Experimental Techniques in Particle Physics

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Physics 312, April 24th 2000

Some Definitions…

- **Particle** – the propagation of momentum, energy, and other "information" through space-time.
- **Force -** something which changes a particle in some way (sometimes to a different particle).

The Standard Model – The Fundamental Particles

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

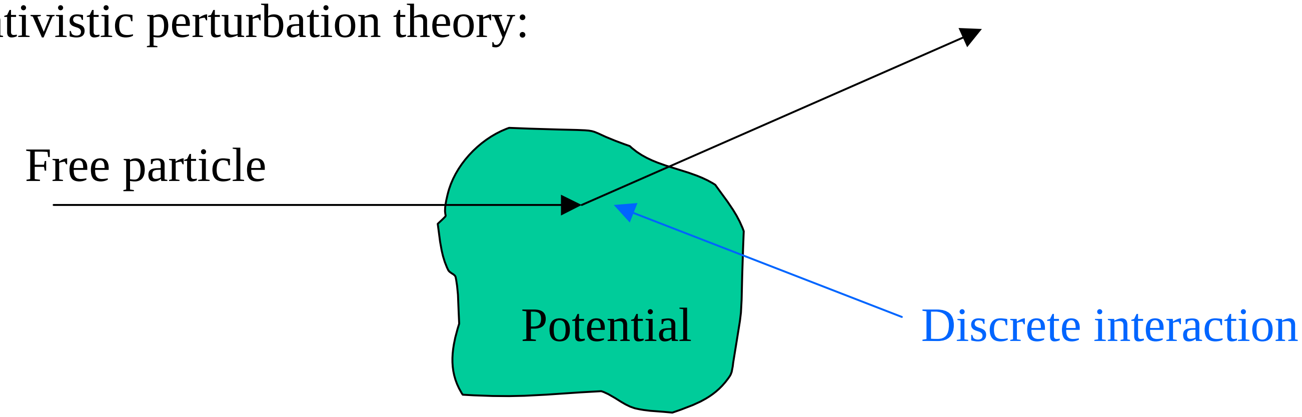
Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	−1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	−1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	−1

Quarks spin = 1/2

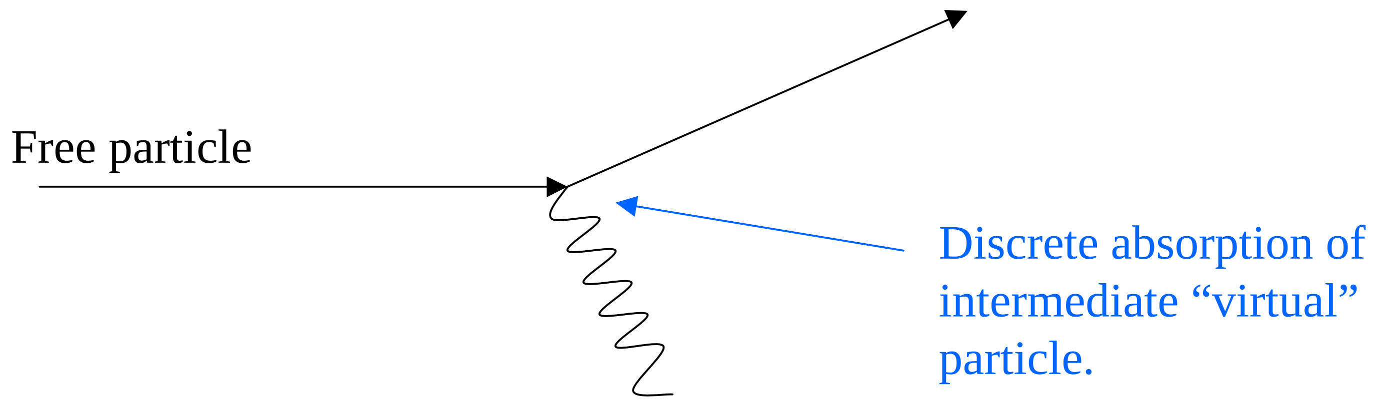
Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	−1/3
c	charm	1.3	2/3
s	strange	0.1	−1/3
t	top	175	2/3
b	bottom	4.3	−1/3

Relativistic Quantum Mechanical Perturbation Theory

Non-relativistic perturbation theory:



Relativistic perturbation theory “Feynman Diagram”:



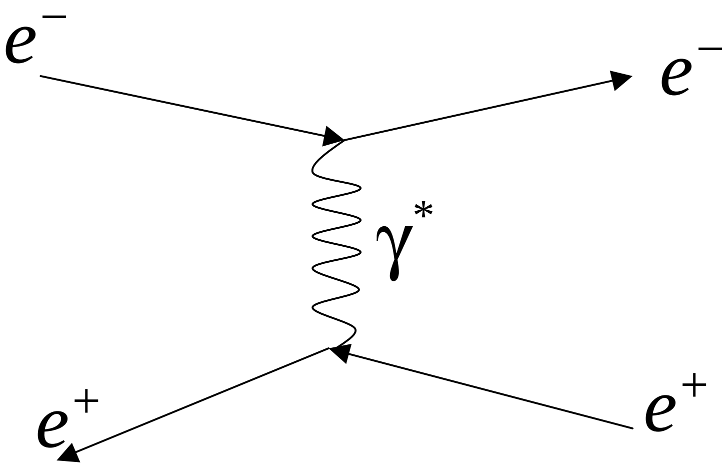
The Intermediate Vector Bosons (Mediators of Force)

BOSONS force carriers spin = 0, 1, 2, ...

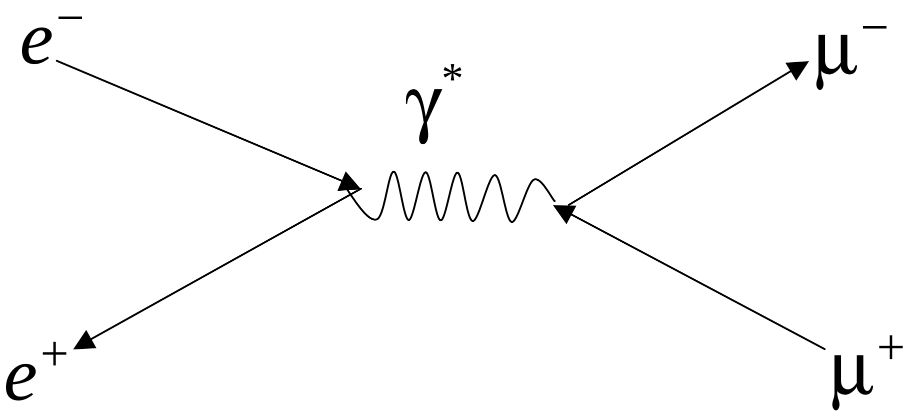
Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Some Basic QED Interactions

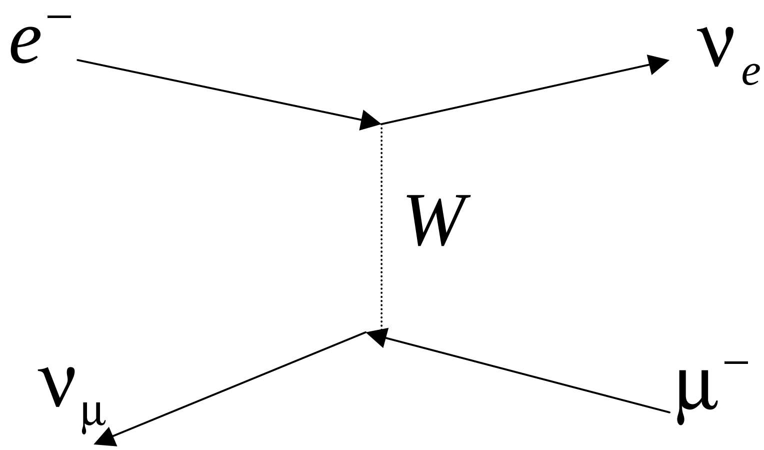


e^+e^- scattering

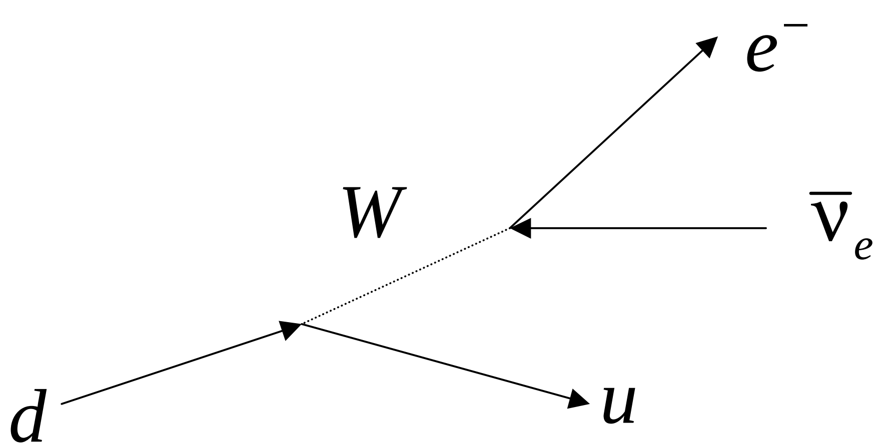


e^+e^- annihilation

Some Basic Weak Interactions

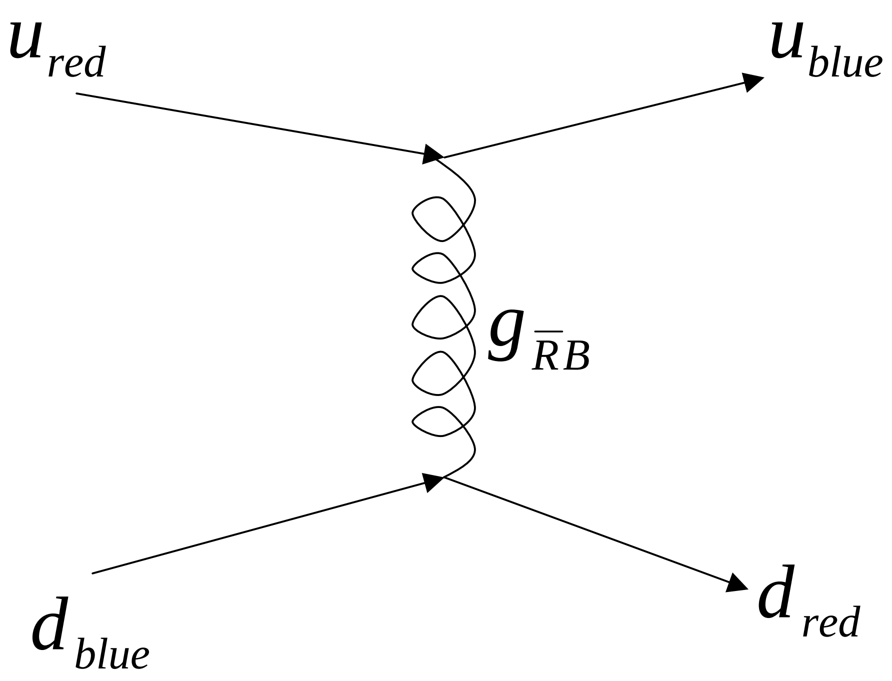


eν scattering



β decay

Some Basic Strong Interaction (QCD)



The Fundamental Forces

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	60	Not applicable to quarks
Strength relative to electromag for two protons in nucleus	10^{-36}	Not applicable to hadrons	20

Property \ Interaction	Weak (Electroweak)	Electromagnetic (Electroweak)
Acts on:	Flavor	Electric Charge
Particles experiencing:	Quarks, Leptons	Electrically charged
Particles mediating:	W^+ W^- Z^0	γ
Strength relative to electromag for two u quarks at: 10^{-18} m	0.8	1
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-4}	1
Strength relative to electromag for two protons in nucleus	10^{-7}	1

How Quarks Combine

- Quarks come in three "colors": red, green, blue
- Combine to form "colorless" (white) particles:
  - Three quarks (or antiquarks), one of each color ⇒ "Baryons"
  - A quark of one color and an anti-quark of the associated anti-color ⇒"Mesons"

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

The Big Questions in Particle Physics

- What is the origin of mass?
  - The standard model diverges if we just “plug-in” a mass for all the particles.
  - An *effective* mass comes in through the interaction with a pervasive field with a non-zero vacuum expectation value.
  - Perturbations about this vacuum give us a “Higgs Particle”, which probably has a mass 100 GeV< m < 1TeV
- What is the nature of CP violation?
  - The physics of matter in a right-handed universe is *almost* the same as that for anti-matter in a left-handed universe.
  - This small difference is *accomodated* in the standard model by complex terms in the quark mixing matrix.
  - This must be firmly established, and if true, the associated parameters must be measured.

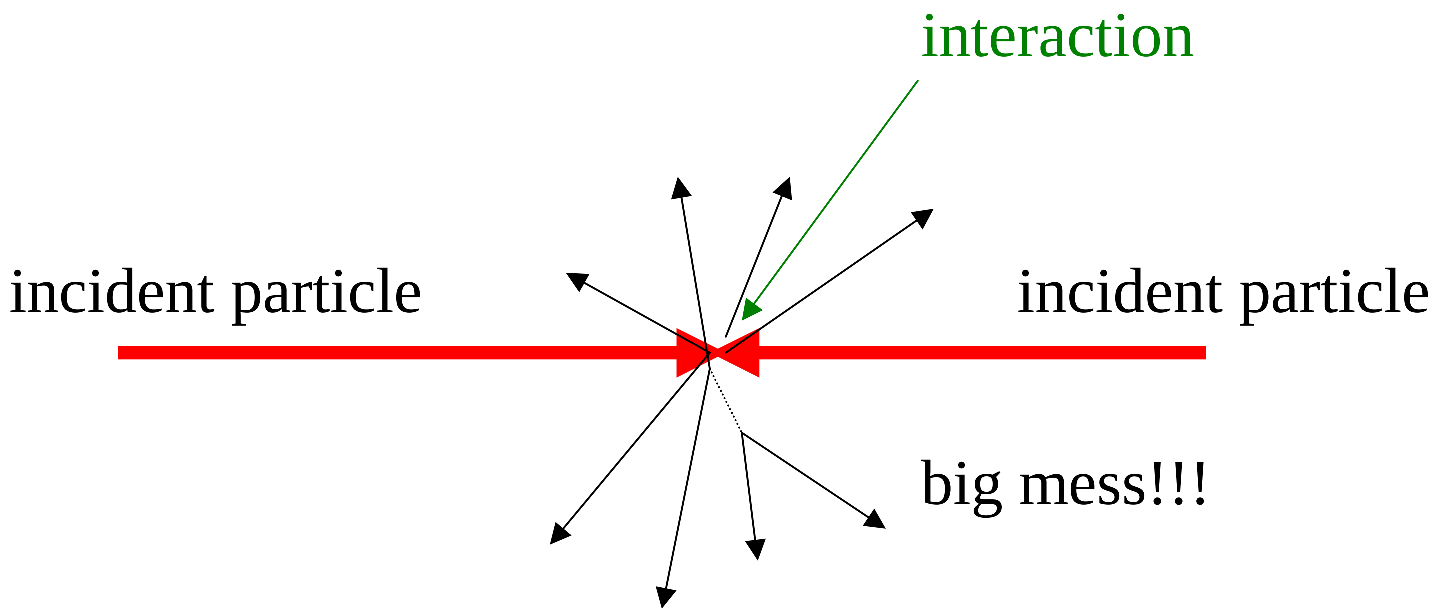
Big Questions (cont'd…)

- Do neutrinos have mass/do they mix?
  - In the Standard Model, all neutrino masses are zero *by definition.*
  - There is growing evidence that neutrinos do have mass.
    - Solar neutrino deficit.
    - Atmospheric neutrino "problem".
    - LSND result.
  - If true this could explain the "dark matter" in the universe, at least partially.
  - Must be verified, and if true, the details must be studied.

Big Questions (cont'd…)

- What lies beyond?
  - The standard model eventually diverse
  - There is a philosophical (aesthetic? religious?) impulse to unify the quark and the lepton sectors, as well as include gravity.
    - Supersymmetry (SUSY):
      - Every fermion is associated with a boson.
      - Predicts a veritable zoo of new particles, the lightest of which should have m<2TeV.
    - String theory
      - All particles are states of fundamental objects (strings)
      - Supersymmetry is a consequence.
  - As yet, absolutely no experimental evidence for either of these theories. Must keep looking.

What we Actually Study



What We Actually Detect

- Almost all of the particles of most interest to us are very unstable; we must detect them *indirectly* through their decay products.
- Everything in the universe ultimately decays to

$$\gamma, e^-, p, \boxed{\nu_e, \nu_\mu, \nu_\tau} + \text{anti-particles}$$

CANNOT be individually detected

- In addition, the following particles live long enough ($c\tau > 1$m) to be detected *directly*:

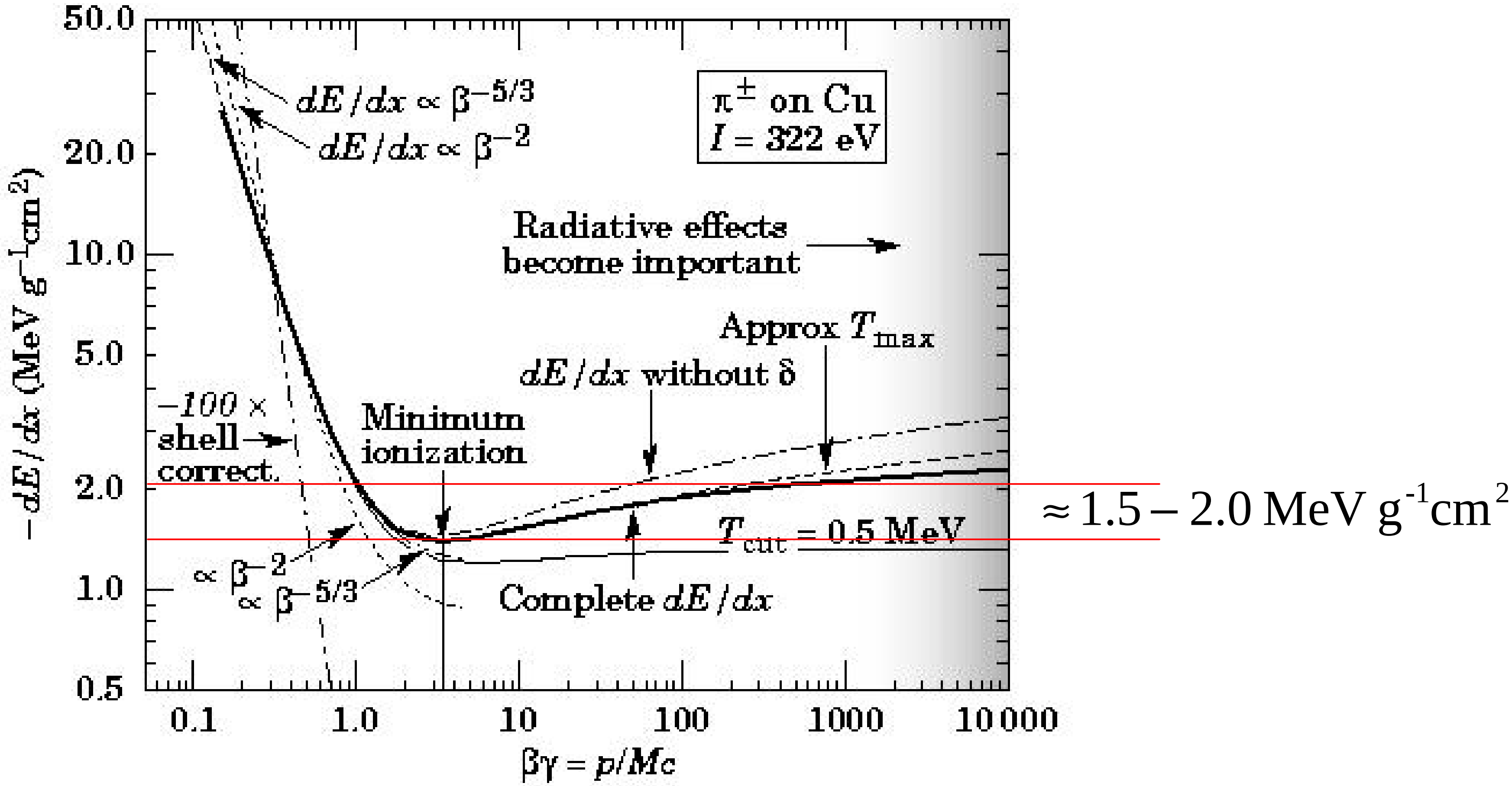
$$n, \pi^+, \mu^-, K^+, K_L + \quad \text{anti-particles}$$

Classes of Particle Detection

- Charged Particle Tracking
  - Precision: decay position determination.
  - Spectroscopy: measure momentum in conjunction with magnetic field.
  - Projection: match information from different detectors.
- Calorimetry
  - Electromagnetic: measure energy of photons, identify electrons.
  - Hadronic: measure energy of neutral hadrons, identify types of charged particles.
- Particle Identification
  - Indirect: based on interaction characteristics
  - Direct: determine mass by measuring velocity
    - dE/dX
    - Time-of-flight
    - Cerenkov Radiation

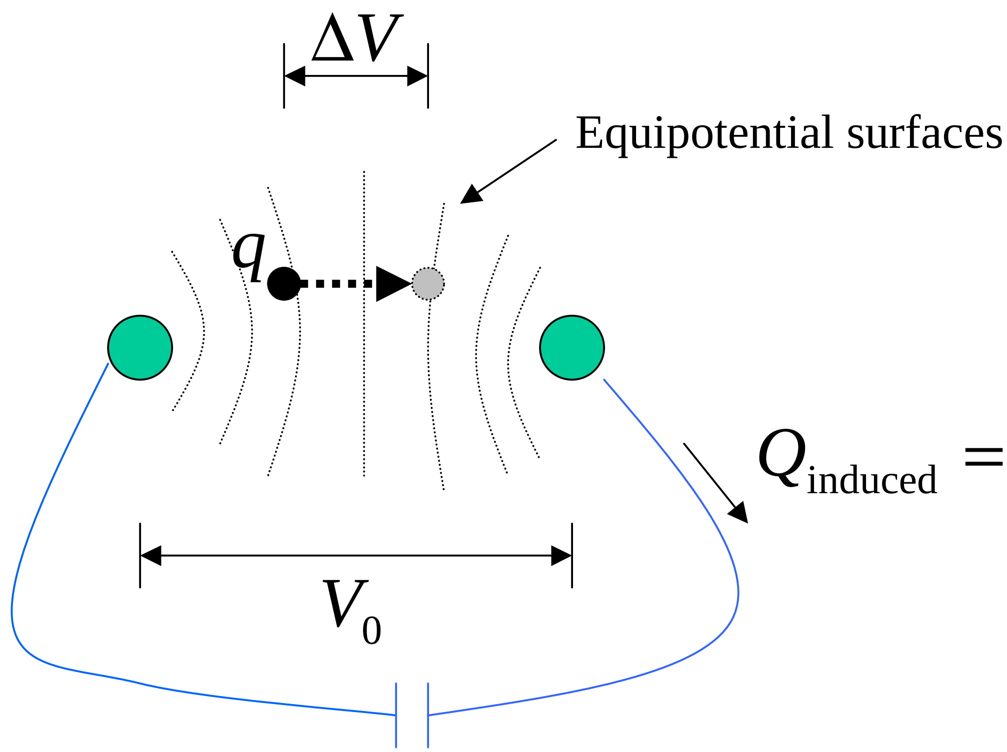
Charged Particle Tracking

- As charged particles traverse matter, they deposit energy according to the Bethe-Bloch equation:



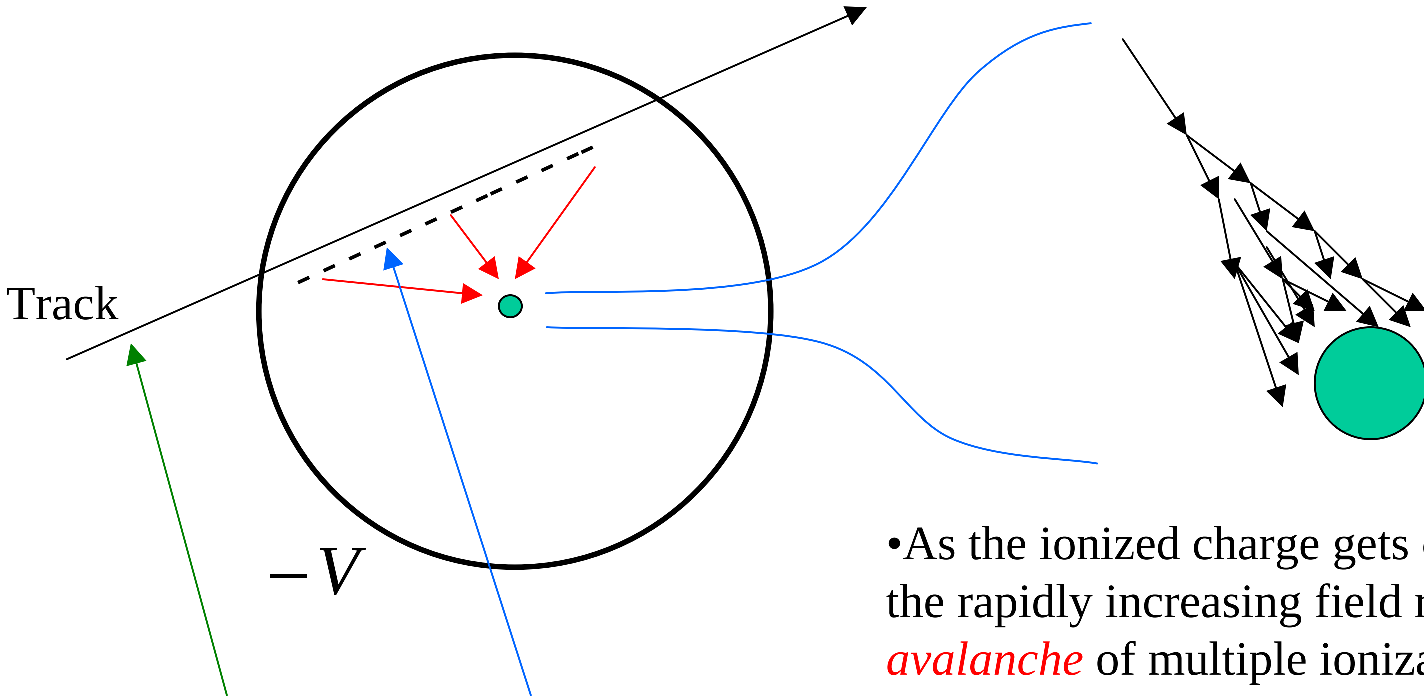
The Detection of Charge

- Ultimately almost all types of detectors work through the detection of *ionized charges*, which *induce* electrical signals as they *move*.



$$Q_{\text{induced}} = q\frac{\Delta V}{V_0}$$

Proportional Wire Chambers



•A charged particle ionizes gas molecules as it passes.

•This ionized charge *drifts* toward a wire which is held a relatively positive potential.

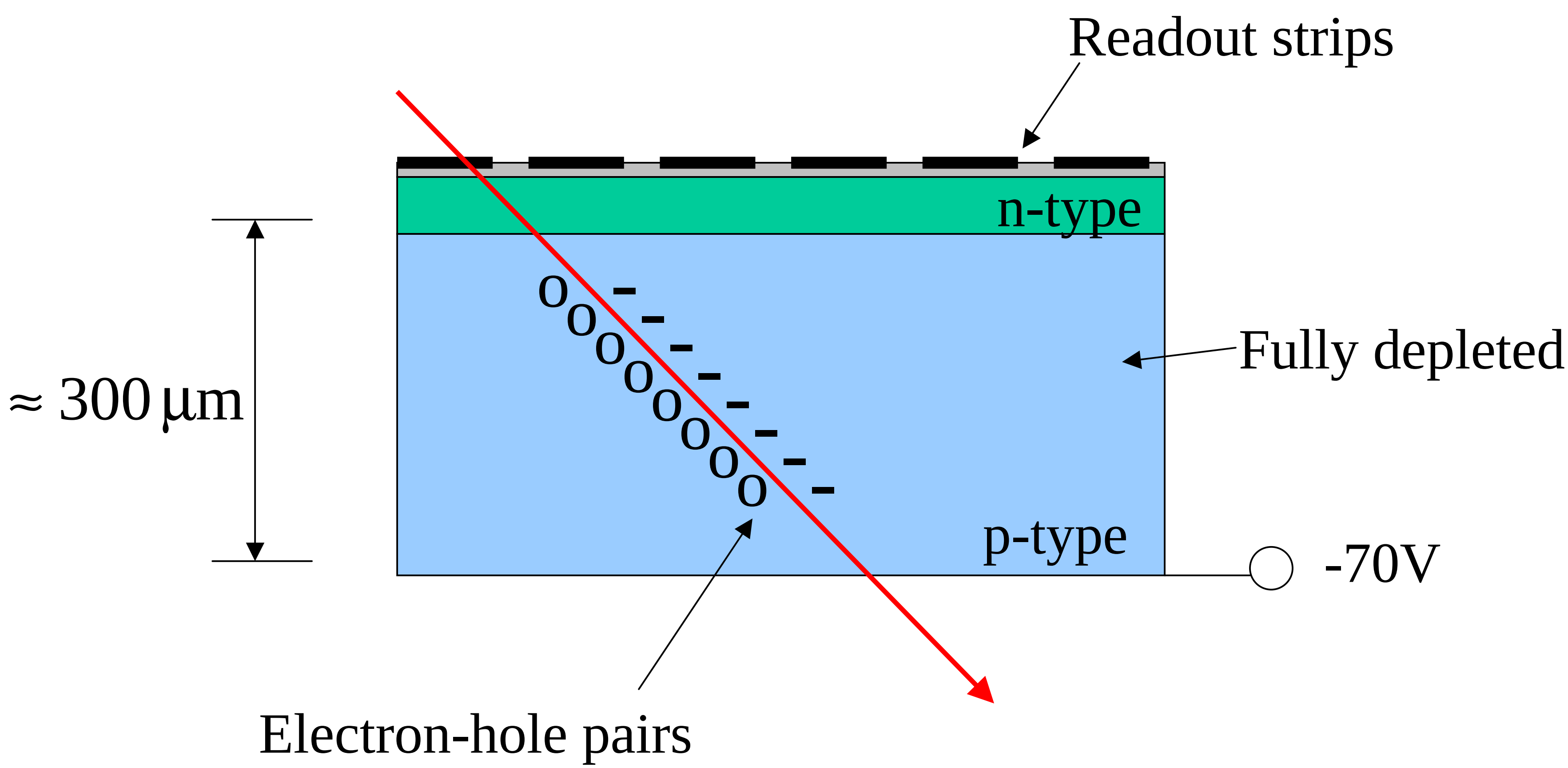
•As the ionized charge gets close to the wire, the rapidly increasing field results in an *avalanche* of multiple ionization.

•The motion of the resulting *ions* away from the wire *induces* a signal.

•The total signal is *proportional* to the total ionized charge.

•The *time* of the signal can accurately measure the *position* of the track.

Silicon Detectors



Typical Charged Tracking Resolution

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10 to 150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	$\geq$ 300 μm[b,c]	50 ns	200 ns
Drift chamber	50 to 300 μm	2 ns[d]	100 ns
Scintillator	—	150 ps	10 ns
Emulsion	1 μm	—	—
Silicon strip	$\frac{\text{pitch}}{3\text{ to }7}$[e]	[f]	[f]
Silicon pixel	2 μm[g]	[f]	[f]

[a] Multiple pulsing time.

[b] 300 μm is for 1 mm pitch.

[c] Delay line cathode readout can give $\pm$150 μm parallel to anode wire.

[d] For two chambers.

[e] The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim$ 25 μm) with pulse-height-weighted center finding.

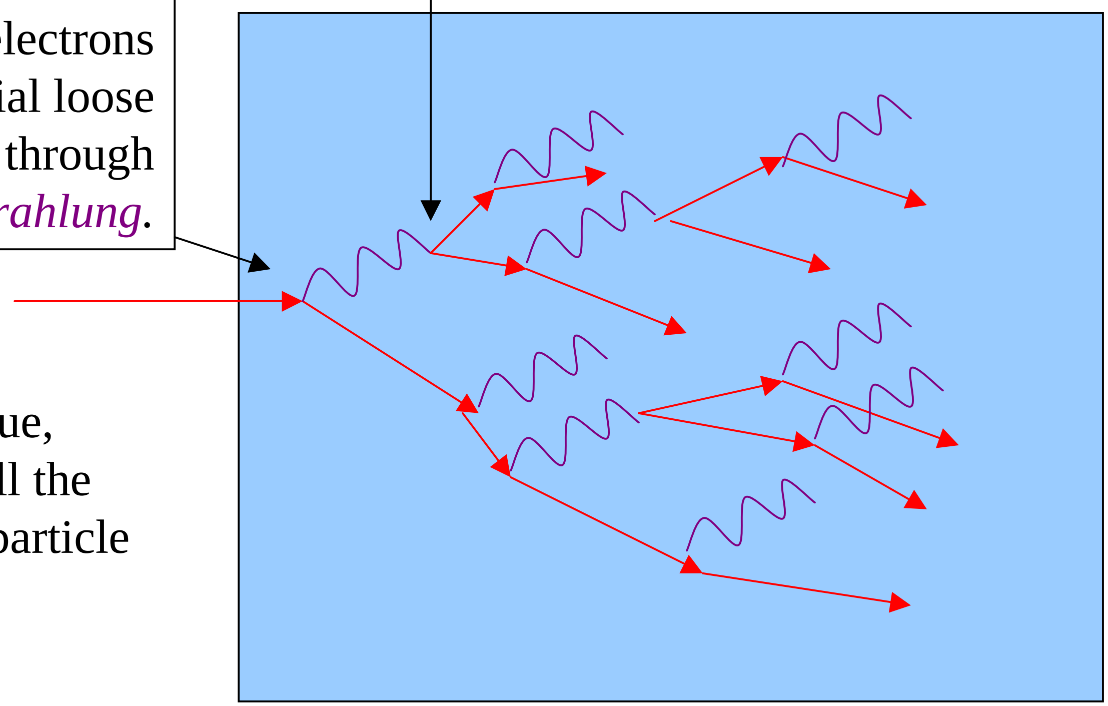
[f] Limited at present by properties of the readout electronics. (Time resolution of $\leq$ 15 ns is planned for the SDC silicon tracker.)

[g] Analog readout of 34 μm pitch, monolithic pixel detectors.

Electromagnetic Calorimetry

Energetic photons in material can convert to e+e- pairs through Bethe-Heitler pair production

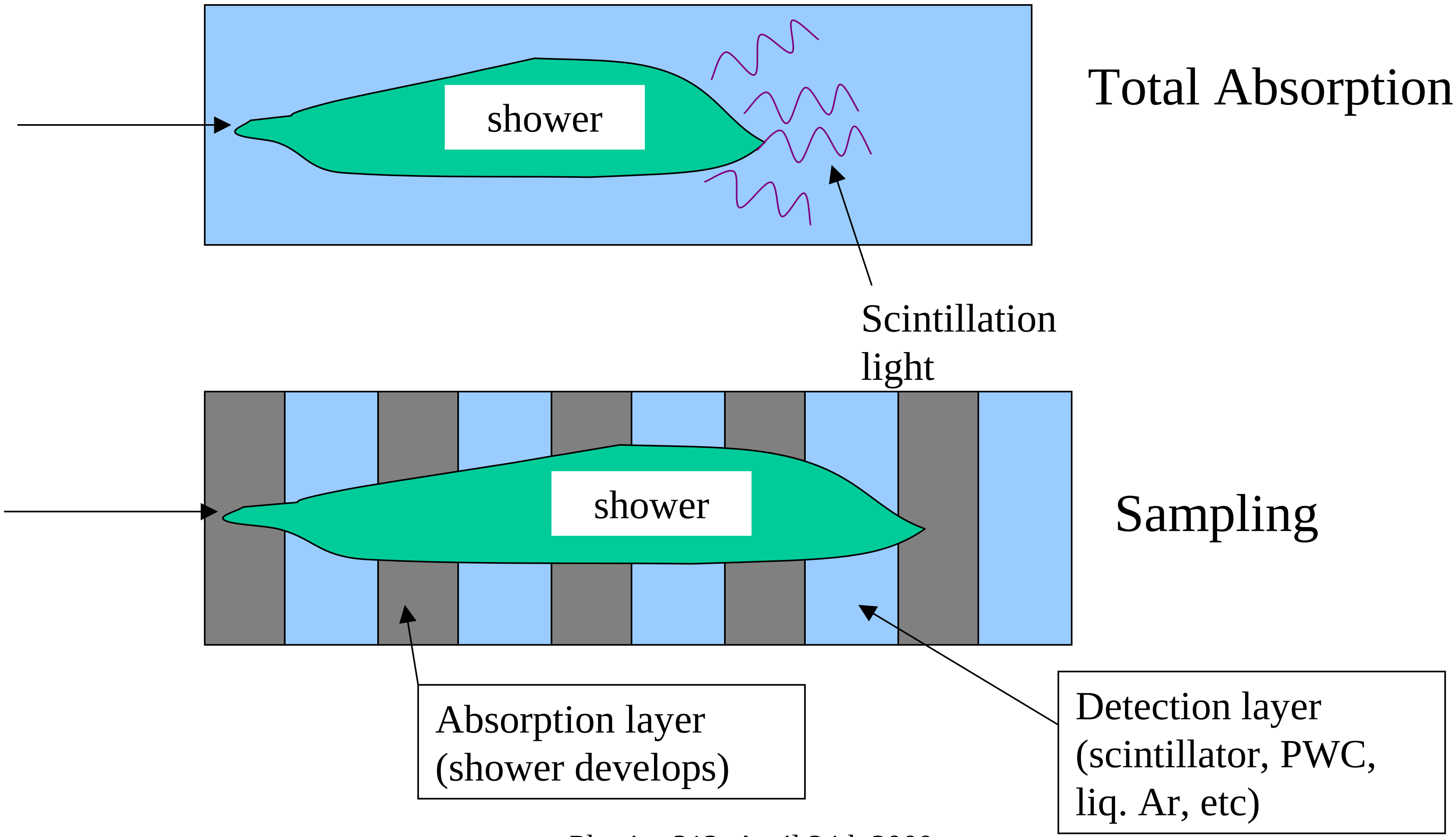
Energetic electrons in material loose energy through *bremsstrahlung*.



These processes continue, ultimately depositing all the energy of the incident particle (e+, e-, or γ) in a well characterized *shower*.

Electromagnetic Calorimetry (cont’d)

There are basically two types of EM calorimeters...

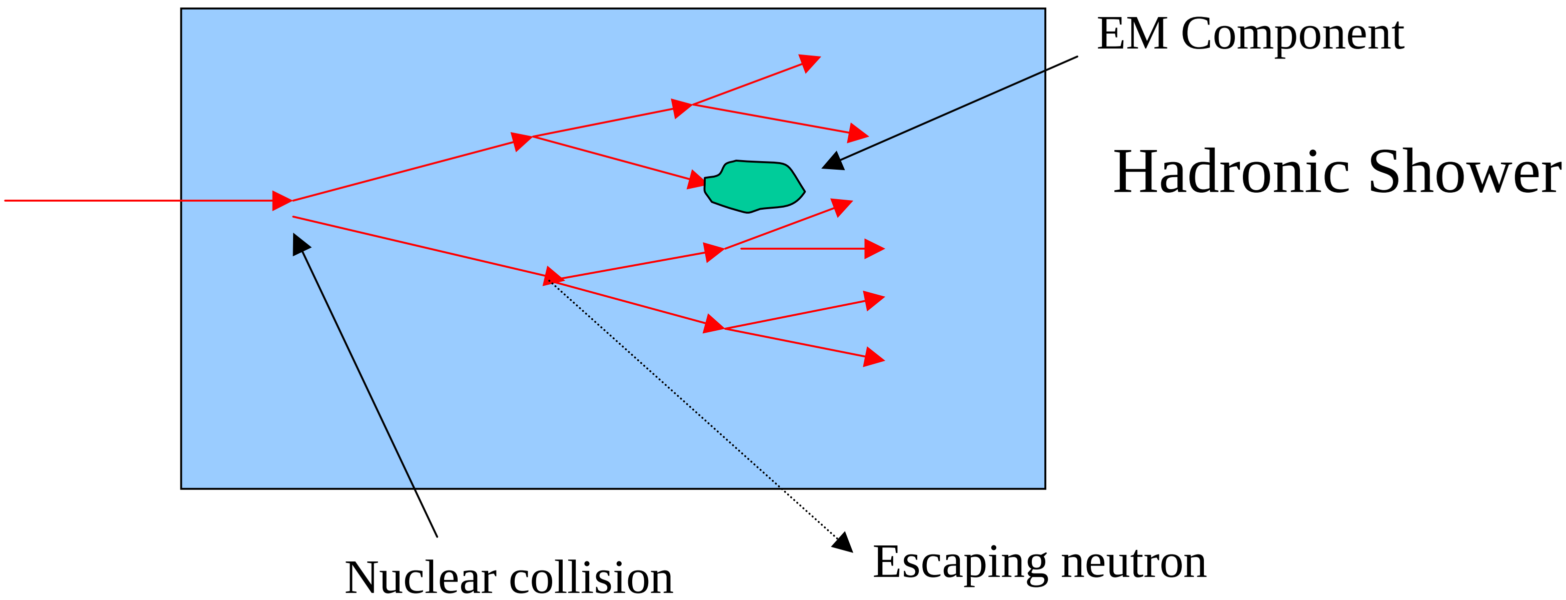


Electromagnetic Calorimeter Resolution

Detector	Resolution
NaI(Tl) (Crystal Ball [52]; 20 X_0)	$2.7\%/E^{1/4}$
Lead glass (OPAL [53])	$5\%/\sqrt{E}$
Lead-liquid argon (NA31 [54]; 80 cells: 27 X_0, 1.5 mm Pb + 0.6 mm Al + 0.8 mm G10 + 4 mm LA)	$7.5\%/\sqrt{E}$
Lead-scintillator sandwich (ARGUS [55], LAPP-LAL [56])	$9\%/\sqrt{E}$
Lead-scintillator spaghetti (CERN test module) [57]	$13\%/\sqrt{E}$
Proportional wire chamber (MAC; 32 cells: 13 X_0, 2.5 mm typemetal + 1.6 mm Al) [58]	$23\%/\sqrt{E}$

Energy in GeV

Hadronic Calorimetry



•Based on nuclear interactions.

•Longer and messier than EM showers.

•Always use sampling calorimeters (e.g. steel+scintillator)

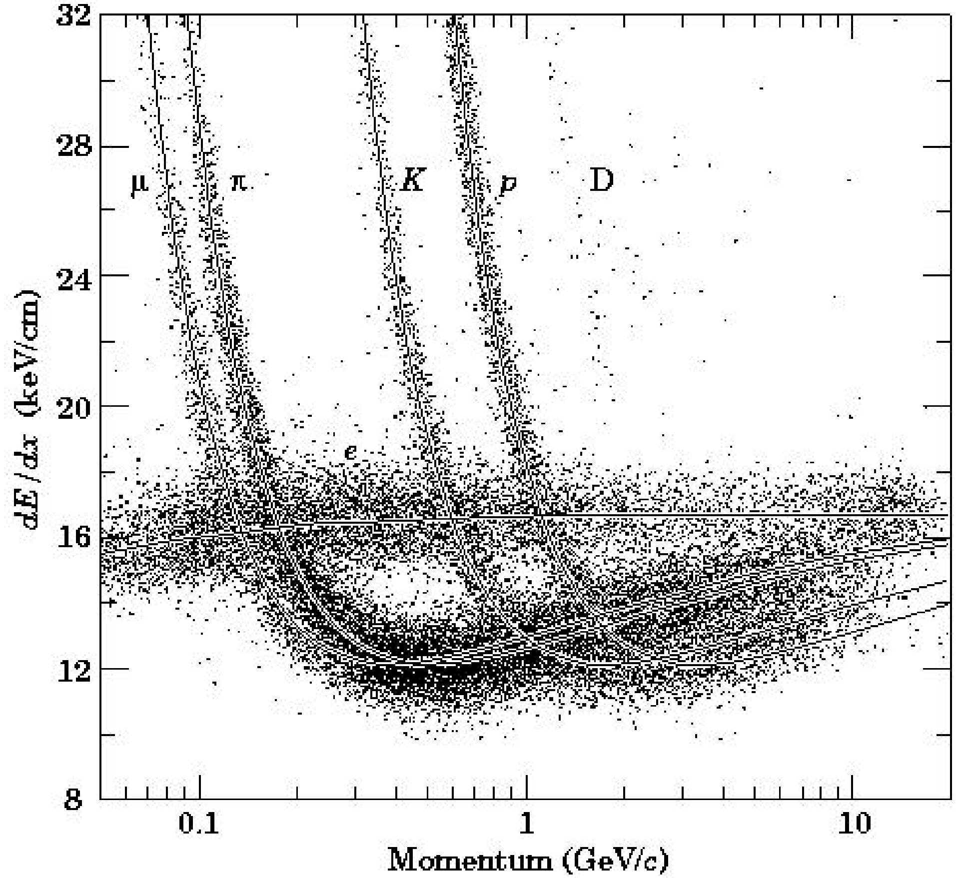
•Very good resolution would be $50\% / \sqrt{E}$

Particle Identification

- We can broadly distinguish particles by how they interact (we'll discuss this in a minute).
- But particles of the same time class (eg charged hadrons) must be distinguished by their different *masses*.
- We determine the mass by independently measuring the *momentum* and *velocity*.
- One way to do this is to directly measure the time of flight
  - Can usually measure time to better than 100 ps
  - In a central detector, this can separate π and K up to about 1 GeV
- In addition, there are common *indirect* ways to measure velocity.

dE/dx

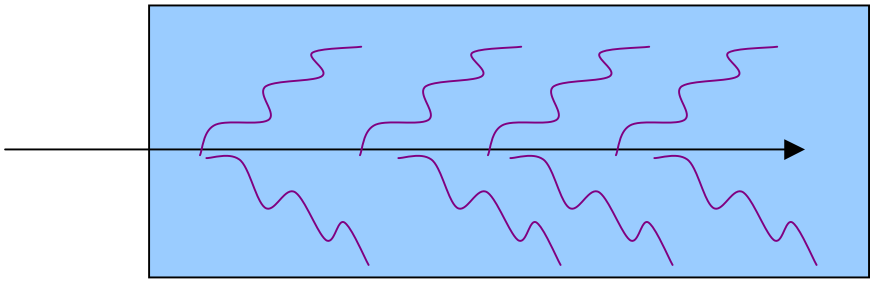
- Recall that as particles traverse matter, the energy they deposit is dependent only on the *velocity*.
- ⇒particles of the *same momentum* will deposit *different amounts of energy* if their masses are different.
- This can be easily measured with proportional wire chambers.



Cerenkov Radiation

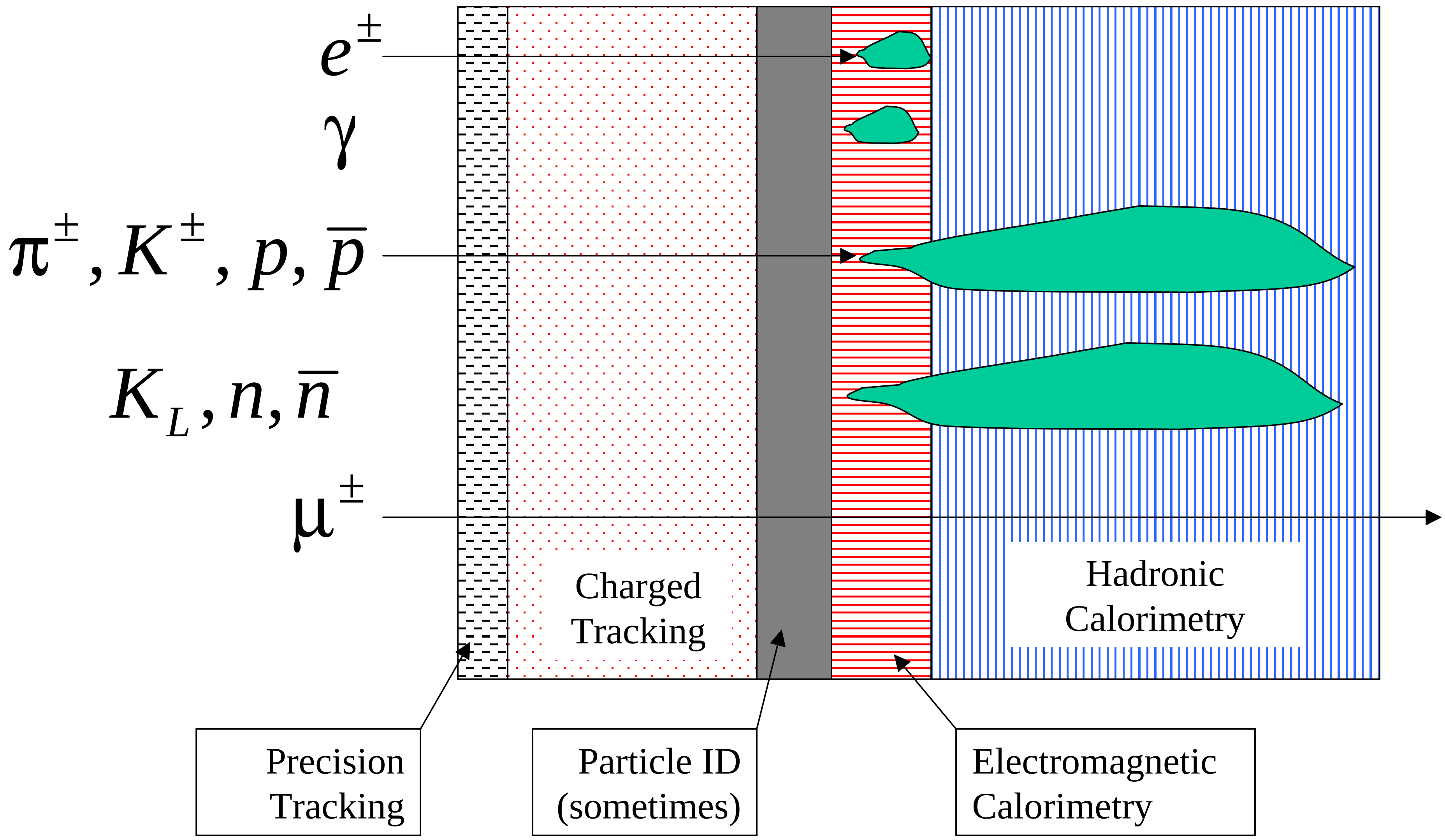
- A charged particle which is traveling faster than the speed of light in a particular medium will radiate its energy in the form of photons in a cone whose angle is

$$\cos\theta = \frac{1}{n\beta}$$

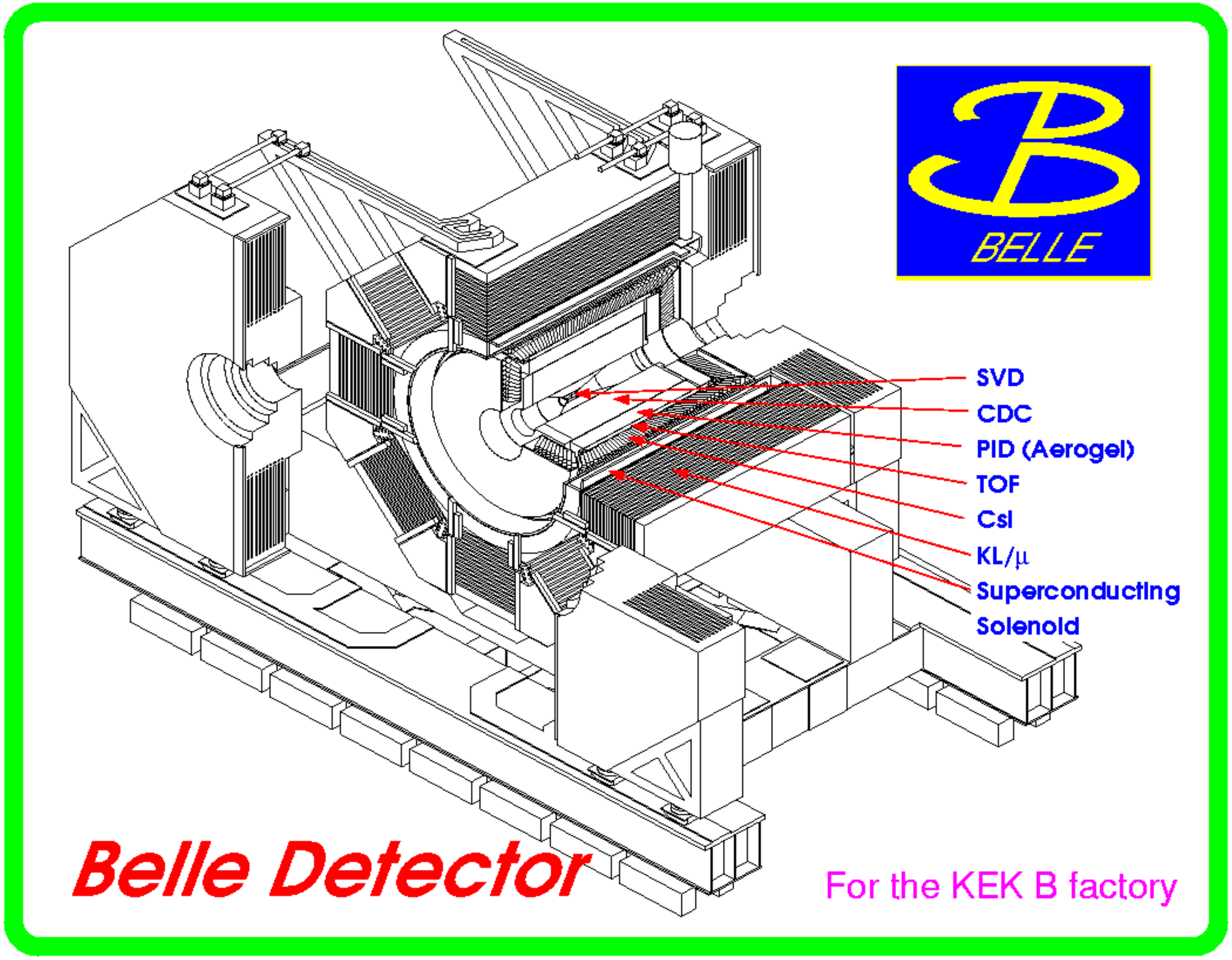


- The existence of such light can be used to *discriminate two particles* of different masses for a range of momenta (threshold Cerenkov detector).
- OR the angle can be *directly measured* (more accurate but more difficult).

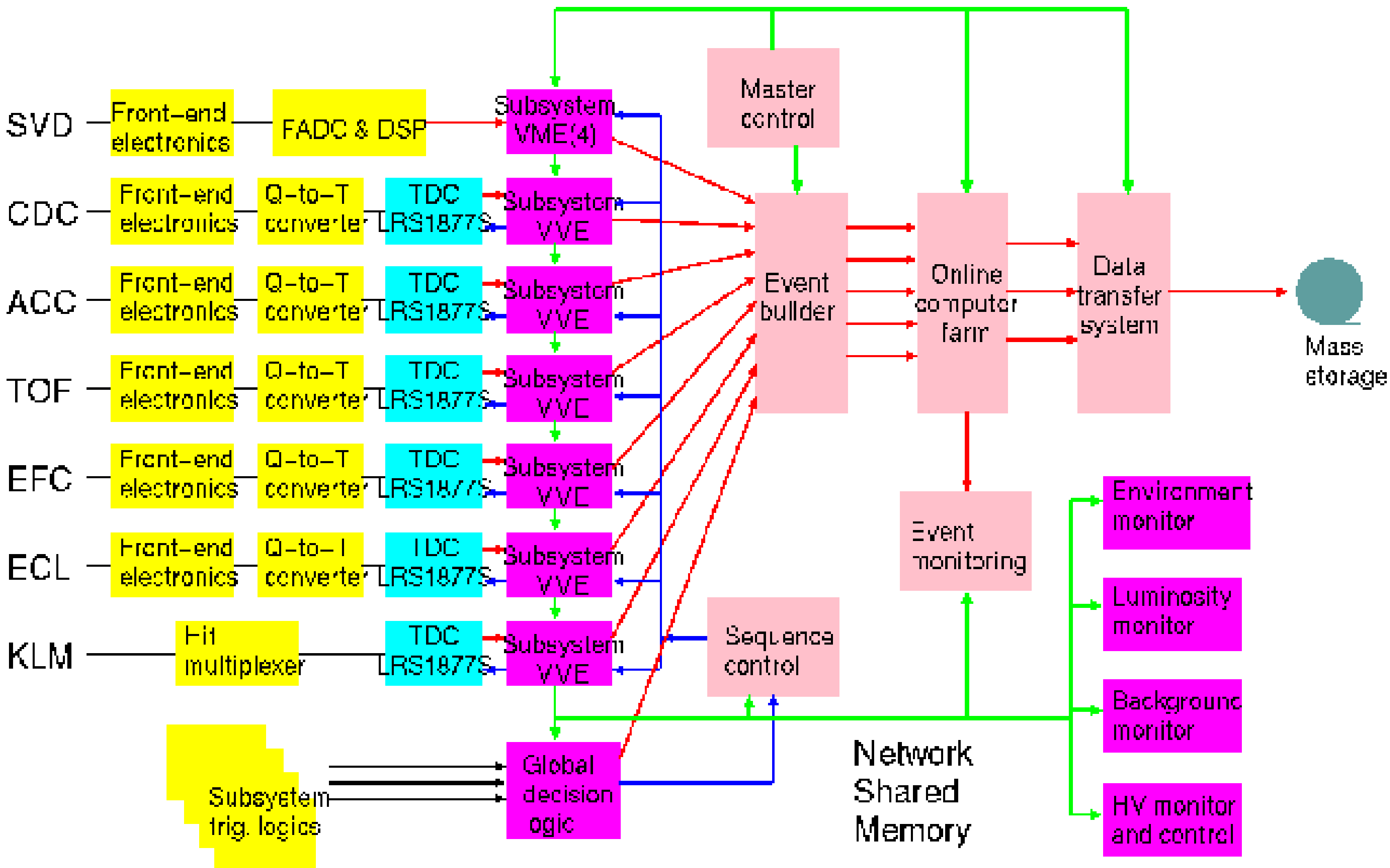
General Detector Layout and Classes of Particles



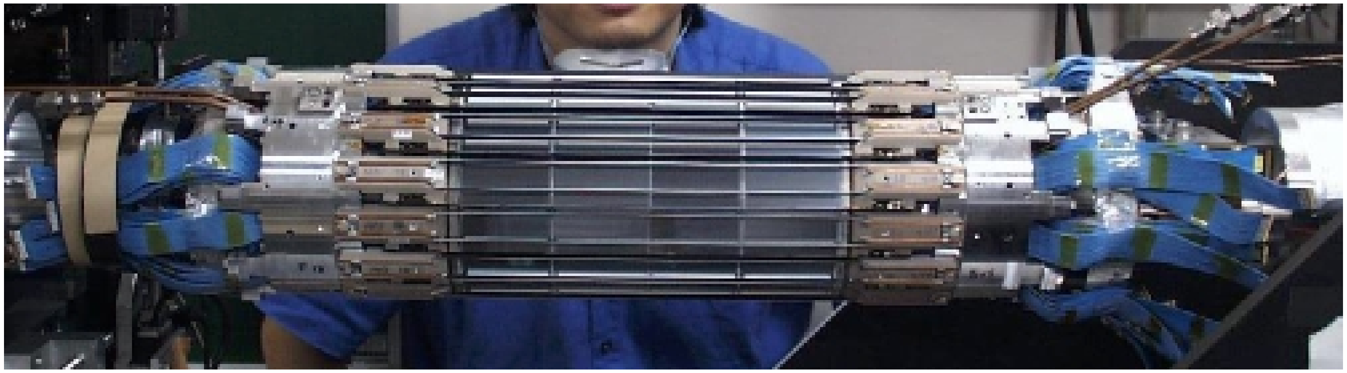
Example – the BELLE Detector



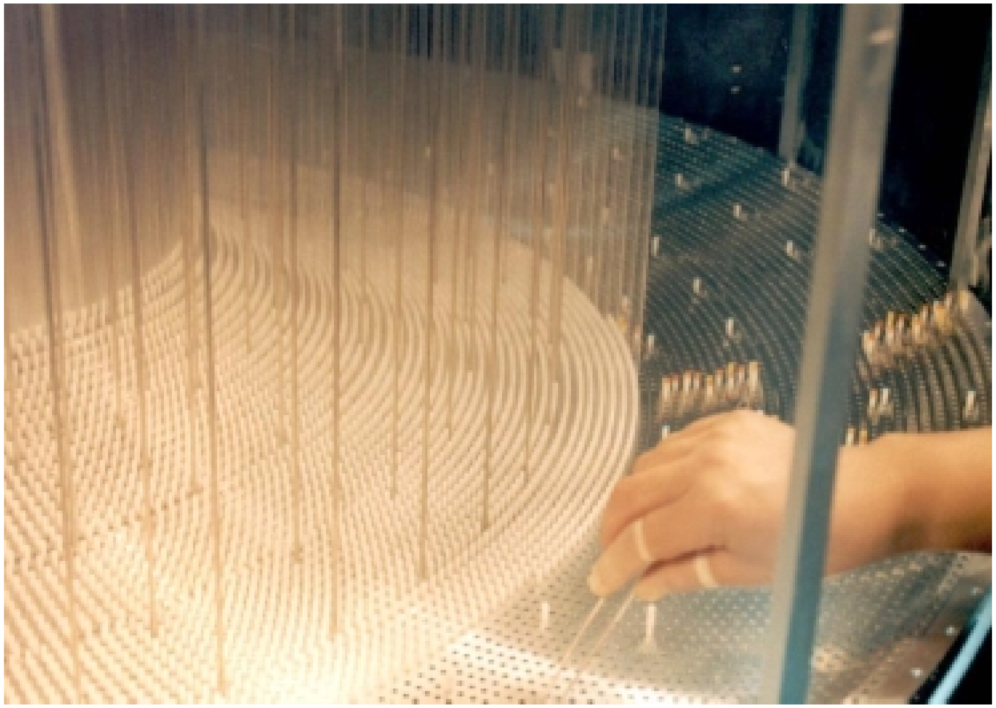
DAQ Overview



Pictures (Tracking)



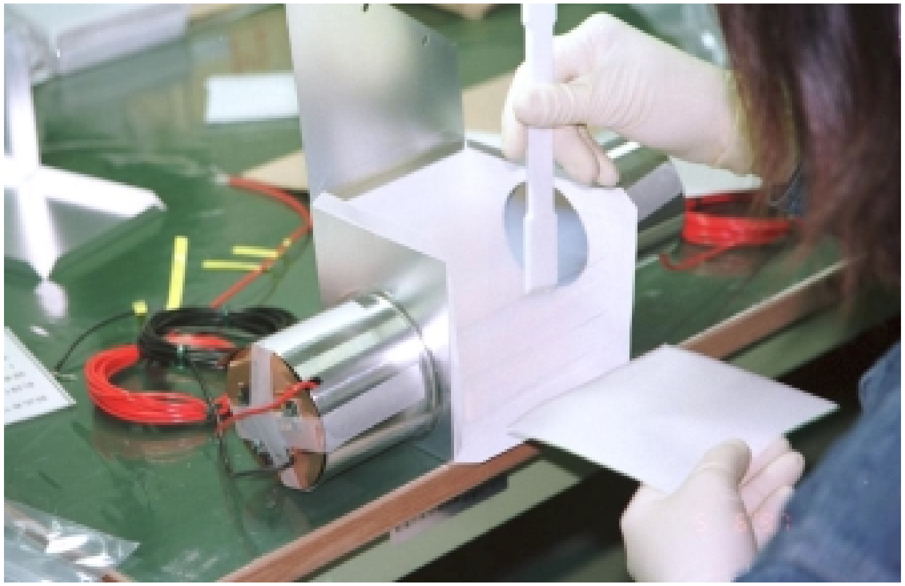
SVD



Central Drift
Chamber

Pictures (Electromagnetic Calorimeter)

Pictures (Particle ID)

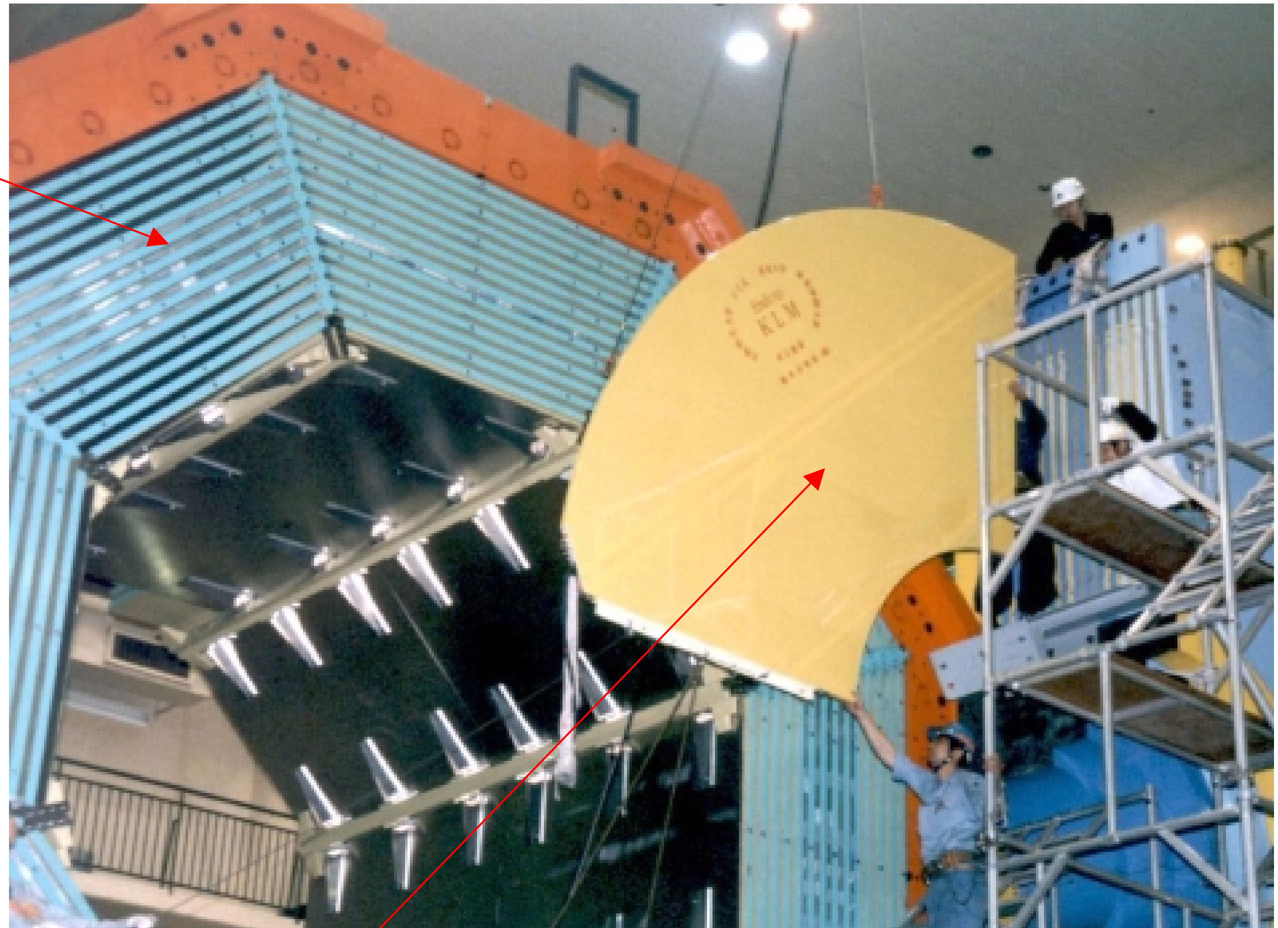


Module Assembly

Barrel Detector

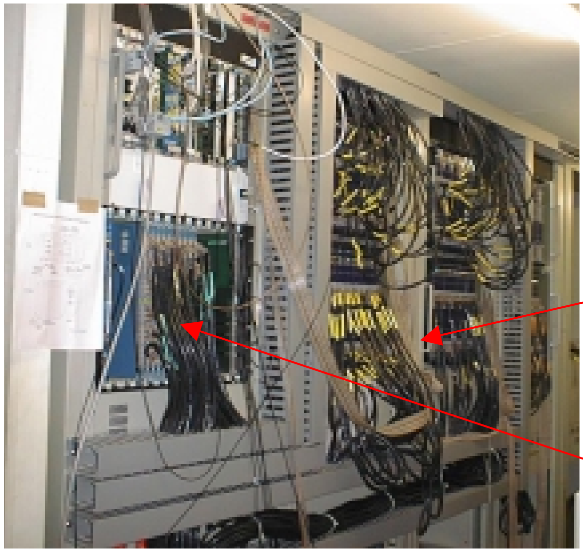
Pictures (K-long Catcher/Muon Tracker)

Barrel Module



Endcap Module

Pictures (DAQ/Control)



Readout
Electronics

Custom

LeCroy 1877

Event
Builder

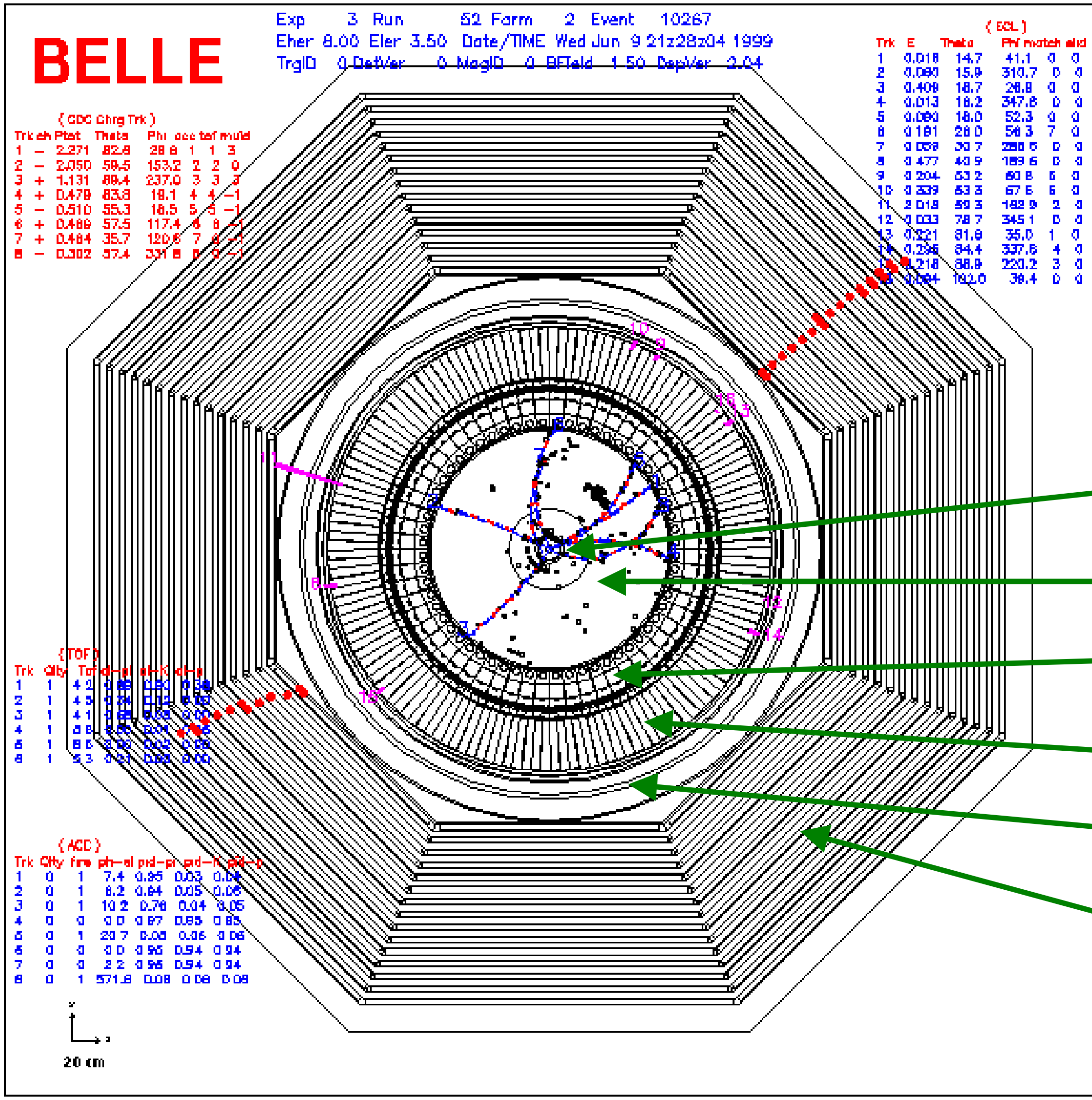
Champaign
Bottles

Control
Room

All Finished!!

Me

What an Event Looks Like



- $J/\psi \rightarrow \mu\mu$
  - $M(\mu\mu) = 3.1$ GeV

- Precision Tracking
- Charged Tracking
- Particle ID (Cerenkov)
- Electromagnetic Calorimetry
- Solenoidal Magnet
- Muon ID/Hadronic Calorimetry