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Differentiable Programming for Experiment Design
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Optimisation of muon tomography scanners for border controls using TomOpt

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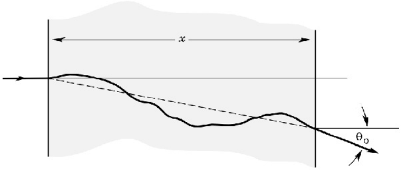
MODE Silent Border UCLouvain

Muon Tomography: An Overview

- Primary cosmic ray protons interact with nuclei of Earth's upper atmosphere
- Secondary cosmic ray particles produced ($\pi^{\pm}$)
- $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$

Muon Tomography: An Overview

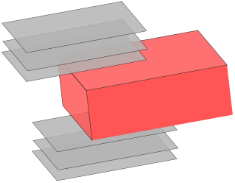
- At sea level: $p_\mu \approx 4\ GeV$
- Highly penetrating, multiple small Coulomb scatterings
- For muon with momentum p traversing a macroscopic material thickness $x[m]$:



$$\sigma_{\theta_0} = \frac{13.6\ MeV}{\beta c p}\sqrt{\frac{x}{X_0}}\left[1 + 0.038\ ln(\frac{x}{X_0 \beta})\right] \quad (1)$$

scattering angle distribution (σ_{θ_0}) $\rightarrow$ material identification (X_0)

TomOpt: Muon Scattering Tomography Optimisation



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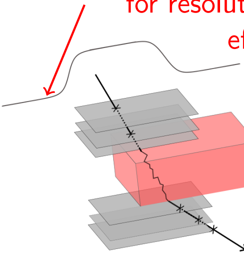


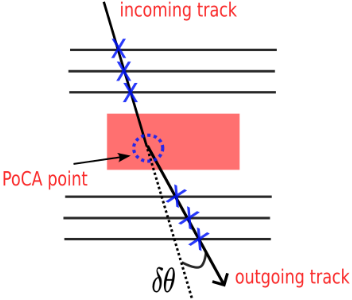
2

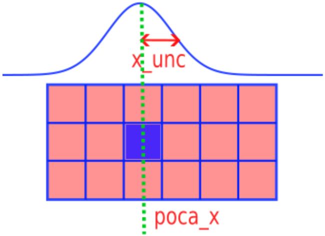
-Initial detector parameters: position, area
-Passive volume (red) with true assigned voxel-wise X_0

- Muons generation
- Hits recorded in detector panels
- Scattering model used to propagate muons in passive volume in short steps of $\mathcal{O}(1\ cm)$

TomOpt: Muon Scattering Tomography Optimisation

3 PoCA reconstruction and volume inference





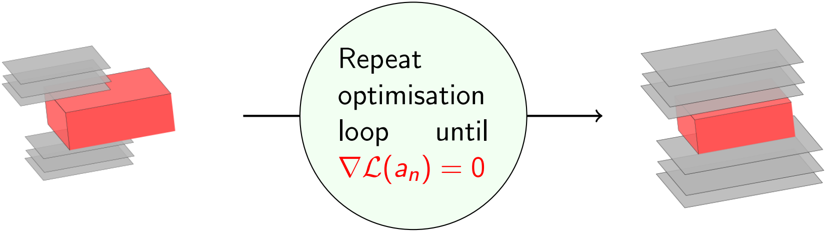
- Tracking of reco hits
- Point-of-closest-approach of incoming/outgoing tracks

- Extended PoCA pdf → PoCA prob per voxel
- Muon batch per voxel → RMS of PoCA variables for each voxel
- Volume X_0 inference by inversion of approximated Eq.(1)

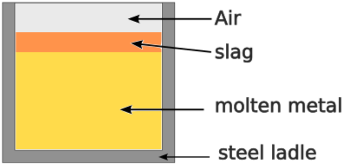
$$\theta_{0_{RMS}} = \frac{13.6\ MeV}{\beta cp}\sqrt{\frac{voxel\ size}{X_0}}$$

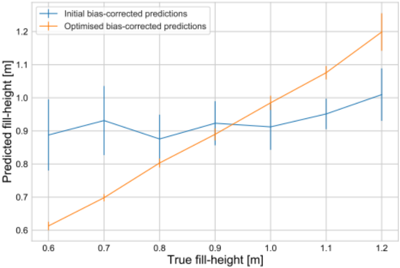
Backpropagation and parameter update

- Differential optimisation = minimisation of loss function $\boldsymbol{\mathcal{L}(a_n)}$ where a_n : detector parameters
- $\mathcal{L}(a_n)$ = **inference error** + constraints
- Gradient descent : $\boldsymbol{a_{n+1}} = a_n - \gamma.\nabla\mathcal{L}(a_n)$



Industrial application: Fill height estimation of furnace ladle

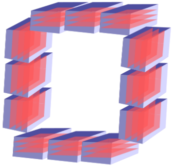


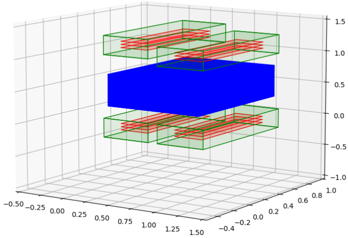


- 1^{st} TomOpt publication (Giles C Strong et al. 2024 Mach. Learn.: Sci. Technol. 5 035002)
- Molten metal transferred to furnace with ladle
- Slag formation prevents optical methods to estimate fill height of liquid metal
- Insufficient metal → partially filled moulds
- Too much metal → formation of scraps
- Fill level inference using z_{PoCA}

Application on cargo scanning (Dev)

- Silent Border project (https://silentborder.eu/): muon tomography scanners for border controls
- modular design: hodoscope containing detector panels

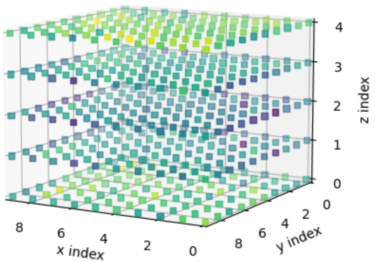


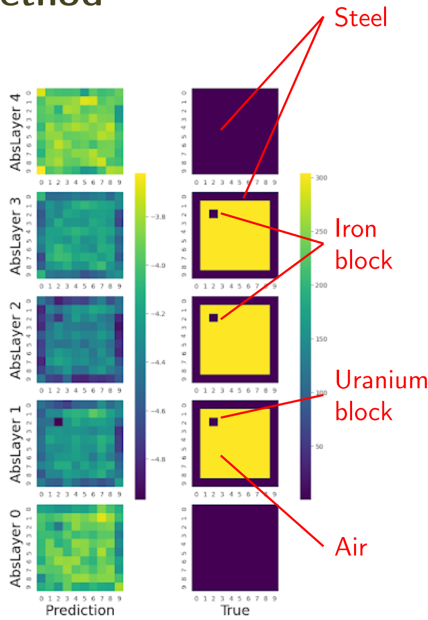


- hodoscope unit instead of panels
- Detector parameters: hodoscope position
- Panels are fixed inside hodoscopes

Inference method

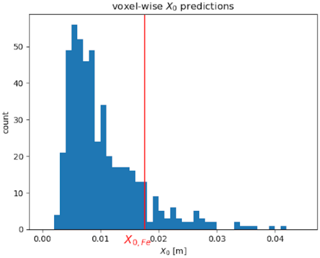
- For cargo scanning, need to infer volume material → X_0 inference using weighted RMS of PoCA variables
- Volume X_0 prediction is 'good' for high-Z materials with low-Z background



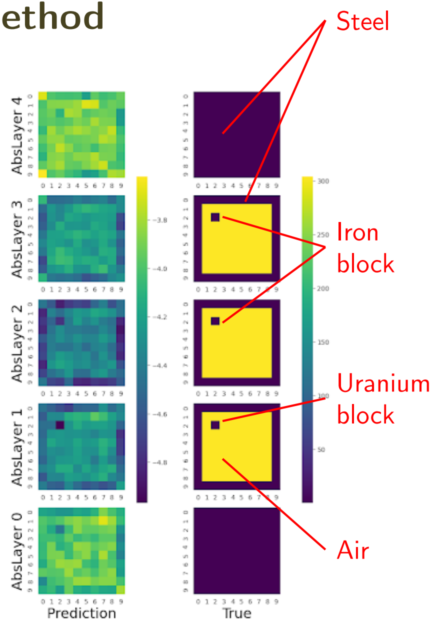


Inference method

- Volume X_0 prediction is 'good' for high-Z materials with low-Z background
- Systematic bias towards lower values



- Fluctuations in MSE loss $= \frac{1}{n}\sum_{i=1}^{n}(true_{X_0} - pred_{X_0})^2$

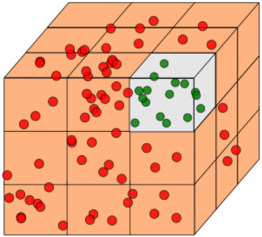


Binned clustering algorithm (BCA)

A binned clustering algorithm to detect high-Z material using cosmic muons (C Thomay et al. 2013 JINST 8 P10013)

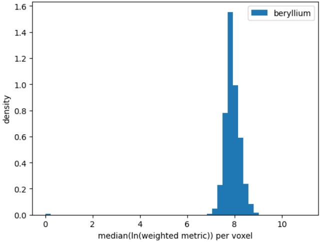
For each voxel k in passive volume:

- Select $n_{max} = 40$ PoCA's with largest $\theta_{scatter}$
- For i, j in voxel k:
  - Calculate $m_{ij} = \frac{||\overrightarrow{poca_i} - \overrightarrow{poca_j}||}{\theta_i \theta_j}$
  - Fill histogram with $ln(m_{ij})$
  - Take median of distribution
- Per voxel values $\rightarrow$ volume distribution

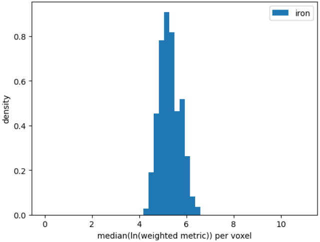


BCA weighted metric distributions

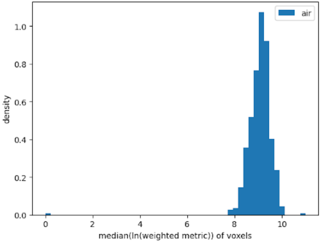
Beryllium



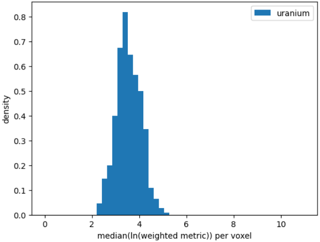
Iron



Air

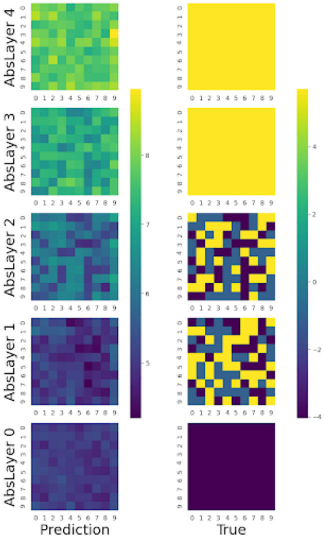


Uranium

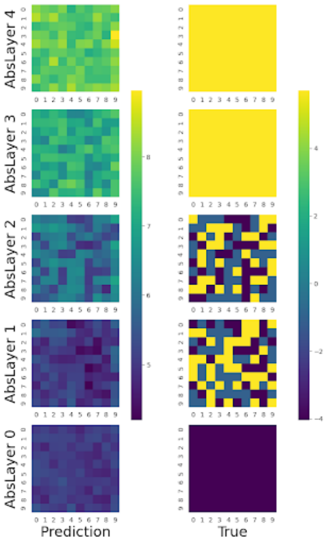


BCA predictions

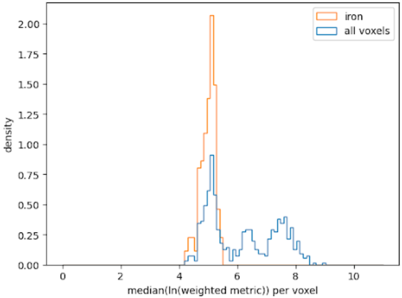
- Passive volumes (with/without) U-blocks randomly generated
- Material is iron+beryllium+air blocks
- Uranium block randomly placed
- 100k muons generated



BCA predictions: no uranium block

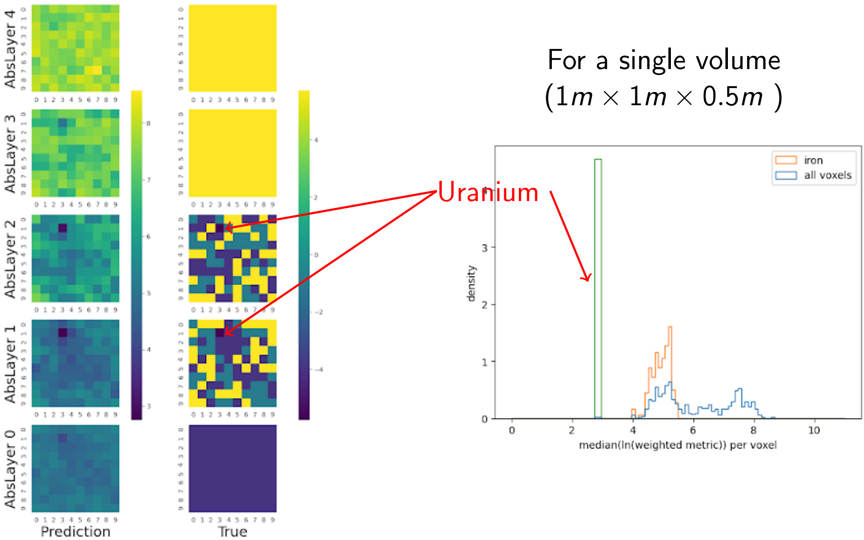


For a single volume
$(1m \times 1m \times 0.5m)$



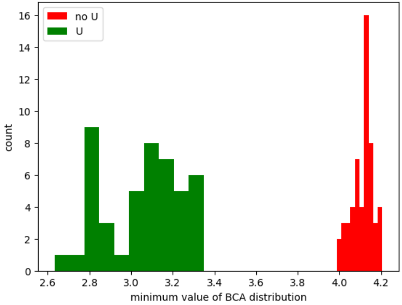
BCA predictions: uranium block

For a single volume
$(1m \times 1m \times 0.5m\ )$



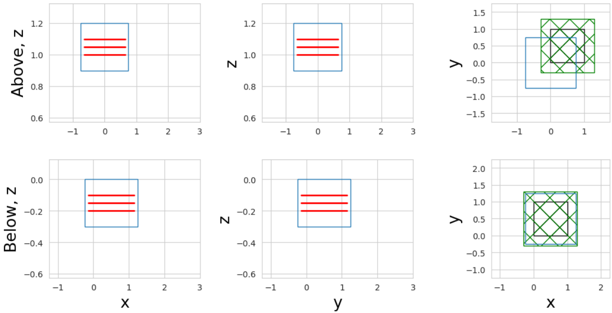
Classification of BCA volume predictions

- 100 volumes randomly generated with equiprobability of containing uranium
- background materials: iron+air
- $n_{muons} = 100,000$ (resampling of muons that do not cross the volume)
- discriminator of each volume = minimum of the distribution of $median(weighted_{metric})$
- powerful classification (AUC = 1)

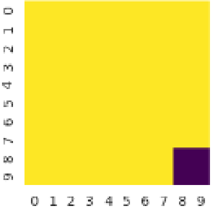


Optimisation with BCA classification

- Binary-cross-entropy loss function
- target (truth) = 0 (no U) / 1 (U)
- discriminator passed to a sigmoid activation function

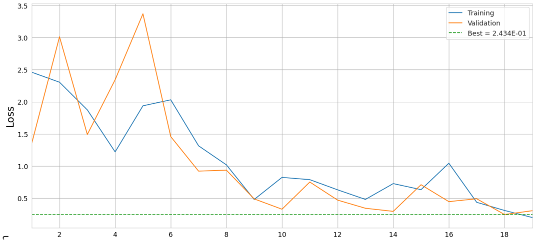


initial detector configuration
upper hodoscope at $x = y = 0$
(on other side of U-block)

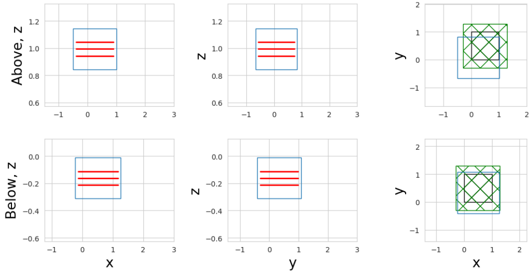


layer 3 containing U-block in a volume of beryllium

Optimisation with BCA classification

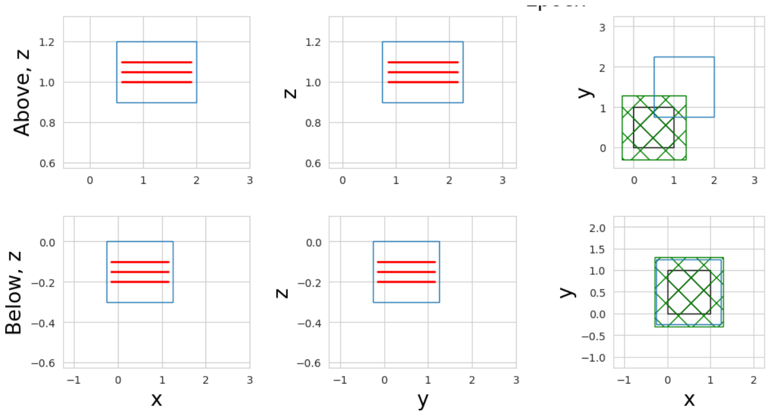


evolution of loss over 20 epochs (first 5 are warm-up epochs where hodoscope positions are not updated)



final detector configuration

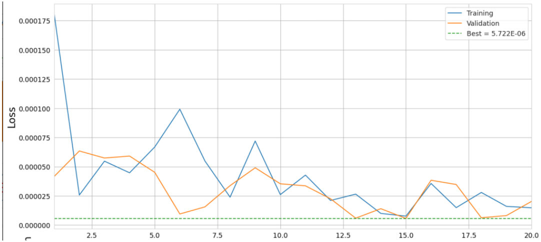
Optimisation (upper hodoscope above U-block)



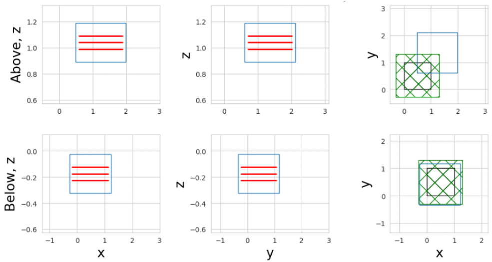
initial detector configuration

upper hodoscope at $x = y = 1.5m$

Optimisation with BCA classification



evolution of loss over 20 epochs (first 5 are warm-up epochs where hodoscope positions are not updated)



final detector configuration (same as initial one)

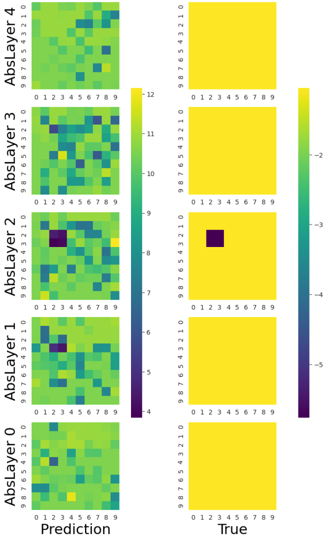
How to correct gradient behaviour?

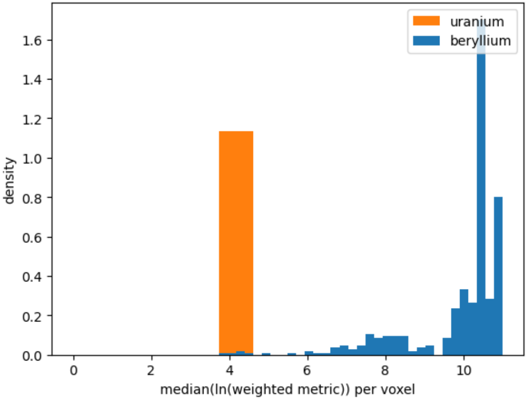
Possible solution/ongoing study

- Extended PoCA pdf $\mathcal{G}(xyz, xyz_u nc) \rightarrow$ per voxel probability of PoCA's
- For each voxel j:
  - All PoCA points are taken
  - PoCA weight = PoCA probability in voxel j $\times$ muon efficiency
  - score of voxel is 'weighted median'
- $100k$ muons $\rightarrow$ 1000 muons (comparable computation time)

BCA with Extended PoCA

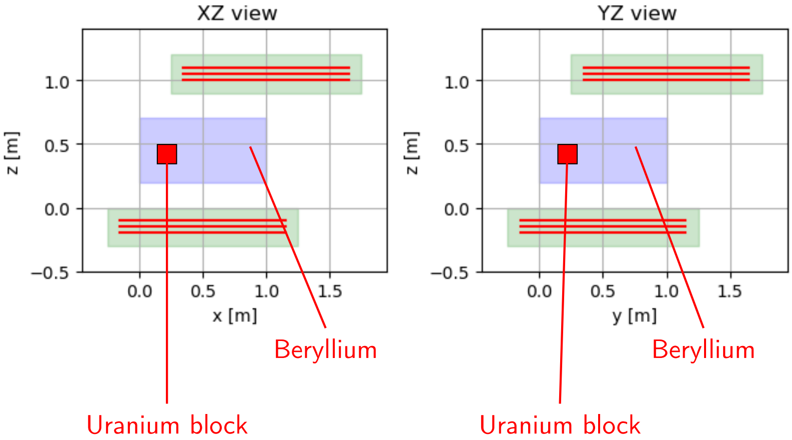
Centered upper hodoscope





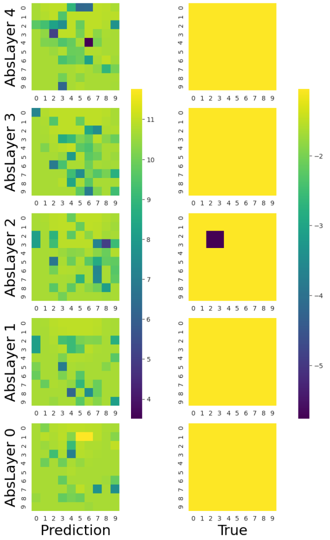
BCA with Extended PoCA

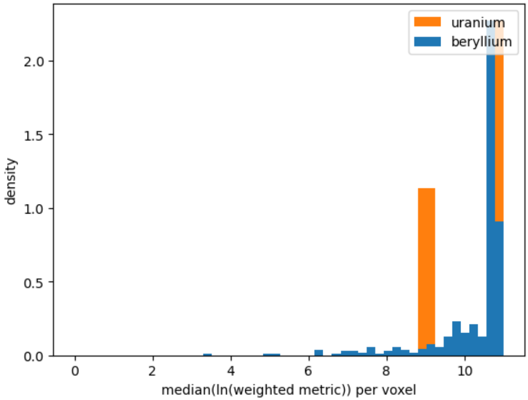
Off-centered upper hodoscope



BCA with Extended PoCA

Off-centered upper hodoscope





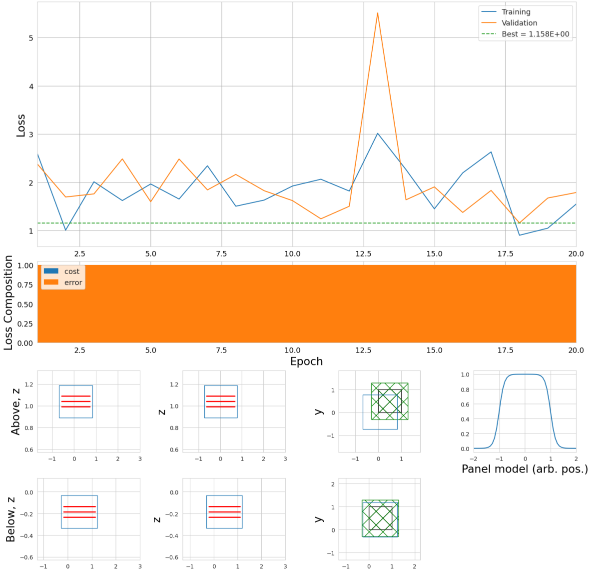
Conclusion

- TomOpt optimisation is inference-aware and fully-differentiable
- Studying different inference methods for better optimisation performance
- BCA classification shows good discrimination of U-lorry volumes
- Using extended PoCA pdf may improve gradient behaviour
- work in progress. . .

Thank you for your attention!
Any questions?

Backup Slides

Optimisation with 30 randomly generated volumes per epoch



- 60k muons instead of 100k
- computation time ≈ 5 days