# Positron discrimination in large-volume liquid scintillator detectors using 3D topological reconstruction

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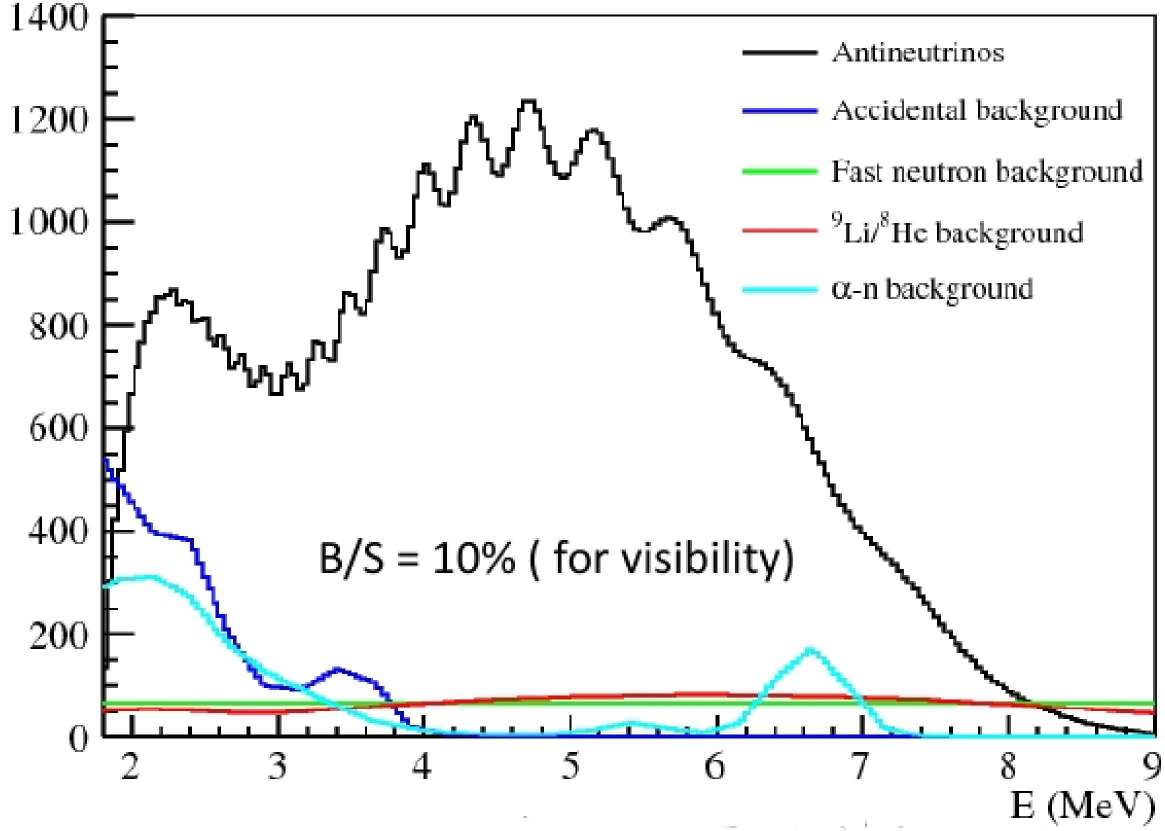
DER FORSCHUNG | DER LEHRE | DER BILDUNG

# Motivation I: Reactor Neutrinos

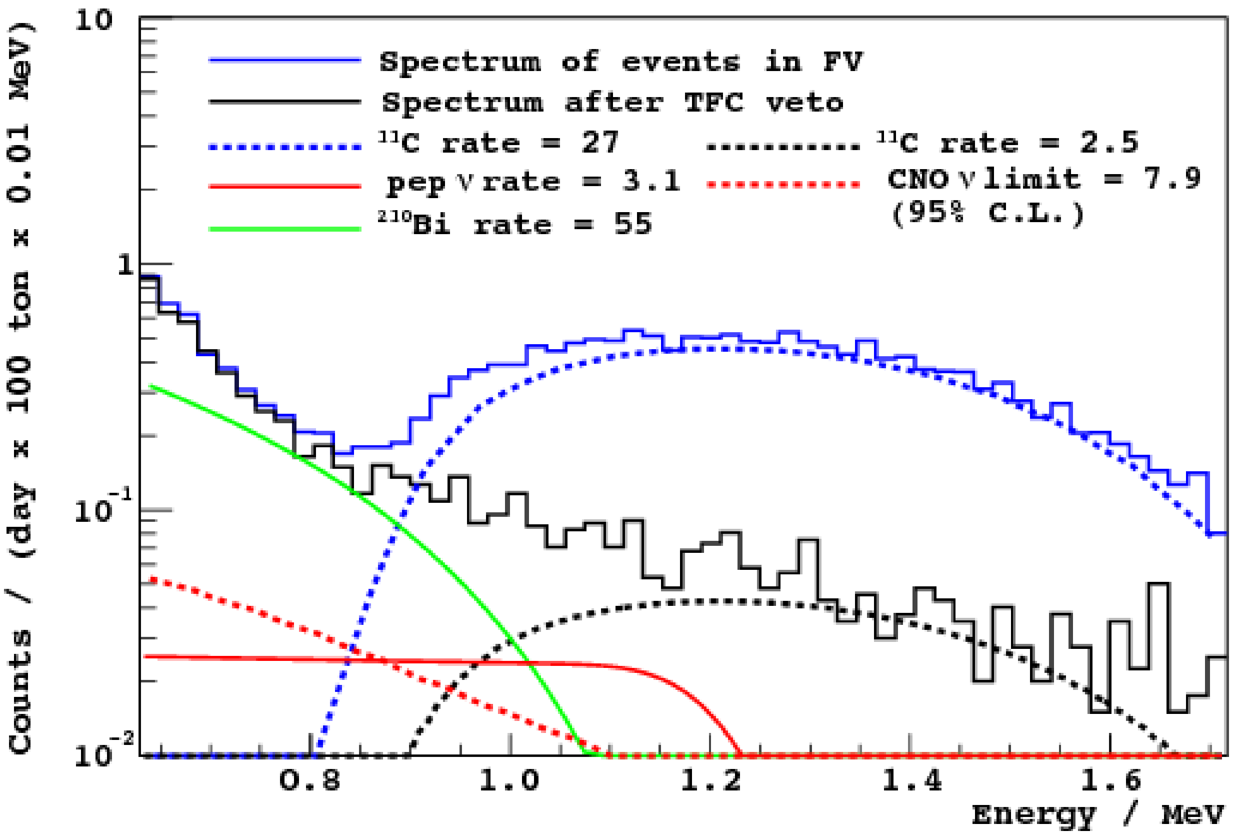
- **Inverse beta decay (IBD):** $\bar{\nu}_e + p \rightarrow n + e^+$
- **Background does not contain possitrons**



# Motivation: Solar Neutrinos

- **Neutrino-electron scattering:** $\nu_e + e^- \rightarrow \nu_e + e^-$
- **Important Background for CNO and pep $\nu$:**

$^{11}C \rightarrow {}^{11}B + e^+$ (Q = 1982.4 keV)




Borexino collaboration, Phys.Rev.Lett. 108 (2012) 051302

# My 3D Tracking in a Minute

- Need a reference point
- Draw drop-like probability surfaces for each PMT

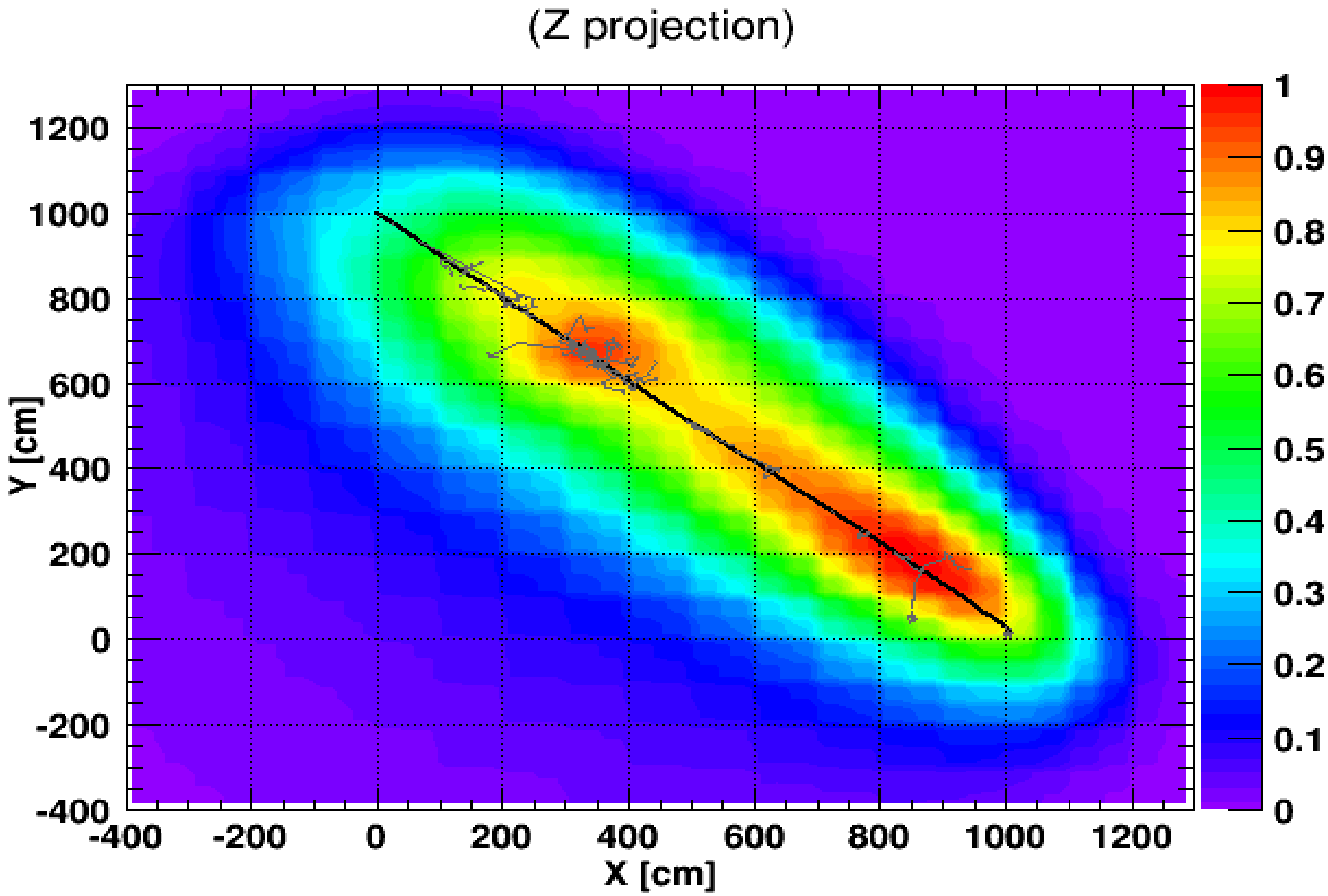
  → 3D topological picture

- Iterative process using previous result to reevaluate probabilities

  → refined 3d picture

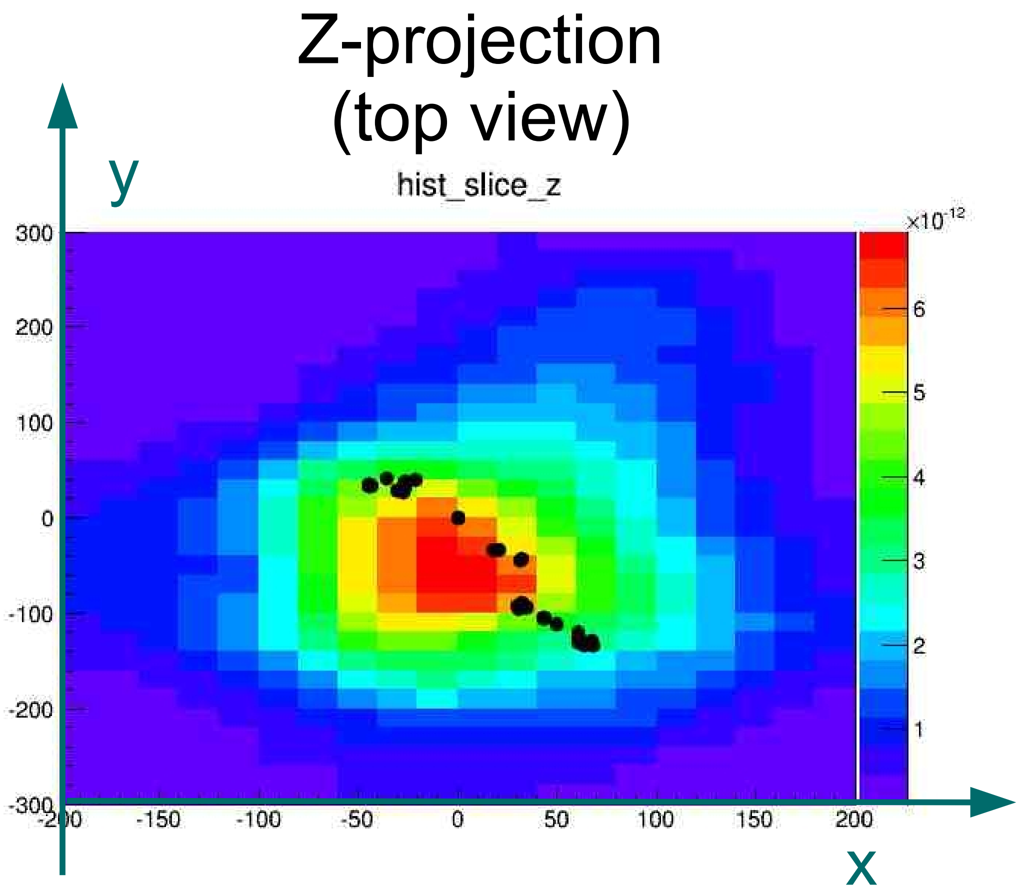
# 3D Topology

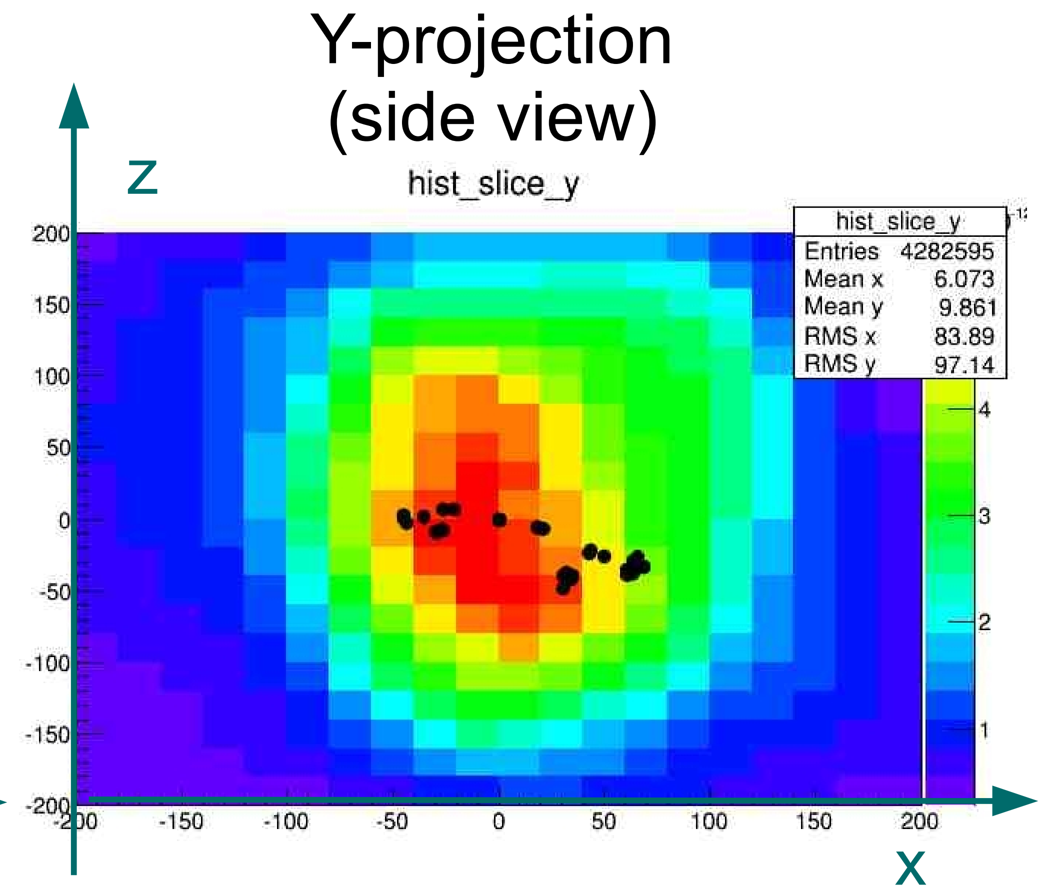
Probability distribution projected into the xy plane




**Color:** Total photon emission probability in arbitrary units
→ Measure for dE/dx

# Result 2nd Iteration Sum (Zoom)

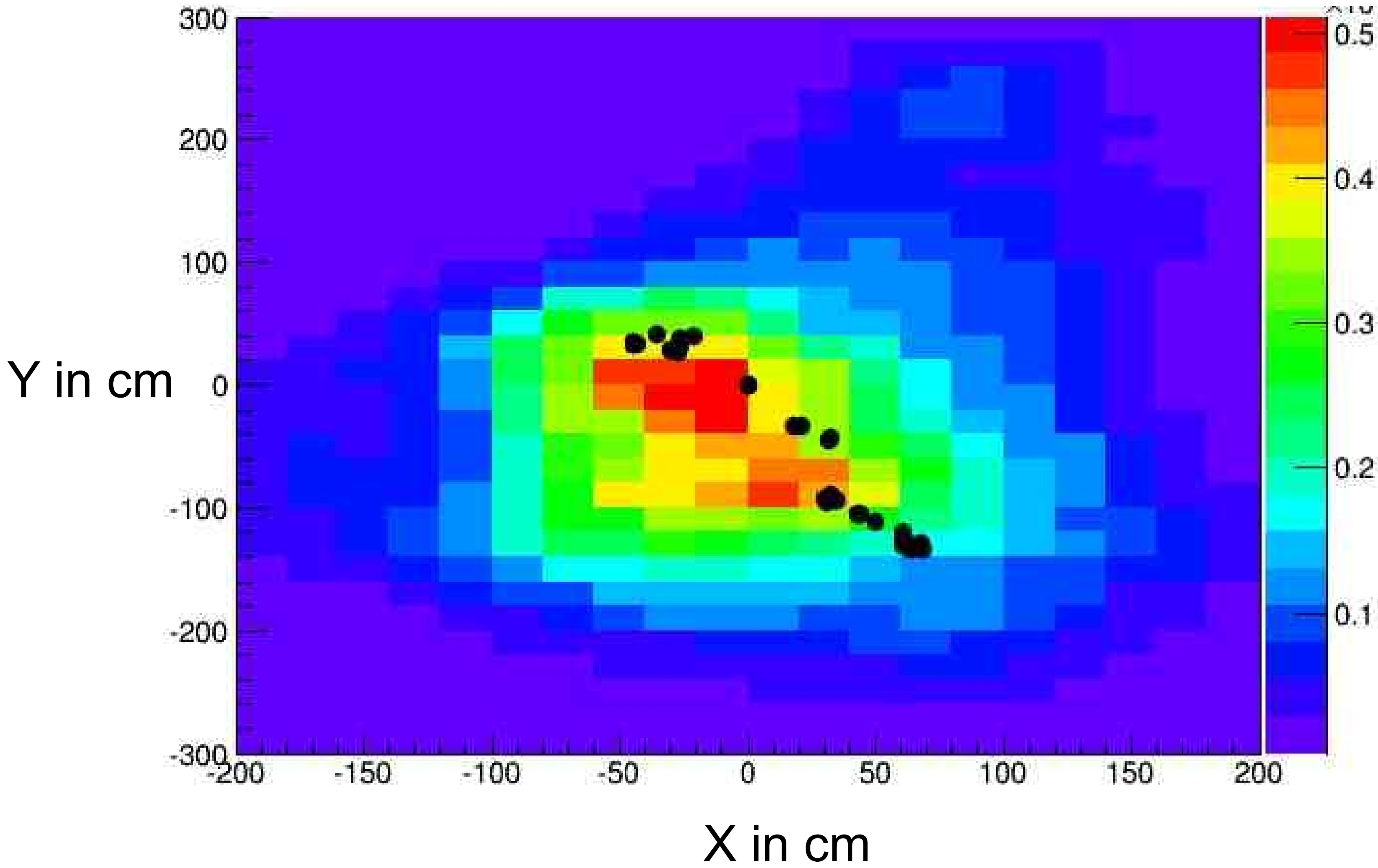



1MeV positron at center

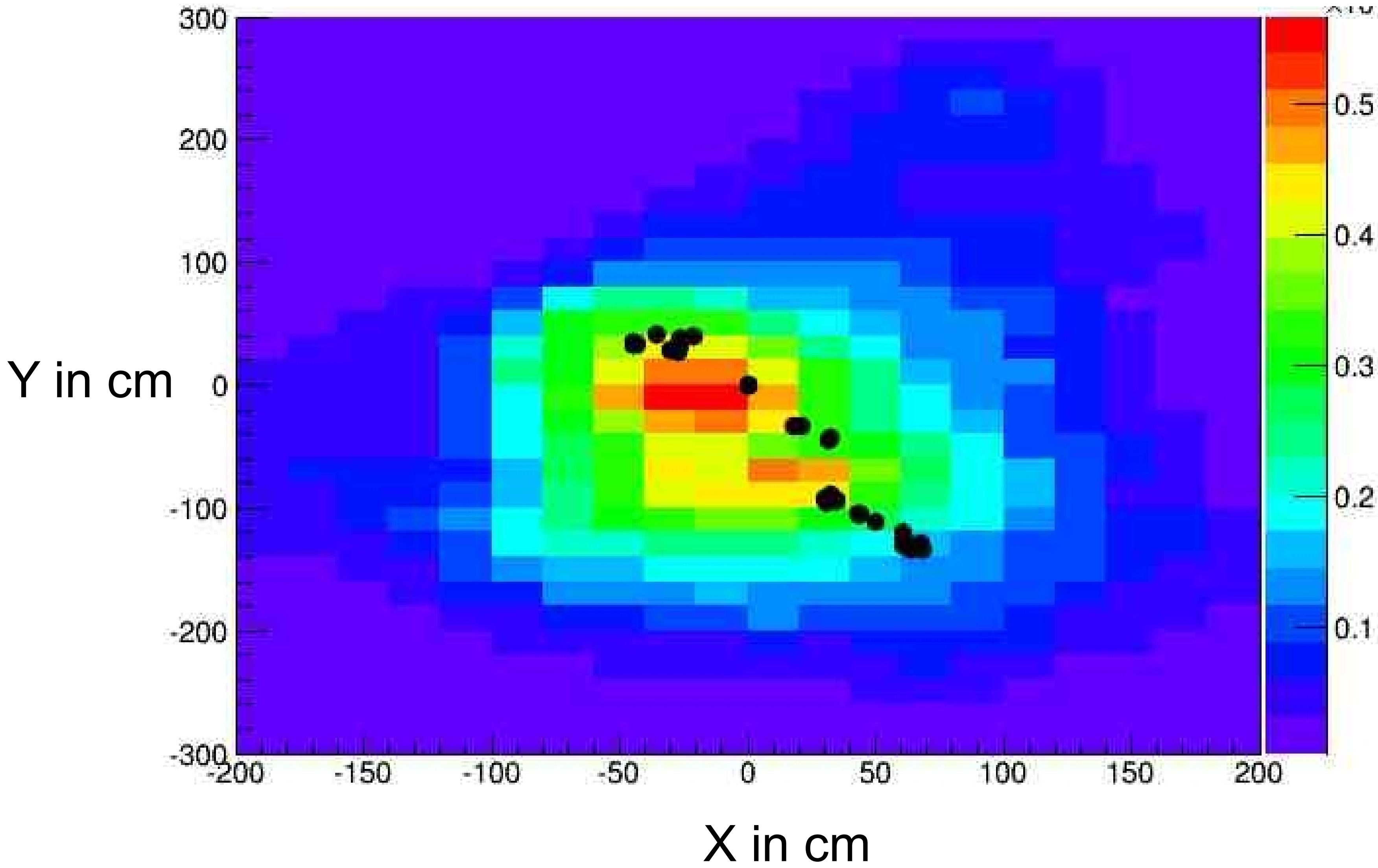
# Result 2nd Iteration Slice 241

XY-slice of 3d probability density distribution



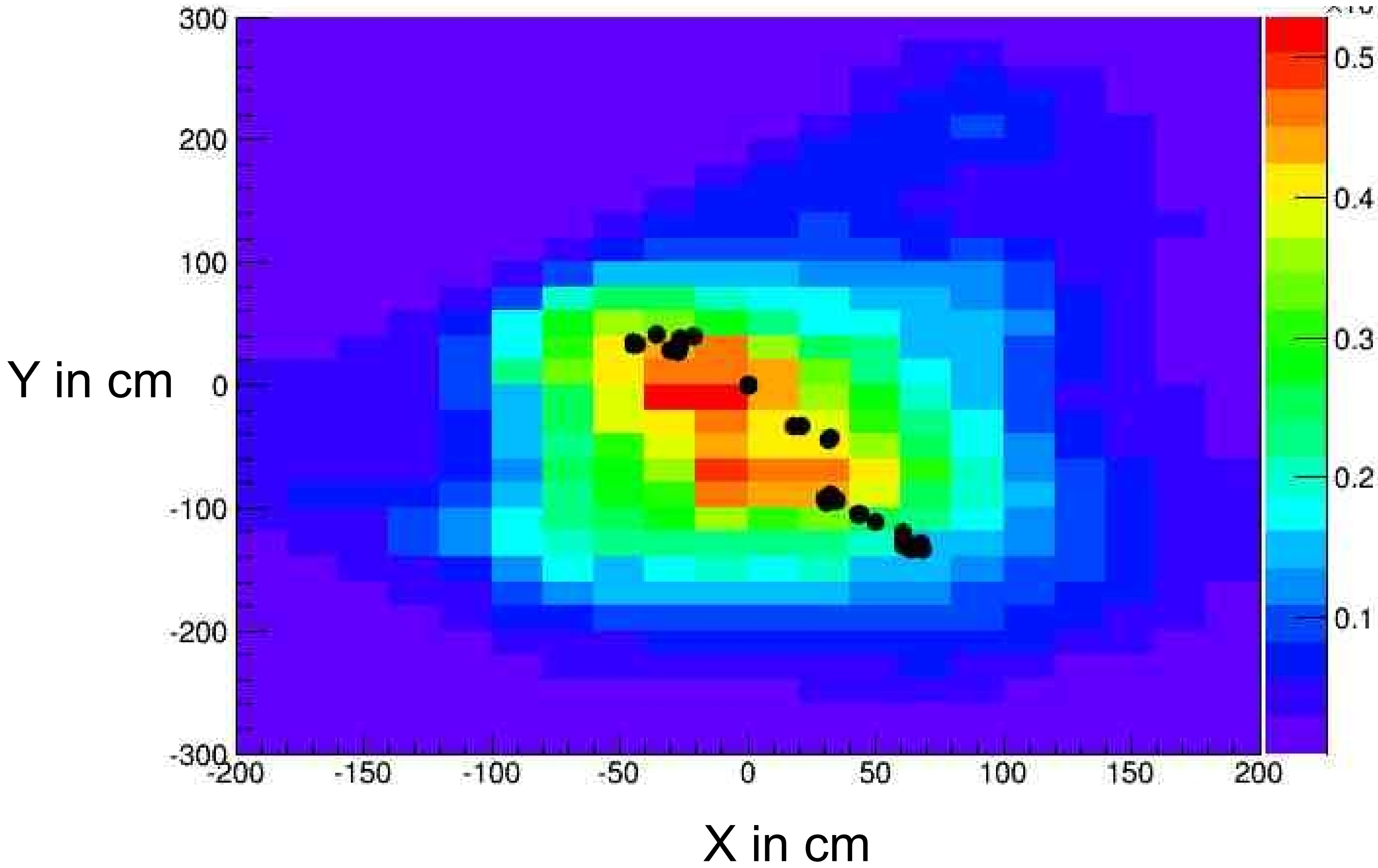
# Result 2nd Iteration Slice 240

XY-slice of 3d probability density distribution



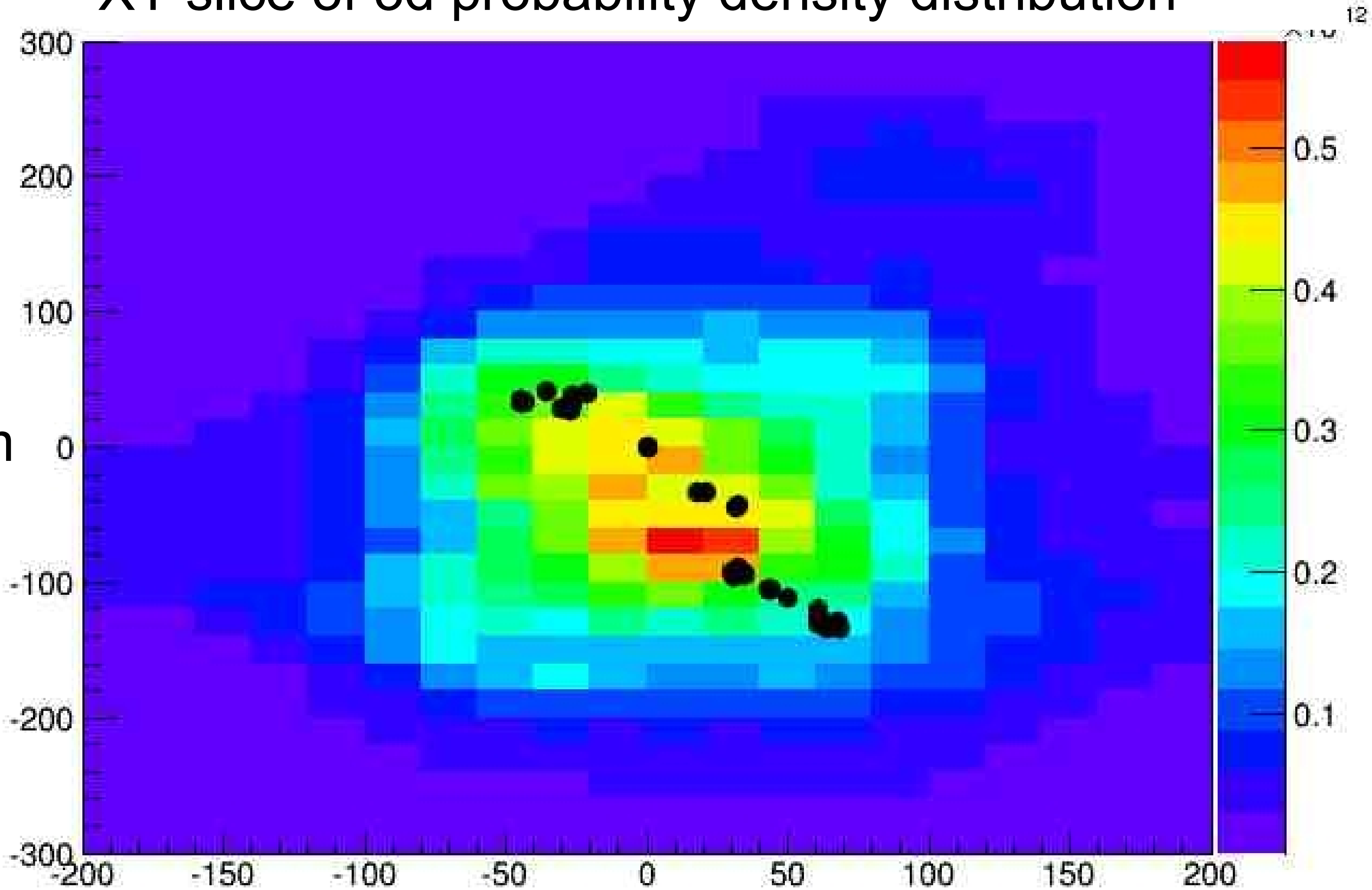
# Result 2nd Iteration Slice 239

XY-slice of 3d probability density distribution



# Result 2nd Iteration Slice 238

XY-slice of 3d probability density distribution

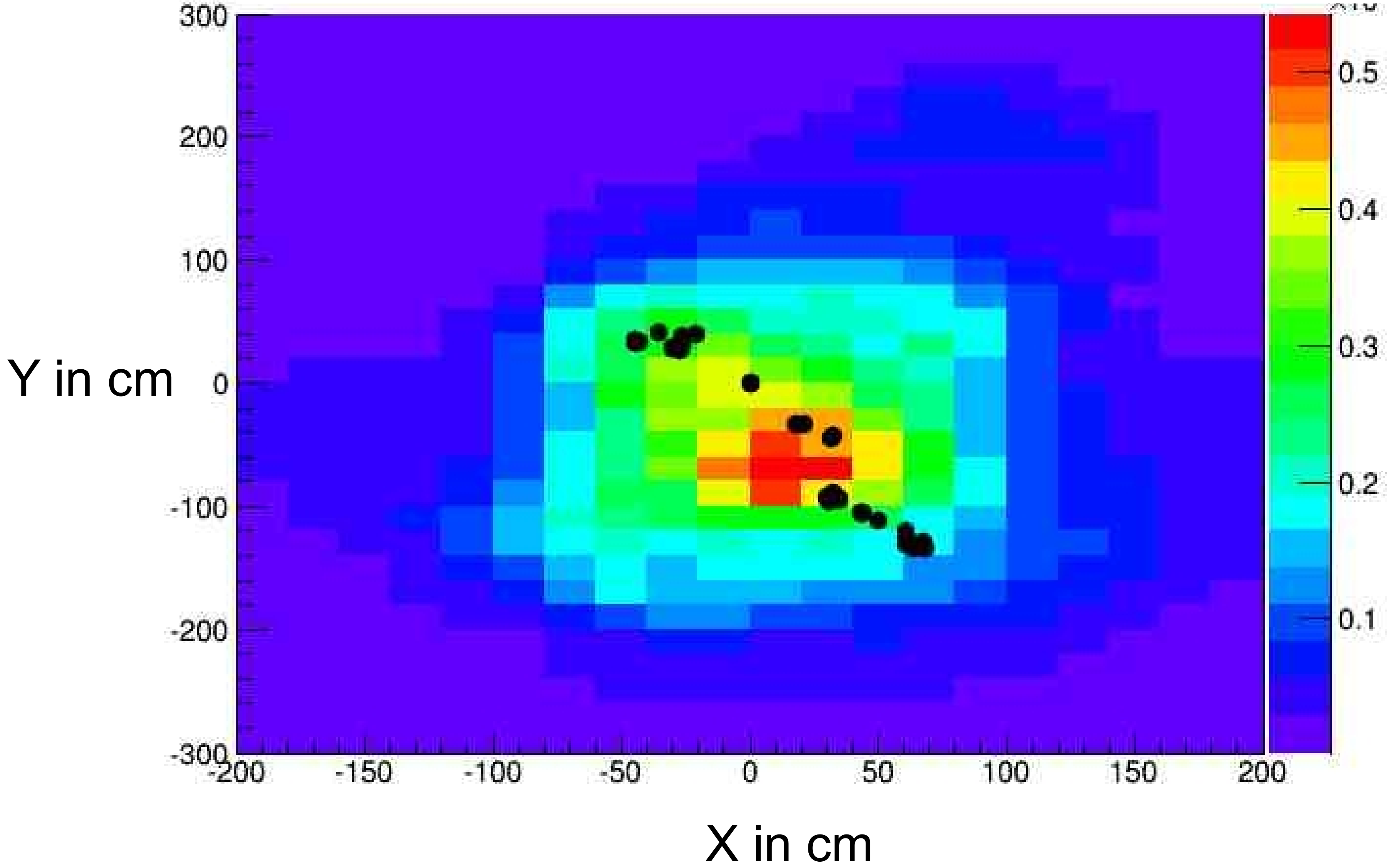



Y in cm

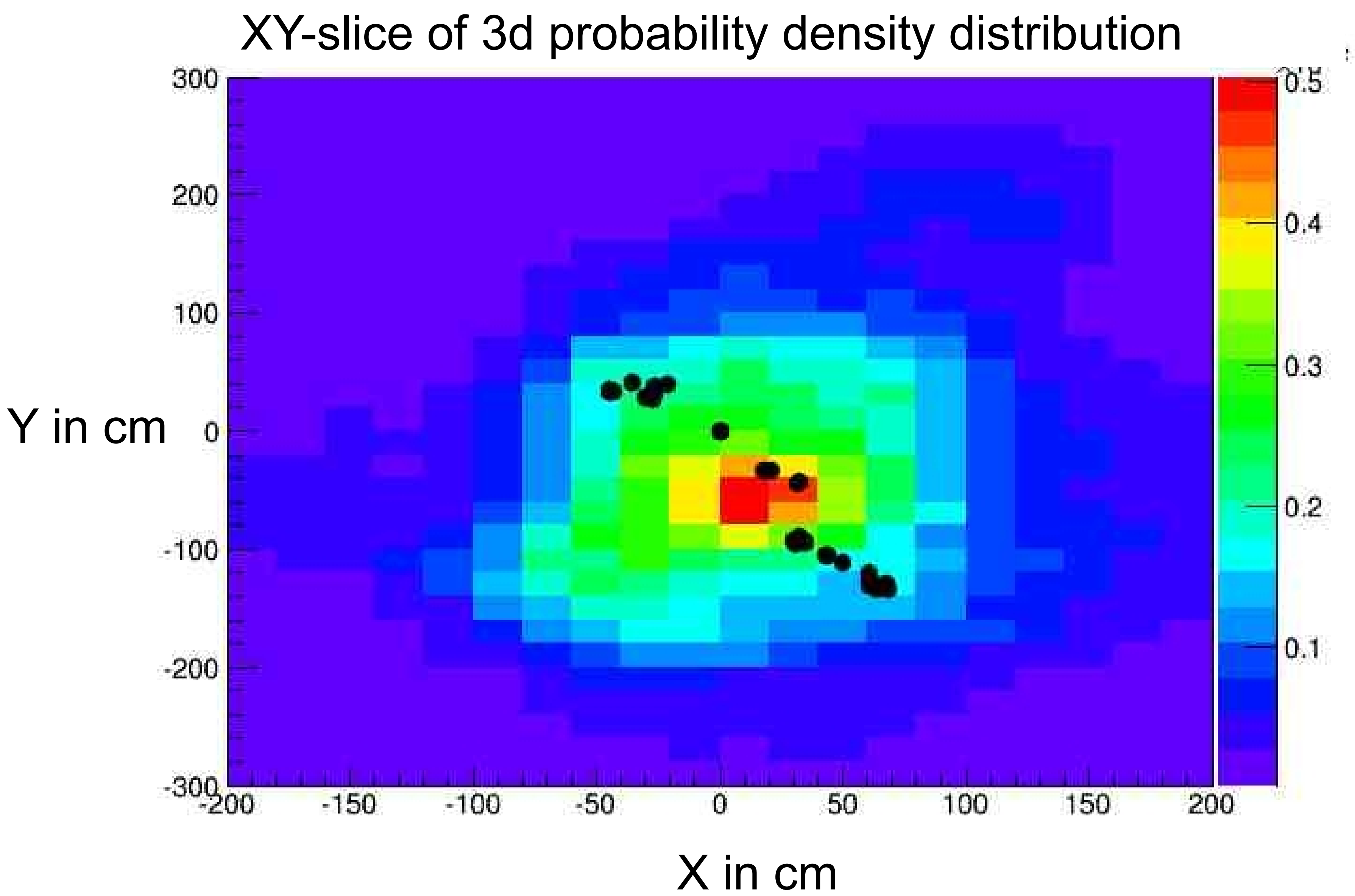
X in cm

# Result 2nd Iteration Slice 237

XY-slice of 3d probability density distribution



# Result 2nd Iteration Slice 236

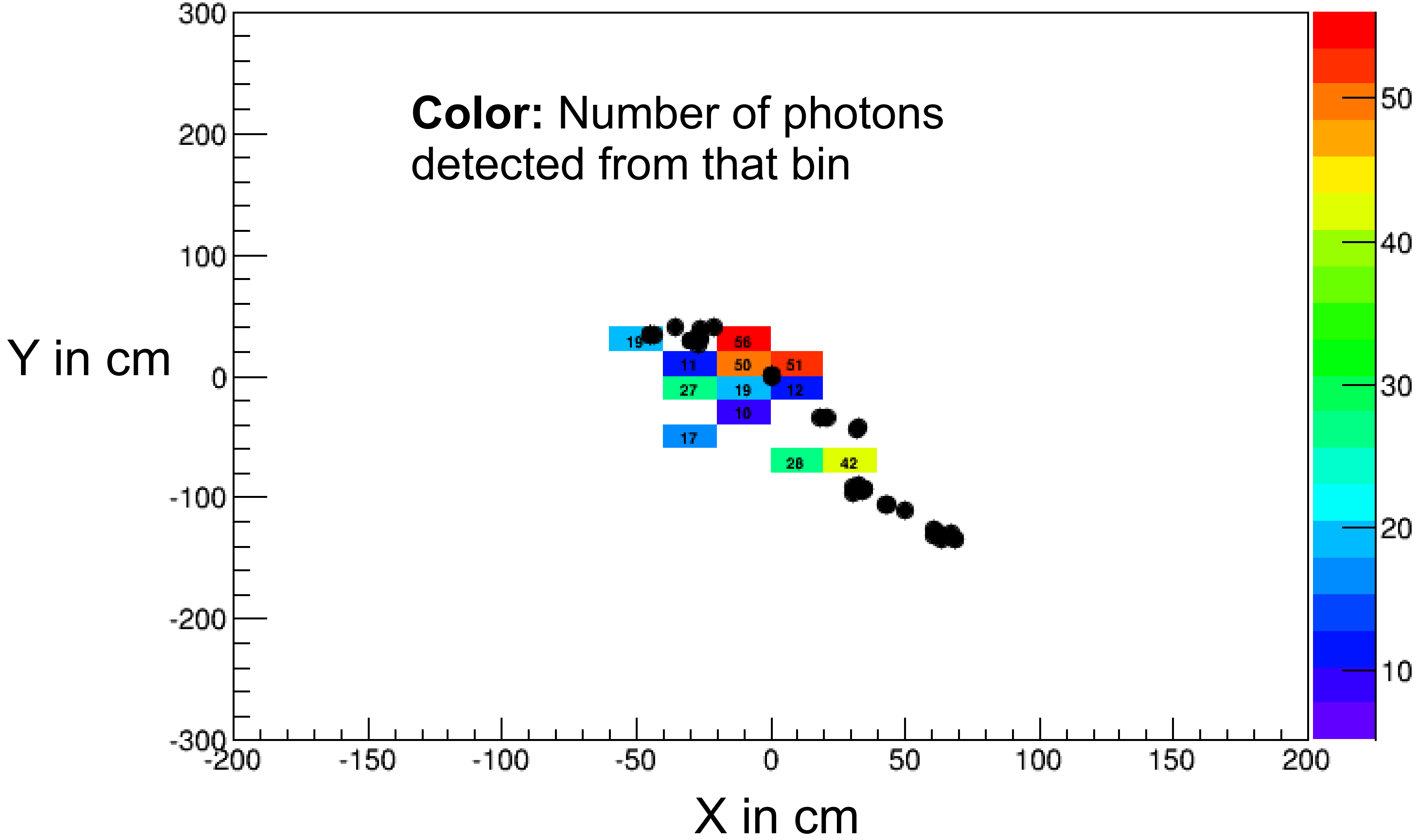


# Crystalisation of the Result

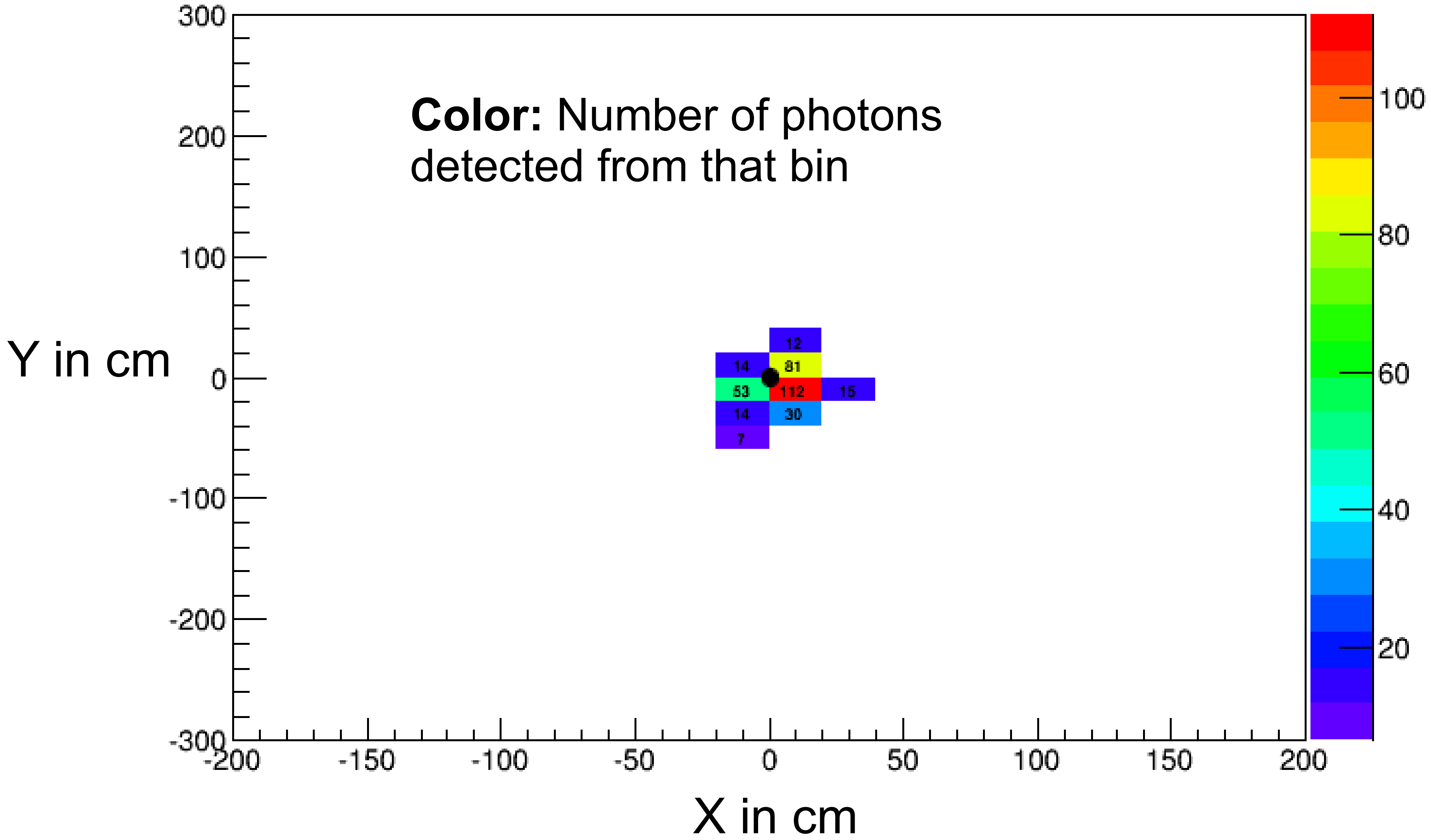
- Use well defined probability mask
- Do reconstruction for each photon
- Identify bin with highest probability
- Associate photon with this bin

  → number of photons from that bin

# Crystalisation: 1 MeV Positron

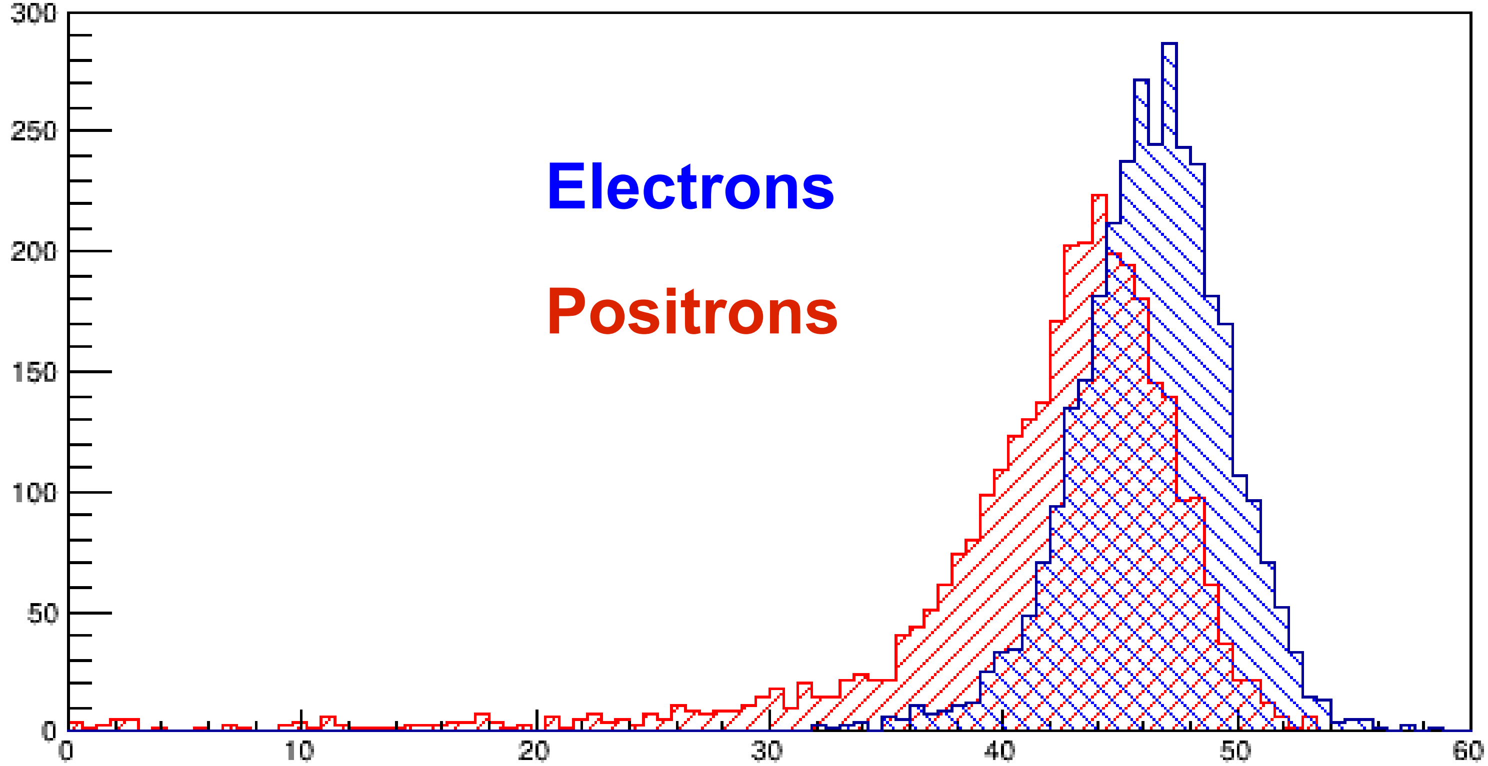


# Crystalisation: 2 MeV Electron



# Electron vs. Positron Discrimination: First Try Results I

Ratio R of light reconstructed near vertex vs. total light

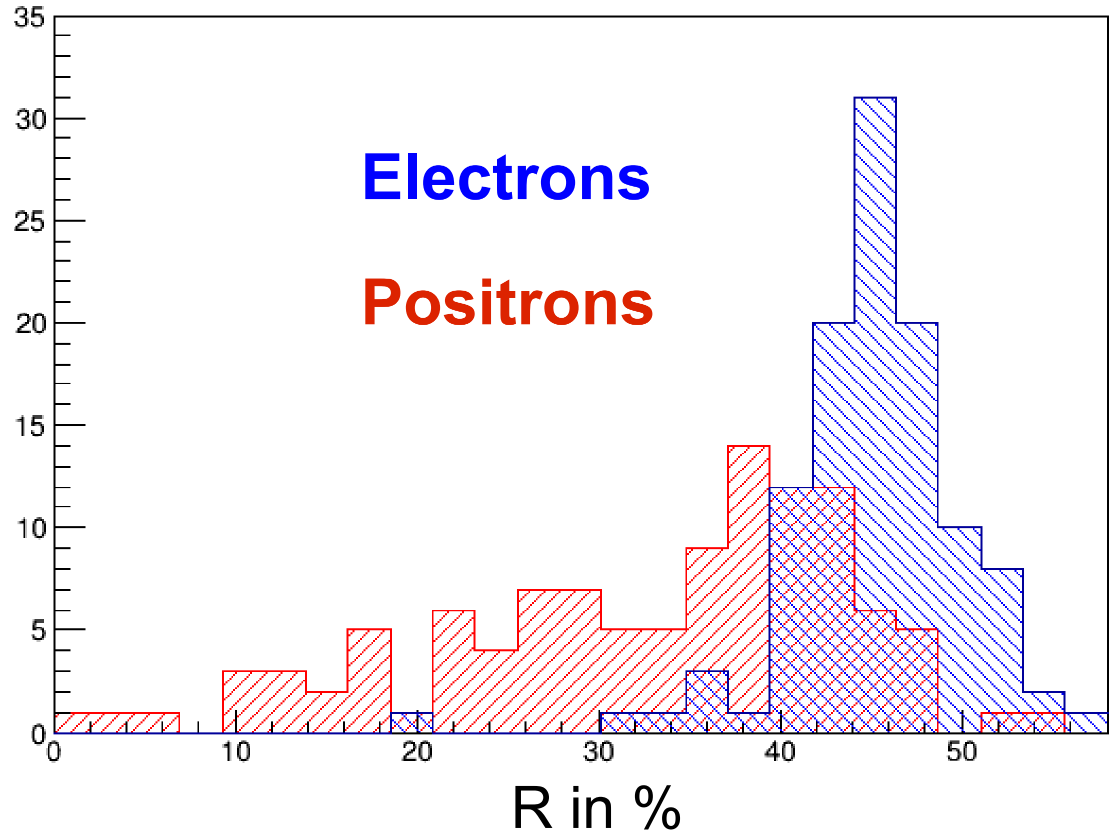



R in %

- 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

# 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

# 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)

# Remarks on Potential

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

- **Other ideas:**
  - Gradient information (Sobel-Filter)
  - Time variation

# Other Possible Applications

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

**Influence on non-stochastic term of energy resolution**

- **IBD directional information** — **Supernova neutrinos**
- **Charge of stopping muons** — **Atmospheric neutrinos**

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

**$\gamma$-cacade vs. point-like**

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

# Conclusion

- **Positron-Discrimination:**
  - Promising first results
  - Separation seems possible at low energies
- **Tracking at low energies:**
  - Topological dE/dx will be challenging
  - Wide range of possible applications

Backup Slides

# My Basic Idea

**Assumption:**

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

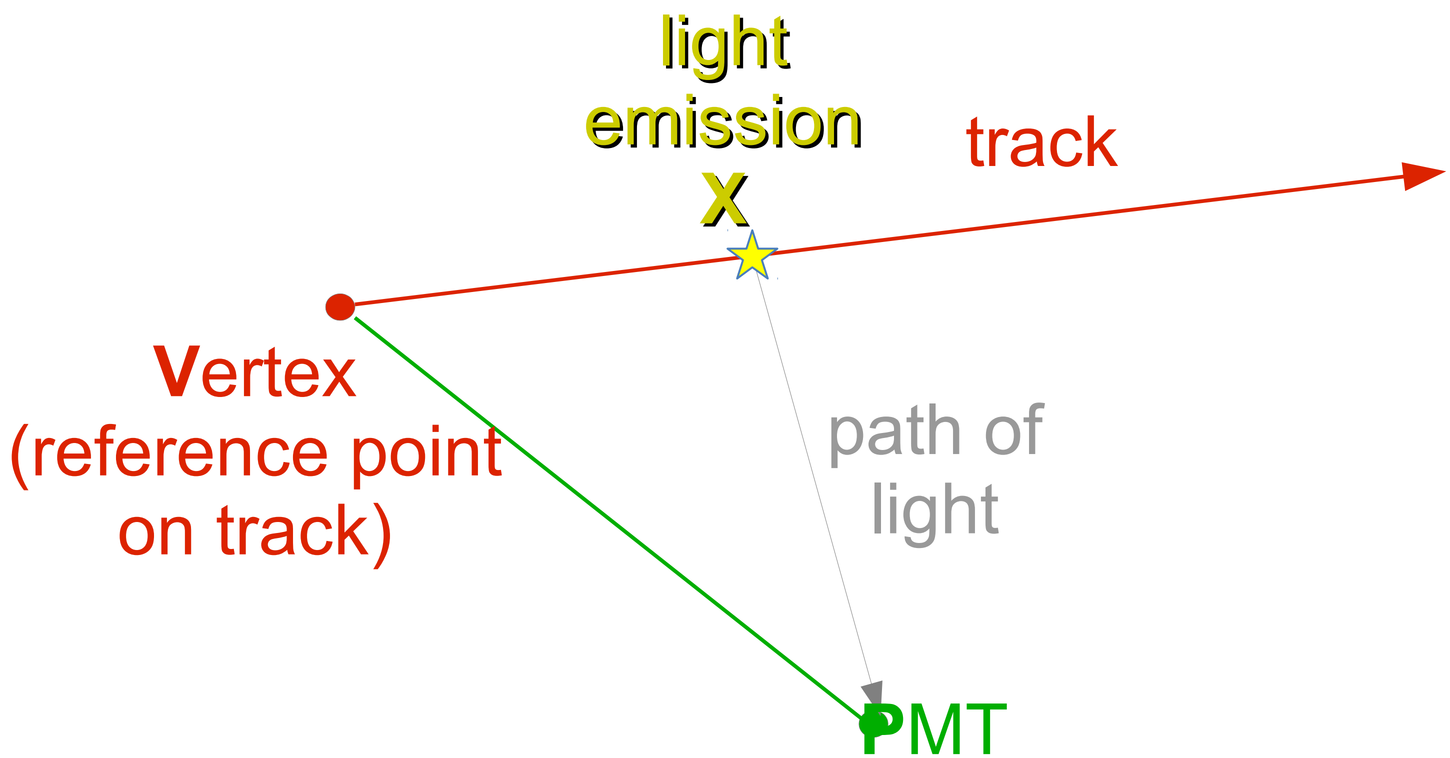
**Concept:**

- Take this point as reference for all signal times

# The Drop-like Shape

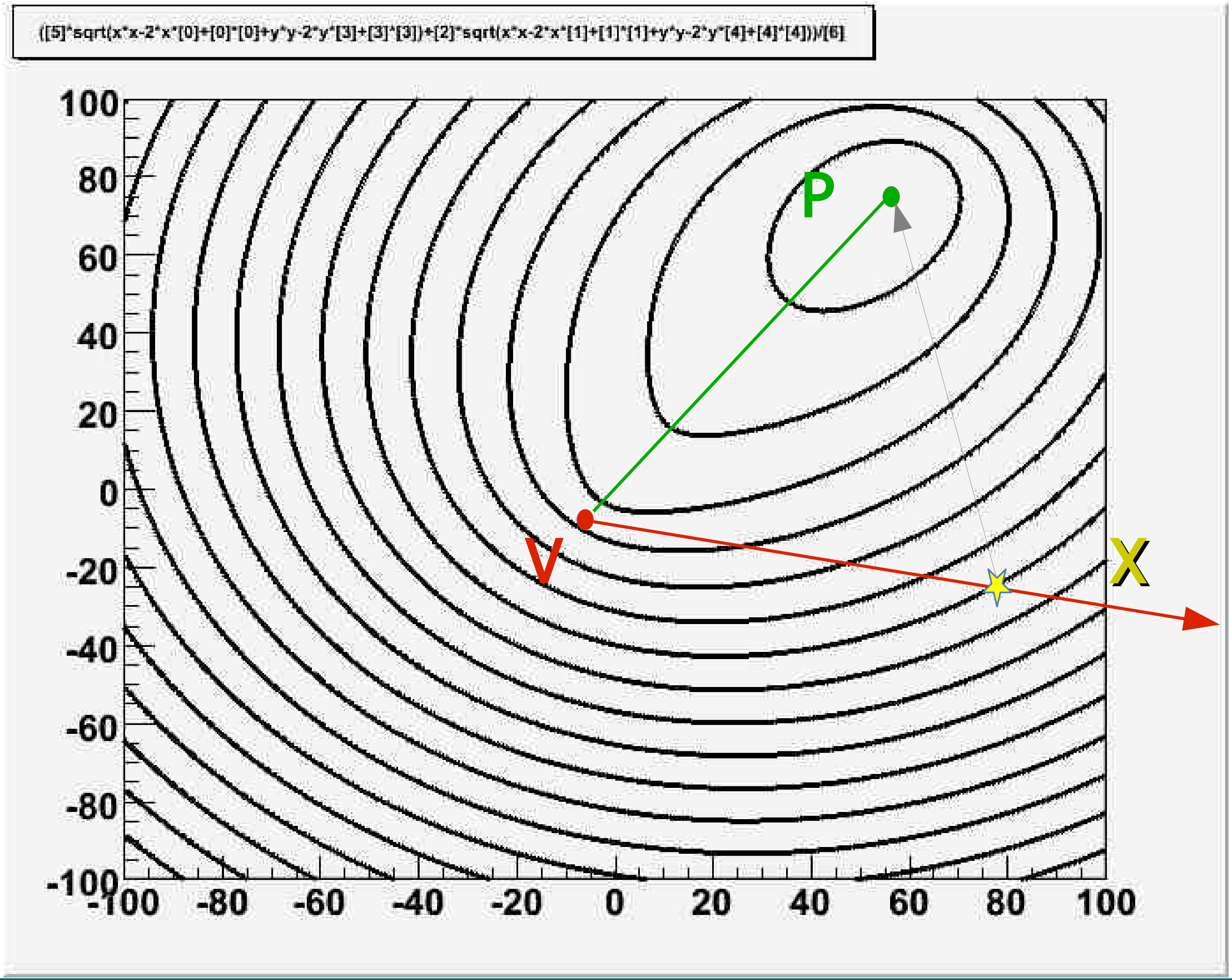
**Signal time = particle tof + photon tof**

**→ ct = |VX| + n*|XP|**



# The Drop-like Shape

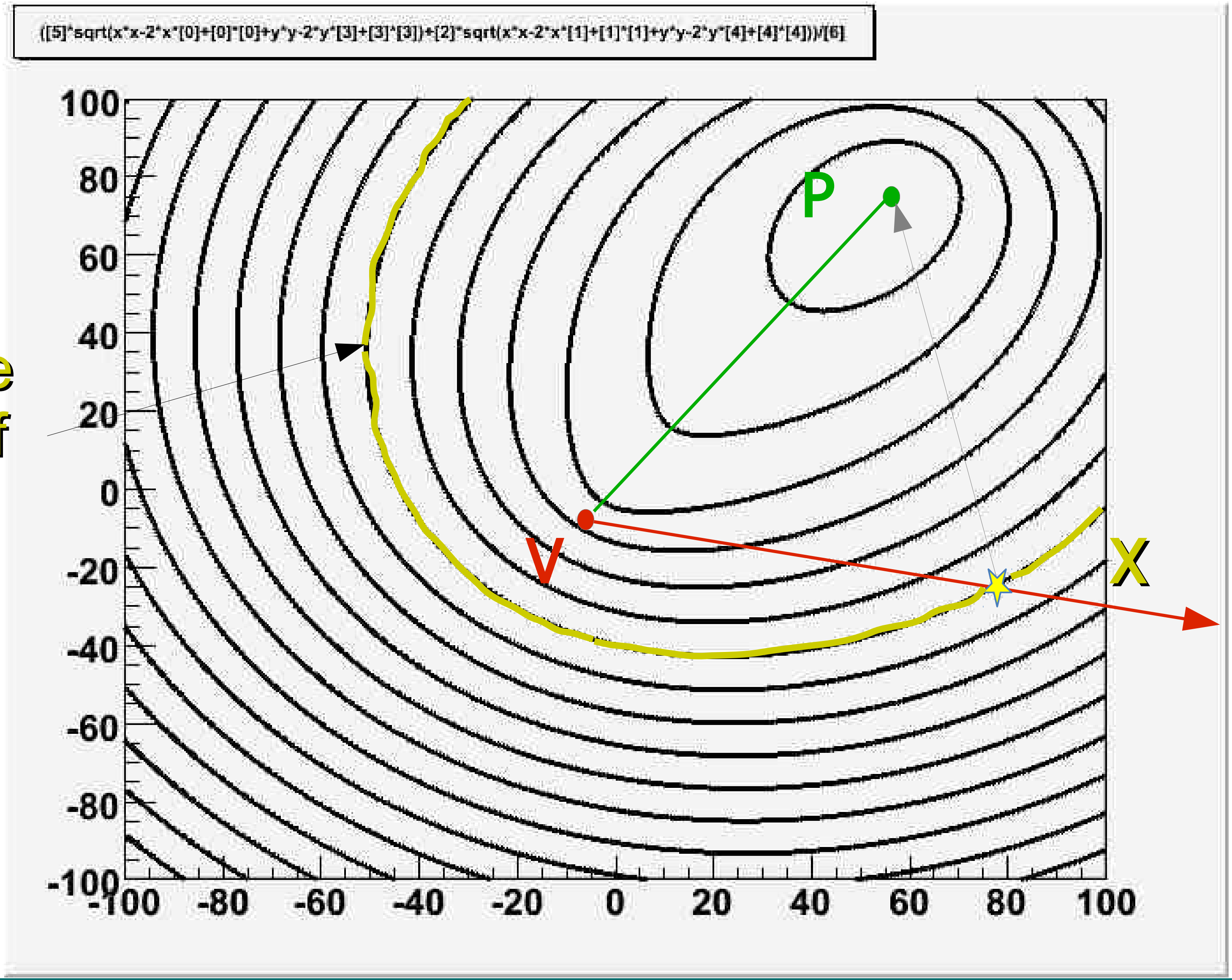
## ct = |VX| + n*|XP| → drop-like form



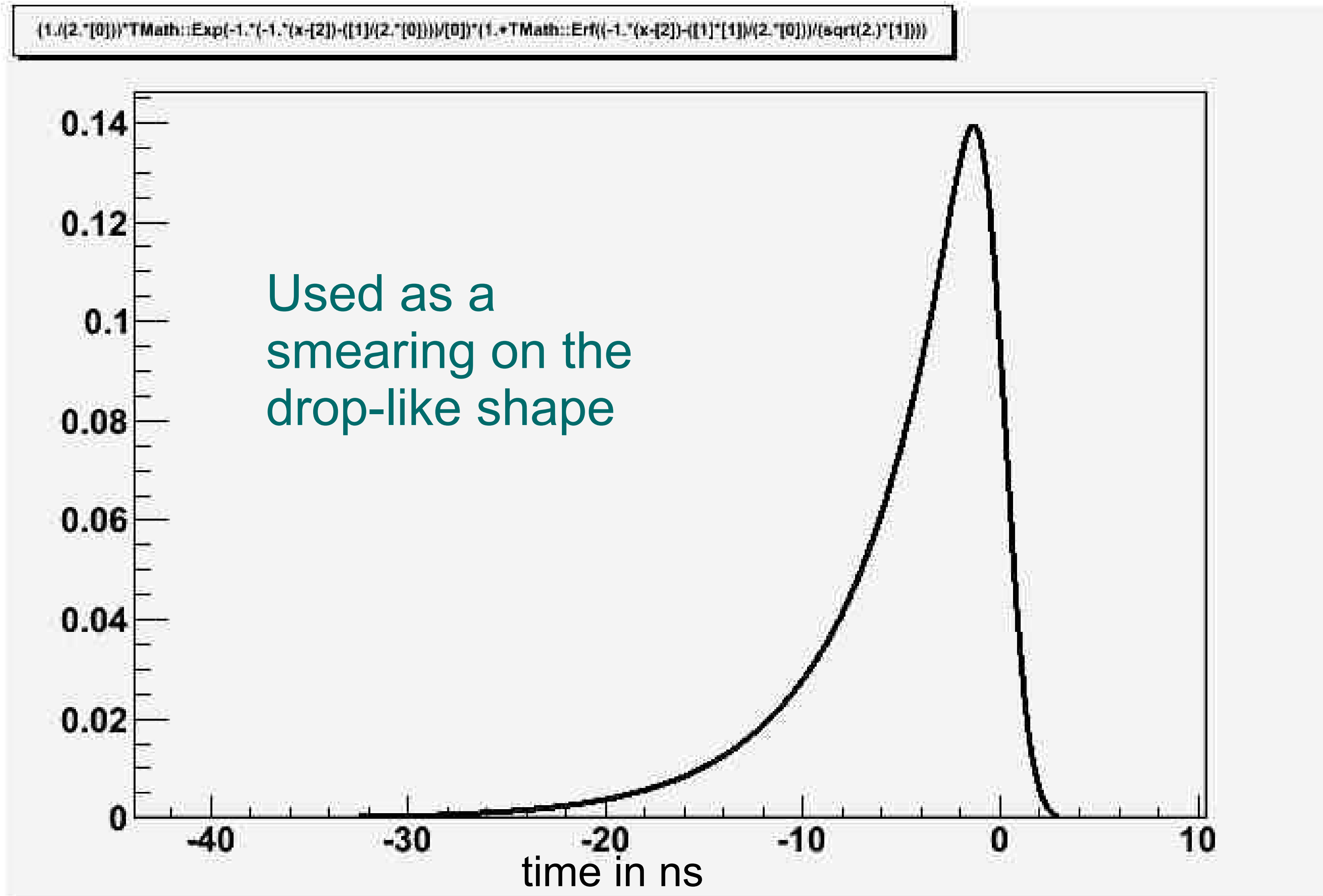
# The Drop-like Shape

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

Possible origin of light

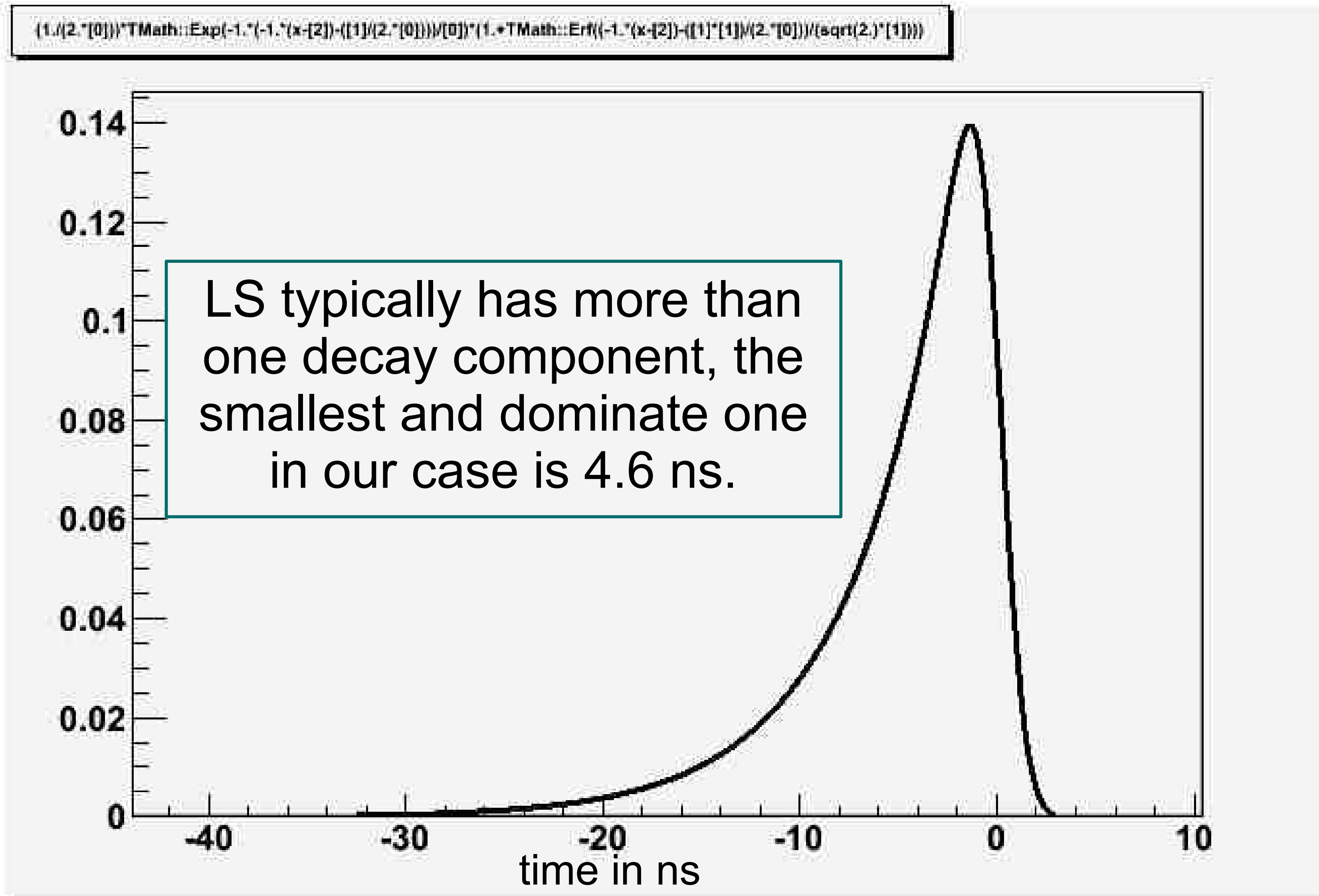


# Time Distribution



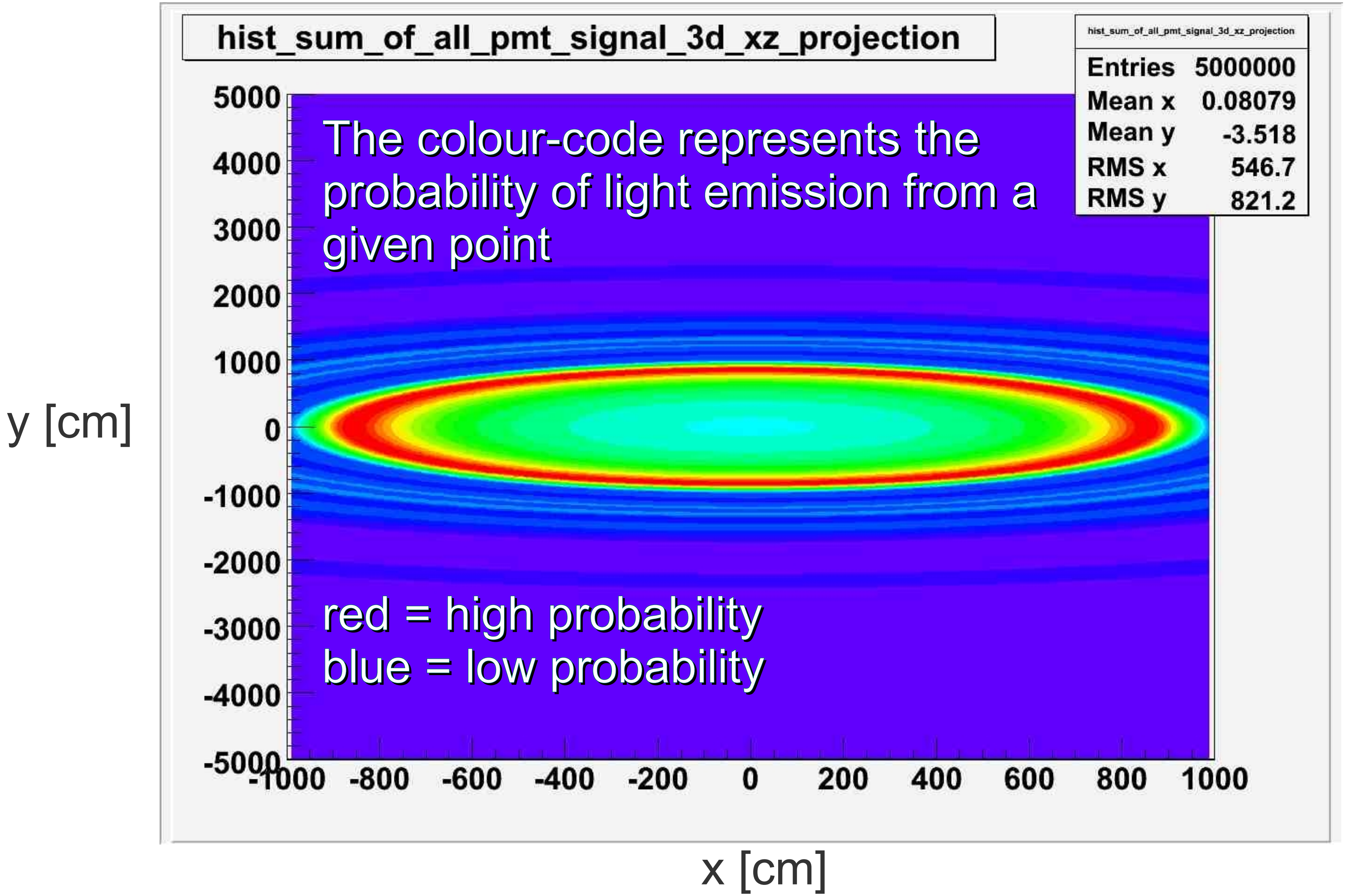

Convolution of Gaus and Exponential-Function

# Time Distribution

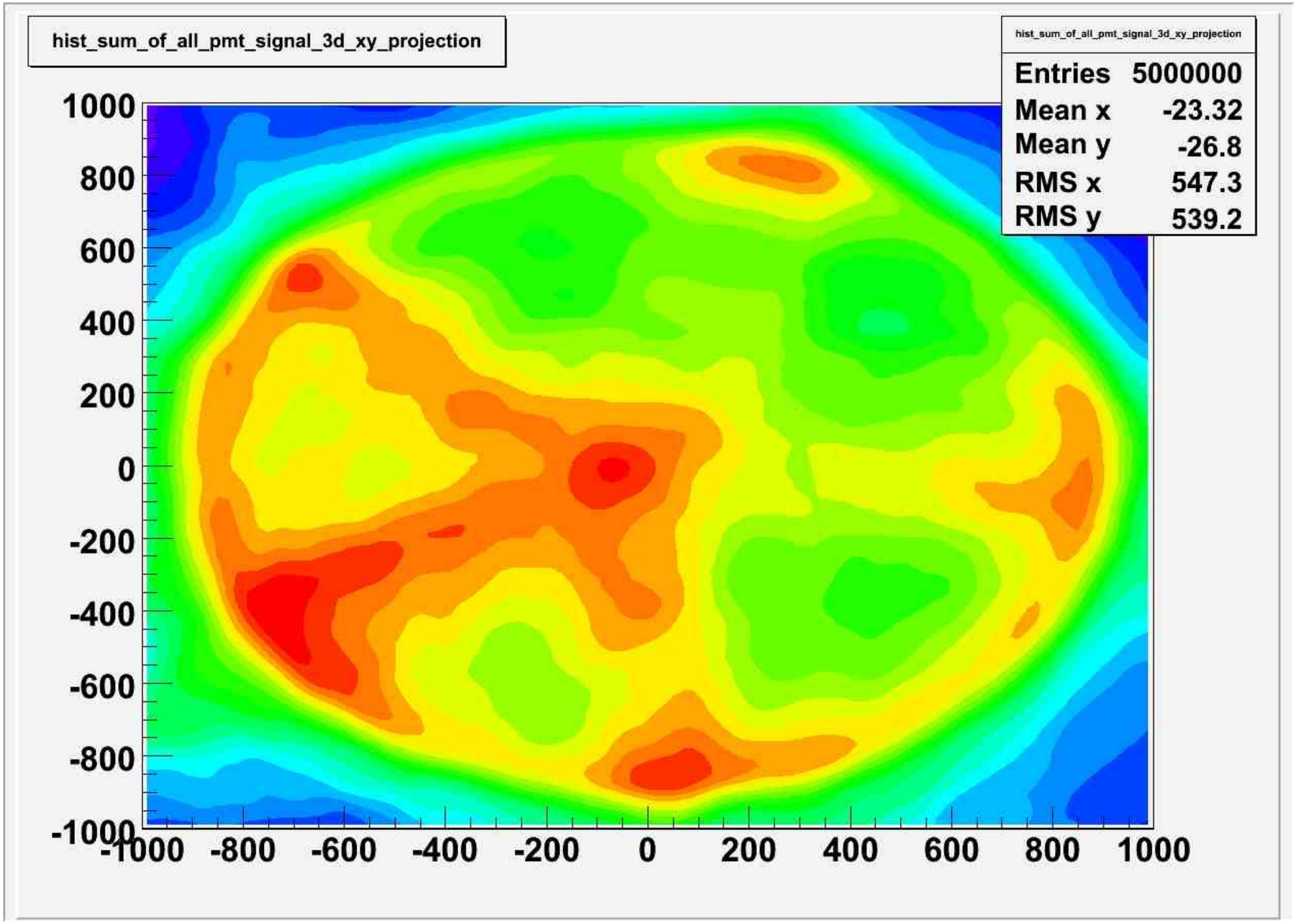



Convolution of Gaus and Exponential-Function

# Result 1 PMT


hist_sum_of_all_pmt_signal_3d_xz_projection
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]
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-1000
-800
-600
-400
-200
0
200
400
600
800
1000
x [cm]

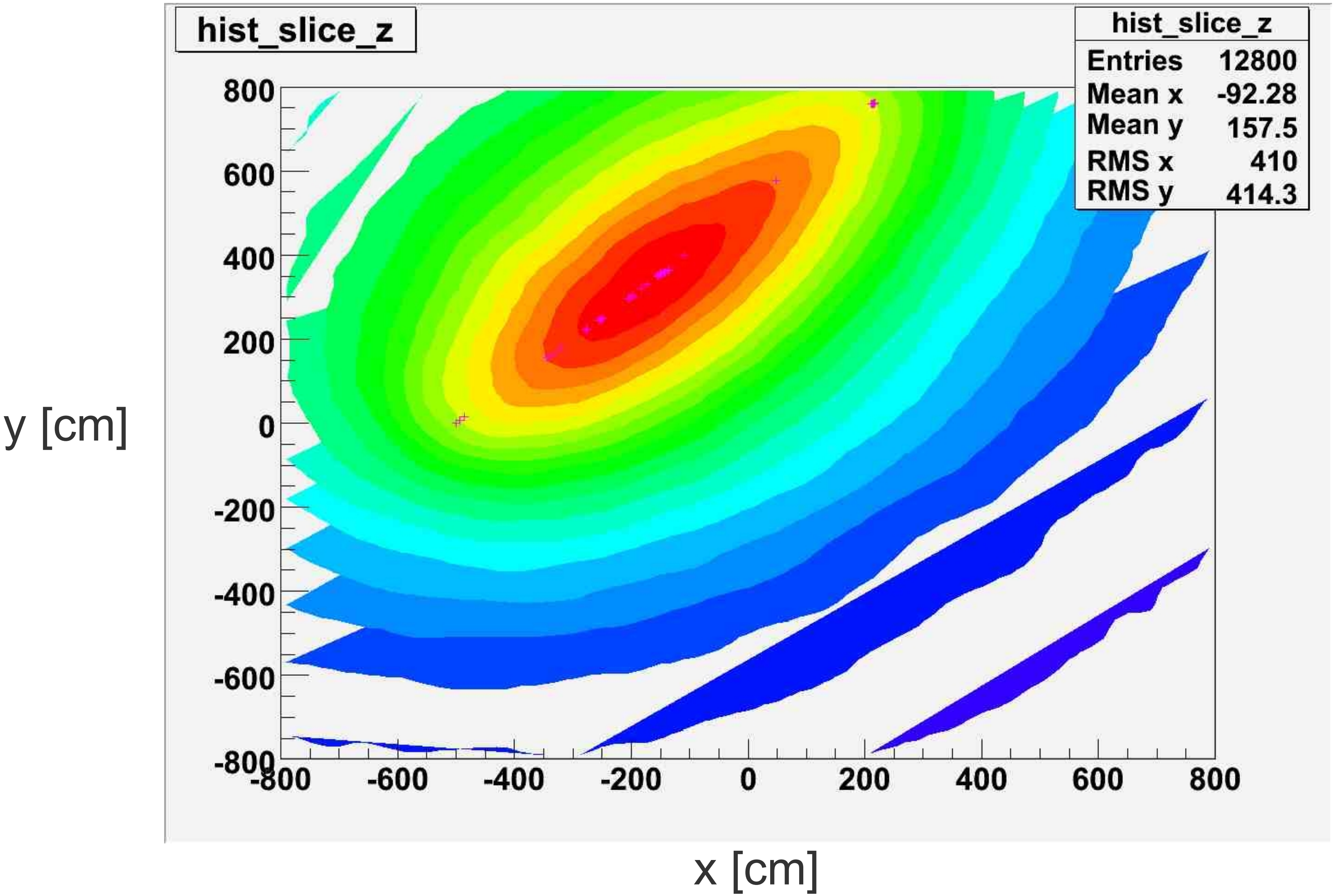
# Result a Few PMTs




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:**

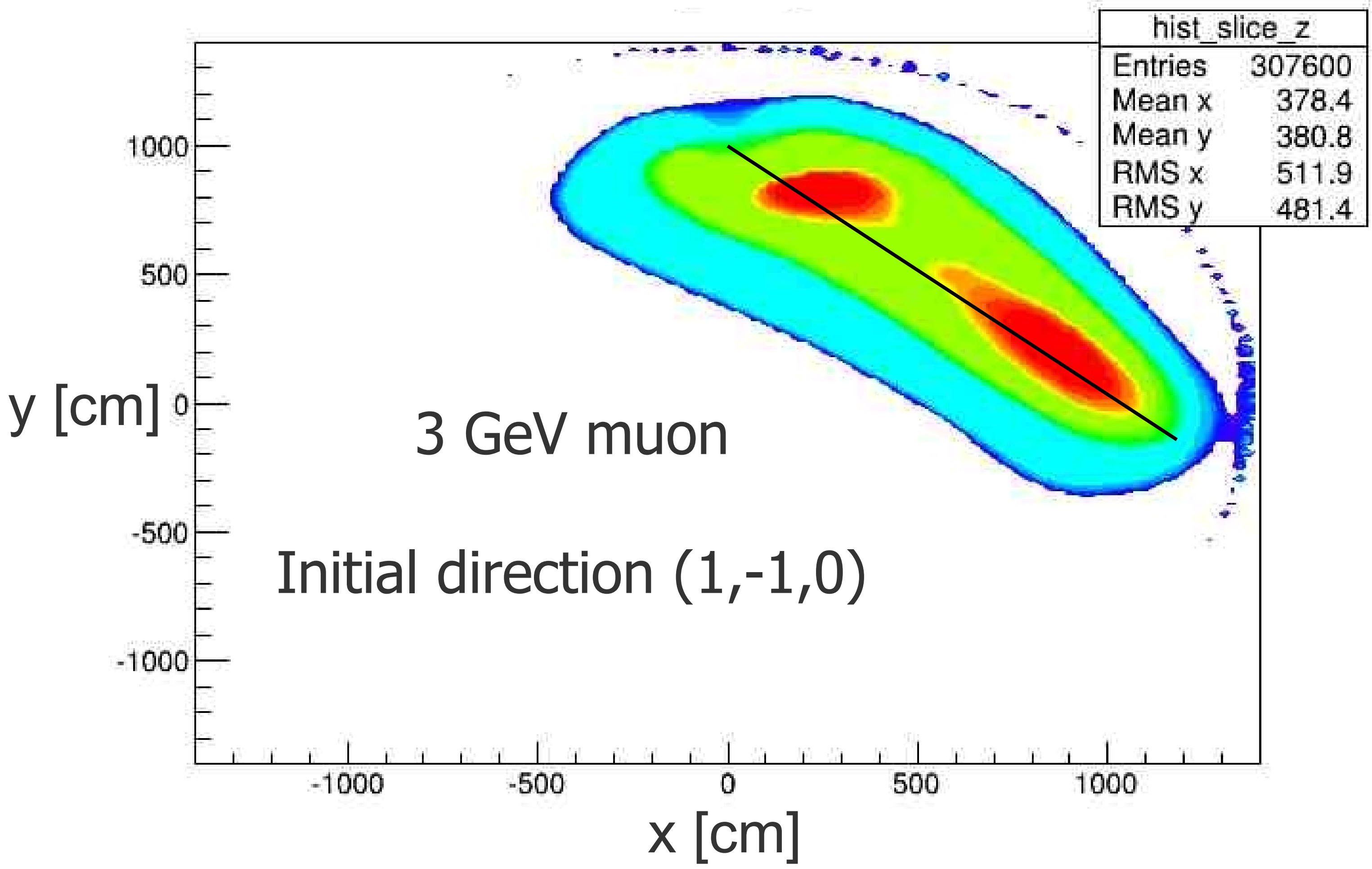
- they are closer
- directly in front of the PMT

**→ Need to consider:**

- solid angle of PMT area
- attenuation
- angular acceptance

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

# Result all PMTs



# Probability Mask

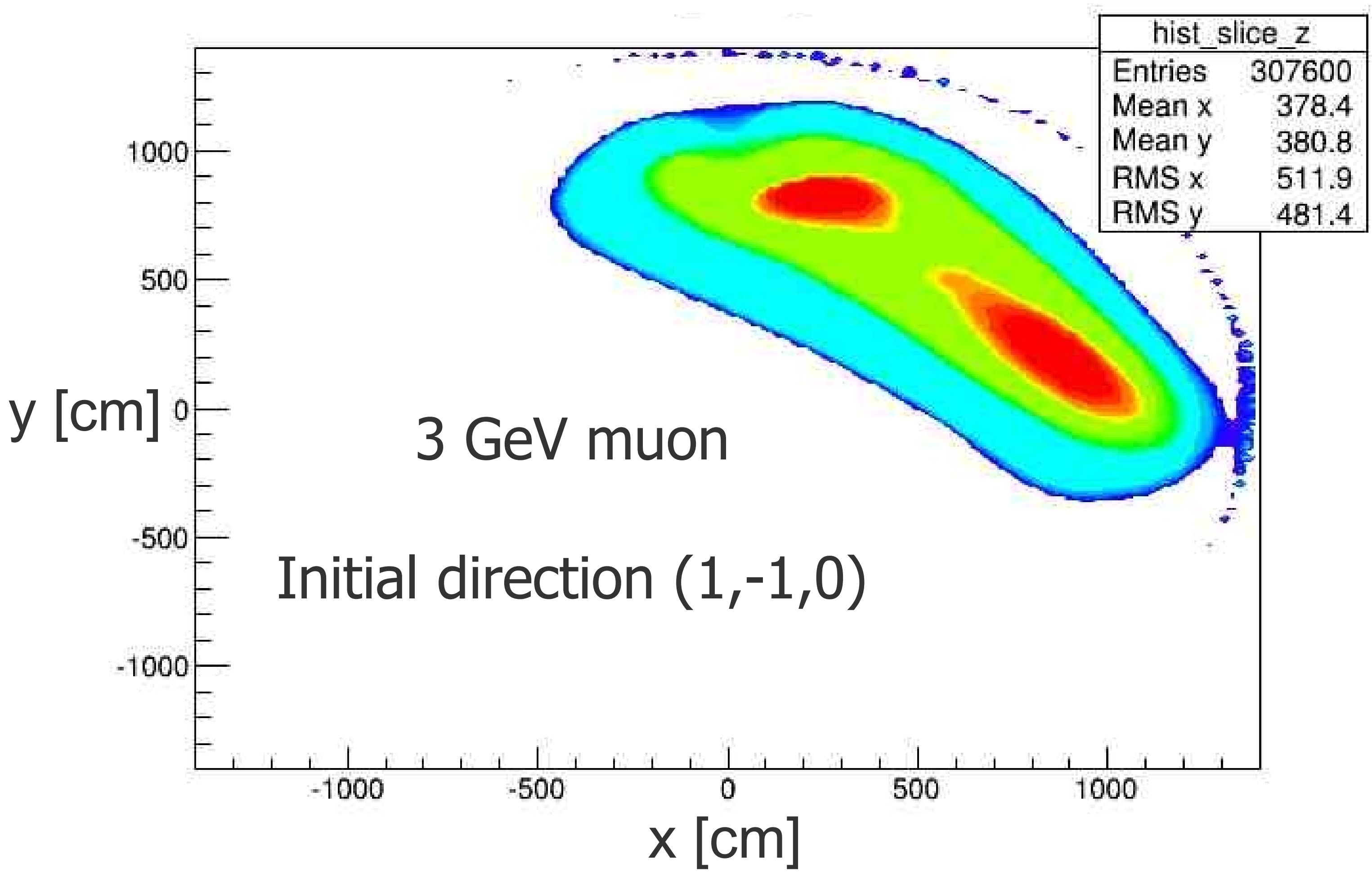
So far probabilities have been added!
→ correct for **independent information**

**However:**

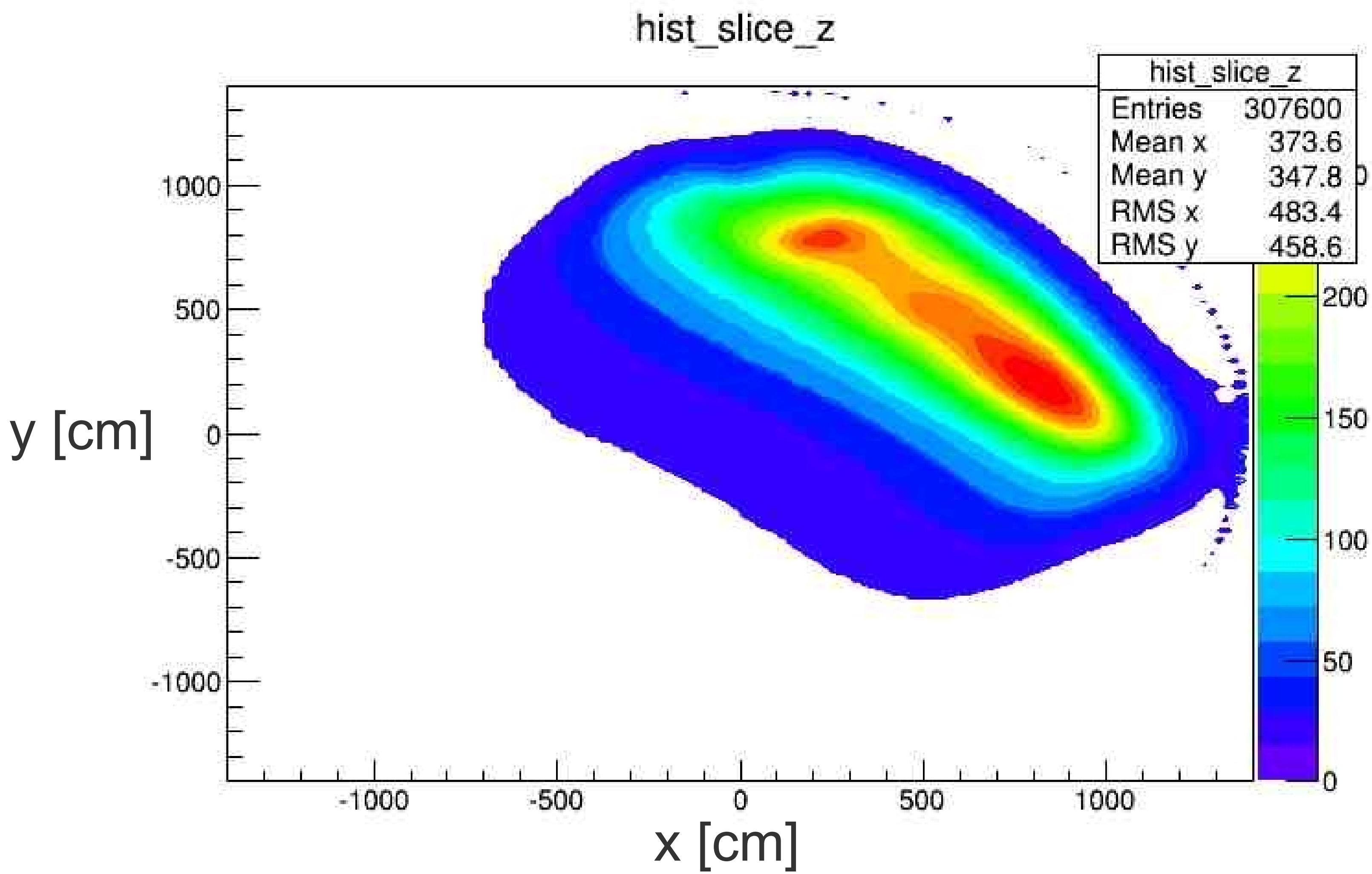
Light signals are **not completely independent** from each other, because they belong to the same track.

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

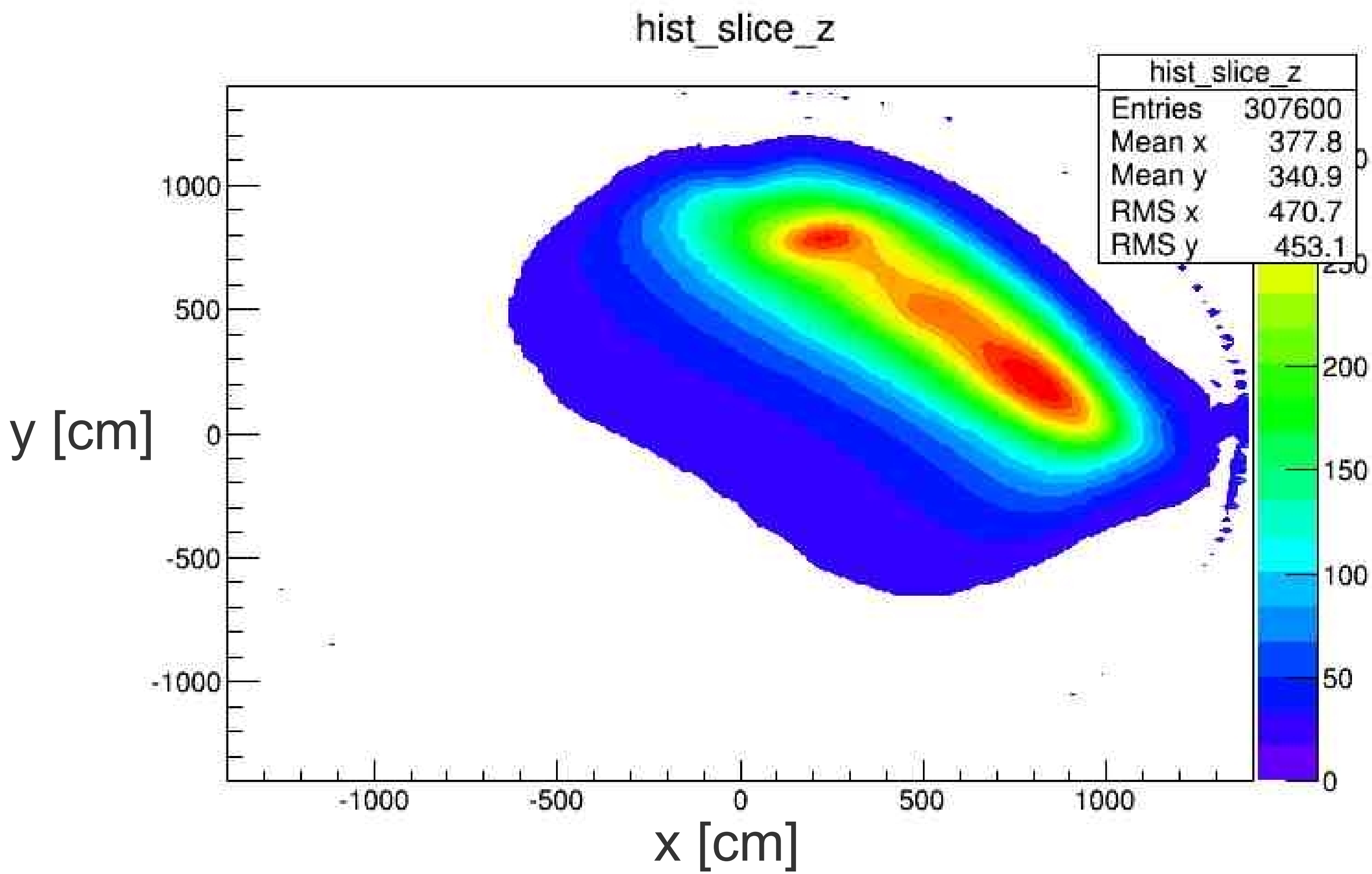
# Result I


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

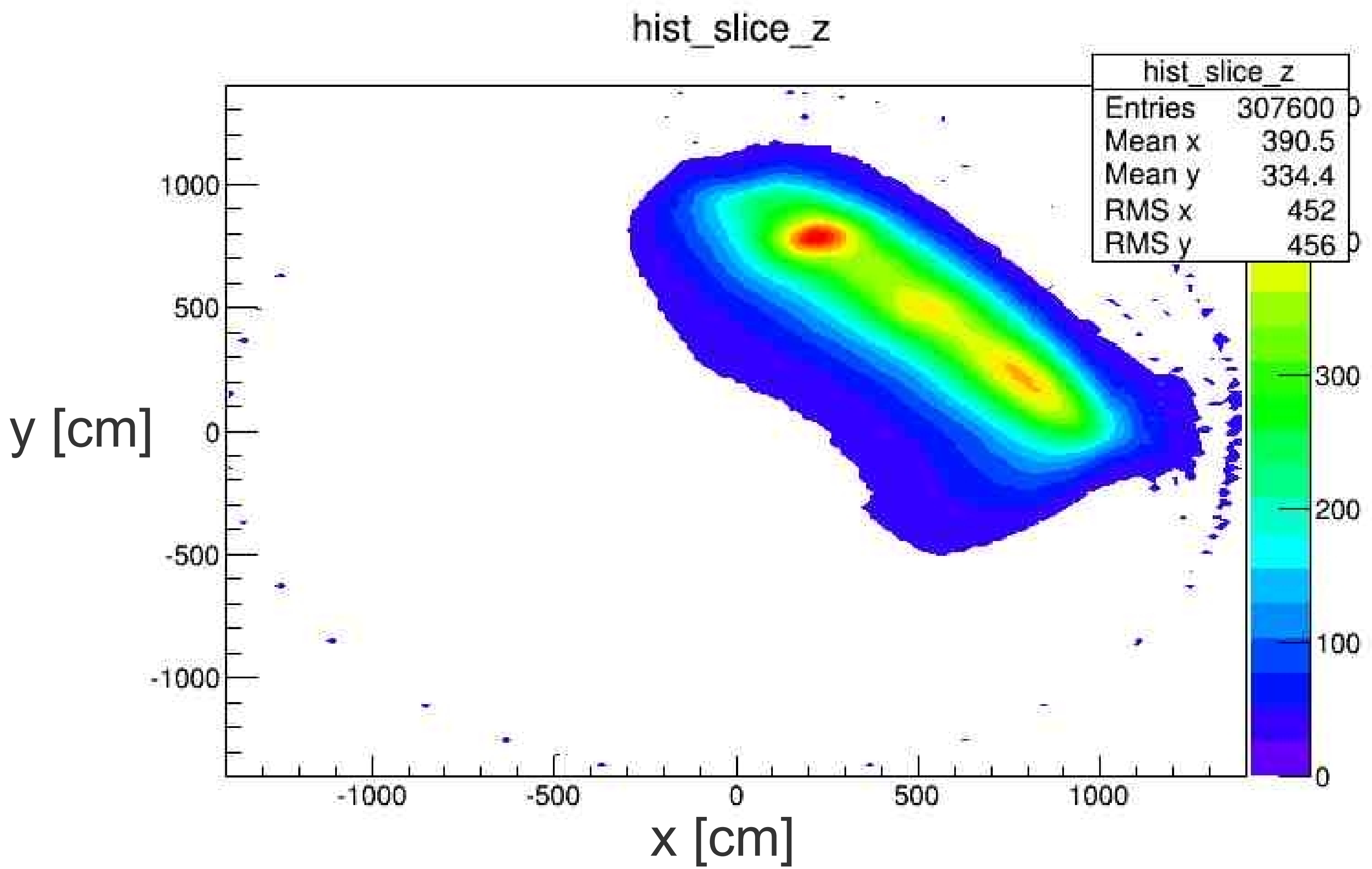
# Result 2nd Iteration



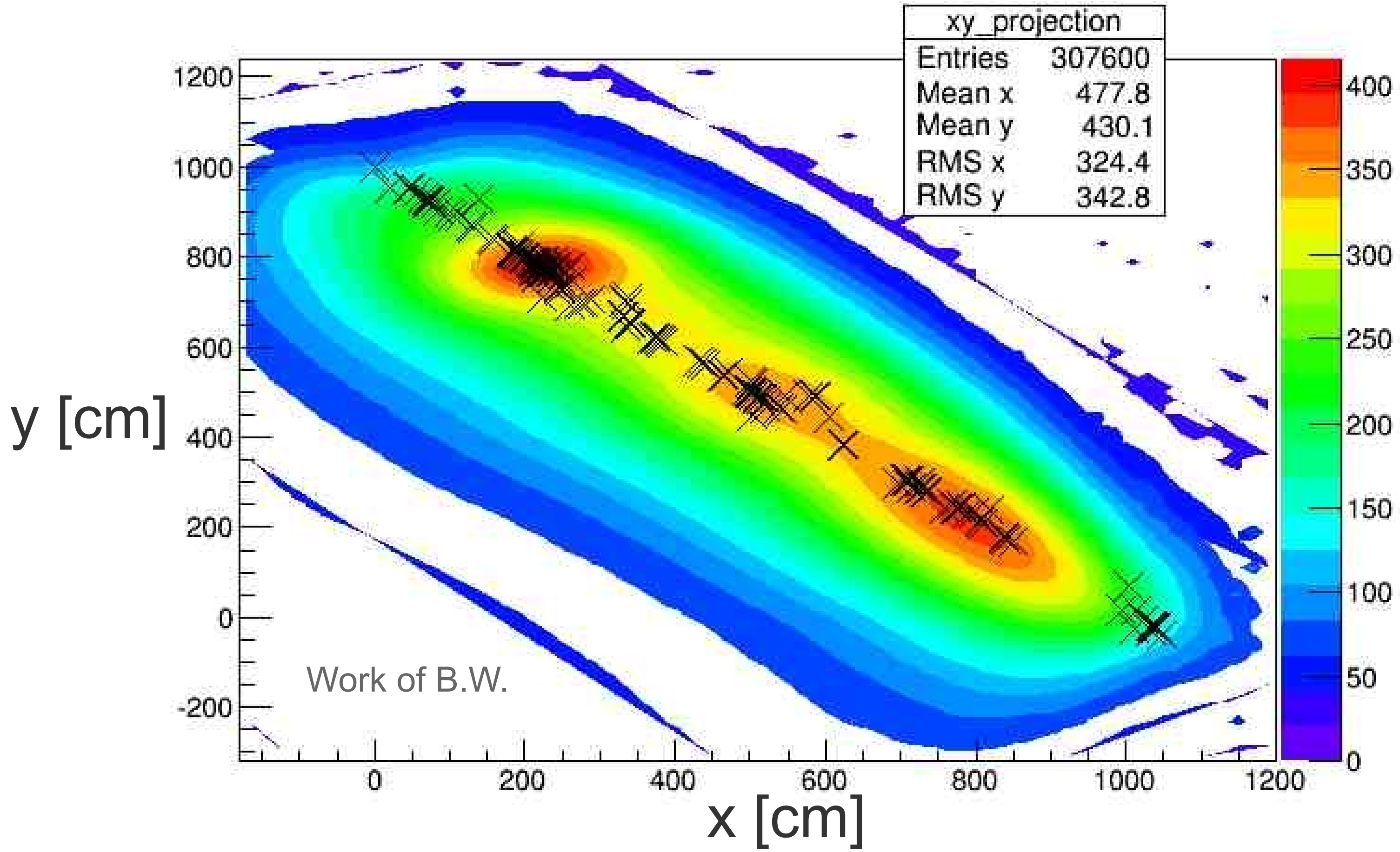
# Result 3rd Iteration



# Result 9th Iteration

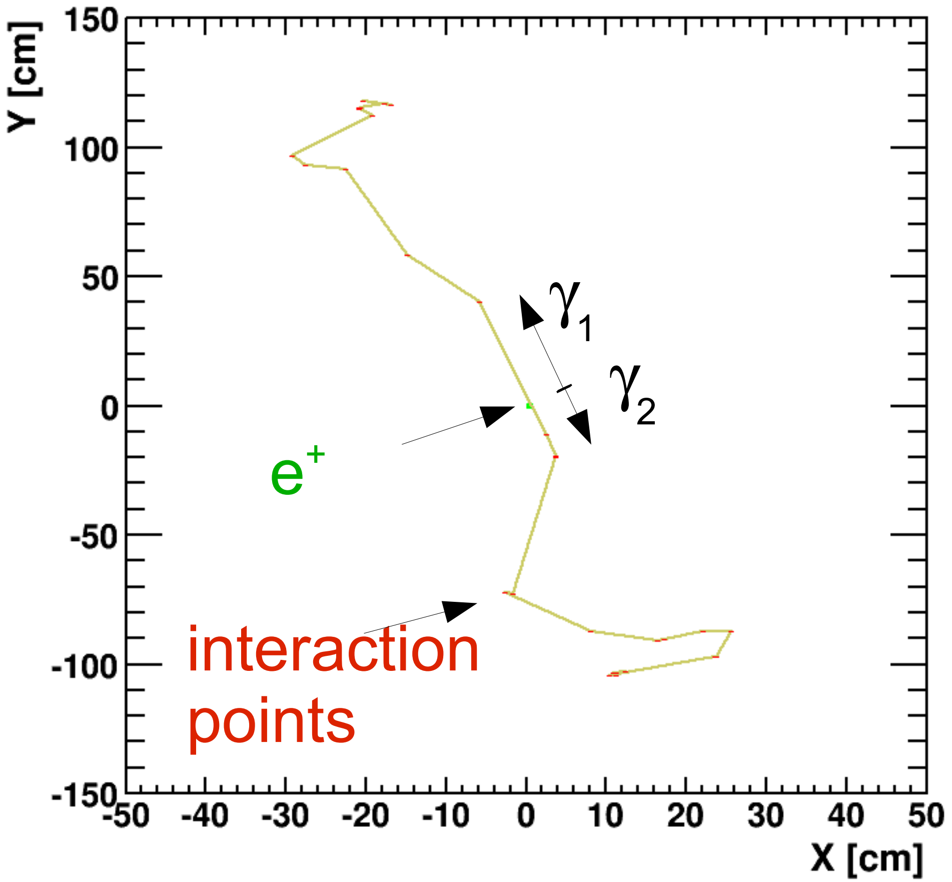


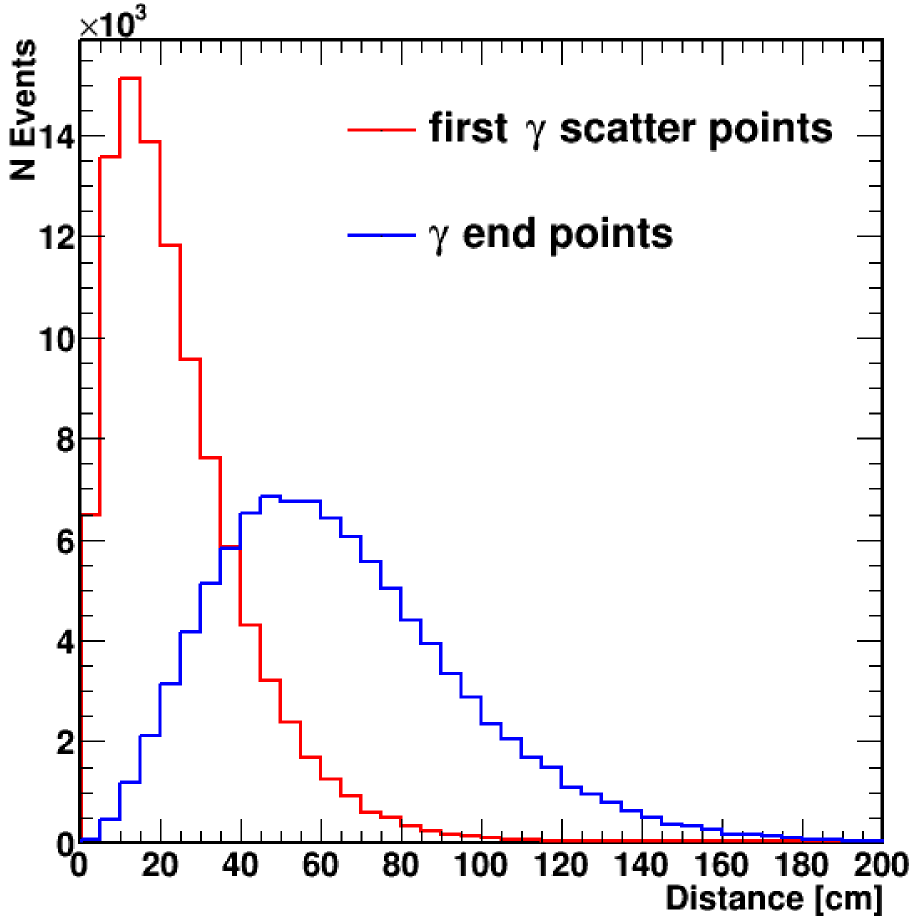
# Result 12th Iteration




Measurement of dE/dx is possible!
→ Full kinematical analysis possible

# Low Energy Reconstruction

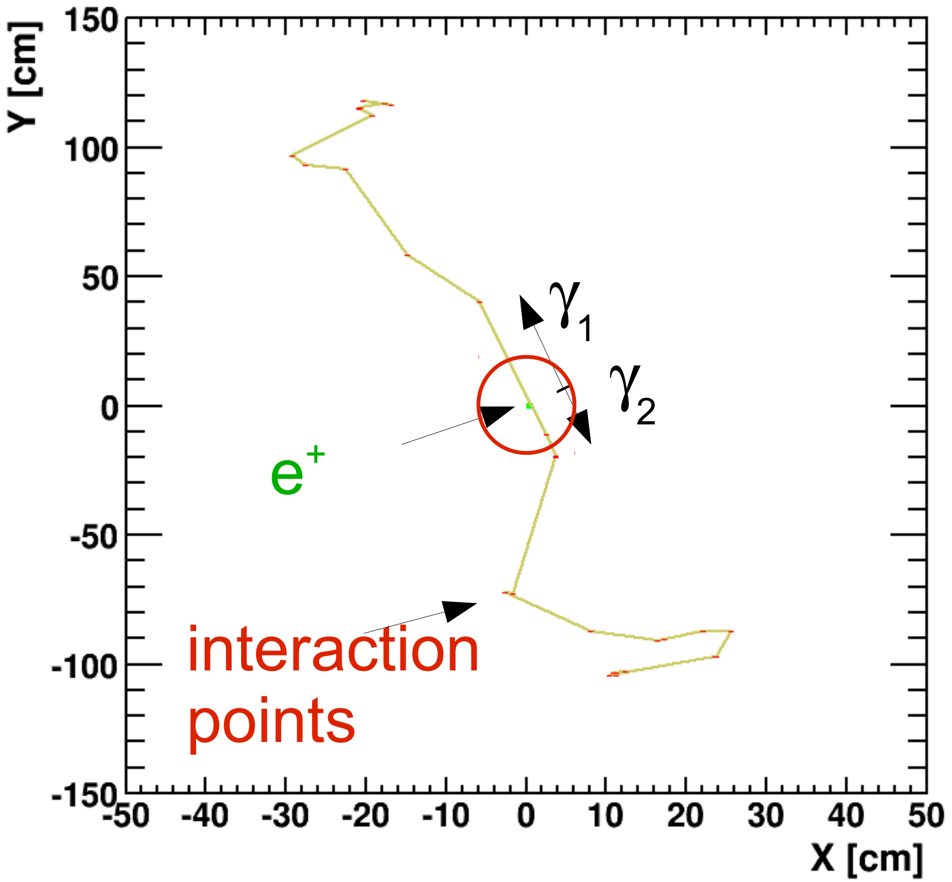


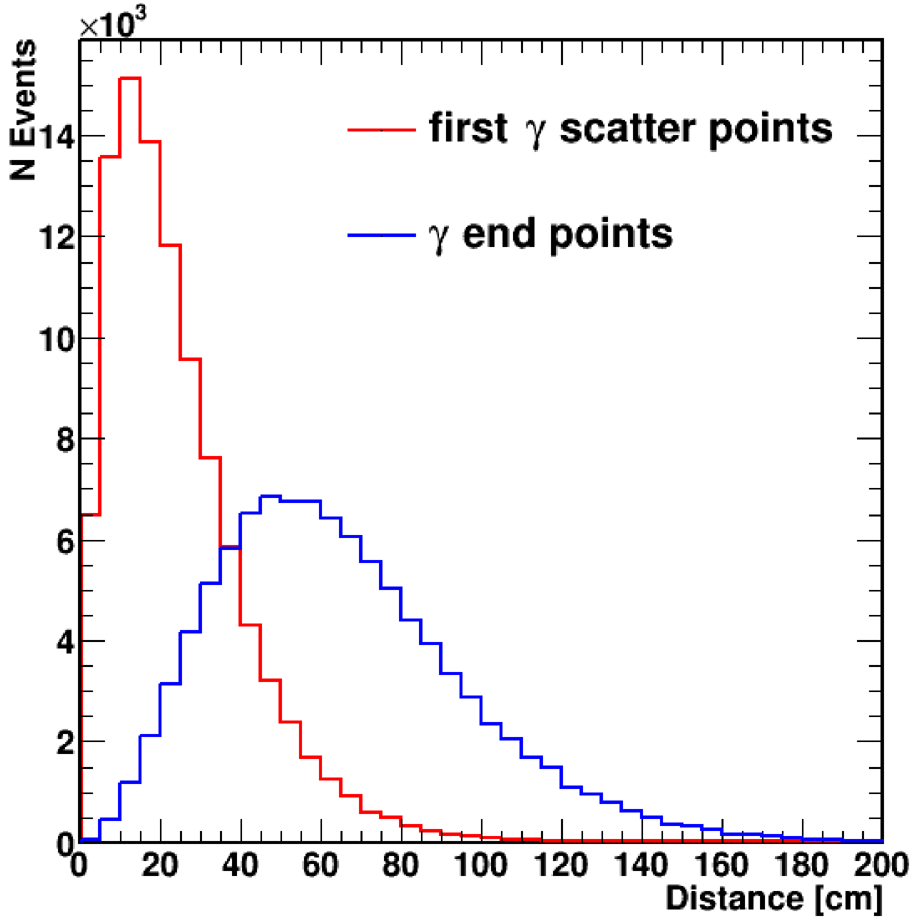




**Plan:** Use my reconstruction to see linear shape of $\gamma$-$e^+$-$\gamma$ !

→ Positron discrimination → background reduction

# Influence on Energy Resolution

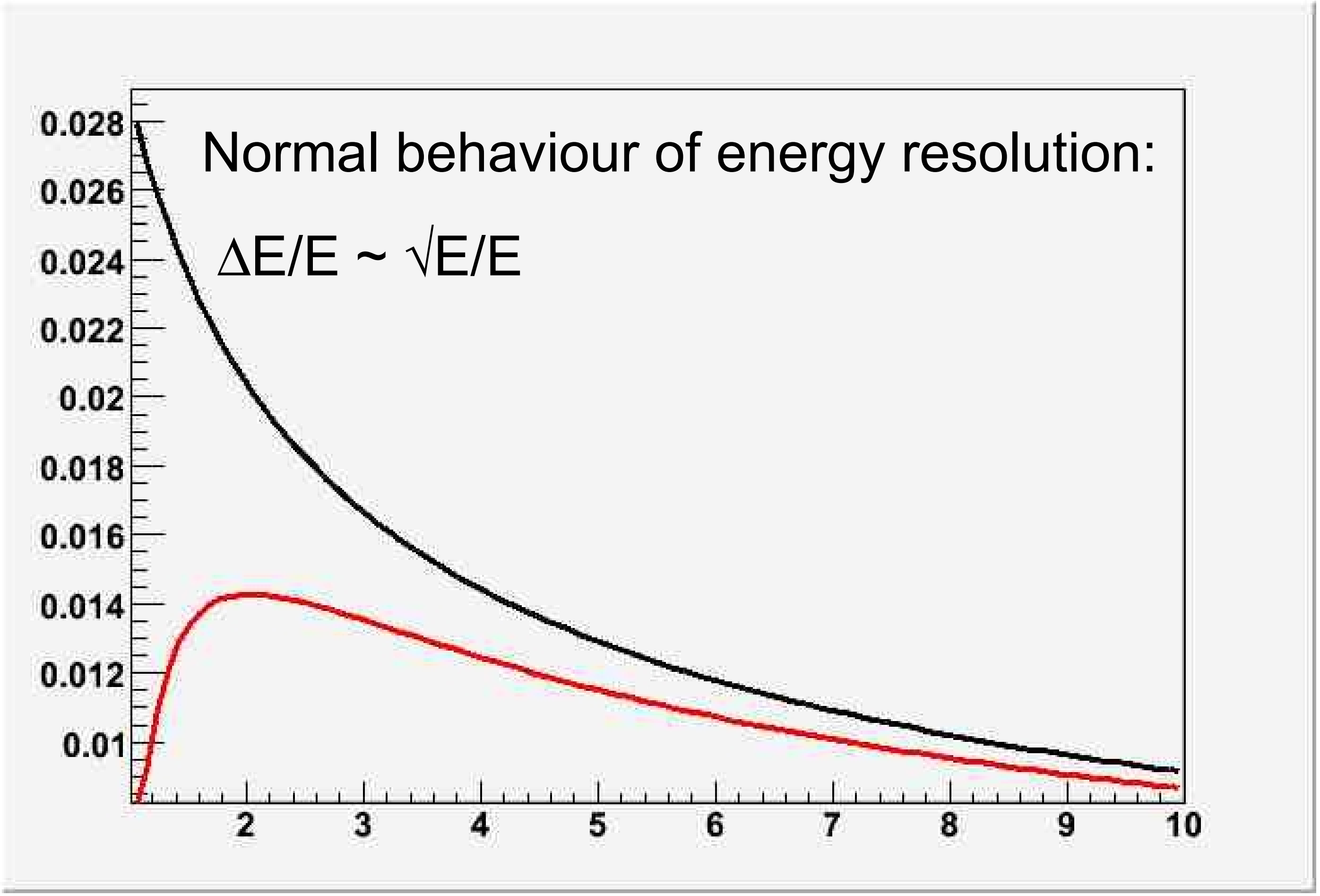



**Plan:**

- only calculate the energy within a circle arround the reconstructed vertex
- Then add 1022 keV to it

# Influence on Energy Resolution



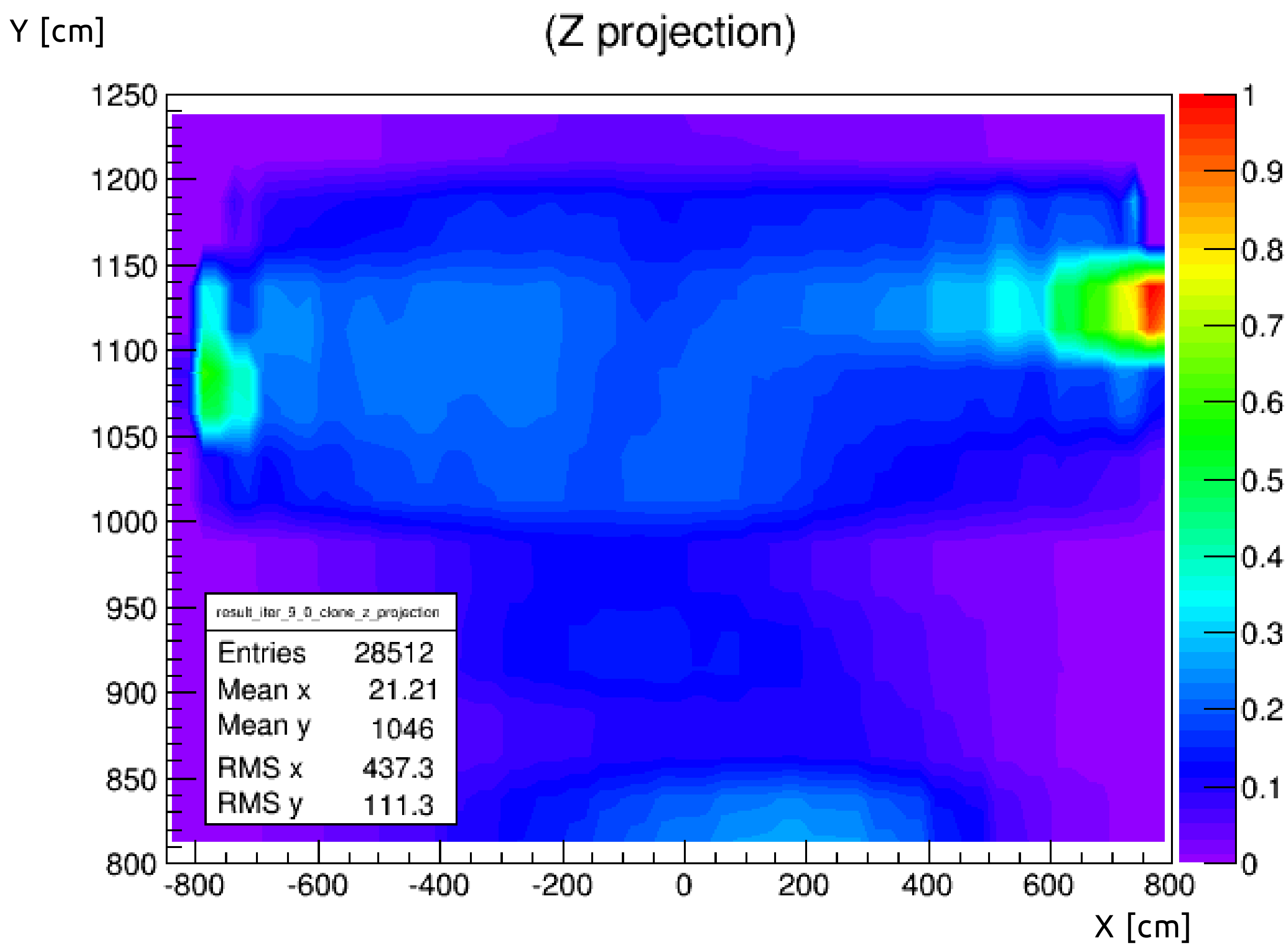

ΔE/E

E in MeV

Theoretical best case for improved energy resolution:

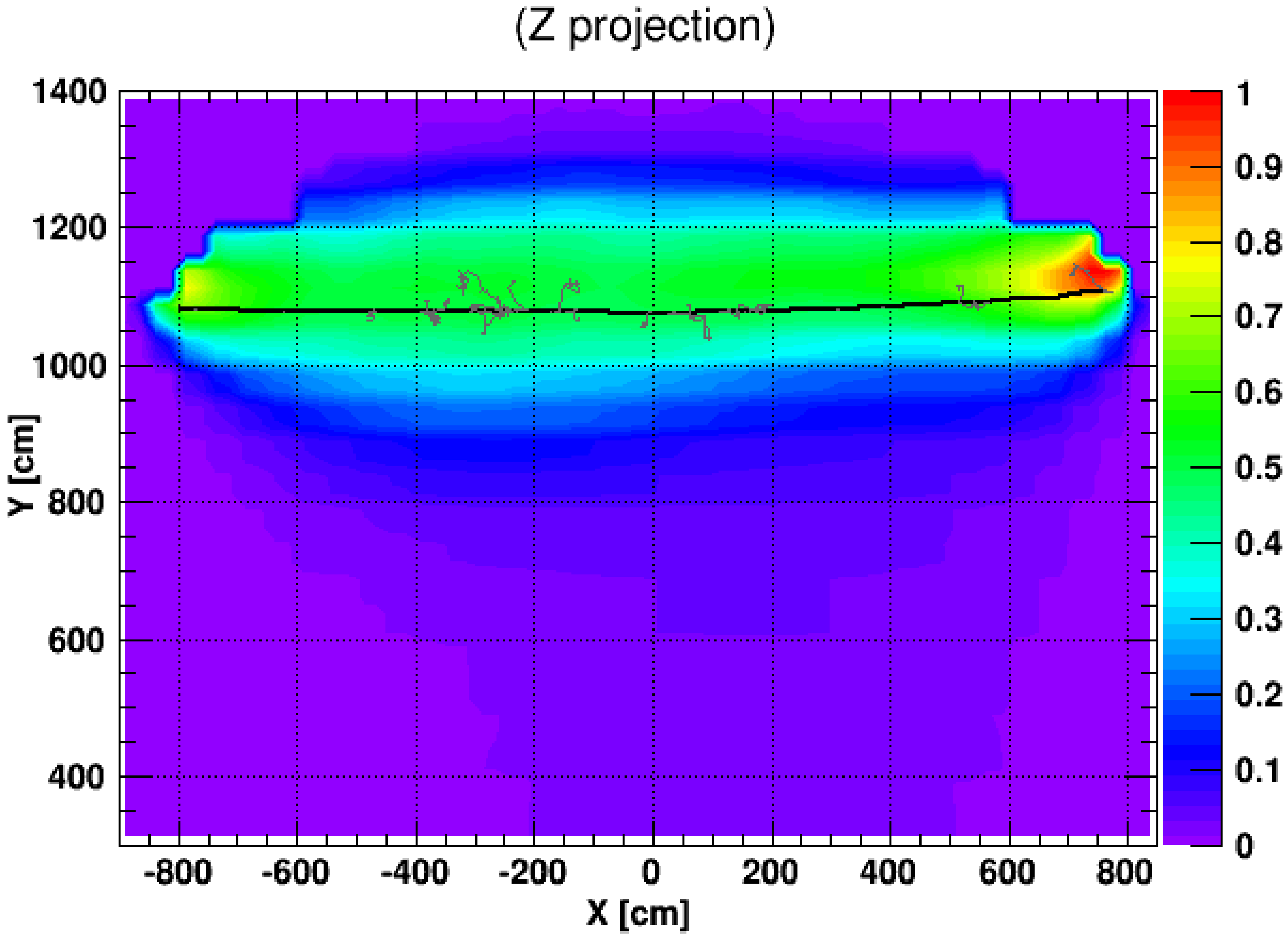
$\Delta E/E \sim \sqrt{(E - 1\,\mathrm{MeV})}/E$

# Edge Event: Bad Result

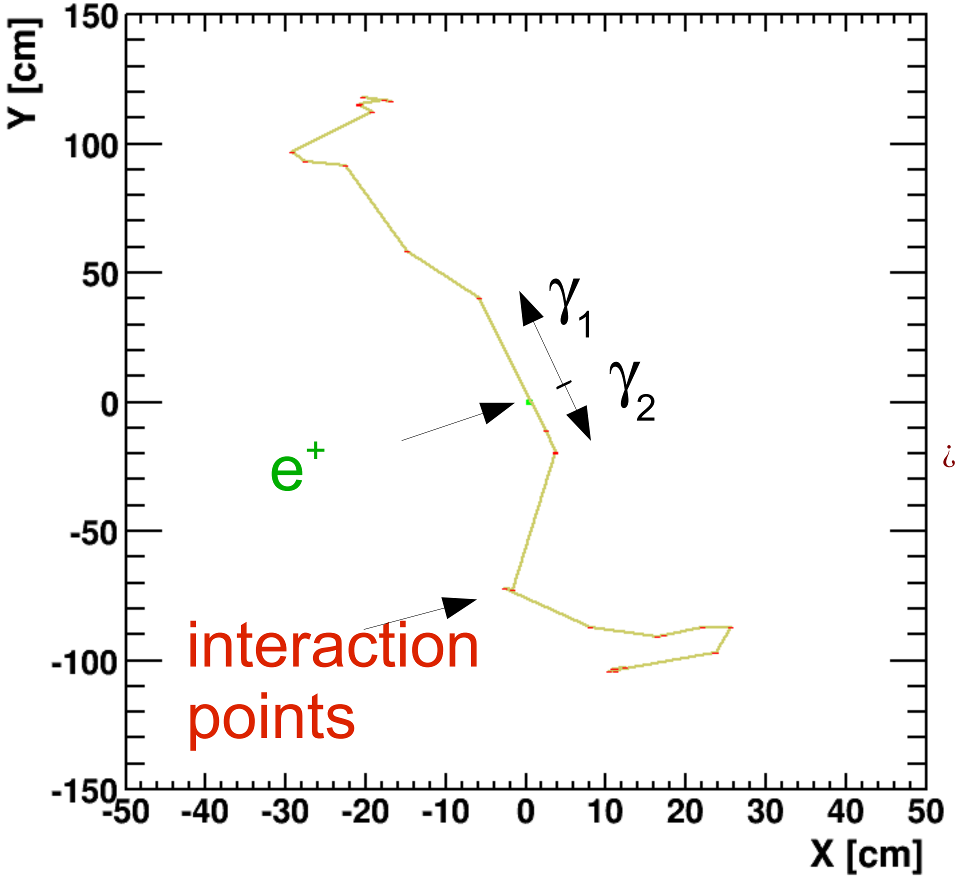


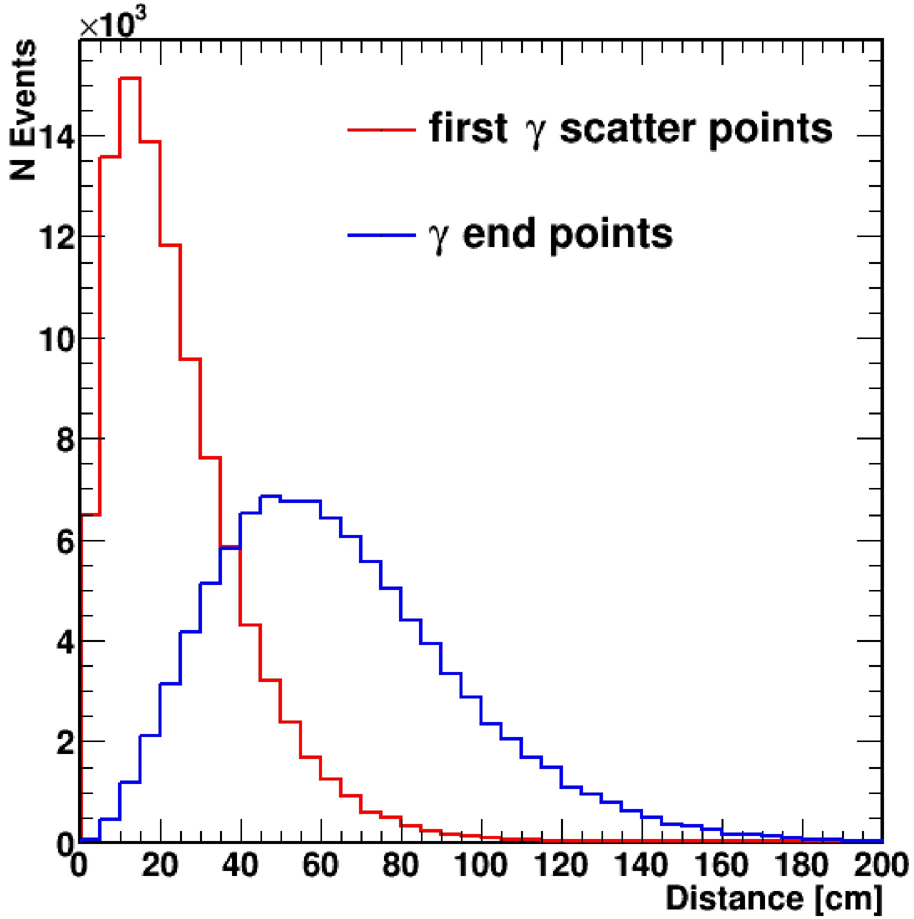

3 GeV muon starting from (-800,1080,0) cm with direction (1,0,0); z-projection from 300 cm to -300 cm of 10th iteration and normalized w.r.t. maximum bin content of projection; 25 cm bin size; detected light only

# Edge Event: After Recent Improvements



# Low Energy Reconstruction

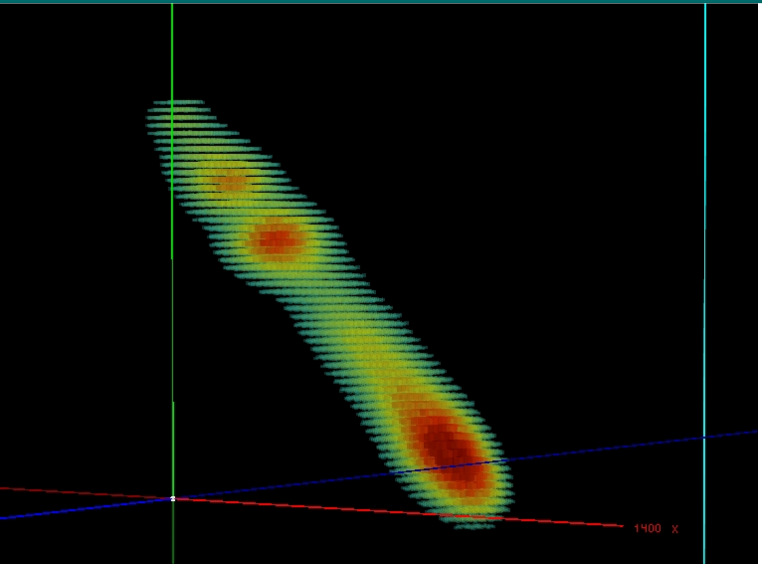


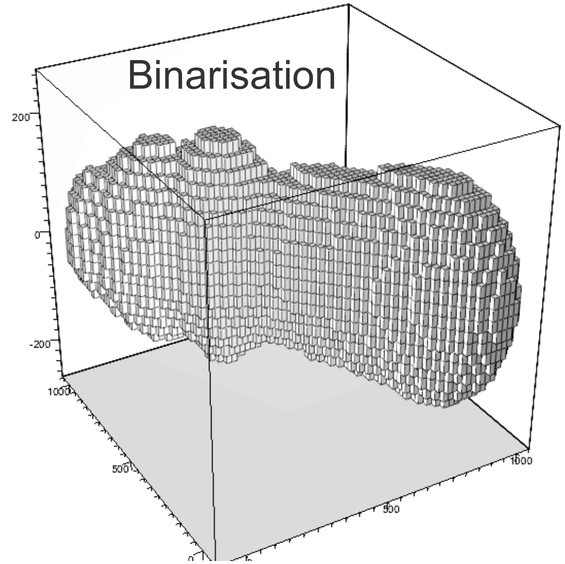



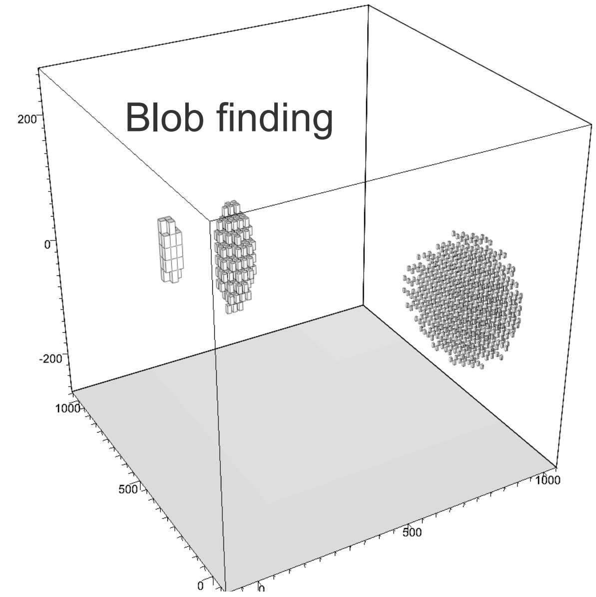

**Observation:** Elongation of topology ≥ vertex resolution

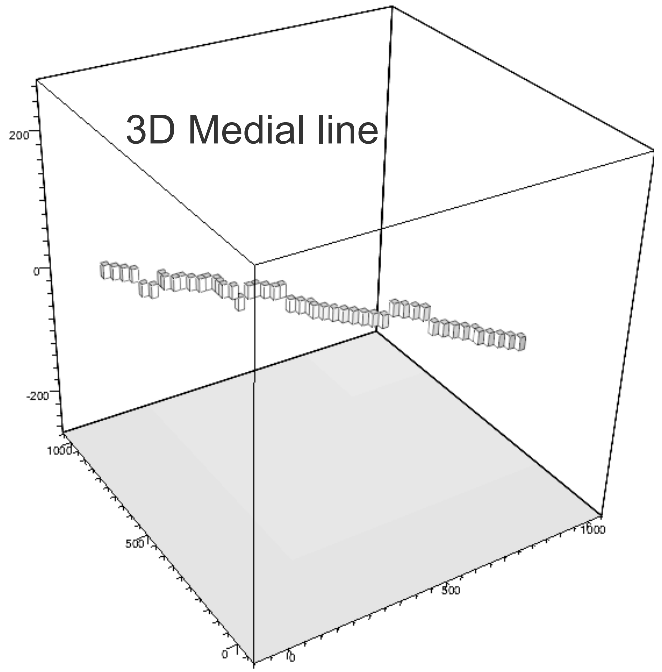
**Idea:** Use my reconstruction to see linear shape of $\gamma$-$e^+$-$\gamma$ !

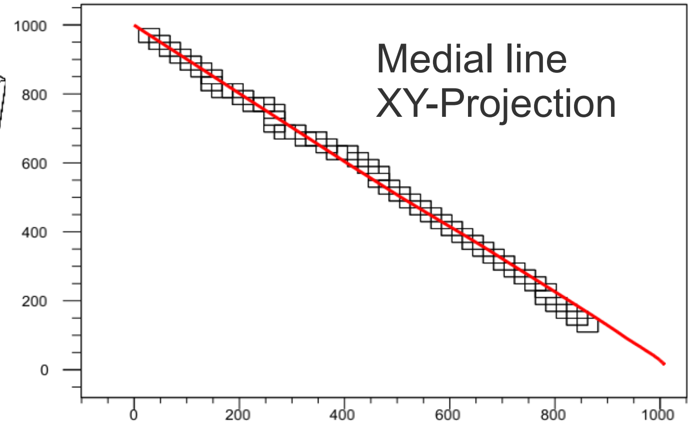
# Image Processing

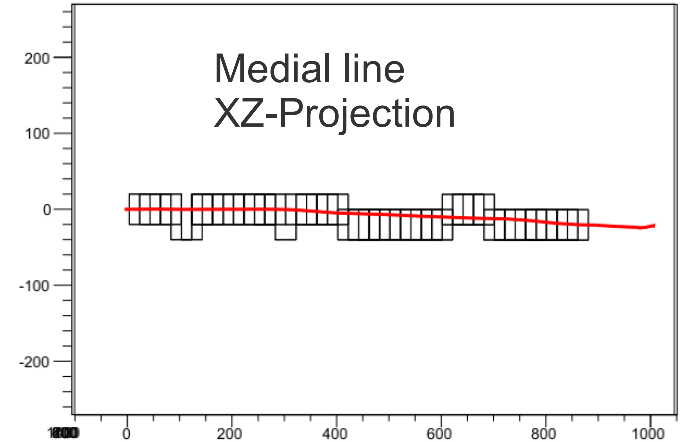





Ph. D. student Sebastian Lorenz

## Resolution < 20 cm