# The discovery of Neutral Currents


Andrea Giammanco


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**Physique des Particules Elementaires**

# Next 3 topics

- Neutral currents
- $J/\psi$ (charm quark)
- W and Z

These 3 discoveries killed the old particle physics paradigmas, and imposed what we now call the Standard Model. (Which is the paradigma that could be killed by LHC experiments...)

A bit of theory will be spread across the next lessons, with the purpose of encouraging you to think yourself about the data↔theory link.

But, as the original experimenters, you must not believe a theory until the data that you see <u>oblige</u> you to take it as the explanation!

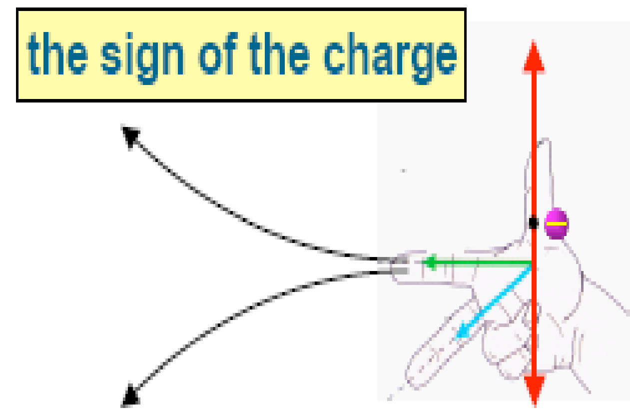
# Bibliography

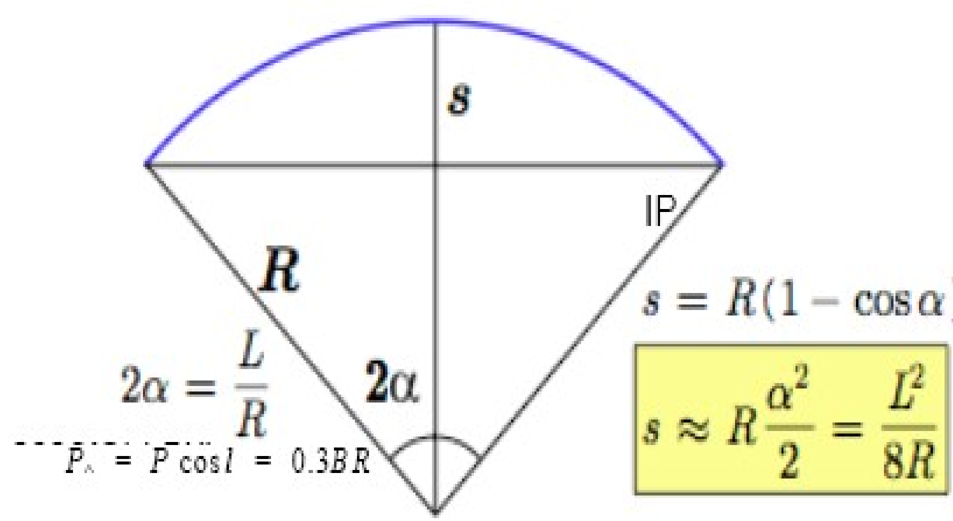

- Textbooks:
  - Perkins, “Introduction to High Energy Physics”
  - Cahn, Goldhaber, “The experimental foundations of Particle Physics”
- Historical books:
  - Pickering, “Constructing quarks”
  - Galison, “How experiments end”

# Some experimental tools

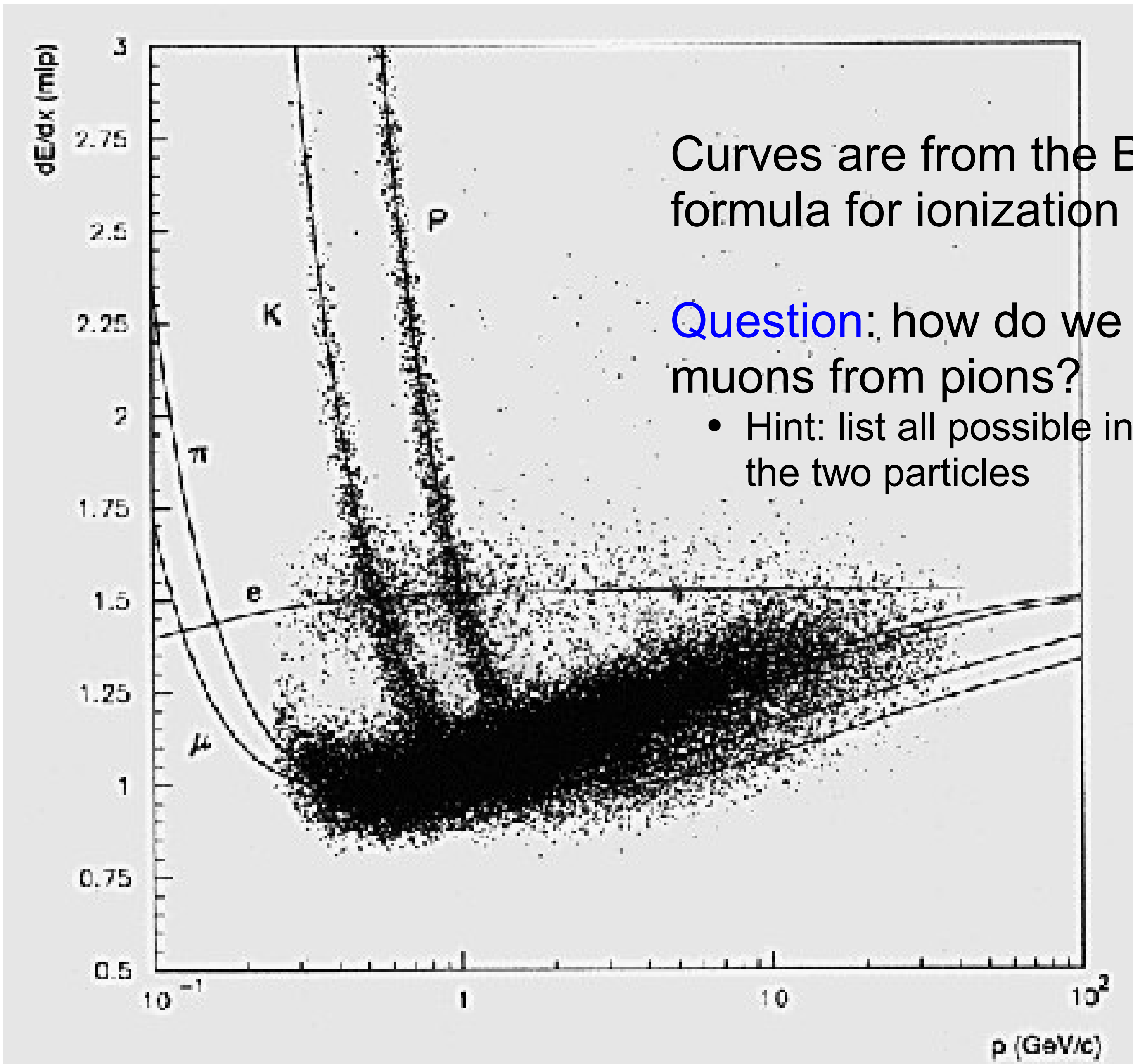
# Momentum measurement

- Fundamental formula: $q*p_T=B*r$
  - ➔ $p_T[GeV]=0.3*B[T]*r[m]$
- In a solenoidal field, B is uniform
- To measure $p_T$, you need at least 3 points
- <u>Homework</u>: demonstrate that
  - ✓ $p_T=0.3*B*L^2/8s$
  - ✓ $\delta p_T \sim p_T^2$
    - Hint: first demonstrate $\delta p_T/p_T=\delta s/s$ ($\delta s$ is the spatial resolution, which is constant)



# Specific energy loss by ionization



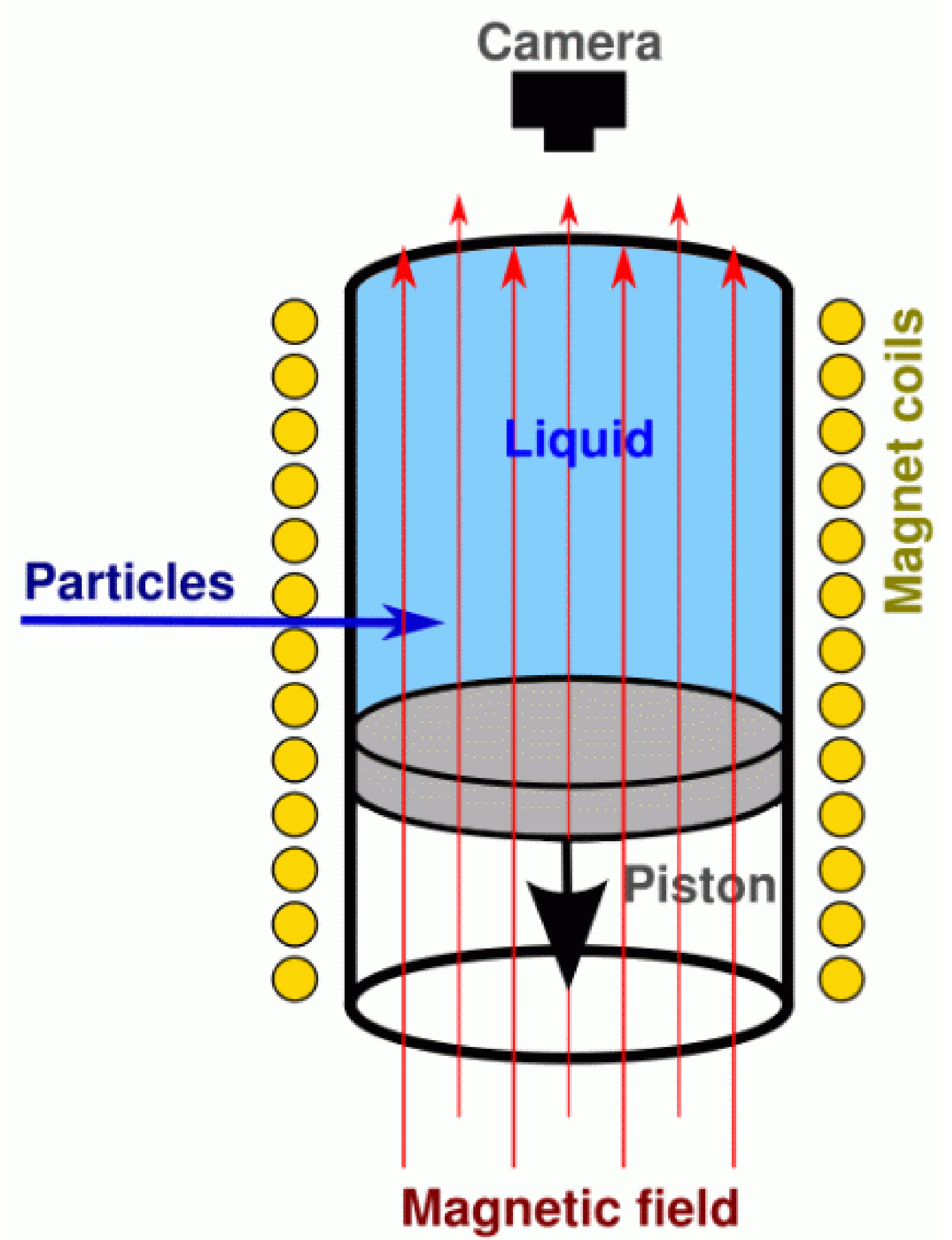

Curves are from the Bethe-Bloch formula for ionization

Question: how do we distinguish muons from pions?

- Hint: list all possible interactions for the two particles

# Bubble chambers

- A sudden reduction of pressure (by moving the piston) puts the liquid in a super-heated state
  - This means that normally, at that pressure, the liquid should boil
  - But if there is a very good homogeneity, no bubbles form spontaneously
- The passage of a charged particle perturbs the liquid, and small drops form along its trajectory
  - A picture is taken
  - Then the piston moves back, destroying the drops before a new cycle of the accelerator



# Theoretical context

- In the next slides, I'll tell you only things that a physicist in 1970 could have thought
- At the blackboard, I'll “translate” them into the concepts that a physicist would use in 2010

# Neutral and charged "currents"

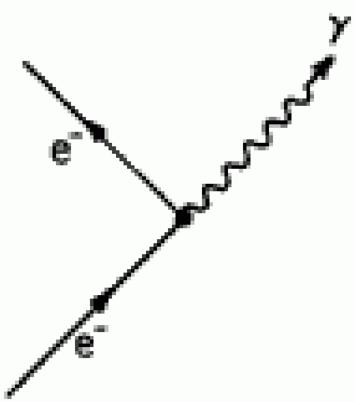



FIGURE 4.10. Electromagnetic current. This is just the ordinary passage of an electron, making a current. Here the electron has radiated a photon. Pedantically, one could call this a "neutral electromagnetic current" since the electron does not change its charge.

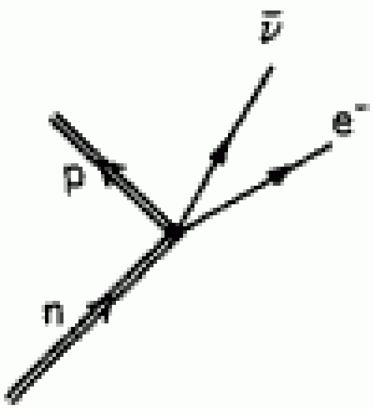
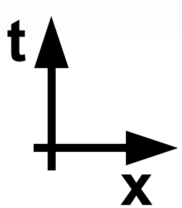



FIGURE 4.11. Example of charged weak current: beta decay. By analogy with the electromagnetic current, one considers the heavy nucleon (by definition a neutron or proton) to constitute a current that "radiates" an antineutrino and an electron. Since the nucleon changes charge—from neutron to proton—the process is called a "charged current."




(Most textbook figures taken from Galison; in its convention for Feynman diagrams, time flows vertically)

# Neutral and charged "currents"

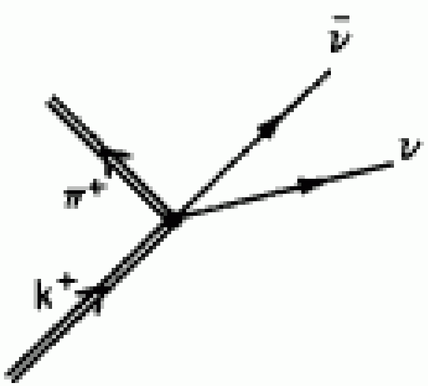



FIGURE 4.12. Argument for no neutral currents. During the 1960s, physicists placed extremely low experimental limits on neutral-current decays like this one ($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) in which a particle with a nonzero "strangeness" quantum number (the kaon) decayed into nonstrange matter (pion and neutrinos). At the time there were no compelling reasons to think that this type of neutral current was fundamentally different from neutral currents that were not "strangeness-changing." Most physicists, quite understandably, concluded that neutral-current events simply did not occur at the same order of magnitude as charged-current events.

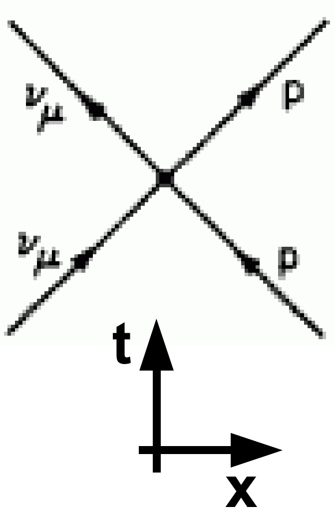
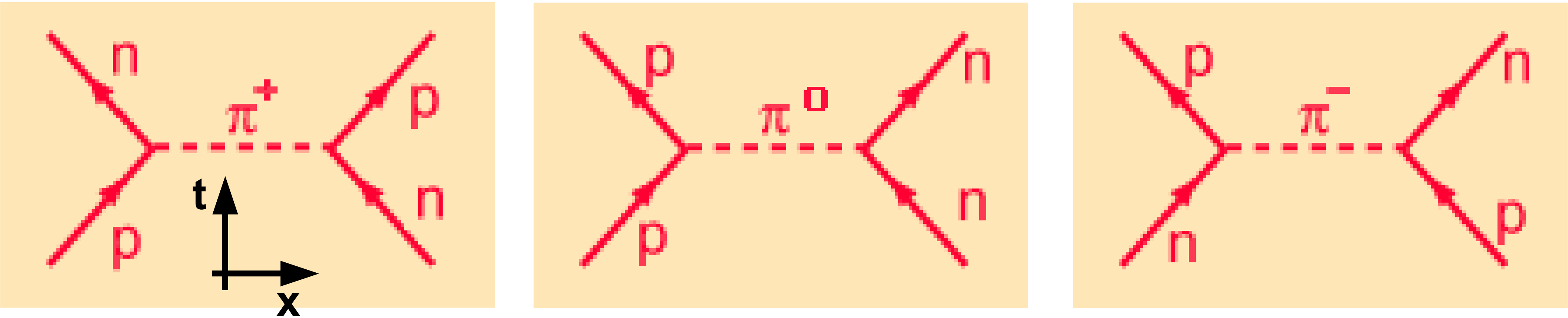



FIGURE 4.13. Neutral-current neutrino scattering. Neutrino neutral currents were much harder to study than the kaon decays. Nonetheless a few experiments did explore the possibility that a neutrino could scatter from a proton.

# Analogy with the N-N interaction




- Both the strong interaction (at the N-N level) and the weak interaction are short range forces
- Explained in Yukawa theory by the exchange of massive bosons, π and W respectively
- Weak force: $W^+$, $W^-$ ; Strong force: $\pi^+$, $\pi^0$, $\pi^-$
- No compelling reason for "$W^0$", but also no fundamental reason preventing it to exist

# How to look for (weak) neutral currents: why using neutrinos

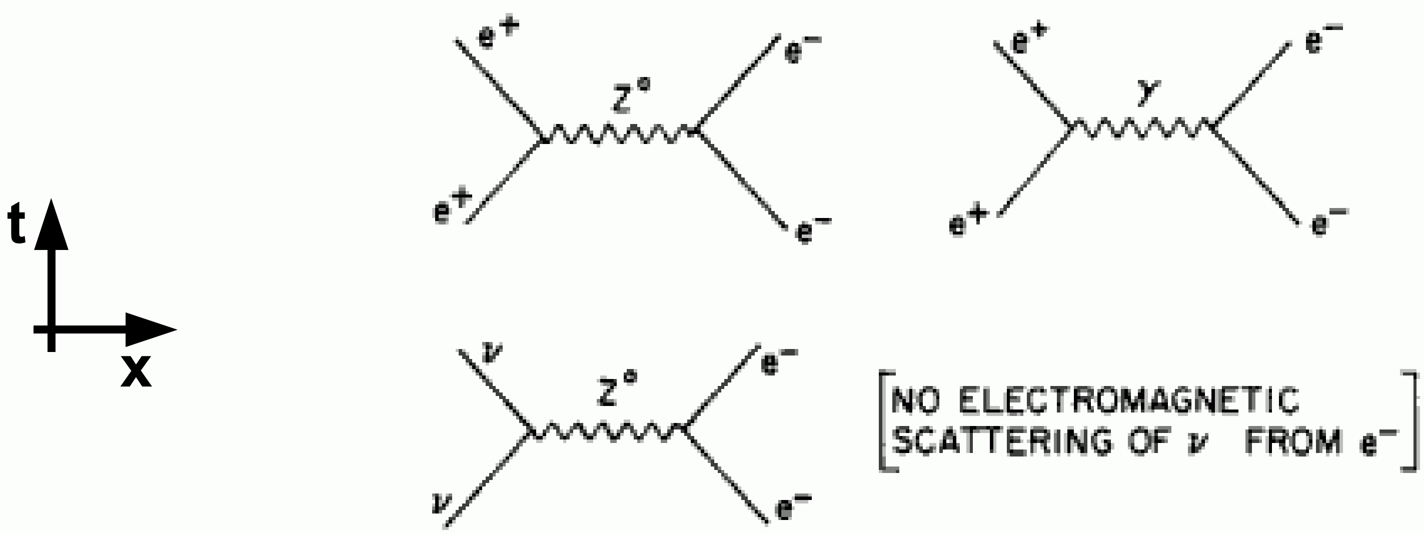
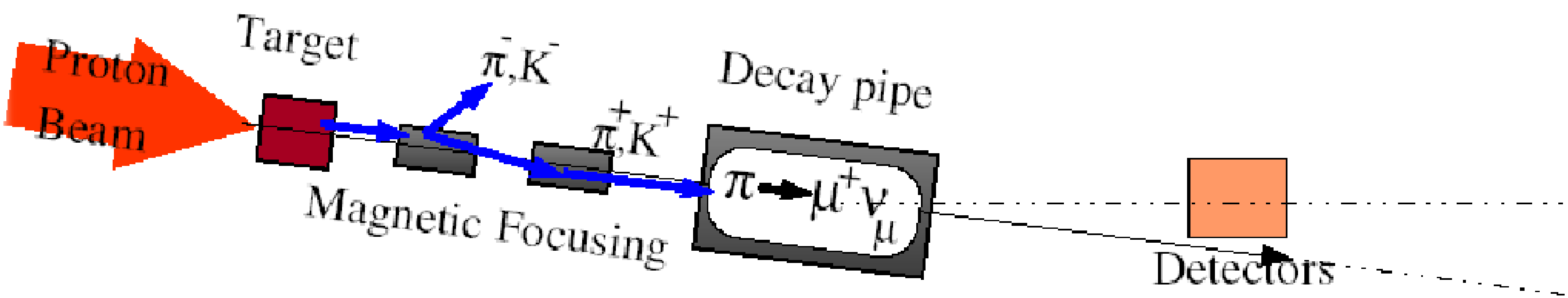



FIGURE 4.20. Electromagnetic background. In events where two interacting particles are charged and there is no change of strangeness, electromagnetic interactions occur as well as weak interactions. At the accelerator energies available in the 1960s and early 1970s, large electromagnetic effects swamped the much smaller weak interactions. For example, weak electron-positron scattering (*upper left*) would be overwhelmed by the electromagnetic scattering (*upper right*). E1A and Gargamelle avoided this problem by using neutrinos, which, because they are neutral, cannot interact with photons. Therefore the process illustrated in the lower left has no electromagnetic competitor.

Note: why is it not called $W^0$? See appendix

# Neutrino beams: general idea




- Protons are shot against a target
- Several hadrons are produced, mostly $\pi$ and K
- Magnets select the desired charge (and momentum)
- Pions and kaons travel long enough that most of them decay (favored decay mode: $\mu^+\nu_\mu/\mu^-\bar{\nu}_\mu$)
- Before reaching the detector, a shield of concrete absorbs most of the hadrons that did not decay

# Accelerator schematics

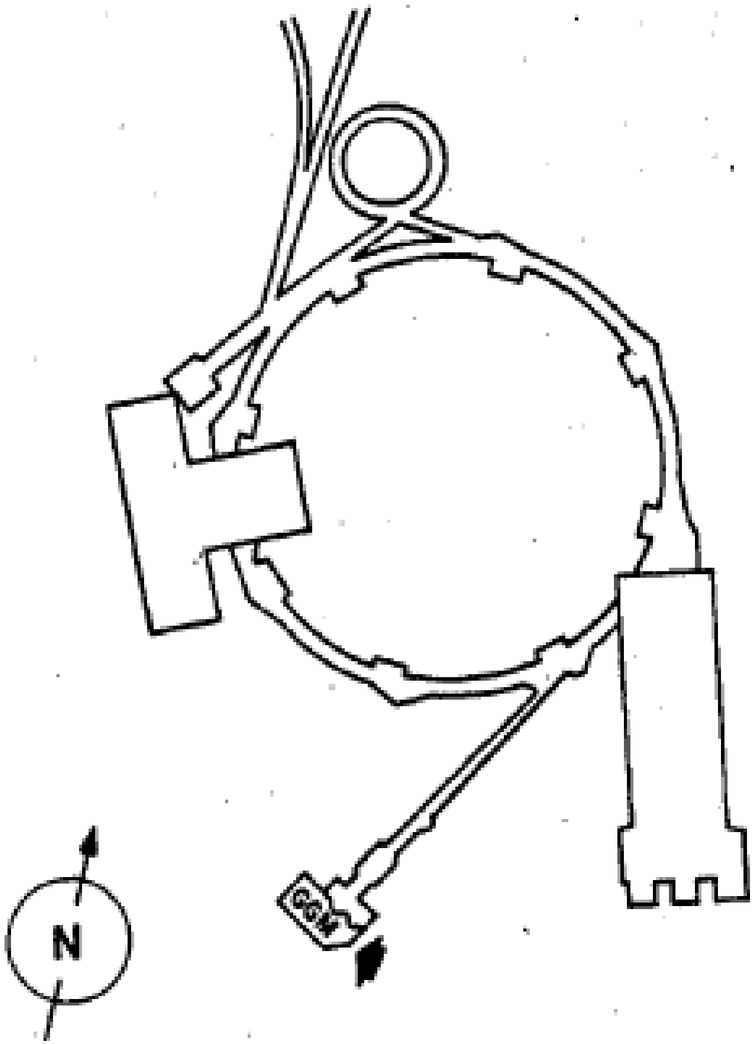
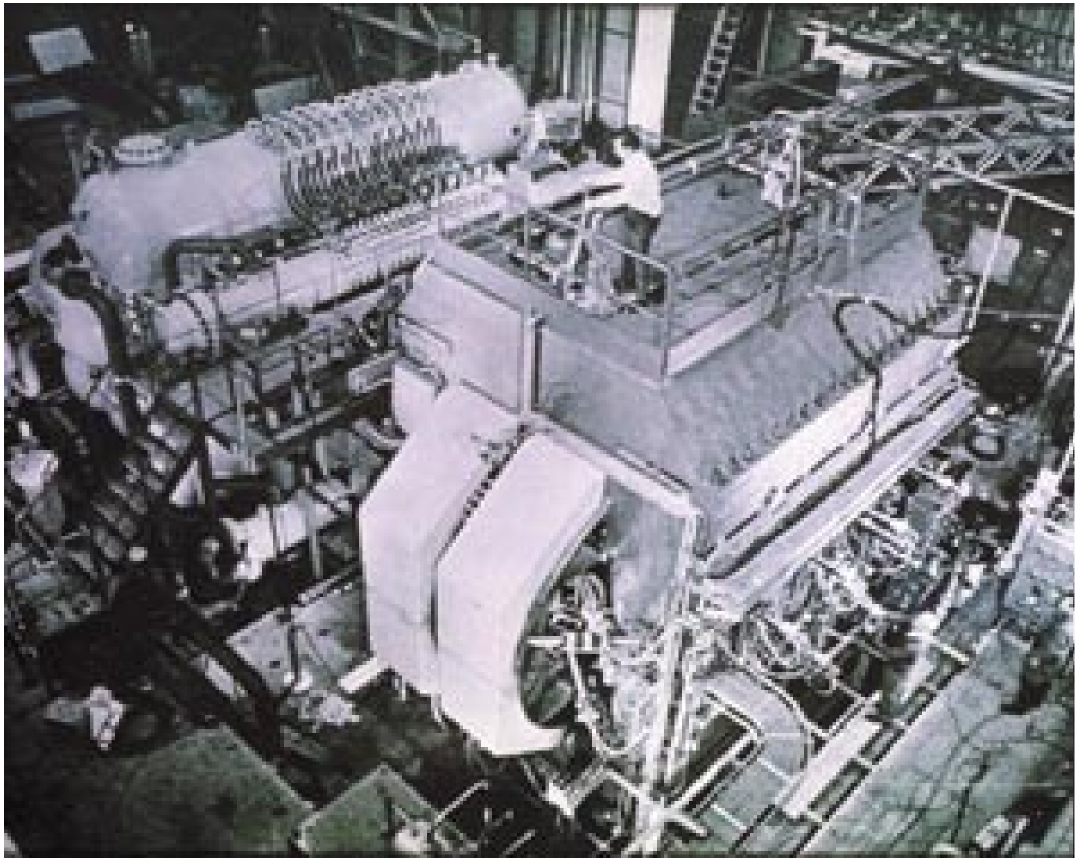



FIGURE 4.18. Gargamelle site and the neutrino beam, 1967. The main ring shown in the schematic diagram is the CERN Proton Synchrotron that accelerated protons to 24 GeV. Some of these protons were ejected along the beam pipe connecting the ring to Gargamelle (GGM). When the high-energy protons slammed into a target of beryllium or aluminum, they created a burst of pions and kaons. These light, unstable new particles continued toward Gargamelle, and some of them decayed into neutrinos. Most particles that do not decay into neutrinos are stopped by over 3000 tons of iron along 22 m. Source: schematic picture, CERN/PIO/RA 77-4.

Question: draw the diagrams for pion ($u\bar{d}$) and kaon ($u\bar{s}$) decay.

# Gargamelle

- Bubble chamber
- Length: 4.8 m
- Diameter: 1.9 m
- Liquid: freon
- Strong magnetic field



# Gargamelle's priority list

- 1 - W search
- 2-7 ...
- 8 – Neutral currents search

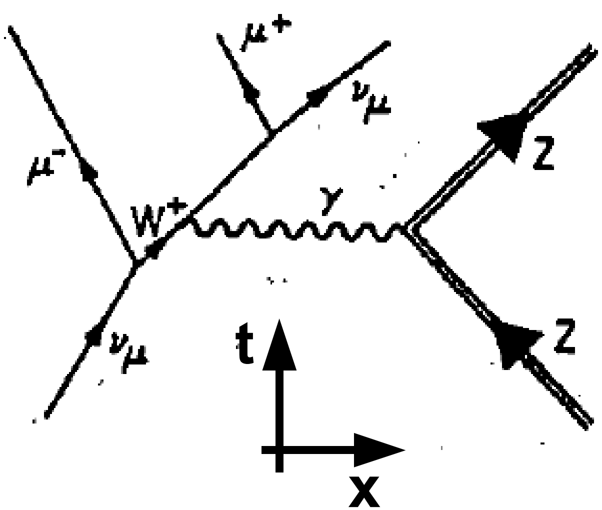



FIGURE 4.32. Looking for *W*'s. If *W*'s could be produced as in fig. 4.31, then the *W*'s could be detected when they decayed. As indicated in this figure, the signal for the *W* was to have been a positive and a negative muon. The neutrino would remain unseen.

Z: atomic nucleus of charge Z*e; the highest the charge, the more probable is the interaction with a virtual photon.

Very often, big experiments have one single strong motivation but the same data can be analysed for studying other processes. A modern example: LHC's main motivation is to search for the Higgs boson, but we will also test other theories.

# Event classification

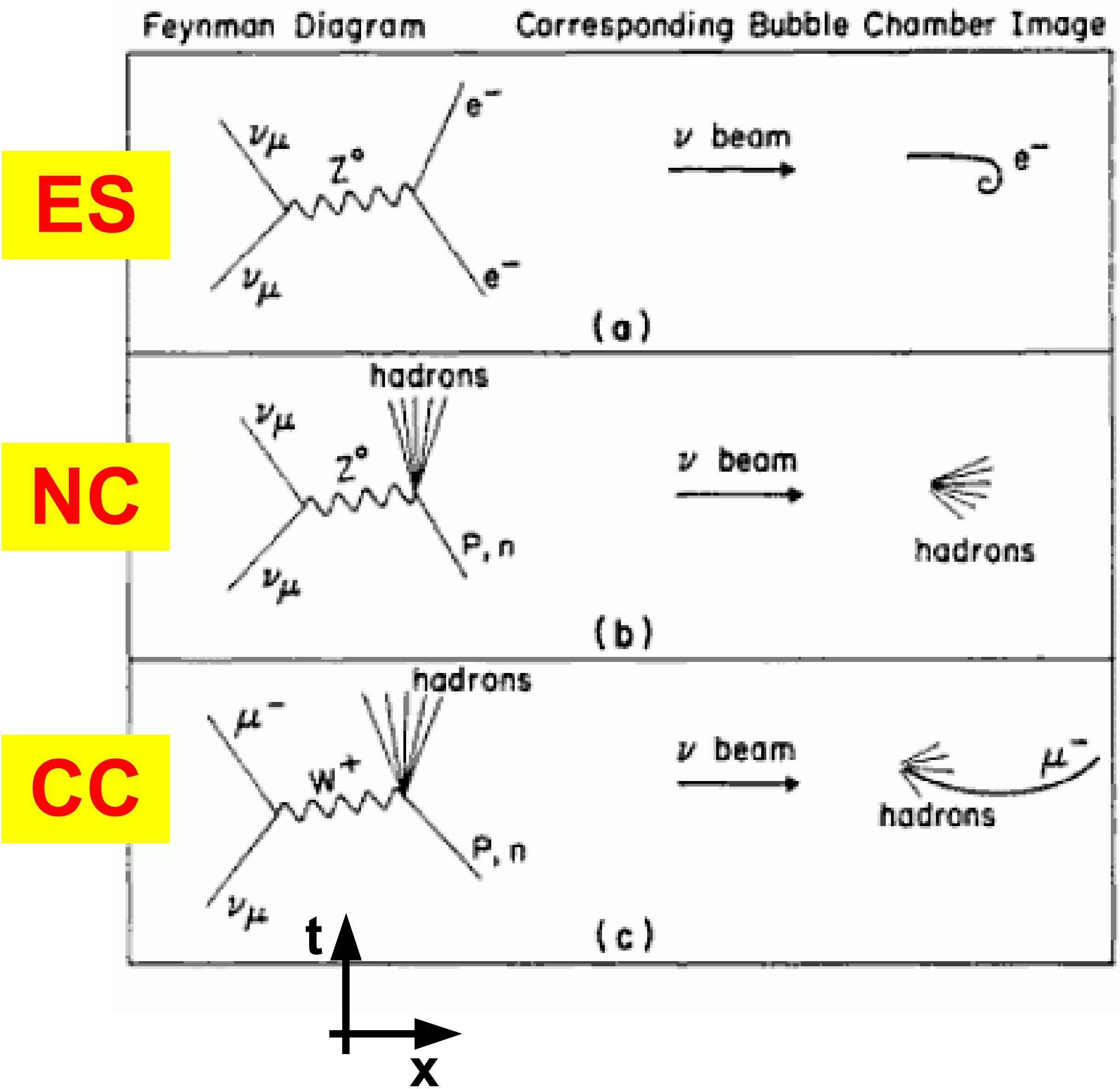



FIGURE 4.21. Feynman diagrams and bubble-chamber images. This figure illustrates the correspondence between the tracks that are seen in the chamber and the theoretical representation of the process "behind" the process. (*a*) Leptonic neutral current. A muon-neutrino emits a $Z^0$ and scatters an electron, which can be seen recoiling in the bubble-chamber film. The neutrino, because it is neutral, leaves no track. (*b*) Hadronic neutral current. A muon-neutrino emits a $Z^0$ that breaks up a proton or neutron into many hadrons. (*c*) Charged-current event. A muon-neutrino emits a $W^+$ upon which the neutrino turns into a negative muon. When the $W^+$ is absorbed by the proton or neutron, the latter breaks up into hadrons.


ν↑

Example of CC:

$\nu_\mu + p = \mu^- + \Sigma_c^{++}$

$\Downarrow$

$\Lambda_c^+ + \pi^+$

$\Downarrow$

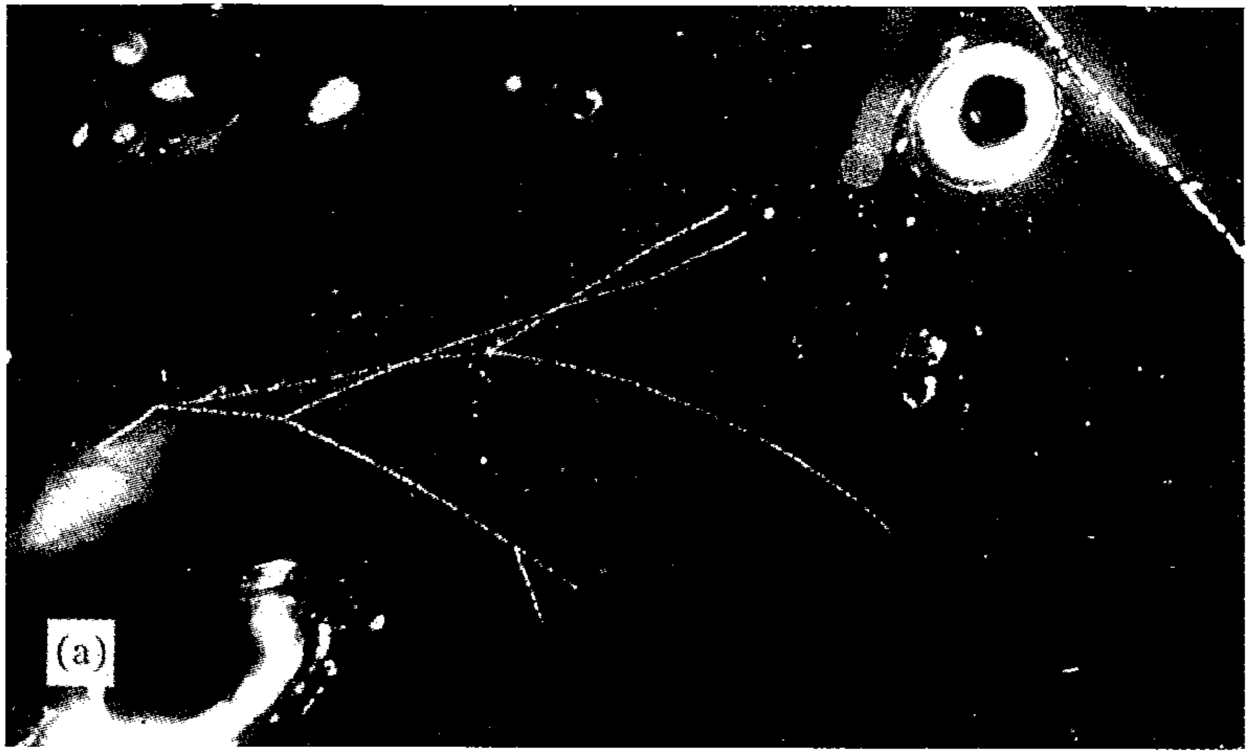
$e^+ + \Lambda^0 + \nu_e$

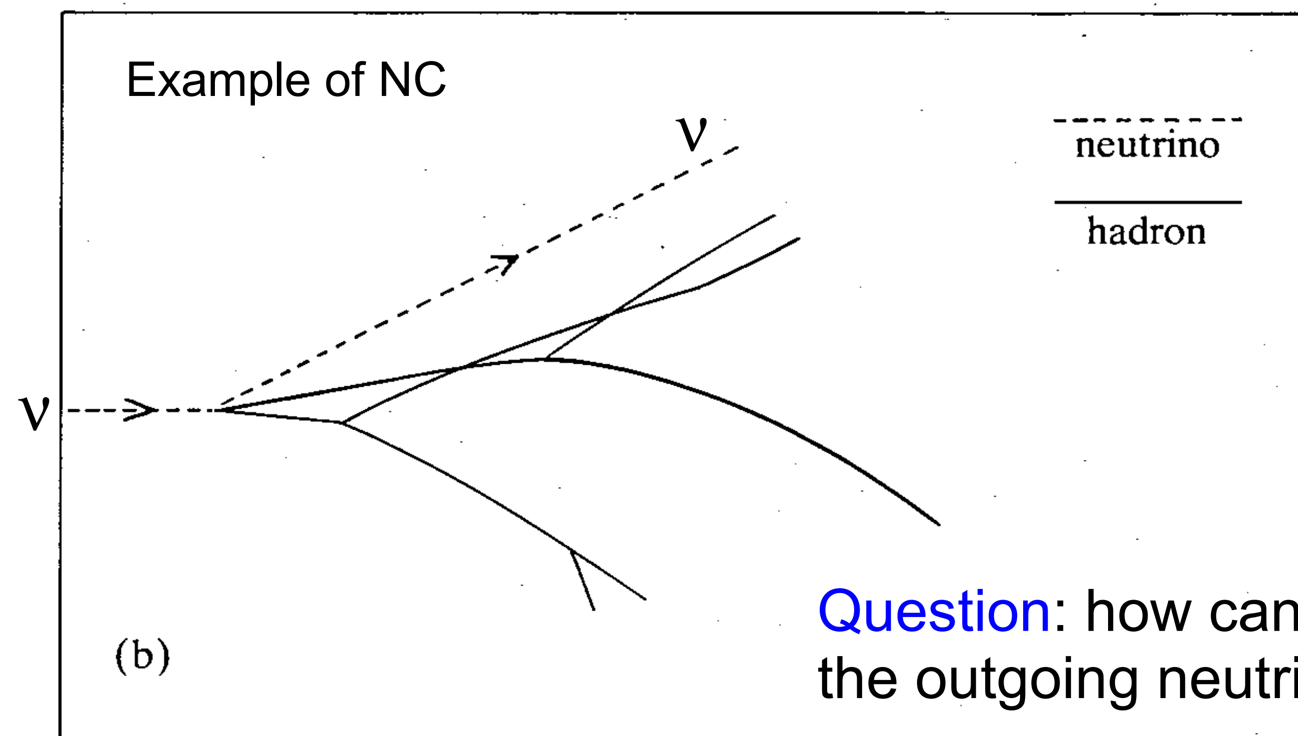
Interpretation with quarks:

$\nu_\mu + d = \mu^- + c$

$\Downarrow$

$e^+ + \nu_e + s$




Question: how can you deduce the outgoing neutrino direction?

# CC faking NC

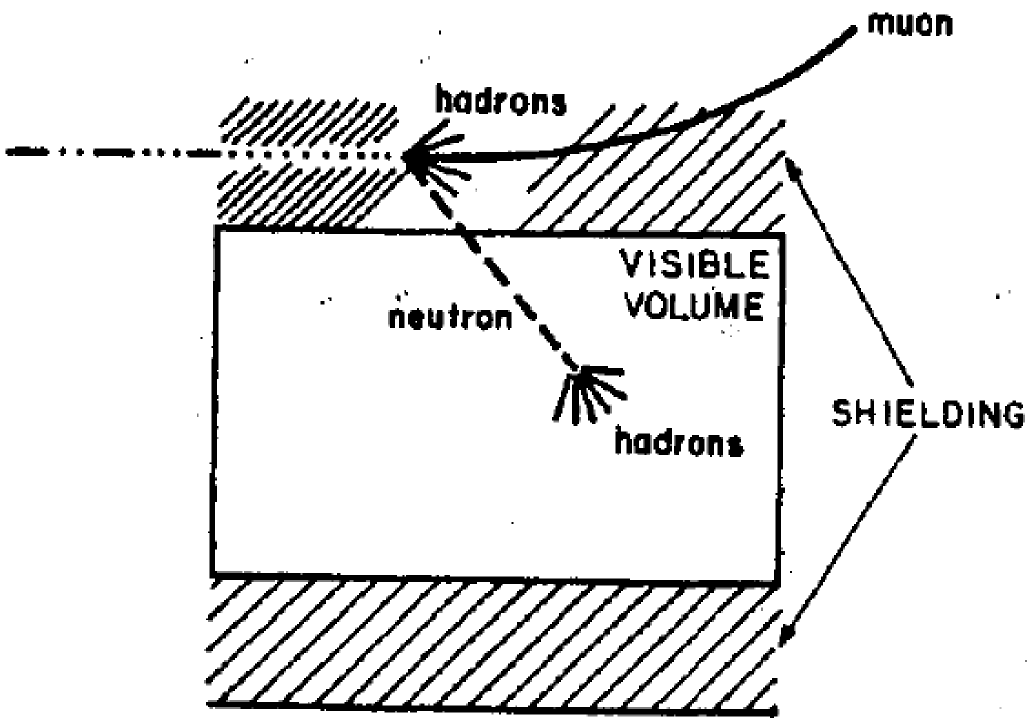



FIGURE 4.23. Neutron-induced "fake" neutral-current event. The principal background in the Gargamelle experiment was due to neutron-induced muonless events that "looked like" real neutrino events. These are exactly like the events of fig. 4.22, except that the source of the neutron is not seen. In the prototype background event shown here, the charged-current event occurs outside the visible volume, usually in the massive concrete shielding. A neutron penetrates unseen into the chamber, breaking up a nucleus in a way that looks like a "real" neutrino-induced neutral-current event.

# Associated event, or “neutron star” (AS)

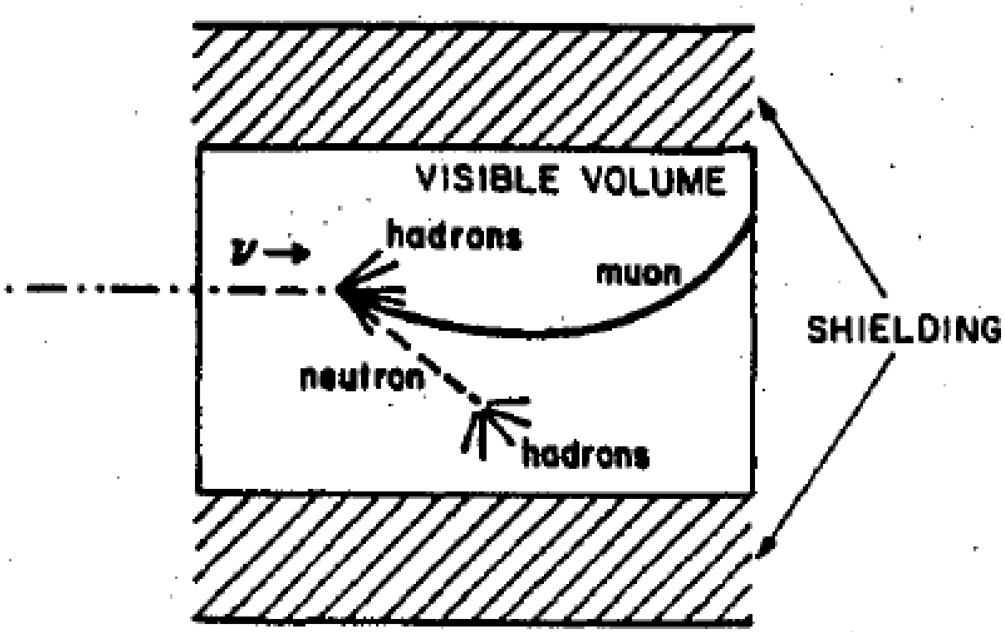
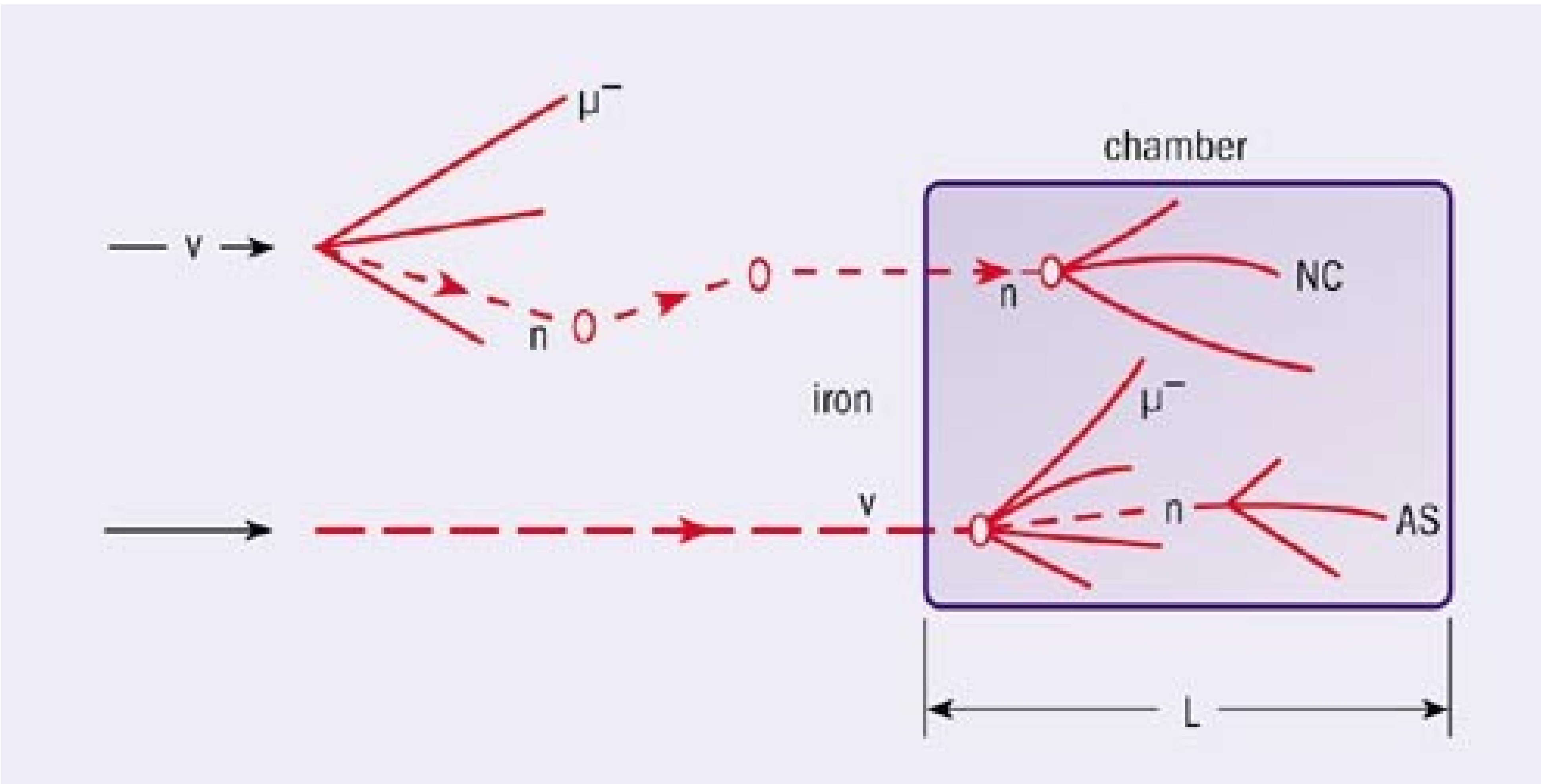


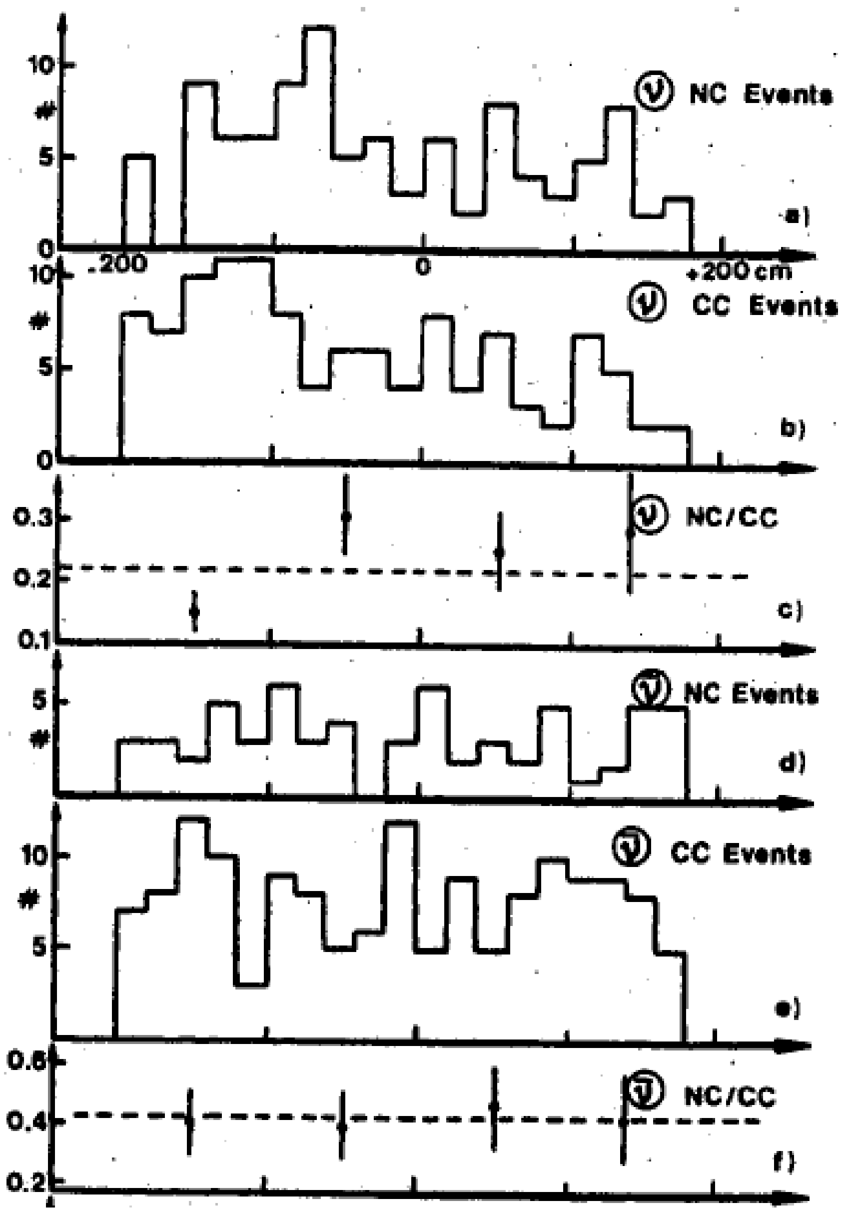

FIGURE 4.22. Associated event. By definition an associated event is one in which a charged-current event occurs inside the visible volume, releasing a neutron. The neutron hits a nucleus, producing a muonless shower in the same picture that can be *associated* with the neutrino event. By studying events like these, the Gargamelle team could determine the energy and angular distributions of neutrons produced in charged-current interactions. This information could then be fed into computers to simulate the behavior of neutrons released in the walls.

Note: AS is a subset of the CC category.

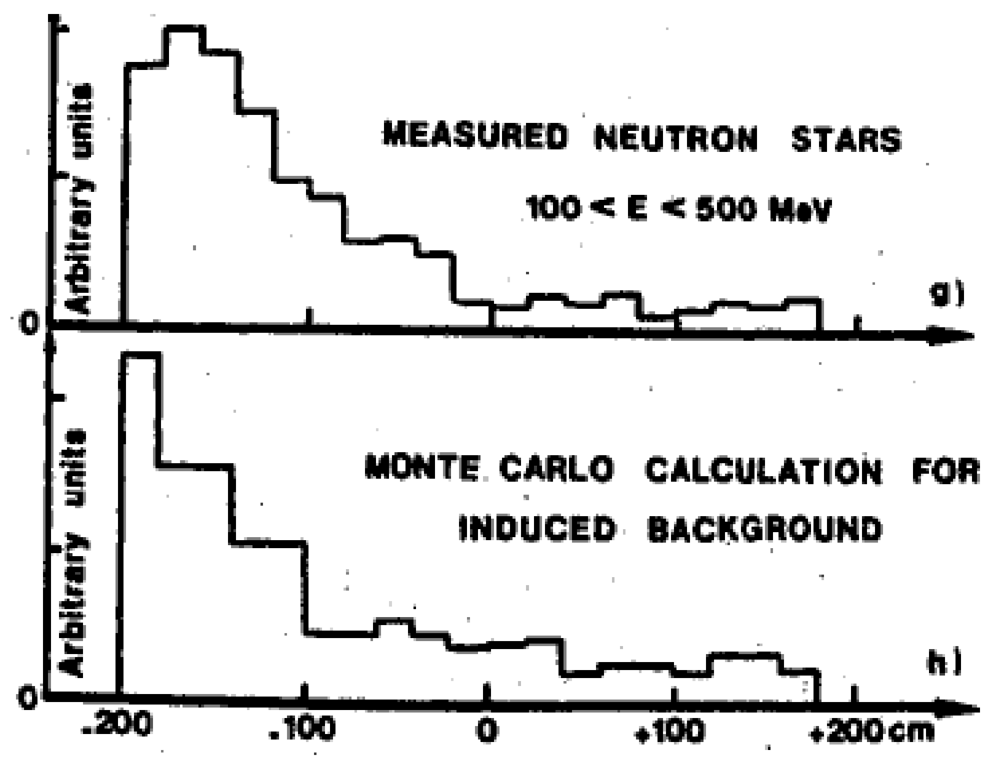
# AS as a "control sample" for estimating fake-NC properties



# Gargamelle's final results




Run ν: 102 NC, 428 CC, 15 AS
Run ν̄: 64 NC, 148 CC, 12 AS



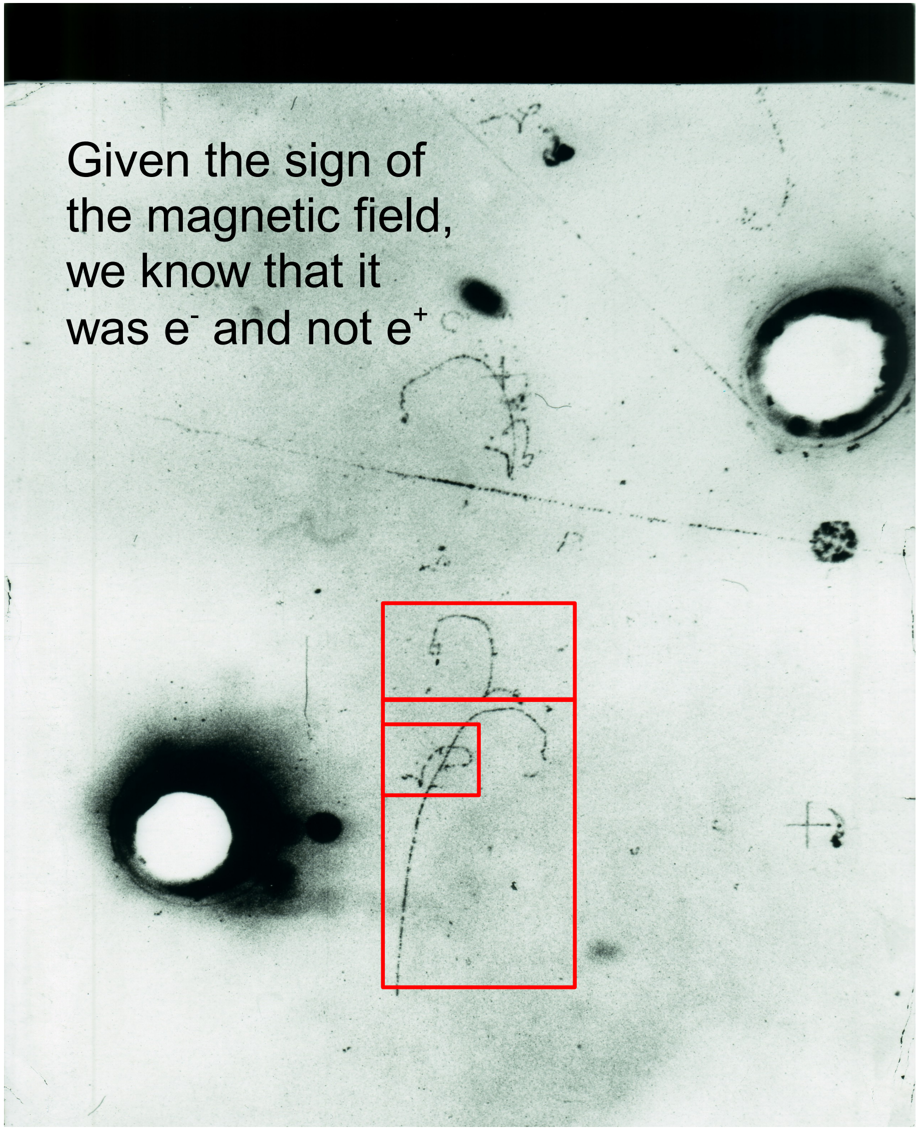

X axis: position of interaction along the Gargamelle axis

# Background estimation (simplified)

- We want to estimate B, the number of fake NCs
- Total neutron interactions (in CCs): N = B + AS
- On the other hand, AS = N<P>
  - P: probability for a neutron to interact before leaving the detector; $P = 1 - \exp(-L/\lambda)$
  - L: distance between point of interaction and detector end
  - $\lambda$: neutron interaction length (in principle a function of energy), extracted by other experiments or by fitting AS data
  - < ... >: average over detector volume, neutron energies, ...
- Result: $B/AS = (1/\langle P \rangle)-1$ (and this gave $B/AS<1$)
- More precise estimations with Monte Carlo, simulating the quantity and density of material around detector

# ES: the "golden" event

- Experimenters were worried that $\nu N$ interactions were not clean enough, from two points of view: experimental (backgrounds) and theoretical (protons are not elementary)
- ES events ($\nu_\mu e \rightarrow \nu_\mu e$) were the most clean, but also the rarest:
  - $\sigma(\nu X \rightarrow \nu X) \sim m_X E$
- Only 1 event was found
  - It was during an anti-$\nu_\mu$ run




$\nu \uparrow$

# What can be a background to ES

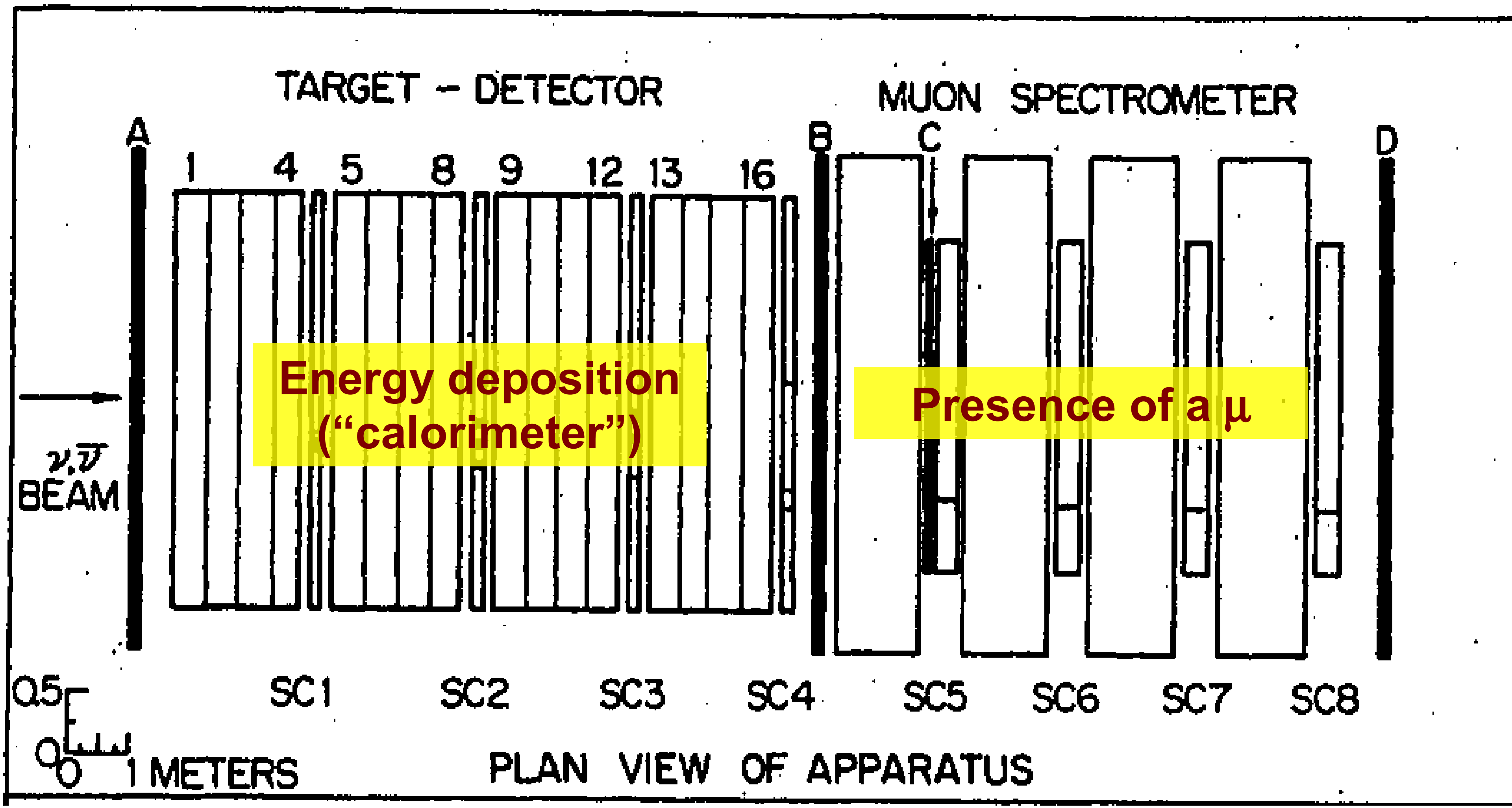
- A small fraction of $\nu_e$ contaminates $\nu_\mu$ beams
  - $BR(\pi^+ \rightarrow e^+ \nu_e)/BR(\pi^+ \rightarrow \mu^+ \nu_\mu) \sim 10^{-4}$
  - Muon decay: $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ (but most muons are wiped out by magnets)
  - But there are no $\nu_e$ (but anti-$\nu_e$) in pure anti-$\nu_\mu$ beams! Only if the beam is not pure, some $\nu_e$ can sneak in...
- Inverse beta ($\nu_e n \rightarrow e^- p$), with p not seen (reabsorbed)
  - The probability of missing a proton could be estimated from $\nu_\mu n \rightarrow \mu^- p$: 3% of these CC events had no proton
  - Multiplying this by the number of observed $\nu_e n \rightarrow e^- p$, gave 0.09(±0.07) events as estimated background

# So, Neutral Currents were proved to exist...

- And a theory existed already, which predicted their existence: the Standard Model
  - Because of the ElectroWeak Unification (see Appendix) it predicted the existence of an additional massive boson, the Z
  - The strength of the Z-mediated interaction between $\nu e$, $\bar{\nu} e$, $\nu u$, $\bar{\nu} u$, $\nu d$, $\bar{\nu} d$ as predicted by the SM was compatible with the NC/CC ratios observed in $\nu_\mu$ and $\bar{\nu}_\mu$ runs

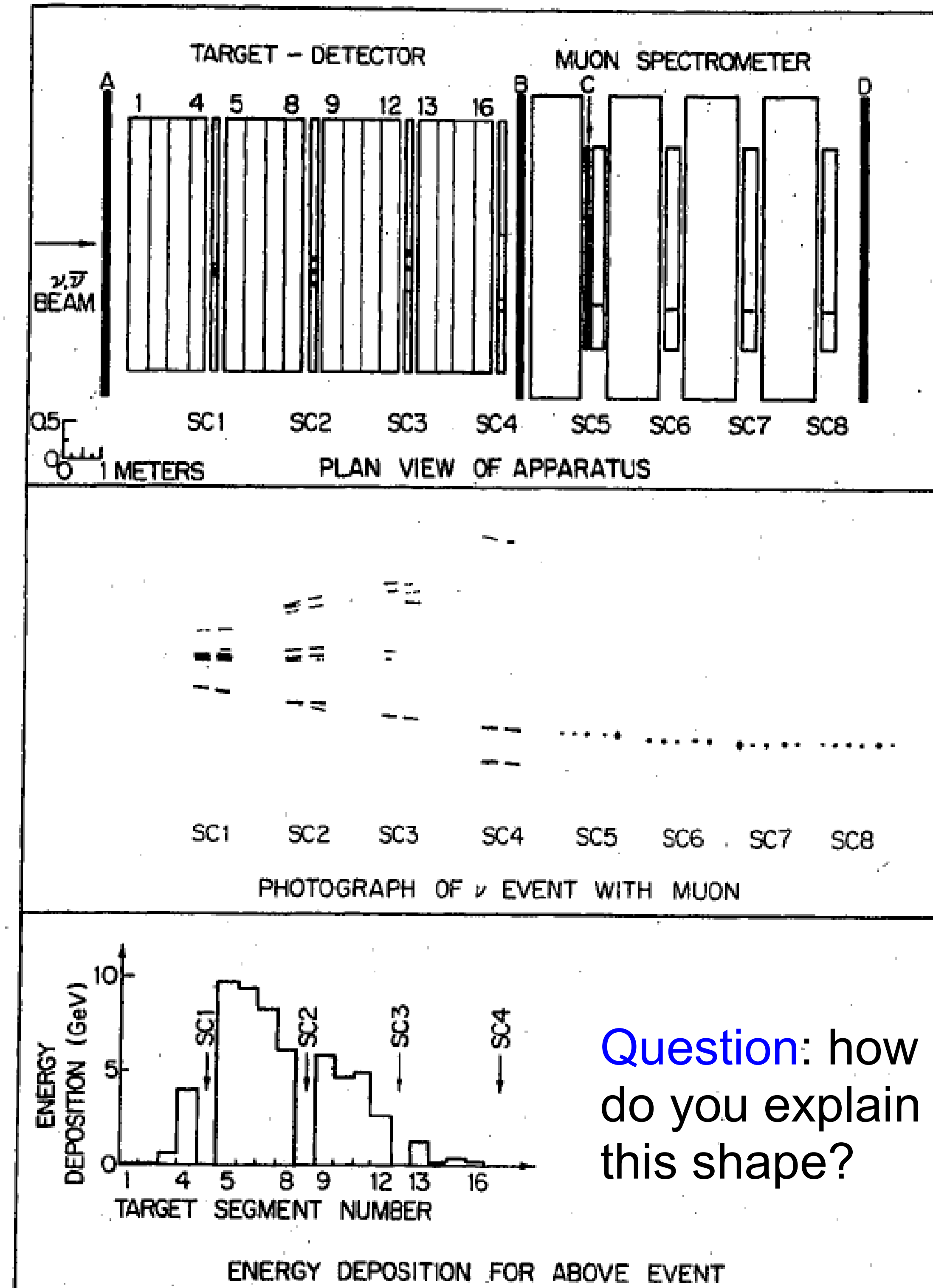
# E1A, a.k.a. HPWF

(Harvard, Pennsylvania, Wisconsin, Fermilab)




The primary proton beam at Tevatron had P=300-400 GeV.
To be compared with 24 GeV at CERN (for Gargamelle)

- ABCD: fast counters
  - Used to "trigger" the rest of the detector
  - Question: make sure you don't miss NC & CC
- 1-16: liquid scintillators
  - Light output proportional to deposited energy
- SC1-8: spark chambers
  - Used for offline tracking
- Muon Spectrometer:
  - Iron slabs between SCs
  - Magnetic field

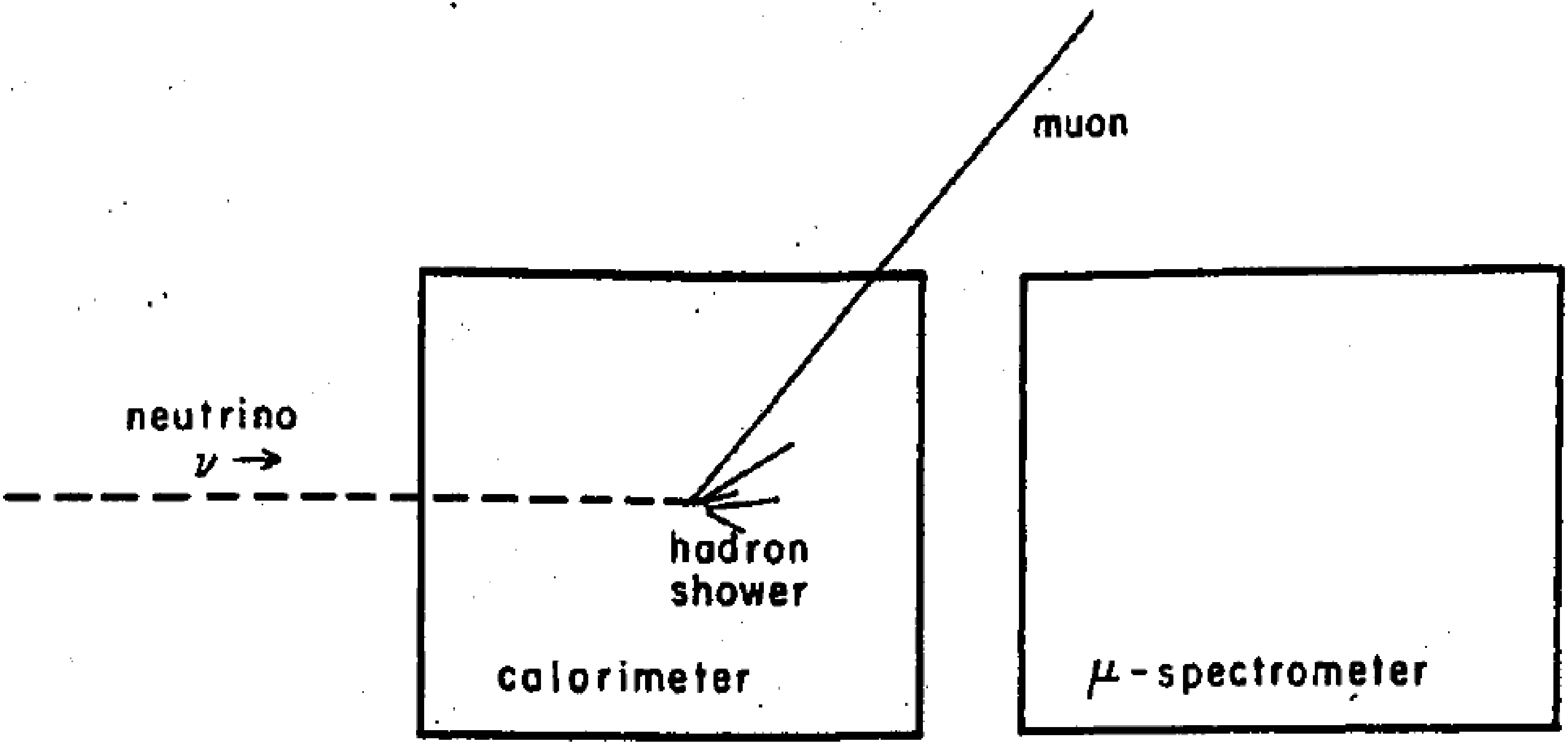



Question: how do you explain this shape?

# E1A versus Gargamelle

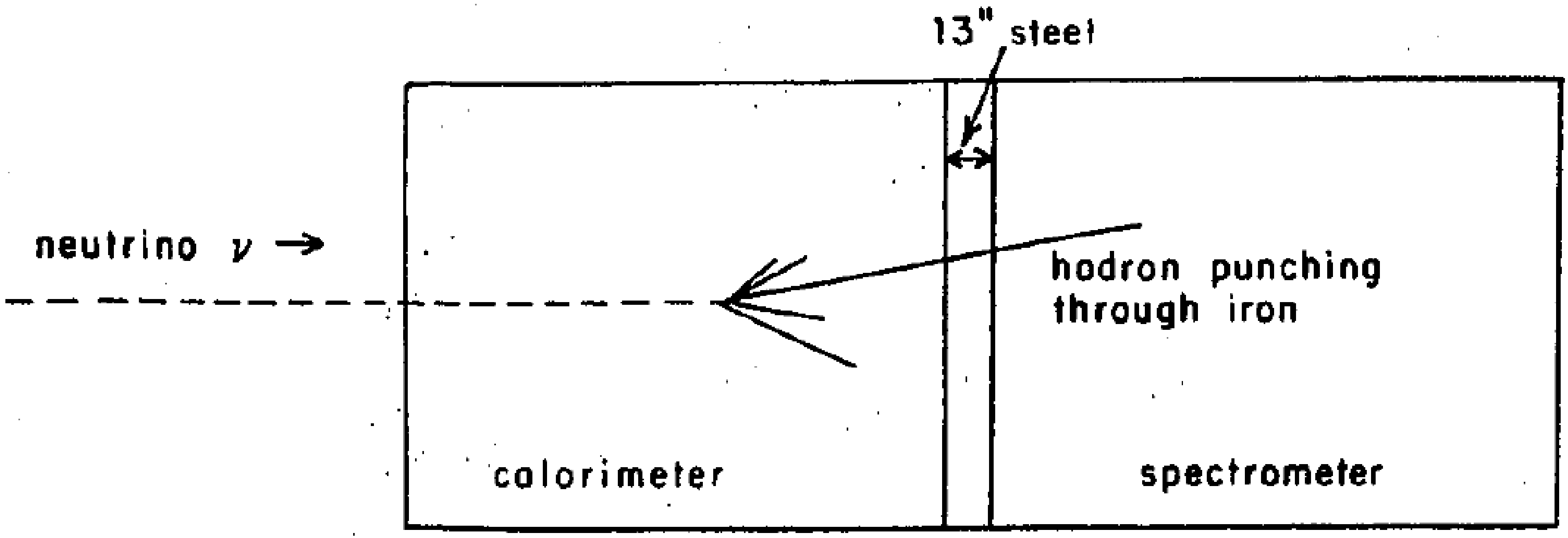
- Gargamelle gave a complete description of the event
- E1A had to be **triggered**: only interesting events were recorded; dangerous, but offline analysis was much faster
- Easier to increase the volume of a spark chamber system than of a bubble chamber
  - E1A's volume was ~10x Gargamelle
- $<E_\nu>$ ~ 2 GeV Gargamelle, ~ 20 GeV E1A
  - And $\sigma(\nu X \rightarrow \nu X) \sim m_X E$
- Gargamelle had an advantage in statistics, at start:
  - E1A: $5\times10^9$ protons/pulse (1972) → $8\times10^{12}$ protons/pulse (1974)
  - GGM: $2\times10^{12}$ protons/pulse (1972) → $5\times10^{12}$ proton/pulse (1973)

# CC seen as NC: escaping muons




Question: how do you expect this to depend on neutrino energy?

# NC seen as CC: "punch-through"




Questions: how do you expect this to depend on neutrino energy? How would you measure this effect from CC data?

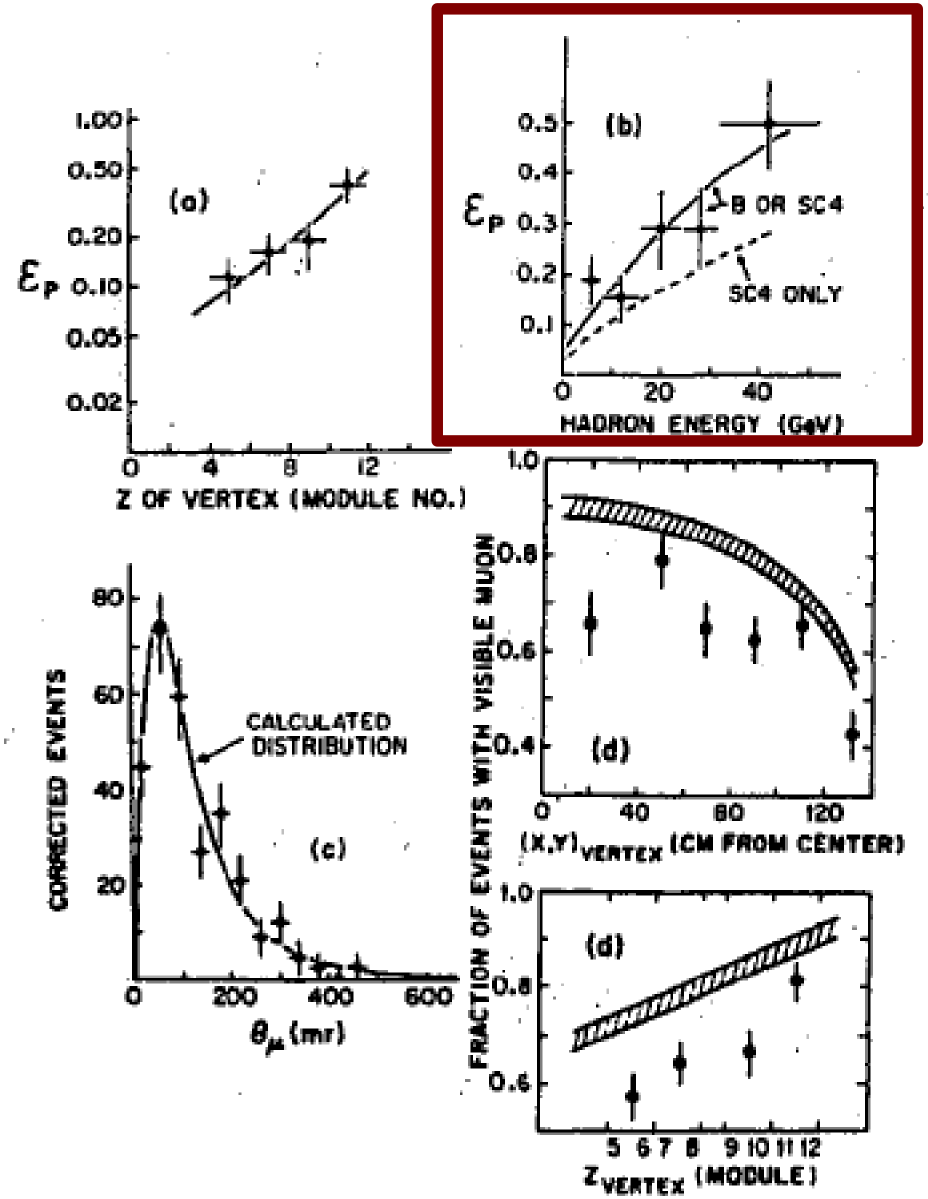



FIGURE 4.49. Published E1A data I, 1974. Evidence for neutral currents from E1A's second neutral-current publication. (*a*) The measured punchthrough probability $\varepsilon_p$ of hadrons accompanying *$\bar{A}EBC$* events (for all hadron energies) as a function of *z* (number of the scintillation section counting from downstream to upstream), and (*solid line*) the expected shape of the distribution based on other experiments. (*b*) The measured punchthrough probability (for *z* between 5 and 12) as a function of the hadron energy compared with the expected variation. (*c*) The corrected angular distribution of muons as measured in SC4 compared with the predicted distribution. (*d*) Fraction of events with muon observed (does not escape) as a function of the position of the event vertex. (*Upper part of d*) Fraction of events $\varepsilon_\mu$ with muon as measured by SC4 alone and in hatching the fraction of muons that are expected to reach SC4 on purely geometrical grounds using the distribution of (*c*). The hatching indicates the uncertainty arising from the statistics of the data in (*c*). (*Lower part of d*) Same as upper part of (*d*) except as function of *z*. Source: Aubert et al., "Further Observation," *Phys. Rev. Lett.* 32 (1974):1456.

$\bar{A}$EBC events: no signal in A, signal in B&C, total calorimeter E above some threshold

# Final results

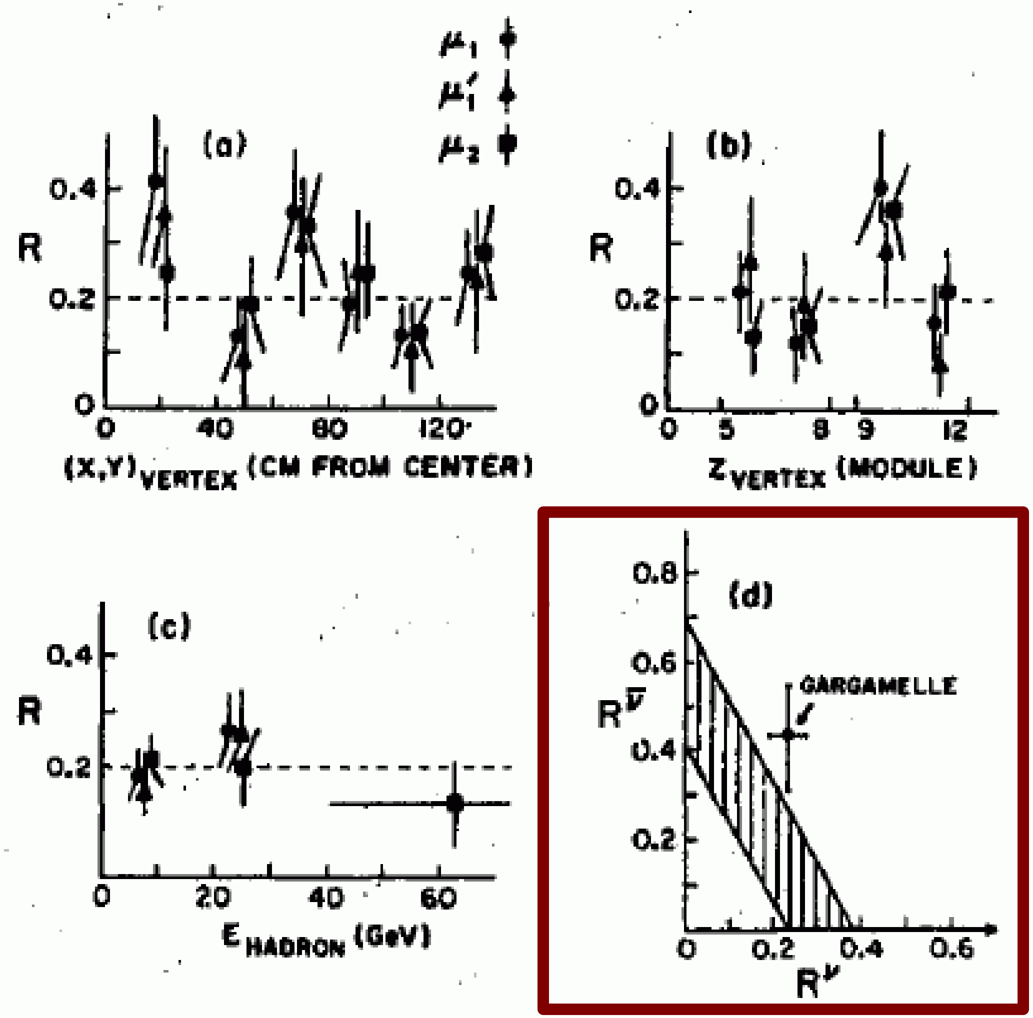
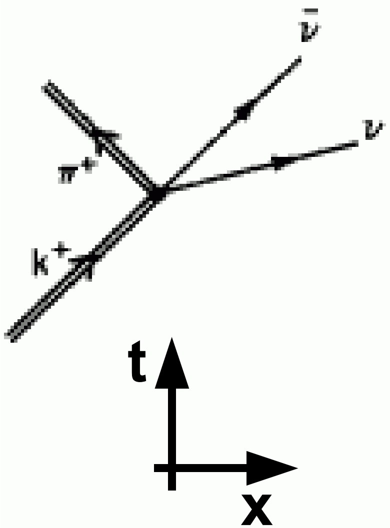



FIGURE 4.50. Published E1A data II, 1974. Additional evidence for neutral currents from E1A's second neutral-current publication. (*a*) *R* obtained from three different muon identifiers—black circle is mu1 (SC4 or counter *B*); black triangle is mu1′ (SC4 alone); black square is mu2 (SC5 or counter *C*)—as a function of the transverse distance from the center of the calorimeter. (*b*) The variation of *R* with longitudinal position for these three different muon identifiers. (*c*) The variation of *R* with hadron energy ($E_H$) from the three muon identifiers. (*d*) The allowed region of $R^{\nu}$ (for neutrino beams) and $R^{\bar{\nu}}$ (for antineutrino beam) from E1A compared with *R* for neutrino and antineutrino beams in the Gargamelle collaboration. Source: Aubert et al., "Further Observation," *Phys. Rev. Lett.* 32 (1974): 1456.

The neutrino beam was mixed

Question: explain this stripe

# Let's go back to the beginning...

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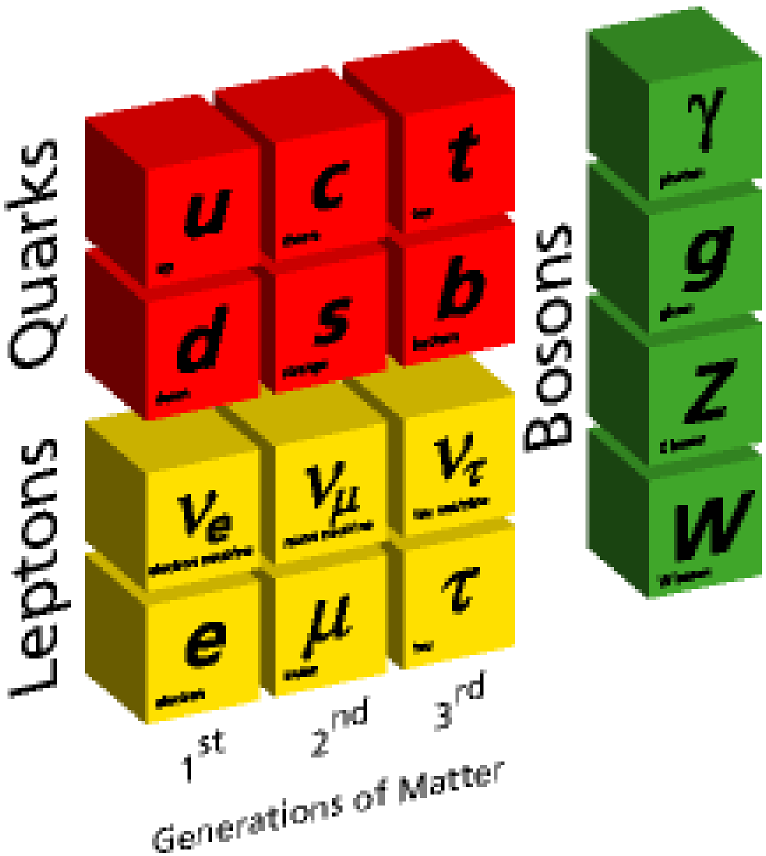
- How to concile the absence of this process with what we have just seen today?
  - I will tell you in the next lesson...

# Appendix: introducing the Standard Model

- Warning: you still don't know what is a gauge theory (and why it is so important to know what it is)

# The Standard Model



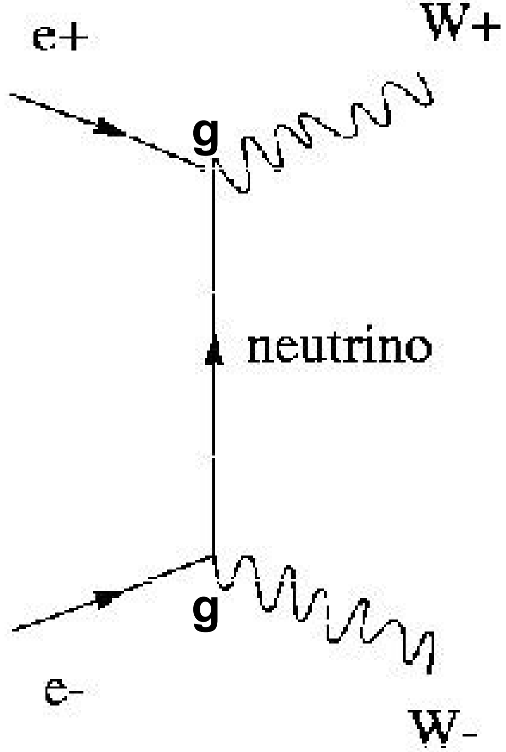

- Forces are carried by bosons: photons, W/Z, gluons, gravitons
- Matter (fermions) is composed of quarks (sensitive to QCD) and leptons (neutral to QCD), grouped in 3 generations
- What we call “Standard Model” of High Energy Physics is Electro-Weak Theory (with Higgs mechanism) + QCD
  - Gravity is not really included!

# Electro-Weak Unification

- QED is a gauge theory
- Gauge theories imply mass=0 for the force carriers (e.g. the photon in QED)
- At least two weak force carriers exist, charged ($W^+$ and $W^-$), since weak decays affect the charge
  - $n \rightarrow p e \bar{\nu}$ interpreted as $n \rightarrow p W^{-(*)}$, $W^{-(*)} \rightarrow e \bar{\nu}$
- The phenomenology of the weak interaction suggests that the range is short, which can come in a natural way if the force carriers are quite massive (Yukawa)
- So, weak interaction seemed not to be explainable with a gauge theory

# Electro-Weak Unification

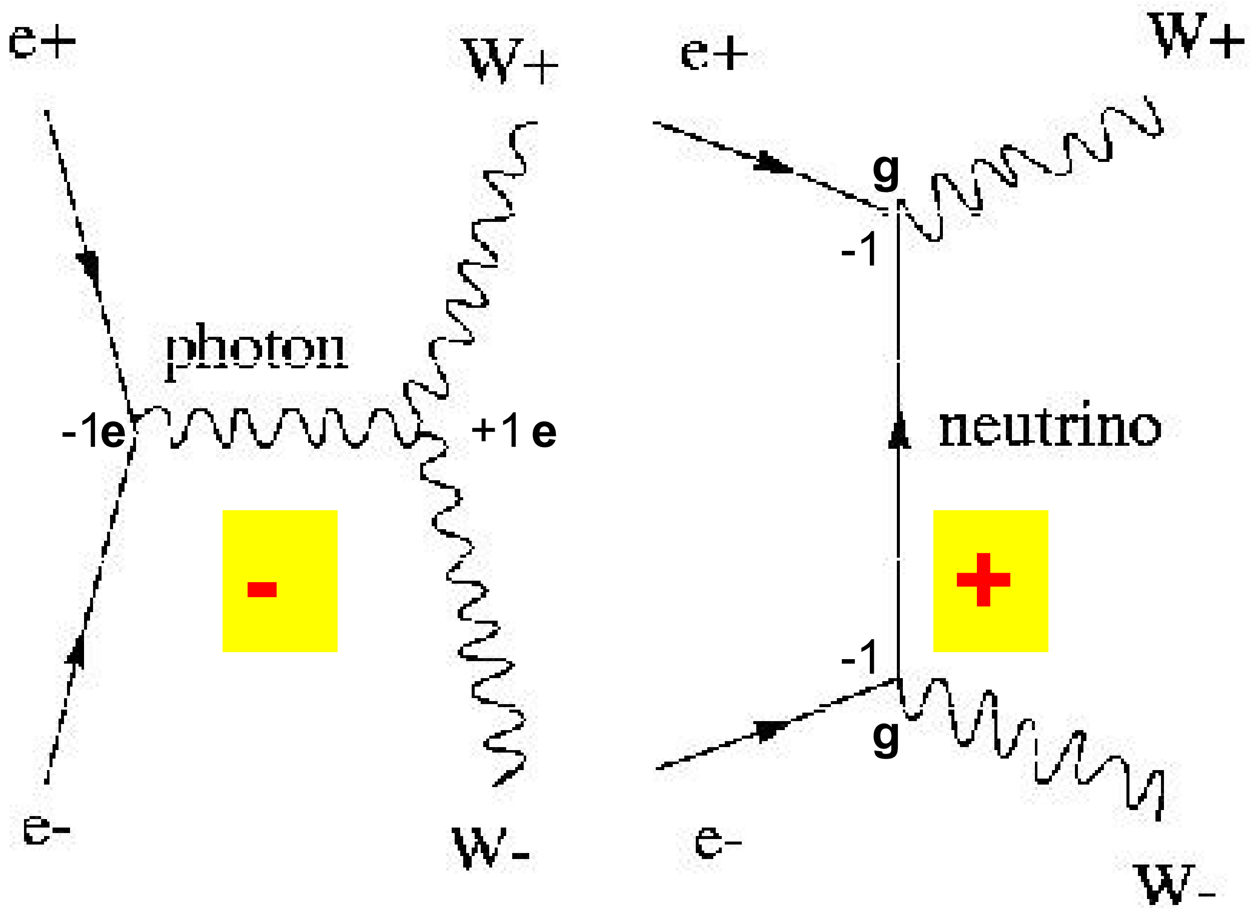
- Why a gauge theory is desirable: you can reabsorb all the possible divergences of your theory in a finite number of empirical terms
- A non-gauge quantum field theory will always contain somewhere some divergence that you cannot reabsorb




A different way to see the problem: if you calculate the probability that this process occurs in an $e^+e^-$ collision, you get that starting from some energy the probability is >100%, i.e. $\sigma(e^+e^- \rightarrow W^+W^-) > \sigma(e^+e^- \rightarrow \text{anyth.})$! Complete nonsense...

# Electro-Weak Unification

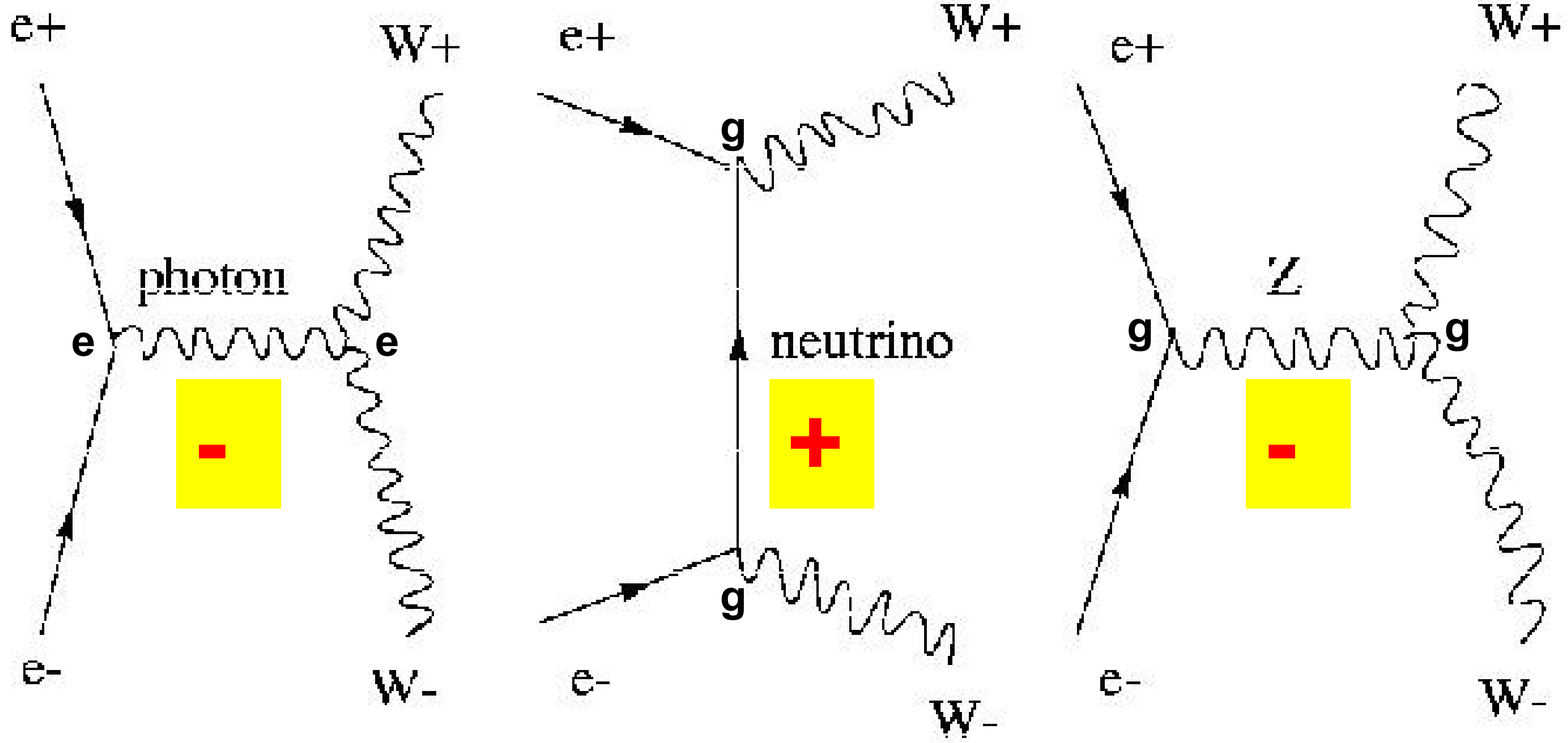
- A suggestive coincidence: if you assume g~e, summing the amplitudes of these two diagrams gives a cancellation up to some higher energy:



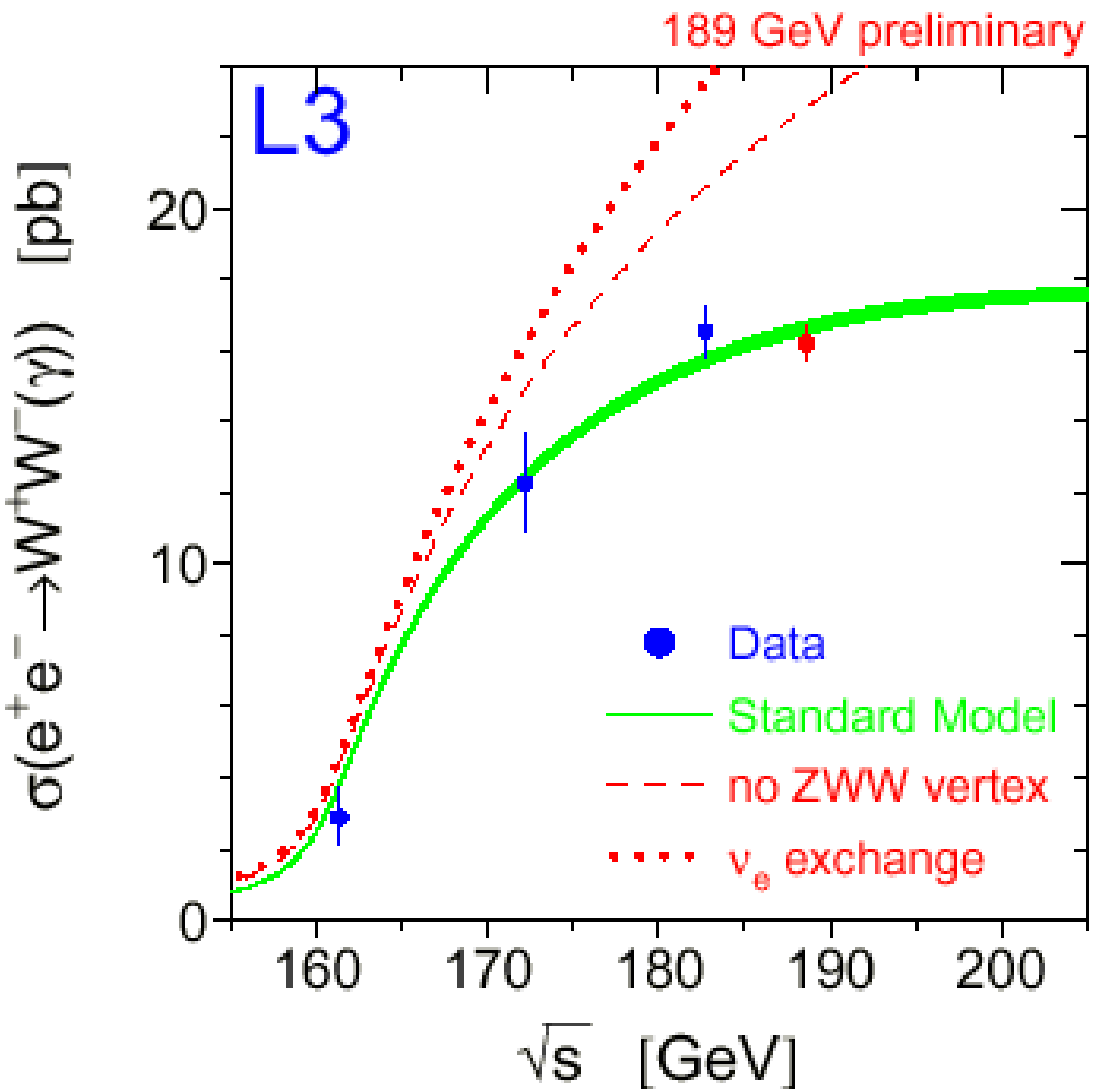

This delays the problem to higher energy, but does not solve it...

# Electro-Weak Unification

- Hypothesis by Glashow, Salaam, Weinberg (1967): a new process where a new boson is present in the intermediate state (so that the sign of the amplitude is the same as for the diagram with the photon)



# Experimental check




This check could be done only in the late '90s, when the LEP energy was sufficient to probe the energy regions where the old theory started to have problems.

At the time when the EW Unification was proposed, the problem just concerned the inner mathematical consistency of the theory.

(This doesn't mean that it wasn't serious.)

# Electro-Weak Unification

- If g=e, and $\gamma$, W and Z masses are equal, the cancellation is exact!
- But of course masses are not equal
  - photon is massless
  - W is not massless, otherwise weak force would have long range
  - Z is not massless, otherwise we would have observed it since long time, exactly as the photon
- But when you consider energies $>>M_W,M_Z$, you get the desired cancellation and your theory has a perfect symmetry between the EM and the Weak aspects