# Implementation of the dual phase in LArSoft

## and first results on muon reconstruction efficiency

Christoph Alt

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ETH zürich

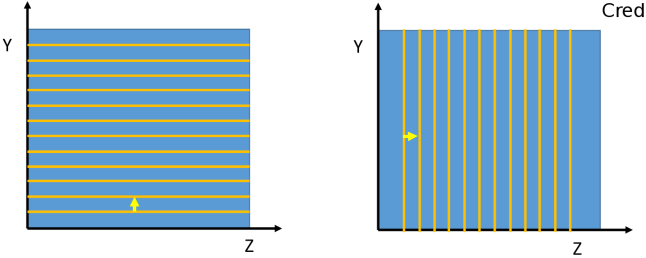
# Outline

Part 1: Overview: Current status of charge sim/reco in LArSoft & ongoing work

## Part 1: Overview: Current status of charge sim/reco in LArSoft & ongoing work

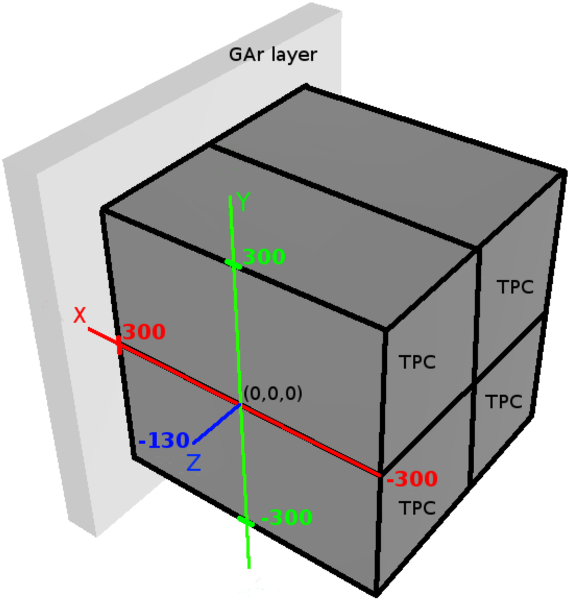
- Core element of the geometry is the TPC volume:
  - Charge readout module of 3x3 $m^2$ on top (CRM)
  - Active liquid argon volume covered by CRM
  - 1 cm gap between TPC's modules (dead volume)

- CRM: two perpendicular wire planes with 960 wires each




Credit: Slavic

- Geometries ready to use:
  - protoDUNE: 4 TPC's & 6 m drift (picture next slide)
  - 10 kton far detector: 90 TPC's & 12 m drift (+workspace)



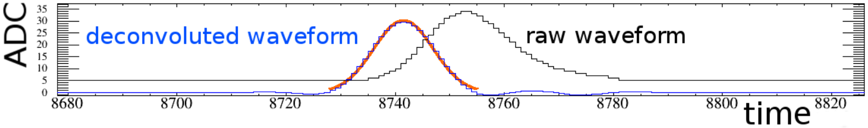

- drift in $+x$
- scale: cm
- Charge readout at $x \approx 300$ cm

# Part 1.1: Geometry: ongoing work by Balint Radics

- Rotate geometry to change drift from x to y (=vertical)
- Check if charge projection works for the new orientation (thanks to Gianluca Petrillo)
- Add crucial materials for beam simulation (beam window, beam plug and field cage)
- Recover charge that is lost in gaps between TPC's

# Part 1.2: Charge sim & reco chain: current status

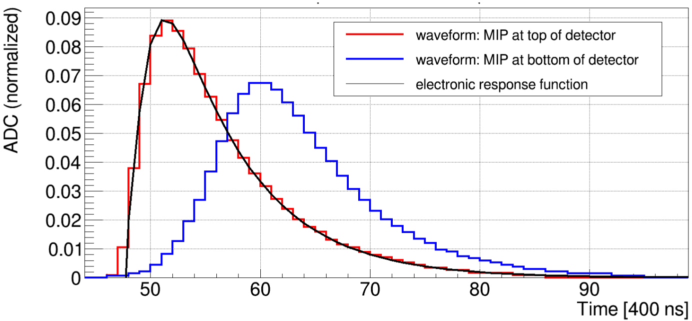
1. g4 calculates $\#e^-$ for each voxel and packs $e^-$ into clusters
2. Attenuation & gaussian diffusion: $\sigma_{L/T} = \sqrt{\frac{2 \cdot D_{L/T} \cdot x_{drift}}{v_{drift}}}$
3. Clusters are projected on readout plane (CRM) and assigned to nearest wire and scaled with gain. For each wire: $\#e^-(t)$
4. Electronic response: $\#e^-(t) \rightarrow ADC(t)$ (=raw waveform)
   $\rightarrow$ needs to be adapted to dual phase (see Part 1.3)
5. Deconvolution: remove electronics response, fit Gaussian $\rightarrow$ input for clustering and tracking
   $\rightarrow$ we want to get rid of this! (see Part 1.3)



- implement electronic response function for dual phase

$$f_{FastPreAmp}(t) = \frac{\tau_D \cdot e^{\frac{-(t-t_0)}{\tau_D}} - \left(\tau_D + (t-t_0)\frac{\tau_D - \tau_I}{\tau_I}\right) \cdot e^{\frac{-(t-t_0)}{\tau_I}}}{(\tau_D - \tau_I)^2}$$

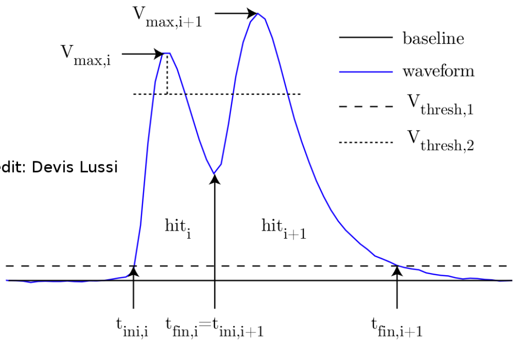
with: $\tau_D = 2.83\mu s, \quad \tau_I = 0.47\mu s$




- add pedestal and noise based on 3x1x1 measurements

→ for now: Ped. = 5 ADC & white noise with RMS = 2.4 ADC

# Part 1.3: Hit finding: ongoing

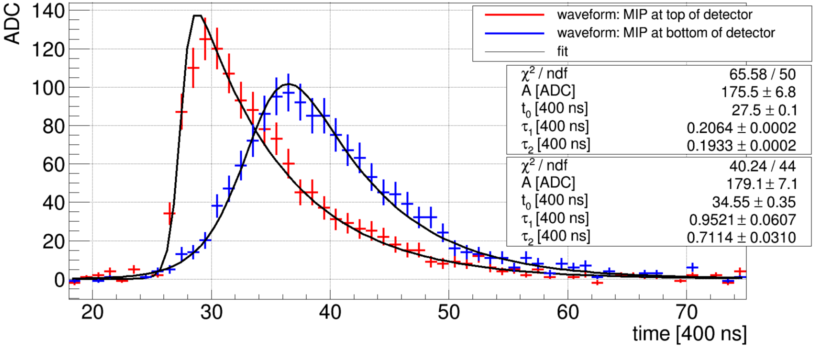



Credit: Devis Lussi

- Use raw hits for further reco (not deconvoluted ones!)
- Scan for peaks $> V_{thresh,1}$ & $t_{ini} - t_{fin} > \Delta T$
- Define region of interest of $\pm$ 50 ticks around this peak
- Define (multiple) peaks in this ROI
- $V_{thresh,1}$, $V_{thresh,2}$ & $\Delta T$ still to be tuned...

# Part 1.3: Hit fitting: ongoing

- Fit every identified peak with: $f(t) = A \cdot \frac{e^{\frac{t-t_0}{\tau_1}}}{1+e^{\frac{t-t_0}{\tau_2}}}$




- Fitter works well for single hits ($\rightarrow$ check for multi hits)
- Need to check integral (charge calibration) and performance of clustering and tracking with new input (width & $t_0$)

# Part 1.3: Hit shaping, finding and fitting: to do

- Simulate charge smearing in gas phase
- Implement more accurate noise model
- Tune hit finding parameters ($V_{thresh}$ & $\Delta T$)
- Quantify performance of hit finding & fitting
  - Missed hits?
  - Fake hits?
  - Cluster and track reconstruction efficiencies

# Part 1.4: Just getting started

| | |
|---|---|
| • Cosmics simulation | Kai Loo, Univ. of Jyväskylä |
| • 3x1x1 with LArSoft | Kevin Fusshoeller, ETH Zurich |
| • Light sim/reco & low energy | Andrea Scarpelli, APC Paris<br>Alessandra Tonazzo, APC Paris<br>Clara Cuesta, CIEMAT<br>Chiara Lastoria, CIEMAT<br>Ana Gollego, CIEMAT<br>Jose Alfonso, CIEMAT |

# Part 2: Muon reconstruction efficiency

# Part 2: Muon reco: LarSoft config and Data set

**LArSoft config:**

- 10kt dual phase workspace geometry (12m drift, 9 TPC's)
- standard 10kt dual phase .fcl's, including:
- Waveform deconvolution
- Hits: 'GausHitFinder'
- Cluster: 'linecluster'
- Tracks: 'pmtrack'

**Data set:**

- 28400 single $\mu^-$
- $P_{\mu^-} = 500\,\text{MeV}$ (stopping inside)
- isotropic distribution, particle gun in the center of detector

# Part 2: Muon reco: Efficiency definition

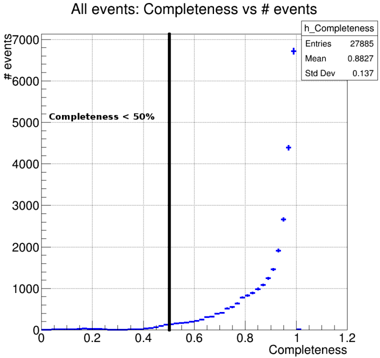
- **Completeness**: energy fraction of the simulated muon that is in a reconstructed track
- **Purity**: energy fraction in a reconstructed track that comes from the simulated muon

- **Reconstructed muon tracks**: largest energy contribution of these tracks come from the simulated muon
- **Leading muon track**: Muon track with highest Completeness

- **Efficiency criteria** (for leading muon track)
  1. Completeness $\geqslant 50\,\%$
  2. Purity $\geqslant 50\,\%$
  3. $75\% \leqslant \frac{L_{reco}}{L_{truth}} \leqslant 125\%$

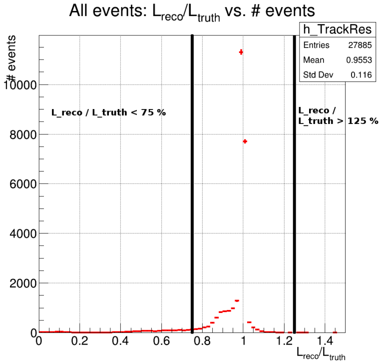
# Part 2: Muon reco: Completeness and $L_{reco}/L_{truth}$

## Completeness:




- Completeness peaks at 1 ✔

## $L_{reco}/L_{truth}$:




- $L_{reco}/L_{truth}$ peaks at 1 ✔

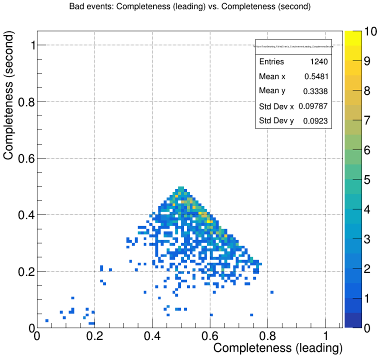
**Efficiency: 93 %** (26410/28400)

| | # events | % total |
|---|---|---|
| Total events | 28400 | 100 % |
| Good events | 26410 | 93 % |
| Bad events | 1990 | 7 % |
| No reco (muon) track | 515 | 1.8 % |
| $L_{reco}/L_{truth} < 75\,\%$ | 1419 | 5 % |
| Completeness $< 50\,\%$ | 579 | 2 % |
| $L_{reco}/L_{truth} > 125\,\%$ | 13 | 0.05 % |
| Purity $< 50\,\%$ | 6 | 0.02 % |

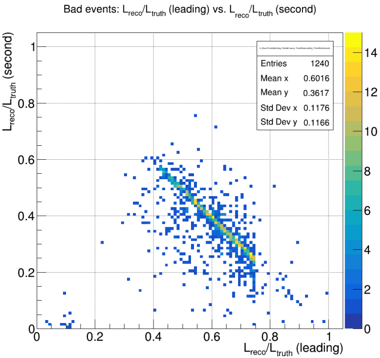
- Some muons are split into two or more reco tracks → add up leading plus second reco muon tracks

Leading reco muon track vs. second reco muon track (bad events):

Completeness:




$L_{reco}/L_{truth}$:

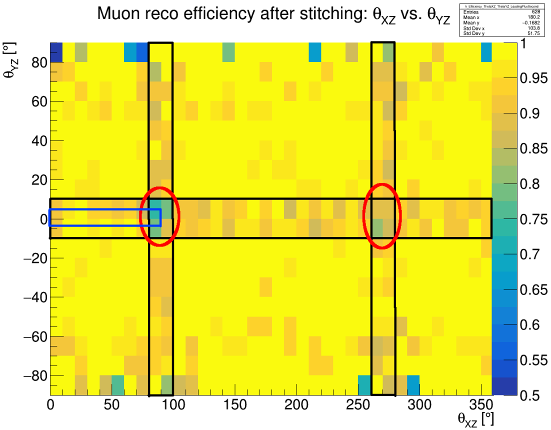



- Completeness: leading + second $\simeq 1$ ✔
- $L_{reco}/L_{truth}$: leading + second $\simeq 1$ ✔

leading reco muon track → leading + second reco muon track (stitching)

| | # events | % total |
|---|---|---|
| Total events | 28400 | 100 % |
| Good events | 26410 → 27596 | 93 % → 97.2 % |
| Bad events | 1990 → 804 | 7 % → 2.8 % |
| No (muon) track | 515 → 515 | 1.8 % → 1.8 % |
| $L_{reco}/L_{truth} < 75\,\%$ | 1419 → 260 | 5 % → 0.9 % |
| Completeness $< 50\,\%$ | 579 → 226 | 2 % → 0.8 % |
| $L_{reco}/L_{truth} > 125\,\%$ | 13 → 16 | 0.05 % → 0.06 % |
| Purity $< 50\,\%$ | 6 → 6 | 0.02 % → 0.02 % |

- Stitching increases efficiency by 4.2 %
- 94 % of the 804 bad events left after stitching have 0 or only 1 reco muon track → can not be recovered with stitching




- Large errors for large $\theta_{YZ}$ (due to low statistics)
- black boxes: muon is seen only a few channels in one view
- red circles: muon along drift direction

- Efficiency for isotropic muons: 97.2 % (close to 100 % for non-problematic directions)
- Problematic directions: along a few wires in one view (problem: track reco) & along drift direction (problem: hit finding)

→ improve this further by working on hit shaping, finding and fitting

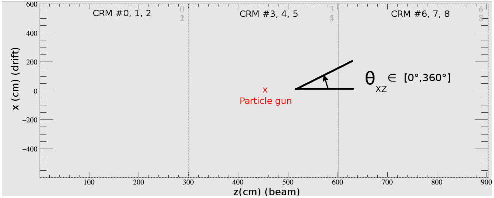
Thanks for your attention!

# Backup slides

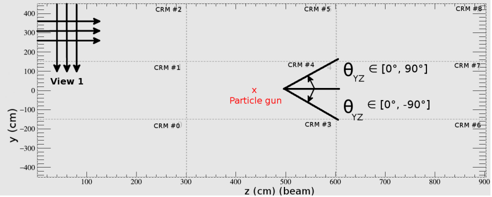
# Dual phase (workspace) geometry

- 9 TPC's / 960x960 channels each
- Maximum drift: 12 meters

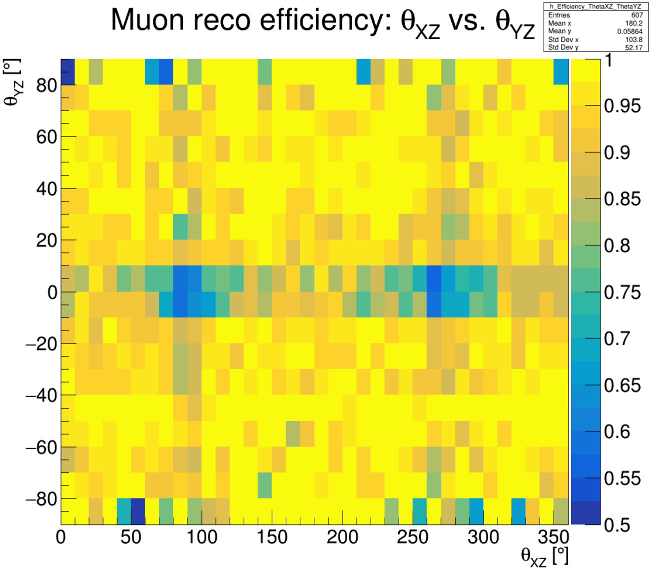
Side view




Top view (anode view)

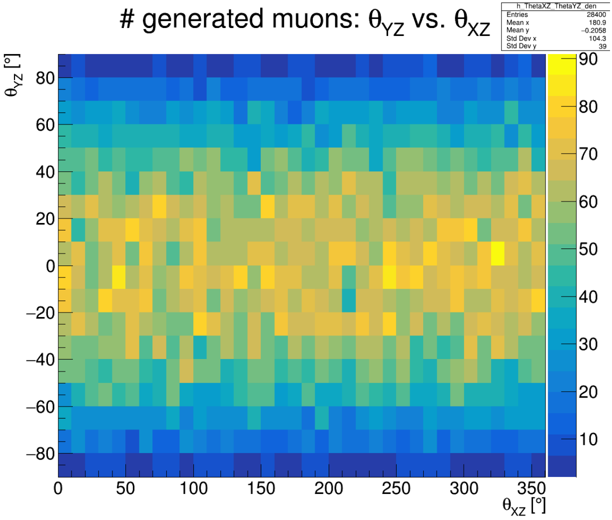


# Isotropic muons: efficiency map for leading muon track



# Isotropic muons: data set

- 28400 $\mu^-$, $P_{\mu^-} = 500\,\mathrm{MeV}$, stopping inside
- Low statistics for large $|\,\theta_{YZ}\,|$



# Isotropic muons: stitching

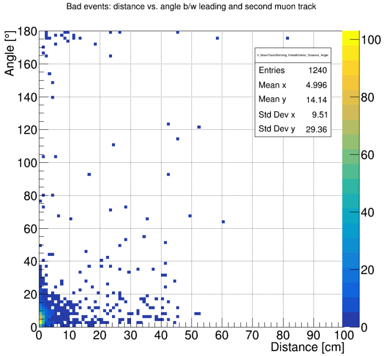
- pmtrack splits muon into two (ore more) reco muon tracks if there is a kink in the truth track

| # reco muon tracks | good events (93 %) | bad events (7 %) |
|---|---|---|
| 0 | 0 % | 25.9 % |
| 1 | 75.8 % | 11.8 % |
| 2 | 21.8 % | 48.3 % |
| 3 | 2.2 % | 13.2 % |
| $\geqslant$4 | 0.2 % | 0.8 % |

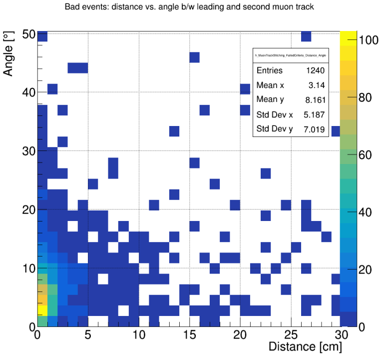
- Solution for bad events: choose second reco muon track (reco muon track with second highest Completeness)

$\rightarrow$ Add up leading + second reco muon track ('stitching')

3D distance vs. 3D angle b/w closest endpoints of leading and second reco muon track (bad events):



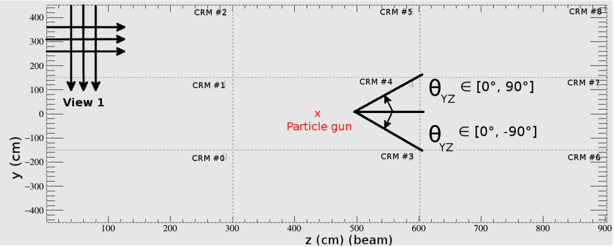

Zoom



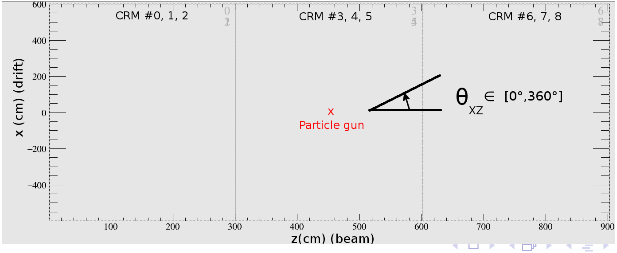

- Most events have small angle and distance b/w the two tracks ✔
- Cluster at large angles due to $\sim 180^\circ$ kinks in the reco at the end of one track (not understood) ✗

# Reminder: dual phase workspace geometry

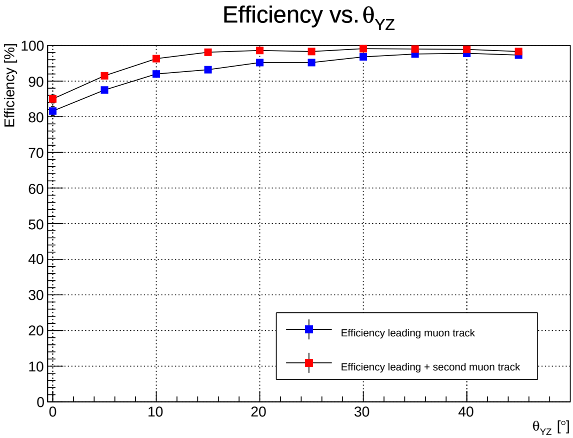
Top view (anode view)




Side view



# Efficiency vs. muon direction: $\theta_{YZ}$



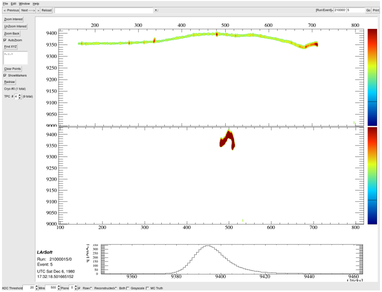

- Every dot: 1000 $\mu^-$ with $P_{\mu^-} = 500\,\mathrm{MeV}$
- $\sigma_{\mu^-} = \sqrt{\varepsilon \cdot (1-\varepsilon)/1000}$

# Efficiency vs. muon direction: $\theta_{YZ}$ (example events)

$\theta_{YZ} = 0°$, $\theta_{XZ} = 0°$

- crosses only a few wires in view 2
- isochronic
- waveform:

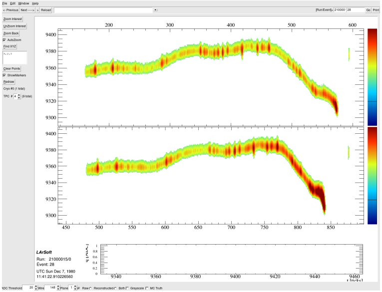
→ can cause problems for reco

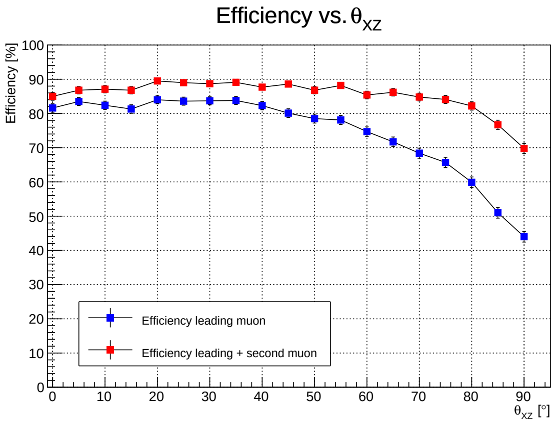


$\theta_{YZ} = 45°$, $\theta_{XZ} = 0°$

- crosses many wires in both views
- isochronic
- waveform okay

→ no problems for reco



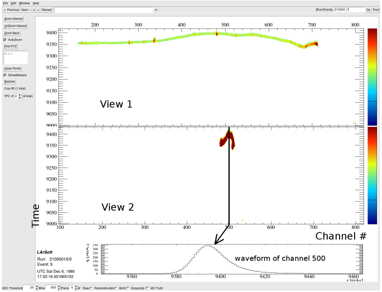



- Each dot: 1000 $\mu^-$ with $P_{\mu^-} = 500\,\mathrm{MeV}$
  binomial error: $\sigma_{\mu^-} = \sqrt{\varepsilon \cdot (1-\varepsilon)/1000}$
- Track splitting increased & lower efficiency for $\theta_{XZ} \to 90^\circ$
- Pick two example events: $\theta_{XZ} = 0^\circ$ and $\theta_{XZ} = 90^\circ$

# Efficiency vs. muon direction

## Example events (raw data):

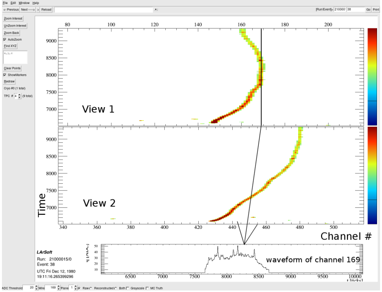
$\theta_{YZ} = 0°, \theta_{XZ} = 0°$




- isochronous
- muon is seen by only a few wires in view 2

→ problem for track reco

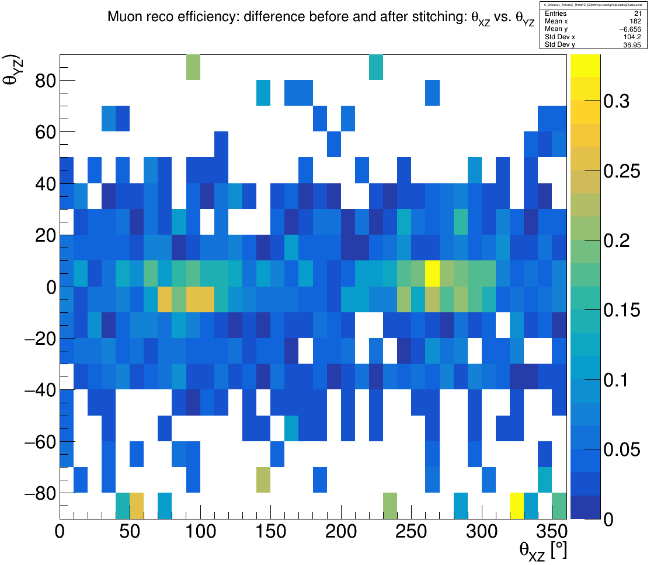
$\theta_{YZ} = 0°, \theta_{XZ} = 90°$



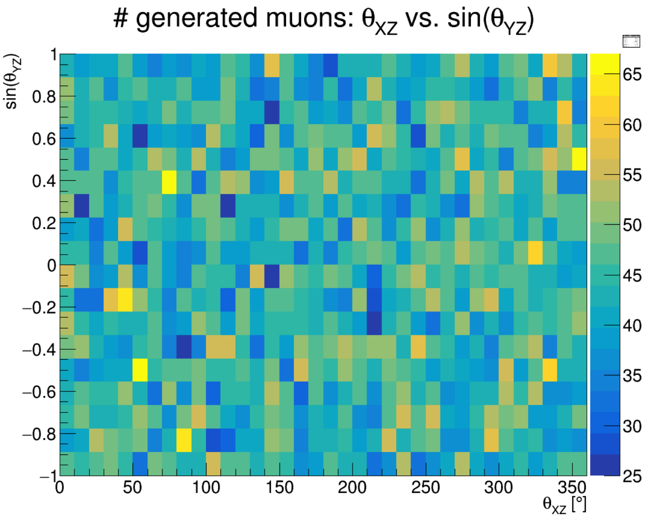

- not isochronous
- muon is seen by only a few wires in both views

→ problem for hit finding

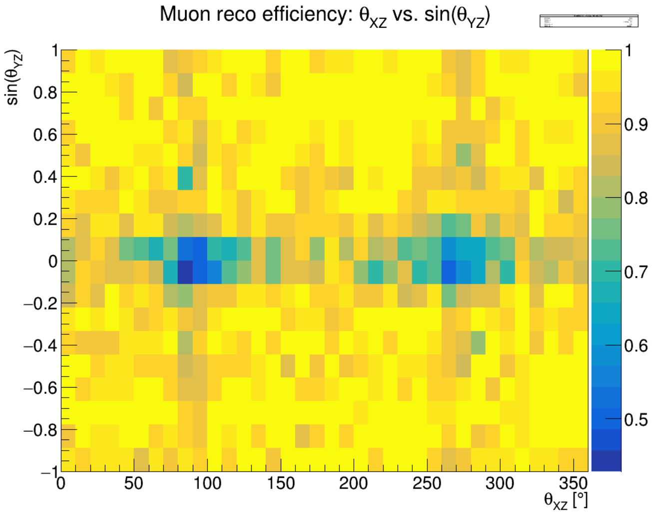
# Isotropic muons: Δ efficiency before and after stitching



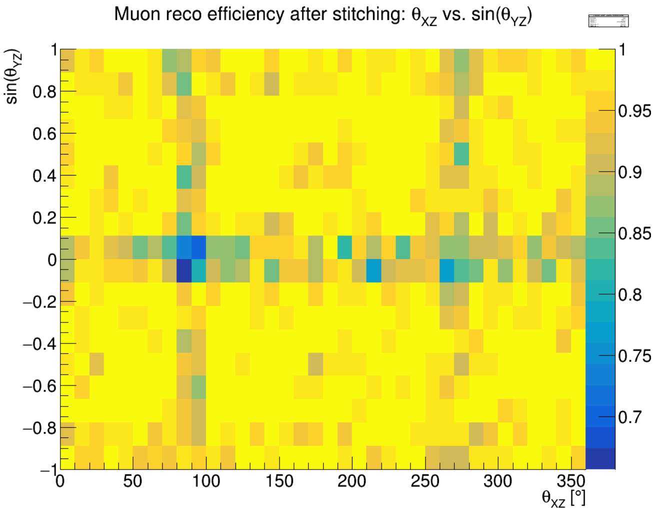
# Isotropic muons: generated muons ($sin(\theta_{YZ})$)



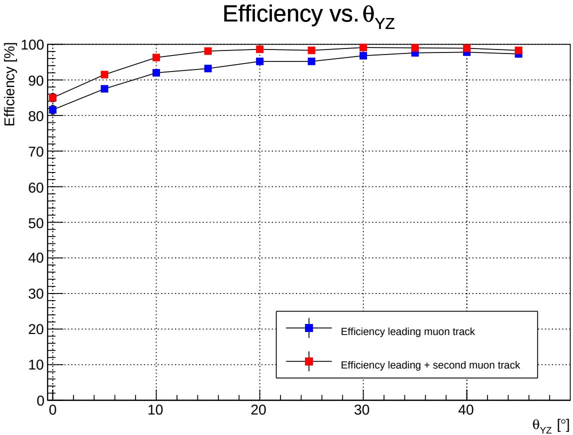
# Isotropic muons: efficiency map for leading muon track ($sin(\theta_{YZ})$)



# Isotropic muons: efficiency map after stitching ($sin(\theta_{YZ})$)



# Efficiency vs. muon direction ($\theta_{XZ} = 0^\circ$)




- Each dot: 1000 $\mu^-$ with $P_{\mu^-} = 500\,\mathrm{MeV}$
  $\sigma_{\mu^-} = \sqrt{\varepsilon \cdot (1-\varepsilon)/1000}$
- Track splitting decreased & higher efficiency for $\theta_{YZ} \rightarrow 45^\circ$