Track Reconstruction in the CMS Tracker

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Tracking at LHC

- proton-proton collisions at $\sqrt{s}$ = 14 TeV
- bunch spacing of 25 ns
- Luminosity:
  - low-luminosity: $2 \cdot 10^{33}$ cm^{-2} s^{-1} (10 fb^{-1} per year - for the first 3 years)
  - high-luminosity: 10^{34} cm^{-2} s^{-1} (100 fb^{-1} per year)
    - ~ 20 minimum bias events per bunch crossing
    - ~ 5000 charged tracks per event

Radius:	2cm	10cm	25cm	60cm
$N_{Tracks}/(cm^2*25ns)$	10.0	1.0	0.10	0.01

  - Fast response time to resolve bunch crossing
  - Fine granularity to resolve nearby tracks
- Reconstruction of narrow heavy objects: ~ 1-2 % p_T resolution at ~100 GeV/c

  4 T field - ~1.1m Tracker radius: 1.80 mm sagitta for 100 GeV/c p_T track!
- Ability to tag b/τ jets through secondary vertices: good impact parameter resolution

The CMS Experiment

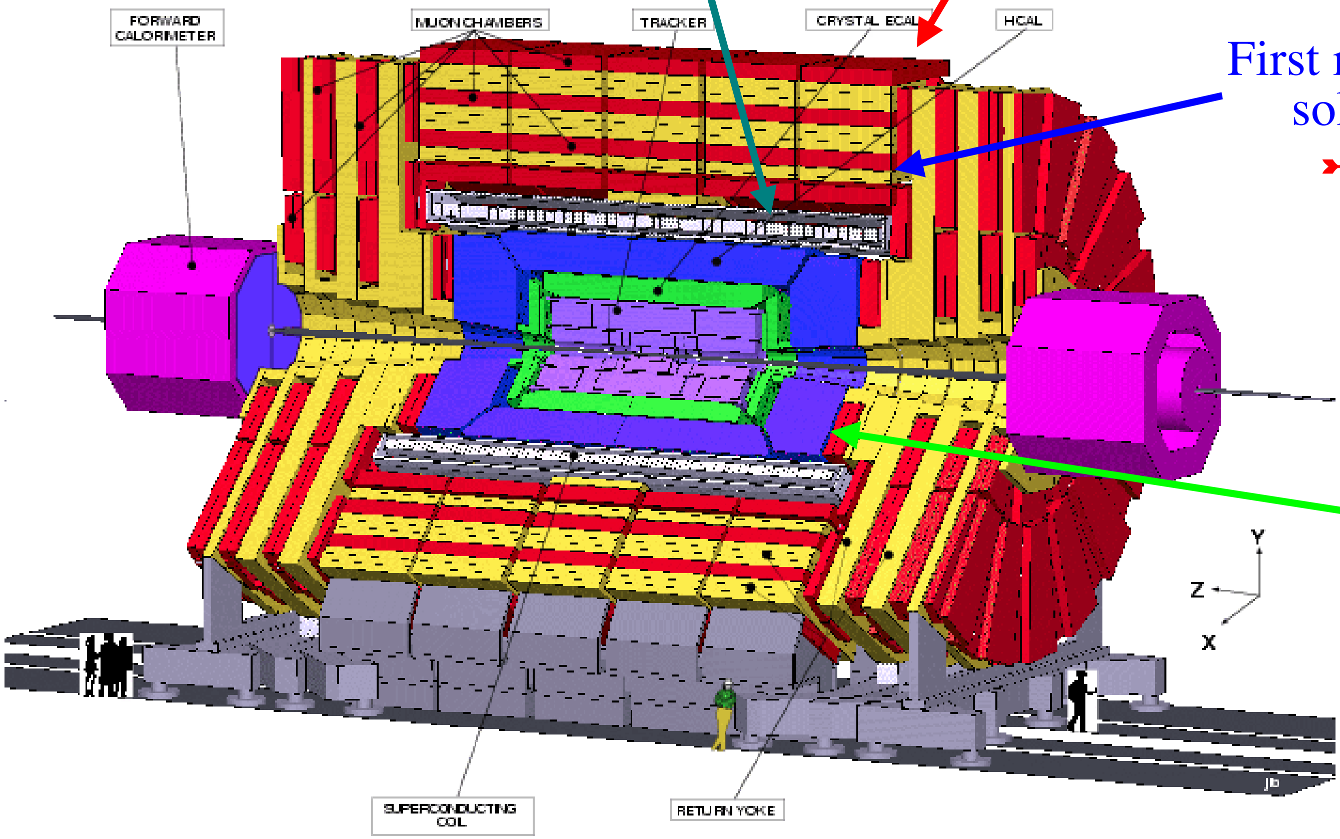
13x6 m Solenoid: 4 Tesla Field

- Tracking up to $\eta \sim$ **2.5**

Muon system in return yoke

First muon chamber just after solenoid

- extend lever arm for p_T measurement



ECAL & HCAL inside solenoid

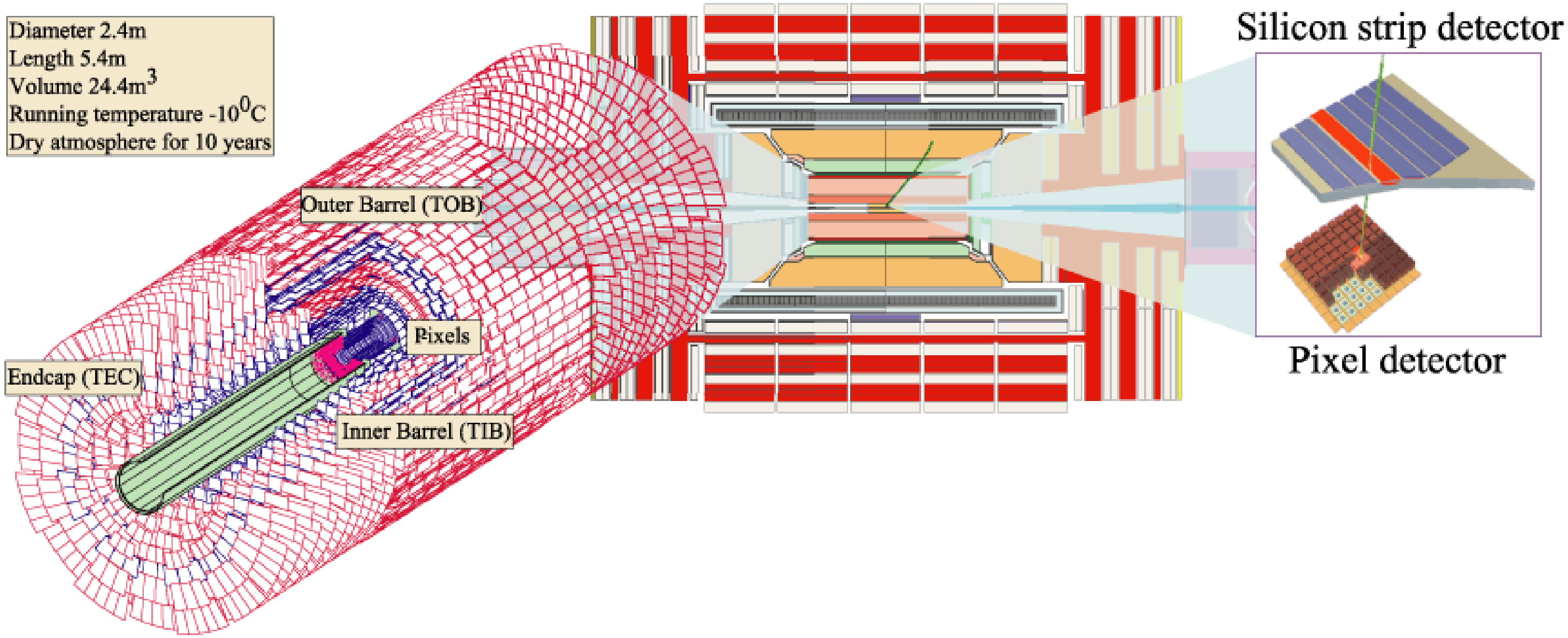
- 22m Long, 15m Diameter, 14'000 Ton Detector

The CMS Tracker

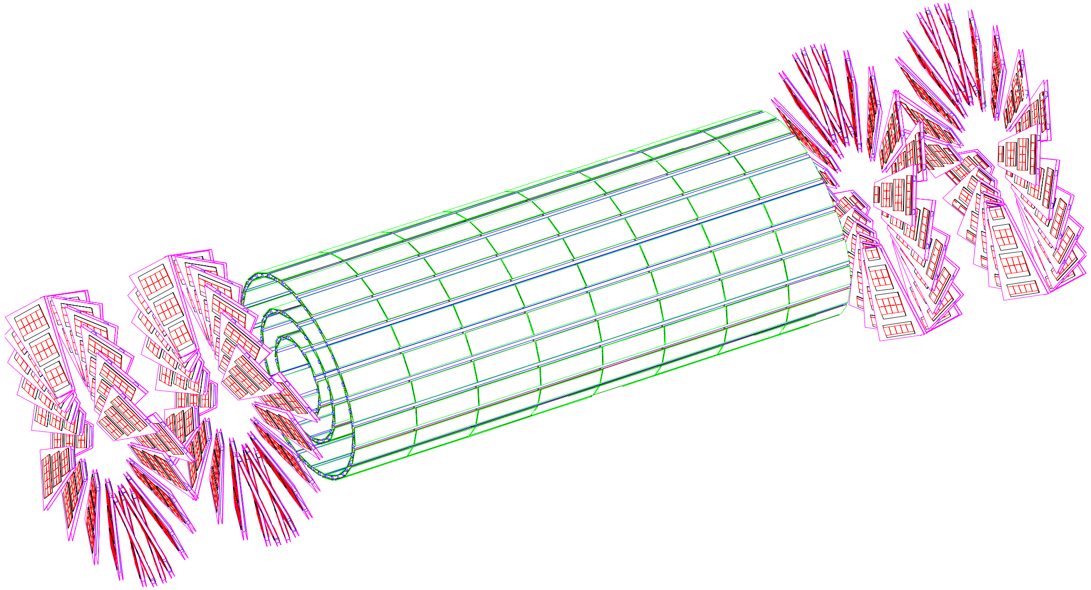
➣ CMS has chosen an all-silicon configuration

Rely on "few" measurement layers, each able to provide robust (clean) and precise coordinate determination:

- Pixel detector: 2 - 3 points
- Silicon Strip Tracker: 10 - 14 points



The Pixel system



Active area ~ 1m^2 - 66·10^6 pixels

Geometry:

- 3 Barrel layers
  r = 4.4 cm, 7.3 cm, 10.2 cm
- 2 Pairs of Forward/Backward Disks
  r = 6 cm-15 cm ; z = 34.5cm, 46.5cm

➣ 3 high resolution measurement points for **$|\eta| < 2.2$**

Pixel-size: 100 µm x 150 µm

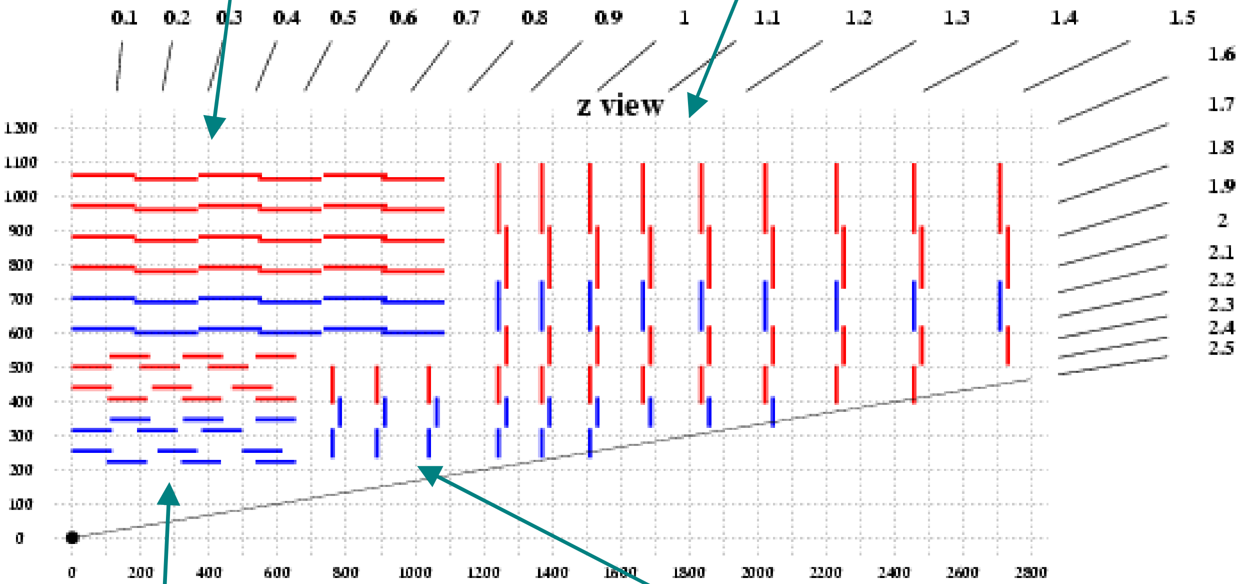
Hit-resolution:

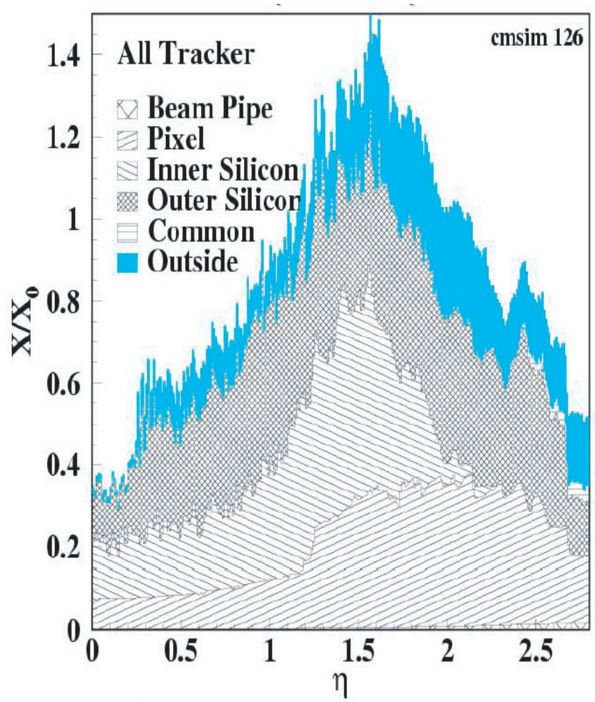
- r-ϕ : $\sigma \sim 10$ µm
  (Lorentz angle 23° in 4 T field)
- r-z : $\sigma \sim 20$ µm

The CMS Silicon Strip Tracker

Outer Barrel (TOB): 6 layers
- Thick (500 μm) sensors
- Long Strips

Endcap (TEC): 9 disks pairs
- r<60cm: Thin sensors
- r>60cm: Thick sensors





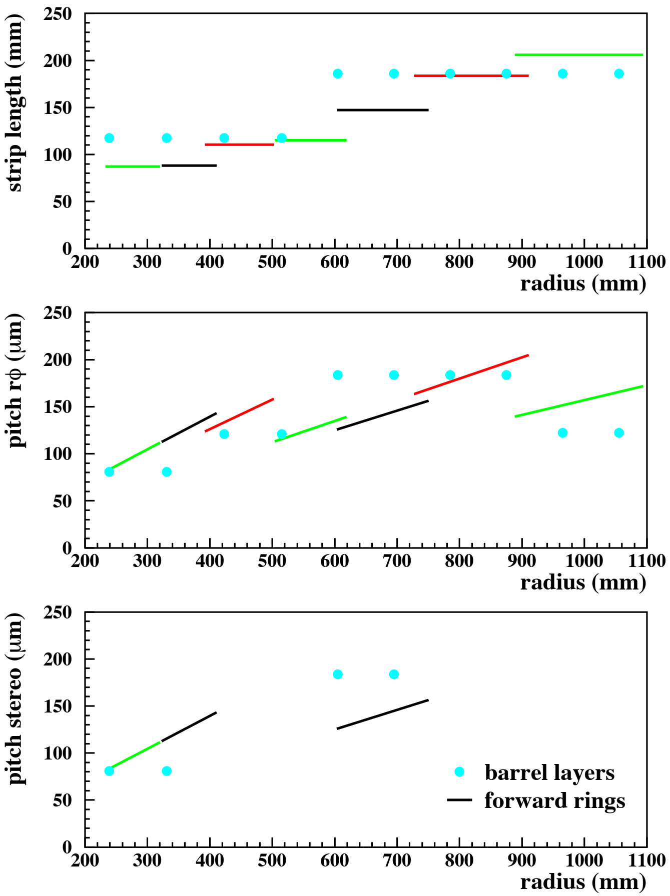
Material budget of the tracker

Inner Barrel (TIB): 4 layers
- Thin (320 μm)sensors
- Short Strips

Inner Disks (TID): 3 disks pairs
- Thin sensors

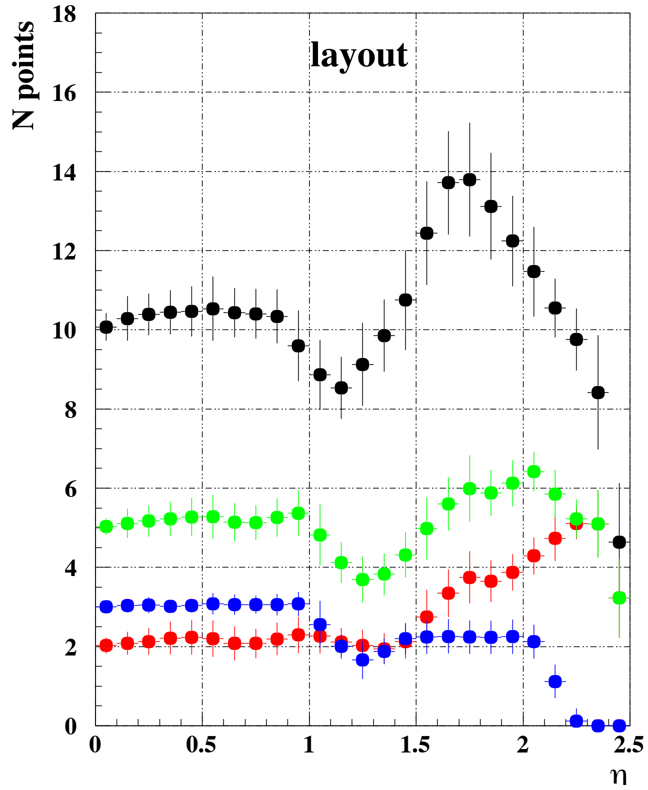
blue: double-sided detectors
red: single-sided detectors

The CMS Silicon Strip Tracker



➣ 14 different sensor geometries

Number of SST hits by tracks:



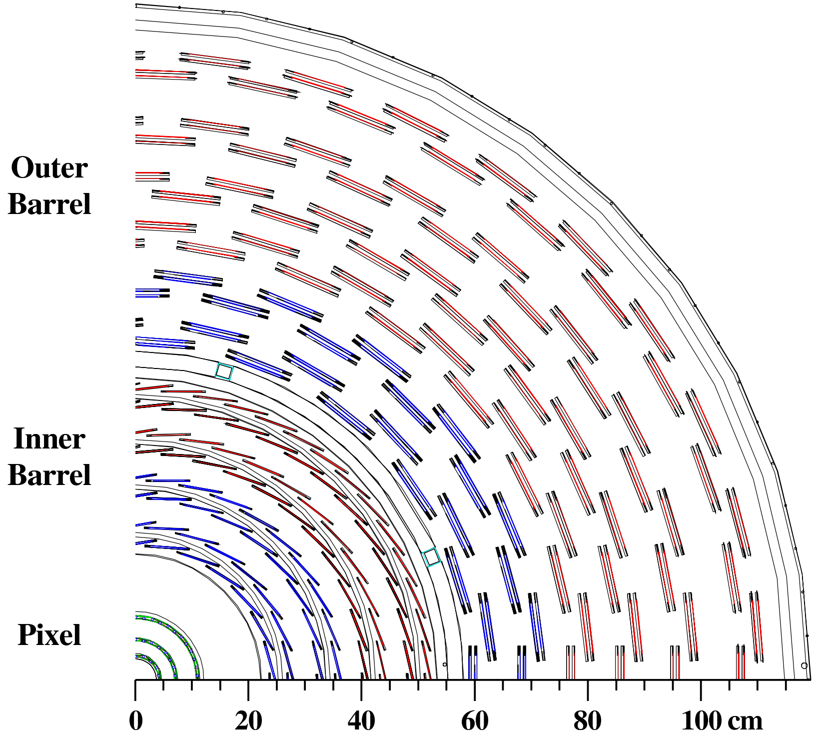
Black: Total number of hits
Green: double-sided hits
Red: double-sided hits in thin detectors
Blue: double sided hits in thick detectors.

Track reconstruction

- The Combinatorial Kalman Filter is the main algorithm used to reconstruct charged tracks
  - ➢ Local method: one track reconstructed at a time, starting from an initial trajectory.
  - ➢ Recursive procedure: track parameters estimated from a set of reconstructed hits
  - ➢ Takes into account the energy loss and multiple-scattering between layers
  - ➢ Integrates pattern recognition and track fitting
- The Kalman Filter is mathematically equivalent to a global least square minimization (LSM), optimal when
  - ➢ model is linear
  - ➢ random noise Gaussian
- For non-linear models or non-Gaussian noise, it is still the optimal linear estimator

The Combinatorial Kalman Filter

- *Inside-out tracking:* start in the first Pixel layers, grow tracks layer by layer to the outer layer of the SST.
  - ➢ Initial trajectories (*seeds*): pixel hit pairs (every combination of 2 pixel layers, compatible with the beam spot and a minimum p_T cut)



Cross section of a quadrant of the barrel of the tracker

The Combinatorial Kalman Filter

- *Inside-out tracking:* start in the first Pixel layers, grow tracks layer by layer to the outer layer of the SST.
  - Initial trajectories (*seeds*): pixel hit pairs (every combination of 2 pixel layers, compatible with the beam spot and a minimum p_T cut)
  - Reasonable number of seeds, with good quality
    - Fine granularity: low occupancy, high purity
    - High precision
  - Hadrons: high interaction probability in the tracker (~20% of 1 GeV pions do not reach the outer layer)
  - Favour tracks with pixel hits: precision on track parameter at the vertex (needed for vertex reconstruction, *b*-tagging, etc...)
- *Outside-in tracking*:
  - Muon reconstruction: seeds in the outer layers based on muon-chamber seeds
  - Electrons from γ conversions: seeds in the outer layers based on ECAL clusters

The Combinatorial Kalman Filter

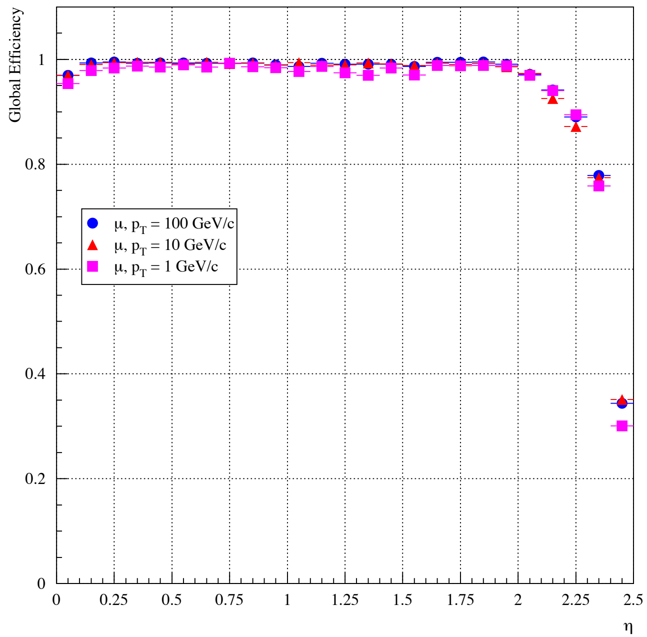
Track reconstruction is decomposed in 4 modular, independent, components:

- Generation of *seeds*
- Trajectory Building: construction of trajectories for a given seed
  - ➢ Trajectories are extrapolated from layer to next layer, accounting for multiple scattering and energy loss
  - ➢ On the new layer, new trajectories are constructed, with updated parameters (and errors) for each compatible hit in the layer.
  - ➢ All trajectories are grown to the next layer in parallel to avoid bias.
  - ➢ The number of trajectories to grow is limited according to their χ^2 and the number of missing hits.
- Trajectory Cleaning: hit assignment ambiguity resolution
- Trajectory Smoothing: final fit of trajectories
  - ➢ Obtain optimal estimates at every measurement point along the track.
  - ➢ In addition to providing tracks accurate at both ends this procedure provides more accurate rejection of outliers

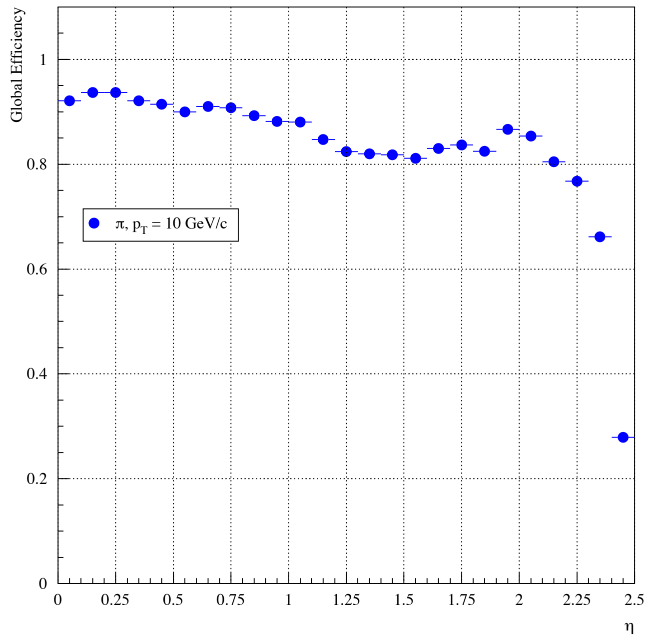
The Combinatorial Kalman Filter

Track reconstruction efficiency for single tracks:

muons, p_T = 1, 10, 100 GeV/c



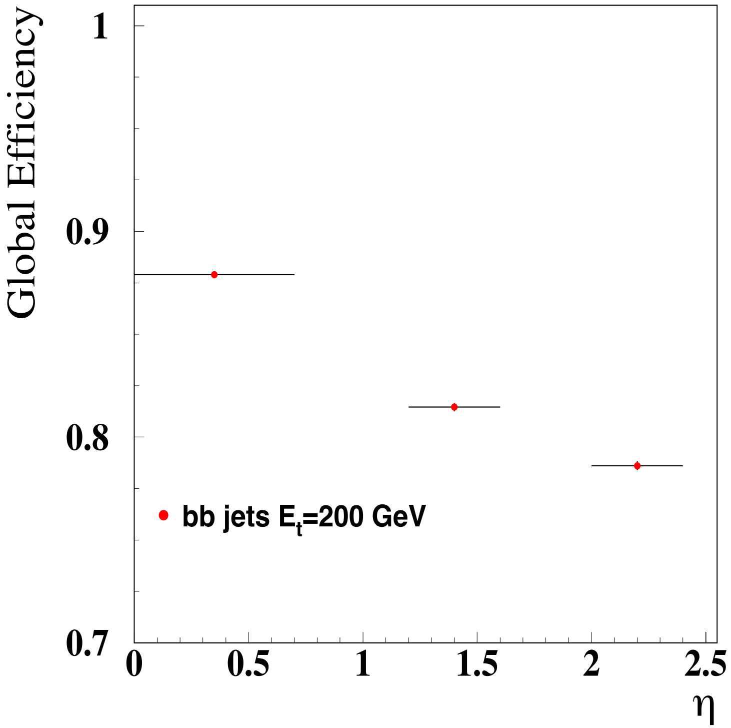
pions, p_T = 10 GeV/c



For pions: lower efficiency due to nuclear interactions in the tracker

The Combinatorial Kalman Filter

Track reconstruction efficiency for *b*-jets (E_T=200 GeV), tracks with $p_T > 0.9$ GeV/*c*, min. 8 hits:



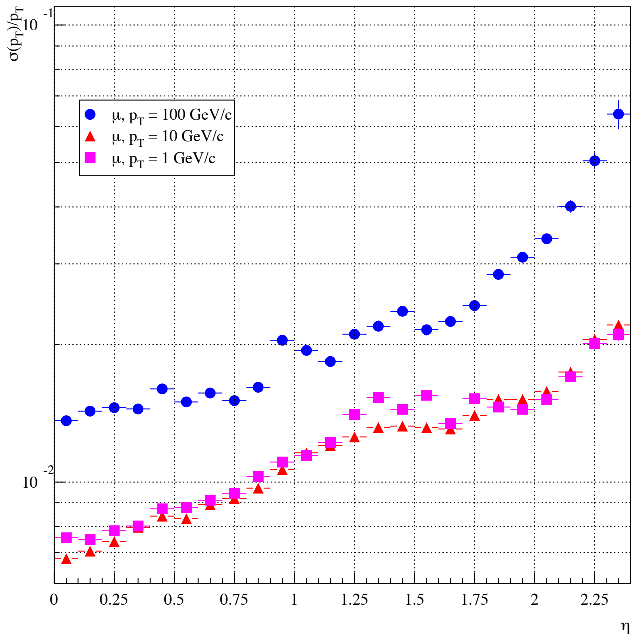
Loss dominated by π interaction

Efficient and robust pattern recognition:

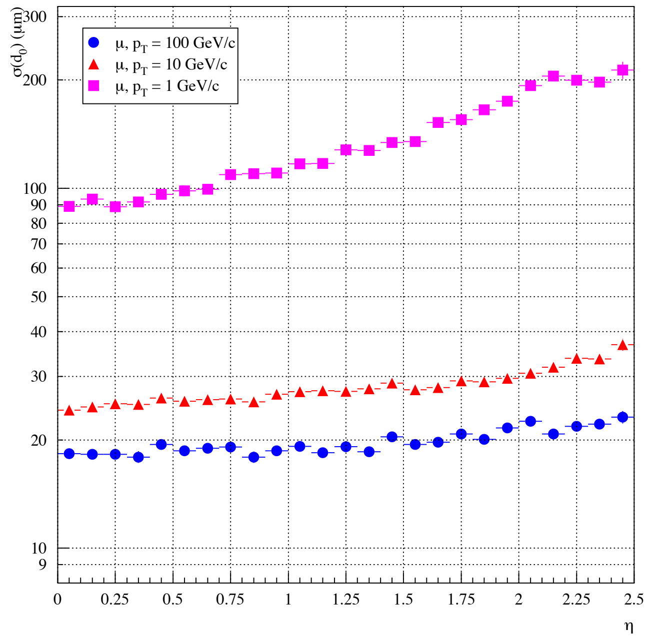
- Low contamination from spurious hits, even with PU
- Reconstruction ambiguities are solved after the first few layers.

The Combinatorial Kalman Filter

Track parameter resolutions (muons, p_T = 1, 10, 100 GeV/c)



p_T resolution
Dominated by the lever-arm



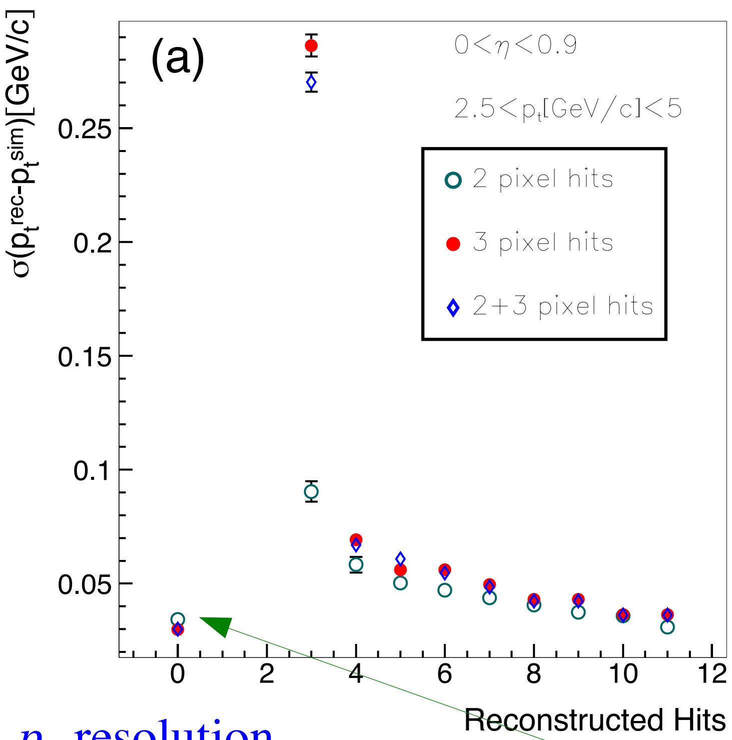
Transverse impact parameter resolution
Dominated by the resolution of the hits in the pixel detector.

Partial reconstruction

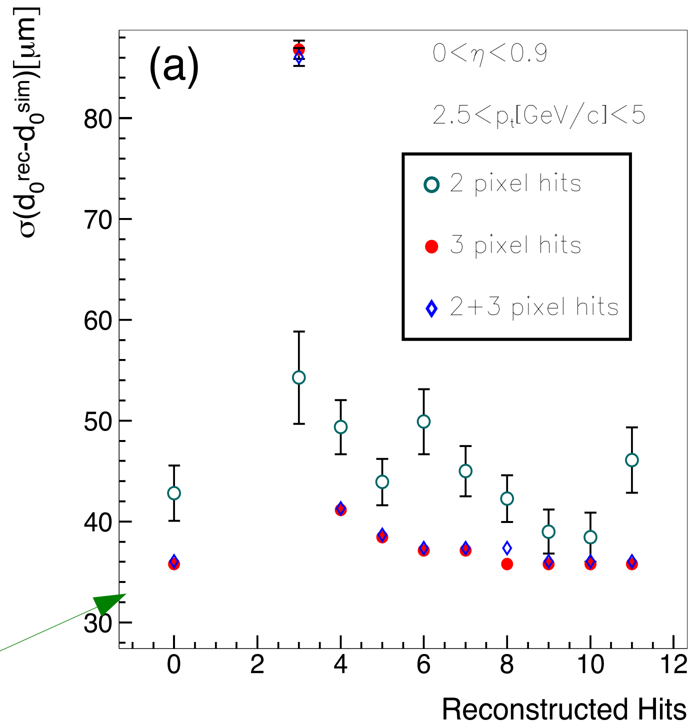
Combinatorial KF also suitable for usage in the High-Level Trigger (HLT):

- Track parameter resolutions reach an asymptotic value after using only first 5/6 hits

Resolutions as a function of the number of hits used: (b-jets, $2.5<p_T<5$, $|\eta|<0.9$)



p_T resolution



Transverse impact parameter resolution

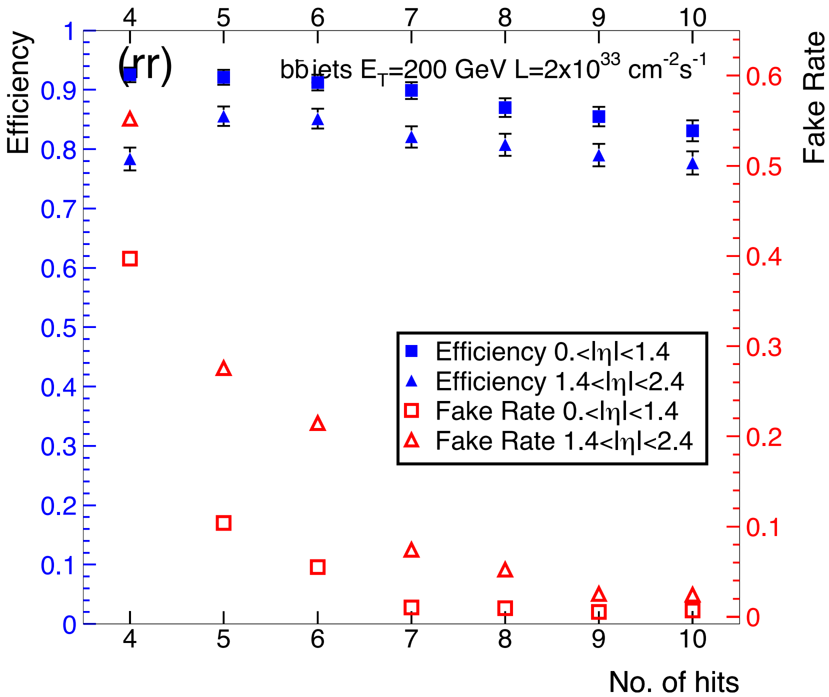
("0 hits" indicates full track reconstruction!)

Partial reconstruction

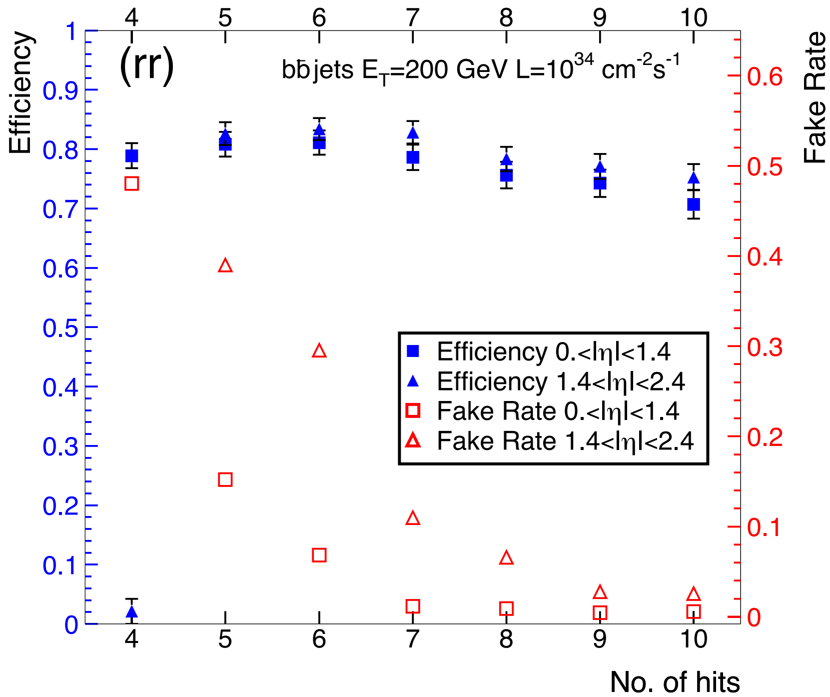
Partial reconstruction: stop track reconstruction once enough information is available to answer a specific question

Same components, algorithms used.

Precision sufficient for most HLT applications: vertex reconstruction, *b*-tagging



b-jets, E_T = 200GeV, low luminosity



b-jets, E_T = 200GeV, high luminosity

Adaptive filters

Several adaptive algorithms have been implemented:

- LSM optimal when
  - ➢ Model is linear
  - ➢ Random noise Gaussian (measurement errors, process noise)

- *Pdf* involved are usually non-Gaussian:
  - ➢ Measurement errors have Gaussian core, with tails
  - ➢ Energy loss and multiple scattering (tails)
    - ➵ Gaussian-sum Filter

- Large background noise (electronic noise, low p_T tracks, δ electrons, etc.)
  - ➢ Hit degradation
  - ➢ Hit assignment errors
    - ➵ Deterministic Annealing Filter & Multi-Track Fit

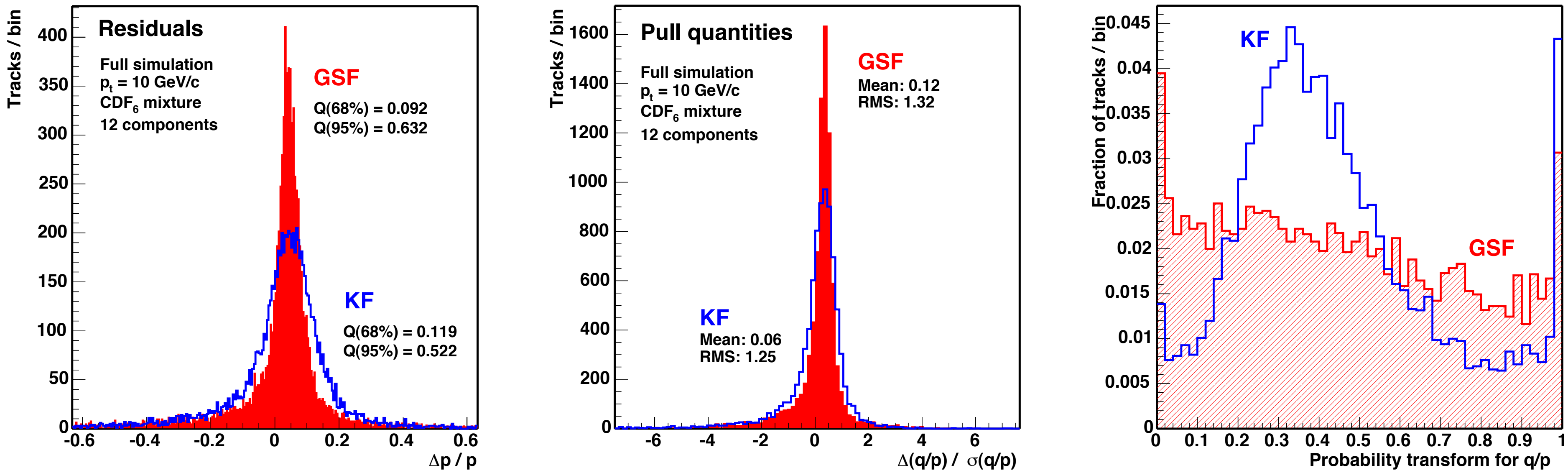
The Gaussian-sum Filter

- *Pdf* involved are usually non-Gaussian:
  - ➢ Measurement errors have Gaussian core, with tails
  - ➢ Energy loss and multiple scattering (tails)
- Gaussian-sum Filter (GSF): instead of single Gaussian, model the *pdfs* involved by mixture of Gaussians:
  - ➢ Main component of the mixture would describe the core of the distribution
  - ➢ Tails would be described by one or several additional Gaussians.
- For electrons, above ~100MeV/c, energy loss dominated by bremsstrahlung
  - ➢ Bethe and Heitler energy loss model is highly non-Gaussian
  - ➢ In the standard KF, distribution approximated by single Gaussian
- Model the Bethe-Heitler distribution by a mixture of Gaussians

The Gaussian-sum Filter

- All involved distributions are Gaussian mixtures
- State vector is also distributed according to a mixture of Gaussians
- GSF: Non-linear generalization of the Kalman Filter
- Weighted sum of several Kalman Filters
  - ➢ GSF is implemented as a number of Kalman filters run in parallel
  - ➢ The weights of the components are calculated separately
- Exponential growth: combinatorial combination of the state vector components with energy-loss components
  - ➢ Number of components have to be limited to a predefined number at each step
  - ➢ Cluster (collapse) components with the smallest 'distance' (Distance measurements: Kullback-Leibler Distance or Mahalanobis Distance)
- Output is full Gaussian mixture of state vector
  - ➢ Can be used in subsequent application (GSF vertex fit already implemented)

The Gaussian-sum Filter



- Improvement of the core of the residual distribution
- Little reduction of the tails:
  - ➢ Radiation in the first layer can not be detected
    - ➼ can be compensated by vertex constraint
  - ➢ Non-Gaussian measurement errors in the Pixel detectors
- Incorporate Gaussian mixtures of measurement errors (also for non-electron fits!)
- Most efficient for low energy electrons (a few tens of GeV), little gain at 100 GeV
- Pattern recognition needs to be evaluated

Adaptive filters: the DAF and the MTF

- In very dense environments (e.g. high E_T *b*-jets, τ jets), degradation due to large background noise
  - ➢ High track density: hit degradation due to contamination of nearby tracks
  - ➢ High hit density: wrong hit assignment
- Kalman Filter: hard hit assignment
- Soft hit assignment may be more suitable
- Global approach of hit assignation, using full track information
  - ➢ Part of the hit assignment done in the final track fit
- Expect better hit assignment

Adaptive filters: the DAF and the MTF

- Deterministic Annealing Filter (DAF): single track fit
  - ➢ Competition between hits: on a same surface, several hits may compete for a track
  - ➢ hit weights (assignment probability) based on hit-track distance (residual) and competing measurements
- Multi-Track Fit (MTF): concurrent multi-track fit on collection of hits
  - ➢ Competition between tracks and hits
  - ➢ Each hit on a layer can belong to each of several tracks

Iterative Kalman Filter with annealing

Both need initial hit collection and track seed(s): basic pattern recognition and track parameters from KF

- ➢ DAF: initial hit collection around a KF track.
- ➢ MTF: collection of tracks from KF (or even DAF), close in momentum space, hits collected around these tracks

With this seeding, track finding efficiencies can not be improved w.r.t. KF

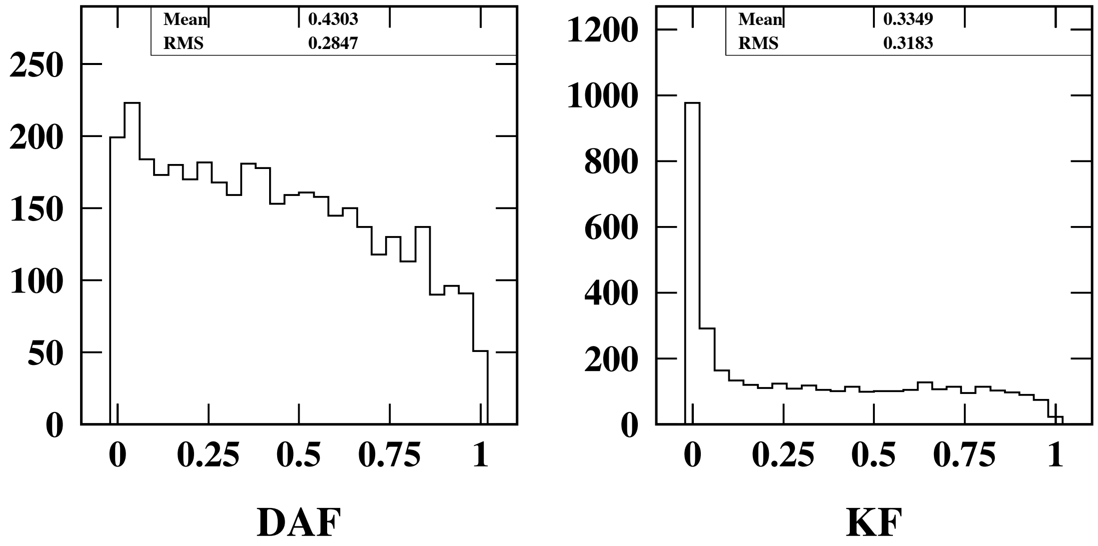
The Deterministic Annealing Filter

- For "isolated tracks", even at high luminosity, the DAF does not provide a measurable improvement in track quality
- "dense environment": b-jet with E_T=200 GeV,

  Tracks with $p_T > 15$ GeV/c, min. 8 hits:

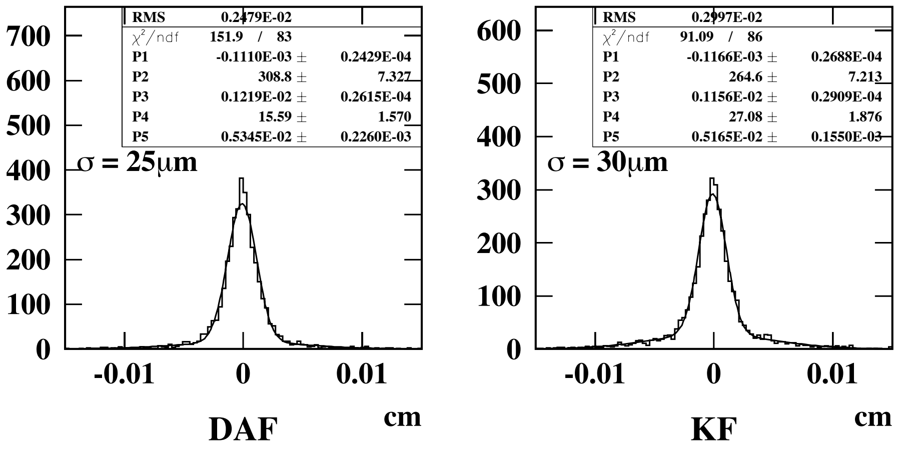
  ➢ Better track quality (χ^2)

χ^2 probability - $|\eta|<0.7$

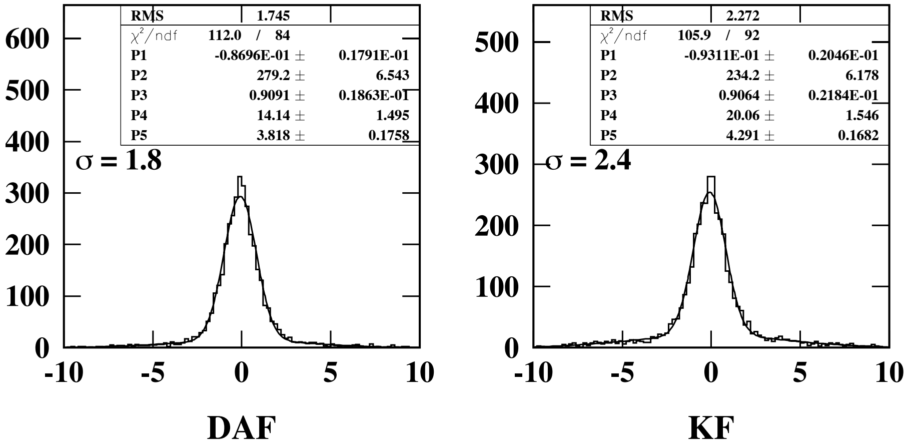


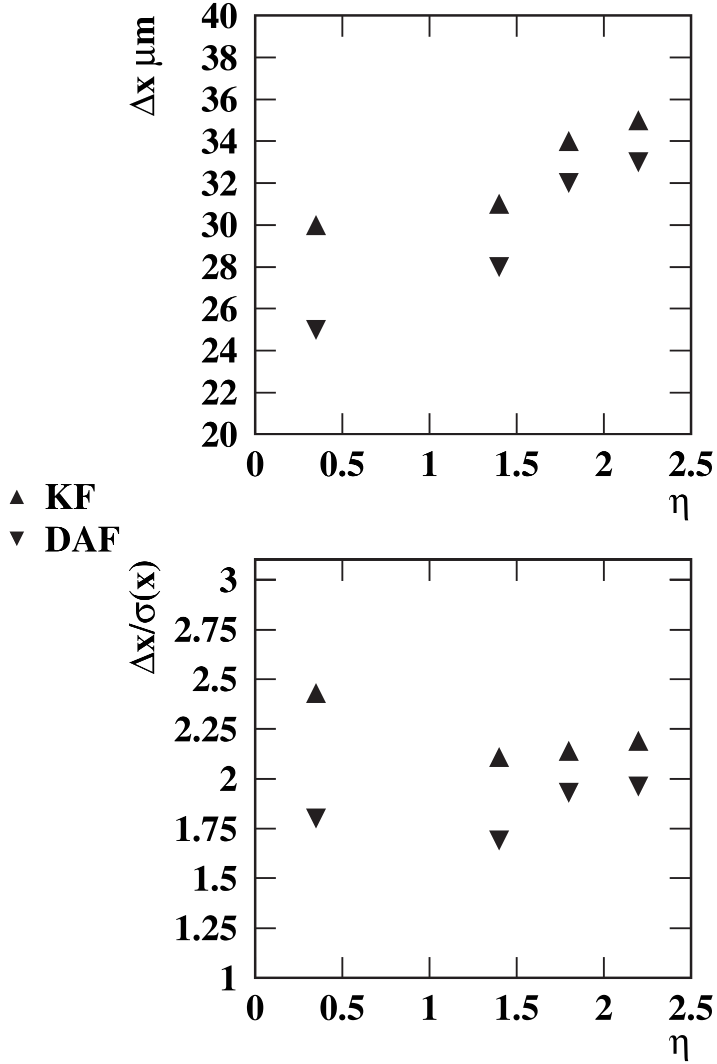
The Deterministic Annealing Filter

Transverse IP resolution - |η|<0.7



Transverse IP pull - |η|<0.7





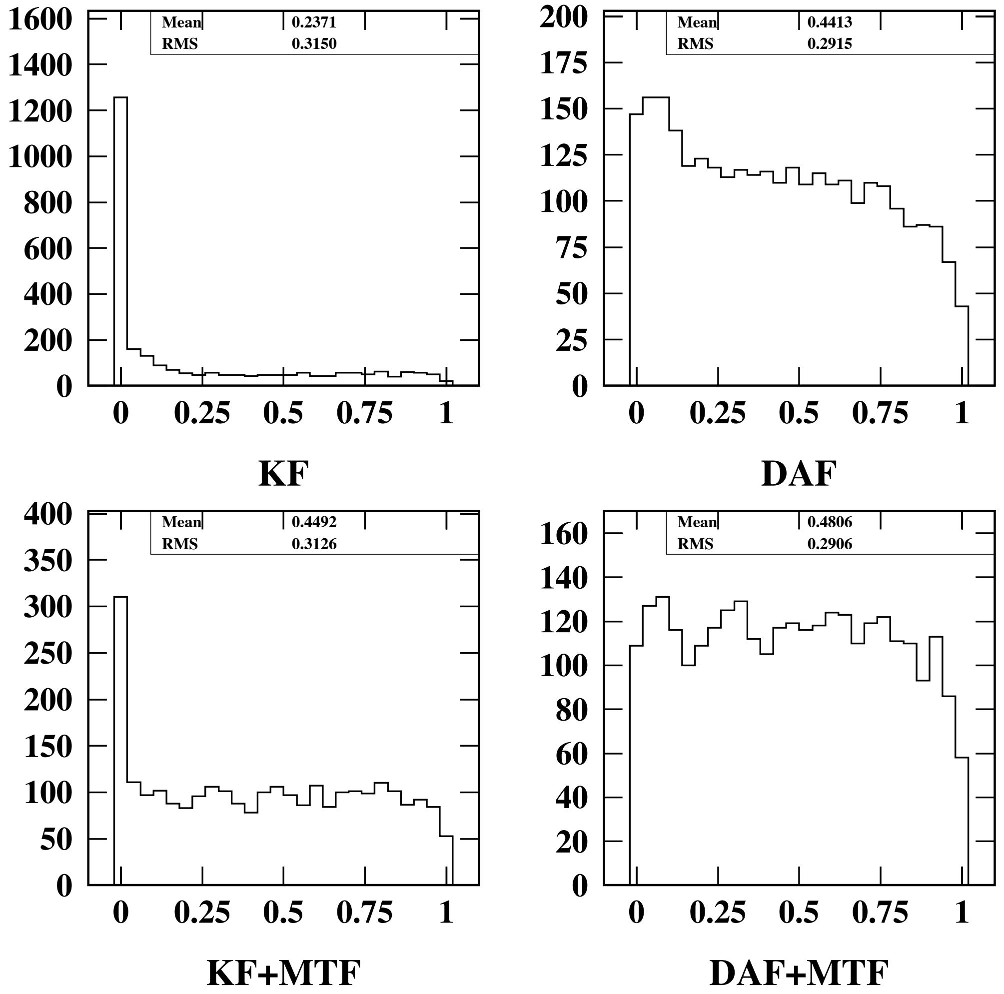
Adaptive filters: the DAF and the MTF

Reconstruction of π tracks from the decay of high-p_T τ:

$H^0 \rightarrow \tau^+\tau^-$, $m(H^0) = 500$ GeV/c^2

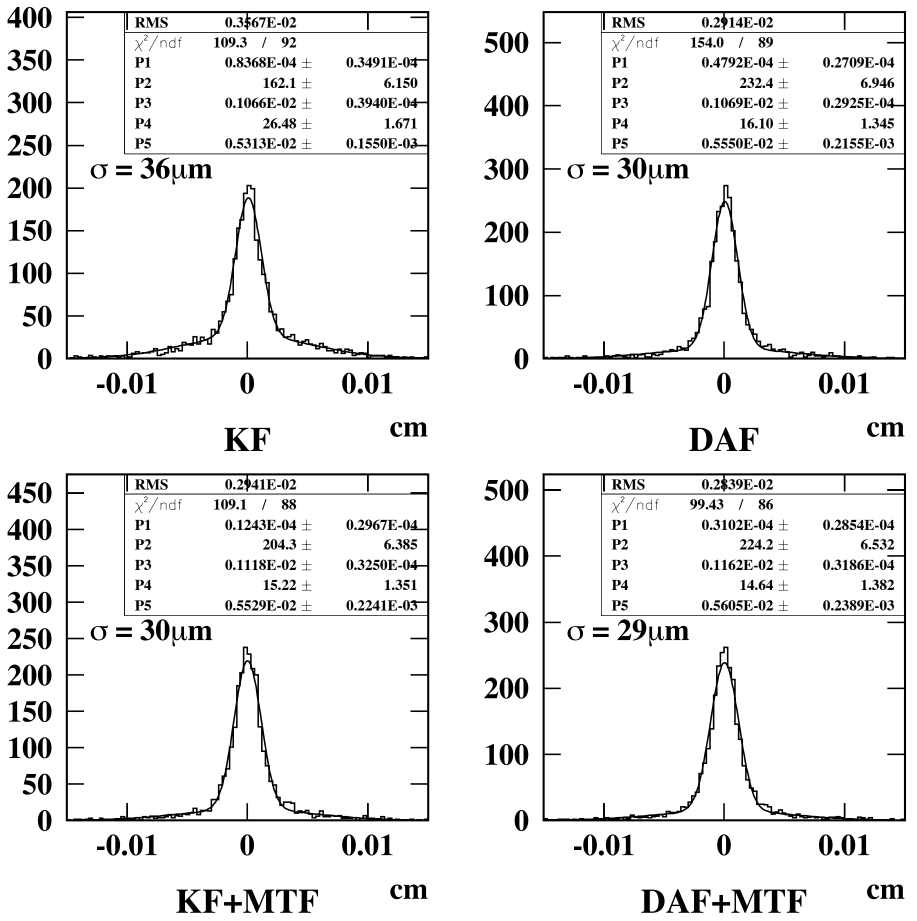
- KF: Kalman Filter alone
- DAF: DAF with seed from KF
- KF+MTF: MTF tracks, seeded with KF tracks
- DAF+MTF: MTF tracks, seeded with DAF tracks

χ^2 probability

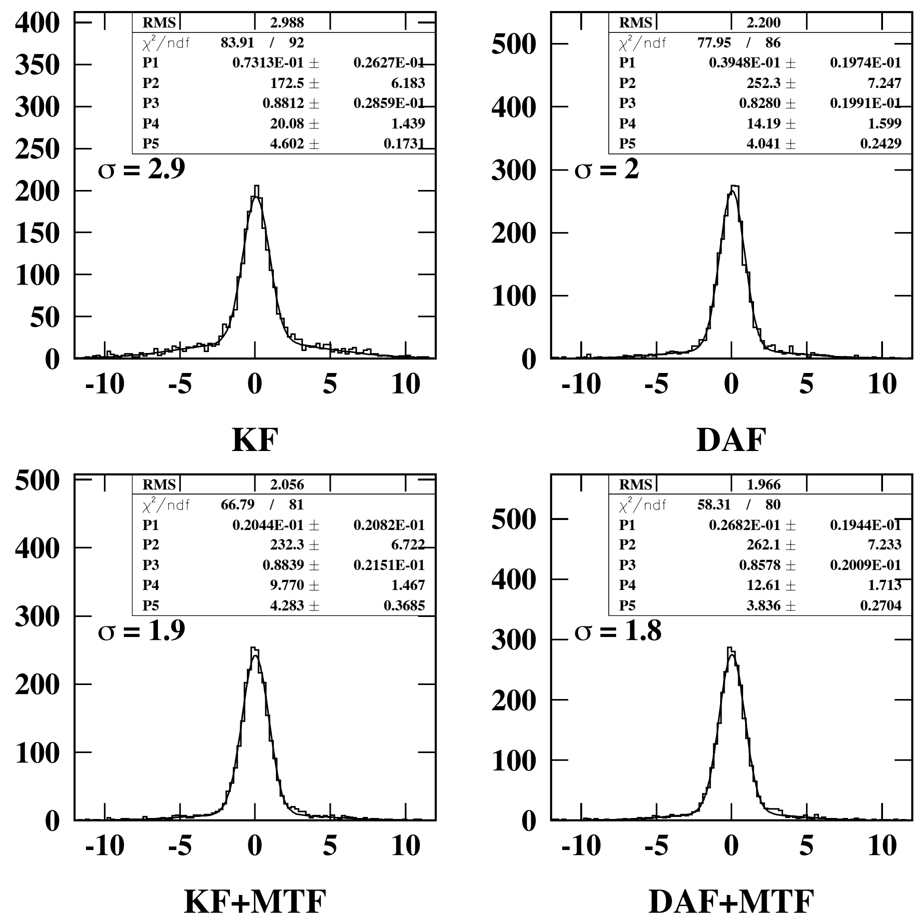


Adaptive filters: the DAF and the MTF

Transverse IP resolution



Transverse IP pull



Little improvement with the MTF over the DAF

Adaptive filters: the DAF and the MTF

- For "isolated tracks", even at high luminosity, the DAF and/or the MTF do not provide a measurable improvement in track quality
- DAF: "dense environment", e.g. *b*-jet with E_T=200 GeV , τ jets:
  - Better track parameter resolutions and error estimates
  - Better track quality (χ^2)
- MTF: little improvement over DAF at the expected track densities!
  - little improvement on track parameter resolution
  - slightly better error estimate
  - slightly better overall track quality
- Better hit assignment (slightly lower fake rate)
- Seeding delicate (esp. MTF)
  - Better seeding methods would be needed
- Slower then standalone KF, use where appropriate

Conclusion

- CMS has a very robust and versatile tracker and track reconstruction algorithms, with sufficient redundancy to operate in a very challenging environment
- Very capable tracker
  - ➢ Low occupancy
  - ➢ Reconstructed hits have a high purity
- Combinatorial Kalman filter shown to give very good results even in difficult environments:
  - ➢ good performance, suitable for high luminosity or heavy ion collisions
  - ➢ high efficiency, low fake rate
- Efficient and robust pattern recognition
  - ➢ Low contamination from spurious hits, even with PU
  - ➢ Reconstruction ambiguities are solved after the first few layers
- Fast enough for to be used in the HLT
  - ➢ Good track parameter resolutions after using only the first five to six hits
- More sophisticated methods available for specific applications (GSF, DAF, MTF): adaptive algorithms show improvements w.r.t. LSM in difficult situations