PHYSICS 489/1489

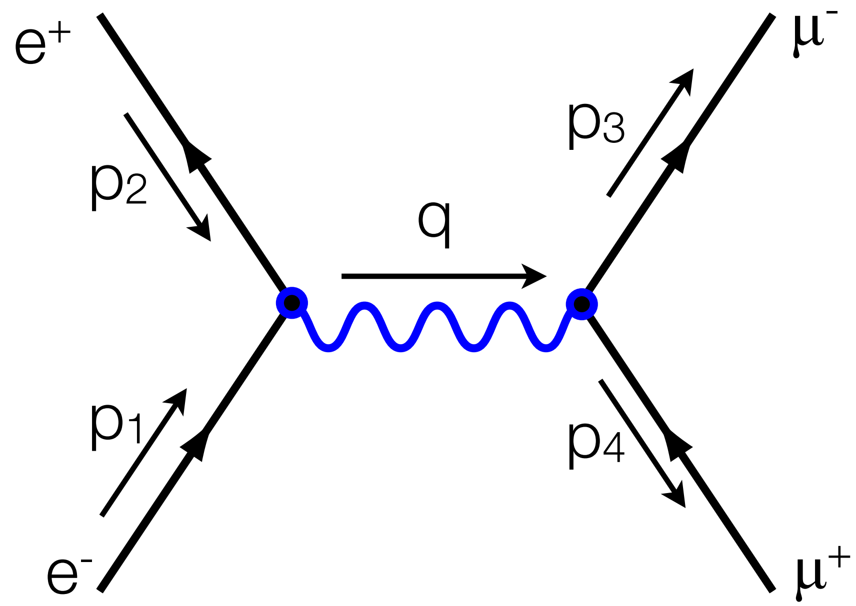
LECTURE 9: QED EXPERIMENTS

A FEW NOTES

- There were a few typos in the last lecture
  - I've placed an updated version of the slides on the website
- Please note that Problem Set 2 is posted
  - due 25 October

LAST TIME

- We calculated the cross section for e+e->m+m-



$$\mathcal{M} = -\frac{g_e^2}{(p_1+p_2)^2}\left[\bar{u}(3)\ \gamma^\mu\ v(4)\right]\left[\bar{v}(2)\ \gamma_\mu\ u(1)\right]$$

- Evaluated the matrix element with various helicity combinations in the massless limit

$$\mathcal{M}_{LR\to LR} = -\frac{e^2}{4E^2}[\bar{u}_{3L}\gamma^\mu v_{4R}]\ [\bar{v}_{2R}\gamma_\mu u_{1L}] = e^2(1+\cos\theta) = \mathcal{M}_{RL\to RL}$$

$$\mathcal{M}_{LR\to RL} = -\frac{e^2}{4E^2}[\bar{u}_{3R}\gamma^\mu v_{4L}]\ [\bar{v}_{2R}\gamma_\mu u_{1L}] = e^2\times(-\cos\theta+1) = \mathcal{M}_{RL\to LR}$$

- Obtain the differential (unpolarized, spin-summed) cross section

$$\frac{d\sigma}{d\Omega} = \frac{e^4}{256\pi^2E^2}(1\pm\cos\theta)^2 \qquad \frac{d\sigma}{d\Omega} = \frac{e^4}{64\pi^2 s}(1+\cos^2\theta)$$

A FEW NOTES:

- The derivation applies to any spin 1/2 fermion so long as
  - massless approximation(s) is appropriate
  - charge is appropriately scaled
- We can integrate over angles to get the total cross section

$$\frac{d\sigma}{d\Omega} = \frac{e^4}{64\pi^2 s}(1+\cos^2\theta) \quad \Rightarrow \int d\phi \int d\cos\theta \, \frac{e^4}{64\pi^2 s}(1+\cos^2\theta)$$

$$\int d\cos\theta \, \frac{e^4}{32\pi s}(1+\cos^2\theta)$$

$$\frac{e^4}{12\pi s} = \frac{4\pi\alpha^2}{3s}$$

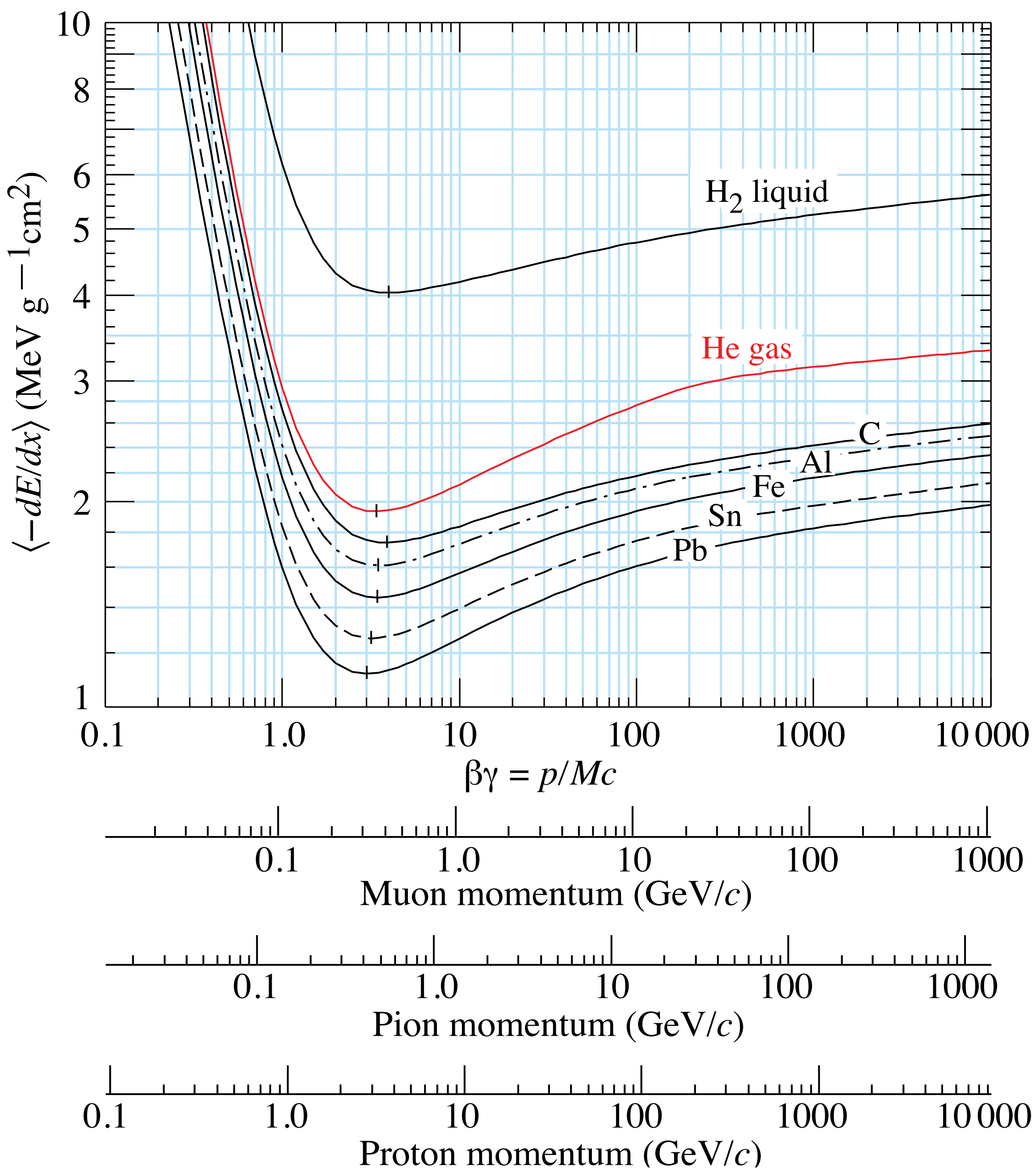
- If we did not neglect the masses, we would obtain:

$$\langle|\mathcal{M}|^2\rangle = g_e^4 \left[1 + \left(\frac{mc^2}{E}\right)^2 + \left(\frac{Mc^2}{E}\right)^2 + \left[1-\left(\frac{mc^2}{E}\right)^2\right]\left[1-\left(\frac{Mc^2}{E}\right)^2\right]\cos^2\theta\right]$$

DETECTING PARTICLES

- For the most part, we can only detect charged particles
  - neutral particles can be detected if they
    - interact with charged particles which are in turn detected
    - decay to produce charged particles
- Detection methods:
  - ionization
  - scintillation
  - Cherenkov radiation
  - acoustic
  - . . . . ..

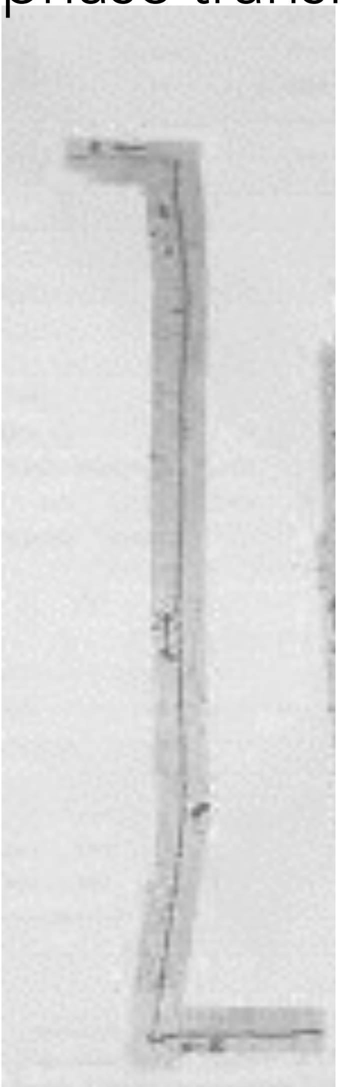
IONIZATION:

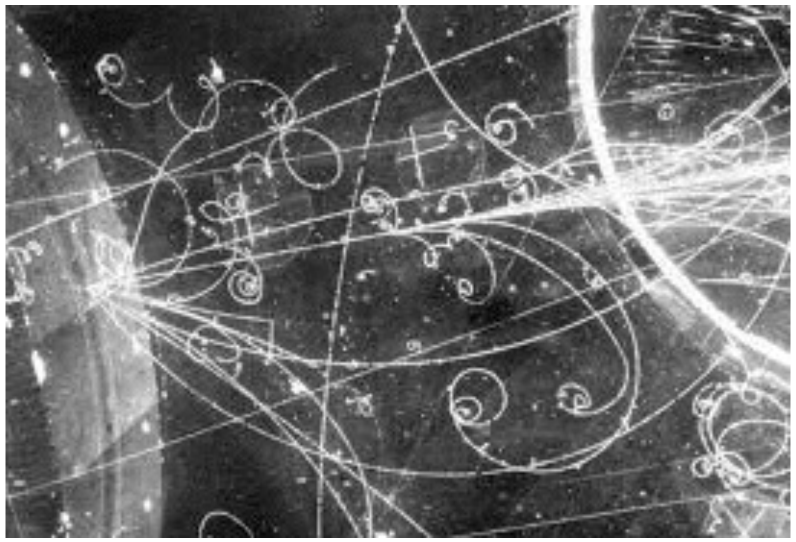


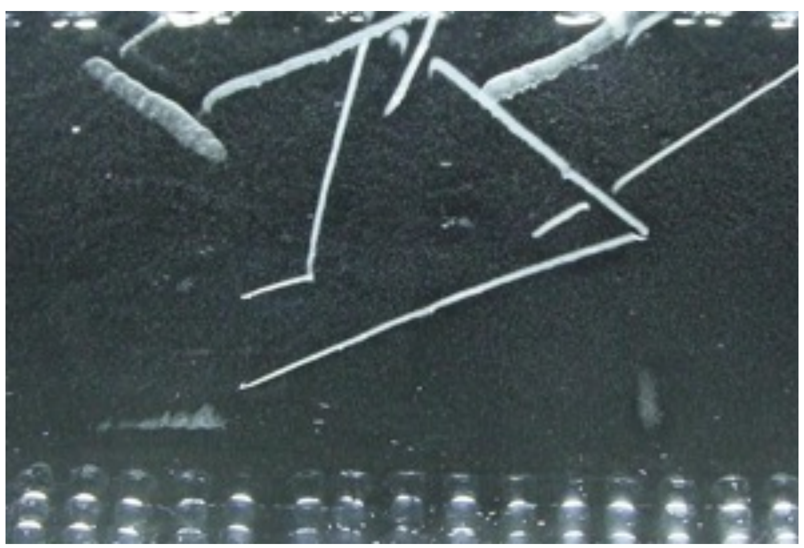
- Knock out of electrons from atom as a charged particle passes through a medium
- Ionization rate depends on velocity of particle
  - if we independently know the velocity of momentum of the particle, we can determine the particle identity
  - e.g. if the medium of
- "Tracking" detectors which determine the trajectory of a particle typically use ionization

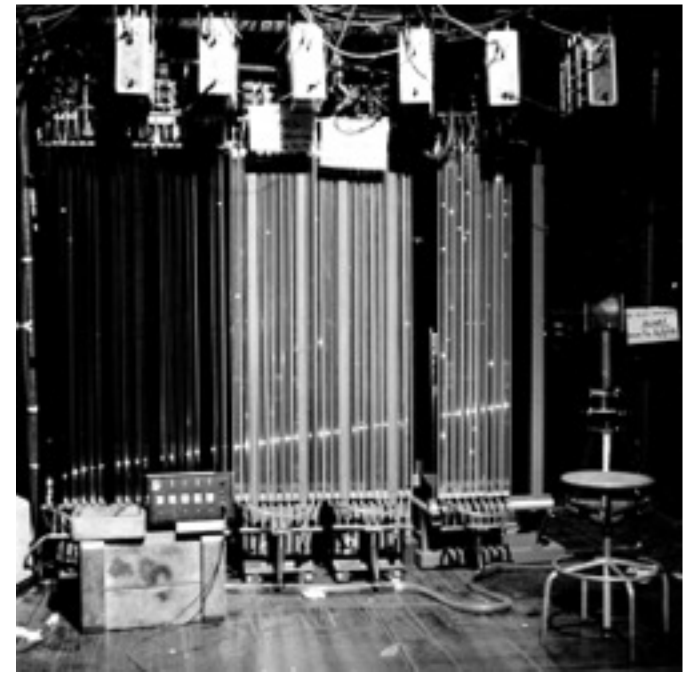
HOW TO DETECT IONIZATION

phase transitions

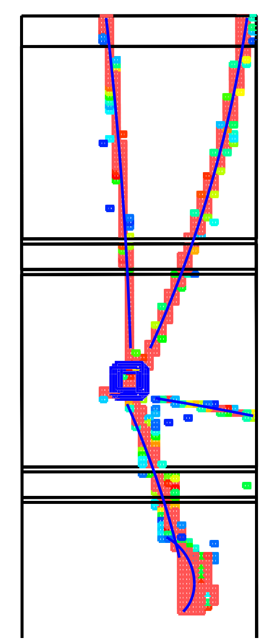


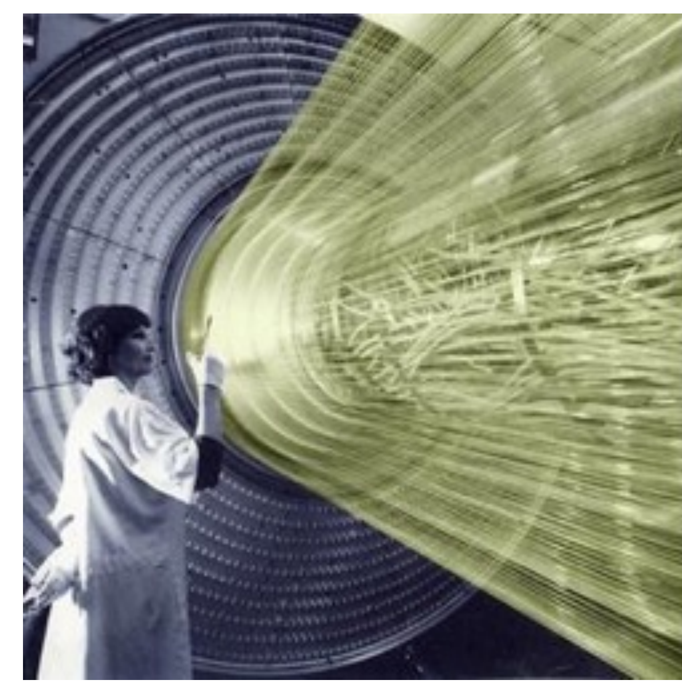






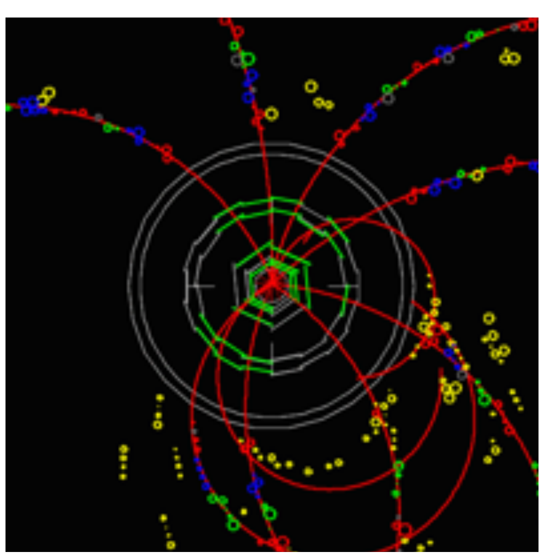
sparking, streaming

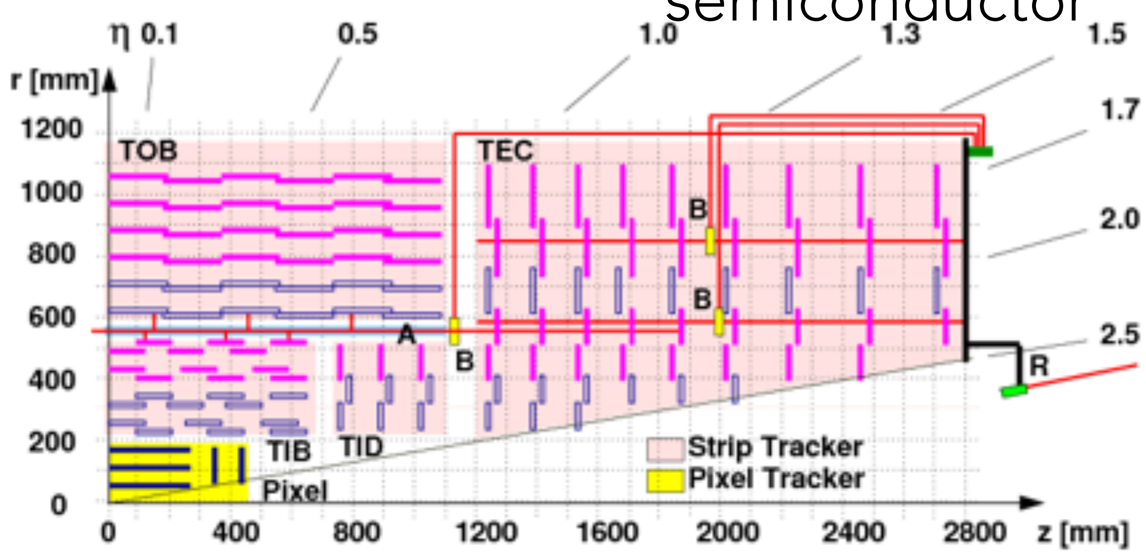




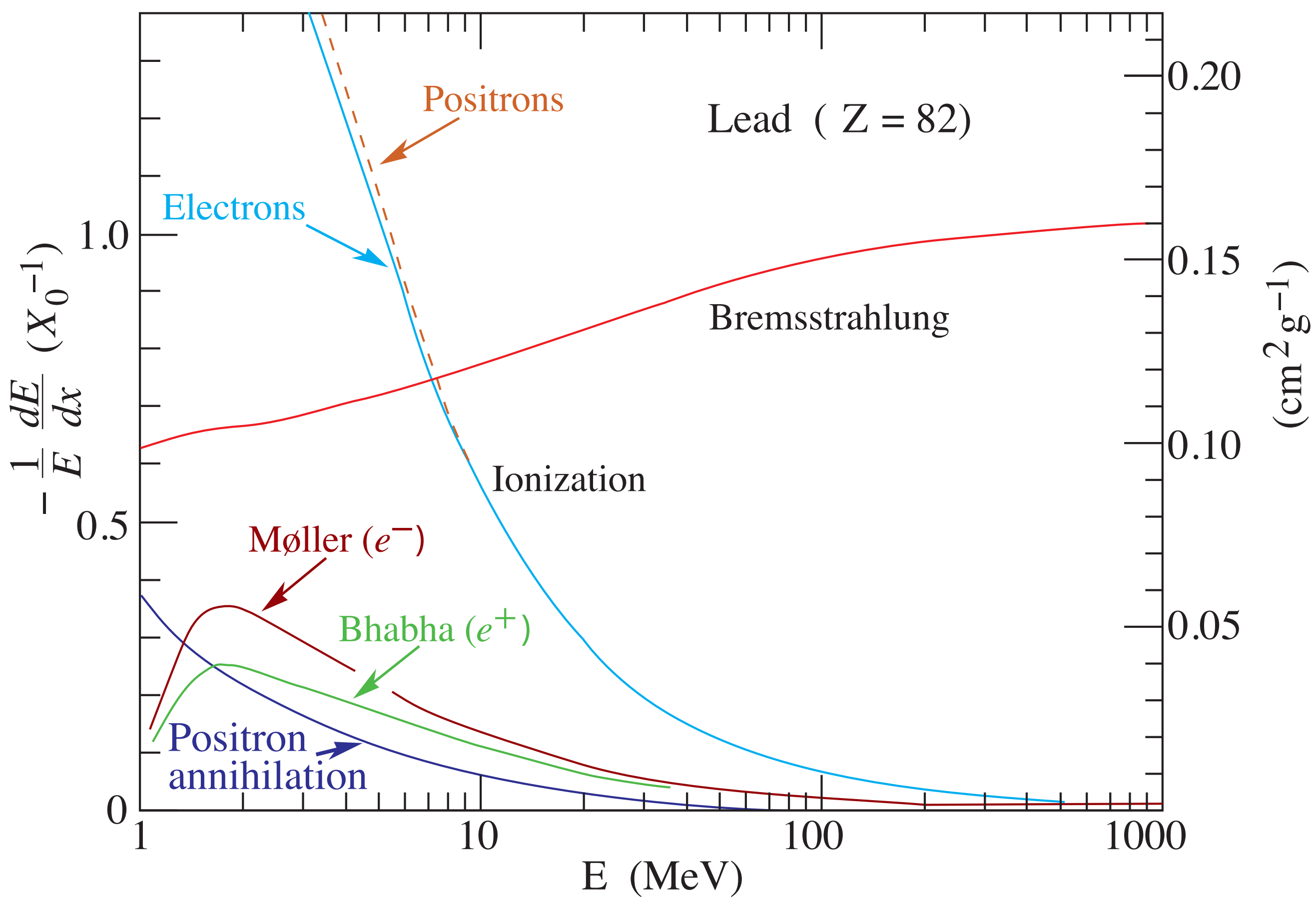
drifting in gas/liquid

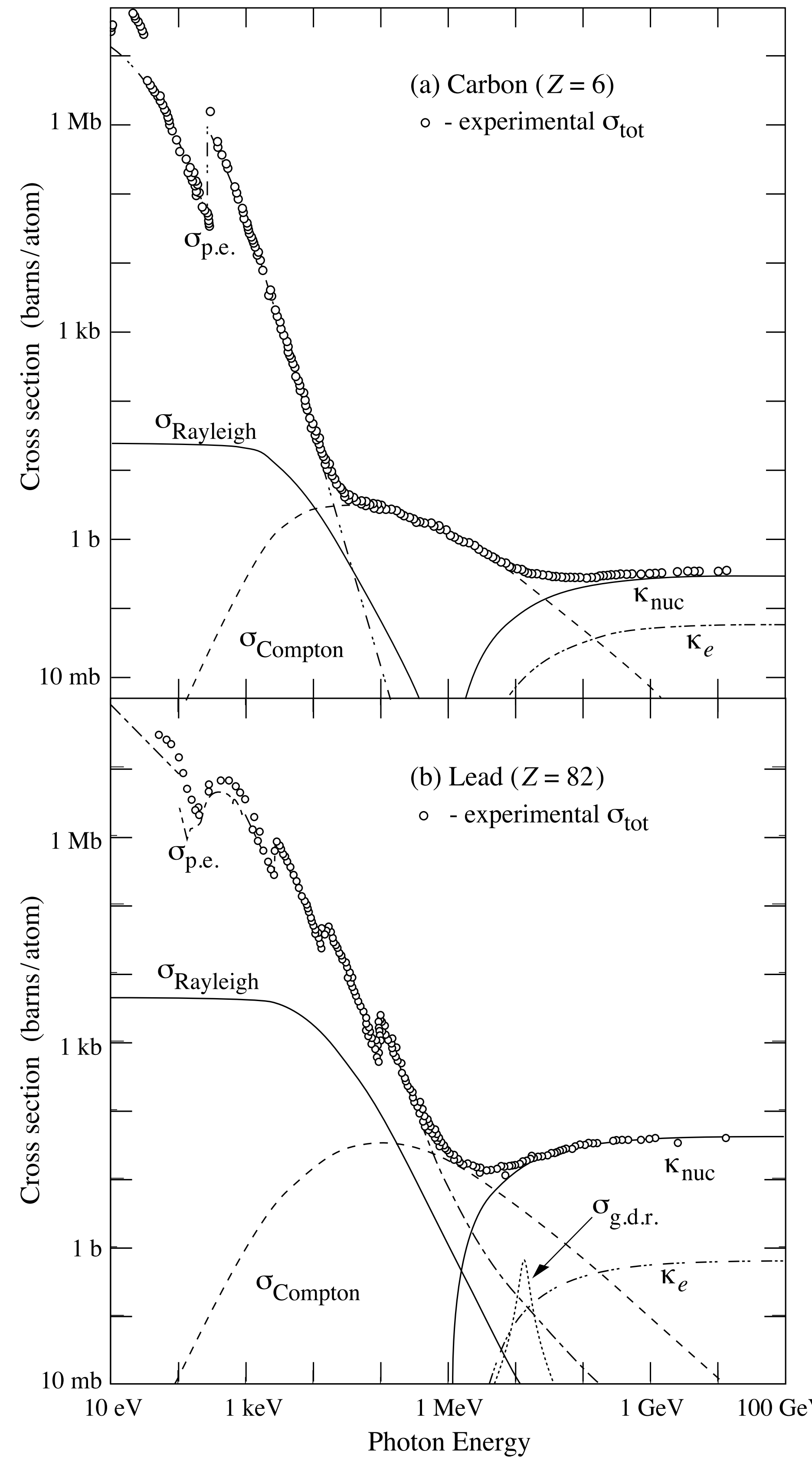
semiconductor





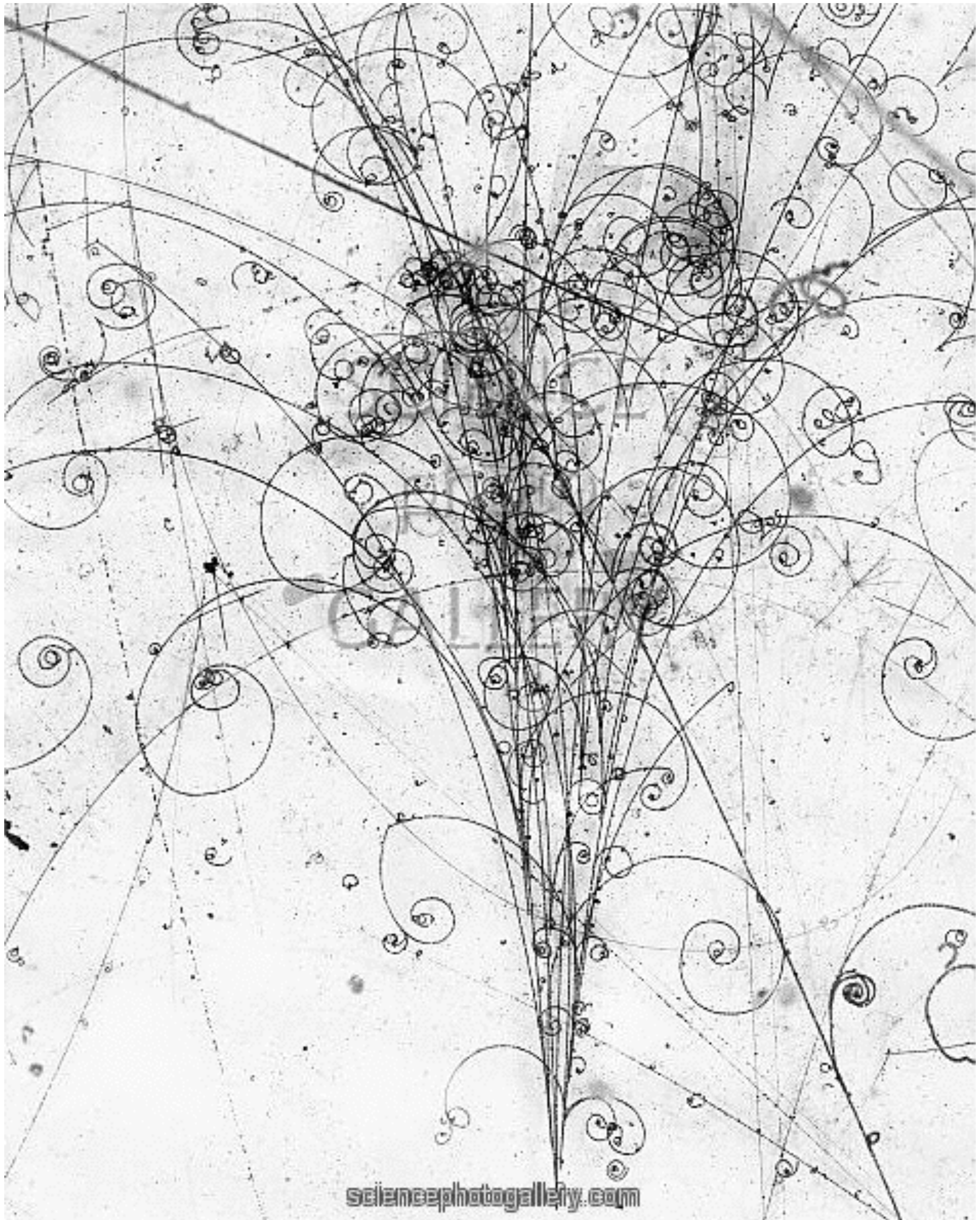
ELECTRONS AND PHOTONS

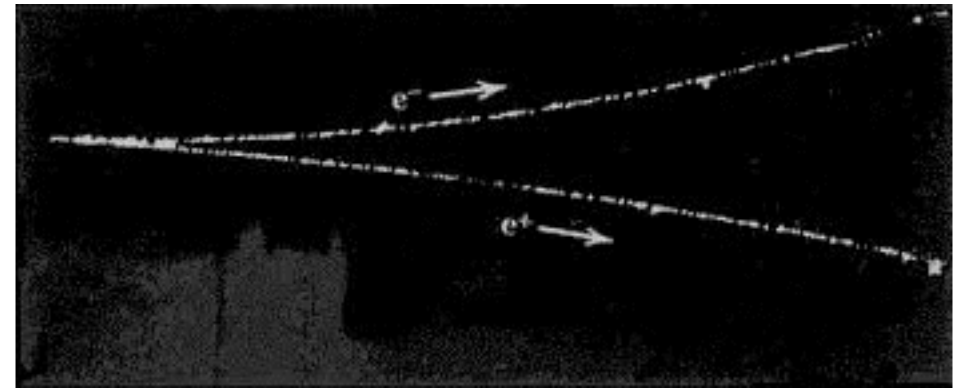




- electrons differ from other charged particles by their lightness and the presence of electrons in media
  - nuclear field can induce acceleration leading to radiation "bremsstrahlung"
- Photons will interact via Compton scattering or pair production at high energies

ELECTROMAGNETIC SHOWERS



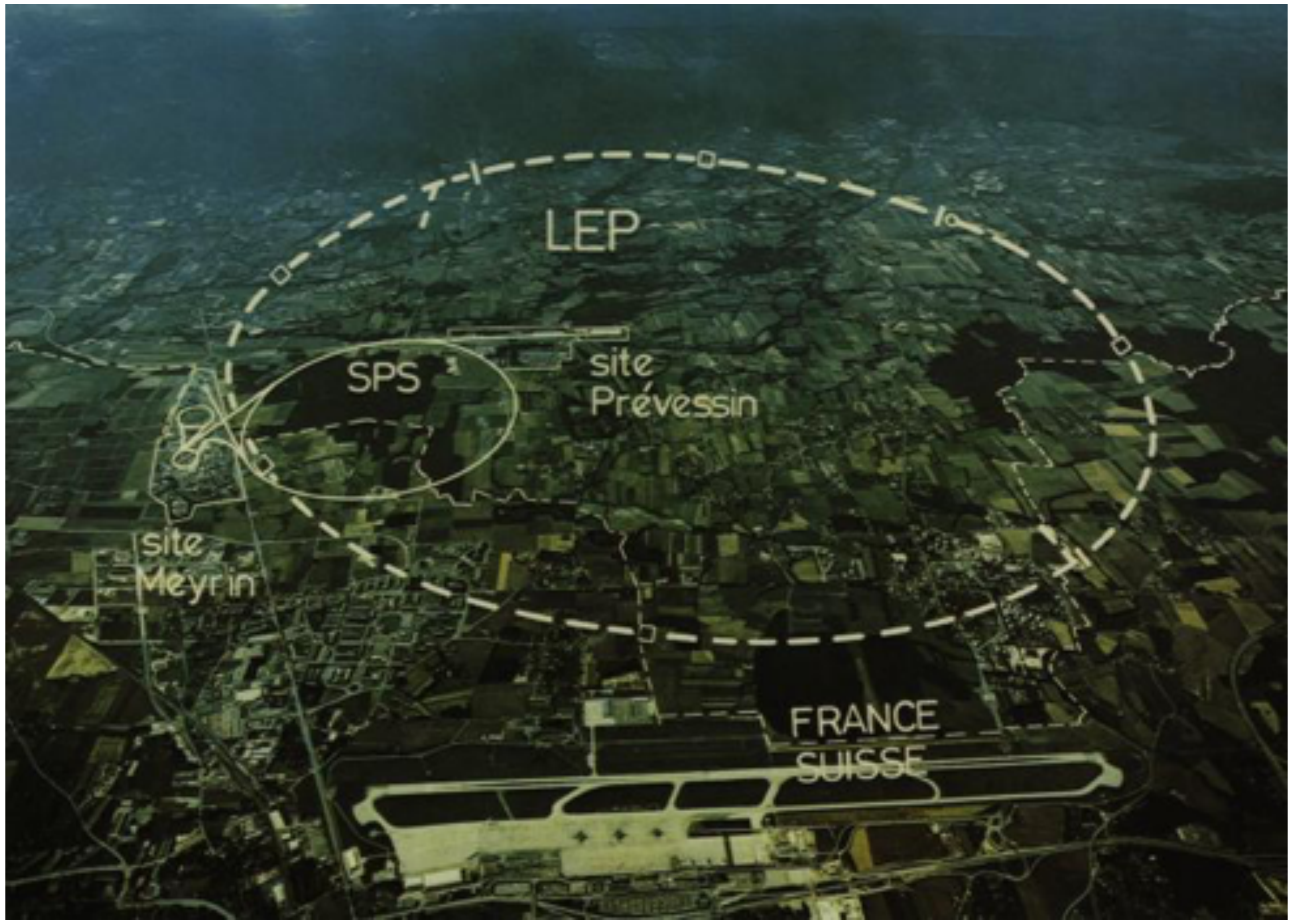


- Cascade of Bremsstrahlung, pair production, compton scattering, etc.

ACCELERATORS

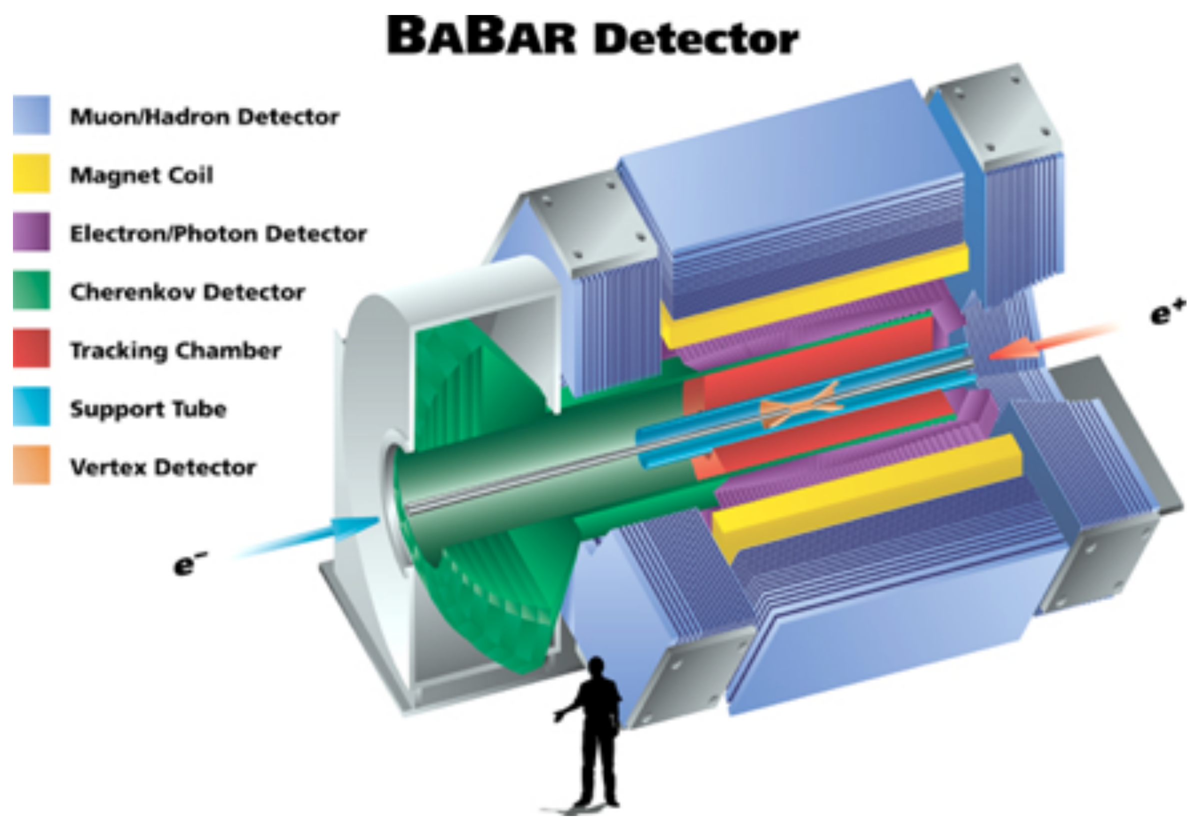
- Several generations of electron accelerators
  - CESR @ Cornell
  - SLAC linear accelerator
  - SLAC collier
- Also
  - PETRA at DESY (Hamburg, Germany)
  - TRISTAN at KEK (Tsukuba, Japan)
  - VEPP at BINP (Novosibirsk, Russia)
  - BES (Beijing, China)

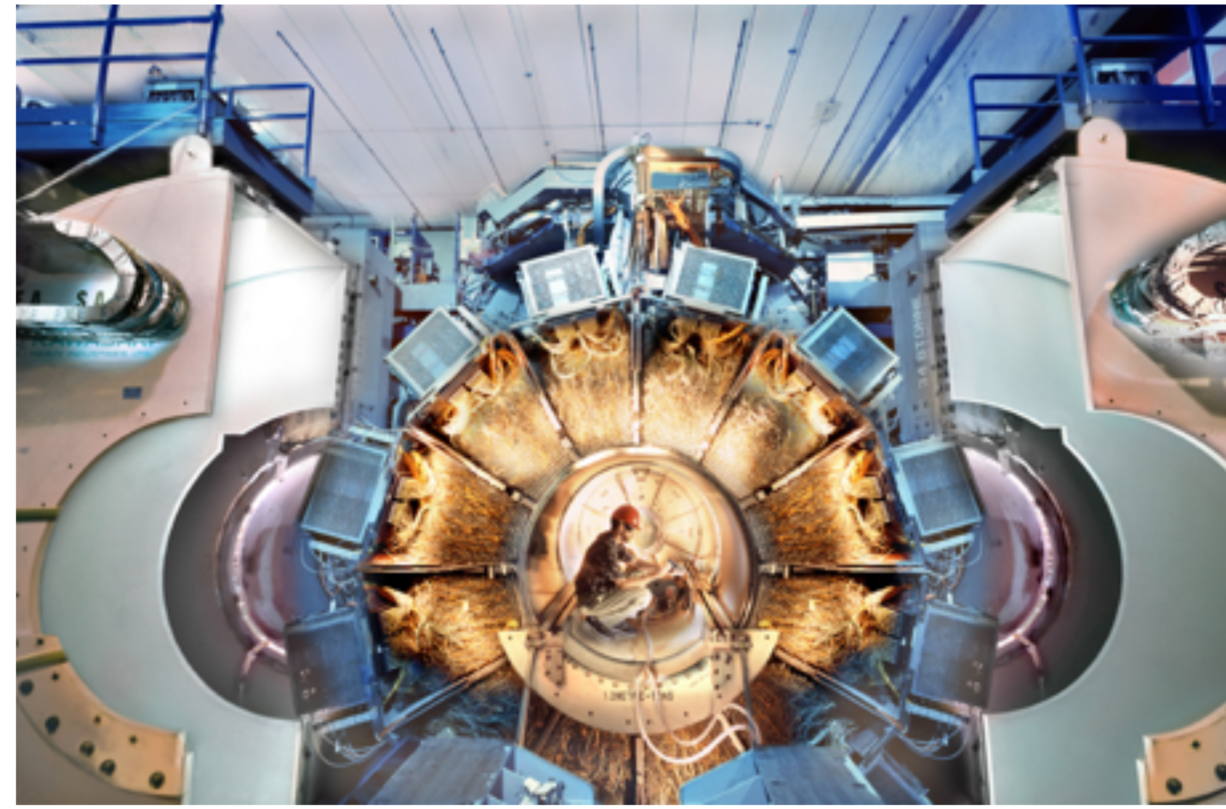
LEP



- Before the LHC there was LEP:
  - "large electron positron collider"
  - operated primarily at 91 GeV to study Z production and decays
- "LEP-II":
  - increase of energy up to 209 GeV

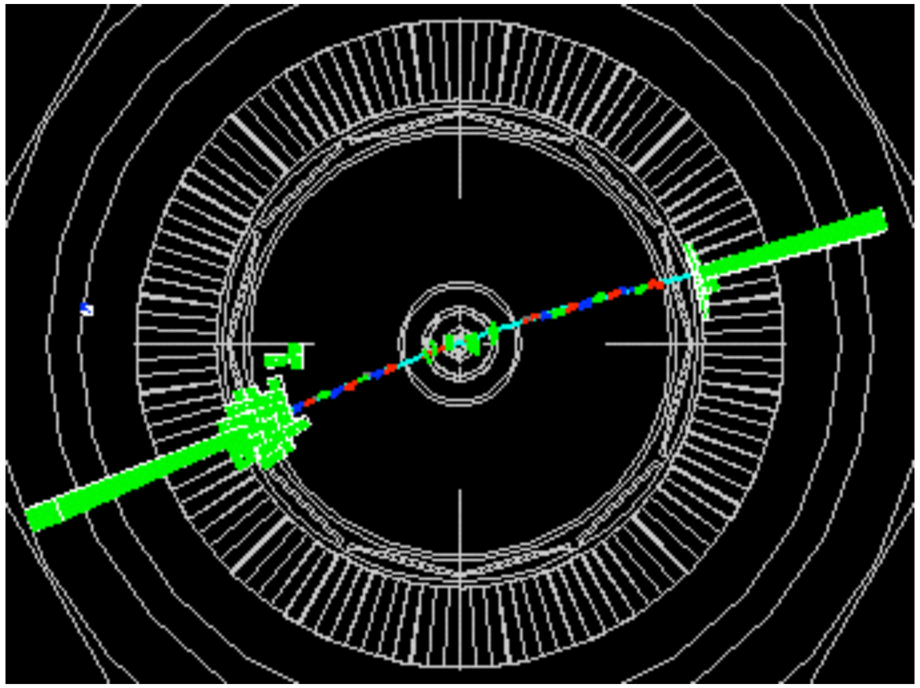
DETECTORS



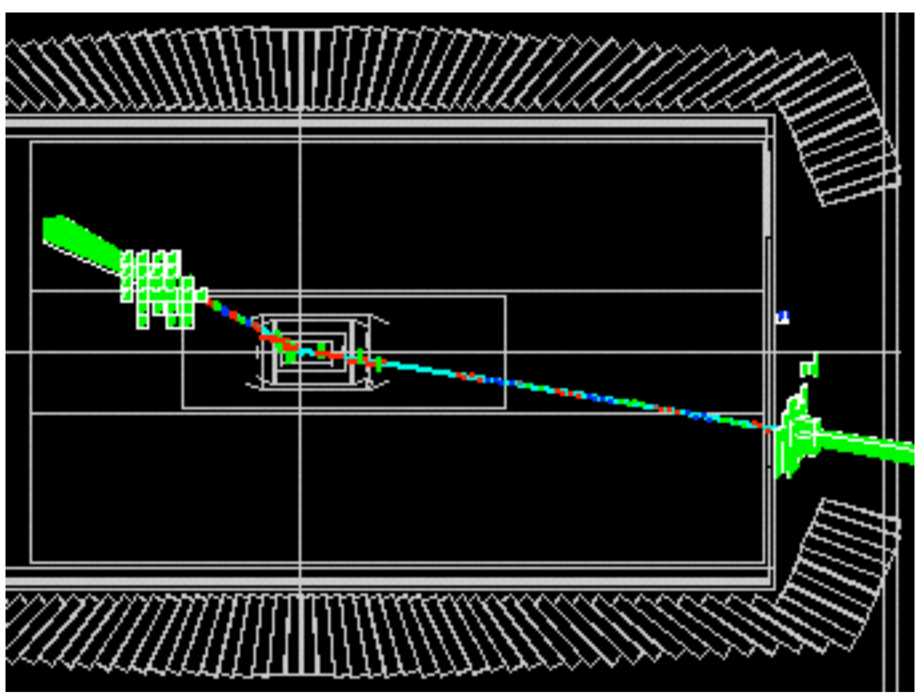


- Most collider detectors share a similar “cylindrical onion” design surrounding the interaction point
  - inner tracking region (silicon, drift chambers, etc.)
  - particle identification (Cherenkov counter, time-of-flight, etc.)
  - electromagnetic calorimeter (measure/identify electron/photon energy)
  - muon detector: identify muons by their penetration through lots of material
  - magnetic field throughout to bend particles and measure sign/momentum

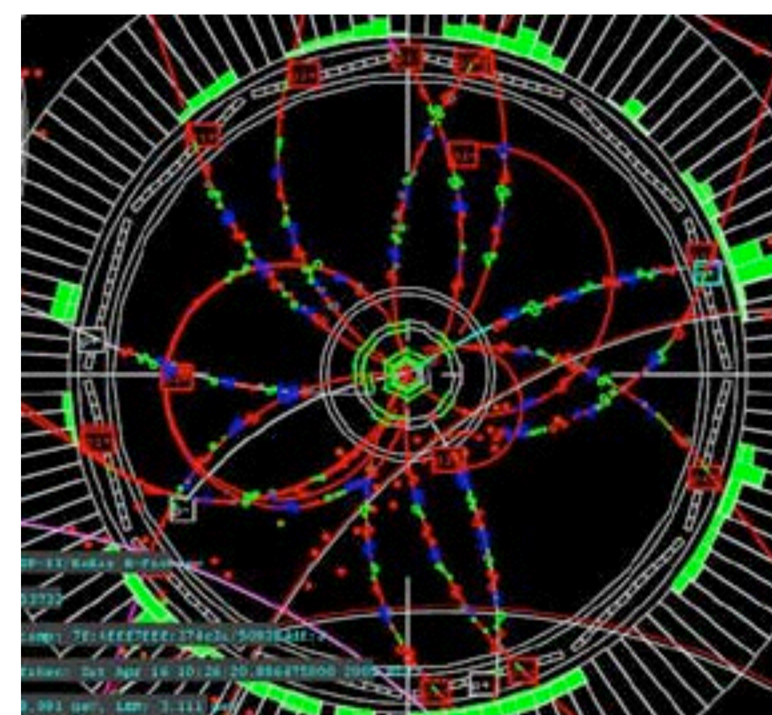
EVENTS AT BABAR



- $e^{+} + e^{-} \rightarrow e^{+} + e^{-}$ event (“Bhabha scattering”)
  - “straight” track: high momentum
  - large deposition in electromagnetic calorimeter (green)
- $e^{+} + e^{-} \rightarrow \mu^{+} + \mu^{-}$ would look similar but with little calorimeter deposition



- “Hadronic” event at BaBar
  - $e^{+} + e^{-} \rightarrow qq$
  - b and c quarks produced



τ PRODUCTION

- General expression without massless assumption:

$$\langle|\mathcal{M}|^2\rangle = g_e^4 \left[1 + \left(\frac{mc^2}{E}\right)^2 + \left(\frac{Mc^2}{E}\right)^2 + \left[1 - \left(\frac{mc^2}{E}\right)^2\right]\left[1 - \left(\frac{Mc^2}{E}\right)^2\right]\cos^2\theta\right]$$

- if we consider e+e- -> t+t-, we can still assume electron mass is ~0, but keep the mass of the t.

$$\langle|\mathcal{M}|^2\rangle = g_e^4 \left[1 + \left(\frac{Mc^2}{E}\right)^2 + \left[1 - \left(\frac{Mc^2}{E}\right)^2\right]\cos^2\theta\right]$$

- Now putting into our cross section formulas

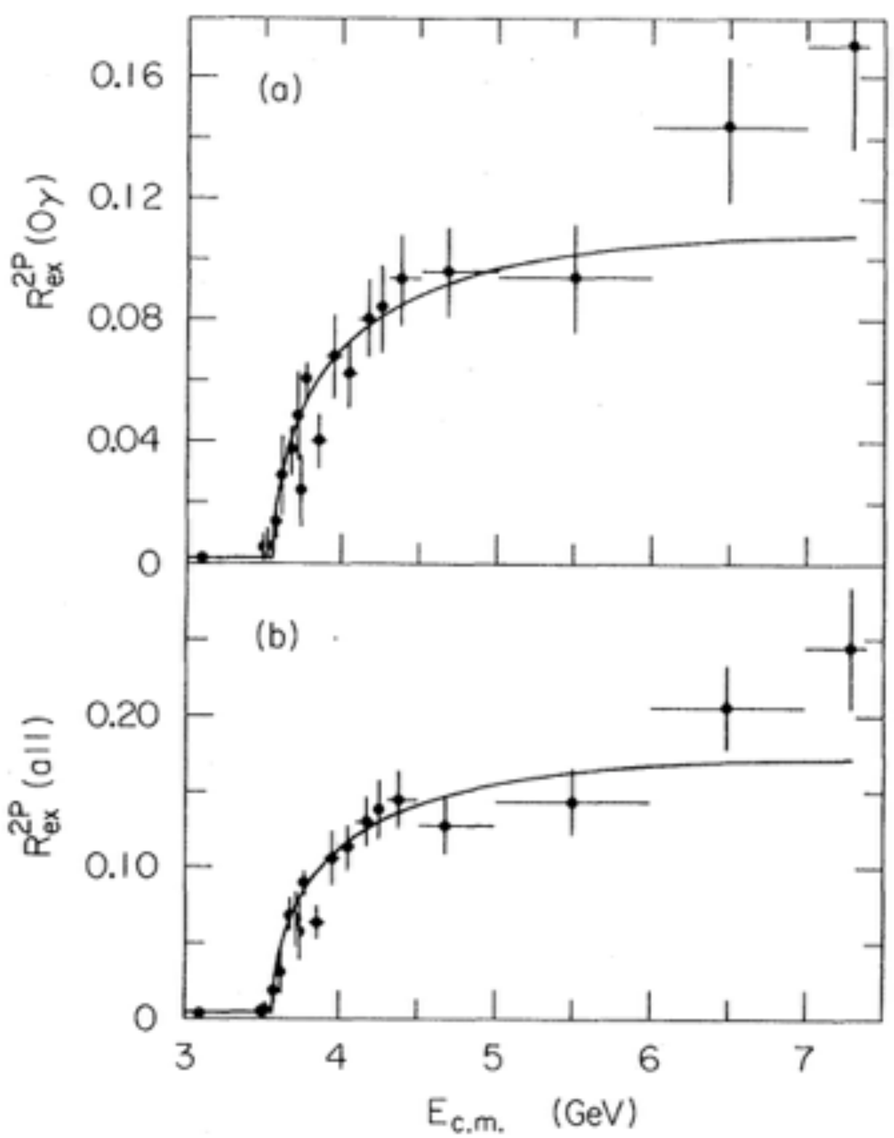
$$\frac{d\sigma}{d\cos\theta d\phi} = \left(\frac{\hbar c}{8\pi}\right)^2 \frac{\langle|\mathcal{M}|^2\rangle}{4E^2}\frac{|p_f|}{|p_i|}$$

- Integrate to obtain total cross section

$$\sigma = \frac{\pi}{3}\left(\frac{\hbar c\alpha}{E}\right)^2 \sqrt{1 - (Mc^2/E)^2}\left[1 + \frac{1}{2}\left(\frac{Mc^2}{E}\right)^2\right]$$

RATIO OF CROSS SECTIONS

- $e^{+} + e^{-} \rightarrow \mu^{+} + \mu^{-}$ has a very distinct signature in the detector.
- predict the ratio of **τ** production to μ production:

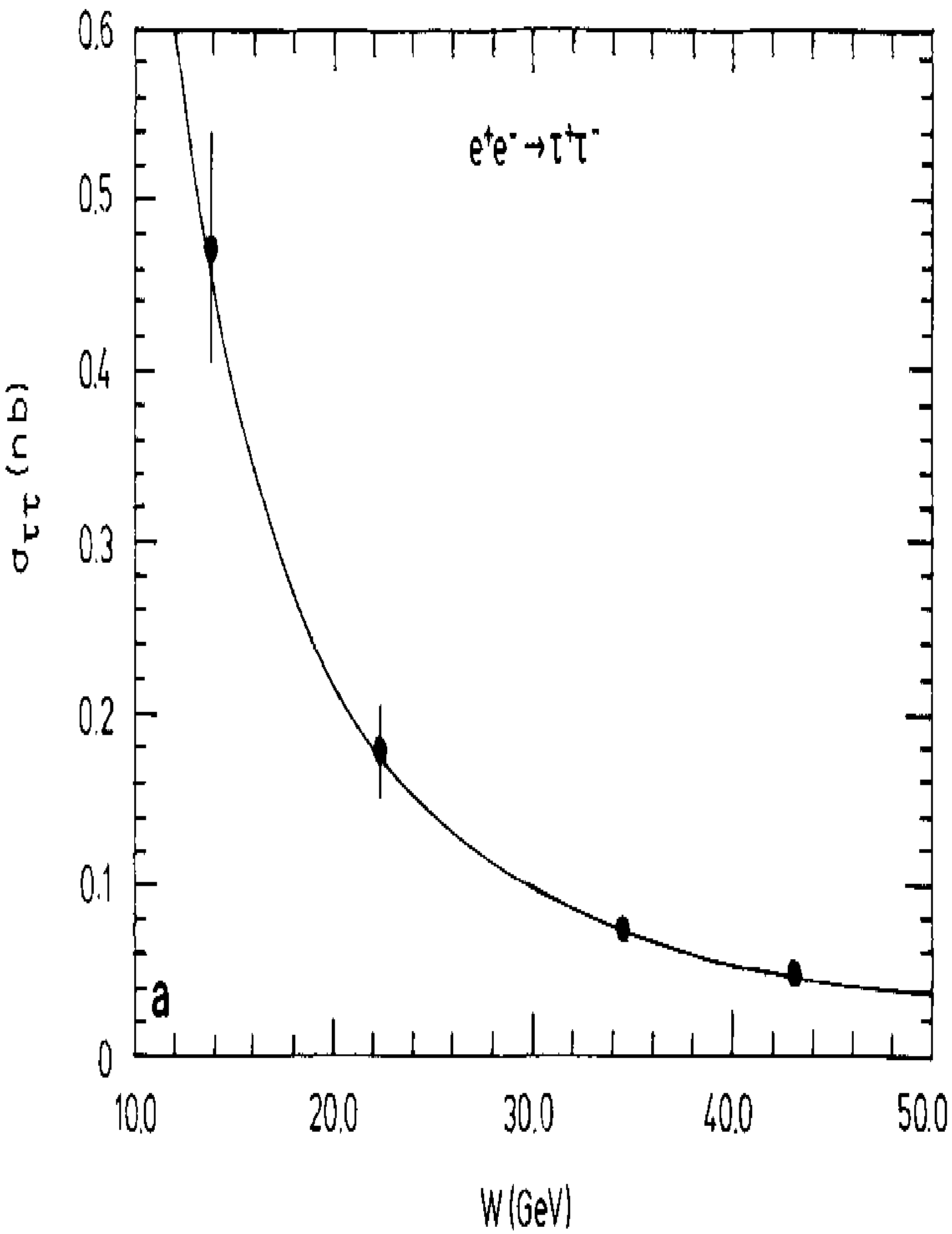


$$R_{\tau\mu} = \frac{\sigma_{\tau^+\tau^-}}{\sigma_{\mu^+\mu^-}} = \frac{\sqrt{1-(M_\tau c^2/E)^2}}{\sqrt{1-(M_\mu c^2/E)^2}} \times \frac{1+\frac{1}{2}(M_\tau c^2/E)^2}{1+\frac{1}{2}(M_\mu c^2/E)^2}$$

- Step the accelerator in energy
  - count the number of **τ** and μ produced at each energy
- Plot the ratio vs. beam energy
- Ratio depends on:
  - Dirac nature of **τ**
  - **τ** mass

TOTAL CROSS SECTION

- If we go to high energy ($E \gg m_\tau \sim 1.777$ GeV)



$$\sigma = \frac{\pi}{3}\left(\frac{\hbar c \alpha}{E}\right)^2 \sqrt{1-(Mc^2/E)^2}\left[1+\frac{1}{2}\left(\frac{Mc^2}{E}\right)^2\right]$$

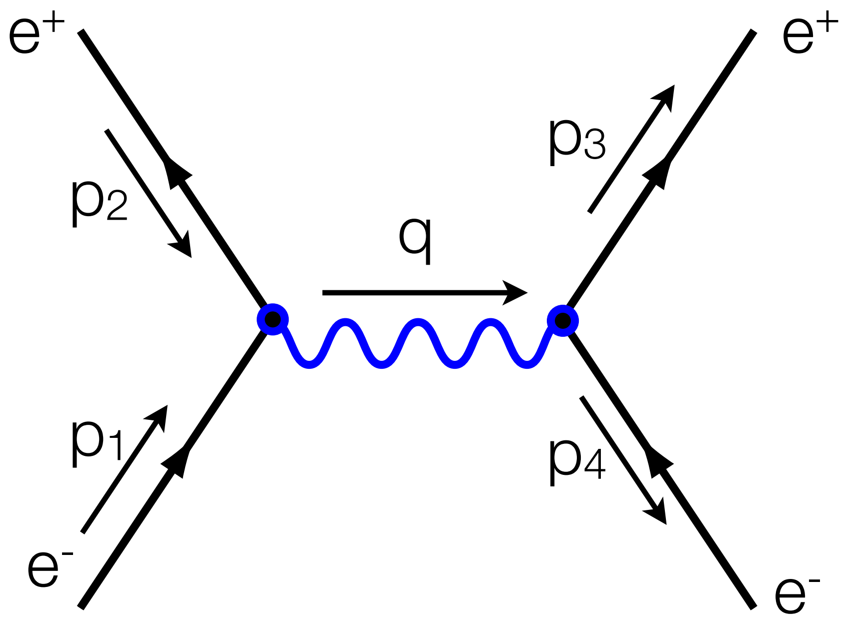
$$\sigma = \frac{\pi}{3}\left(\frac{\hbar c \alpha}{E}\right)^2$$

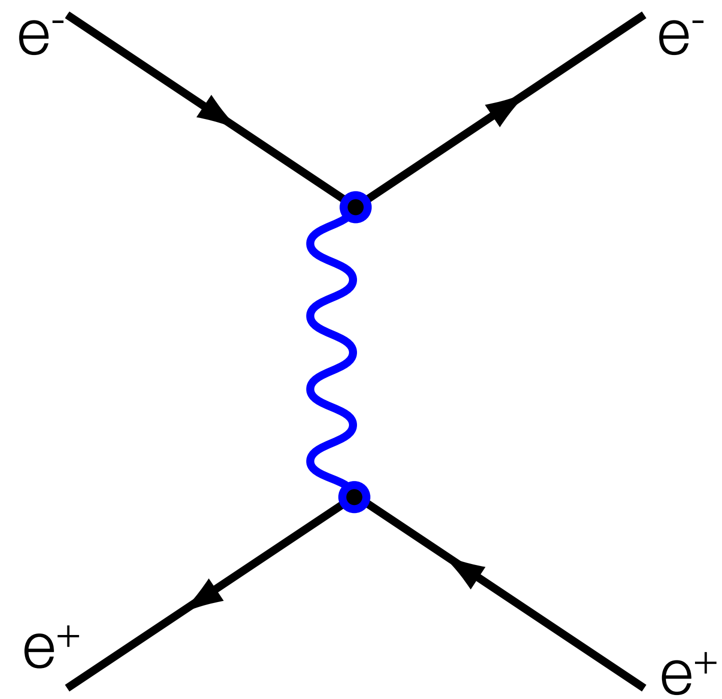
$= 2.2\text{x}10^{-5}$ mb/E^2(GeV^2)
$= 22$ nb/E^2(GeV^2)

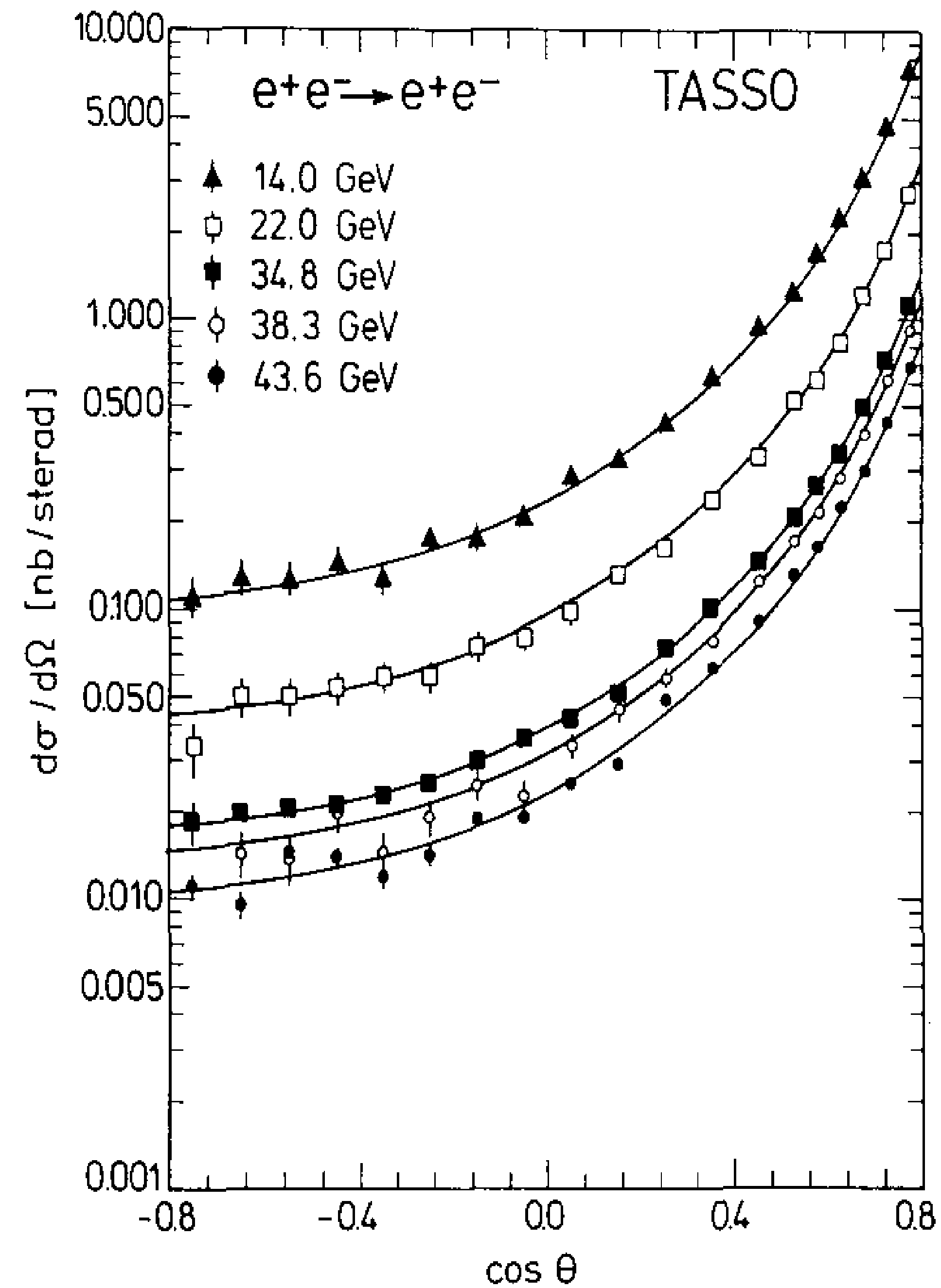
E (GeV)	Cross section (nb)
14	0.44
22	0.18
34	0.075
43	0.047

BHABHA SCATTERING

- $e^{+} + e^{-} \rightarrow e^{+} + e^{-}$
- additional diagram contributes





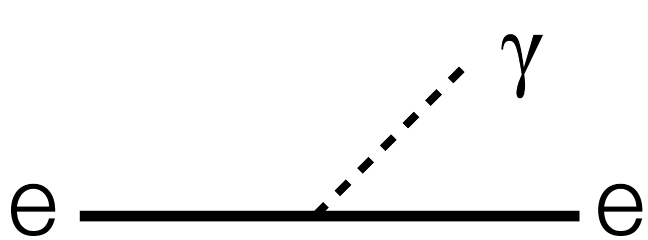


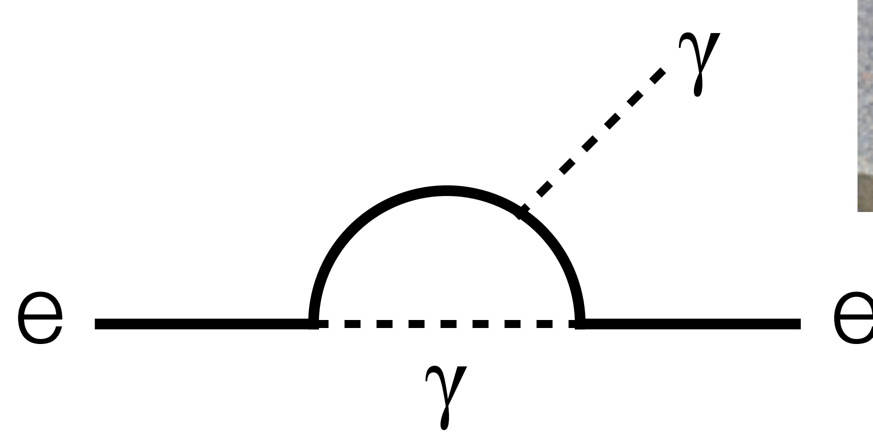
$$\frac{d\sigma}{d\cos\theta d\phi} = \left(\frac{\hbar c}{8\pi}\right)^2 \frac{g_e^4}{4E^2} \left(\frac{3+\cos^2\theta}{1-\cos\theta}\right)^2$$

THE "GYROMAGNETIC RATIO"

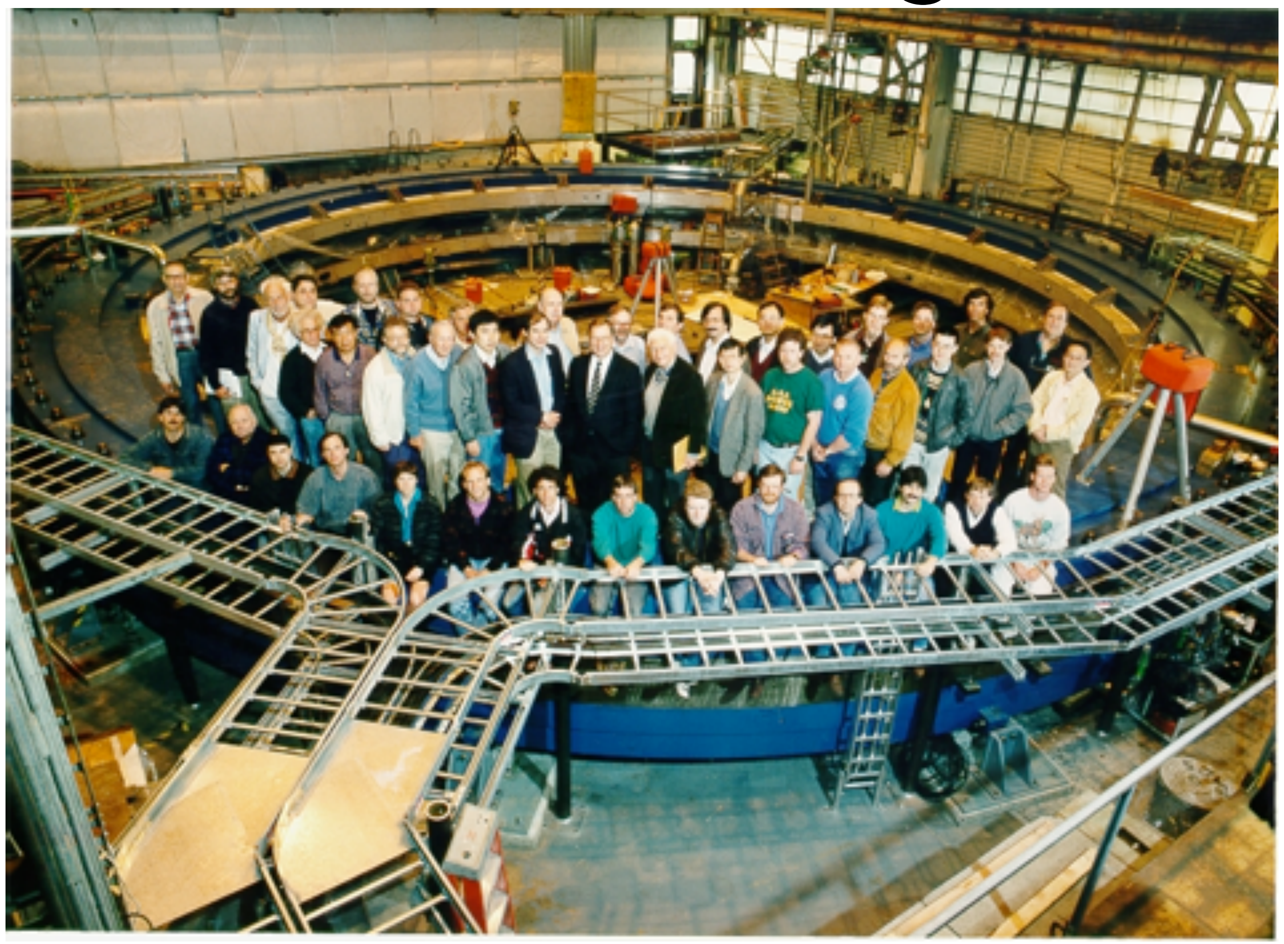
$$\mu = g\mu_B s/\hbar \qquad \mu_B = \frac{e\hbar}{2m}$$

- Ratio of magnetic moment to the spin x Bohr magneton
- This is not exactly 2 for an electron
  - higher order electromagnetic corrections
  - a = (g-2)/2 = ~ 0.0011596521807328
  - "anomalous" moment
  - first calculated by Julian Schwinger in 1948
    - a ~$\alpha/2\pi$ = 0.0011614





THE MUON g-2 EXPERIMENT



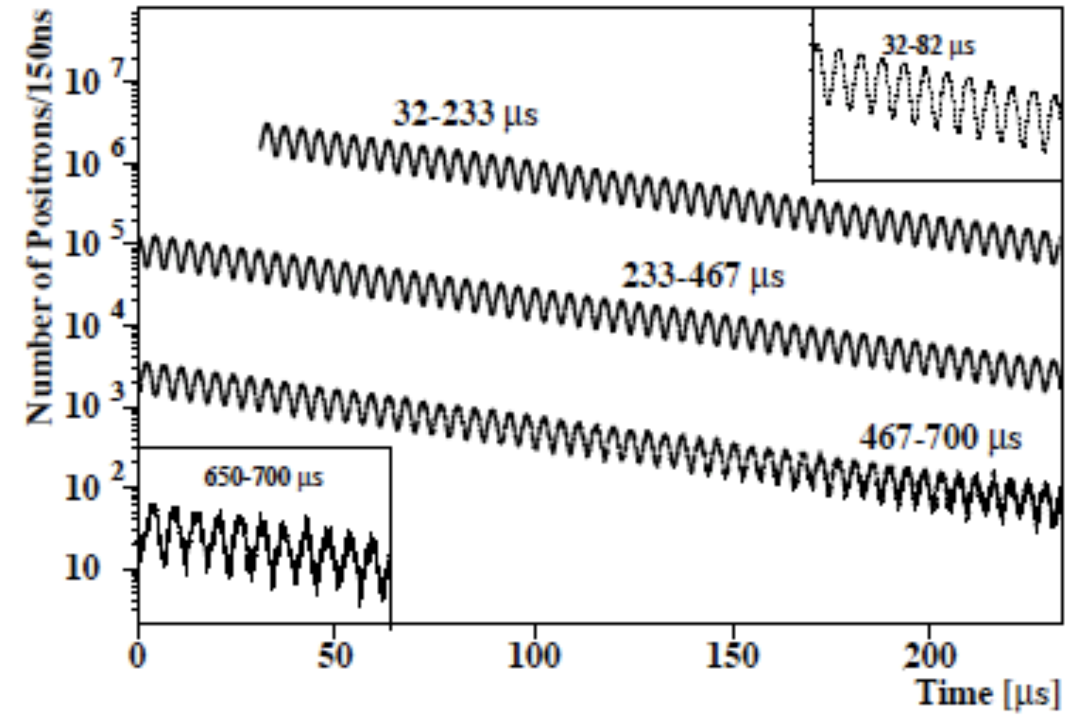
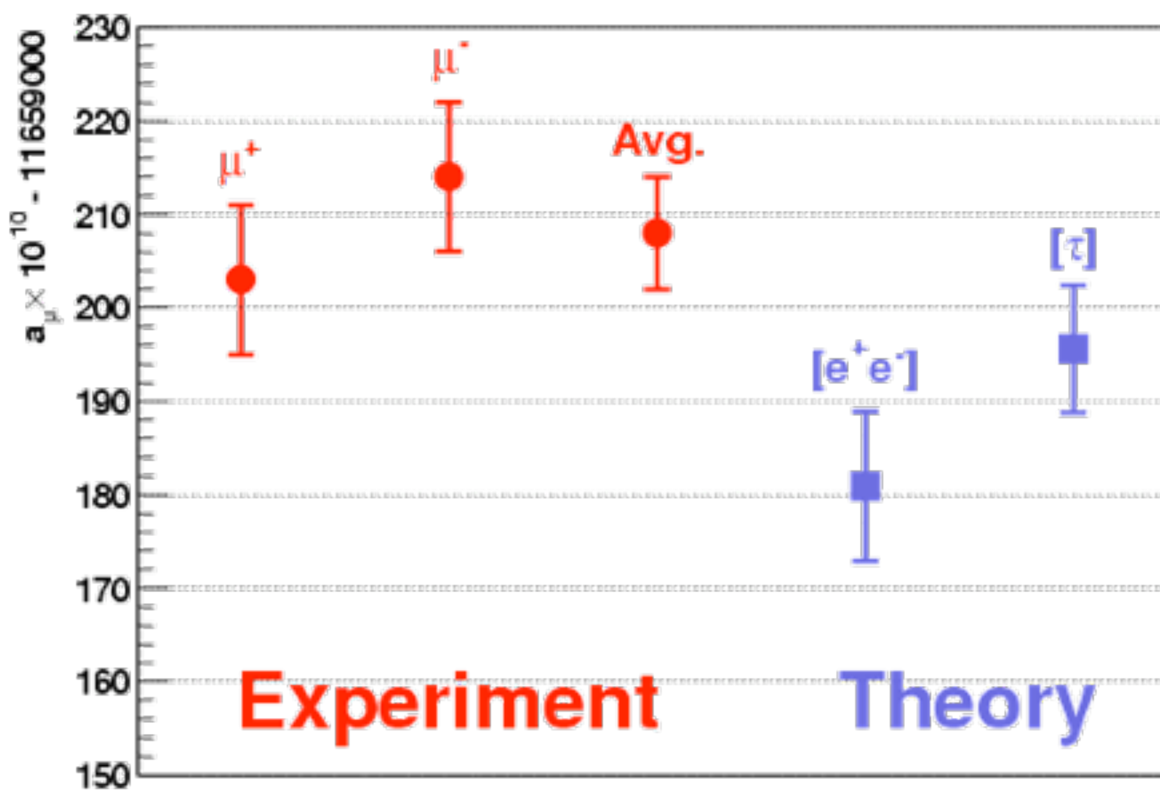


FIG. 3. Positron time spectrum overlaid with the fitted 10 parameter function (χ^2/dof= 3818/3799). The total event sample of 0.95×10^9 e^+ with $E \geq 2.0$ GeV is shown.

- Precess muon spin in a magnetic field as it circulates around a ring
  - direction of electron emerging from muon decay is correlated with its polarization
  - measure the precession of the spin to extract magnetic moment
- Predicted (g-2)/2=(1165918.81±0.38)x10^{-9}
- Measured (g-2)/2=(1165920.80±0.63)x10^{-9}



SUMMARY

- Please read Chapter 7 for next time