Tracking for the ILC

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Introduction

- Disclaimer
  - I am a "silicon guy", hence there will be a certain focus on silicon trackers
- This talk should serve as an introduction
  - Overview on relevant issues
  - Neither encyclopaedic nor complete
- Goal
  - Understand the issues and "what people talk about"
  - Get you interested in tracking detectors

Roadmap

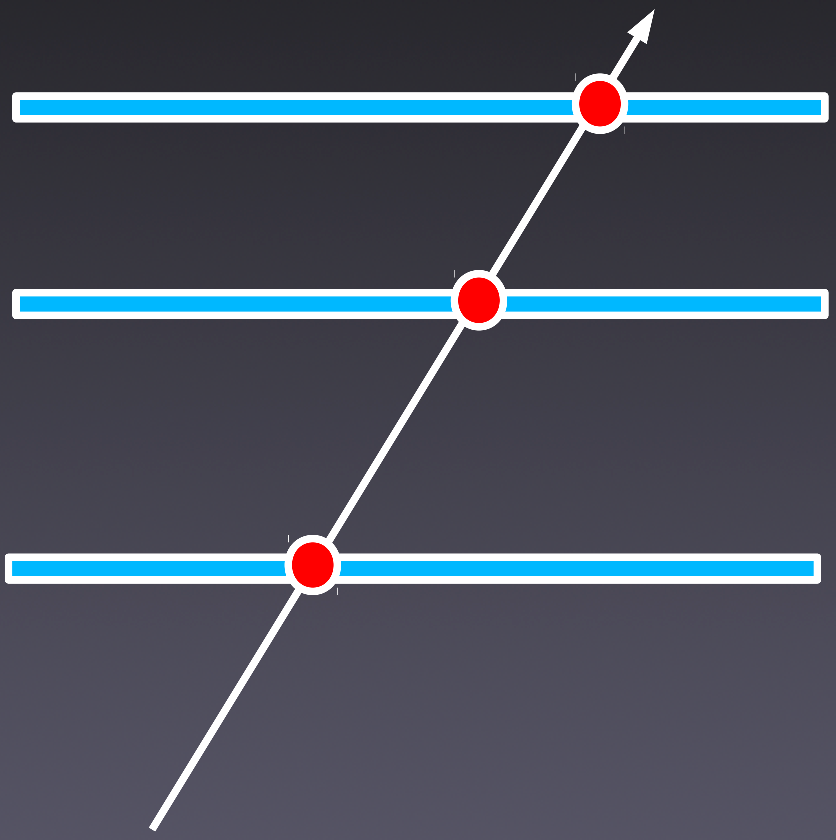

Basics
Tracking Detectors
Readout & Digitization
Track Recon-struction

Tracking -What is it ?

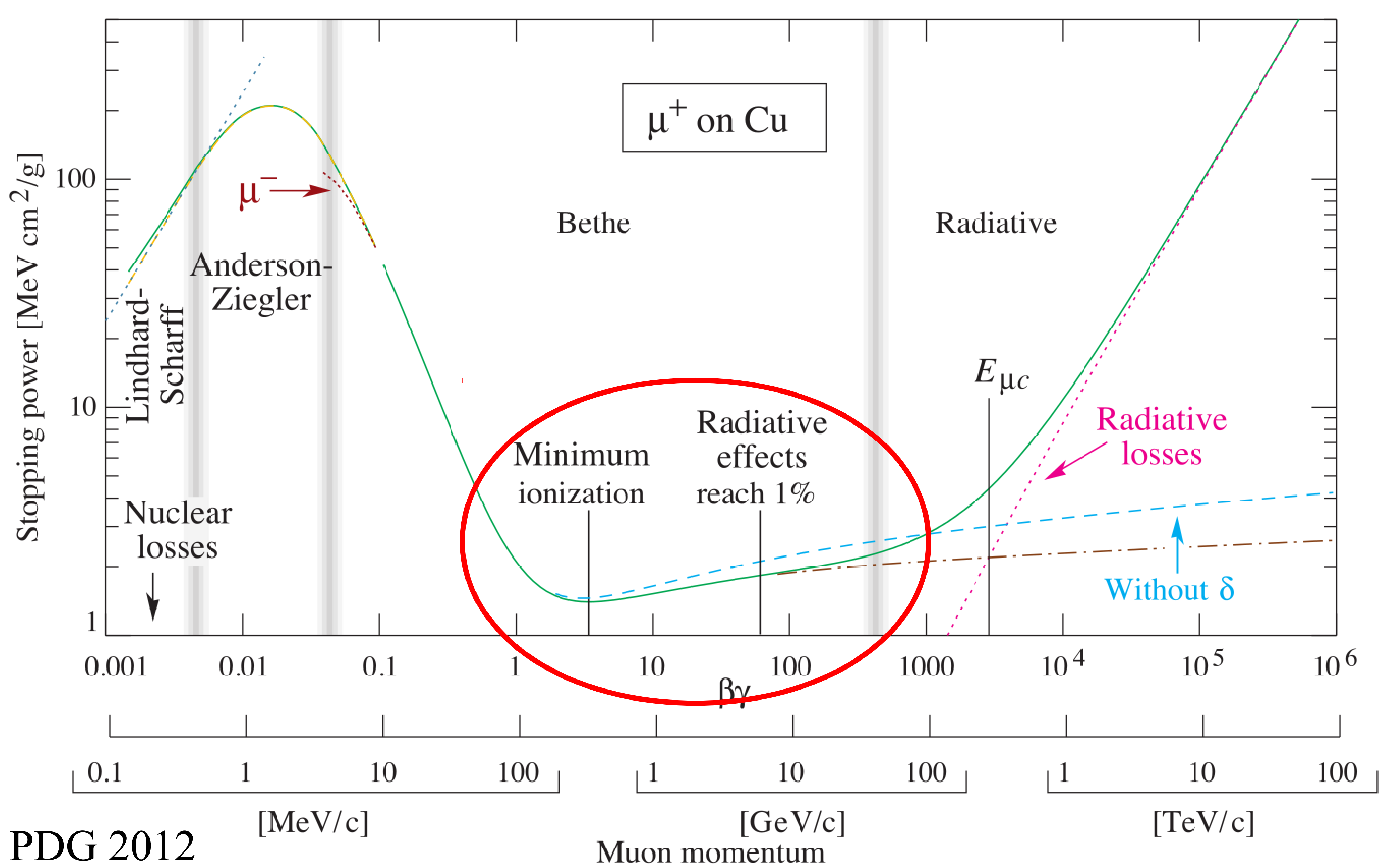
Tracking:
to follow or pursue the track, traces, or footprints of.

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



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Particles through matter

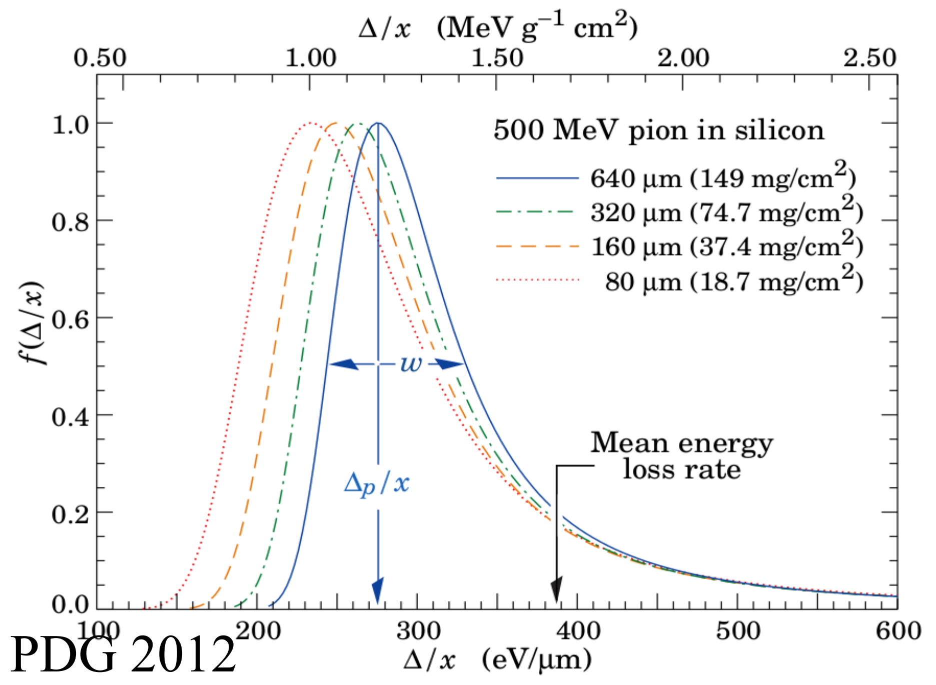
- We're mostly dealing with minimum ionizing particles
  - Track momenta usually between 1-100 GeV
- Particles traversing thin material layers
  - Small deviations caused by mainly Coulomb-Scattering
  - Deviations depend on Material (Z,A and ρ)

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

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

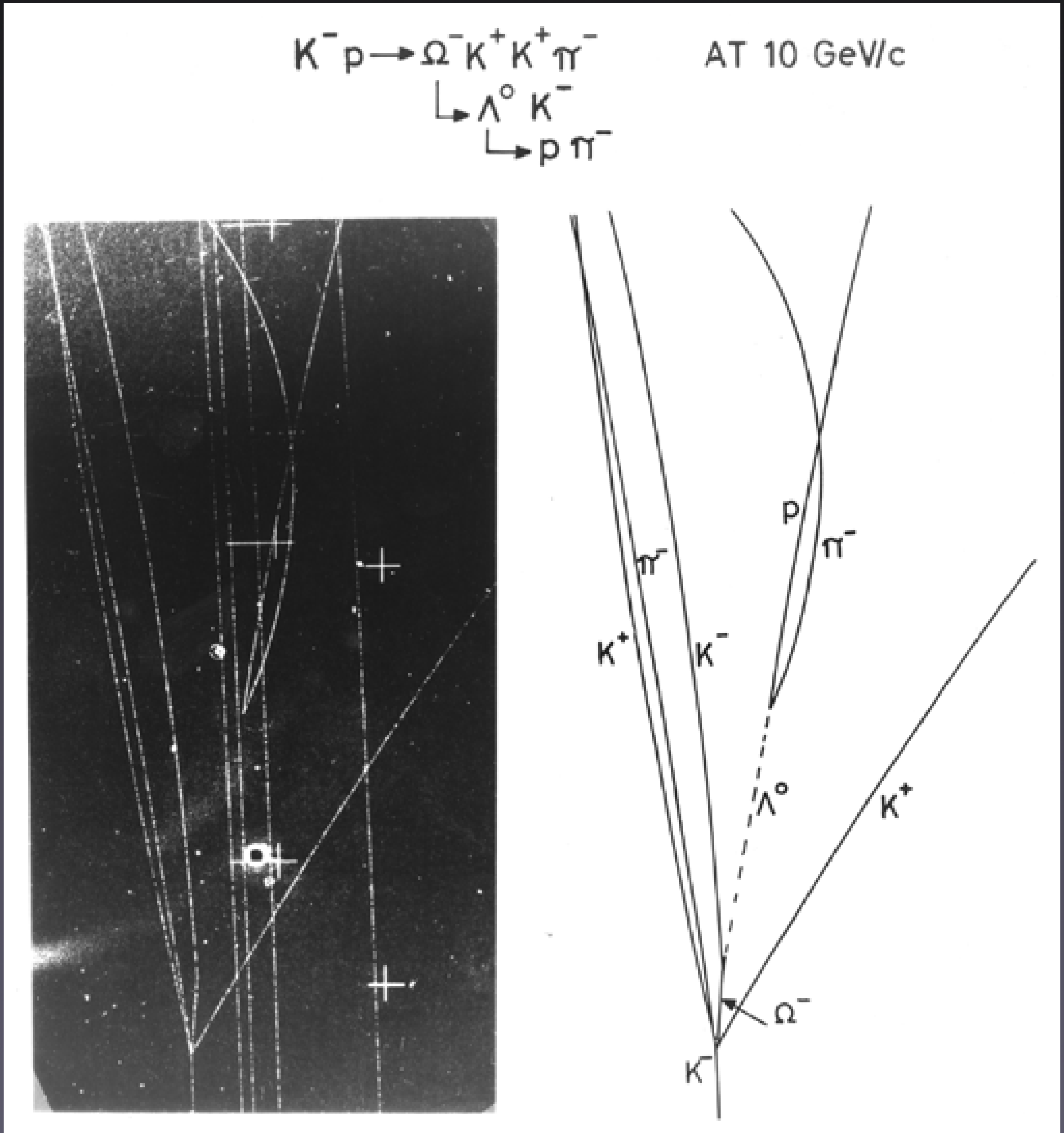
Modeling the Energy loss

- 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



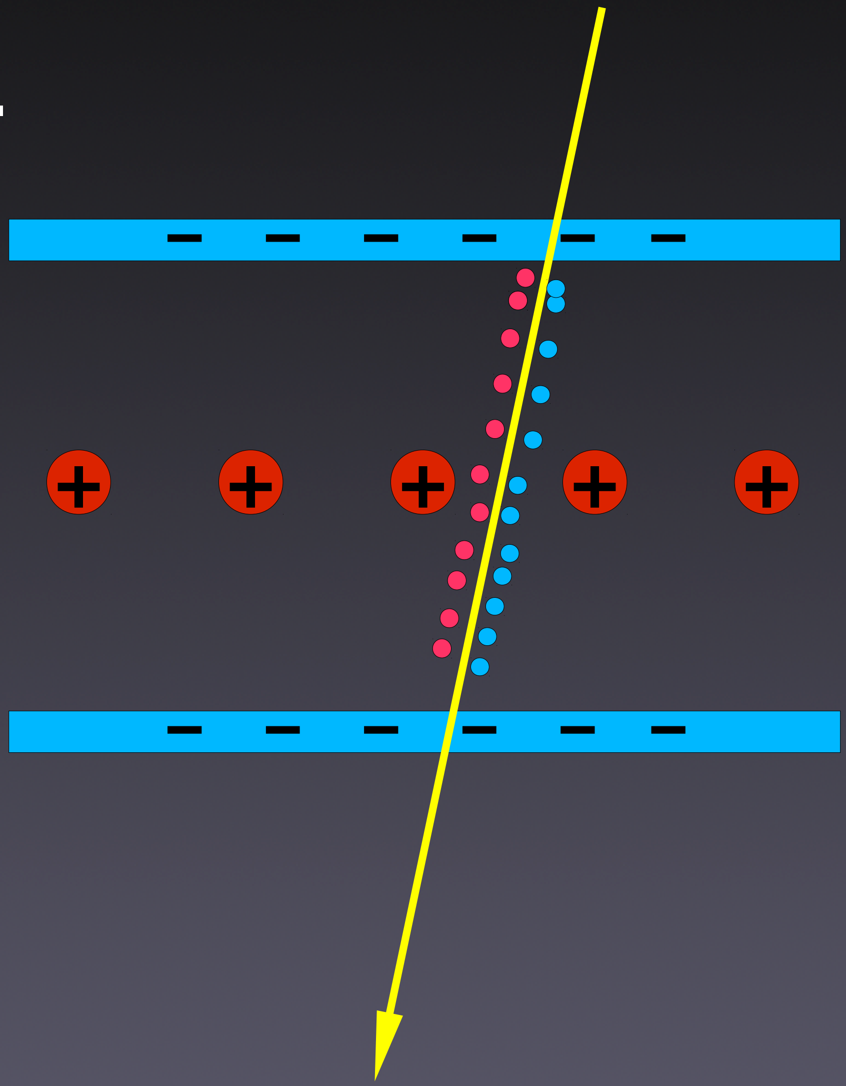
Note:
The Landau-Function itself is an approximation for thin tracking layers

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

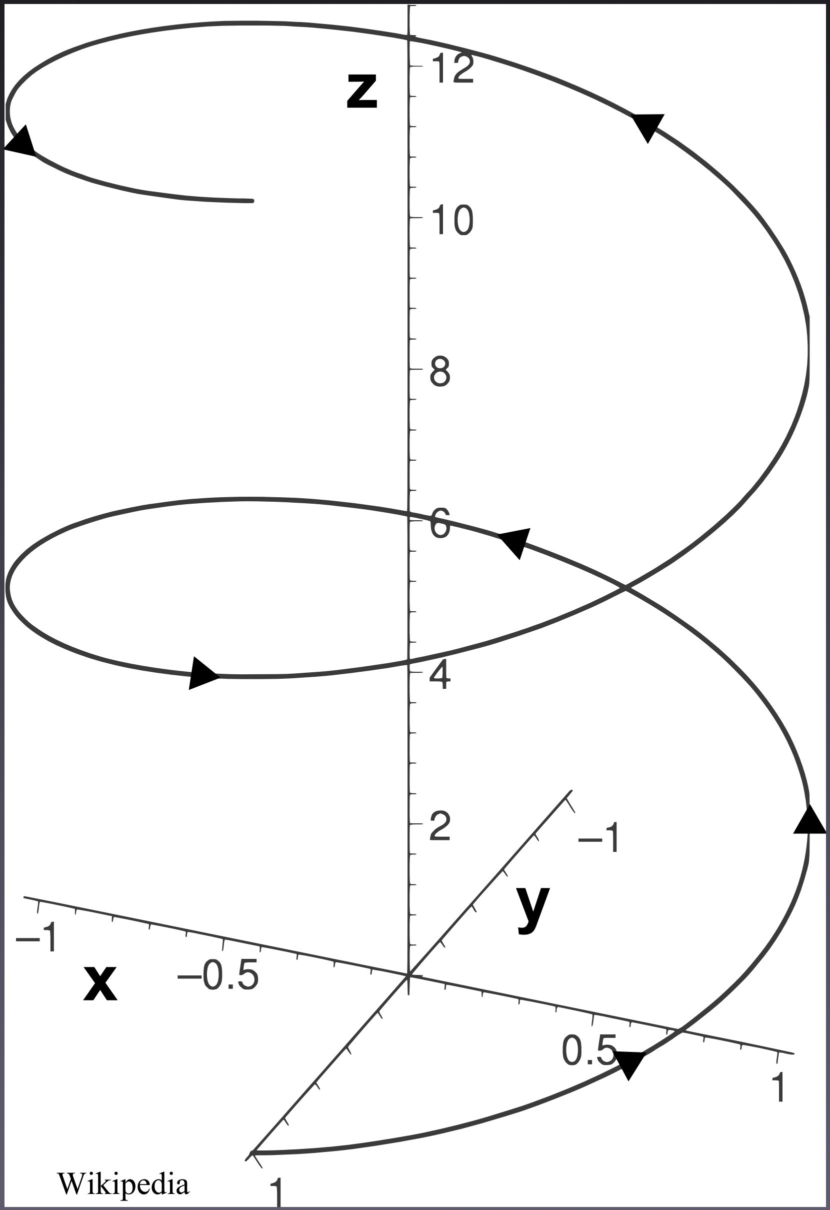


Particles in a magnetic field

- All driven by the Lorentz Force

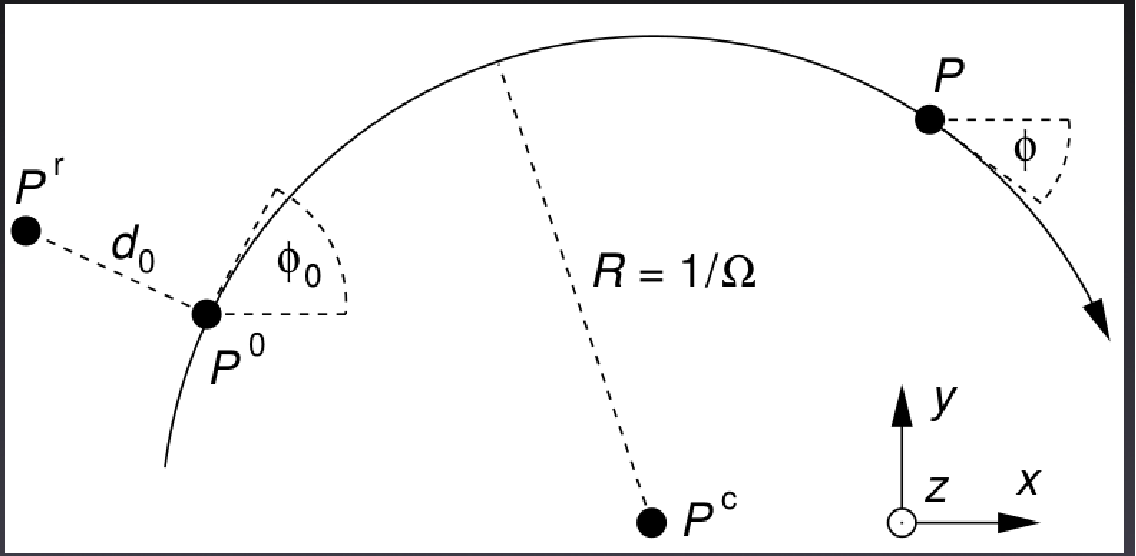
$$\vec{F} = q \cdot \vec{v} \times \vec{B}$$

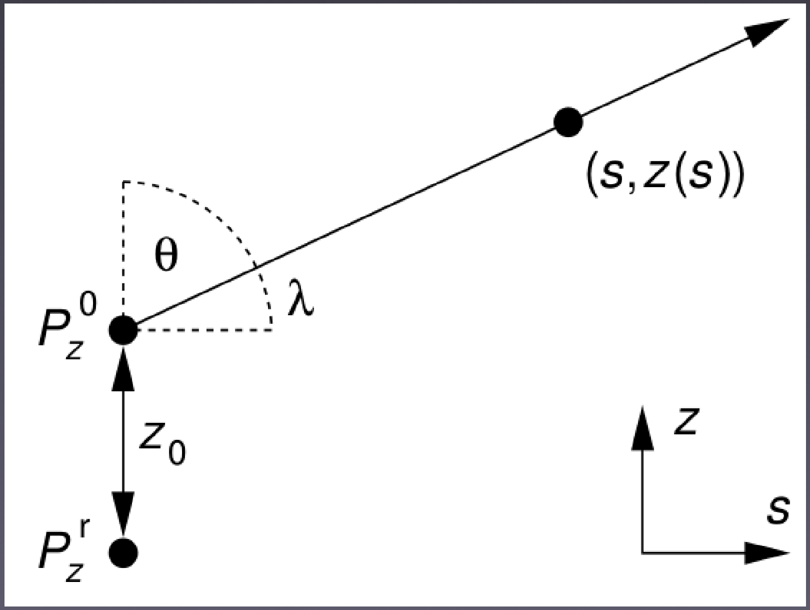
- Particles trajectories follow a helix
  - Arc/Circle in xy
  - Line in z
- Various parametrizations
  - Each experiment has one...



LCIO Helix Parametrization

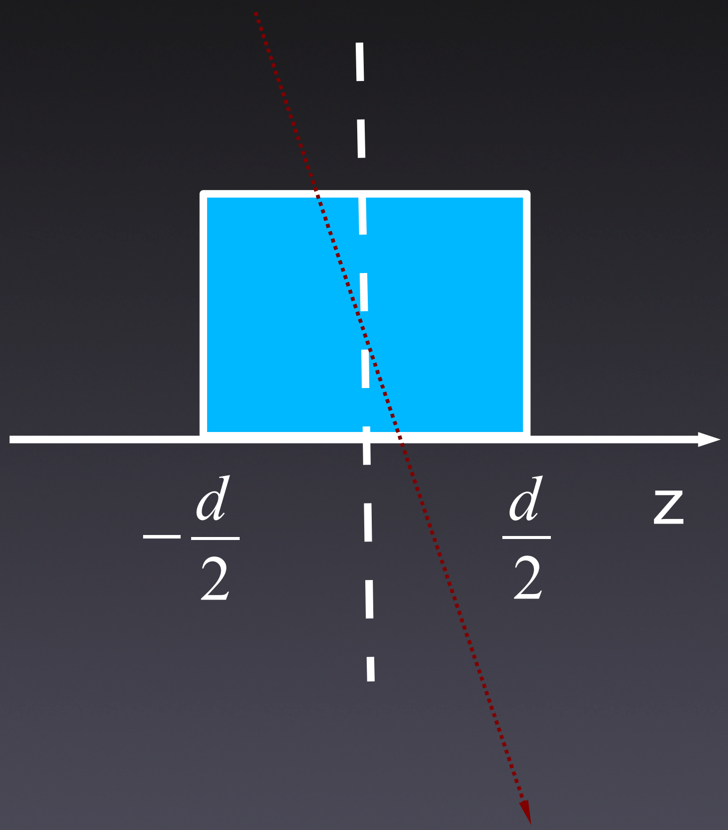
- 5 Parameters
  - φ_0 :azimuthal angle of the momentum at the p. c. a.
  - Ω : track curvature t
  - d_0:signed impact parameter in xy
  - $\tan\lambda$ is the slope dz/ds of the straight line in the sz plane
  - z_0: position of the track at the p. c. a.
- See LC-DET 2006-004





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)



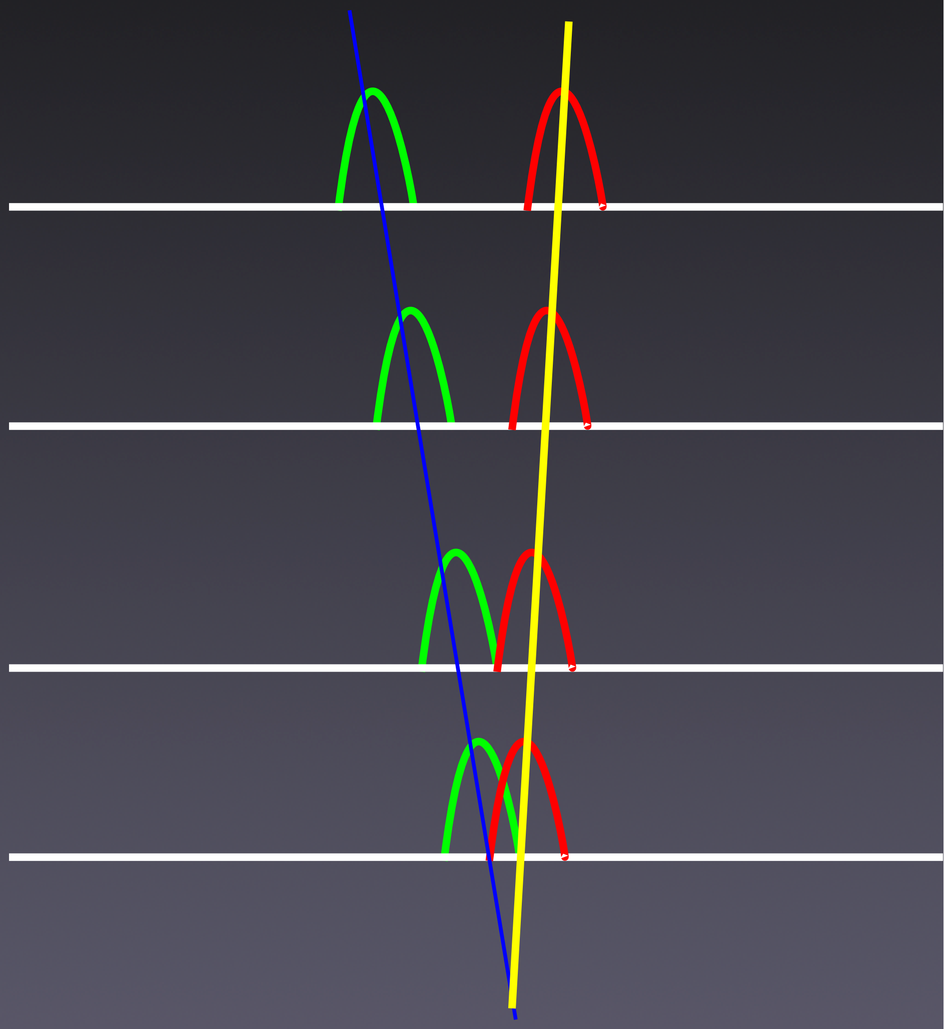
- Variance is: $\sigma_z^2 = \int (z - \langle z \rangle)^2 dz / \int D(z)\, dz \qquad \langle z \rangle = 0$

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

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

Two-Track Separation

- How well can one separate tw0 adjacent tracks
- Driven by single point resolution (d/√12)
- Important in dense environments
  - e.g. Tracking within Jets
- Improving separation...
  - More granularity
  - Smarter Tracking



Tracking resolution

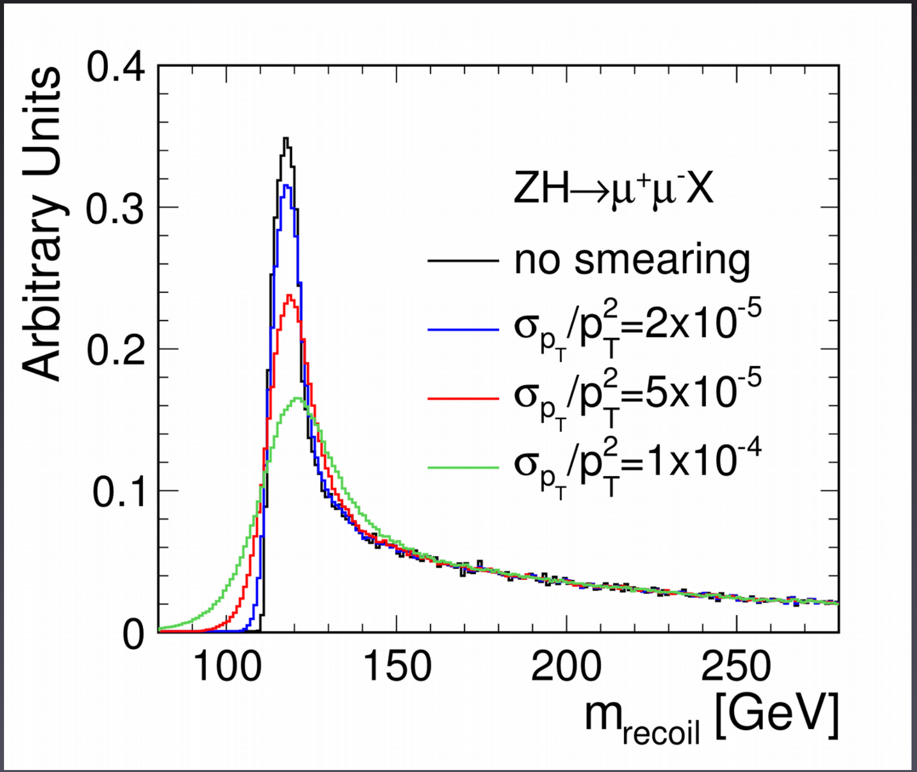
- Ultimately Tracking resolution driven by
  - Single Point Resolution
  - Multiple-Scattering
- Hence
  - $\sigma_{Track} = \sqrt{\sigma_{Hit}^2 + \sigma_{MS}^2}$
- Notes
  - Multiple Scattering dominates at low momenta (~ < 10-20 GeV)
  - At higher momenta the single-point resolution becomes the limiting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

Roadmap

Basics
Tracking Detectors
Readout & Digitization
Track Recon-struction

Tracking at the ILC

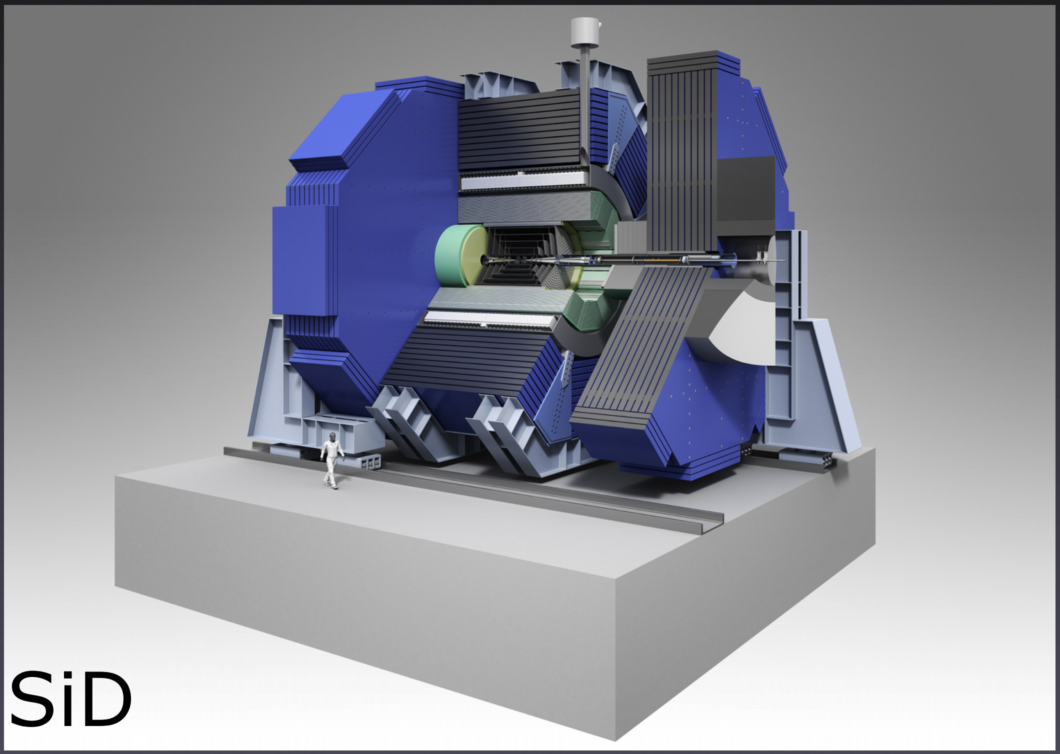
- LC tracking showcase
  - $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- X$
  - Measuring the Z recoil mass
- Excellent Tracking resolution is key to this measurement
- Trade-off between resolution and required luminosity

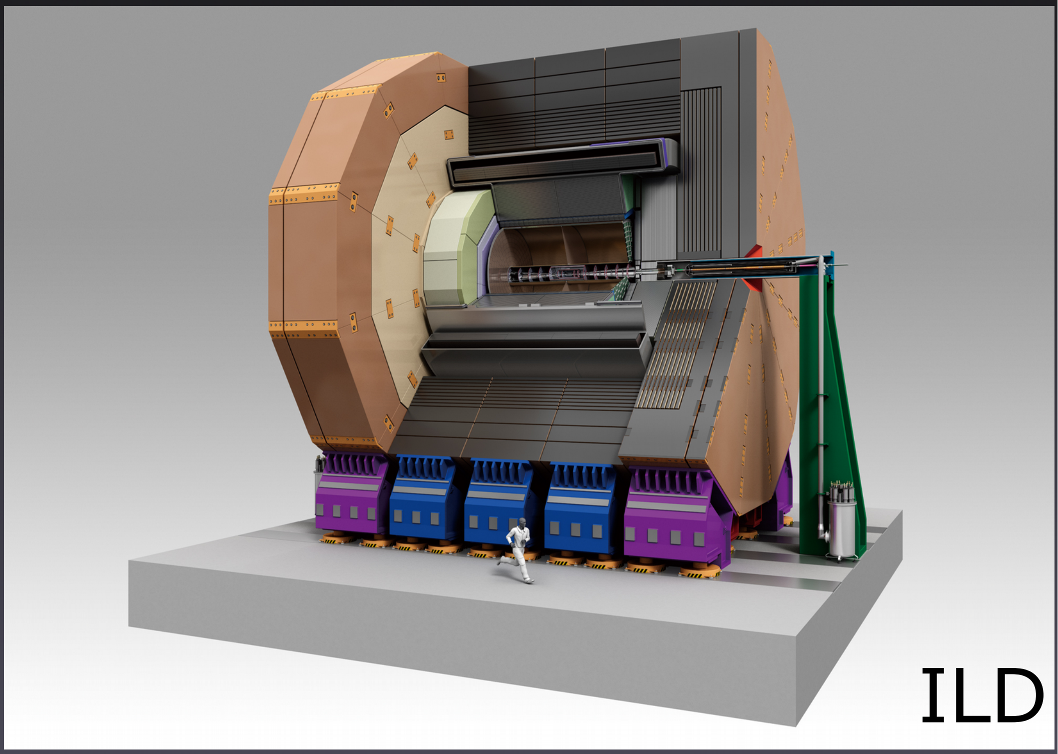


Tracking at the ILC (II)

- Linear Collider Detectors are build around Particle-Flow paradigm (see Mark's Talk)
- This means combing the tracking and the calorimeter information
  - LC physics is very frequently multi-jet physics
  - Note that in a PFA detector ~ 60 % of the jet energy is measured using the tracker
- Excellent track resolution and track separation are essential for the PFA reconstruction

SiD & ILD





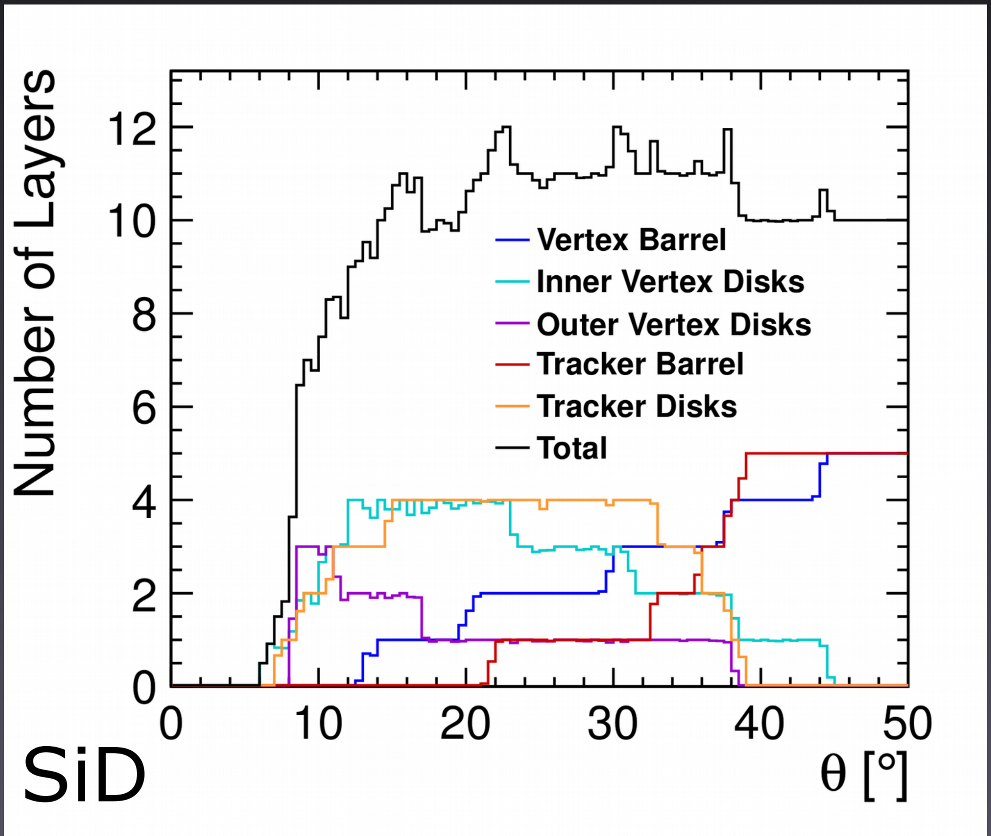
- SiD
  - $r_{Tracker}$=1.2 m
  - B = 5 T
- ILD
  - $r_{Tracker}$=1.8 m
  - B = 3.5 T

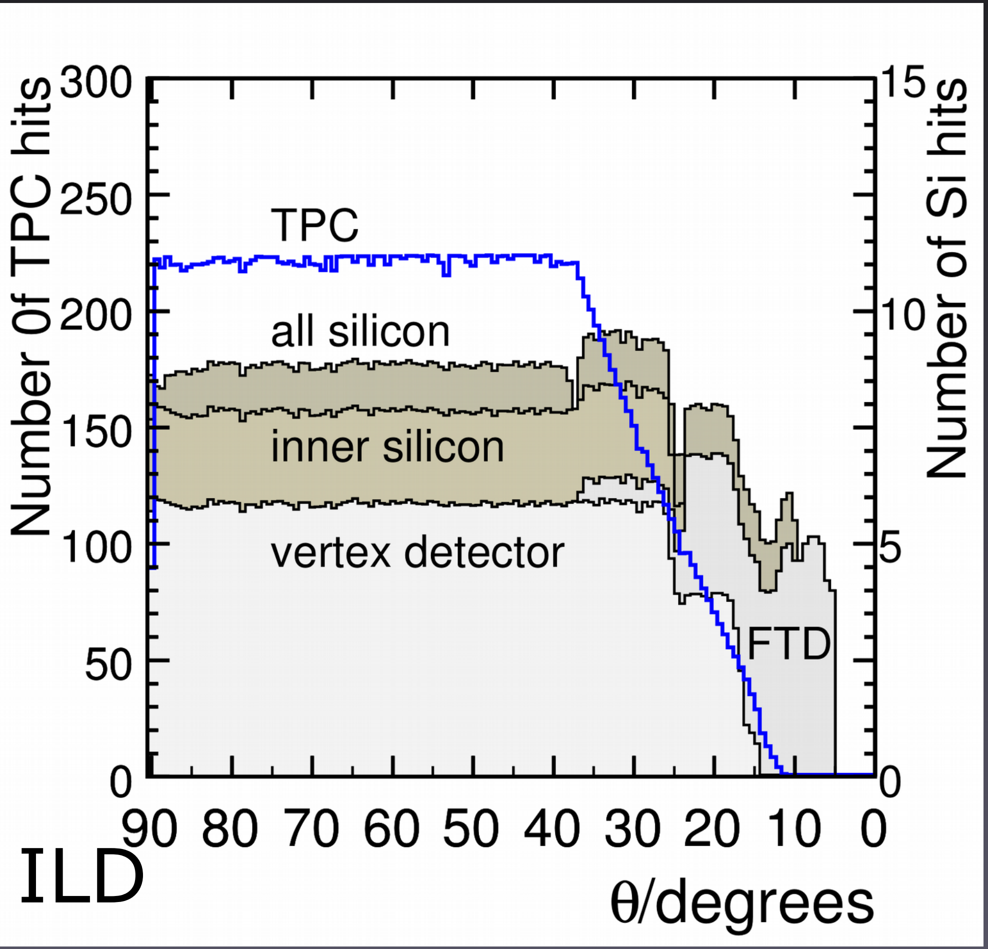
Two Approaches

- All-silicon Tracking
  - SiD's choice
- Tracking system
  - 5 layer pixel Vertex detector
  - 5 layer Silicon strip tracker
- Few highly precise hits
  - Max 12 hits
- Low material budget
- Concept proven by CMS

- Gaseous Tracking
  - ILD's choice
- Tracking System
  - 3 double layer Vertex detector
  - Intermediate silicon layers
  - TPC
- Max number of hits
  - 228
- High hit redundancy
- Classical approach

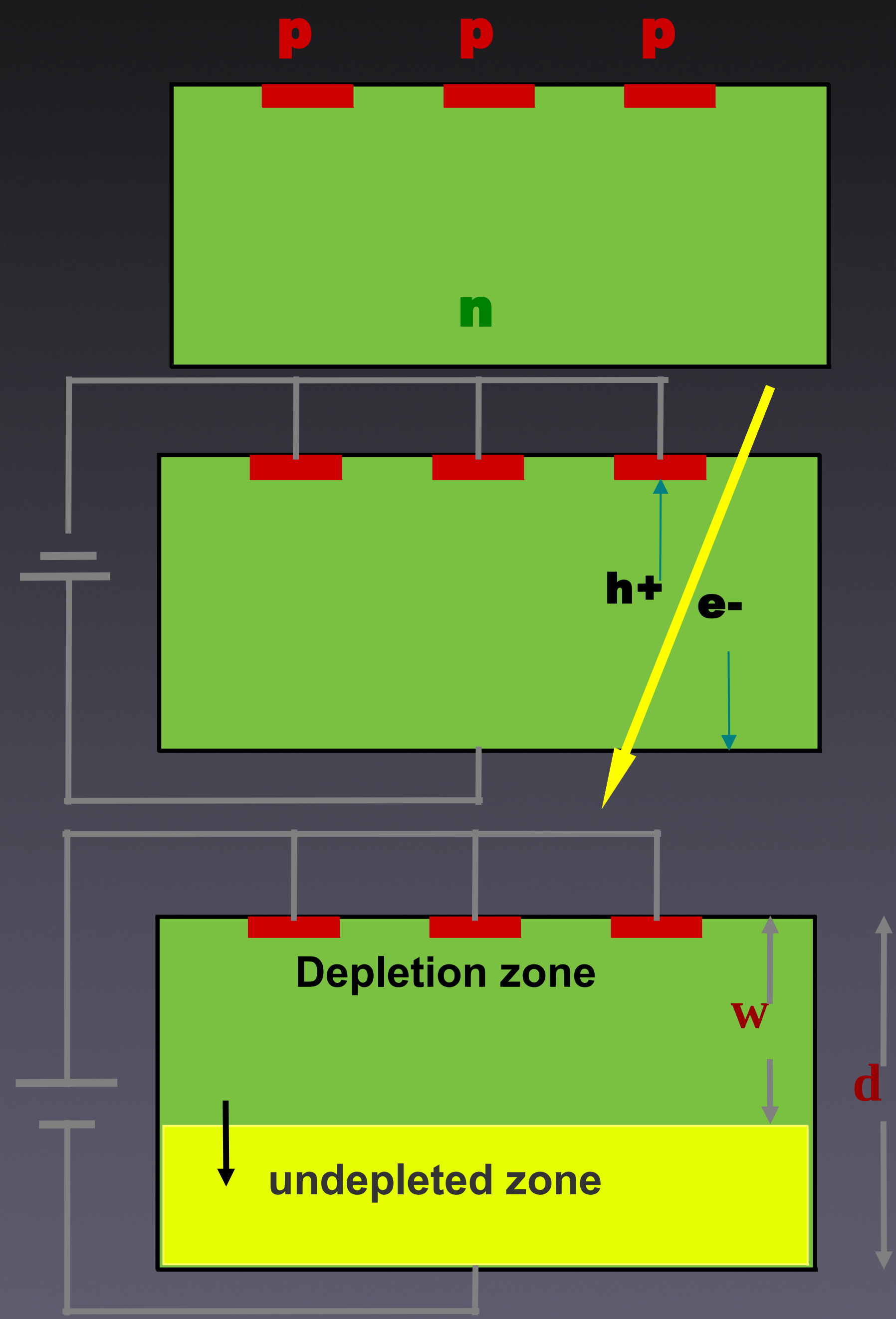
Available Hits





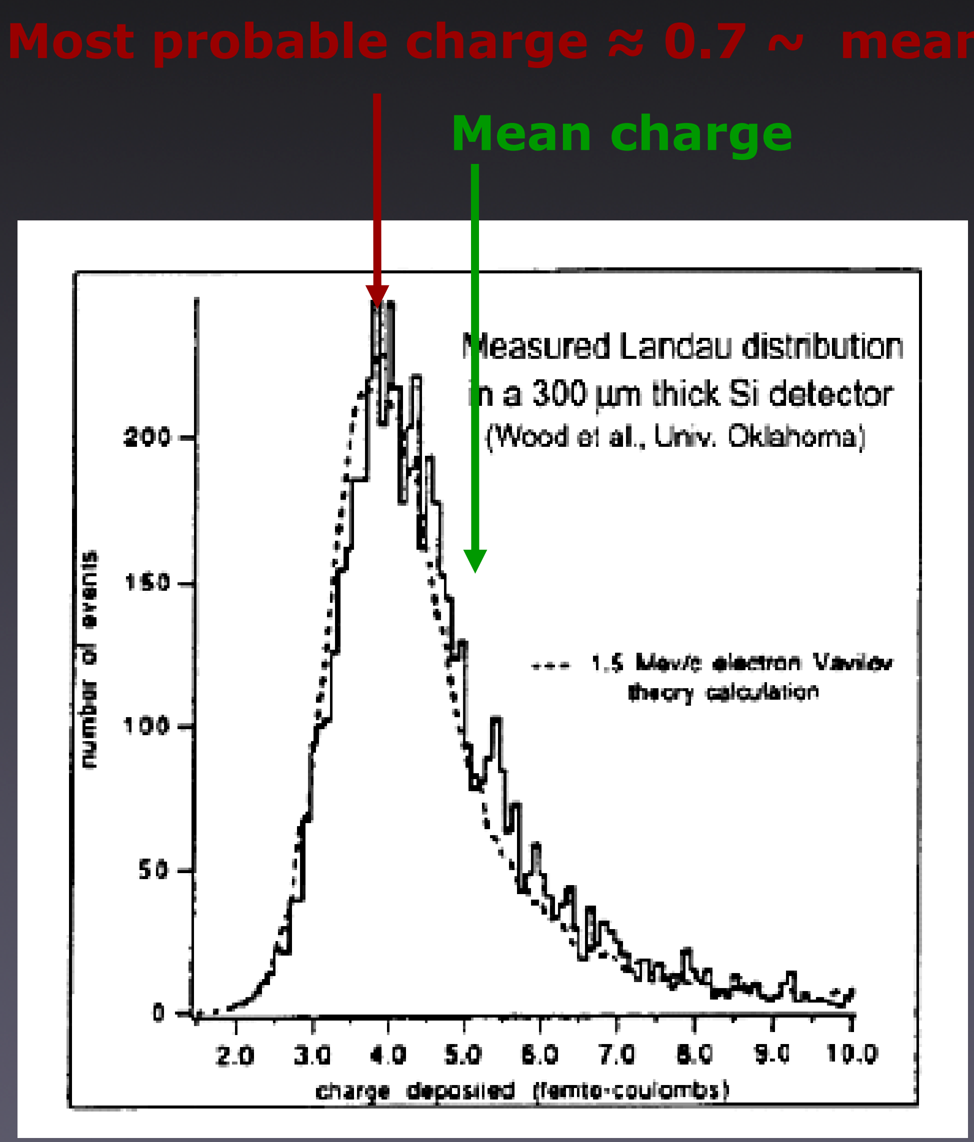
Silicon Detector Basics

- Basic building block
  - pn-junction (aka diode)
  - Reverse-bias
  - Fully depleted
- Collecting the charge
  - Either holes or electrons
  - Using charge drift and diffusion
- Thickness ~ 300 μm



The collected Charge

- Assuming Minimum Ionizing Particle (MIP)
- Mean Energy loss
  - dE/dx_{Si} = 3.88 MeV/cm, for 300 µm thick = 116 keV
- Most Probable Loss (0.7 mean) = 81 keV
  - 3.6 eV needed to make e-h pair
  - 22500 e^- produced

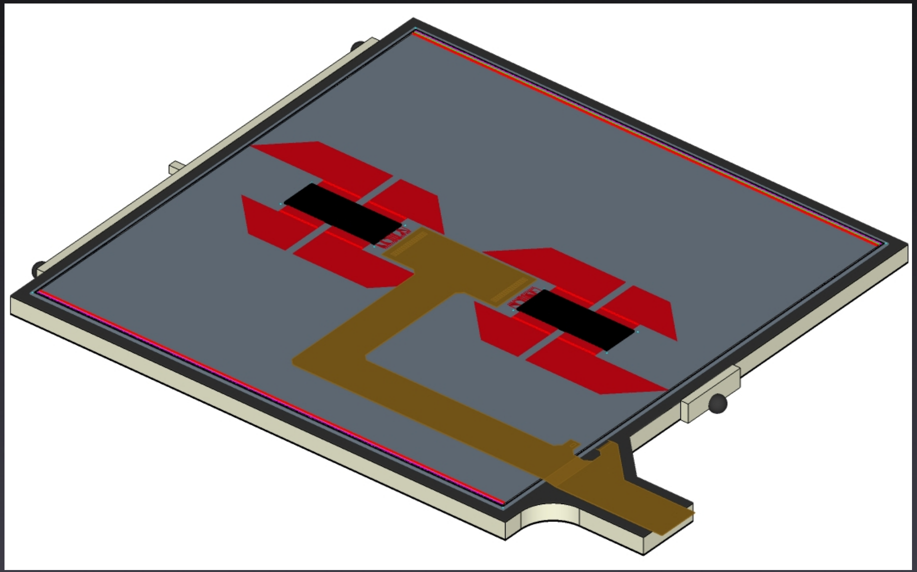


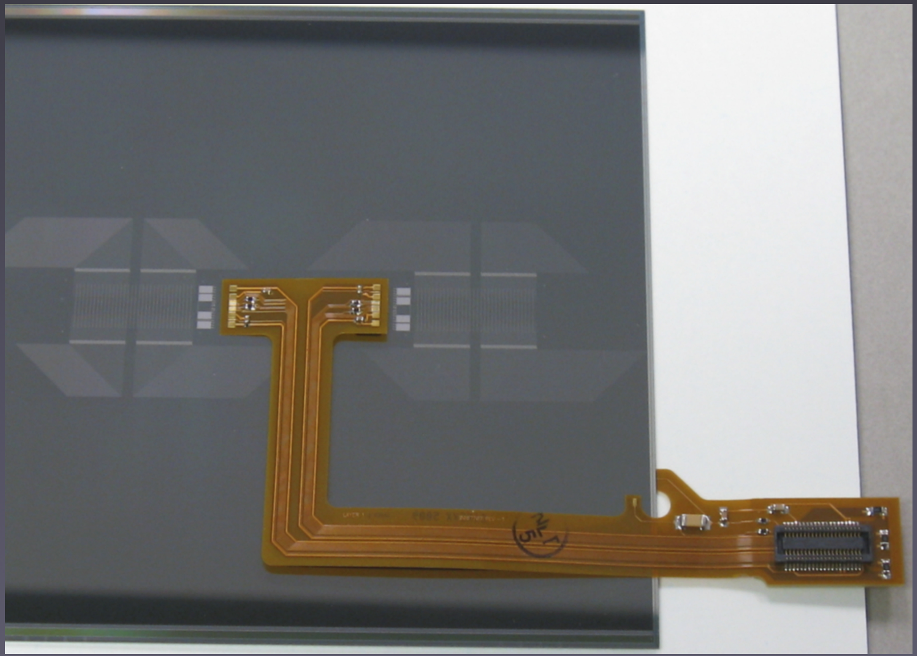
Strips, Strixels, Pixels

- Silicon detectors come in various flavors
- Silicon Strips
  - Small pitch strips (~ 50-75 μm), ~ several cm long
  - Gives a 2D hit (usually in rφ)
  - Z information is weak (cm level)
- Silicon Pixels
  - Can be as small as 10x10 μm
  - Real 3D hits
- Strixels
  - Basically very short strips

From Sensor to Module

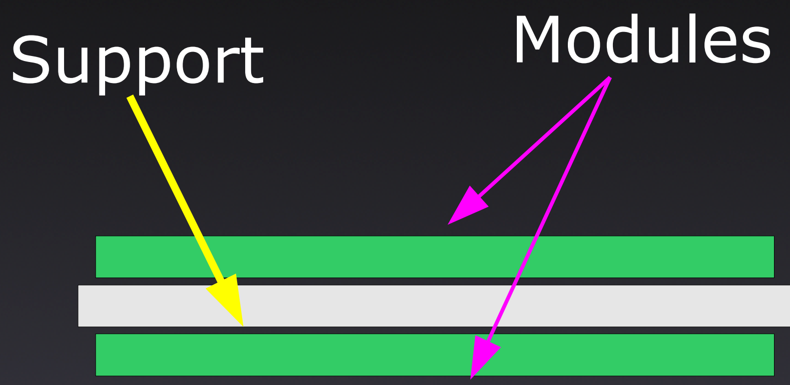
- The module is the tracker building block
- A typical Module consists of
  - The sensor itself
  - Interconnects
  - Readout ASIC
  - Power and data cables
  - Mechanical support structures

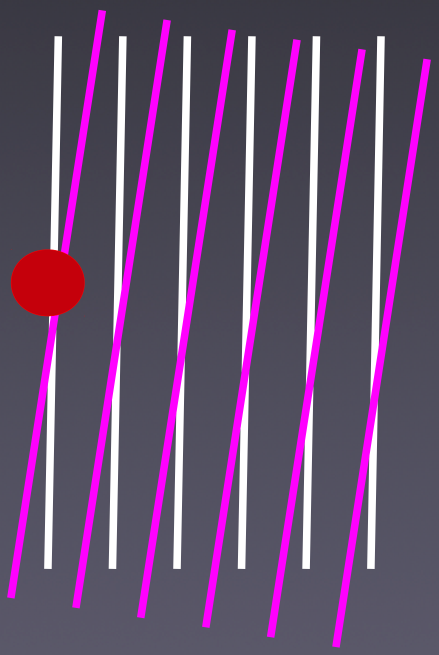




Double-Sided Strip Modules

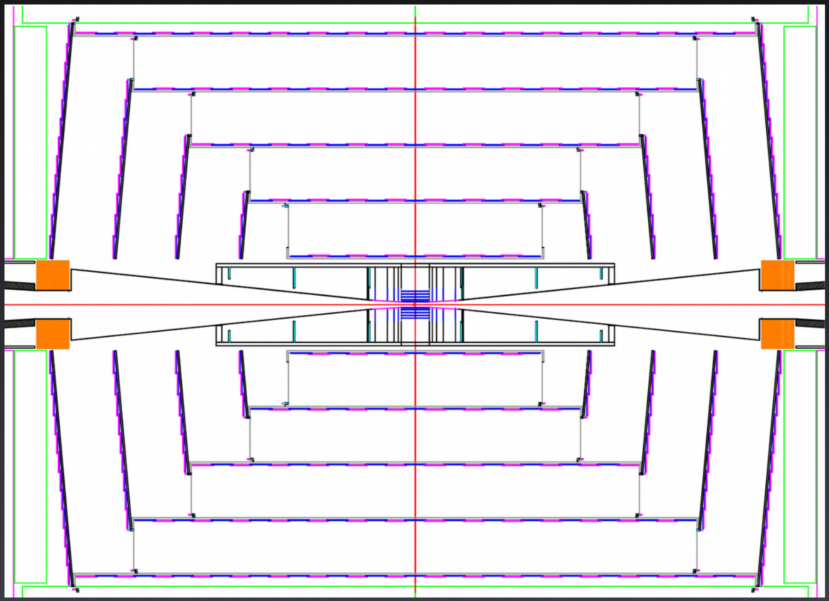
- Everyone likes 3D Hits
  - But pixels are expensive
- Idea
  - Strip modules that deliver ~ 3D Hits
- Today
  - Sandwich of two strip modules
  - Either 90 degree (rare)
  - Small angle stereo

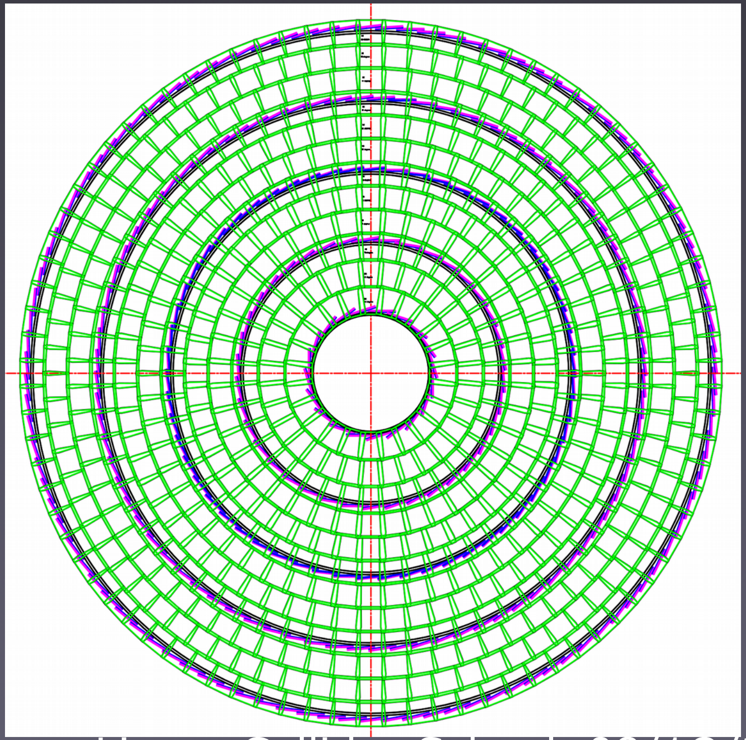




The SiD Tracker

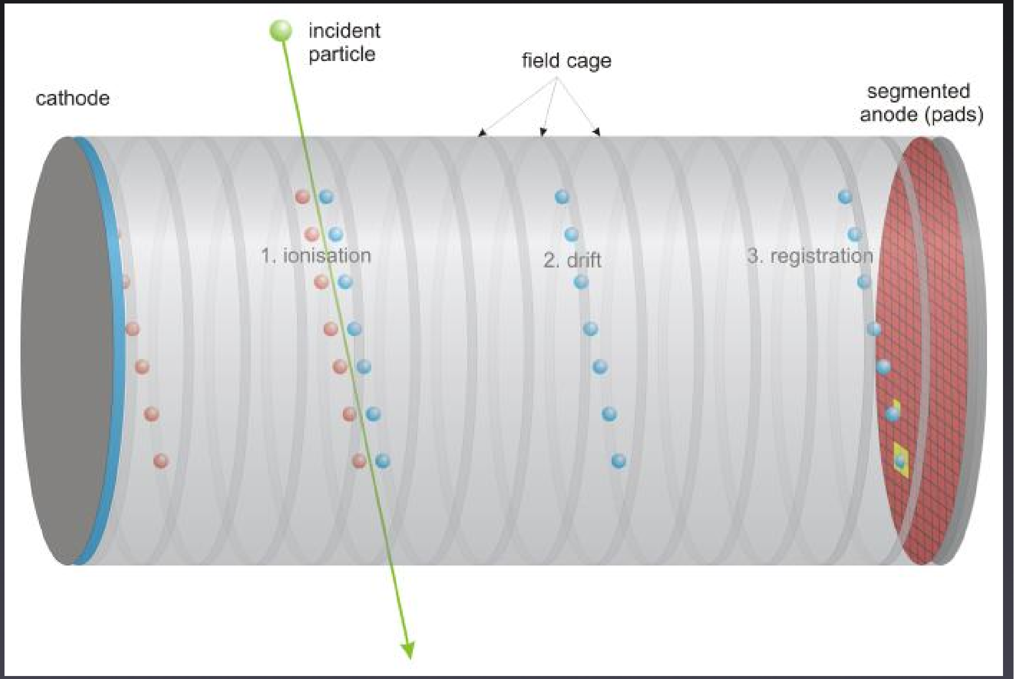
- All silicon tracker
  - Using silicon micro-strips with Double metal layers
- 5 barrel layers and 4 disks
- Cooling
  - Gas-cooled
- Material budget
  - less than 20 % X0 in the active area
- Readout using KPiX ASIC
  - Bump-bonded directly to the modules

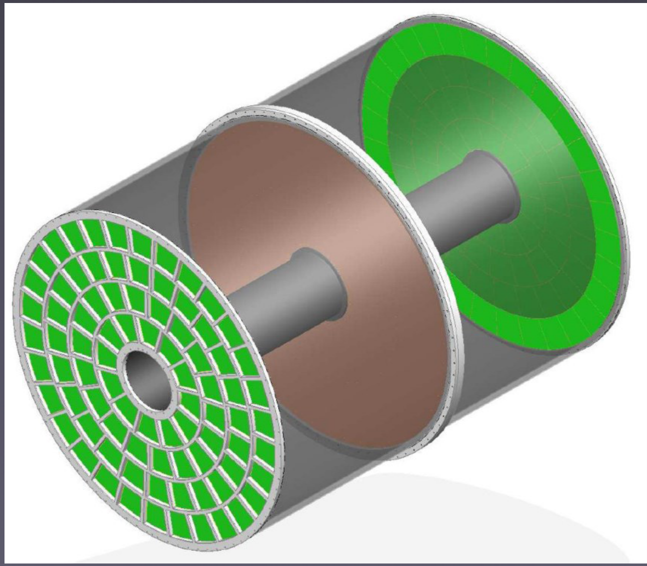




Time Projection Chamber

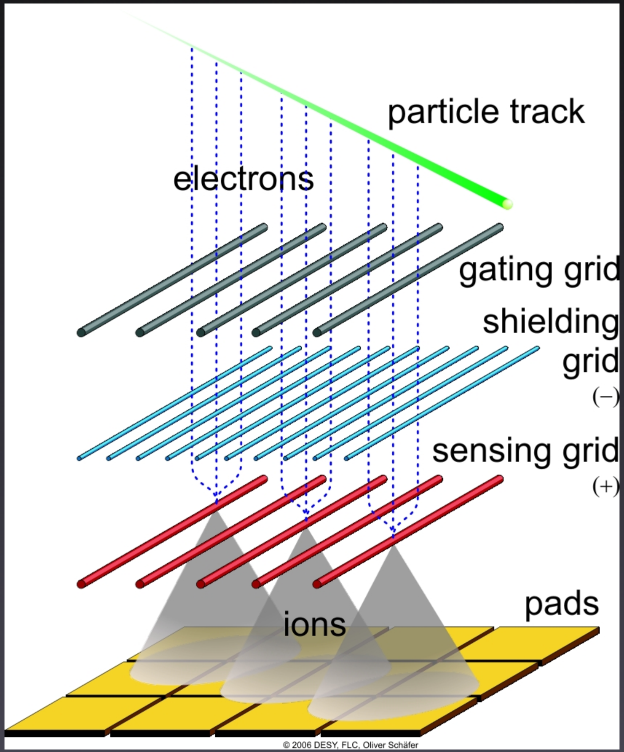
- Invented in the 70's
- Uniform electric field
  - drifts tracks of electrons towards into 2D readout pads at the endplate.
  - The signal amplitudes and arrival times provide 3D information
- Inside solenoid B field
  - Particle momenta can be estimated from the track curvature

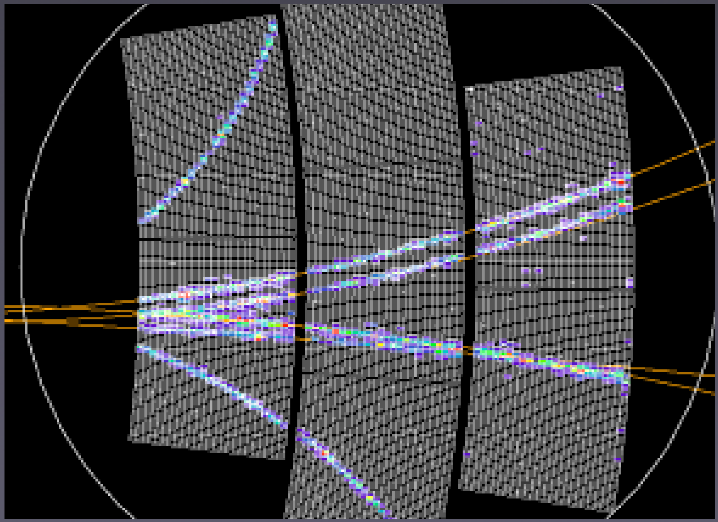




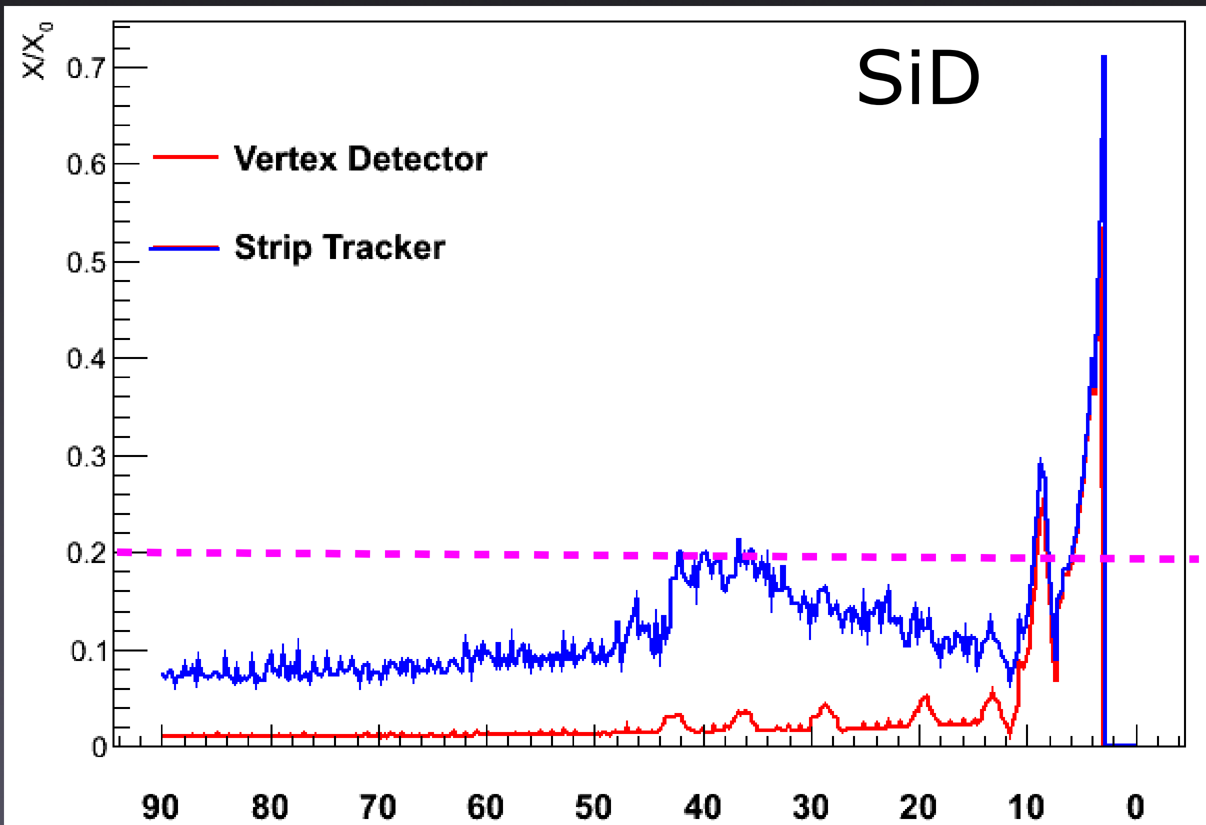
Endplate

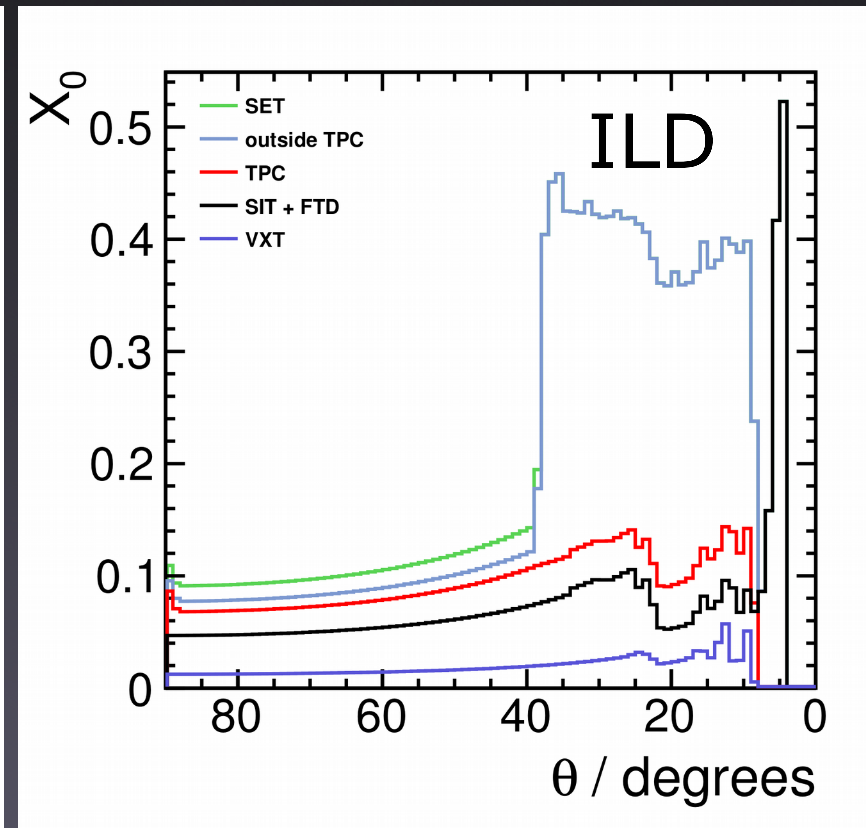
- Drifted charge is amplified at the TPC endplate
- Today:
  - Two main options for gas amplification: GEM or Micromegas
  - Readout pad size ~ $1x6mm^2$ 10^6 pads/endplate
- Readout electronics integrated in the endplate





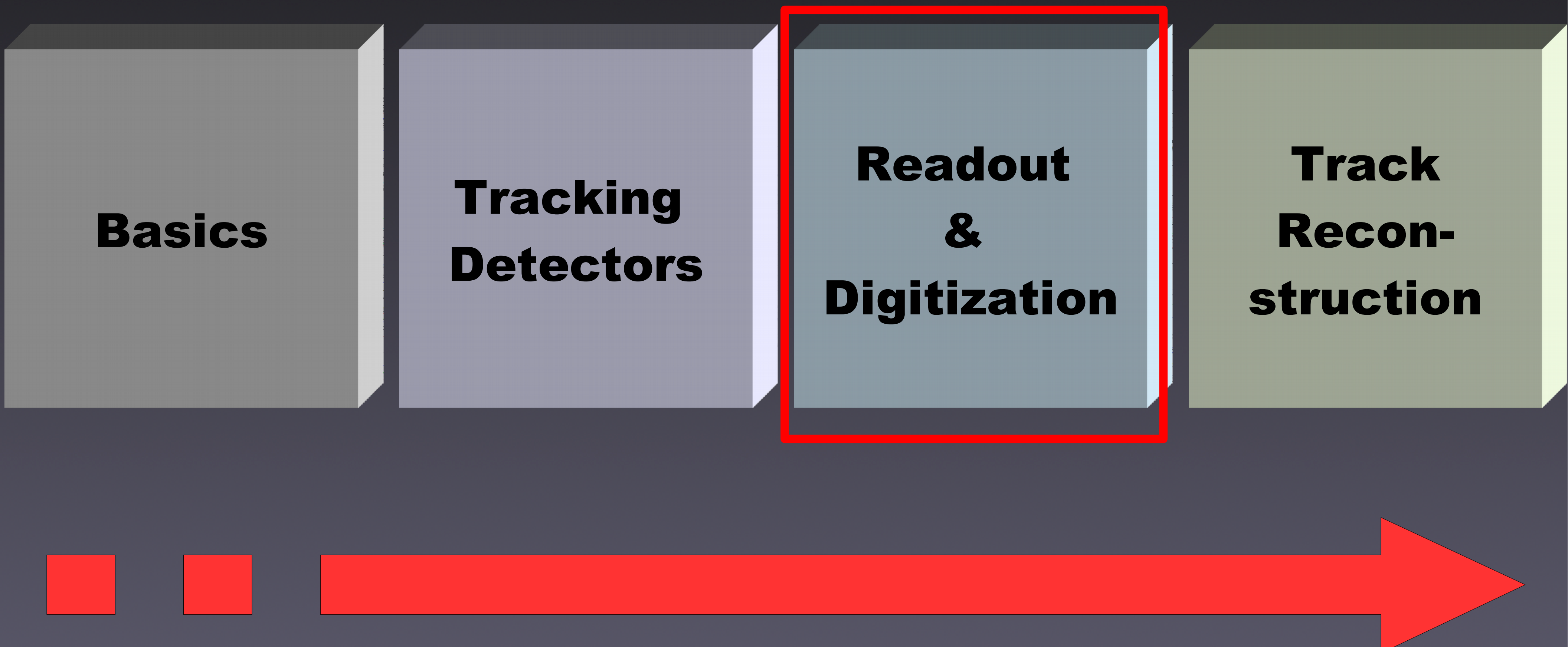
Material Budget





Both concepts have very aggressive material budget

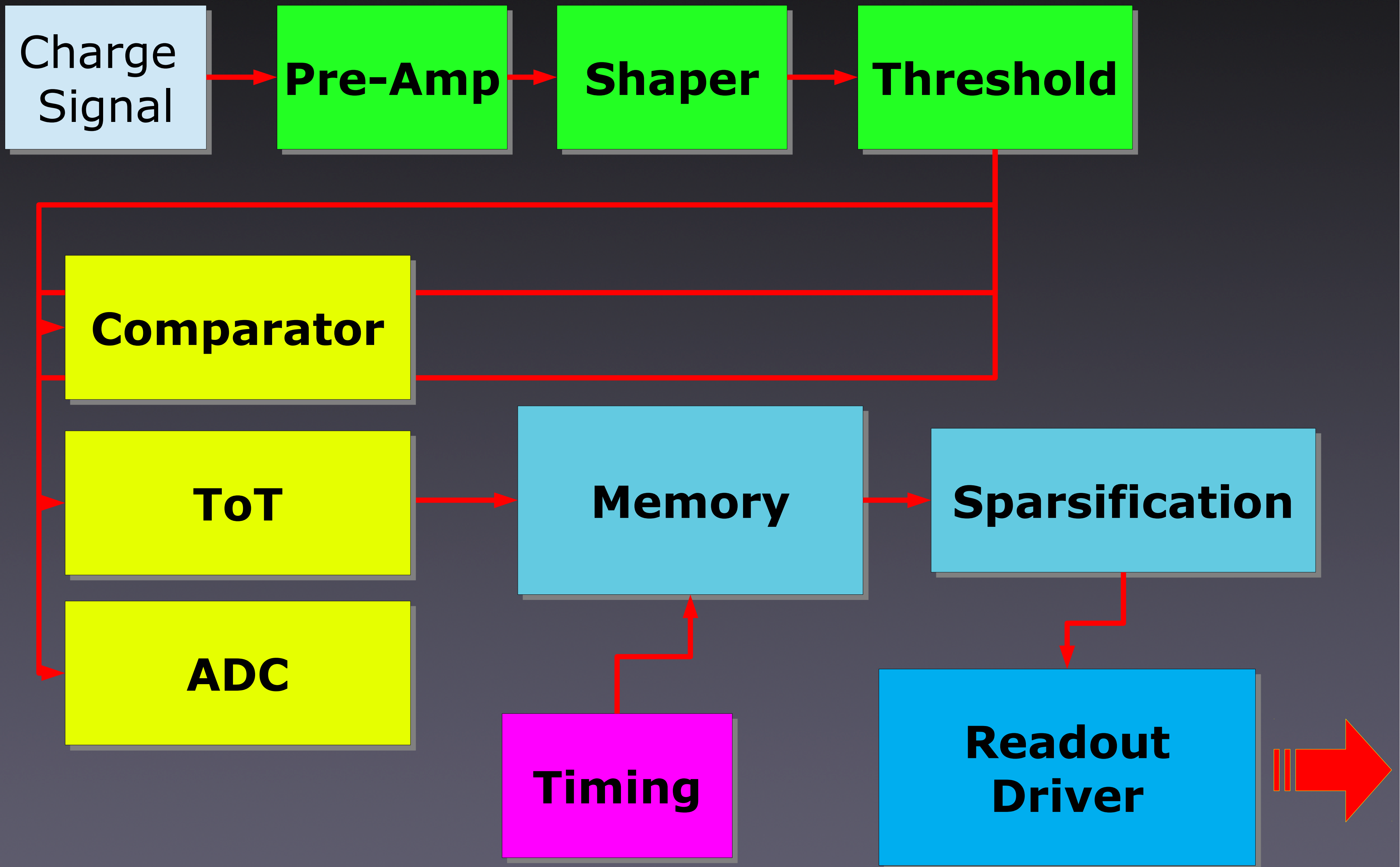
Roadmap


Basics
Tracking Detectors
Readout & Digitization
Track Recon-struction

Readout ASICS

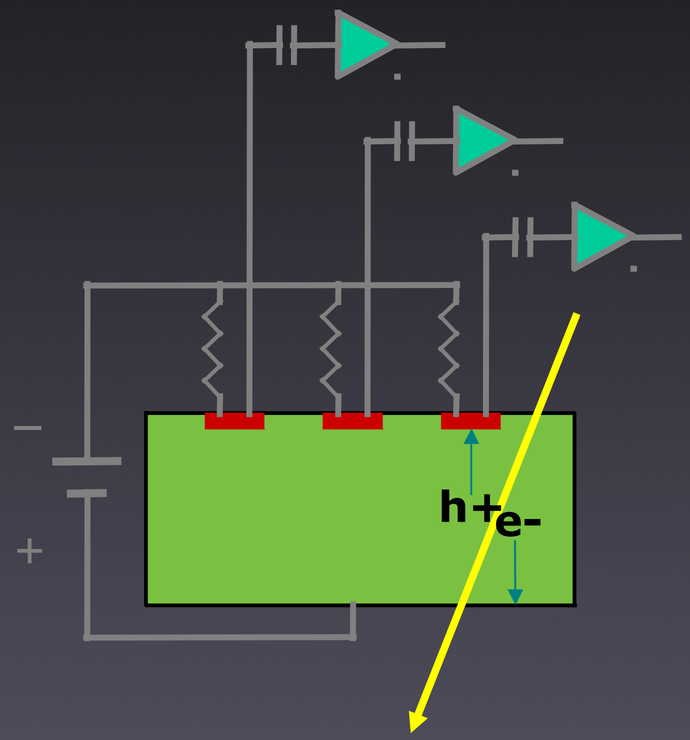
- The Readout ASIC is a key ingredient to an excellent tracker
- The ASIC
  - Amplifies and digitizes the charge
  - Provides timing information
  - Buffering
  - Transfers data to the DAQ
- ASIC are specifically designed for each tracker
  - Industry-level CMOS design
  - Making a good ASIC is an art

ASIC building blocks



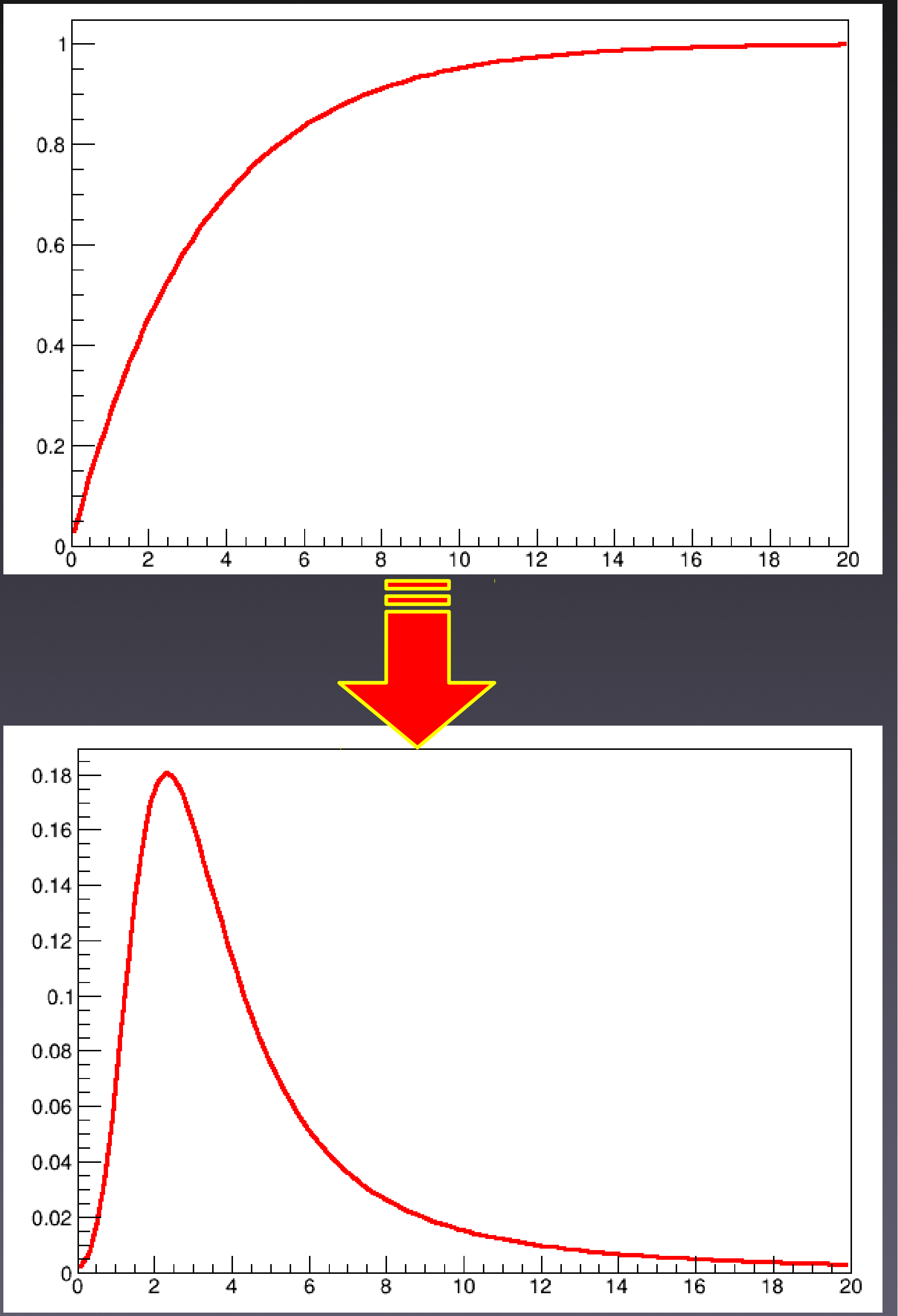
Readout and Pre-Amp

- isolate strips from each other
  - collect/measure charge on each strip
  - high impedance bias connection (resistor or equivalent)
- Usually AC (capacitive) coupling for input amplifier t
  - avoid large DC input from leakage current.
- Both structures are often integrated directly on the silicon sensor
  - Bias resistors via deposition of doped polycrystalline silicon, and
  - capacitors via metal readout lines over the implants but separated by an insulating dielectric layer (SiO_2 , Si_3N_4)



Shaper

- Pre-Amp usual very "simple" and integrating
- 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

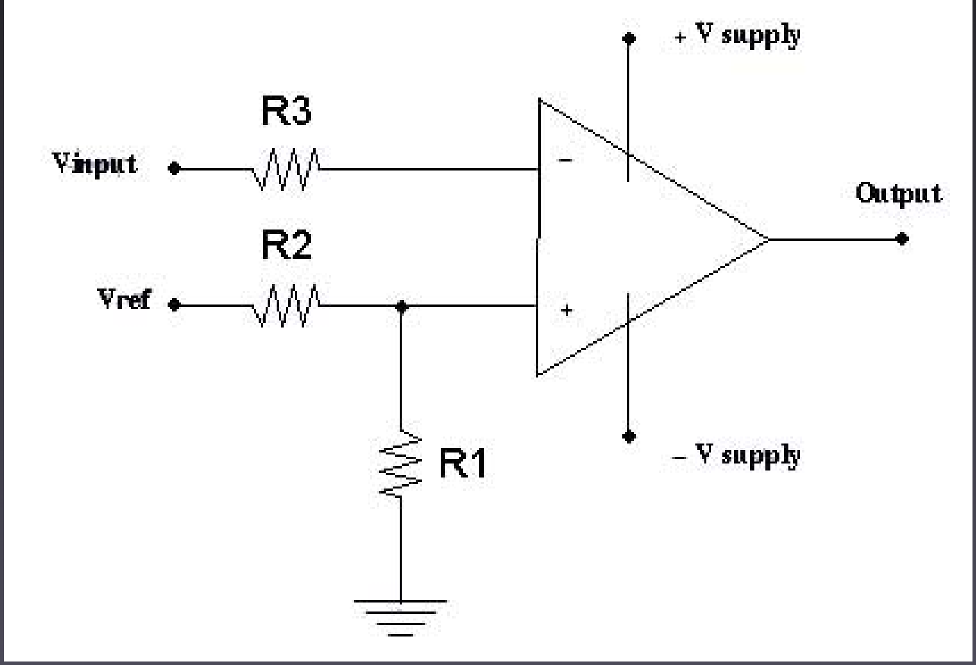


Thresholding & Digitization

- Now the analog signal is 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

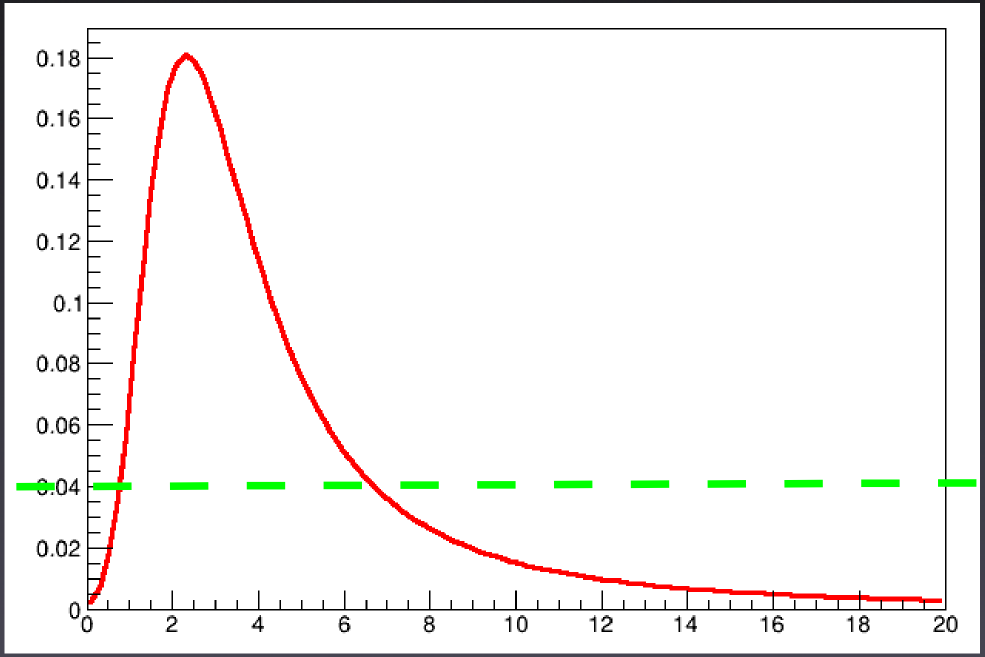
Comparators

- 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 and signal shape



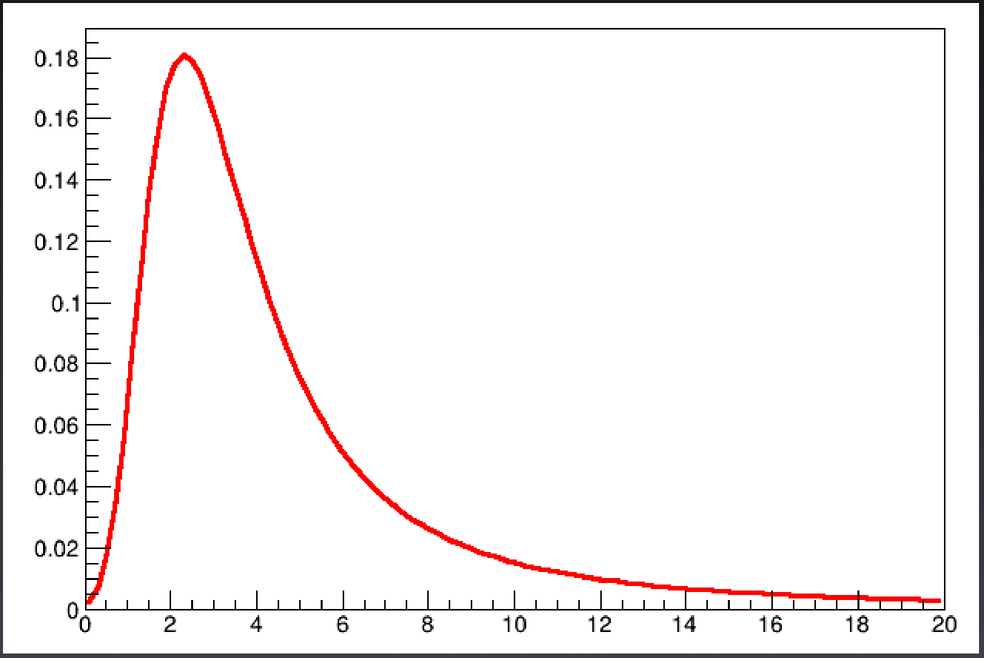
Basic Assumption
Pulse Width ~ Pulse Height

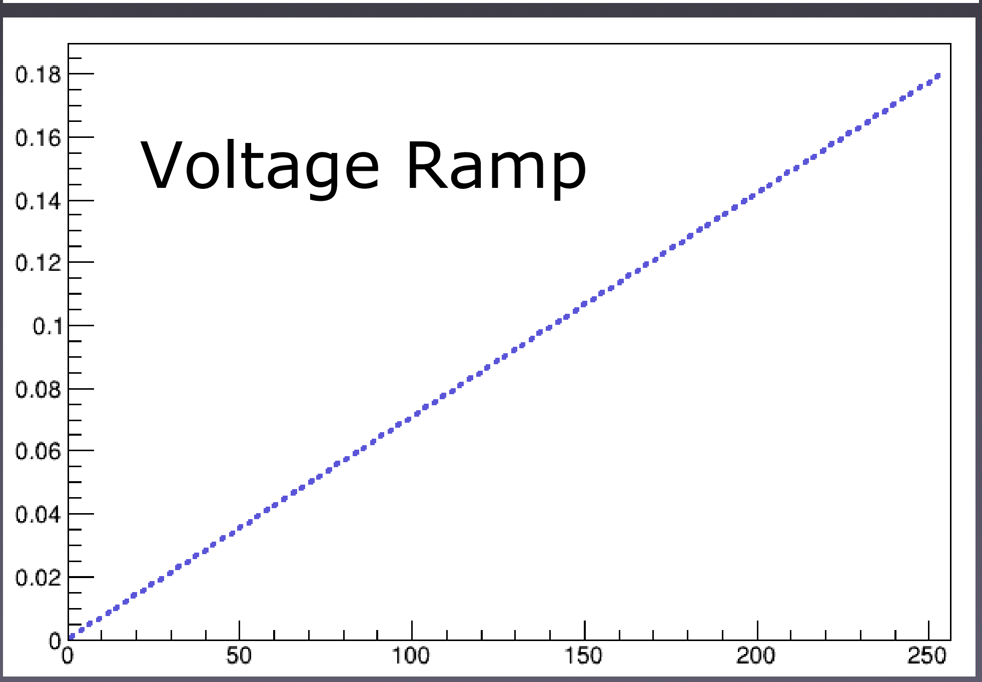
ADC

- 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

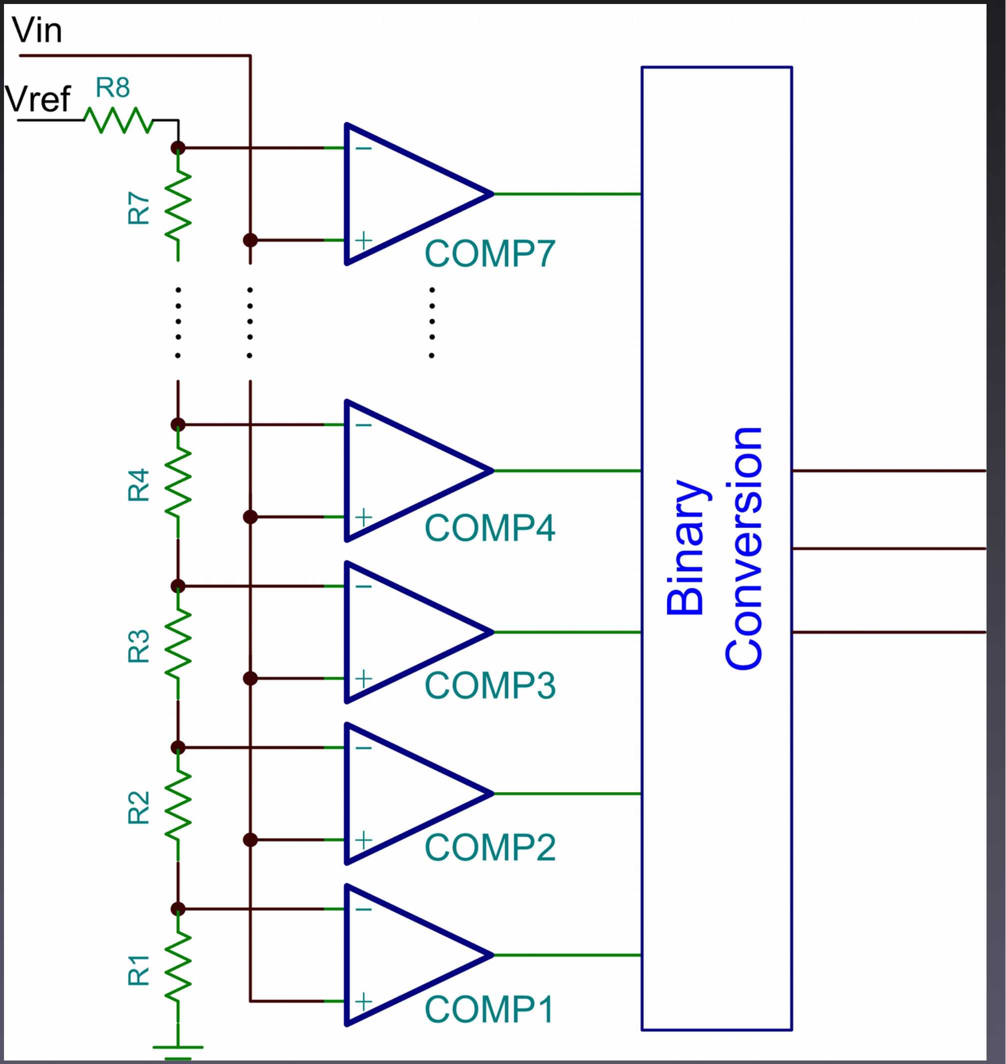
- This is a very simple ADC
- At t=0
  - Counter starts
  - ADC generates voltage ramp
- If $V_{ramp}=V_{input}$
  - Counter is stopped
  - N_{counts} is digitized information
- Speed driven by counter clock
  - Slow but low-power





FLASH ADC

- Speedwise this is the Ferrari of ADC's
  - Conversion in 1 clock cycle
- Complex with loads of circuitry
  - Power-hungry
  - N bits 2^n-1 Comparators needed
- 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

- Example
- Raw data (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
- Depends on applications
  - e.g Calorimeter chips have to deal with very high local occupancies

Analog vs Binary

- 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
  - LC detectors plan to do analog

Roadmap

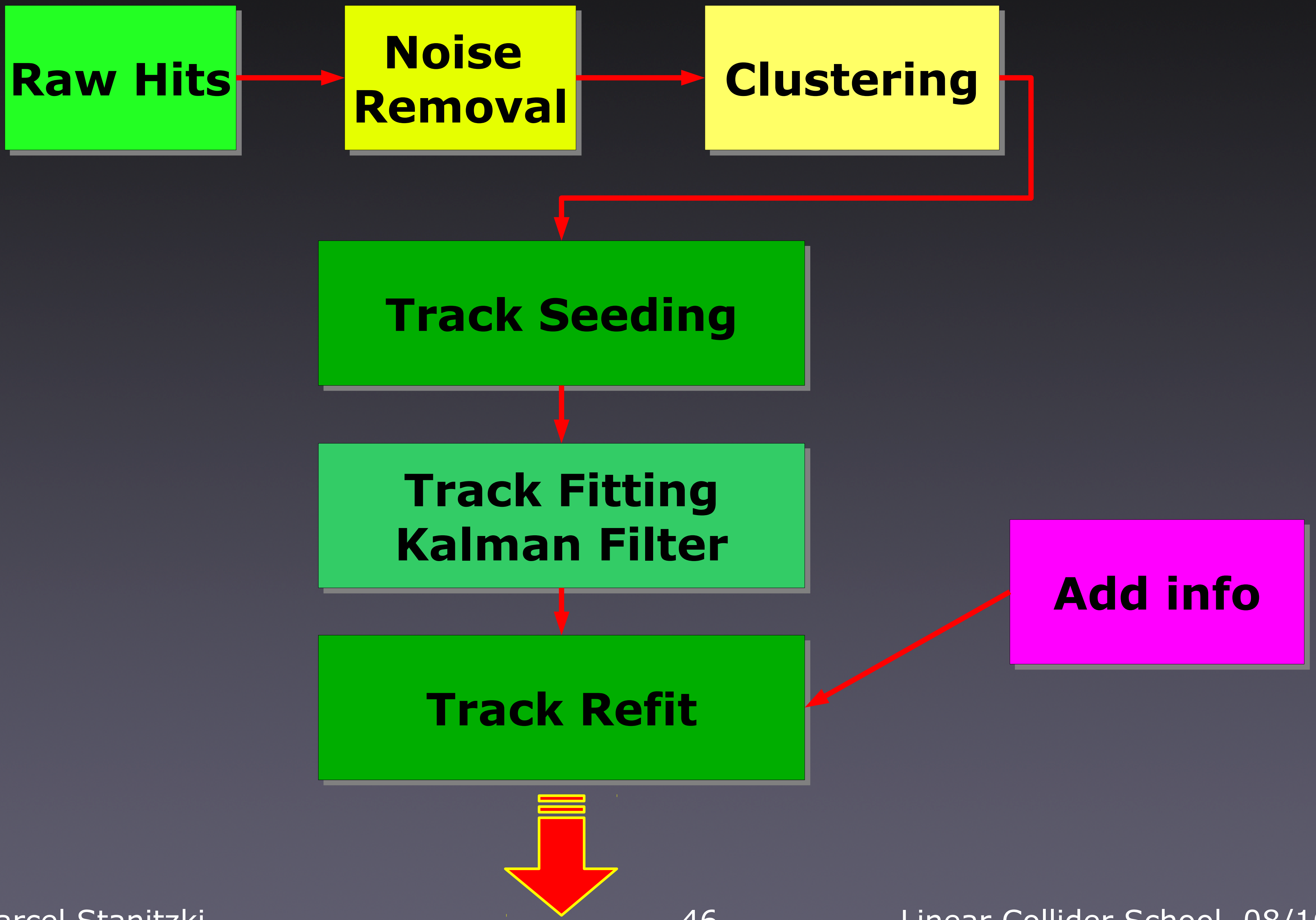
Basics

Tracking Detectors

Readout & Digitization

Track Recon-struction

Track reconstruction



Noise Removal

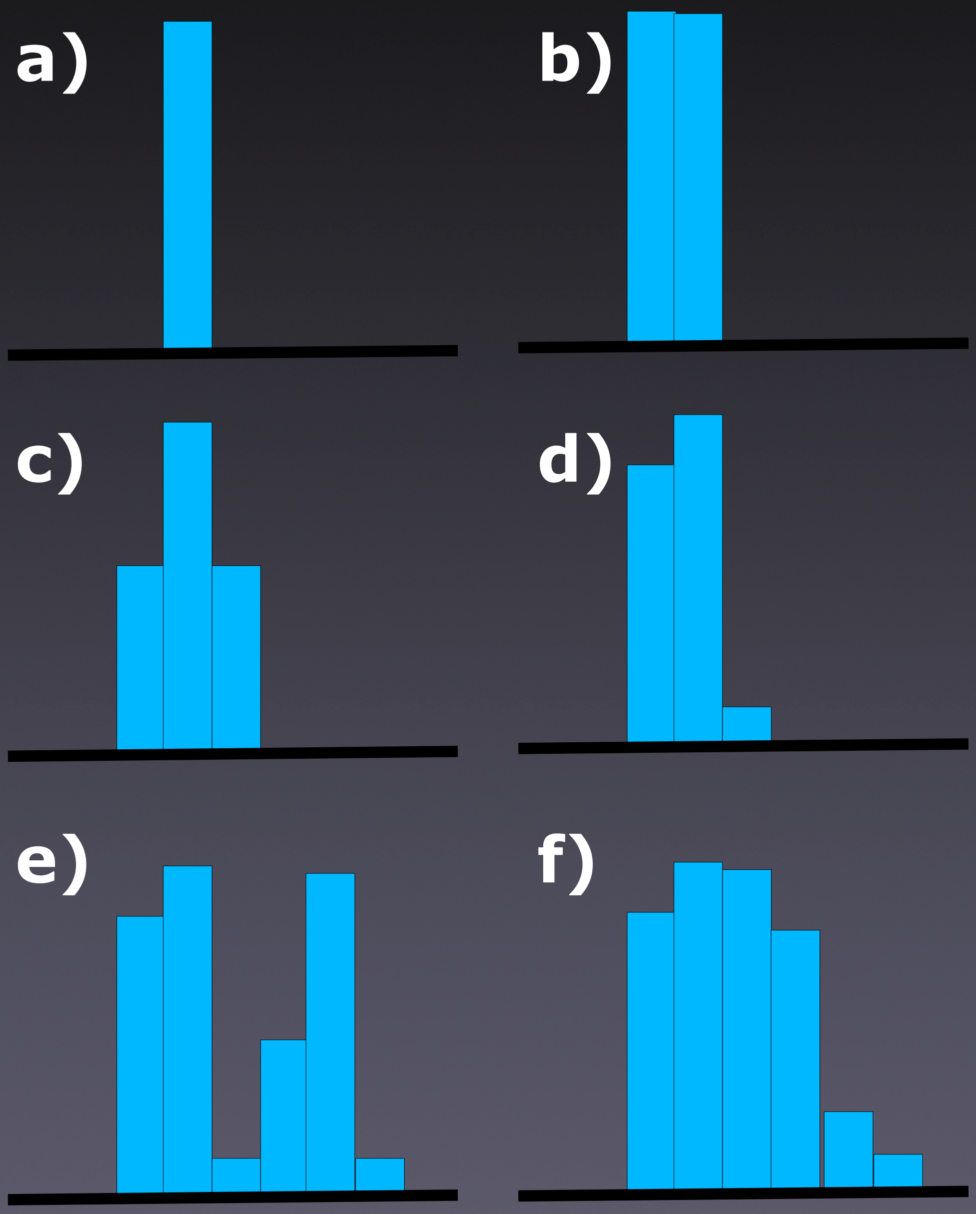
- In Reality no detector is completely noise-free
- Noise Source
  - Random (Noise floor 10^{-5}, 10^{6} channels ...)
  - Hot channels
  - Pick-up Noise (from somewhere else)
- Tracking is an $\sim n^2$ problem
  - Remove as many noise hits as possible
- Classic approaches
  - Remove all channels with 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 causing several hits
  - So not every hit corresponds to a particle
  - So need to reconstruct the particle hit
- Hence 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

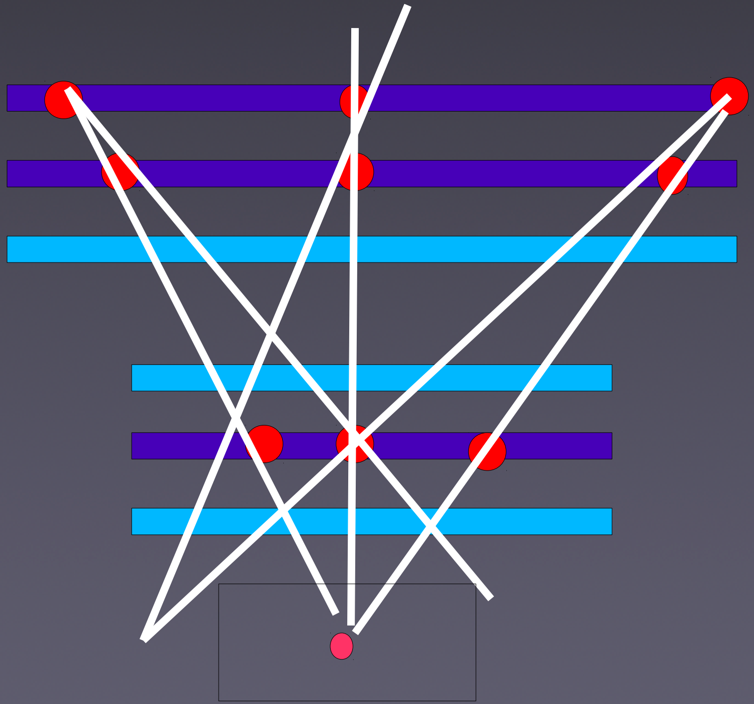


Tracking Strategies

- 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



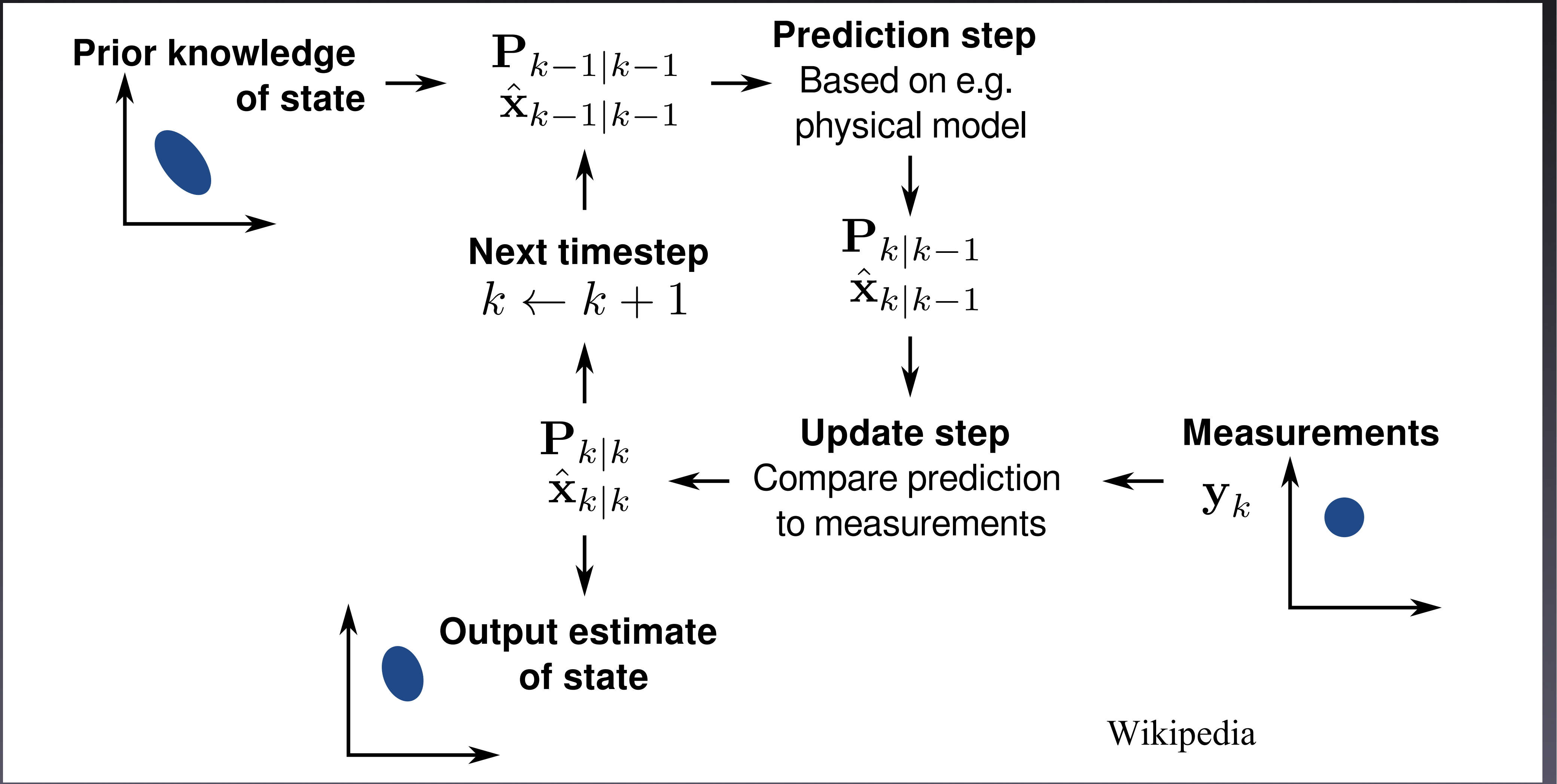
Tracking & Fitting

- 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
  - Loopers
  - low momentum tracks
  - tracks that have smaller number of hits
- Kalman Filter (see next slides)
  - Best tool for this, used by most experiments

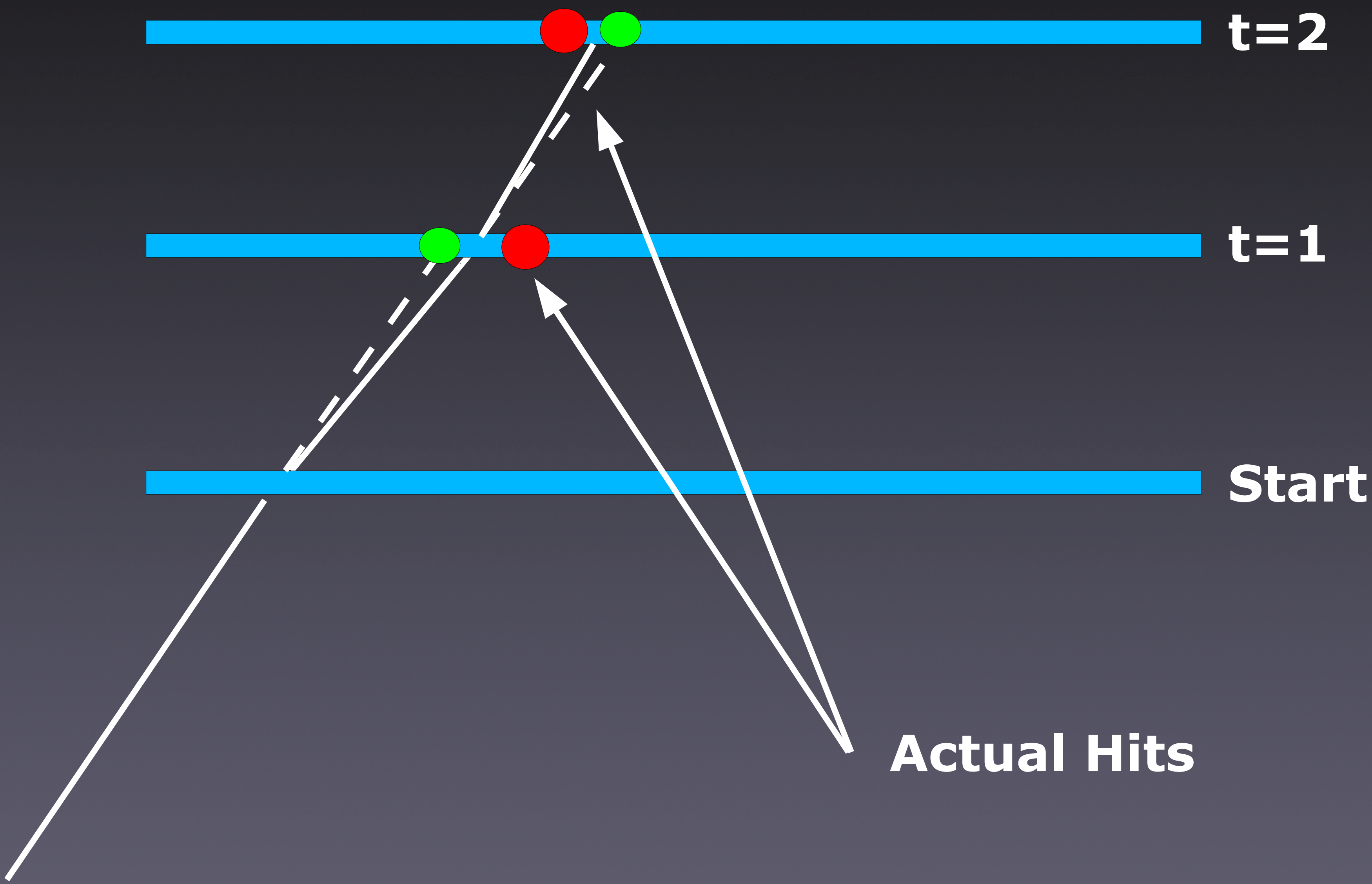
Kalman Filter

- What is it ?
  - Recursive algorithm using "noisy" input data
  - Statistically optimal estimate of the underlying system state
  - Needs physical propagation model
- Kalman Filters are the tool of choice for tracking objects
  - Particles
  - Airplanes
  - Missiles

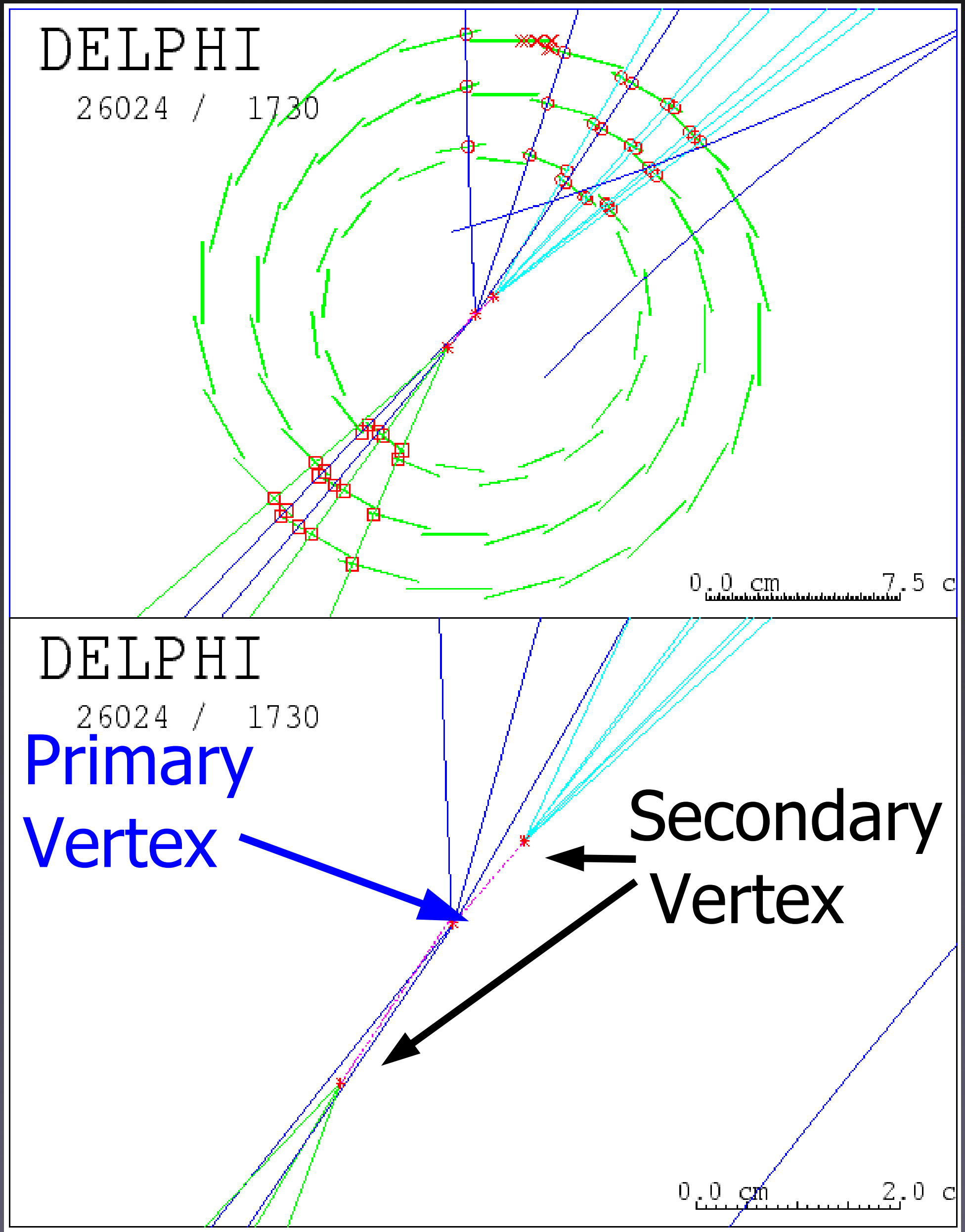
Kalman filter Sketch

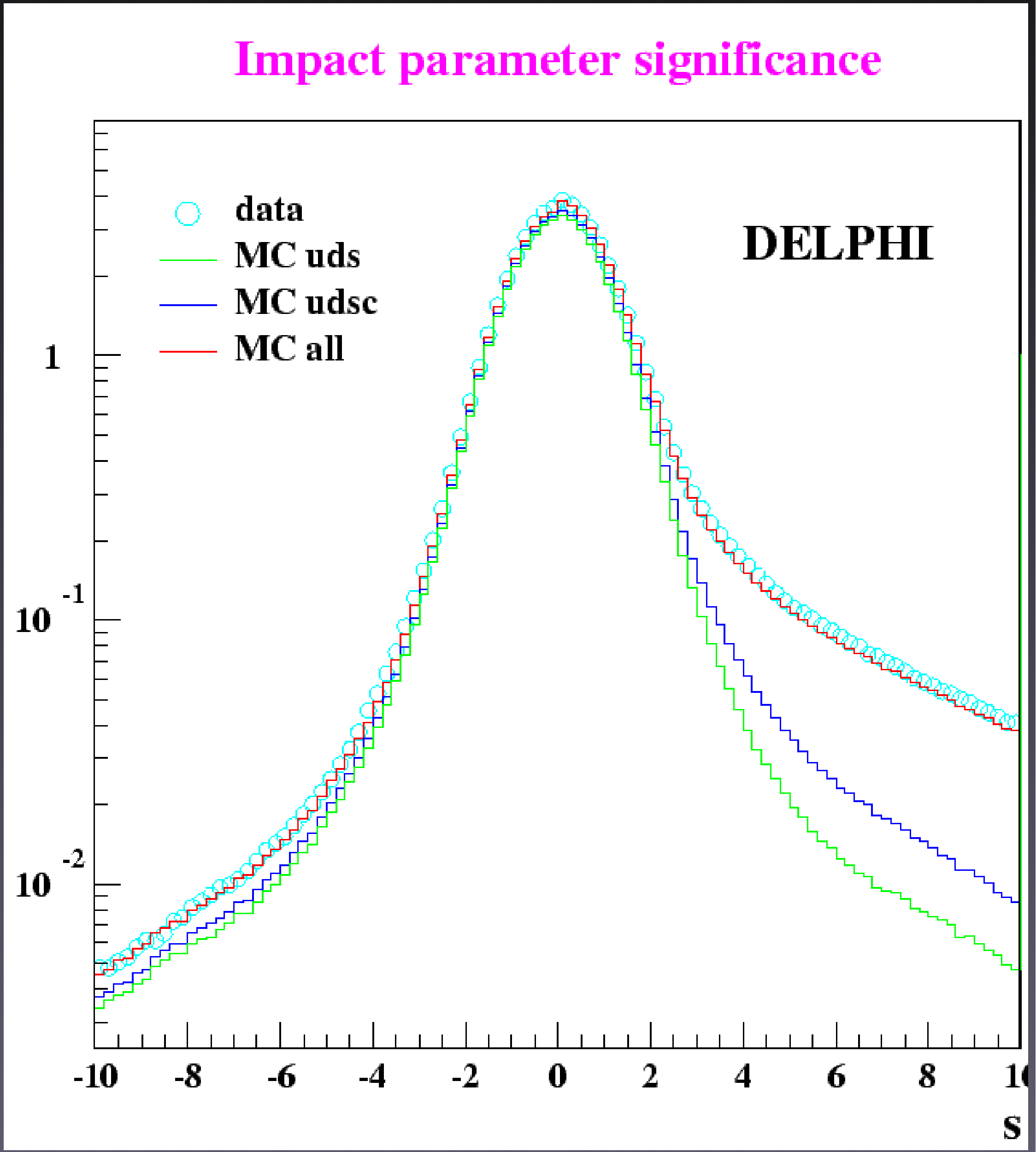


Tracking Example



Vertexing


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

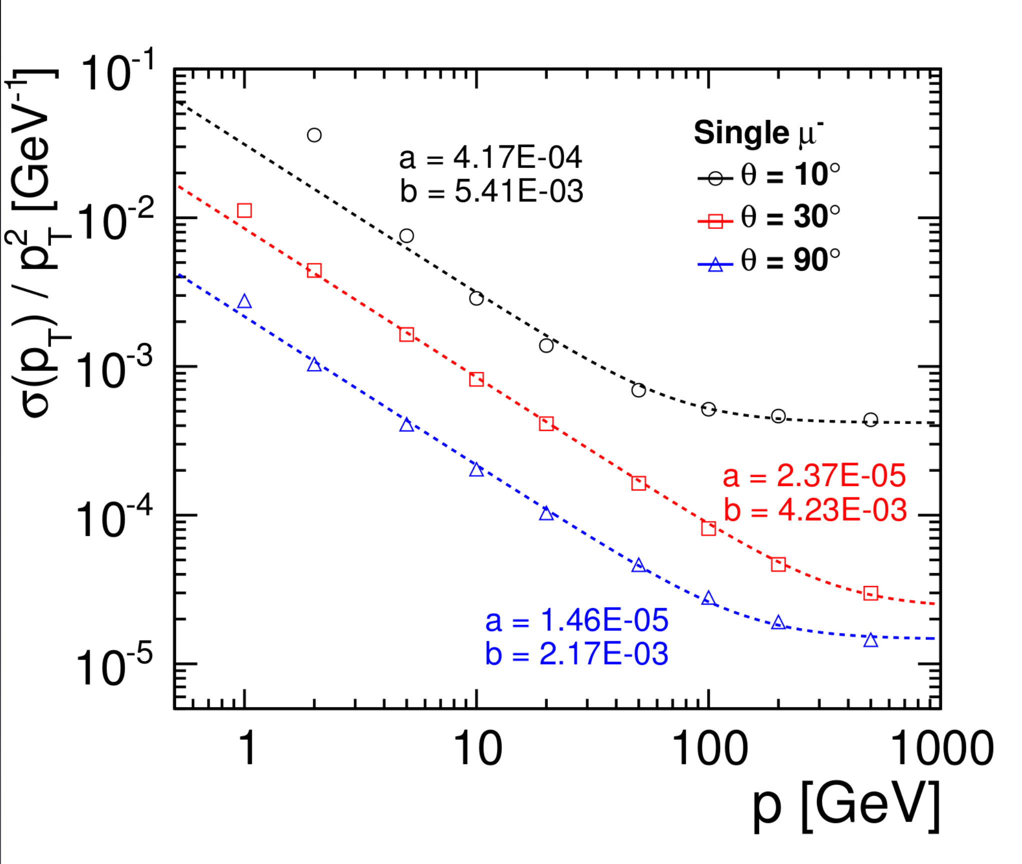

Impact parameter significance
data
MC uds
MC udsc
MC all
DELPHI
1
10 -1
10 -2
-10
-8
-6
-4
-2
0
2
4
6
8
S

Adding Information - Refitting

- In many cases, one has additional information about the track
- E.g. Track origin
  - If the Primary vertex is well know (as in a Linear collider)
  - Can Re-fit track using that information
- If track belongs to a secondary vertex
  - Use this constraint as well

SiD Tracking Performance

- SiD tracking is integrated
  - Vertex and Tracker
  - 10 Hits/track coverage for almost entire polar angle
- Tracking system
  - Achieves desired $\Delta p_T/p_T$ resolution of $1.46 \cdot 10^{-5}$
  - >99 % efficiency over most of the phase space



$$\frac{\sigma(p_T)}{p_T^2} = a \oplus \frac{b}{p \sin\theta}$$

Pointing resolution

Multiple scattering

Things I've skipped

- A lot of details about silicon detectors and TPC's
- Calibration
- Interconnects
- Advanced Pixel detectors
- Alignment
  - Hardware-based
  - Software-based
- Fake tracks and Fake rate
- Advanced tracking tools

Some Literature

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


"That's all Folks!"