3d-Topological Reconstruction in Liquid Scintillator

Presented by

Björn Wonsak

on behalf of

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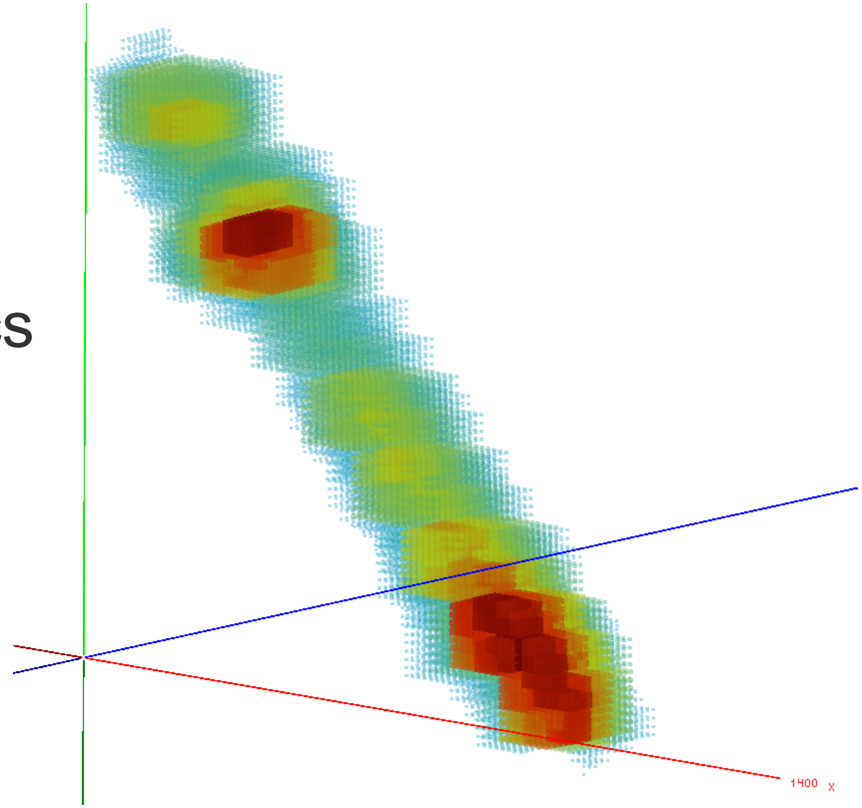
PRISMA Cluster of Excellence

Deutsche Forschungsgemeinschaft

What is 3d Topological Reconstruction?

- **Spatial distribution of the energy deposit**
  → Same abilities as fine grained detector

- **Motivation:**
  - Particle discrimination
  - Identify shower locations
    → Better vetoing of cosmogenics



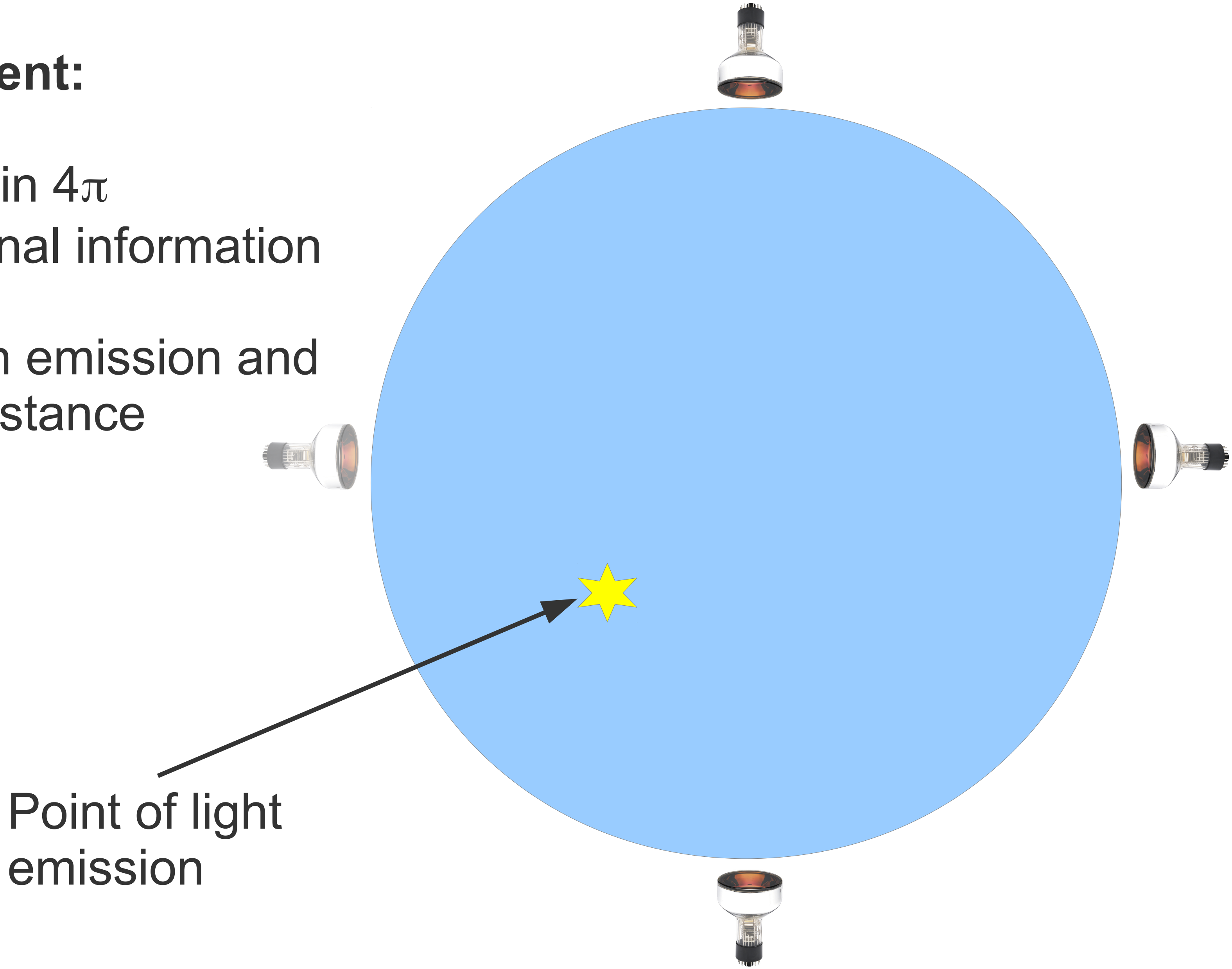
Why no 3D Tracking (so far)?

Point-like event:

Light emitted in 4π
→ no directional information

Time between emission and detection = distance

→ Circles



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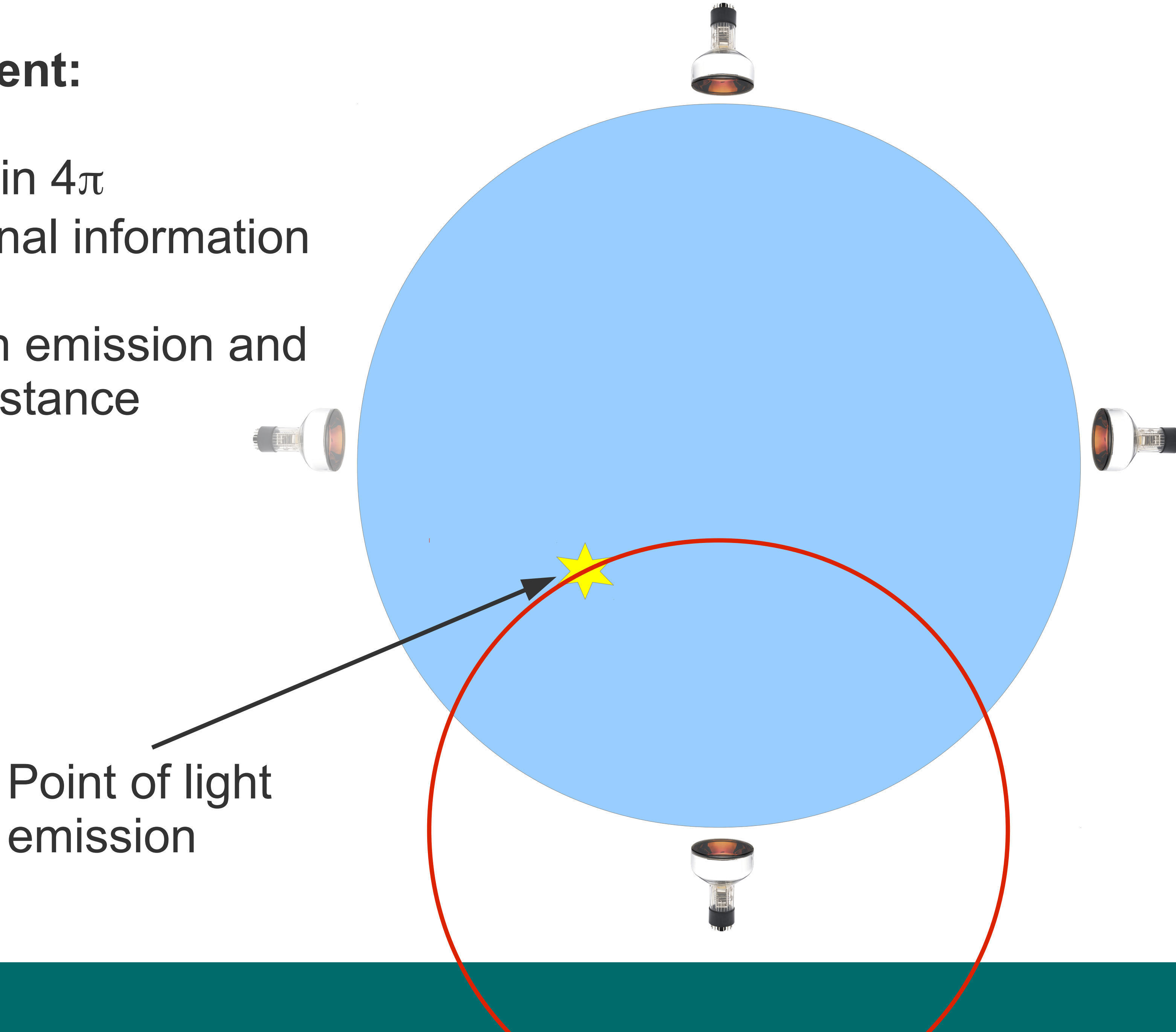

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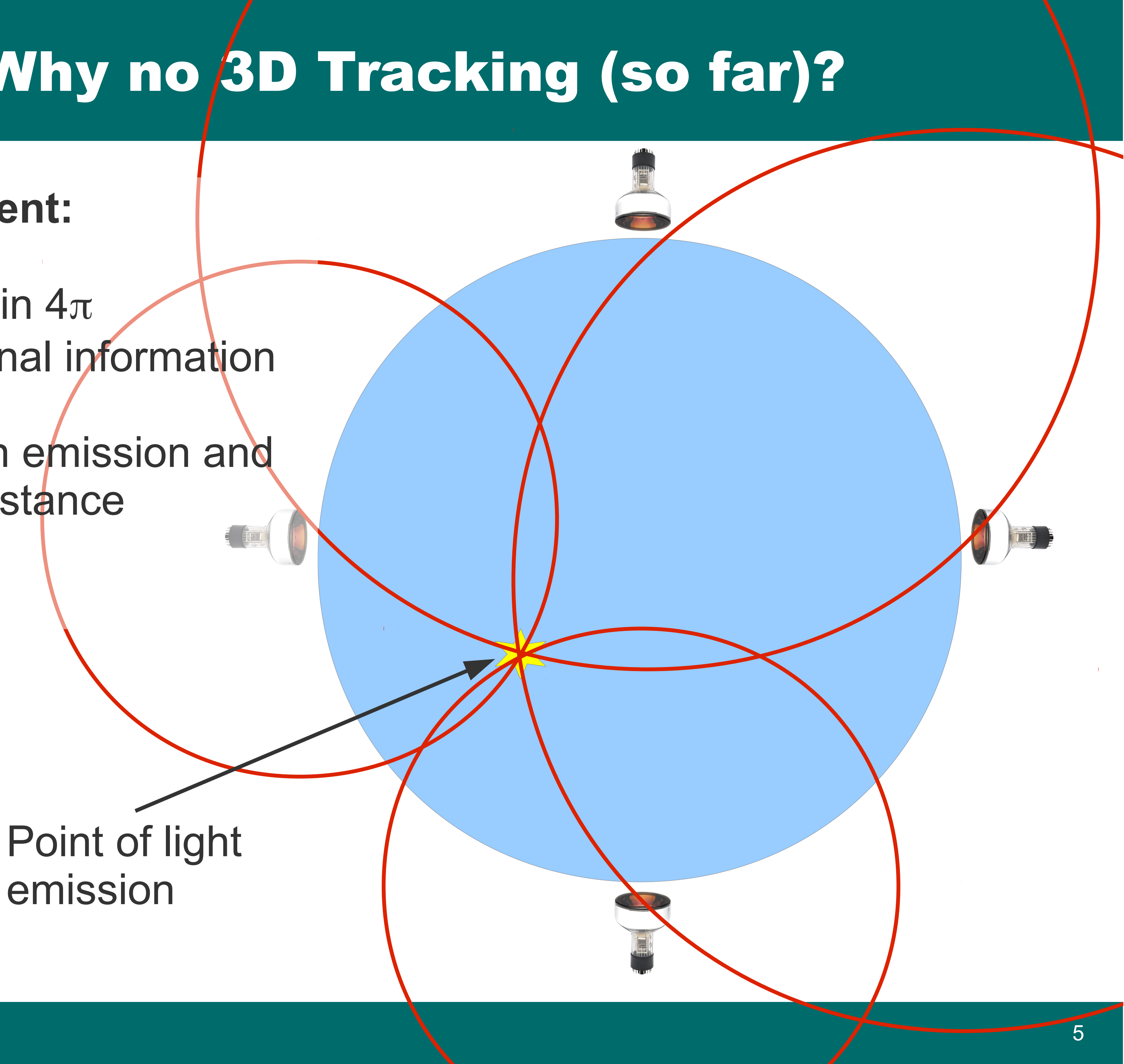
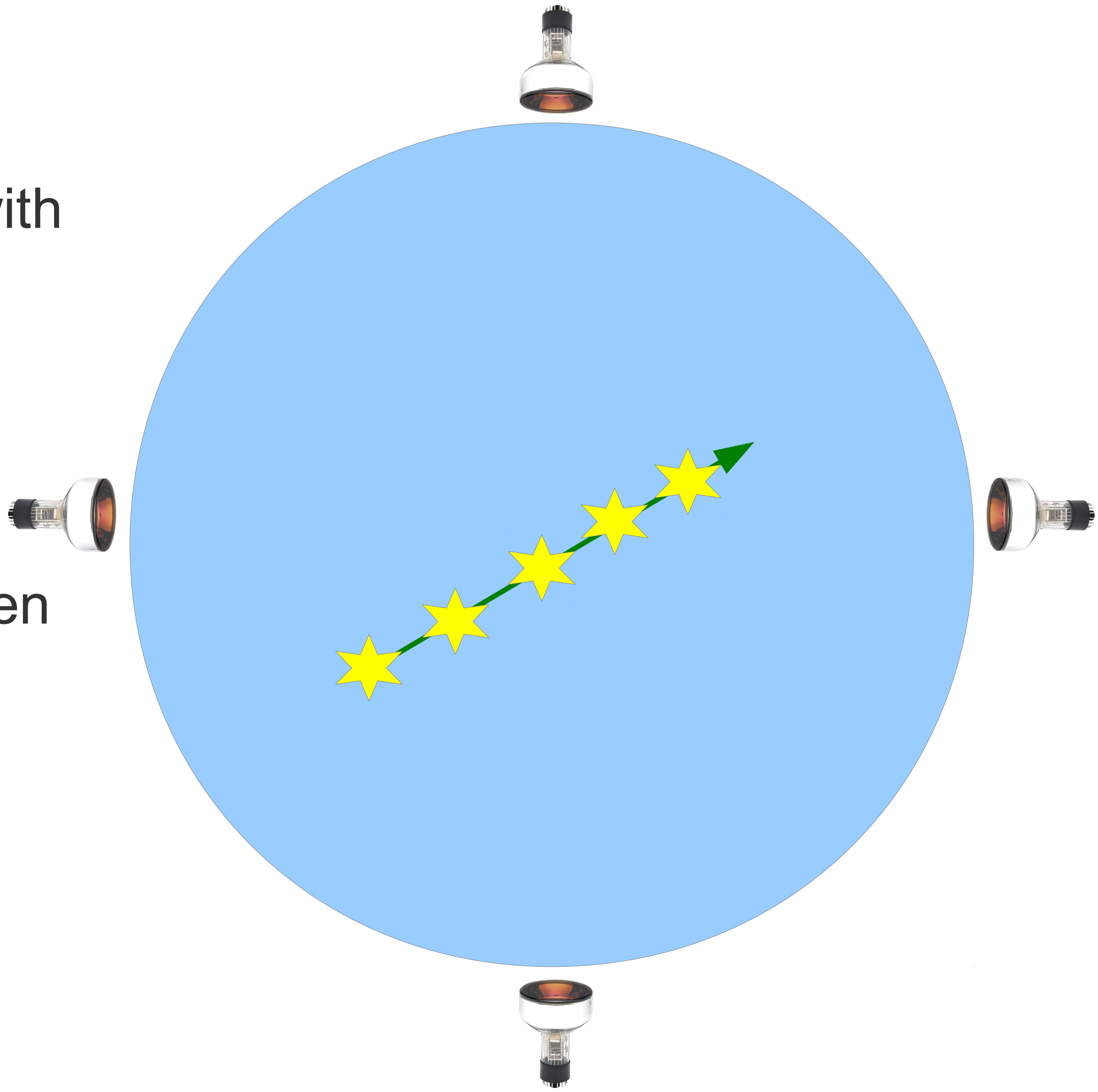


Why no 3D Tracking (so far)?

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
- Single hit times available

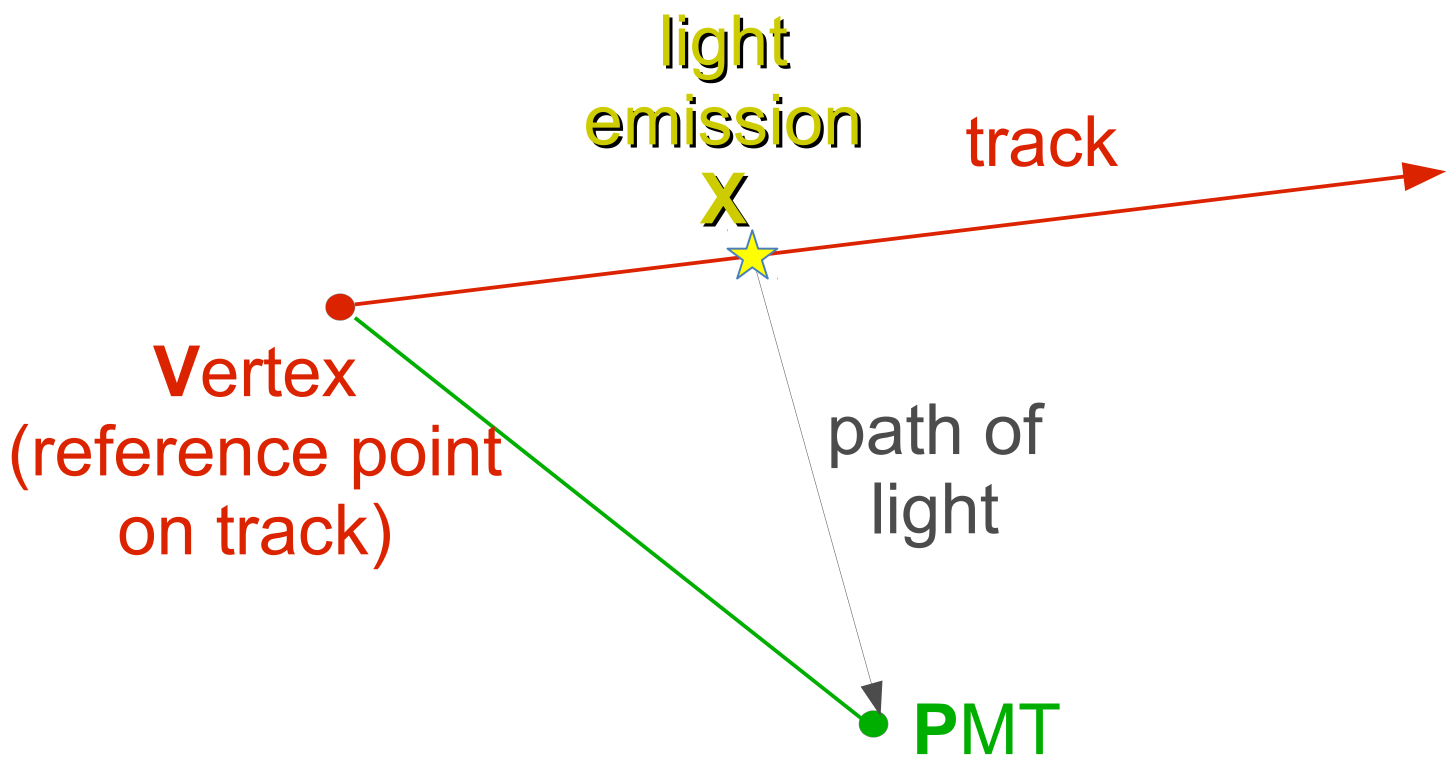
Concept:

- Take this point as reference for all signal times

The Drop-like Shape

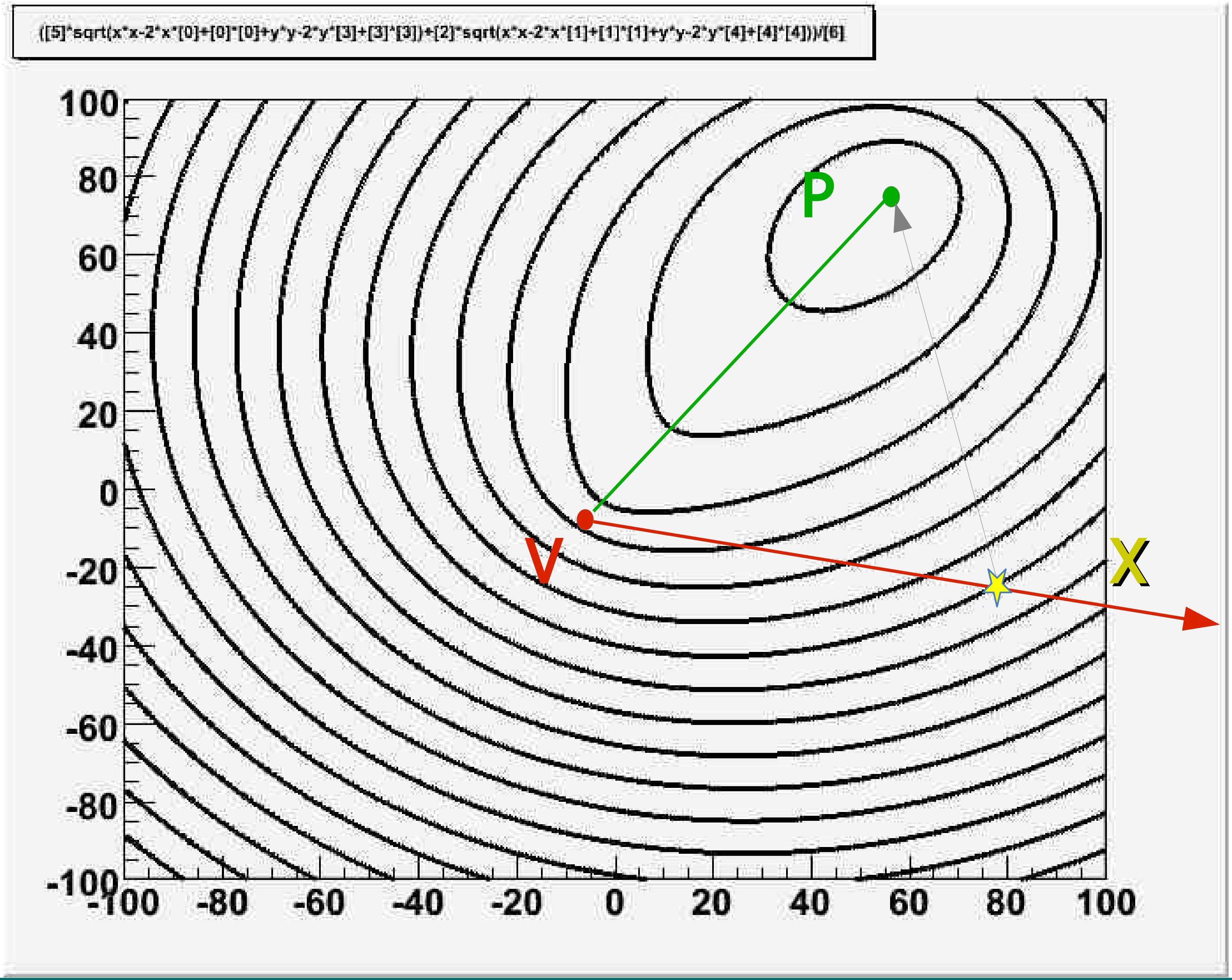
Signal time = particle tof + photon tof

→ ct = |VX| + n*|XP|



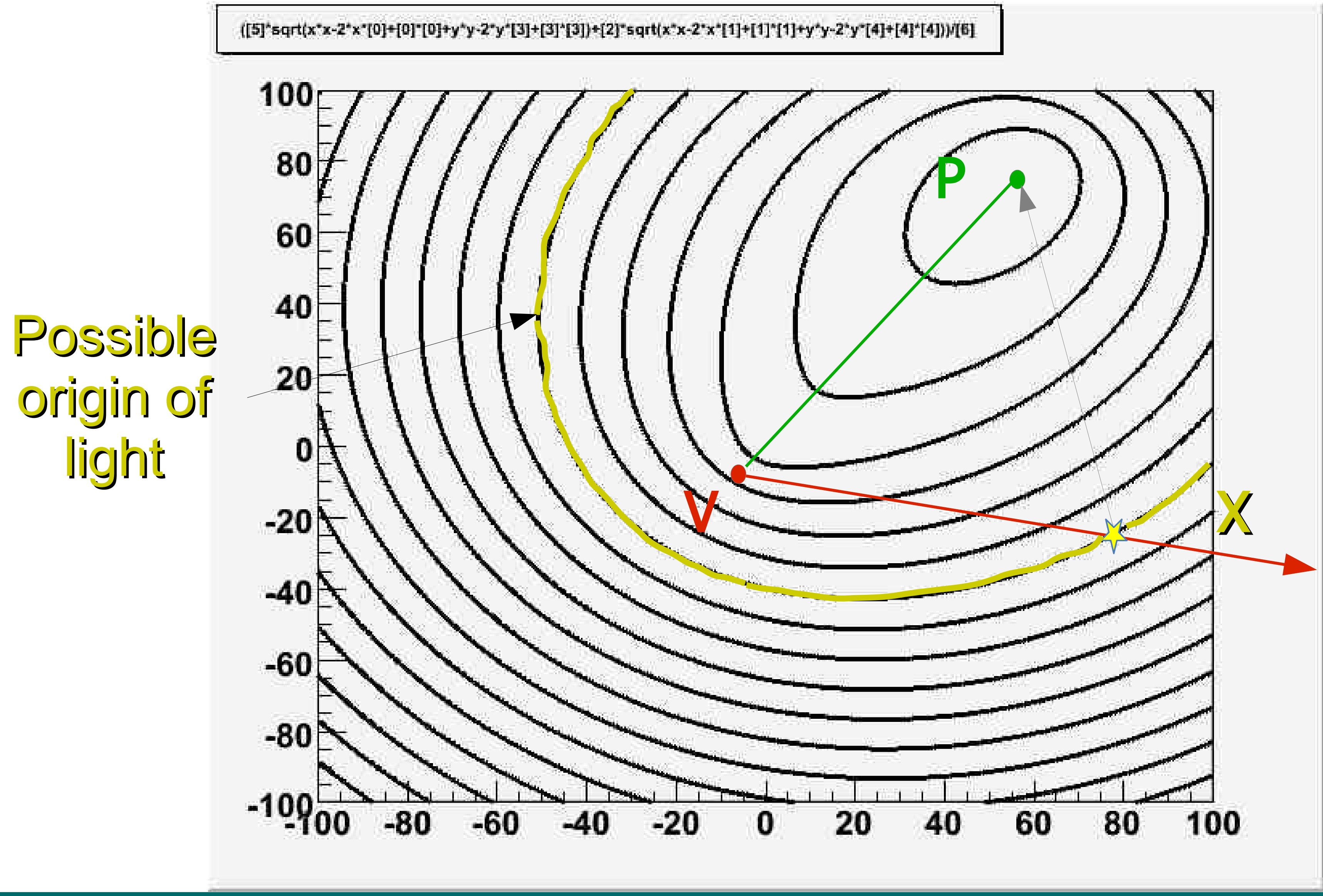
The Drop-like Shape

ct = |VX| + n*|XP| → drop-like form



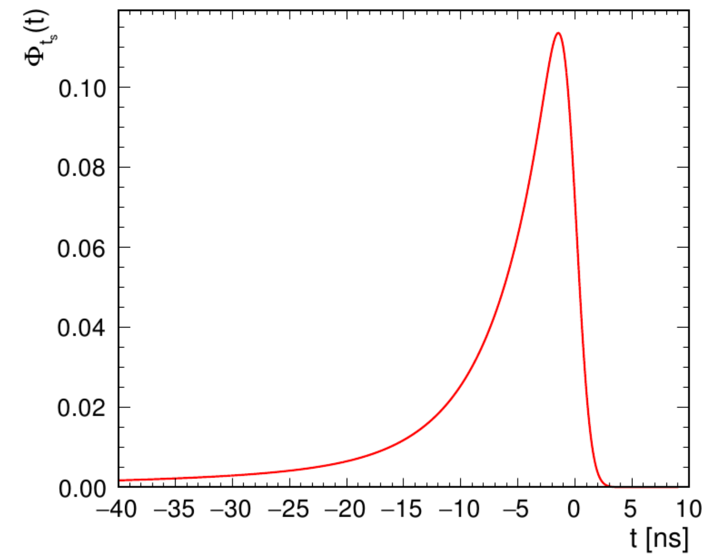
The Drop-like Shape

ct = |VX| + n*|XP| → drop-like form



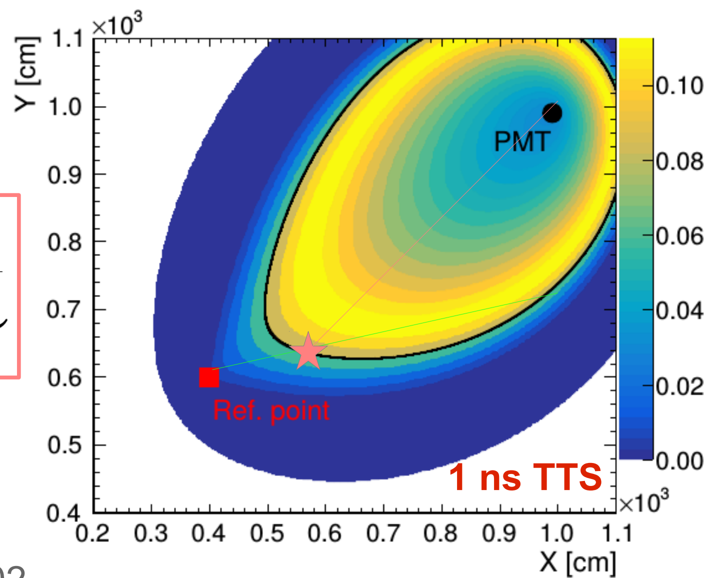
Working Principle Part I Summary

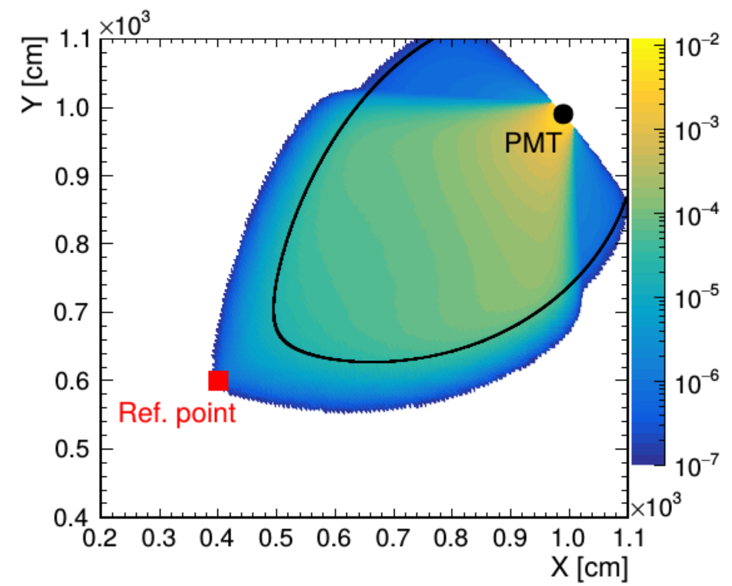
- For each signal:
  - Time defines drop-like surface
  - Gets smeared with time profile
    (scintillation & PMT-timing)
  - Weighted due to spatial constraints
    (acceptance, optical properties, light concentrator, …)



- → Spatial p.d.f. for photon emission points

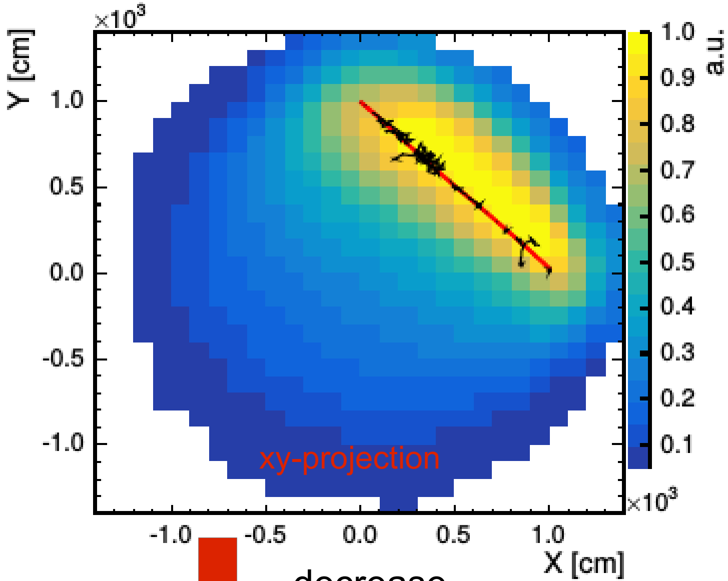
$$t(\mathbf{x}) = t_{\mathrm{ref}} \pm \underbrace{\frac{|\mathbf{x}-\mathbf{r}_{\mathrm{ref}}|}{c_0}}_{\text{particle}} + \underbrace{\frac{|\mathbf{r}_j-\mathbf{x}|}{v_g(\epsilon)}}_{\text{photon}}$$





See B.W. et al., arXiv:1803.08802

Working Principle Part II



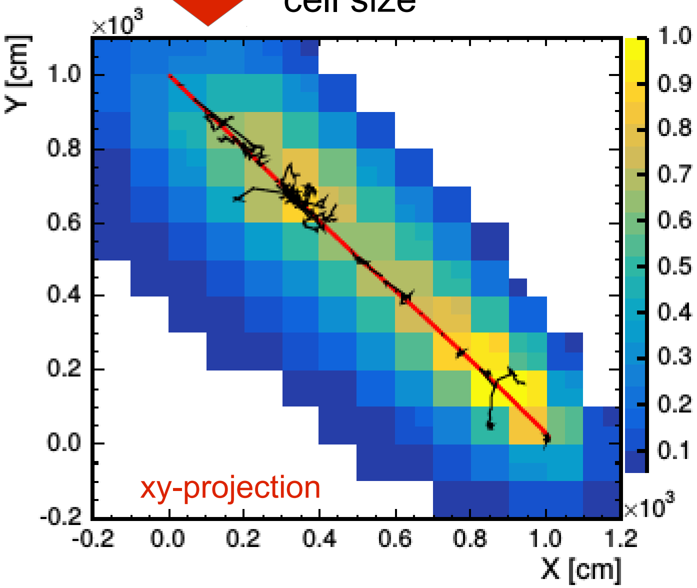
- Add up all signals (Need arrival time for every photon)
- Divide result by local detection efficiency

  → Number density of emitted photons
- Use knowledge that all signals belong to same topology to 'connect' their information

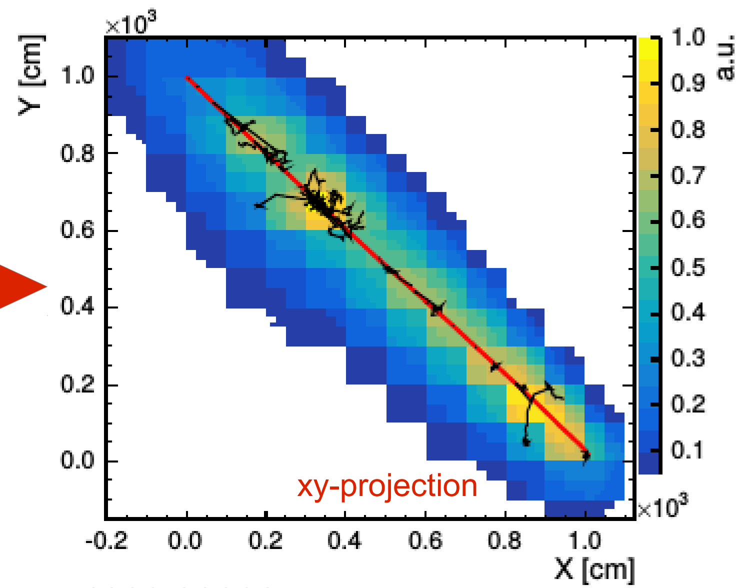
  → Use prior results to re-evaluate p.d.f. of each signal

That is what I call probability mask (PM)

decrease cell size



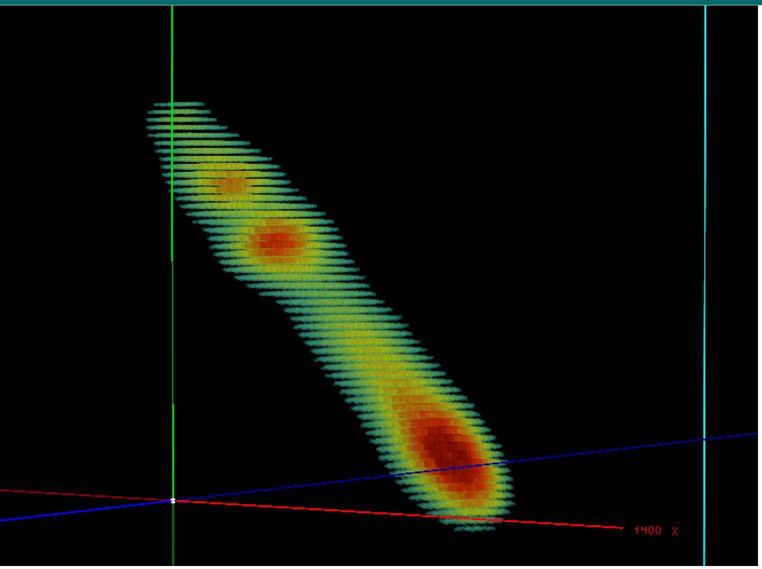
decrease cell size

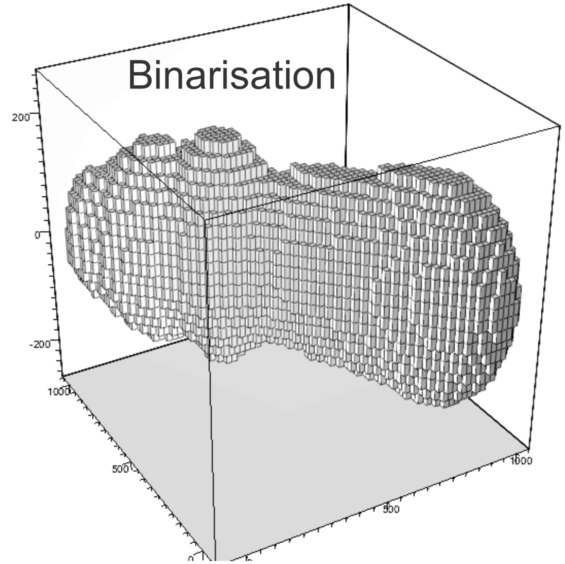


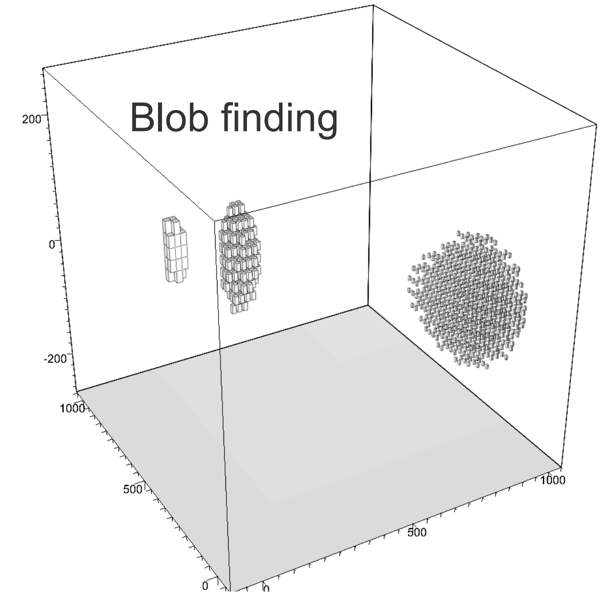
dE/dx accessible

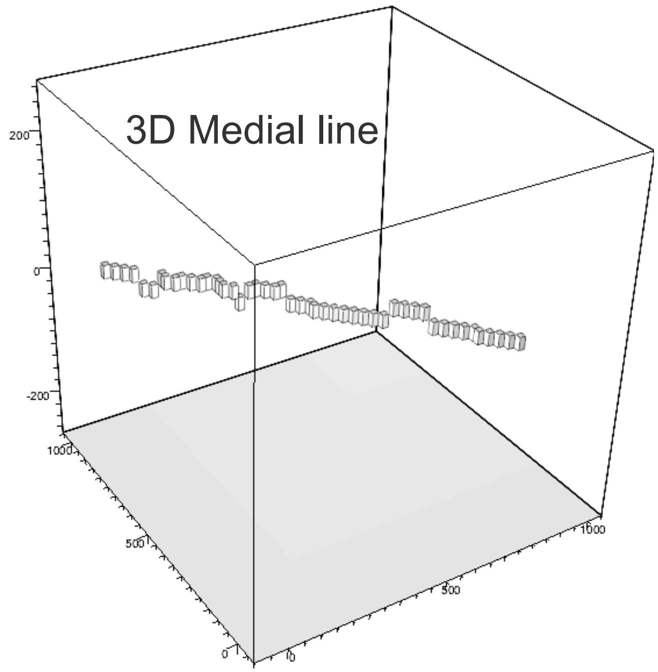
See B.W. et al., arXiv:1803.08802

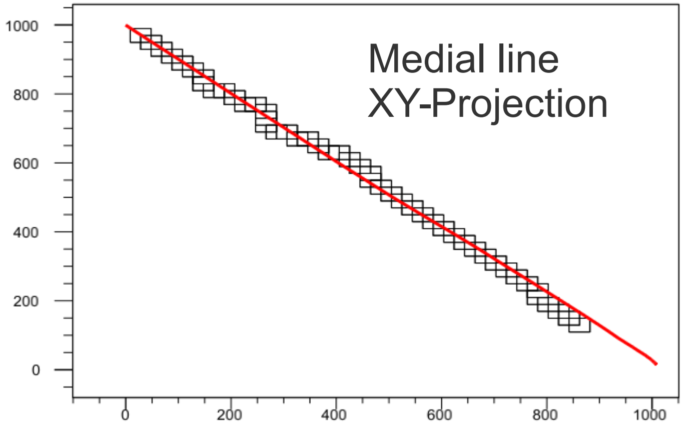
Image Processing

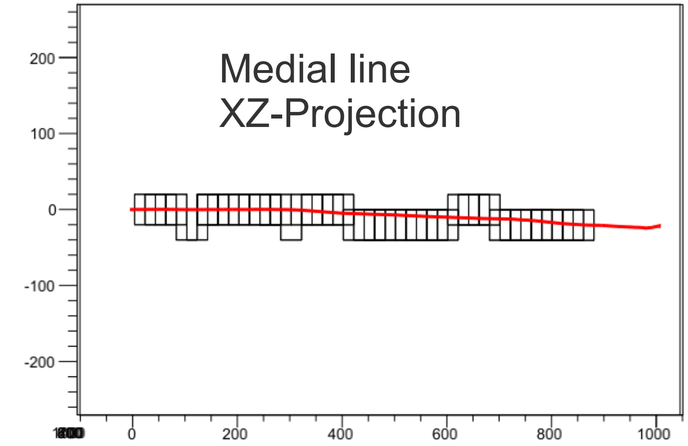












Work of Sebastian Lorenz

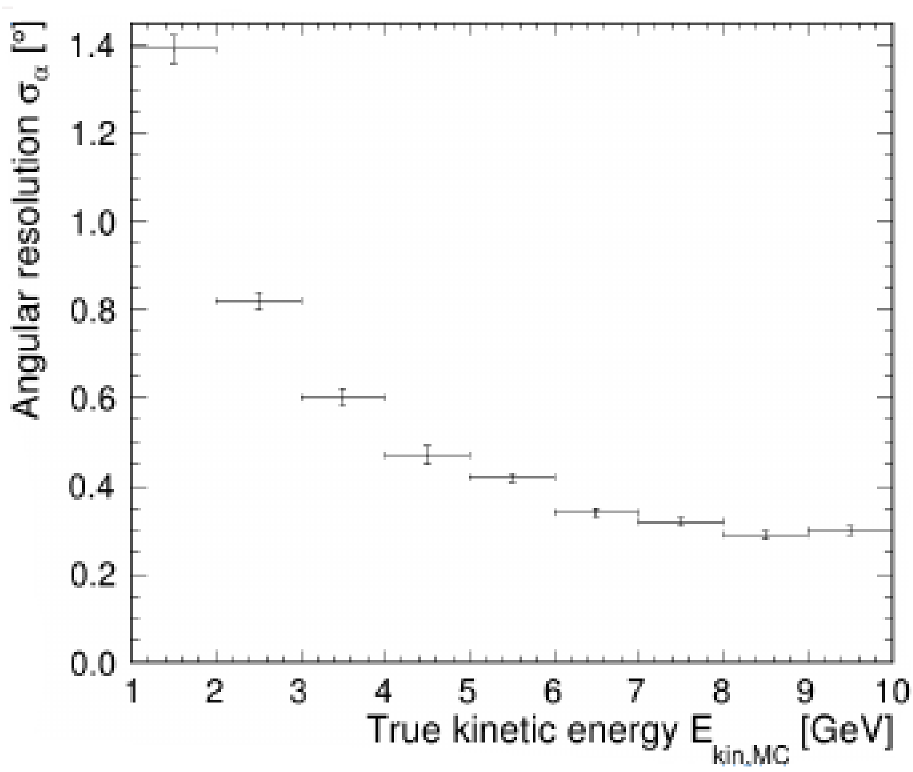
Resolution < 20 cm

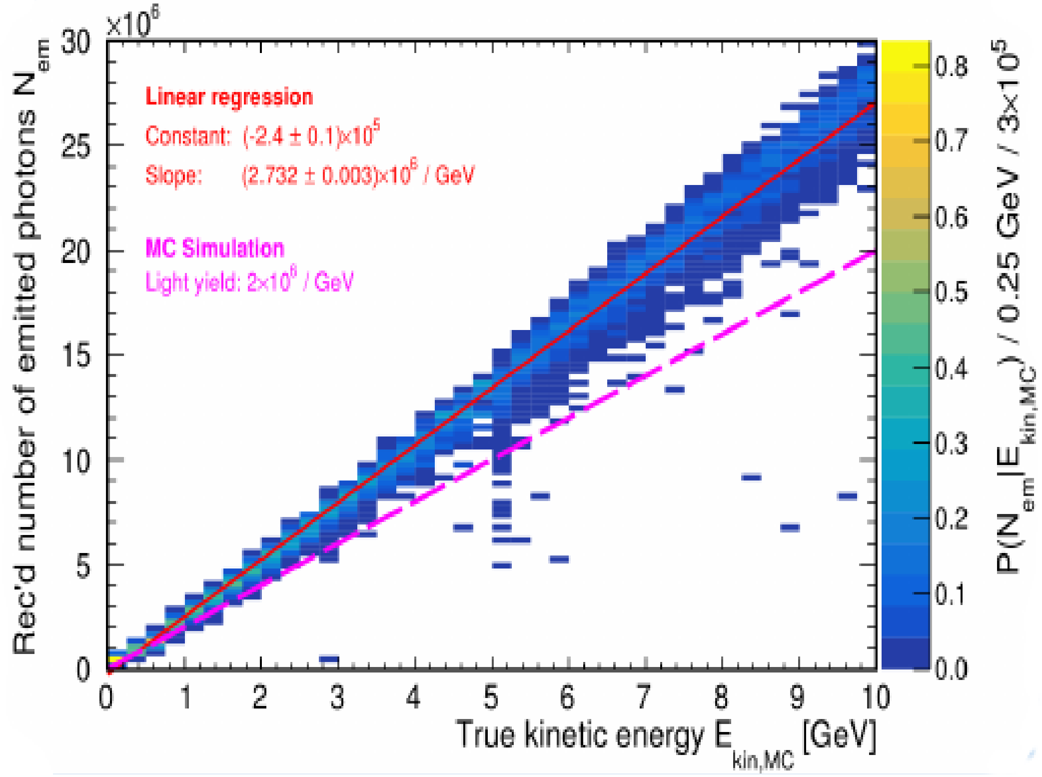
Future:
Machine learning

Performance with Muons in LENA

- **Fully contained muons with 1-10 GeV**
  - Angular resolution: <1.4° for E ≥ 1 GeV
  - Energy resolution: 10% · sqrt(E/1 GeV) + 2 %

(Gets better if scattered light is treated correctly)

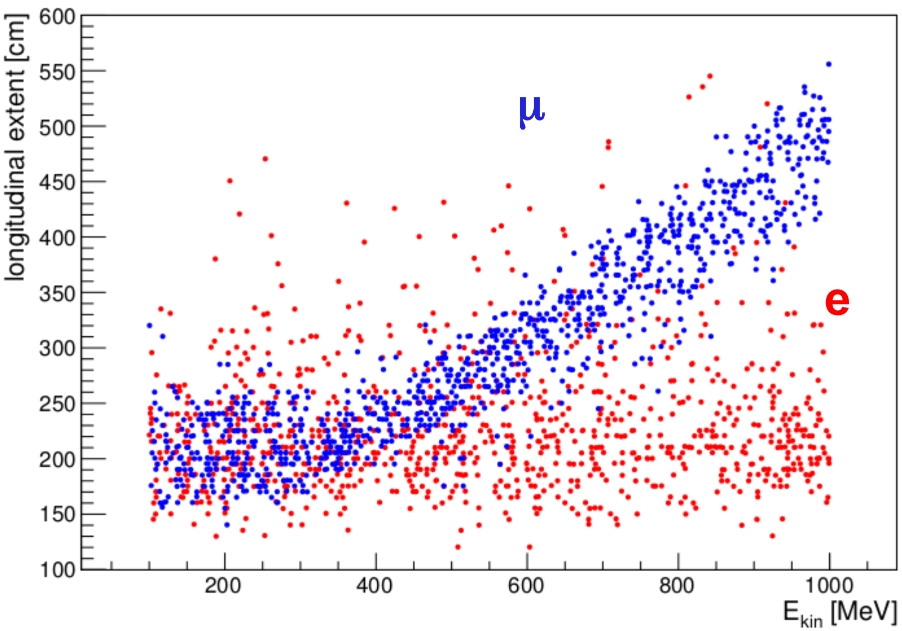


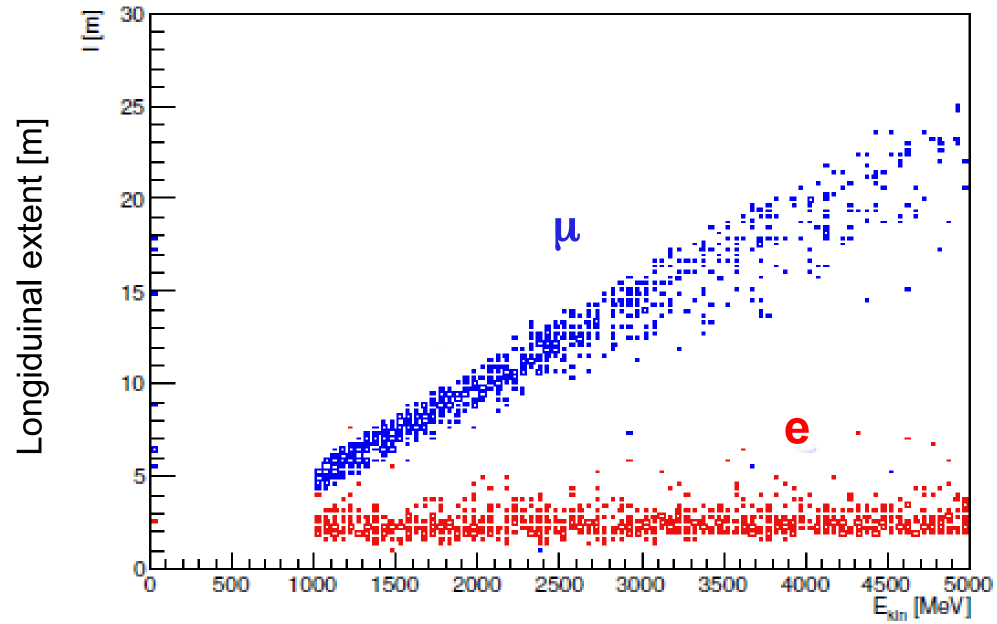


See B.W. et al., arXiv:1803.08802

Electron/Muon Separation

- **Use longitudinal extent**
  → Clear separation down to 600 MeV
- **Additional Parameters like dE/dx might improve this**

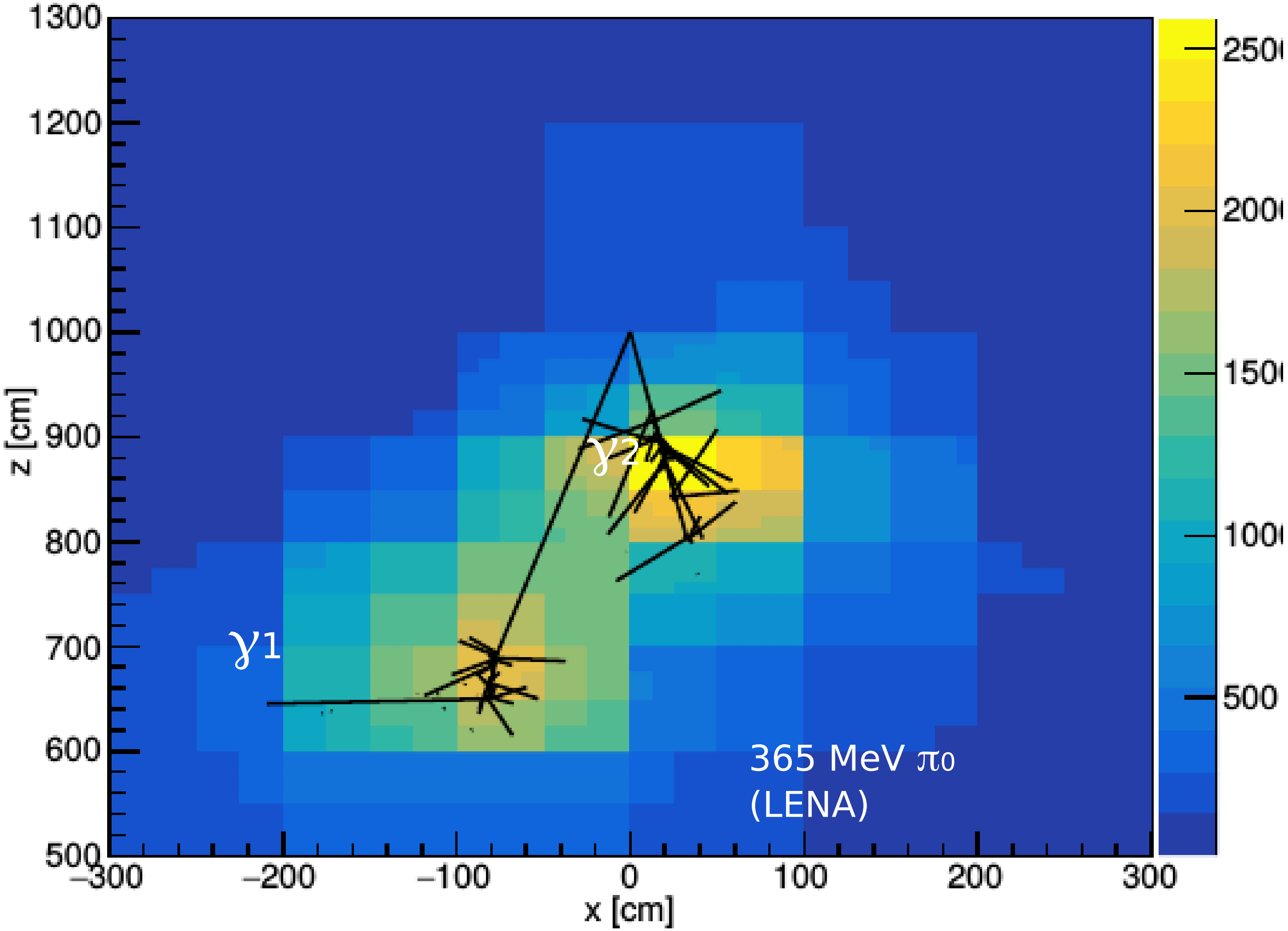




Bachelor thesis of Daniel Hartwig

NC Background

- **Started to look at π_0 in LENA**

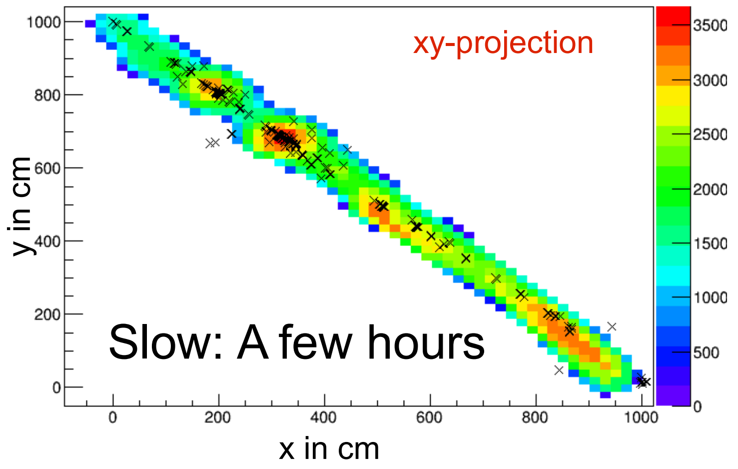


Bachelor thesis of Katharina Voss

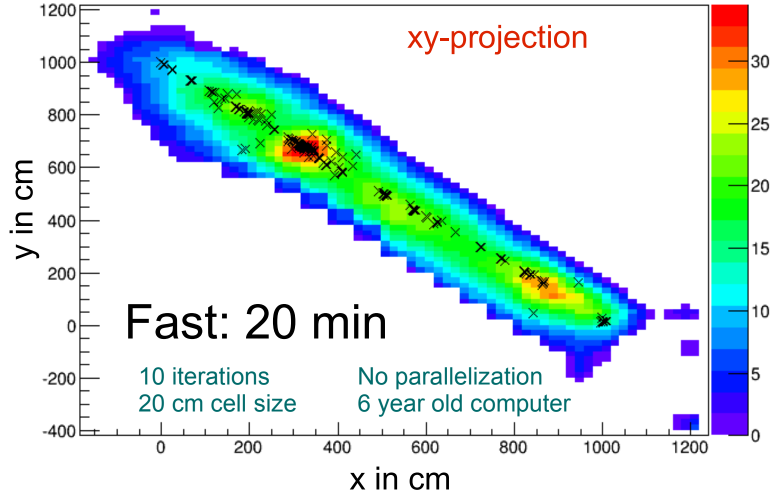
Caveat:
Used smeared but true π_0 vertex

Computing Time

- **Full fine grained reconstruction is very time consuming**
  (21 iterations, 12.5 cm binning → a few hours for a few GeV muon in LENA)
- **However:**
  - Easy to implement parallel computing techniques (already some success)
  - Reconstruction strategy can be adapted with a configuration file
  - Can use prior track information
  - Already the first iteration with coarse grains includes a lot of information
- **→ Need to find balance for a given question**
  - Cell size, number of iterations and number of PMTs used

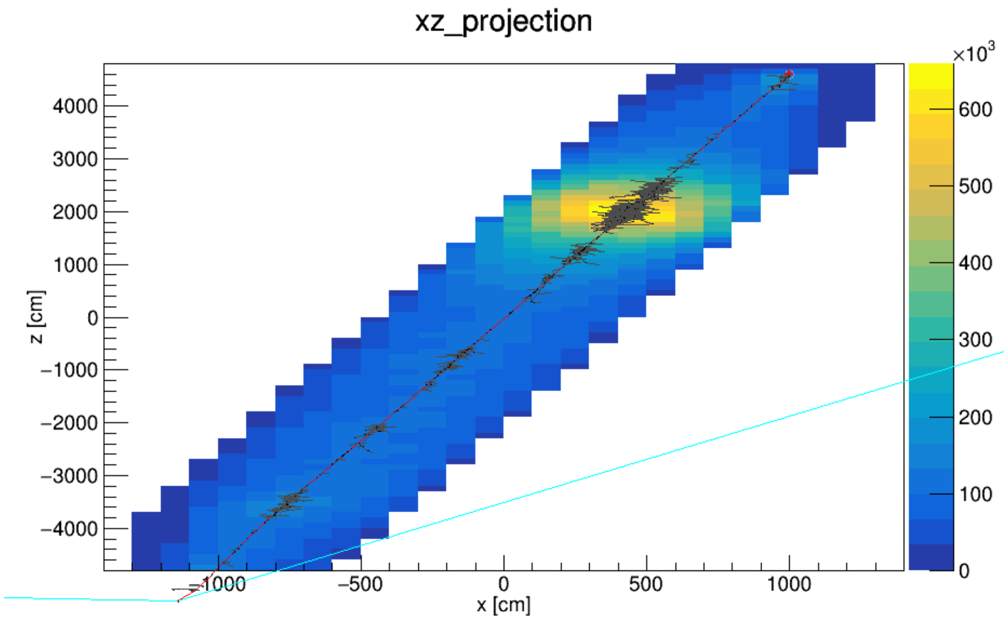


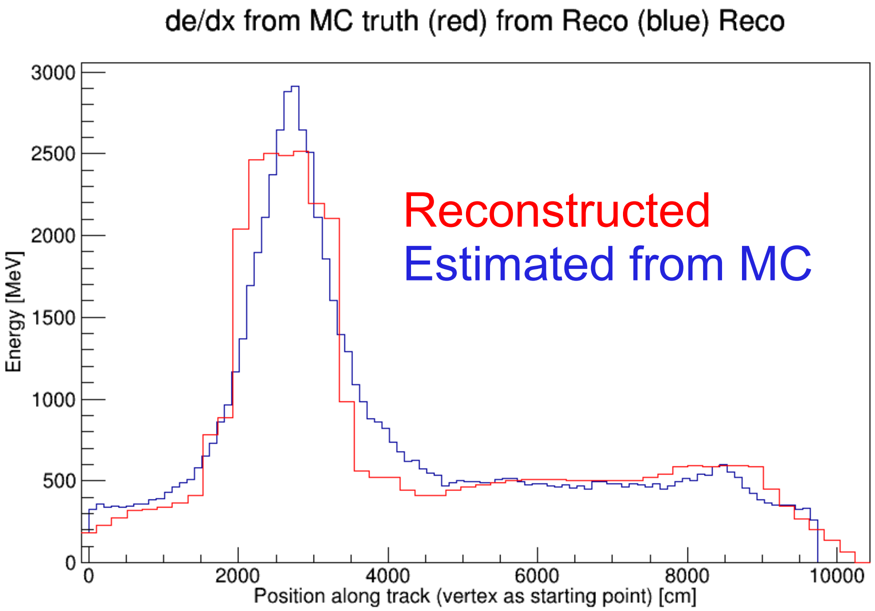
GPU could help a lot !



Looking for Shower in Cosmic Events

- **Result:**
  - 40 GeV muon crossing the whole detector
  - With hadronic shower
  - Used PM generated from fast track reconstruction
  - 1m cell size, 1 iteration only → much faster reconstruction



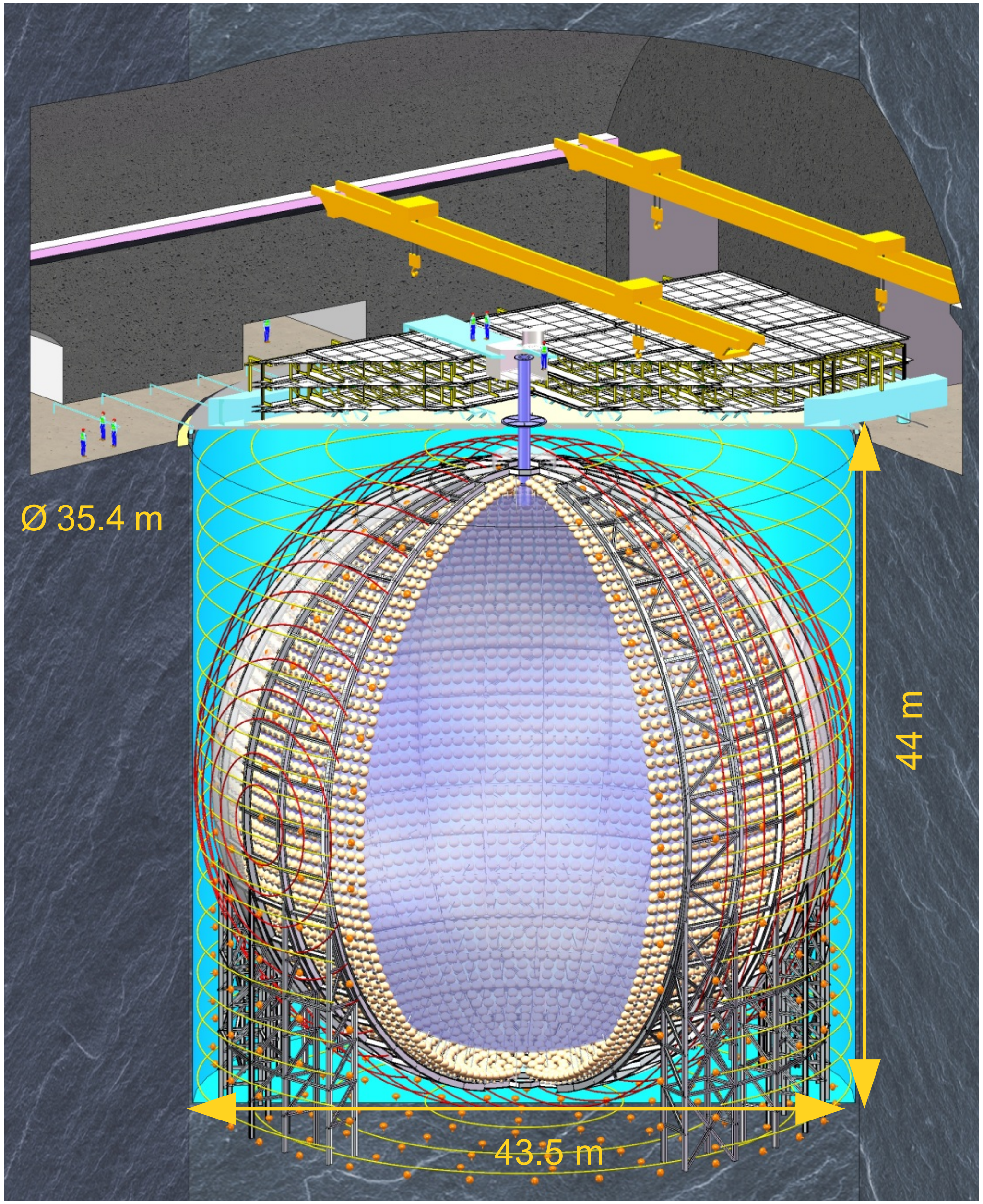


Bachelor thesis of Felix Benckwitz

Tracking at Low Energies
(a few MeV)

JUNO

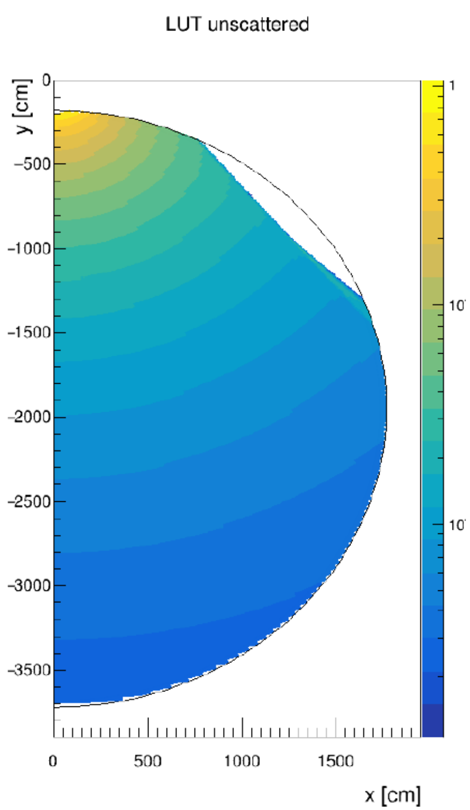
- **Central detector**
  - ~78% PMT coverage
  - 18000 20” PMTs + 25000 3” PMTs
    → 1200 photons/MeV
  - Acrylic sphere with liquid scintillator
  - PMTs in water buffer
    → Refraction, but no near field
  - Time resolution < 1.2 ns (σ)
  (5000 Hamamatsu PMTs)

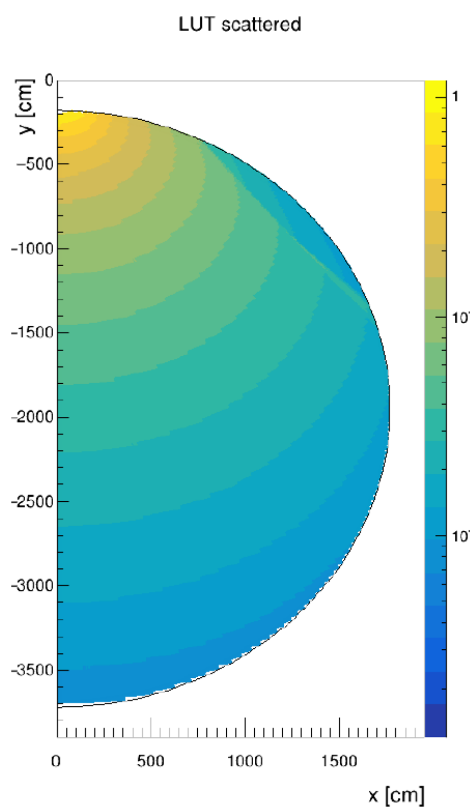


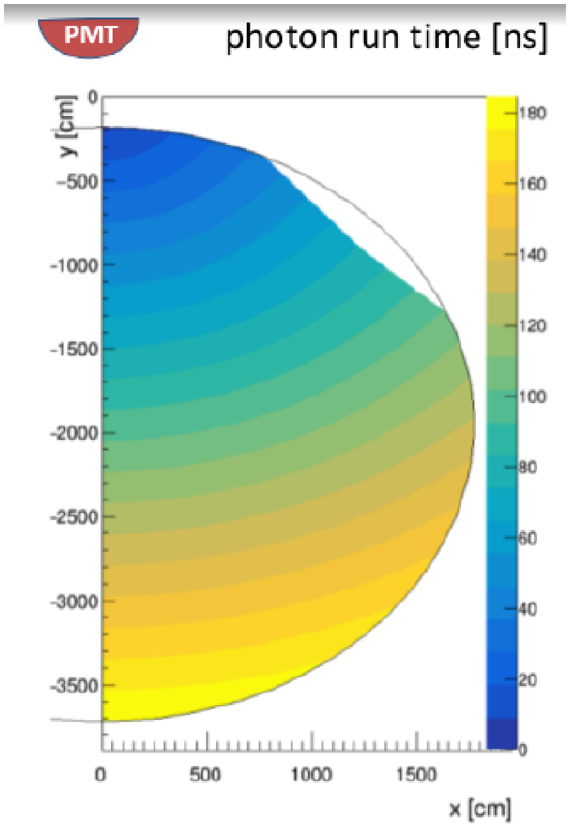
Implementation in JUNO

- LENA-MC: Only effective optical model
- JUNO: Full optical model + complex optics due to refraction at acrylic sphere

Includes Cherenkov-light





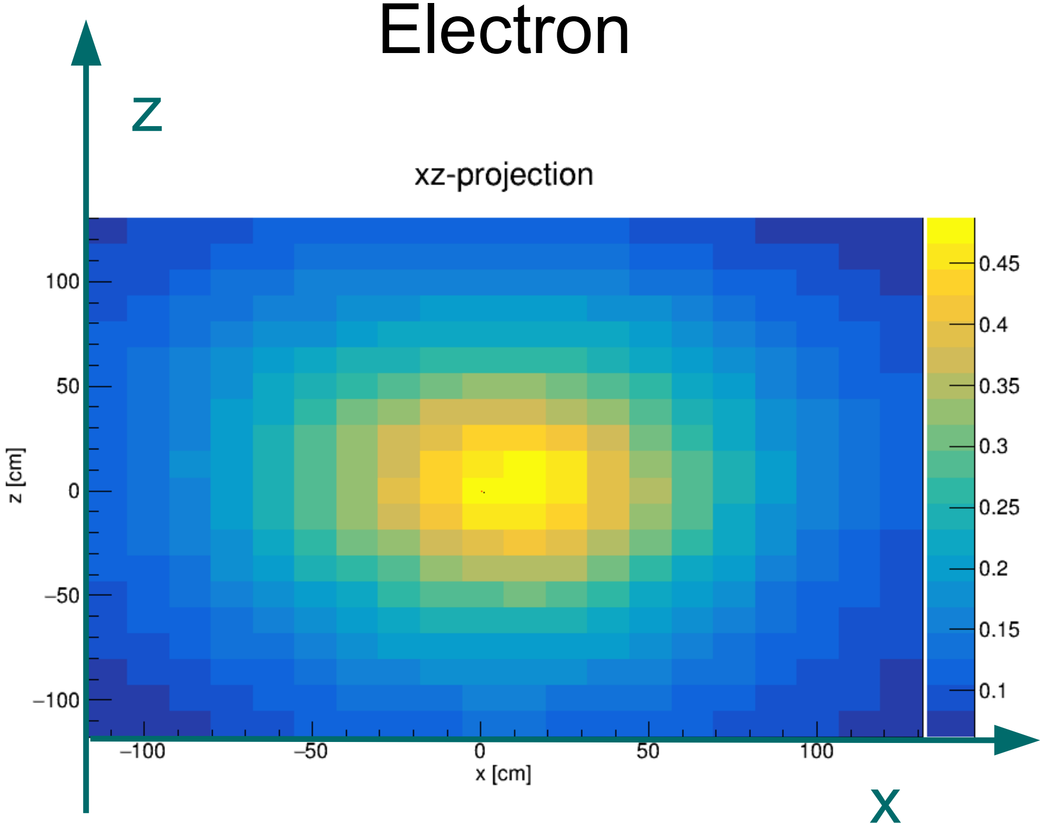


Work by Henning Rebber

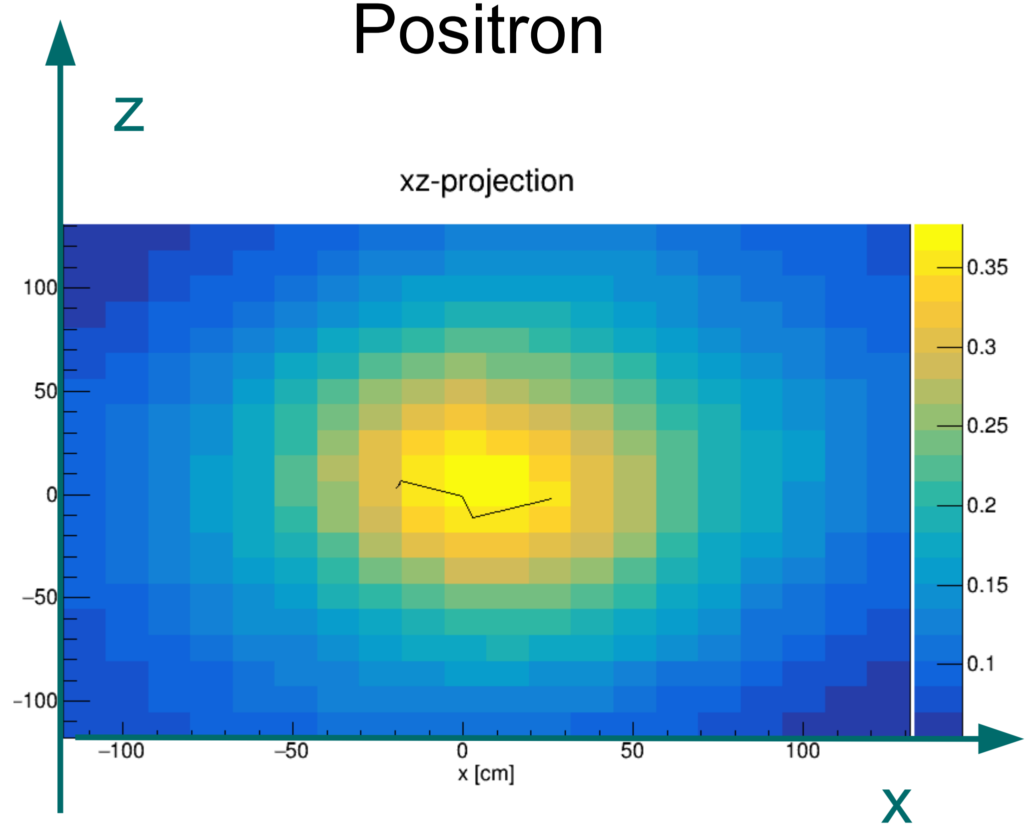
Electrons vs. Positrons in JUNO

Result after 5th iteration

Electron



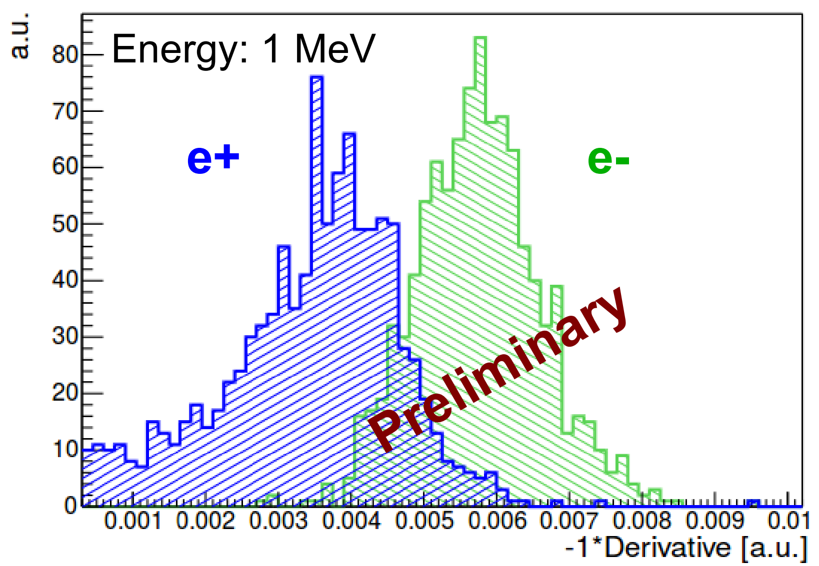
Positron

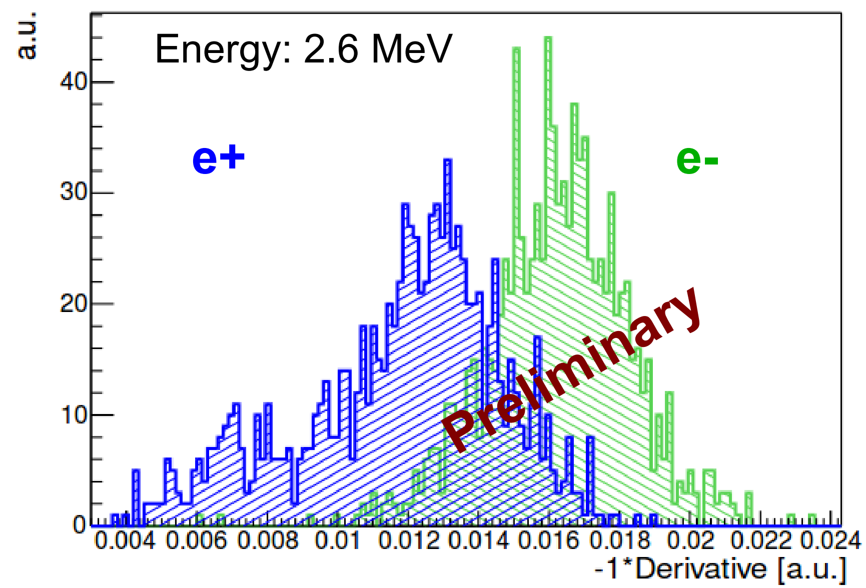


3.6 MeV visible energy

Electron/Positron Discrimination in JUNO

- **So far:** Only 1-dimensional analysis based on contrast
- **Future:** Multivariate decision tree or neural network
- **Effect of Ortho-Positronium already included**





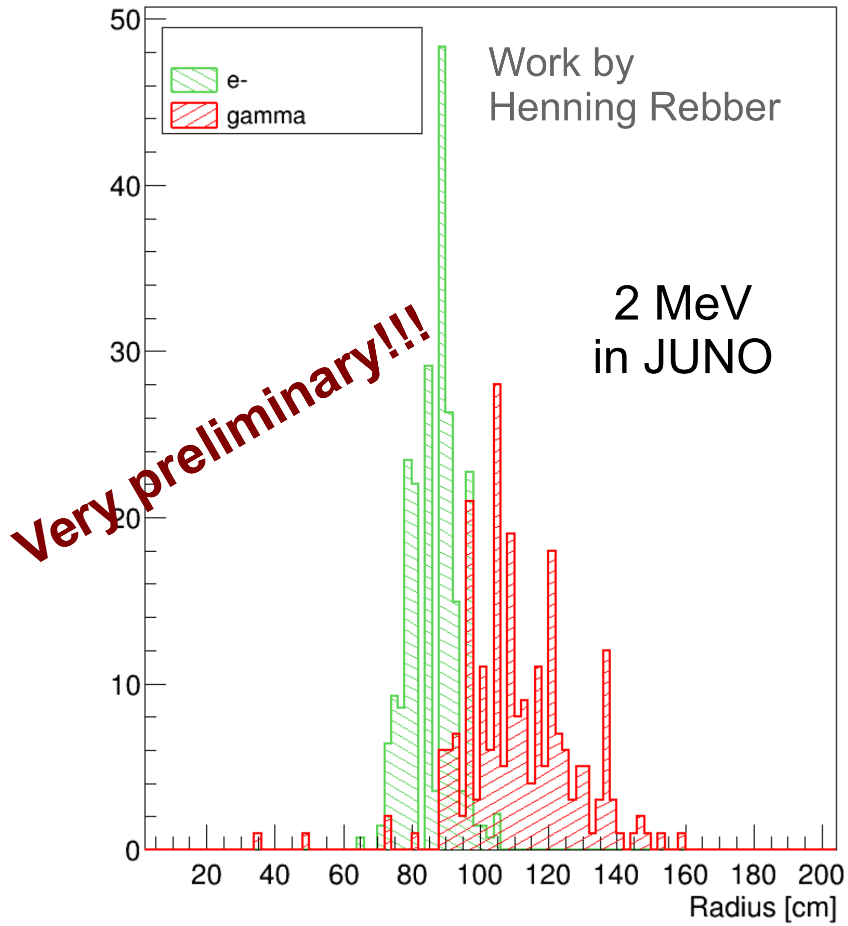
e+	95%	90%	80%	75%	68%	50%
e-	21%	13%	6%	4%	2%	1%

e+	95%	90%	80%	75%	68%	50%
e-	40%	28%	13%	11%	8%	3%

Work by Henning Rebber

Gamma Discrimination in JUNO

- **Used only time based vertex reconstruction to get reference point**



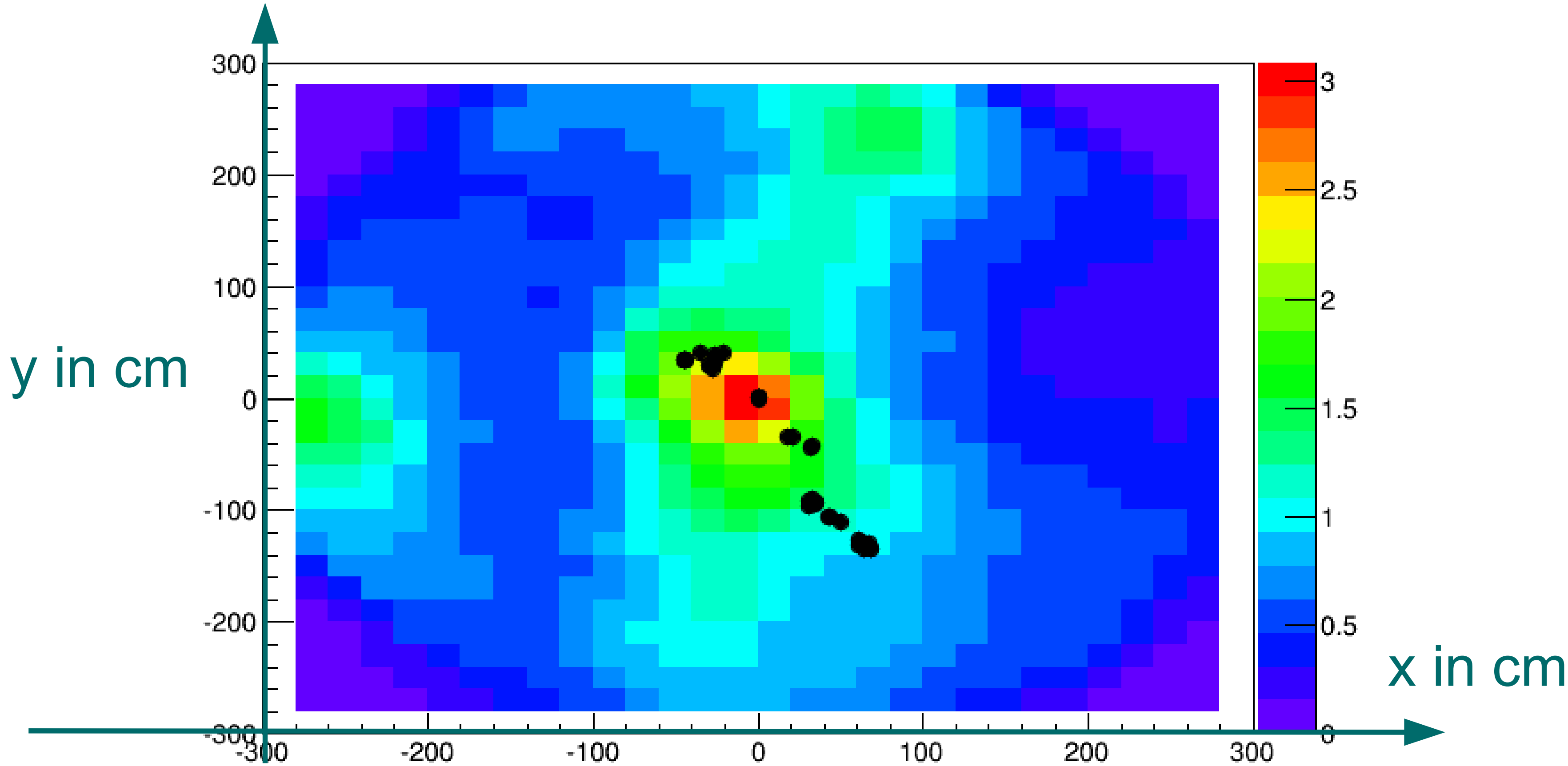
318 electrons
226 gammas

Radius containing 80% of light emission probability

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



Result **before** removal of scattered light!

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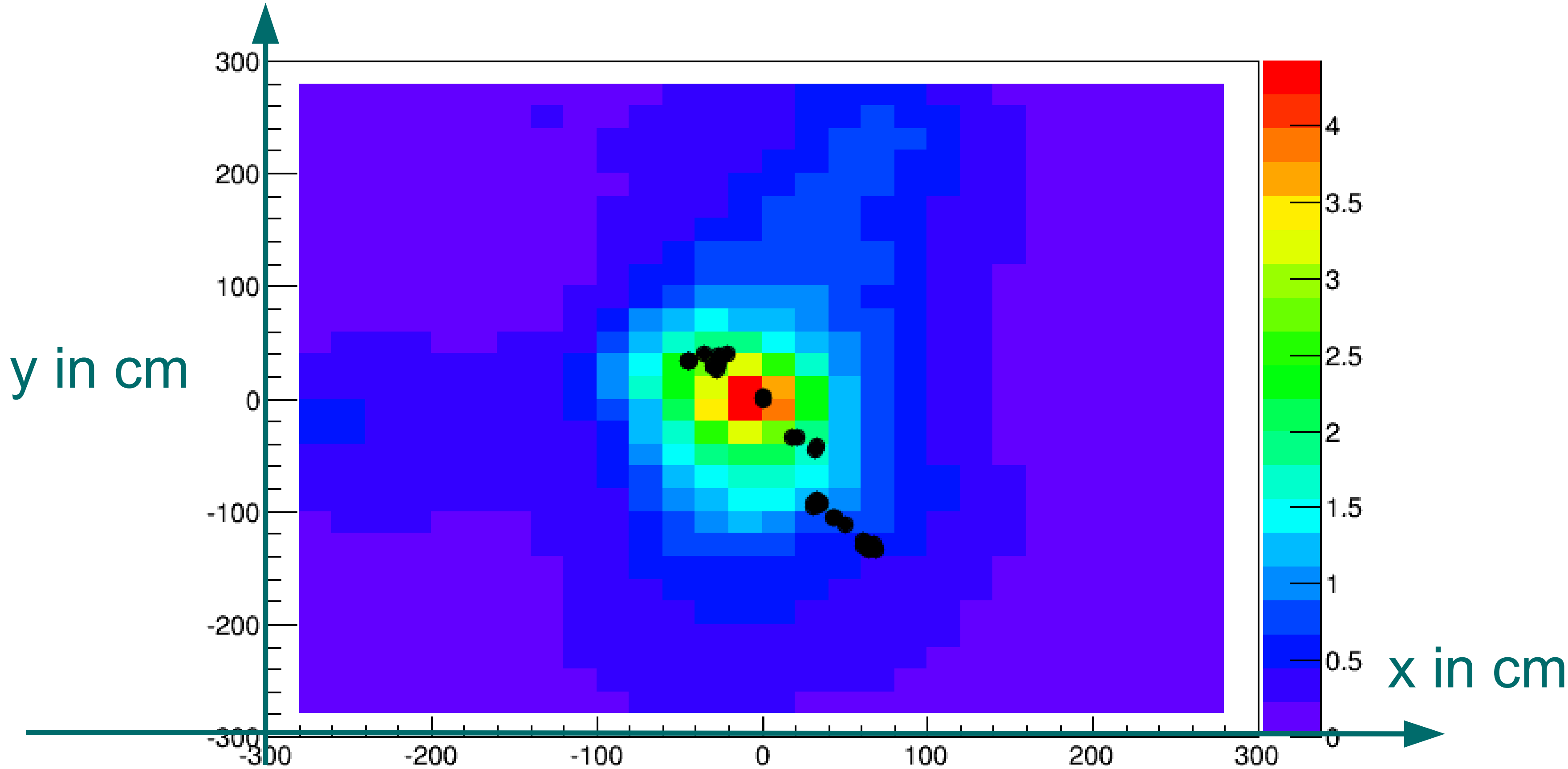


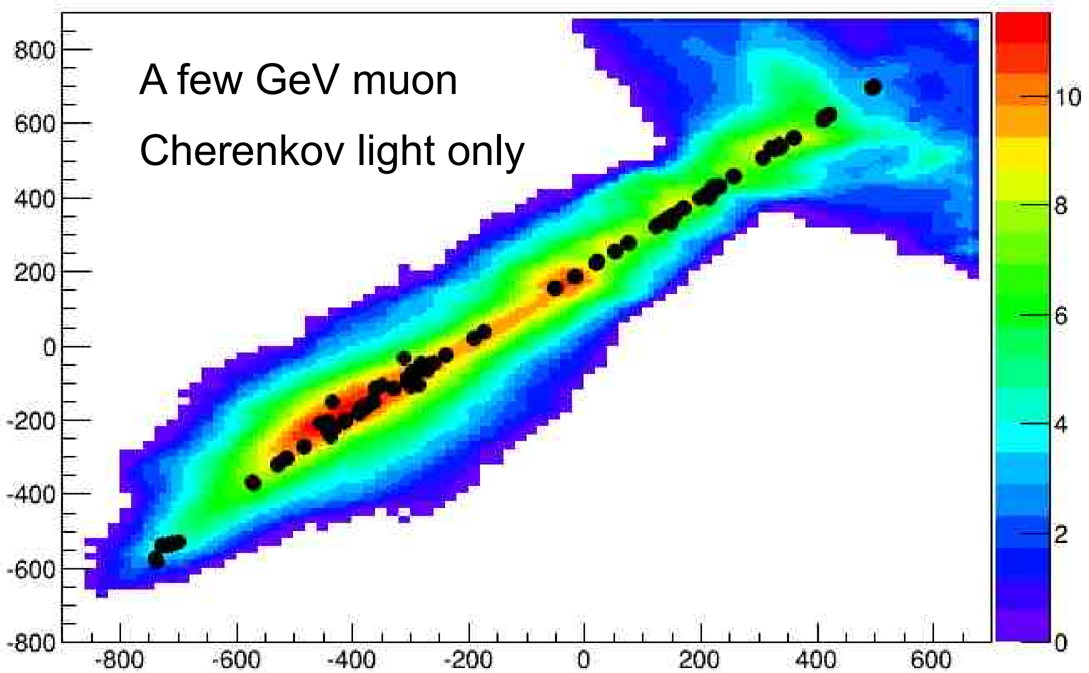
Result **after** removal of scattered light!

Cherenkov Light

- **Much better time information**
  → Good reconstruction without changes to algorithm
- **Additional information from Cherenkov-angle**
  → Need direction dependent local detection efficiency
  → Need dedicated Look-Up-Tables (LUT)

Result without dedicated LUTs

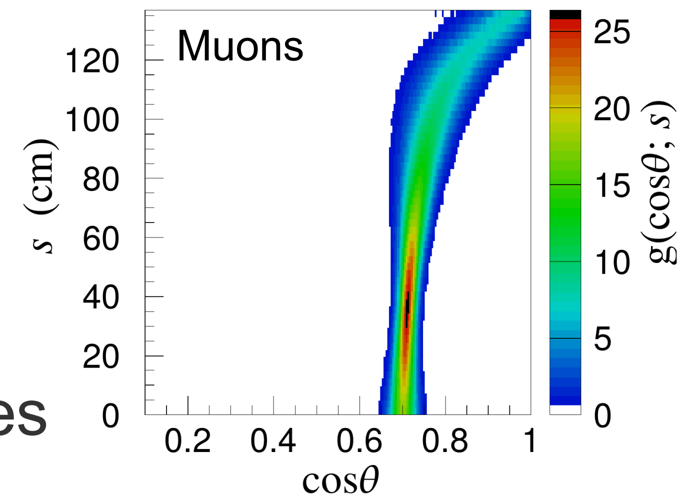
Work in progress!



Complication

- **Angular distribution of Cherenkov-light modified by multiple scattering**

  → Depends on particle typ

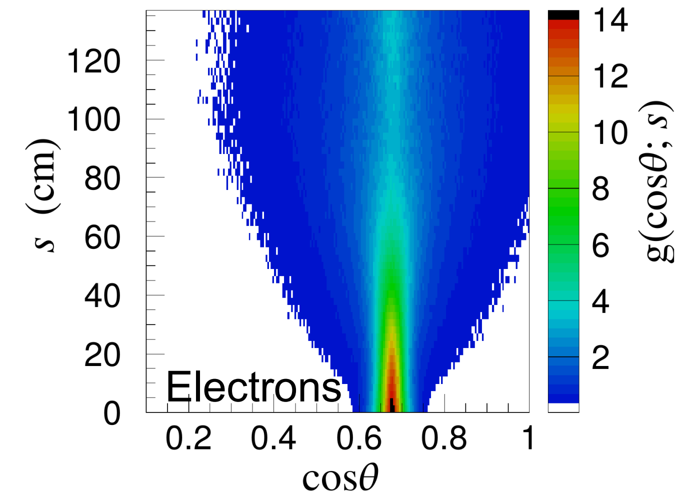


- **Consequences:**
  - Need different photon detection efficiencies

    + hypthesis about particle typ

I do not like this!

→ Another idea!



Plots from R. B. Patterson et al., Nucl.Instrum.Meth. A608 (2009) 206-224

Idea to Measure Cherenkov Light

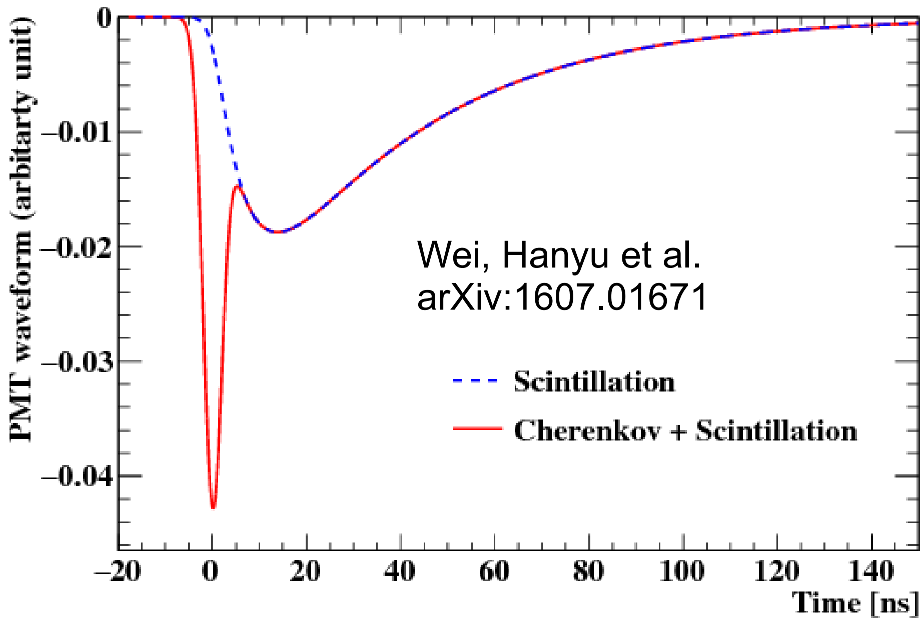
- **Assumption:** Already have a 3D topology
- **Observation:** Cherenkov-angle not used yet
- **Strategy:**
  - Go to each point on track/topology
  - Collect signal that match in time
  - Calculate angle of signal against direction towards vertex

    → Angular spectrum

    → Get Cherenkov-angle, Cherenkov-intensity and the spread of its distribution

Cherenkov vs. Scintillation Separation

- **What happens if I have both light species?**
- **Critical point:**
  - Both light sources have very different timing behaviors
  - The whole reconstruction is based on good time information
  - Attributing the wrong time distribution to a signal will automatically introduce a bias



Cherenkov vs. Scintillation Separation II

- **Could use similar strategy as for scattered light**
  - Assign every photon a probability to be Cherenkov-light based on results of previous reconstruction

→ **Separation seems possible**

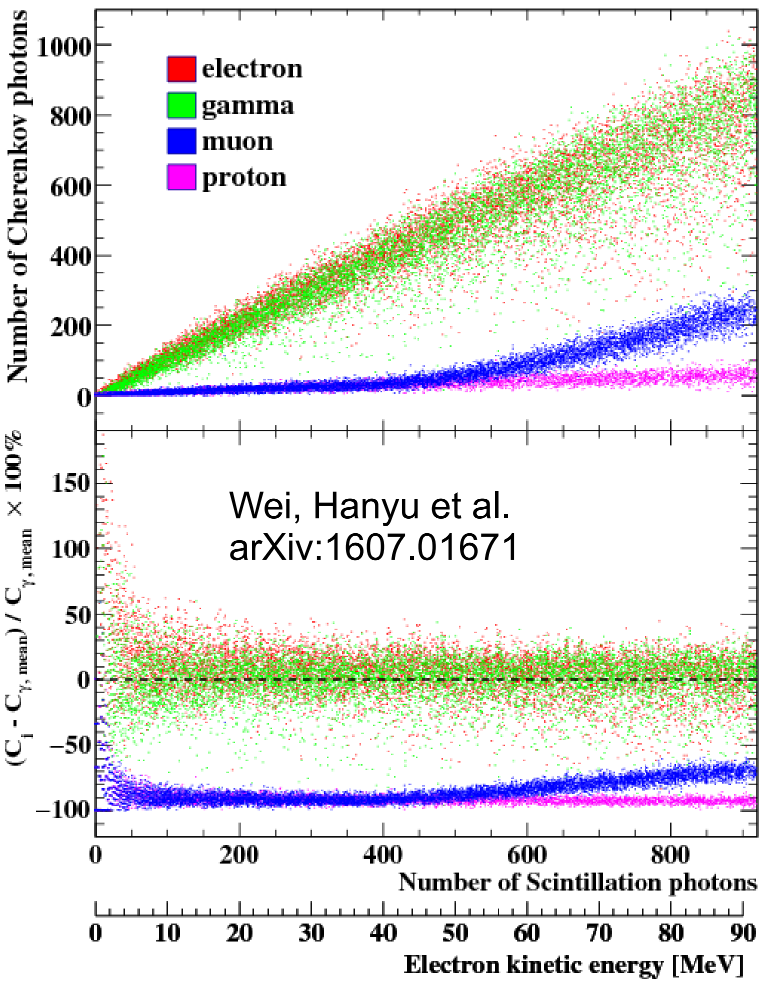
- **Will depend on:**
  - Cherenkov/Scintillation light ratio
  - Time responds of scintillator & sensors
  - Wavelength dependencies

} **THEIA**

Work in progress!

Advantages of Cherenkov Separation

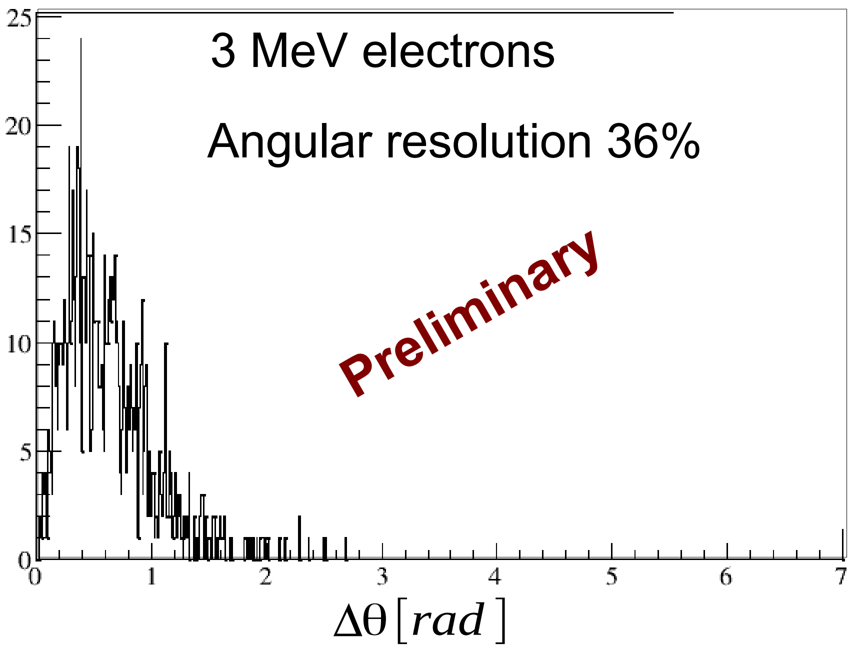
- **Can improve spatial resolution if fast light sensors are used**
- **Contains additional information**
  - Angle and intensity → Particle velocity
  - Sharpness of ring
    → Showers or multiple scattering
- **Scintillation light delivers**
  - Energy deposition
  - Low threshold
- **Together:** Particle identification
  + direction



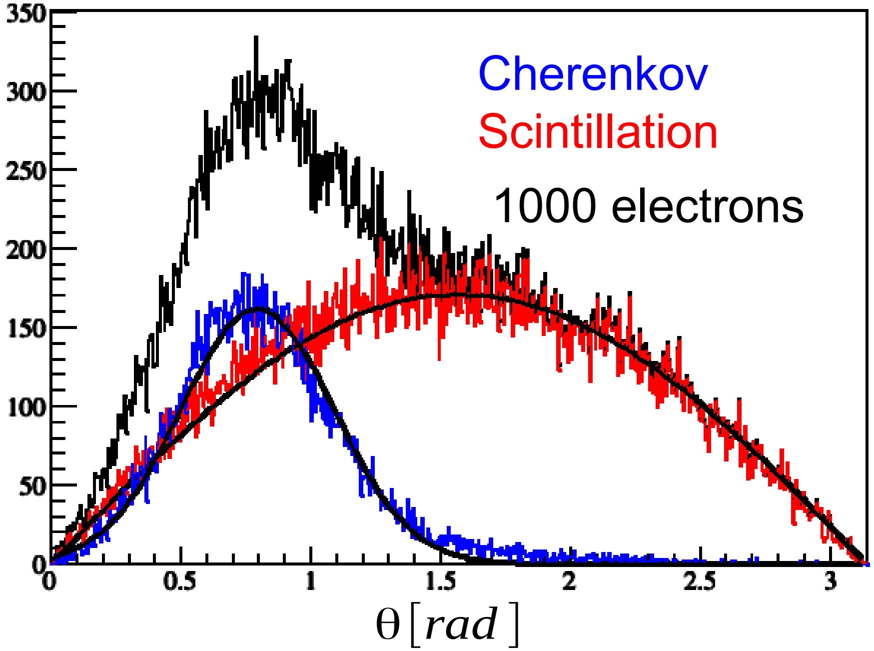
First Result Directionality

- **Theia with 5% water-based liquids scintillator (WBLS)**
- **Used directional sum**
- **Angular resolution depends on vertex resolution**

→ Resolution needs to be confirmed with full reconstruction chain



(From full Theia MC+Reco including scattering)



(Just for illustration, does not include scattering)

Summary/Conclusion

- **3d topological reconstruction**
  - Versatile tool
  - A lot of potential
  - Needs to get faster (working on it)
  - Need to go to waveforms

- **Cherenkov separation**
  - Non-trivial
  - Seams to be feasible
  - Would have a lot of advantages

Backup slides

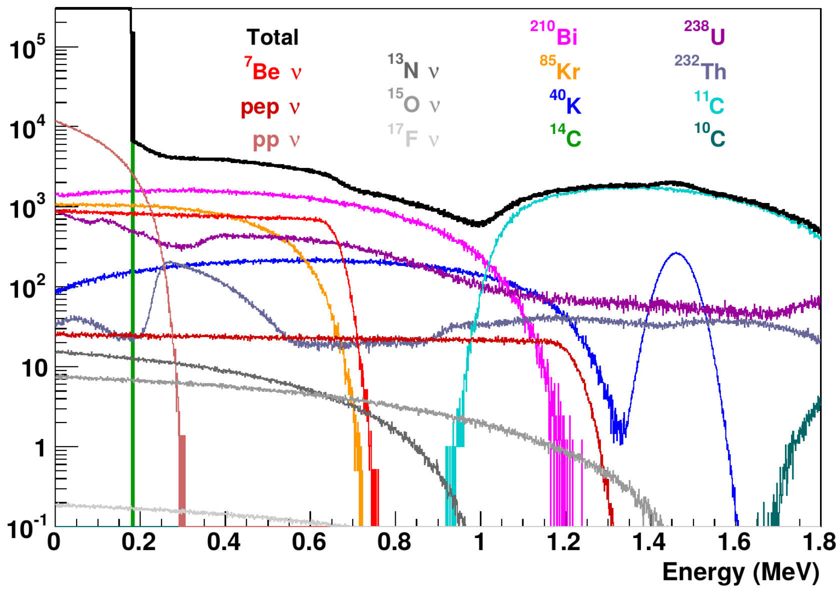
Solar Neutrinos in JUNO

- **Main challenge:**
  - Radio-purity
  - Cosmogenic background, e.g. long living spallation ^{11}C
- **Potential:**
  - ^{7}Be and low tail ^{8}B (large mass)
  - Discriminate pp from ^{14}C (energy resolution)

Internal radiopurity requirements		
	baseline	ideal
^{210}Pb	5×10^{-24} [g/g]	1×10^{-24} [g/g]
^{85}Kr	500 [counts/day/kton]	100 [counts/day/kton]
^{238}U	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{232}Th	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{40}K	1×10^{-17} [g/g]	1×10^{-18} [g/g]
^{14}C	1×10^{-17} [g/g]	1×10^{-18} [g/g]
Cosmogenic background rates [counts/day/kton]		
^{11}C	1860	
^{10}C	35	
Solar neutrino signal rates [counts/day/kton]		
pp ν	1378	
^{7}Be ν	517	
pep ν	28	
^{8}B ν	4.5	
$^{13}N/^{15}O/^{17}F$ ν	7.5/5.4/0.1	

KamLAND-like Borexino-like

JUNO collab., arXiv:1507.05613



Baseline background

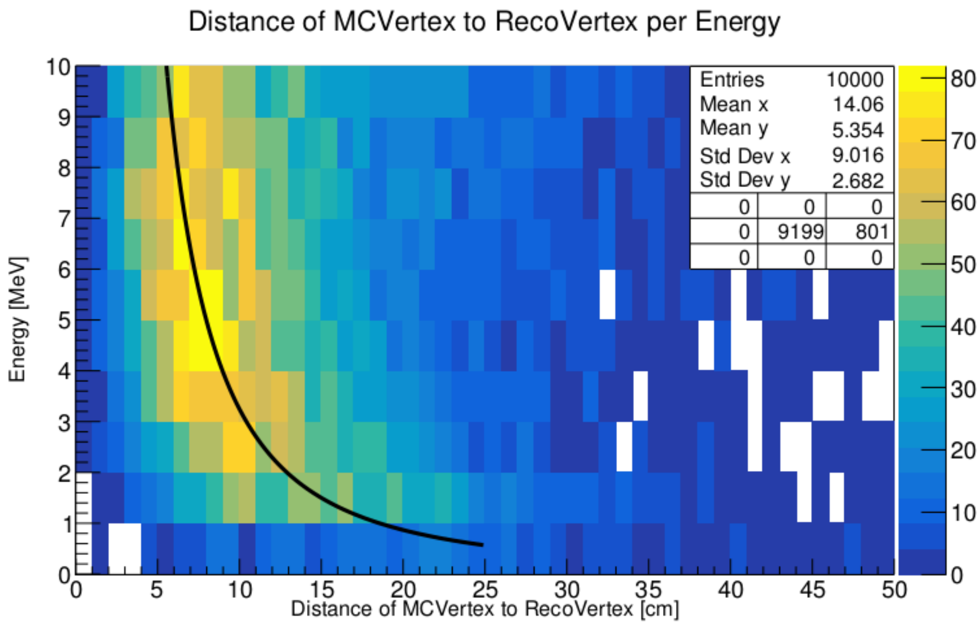
Vertex Reconstruction

- Use backtracking-like algorithm to find primary vertex

  (i.e. signals matching in time corresponding to position)
- Results for low energies already within expectations
- For high energy: Average distance to track 30 cm

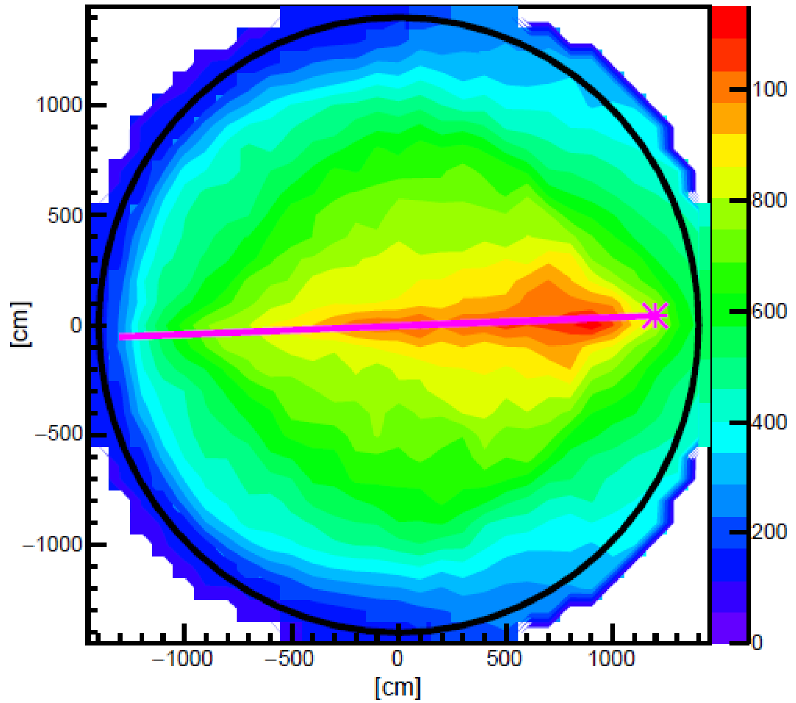
  → Room for improvement

  (likelyhoods methods in LENA yielded <10 cm vertex resolution)



Master thesis of David Meyhöfer

XY-projection



What Kind of Detector Would be Best?

- Good balance between amount of Cherenkov and Scintillation light

  → WbLS or lightly doped oil-based LS

- Very fast sensors for Cherenkov separation

  → LAAPD (time resolution 50ps)

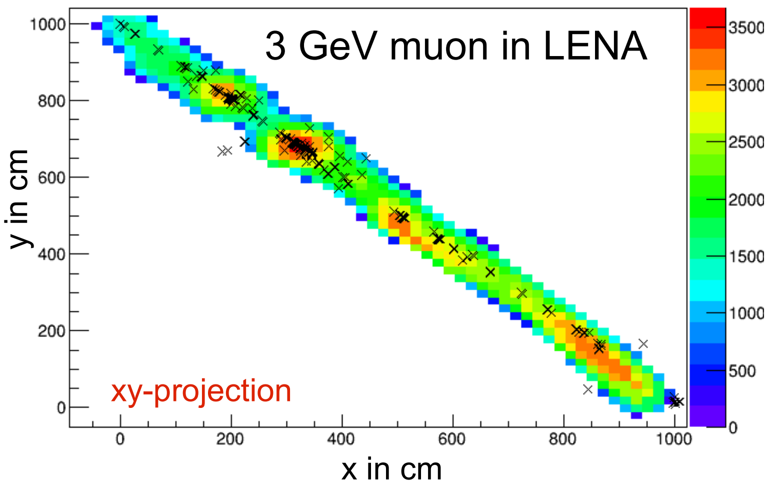
- Single photon timing

  → Pixels of LAPPD

- Fast scintillation light, but not too fast for Cherenkov separation

→ **THEIA-like detector!**

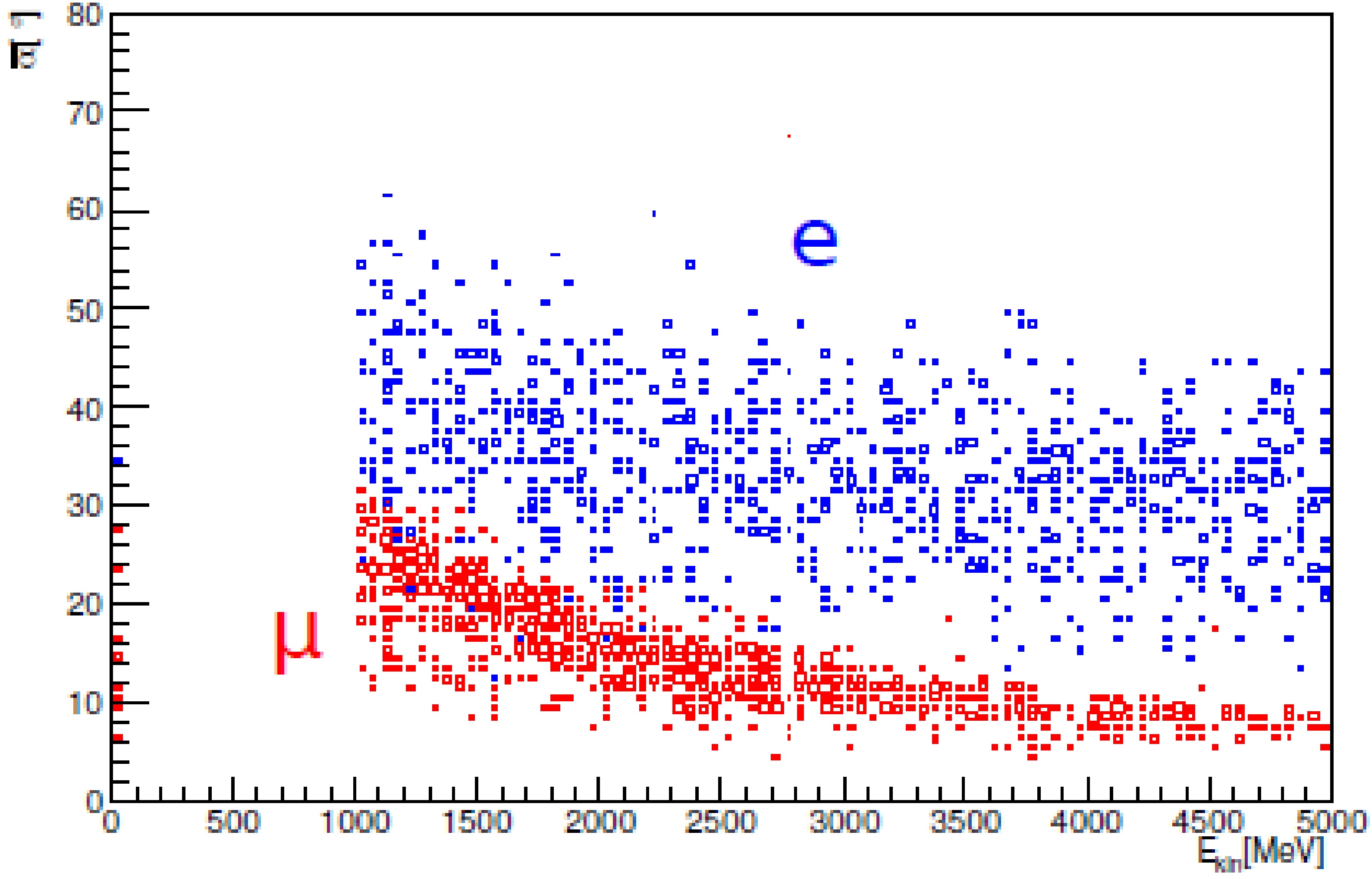
Reconstruction: Overview



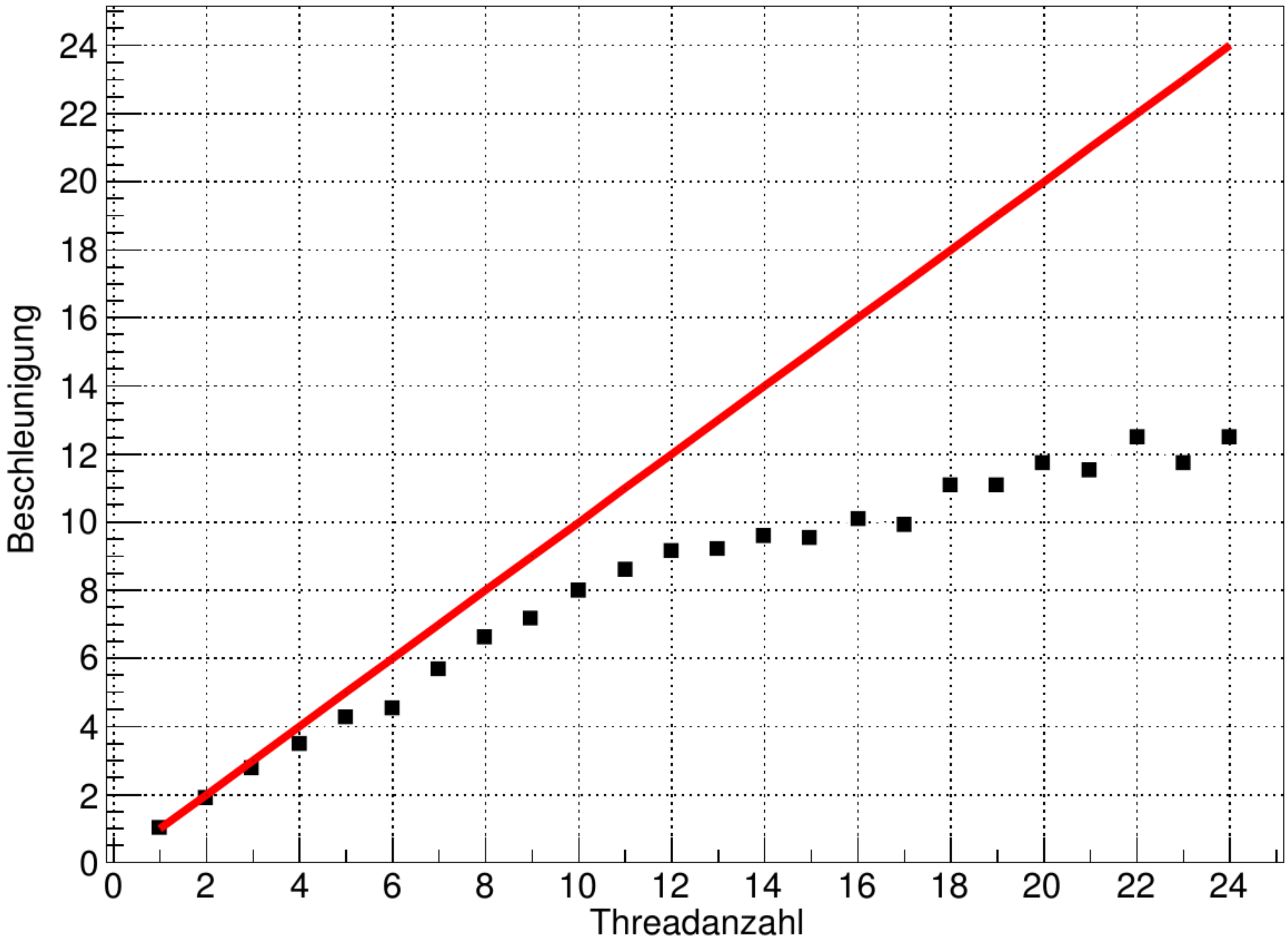
- 3D toplogical reconstruction
  → Spatial distribution of emission density
- Using full time information
- Iterative process
  - Using a probability mask (PM)
  - Usually result of previous iteration
- Operating on a grid → bin size is important
- Only assumptions:
  - One known reference point (in space and time)
  - Single photon hit times available

- **Potential at high (GeV) and low (MeV) energies**

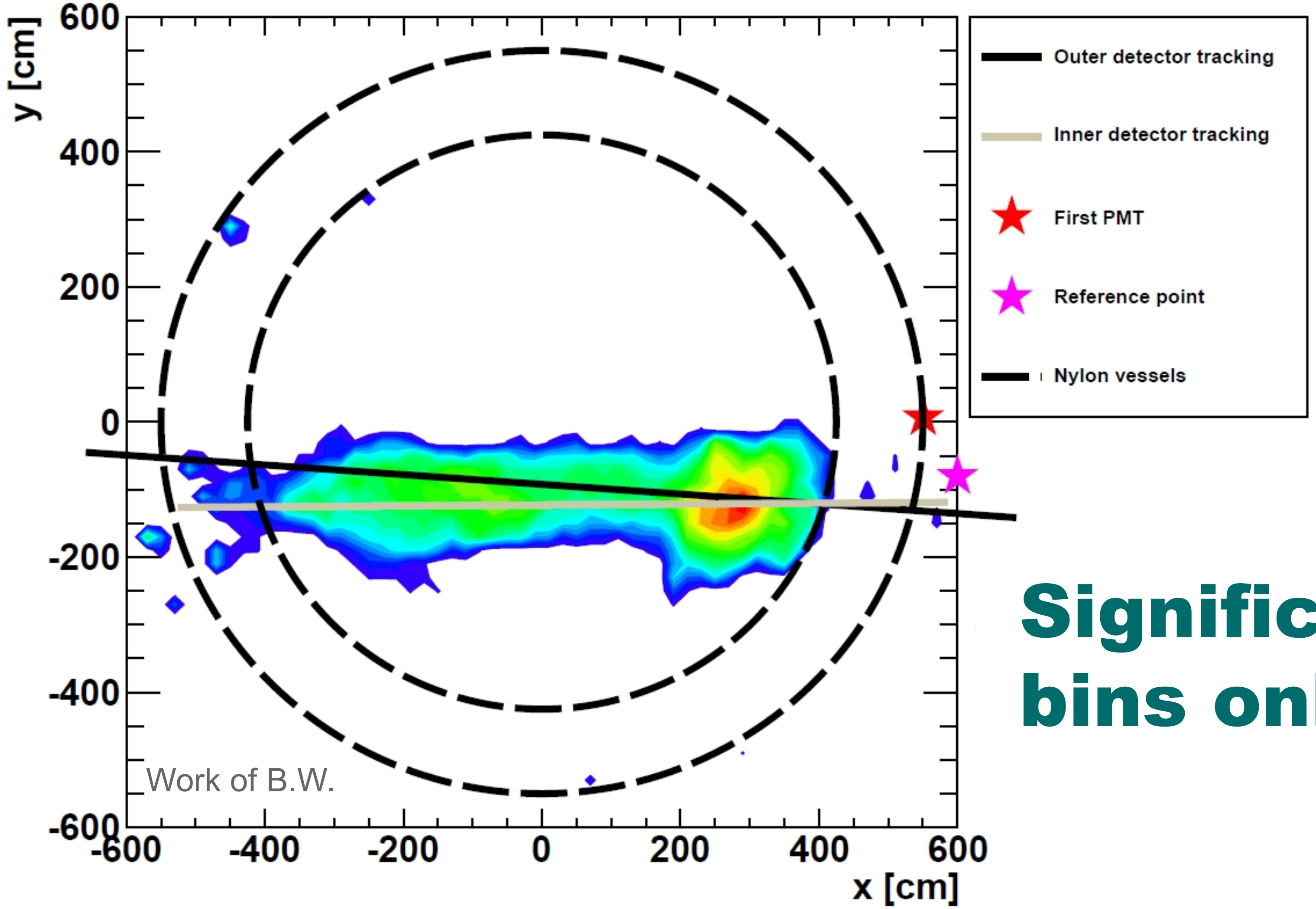
Mu/e-Separation: Angular Width



Parallel Computing



Example: Real Borexino Data



Significant bins only

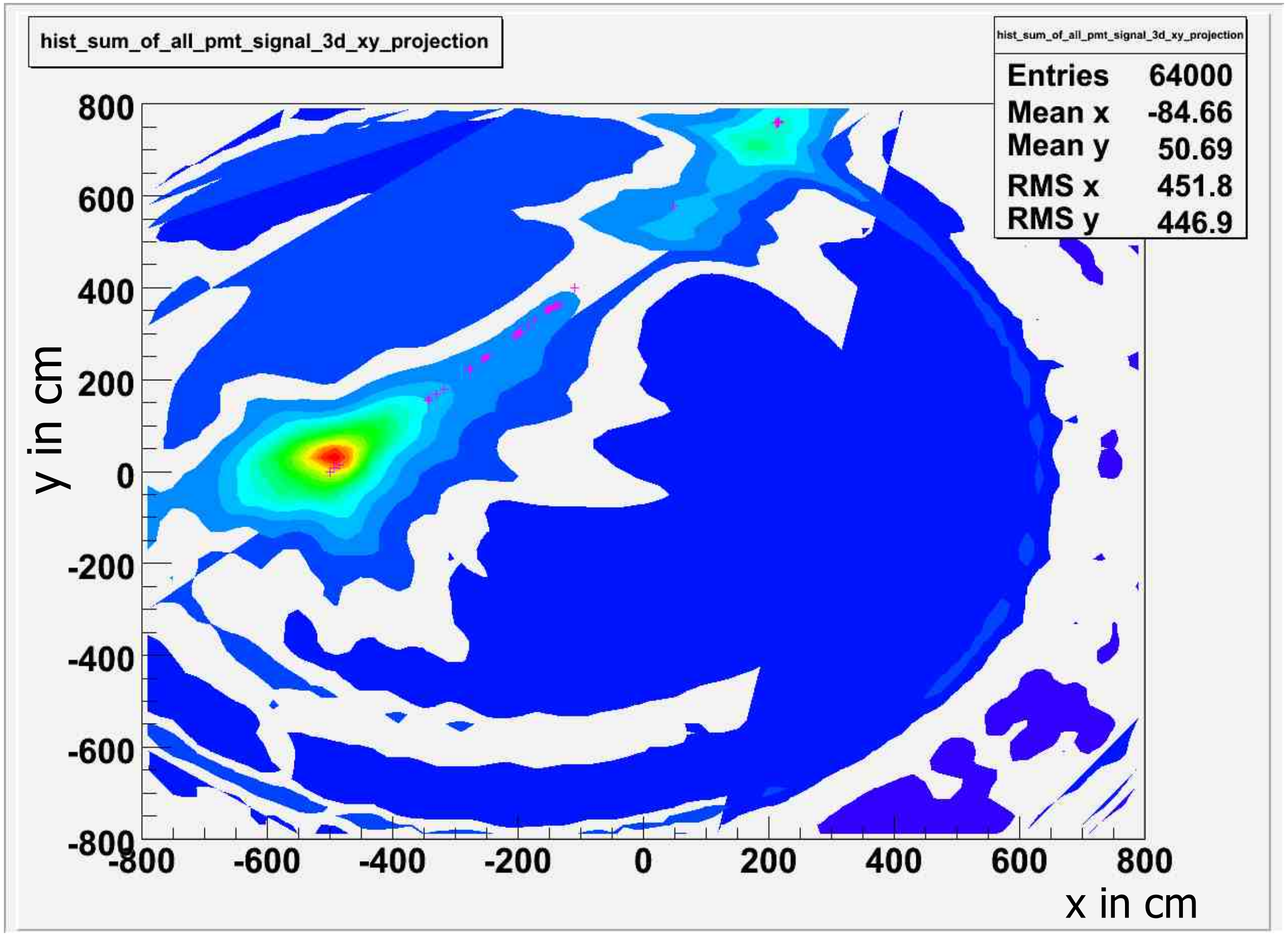
Used first hit times only!

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

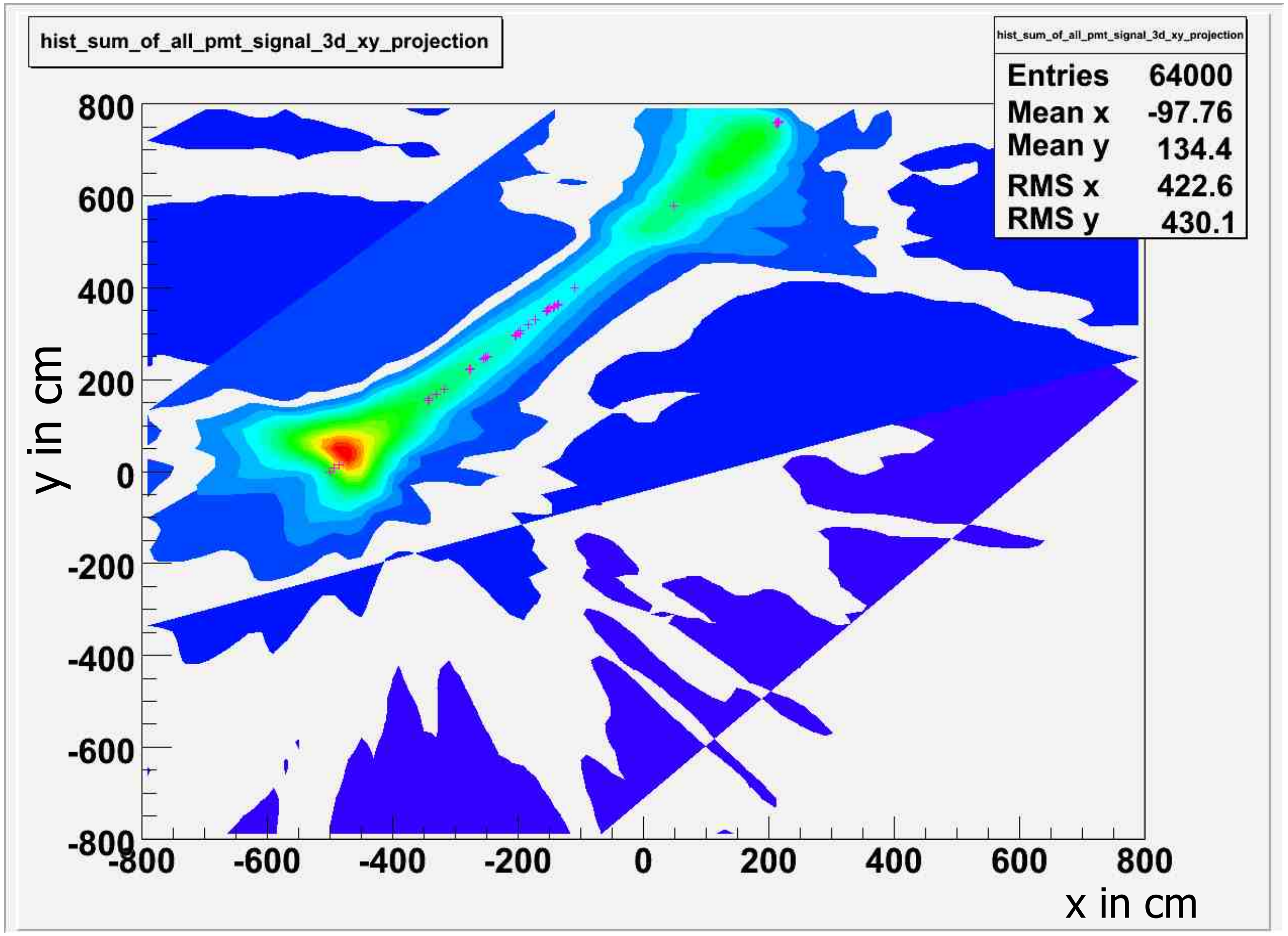
- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**



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

2GeV Muon, First Hit, Backwards

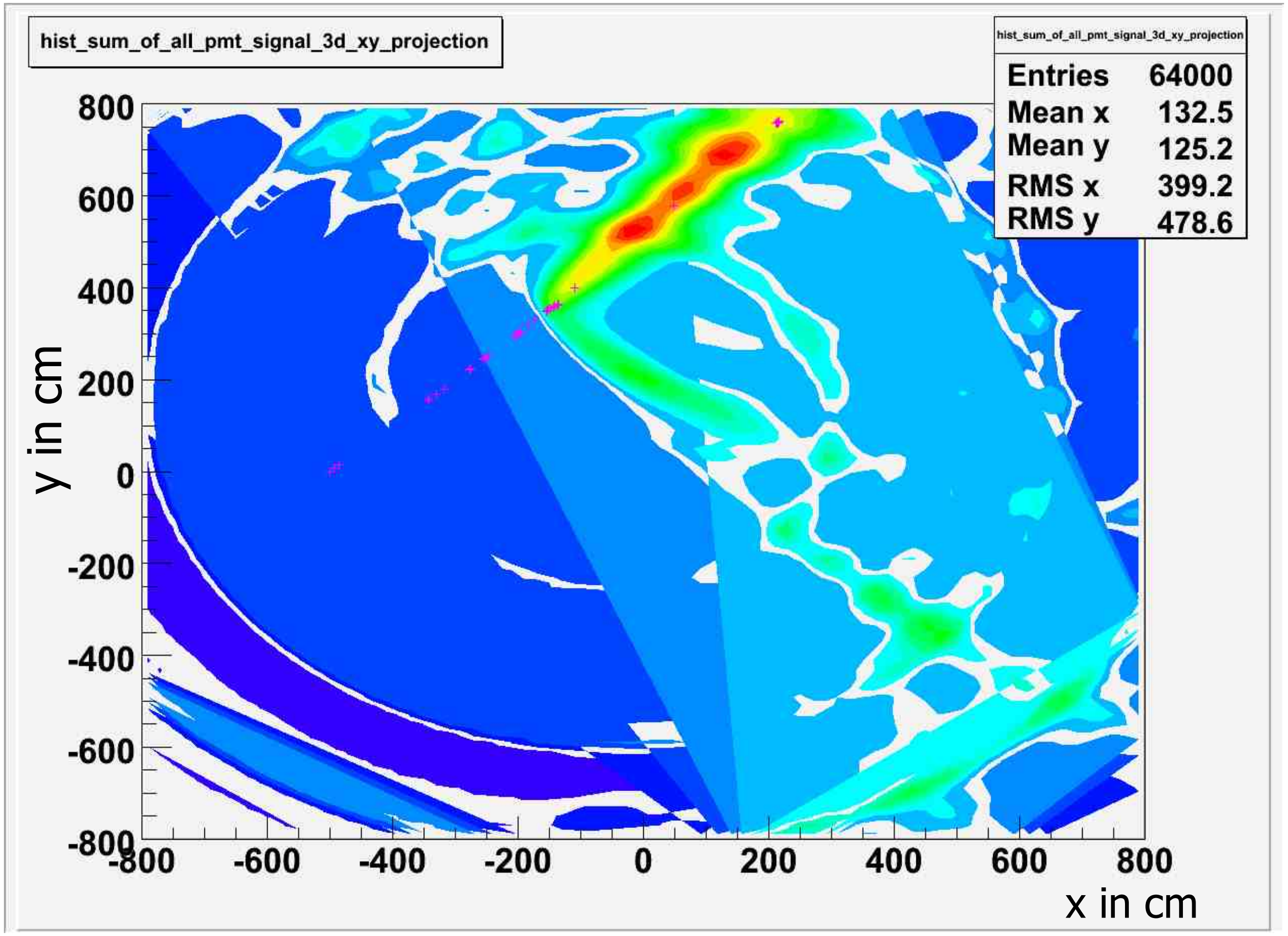
- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**



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

2GeV Muon, First Hit, from Middle

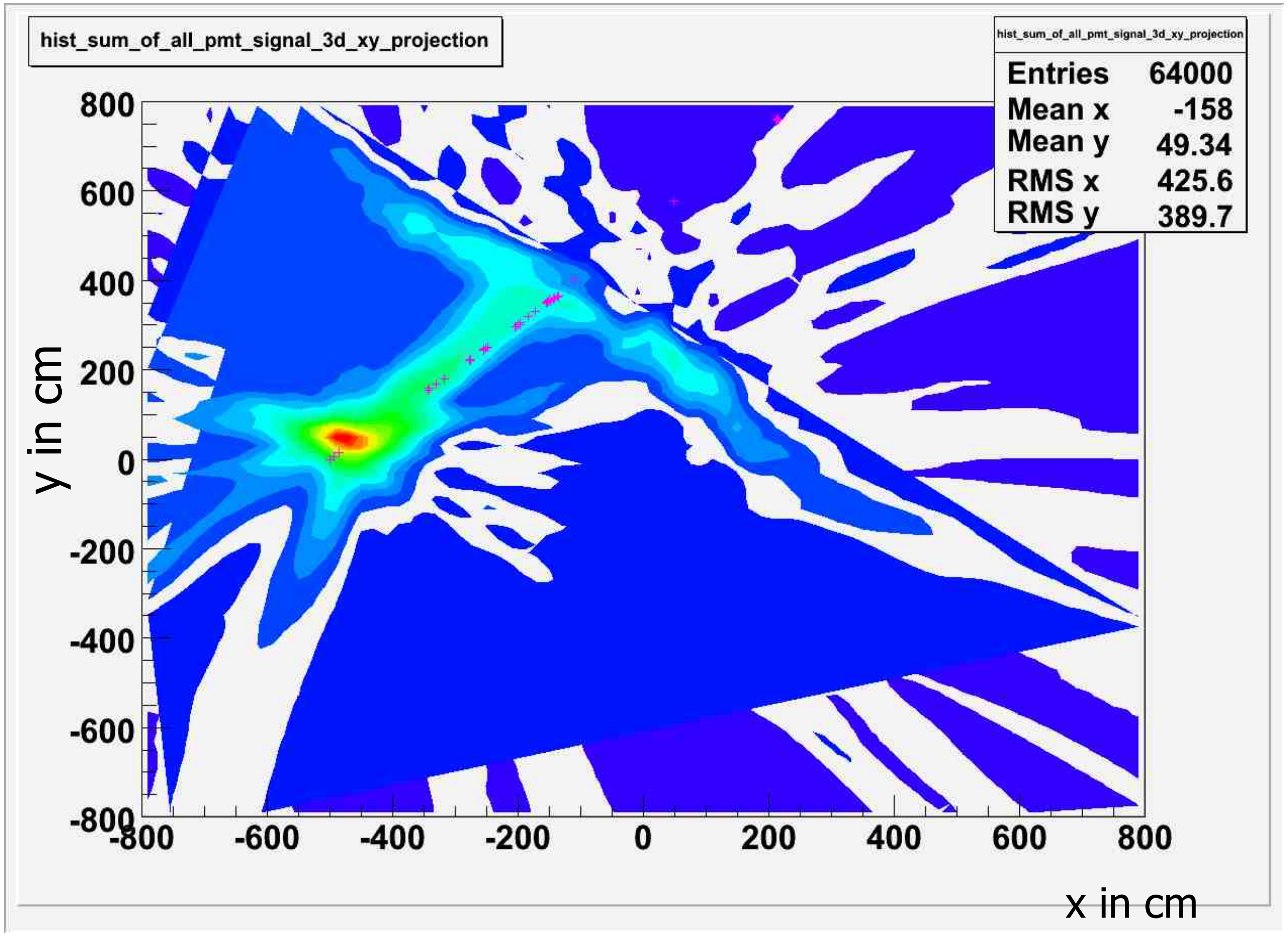
- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**



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.)**



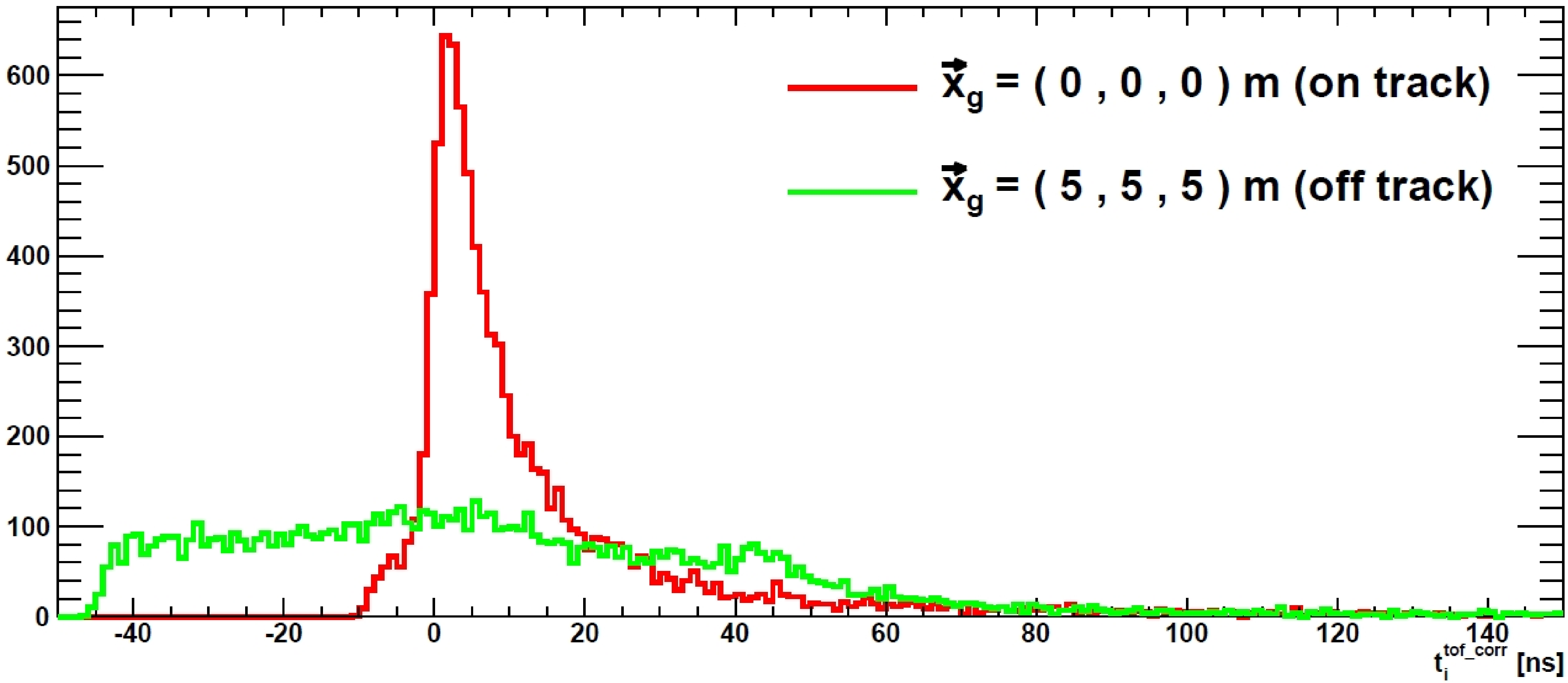
10% of PMTs at +-500 cm in z with respect to vertex

Vertex Finding/Backtracking

Basic idea:

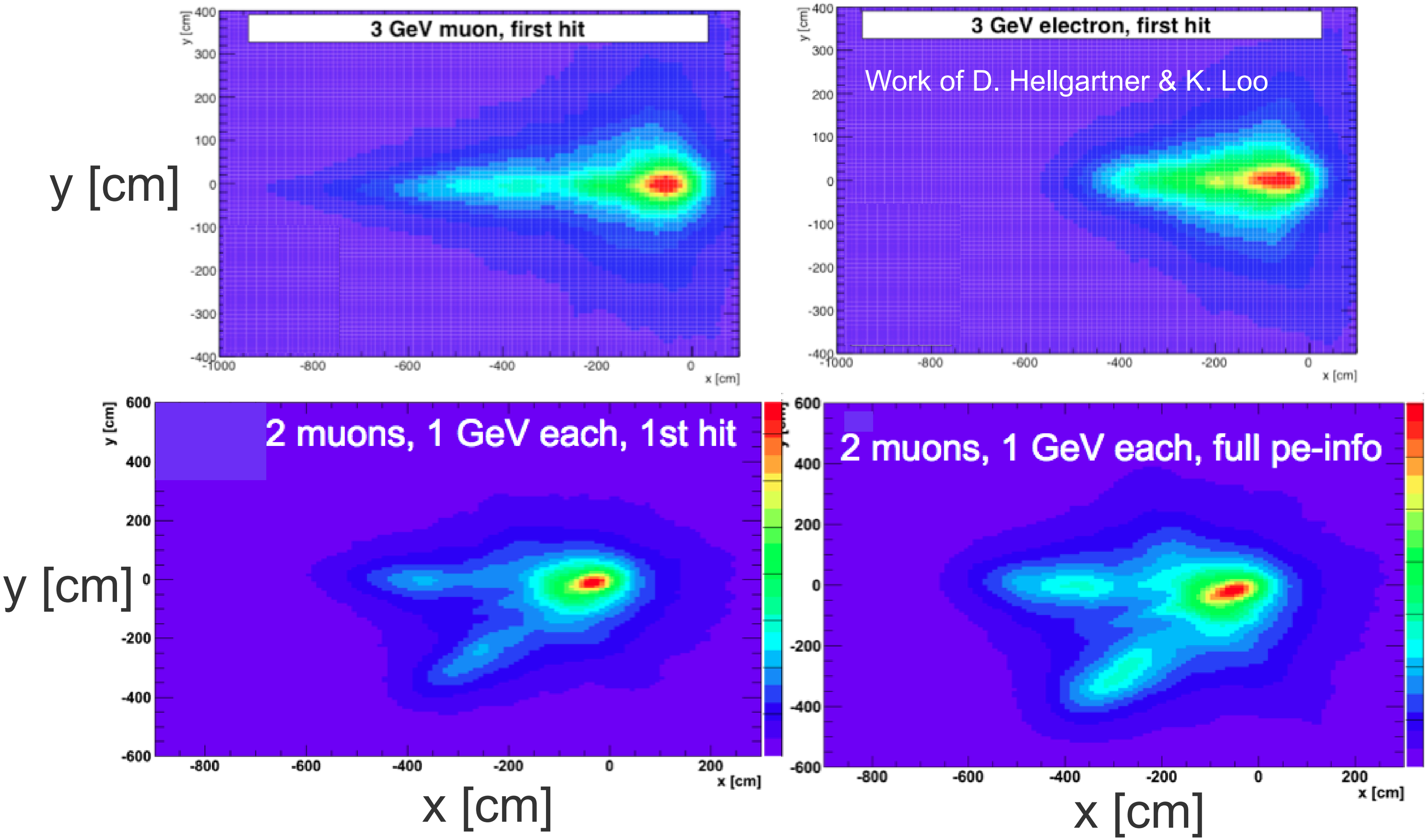
from Domenikus Hellgartner

- 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

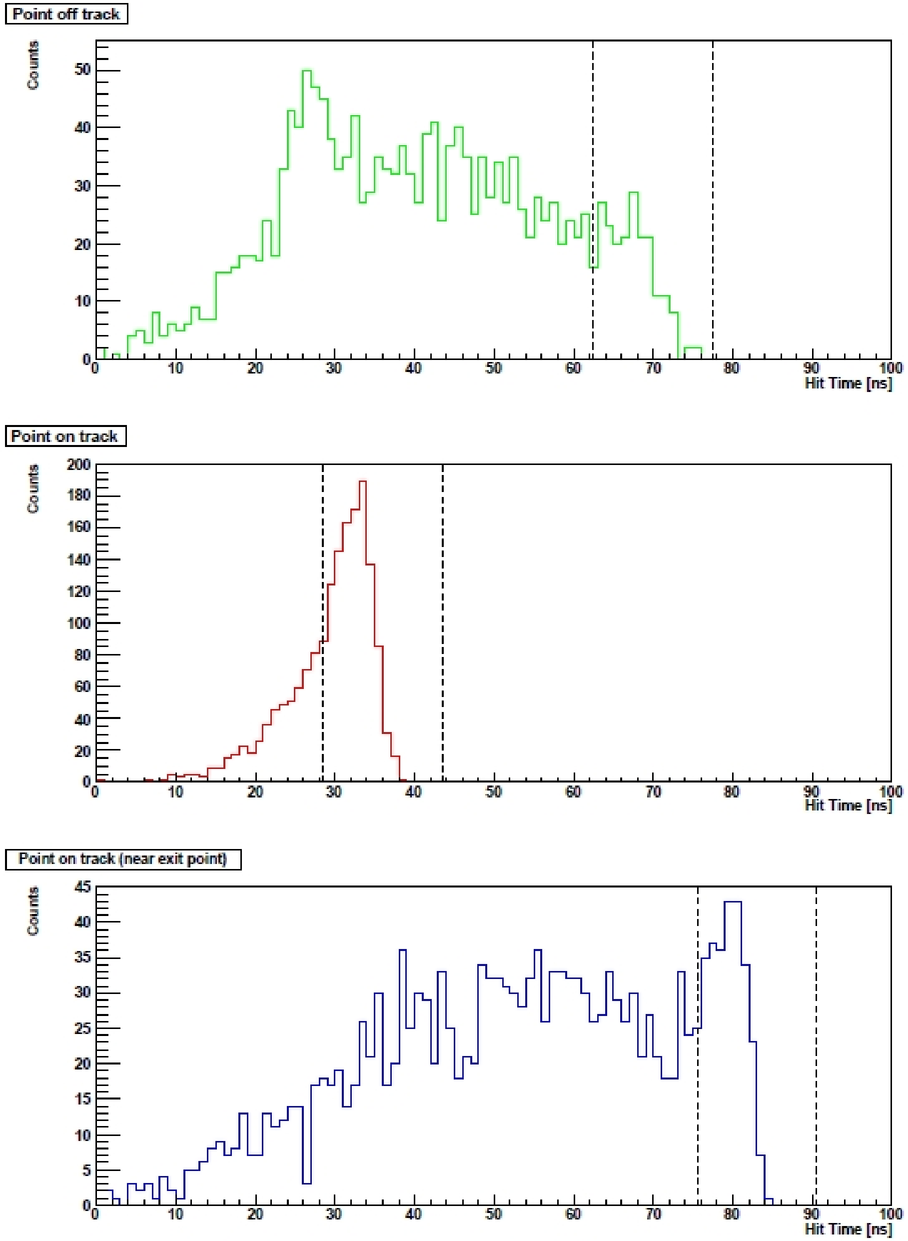


How to improve Backtracking

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

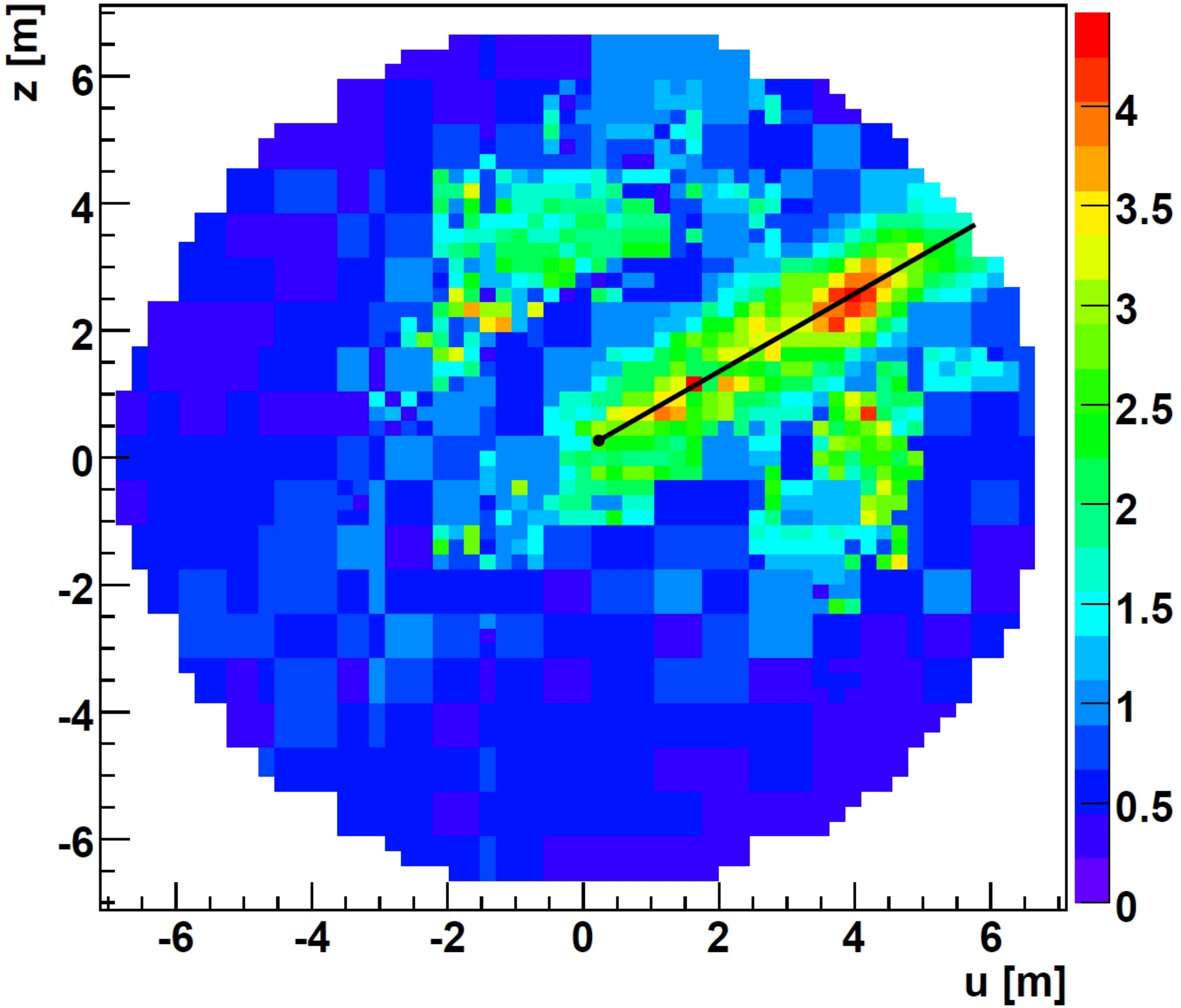
→ Need to look more closely at timing patter (tof corrected)

→ **whole track**

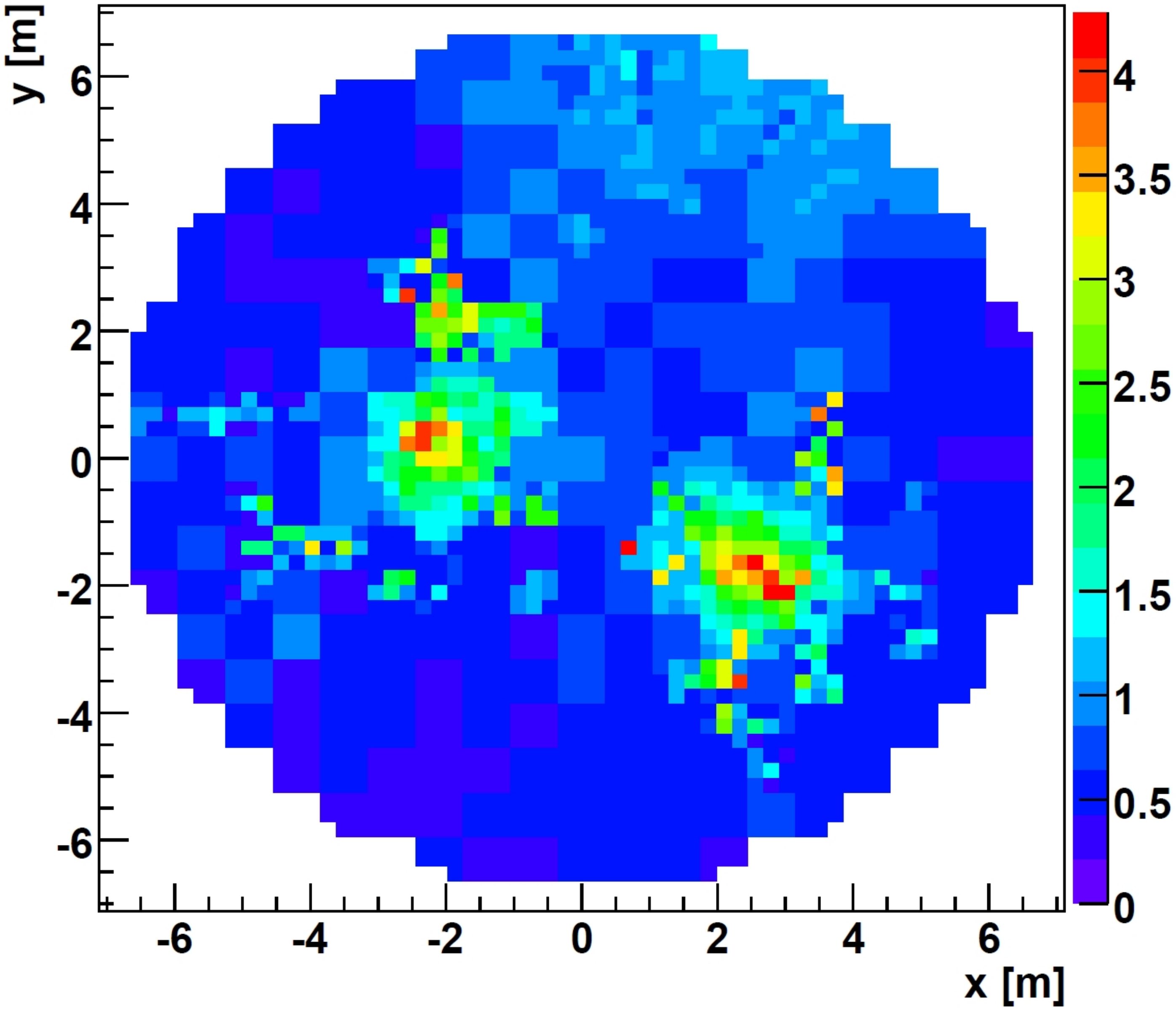


	Backtracking	Inner Detector Tracking	Outer Detector Tracking
σ_α [°]	1.63 ± 0.10	2.44 ± 0.19	3.01 ± 0.15
σ_y [cm]	35 ± 4	36 ± 5	28 ± 7
σ_z [cm]	38 ± 4	31 ± 6	45 ± 7

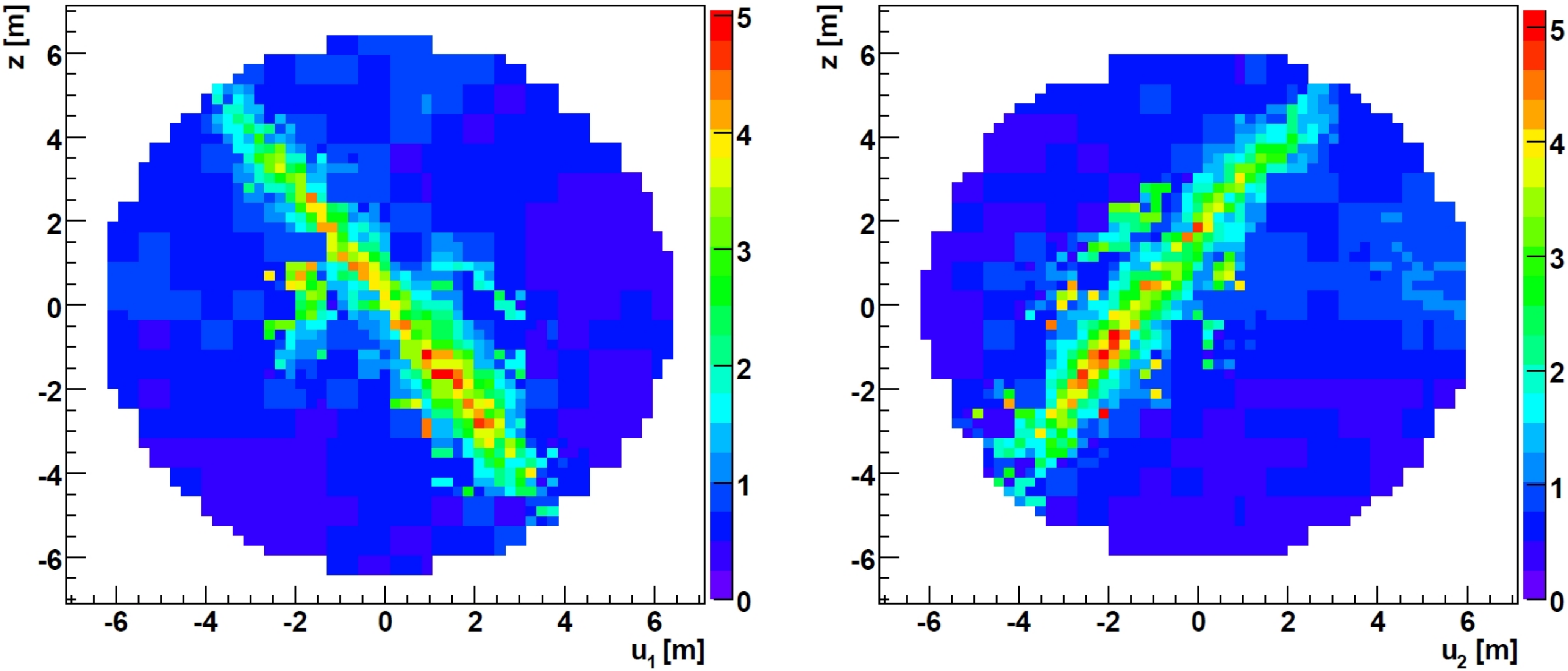
Stopped Muon in Borexino



Double Muon Event in Borexino



Double Muon Event in Borexino

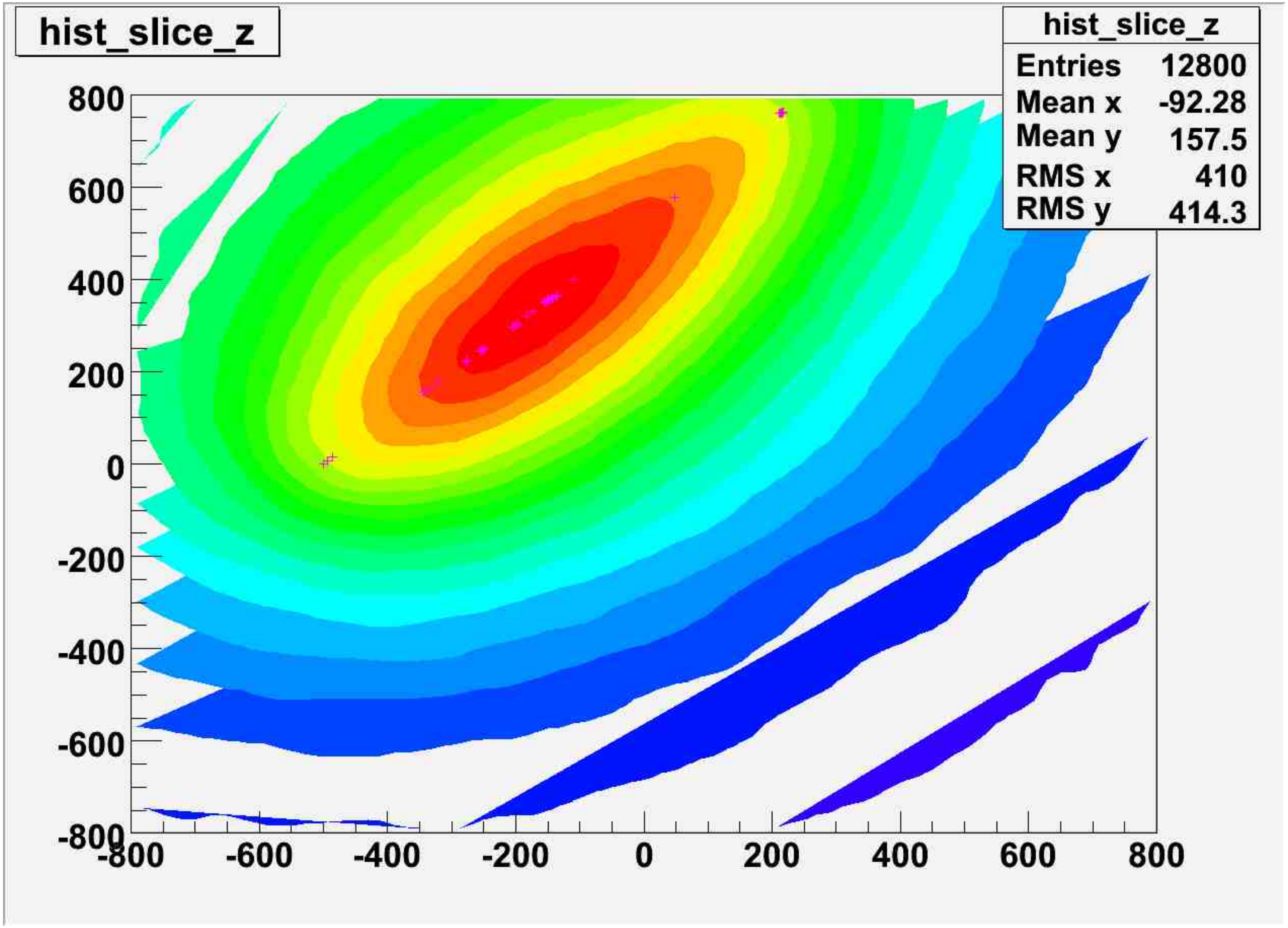


Both tracks cut out!

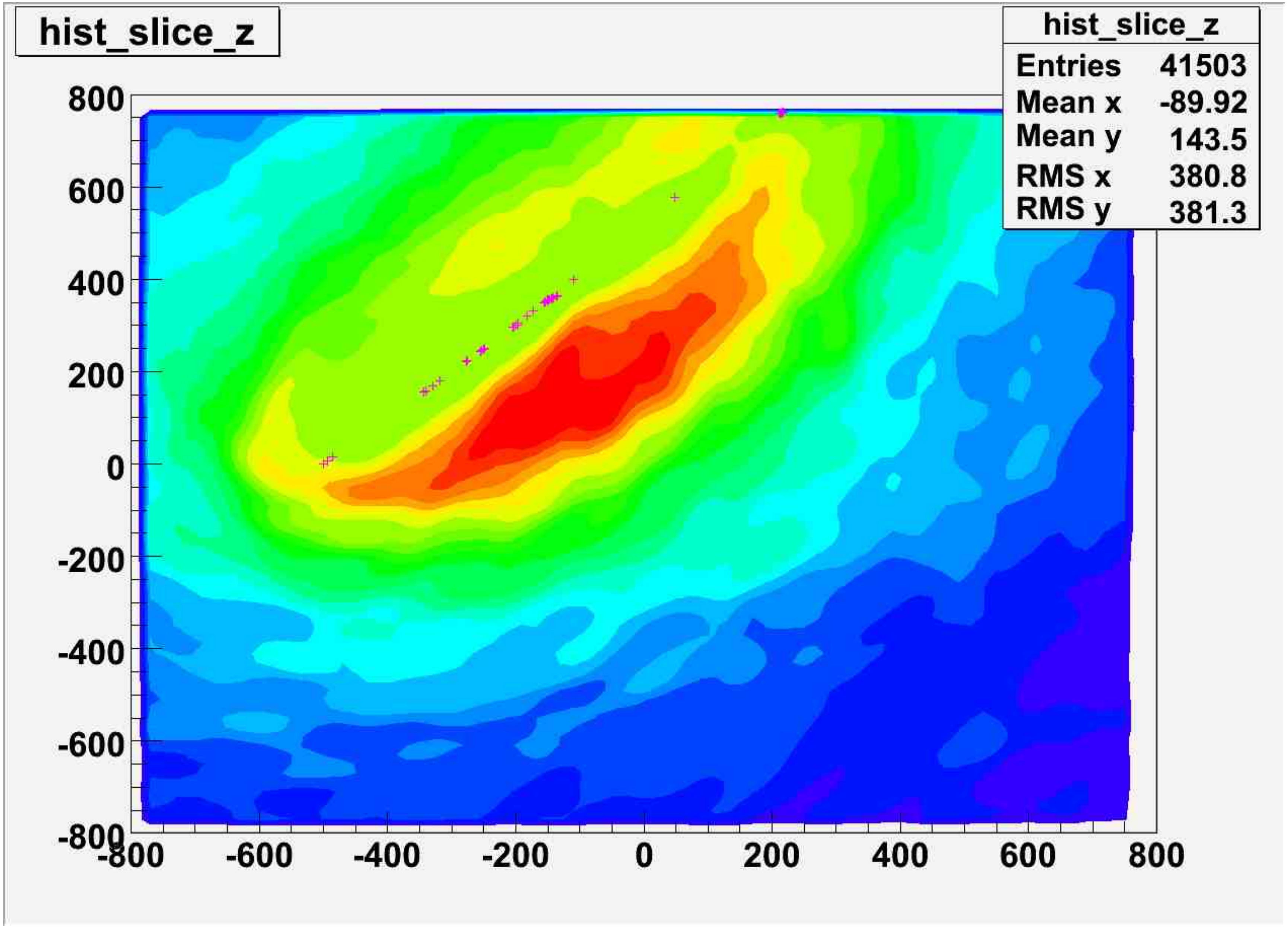
The power of the 4th dimension

4d Canny Algorithm

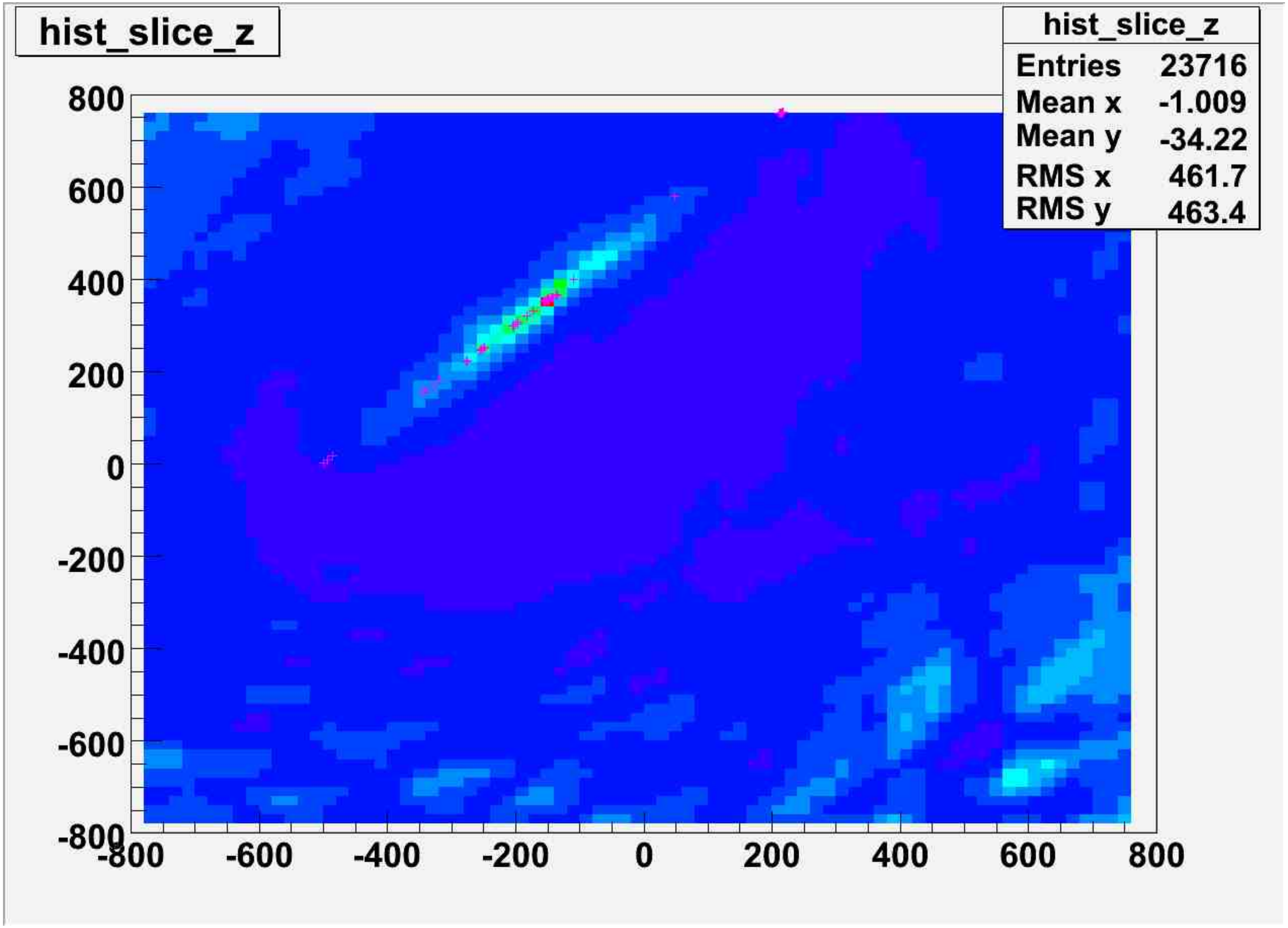
The Reco Result (266 PMTs)



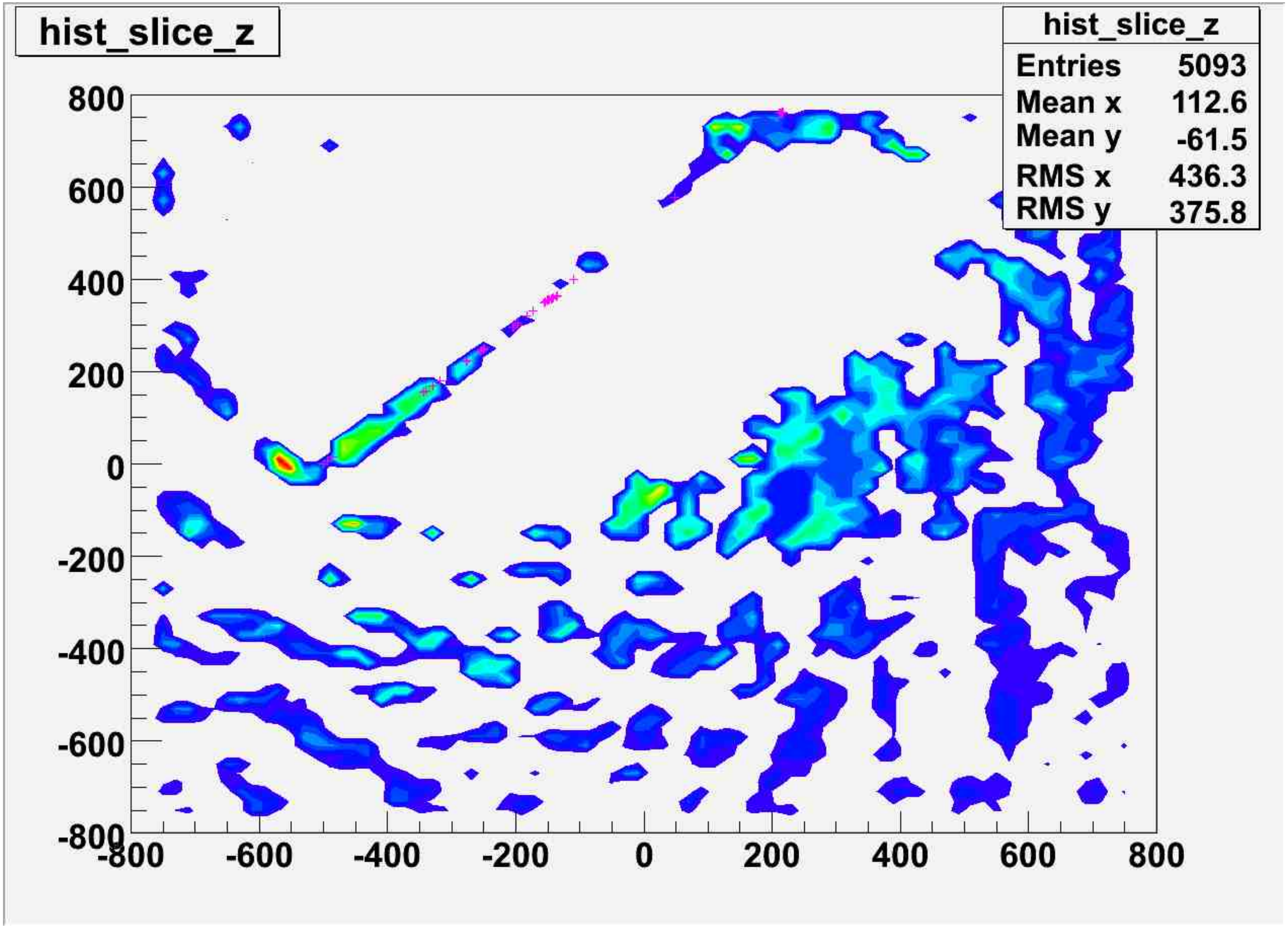
4d-Sobel Result



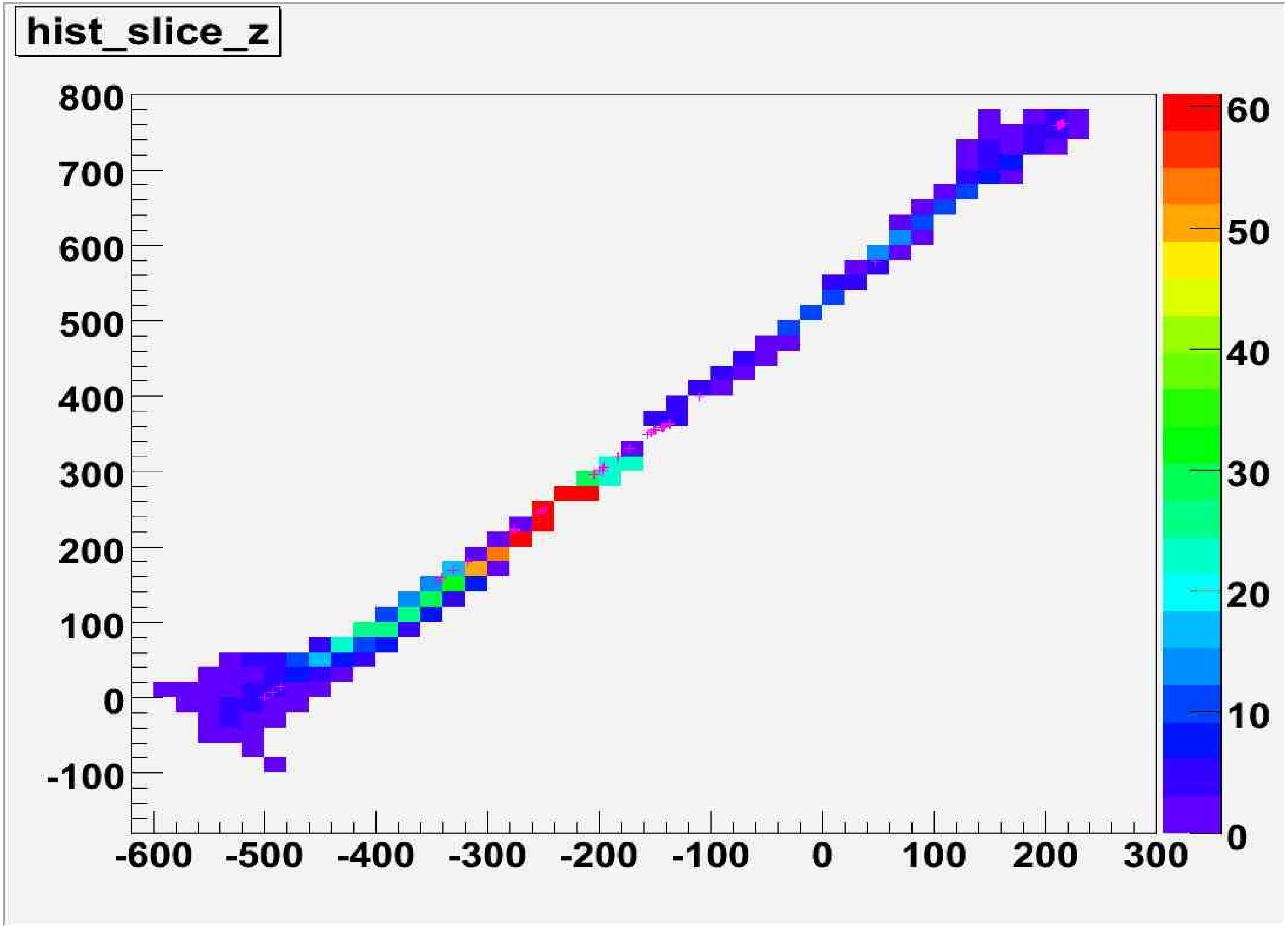
Reco Result divided by 4d-Sobel



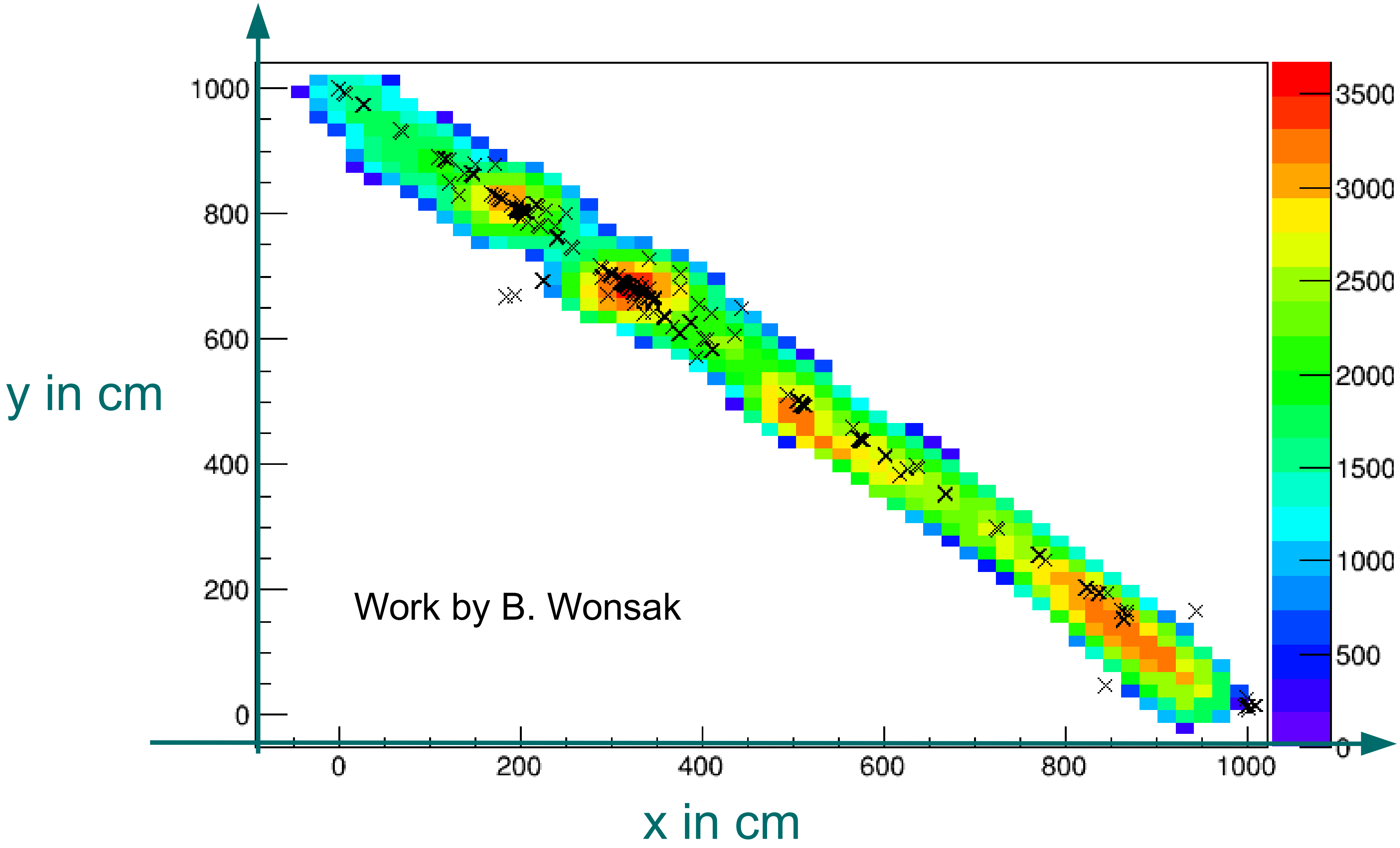
Minima of 4d-Sobel



Result after Follow-up



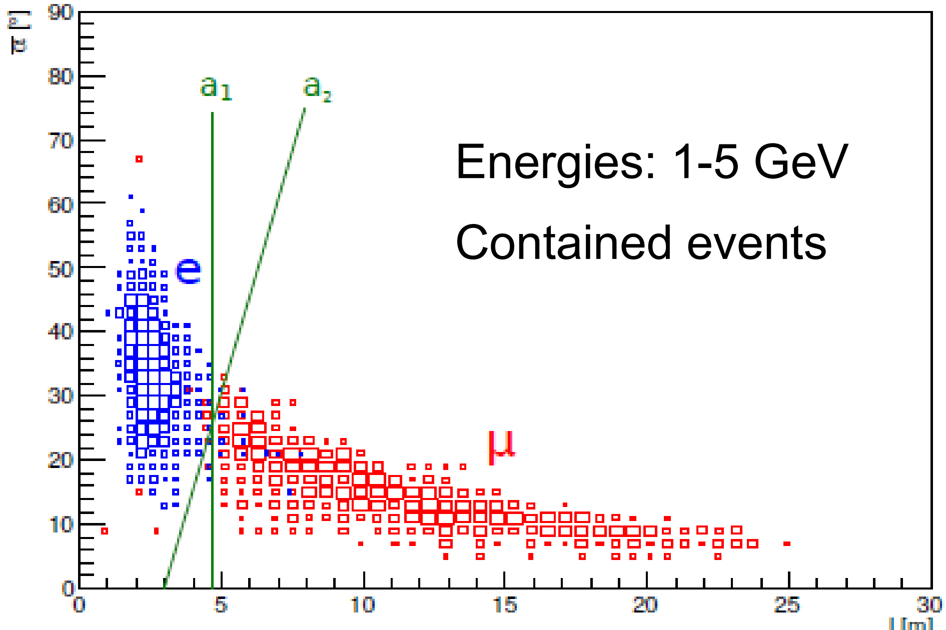
Result for 3GeV Muon Track



Electron/Muon Separation

- **Used two parameters:**
  - Length of track
  - Angular width of track
    (with respect to reference point)

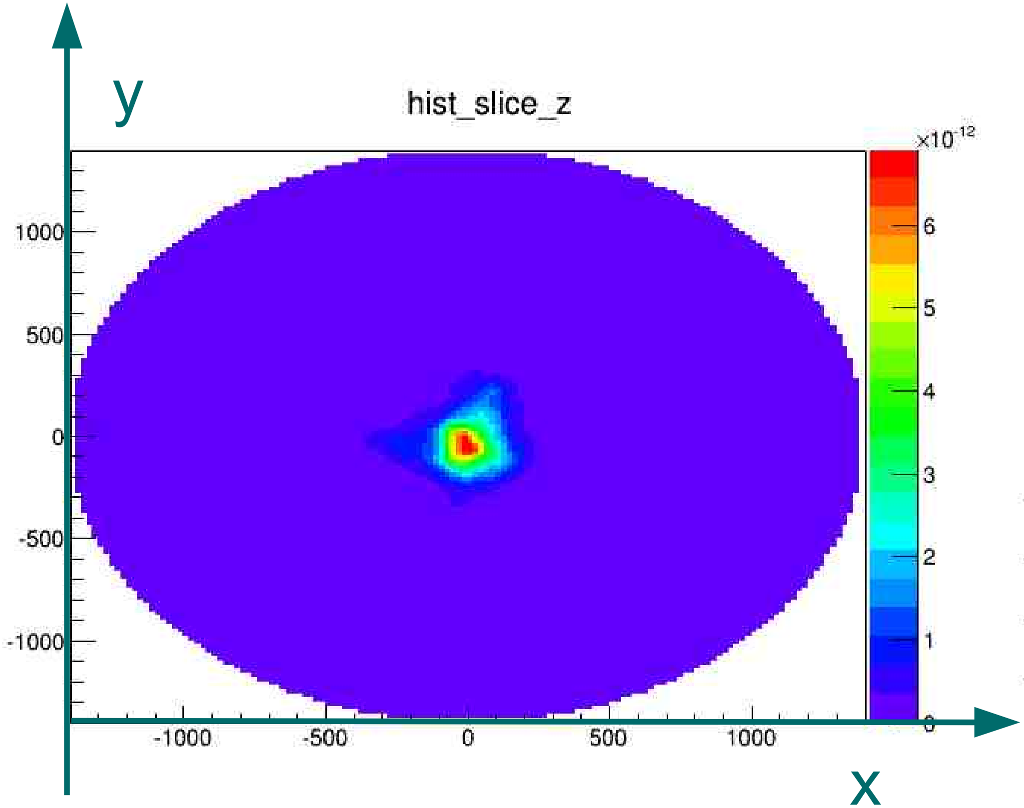
- **Result:** 1.5% impurity, 98% efficiency



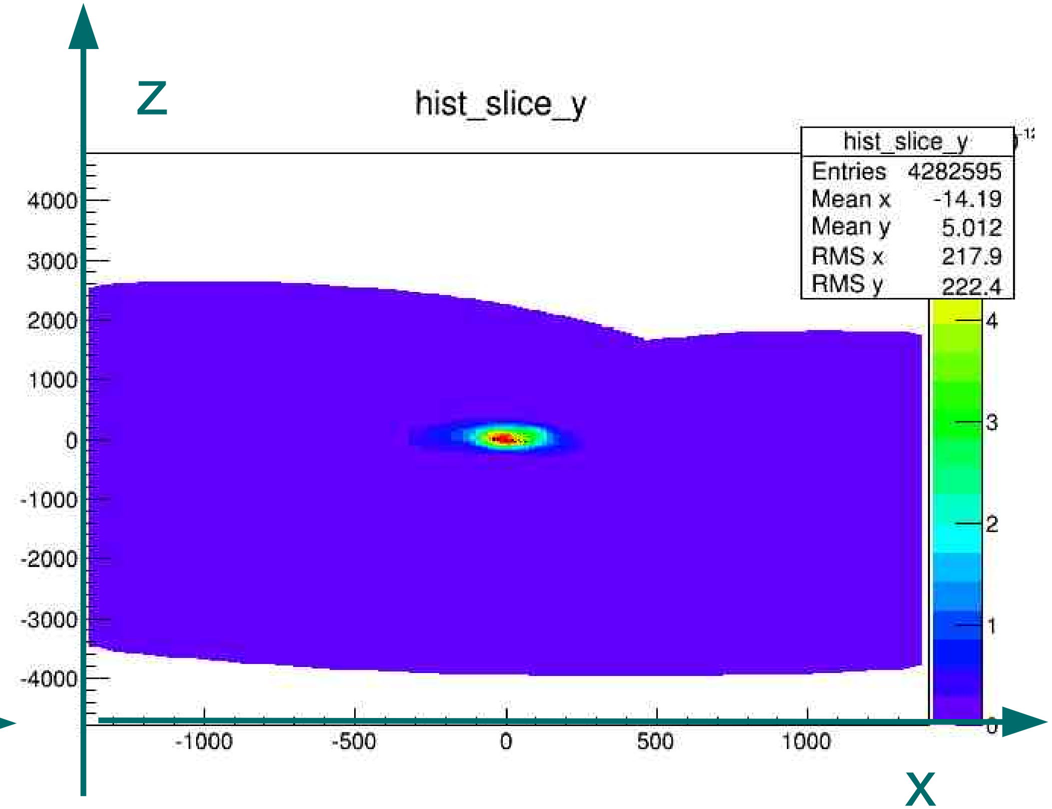
Bachelor thesis of Daniel Hartwig

Result 2nd Iteration

z-projection



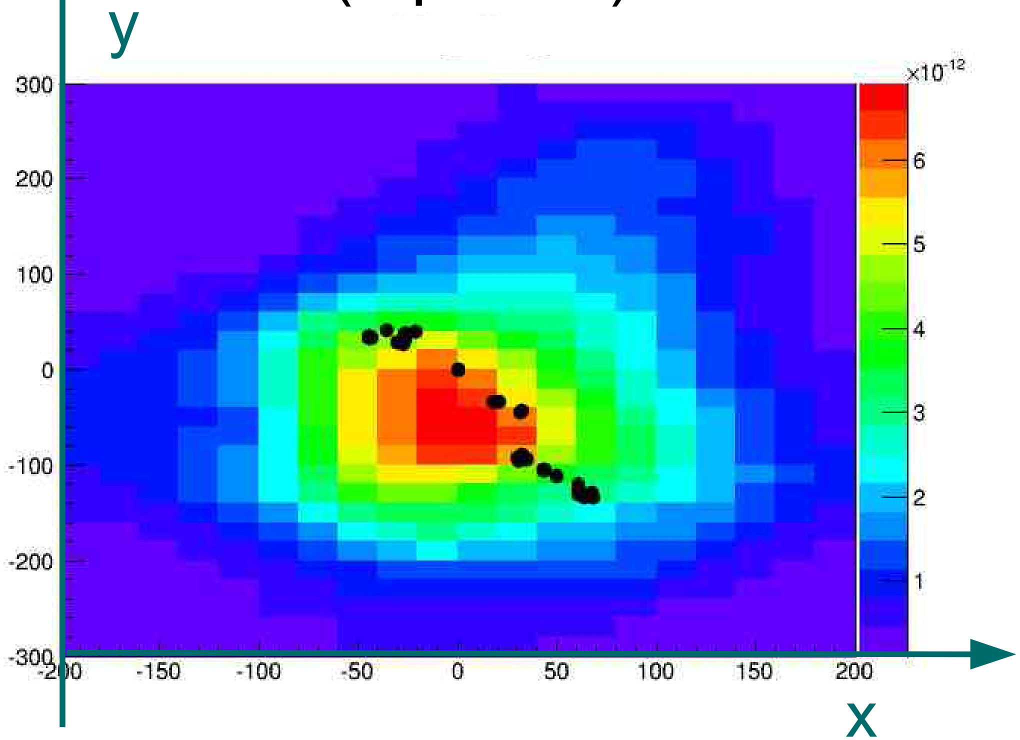
y-projection



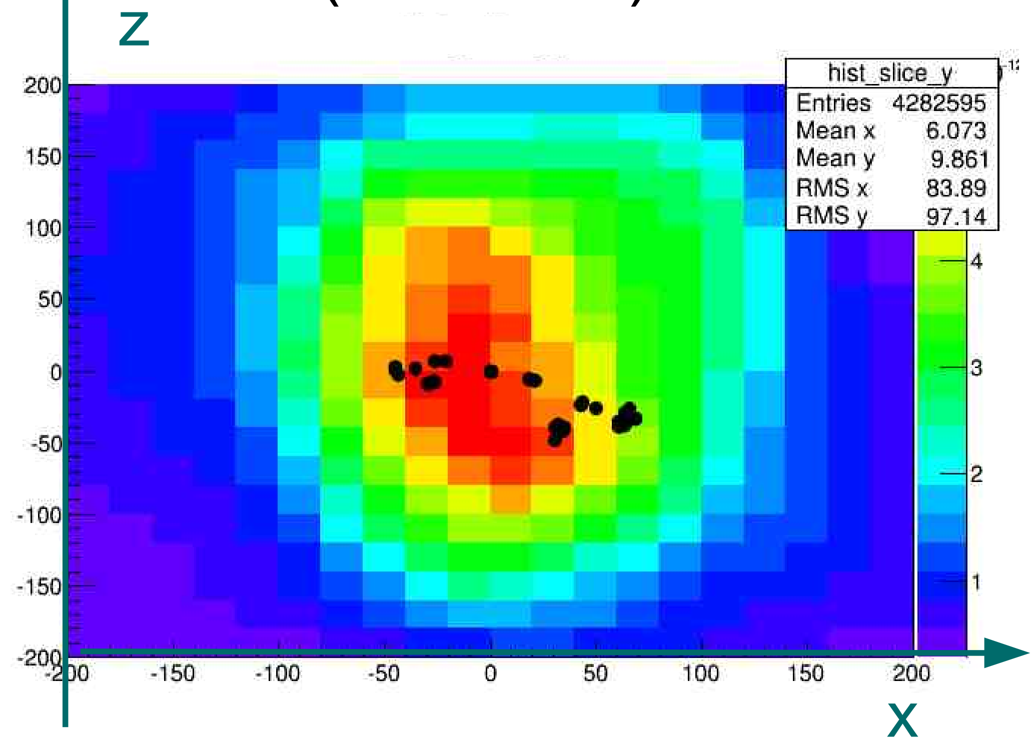
1MeV positron at center

Result 2nd Iteration (Zoom)

Z-projection
(top view)

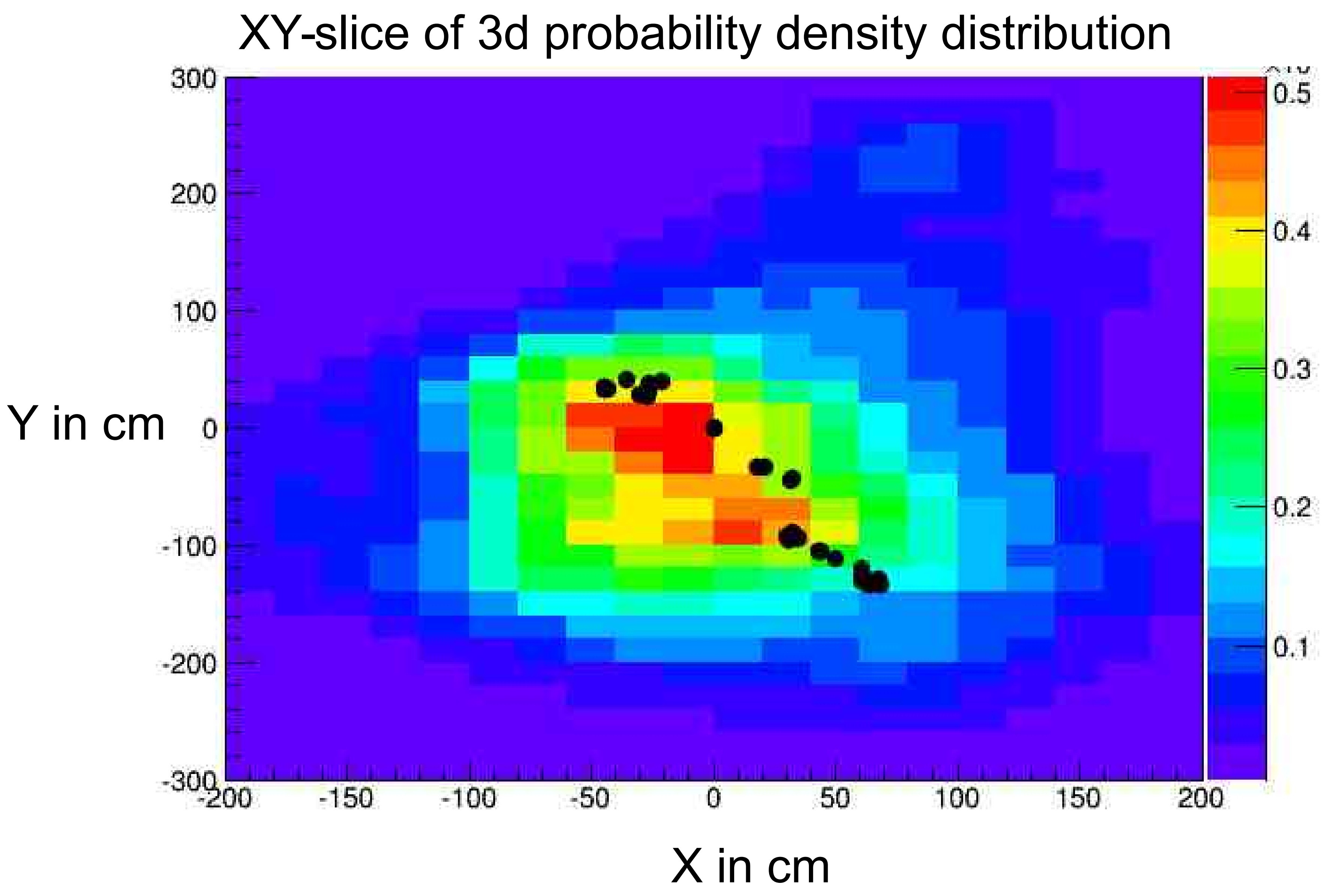


Y-projection
(side view)

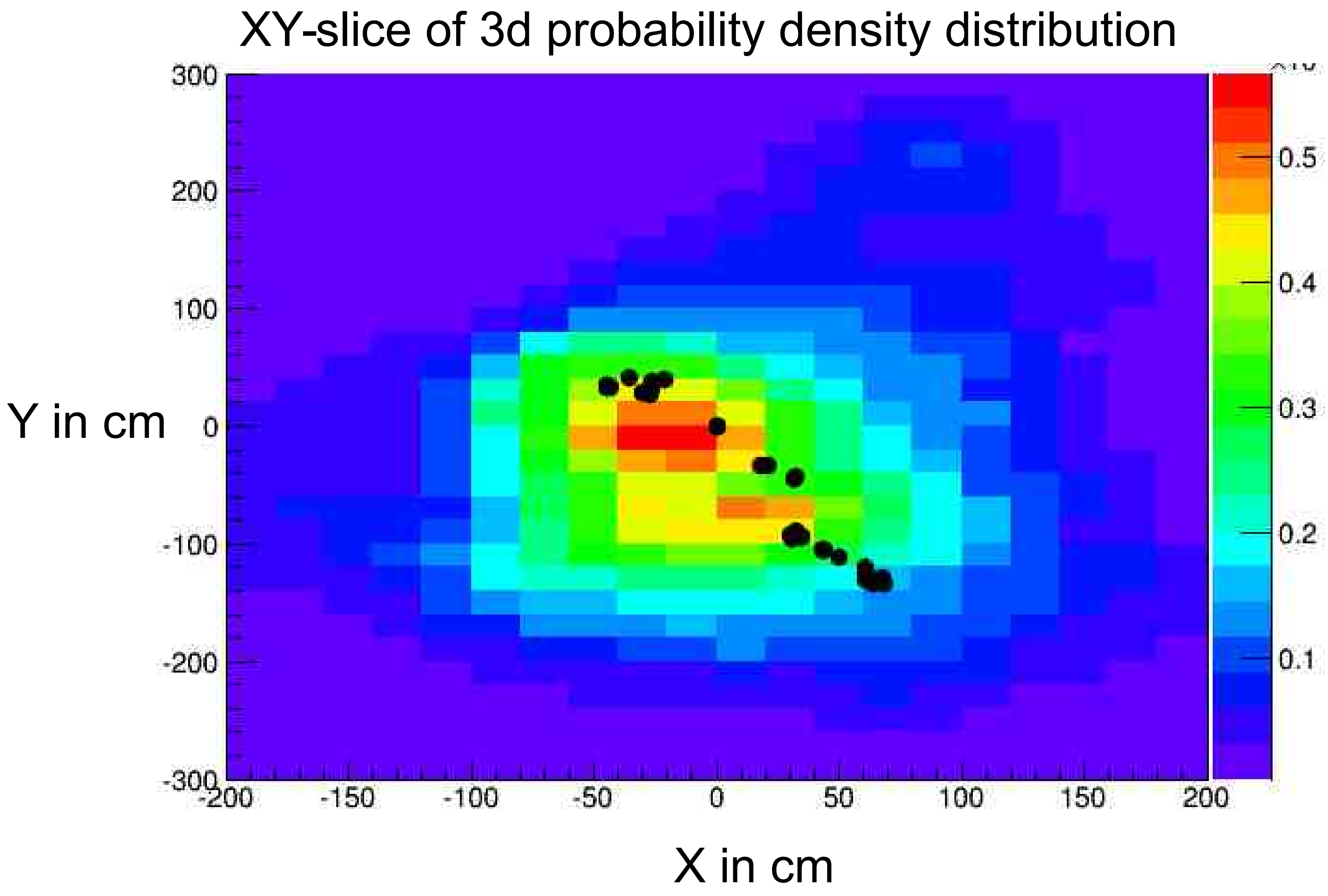


1MeV positron at center

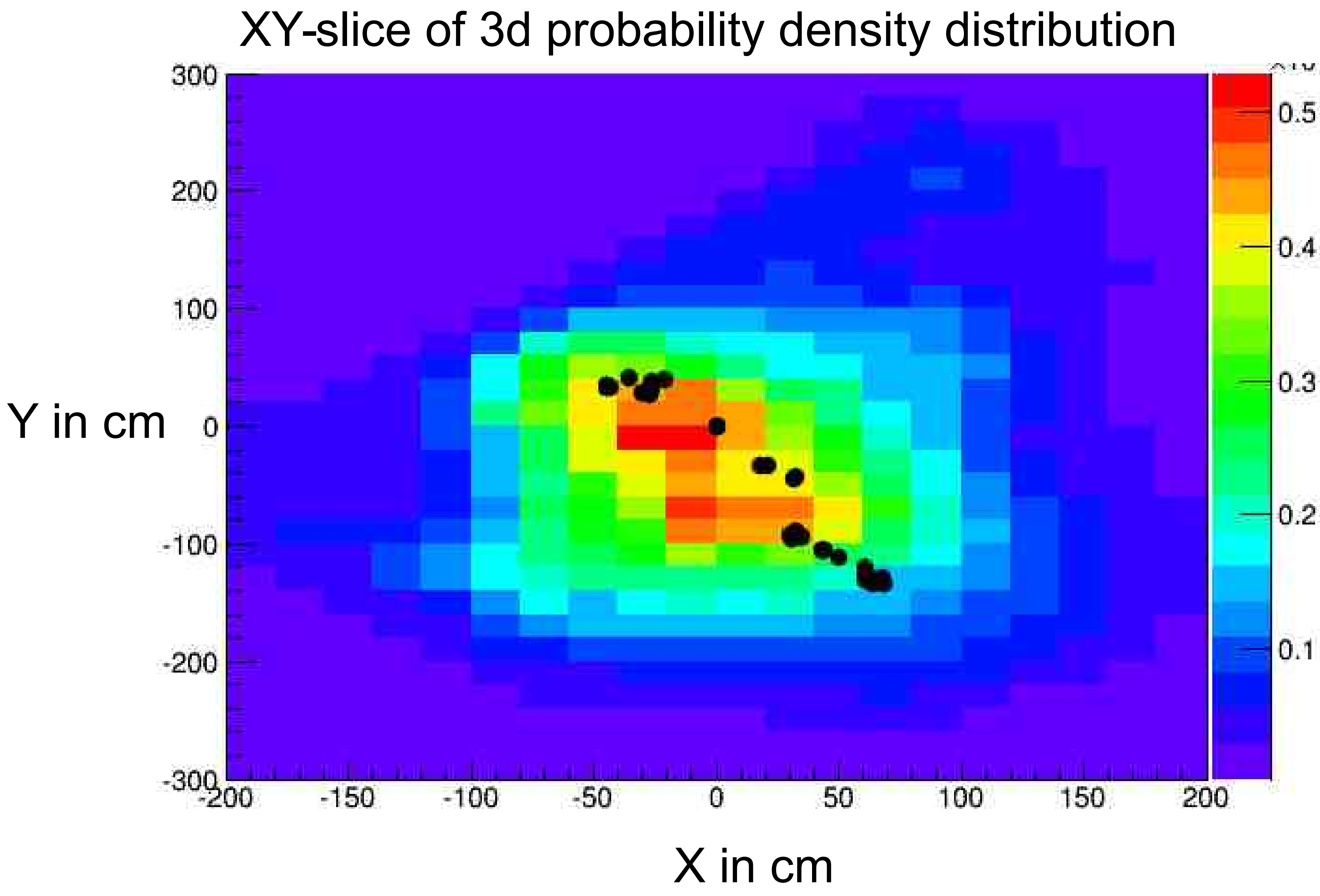
Result 2nd Iteration Slice 241



Result 2nd Iteration Slice 240

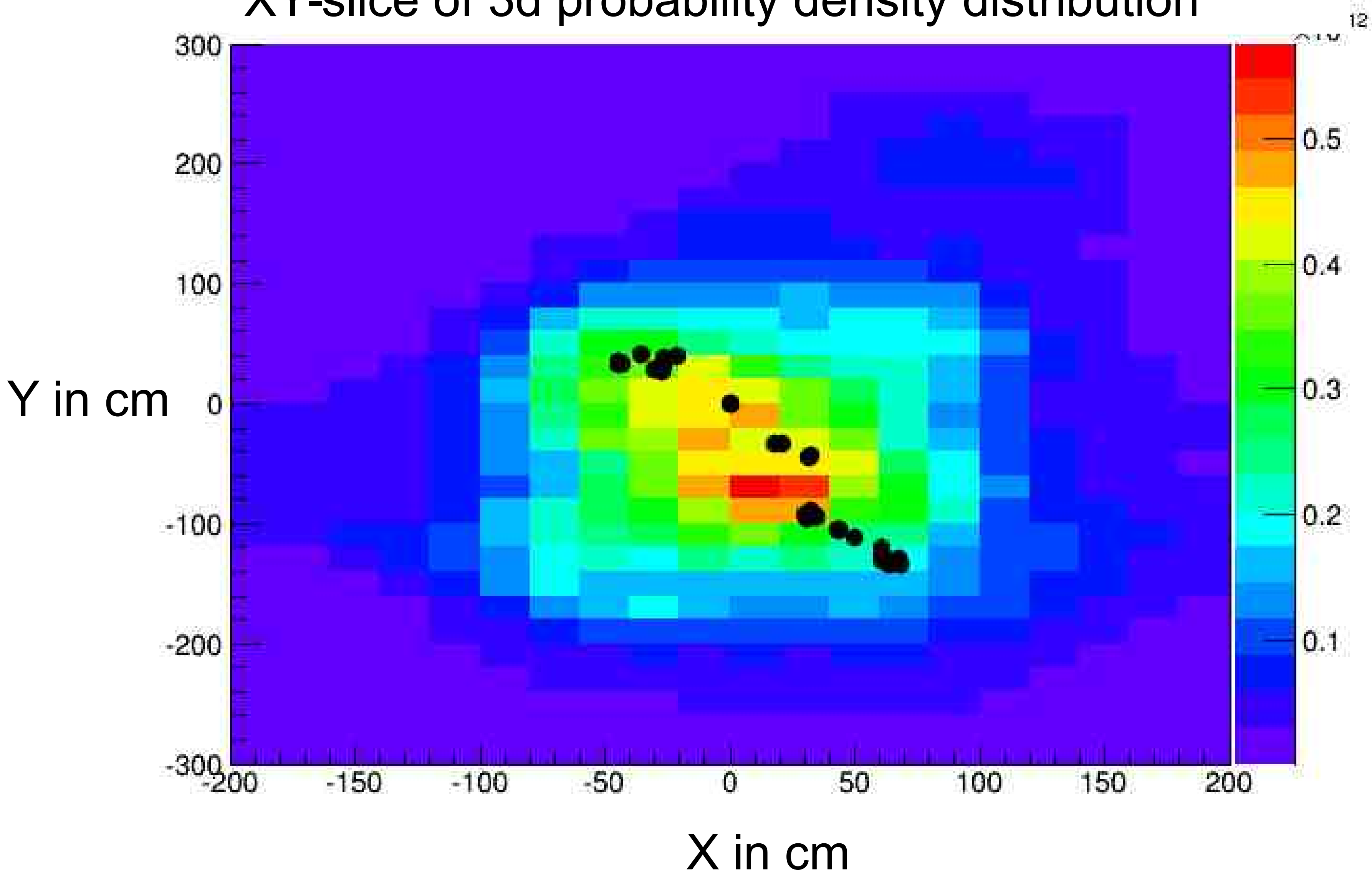


Result 2nd Iteration Slice 239

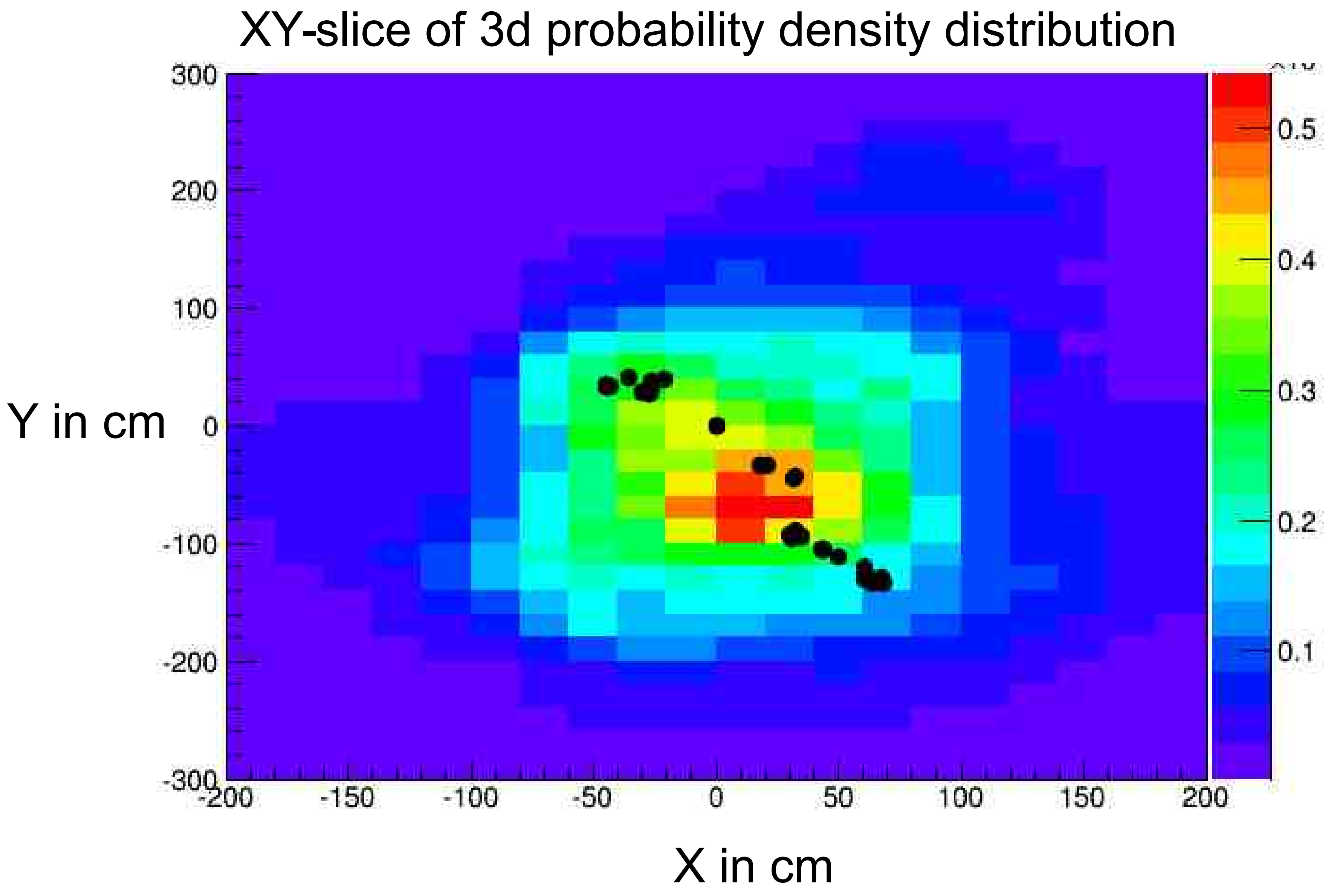


Result 2nd Iteration Slice 238

XY-slice of 3d probability density distribution



Result 2nd Iteration Slice 237



Result 2nd Iteration Slice 236