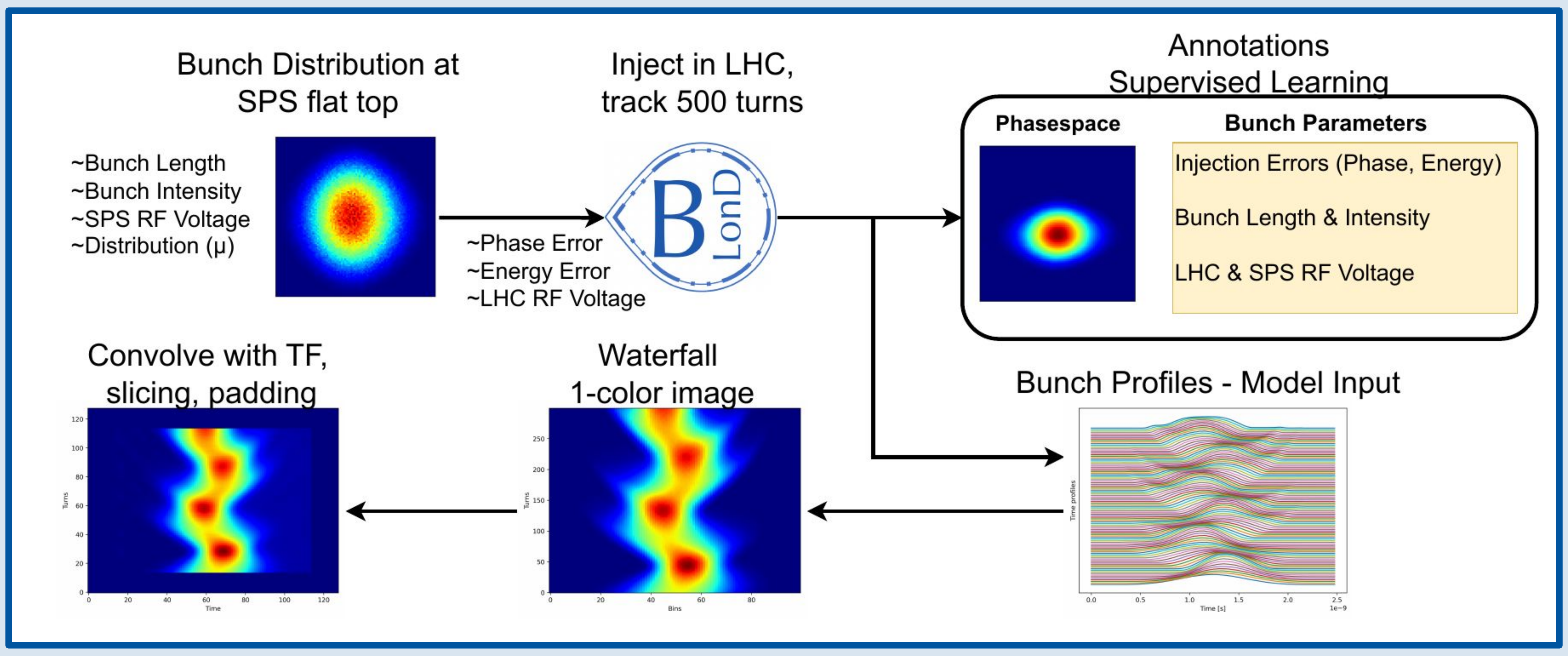
Longitudinal Beam Diagnostics and Phase Space Reconstruction in the LHC Using ML

K. Iliakis[1], S. Albright, T. Argyropoulos, A. Lasheen, H. Timko, G. Trad
European Organization for Nuclear Research (CERN), Geneva, Switzerland
[1]konstantinos.iliakis@cern.ch

Abstract

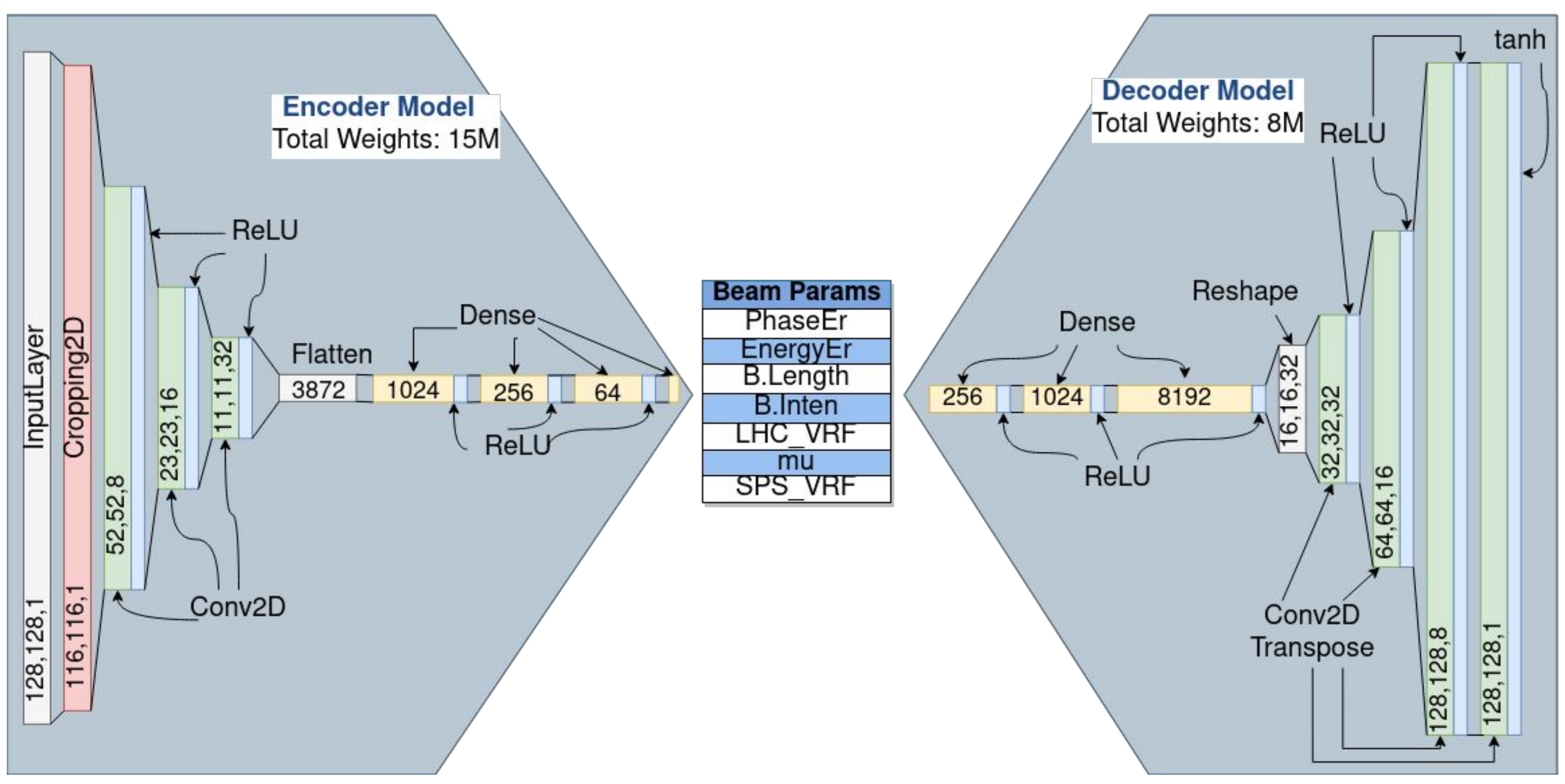
- Accurate knowledge of **longitudinal beam parameters** (e. g. energy error, phase error, bunch length and intensity) is **essential for beam performance**
- Leveraging the **high-resolution measurements of longitudinal bunch profiles**:
  - Using **fitting methods**, bunch length, intensity, injection errors (phase, energy) can be calculated
  - Using **longitudinal tomography**, bunch distribution and emittance can be calculated
- However, these methods are **too time consuming for online use**, limited to single bunch
- **Develop ML mode**l to:
  - Obtain the desired **beam parameters**,
  - and the 2D **longitudinal beam distribution**
  - **Fast** enough to allow for **online** use with **multi-bunch beams**

Training Data Generation



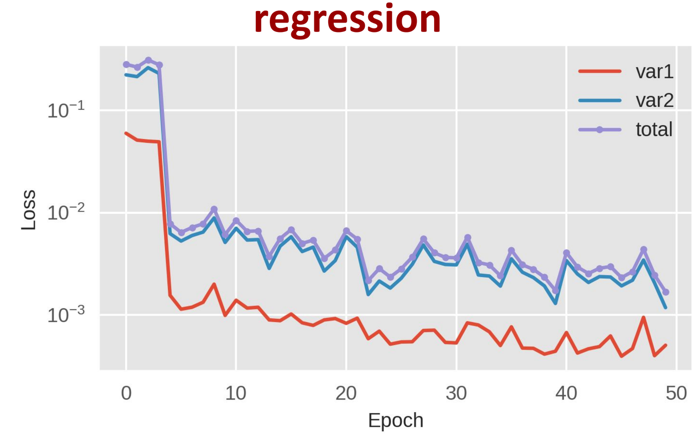
Original Model Architecture

- **Encoder**: Conv2D at first, then fully connected
- **Decoder**: Mirrors the Encoder, with Conv2D transposed
- Alternative designs tested:
  - **Transformer** ⇒ Similar accuracy
  - **Pix2Pix***: U-Net + GAN ⇒ Worse accuracy
  - (Variational) **Autoencoder** ⇒ Worse accuracy



Improved Design & Optimization

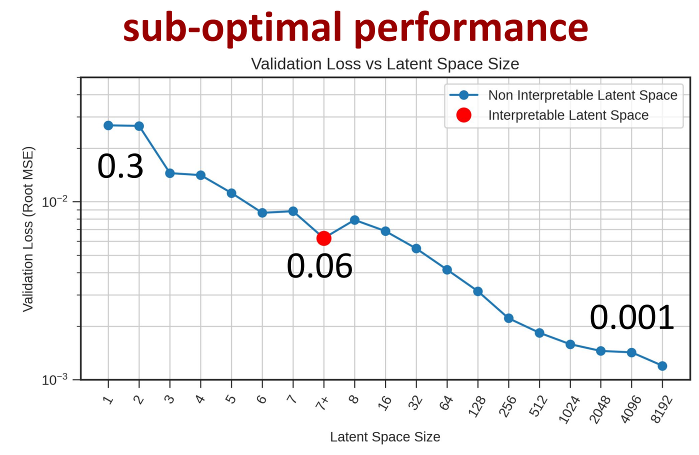
Limitation 1: Bottlenecks in Multi-output regression



Solution: Ensemble of Encoders

- No bottlenecks
- More weights (60M)

Limitation 2: Restricted latent space provides sub-optimal performance

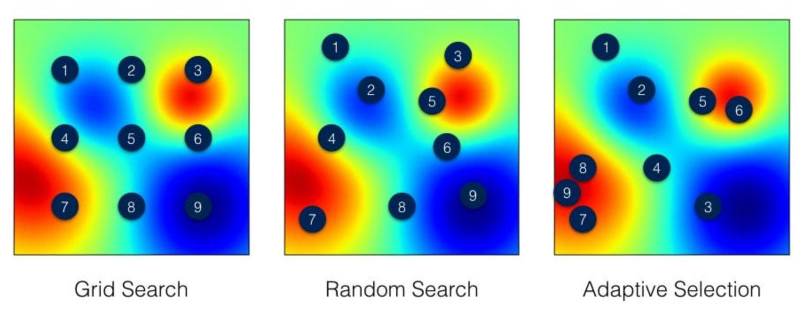


Solution: Unsupervised latent space

- Improved precision (~25%), no beam parameters, More weights (151M)

- **Huge Parameter Space**
  - 8 Models
  - Convolution layers
  - Dense layers
  - Regularization
  - Learning rate, epochs, batch size
  - Input cropping, etc…
- **Exhaustive search prohibitive**
- **Tuning is essential**
- Grid search optimisation with **Optuna**:
  - Intelligent sampling
  - Early-stopping

Search algorithms on 2D space



Grid space search time

Method	Total Configs	Total Run	Total Pruned	Best solution	Time taken
Optuna	154	26	128	6.78E-06	1.5h
Exhaustive	154	154	0	6.75E-06	6h

Synthetic Data Evaluation

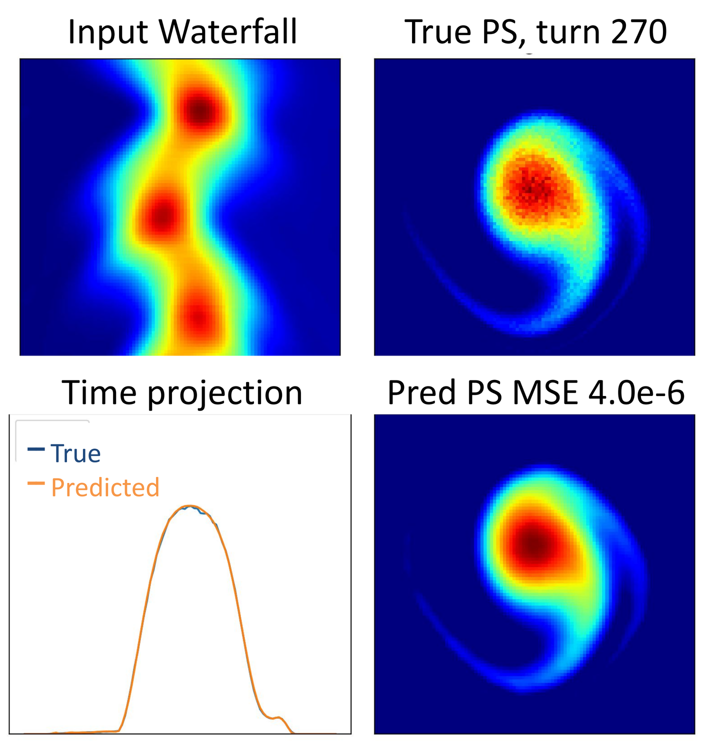
Encoder Ensemble Evaluation

- Matches or surpasses precision of classical methods
- Independent set of parameters
  - Easy to add/ remove parameters

	95-percentile
Phase Error	0.3 deg
Energy Error	1.56 MeV
LHC V_RF	0.05 MV
Bunch Length	13.2 ps
Intensity	1.2e9 p
SPS V_RF	0.16 MV
Distribution μ	0.14 a.u.

Tomoscope

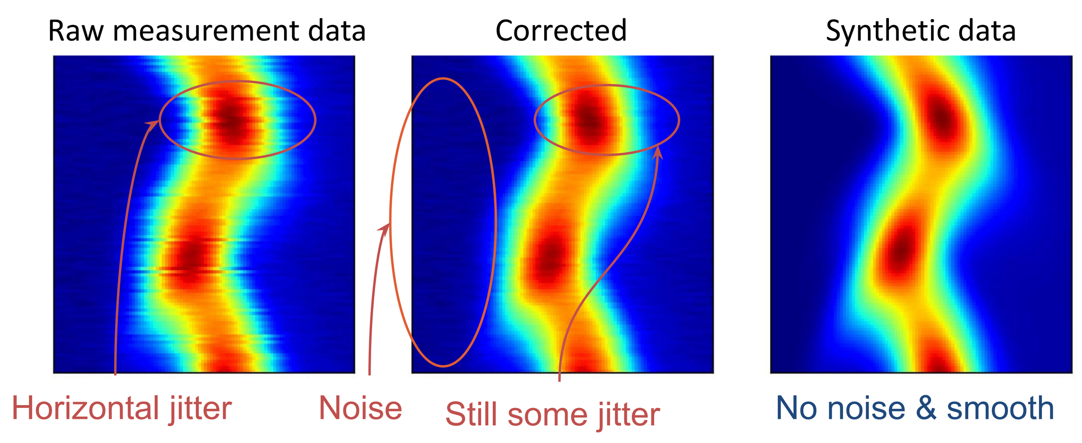
- Pixel-Pixel **MAE: 0.001**
- **Visually indistinguishable**



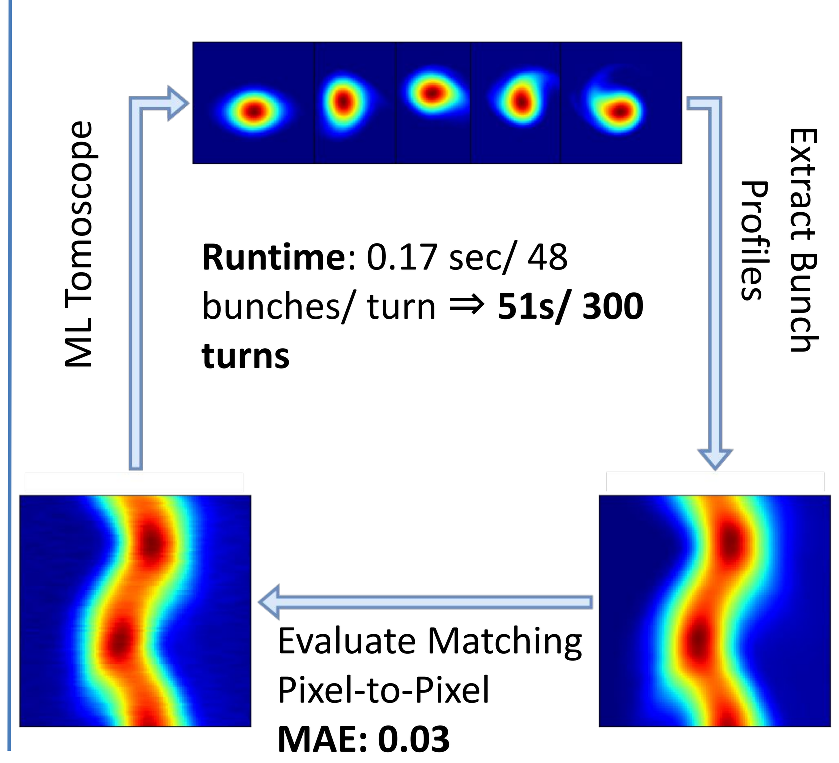
Real-Data Evaluation

Reality Gap

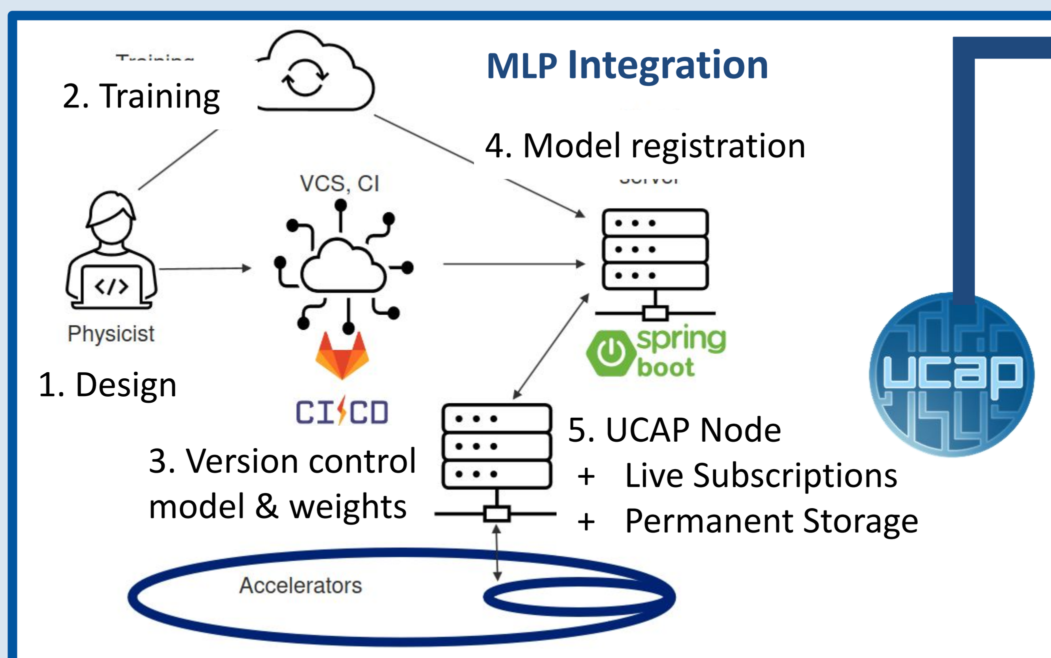
- **Horizontal jitter** due to collection trigger
- **Random noise**
- **Ground truth not available**
- Multi-bunch measurements, single-bunch simulations



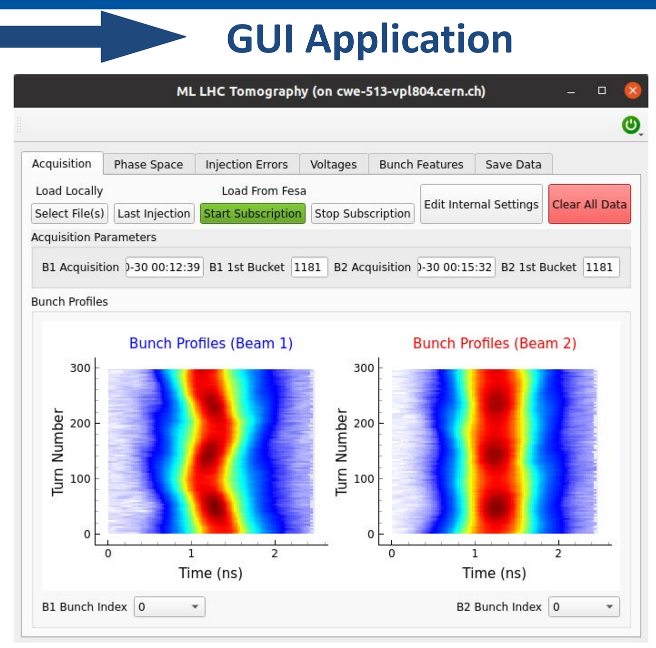
Evaluation



Deployment



GUI Application



Capabilities:

- Minimal UI
- Subscribe to UCAP
- Inspect Bunch Profiles
- Beam diagnostics
- Longitudinal tomography
- Edit settings, save to file

Conclusions

- ML model proves to be a powerful and promising solution for:
  - **Real-time** extraction of essential **beam parameters**
  - **Real time** multi-bunch **tomography**
  - **Remarkable speed**, <1' for 300 turns reconstruction with 48 bunches
- Tool in **operational state**
  - To be tested in next run
  - GUI to assist operators, live display
  - Output stored for post-processing
- Simulated data need to closely reproduce measurements
  - A ML **model** is only **as good as the data** it is fed.