Recapitulate:

- We discussed how nuclei are composed from their constituents – protons and neutrons – including how we can understand their observed masses
  (< than sum of parts!)
- We have some initial feeling for the force between protons and neutrons
- We have gained some understanding about which nuclides are unstable and why, and how they can decay
- => We have a basic understanding about the masses and charges of nuclei.
- Next question: How can we study their shapes, sizes and internal structures?

How Do We Study Nuclear Structure?

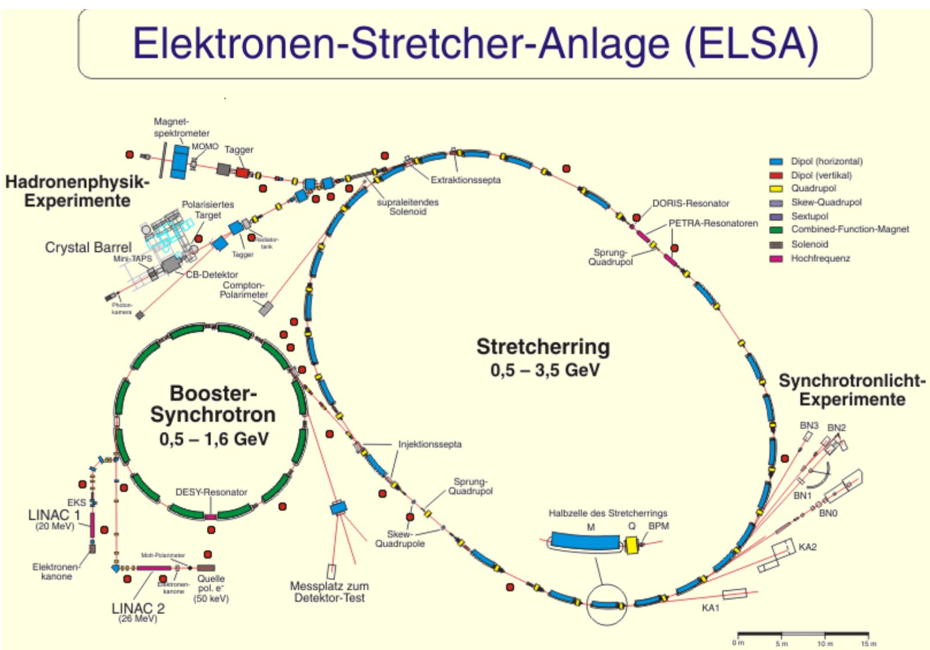
- Energy levels: Nuclear masses, excitation spectra, excited state decays -> Spectroscopy
  (What states exist?)
- Decays, Elastic and Inelastic Scattering, Particle Production, Reactions
  (*How do they interact?*)
- [Probing the internal structure directly
  Imaging, "Tomography" and "Holography"
  (*Shape and Content?*)]

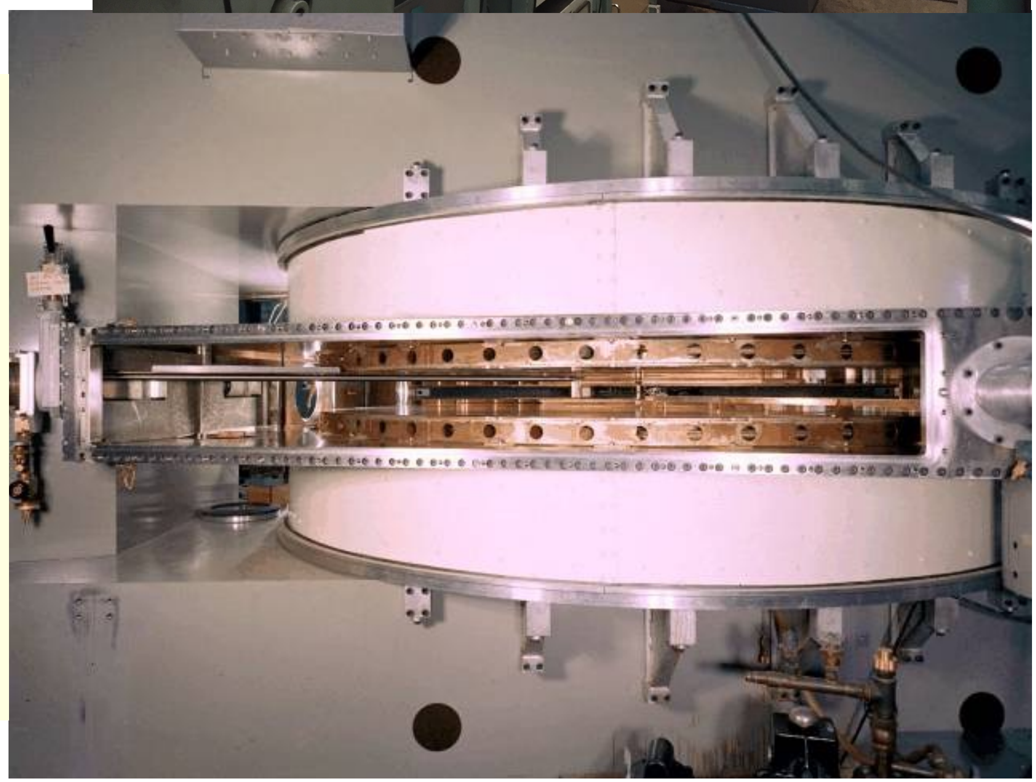
Basic Approach: Scattering

- Direct a beam of particles towards a target made of a huge number of (identical) nuclei
- Record what happens to the beam particles (scattered, absorbed, lost energy,…)
- Record what other things emerge from the interaction (nuclear fragments, other particles…)
- Understand what we see via the underlying nuclear structure
- Huge variety of probes (electrons, photons, nucleons, other nuclei,…) at a huge variety of energies (keV to TeV)
- Huge variety of nuclear targets and detectors

Low-Medium Energy Accelerators

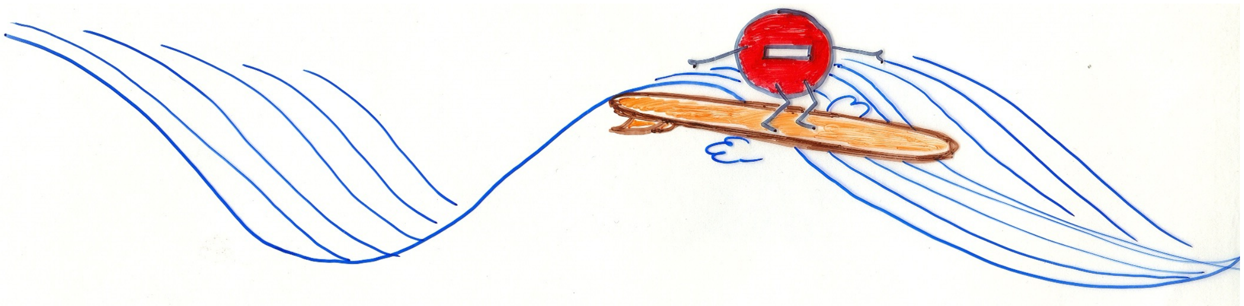
- (Tandem) Van de Graaf
- Cyclotron
- Synchrotron





Example: Jefferson Lab

Electrons get accelerated to 99.9999999% of the speed of light (12 GeV)…



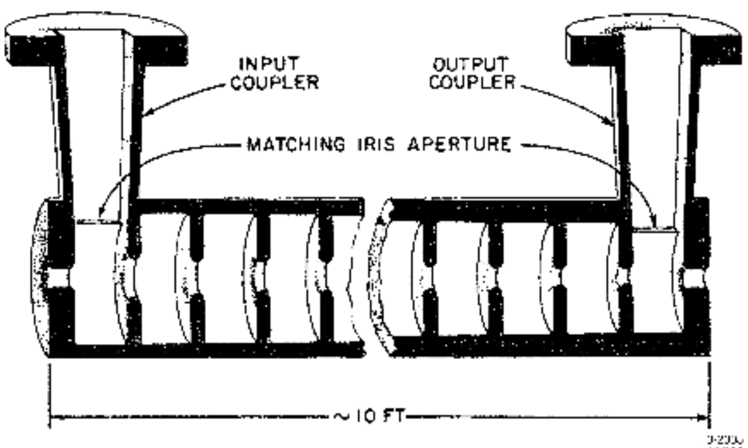
Surf the microwaves!

Accelerating cavity: disk loaded cylindrical wave guide

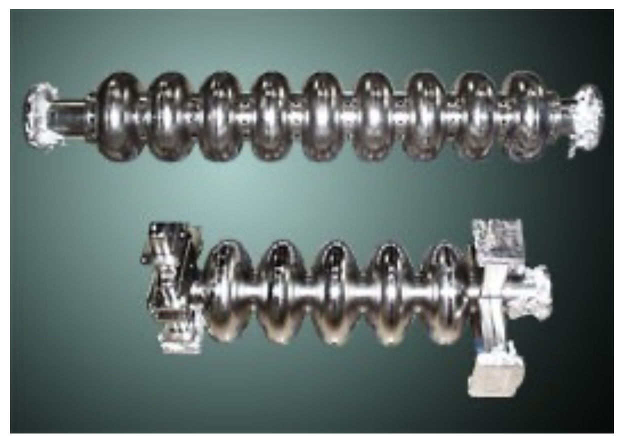
use TM_{01} mode to get a longitudinal electric field

match phase and velocity

Accelerators



DESY

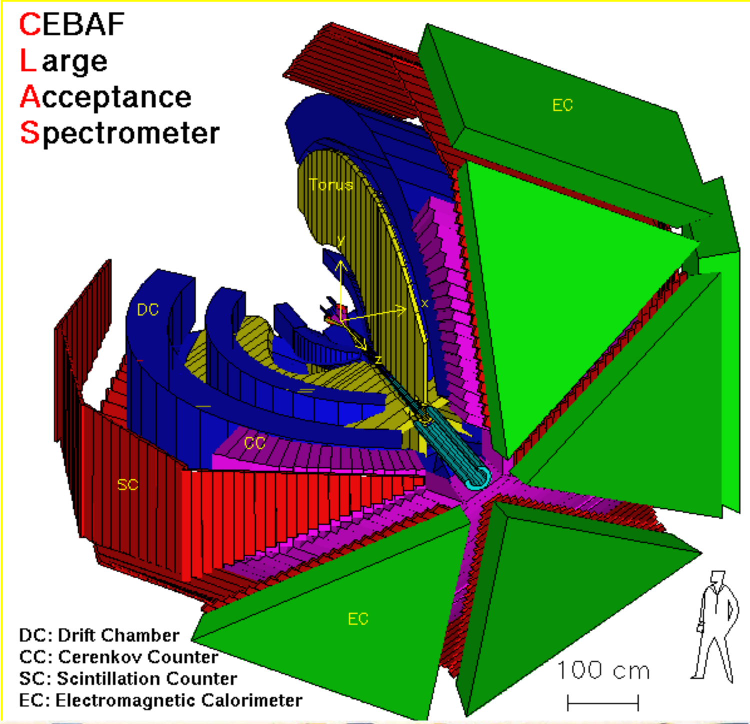


new

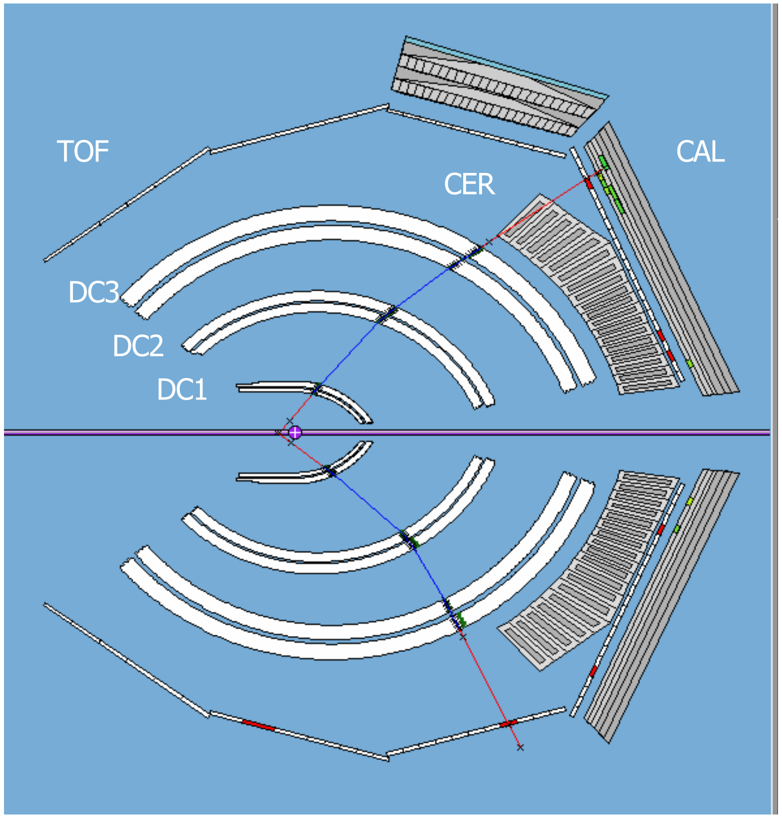
old

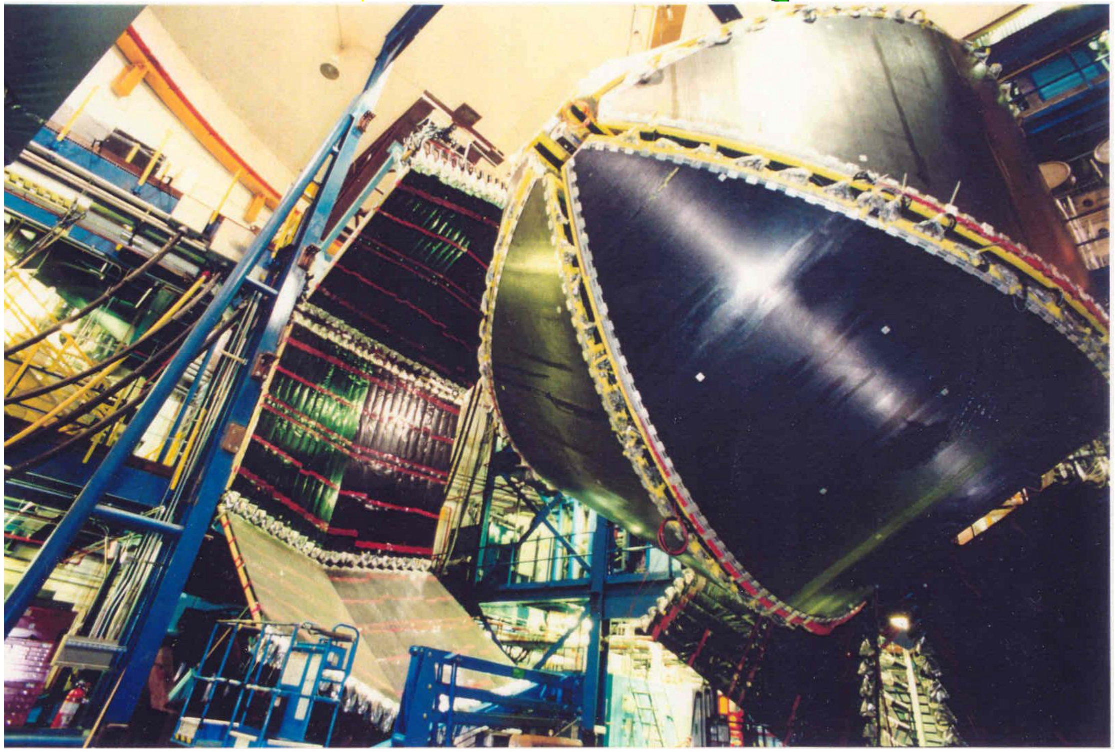
Jefferson Lab

Example: Jefferson Lab

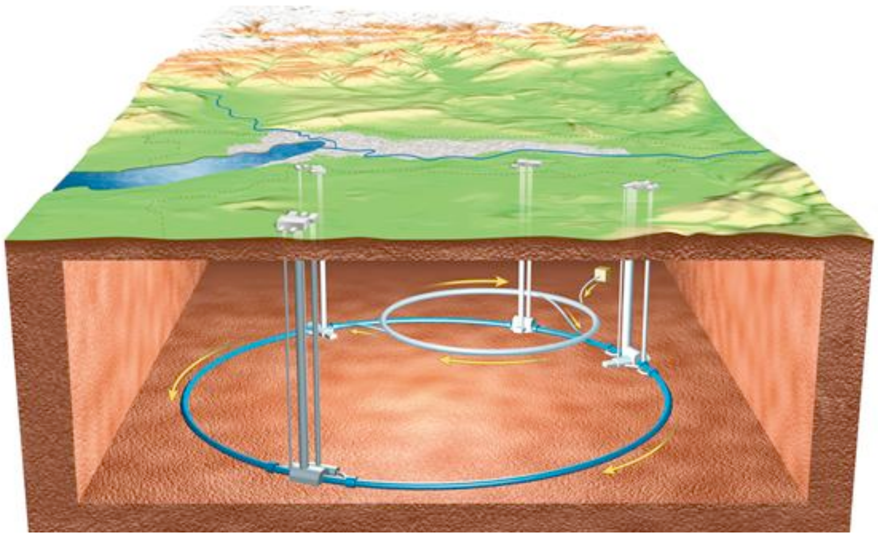


…and smashed into a "target".
The debris is detected and measured.

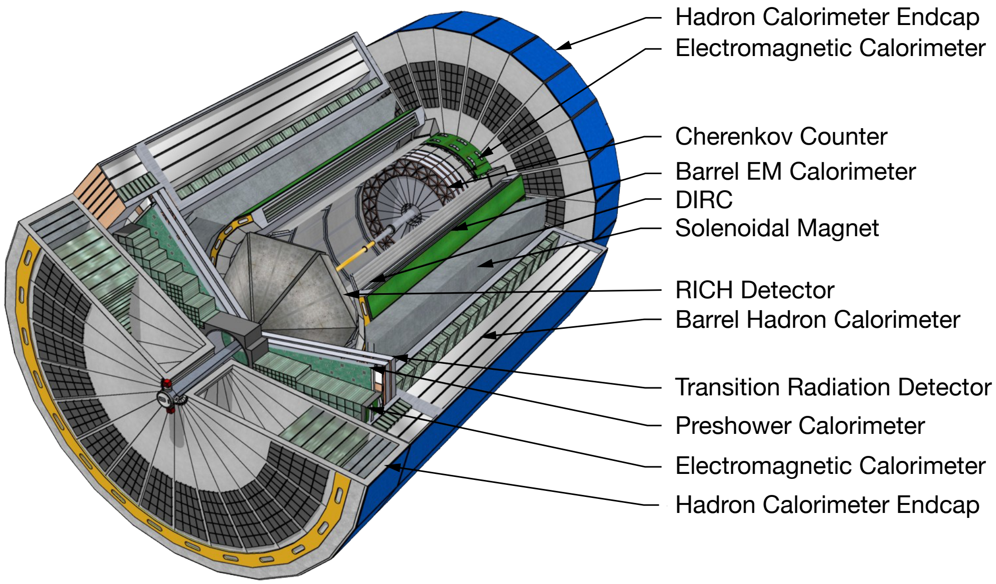




“Typical” accelerator (CERN)



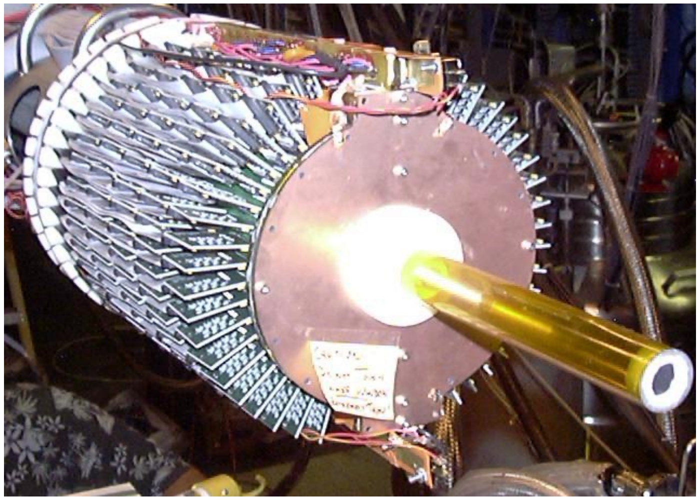
Typical detector (EIC)

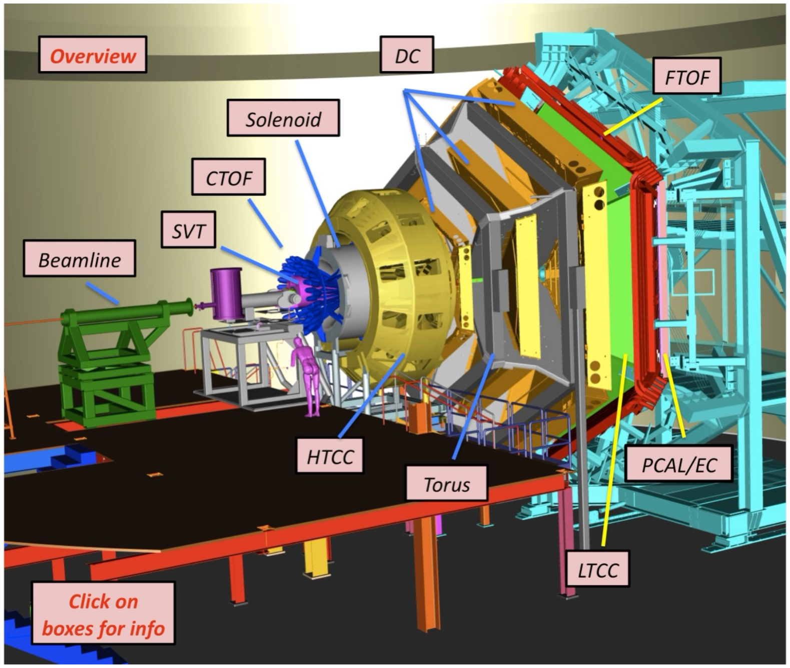


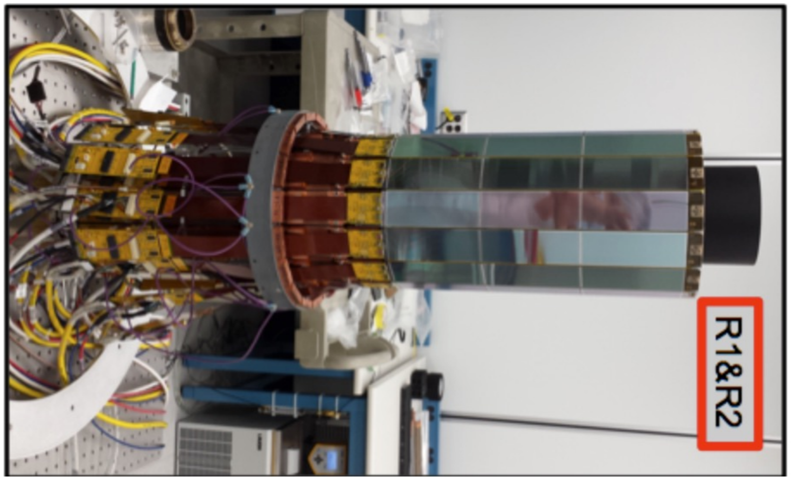
More detectors

We build particle detectors big…

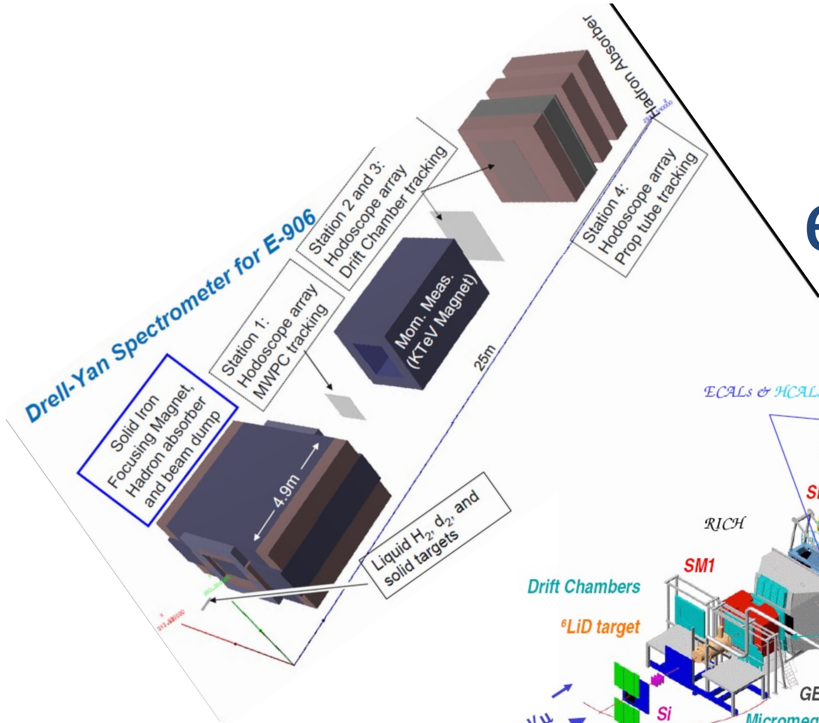
…and small:

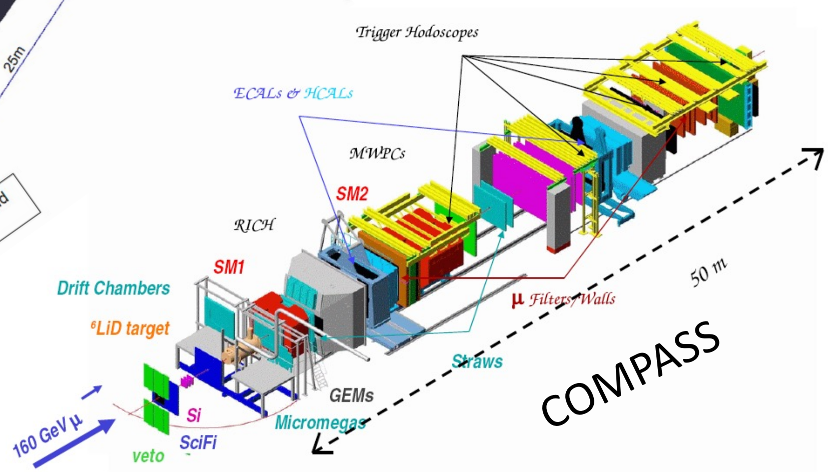


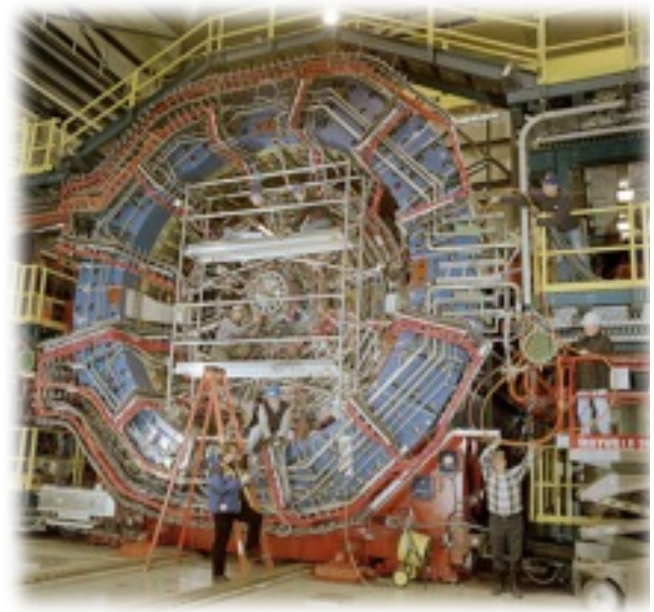




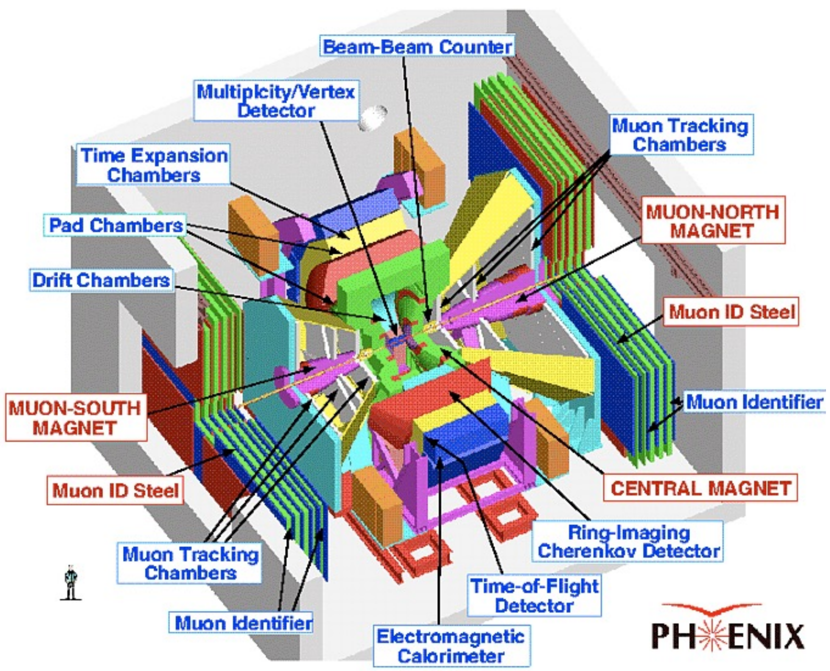
More experiments

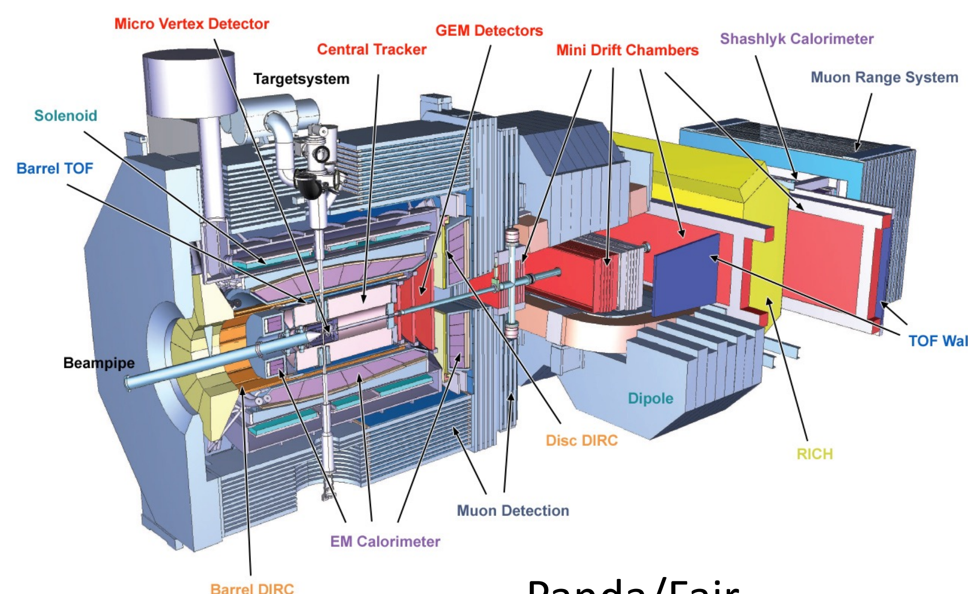






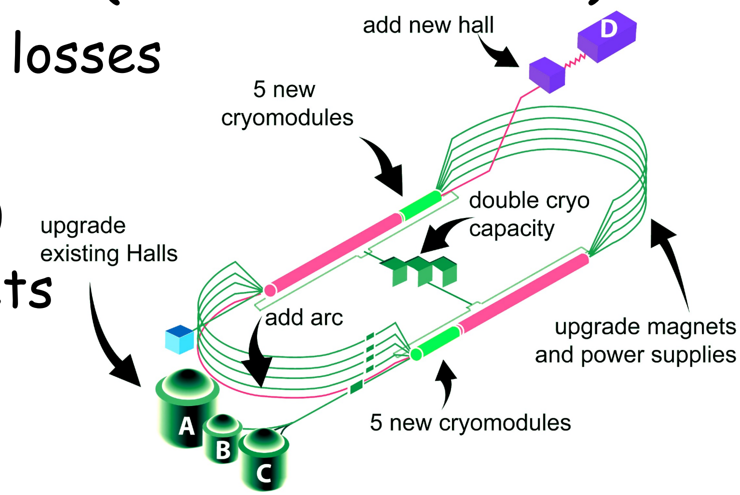
STAR





Panda/Fair

- Superconducting Linear Accelerators (CEBAF at JLab)
  - 2K niobium cavities, very low resistive losses
  - Recirculate few times, 100's of μA
  - High gradient (5-50 MeV/m ⇒ 4-12 GeV)
  - CW extracted beam on external targets
  - Thick targets ⇒ high luminosity



- Storage rings (HERA at DESY, RHIC at BNL, LHC at CERN)
  - Large circulating currents (mA)
  - Recirculate millions of times
  - Require only modest (re)acceleration
  - CW internal beam on thin gas targets or counterrotating beams (typically lower Luminosity)

The future landscape of Nuclear Physics

1. Study how nucleons are made up from quarks ("flavor", **p**, **L**, **S** -> 3D tomography)
2. Study how hadronic quark structure is influenced by the nuclear environment
3. Understand nuclear structure and dynamics in terms of quark degrees of freedom
4. Study extreme forms of nuclear matter: high energy (Quark-Gluon plasma), high density (short range correlations, n stars, "color glass condensates",…), non-zero strangeness (hypernuclei, strangelets, …), large n/p imbalance (radioactive beams)…
5. Study fundamental symmetries, neutrinos, nuclei in the universe
6. Develop new applications in medicine, energy, materials, homeland security, …

Hadron Machines

FAIR

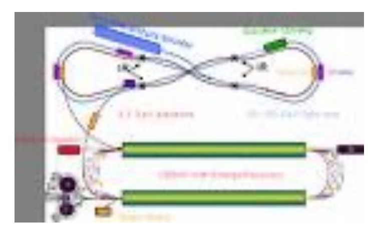
J-PARC

LHC

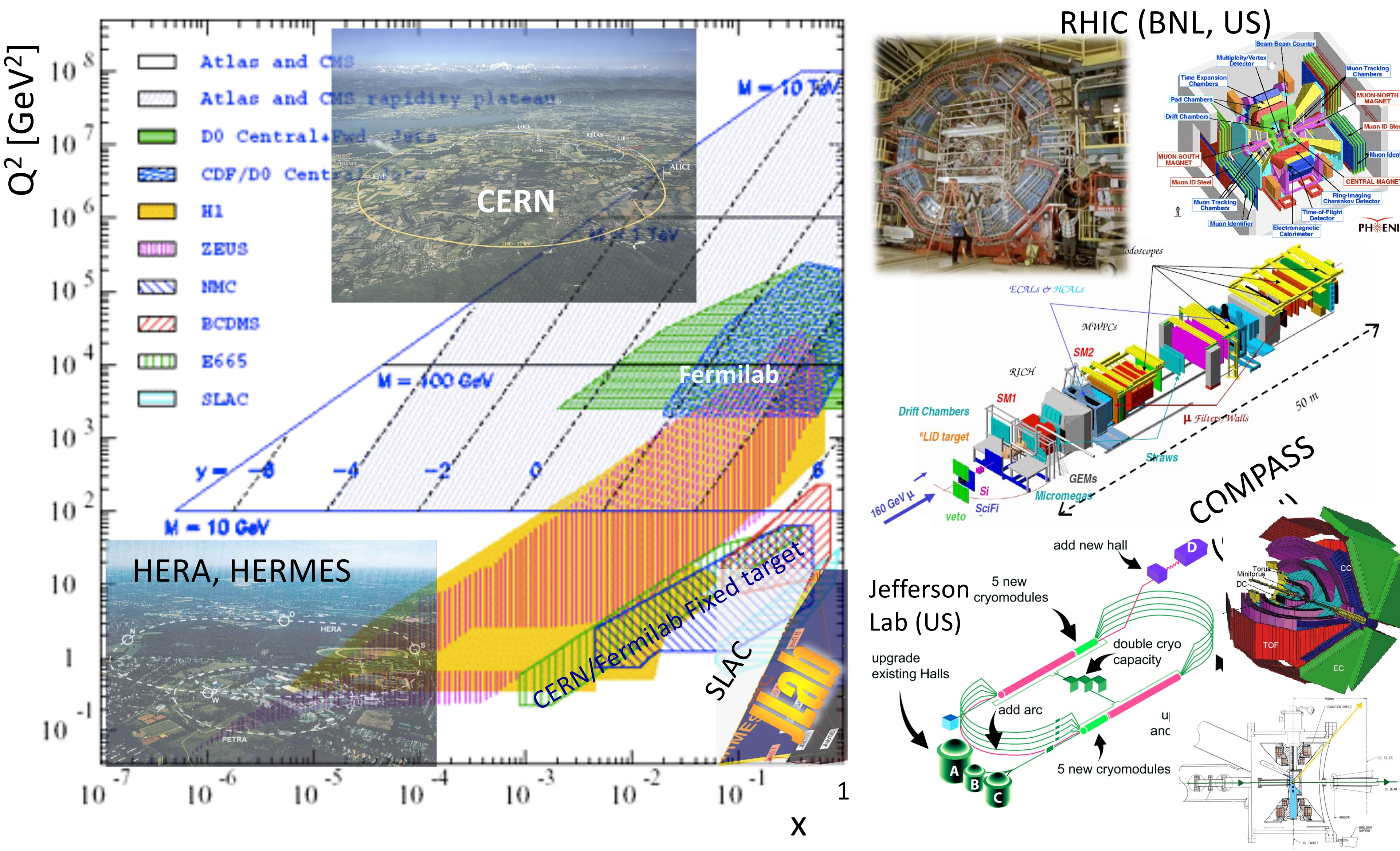
Electron machines

Jlab

Electron-Ion-Collider (2025?)



Experimental Facilities



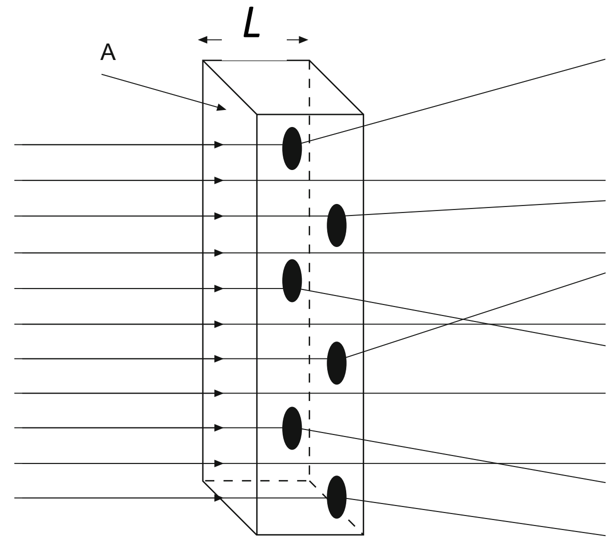
What do we measure in scattering?

- Cross Sections! (What is that?)


- Probability to crash is proportional to
  - n_T = Density of asteroids
  - Distance L to traverse entire field
  - Size σ of asteroids (actually: cross sectional area)

Prob. = $n_T \cdot L \cdot \sigma$

Cross Section cont'd



- Take a box filled with nuclei
  - n_T = # of nuclei/volume = $\#/L{\cdot}A$
  - L = length of box in beam direction
  - Project all nuclei onto the front face of the box (surface area A)
  - "Areal Density" $n_T L$ = number of nuclei per unit surface area
  - Unit: $1/\text{cm}^2$
- Probability for a reaction to occur must be dimensionless – hence we have to multiply with something of dimension area (unit cm^2) => cross section σ
- $n_T L \sigma$ = "fraction of surface area covered"

What if we have a beam of "spaceships" (= incoming beam particles)?

- Incoming "current": $\dot{n}_b$ (beam particles/s)
- Target areal density: $n_T L$ = number of nuclei per unit surface area
- Cross section $\Delta\sigma$ for a specific reaction to happen
- => number of times this reaction happens per second (event rate): $\dot{N} = \dot{n}_b \, n_T L \, \Delta\sigma$
- Call $\mathcal{L} = \dot{n}_b \, n_T L$ the luminosity of the experiment

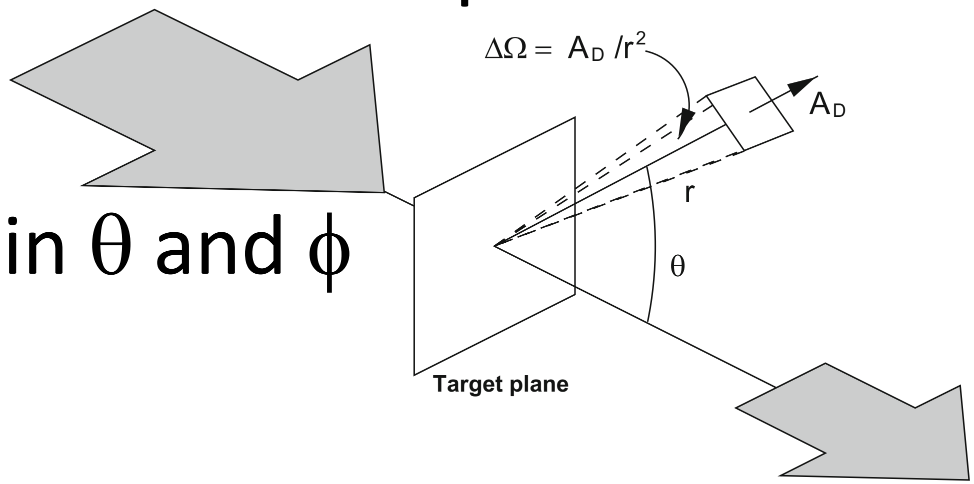
$$N = \int \mathcal{L} \, \Delta\sigma \; dt$$

Example: Luminosity and cross sections

- On white board
- Remember: If atomic mass is *A*, then 1 g of the material contains 1/*A* mol
- 1 mol = $6.022 \cdot 10^{23}$ atoms (and hence nuclei)
- 1μA of electrons contain $10^{-6}\,{}^{C}/_{s}\,/\,1.6 \cdot 10^{-19}$ C = $6.25 \cdot 10^{12}$ e/s
- 1 "barn" 1 b = 10^{-24} cm^2
  - mb(arn), μb, nb, pb,…

Example partial cross section: scattering into a detector

Look only at events where the beam particle is scattered into a specific detector area = a specific angular range in θ and ϕ
=> Solid angle $\Delta\Omega$



$\Delta\sigma$ proportional to $\Delta\Omega$

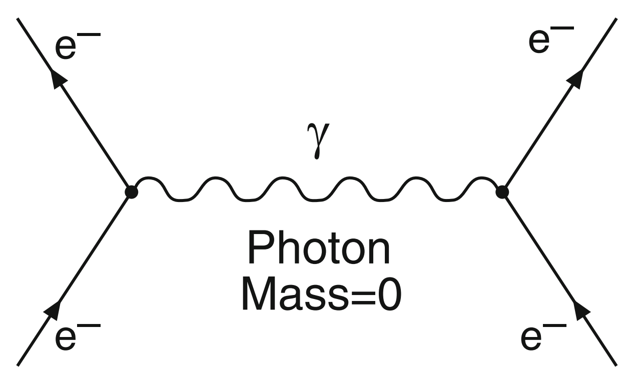
=> Use ratio $\Delta\sigma/\Delta\Omega$ to express the "intrinsic" scattering strength (independent of detector used)

$$\dot{N}(E, \theta, \Delta\Omega) = \mathcal{L} \cdot \frac{\mathrm{d}\sigma(E, \theta)}{\mathrm{d}\Omega} \Delta\Omega$$

How do we calculate cross sections? Feynman diagrams

- Theoretical ansatz: Look at single scattering centers, incoming beam = current density j_b. Event rate $\dot{N} = \Delta\sigma \cdot j_b$.
- "Infinitesimal" cross section: $^{d\sigma}/_{d\Omega}(\theta,\phi)$.
- Differential cross section depends only on physics of interaction (potential…) and available final state "phase space".
- Interaction often depicted with Feynman diagrams.

$$\sigma = \frac{2\pi}{\hbar \cdot v_a} \left|\mathcal{M}_{fi}\right|^2 \cdot \varrho\left(E'\right)$$



Recap: Relativistic Kinematics

- Often in high energy nuclear/particle physics, particles move with close to the speed of light, *c*, hence we have to use special relativity
- Recall: $\gamma = (1-v^2/c^2)^{-1/2}$, $\beta = v/c$, $E = \gamma M c^2$, $p=\gamma M v$. (Note: we'll simplify our lives by often ignoring factors of *c*.)
- 4-vectors: $v^\mu = (v^0, v^1, v^2, v^3)$. $x^\mu = (ct, x, y, z)$.
  $P^\mu = (E/c, \vec{p})$ ($\vec{p}$ = "3-vector part" of P^μ).
- General transformation: Lorentz Matrix
- Very useful in relativistic kinematics: Invariants (same in all coordinate systems). *E.g.*:
  Scalar product $P^\mu P_\mu = (P^0)^2 - \vec{p}^{\,2} = M^2c^2$.