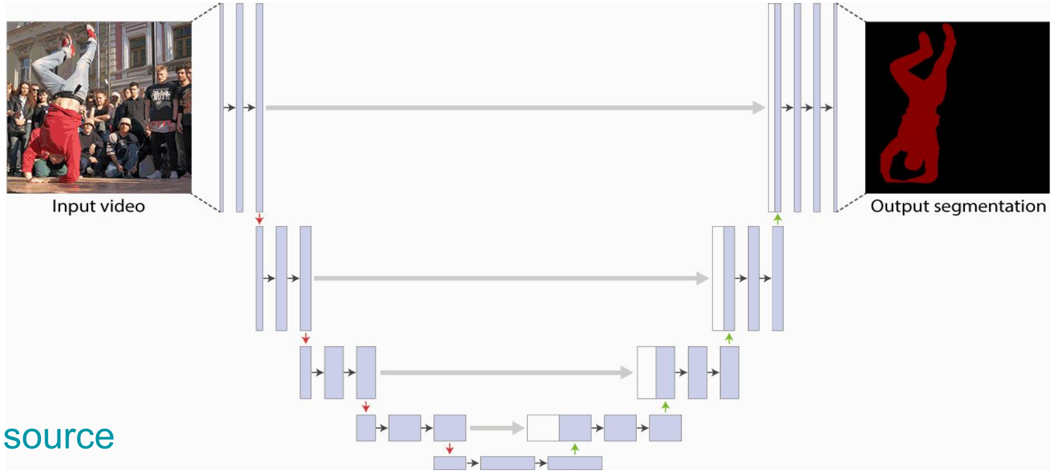
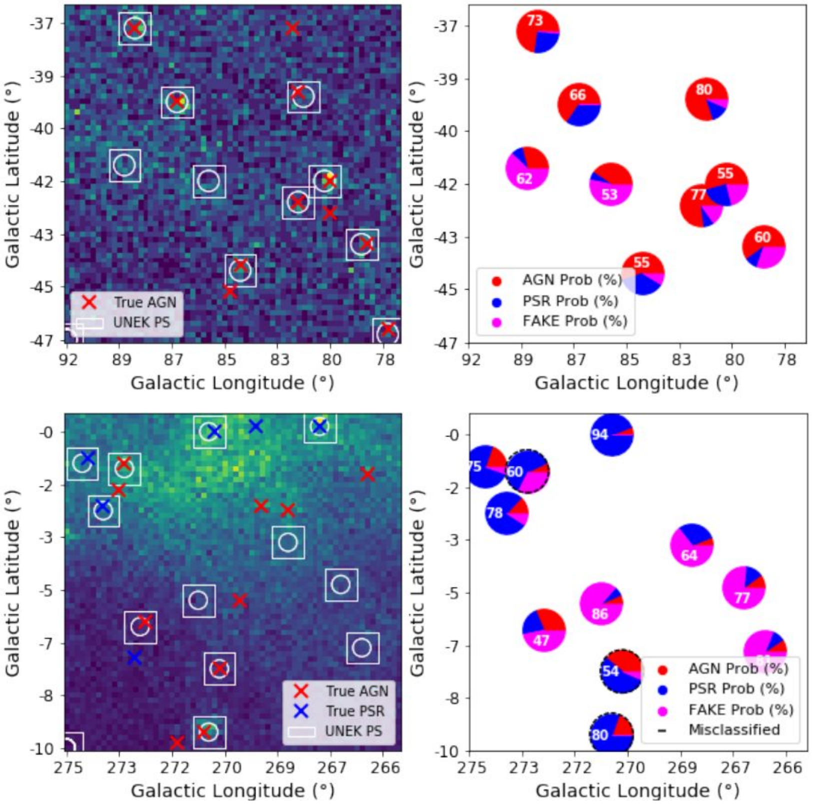
Position reconstruction of photon pulses using UNET

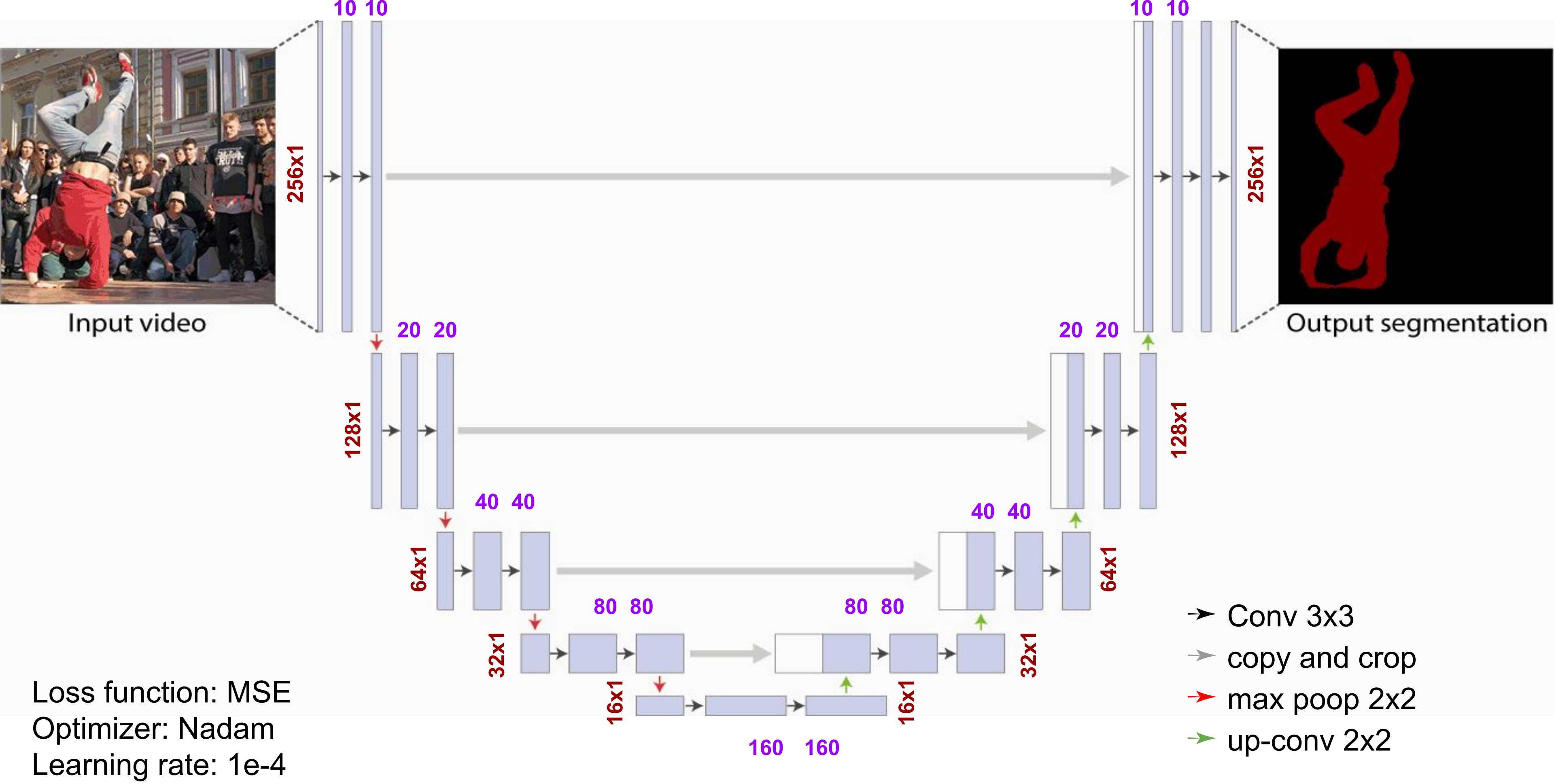
Segmentation



source

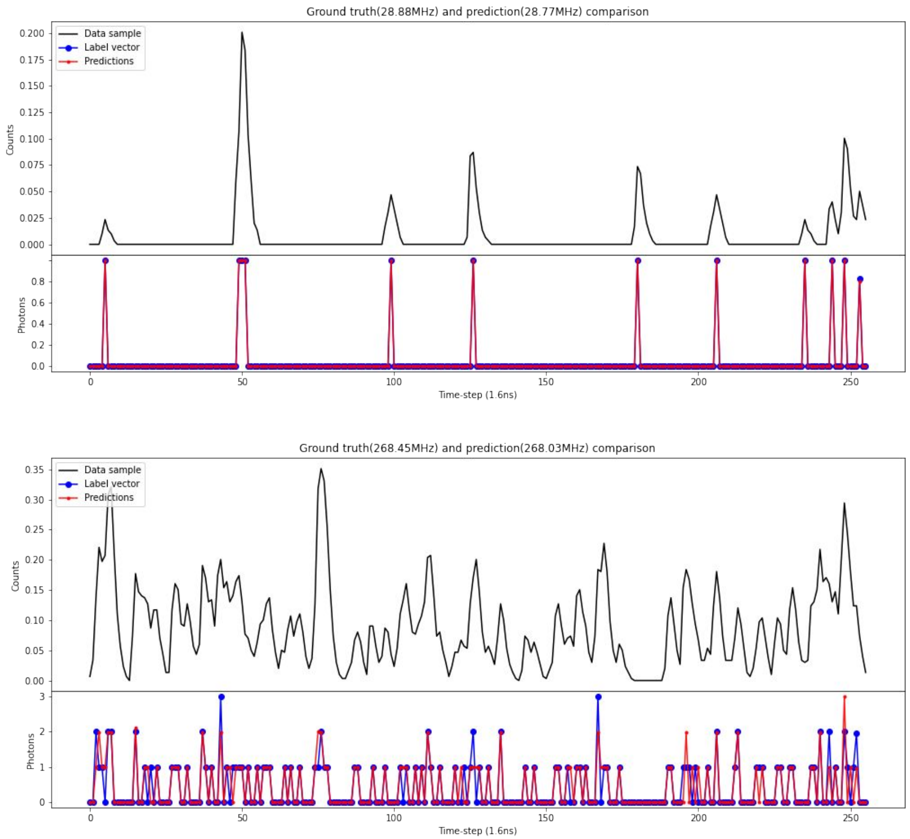


Panes et al(2021)



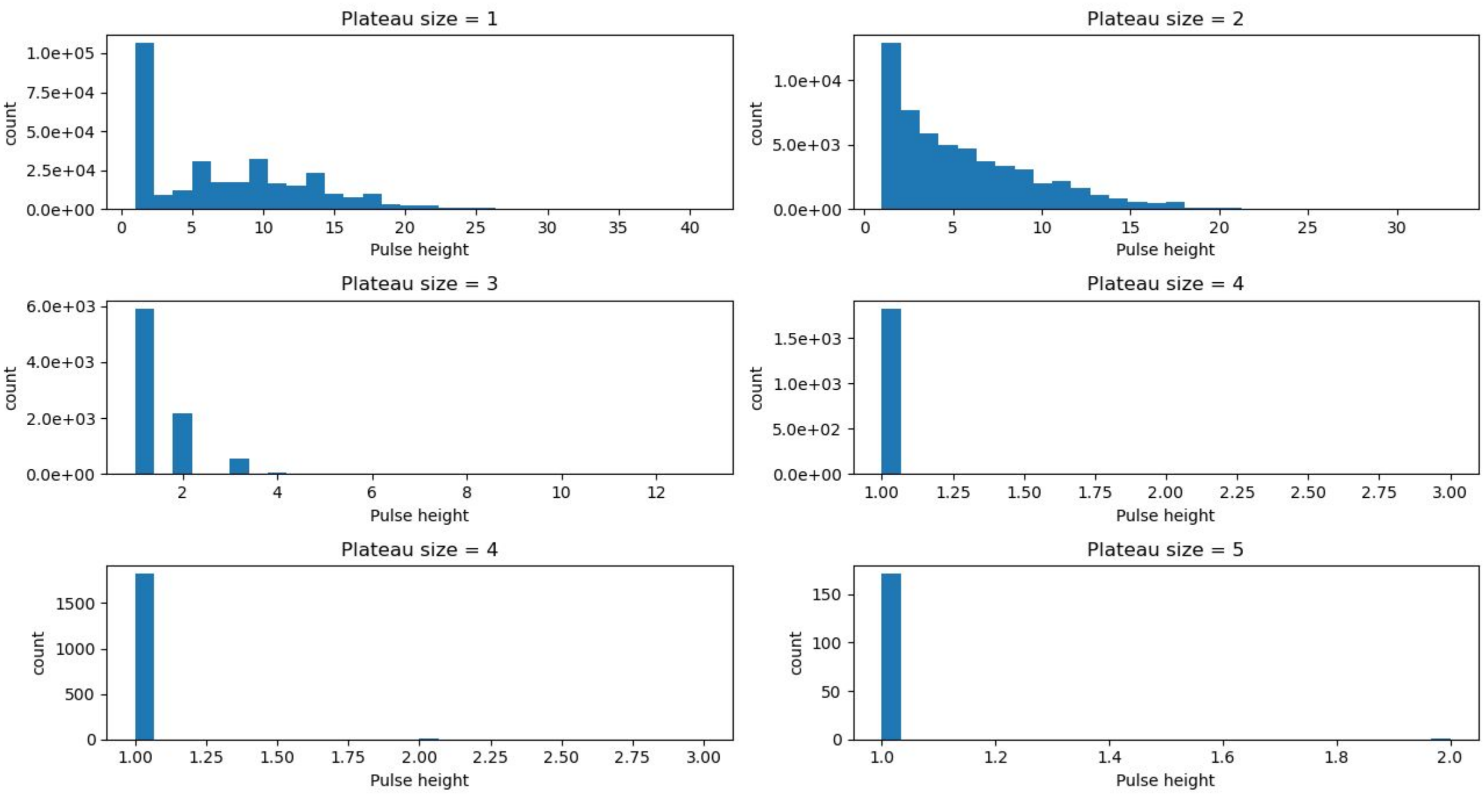
Input video
Output segmentation
10 10
256x1
20 20
128x1
40 40
64x1
80 80
32x1
16x1
160 160
16x1
80 80
32x1
40 40
64x1
20 20
128x1
10 10
256x1
Conv 3x3
copy and crop
max poop 2x2
up-conv 2x2
Loss function: MSE
Optimizer: Nadam
Learning rate: 1e-4

Data generation and preprocess



- Monte-Carlo simulation
  - Select required sample size(256 time-steps)
  - Select desired number of samples as an example for each rate (1920 examples) ⇒ this provides range of rate covered 0-1464 MHz with 1.6 ns binning
  - Labels: Each time-step indicates number of photon peaks present at particular position
  - Generate data for training, validation and testing individually
- Build simplest 1D U-Net (239,261 parameters) and train using Nadam optimizer and loss function MSE
- Data generation: samples are selected randomly from unique shapes, and data generation algorithm is used individually for train, val and test datasets
- Used data: calibration data from H.E.S.S. campaign(150-200 MHz and 350-400 MHz)

Data generation and preprocess

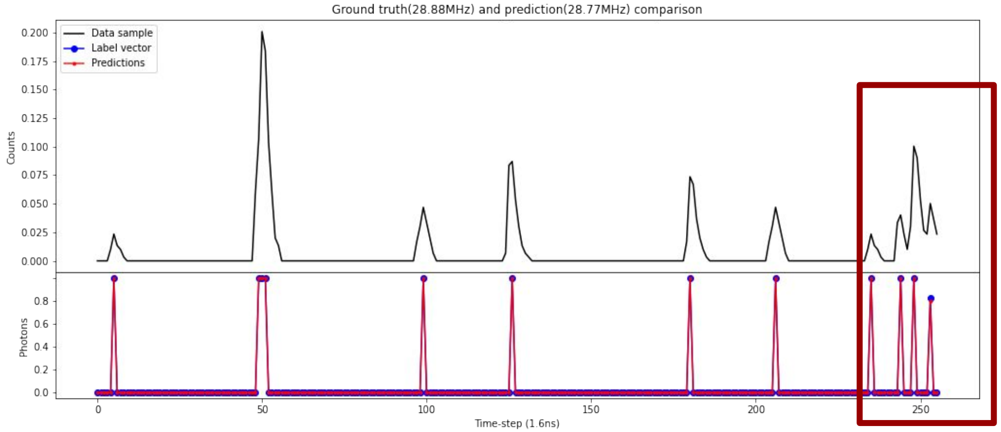


- Possibility of back to back pulse from calibration data ⇒ plateau in pulse
- Identify shapes with plateau from extracted pulses
- Exclude these pulse from set of pulses which is used for MC data creation

After pulse analysis, we perform model(U-Net) training and then it is important to figure out in which region predictions are more accurate. Because significant number of pulses are highly right-skewed, it affects each MC data.
In our problem, what we seek to predict is, do we have peak(full pulse) available at specific bin or not. And if there is peak, then how many peaks are there at specific bin. Let’s call it **peak-no-peak scenario.**
Number of peaks at specific bin depends on following cases,

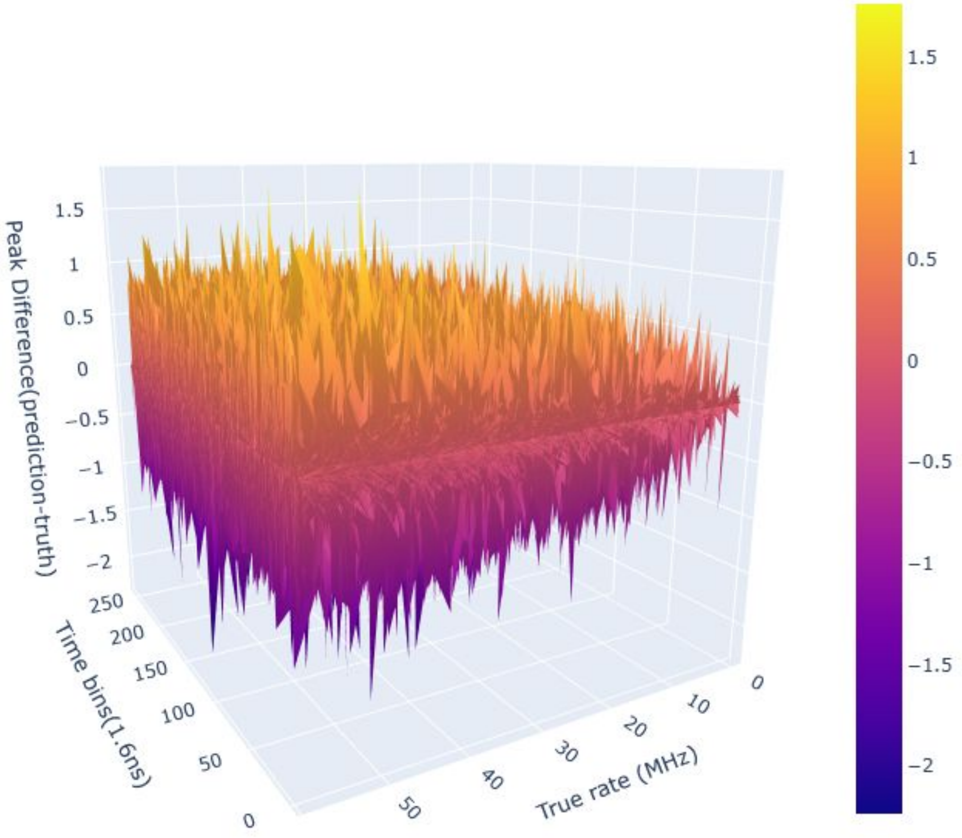
- Actual rate of sample: High enough rate increases probability of having multiple overlapped peaks
- Edges of the sample:
    - Left edge: first bin of the samples can have more variety of sliced samples, resulting in fractional peak in ground truth (because of the right skewness)
    - Right edge: last few bins of the sample have sliced pulses, therefore in ground truth of such samples have fraction of pulse distributed in last few bins, depending on added pulse width of specific pulse

Consideration of both cases allows MC to add more complexity. Especially at higher rate it is more difficult scenario than identifying overlapped full pulses.
In this way, we expect that the trained neural network, predicting more accurately on region far from left and right edges of the sample, due to chances of less complexity.



Consideration of sliced pulses:

1. It covers entire range of rate, instead of covering specific rate examples (based on only number of pulses added in a sample; unlike previous attempts where the aim was to train model for flux calculation).
2. This comes with requirement of extremely huge data requirement to train and get efficiently predicting model. And if not satisfied, then imbalance data can degrade the training of NN.
3. In present MC, I tried to minimize drawback of point 2, by increasing number of examples.



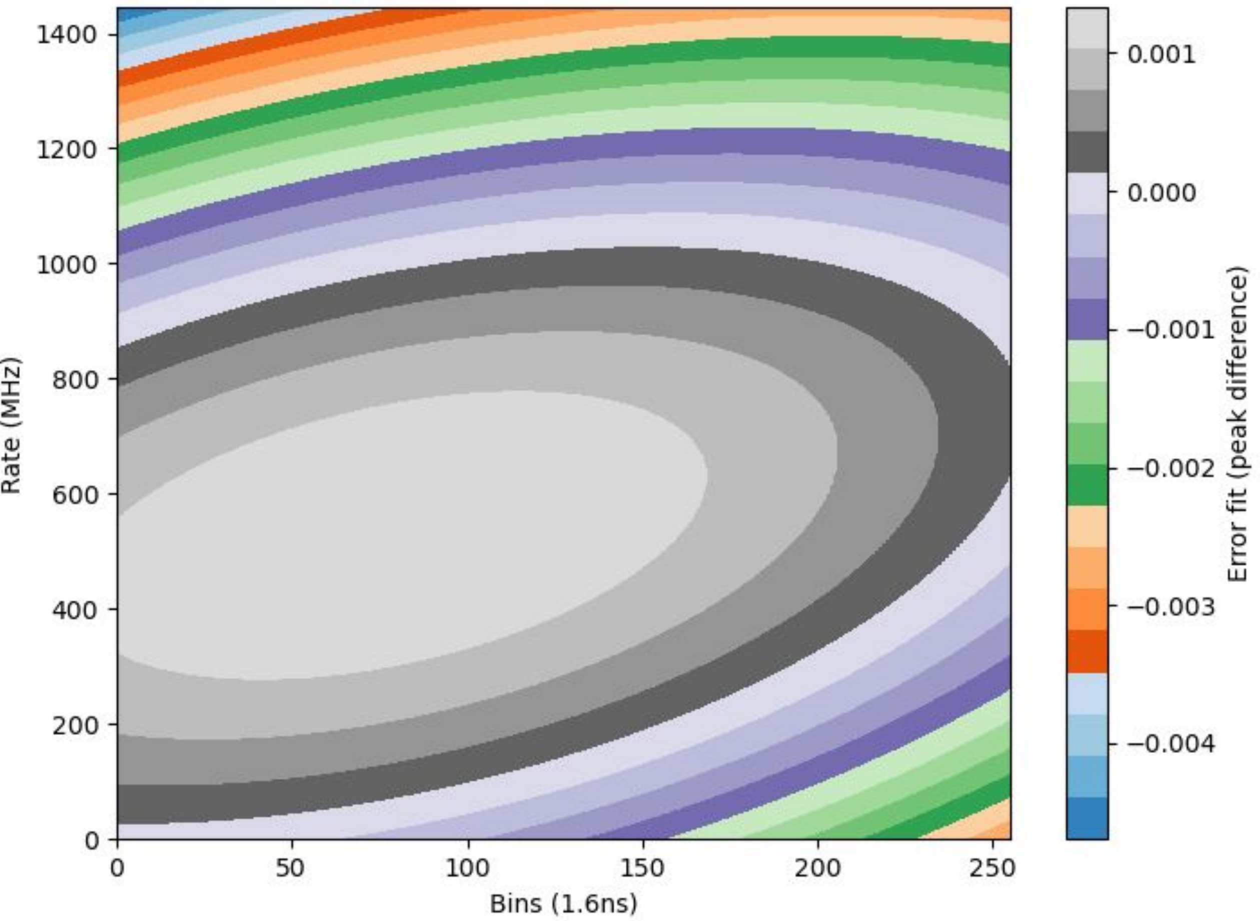
After training the model, in evaluation step, we need to simply compare the prediction over test data and its true label. The simplest attempt is to simply perform prediction-true label, over entire rate range of test dataset and bins of samples. This gives possible instances of over prediction, underprediction and accurate prediction as shown in 3D figure in left (small sample).

However, visually it is very complicated to determine regions of prediction in which NN performs optimally.

For that we need to plot polynomial surface plot, and in this work fitting is performed by considering following equation, and the plot is shown in next slide.

$$f(R,B) = c + aR^2 + bB^2 + dRB + eR + fB$$

Here f(R,B) is surface for peak difference, R is rate and B is bin in sample



In the polynomial fit of error shown in left contains regions of overprediction, underprediction and close to truth.

- Each sample are predicted mixture of error regions
- The light purple band is the best prediction area
- At higher rate, predicted rate are smaller than truth
- There is a large region between 200-1050 MHz the NN predictions are close to truth, with minimal error fluctuations
- Completely over predicting region is 600-800 MHz

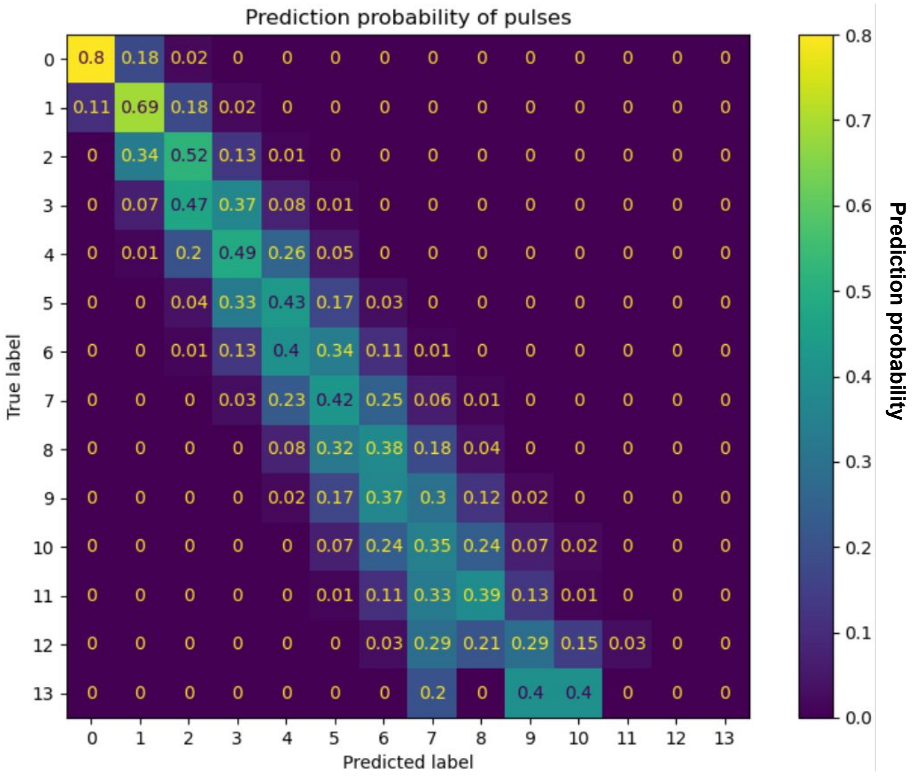
As mentioned in slide 6, we are interested only in **peak-no-peak** scenario, because actual measurements have only full pulses, and for correlation of photons patterns from both PMT we need only full pulses, whether overlapped or not overlapped.

Therefore, there are two ways one can tackle this problem for NN predictions in evaluation step.

1. Rounding of predictions over after veto is applied: this is because we have adopted regression method
2. Apply veto over predictions and ground truth of the test dataset. Why? Because we want to avoid sliced pulse truths and related predictions (first line of this slide).

Here, after implementing step-1, veto of total 16 bins (Left-edge: 6 and Right-edge: 10 bins) is applied and confusion matrix is plotted for number of peaks available in ground truth and prediction. After veto applied, the data is of 0.1458 seconds. From this comparison,

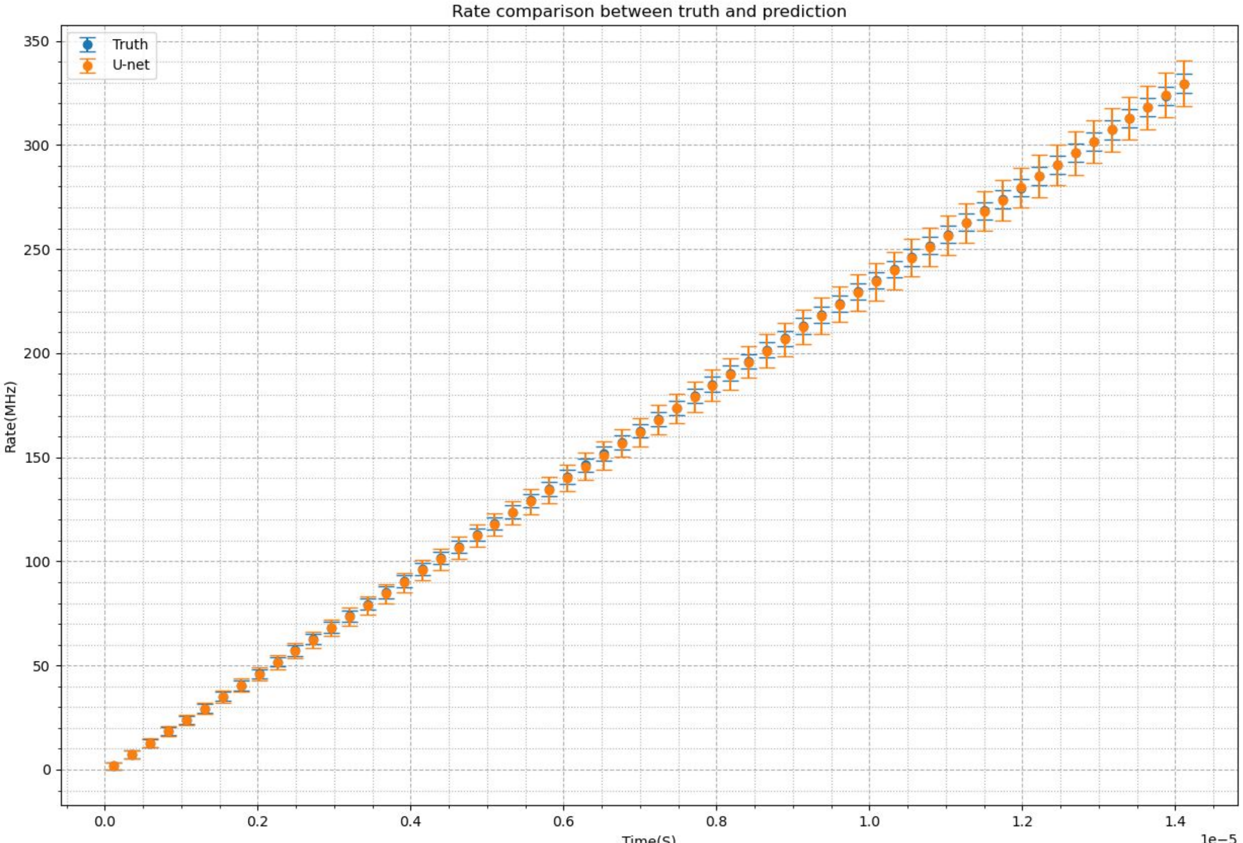
- 80% of the no-peak regions are identified as no-peak, however there 18% are identified with single peak, and 2% are identified as double peak
- 69% of the single peaks and 52% of completely overlapped double peaks are perfectly identified



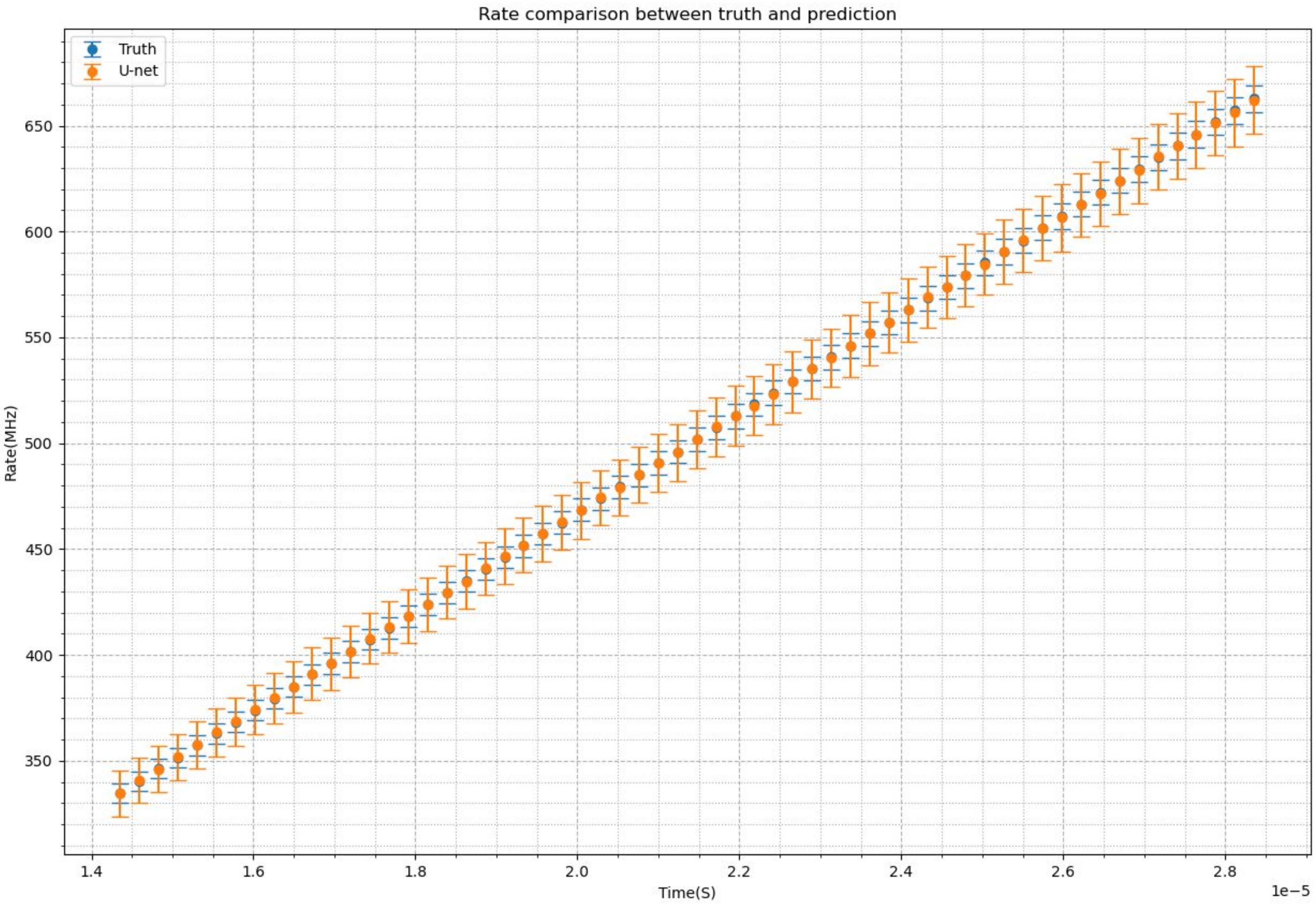
After implementing rounding of the predictions, the next important comparison is of flux calculations (next slides).

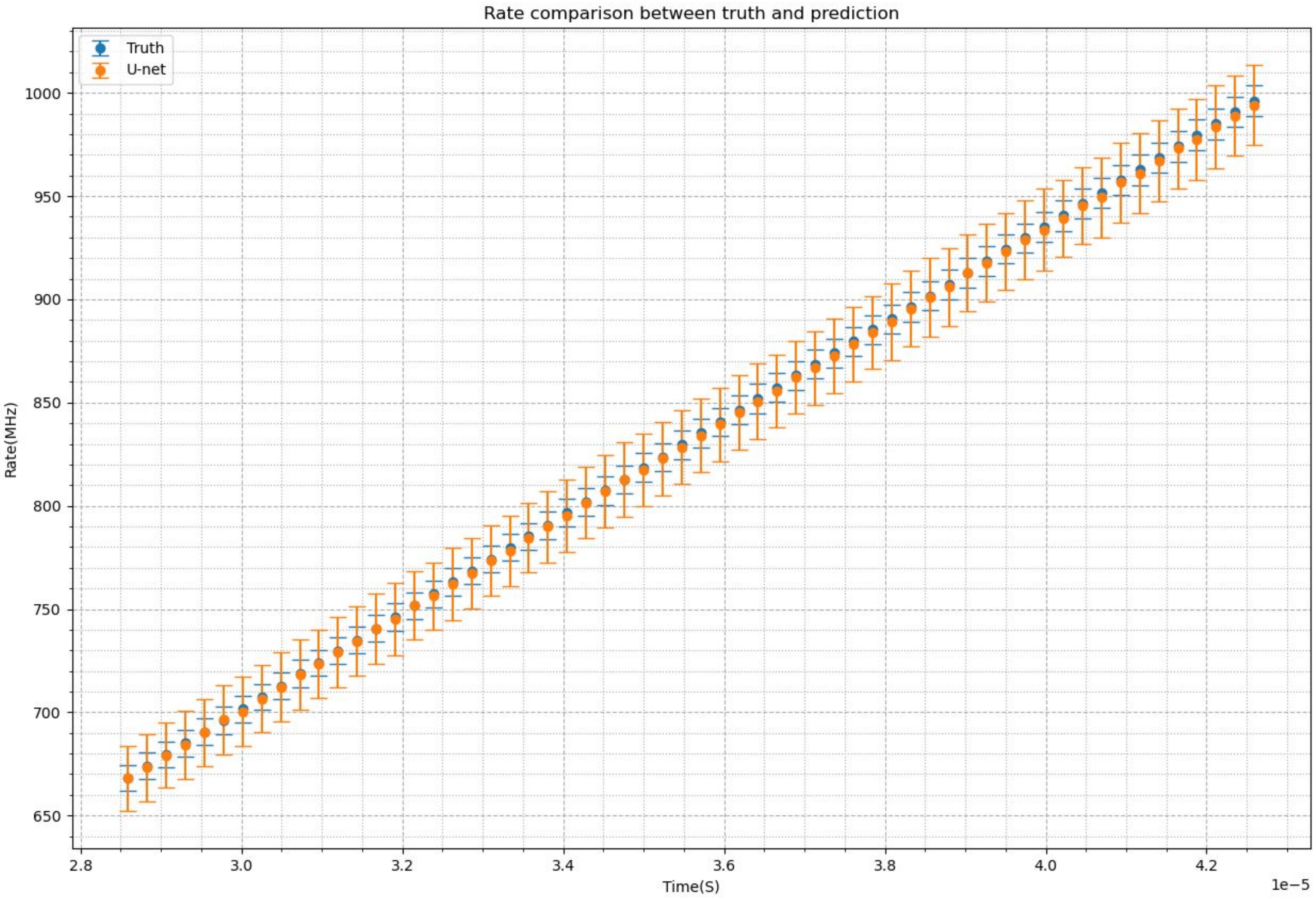
Flux comparison

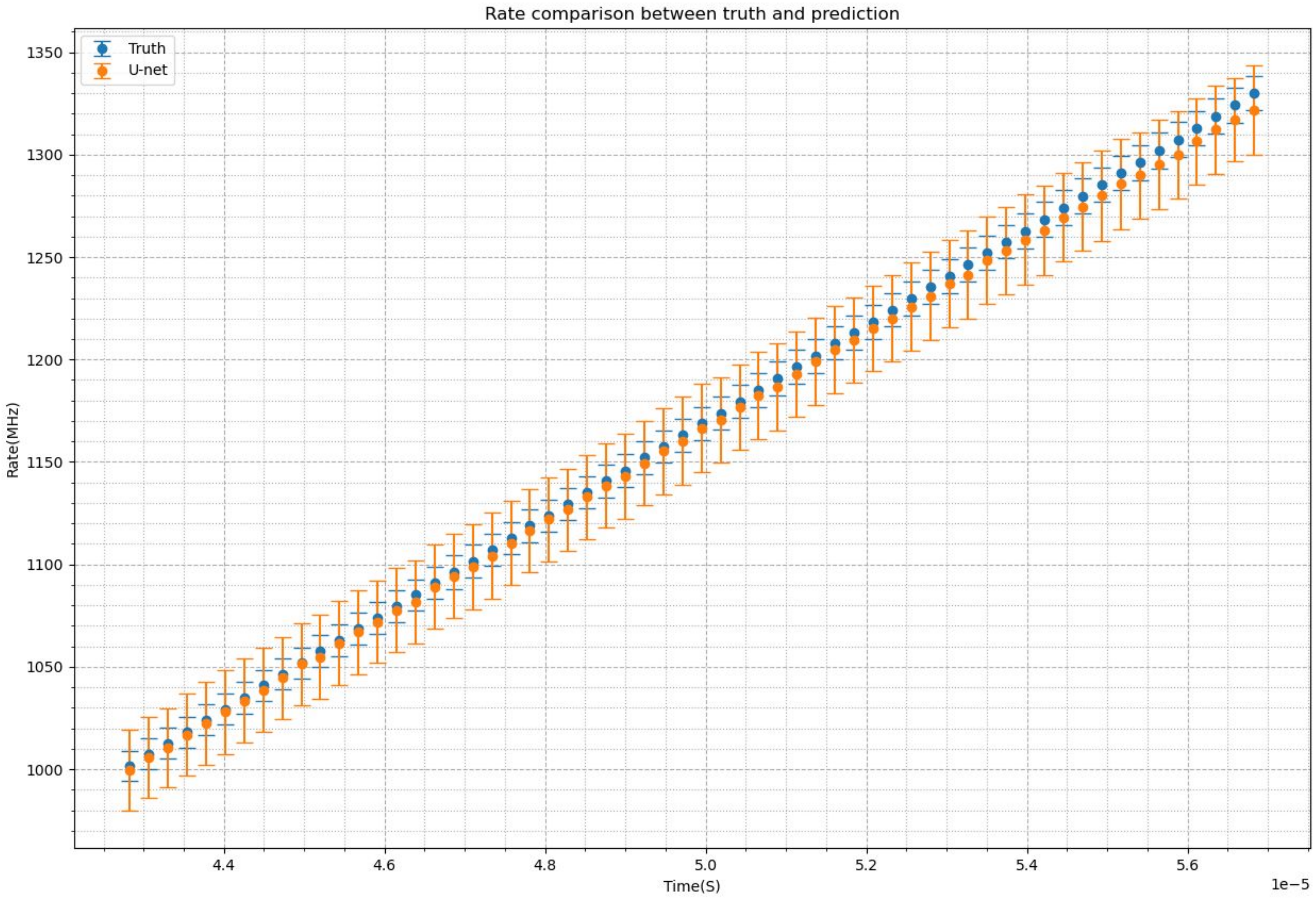
- After rounding the predictions (not at the edge regions), sum of entire prediction for each samples for both ground truth from MC test data and predictions and rate of each sample is calculated
- Here, truth also have uncertainty (sample uncertainty) because of consideration of sliced pulses.



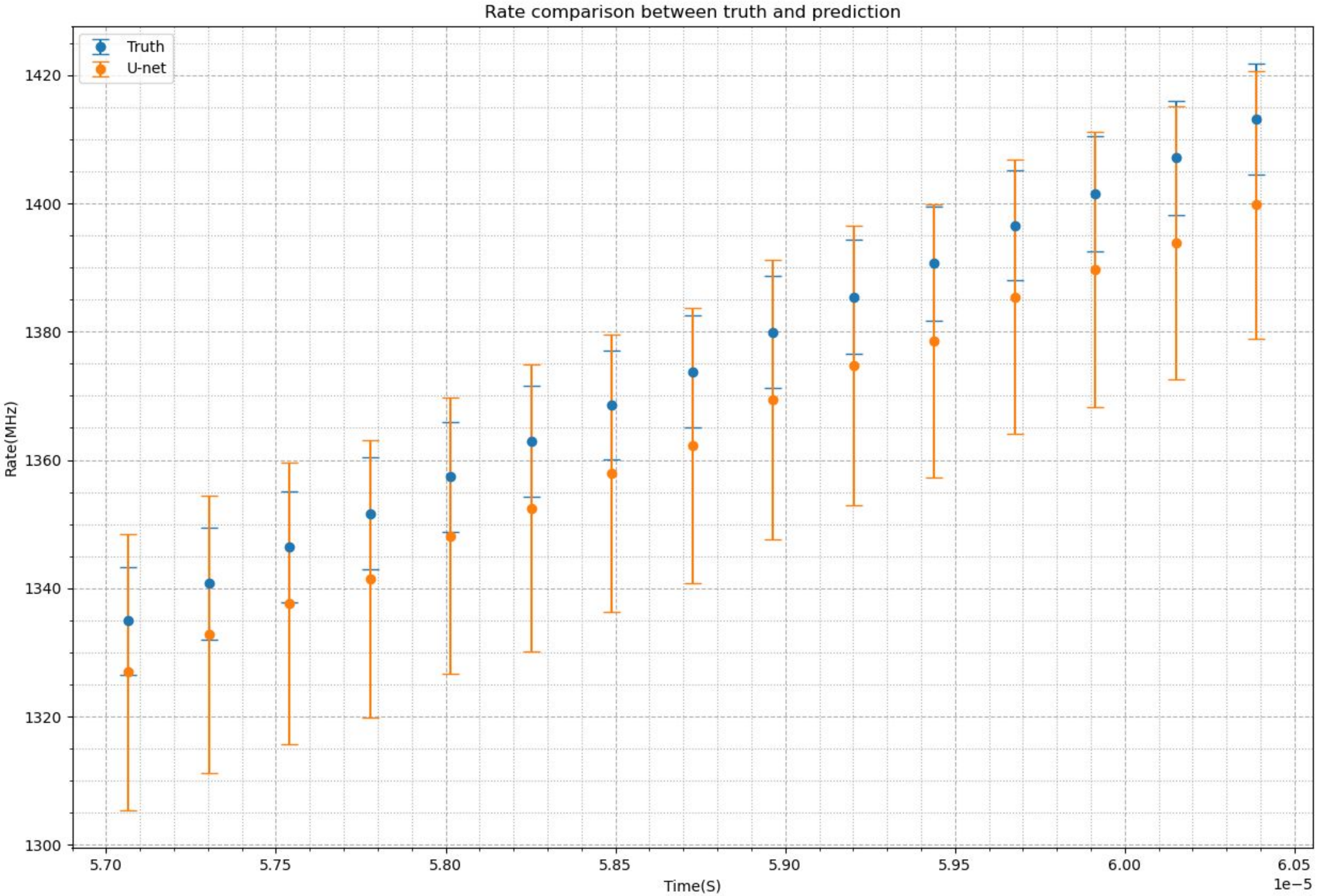
Here, implementation of veto cut to truth and predictions is not necessary because here our task is to correlate flux, not photon peak positions. Therefore, rounding is applied only over central bins.


Rate comparison between truth and prediction
Truth
U-net
650
600
550
500
450
400
350
Rate(MHz)
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Time(S)
1e−5


Rate comparison between truth and prediction
Truth
U-net
1000
950
900
850
800
750
700
650
Rate(MHz)
2.8
3.0
3.2
3.4
3.6
3.8
4.0
4.2
1e−5
Time(S)



Rate comparison between truth and prediction
Truth
U-net
Rate(MHz)
Time(S)
1e−5
1000
1050
1100
1150
1200
1250
1300
1350
4.4
4.6
4.8
5.0
5.2
5.4
5.6


Rate comparison between truth and prediction
Truth
U-net
Rate(MHz)
1300
1320
1340
1360
1380
1400
1420
5.70
5.75
5.80
5.85
5.90
5.95
6.00
6.05
1e−5
Time(S)

Conclusion

- NN predictions errors are minimal from 200-1050 MHz
- Unet prediction errors are larger in edge-regions due to sliced pulses
- Chances of right edge prediction error is bit higher than the left edge predictions, this could be due to the right-skewness of the pulses.
- Network identifies background and single pulse most efficiently over the entire rate range
- Network predicts complete overlap of two peaks ~52% of the time
- Average prediction error over the entire range is from around -1MHz to 8MHz
    - 400 MHz: prediction with average error ~1.7 MHz with uncertainty ~11 MHz
    - 200 MHz: prediction with average error ~1.8 MHz with uncertainty ~7 MHz