Experimental Demonstration of Longitudinal Phase-space Prediction Using Deep Learning at the Injector

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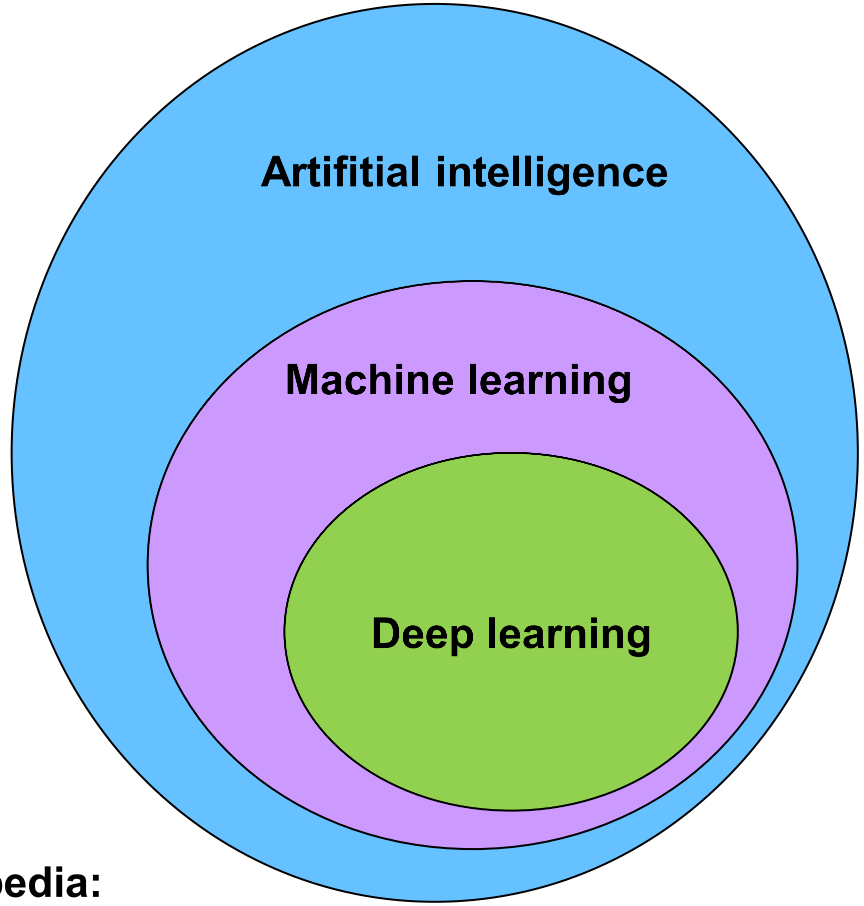
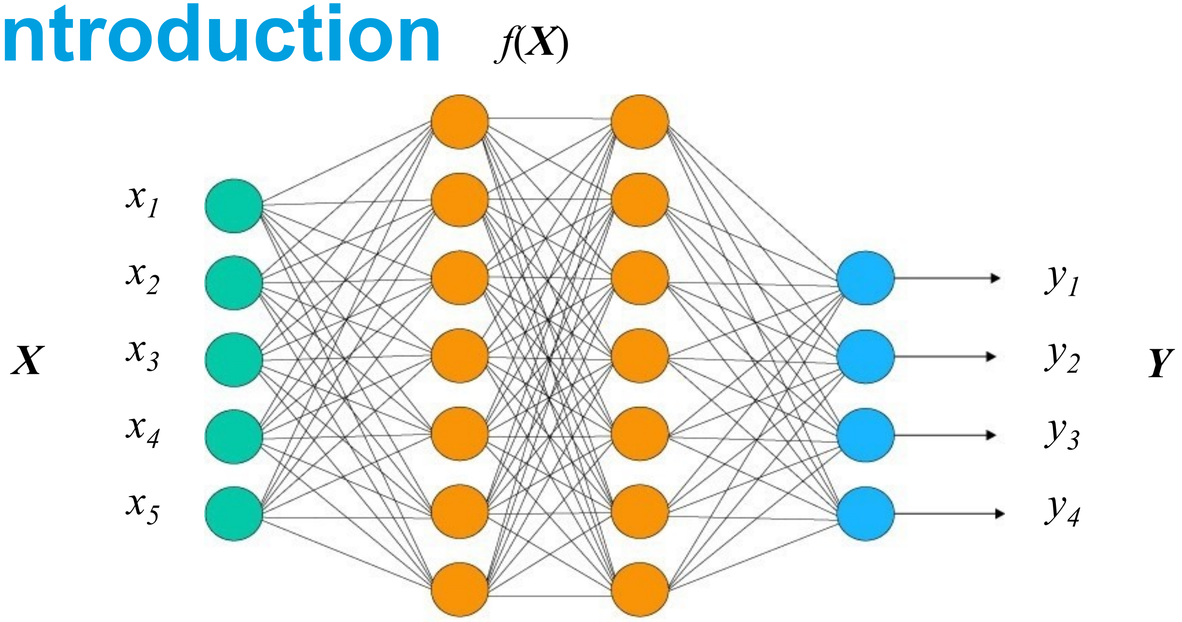
Hamburg, 15.12.2020

Outlines

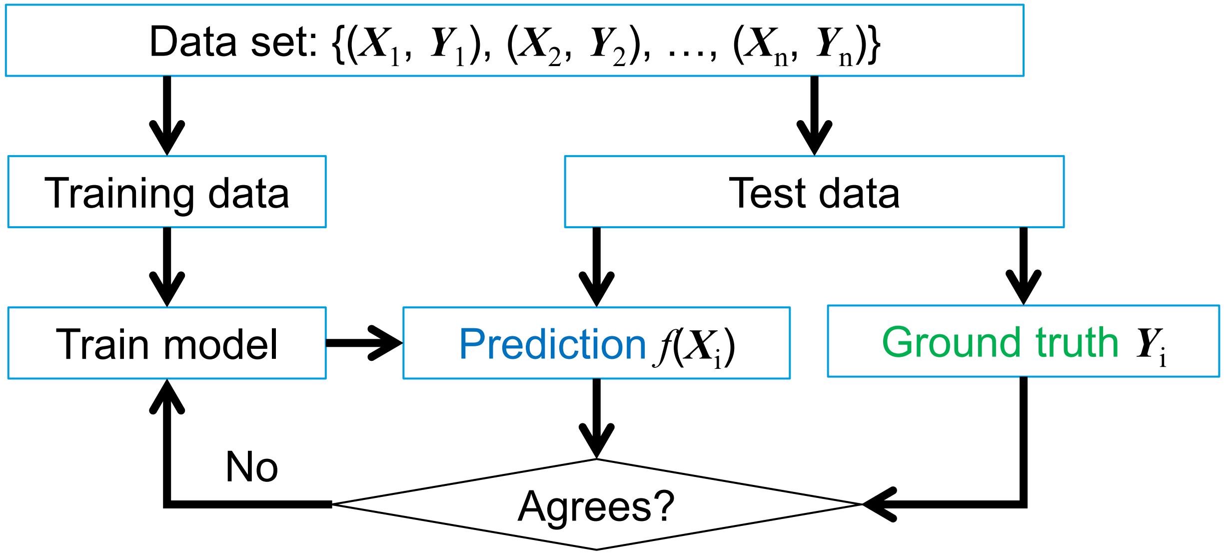
- Supervised deep learning
- Longitudinal phase space prediction (virtual diagnostic)
- RF phase inference from the longitudinal phase space
- Reflection

Supervised deep learning - introduction





Artificial neural network is a universal function approximator!

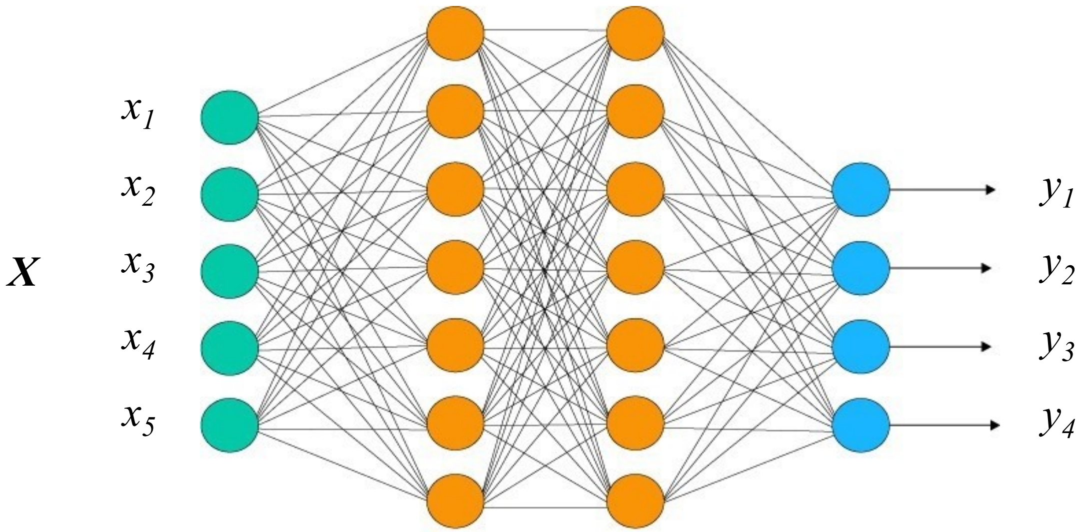


Wikipedia:

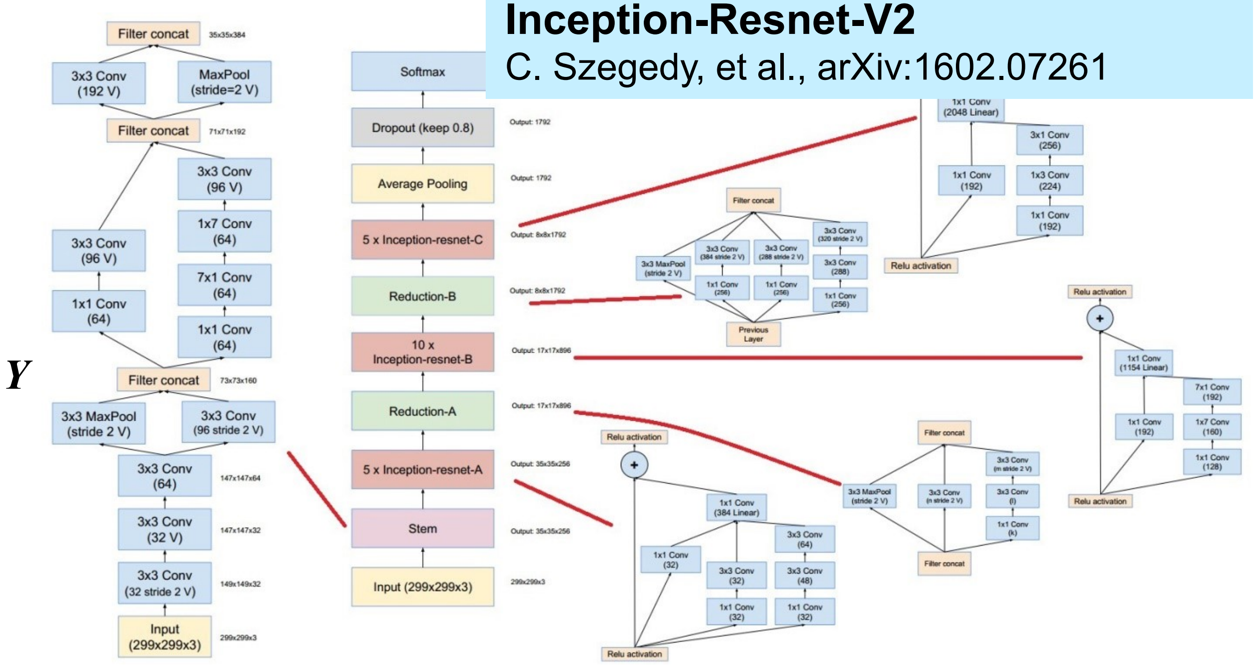
Deep learning is part of a broader family of machine learning methods based on artificial neural networks with representation learning.

Supervised deep learning – neural network structures

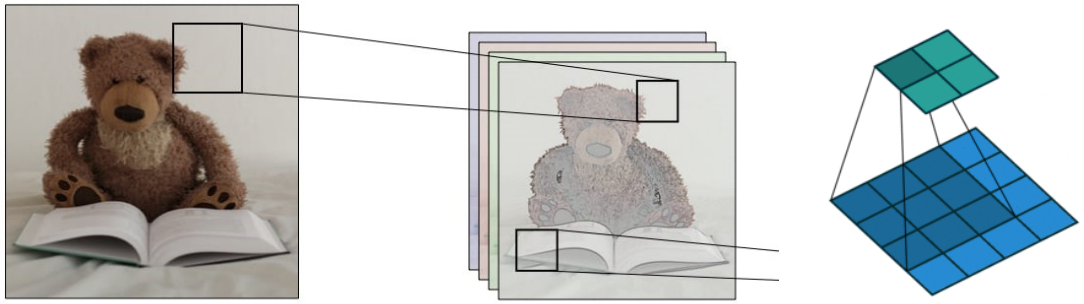
Multi-layer perceptions (MLP)



Inception-Resnet-V2
C. Szegedy, et al., arXiv:1602.07261



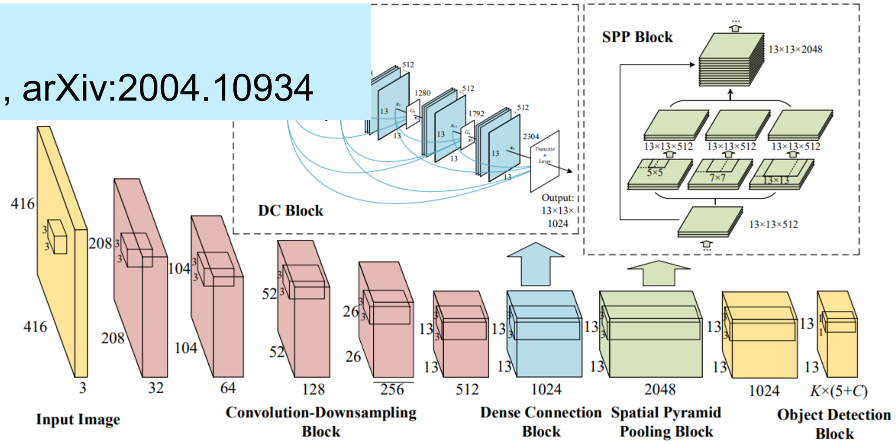
Convolutional operation - CNN



Input image

Convolutions

YOLO-V4
A. Bochkovskiy, et al., arXiv:2004.10934



Supervised deep learning – when and where

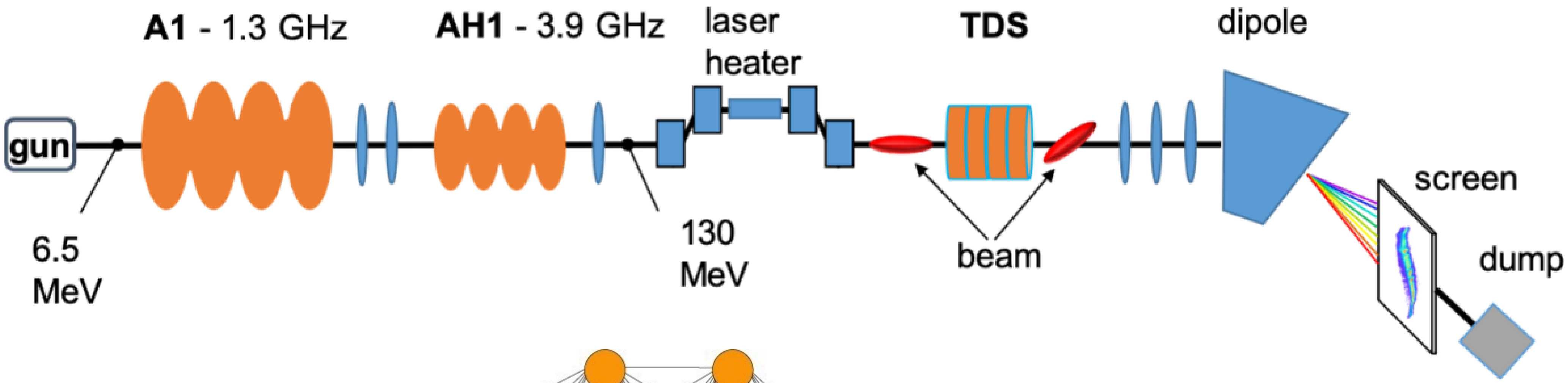
When to apply?

- Enough data
- A lot of computing power
- **Stationary environments**

Where to apply?

- Traditional algorithms are slow
  - Object detection, image segmentation, etc.
  - **Beam dynamics simulation (~ minutes) vs. surrogate model (~ ms)**
- Traditional algorithms are not good enough
  - Image classification, language translation, etc.
  - **Model an accelerator with imperfections and computationally expensive collective effects**

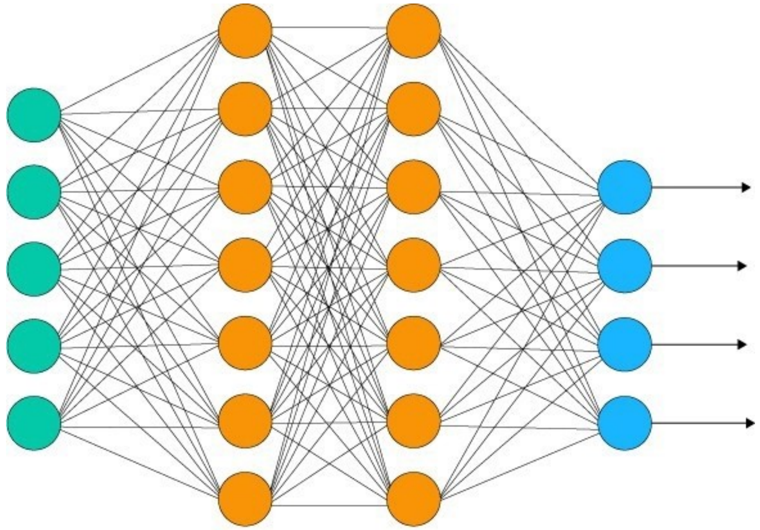
Longitudinal Phase Space Prediction – Virtual Diagnostic

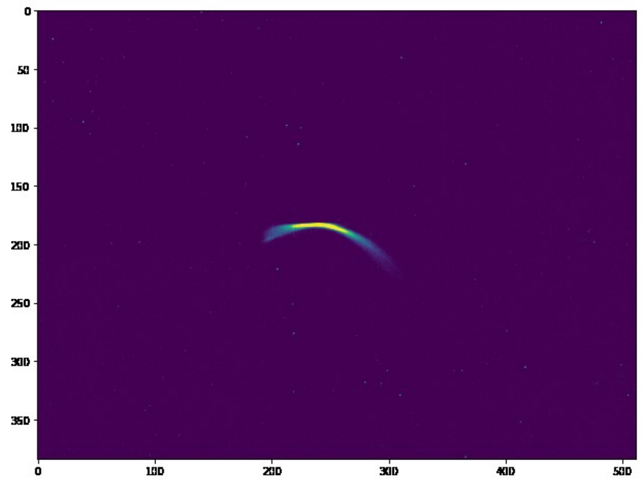


Gun phase

A1 phase

AH1 phase





Virtual diagnostic is a technique which could bring destructive diagnostics online.

Longitudinal Phase Space Prediction

Previous work (LCLS exit)

- Image size: **100 x 100** pixels
- Result is critically sensitive to centering and cropping of the distribution.
- **4000** shots in total
- Inputs:
  - L1S phase **(-27.8 ~ -21.0** degrees)
  - L1S amplitude
  - L1x amplitude
  - Coherent radiation monitors after BC1 and BC2

Emma, et. al., PRAB 21, 112802, 2018

This study (European XFEL injector)

- Image size: **384 x 512** pixels
- The whole image is used as input

  1750 x 2330 → 1536 x 2048 → 384 x 512

  Most information is preserved!
- **3000** shots in total
- Inputs:
  - Gun phase **(-3 ~ 3** degrees)
  - A1 phase **(-6 ~ 6** degrees)
  - AH1 phase (**-6 ~ 6** degrees)

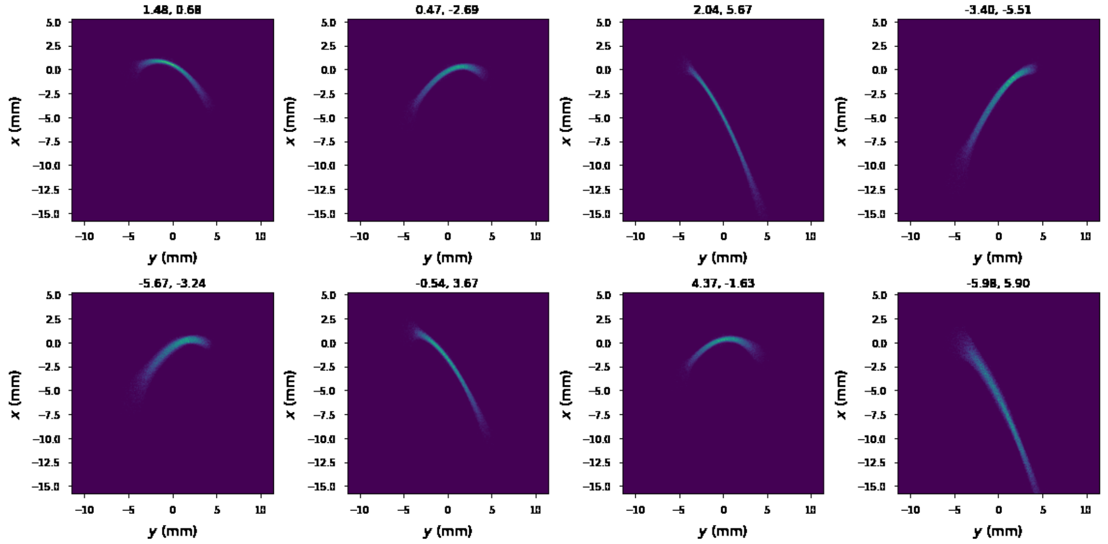
Longitudinal Phase Space Prediction - Simulation

ASTRA + ELEGANT simulation:

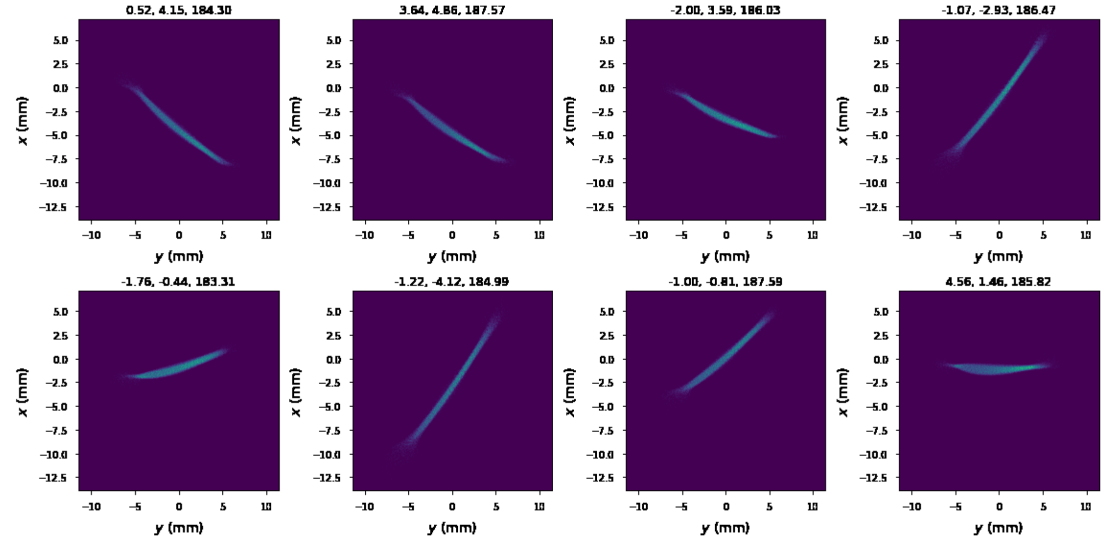
- 20 k particles
- The following highlighted parameters were randomly sampled within the given range.

Parameters	Sample range
Charge (pC)	250
Laser pulse duration (ps)	3
Laser spot size (mm)	0.25
Gun solenoid (T)	0.216
Gun phase (degree)	**-6 ~ 6**
Gun gradient (MV/m)	56.3
A1 phase (degree)	**-6 ~ 6**
A1 gradient (MV/m)	33.3
AH1 phase (degree)	**182 ~ 188**
AH1 gradient (MV/m)	**0, 14**
Q37 gradient (T/m)	-1.156
Q38 gradient (T/m)	1.093

2000 simulations (~150 MeV, AH1 off)



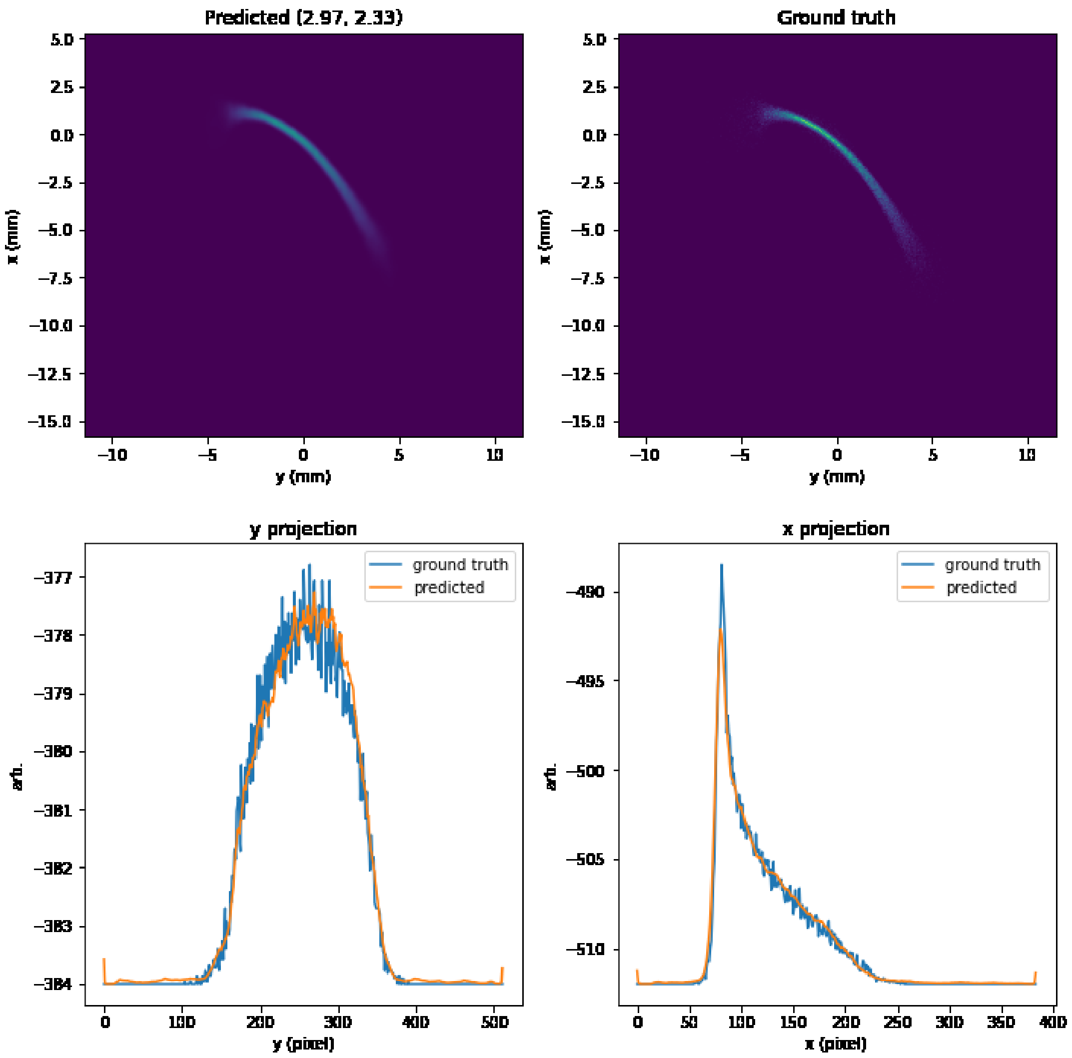
2000 simulations (~130 MeV, AH1 on)



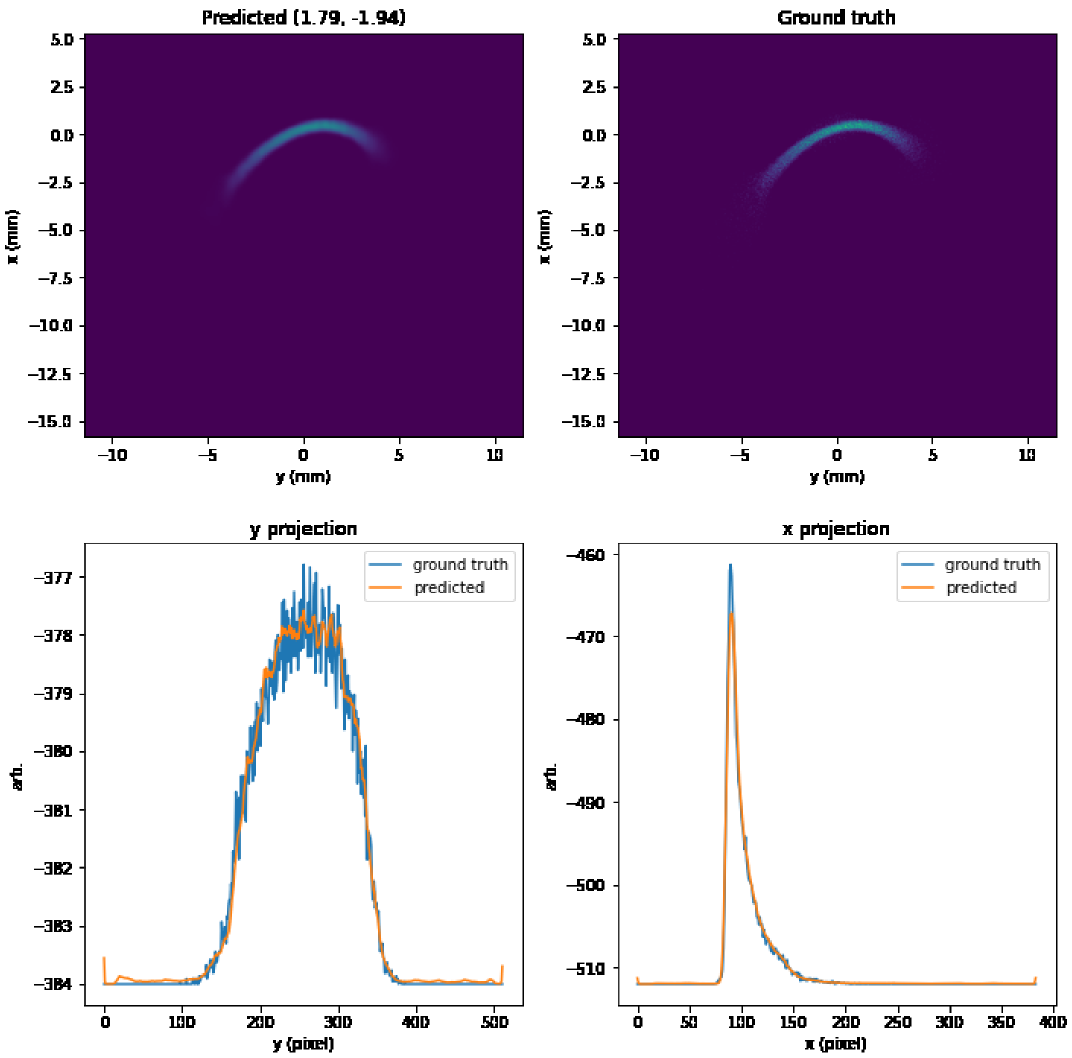
Longitudinal Phase Space Prediction

400 simulations used in test (AH1 off)

Result 1



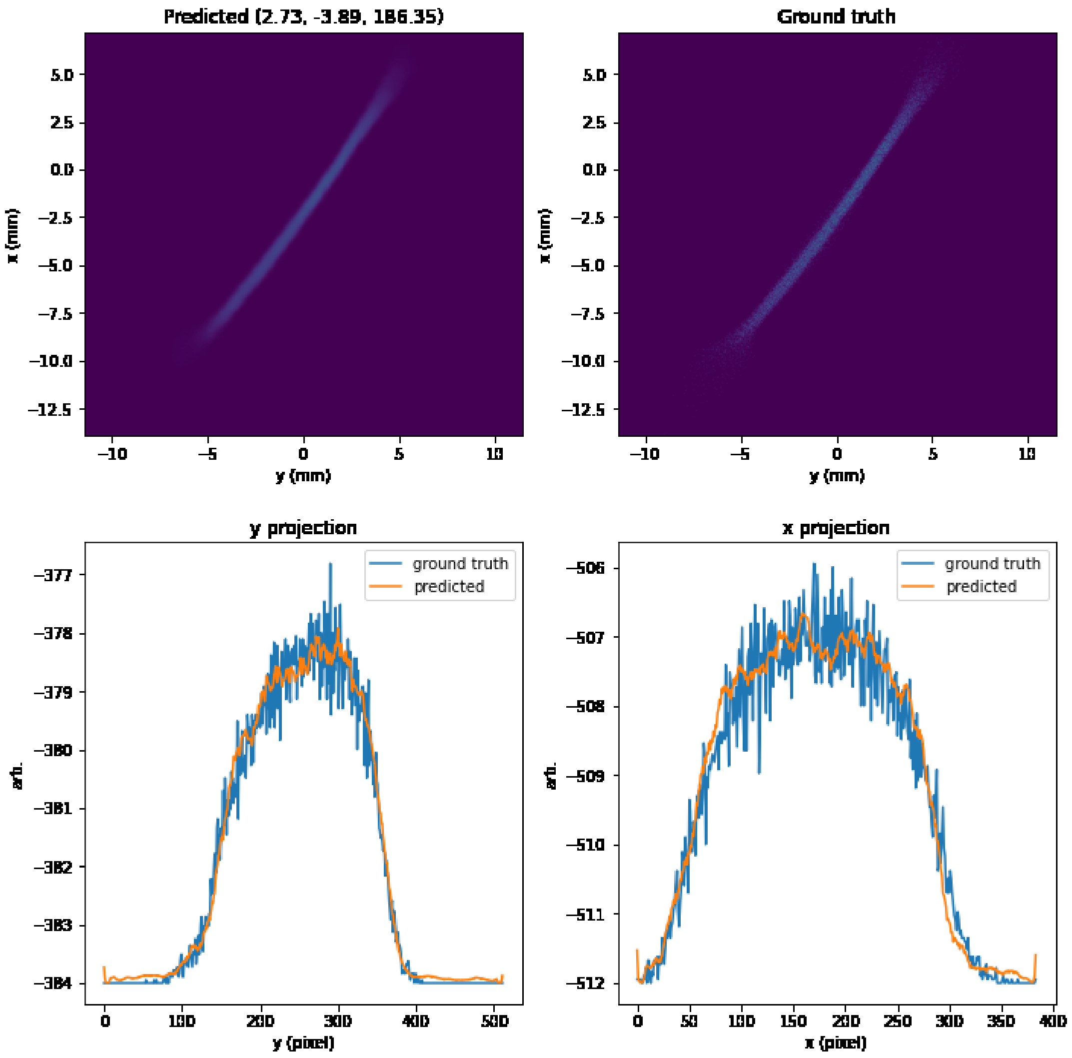
Result 2



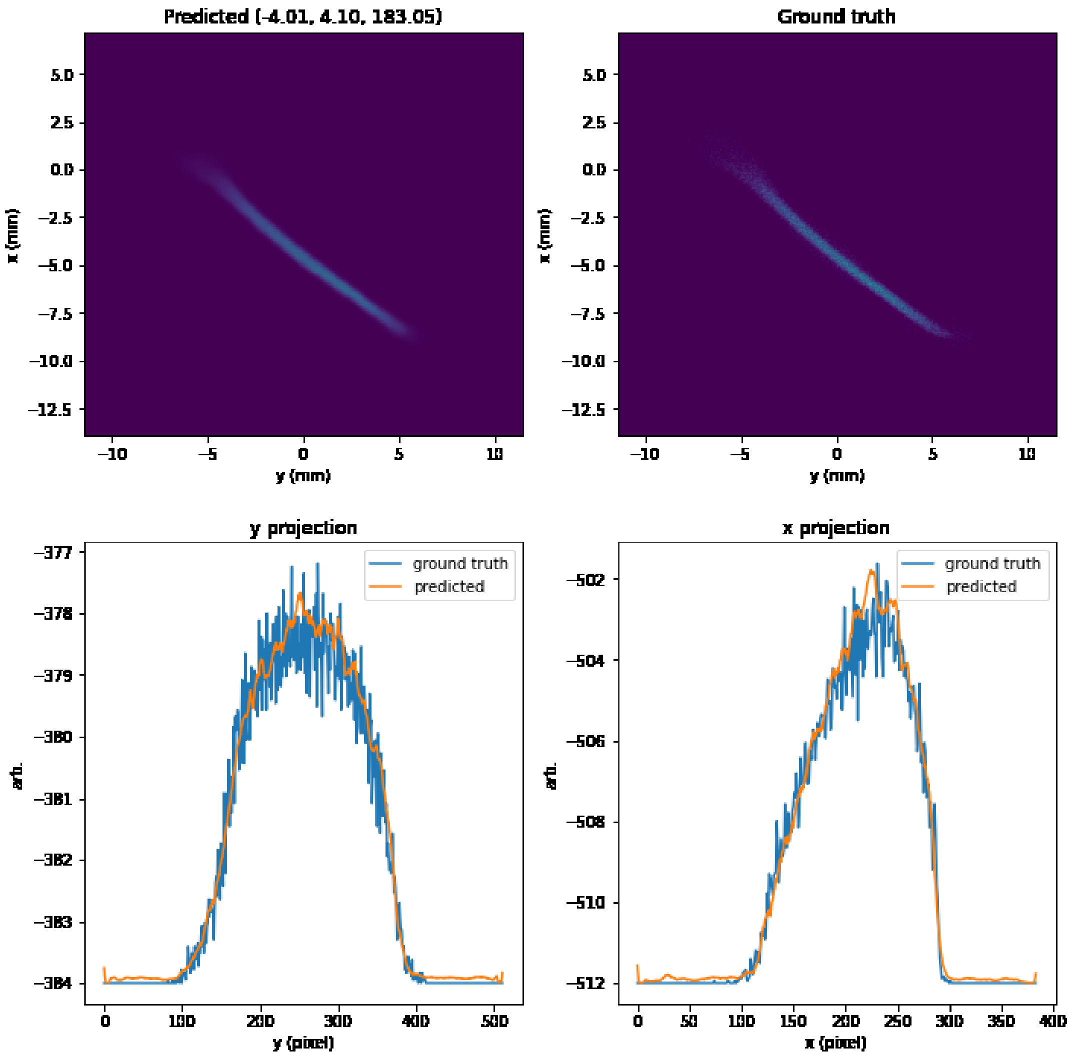
Longitudinal Phase Space Prediction

400 simulations used in test (AH1 on)

Result 1



Result 2

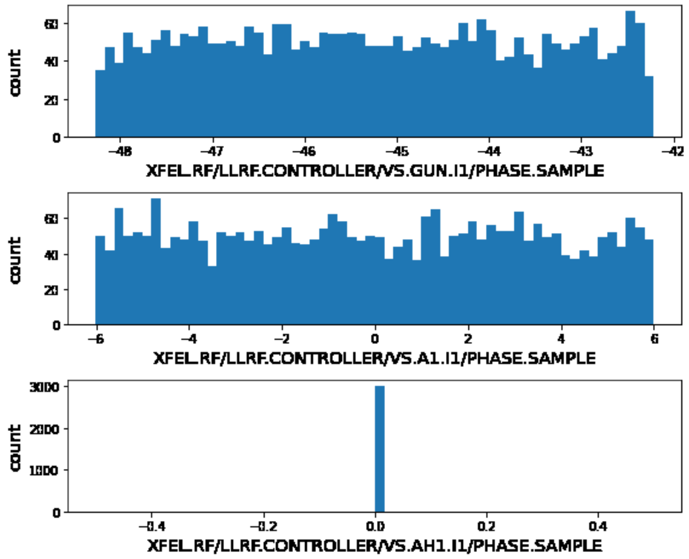


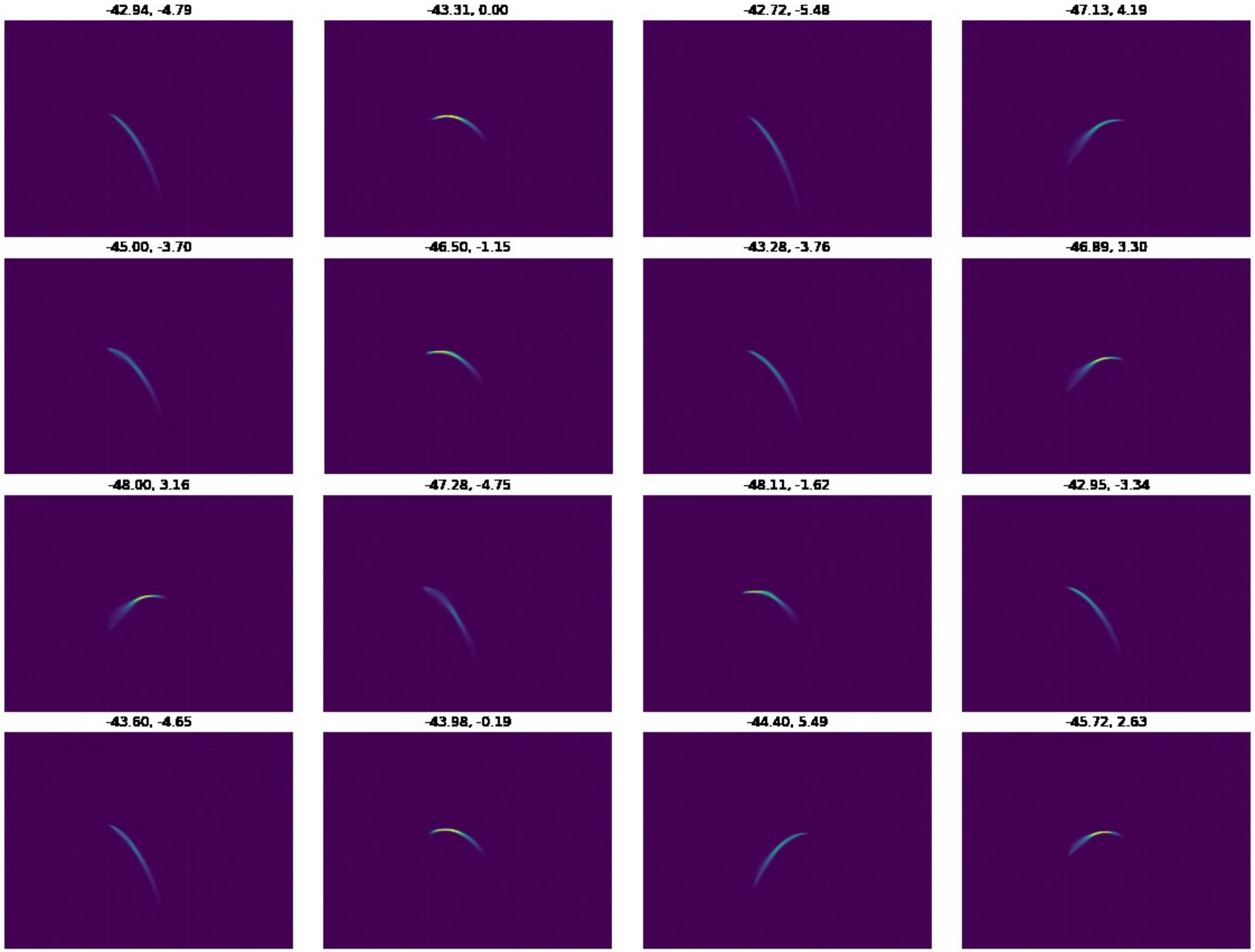
Longitudinal Phase Space Prediction - Experiment

WP2: 130 MeV, AH1 off

3000 random sampled data points:

- Gun phase: -3 ~ 3 (with respect to MMMG)
- A1 phase: -6 ~ 6



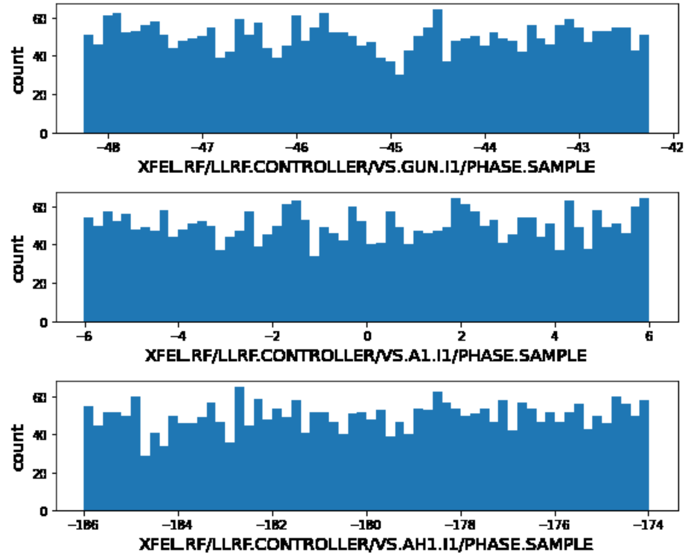


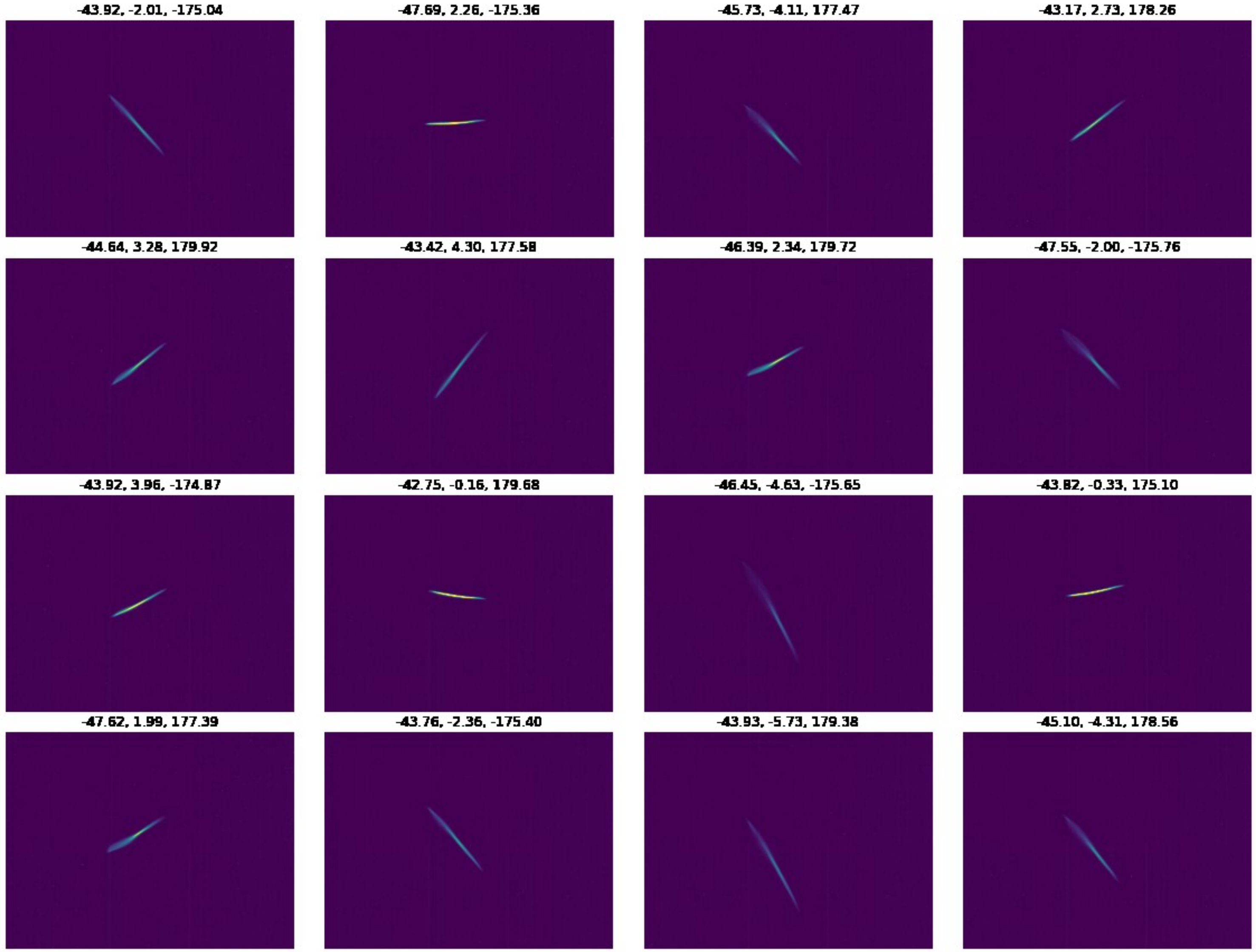
Longitudinal Phase Space Prediction - Experiment

WP1: 130 MeV, AH1 on

3000 random sampled data points:

- Gun phase: -3 ~ 3 (with respect to MMMG)
- A1 phase: -6 ~ 6
- AH1 phase: -6 ~ 6

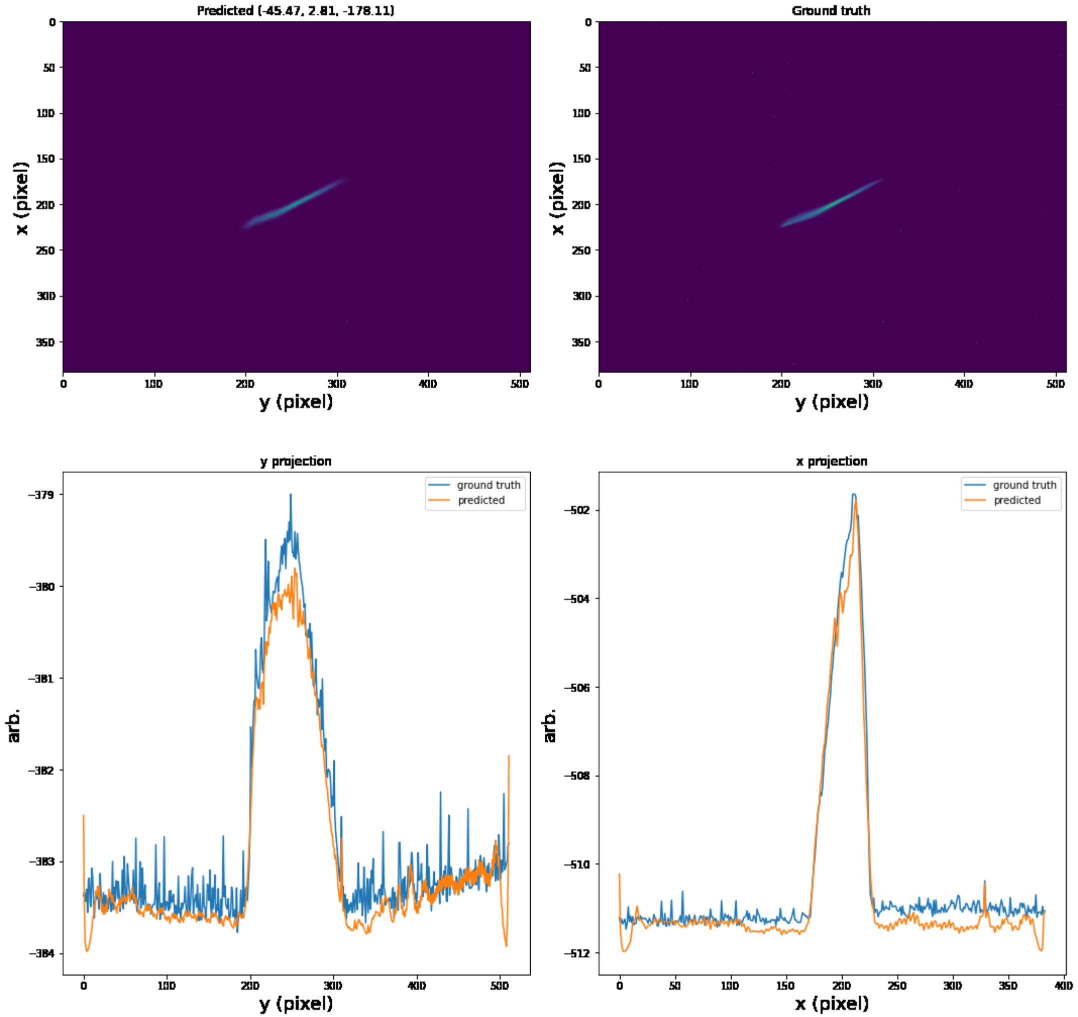




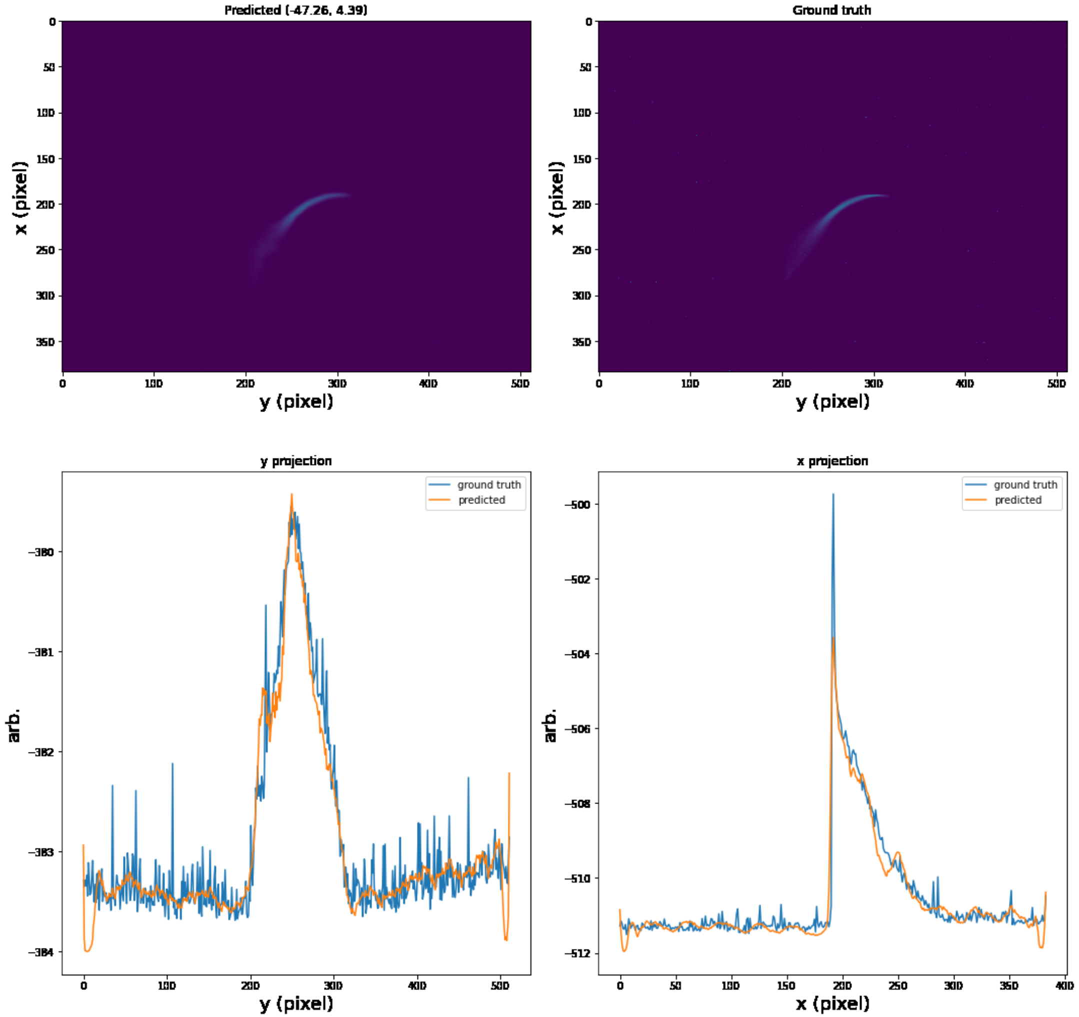
Longitudinal Phase Space Prediction - Experiment

600 simulations used in test

AH1 ON



AH1 OFF



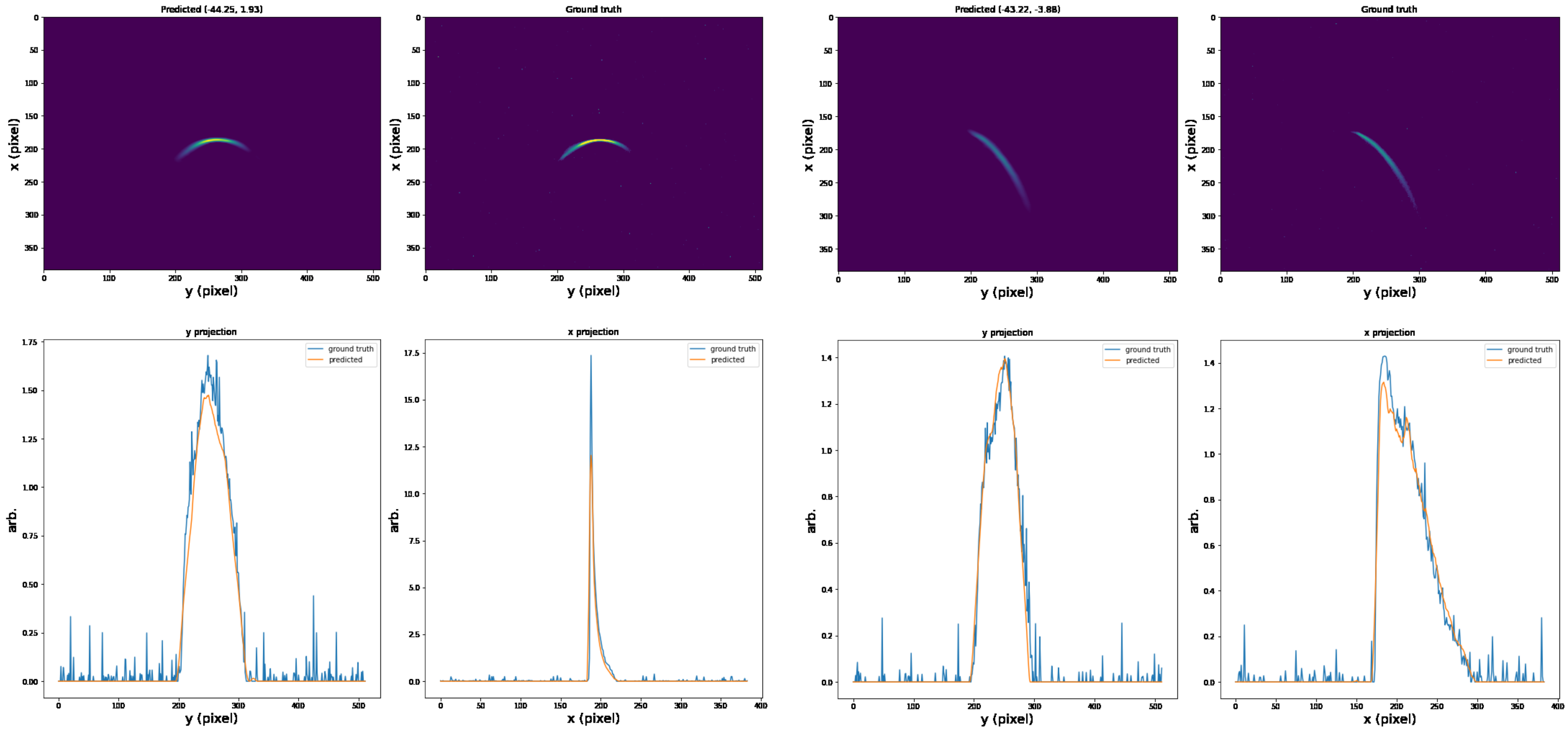
Longitudinal Phase Space Prediction - Experiment

600 simulations used in test (AH1 off)

Result 1

Noise was not learned!

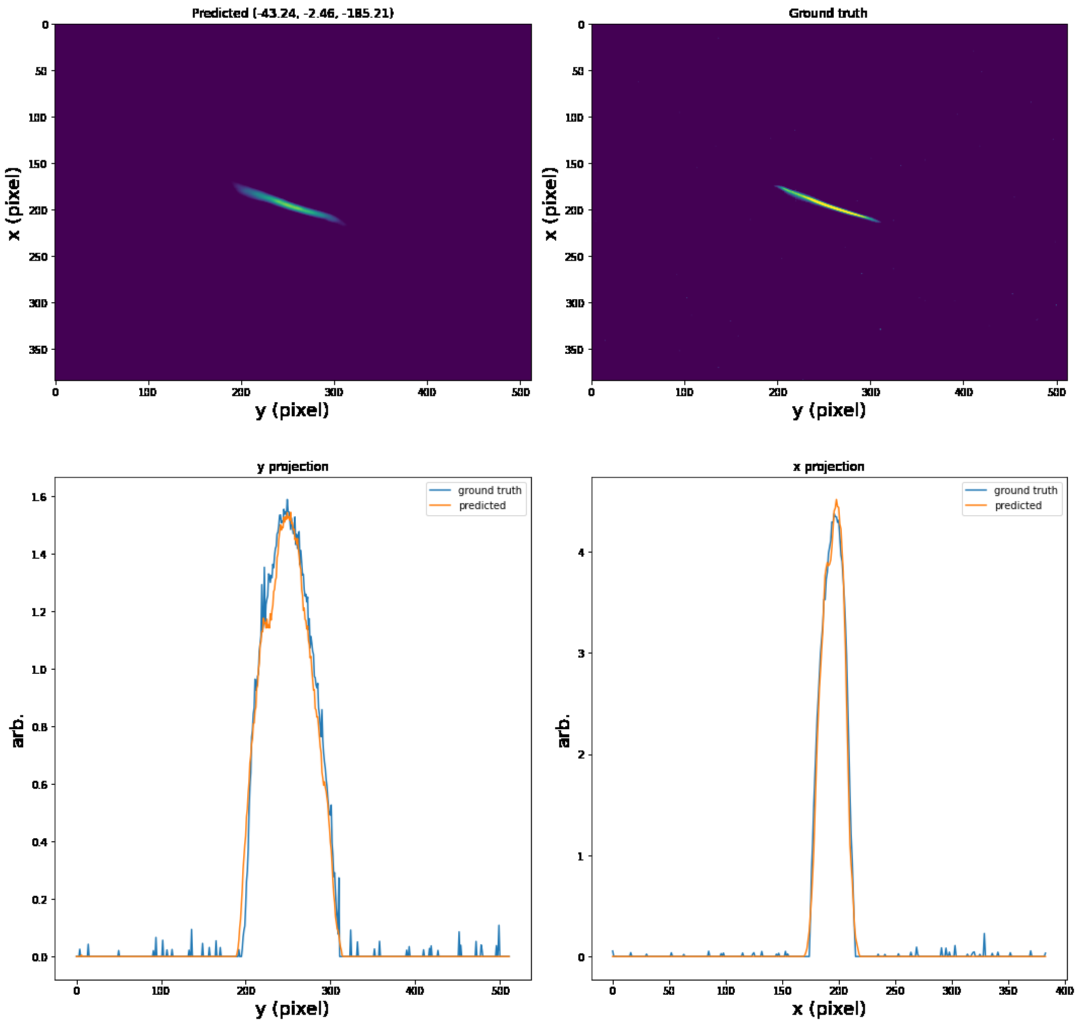
Result 2



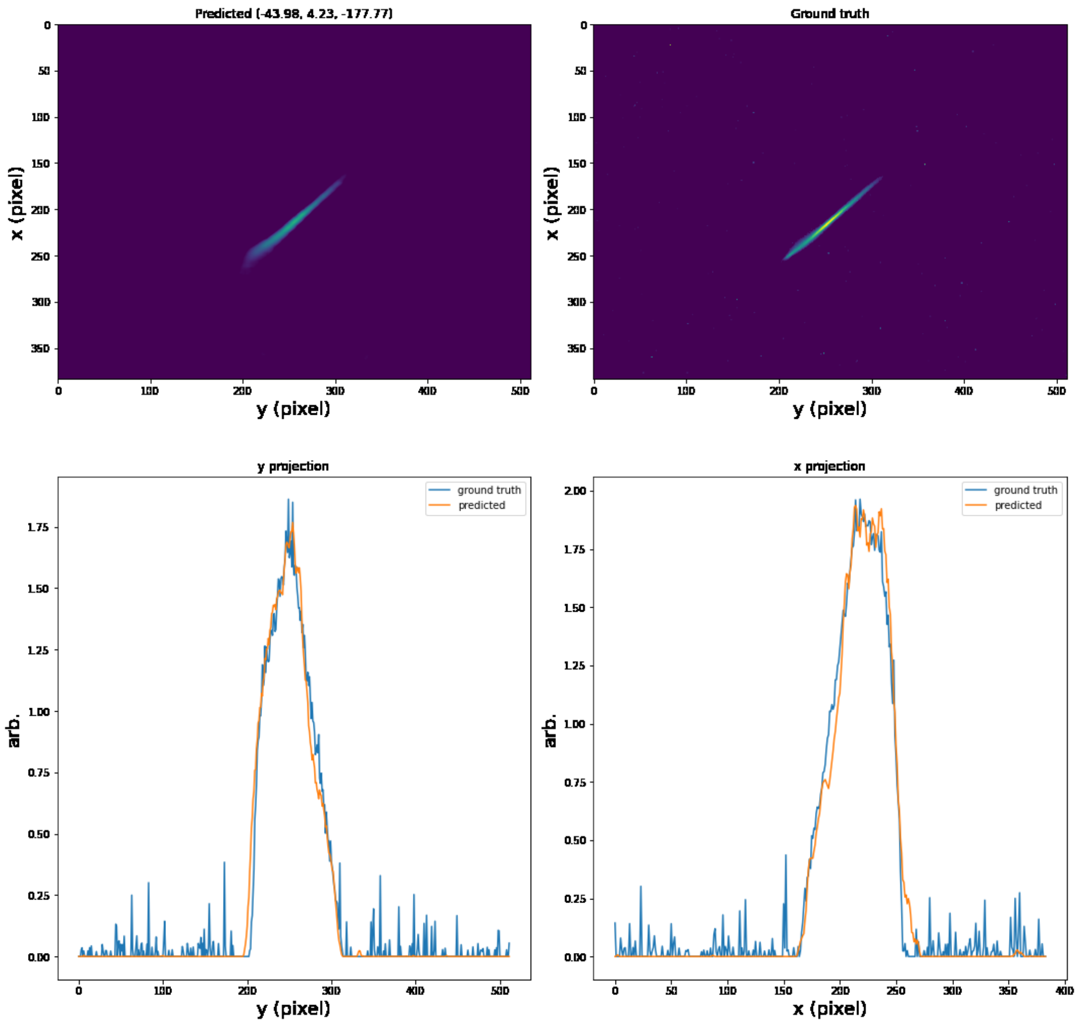
Longitudinal Phase Space Prediction - Experiment

600 simulations used in test (AH1 on)

Result 1

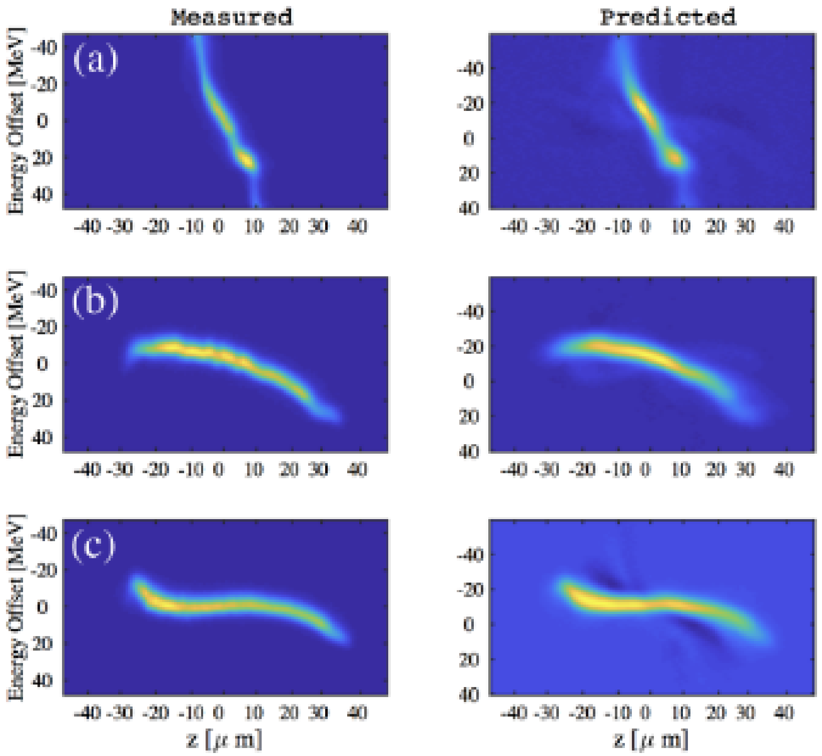


Result 2



Longitudinal Phase Space Prediction - Comparison

Result from a MLP model

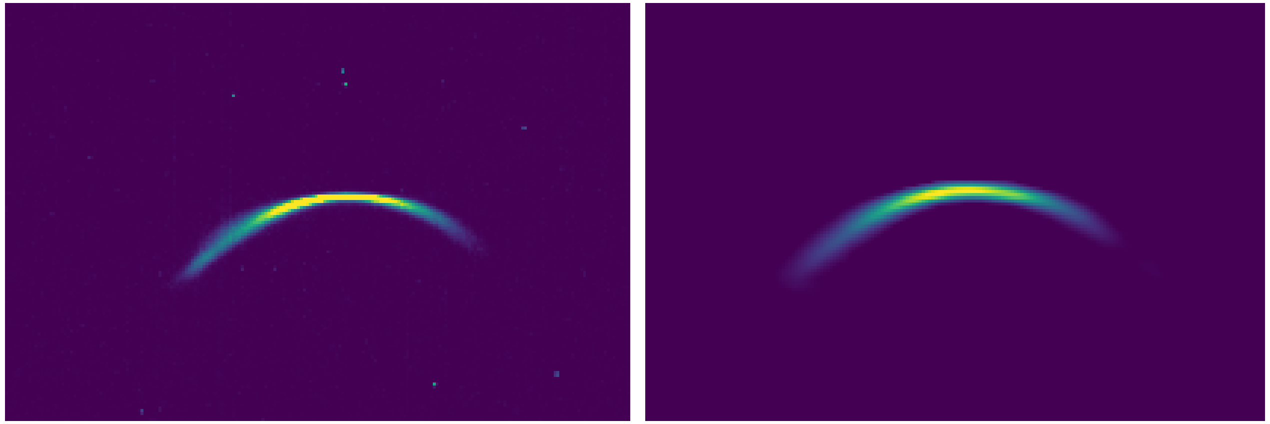


Emma, et. al., PRAB 21, 112802, 2018

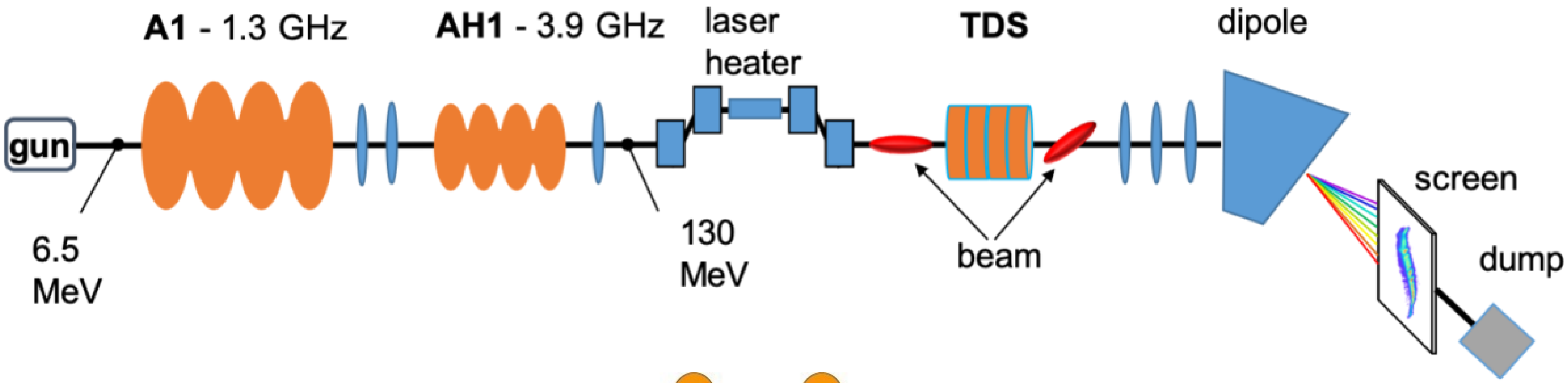
Result from our CNN model

Measured

Predicted



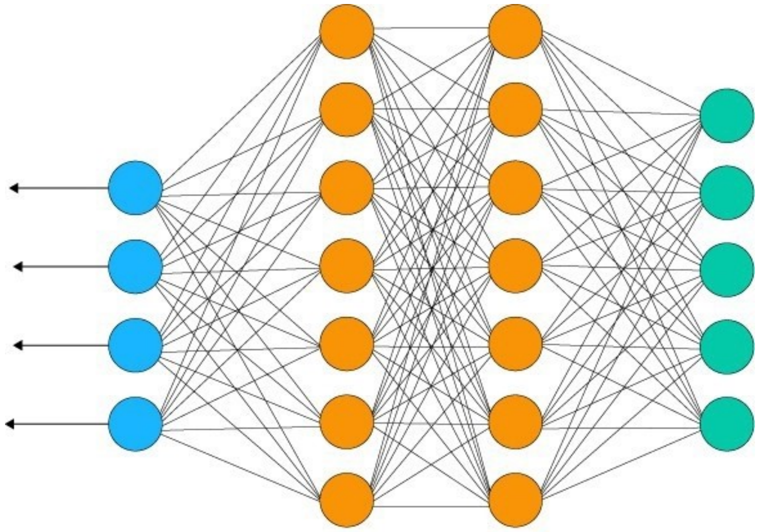
Longitudinal Phase Space Prediction – Phase Inference

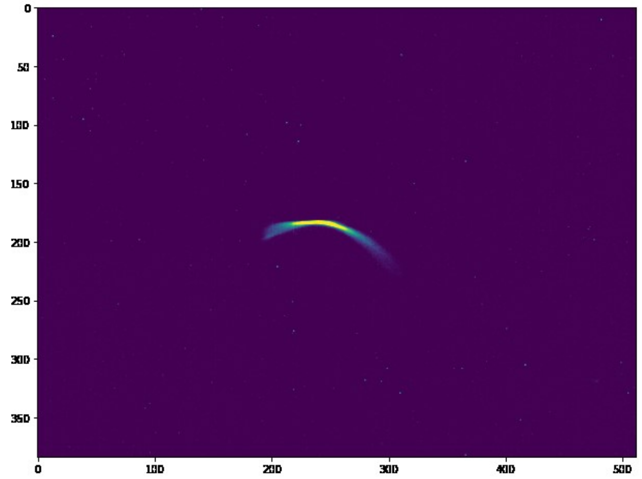


Gun phase

A1 phase

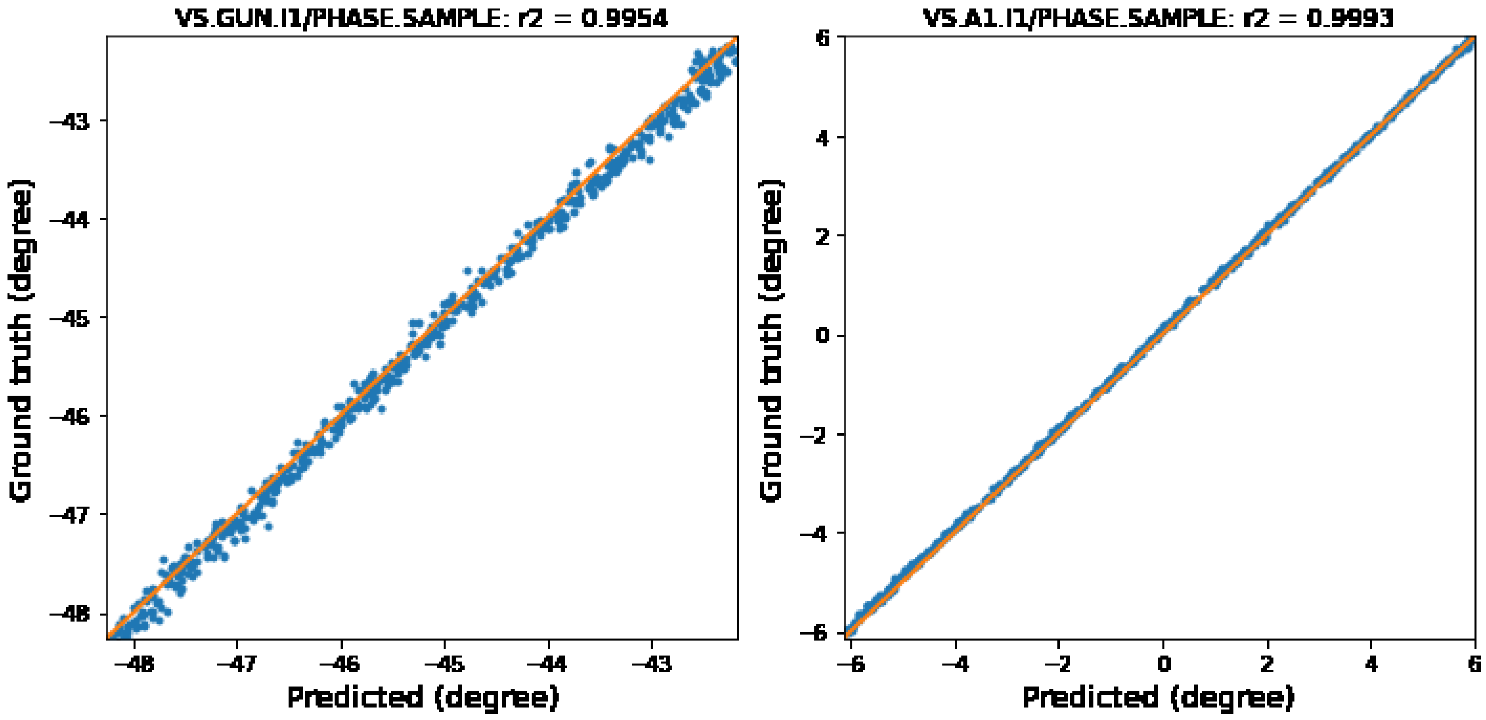
AH1 phase





RF Phases Inference using Longitudinal Phase Space

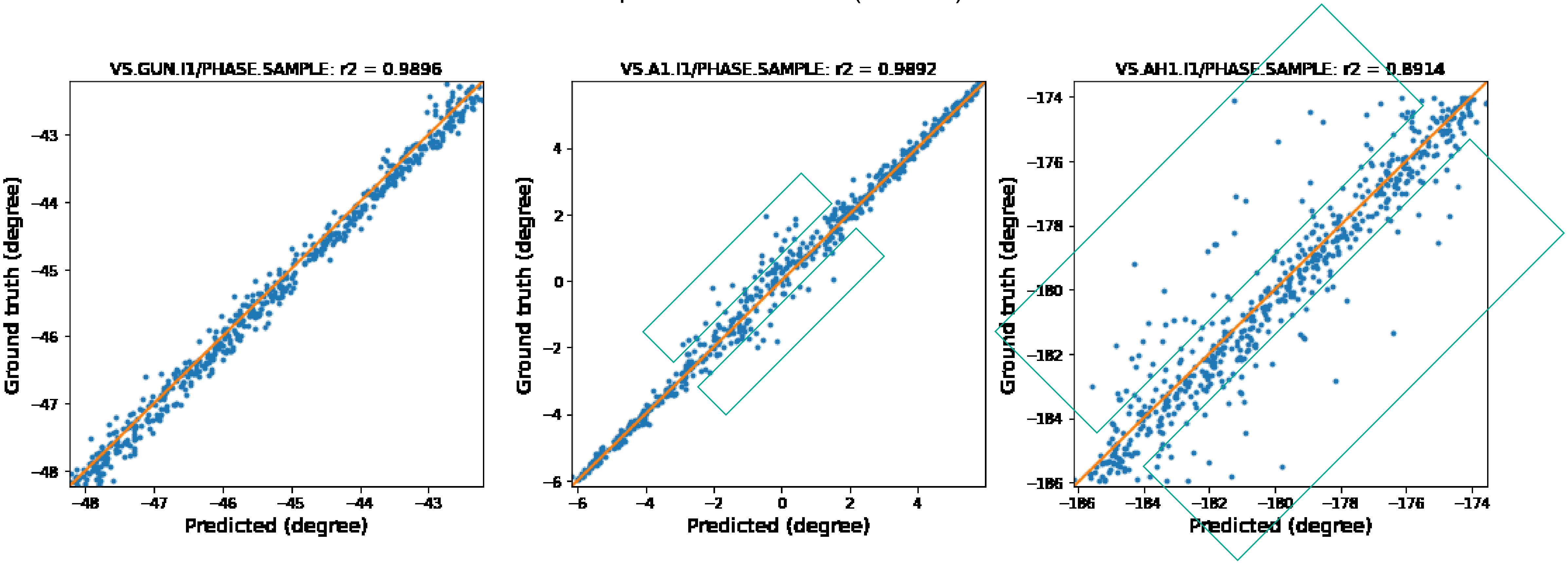
600 data points used in test (~130 MeV, AH1 off)



Coefficient of determination: $$r^2 = 1 - \frac{\sum_i (y_i - f(x_i))^2}{\sum_i (y_i - \bar{y})^2}$$

RF Phases Inference using Longitudinal Phase Space

600 data points used in test (AH1 on)



Next step: Single out those “bad” data points to check the phase-spaces.

Reflection

- **Data collection**
  - Correlating data (by macropulse ID) is highly desired
  - Querying an image data takes > 100 ms
  - Update rate of data (macro-pulse ID) at the camera server is about 3 Hz
- **Test**
  - Test in production environment
- **Further improvements**
  - Reproduce the experiment in simulation
  - Prediction in real-time (GPU?)
  - Combine with data from non-destructive diagnostics
  - …

Thank you
for your attention!