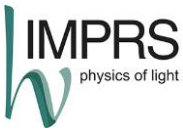
Tau neutrino appearance studies with KM3NeT/ORCA using Deep Learning techniques

Michael Moser,
Astroparticle School 2018, 06.10.2018

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



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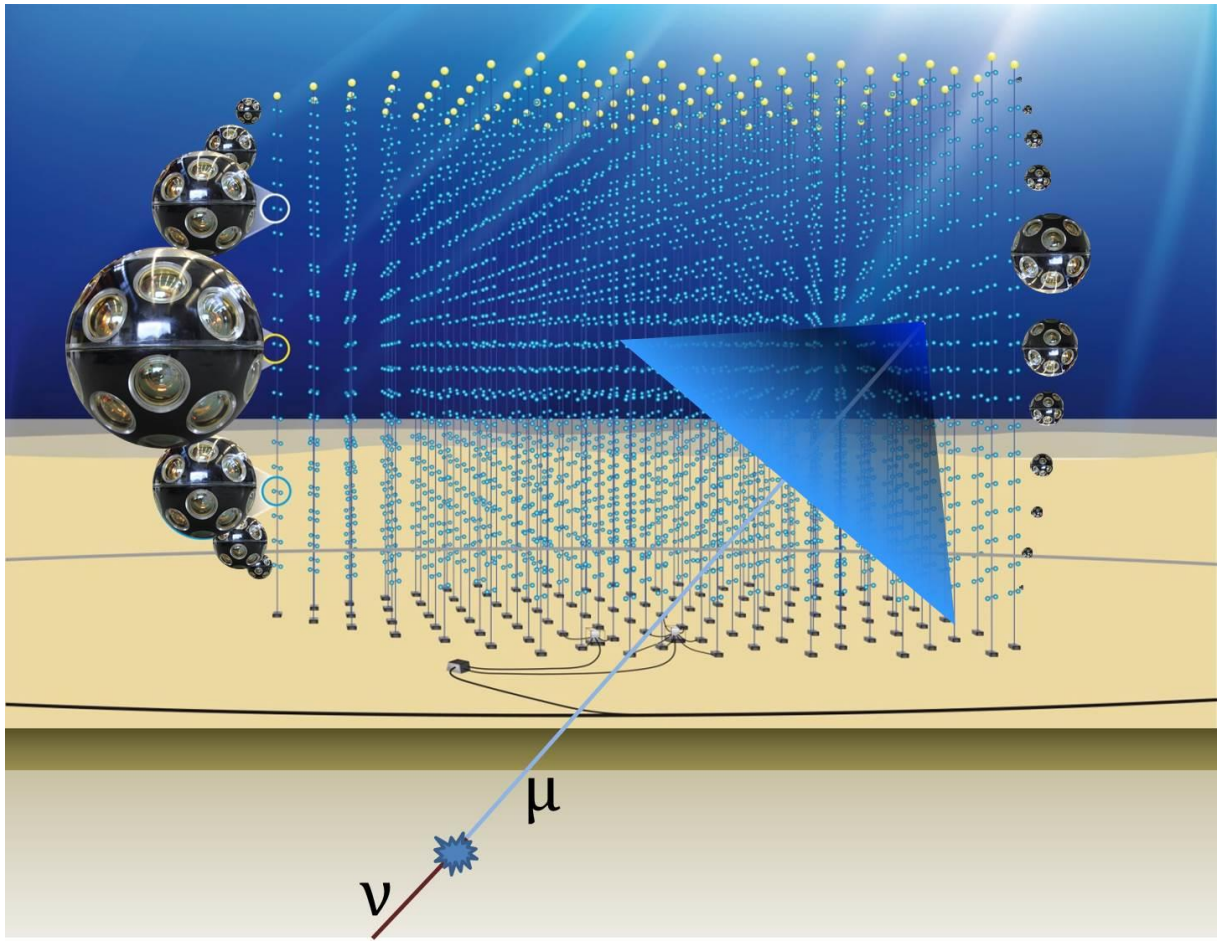
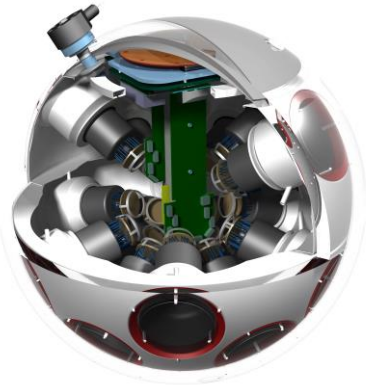
ORCA: a neutrino detector

Aim: measure atmospheric neutrino interactions in 1-100 GeV range



ORCA DOM

43 cm



31 PMTs

Tau neutrino appearance with ORCA

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- Currently being built in the Mediterranean sea, south of France
- 115 strings, 18 DOMs / string
- ≈ 200 m diameter and height
- Main goal: resolve neutrino mass hierarchy

- ORCA has a large target mass, 8 megaton instrumented volume
- Detect tau neutrinos from atmospheric $\nu_\mu \rightarrow \nu_\tau$ oscillations
- > 3000 ν_τ / year (Super Kamiokande: 20 ≈ ν_τ / year)
- Probe unitarity of the neutrino mixing matrix

Detection of tau neutrinos

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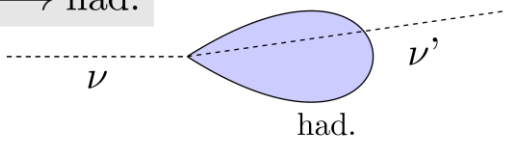
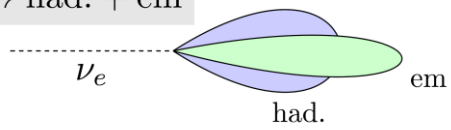
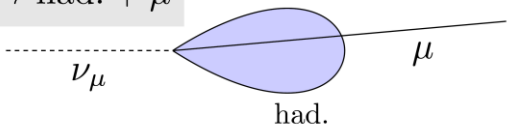
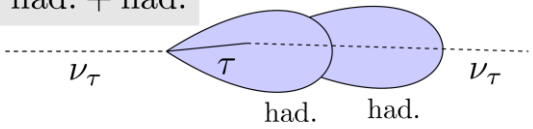
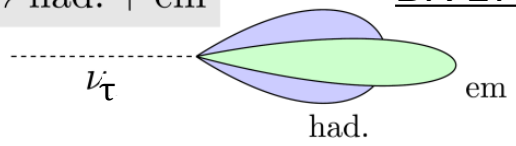
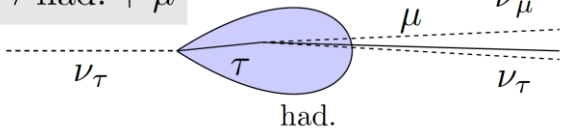
shower-like	track-like
$\nu + N \xrightarrow{NC}$ had. 	
$\nu_e + N \xrightarrow{CC}$ had. + em 	$\nu_\mu + N \xrightarrow{CC}$ had. + μ 
$\nu_\tau + N \xrightarrow{CC}$ had. + had. BR 65.8%  $\nu_\tau + N \xrightarrow{CC}$ had. + em BR 17.8% 	BR 17.4% $\nu_\tau + N \xrightarrow{CC}$ had. + μ 

Detection of tau neutrinos

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How to detect tau neutrinos?

Measure track / shower composition of atmospheric neutrino flux dependent on energy and direction

Detection of tau neutrinos

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

How to detect tau neutrinos?

Measure track / shower composition of atmospheric neutrino flux dependent on energy and direction

Detect an excess of shower events compared to the expectation without ν_τ

Detection of tau neutrinos

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

How to detect tau neutrinos?

Measure track / shower composition of atmospheric neutrino flux dependent on energy and direction

Detect an excess of shower events compared to the expectation without ν_τ

Measure tau neutrino appearance on a statistical basis

Detection of tau neutrinos

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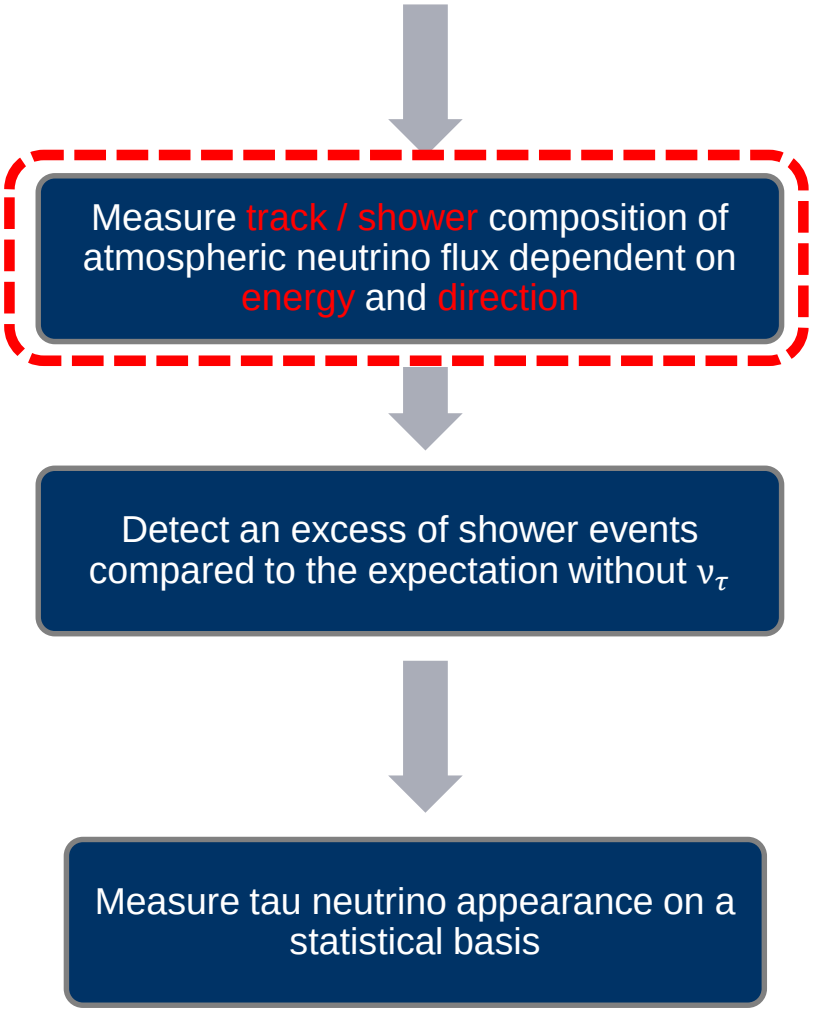
How to detect tau neutrinos?



Event reconstruction in ORCA

How to reconstruct event properties like energy and direction?

- Standard reconstructions in ORCA inspired by the physical properties of neutrino events
- Not clear if these algorithms yield the best possible performance

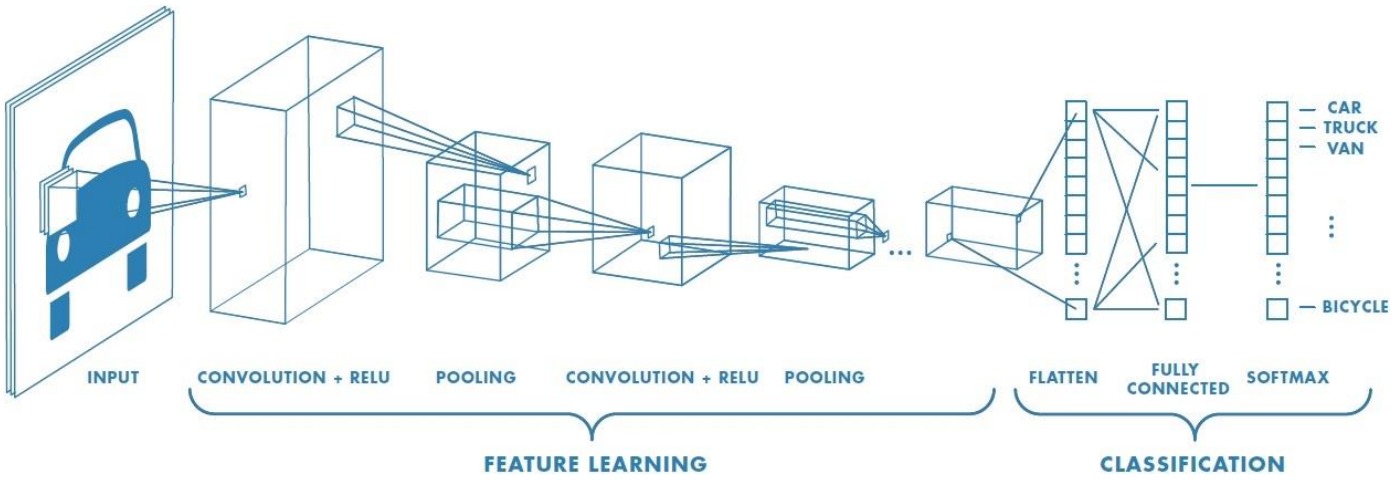
- What if an algorithm could learn the event properties of neutrinos by itself, based on the raw detector data (photon “hits”)?
- Possible with recently emerging machine learning algorithms like deep neural networks, also called “Deep Learning” techniques

Deep Learning in ORCA

- How can we apply Deep Learning methods to ORCA data?
- Physics events in ORCA can be interpreted as pictures in time

Successful model architecture in image recognition:

Convolutional neural networks (CNNs)

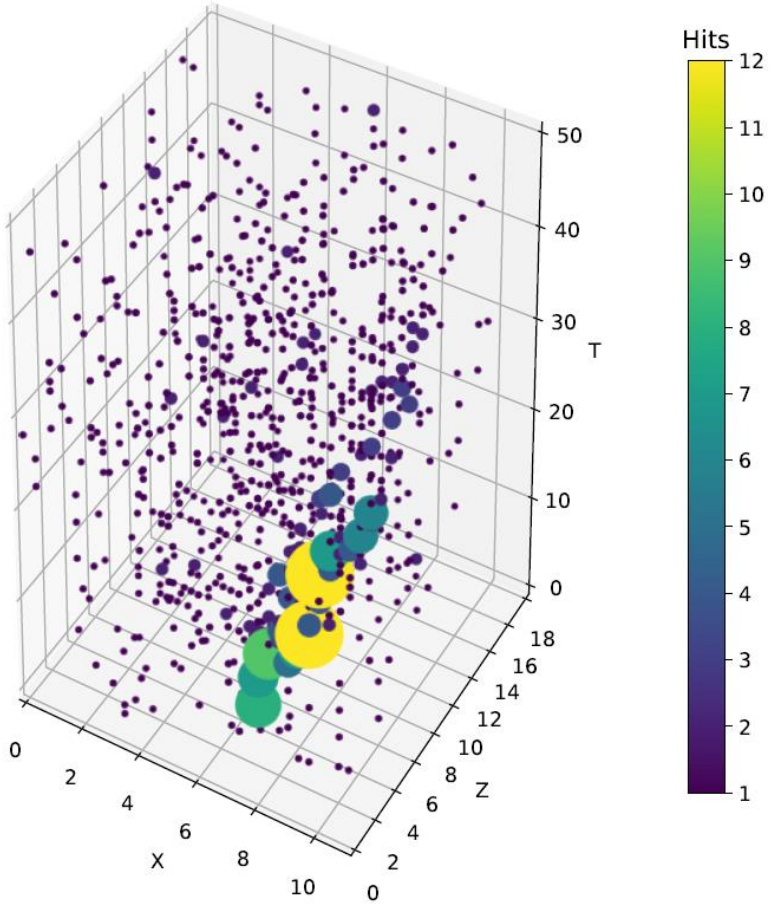


Simplified convolutional neural network (CNN)

How to produce images in ORCA?

- ORCA records 6D data
  (XYZ, T, 2 x PMT orientation)
- Bin dimensions in order to get images
- E.g. bin spatial dimensions such that 1 DOM / bin → 11 x 13 x 18

Up-going ν_μ - CC, 65 GeV



3D XZT projection

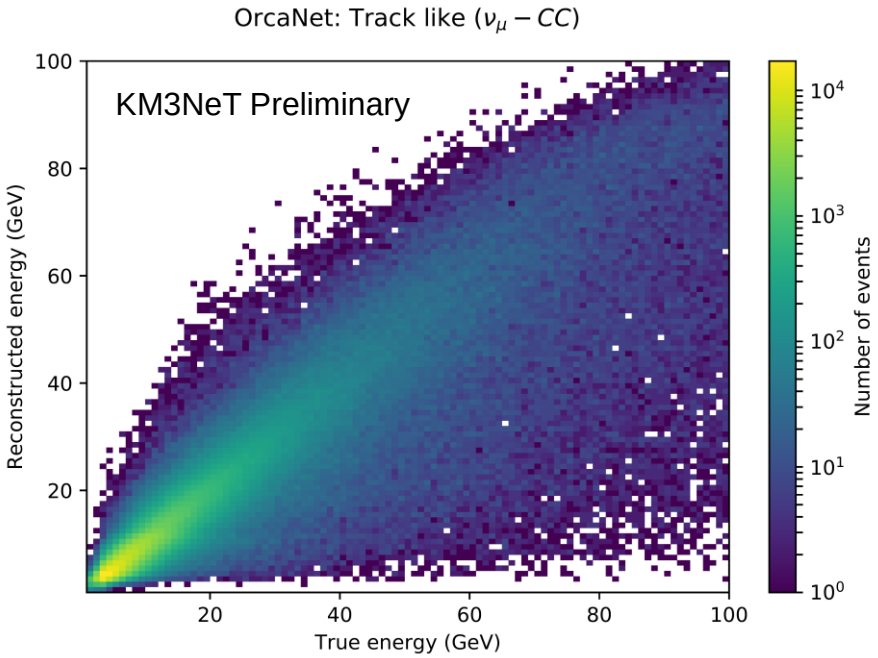
Event reconstruction with OrcaNet

- Deep Learning framework for ORCA is called „OrcaNet“
- Network needs to be trained in order to learn the event properties
  - Use 12 Mio. events for training
  - ν_μ - CC, ν_e - CC and ν_e - NC events
  - Neutrino energies from 1 – 100 GeV
  - CNN architecture with 8 layers
  - Reconstructs energy, direction, bjorken-y and uncertainty estimation
  - Trained at the TinyGPU cluster in Erlangen

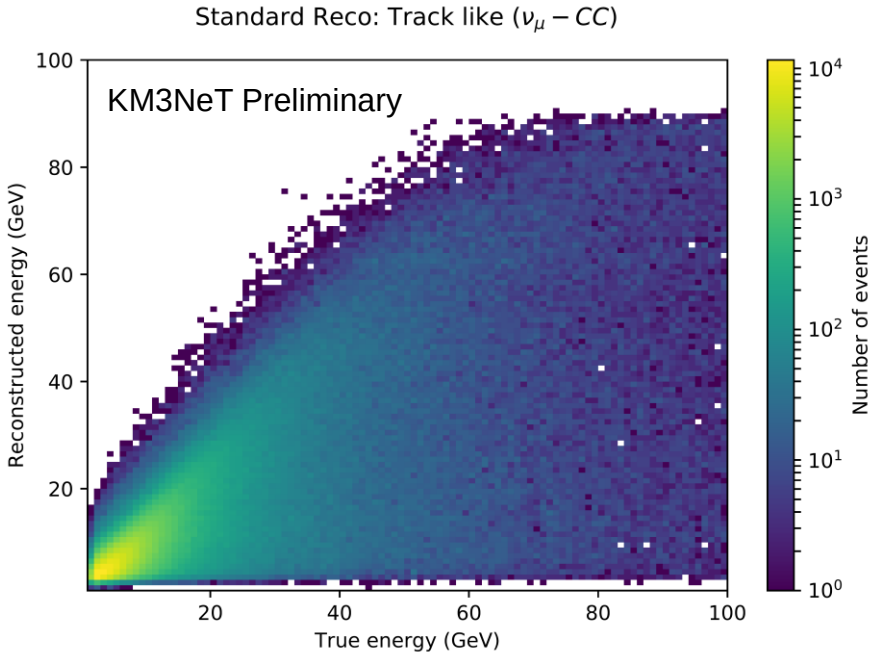
- All of my code is open source and can be found at: github.com/ViaFerrata/OrcaNet

OrcaNet results – track energy

- OrcaNet ν_μ - CC energy reco is significantly better than standard reco



OrcaNet

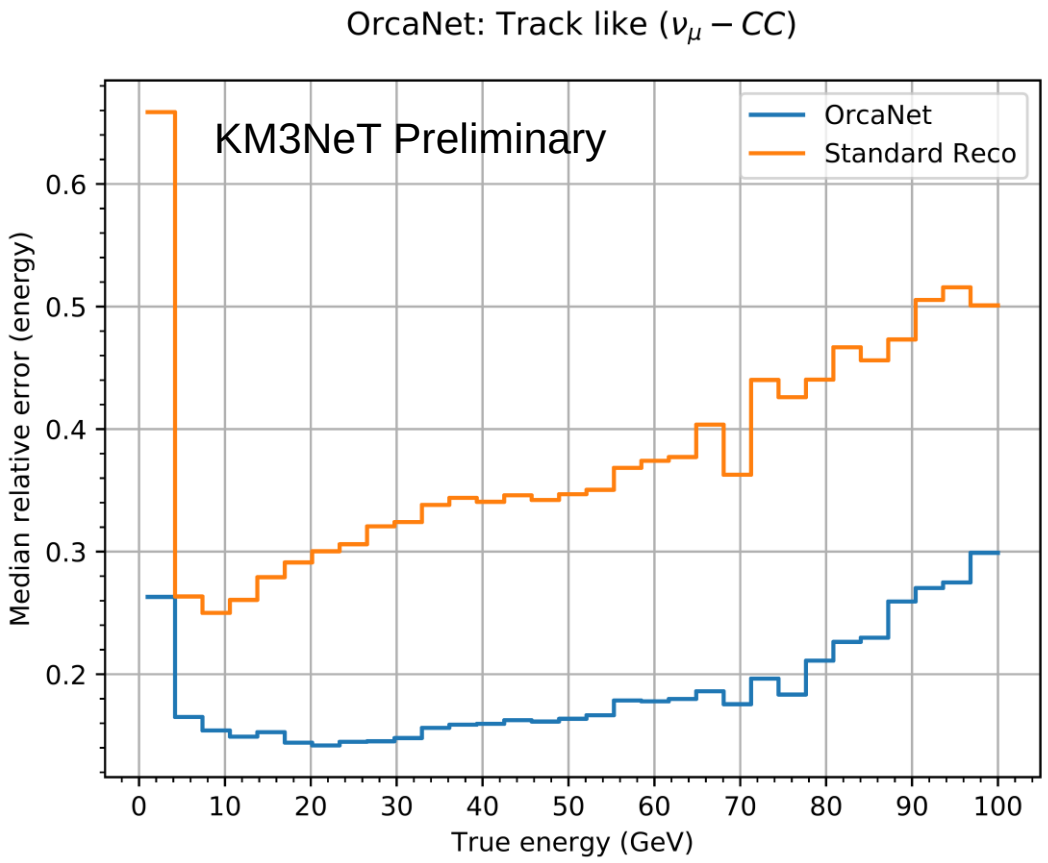


Standard ORCA reco

OrcaNet results – track energy

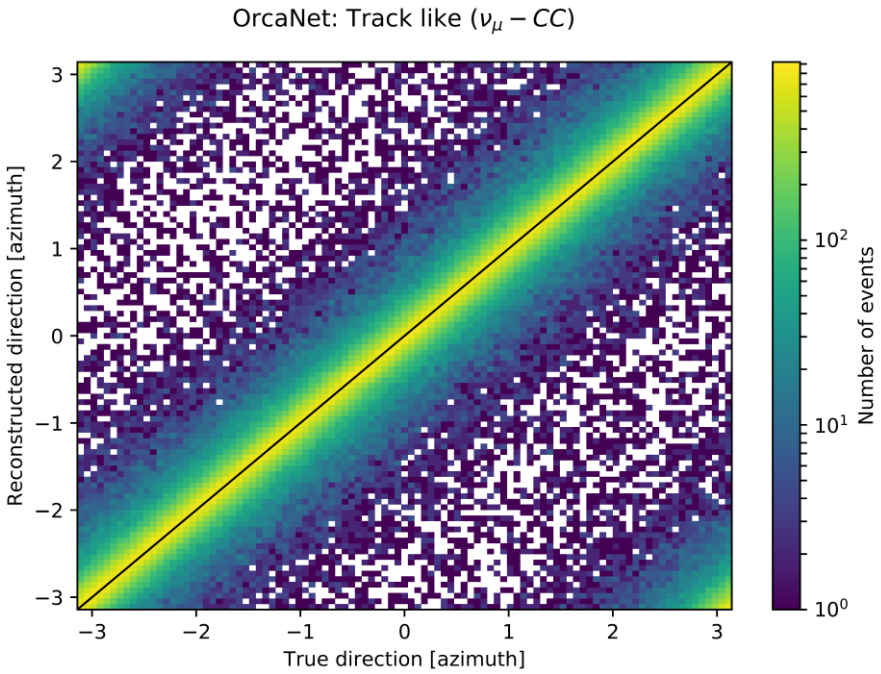
- OrcaNet ν_μ - CC energy reco is significantly better than standard reco

Y-axis: Median Relative Error (E) = Median(| E_{reco} - E_{true} |)

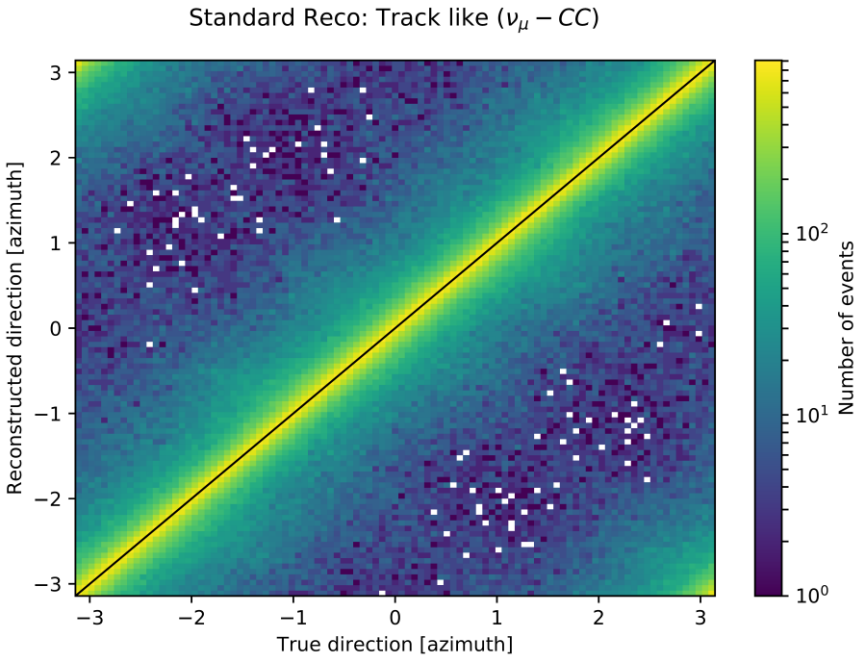


OrcaNet results – direction

- OrcaNet ν_μ - CC direction reco can reduce outliers significantly



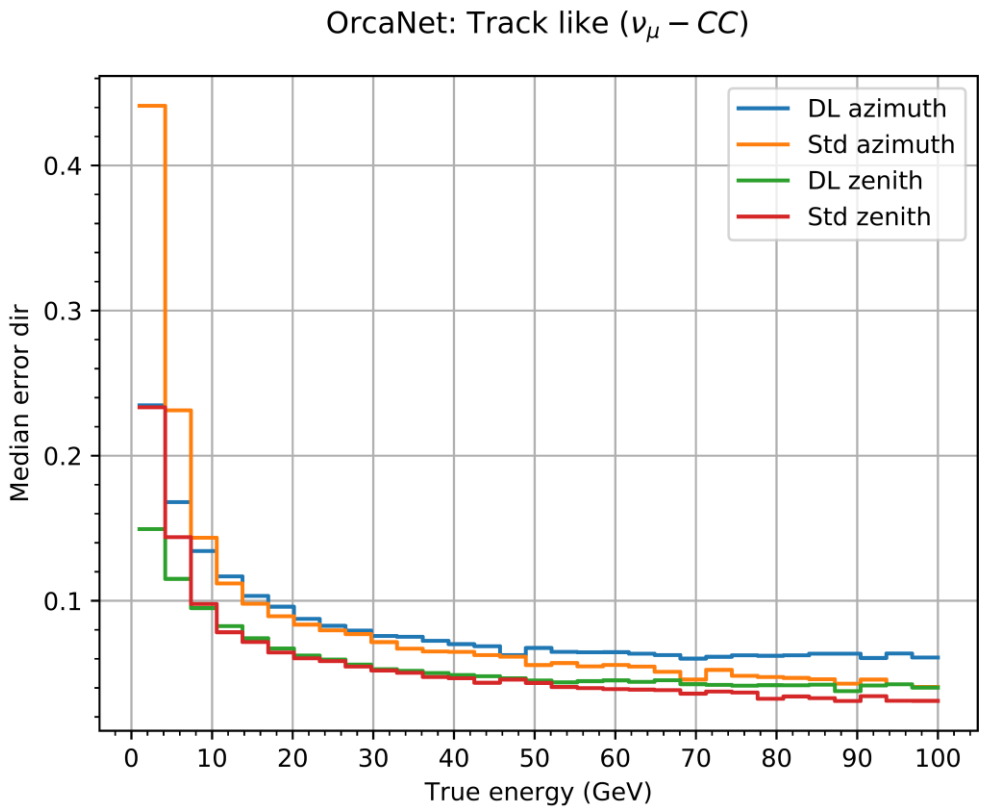
OrcaNet



Standard ORCA reco

OrcaNet results – direction

- OrcaNet ν_μ - CC azimuth / zenith reco is better at lower energies, but slightly worse at higher energies compared to the standard reco
- Still lots of optimization left for OrcaNet!



Outlook

- Not shown: OrcaNet also features track-shower separation, which is significantly better than the traditional approach
- Very little optimization of OrcaNet so far
- Future: offer a second, fully independent reconstruction branch for ORCA data based on Deep Learning methods

Emerging machine learning algorithms are new powerful tools in (astro)particle physics!

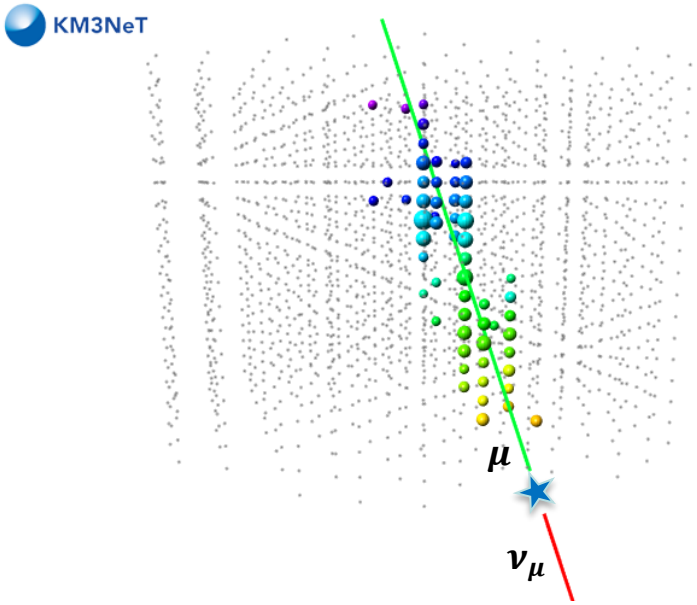
Thank you for your attention!

Backup

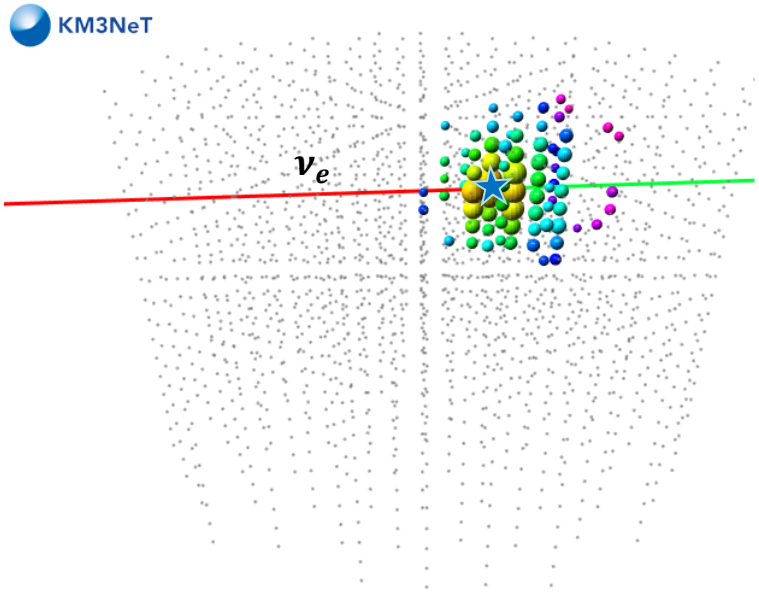
Track / shower classification

How to classify tracks & showers in ORCA?

Up-going ν_μ – CC track-like event



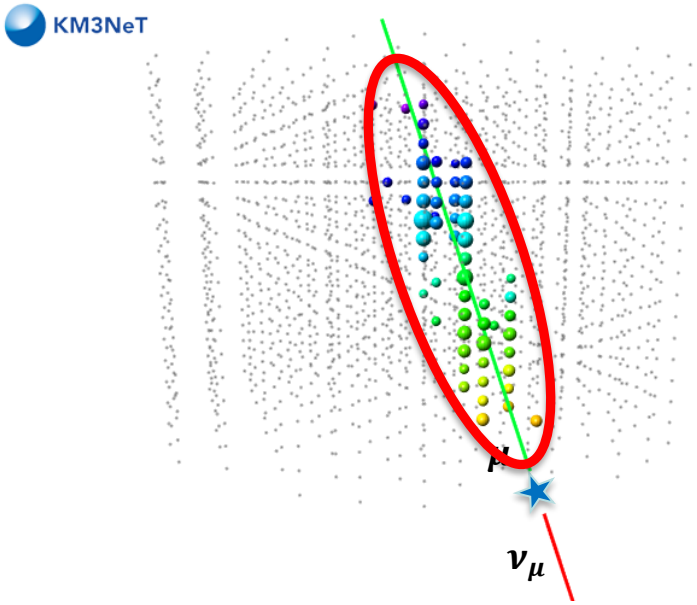
ν_e – CC shower-like event



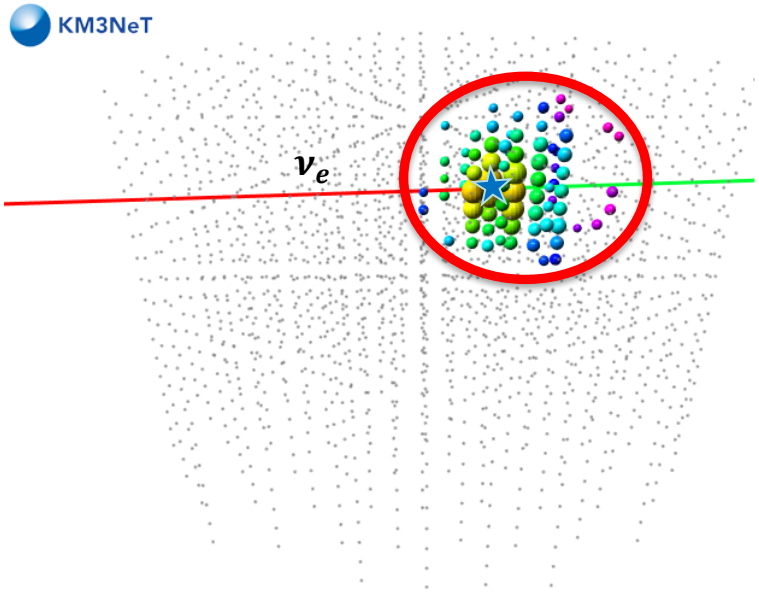
Track / shower classification

How to classify tracks & showers in ORCA?

Up-going ν_μ – CC track-like event



ν_e – CC shower-like event



Handcrafted feature: Sphericity

Track / shower classification

How to classify tracks & showers in ORCA?

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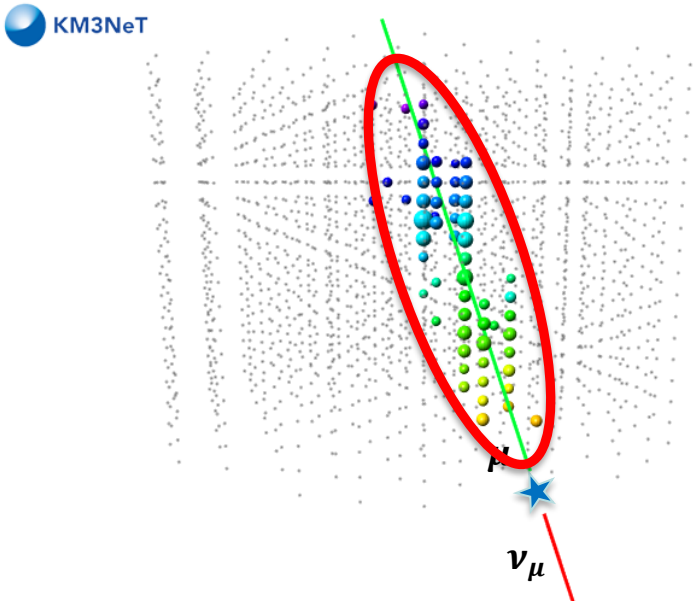
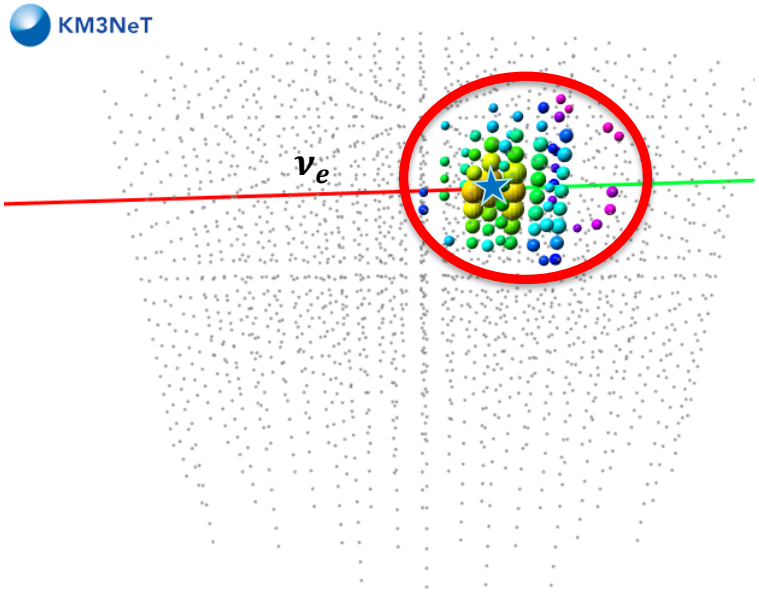


ν_e – CC shower-like event



Handcrafted feature: Sphericity

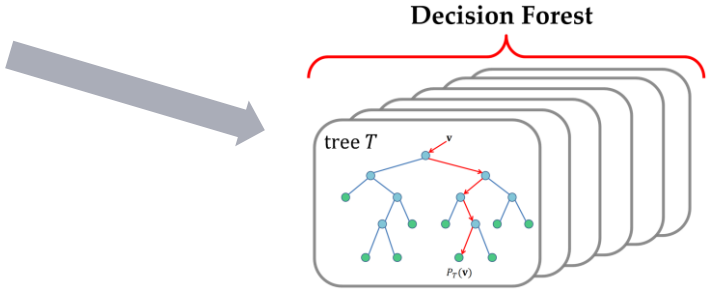


Image taken from [1]

Track / shower classification

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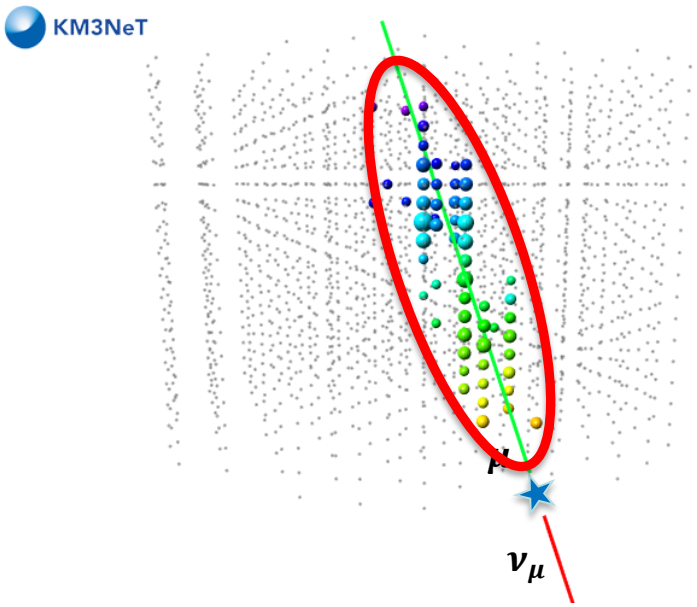
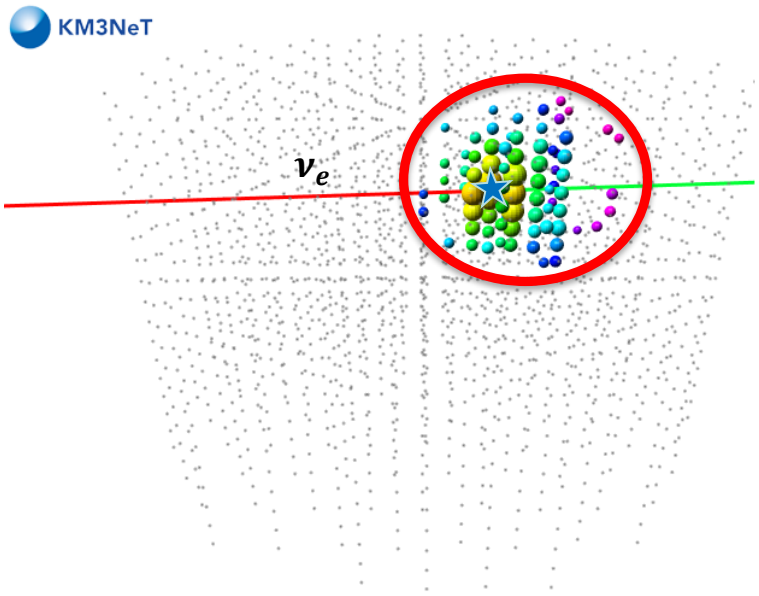
How to classify tracks & showers in ORCA?

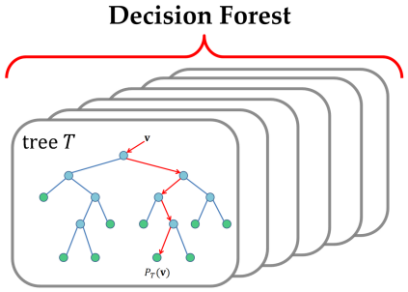
Up-going ν_μ – CC track-like event



ν_e – CC shower-like event



Handcrafted feature: Sphericity

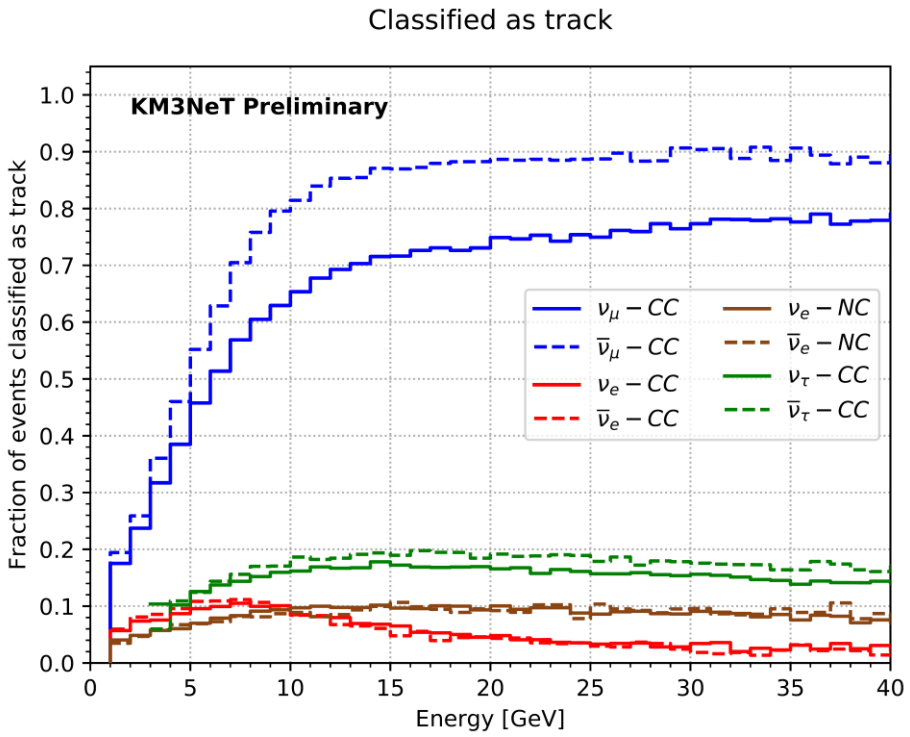


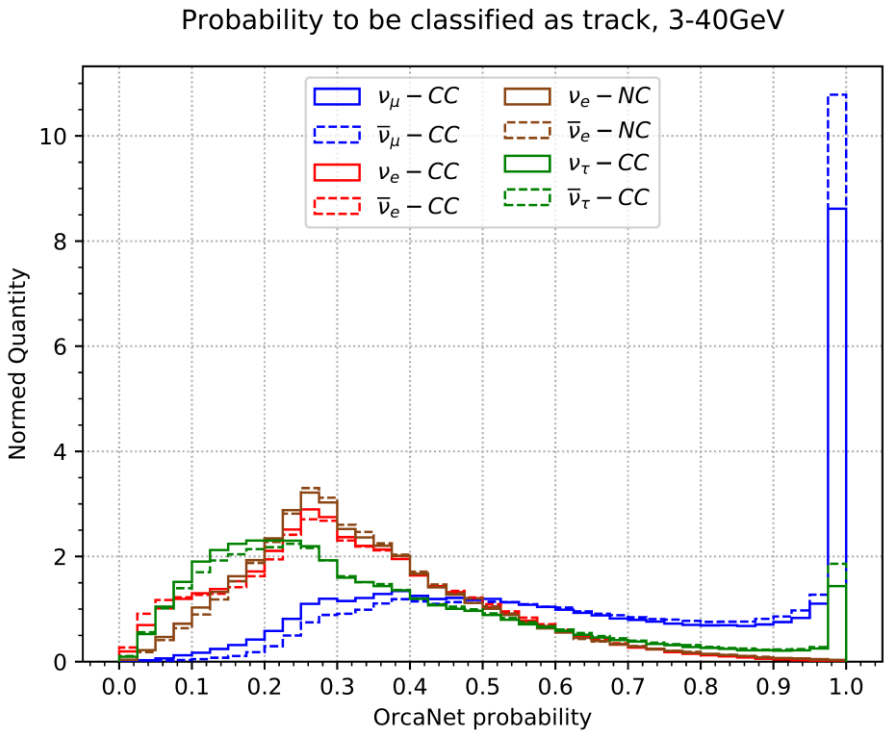
Difficult to define all relevant physical features

Image taken from [1]

Track-shower separation

- OrcaNet track-shower separation outperforms standard ORCA reco

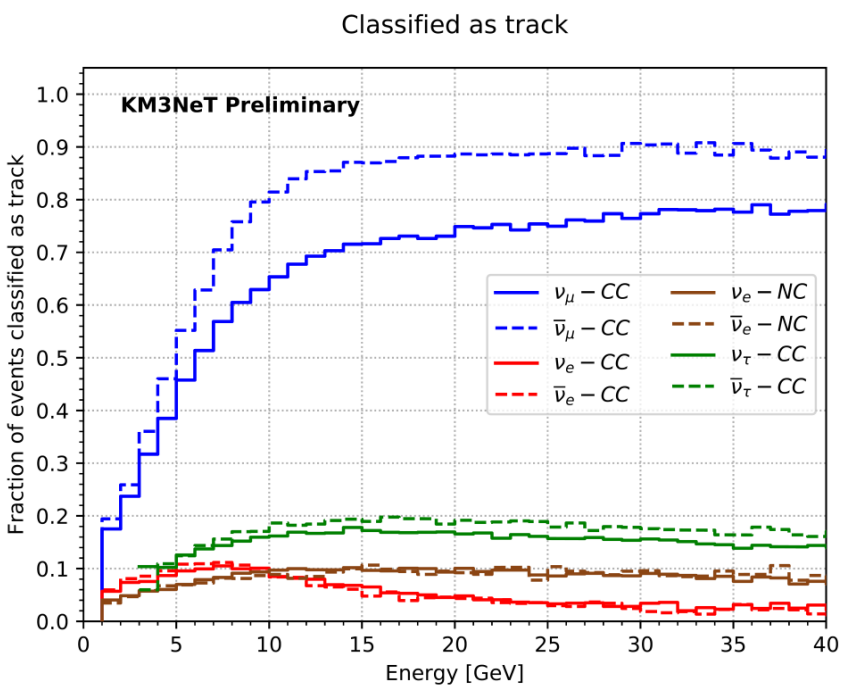




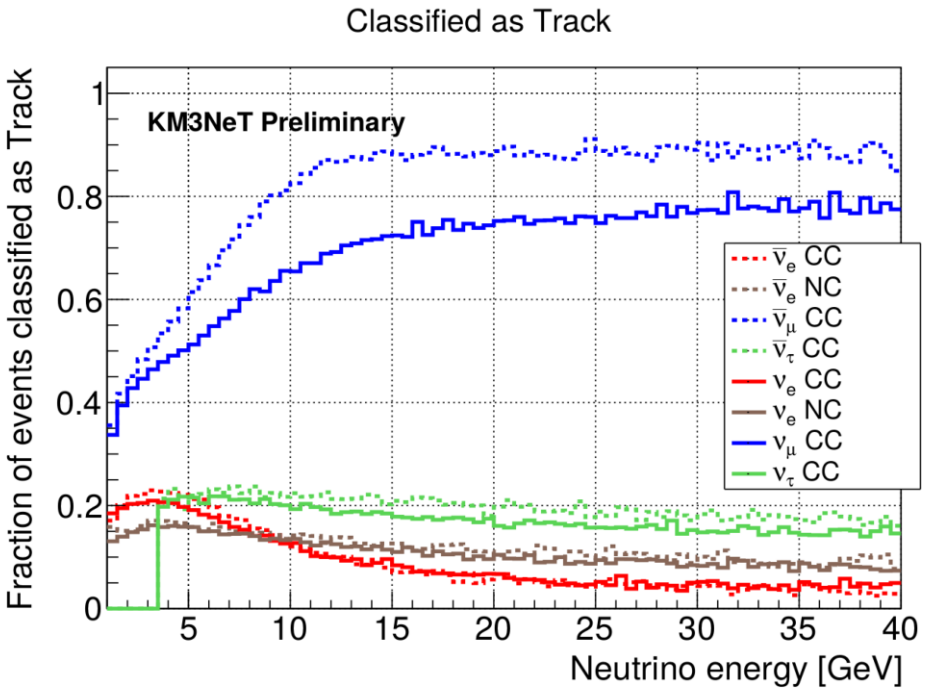
$$P_{track} > 0.6 = \text{track}$$

Track-shower separation

- OrcaNet track-shower separation outperforms standard ORCA reco
- 5%/4% better separation at 5/10 GeV than standard (ν_μ - CC to ν_e - CC)



OrcaNet



Standard reco

$$P_{track} > 0.6 = \text{track}$$

Introduction to OrcaNet

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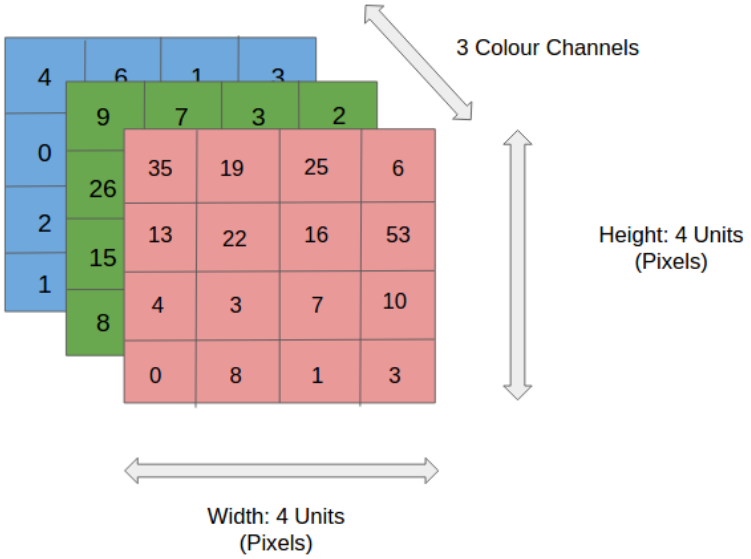
Reminder:

- 4D convolutions are not yet supported by the NN framework Tensorflow, which I use for OrcaNet
- => Use 4th dimension (e.g. time) as the **channel input** of a 3D CNN
- 4th channel dimension of the input is only partially used by the network:

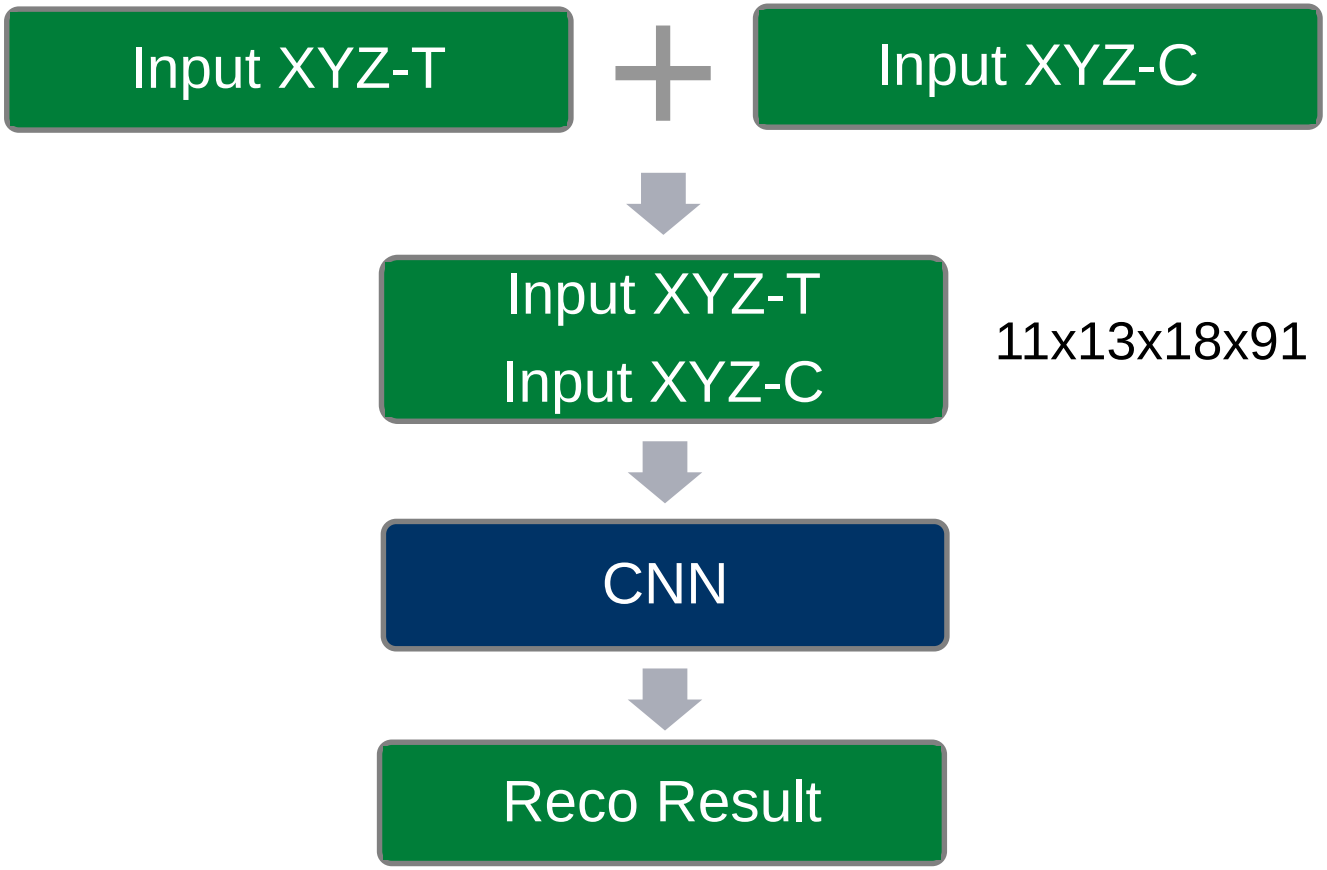
  Network can only train on channel sensitive features in the first layer!



Array representation of a 4x4 RGB image

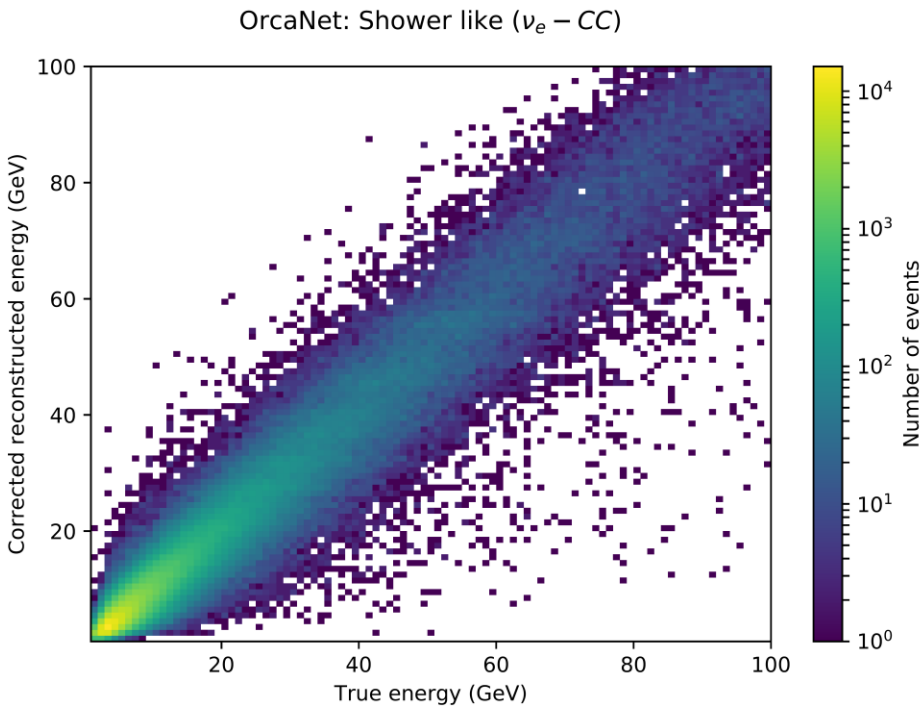
Update on event regression

- Include single PMT info in the input:
  - Make second image of the event, XYZ-C (11x13x18x31)
  - Stack this image with the main event image, XYZ-T (11x13x18x60)

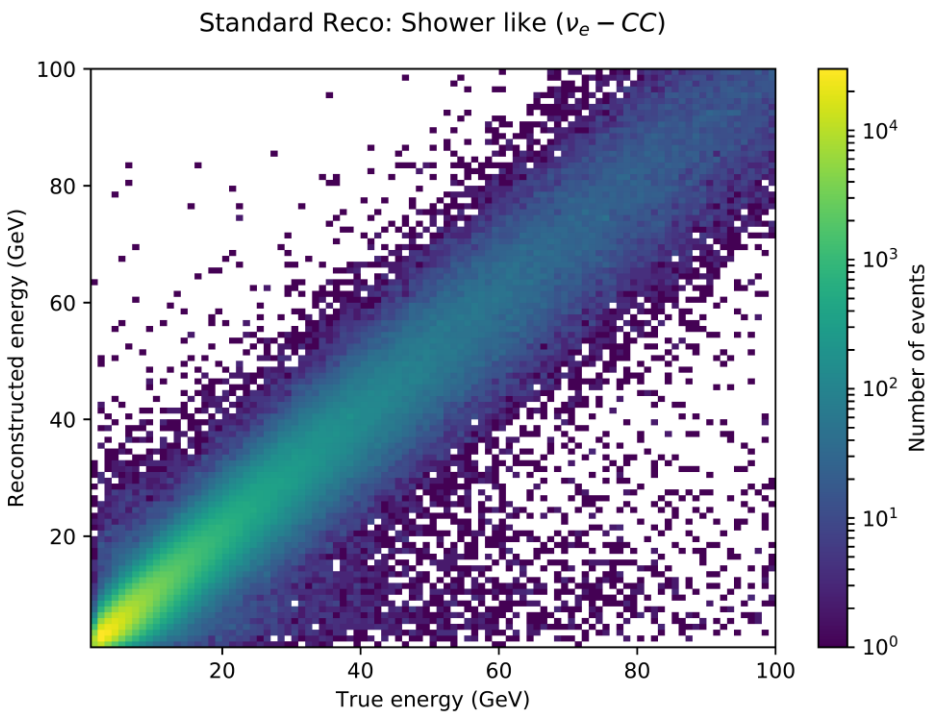


OrcaNet results – shower energy

- OrcaNet shower energy reco is comparable to Dusj reco



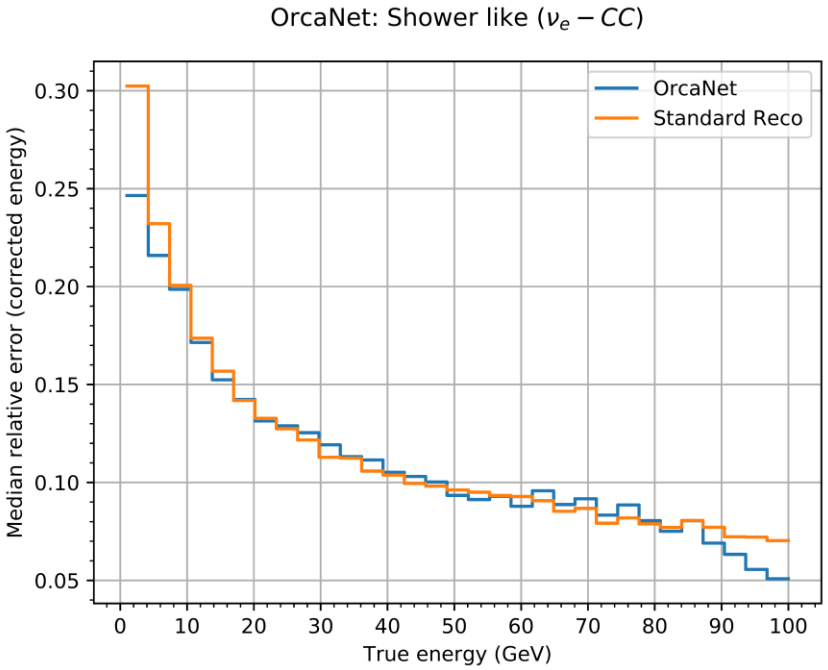
OrcaNet



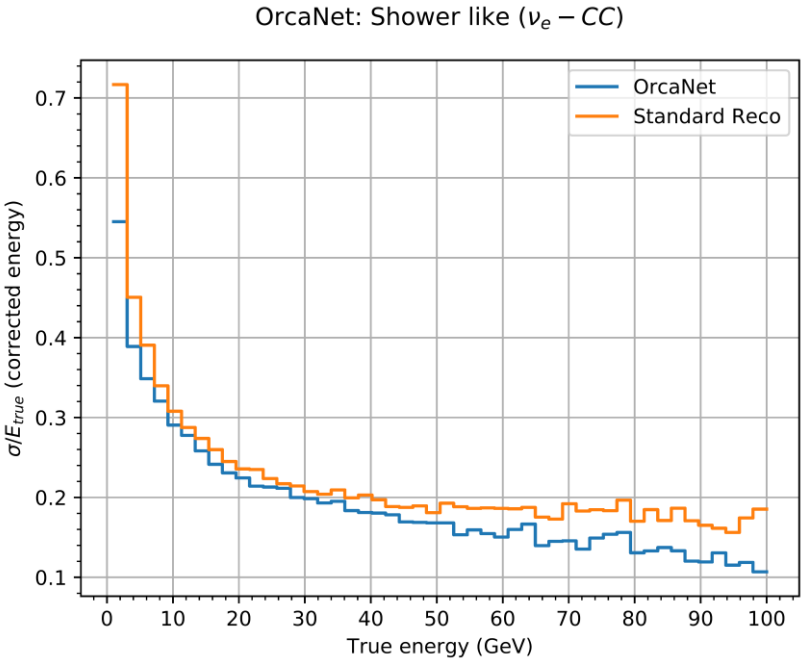
Dusj

OrcaNet results – shower energy

- Corrected OrcaNet ν_e - CC energy reco is comparable to Dusj reco
- OrcaNet reco agrees very well with the Dusj reco till 40 GeV (σ)

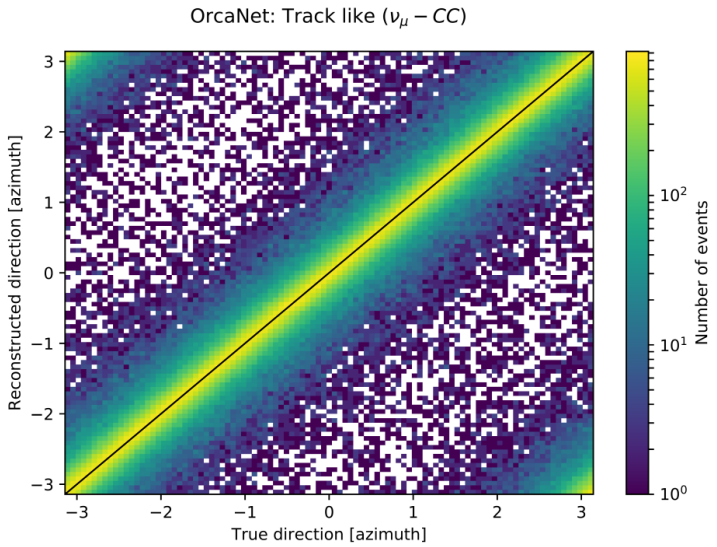


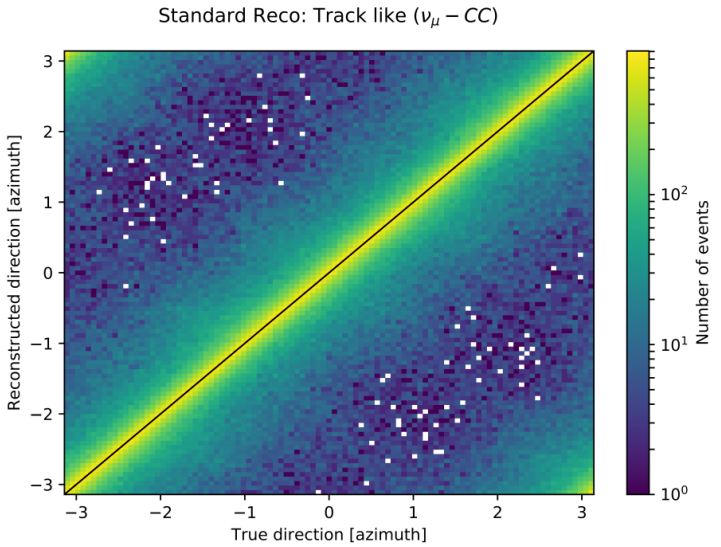
Median relative error

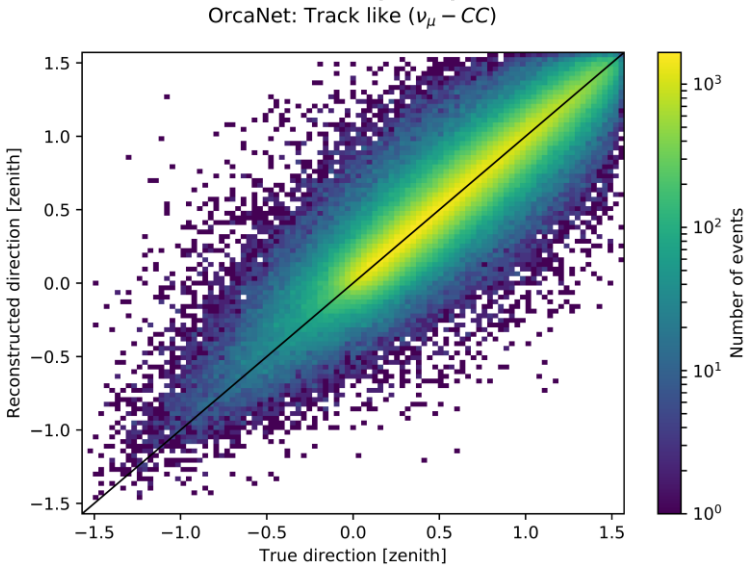


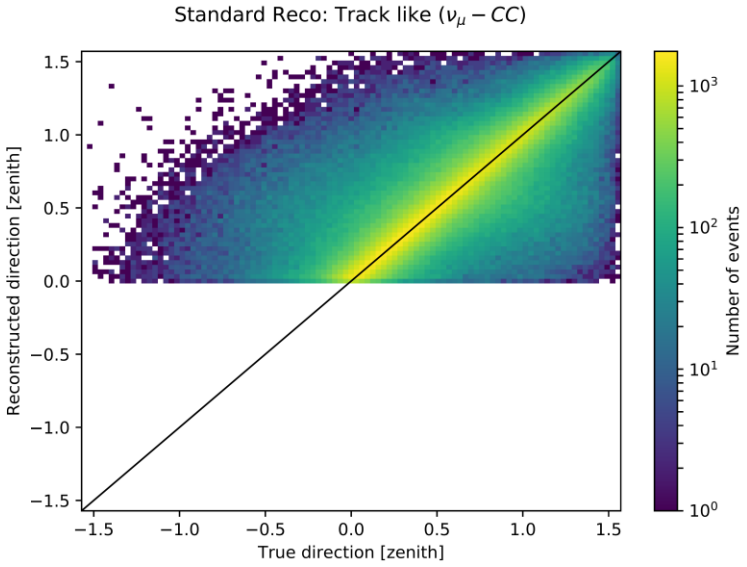
Relative standard deviation

OrcaNet results – direction



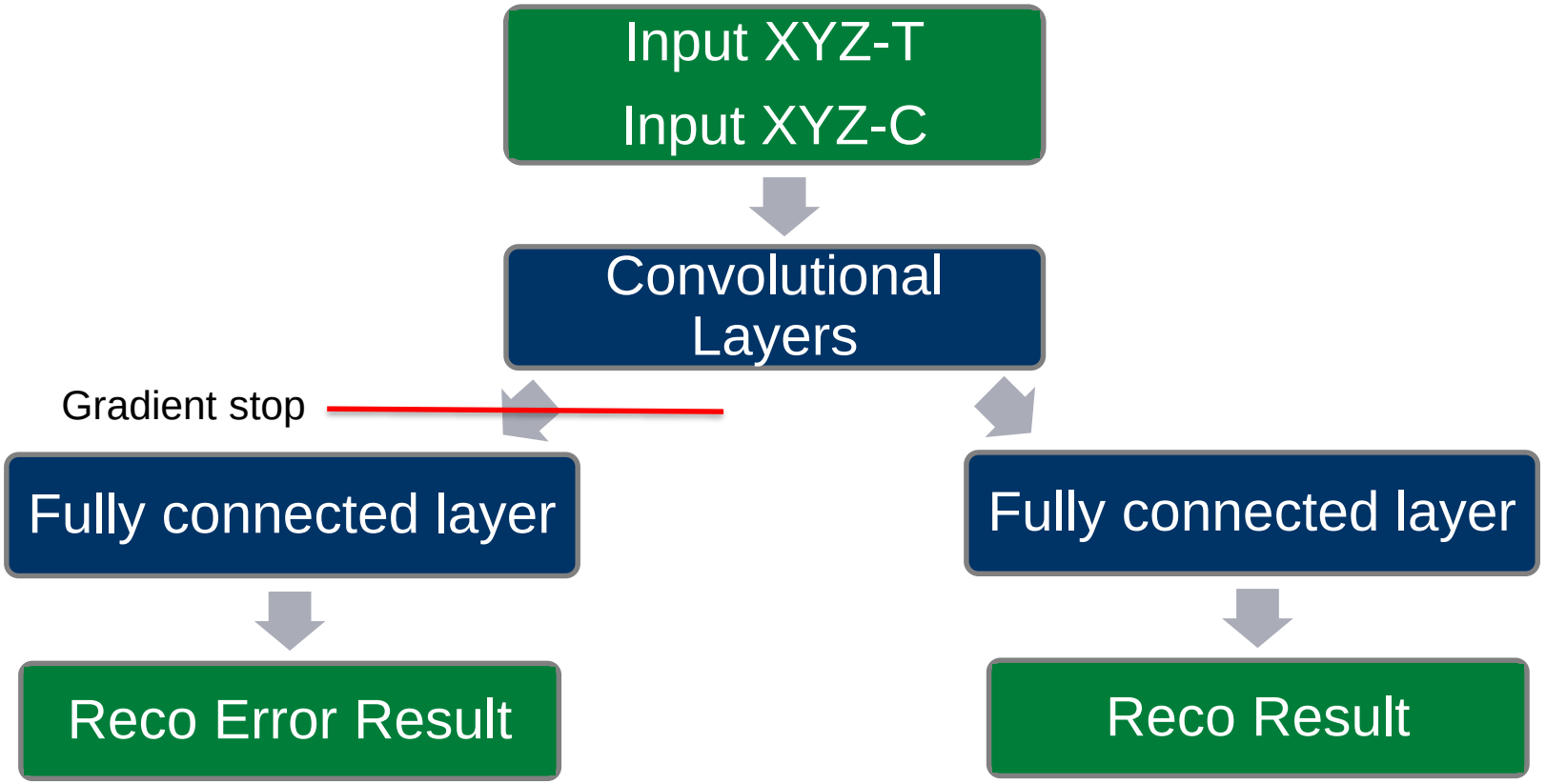






OrcaNet results – uncertainty

- OrcaNet can now also (try to) predict the standard deviation of any regression variable
- Done by adding a second dense network at the end

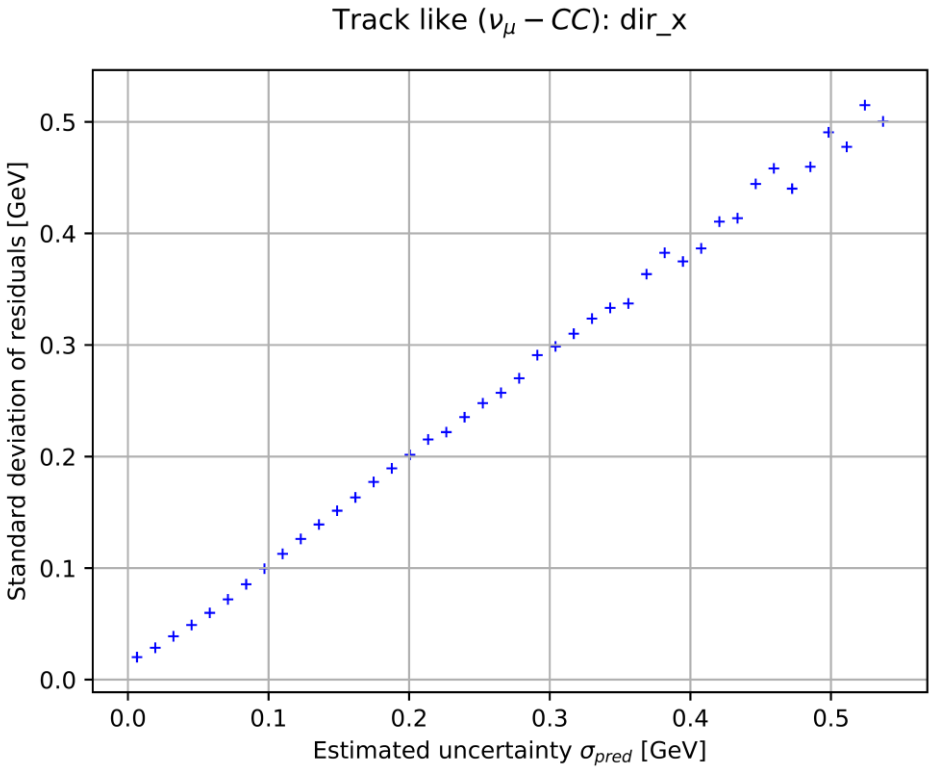


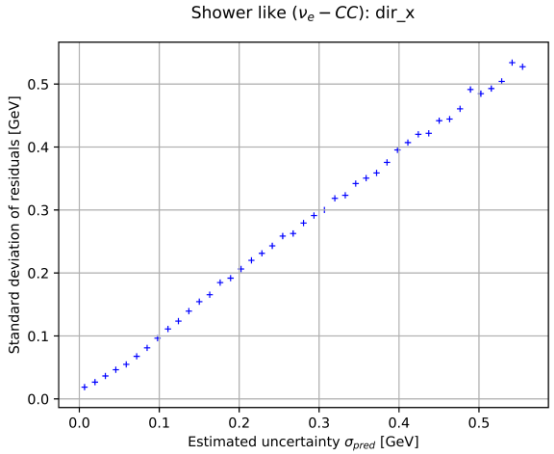
OrcaNet results – uncertainty

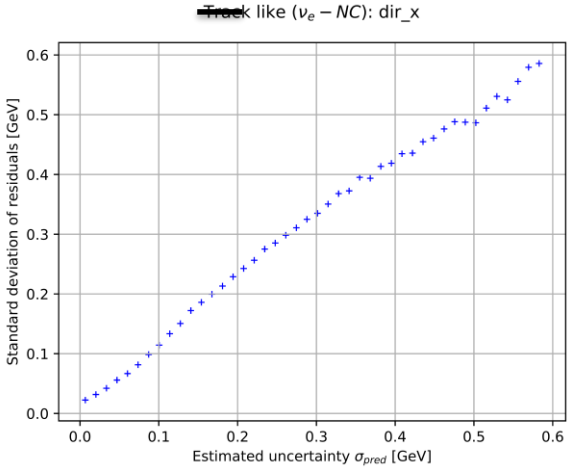
- Trained with mean squared error loss:
  - $L = \frac{1}{n}\sum_{i=1}^{n}(\sigma_{pred} - \left|y_{true} - y_{pred}\right|)^2$
- Network learns to estimate the absolute residual on average
  - $\sigma_{pred} \approx \langle y_{abs} \rangle$
- If residuals are normally distributed, the mean absolute residual can be converted to the standard deviation:
  - $\sigma = \sqrt{\frac{\pi}{2}} \cdot \langle y_{abs} \rangle \approx 1.253 \cdot \langle y_{abs} \rangle$
- Error estimation not optimized yet!!

OrcaNet results – uncertainty

- Uncertainty estimation works very well for direction reconstruction, but worse for energy and bjorken-y (depending on the event type)







OrcaNet results – uncertainty

- Uncertainty estimation works very well for direction reconstruction, but worse for energy and bjorken-y (depending on the event type)