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Vertexing Software and Methods for the ILC

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Outline

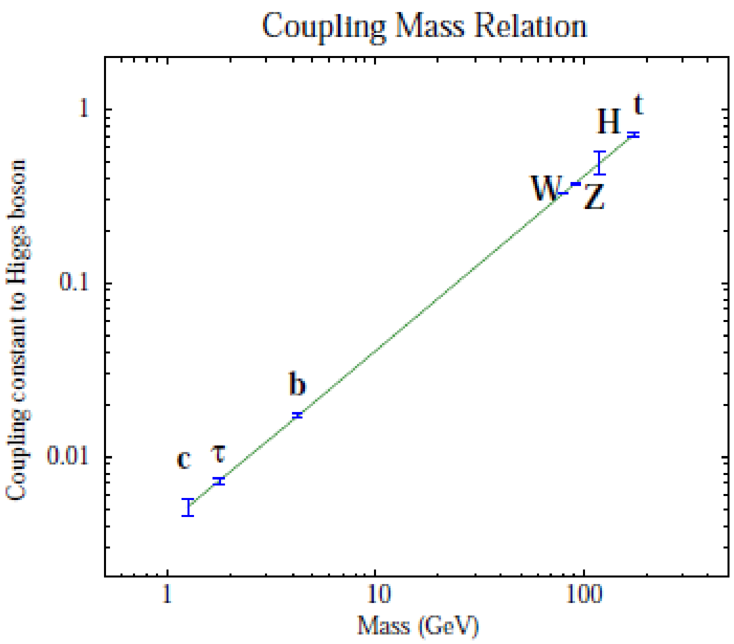
- Physics motivations
- ILD – SiD

} See August's Besson slides

- Tracking algorithms
- Finding vertices
- Flavour tagging

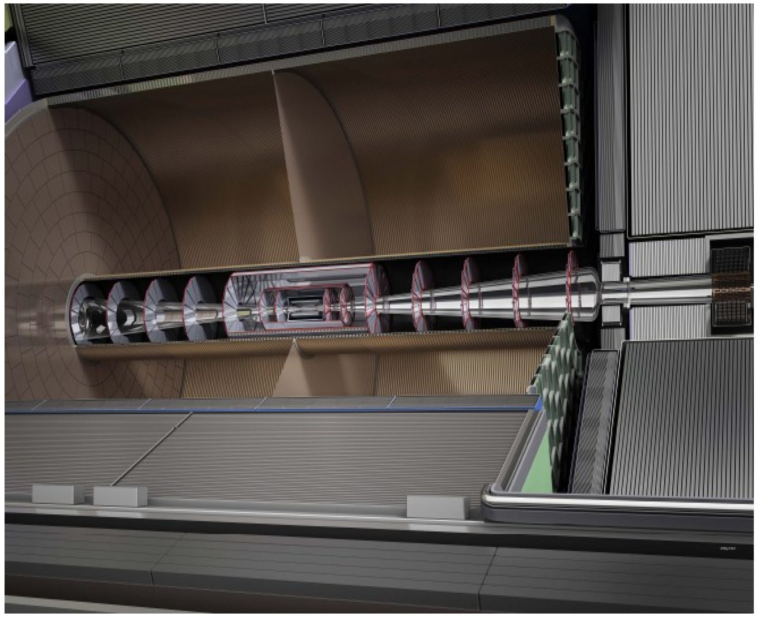
Physics motivations

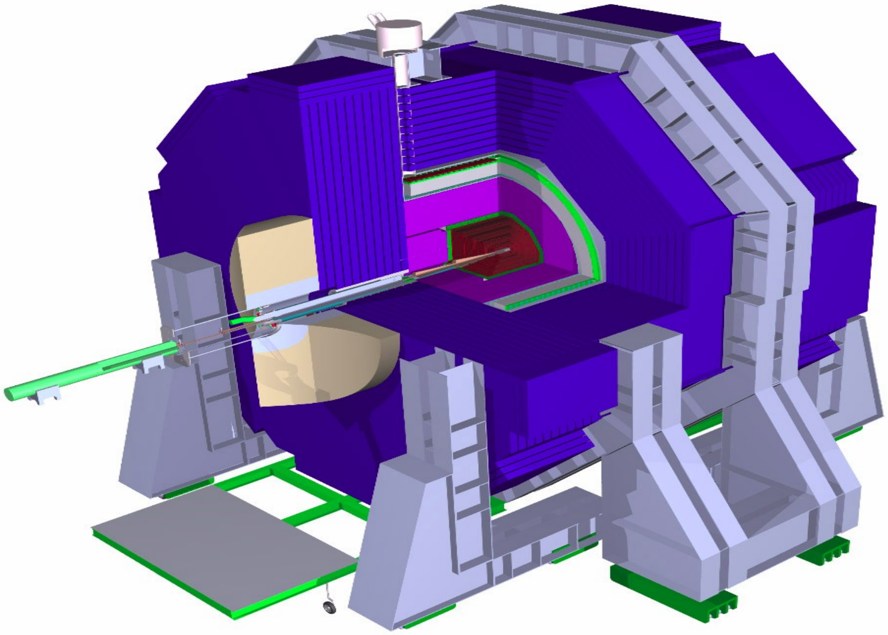
- Higgs couplings
- Expected precision
  - 1 – 2 % to weak bosons, 2 – 4 % to fermions (t, b, c, τ) : global fit, HFITTER, LC-PHSM-2001-053
  - May allow to discriminate, for example, between SM and the lightest SUSY Higgs
    - **Therefore an excellent b,c & τ tagging**



- ZHH → qqbbbb
- tth → bWbWbb
- Vertex charge determination
  - $e^+e^- \rightarrow$ ttbar fwd – bwd asymmetry

Detectors for ILC





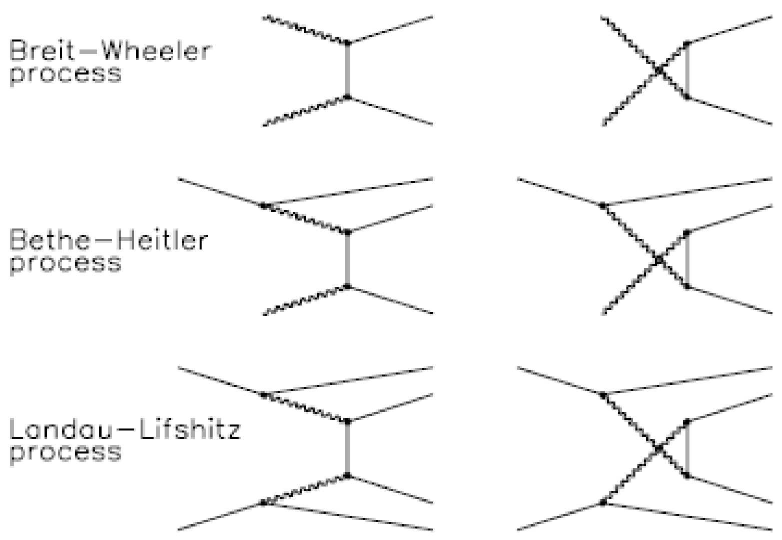
- 2 proposed multipurpose detectors, ILD & SiD
- Optimised for Particle Flow
  - Individually reconstruct every particle inside a jet
    - Highly granular calorimeters
    - Ultra light – high precision trackers
- ILD – SiD main difference
  - ILD: TPC as a main tracker
  - SiD: all silicon tracking
- Main challenge: beam induced bkg
- ILC detectors in simulation
  - Have a sophisticated G4 simulation model
  - Support structures, cabling, cooling infrastructure have been described in details

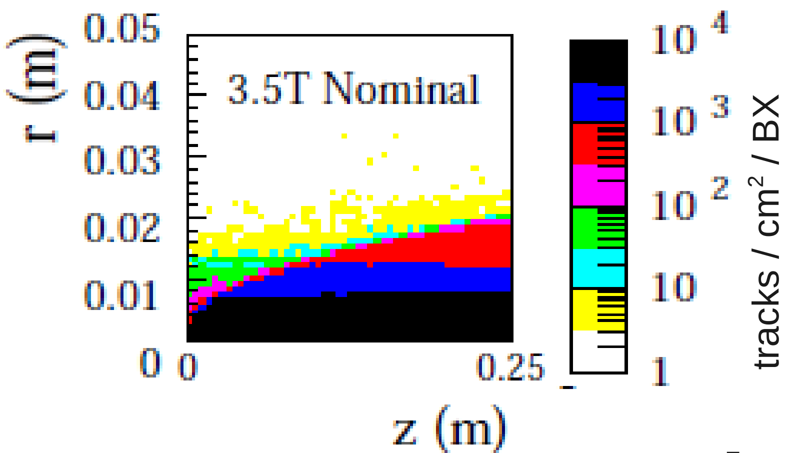
Beam induced background

- ILC offers a very clean environment
- Beam induced bkg the most important bkg source
  - Affects mostly the VXD and the forward trackers
- Beam background dictates pixel occupancy
  - rate of EW interactions < 1 Hz (+bhabha)
  - 1 – 2 % occupancy considered acceptable
  - Hit density decrease ~ exponentially with radius
- Fast enough sensors => ~ 15 mm from the IP
- If not we should move away (~20 mm)
- Main source of radiation damage
  - Rather moderate

- What is the effect of 1 – 2 % occupancy to the physics potential (flavour tagging – Higgs BRs extraction) ?

beamstrahlung





Vertex detector requirements

- Design driven by the need to tag c – hadrons (cτ ~ O(100 μm)) and τ leptons (cτ = 87μm)

- Translated into the Impact Parameter resolution

$$\sigma_{IP} = a \oplus b/p \cdot \sin^{\frac{3}{2}}(\theta)$$

  - $a \leq 5$ μm
  - $b \leq 10$ μm GeV/c

↓

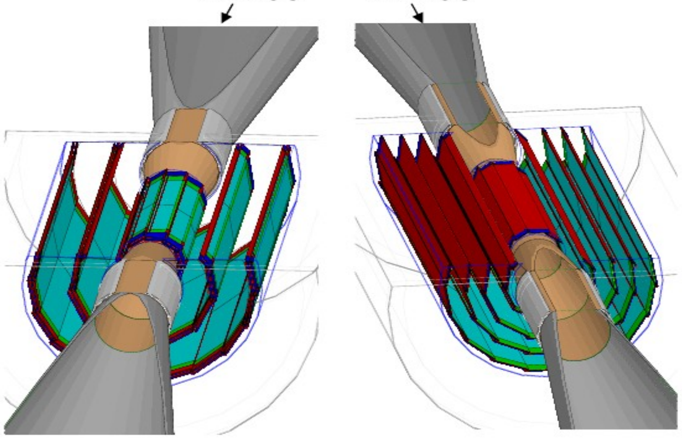
- VXD physics driven requirements:
  - Sensor's single point resolution ~ 3 μm
  - Distance of innermost layer from the IP: 15 – 16 mm
  - Material budget (MB)< 0.2 % X_0 per layer
    - Low power dissipation

Accelerator	a (μm)	b (μm·GeV/c)
LEP	25	70
SLC	8	33
LHC	12	70
RHIC-II	13	19
ILD	< 5	< 10

- ILC running constraints requirements:
  - Pixel occupancy ≤ 1 – 2 %
    - Different strategies for each design / technology
      - Time resolution, very high granularity (FPCCD)
  - Radiaton tolerance: 0.3 MRad / y, few 10^{11} n_{eq} / cm^2 y (safety factor of 3)

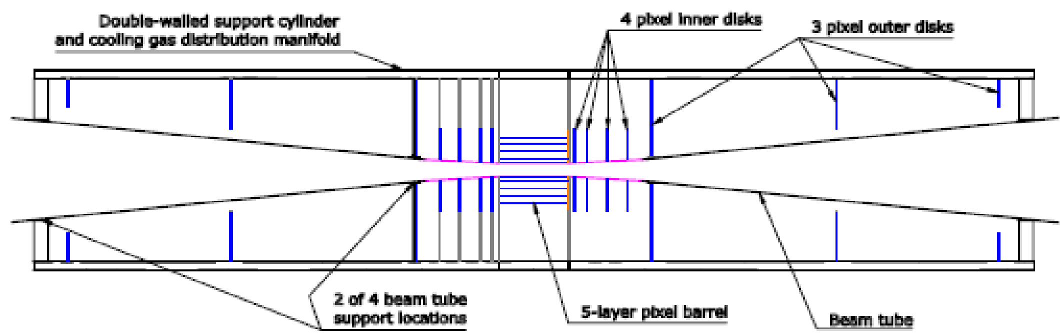
Vertex detectors for ILC

- ILD
- 5 single or 3 double sided layers design
- Complemented by 2 layers strip detector (SIT) & fwd tracking disks (FTD)



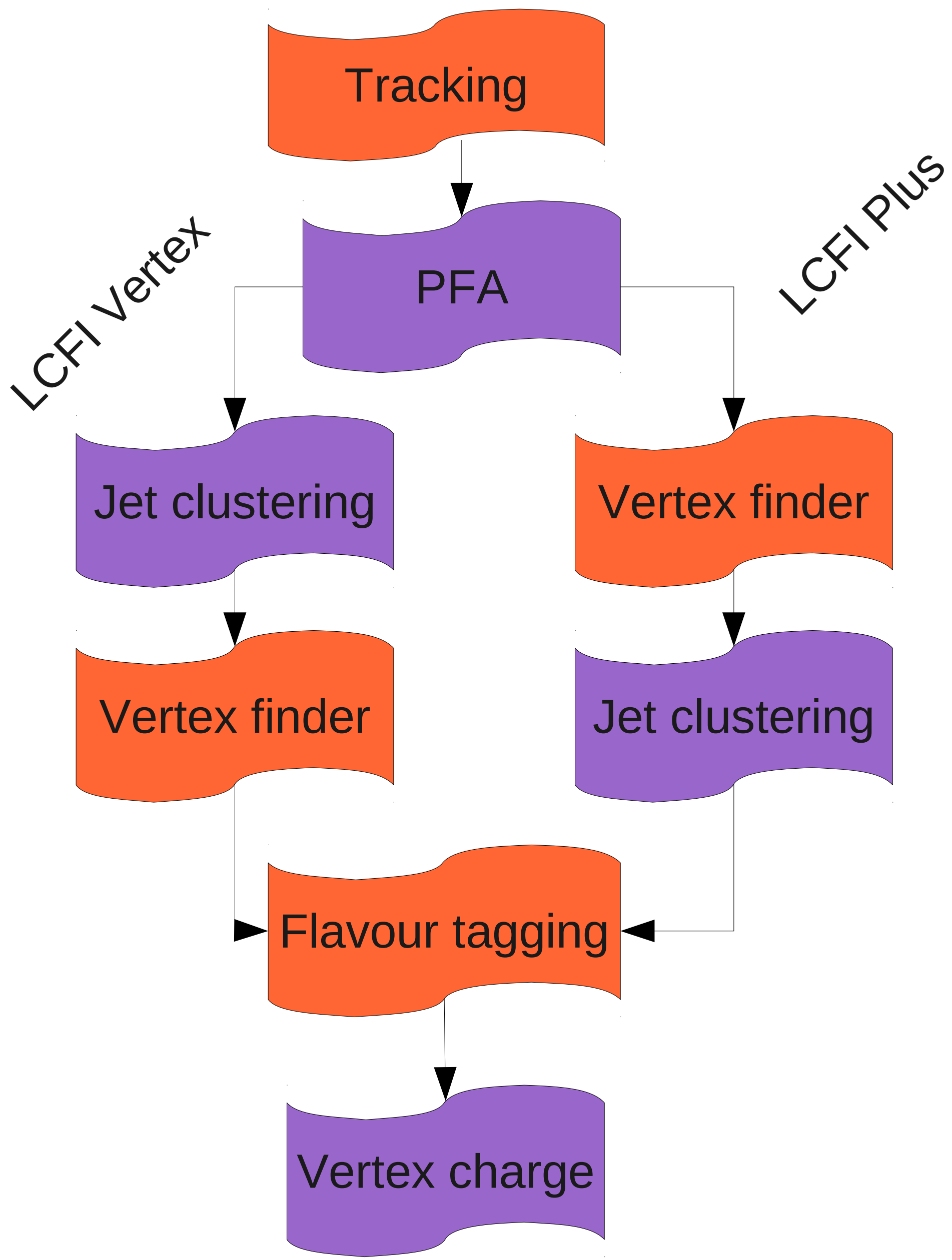
- CMOS Pixel Sensors (A. Besson)
- FPCCD
  - Very high granularity (~5μm pitch) full bunch train integration
- DEPFETs (C.Koffmane's talk)

- SiD
- 5 single layers complemented by 4 inner and 3 outer pixel disks



- 3D integrated sensors
- Chronopixels

Vertexing strategy in ILC



Tracking

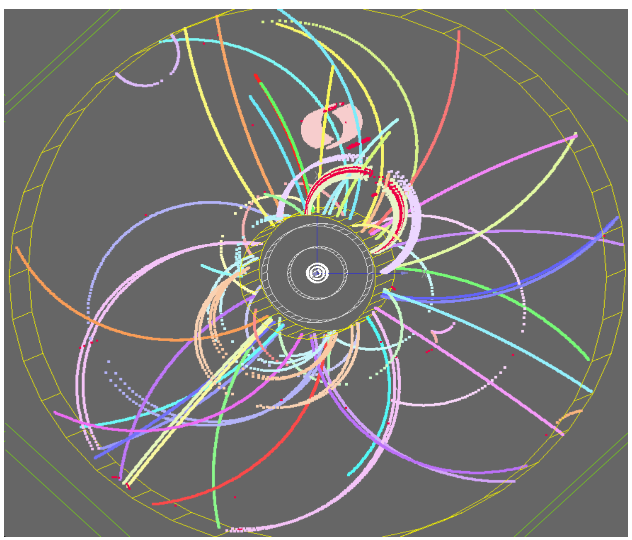
Tracking in SiD

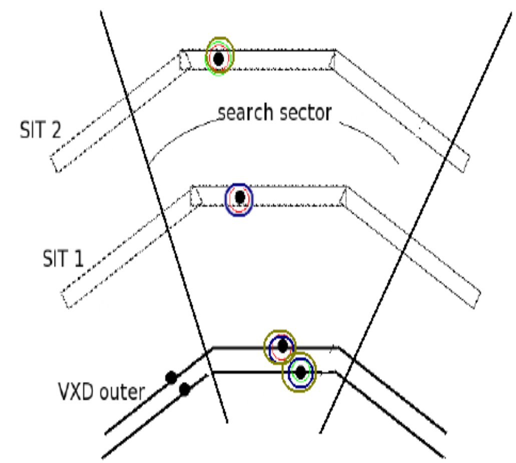
- SiD features all Si tracking
  - ~ 10 hits / track, measured with high precision
- Assuming single BX time resolution
- Seeding
  - Brute force hit triplet search in “seed” layers (VXD)
  - Keep the triplets that satisfy the helix hypothesis
- Require hit at one “confirmation” layer
  - Substantially reduces combiantorics
- Track is extrapolated to the “extension” layers
  - Adding hits – fulfilling the minimum required # of hits
  - Each time a hit is added, a global χ^2 decides whether to keep the new candidate
- MSC angle is added to the uncertainty in track extrapolation
- Case of hit sharing:
  - Best track (#hits or χ^2) kept

Tracking in ILD

- **Clupatra processor**
- Form seeds using Nearest Neighbours hit clustering
- Propagate seeds both inwards & outwards using Kalman fitter
- Associate best matching hit
- Update track state
- So on...

- **SiliconTracking**
- Divide VXD – SIT into angular sectors
- brute force triplet search in phi sectors based on a set of seed-layer-triplets
- Fit a helix to the seed triplets
- Follow the seed inwards – attach hits according to the distance from the helix
- Refit with Kalman fitting



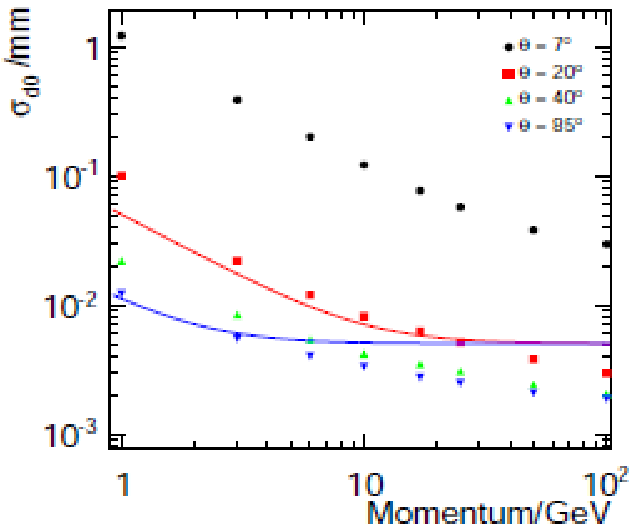


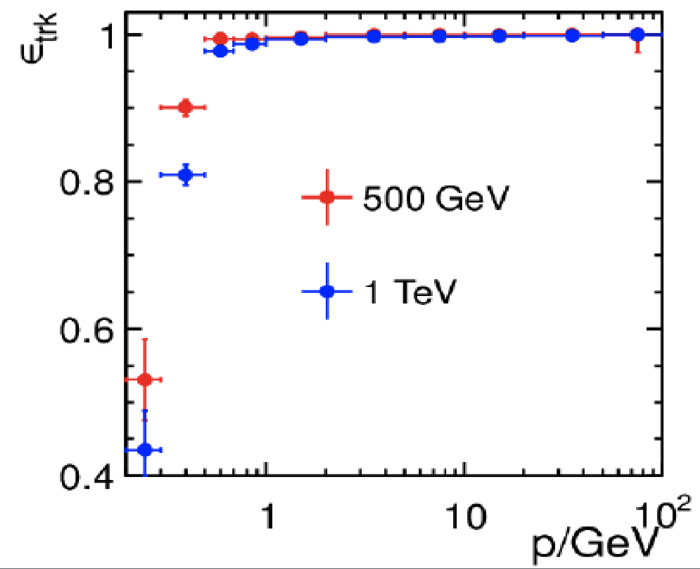
- **Forward Tracking**
- Standalone tracking algorithm at FTD
- Pattern recognition: Cellular automaton
- Fitting: Kalman filter
- Ambiguities resolution: Hopfield NN

- **FullLDCTracking**
- Combines track from TPC – FTD – Silicon tracking
- Based on track parameter compatibility
- Adding spurious leftover hits
- Final track fit

Performance – challenges in ILD tracking

- IP resolution meets the goals
- Impressive track finding efficiency for TPC
  - Efficiency def: 90% purity
    - TPC dominated
  - Low P_T tracks reconstruction not satisfactory
- Hundreds of Bxs overlaid – depending on the layer and the sensor technology
  - Vast combinatorial bkg
- Silicon tracking
  - Doesn't appear to have optimal performance under realistic conditions
  - Can't cope with combinatorics induced by pair bkg
- New approaches currently investigated
  - FPCCD Tracking (T. Mori et al, Tohoku Univ.)
  - Cellular automaton for VXD tracking based on mini – vectors (DESY)

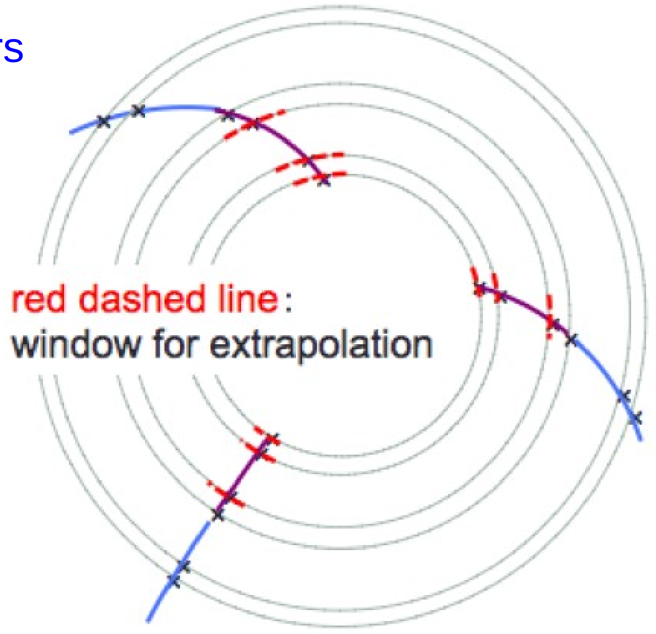




Plots from DBD – ttbar sample, pair bkg included
~ 99.7% eff, P≥ 1 GeV, ≥ 99.8%, cos(θ) < 0.95

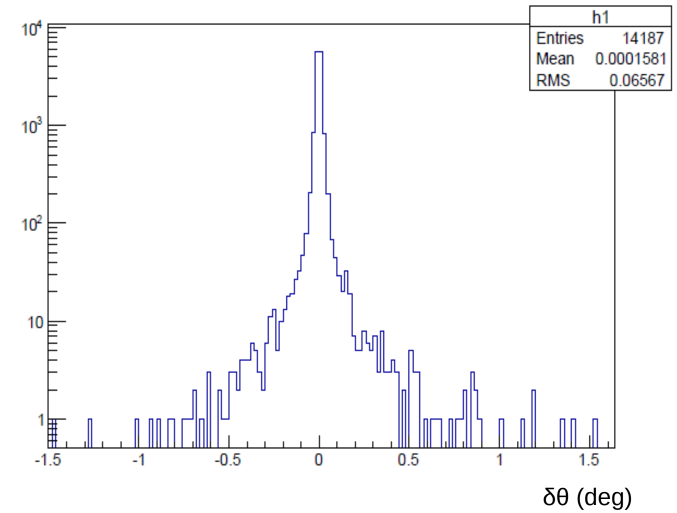
FPCCD tracking

- Following the std silicon tracking philosophy
- Has improved the following crucial steps:
- Seed formation:
  - Angular sectors: φ width enough to generate seeds with minimum P_T 180 MeV
- Track extrapolation
  - Extrapolate seeds using Kalman filter instead of simple helix fit
    - More efficient for low P_T tracks, takes into account MSC
  - φ width for extrapolation flexible, defined by track parameters
    - It catches true hits and avoids most of bkg hits



Striking improvement in Silicon tracking performance
in terms of efficiency, ghost rate, time
in the presence of pair bkg compared to std algorithm

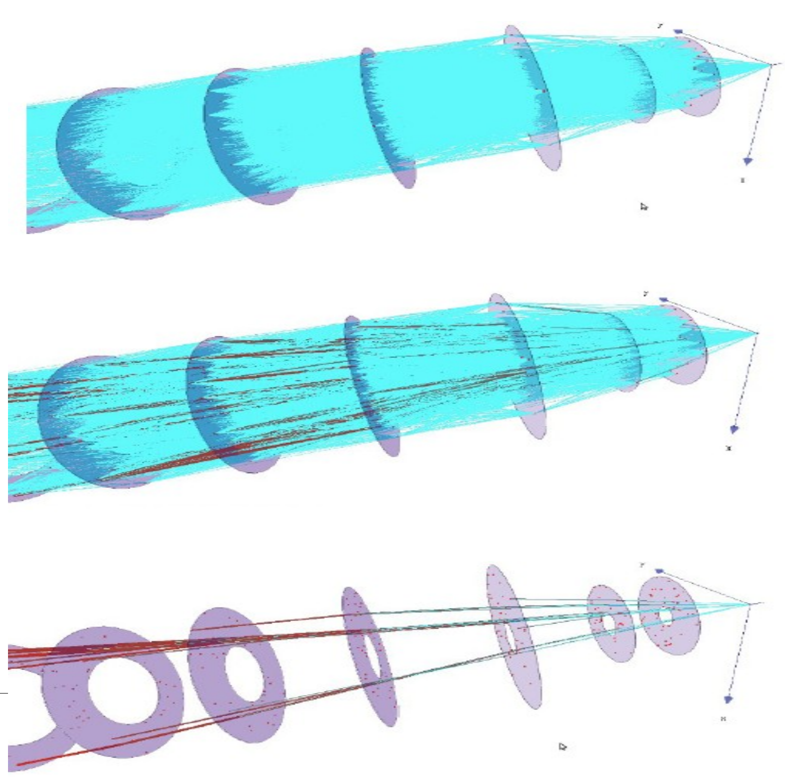
Mini – vector cellular automaton VXD tracking



ttbar, δθ of hits belonging to a MV based on MC info

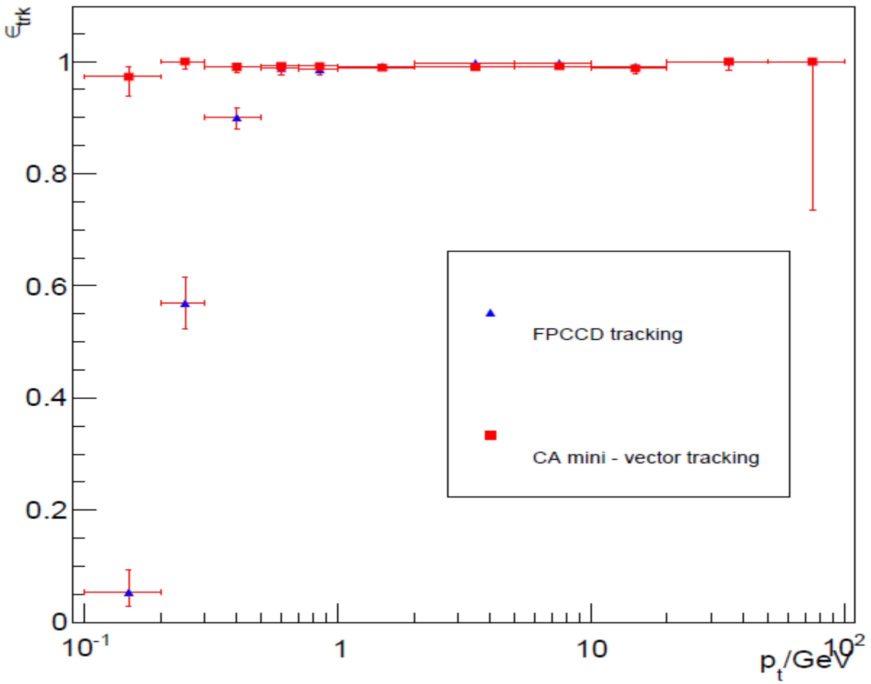
- Exploits the double sided ladder structure of VXD
- Up to now, has been applied in various CMOS VXD configurations (see table)
- Mini – vector formation
  1) Hits in adjacent layers (dist 2mm) with max distance 5mm
  2) Or δθ between hits in adjacent layers (cut can go up to 0.1^0)
- Divide VXD into θ, φ sectors
  - Try to connect mini – vectors in neighbouring sectors using a cellular automaton algorithm
- Cellular automaton is already there for the FTD tracking
- Very flexible
  - Appealing to be used for pattern recognition in other detectors
  - See R. Glattauer Diploma thesis

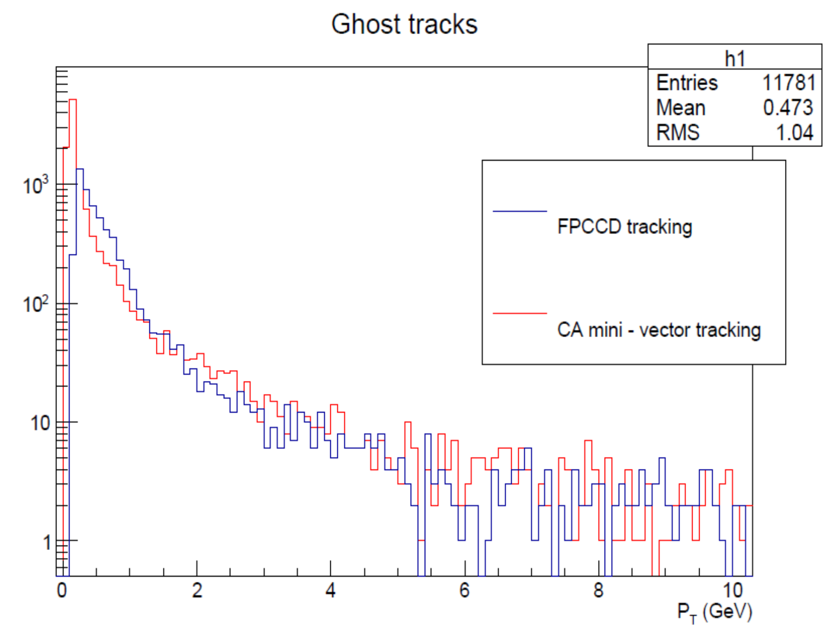
http://www.hephy.at/fileadmin/user_upload/Publikationen/DiplomaThesis.pdf



Performance of new VXD tracking tools

Sample: ttbar, √s = 500 GeV, fast CMOS VXD, pair bkg overlayed





- We have the tools to probe to VXD performance in realistic conditions
  - Cellular automaton MV tracking optimised for a faster CMOS detector
  - FPCCD tracking can cope with higher bkg rates → FPCCD VXD
- Effect of “bad” tracks in vertexing – flavour tagging should be evaluated

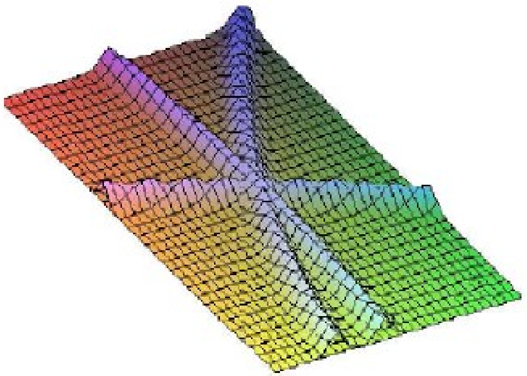
Vertexing

Vertexing in ILC

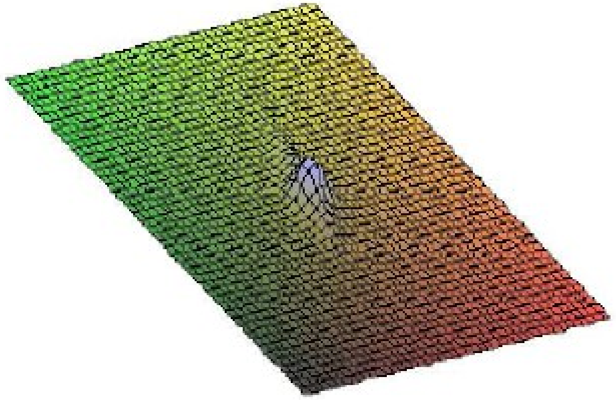
- Both experiments share the same tools
- 2 ideas
- LCFIVertex
  - First realistic vertexing – flavour tagging tool for ILC
  - Developed by LCFI group
    - UK – NIM A, 610 573 2009
  - Searching for secondary – tertiary vertices inside jets

- LCFIPlus
  - Extension / improvement of LCFIVertex
  - Motivated mainly by the ZHH study
  - T. Tanabe, T. Suehara ICEPP
    - https://confluence.slac.stanford.edu/display/ilc/LCFIPlus
  - Vertex reconstruction in event level

ZVTOP Vertex Finder



- Re-implementation of the topologocal vertex finder of SLD, ZVTOP
  - D. Jackson, NIM, A388 (1997), 247
- Jet – based vertexing sw
- Track selection
  - Removal of tracks originating from γ conversions, K_s / Λ decays
- Tracks are represented by 3D probability tubes
- Combine track probabilities→ vertex density function
  - Local maxima: candidate vertices



- Provides criterion to resolve vertices
- Heavy hadrons expected to decay close to jet axis
  - Vertex function is weighted outside a cylinder around jet axis

From LCFIVertex to LCFIPlus

- Motivation to develop an event-based vertexing
  - Tracks from a secondary vertex might be assigned to wrong jets
    - More significant in many jets events
- LCFIPlus focuses on many – jets environment
- Tear down primary vertex finding
  - Fit a set of tracks to a common vertex
  - Remove track with highest χ^2 & refit until χ^2 threshold reach
- Build up secondary vertex finding
  - Remove all tracks assigned to IP vertex
  - Starting by creating pair of tracks
  - Fit them at their common vertex (PCA of the tracks)
  - Try to assign other tracks to the pairs & refit

Flavour Tagging

Jet clustering

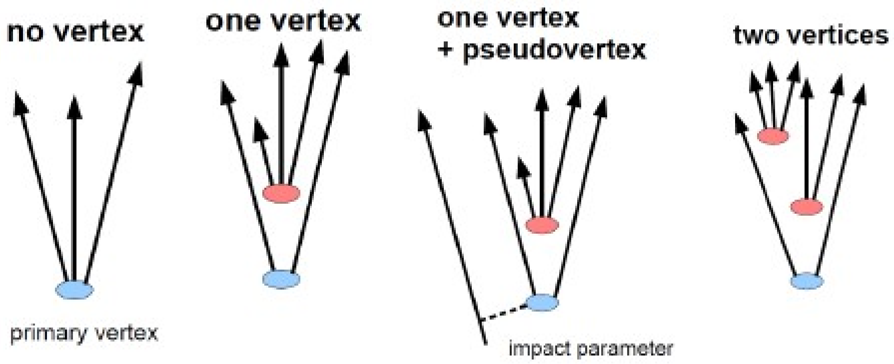
- Uses vertex info in jet clustering
- Divide jets into 4 categories, depending on jet's vertex multiplicity
  - Each class has different set of input variables, undergo dedicated training

1) Only IP vertex is found

2) 1 secondary vertex is found

3) 1 secondary vertex is found + single track vertex

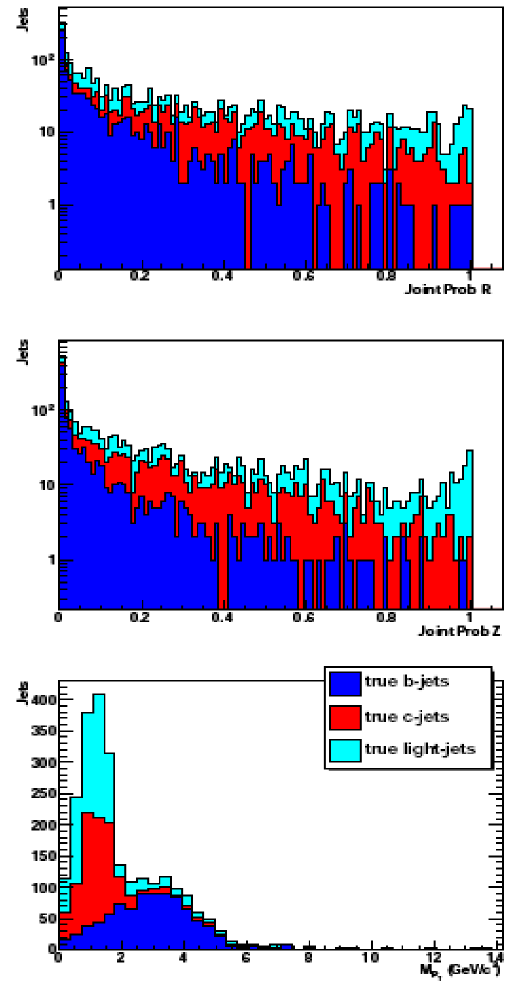
4) > 1 secondary vertices found



From P. Roloff

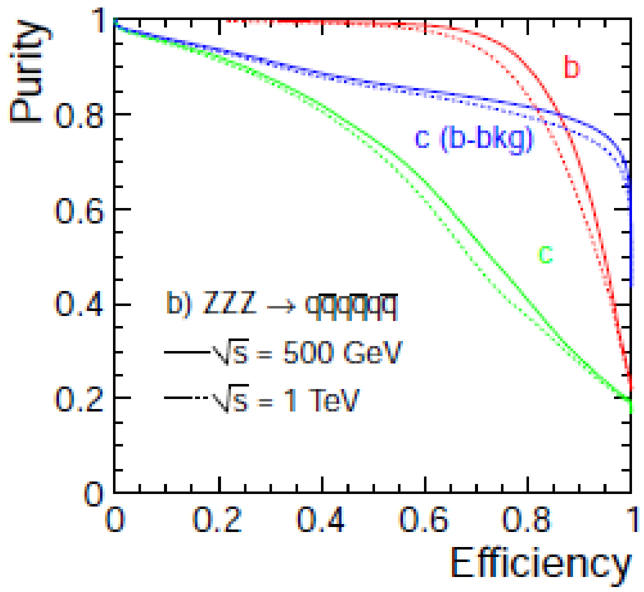
Flavour tagging

- Neural nets based flavour tagging (LCFIVertex)
- Succeded by BDTs (LCFIPlus)
- ~ 20 – 30 discriminating variables are used
- Different set of discriminating variables used for each jet class
  - Main variables when only primary vertex is found
    - Impact parameter significance and P_T of the 2 most significant tracks
      - Crucial to identify one – prong decays
    - Joint probability that all tracks coming from primary vertex
  - When the jet has 2 or more vertices
    - Mostly use observables from the additional vertices
      - P_T corrected vertex mass



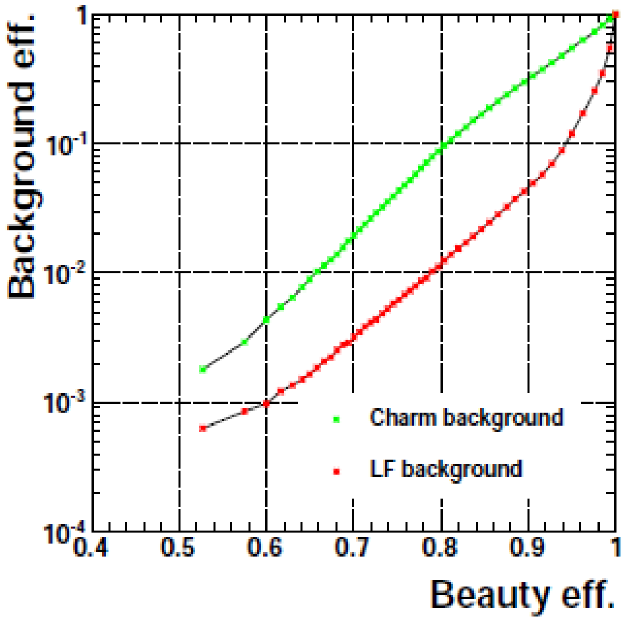
$e^+e^- \rightarrow HZ$

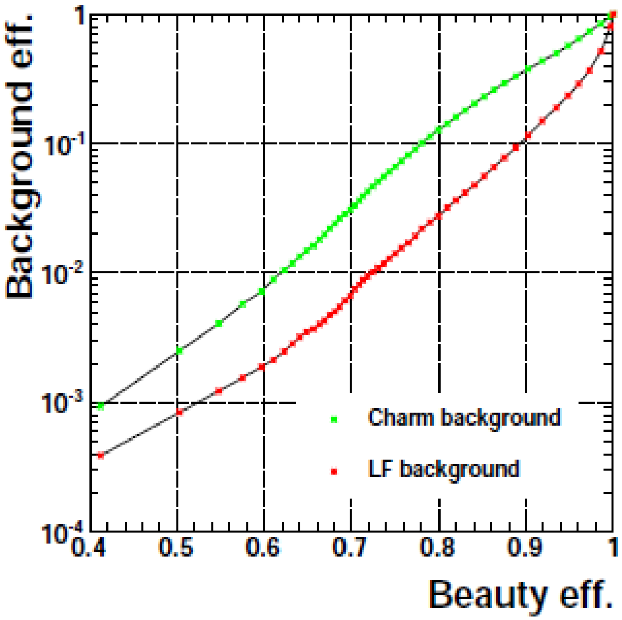
Performance



- ILD
- 6-jets event
- Slight degradation for higher energies under study

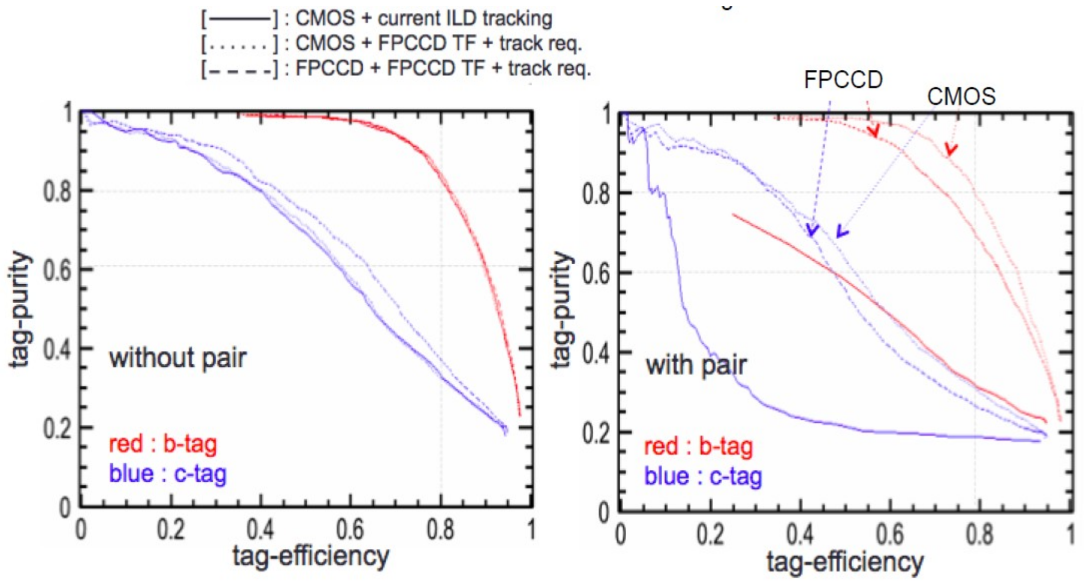
- SiD
- b-quark sample
- Training: di-jets, √s 91 GeV
- Right: no beam bkg
- Left: + beam bkg





Performance in presence of beam bkg

Results from J. Strube talk at AWLC14
Using the FPCCD tracking algo



- We examine 2k evts of Z→bb, cc, uds
  - One bunch train of pair bkg overlayed
- LCFIPlus trained with 14k evts
  - No pair bkg

Detector	Algorithm	Pairs	b – tag purity (%) (efficiency 80%)	c – tag purity (%) (efficiency 60%)
DBD	STD	No	82.8	56.4
DBD	STD	Yes	30.4	20.0
DBD	FPCCD	Yes	77.6	49.4
FPCCD	FPCCD	Yes	67.8	41.6

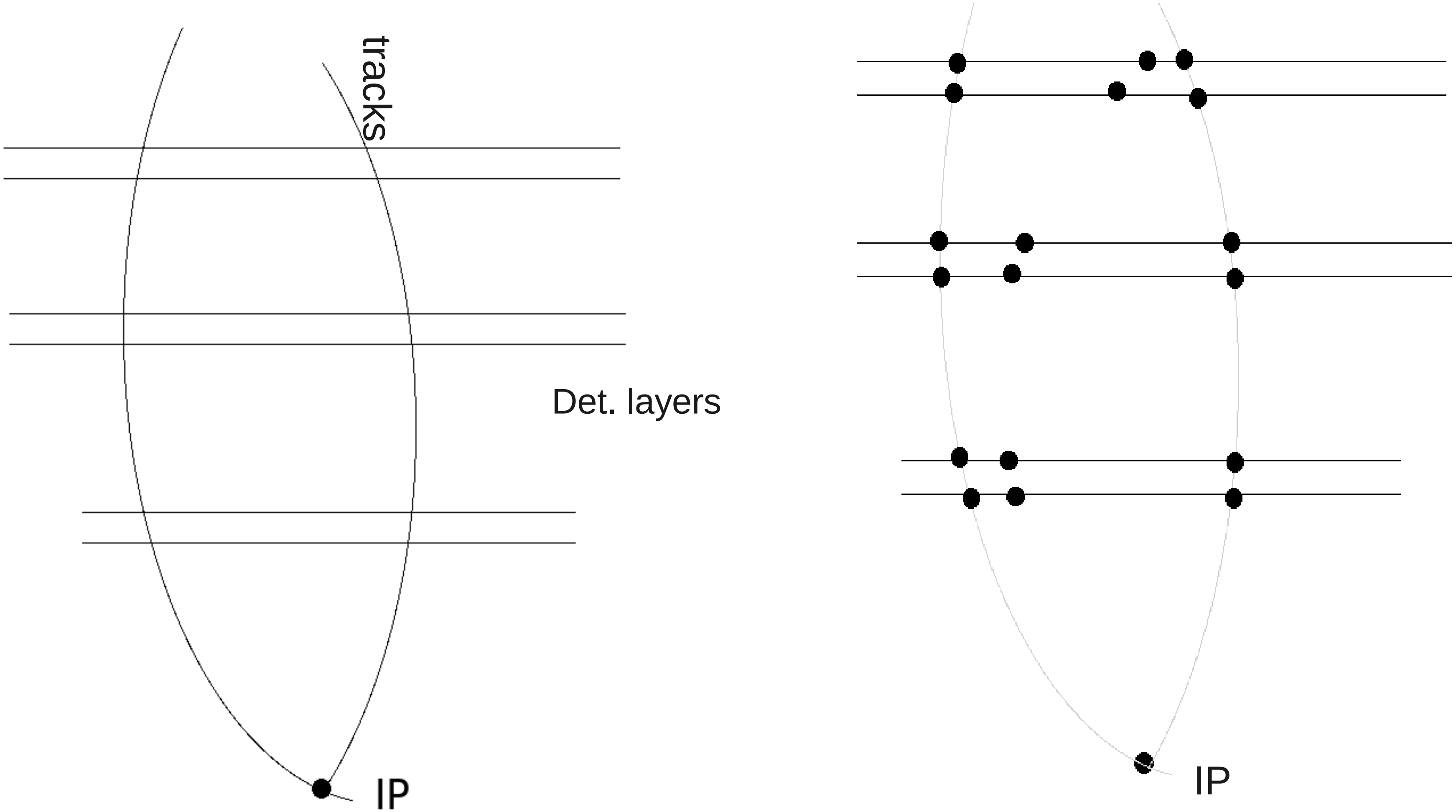
- Pair bkg degrades significantly the flavour tagging performance
- FPCCD track finder substantially improves the flavour tagging performance, compared to std silicon tracking algorithm

Summary

- Diverse tracking pattern recognition methods, adapted to detector concepts
  - Excellent finding efficiency for P > 1 GeV, meets the goals in IP – momentum resolution
  - ➔ Issues on low P_T track reconstruction due to beam bkg are being addressed
- Common tools for vertexing – flavour tagging
- Event based vertex finding
- Classification of jets w.r.t. vertices found
- TMVA BDTs flavour tagging
- ➔ Currently under study in realistic conditions (beam bkg)

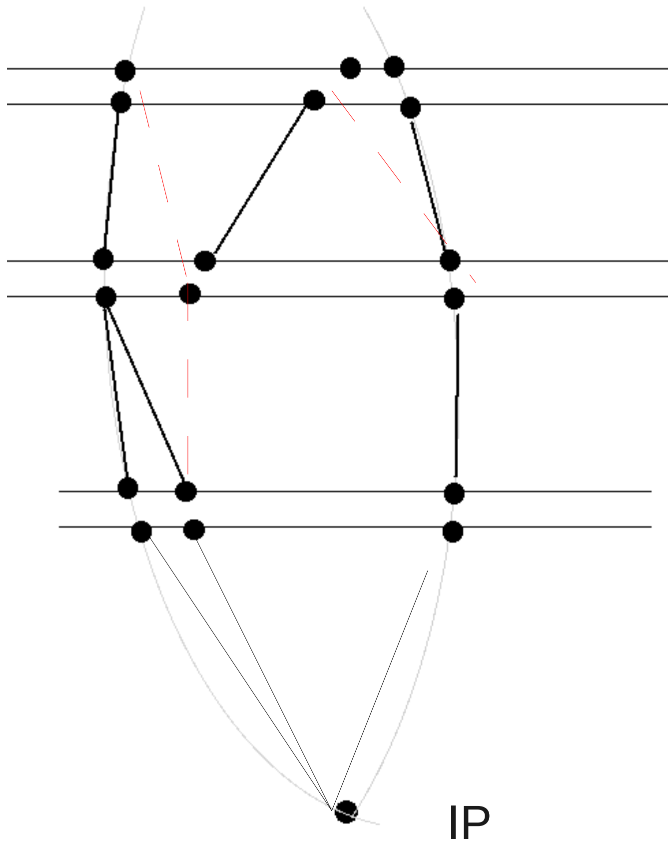
BACKUP

Cellular Automaton



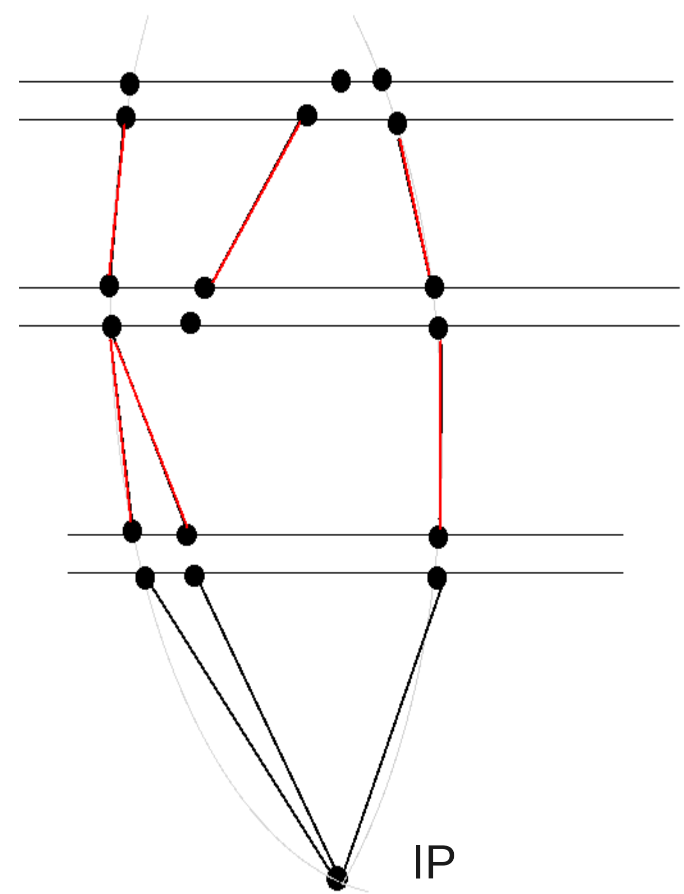
Next: try to connect the 2-hit segments
Sets of criteria (e.g. φ pointing of MV) decide whether the connection is valid

Cellular Automaton – first pass



Connection filtered out by MV φ angle crit.

- First pass of cellular automaton
  - Every cell starts with state 0
  - Connect only cells having the same state
  - If a cell is connected with another, its state is raised by 1 (red segments)

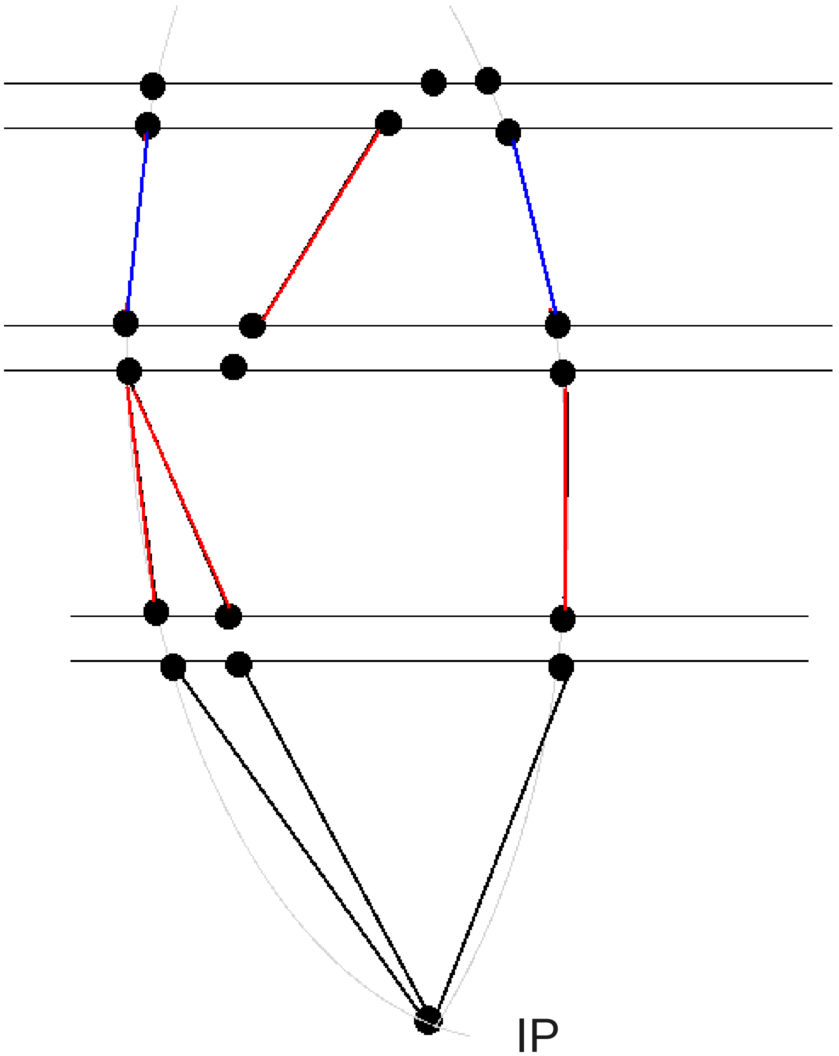


Cellular Automaton – second pass

- Second pass of cellular automaton
  - State 2
  - State 1
  - State 0
- CA continues up to the point no other changes occur in cell's states
- Consider segments where

  state = layer number

  as good

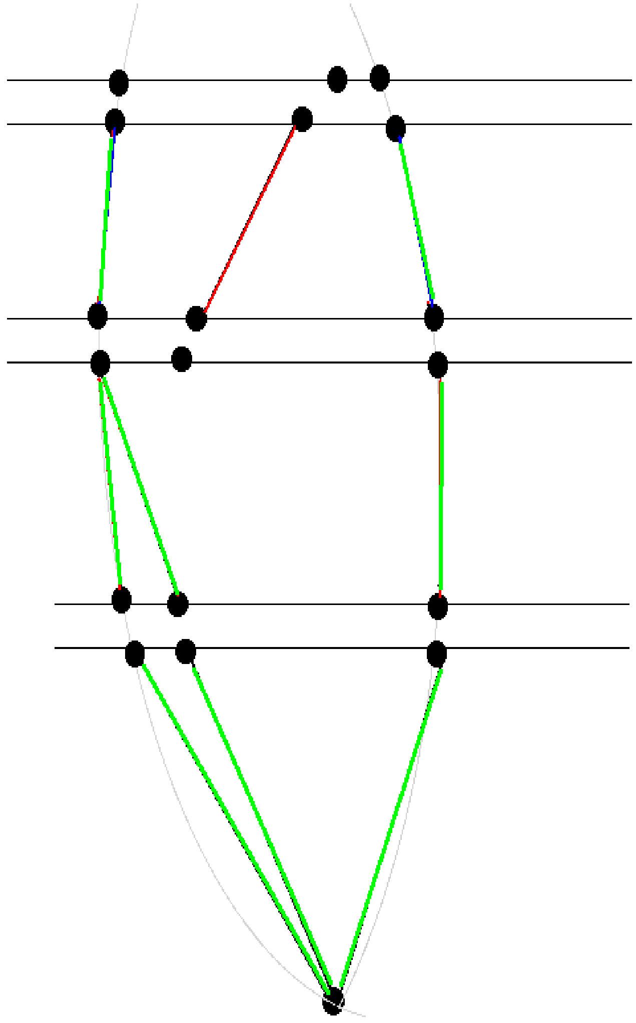


Cellular Automaton – collect tracks

- Second pass of cellular automaton
  - State 2
  - State 1
  - State 0
- CA continues up to the point no other changes occur in cell's states
- Consider segments where

  state = layer number

  as good
- Form track candidates



ZVTOP maths

$$f_i(r) = exp\{-\frac{1}{2}(\vec{r}-\vec{p})V_i^{-1}(\vec{r}-\vec{p})^T\}$$

$$V(\vec{r}) = \sum_{i=1}^{N} f_i(r) - \frac{\sum_{i=1}^{N} f_i^2(r)}{\sum_{i=1}^{N} f_i(r)}$$

$$\frac{min\{V(\vec{r})\} : \vec{r} \in \vec{r_1} + \alpha(\vec{r_2} - \vec{r_1}), 0 \leq \alpha \leq 1}{min\{V(\vec{r_1}), V(\vec{r_2})\}} \leq R_0$$