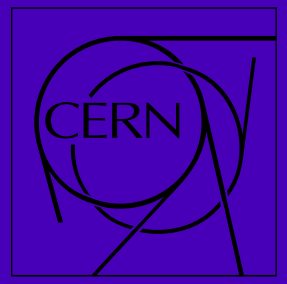
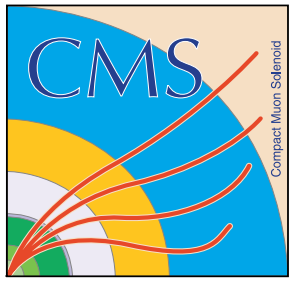
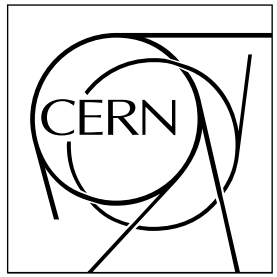


Recent Results on Adaptive Track and Multitrack Fitting in CMS

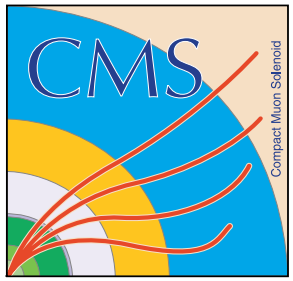
R. Frühwirth (HEPHY Vienna)
A. Strandlie (CERN)
T. Todorov (IReS Strasbourg)
M. Winkler (CERN)



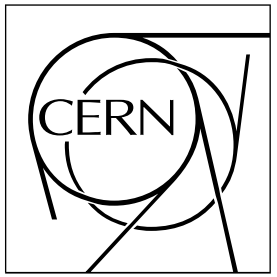
Outline



- ✔ **Adaptive algorithms − a brief review**
- ✔ **Results − simulation study in ATLAS TRT**
- ✔ **Results − simulation study in CMS tracker**
- ✔ **Conclusions**



Adaptive tracking



- **Originally, two elastic tracking algorithms were independently developed:**
  1) **The Elastic Arms (EA) algorithm (Ohlsson, Peterson, Yuille, CPC 1992)**
  2) **The Elastic Tracking (ET) algorithm (Gyulassy, Harlander, CPC 1991)**
- **The ET algorithm is based on the minimization of an interaction energy**

$$R_V(\boldsymbol{p}_T) = \int d\boldsymbol{x} d\boldsymbol{x}' \rho(\boldsymbol{x}) V(\boldsymbol{x} - \boldsymbol{x}') \rho_T(\boldsymbol{x}').$$

Adaptive tracking

- The template track is attracted to the measurements
- The interaction potential was by Gyulassy and Harlander chosen to be of the Lorentzian type:

$$V(\boldsymbol{x}) = \frac{w^2}{w^2 + \boldsymbol{x}^2}.$$

- Finding several tracks is done by sequentially introducing more template tracks
- The most recently introduced template track is attracted to the measurements and repelled by the existing tracks

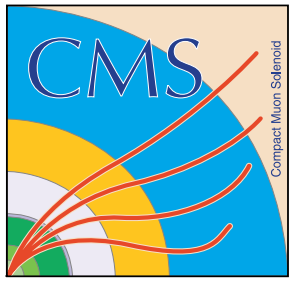
Adaptive tracking

- **The EA algorithm works by introducing the following energy function:**

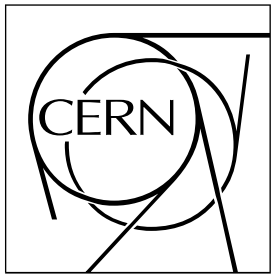
$$E\left(\{S_{ia}\};\boldsymbol{p}\right) = \sum_{ia} S_{ia} M_{ia} + \lambda \cdot \sum_{i} \left(\sum_{a} S_{ia} - 1 \right)^2 .$$

and finding the minimum of the energy with respect to the assignment variables and the parameters of the tracks

- **In order to simplify the problem, the configurations of the system are required to obey the Boltzmann distribution of statistical mechanics**



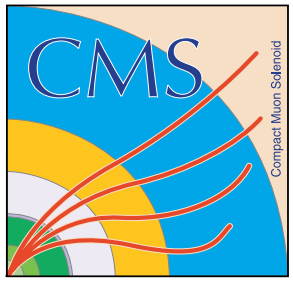
Adaptive tracking



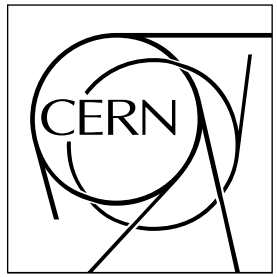
- **The assignment variables are removed by summing up their effects in a marginal probability density, which in turn defines the effective energy**

$$E_{\text{eff}}(\boldsymbol{p}) = -\frac{1}{\beta}\sum_i \log\left(e^{-\beta\lambda} + \sum_a e^{-\beta M_{ia}}\right).$$

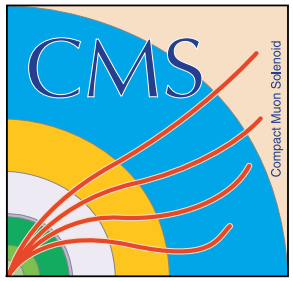
- **The strategy is then to find the minimum of this effective energy with respect to the track parameters at successively lower temperatures and taking the zero temperature limit in the end**



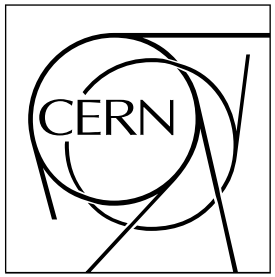
Adaptive tracking



- **The EA algorithm is known to have some unwanted features:**
  1) **Crucially dependent on good initialization − track finding has to be done by a separate procedure**
  2) **Slow and painful minimization of effective energy**
  3) **Not optimal in situations with non−negligible multiple scattering and/or energy loss**
- **An attempt of speeding up the algorithm would be to formulate it as a robust, single−track fitting method**



Adaptive tracking



- **Such an approach yields (Frühwirth and Strandlie, CPC 1999)**

$$E\left(\{S_k, s_{ik}\}, \boldsymbol{p}\right) = \sum_k \left[S_k \left(\sum_{i=1}^{n_k} s_{ik} M_{ik} \right) + \lambda \left(S_k - 1 \right)^2 \right],$$

which in turn defines the effective energy

$$E_{\text{eff}} = -\frac{1}{\beta} \sum_k \log \left(n_k \cdot e^{-\beta\lambda} + \sum_{i=1}^{n_k} e^{-\beta M_{ik}} \right),$$

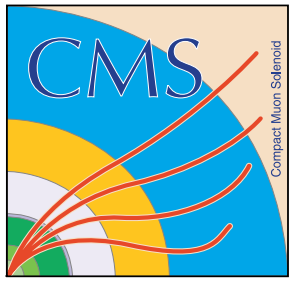
Adaptive tracking

- Instead of numerically minimizing the full effective energy, the EM algorithm (Dempster, Laird, Rubin, JRSS 1977) can be applied to yield an M−step which amounts to minimizing

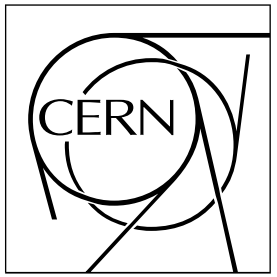
$$Q\left(\boldsymbol{p}|\boldsymbol{p}'\right) = \sum_{k} \sum_{i=1}^{n_k} M_{ik} p'_{ik}$$

with respect to the parameters of the track

- Since this is nothing but a weighted least−squares problem, the M−step can be performed by any least−squares estimator, for instance the Kalman filter



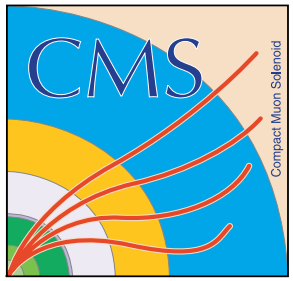
Adaptive tracking



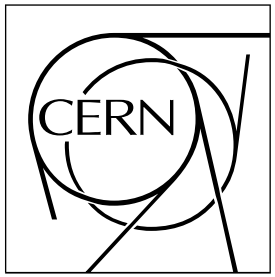
- **The EA algorithm is thus seen to be equivalent to an iteratively reweighted Kalman filter with annealing (Frühwirth and Strandlie, CPC 1999)**
  - **DETERMINISTIC ANNEALING FILTER (DAF)**

with the added advantages

1) **No elaborate, numerical minimization**
2) **Multiple scattering and energy loss can straightforwardly be taken into account**



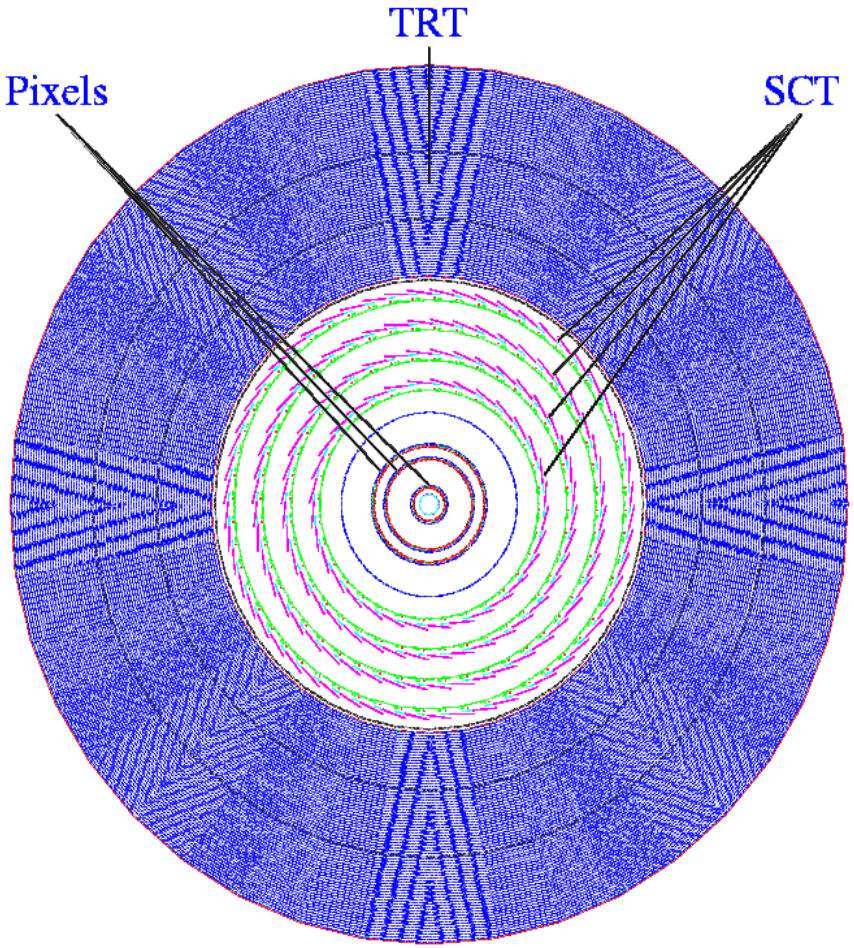
Adaptive tracking



- **The multitrack version of the EA algorithm can in exactly the same manner be generalized to a procedure which iteratively and with annealing runs several Kalman filters in parallel (Strandlie and Frühwirth, CPC 2000)**
  - **THE MULTITRACK FILTER (MTF)**

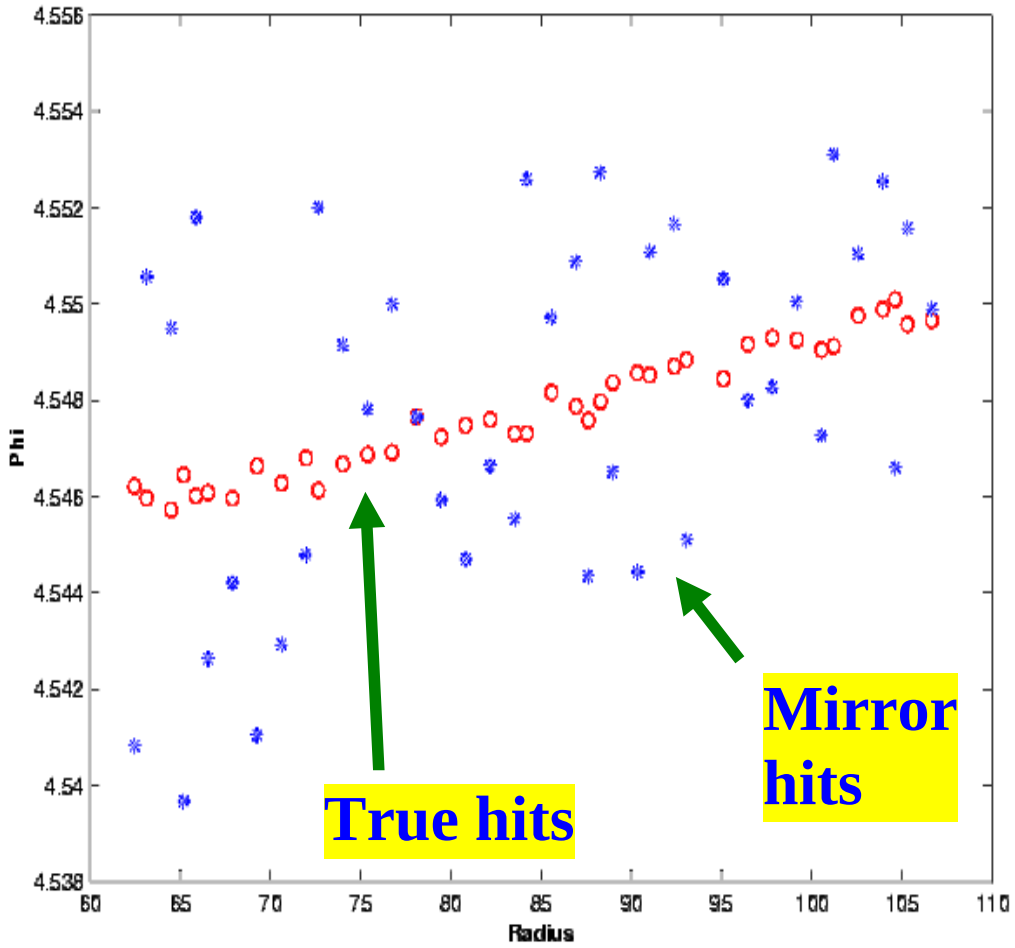
with the same advantages as the DAF with respect to the original EA algorithm

Study – ATLAS TRT



- Drift−tube detector−> left/right ambiguities
- About 35 measurements per track in barrel part of TRT
- Radius of barrel extending from about 50 to 100 cm from the beam

Study – ATLAS TRT



- Evaluating the abilities of the algorithms to solve left/right ambiguities (A. Strandlie, PhD thesis 2000)
- Assuming separate pattern recognition has been done first
- Initialization by least–squares fit to straight line in R–Phi–plane

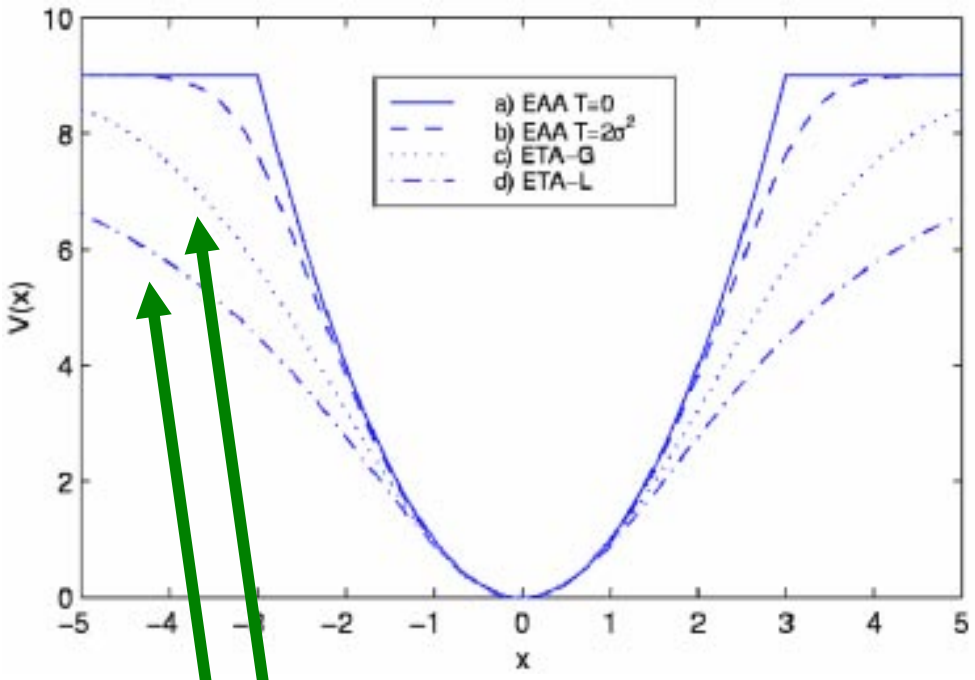
Study – ATLAS TRT

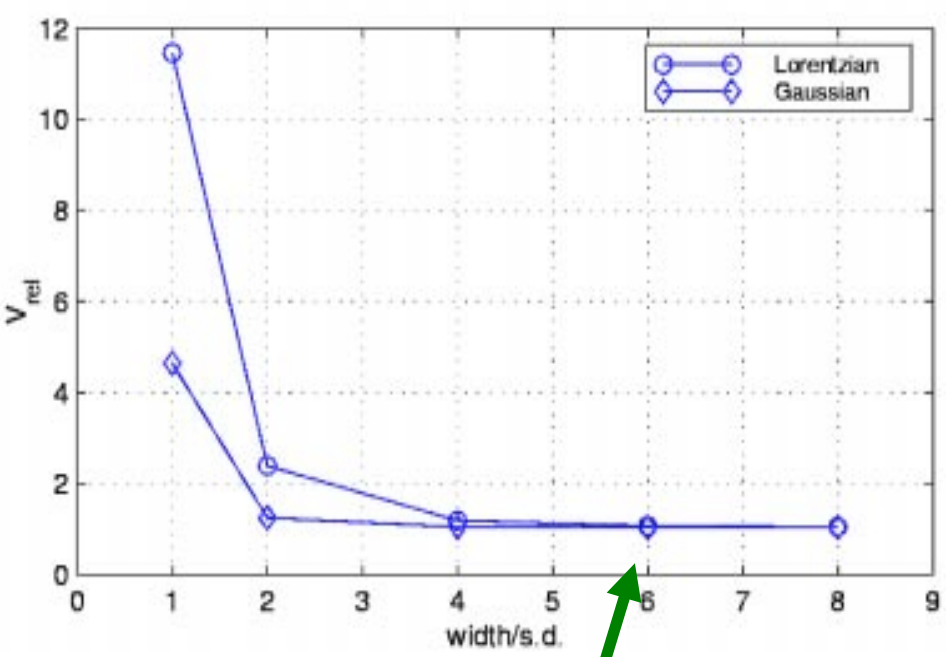
Method	V_{rel}	t_{rel}
DAF	1.00	1.00
GSF	1.00	0.44
EAA with GD	8.83	1.49
EAA with DFP	1.03	1.63
ETA-G with GD	1.79	0.73
ETA-G with DFP	1.05	1.41
ETA-L with GD	125.6	0.65
ETA-L with DFP	1.07	1.67
KF	1.00	0.07

No mirror hits

- **Baseline: DAF**
- **GSF = Gaussian−sum filter (Frühwirth, CPC 1997, Frühwirth and Strandlie, CHEP 1998)**
- **Gradient descent not competitive to quasi−Newton method**

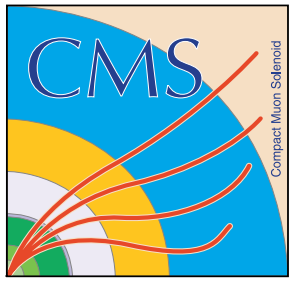
Study – ATLAS TRT



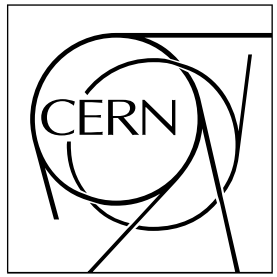


ET is not LS method!

Must operate at large widths



Study – ATLAS TRT

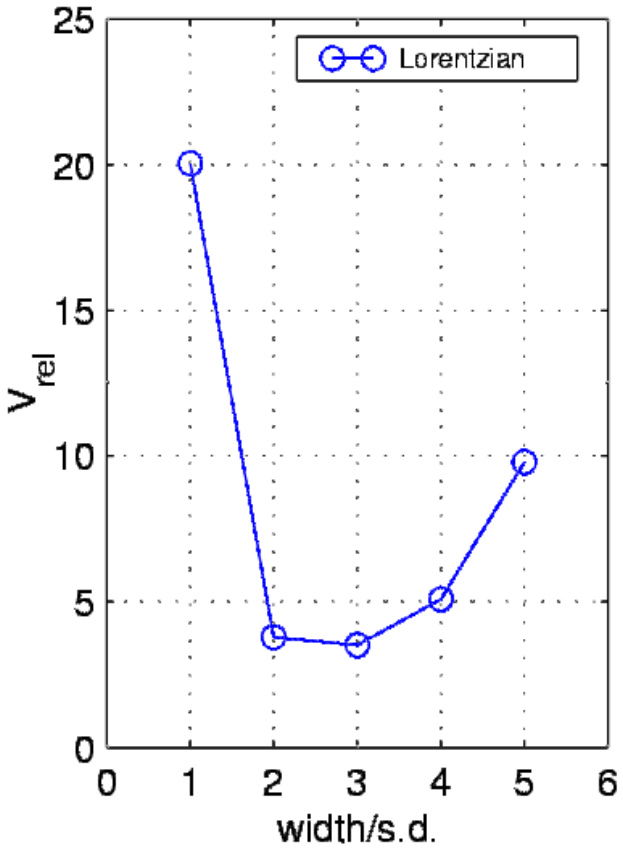


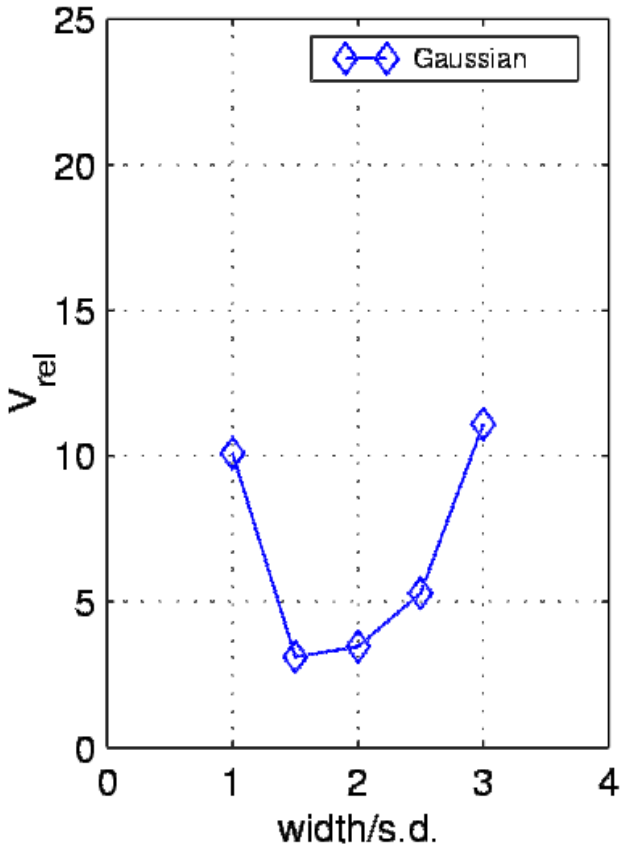
Method	V_{rel}	t_{rel}
DAF nominal	1.54	1.21
DAF frozen	1.74	1.41
GSF all	1.59	7.04
GSF best	1.78	7.04
EAA nominal	1.56	2.12
EAA frozen	1.71	2.44
ETA-G with DFP	3.11	2.38
ETA-L with DFP	3.51	2.87
KF	$\sim$ 1500	0.08

Mirror hits

- **DAF, GSF and EA equally precise (MS turned off), DAF fastest**
- **Zero−temperature limit not optimal**
- **ET less precise than EA**

Study – ATLAS TRT





- **The optimal width is a trade−off between robustness and statistical optimality**

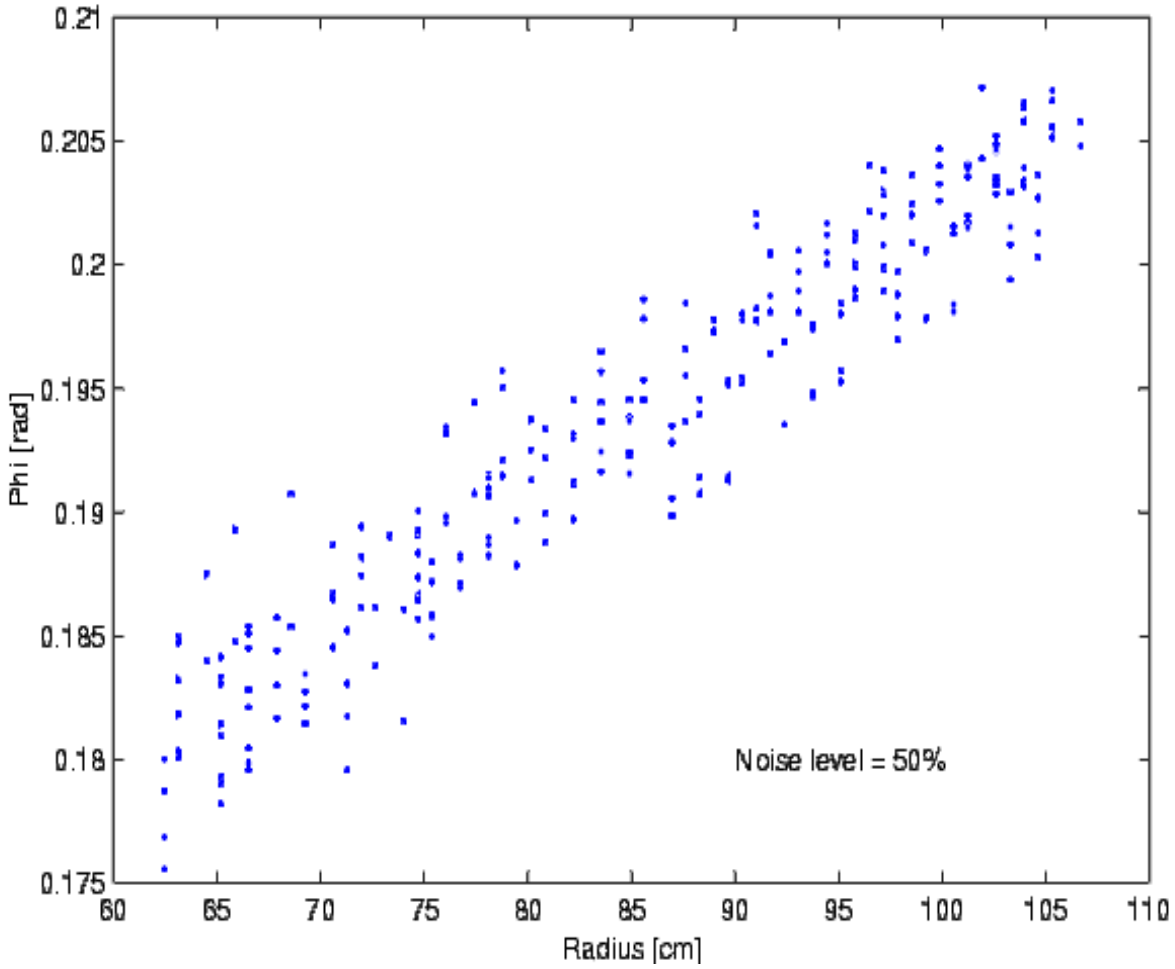
Study – ATLAS TRT

Method	V_{rel}	t_{rel}
DAF	3.96	1.19
GSF	27.33	6.86
ETA-G with DFP	5.77	2.72
ETA-L with DFP	6.56	2.89
LS	$\sim$ 1600	0.08

Mirror hits + 10 % noise

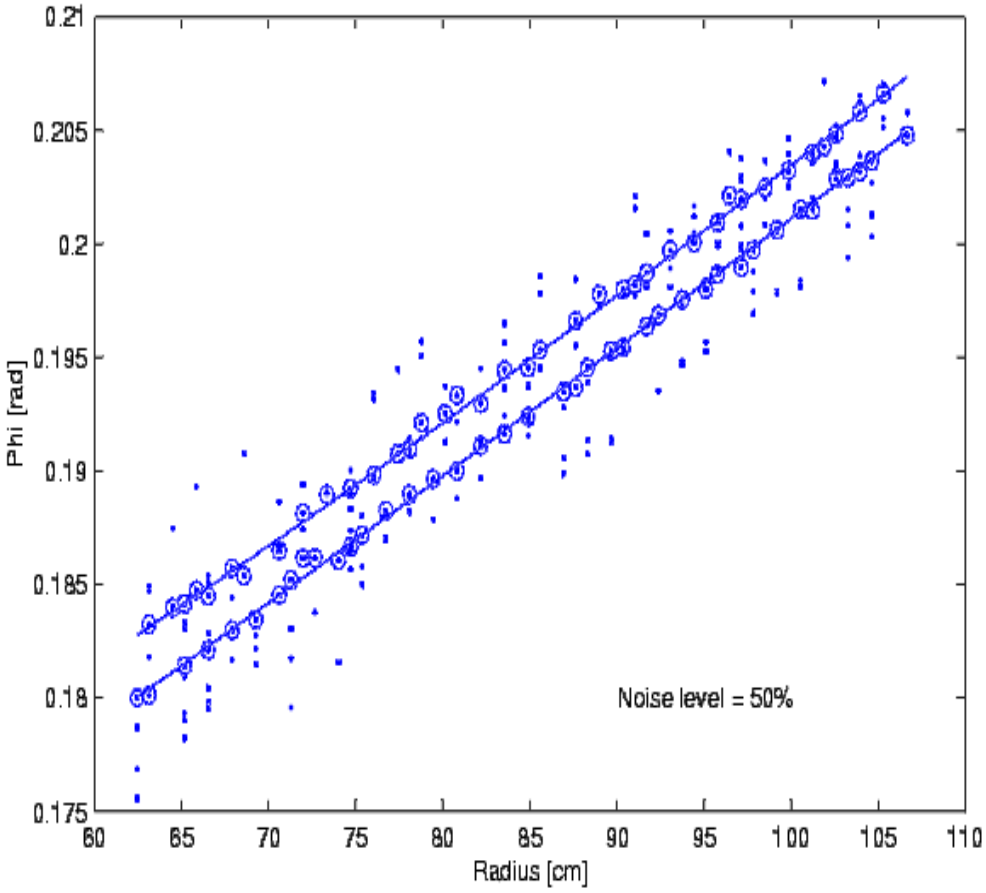
- **GSF is no more optimal due to lack of robustness**
- **ET continues to be not competitive**

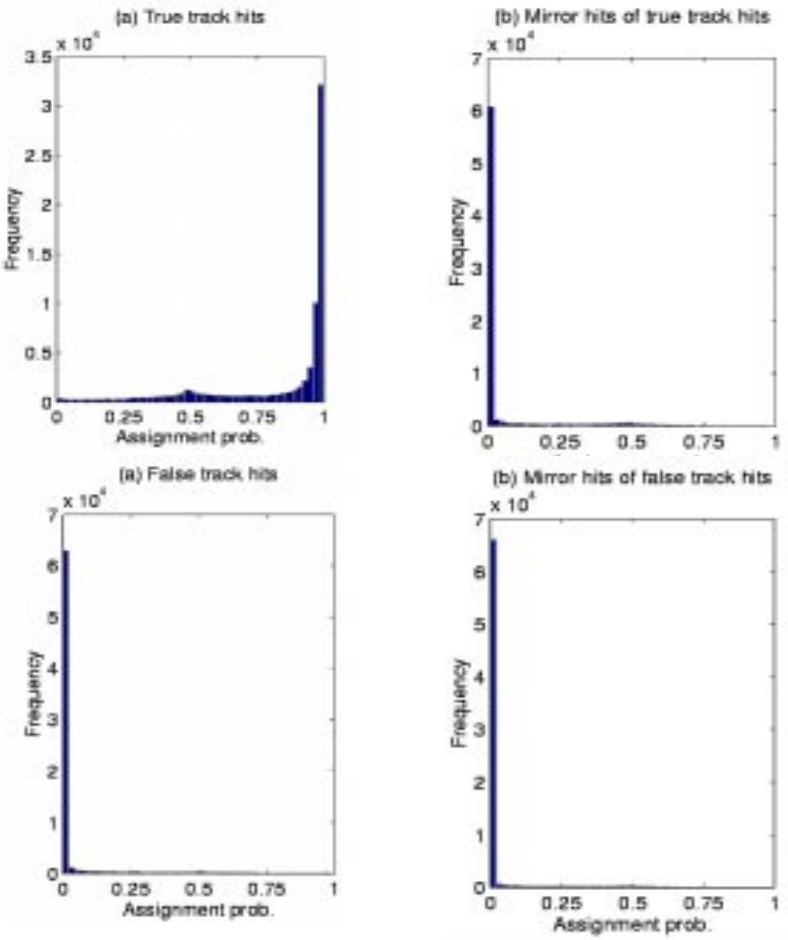
Study – ATLAS TRT



- Next, simulation experiment of two nearby tracks
- Comparing MTF and DAF
- Assuming measure-ments of track pair to be found by track finder
- Initialization by "centre-of-gravity"

Study – ATLAS TRT



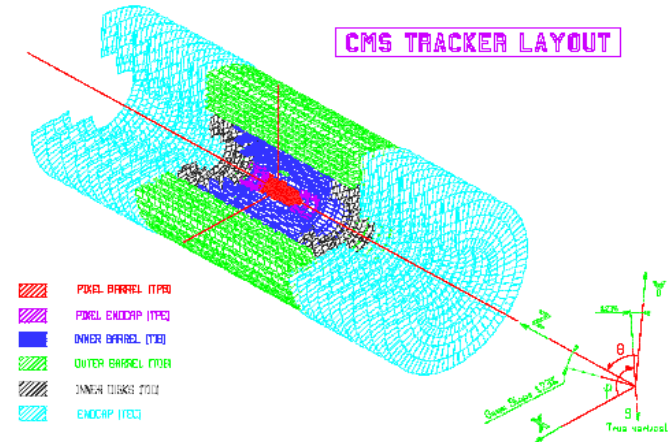


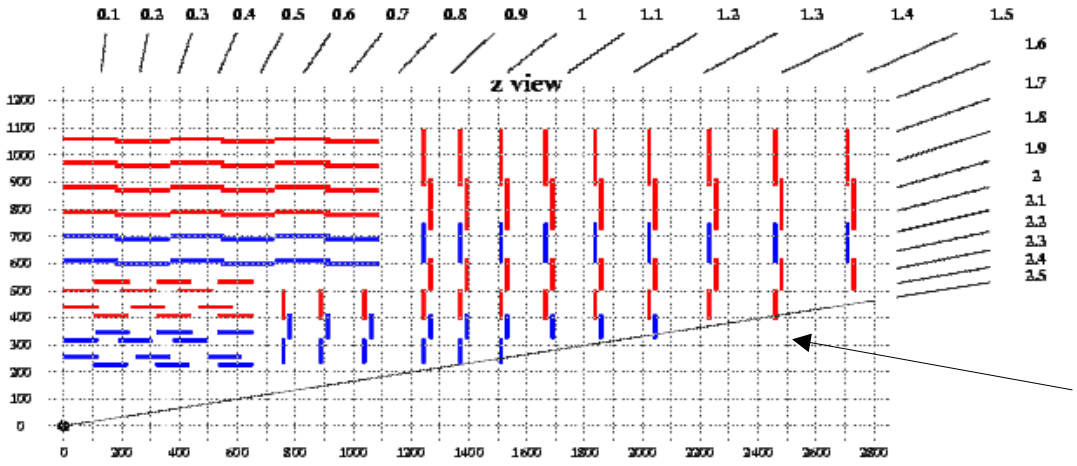
Study – ATLAS TRT

Noise level	Method				
	1	2	3	4	4/3
0%	7.6E5	1837	72.2	11.9	15.3
10%	7.5E5	2698	101.6	22.0	22.2
20%	9.7E5	3532	313.6	40.6	33.0
30%	9.8E5	3800	248.6	43.5	32.6
40%	9.3E5	4449	193.0	65.9	45.7
50%	1.1E6	4817	388.4	96.0	68.8

- DAF (method 1) is for sure confused by the nearby track
- Methods 2, 3 and 4 all using MTF, difference in structure of assign−ment probabilities
- Baseline is generalized variance of fit to each track separately, no noise and no mirror hits

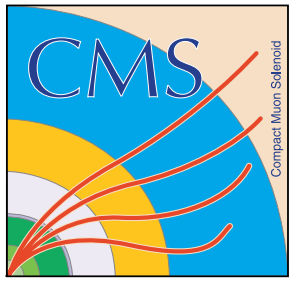
Study – CMS tracker



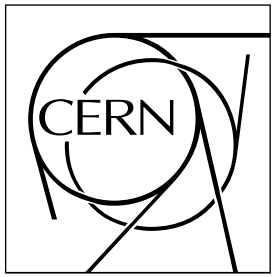


- **All−silicon based tracker with pixels closest to the beam and silicon strip detectors outside**
- **Radial extension: ~110 cm Longitudinal: ~2*270 cm**

R−z view of one quadrant of CMS tracker



Study – CMS tracker

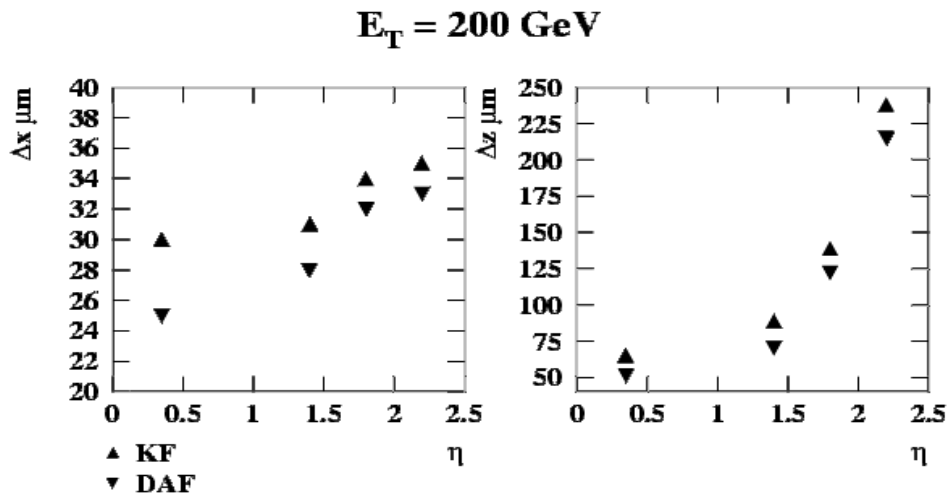


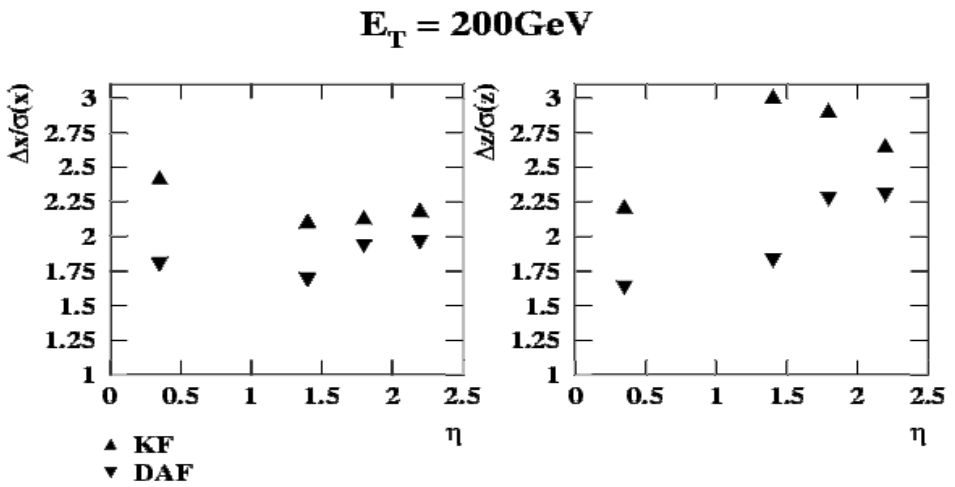
- **Both DAF and MTF have been implemented in the official reconstruction framework of CMS – ORCA (M. Winkler, PhD thesis 2002)**
- **Performance of methods has been thoroughly evaluated and systematically compared to the Kalman filter**
- **Track finding (initialization) done by combinatorial Kalman filter, smoothing either by KF, DAF or MTF**
- **Will focus on two channels:**

  1) **200 GeV transverse energy b–jets**

  2) **3–prong tau jets from 500 GeV SUSY Higgs decay**

Study – CMS tracker





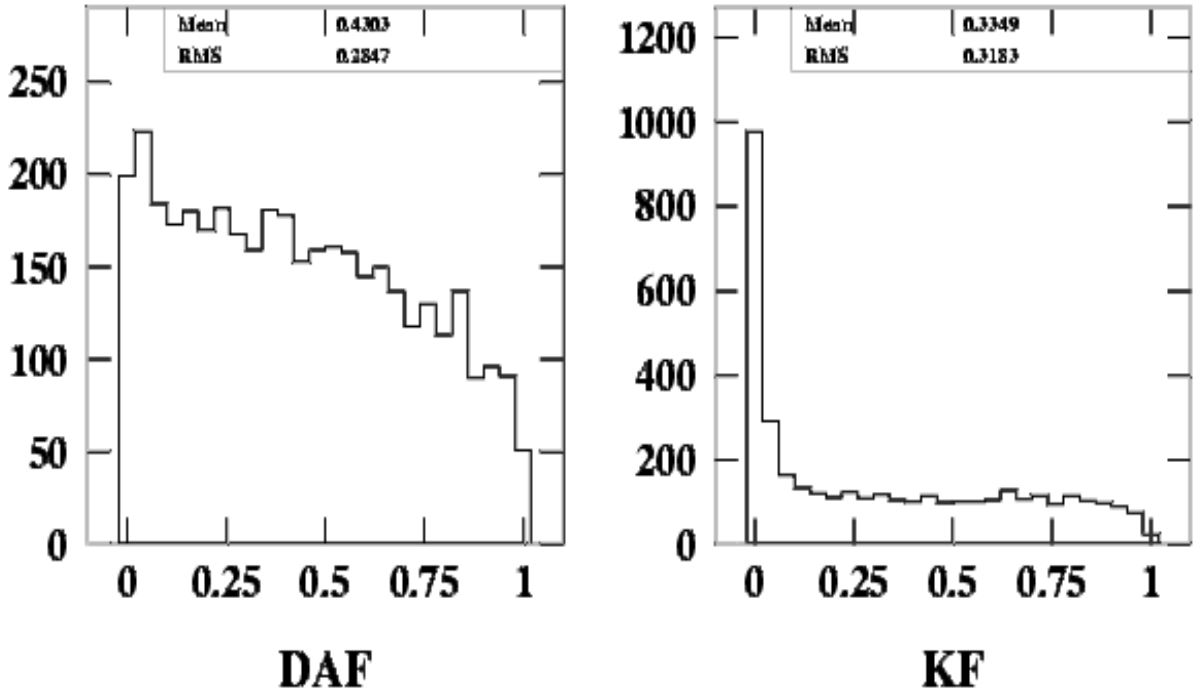
Impact parameter resolutions and pulls of tracks (transverse momentum larger than 15 GeV) in 200 GeV b−jets

DAF is significantly more precise and has better pulls

Tails of residual distributions much smaller with DAF

Study – CMS tracker

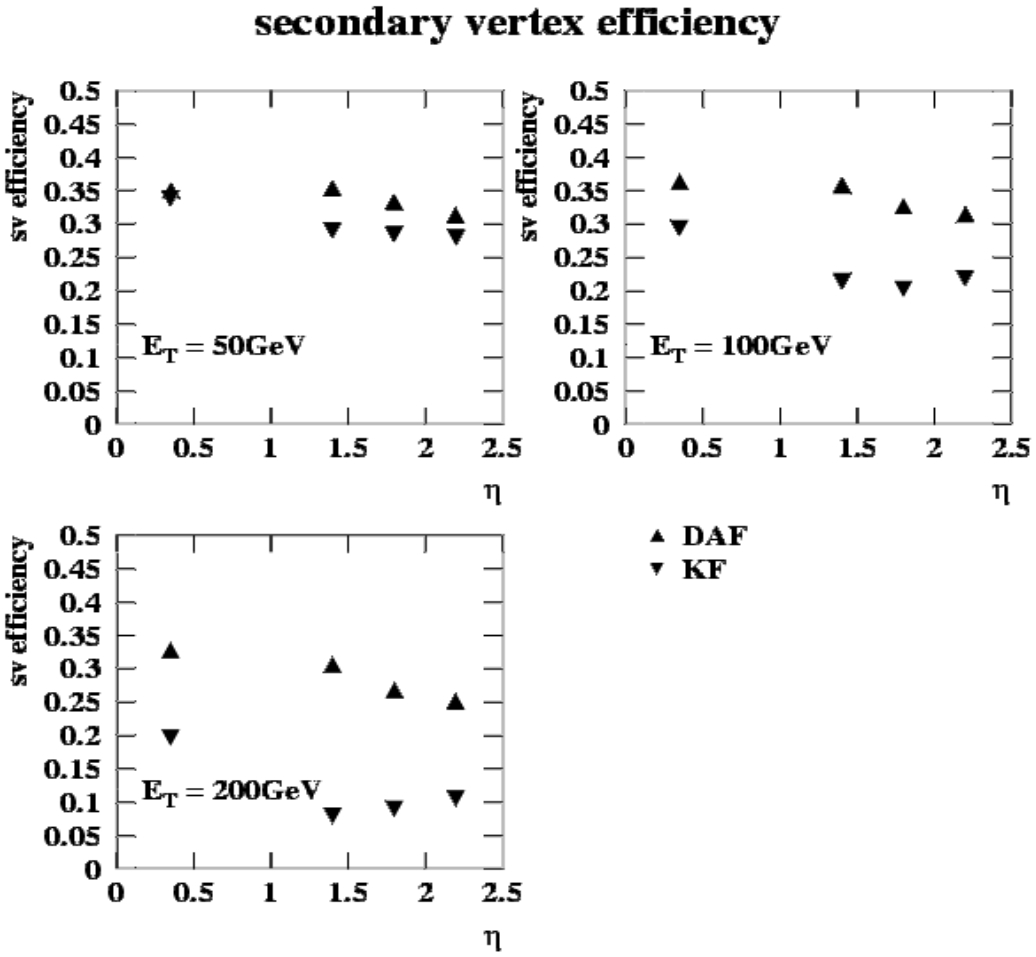
χ^2 probability



Consequently, quality of error estimation is better with the DAF

Histogram not flat –> still room for improvement !!

Study – CMS tracker

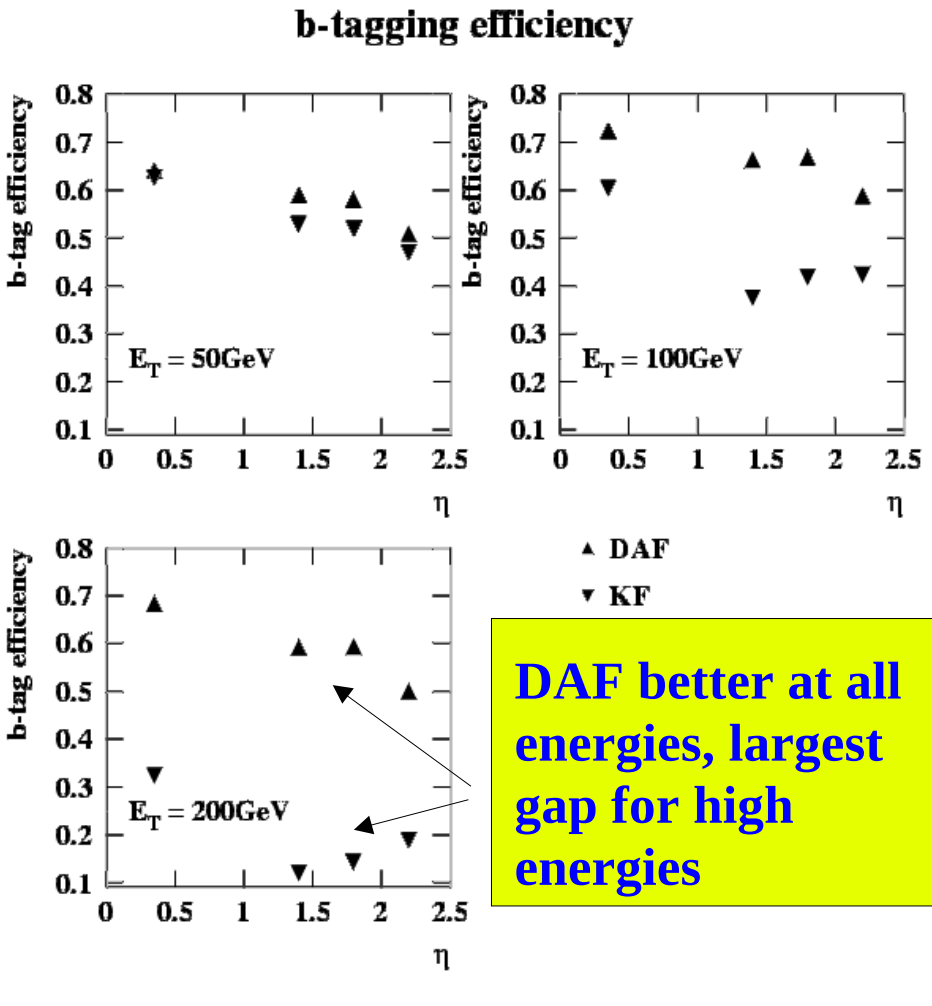


SV finding efficiency for KF depends strongly on jet energy

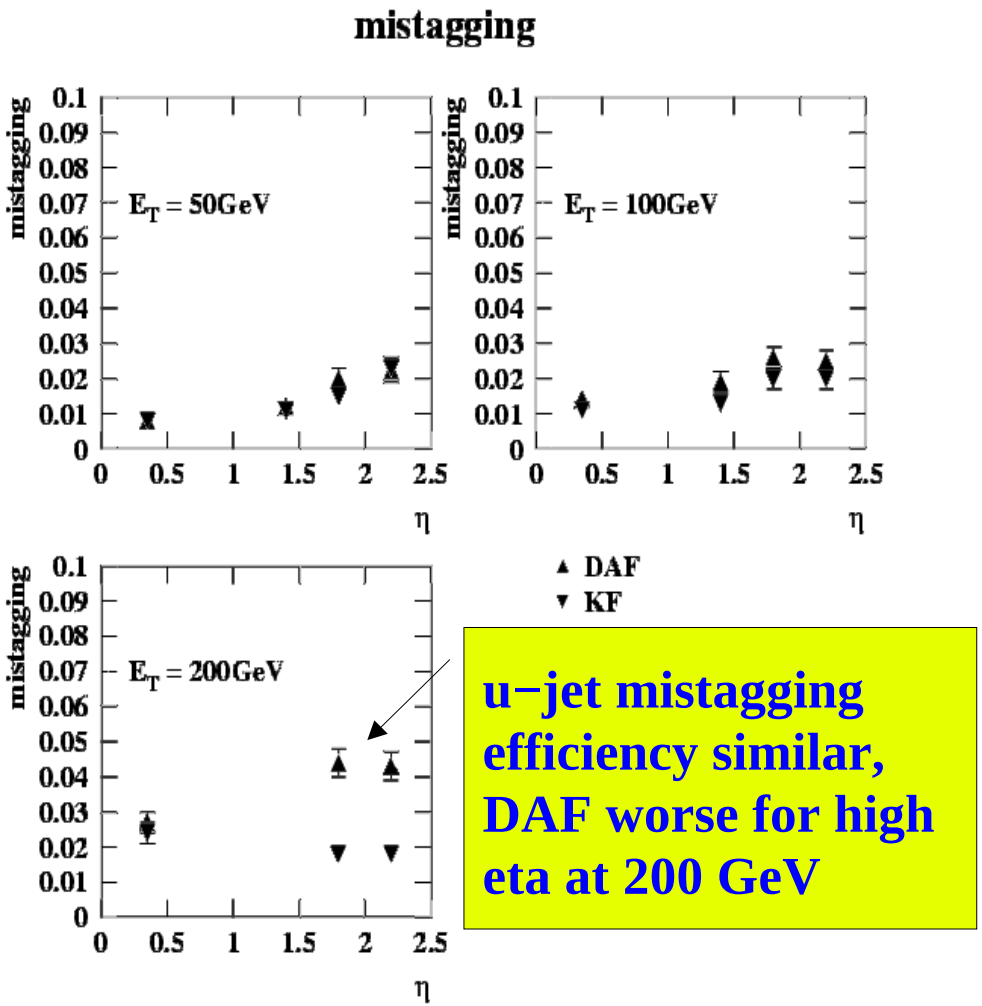
For DAF: efficiency virtually independent of energy

DAF significantly better, particularly at high energies

Study – CMS tracker

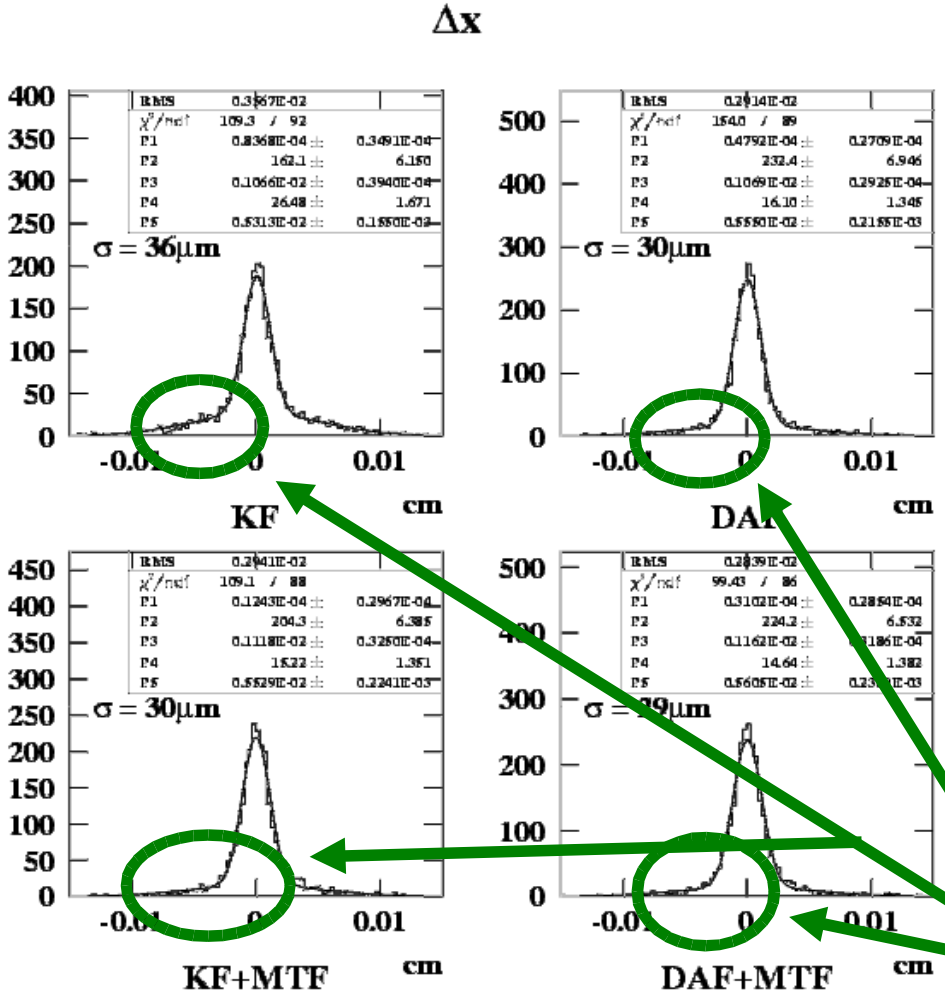


DAF better at all energies, largest gap for high energies



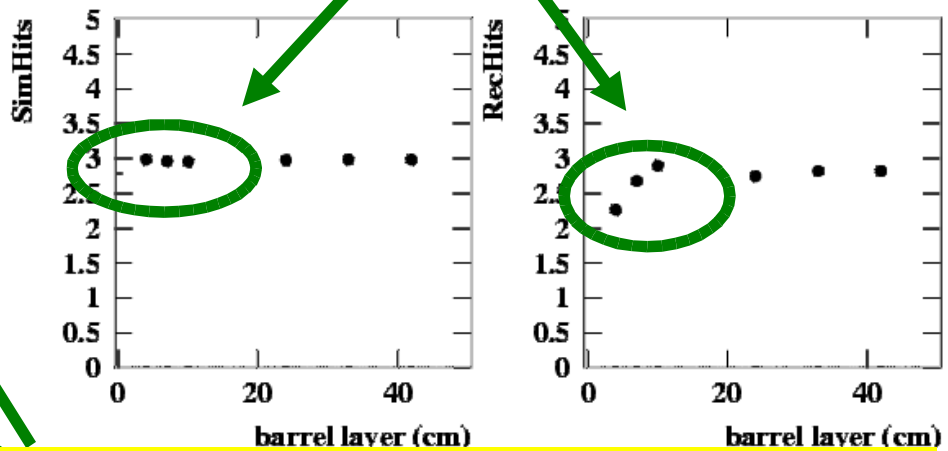
u−jet mistagging efficiency similar, DAF worse for high eta at 200 GeV

Study – CMS tracker



3–prong tau decays from heavy Higgs

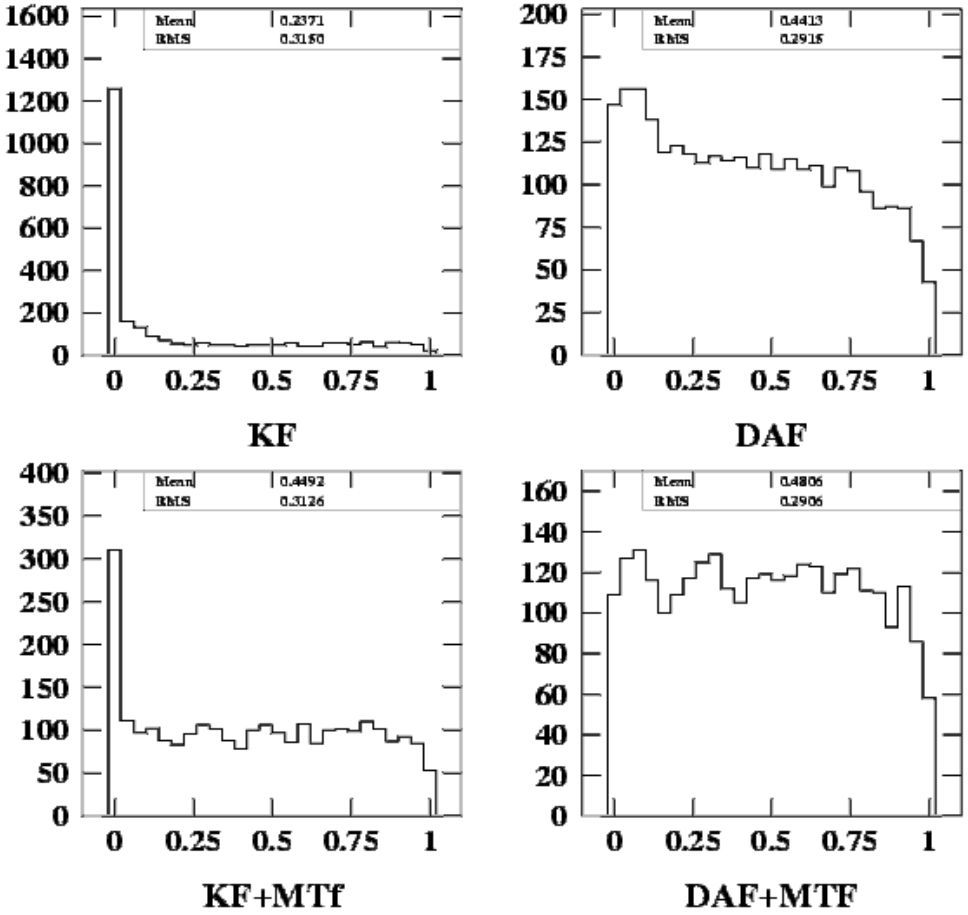
No improvement in resolution with MTF, environment not hostile enough!



Tails again reduced significantly

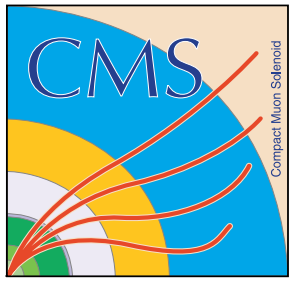
Study – CMS tracker

χ^2 probability

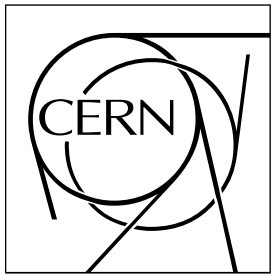


However, due to different and more correct structure of assignment weights, quality of error estimate is better with the MTF

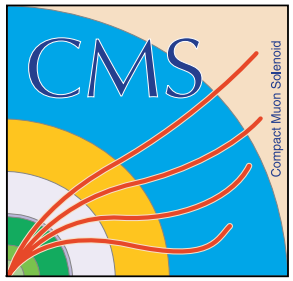
Could expect small improvement in tagging efficiency with respect to DAF (not studied yet)



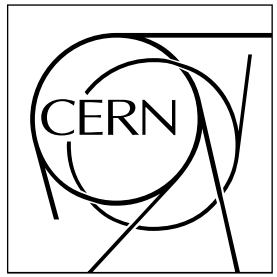
Conclusions



- **Performance of recently developed, adaptive algorithms on reconstruction problems in the CERN LHC detectors ATLAS TRT and CMS tracker has been discussed**
- **Adaptive algorithms show no gain with respect to standard algorithms in clean environments (little noise, no ambiguities, good track separation)**
- **Significant improvements can be achieved under harsh conditions, such as very high energy b−jets and narrow jets from tau decays**



References



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