Muon Track Reconstruction in the Double Chooz Experiment

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Structure

- Neutrino Oscillations
- The Double Chooz Experiment
- Track Reconstruction
  - Inner Detector
  - Inner Detector and Outer Veto
- Test with Monte Carlo Data
- Test with Real Data: Energy Loss

Neutrino Oscillations

- The flavor eigenstates are linear combinations of the mass eigenstates:

$$|\nu_\alpha\rangle = \sum_j U_{\alpha j}|\nu_j\rangle$$

  $\rightarrow$ Neutrino Oscillations

- Oscillation Probability:

$$P(\alpha \rightarrow \beta; t) = |\langle \nu_\beta | \nu(t) \rangle|^2 = \left| \sum_i U_{\alpha i} U^*_{\beta i} \cdot e^{-i \frac{m_i^2}{2E} L} \right|^2$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

with $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

- Three mixing angles θ_{12}, θ_{23} and θ_{13} and one Dirac CP violating phase
- Three mass square differences: Δm^2_{21}, Δm^2_{31}, Δm^2_{32}

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The Double Chooz Experiment

- Measurement of θ_{13}
- $\bar{\nu}_e$ disappearance experiment

  $$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right)$$

- Source of the $\bar{\nu}_e$: Two reactors
- Two identical liquid scintillator detectors (near detector still under construction)

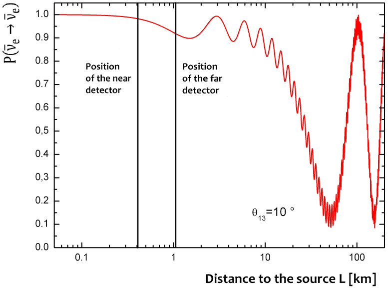

Figure: Survival probability of $\bar{\nu}_e$ [1]

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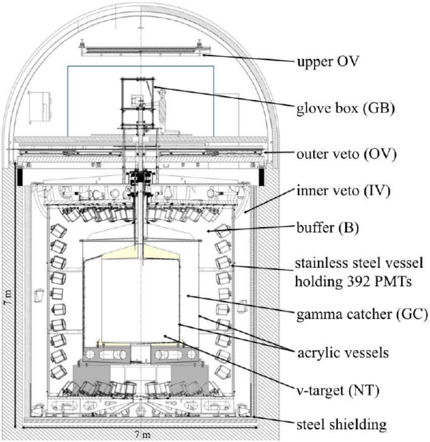
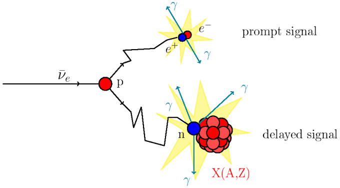
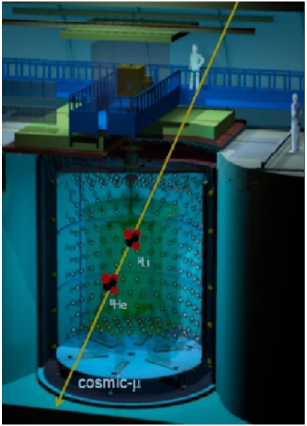


Figure: The Double Chooz detector [2]

The Double Chooz Experiment

- Detected via the inverse beta decay: $\bar{\nu}_e + \mathrm{p} \rightarrow e^+ + \mathrm{n}$
- Background mostly induced by muons:
- Cosmogenic isotopes (βn-emitters): ^{9}Li ($\tau = 257\,\mathrm{ms}$) and ^{8}He ($\tau = 172\,\mathrm{ms}$)
- Time and space correlated
  $\rightarrow$ Muon track reconstruction is important for background studies





Track Reconstruction

Inner Detector

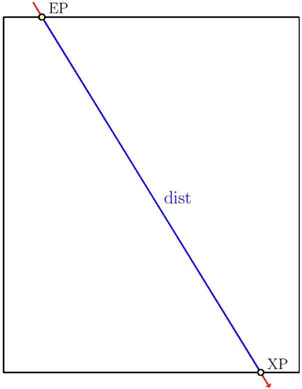


Figure: Principle of the inner detector tracking

- Start value of the entry point (EP): First PMT which measures a signal
- Start value of the exit point (XP): The PMT with the smallest value of $\Delta t_i = t_{hit,i} - t_{tof,i}$
  - $t_{hit,i}$: the time when the PMT i measures a signal for the first time
  - $t_{tof,i}$: the calculated time until the muon reaches the PMT i $t_{tof,i} = \frac{dist}{c} + t_0$

Track Reconstruction

Inner Detector

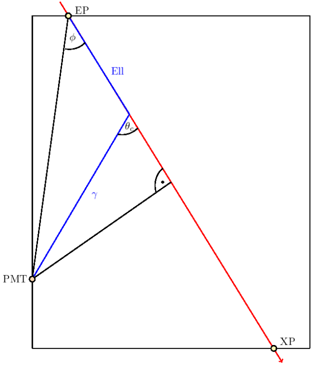


Figure: Principle of the inner detector tracking

- EP and XP are varied to minimize the difference between the measured $t_{hit,i}$ and the expected arrival time of the light cone $t_{tof,i}$
- $t_{tof,i} = \frac{Ell}{c} + \frac{\gamma}{c_{medium}} + t_0$
- The minimization is only applied if enough photo electrons were detected.

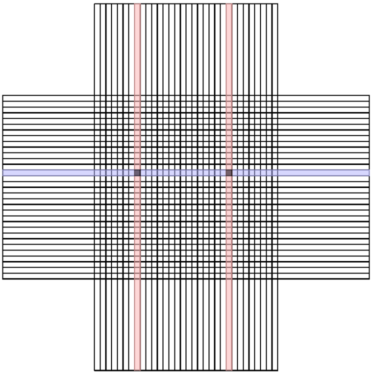


Figure: Ambiguities of the OV reconstruction principle

- Many events with more than one outer veto point (OVP)
  $\rightarrow$ The **OVP** with the **shortest distance** to the reconstructed track is used
- MINUIT is used for the minimization

Track Reconstruction

Inner Detector and Outer Veto

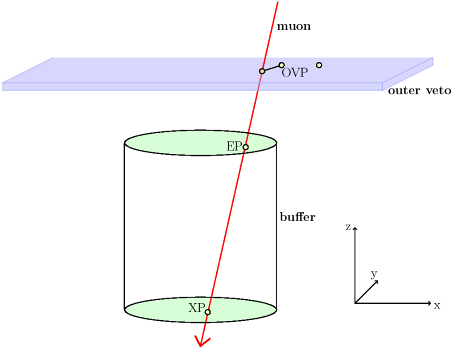


Figure: Track reconstruction principle

- Many events with more than one outer veto point (OVP)
  → The **OVP** with the **shortest distance** to the reconstructed track is used
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Track Reconstruction

Parameter of the Straight Line

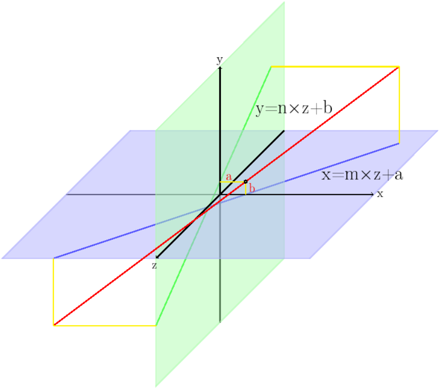


Figure: Straight line in the three-dimensional space

- $T(z) = \begin{pmatrix} m \cdot z + a \\ n \cdot z + b \\ z \end{pmatrix}$
- Two χ^2-minimizations:
- $X_{fit,i} = m \cdot z_i + a$

$$\chi^2 = \sum_{i=1}^{n=3} \left(\frac{x_i - X_{fit,i}}{s_{x,i}} \right)^2$$

- $Y_{fit,i} = n \cdot z_i + b$

$$\chi^2 = \sum_{i=1}^{n=3} \left(\frac{y_i - Y_{fit,i}}{s_{y,i}} \right)^2$$

Test with Monte Carlo Data

Comparison of the Old (reco) with the New (minuit) Method

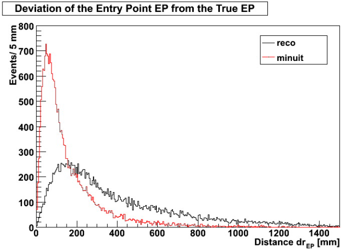


Figure: Deviation of the reconstructed entry point EP from the true EP

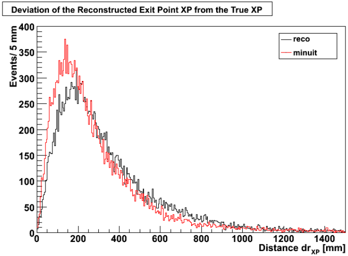
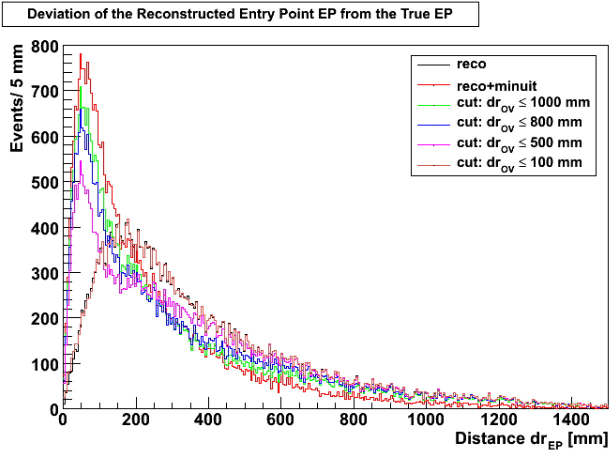


Figure: Deviation of the reconstructed exit point XP from the true XP

Test with Monte Carlo Data

The Old Method Combined with the New Method



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Energy Loss

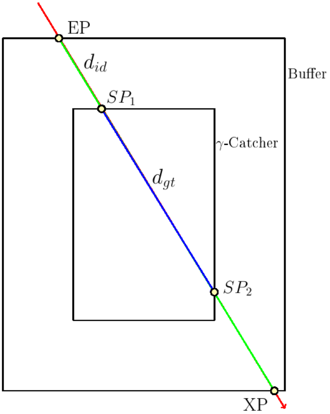


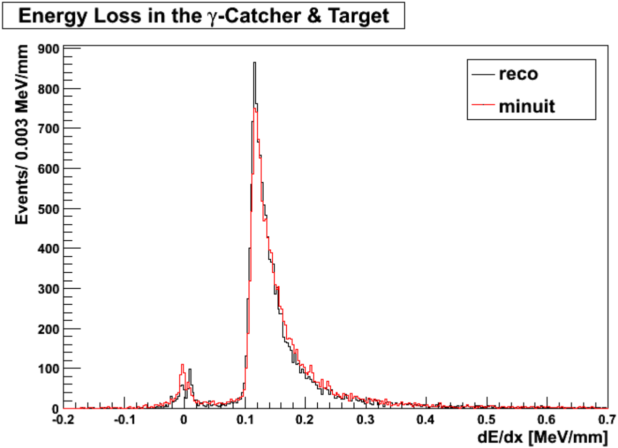
Figure: Energy loss

- Muons deposit on average 1.6 MeV/cm in the detector
  $\rightarrow$ Peaked visible energy loss distribution
- Lower light output in the buffer
  $\rightarrow$ Visible energy loss in the buffer has to be determined separately
- $E_{vis,b} = \frac{dE}{dx}|_b \cdot d_b$

  with $\frac{dE}{dx}|_b \approx 0.006$ MeV/mm
- $E_{vis,gt} = E_{vis} - E_{vis,b}$

Energy Loss

in the γ-Catcher and Target



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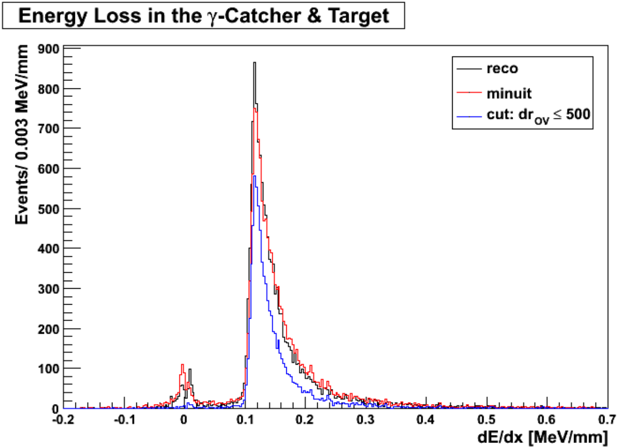

Figure: Energy loss in the γ-Catcher and target

Summary

- The outer veto information was added to the track reconstruction
- Many events with several outer veto points
  $\rightarrow$ Using the OVP with the shortest distance to the ID track
- Two χ^2-minimizations (in the xz and yz plane) with three points (EP,XP,OVP)
- Test with Monte Carlo data: The new method improves the spatial resolution by 58% for EP and 10.7% for XP
- Test with real data (energy loss): The new method is better if cuts on the shortest distance are set
- Combined method with $dr_{OV} \leq 1000$ mm: improvement of 20.5% for the EP and 6.6% for the XP

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Bibliography

- http://doublechooz.in2p3.fr/Public/German/welcome.php (10/28/2013)
- Y. Abe et al., Double Chooz: Reactor $\bar{\nu}_e$ disappearance in the Double Chooz experiment, Physical Review D 86,052008 (2012)
- Michael Wurm, Status update on RecoMuHamID, (February 2012, intern)
- θ_{13}: Phänomenologie und Status, Mikko Meyer (talk, May 2012)
- J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)
- Mauro Mezzetto and Thomas Schwetz, θ_{13}: phenomenology, present status and prospect, arXiv:1003.5800v2 (August 2010)

Backup

Neutrino Oscillation Parameters

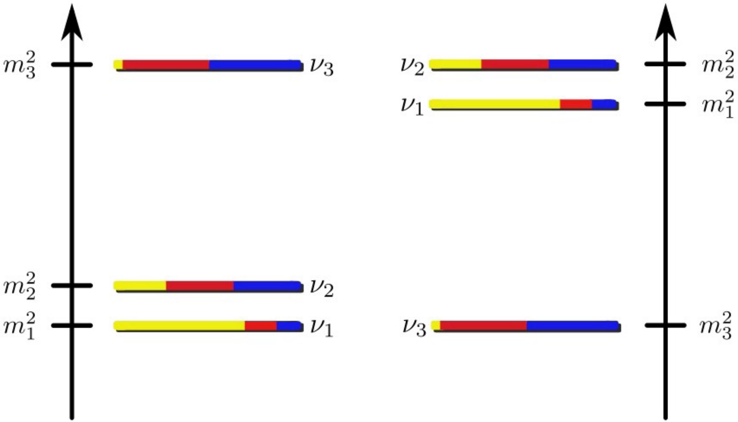
- Three mixing angles θ_{12}, θ_{23} and θ_{13} ($\theta_{ij} = [0, \frac{\pi}{2}]$)
- One Dirac CP violating phase $\delta = [0, 2\pi]$
- Three mass square differences: Δm^2_{21}, Δm^2_{31}, Δm^2_{32}
- The data shows that one mass square difference is much smaller than the other two:

$$\left|\Delta m^2_{21}\right| \ll \left|\Delta m^2_{32}\right| \approx \left|\Delta m^2_{31}\right|$$

Table: Current values of the neutrino oscillation parameters [5]

$\sin(2\theta_{12})^2$	0.857 ± 0.024
$\sin(2\theta_{23})^2$	> 0.95
$\sin(2\theta_{13})^2$	0.098 ± 0.013
Δm^2_{21}	$(7.50 \pm 0.20) \times 10^{-5}\text{eV}^2$
$\left|\Delta m^2_{32}\right|$	$(2.32^{+0.12}_{-0.08}) \times 10^{-3}\text{eV}^2$

Mass Hierarchy



Reactor Experiments

Table: The current structure of the three reactor experiments (Daya Bay, Double Chooz and RENO and their first results

Experiment	$\sin(2\theta_{13})^2 \pm$ stat. $\pm$ syst.	Reactors	Detectors	Live time [d]
Daya Bay	$0.092 \pm 0.016 \pm 0.005$	6	6	55
Double Chooz	$0.109 \pm 0.030 \pm 0.025$	2	1	227.93
RENO	$0.113 \pm 0.013 \pm 0.019$	6	2	229

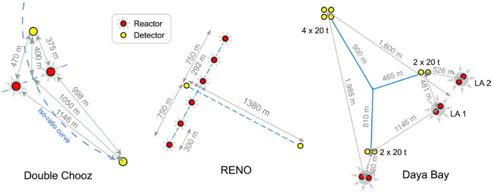


Figure: The construction of the three reactor experiments [6].

Signal and Background Predictions [2]

Table: Signal and background predictions [2]. IBD stands for inverse β-decay, FN for fast neutrons and SM for stopping muons.

	Reactors Both On	One Reactor $P_{th} < 20\%$	Total
Livetime [days]	139.27	88.66	227.93
IBD Candidates	6088	2161	8249
ν Reactor B1	2910.9	774.6	3685.5
ν Reactor B2	3422.4	1331.7	4754.1
Cosmogenic Isotope	174.1	110.8	284.9
Correlated FN & SM	93.3	59.4	152.7
Accidentals	36.4	23.1	59.5
Total Prediction	6637.1	2299.7	8936.8

$\sin^2\theta_{13} = 0.109$, $\quad \Delta m^2_{13} = 2.32 \times 10^{-3}\,\text{eV}^2$

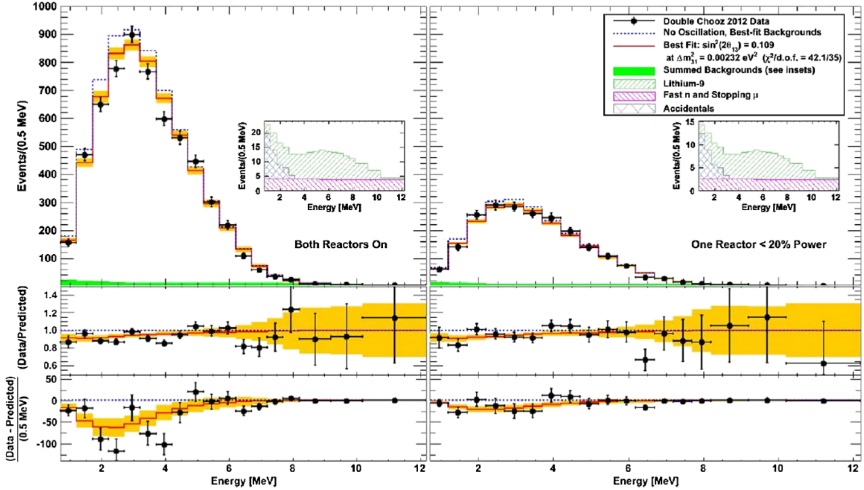
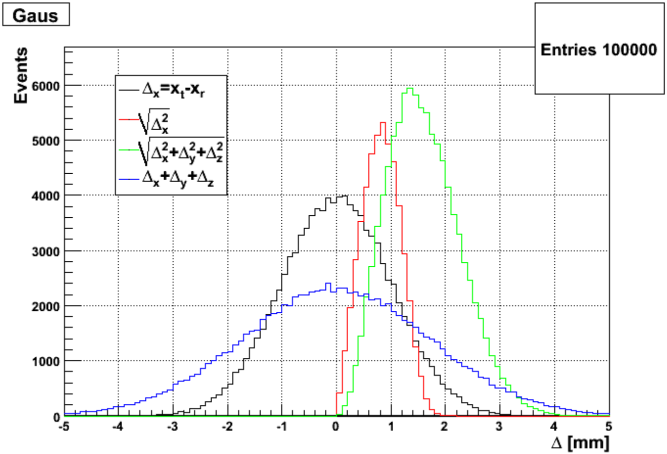


Figure: Measured prompt energy spectrum [2]

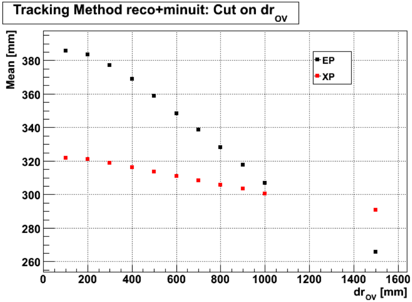
Deviation of the reconstructed from the true points



$$dr = \sqrt{(x_{true} - x_{reco})^2 + (y_{true} - y_{reco})^2 + (z_{true} - z_{reco})^2}$$

Test with Monte Carlo Data

Comparison of the Old (reco) with the New (minuit) Method



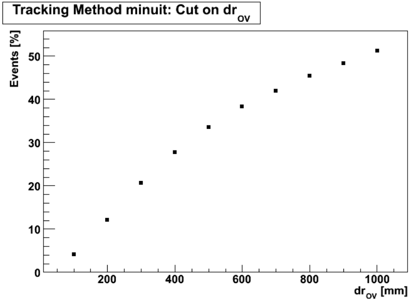


Table: Deviation of the reconstructed points to the true EP and XP

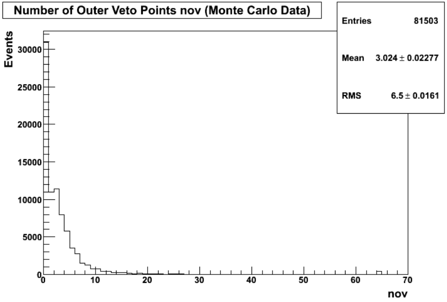
Tracking method	EP Mean [mm]	XP Mean [mm]
reco	386.1	321.8
minuit	163.6	287.4
reco+minuit	241.3	290.6

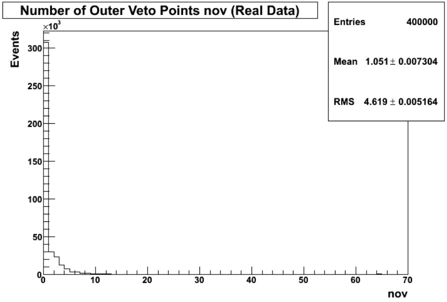
Cuts on the shortest distance

Table: Cuts on the shortest distance

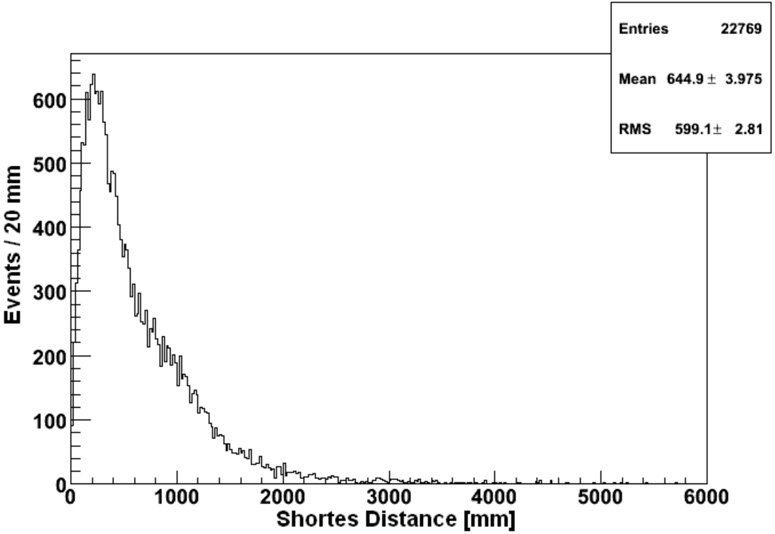
	Events	Events [%]
old method	35610	100
no cuts	22769	63.9
1000	18233	51.2
900	17231	48.4
800	16184	45.4
700	14963	42
600	13638	38.3
500	11961	33.6
400	9890	27.8
300	7371	20.7
200	4307	12.1
100	1446	4.1

Number of Outer Veto Points





Shortest Distance



Energy Loss

in the Buffer

- Only events are used whose muon track went only through the buffer
  $\rightarrow$ visible deposited energy in the buffer (E_b) is equal to the visible deposited energy in the inner detector (E_{vis}):
  $E_b = E_{vis}$
- Energy loss: $\frac{dE}{dx}|_b = \frac{E_b}{d_b}$
- Average visible dE/dx in the buffer: ~ 0.006 MeV/mm

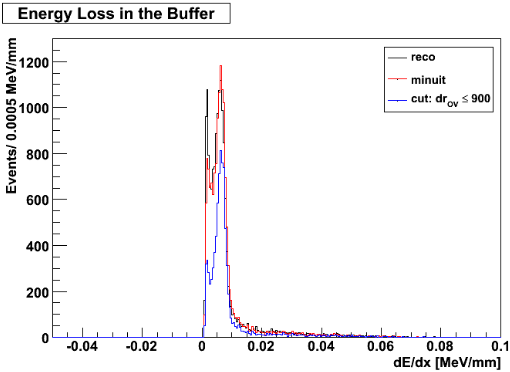


Figure: Energy loss in the buffer

Energy Loss

in the γ-Catcher and Target

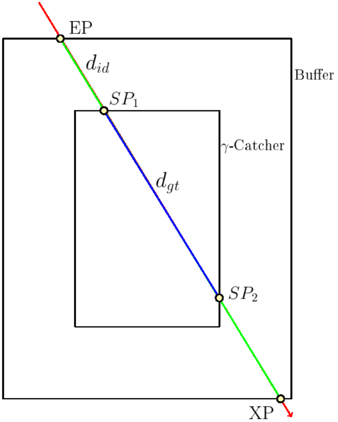


Figure: Energy loss

- Calculating the intersection points SP_1 and SP_2 $\rightarrow \mathrm{d_b}$, $\mathrm{d_{gt}}$
- $\mathrm{d_b} = \mathrm{d_{id}} - \mathrm{d_{gt}}$
- $\mathrm{E_b} = \frac{dE}{dx}|_b \cdot \mathrm{d_b}$

  with $\frac{dE}{dx}|_b \approx 0.006$ MeV/mm
- $\mathrm{E_{gt}} = \mathrm{Evis} - \mathrm{E_b}$
- Energy loss: $\frac{dE}{dx}|_{gt} = \frac{E_{gt}}{d_{gt}}$