ITS2 alignment : AI approach

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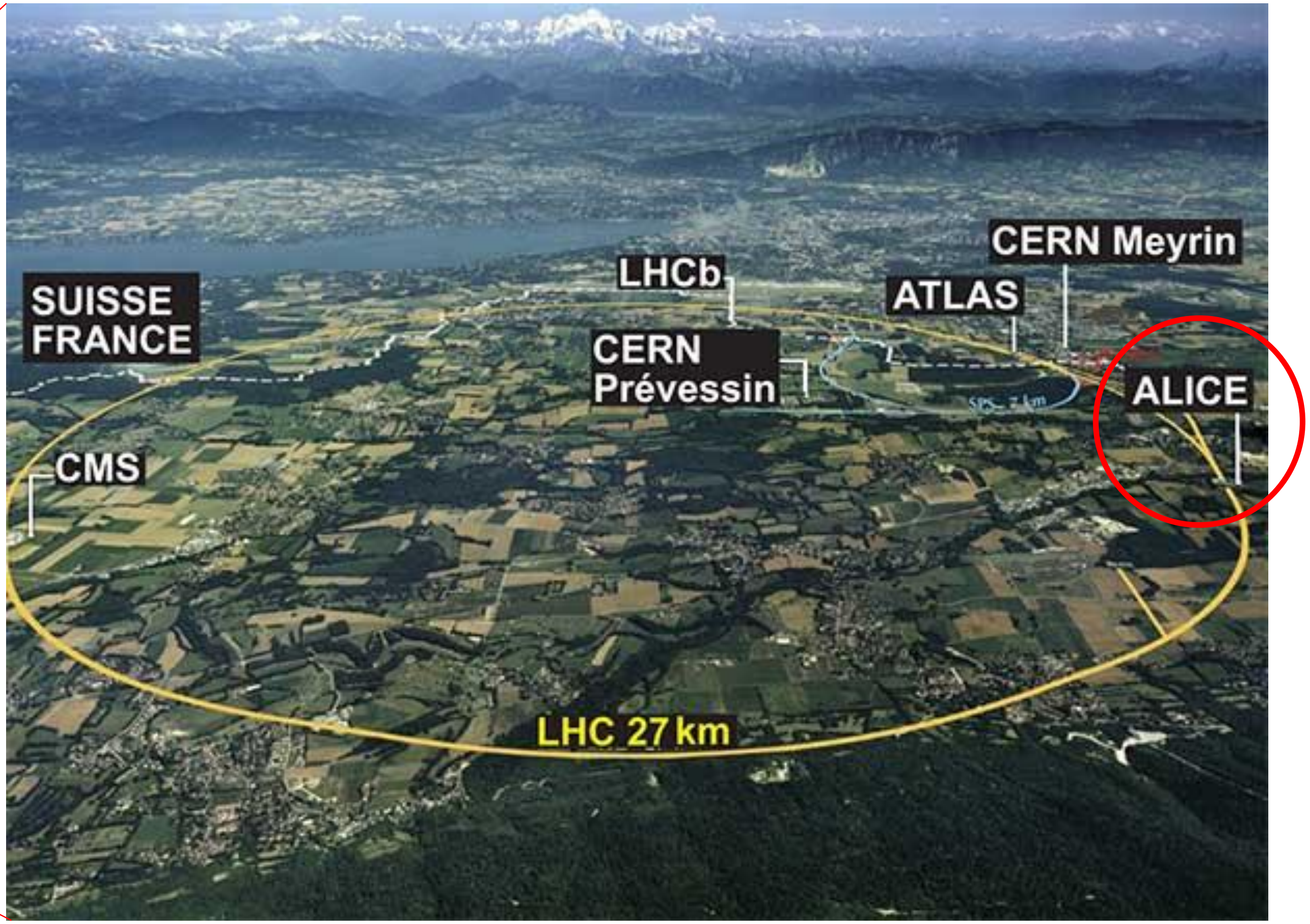
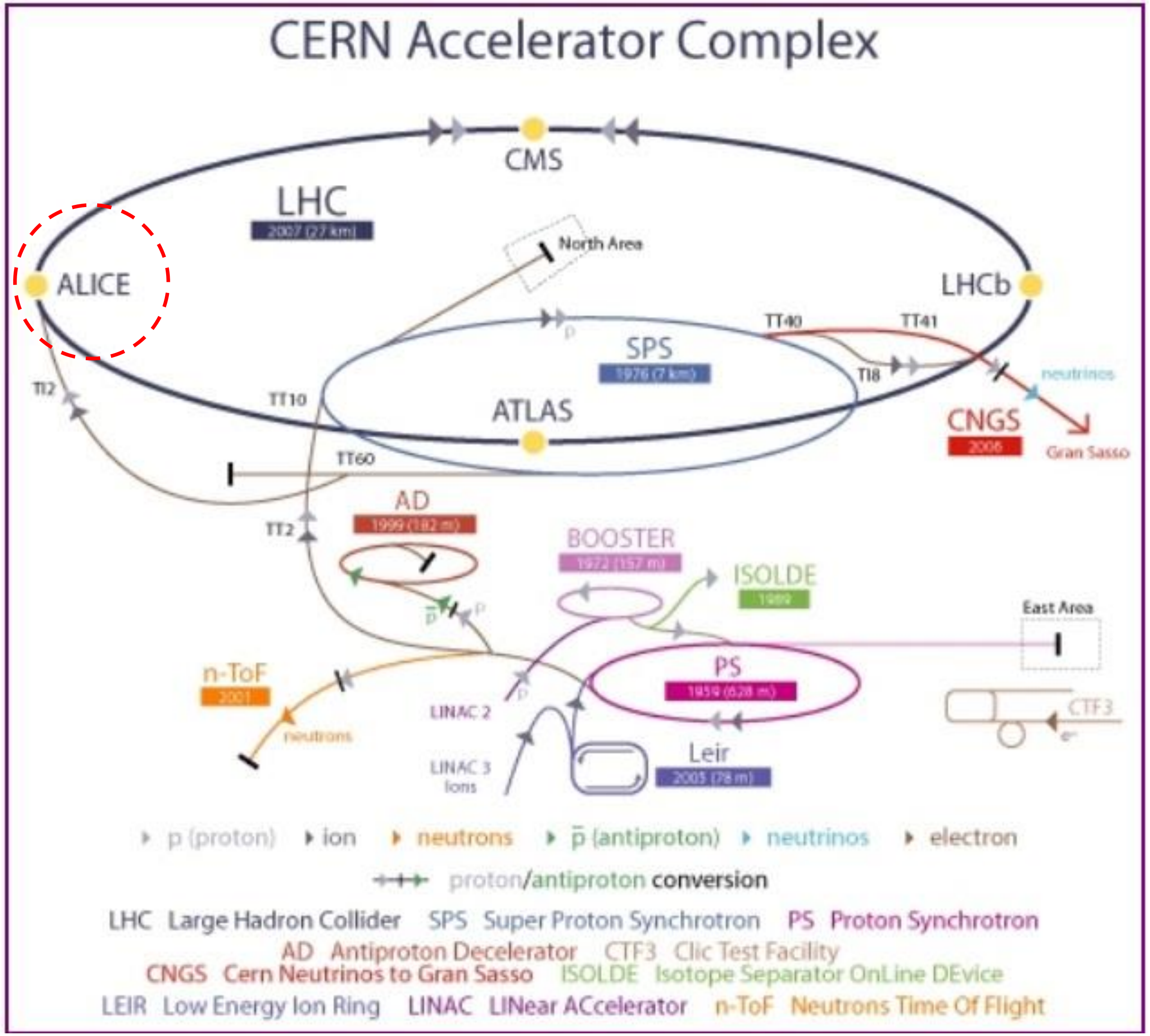
CERN, LHC Experiments, ALICE



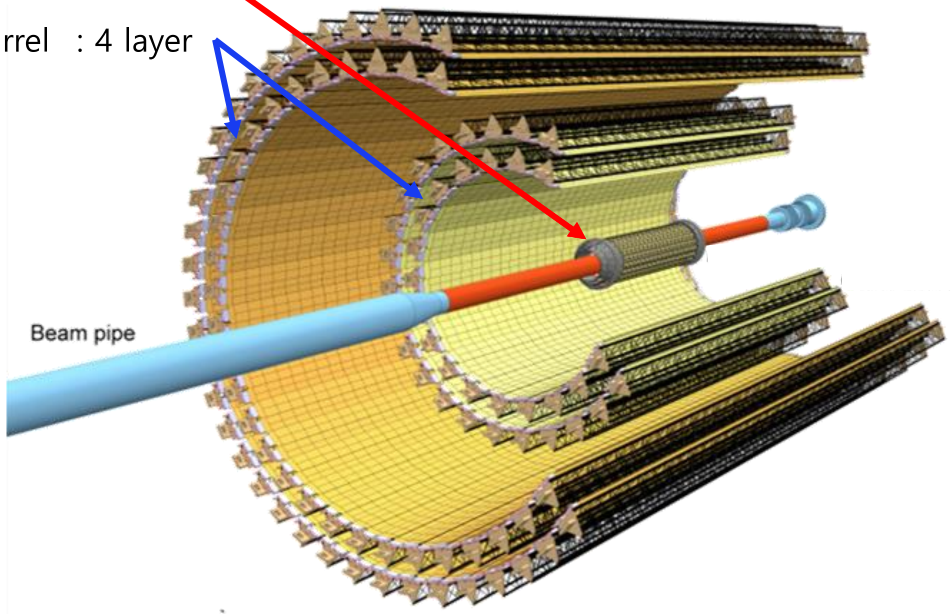
CERN, LHC Experiments, ALICE

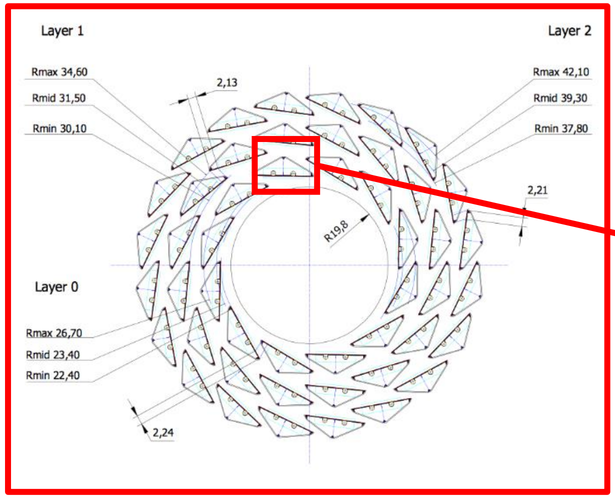


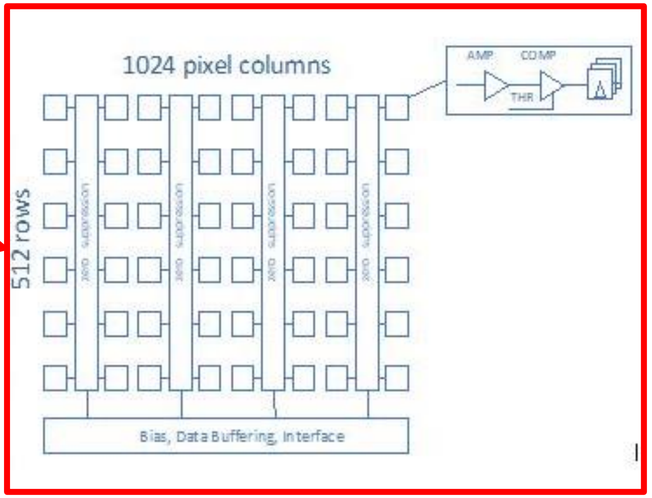
Accelerator	Experiments	Overview
LINAC2		accelerates proton from the source and sends them to the booster (PSB)
LINAC3		accelerates ions from the source and sends them to LEIR
PSB		accelerates protons and sends them to the PS and ISOLDE
PS	EA	East Area - various experiments
	nTOF	neutron time-of-flight
	DIRAC	to observe and then measure lifetimes of Muons and Kaons
	CLOUD	to study possible links between cosmic rays and cloud formation
	SPS	sends beam to SPS (CNGS, fixed target, LHC)
ISOLDE		to produce a range of isotopes for research
AD	ALPHA	to make, capture and study atoms of antihydrogen and compare these with hydrogen atoms
	ASACUSA	to compare anti-protons and protons using antiprotonic helium
	ATRAP	to compare hydrogen atoms with their antimatter equivalents
LEIR		accelerates ions and sends them to the PS
SPS	NA	North Area - various experiments
	CNGS	to send muon neutrinos to to the Gran Sasso National Laboratory in Italy
	COMPASS	to study how elementary quarks and gluons work together to give particles we observe
	LHC	injects beam into the LHC at 450 GeV
LHC	CMS	to search for the Higgs boson, extra dimensions, and particles that could make up dark matter
	ATLAS	to search for the Higgs boson, extra dimensions, and particles that could make up dark matter
	LHCb	to understand why we live in a Universe composed almost entirely of matter, but no antimatter
	ALICE	to study a state of matter known as quark-gluon plasma
	TOTEM	to measure the size of the proton and also monitor the LHC's luminosity
	LHCf	to simulate cosmic rays to interpret and calibrate large-scale cosmic-ray experiments

Introduction

Inner Barrel : 3 layer
Outer Barrel : 4 layer





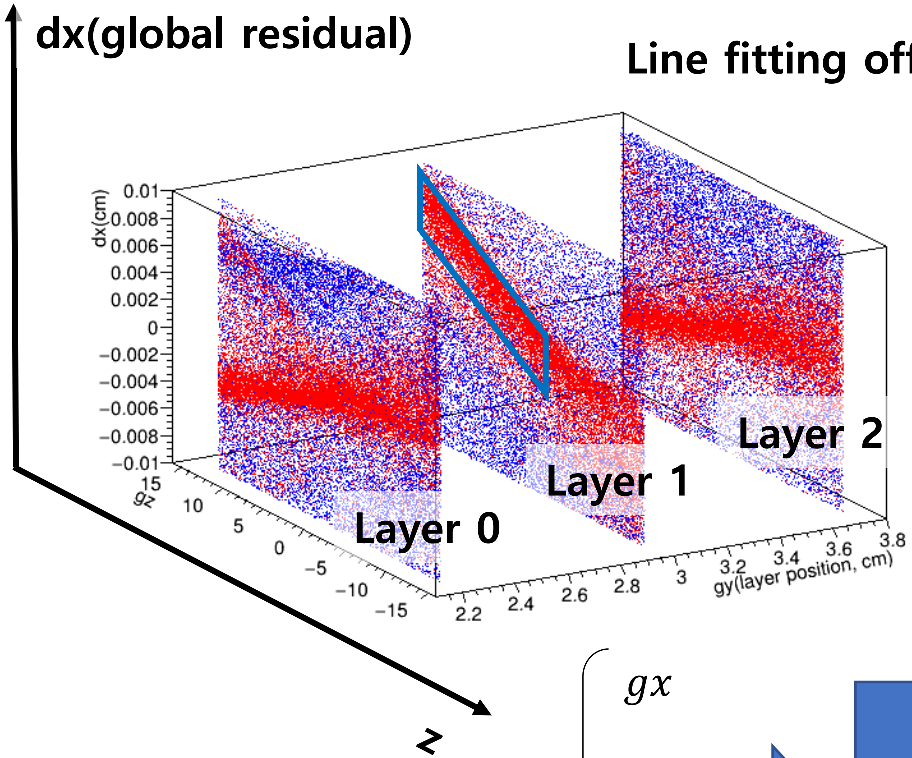


The new ITS is an all-pixel silicon detector based on CMOS monolithic active pixel sensor (MAPS).
https://ep-news.web.cern.ch/content/alice-its-upgrade-pixels-quarks

- Precision trackers are used for the high energy and nuclear physics.
- The trackers measure precise positions of the hits produced by the particles and associate hits to a trajectory when the associated positions are consistent.
- Any small misalignment or deformation of detector caused by various factors significantly affects the precise position measurements and its correction frequently appears as a major issue in the tracker operation.

Motivation

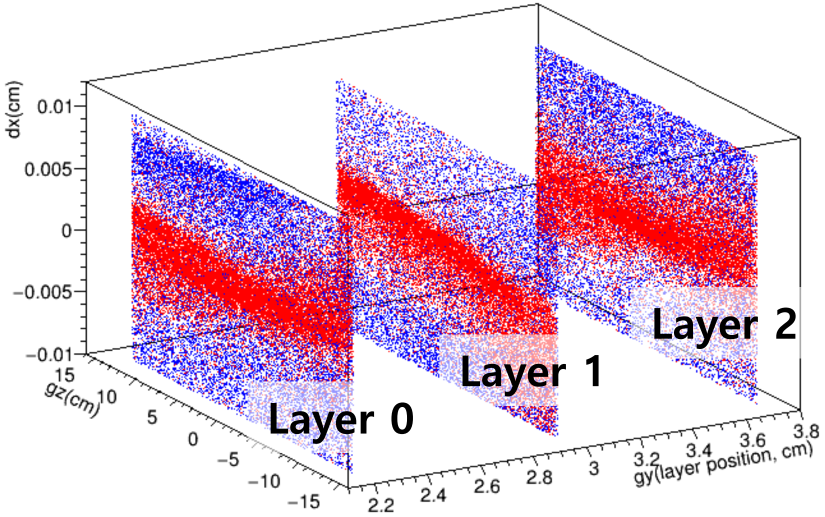
Line fitting offset in x direction(dx) plot, cosmic muon



Apply Simple Correction

$$\mathrm{F_C} : gx \rightarrow gx' = gx + C_x$$

$$C_x = \left(\frac{0.01}{15}\right) \cdot gz + 0.001$$



Global hit position $\{gx, gy, gz\}$ → **Correction Function** $\mathrm{F_C}$ →

$$gx' = gx + C_x$$

$$gy' = gy + C_y$$

$$gz' = gz + C_z$$

We can see the deformation structure from cosmic muon events but there is no way to verify the right answer.

Artificial Intelligence Model : Neural Network

A Neural Network can approximate any function!

Approximation by Superpositions of a Sigmoidal Function*

G. Cybenko†

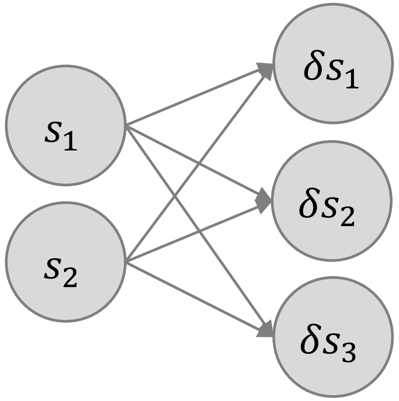
Abstract. In this paper we demonstrate that finite linear combinations of compositions of a fixed, univariate function and a set of affine functionals can uniformly approximate any continuous function of *n* real variables with support in the unit hypercube; only mild conditions are imposed on the univariate function. Our results settle an open question about representability in the class of single hidden layer neural networks. In particular, we show that arbitrary decision regions can be arbitrarily well approximated by continuous feedforward neural networks with only a single internal, hidden layer and any continuous sigmoidal nonlinearity. The paper discusses approximation properties of other possible types of nonlinearities that might be implemented by artificial neural networks.

Key words. Neural networks, Approximation, Completeness.

Cybenko, G. (1989) "Approximation by superpositions of a sigmoidal function", *Mathematics of Control, Signals, and Systems*, 2(4), 303–314. doi:10.1007/BF02551274

Network Construction

Network Design



$$\delta s_1 = w_{11}\tilde{s_1} + w_{21}\tilde{s_2} + b_1$$

$$\delta s_2 = w_{12}\tilde{s_1} + w_{22}\tilde{s_2} + b_2$$

$$\delta s_3 = w_{13}\tilde{s_1} + w_{23}\tilde{s_2} + b_3$$

w_{ij}, b_j : cm

$\tilde{s_1}$, $\tilde{s_2}$: normalized to be [-0.5, 0.5]

Cost Definition

Fit residuals in sensor plane

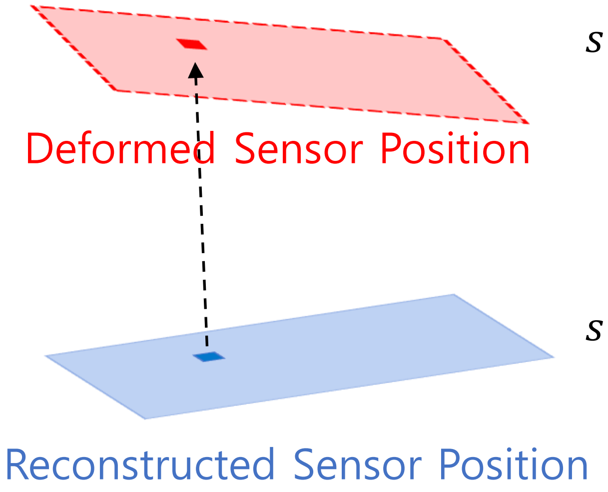
Vertex consistencies

$$C = \frac{\chi^2}{\nu} = \frac{1}{\nu}\left(\sum_{t=track}\left[\sum_{j=layer}\left(\sum_{i=1,2}\left(\frac{1}{\sigma_{ij}^2}\left(\bar{s}_{ij} - \left(s_{ij} + \delta s_{ij}\right)\right)^2\right)\right) + \frac{\left(V_t - \tilde{V}_{track}\right)^2}{\sigma_t^2}\right]_t + \frac{\left(V_{evt} - \tilde{V}_{track}\right)^2}{\sigma^2}\right) \rightarrow 1\ (best\ fit)$$

$$\sigma = \sigma_{MEAS} \oplus \frac{\sigma_{MSC}}{p}, MEAS = Align + Res(digitization, \ldots)$$

Deformation expressed by given network

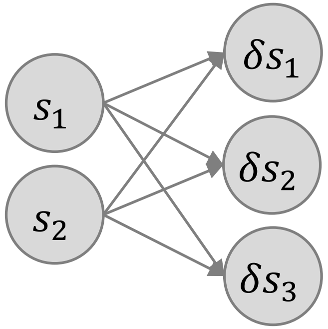
Alignment in the sensor coordinate



$$s' = s + f(s_1, s_2)$$
$$= (s_1, s_2, 0) + \boxed{(\delta s_1, \delta s_2, \delta s_3)}$$

Correction Function

$$s = (s_1, s_2, 0)$$

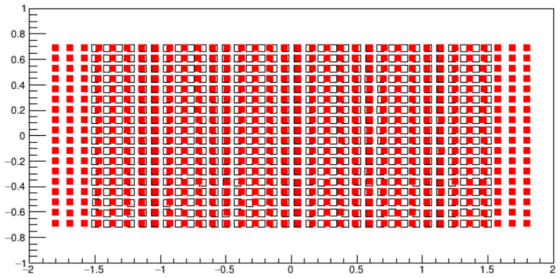


Sensor level alignment : 1 NN / sensor

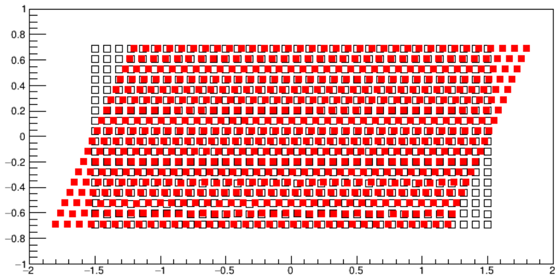
NN topology can express the translation and rotation **of the individual sensors**.

Also, the given NN topology can describe other deformations, Tensile (Scale up and down) and Shear.

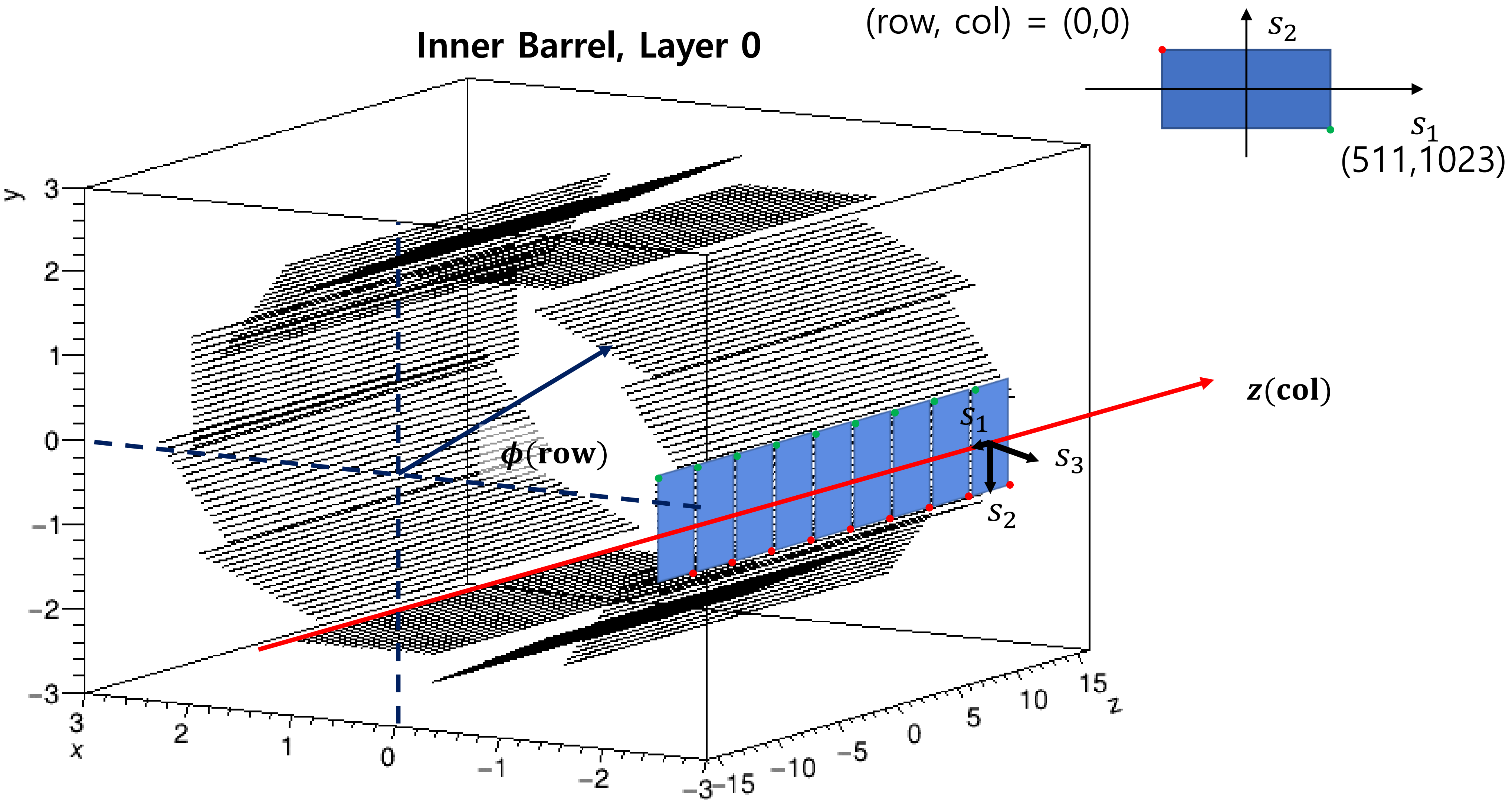
Tensile(Scale up)



Shear

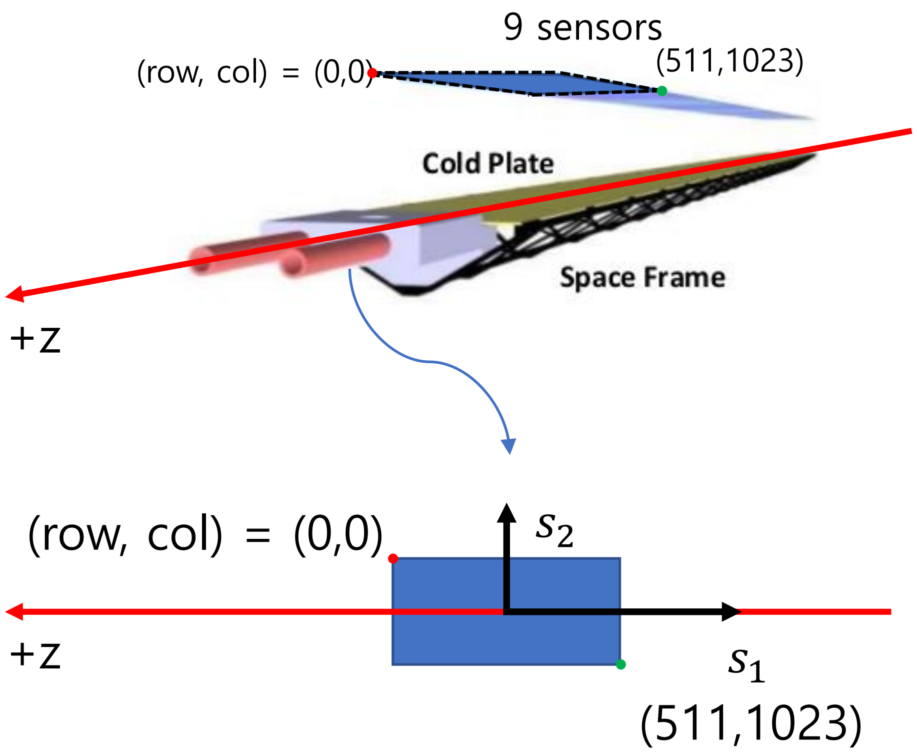


Sensor Coordinate for Alignment



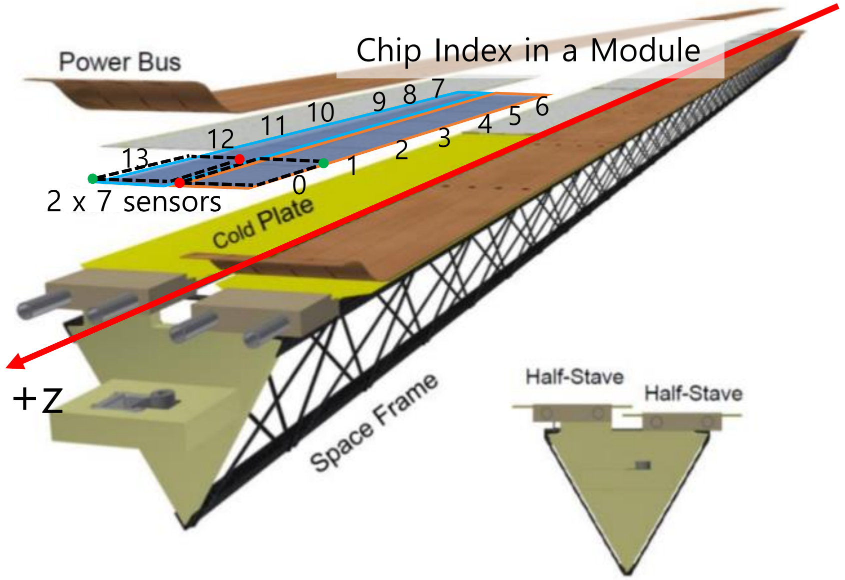
Sensor Coordinate for Alignment

Inner Barrel

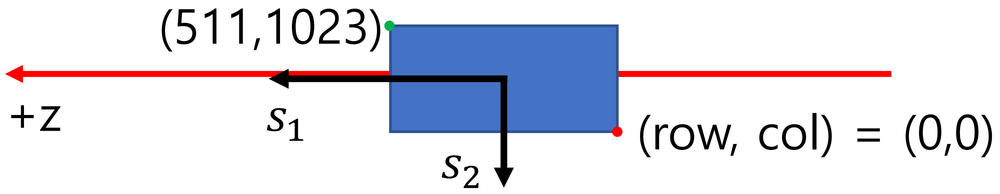


$+z\ //\ -s_1$

Outer Barrel

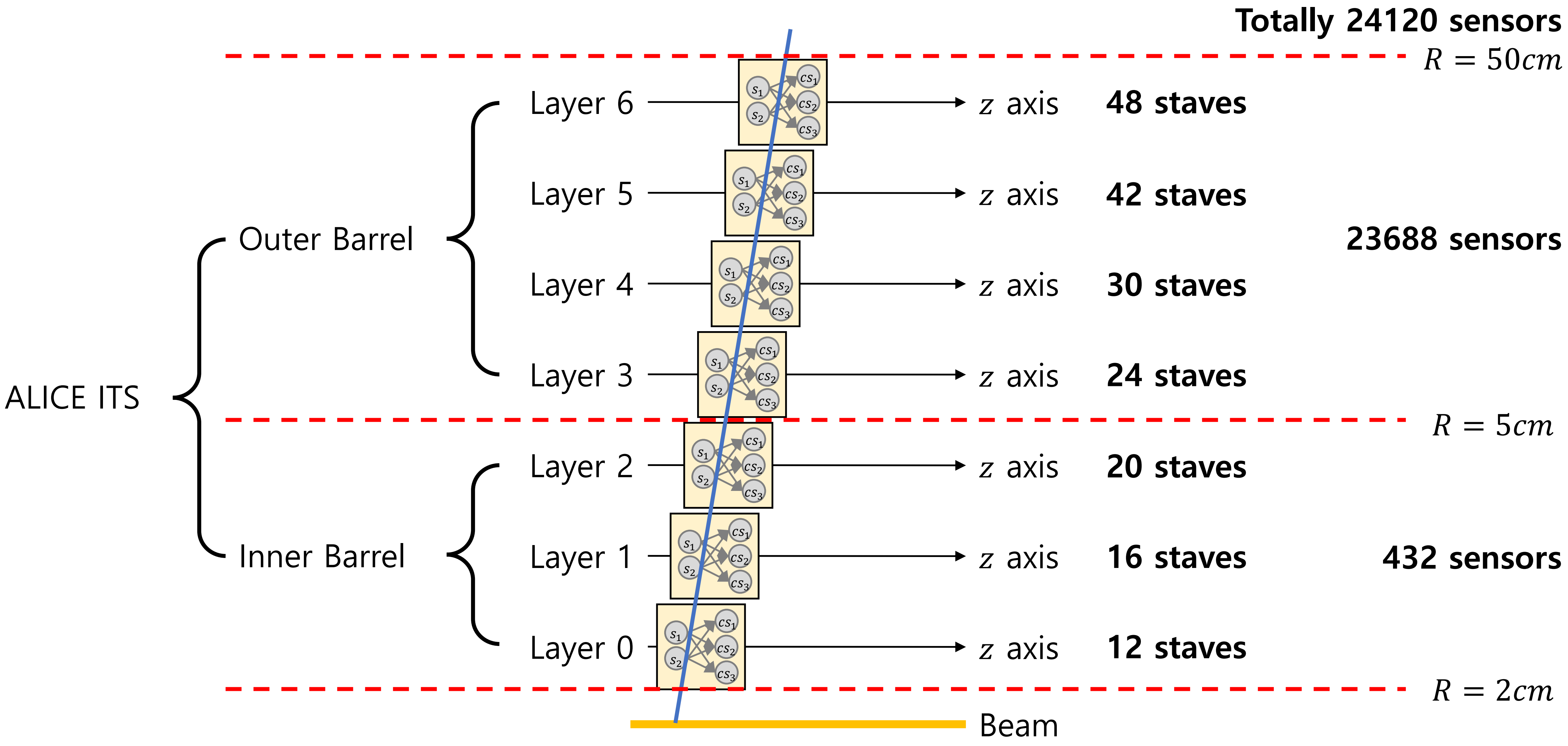


1. Chip Index in a Module < 7
   Same as Inner Barrel, $+z\ //\ -s_1$
2. Chip Index in a Module ≥ 7



$+z\ //\ +s_1$

Alignment Module for ITS detector



Training Strategy

Gradient Descent (Full Batch)

C : Cost (dimensionless)

η : Learning Rate including dimension $(= 4 \cdot 10^{-6} = 4 \cdot 10^{-4} \cdot (1000\mu\text{m})^2)$

Experimentally determined.

- Pixel size
- # of data
- Noise tolerance

$$\Delta w_i = -\eta \cdot \left(\frac{\partial C}{\partial w_i}\right)$$
$$w_i' = w_i - \Delta w_i$$

- We follow the steepest descent path to minimize the cost by taking the cost gradient.

Environments

Program Language : C, C++

Library : ROOT (TMultilayerPerceptron)

ROOT is an object-oriented program and library developed by CERN. It was originally designed for particle physics data analysis and contains several features specific to this field, but it is also used in other applications such as astronomy and data mining.

Implemented training methods : Gradient Descent

Data format : root (tree, ntuple)

In order to store large quantities of same-class objects, ROOT has designed the **TTree** and **TNtuple** classes specifically for that purpose. The **TTree** class is optimized to reduce disk space and enhance access speed. A **TNtuple** is a TTree that is limited to only **hold floating-point numbers**; a TTree on the other hand can hold all kind of data, such as objects or arrays in addition to all the simple types.

ITS Alignment : AI approach with Pilot Beam

Steps to alignment

Data Collection → Tracking → Alignment

Simulation

- Pythia8
- HIJING for the heavy Ion collision

Real Event

- pp collision
- AuAu collision

Preparation for alignment

"Focus on"

- Purity of data sample (multiplicity)
- Tolerance of the inefficiency
- Minimize dependence on the track finding **(ex. # of Clusters)**

Strategy construction

- Input data management
- AI optimizer selection
  - Gradient Descent (Batch) (Tolerance for mis-alignment)
  - Stochastic Gradient Descent (Fine alignment)
- Verification / Event Display

Phase I

Phase II

Raw Data

Clusters

- Pixel (row, col)
- Chip ID
- Time

Clusterer / Digitizer →

Cluster-based Data

Event ($\overline{N_{cl}} \leq \mathbf{100}$)

- Clusters

Tracker →

Track-based Data

Event

- Track ($\overline{N_{trk}} \sim 8$)
  - Clusters

for pilot beam (pp 900GeV)

Alignment Module Test for MC

- Event Generation : Pythia8pp(14TeV pp with collision vertex width 5cm)

  o2-sim –g pythia8pp –configKeyValues "Diamond.position[2]=0;Diamond.width[2]=5;..."

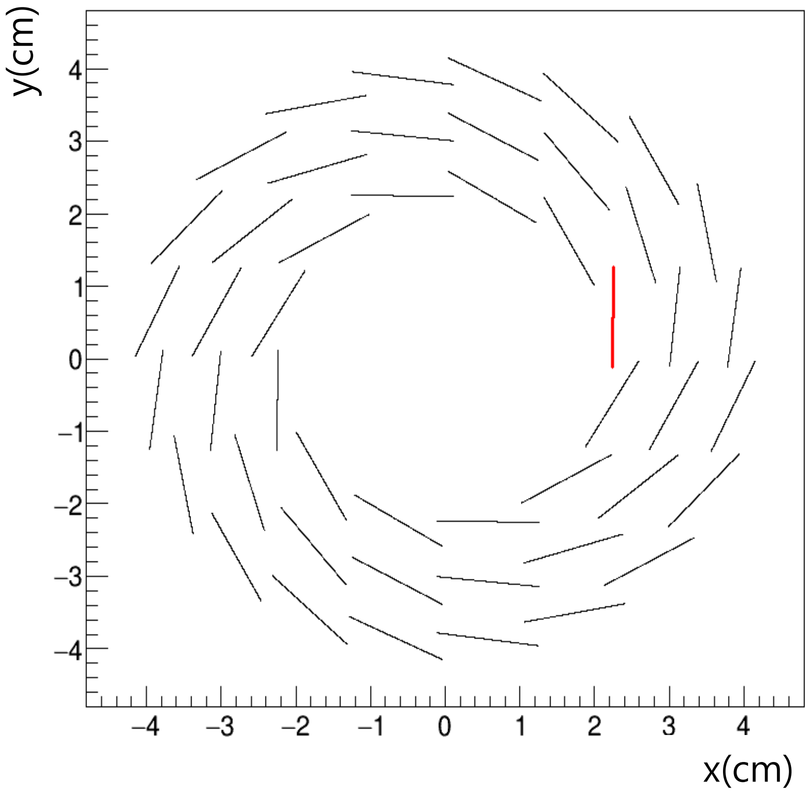
- Deformation
  - Layer0, Chip4 (ChipID=4) $s_1(=z)\ 500\mu m$

- Result

# of tracks / deformed sensor : ~1000 tracks

Alignment module reports 480μm for deformed sensor and zero for ideal sensors.

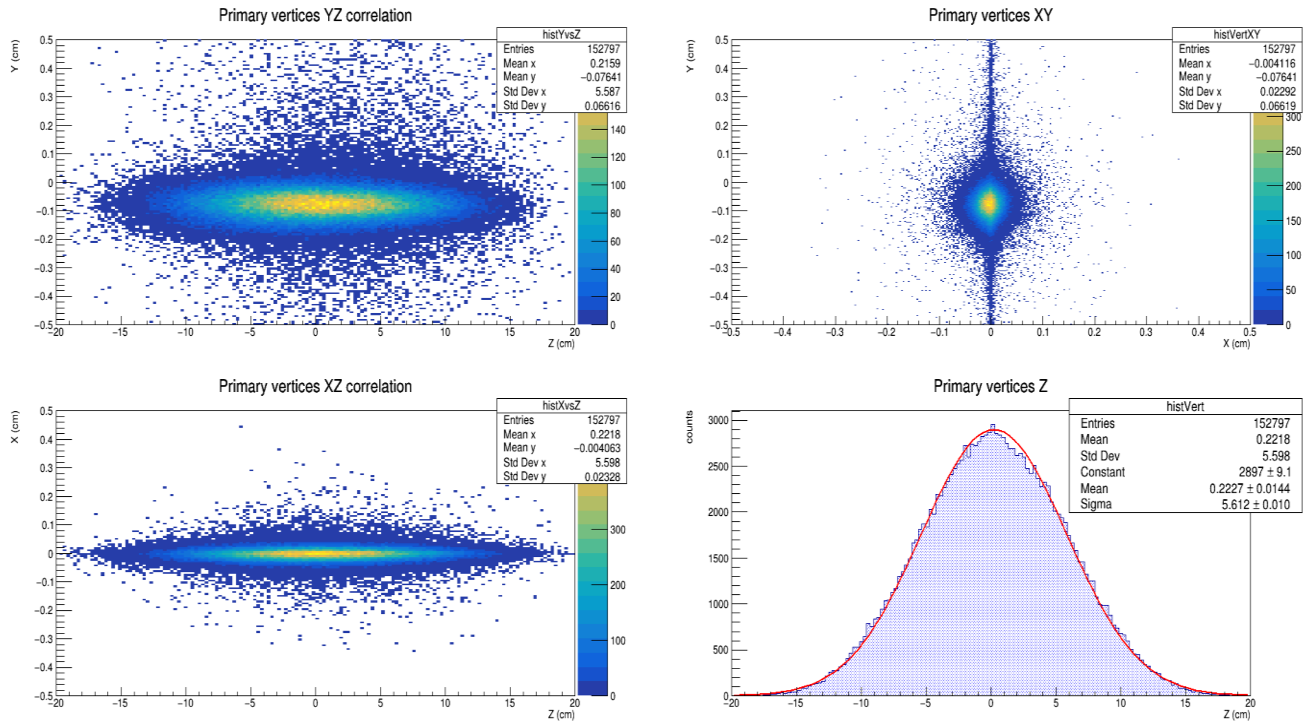
ITS Inner Barrel



Pilot Beam
summarized by I. Ravasenga & J. Liu, 01/11/2021

- Stable beams Oct. 27-31
- 12 fills with different filling schemes
- Interaction point shifted on Oct. 27 and corrected on Oct. 28
- **19 GOOD runs (~58M events)**

- Field on Run
  → ~30M events

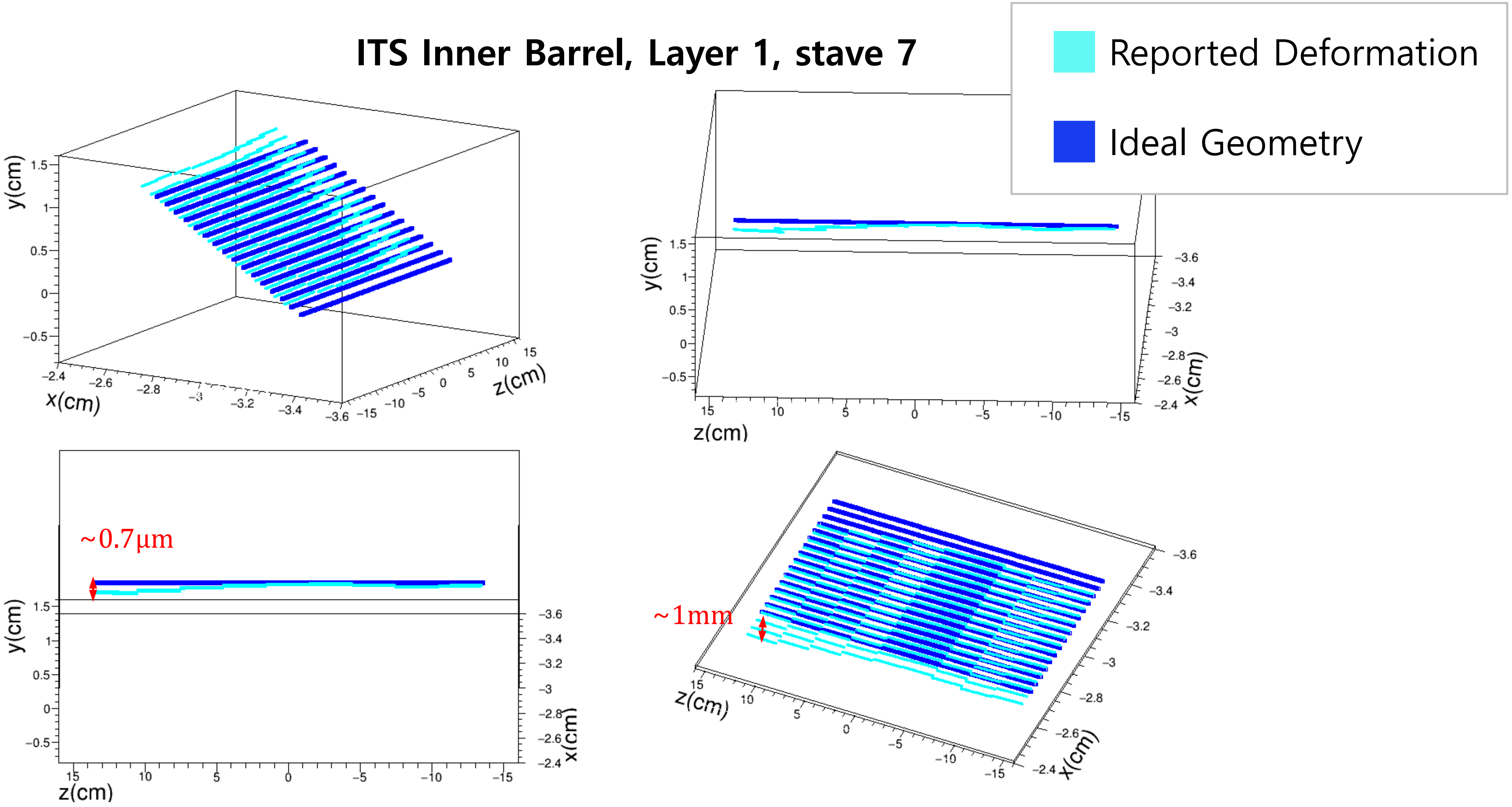


01/11/2021 I. Ravasenga & J. Liu

Data Management for training

- Total : 8M events, 64M tracks
  - **Events in our definition : Number of clusters in IB >10**
- Training Set : 5M events, 40M tracks
  - Adjustment of the network parameters
  - Key variable "Cost" assumes the exact circular trajectory in XY and linear trajectory in RZ plane. Hence, no multiple scattering and all tracks from collision location is assumed.
- Validation Set : 1.5M events, 12M tracks
  - Monitoring of the training process
- Test Set : 1.5M events, 12M tracks
  - Sample decoupled from training and validation set, left for independent and ultimate verification
  - Used for the plots in this report
  - XY plane : fit to a quadratic function (extraction of sagitta)
  - RZ plane : fit to a line

Deformation reported by AI (an example)



Communication with detector experts is desired.

Status Report : Phase I alignment

- We are using average-over multiple track samples for crude alignment considering fluctuations due to noise such as
  - wrong hits which associated to tracks
  - non-vertex tracks
  - and low momentum tracks.

- Residuals after alignment(integrated over $p_T \geq 0.3$ GeV), **Not Final**
  - Inner Barrel : $50\mu\mathrm{m}(\mathrm{ds}_1)$, $40\mu\mathrm{m}(\mathrm{ds}_2)$
  - Outer Barrel : $\mathbf{300\mu m(d}\boldsymbol{s}_1\mathbf{)}$, $80\mu\mathrm{m}(\mathrm{ds}_2)$

- Communication/Implementation of alignment constants obtained by AI
  → finalizing effort in progress

Residual distribution for ITS detector

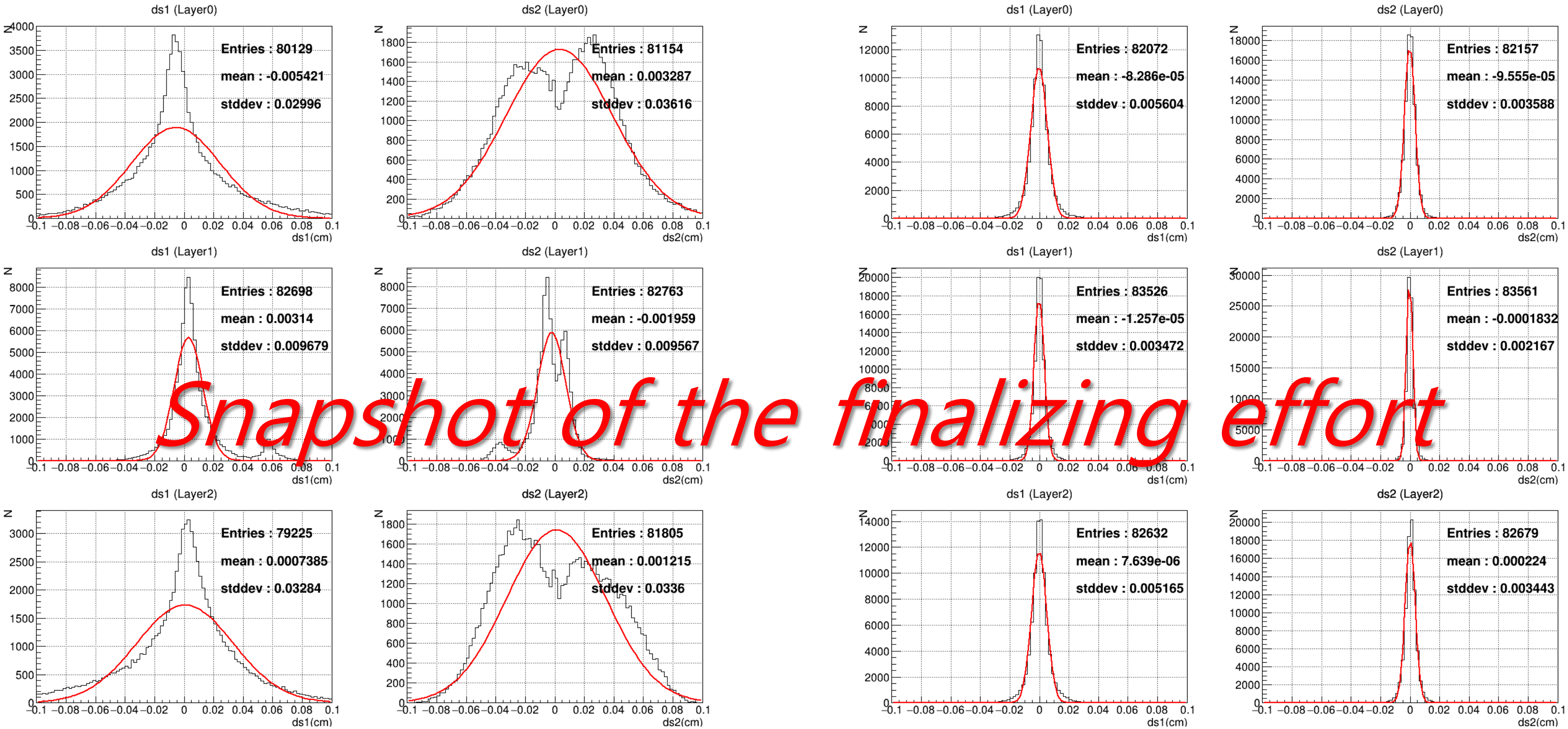
Before alignment | **After alignment**

Residual in s_1(=z or col) | Residual in s_2(=ϕ, row) | Residual in s_1(=z) | Residual in s_2(=ϕ)

L0

L1

L2

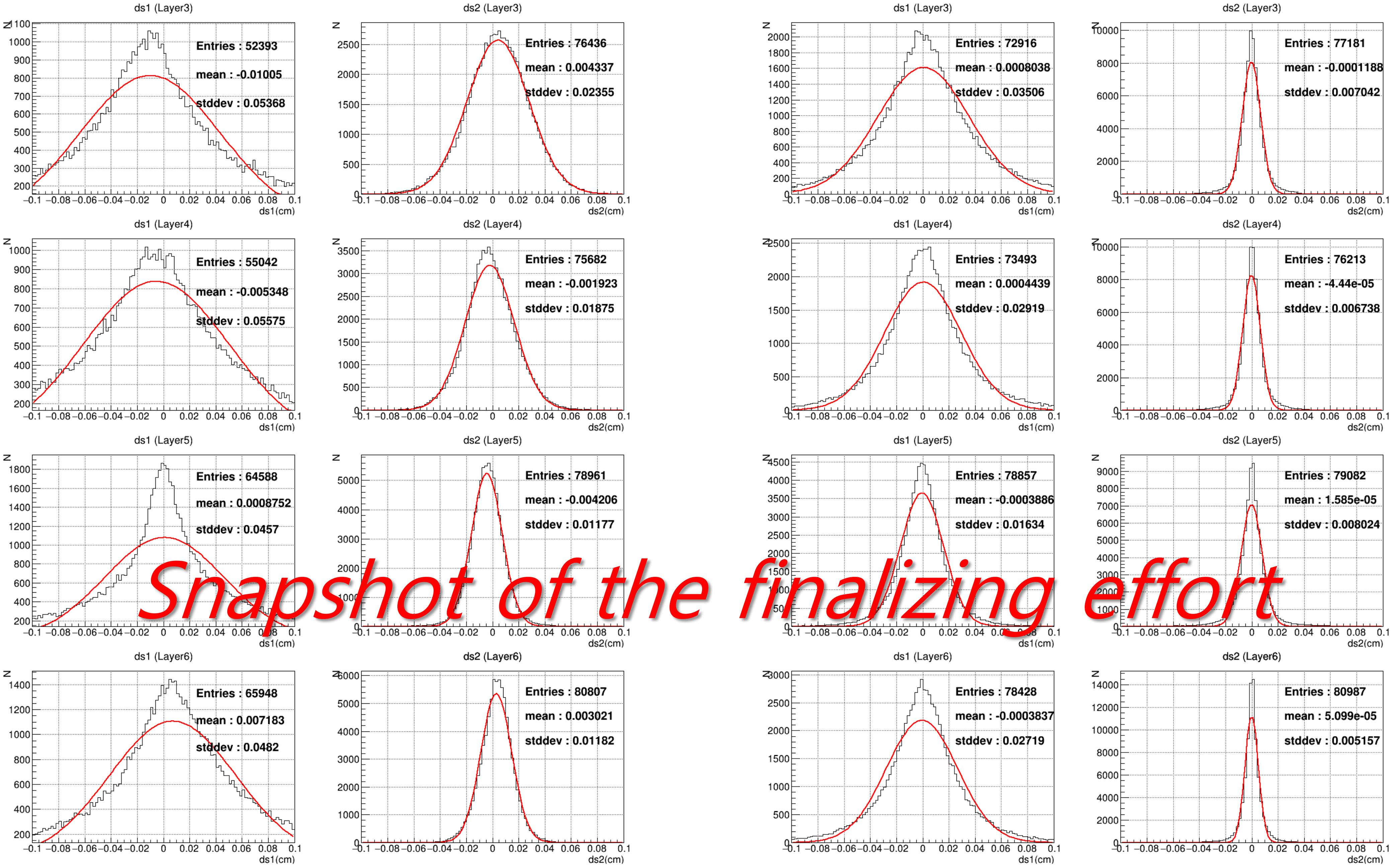


L3

L4

L5

L6



Snapshot of the finalizing effort

Plan : Phase II alignment

- Data
  - **pp collision in 2022**
  - Required # of events for training : at least 200 tracks per sensors in IB
- Training strategy
  - Parallelization (KIAF, Collaboration plan with Prof. Rho and Mr. Shin, CBNU)
  - Gradient Descent : averaged entire event(batch), event by event (to be implemented)
  - Fit method : Weighted Least Squares, TrackerCA(to be implemented)
- Target
  - Under **5μm** precision