



Tracking software in CMS and first reconstruction results from detector commissioning



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on behalf of CMS collaboration



Outline



- **The challenge of track reconstruction at LHC**
- **Description of the CMS Tracker**
- **Software for track reconstruction**
 - **description of the algorithm**
 - **performance**
 - **recent improvements**
- **Results from Tracker commissioning at the Tracker Integration Facility**



The challenges



pp-collisions at design luminosity ($10^{34}\text{cm}^{-2}\text{s}^{-2}$, 14TeV)

- 40 MHz crossing rate
- O(20) superimposed pileup (PU) events / crossing
- O(2000) charged tracks / crossing

Charged track density

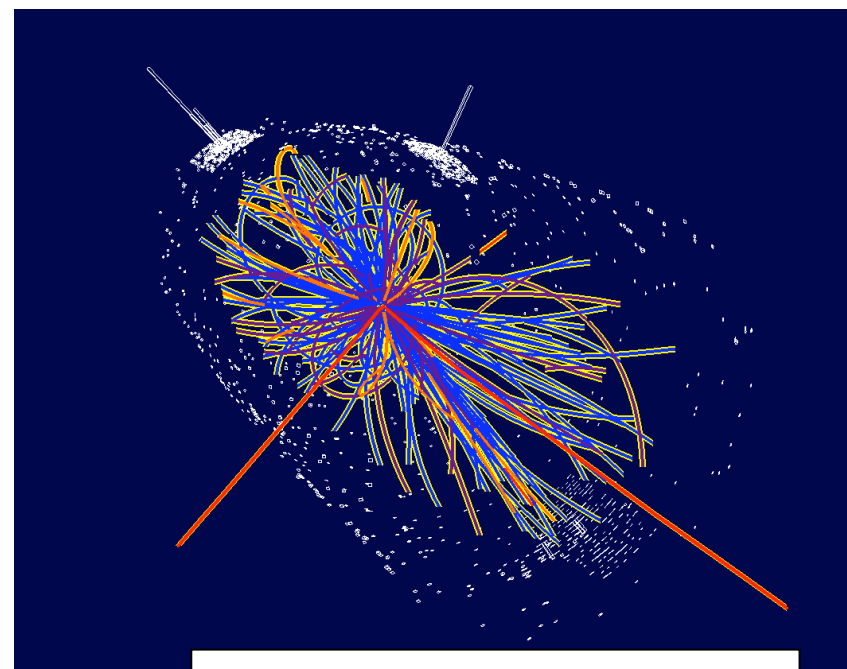
Radiation hardness

Trigger

- Levels 2-3 (HLT) includes track reconstruction:
Reduction from 100kHz to ~300Hz

Material budget

- high granularity and radiation hardness is obtained by means of a “heavy” tracker ($0.4\text{-}1.8 X_0$)

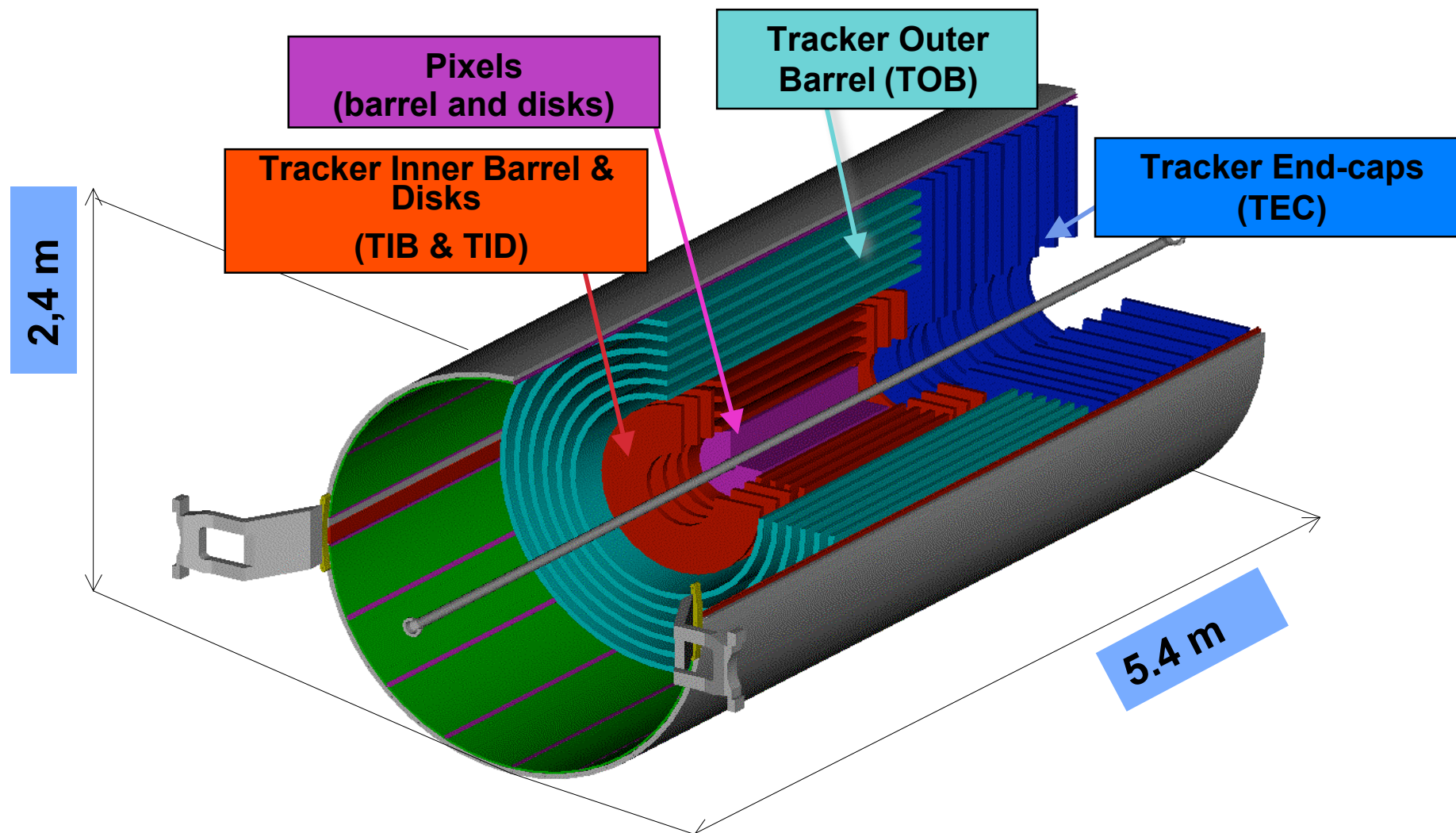


**Higgs \rightarrow $e e \mu \mu$ event
with Low Luminosity PU**



The detector

sub-structures of the full-silicon CMS tracker





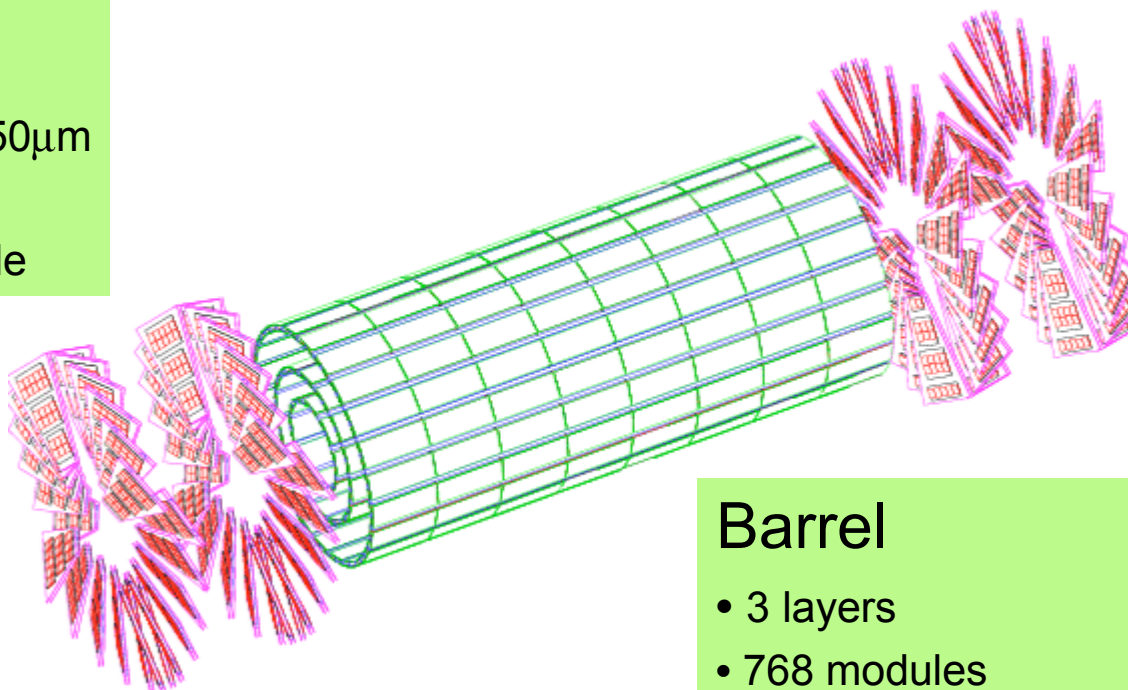
The detector

sub-structures of the full-silicon CMS tracker



Endcaps

- 2 x 2 layers
- 672 modules
- $|z| = 34.5 / 46.5$ cm
- Pixel size $100\mu\text{m} \times 150\mu\text{m}$
- 18 M pixels
- Tilted for Lorentz angle



Barrel

- 3 layers
- 768 modules
- $R = 4.4 / 7.3 / 10.2$ cm
- Pixel size $100\mu\text{m} \times 150\mu\text{m}$
- 48 M pixels
- Lorentz angle 23°

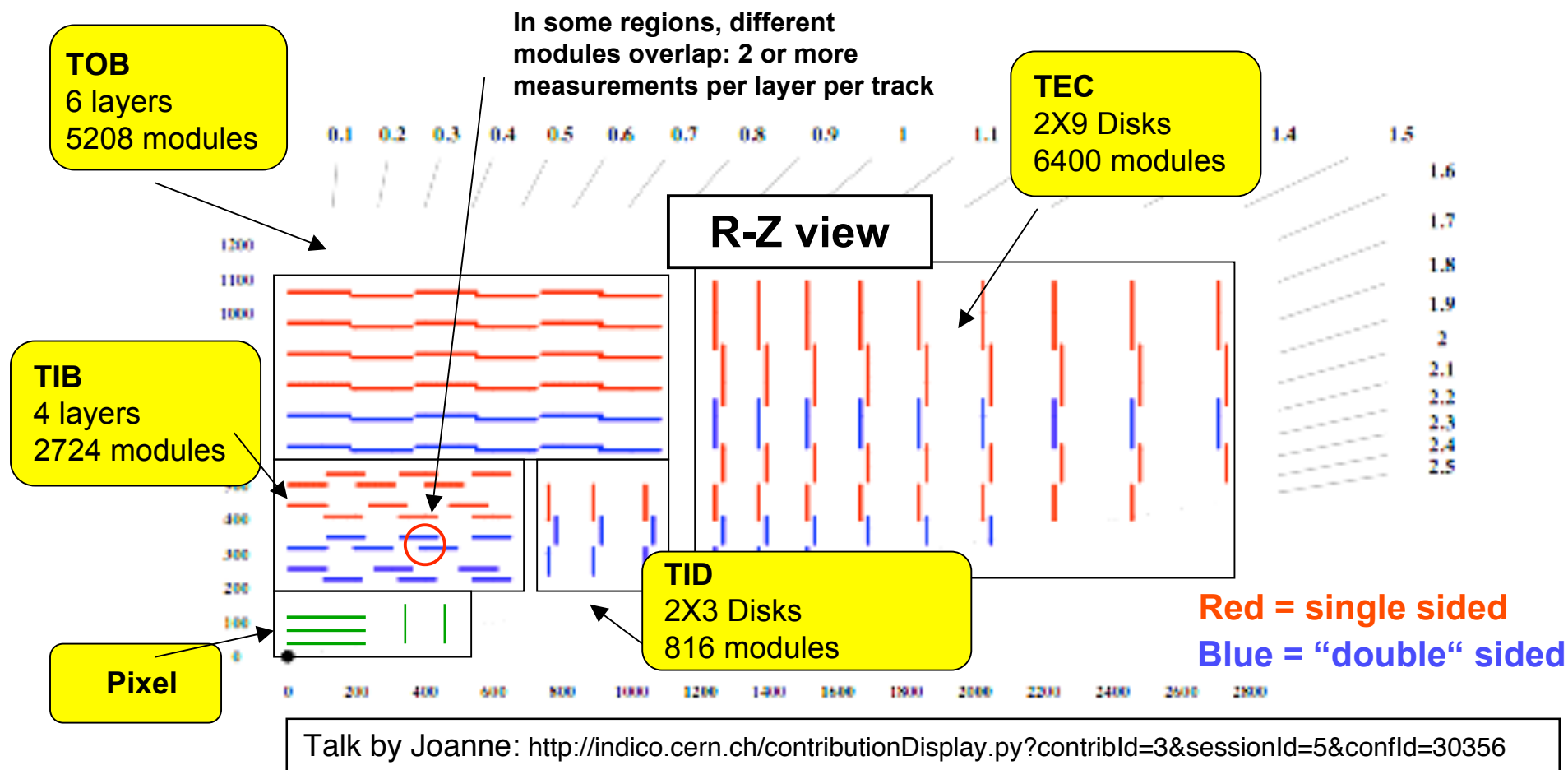
Talk by Hans-Christian:

<http://indico.cern.ch/contributionDisplay.py?contribId=7&sessionId=6&confId=30356>



The detector

sub-structures of the full-silicon CMS tracker



Strip lengths range from ~10 cm in the inner layers to ~20 cm in the outer layers.
Strip pitches range from 80 μm in the inner layers to near 200 μm in the outer ones.



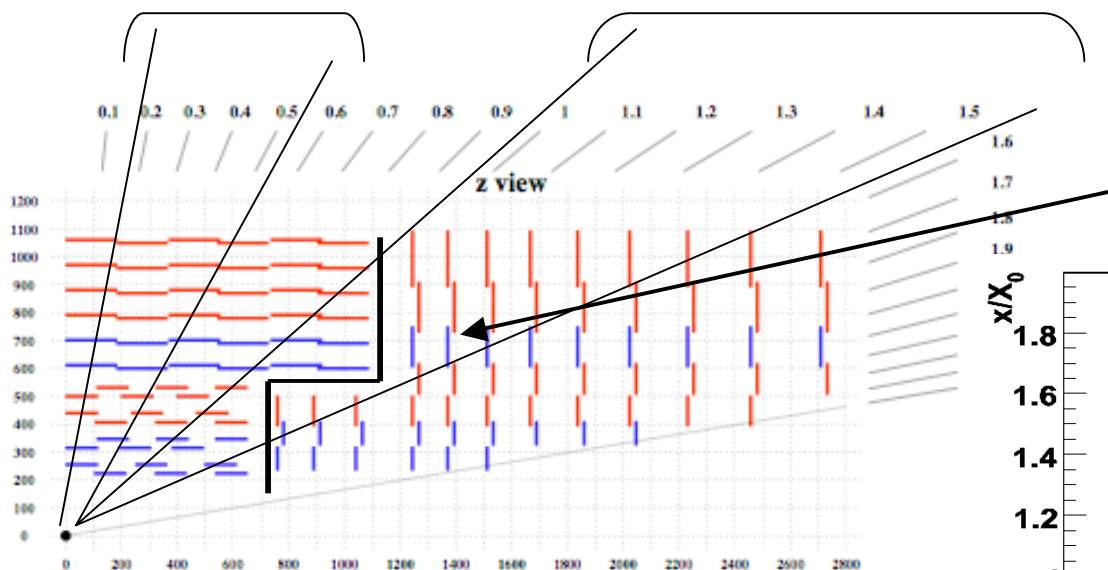
The detector

Material budget

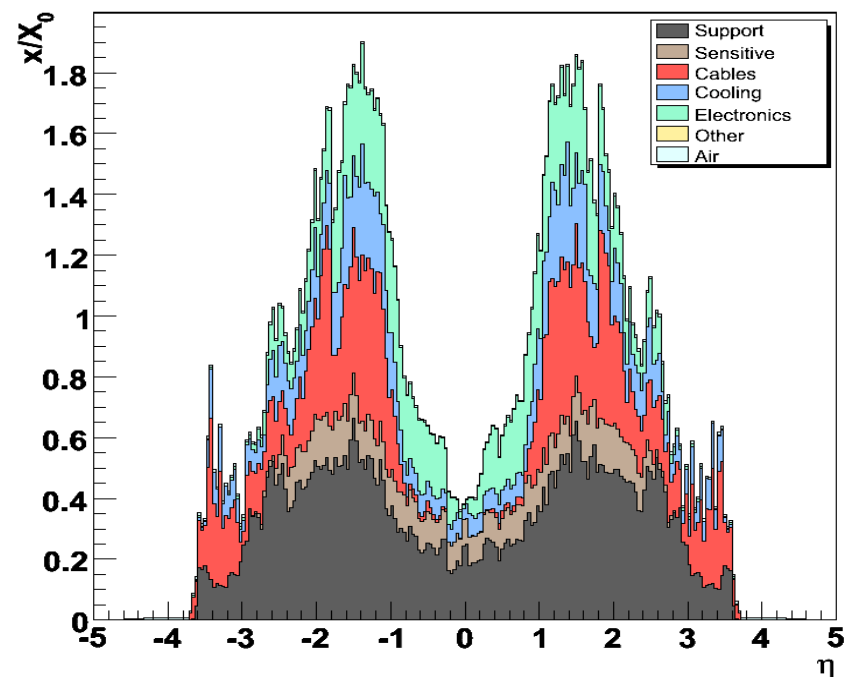


material crossed by a primary track increases for a geometrical effect: $l = h/\sin(\theta)$

most of the services are concentrated in this “barrel-endcap transition region”.



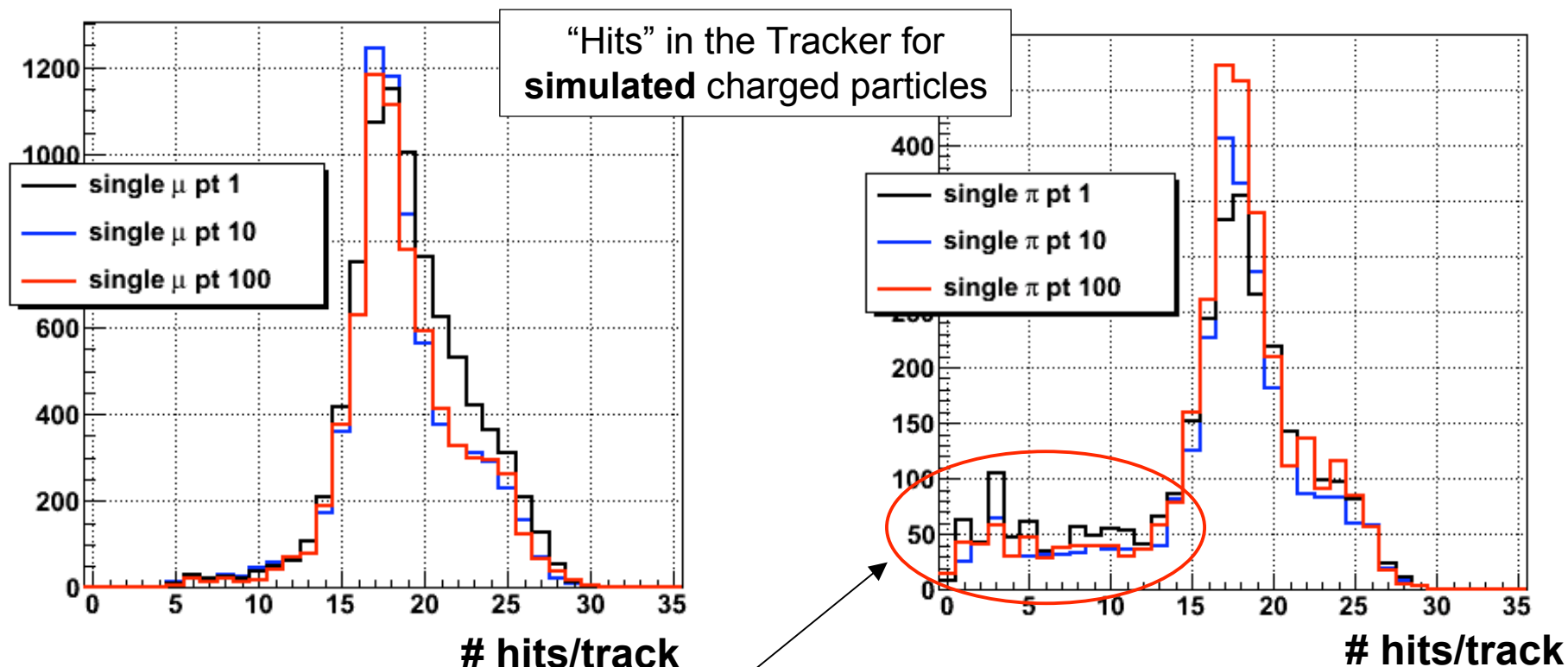
Path where many of the cables, fibers and services are.





The detector

Material budget



Because of inelastic nuclear interactions, many primary charged pions are detected only on the few innermost layers of the tracker: such particles can be reconstructed only as short tracks.



general purpose tracking

reconstruction algorithms in CMS



pixel and strip clustering

Strip and pixel signals are clustered. Positions and corresponding error matrices of each “hit” are evaluated

Trajectory seeding

Initial estimate of trajectory parameters from a small subset of tracker measurements (hits on seeding layers).

Trajectory building

An iterative process which collects all the measurements associated to the same charged particle.

Trajectory fitting

Estimate of final track parameters from the fit of the full set of measurements associated to the same charged particle.

Track collection
filtering

Removal of “ghost” tracks + quality filter.



general purpose tracking

reconstruction algorithms in CMS



Two different general purpose tracking algorithms are currently implemented:

1. Combinatorial Track Finder (CTF) is the default one:

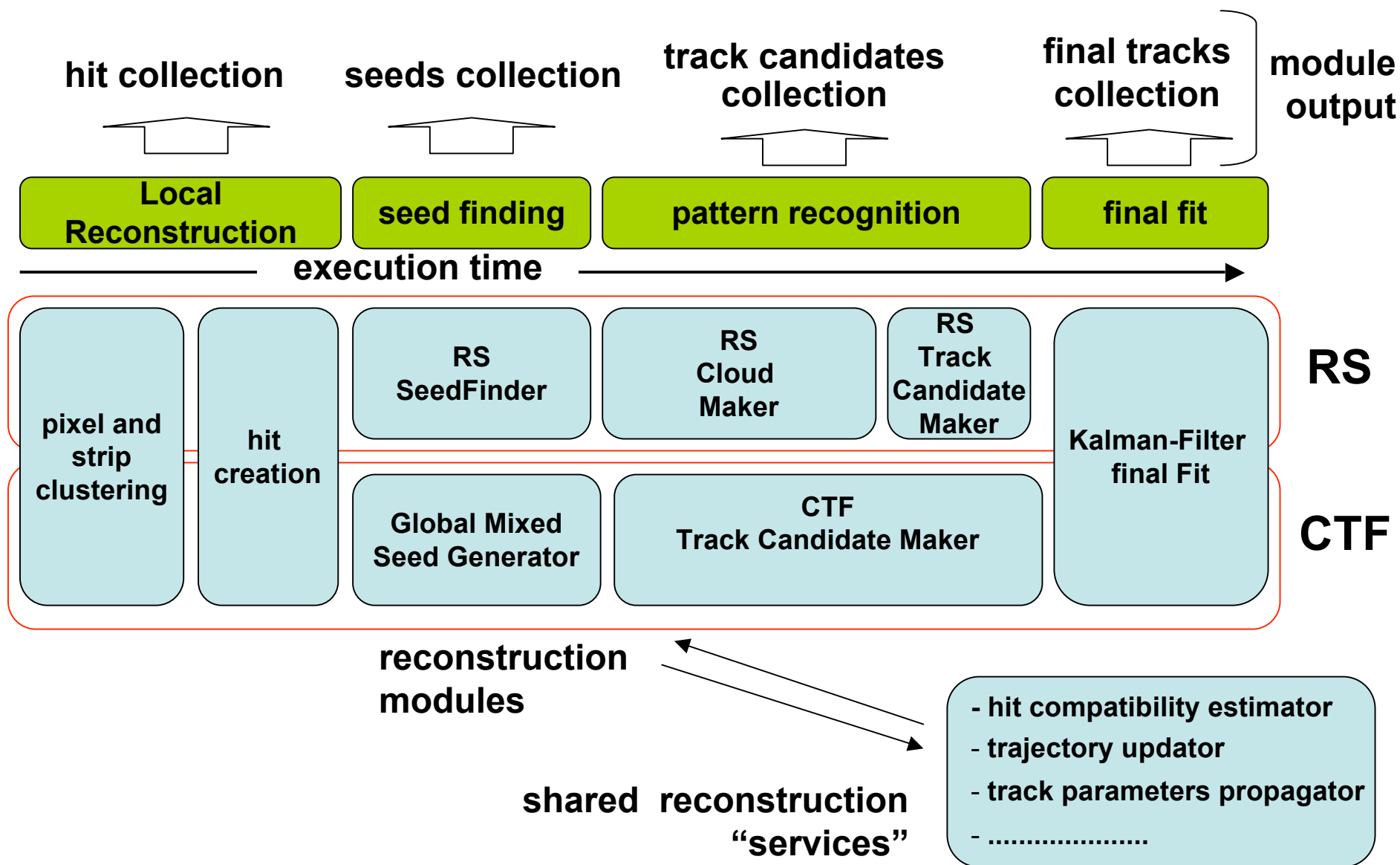
- the seeding uses innermost tracker's layers.
- the pattern recognition uses a track-following approach: every time a new hit is associated to the track candidate, the parameters of the “partially reconstructed” trajectory are re-evaluated and the search window on the next tracker layer is narrowed, according to the smaller uncertainty on the track parameters themselves.
- The final set of hits is fitted using a Kalman-Filter fitting/smoothing logic.

2. Road Search (RS):

- the seeding is based on hits from modules on inner and outer layers of the tracker.
- the pattern recognition initially uses a set of pre-calculated trajectory's *roads* to collect *clouds* of hits along the direction of the seed. The final set of compatible hits is then obtained after a subsequent cleaning of the hits collection.
- The final fit is identical to the one used by the CTF algorithm.



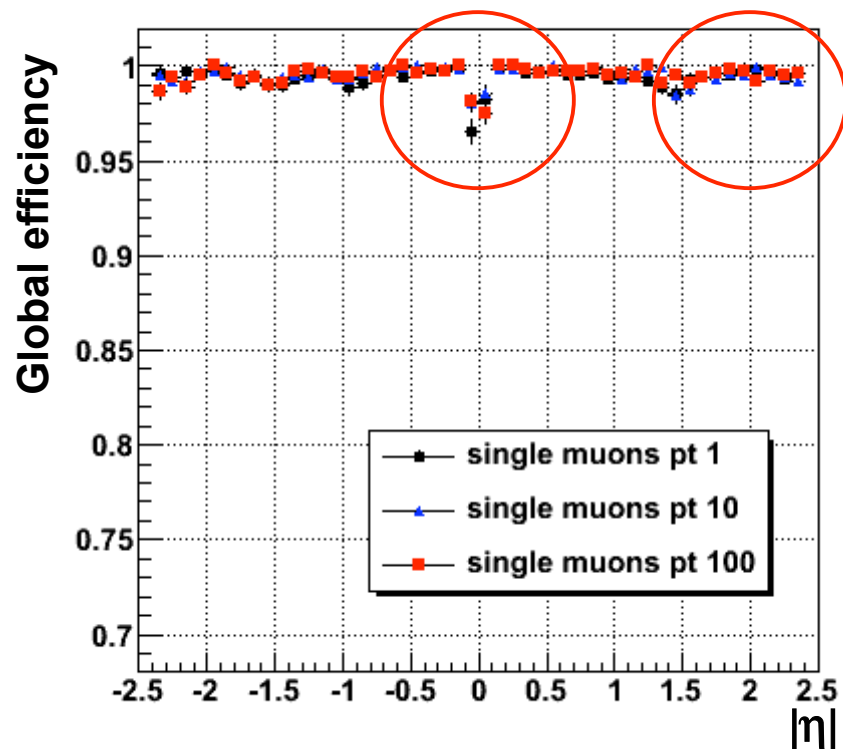
Tracking modules in CMS software



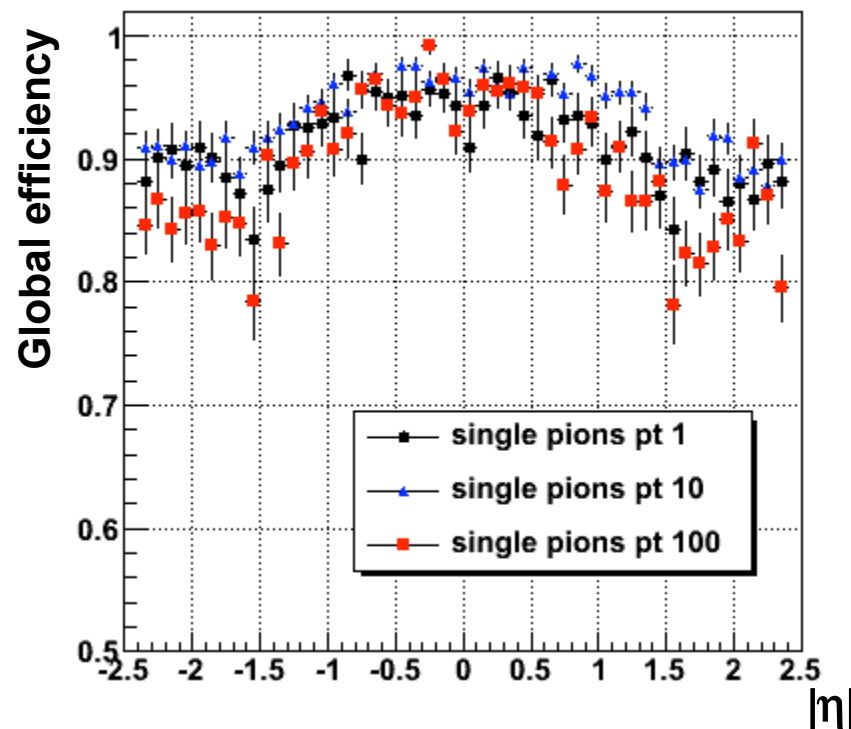


Track reconstruction performance

Global efficiency



- Recent efforts to maximize the efficiency at high η : new seeder combining pixel and strip hits.
- work in progress to fix remaining efficiency hole at $\eta \sim 0$.



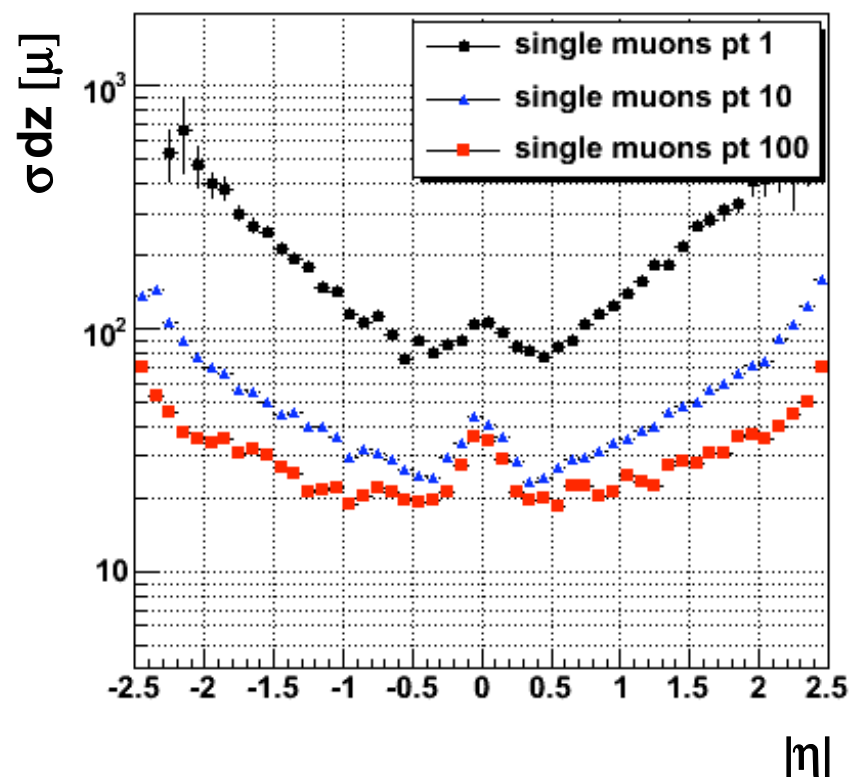
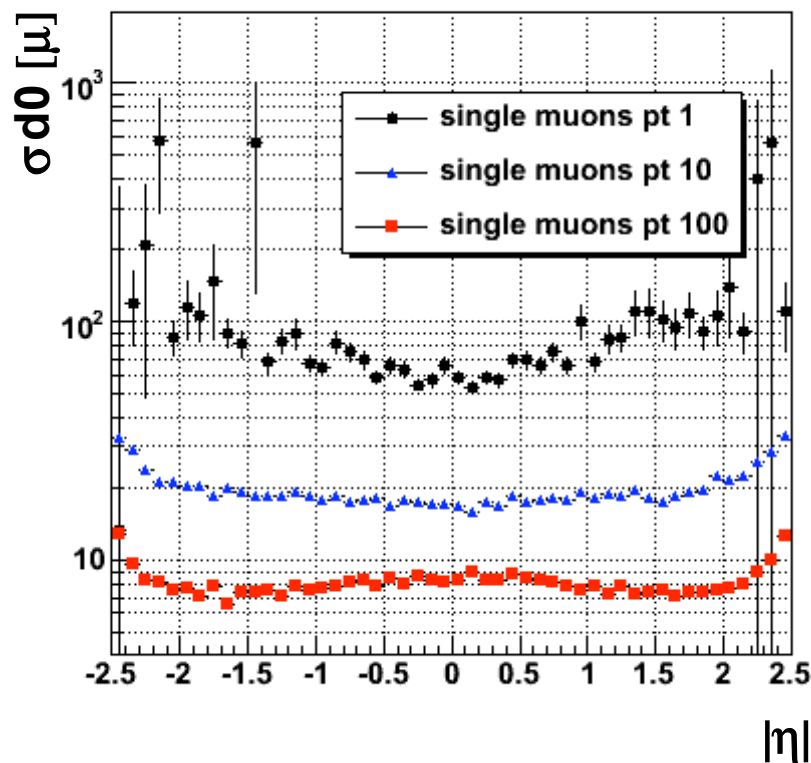
- Because of inelastic nuclear interactions, around 10% of pions cannot be reconstructed: # available measurements < 3 .



Track reconstruction performance



Impact parameter resolution



Resolution on transverse impact parameter is expected to be:

~50-60 microns for ~1 GeV particles

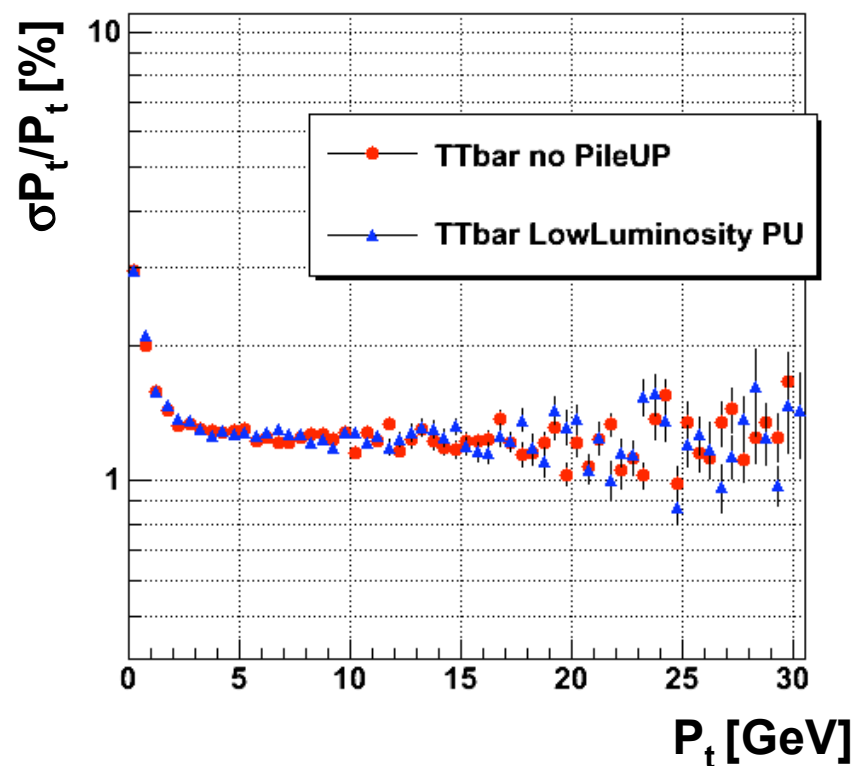
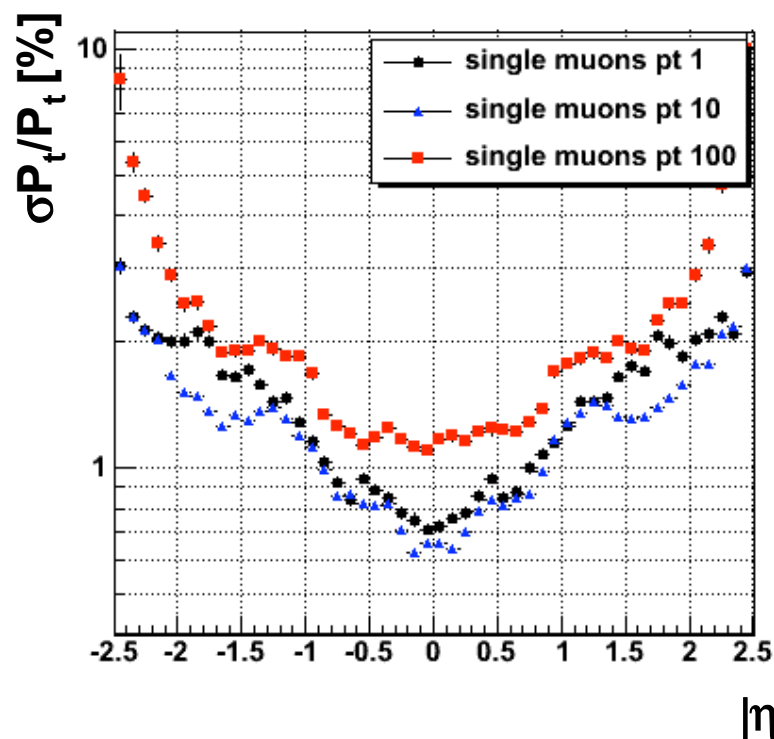
~10 microns for 100 GeV particles



Track reconstruction performance



Transverse momentum resolution



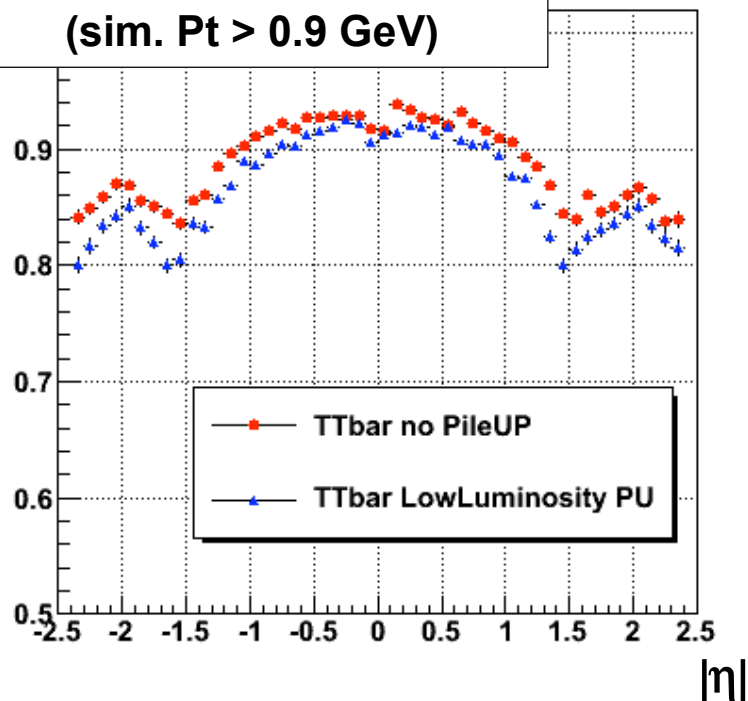
- In the barrel region, the resolution on transverse momentum is $\sim 0.5\%$ for particles with $P_t = 10$ -100 GeV.
- In the high eta regions of endcaps, the resolution on transverse momentum degrades to $\sim 3\%$ because of the smaller lever arm used to evaluate the curvature of the tracks.



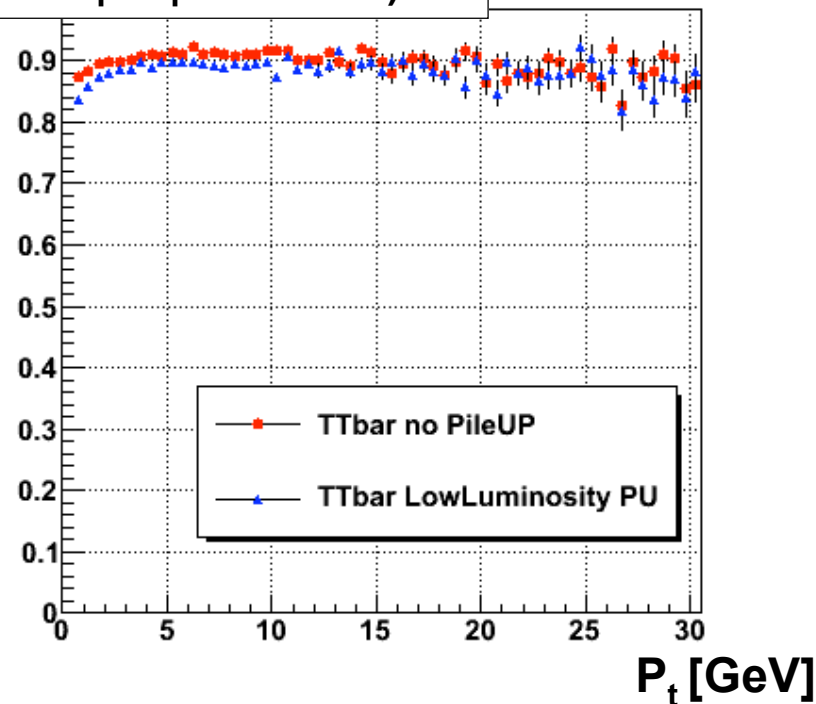
Track reconstruction performance



Global efficiency vs $|\eta|$
(sim. $P_t > 0.9$ GeV)



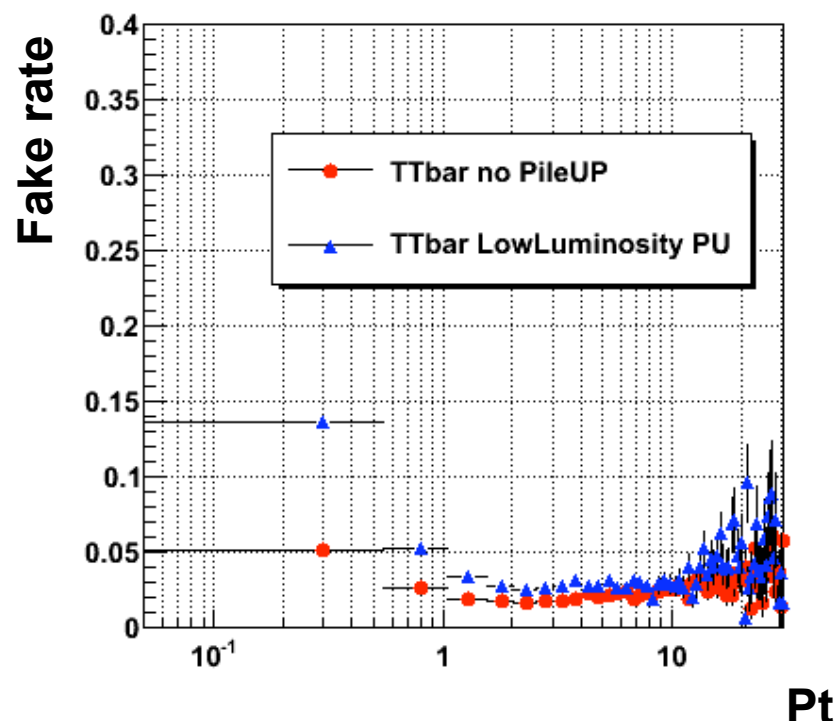
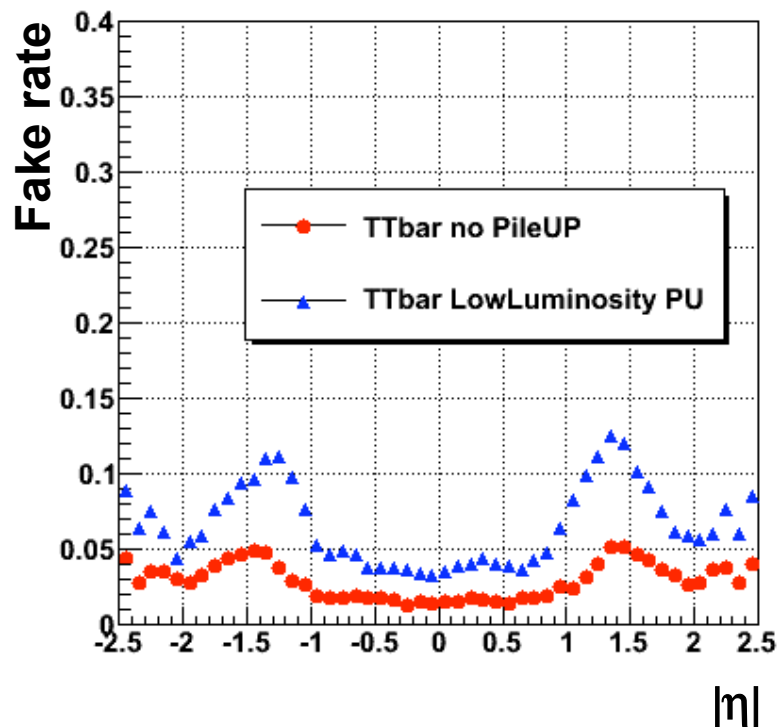
Global efficiency vs P_t
(sim. $|\eta| < 2.5$ GeV)



- reconstruction efficiency on multi-track events is dominated by pion reconstruction efficiency
- efficiency is lower in the barrel-endcap transition region ($\eta \sim 1.5$) where the material budget has its maximum value.



Track reconstruction performance



$$\text{Fake rate} = \frac{(\# \text{ tracks NOT associated to simulation})}{(\# \text{ reconstructed tracks})}$$

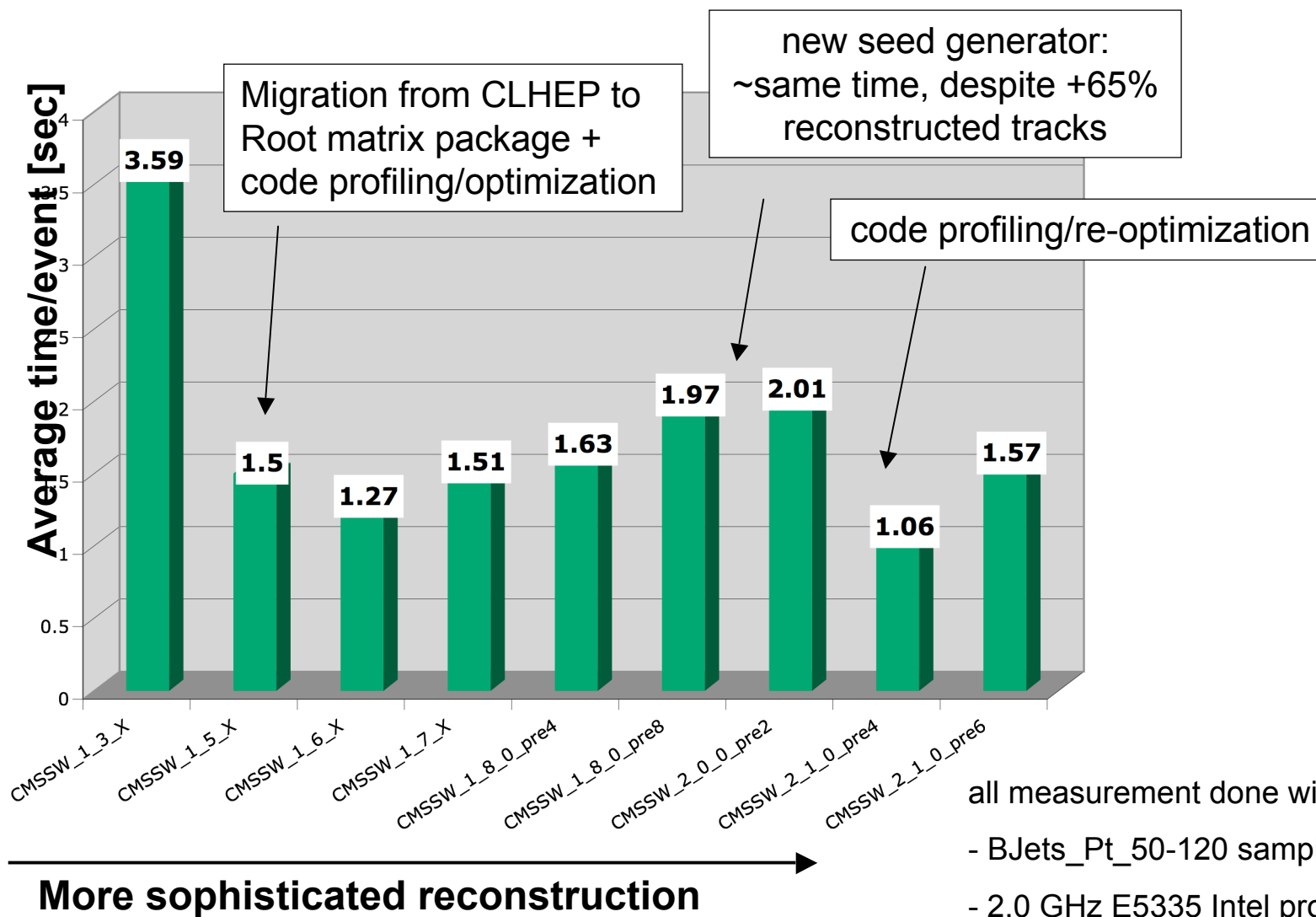
A reconstructed track is associated to a simulated one if more than 75% of its hits are “matched” to the ones of the simTrack.

Most of the fakes are in:

- the low p_t region
- barrel-endcap transition eta region



Timing optimization

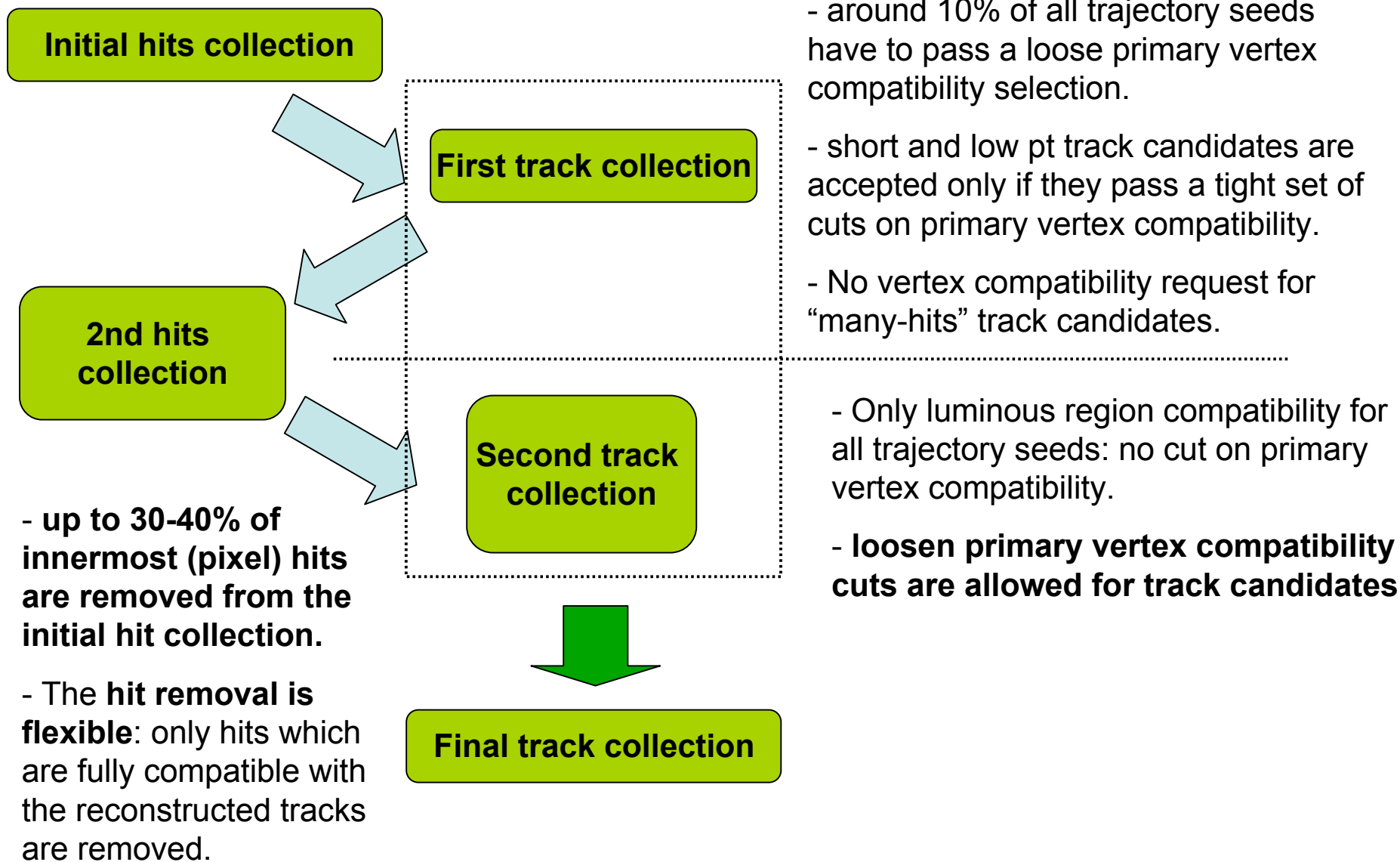


all measurement done with:

- BJets_Pt_50-120 sample w/o PU
- 2.0 GHz E5335 Intel processor
- code compiled with gcc345



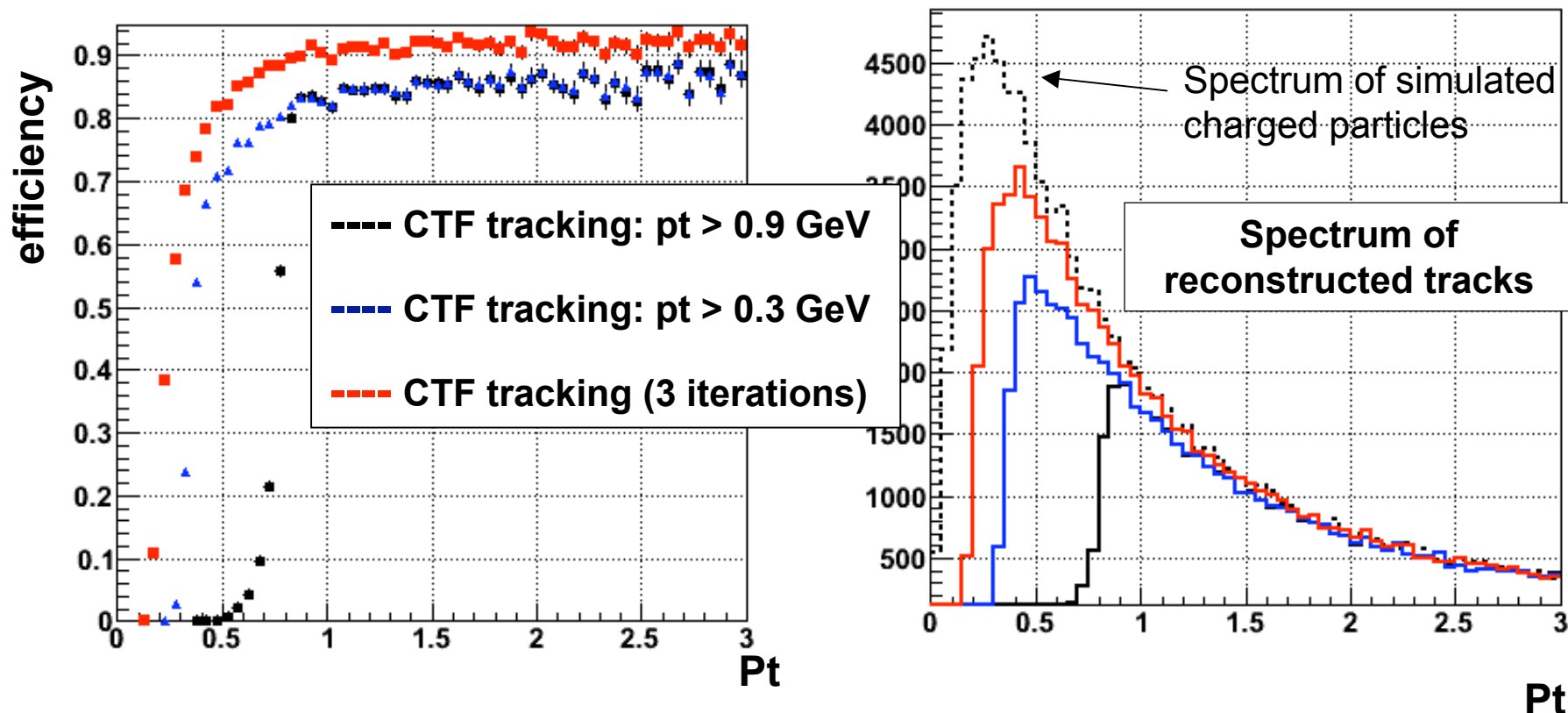
Iterative tracking





Iterative tracking

recovery of low pt particles

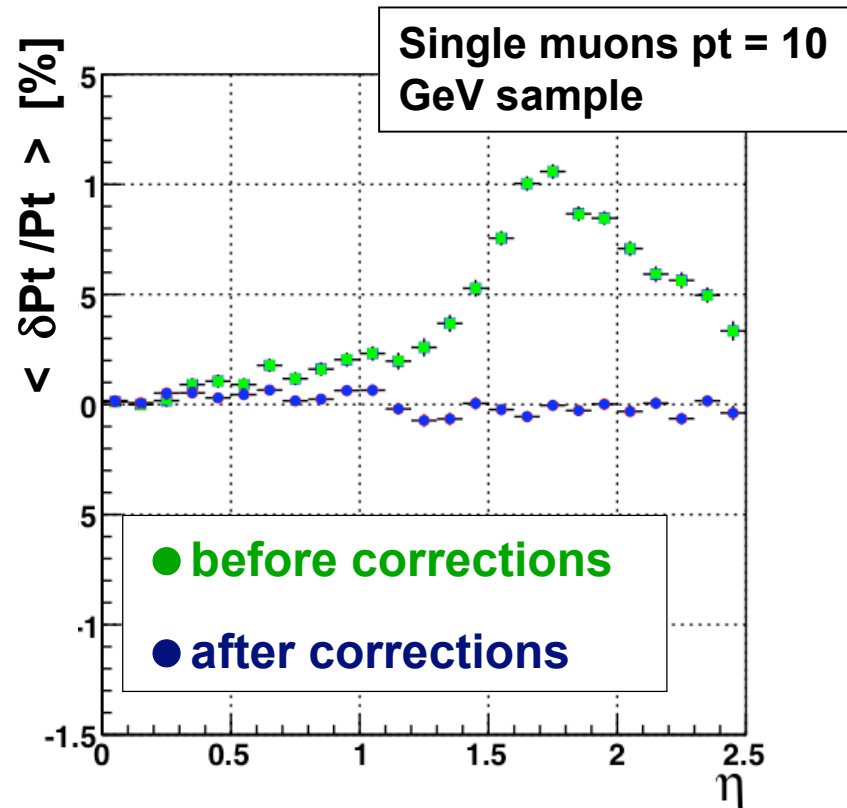


- + 3-5% of tracks are recovered in the $Pt > 1$ GeV region thanks to the looser vertex compatibility cuts for seeds and short track candidates of the 2nd and 3d iterations.
- up to +40% tracks in the $pt < 0.5$ GeV region are recovered thanks to the much looser vertex compatibility cuts for low pt tracks



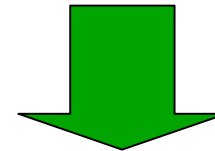
Runge-Kutta propagator

reduction of bias on reconstructed pt



In the tracker endcaps the magnetic field cannot be considered homogeneous between 2 consecutive tracker layers.

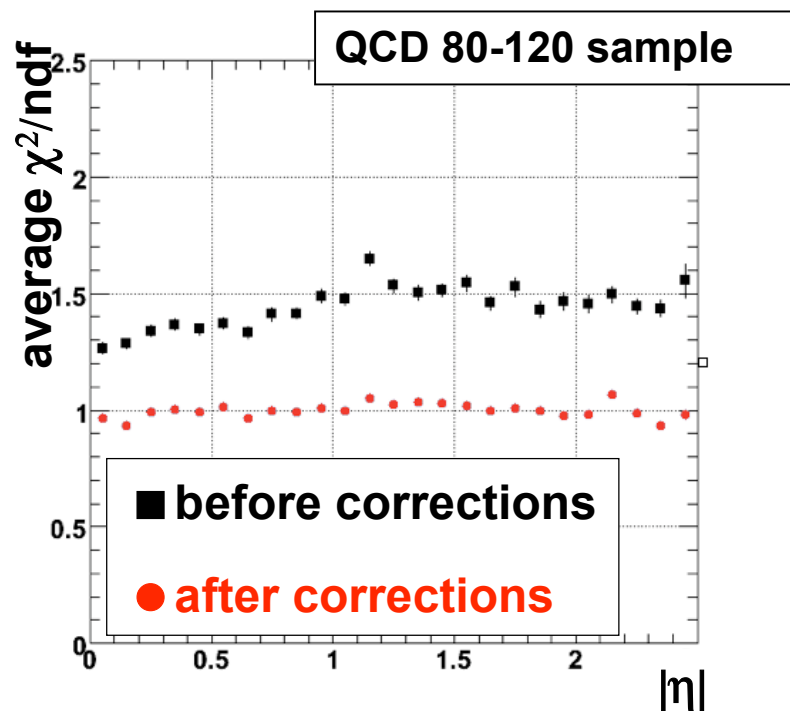
A track parameters propagator based on Runge-Kutta methods takes into account magnetic field non-homogeneity during the final fit of tracks.



Bias on reconstructed Pt is reduced from 1% to less than 0.1%



Other improvements to final track fit



- reconstruction software is using now a more accurate parameterization of material budget
- better handling of magnetic field non-homogenities (Runge-Kutta propagator)
- more advanced “cluster parameter estimator” for pixels (templates based)
- rejection tool for “outlier hits”

Talk by Vincenzo for pixel Templates:
<http://www.tsl.uu.se/vertex2008/page3/page3.htm>



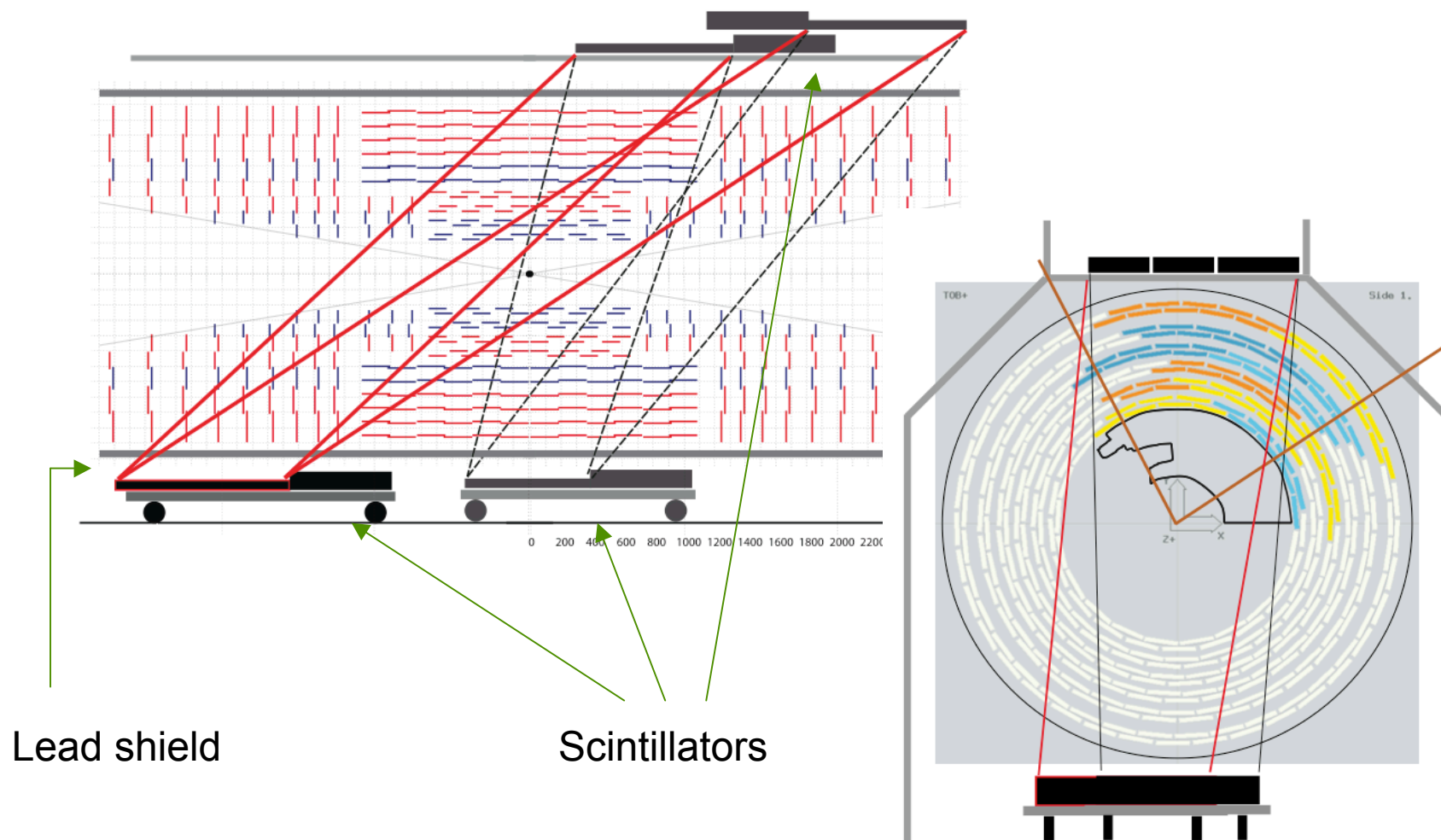
CMS Tracker commissioning at the Tracker Integration Facility



- **Opportunities**
 - First large-scale common test of all the strip sub-detectors.
 - A wealth of data:
 - More than 4 M „good“ events at different readout settings, temperatures and trigger configurations
 - Taken in conditions close to the final ones
 - Allowed for verification of HW, SW and calibration procedures
- **Challenges**
 - Cosmics on surface: weak constraints and low momentum
 - Code needed to be adapted: trigger conditions, partial readout of the tracker, no momentum measurement.



CMS Tracker commissioning at the Tracker Integration Facility





CMS Tracker commissioning at the Tracker Integration Facility

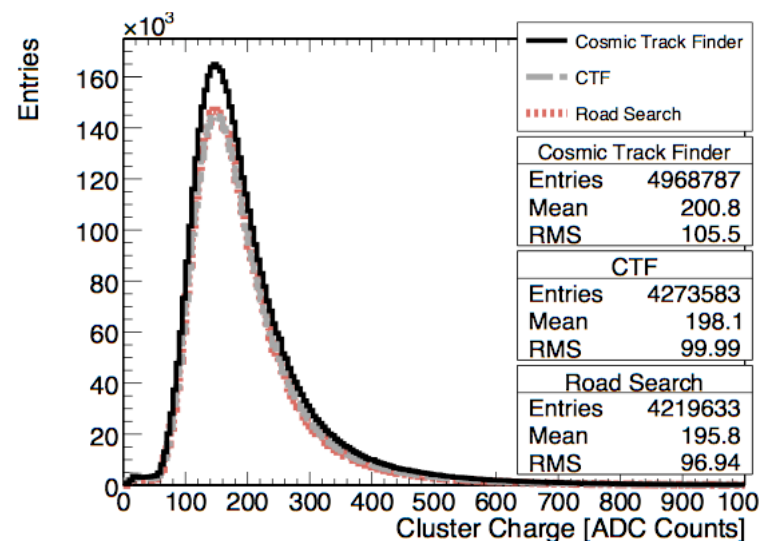
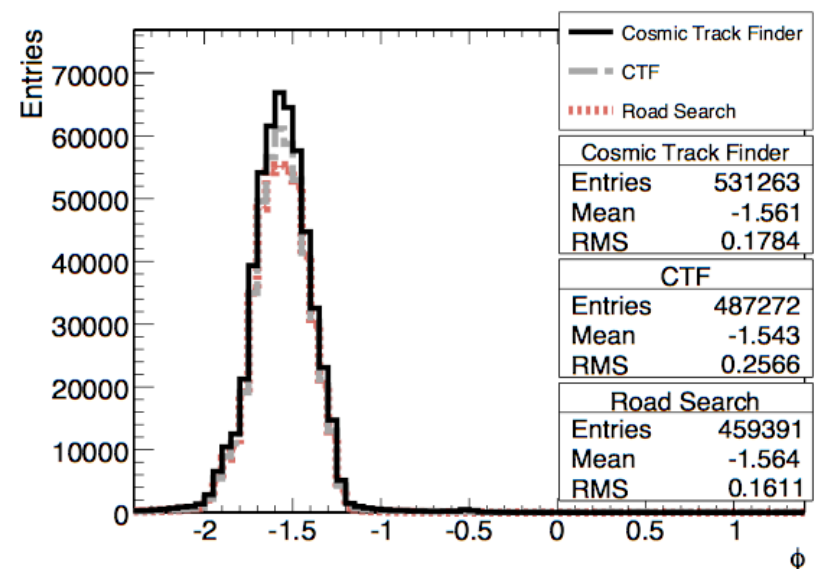


3 reconstruction algorithms used for cosmic data taking:

- CTF with seeder for cosmic
- RS with seeder for cosmic
- Cosmic Track Finder (CosmicTF):
ad-hoc algorithm for cosmic tracks

Result of the 3 algorithms were comparable.

**Opportunity to debug and improve
(80% of) the standard track
reconstruction sequence ON REAL
DATA**



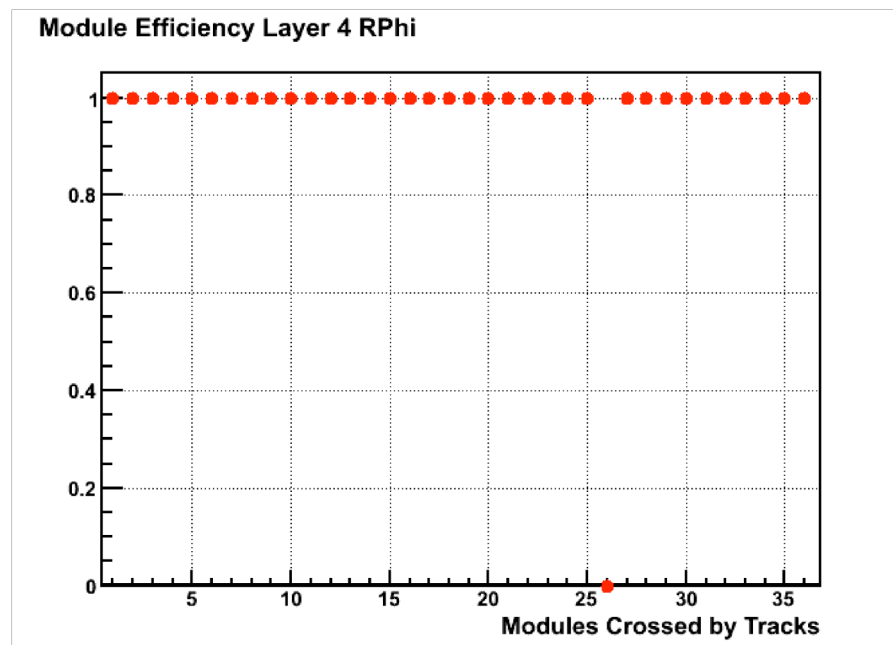
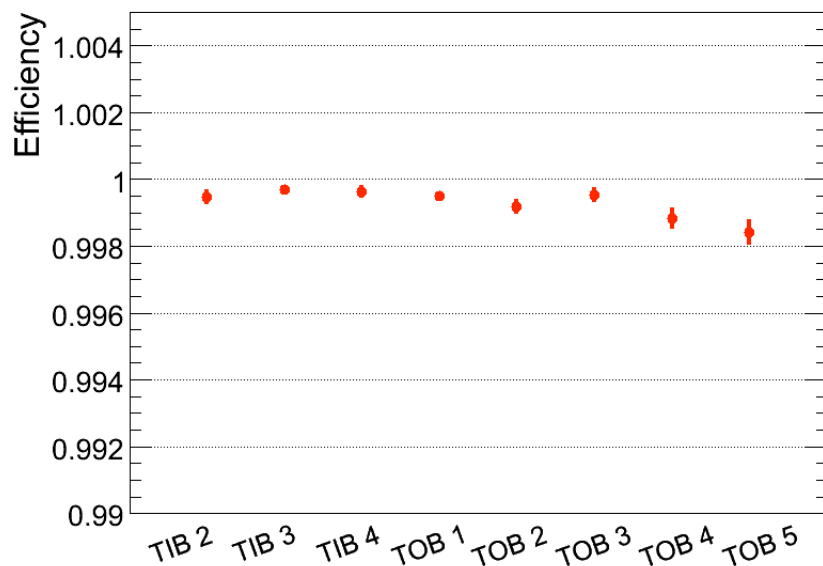


CMS Tracker commissioning at the Tracker Integration Facility



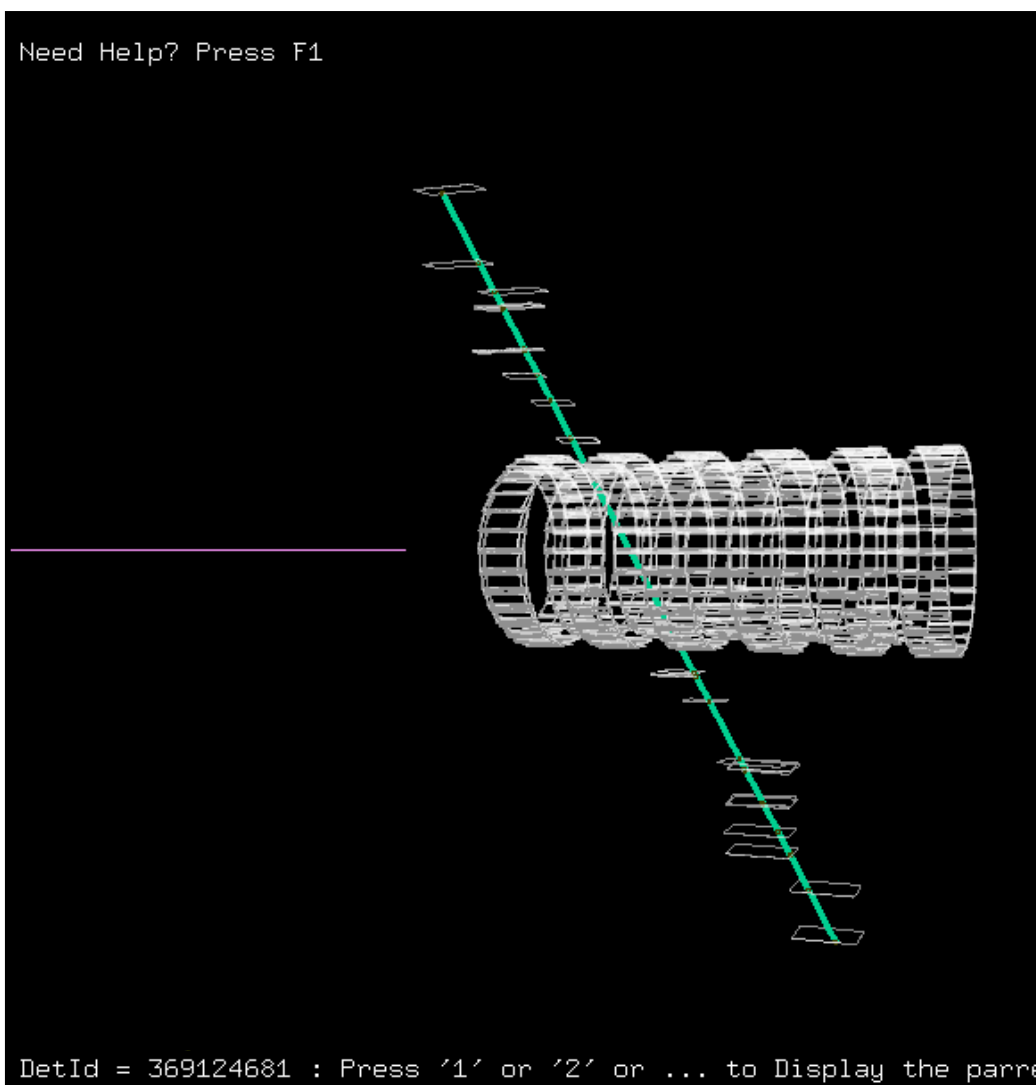
Hit efficiency

- Checks for hits if the (unbiased) track prediction is well within the fiducial area of a module
- Shows (fortunately!) the obvious result: very high and stable efficiency





CMS Tracker commissioning at P5



- almost complete silicon strip Tracker system has been readout simultaneously:

97% TIB/TID/TOB

95% TEC+

- ~200k cosmic tracks have been reconstructed and being used for alignment

- 81% TEC- readout separately

- Pixel detector being inserted during these days



Conclusions



- CMS tracker has been designed to cope with LHC conditions of radiation and track multiplicity.
- The material budget of the CMS tracking system is a challenge for track reconstruction concerning with efficiency and fake rate.
- The reconstruction software of CMS has been designed to:
 - be modularized and flexible
 - cope with “not negligible” tracker material budget
- Recent extensions of the tracking algorithms have increased the track efficiency (in particular at low pt), improved the quality of the reconstructed tracks and sensibly decreased the execution timing.
- Most of the offline tracking modules have been successfully used to reconstruct millions of cosmic tracks at TIF and P5.