Seminar on Particle and Astrophysics

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Tracking In High Multiplicity Environments

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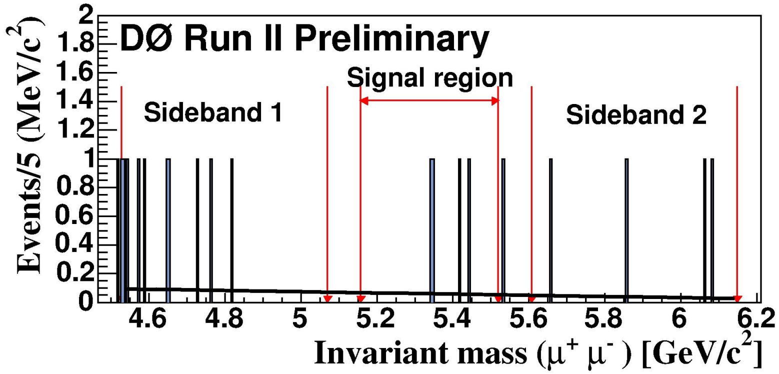
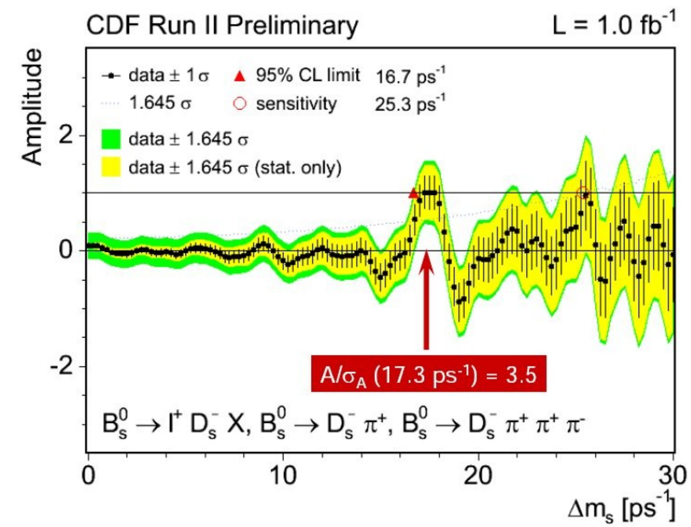
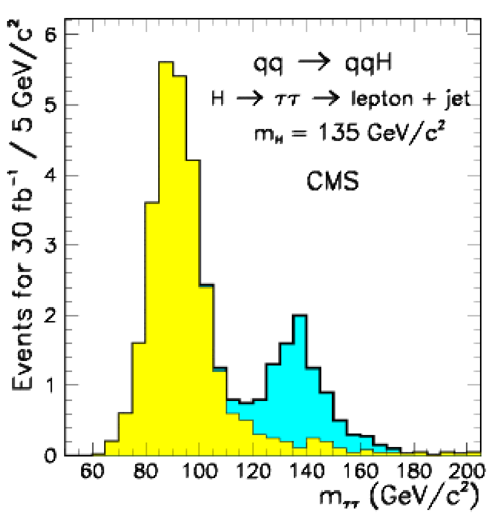
Tracking Is Everywhere



D0 upper limit on $B_s \to \mu\mu$ invariant mass resolution

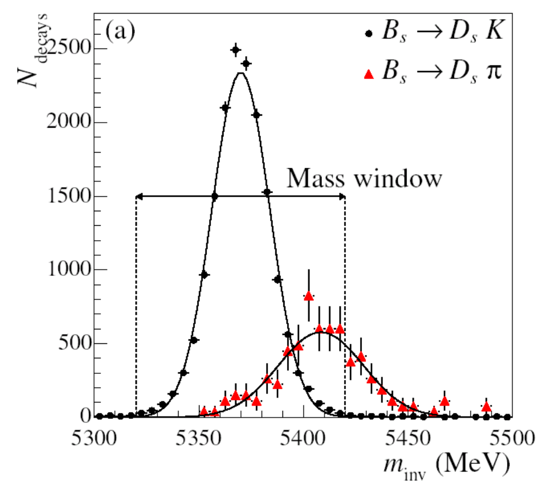


CDF measurement of B_s oscillations: B_s momentum and decay length

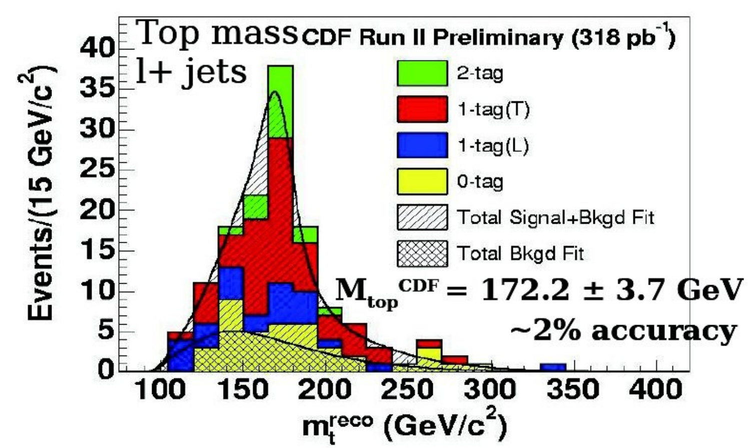


CMS simulation of $H \to \tau\tau$

τ jet, τ lifetime tagging



LHCb simulation of $B_s \to D_sK$ and $B_s \to D_s\pi$ invariant mass resolution



CDF measurement of top mass: tracking in jets, b tagging

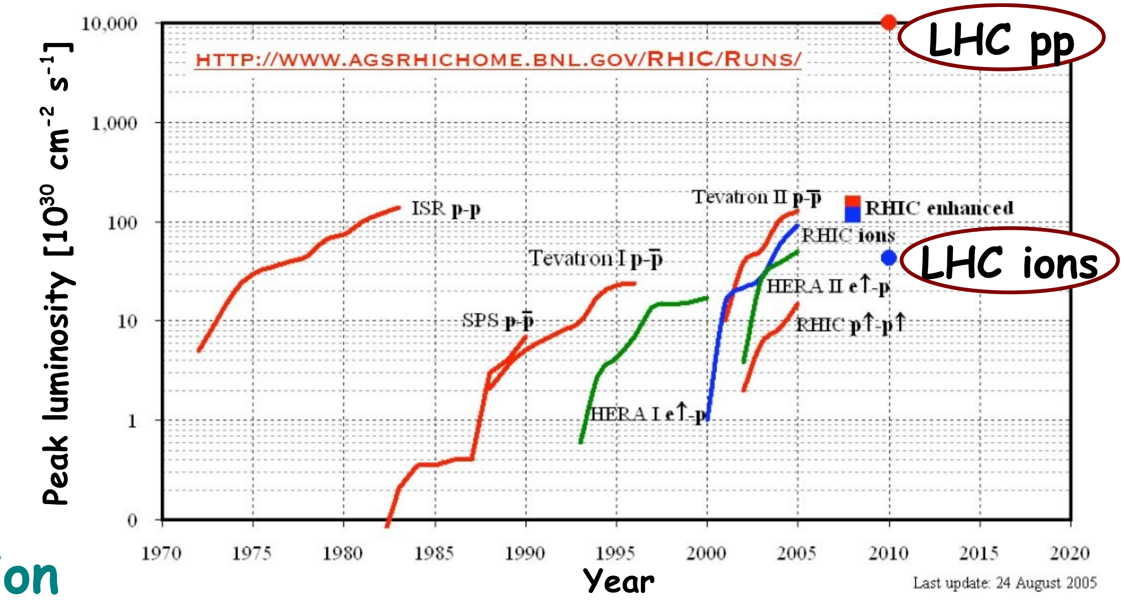
Tracking at the LHC

ATLAS/CMS (L = 10^{34} $cm^{-2}s^{-1}$)

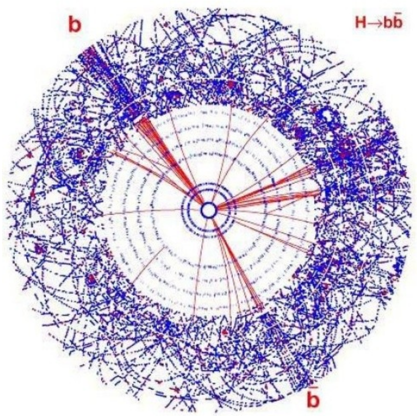
- ~ 25 pp interactions per BX
- ~ 2000 charged tracks

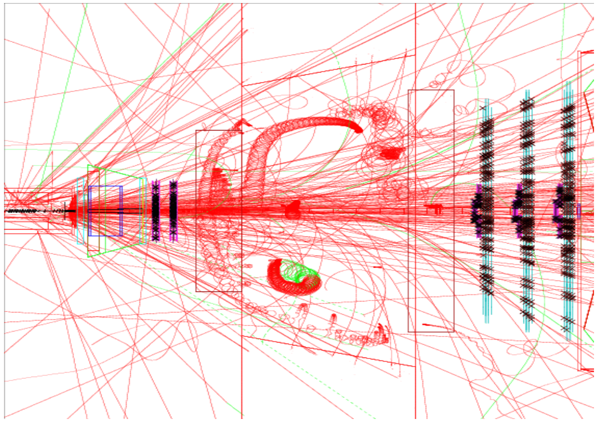
LHCb (L = 2 x 10^{32} $cm^{-2}s^{-1}$)

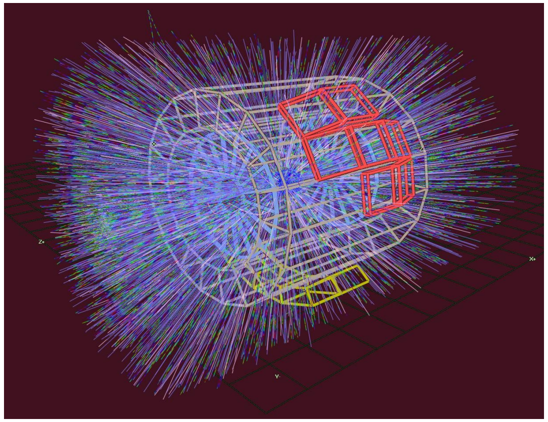
- ~ few pp interactions per BX
- ~ 100 charged tracks, mostly concentrated in forward direction



ALICE (heavy-ions, L = 2 x 10^{31} $cm^{-2}s^{-1}$): $dN_{ch}/d\eta$ ~ 1500 - 6000



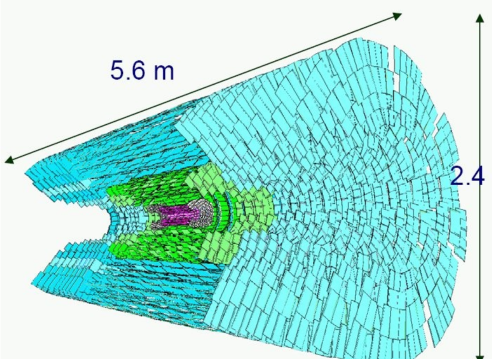




=> a daunting environment for detectors and reconstruction algorithms

Detectors

High track densities require fine readout granularity, e.g. CMS tracker



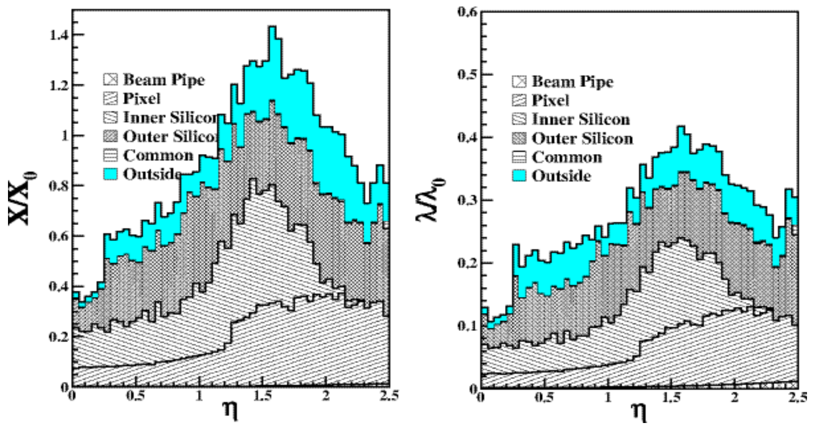
- pixel detector: 800 modules, 12k chips, 50M channels
- silicon tracker: 15k modules, 100k chips, 10M channels
- huge challenge to build, commission and maintain, some failures almost unavoidable (-> examples later)

Large particle fluences mean high radiation load, e.g. ATLAS tracker

- ionizing dose up to 50 MRad/year
- non-ionizing energy loss up to equiv. 3×10^{14} 1-MeV neutrons / cm^2 / year
- mobile phone would survive ~ 1 sec

LHC bunch-crossing frequency of 25 ns requires fast readout electronics:

- power consumption -> cooling -> material
- X_0: multiple scattering, energy loss
- Λ_0: hadronic interactions, "loss" of particles



Reconstruction Algorithms

Large number of tracks means large number of hits to process:

- computing time is an issue (especially for trigger applications)
  - need clever pattern recognition algorithms to limit combinatorial loops
  - need clever caching to gain fast access to relevant data
- ultimately: compromise between computing time, efficiency and purity

High track density can mean overlapping hits or clusters of hits, imperfect detectors mean noise hits and inefficiencies:

- need very good understanding of detector performance
  to minimise effect on reconstruction efficiency and resolution

Detector material means multiple scattering and energy loss:

- need good understanding (and description) of material distribution
  - to optimise search windows during pattern recognition
  - to optimise use of information in track fits

=> interaction between hardware people and software people crucial !

Standing on the Shoulders of Giants ...

Earlier experiments had to face “similar” challenges:

- H1 and ZEUS at HERA (ep), HERA-B (pA)
- D0 and CDF at the Tevatron ($p\bar{p}$)
- Heavy ion experiments at RHIC and the SPS

=> learn from the experience made in these experiments

Workshop on
Tracking In High Multiplicity Environments
Zürich, October 3-7, 2005

Encourage dialogue between
hardware and software experts

Transfer knowledge from
running to future experiments

TIME '05

10 invited speakers, 44 presentations, 52 participants, a.o. from

- ATLAS, CMS, LHCb, ALICE, P236, CBM
- CDF, D0, H1, HERA-B, STAR, PHOBOS

Topics covered:

- operational experience
- tracking algorithms
- tracking and vertexing
- tracking and triggering
- alignment algorithms
- radiation hardness / ageing
- new detector technologies

Programme and slides:

- http://www.physik.unizh.ch/time05, proceedings to be published in NIM A

Organisation: R.Bernhard, J.Gassner, F.Lehner, M.Needham, O.S., U.Straumann, A.Vollhardt

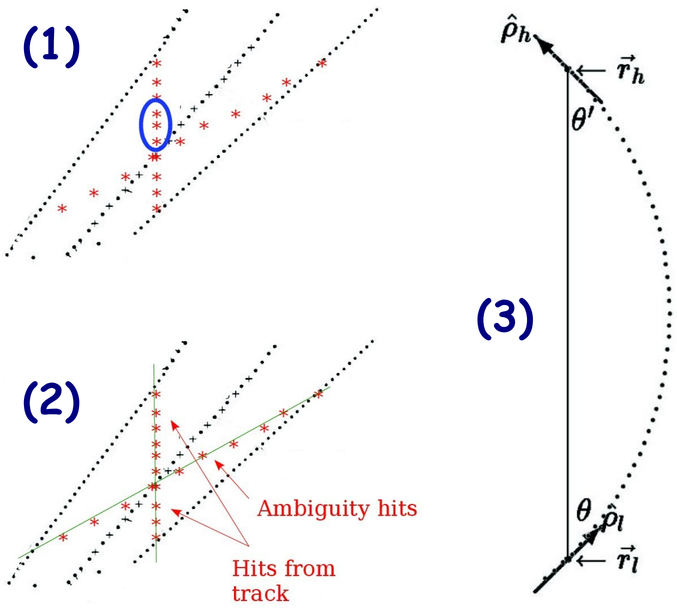
CDF Experience

<u>Run I</u> (1992-1995, up to $2 \times 10^{31} cm^{-2}s^{-1}$):

- CTC: Central Tracking Chamber
  - jet chamber geometry with 8 superlayers
- VTX: drift chamber for z measurement
- SVX: 4 layers of silicon strip detectors
- main tracking algorithm:
  - seeding in CTC superlayers (1,2)
  - linking of CTC track segments (3)
  - extrapolation into SVX, pick up hits (4)
- tracking at high luminosity suffered from
  - lack of standalone tracking capability in silicon
  - too few silicon layers, none at large radius
  - lack of 3D measurement in silicon

(1)

(2)



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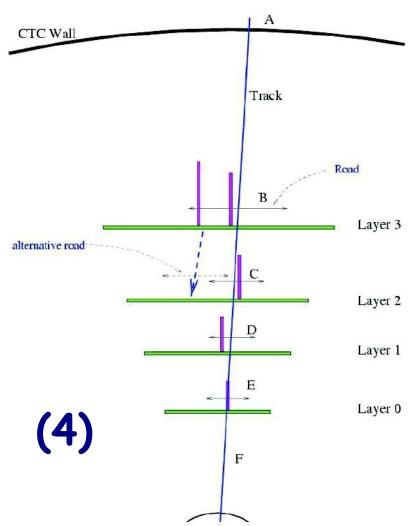

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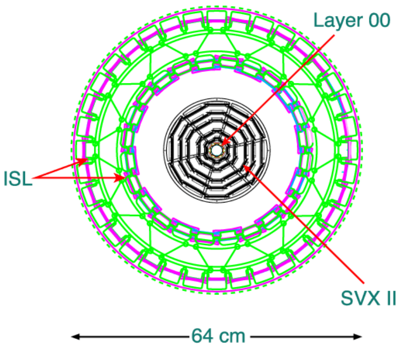
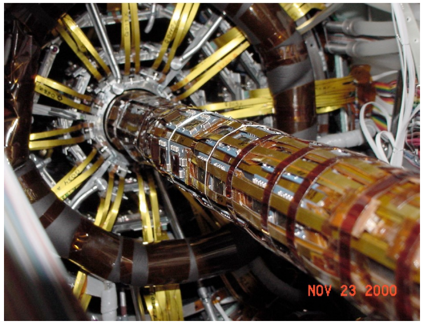
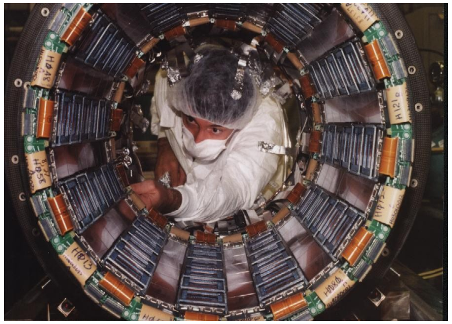
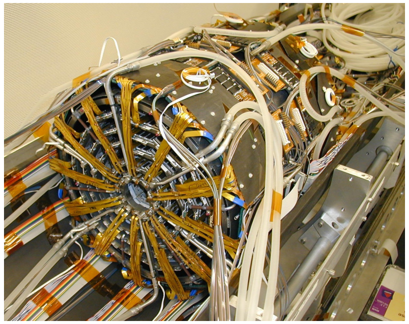
CDF Experience

<u>Run II</u> (since 2002, up to $2 \times 10^{32} cm^{-2} s^{-1}$)



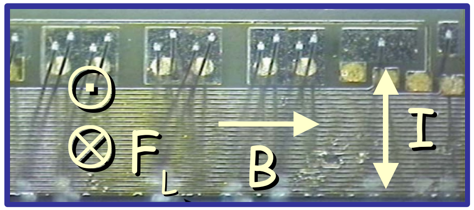






- learn from experience gained in Run I
  - 8 layers of silicon (L00, SVXII, ISL)
  - outermost layer at r = 32 cm
- add complementary tracking strategies
  - standalone silicon tracking,
  - extrapolation to COT (replaced CDC)
  - silicon seeding for displaced tracks, ...

<u>A large and complicated system -> long commissioning phase</u>

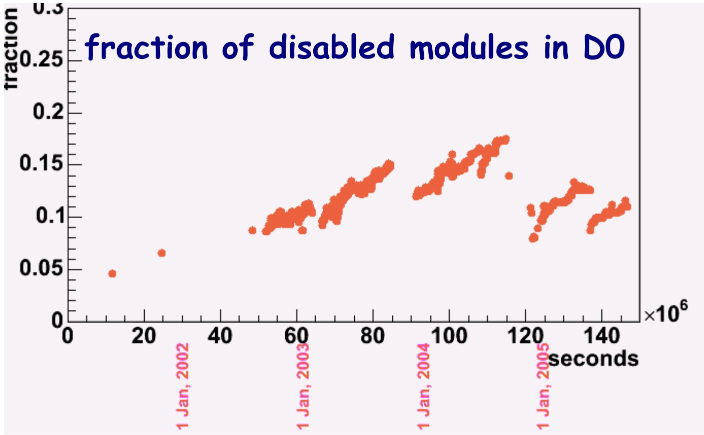


- high re-work rate on SVX ladders (double-sided silicon)
- blocked cooling pipes, breaking of wire bonds in magnetic field, radiation-induced power supply failures, ...
- now ~ 92% of ladders operational, 85% of ladders with < 1% error rate
  -> continuous and significant effort required to maintain this level

Silicon Experience

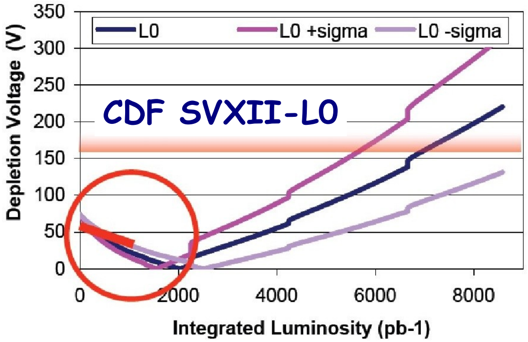
Similar experience in other experiments

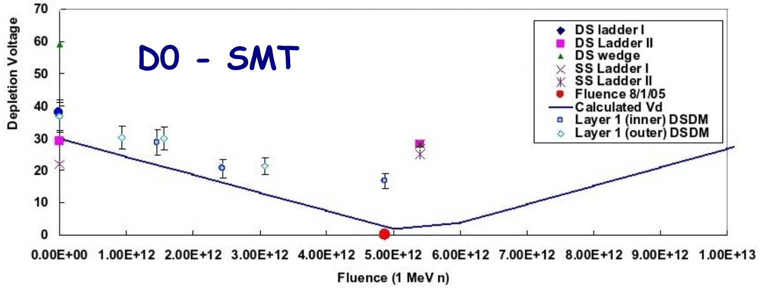
- D0: typically ~ 10% of ladders disabled
- STAR SVT (38 ladders):
  - beginning of runIII ~10% bad channels
  - at end of runIV ~ 16% bad channels



Good news: radiation damage seems well understood and predictable

- main worry: defects in silicon lattice caused by NIEL
- additional energy levels in band gap
  - causes increase of sensor leakage current
  - compensate by operating at low temperature
- change of effective doping concentration
  - causes change of full depletion voltage
  - ultimately limits lifetime of detector
- observation so far follows optimistic prediction

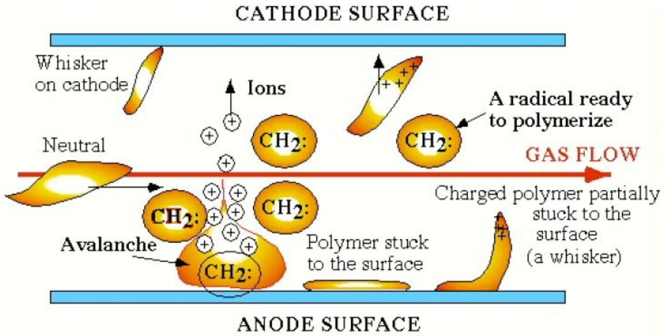


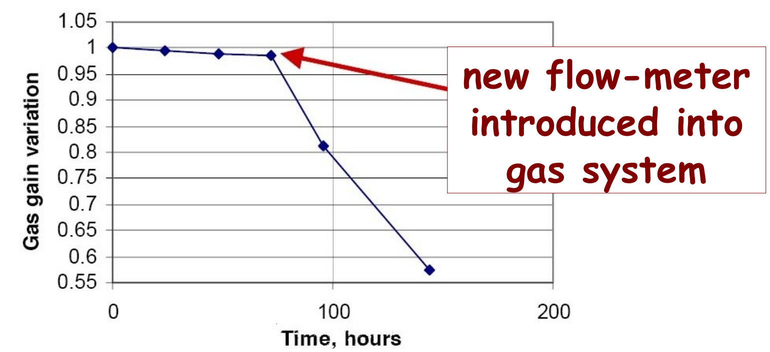


Wire Chamber Ageing

"Classical" ageing: gain loss due to formation of deposits on anode wires

- often parametrised as function of accumulated charge per cm wire length
  - at LHC expect ~ 1 C/cm per year (past experiments typically 10 mC/cm)
- extensive R&D programs, e.g. at CERN, comparison with plasma chemistry
- better qualitative understanding of process:
  - production of radicals in avalanche (CH_2)
  - polymerisation, condensation on electrodes
- long list of "do's and dont's": gas mixtures, construction materials, assembly procedures
- but: many factors involved and minor changes can cause huge effects
- ageing tests mandatory but never conclusive



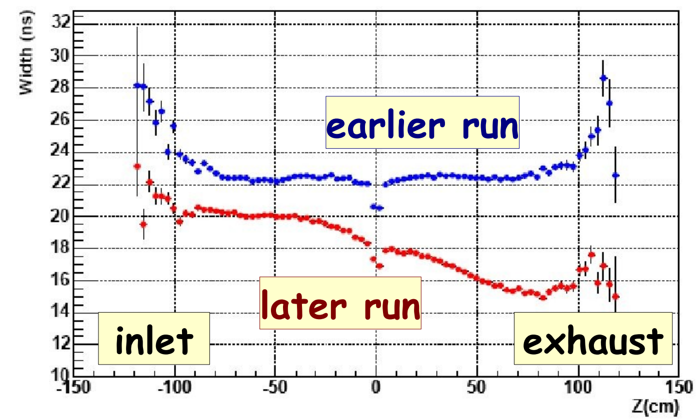


"However, despite all precautionary measures, the final answer on the radiation hardness of a detector will always have to come from the experiment." (C.Niebuhr, proc. TIME'05)

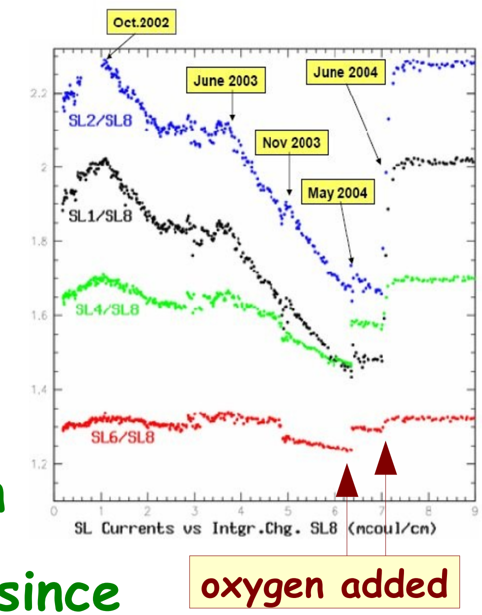
Example: CDF-COT

<u>Central Outer Tracking chamber, newly installed for RunII</u>:

- Argon/Ethane 50/50 with 1.7% Iso-propanol
- Oct/Nov 2003: definite evidence for ageing
  - gain reduction in inner vs outer layers
  - more pronounced at gas exhaust than at inlet
  - more pronounced below beam pipe than above



- evidence for deposits, mainly C and H, chemical bonds mainly CH and CC
  - increase gas-flow to remove radicals more quickly ?
  - increase temperature to inhibit condensation ?
  - change of gas mixture (e.g. Ar/CO_2, Ar/CF_4) ?
- (accidental) addition of oxygen during maintenance
  - observe rapid and complete recovery of gas gain
- hypothesis: O_2 combines with CH_2, inhibits polymerisation
- now running with 100 ppm of O_2, no evidence for ageing since



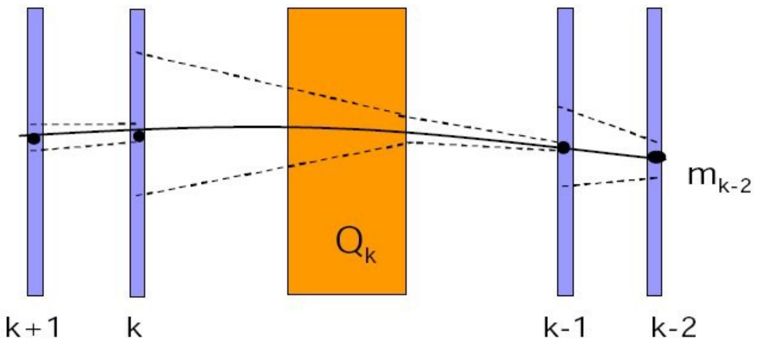
Track Finding

Global methods: find all tracks in parallel, use all hits at the same time

- histogramming methods (e.g. Hough transform)
- neural nets (e.g. Hopfield network), cellular automata

Local methods: find tracks sequentially, using subsets of hits (need a seed)

- track road, track following
- Kalman Filter: recursive method for simultaneous track finding and fitting
  - alternating propagation and update steps, starting from a track seed
  - use current knowledge of track parameters to propagate candidate to next layer
  - search for compatible hits in that layer, add the closest hit (χ^2) to the candidate
  - update track parameters and iterate
  - very popular but as such not good enough for high track density



Extentions of Kalman Filter

Combinatorial Kalman Filter: build up a tree of candidates for each seed

- starting from a set of seeds, extrapolate all candidates to the next layer
- for each candidate, create a new "branch" with each compatible hit
  - in addition, create one branch with a missing hit (inefficiencies)
- cleanup after each iteration: drop branches with too many missing hits, or too bad overall χ^2, and branches that are subsets of other branches
- final cleanup: select the best branch for each seed (χ^2, number of hits)

Adaptive Filters: introduce competition between the candidates

- same basic strategy and cleanup procedure as for CKF
- define for each candidate i and hit j a weight $$w_{ij} = \frac{\exp(-\chi^2_{ij}/2)}{\sum_j \exp(-\chi^2_{ij}/2) + \exp(-\chi^2_{cut}/2)}$$
- "hard" assignment: accept hits with w_{ij} above a cut
- "soft" assignment: apply cut on w_{ij} and use w_{ij} as a down-weighting factor

Extentions of Kalman Filter

Deterministic Annealing Filter: iterated Kalman Filter with annealing

- do not build candidate tree but use all hits compatible with extrapolation
- initialise all hits with a low weight and set an initial temperature T
- then iterate:
  - forward filter, using current weights
  - backward filter, using current weights
  - form weighted mean of forward and backward filter ("smoother")
- at each detection layer, calculate compatibility χ_j^2 of hit j with the smoothed track candidate and update the current weights according to

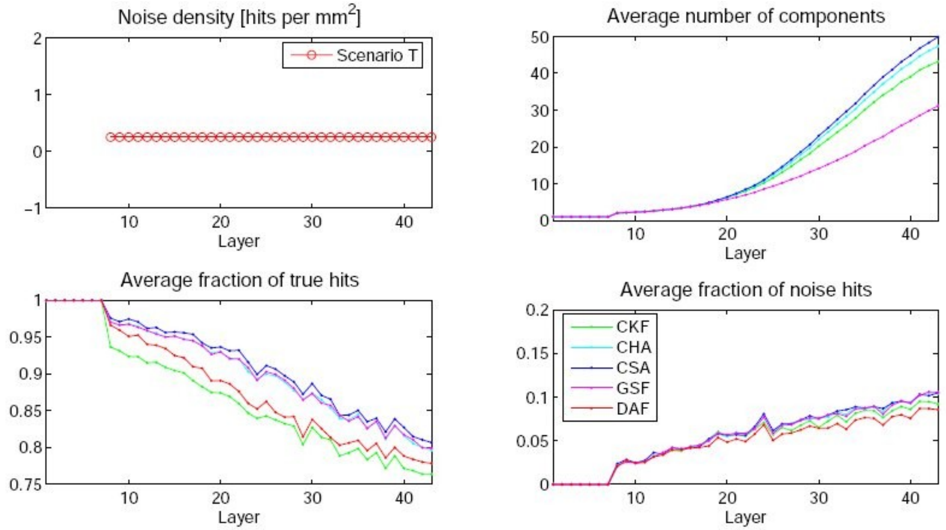
$$w_j = \frac{\exp(-\chi_j^2/2T)}{\sum_j \exp(-\chi_j^2/2T) + \exp(-\chi_{cut}^2/2T)}$$

- after each iteration, lower the temperature T
- stop after a few iterations with temperature T = 1

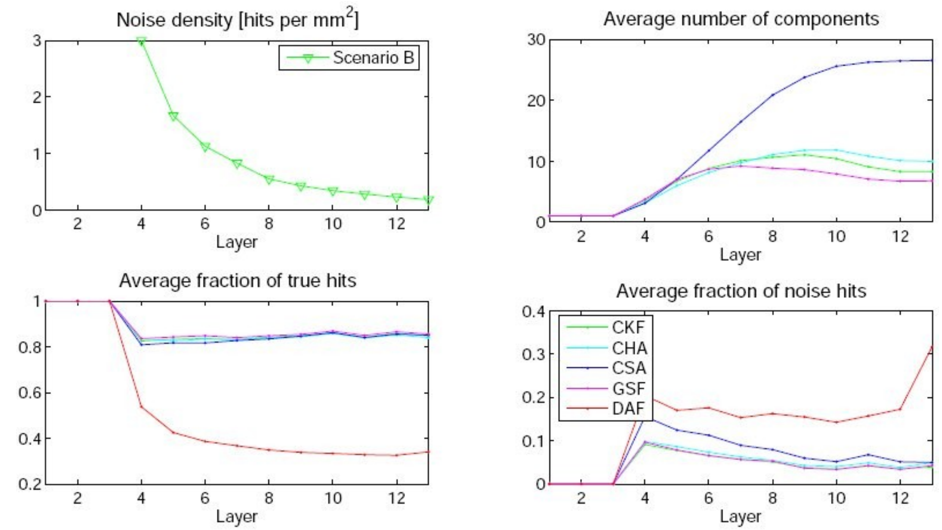
Comparison of Methods

Series of simulation experiments: (Frühwirth and Strandlie)

- two toy experiments, similar to CMS tracker and ATLAS Inner Detector
  - magnetic field, detection layers, resolutions and material budget
- generate 2500 events:
  - one track with p_T = 10 GeV plus "noise" hits to simulate underlying event
  - various scenarios for density distribution of noise hits
- just two out of many examples:



ATLAS: seeds from 7 silicon layers

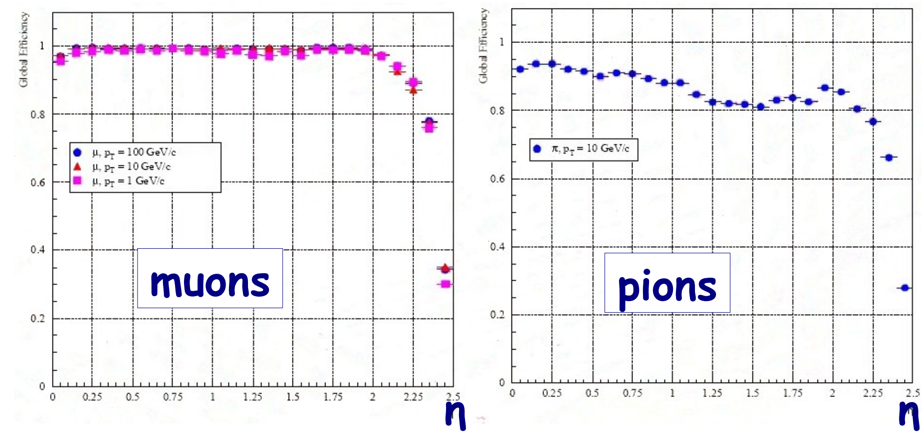


CMS: seeds from 3 pixel layers

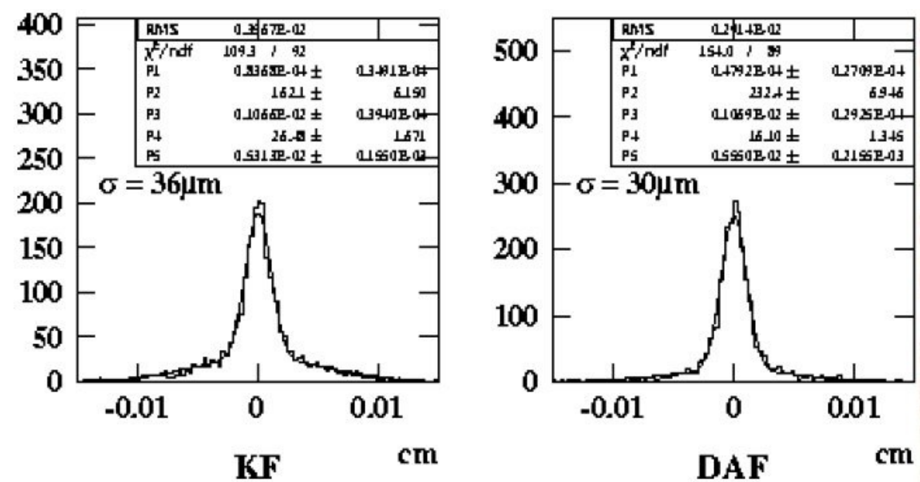
CMS Tracking Study

Combinatorial Kalman Filter in Silicon Tracker (seeds from Pixels)

- efficiency close to 100% for muons
- but only 80-90% for pions
  - due to hadronic interactions
  - 10-20% of pions disappear before leaving 8 hits in Silicon Tracker



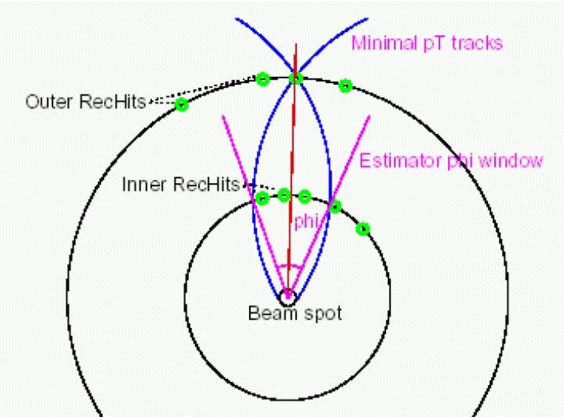
- efficiency in high-density environment (e.g. core of 100 GeV/c jet) close to single-track efficiency (within few %)
- but under extreme conditions observe significant gain from fancier methods
  - example: τ-jets from $H^0 \rightarrow \tau^+\tau^-$
  - Combinatorial Kalman Filter (KF)
  - Deterministic Annealing Filter (DAF)



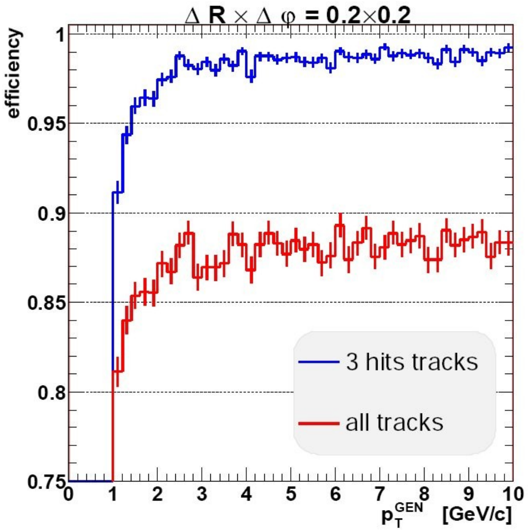
Transverse impact-parameter resolution

CMS Tracking Study

Seeding: based on triplet-search in three Pixel layers (at r = 4, 7, 10 cm)



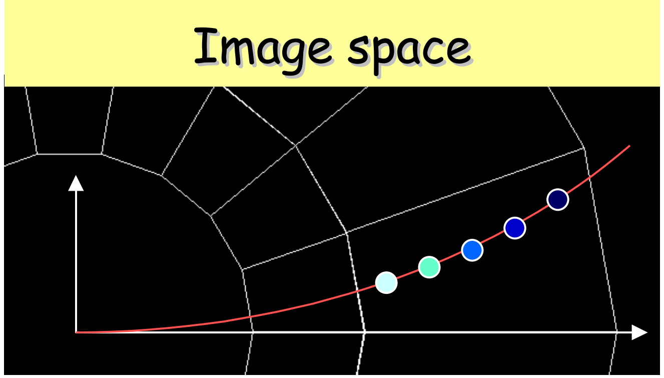
- demand compatibility with interaction region
  - typically 1-2 mm in radius, ±15 cm in z
- demand minimum transverse momentum
  - defines search window in azimuthal angle φ
- demand that within η acceptance
  - defines search window in r/z
- three 3D points: determine all 5 track parameters
- close to 100% efficiency if track has three hits
- but: 10% of tracks leave hits in only two layers
  - purely due to geometrical acceptance
  - detector inefficiency not taken into account
- to recover these 10%, have to do doublet search
  - very CPU intensive (20-30.000 pairs at 10^{34} $cm^{-2}s^{-1}$)
  - worse quality seed: track parameters much less well constraint

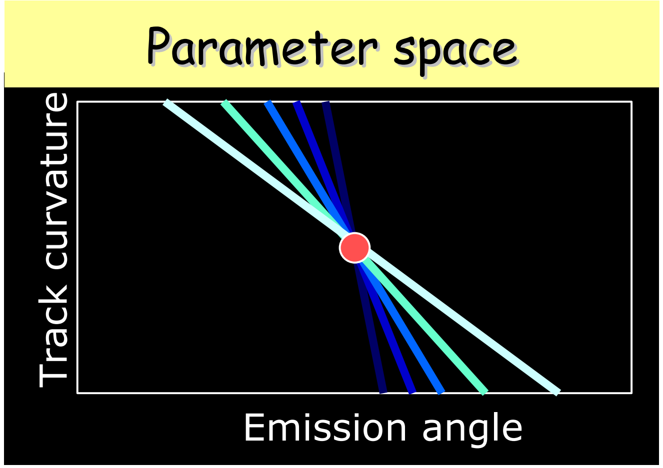


Hough Transform

Global histogramming method:

- transform hit information from "image space" (measured positions) to "parameter space" (track parameters compatible with hit positions)
- hits belonging to the same track form clusters in the parameter space
- binning of parameter space -> histogram
- find peaks in histogram -> track candidates
- bin size determines efficiency / resolution but also computing time





- advantage: fast and highly parallelisable -> ideal for trigger applications
- limitation: fast only if parameter space one- or two-dimensional -> only very simple track models (e.g. straight line or circle)

ALICE TPC

Fast Hough Transform for HLT tracking:

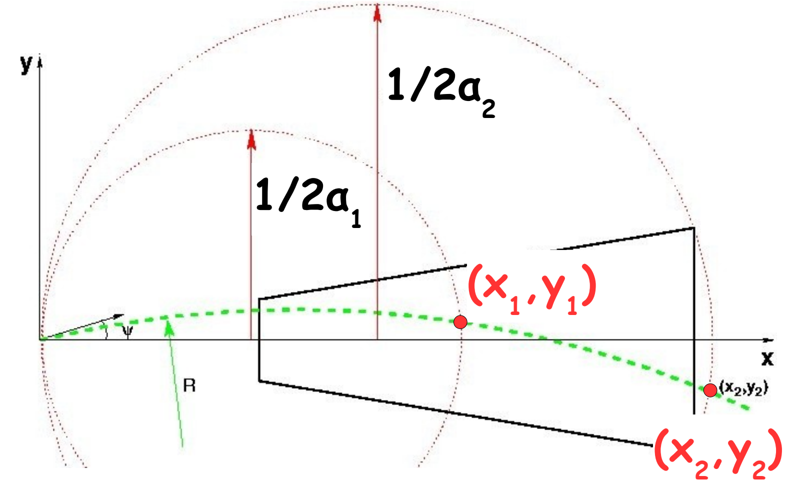
- consider only tracks from primary vertex, neglect energy loss and multiple scattering, divide data into slices in pseudo-rapidity
  -> 2D tracks, described by circles in x,y
- conformal mapping of image space:

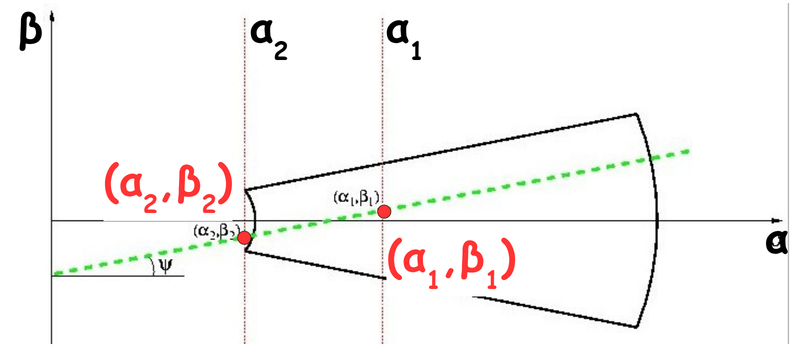
  $$x,y \rightarrow \alpha = x/(x^2+y^2),\ \beta = y/(x^2+y^2)$$

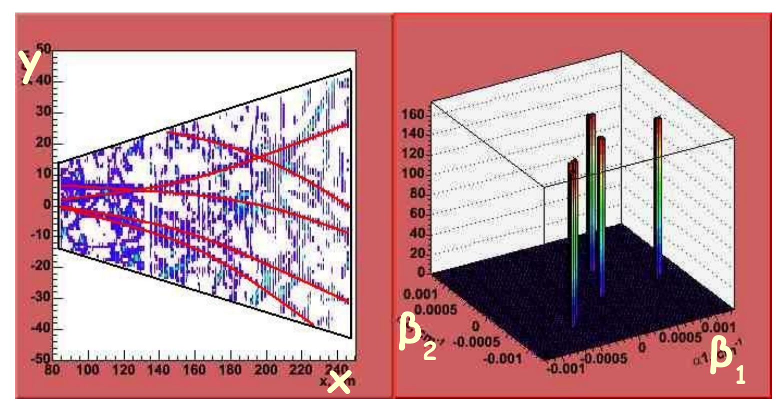
  -> tracks are straight lines in α,β
- parameter space: fix two values α_1,α_2
  -> tracks defined by intersections β_1,β_2
- performance for 80 (β_1) x 120 (β_2) bins:
  - efficiency > 95%
  - pT resolution ~ few %

  } for dN/dη < 8000

  - fake track rate < 2% up to dN/dη < 4000







Track Fitting

Track fit should provide:

- optimal track parameters and covariance matrix at both ends of track
  -> for physics analysis (vertex) and extrapolation into other detectors
- overall χ^2 of the track to test quality of pattern recognition
- the χ^2 for each hit on the track to permit outlier selection and removal

Methods:

- simple least squares fit with ideal track parametrisation (e.g. helix)
  -> fast, but not good enough in presence of multiple scattering
- global track fit (e.g. describe trajectory by $n \times n$ covariance matrix)
  -> computing time grows with n^2-n^3, too slow if number of hits n large
- Kalman Filter: add measurements one by one, improving track parameters and covariance matrix at each step -> computing time $\propto$ n
  -> incorporate multiple scattering as process noise
  -> second path needed to obtain track parameters at both ends of track

“Broken Line” Fit

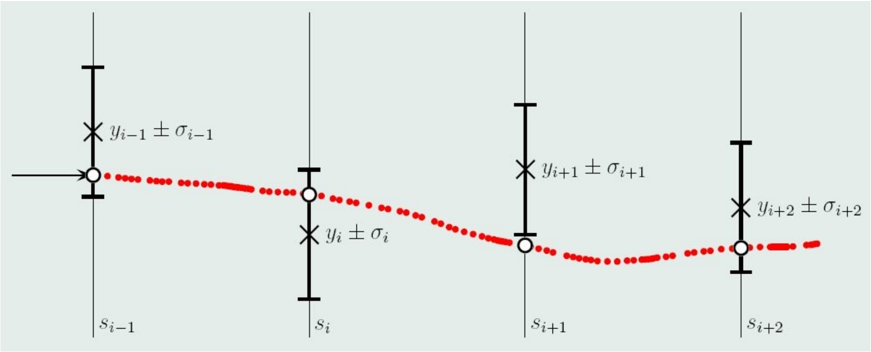
New proposal for a fast global fit (Volker Blobel):

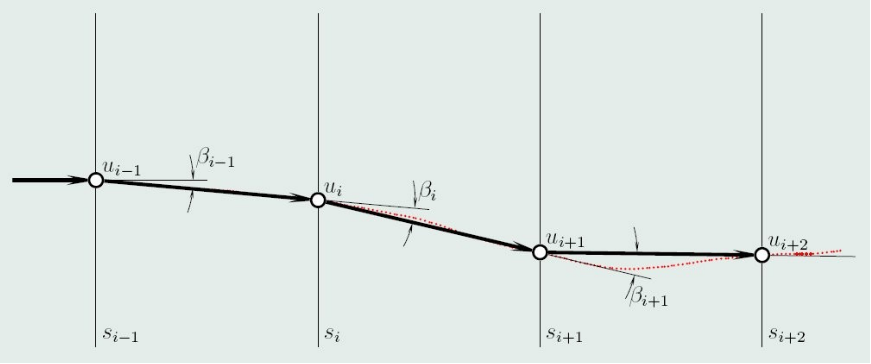
- perform LS fit to an ideal track model to get rough estimate of momentum
- model track by broken lines between detection planes, determine intersection points u_i and “kick angles” β_i in a LS fit
- assume B = 0 for now -> kick angles β_i:
  - have expectation value zero
  - have variance given by m.s. theory
  - are (to good approximation) given by

$$\beta_i \approx \frac{u_{i-1}}{s_i - s_{i-1}} + \frac{u_i\,(s_{i+1}-s_{i-1})}{(s_{i+1}-s_i)(s_i - s_{i-1})} + \frac{u_{i+1}}{s_{i+1}-s_i}$$

- perform LS fit by minimising function:

$$S(u) = \sum_{i=1}^{n} \frac{(y_i - u_i)^2}{\sigma_i^2} + \sum_{i=2}^{n-1} \frac{\beta_i^2}{\sigma_{\beta,i}^2}$$





s_i = positions of detection planes
u_i = particle intersection points
β_i = kick angles
y_i = measured coordinates
σ_i = measurement errors

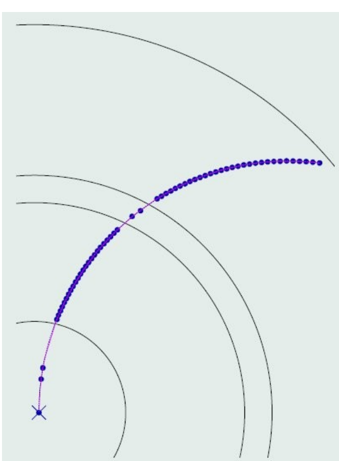
“Broken Line” Fit

- find the u_i that minimise $S(u)$:
  solve the normal equations $C \cdot u = r$
- C is sparse $n \times n$ matrix: non-zero elements only in a narrow band around the diagonal

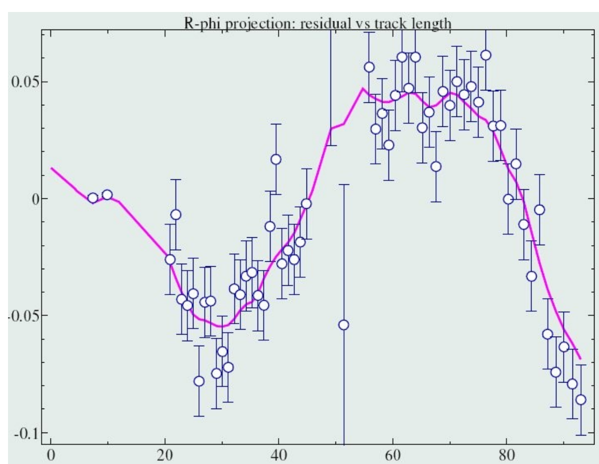
$$C = \begin{pmatrix} C_{11} & C_{12} & C_{13} & & \\ C_{21} & C_{22} & C_{23} & C_{24} & \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} \\ & C_{42} & C_{43} & C_{44} & C_{45} \\ & & C_{53} & C_{54} & C_{55} \\ & & & & \ddots \end{pmatrix}$$

- fast algorithms exist for inverting the matrix: computing time $\propto n$
- with magnetic field: have to take track curvature into account
  -> expectation value of “kick angles” no longer zero
  -> complicates equations somewhat, but not too much

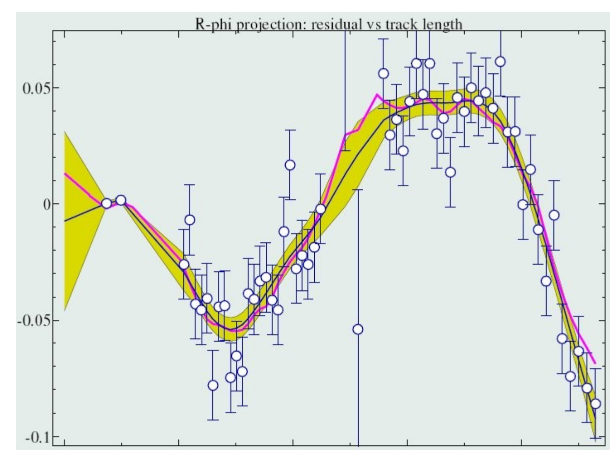
in toy Monte Carlo
~ 6 times faster than
Kalman Filter



circle fit



broken lines fit



TIME for Conclusions

Olaf's main lessons:

- detectors are complex systems, they will never be perfect
  -> build sufficient redundancy into the system
  -> algorithms must be able to cope with missing information
- a good understanding (and modelling) of detector performance is crucial for tuning algorithms and getting the most out of the available information
  -> material distribution, cluster shapes, overlapping clusters ...
- many different tracking algorithms are available or have been proposed
  - encourage parallel developments within the collaboration
  - for specific physics / detector problems
  - competition leads to better algorithms
- tracking in high multiplicity environments IS a real challenge, but ...

"... there is confidence that good ... strategies will be available at the time when they will be needed." (V.Blobel, proc. TIME'05)

Hungry for more ?

Obviously, this could only be a very brief and superficial overview:

- strongly biased by my own interests
  (and the selection of the papers I had to review)
- said nothing at all about several topics discussed at the workshop
  (e.g. vertexing, triggering, new detector technologies)

If you want to learn more, have a look at:

- slides from all presentations, on our web page:
  http://ckm.physik.unizh.ch/time05
- proceedings, submitted to Nucl Instr and Meth, should soon appear on:
  http://www.sciencedirect.com/science/journal/01689002