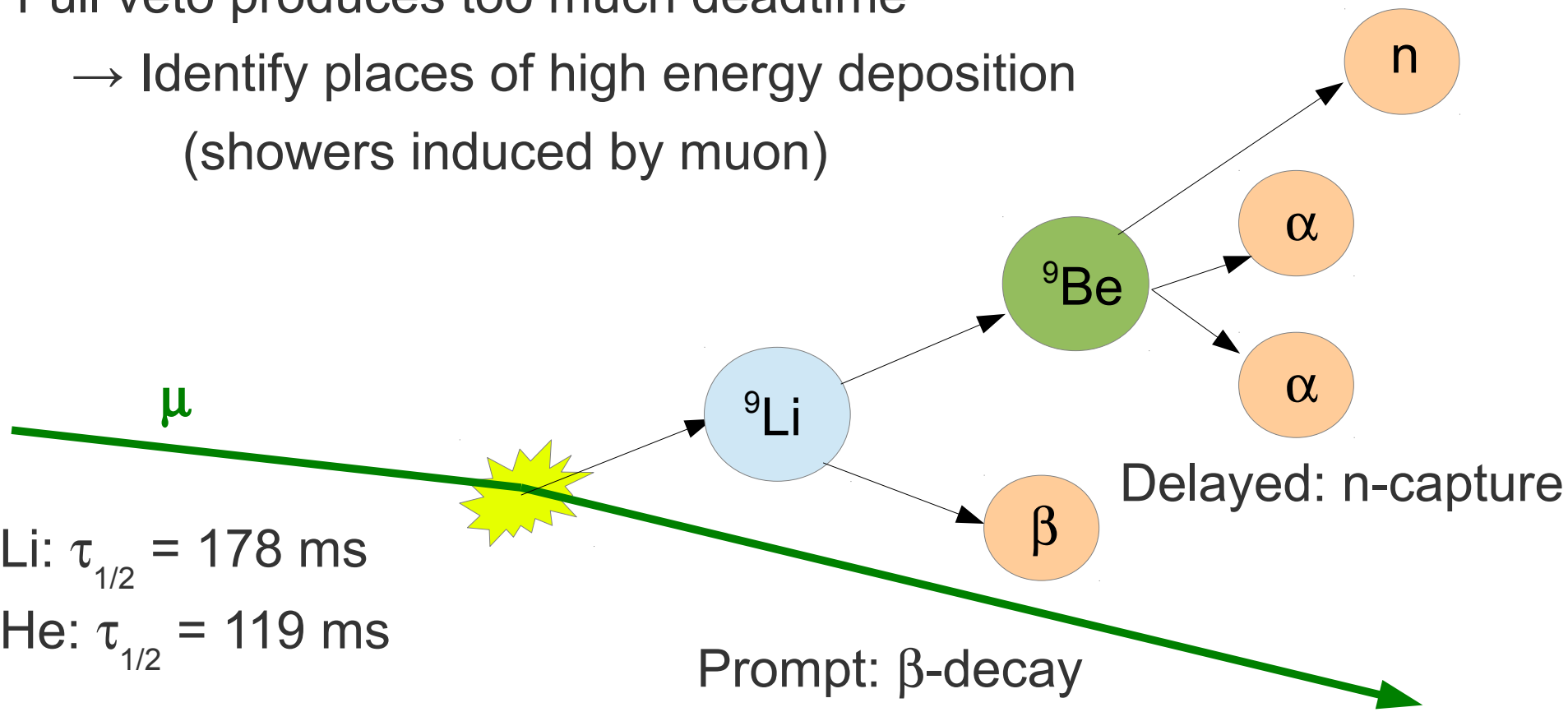
# Motivation for Tracking

**Low energy:**

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)




$^{9}$Li: $\tau_{1/2}$ = 178 ms

$^{8}$He: $\tau_{1/2}$ = 119 ms

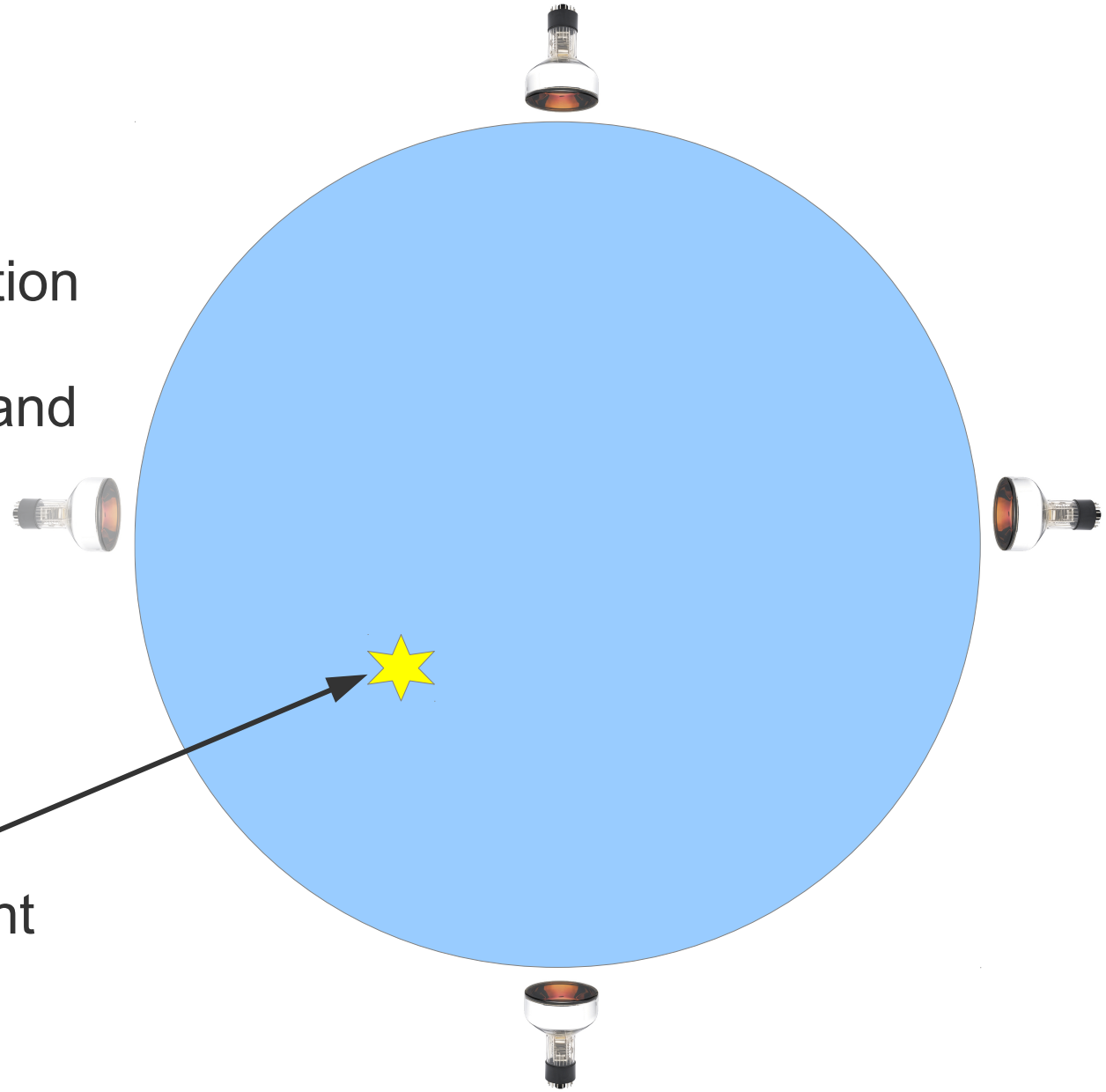
# Why no 3D Tracking (so far)?

**Point-like event:**

Light emitted in $4\pi$
→ no directional information

Time between emission and detection = distance

→ Circles



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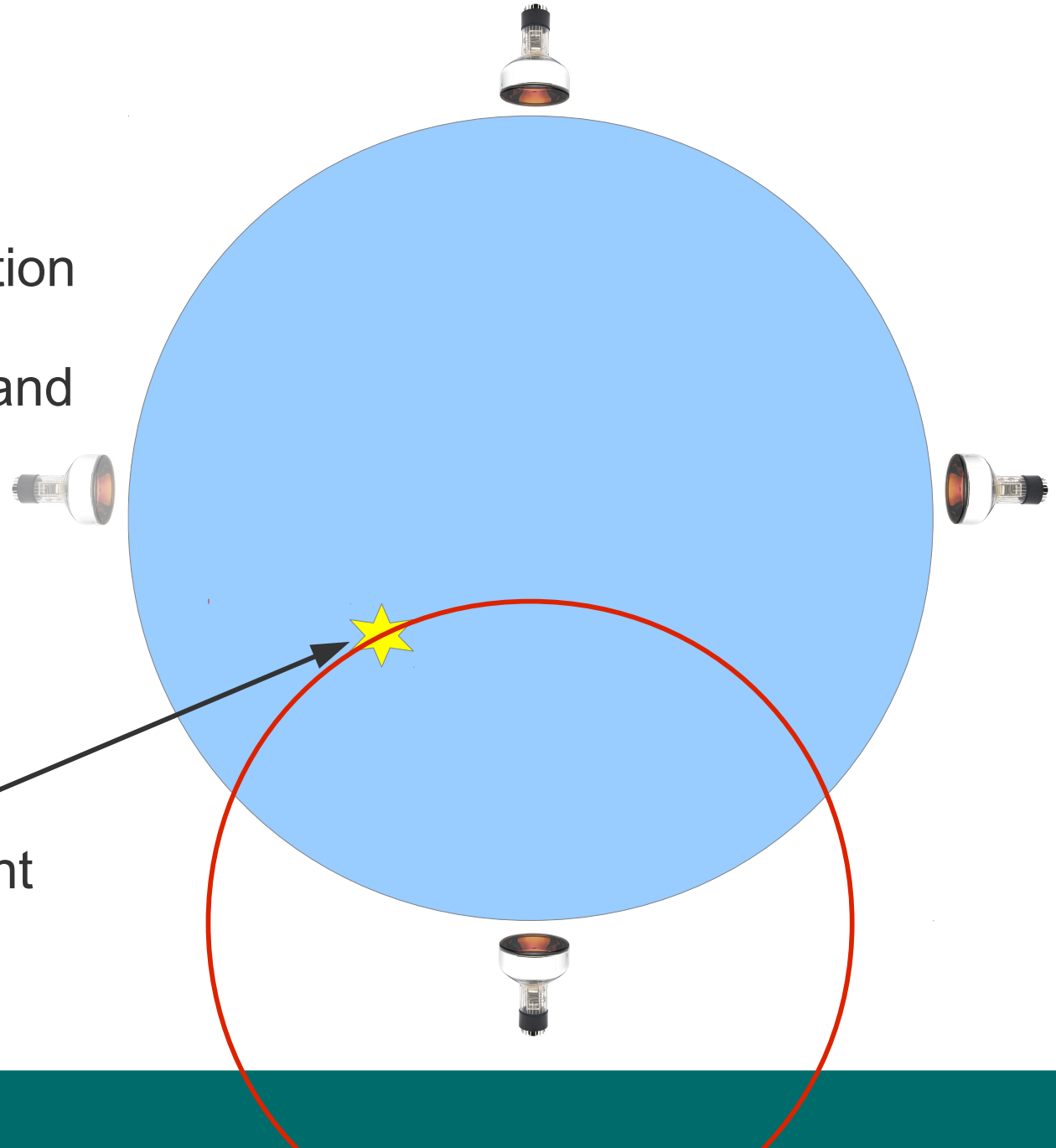

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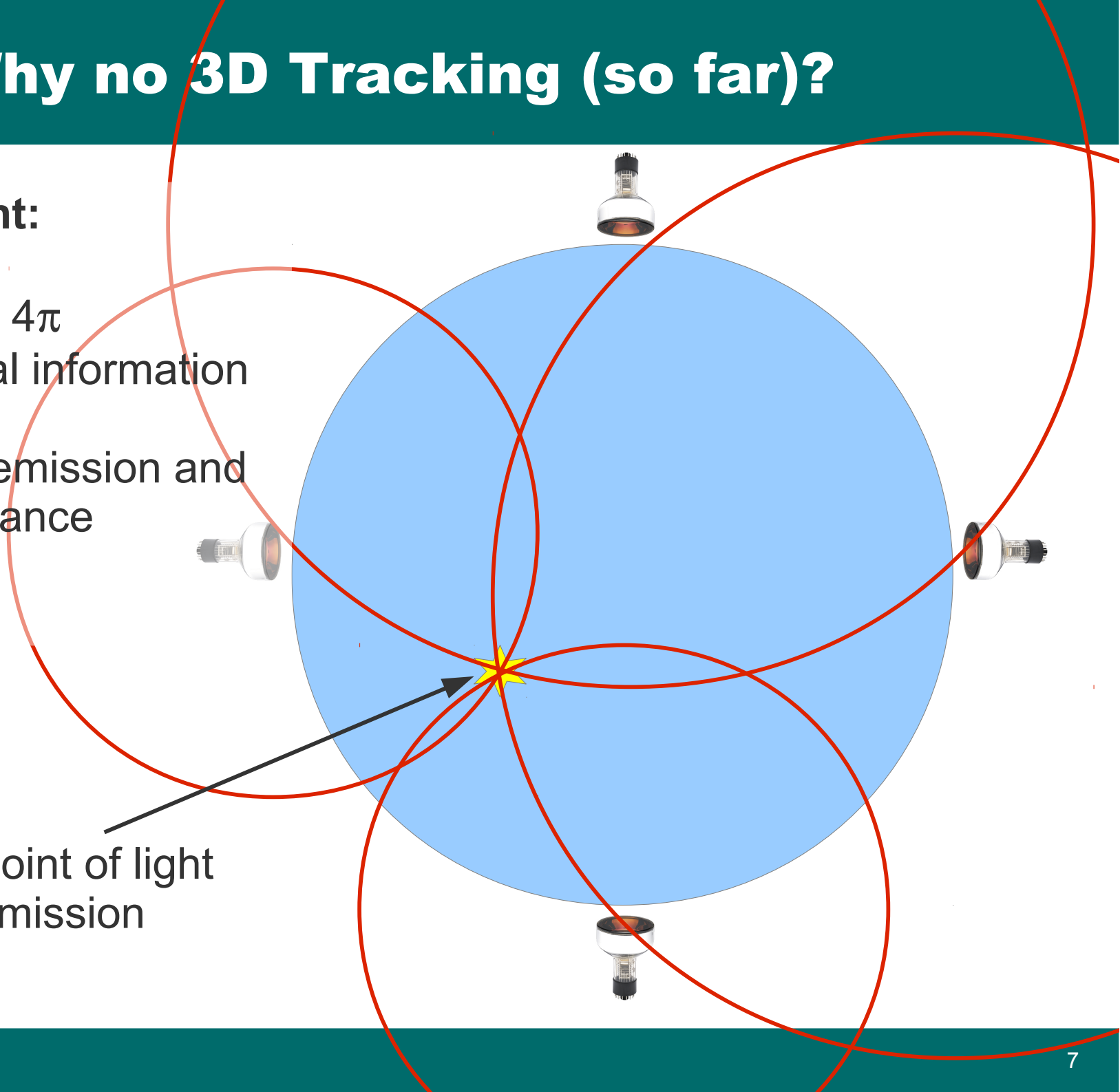
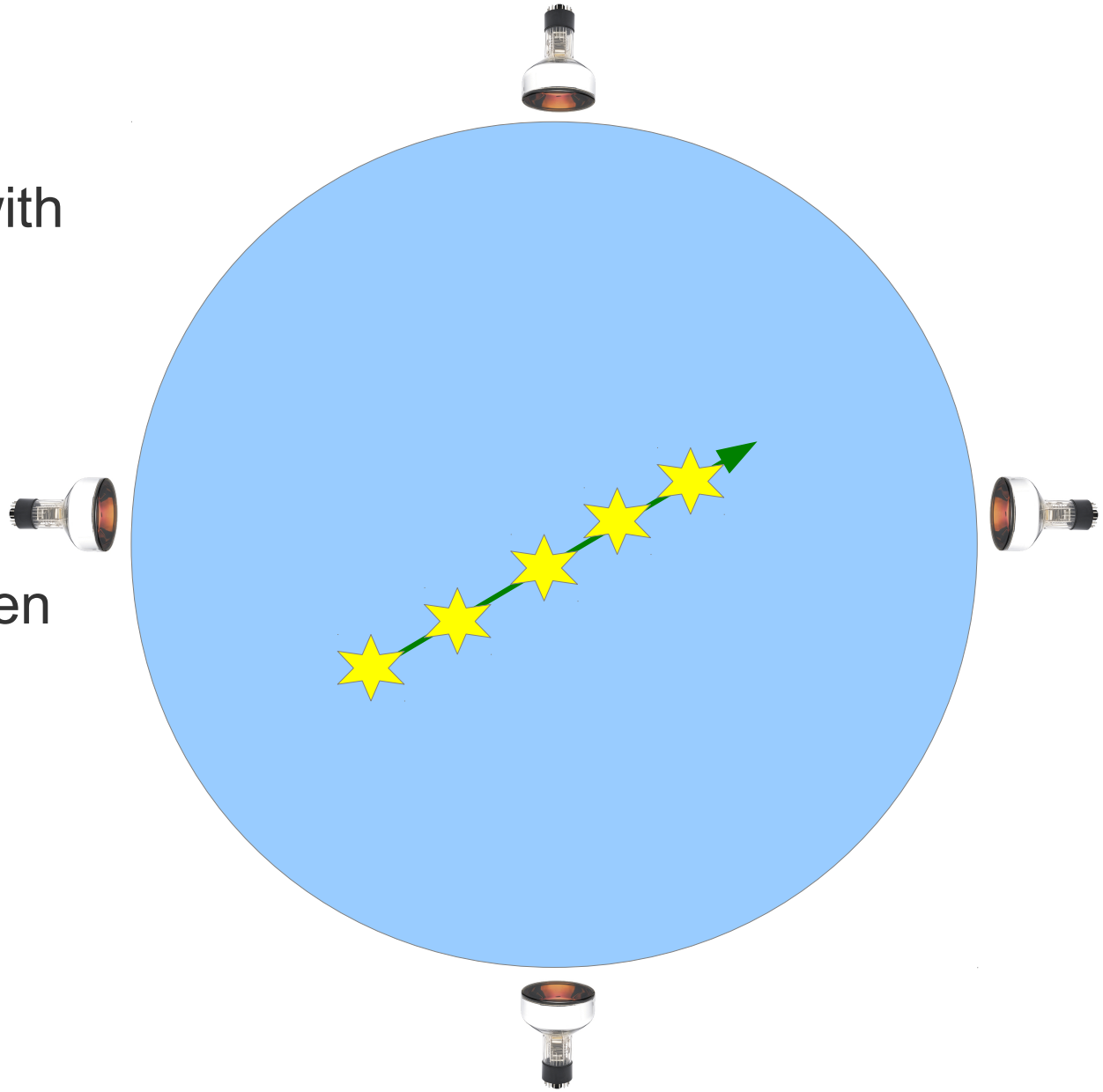


# Why no 3D Tracking (so far)?

**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

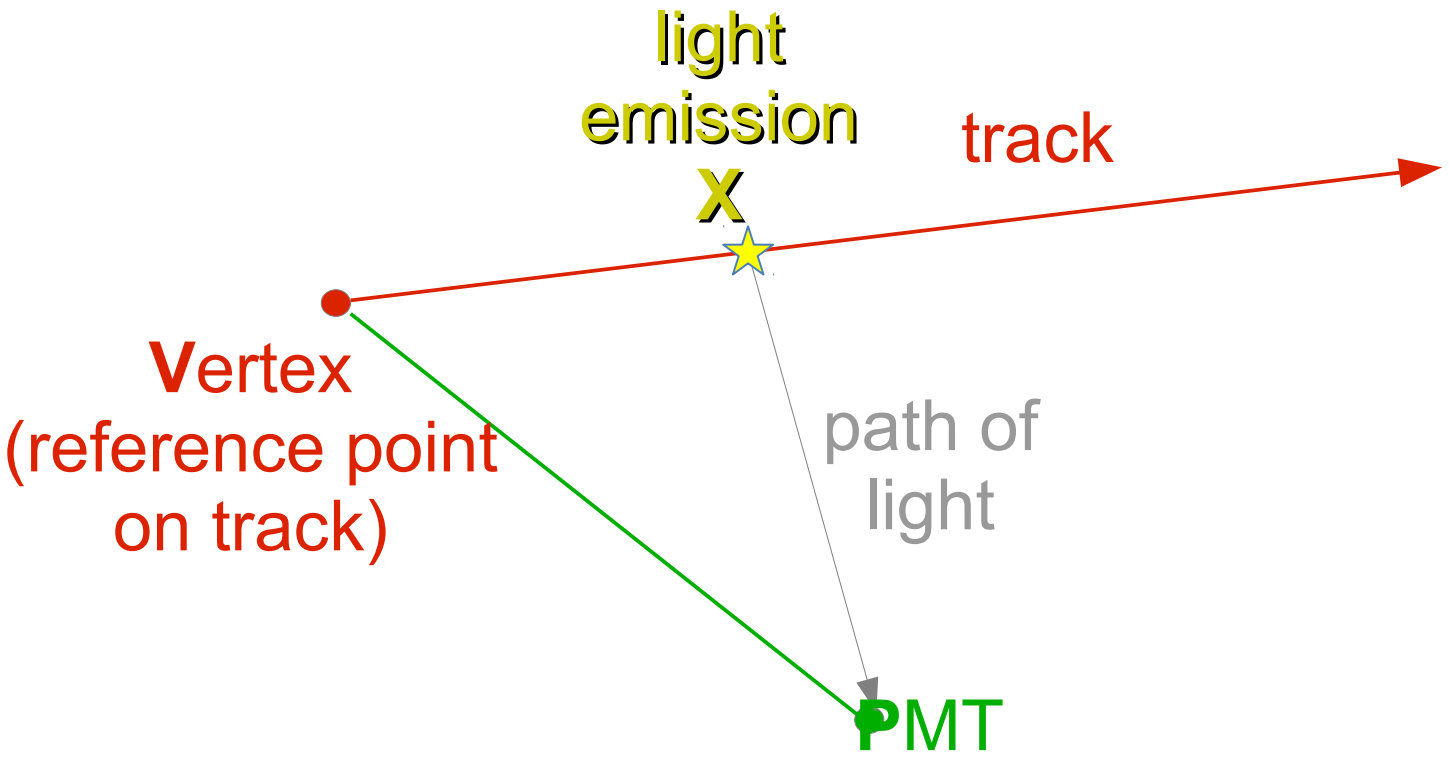
**Concept:**

- Take this point as reference for all signal times

# The Drop-like Shape

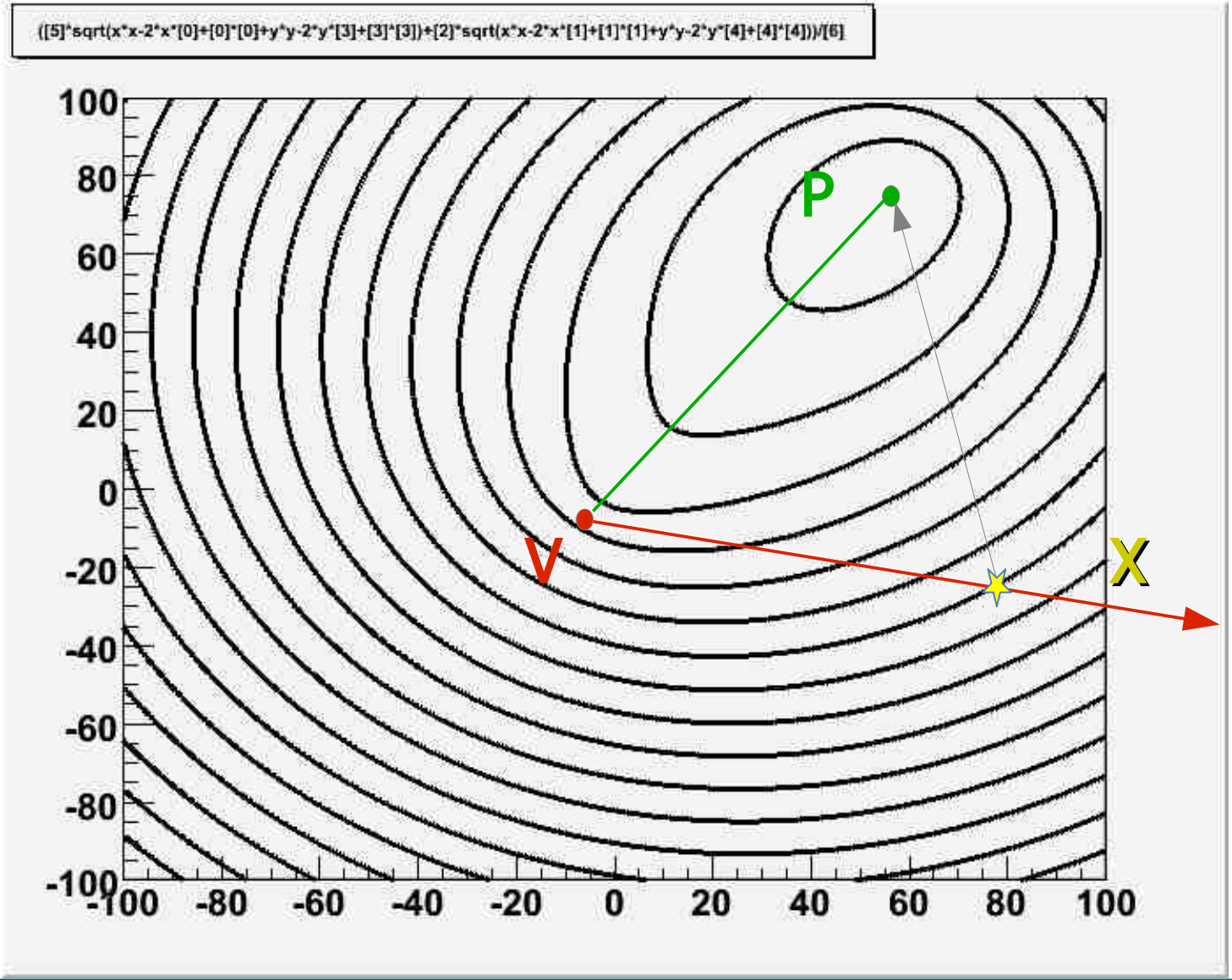
**Signal time = particle tof + photon tof**

**→ ct = |VX| + n*|XP|**



# The Drop-like Shape

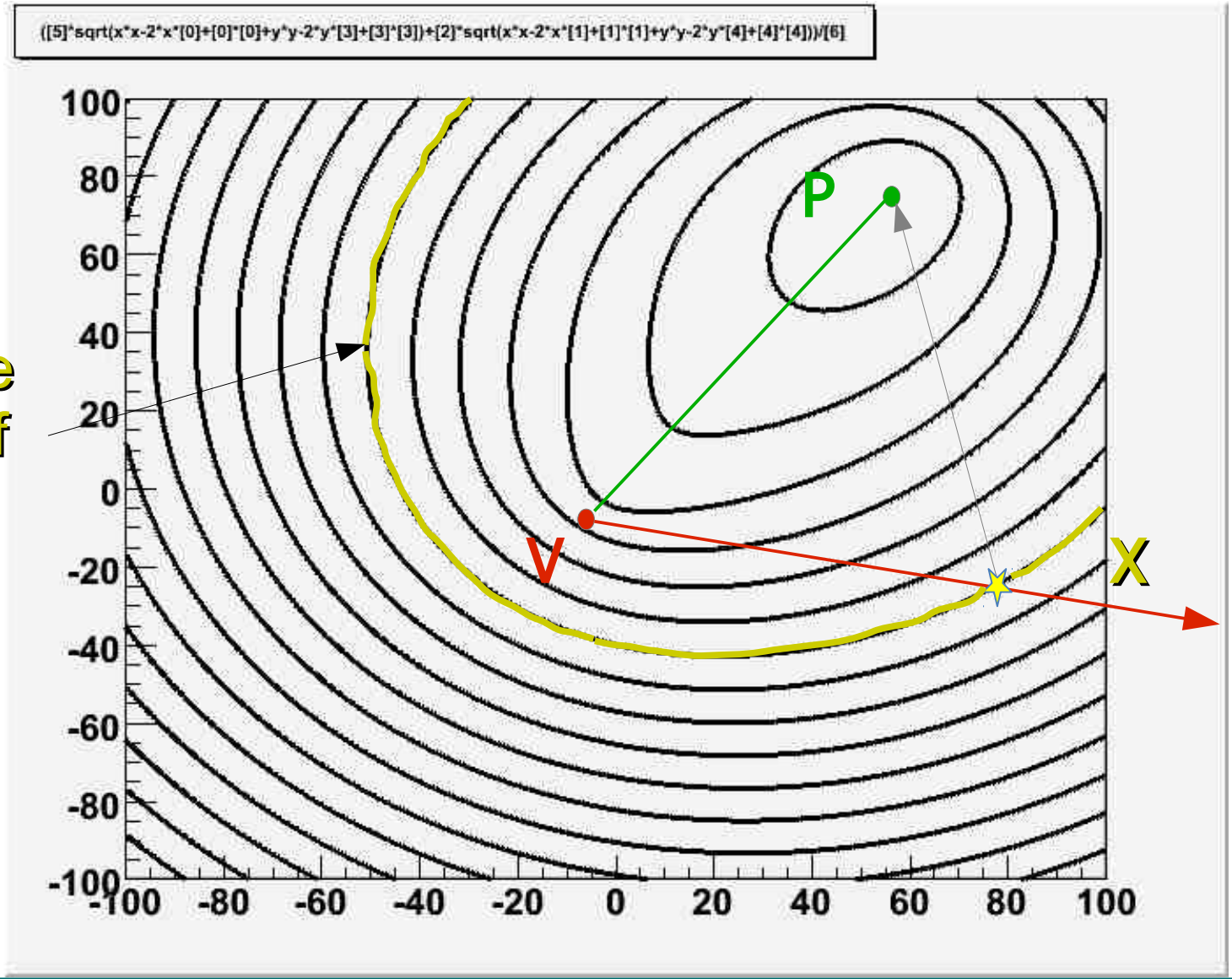
**ct = |VX| + n*|XP| → drop-like form**



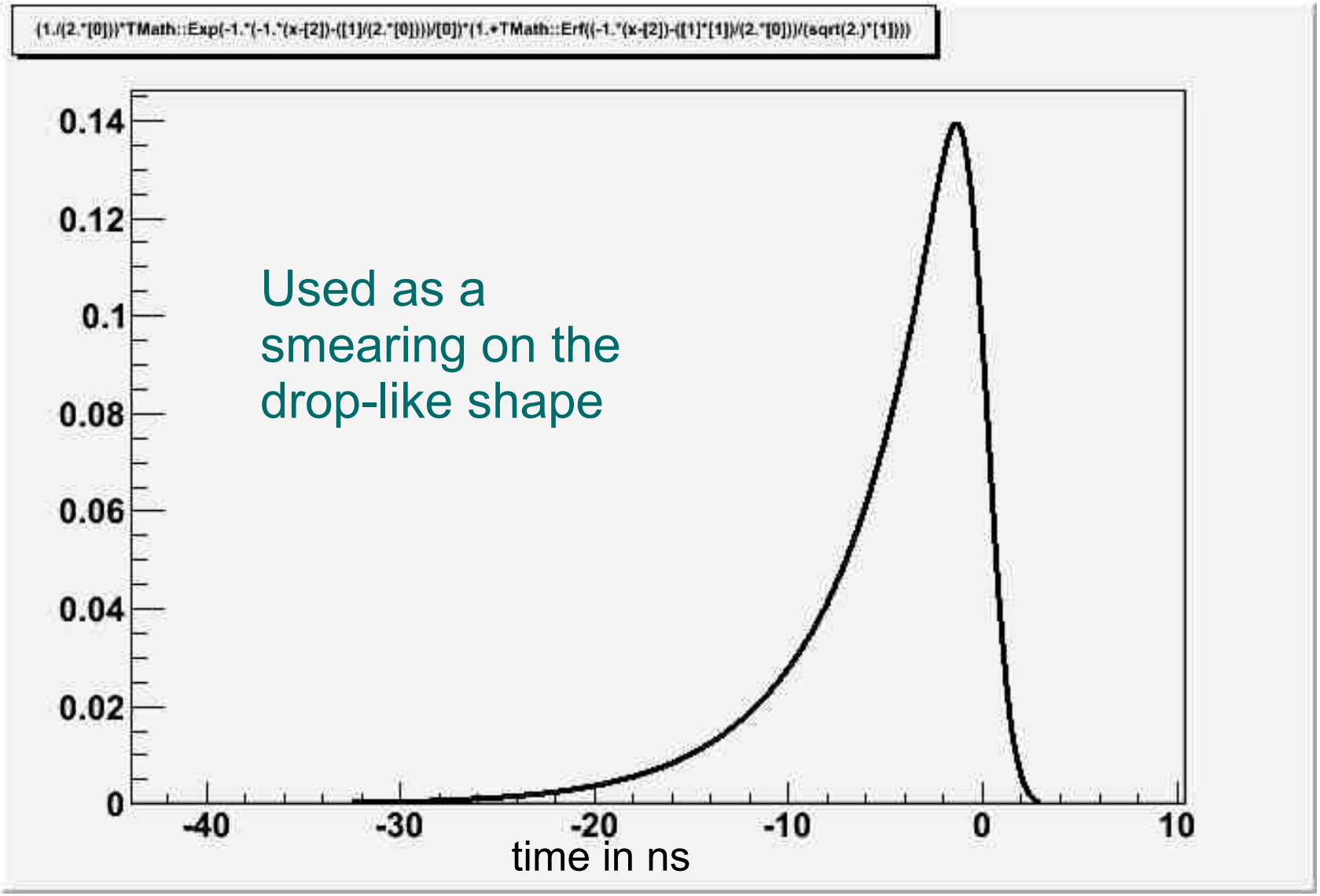
# The Drop-like Shape

**ct = |VX| + n*|XP| → drop-like form**

Possible origin of light

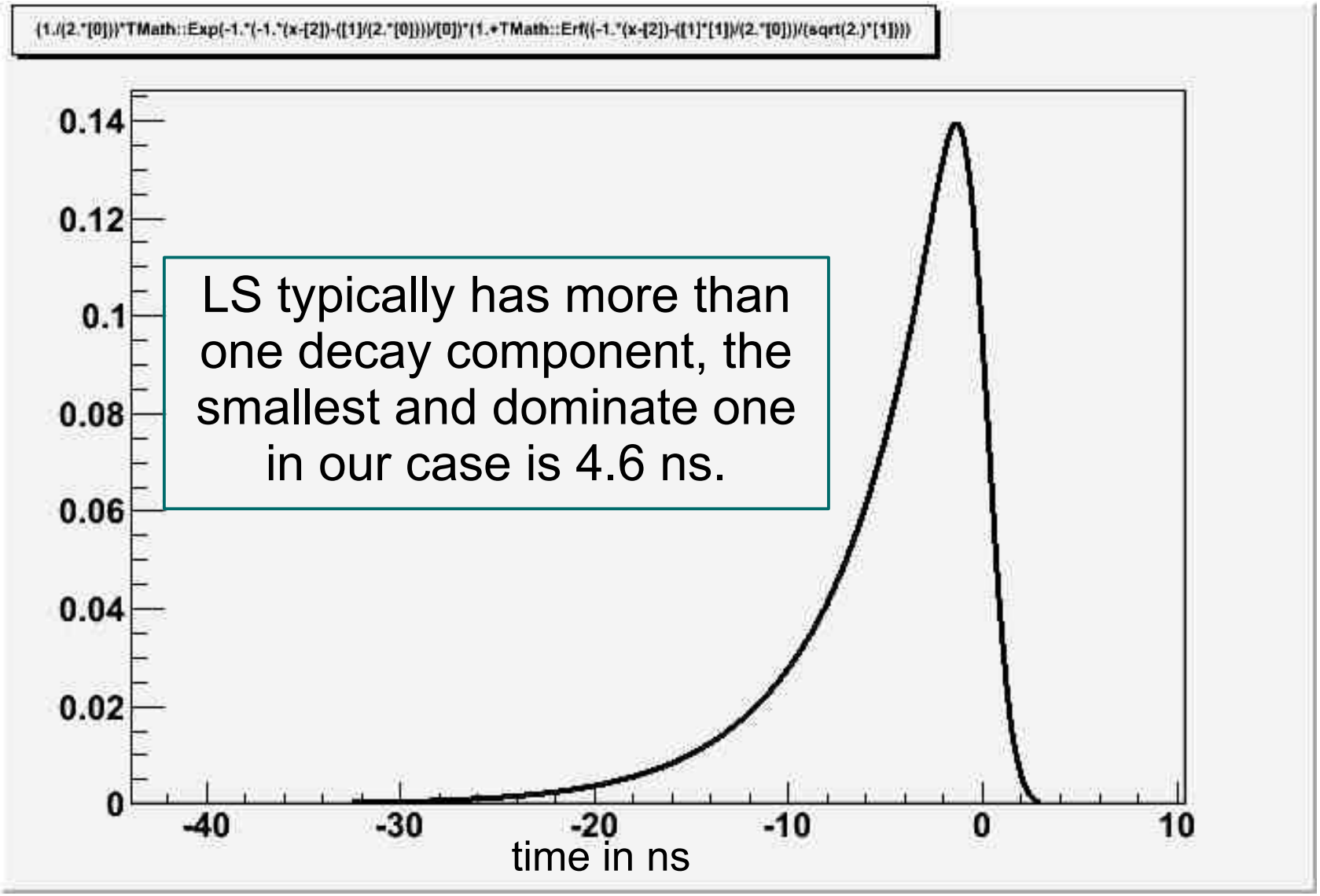


# Time Distribution



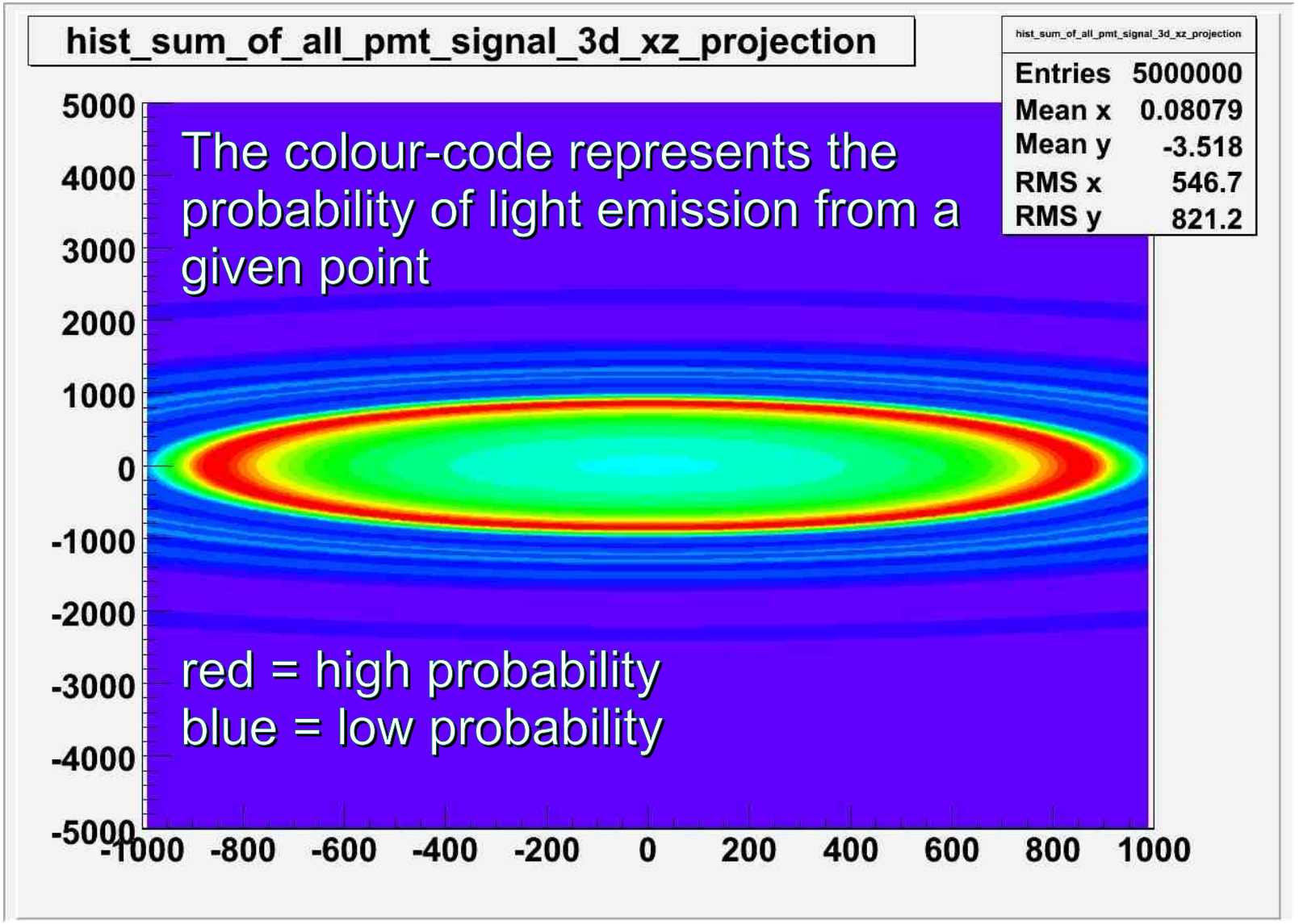

Convolution of Gaus and Exponential-Function

# Time Distribution




Convolution of Gaus and Exponential-Function

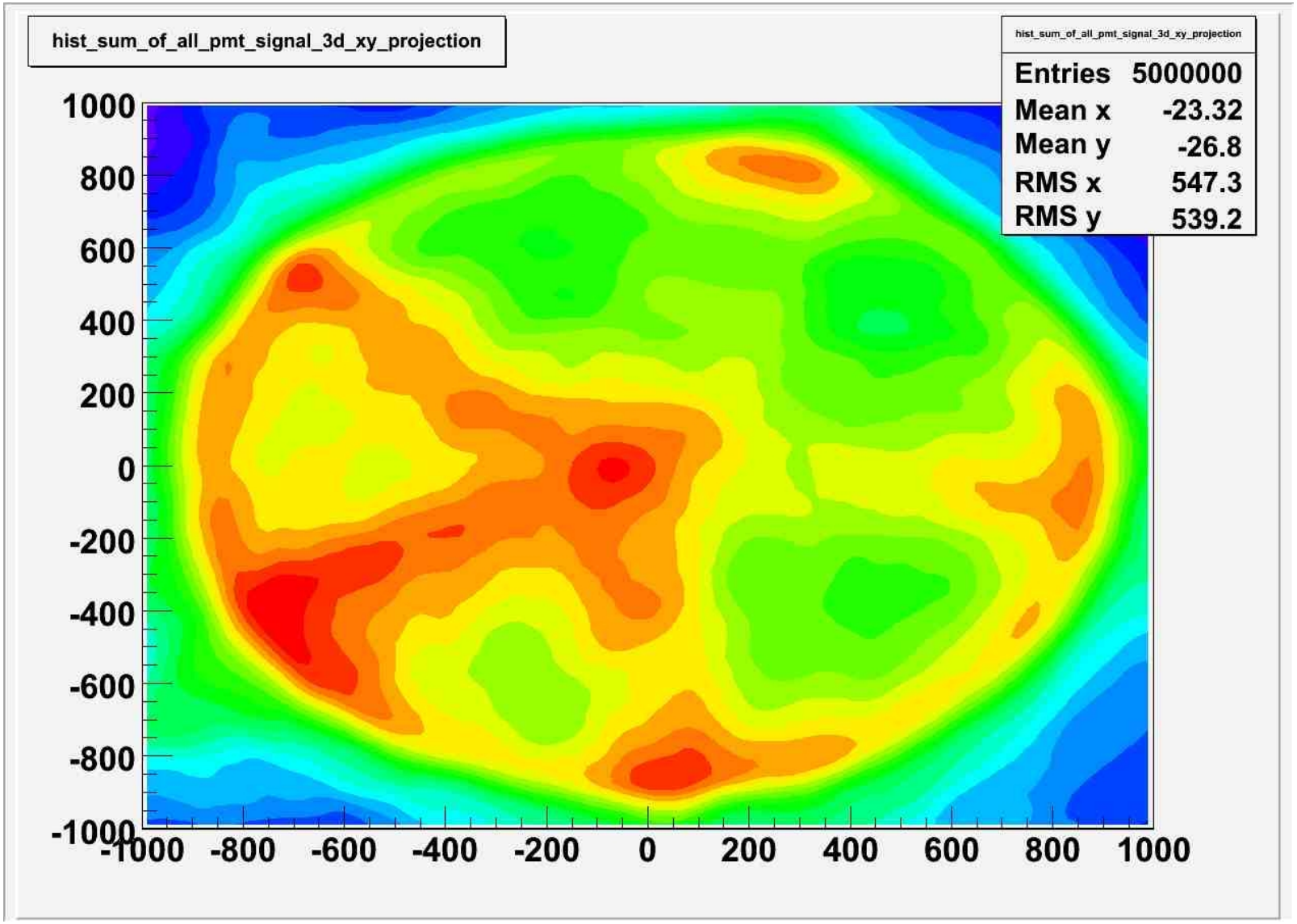
# Result 1 PMT




y [cm]

x [cm]

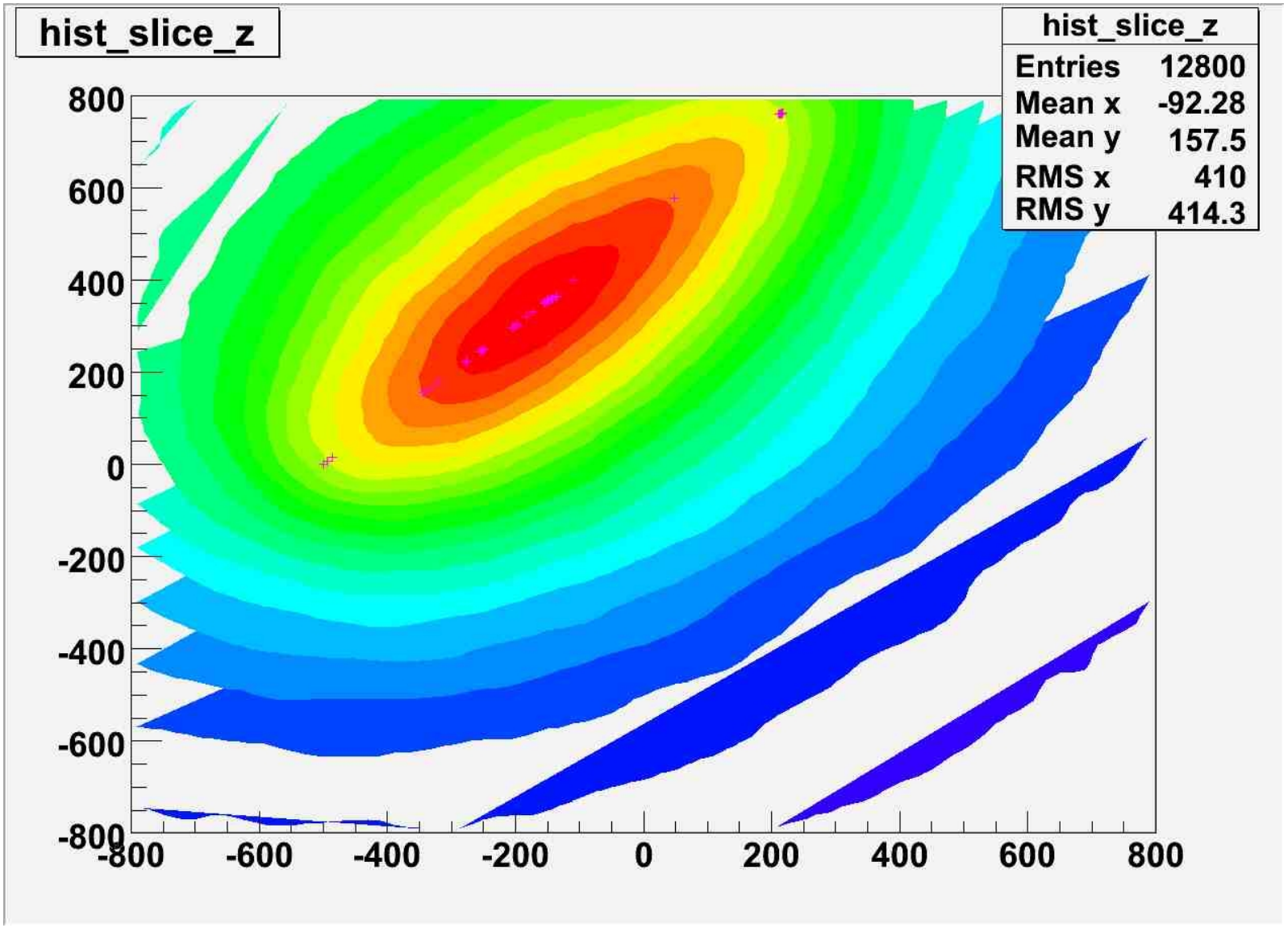
# Result a Few PMTs




y [cm]

x [cm]

# Result 266 PMTs




y [cm]

x [cm]

# 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:**

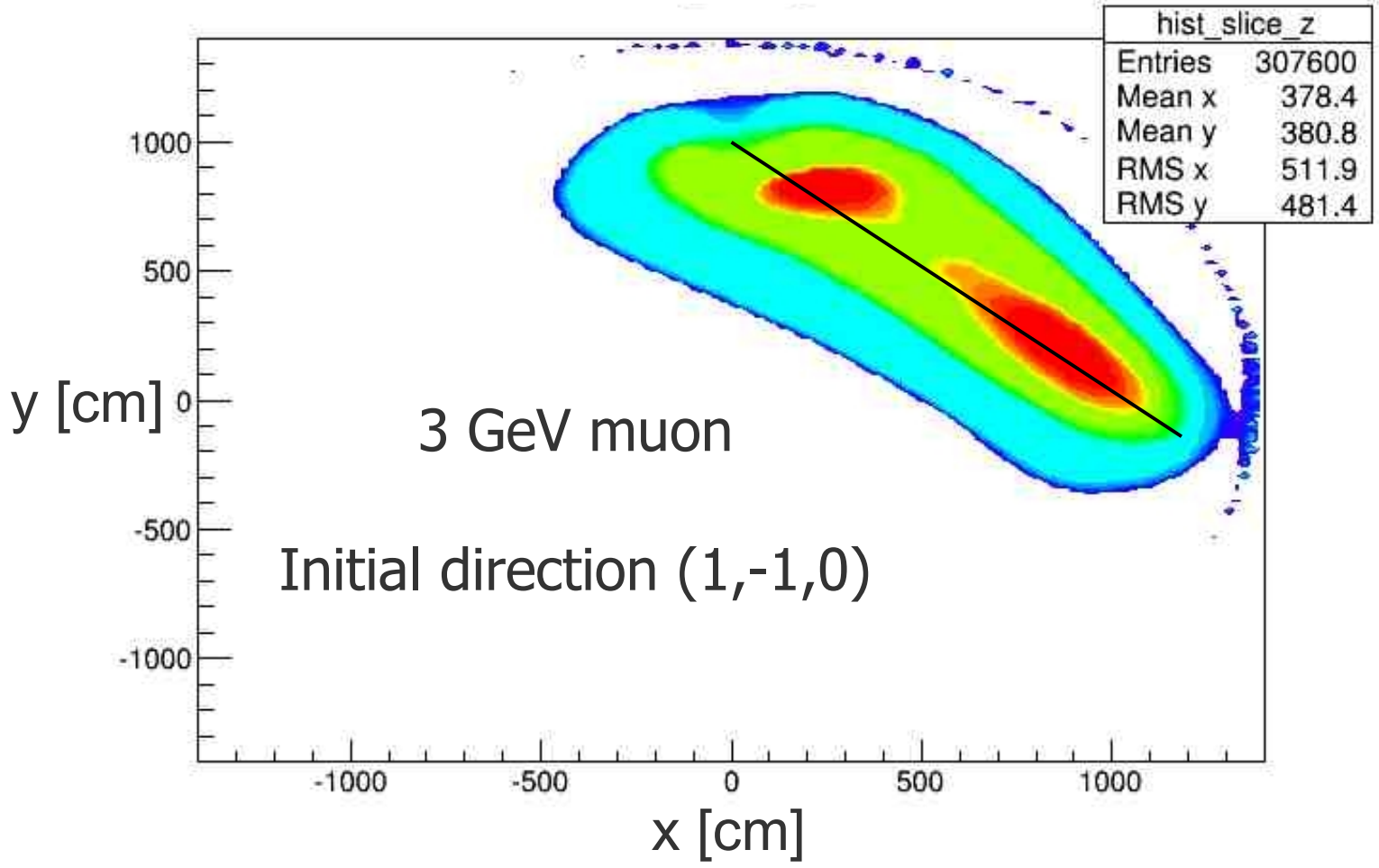
- they are closer
- directly in front of the PMT

→ **Need to consider:**

- solid angle of PMT area
- attenuation
- angular acceptance

**Finally I have to normalise the resulting pdf !**

# Result all PMTs



# Probability Mask

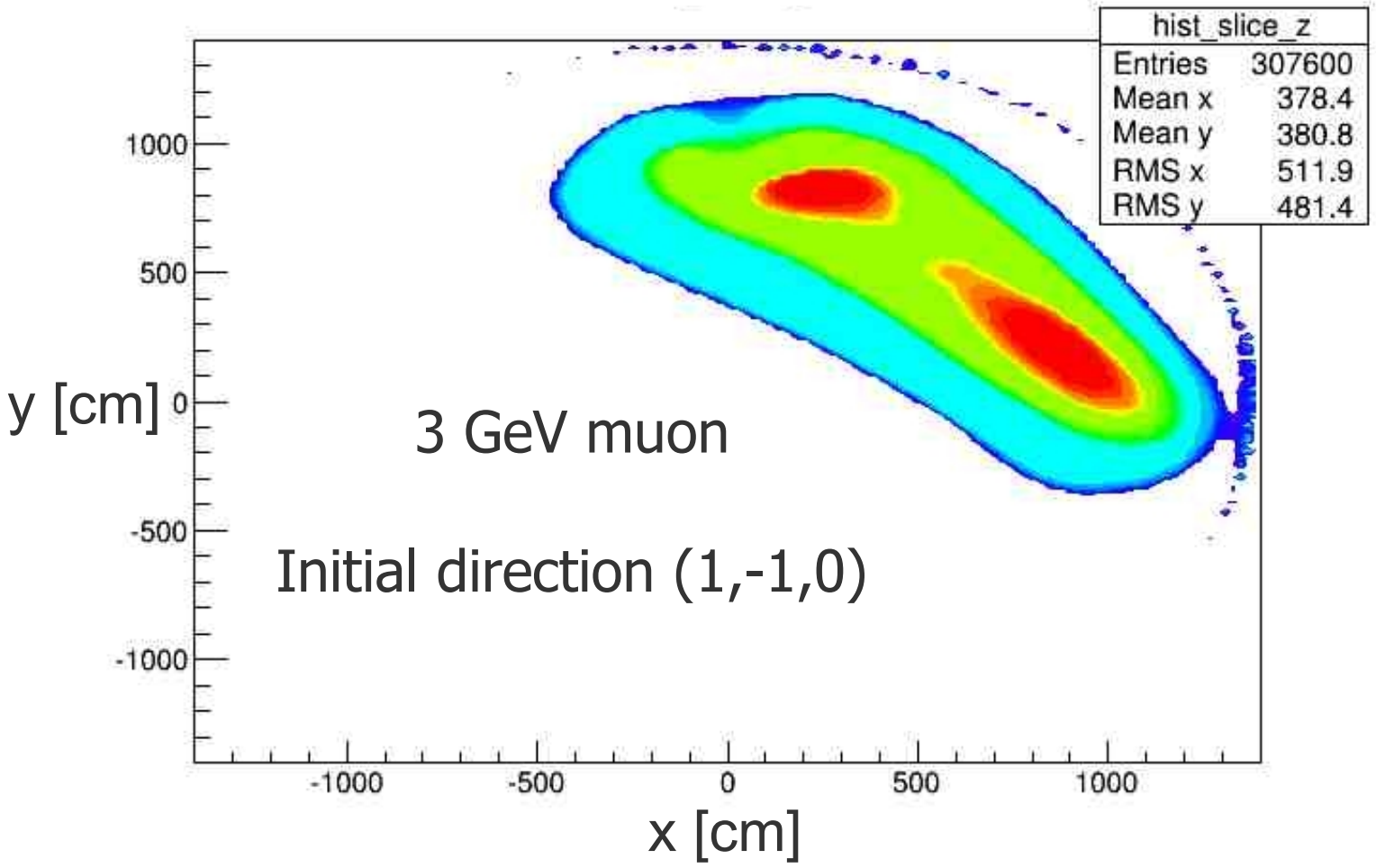
So far probabilities have been added!
→ correct for **independent information**

**However:**

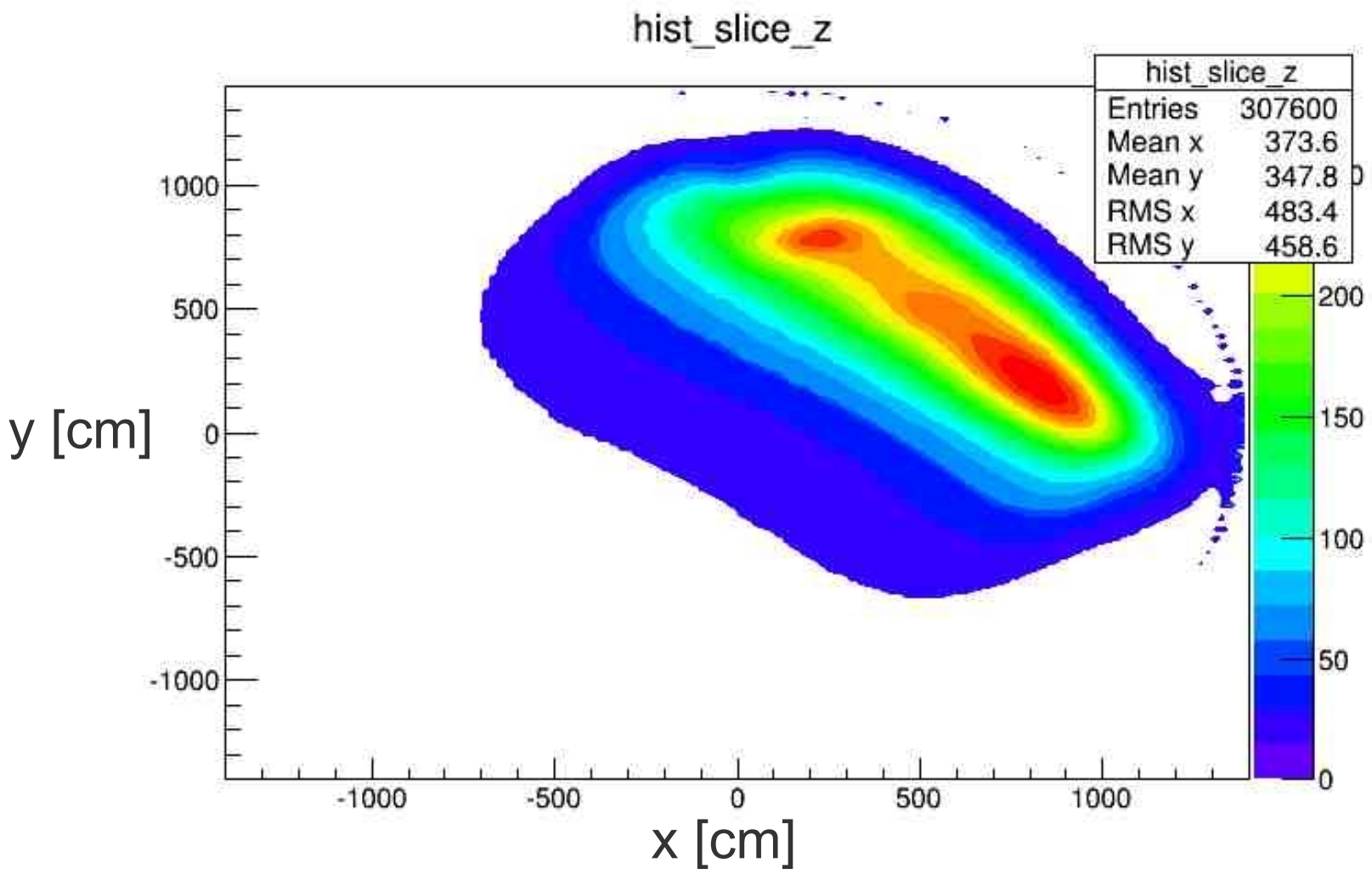
Light signals are **not completely independent** from each other, because they belong to the same track.

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

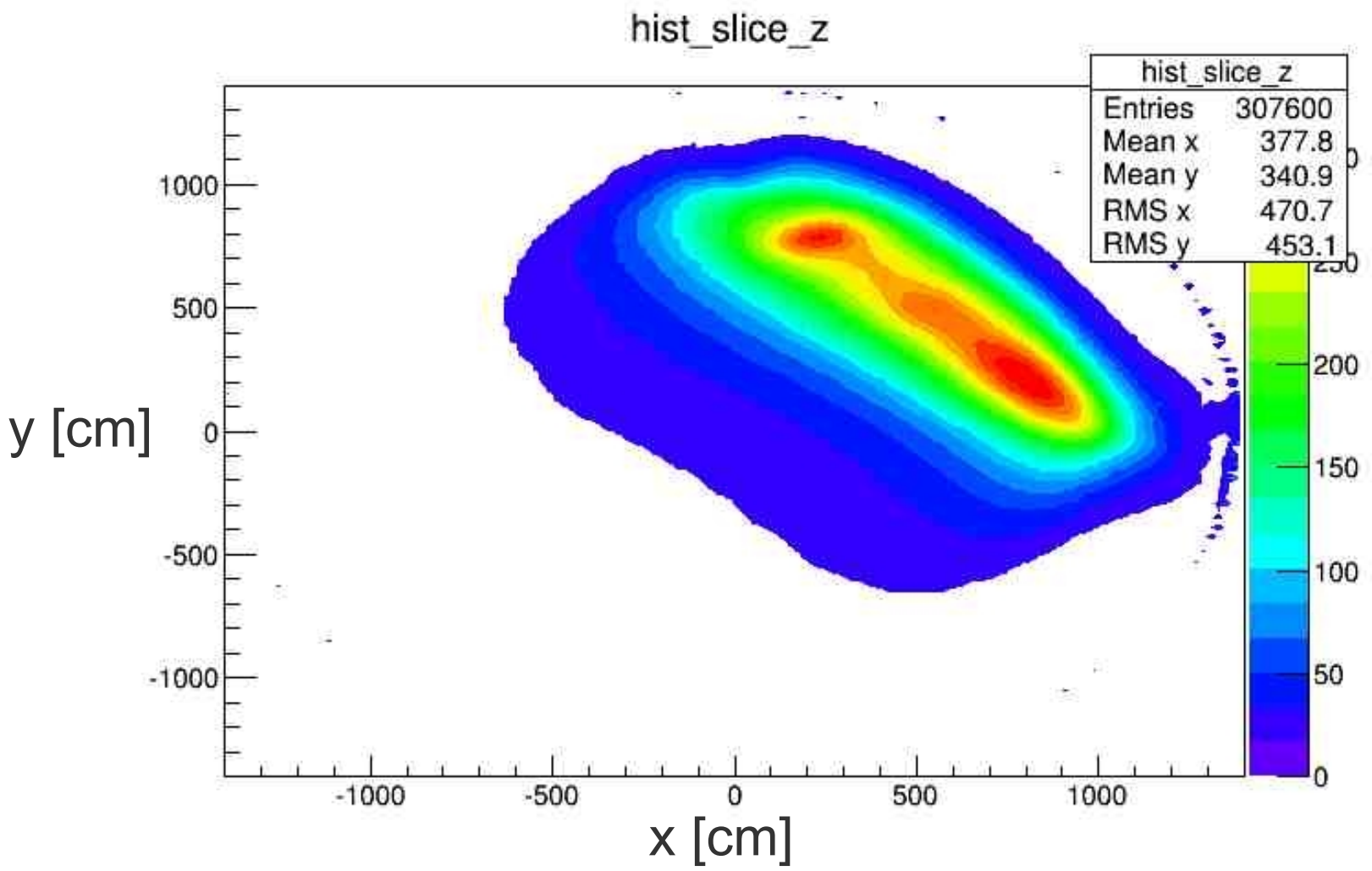
# Result I


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

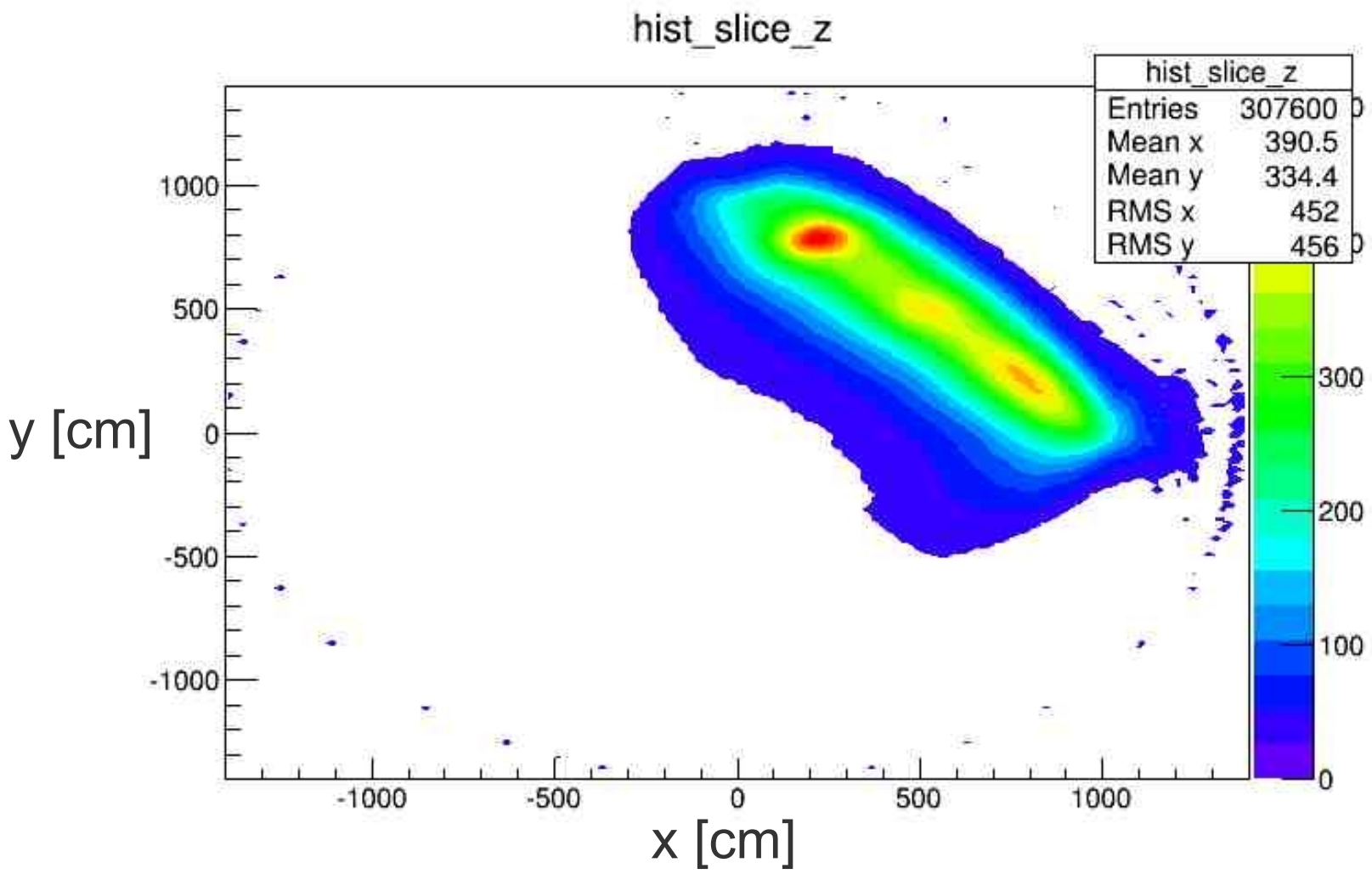
# Result 2nd Iteration



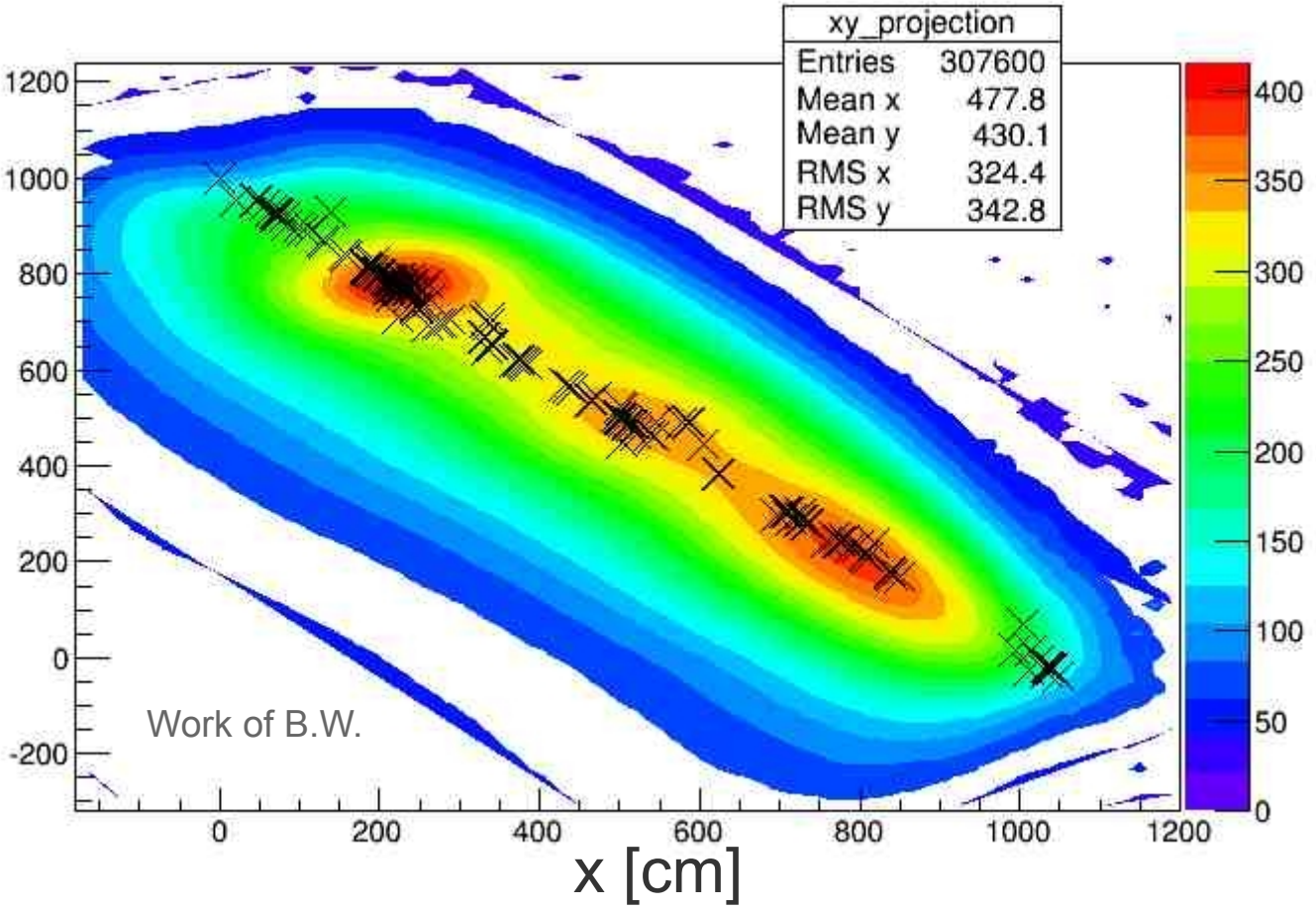
# Result 3rd Iteration



# Result 9th Iteration

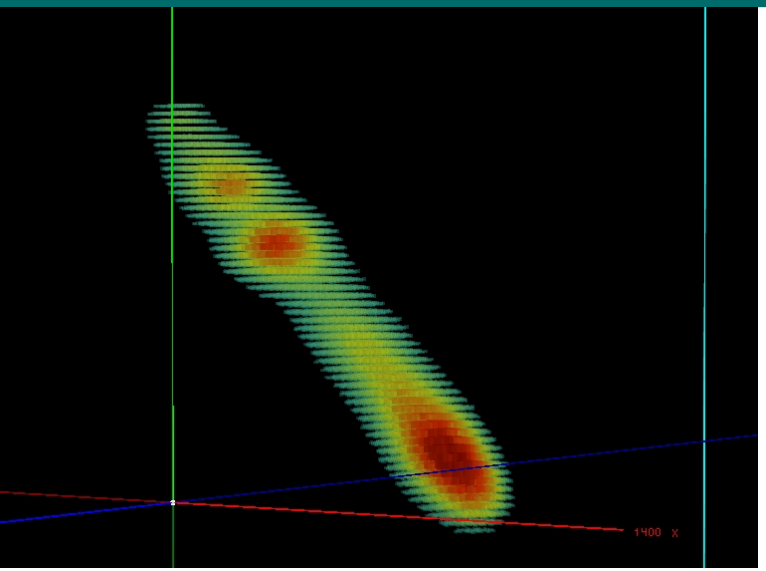


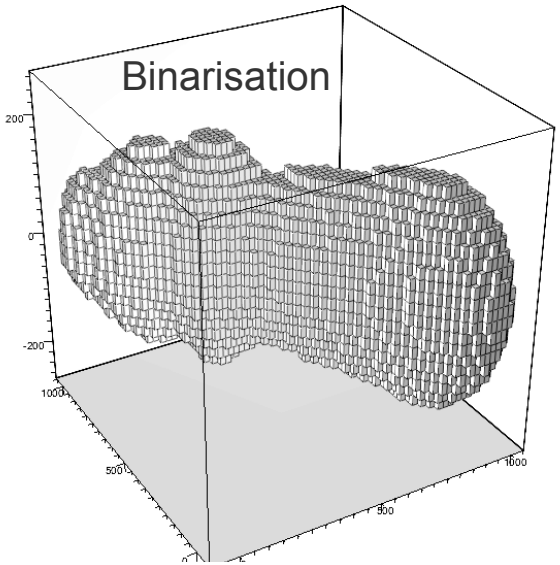
# Result 12th Iteration

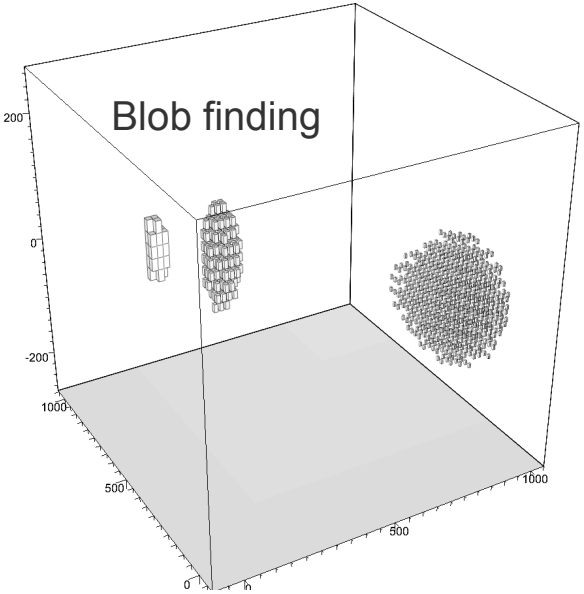


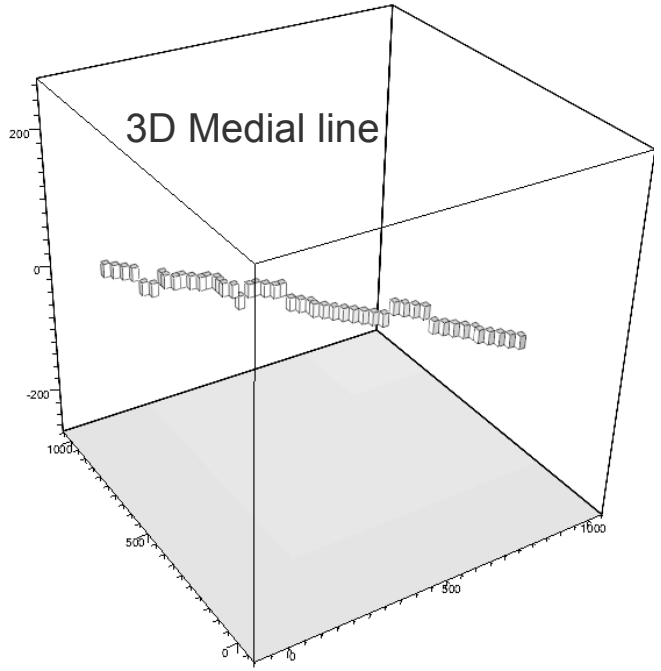

Measurement of dE/dx is possible!

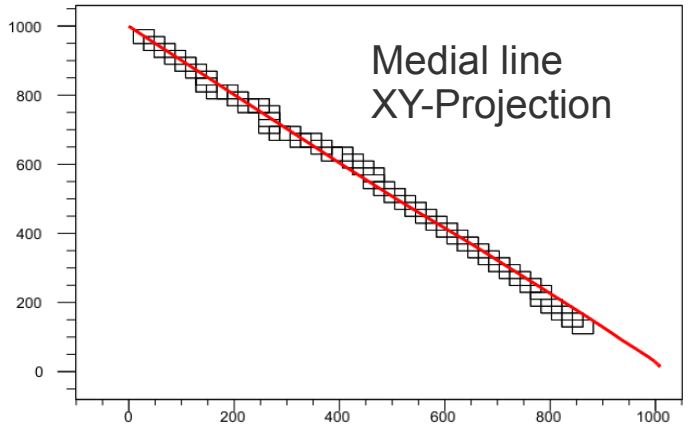
# Image Processing

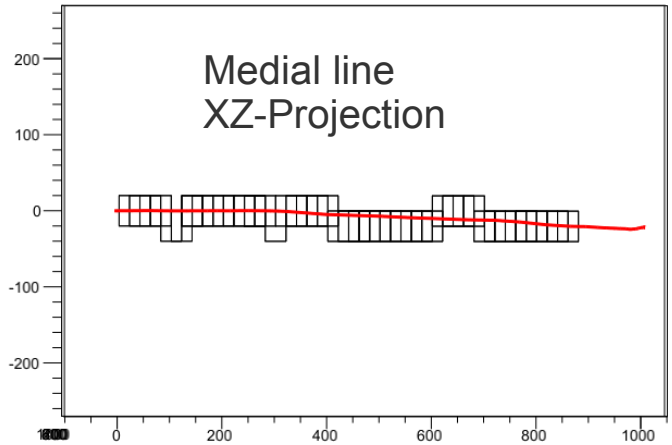





Ph. D. student Sebastian Lorenz

Resolution < 20 cm

# Computing

One 3 GeV event, 20cm bins, full light, 10 iterations in LENA
→ **several hours,** even if I cut out interesting volume

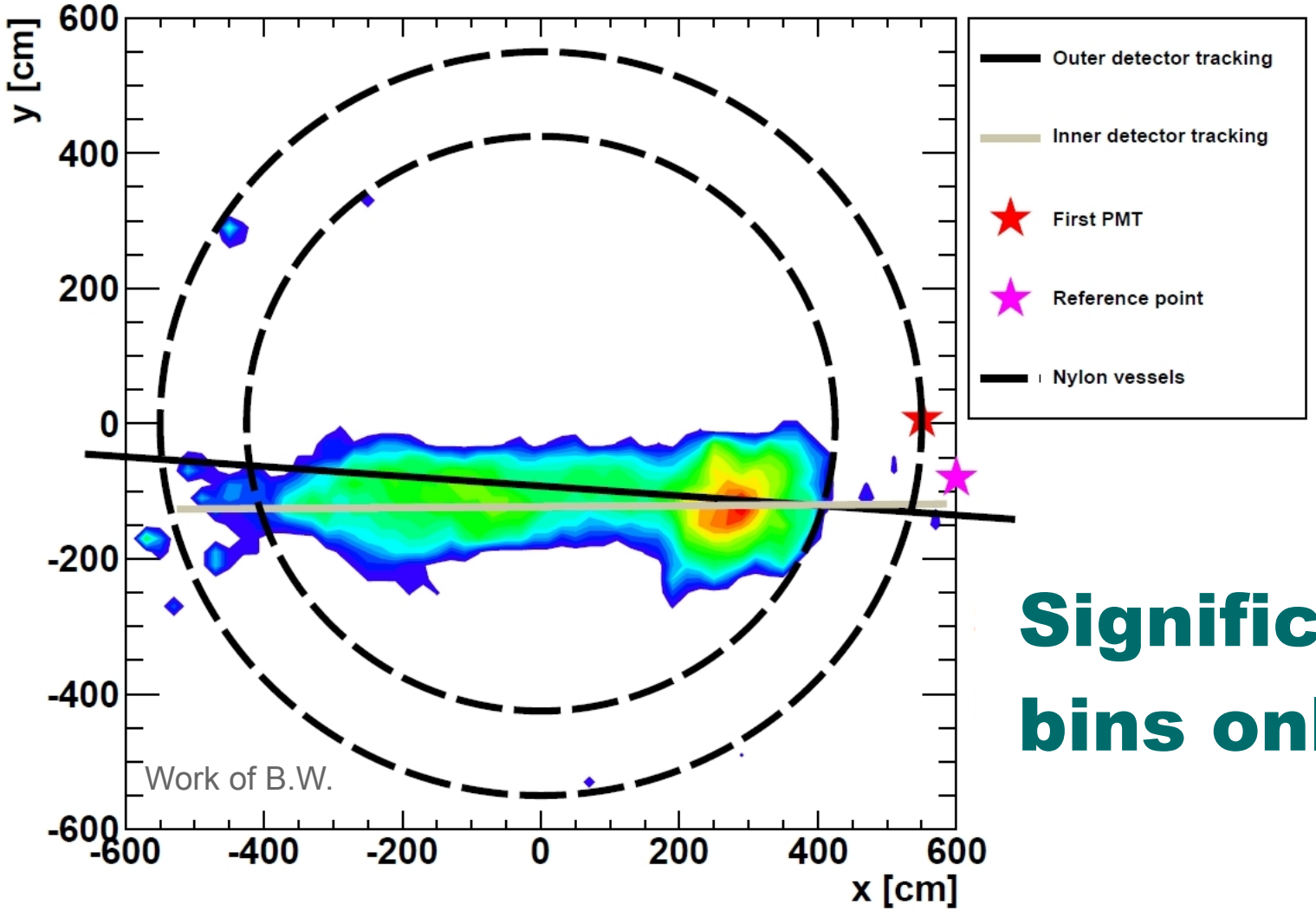
**However:**

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

- In principle many more iterations are allowed

**But algorithm highly parallisable**
**→ GPUs, etc.**

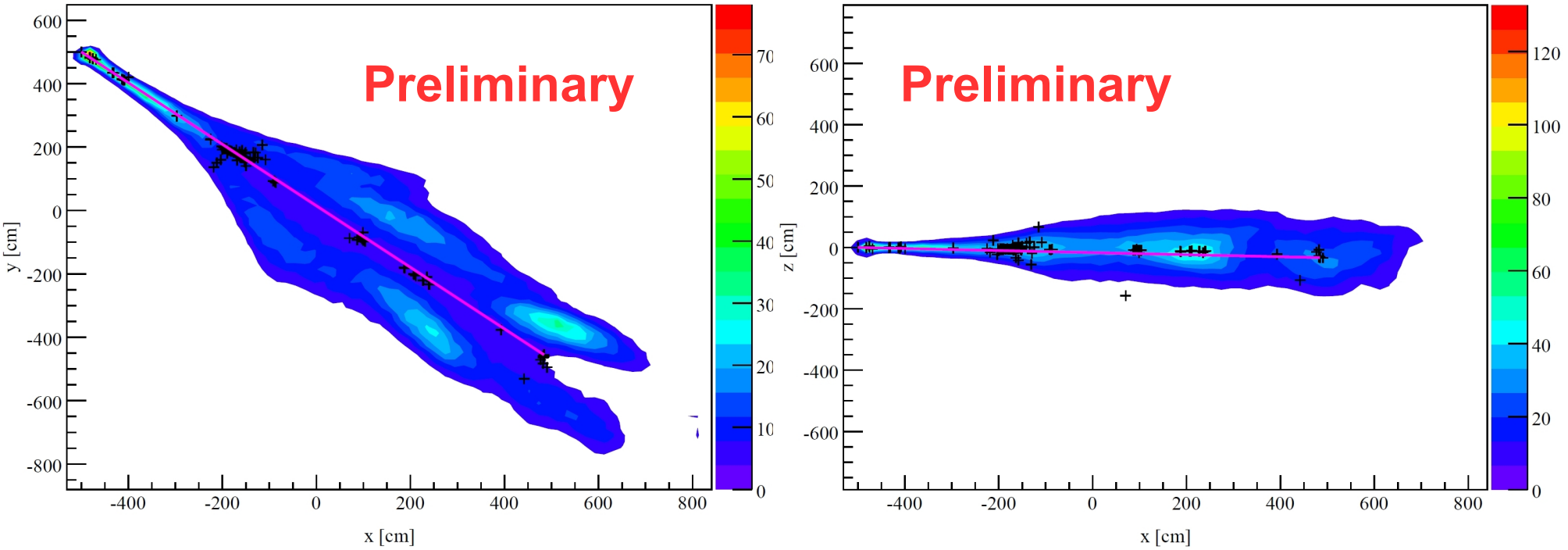
# Example: Real Borexino Data




**Significant bins only**

# 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

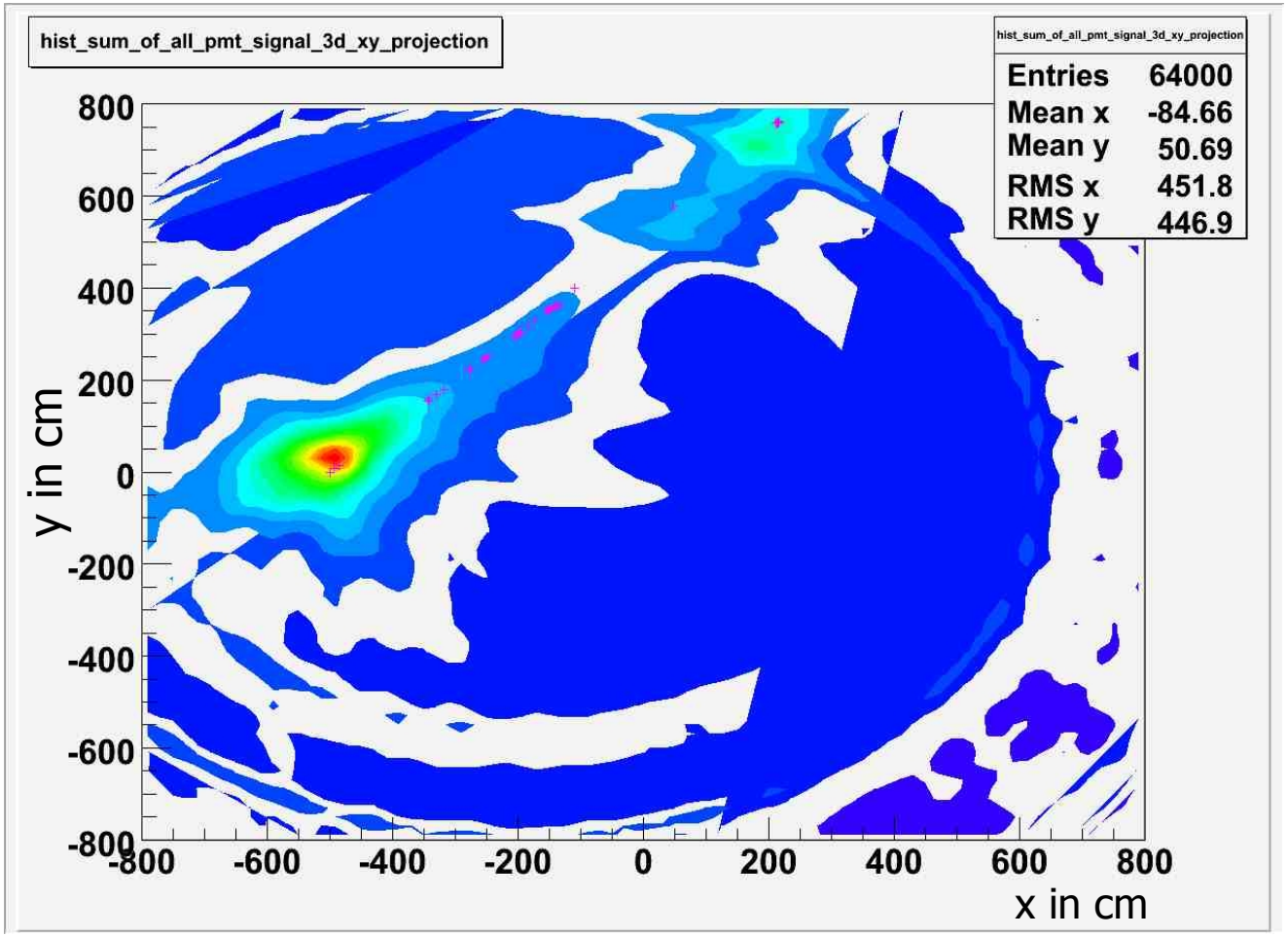
Also suitable for water Cherenkov detectors!  Perfect for WbLS!

**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

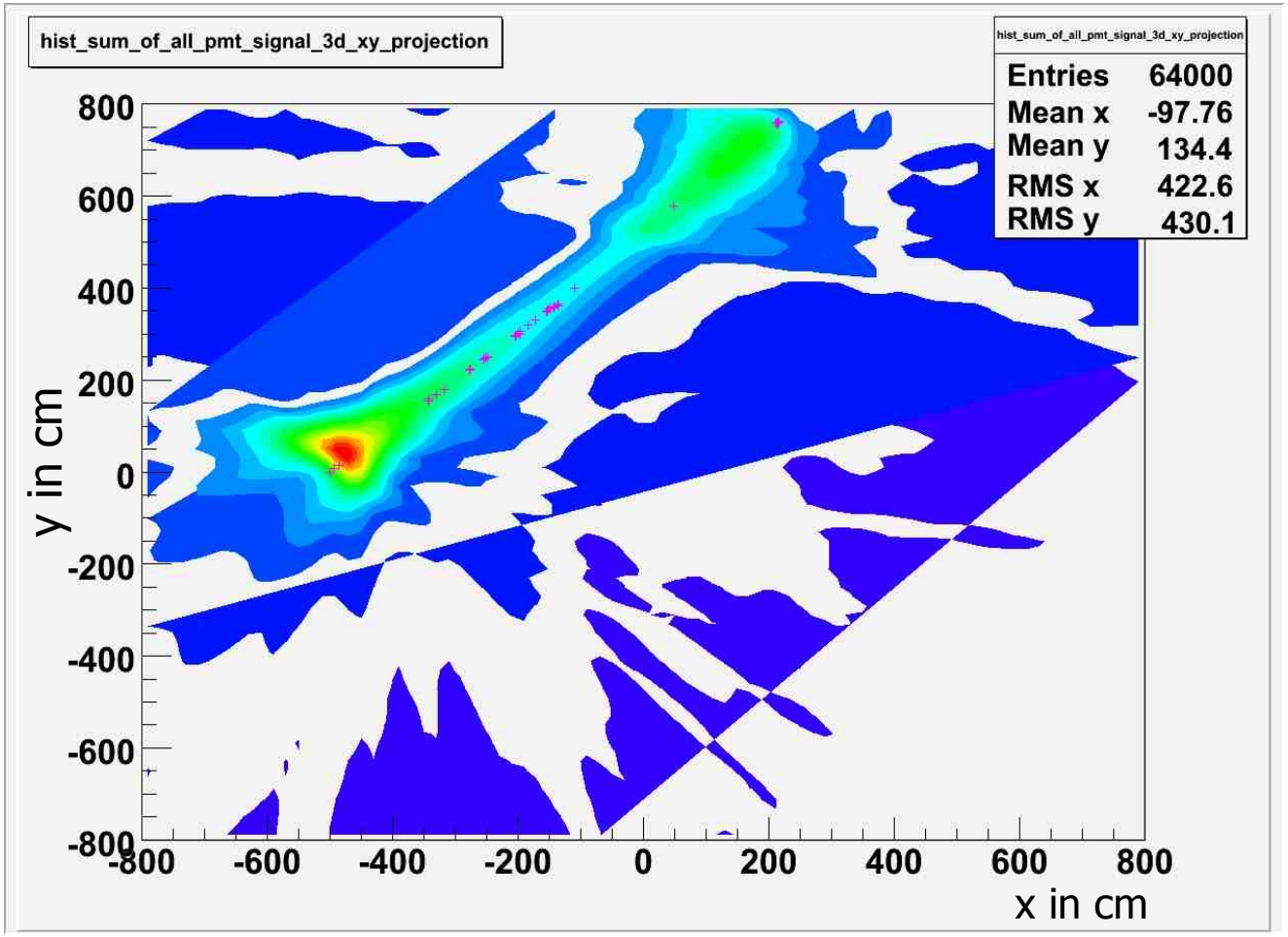
- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**




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

# 2GeV Muon, First Hit, Backwards

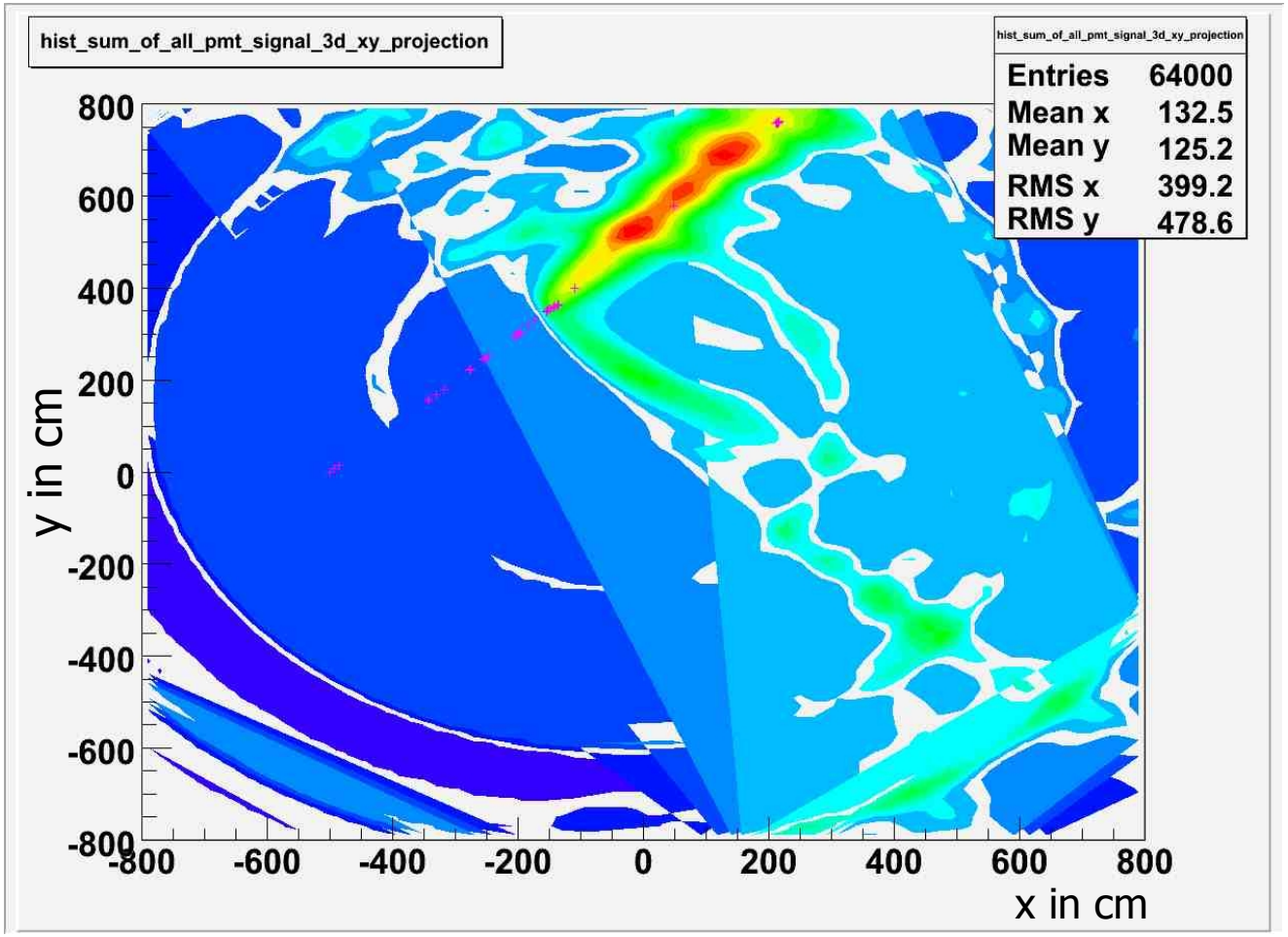
- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**




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

# 2GeV Muon, First Hit, from Middle

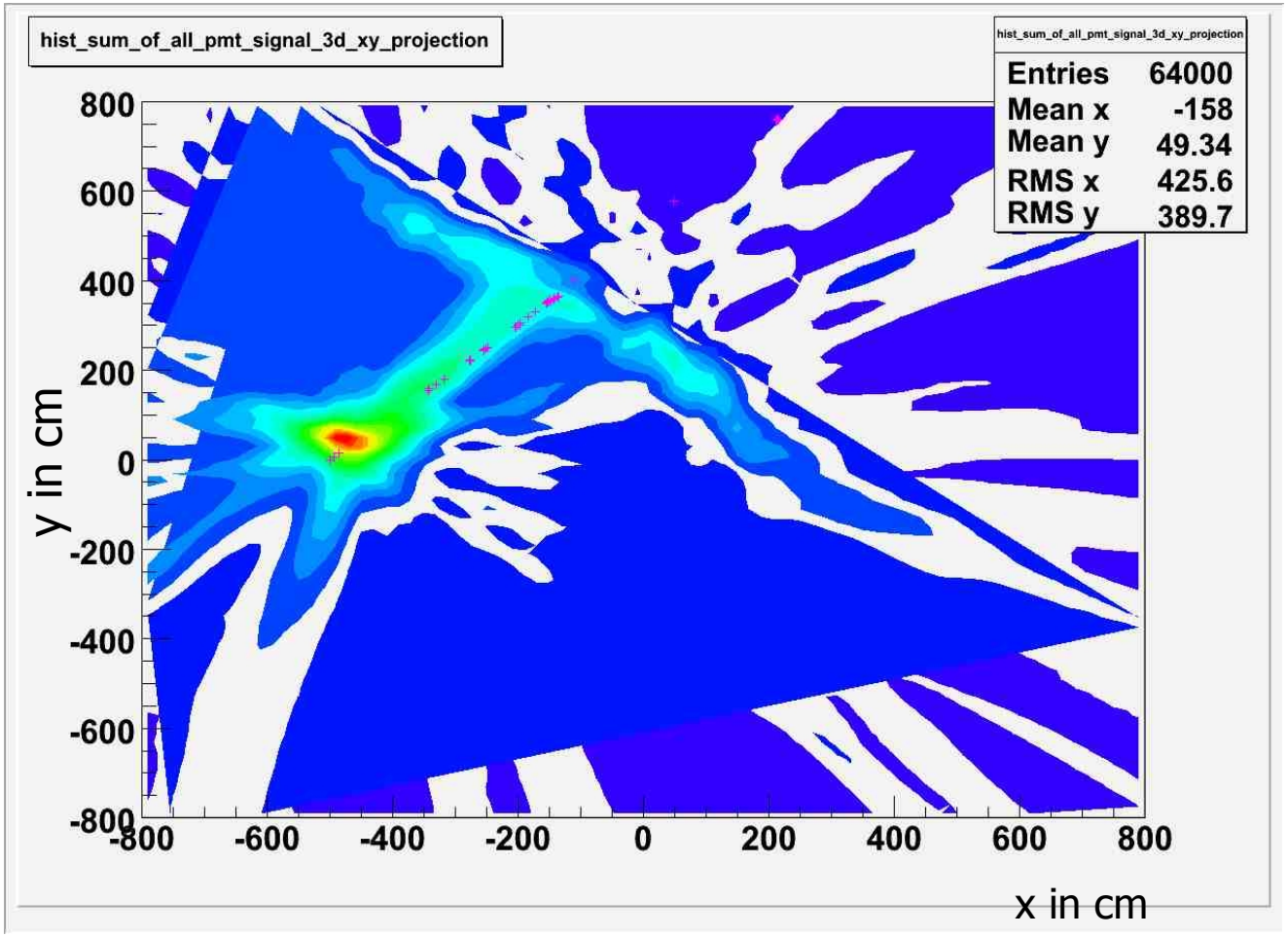
- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**




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

# 2GeV Muon, First Hit, Back from Middle

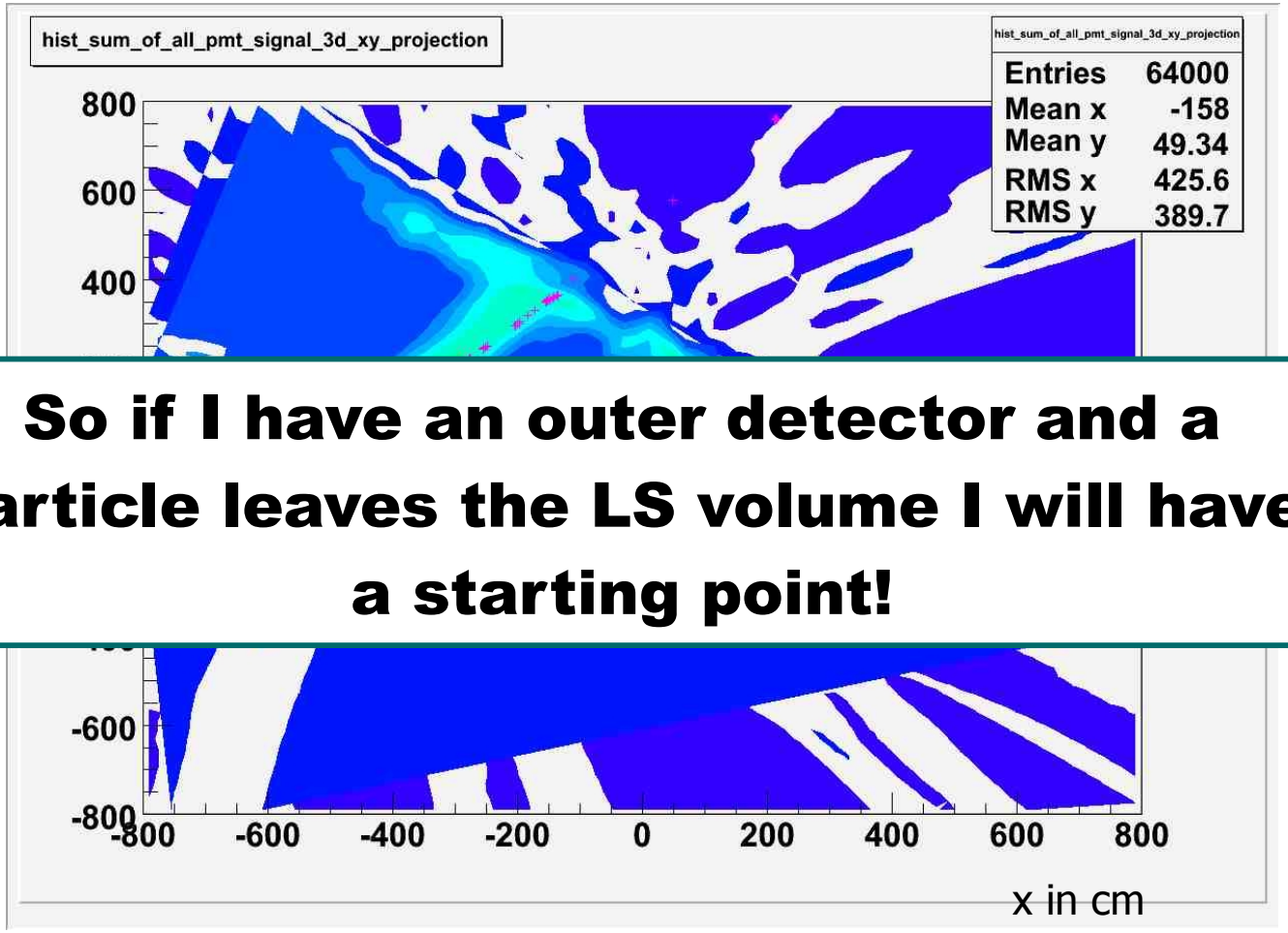
- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**




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.)**



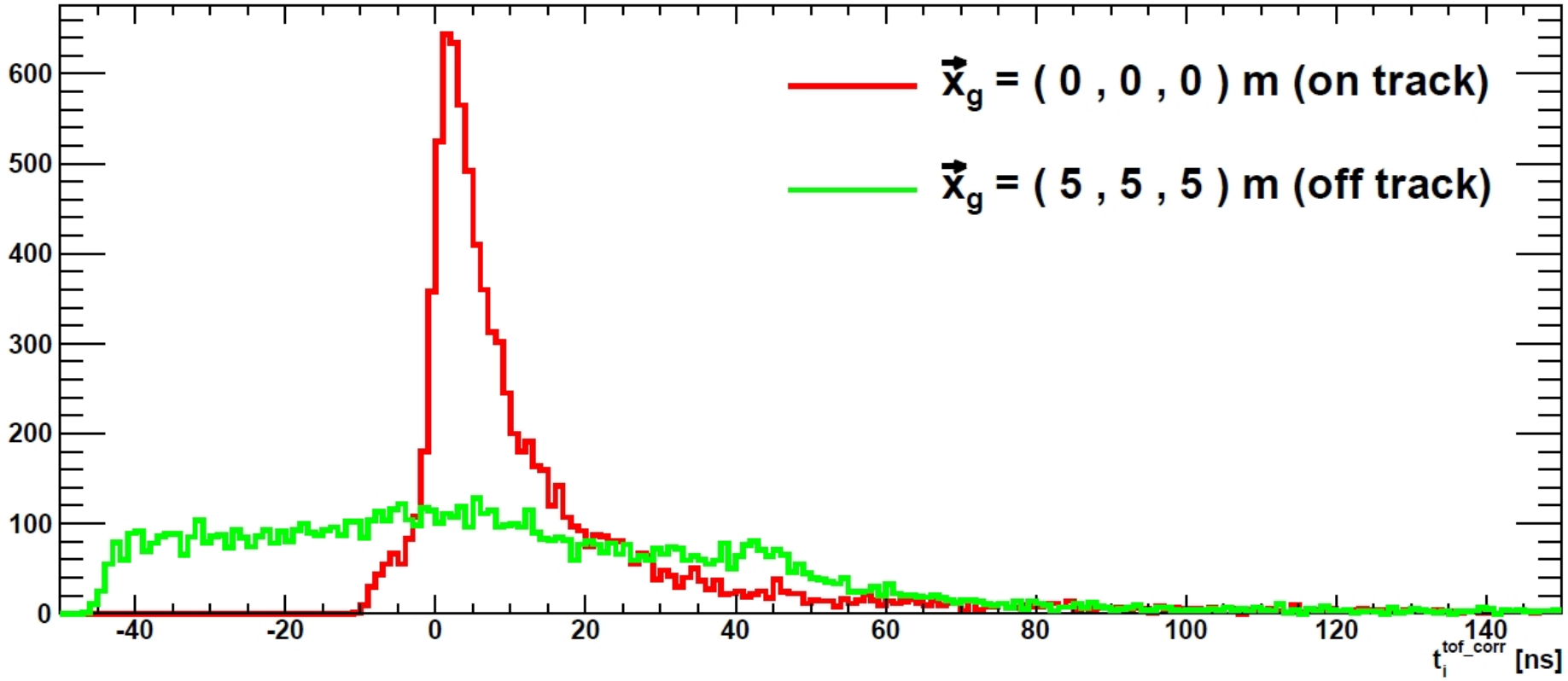

**So if I have an outer detector and a particle leaves the LS volume I will have a starting point!**

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

# Vertex Finding/Backtracking

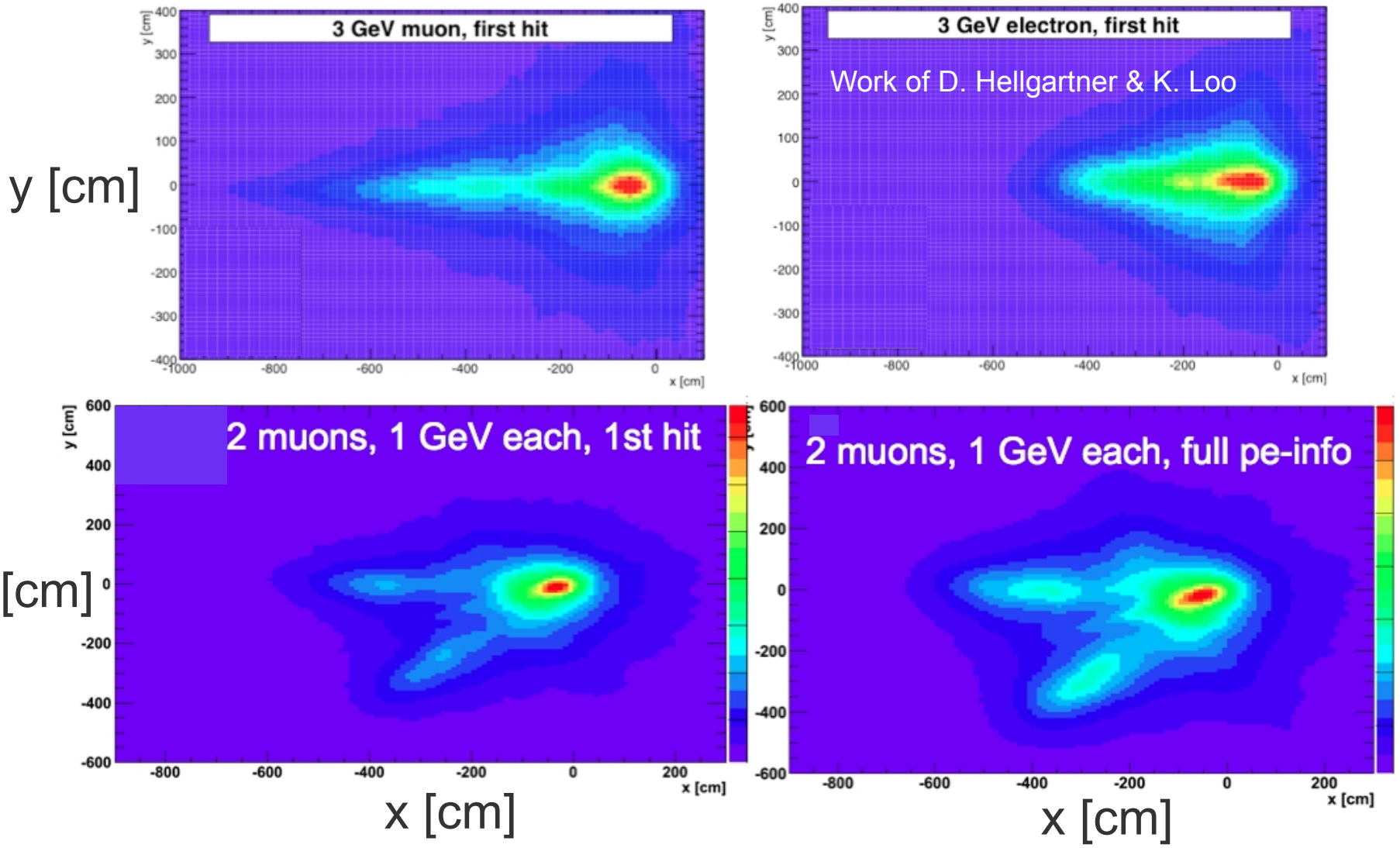
**Basic idea:** from Domenikus Hellgartner

- 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

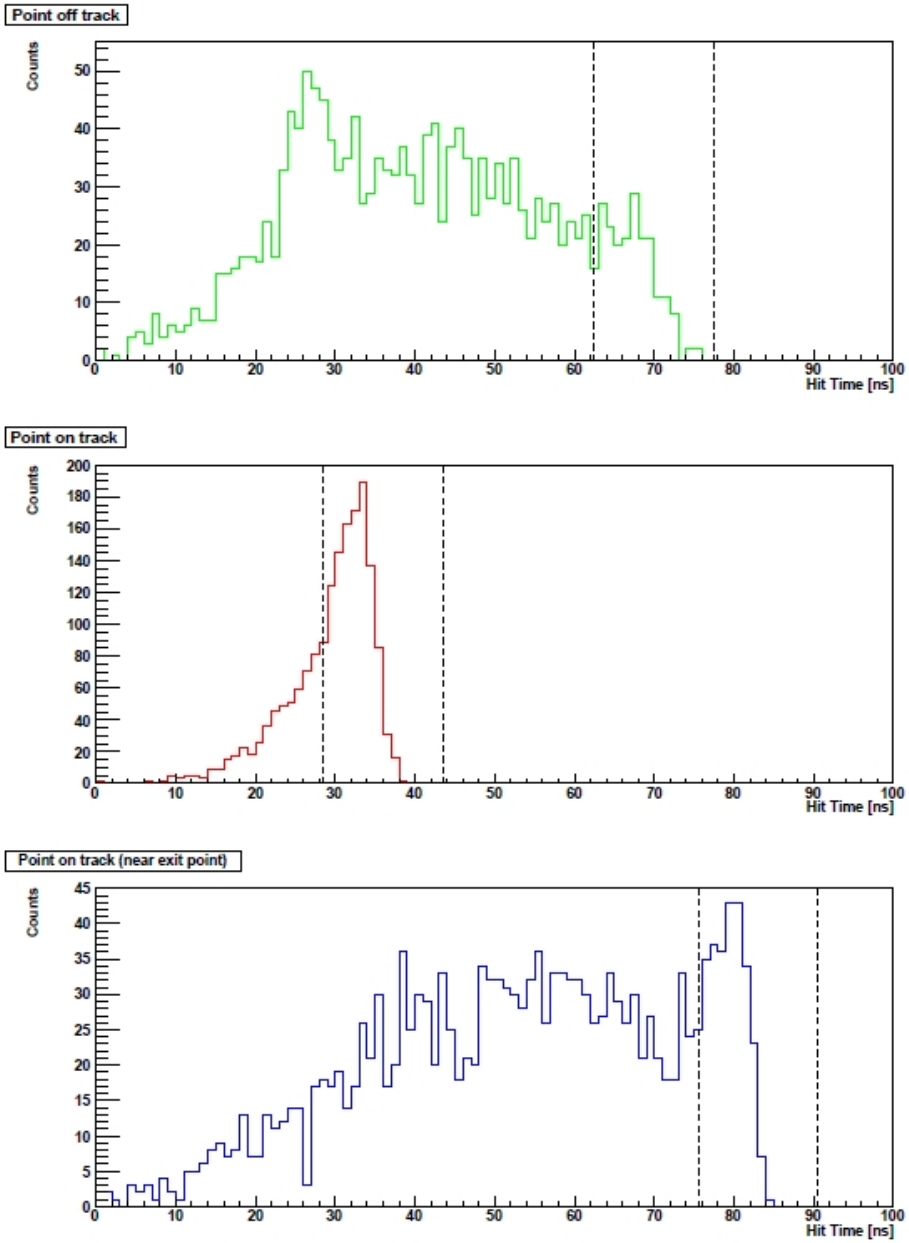


# How to improve Backtracking

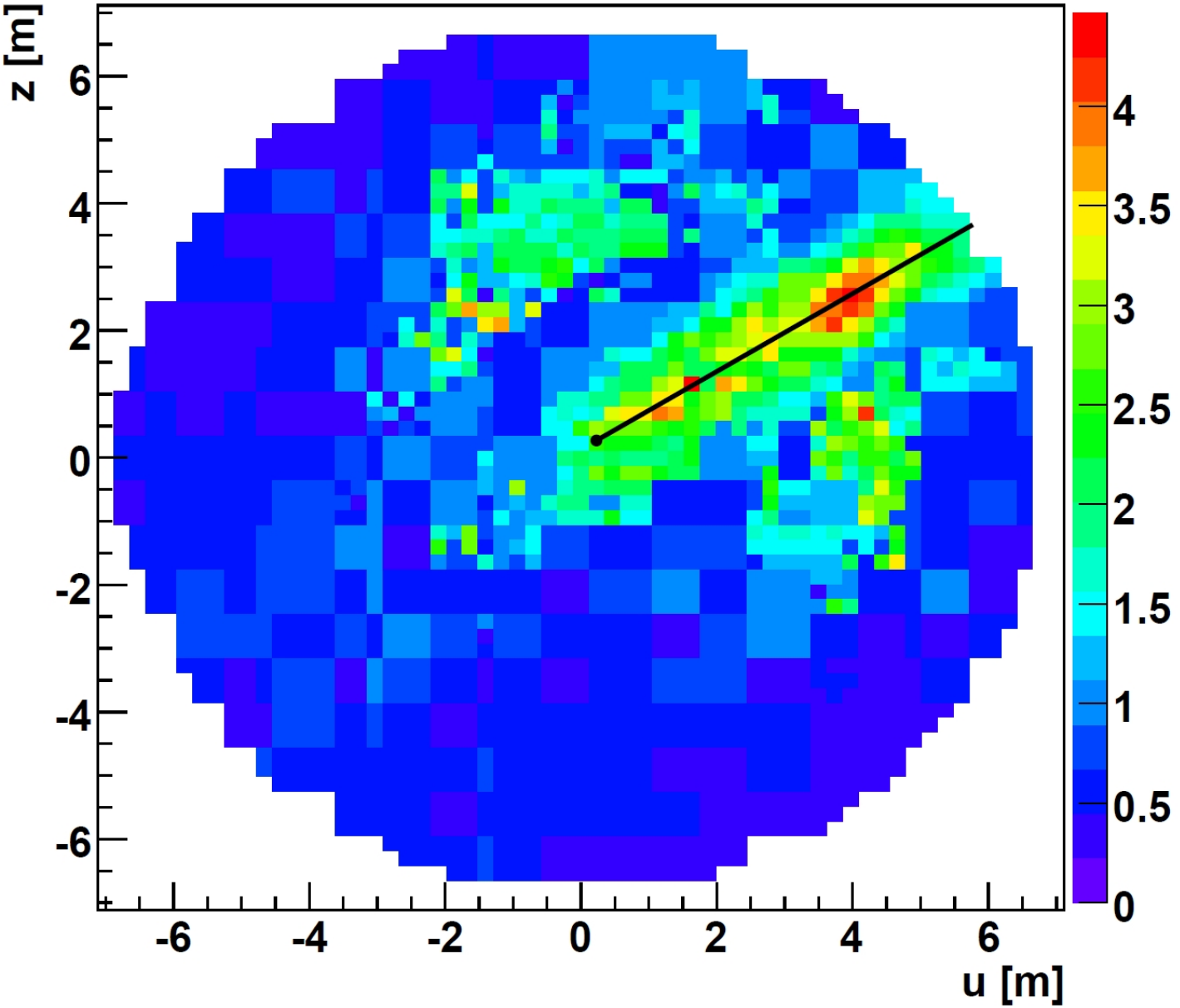
Some regions on track do not produce many 'first hits'

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

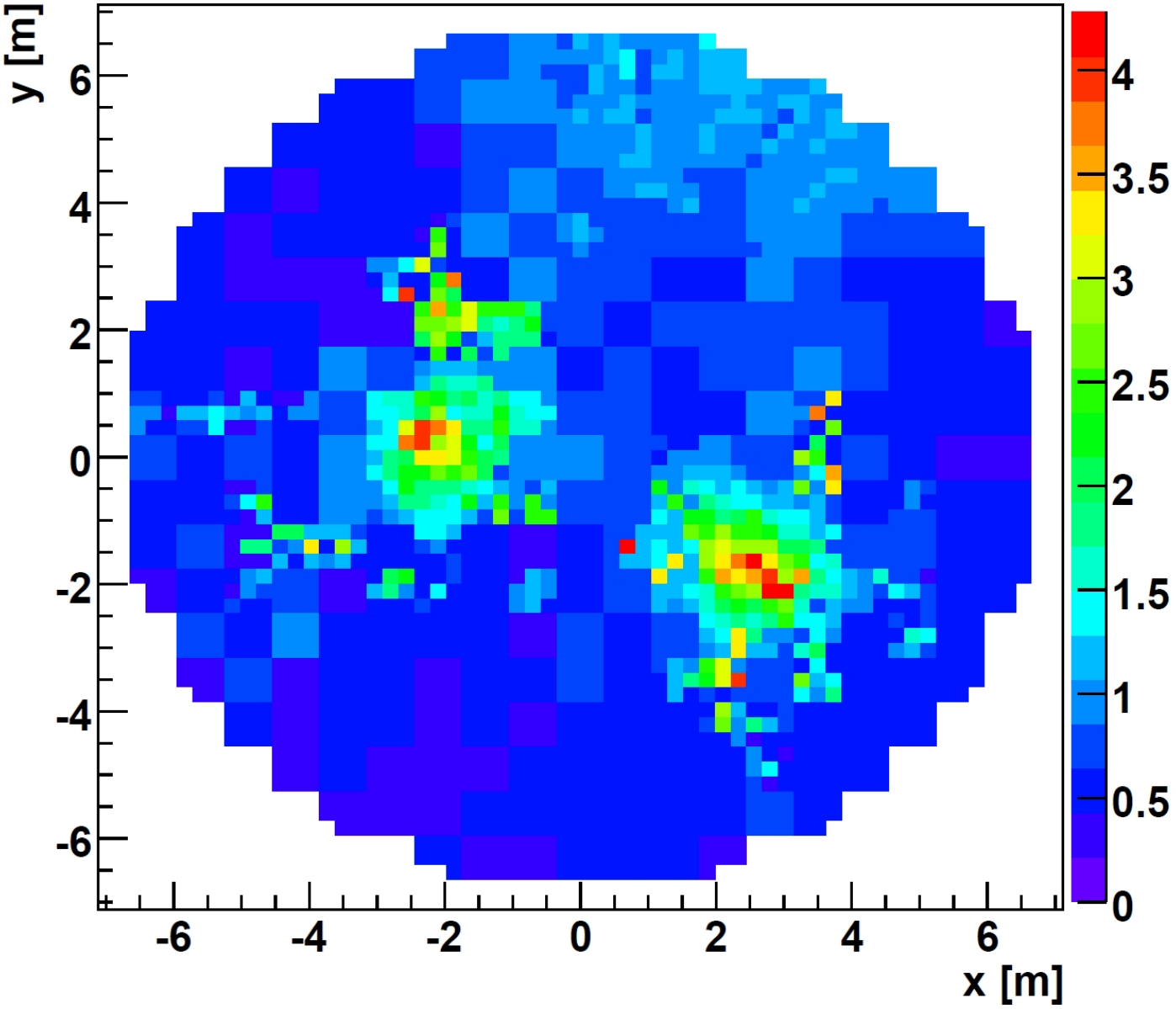
→ **whole track**



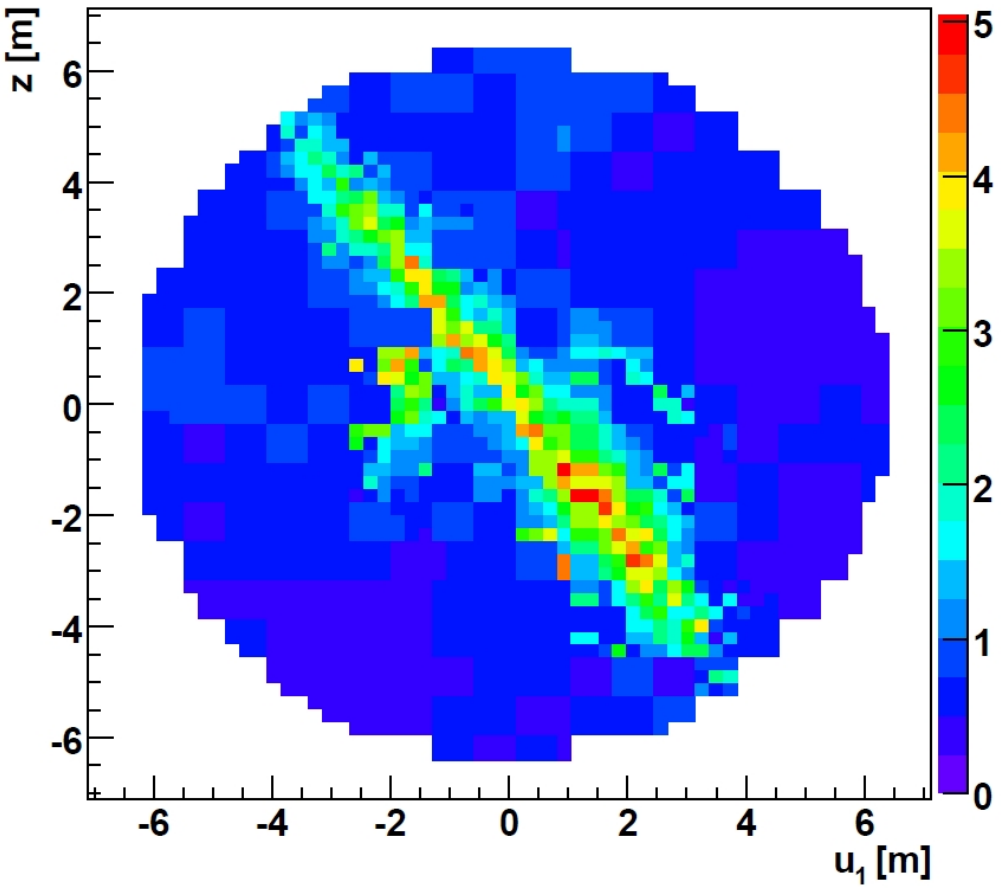
# Stopped Muon in Borexino

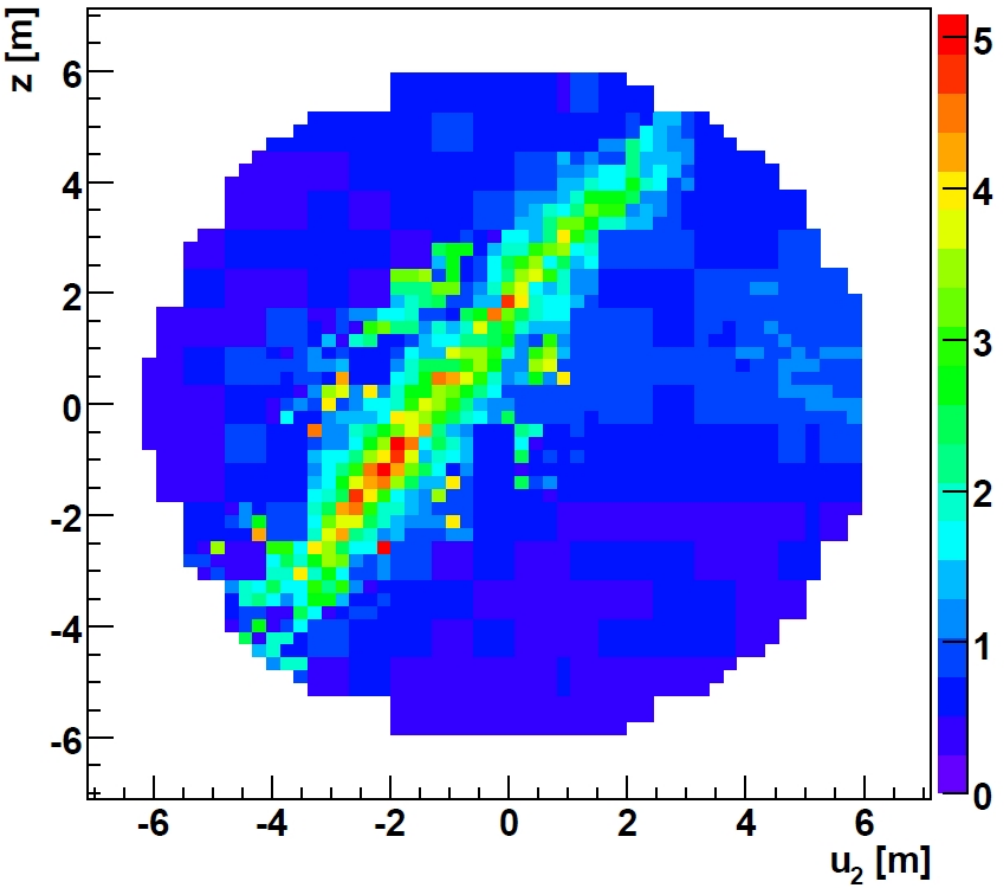


# Double Muon Event in Borexino



# Double Muon Event in Borexino




**Both tracks cut out!**

# Conclusions

**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

# Conclusions

**Limitations:**

- Only limited study of more complicated events so far
- Reference point is crucial **already solved**
- Need more **computing power** for:
  - finer binning/resolution
  - more iterations
  - faster simulation

However its just getting started!

A generic reconstruction framework already on the way

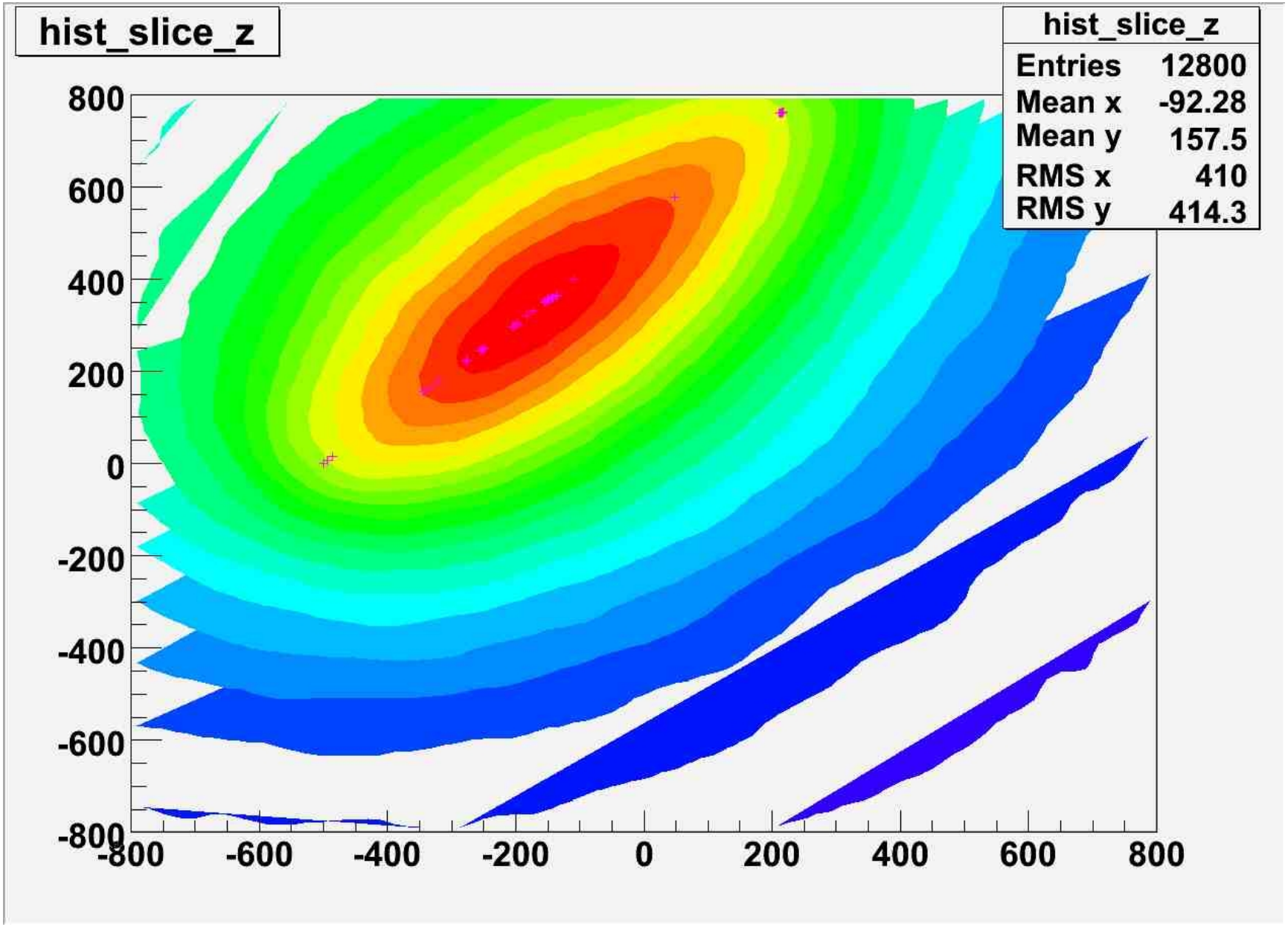
Needs to be reprogrammed for GPUs

Backup slides

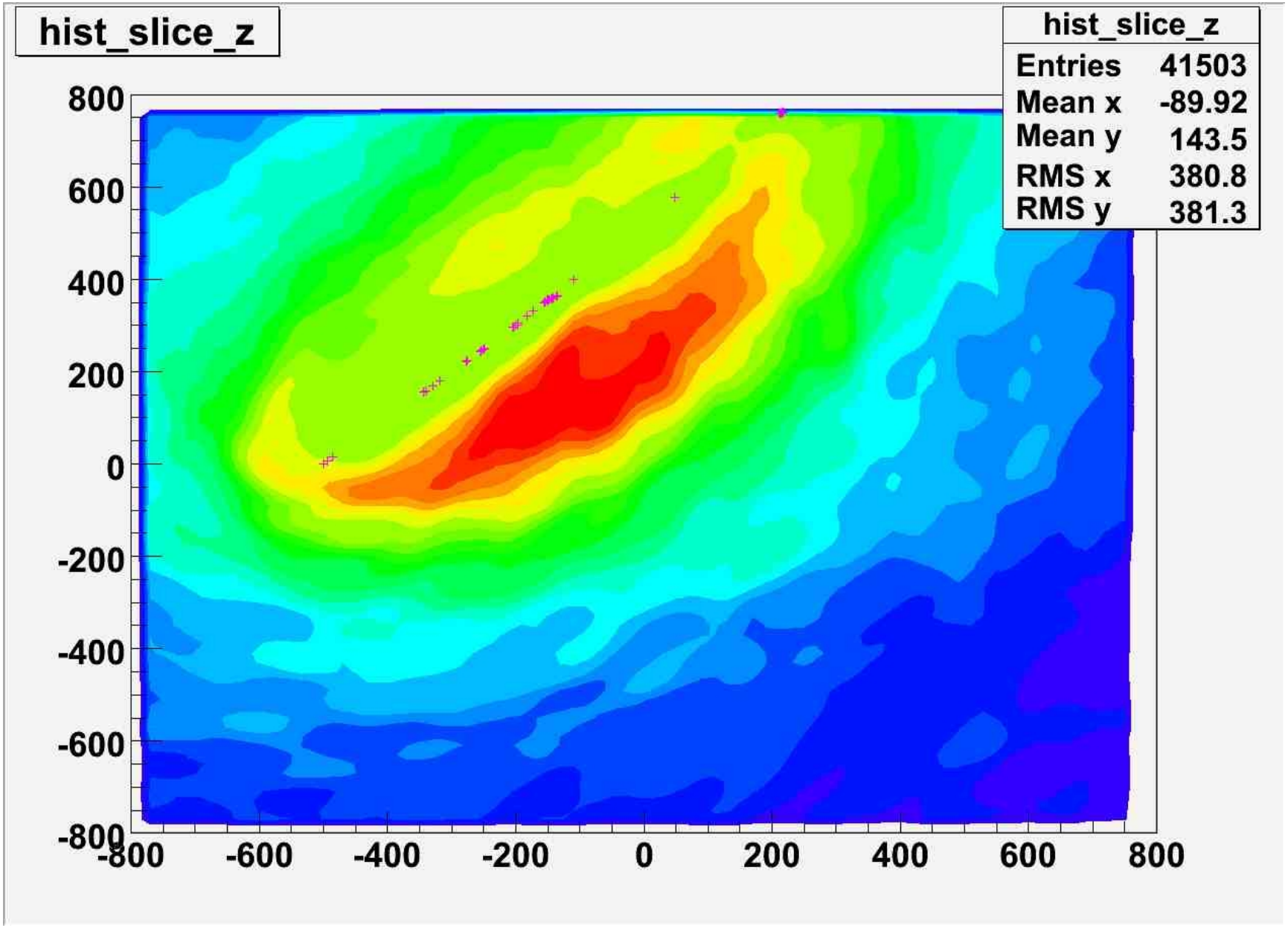
# The power of the 4th dimension

4d Canny Algorithm

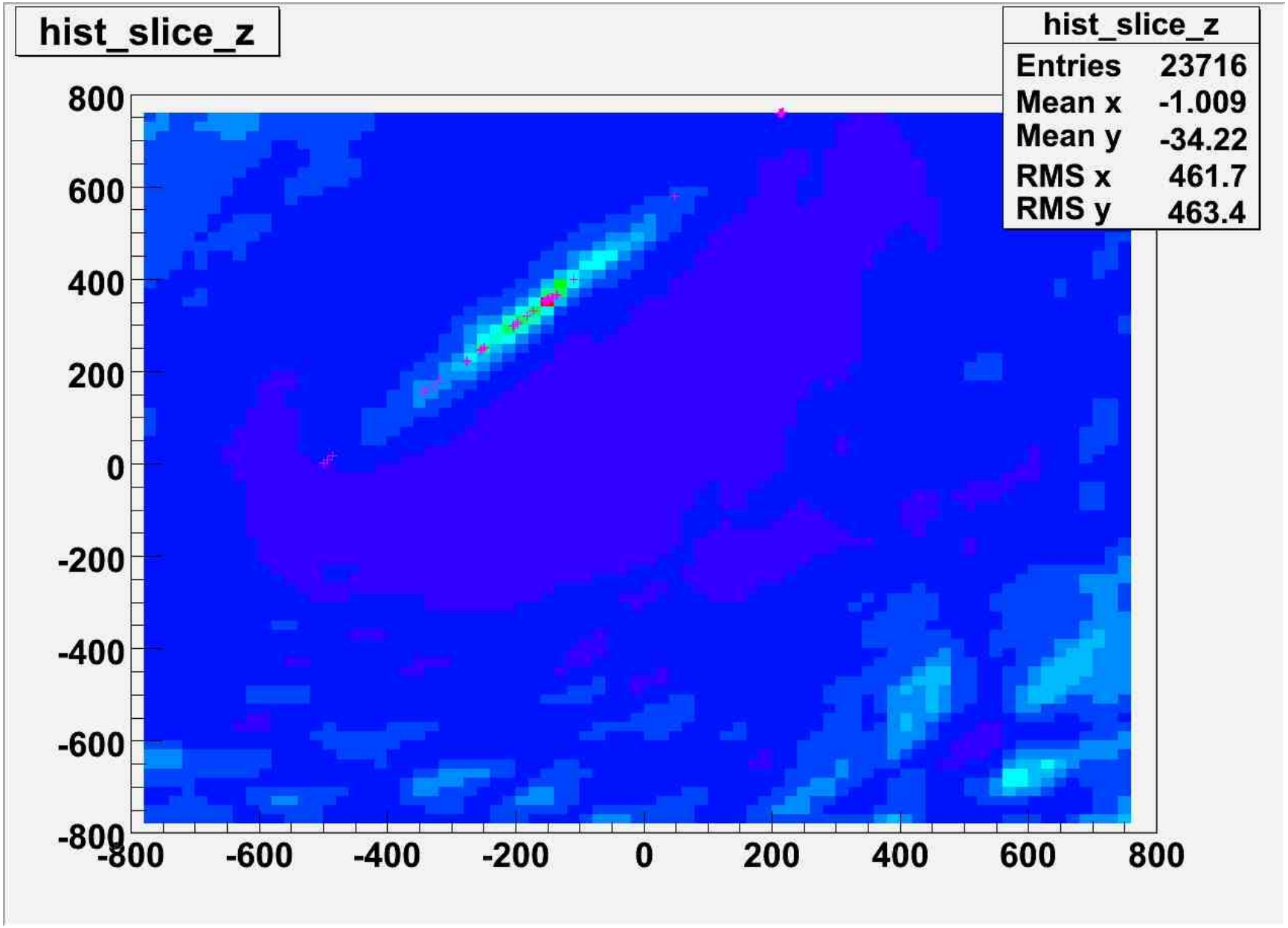
# The Reco Result (266 PMTs)



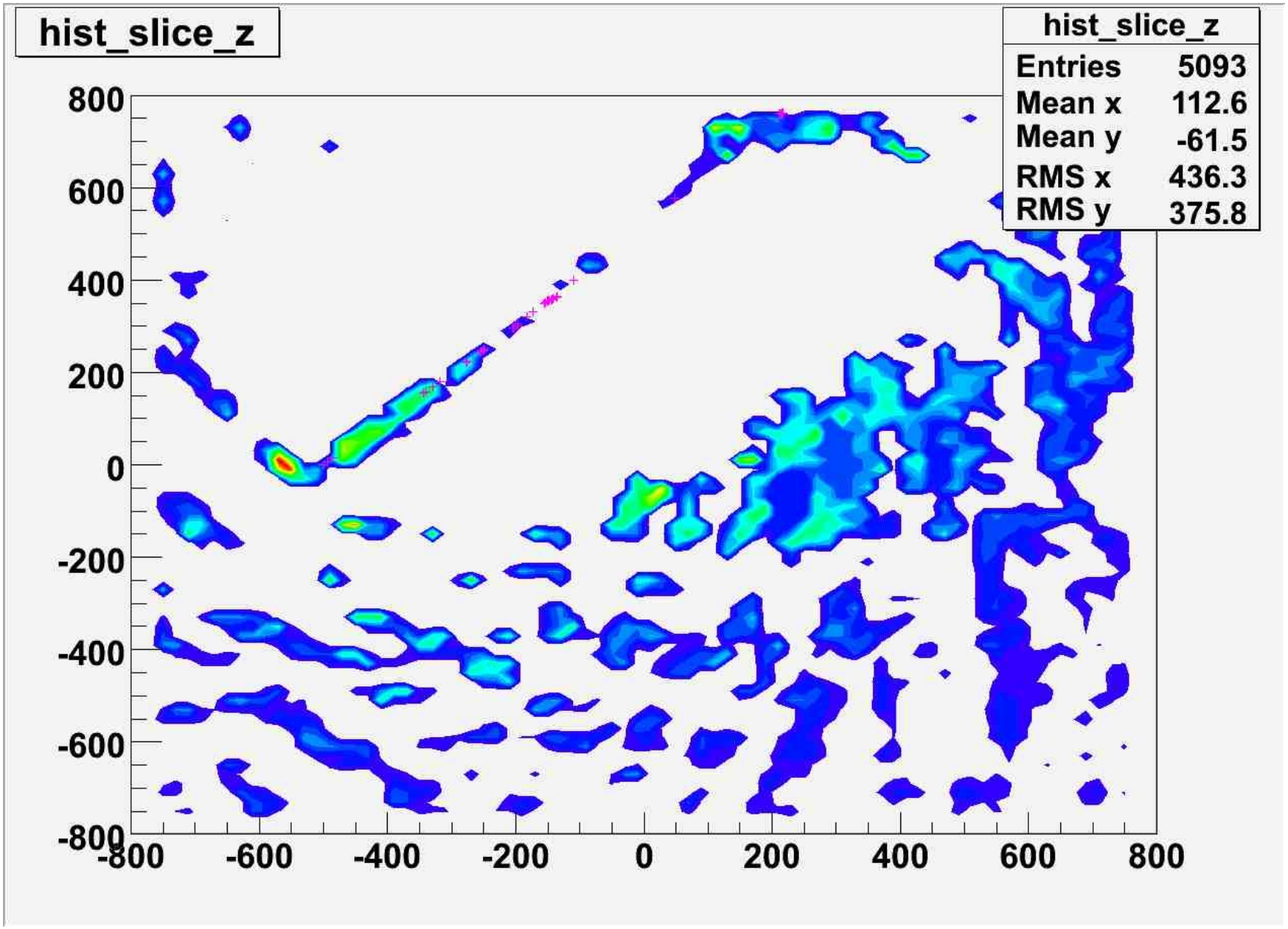
# 4d-Sobel Result



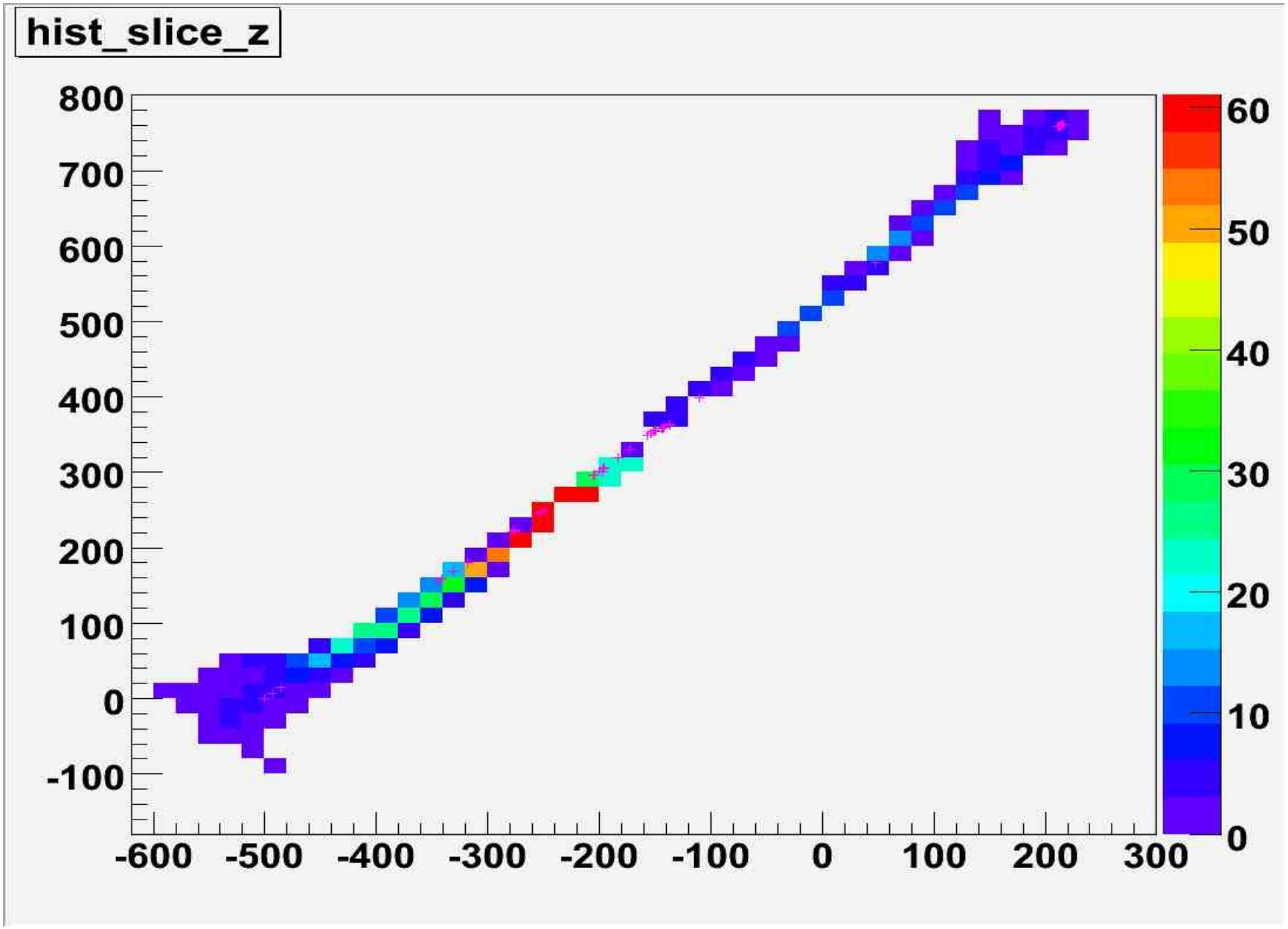
# Reco Result divided by 4d-Sobel



# Minima of 4d-Sobel



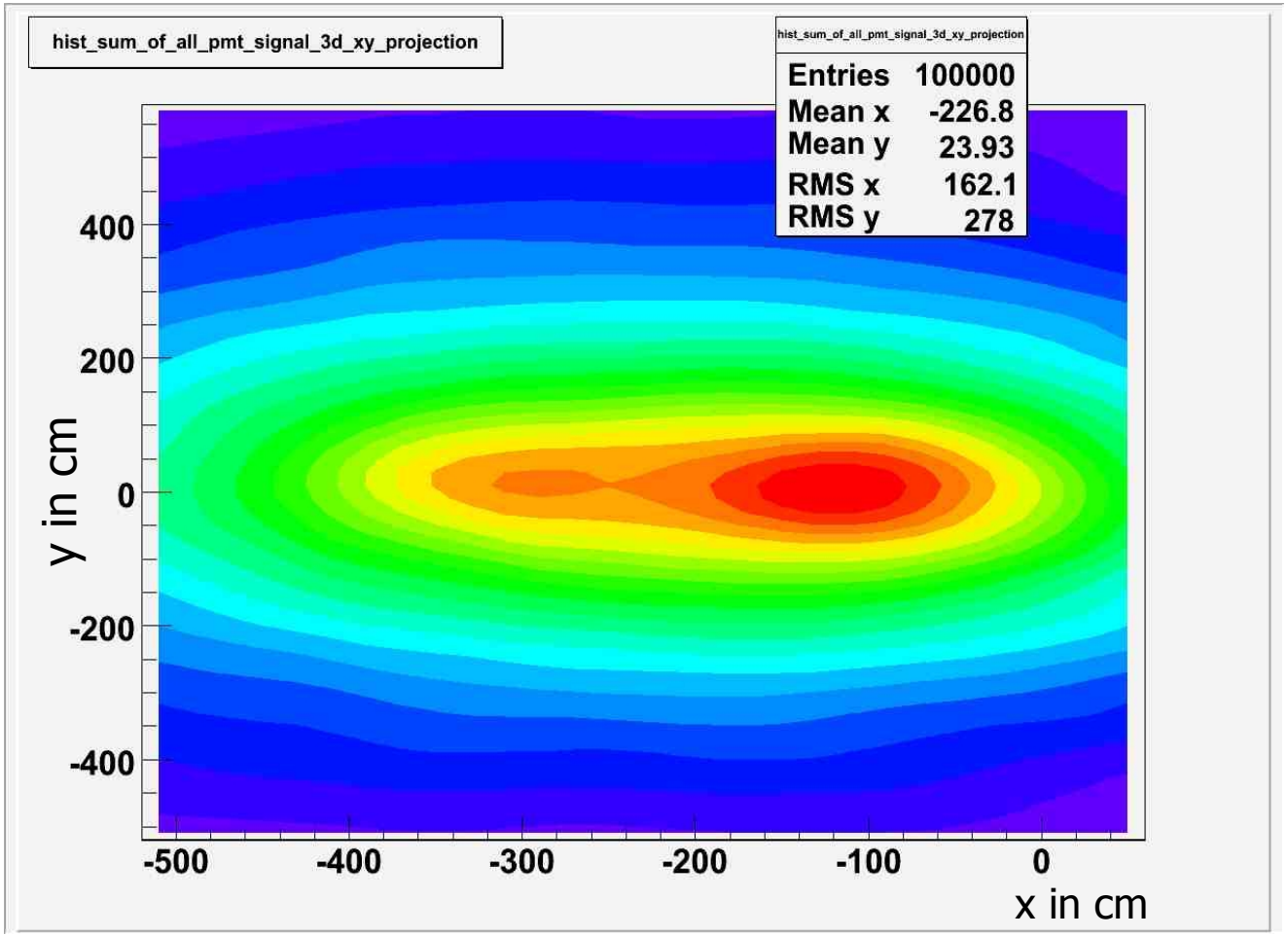
# Result after Follow-up



# Some early examples with different particles

# 465 MeV $\pi_0$

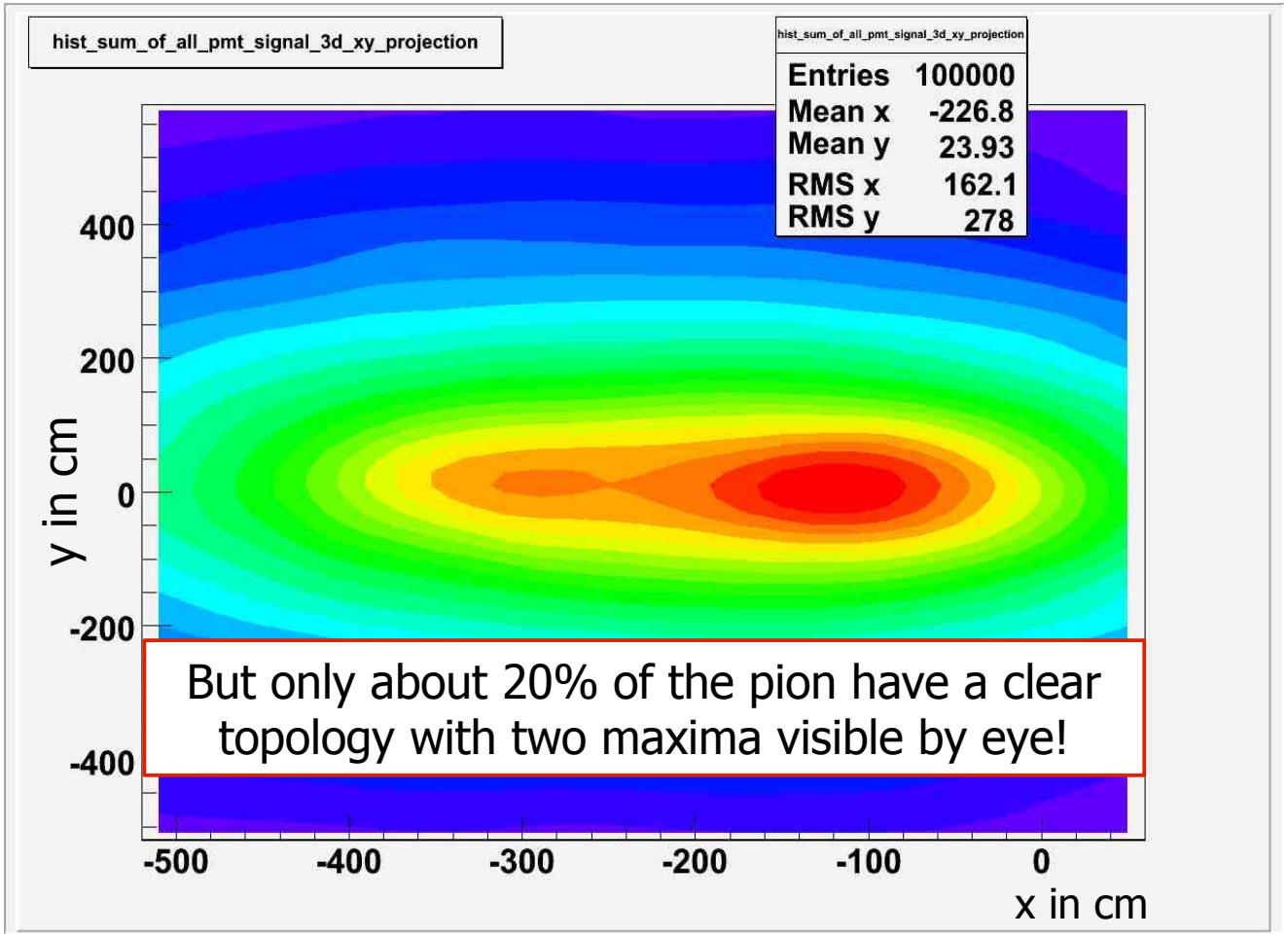
- **Vertex (0.,0.,0.), Orientation (-1.,0.,0.)**




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

# 465 MeV $\pi_0$

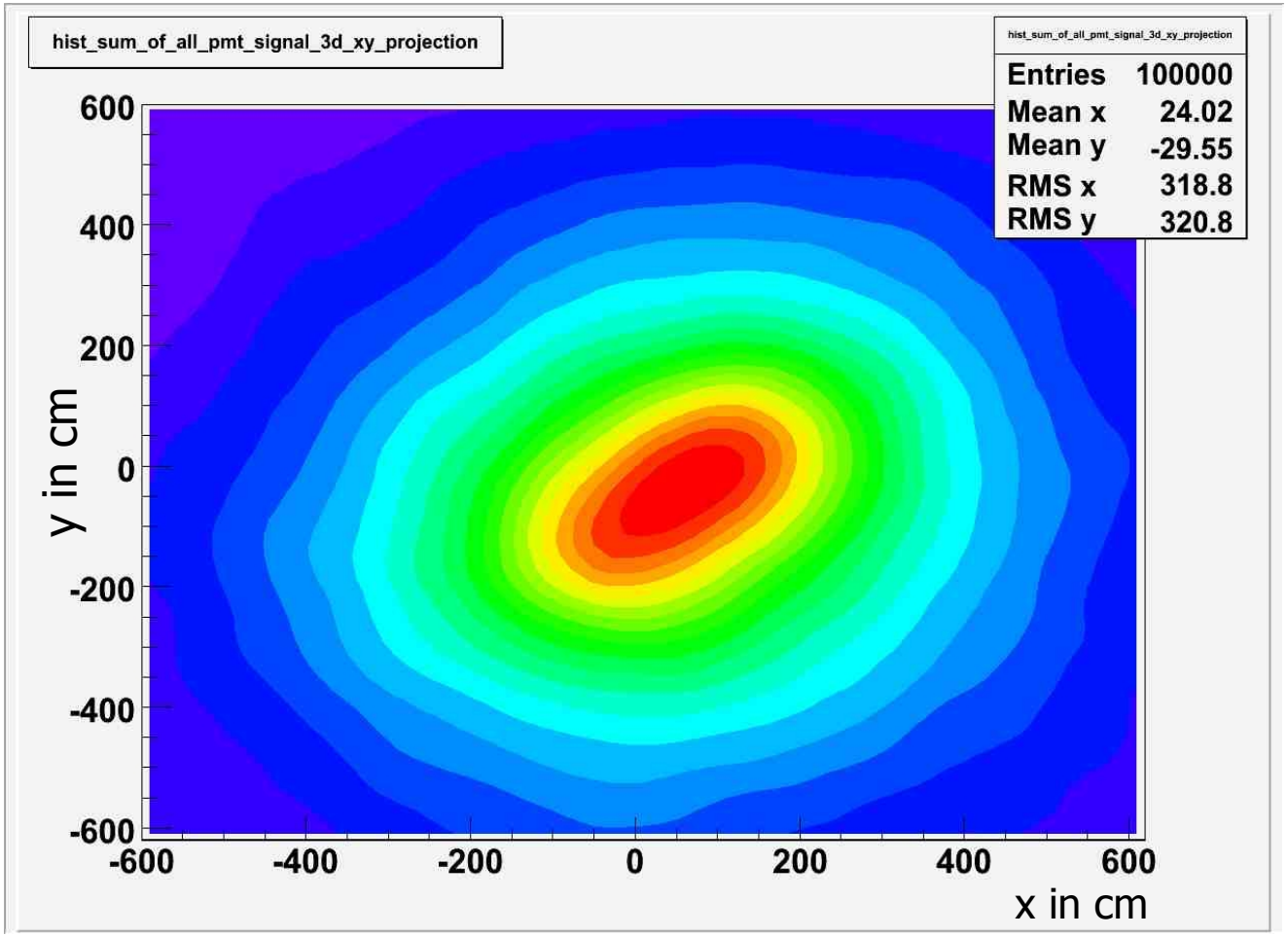
- **Vertex (0.,0.,0.), Orientation (-1.,0.,0.)**




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

# Muon 800 MeV

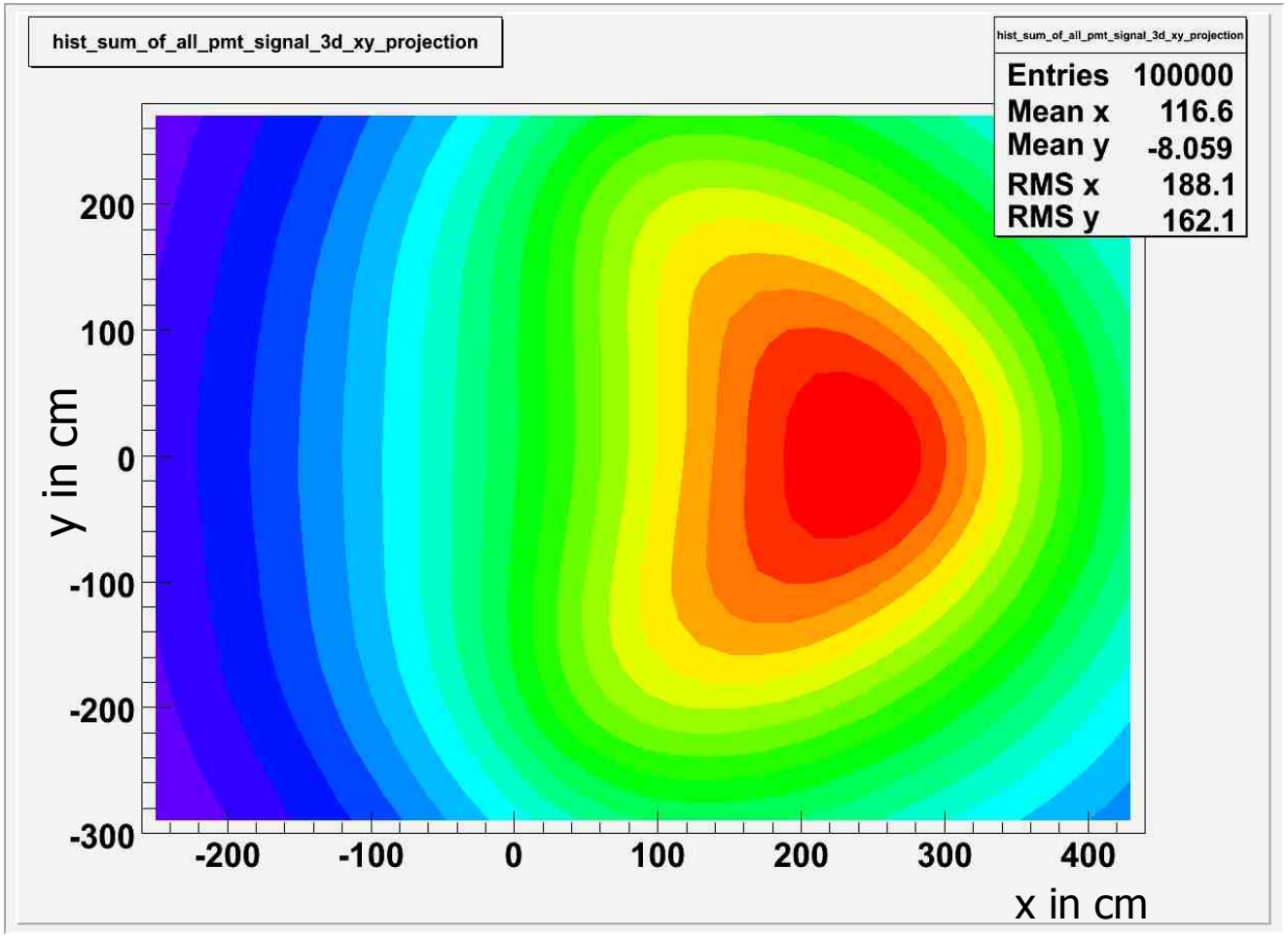
- **Vertex (200.,100.,0.), Orientation (-1.,-1.,0.)**




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

# 2 Muons with 750 MeV each

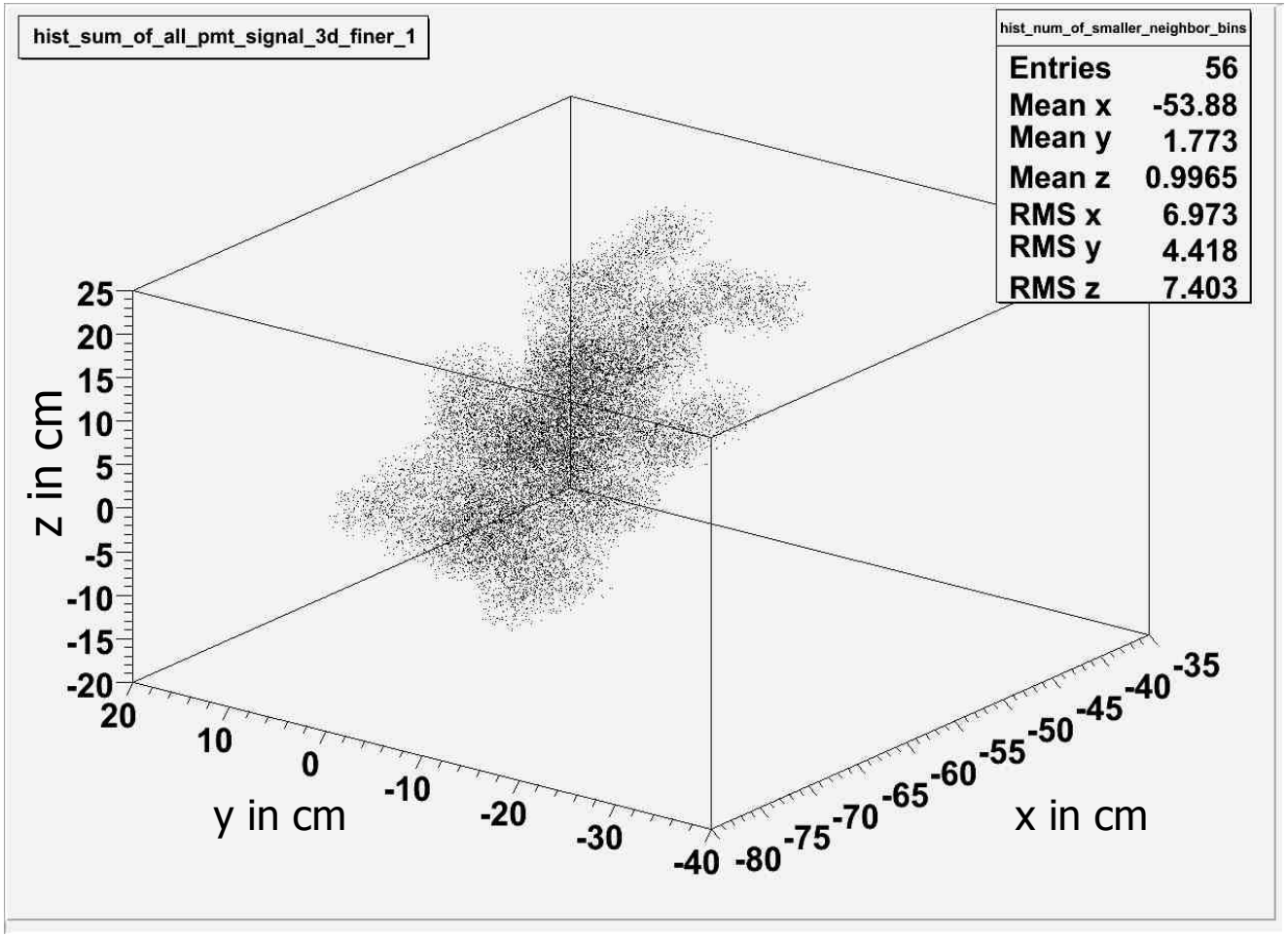
- **Vertex (300.,0.,0.), Orientation +-45°**




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

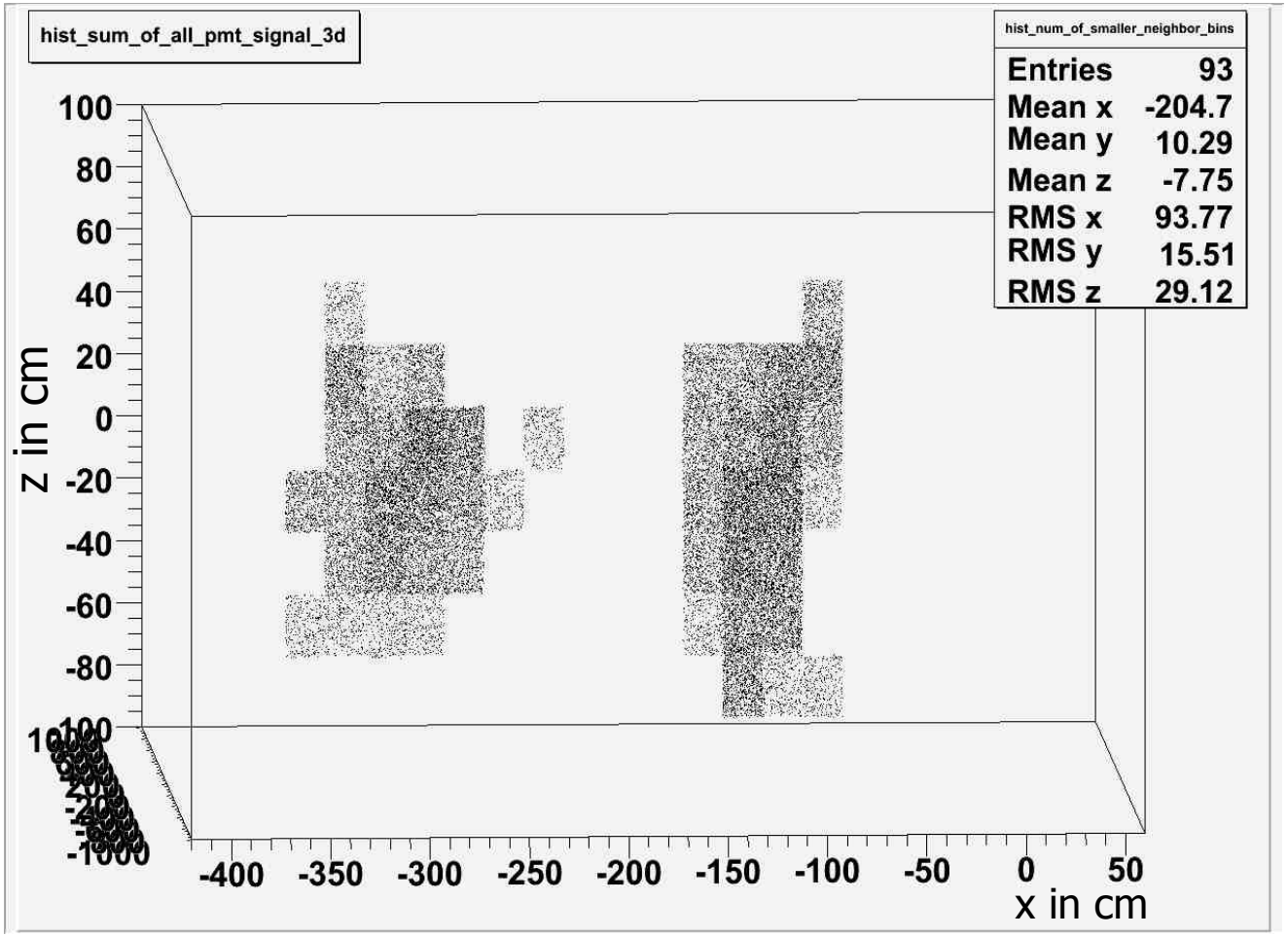
# Resultat: 500 MeV Electron

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



# 465 MeV $\pi_0$

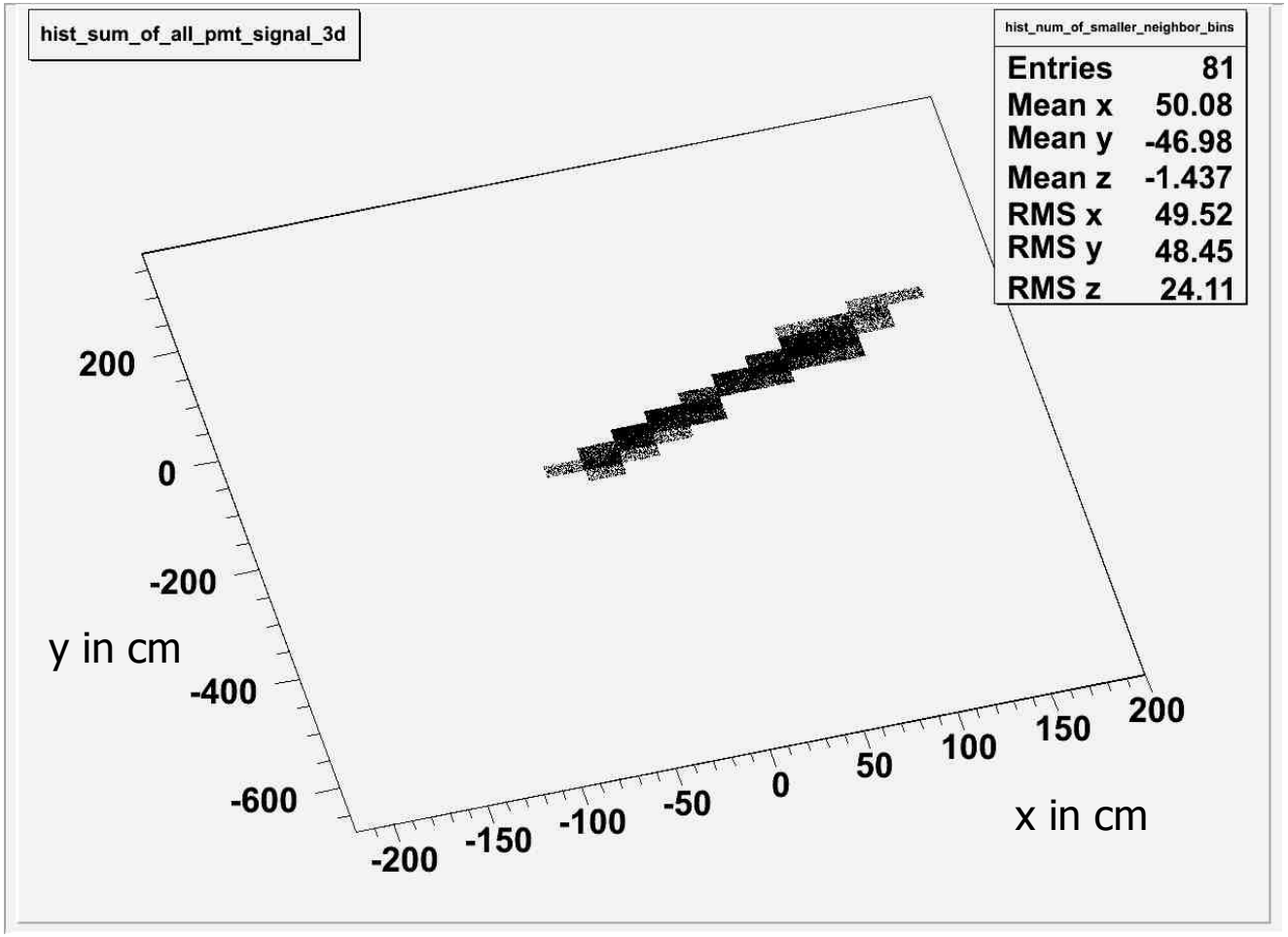
- **Vertex (0.,0.,0.), Orientation (-1.,0.,0.)**




10% of PMTs

# Muon 800 MeV

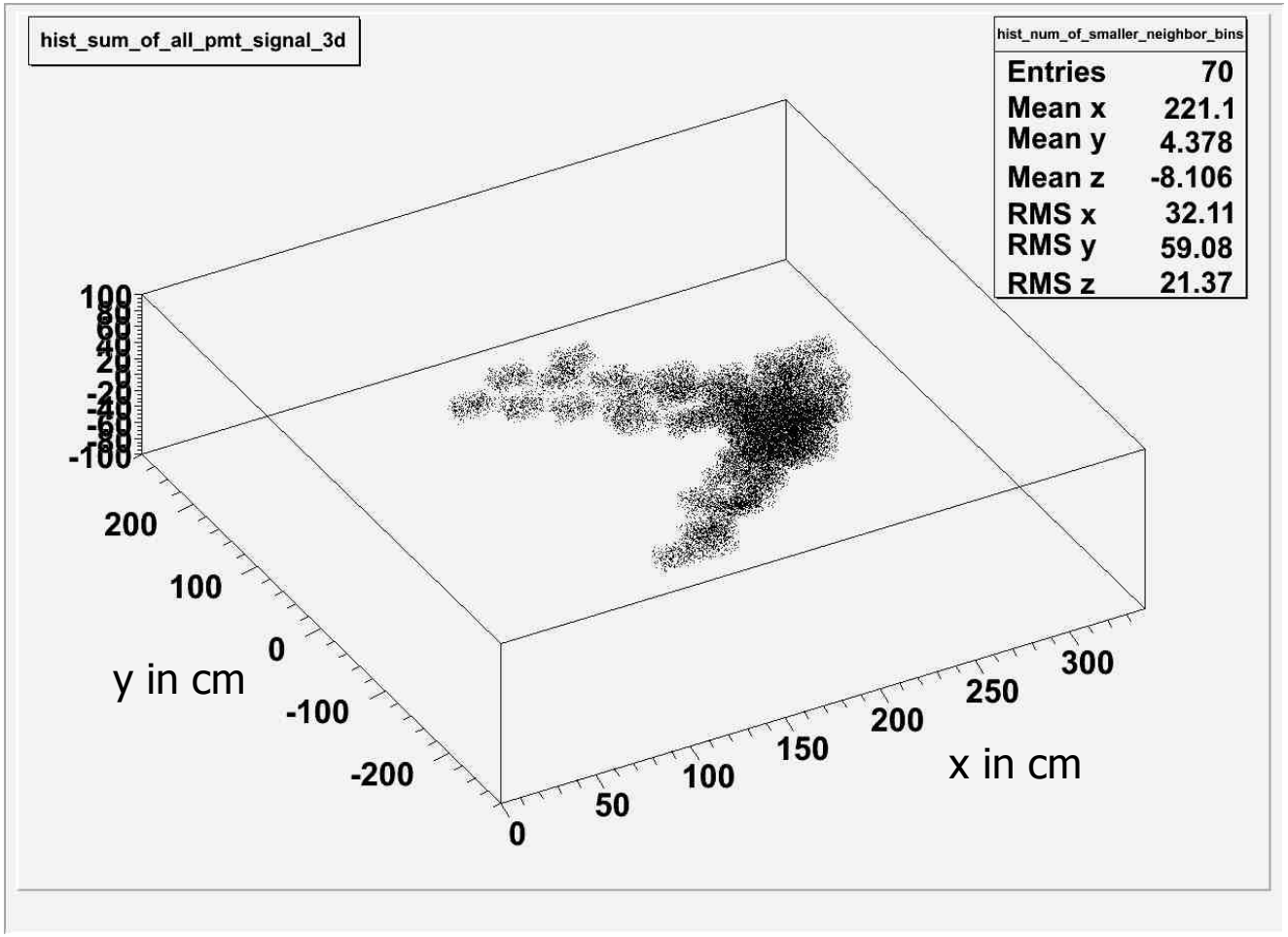
- **Vertex (200.,100.,0.), Orientation (-1.,-1.,0.)**




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

# 2 Muons with 750 MeV each

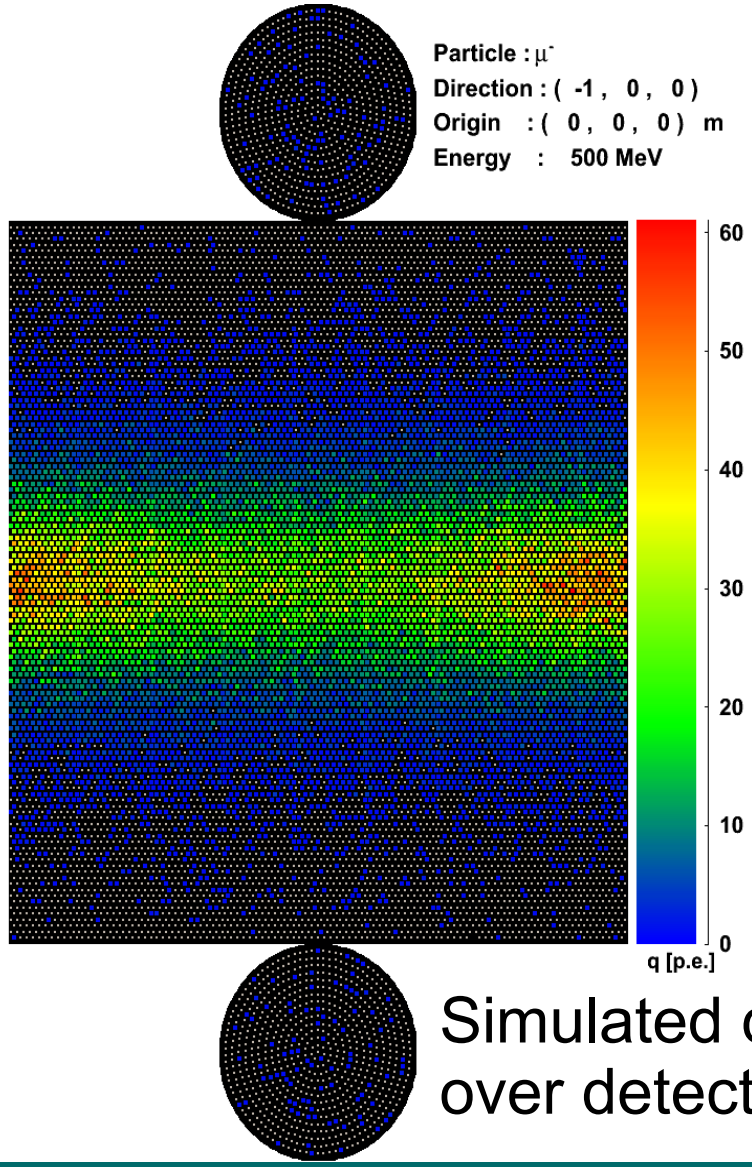
- **Vertex (300.,0.,0.), Orientation +-45°**



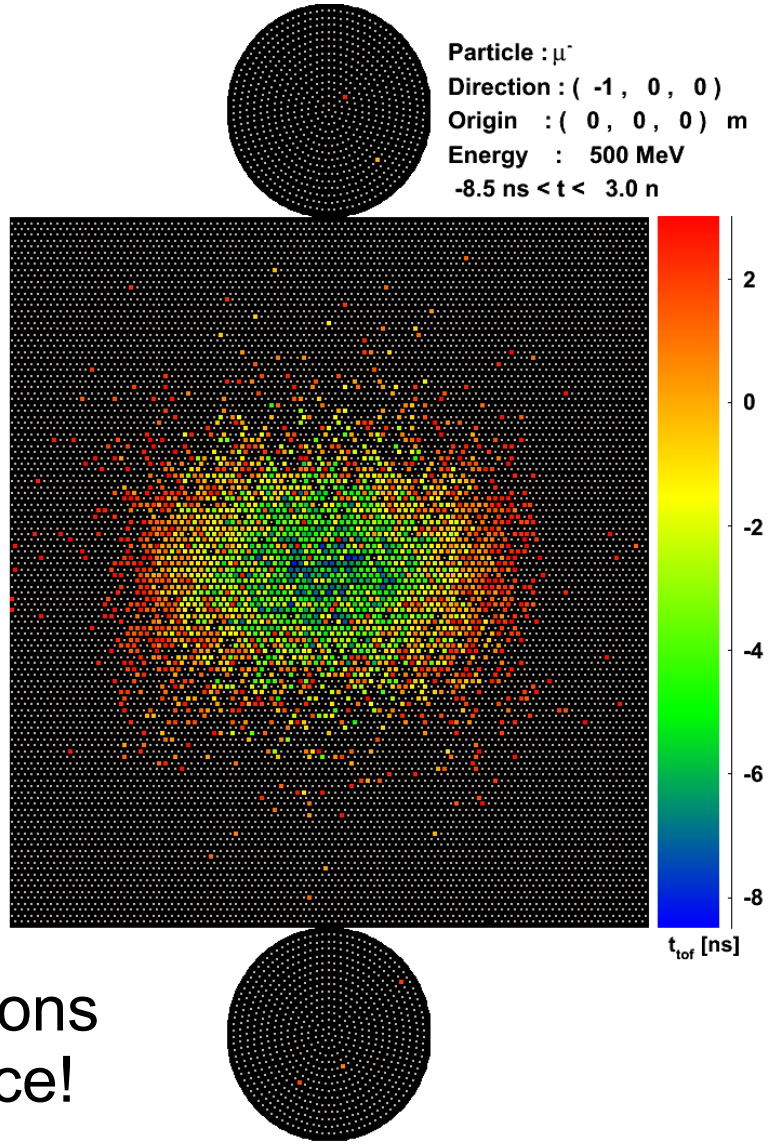

10% of PMTs at +-500 cm in z with respect to vertex

# Event Signature for Tracking

Charge




(First) Hit time




Simulated distributions over detector surface!