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Using Allpix Squared for proton computed tomography

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TU Dortmund
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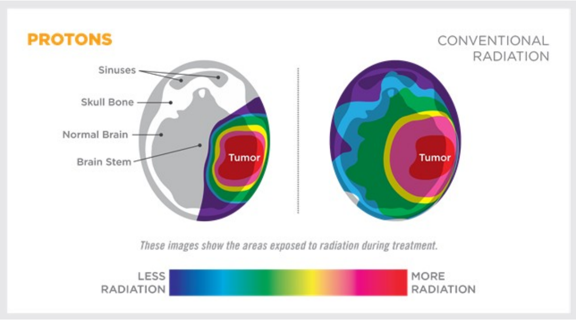
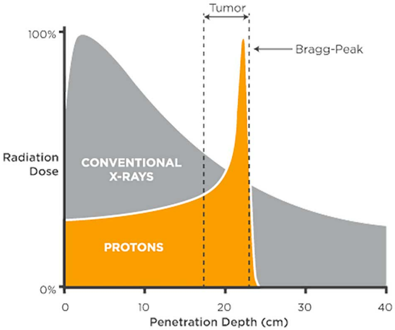
Proton therapy

- Proton therapy uses the energy deposition of protons to irradiate tumors
- Advantage: Less damage for healthy tissue due to different energy deposition



[The National Association for Proton Therapy: Provision Brain Graphic]



[Provision Cares Cancer Network]

Proton computed tomography

- Irradiation plan is based on CT scan
- Using X-ray CT scans causes uncertainties for the irradiation plan
  - Safety margin increases with travel distance

Source of range uncertainty in the patient	Range uncertainty without Monte Carlo	Range uncertainty with Monte Carlo
Independent of dose calculation		
Measurement uncertainty in water for commissioning	±0.3 mm	±0.3 mm
Compensator design	±0.2 mm	±0.2 mm
Beam reproducibility	±0.2 mm	±0.2 mm
Patient setup	±0.7 mm	±0.7 mm
Dose calculation		
Biology (always positive) ˆ	+~0.8%	+~0.8%
CT imaging and calibration	±0.5%[a]	±0.5%[a]
CT conversion to tissue (excluding I-values)	±0.5%[b]	±0.2%[g]
CT grid size	±0.3%[c]	±0.3%[c]
Mean excitation energy (I-values) in tissues	±1.5%[d]	±1.5%[d]
Range degradation; complex inhomogeneities	−0.7%[e]	±0.1%
Range degradation; local lateral inhomogeneities *	±2.5%[f]	±0.1%
Total (excluding *, ˆ)	2.7% + 1.2 mm	2.4% + 1.2 mm
Total (excluding ˆ)	4.6% + 1.2 mm	2.4% + 1.2 mm

[Harald Paganetti 2012 Phys. Med. Biol. 57 R99]

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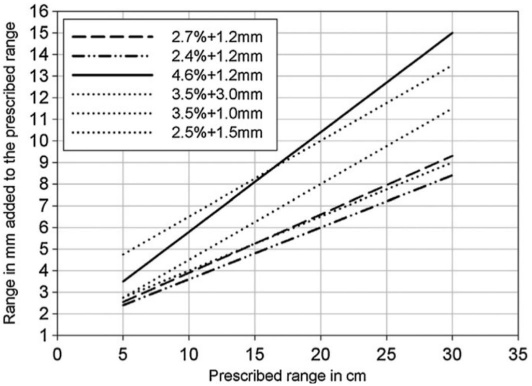
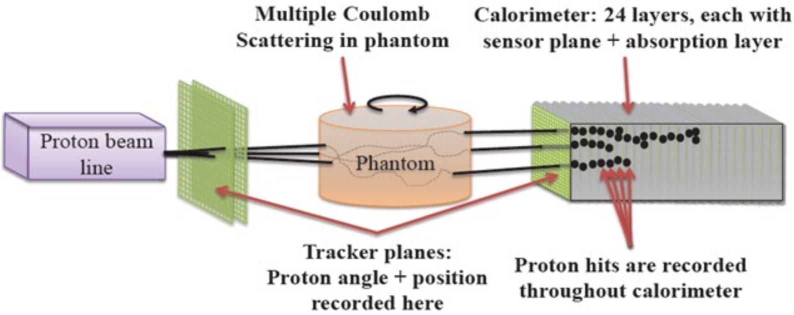


Proton computed tomography

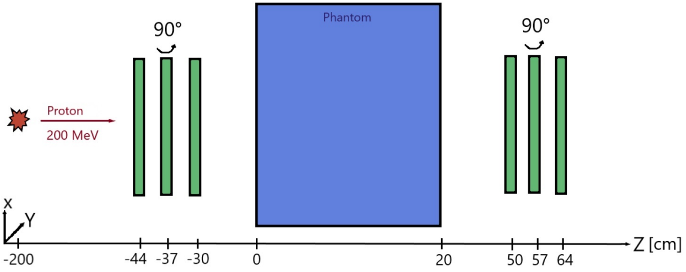
- Track reconstruction is necessary in creating proton computed tomography scans
- Using Allpix^2 to simulate proton beam and telescope [Allpix^2: 10.1016/j.nima.2018.06.020]



Helge Egil Seime Pettersen, University of Bergen

Proton beam setup

- Telescope setup: 6 $\times$ IBL planar sensors
- Middle sensor of triplets is rotated by 90° to increase resolution in horizontal direction
- 50k protons are simulated with Allpix^2 and reconstructed with Corryvreckan
  [Corryvreckan:10.1088/1748-0221/16/03/P03008]



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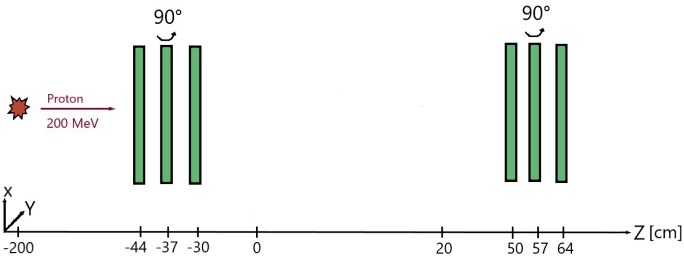
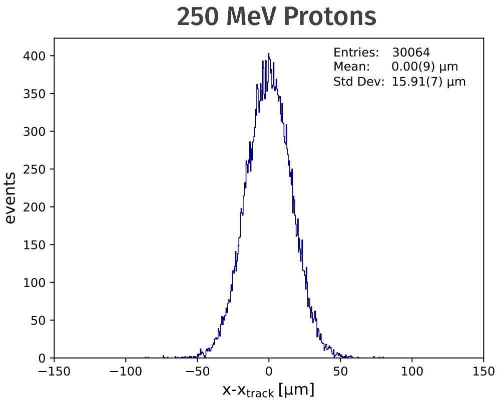
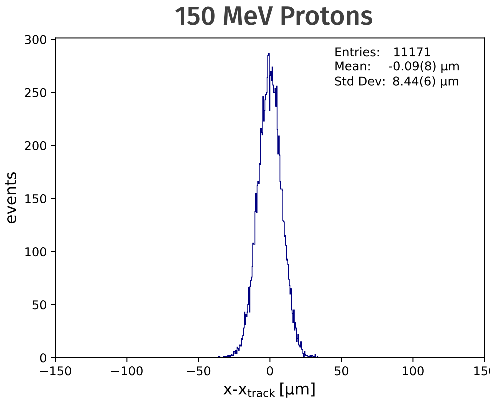


Performance test: Energy

- Simulations with proton energies used for proton computed tomography
- Hit on all six sensors required for track reconstruction
  - Significant amount of particles can not be reconstructed due to stronger scattering

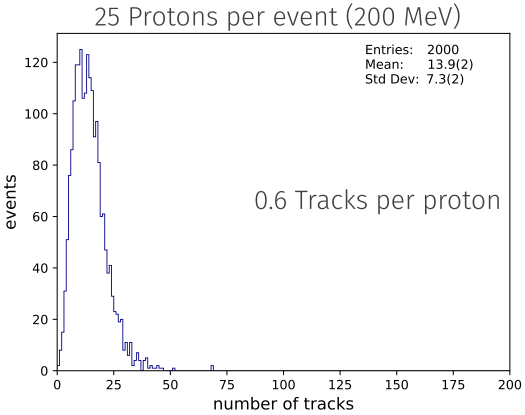


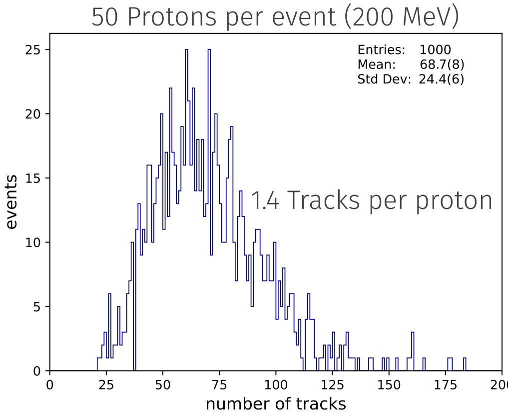


- Smaller statistics can be countered by taking more data ⟶ Higher dose deposition

Performance test: Track density

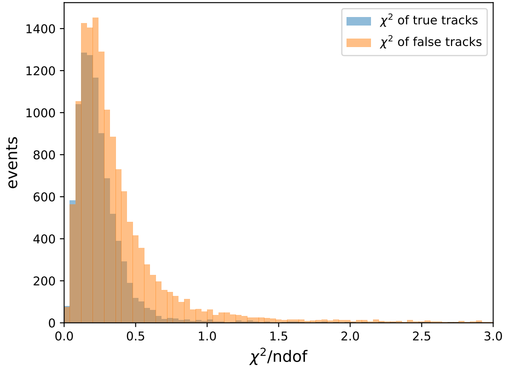
- Simulations with proton densities possible for proton computed tomography
- More particles per event lead to higher amount of tracks with false hit combinations

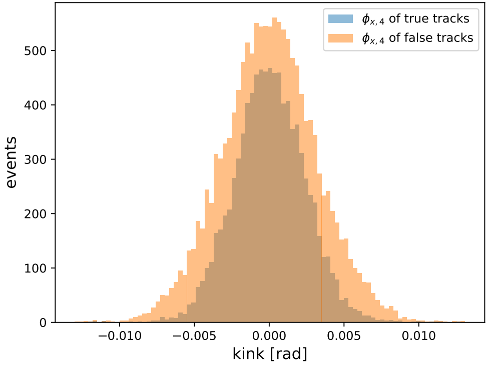




Separating features

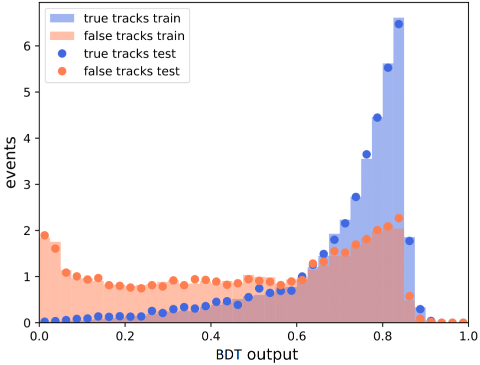
- Reject false tracks by implementing cuts on track features
- 100k Protons (200 MeV), 10 protons per event
- Useful features: χ^2 value, scattering angles $\phi_{x,3}$ and $\phi_{x,4}$
- How does a machine learner perform in comparison?

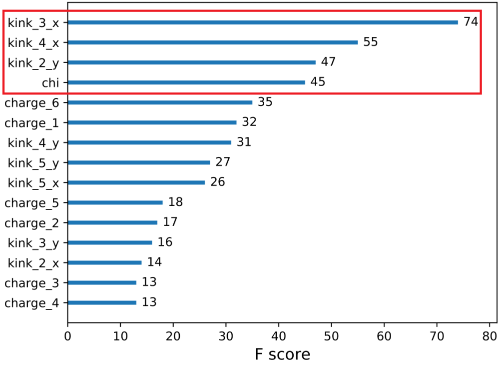




XGBoost

- Using Boosted Decision trees from XGBoost library
- Training data set: 400k protons (200 MeV, 10 per event)
- Test data set: 100k protons (200 MeV, 10 per Event)
- Probability distribution of true and false tracks different



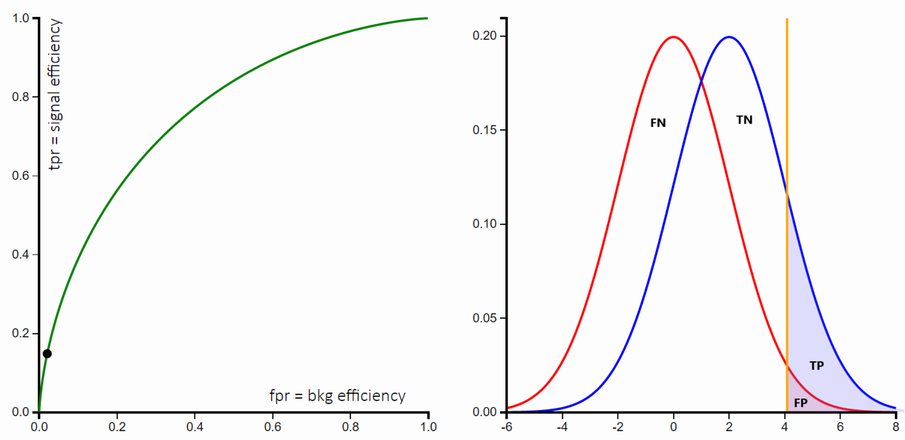


ROC curve

- Evaluate classification $\longrightarrow$ ROC curve
- Each cut describes one point of the curve

tpr = TP/(TP + FN)

fpr = FP/(FP + TN)



[Alex Rogozhnikov, ROC curve demonstration]

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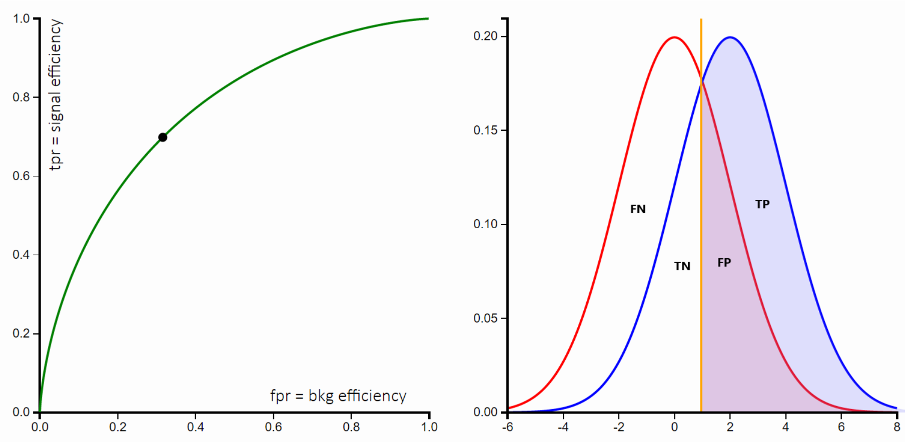

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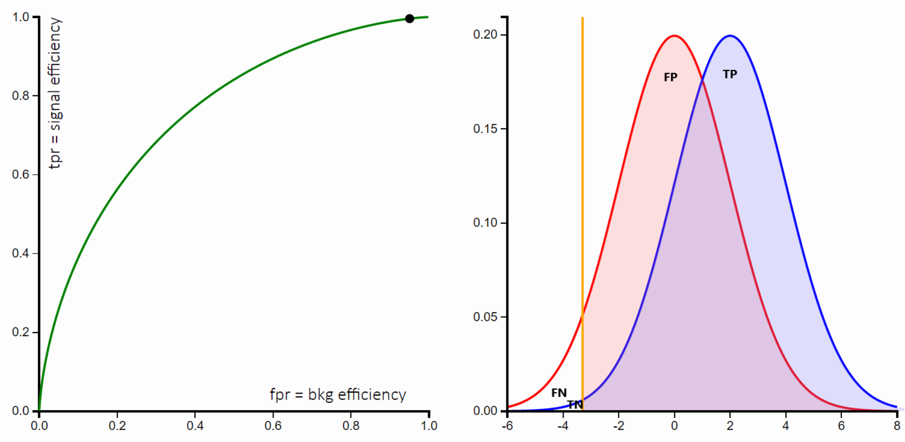


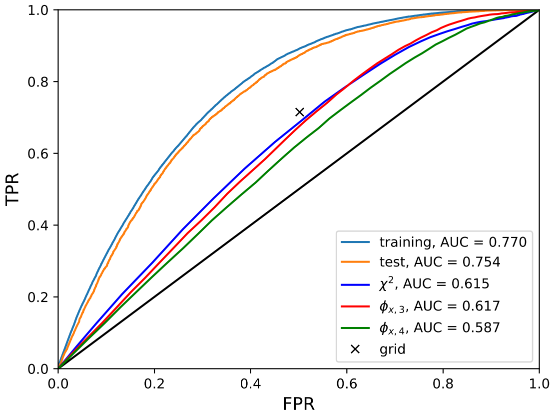
[Alex Rogozhnikov, ROC curve demonstration]

ROC curves result

$$tpr = TP/(TP + FN)$$

$$fpr = FP/(FP + TN)$$

- Area Under Curve (AUC) is a good measure to evaluate ROC curves
  - Higher AUC means higher tpr, lower fpr
- AUC of the learner is higher
  $\longrightarrow$ Better classification

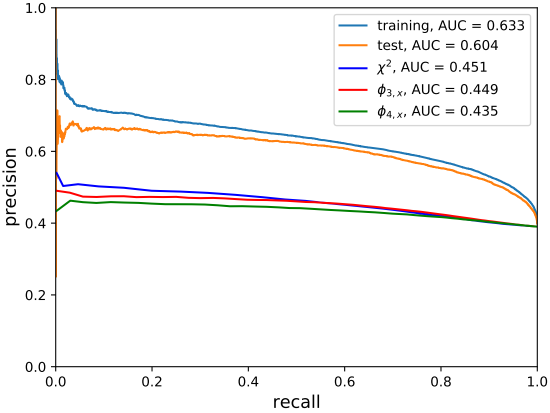


Precision-Recall curves

Recall = TP/(TP + FN)

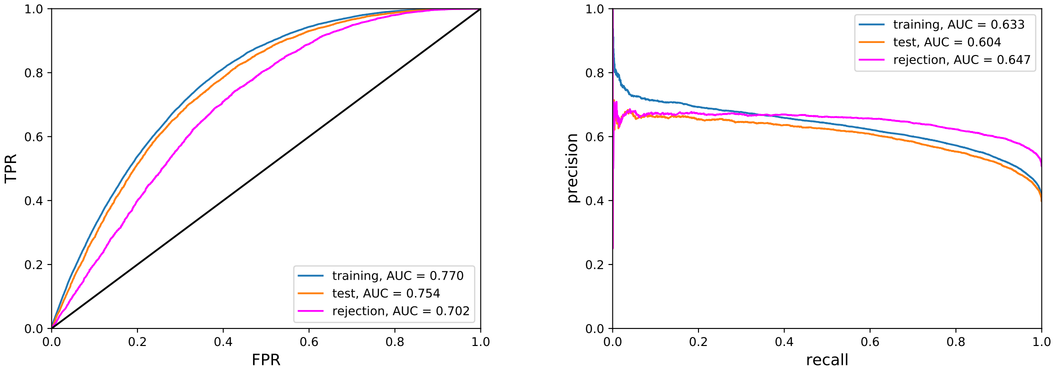
Precision = TP/(TP + FP)

- Precision: Classifiy false tracks as false
- Recall: Finding all true tracks
- Precision is stable for most recall values
    - High recall achievable
- AUC of the learner is higher
  $\longrightarrow$ Higher precision scores



Further rejection

- Rejecting all but one track from cluster on first and last plane
- Only keeping track with highest probability of being true



- Precision increases, but FPR increases too due to the decrease of true negative tracks

Summary and Outlook

- **Goal**: Track reconstruction of simulated low energy protons with high track density
- **Problem**: Low energy particles cause problems in track reconstruction due to scattering
  - More particles get deflected
  - Standard deviation of residuals decreases
- **Problem**: High track densities cause a combinatorics problem
  - Many unwanted false tracks decrease the resolution of the ct image
- **Result**: Classification with a boosted decision tree is superior to 1D cuts on track features

Outlook:

- Advanced track finding algorithm: Tracking Multiplet
- Neural Networks for track classification