Track reconstruction in CMS high luminosity environment

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on behalf of
CMS collaboration

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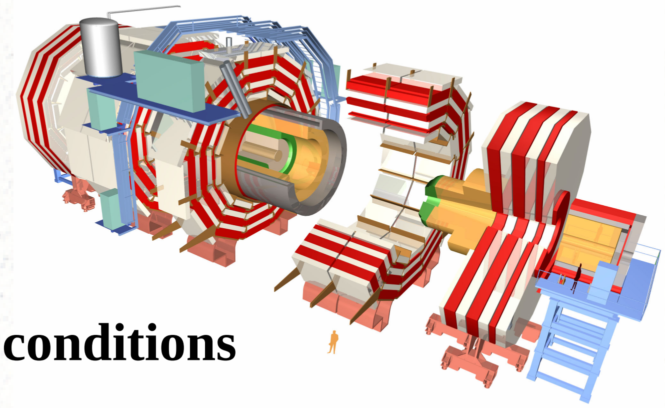
Outline

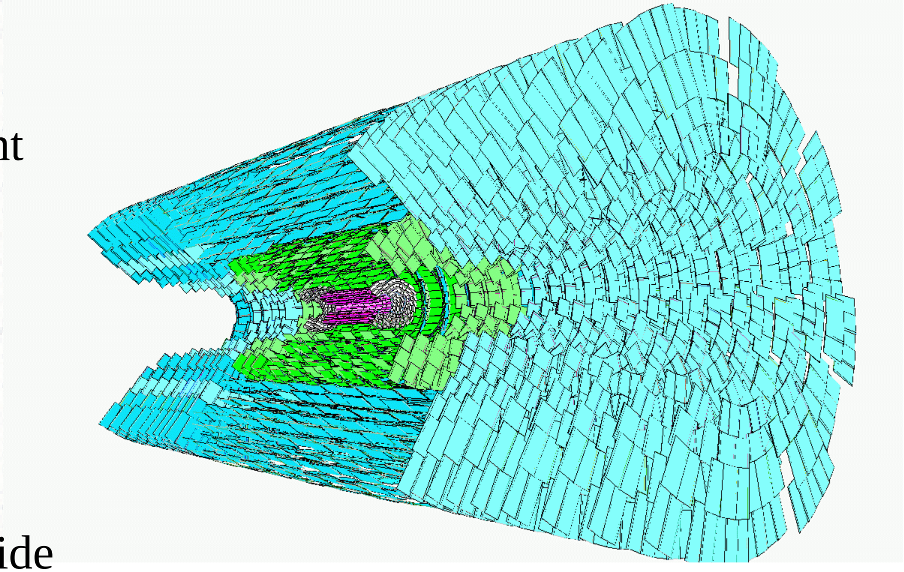


- **The CMS silicon tracker**
  - Pixel detectors
  - Microstrip detectors
- **Hit reconstruction performances under LHC conditions**
  - Pixel efficiency vs occupancy
  - Pixel resolution vs irradiation
- **Track reconstruction in high occupancy environment**
  - Track reconstruction steps
  - Iterative tracking
  - Algorithm optimization : gain in CPU time and efficiency
- **Conclusions**

The CMS tracker

100 % silicon tracker

- Pixel detectors close to interaction point
- Microstrip detectors in the outer parts

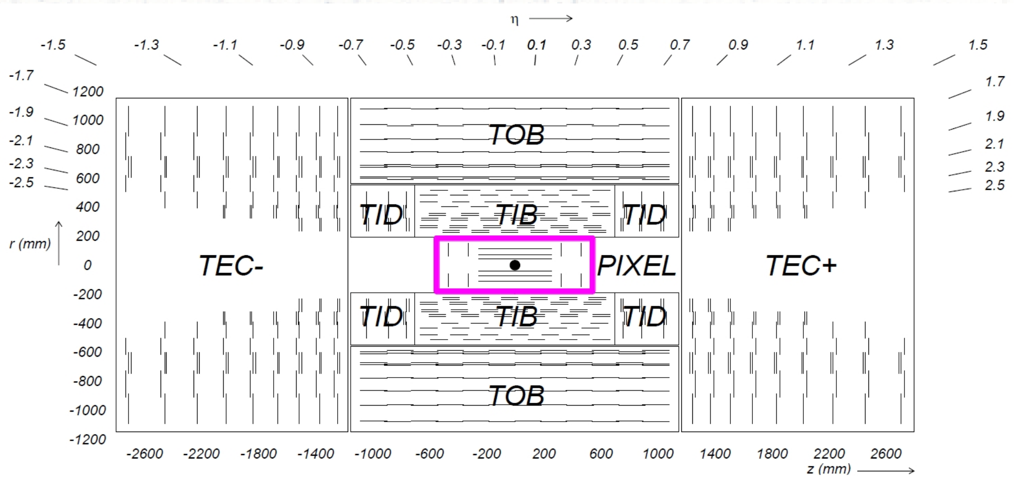


Largest silicon tracker ever built

- Radius : 110 cm / Length : 540 cm
- Barrel : 13 cylinders (3 pixels)
- Endcaps : 14 disks (2 pixels) on each side

Reconstruction of charged particles tracks

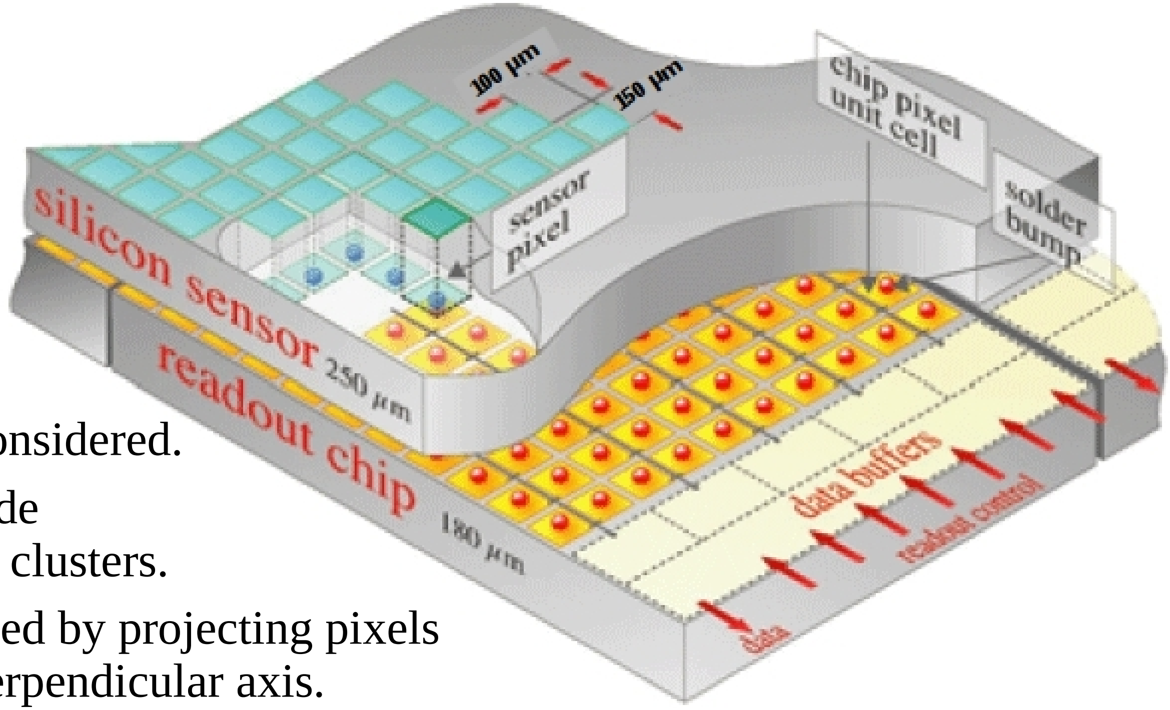
- Measure charge and transverse momentum.
- Estimate the positions of interaction vertices using tracks informations



The pixel detector

Pixel size : 100 x 150 µm²

Each Read Out Chip (ROC) reads 80x52 pixels



Hit reconstruction

- Pixels with a charge above a configurable threshold are considered.
- Adjacent pixels (sharing a side or a corner) are grouped into clusters.
- *Projected-clusters* are obtained by projecting pixels charges onto local *u* and *v* perpendicular axis.

First-Pass reconstruction

- Fast, used in track reconstruction
- Charge-weighted mean used to estimate *u* and *v* position, corrected in transverse direction to account for Lorentz drift

Template-Based reconstruction

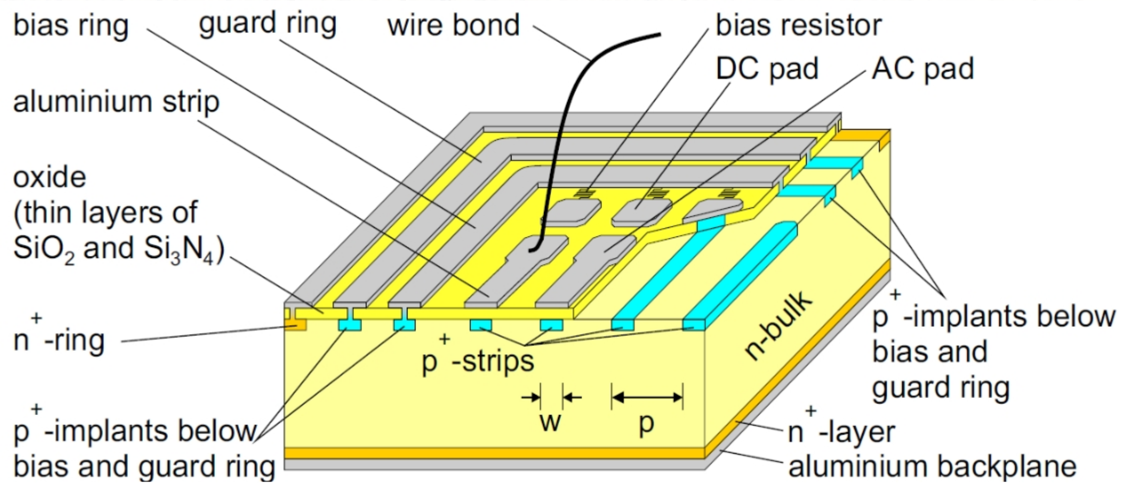
- More accurate, used in track final fit
- Projected distributions are compared with templates obtained from simulation
- Account for aging, crossing angle

The microstrip detector

9,3 millions microstrips
in 15148 modules.

Characteristics adapted to the different regions :

- Pitch : from 80 to 205 µm
- Thickness : 320 or 500 µm



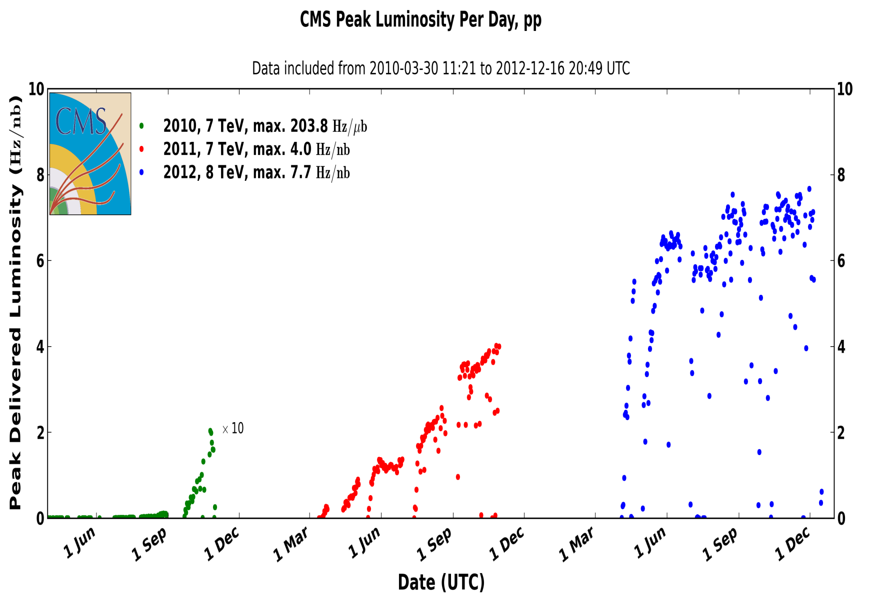
Hit reconstruction

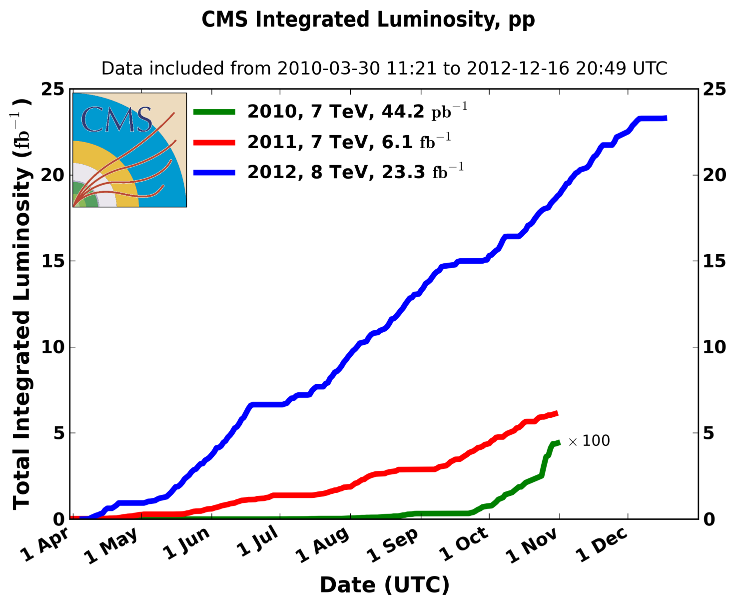
- Signal is read by analogic chips (128 channels by chip) and send to an electronic table
- Channels with S/N > 2 are kept for hit reconstruction
- Selected microstrips are grouped into clusters.
- Position estimated by charge-weighted mean, corrected for Lorentz drift.

Stereo layers (2 in TIB, TIDs, and TOB and 3 in TECs) associate back to back 2 microstrip detectors with a relative 100 mrad angle, providing 2D resolution

The LHC conditions

Tracker performances are impacted by instantaneous and integrated luminosity





Instantaneous luminosity

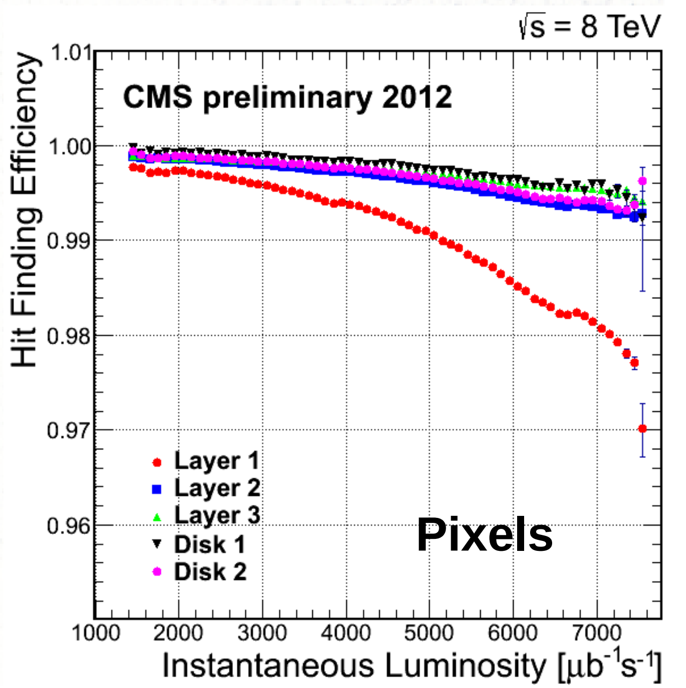
Higher **occupancy** could cause inefficiencies. At maximum luminosity, average number of **« pile-up » vertices is ~ 25**.

Integrated luminosity

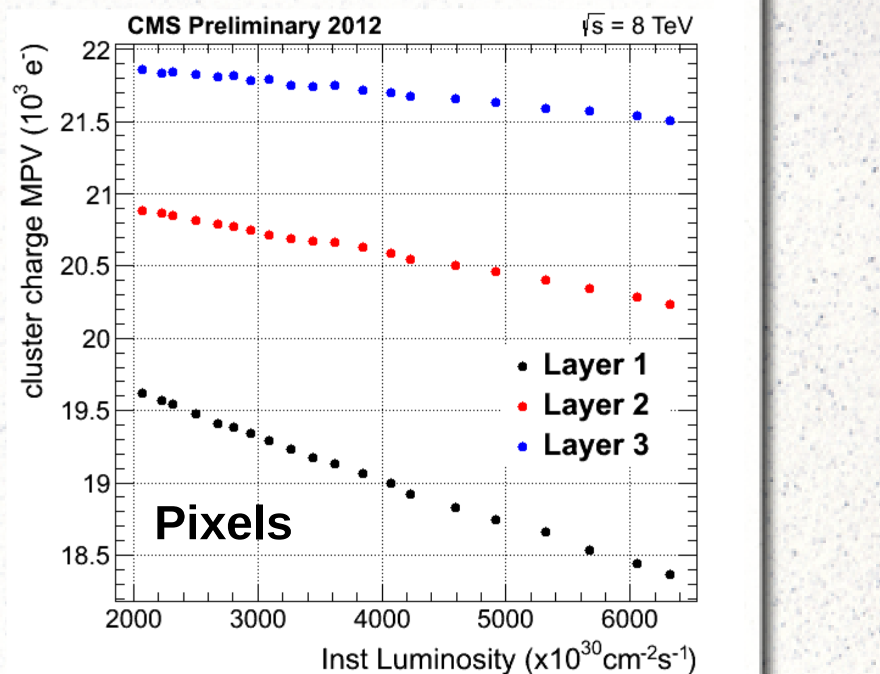
The level of radiation recieved over time affect the performances of the sensors. Especially for **inner pixel layers**.

Pixel efficiency vs occupancy

Hit efficiency : probability to reconstruct a hit when a charged particle crosses a sensor



Particle flux in pixel layer 1 : ~ 30 M/s/cm²
At max 2012 luminosity

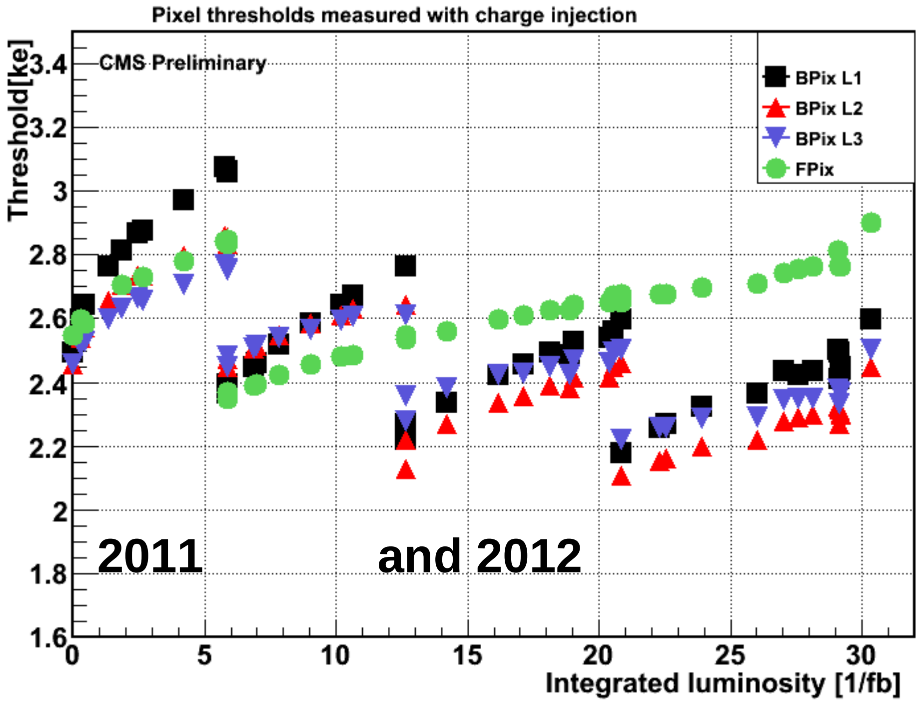


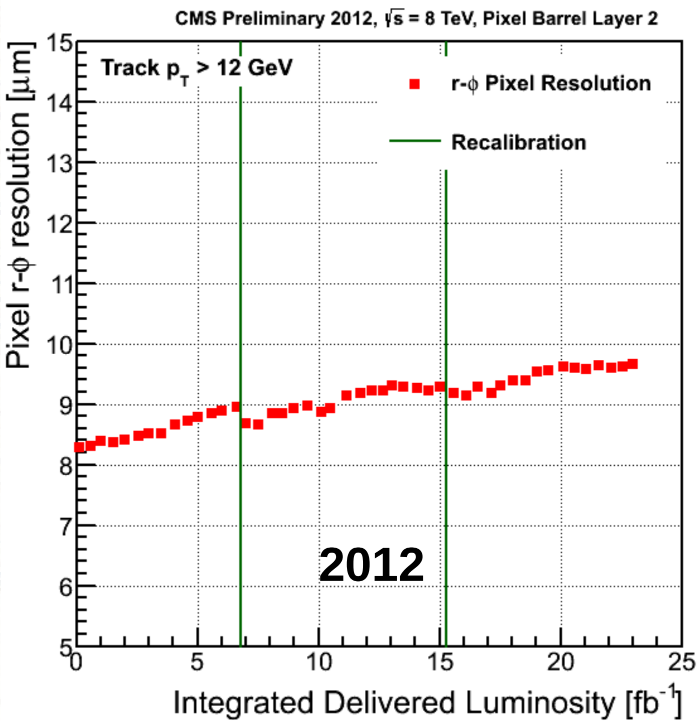
High occupancy impact on efficiency

- Increase temperature in ROCs : charge gain is lowered (right plot)
- Higher probability of ROCs buffer overflow
- Higher probability of charged particles flipping bits in electronics

Pixel resolution vs irradiation

Pixel thresholds increase with integrated luminosity, reducing cluster size and affecting resolutions. **Recalibrations** are performed during LHC technical stops.



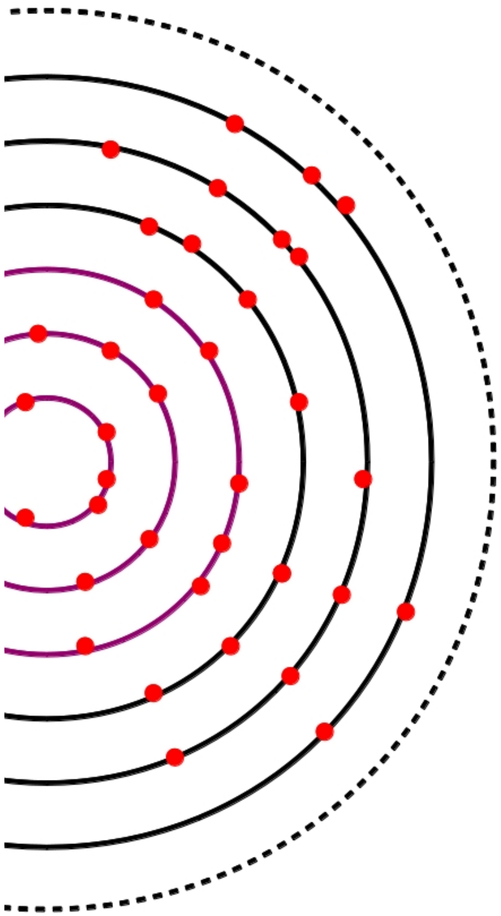


***rφ* resolution of ~ 9 μm** is maintained in pixel barrel through 2012 data taking

Track reconstruction

Track reconstruction is challenging due to a large number of hits per event

Tracking algorithm is composed of 4 steps :



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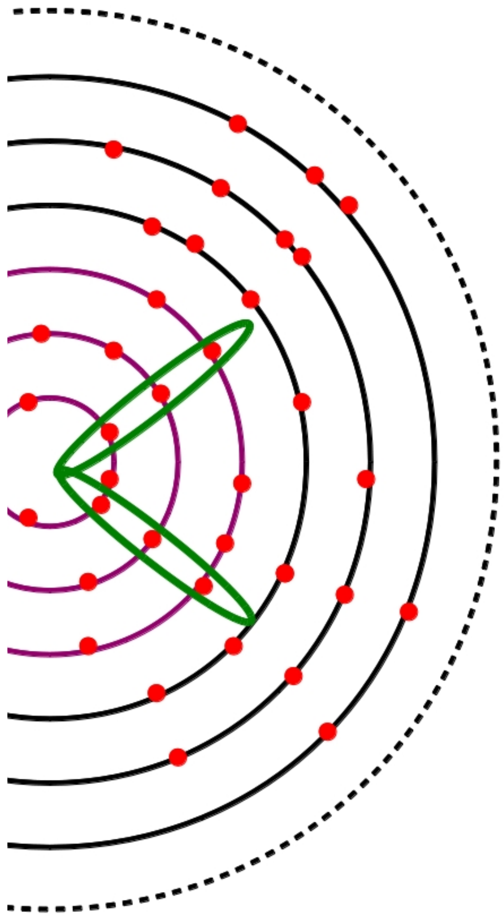
  First estimation of track parameters from minimal number of hits (3 hits, or 2 hits and a vertex constraint)



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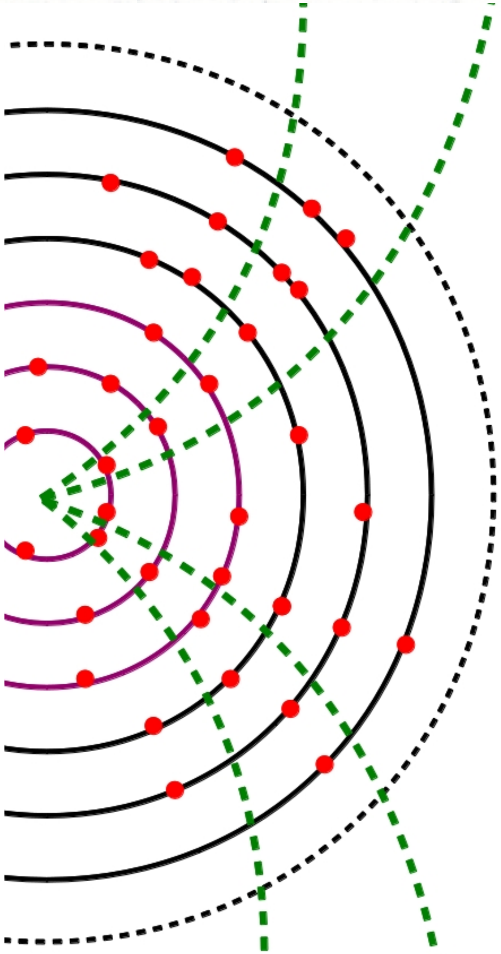
  Propagate seed through tracker (inside-out propagation)



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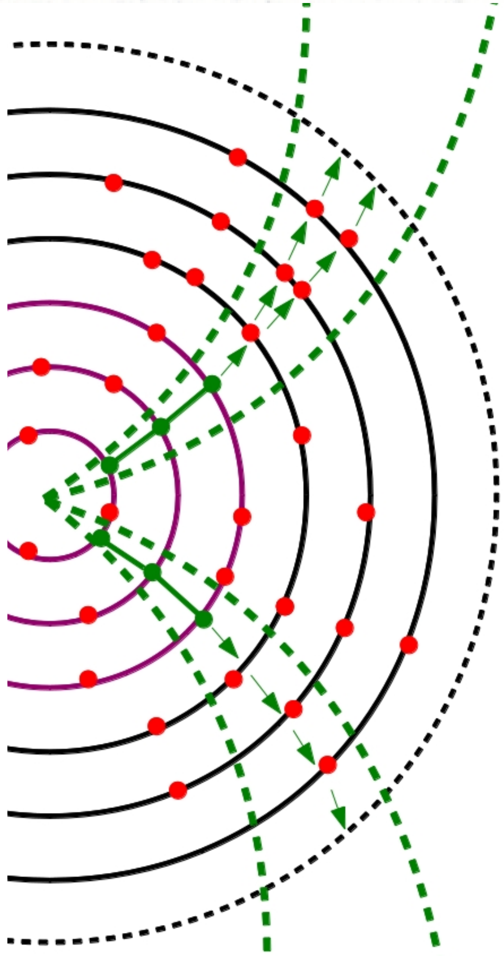

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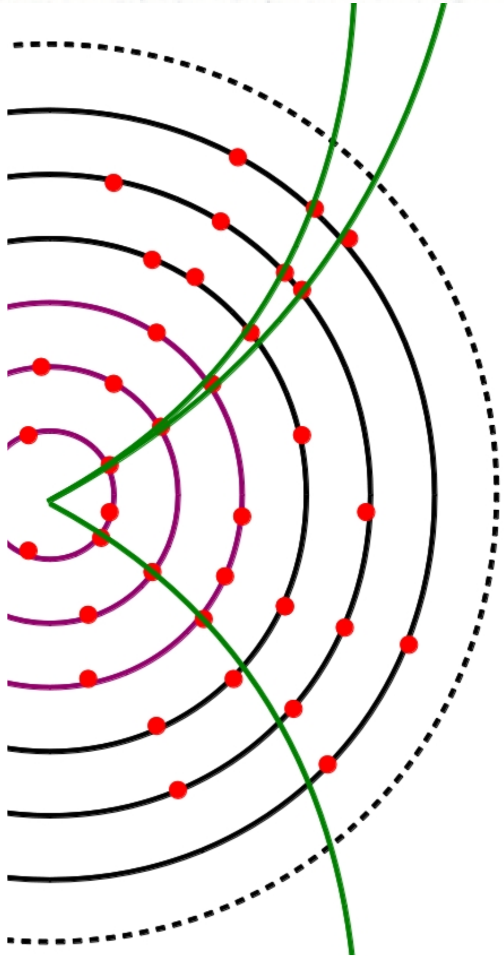

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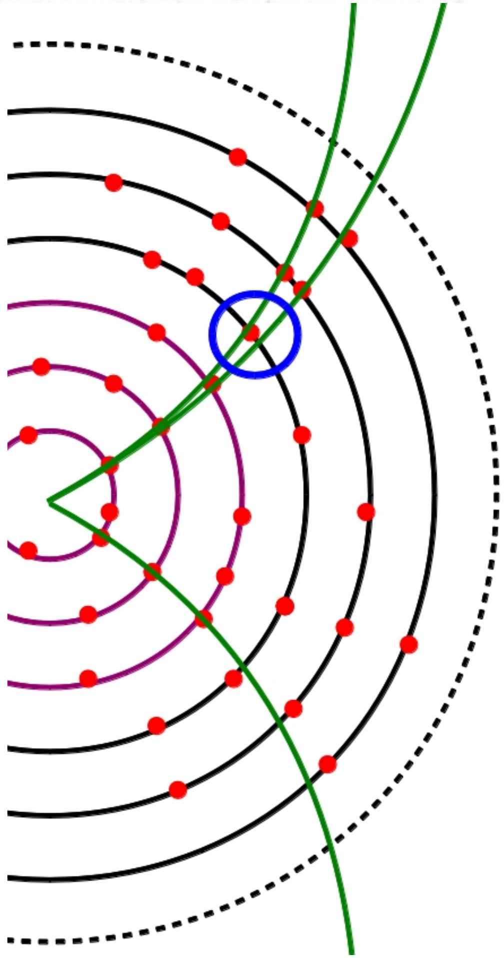

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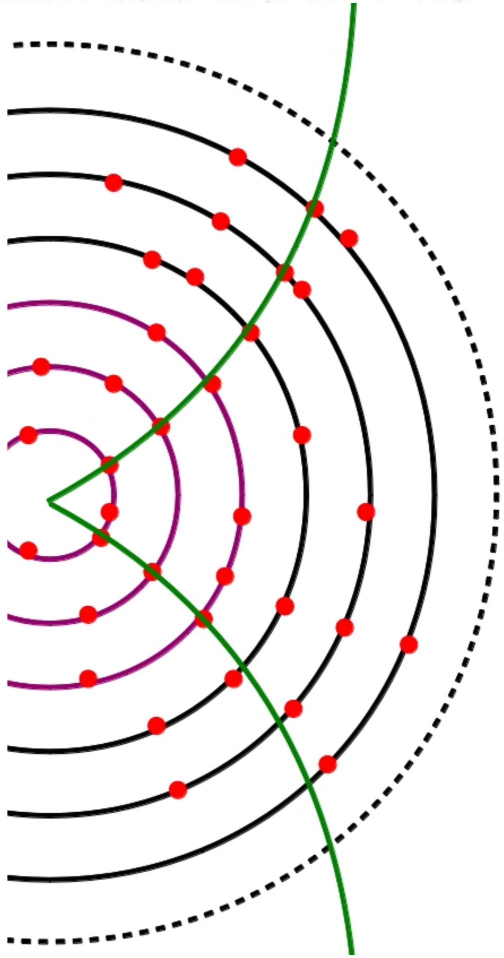

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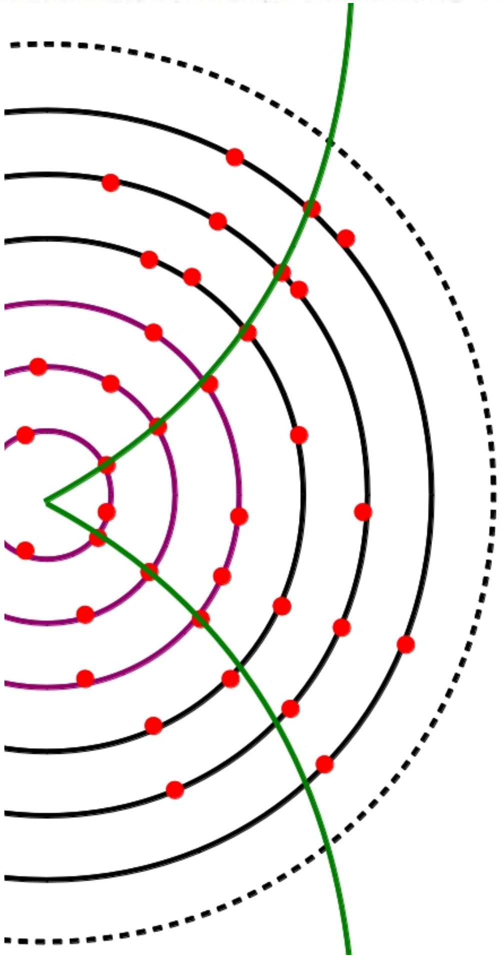
- **Track final fit**

  Estimation track parameters out of all the associated hits



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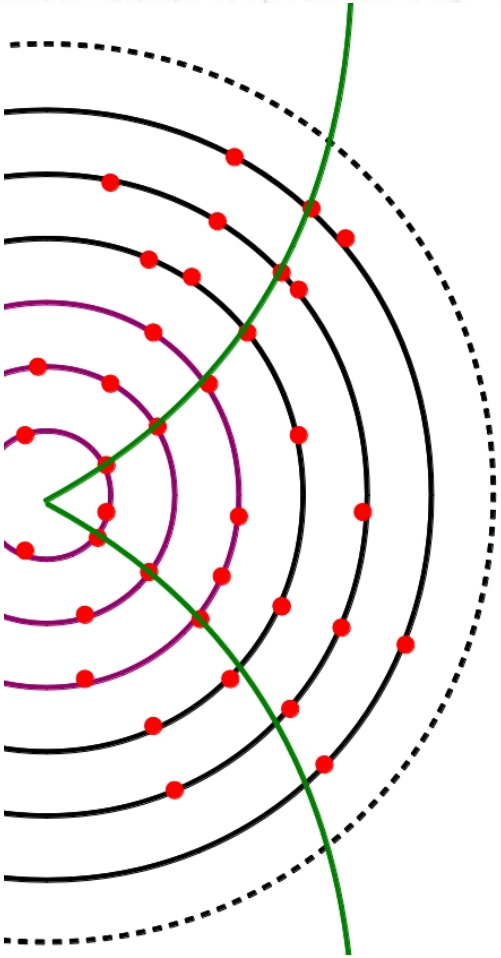

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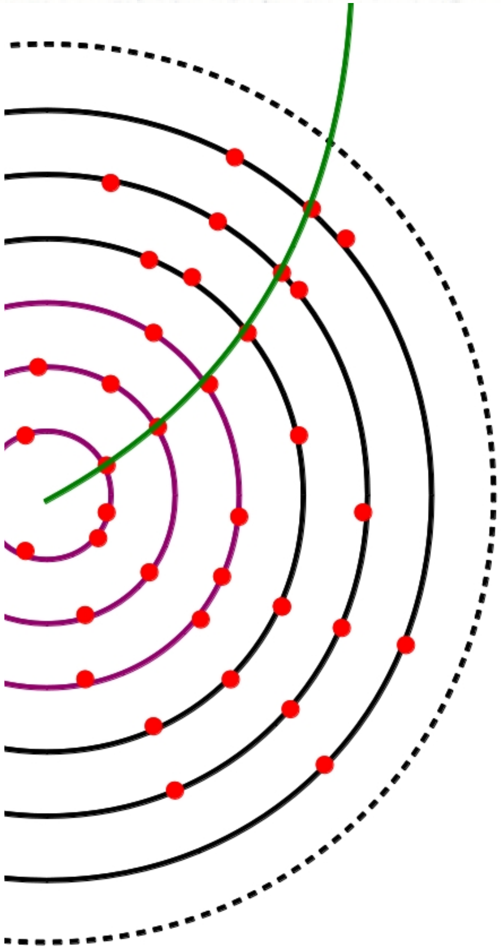

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Iterative tracking

- The tracking algorithm is run in **several successive iterations**
- Each iteration is defined by the **configuration of seed generation**
- Once an iteration is over, all hits affected to a track are removed from the hit collection
- Next iteration is then launched, on a **reduced number of hits**

#step	seed type	seed subdetectors	$P_T^{\rm min}$ [GeV/c]	d_0 cut	z_0 cut
0	triplet	pixel	0.6	**0.02** cm	4.0σ
1	triplet	pixel	0.2	**0.02** cm	4.0σ
2	pair	pixel	0.6	**0.015** cm	0.09 cm
3	triplet	pixel	**0.3**	**1.5** cm	**2.5**σ
4	triplet	pixel/TIB/TID/TEC	**0.5-0.6**	**1.5** cm	10.0 cm
5	pair	TIB/TID/TEC	0.6	2.0 cm	10.0 cm
6	pair	TOB/TEC	0.6	2.0 cm	30.0 cm

Characteristics of the different iterations after spring 2012 improvements campaign.

Iterative tracking

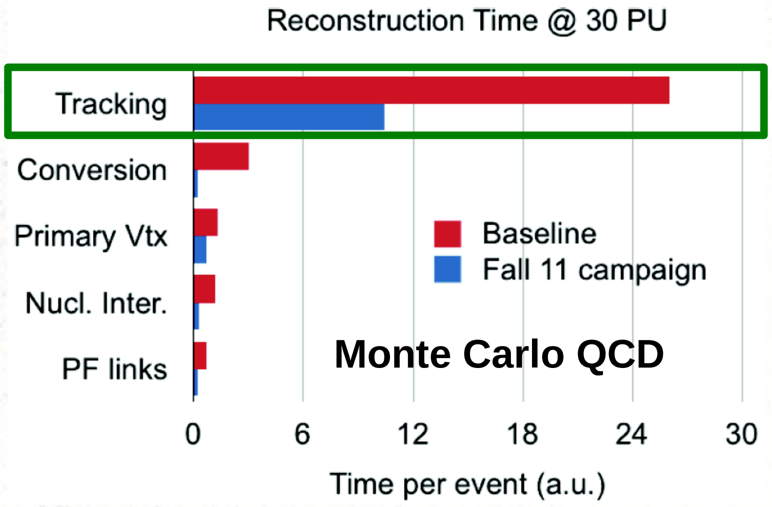
Fully configurable software : optimize iterative tracking for high luminosity

#step	seed type	seed subdetectors	P_T^{min} [GeV/c]	d_0 cut	z_0 cut
0	triplet	pixel	0.8	0.2 cm	3.0σ
1	pair	pixel/TEC	0.6	0.05 cm	0.6 cm
2	triplet	pixel	0.075	0.2 cm	3.3σ
3	triplet	pixel/TIB/TID/TEC	0.25-0.35	2.0 cm	10.0 cm
4	pair	TIB/TID/TEC	0.5	2.0 cm	12.0 cm
5	pair	TOB/TEC	0.6	6.0 cm	30.0 cm

Baseline configuration

#step	seed type	seed subdetectors	P_T^{min} [GeV/c]	d_0 cut	z_0 cut
0	triplet	pixel	**0.6**	**0.03** cm	**4.0**σ
1	**triplet**	**pixel**	**0.2**	**0.03** cm	**4.0**σ
2	pair	**pixel**	0.6	**0.01** cm	**0.09** cm
3	triplet	pixel	**0.2**	**1.0** cm	**4.0**σ
4	triplet	pixel/TIB/TID/TEC	**0.35-0.5**	2.0 cm	10.0 cm
5	pair	TIB/TID/TEC	**0.6**	2.0 cm	**10.0** cm
6	pair	TOB/TEC	0.6	2.0 cm	30.0 cm

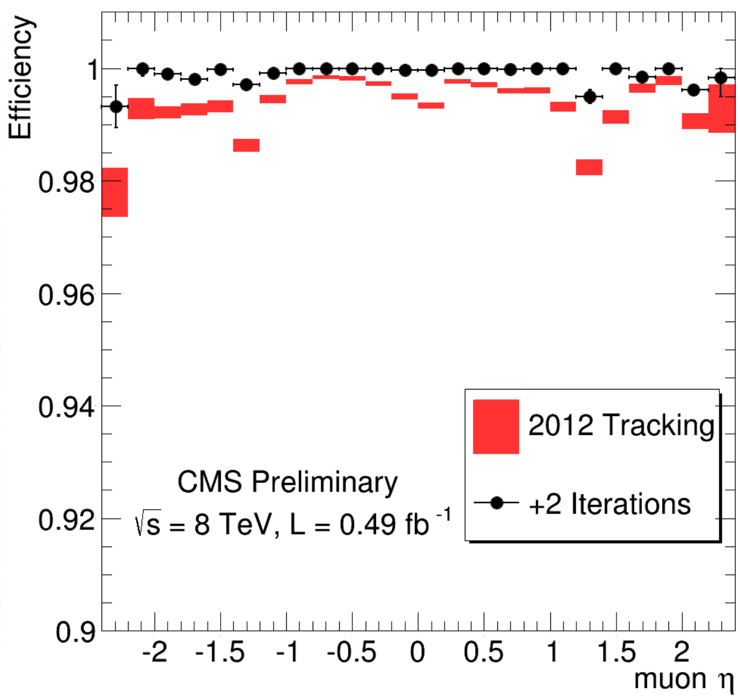
Fall 2011 improvements



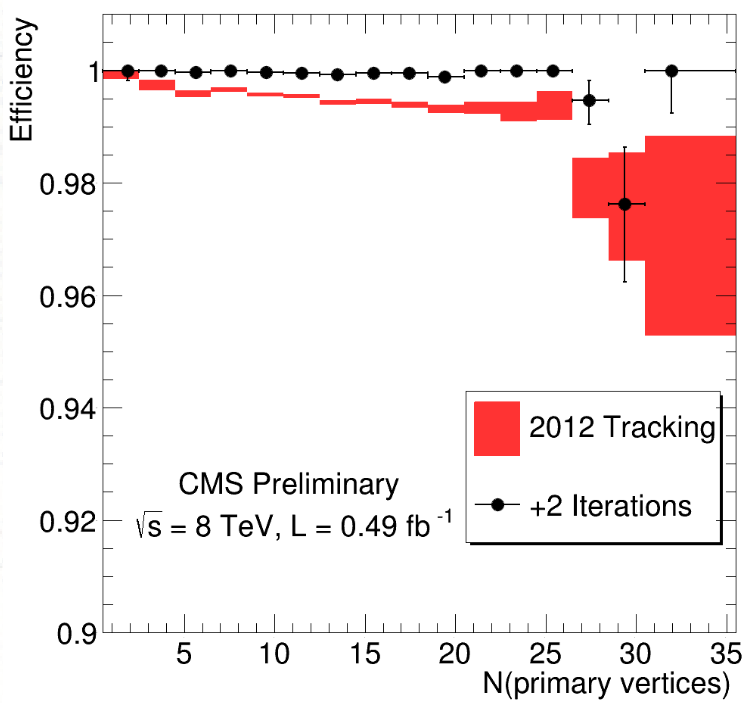
At 30 pile-up, optimization improves tracking CPU time by a factor 2.5

Iterative tracking

New iterations can be added to **improve efficiency**. Here 2 new iterations for **muons** :



- Outside-In tracking : seeds from muon chambers
- Inside-Out tracking : to re-reconstruct tracks tagged as muons, with looser requirements



Efficiency estimated via Tag and probe method : use muons chambers to select muons from Z^o to μμ events

Conclusions and Perspectives

- **LHC run 1 lasted from 2010 to 2013**
- **The CMS tracker has maintained satisfaying performances through 7 TeV and 8 TeV proton-proton collisions**
- **Robustness up to an average value of 25 pile-up vertices per event**
- **Luminosity will still increase : future upgrades**
  - Phase 1 (2017) : new pixel detector with 4 barrels and 3 disks.
  - Phase 2 (2022) : entirely new tracker. Conception still ongoing.

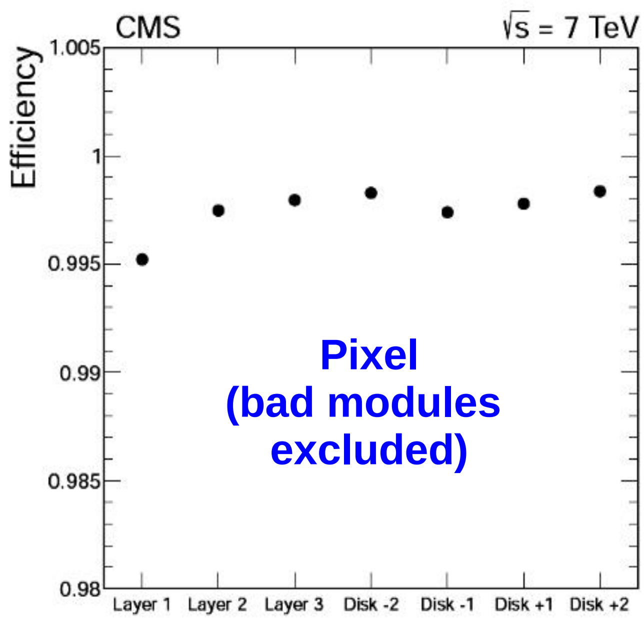
Thank you for your attention

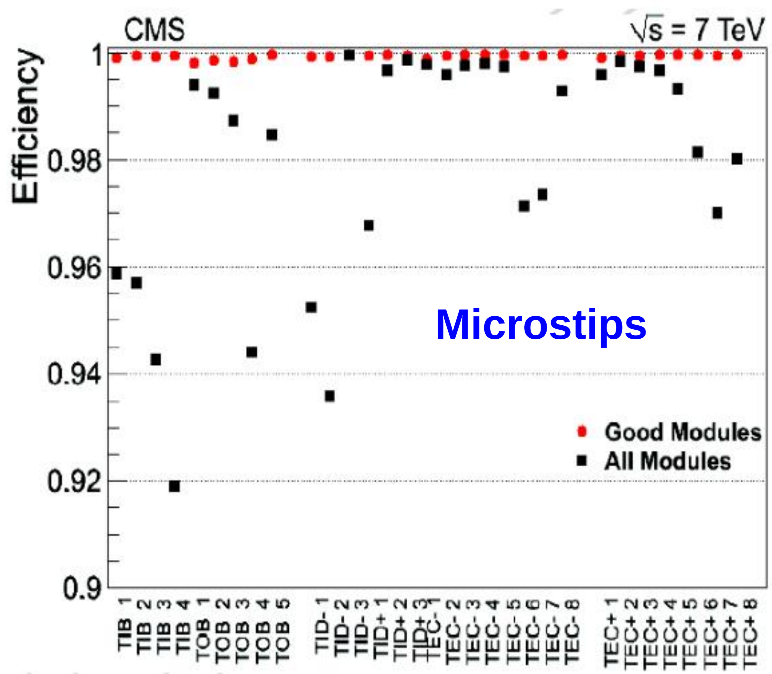
Backup slides

Hit efficiencies

Hit efficiency : probability to reconstruct a hit when a charged particle cross a sensor

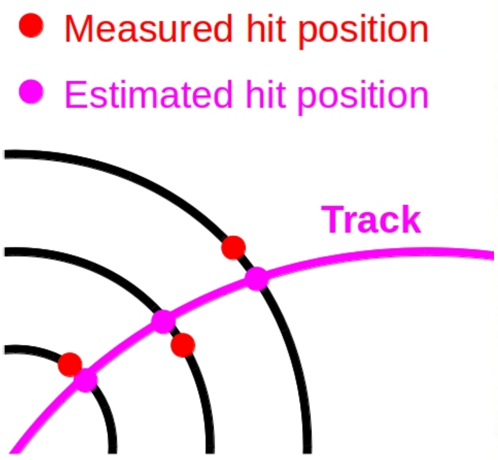
Measured for each layer using well reconstructed tracks with hits on previous and next layer

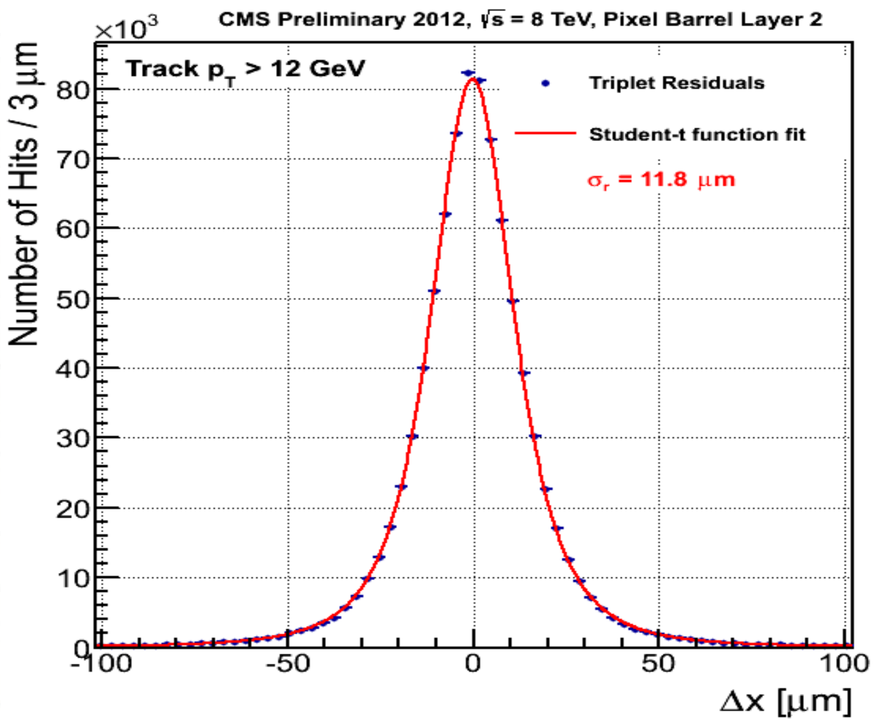




Hit resolutions

Hit resolutions are measured from residuals : differences between expected hit position (from track fit), and measured hit position (from hit reconstruction) on a given layer.





Typical residuals distribution obtained from a 8 TeV run

Pixel, barrel, layer 2 :

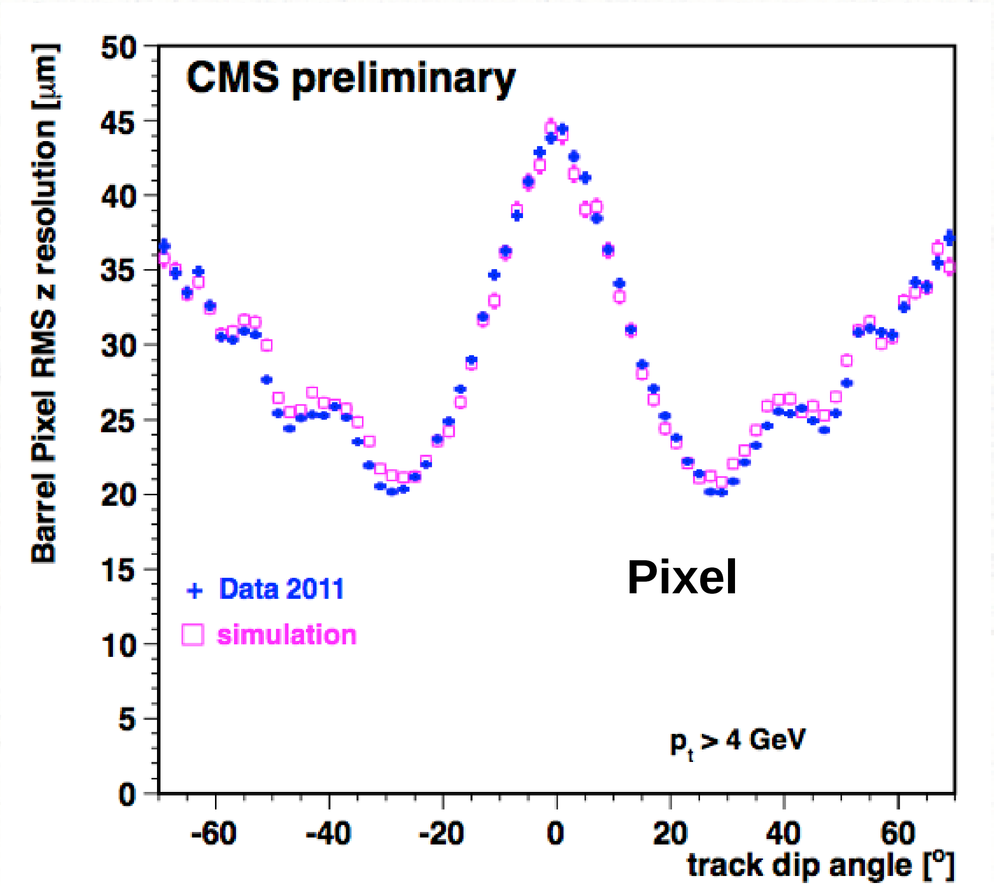
- 9.4 µm in *rφ* (transverse plan)
- 20 to 46 µm in *z*

Microstrip, barrel :

- 10 to 42 µm in *rφ*
- Resolution in *z*, from stereo layers, is typically 10 times larger

Hit resolutions

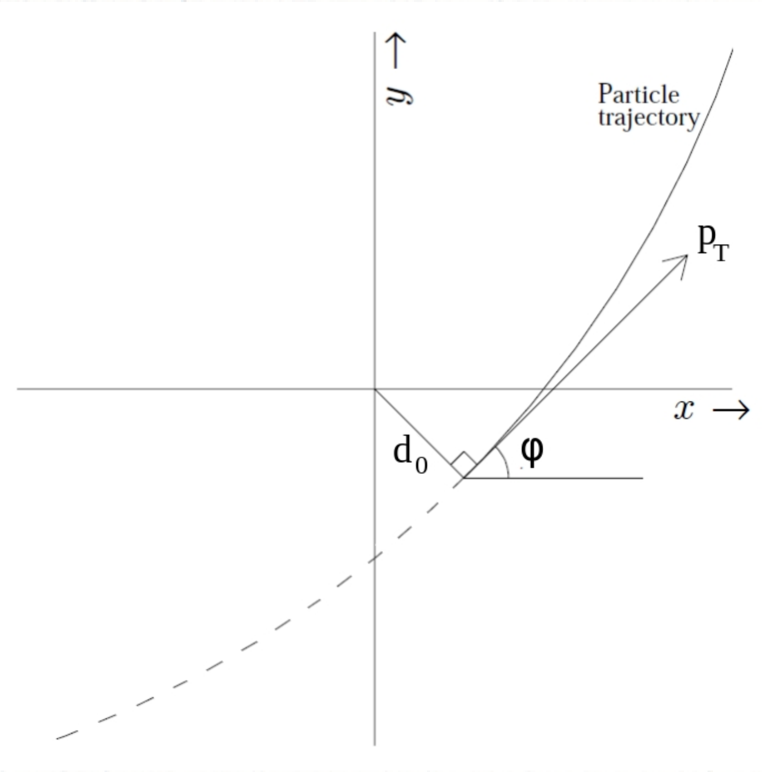
Pixel hit resolutions depends on the crossing angle of the incoming charged particle



Track reconstruction

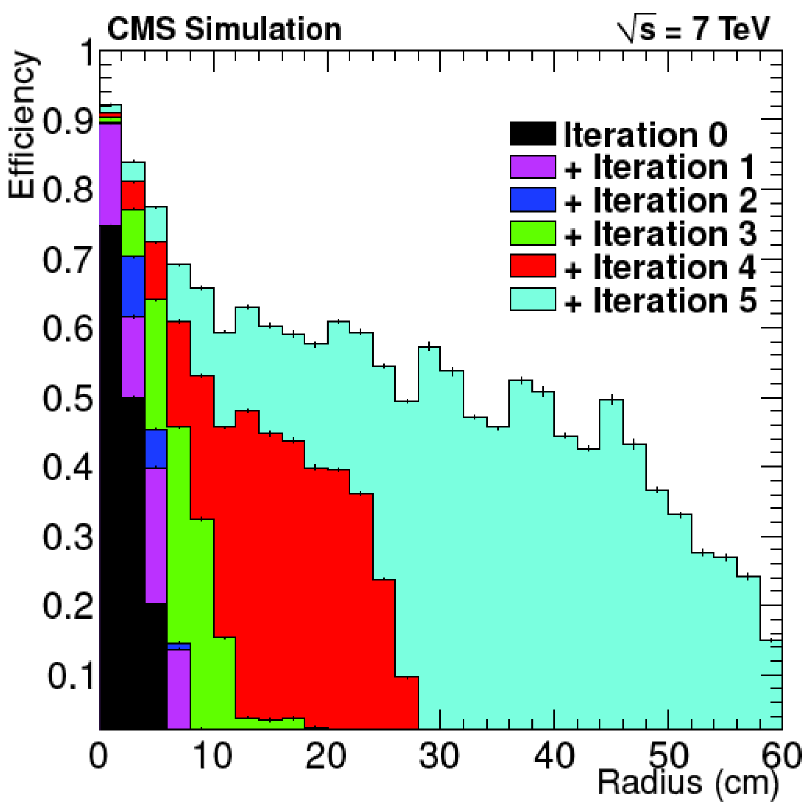
Five parameter are needed to describe a track. A possible set is :

- d_0: Transverse impact parameter (signed)
- z_0: Longitudinal impact parameter
- φ : track direction in transverse plane
- $\cot\theta$: angle between track and beam line
- p_T: transverse impulsion



Iterative tracking

Each iteration enables the reconstruction of tracks produced in different region of the tracker



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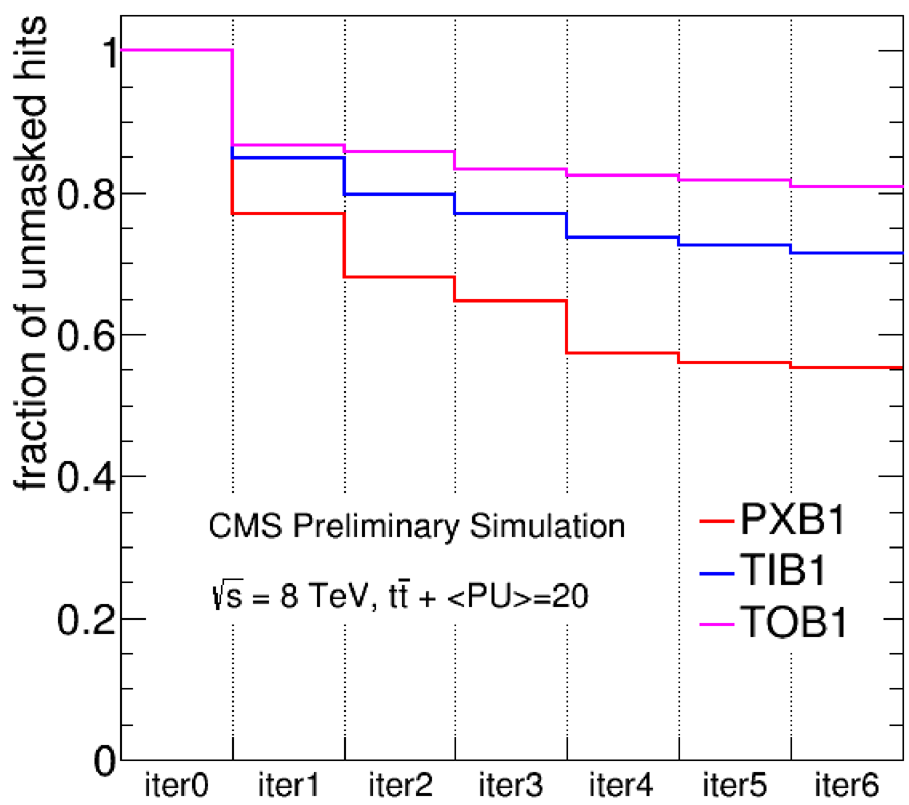
0	triplet	pixel
1	pair	pixel/TEC
2	triplet	pixel
3	triplet	pixel/TIB/TID/TEC
4	pair	TIB/TID/TEC
5	pair	TOB/TEC

Contribution of the different iterations to tracking efficiency wrt the radius of track origin

Results are shown for a previous algorithm configuration (before fall 2011)

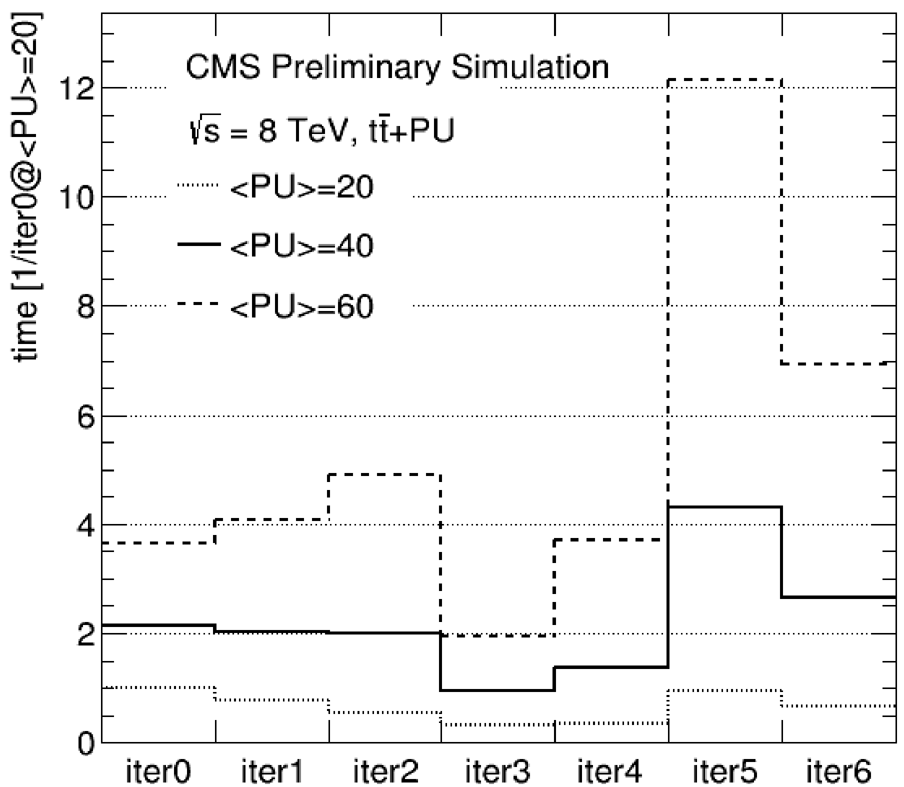
Iterative tracking

Once an iteration is over, hits associated to high quality tracks are masked, and the next iteration is run on a reduced number of hits.



Iterative tracking

The CPU time needed for each iteration is strongly pile-up dependent.



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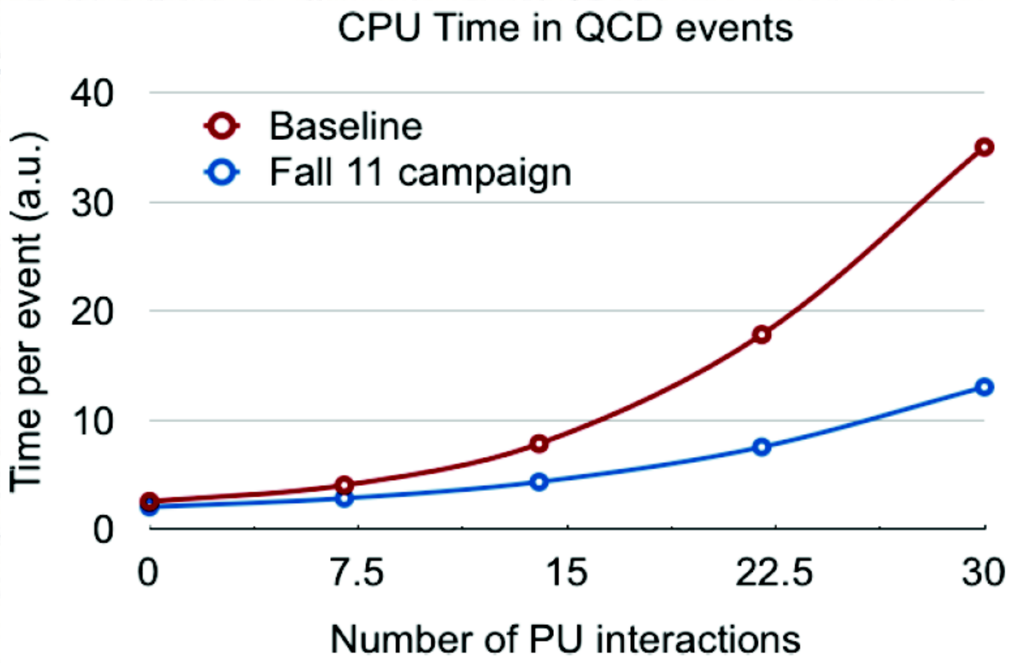
4	triplet	pixel/TIB/TID/TEC	**0.5-0.6**	**1.5** cm	10.0 cm
5	pair	TIB/TID/TEC	0.6	2.0 cm	10.0 cm
6	pair	TOB/TEC	0.6	2.0 cm	30.0 cm

Spring 2012
tracking configuration

Tracking improvements

2011 improvements campaign :

- Iterative tracking
- Photon conversions
- Primary vertices
- Nuclear interactions
- Particle Flow links



Tracking efficiency

Efficiency from Monte-Carlo studies

A track is considered as **efficiently reconstructed** if 75 % of its hits come from the same generated charged particle. Otherwise it is considered as a « **fake track** »

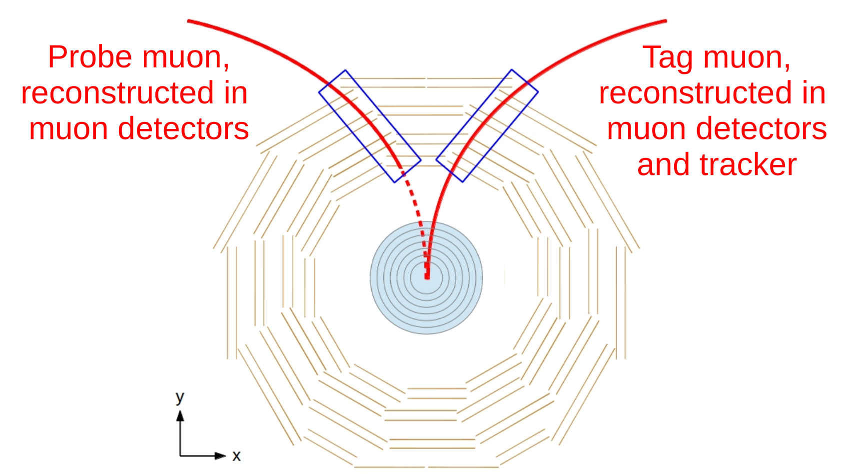
2 types of Monte-Carlo events are used :

- **Single particle** events : only one isolated muon, electron or pion
- **High occupancy** events : $t\bar{t}$ events, with or without pile-up vertices

Efficiency from data

The information from muon chambers are used to select Z° to μμ events. Efficiency are then estimated with a « **Tag and Probe** » method.

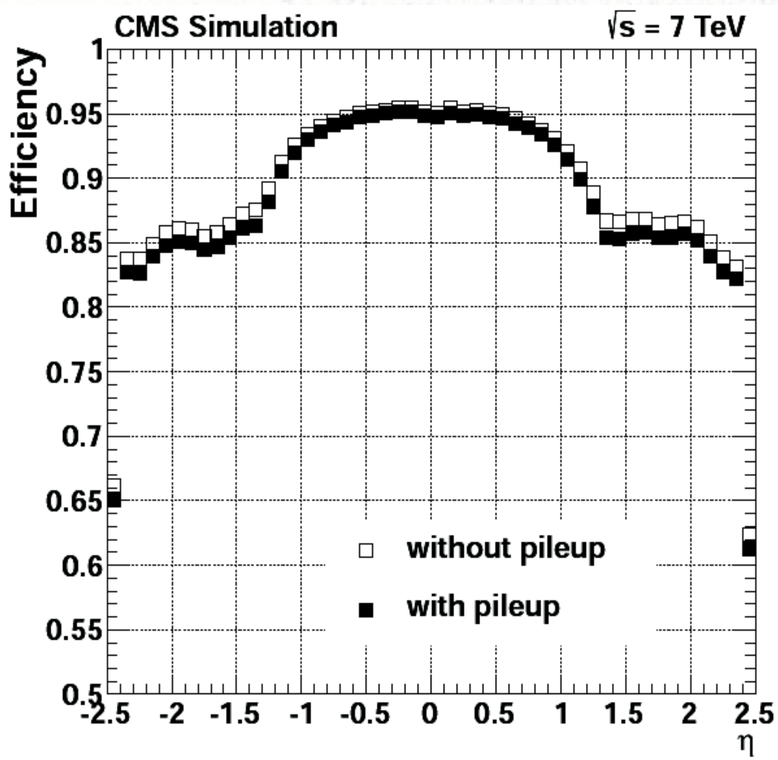
Efficiency is the probability that the second muon was well reconstructed in tracker.

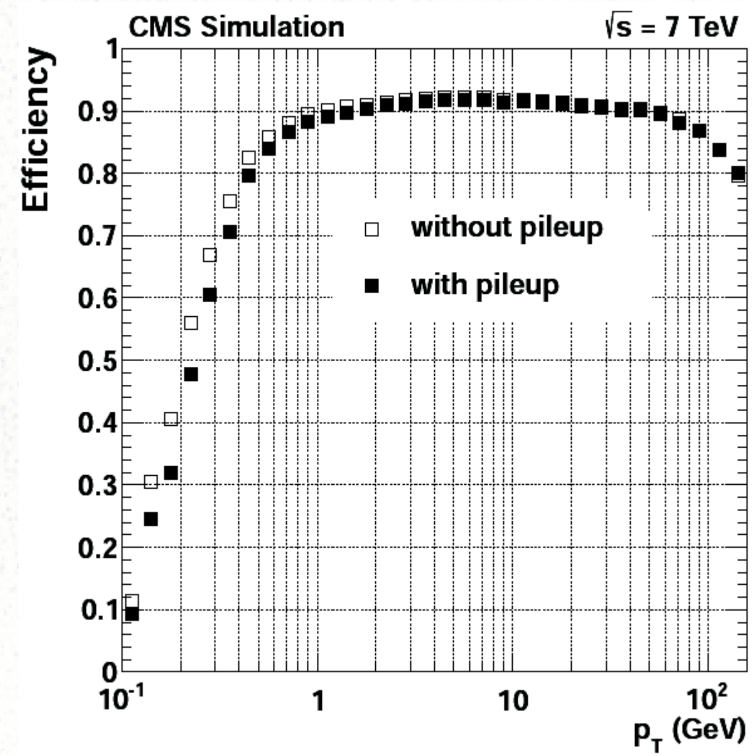


Tag and Probe methode with Z° to μμ events

Tracking efficiency

Efficiencies from Monte Carlo : $t\bar{t}$ events with and without pile-up (7 TeV conditions)

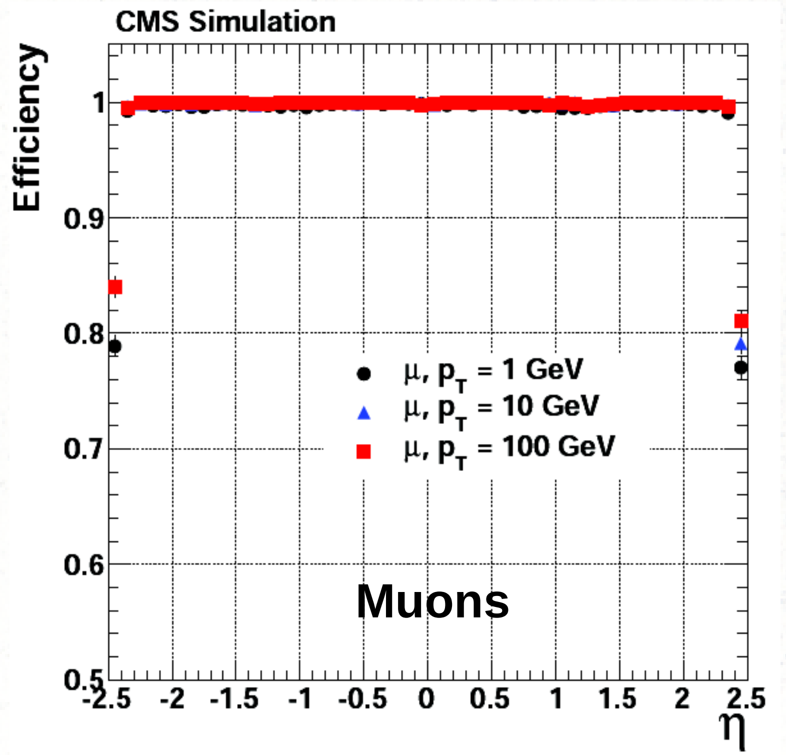


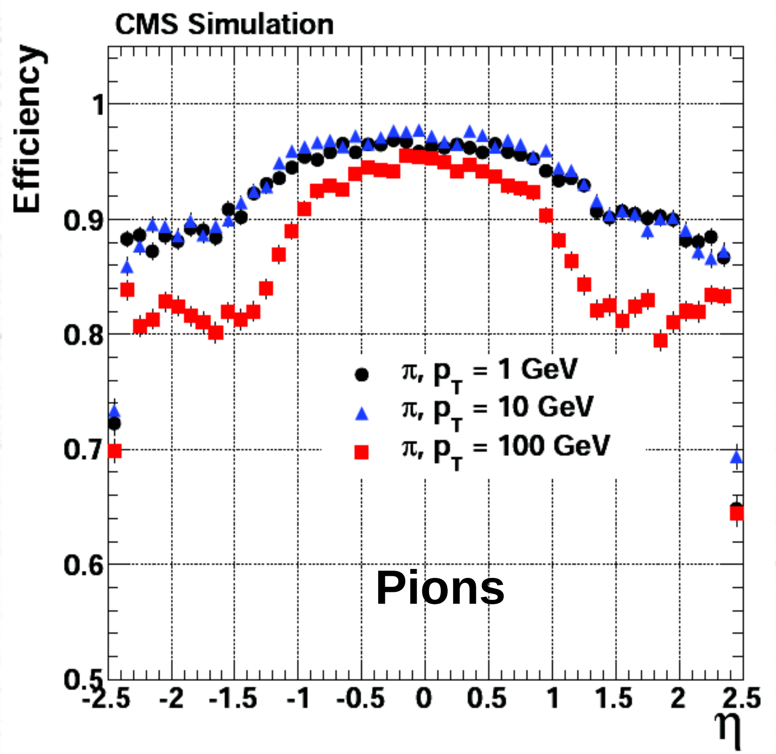


Number of pileup vertices is randomly generated from a Poisson distribution peaking at 8.

Tracking efficiency

Efficiency from Monte Carlo : isolated muons and pions



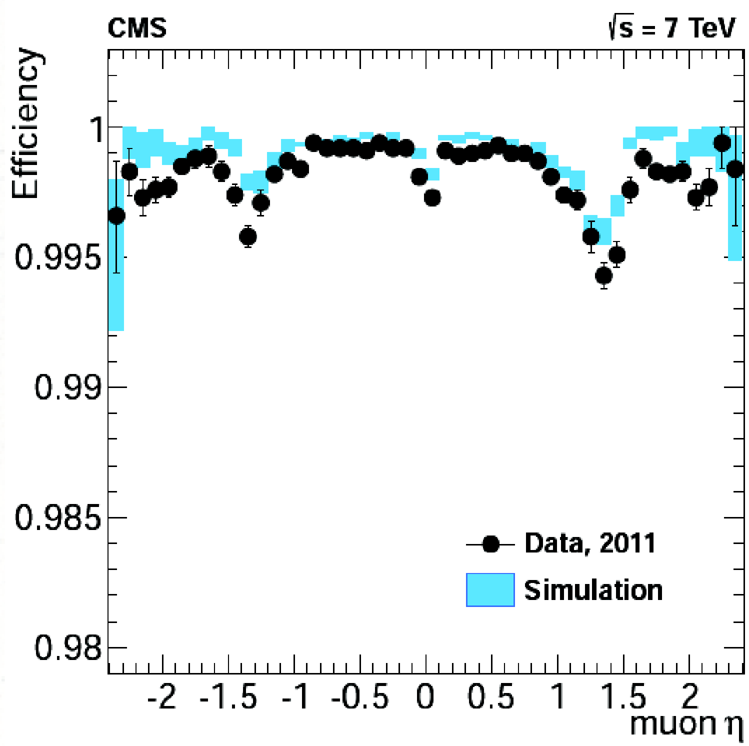


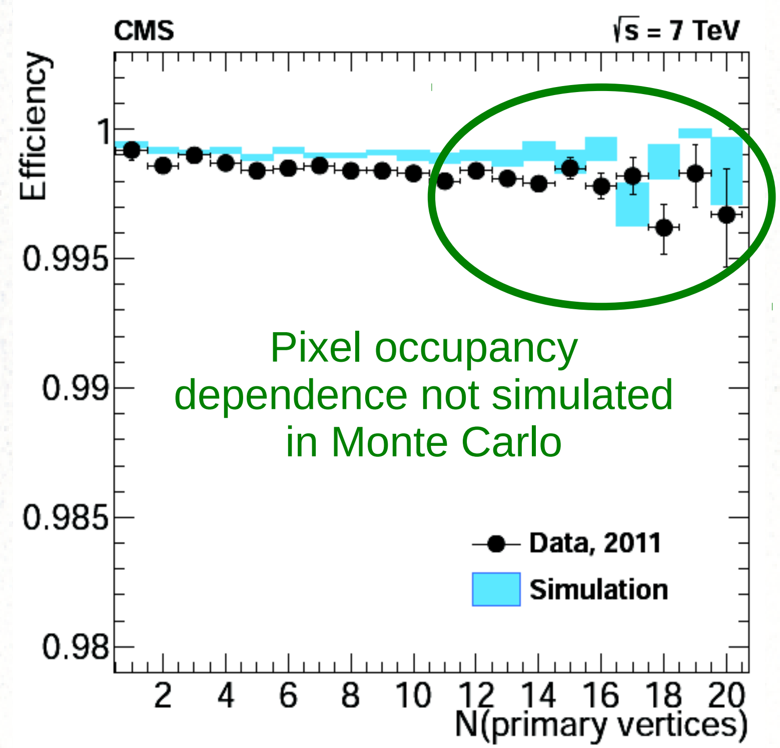
Efficiency as a function of the pseudo-rapidity η.

Tracking efficiency

Efficiency from 2011 data : estimated from muons

Tag and probe method : use muons chambers to select muons from Z^o to μμ events.



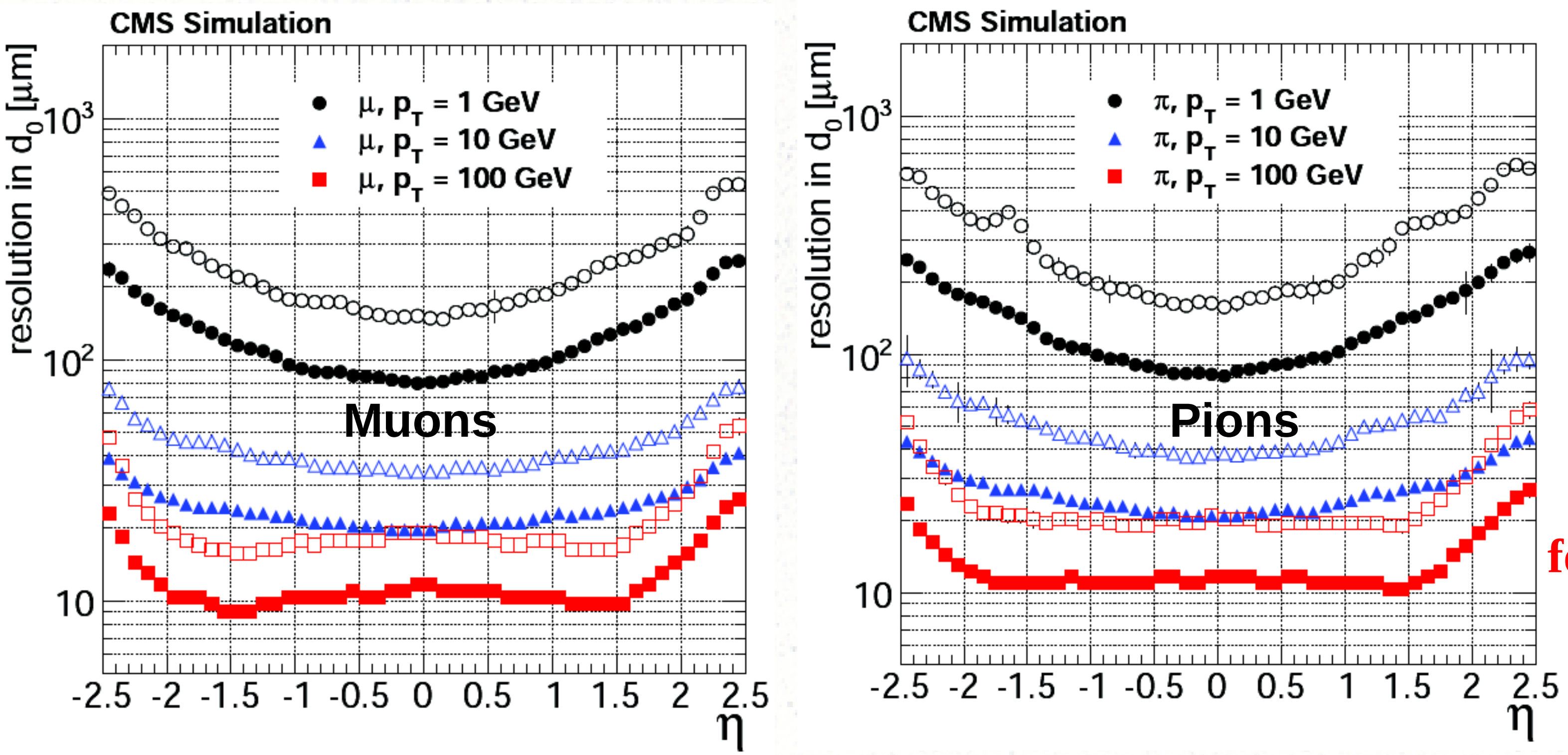


Robust tracking efficiency under 2011 pile-up conditions

Track resolutions

Resolutions from Monte Carlo : isolated muons and pions

Obtained by comparing generated and reconstructed track parameters.

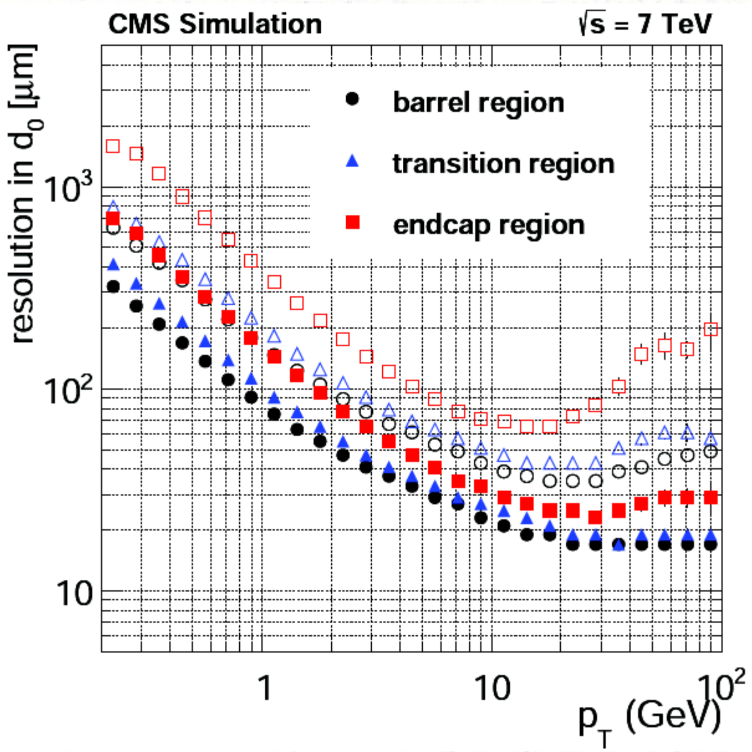


~ 10 μm
for 100 GeV
particles

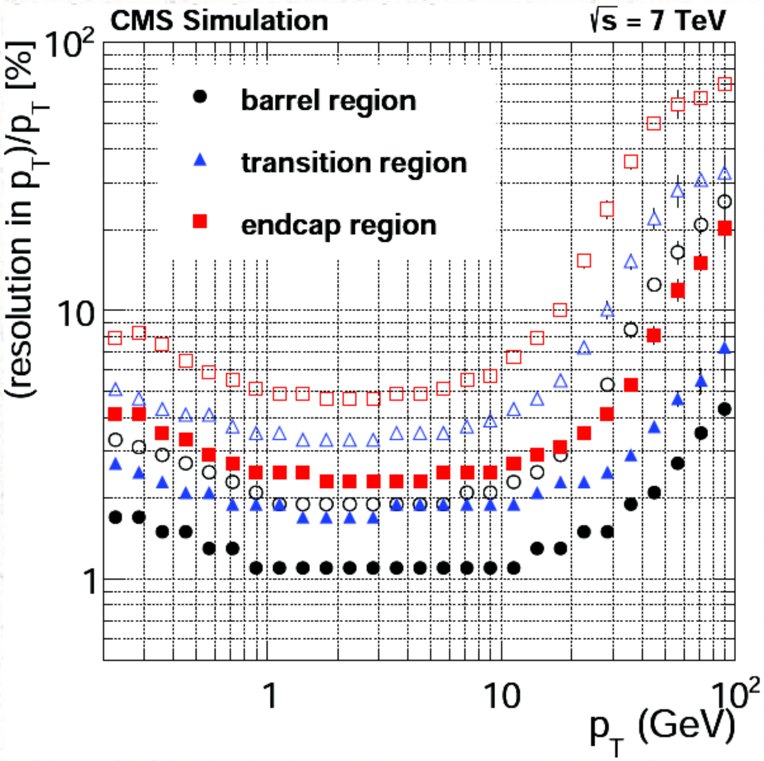
Resolutions in transverse impact parameter as a function of η. Obtained from half-width of an interval containing 68 % (solid symbols) and 90 % (open symols of residuals distribution

Track resolutions

Resolutions from Monte Carlo : $t\bar{t}$ events with pile-up



About 20 μm for 100 GeV particles in central and transition regions



Minimum p_T resolution obtained in central region is 1.5 %