Innovative Experimental Particle Physics through Technological Advances –

Past, Present and Future

Harry W.K. Cheung – Fermilab

Talk Outline

- A fancy title but just an excuse to talk about some experimental topics:
  - Impact of advances in tracking detectors
  - Development of particle identification
  - Comparisons of beam types and colliders
  - Evolution of Trigger systems
  - Effect of High Performance Computing
- But in a more informal/personal manner:
  - Discovery and subsequent study of charm
  - Present and future of B physics
- Intended for the graduate student/postdoc level and (with respect) for theorists also

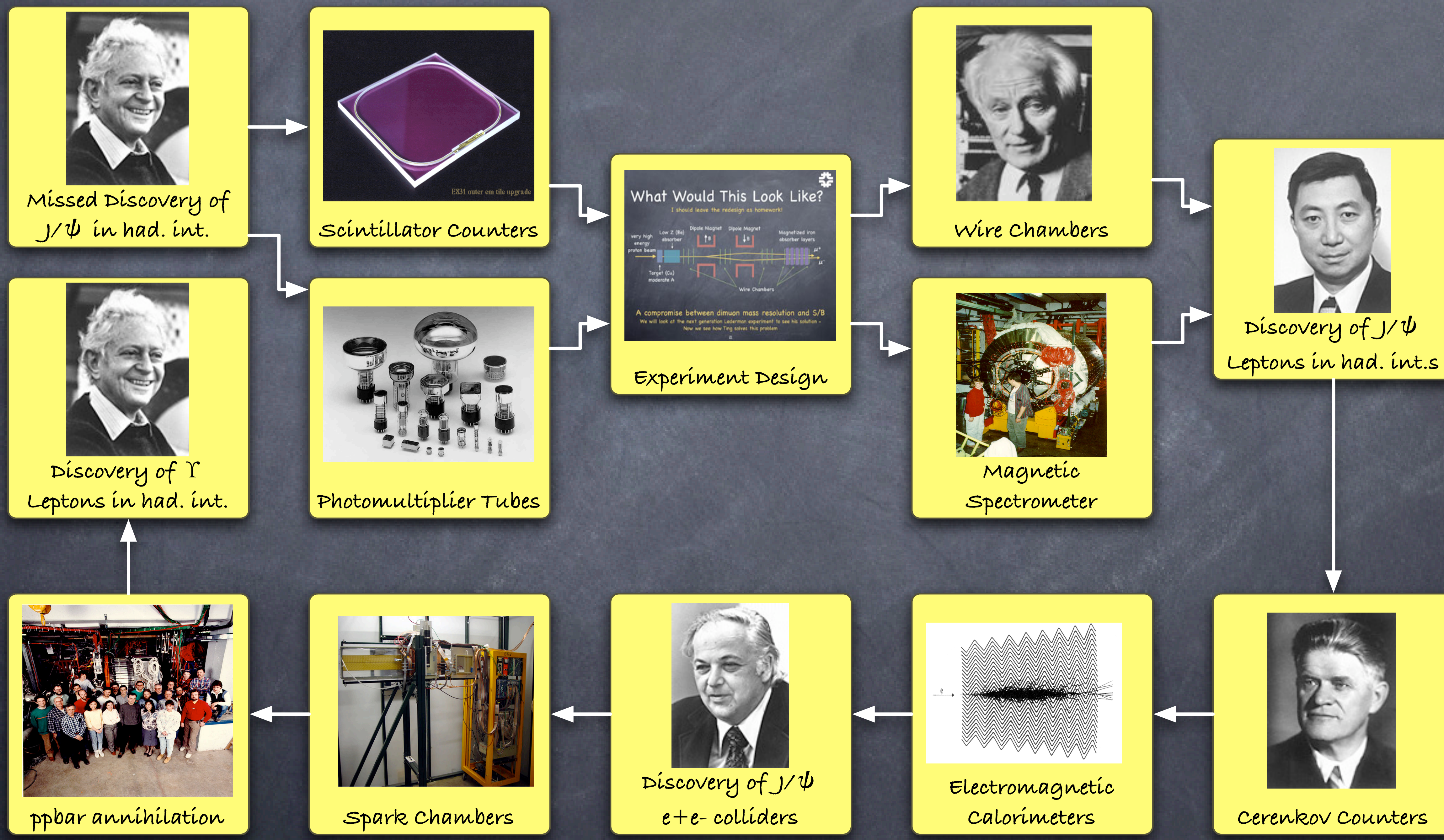
Progress in Steps

Steady improvements in Experimental techniques

- Higher energy available or/and production rate
- Improvements in momentum or/and position resolution
- Better particle identification methods
- Increase in coverage or energy resolution
- More powerful signal extraction from background
- Higher accuracy (statistics, theoretical uncertainties)

Discovery is often through a series of steps
though the discovery itself can be in a surprising direction!

Selected Topics



J/ψ Discovery

Hadron interactions through "Lepton eyes"

Outline and Experimental resolutions matter!

- Events are less complicated with leptons
- Look at high mass lepton pairs in pX interactions
- Missed J/ψ discovery in a $p+U \rightarrow \mu^+\mu^- X$ at Brookhaven National Laboratory (BNL) using the AGS (Alternating-gradient synchrotron) by Lederman's group in 1970
- Discovery of the J/ψ by Ting's group at BNL using $p+Be \rightarrow e^+e^- X$ with the AGS in 1974

Hadron Interactions

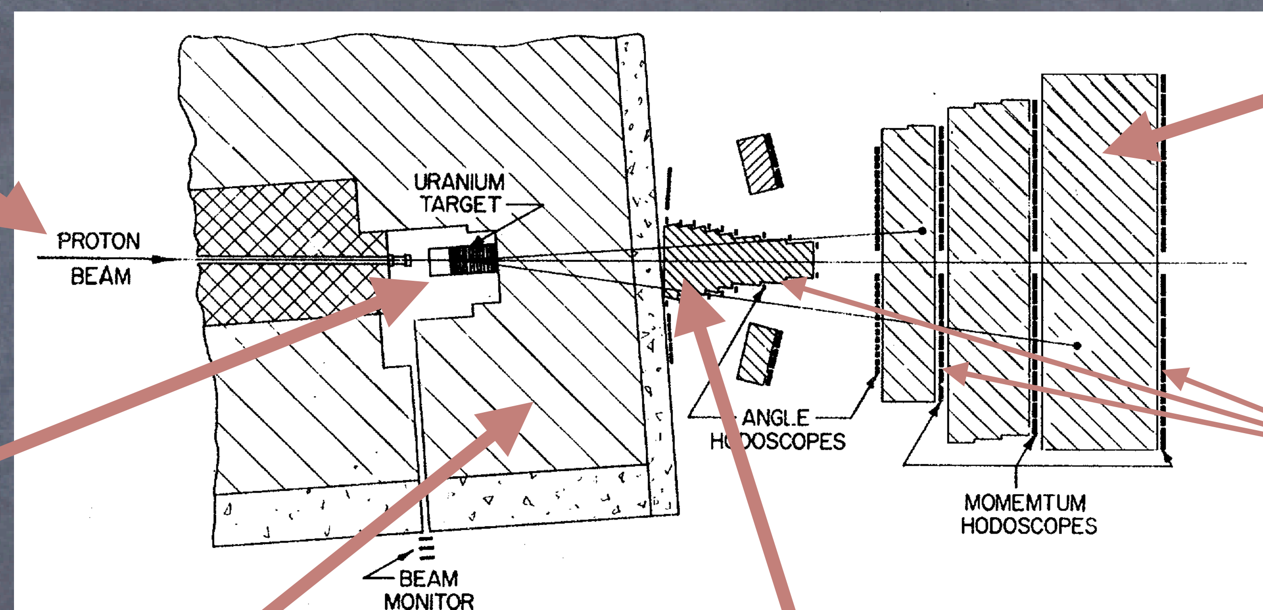
- Some of the interests at the time in looking at proton interactions include:
  - Electromagnetic structure of hadrons with lepton pair production
  - "Heavy photons", ρ, ω and ϕ mesons
    - Search for "heavy photons" in $p+p \to V^0 X$, $V^0 \to e^+e^-$ with V^0 produced by strong interactions (rate), the e^+e^- decay limits $J^P=1^-$, larger mass range in search
  - Neutral intermediate vector boson Z^0

Leon Lederman
1970 Experiment

A Lack of Resolution

Muon pairs from proton on a Uranium Target

High intensity 22-30 GeV proton beam



Absorbers to range out muons

Uranium Target (absorbs π and K before they decay)

Scintillator hodoscopes to measure range and direction of muons

Absorber for non-muonic backgrounds + low E muons

Absorber for background muons

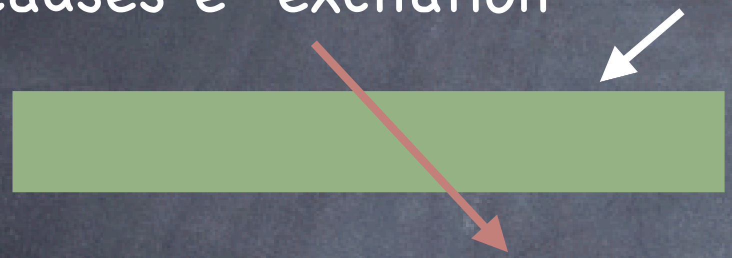
- ★ Designed to get clean directly produced dimuons from target
- ★ Dimuon mass resolution limited by multiple scattering (MCS)
- ★ Dimuon mass resolution at 3 GeV ≈ 13% (≈ 400 MeV/c^2)

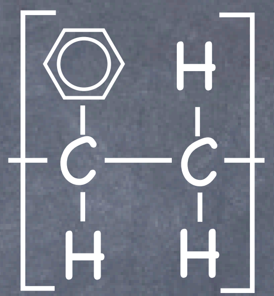
Scintillators

The scintillation effect for organic scintillators

charged particle
causes e^- excitation

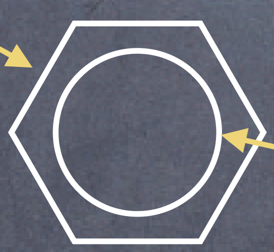
polystyrene
(plastic)





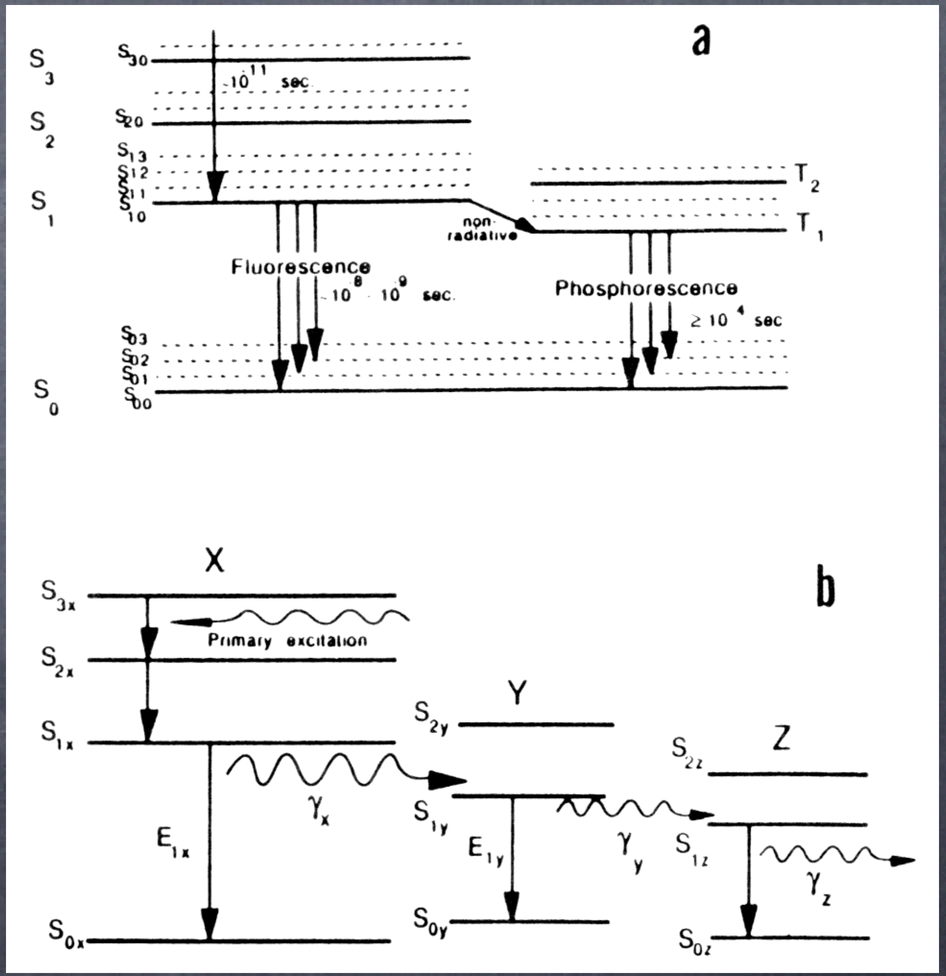
σ-electrons

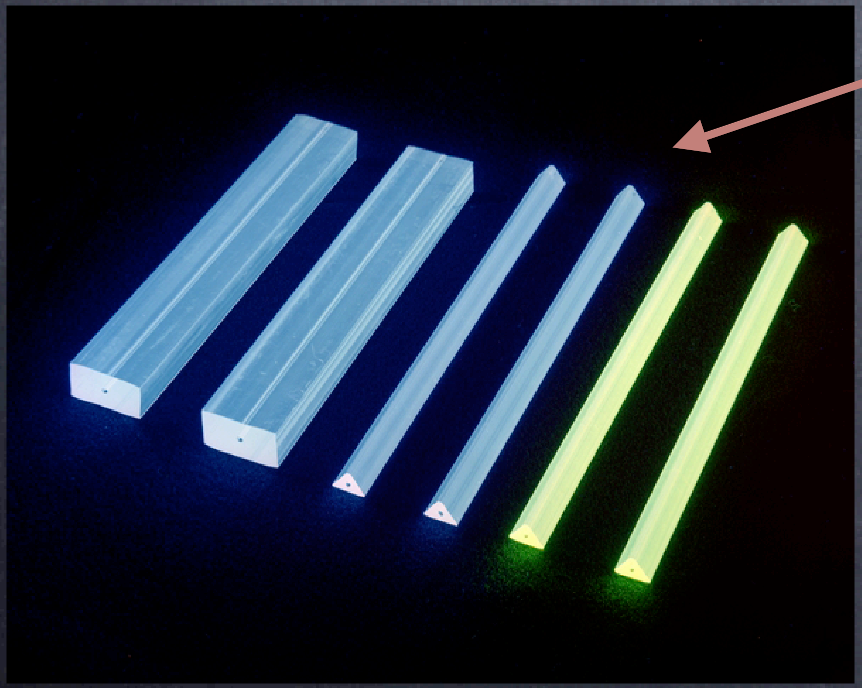
Benzene
molecule



π-electrons

Raises π-electrons into excited energy levels, with emission of UV photons in 1-10 ns



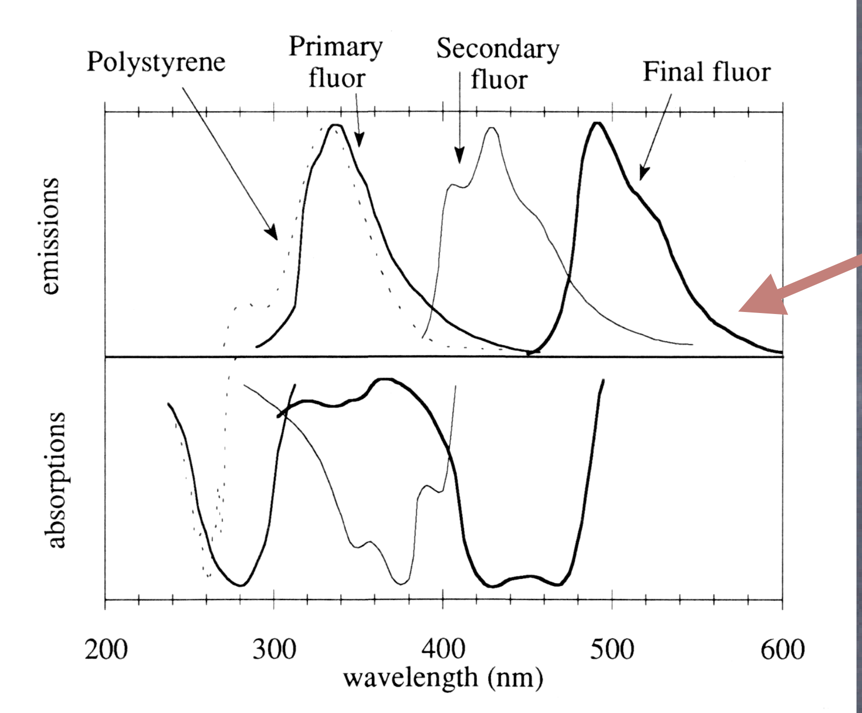


Scintillators produced for the MINOS neutrino experiment at Fermilab

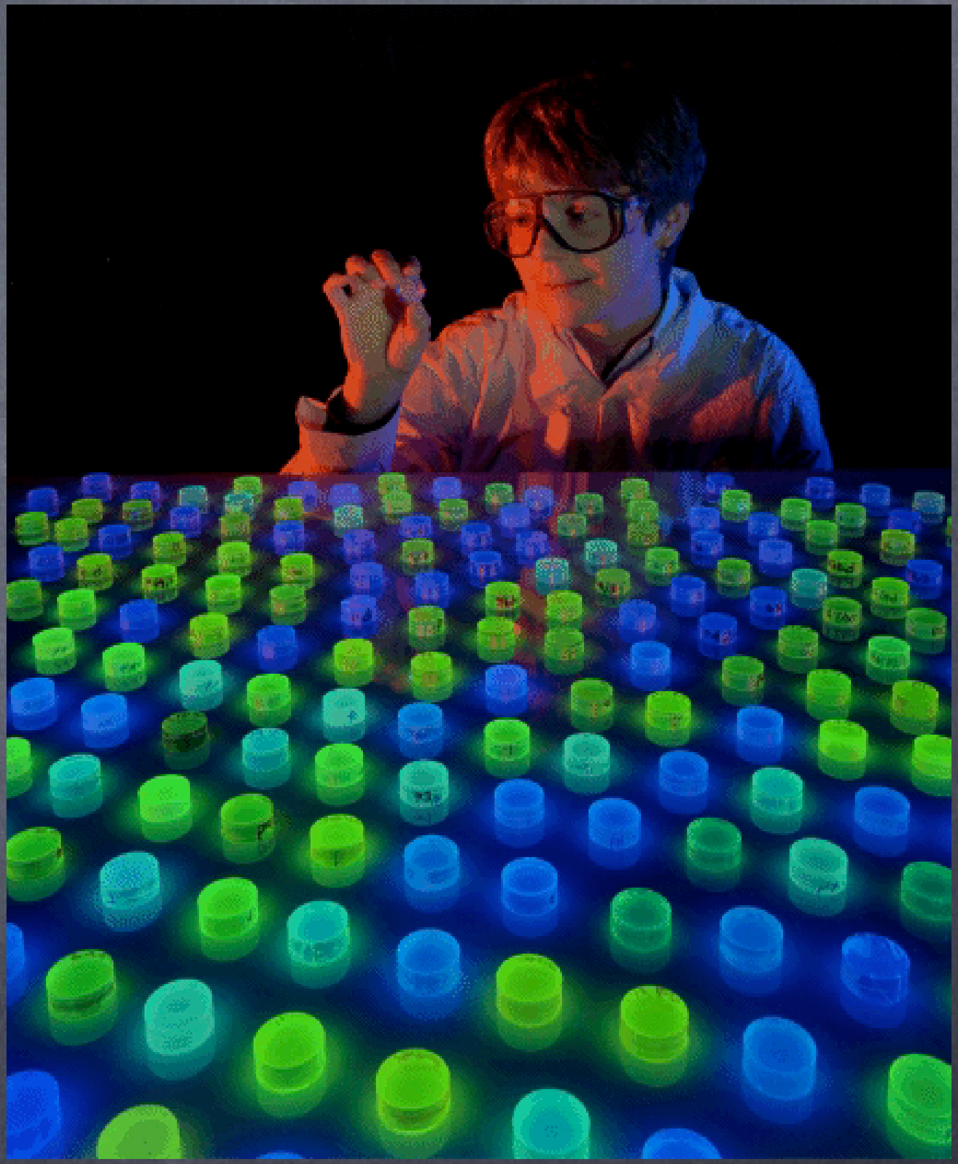
Add additional small amount (0.1-1%) of fluors to change the emission wavelength

Scintillators

The scintillation effect for organic scintillators

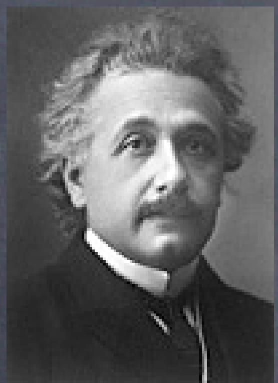


Add additional small amount (0.1-1%) of fluors to change the emission wavelength to match the photon detector



The charged particle can cause excitation and/or ionization of the π-electrons and/or σ-electrons

- Excitation of σ-electrons relaxes non-radiatively
- Ionization of σ-electrons causes radiation damage (coloration and reduction in light output)
- Excitation of π-electrons to triplet states causes a a long tail in the light output

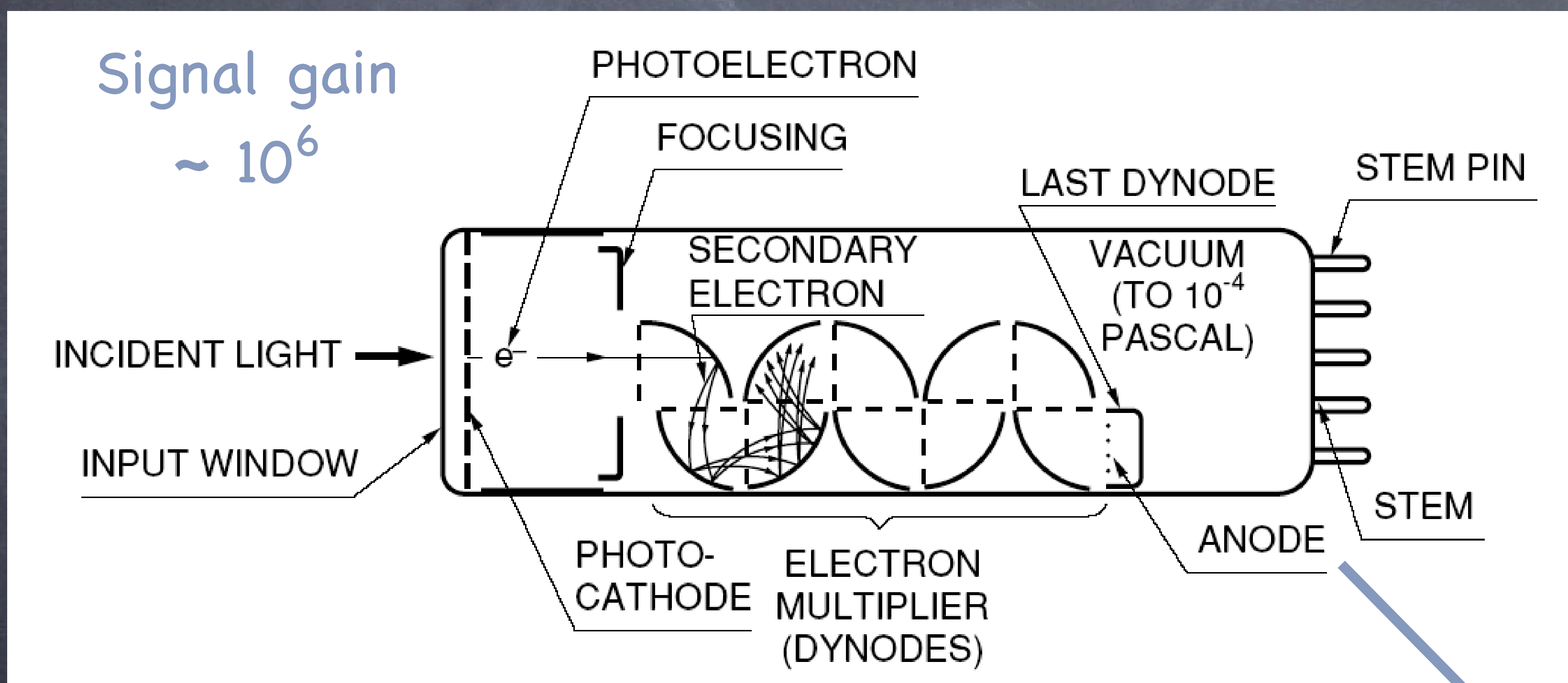


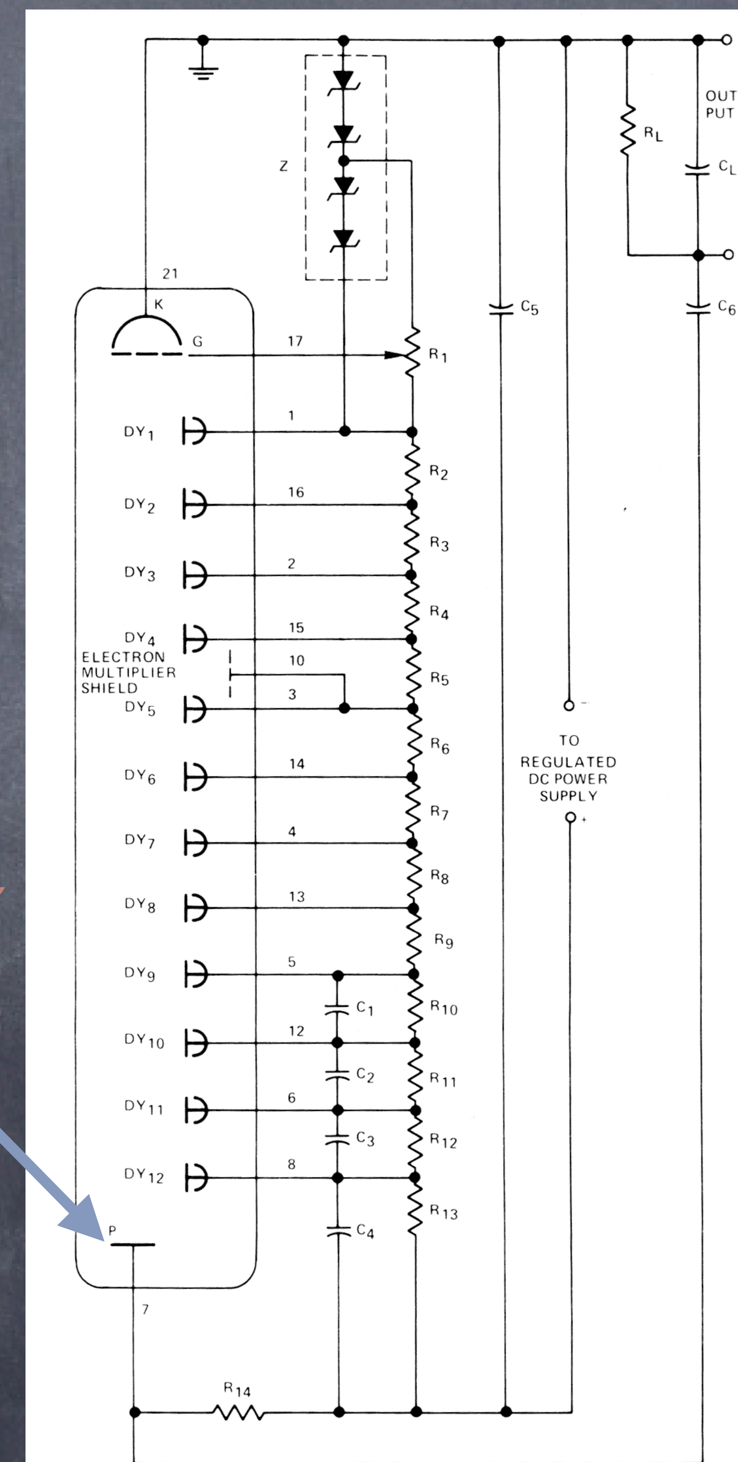
Photon Detectors

Photomultiplier tubes (PMT's)

Uses the photoelectric effect (Einstein's Nobel Prize 1921)

Signal gain ~ 10^6





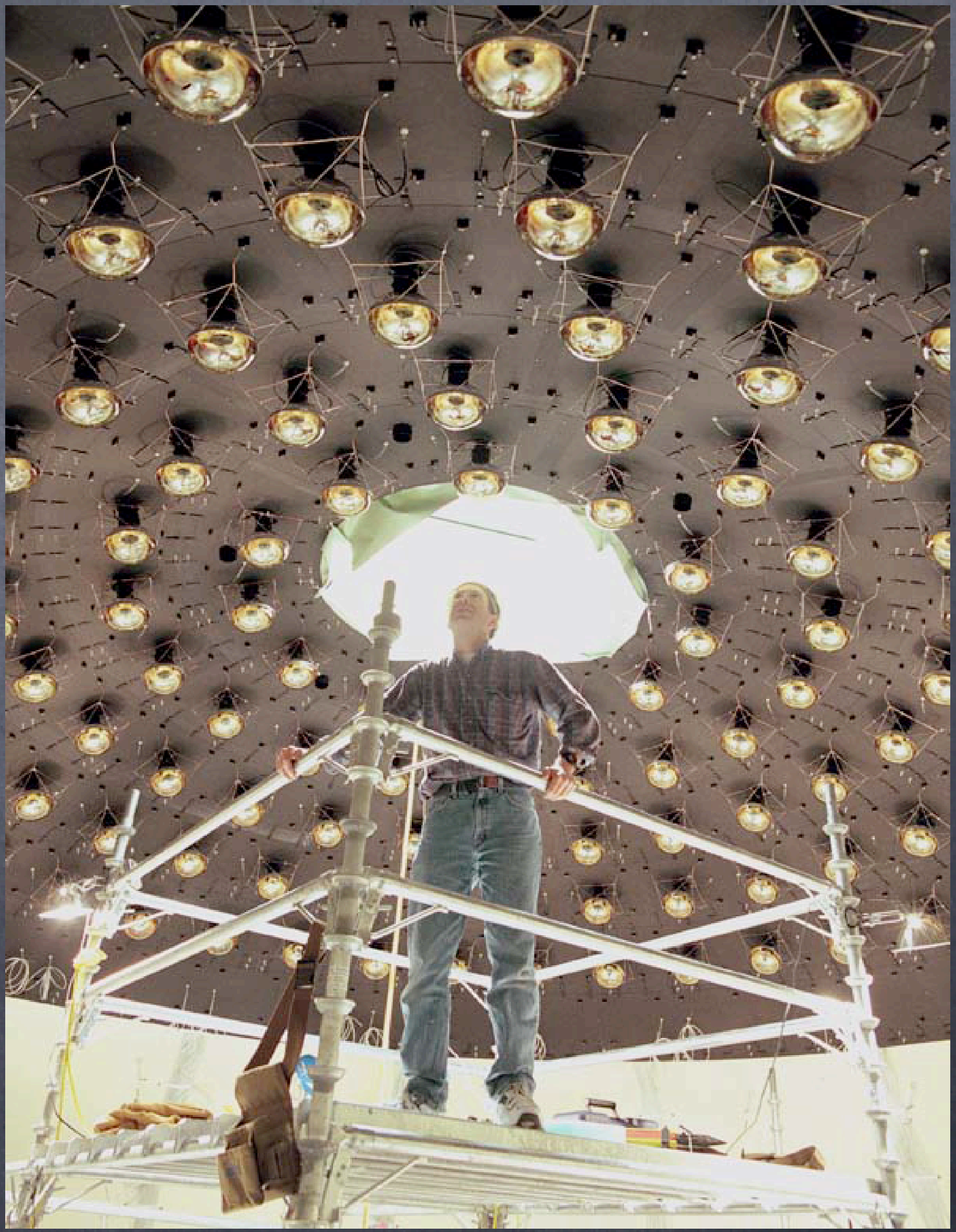
Voltage divider networks - many designs (the PMT base)

Typical PMT+base assembly

Photon Detectors

Photomultiplier tubes (PMT's)

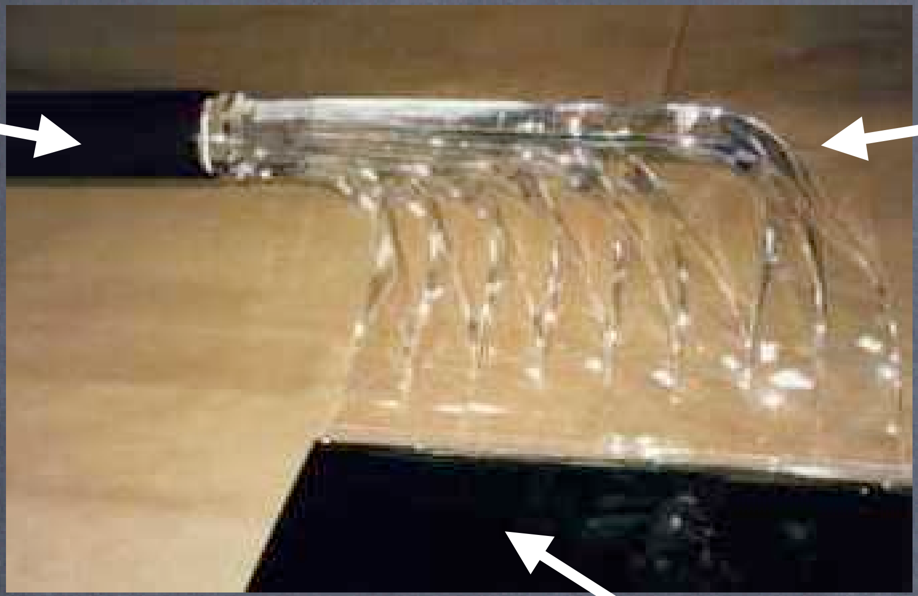
Many types and designs of PMT's



Large PMT's used in the mini-BOONE neutrino oscillation experiment at Fermilab viewing a large spherical tank of liquid scintillator

Scintillator Hodoscopes

Charged particle Counters

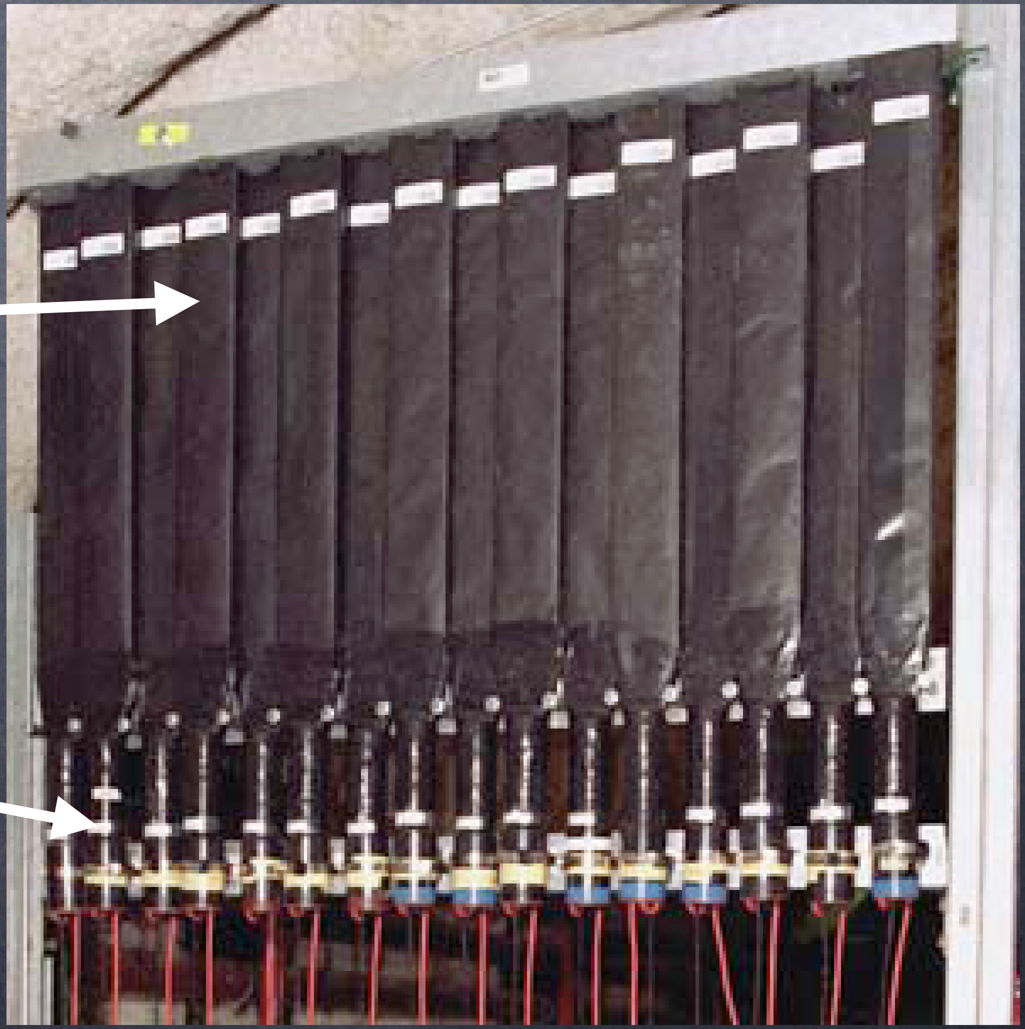


PMT

Lucite light guides to transmit light to PMT

Counters arranged in overlapping vertical (and horizontal) strips

Scintillator and light guide in light-tight wrapping



PMT+base

Scintillator and PMT's

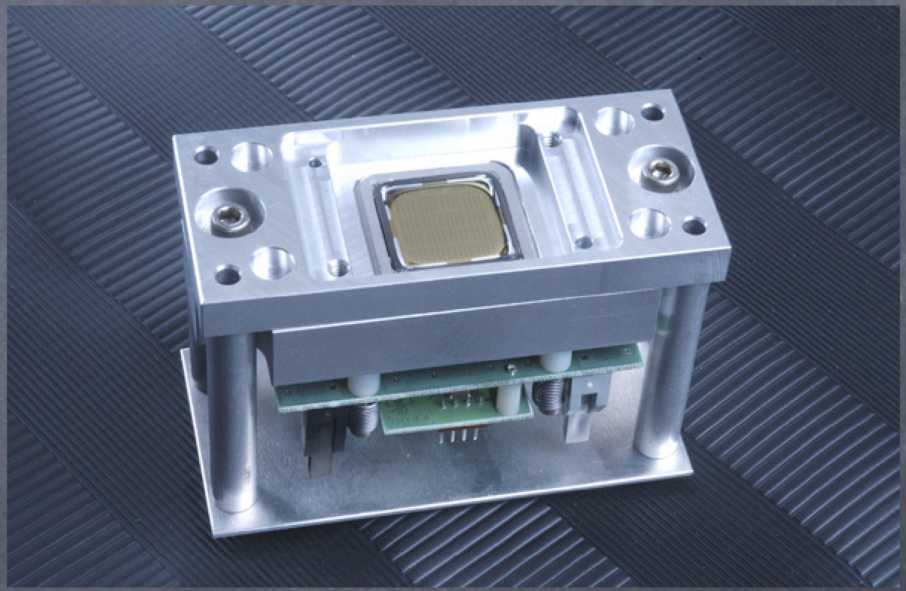
Just a taste of each technology

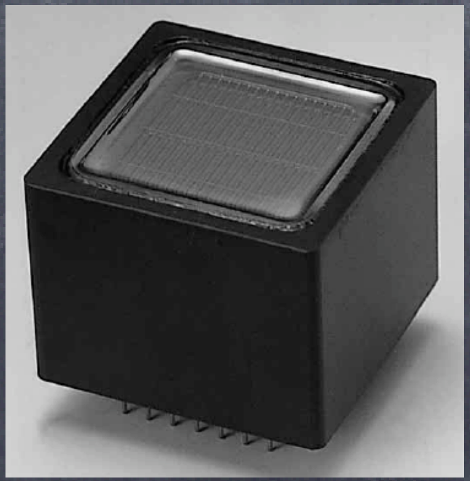
Each detector (system) is very complicated and some physicists devote their career to designing, building, improving just one type of detector

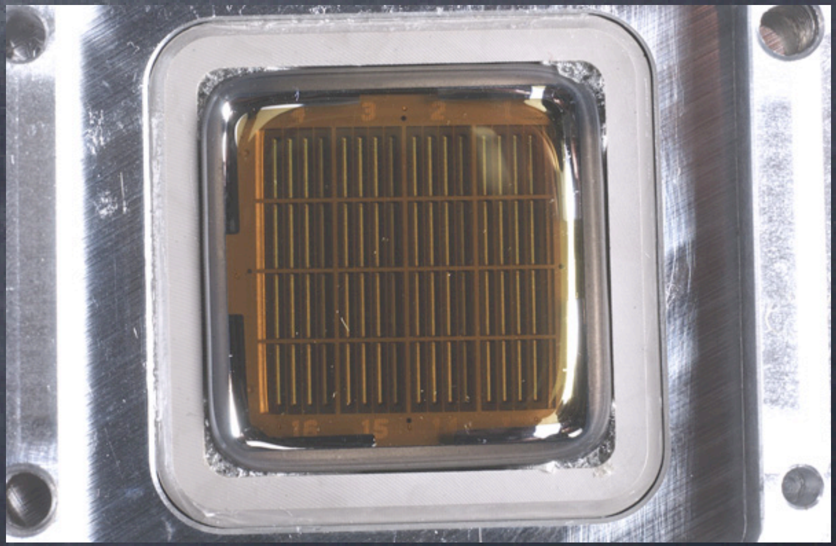
E.g. PMT's (+ Bases)

- Many designs: e.g. Head-on, side-on
- Extra large PMT's
- Photocathode material (efficiency)
- Length of life and stability vs time
- Designs to optimize/compromise:
  Gas gain, time jitter, magnetic field sensitivity, number of stages, cost
- PMT window material
  quartz is transparent to UV
  MgF2 coating to improve UV efficiency
- Multianode PMT's →
- Base design:
  linearity and dynamic range, stability, anode damage

MAPMT for MINOS neutrino experiment







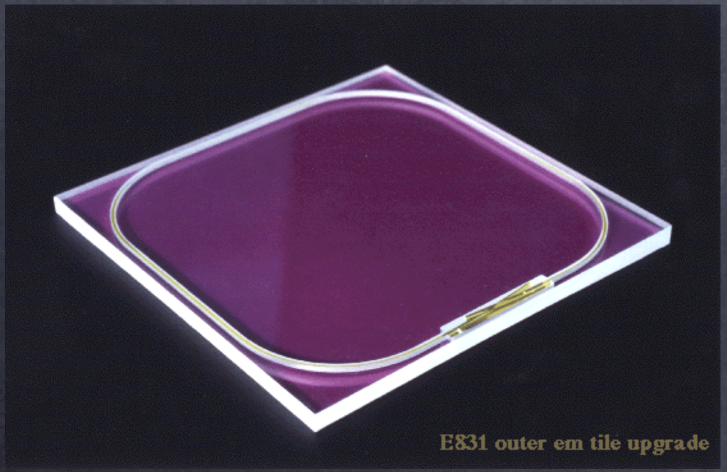
Scintillator and PMT's

Just a taste of each technology

Each detector (system) is very complicated and some physicists devote their career to designing, building, improving just one type of detector

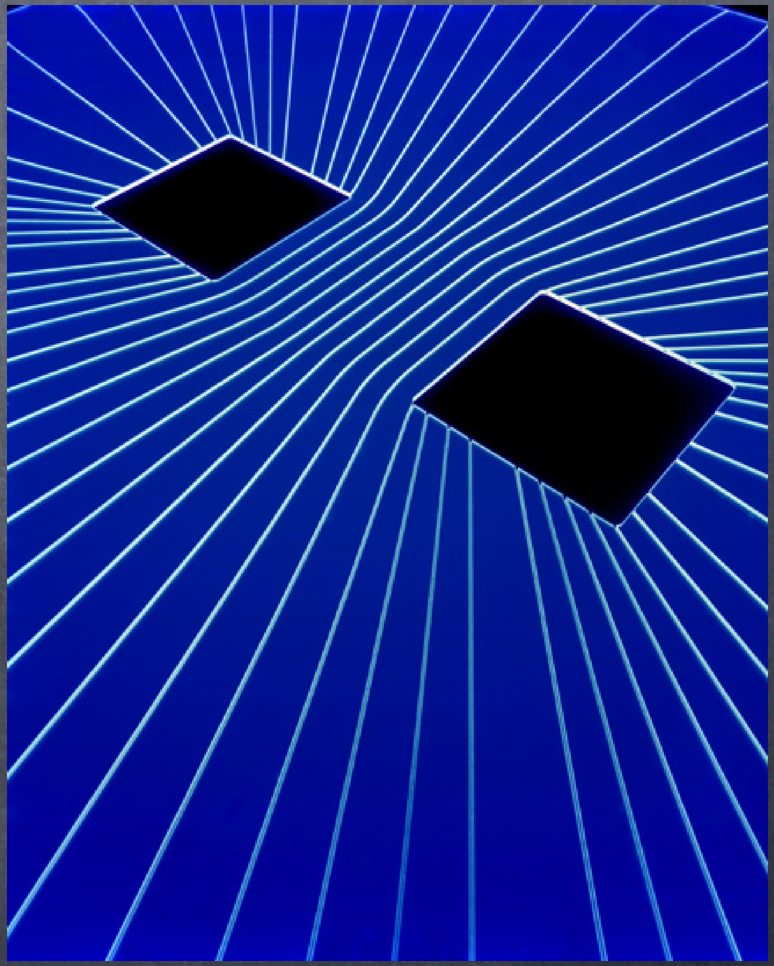
E.g. Scintillators

- Plastic, liquid, crystals
- Light yield, % + type of fluors
- Radiation damage
- Wavelength-shifting readout
- Scintillating Fiber trackers + light guides
  low T detectors for low light yields
  attenuation length of signals
- Dependence on magnetic field
- New geometries with fiber readout



Can create "any" needed shapes not just long strips.

E.g. a hodoscope with holes for 2 beams in the KTeV' ε'/ε kaon experiment

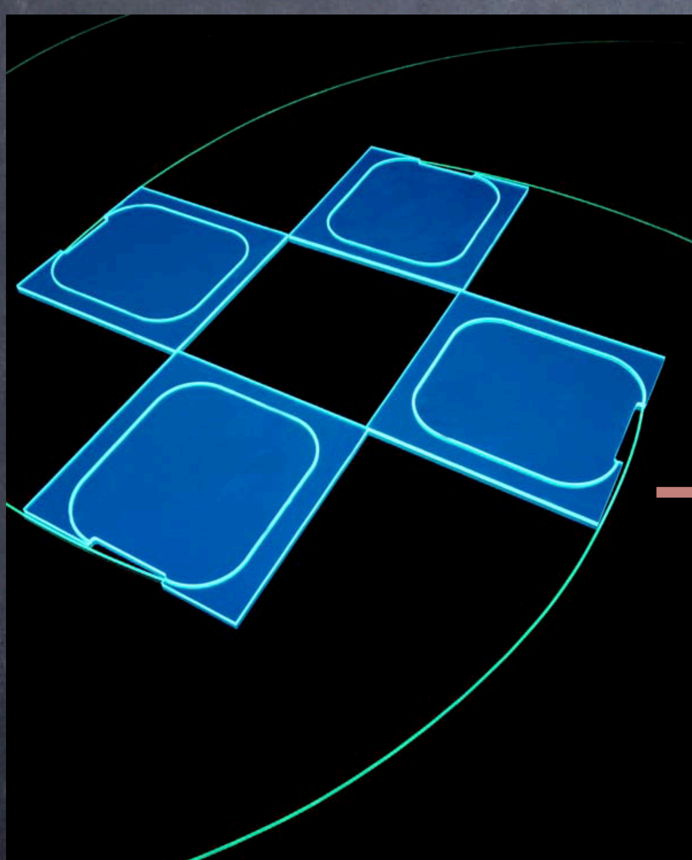


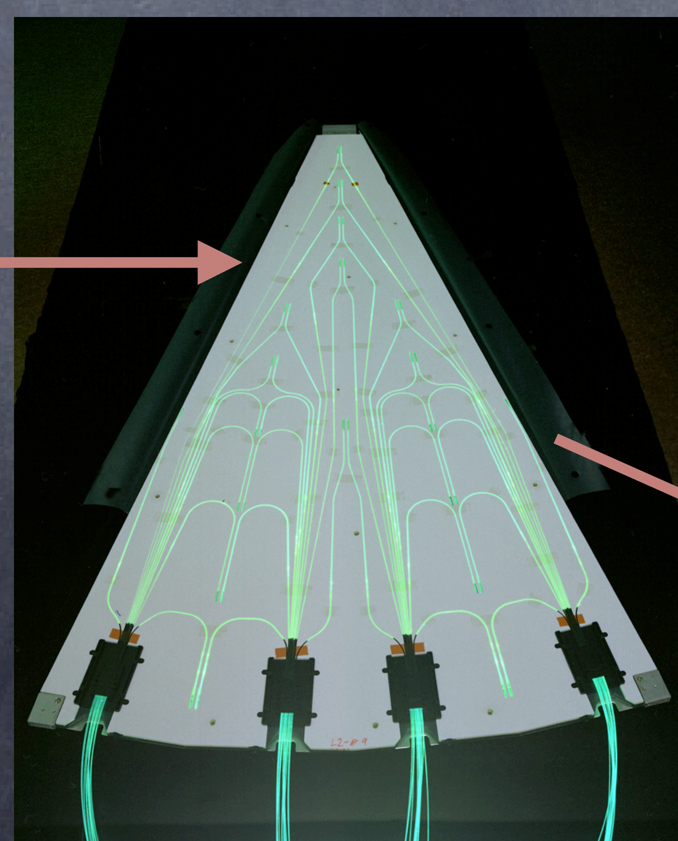
Scintillator and PMT's

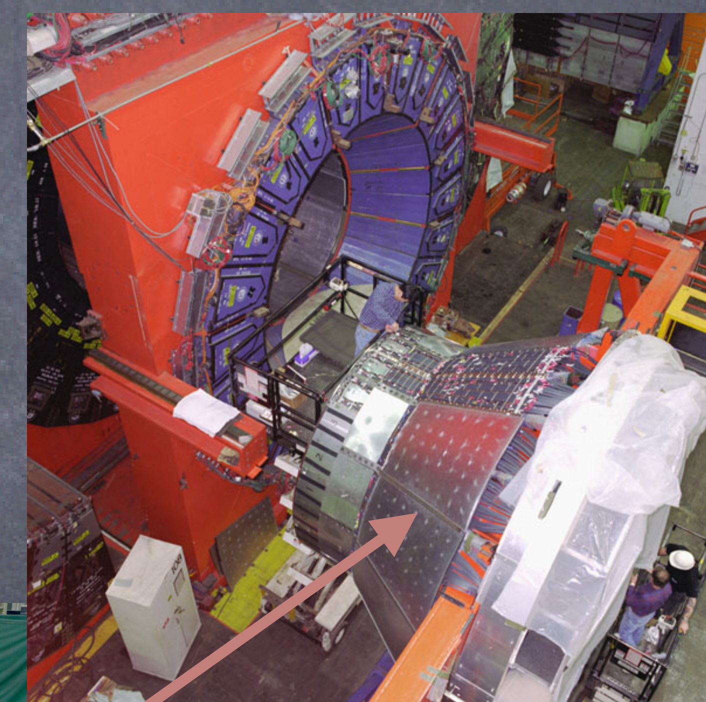
Just a taste of each technology

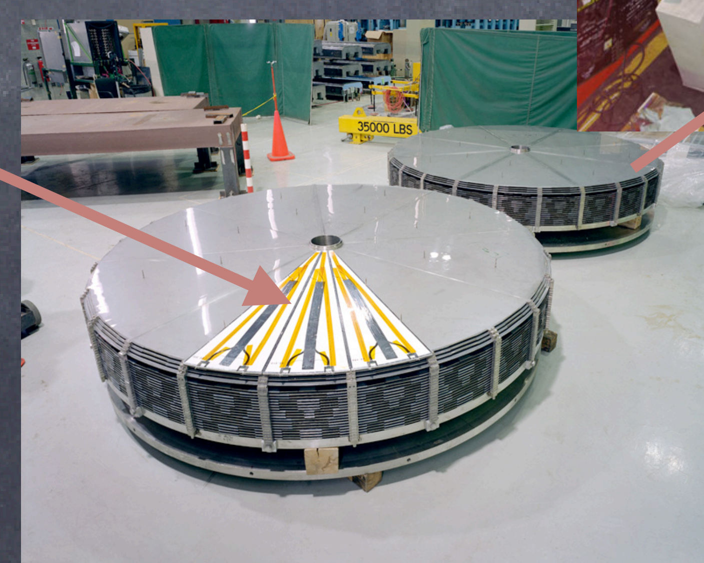
Each detector (system) is very complicated and some physicists devote their career to designing, building, improving just one type of detector

Can create "any" shapes not just long strips.
E.g. CDF endplug calorimeter
(I'll talk about calorimeters later)







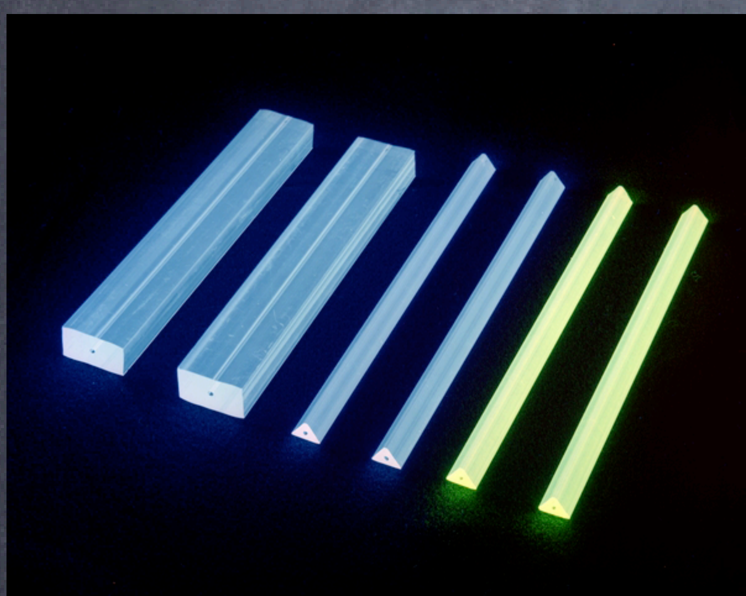


Scintillator and PMT's

Just a taste of each technology

Each detector (system) is very complicated and some physicists devote their career to designing, building, improving just one type of detector

Another advance has been to make scintillators cheaper e.g. extruded scintillators used in the MINOS neutrino experiment which requires a lot of scintillators



These have fiber readout with multianode-PMT's as PMT's are expensive also

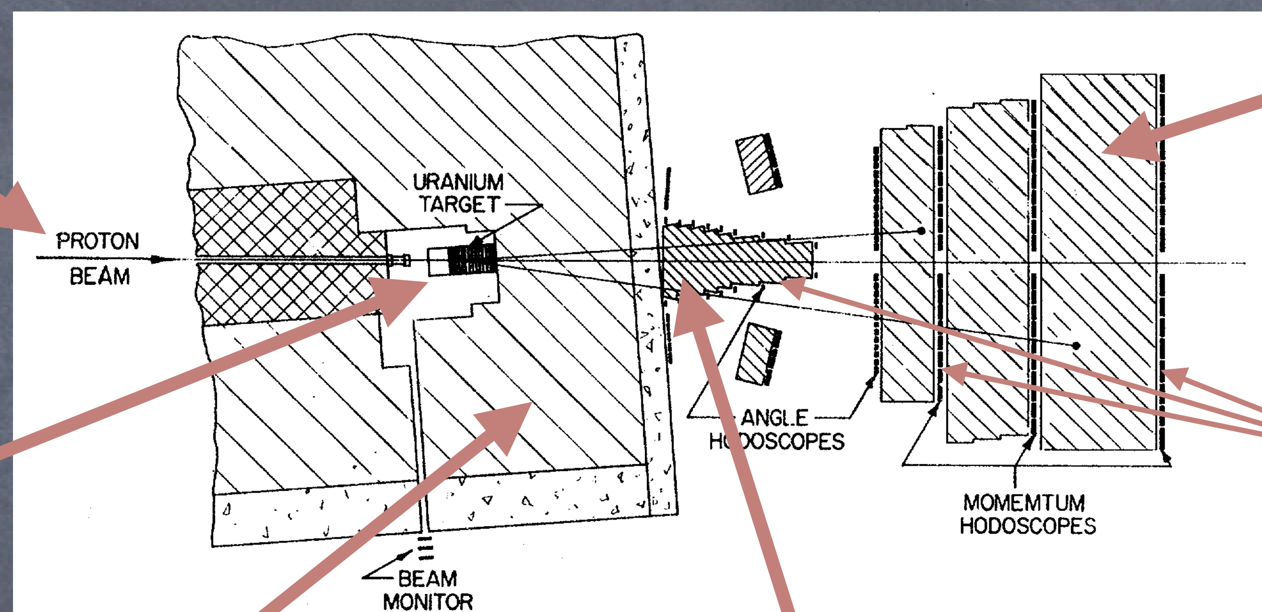
Leon Lederman
1970 Experiment

A Lack of Resolution

Muon pairs from proton on a Uranium Target

High intensity 22-30 GeV proton beam

Absorbers to range out muons



Uranium Target (absorbs π and K before they decay)

Scintillator hodoscopes to measure range and direction of muons

Absorber for non-muonic backgrounds + low E muons

Absorber for background muons

- ★ Designed to get clean directly produced dimuons from target
- ★ Dimuon mass resolution limited by multiple scattering (MCS)
- ★ Dimuon mass resolution at 3 GeV ≈ 13% (≈ 400 MeV/c^2)

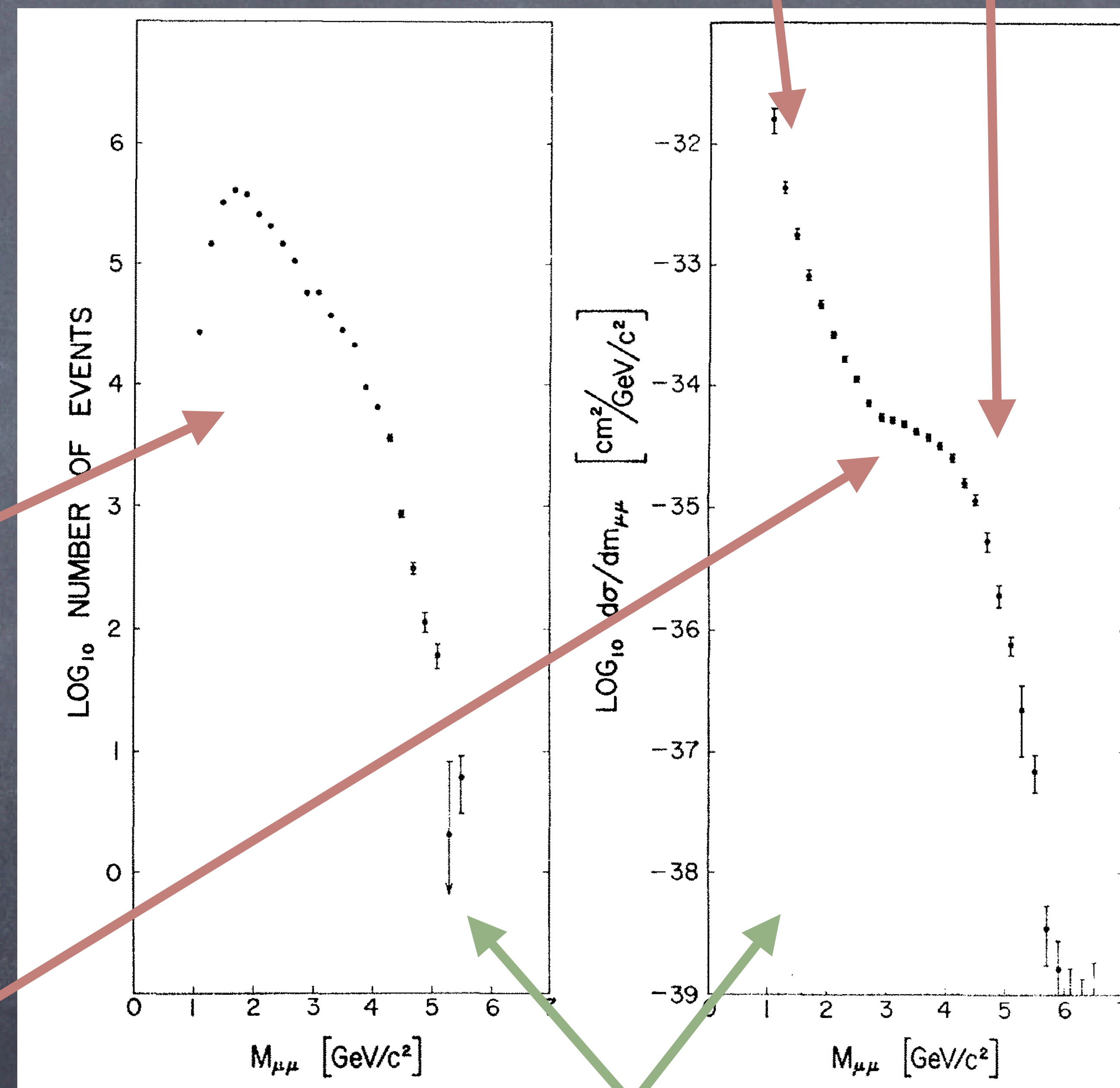
Not so Simple?

Signal-to-background and efficiencies

- Signal-to-background
  - ★ Muon singles rate ≈ 10^6/arm
  - ★ Double coincidence rate ≈ 1000
  - ★ Real dimuon signal ≈ 80, S/B ≈ 4% (small)
  - ★ Large subtraction is needed
  - ★ Uncertainties in
- Acceptances + Efficiencies
  - ★ Low at smaller dimuon masses
  - ★ Need to large corrections
- Poor dimuon mass resolution
  - ★ ±15% ($2GeV/c^2$), ±8% ($5GeV/c^2$) (≈400 MeV/c^2 at $3GeV/c^2$)

S/B=2%

S/B=50%



No fits?

Not so Simple?

Large Uncertainties in the measurement

- Tests for possible distortions from bkgd subtraction include
  - ★ Extra 5ns delay in coincidence circuit (zero consistent)
  - ★ Consistent results with different proton intensities
  - ★ Change U target "effective density" by factor of 3
- Uncertainties in Monte Carlo Acceptance + Efficiency
  - ★ Empirical production model of dimuon pairs (kinematics + angles)
  - ★ Compare MC model of single muon production (π + K decays)
- "No forcing evidence of resonant structure" - gave limits for a narrow state using a MC. (They talk about steep falloff)
  - ★ No fits or background functions (distributions) shown

How would you Improve the Experiment?

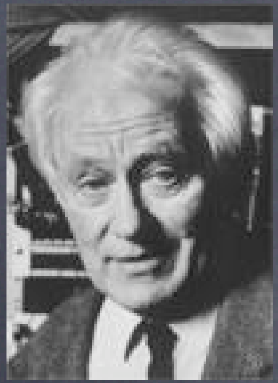
- Improve the momentum resolution
  - Less material to give less scattering
  - Momentum determination using a magnet
  - Finer position resolution detectors than scintillators
- Improve the signal-to-noise
  - Separate leptons better from π, K and protons
  - Enrich real dileptons vs single leptons
- Improve the efficiency vs dilepton mass
  - Achieve a flatter efficiency vs dilepton mass
    - A smooth efficiency vs dilepton mass is probably fine

What Would This Look Like?

I should leave the redesign as homework!

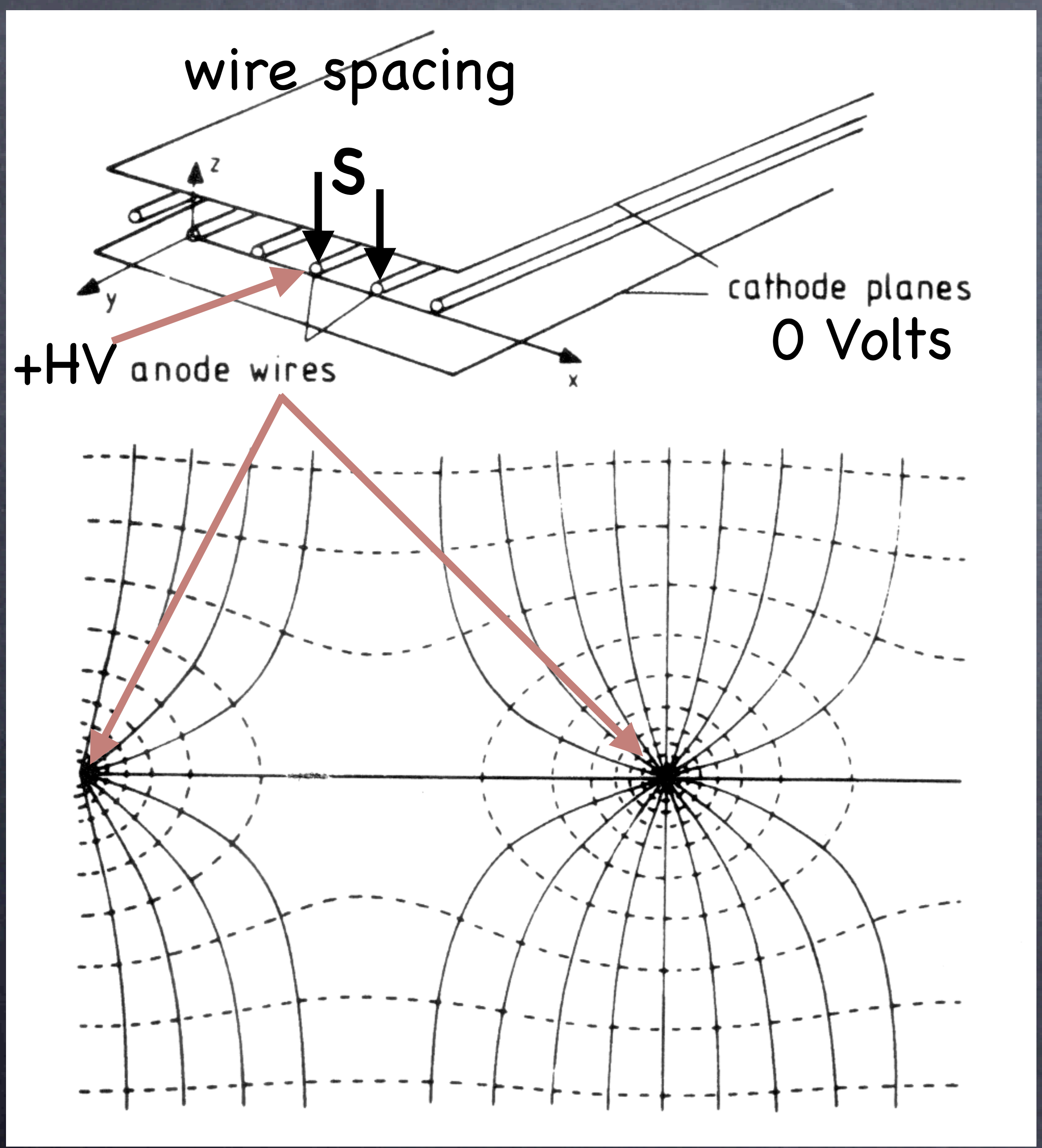
- Target material and thickness:
  - Want high dimuon signal rate ~ A_{Target}
  - Less scattering of (signal) muons
    - Multiple scattering $\vartheta_{MCS} \sim (Z_{Target}/p_{\mu}) \times \sqrt{L_{Target}} \sim (1/p_{\mu}) \times L_T/L_R)$
    - Want high energy beam ($\sqrt{s}$ = 7.7 GeV for p_{beam}=30 GeV)
  - Absorption of produced pions and kaons before they decay to muons, absorption probability ~ $A_T^{0.7}$
- Momentum determination:
  - Use a magnetic spectrometer
  - Low mass wire chambers before hadron absorber

Wire Chambers



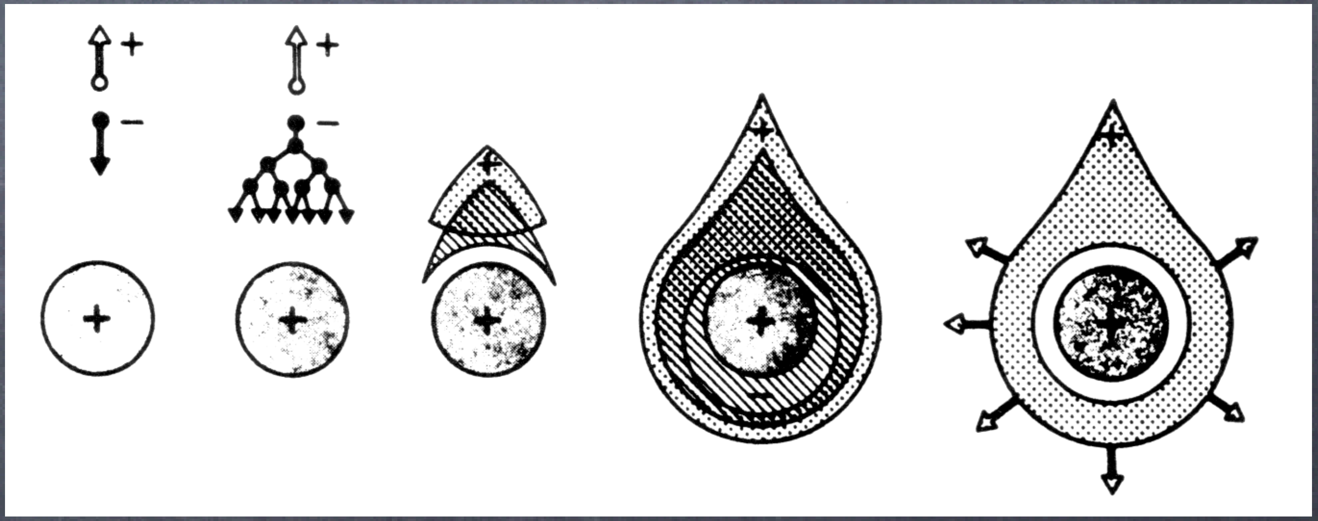
Low mass charged particle position detector

Multiwire proportional Chamber (MWPC)
Charpak's Nobel Prize (1992)



Charged particle ionizes (Argon) gas, electrons drifts in E-field and creates an avalanche near wire. Signal from positive ions and reflected signal

Resolution $\sigma \approx s/\sqrt{12}$
for s=2 mm, σ=577 μm



- Construction design, construction quality, and gas mixtures affect rates, efficiency, aging
- signal readout electronics
- Many other types of wire chambers

Wire Chambers

Low mass charged particle position detector

Wire chambers can come in different sizes, shapes and geometries

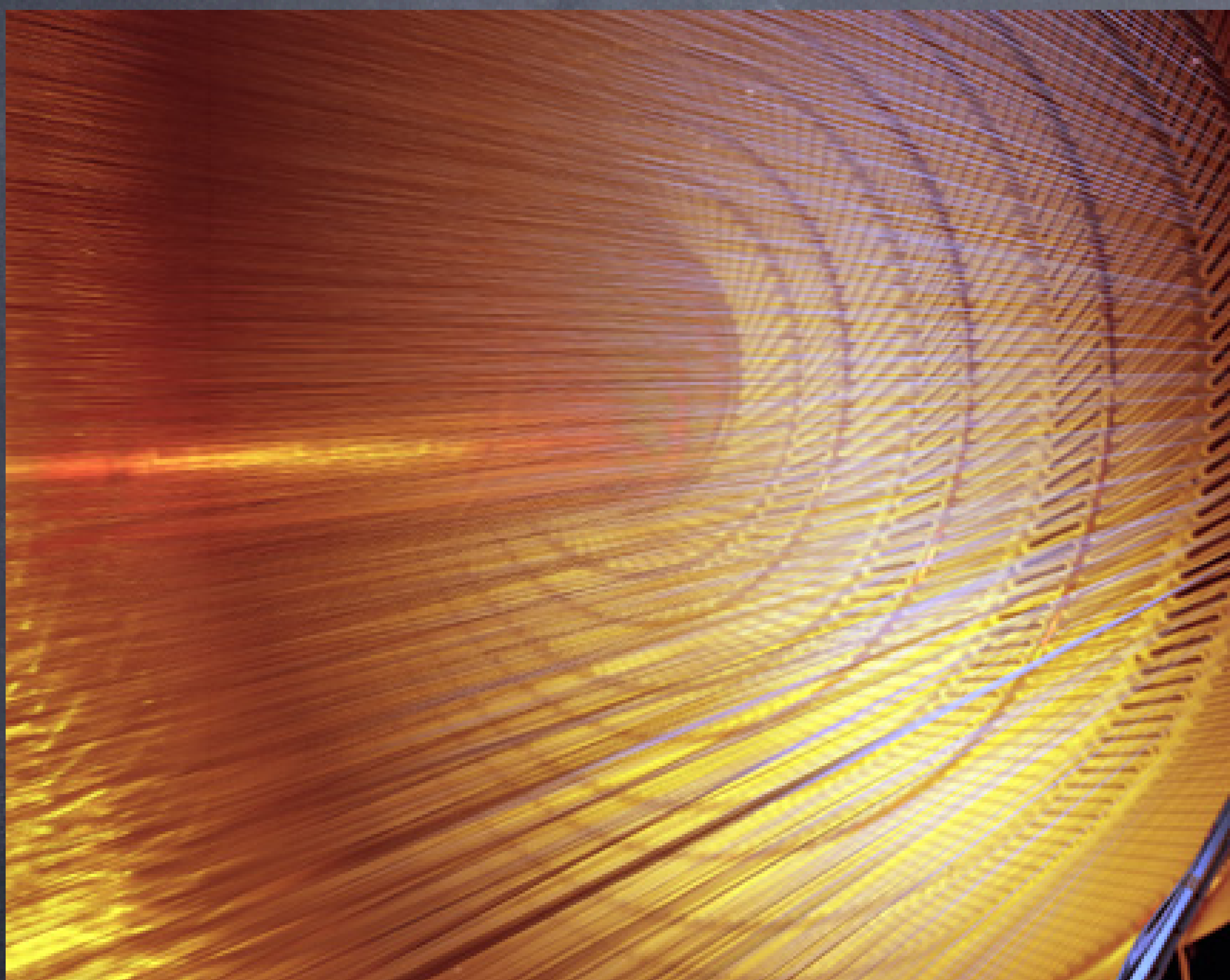
E.g. planar wire chambers from the Fermilab MIPP multi-particle production experiment

Testing and calibration using cosmic rays

Wire Chambers

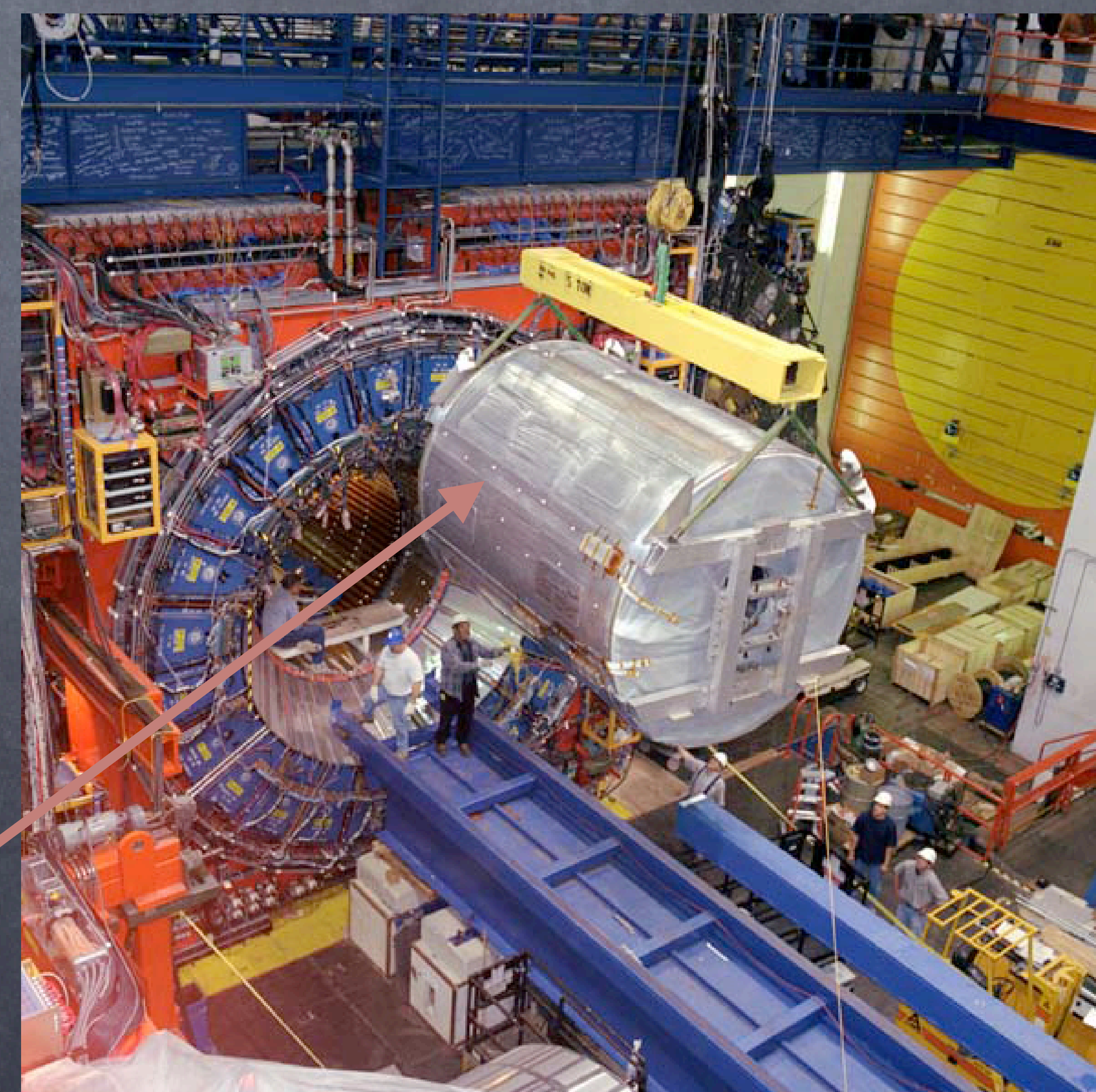
Low mass charged particle position detector

Wire chambers can come in different sizes, shapes and geometries



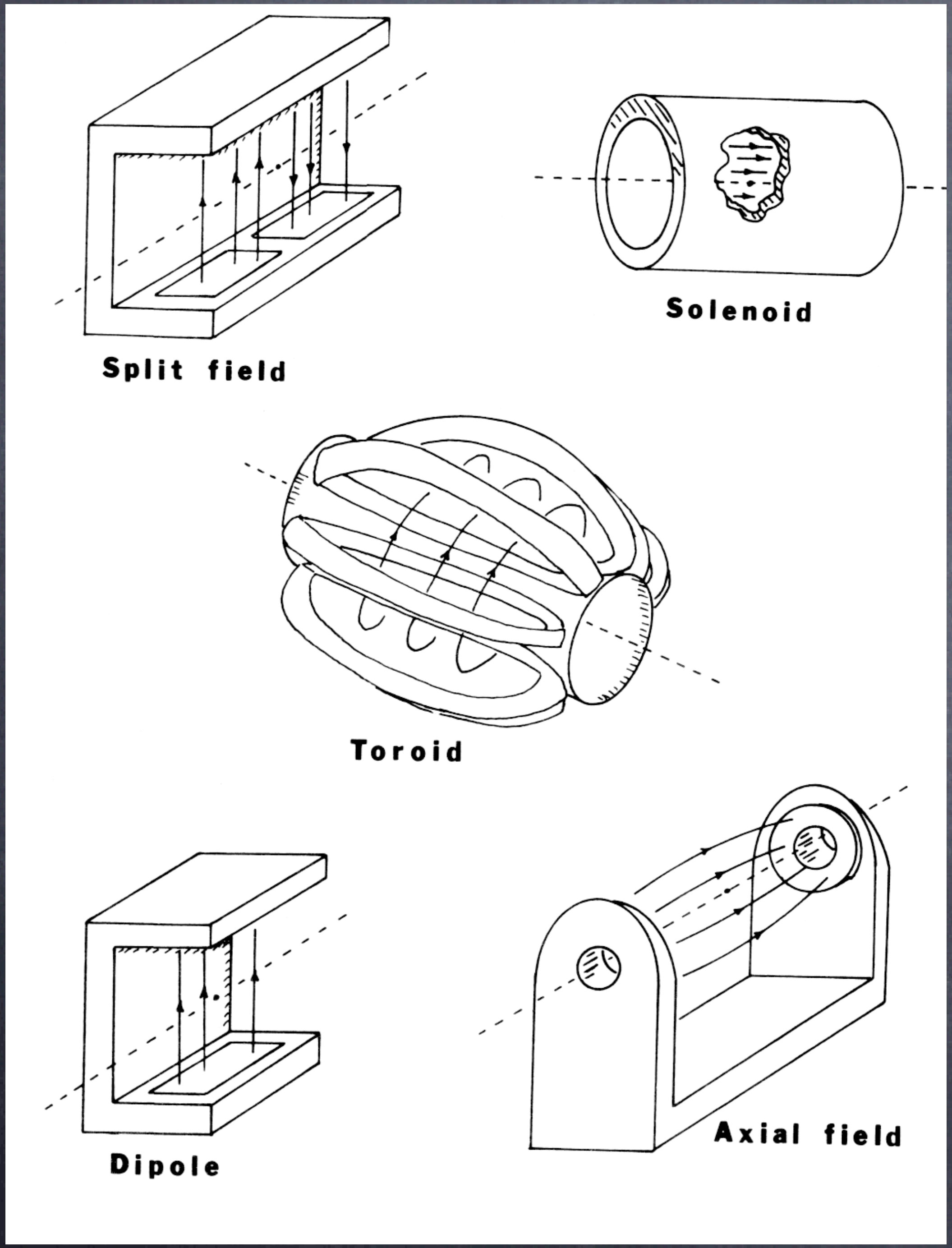
E.g. cylindrical (drift) central tracker from the Fermilab CDF experiment that saw the top quark

Installation in CDF



Magnetic Spectrometer

Determining the charged particle's momentum



There are a choice of magnetic field types depending on experiment

Want uniform field (measure it!) and no fringe fields affecting detectors

Momentum resolution:

$$\frac{\sigma_p}{p} \propto \frac{\sigma_s}{R} \cdot \frac{p}{\int B d\ell} \oplus \frac{MCS}{p}$$

Lever arm

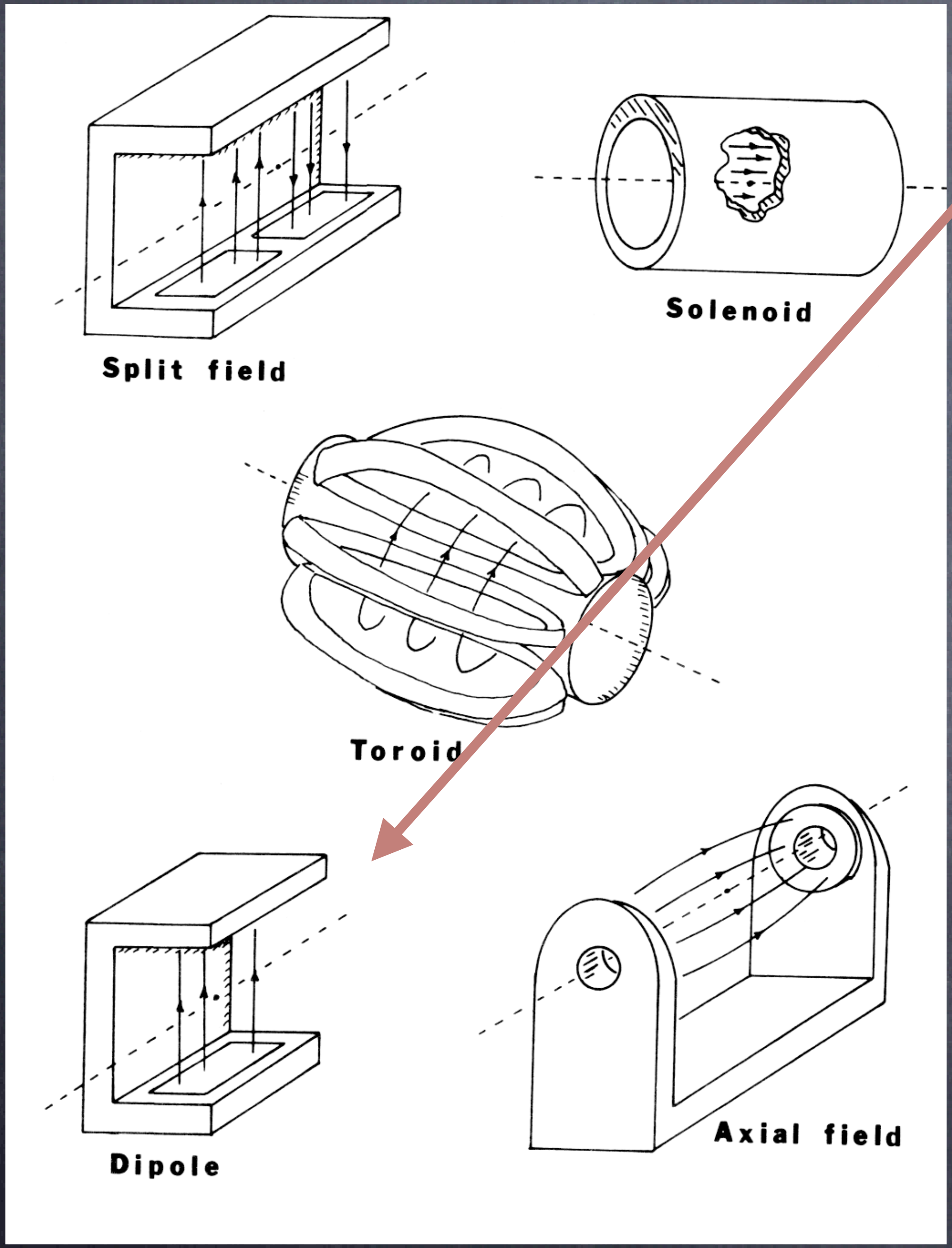
~1% for p=100 GeV/c

MCS contribution

- Uniform field over long lengths
- Strength of field
- Eliminate fringe/edge fields

Magnetic Spectrometer

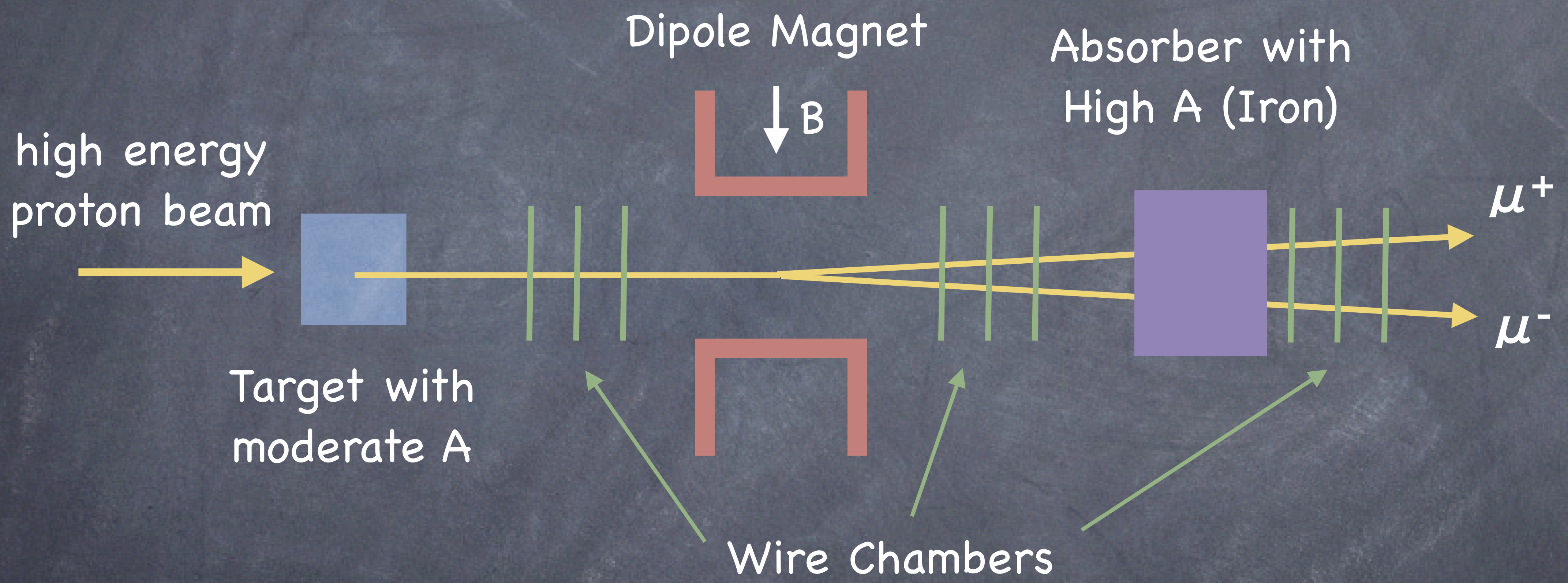
Determining the charged particle's momentum



E.g. a large dipole magnet for the MIPP multi-particle experiment at Fermilab (studying particle production in detail for neutrino beam production details

What Would This Look Like?

I should leave the redesign as homework!



What about Signal-to-background and efficiency?

S/B in the Lederman experiment is ~ 0.04

without all the absorbers may have S/B ~ 10^{-6} !

What Would This Look Like?

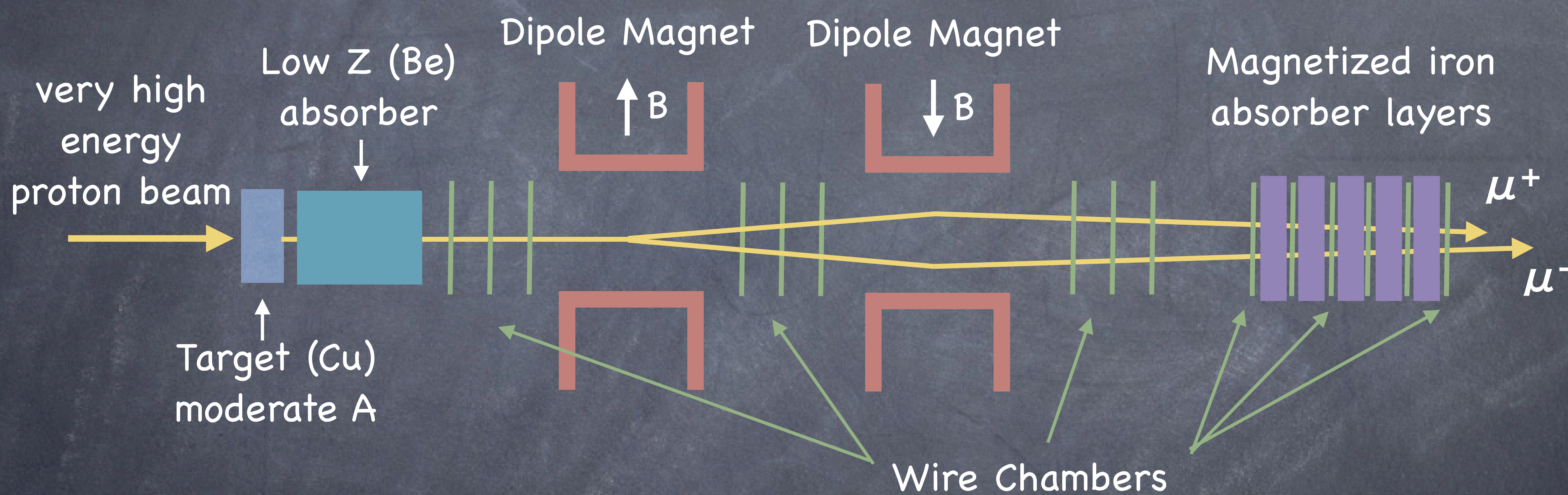
I should leave the redesign as homework!

- Sources of background muons:
  - Direct single muons - small (through EW processes)
  - Muons from decays of charged pions and kaons
    - Lifetime ~ $e^{-t/\tau}$, $c\tau_{\pi}$=7800 cm, $L_{decay}=\beta\gamma c\tau_{\pi}= c\tau_{\pi}\ (p_{\pi}/m_{\pi})$
    - Most decay early (absorb them early)
    - More decays from softer hadrons and decay muons are softer eliminate the softer muons from analysis
    - Measure momentum more than once to reject decays in flight
  - "Punch through" background from hadrons in absorber
    - Multi-absorber layers and detect particles throughout absorber
- Trigger on higher dimuon mass:
  - Momentum analyze through the absorber
    - potentially reduce backgrounds further

Break?

What Would This Look Like?

I should leave the redesign as homework!



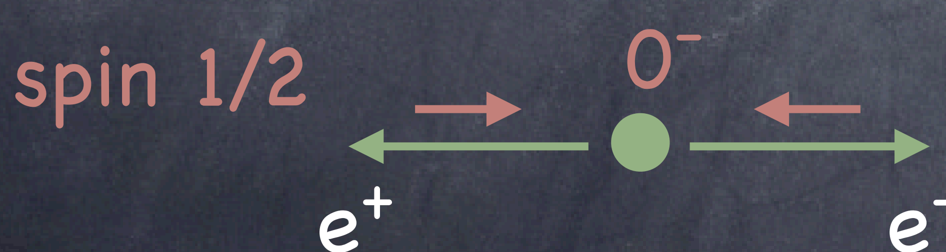
A compromise between dimuon mass resolution and S/B

We will look at the next generation Lederman experiment to see his solution - Now we see how Ting solves this problem

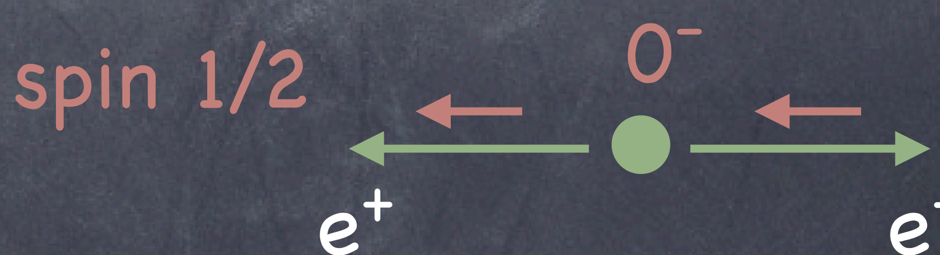
Discovery with Electron Pairs

- Should we expect to see the same physics with e^+e^-?
  - Electrons have the same interactions as muons
  - Electrons have the same J^P as muons:
    - Good for making $J^P = 1^-$ particles (ρ, ω, ϕ, J/ψ)
  - Electrons are ~ 200 times lighter than muons
    - Electrons undergo more scattering and absorption than muons
    - Electron mass is quite different from the pion mass
    - Not good for making e.g. $J^P = 0^-$ particles

      (e.g. $K_L \to e^+e^- / \mu^+\mu^-$, or $K^+ \to e^+\nu_e / \mu^+\nu_\mu$ - weak decay)



Allowed (angular momentum)
Disfavoured by V-A weak decay

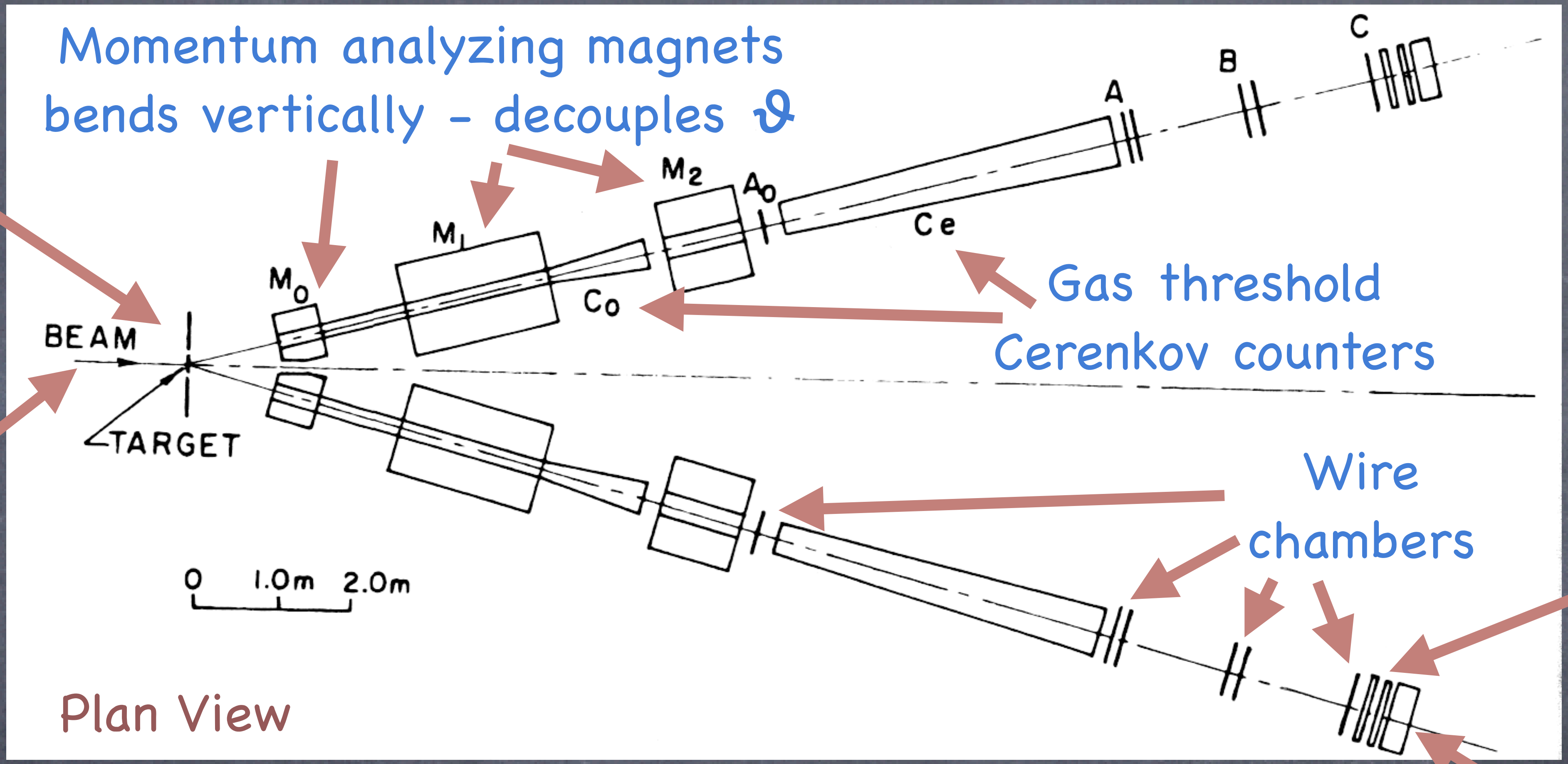


Forbidden (angular momentum)
Favoured by V-A weak decay

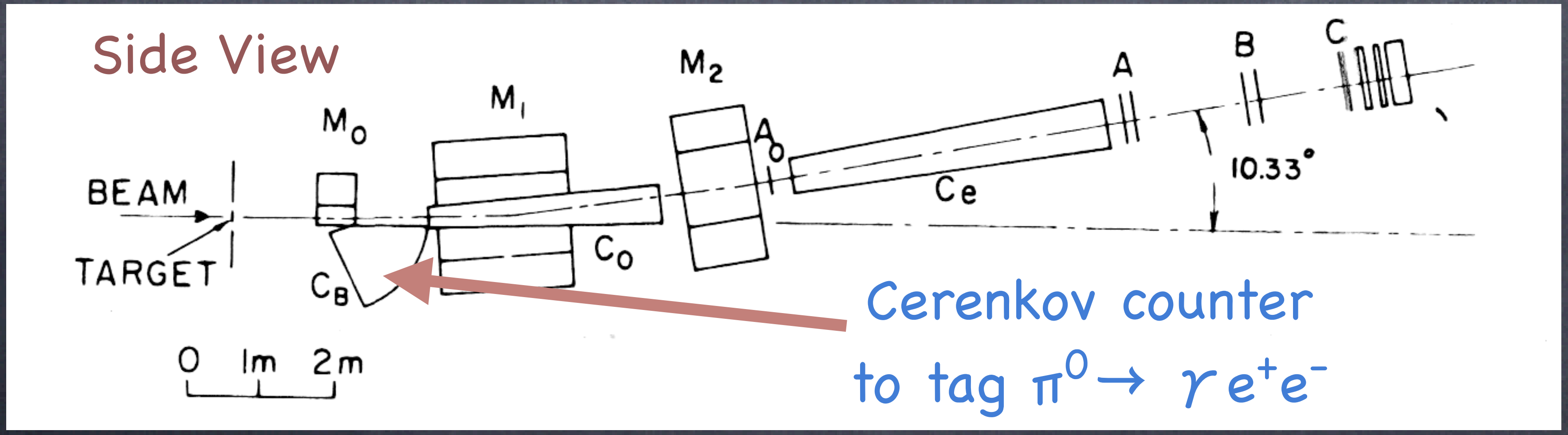
Ting's Spectrometer

Be Target
9 pieces

High
intensity
30 GeV
proton beam



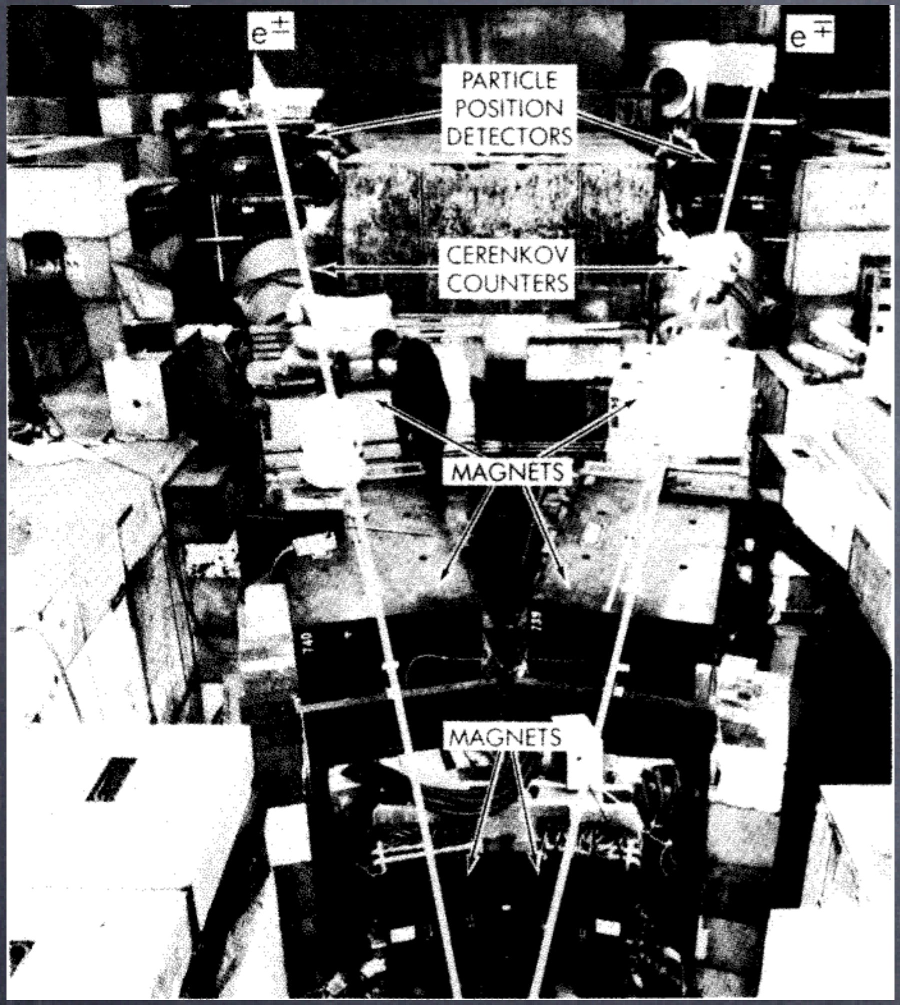
2 Scintillator
hodoscopes

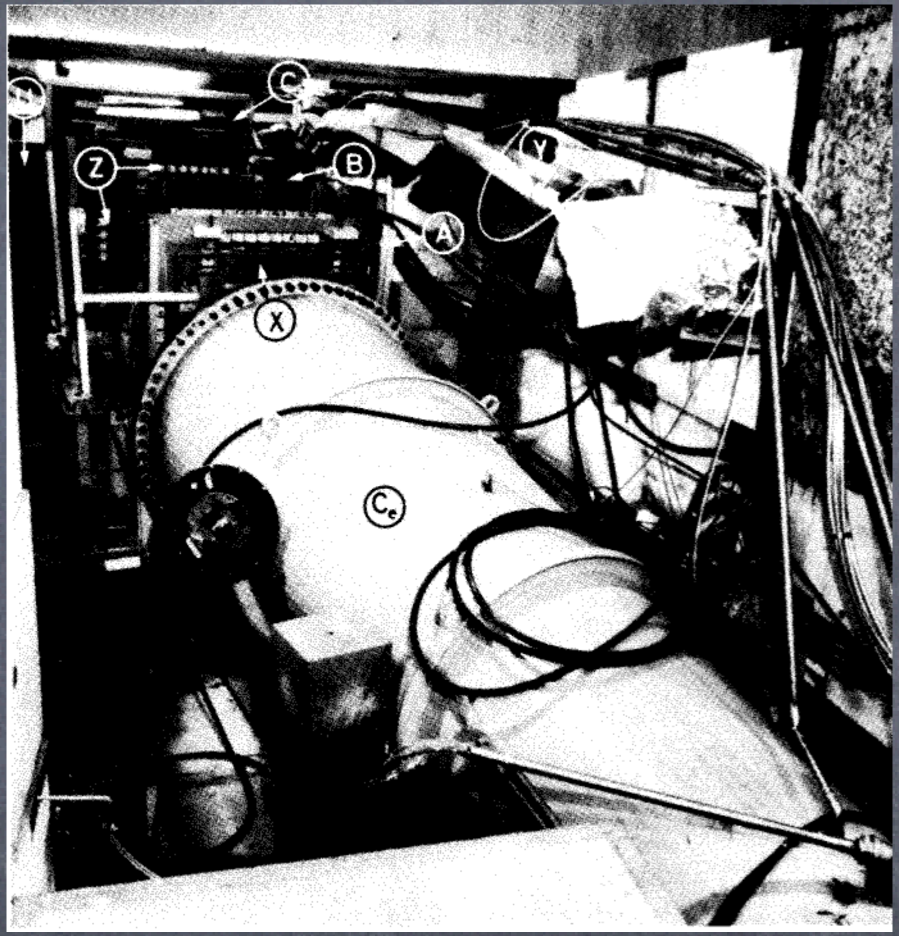


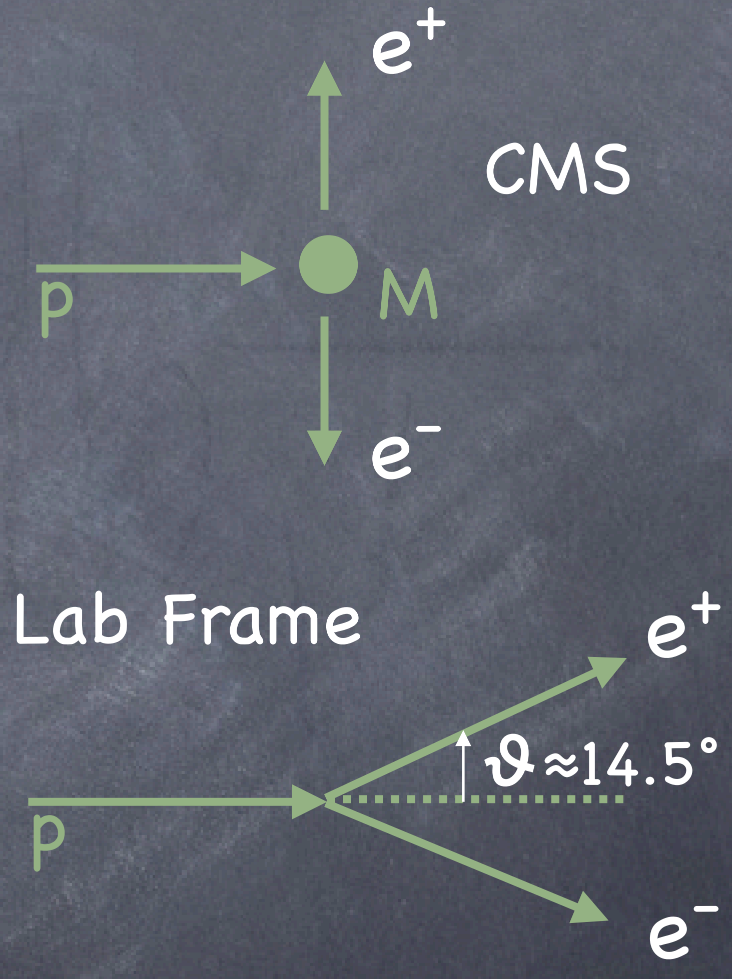
Electromagnetic
Calorimeter with
longitudinal
segmentation
(lead glass +
lead/lucite)

Ting's Spectrometer

Not as simple as the schematic might show!







Why two arms? Bad for acceptance?

Acceptance is only ±1° in ϑ, but is ≈ 2 GeV/c^2 in M_{ee} from 1.5–5.5 GeV/c^2

Signal rate is maximum with M at rest in CMS, for 90° decay of e^+e^-

$\vartheta \approx 14.5°$ independent of M_{ee}

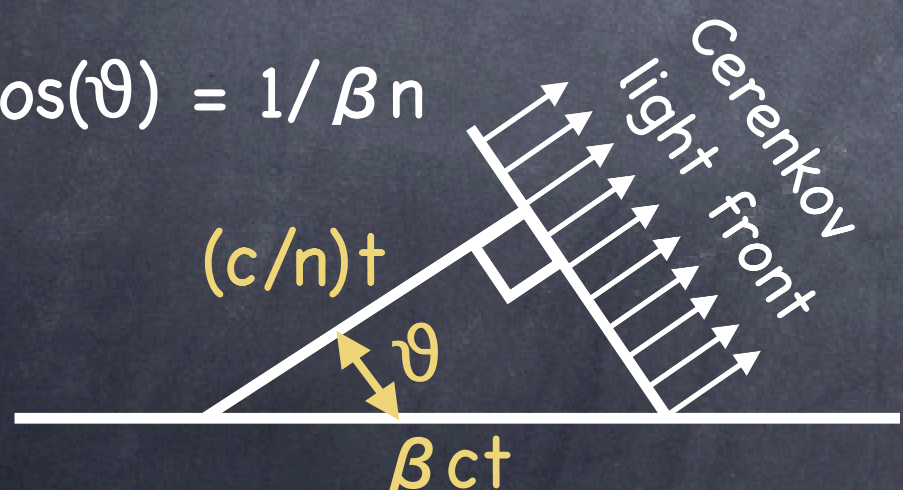
The Čerenkov Effect

Going faster than light!

The Cerenkov effect (Cerenkov's Noble Prize 1958) is used for Particle ID

In a medium of refractive index n, light travels at velocity (c/n), when a charged particle of velocity βc travels faster than light, Cerenkov radiation is emitted at angle ϑ

$\cos(\vartheta) = 1/\beta n$

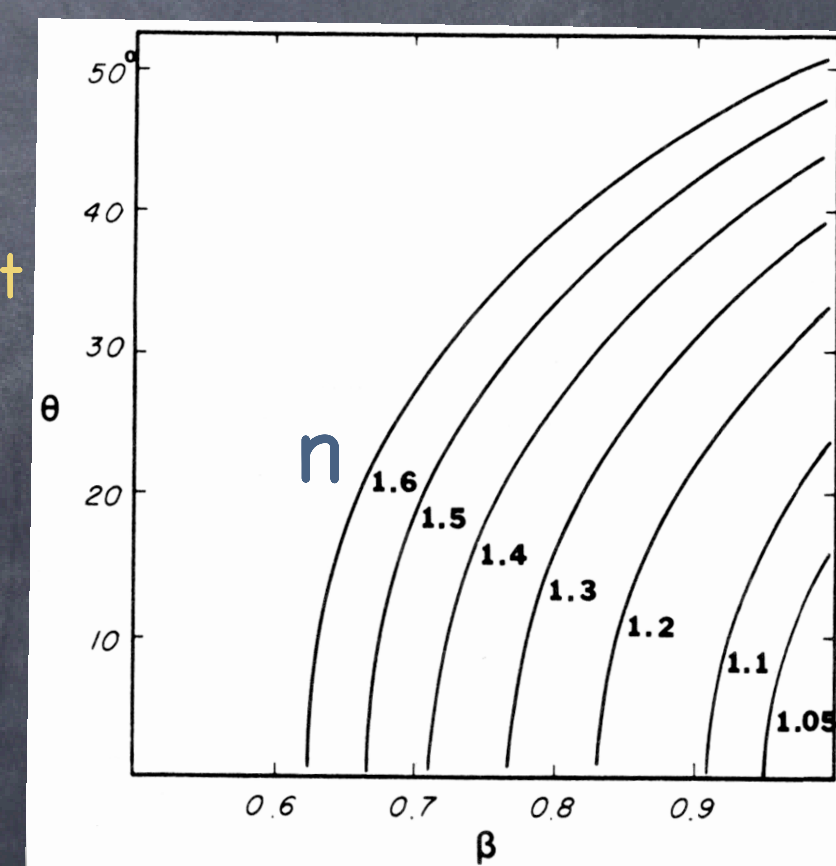


Asymmetric polarization of atoms behind and in front of particle emit coherent light

Number of photons emitted:

$$\frac{dN}{d\lambda} = 2\pi\alpha\frac{L}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$$

- Peaked at low wavelengths
- Small for $n \rightarrow 1$
- 100× less than scintillation light
- angle depends on value of n:



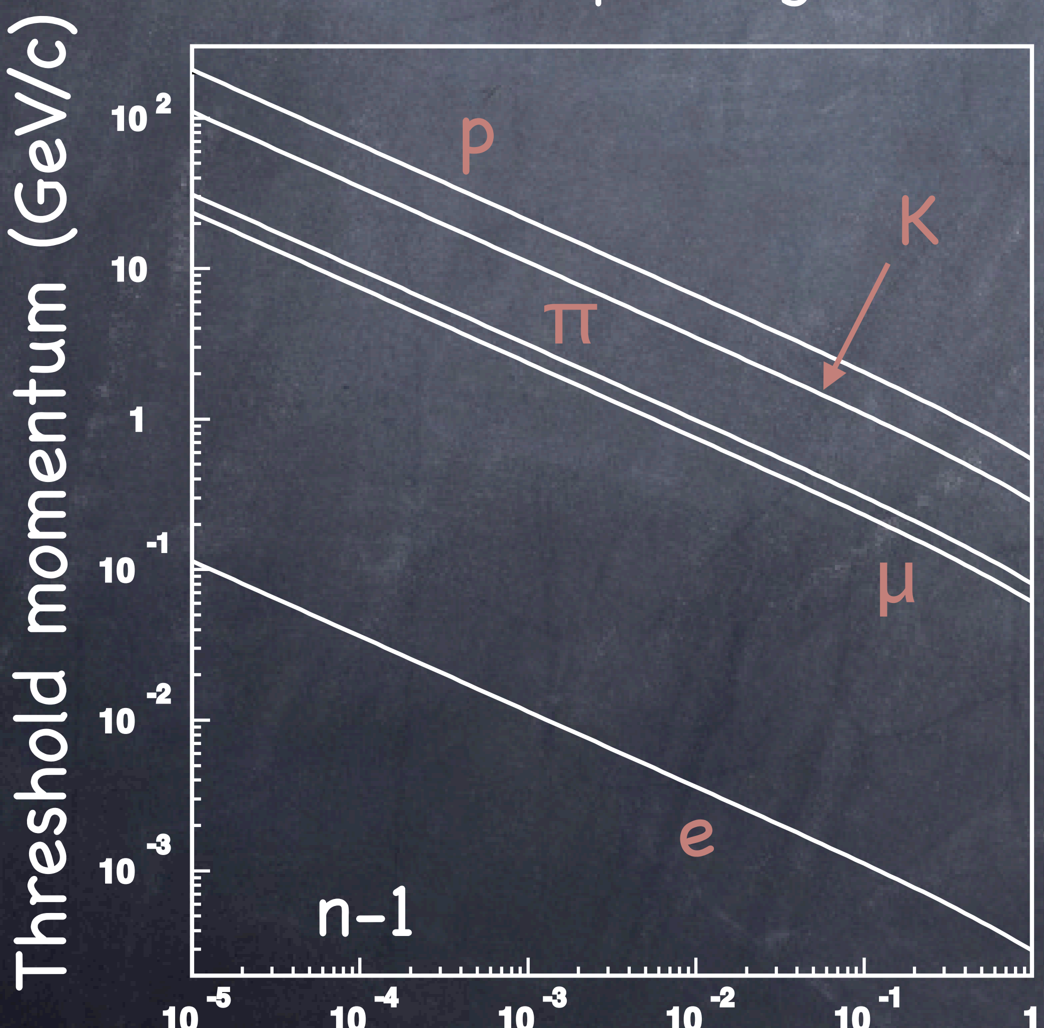
Čerenkov Counters

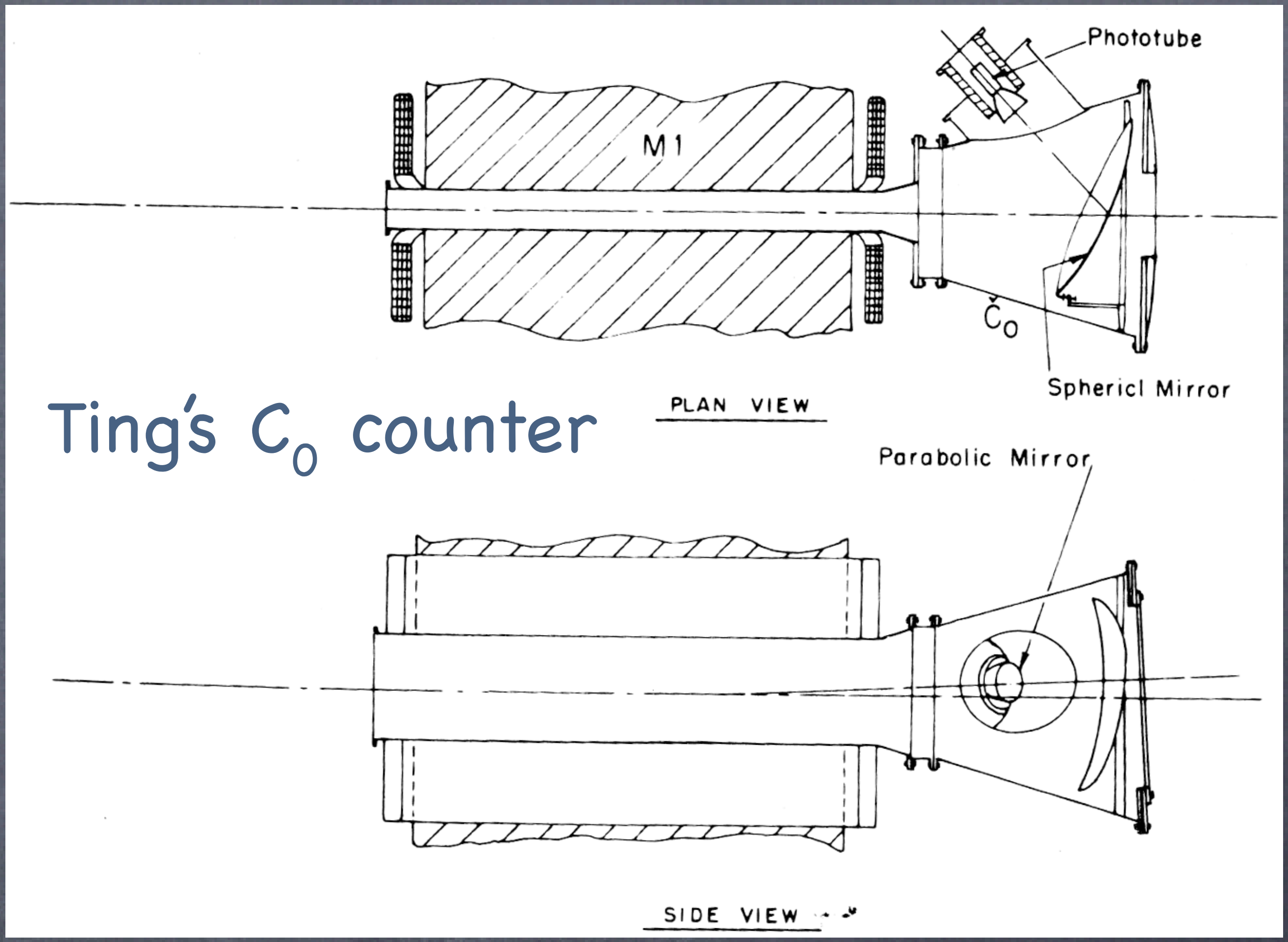
Threshold Counters

Threshold counters for particle ID:

Particles emit radiation when velocity = $\beta c > c/n$

particles with the same momentum have velocities depending on mass





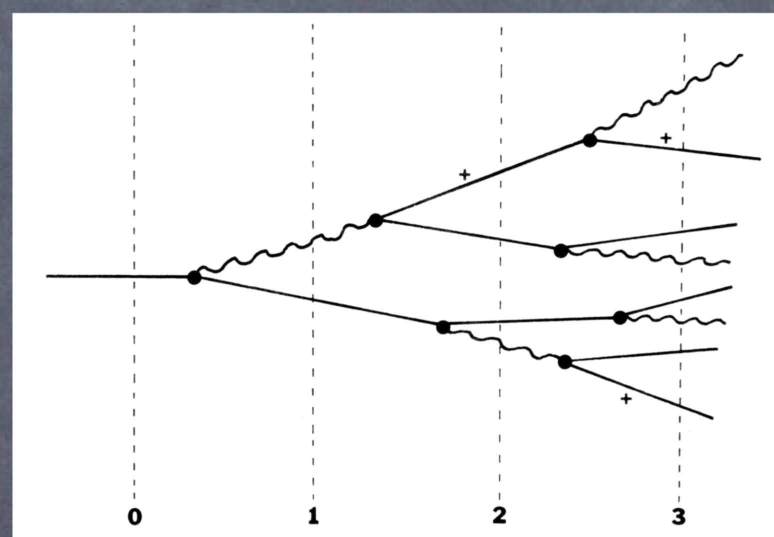
Can use a combination of Cerenkov counters with different "n" to ID protons, kaons, pions and electrons over a wide momentum range

Electromagnetic Calorimetry

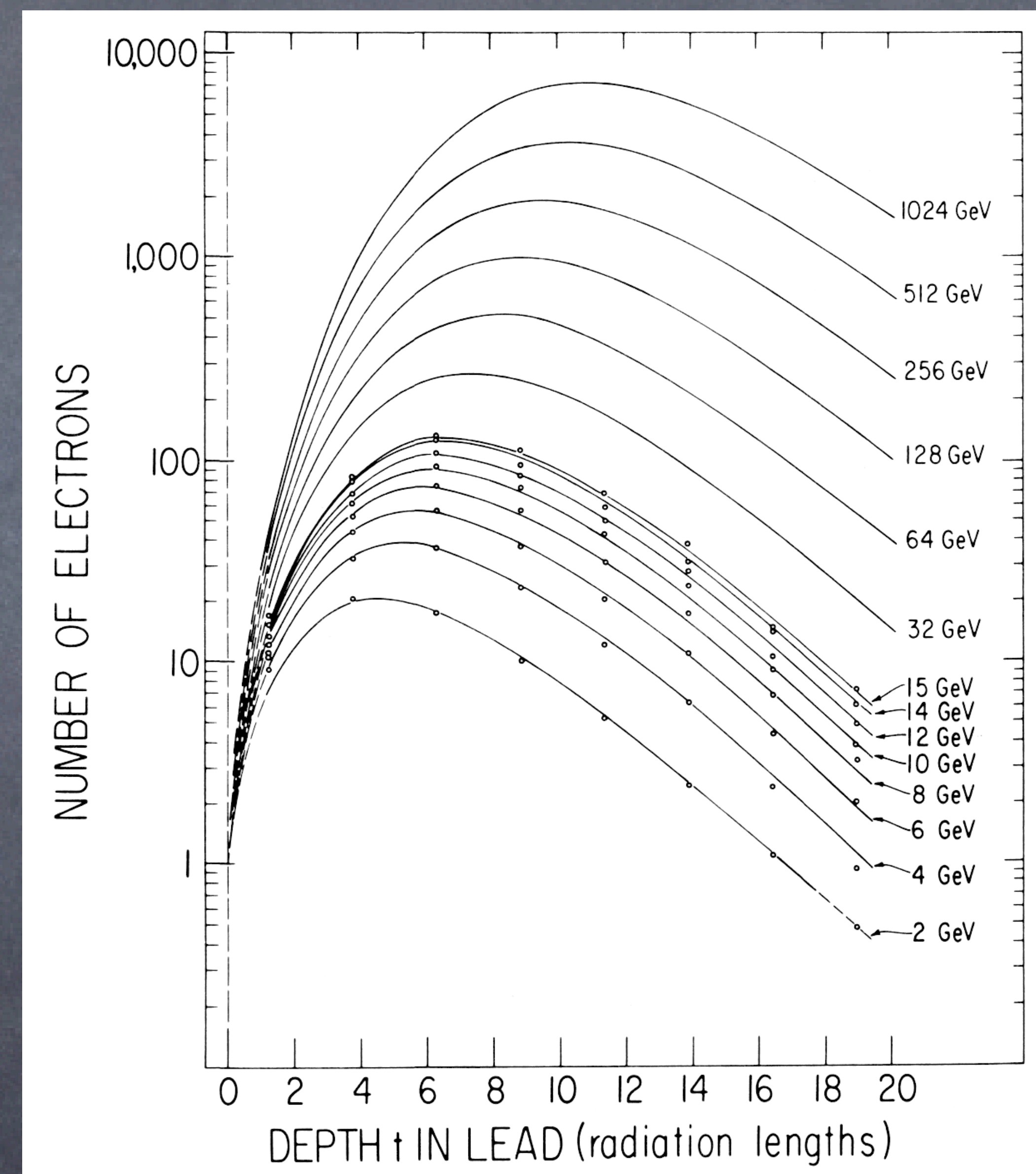
Measurement and ID of electrons and photons

For E_e & E_γ > 1 GeV energy loss is by Bremsstrahlung and e^+e^- pair creation

Leads to an EM shower



~ same profile for all materials, $25\lambda_0$ contains ~99% of the shower



Electron Radiation length λ_0:

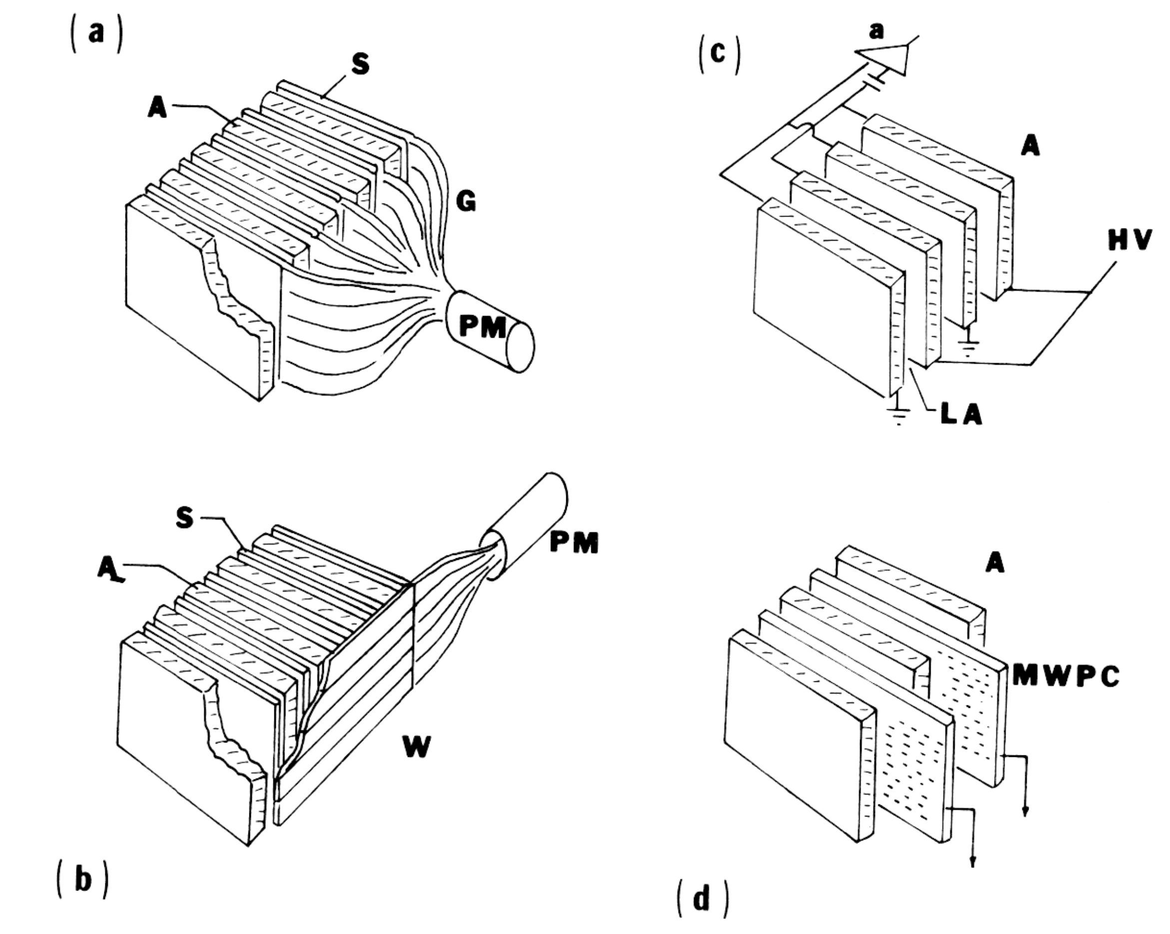
$$E(x) = E(0)e^{-x/\lambda_0}$$

Sampling Calorimeter

Measurement and ID of electrons and photons

Number of e^+e^- ~ initial E_e

Measure along shower between layers of high Z absorber (sampling)



(sampling ↔ sampling fluctuations, photon statistics, shower leakage)

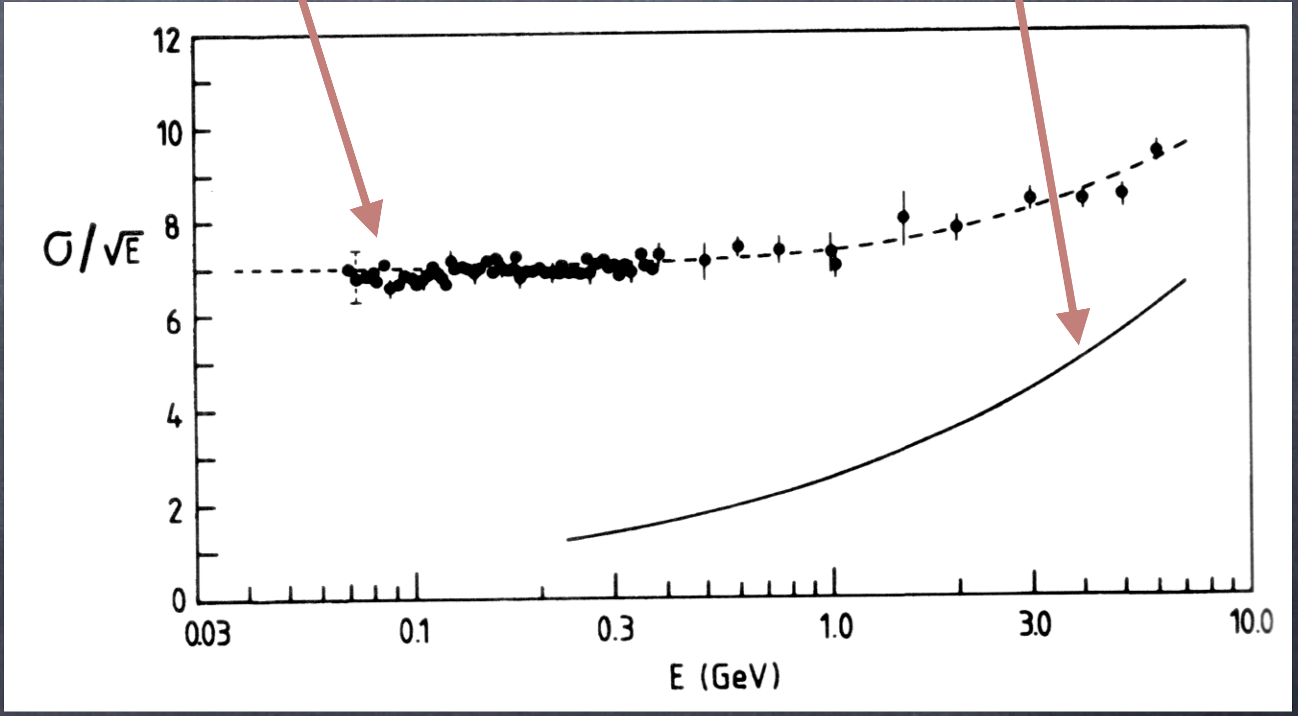
Energy resolution from fluctuations:

Sampling

"Noise"

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

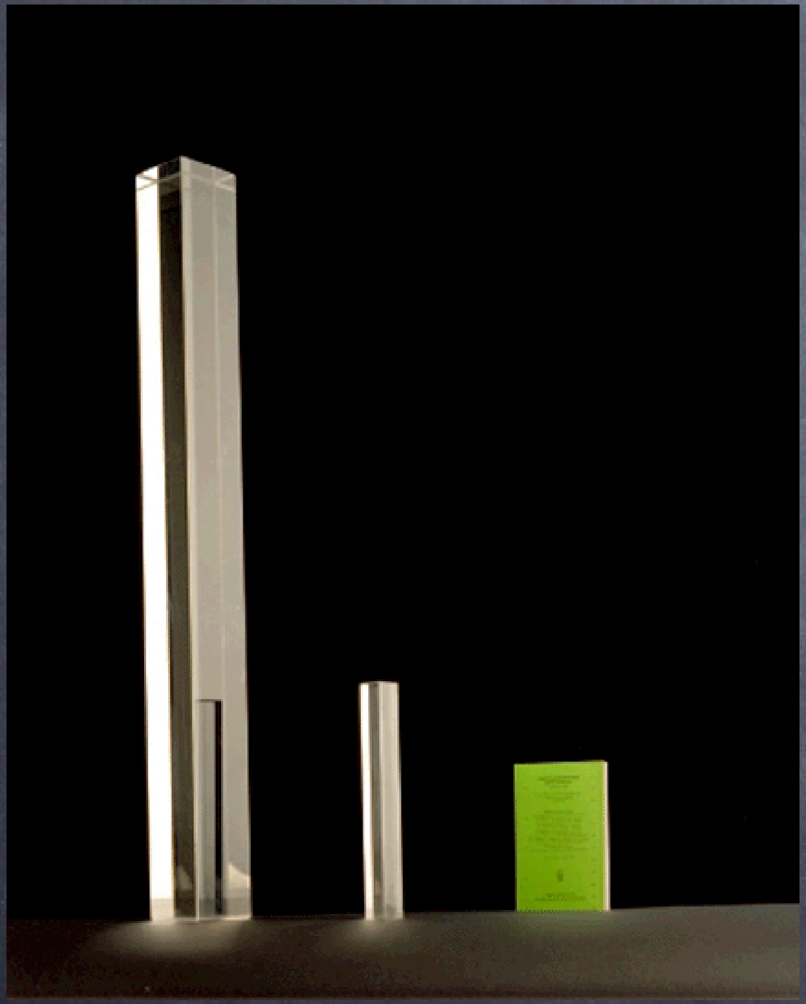
Calibration & Leakage



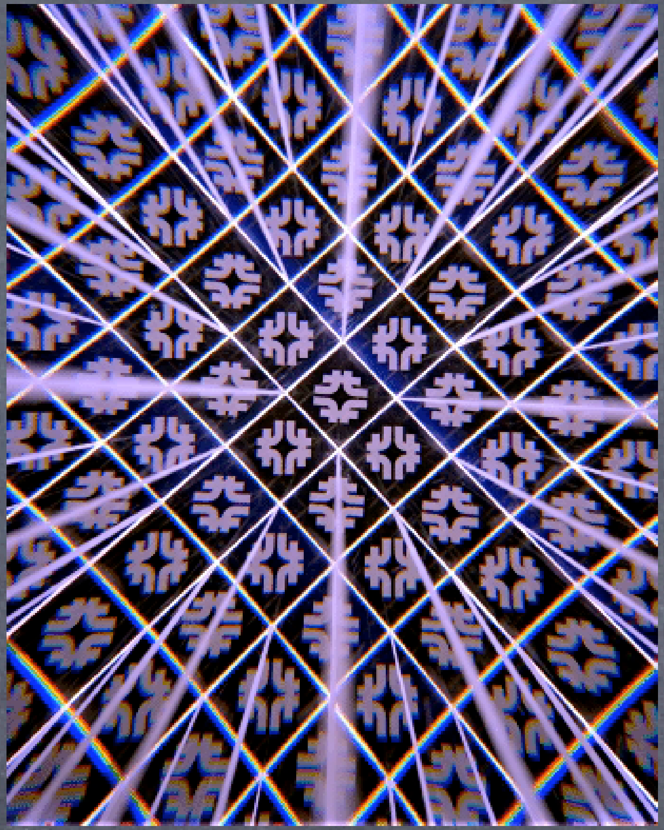
(calibration ↔ uniformity)

Crystal Calorimeter

Lead glass (Pb-glass) crystals gives Cerenkov light

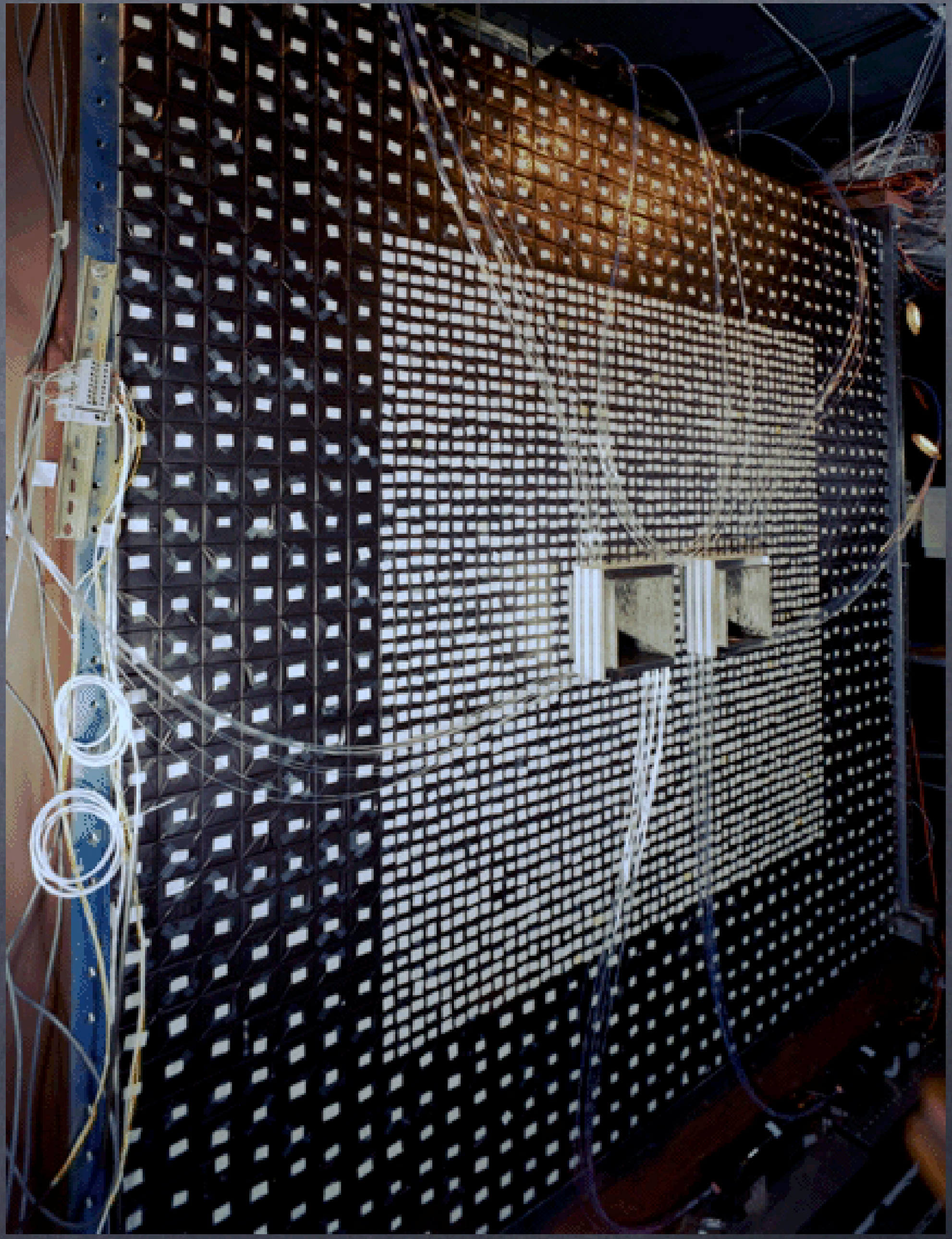


Typically better sampling resolution, e.g. "a" ≈ 1-3% compared to ≈ 8-15% for sampling calorimeters



Head on view through a stack of PB-glass crystals

Sometimes really need the resolution, e.g.



KTeV CsI (scintillating) crystal calorimeter

ID with EM Calorimetry

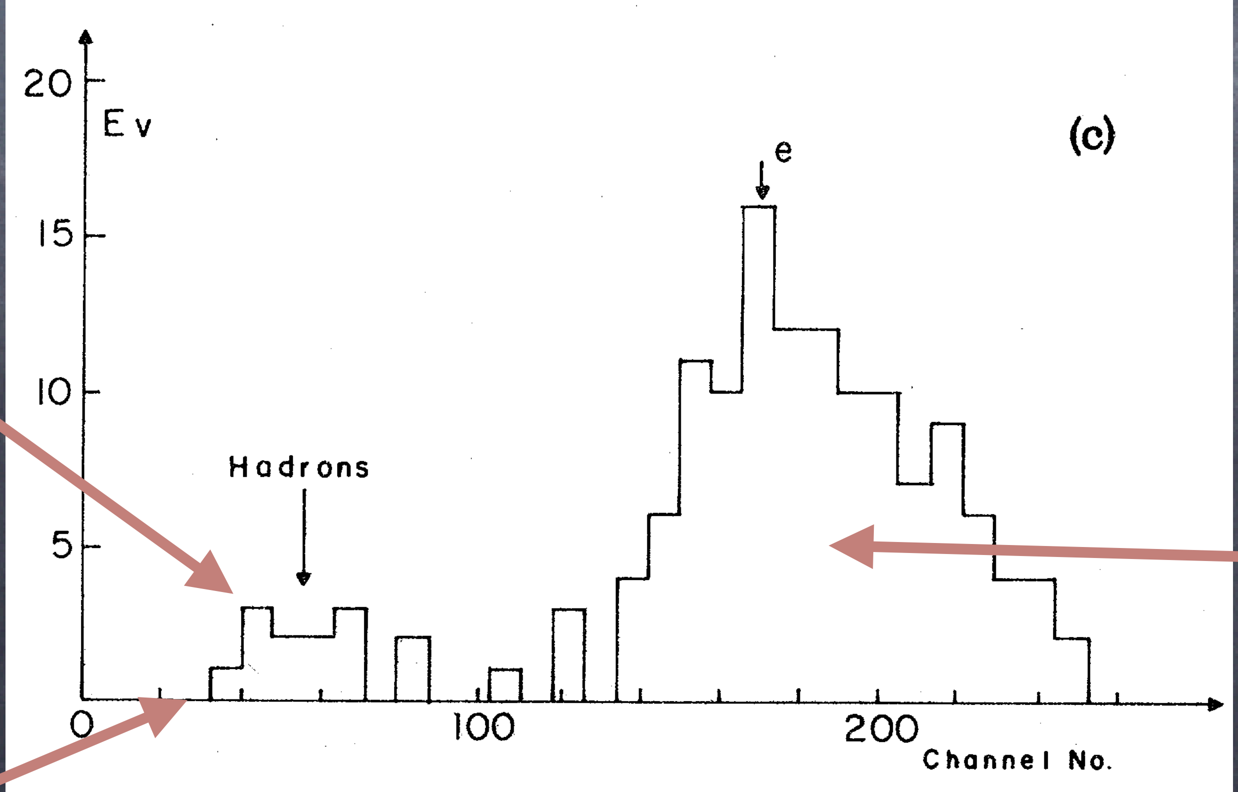
Hadrons deposit a small amount ~$\mathcal{O}$(10%) of energy in an EM calorimeter so E(deposited)/E(particle) [E/p] is small, but ≈ 1 for e and γ

- Ting's EM calorimeter conists of:
  - 2× $3\lambda_0$ Lead glass crystals
  - followed by 7× $10\lambda_0$ lead lucite shower counters
  - Typically hadron rejection is 10^2–10^3:1

Calorimeters can be homogeneous, e.g. crystals NaI, BGO, CsI, $PbWO_4$, and can scintillate or emit Cerenkov radiation

Hadrons

Total energy scale (not E/p as narrow range in p acceptance



Electrons

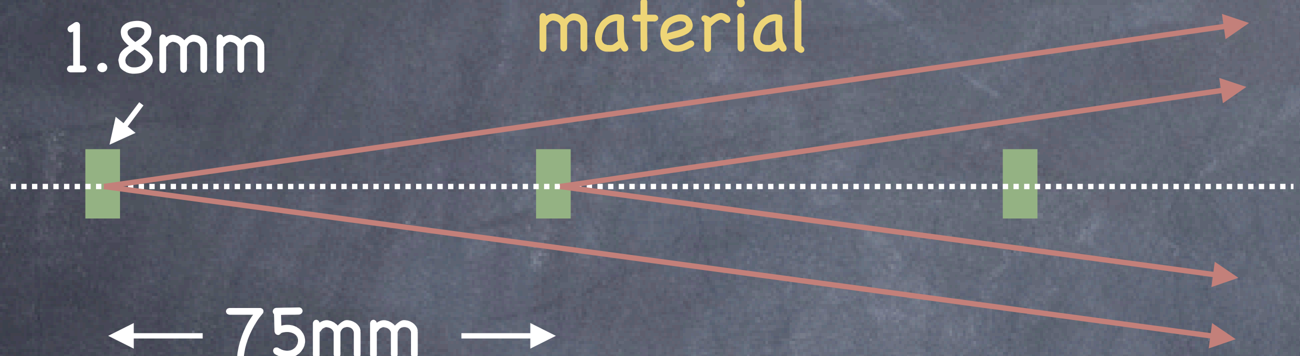
Signal-to-Background

Some challenges in the experiment

- S/B without electron identification ~ 10^{-6}; need 10^{6}-10^{8} rejection
  - Want to keep good mass resolution (≈5 MeV/c^2)
  - Typical particle ID gives 10^2:1 to 10^3:1 background rejection
    - Must combine Cerenkov and Calorimeter methods
    - Also need to reject $\pi \rightarrow \gamma e^+e^-$ specifically
  - Pion/kaon decay to electrons is no problem as BR is small
  - Reduce material to reduce photon conversion to e^+e^- pairs
- Need to handle high rates to get enough signal
  - Special target arrangement with 9 Be targets
  - Hodoscopes and EMCAL do not see target directly
- Was thought to be very complicated and expensive at the time

Signal-to-Background

Target arrangement (9 Be pieces) - rejects pair accidentals and less material

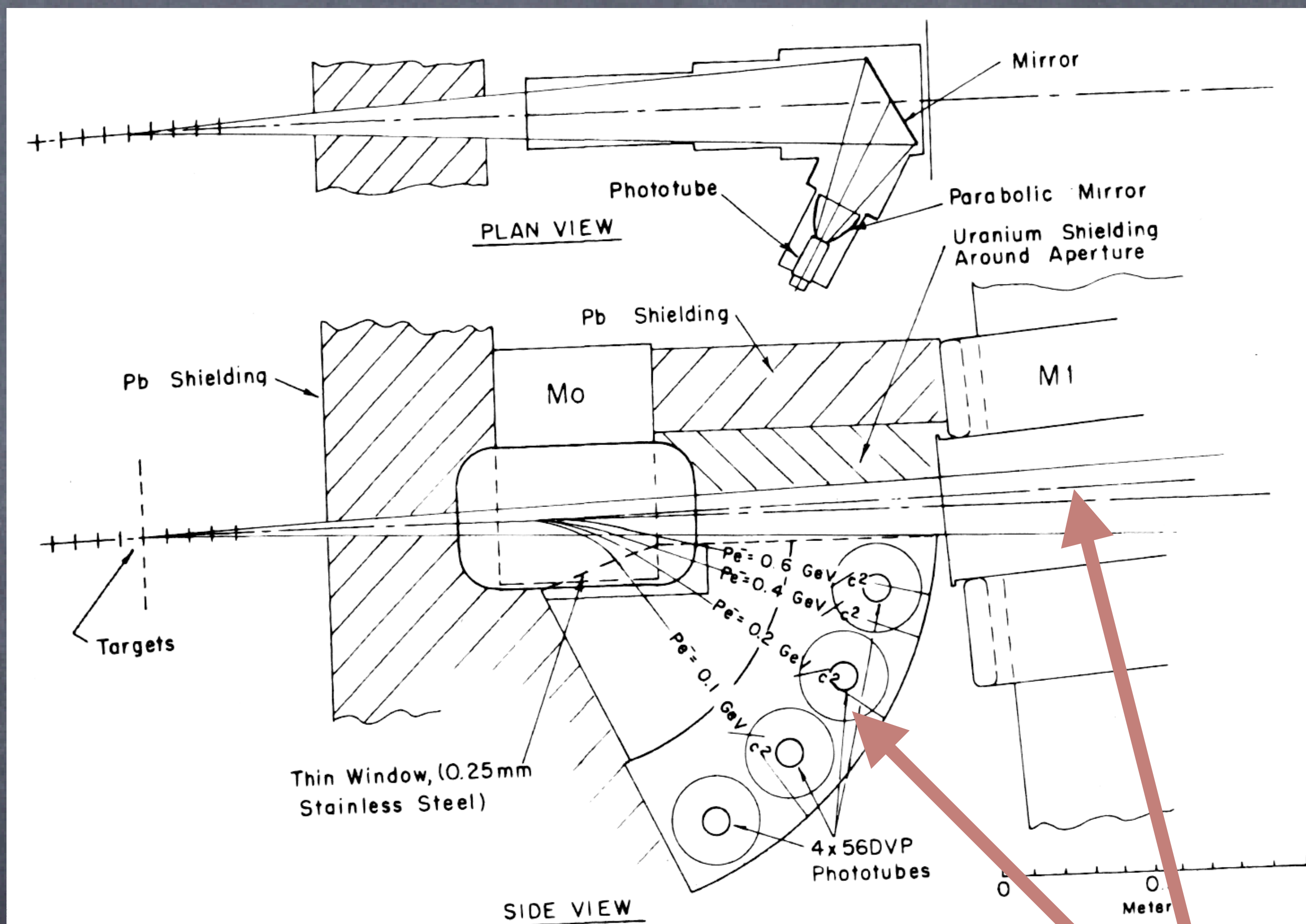


Target needs to have high probability for hadronic interaction (signal rate) and low EM interactions -

Want largest λ_0/λ_I

Reduce the material seen by the electrons, e.g. thickness of windows and hodocopes, and care in shielding

Two Cerenkov detectors reduces electron misid due to knock-on electrons

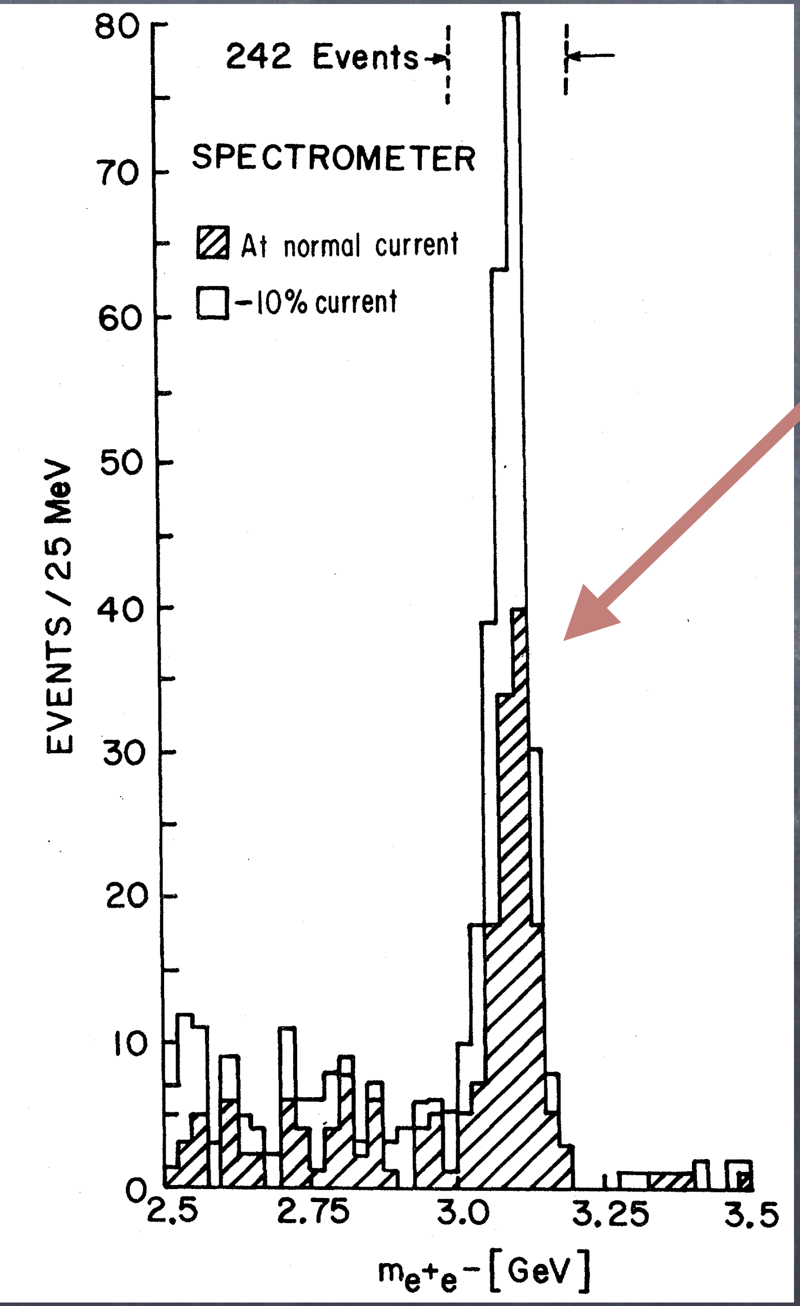


Third Cerenkov to tag $\pi \rightarrow \gamma e^+e^-$ to reject this + gives clean source of single electrons for calibrations

J/ψ Discovery

Ting's results

- Achieved 5 MeV/c^2 mass resolution
- Study ≈2 GeV/c^2 range in M_{ee} from 1.5–5.5 GeV/c^2 in 3 overlapping regions
- Achieved 10^8 rejection of background in J/ψ region
- A whopping signal peak at M_{ee} = 3.112 GeV/c^2 !
  - no errors (statistical or systematic) quoted!



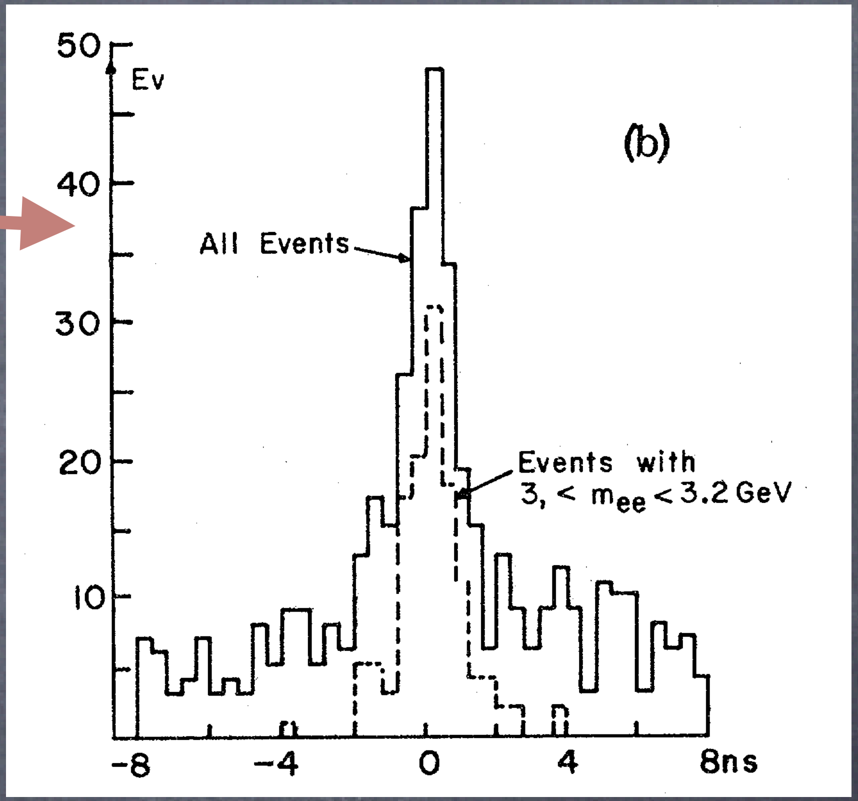
$J/\psi \to e^+e^-$

Sam Ting 1976 Nobel Prize

Many Checks

Many different checks of the signal including:

- Usual calibrations and efficiency checks
  - (need attention to detail)
- Timings for the 2 arms
  - check as expected for signal
- Change the magnet current (10%)
  - check peak in same mass
- Change target thickness
  - check 2nd order target effects
    signal $\propto$ $(\text{target})^2$ not $(\text{target})^4$
- Change voltage on lead glass
  - check pileup effects
- Select aperture acceptance
  - check interaction with magnet
- Different beam intensity
  - check 2nd order beam effects



Next:
Discovery of the J/ψ
Elsewhere →

J/ψ Discovery

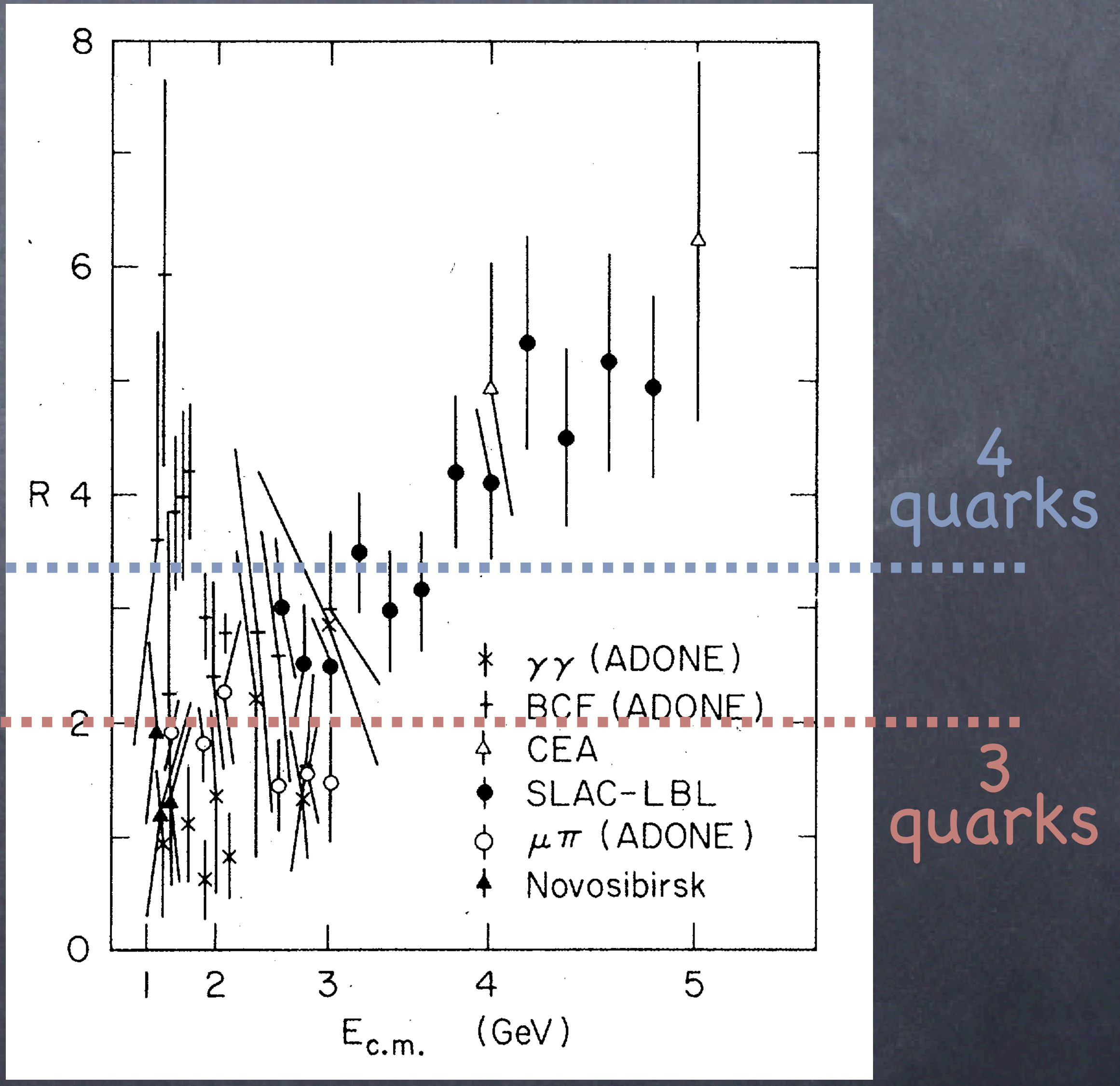
e^+e^- Colliders

- "Heavy photons", ρ, ω and φ mesons can decay to e^+e^-, ($J^P=1^-$) so they can be formed by e^+e^- annihilation
- Study of QED at short distances
- Study of hadrons in a known initial state (cleaner than hadron-hadron collisions)
- For discovery in direct $e^+e^- \rightarrow V^0$ we need to know the V^0 mass, clues from

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = 3 \times \sum_q Q_q^2$$

Complications from τ lepton decays

Data on R in July 1974



Spear e^+e^- Collider

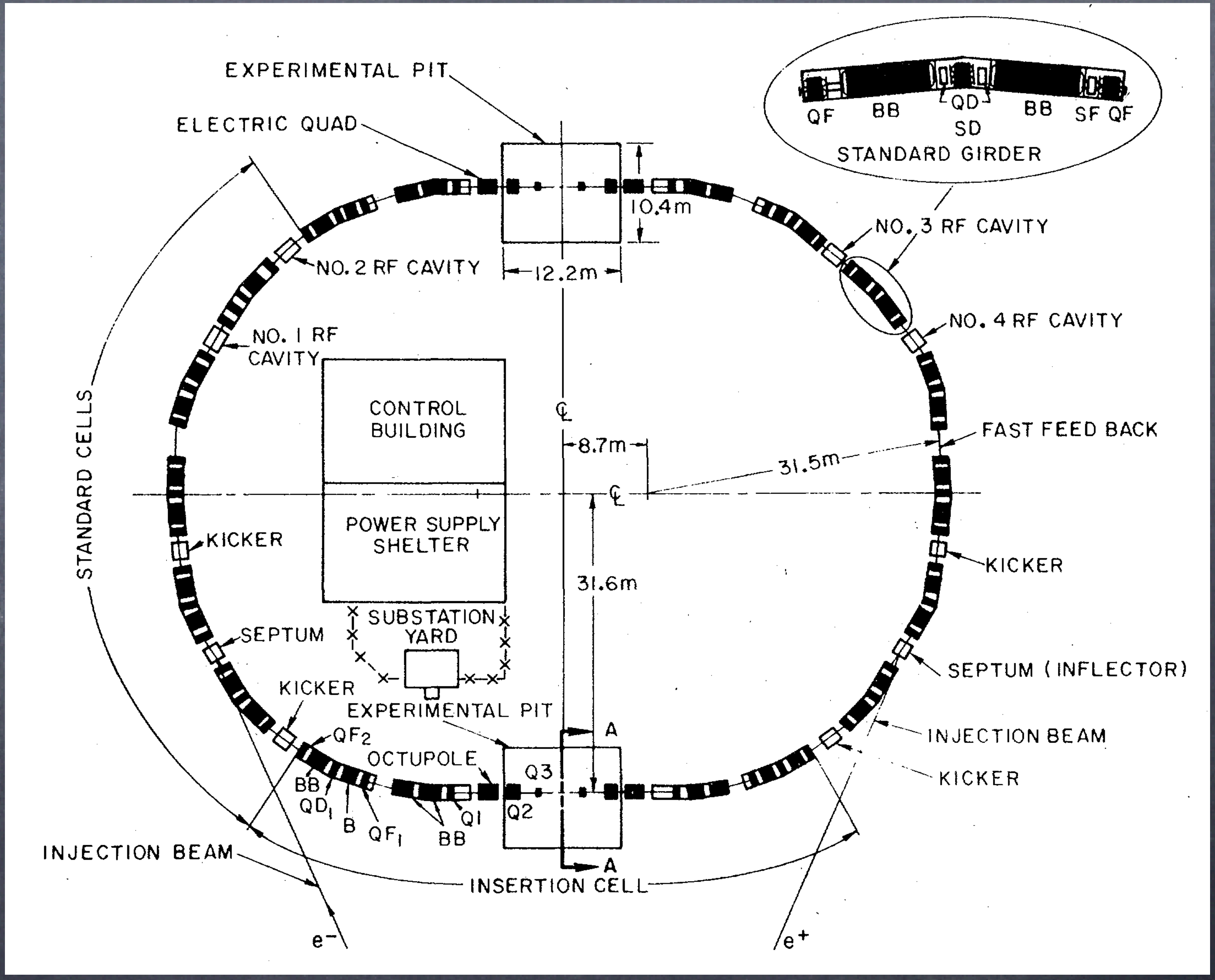
Building a Collider

Diagram to show that the Spear e^+e^- collider is a complex machine/system

HEP physicists helped to design and build this machine (SLAC). Also there were other pioneers at Frascati and Novosibirsk

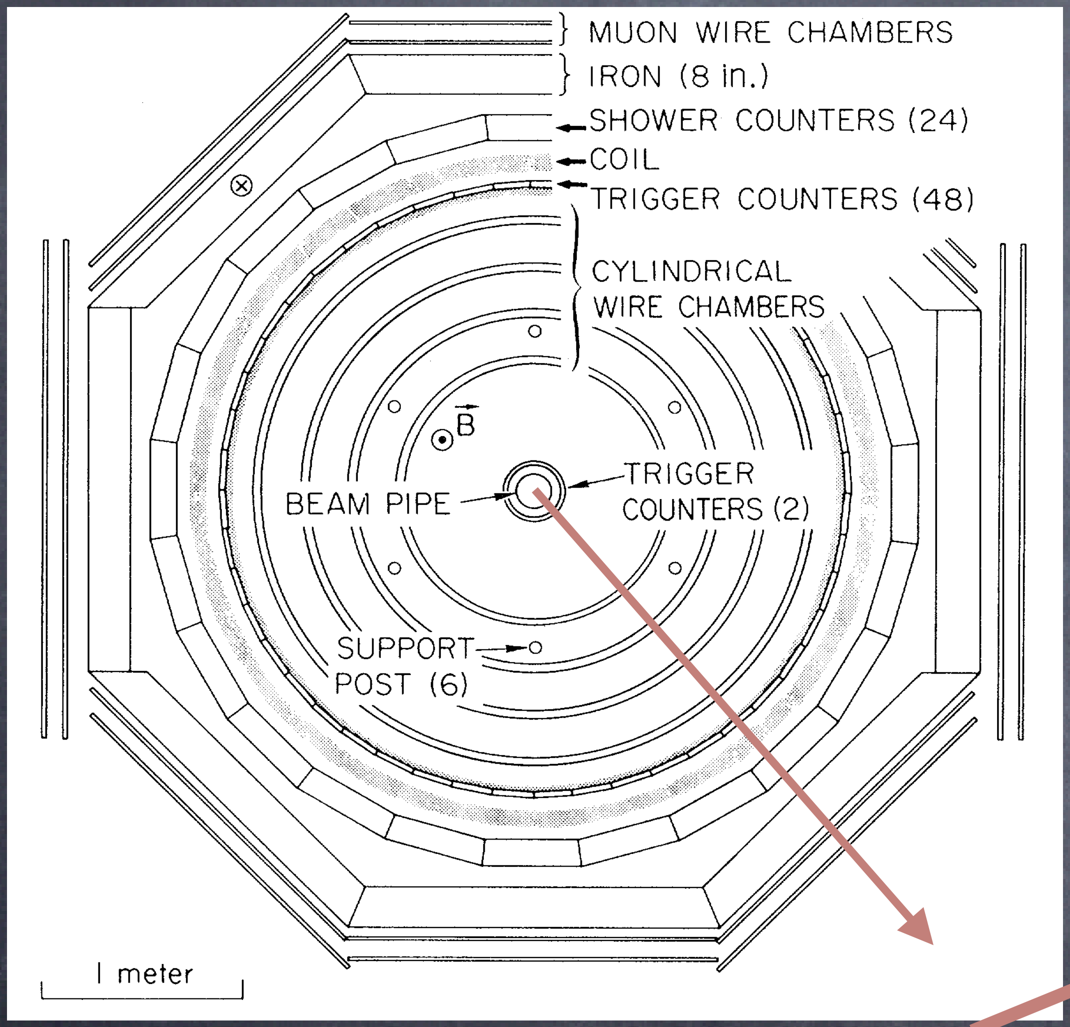
Designed and proposed in 1965, funding in 1970, first beams in 1972, data in 1973

Now we have a large split in accelerator/beam design and detector design ☹

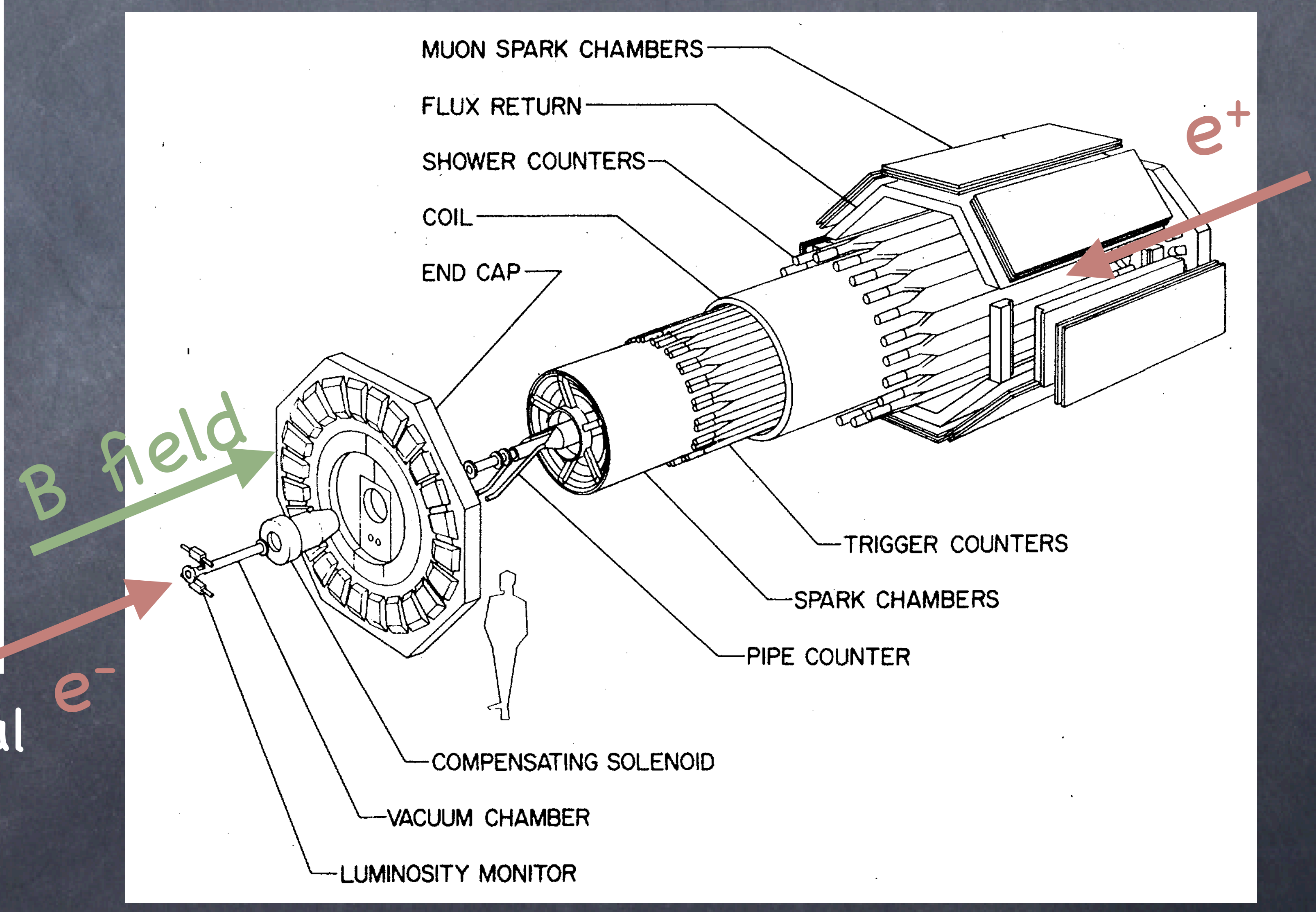


Richter's Spectrometer

An almost "4π" Detector



Produced particle sees the usual layers of detectors scintillators, tracking planes, EMCAL, muon planes



An exploded view of the Mark 1 Detector

Spark Chambers

Spark chambers used to measure the tracks of charged particles

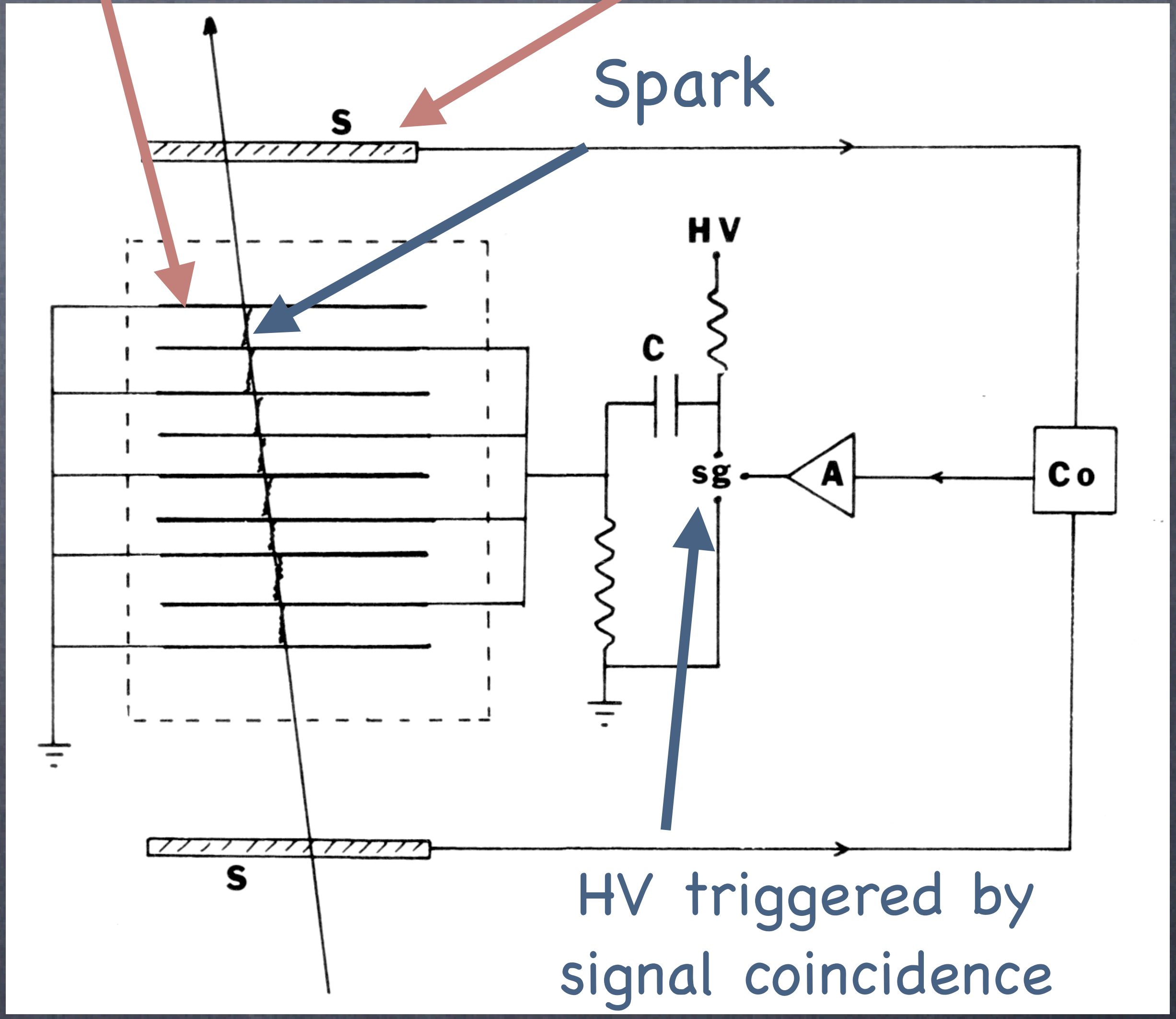
Like in a MWPC, a noble gas is ionized, but there is no quenching of the electron avalanche or photons so a short spark is seen.

Readout can be optical or magnetostrictive (detects mechanical motion) can get 200µm resolution

Large deadtime due to power supply and clearing of ions (using a reverse biased field)

Metallic planes of wires in gas (e.g. He-Ne)

Scintillator counter



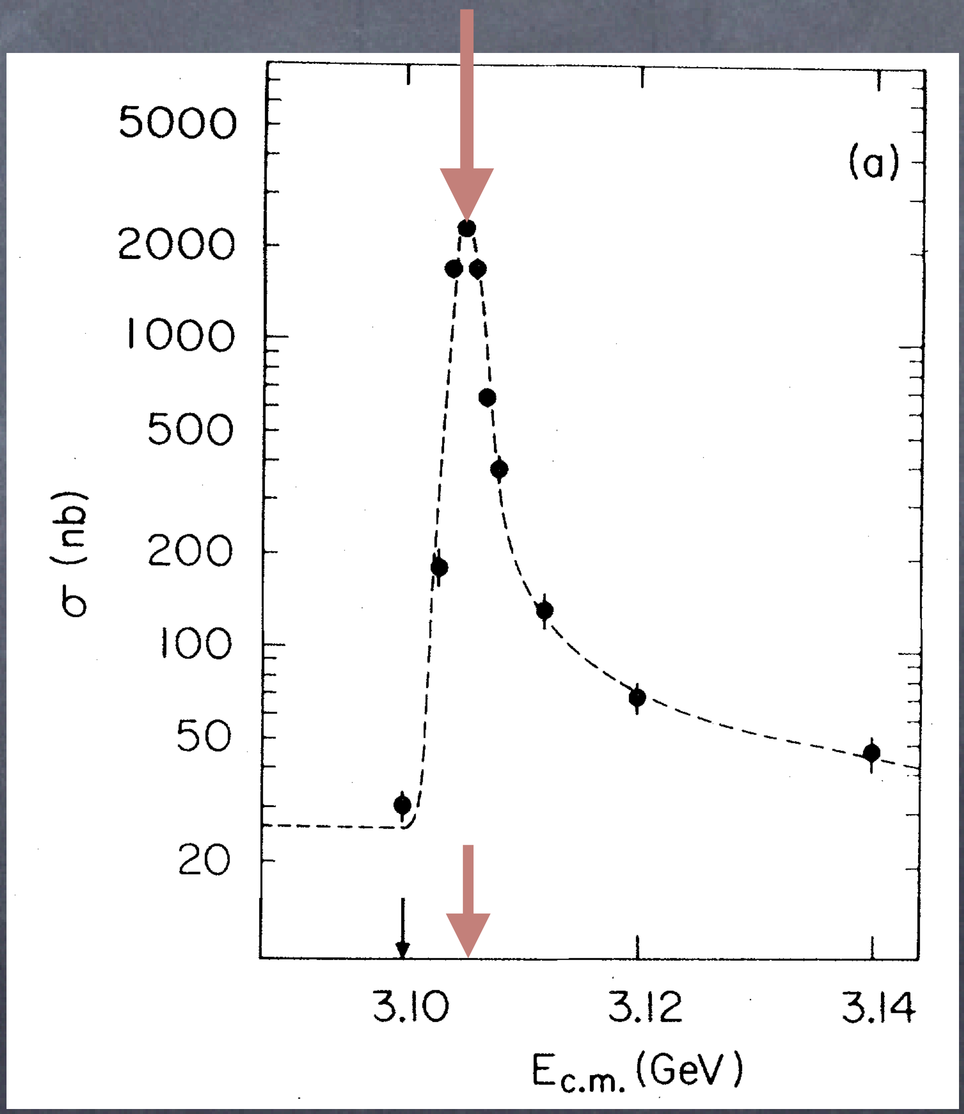
Spark chambers used in 1960-1975 but replaced by MWPC's and drift chambers

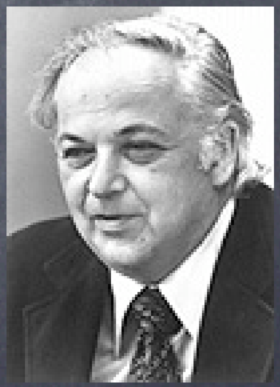
J/ψ Discovery

Richter's results

- Great resolution determined by knowledge of the beam energy
  - ≈ 0.01% (0.3 MeV) relative E
  - ≈ 0.1% (3 MeV) absolute E
- Showed J/ψ FWHM < 1.3 MeV
- Really clean and narrow signal peak at
  $M_{ee} = 3.105 \pm 0.003$ GeV/c^2

$e^+e^- \to J/\psi \to$ hadrons





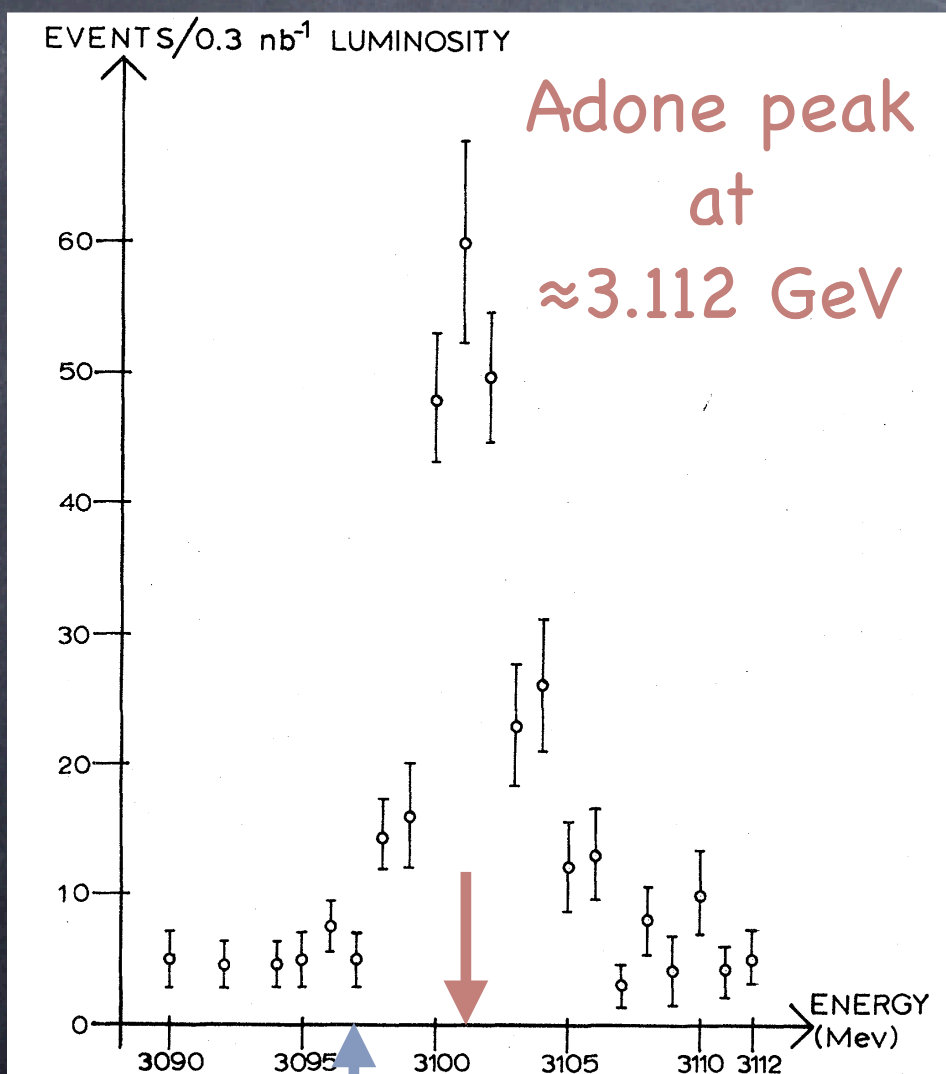
Burt Richter
1976 Nobel Prize

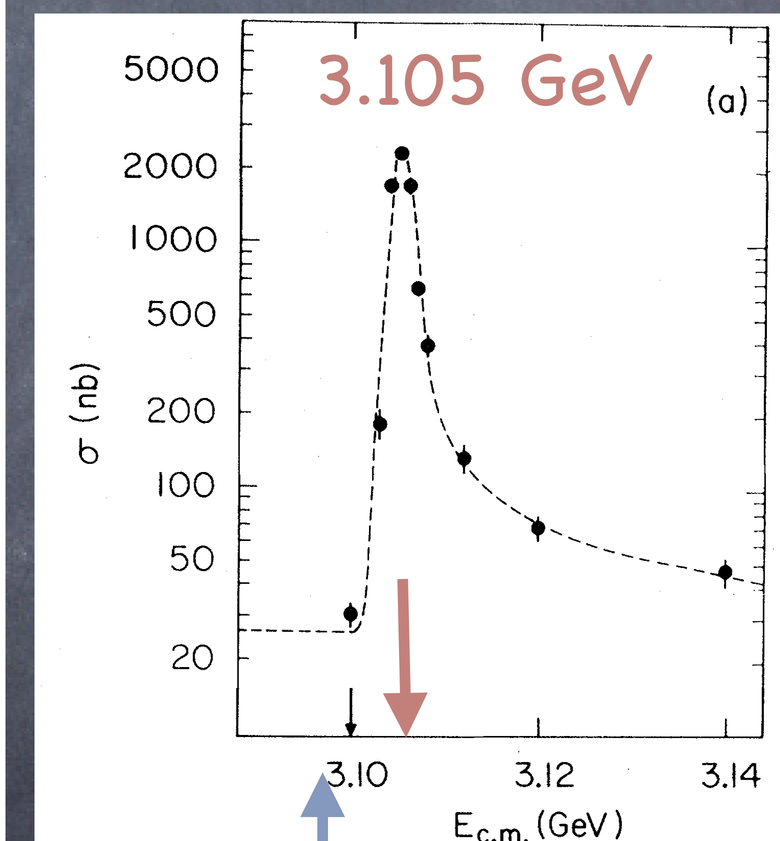
Adone in Frascati

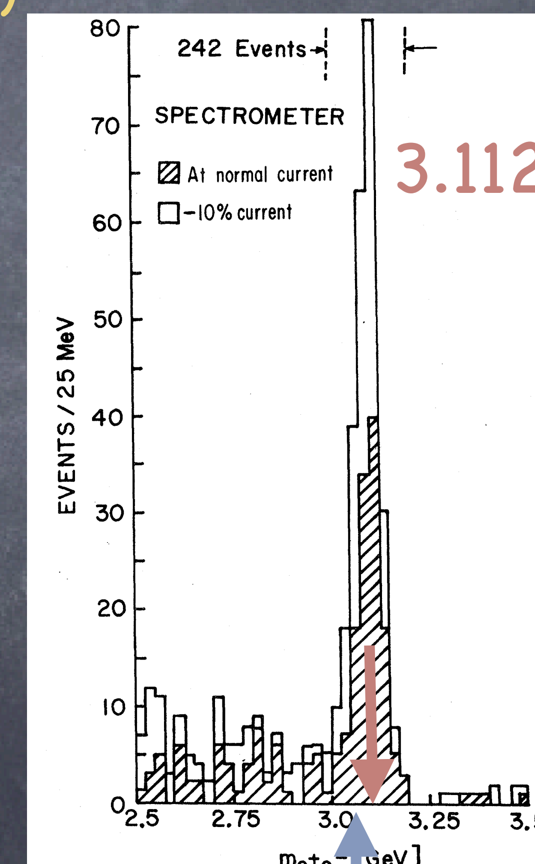
Energy matters! (Plus a little luck?)

Researchers at Frascati after notified by Ting, confirmed the J/ψ by pushing the e^+e^- energy just above the 3.0 GeV design limit

Interesting mass shift (absolute E miscalibration, c.f. relative E)







3.112 GeV

Correct mass

1976 Spear/Mark 1 results have the correct mass of 3.097 MeV

e^+e^- Colliders as a Study Tool

Ting's take on things detailed studies taken from his proposal

The best way to search for vector mesons is through production experiments of the type $p + p \rightarrow V^0 + X$. The reasons are:
$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow e^+e^-$

(a) The V^0 are produced via strong interactions, thus a high production cross section.

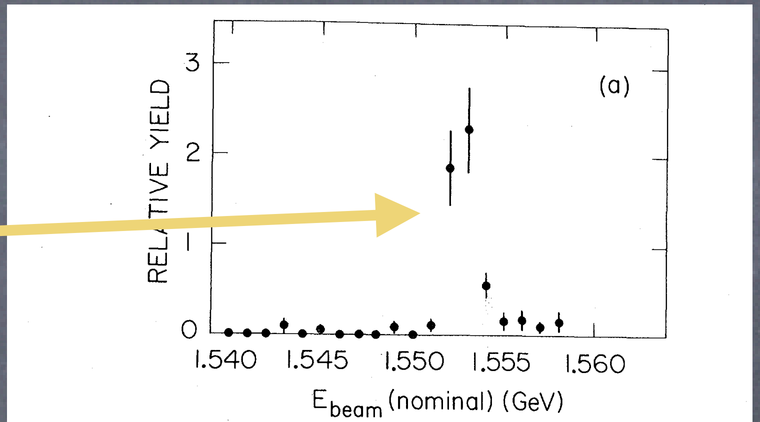
(b) One can use a high intensity, high duty cycle extracted beam.

(c) An e^+e^- enhancement limits the quantum number to 1^-, thus enabling us to avoid measurements of angular distribution of decay products.

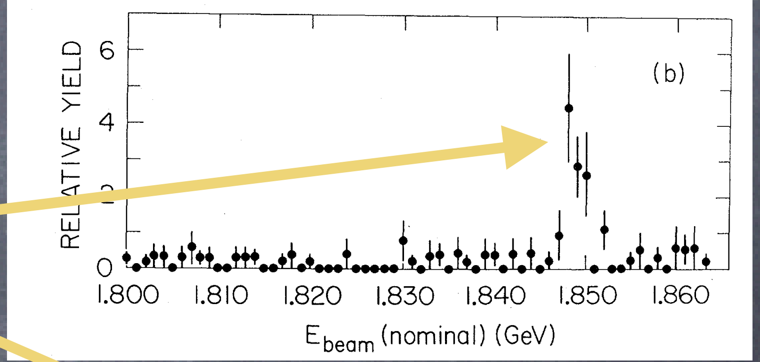
Contrary to popular belief, the e^+e^- storage ring is not the best place to look for vector mesons. In the e^+e^- storage ring, the energy is well-defined. A systematic search for heavier mesons requires a continuous variation and monitoring of the energy of the two colliding beams—a difficult task requiring almost infinite machine time. Storage ring is best suited to perform detailed studies of vector meson parameters once they have been found.

Now well recognized, e.g. LEP at CERN and SLD at SLAC to study the Z^0

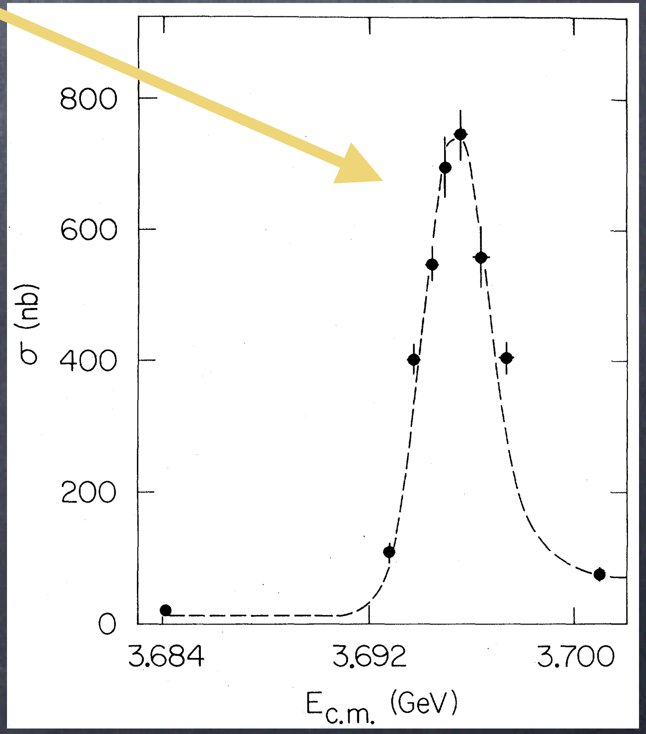
J/ψ



Mark 1 scan finds ψ' an excited $c\bar{c}$ state



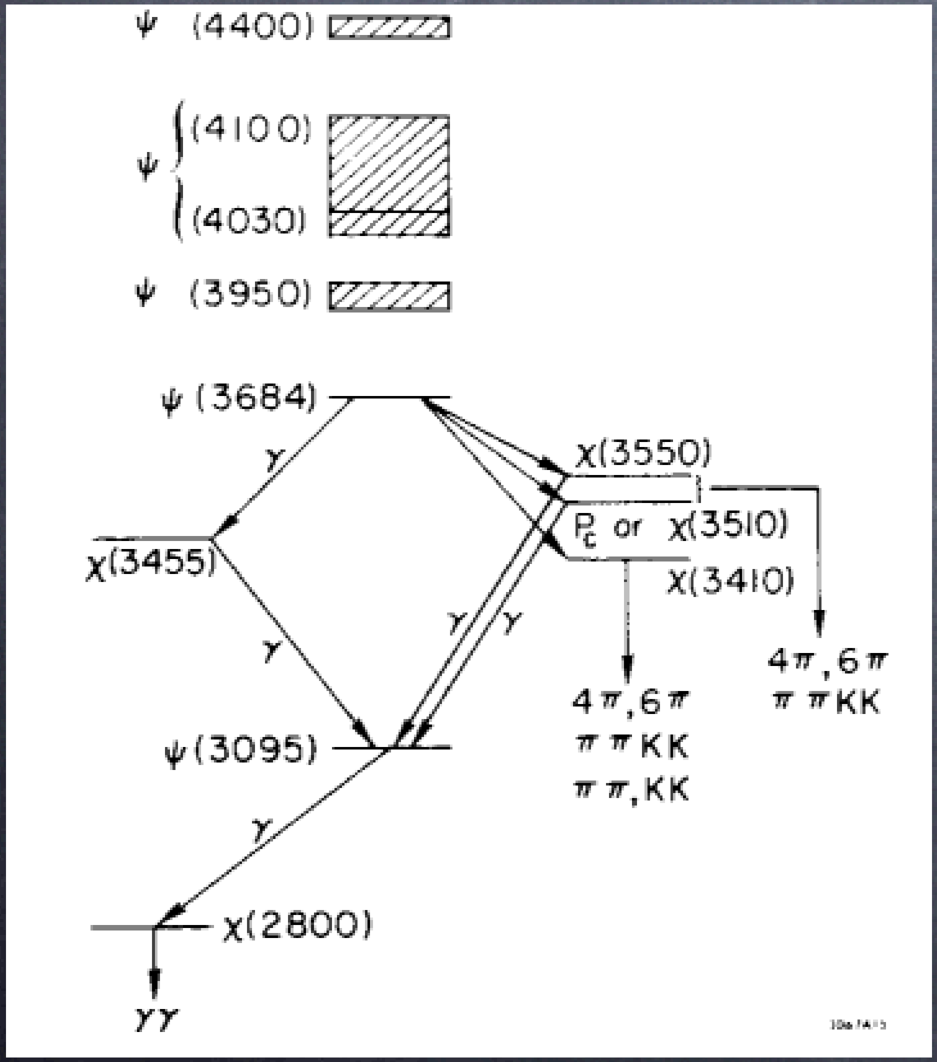
Can also measure decay branching ratios, discover other $c\bar{c}$ states through radiative decays and study the J^{PC} of the particles



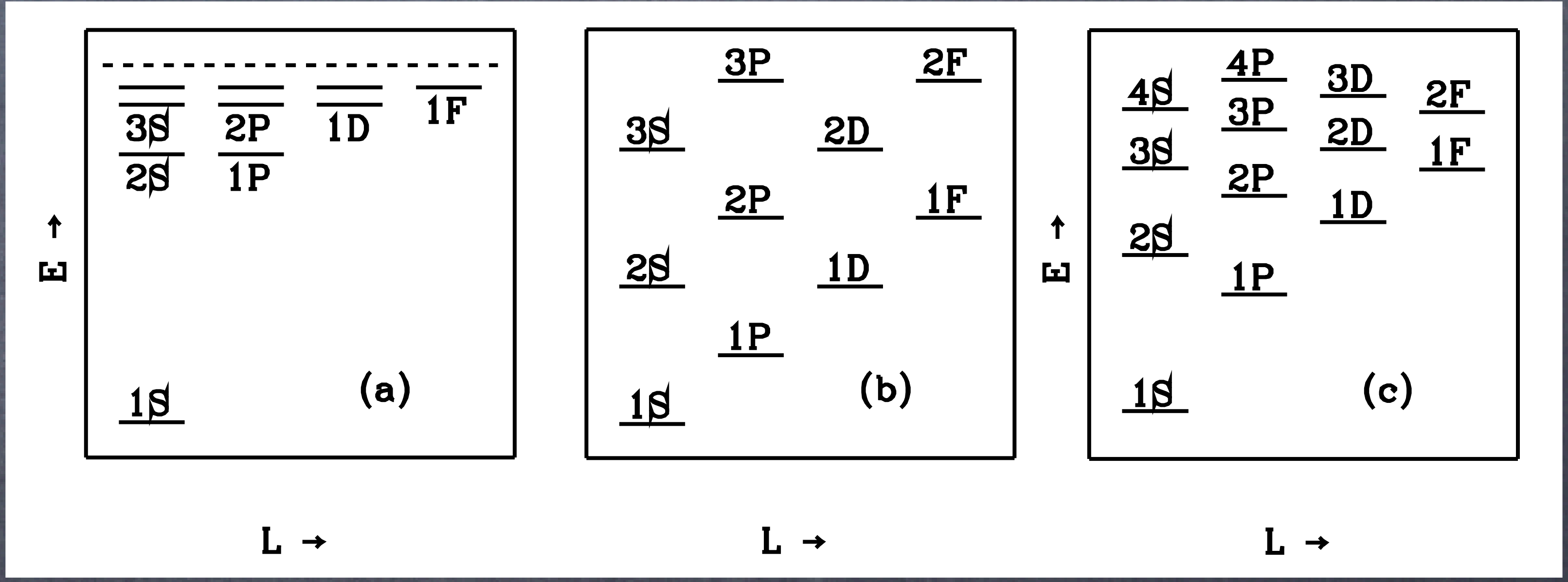
e^+e^- Colliders as a Study Tool

Detailed studies of $c\bar{c}$ spectroscopy detailed studies

Studies at SPEAR quickly lead to many energy levels



Can use the data to study the (strong force) potential between c and $\bar{c}$ quarks

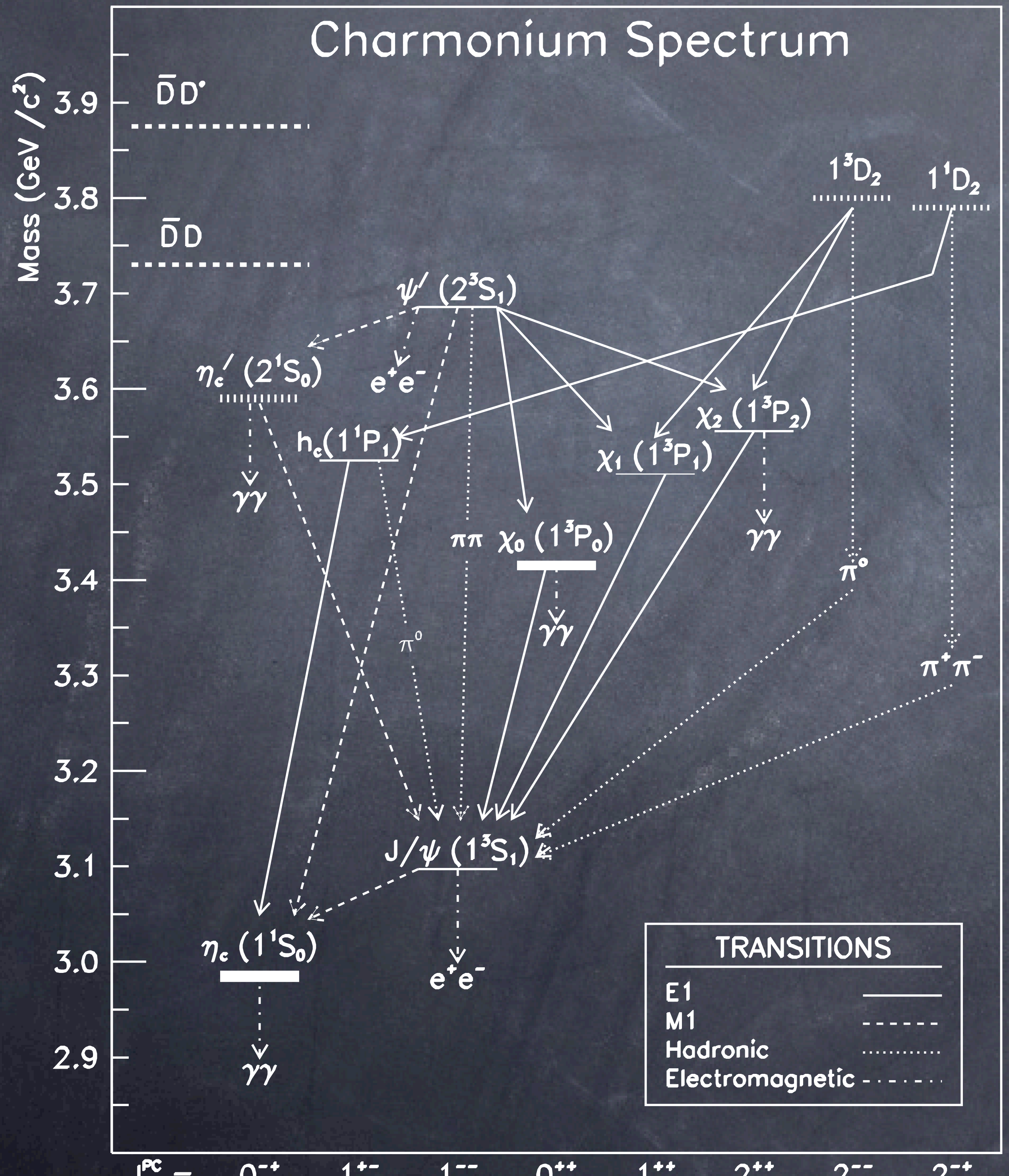


$$V(r) \sim \frac{1}{r} \qquad V(r) \sim r^2 \qquad V(r) \sim \ln(r)$$

We need to see more energy levels

Resolutions Again

e^+e^- can only produce $J^{PC} = 1^{--}$ states directly



Difficult to see states above the open charm threshold (strong decay)

See non-$J^{PC} = 1^{--}$ states via EM decays of ψ' and J/ψ states. Resolution limited to EM calorimeter resolution and the level of background can be high

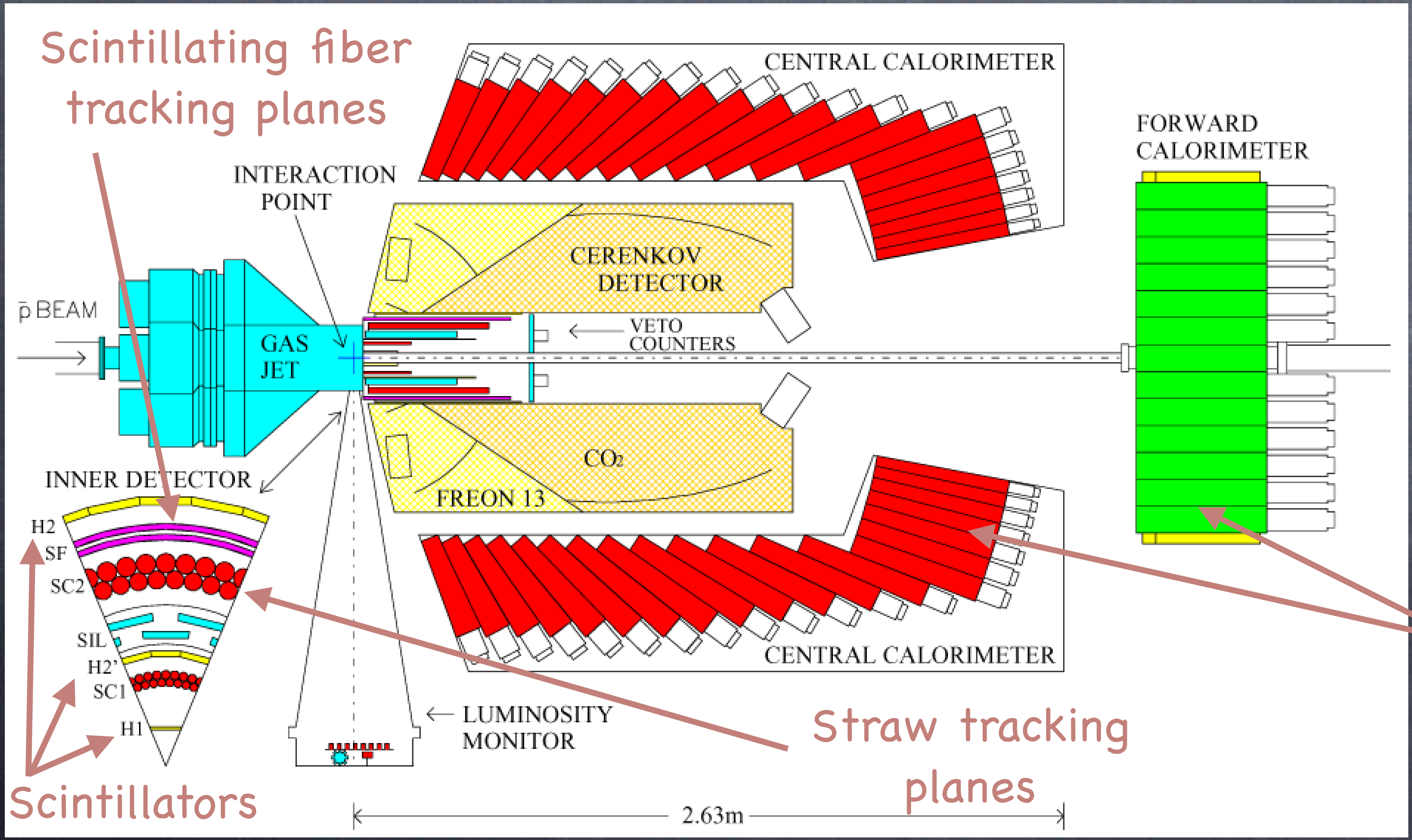
How can we do better?

Low Energy $p\bar{p}$

R704 at CERN ISR and E760, E835 at Fermilab

$p\bar{p}$ annihilation can create $c\bar{c}$ states of any JPC

Use an antiproton accumulator and a hydrogen-jet target

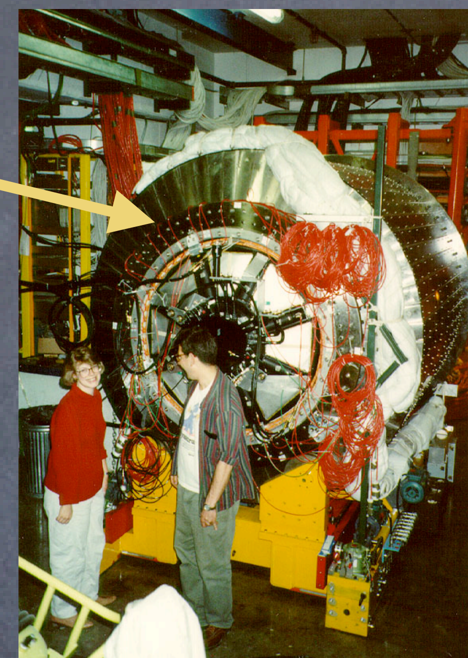


- H-jet of 10^{13-14} atoms/cm^3
- decelerate to required $\bar{p}$ Energy
- cool $\bar{p}$ to get $\Delta p/p = 2\times10^{-4}$
- 0.01% (0.5MeV) in M_{pp} resolution

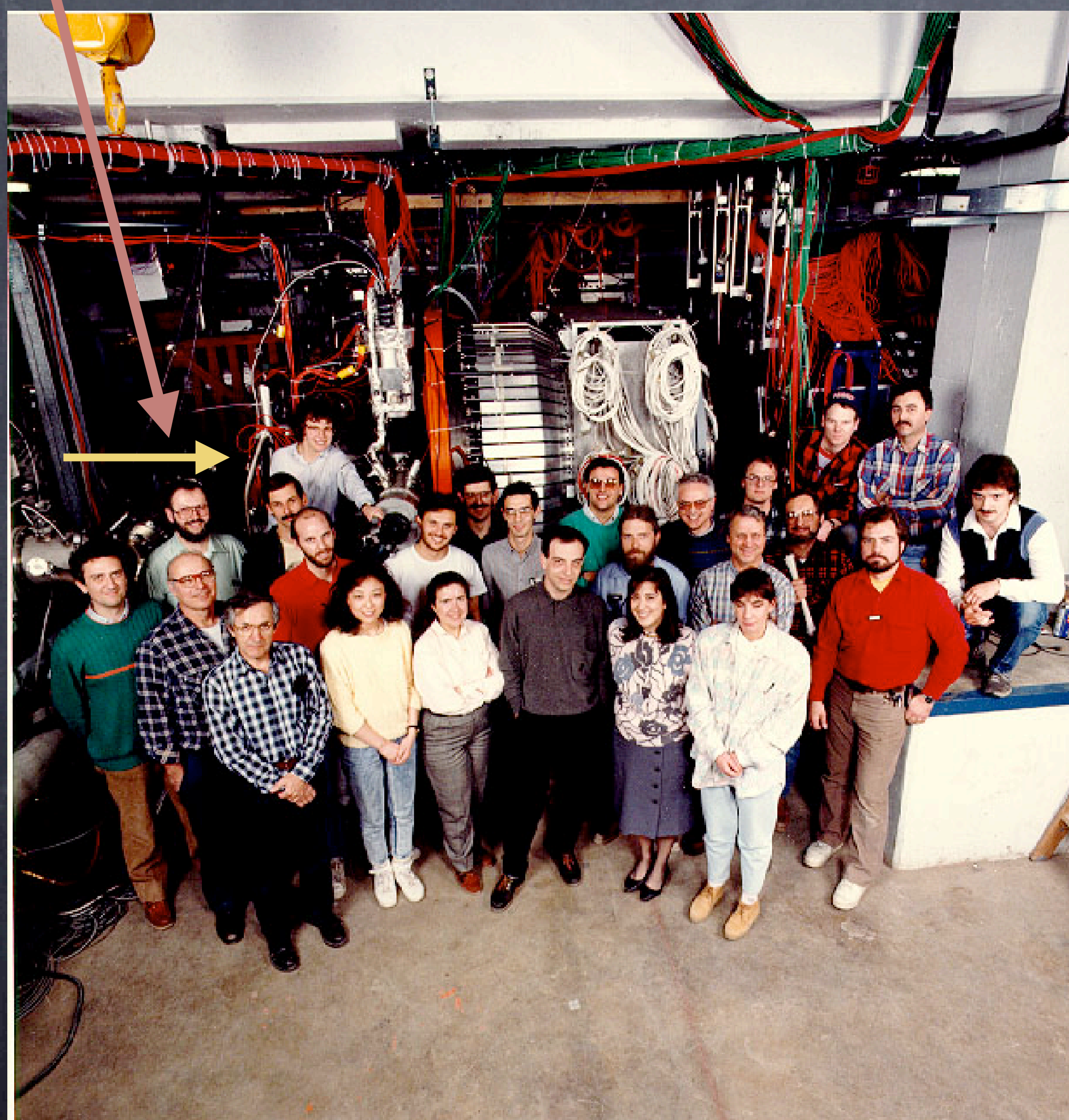
Pb-glass blocks EM calorimeter

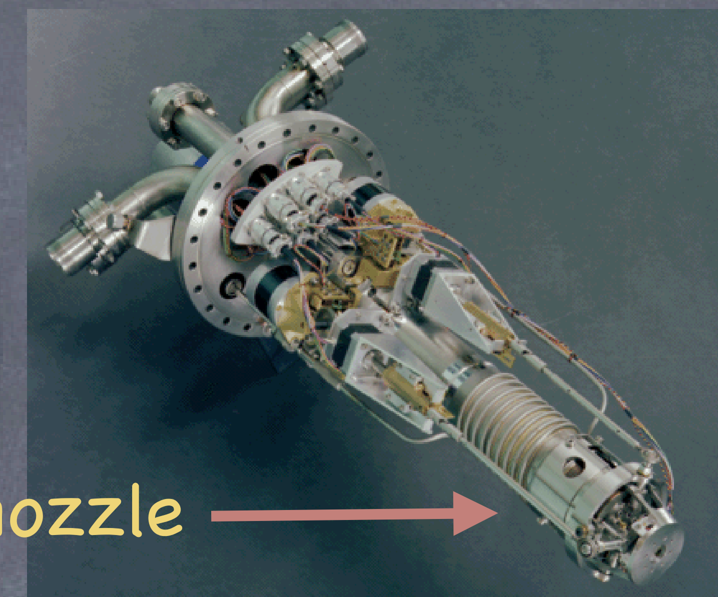
Fermilab E760 and E835

Pb-glass calorimeter



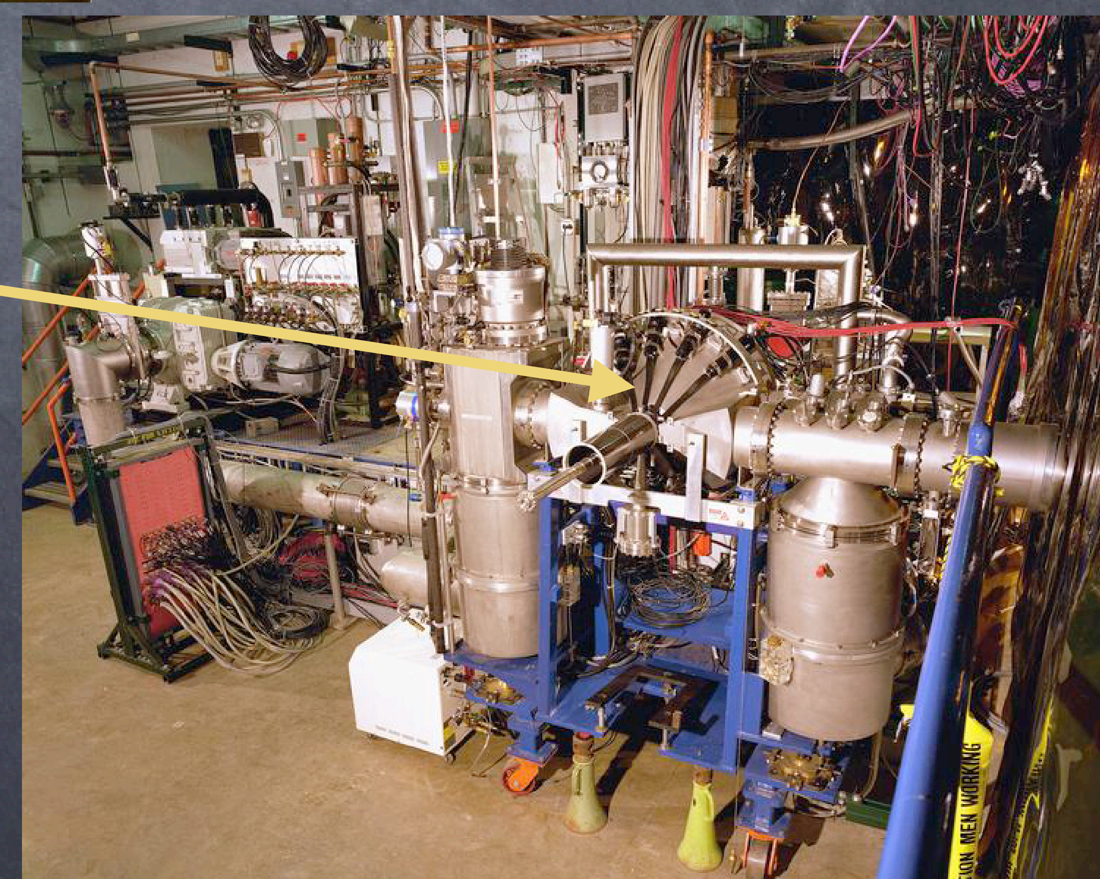
Beam





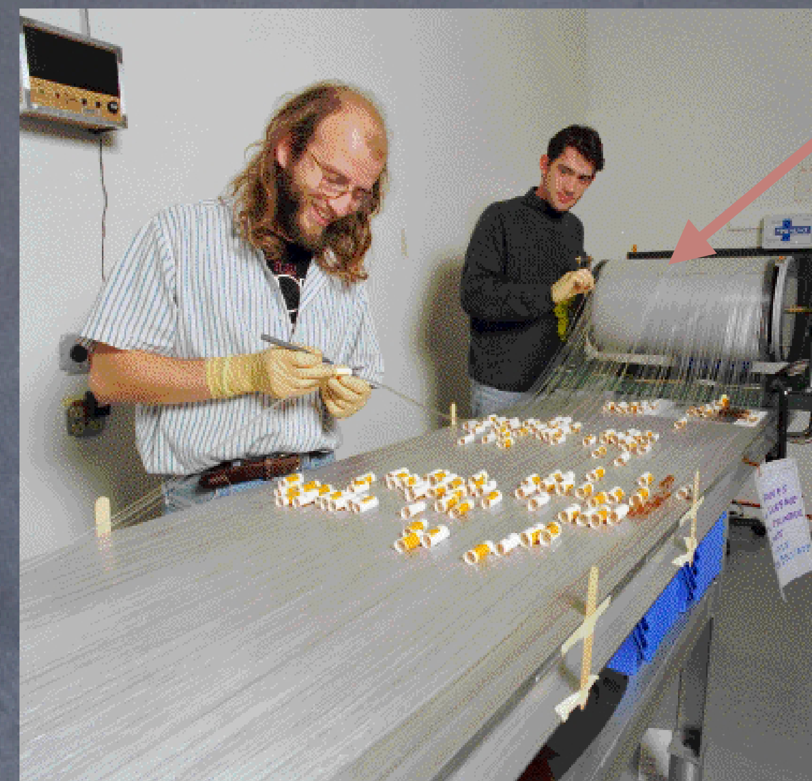
Jet nozzle

Jet target



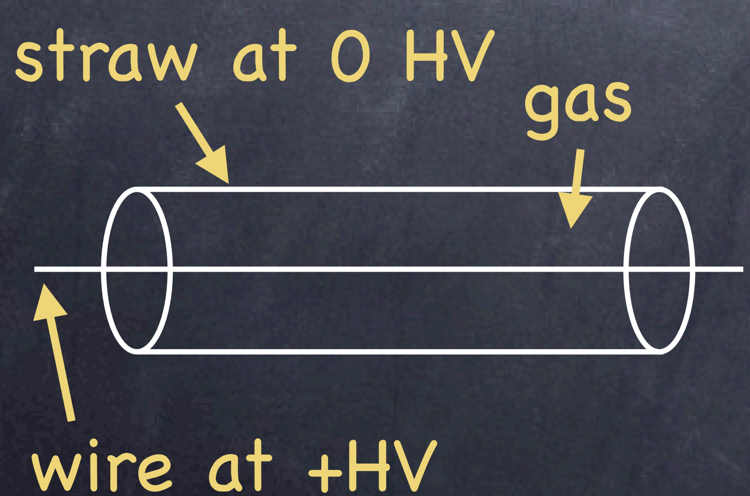
Fermilab E760 and E835

Lead glass blocks

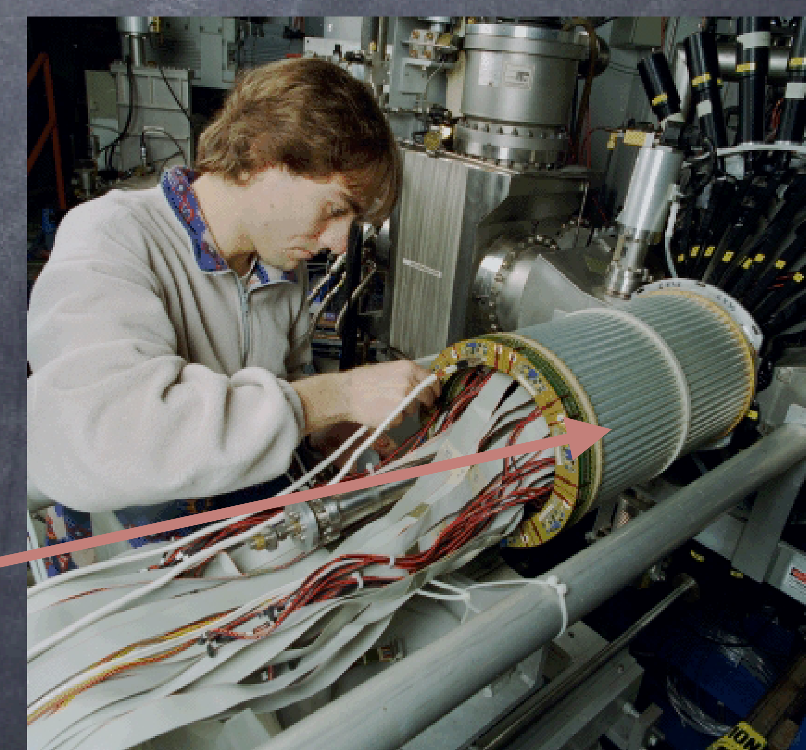


Scintillating fiber detector uses scintillator fibers ~ 1mm diameter

Requires special low photon detectors



Straw chambers are like MWPC's but each wire is inside a straw (cathode) and is its own little wire chamber (good for high rates) diammeters ~ 4-10mm

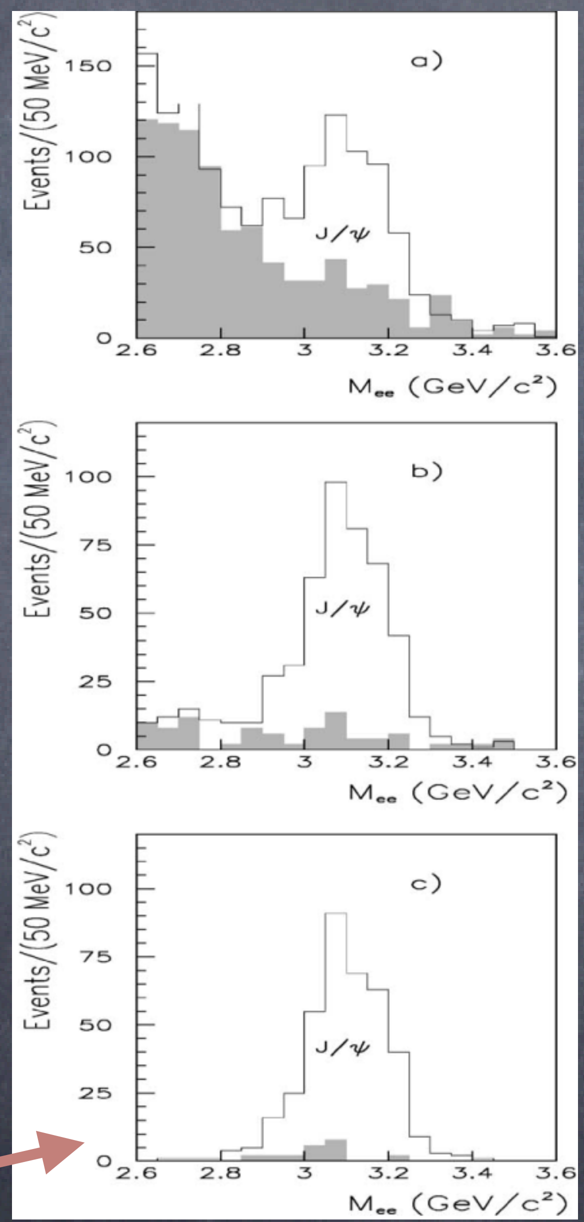


E760/E835 Results

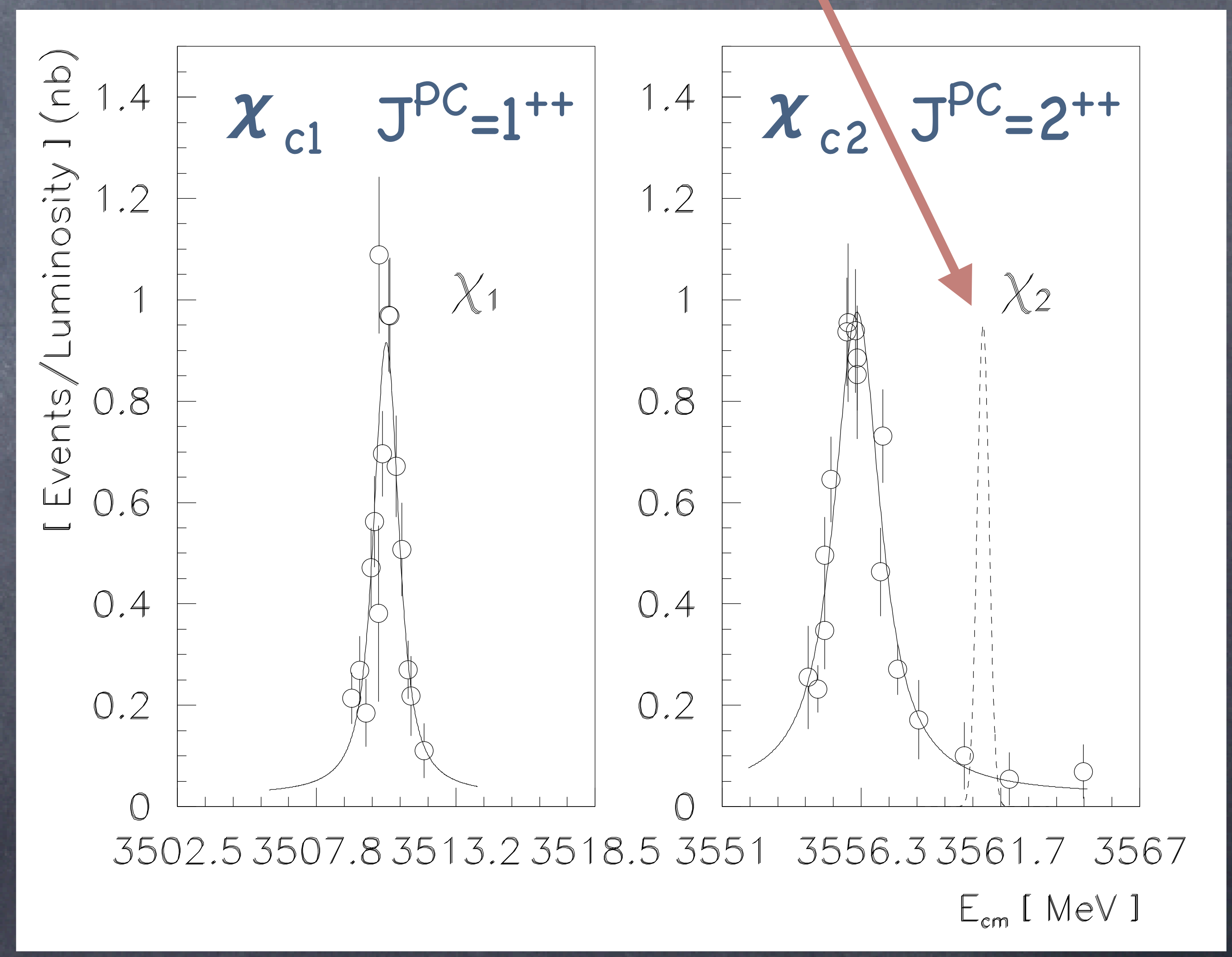
Electron and photon tagging

The challenge is the probability of producing charm is only 10^{-5} compared to all hadrons

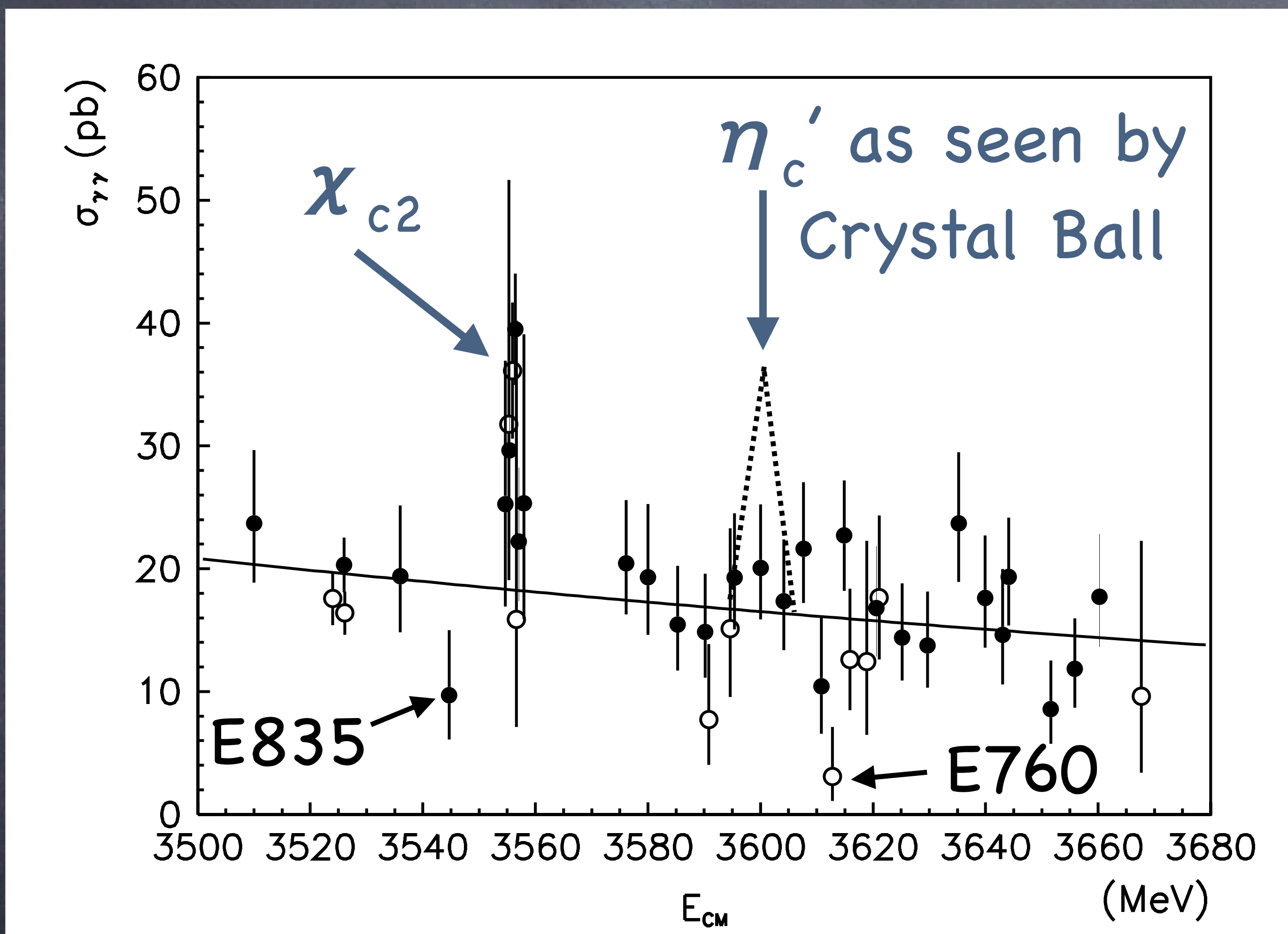
But can get good S/B by looking at EM decays to $e^{\pm}$, photons or π^0 e.g.



Get excellent 0.5 MeV mass resolution by counting signal events at each beam energy



Future in cc Spectroscopy?



There is no future planned experiment
<u>Usually experiments are driven by the physics</u>
Probably awaiting better Lattice QCD results!

Even now the situation is still not clear, the η_c' ($J^{PC}=0^{-+}$) was reported by Crystal Ball but not confirmed by E835

The h_1 ($J^{PC}=1^{+-}$) state seen by E760 is not yet confirmed by E835

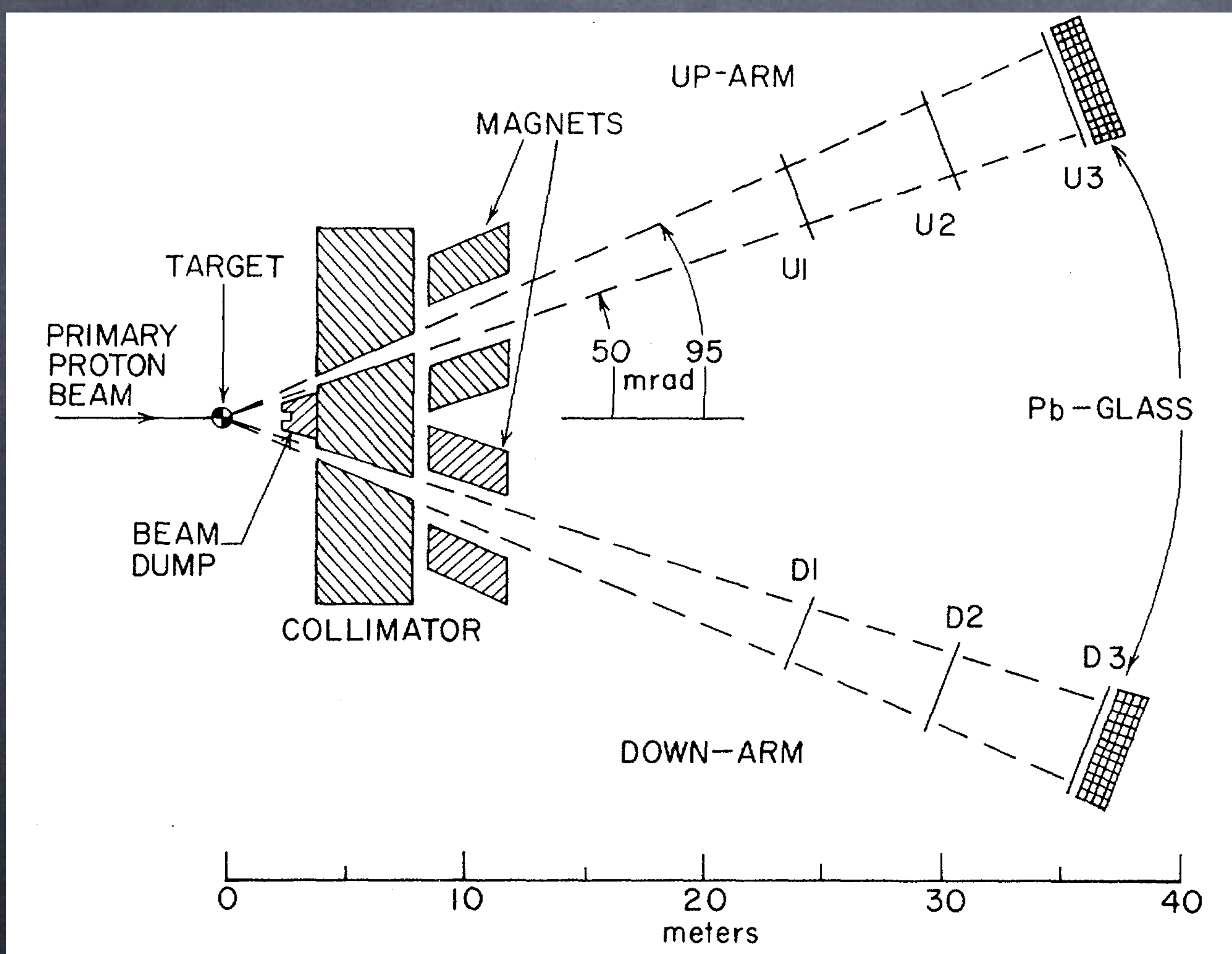
Would like better Lattice QCD results, e.g. for 1P-1S splittings to extract a competitive value for $\sin^2\theta_W$

End by Looking at 2 Solutions to the $\mu^+\mu^-$ Design Problem

Lederman's Solution

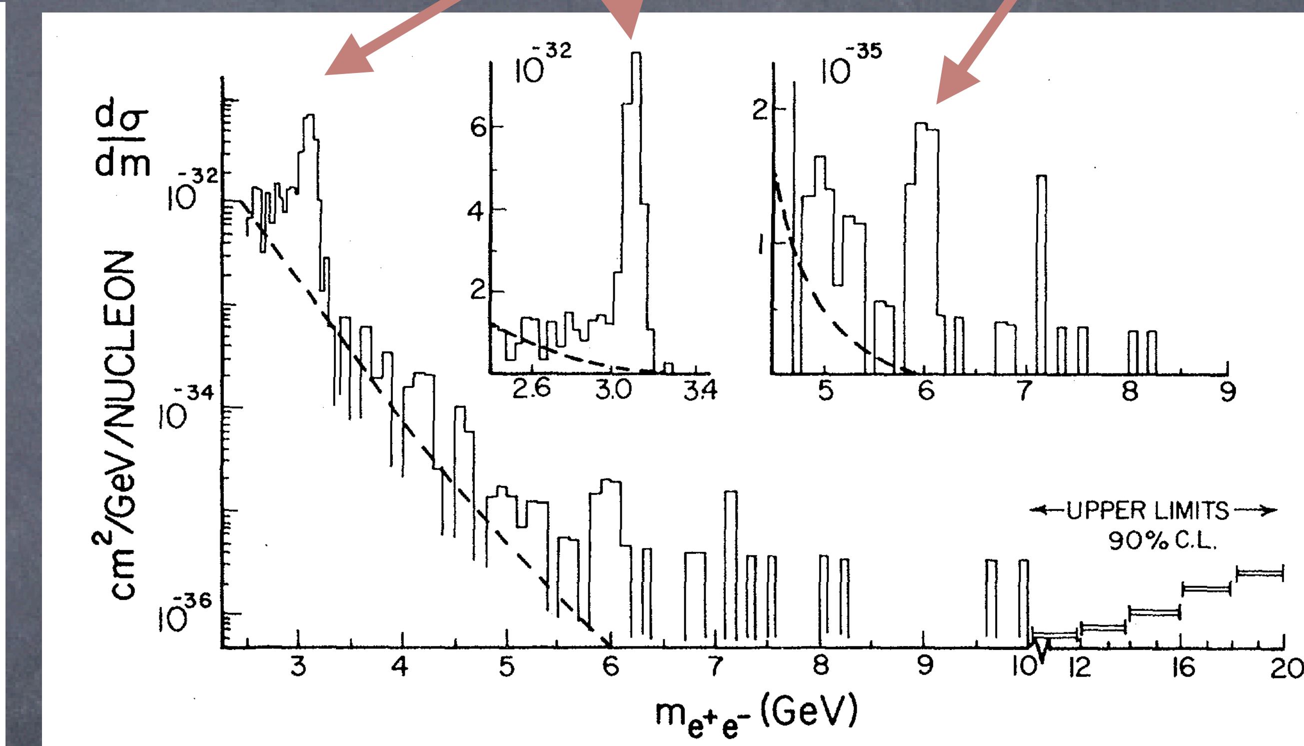
A Solution for e^+e^-

Studied hadronic interactions at higher energies at Fermilab (1976). First with electrons



J/ψ

Peak?



Observed the J/ψ with electrons

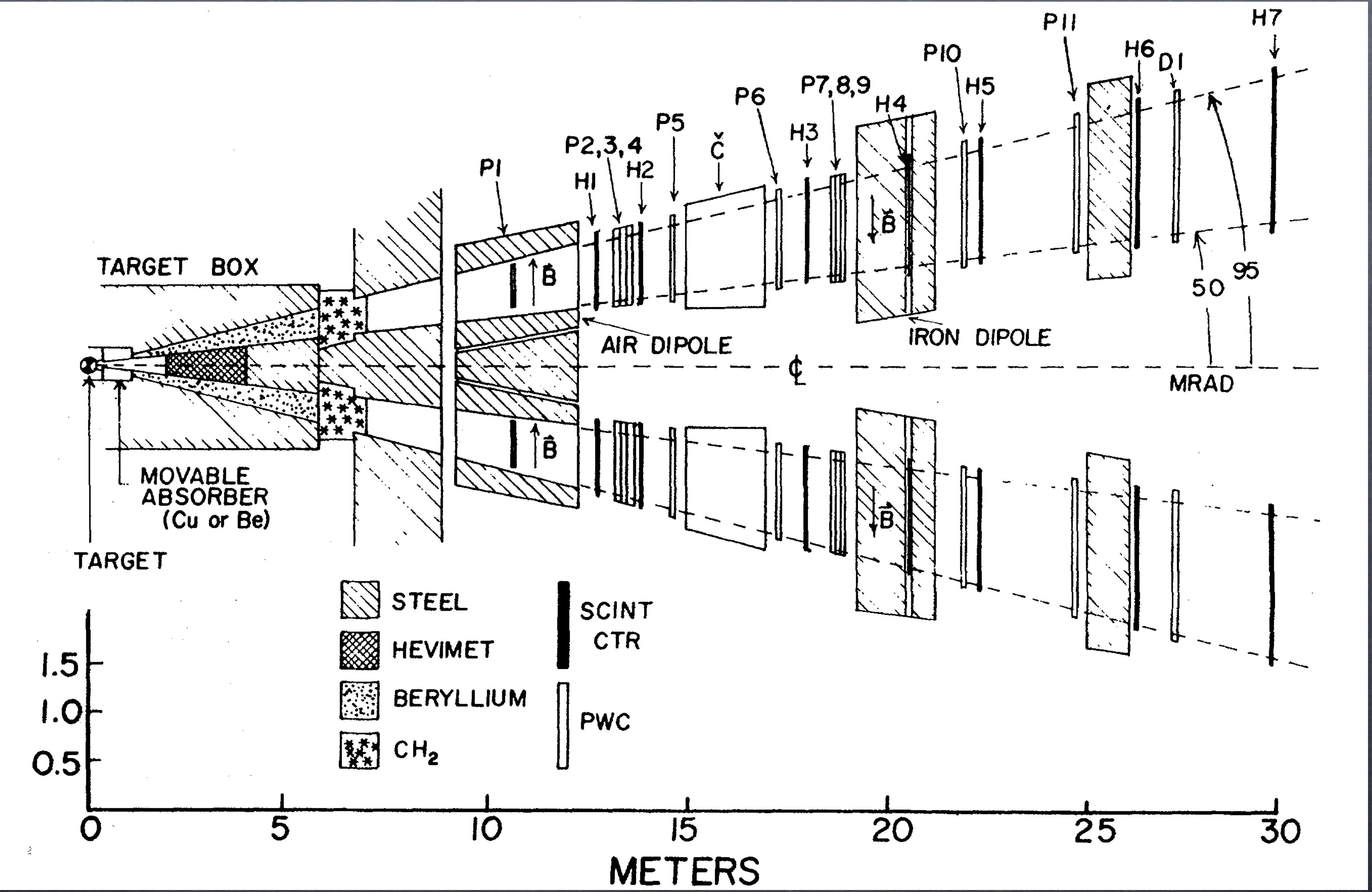
They claimed an possible observation of a narrow peak at M_{ee} = 6 GeV/c^2 turned out to be wrong....

Lederman's Solution 2

A Solution for $\mu^+\mu^-$

This 1977 version is a vastly more complicated spectrometer than the one in 1970!

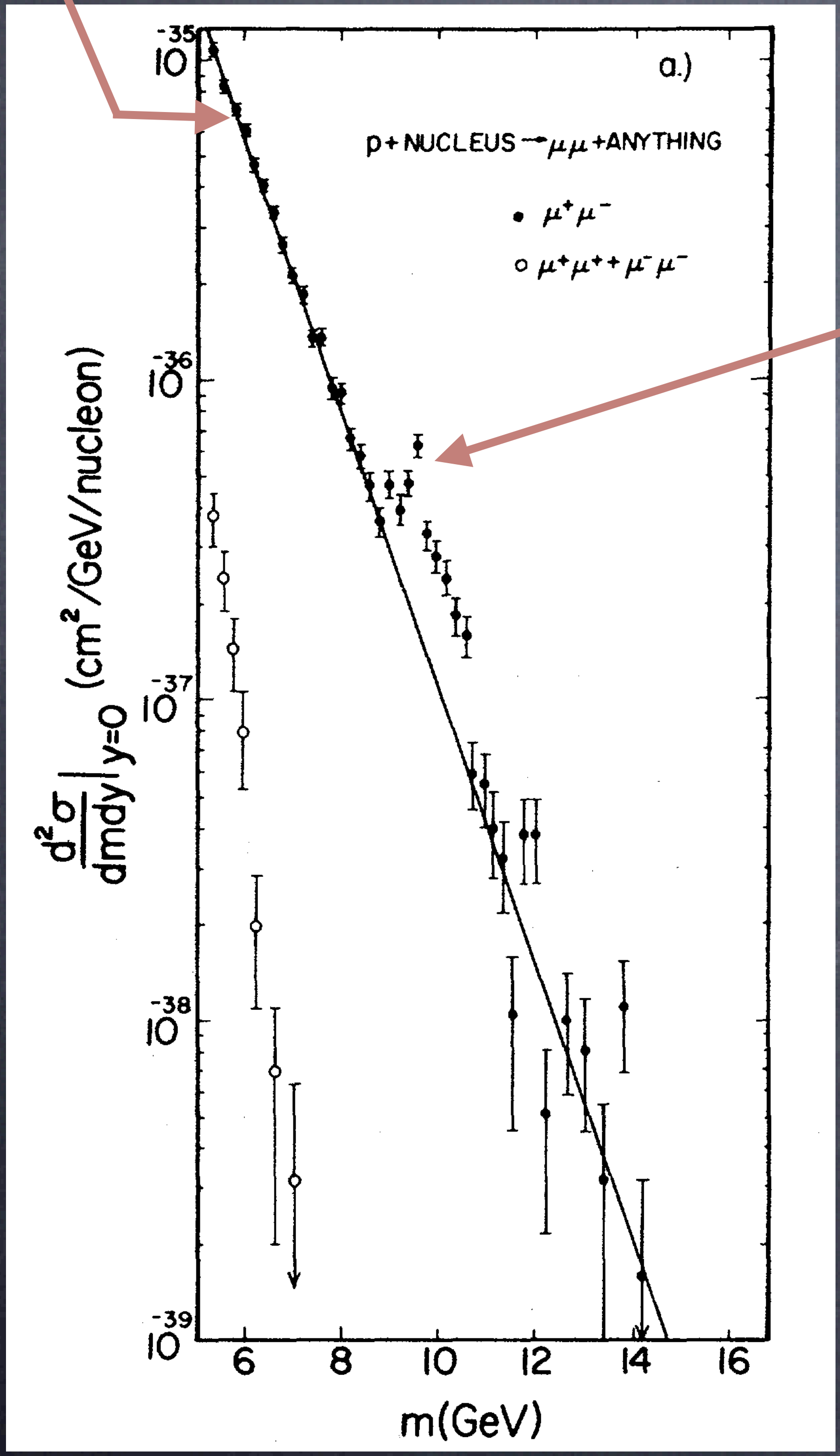
However you should recognize all the parts and what they are for



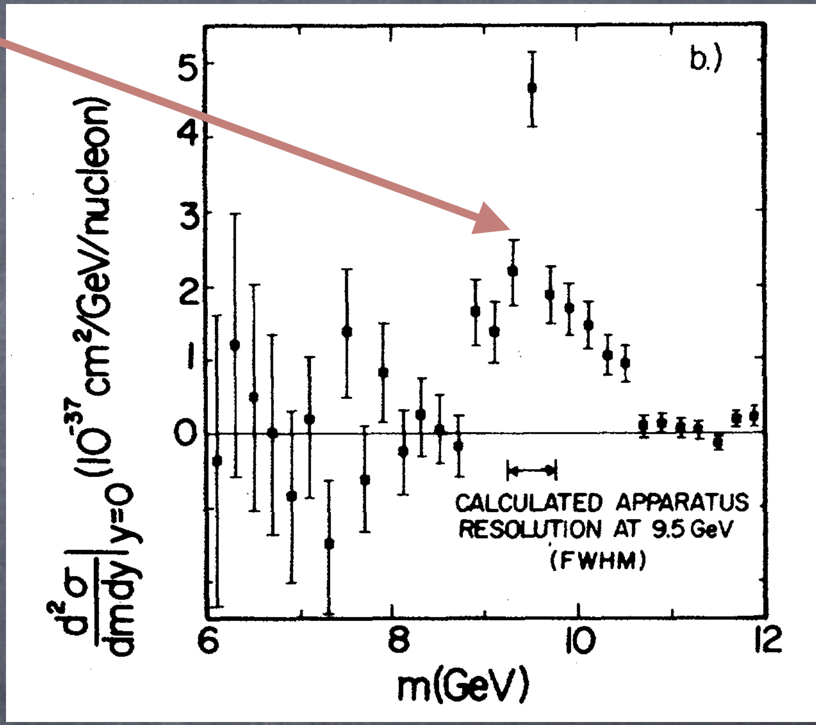
Lederman's Solution 2

Discovery of ϒ and the 5th quark

A fit to background



The $M_{\mu\mu}$ spectrum shows a clear peak!



The $M_{\mu\mu}$ peak is actually due to the ϒ and excited ϒ states that are not resolved

So Lederman finds the ϒ but no longer worthy of a Nobel!

However Leon Lederman gets a Nobel Prize (1988) anyway for the discovery of the muon-neutrino in 1962

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.