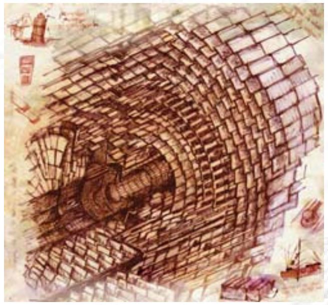


Track Reconstruction in the CMS Tracker

Frank-Peter Schilling (CERN/PH)

D-CMS Meeting

Hamburg, 21/02/2006

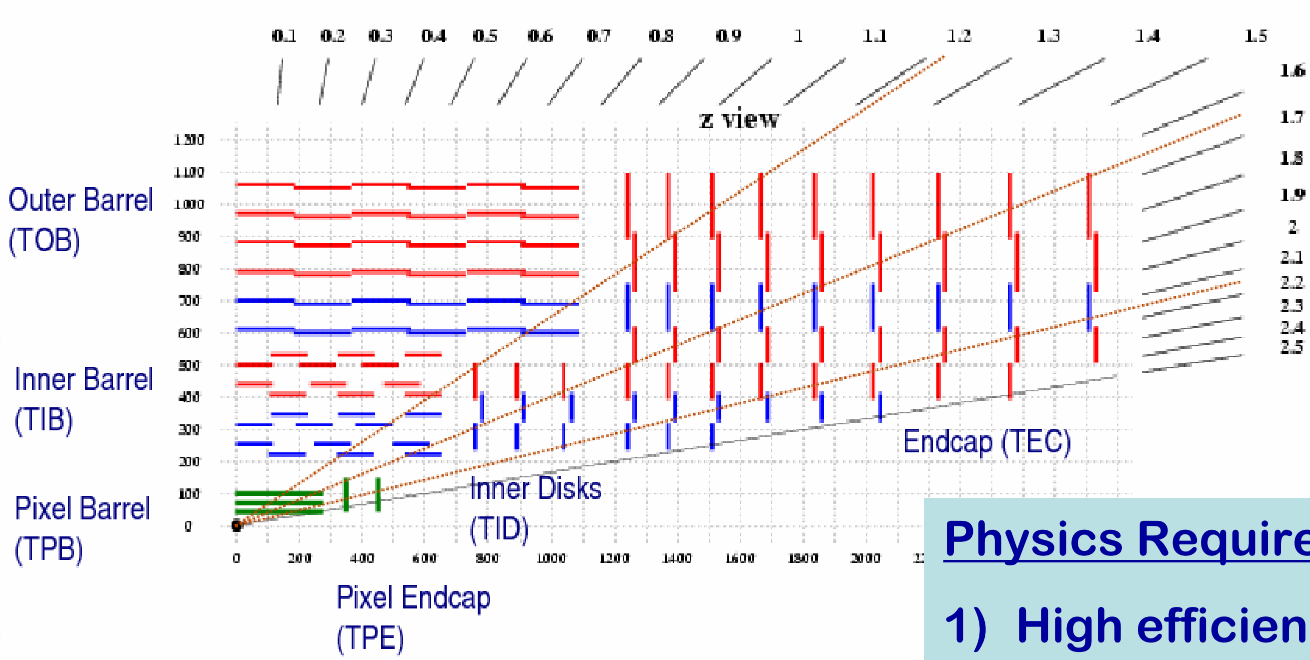
- Introduction
- Baseline algorithm: Kalman Filter
- Advanced algorithms
- Road Search
- Recent developments
- Alignment

Outline

- **Baseline algorithm (Combinatorial Kalman Filter)**
  - Algorithm description
  - Performance
  - Special cases (regional/partial tracking (HLT))
- **Advanced algorithms: Adaptive Filters**
  - Deterministic Annealing Filter, Multi-track Filter
  - Gaussian Sum Filter
- **Alternative approach: RoadSearch**
- **Recent Developments**
  - Pixel-less tracking
  - Inclusion of hit pairs in overlap regions
  - (Tracking for cosmics)
  - (Reconstruction of V0's)
- **A few words on track-based Alignment**

Introduction

- **High hit resolution and granularity**
- **A few (10+3 barrel layers), but precise (10-50μm) measurements**
- **4T solenoidal magnetic field: Pt>0.6 GeV to reach outer layer**
- **Large track multiplicity (pileup!), most hits from low p junk**
- **A lot of material: multiple scattering!**



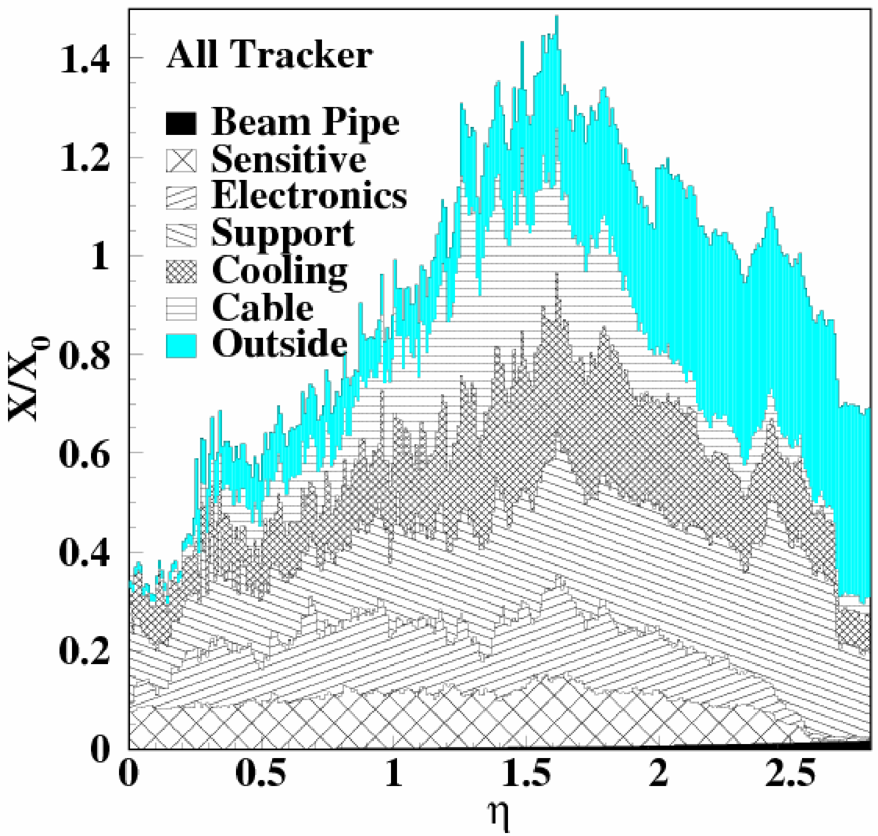
Physics Requirements:

1) **High efficiency**
2) **Momentum resolution**
3) **Impact parameter resolution**

For details on HW, see talk of K.Klein

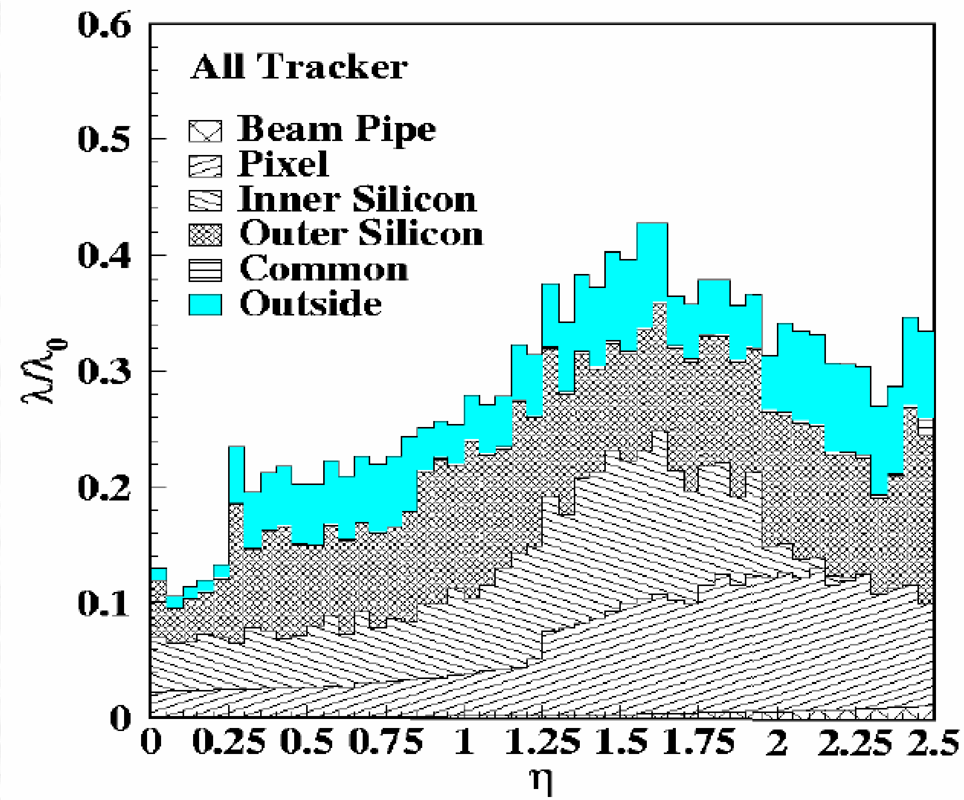
Material Budget

- **Radiation lengths**



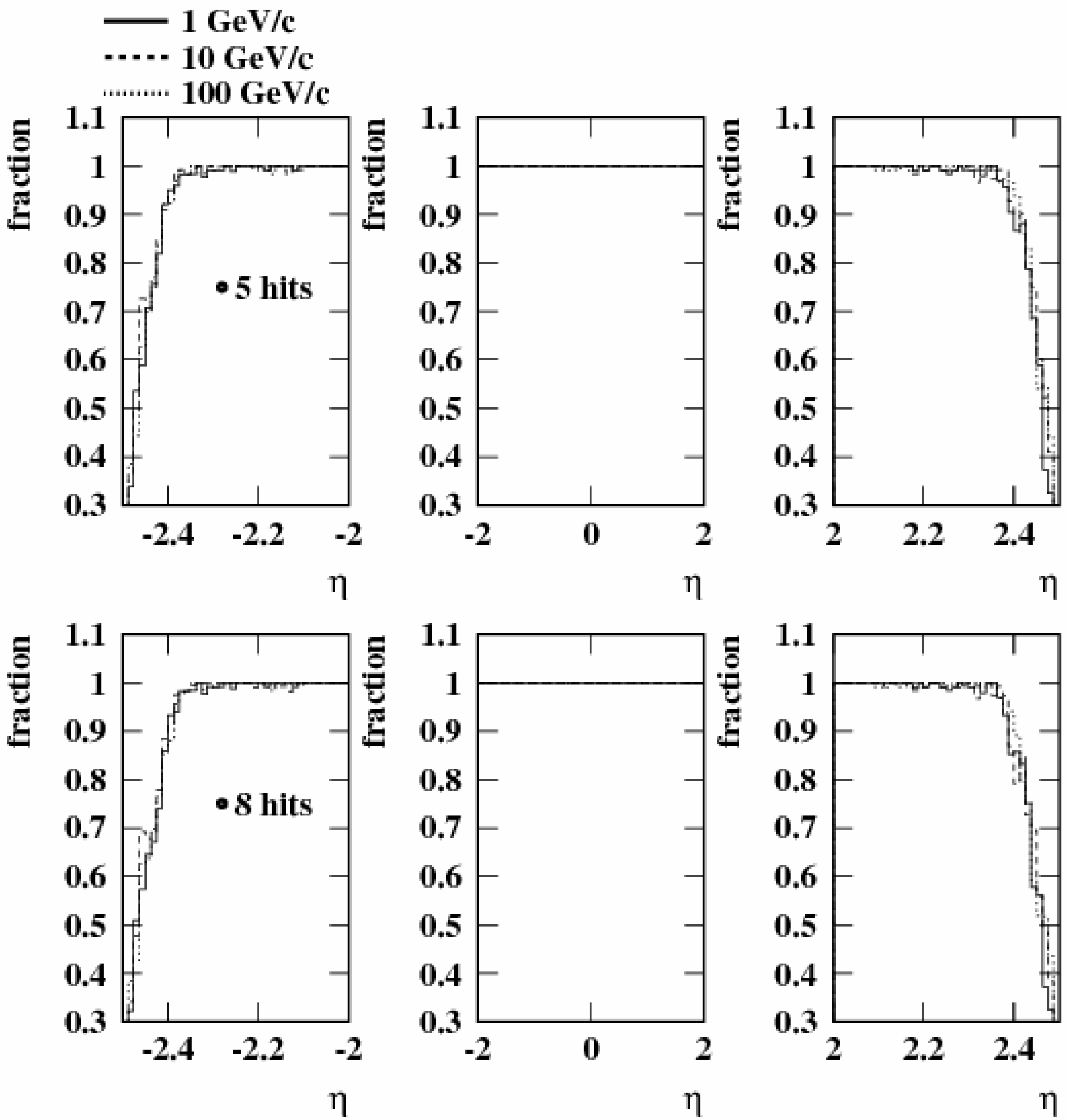
- **Multiple scattering**
- **Bremsstrahlung for electrons**

- **Interaction lengths**



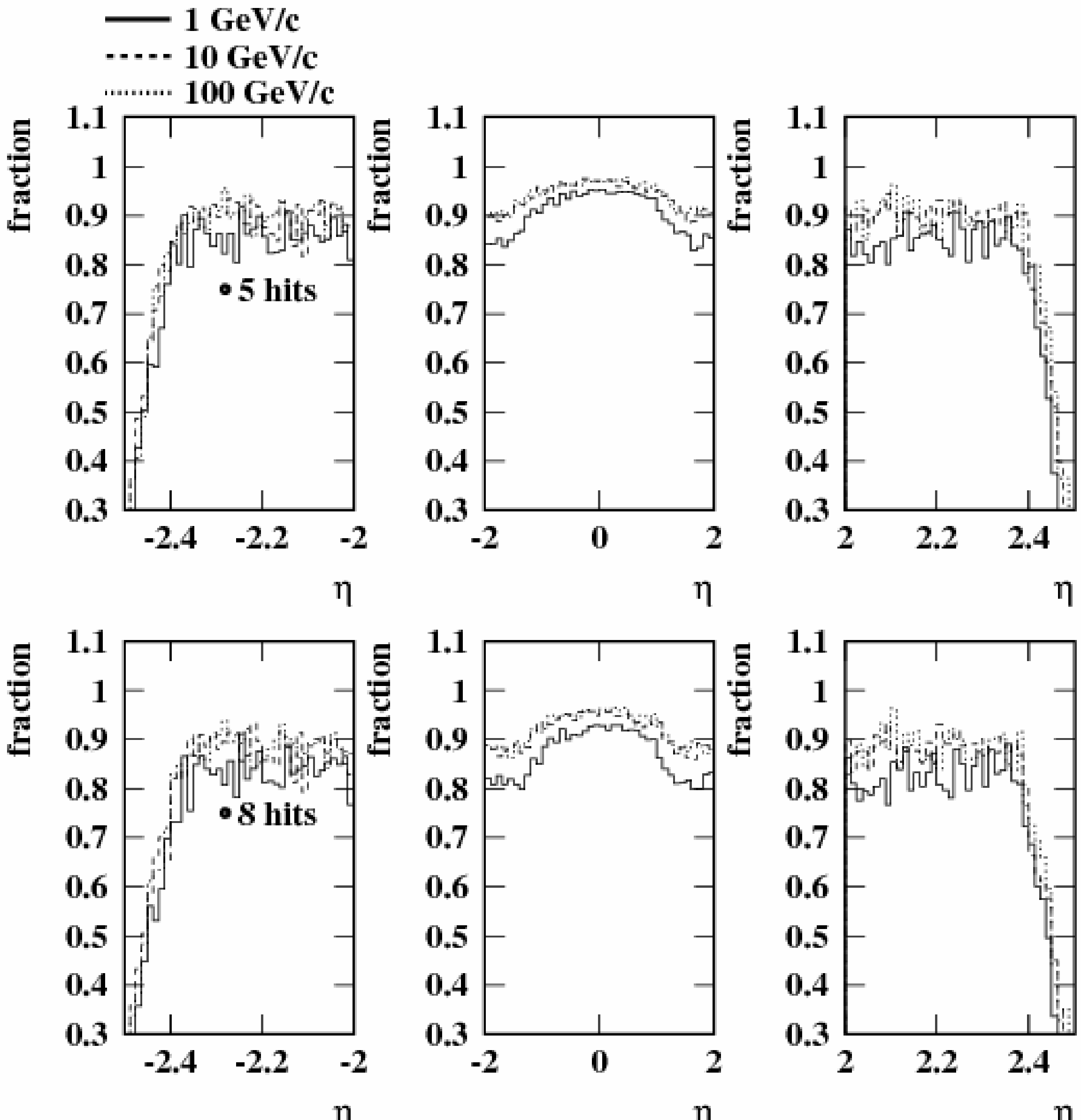
- **Hadronic interactions**
- **Kills tracks!**

5(8) layer crossing probability: muons



- **Muons mostly unaffected**

5(8) layer crossing probability: pions



- **Pions suffer substantial losses**
- **Must consider material effects during pattern recognition!**
- **No sense to track outside-in (for primary tracks):**
- **Up to ~20% don't reach outside!**

Baseline Algorithm

Standard algorithm in CMS: Combinatorial Kalman Filter

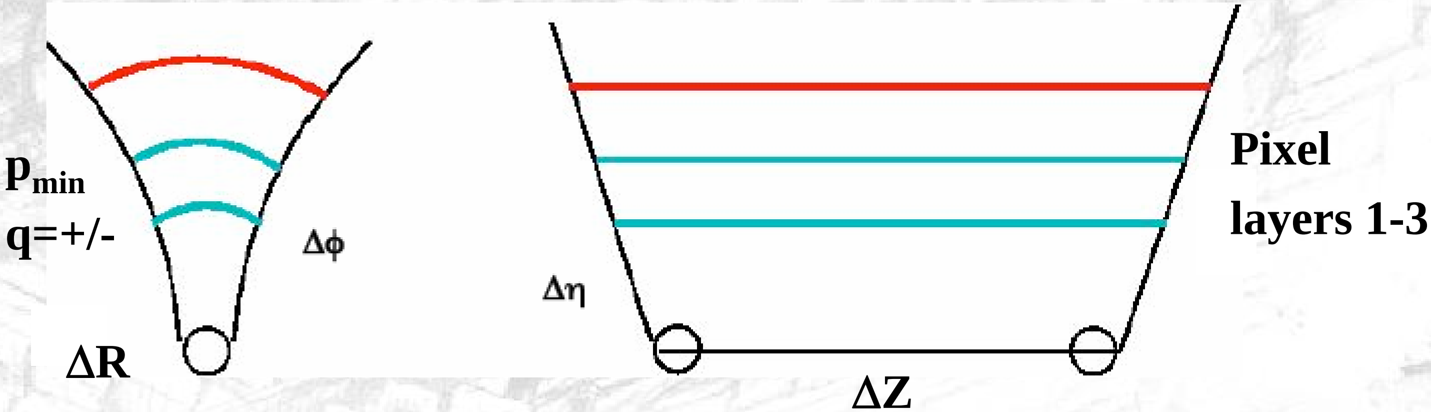
- Equivalent to global least-squares minimization
  - optimal estimator if model is linear and random noise is gaussian
  - For non-linear models / non-gaussian noise, optimal linear estimator
- Local: one track reconstructed at a time
- Recursive: parameters updated with each successive hit
- Energy loss / multiple scattering can be taken into account

Modular Building blocks for track reconstruction:

- Starting point
  - Seed generation
- Pattern recognition
  - Trajectory building
- Reduction of remaining combinatorics
  - Trajectory cleaning
- Parameter estimation
  - Track fitting and smoothing

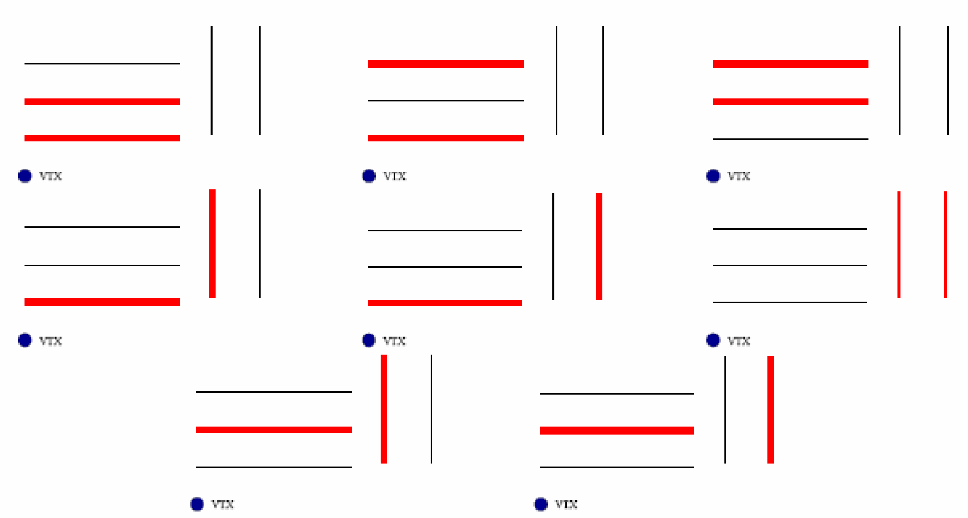
Seed generation

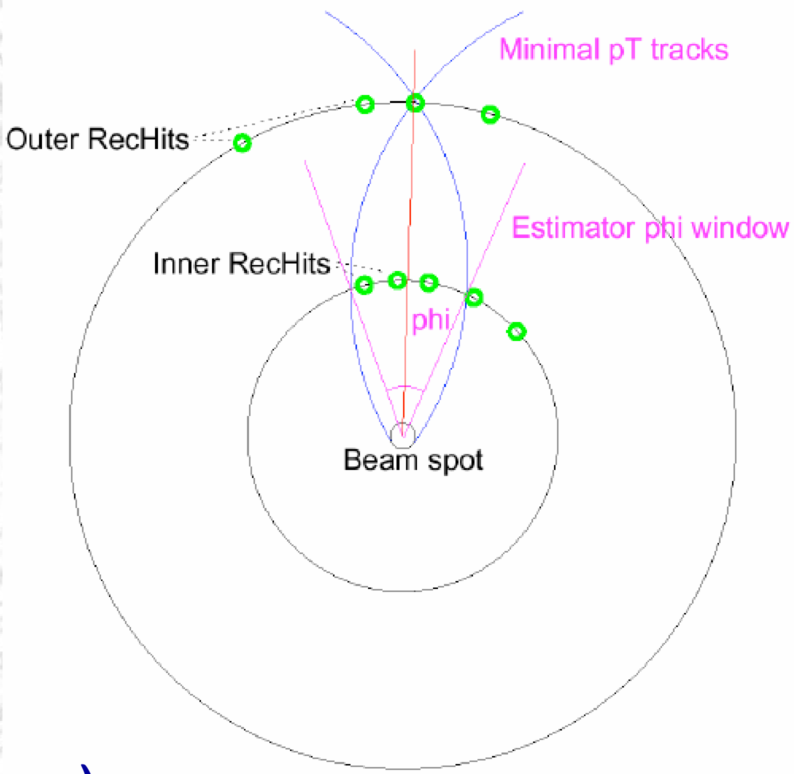
- **Defines the starting point for pattern recognition**
  - Seeds should constrain all 5 track parameters:
  - reasonable seach region
  - sufficiently close to true values: linear regime
- **Needs to be fast and efficient**
- **Baseline seeding:**
  - innermost layers: Pixel
  - High track density compensated by high granularity
- **Fast hit pair finding: start with primary hit in outermost Px layer**
  - Can be restricted to region of interest



Seed generation (cont.)

- **Complemented by 2nd hit in other layers and vertex constraint (Δ z=30cm, ΔR=1mm) → 2 2d hits + vertex**
- **Fast geometrical search**
- **Hit finding efficiency ~100%**
- **Time small (~10%) w.r.t full track reco**





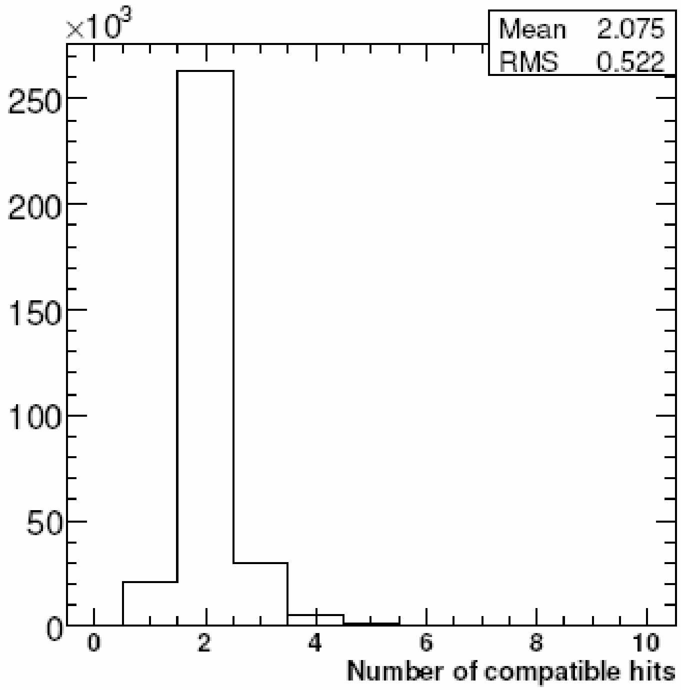
- **Alternative seedings (not discussed here):**
  - **Outside-in (e.g. photon conversions)**
  - **External seeds (ECAL or Muon + Vertex)**

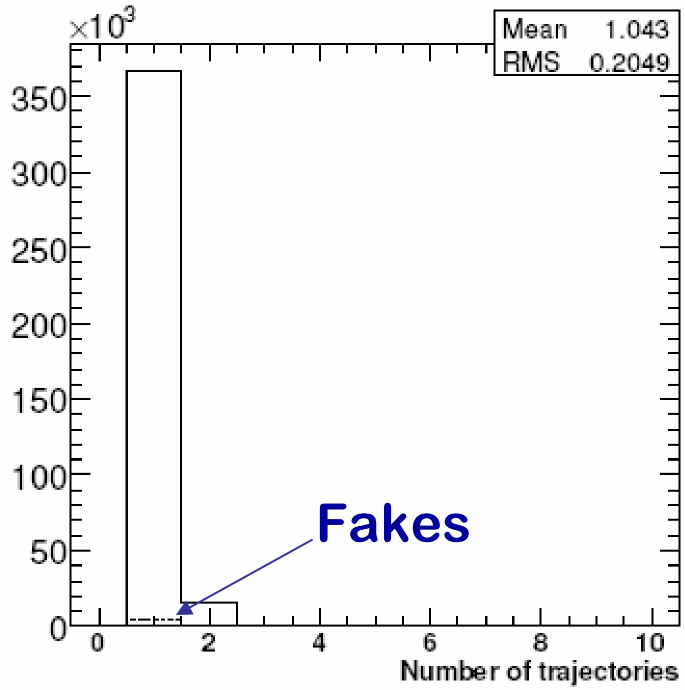
Trajectory Building

- Based on Kalman filter
  - Simultaneous trajectory extension and hit selection
- Propagation from layer to layer, accounting for energy loss and multiple scattering (requires efficient layer navigation)
- Propagation of track to next layer, search for compatible hits
  - New trajectories constructed with updated parameters + errors for each compatible hit
  - In addition one furher trajectory without hit to account for inefficiencies
  - All trajectories propagated to next layer
- Procedure repeated until outermost layer is reached
- To avoid bias, all trajectories propagated in parallel
- Parameters
  - Max. number of candidates retained per step (ranked in χ^2)
  - Number of missing hits

Example: Pattern recognition in the Barrel

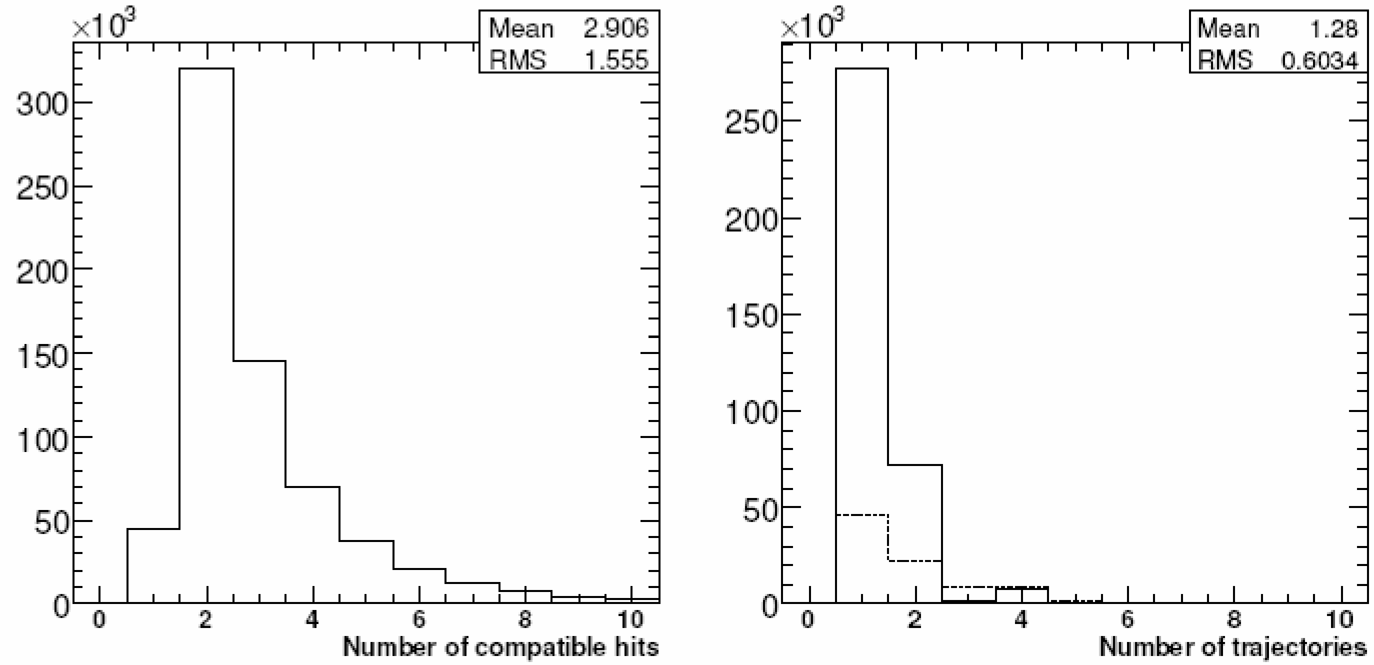
- **Most seeds are composed of a hit pair in Px layers 1+2**
- **1st step: Propagation to Px layer 3**
  - **Trajectory not yet well defined; uncertainties ~500 (80) μm in rϕ (rz)**
  - **Few fakes, mostly 1 (+1 invalid) compatible hits, thanks to Pixel granularity**





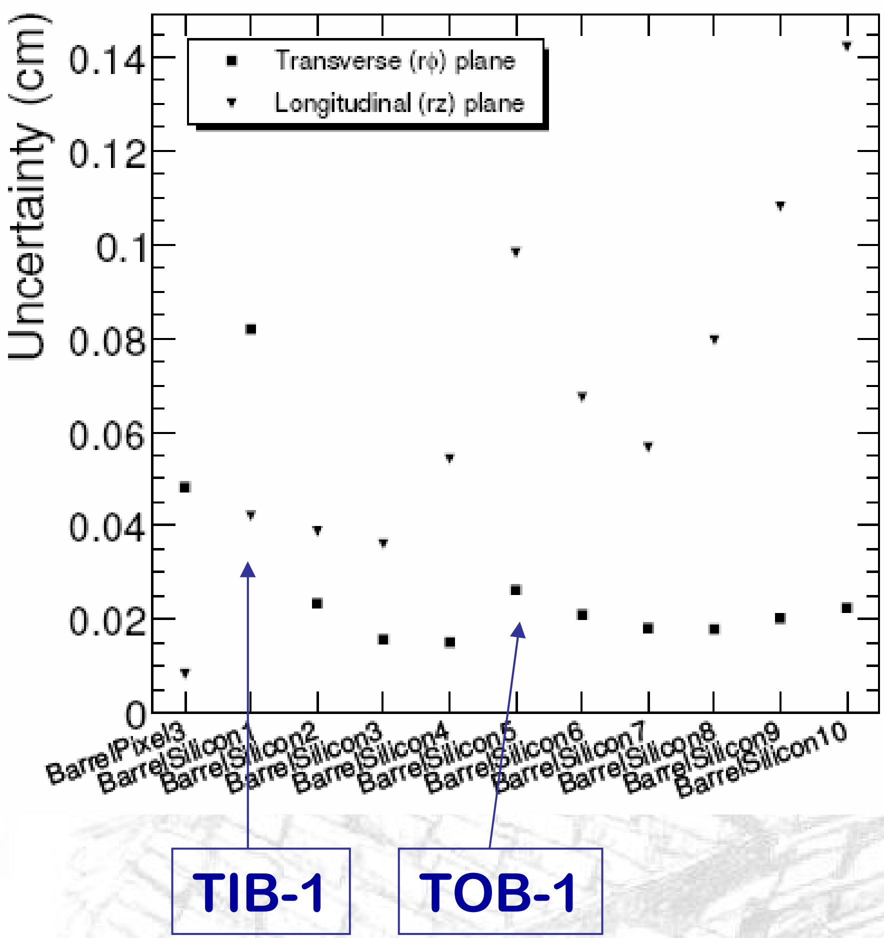
Pattern recognition in the Barrel (cont.)

- **2nd step: Propagation to TIB layer 1**
  - **Uncertainties of predicted state increases (800 / 400 μm) due to large extrapolation distance (~13 cm) and small lever arm of initial trajectories (~6 cm)**
  - **More compatible hits due to bigger occupancy in strip detector**

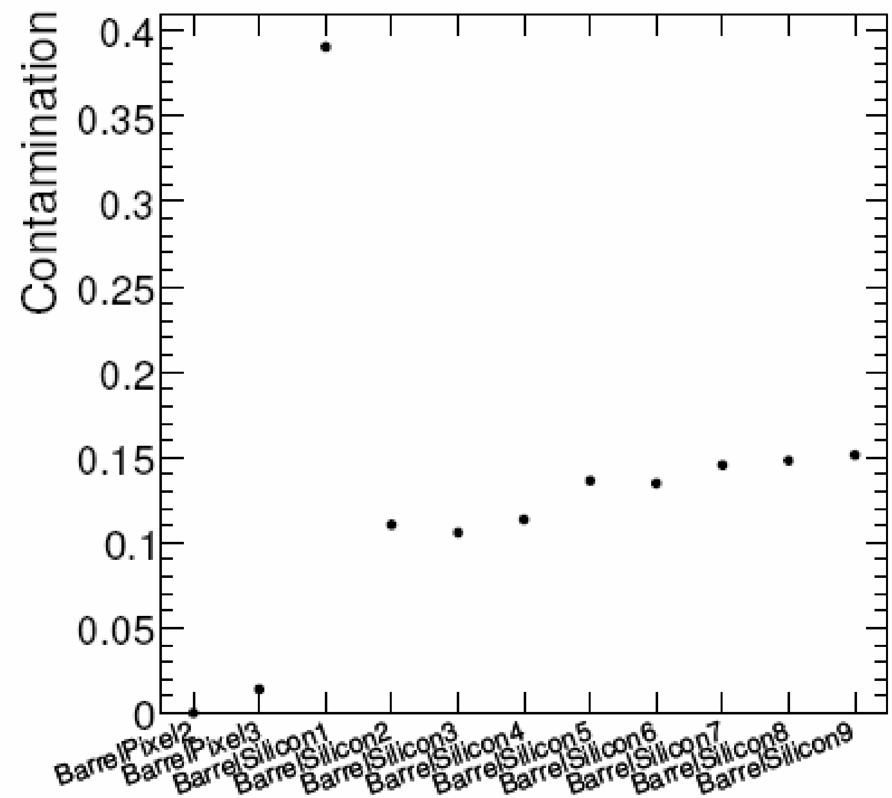


- **From TIB layer 2 on, uncertainties reduced (trajectories ~well defined); many trajectories with spurious hits discarded**

- **Uncertainties in rϕ and rz planes per layer**

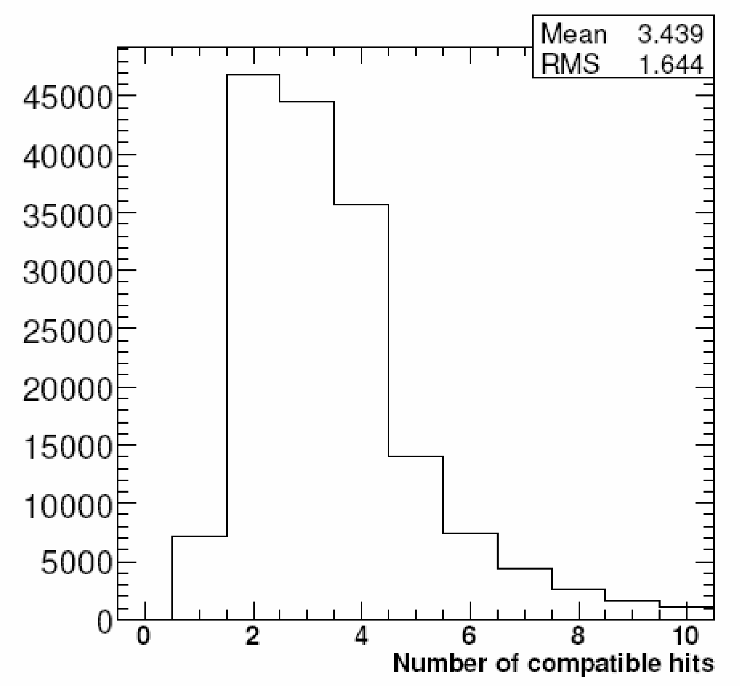


- **Fraction of trajectory candidates with at least one spurious hit**

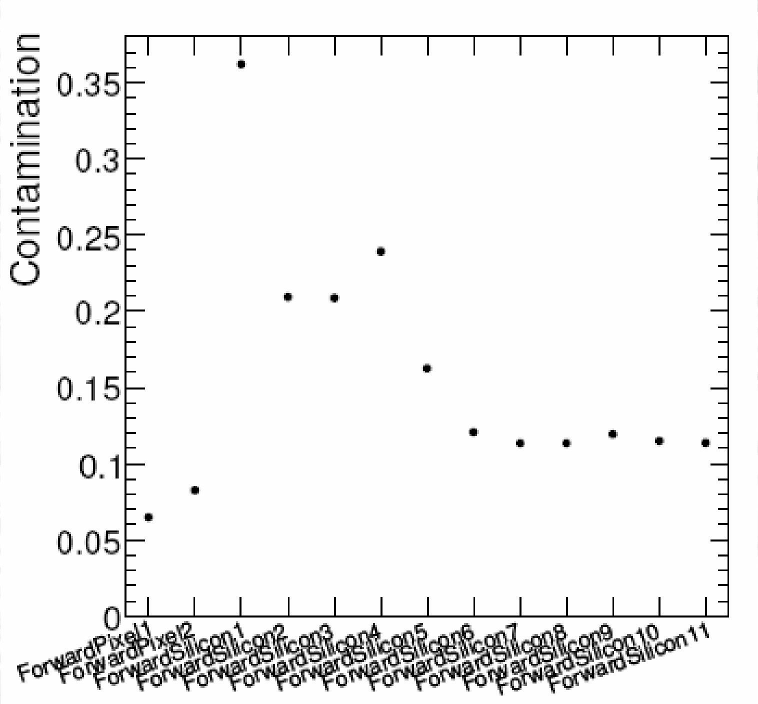


Pattern recognition in endcap

- **Navigation more complex than in barrel**
  - **E.g. for high η tracks leaving PX disk 2, all 3 TID disks and 3 of TEC disks could be compatible: many trajectory candidates**
  - **Large propagation distances possible: more spurious hits**
- **Once in TEC, situation improves**



- **Compatible hits when leaving PX disk 2**



- **Fraction of trajectories with spurious hit**

Trajectory cleaning

- **Resolve ambiguities to avoid double counting of tracks**

- **Ambiguities may arise from**
  - **One seed leading to >1 trajectory candidates**
  - **A given track is reconstructed starting from different seeds**

- **Based on fraction of shared hits f:**
  - **f= N-shared / min(N1,N2)**
  - **If f>0.5 for a given pair of tracks, the one with the smaller number of hits is discarded (if N1=N2, the one with the bigger χ^2)**

- **Cleaning applied twice:**
  - **On all tracks resulting from a single seed**
  - **On all tracks from all seeds**

Track fitting and smoothing

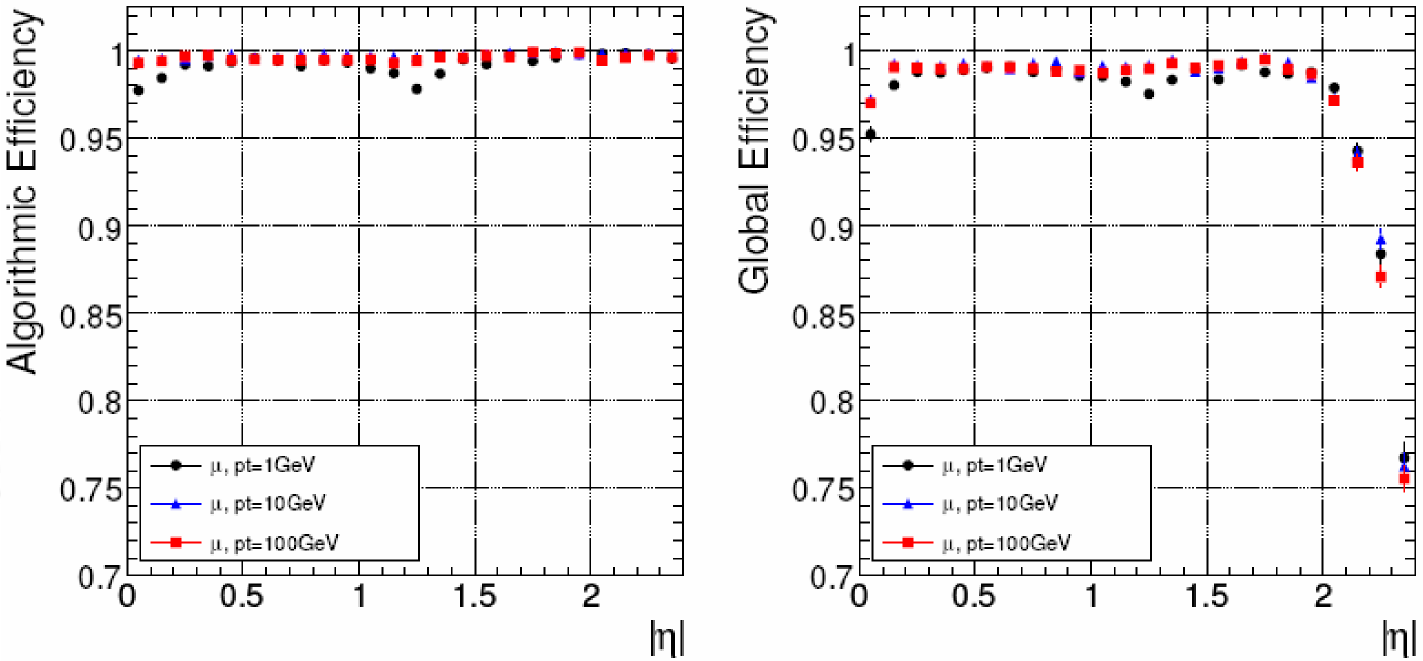
- **For each trajectory, building stage results in collection of hits and estimate of track parameters, but**
  - full information only available at last hit
  - estimate can be biased by constraints applied at seeding stage
  - Therefore, a re-fit is performed, implemented as a combination of a Kalman filter and smoother

- **Filter: is Initialized at innermost hit with seeding estimate**
  - Covariance matrix scaled by large factor to remove seeding bias
- **Iterative processing of hit list:**
  - Re-evaluation of hit position estimate
  - Update of track parameters and covariance matrix
  - Trajectory propagation, modification of parameters and cov. matrix according to estimates for energy loss and multiple scattering

- **Smoothing: 2nd filter outside-in**
  - Smoothed states: weighted mean of forward and backward fits

Performance: Efficiency for Muons

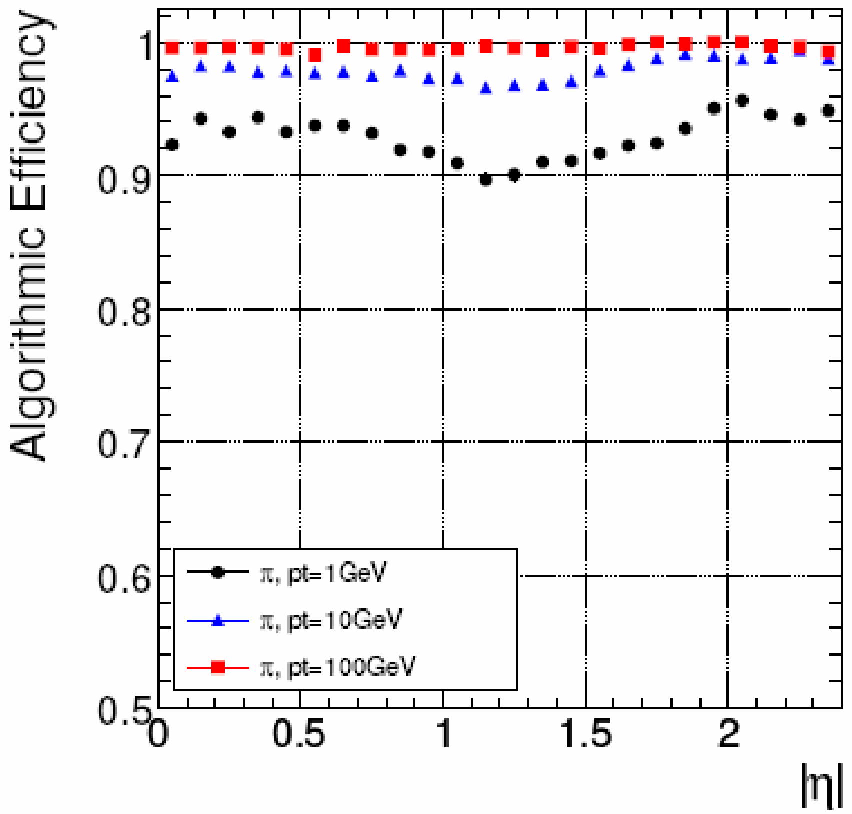
- **Two definitions of efficiency used:**
  - **Algorithmic efficiency:** efficiency of pattern recognition (defined wrt sim. Tracks which are reconstructable: no of PX/strip hits, pt, etc)
  - **Global efficiency:** efficiency for all tracks with pt>pt-cut and production vertex inside beam-pipe (includes acceptance, hit eff.etc)
- **Cuts: Pt>0.9 GeV, at least 8 hits, at most one missing hit**

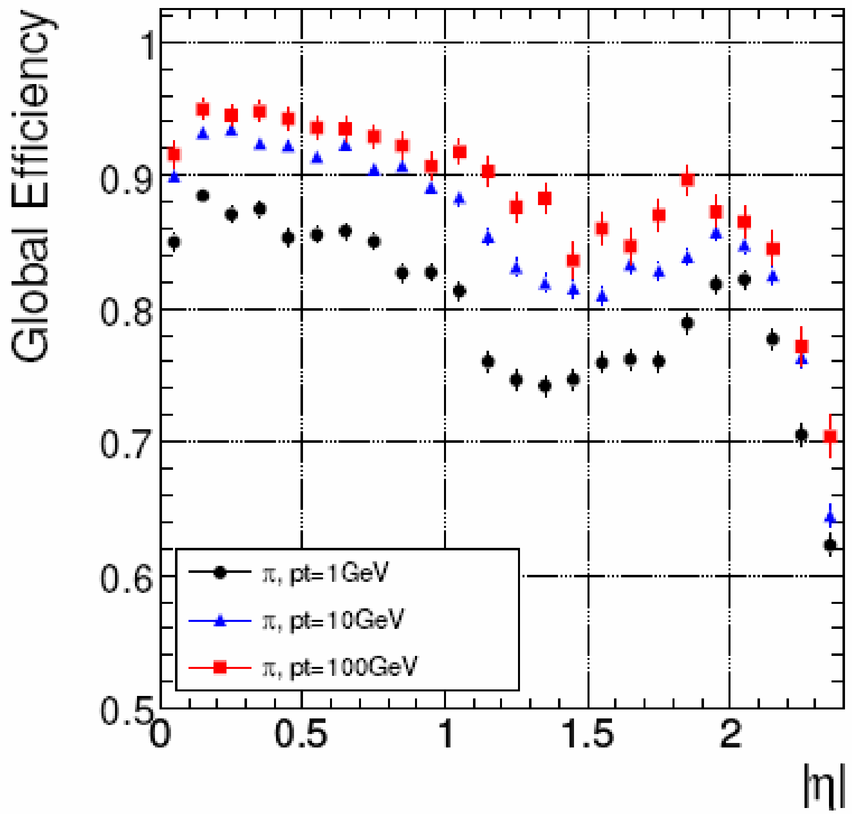


- **Pattern recognition fully efficient**

- **Loss of acceptance at large η**
- **η~0: alignment of Px ladders**

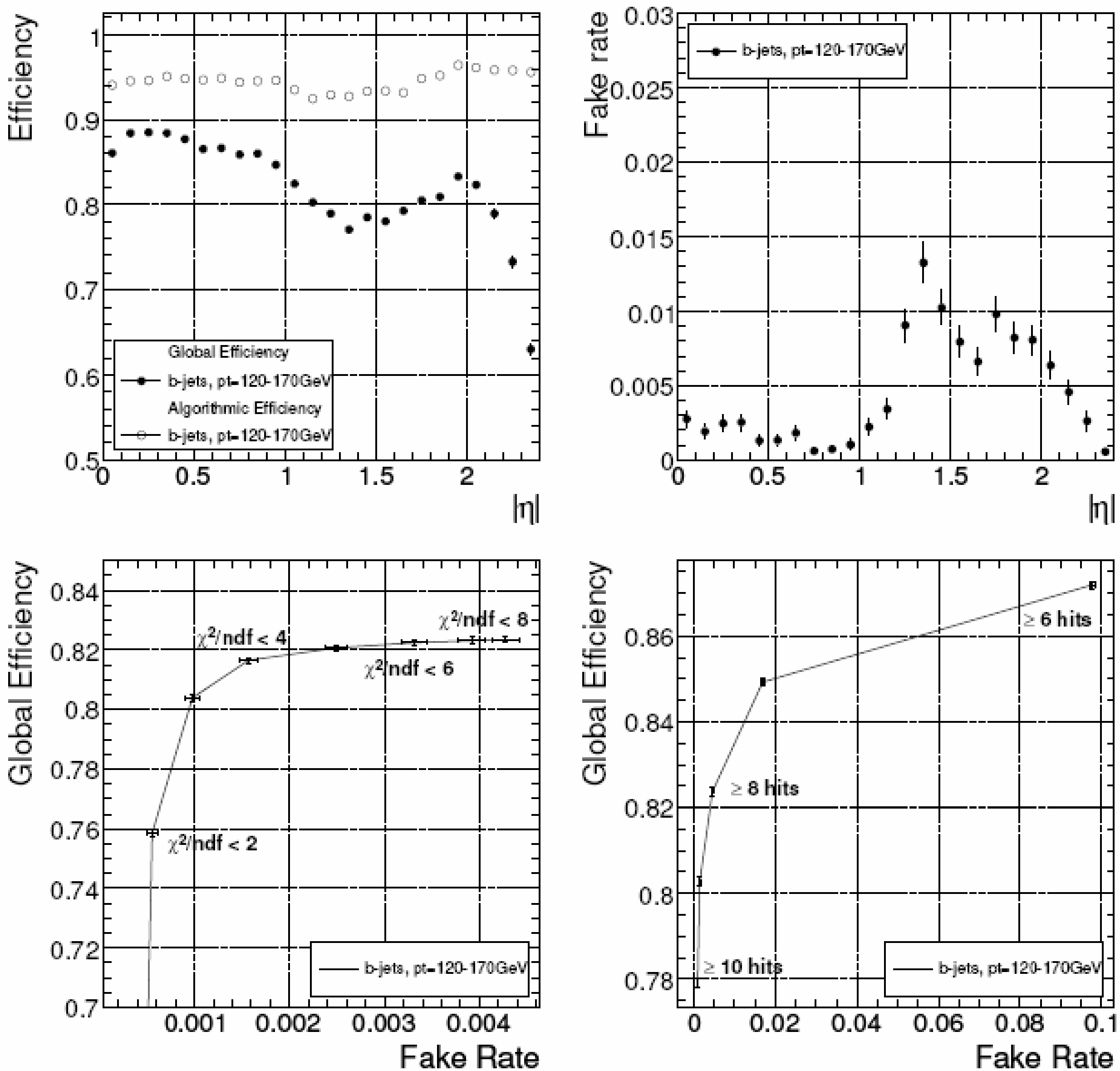
Performance: Efficiency for Pions





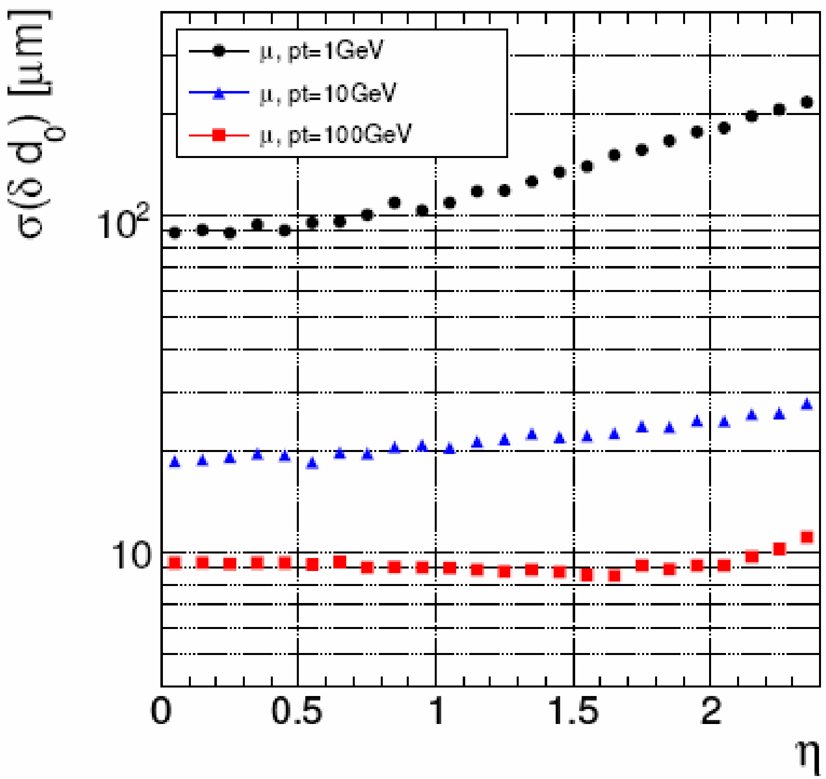
- **Algorithmic efficiency reduced at low pt due to elastic scattering**
- **Lower global efficiency due to hadronic interactions in tracker material (tracks don't reach outside)**

Tuning: Efficiency vs fake rate for b jets

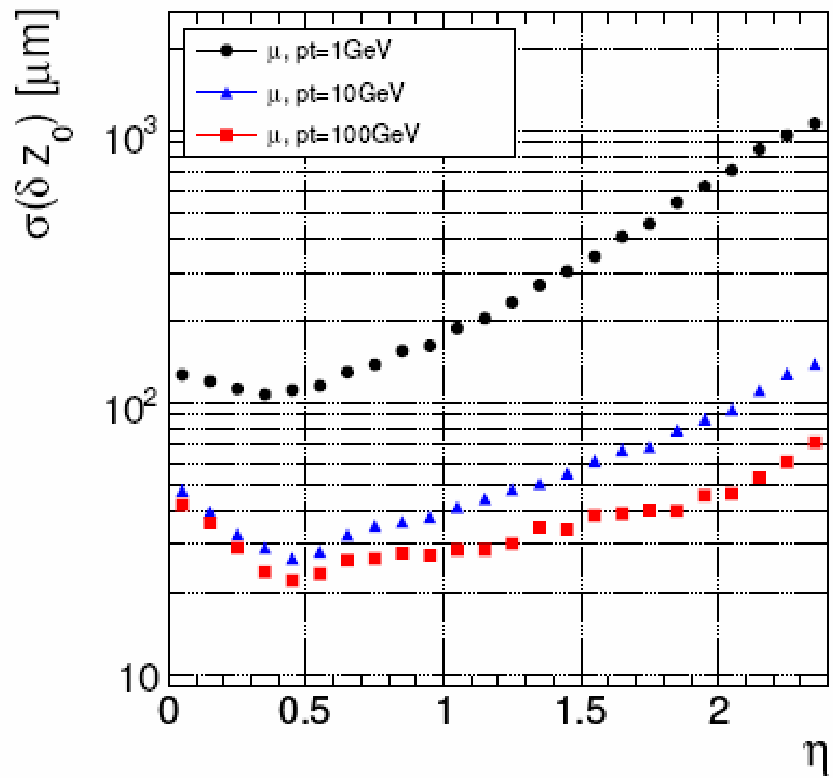


- **Algorithmic eff ~95%**
- **Global eff ~80-90%**
- **Fake rate <1%**
- **Tuning of normalized χ^2 and/or N-hit**
- **Fake rate explodes for N-hit<7**

- Transverse impact parameter d0



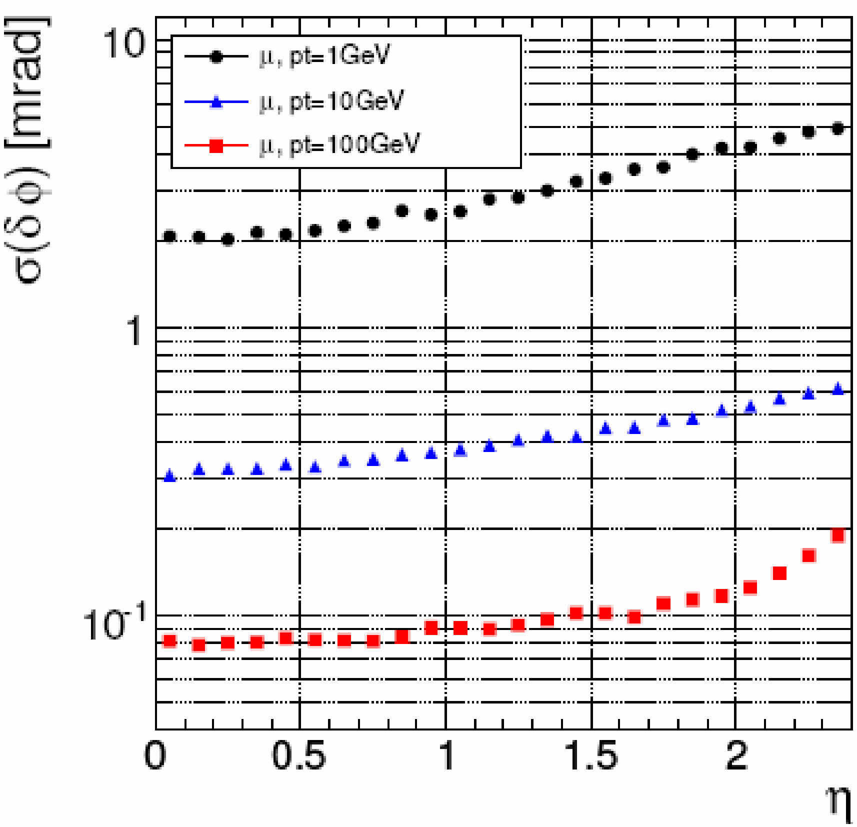
- Longit. impact parameter z0



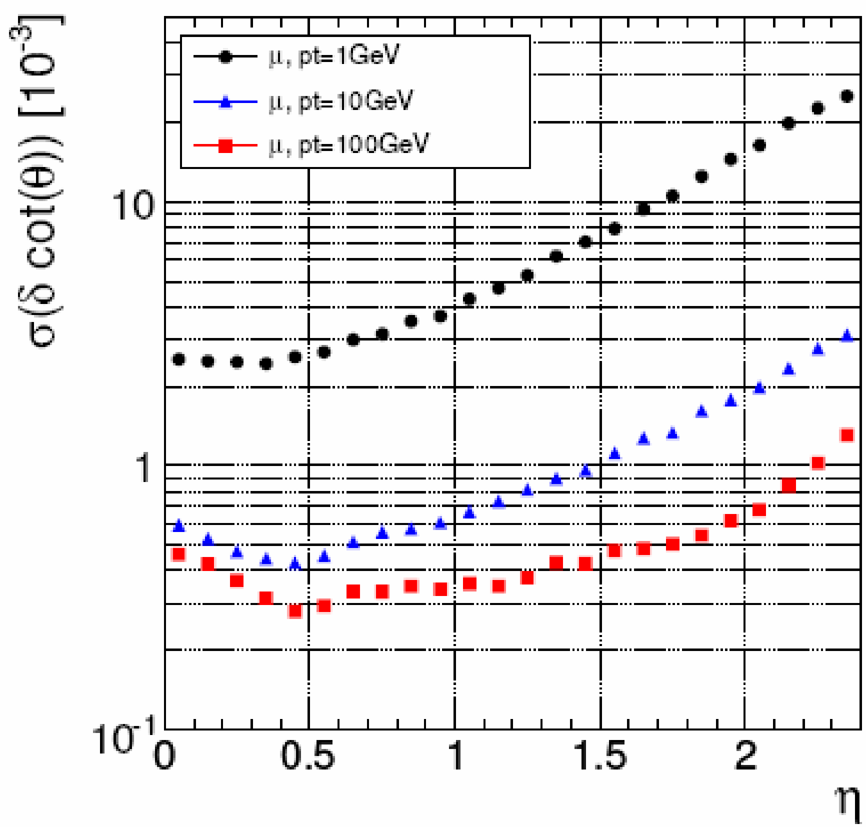
- **10μ resolution in d0 at 100 GeV: pixel hit resolution**
- **Degrading at lower pt due to multiple scattering**
- **z0 resoluton improving from η=0 up to ~0.5 due to widening of Px clusters , improving resolution**

Resolutions (cont.)

- **Azimuthal angle ϕ**

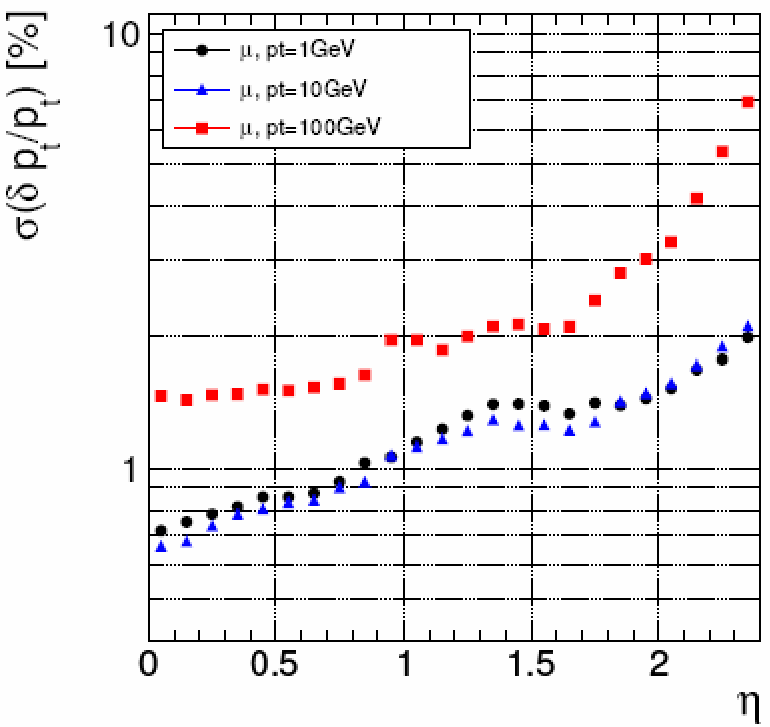


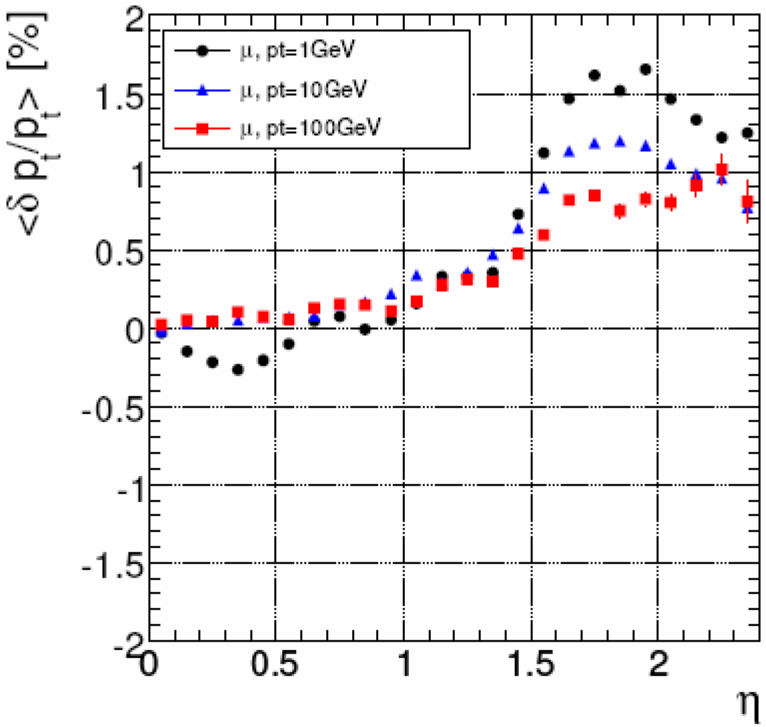
- **Polar angle: cot(θ)**



Resolutions (cont.)

- **Transverse momentum**
- **Pt bias**





- **Pt resolution ~1-2% in barrel**
- **At 100 GeV, tracker material accounts for 20-30% of Pt resolution**
- **At lower Pt, dominated by multiple scattering**
- **Small Pt bias in endcap due to B-field inhomogenities not (yet) accounted for**

Special modes

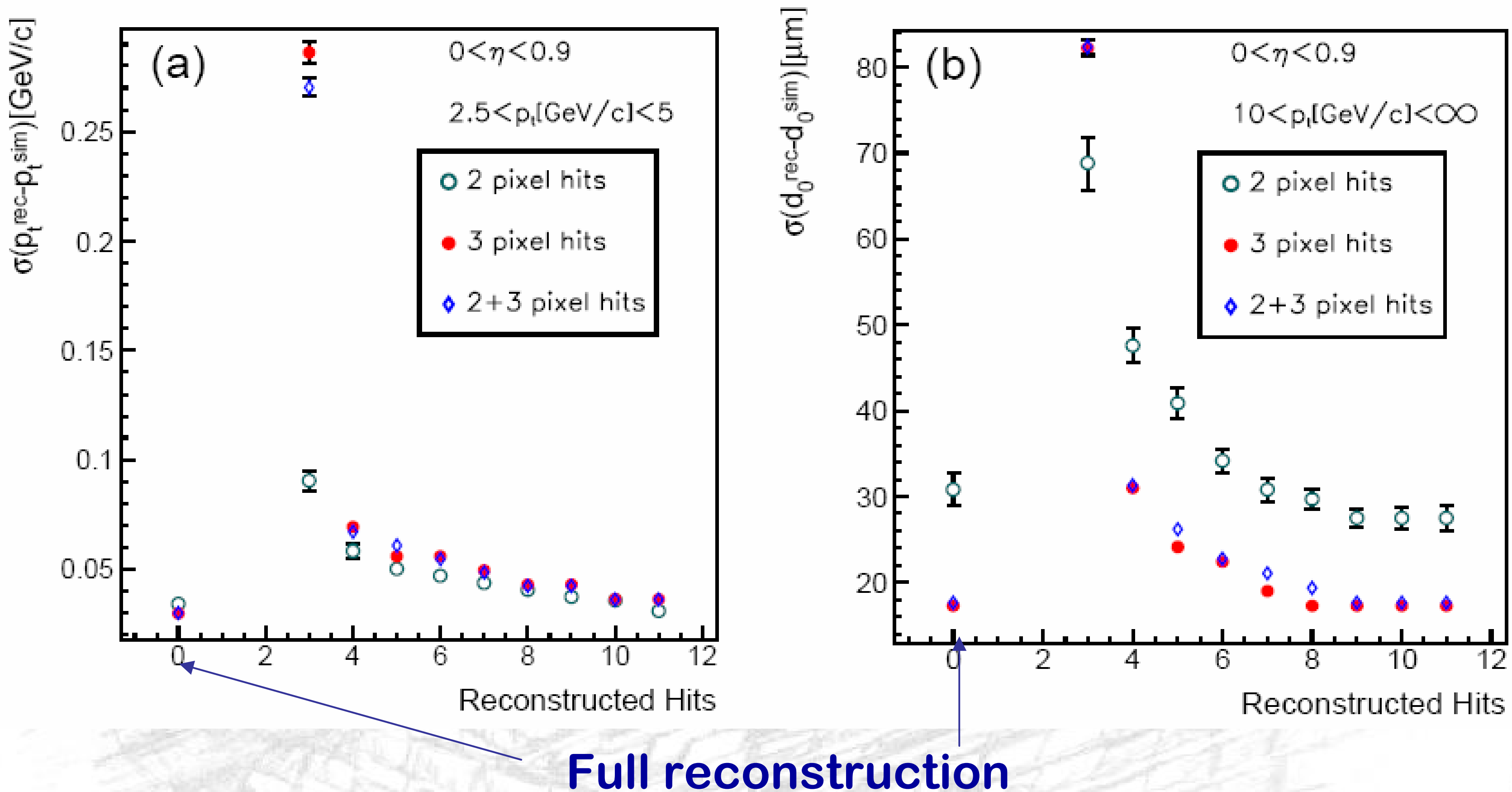
- What has been shown so far represents the current CMS default
- This is what you will get (also on DST) if you request `RecQuery("CombinatorialTrackFinder")`
- Documentation: CMS-Note-2006/041, CMS-Note-2006/026, PTDR1

Special modes:

- limited reconstruction to save CPU (HLT):
- Regional reconstruction
  - Region of interest (ROI) derived from L1 trigger
  - Seeding and pattern recognition limited to this region
- Partial reconstruction
  - Don't need full resolution e.g. for isolation
  - Stop trajectory building when errors are small enough

Partial reconstruction (HLT)

- **Pt resolution**
- **Impact parameter resolution**



- **Reasonable precision already with 5 hits**

(see DAQ TDR)

Advanced algorithms

- **Advantages of default reconstruction**
  - Based on simple, well-known algorithms
  - Efficient and robust
  - Few parameters
  - Works (with retuning) even for Heavy Ion collisions
- **Drawbacks:**
  - Limit on number of candidates in trajectory building is compromise between speed and risk to loose right track
  - No differentiation between noise and hits from other tracks
  - Hard hit assignment sub-optimal in dense environments
- **Advanced algorithms: Adaptive filters**
  - Avoid hit assignment errors at high track density (1+2)
  - Consider non-gaussian tails (e.g. Bremsstrahlung) (3)

1. Deterministic Annealing Filter (DAF)
2. Multi-track Filter (MTF)
3. Gaussian Sum Filter (GSF)

Adaptive Filters: DAF and MTF

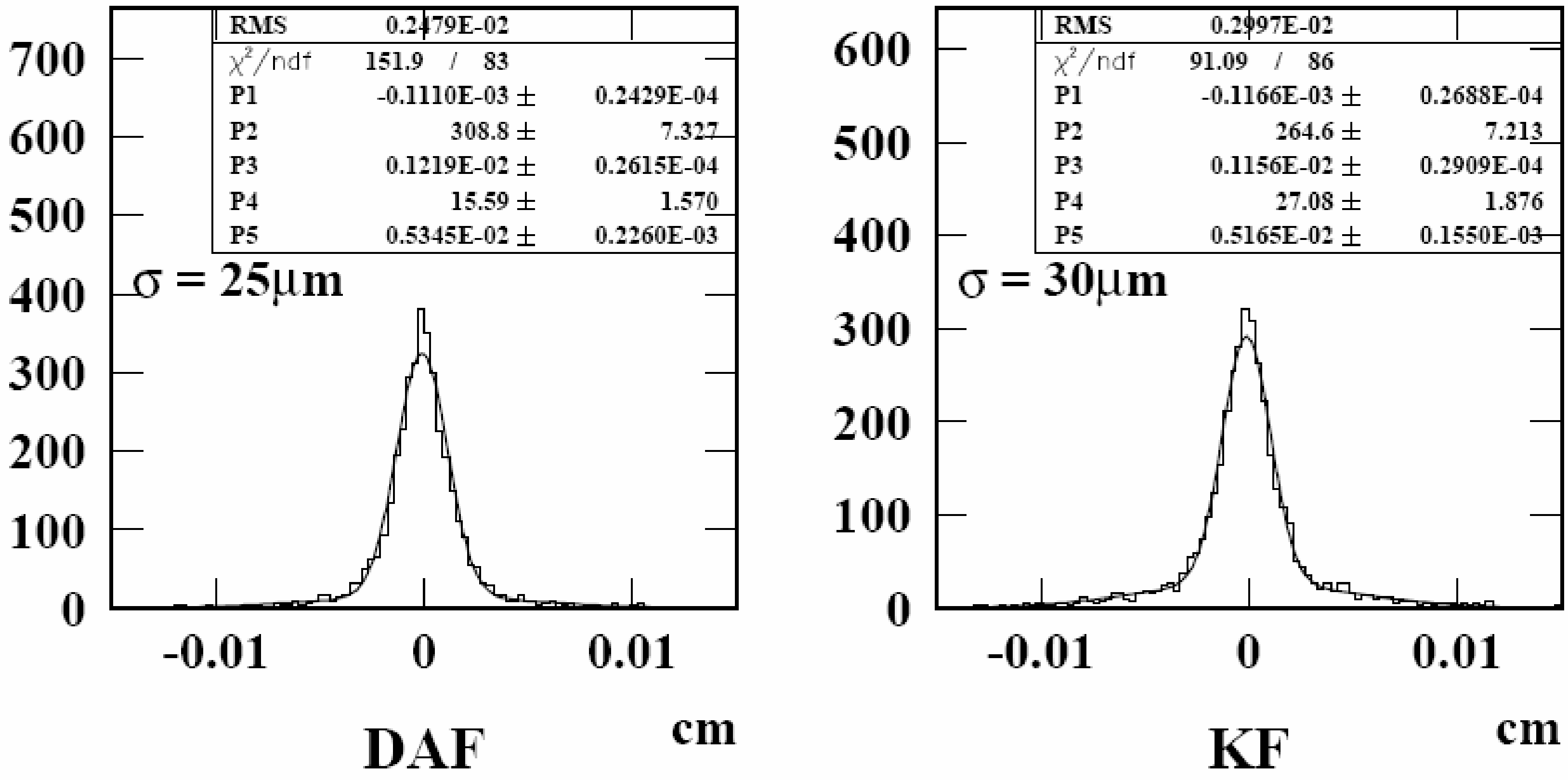
- **Dense track environments e.g. in b- or tau-jets:**
  - **Hit degradation due to contamination from nearby tracks**
  - **Large hit multiplicity in search window: wrong hit assignment**
- **Try soft hit assignment during pattern recognition**

- **Deterministic Annealing Filter (DAF): CMS-IN-2003/043**
  - **Iterative Kalman Filter**
  - **Competition between hits on same surface to belong to track**
  - **Soft Assignment probabilities 0…1**
  - **Fitter and smoother iterated until convergence**
  - **To avoid local minima use annealing**

- **Multi-track filter (MTF): CMS-IN-2003/042**
  - **Extension to concurrent multi track fit**
  - **Competition between tracks and hits (assignment prob. matrix)**
  - **Each hit can belong to each of several tracks**

Deterministic Annealing Filter (DAF)

- **B-Jets in the barrel, Pt=200 GeV**
- **Transverse impact parameter resolution**



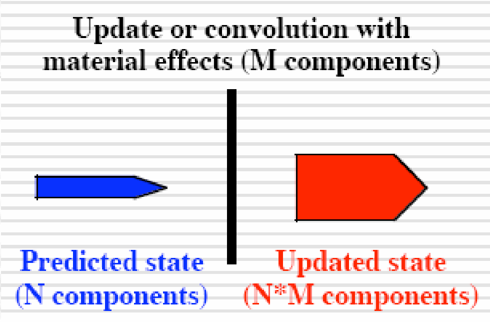
- **DAF: tails are reduced**

Gaussian Sum Filter (GSF)

- **Linear least square estimators (==KF) only optimal in linear systems with Gaussian measurement errors and process noise**
- **GSF used for electron reconstruction in CMS**
  - **Bremsstrahlung highly non-gaussian**

CMS-Note-2005/001

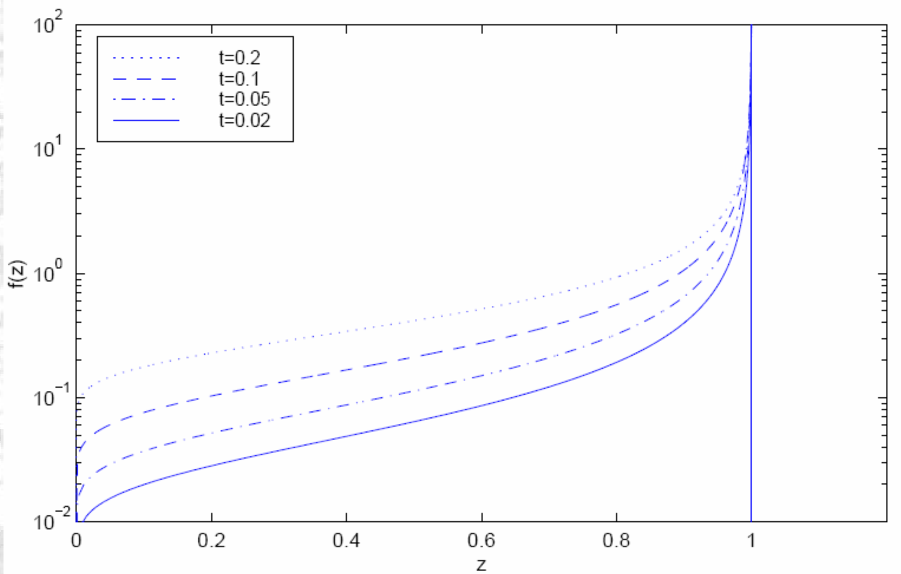
- **Basic idea:**
  - **Non-linear generalization of KF**
  - **Describe non-gaussian probability density functions (pdf's)by mixture of multivariate Gaussian pdf's**
  - **Main component: Core of distributions**
  - **Tails: One or more additional Gaussians**
  - **Weighted sum of several Kalman Filters, run in parallel**
  - **At each step, convolution of state vector mixture with energy loss mixture ⇒ exponential rise of number of components**
  - **Way out: collapsing of components which are "close"**



Gaussian Sum Filter (cont.)

- **Application of GSF to electron reconstruction**
- **Bethe-Heitler model:**
  - **f(z): pdf of electron energy loss**
  - **t: path length (units of rad. length)**
  - **z: remaining energy fraction**

$$f(z) = \frac{[-\ln z]^{c-1}}{\Gamma(c)} \;;\; c = t/\ln 2$$

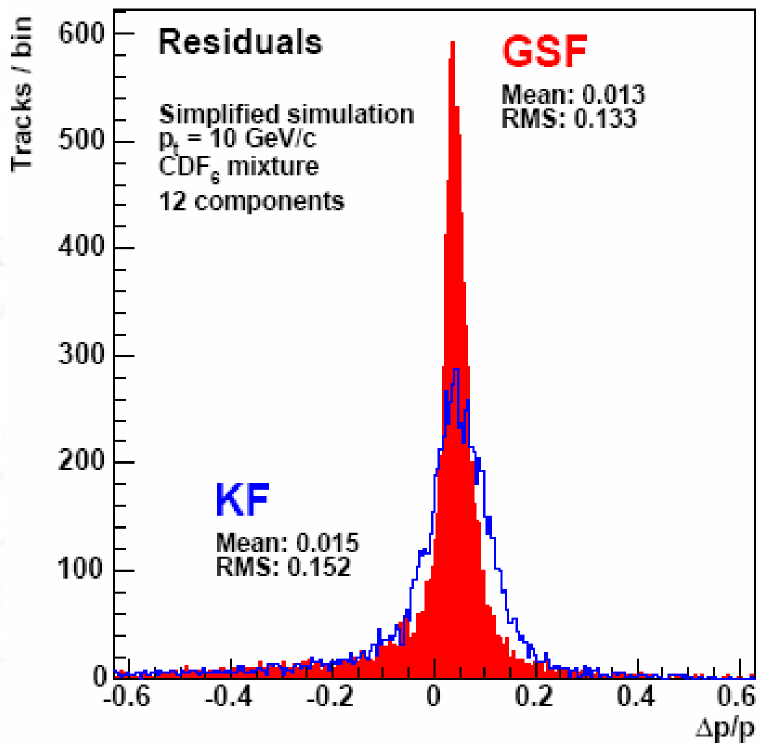


- **Fit parameters of Gaussian mixture to known energy loss distribution**

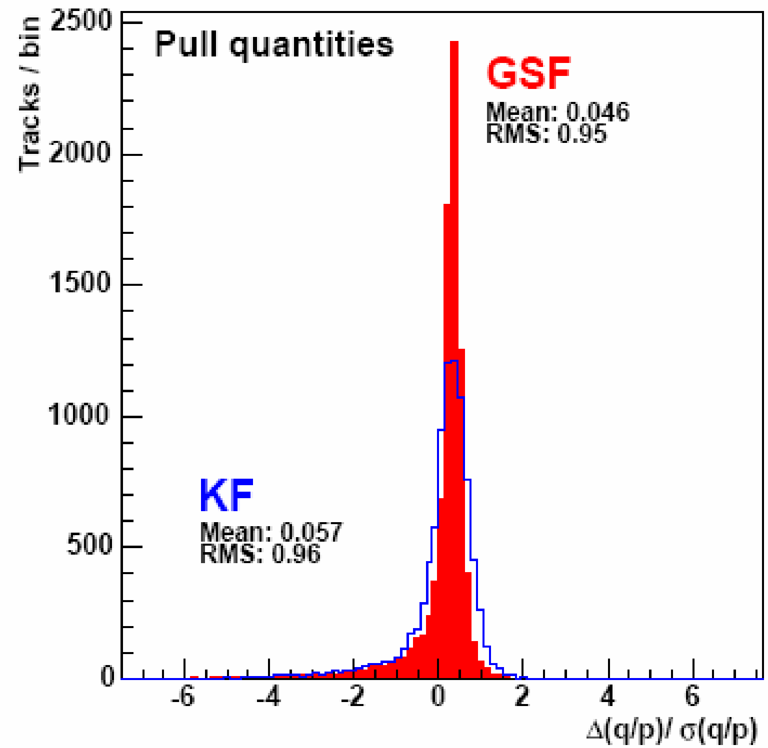
GSF electron reconstruction (cont.)

- **6 component mixture for energy loss**
- **Number of components limited to 12 in fit**

- **Momentum residuals:**



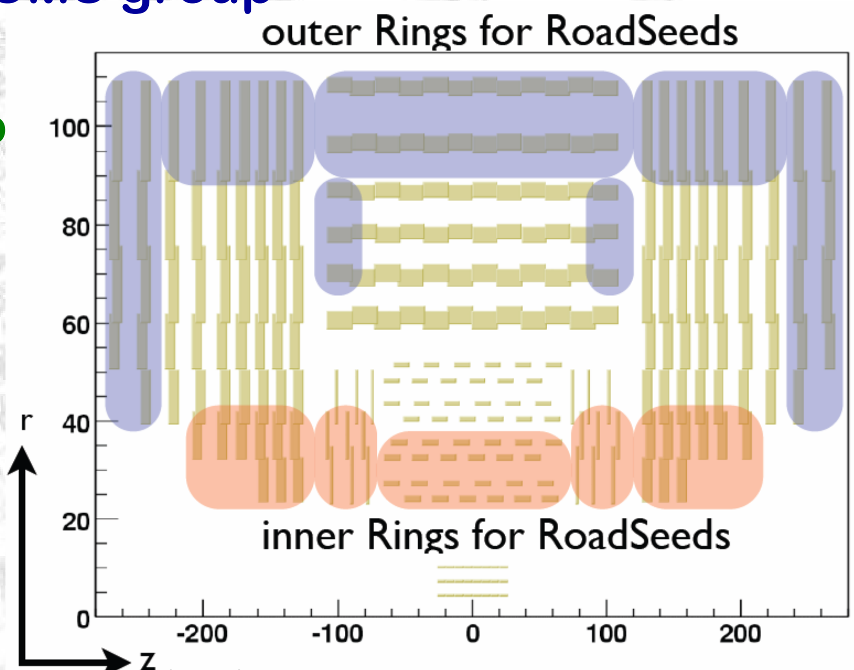
- **q/p pulls (both at TiP surface):**



- **Clear improvement in momentum resolution (but similar to KF at high Pt)**

RoadSearch Algorithm

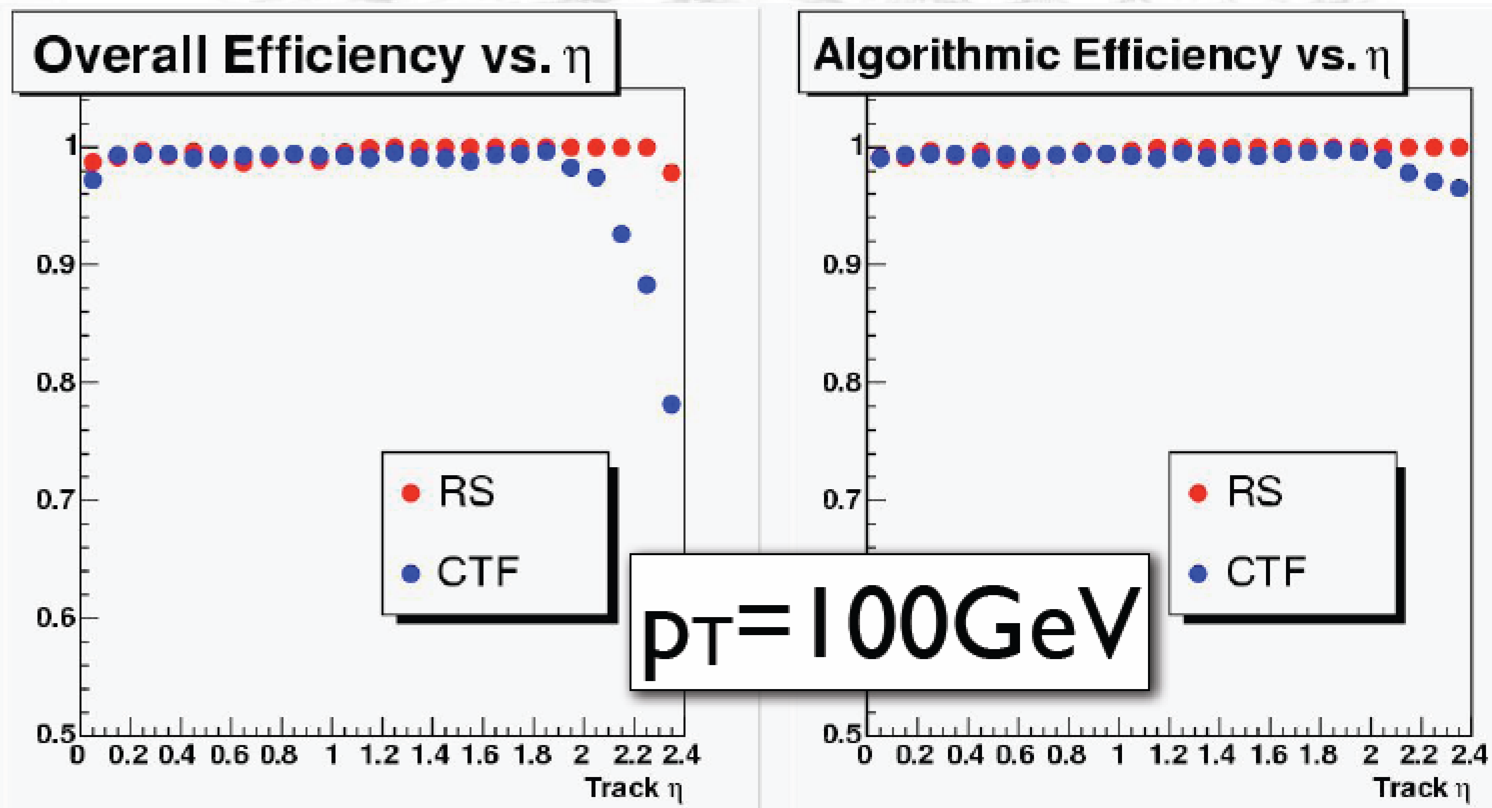
- **New development pursued by the USCMS group**
  - **Complementary to Kalman Filter**
  - **Robust tracks, in particular at start-up**
  - **Always good to have alternative**



- **Basics of RoadSearch algorithm:**
  - **Tracker subdivided in "Rings" in phi at given (r,z)**
  - **Seeds built from hits in predefined inner and outer seed ring combination (RoadSeed) passing $\Delta\phi$ cut**
  - **RoadSeed: all lin. Extrapolations of inner/outer seed ring combinations compatible with beam spot**
  - **Collect hits (cloud) in window around trajectory in road**
  - **Clean hit collection; final track fit**

RoadSearch (cont.)

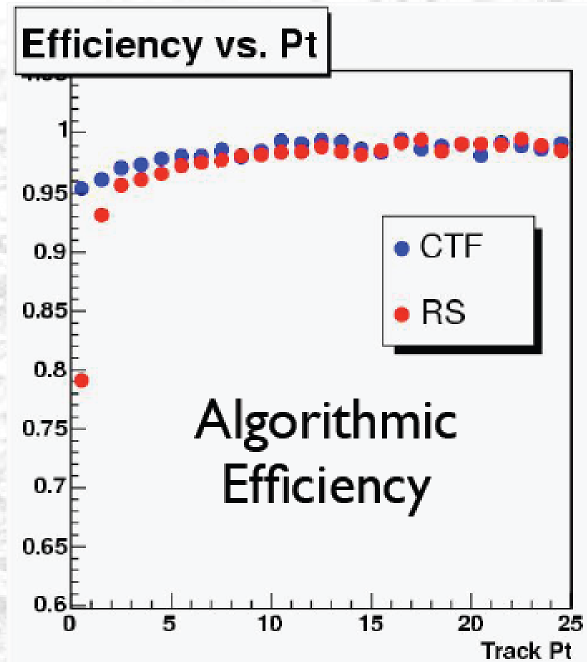
- **Efficiency for single muons with Pt=100 GeV**

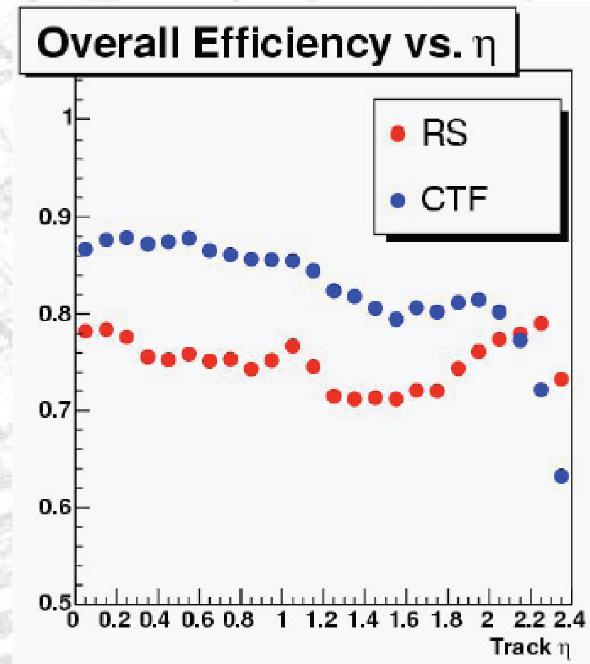


- **Better RS efficiency in fwd region (no PX requirement)**
- **Meanwhile compensated by KF Pixelless seeding (see later)**

RoadSearch (cont.)

- Efficiency for $H \to ZZ \to ee\mu\mu$
- RS inefficiency at low pt, mainly in barrel (roads too narrow?)





- Timing:

sample	mean number of tracks		time per event	
	CTF	RS	CTF	RS
single muon	1	1	0.09	0.06
$h \to ZZ \to ee\mu\mu$	33.7	29.8	3.7	7.6
$W \to \mu\nu$ + pileup	43.3	40.7	14.3	23.9
b jets ($120 \le pT \le 170$GeV)	60.0	56.2	17.3	52.0

- No fake rate studies yet
- Work in progress

Other recent developments

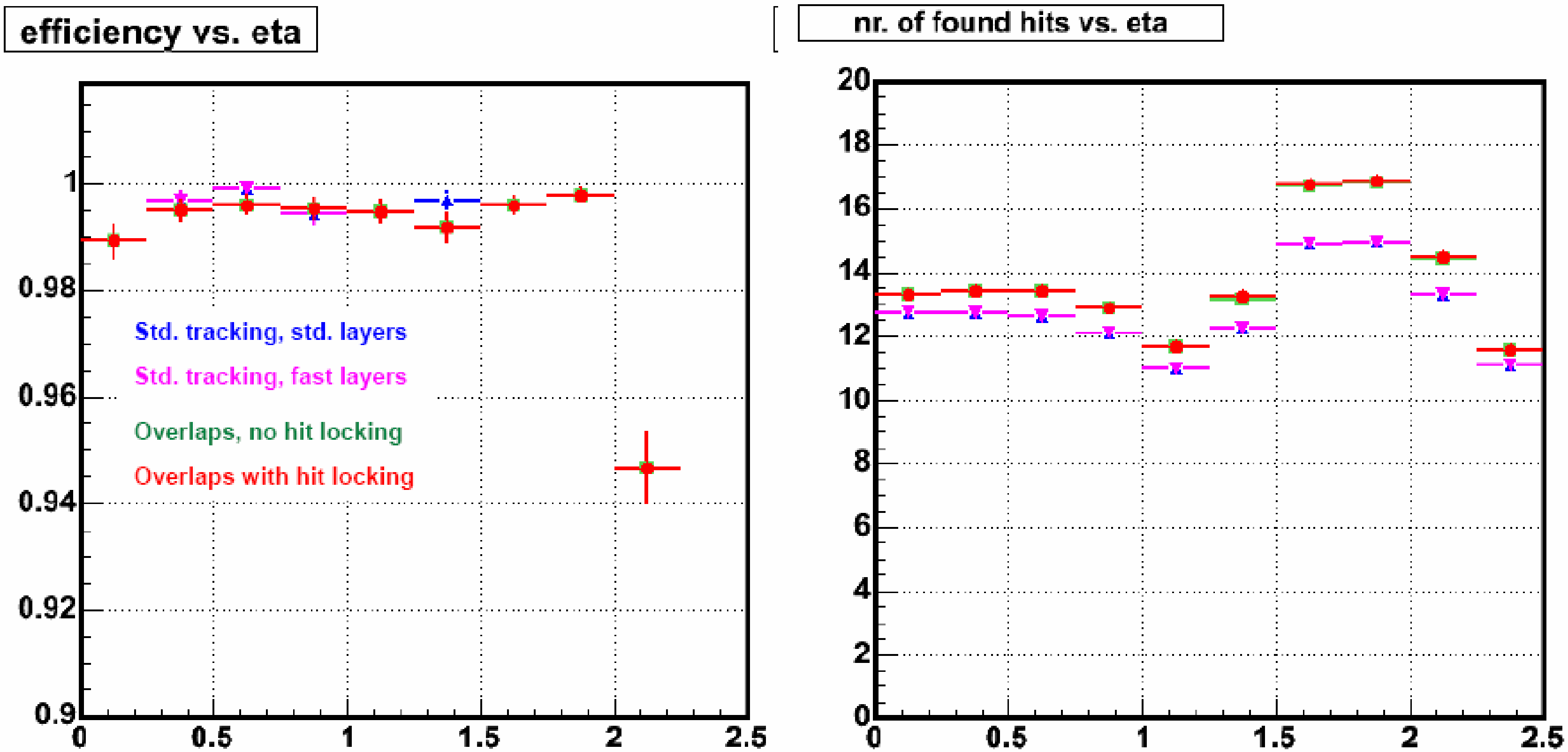
In addition the the new RoadSearch approach, extensions an improvements of existing KF tracking are ongoing:

- **Tracking with overlaps**
- **Tracking without Pixels**
- **Cosmics tracking (see talk of M.Stoye)**
- **(V0 tracking)**

- **… and of course porting of the track reconstruction to the new software framework CMSSW**

Tracking with overlaps

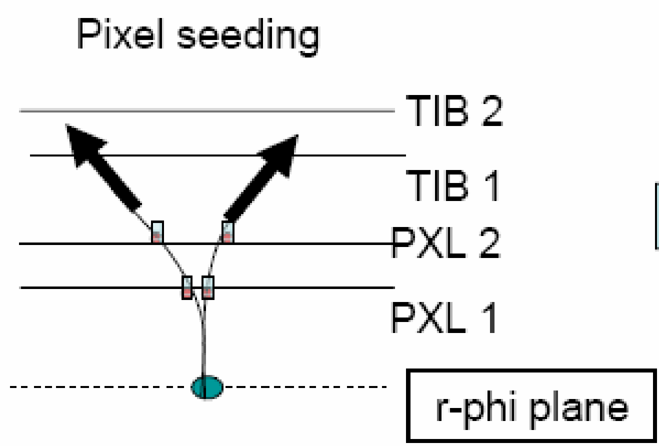
- Standard CTF **uses only one hit per layer**, even if tracks crosses overlap region between two modules, leaving two hits
- **Tracking with overlaps potentially interesting e.g. for alignment!**

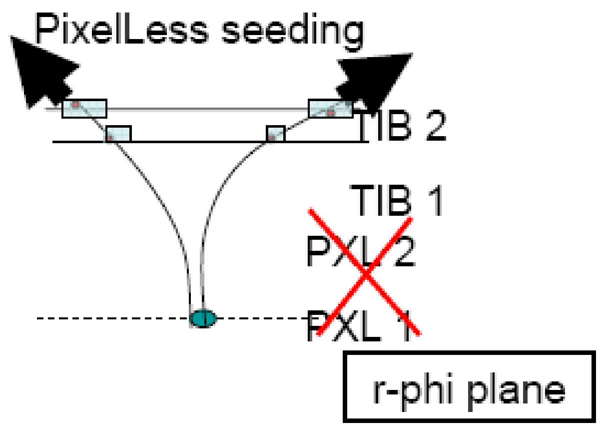


- **~0.5…1 more hits per track found**
- **Performance similar (efficiency, resolution)**

Pixel-less tracking (seeding)

- **Standard tracking uses seeds from Pixel detector**
- **At the CMS start-up, there will be no pixel!**
- **Implement alternative seeding, using the innermost layers of strip tracker**





- SiliconStrip hits have position error bigger than silicon ones.
- The innermost SiStrip layer is farther from the beam line than the pixel one.

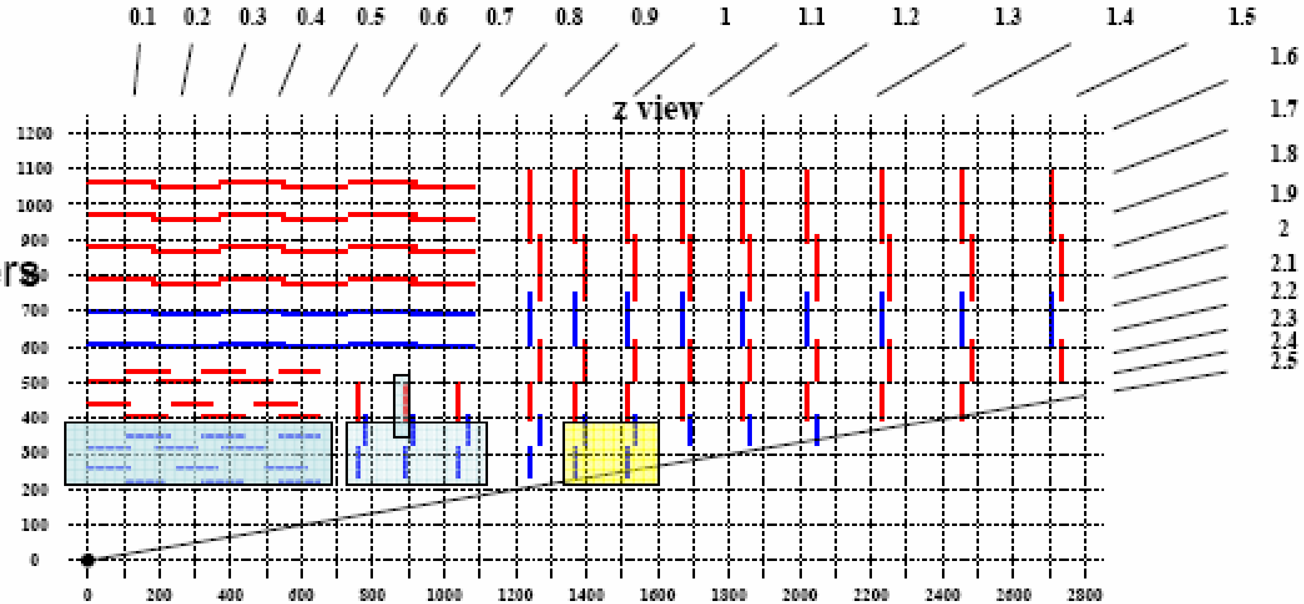
In comparison with a pixel seed generator, a NoPixel one gives seeds with bigger uncertainties on their parameters

⇒ **Bigger number of trajectory candidates**

Pixel-less seeding (cont.)

In order to **reduce the number of seeds generated** and the number of **calls to the trajectory builder**:

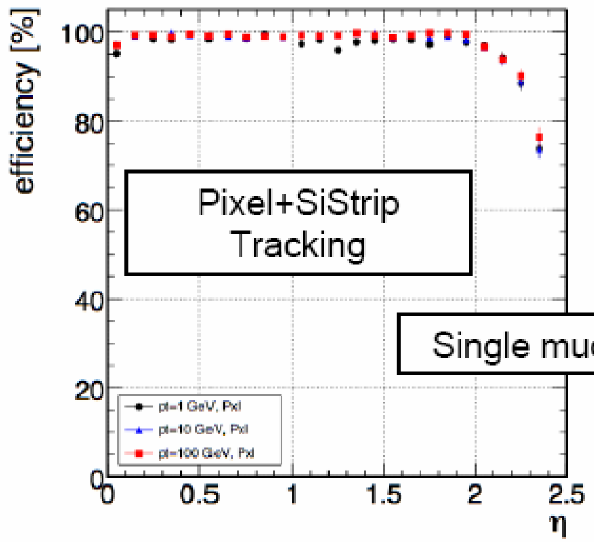
Optimization of the layers set used during seed generation

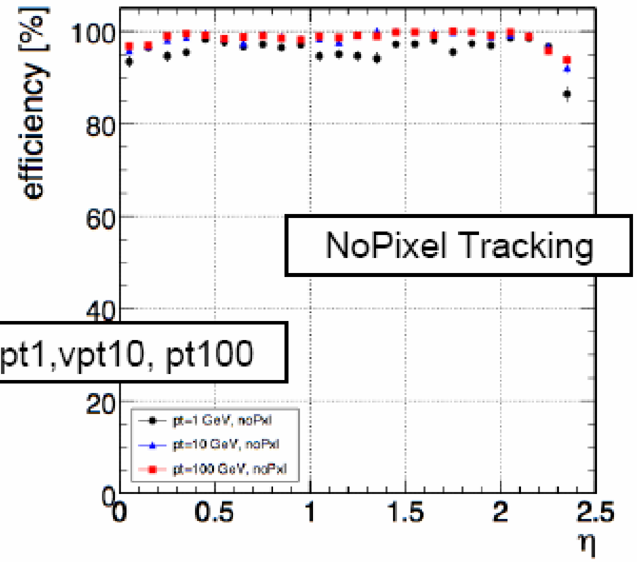


The best arrangment (between seed efficiency and track reconstruction speed) resulted in this layers combination:

- TIB1 and TIB2 layers
- 2 innermost rings of TID1 + complete TID2 + 2 innermost rings of TID3
- 2 innermost rings of TEC2 and TEC3

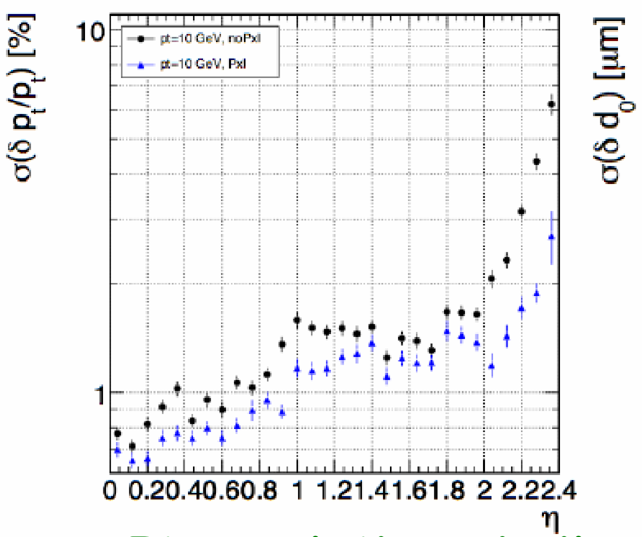
Pixel-less seeding: performance

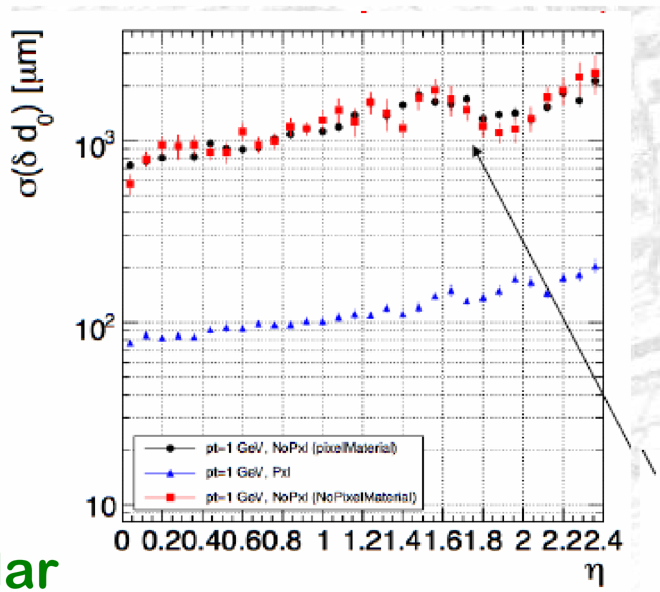




Single muons pt1,vpt10, pt100

- **Higher efficiency in fwd region**
- **mixed seeding coming!**





- **Impact parameter resolution degraded**

- **Pt resolution similar (strip leverarm)**

5000 events have been simulated without pixel “dead” material. There are no apparent improvements in the resolution.

A few words on Alignment

CMS tracker consists of ~16.000 indiv. Modules

- Knowledge of position and orientation should be comparable or better than intrinsic resolution
- Laser alignment: only for of larger structures in TIB / TOB / TEC
  - See talk by M. Thomas
- Determination of ~100k alignment parameters to 10μ necessary
- Only possible with track-based alignment!

Three algorithms presently studied in CMS:

- Kalman filter (Vienna, Aachen), CMS-Note-2006/022
  - See talk by M. Weber
- Millepede (Hamburg), CMS-Note-2006/011
  - See talk by M. Stoye
- HIP (Helsinki, CERN), CMS-Note-2006/018

Summary of work documented in PTDR Vol. 1, section 6.6

Status: Software

- **Simulation of Misalignment**
  - **Development of two "Misalignment scenarios" (short- and long-term)**
  - **Documented in CMS-Note-2006/008**
  - **Used for many PTDR physics studies, see also CMS-Note-2006/029**
- **Common Software Framework for track-based Alignment**
  - **Presently implemented in ORCA**
  - **Documented in CMS-IN-2005/051**
  - **Used for interfacing alignment algorithms to CMS software**
- **Software devlopments relevant for alignment**
  - **Track refit at DST level (~25 ev/sec), if only relevant tracks are refitted, e.g. μ from $W \rightarrow \mu\nu$)**
  - **miniDST format for alignment (retain *only* relevant tracks): improvement in performance (~75 ev/sec) and diskspace (~1/100) precursor of alignment HLT stream?!**

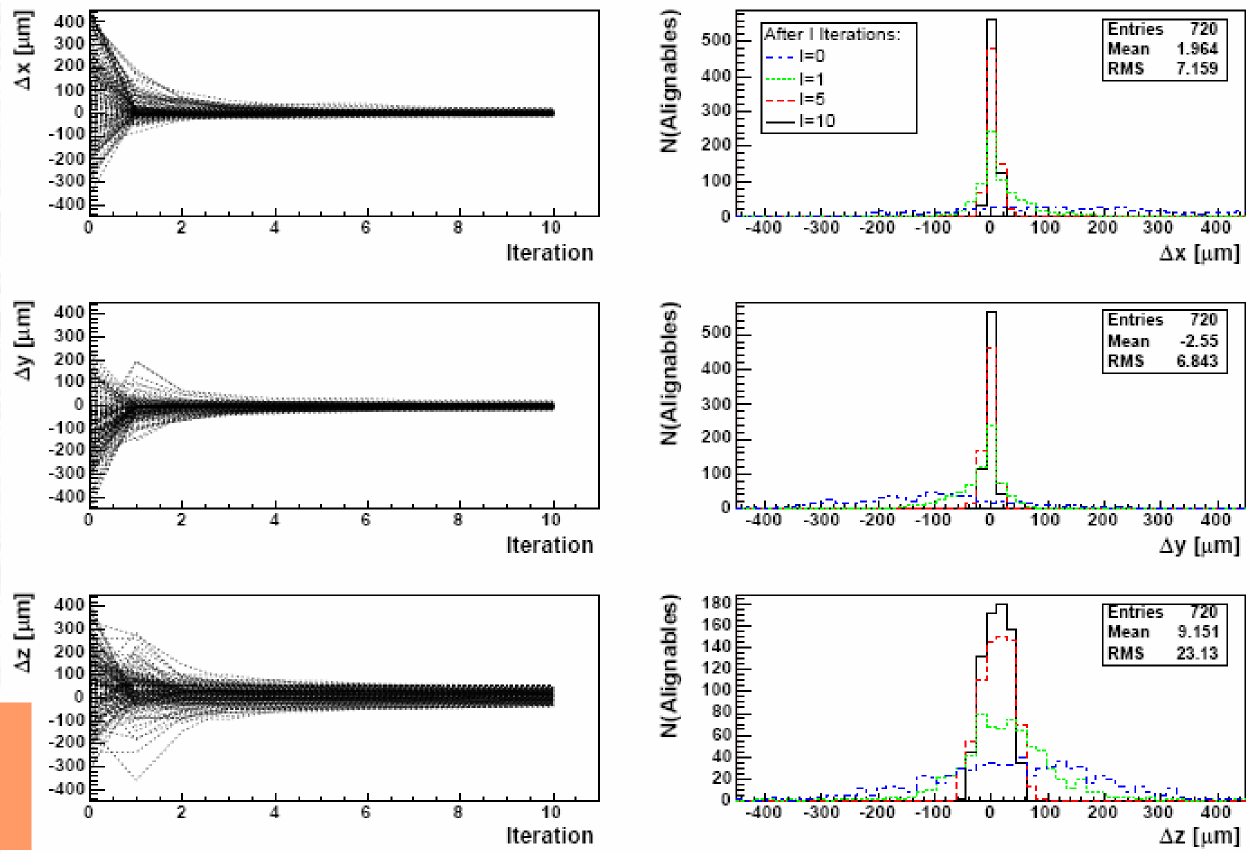
    Only these make large scale alignment possible with reasonable turnaround!

HIP Algorithm (Helsinki, CERN)

- **Linearized χ^2 minimisation**
- **Derivatives of impact point on sensor w.r.t. alignment parameters**
- **No correlations between sensors, no large matrices**
- **Implemented for indiv. sensors as well as for composite objects (rods, ladders etc.)**

- **Alignment of 720 Pixel barrel modules**

- **Short term misalignment scenario *10 (CMS startup)**



Current status doc. in CMS-Note-2006/018

Impact of misalignment

- **Misalignment implemented at reconstruction level (ORCA) by moving/rotating modules/layers etc**
- **Can be studied even at DST level using track refitter**

Two misalignment scenarios developed for PTDR studies:

- **"first data" scenario**
  - **Situation at LHC start-up (first few 100 pb-1)**
  - **Construction information, LAS, pixel aligned with tracks**
- **"long term" scenario**
  - **After first few fb-1 have been taken**
  - **Tracker aligned at the sensor level to ~20 μm**

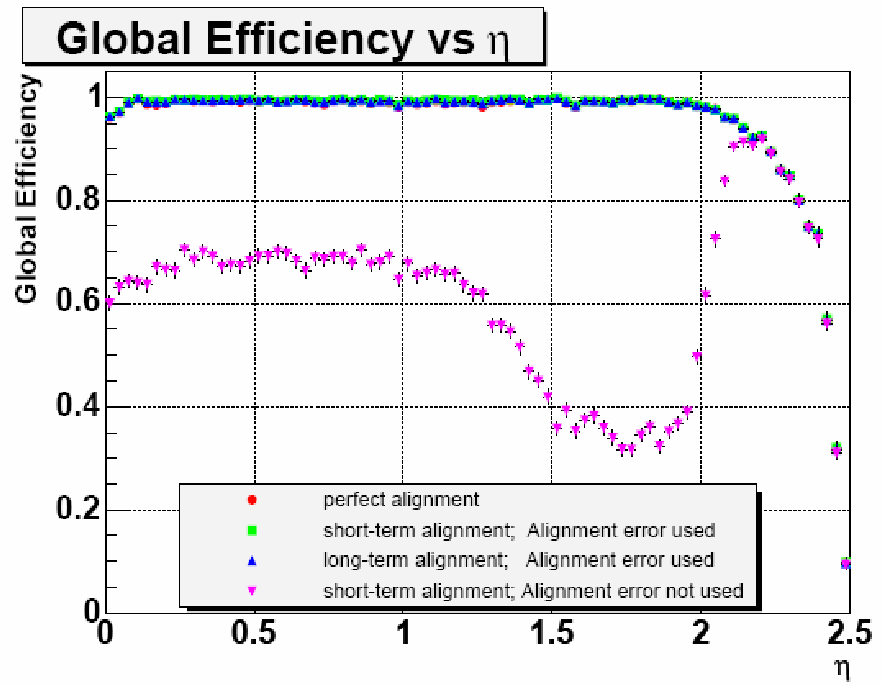
	Pixel		Silicon Strip			
	Barrel	Endcap	Inner Barrel	Outer Barrel	Inner Disk	Endcap
First Data Taking Scenario						
Modules	13	2.5	200	100	100	50
Ladders/Rods/Rings/Petals	5	5	200	100	300	100
Long Term Scenario						
Modules	13	2.5	20	10	10	5
Ladders/Rods/Rings/Petals	5	5	20	10	30	10

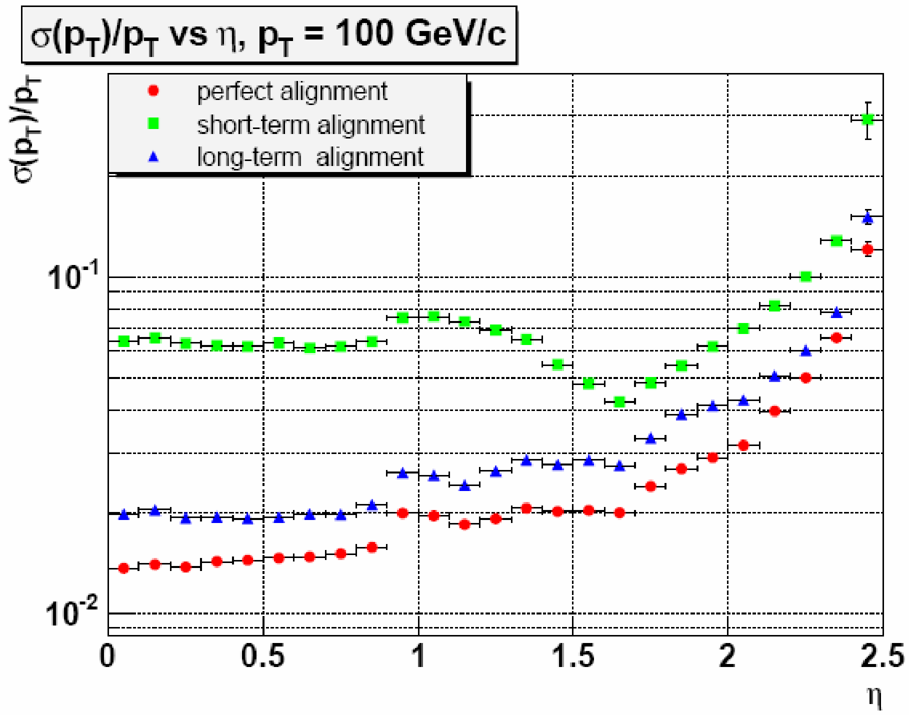
CMS-Note-2006/008

CMS-Note-2006/029

Impact of misalignment

- **Single muons with Pt=100 GeV (typical scale for LHC physics, resolutions not dominated by multiple scattering)**

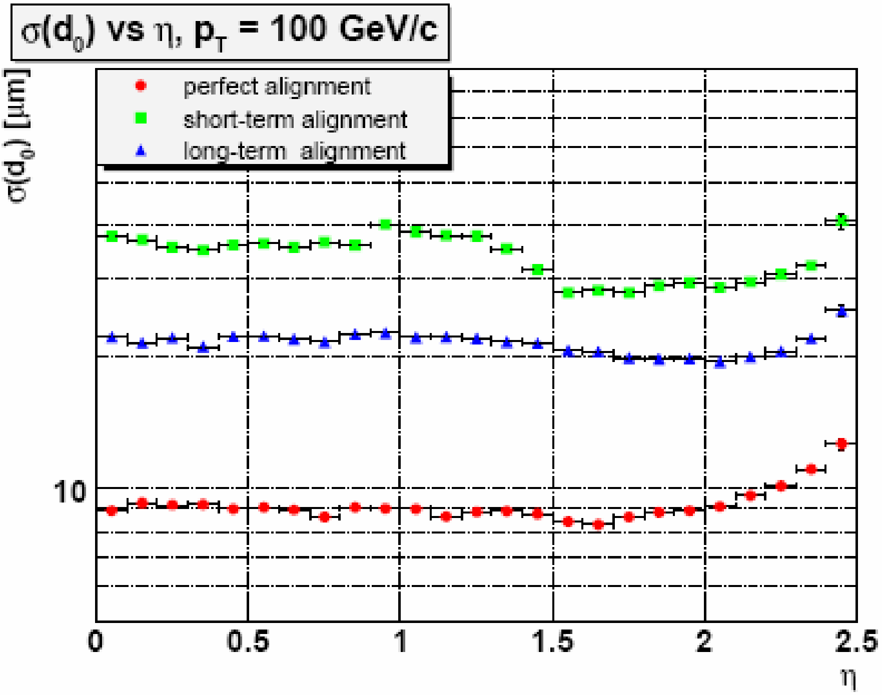


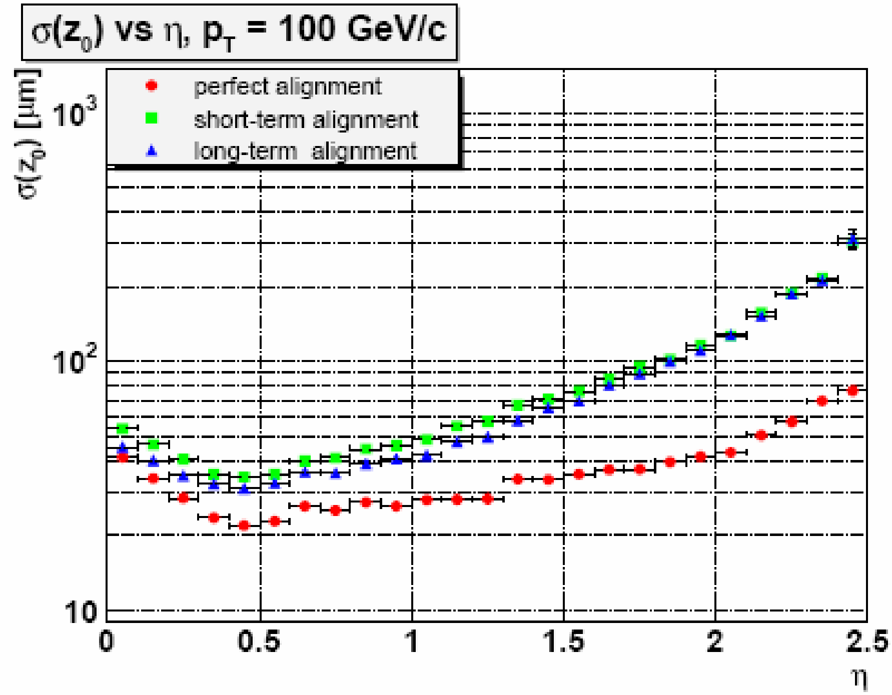


- **Inefficiency in barrel, if alignment unc. not added to meas. error**
- **Worse in TID region (larger initial uncertainty from mounting)**
- **Pt resolution worse by factor ~5 for short-term scenario**

Impact of Misalignment

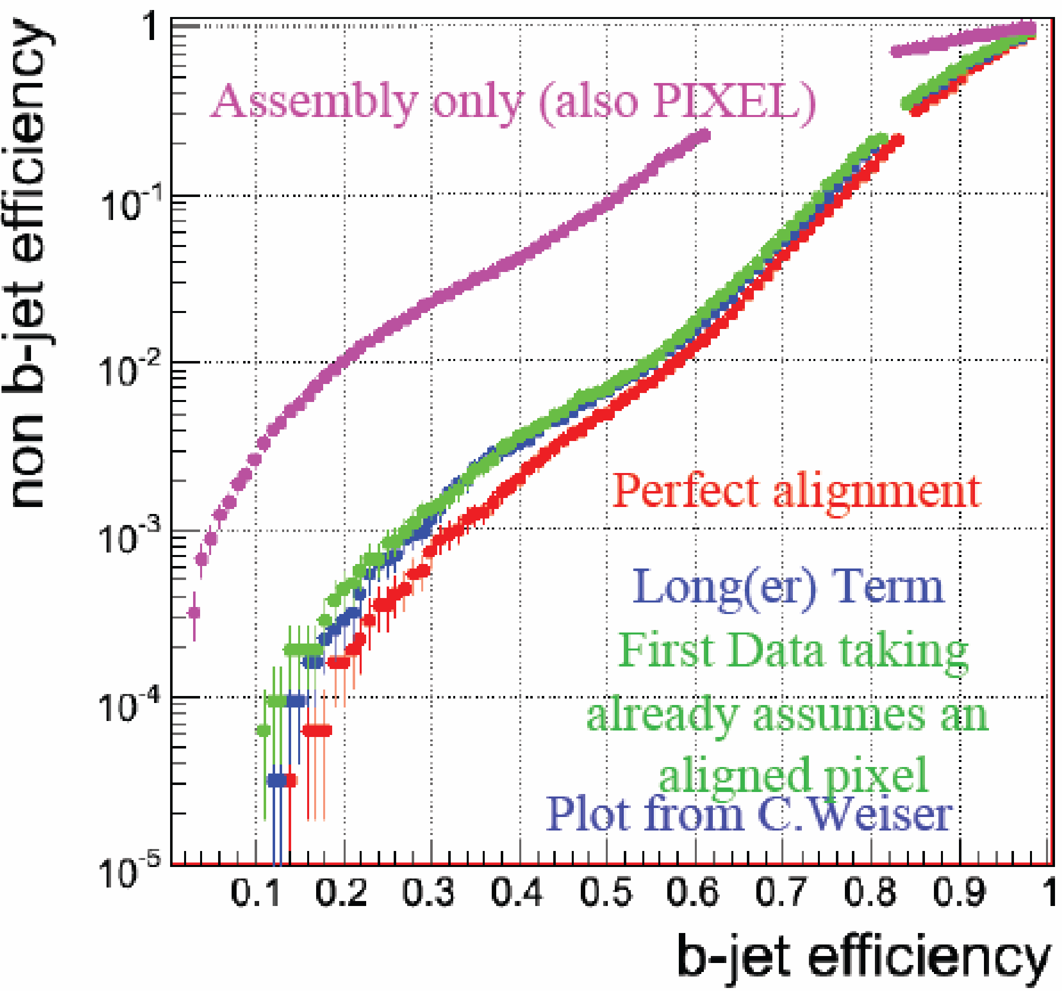
- **Transverse and longit. Impact parameter resolution**





- **d0 resolution ~9, 35, 20 μm (ideal, short term, long term)**
- **Note: Pixel detector assumed aligned even in short term scenario**

Impact of Misalignment



- **No b-tagging performance with currently assumed assembly precision for pixel**
- **Fast Pixel alignment mandatory (also to provide reference for strip alignment)!**

Conclusions

- **CMS has (had?) a modular / oo oriented track reconstruction**
  - **Details of detector geometry hidden from reconstruction**
  - **Modular structure allows easy exchange of components**
- **Efficient baseline track reconstruction based on Kalman filter**
- **Advanced algorithms available (building upon baseline KF)**
  - **Soft assignment algorithms**
  - **Gaussian sum filter**
- **Recent (ongoing) developments**
  - **Overlaps**
  - **Pixel-less seeding**
  - **Cosmics**
  - **Tracking of V0's**
  - **RoadSearch**
  - **Porting to CMSSW!**
- **Alignment cruical for physics performance of tracker!**

Additional manpower in tracking/alignment welcome!!