High speed automatic scanning systems

(past, present and future R&D in Italian labs)

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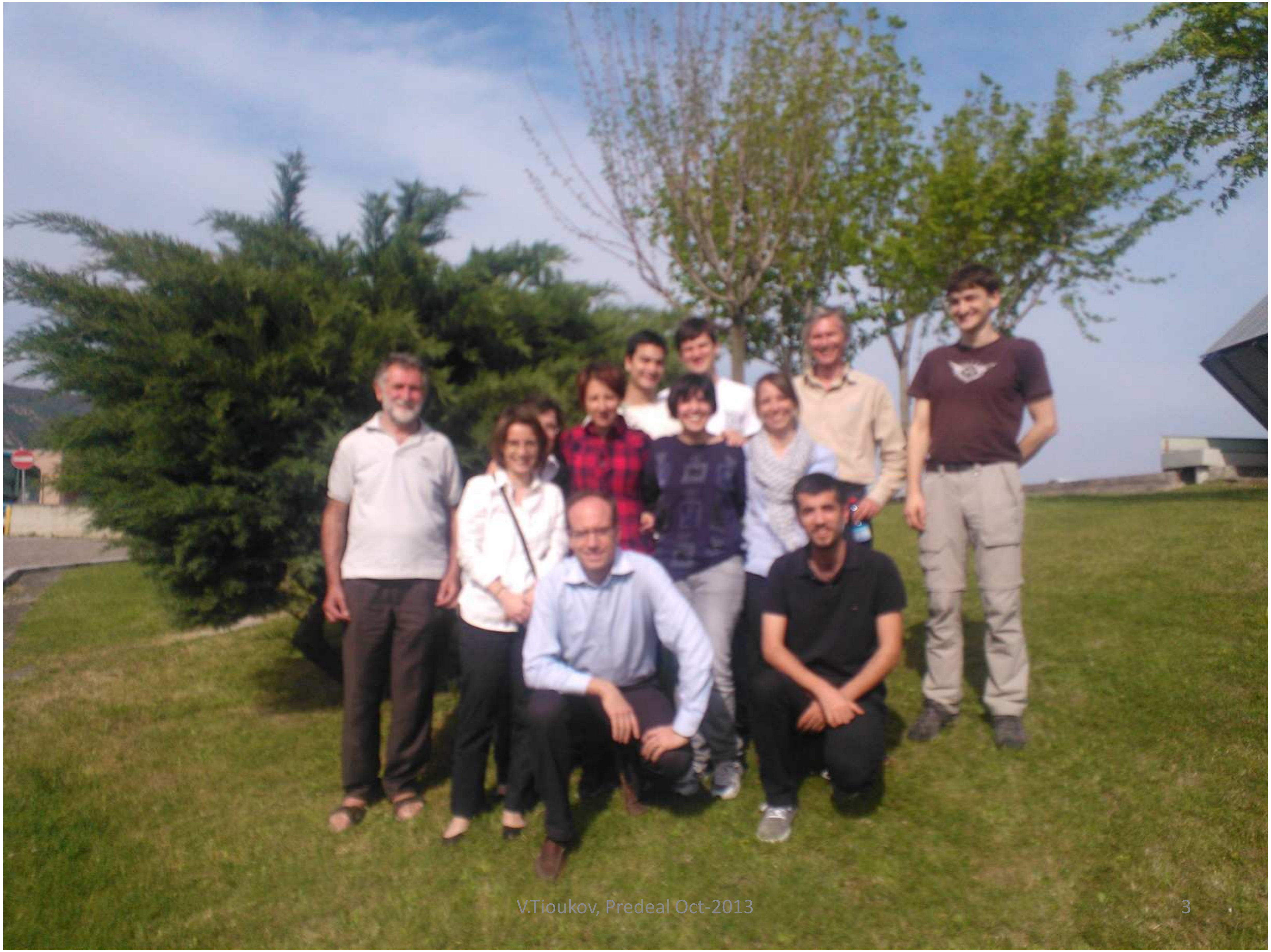
Emulsion activities in Napoli lab

- OPERA analysis – is the main task now (for another year at least)
- Muon Radiography: Unzen, Stromboli, Teide exposures – see my afternoon talk
- Medical Physics: Carbon fragmentation study, proton beam study (see Adele Lauria talk on Friday)
- Directional dark matter search R&D in the collaboration with Nagoya group
- Fast Scanning Systems R&D (this presentation)
- High precision Scanning System R&D



Toward the automatic emulsion analysis

Before 1974 – the only way to find the charged particle tracks and decays in the nuclear emulsions was the eye inspection using manual microscopes

1974 K. Niwa: Track recognition by superimposing tomographic images from different focal planes

This was the first idea of the automatic scanning but the digital technology was not ready yet in that time
(the first Digital Camera prototype -1975)

- 1980 – First semi-automatic scanning (Nagoya)
- 1985 – "Track Selector" (TS) the first automatic scanning system based on tomographic image processing. Started TS-NTS-UTS-SUTS development line (Nagoya)
- 1994 – CHORUS data analysis – Napoli group enter into scanning business: 2 microscopes equipped with NTS systems arrive to Naples
- 2004 – the first prototype of the European Scanning System dedicated for OPERA scanning operational in Naples, developed in collaboration with other Italian groups

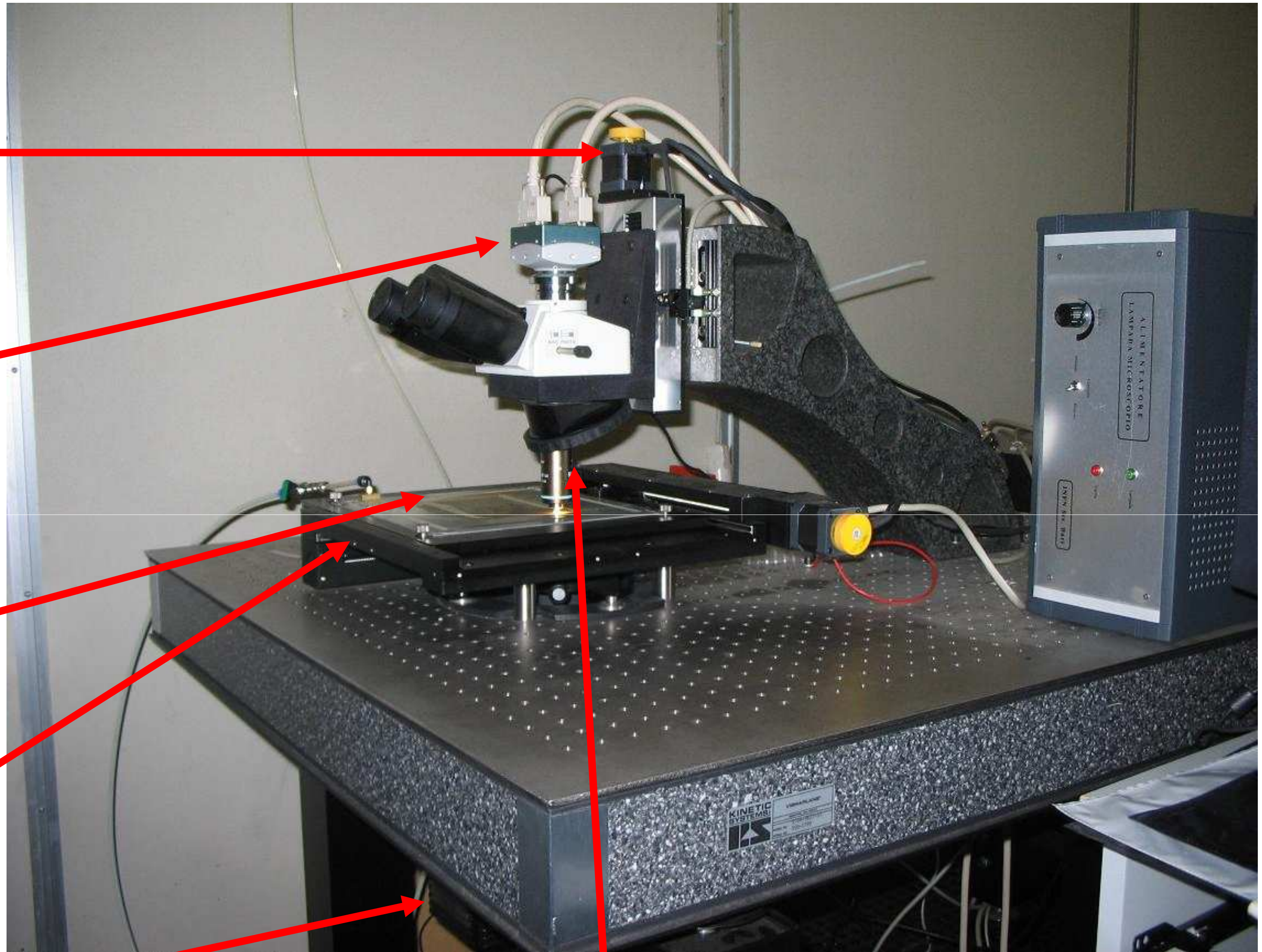
Closer view to the ESS

Z stage (Micos)
0.05 μm nominal
precision

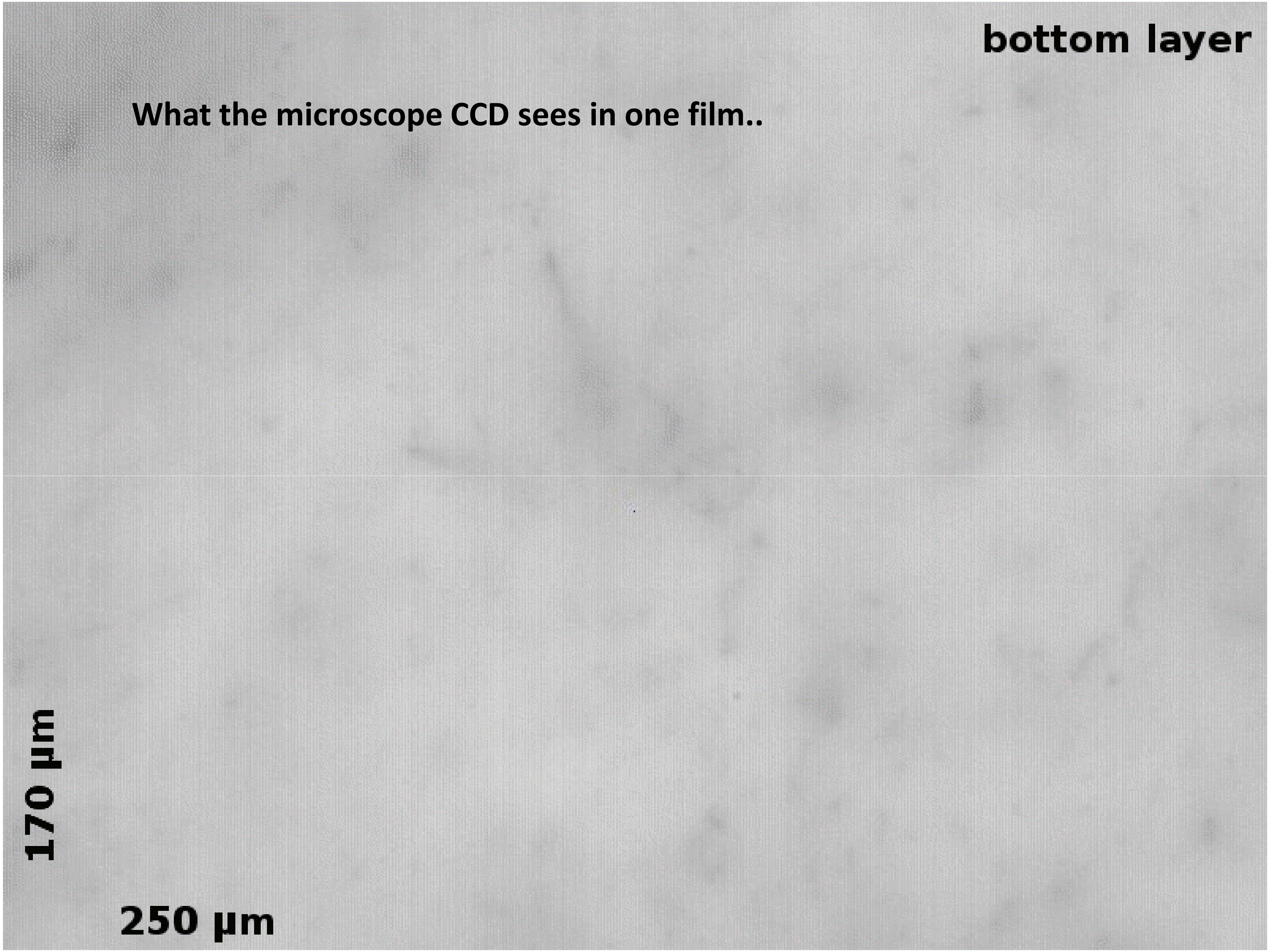
CMOS camera
1280×1024 pixel
256 gray levels
376 frames/sec
(Mikrotron MC1310)

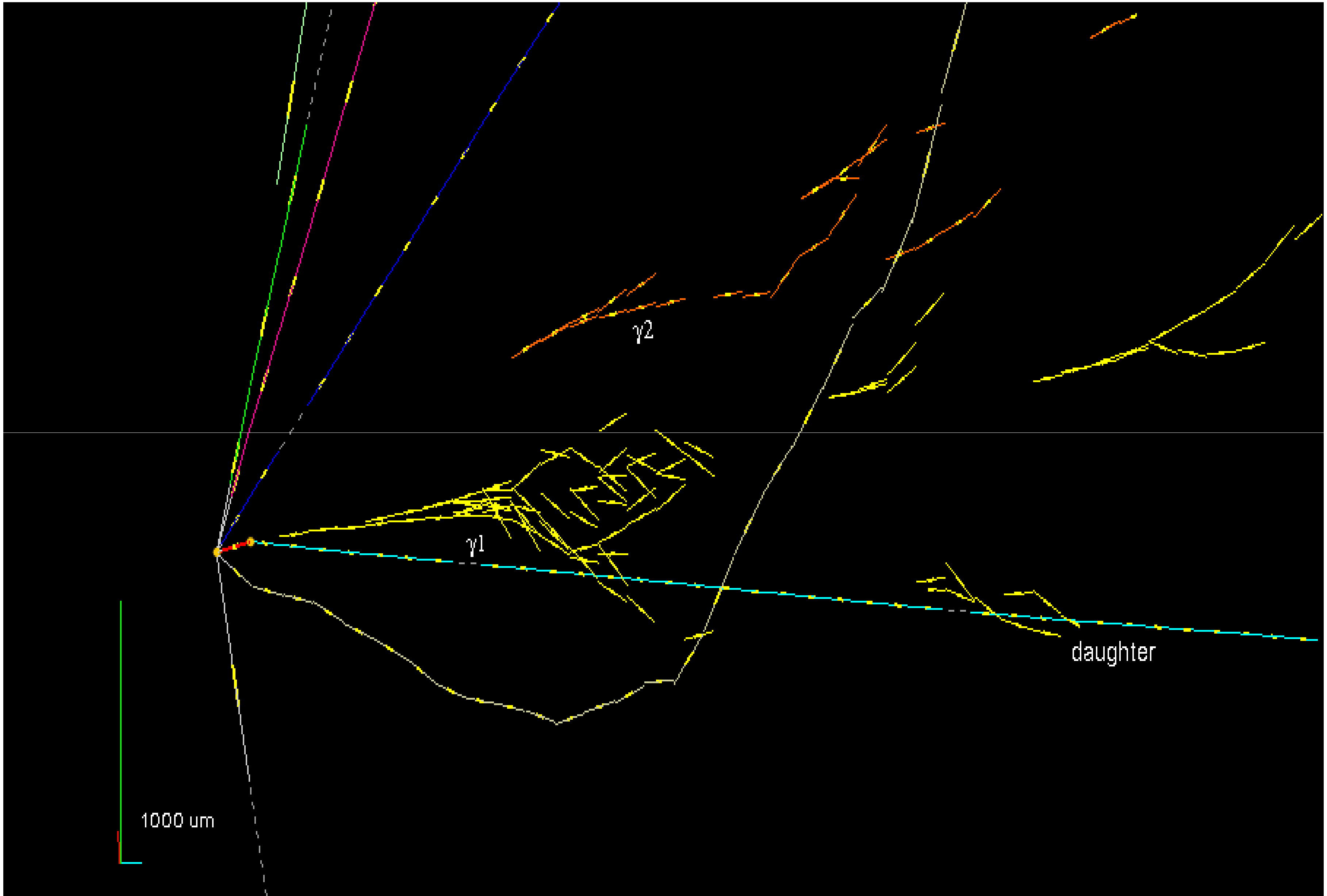
Emulsion Plate

XY stage (Micos)
0.1 μm nominal
precision

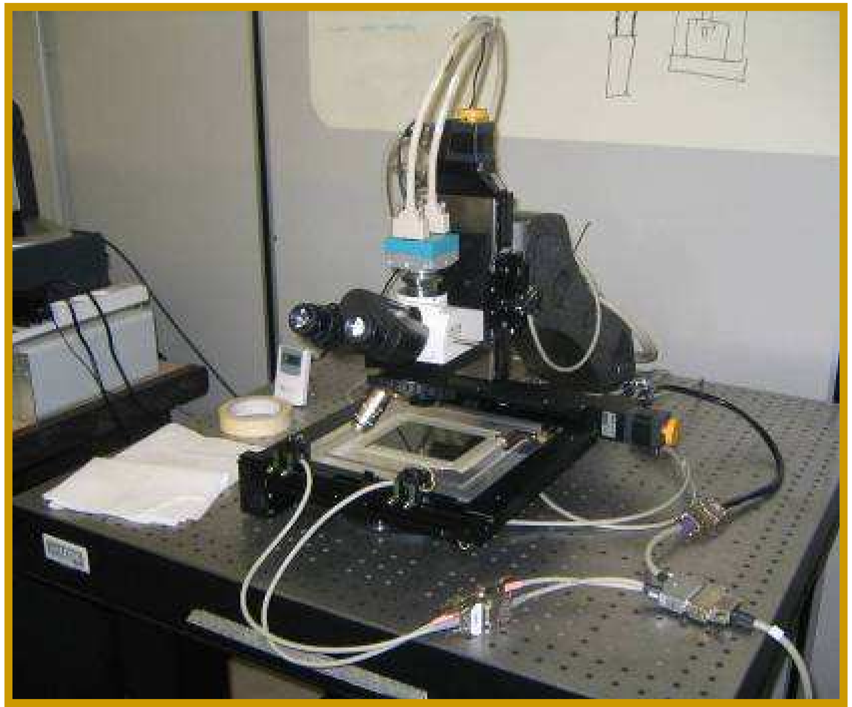


Illumination system, objective (Oil 50× NA 0.85)
and optical tube (Nikon)


bottom layer
What the microscope CCD sees in one film..
170 μm
250 μm


γ2
γ1
daughter
1000 um

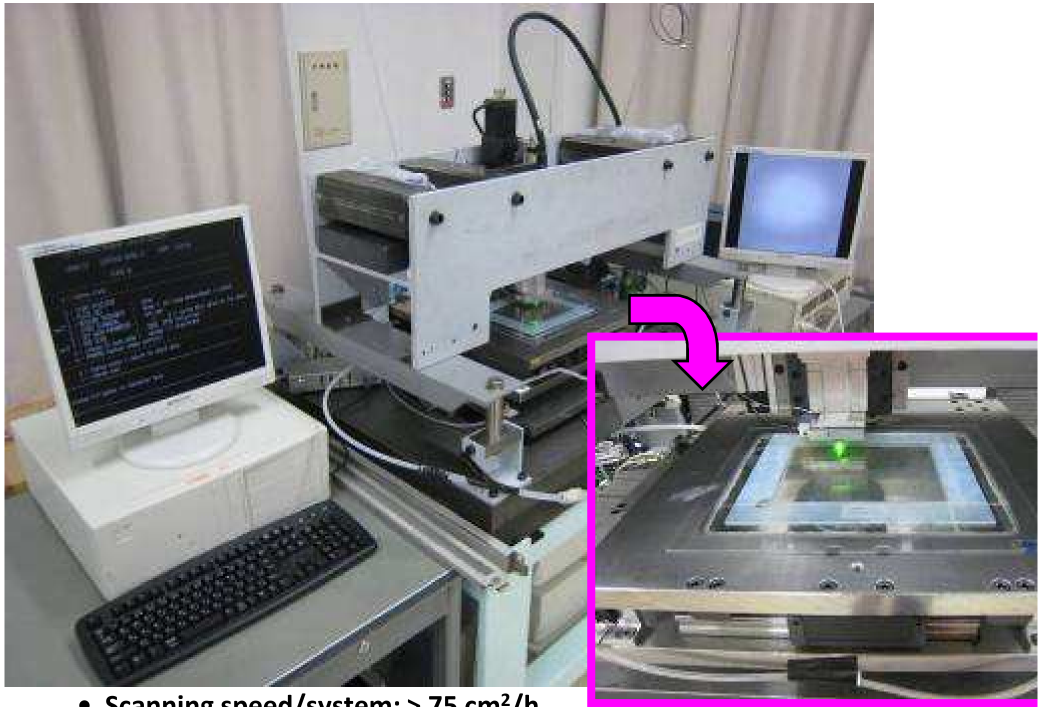
EU: ESS (European Scanning System)



- **Scanning speed/system: 20 cm^2/h**
- **Customized commercial optics and mechanics**
- **Asynchronous DAQ software**

Relatively cheap and easy to clone

Japan: SUTS (Super Ultra Track Selector)



- **Scanning speed/system: > 75 cm^2/h**
- **High speed CCD camera (3 kHz), Piezo-controlled objective lens**
- **FPGA hard-coded algorithms => GPU**

Expansive system based on home-made
Image processing electronics

Both systems demonstrate:

- ~0.3 μm spatial resolution
- ~2 mrad angular resolution
- ~95% base track detection

Scanning laboratories equipped with European Scanning Systems (ESS)

- Napoli: 6 microscopes (5 OPERA & 1 R&D)
- Salerno: 4 (3&1)
- Bologna+Padova: 5
- Bari: 4
- Frascati: 2
- LNGS: 10 dedicated to OPERA CS scanning
- Bern: 6
- Russia: 4
- Tokyo: 2
- **Total scanning power in Italy is equivalent to 31 ESS**

Evolution of the European Scanning System

- Why new R&D?
  - The project is based on 10 years old components, some of them went out of production
  - New requirement for a fast scanning of a large surfaces (as muon radiography) or large angles (as medical applications)
  - New ideas for improving the performance
- Two (complimentary) lines of Italian R&D
  - Based mainly on the software and algorithmic improvements (LASSO)
  - Based mainly on the HW improvements (QSS)

LASSO development history

- 2011: ESS limits study as a part of upgrade R&D
- 2011: Idea of the continuous scan: possibility to double the scanning speed without additional HW investment
- 2012: New 3-d grains-based tracking is developed for the Continuous Motion scan
- 2012: fine image corrections and merging study
- 2012: First tests of a new tracking at the big angle using S&G data
- presented the Large Angle TB data analysis in Stop&Go mode
- 2013 all wide area and large angle scanning in Napoli lab we perform with LASSO in S&G mode
- 2013: Final tests and start production with the Continuous Motion mode scanning

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Standard hardware

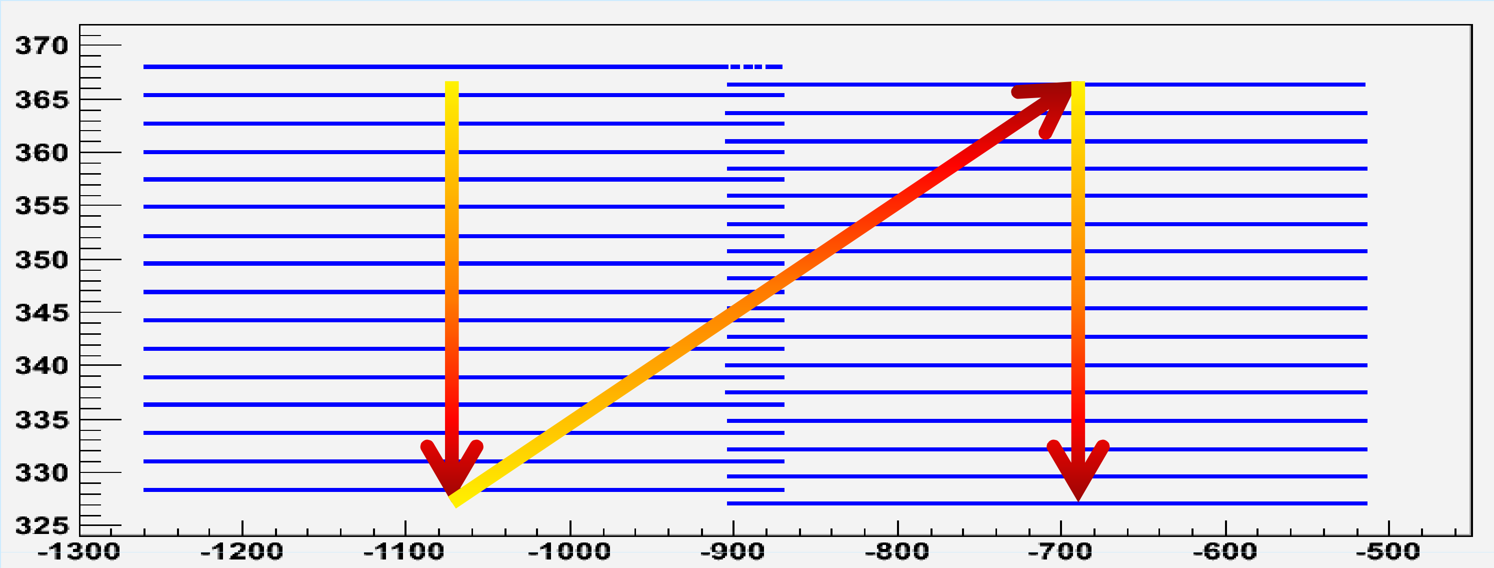
Hardware Limits Summary

Calculated for the standard ESS optics

Camera	376 fps, If every frame is used	< 100 cm^2/h
Stage-Z	50 µm cyclic motion, camera @ 376 fps	< 53 cm^2/h
Odyssey	16 images/view, camera @ 376 fps, byte image transfer	< 50 cm^2/h

- Odyssey and the stage defines the theoretical limit to the scanning speed of 50 cm^2/h with the existing HW
- **Scanning with the speed > 20 cm^2/h should be possible even with the existing hardware**

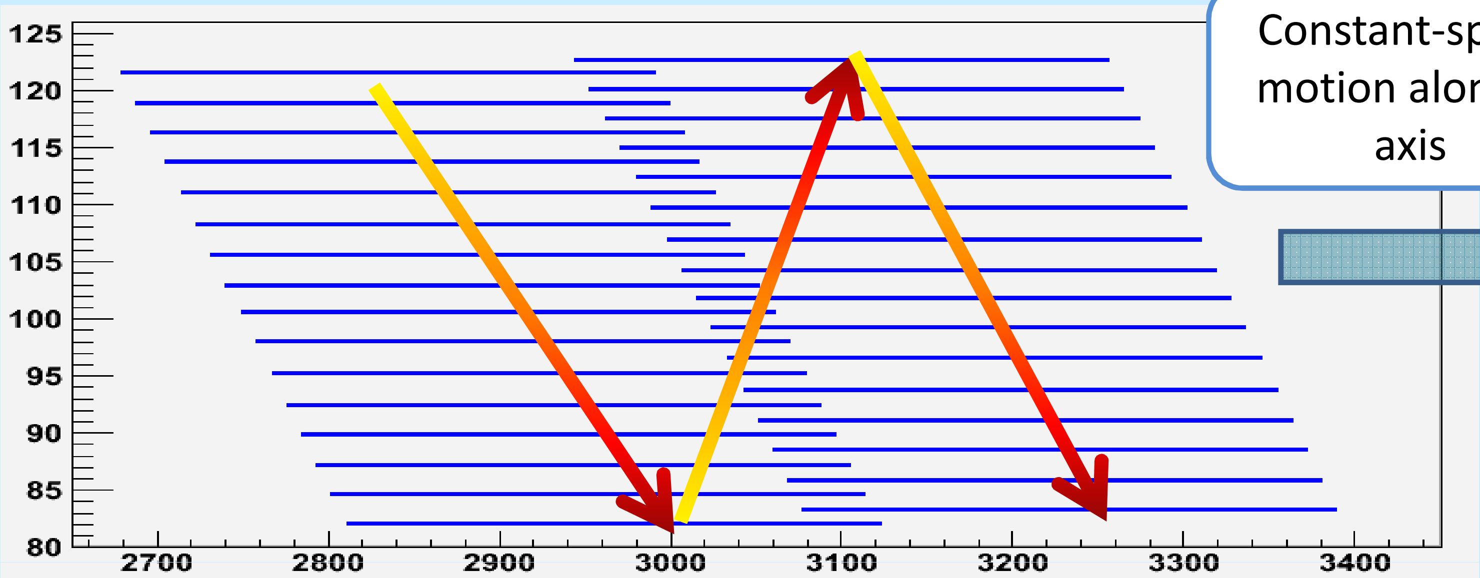
Standard 'Stop&Go' Motion



55 ms data acquisition + 95 ms back motion = 150 ms duty cycle

- Data acquisition is performed in movement along Z axis while X and Y axes are in rest
- For thin emulsions and large field of view movement to the next view can become a speed-limiting factor
- The ESS scanning speed is limited to 20-25 cm^2/h (with standard HW)

Continuous Motion



Constant-speed motion along Y-axis

55 ms data acquisition + 25 ms back motion = 80 ms duty cycle

- Continuous cyclic motion in Z (80-90 ms/view)
- Continuous constant speed motion in Y (speed = 280 microns/80 ms = 3500 micron/s)
- Serpentine-like path in a horizontal plane
- horisontal shift of consecutive frames is of 9 µm
- The ESS scanning speed increases to 40-45 cm^2/h without any hardware modification

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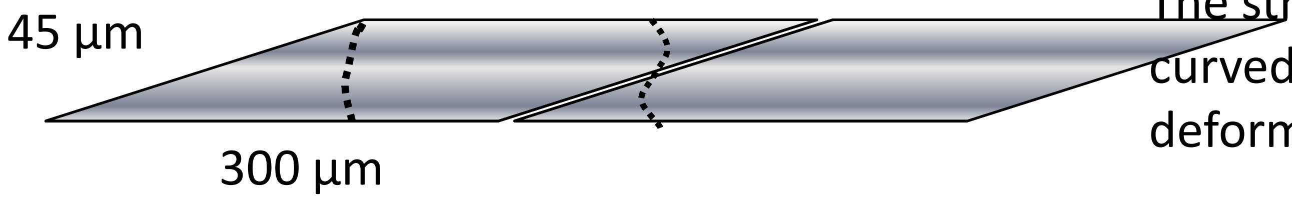
Importance of the view deformation corrections in case of CM

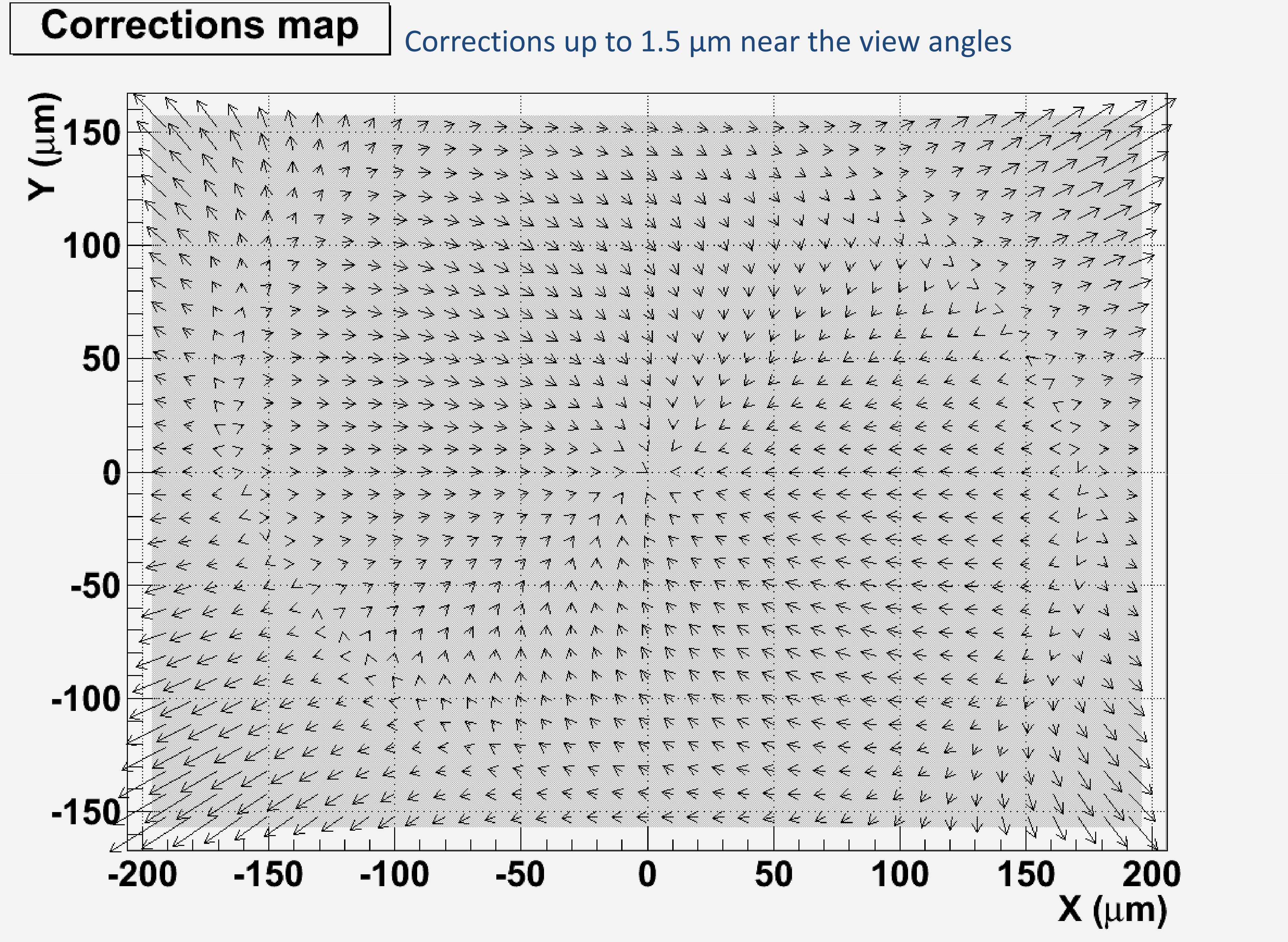
- There are many effects (summary is on the next slide) leading to the image deformations so that the accuracy of our knowledge of the real grain position depends on it's location inside the microscope view. The overall effect is normally is **of the order of one micron**.
- Usually we neglect this effects because in the standard scan the images pile in the View is vertical (no XY movement while data taking) and in practice all these effects leads mainly just to the microtracks angle deviation depending on it's position inside the view. These deviations are usually inside the accepted measurement errors.
- But them can not be ignored in case of the continuous motion:



The straight tracks leave curved path due to image deformations

Summary of the main deformation effects

- XY 2-dimensional effects:
  - Matrix (camera) rotation in respect to the stage
  - Pixel to micron ratio error
  - 2-d image distortion (pixel/micron is not uniform inside the view!)
  - Optical axes (one or more) are not parallel and/or not centered
- XYZ 3-dimensional effects:
  - Specimen focal plane curvature
  - Focal plane inclination
- Off-axis grains inclination



Corrections map
Corrections up to 1.5 µm near the view angles
Y (µm)
150
100
50
0
-50
-100
-150
-200
-150
-100
-50
0
50
100
150
200
X (µm)

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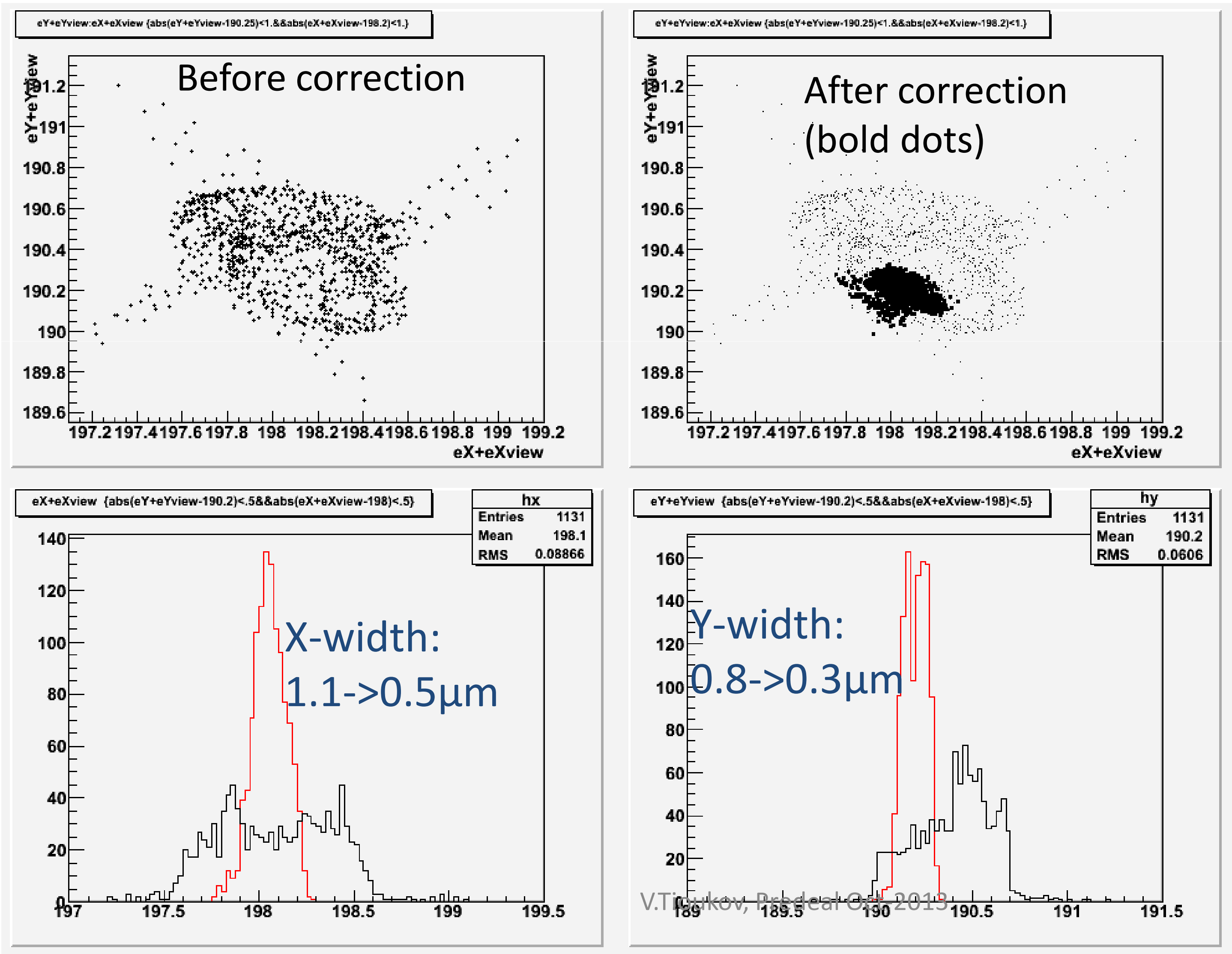
Accuracy before and after correction

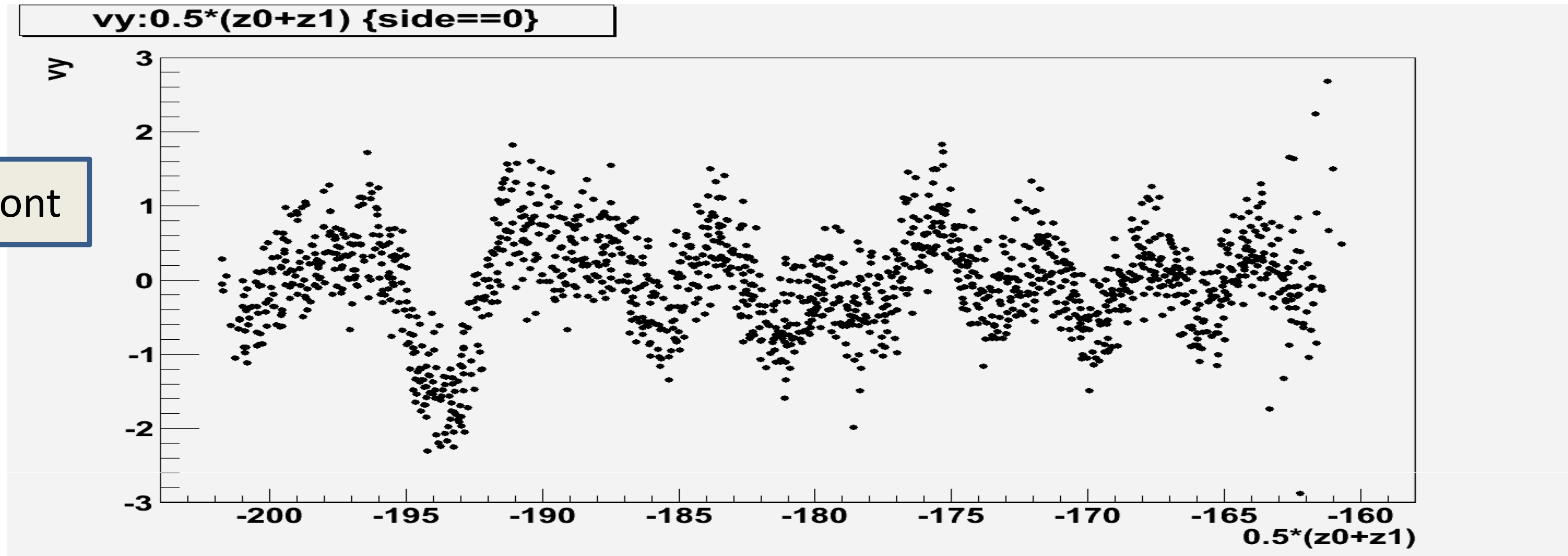


The single grain was observed 1131 times in a views shifted 10 µm

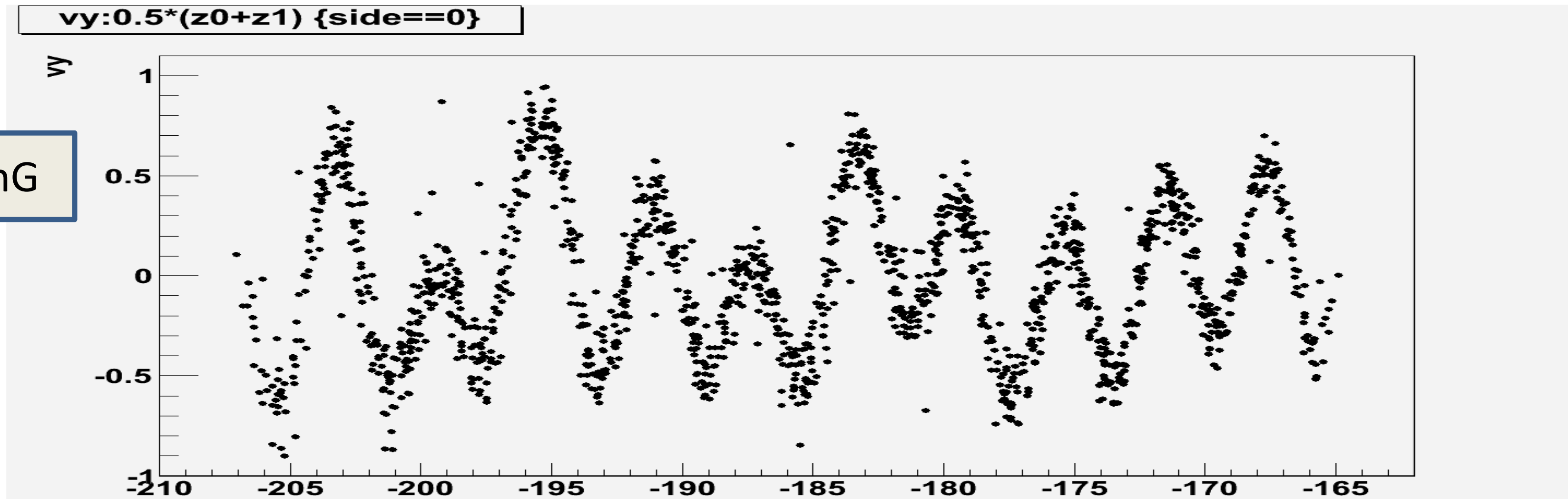
After application of the correction matrix the spread reduced 2-3 times

Vibrations correction using grains shadows

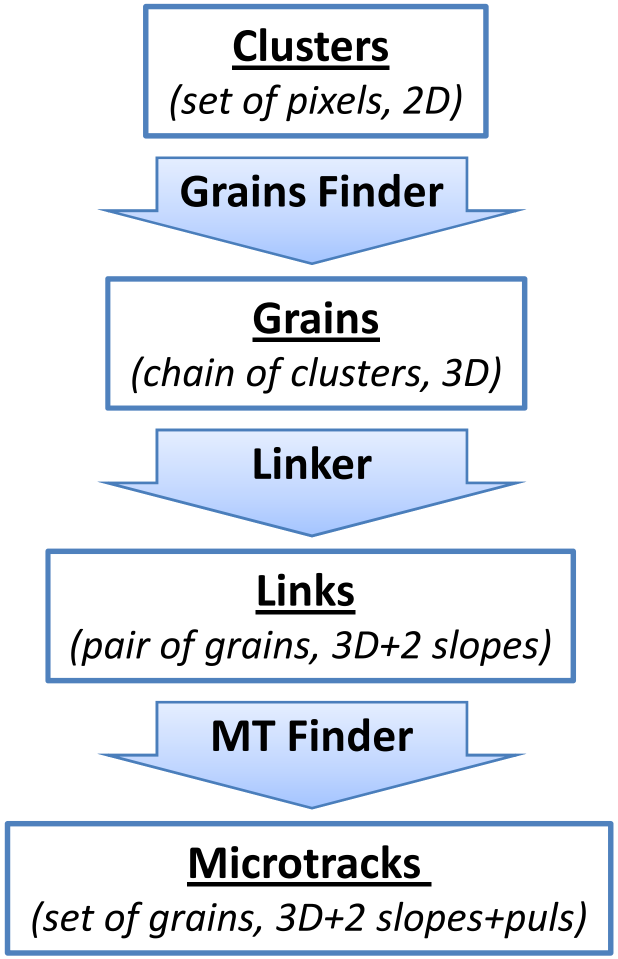
Cont



SnG

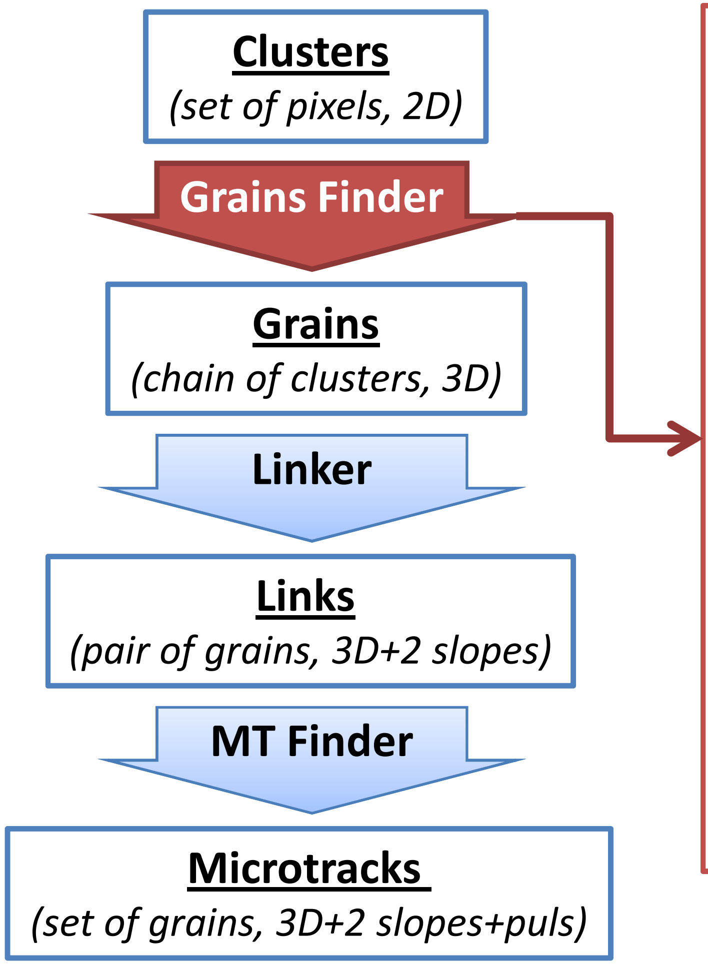


Microtracker Processing Chain Overview



Microtracks reconstruction in case of Continous Motion has many complicate aspects in respect to S&G case.
To handle this task the new dedicated tracker was developed

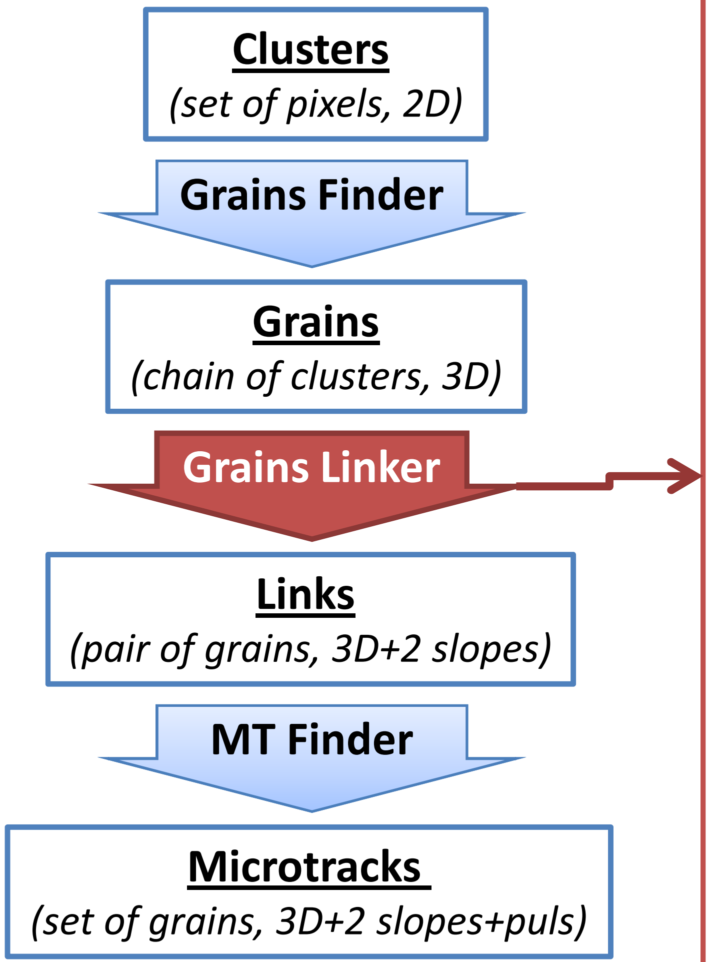
Microtracker Processing Chain



Grains Finder

- Creates 3D objects, grains, required for an efficient large angle scanning
- Searches for (almost) vertical chains of clusters
- If a cluster chain is too long to represent a grain then the chain is split into several grains
- Reduces the number of objects to be processed by the factor of 2

Microtracker Processing Chain



Grains Linker

- Creates objects that possess directional information, links, by connecting two grains within the specified radius
- Two strategies were implemented:
  - Blind linker (CPU optimized):
    - Simple, reliable and relatively fast
    - Unpractical at large link length scale since number of links grows rapidly
    - Ineffective with poor tracks (few grains, large gaps between grains)
  - Total linker (GPU optimized):
    - Calculates number of grains along the link and performs density cut
    - Should be more effective due to its far-reach (especially with poor tracks)
    - Ineffective at short link length scale due to large density fluctuations

Microtracker Processing Chain

Clusters
(set of pixels, 2D)

↓ **Grains Finder**

Grains
(chain of clusters, 3D)

↓ **Grains Linker**

Links
(pair of grains, 3D+2 slopes)

↓ **MT Finder**

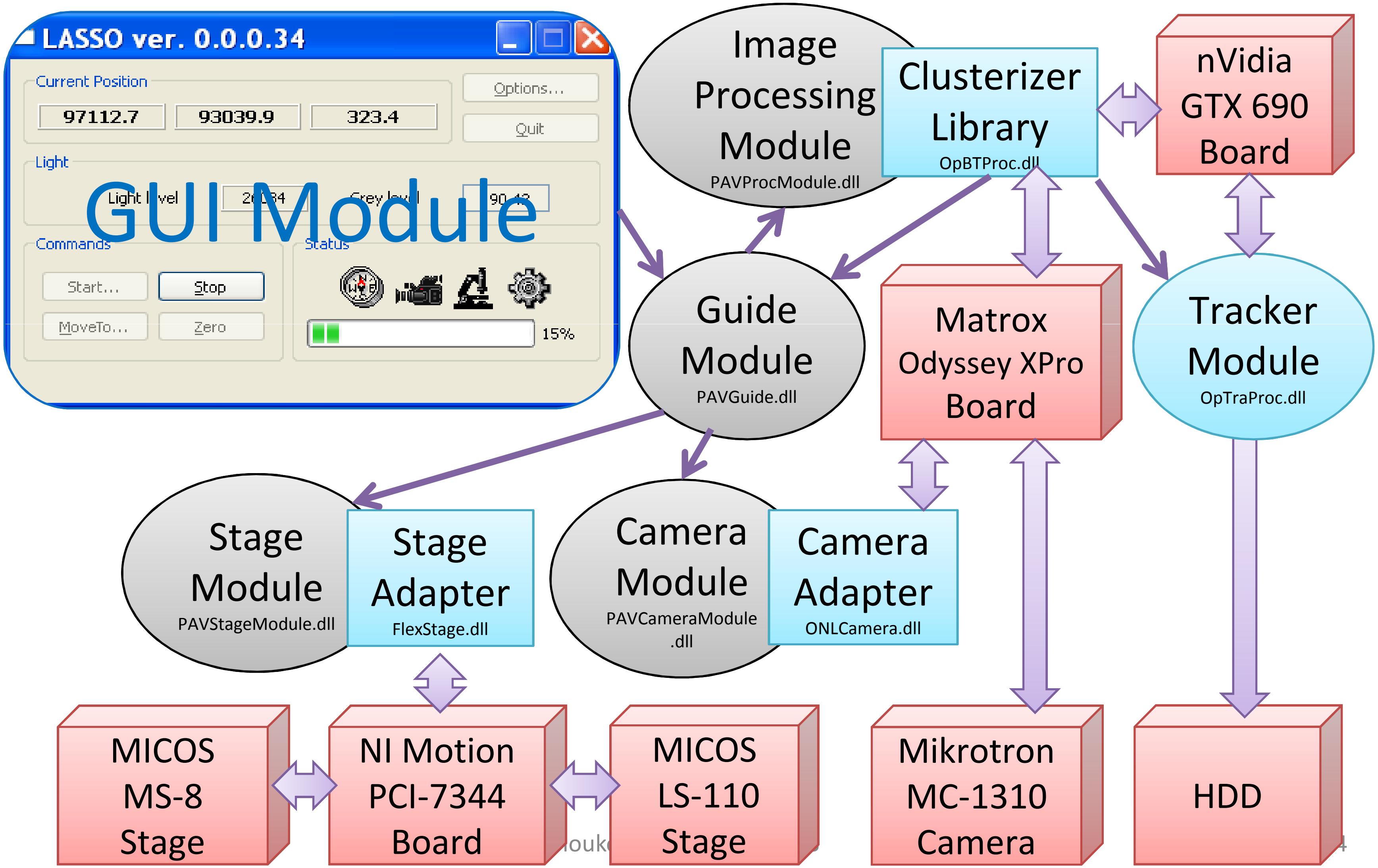
Microtracks
(set of grains, 3D+2 slopes+puls+ χ^2)

No internal angular limits: horizontal tracks can be reconstructed as well as vertical ones

Microtracks Finder

- Locates linear grain density anomalies (grain density increase along a particle's track) in 3D-space by performing a 4D-histogramming of links
- In order to improve efficiency at large angles 4D-historgamming is performed in two steps:
  1. 2D-hist in the angular space (φ,ϑ)
  2. 2D-hist in the coordinate space projected onto plane normal to the selected slope
- All slope calculations are performed in (φ,ϑ)-space (not using tx-ty)
- All slope and spatial acceptances and thresholds depend on ϑ and are calculated in accordance with the grain model used
- Performs calculation of track parameters (position, slopes, puls, χ^2, etc)

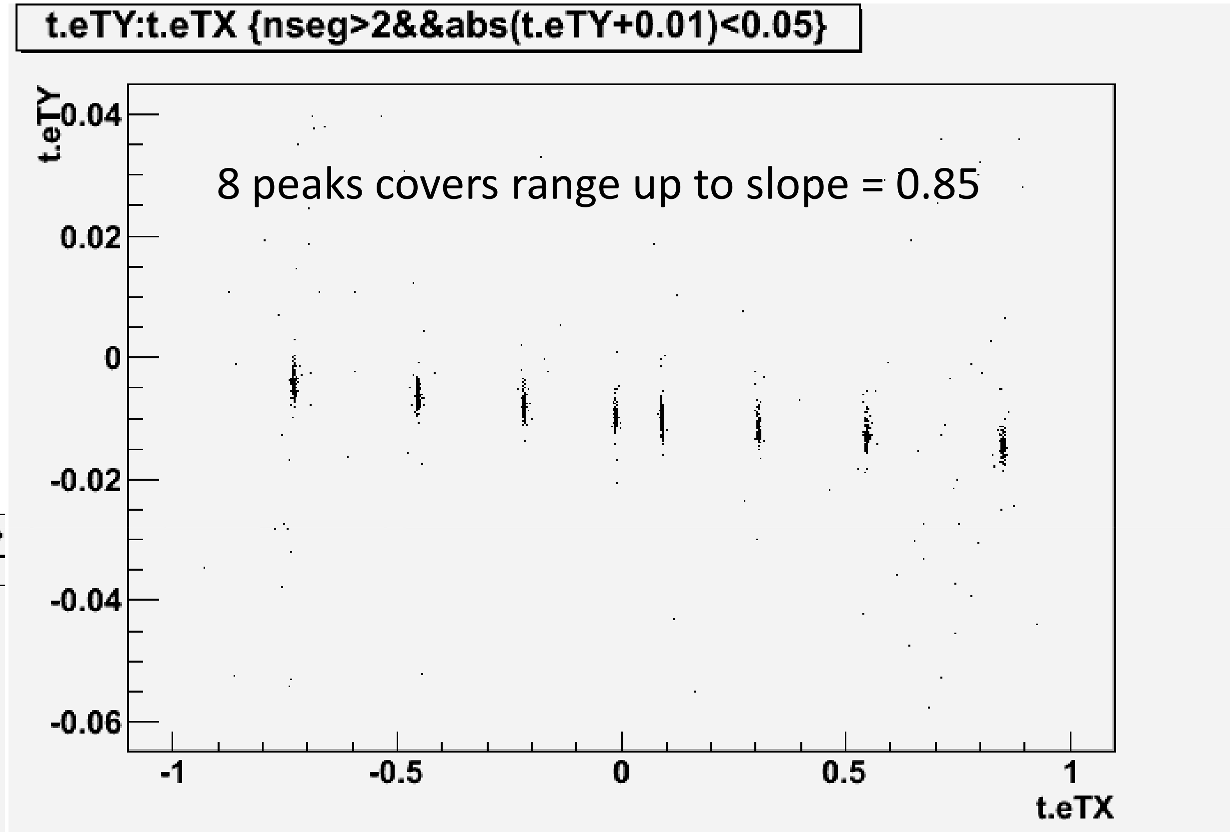
LASSO Structure
(Standard HW)

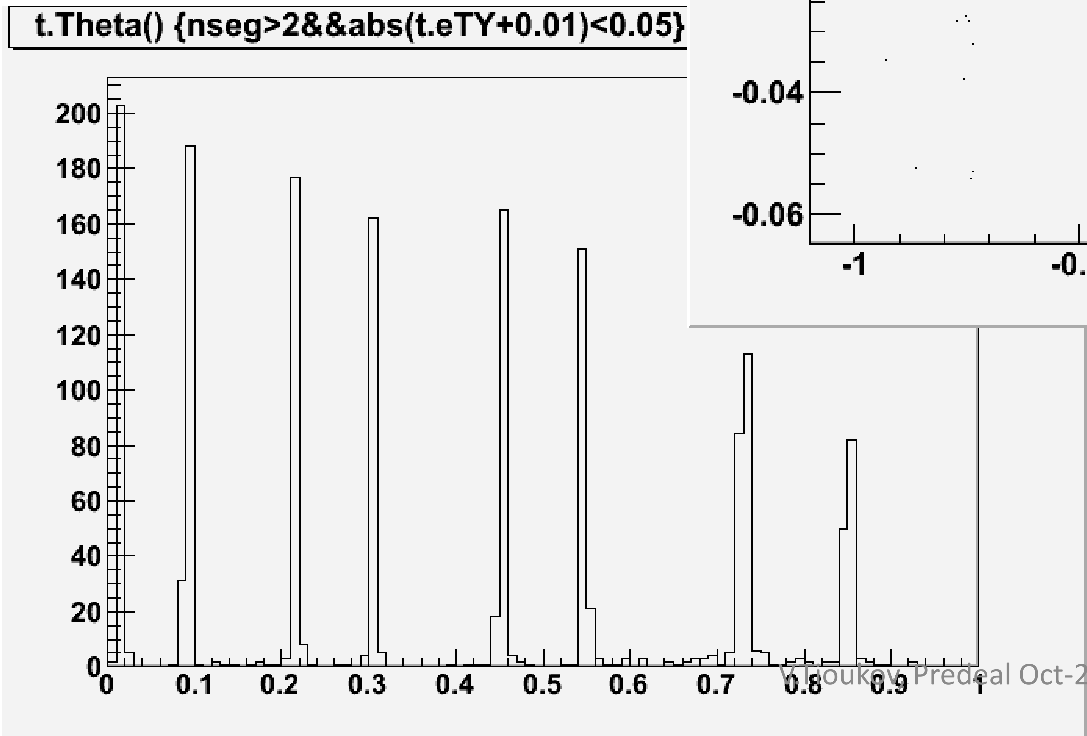


Pions test beam (2007) data

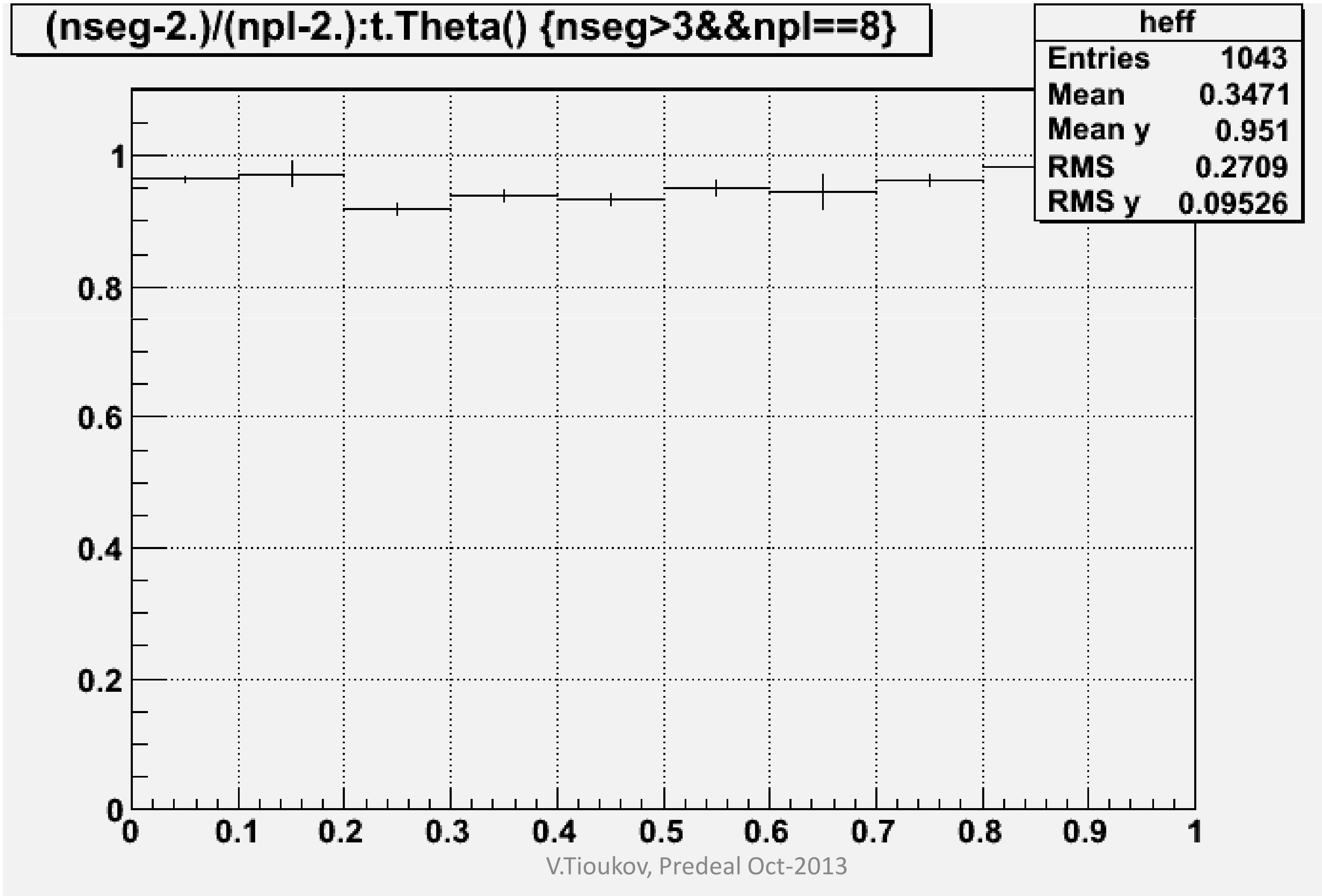
The data from the CERN pions test-beam of 6-7 years ago typically used for this kind of test. Emulsions are little bit yellow-green, but still usable.

8 plates without lead



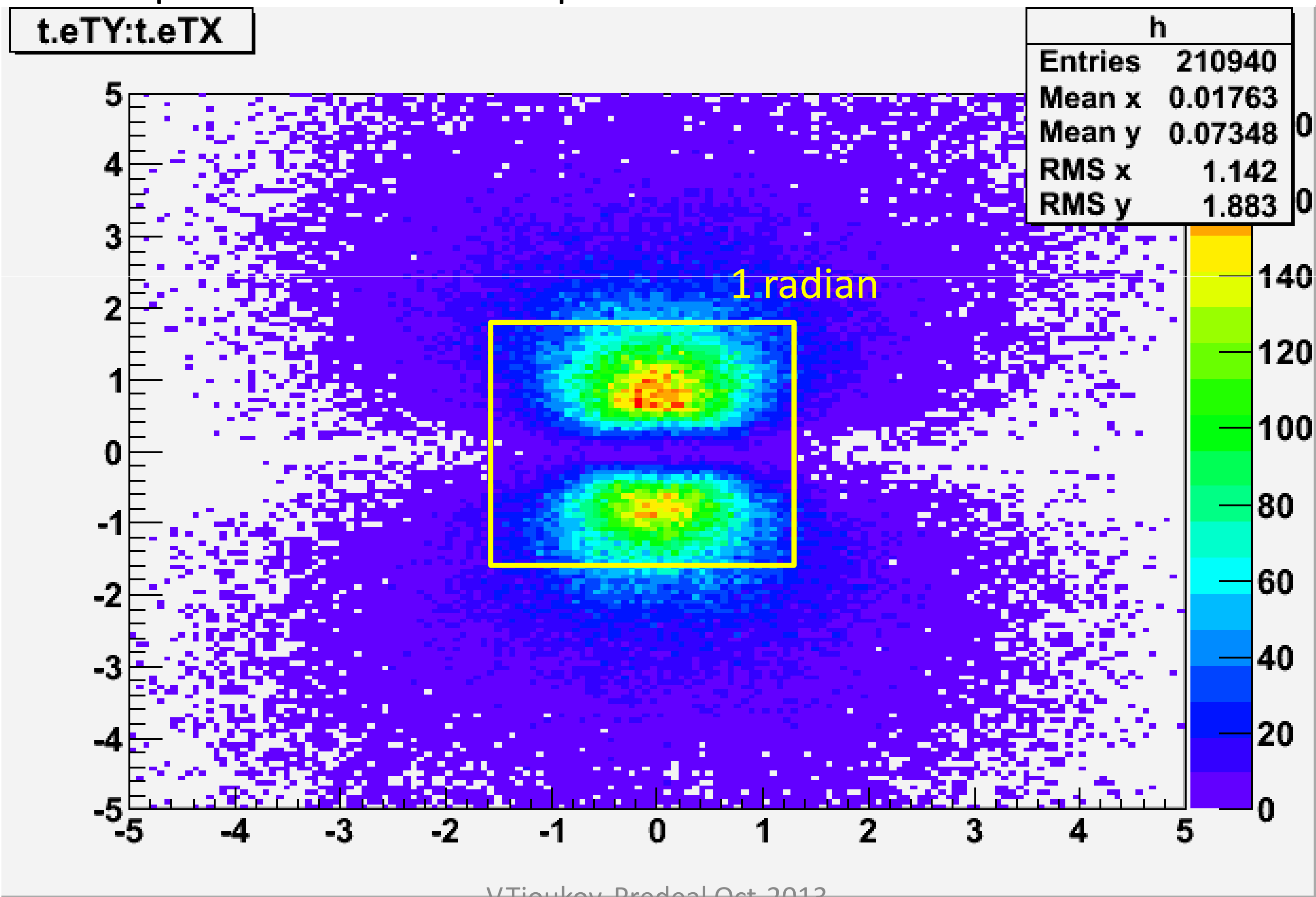


Effect of the resent improvements on the basetracks efficiency
(2007 test beam data, S&G mode scan)



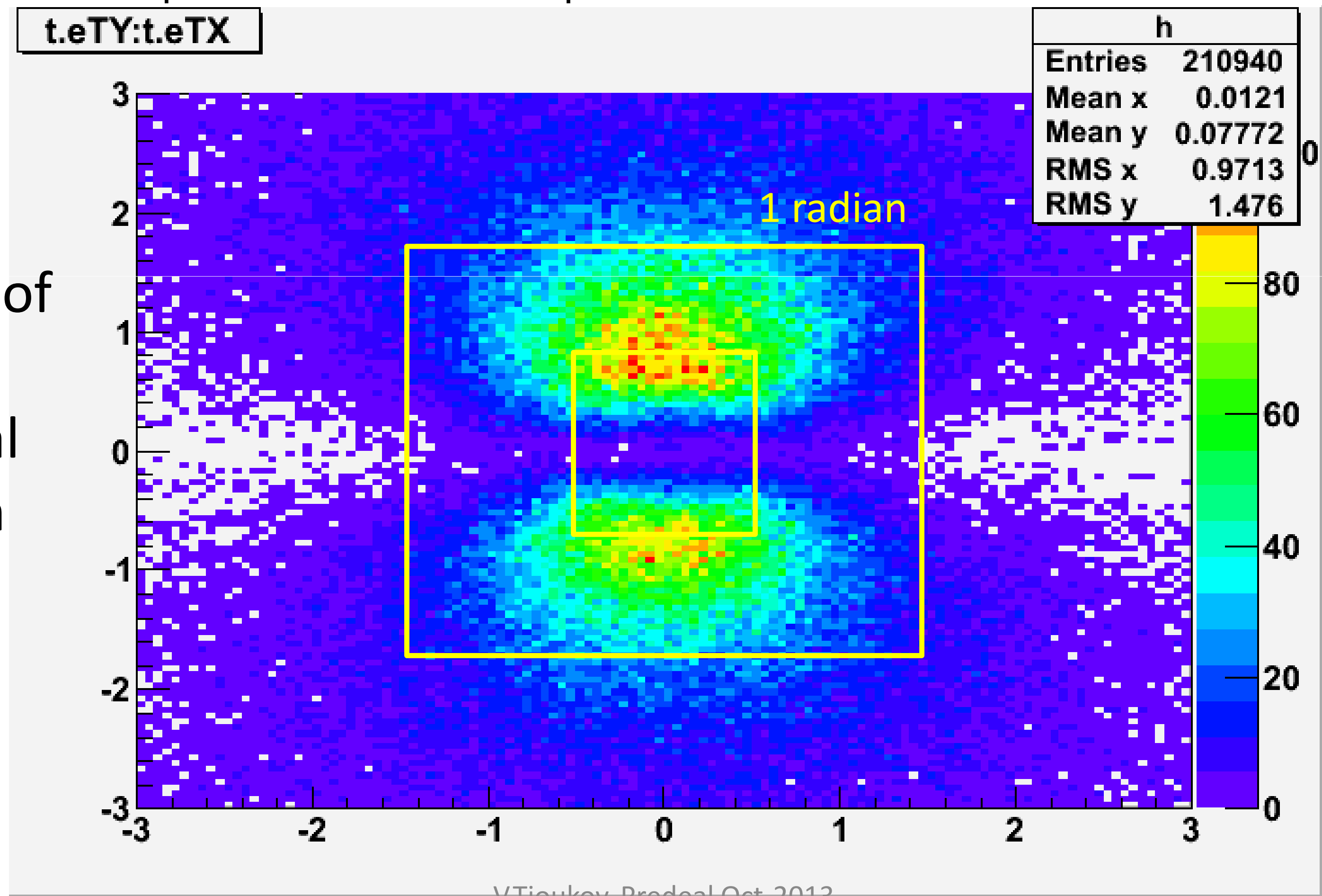
Nagoya Tau plates reconstructed in the transportation order

All scanned plates we aligned in the transportation order: with Zgap = 300 microns
Long passing throw transportation tracks were used for efficiency estimation
Angular acceptance in this test is up to tan = 5.5



Nagoya Tau plates reconstructed in the transportation order

All scanned plates we aligned in the transportation order: with Zgap = 300 microns
Long passing throw transportation tracks were used for efficiency estimation
Angular acceptance in this test is up to tan = 5



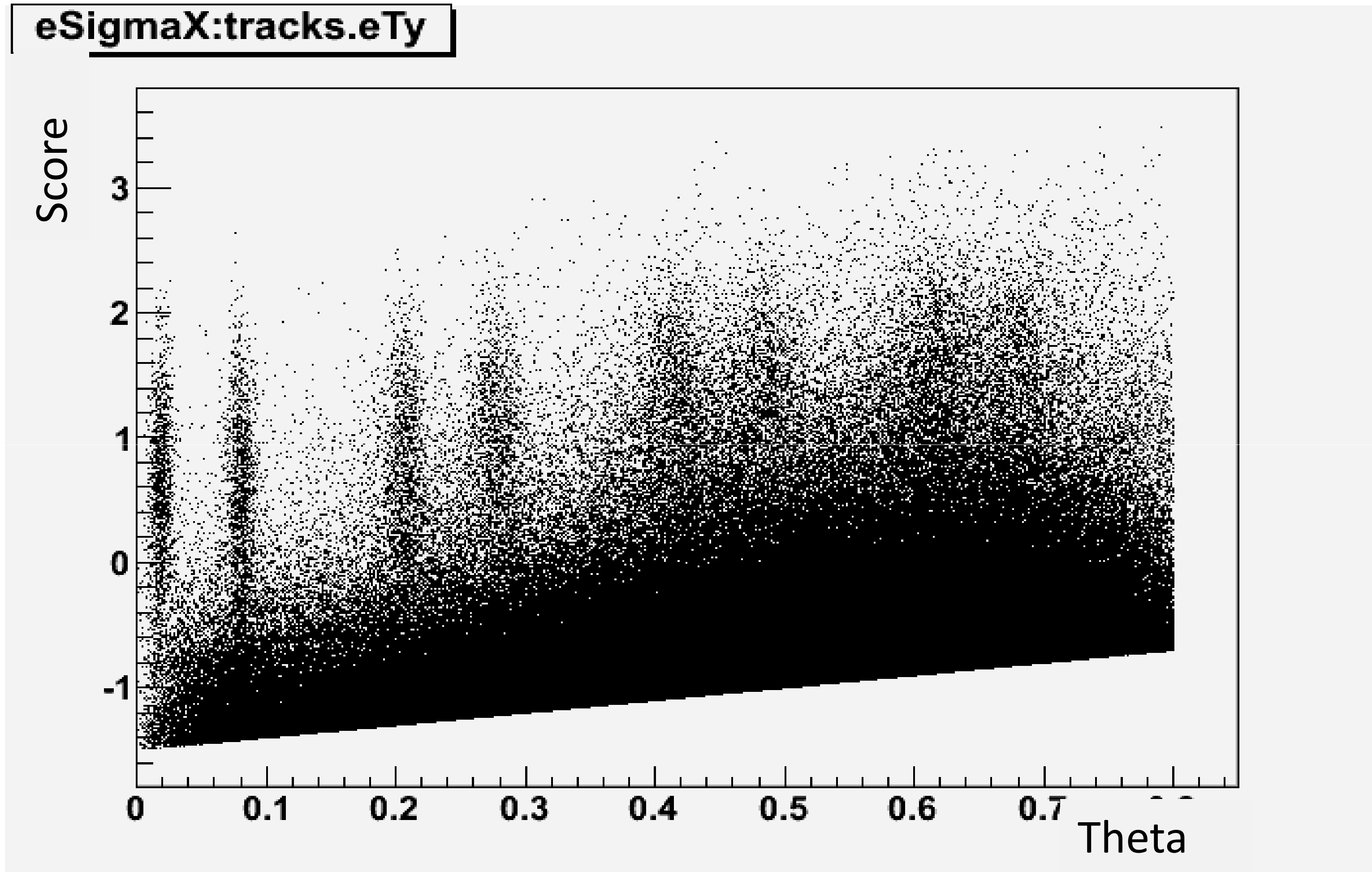
Zoom of the central region

Microtracks likelihood study

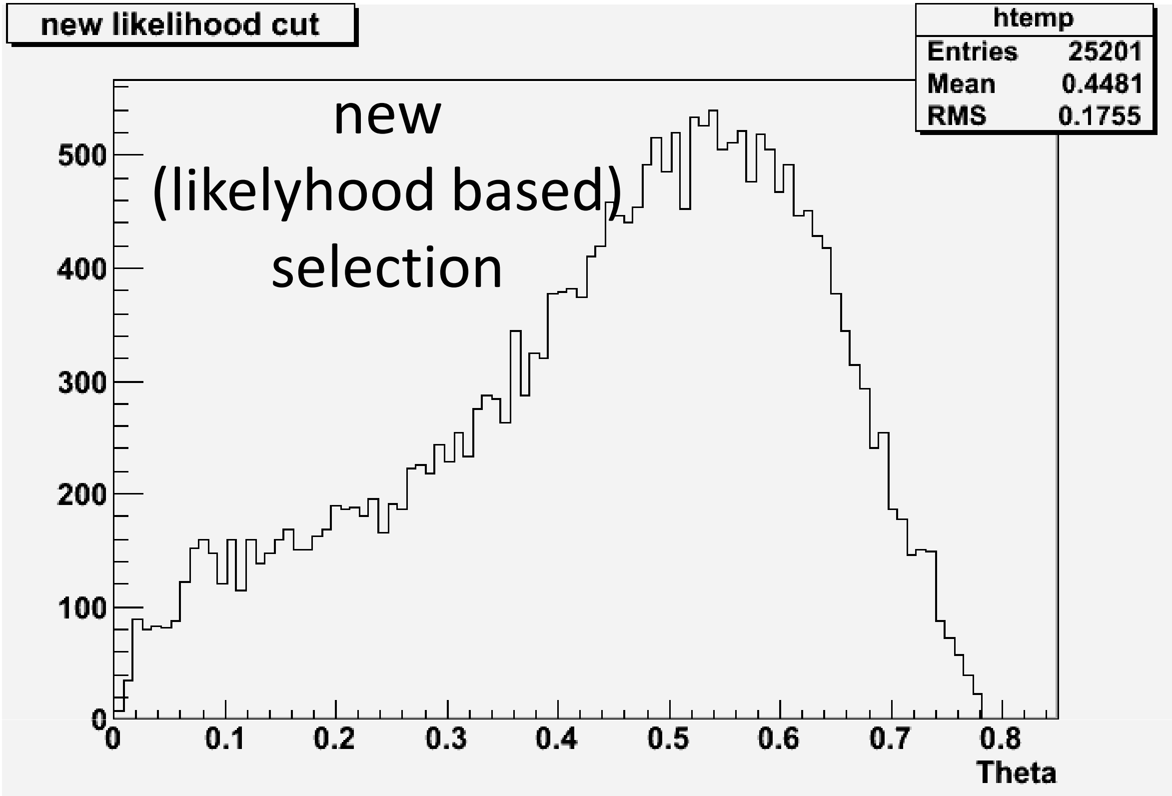
Score = $\mathrm{Log}((N_{grain}/N_{mip})*(N_{eff}/N_{mip})*(L_{track}/L_{view})*(L_{track}/MaxGap))$

N_{grain} – found grains number using splitting
N_{mip} – expected for mip grains number
$N_{eff\ v}$ – grains number estimated using microtrack volume
L_{track} – microtrack length from first to the last grain
L_{view} – maximal possible microtrack path in this view
MaxGap – biggest gap inside microtrack

Score vs Theta

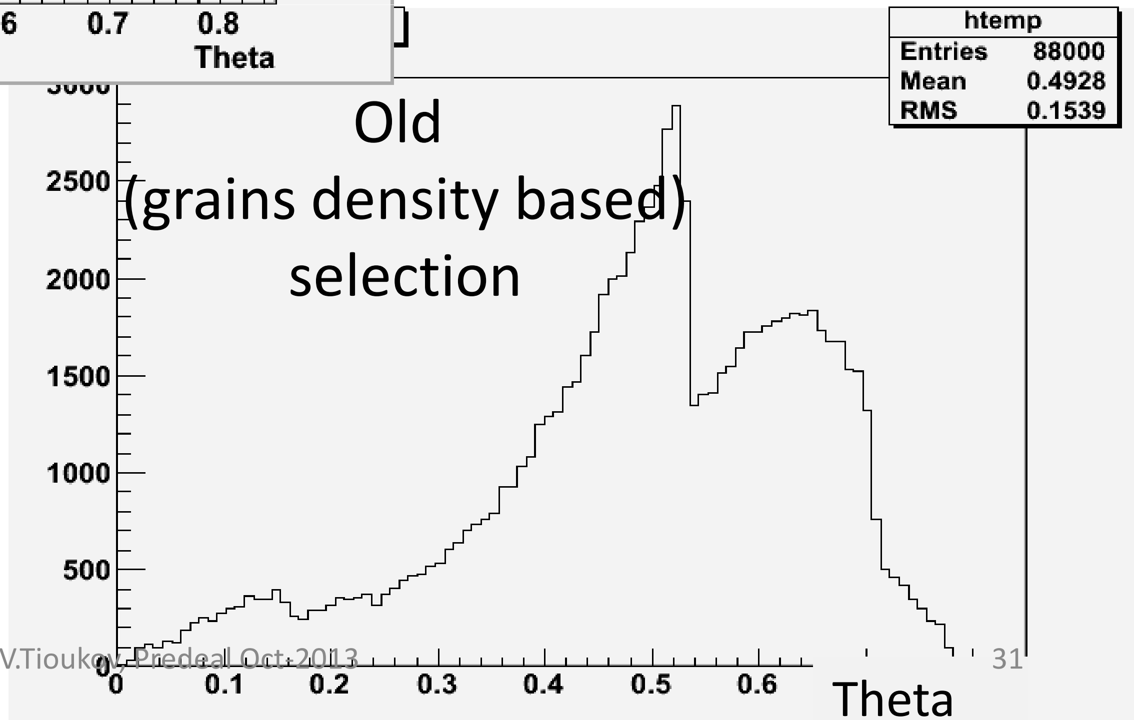


$$Score = Log((N_{grain}/N_{mip})*(N_{eff}/N_{mip})*(L_{track}/L_{view})*(L_{track}/MaxGap))$$



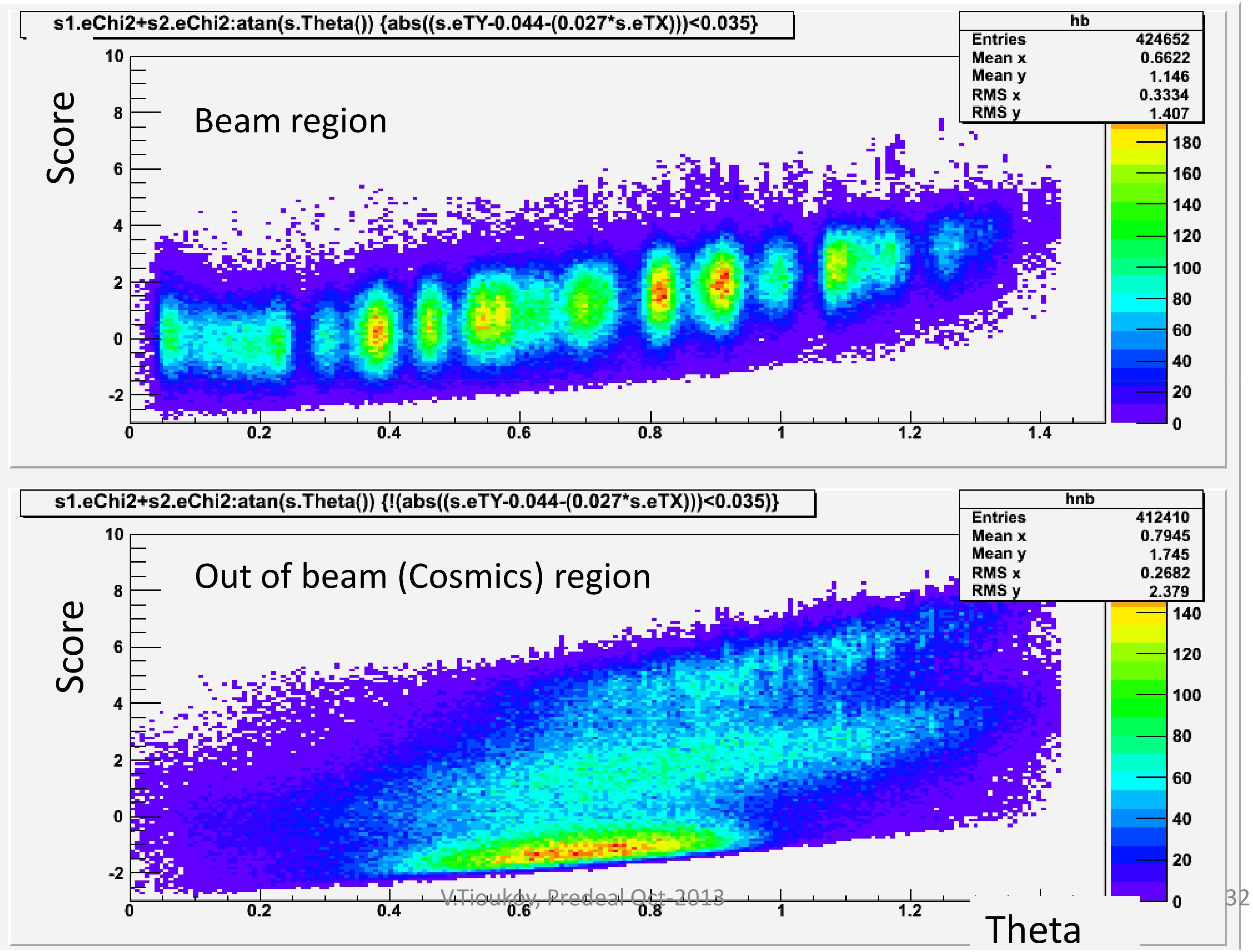
Effect of the new cut

3-4 times less mt/view
Same efficiency
Smooth distribution



Effect of the likelihood selection on the basetracks

Large angle test beam data were used

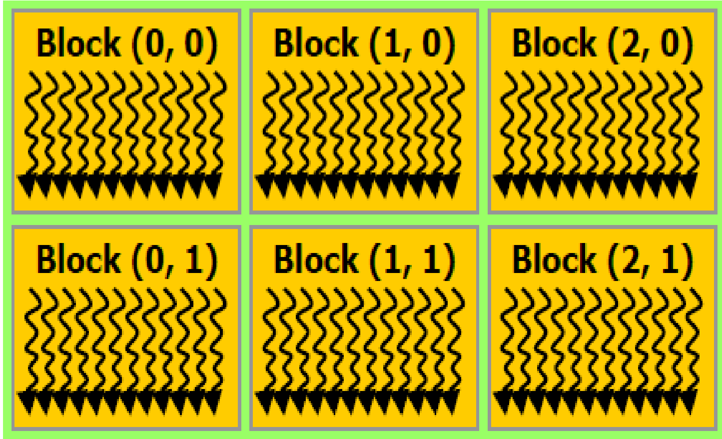


Processing on GPU: image

Modern graphics processors have thousands of arithmetic logic units, which can be used for general purpose computation.

Image processing is ideal for GPU.

Whole image processing cycle in LASSO was implemented in CUDA:



1. Lightfield normalization
2. Filtration (5x5 FIR)
3. Applying threshold map
4. Field equalization
5. Binarization

Great performance gain was obtained in comparison to processing on Matrox Odyssey board, where processing was done before:

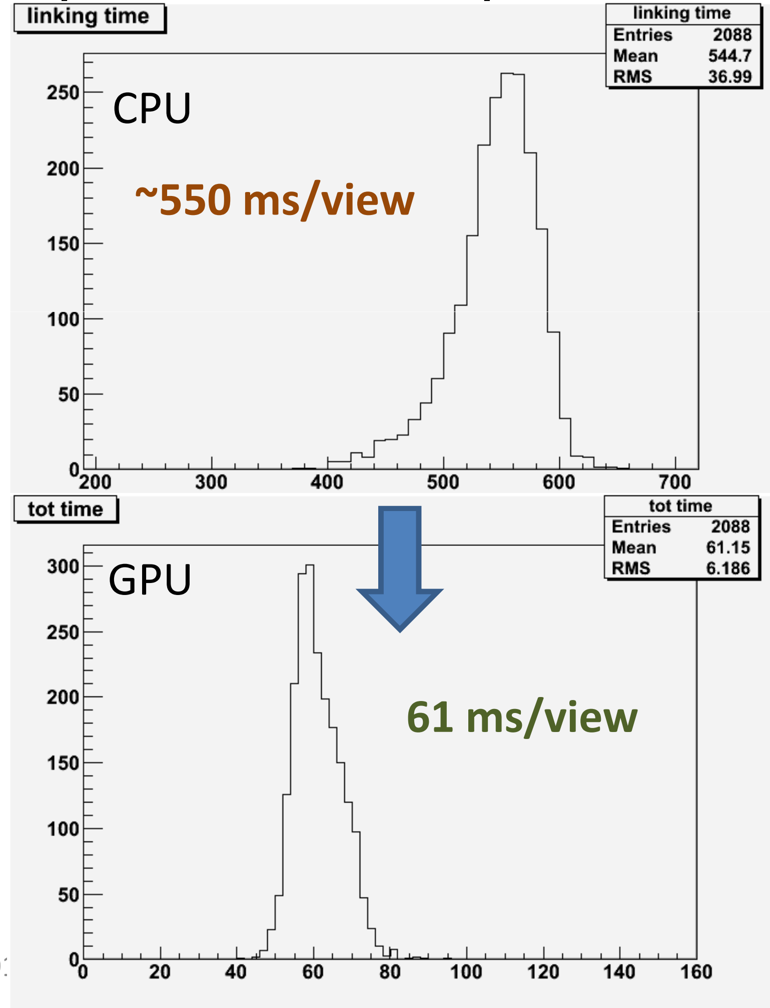
Model	Time ms/frame
MATROX Odyssey Xpro	
OP310G5MSFCL	6.6
OP413G1GSFCL	5.4
NVidia GForce	
GTX 570	**0.65**

Processing on GPU: Tracking

Tracking procedure consists of few steps. One of them ("Linking") is the most computation power consumptive. It was also implement it in CUDA.

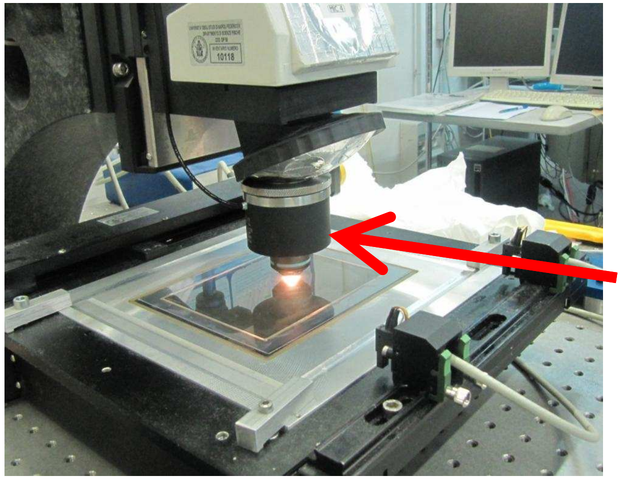
Dell T7500, Xeon X5650 2.66 GHz, 6 cores * 2 CPU *HT = 24 logical processors

NVIDIA GTX 690



ESS HW Upgrade for the fast scan

Passing to new 4Mpix Bonito CMC 4000 camera and 20x objective will allow to triple the field of view area keeping the pixel size at the same value which will allow to use already existing image processing modules.



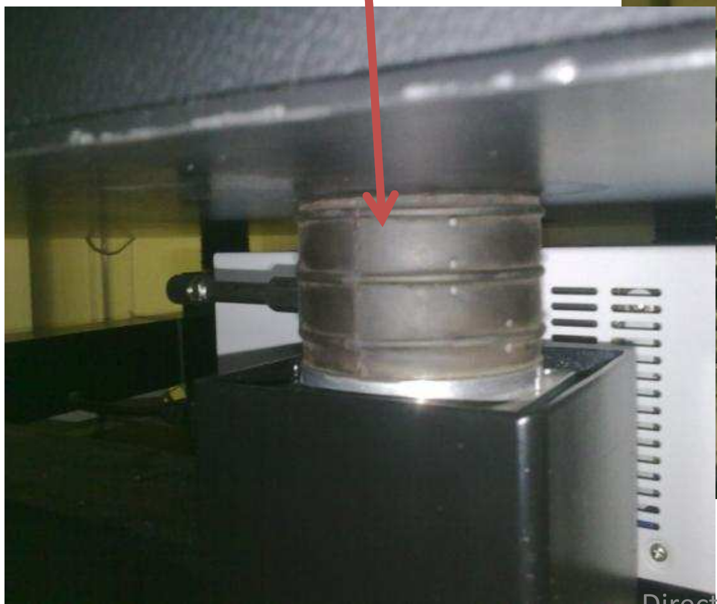
PIFOC Pi-726 piezo-drive was successfully tested with 57 ms/view duty cycle which is already 40% faster than the LS-110 stage. Duty cycle time reduction to ~50 ms/view is foreseen possible. The resulting gain in speed will be 50-60% compared to the LS-110 stage

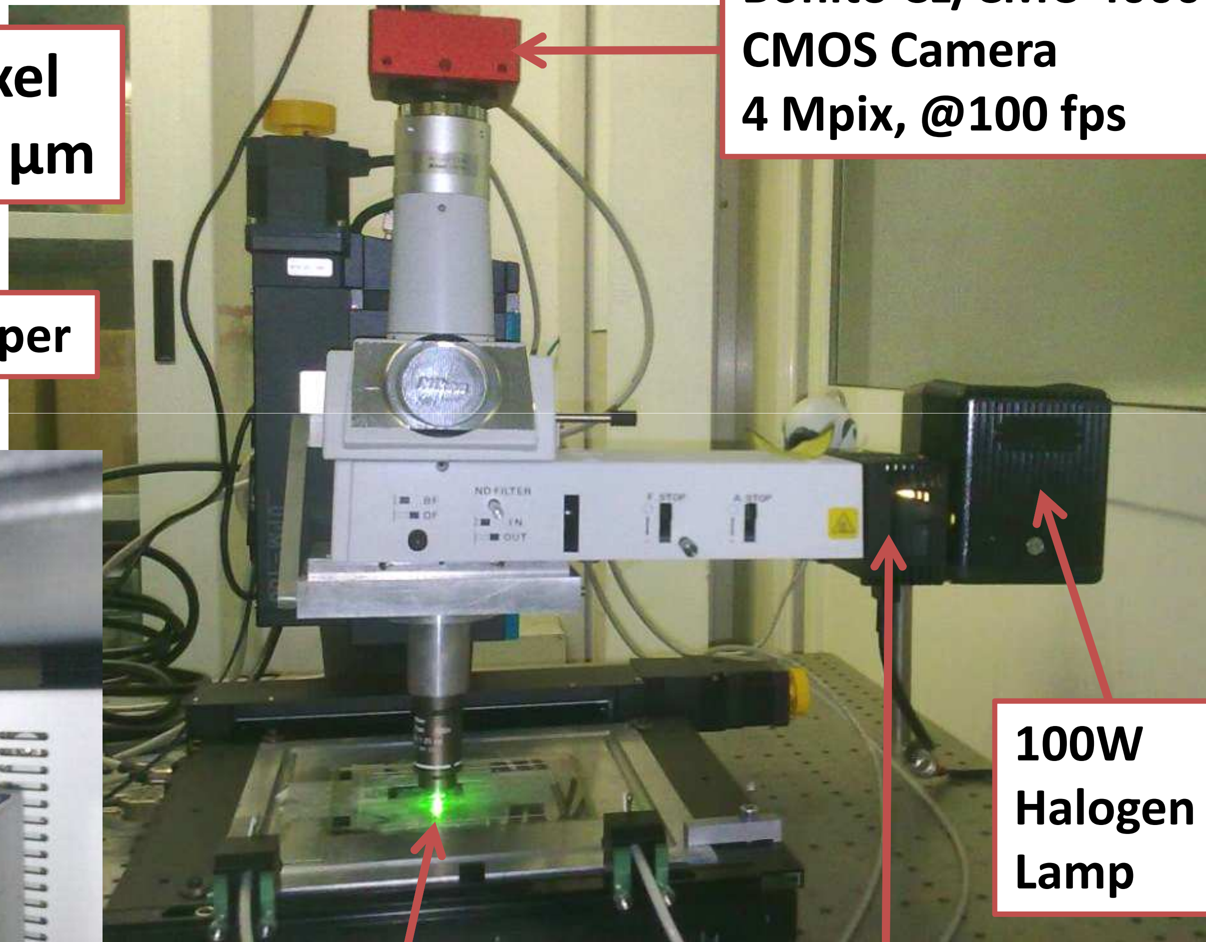
The overall gain of migrating to the new hardware is estimated to be ~4 times or about 150 cm^2/h for OPERA-like emulsion films

High resolution R&D for the directional DM search

Resolution: 28 nm/pixel
View Size: 65.2 x 48.3 µm

Pneumatic Vibration Dumper





Bonito CL/CMC-4000
CMOS Camera
4 Mpix, @100 fps

100W
Halogen
Lamp

Nikon Oil Objective
100x, 1.25 N.A., Plan

Green Optical
Filter

Conclusion

- Strong progress in a last two years in a scanning system development
- A new scanning system software LASSO permit to double the ESS scanning speed without HW modification and get to 40 cm^2/h
- New tracking has no intrinsic angular limits and demonstrated to be efficient from 0 to 85 degrees
- We started LASSO usage for the mass production: about 50000 cm^2 emulsion area for OPERA and other (medical tests, muon radiography, etc) scannings were acquired

Outlook

- Fast speed R&D is continued and with the hw upgrade we plan achieve 150 cm^2/h in a near future
- High resolution R&D is ongoing for the directional DM search – we are close to the required values (0.1 micron)
- With the introduction of the piezo-drive the speed of the high resolution system will reach 2-4 cm^2/h