HERA-B

HERA B

Reconstruction of Multiple-Interaction Events

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Institute Seminar, Zeuthen, 7-Jan-98

HERA-B Challenges

Hardware:

- New detector technologies
- Complexity & size
- Radiation hardness
- Rate capability
- Alignment
- Readout
- DAQ
- Triggering

Software:

- Complexity
- Detector material
- Track/Hit densities
- Online reconstruction (farm)
- Distributed code development
- Dedicated reconstruction techniques

Outline

- CP violation
- HERA-B detector
- Reconstruction concept
- Methods & performance
  - Track Reconstruction
  - RICH
  - Muon System
- Summary

Note: all performance figures are preliminary

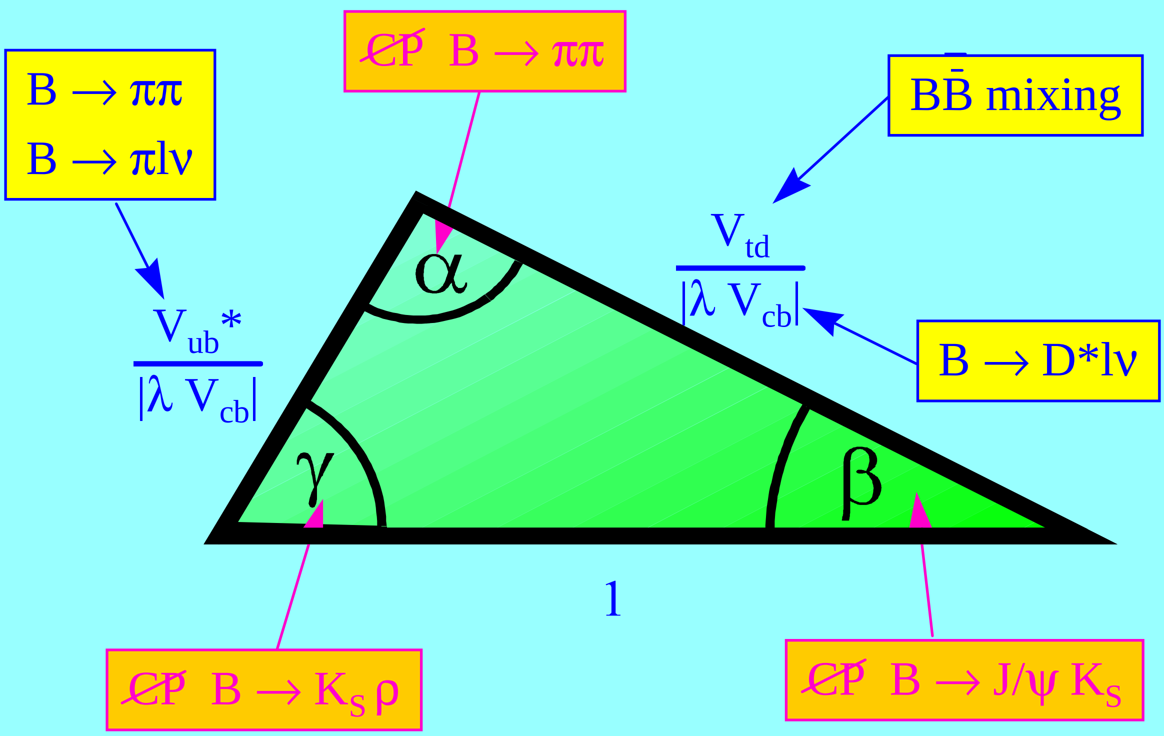
Weak Flavour Mixing

Charged hadronic current (V-A structure)

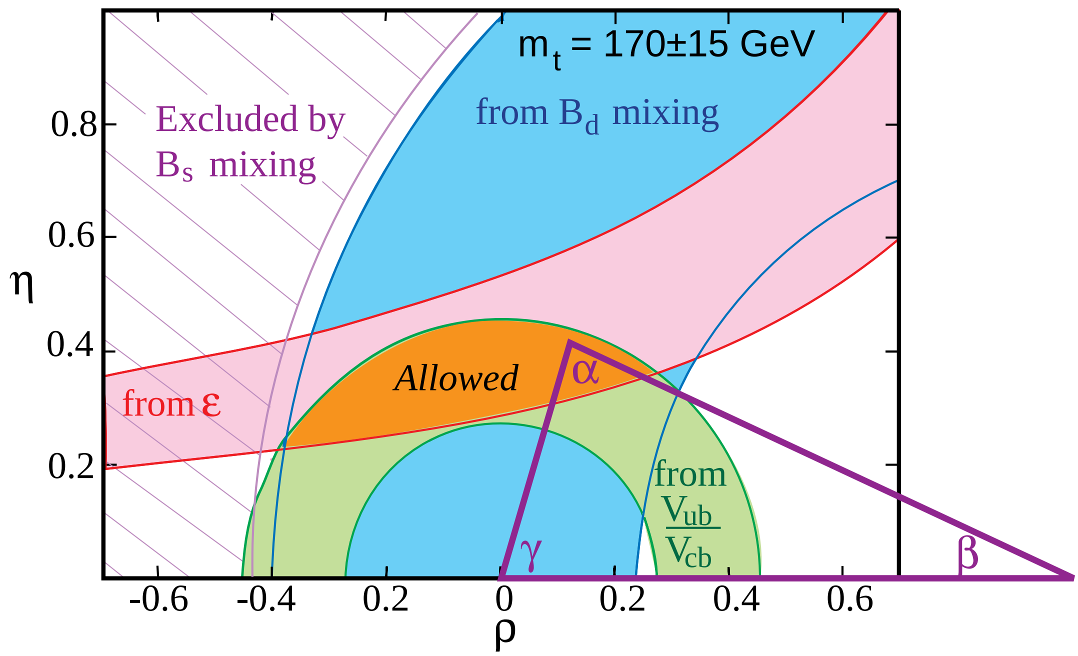
$$\sim \left(\bar{u},\bar{c},\bar{t}\right)_L \gamma_\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{td} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

CKM matrix (Cabbibo-Kobayashi-Maskawa)

Unitarity Triangle

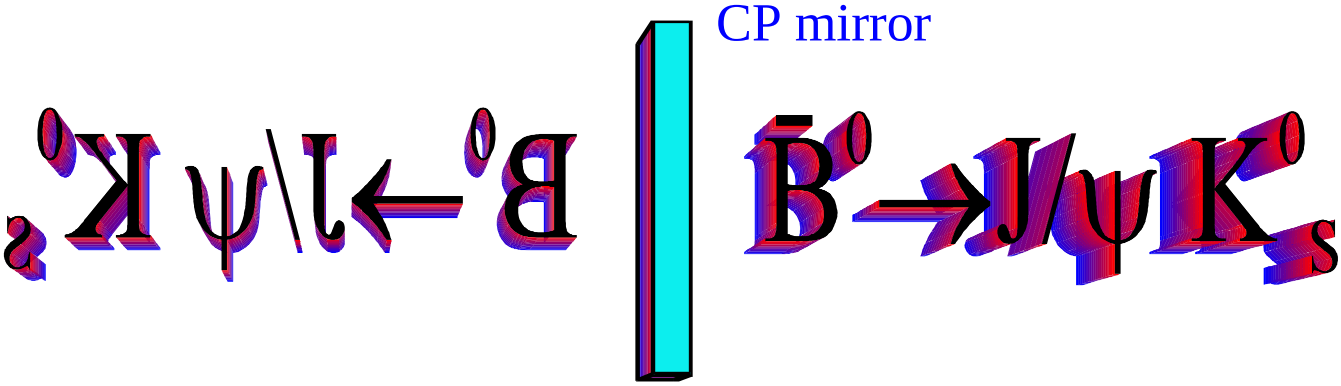


Status of the Unitarity Triangle



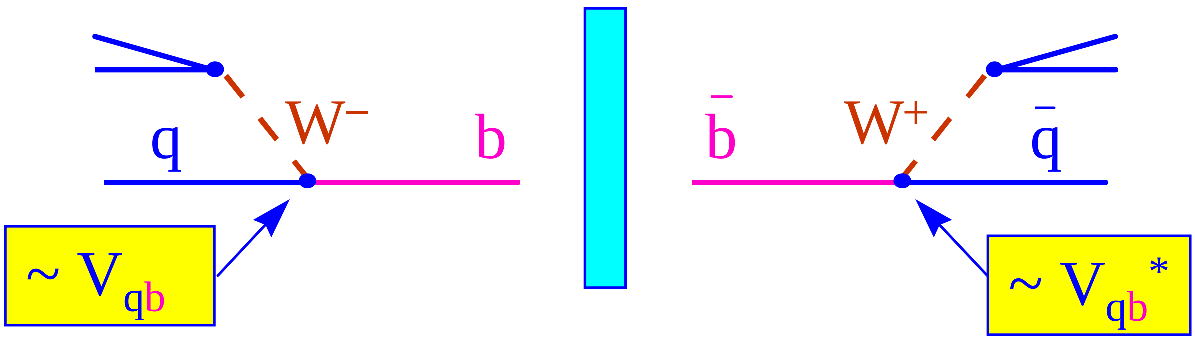
- $V_{ub} = A\lambda^3(\rho - i\eta)$
- $V_{td} = A\lambda^3 (1 - \rho - i\eta)$
- CP-violating $K^0 K^0$ mixing ($\rightarrow \varepsilon$):
  - $V_{cd} = -\lambda - A^2\lambda^5(\rho + i\eta)$
- non-degenerate triangle ($\eta > 0$) likely, but not certain

~~CP~~ in the B system?



$\Gamma(B^0 \rightarrow f) \neq \Gamma(\bar{B}^0 \rightarrow f) \rightarrow$ **CP violation**

~~CP~~ in the standard model:

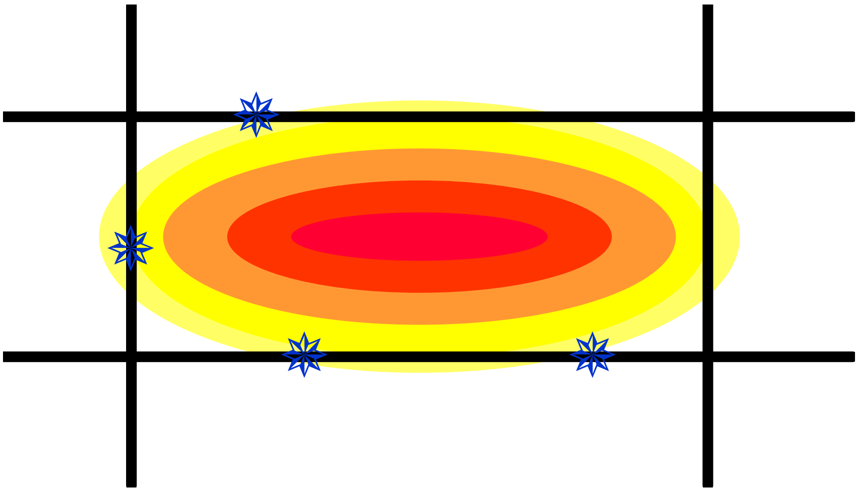


CKM phase measurement: Interference between $b \rightarrow c$ transition amplitude and $\mathbf{B^0\bar{B}^0}$ mixing amplitude.
"Golden decay mode" $B \rightarrow J/\psi K^0_S$

$$\frac{N(B^0 \rightarrow f) - N(\overline{B^0} \rightarrow f)}{N(B^0 \rightarrow f) + N(\overline{B^0} \rightarrow f)} \sim \sin\left[\arg \frac{V_{td} V_{cb}}{V^*_{td} V^*_{cb}}\right] \sim -\sin 2\beta$$

HERA-B: a hadronic B Factory

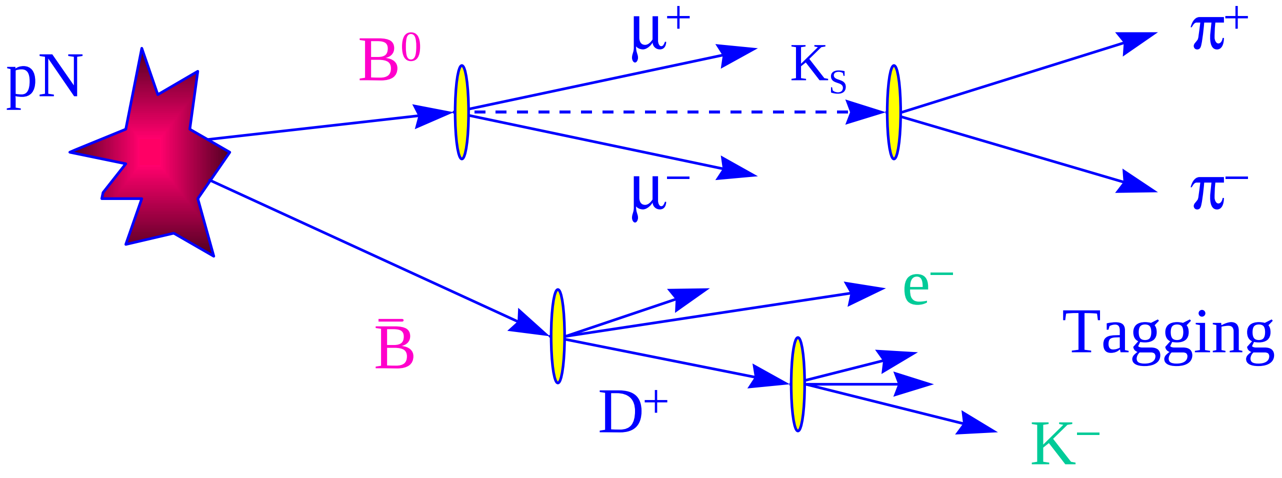
- Idea: convert the HERA proton ring into a B factory
- suspend wire target in halo of proton beam



- 40 MHz interaction rate possible without disturbing the other HERA experiments
- 820 GeV protons → huge Lorentz boost → forward spectrometer
- $\sigma_{bb} / \sigma_{inel} \sim 10^{-6}$

  → 4…5 superimposed interactions

Principle of the (dedicated) Hadronic B Factory



Determination of B initial state:

$\bar{B}$ $\rightarrow e^- \ldots, \mu^- \ldots$ Lepton tag

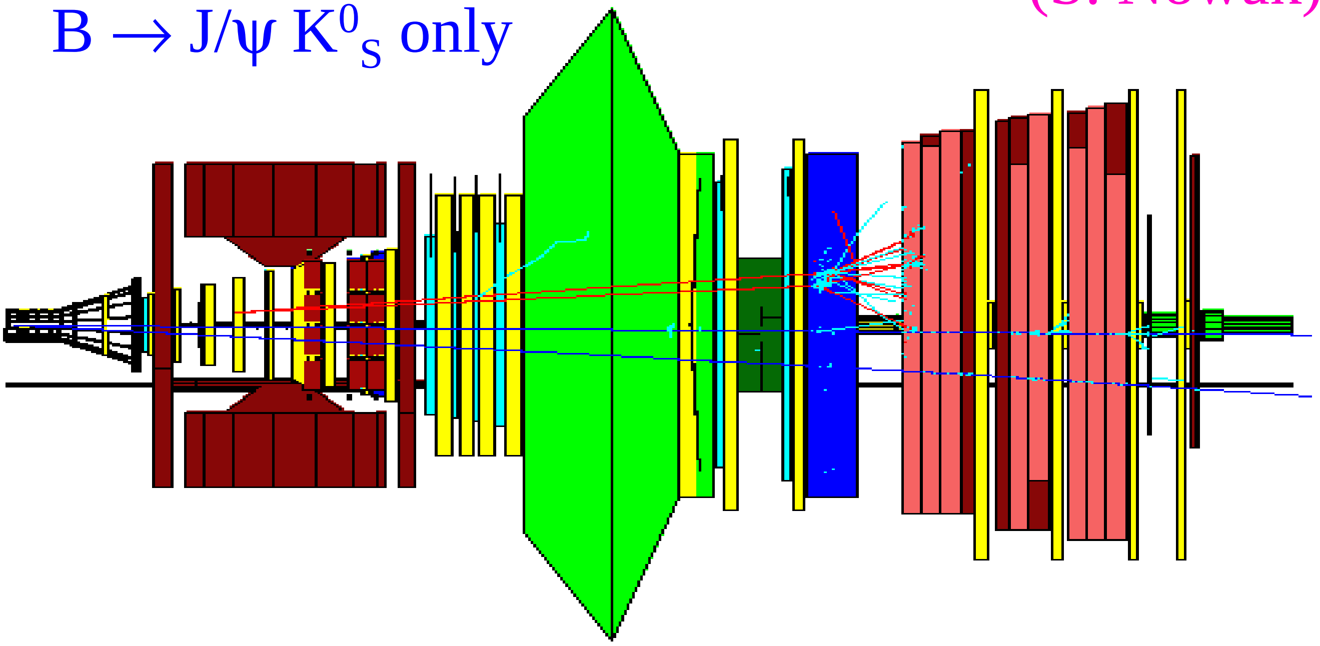
$\rightarrow K^- \ldots$ Kaon tag

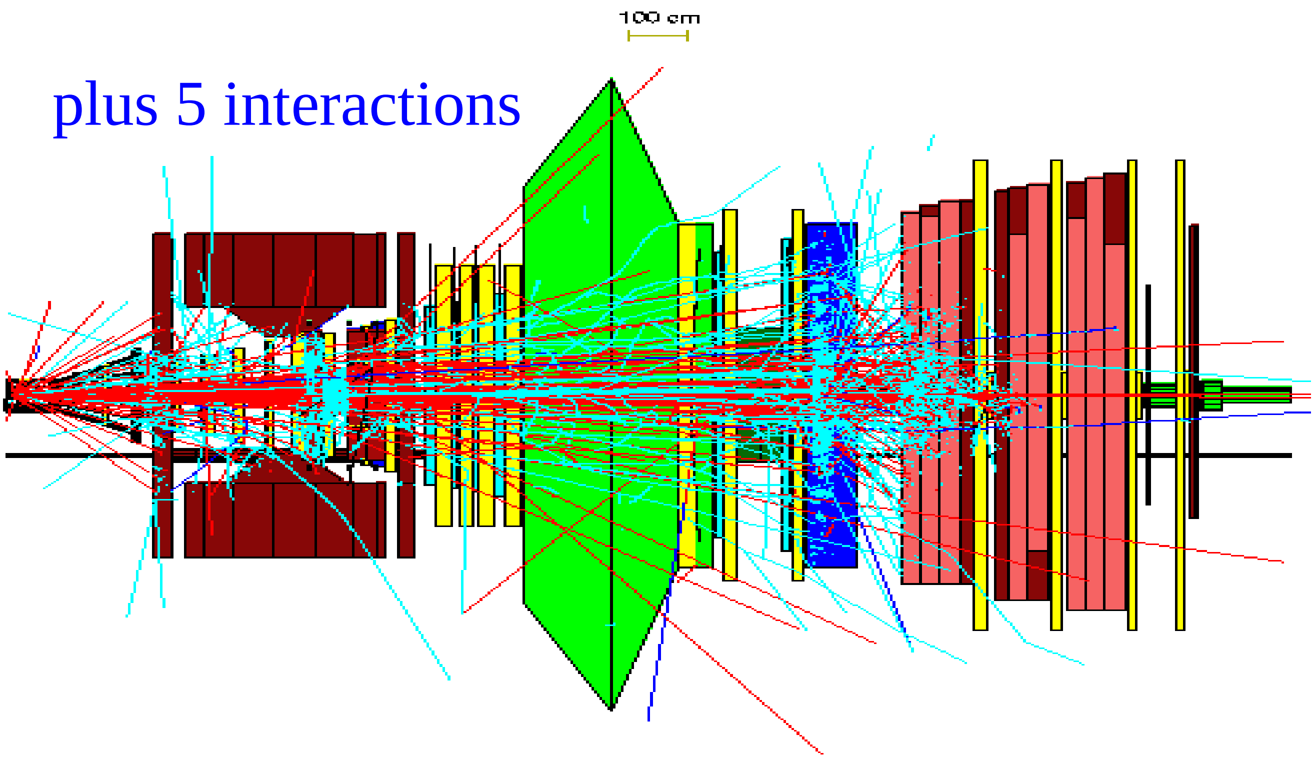
- → Forward spectrometer
- → excellent track and vertex reconstruction
- → particle identification (e, μ, K/π)

The Detector Simulation

(S. Nowak)

$B \rightarrow J/\psi\ K^0_S$ only





plus 5 interactions

The Detector Simulation (cont'd)

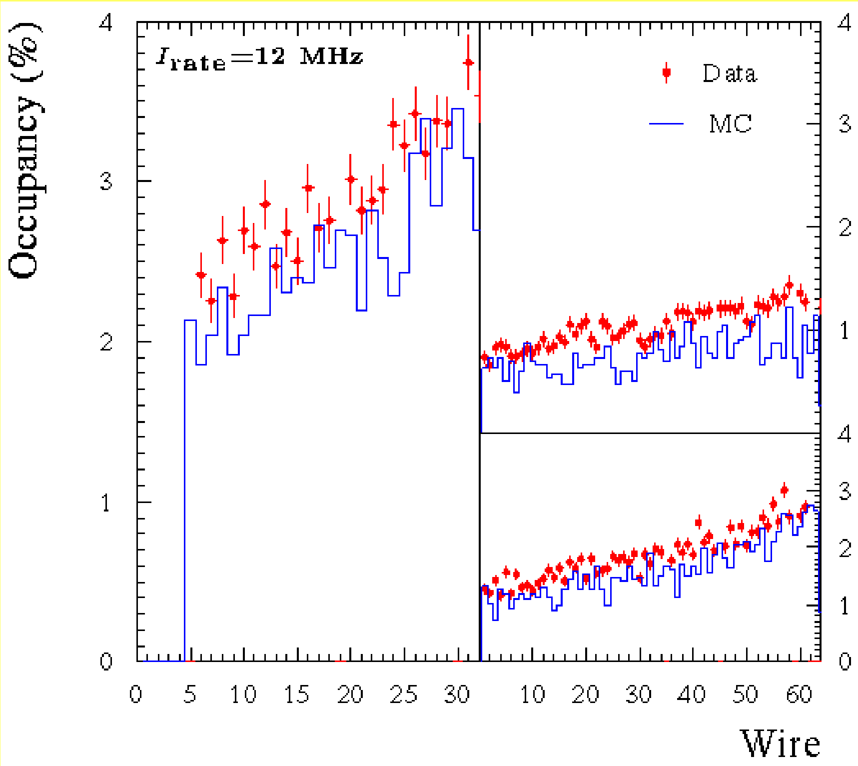
- crucial for detector design & SW development
- based on Geant 3.21
- ~18000 detector volumes
- integrated into HERA-B software frame
- common geometry definition for simulation and reconstruction

<u>Testrun 1997:</u>

OT occupancy compared to HBGEAN

→ agreement data/MC within 10…15%

→ similar for other devices



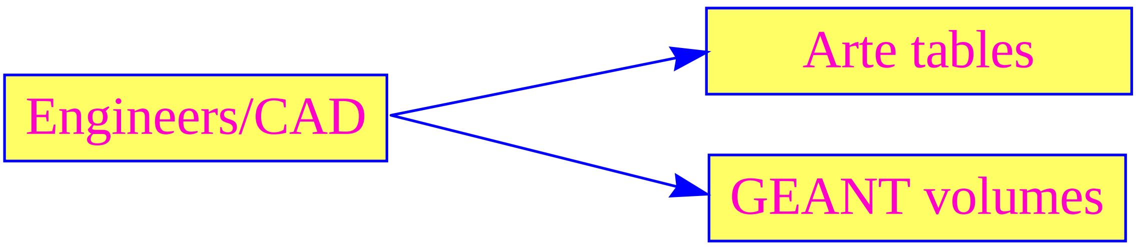
Geometry Generation (OT)

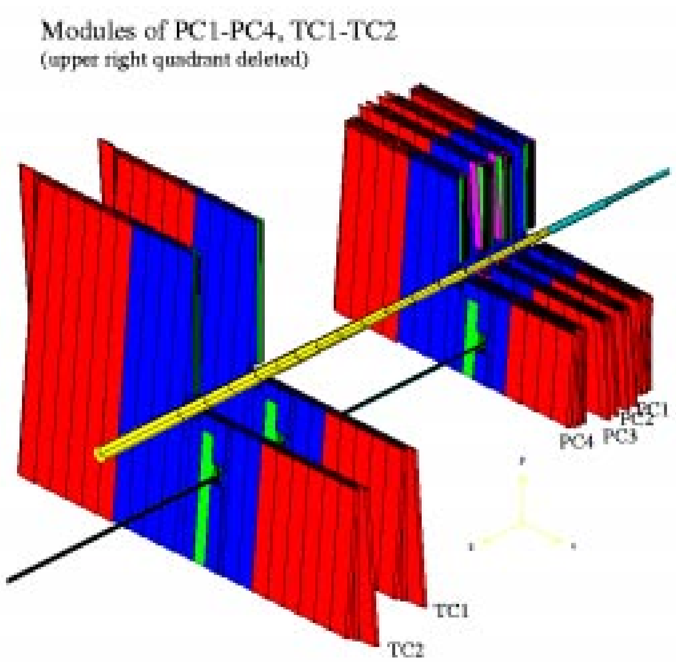
A. Lanyov

<u>Example: Outer tracker</u>

- Geometry constants for O(1000) outer tracker modules needed

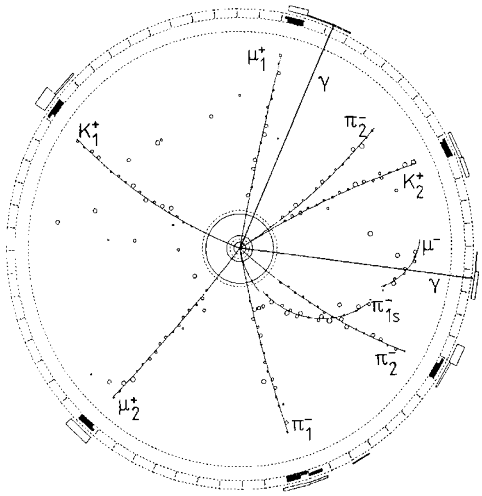
→ automatic conversion from engineer's data sheets to experiment data model





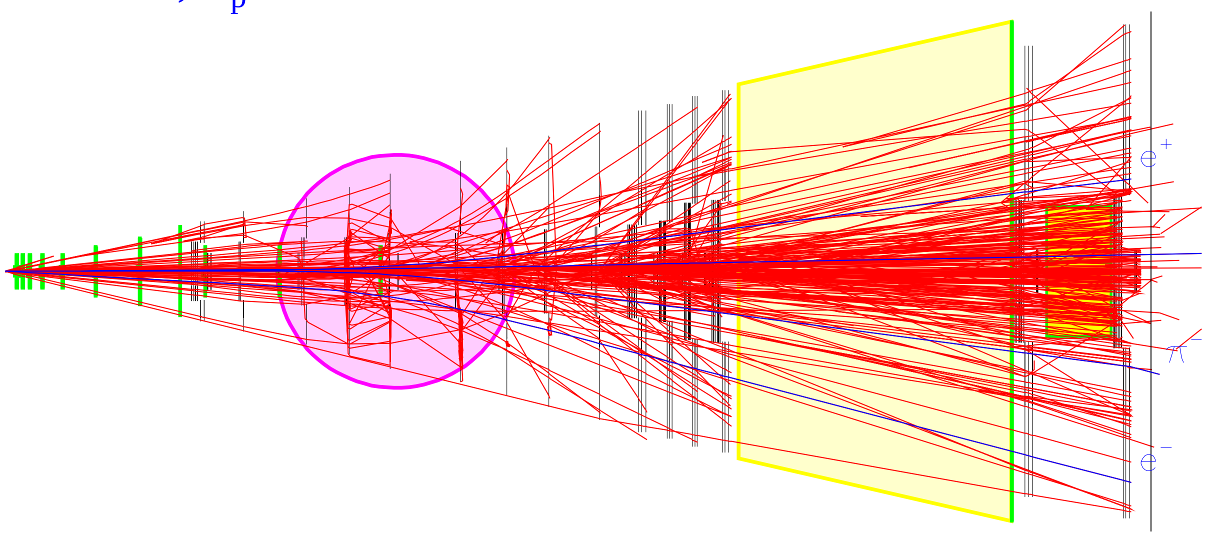
Comparing Event Topologies

ARGUS/CLEO, √s = 10.45 GeV



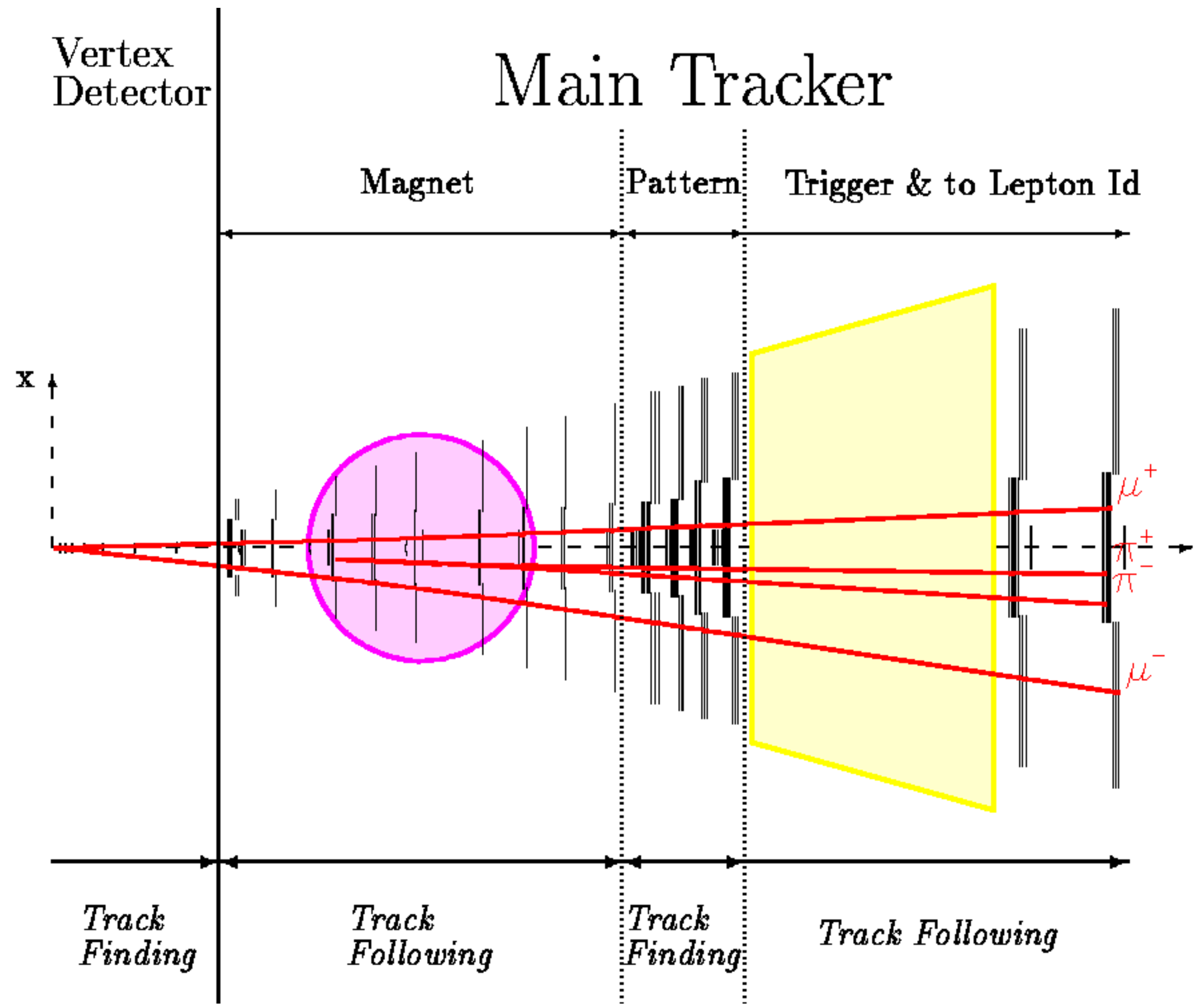
LEP, √s = 90 GeV

HERA-B, E_p=820 GeV



→ high demands on event reconstruction!

Track Reconstruction Concept

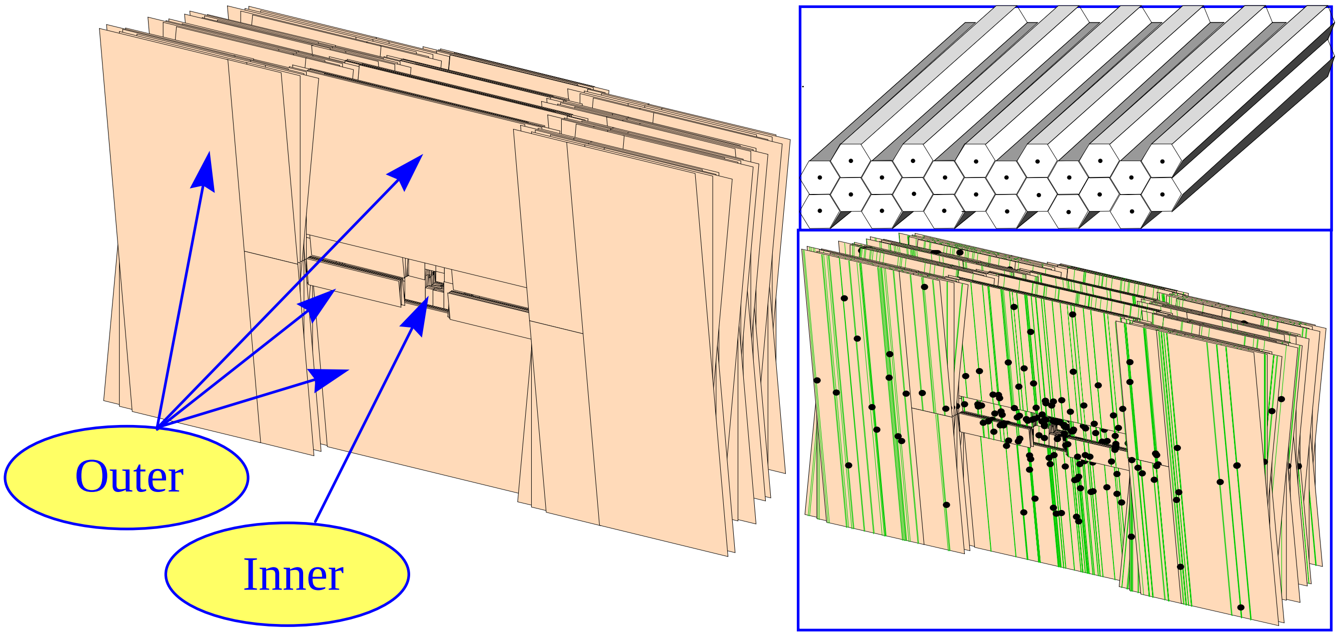


- Magnetic field very inhomogeneous
  →start pattern recognition in field-free area
- "Pattern tracker" = field-free area of main tracking system

The HERA-B Main Tracker

- **Outer tracker (d>20cm):**
  - Honeycomb Drift Chambers (75 µm Pokalon-C)
  - ∅ 5 and 10 mm
  - resolution < 200 µm
  - peak occupancy < 20 %

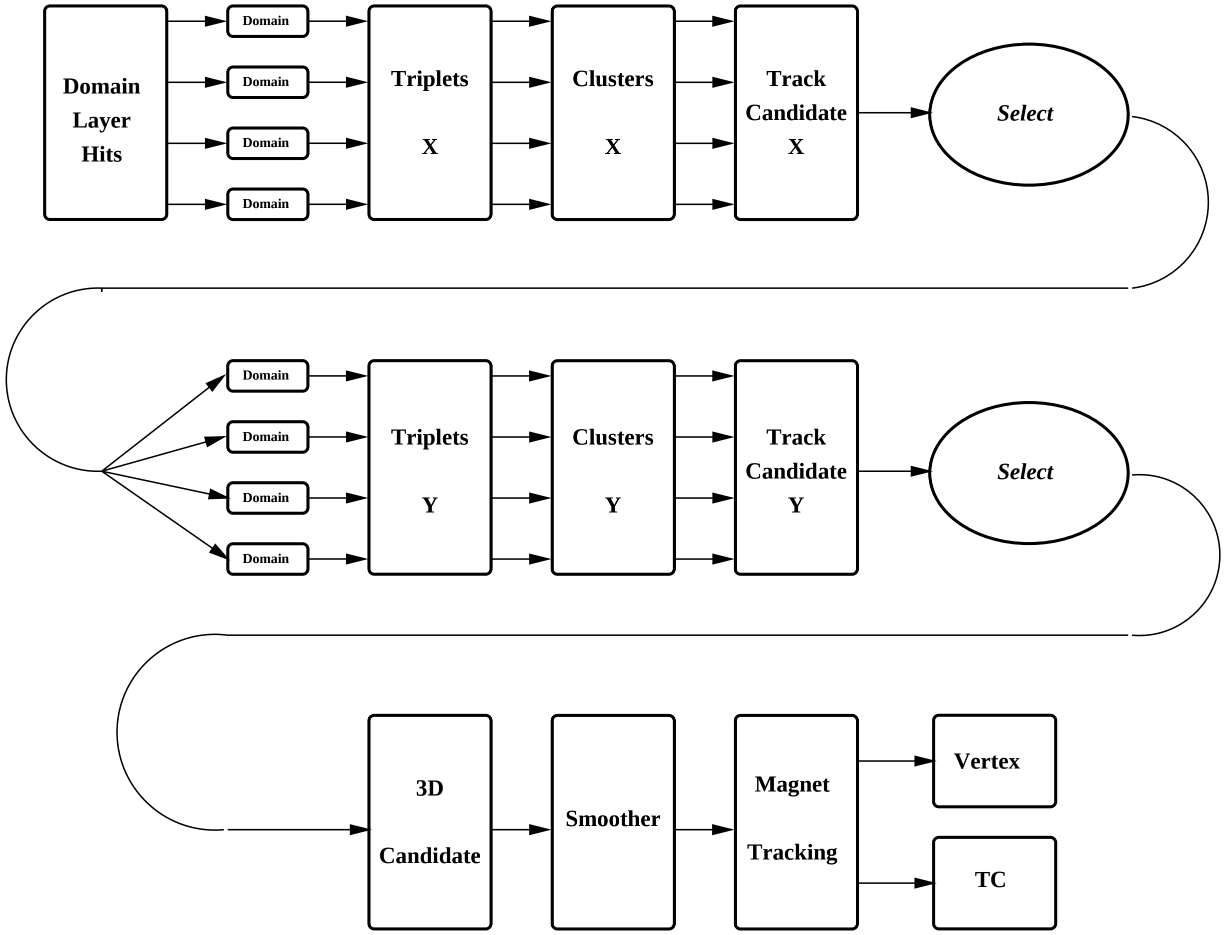
stereo angles 0°, ±5°



- **Inner tracker (6cm < d < 20cm):**
  - Micro-Strip Gaseous Chambers (MSGC)
  - Pitch 300 µm
  - resolution < 80 µm
  - peak occupancy ~ 3 %

Pattern Recognition

- complicated geometry
- mix of different detector technologies
- high occupancy, frequent track overlap

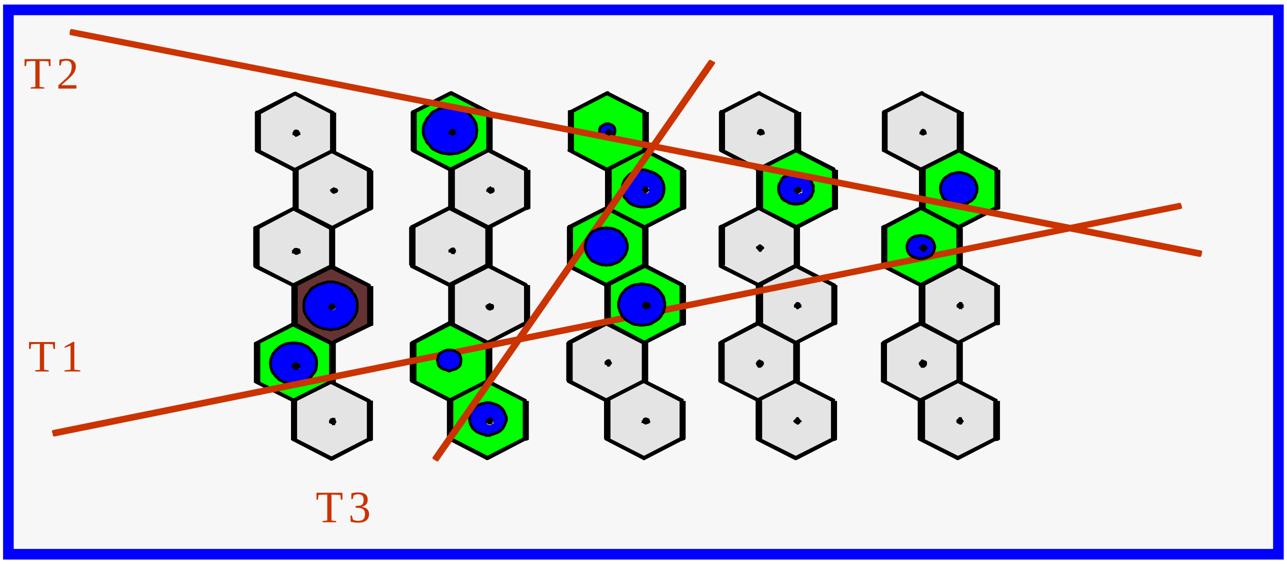


➔ Full exploitation of track model
➔ Kalman filter technique
➔ Triplet seeding
➔ Concurrent track evolution

Concurrent Track Evolution

Challenge:

- Occupancy ⇒ Track following confused by many available paths
- Vast combinatorics
- Delicate optimization process

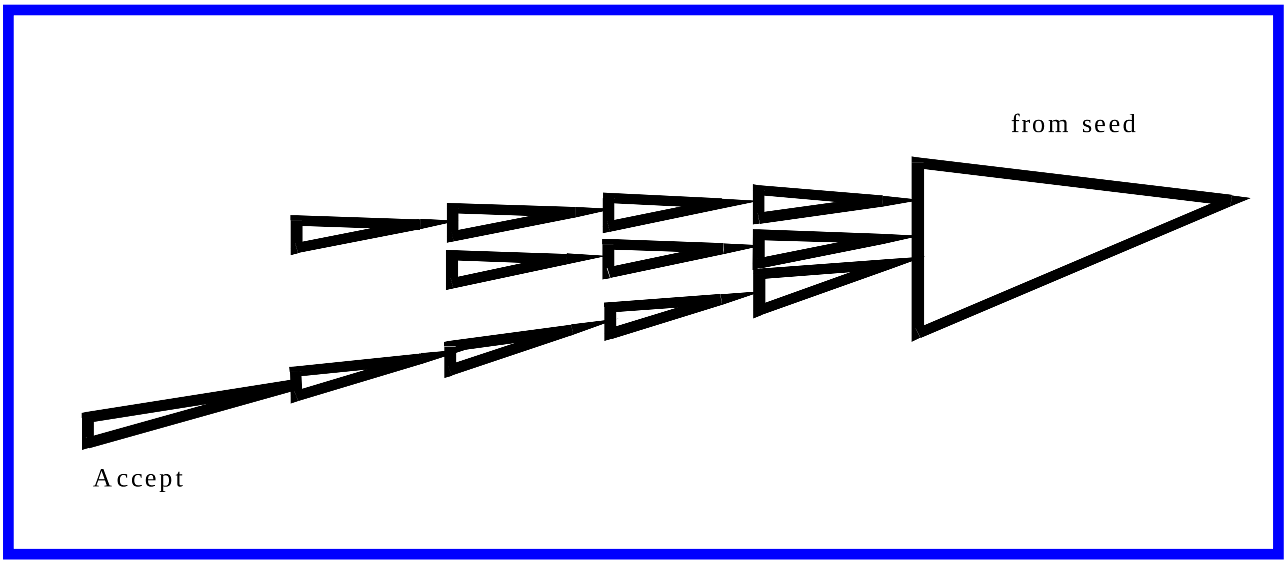


Solution: Concurrent Track Evolution

- combines virtues of track following and combinatorial approaches
- propagate all branches in parallel, but inferior branches ‘die out’
- maximize quality estimator

$$Q = \#Steps - \#Faults - w_{\chi^2} \sum \chi_i^2$$

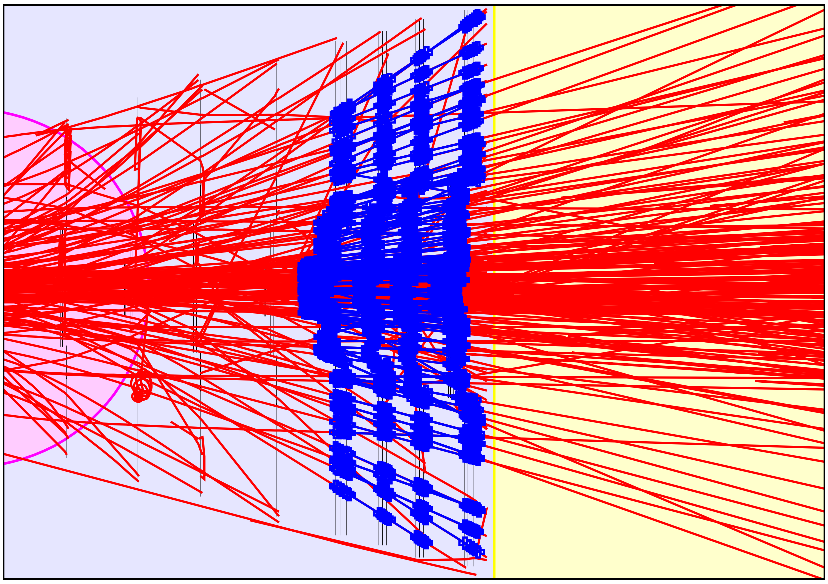
- Kalman filter


from seed
Accept

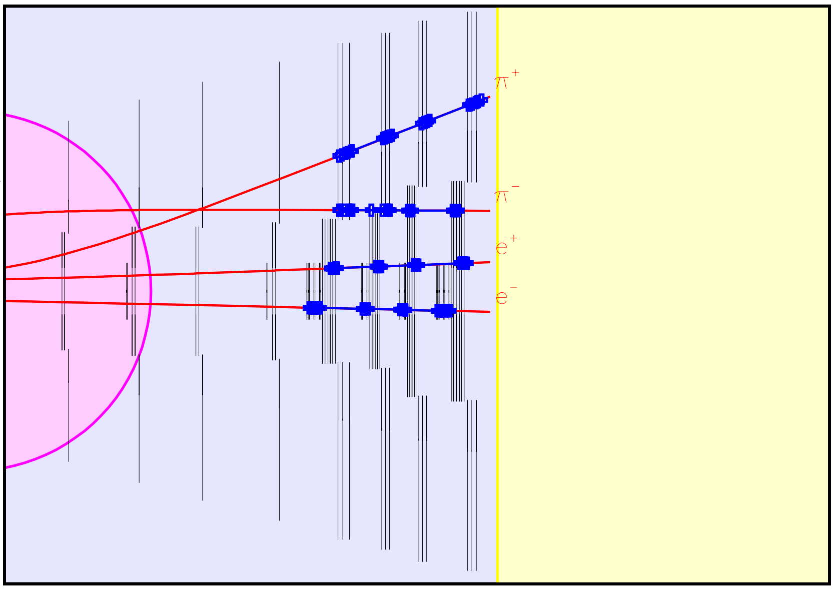
Simulated Event

- pAl $\rightarrow$ B^0+X superimposed with 6 inelastic interactions

all tracks



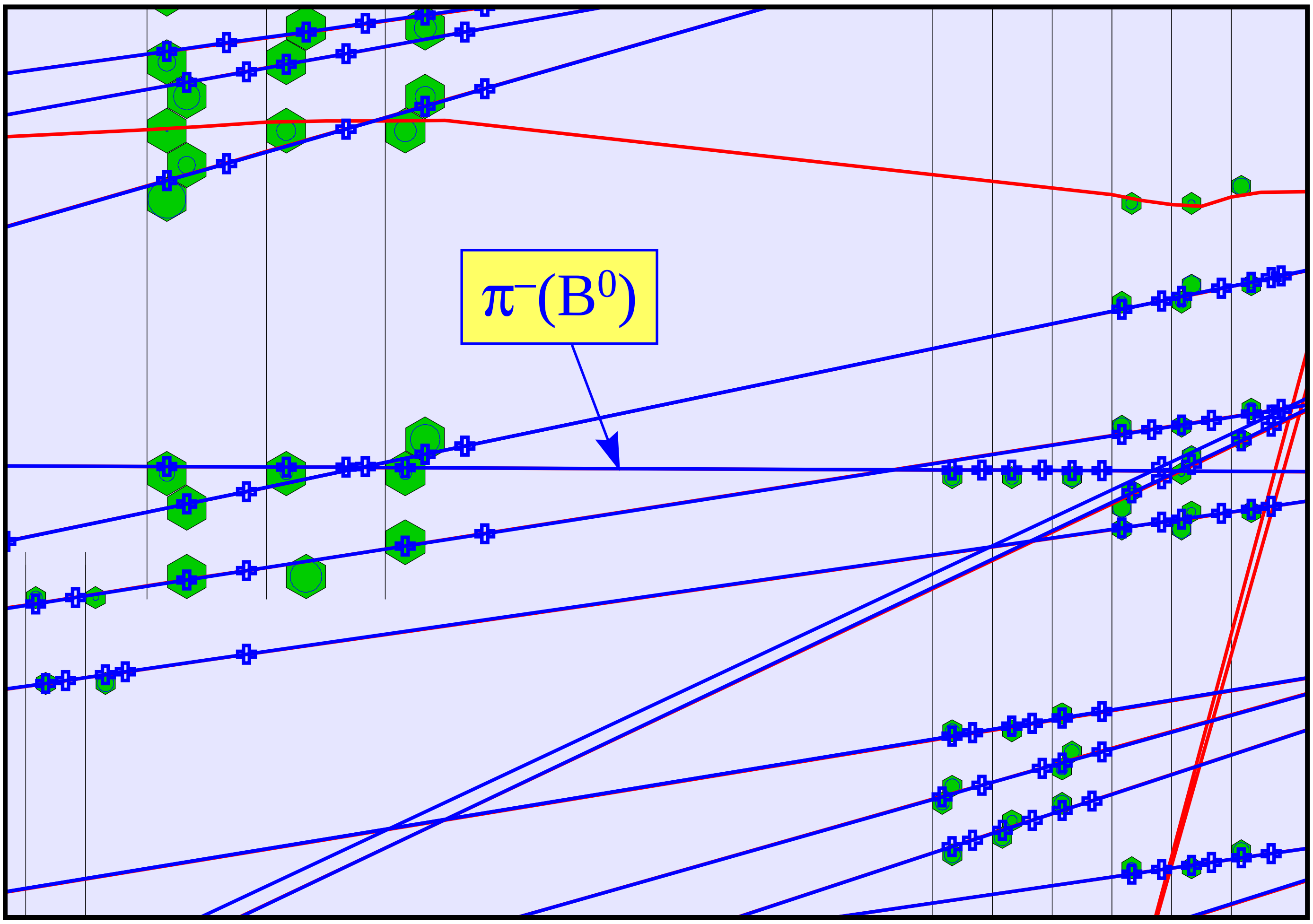
golden B^0



➔ good track separation through efficient use of track model

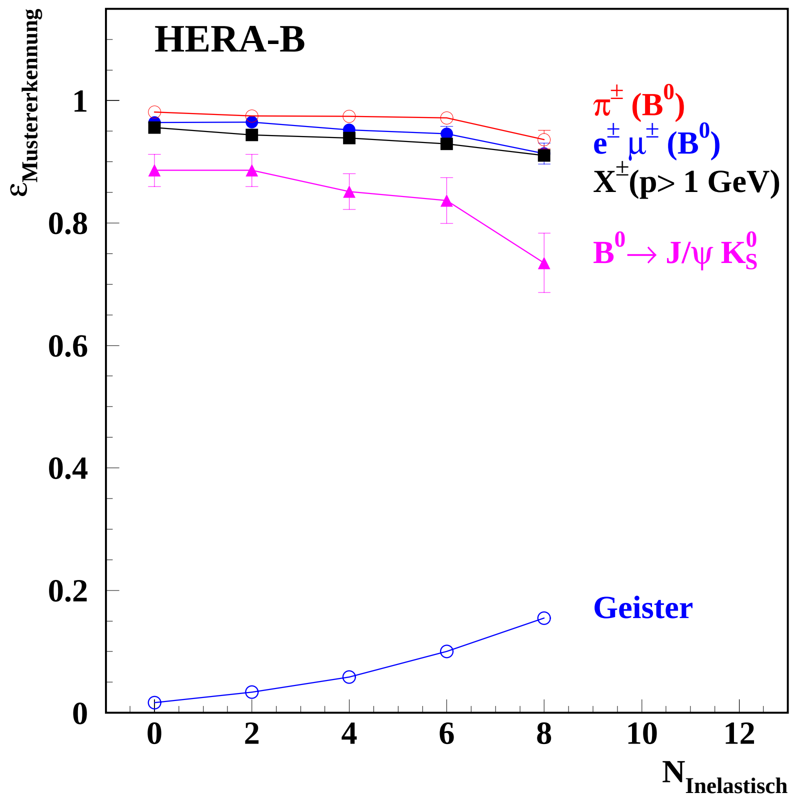
Detail

- reconstruction of pion from the golden decay $B^0 \rightarrow J/\psi\ K_S$



Pattern Recognition Efficiency

- Mean efficiency for tracks from the golden B decay (5 superimposed interactions) **> 96%**
- fraction of "ghost" tracks < **8%**

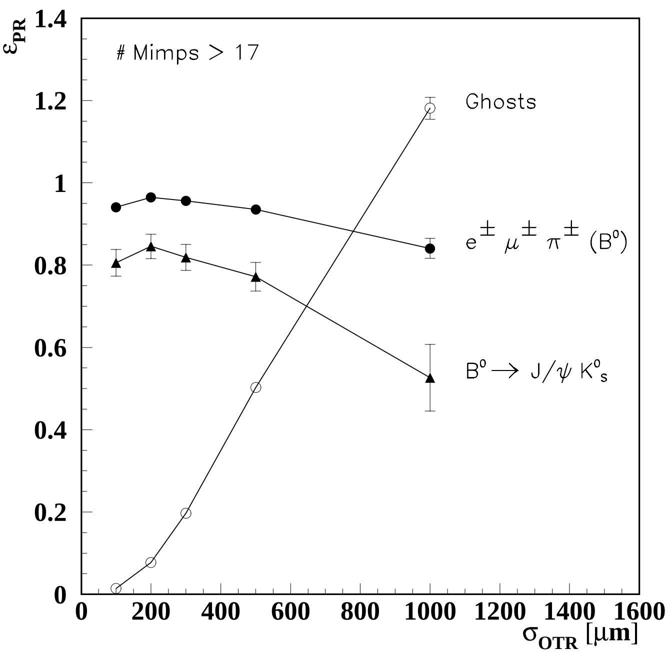


➔ in spite of high track density high track finding efficiency feasible

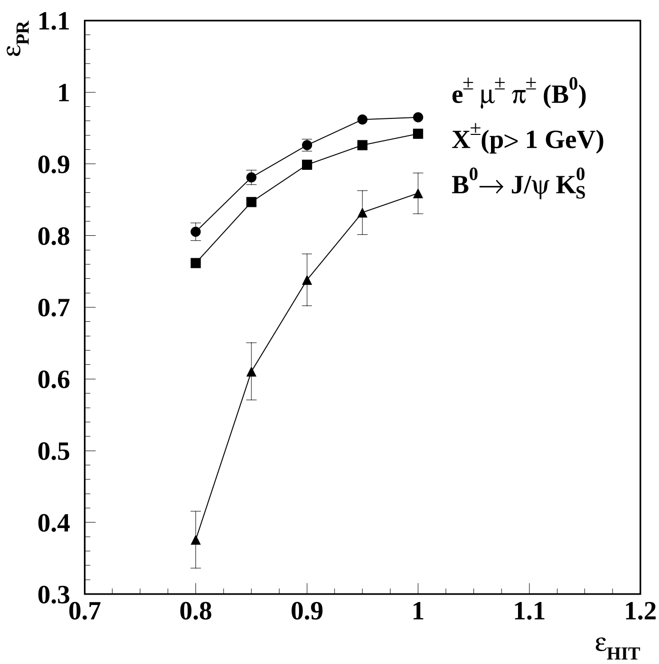
➔ ultimately limited by track overlap in drift chamber cells

Influence of Resolution and Hit Efficiency in Outer Tracker

OT resolution

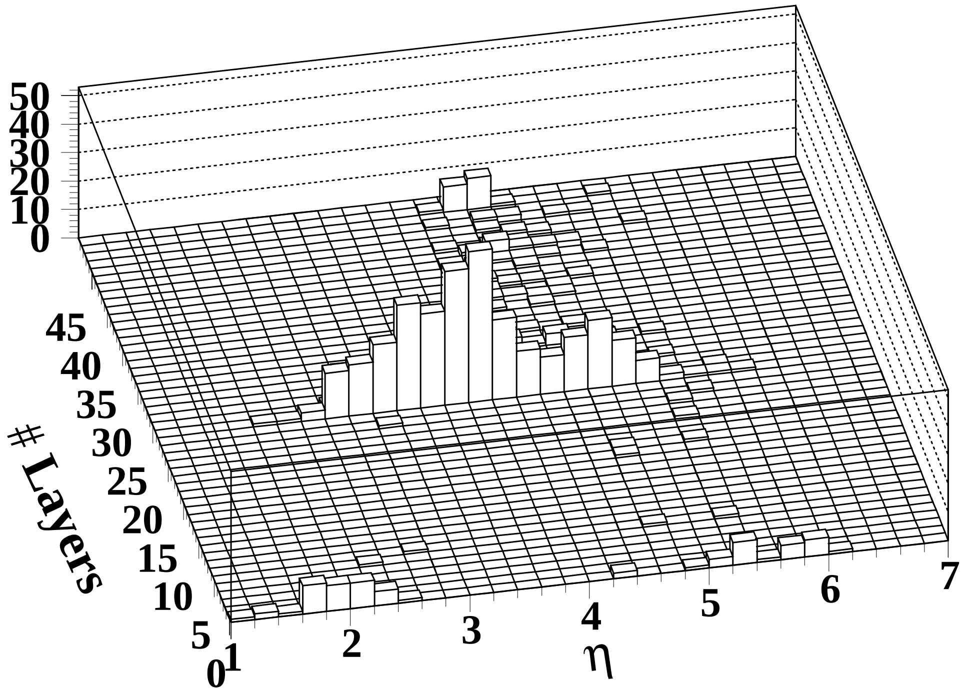


Hit efficiency



- ➔ resolution $\sigma \leq 200\mu m$ *important* for suppression of *ghosts*
- ➔ hit efficiency should be in 90% area
  - – 98% (outer tracker)
  - – >95% (inner tracker)
- ➔ fault tolerance is important parameter of algorithm

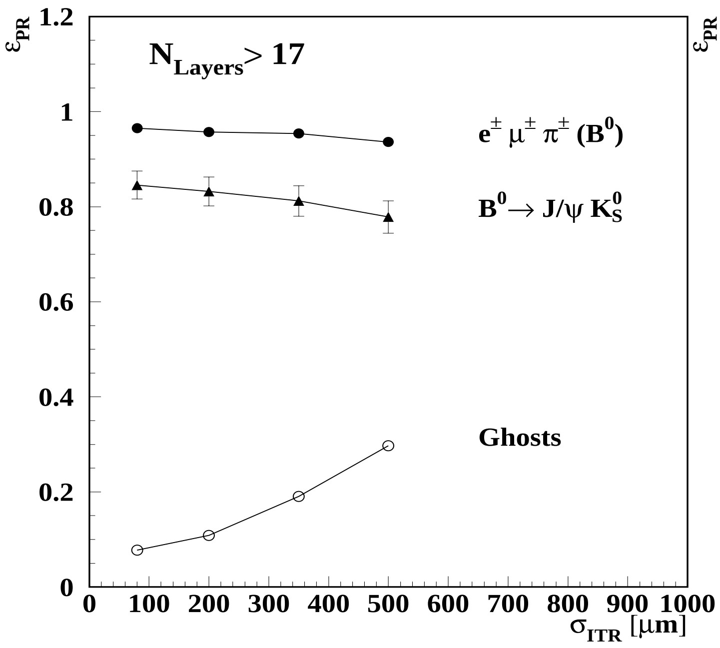
Geometrical Acceptance



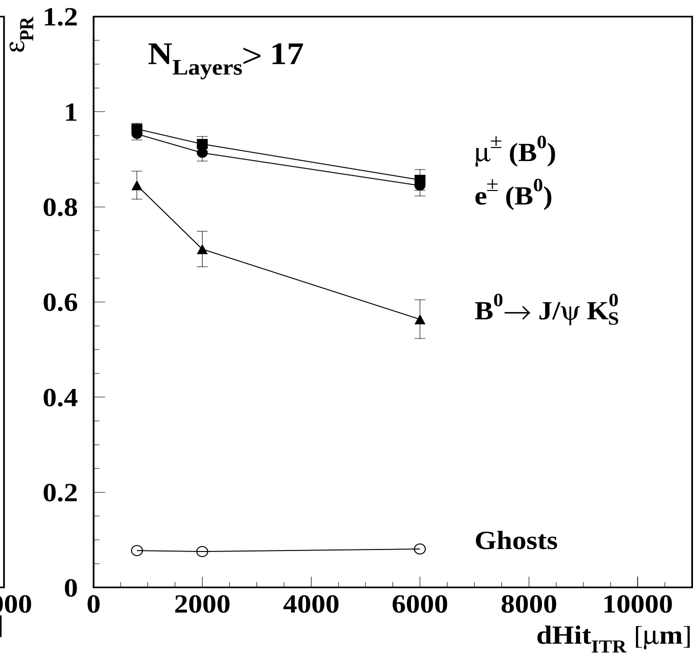
- Acceptance defined by pattern tracker:
  - 88% for leptons from golden B decay
  - 78% “ pions “ “ “

Resolution and Granularity of Inner Tracker

Resolution



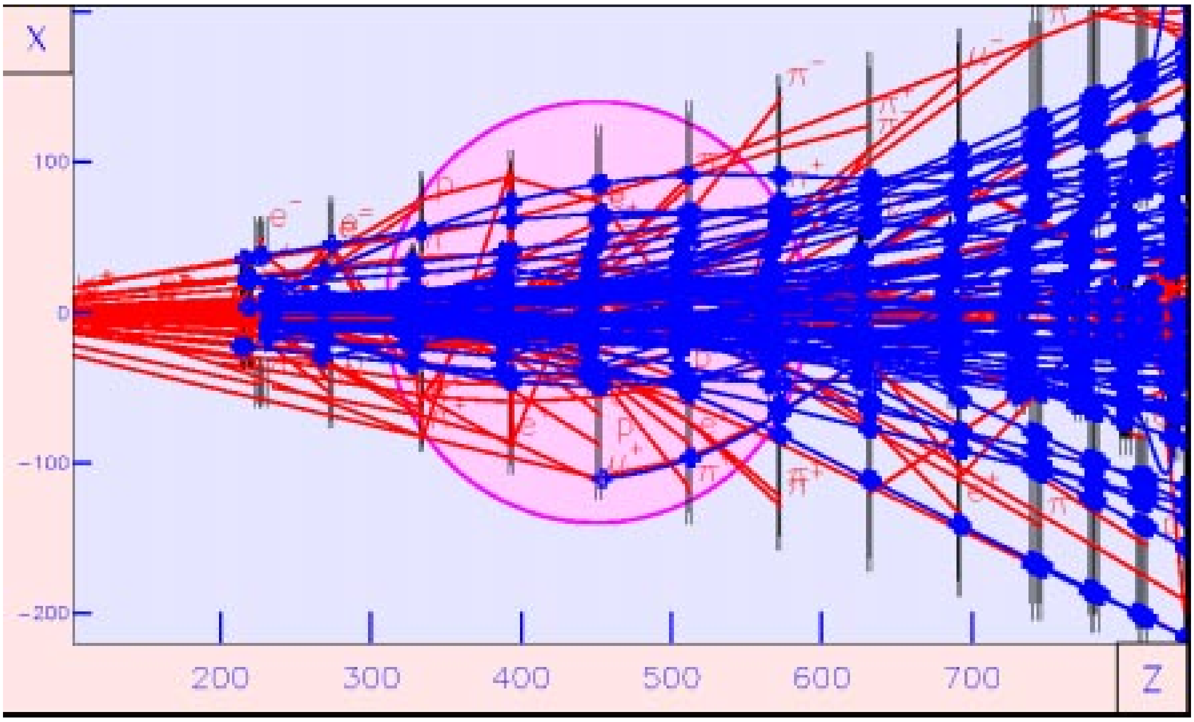
Double track separation



- ➔ resolution O(100μm) sufficient for pattern recognition
- ➔ double track resolution crucial
- ➔ ideal hardware solutions:
  - – micro strip gaseous chambers (MSGC)
  - – scintillating fibres

R. Nahnhauer et al.

Magnet Tracking

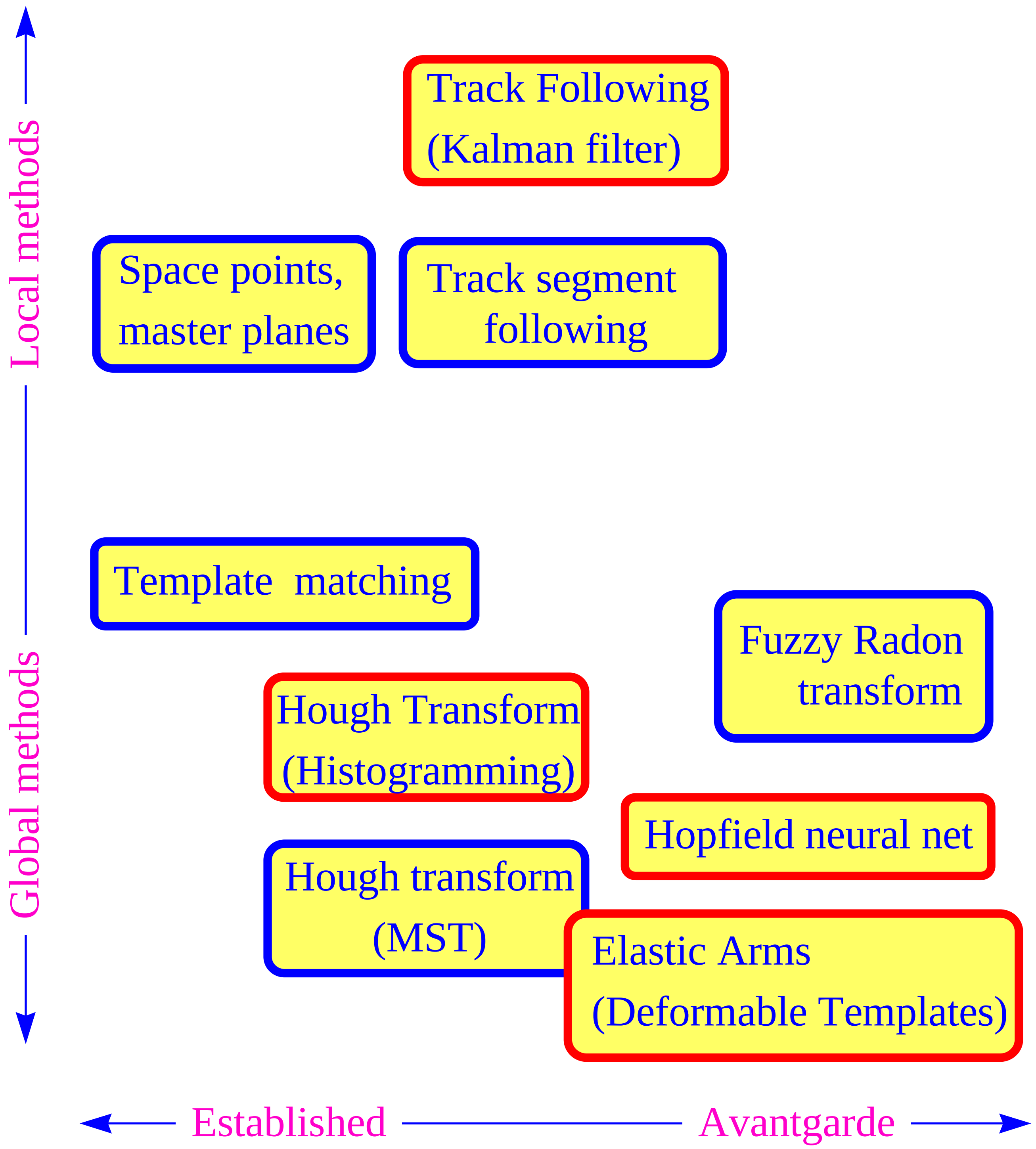


- magnetic field measured and parametrized with polynomials in boxes

A. Spiridonov

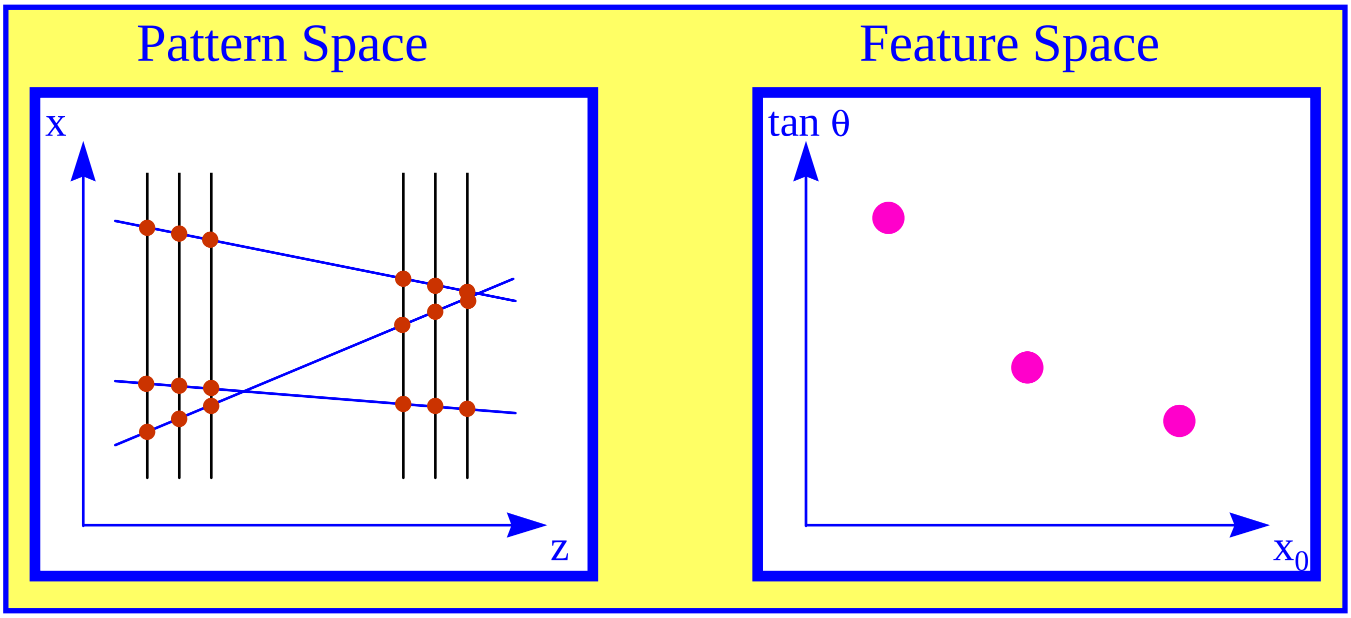
- 3D Kalman filter propagation
- treat inhomogeneous field with 5th order embedded Runge-Kutta method
$\rightarrow \varepsilon_{\mu(B)} \sim 92\%$ (still preliminary)

Pattern Recognition Toolkit

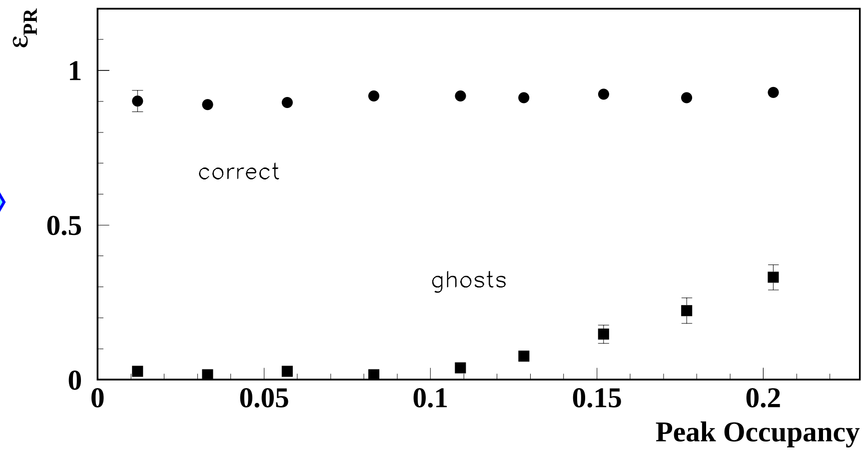


Hough Transform

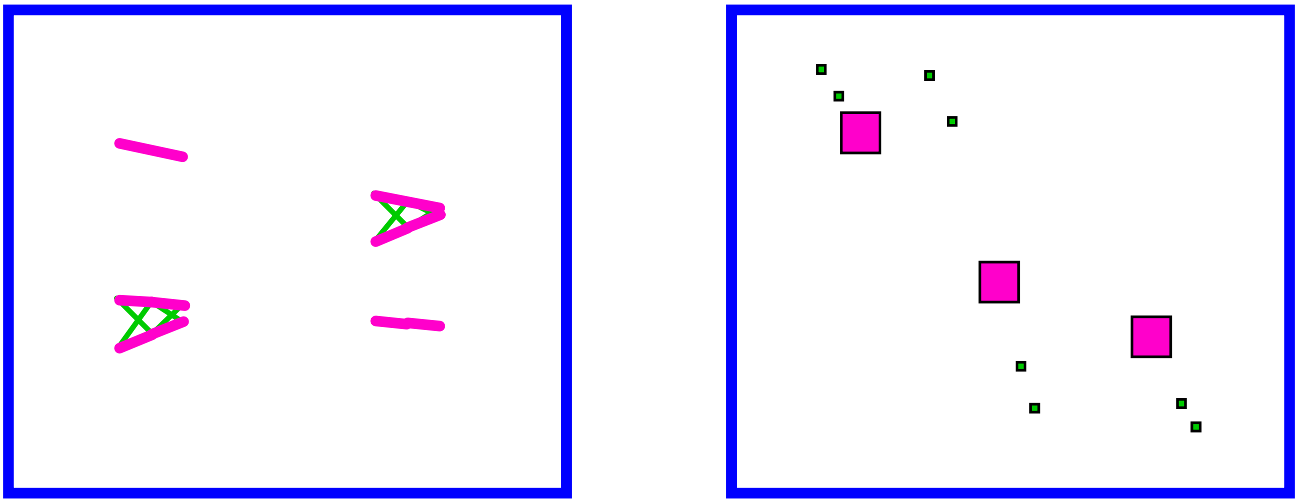
(T. Schober)



Simple model detector,
12 layers,
no stereo views,
no left/right ambiguity



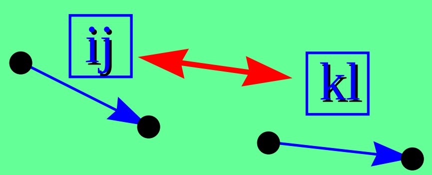
- ➔ high efficiency only with complicated cluster search
- ➔ memory & cpu time demands (~36s)
- ➔ left/right ambiguity addional challenge
- ➔ 3D generalization?



Neural Network Methods

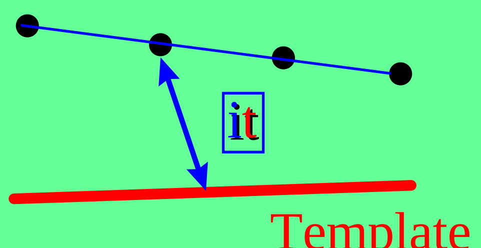
- Dynamic systems of (non-linearly) interacting units (neurons)
- Neuron ‘active’ or ‘inactive’
- Goal: intrinsically simple methods, flexible & robust

Hopfield neuron:



Denby-Peterson

Potts neuron:

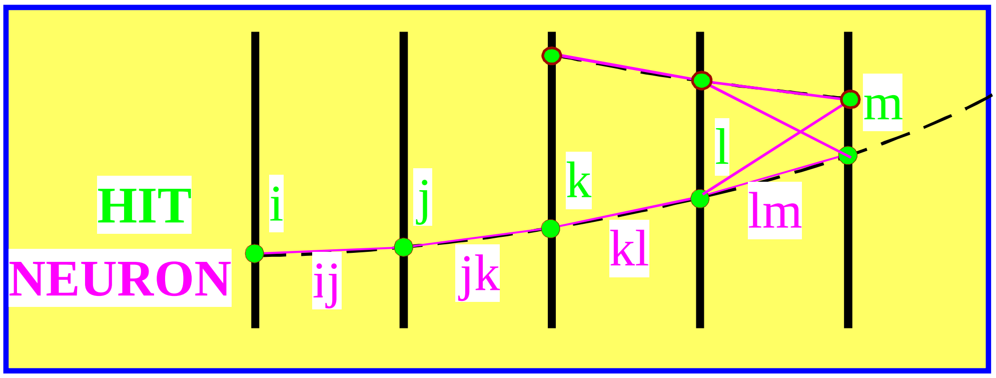


Elastic arms (Ohlsson-Peterson)

Denby-Peterson Algorithm

(C. Borgmeier)

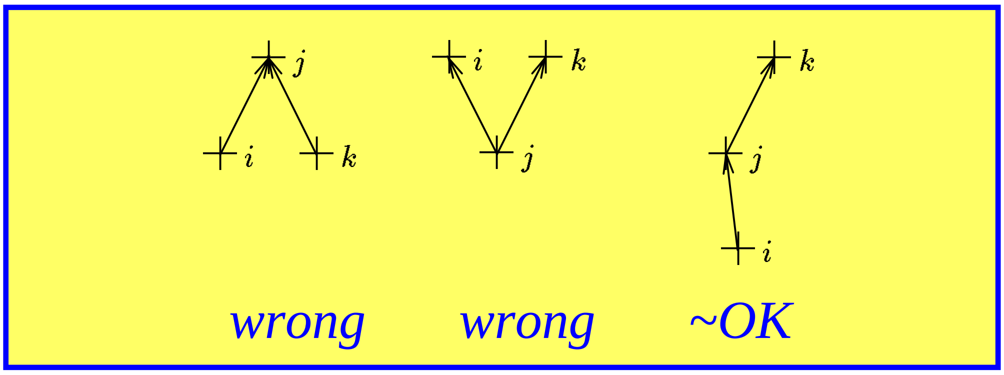
- Hopfield net implementation
- no explicit track model
- assign neuron to every possible *connection* of 2 hits



- Activation

$$S_{ij} = \begin{cases} 1, & \text{segment part of a track} \\ 0, & \text{otherwise} \end{cases}$$

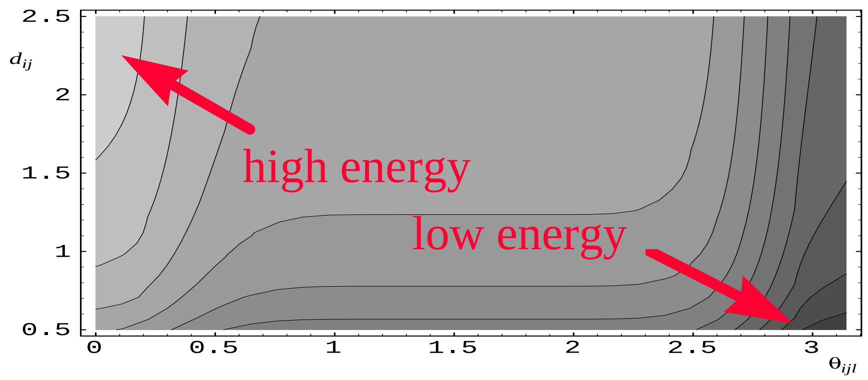
- Define interaction



Energy Function

- suppress both large angles and large distances

d_{ij}

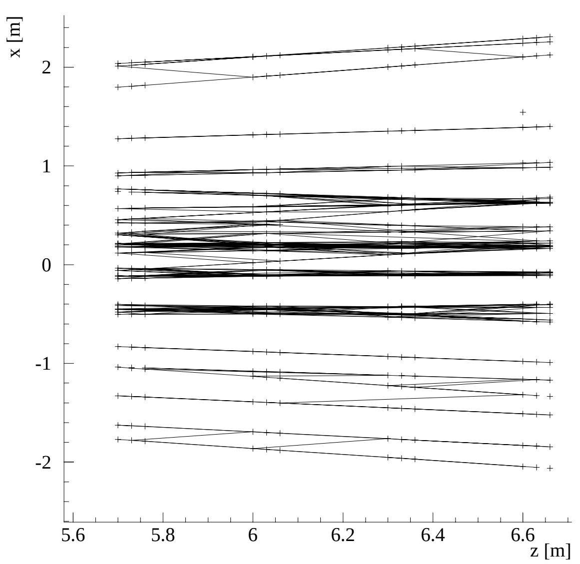


θ_{ijkl}

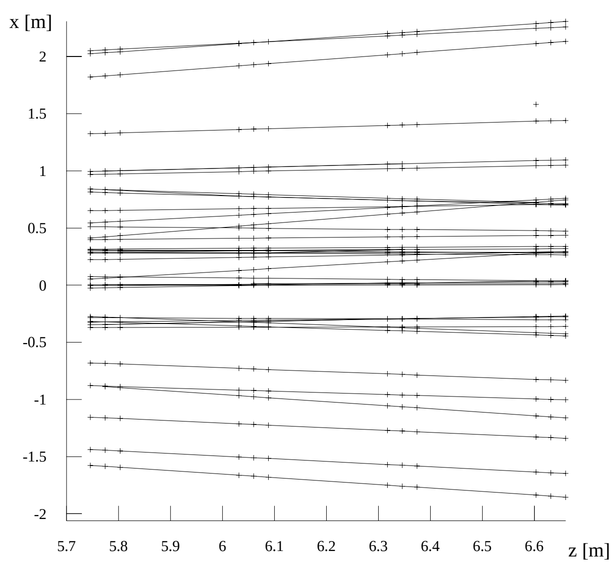
- Update Rule

$$S_{ij} = \Theta\left(\sum_{kl} \left(-\frac{\partial E_{ij;kl}}{\partial S_{ij}}\right)\right)$$

<u>First Iteration:</u>

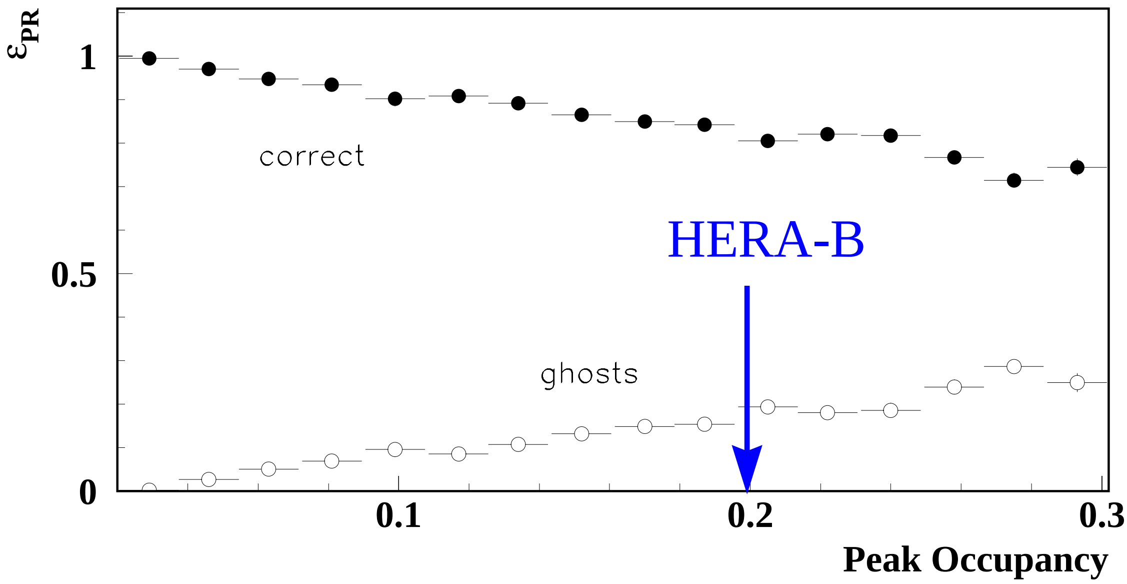


<u>36 Iterations (convergence):</u>



Results (Denby-Peterson)

- 2D model detector

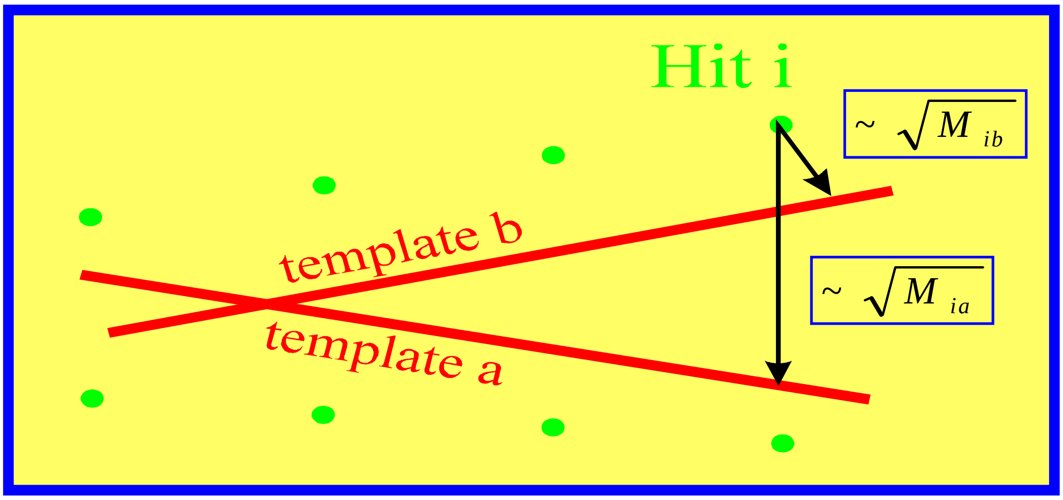


- Many ghosts consist of improperly merged track fragments $\Rightarrow$ recoverable?
- Computing time ~500s for ρ=20%
- 3D implementation non-trivial
- Need track model to resolve close tracks

Elastic Arms

(C. Borgmeier)

- Let 'track templates' search their hits
- Explicit track model



- Optimize energy function:

$$E = \sum_{Hits} \sum_{Templ} S_{iu} M_{iu}$$

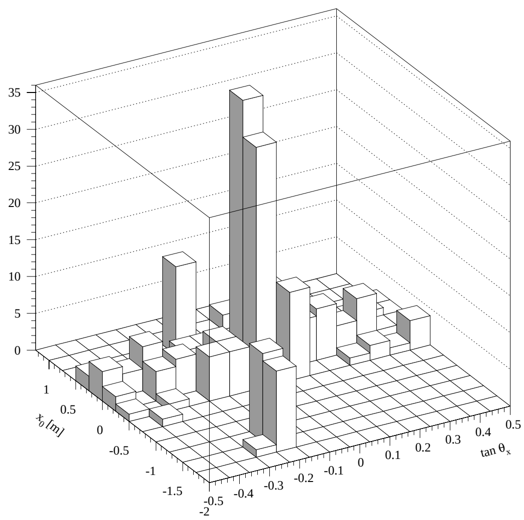
M_{iu}: distance^2

S_{iu}: =1 if hit assigned to template, =0 otherwise

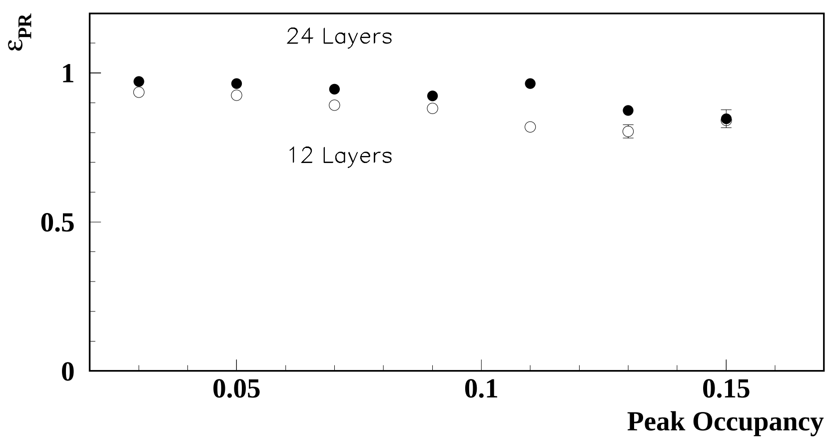
with gradient descent & simulated annealing

Elastic Arms (cont'd)

- Initialize templates with local Hough transform



- 2D pattern recognition efficiency

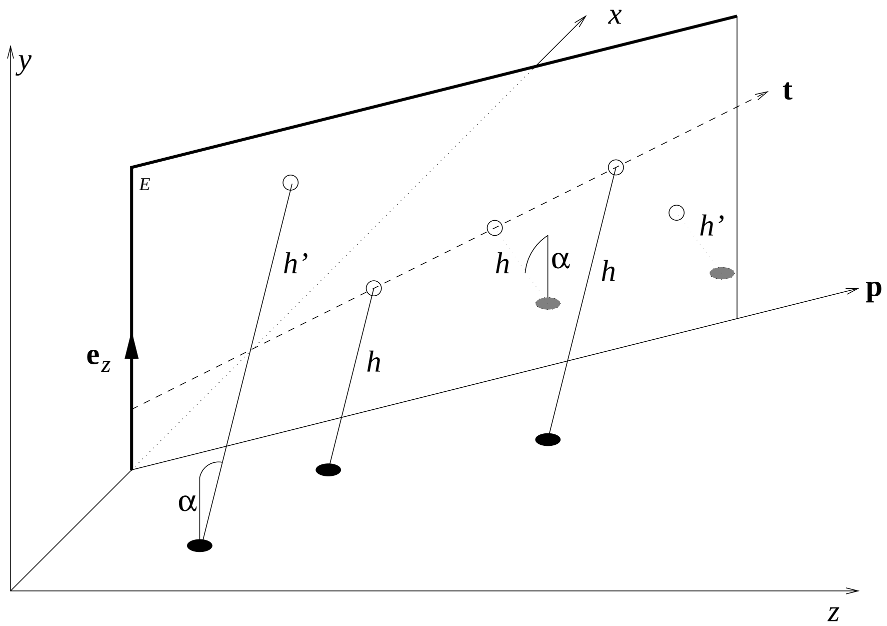


- Works nicely, but considerable computing effort for HERA-B occupancies (~3000s for ρ=0.17)

Elastic Arms (cont'd)

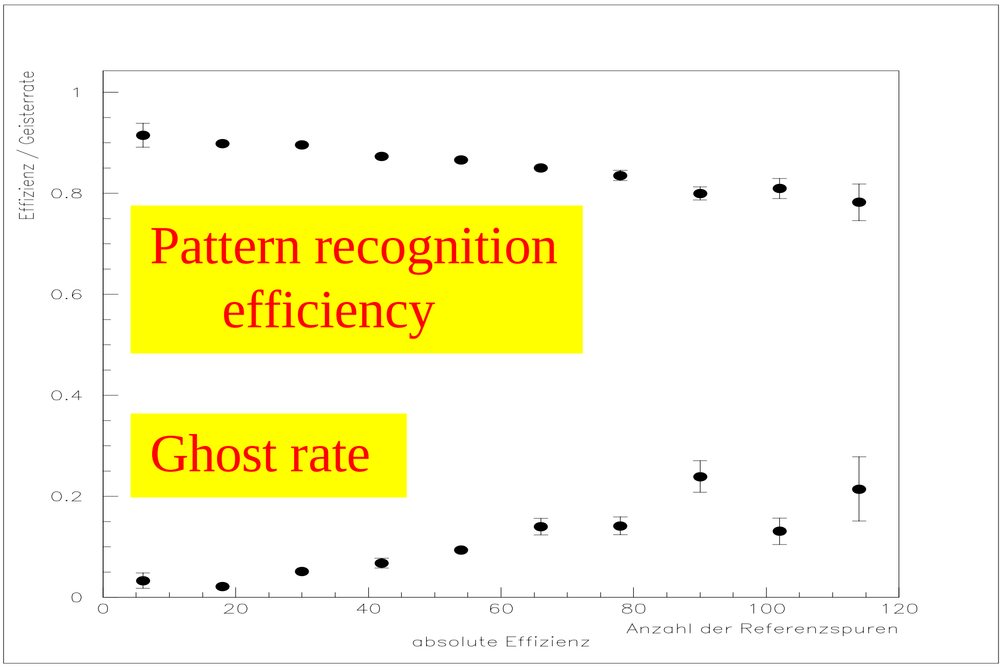
A. Paus

- "Real" 3D tracker requires a more sophisticated template initialization:
  - 0^o triplets in each superlayer
  - two triplets define 0^o segment
  - stereo superlayer triplets
  - full candidate seed

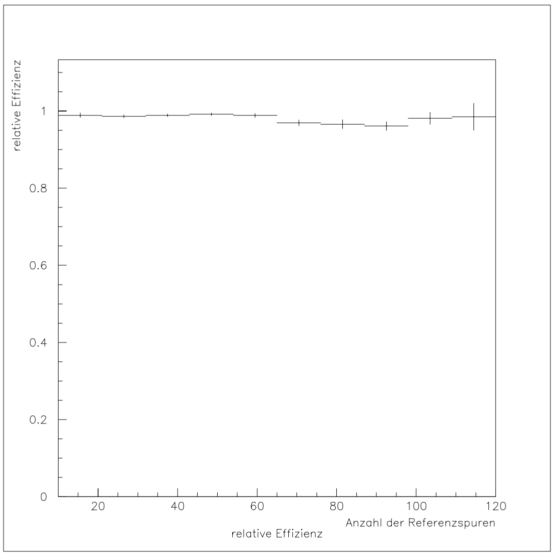


- Acceleration of convergence:
  - lower initial temperature (better initialization)
  - early weedout of far-off hits
  - resilient propagation instead of gradient descent
  - ➔ ~1000 times faster !

Elastic Arms (cont'd)



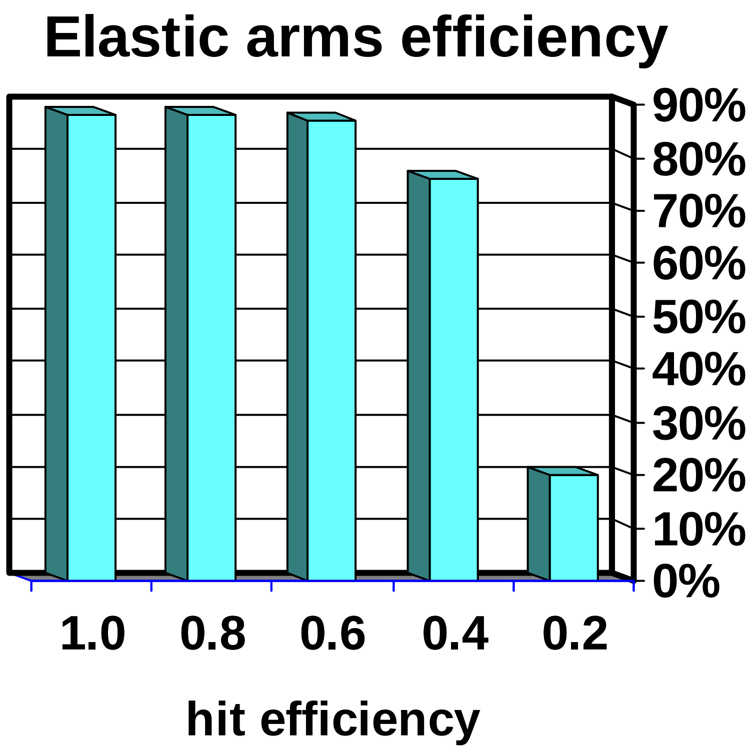
ε relative to initialization:



- ~100s/evt cpu time
- ~92% of all hits correctly assigned
- efficiency governed by initialization

Elastic Arms (cont'd)

- Expect: global algorithm more stable against hit inefficiencies, failed modules etc



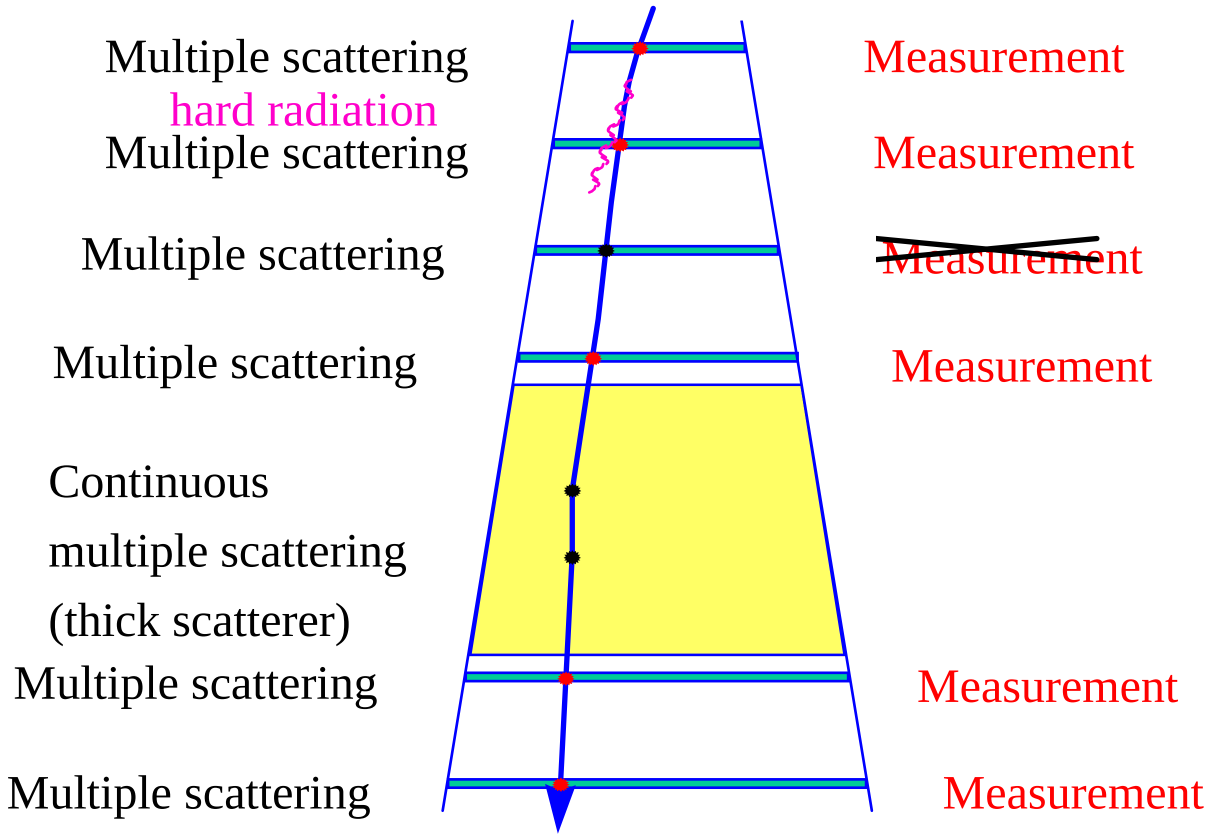
➔ potential of robustness & independence of complicated detector structure already visible

➔ track following methods are still ahead, but:

➔ performance approaches regime of practical useability

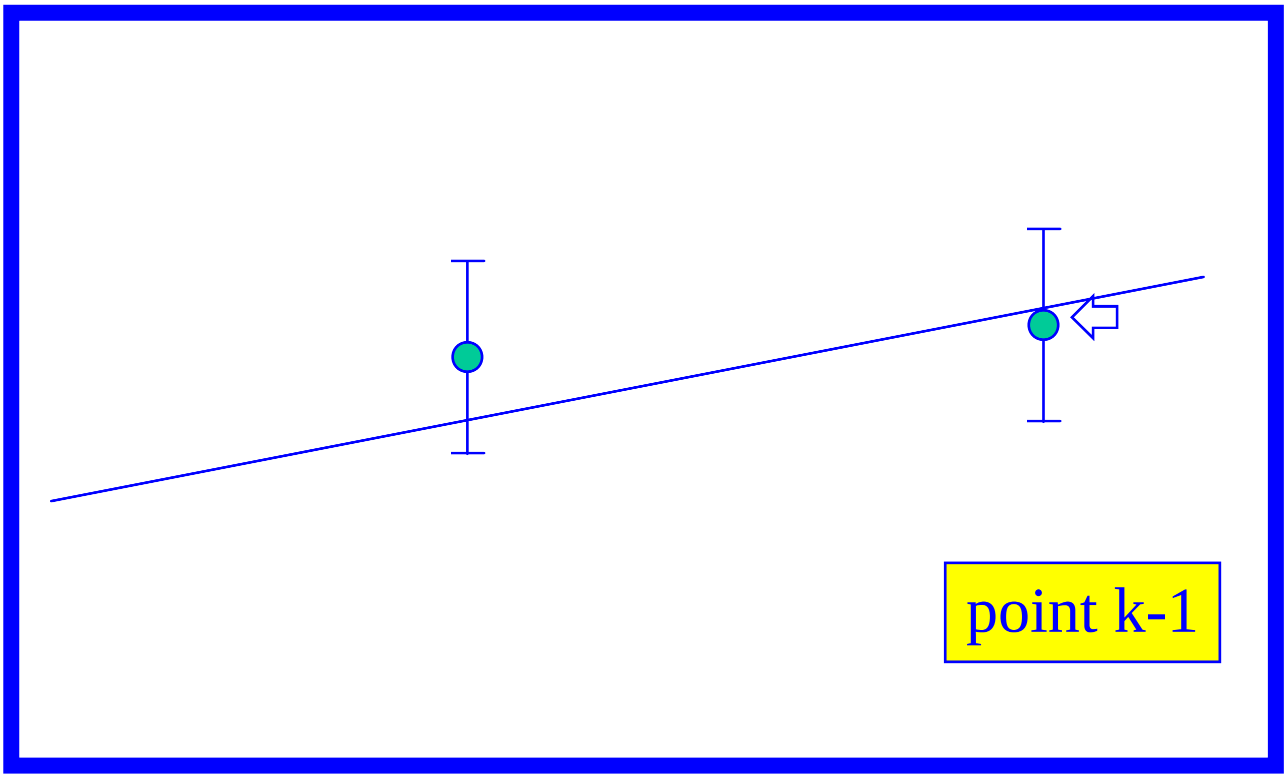
Track Fit

- Track fit has to provide the best possible estimate of particle parameters
- should include various kinds if detector information as
  - 1D coordinates (strips, drift distances)
  - 2D coordinates (pads, pixels)
  - cluster information (x,y,E) from ECAL
  - photon radiation (δE)
- substantial multiple scattering effects (~ 60% of a radiation length)

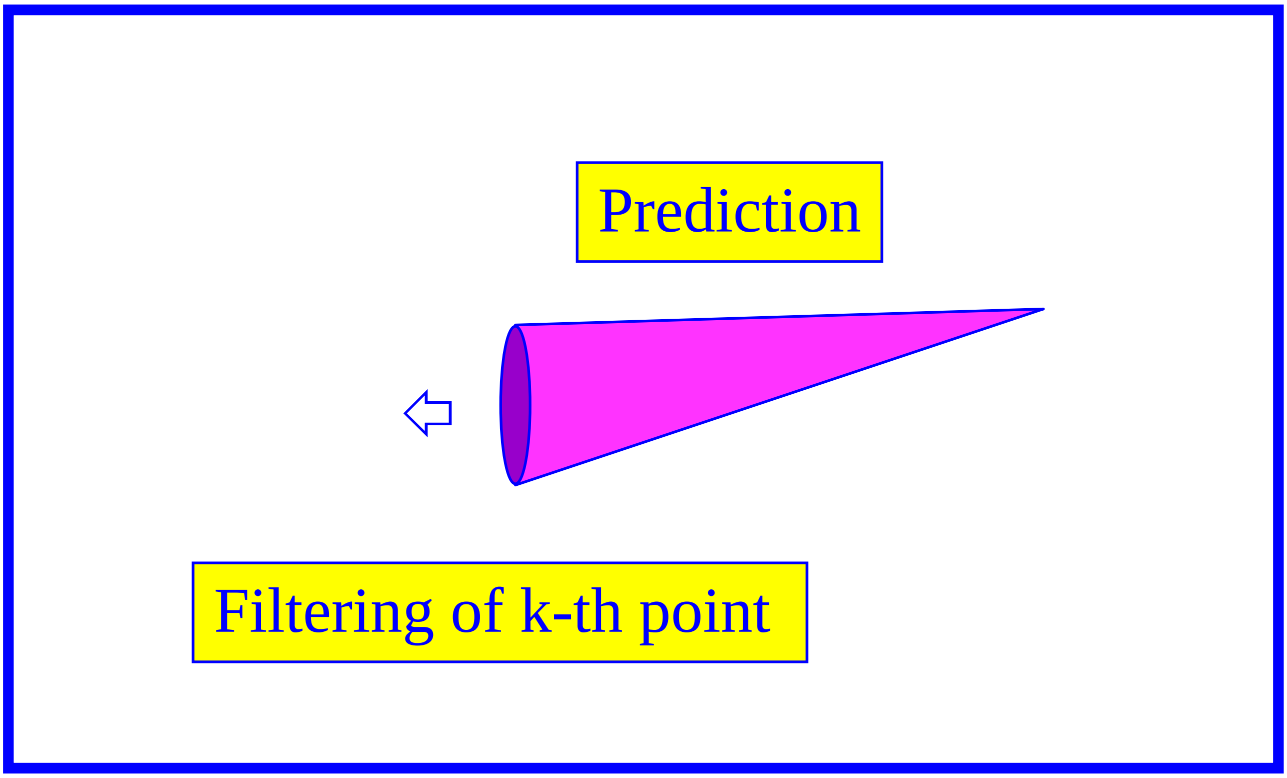


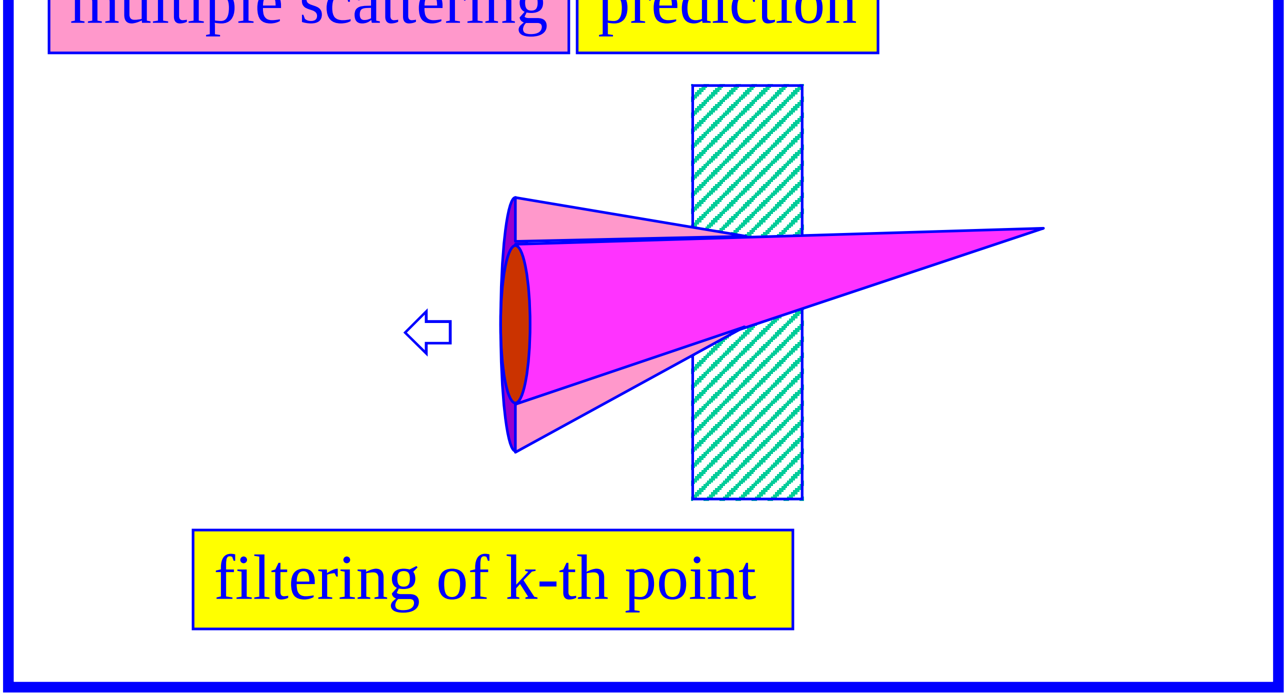
The Kalman-Filter Method

- Progressive least-squares fitting of parameters of a trajectory
- Iterative cycle prediction/filter



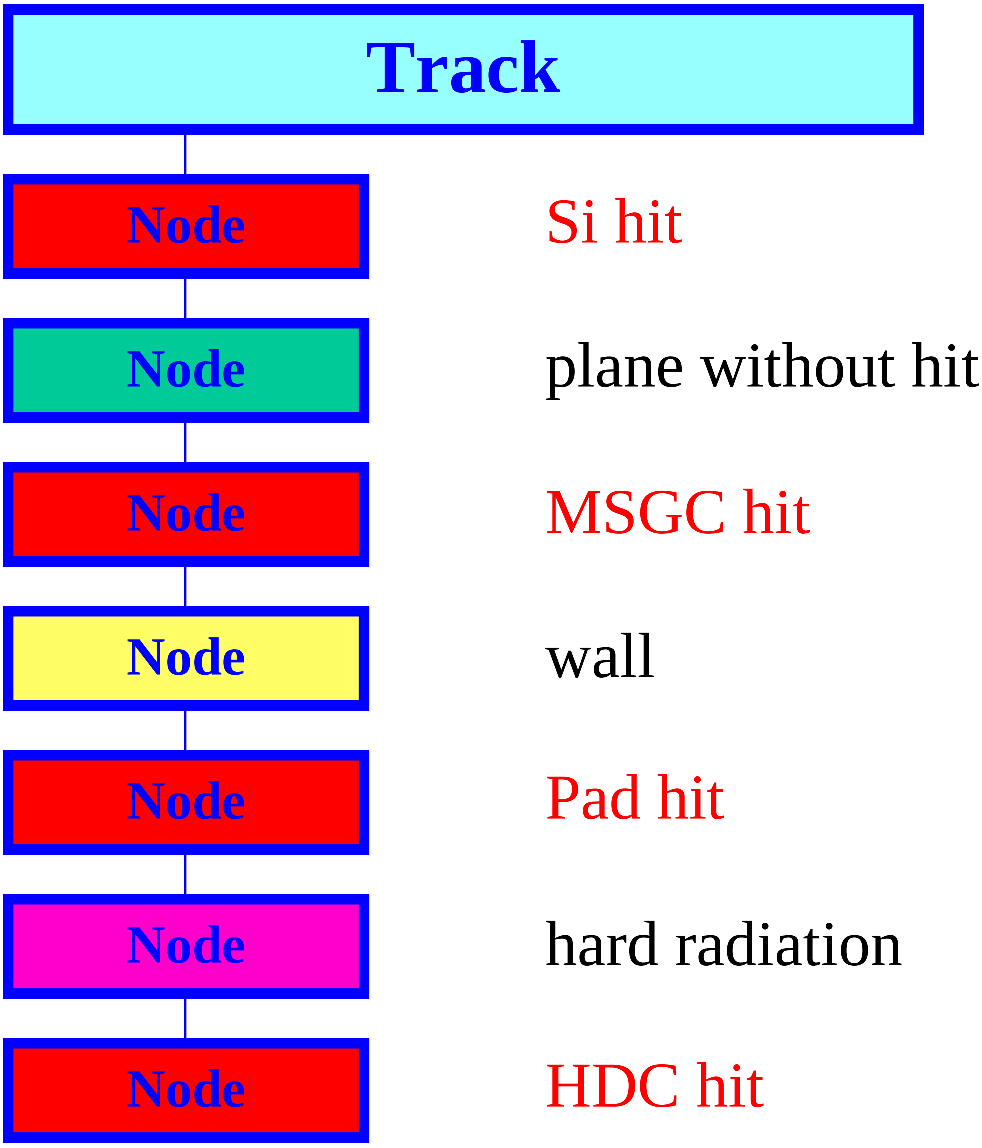
- include stochastic perturbations
  - multiple scattering (Molière theory)
  - energy loss (dE/dx, Bremsstrahlung)
- Kalman-Filter is most effective method of *Least Squares Fit* in presence of multiple scattering


Prediction
Filtering of k-th point



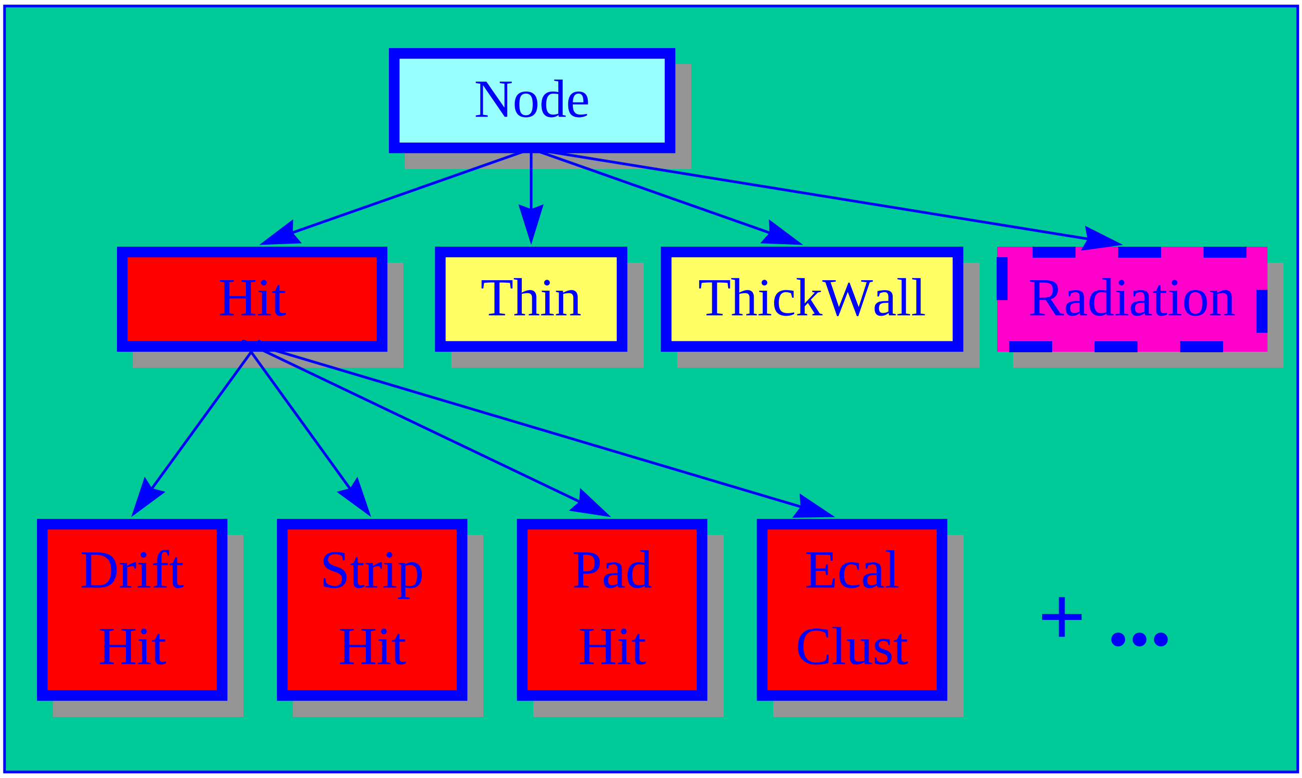
multiple scattering
prediction
filtering of k-th point

Object-oriented Implementation (C++)



- track consists of “nodes”
- filter formalism in each node depends on <u>type</u> of node

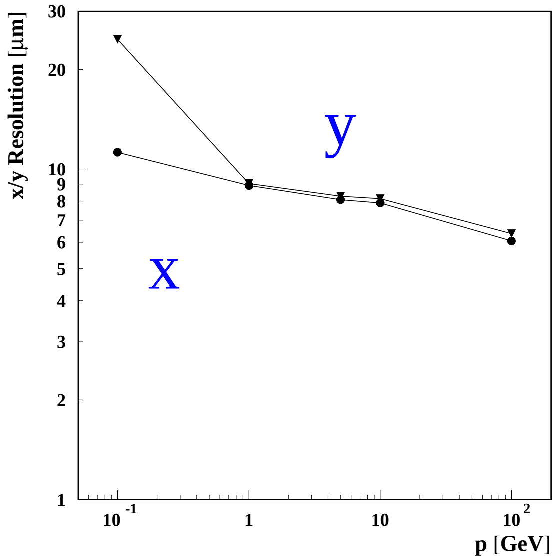
Node Classes

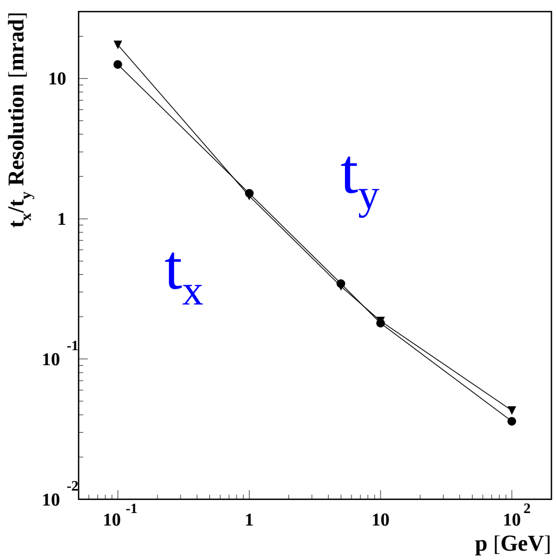


- inherent polymorphism
- implementation using inheritance & virtual functions
- hit type specific parts of filtering in derived classes
- flexible, scalable

Spatial & Angular Resolutions

- μ's traversing SiVD and outer tracker
- resolution at first point

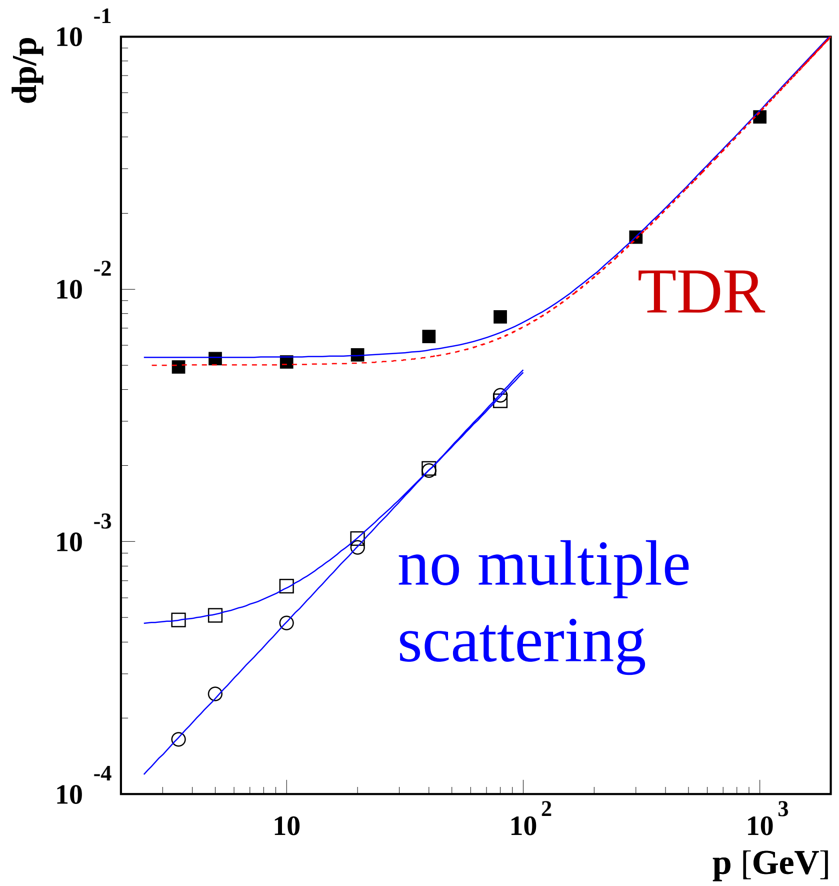




➔ explained by
- coordinate resolution of SiVD
- multiple scattering

Momentum resolution

- μ's traversing SiVD and outer tracker



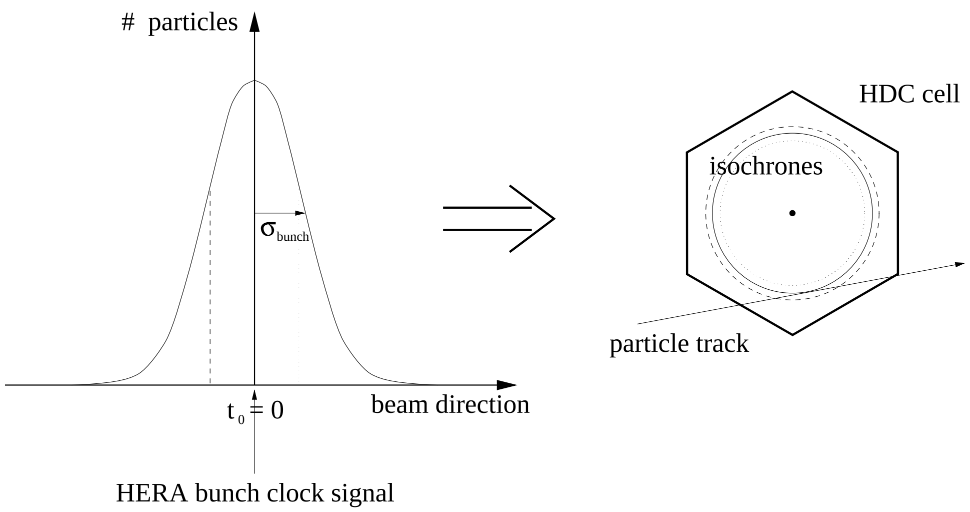
➔ compensation of multiple scattering works

➔ track fit reproduces design resolution

Interaction Time Shift

H. Deckers et al.

- HERA bunch length $\longrightarrow$
  interaction $t_0 \neq$ time of bunch clock signal



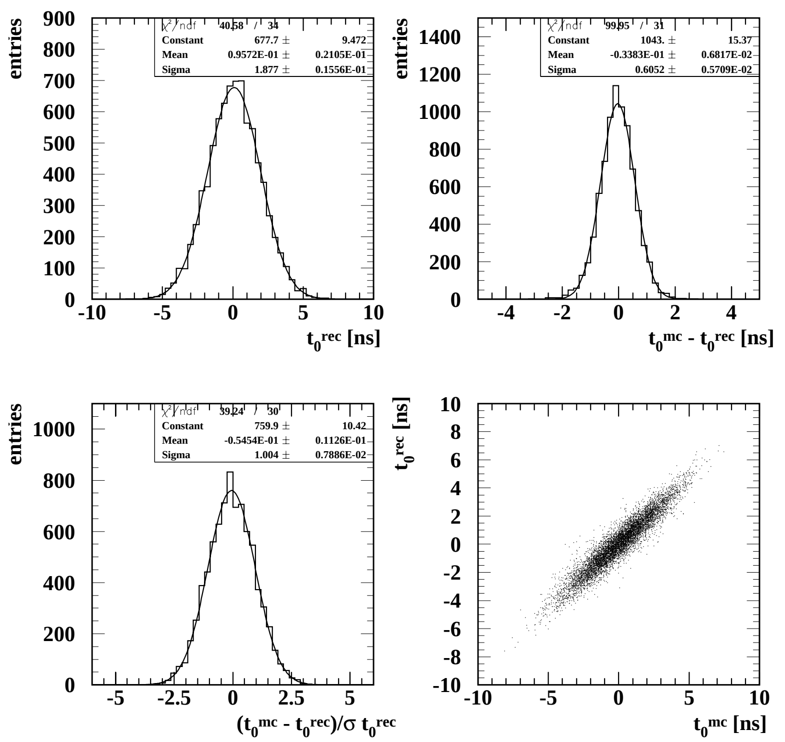
➔ affects coordinate measurement in drift chambers

➔ widens residual distributions

➔ must be compensated in track fit

Interaction Time Shift (cont'd)

- introduce interaction time as additional (global) parameter
- test with 96/97 run geometry (9 HDC layers)



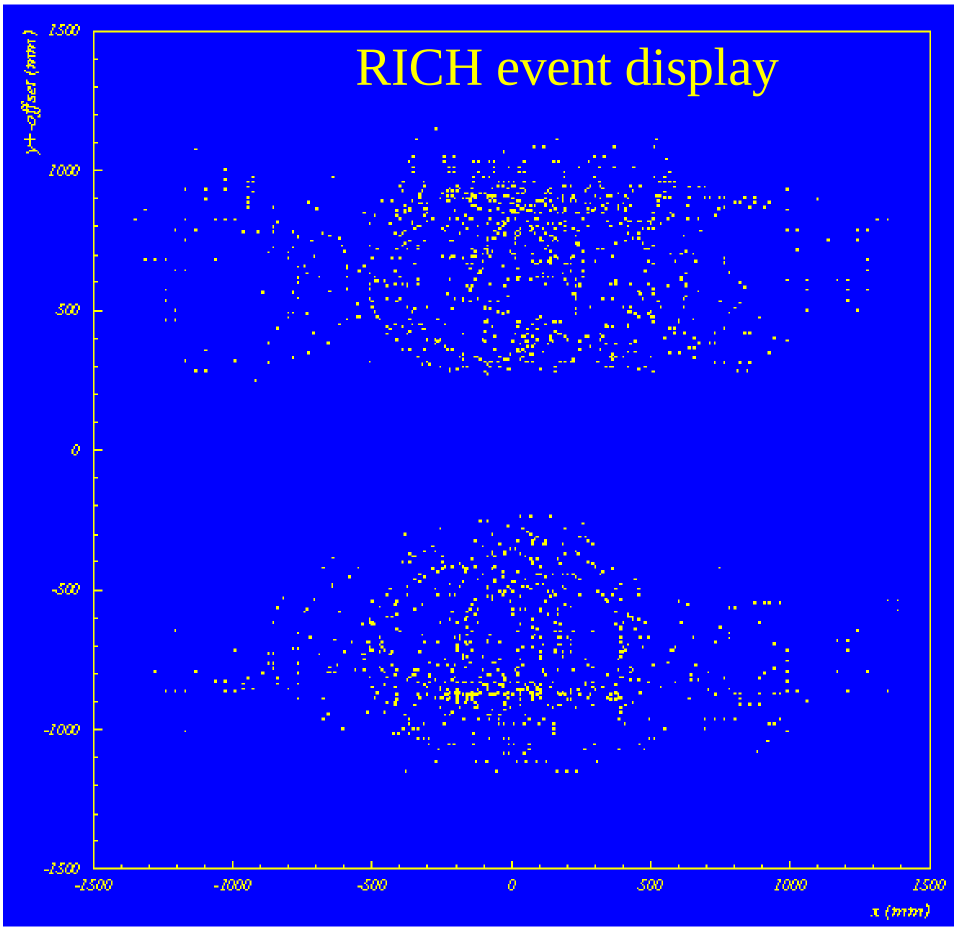
➔ track fit can "reconstruct" t_0 to a certain extent

➔ residual spread decreases 260µm → 190µm

❄ for multiple interactions: each interaction has its own t_0

Reconstruction in the RICH

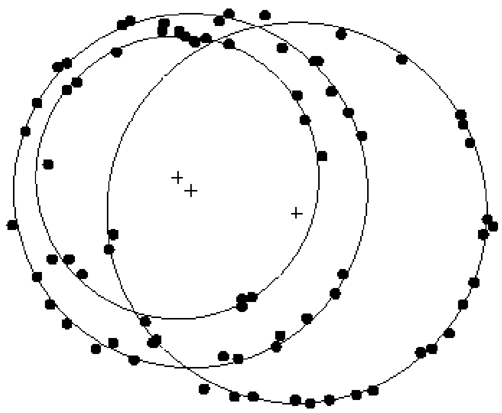
- essential for K tagging
- high occupancy (< 10%)
- Principle: use tracking system information
  → center of ring known
- Standard method: calculate likelihood functions (signal + a linear background) for each hypothesis
- Main problem: ring overlap

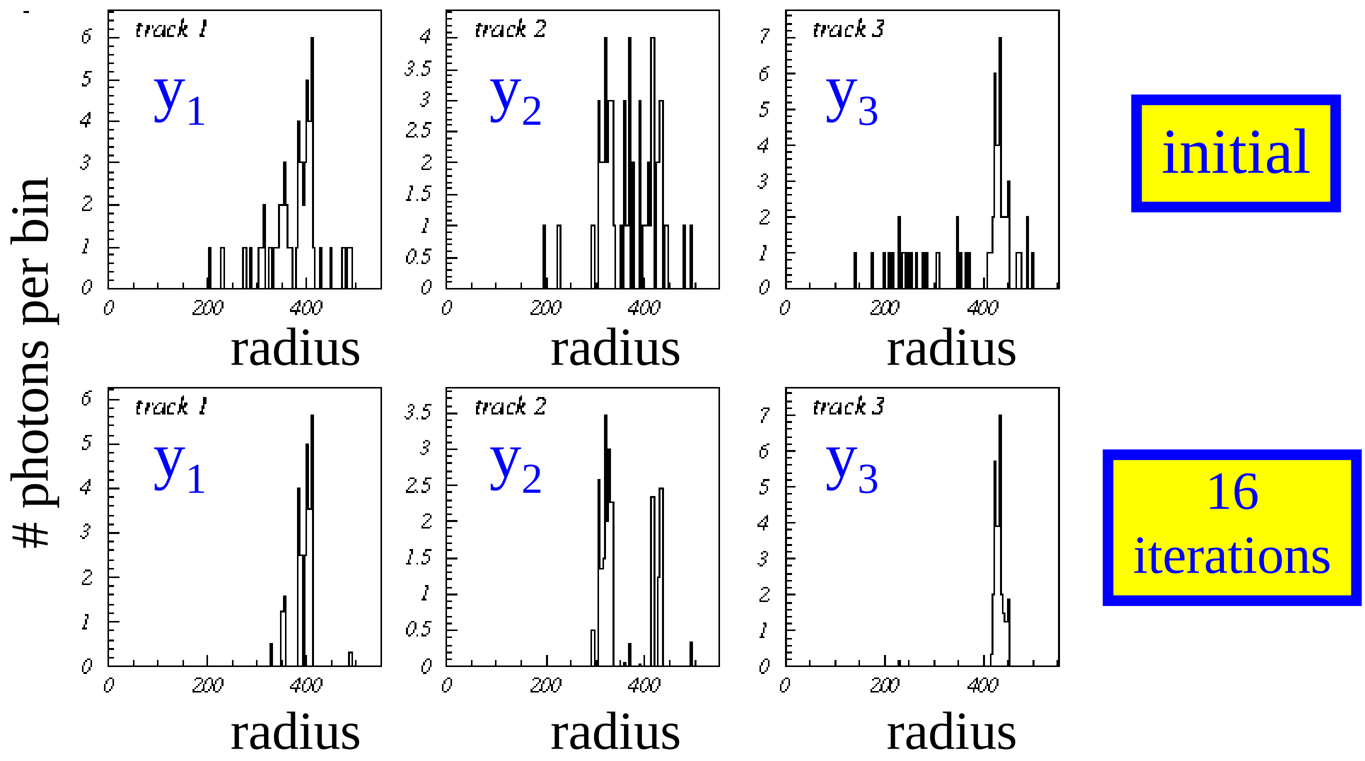


Reconstruction in the RICH (cont'd)

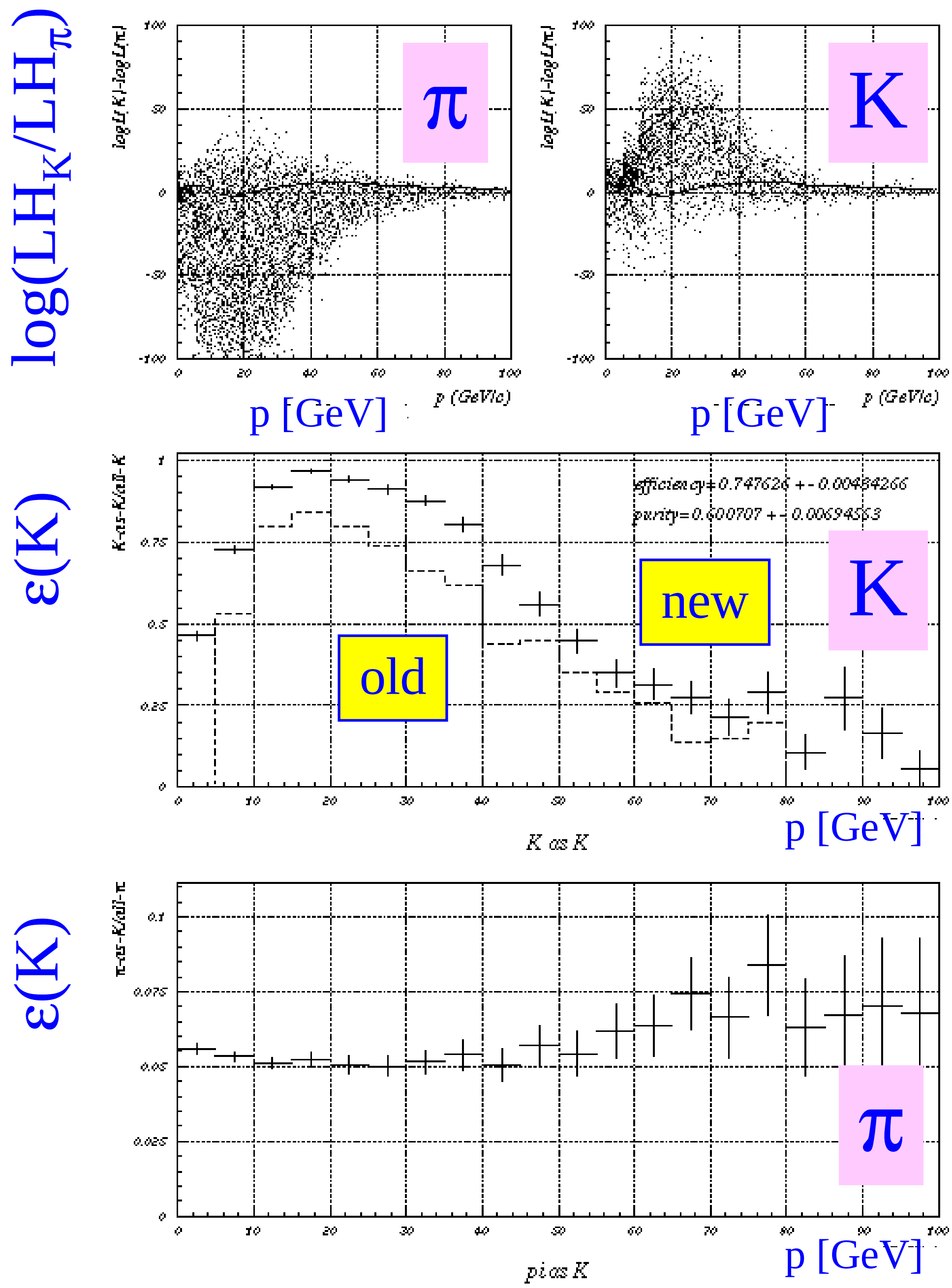
M. Staric, P. Krizan

- "Background" is mainly due to other rings
- **Idea:** use iterative procedure to assign hits to rings
- Weight hit with $w_i = y_i / \Sigma y_i$
- ~20 iterations





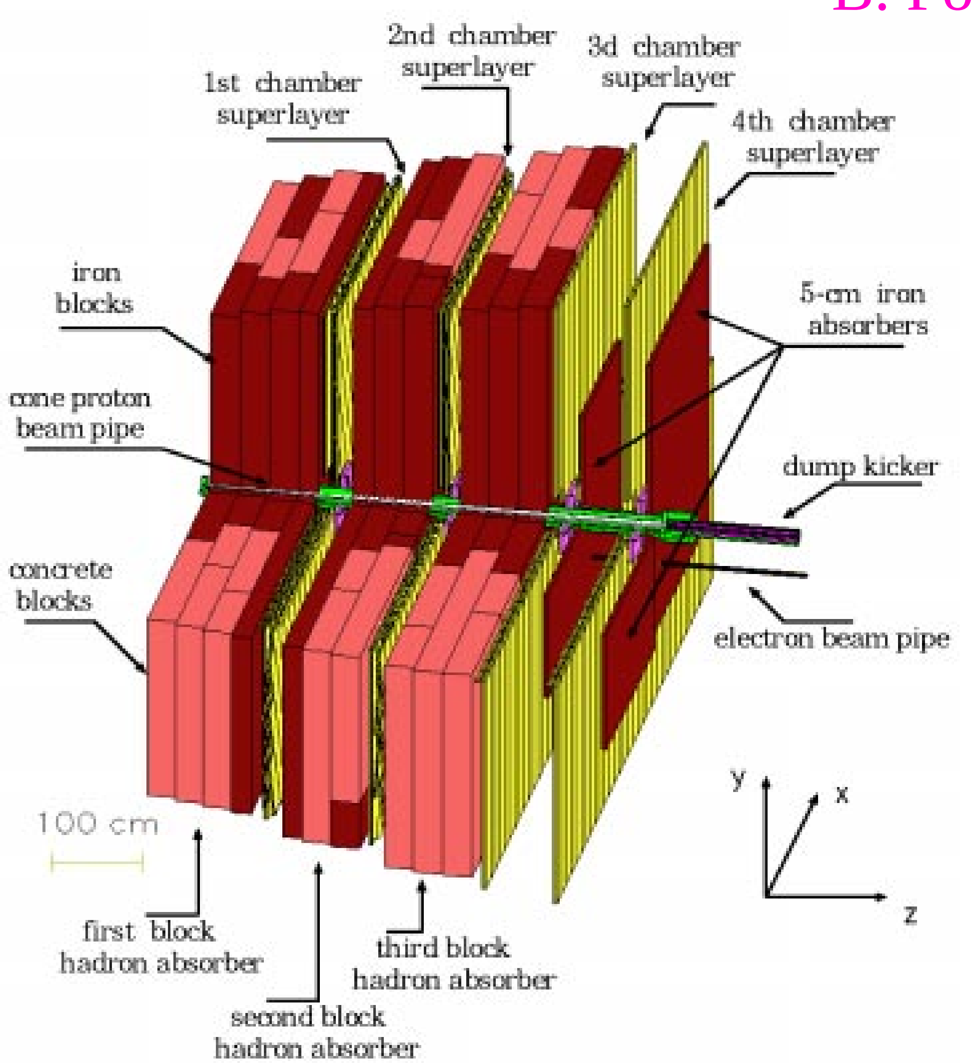
RICH reconstruction performance



- ➔ $\varepsilon_K \geq 90\%$ at 5% misid for p=10…35 GeV
- ➔ improvement over classical method

Muon Reconstruction

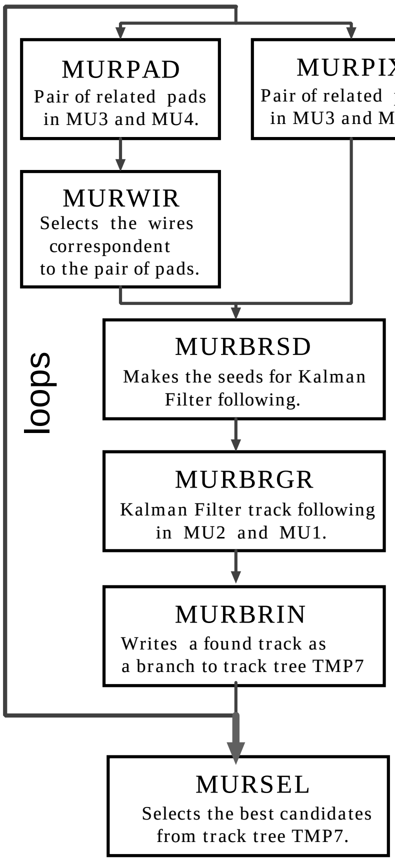
B. Fominykh

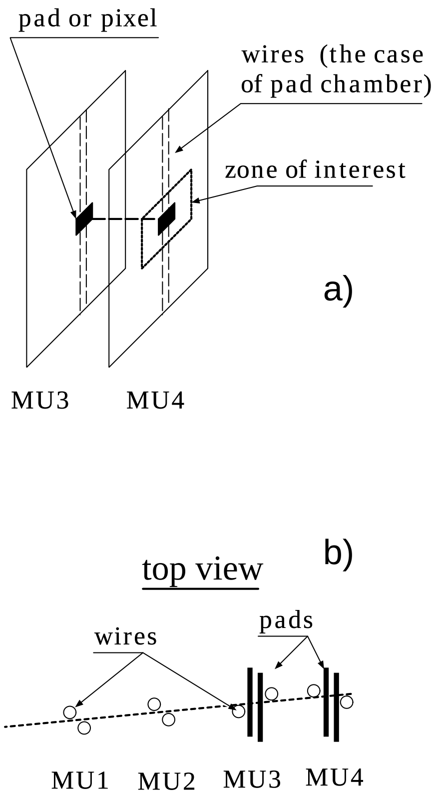


- Combines information from tube, pad and pixel chambers

Muon reconstruction (cont'd)

- Normally, track candidate from main tracker will be used as starting point
- for special studies (commissioning, partial detector setups) a standalone reconstruction method is needed

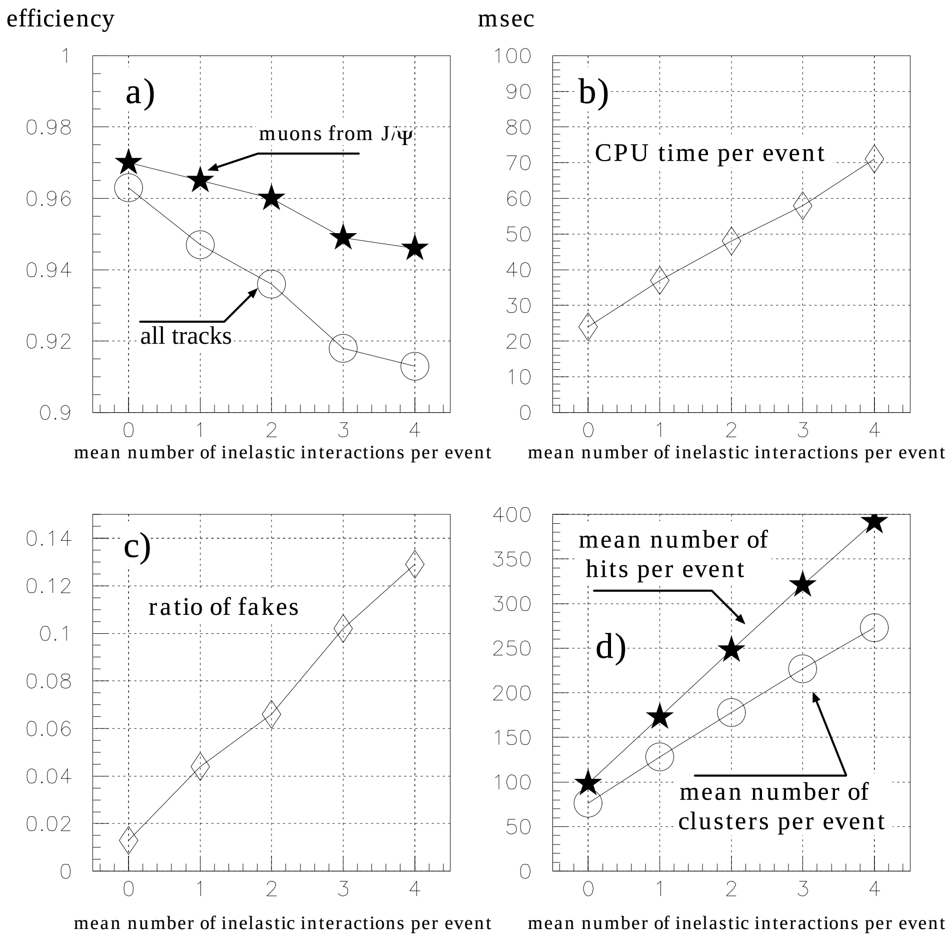




- use seed from pads/wires/pixels in superlayers 3 and 4 as starting point (no absorber in between)
- Kalman filter propagation into superlayers 1 and 2
- transport through first absorber shield

Performance of muon reconstruction

- reasonable performance even in standalone mode for moderate number of interactions
- efficiency limitation due to unknown momentum



➔ use of main tracker segments will improve further both efficiency and fake rate

CP Reach

	BABAR	HERA-B
P for $J/\psi K_S$ ($\pi^+\pi^-$)	0.31	0.31 (0.37)
$J/\psi K_S$ events	1100	1400
Δ sin 2β	$\pm$0.098	$\pm$0.13
All channels combined		
Δ sin 2β	$\pm$0.059	
$\pi^+\pi^-$ events	400	850
Δ sin 2α (1+B/S)	$\pm$0.20	$\pm$0.14
$\rho\pi$ events	400	
Δ sin 2α	$\pm$0.11	
All channels combined		
Δ sin 2α	$\pm$0.085	

- attractive precision on sin 2β after 1 year of data taking

Summary

- HERA-B events hold many interesting challenges for reconstruction
- suitable concepts have been/are being developed
- performance in accord with design expectations
- methods developed for HERA-B appear applicable in LHC environment (LHC-B)