Intro to Nuclear and Particle Physics (5110)

March 23, 2009

From Nuclear to Particle Physics

Nuclear Physics $\rightarrow$ Particle Physics

"Two fields divided by a common set of tools"

- Theory: fundamental theories of strong, electromagnetic, and weak interactions
- Experiment: accelerators, detector technology, data analysis technique

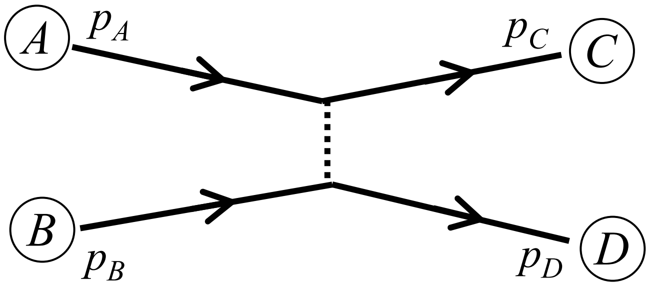
Nuclear $\rightarrow$ Particle Physics is a big leap in ambition. We go from hoping our phenomenological models have some reality and predictive value to attempting to reveal the fundamental building blocks and interactions of the Universe (Trying to "*Define Reality*" as (we think) we know it

(Have I mentioned that nuclear physicists often find particle physicists to be insufferable?)

Our "bridges" from NP to PP are the processes by which elementary particles and nuclei leave trails that we can use to detect them and the kit of experimental and analytical tools we use to interpret them

Scattering revisited

Feynman Diagram



$$s = (p_A + p_B)^2 = E_{CM}^2$$ (CM energy)^2

$$t = (p_A - p_C)^2 = -q^2$$ (4-momentum transfer)^2

Upgrade the picture of the interaction with a crucial detail:

What is the mechanism for the interaction?

- Virtual Particle Exchange
  - Characteristic carrier of the force (EM, strong, weak)
  - Everything that is transferred from A *to* B: energy, momentum, electric charge, etc.
  - Existence *temporarily* violates conservation of energy-momentum. (Exchanged virtual particle in diagram above has negative mass^2.)
- Feynman Diagram
  - Invented for quantum electrodynamics. (Tomonaga and Schwinger had the content of QED too, but Feynman made it intuitive and useful.)
  - Not just a visual aid – organizes computation of decay rates and cross sections (via amplitudes) through "Feynman Rules"
  - Applies to all quantum field theories

Measurements in Particle Physics

Experimental Observables

- Bound state properties
  - Spectroscopy: masses, etc.
- Decays
  - Lifetimes, partial widths
- Scattering
  - Cross Sections

Theoretical Tools

Nonrelativistic QM – Schrödinger Equation

Relativistic QM – K-G, Dirac Equations

Quantum Field Theory

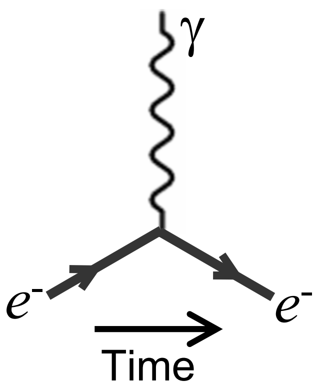
$$\text{Fermi's Golden Rule}: \ \lambda = \frac{2\pi}{\hbar}\left|V_{if}\right|^2 \rho\left(E_f\right)$$

Transition Rate — Amplitude (dynamics) — Phase Space (kinematics)

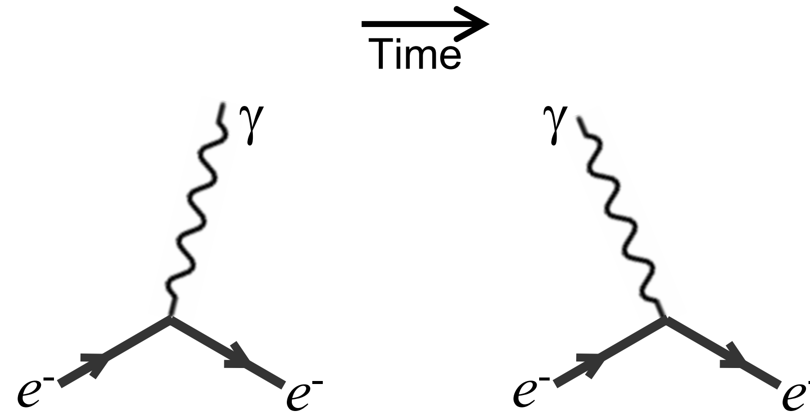
Feynman diagrams ***pictorially represent an analytical expression*** for a matrix element to some order in a perturbation expansion. The Feynman Rules provide the translation table from the parts of a Feynman diagram to factors in the calculation of the matrix element

Quantum Electrodynamics (QED) via *comic strip* (Feynman Diagrams)

- Feynman diagrams for Electro-magnetic (EM) processes will be relevant to our next task: describing interactions of charged particles in matter, so start with the basic vertex of Quantum Electrodynamics (QED):

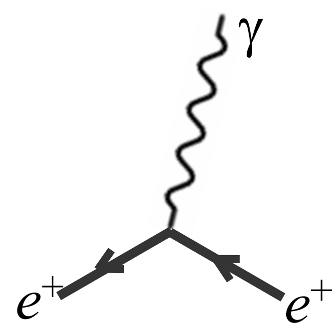


Not a real-world "picture" of the process. **One space** and **one time** dimension.

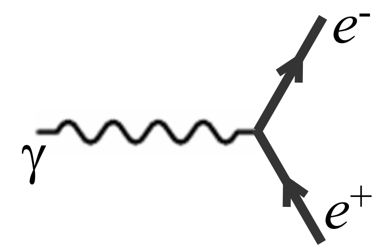


electron emits photon

electron absorbs photon



positron emits photon



photon materializes into electron-positron pair (flip for annihilation)

- The basic QED vertex can represent several distinct physical transformations

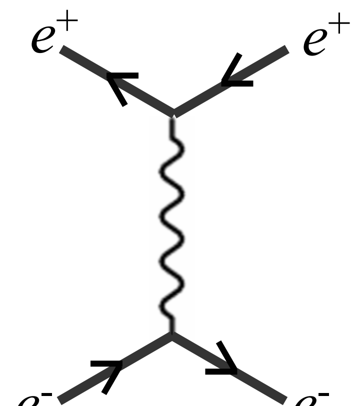
An example: Bhabha Scattering

- A bare QED vertex does not make a process.
- Emission or absorption of a photon by an isolated electron violates energy-momentum conservation (see Homework #7).
- Real processes must be built up from (at least) two vertices.

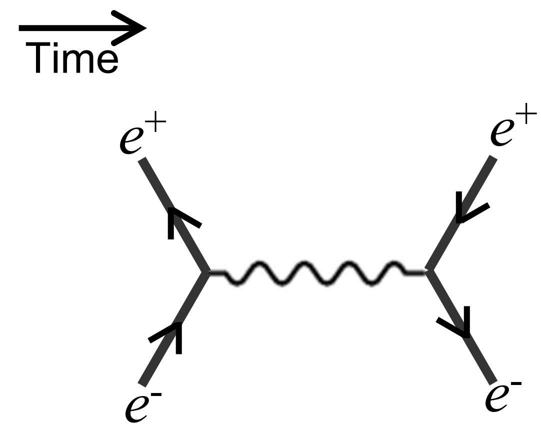
Bhabha Scattering

$$e^{+} + e^{-} \rightarrow e^{+} + e^{-}$$

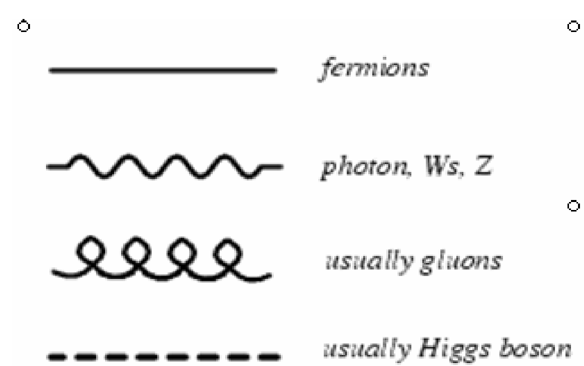
Total amplitude is the sum of all of the amplitudes from contributing diagrams.



Exchange



Annihilation



The same drawing principles apply to the other interactions, except that they have their own mediators, strengths, etc.

Feynman "Rule of Thumb"

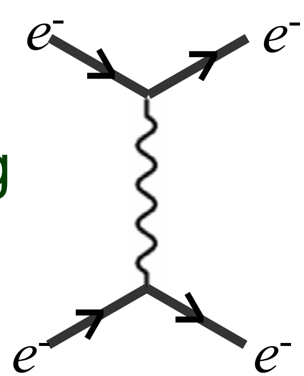
- Each vertex brings in a factor proportional to the charge: $\sqrt{\alpha}$
- "Order of a process" ~ # vertices

$$\frac{\text{Rate for Process of Order } n+1}{\text{Rate for Process of Order } n} \sim \alpha$$

Since $\alpha = \dfrac{1}{137} << 1$ in QED, higher-order EM processes are greatly suppressed. This is not necessarily true for other interactions, and $\alpha_S \sim 1$ is what makes the strong interaction (QCD) so difficult

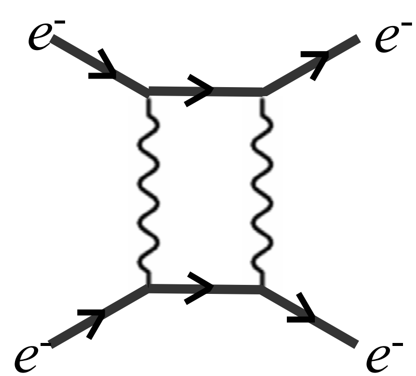
Møller Scattering

$e^- + e^- \rightarrow e^- + e^-$



Single-photon exchange

+



Two-photon exchange

+ ...

PRL 97, 030802 (2006) PHYSICAL REVIEW LETTERS week ending 21 JULY 2006

New Determination of the Fine Structure Constant from the Electron g Value and QED

G. Gabrielse,[1] D. Hanneke,[1] T. Kinoshita,[2] M. Nio,[3] and B. Odom[1,*]

[1]*Lyman Laboratory, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Laboratory for Elementary-Particle Physics, Cornell University, Ithaca, New York, 14853, USA*
[3]*Theoretical Physics Laboratory, RIKEN, Wako, Saitama, Japan 351-0198*

(Received 17 May 2006; published 17 July 2006)

Quantum electrodynamics (QED) predicts a relationship between the dimensionless magnetic moment of the electron (g) and the fine structure constant (α). A new measurement of g using a one-electron quantum cyclotron, together with a QED calculation involving 891 eighth-order Feynman diagrams, determine $\alpha^{-1} = 137.035\,999\,710\,(96)$ [0.70 ppb]. The uncertainties are 10 times smaller than those of nearest rival methods that include atom-recoil measurements. Comparisons of measured and calculated g test QED most stringently, and set a limit on internal electron structure.

DOI: 10.1103/PhysRevLett.97.030802 PACS numbers: 06.20.Jr, 12.20.Fv, 13.40.Em, 14.60.Cd

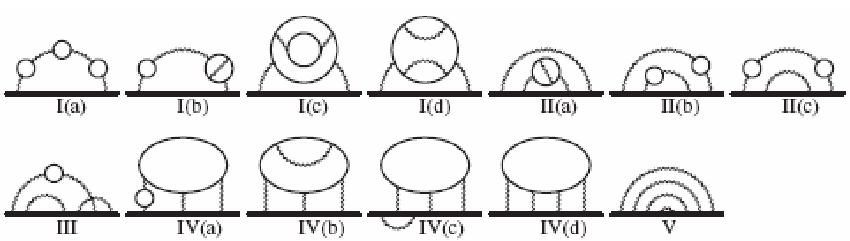


FIG. 3. Typical diagrams from each gauge invariant subgroup that contributes to the eighth-order electron magnetic moment. Solid and wiggly curves represent the electron and photon, respectively. Solid horizontal lines represent the electron in an external magnetic field.

Next up: 12,672 diagrams

"In QED, as in other quantum field theories, we can use the little pictures invented by my colleague Richard Feynman, which are supposed to give the illusion of understanding what is going on in quantum field theory."

- Murray Gell-Mann

Experiments in Particle and Nuclear Physics

- Goal: Discover new particles and determine their properties by measuring and analyzing the 4-momenta of the well understood particles that scatter off of them or that they decay into
- To accomplish this goal we need to…
  - Understand interactions of “stable” particles with matter
    - Energy loss of charged particles through ionization
    - Absorption of photons by matter
    - Electromagnetic showers
    - Hadronic showers
  - Develop detector technologies based on these processes
    - Tracking detectors
    - Particle ID detectors
    - Electromagnetic calorimeters
    - Hadron calorimeters/muon detectors

"Stable" vs. "Unstable" Particles

- Stable particles
  - Live long enough to deposit all of their energy or leave a measurable trail that can be detected
  - Photons (γ), leptons (e^-, μ^-, neutrinos: ν_e, ν_μ, ν_τ, and antiparticles), hadrons (p, n, π^+, K^-, and antiparticles)
- Unstable particles
  - Detected by full reconstruction of their decay products

$$\pi^0 \to \gamma + \gamma \qquad K_S^0 \to \pi^+\pi^- \text{ or } \pi^0\pi^0 \qquad \cdots$$

  - Detected by "partial reconstruction" based on knowledge of overall properties of event. For example, if you know the 4-momentum of the parent particle and measure all but one daughter

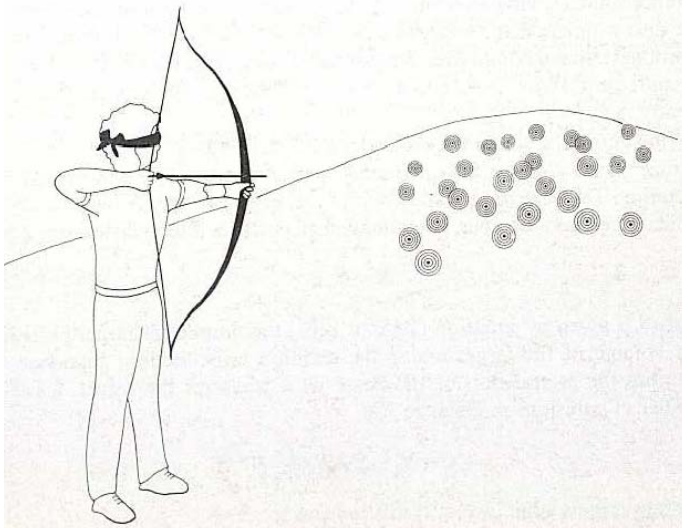
$$D^+ \to K_S^0 + e^+ + \nu_e \leftarrow \boxed{\text{unobserved}}$$

    - Tools: missing momentum, missing energy, displaced decay vertices

Components of an PP/NP Experiment

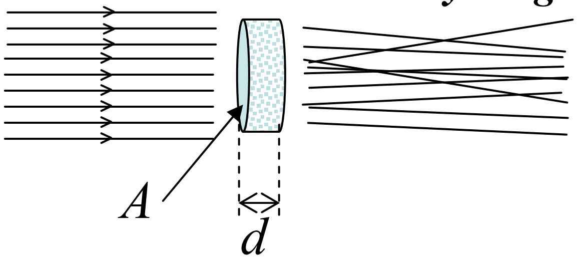
- Charged particle tracking: multiple measurements of 3D space points along the trajectory of the particle
  - Electric charge and momentum determined from curvature in $\boldsymbol{B}$
  - Long (relatively) lifetime and/or high precision $\rightarrow$ decay length
- "Shower" reconstruction: measure deposition of energy by neutral particle, ideally with full containment
- Particle ID: measure speed (time-of-flight, rate of ionization, Cerenkov), combine with momentum to get mass
- Triggering: Fast decision to initiate readout and storage of "event" when there is indication of something of potential interest
- Data acquisition: Readout of all significant information in the detector when trigger declares an event. Highly parallelized, "sparsified"
- Off-line analysis: Make the measurement. Pattern recognition, determination of measurable properties (generally by fitting). Understanding of detector and results relies on…
  - Event simulation (Monte Carlo): efficiency and background

Cross Section



- Probability of a “hit” depends on…
  - # of projectiles
  - Sizes of projectiles & targets
    - Effective area of target <u>and</u> target density,

$$a + b \rightarrow anything$$



- Assumptions:
  - Beam well collimated, covers target, monoenergetic, low density (no intrabeam interactions), high energy.
  - Target is uniform, thin (no multiple interactions), with target-particle spacing large compared to beam λ (no diffraction).

Scattering rate is proportional to

Beam Density

Beam-Particle Velocity

Beam Flux $\Phi_a = n_a v_a$

Targets $N_b = n_b A d$

Target Density

Target Volume

Cross Section (Size of Target) σ_b

Rate of Scattering Events $\dot{N} = \Phi_a N_b \sigma_b \quad \Rightarrow \quad \sigma_b = \dfrac{\dot{N}}{\Phi_a N_b}$

Express this "per beam particle":

$$\text{Probability of Interaction} = \text{Fraction of Area Covered} = \frac{\#\,\text{Targets} \times (\text{area}/\text{target})}{\text{Total Area}} = \frac{(n_b A d)\sigma_b}{A} = n_b \sigma_b d$$

$$\#\,\text{Interactions per Unit Length} = n_b \sigma_b$$

$$\text{Length per Interaction} = \frac{1}{n_b \sigma_b}$$

Mean Free Path

Interaction Length

Luminosity !

$$\dot{N} = \Phi_a N_b \sigma_b$$

$\dot{N} = \mathrm{L}\,\sigma_b$ where $\mathrm{L} = \Phi_a N_b$ is the "luminosity"

Generally applied to colliding beam accelerators:

Frequency of "bunch" collisions

Numbers of particles per bunch

$$\mathrm{L} = \frac{f n_1 n_2}{A}$$

Bunch cross-sectional area

$$\mathrm{L} = \frac{f n_1 n_2}{4\pi\sigma_x\sigma_y}$$

Gaussian beams moving in z direction

Big luminosity $\Rightarrow$ lots of particles (current), small beams

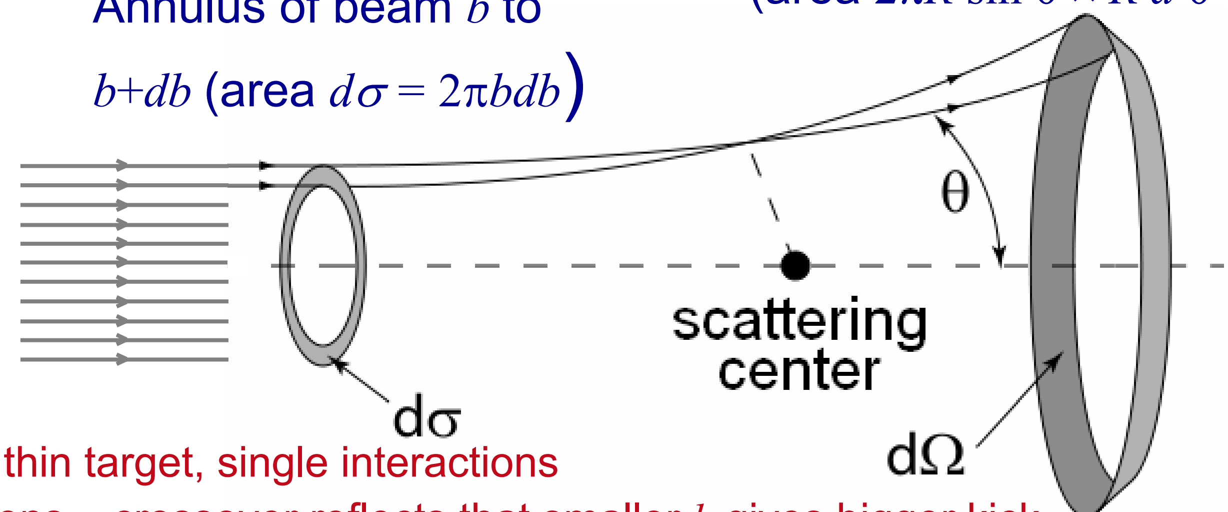
Review: Differential Cross Section: for Rutherford Scattering

Our $b \leftrightarrow \theta$ mapping tells us how an annular region of beam maps into an angular range at the detector.

Downstream (detector) annulus (area $2\pi R \sin\theta \times R\, d\theta = R^2\, d\Omega$)

Annulus of beam b to $b+db$ (area $d\sigma = 2\pi b db$)

Beam Intensity N_0 ($\mathrm{s^{-1}\, m^{-2}}$)



- As before, thin target, single interactions
- Not like a lens – crossover reflects that smaller b gives bigger kick
- Azimuthal symmetry - not general, but a feature of Coulomb force

$$d\sigma = 2\pi b db = -\frac{d\sigma}{d\Omega}(\theta)\, d\Omega = -\frac{d\sigma}{d\Omega}(\theta)\; 2\pi \sin\theta\, d\theta$$

Everything that passes through here

Ends up here

Differential Cross Section

Example Measurement

Find the *inclusive cross section* for production of *oinks* in pp collisions at $14\ \mathrm{TeV}$ (CM)

- With predetermined selection criteria, count the number of *oinks* in the $14\ \mathrm{TeV}$ pp data sample, imposing no requirements on the other particles in the event ("inclusive") N_{o}
- Using data away from the oink signal region and Monte Carlo estimate the background (things that pass *oink* selection but aren't real *oinks*) N_{b}
- Using Monte Carlo, validated as much as possible with data, determine the efficiency for counting a true *oink* by your procedure ε_{o}
- Determine the integrated luminosity for your data sample L

Not to be forgotten: proper evaluation and propagation of statistical uncertainties of counting and systematic uncertainties from all identifiable sources (efficiency, BG, luminosity,…)

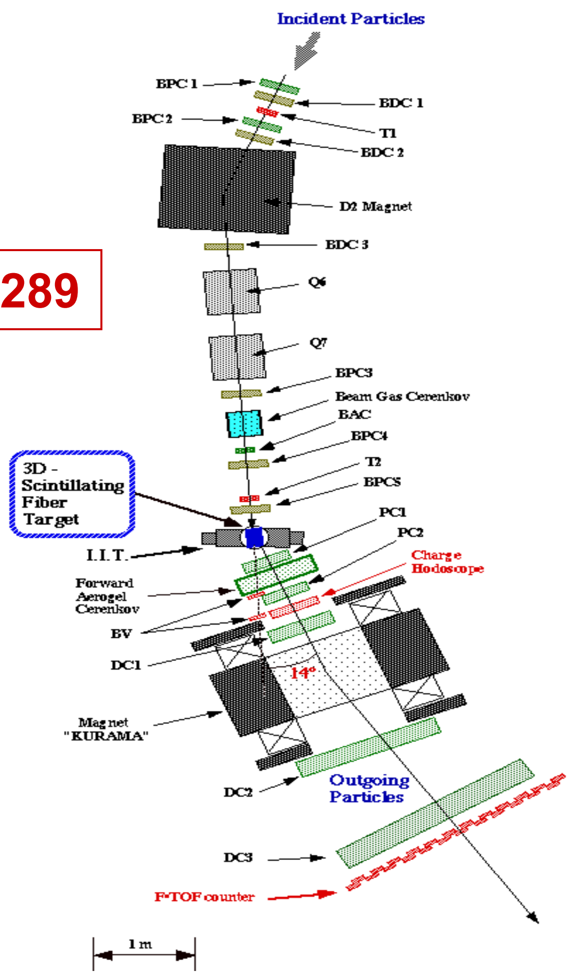
$$\sigma = \frac{N_{\mathrm{o}} - N_{\mathrm{b}}}{\varepsilon_{\mathrm{o}} \mathrm{L}}$$

Experimental Design:

Special-Purpose Detector

- Measure just what's needed for a specific task, like Rutherford

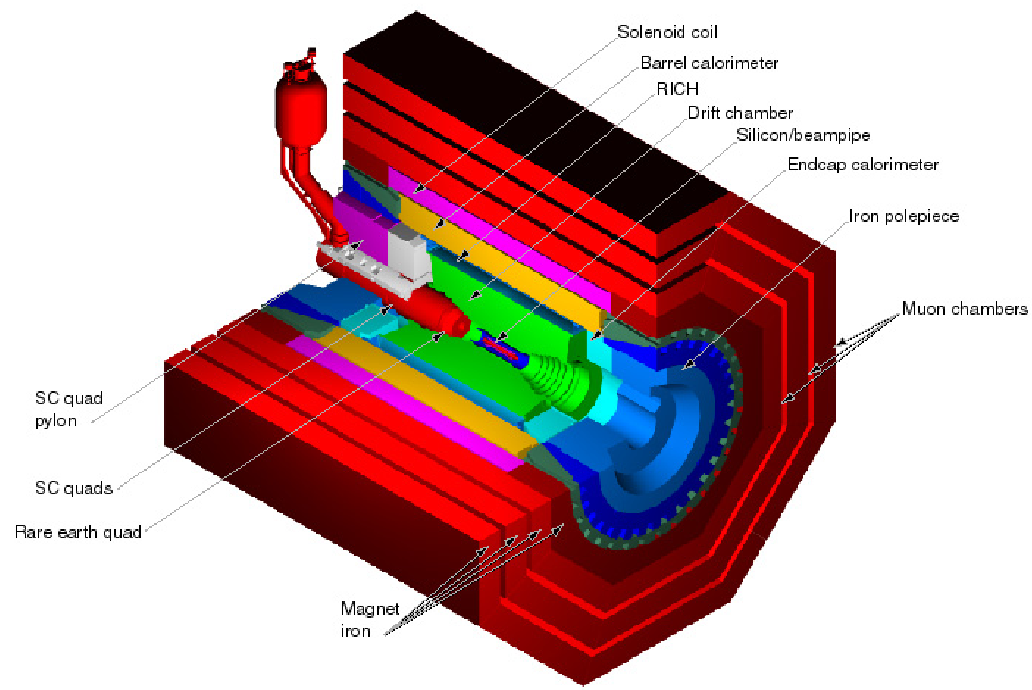
KEK-289



General-Purpose Magnetic Spectrometer

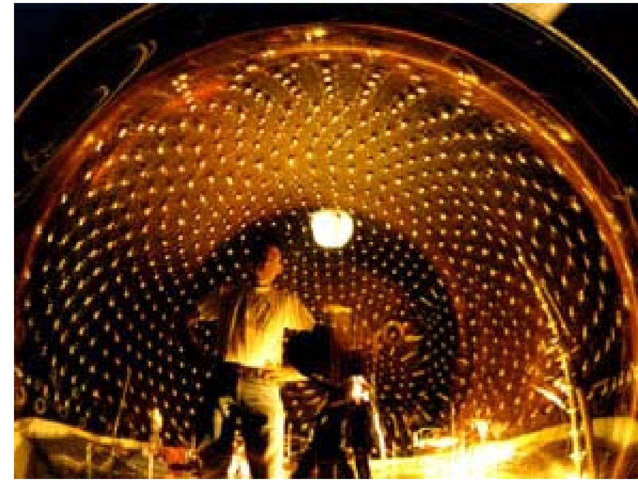
- Measure as much about every particle as possible, like every modern collider detector

CLEO III



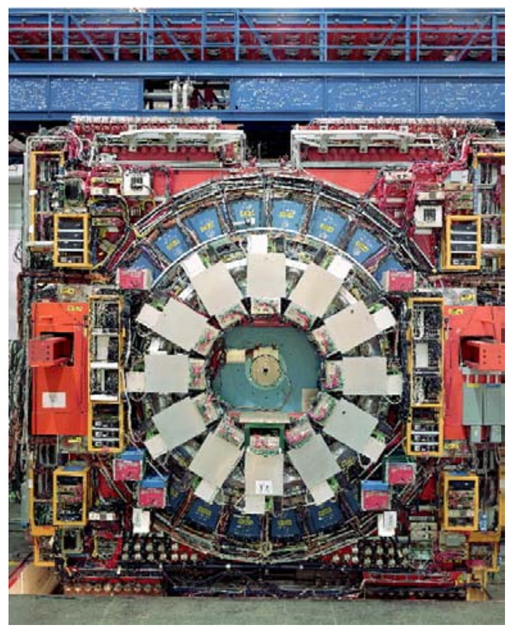
Example Detectors

Fermilab E-288

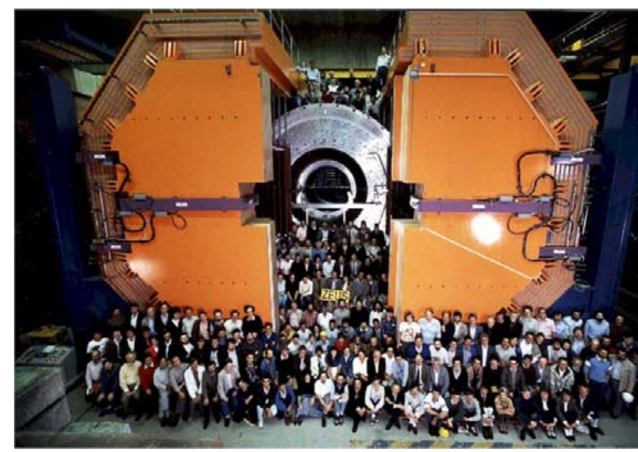


MiniBooNe
at Fermilab Booster

CDF II
at Fermilab Tevatron



BaBar at SLAC PEP II



Zeus
at DESY HERA