Introduction to Tracking

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Introduction

- Disclaimer
  - I am a "silicon guy", hence there will be a certain bias towards silicon trackers
- This talk should serve as an introduction
  - Overview on relevant issues
  - Neither encyclopedic nor complete
- More details on Tracking Detector Technologies
  - I. Gregor on Silicon Detectors
  - M. Titov on Gaseous Detectors
- Goal
  - Understand the issues and "what people talk about"
  - Get you interested in tracking detectors

Roadmap

Basics

Tracking Detectors

Readout & Digitization

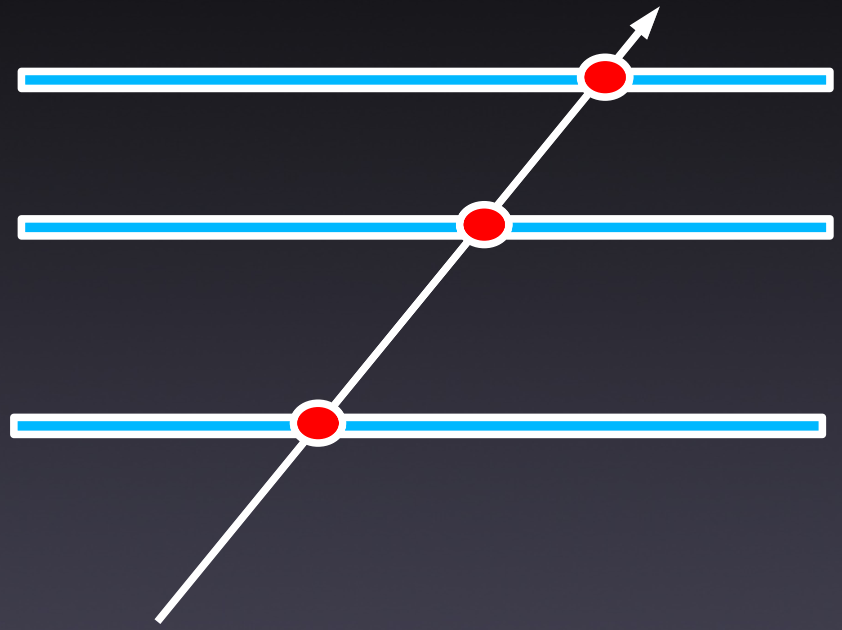
Track Recon-struction

Tracking -What is it ?

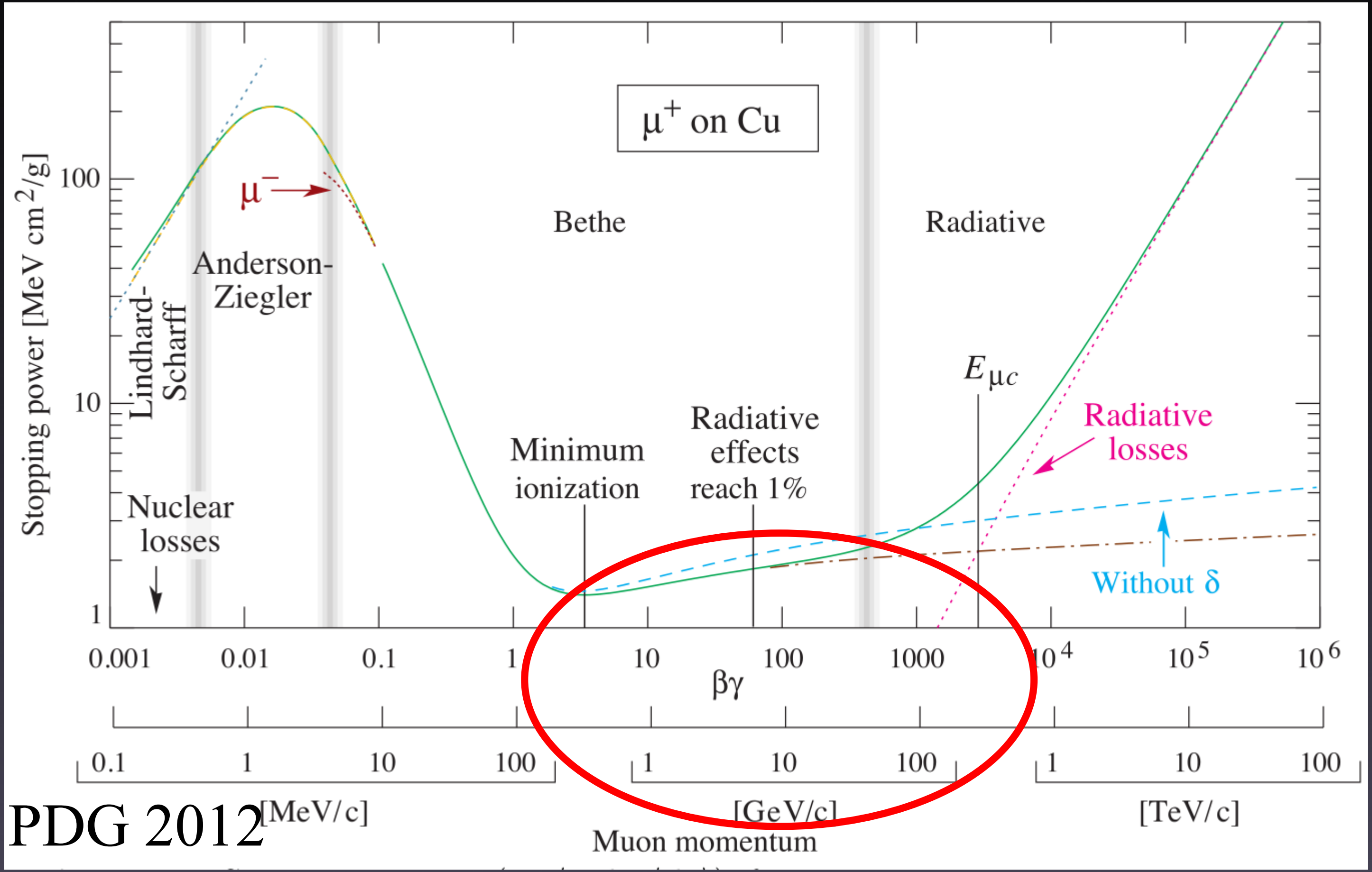
Tracking:
to follow or pursue the track, traces, or footprints of.

Basic idea

- Reconstruct the charged particle's trajectory through the detector
  - Obtain several position measurements
- Minimal interruption of the track
  - Minimize material
- Adding magnetic field
  - Get particle momentum
  - Charge information



Particles through matter



Particles through matter

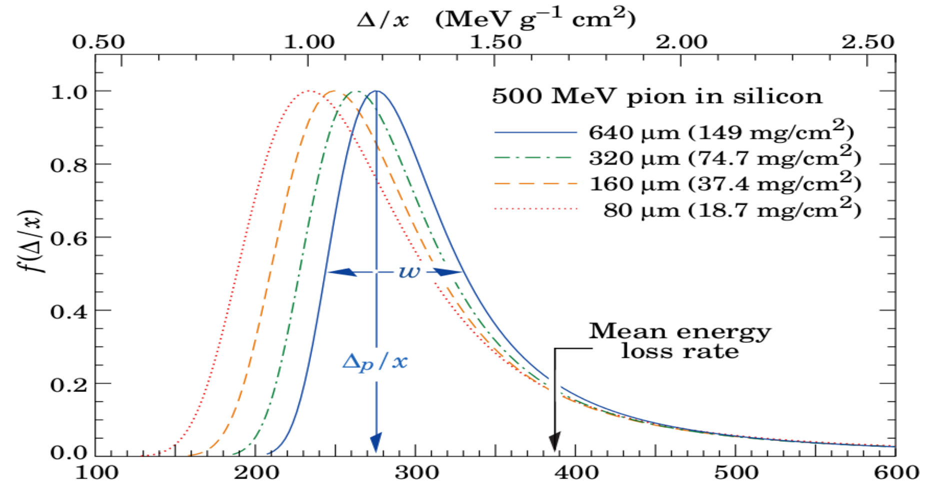
- We're mostly dealing with minimum ionizing particles
  - Track momenta usually between 1-100 GeV
- Particles traversing thin material layers
  - Small deviations caused by mainly Coulomb-Scattering
  - Deviations depend on Material (Z,A and ρ)

$$\theta_0 = 13.6 \frac{\mathrm{MeV}}{\beta c p} \cdot Z \sqrt{x/X_0}\left[1 + 0.0038 \ln\left(x/X_0\right)\right]$$

$$X_0 = \frac{716.4\,A}{Z(Z+1) \cdot \ln\left(287/\sqrt{Z}\right)} \cdot \frac{1}{\rho}$$

Modeling the Energy loss

- For single particles
  - Strong fluctuations on the individual particle level
  - Pure Bethe Approach not useful
- Best described by a Landau-Function
  - 90 % of interactions have less than mean energy loss rate
  - But large tail of large energy loss events



PDG 2012

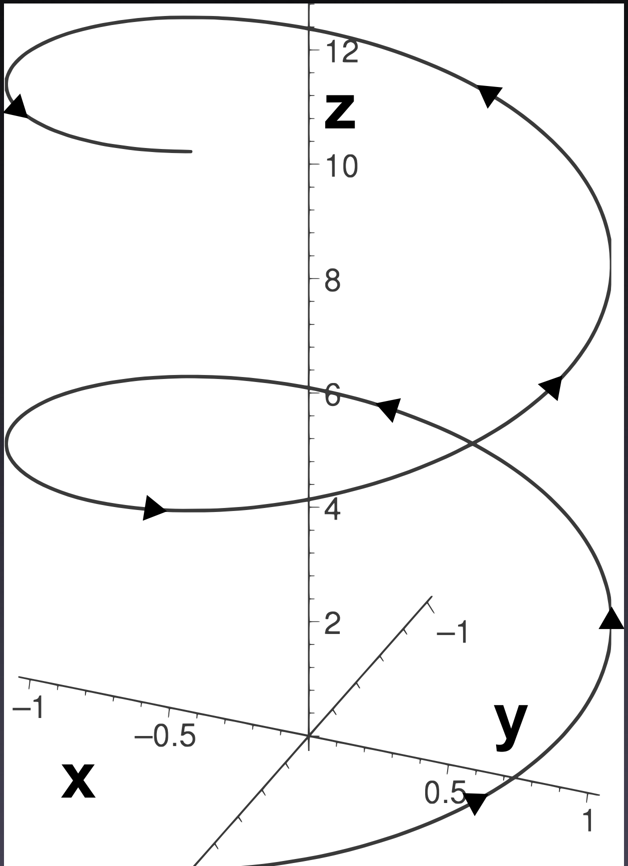
Note:
The Landau-Function itself is an approximation for thin tracking layers

Particles in a magnetic field

- All driven by the Lorentz Force

$$\vec{F} = q \cdot \vec{v} \times \vec{B}$$

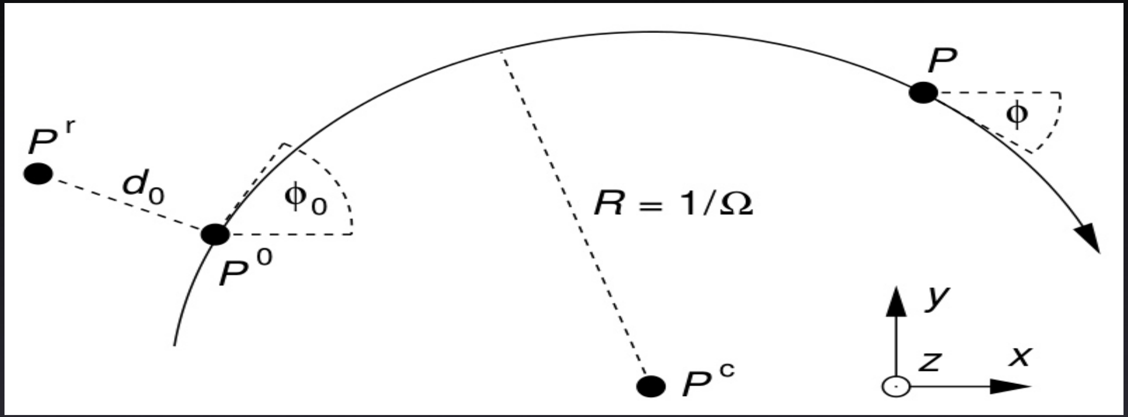
- Particles trajectories follow a helix
  - Arc/Circle in the xy plane
  - Line in z
- Various parametrizations
  - Each experiment has one...

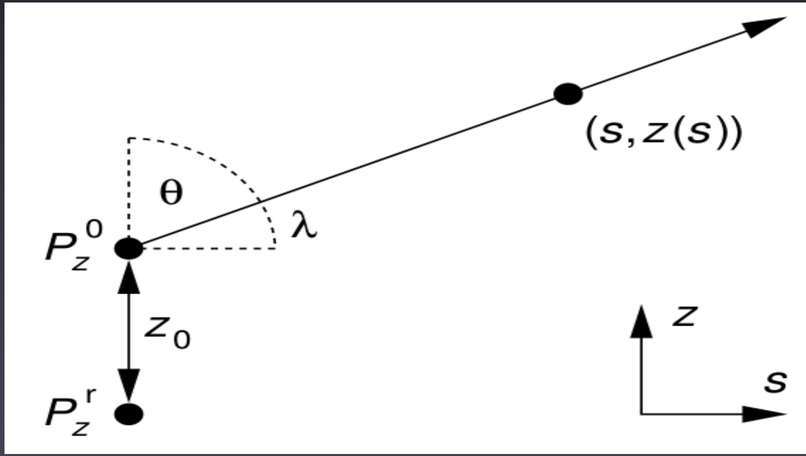


Wikipedia

Example - LCIO Helix Parametrization

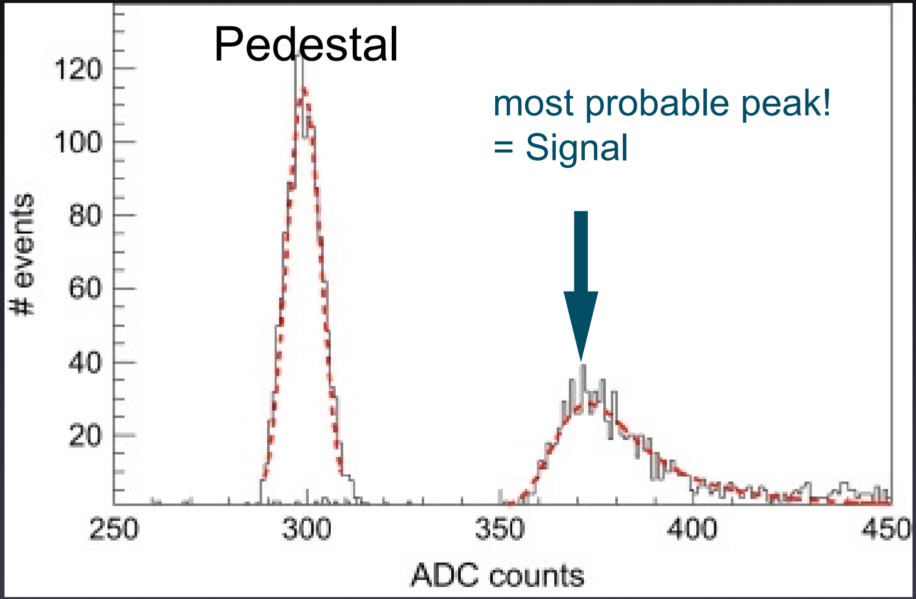
- 5 Parameters
  - P_0 is the point of closest approach (p. c. a.)
  - φ_0 :azimuthal angle of the momentum at p.c.a
  - Ω : track curvature t
  - d_0:signed impact parameter in xy
  - tanλ is the slope dz/ds of the straight line in the sz plane, with s being the arc length
  - z_0: position of the track at the p. c. a.
- See LC-DET 2006-004





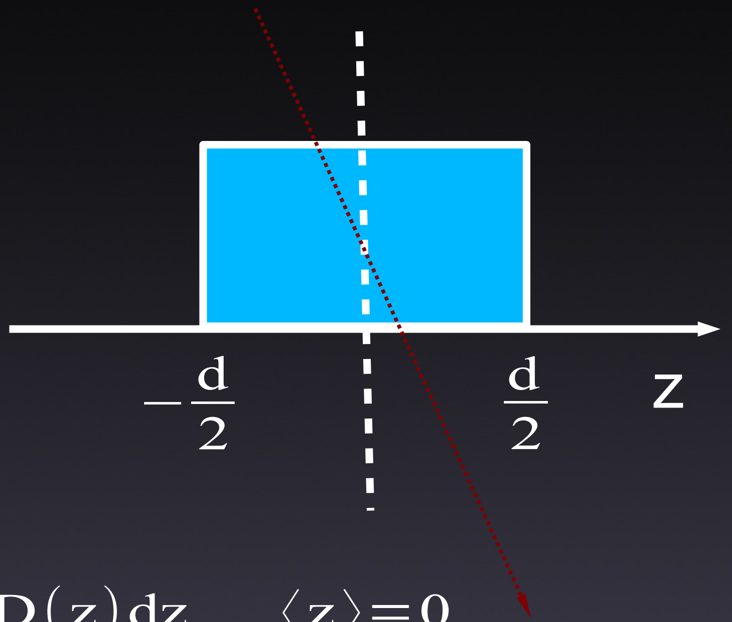
Signal-to-Noise

- Signal/noise ratio: signal size for a certain input signal over the intrinsic noise of the detector
  - parameter for analog signals
  - good understanding of electrical noise charge needed
- Signal induced by source or laser or test beam particles
- optimal S/N for a MiP is larger than 20
- N.B.
  - Noise = sigma of pedestal distribution
  - signal = most probable peak - pedestal



Single Point Resolution

- The figure-of-merit of any tracking detector
- Single Detector element
  - Pitch d
- Track Probability (D(z) is flat
  - Expectation value is 0 (center)
- Variance is:



$$\sigma_z^2 = \int (z - \langle z \rangle)^2 dz / \int D(z) dz \qquad \langle z \rangle = 0$$

$$\sigma_z^2 = \int_{-\frac{d}{2}}^{+\frac{d}{2}} z^2 dz / d$$

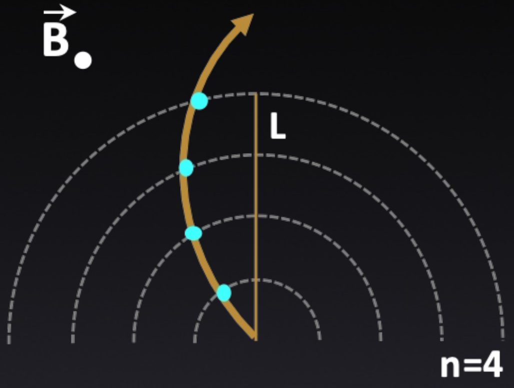
$$\sigma_z^2 = \frac{d}{\sqrt{12}}$$

Momentum Resolution

- Precise measurement of track and momentum of charged particles due to magnetic field.
  - depending on many factors:

$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 = \left(\sqrt{\frac{720}{n+4}}\frac{\sigma_y p_T}{0.3BL^2}\right)^2 + \left(\frac{52.3\times 10^{-3}}{\beta B\sqrt{LL_y \sin\theta}}\right)^2$$

Glueckstern Formula NIM, 24, P381, 1963



B = magnetic field

σ^y = spatial resolution

n = number of measurement points

L = length (~radius)

Position resolution

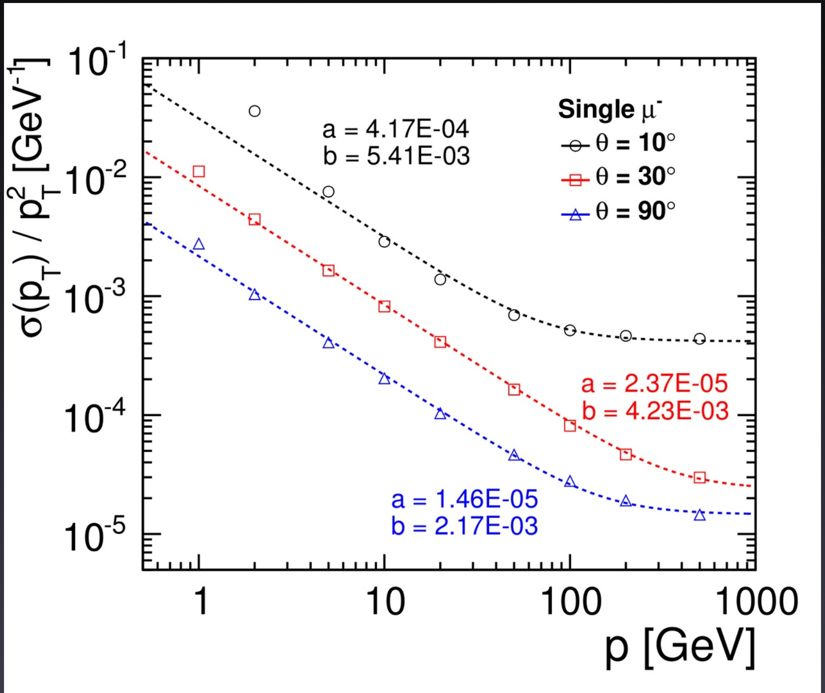
The larger the magnetic field **B**, the length **L** and the number of measurement points **n**, and the better the spatial resolution, the better is the momentum resolution

Multiple scattering

For low momentum (β→0), multiple scattering will dominate the momentum resolution. Reduce material!

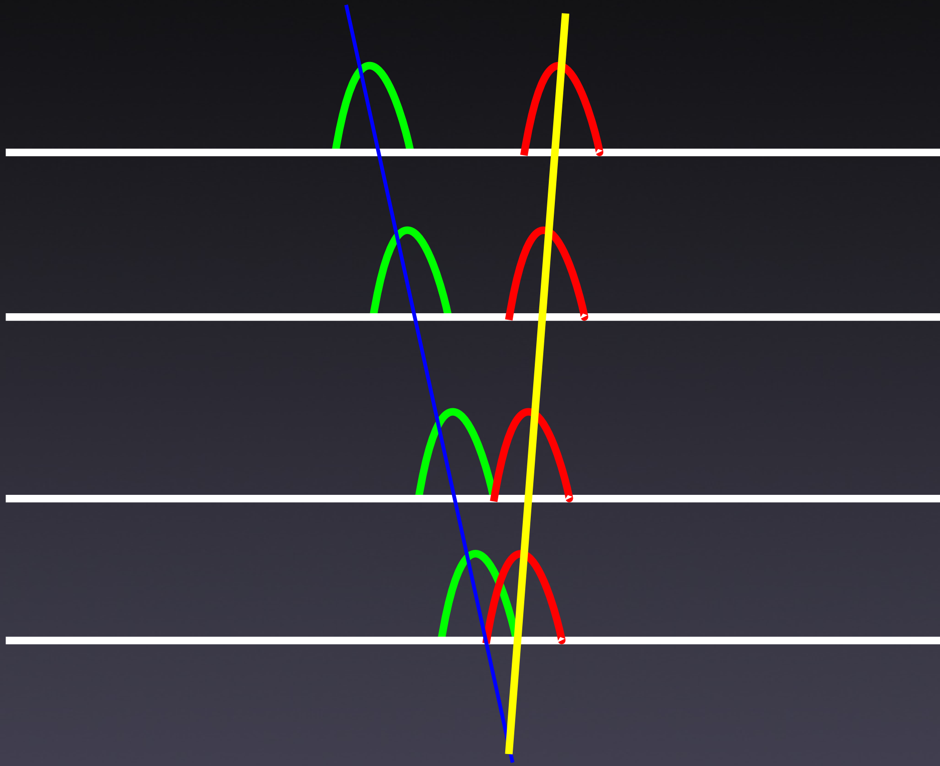
Tracking resolution

- Ultimately Tracking resolution driven by
  - Single Point Resolution
  - Multiple-Scattering
- Hence
  - $\sigma_{Track} = \sqrt{\sigma_{Hit}^2 + \sigma_{MS}^2}$
- Notes
  - Multiple Scattering dominates at low momenta (~ < 10-20 GeV)
  - At higher momenta the single-point resolution becomes the limiting factor (~ > 50 GeV)



Two-Track Separation

- How well can one separate two adjacent tracks
- Driven by single point resolution ($d/\sqrt{12}$)
- Important in dense environments
  - e.g. Tracking within Jets
- Improving separation...
  - More granularity
  - Smarter Tracking



Roadmap

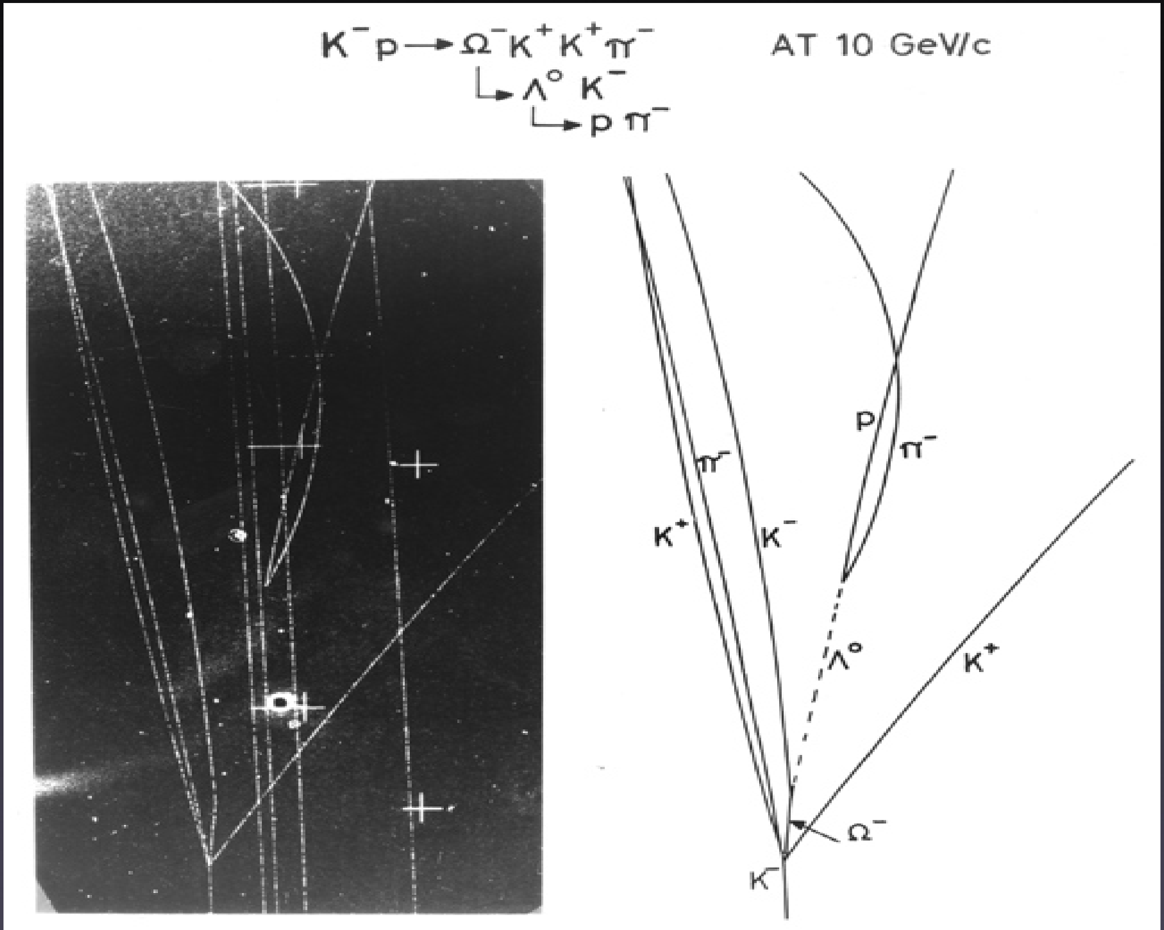
Basics

Tracking Detectors

Readout & Digitization

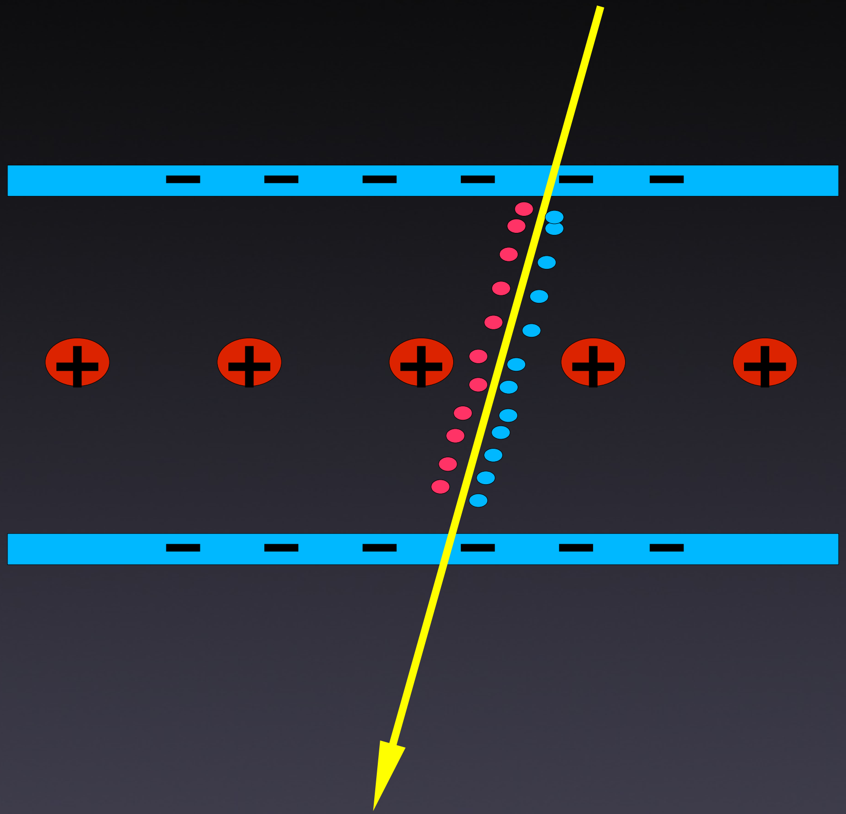
Track Recon-struction

The Bubble Chamber



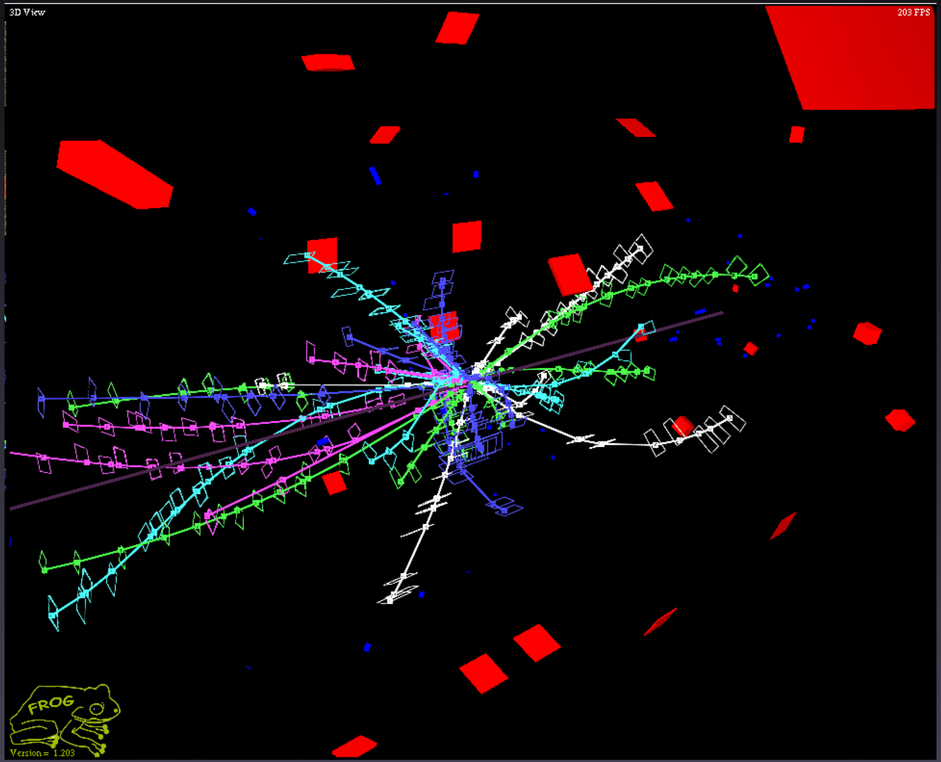
Wire chambers

- Bubble Chambers are great...
  - Slow
  - Readout by photographs
- Mid 60's
  - Wire chambers as most basic electronic tracking chambers
- Basic principle
  - HV Wire in gas-filled volume
  - Electrons drift to the closest wires
  - Avalanche effect to amplify charge

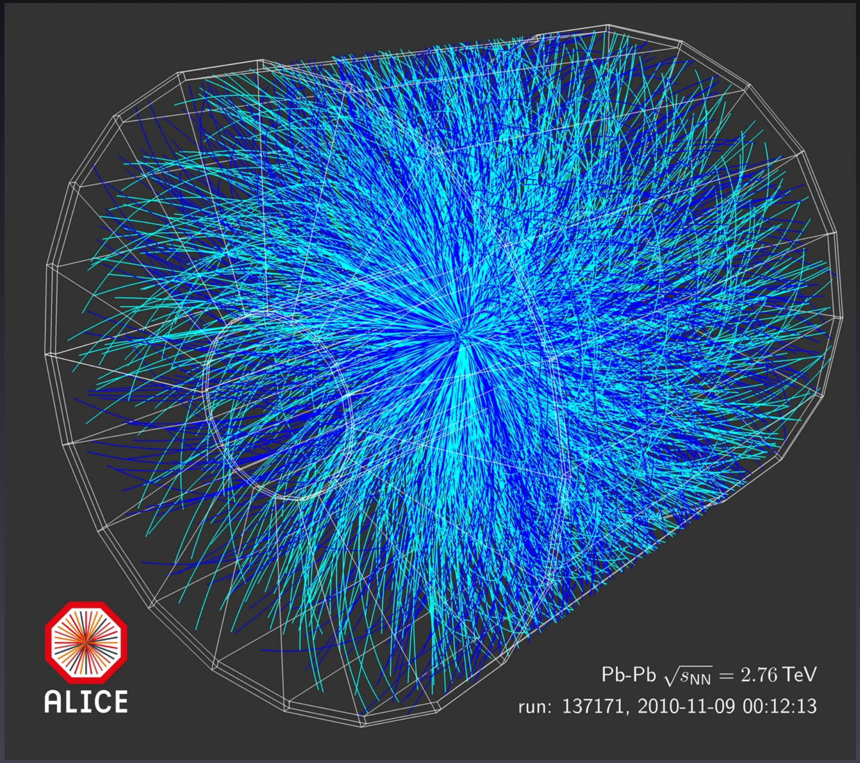


State of the Art

- Silicon Trackers→ Ingrid's Talk



- Gaseous Trackers → Maxim's Talk



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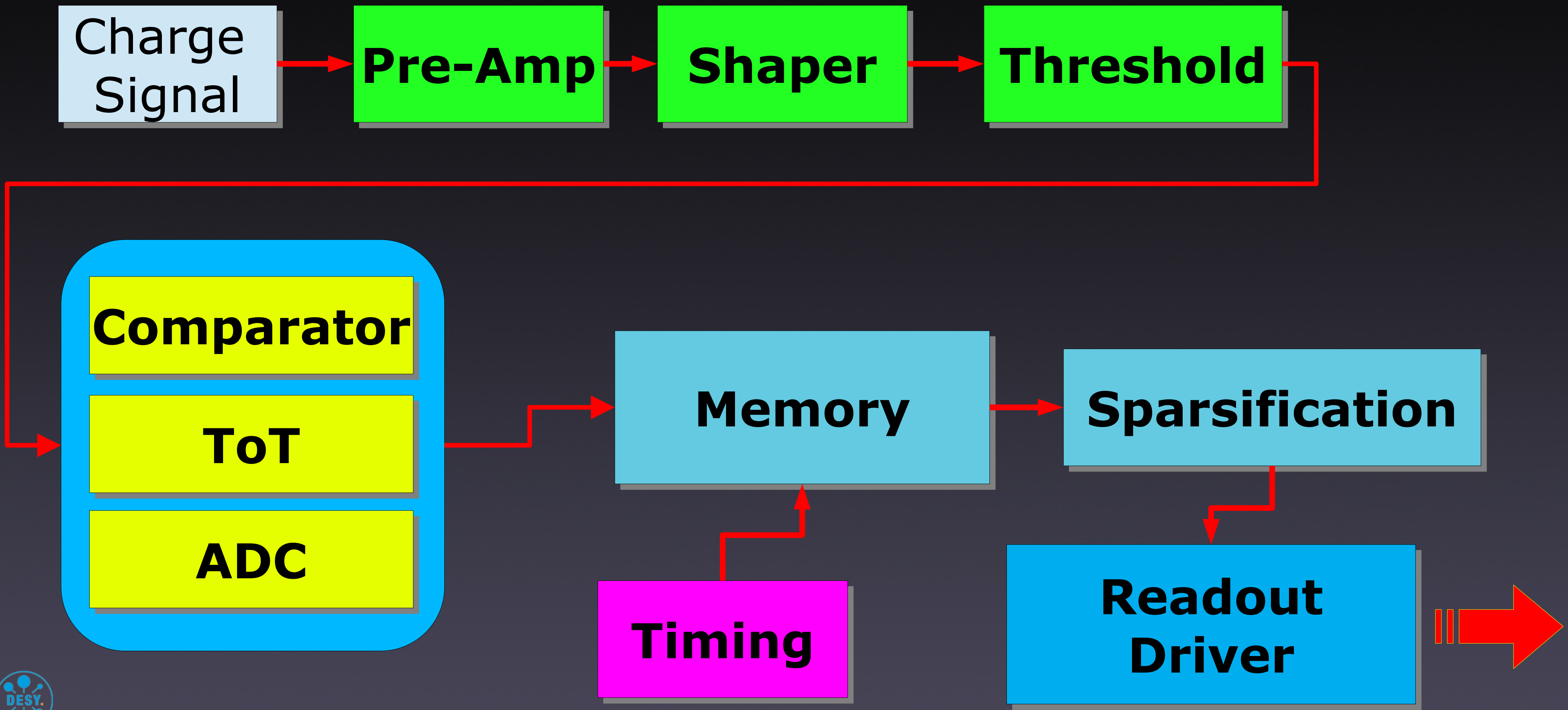
Track Recon-struction

Readout ASICS

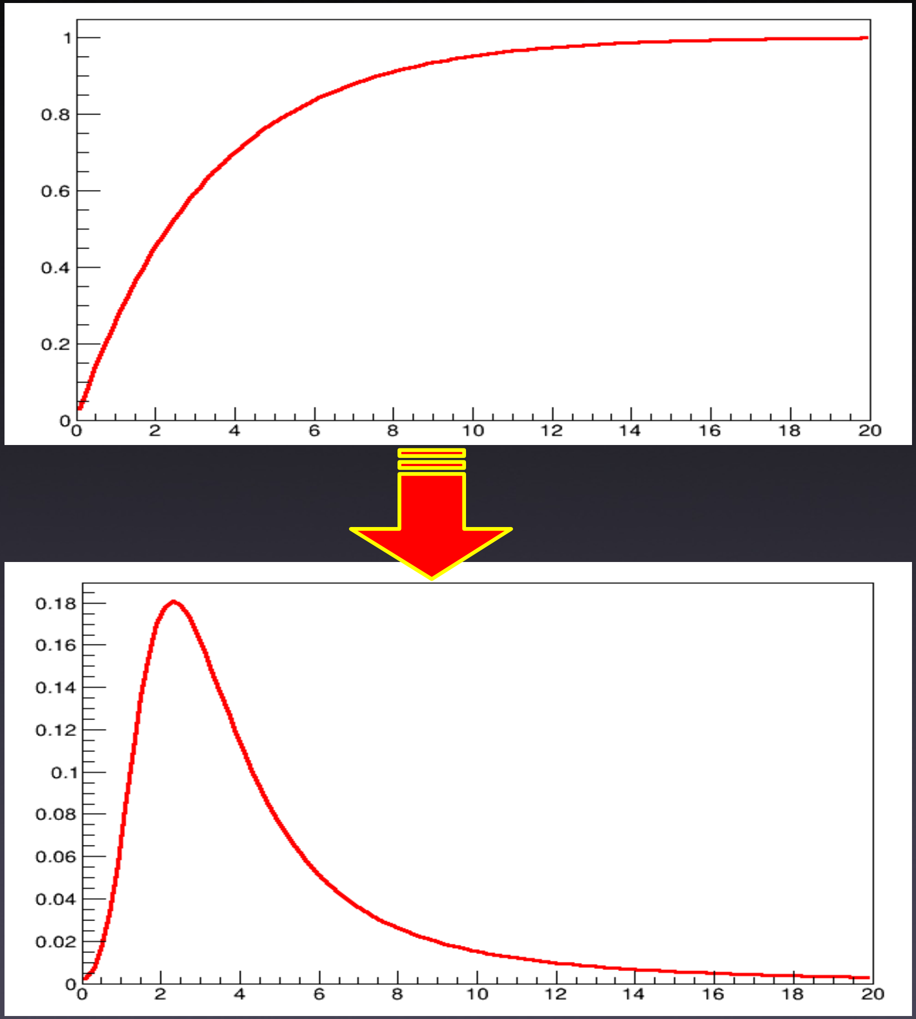
- The Readout ASIC is a key ingredient to an excellent tracker
- The ASIC ("Application-Specific Integrated Circuit")
  - Amplifies and digitizes the charge
  - Provides timing information
  - Buffering
  - Transfers data to the outside world
- ASIC are specifically designed for each tracker
  - Industry-level CMOS design
  - Making a good ASIC is an art

ASIC building blocks



Pre-Amp & Shaper

- Pre-Amp usual very “simple” and integrating
  - Just amplify a very small signal/
- Output signal not optimal for digitization
  - No well defined peak
  - No “clear edge” for timing
- Need to apply some level of “shaping” to make a nice pulse
  - Many shaping circuits on the market

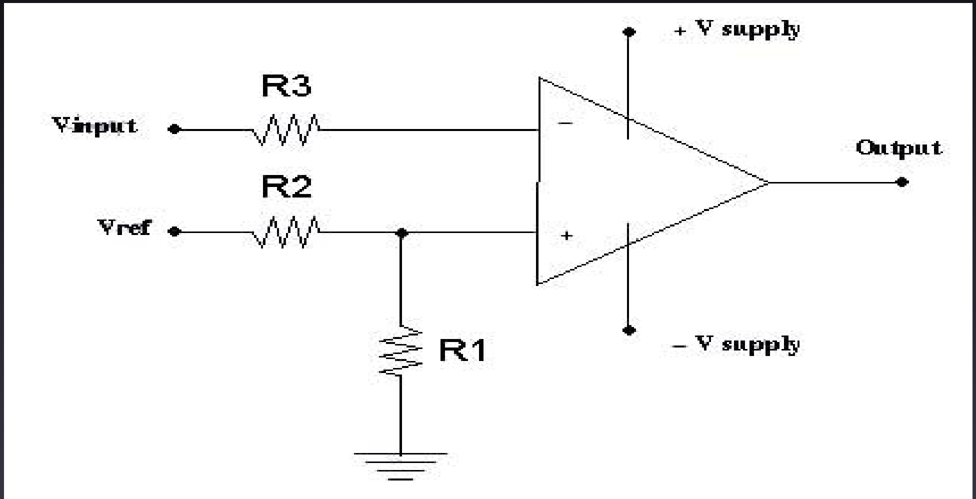


Thresholding & Digitization

- After Shaping → ready for digitization
- However Digitization is costly
  - Time and power
  - Configurable Analog threshold before digitization
- Three basic types of Digitizers
  - Comparators
  - ToT (Time over Threshold)
  - ADC (Analog to Digital Converter)
- Figures of merit
  - Resolution in bits
  - Speed
  - Power consumption

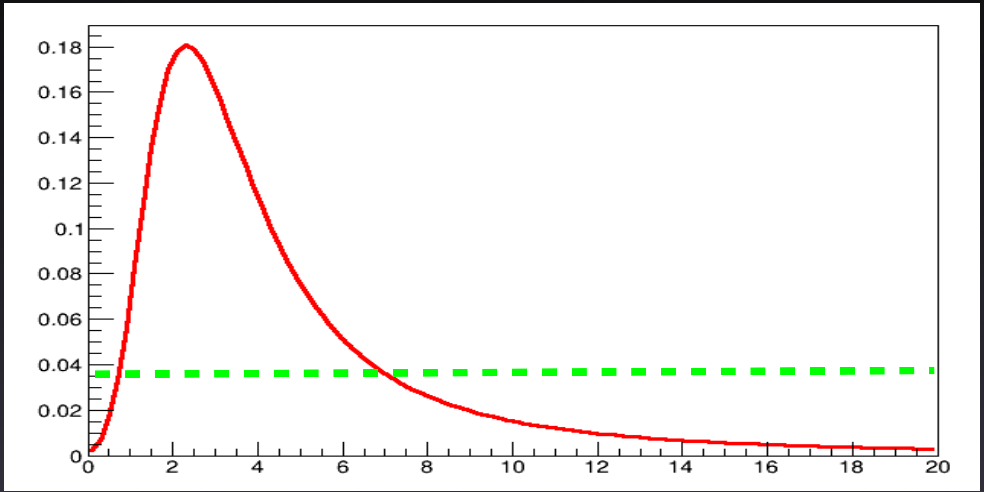
Comparators

- A Comparator is simplest way to digitize
- Compare V_{input} to V_{ref}
  - $V_{input} > V_{ref}$ Output=1
  - $V_{input} < V_{ref}$ Output=0
- Disadvantage
  - Simple binary information
  - “Hit” or “No hit”
- Advantages
  - Simple, fast and low power



ToT

- This is a simple Counter
- If $V_{input} > V_{ref}$
  - Counter starts
- If $V_{input} < V_{ref}$ again
  - Stop counter
- Digitized information
  - Number of counts
- Limited by clock speed and signal shape



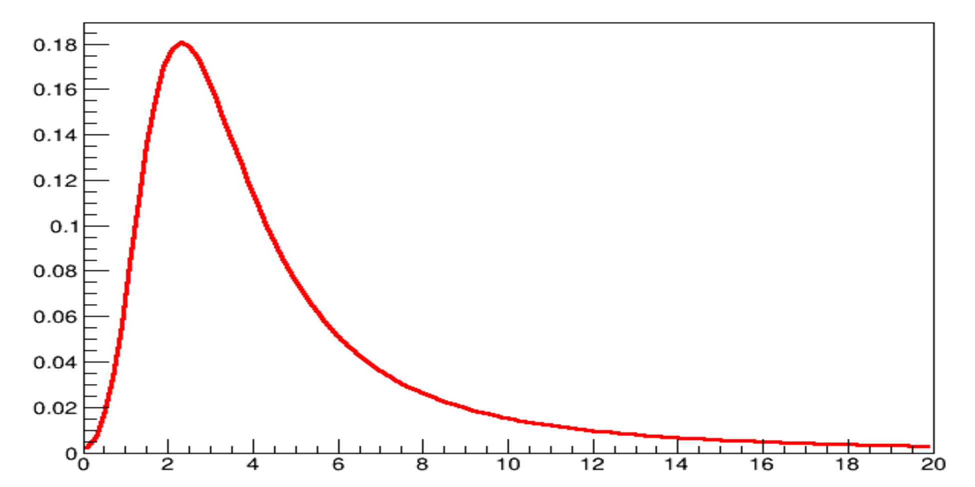
Basic Assumption
Pulse Width ~ Pulse Height

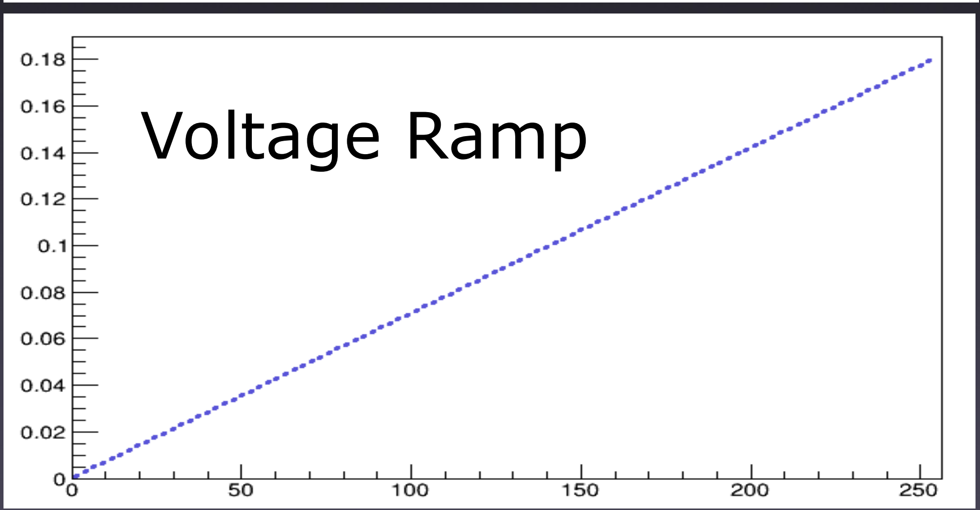
Analog-to-Digital Converters (ADC)

- ADCs are an art form these days
- Many different circuits and ideas
  - Speed of conversion
  - Resolution
  - Robustness
  - ADC design is popular thesis subject
- I'll focus on two basic types
  - Wilkinson ADC
  - FLASH ADC
- This is by far incomplete

Wilkinson ADC

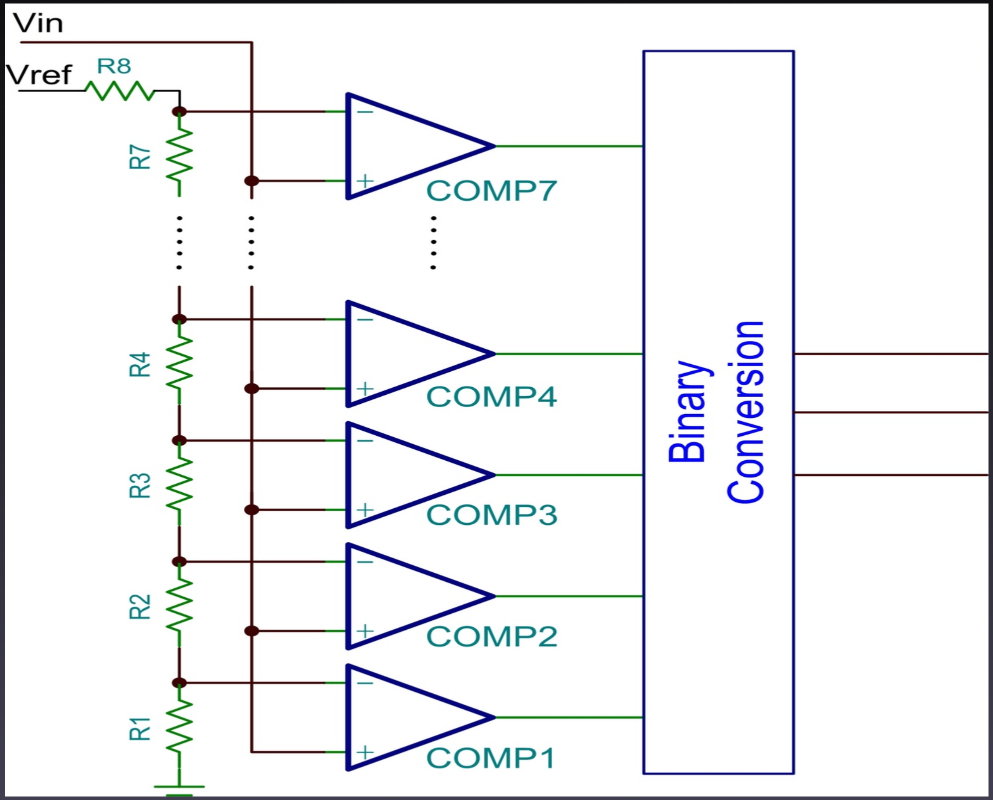
- This is a very simple ADC
- At t=0
  - Counter starts
  - ADC generates voltage ramp
- If $V_{ramp}=V_{input}$
  - Counter is stopped
  - N_{counts} is digitized information
- Speed driven by counter clock
  - Slow but low-power





FLASH ADC

- Speedwise this is the Ferrari of ADC's
  - Conversion in a single clock cycle
  - Up to 8 bits possible
- Complex with loads of circuitry
  - Power-hungry
  - N bits 2^n-1 Comparators needed
  - Lots of space (“real estate”)
- FLASH ADCs are chosen when speed is essential



Writing the Data

- After digitization data is transferred to the buffer memory and combine with the timestamp info
- For a tracker
  - 1 % Hit occupancy
- So for 256 channel Readout ASIC
  - A few hits (2-3)
- Remainder of data could be eliminated
  - Digital Threshold and sparsification

Sparsification

- 2 Examples
- Raw data chip with comparator (16 bytes)
  - 00 01 01 00 02 00 03 00 04 01 05 00 06 00 07 00
- Sparsification-Stage -Select Hits (4 Bytes)
  - 00 01 04 01
- Raw data – ADC readout (16 bytes)
  - 00 01 01 09 02 25 03 9F 04 17 05 01 06 00 07 01
- Sparsification (Threshold > 10) (6 bytes)
  - 02 25 03 9F 04 17
- Sparsification reduces bandwidth requirements
  - Smarter chips have even more elaborate sparsifiers
- Every modern chip has some kind of sparsification circuitry

Analog vs Binary Readout

- An old discussion
- Binary only stores hit/no hit
  - Hit resolution is limited to $d/\sqrt{12}$
  - Robust and simple
- Analog also stores the digitized pulse height
  - More information available
  - Can further improve on hit resolution
  - Better detector monitoring
- Many trackers, many opinions
  - ATLAS is binary
  - CMS is analog
  - ILC detectors plan to do analog

Roadmap

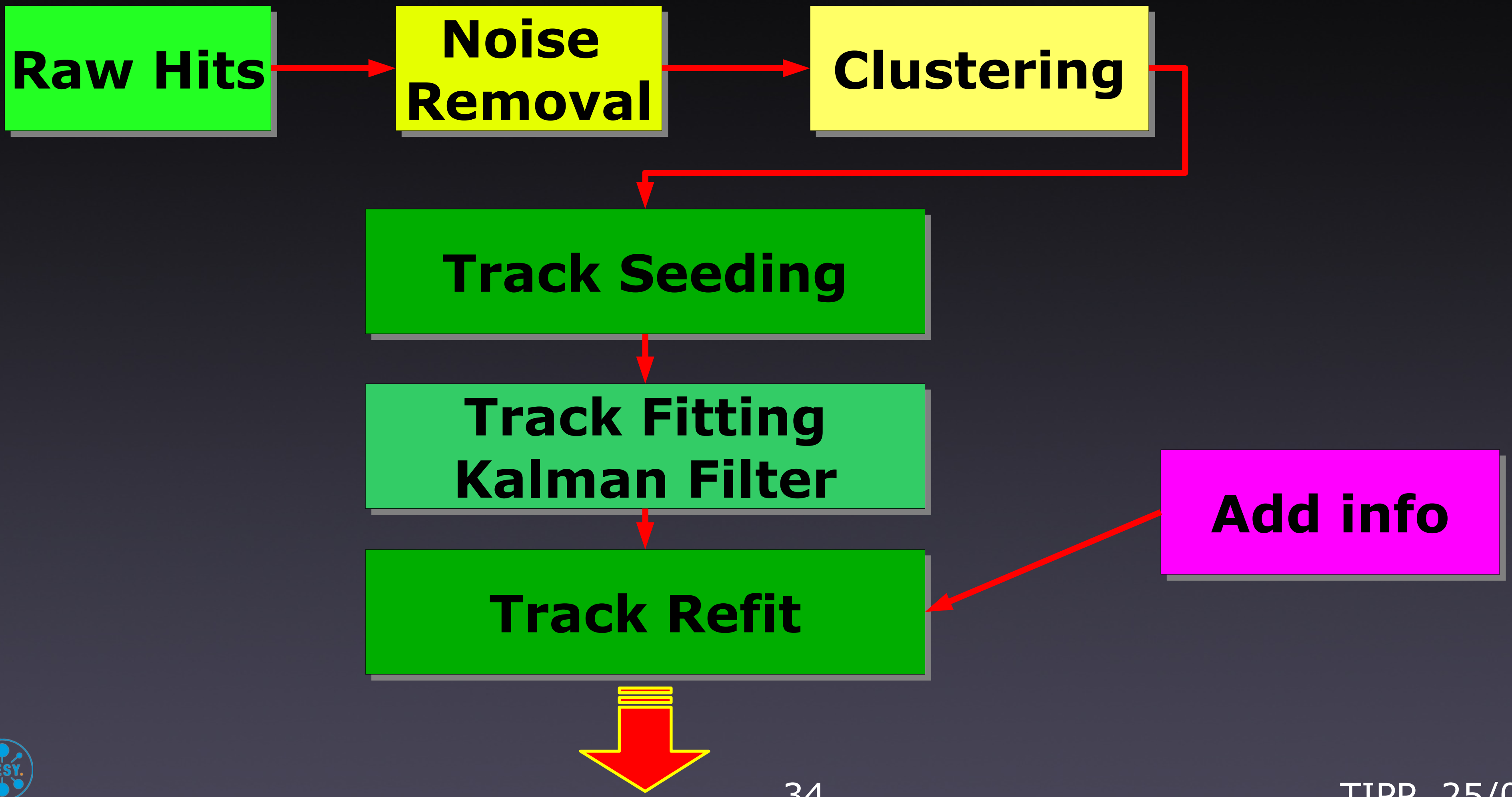
Basics

Tracking Detectors

Readout & Digitization

Track Recon-struction

Track reconstruction



Noise Removal

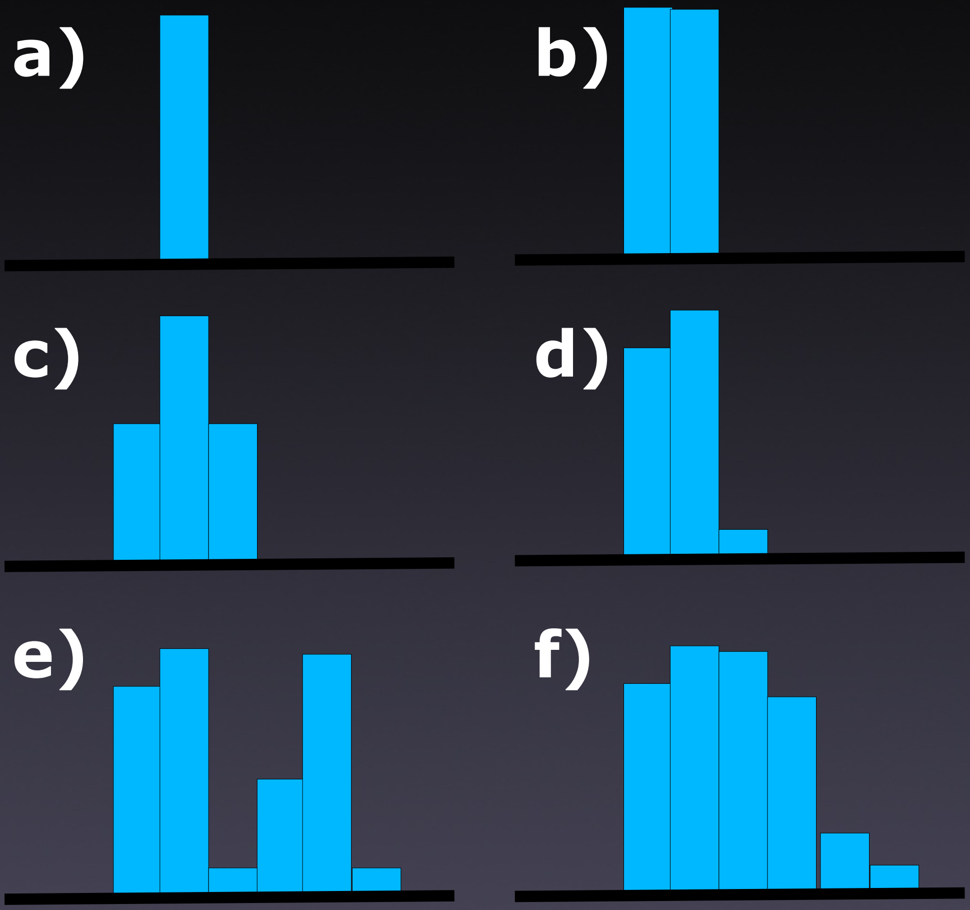
- In Reality no detector is completely noise-free
- Noise Source
  - Random (Noise floor 10^{-5}, 10^{6} channels …)
  - Hot channels
  - Pick-up Noise (from somewhere else)
- Tracking is an $\sim n^2$ problem
  - Beneficial to remove as many noise hits as possible
- Classic approaches
  - Remove all channels with Occupancies > O(10) %
  - Dedicated Noise runs during no-beam
- After Noise Removal we're ready for the first tracking step

From Hits to Clusters

- A particle may deposit charge in several strips/pixels/pads causing several hits
  - So not every hit corresponds to a particle
  - → need to reconstruct the particle hit
- Clustering algorithms are used
  - To merge hits belonging to one particle
- Clustering shows one real advantage of analog readout
  - Here the additional information really adds resolution

Clustering

- Merging
  - Cluster all hits together until there is a channel without a hit
  - Calculate weighted mean for cluster position
- Splitting
  - Occasionally two tracks are very close
  - Hits are merged together
  - Cluster splitting to correct for this behavior
  - This can occasionally be tricky

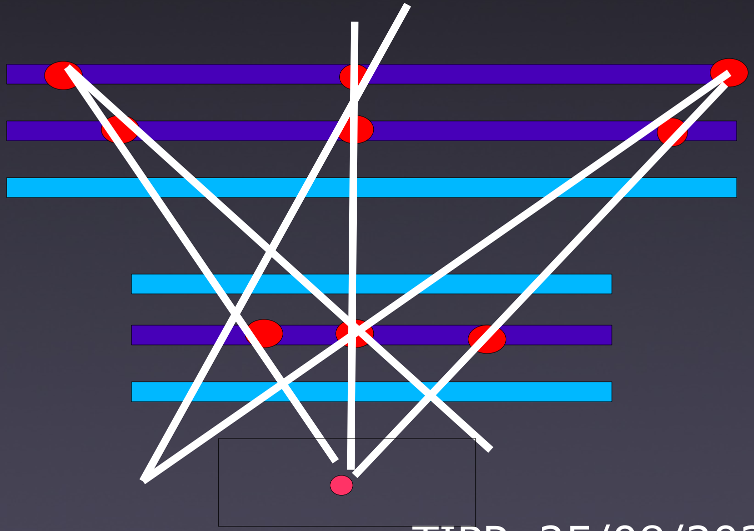


Tracking Strategies

- A lot in tracking evolves around choosing the right “strategy”
- Outside-In
  - Occupancy is a lot small outside, track from the outside and pick up hits on the way
- Inside-Out
  - Higher granularity in the inner layers, so start from there
- Vertex-Standalone
  - Use only the highly granular vertex detector to find tracks
- Reality
  - All of the above to achieve an optimal tracking performance

Seeding

- Need to start from somewhere
- Forming Seed tracks
  - Choose e.g. 3 layers
  - Form tracks from all hit triplets
  - Remove tracks that are not even close to the interaction region (z cut)
- These Seed tracks then form the input the next step
- Problem
  - Combinatorial issue, many seed tracks to evaluate
  - Choice of seed layers important



Tracking & Fitting

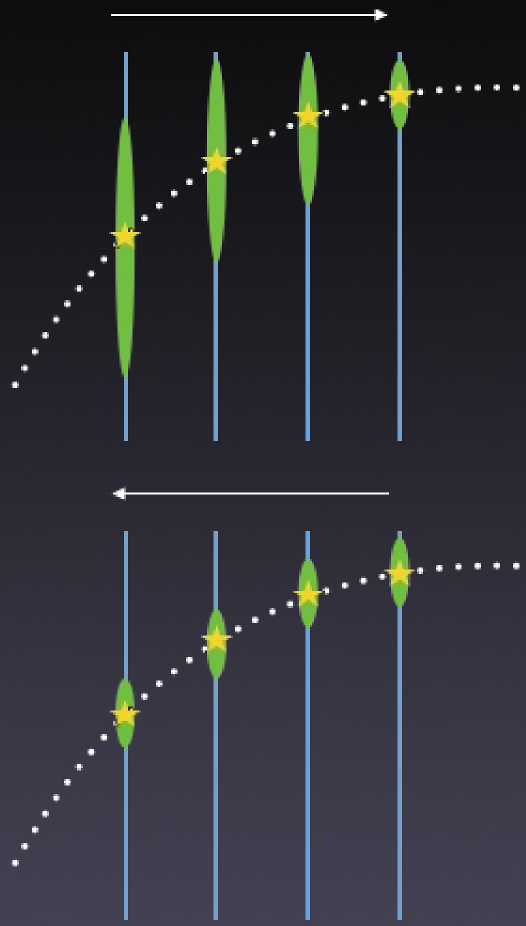
- Take all SeedTracks
- Pick up all hits along seed trajectory
  - Remove tracks with a below minimum number of hits
  - Make a Helix fit
  - Use goodness-of-fit to select good tracks
- Usually several steps
  - "Easy tracks" first
  - Then low momentum tracks (loopers), tracks that have smaller number of hits
- Kalman Filtering and Fitting
  - Best tool for this, used by most experiments

Kalman Filter

- What is it ?
  - Commonly-used method for estimating states of dynamic systems
  - Combines predictions (based on underlying model and knowledge of prior state) and measurements to provide more accurate state estimate than either individually - Original paper by R. E. Kalman from 1960
- How does it work ?
  - Predictions alone accumulate increasingly large uncertainties due to stochastic processes along trajectory (multiple scattering, etc)
  - Measurements alone are “noisy”
  - Nice feature: Need only the state estimate at prior step to have full information needed for the next step!
  - No need to keep track of full history; it is “encoded” in the state estimate plus its covariance
- “Real world” example: Combine telemetry data on thrust with GPS position to estimate the true position and velocity of a projectile

Kalman-Fitting

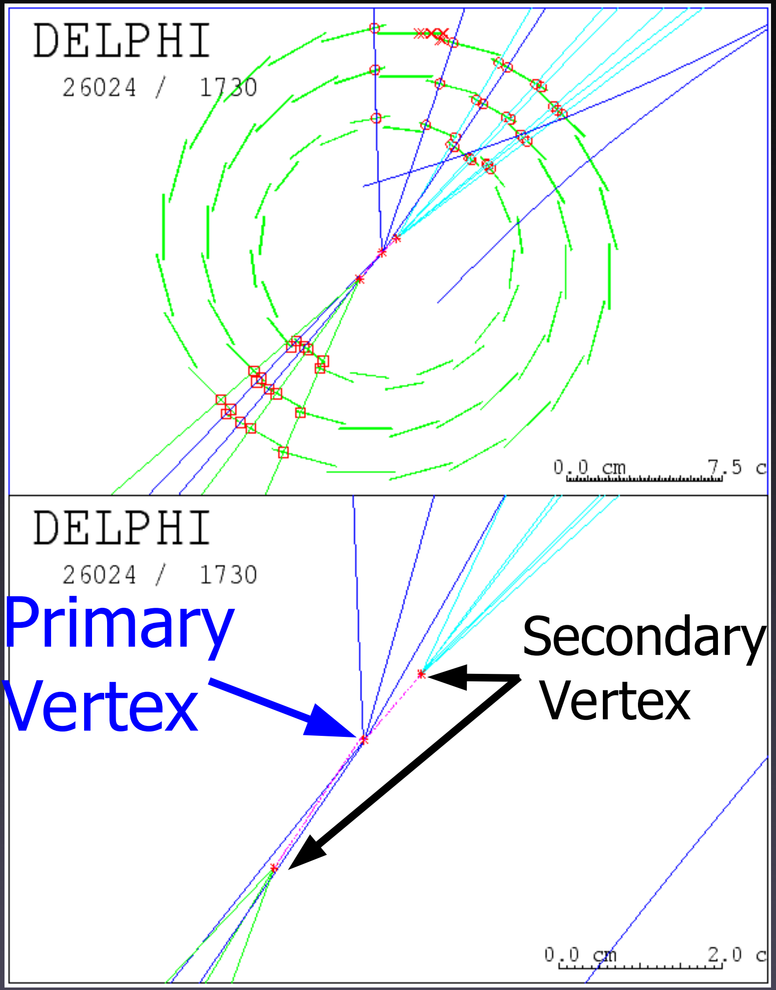
- The Kalman formalism already provides the framework for a track fit
- Due to progressive nature of process, only final step has “full” track information encoded in its state equation
- Therefore, a further stage going back along the track is needed to give best possible estimate at each surface
- This backwards stage is referred to as the smoothing step

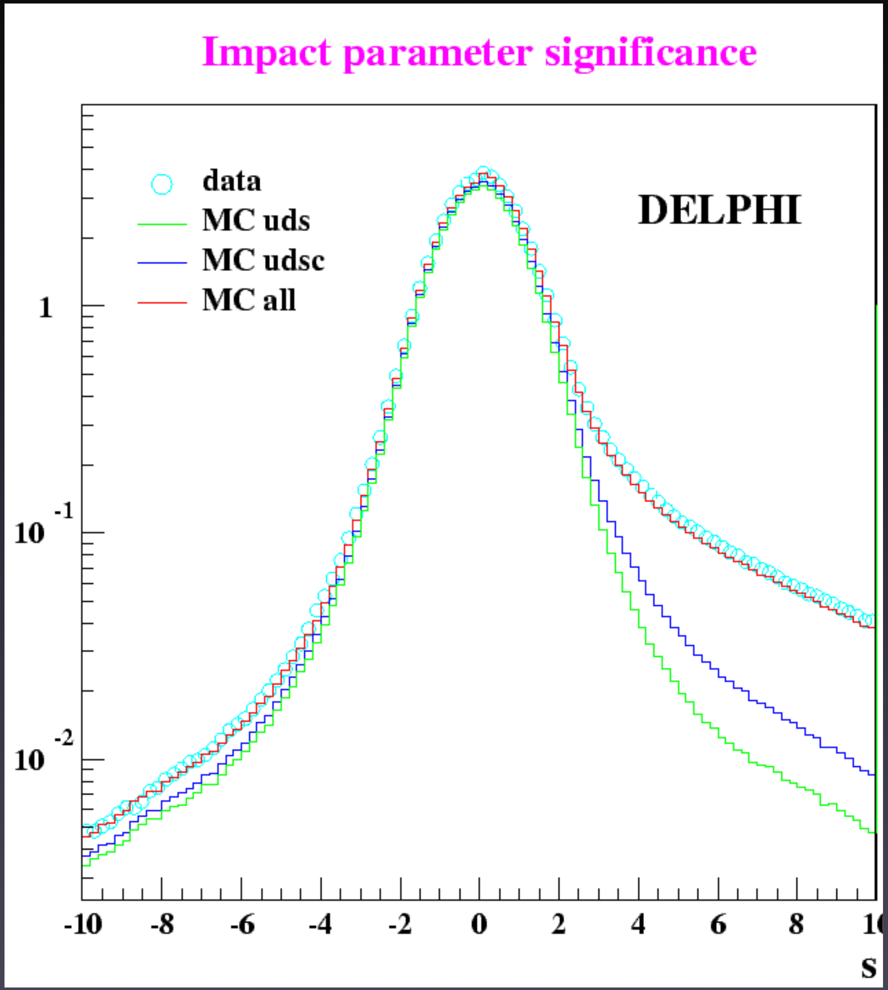


Adding Information - Refitting

- In many cases, one has additional information about the track
- Track origin
  - If the Primary vertex is well know (as in an e^+e^- collider)
  - Re-fit the track using that information
- If track belongs to a secondary vertex
  - Use this constraint as well
- Add timing information - more useful for hadron machines

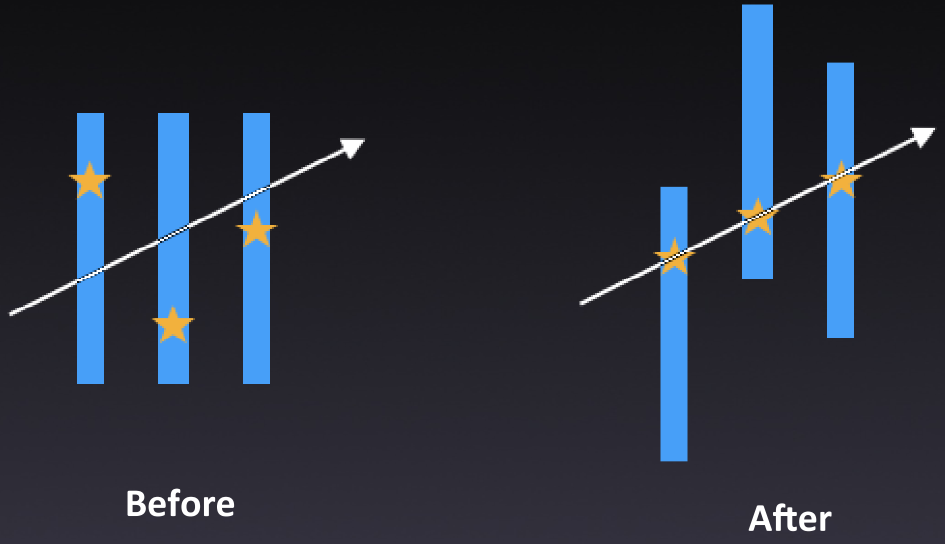
Vertexing


DELPHI
26024 / 1730
0.0 cm 7.5 c
DELPHI
26024 / 1730
Primary
Vertex
Secondary
Vertex
0.0 cm 2.0 c


Impact parameter significance
data
MC uds
MC udsc
MC all
DELPHI
1
10 -1
10 -2
-10
-8
-6
-4
-2
0
2
4
6
8
S

Alignment

- Knowledge of precise location of sensitive elements can be important for achieving necessary track reconstruction performance
  - Even very high placement accuracy (10 μm) can lead to displacements with respect to nominal sensor positions which track reconstruction is sensitive to
  - Can degrade resolution on parameters, or even lead to biases
  - Detectors are “breathing” at this scale
- Surveys, optical alignment systems can help to understand these “misalignments”
- Can also use the tracks themselves to understand this



Conclusion

- A lot of things “need to happen” a particle track in the detector to a full reconstruction
- As always there is more than one way to do it
  - Silicon or gaseous trackers
  - Outside-In vs Inside-out...
  - Kalman Filters vs. Least-square-fits …
- It’s the entire package that matters
  - An excellent tracker hardware is useless without adequate reconstruction
  - Even the best software can’t turn crappy input hits into a precision track

Some Literature

- H. Spieler Semiconductor Detector Systems
- Horowitz & Hill: The Art of Electronics
- C. Grupen Particle Detectors


"That's all Folks!"