Innovative Experimental Particle Physics through Technological Advances – Past, Present and Future

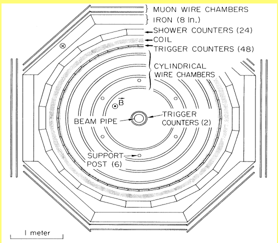
Part 2
Detached vertices

Harry W.K. Cheung – Fermilab

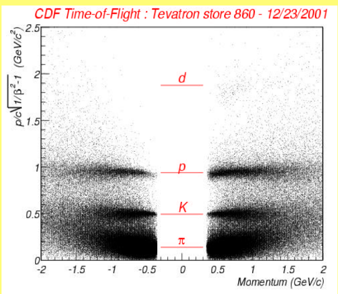
Talk Outline

- In Part 1 I talked about the discovery of charm and the study of $c\bar{c}$ spectroscopy
  - Introduced scintillators, PMT's, wire chambers, magnetic momentum analysis, Cerenkov counters, electromagnetic calorimeters, e^+e^- colliders and $p\bar{p}$ in an antiproton accumulator
  - Introduced basic experimental design concepts
- In Part 2 I'll talk about additional experimental topics:
  - Particle identification systems
  - Detached vertices
  - precision position detectors and beam types
  - Evolution of Trigger systems

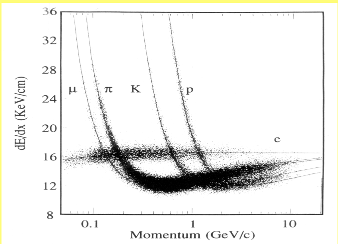
Selected Topics



Open Charm Discovery

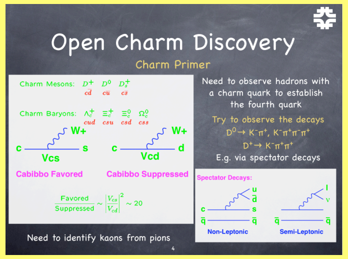


Time of Flight

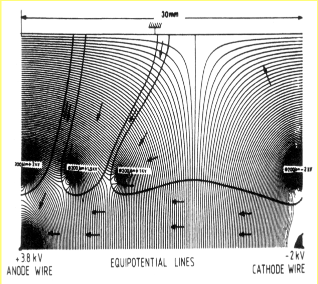


Ionization measurements

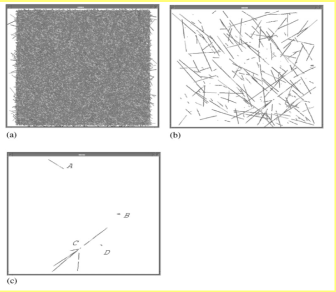
Come join BTeV!



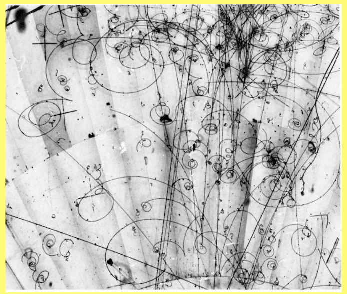
Charm Primer



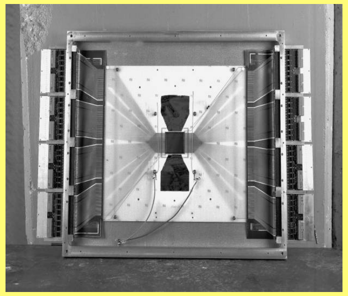
Drift Chambers



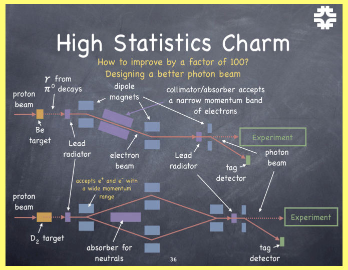
Emulsions



Bubble Chambers



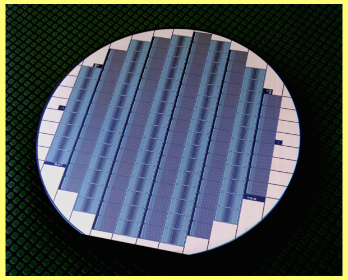
Silicon Microstrips



Beam Design

Data Storage

Trigger Systems



Pixels and BTeV

Open Charm Discovery

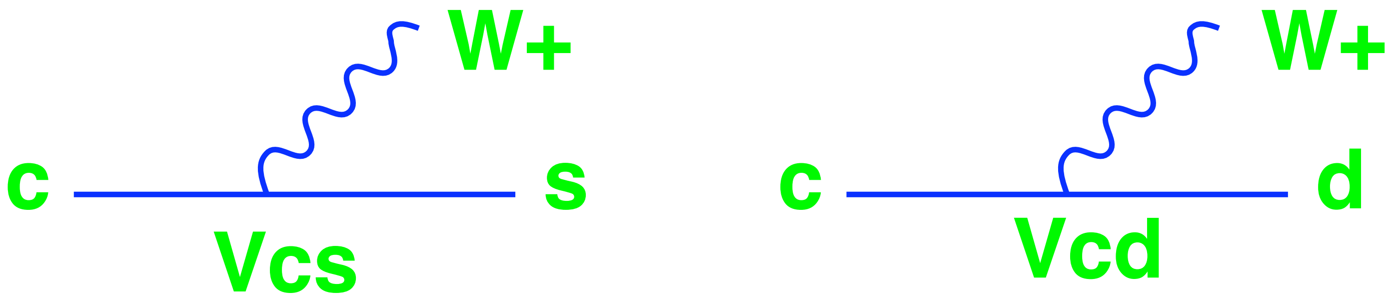
Charm Primer

Charm Mesons: D^+ D^0 D_s^+

$c\bar{d}$ $c\bar{u}$ $c\bar{s}$

Charm Baryons: Λ_c^+ Ξ_c^+ Ξ_c^0 Ω_c^0

cud csu csd css



Cabibbo Favored **Cabibbo Suppressed**

$$\frac{\text{Favored}}{\text{Suppressed}} \sim \left|\frac{V_{cs}}{V_{cd}}\right|^2 \sim 20$$

Need to identify kaons from pions

Need to observe hadrons with a charm quark to establish the fourth quark

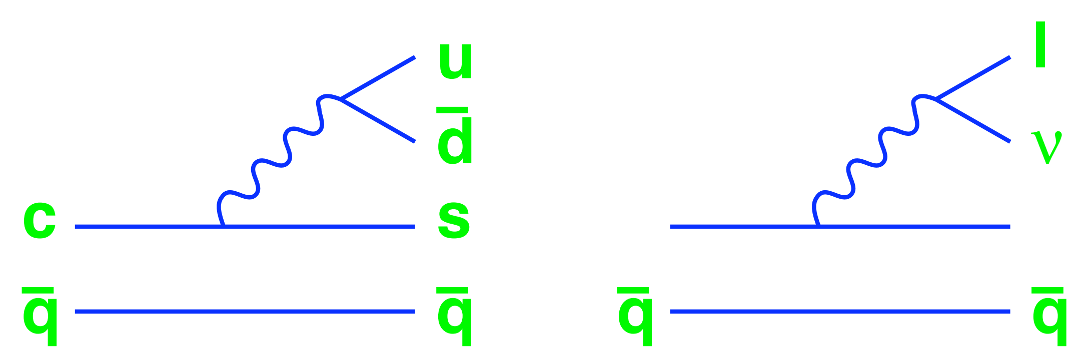
Try to observe the decays

$D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^-\pi^+$

$D^+ \rightarrow K^-\pi^+\pi^+$

E.g. via spectator decays

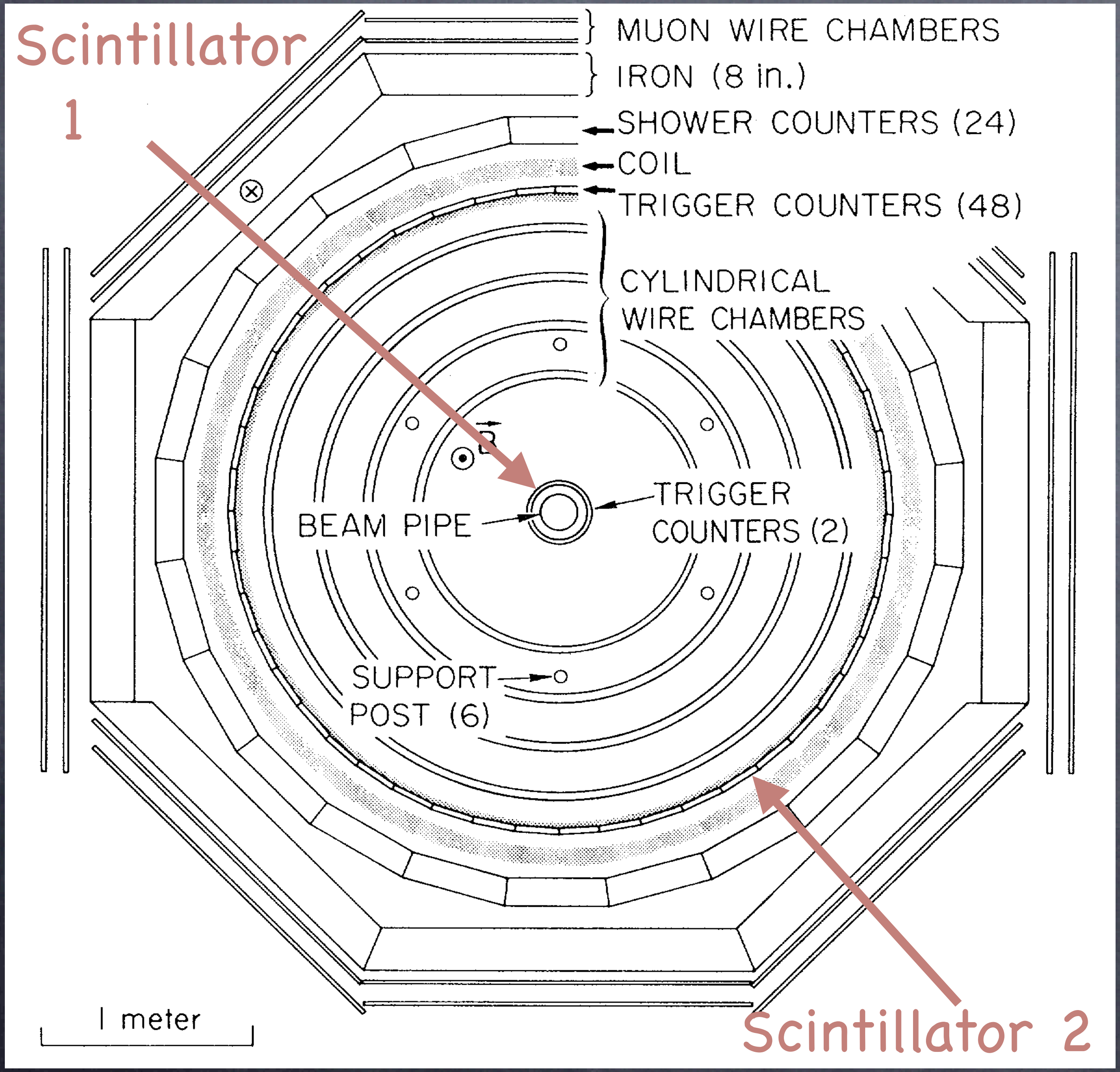
Spectator Decays:



Non-Leptonic **Semi-Leptonic**

Open Charm Discovery

Signal-to-background matters!



SPEAR and Mark I again

Mark 1 at SPEAR discovered the decays

$D^0 \to K^-\pi^+, K^-\pi^+\pi^-\pi^+$

$D^+ \to K^-\pi^+\pi^+$

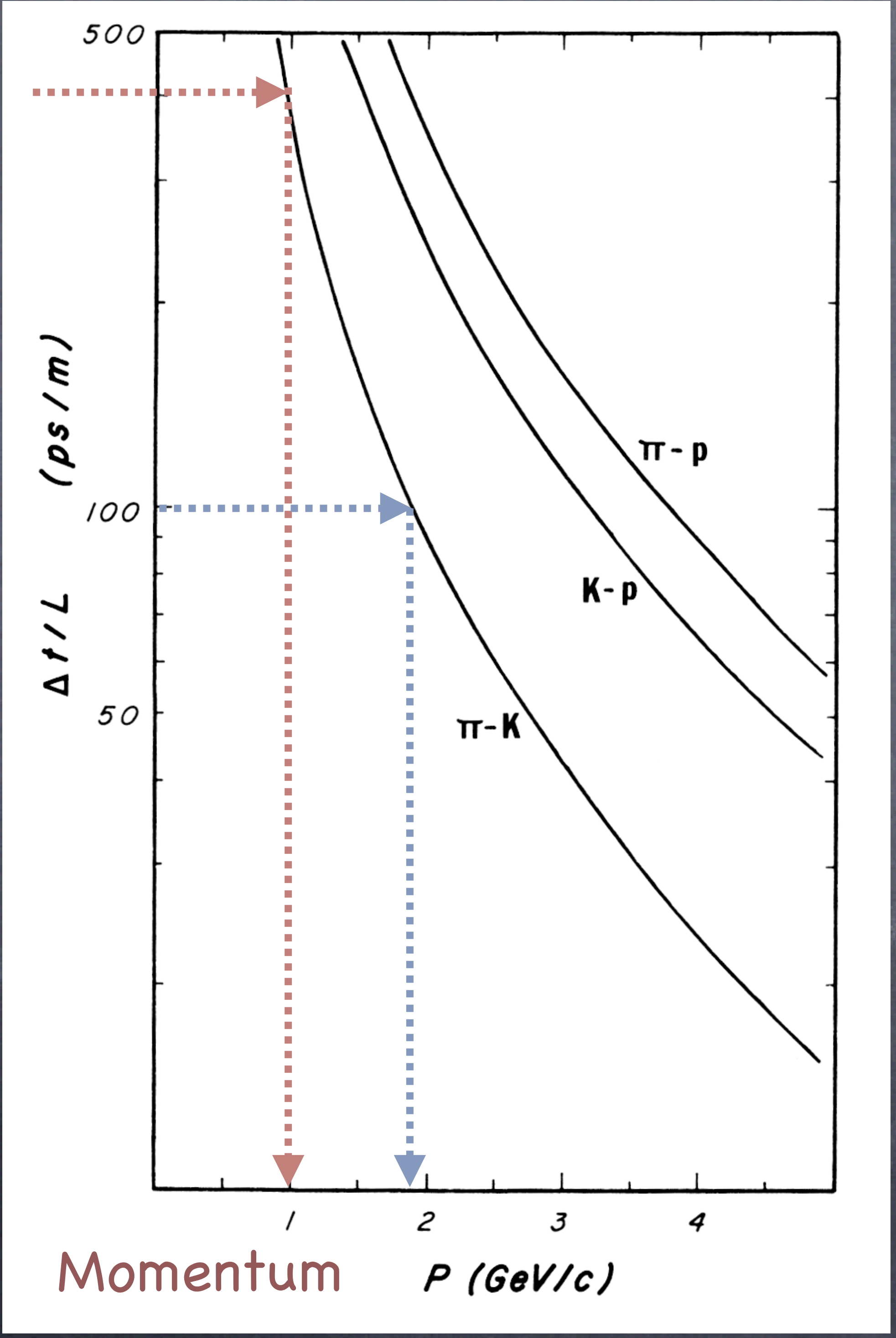
With more data and TOF (Time of Flight) detectors to identify kaons from pions

Also e^+e^- is a clean environment

We measure the time of flight of a particle between scintillators 1 and 2

Time-of-Flight Method

TOF difference between two particles traveling over 1 meter



Scintillators (if thick enough) give clean fast and narrow signals, good for TOF differences

For Mark 1: σ_{TOF} = 400 ps & L≈2m so get 2σ K/π separation for momenta < 1 GeV/c

Usually only good for low momenta

E.g. for the current CDF Run II TOF system: σ_{TOF} ≈ 100 ps

So for L≈2m we get 2σ K/π separation for momenta < 2 GeV/c

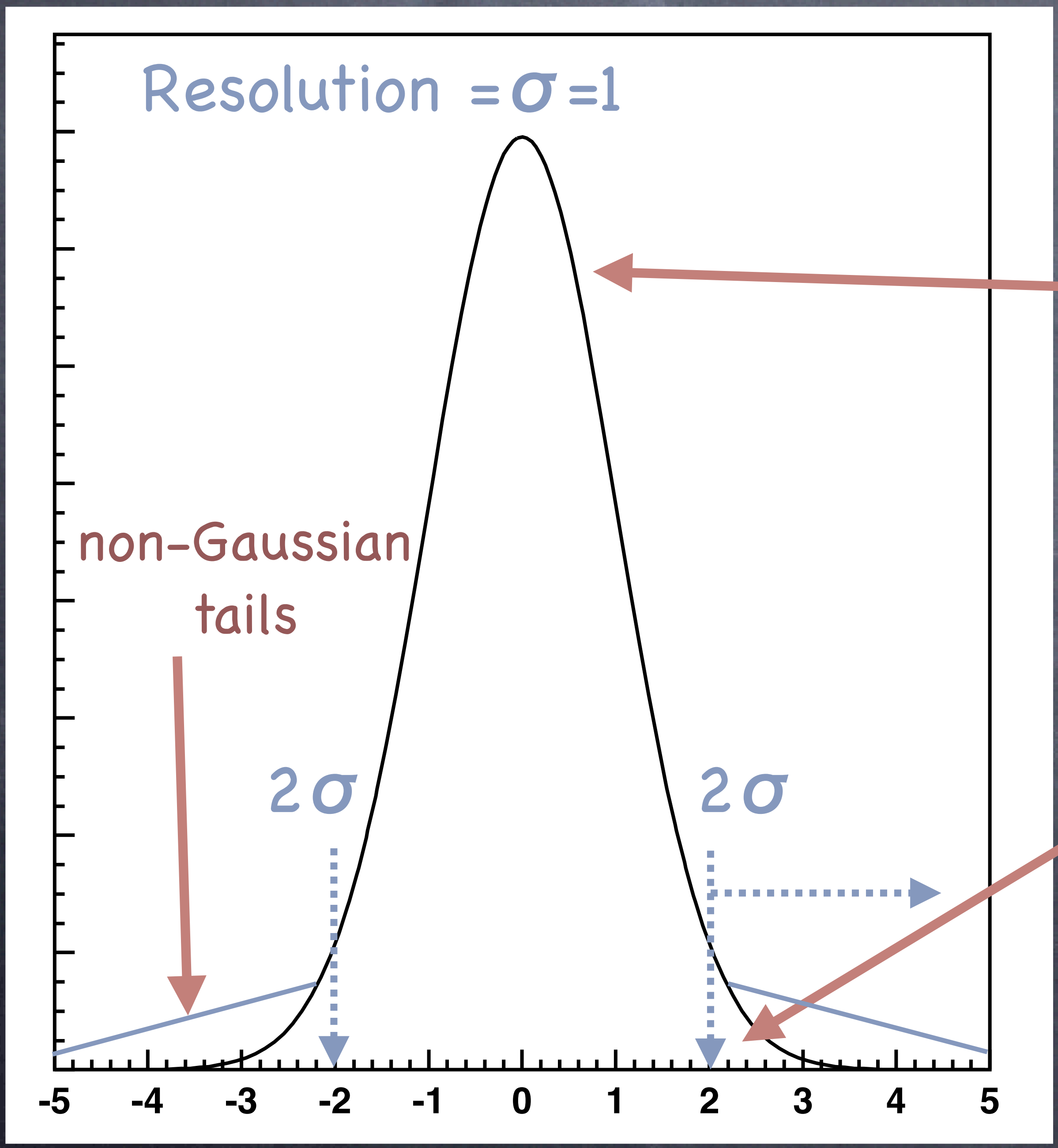
2σ separation (≈20:1 rejection) is not much when there are many more (background) pions than (signal)kaons

Also what does 2σ mean?

Statistics/Probability

Or what should you know when we quote a # of sigma

Gaussian Function for TOF difference



If the TOF difference is distributed as a pure Gaussian then 2 pions traveling the same distance will give a TOF difference given by left figure

a 2σ separation means we take all pions with TOF difference > 2σ this rejects ≈ 97% of pions for a ≈ 33:1 rejection assuming 100% efficiency for kaons

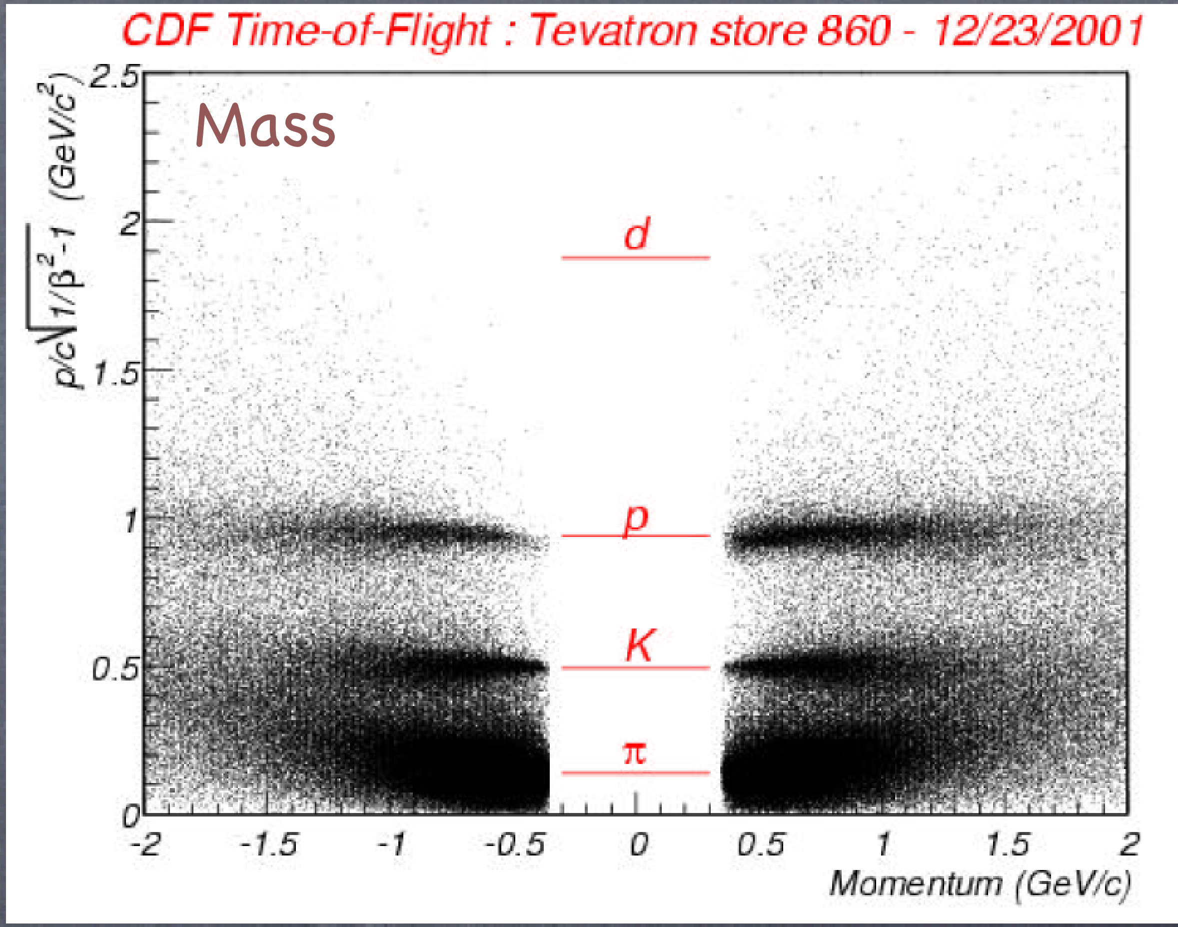
Problem is often distributions are not true Gaussians!

Statistics/Probability

Or what should you know when we quote a # of sigma

Some causes of non-Gaussian tails:

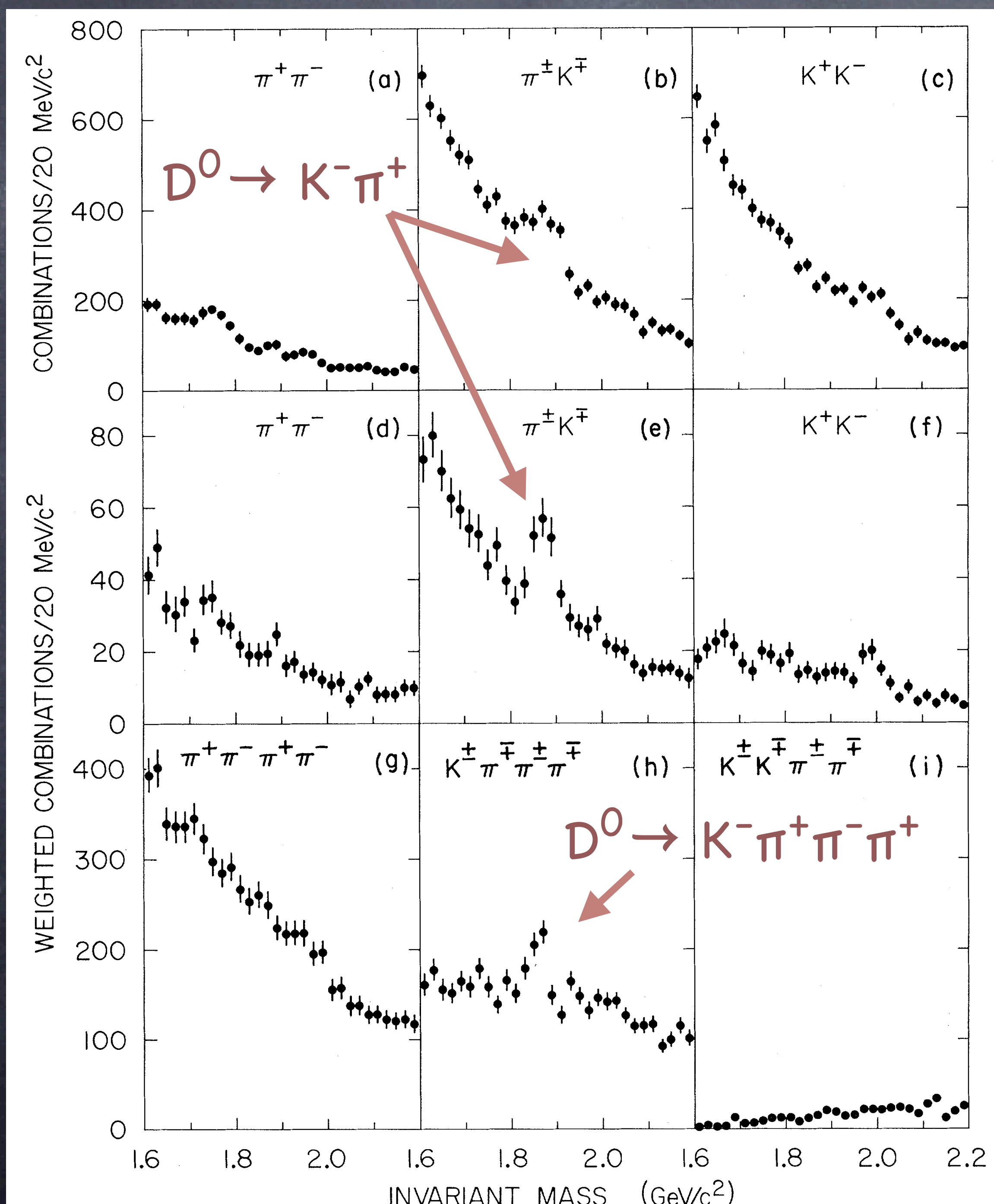
- System made of many counters which are finite in size so TOF is not exactly the same
- The counters are not in the perfect location and the relative timing is not perfect
- The calibration is not perfect, e.g. calibration tracks do not always come from exactly the "origin"/same point, the start time is not perfect
- The σ may not be a constant
- The non-Gaussian tails can be asymmetric



I don't have time to go into statistics which is a really important part of experimental physics, or go into "systematic uncertainties" which is even more important as we spend maybe 90% of our time worrying about this. "Systematics" is also not as well defined and often misunderstood

Open Charm Discovery

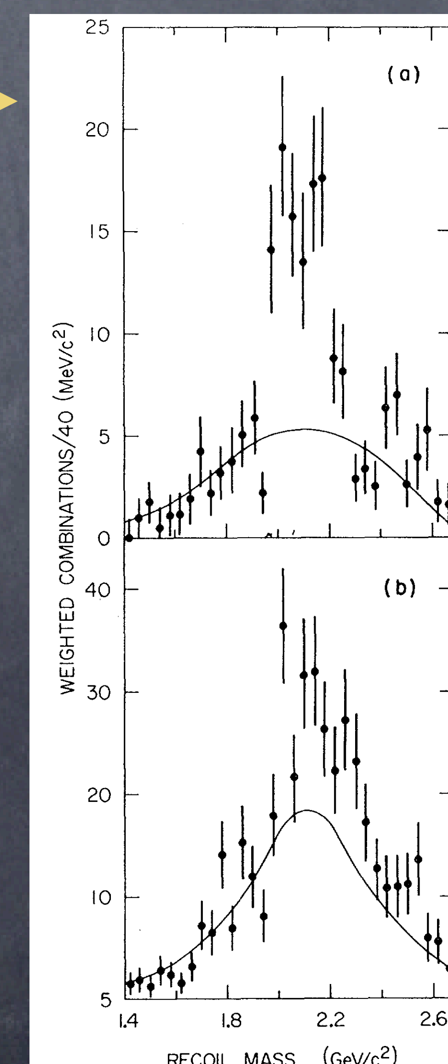
Signal-to-background matters!



Mark 1 results with no TOF

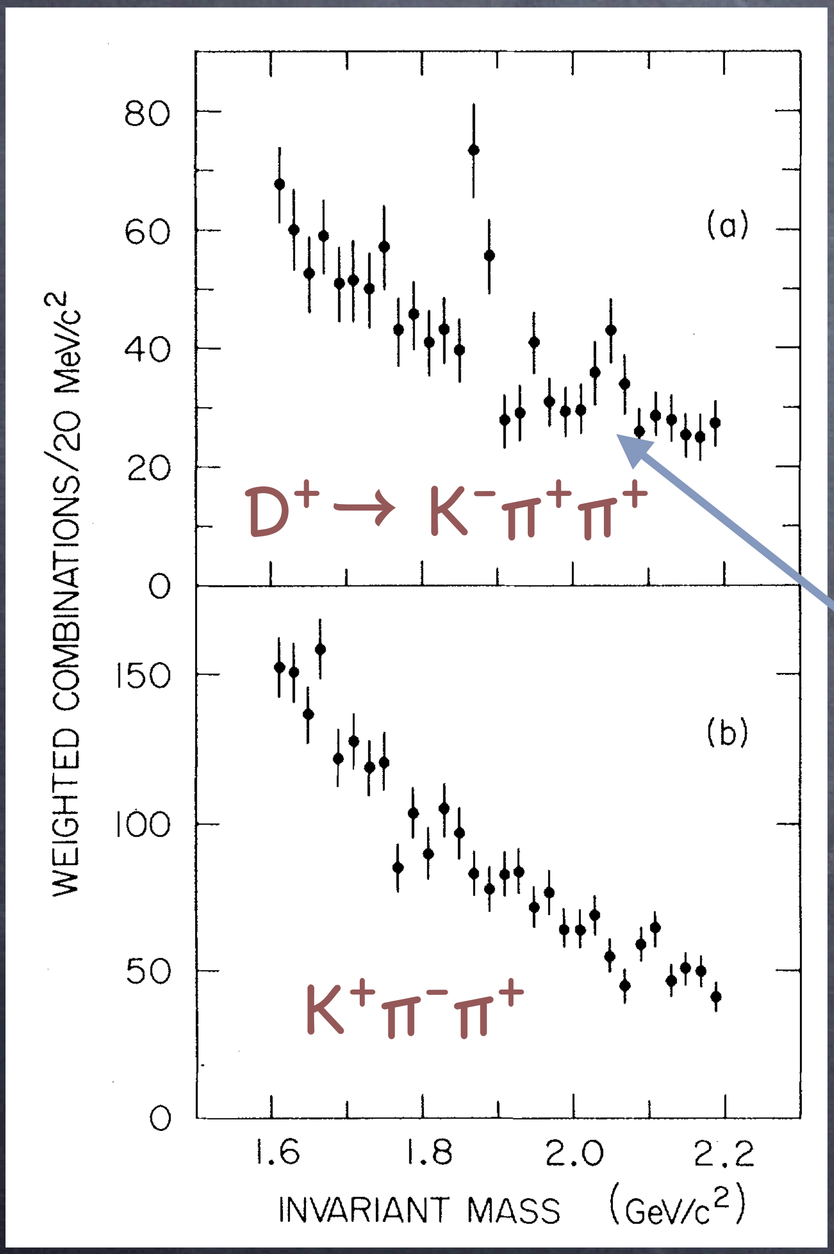
Mark 1 results with TOF

Mark 1 results for "recoil mass" – the invariant mass of what is produced opposite the D^0 which shows probable threshold $D\bar{D}$ production

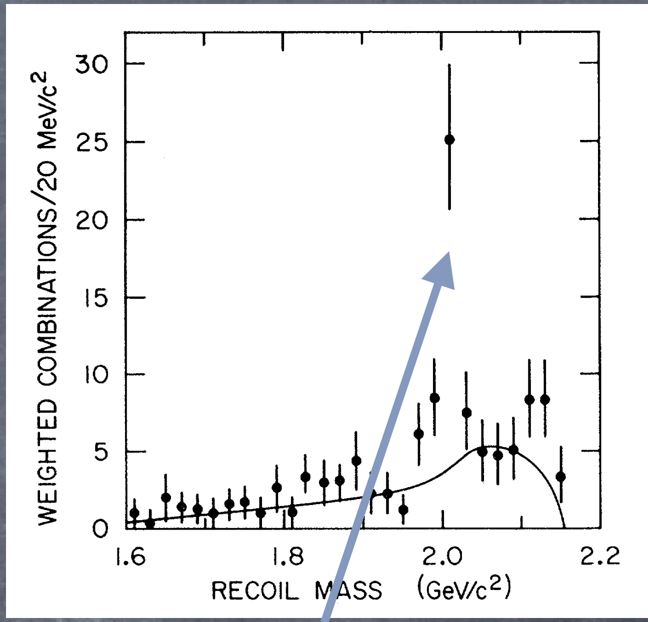


Open Charm Discovery

Signal-to-background matters!



Mark 1 results with TOF showing the $D^+ \to K^-\pi^+\pi^+$ with a recoil mass around 2.01 GeV/c^2



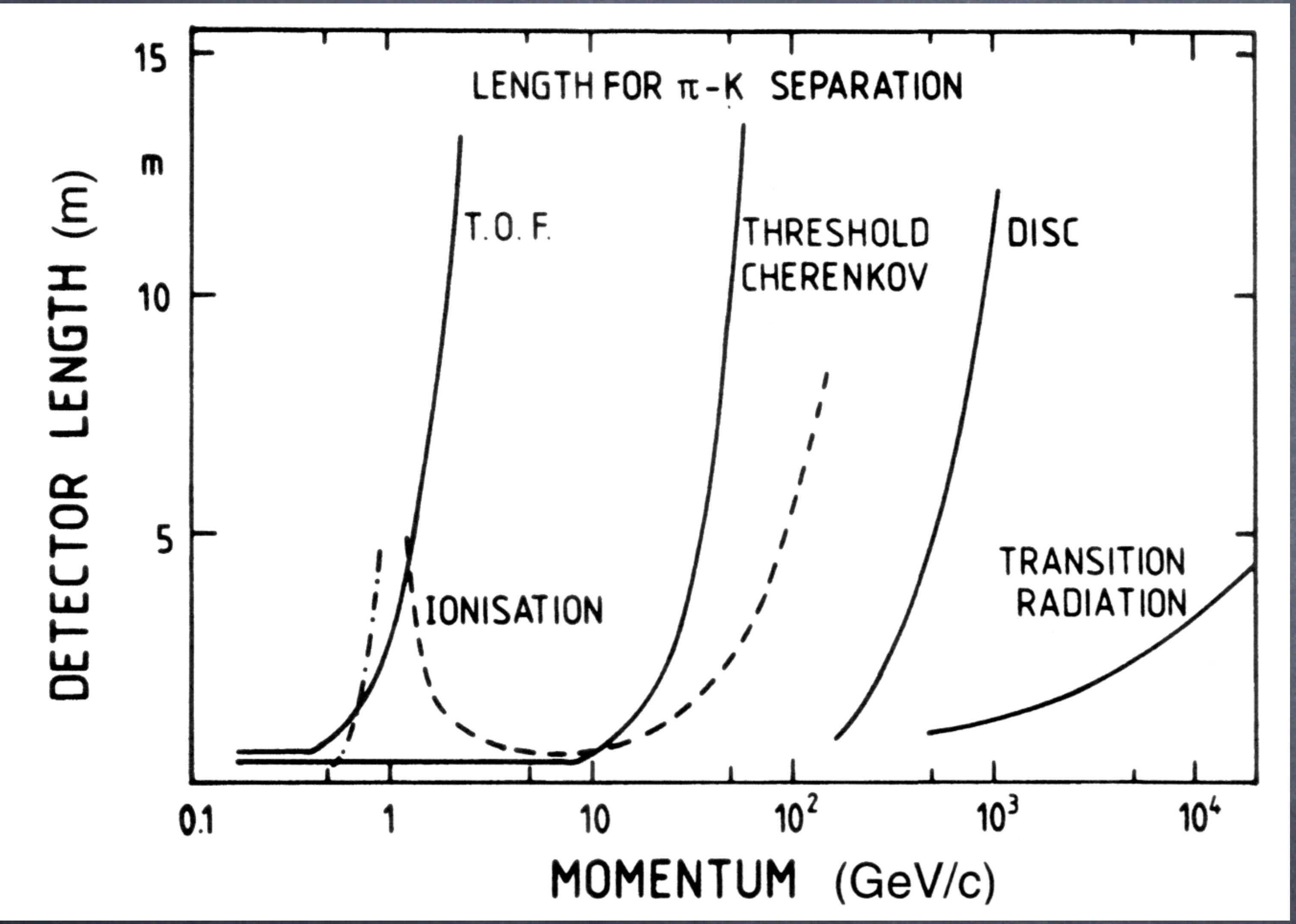
The pattern of masses, decay modes, width and production at threshold all point to the correctness of the quark model and a fourth charm quark

Interesting note:

They missed the $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$ which has a mass of 2.01 GeV/c^2 !

How to Improve S/B?

Are there other Particle ID methods?



TOF measurements need very long decay lengths
Also threshold Cerenkov counters need long detector lengths due to low photon yields

Experiments at e^+e^- and $p\bar{p}$ colliders usually do not have enough space for Cerenkov counters

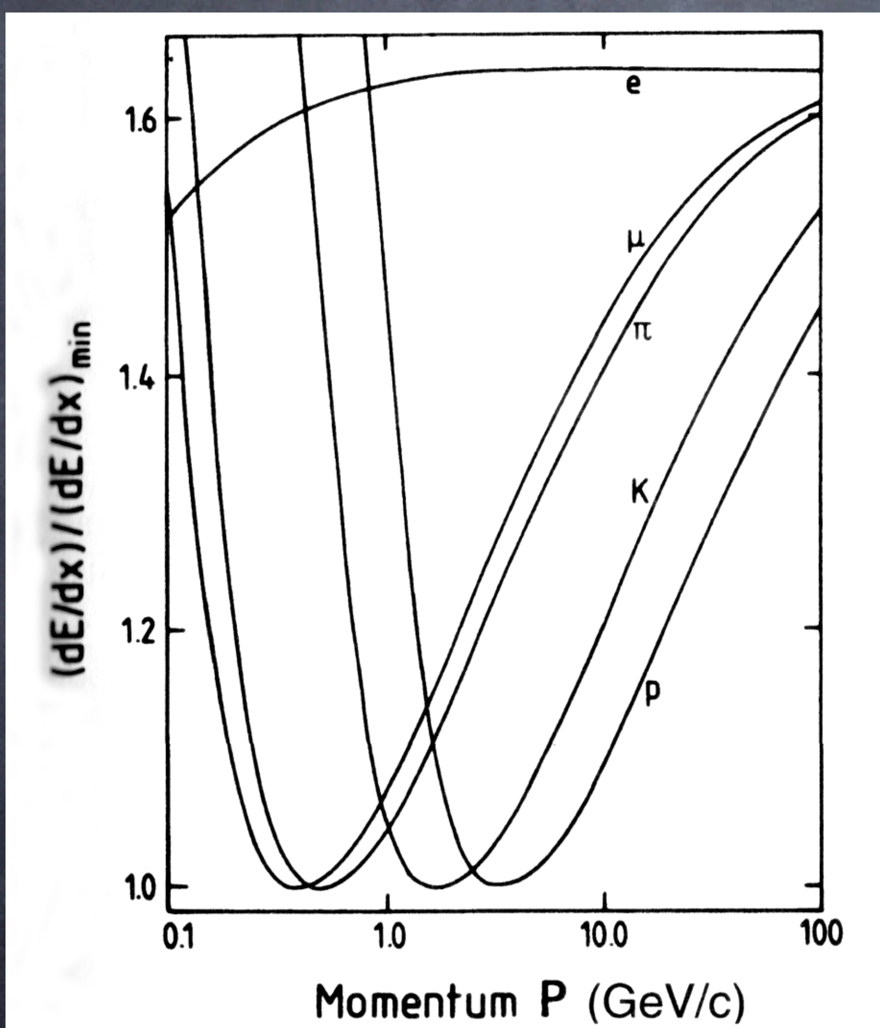
An alternative particle ID method uses wire chambers by measuring the amount of ionization

Later experiments at e^+e^- colliders like SLD and BaBar at SLAC, and CLEO-III at CESR actually used differential or Ring Imaging Cerenkov counters for excellent particle ID

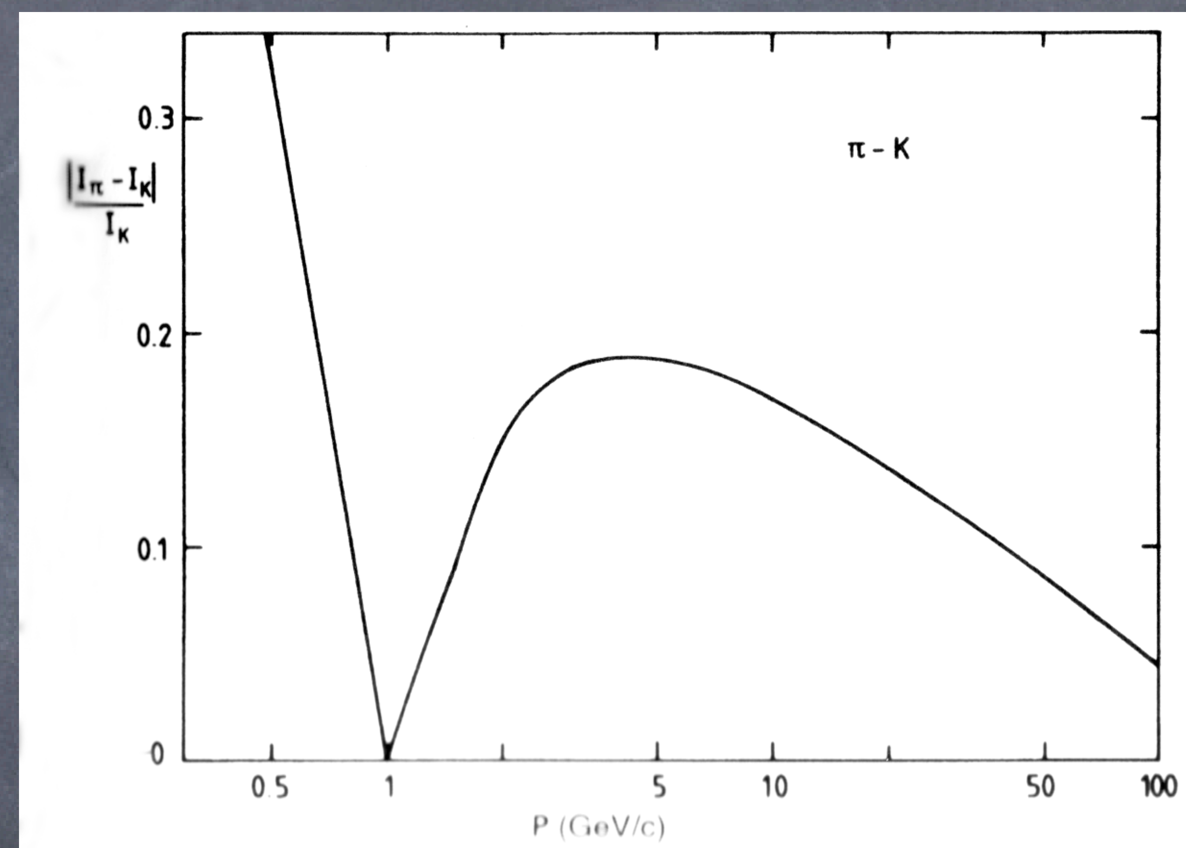
How to Improve S/B?

Are there other Particle ID methods?

Ionization energy lost in 1cm thick 80/20 Ar/methane



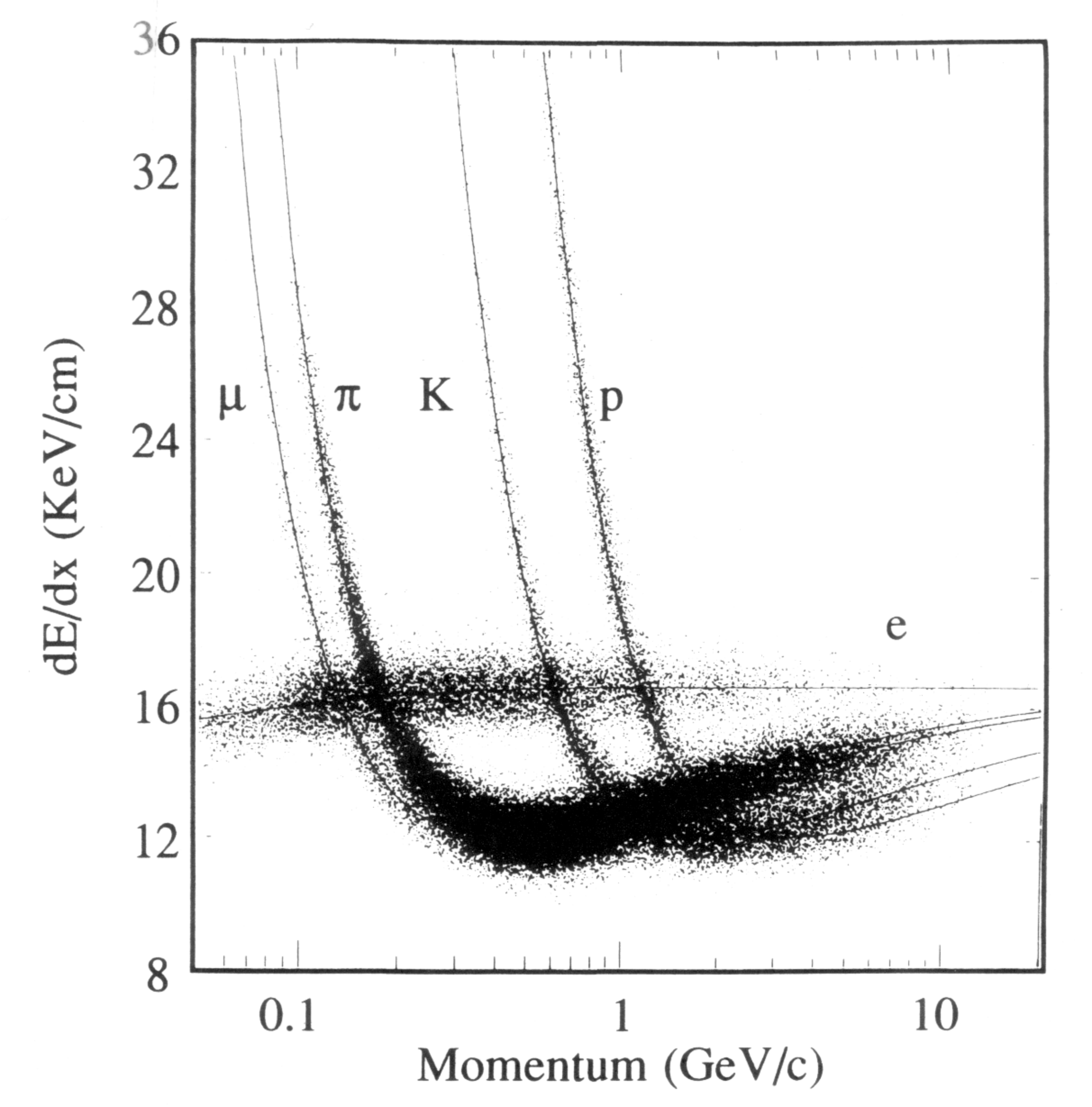
Ionization energy difference between K and pion



In a wire chamber we not only measure which wire is "hit", but also measurement the signal size (amount of charged) which is proportional to the ionization energy lost

How to Improve S/B?

Are there other Particle ID methods?



Still only good at relatively low particle momenta

What about at higher momentum?

E.g. to measure the charm quark lifetime we have to produce them with higher momentum to be more sensitive to shorter lifetimes

We need to identify clean charm decays and measure a decay length

$L = \gamma \beta c \tau = (p/m) c \tau$

charm particle decay proper time (lifetime)

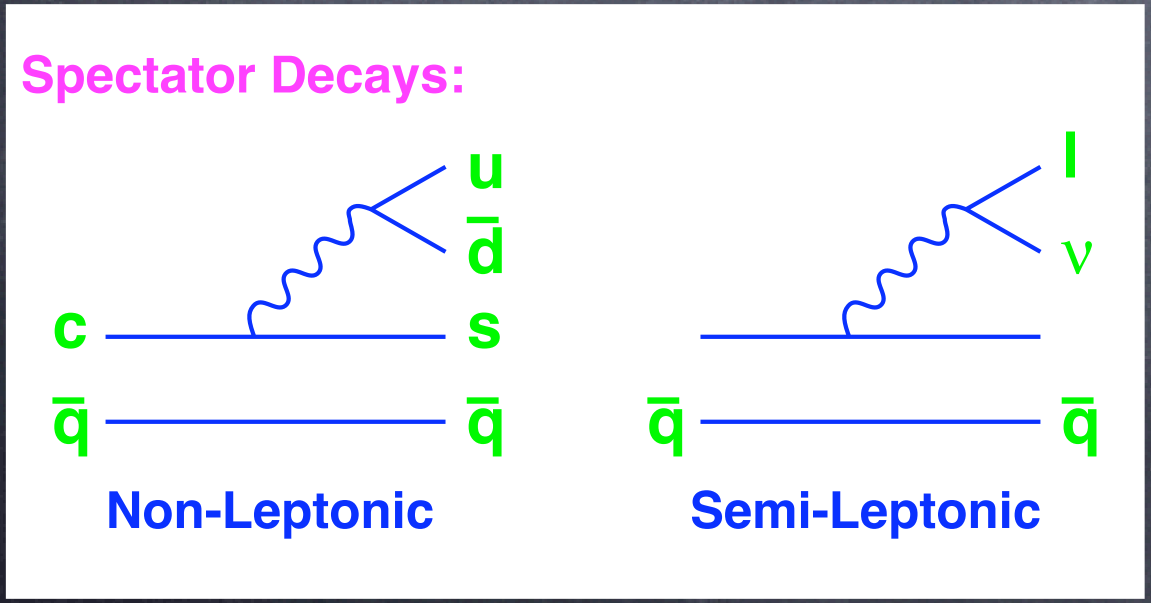
Also backgrounds have zero lifetime so if $\tau > 0$ we could use this to separate signal from background?

Charm Lifetimes

Besides using a finite lifetime to separate signal from background
we can learn some physics from measurements of the charm particle lifetimes

In the simplest example the lifetime tells us what type of force is responsible for the decay of the charm particle:

- Strong Decays ~ α_s : $\tau_{typical}$ ~ 10^{-22} s
- Electromagnetic Decays ~ α : $\tau_{typical}$ ~ 10^{-18} s
- Weak Decays ~ $\alpha/(M_W/m_p)^2$: $\tau_{typical}$ ~ 10^{-12} s



Also the difference in lifetimes between the different charm particles could tell us something about how quarks interact

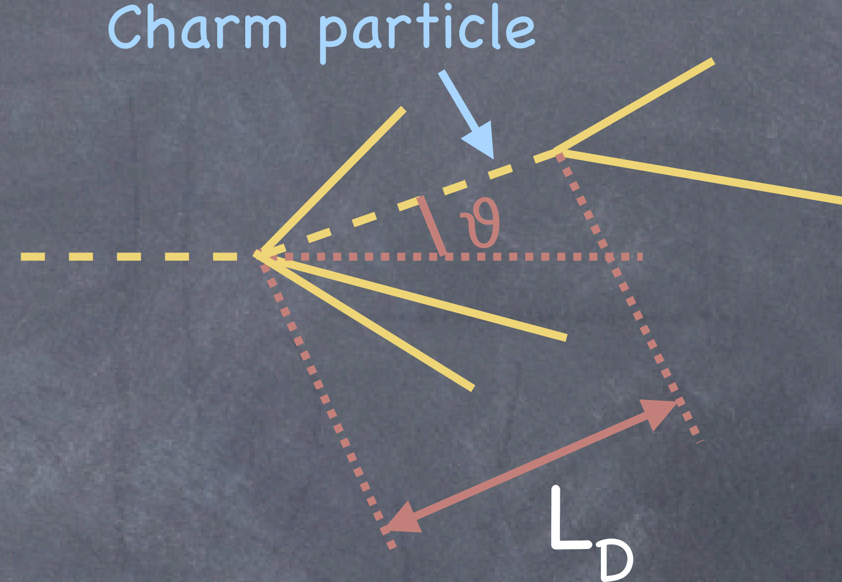
E.g. in the spectator decay all charm particles have the same lifetime

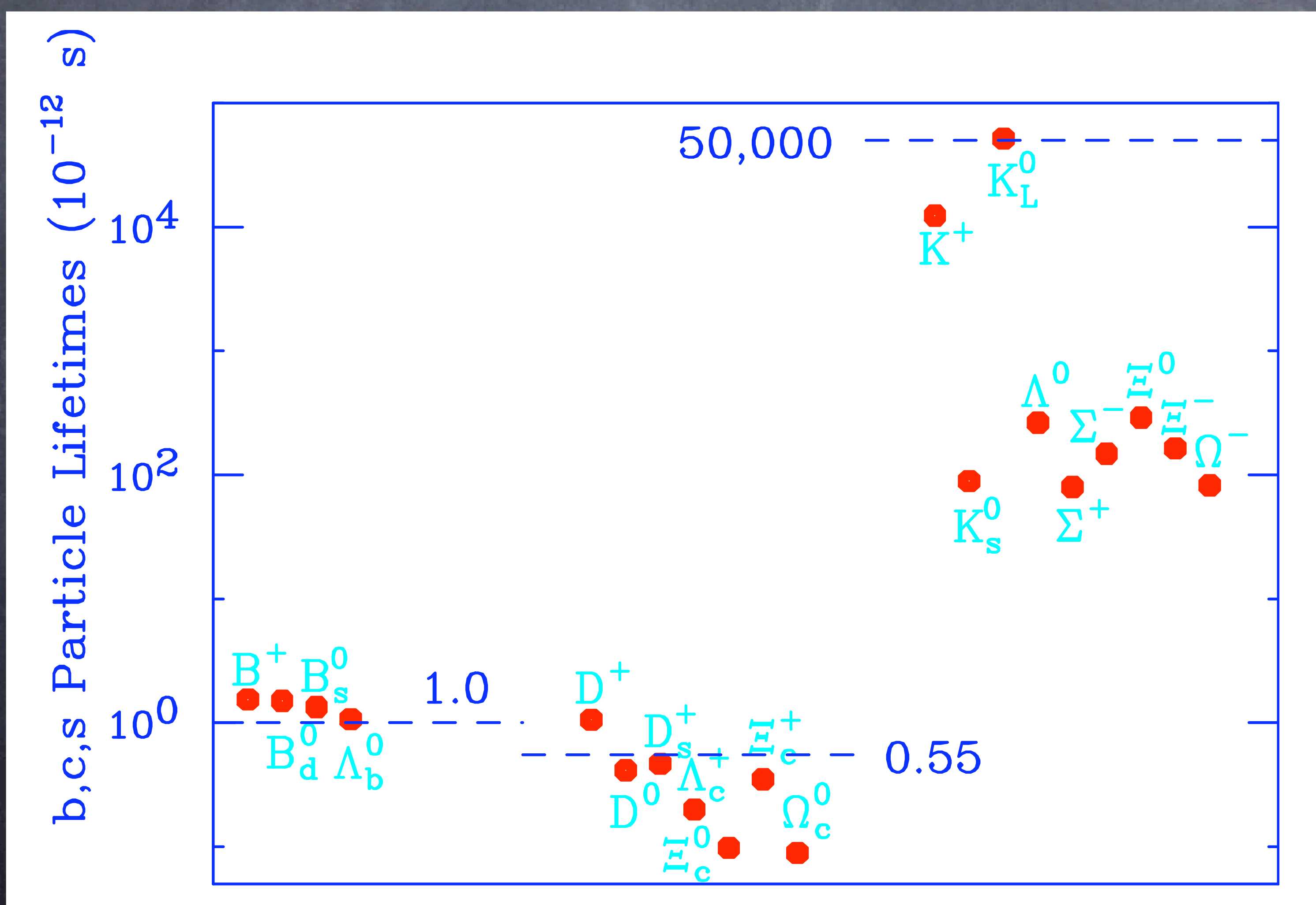
Charm Lifetimes

What sort of resolutions do we need?

Can estimate the lifetime assuming a weak decay of a free quark (compared to muon decay)

$$\Gamma(c) = \frac{G_F^2 m_c^5}{192\pi^3} \times \left(|V_{cs}|^2 + |V_{cd}|^2\right) \times 5 \text{ (W decay channels)}$$





Need $\sigma(L_D) \ll L_D$

$\sigma_{trans} \ll \vartheta L_D \approx c\tau_D$

$c\tau(D^0) = 124\ \mu m$

$c\tau(D^+) = 317\ \mu m$

$c\tau(\Lambda_c^+) = 60\ \mu m$

Drift Chambers

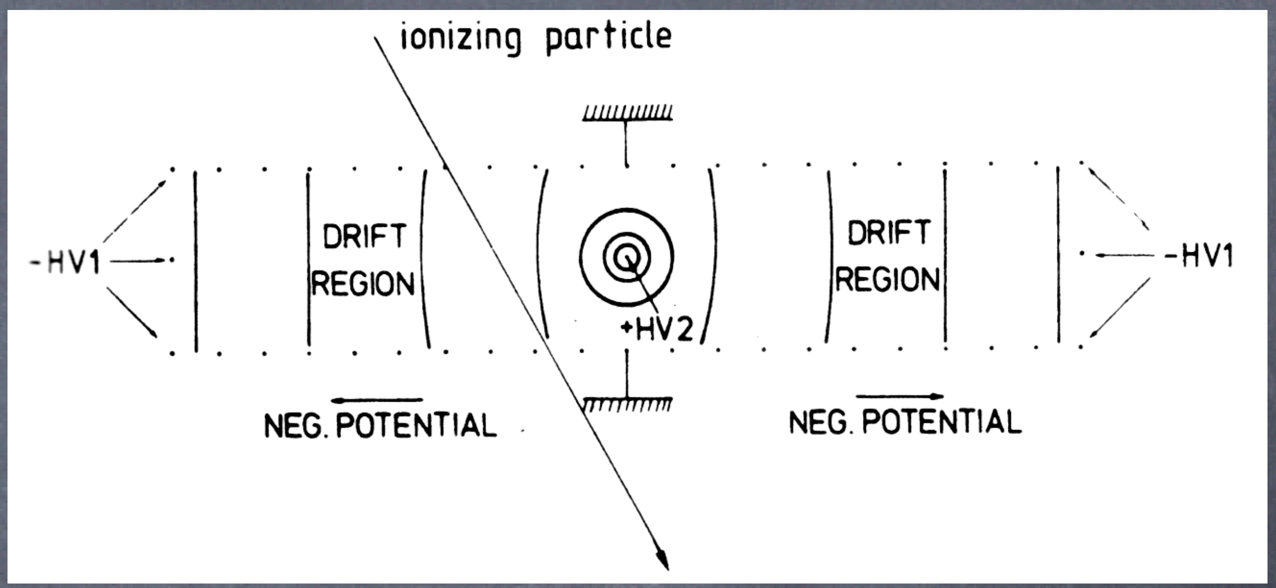
Improving the resolution of MWPC's

The resolution in MWPC's (or PWC's) is given by the wire spacing (s)

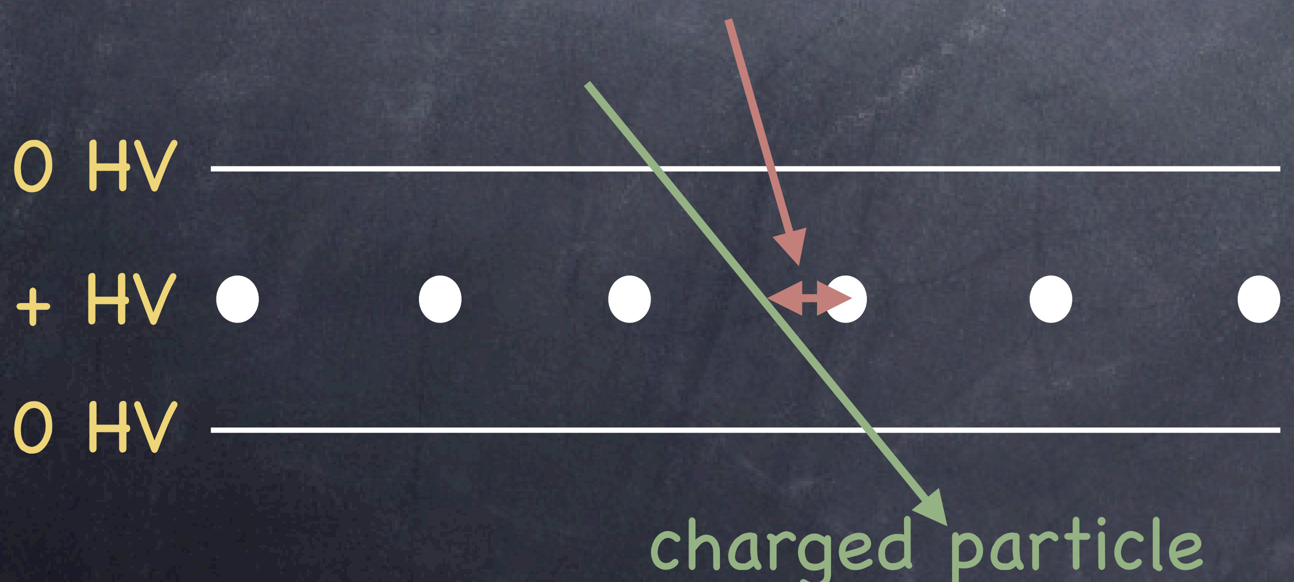
σ(transverse) = $s/\sqrt{12}$

so for s=2mm

σ(transverse) =577μm



We can measure the drift time to the closest wire to better determine the position of the particle track



So as well as measuring the amount of charge for dE/dx (ionization) we now also want to measure the time of arrival

Readout and signal shape is more important now

Drift Chambers

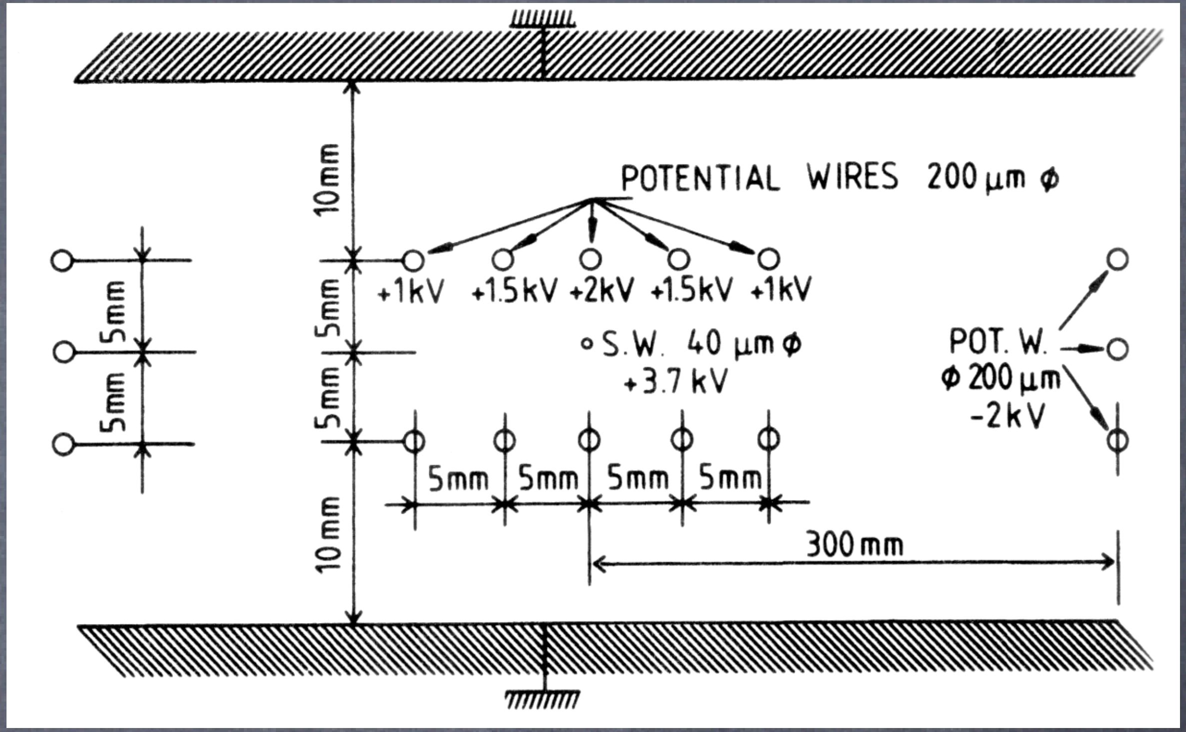
Improving the resolution of MWPC's

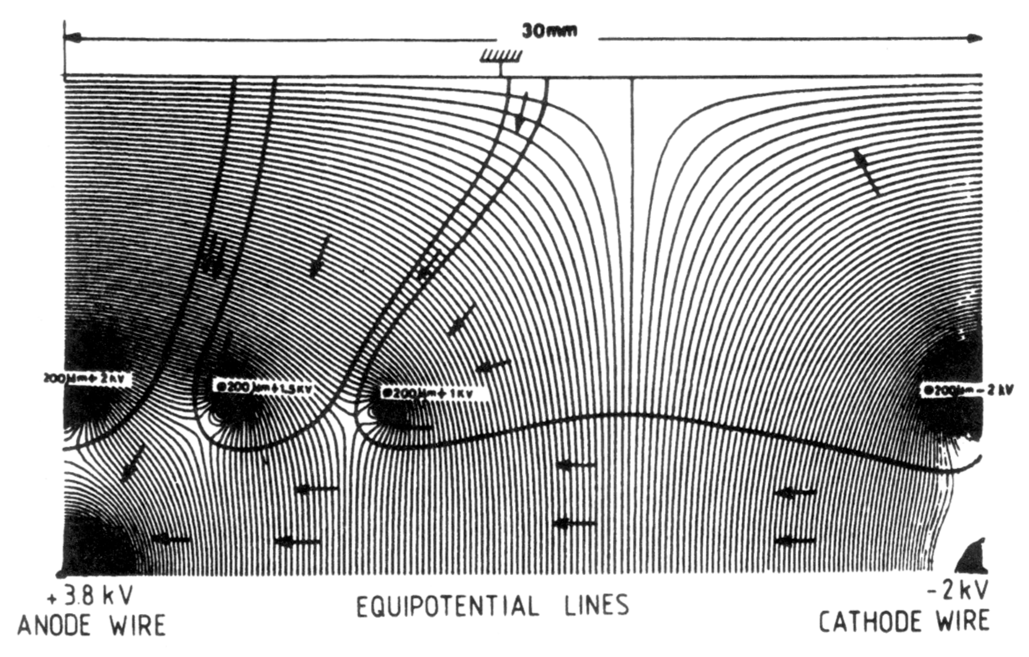
Besides the complications in the readout of the signals we have to worry about the drift velocity.

The drift velocity has to be known and the E-field must be shaped to provide a uniform field since the particle could enter the chamber from different locations and at different angles - can get σ(transverse) = 100μm

There are also rate limitations and choice of gas and aging as for MWPC's

Can we get better spatial resolution?





Emulsions

Detectors with the best spatial resolution

Photographic plates are one of the oldest detectors of radiation. A layer of emulsion ≈ 600μm covers a plate and a charged particle causes the silver halide grains to develop, each grain is ≈ 0.2μm diameter and one gets ≈ 270 developed grains/mm.

In the early days emulsions were sent up in ballons to be exposed to cosmic rays

Charm might have been first seen in such an experiment in 1971

Some problems with emulsions

- Must be scanned, when done by hand this is very slow
- Used by itself, one cannot trigger or know where in the emulsion to look
- Difficult to use in a high rate environment there can be a high track density so one must replace the emulsions often

Can be useful in neutrino beam experiments that require excellent resolution

Observation of ν_τ

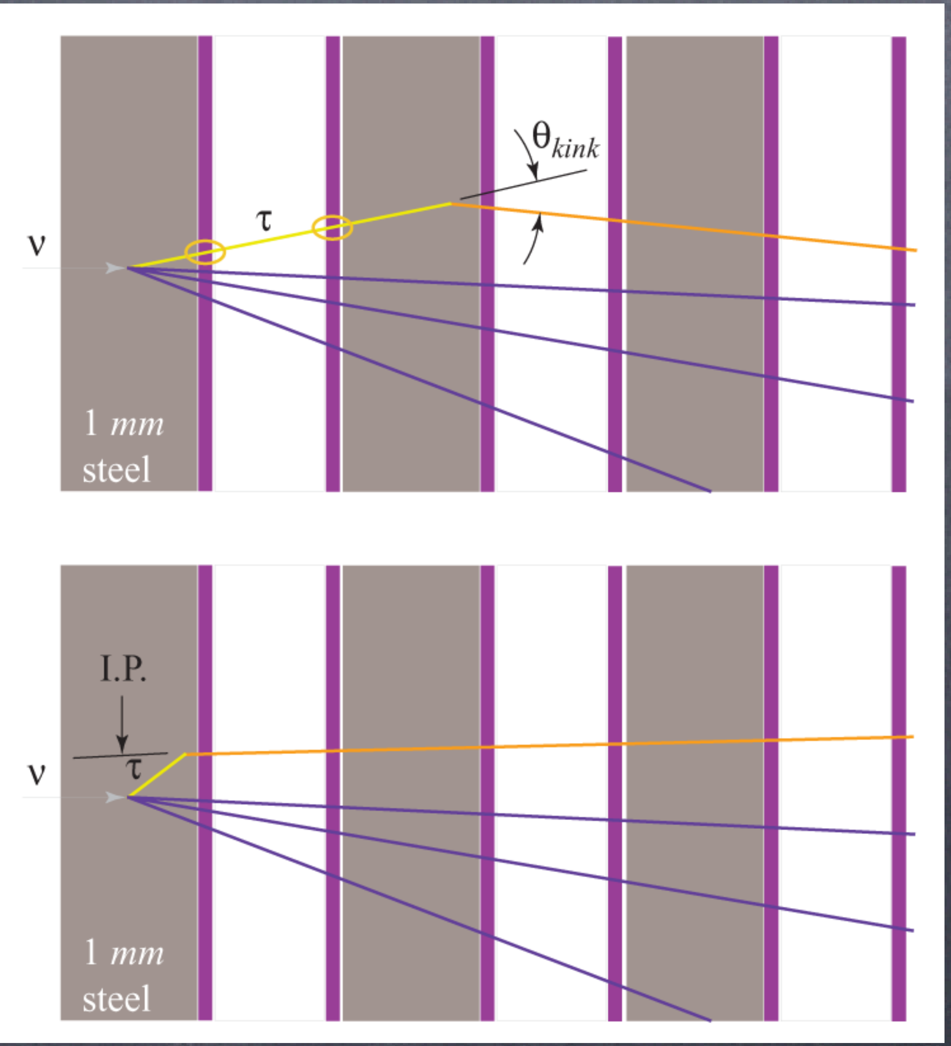
Use of emulsions in DONUT

DONUT, a Fermilab experiment that ran in late 1990's use emulsions to make the first direct observation of ν_τ

DONUT created a ν_τ beam by first producing D_s mesons and about 4% of these decay to $\tau\nu_\tau$

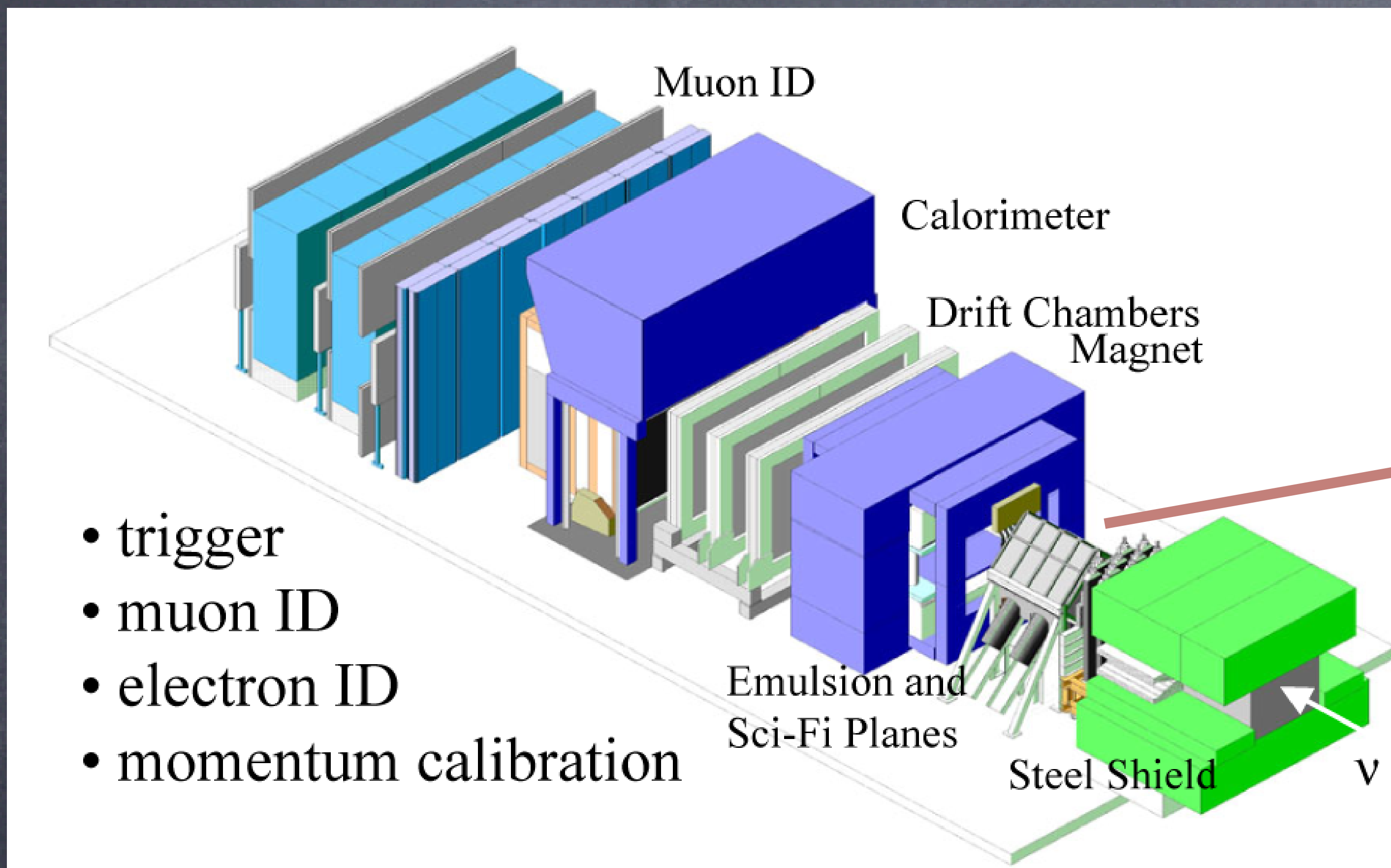
DONUT observes the charged current interaction of a ν_τ with steel between emulsion layers.

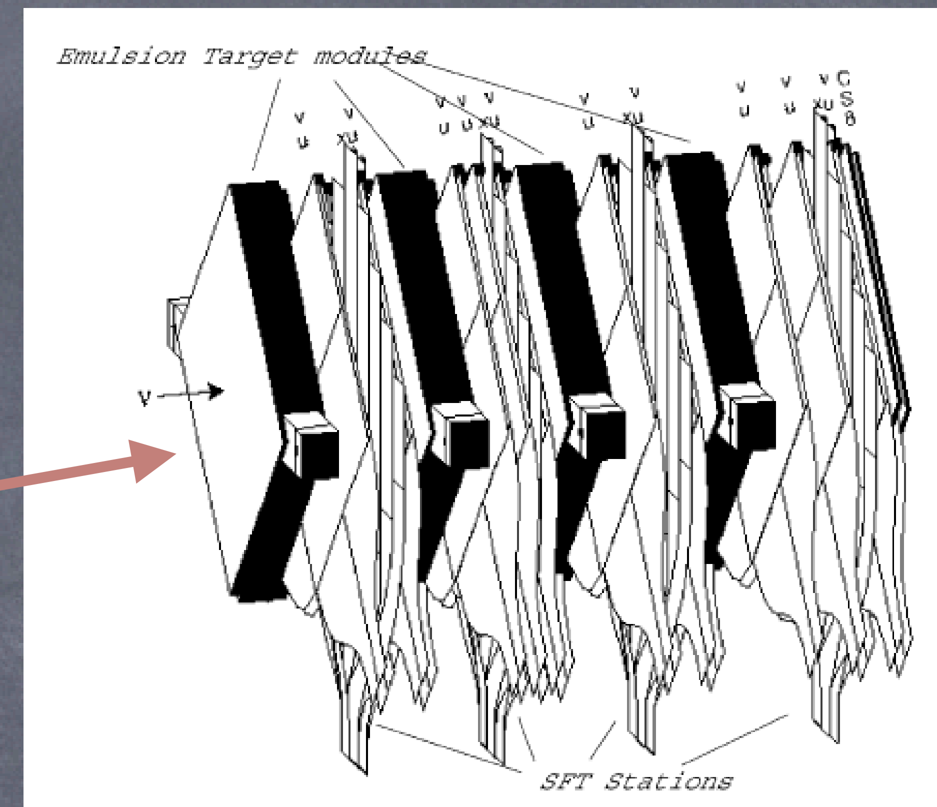
The τ produced will decay to $\mu\nu_\mu\nu_\tau$ giving a "kink"



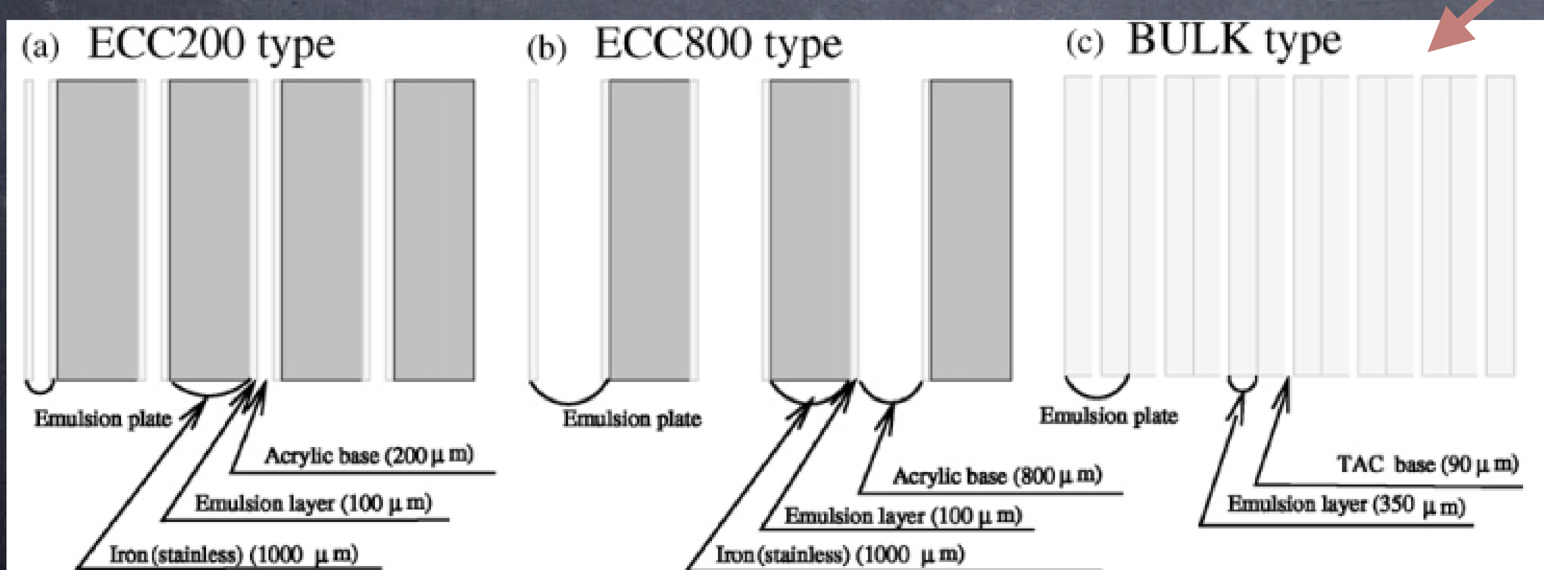
DONUT uses an external spectrometer to trigger and determine where to look for candidate signal vertices

DONUT





Different types of emulsions

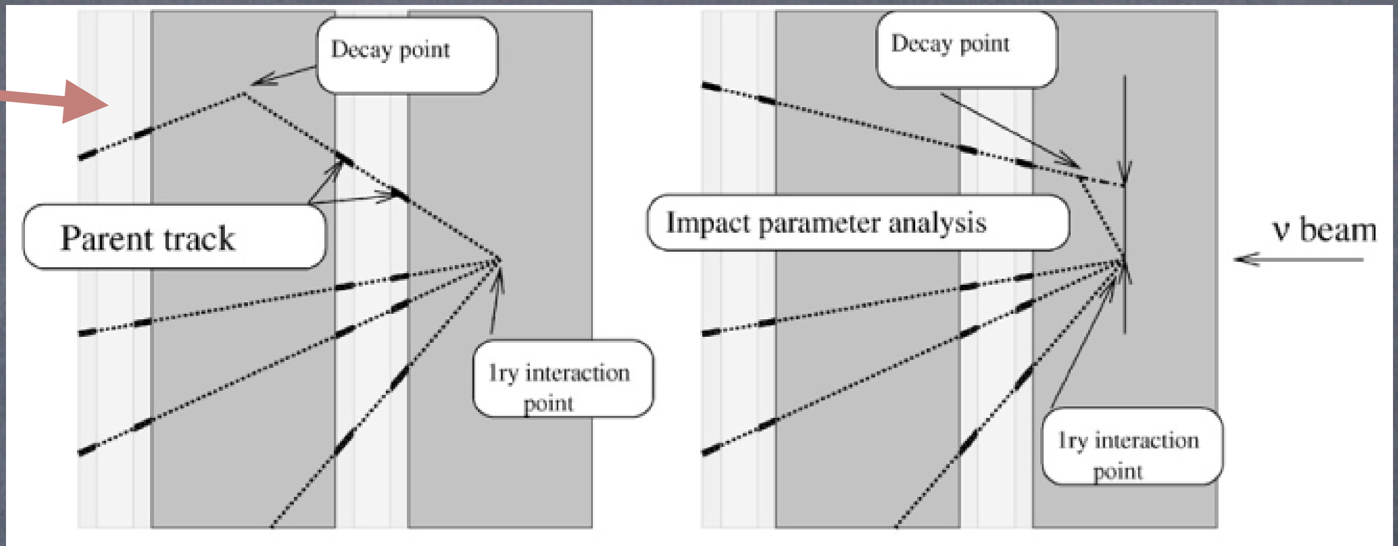


The observation was made possible by:

- automatic scanning machines
- locations of vertex region by external spectrometer
- excellent alignment of emulsions to ≈ 0.2μm

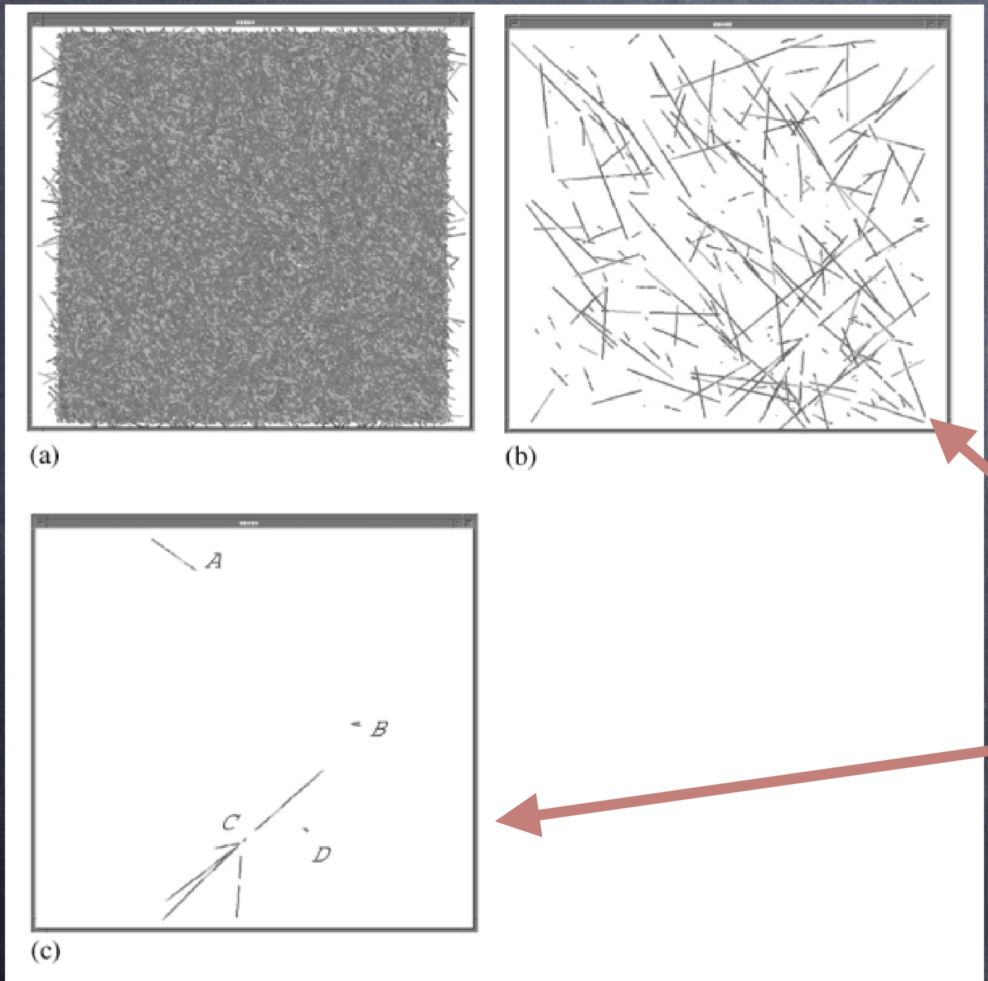
DONUT Results

Long decay sample published first (2000) with 4 ν_τ events and a background of
0.20 ± 0.03 charm
0.20 ± 0.04 hadronic inter.



(a) Long Decay (b) Short Decay

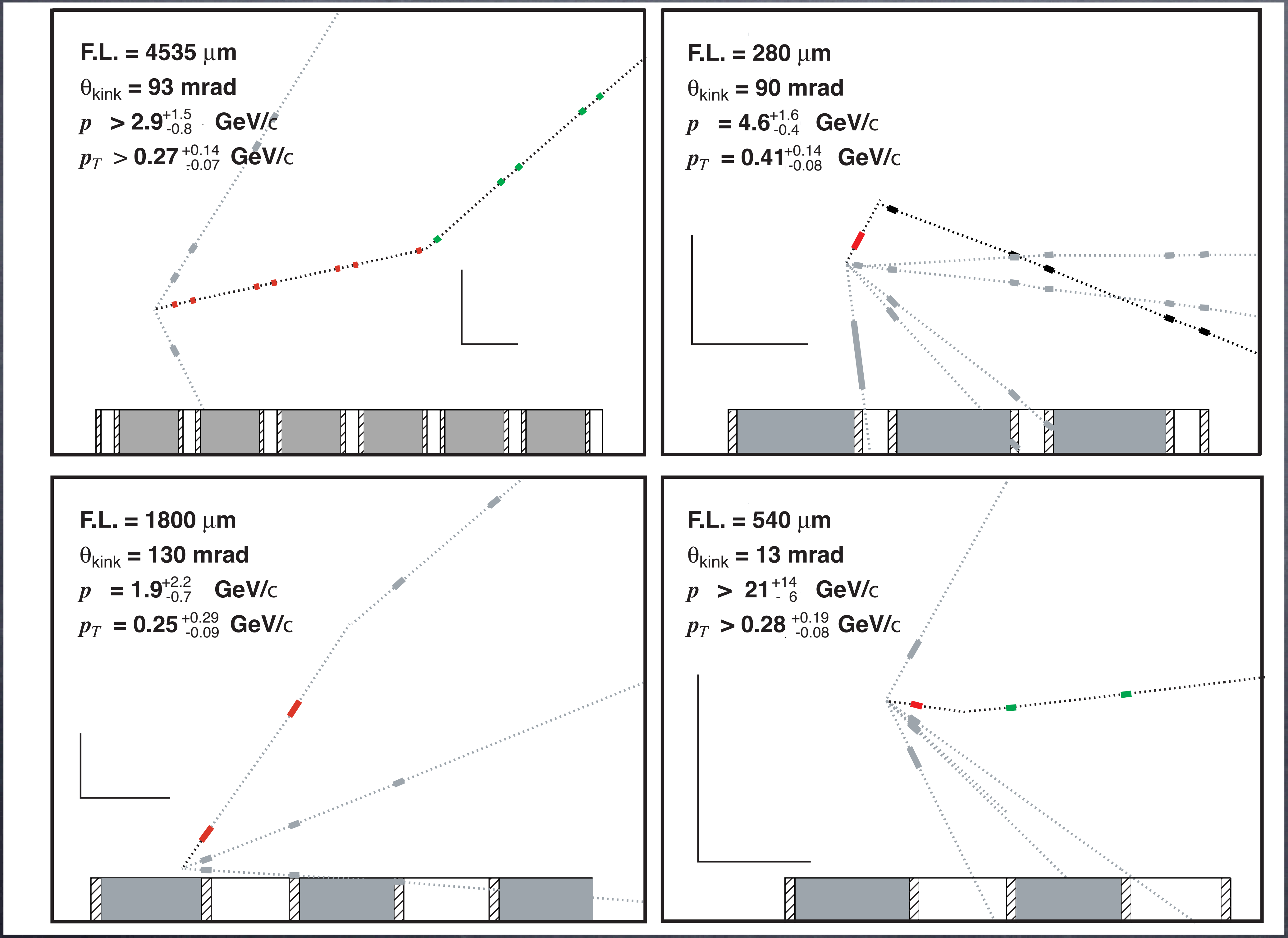
Example of DONUT track selection:



(a) (b) (c)

(a) Vertex location by NETSCAN after alignment
(b) After rejection of penetrating tracks (12000 muons per 5mm×5mm)
(c) After vertex requirement

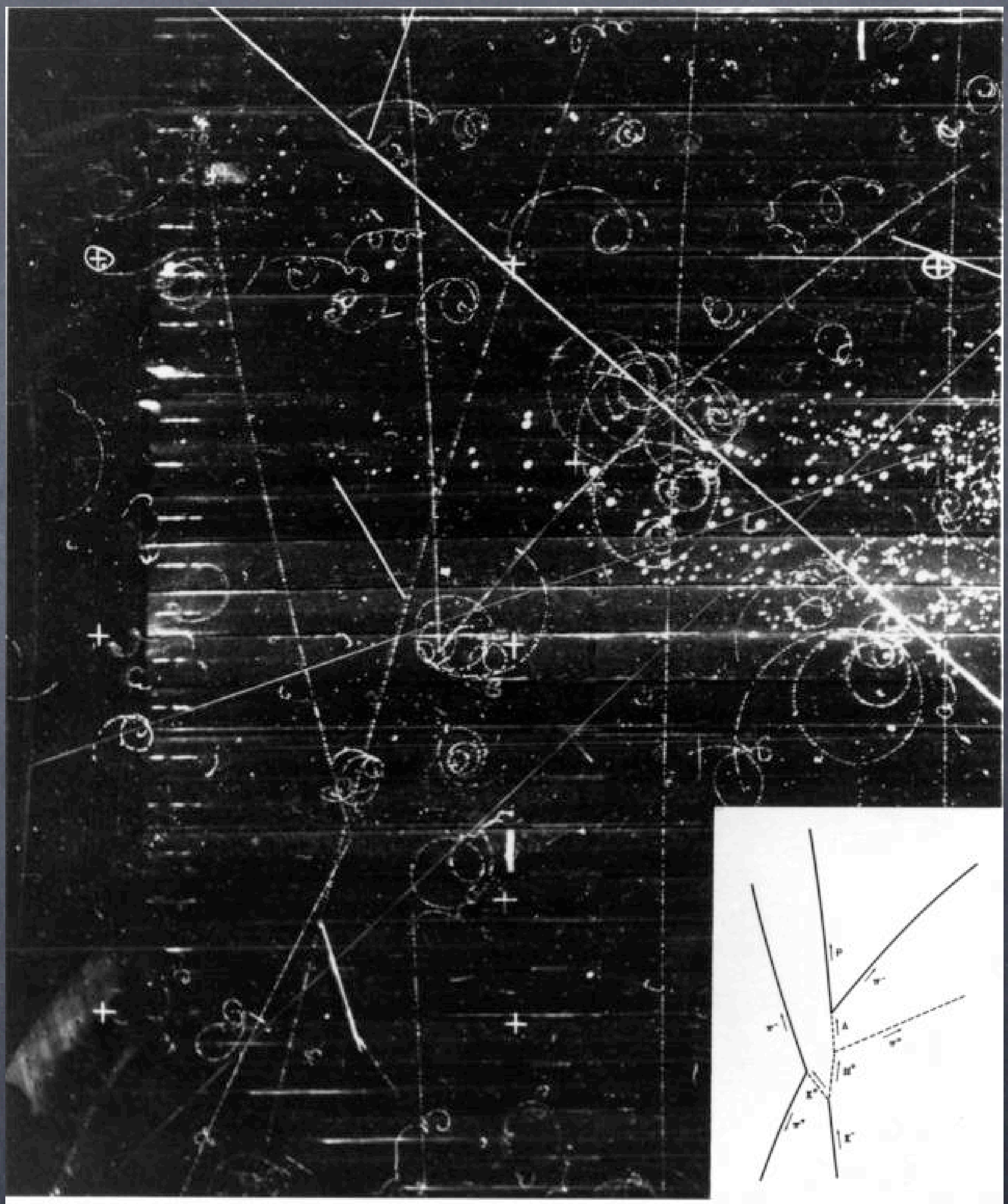
DONUT ν_τ Candidates



Emulsions are poorly suited for a very high statistics charm experiment

What other options are there?

Bubble Chambers

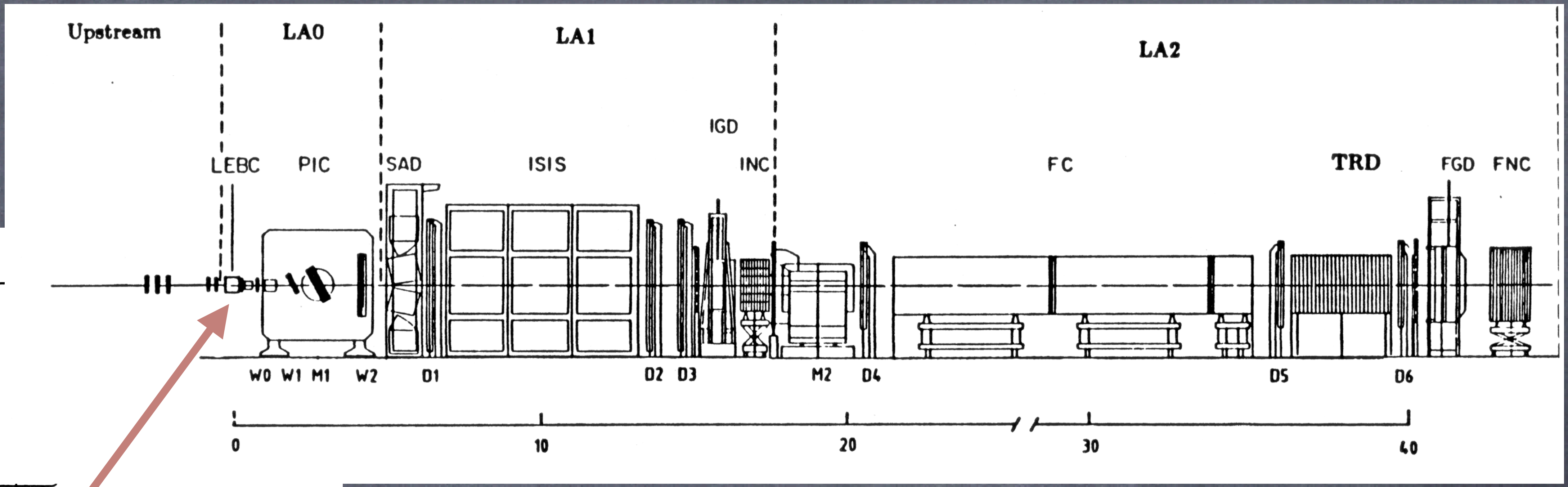


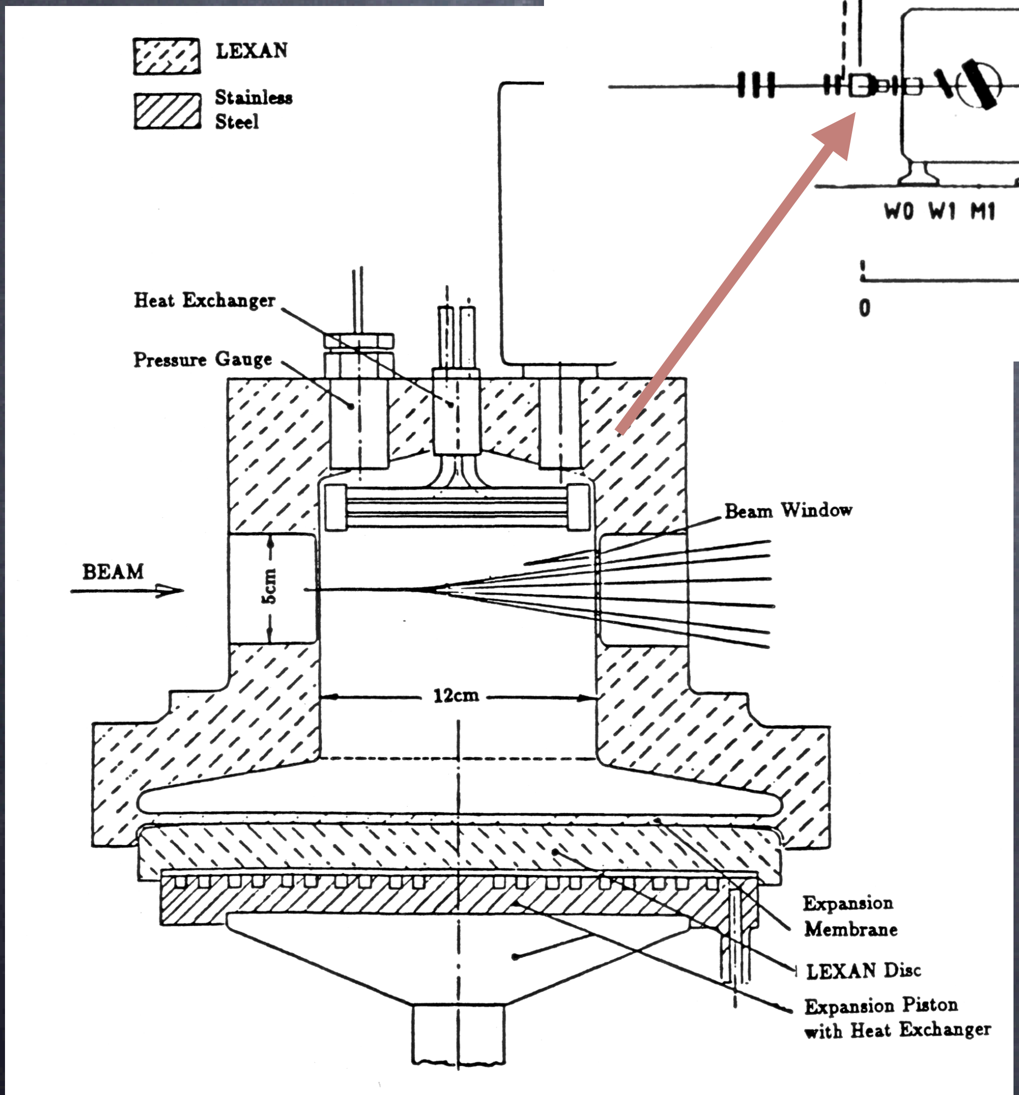
Production and decay of a neutral cascade hyperon (Xi zero).

Maybe used to seeing the historic bubble chamber pictures and in neutrino experiments (e.g. 15 foot at Fermilab) Usually the resolution is not better than a drift chamber....

Bubble Chambers

...But one can make a small chamber with ~10-20 μm resolution that can cycle rapidly e.g. the LEBC-EHS experiment



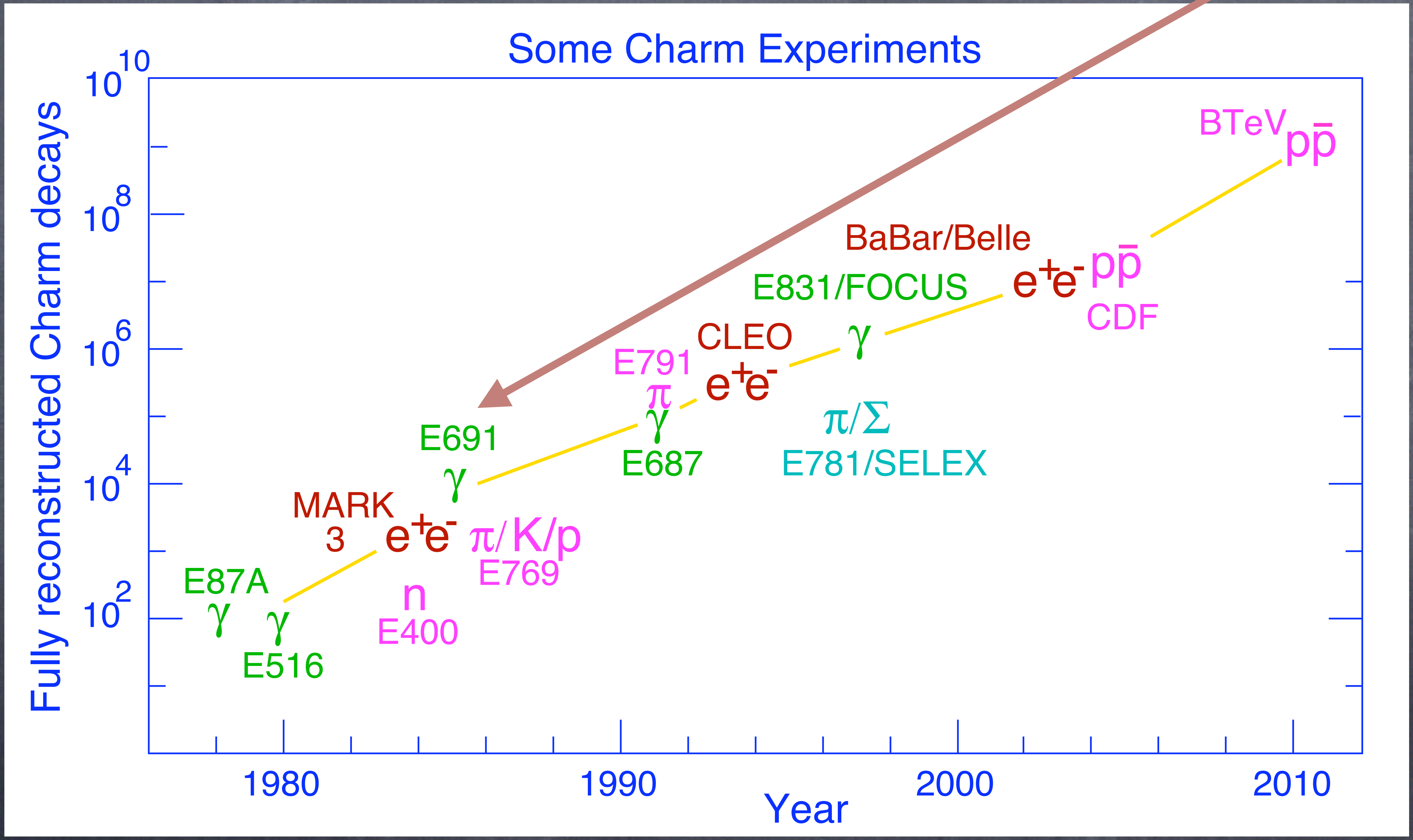


The rest of the spectrometer enables a trigger and ran in the 1980's, however they only had 100-200 reconstructed charm particle (decays)

We need something better!

Road to Higher Statistics

The charm to higher statistics start with Fermilab E691



Photons or hadrons, comparison of beams and e^+e^- colliders

Road to Higher Statistics

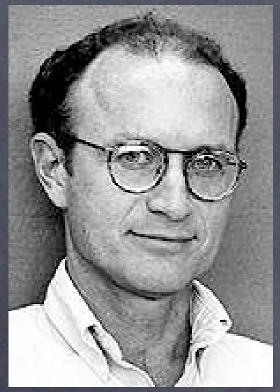
Photons or hadrons, comparison of beams and e^+e^- colliders

- $e^+e^- \rightarrow$ charm: $\psi'''(3770) \rightarrow D\bar{D}$
  - ★ Lower intensity; Low momentum charm (? b, $Z^0 \rightarrow c\bar{c}$)
  - ★ Very clean environment (> 40% of $e^+e^- \rightarrow$ hadrons)
- $\pi N \rightarrow$ charm:
  - ★ Very high intensity; High momentum charm
  - ★ Very high background evironment (~ 0.08% of $\pi N \rightarrow$ hadrons)
- $\gamma N \rightarrow$ charm:
  - ★ High intensity; High momentum charm
  - ★ High background evironment (~ 0.6% of $\gamma N \rightarrow$ hadrons)

Are there other ways besides particle ID to separate signal from background?

Silicon Microstrips

Fermilab E691 and Silicon Microstrip Detector



Mike Witherell
spokeperson of E691
(Panofsky Prize 1990)

Not the first experiment to use silicon microstrips but the first to succeed in using them to get high statistics samples of fully reconstructed charm (10000 compared to e.g. 100-200 in LEBC-EHS)

Remember we

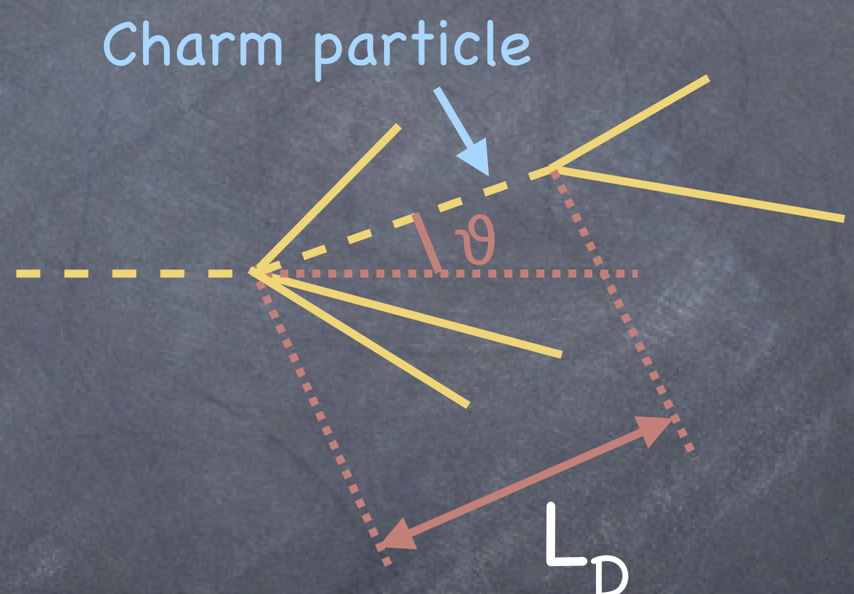
Need $\sigma(L_D) \ll L_D$

$\sigma_{trans} \ll \vartheta L_D \approx c\tau_D$

$c\tau(D^0)$ = 124 μm

$c\tau(D^+)$ = 317 μm

$c\tau(\Lambda_c^+)$ = 60 μm

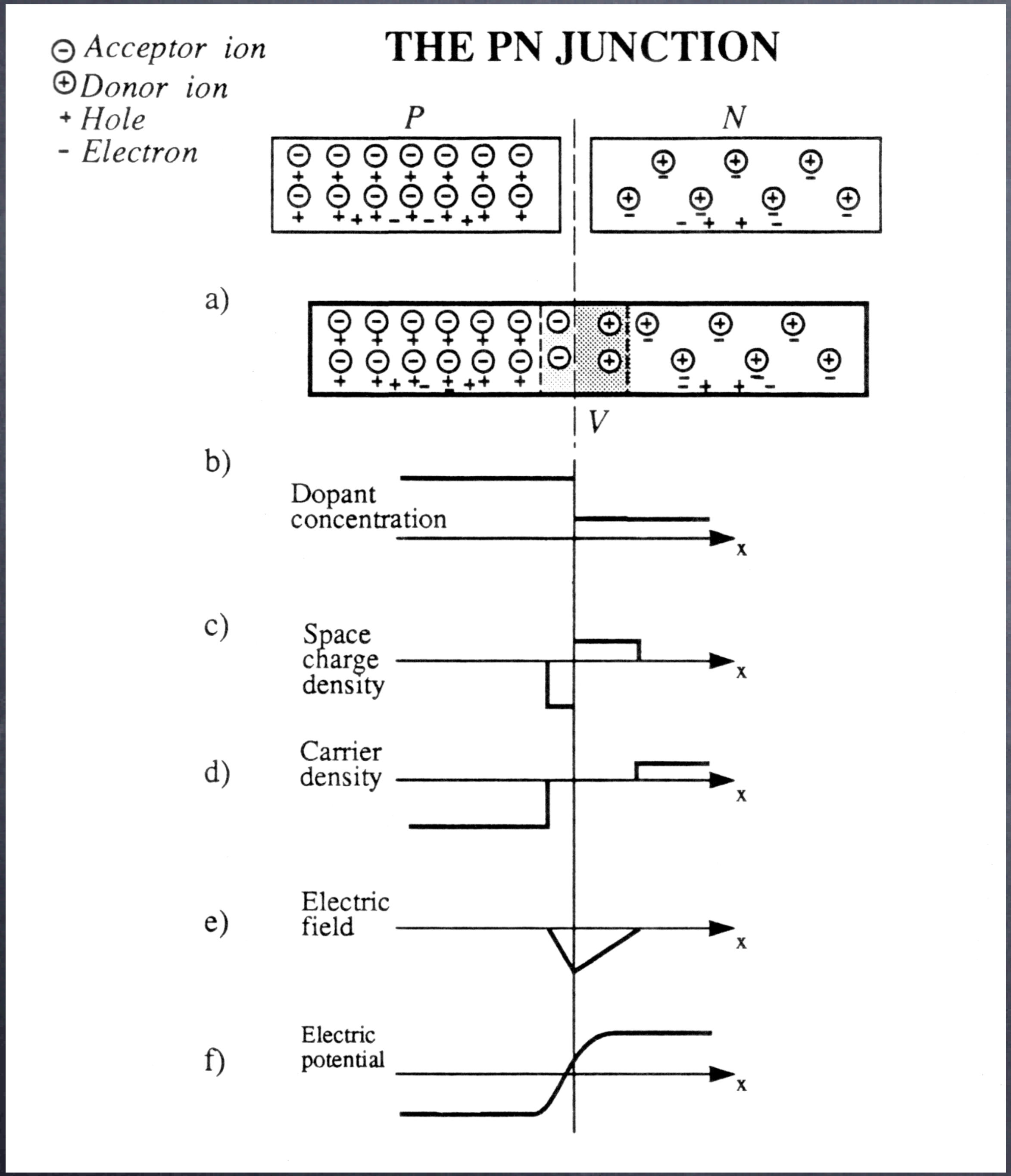


Most uds-quark background have zero lifetime or very long lifetimes 10^{-8} to 10^{-10} s

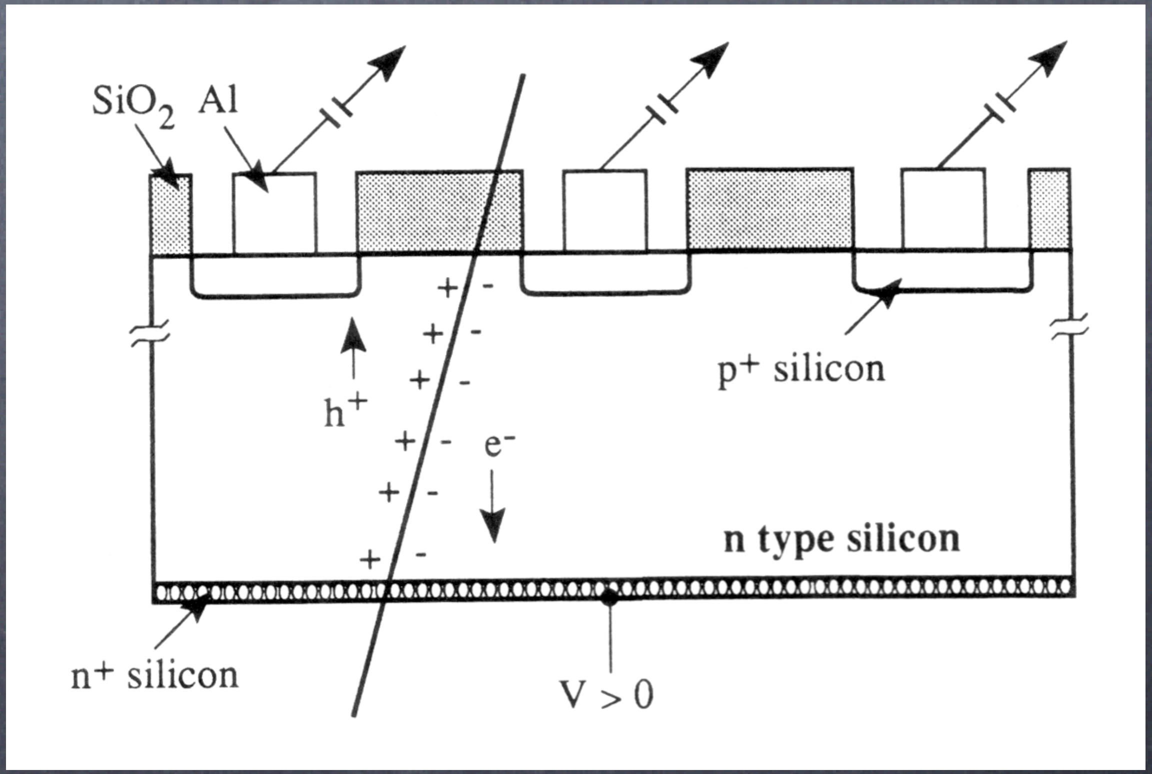
charm with 10^{-12} s lifetimes gives measurable decay vertex separation for $\beta\gamma \sim 50$

Silicon Microstrips

A solid state ionization chamber



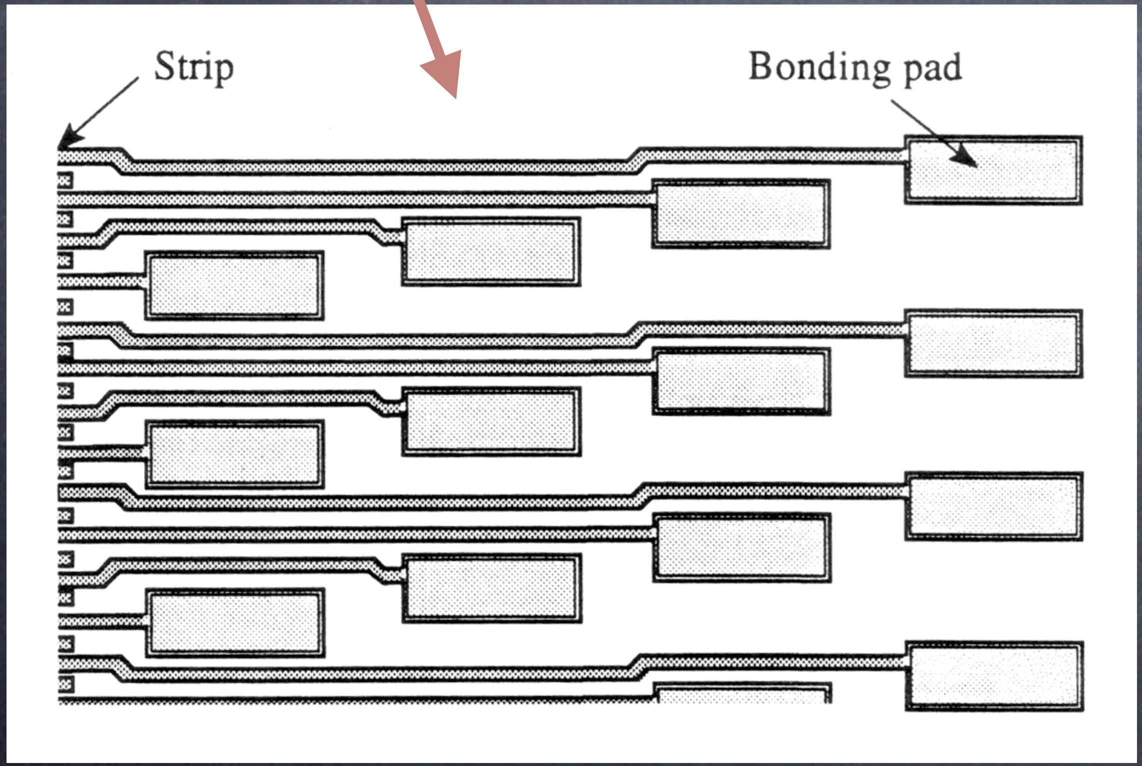
Consider the depletion region as a solid state ionization chamber.
Charged particles liberate a large number of electron-hole pairs and the charge is collected in strips.

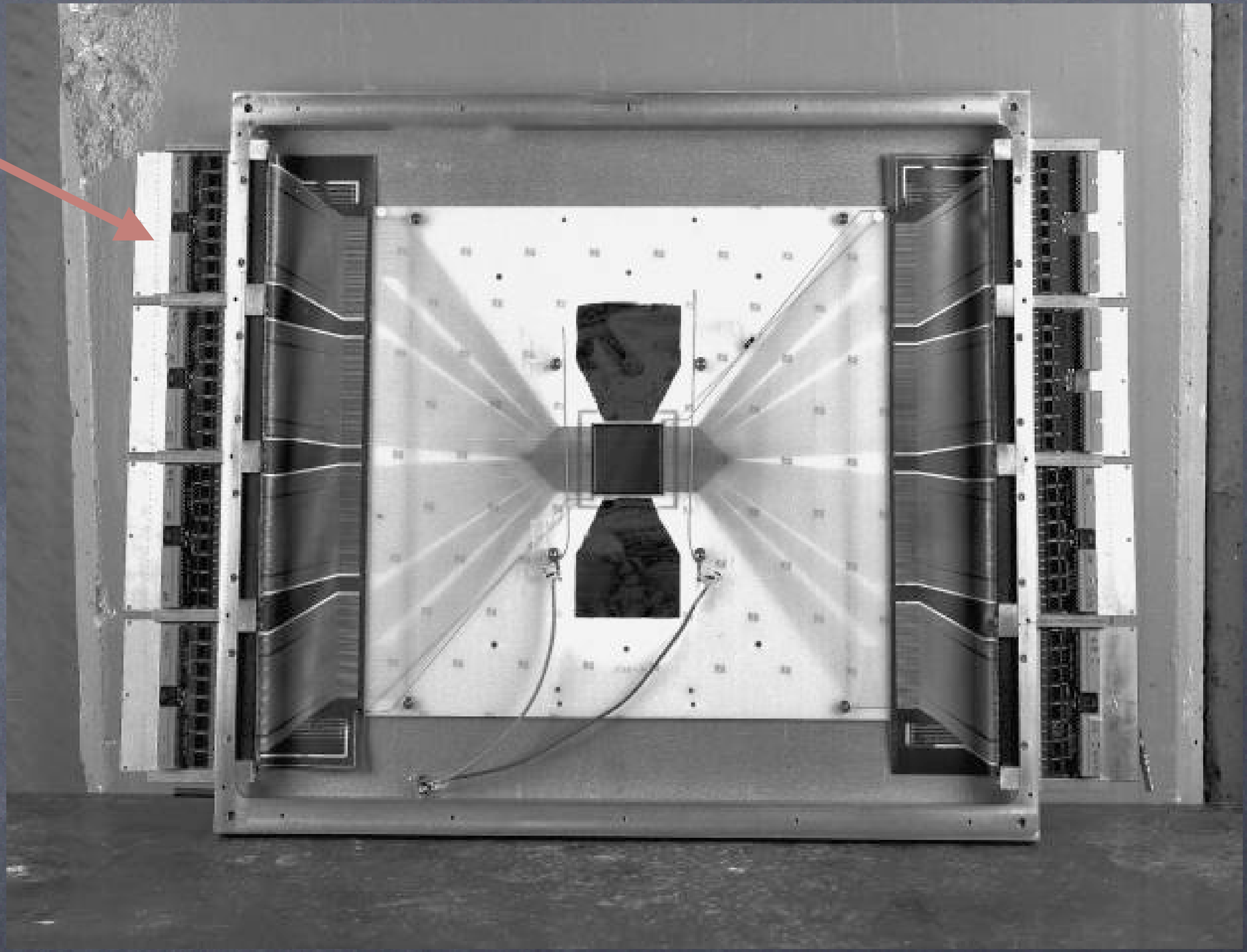


Typical strip spacing is 20-300 μm depending on application so can get excellent resolution

Silicon Microstrips

Examples of strip layout in getting connections to each strip wire bonded to send signals to amplifiers

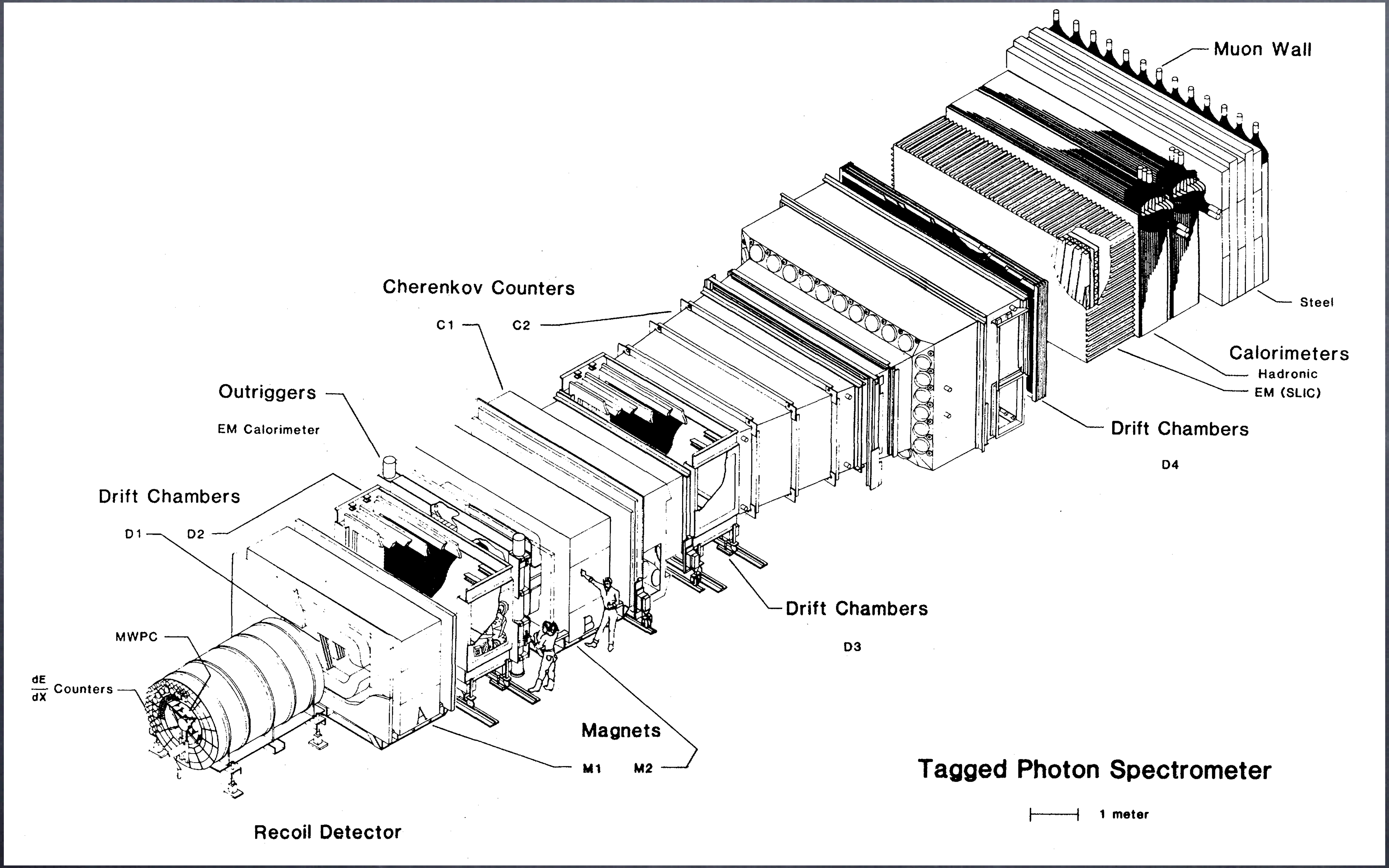




SMD used by E691 with strip spacings of 50 μm achieved σ_{trans}<20 μm for tracks reconstructed using 9 SMD planes with strips in 3 orientations

Fermilab E691

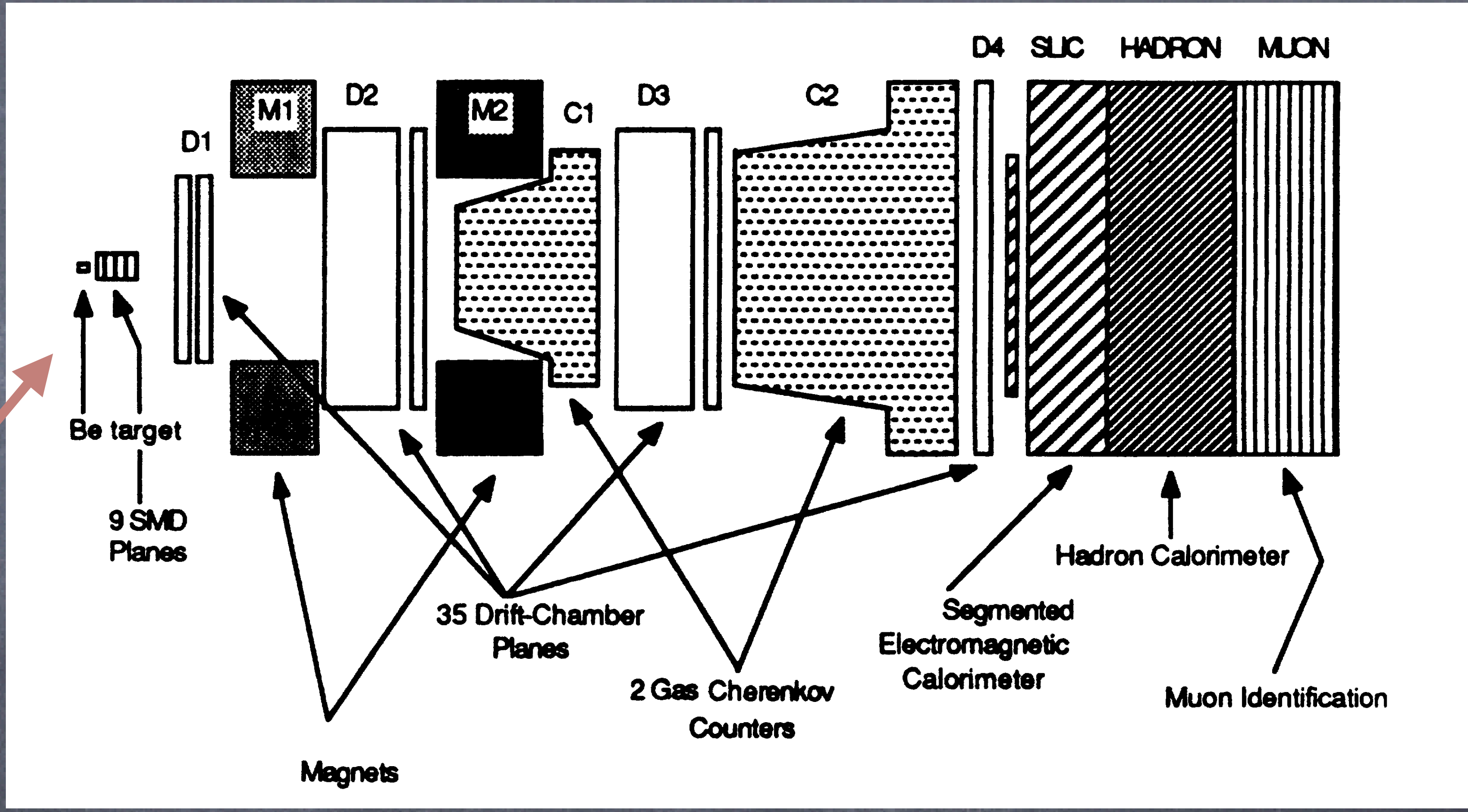
Uses a 90-260 GeV photon beam created by Bremsstrahlung of a 260 GeV electron beam (average photon energy = 145 GeV)



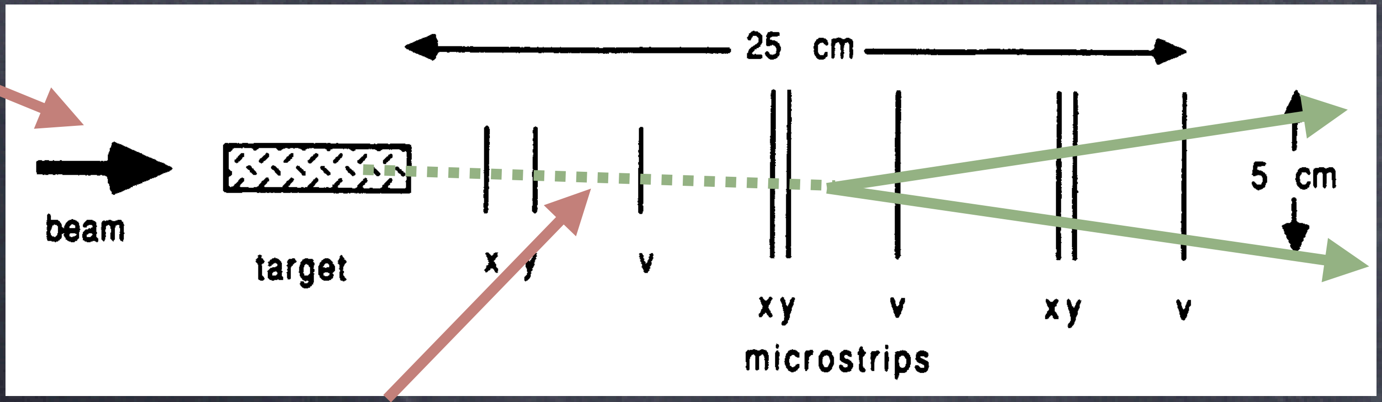
Fermilab E691

Target is Beryllium as we want low Z to reduce e^+e^- pair creatation from the photon beam and we want hadronic interactions so largest λ_0/λ_I

Not D_2/H_2 target as density is too low, target too long and acceptance is small



Target region

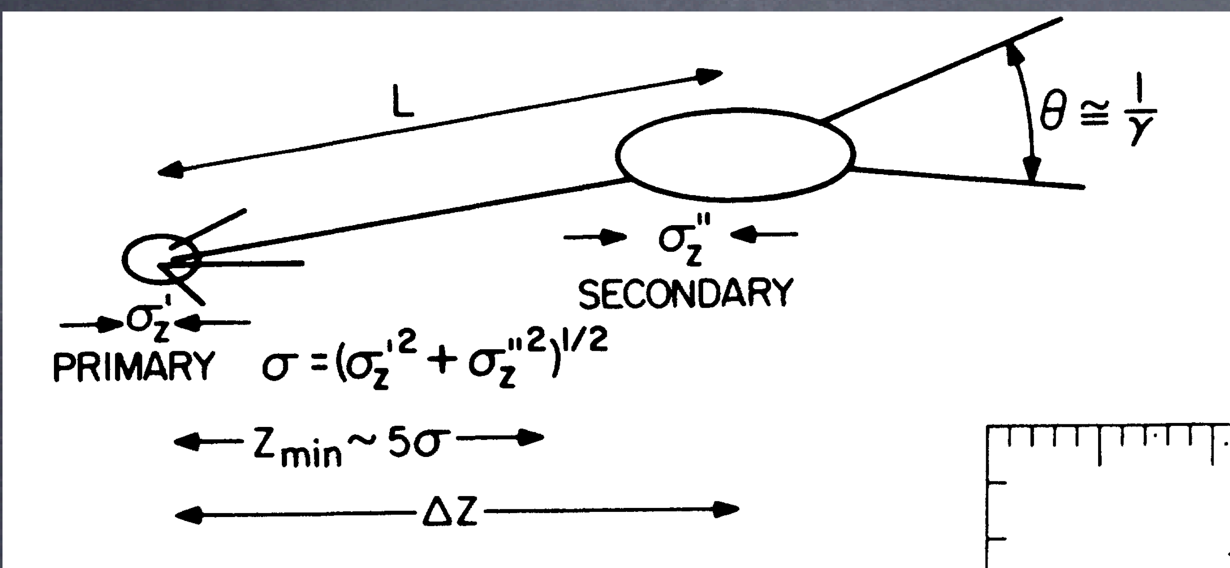


Long lived charm

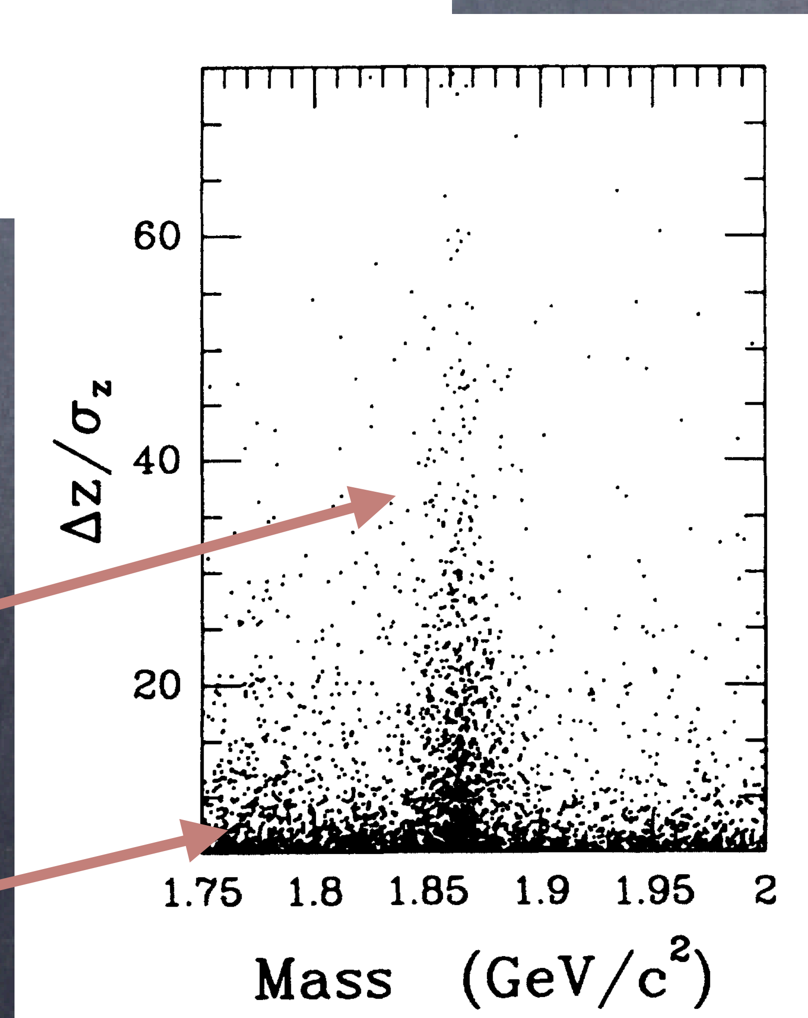
Not efficient for long lived charm decays as tracks are not efficiently reconstructed in the SMD

Fermilab E691

Illustration of background rejection using decay vertex separation

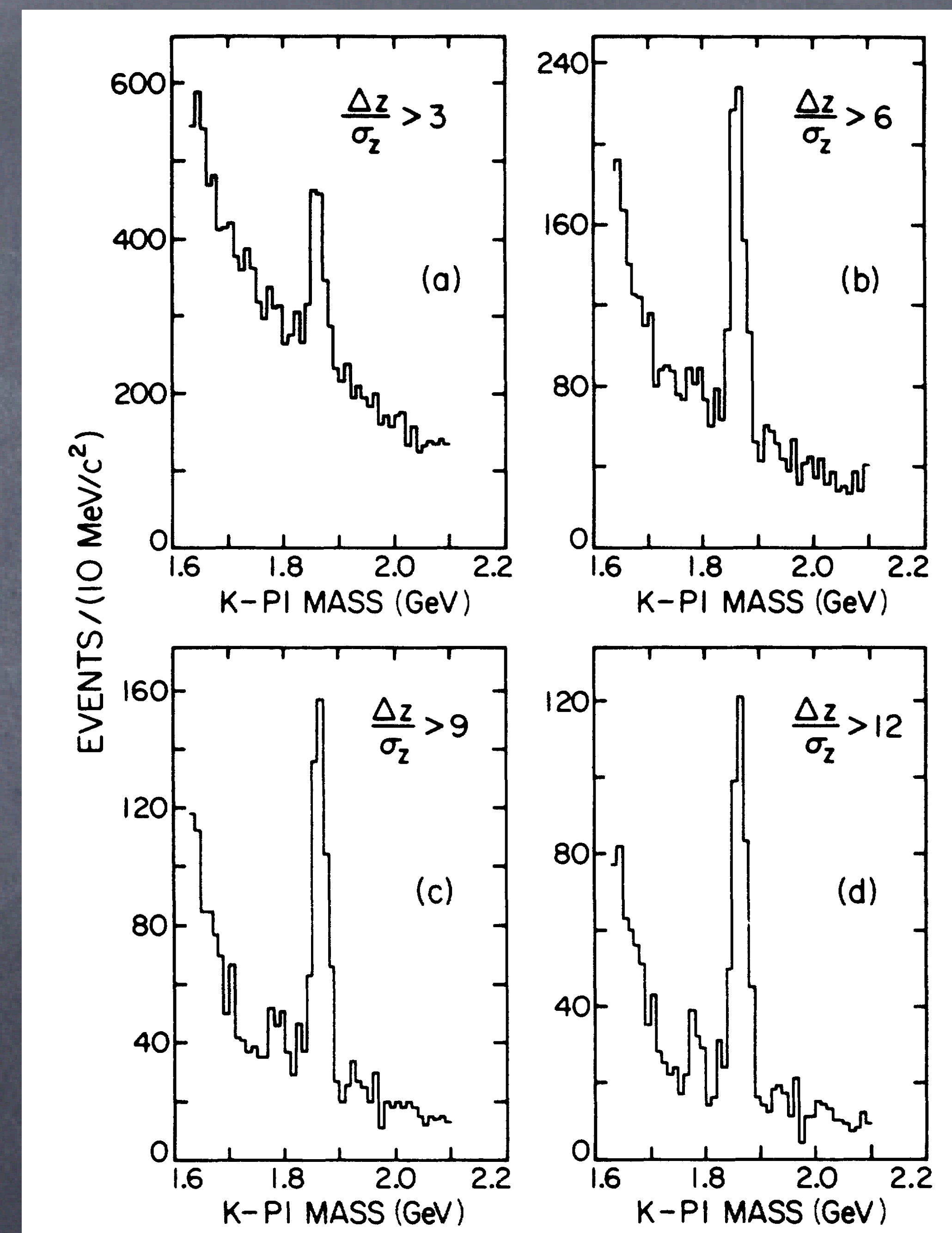


Typical Δz ~ few mm and σ_z = 300 μm



$D^0 \rightarrow K\pi$ signal

Random non-charm $K\pi$ background

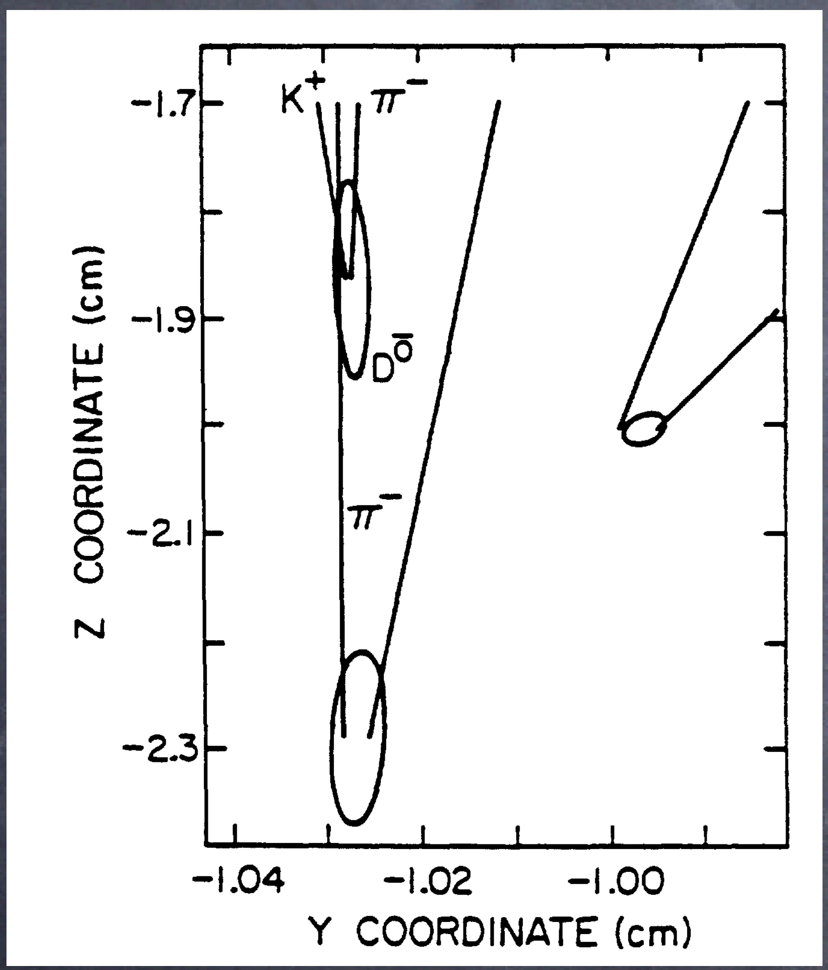


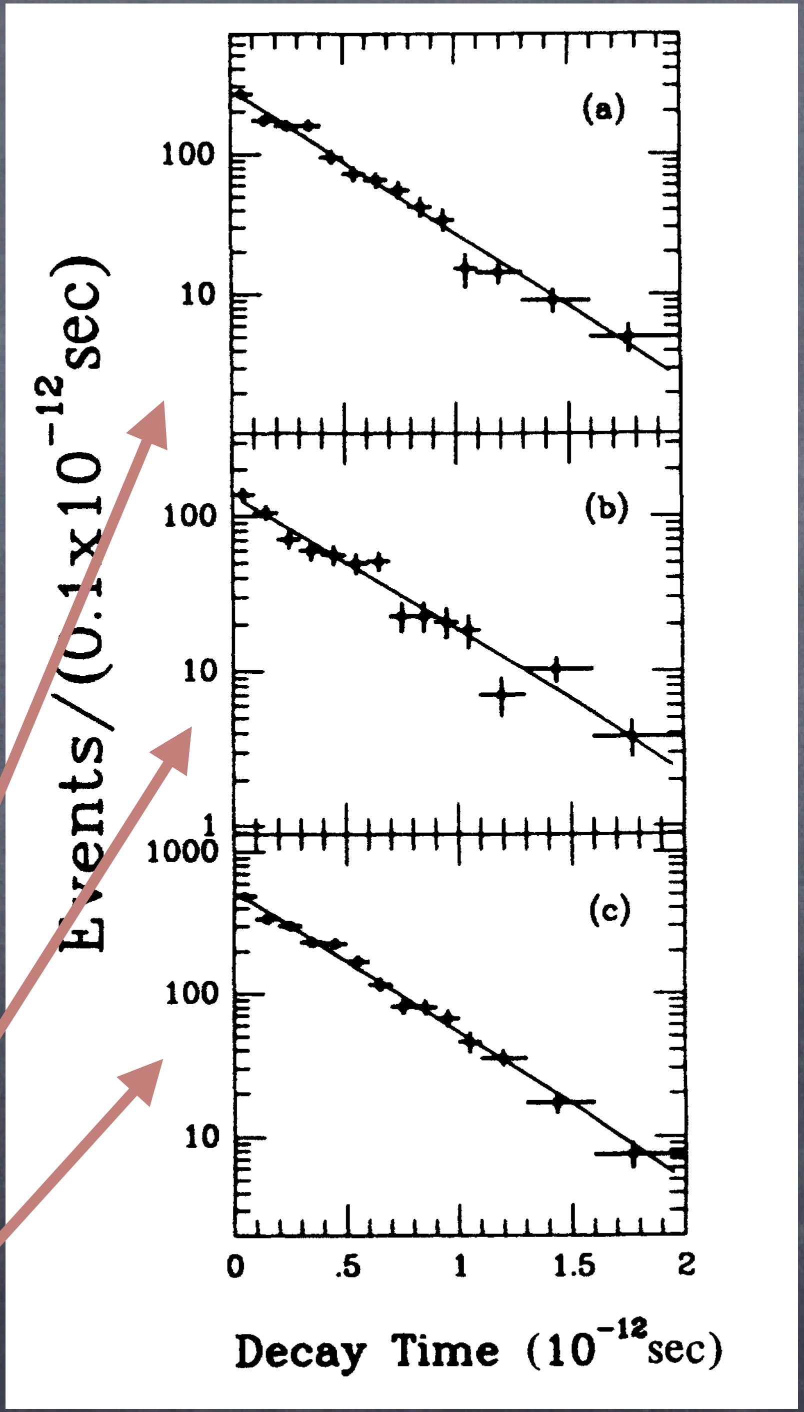
$\Delta z/\sigma_z$ = significance of separation of the production and decay vertices

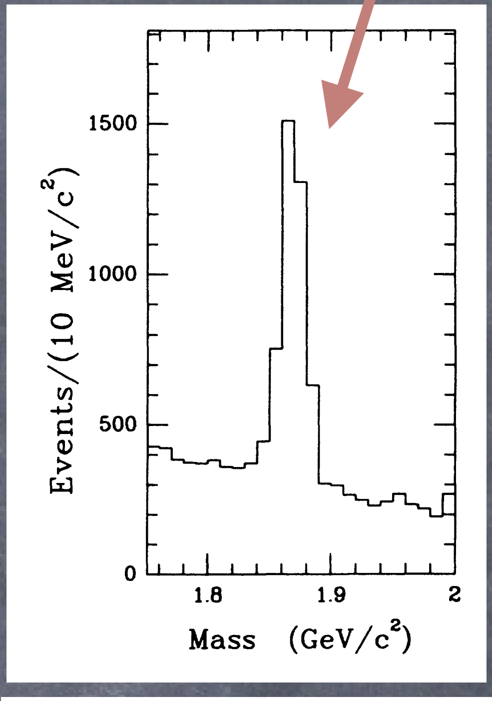
Fermilab E691

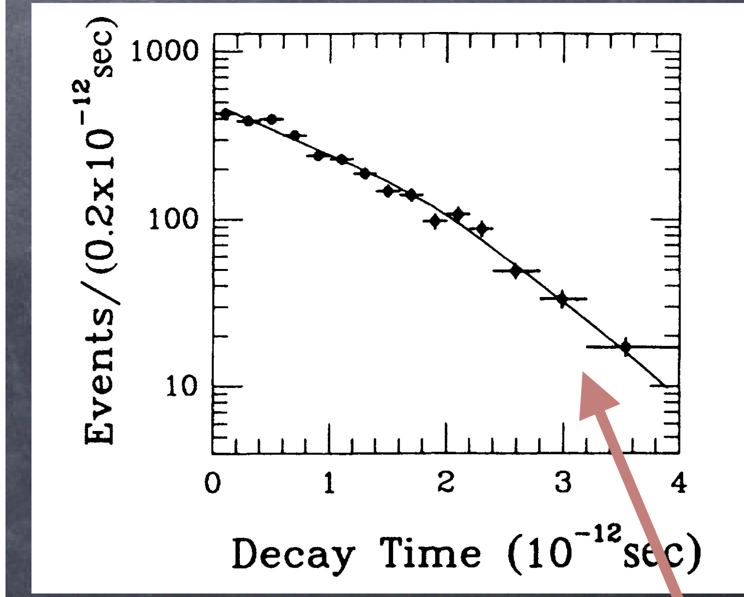
Charm Lifetime results

Typical separation and error ellipses









$D^+ \rightarrow K2\pi$

$D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K\pi$

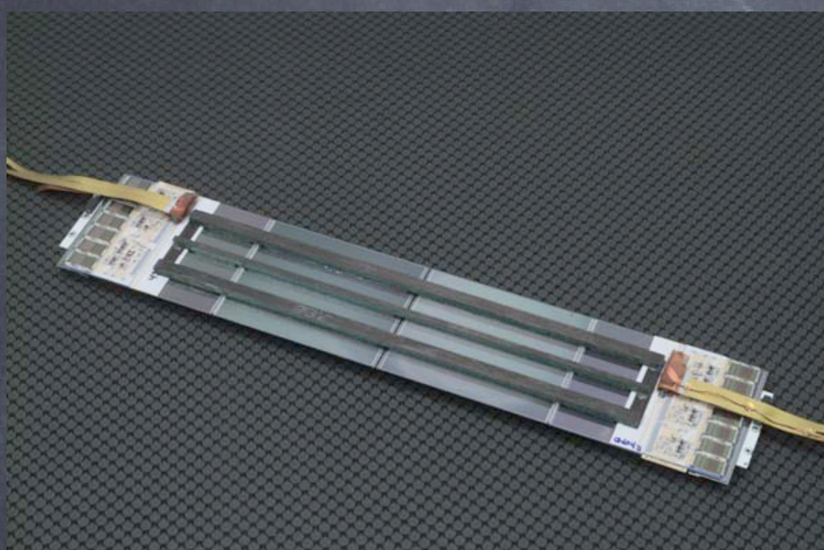
$D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K3\pi$

$D^0 \rightarrow K\pi$

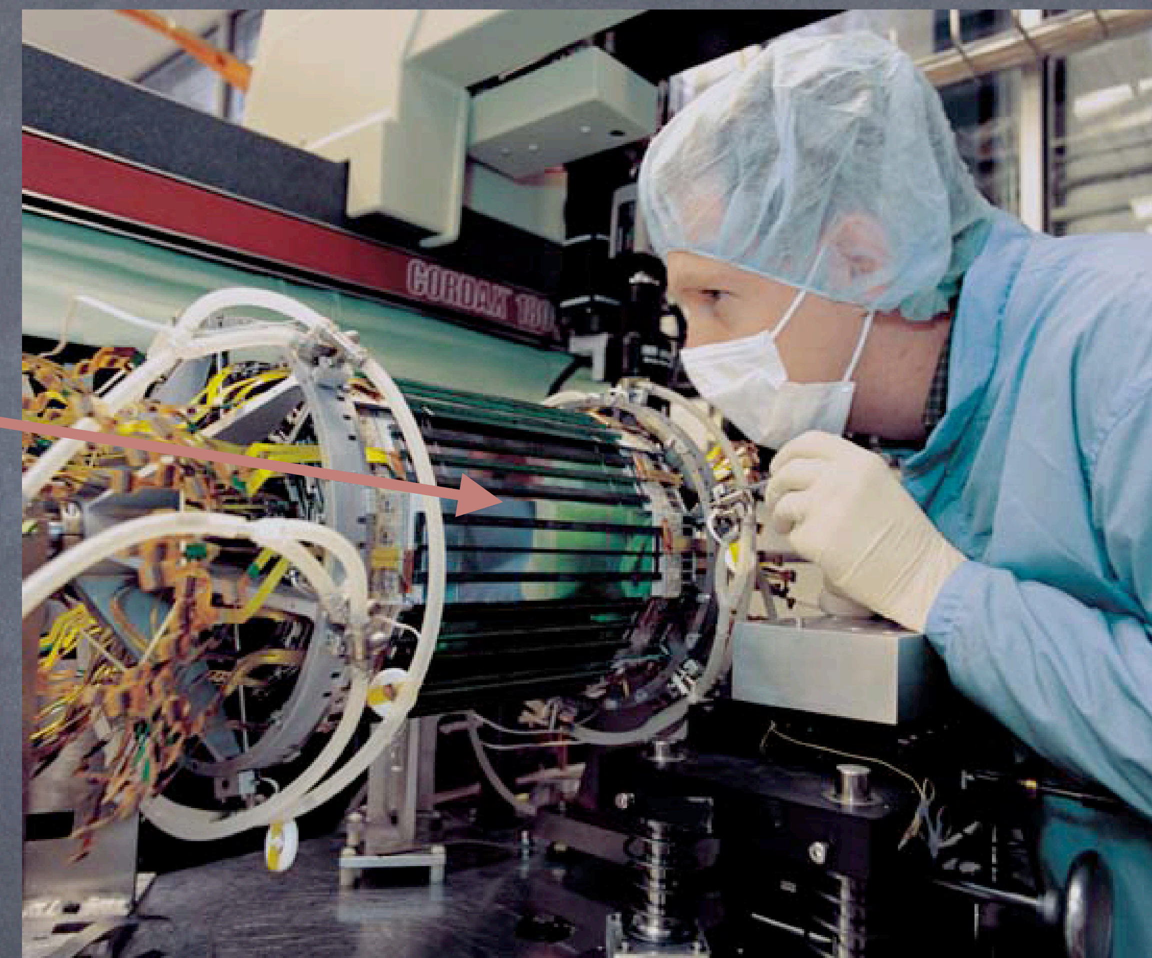
Lower acceptance at long lifetimes must be corrected for

Other SMD's

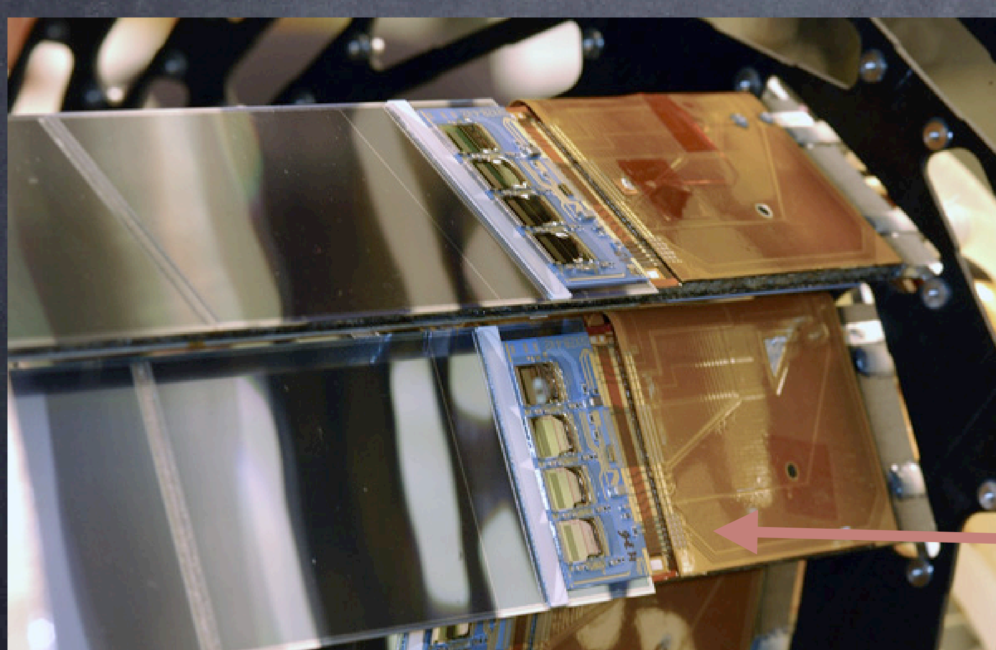
Individual SMD must be bonded together to make larger detectors (ladders) with longer strips



SMD barrel used in the CDF detector that saw the top-quark



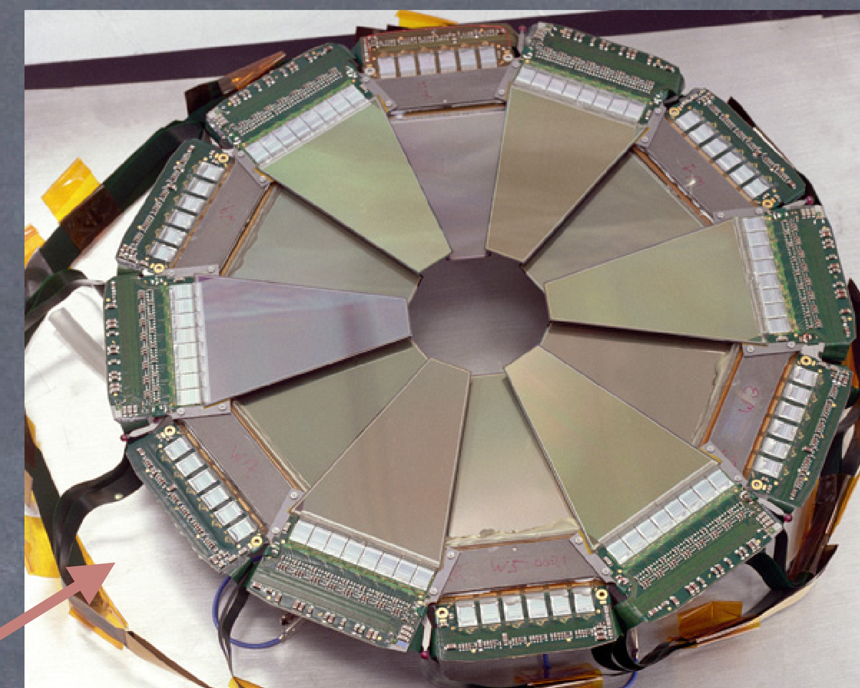
Lengths limited by capacitance which can induce (background) signals in neighbouring strips

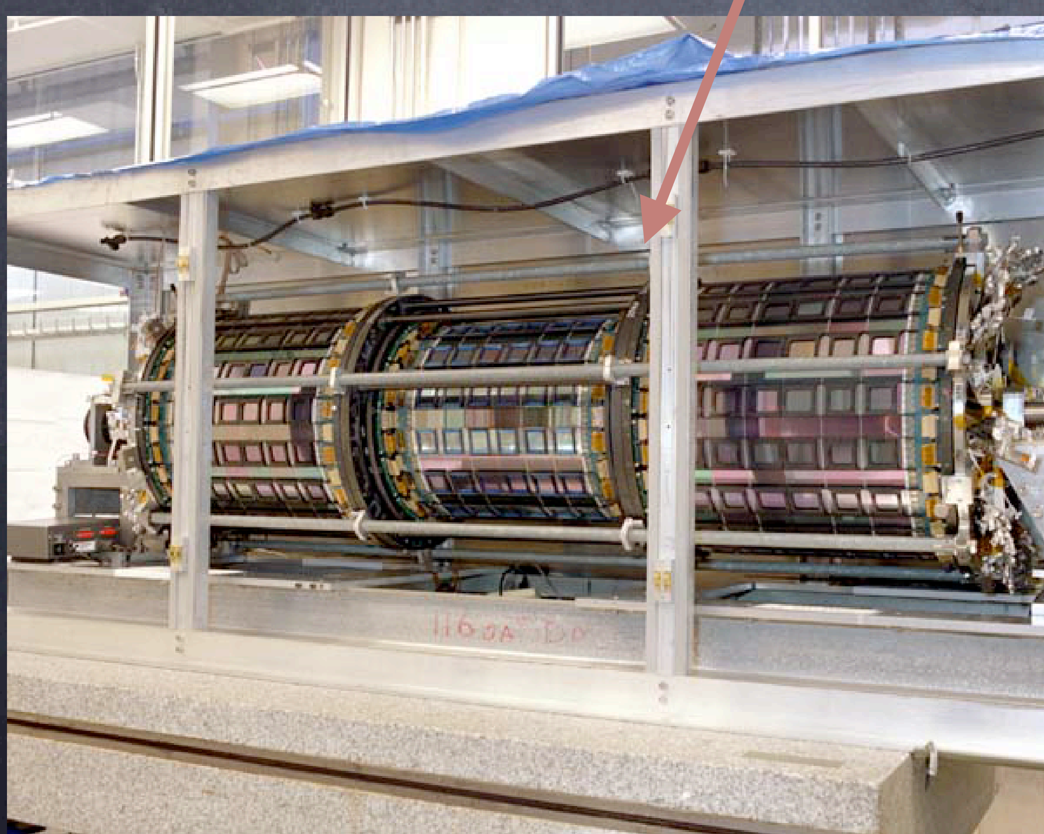


Strips wire-bonded to readout electronics

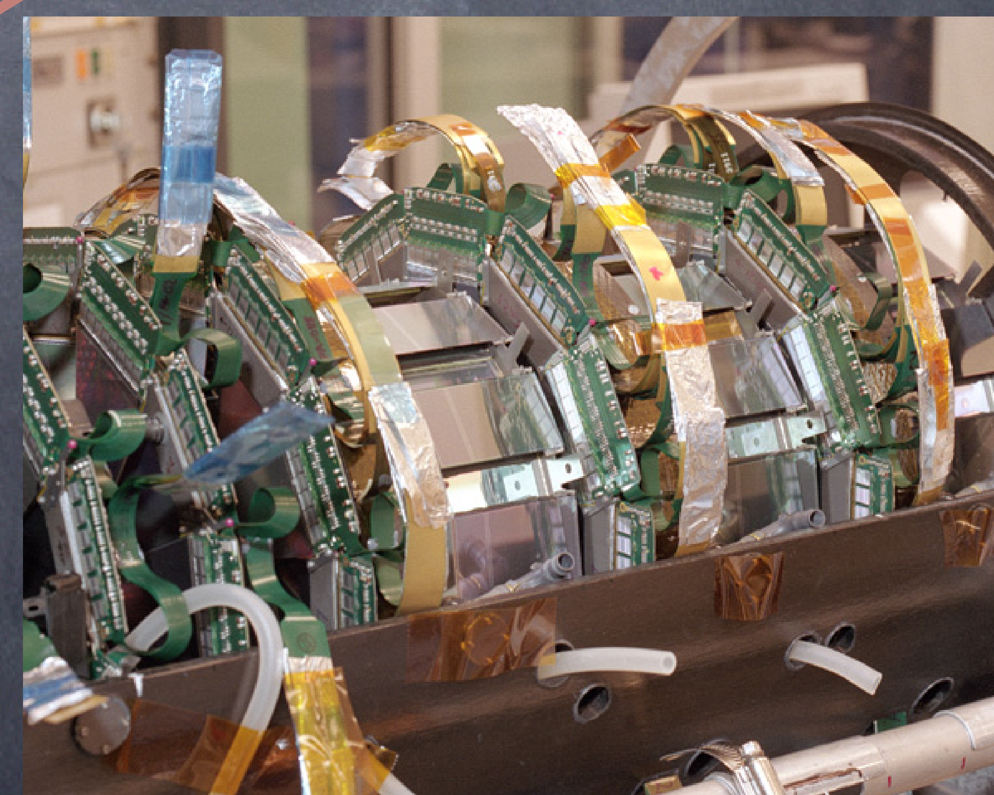
Other SMD's

Longer ladders for Fermilab CDF so they can improve acceptance and have additional silicon layers at large radius to improve resolution for b-(and top-)quark physics studies





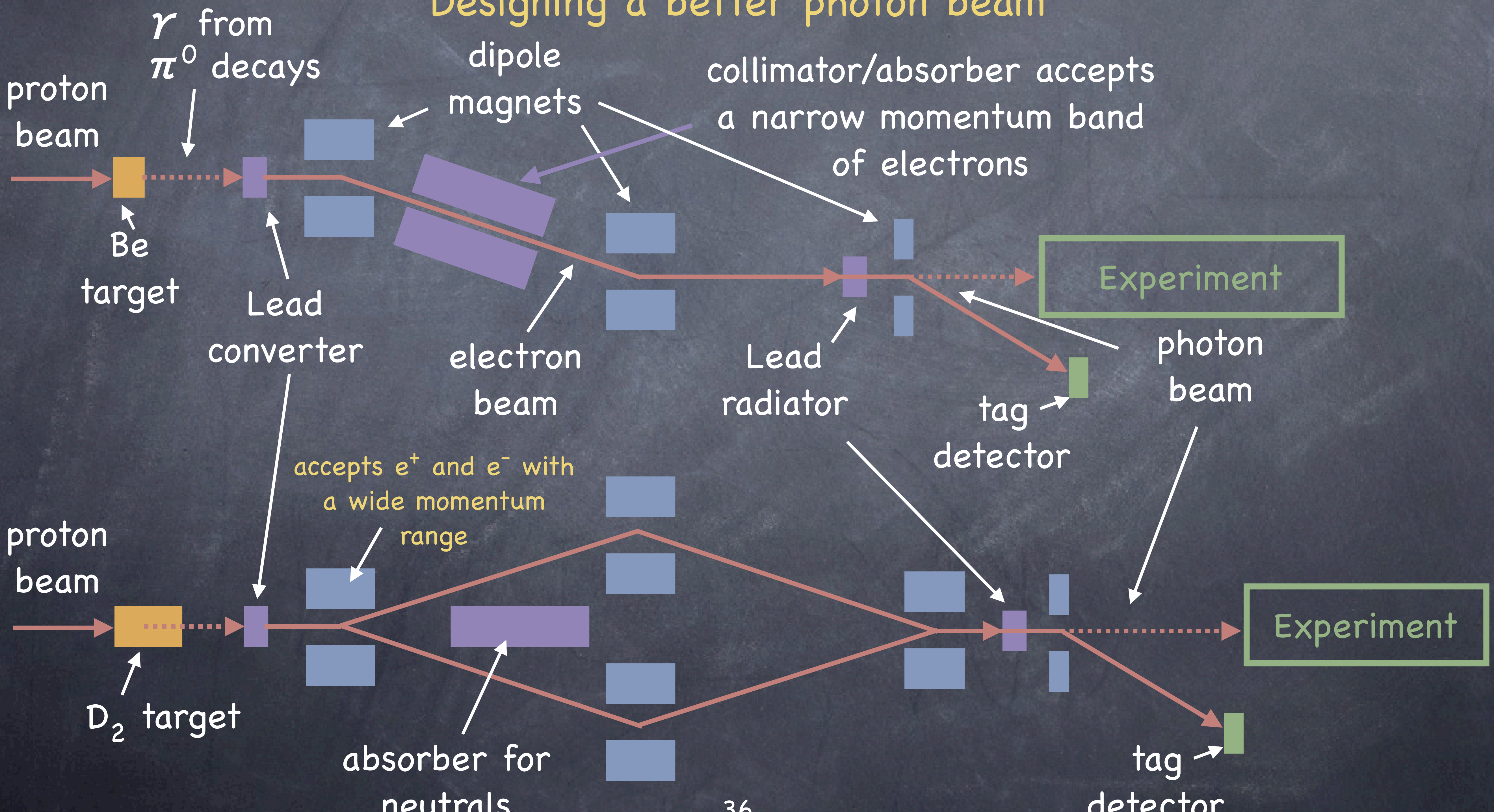
Disk geometry silicon microstrip detectors to improve the forward acceptance of the Fermilab D0 detector



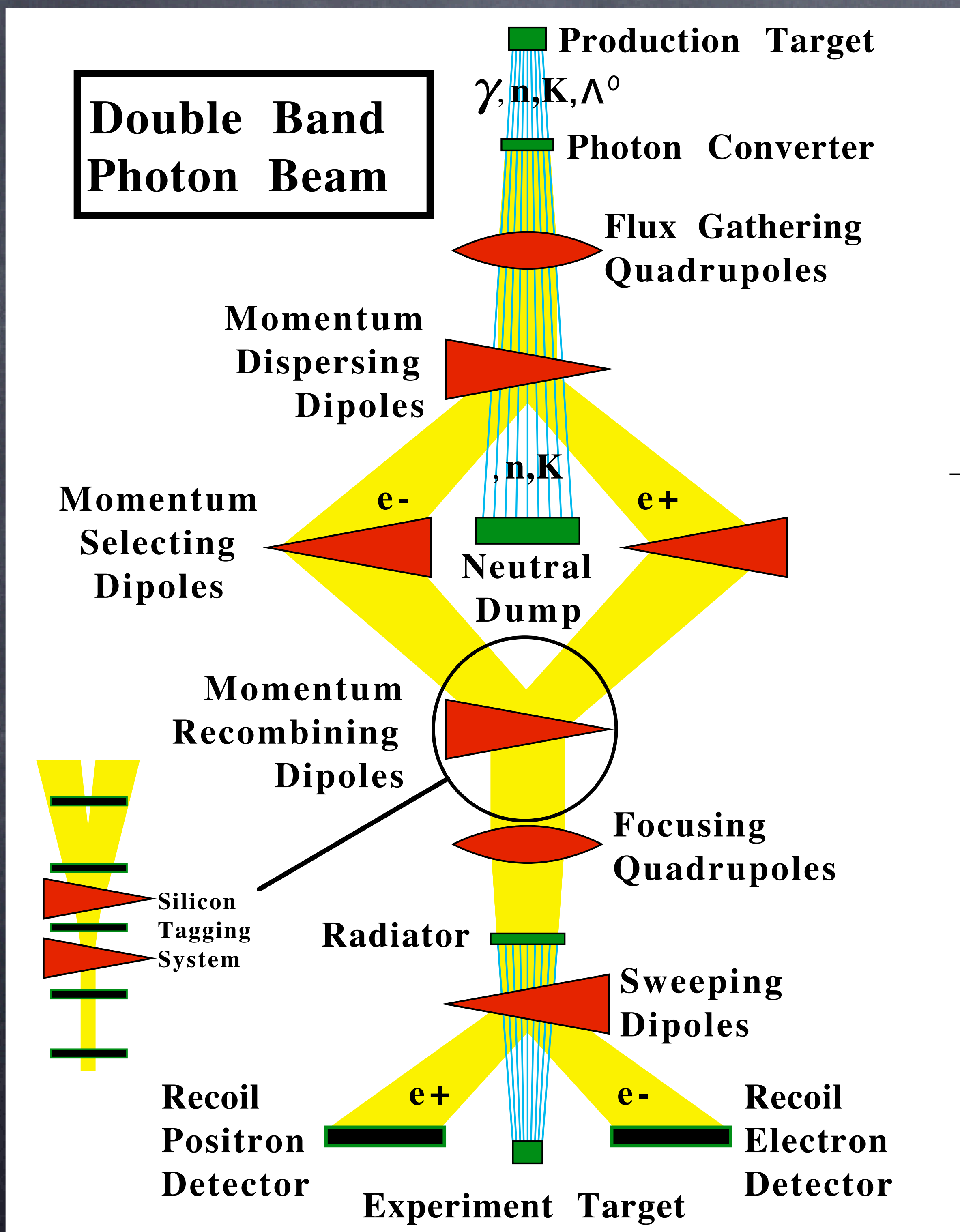
High Statistics Charm

How to improve by a factor of 100?

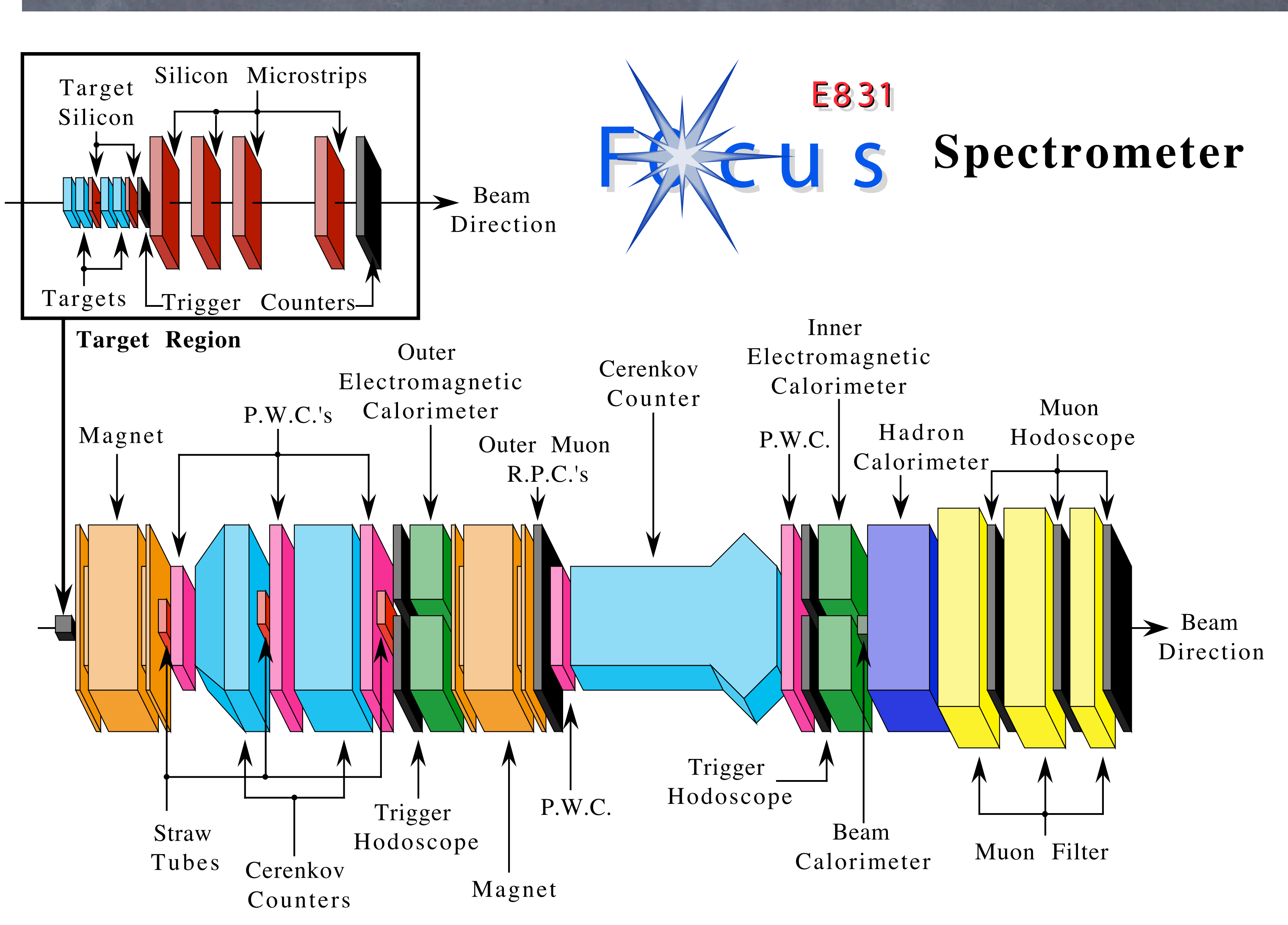
Designing a better photon beam



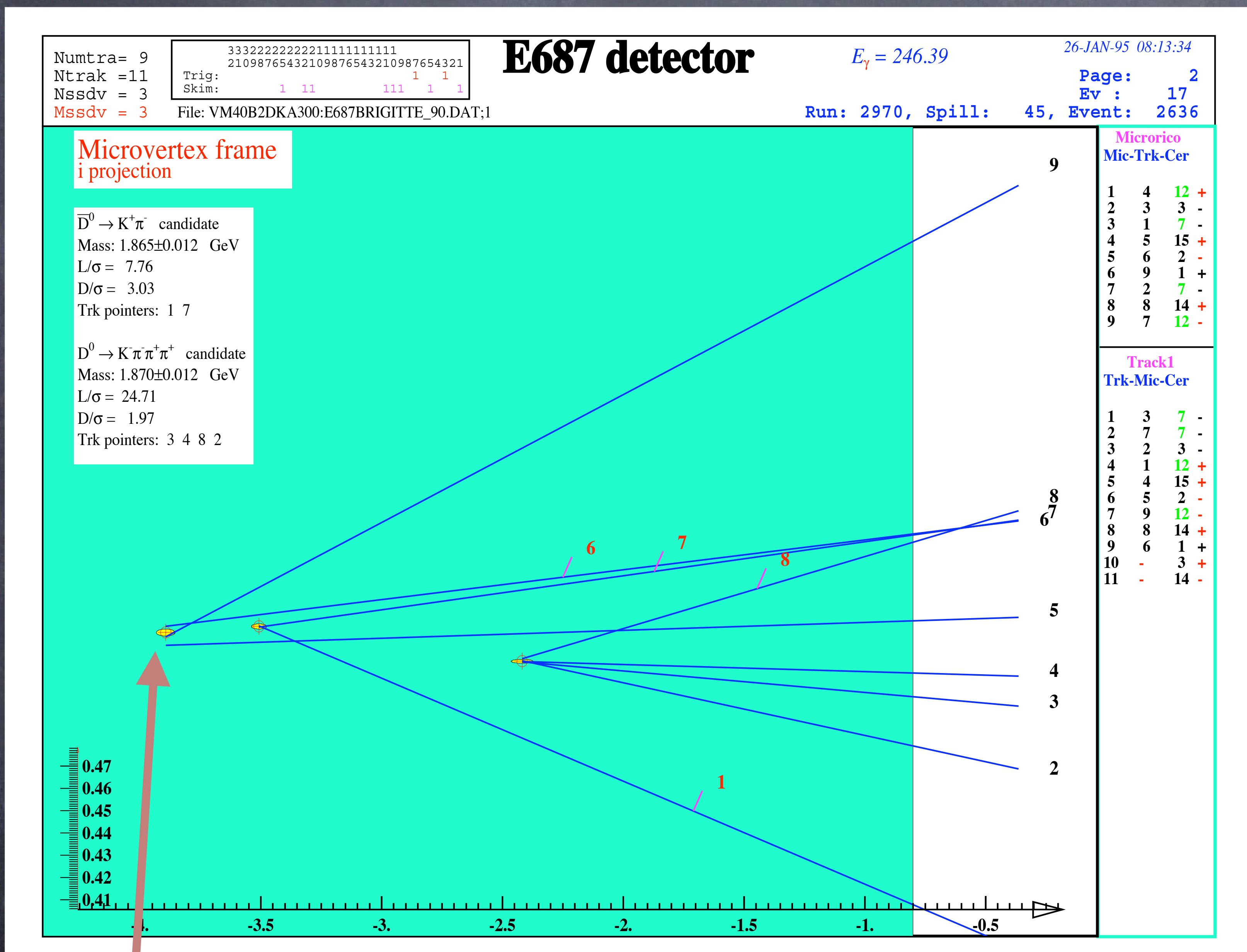
Fermilab FOCUS



An upgrade of E687 and ran in 1996+1997 and collected a sample of 1 million fully reconstructed charm decays



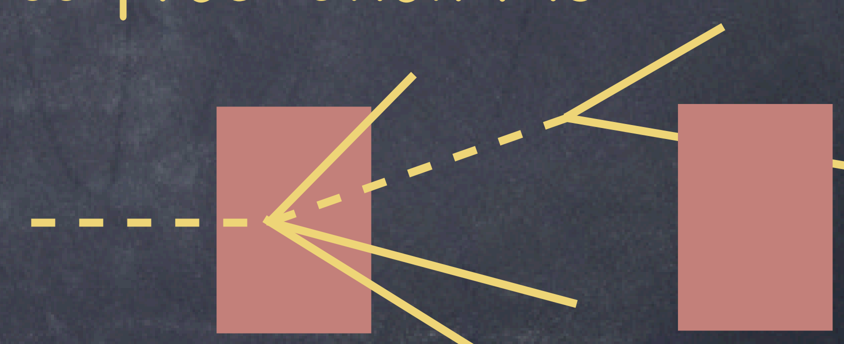
FOCUS Experiment



Error ellipses

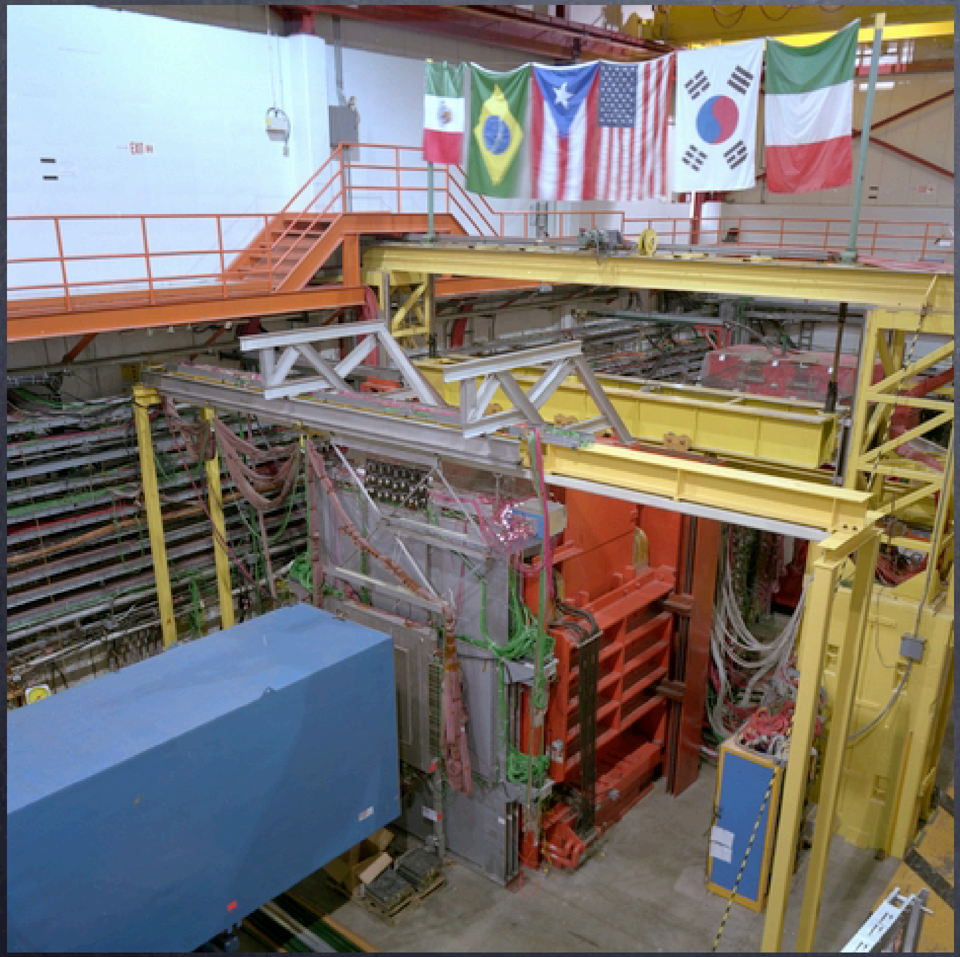
Not only a higher intensity beam, but also many more improvements:

- better SMD detector with better resolution
- better particle ID (background now from charm for rare decays)
- Reduction of systematic uncertainties, e.g.: out of target decays are cleaner and well modeled by just $c\bar{c}$ production MC



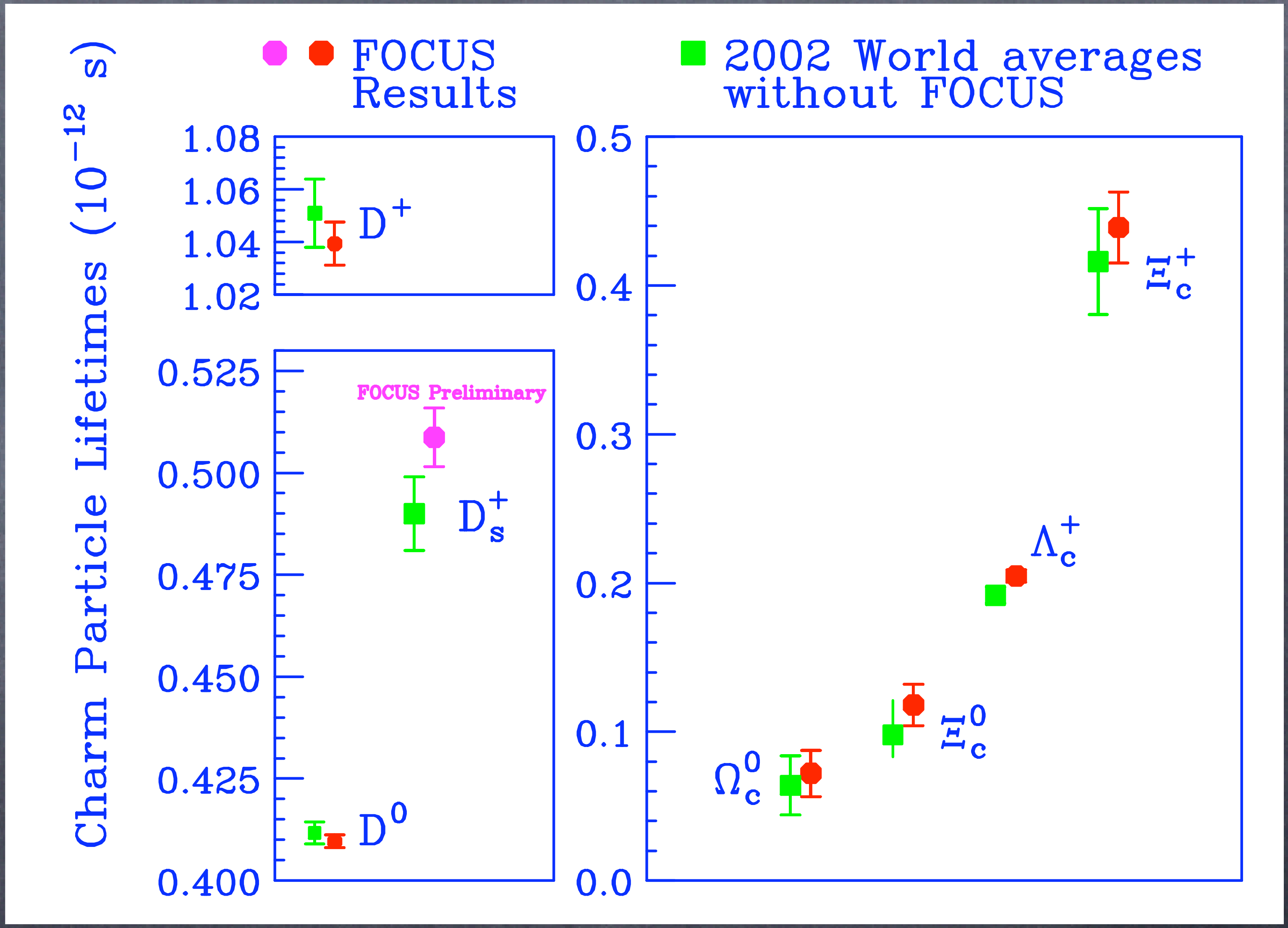
Multiple BeO targets thinner to get more decays out of targets

Target region



FOCUS

FOCUS has measurements of all the singly charm particles



Back to Hadrons

Charm with Fermilab E791 with a pion beam

No good way to tell charm from background at the trigger level - when data is recorded. Record all data and analyze "offline"

E791 pioneered the use of 8mm data tapes for HEP

One weekend of data on round 9-track tapes in E769 (before E791), compared to E791

Data Storage

Data storage vault at the Fermilab Computing Center

9-track tape vault, replaced with...

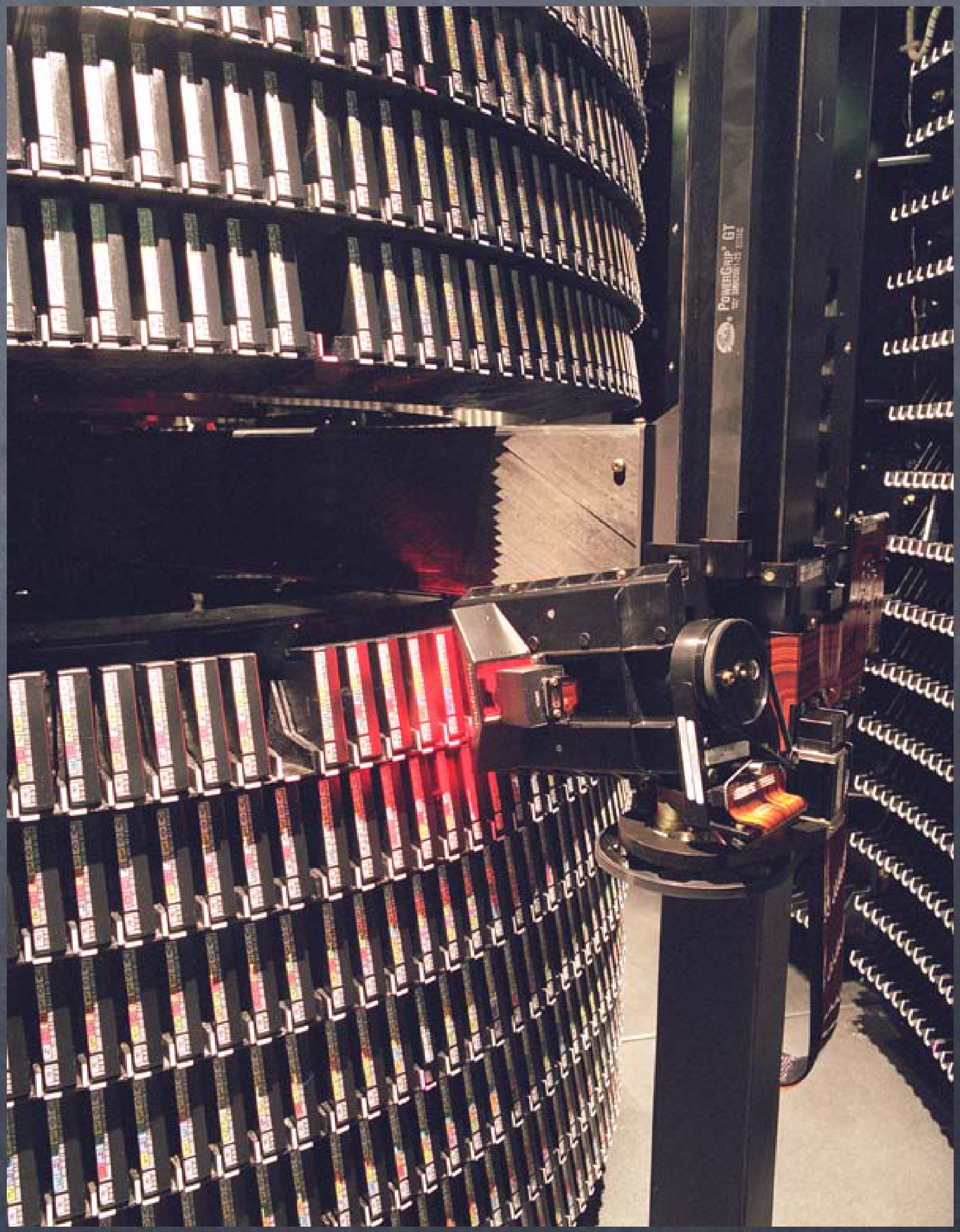
8mm tape vault to be replaced by...

Data Storage

Mass storage robots at the Fermilab Computing Center

IBM tape robot

STK tape robot



These can hold petabytes worth of data, 1 petabyte = 10^6 gigabytes

Analysis Machines

Analysis on "cheap" commodity (rack-mount) PC's

"Oh no! I have to unpack all these PC's?!"

Unpacking 434 PC's, just one shipment of PC'S for CDF and D0 Run II Data

Analysis Machines

Analysis on "cheap" commodity (rack-mount) PC's

Some of the PC's in NML

But even theorists have their share of PC's (Lattice QCD PC cluster)

How can we reduce this "madness"?!

Most of the data recorded is background

The Trigger

How to decide what data to store

Collisions/interactions come at a high rate and S/B may be 10^{-3} to 10^{-8}

Let's take a simple example: FOCUS photoproduction charm experiment

FOCUS uses a 50-300 GeV photon beam on a BeO target

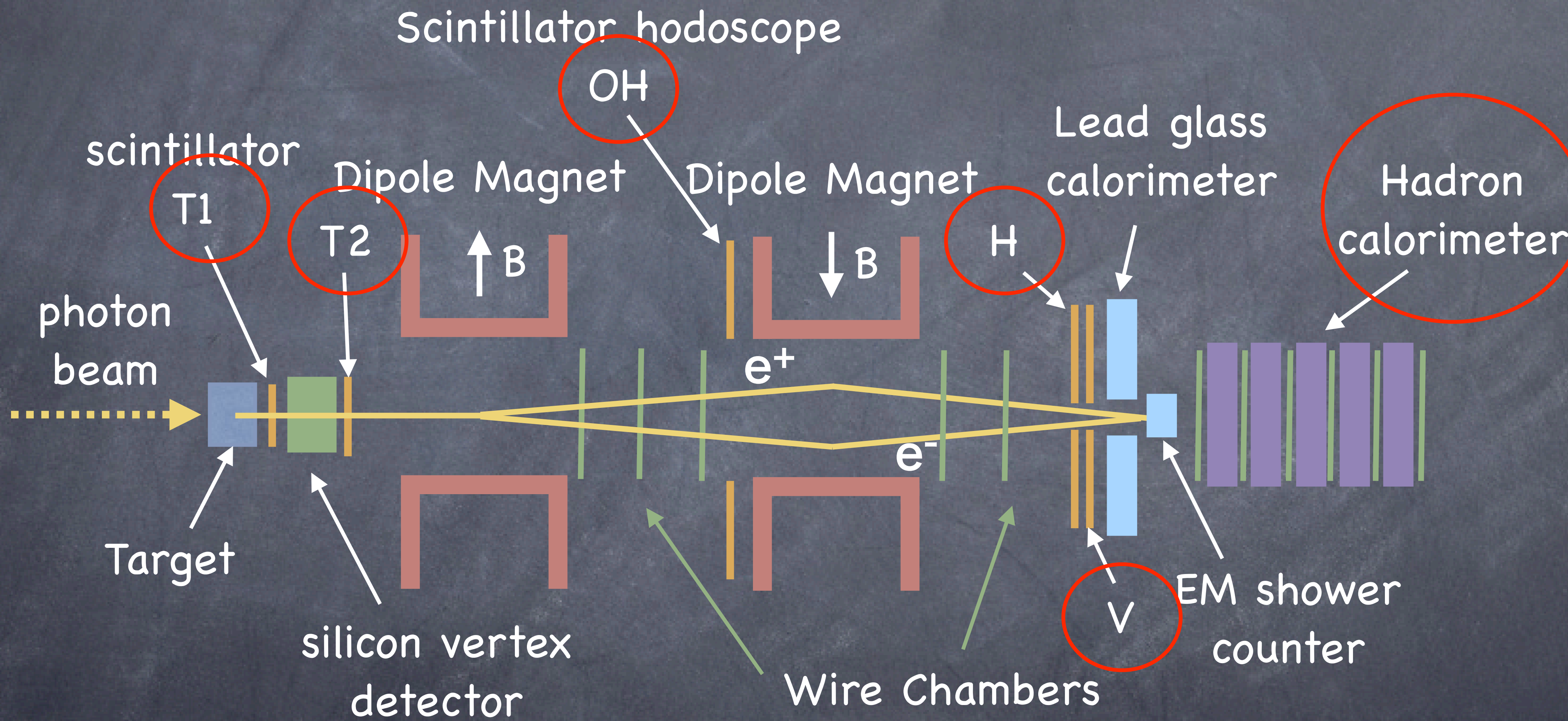
We get ≈ 500:1 e^+e^-:hadrons produced and
≈ 150:1 hadrons:charm produced

So if we can get rid of just e^+e^- pairs we could just store the rest of the data and analyze it offline (since its difficult to separate charm from other hadronic production)

If we use a hadron beam we are down in S/B but a further factor of 10, would want to do something further. E.g. E791 wrote data to >40 8mm tapes simultaneously!

The FOCUS Trigger

A simple trigger example with the FOCUS reduced schematic

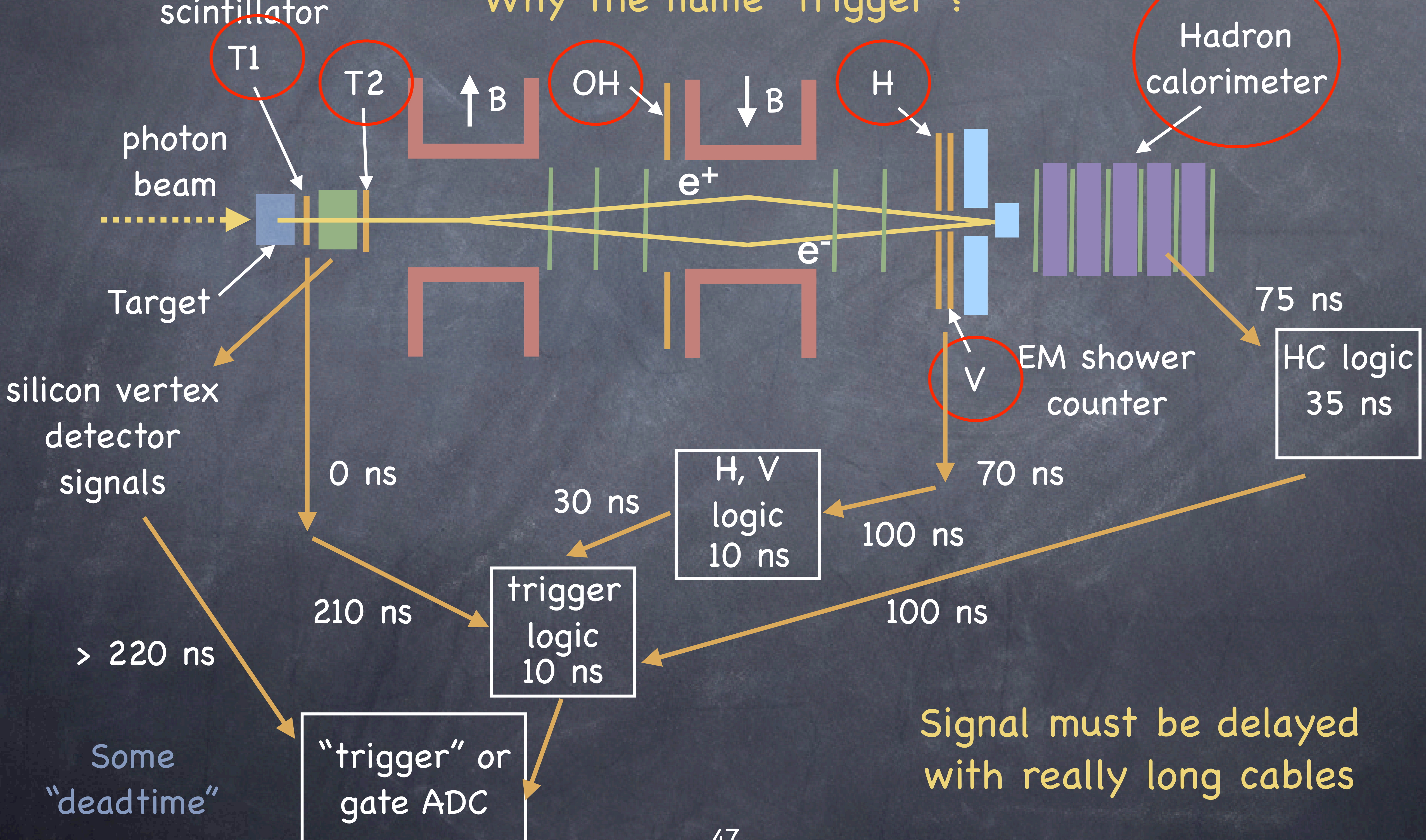


Trigger is T1•T2•[(H•V)$_2$+(H•V)$_1$•OH]•[EHC>20 GeV]

.and.

The FOCUS Trigger

Why the name "trigger"?



Some "deadtime"

Signal must be delayed with really long cables

The FOCUS Trigger

Signal and Trigger cables

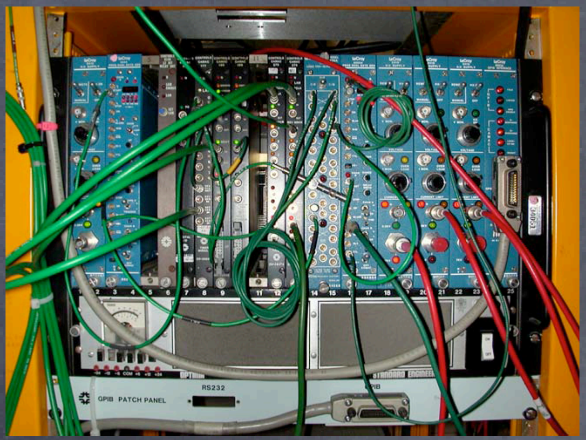
Signal must be delayed with really long cables but long cables attenuate the signal and increases the time spread of the signal

- Use fast trigger and fast trigger cables
  - normal coaxial cable has signal speed = 0.67c
  - air-core coaxial cable has speed = 0.95c (but hard to work with)
  - coax with Gortex™ dielectric has speed = 0.89c but expensive
- Use fat signal cables to reduce signal width spread

Long Ansi flex cables used for wire chamber signals

Electronics Racks

An excuse for more photos



CAMAC crate

Some racks at mini-BOONE

Some racks at D0

Some racks at E871

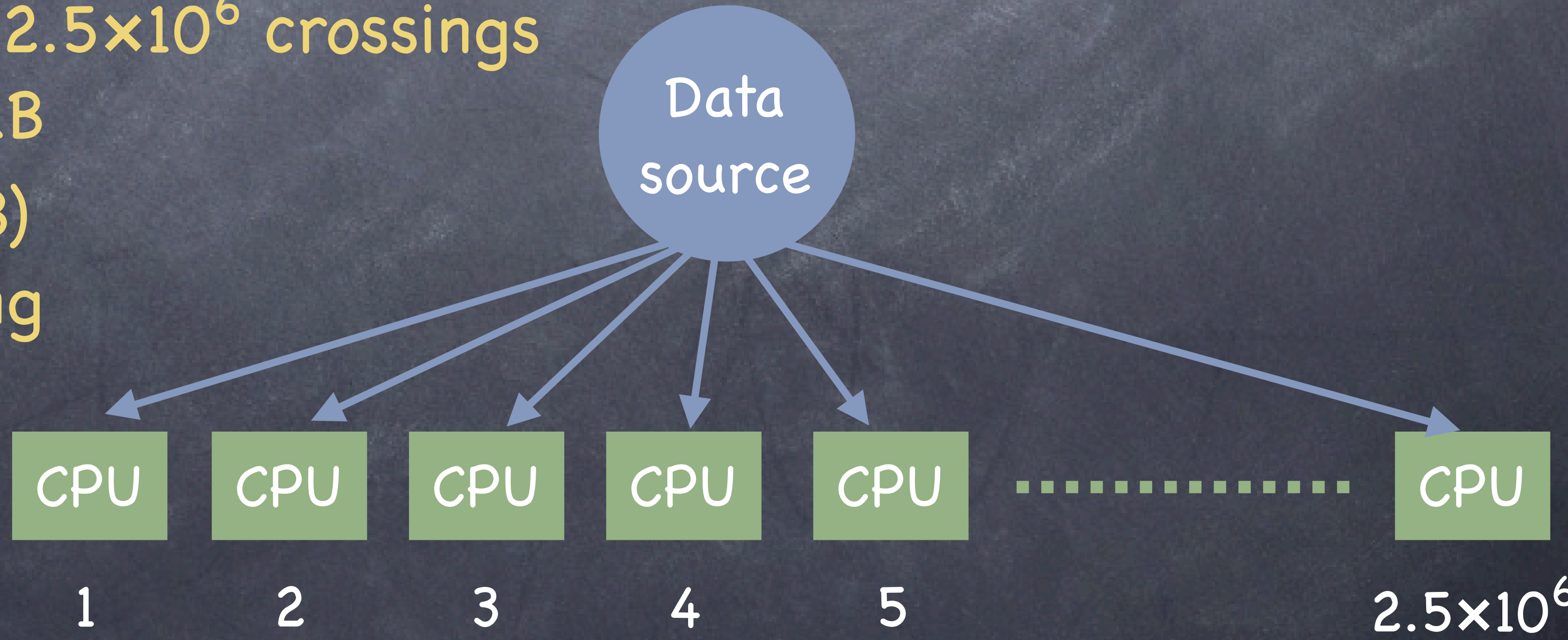
The Ultimate Trigger?

Store and analyze all events

Electronics are fast, small and memory is cheap so maybe we could record all the data and analyze it all to decide which data to store?

Let's illustrate with an example, e.g. CDF or D0 at Fermilab:

- The p and $\bar{p}$ cross every 396ns, or about 2.5×10^6 crossings/second
- If it takes 1 second to analyze the data from one crossing we would need 2.5×10^6 CPU's to not lose any crossings
- Need to store at least 2.5×10^6 crossings each needs about 300KB so need > 1TB (= 10^3 GB) To be safe as 1s/crossing is the average we want 100-1000× more storage = 100-1000TB of RAM (memory)!



We need a Trigger

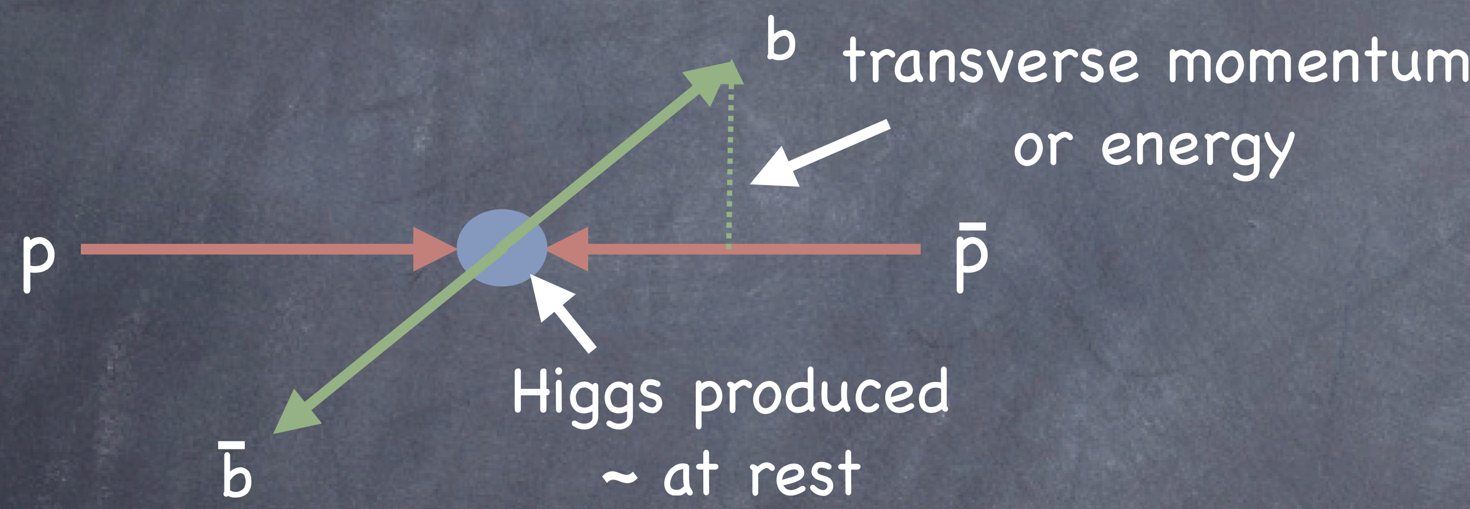
$p\bar{p}$ collider (CDF, D0) example

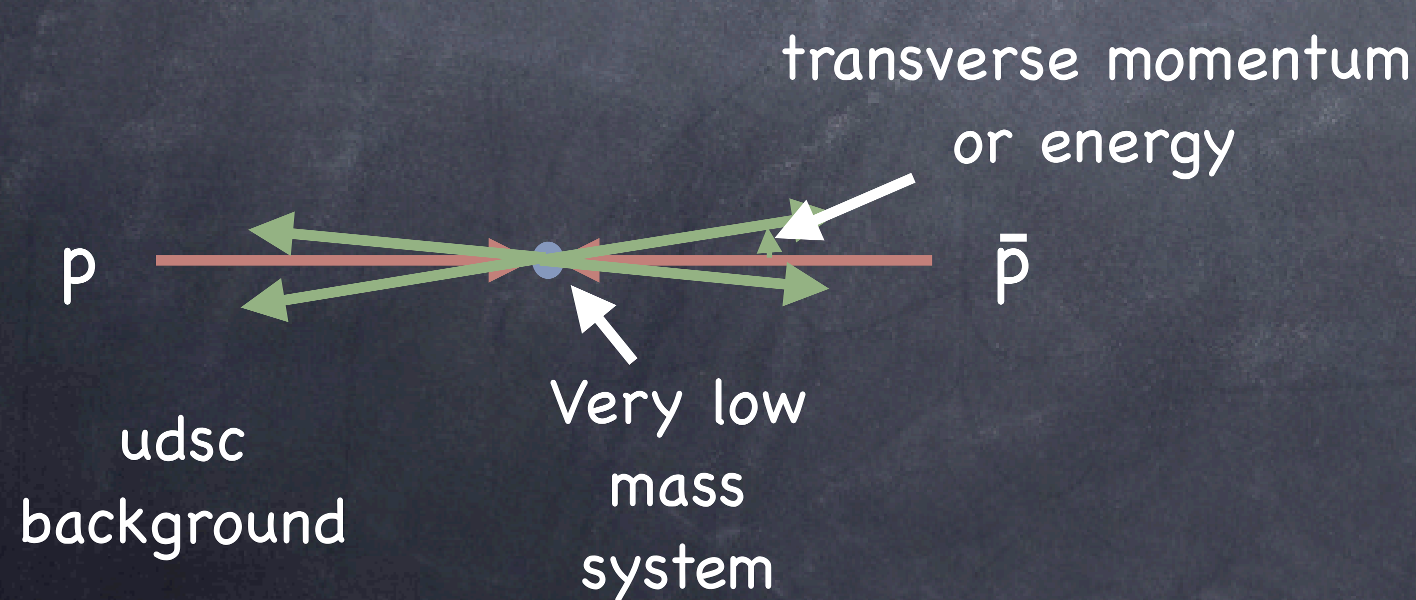
We need a simple and fast way to recognize a crossing with signal

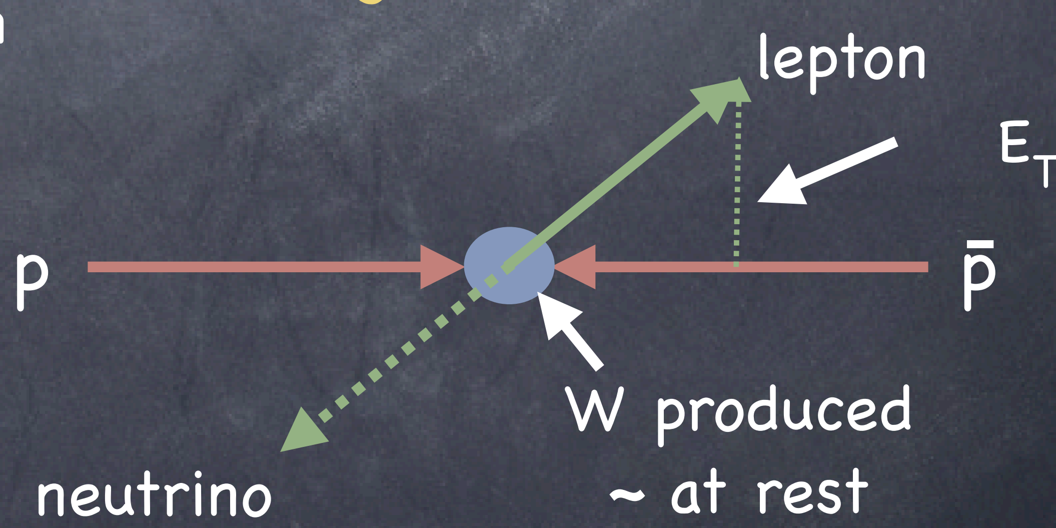
E.g. for CDF and D0:

- For Higgs require large E_T e.g. E_T>30GeV
- For W require large missing E_T and a high E_T lepton

These selections (cuts) loses some signal but we reject the majority of the background



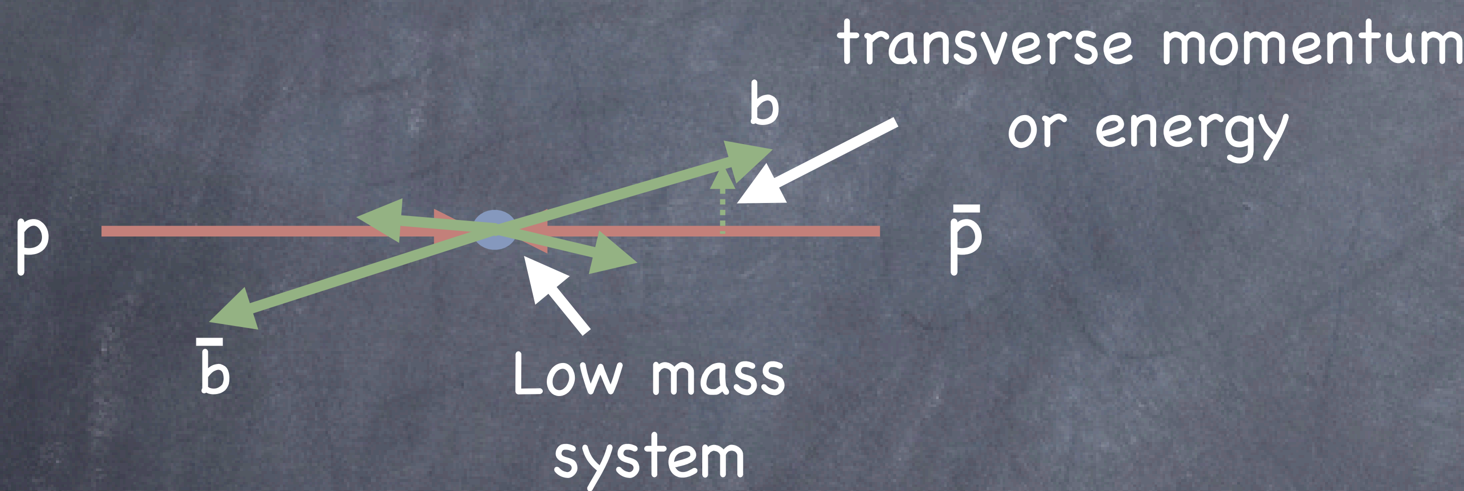


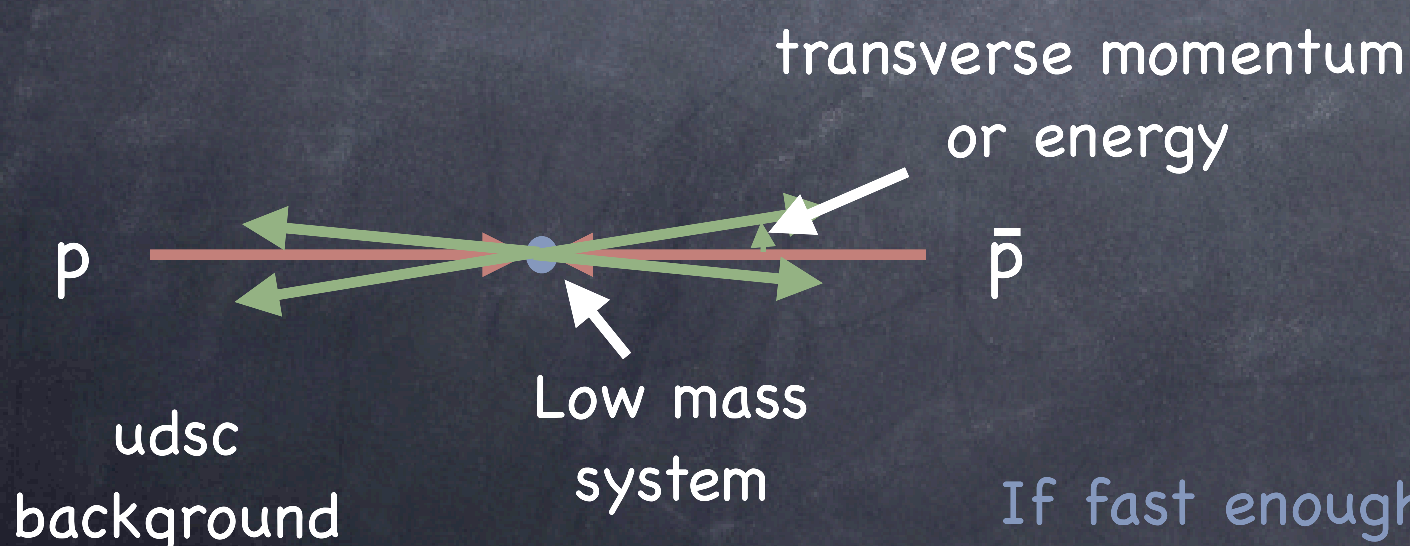


We need a Trigger

pp̄ collider (CDF, D0) example

We need a simple and fast way to recognize a crossing with signal





E.g. for CDF and D0:

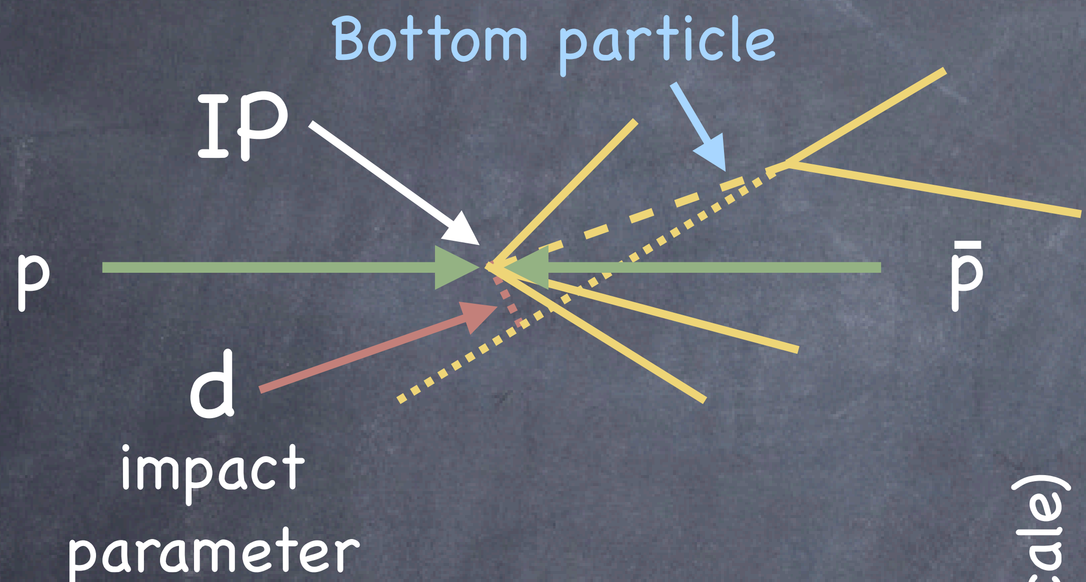
- For bottom quark physics a large E_T selection like e.g. E_T>30GeV would lose too much signal
  - > a lower e.g. jet(E_T)>15GeV would not give enough background rejection
  - > Could ask for two jets with E_T>15GeV, or two jets one with E_T>10GeV and other E_T>15GeV (optimization)

If reduced rate low enough we can go to the store and analyze case at the next trigger "level"

If fast enough and storage "pipeline" long enough can be deadtimeless

Effect of a Trigger

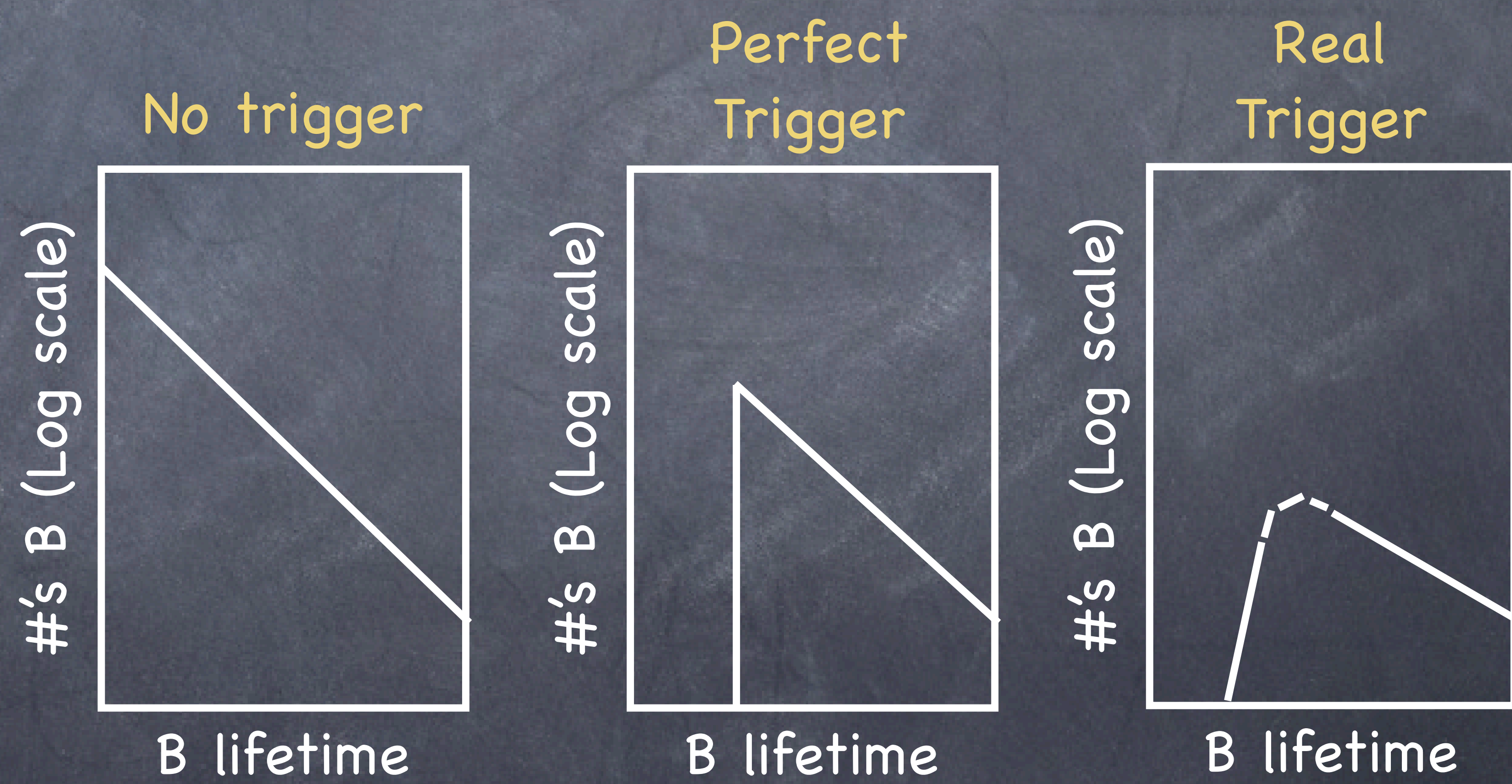
Evidence of a detached vertex



Level 2 CDF trigger for detached vertices would require that one or more tracks have a large impact parameter from the IP.

The IP is obtained from the average over 1000's of crossings

This Level 2 trigger will lose some events at short lifetimes but it also introduces the need for non-trivial trigger corrections



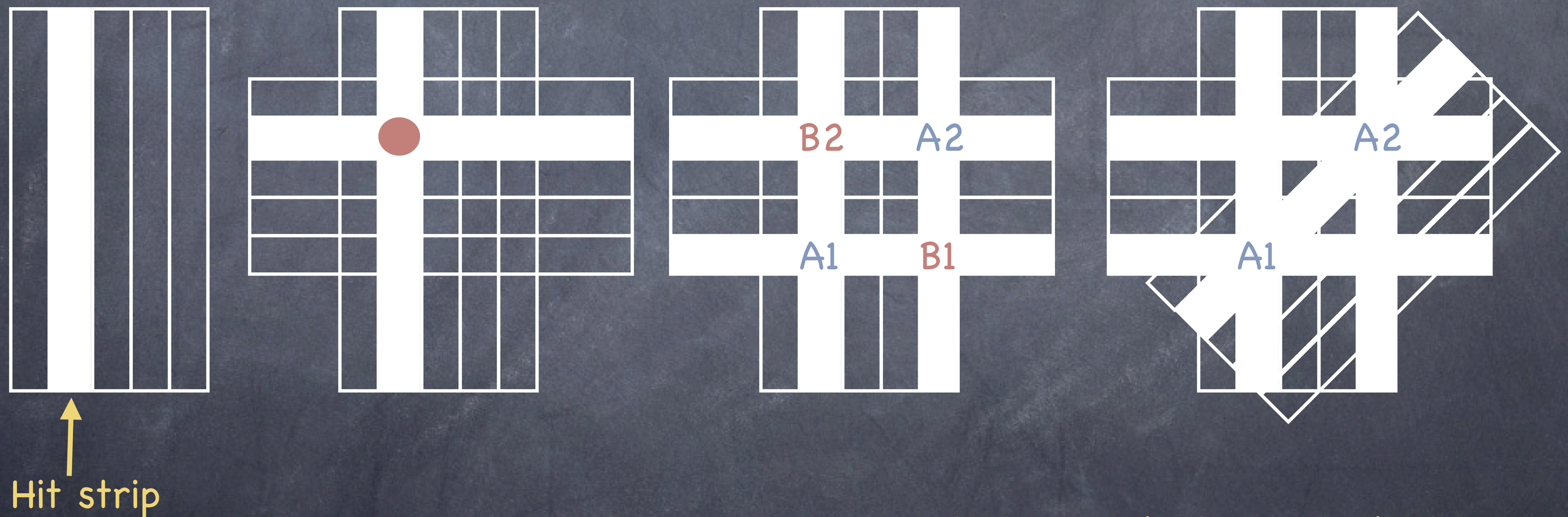
Check Trigger correction (obtained from MC) with data, e.g. same decay using a different trigger (J/ψ) - data limited

The Penultimate Trigger?

The BTeV Trigger looks for a detached trigger for every crossing

The key is fast "pattern recognition" or reconstruction as the storage pipeline is "easy" (e.g. BTeV uses a 1TB memory pipeline - enough for 1 s)

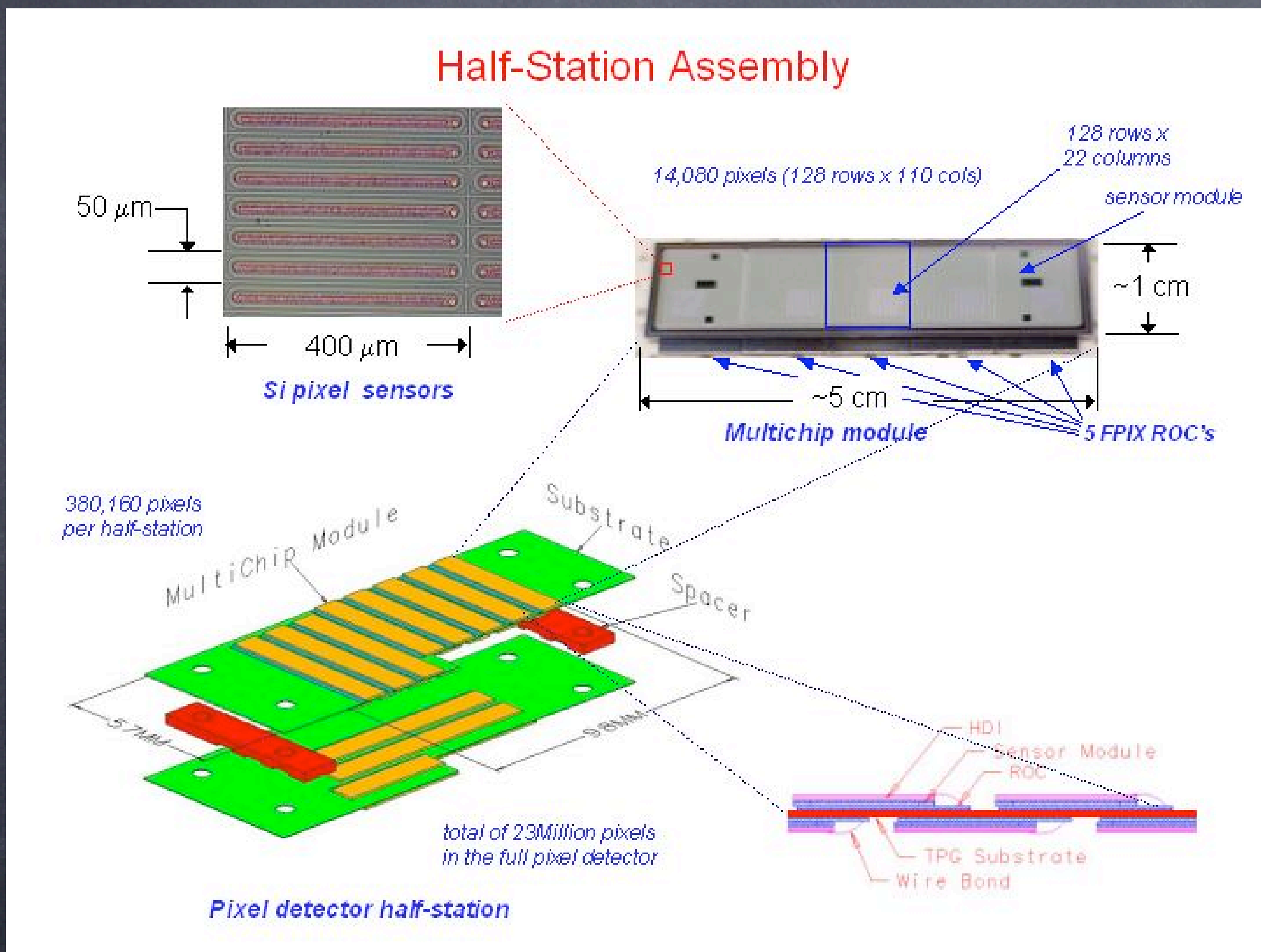
E.g. silicon microstrips



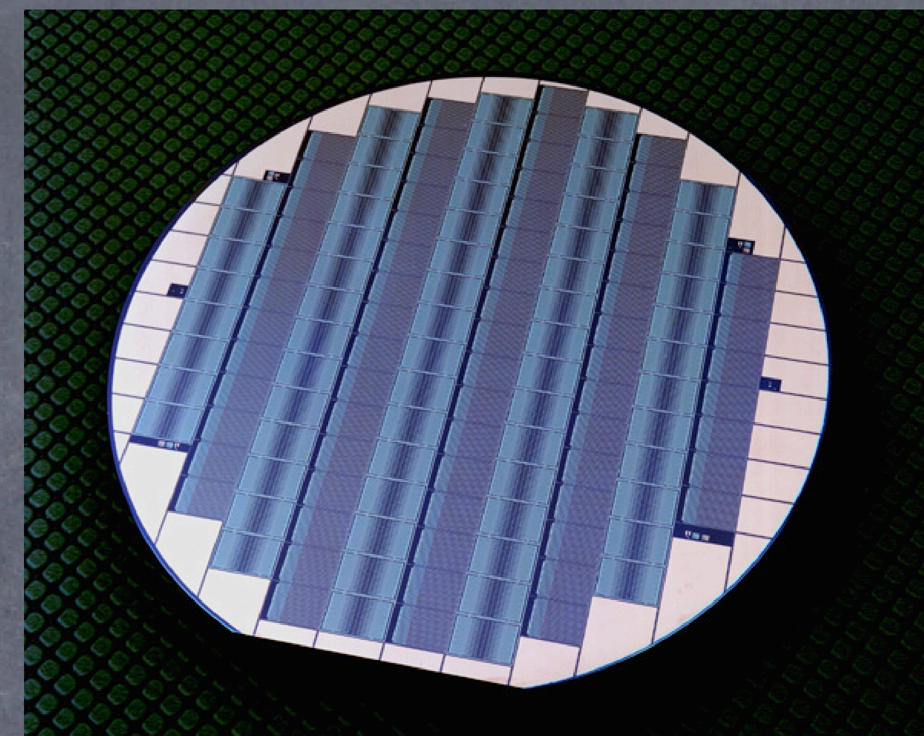
Now imagine many more particles and strips and planes and a magnetic field - solution is pixels!

BTeV Pixels

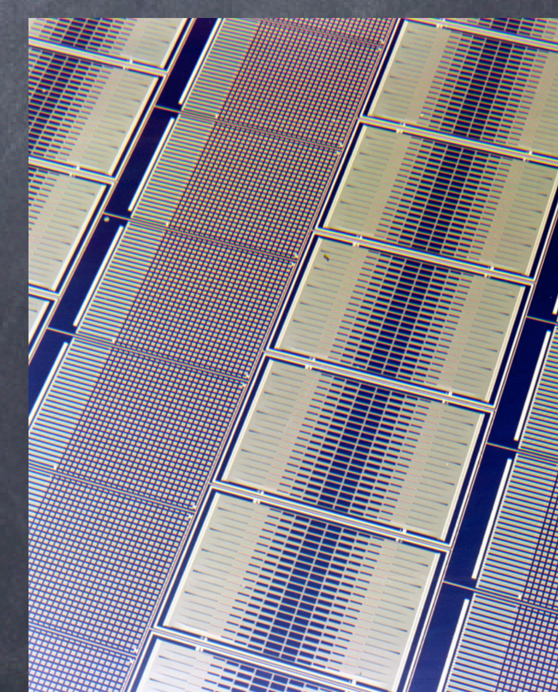
The BTeV Trigger made possible by a pixel detector



The BTeV pixel trigger has 30 million signal channels (compared to ten's of thousands in silicon strip detectors)

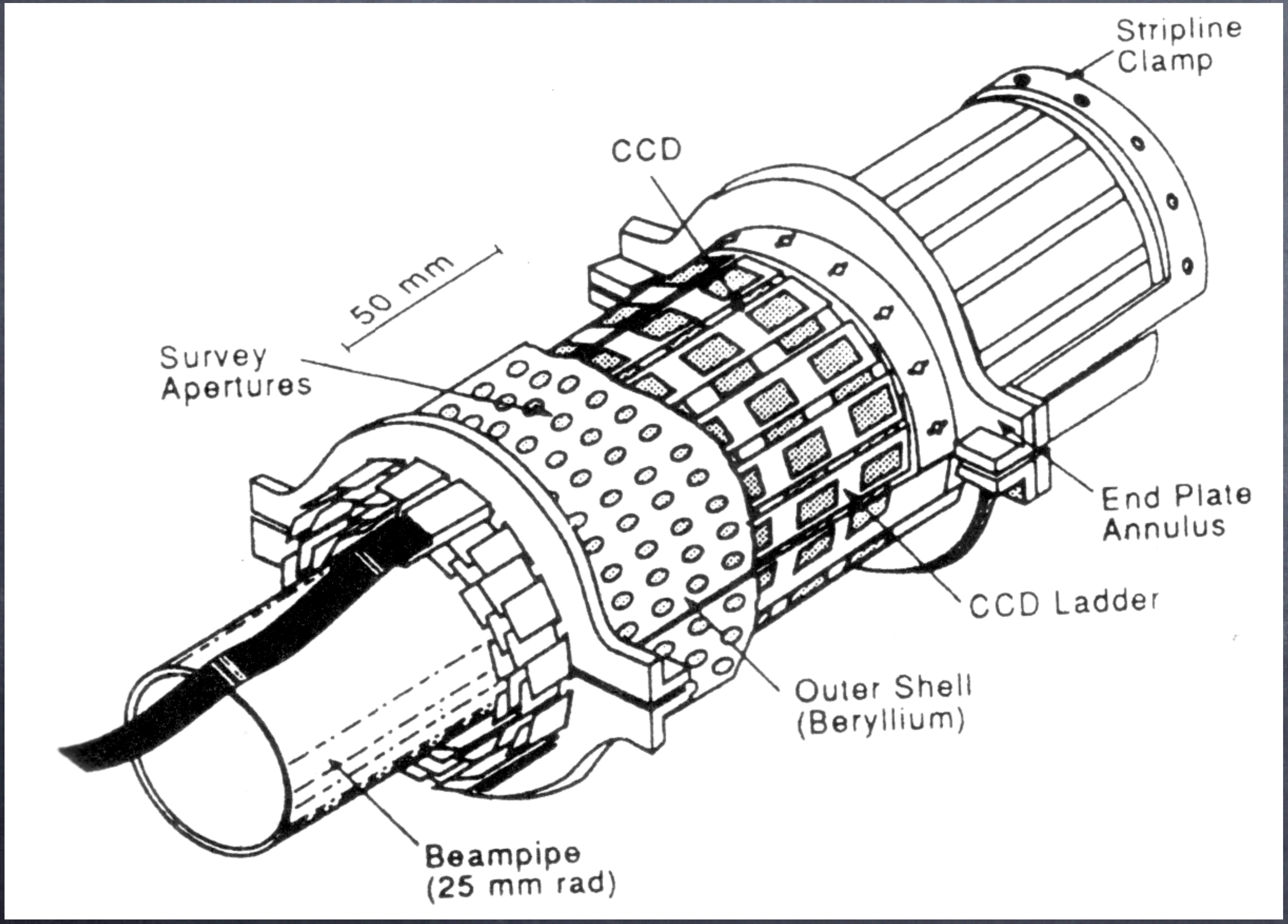


6" silicon wafer of test pixels for BTeV and ATLAS



CCD's at SLAC SLD

Progress in Steps

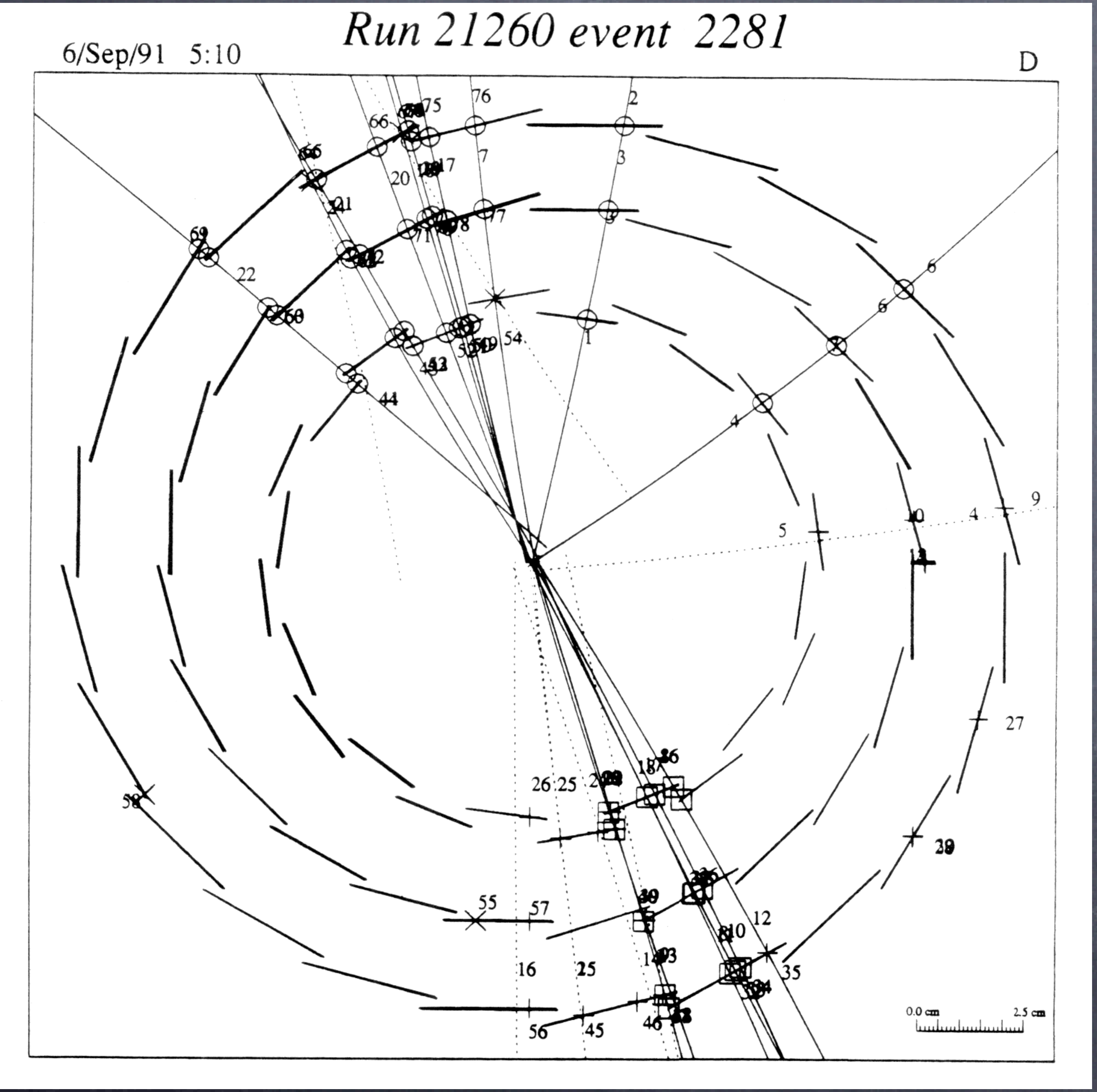


CCD's are like the ones in your digital camera and used at SLAC SLD e^+e^-

However it has a slow readout, (too slow by orders of magnitude for BTeV) Also the signal size is much smaller as the depletion layer is much narrower (not a p-n junction)

LEP Delphi Pixels

Progress in Steps



Delphi experiment had a true pixel detector with 30 million channels and it worked well. None tried in a hadron environment (LHC ATLAS and ALICE experiments will also use pixels)

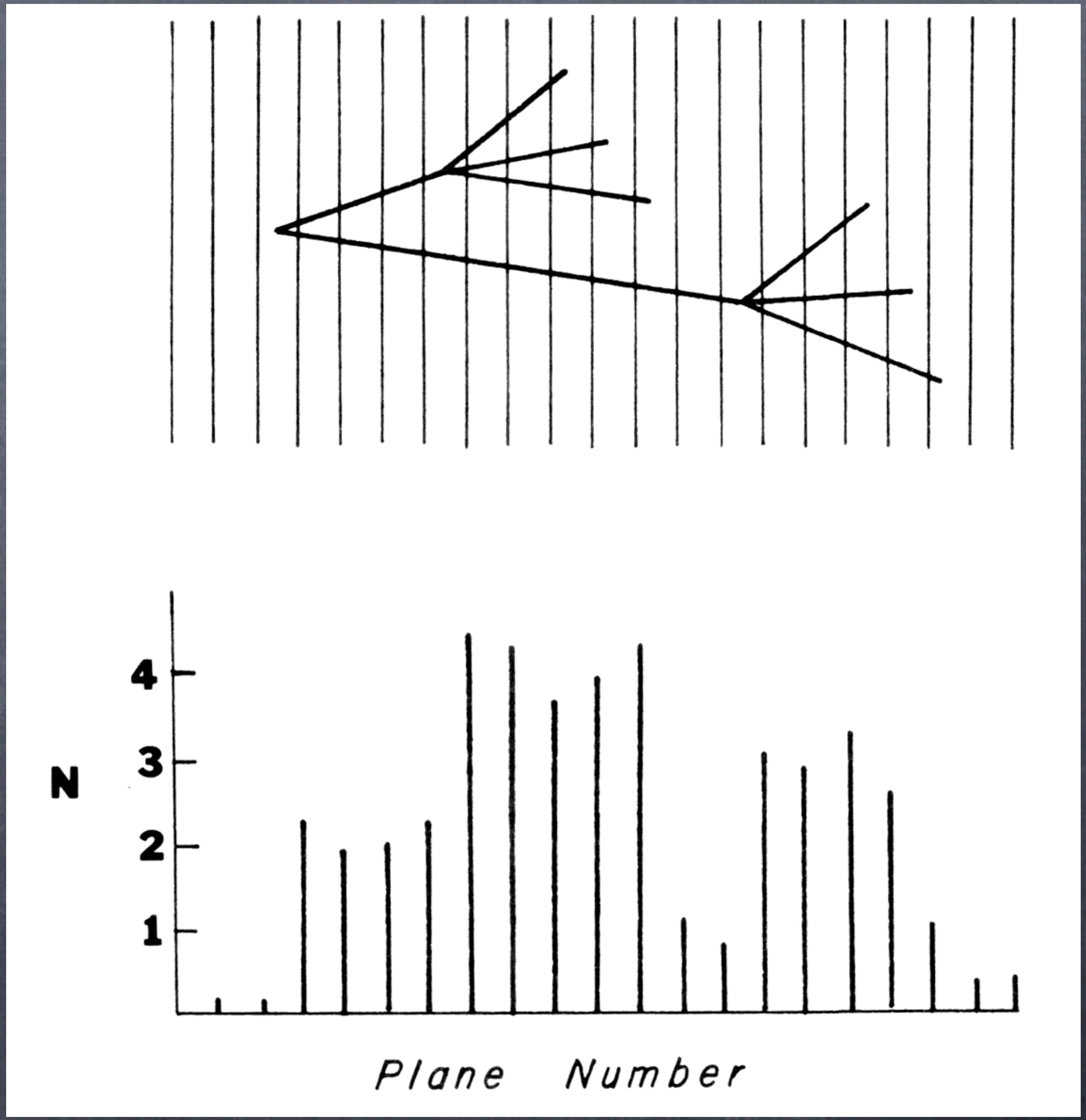
Pixels discussed for CDF and D0 Run II but "not needed" for high p_T physics and technology was not as advanced at the time

Other Attempts

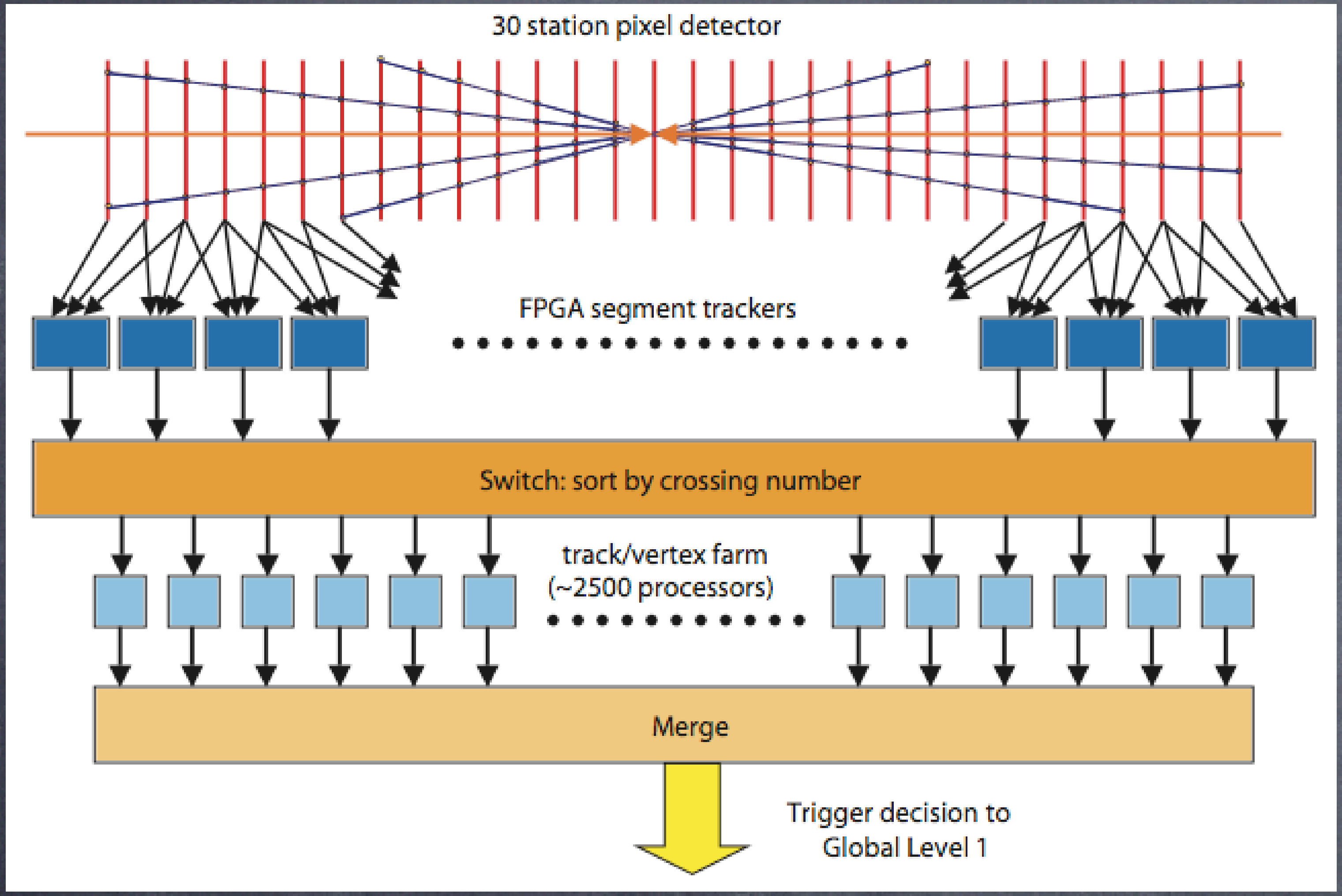
Many other attempts (without pixels)

Attempts made at experiments in labs over the world for a Level 1 trigger for b-quark (or c-quark) decays in a hadronic environment (basically none were very successful)

One example only:
Look for jumps in the multiplicities in the silicon strip detector planes



BTeV Trigger and DAQ



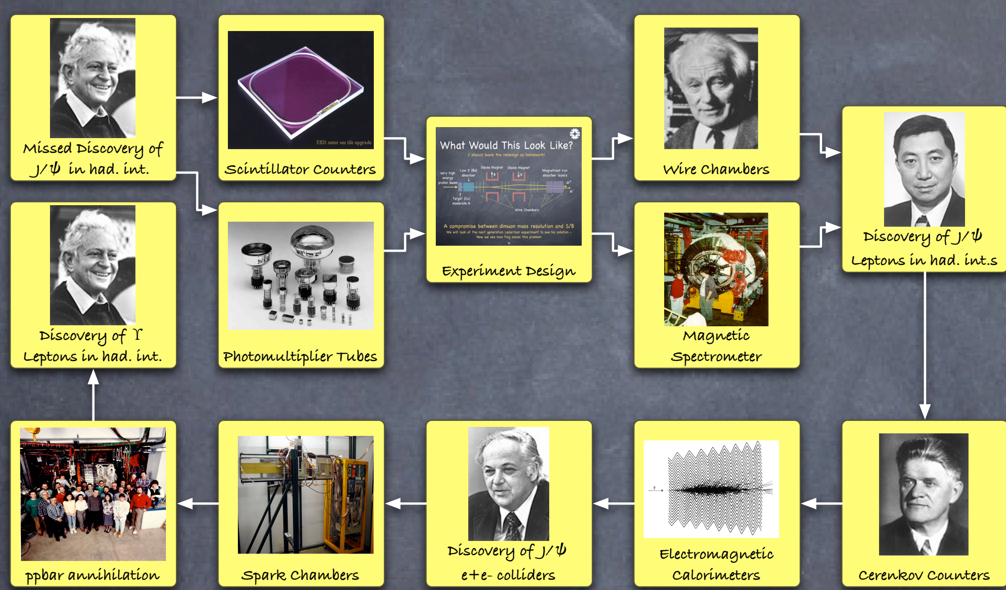
Even with pixels we cannot do a full reconstruction we need help to develop an algorithm that runs in 350 μs using 2500 DSP's (CPU's)

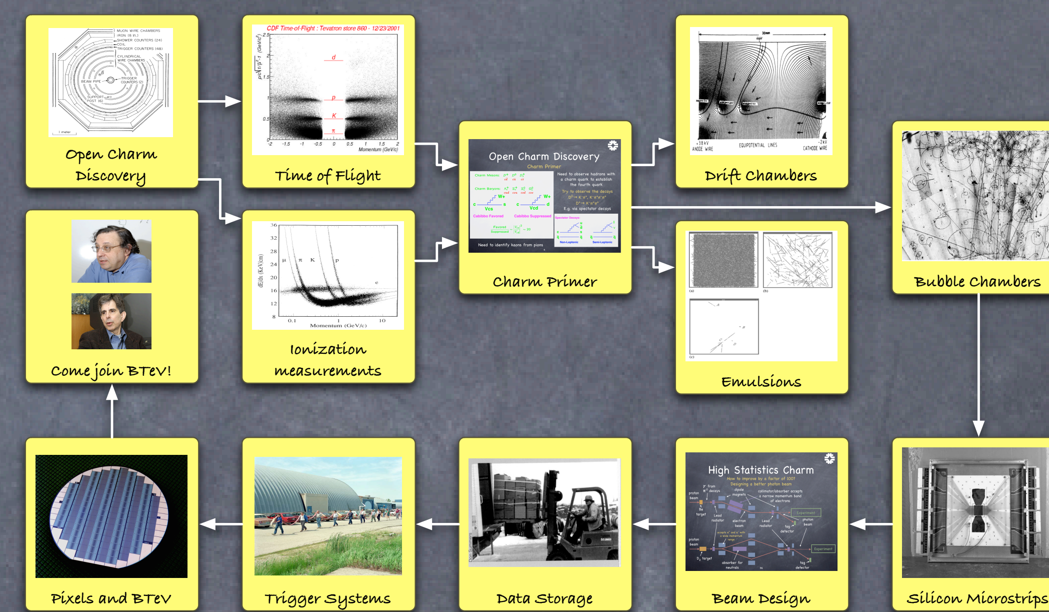
- A "smart limited search" (not as good resolution and lower efficiency, okay for Level 1
- Pixels in a magnet to reject soft (low p) tracks that scatter and fake a decay
- Still need two further levels of triggers (L2/3 on 1600 CPU's running Linux)

Also need a powerful DAQ (data aquisition system) that stores 4000 crossings/s (the rate of interesting b-quark crossings is at least 1000 crossings/s. Compare this to 100-150/s for CDF and D0 and 200/s for LHCb

Summary

Described some experimental detectors and methods in a hopefully more entertaining way in two main storylines:





I want to end with a shameless ad for BTeV in getting collaborators from south and central America (as well as elsewhere)!

Joel Butler Sheldon STone Co-spokespersons for BTeV

This is a rare opportunity to get into BTeV early and be involved in the design of interesting technologies and an innovative experiment with exciting physics prospects

Suggested Reading

Some books/articles on experimental physics and detectors

- R. Fernow, “Introduction to experimental particle physics, CUP (Cambridge University Press) 1986.
- K. Kleinknecht, “Detectors for particle radiation”, 2nd Ed., CUP 1998.
- Fabio Sauli, Ed., “Instrumentation in High Energy Physics”, World Scientific, 1992.
- F. Sauli, “Principles of operation of multiwire proportional drift chambers”, CERN 77-09, 3 May 1977, lectures given in the Academic Training program of CERN 1975-1976, Geneva, 1977

Suggested Reading

Some articles referenced in Lecture 1

- R.N. Cahn and G. Goldhaber, "The experimental foundations of particle physics", CUP 1989.
- J.H. Christenson et al., PRL 21 (1970) 1523
- S.C.C. Ting, Nobel Lecture, 11 Dec. 1976; J.J. Aubert et al., PRL 33 (1974) 1404; Nucl Phys. B89 (1975) 1.
- B. Richter, Nobel Lecture, 11 Dec. 1976; J.E. Augustin et al., PRL 33 (1974) 1406.
- C. Bacci et al., PRL 33 (1974) 1408.
- S. Bagnasco et al., Phys. Lett. B533 (2002) 237.
- D.C. Horn et al., PRL 36 (1976) 1236; S.W. Herb et al., PRL 39 (1977) 252.

Suggested Reading

Some articles referenced in Lecture 2

- G. Goldhaber et al., PRL 37 (1976) 255; I. Peruzzi et al., PRL 37 (1976) 569.
- K. Sliwa et al., PRD 32 (1985) 1053; J.C. Anjos et al., PRL 58 (1987) 311; J.R. Raab et al., PRD 37 (1988) 2391.