Tracking performances in CMS

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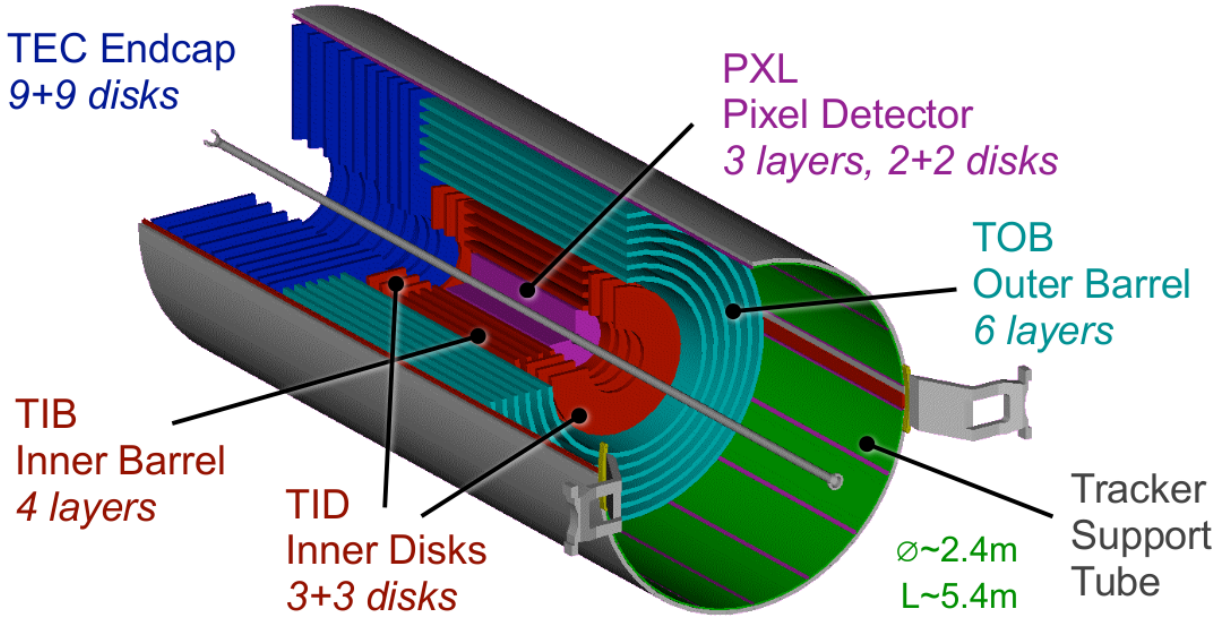
Outline

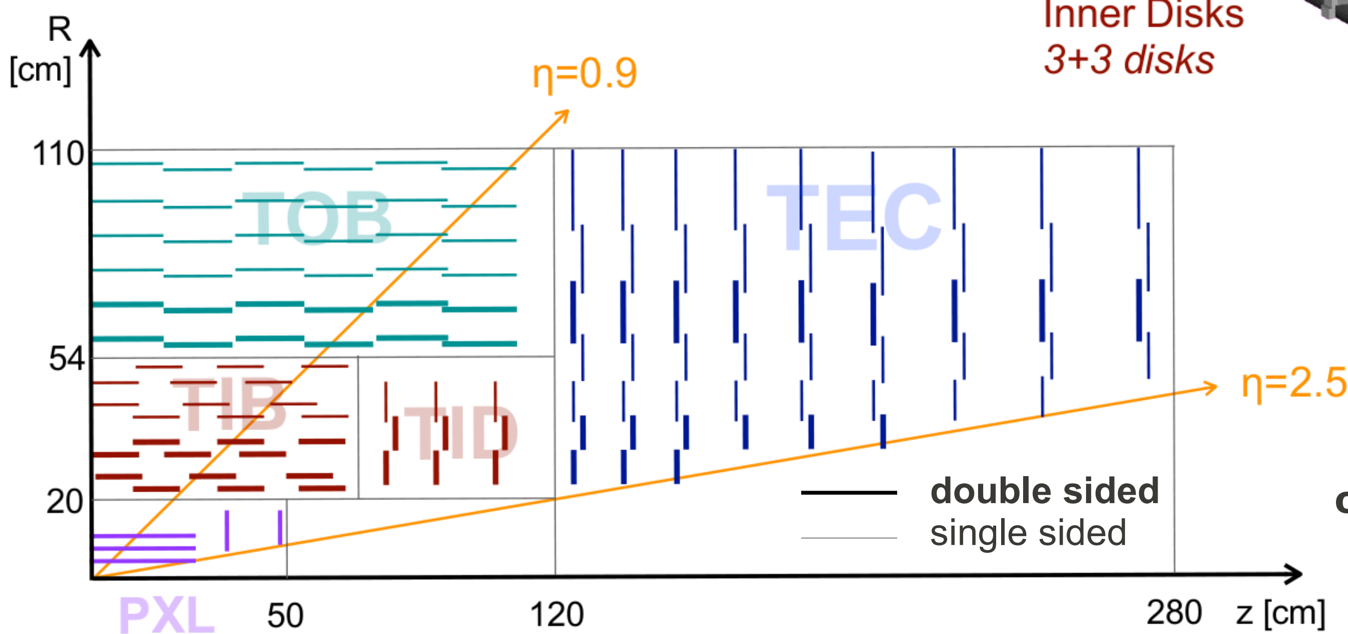
- CMS tracker in a nutshell
- Track and vertex reconstruction in CMS
- Tracking and vertexing performance
- Tracking at HLT
- HLT tracking performance

CMS tracker detector

Silicon pixel detector:
66M readout channels
Each pixel: 100 μm x 150 μm

Silicon strips detector:
9M readout channels
Pitches: 80-180 μm



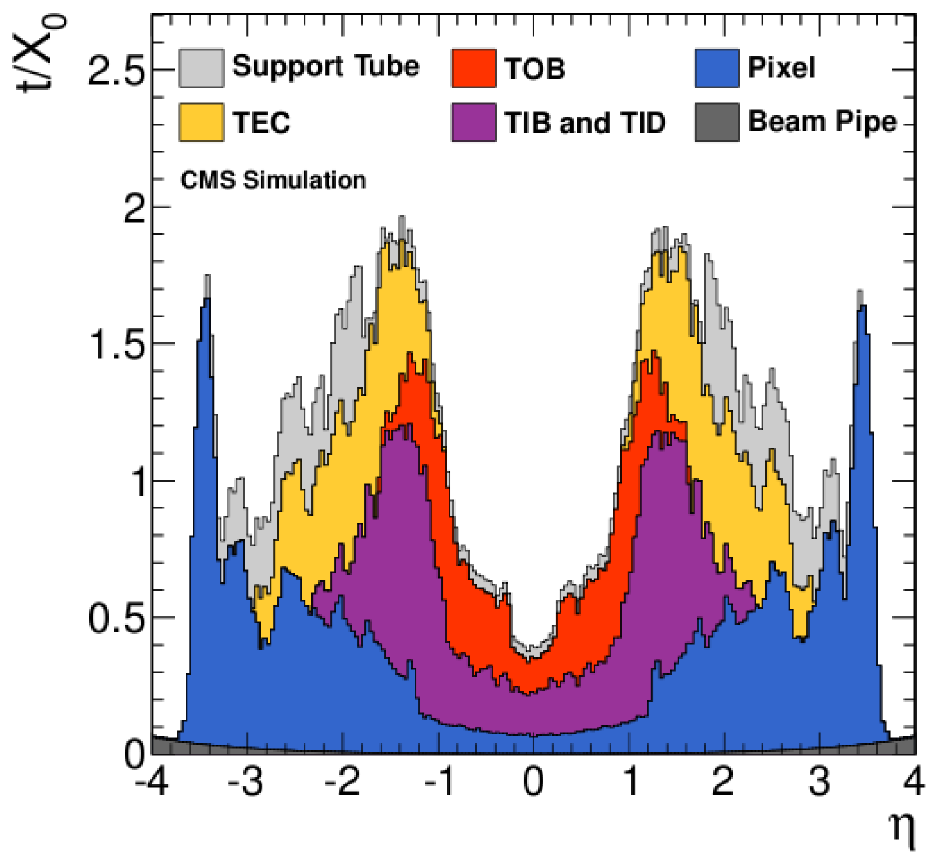


Axial B of 3.8 T

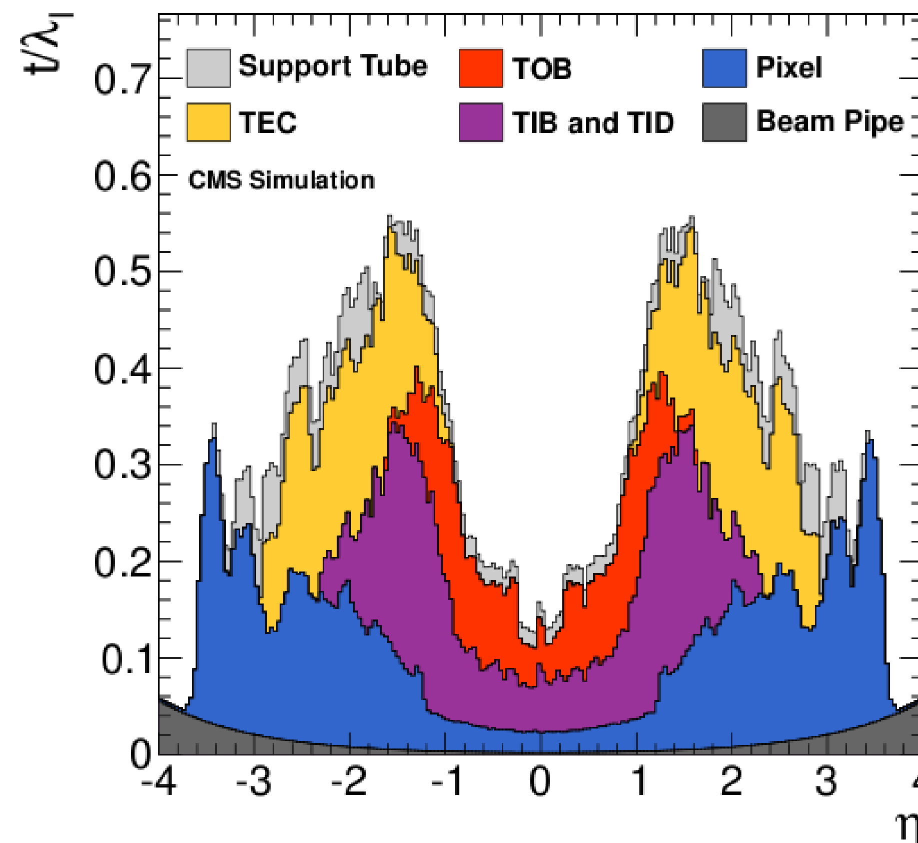
Performance:

σ(pT)/pT ~ 1-2% @ 100 GeV/c
σ(IP) ~ 10-20 μm @ 10-100 GeV/c

Tracker material budget

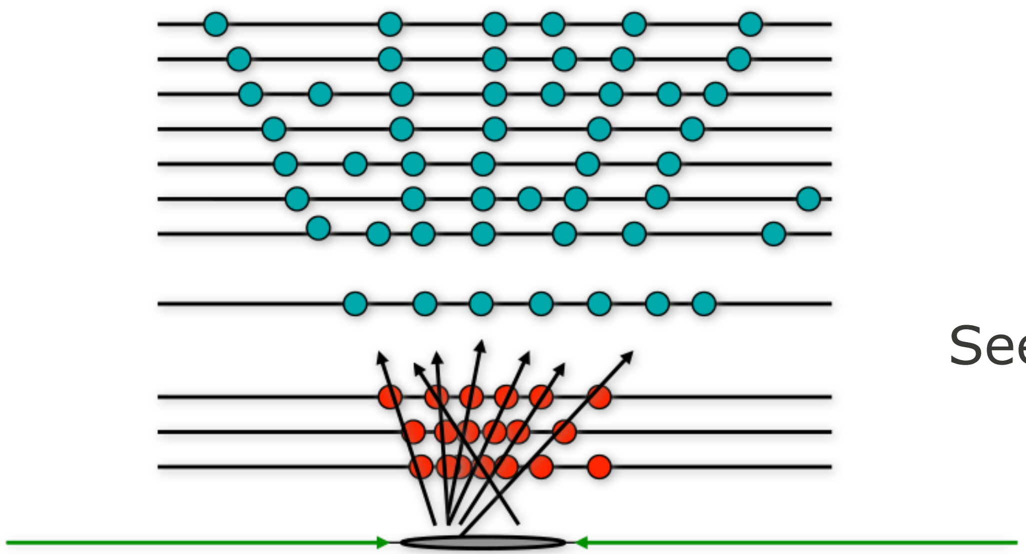


Thickness in units of radiation length



Thickness in units of interaction length

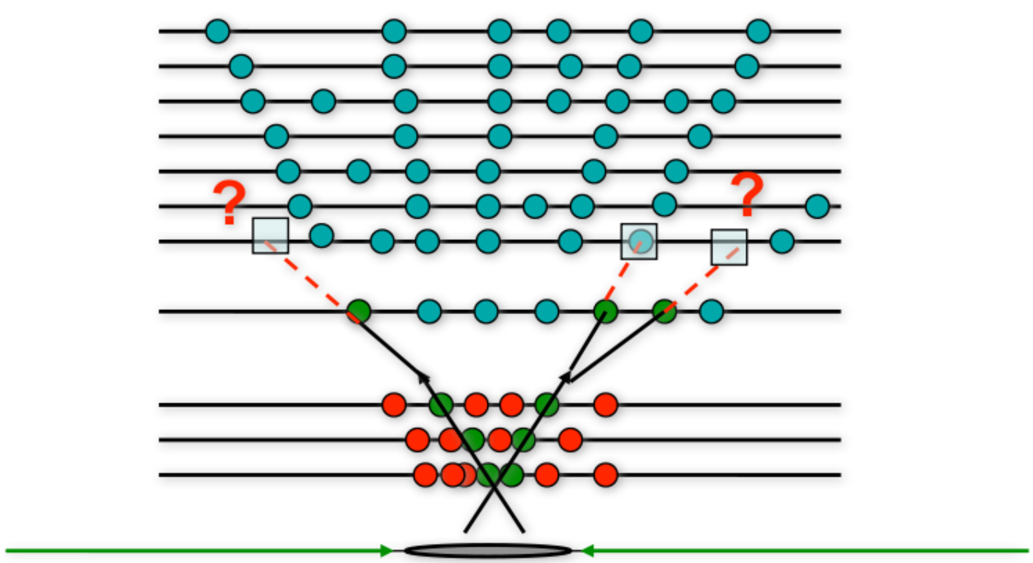
Track reconstruction



Seeding

Starts from the innermost layers.
Made from hits triplets or doublets compatible with the beamspot.
Seeds not compatible with the luminous region are discarded.

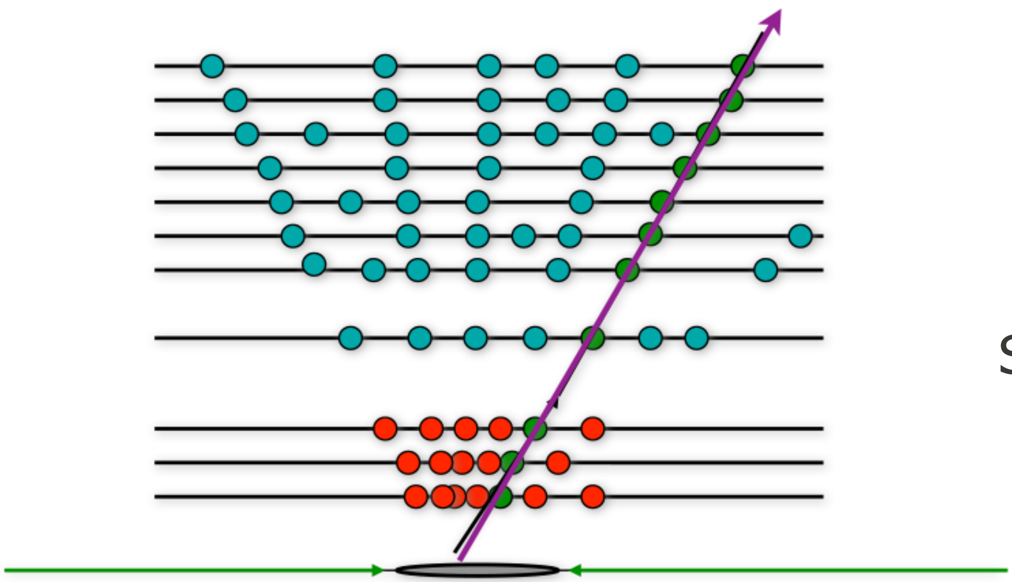
Track reconstruction



Trajectory Building

Each seed is propagated to the successive layers, using a Kalman filter technique (navigation, search for compatible layers, search for compatible hits, update of the trajectory state). Track parameters estimation is updated every time a new hit is found.

Track reconstruction

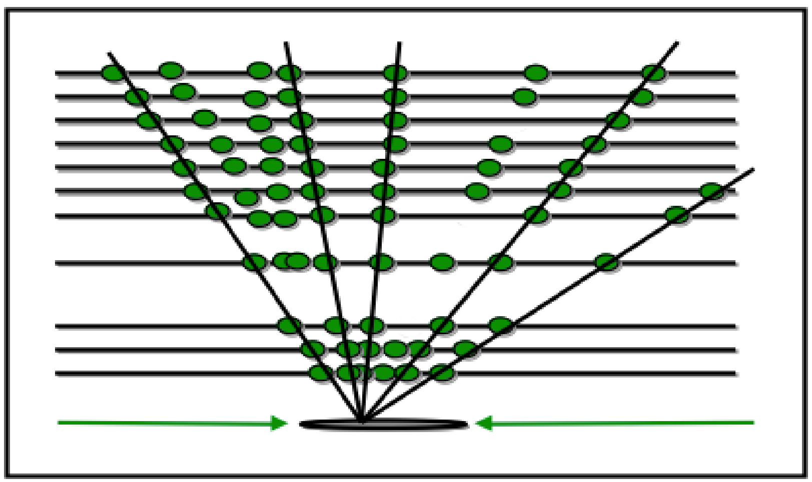


Track Fitting

Track parameters are **re-fitted** with a Kalman Filter technique and a "*smoothing*". First fitting is performed "outwards". Second fitting is performed "inwards", increasing precision on the track parameters at the interaction point.

Iterative tracking

Pattern recognition "step by step"



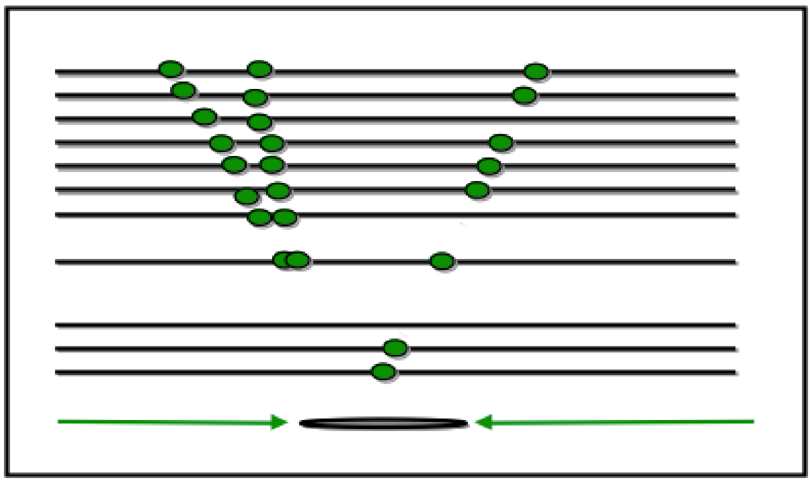
Starts with pattern recognition of "easy" tracks:

- high pT tracks
- tracks with large number of hits
- associated vertex close to the beam-spot

Tight constraints are required.

Iterative tracking

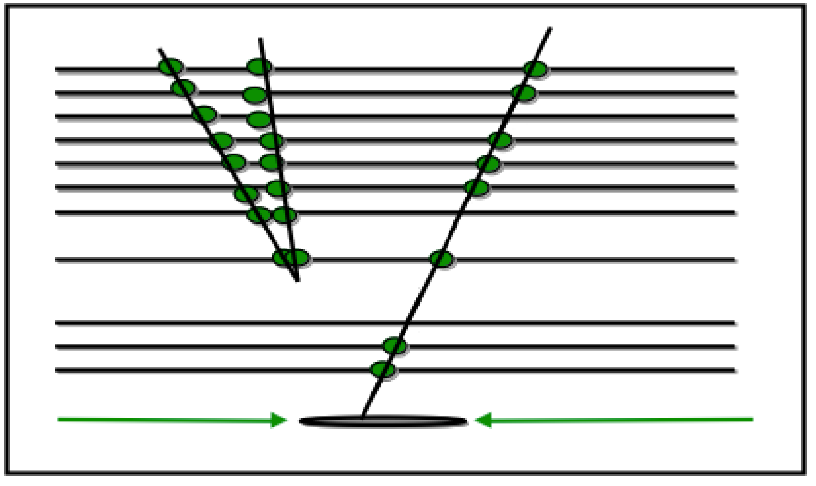
Pattern recognition "step by step"



The clusters associated with the hits of the found tracks are **removed**.

Iterative tracking

Pattern recognition "step by step"

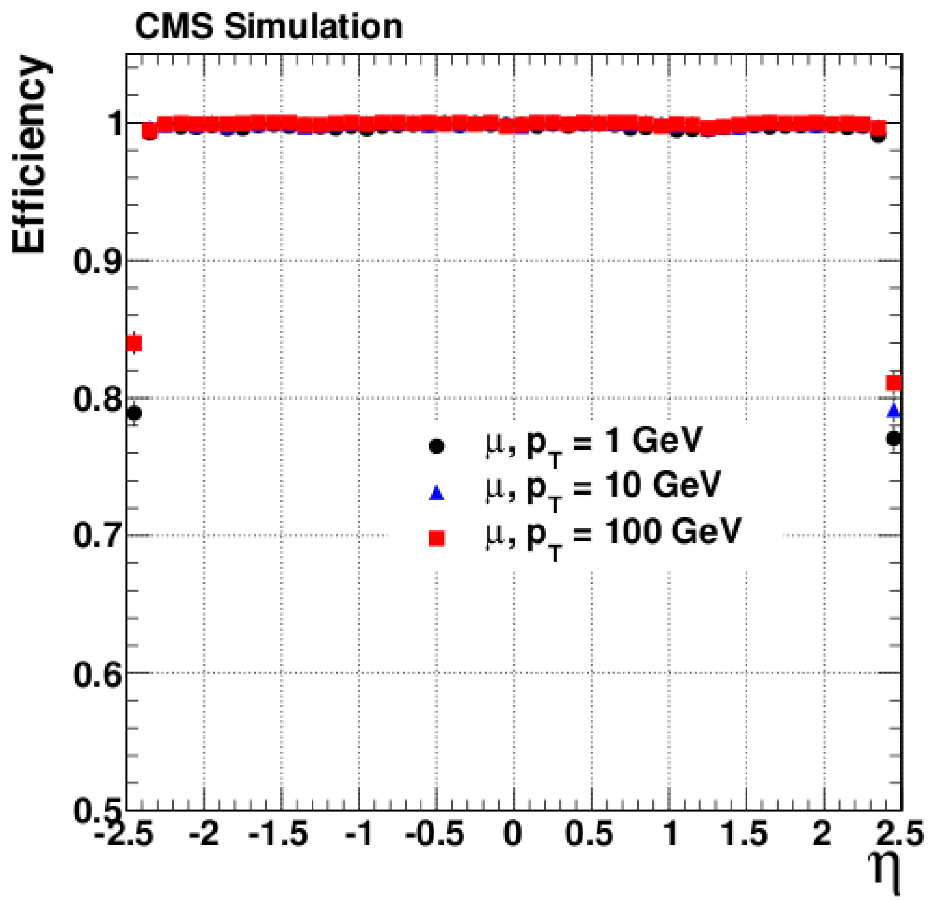


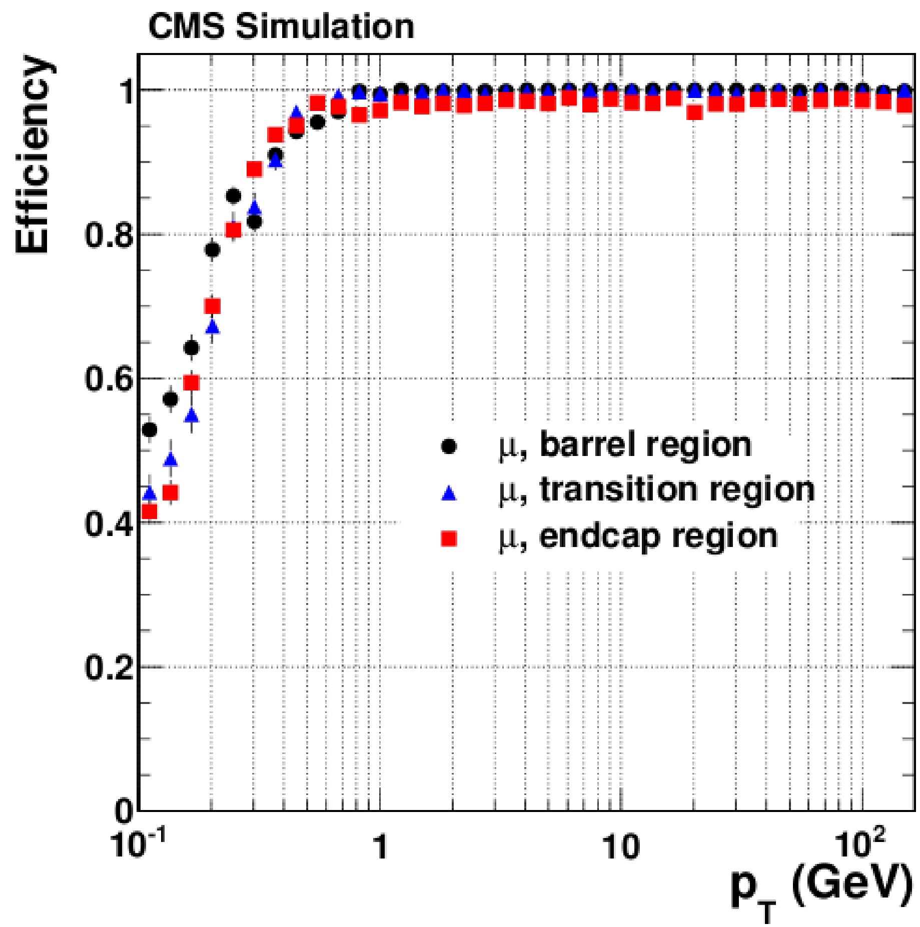
New collections of hits from the remaining clusters are created; pattern recognition is repeated, with looser constraints, in order to reconstruct **lower pT tracks or tracks with an associated vertex displaced from the beam-spot**.

Seeding for iterative tracking

Iteration	Seeds	p_T cut	d0 cut	dz cut
0	pixel triplets	0,8 GeV/c	0,2cm	3,0σ
1	pixel pairs	0,6 GeV/c	0,2cm	0,2cm
2	pixel triplets	0,075 GeV/c	0,2cm	3,3σ
3	pixel,TIB,TID,TEC	0,35 GeV/c	1,2cm	10,0cm
4	TIB,TID,TEC	0,5 GeV/c	2,0cm	10,0cm
5	TOB,TEC	0,6 GeV/c	5,0cm	30,0cm

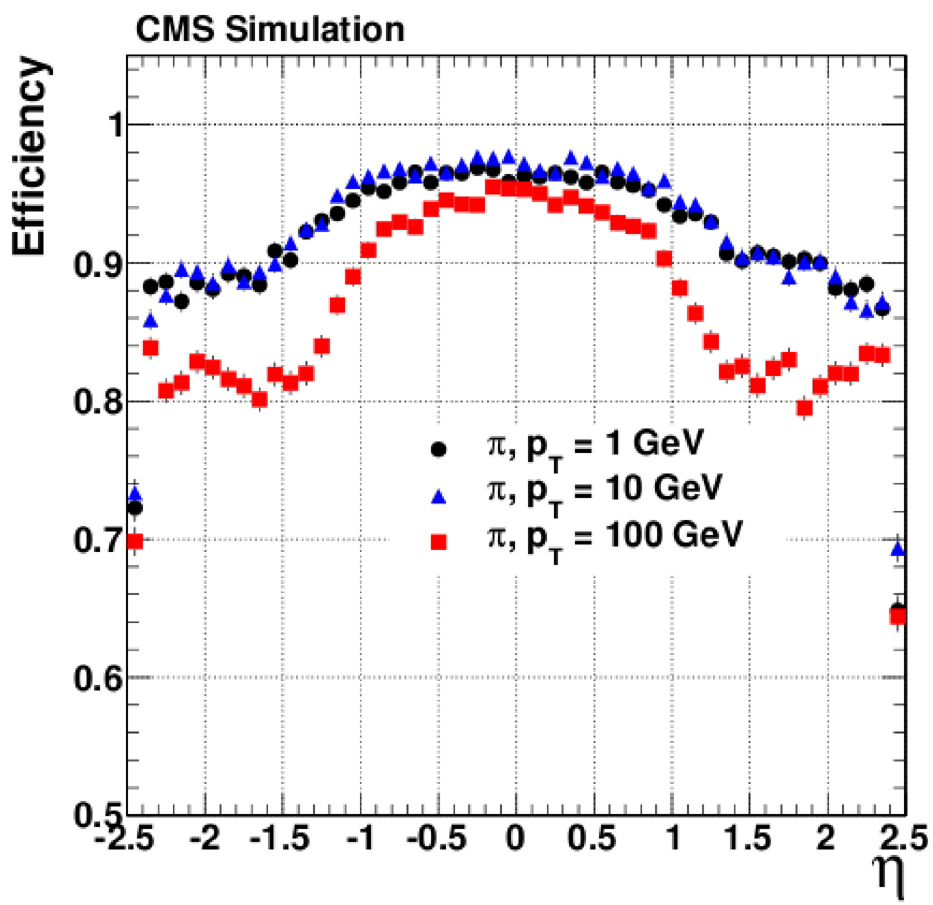
Tracking performance

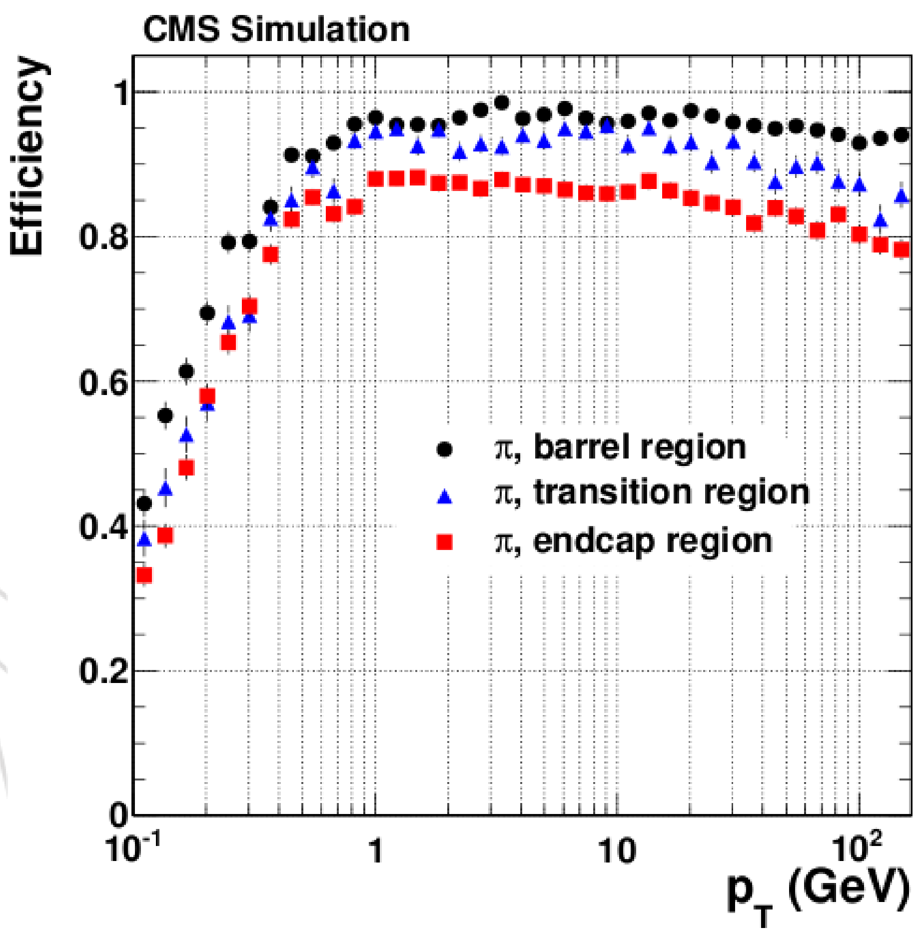




Efficiency is almost 100% for muons.

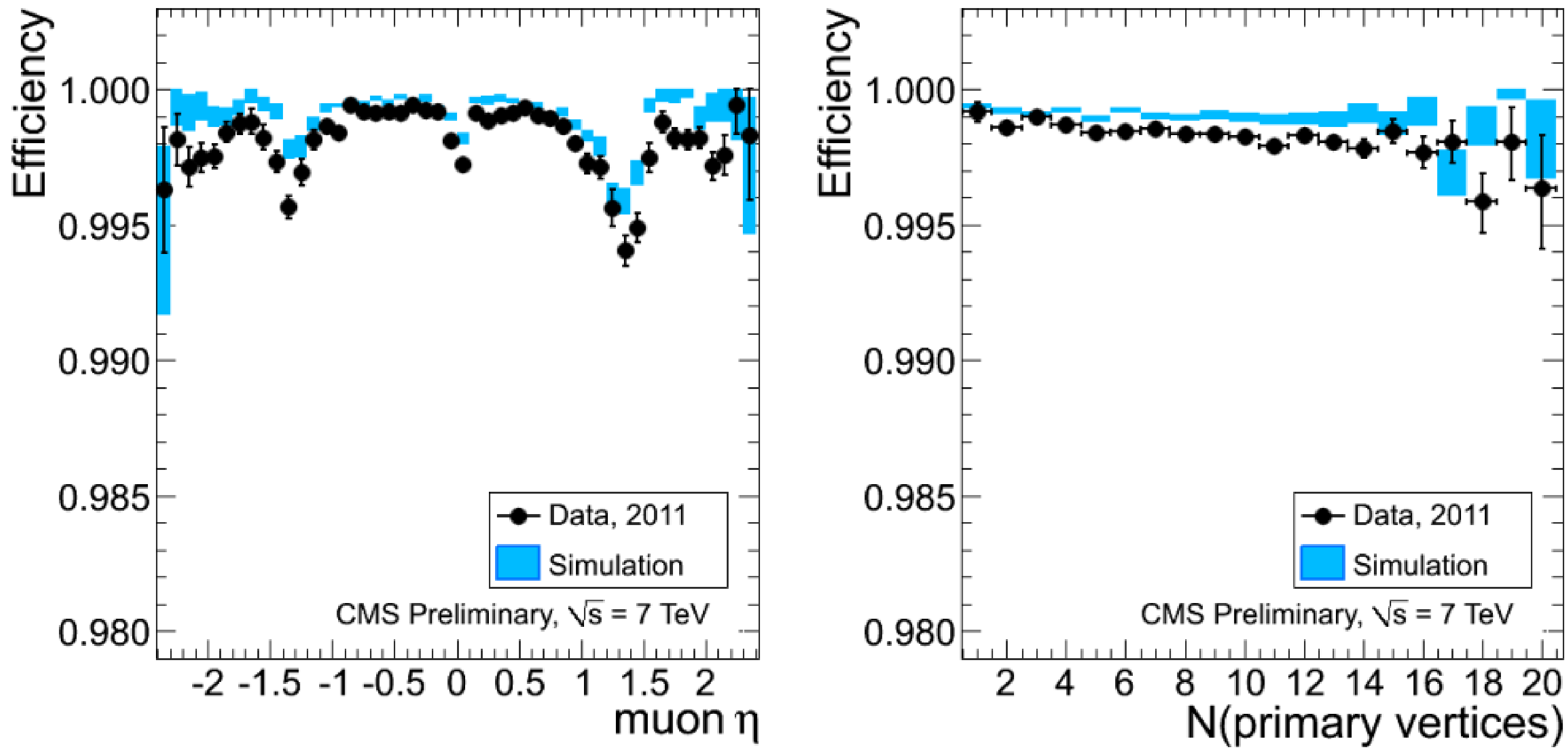
Tracking performance





Efficiency is around 90% for pions.

Tracking performance



Tracking efficiency for muons measured in Z→μμ events, with a **tag and probe** technique.

Efficiency vs η: structure due to the inactive modules and residual misalignment of the tracker.

Discrepancy btw data and MC wrt **efficiency drop with PU** due to a dynamic inefficiency of pixel detector (limited size of the internal buffer of the readout chips).

Primary vertex reconstruction

Three main steps:

i) *selection* of the tracks to be used
ii) *clustering* of the tracks: which ones originate from the same interaction vertex?
iii) *fitting* the vertex position

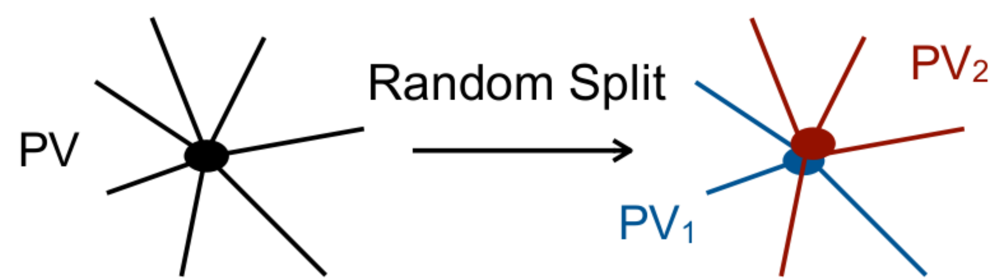
(ii) Clustering with a **Deterministic Annealing** algorithm: tracks assignation to vertices is performed allowing a **soft assignation of tracks to a vertex**.

(iii) Fitting performed with an *adaptive vertex fitter*, accounting for the probability that a track belongs to a vertex.

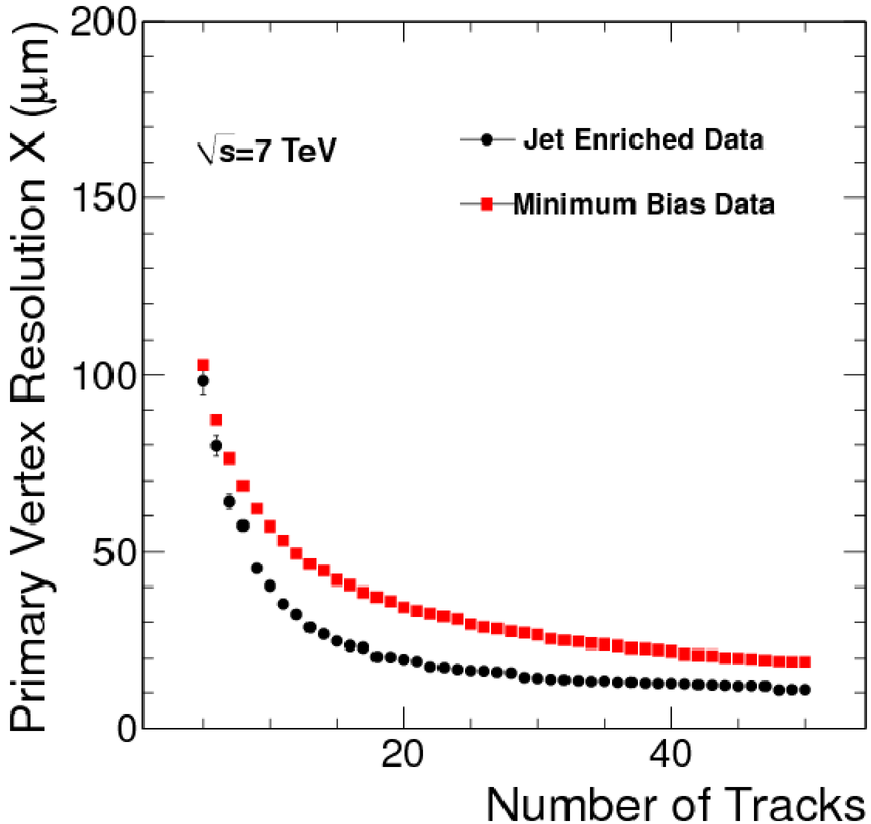
Vertex resolution "data-driven" measurement:

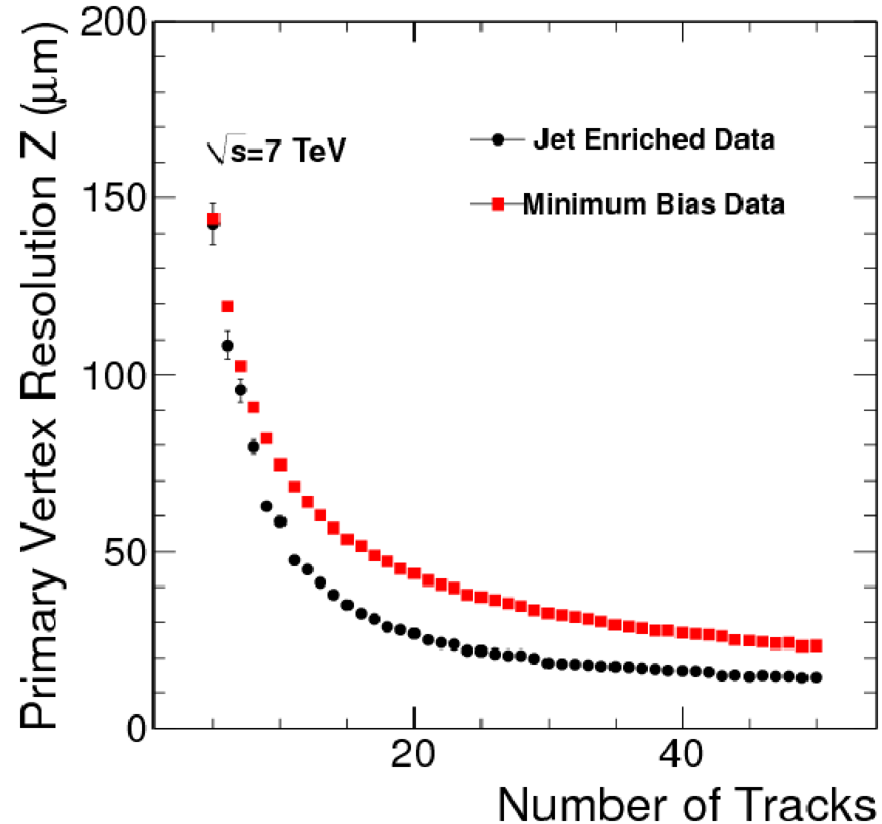
- tracks relative to a single vertex split in 2;
- 2 primary vertices fitted independently.

The position difference gives the resolution.



Primary vertex resolution

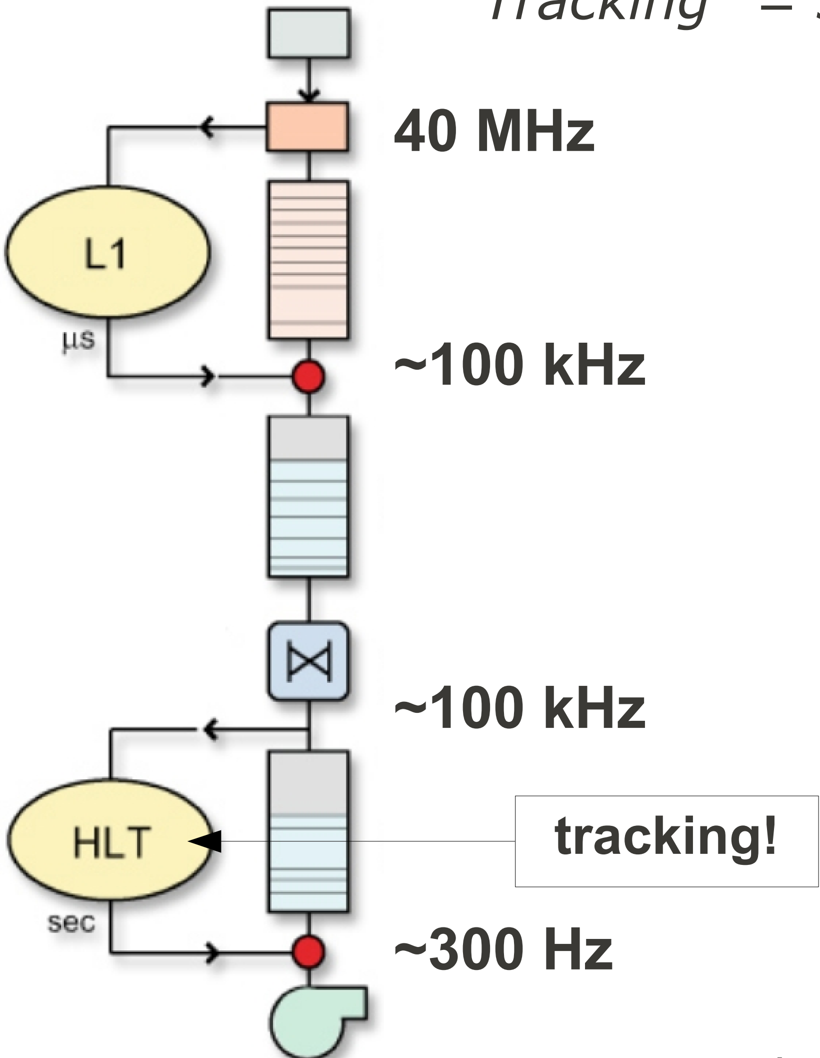




Data samples used: minimum bias and jet-enriched (E_T > 20 GeV ➝ higher mean p_T).
Strong dependence on the number of tracks.
For more than ~40 tracks, resolution is about **10-20 μm**.

Tracking at HLT

"Tracking" = software algorithms for tracks reconstruction



Using tracking information at HLT:

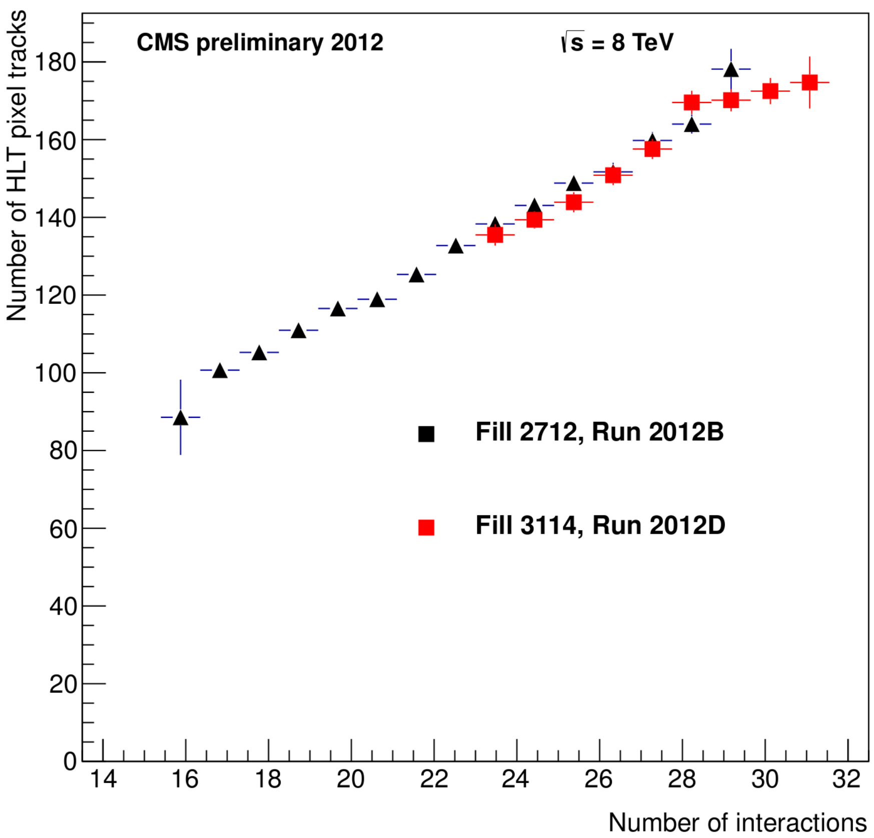
- reduces the event rate
- reduces fake-rate and improves efficiency
- improves isolation in leptonic trigger paths

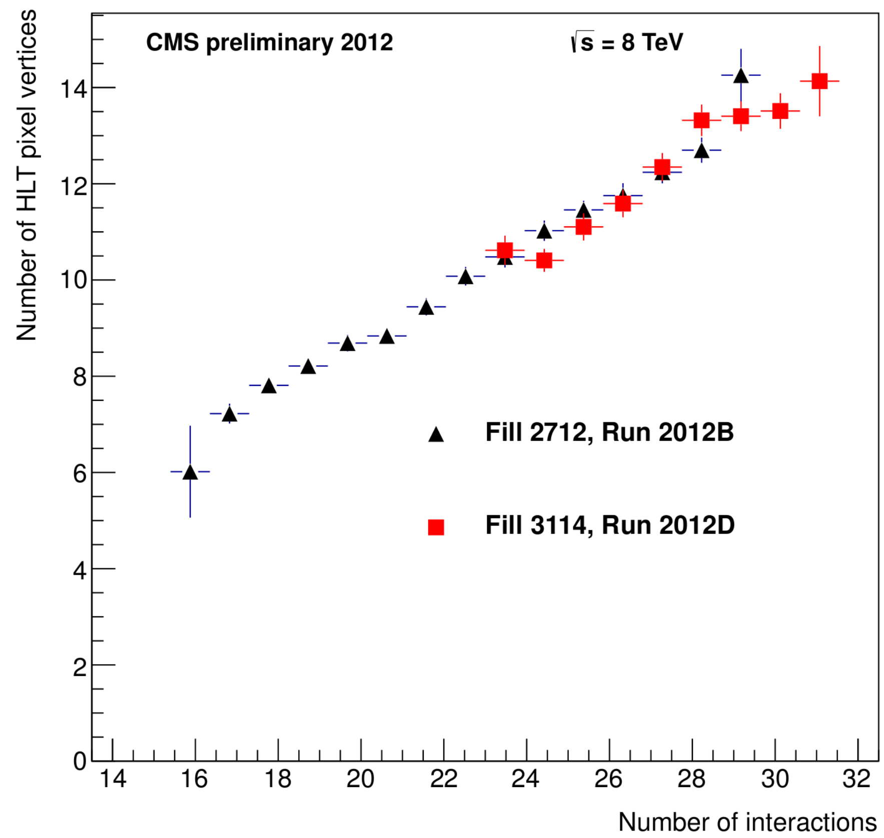
Using *iterative* tracking at HLT:

- reduces the combinatorics
- reduces the CPU-time
- allows PF reconstruction at HLT level:
  - improves jet/MET resolution

Standard algorithms too slow to be used online: O(10 s)
Online version much faster: **O(100 ms)**

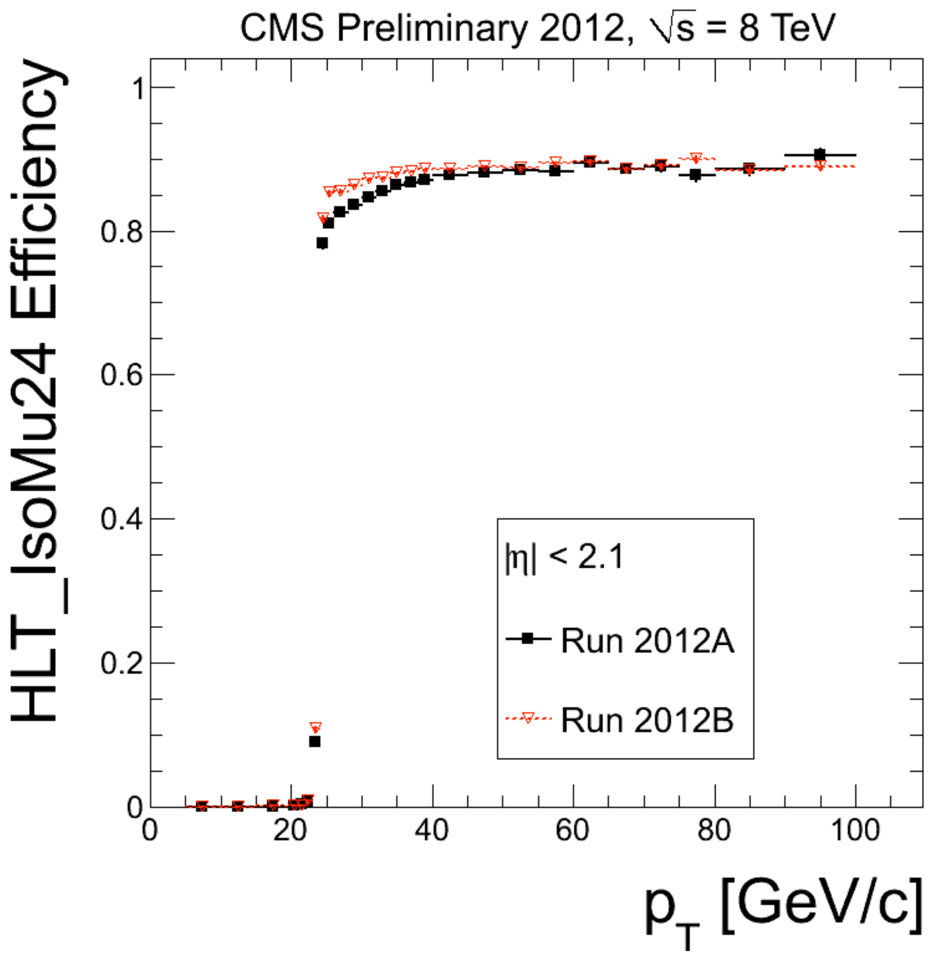
Tracking at HLT





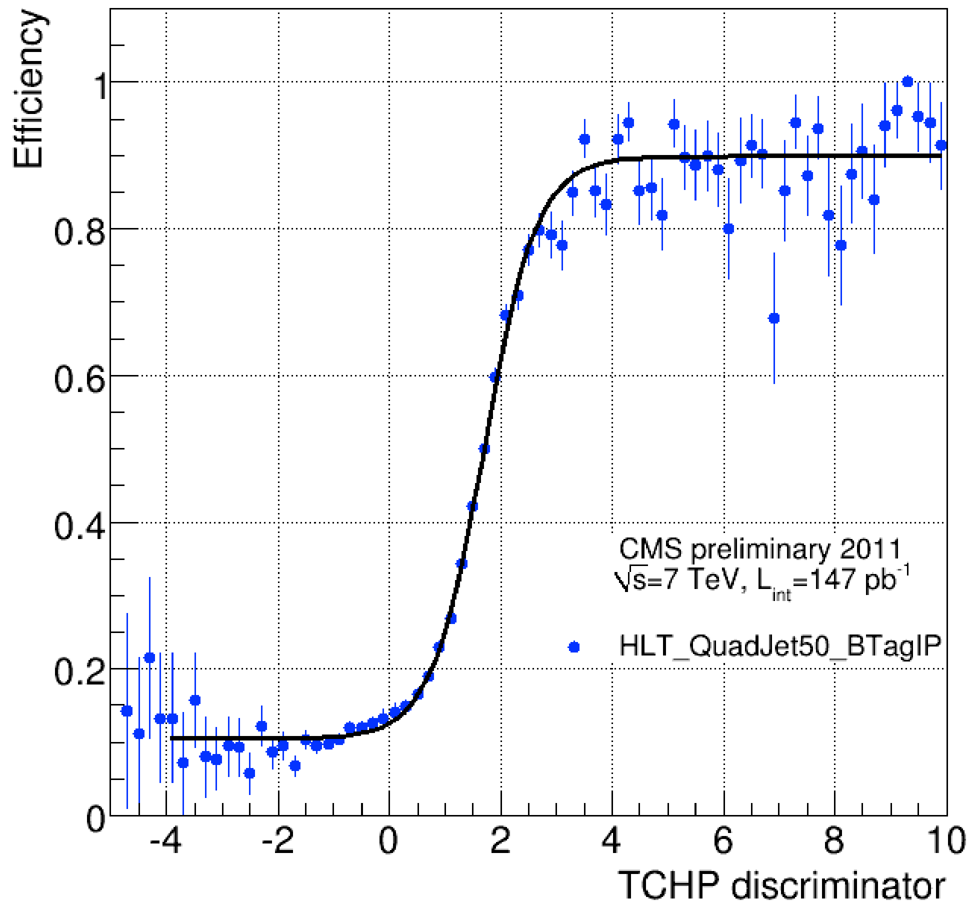
Number of interactions calculated from bunch luminosity measured with HF.

Tracking at HLT: muon reconstruction



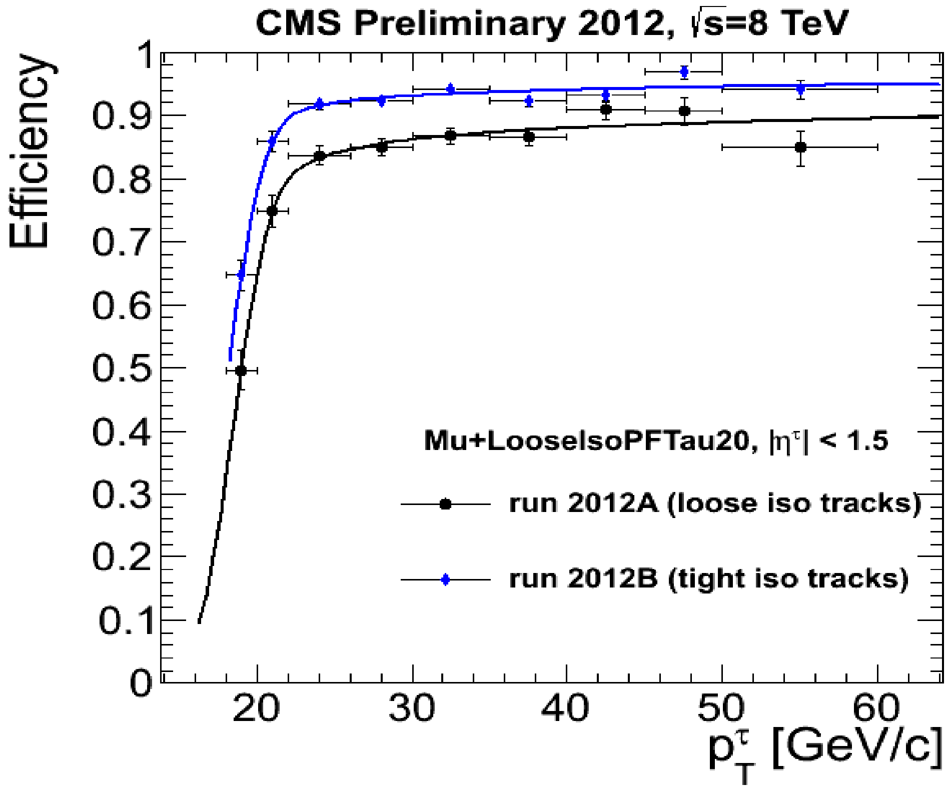
Muon triggers have very sharp turn-on curves, also thanks to tracking.

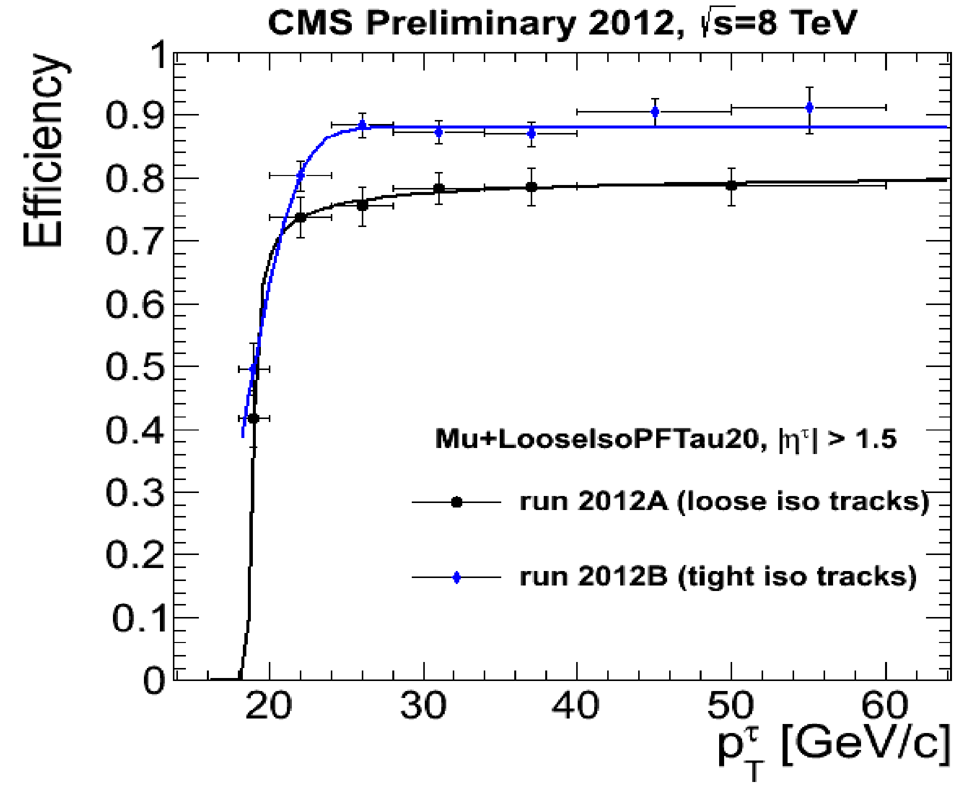
Tracking at HLT: b-tagging



Turn-on curve of the HLT Track Counting High Purity (TCHP) discriminator efficiency, wrt offline.
The TCHP discriminator is the significance of the third track (sorted by decreasing IP sign.).
TCHP cut at 2 for this HLT path.

Tracking at HLT: tau leptons





Efficiency measured using tag-and-probe technique with Z-> tau+ tau-, tau->mu+tau-hadr
Trigger: HLT_IsoMu15_eta2p1_ETM20
- Difference in efficiency between run 2012A and 2012B: different quality criteria of isolation
- Different efficiency in barrel (|η|<1.5) and endcap (|η|>1.5): detector effects + different real tau purity

Summary

• The CMS tracker, the biggest tracker ever built, is performing very well.

• Tracking and vertexing algorithms allow a very high efficiency for tracks and vertices reconstruction and very precise parameters measurements (e.g.: ~ 99% tracking efficiency for muons; IP resolution ~ 10 μm).

• Tracking at HLT allows PF object reconstruction already at trigger level and is important for b-tagging, lepton and jet reconstruction.

• Almost all HLT paths use tracking and/or vertexing.

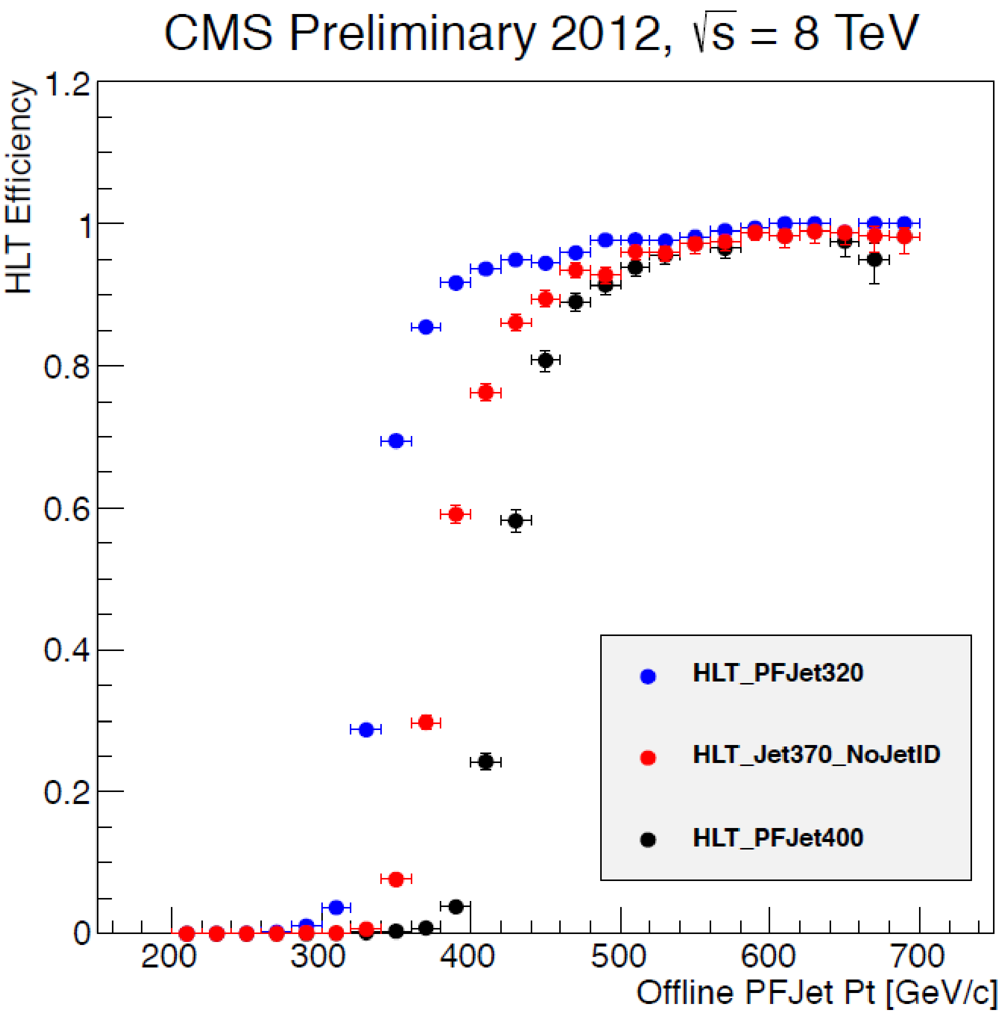
• HLT tracking is coping well with PU.

• Re-tuning and improvements will be needed for the post-LS1 high-PU scenario: work in progress

Spares

Tracking at HLT: jet reconstruction

- Turn-on curves for jet triggers measured vs. offline Particle Flow (PF) Jet p_T
- Trigger efficiency measured w.r.t. HLT_IsoMu24_eta2p1
- Based on 6.397 fb^{-1} from Run2012C (SingleMu Primary Dataset)
- Trigger turn-on curve is shifted to slightly higher value of offline jet p_T due to the different corrections applied to HLT and offline objects (L1FastL2L3 for HLT jets, L1FastL2L3Residual for offline jets).



0.0<|eta|<0.9 barrel
0.9<|eta|<1.4 transition
1.4<|eta|<2.5 endcap

Kalman Filter for trajectory building

Seed

↓

Rough parameters (+ uncertainties) estimation

↓

"Navigation" towards outer detectors

↓

Search for hits compatible with prevision

↓

Parameter (+ uncertainties) updating

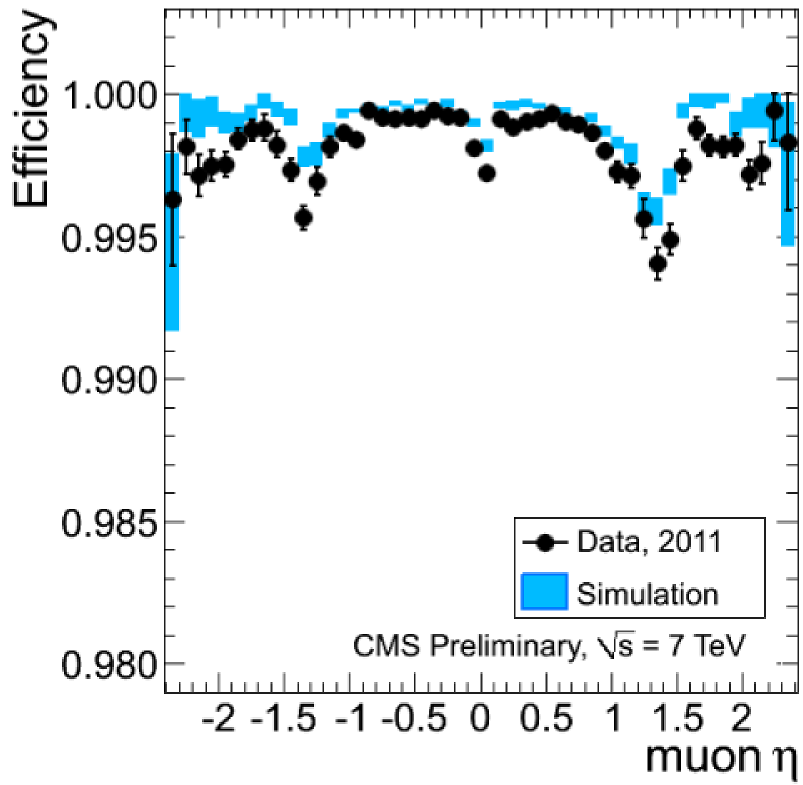
↓

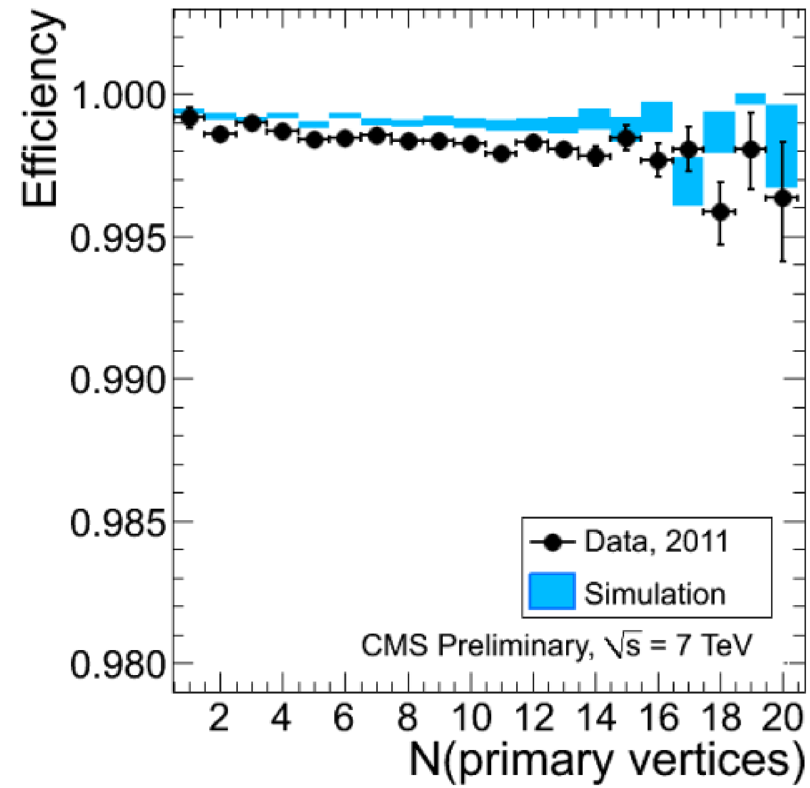
Reiteration

If more than one compatible hit:
several cadidates are created
The "best"* ones are propagated (<5)

(* chi square + valid hits/invalid hits)

Tracking performance





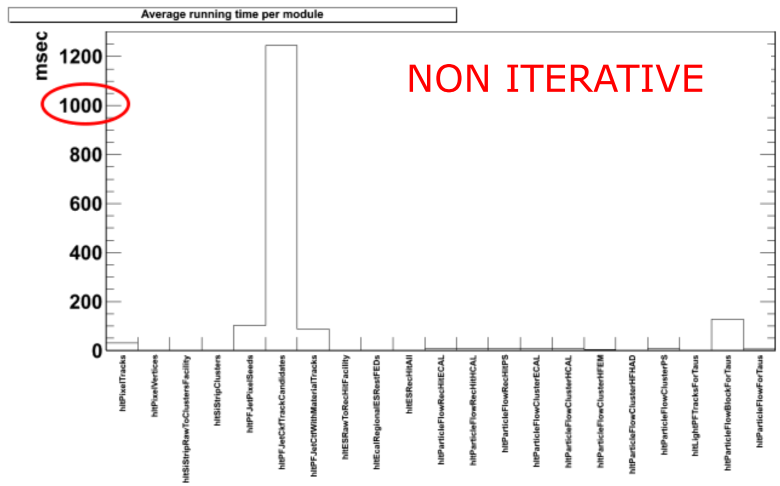
Tracking efficiency for muons measured in Z→μμ events, with a **tag and probe** technique.
Tag muons: reconstructed in both muon chambers and tracker.
Probe muons: reconstructed with muon chambers only.
1) selection of tag events
2) on this sample of tagged events: which ones pass the probe(mu chambers)?
3) on the same sample: which ones pass the probe(mu chambers+tracker)?
Eff = probe(mu+trk)/probe(mu)

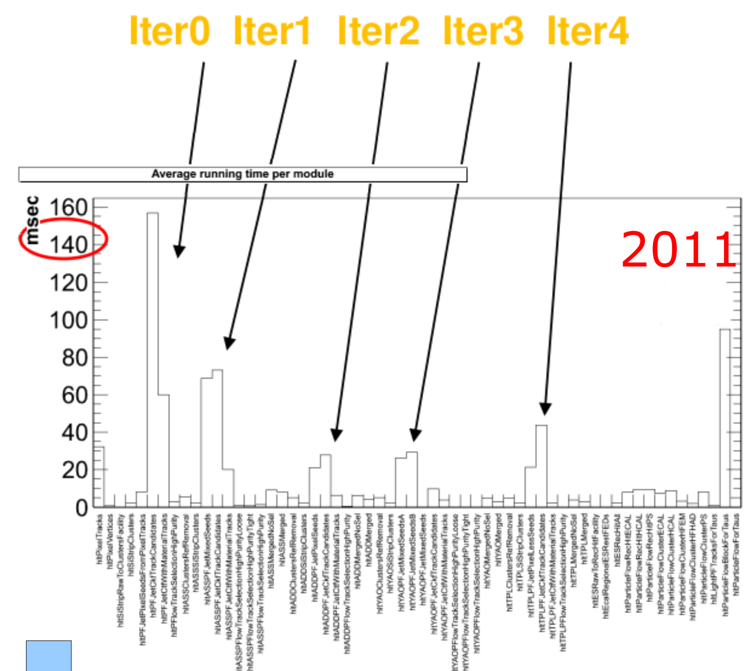
Online vs offline seeding

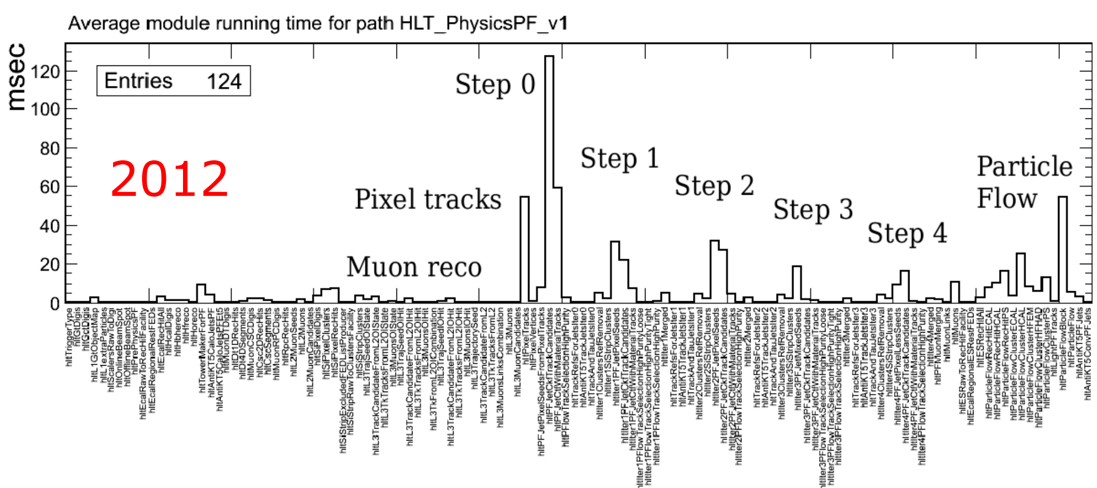
Iteration	Seed	pT cut online	pT cut offline	dz cut	d0 cut
Iter 0	3 pixel hits	0.9 GeV/c	0.8 GeV/c	0.3 cm	0.1 cm
Iter 1	3 pixel hits	0.5 GeV/c	0.6 GeV/c	0.1 mm	0.5 mm
Iter 2	2 pixel hits +beam spot constraint	1.2 GeV/c	75 MeV/c	0.5 mm	0.25 mm
Iter 3	3 (pixel+strip) hits	0.8 GeV/c	350 MeV/c	0.5 mm	0.5 mm
Iter 4	2 strip (TIB) hits	0.8 GeV/c	0.5 GeV/c	1 cm	0.5 cm

Iterative tracking

- Allows to reduce CPU time

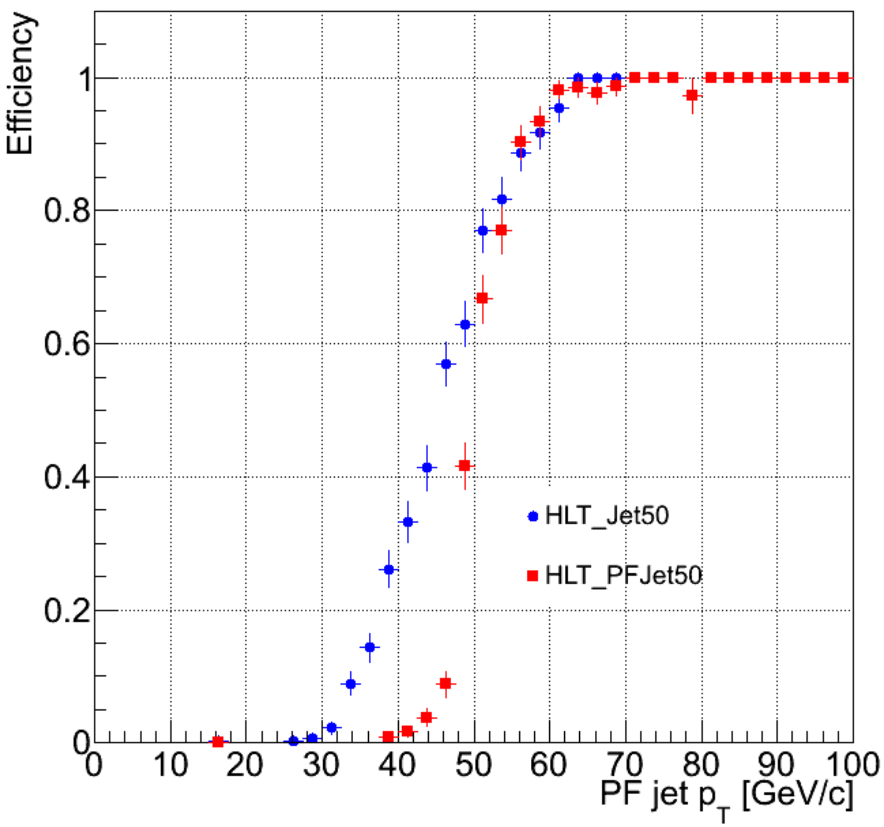




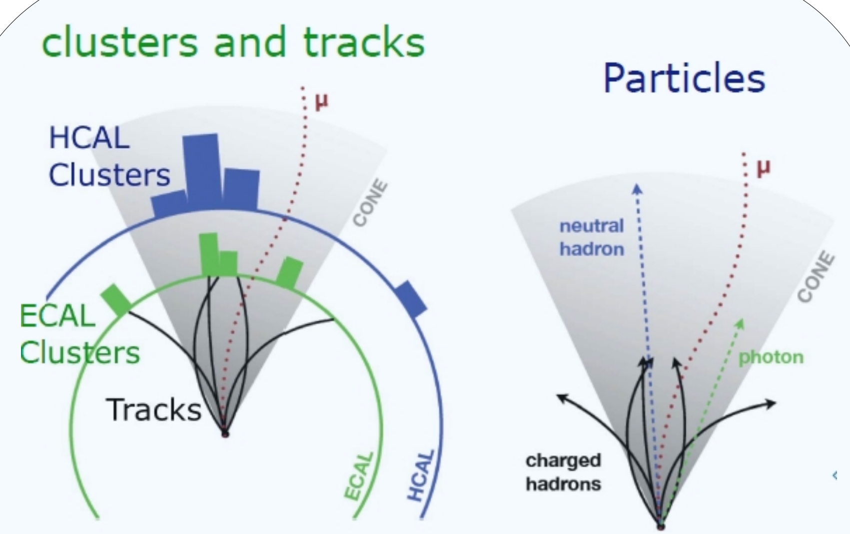


Iterative tracking

- Allows to use PFJets at trigger level



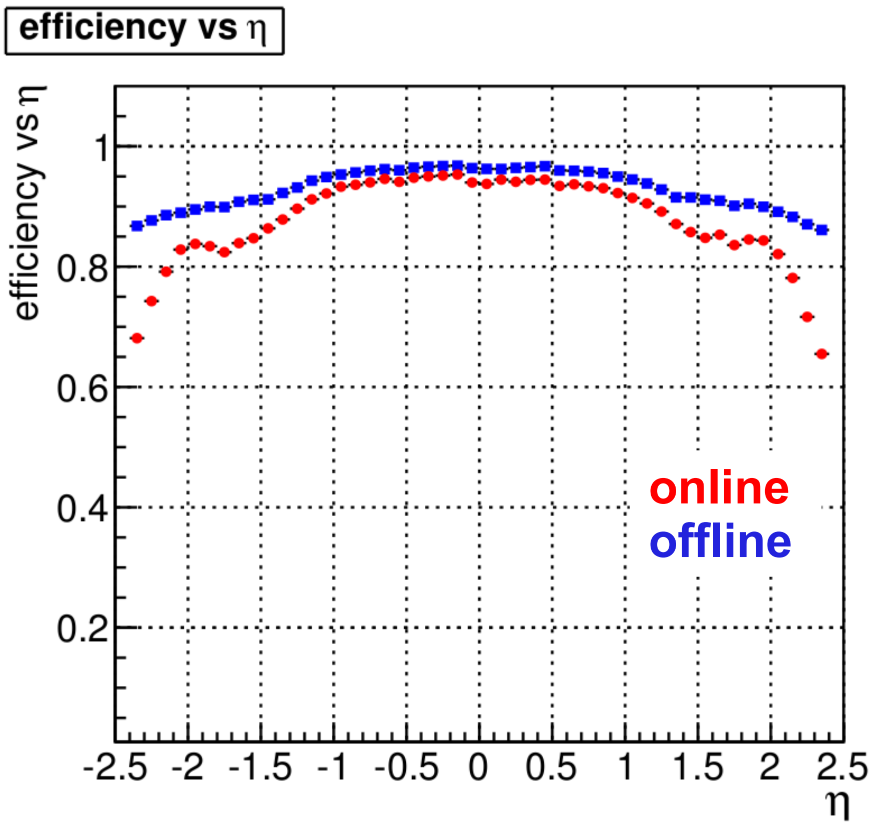
Efficiency turn-on curve (wrt offline) ~3 times steeper than for CaloJets!

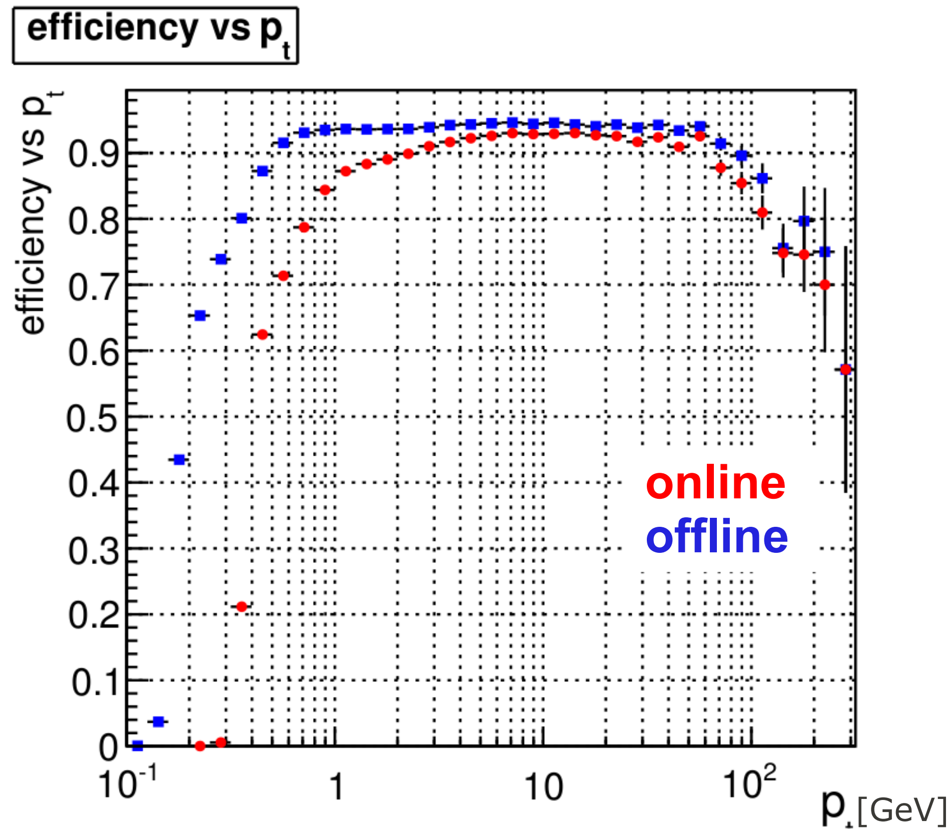


Particle flow: algorithm which allows the reconstruction and identification of muons, electrons, neutral hadrons, charged hadrons, tau leptons and neutrinos exploiting the information from all detectors

HLT tracking performance

HLT tracking vs offline tracking performance



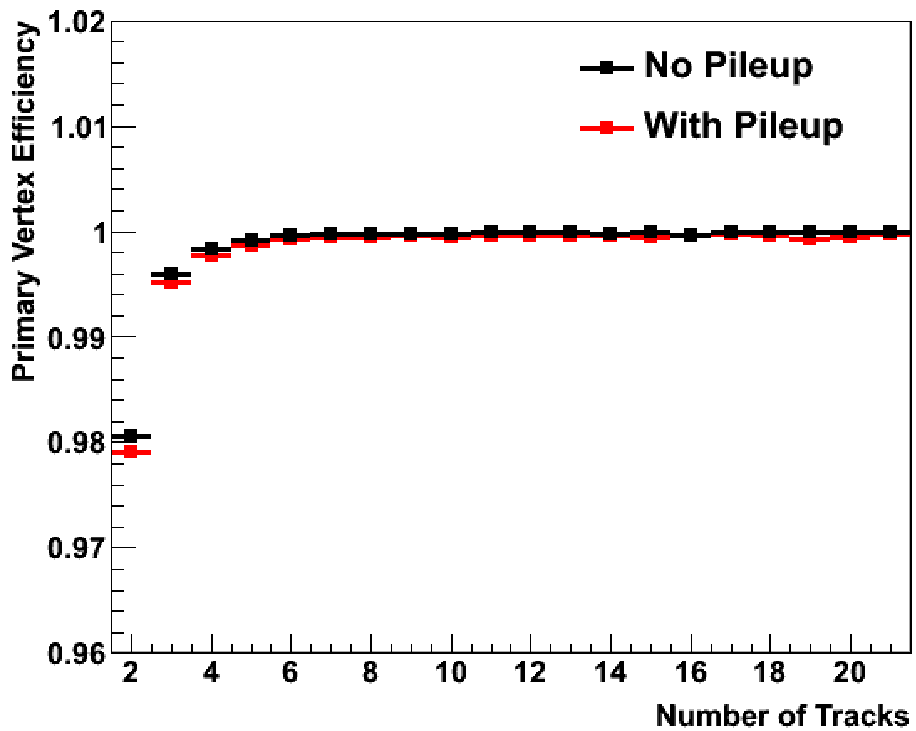


After 5 iterations

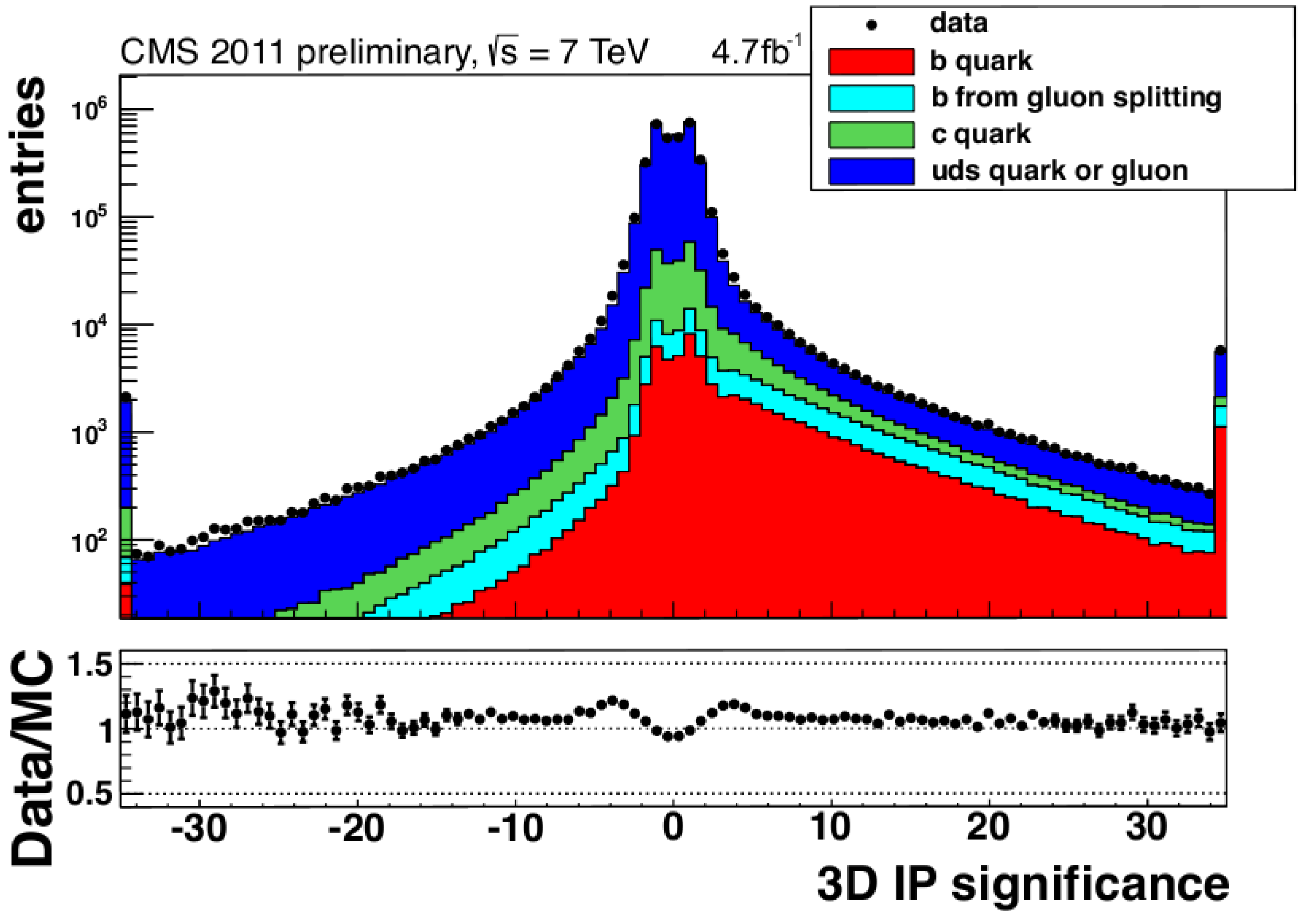
To remove

Primary vertex efficiency

• Split method + tag and probe
• Tracks split in two sets (2/3 tag, 1/3 probe) and fit separately for PV position
• Probe passes if z-position matches within 5 σ the original vertex, given that tag also matches with the real PV (in MC)
• Efficiency ~ 100% if more than 4 tracks

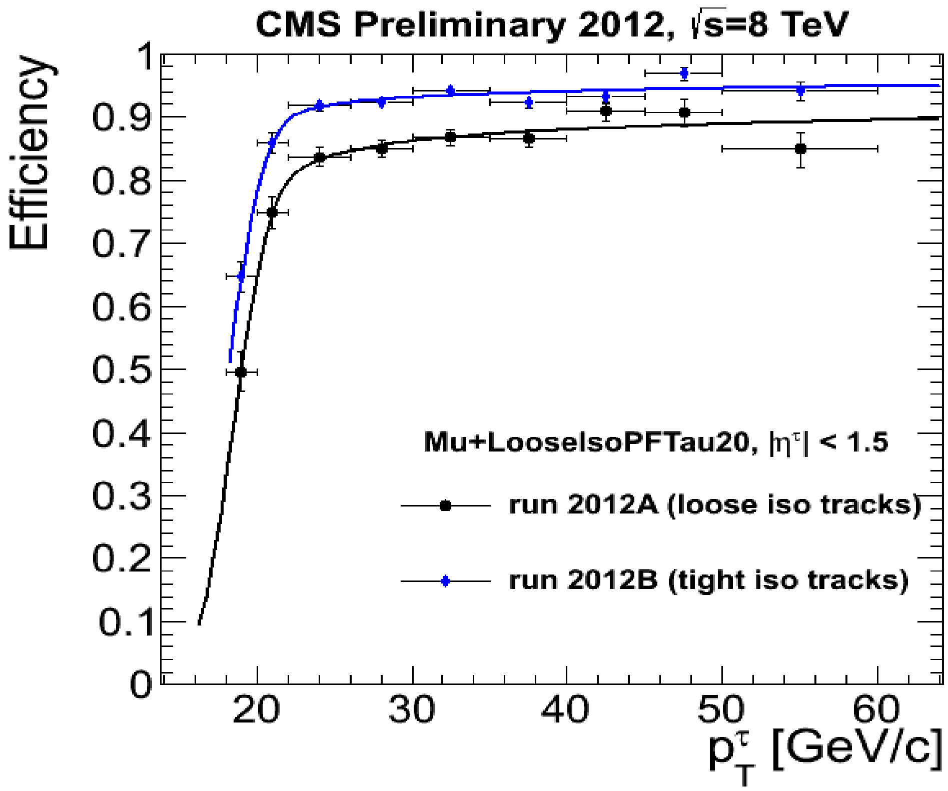


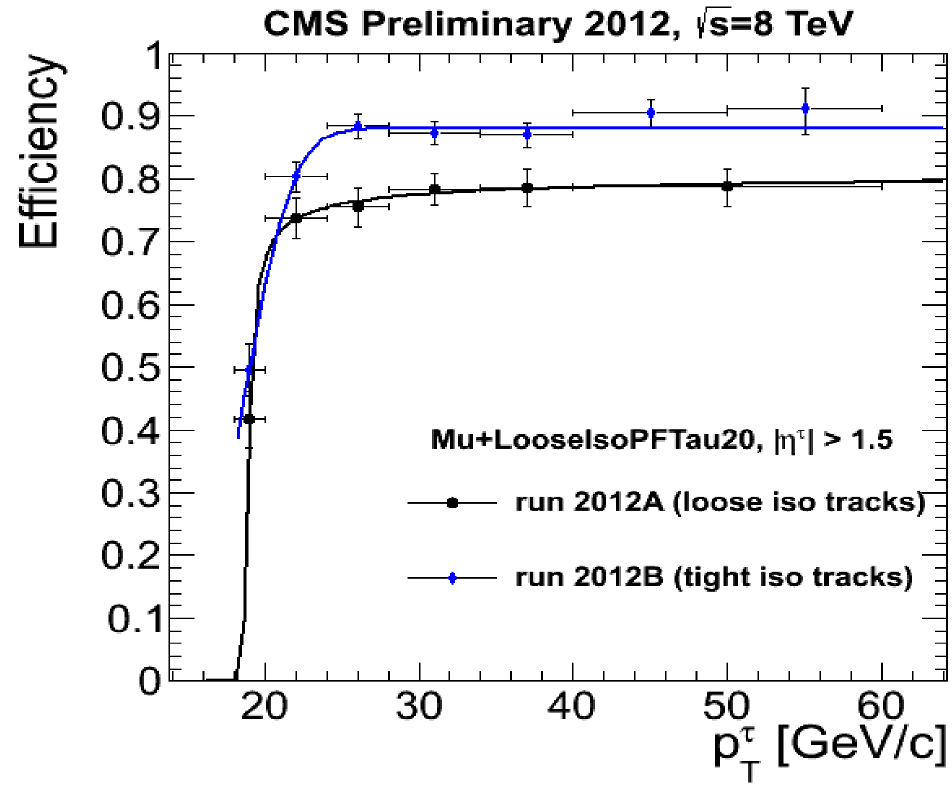
b-tagging variables



Excellent resolution in tracks and vertices reconstruction is used to build b-tagging discriminants, for example the Impact Parameter significance.

Tracking at HLT: tau leptons





Efficiency measured using tag-and-probe technique with Z-> tau+ tau-, tau->mu+tau-hadr
Trigger: HLT_IsoMu15_eta2p1_ETM20
- Tag: isolated offline muon matched to HLT_IsoMu15_eta2p1_ETM20
- Probe: offline HPS tau with reconstructed decay mode, passing MVA-based isolation discriminant, tight muon veto and loose electron veto
- Continuous curves in plots represent an error function of a crystal ball fitted to data points
- Difference in efficiency between run 2012A and 2012B come from different quality criteria of isolation
- Difference between efficiency in barrel (|eta|<1.5) and endcap (|eta|>1.5) come from both detector effects and different real tau purity