Update of ILC Tracker Alignment Based on Frequency Scanned Interferometry

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Outline

➔ Brief reminder of Frequency Scanned Interferometry (FSI) method

➔ Review of improvements & measurements of FSI demonstration system

- Implementation of dual-laser technique
- Results of measurements – estimated precision
- Cross checks

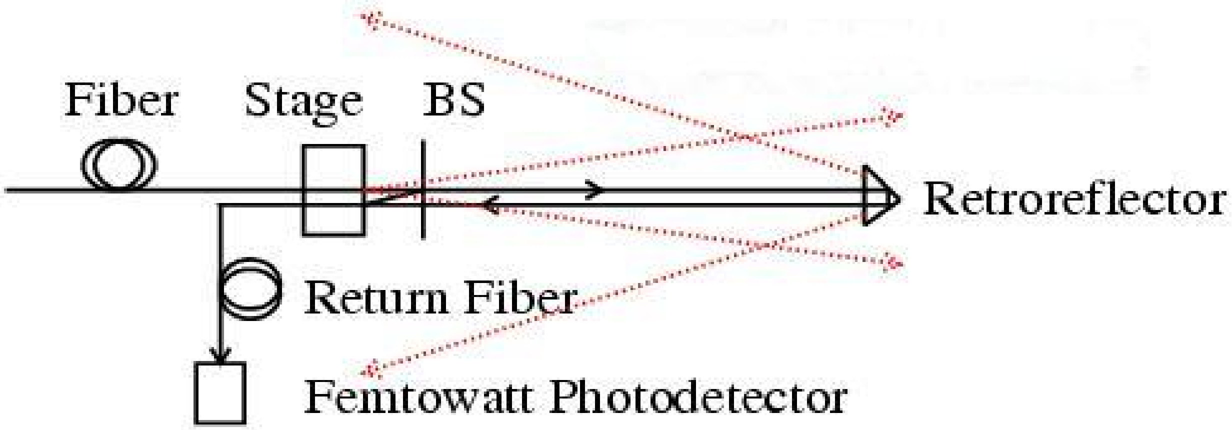
➔ Preliminary simulation results: Impact of silicon ladder distortion on charged track momentum reconstruction

➔ Ongoing work

- Miniaturization
- Multiple channels
- Detailed simulation based on FSI line-of-sight grid constraint

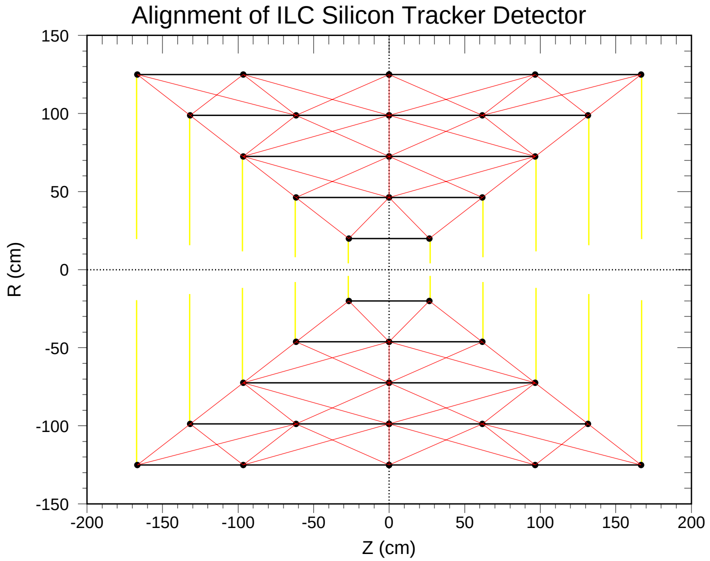
Overview of FSI Method

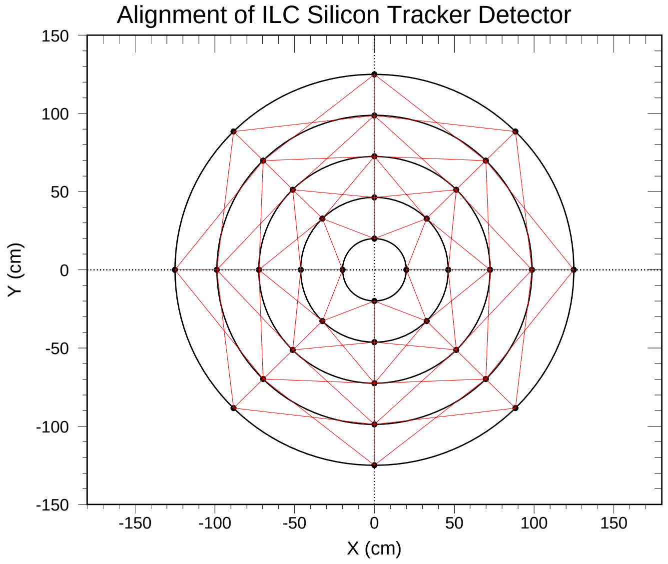
- Measure hundreds of absolute point-to-point distances of tracker elements in 3 dimensions by using an array of optical beams split from a central laser.
- Absolute distances are determined by scanning the laser frequency and counting interference fringes.
- Grid of reference points overdetermined → Infer tracker distortions

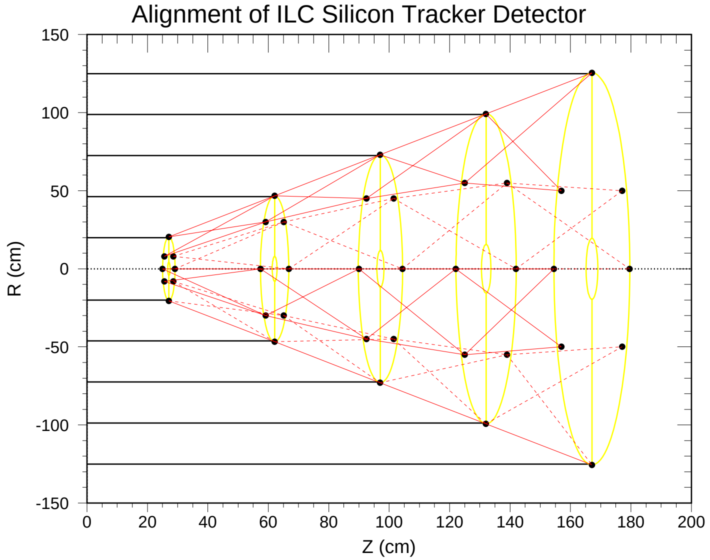


- Technique pioneered by Oxford U. group for ATLAS SCT detector

A Possible SiD Tracker Alignment


Alignment of ILC Silicon Tracker Detector


Alignment of ILC Silicon Tracker Detector


Alignment of ILC Silicon Tracker Detector

752 point-to-point distance measurements

(Goal: $\sigma_{\text{distance}} < 1\ \mu\text{m}$)

Principle of Distance Measurement

- The measured distance can be expressed by

$$R = \frac{c\Delta N}{2\overline{n}_g \Delta \nu} + \text{constant end corrections}$$

c - *speed of light,* ΔN – *No. of fringes,* $\Delta \nu$ - *scanned frequency*

n_g – *average refractive index of ambient atmosphere*

- Assuming the error of refractive index is small, the measured precision is given by:

$$(\sigma_R / R)^2 = (\sigma_{\Delta N} / \Delta N)^2 + (\sigma_{\Delta \nu} / \Delta \nu)^2$$

Example: $R = 1.0$ m, $\Delta\nu = 6.6$ THz, $\Delta N \sim 2R\Delta\nu/c = 44000$

To obtain $\sigma_R \simeq 1.0\ \mu m$, *Requirements:* $\sigma_{\Delta N} \sim 0.02$, $\sigma_{\Delta\nu} \sim 3$ MHz

Background

Previous reports:

➔ FSI I – Single-laser demonstration with air transport of beam

➔ FSI II – Single-laser measurements with fiber transport
→ Results published in *Applied Optics*, ***44,*** *3937-44 (2005)*
Results (~ 50 nm) well within desired precision,
but only for well controlled laboratory conditions

➔ FSI III – Dual-laser measurements with fiber transport
→ Results published in *Nucl. Inst. & Meth. A575, 395(2007)*
More realistic detector conditions (~ 200 nm)

Background

Controlled Conditions

Measured Distances: 10 cm – 60 cm

Distance Precision:

~ 50 nm by using multiple-distance measurement technique under well controlled laboratory conditions.

Vibration Measurement:

0.1-100 Hz, amplitude as low as few nanometers, can be extracted precisely using new vibration extraction technique.

Publication:

"High-precision absolute distance and vibration measurement with frequency scanned interferometry", [Physics/0409110]

H.J. Yang, J. Deibel, S. Nyberg, K. Riles, Applied Optics, 44, 3937-44, (2005)

“Real World”

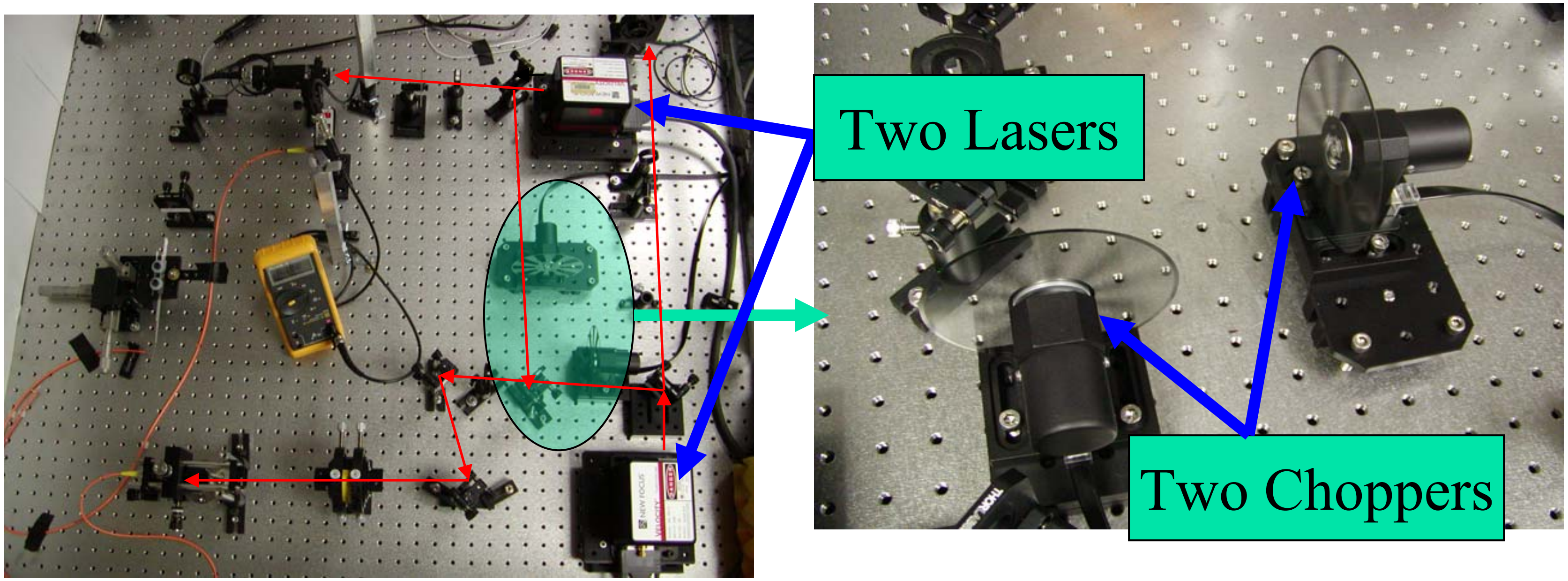
- Cannot count on precisely controlled conditions in ILC detector tracker.
- Thermal fluctuations and drifts likely
  →Refraction index and inferred distance affected
- Can measure temperature, pressure, humidity, etc. and apply empirical formulae, but preferable to measure effects directly and cancel these effects

- Use dual-laser technique (Invented by Oxford ATLAS group):
  → Two independent lasers alternately chopped
  → Frequency scanning over same range but with opposite slope

Dual-Laser FSI (III)

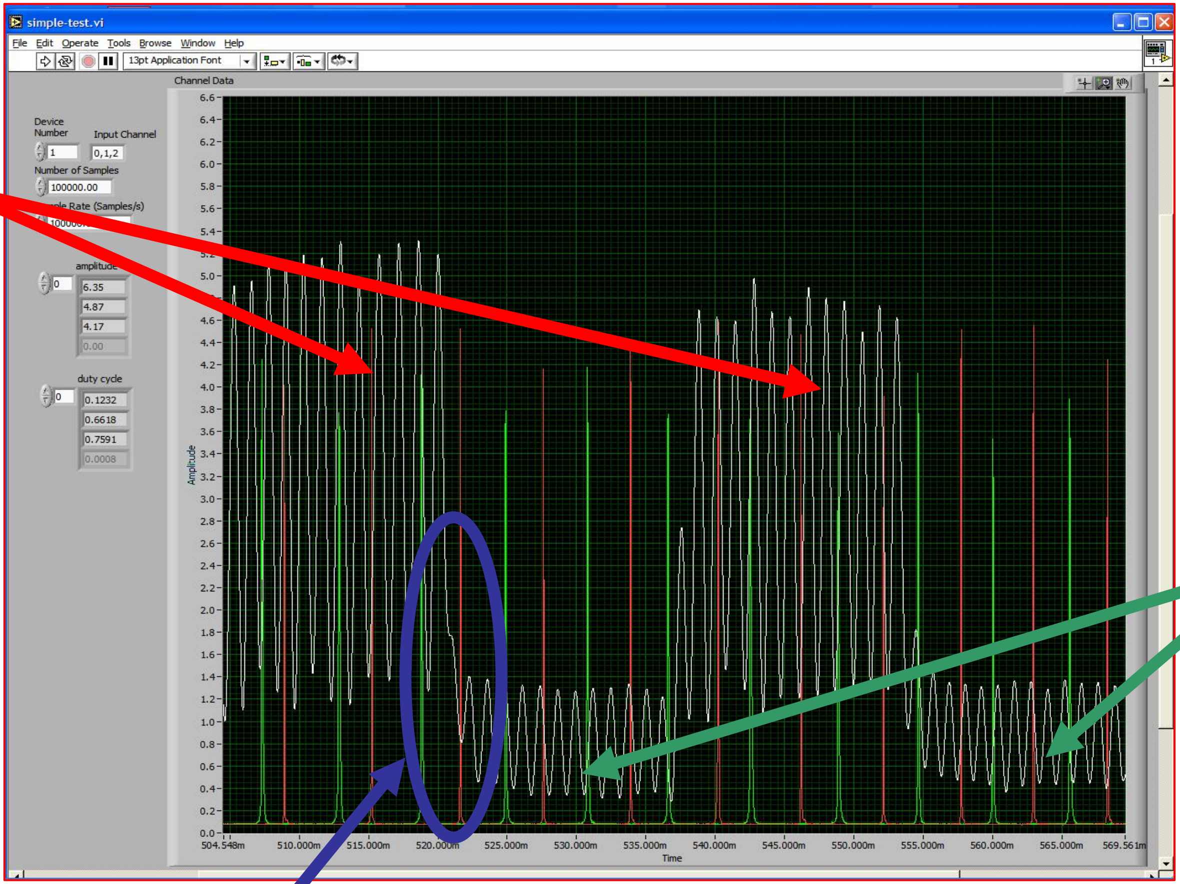
➔A dual-laser FSI (Oxford ATLAS method) has been implemented with optical choppers.

Laser #1: $D_1 = D_{true} + \Omega_1\varepsilon_1$
Laser #2: $D_2 = D_{true} + \Omega_2\varepsilon_2$
Drift errors: $\varepsilon_1 \approx \varepsilon_2 = \varepsilon$
$D_{true} = (D_2 - \rho D_1) / (1 - \rho)$,
Where $\rho = \Omega_2 / \Omega_1$



Fringes & F-P Peaks (dual-laser)

Laser-1



simple-test.vi

Device Number: 1

Input Channel: 0,1,2

Number of Samples: 100000.00

ple Rate (Samples/s): 100000

amplitude: 0 | 6.35, 4.87, 4.17, 0.00

duty cycle: 0 | 0.1232, 0.6618, 0.7591, 0.0008

Laser-2

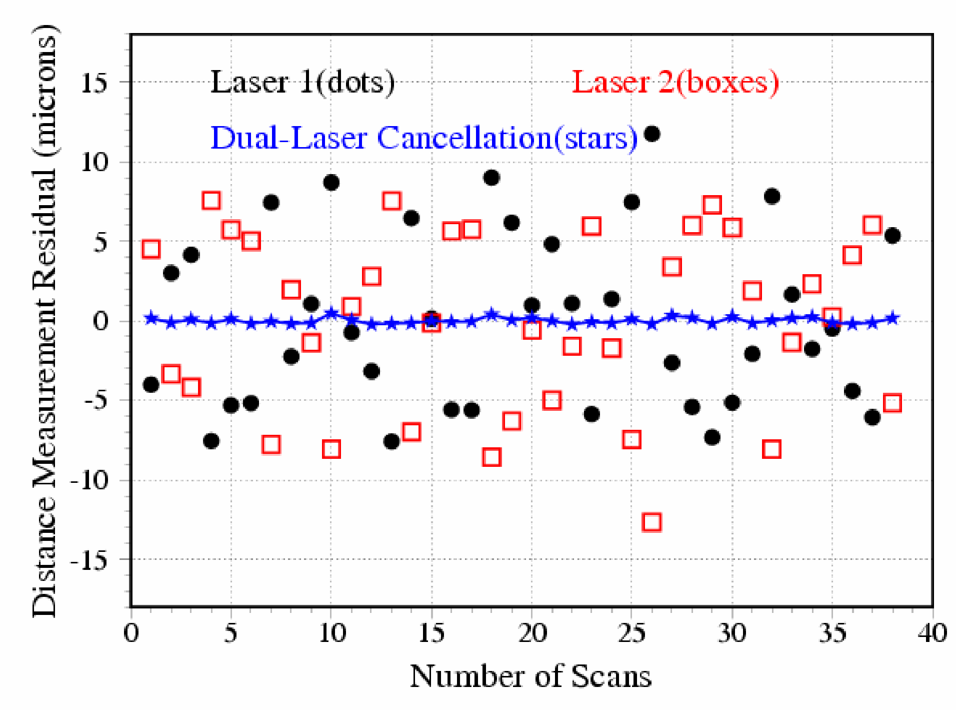
Chopper edge effects and low photodiode duty cycle per laser complicate measurement.

Distance Measurement Precision

- ➔ Distance Measurement Precision (~ 41.1384 cm)
  Laser #1 or #2 only : Precision (RMS) = 3 ~ 7 microns

- ➔ Combining multi-distance-measurement and dual-laser scanning techniques to reduce and cancel interference fringe uncertainties, vibration and drift errors
  Dual-laser precision (RMS) ~ 0.20 microns under realistic conditions

➔ A 2nd report:
"High-precision absolute distance measurement using dual-laser frequency scanned interferometry under realistic conditions", [Physics/0609187], Nucl. Inst. & Meth. A575, 395(2007)



FSI Cross Checks

- ➔ Used a Micrometer to change the position of retroreflector by large amount (127+/- 3 microns), and check FSI performance.

  The measurement precision is ~ 0.5 microns with unstable temperature.

- ➔ Used a Piezoelectric transducer (PZT, 20% tolerance) to change the position of the retroreflector by 2.0 +/- 0.4 microns.

  The measurement precision is ~ 0.1 microns with stable temperature.

- ➔ To verify correct tracking of large thermal drifts, we placed a heating pad on a 1’ x 2’ x 0.5’’ Al breadboard to increase temperature by 4 ~ 7 ^{o}C.

  The measured thermal expansions agree well with expectations, the measurement precision is ~ 0.2 microns.

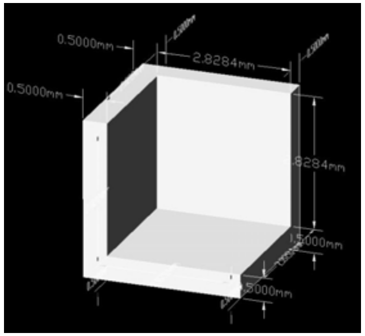
Miniaturization

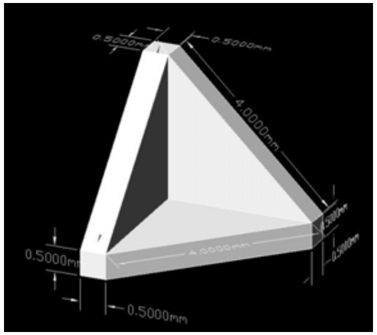
Previously used large commercial optics:

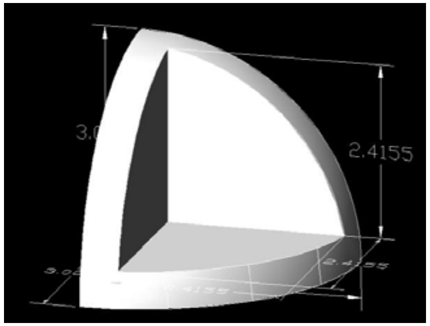
- Retroreflector (Diameter ~ 1’’)
- Beam splitter (Diameter ~ 1’’)

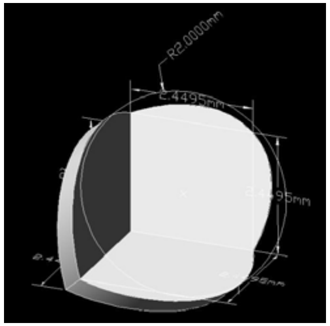
Need miniaturized, low-X_0 components for actual tracker

Obtained customized fabrication quotes for retroreflectors (3~4 mm) from rapid prototyping companies.









Miniaturization

➔ Cheap prototype alternatives: a bicycle reflector:

(all but one pixel masked off)

Measurement precision for a distance of 18 cm: ~ 0.4 µm

Promising indication, given simple design of the reflector pixels

(solid plastic corner cubes with no coating,

but low reflective efficiency)

Miniaturization

- ➔ Now using Edmund corner cube array, 9 X 9 hexagon corner cubes in 35 mm X 35 mm. Center-to-center spacing of two adjacent corner cubes is ~ 4 mm.
- ➔ The reflective efficiency of single corner cube is comparable to large commercial corner cube and hollow retroreflector (D = 1 inch).
- ➔ High reflective efficiency is vital to make qualified fringes and to make more channels.

- ➔ Under controlled conditions
  L = 417198.37 +/- 0.07 microns
- ➔ The corner cube array has high reflective efficiency and qualified fringes. It’s very promising.

Multiple channels

We are implementing multi-channels fed by an optical fiber splitter

- ➔ Double-check systematics
- ➔ Implement multiple distance measurements and test over-constrained algorithm for a prototype set of reference points
- ➔ Preparation for test of silicon ladder prototype alignment

Results not ready yet ! ☹

Simulation

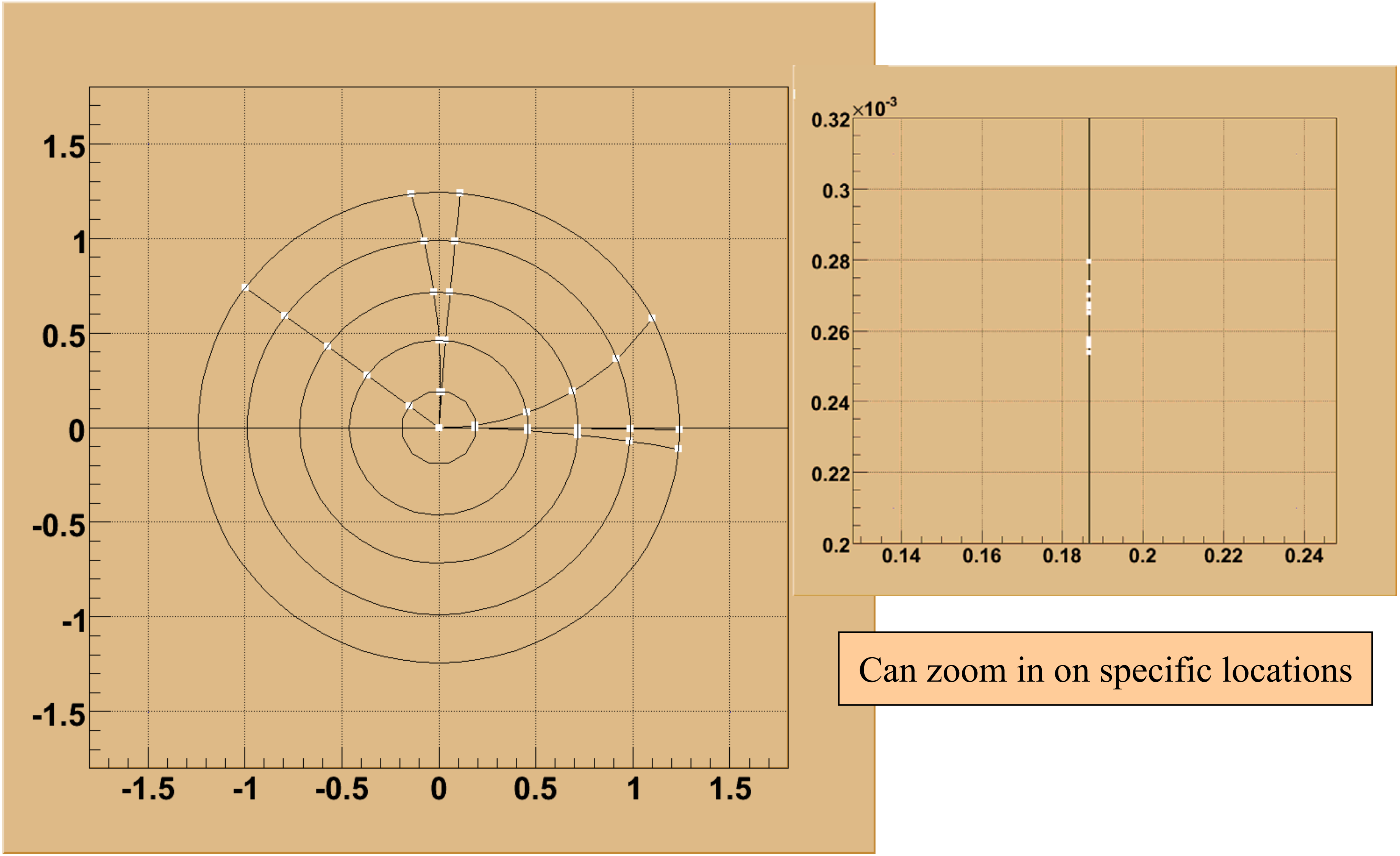
➔ To evaluate the impact of distortion of silicon ladder on charged track momentum reconstruction/measurement.

➔ Integrated track generation, reconstruction and FSI fitting

➔ Inputs: charged track with given momentum, 5 silicon layers based on nominal SiD design, magnetic field B = 5 Tesla.
-- Assume spatial resolution is 7 microns for hits.
-- Distortions: rotations, translations, thermal expansion or contractions of silicon ladders.
-- Applying FSI line-of-sight grid constraint (code not fully debugged – premature to show results, but consistent with earlier simulations.)

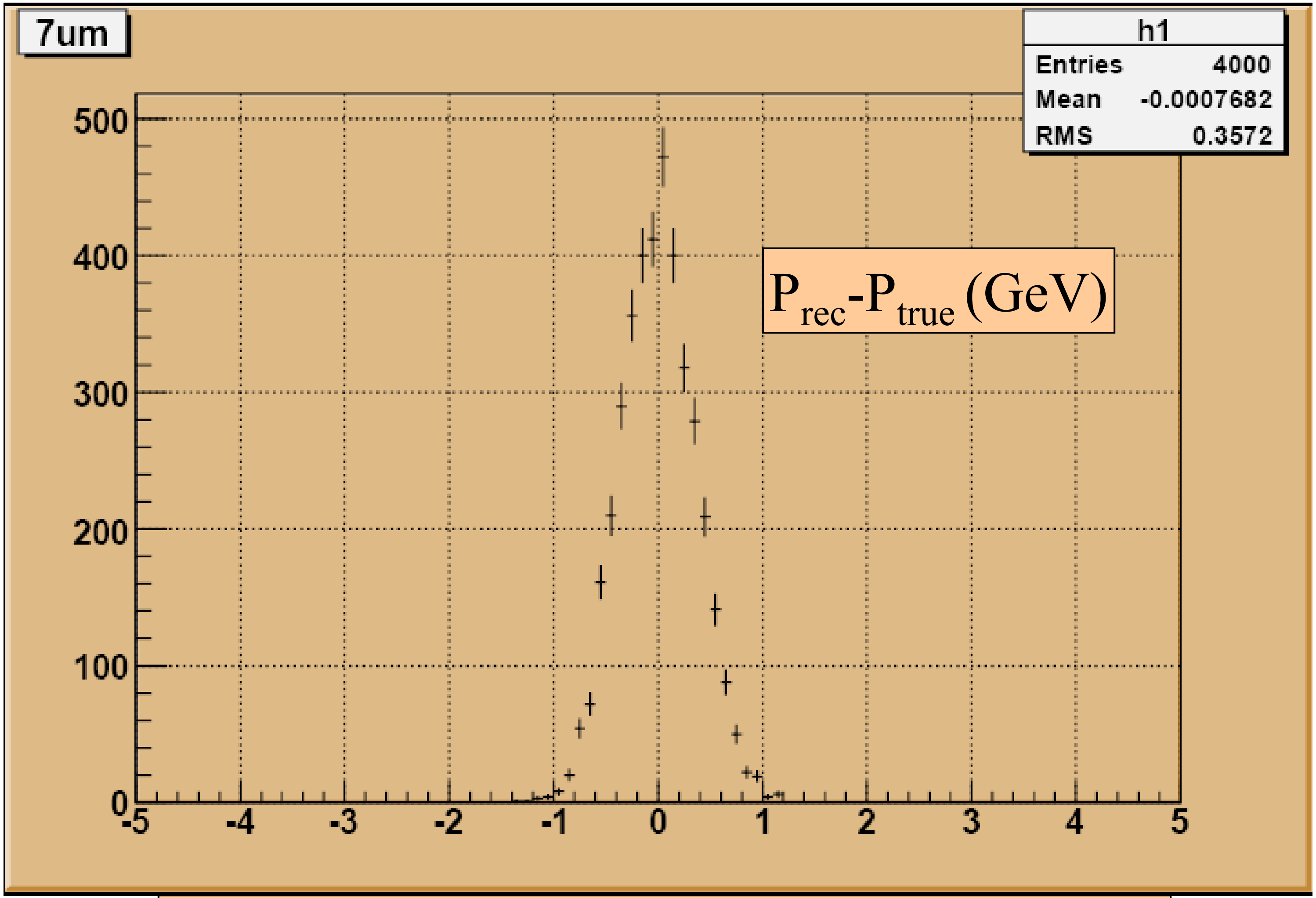
➔ Outputs: reconstructed momentum of charged track, event displays for SiD Tracker

Example Tracks (side view)



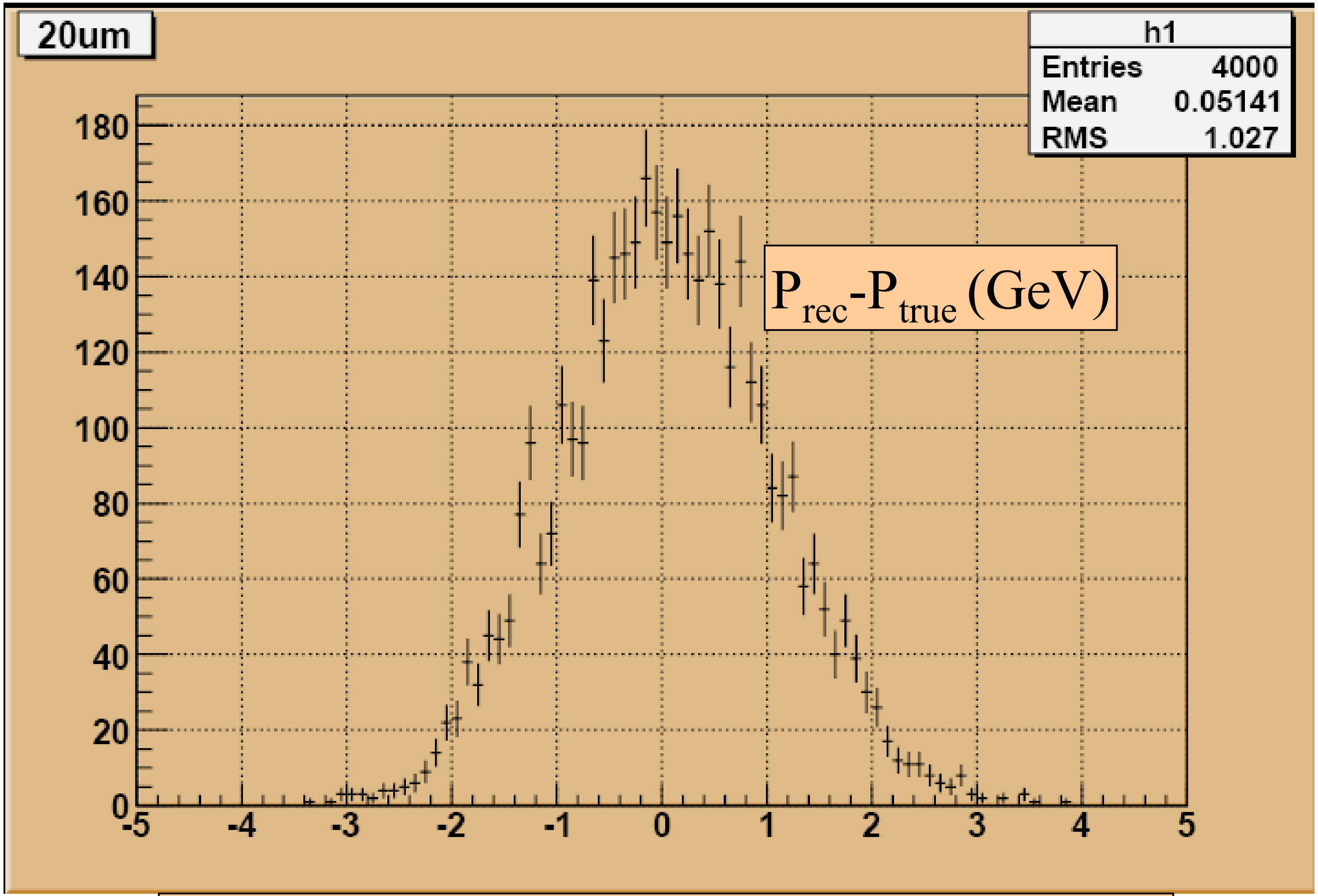
Can zoom in on specific locations

Normal (σ = 7 microns for hits)



P_{true} = 100 GeV, hit smearing ~ 7 microns

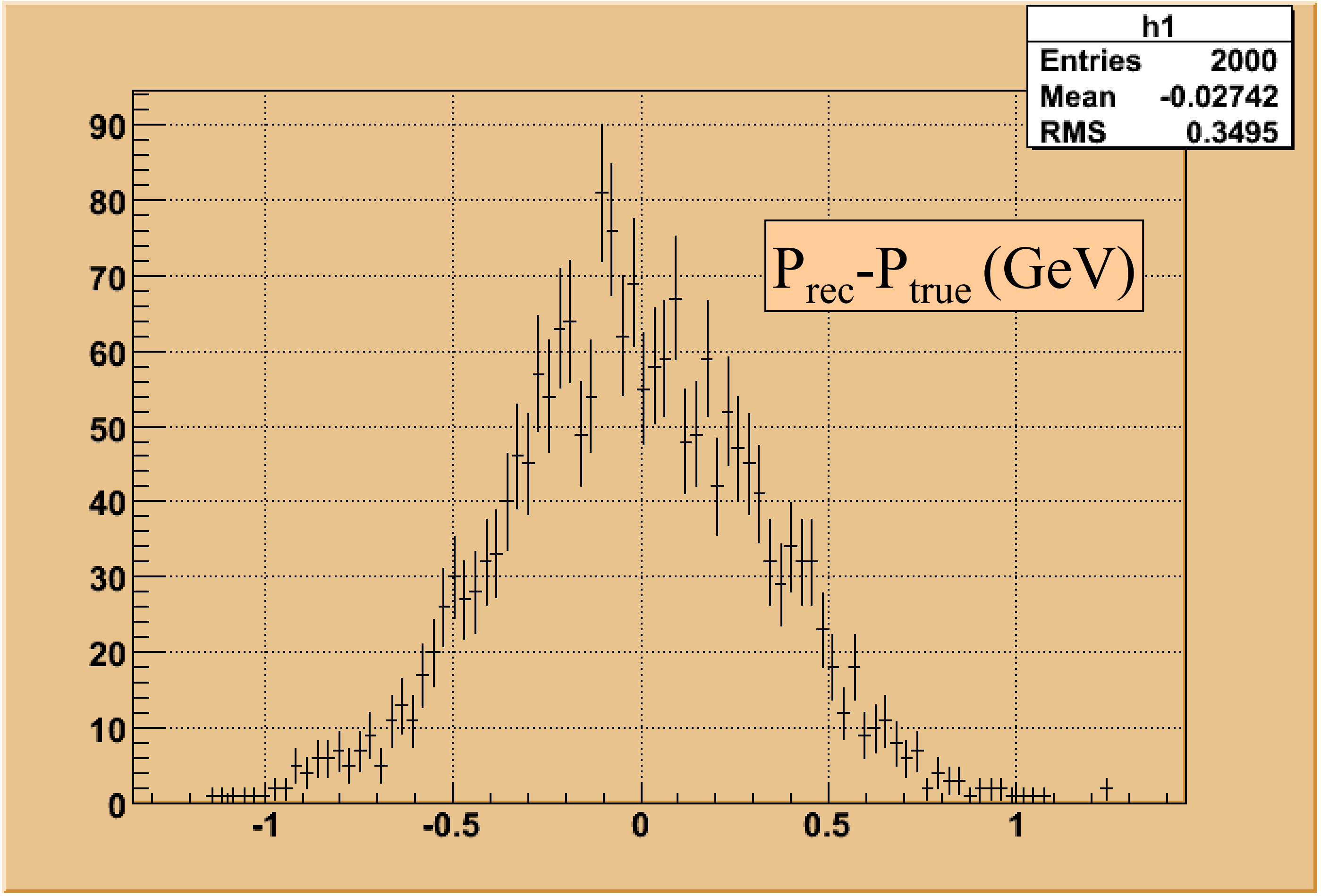
Normal (σ = 20 microns for hits)



P_{rec}-P_{true} (GeV)

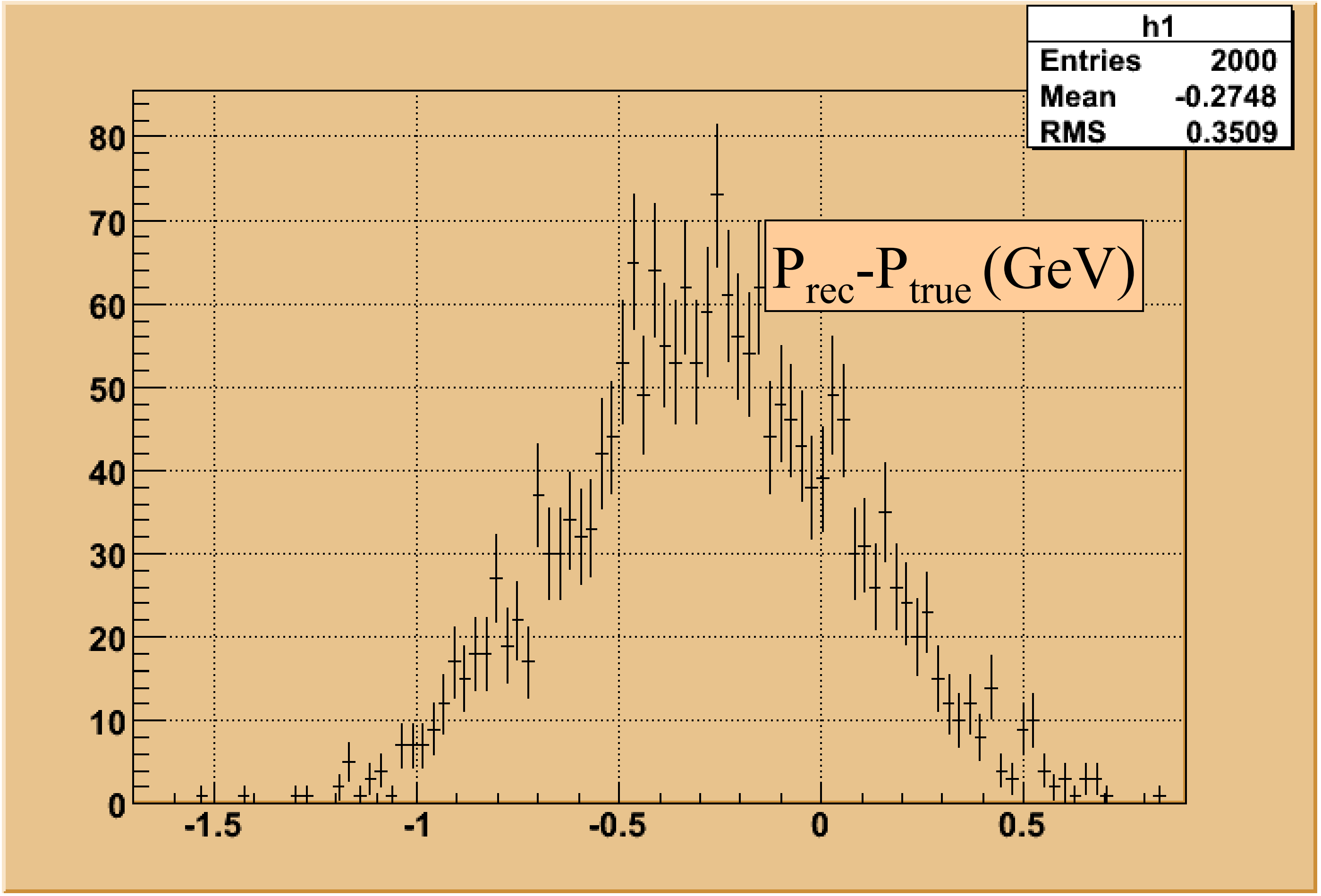
P_{true} = 100 GeV, hit smearing ~ 20 microns

Translation of Silicon Ladder (Middle)



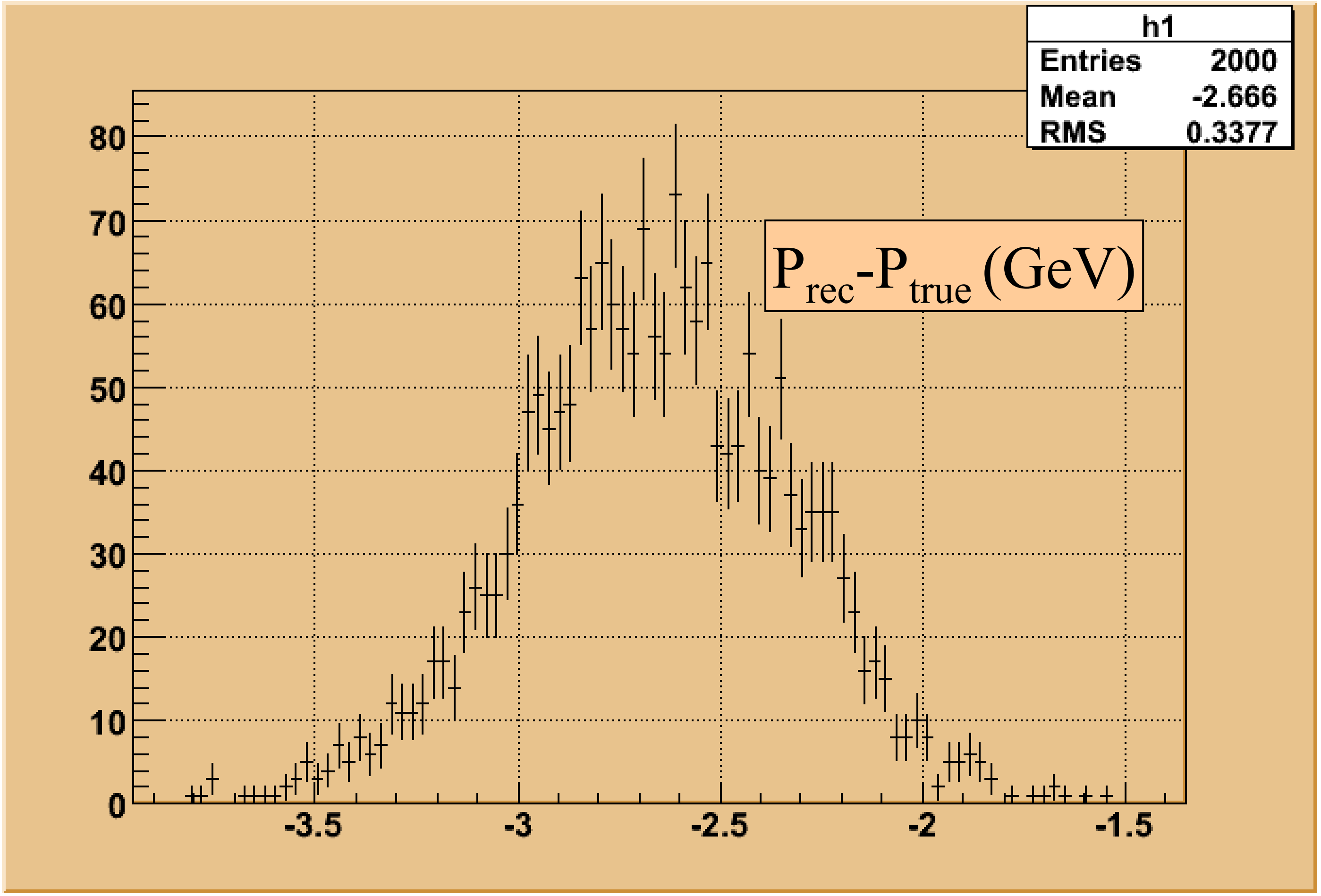
P_{true} = 100 GeV, shift ~ 1 micron

Translation of Silicon Ladder (Middle)



P_{true} = 100 GeV, shift ~ 10 microns

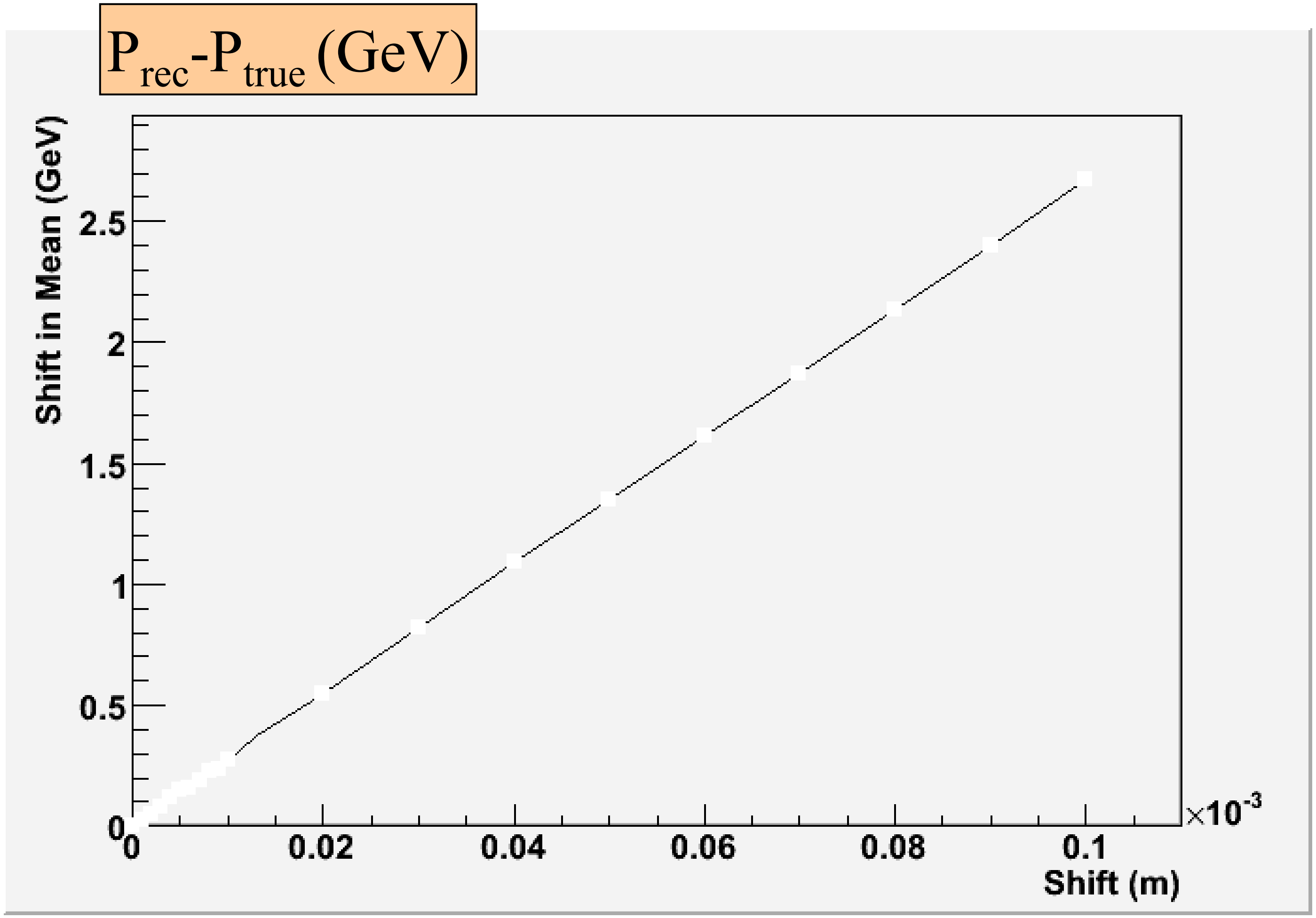
Translation of Silicon Ladder (Middle)



P_{true} = 100 GeV, shift ~ 100 microns

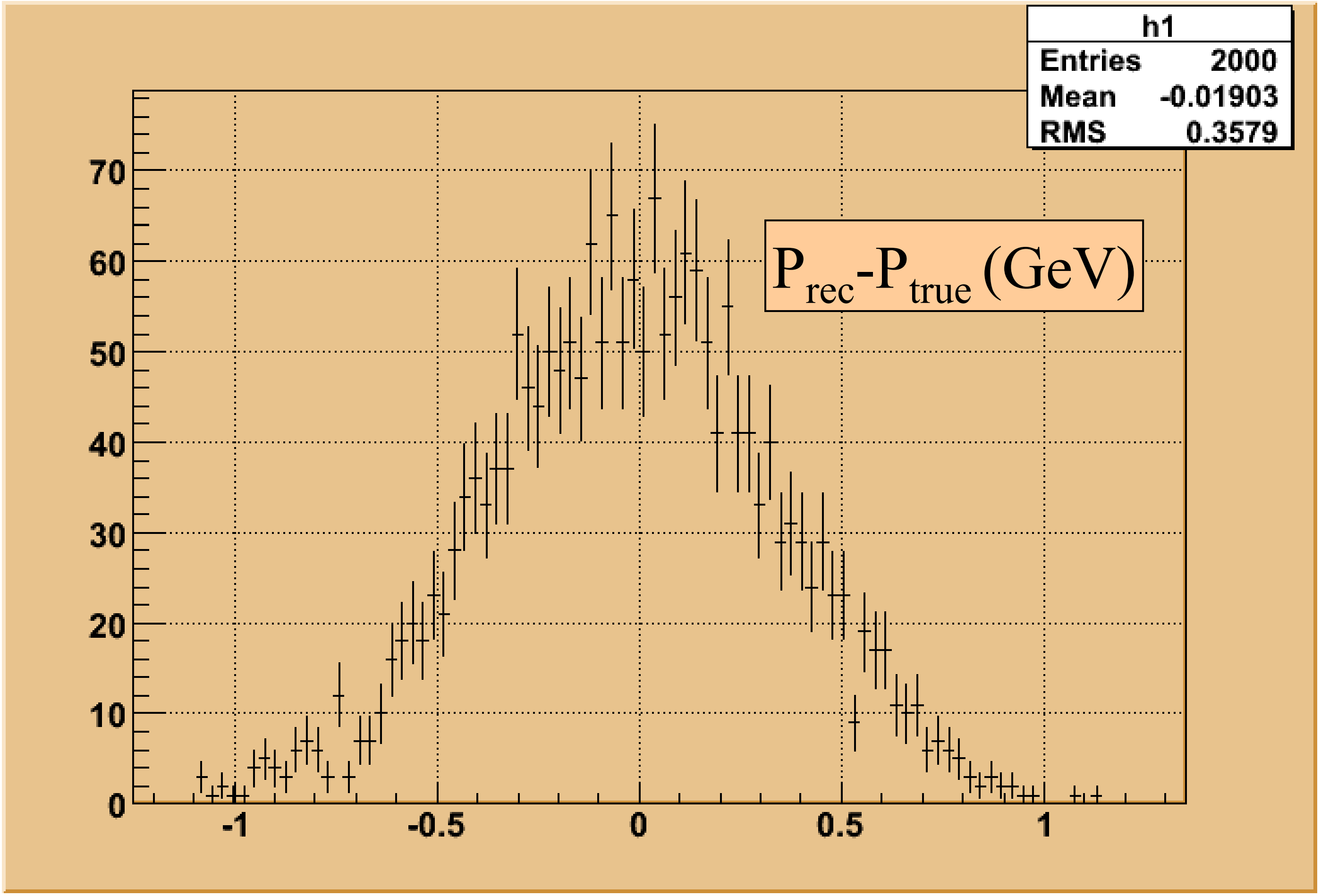
Translation of Silicon Ladder (Middle)

P_{rec}-P_{true} (GeV)



P_{true} = 100 GeV, shift ~ 10 -100 microns

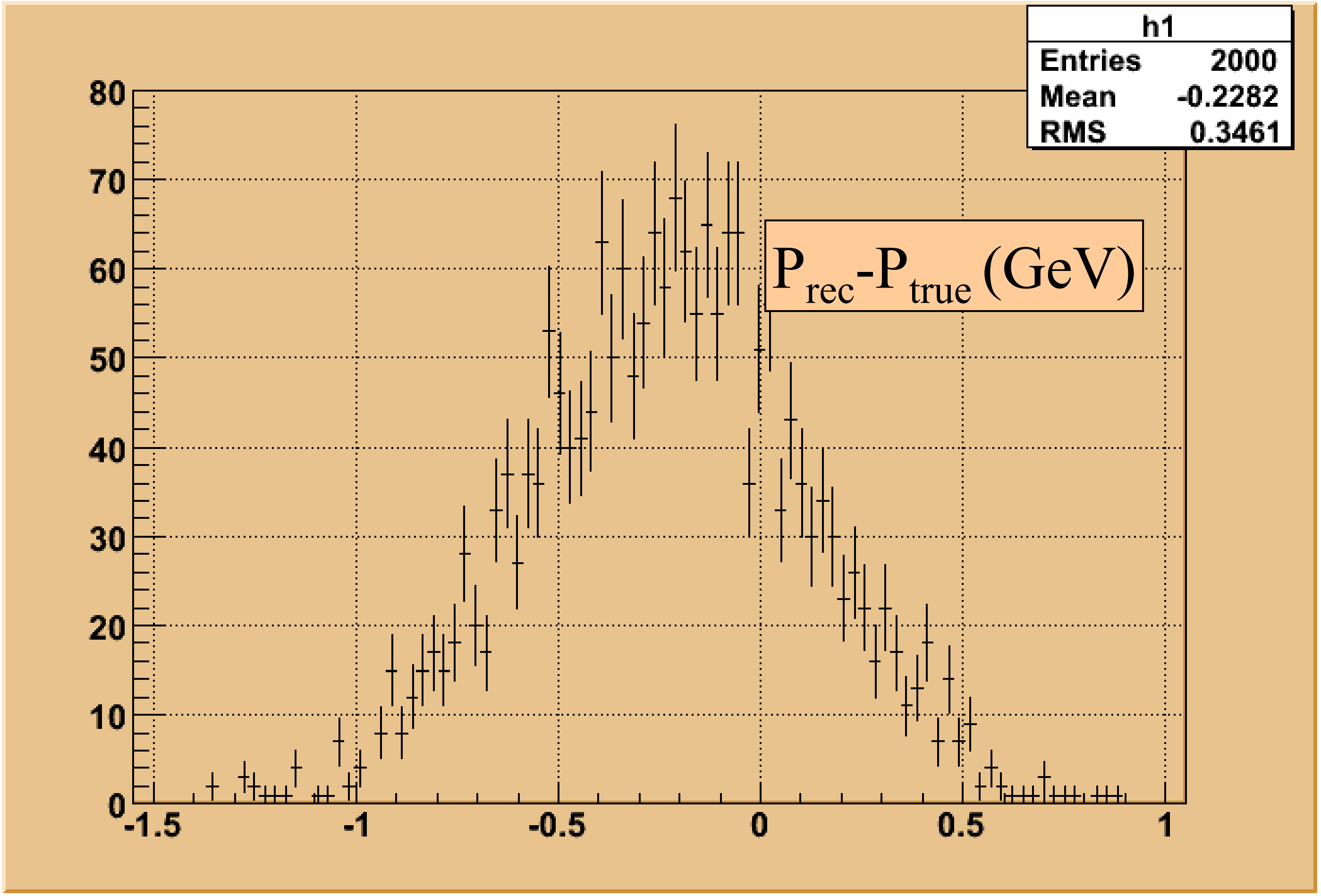
Rotation of Silicon Ladder (Middle)



P_{rec}-P_{true} (GeV)

P_{true} = 100 GeV, Rotate ~ $1*10^{-6}$ rad

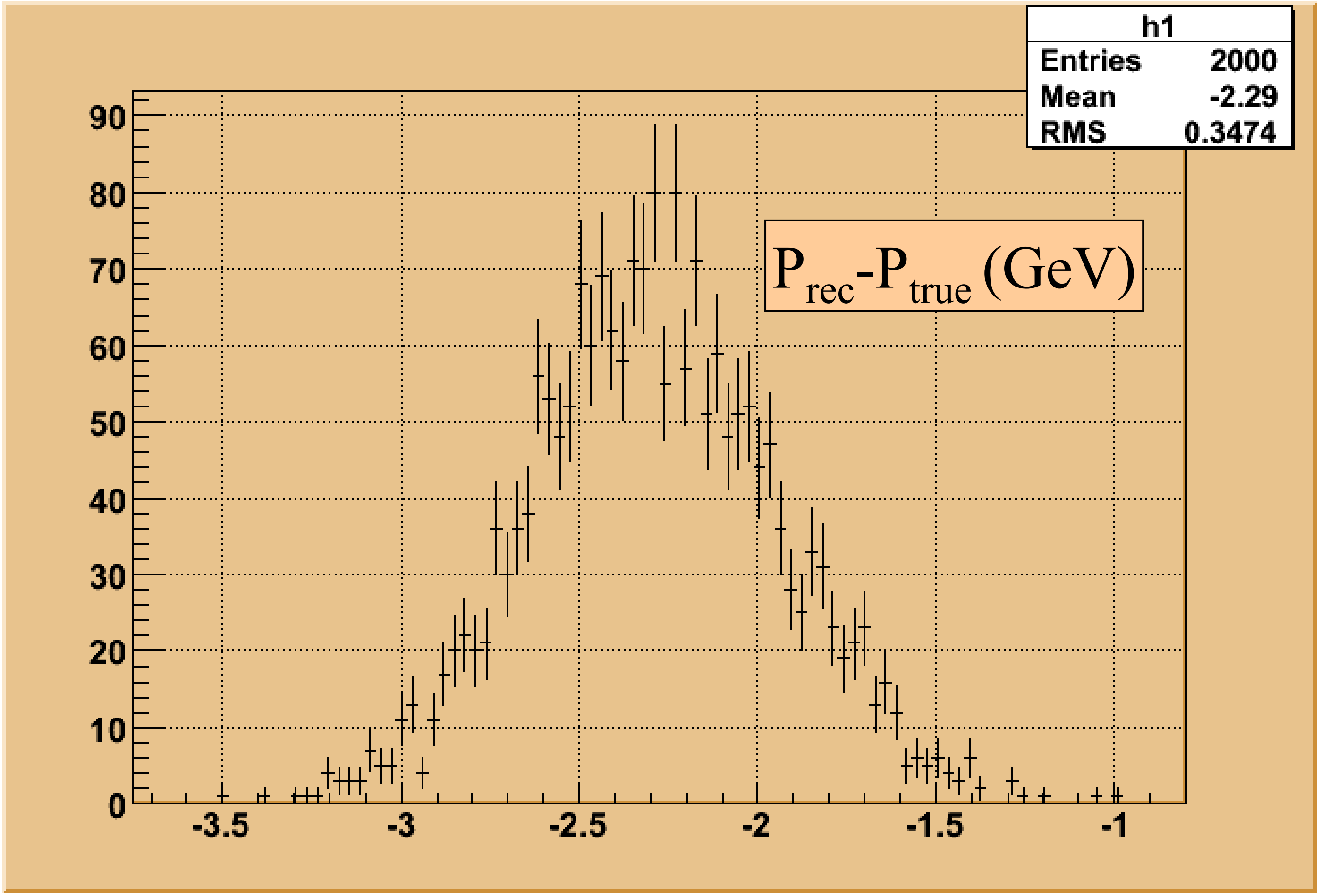
Rotation of Silicon Ladder (Middle)



P_{rec}-P_{true} (GeV)

P_{true} = 100 GeV, Rotate ~ $1*10^{-5}$ rad

Rotation of Silicon Ladder (Middle)



P_{true} = 100 GeV, Rotate ~ $1*10^{-4}$ rad

Summary

➔ **Several FSI demonstration systems with increasing realism have been implemented**

➔ **Results on achievable measurement precision are quite promising (~ 0.2 microns with dual-laser scanning)**

➔ **Published Results**

Hai-Jun Yang, Sven Nyberg, Keith Riles, " *High-precision Absolute Distance Measurement using Dual-Laser Frequency Scanned Interferometry Under Realistic Conditions* ", Nucl. Instrum. & Meth. A575 (2007) 395-401

Hai-Jun Yang, Jason Deibel, Sven Nyberg, Keith Riles, " *High-precision absolute distance and vibration measurement using frequency scanned interferometry*", Applied Optics, Vol.44 (2005) 3937-3944

Summary

- ➔ **Ongoing work:**
  - **Miniaturization:**

    baseline retroreflector is plexiglass, but want to investigate other materials (constrained by available prototyping funds)
  - **Multiple channels:**

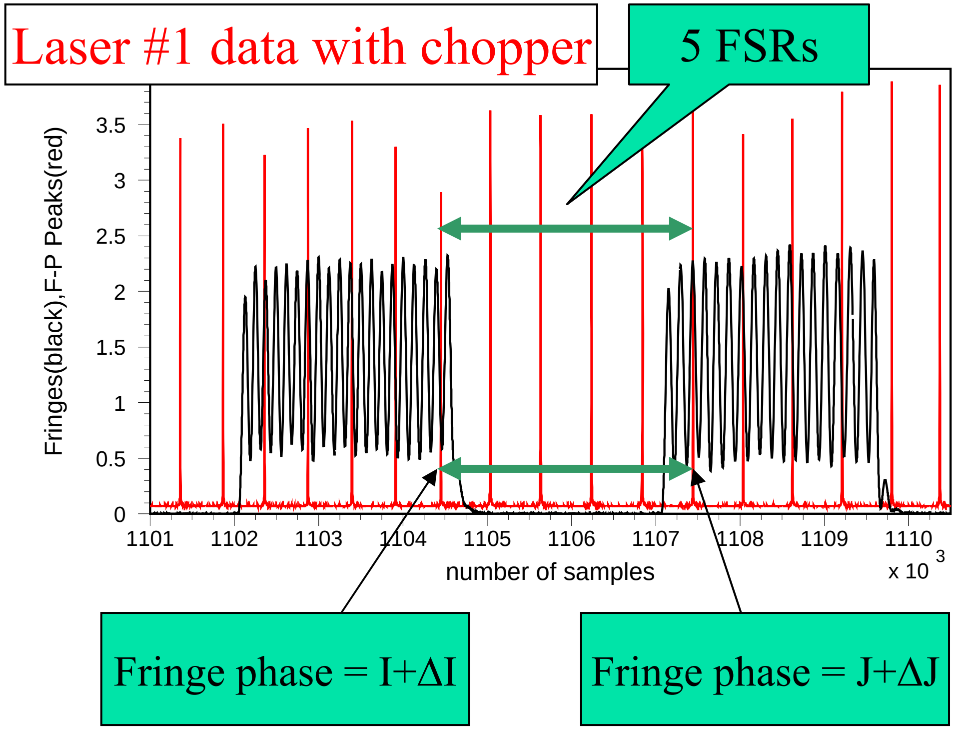
    dual-channel system nearly ready
  - **Simulations:**

    integrated framework nearly complete,

    early results seem promising

Backup Slides

Fringe Interpolating Technique

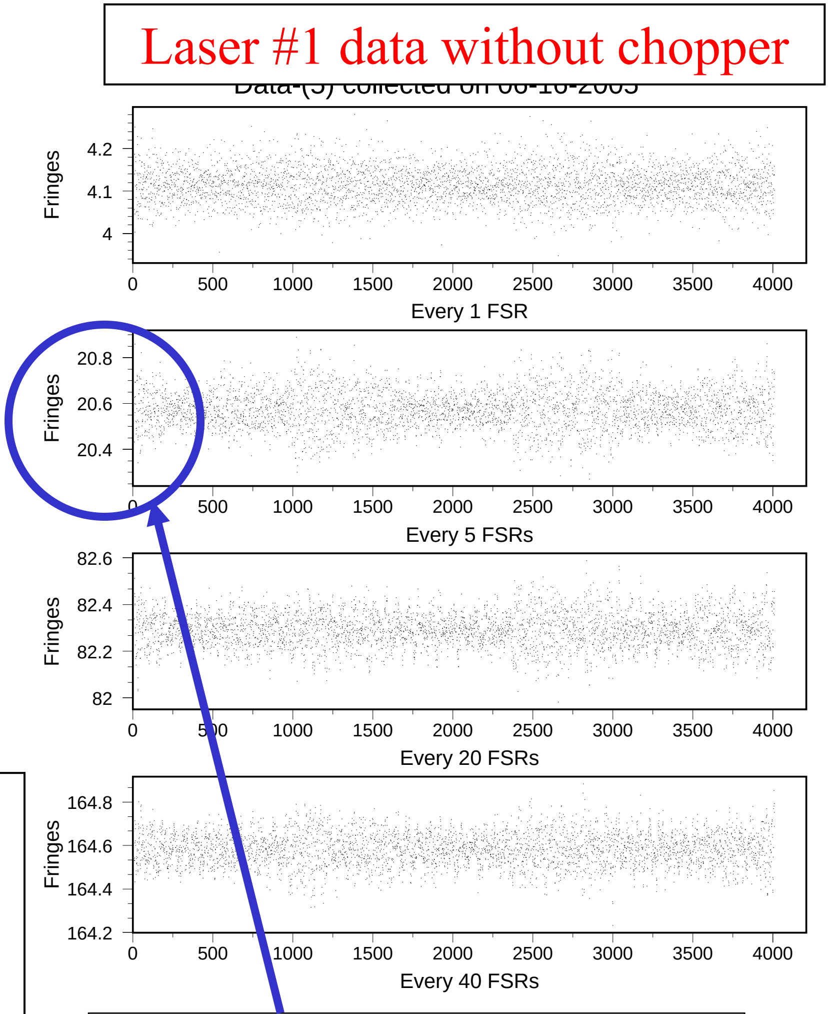


Laser #1 data with chopper

5 FSRs

Fringe phase = I+ΔI

Fringe phase = J+ΔJ



Laser #1 data without chopper

Expected fringes for 5 FSRs

Fringe correction (N_corr) must satisfy:

minimize | N_corr+(J+ΔJ)-(I+ΔI)-N_average |

Where, N_corr is integer number, N_average is expected average fringe numbers (real) for the given number of FSRs.

Distance Measurement Precision

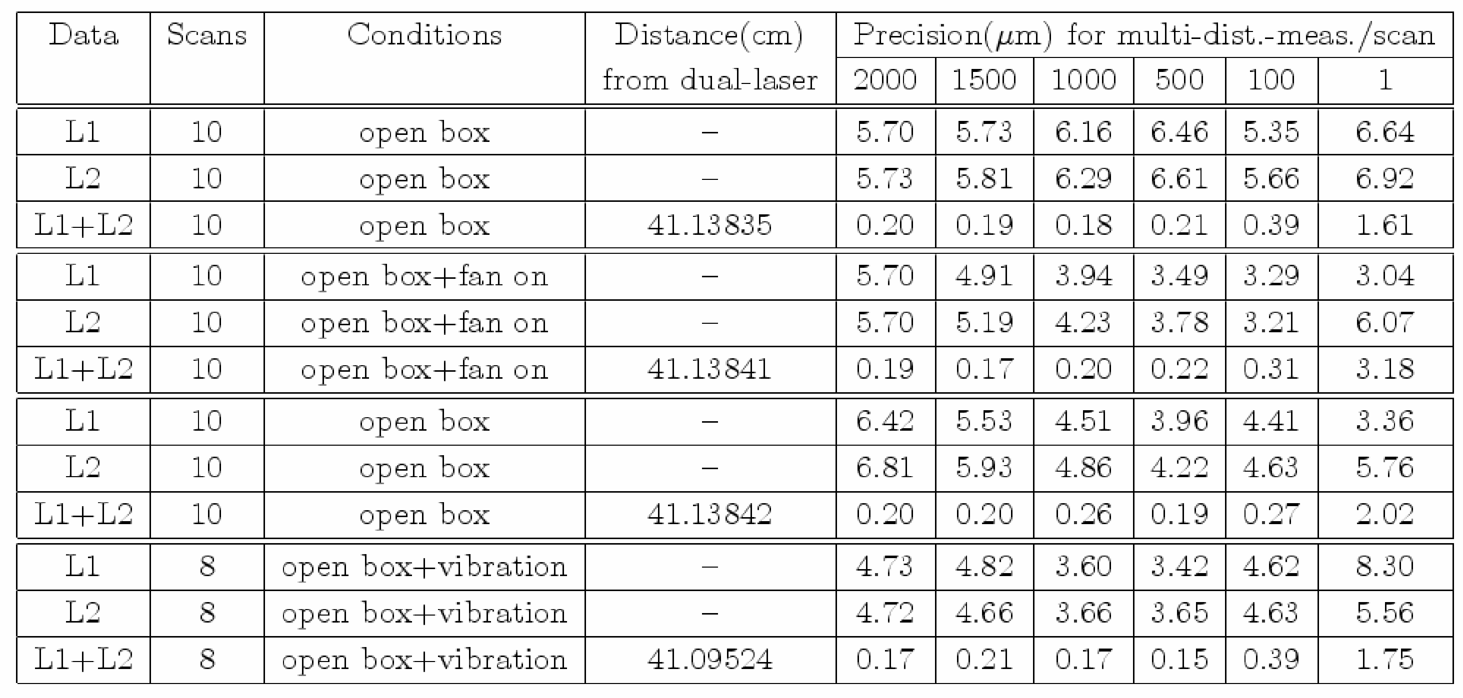
Dual-Laser FSI Data Samples – Under Realistic Conditions

* with box open(20 scans), with fan on (10 scans), with vibration(8 scans).

* Scanning rates for Laser #1 and #2 are -0.4 and 0.4 nm/s, respectively.

* Scanning time is 25 seconds, sampling rate is 100 KS/s.

* Two lasers are operated simultaneously, 2-blade chopper frequency is 20 Hz.



Data	Scans	Conditions	Distance(cm) from dual-laser	Precision(μm) for multi-dist.-meas./scan					
				2000	1500	1000	500	100	1
L1	10	open box	–	5.70	5.73	6.16	6.46	5.35	6.64
L2	10	open box	–	5.73	5.81	6.29	6.61	5.66	6.92
L1+L2	10	open box	41.13835	0.20	0.19	0.18	0.21	0.39	1.61
L1	10	open box+fan on	–	5.70	4.91	3.94	3.49	3.29	3.04
L2	10	open box+fan on	–	5.70	5.19	4.23	3.78	3.21	6.07
L1+L2	10	open box+fan on	41.13841	0.19	0.17	0.20	0.22	0.31	3.18
L1	10	open box	–	6.42	5.53	4.51	3.96	4.41	3.36
L2	10	open box	–	6.81	5.93	4.86	4.22	4.63	5.76
L1+L2	10	open box	41.13842	0.20	0.20	0.26	0.19	0.27	2.02
L1	8	open box+vibration	–	4.73	4.82	3.60	3.42	4.62	8.30
L2	8	open box+vibration	–	4.72	4.66	3.66	3.65	4.63	5.56
L1+L2	8	open box+vibration	41.09524	0.17	0.21	0.17	0.15	0.39	1.75

FSI Cross Checks

➔Used a Micrometer to change the position of retroreflector by large amount (127+/- 3 microns), and check FSI performance. Laser #1, 5 full scan data for each independent test.

dR1 = 128.68 +/- 0.46 microns

dR2 = 129.55 +/- 0.63 microns

dR3 = 127.44 +/- 0.63 microns

dR4 = 124.90 +/- 0.48 microns

Single-laser scans – unstable temps

➔Used a Piezoelectric transducer (PZT, 20% tolerance) to change the position of the retroreflector by 2.0 +/- 0.4 microns. Laser #1, 5 full scans for each test.

dR5 = 2.33 +/- 0.12 microns

dR6 = 2.23 +/- 0.07 microns

Single-laser scans – stable temps

FSI Thermal Test

- To verify correct tracking of large thermal drifts, we placed a heating pad on a 1' X 2' X 0.5'' Aluminum breadboard

➔Test 1: increased temperature by 6.7 +/- 0.1 ^{o}C

dR_expected = 62.0 +/- 0.9 microns

dR_measured = 61.72 +/- 0.18 microns

➔Test 2: increased temperature by 6.9 +/- 0.1 ^{o}C

dR_expected = 64.4 +/- 0.9 microns

dR_measured = 64.01 +/- 0.23 microns

➔Test 3: increased temperature by 4.3 +/- 0.1 ^{o}C

dR_expected = 39.7 +/- 0.9 microns

dR_measured = 39.78 +/- 0.22 microns

➔Test 4: increased temperature by 4.4 +/- 0.1 ^{o}C

dR_expected = 40.5 +/- 0.9 microns

dR_measured = 41.02 +/- 0.21 microns

Dual-laser scans – closed box