Particle Physics 1
Lecture 11: Electroweak discovery

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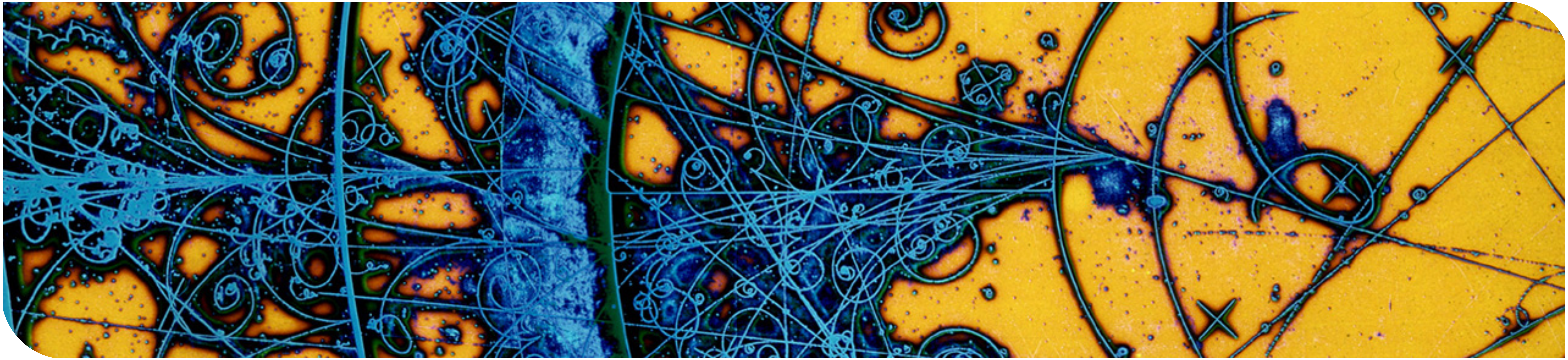
Wintersemester 2023/2024

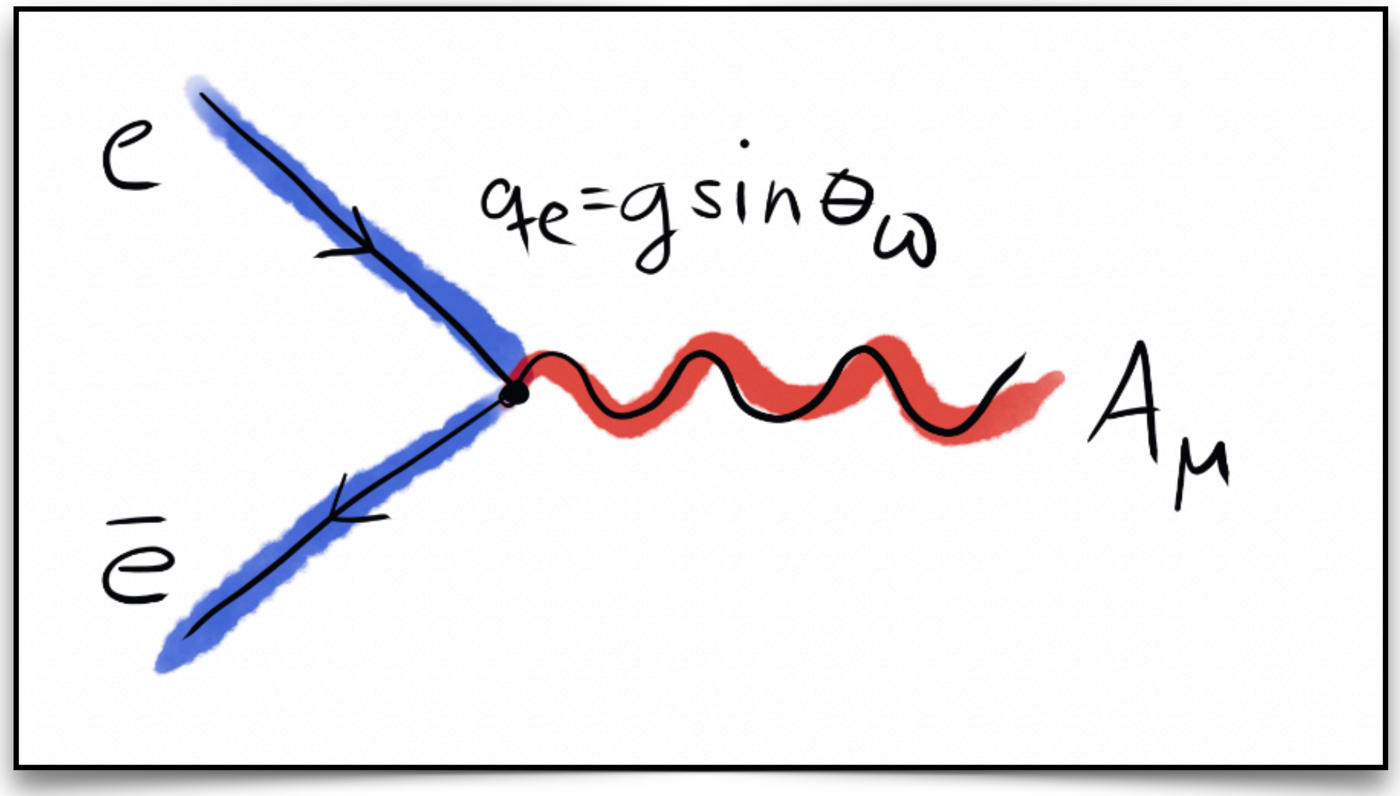

Credit: CERN

Learning goals

- Understand experimental evidence for weak neutral currents
- Understand experimental evidence for W and Z bosons
- Understand basic idea to go from discovery (hadron machine) to precision (e+e- machine)

Electromagnetic interactions

- Photon field A_μ couples to electromagnetic current
  - Photon couples to all charged particles (electron, muon, tau, all quarks, $W^\pm$)
  - Coupling is completely symmetric for left- and right-handed components
  - $\mathscr{L}_{\text{em}} = q_e j^\mu_{\text{em}} A_\mu = \frac{gg'}{\sqrt{g^2 + g'^2}} (\bar{e}\gamma^\mu e) A_\mu$ with $q_e = \frac{gg'}{\sqrt{g^2 + g'^2}} = g \sin\theta_w = g' \cos\theta_W$

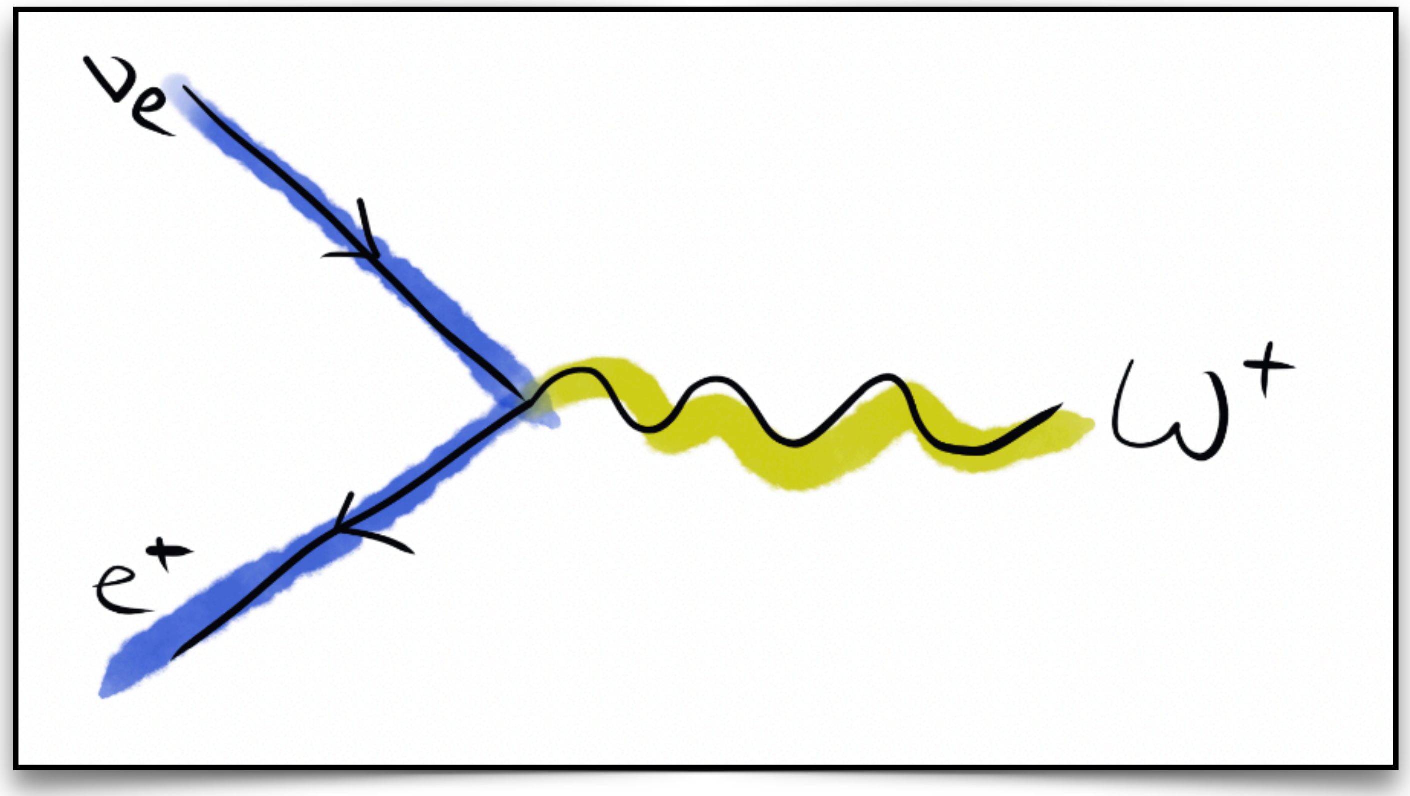


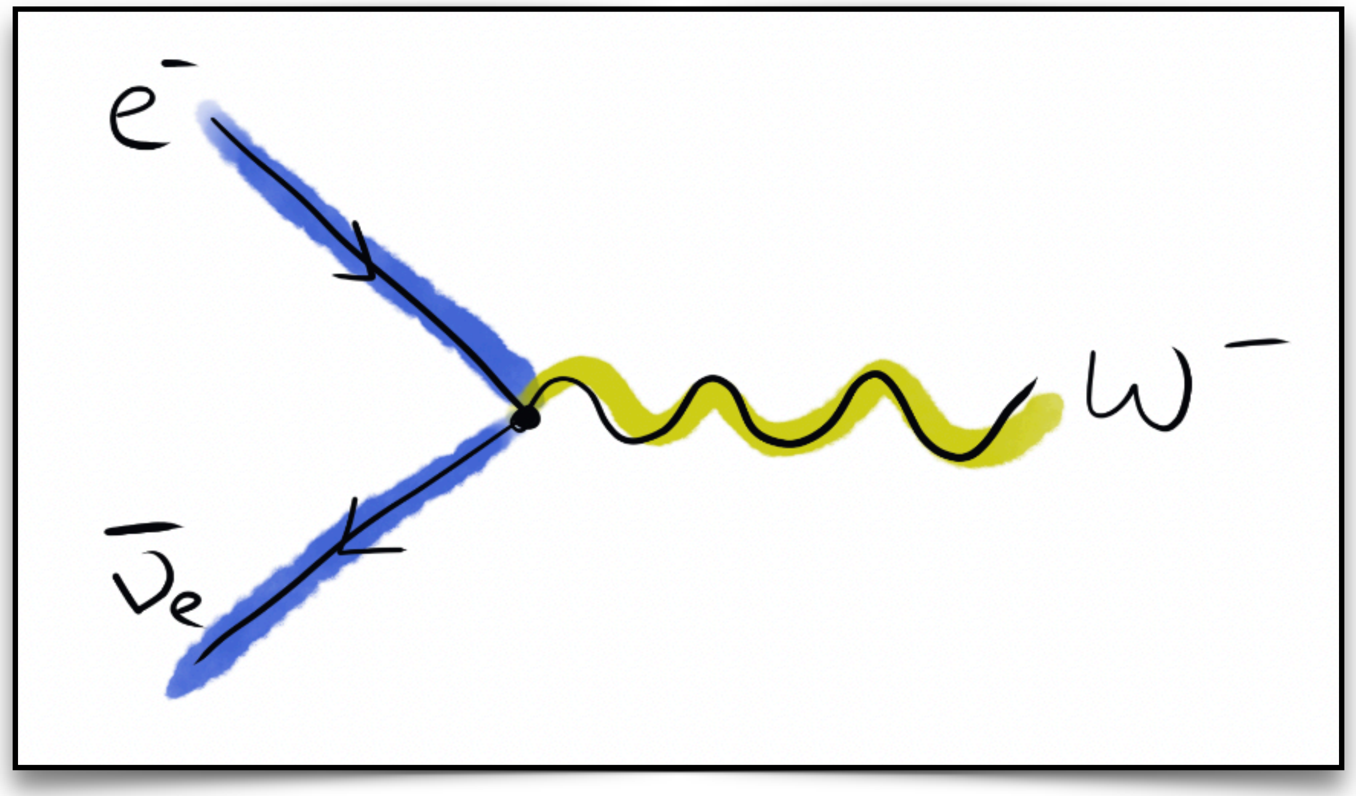
Leptons: Charged currents (CC)

- Charged W bosons couple to leptons:
  - Parity violating: W boson couples to left-handed particles (only left handed particles have a weak isospin). Use chirality operator $P_L = \frac{1}{2}(1-\gamma^5)$ to get left-handed components.
  - $$\mathcal{L}_{\text{CC}} = -\frac{g}{\sqrt{2}}\left(j^{\mu,+}_{\text{CC}} W^+_\mu + j^{\mu,-}_{\text{CC}} W^-_\mu\right)$$

example:
electrons and electron-neutrinos

$$= -\frac{g}{\sqrt{2}}\left[\left(\bar{\nu}_e\left(\gamma^\mu \frac{1}{2}(1-\gamma^5)\right)e\right)W^+_\mu + \left(\bar{e}\left(\gamma^\mu \frac{1}{2}(1-\gamma^5)\right)\nu_e\right)W^-_\mu\right]$$



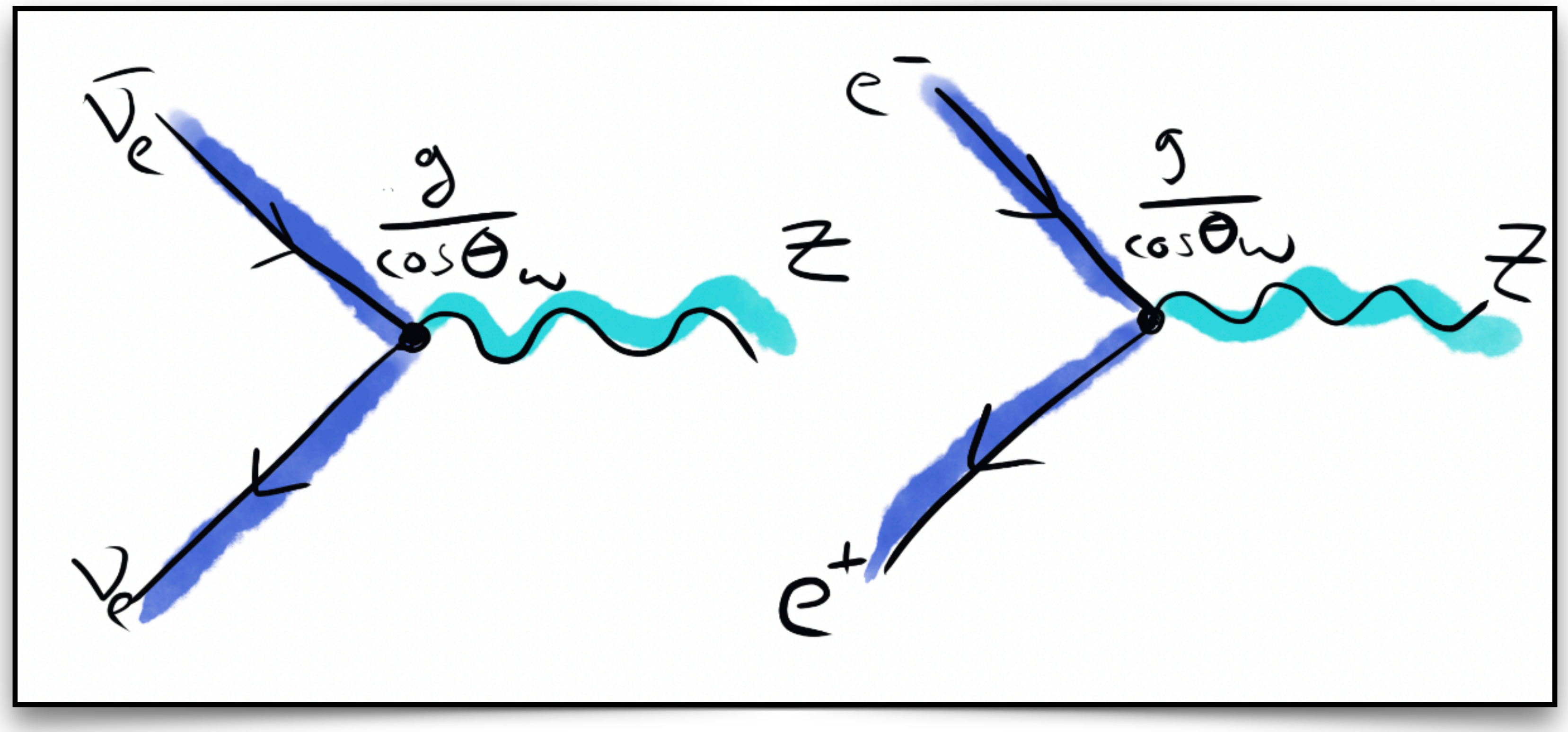


Leptons: Neutral currents (NC)

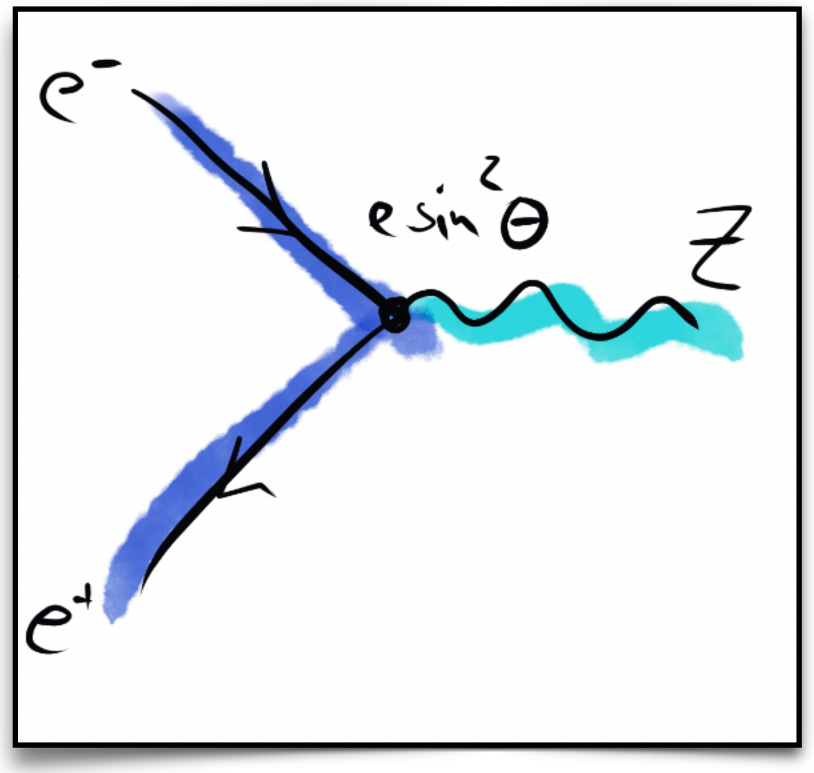
- Neutral Z boson couples to leptons:
  - Experimentally only discovered years after electroweak theory prediction
  - Not a pure V-A current (like CC), but more complicated structure (still only one free parameter)
  - $\mathscr{L}_{\mathrm{NC}} = -\frac{\sqrt{g^2 + g'^2}}{2} j^{\mu}_{\mathrm{NC}} Z_{\mu}$

example:
electrons and electron-neutrinos

$$= -\frac{g}{2\cos\theta_W}\left[\left(\bar{\nu}_e\left(\gamma^{\mu}\frac{1}{2}(1-\gamma^5)\right)\nu_e\right) - \left(\bar{e}\left(\gamma^{\mu}\frac{1}{2}(1-\gamma^5)\right)e\right) - 2\sin^2\theta_W(\bar{e}\gamma^{\mu}e)\right] Z_{\mu}$$



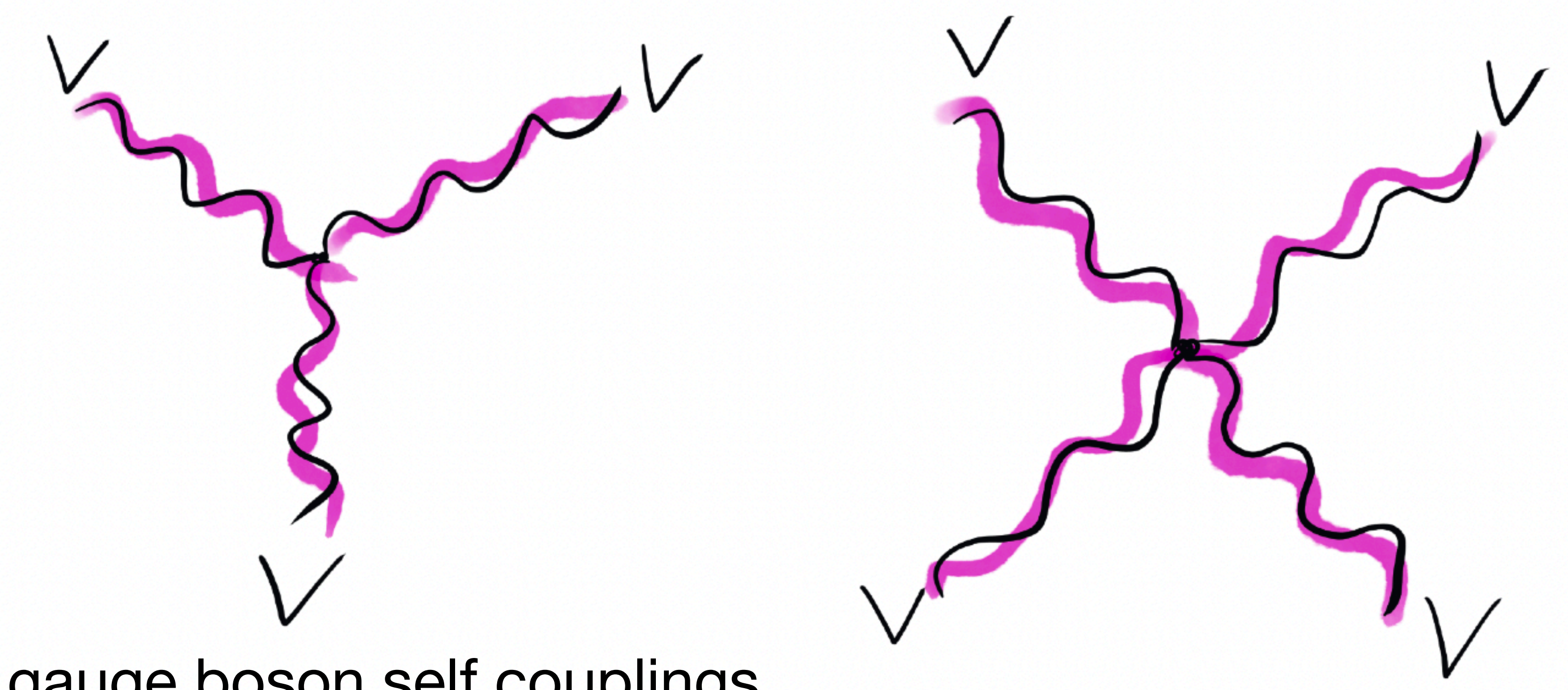
left-handed couplings



vector couplings

Higgs and gauge couplings

VVV=WWγ, WWZ   VVVV=WWWW, WWZZ, WWγγ

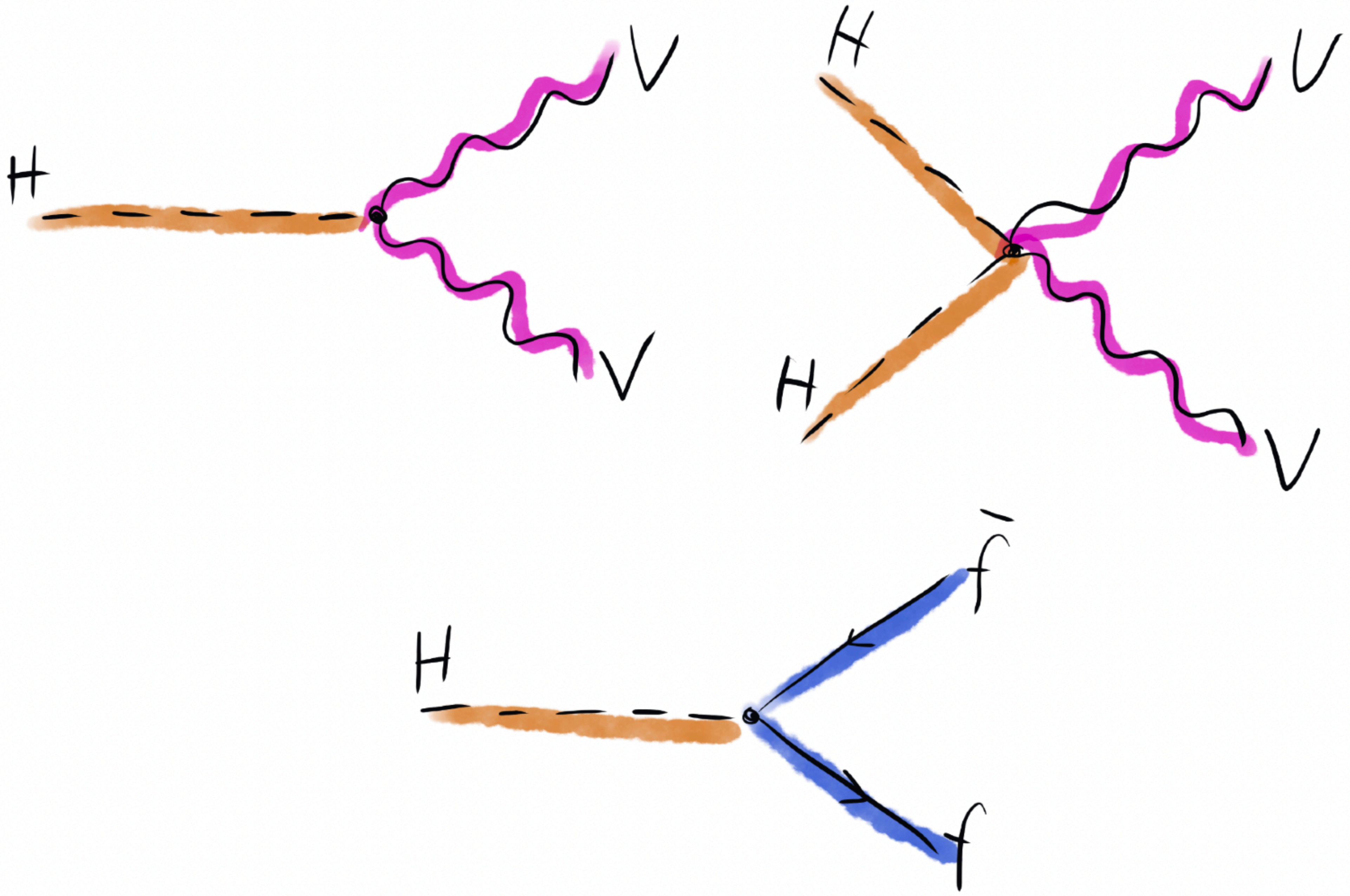


gauge boson self couplings

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

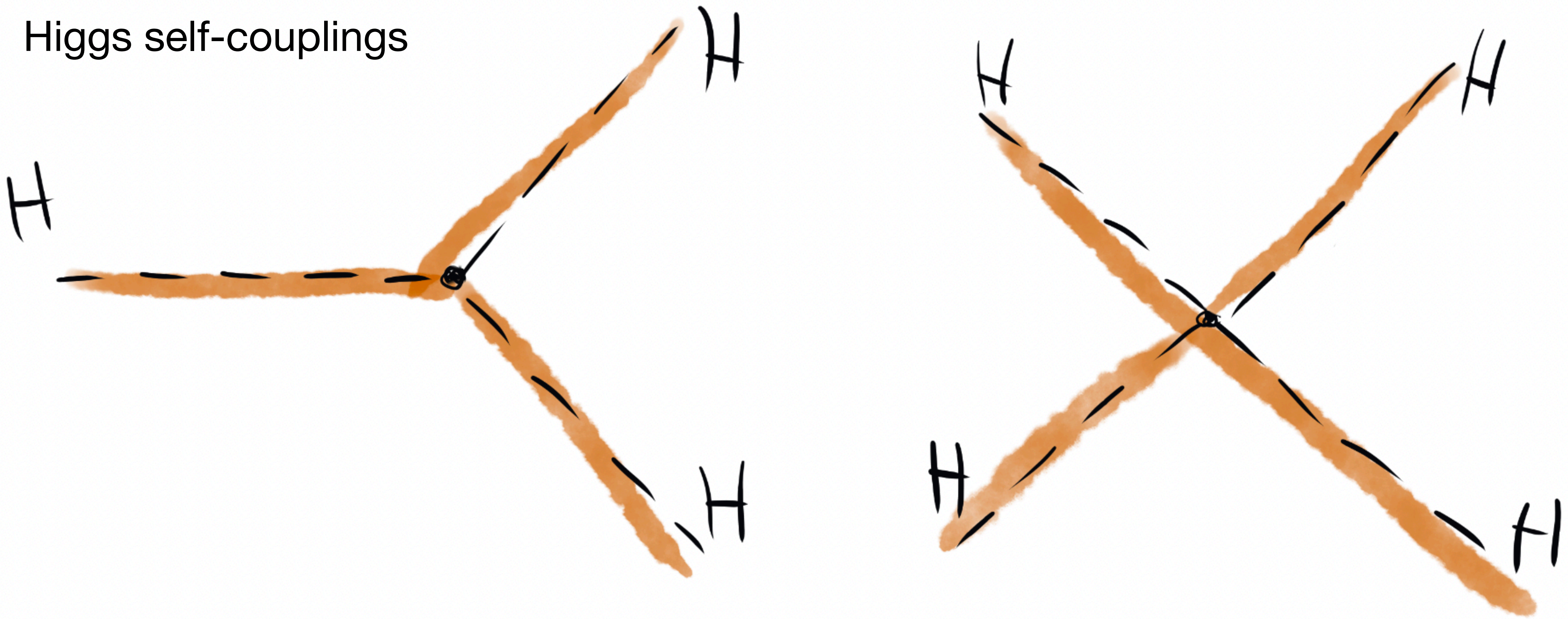
$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - \underbrace{g\epsilon^{ijk} W^j_\mu W^k_\nu}_{\text{gauge boson self-interaction}}$$

V=W, Z



Higgs couplings to bosons and fermions

Higgs self-couplings

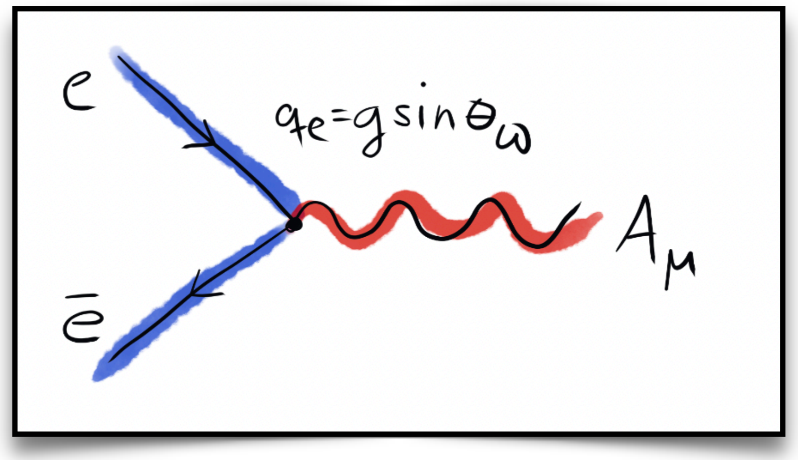


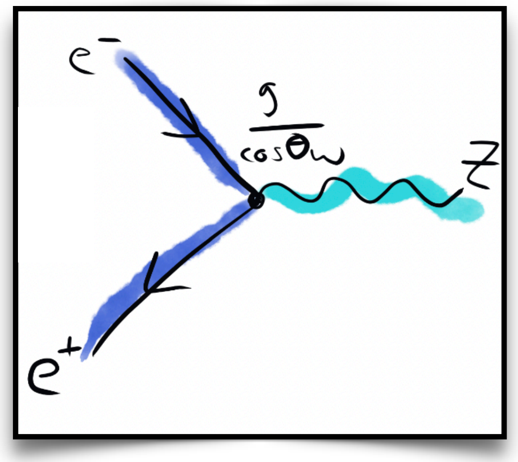
Overview experimental tests electroweak

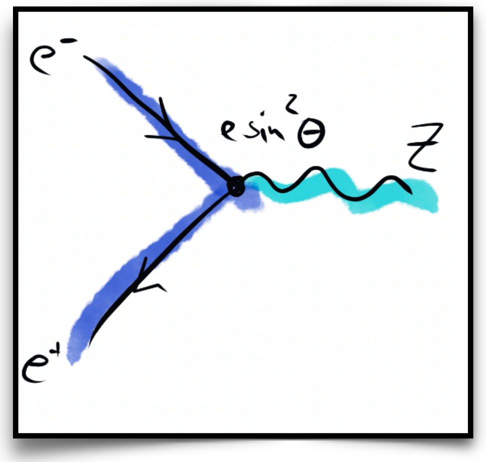
- Early 1970s: electroweak (EW) theory established theoretically
  - Formulation: S. Glashow (1961); A. Salam, S. Weinberg (1967)
  - EW theory is renormalizable: G. ’t Hooft, M. Veltman (1971)
- Experimental questions to test predictions of the electroweak theory:
  - Do neutral currents (NC) exists?
  - Do massive gauge bosons W and Z exist?
  - Are all coupling strengths as predicted?
- This chapter: overview of first steps to establish the electroweak theory experimentally

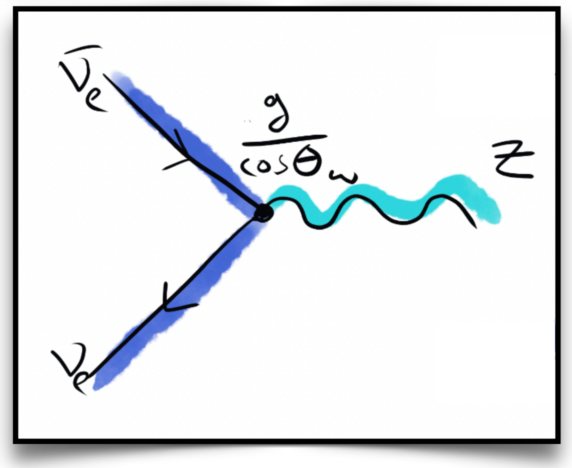
Search for neutral currents

- Two possible search strategies:
  - Charged particle scattering (experimentally clear signature), but: Photon exchange leads to identical signature with much larger cross section
  - Neutrino scattering: No photon exchange!

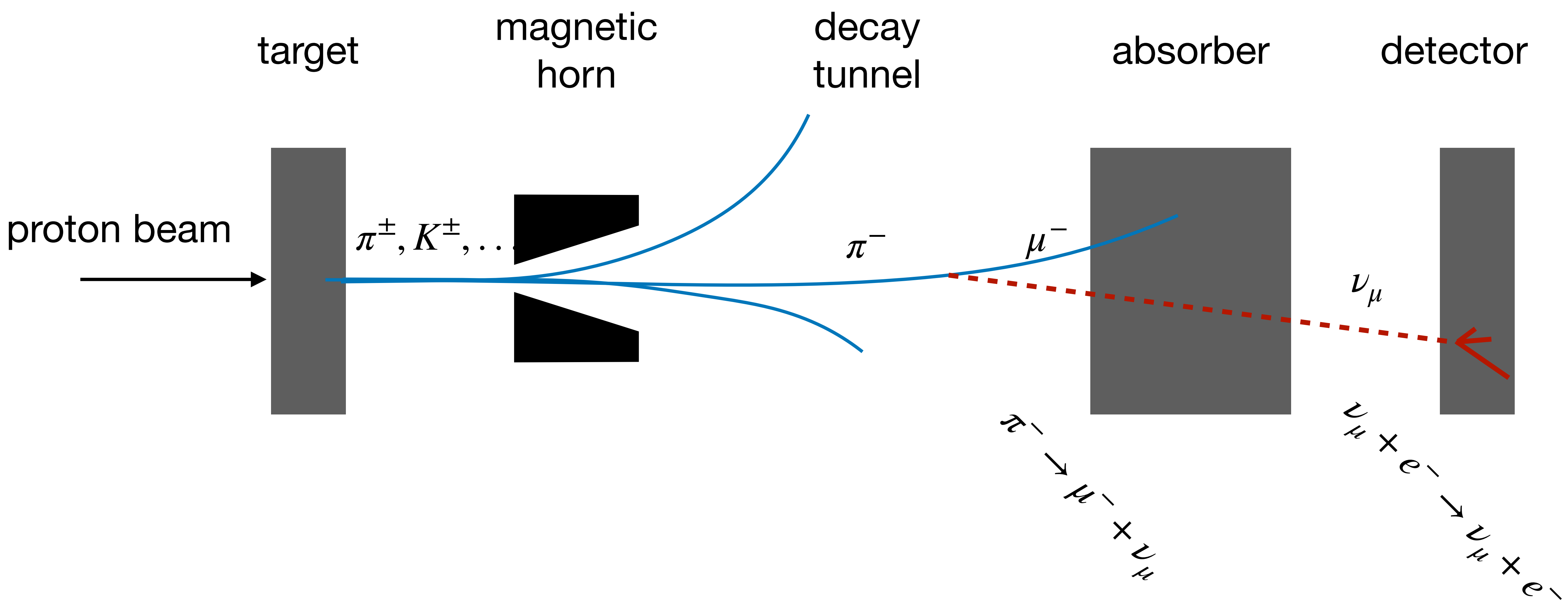








- CERN neutrino beam
  - 26 GeV protons from CERN PS on fixed target → 1-10 GeV Neutrinos
  - detection using bubble chambers

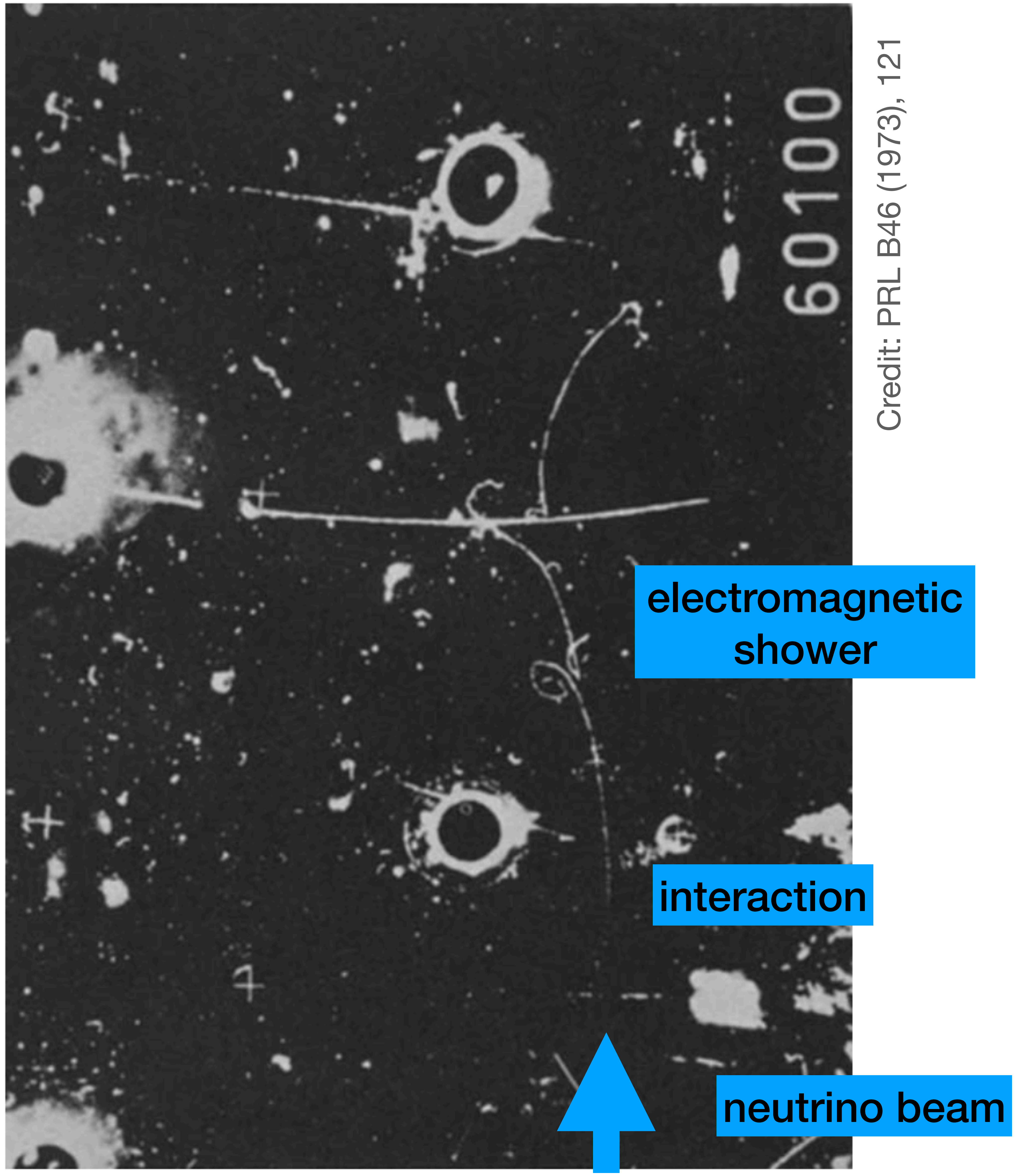


Search for neutral currents: Gargamelle

- Named after the the books “The Life of Gargantua and of Pantagruel” (French: La vie de Gargantua et de Pantagruel) by F. Rabelais written in the 16th century. Gargantua and Pantagruel were two giants - and Gargamelle was Gargantua’s mother…
- Heavy liquid (Freon) bubble chamber: 4.8m long, 2m diameter, 12m^3 Freon.
  - Surrounded by a 2T magnet
  - Watercooled
  - Overall over weight over 1000t
  - Readout triggered by proton beam: Photographs taken, illuminated by flashes


neutrino beam
MAN CDC
MAN CDC
MAN . CDC

Search for neutral currents: Gargamelle results



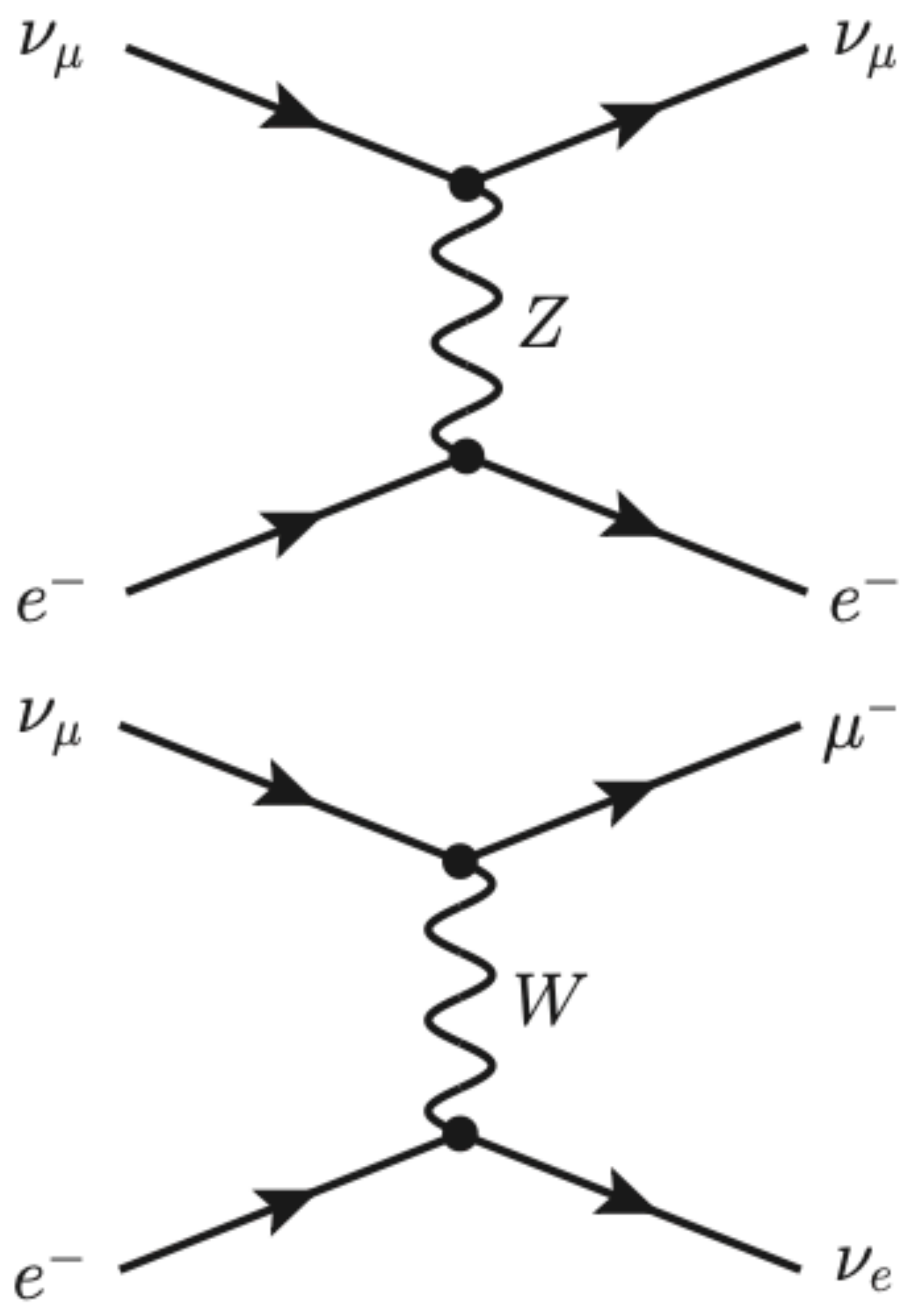
Credit: PRL B46 (1973), 121

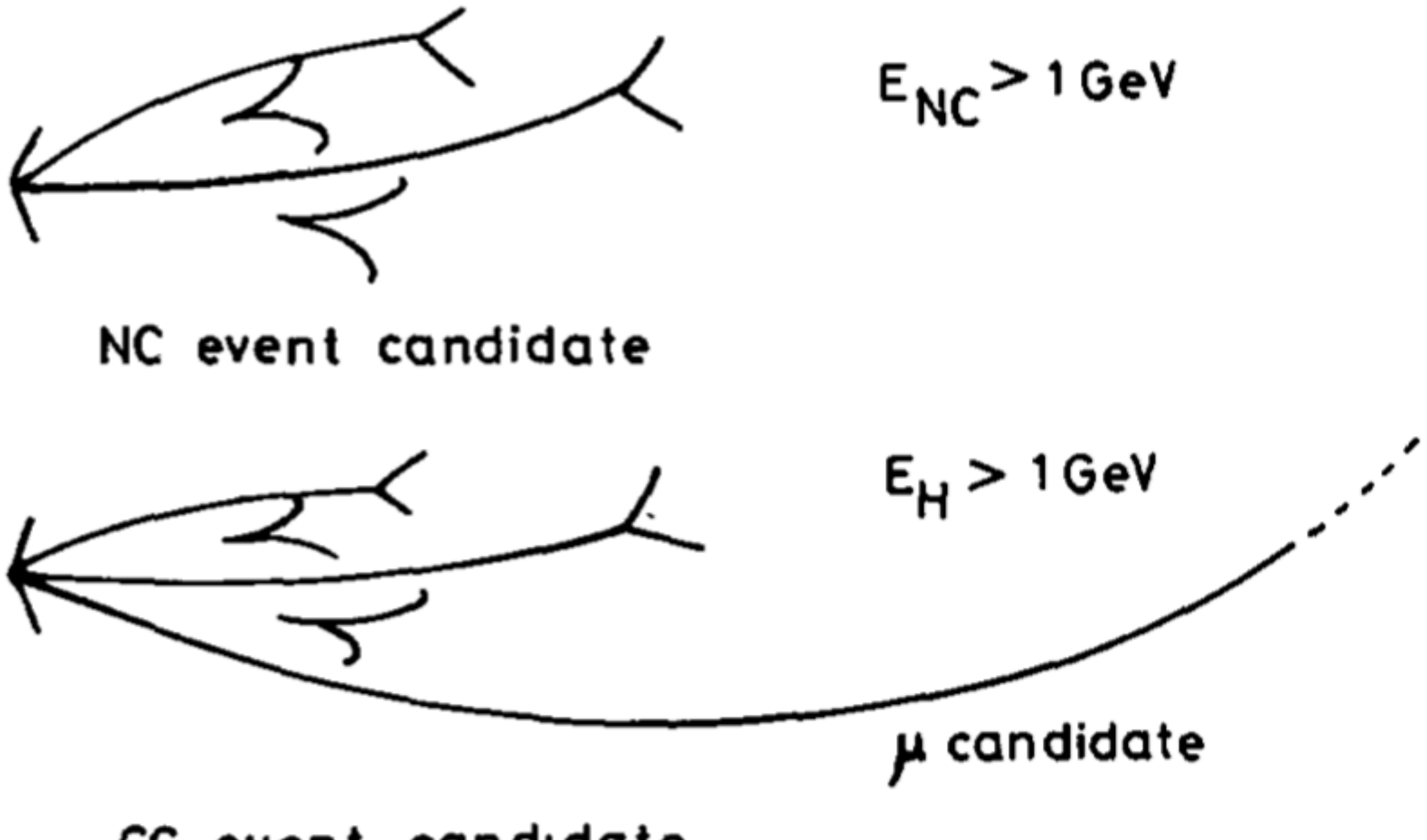
Fig. 1. Possible event of the type $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$.

Search for neutral currents: Gargamelle results

Neutral Current

Charged Current





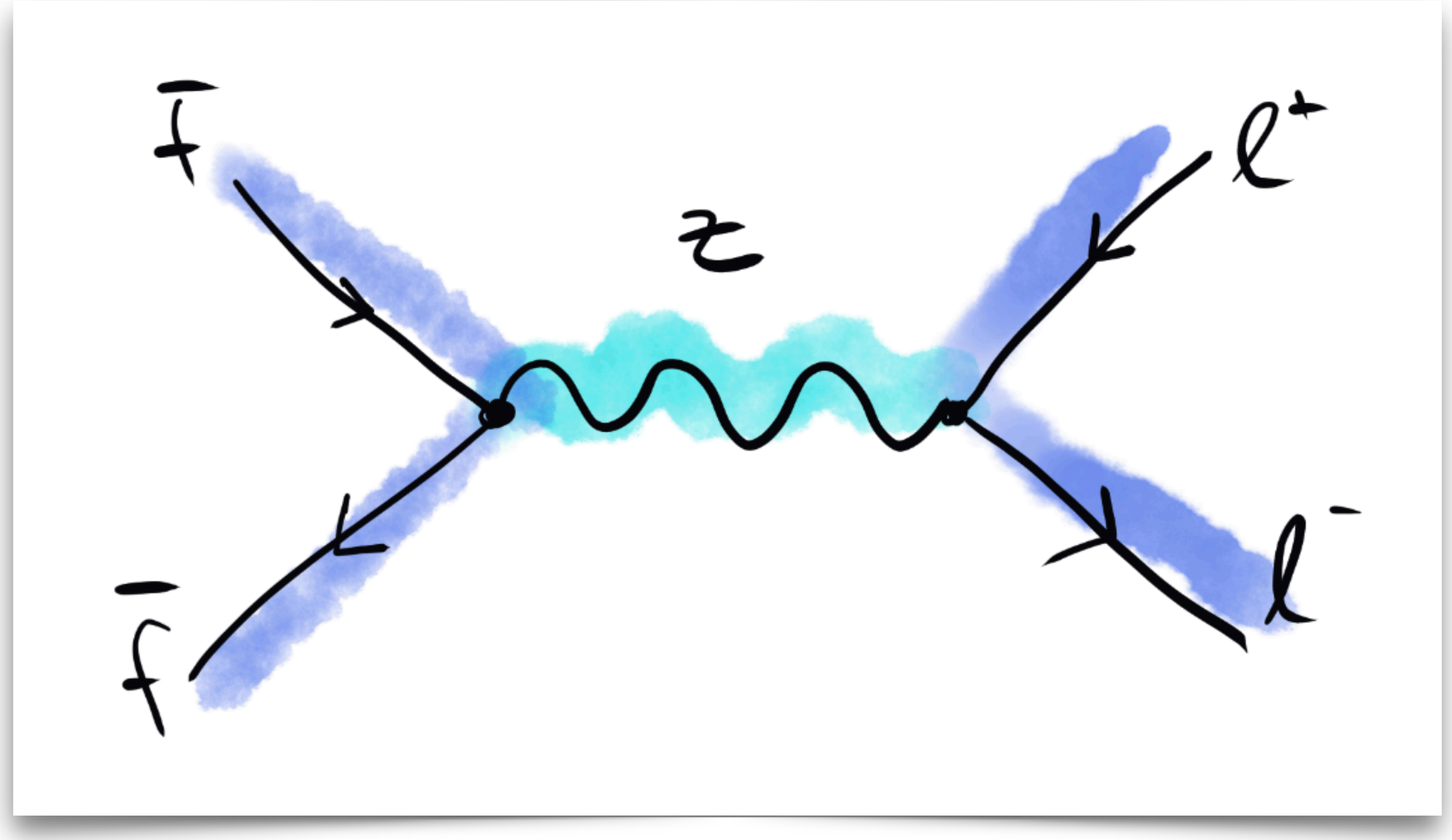
Nucl. Phys. B73 (1974) 1

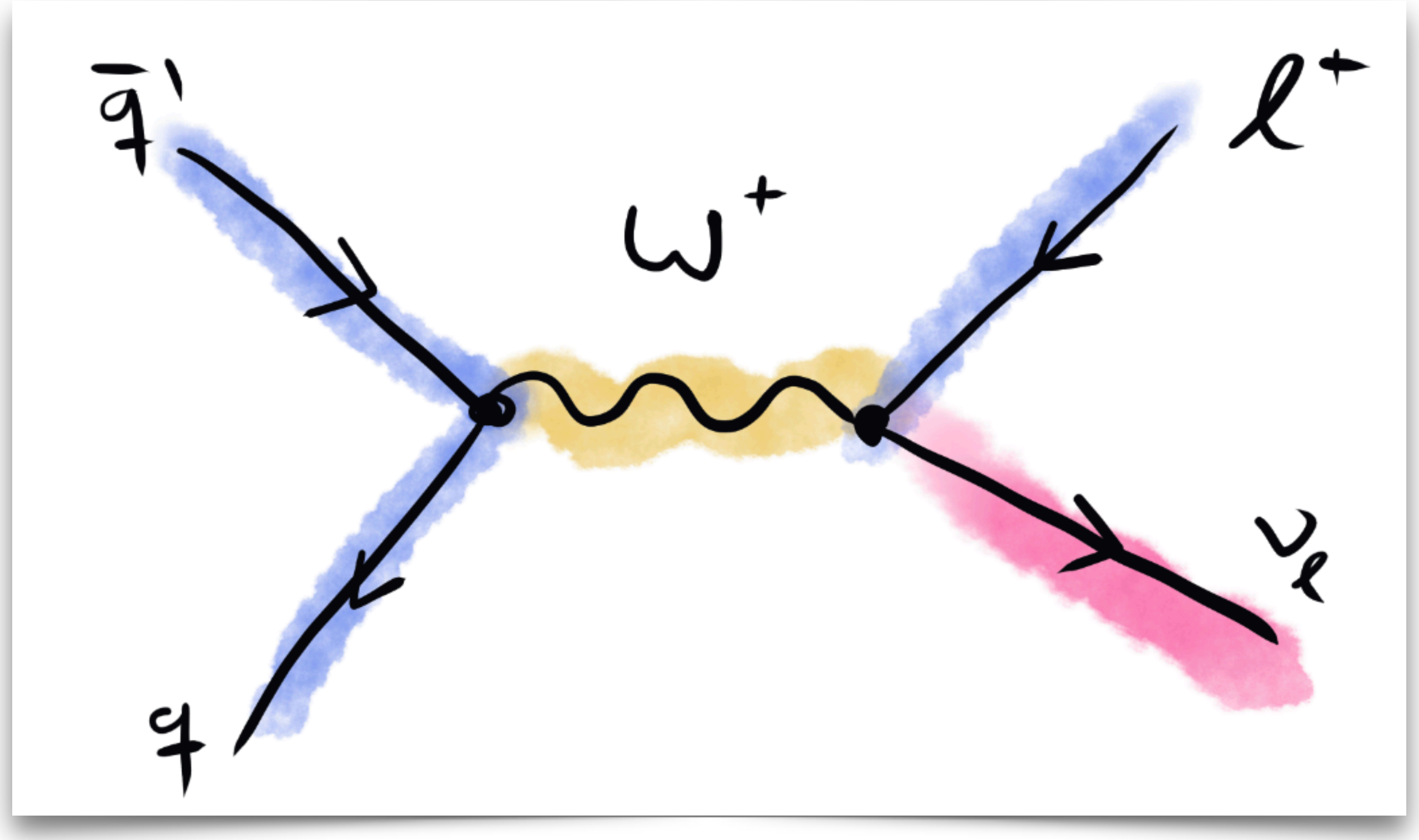
- Neutrinos interact with electrons or atomic nuclei (much more likely)
- Signature for NC: Electromagnetic shower (muon neutrino CC produces no electrons!)
- Background: Neutrons produced in the material arround the chamber

Murrik (by Anuar Sifuentes)

Search for heavy bosons: W and Z

- Experimental evidence by measuring the boson masses directly (not indirectly via neutrino scattering)





- Need center of mass energy of colliding fermions around (or higher than) the expected boson mass
- Based on Gargamelle results, the W-boson mass was expected around 60-80 GeV; the Z-boson around 75-95 GeV.

PINGO

- **PINGO:**
  - Umfrage: Teilchenphysik 1 (WS 23/24)
  - Zugangsnummer: 434521
  - Link: https://pingo.coactum.de/events/434521

PINGO: Measure massive bosons

- Which particle accelerator would you build to discover Z and W bosons?
  - Cheap and proven: Proton fixed target!
  - There are neutrinos in the final state: We need an electron-positron collider!
  - A Proton-antiproton collider to have the correct quarks for the W productions!
  - A proton-proton collider is easier than proton-antiproton and works as well (see LHC)!

PINGO: Measure massive bosons

- Which particle accelerator would you build to discover Z and W bosons?
  - Cheap and proven: Proton fixed target
    - In order to reach 100 GeV collision energy, one needs a $\sqrt{s} \approx \sqrt{2 m_p E} \approx 5000$ GeV beam
  - There are neutrinos in the final state: an electron-positron collider
    - This would indeed be the perfect collider for Z boson production (and W-boson pair production), but technically it was still many years in the future (studies for LEP had started already)
  - **A Proton-antiproton collider to have the correct quarks for the W productions**
    - **At low energies $q\bar{q}$ scattering dominates provides both e.g. $u\bar{d}$ (→W)and e.g. $u\bar{u}$ (→Z) collisions**
  - A proton-proton collider is easier than proton-antiproton and works as well (see LHC)
    - Only at very high LHC energies gluon scattering dominates (and then pp provides higher luminosity)

Super Proton–Antiproton Synchrotron ($Sp\bar{s}S$)

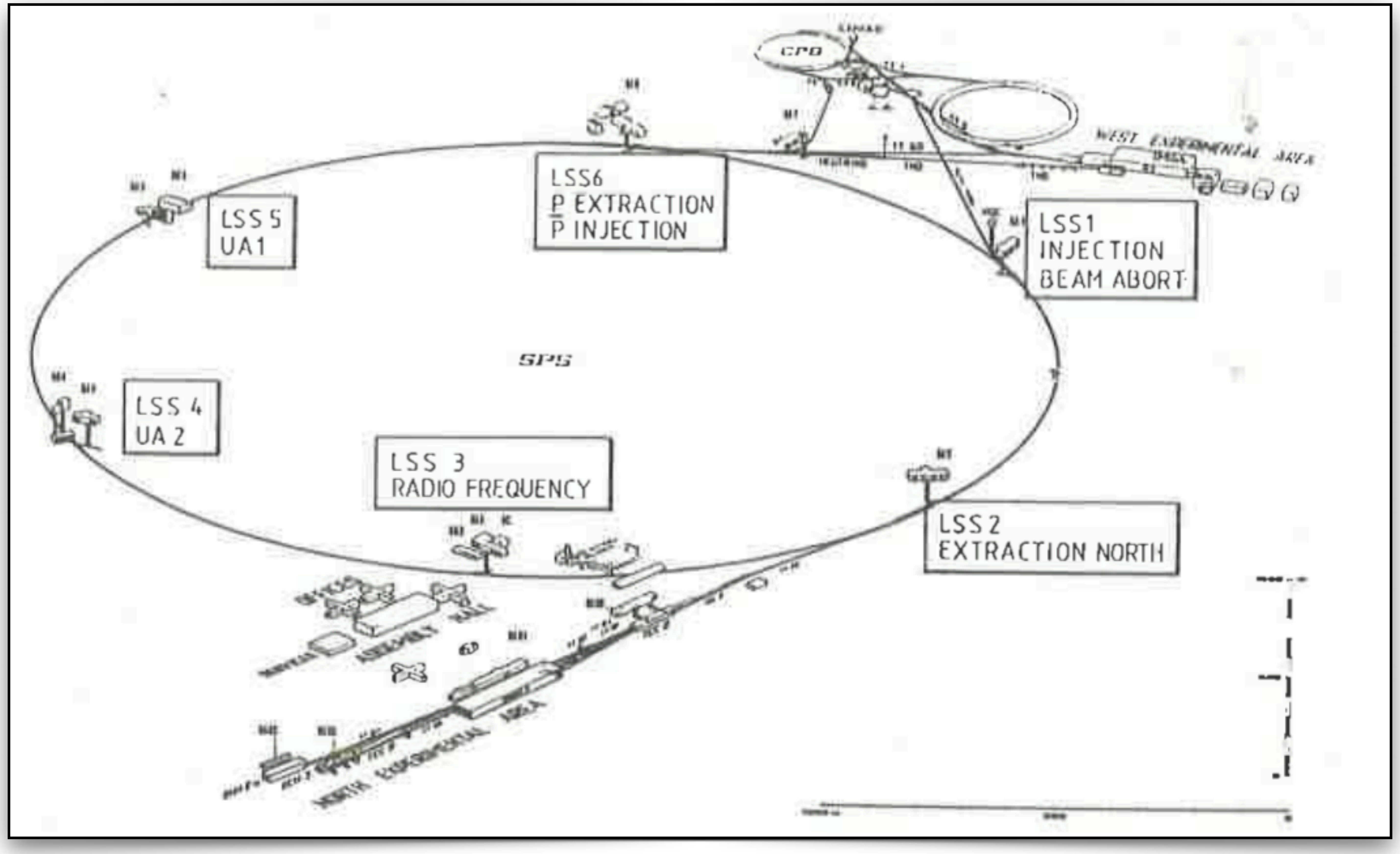
- First proposal presented to use the existing CERN SPS as an anti-proton machine: 1976 (C. Rubbia), considered “unrealistic” by US colleagues, but CERN was positive…
- Design of detectors started 1977, approval 1978
- First beams on July 7 1981
- First collisions on July 10 1981
- Discovery of the W-boson early 1983
- Discovery of the Z-boson late 1983

Super Proton–Antiproton Synchrotron ($Sp\bar{s}S$)

- Momentum fractions of colliding valence (anti)quarks $x_1 \approx x_2 \approx 0.2$
  → estimated center-of-mass energy of valence quarks:
  $\sqrt{\hat{s}} \approx \sqrt{x_1 x_2 s} = 100$ GeV
  →estimated center-of-mass energy of (anti)protons $\sqrt{s} = 500$ GeV

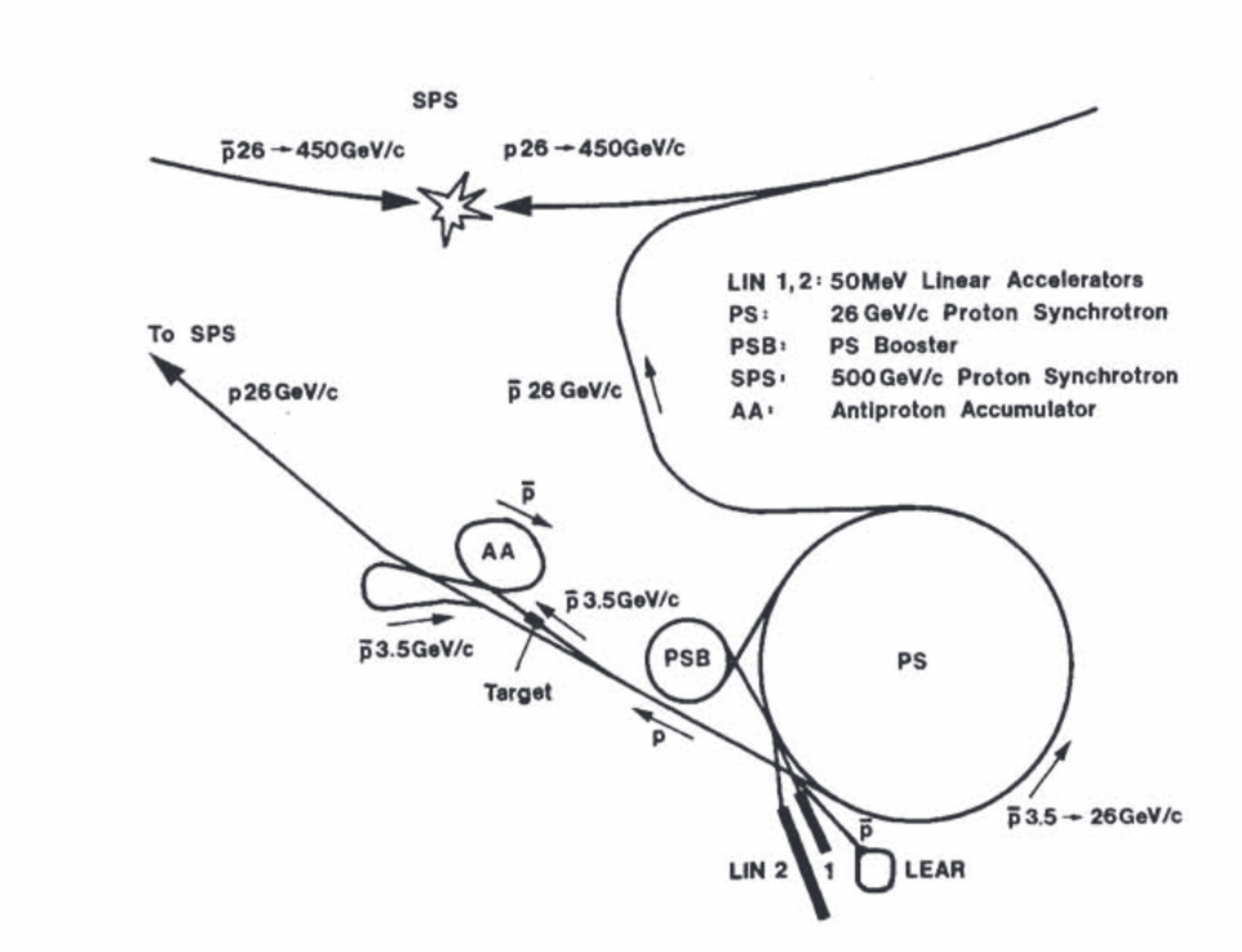
- $Sp\bar{s}S$
  - SPS (Super Proton Synchrotron): new CERN syncrotron (from 1976) 6.9 km circumference, 400 GeV protons
  - Idea (C. Rubbia, 1976): upgrade SPS to a proton-antiproton collider → $Sp\bar{s}S$
  - center-of-mass energy: initially 540 GeV, later upgraded to 630 GeV
  - UA1 and UA2 experiments (“underground area”), data taking from 1981

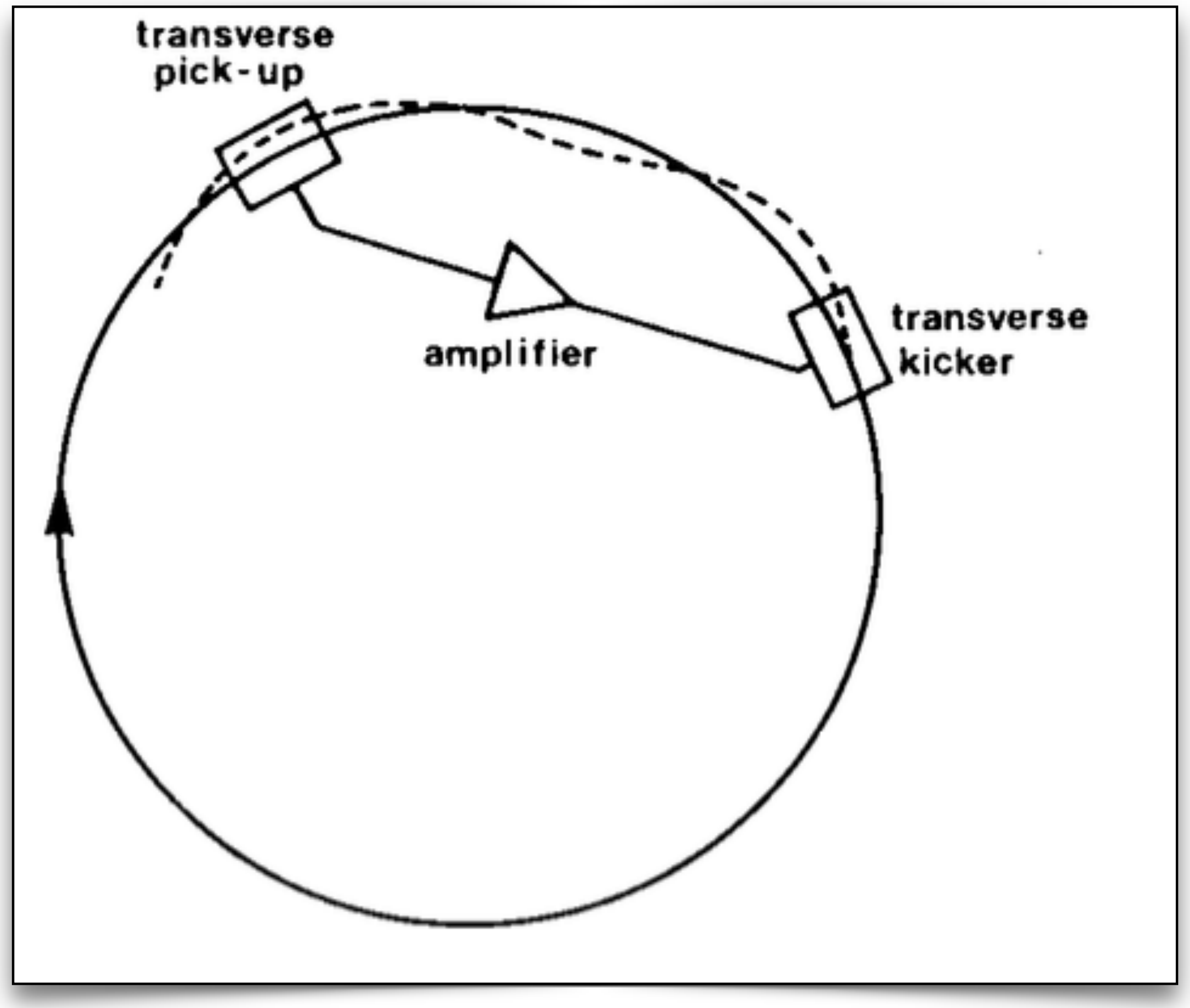
Super Proton–Antiproton Synchrotron ($Sp\bar{s}S$)



Super Proton–Antiproton Synchrotron ($Sp\bar{s}S$)

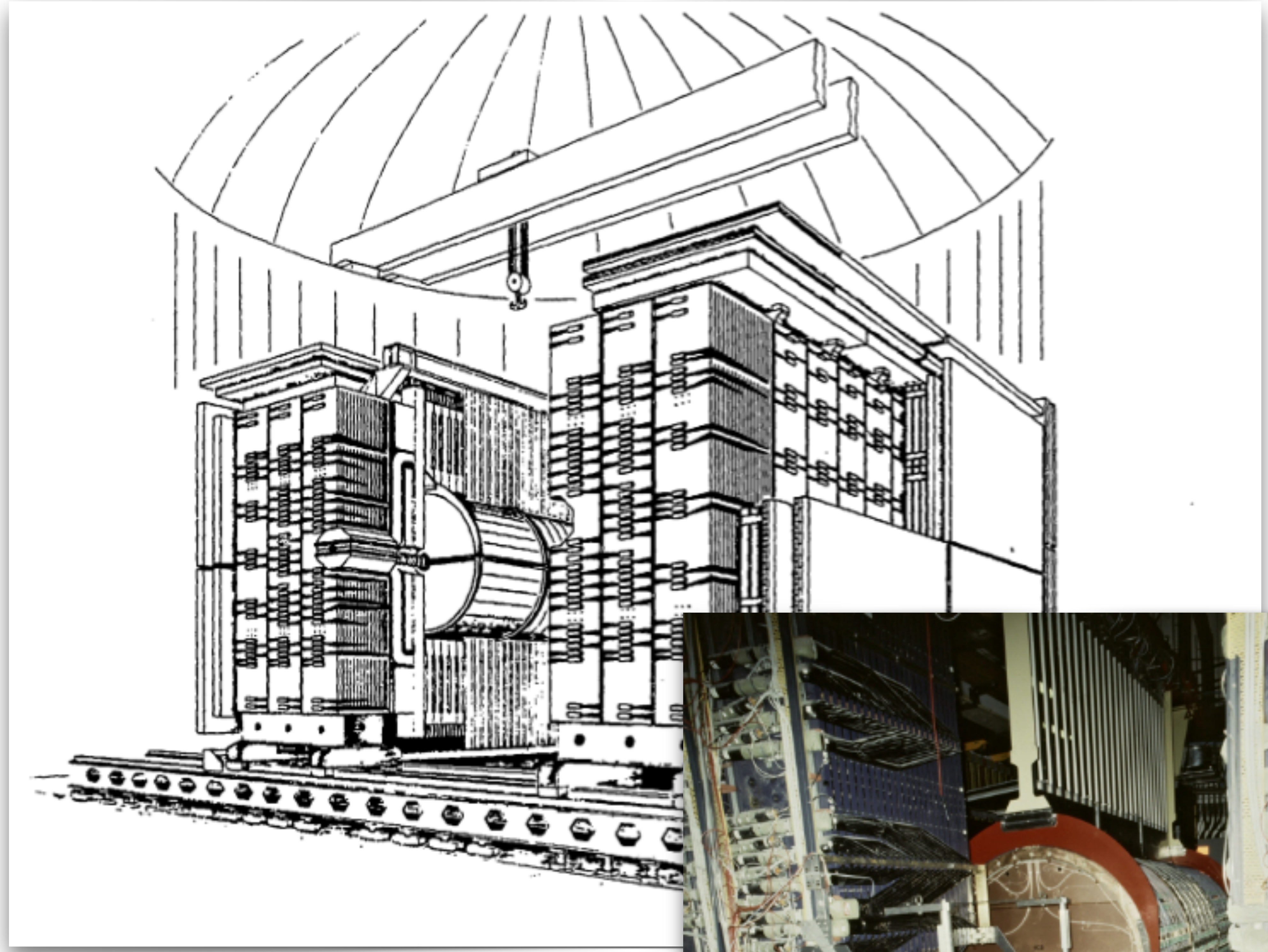
- Antiprotons are difficult:
  - Antiproton production via proton beam on fixed target: 1 antiproton per 10^9 protons
  - Problem: Very large antiproton emittance
  - Idea (S. Van der Meer, 1968): Stochastic cooling ("2πR>2R") using electronic pick up coils and magnets

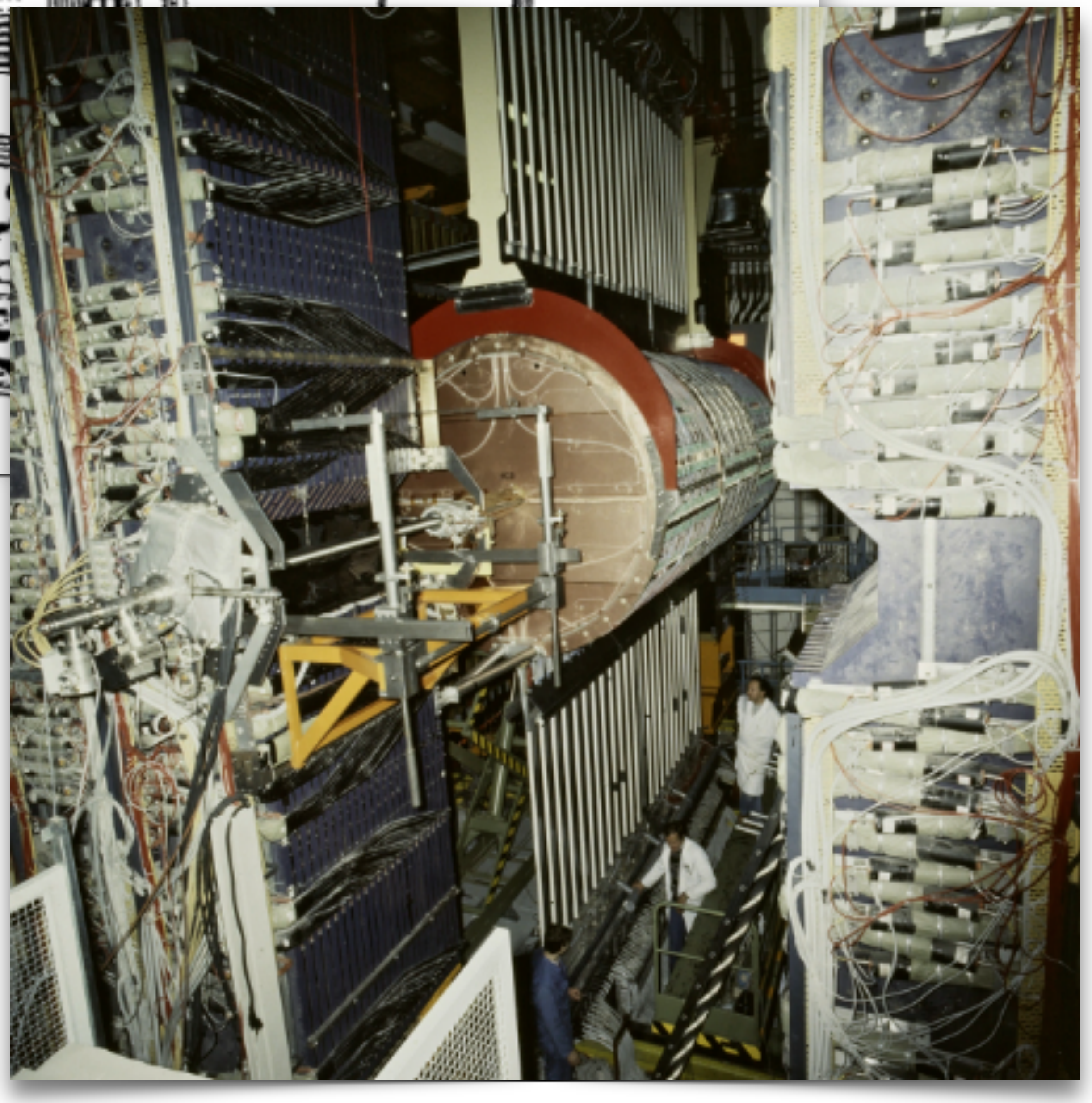


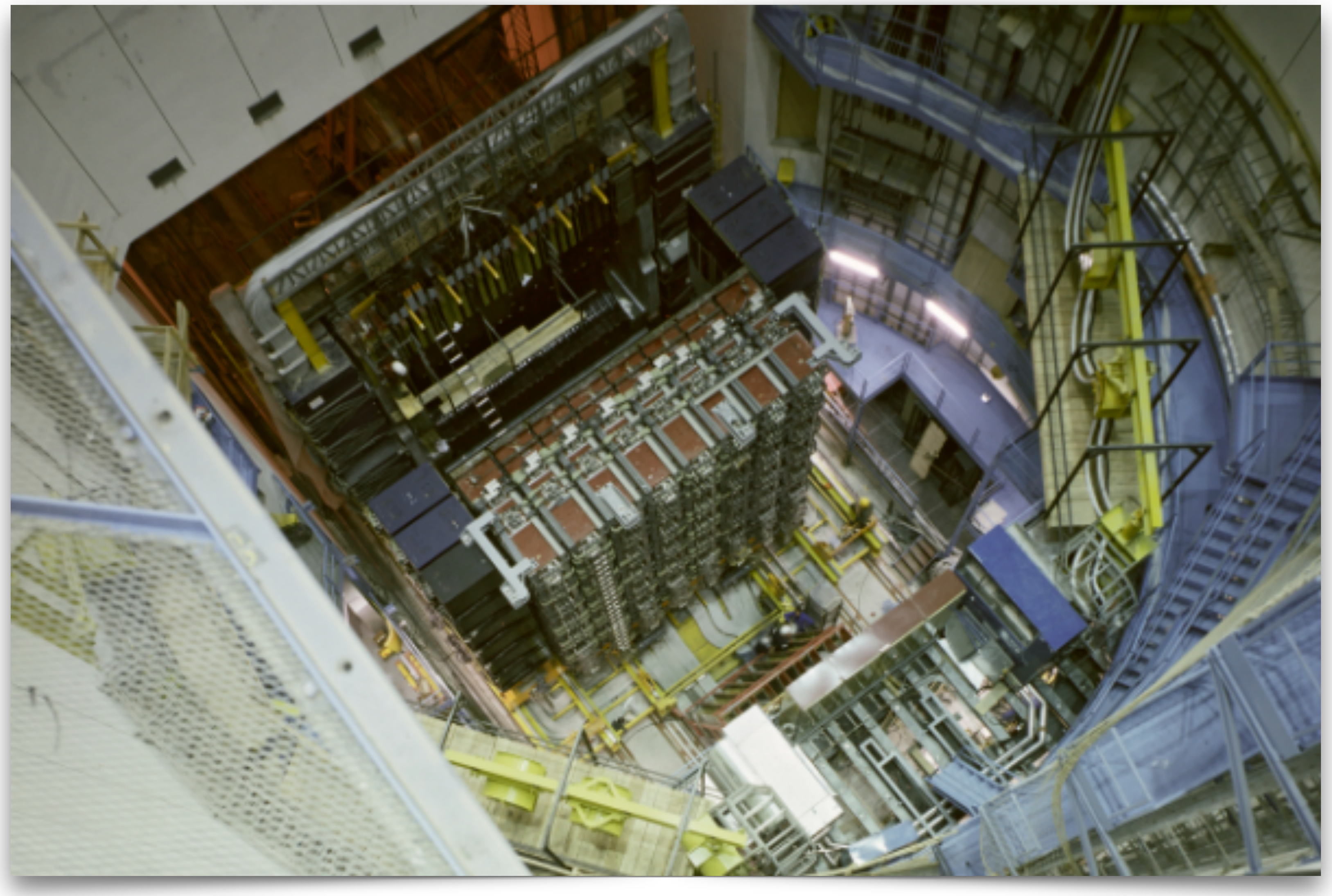


- Further challenges:
  - Protons and antiprotons share the same beampipe
  - Need hermetic 4π detectors

Super Proton–Antiproton Synchrotron ($Sp\bar{s}S$): UA1

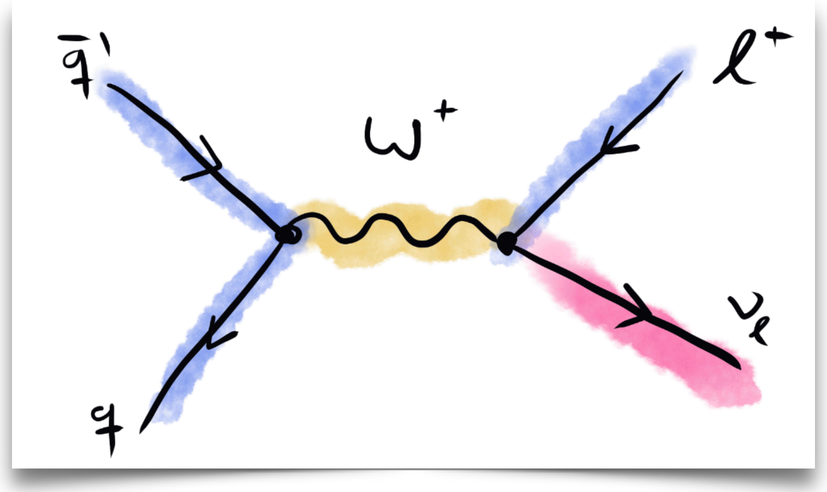


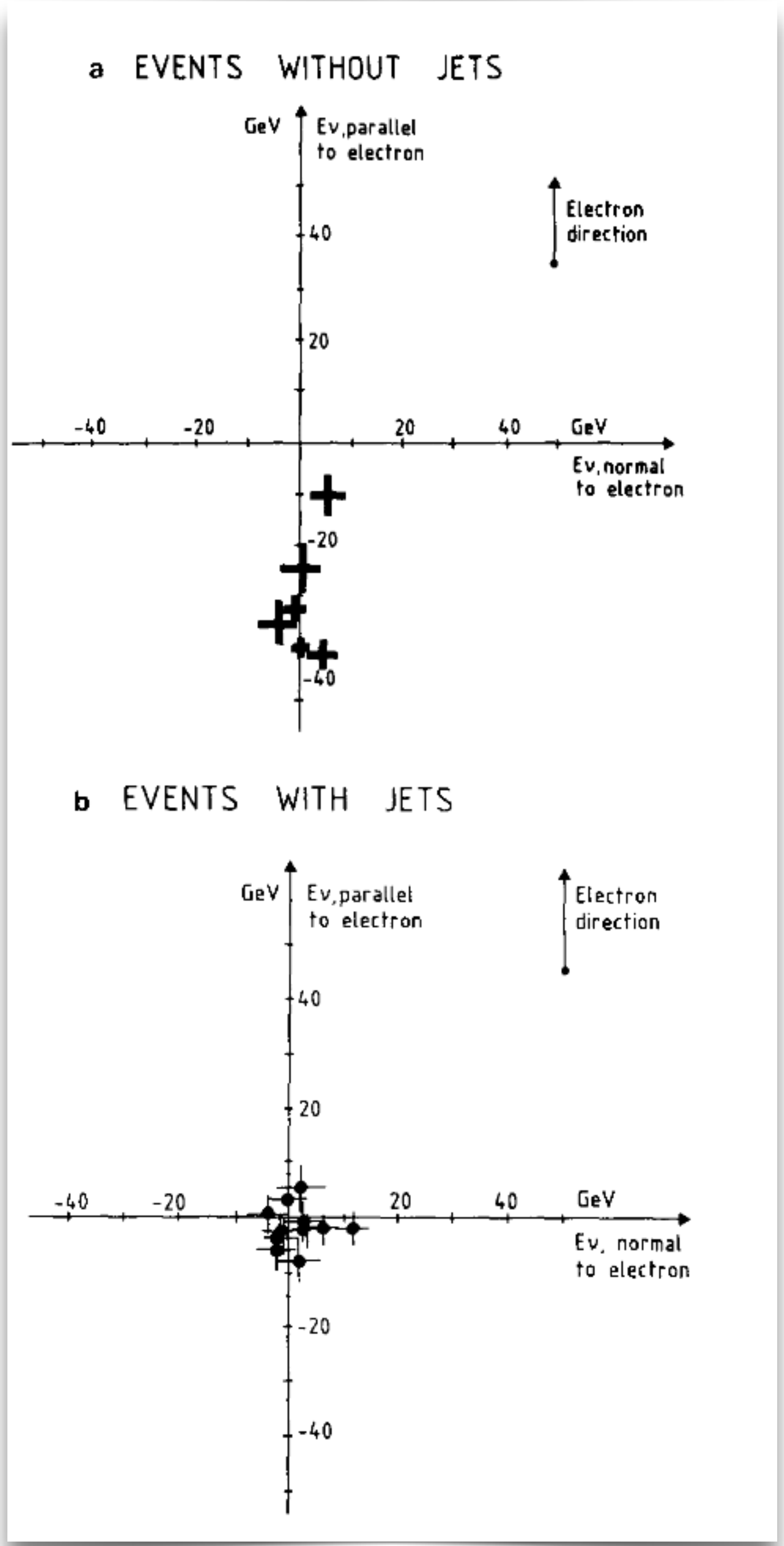




Discovery of the W bosons

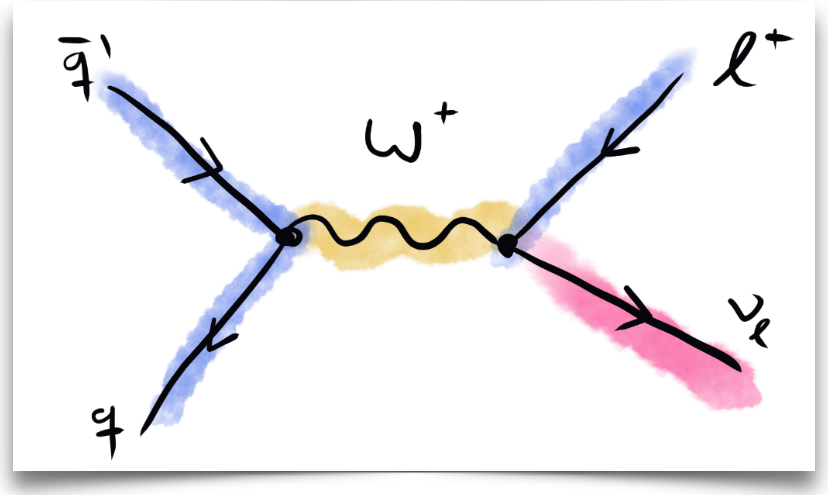
- Analysis strategy
  - Reconstruct charged lepton (electron), clean detector signature
  - Neutrino is detected via missing transverse momentum (MET)
  - $W^+ \to e^+ + \nu_e$ is a two body decay. In the restframe of the W: Electron and neutrino parallel, but in opposite directions
  - Background: QCD jet production (but no preferred relative direction of lepton and MET)

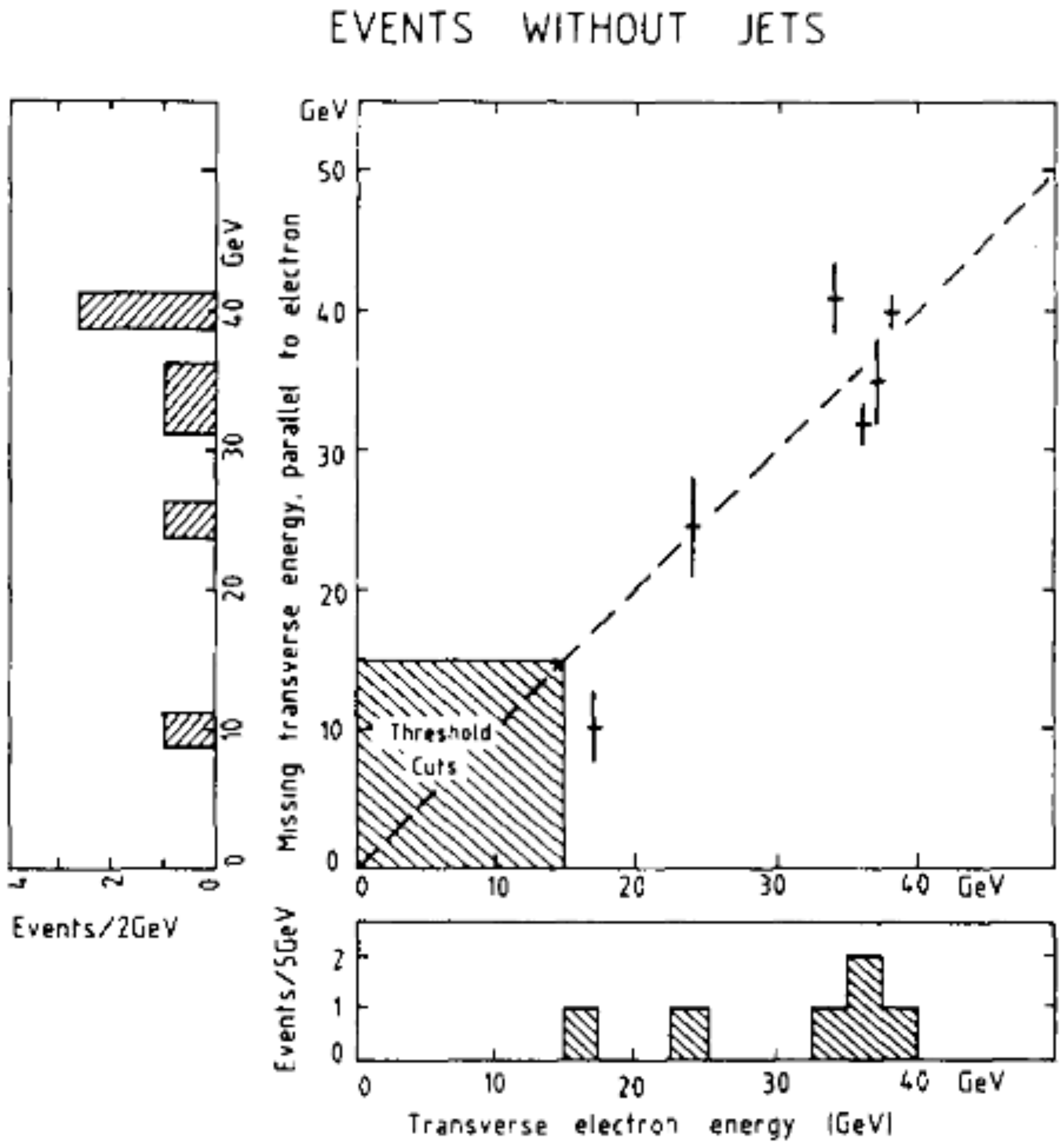




Discovery of the W bosons

- Based on 6 (!) events with identified electrons and fits to angles and momenta: $m_W = 81 \pm 5$ GeV
- Original publications: Phys. Lett. B122 (1983) 103





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PINGO: Measure massive bosons

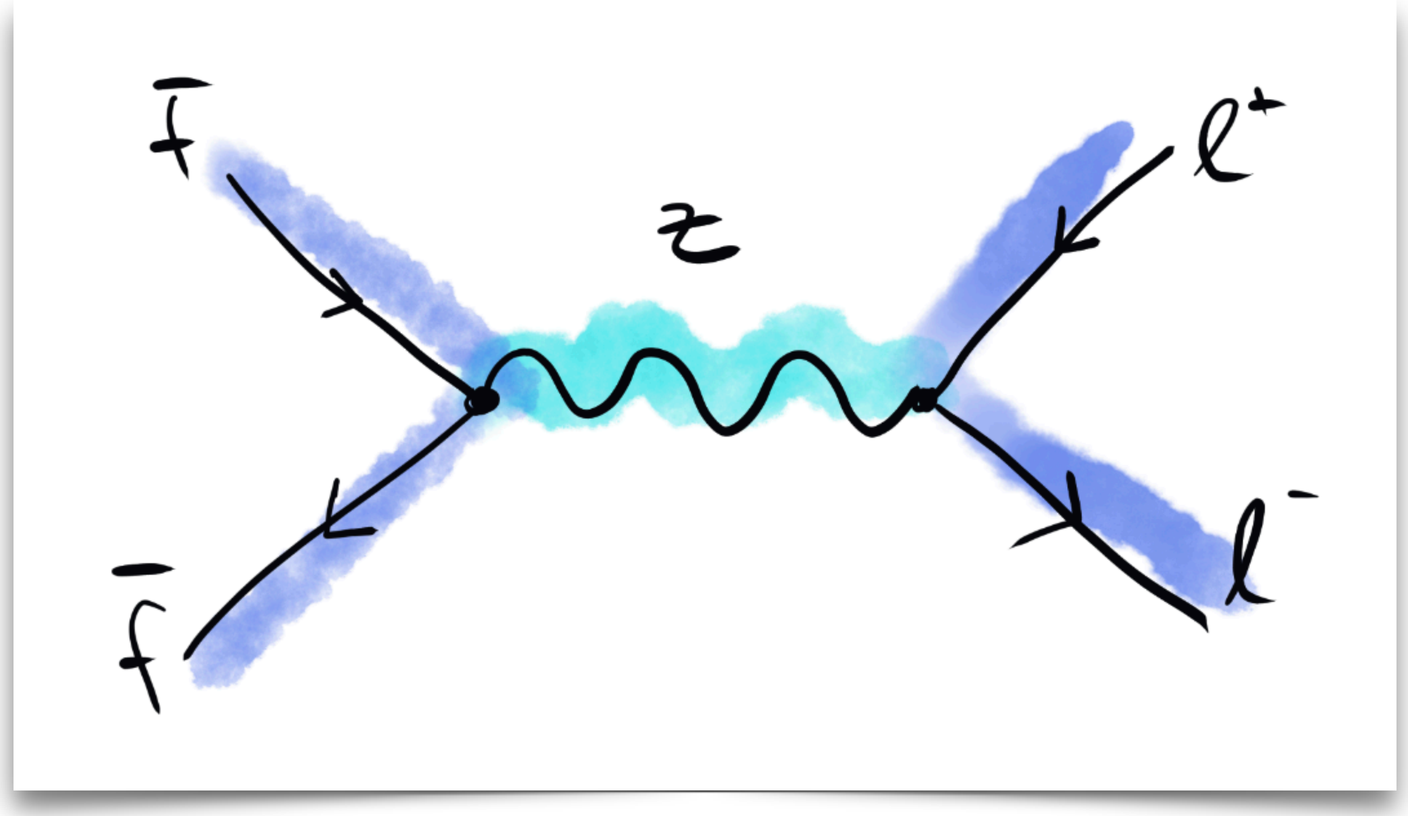
- Why is QCD jet production expected to be the most important background for the decay $W^+ \to e^+ + \nu_e$?
  - Jets may be misidentified as charged leptons.
  - Jets always contain charged leptons.
  - Often QCD jet events contain large missing transverse momentum.
  - Detector noise may “fake” missing transverse momentum.
  - The production cross sections for W bosons and QCD jets are approximately of equal size.

PINGO: Measure massive bosons

- Why is QCD jet production expected to be the most important background for the decay $W^+ \rightarrow e^+ + \nu_e$?
  - **Jets may be misidentified as charged leptons.**
  - Jets always contain charged leptons.
  - **Often QCD jet events contain large missing transverse momentum.**
  - **Detector noise may “fake” missing transverse momentum.**
  - The production cross sections for W bosons and QCD jets are approximately of equal size.

Discovery of the Z boson

- Analysis strategy
  - Reconstruct invariant mass of two charged leptons
  - Production via $p\bar{p} \rightarrow Z + X, Z \rightarrow \ell^+\ell^-$
  - Reaction factor ~10 less probable than $W^\pm$ production



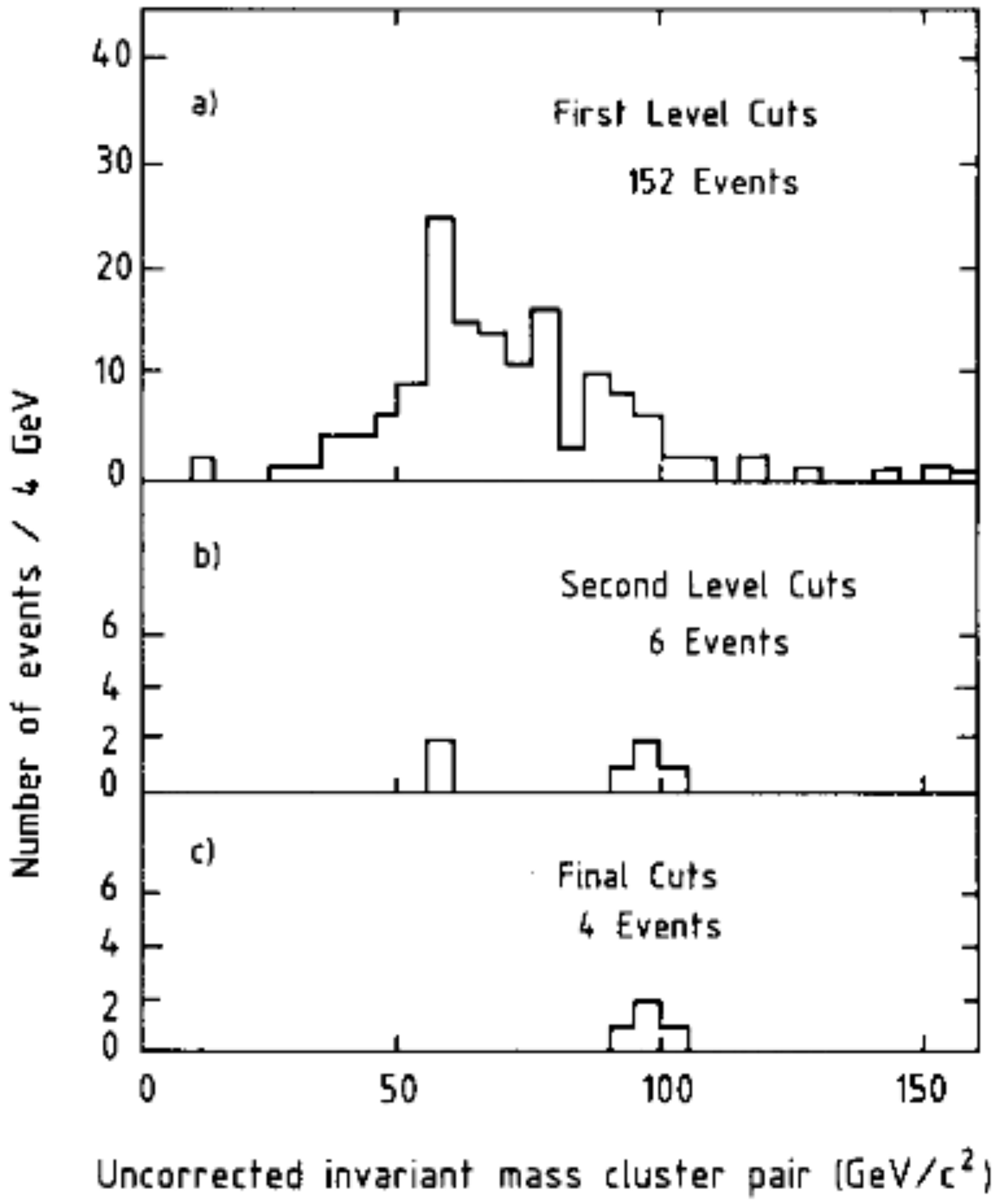
$$m_Z^2 = m_{\ell^+\ell^-}^2 = \left[\begin{pmatrix} E_{\ell^+} \\ \mathbf{p}_{\ell^+} \end{pmatrix} + \begin{pmatrix} E_{\ell^-} \\ \mathbf{p}_{\ell^-} \end{pmatrix}\right]^2$$

$$= m_{\ell^+}^2 + m_{\ell^-}^2 + 2\left(E_{\ell^+}E_{\ell^-} - |\mathbf{p}_{\ell^+}||\mathbf{p}_{\ell^-}|\cos\phi_{\ell^+\ell^-}\right)$$

$$\approx 2|\mathbf{p}_{\ell^+}||\mathbf{p}_{\ell^-}|\left(1 - \cos\phi_{\ell^+\ell^-}\right)$$

Discovery of the Z boson

- Easier e^+e^- events (4 in total, +1 $\mu^+\mu^-$ event)
  - a) $E_T > 25$ GeV
  - b) $p_T > 7$ GeV per track, pointing to ECAL cluster
  - c) no other tracks with large p_T pointing to ECAL cluster (“isolation”)
- Result: $m_Z = 95.2 \pm 2.5$ GeV
- Original publication: Phys. Lett. B126 (1983) 398

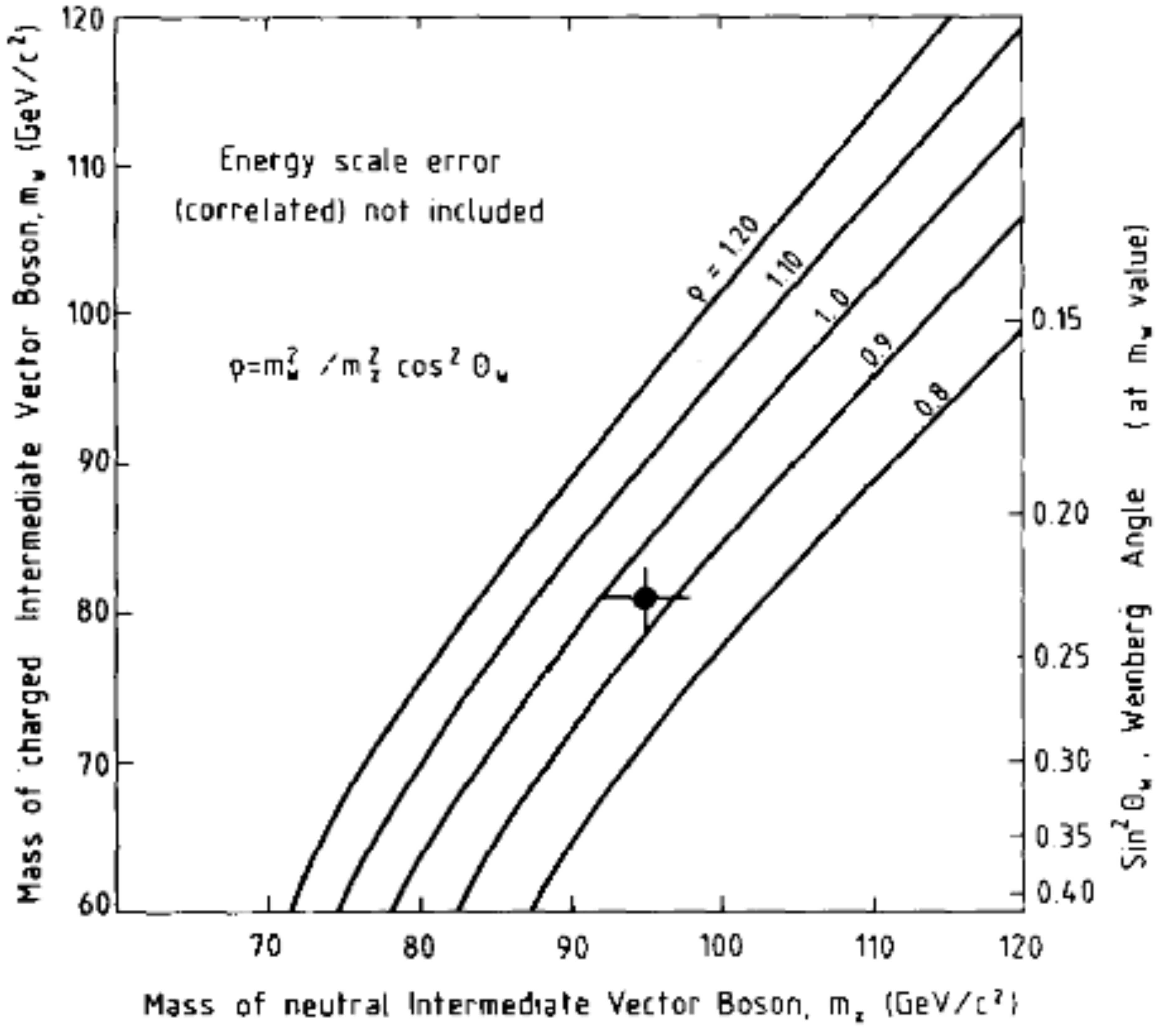


Consistency of the Standard model

- With Gargamelle and the UA1 and UA2 results:
  Consistency checks of the SM

$$m_Z^2 = \frac{m_W^2}{\rho \cos^2\theta_W} \rightarrow \rho = 1?$$

$$\rho = 0.94 \pm 0.06$$



Nobel prize

Prize motivation: “for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction”

Source: https://www.nobelprize.org/prizes/physics/1984/meer/facts/

Simon van der Meer

Born: 24 November 1925, the Hague, the Netherlands

Died: 4 March 2011, Geneva, Switzerland

Carlo Rubbia

Born: 31 March 1934, Gorizia, Italy

Source: https://www.nobelprize.org/prizes/physics/1984/rubbia/facts/

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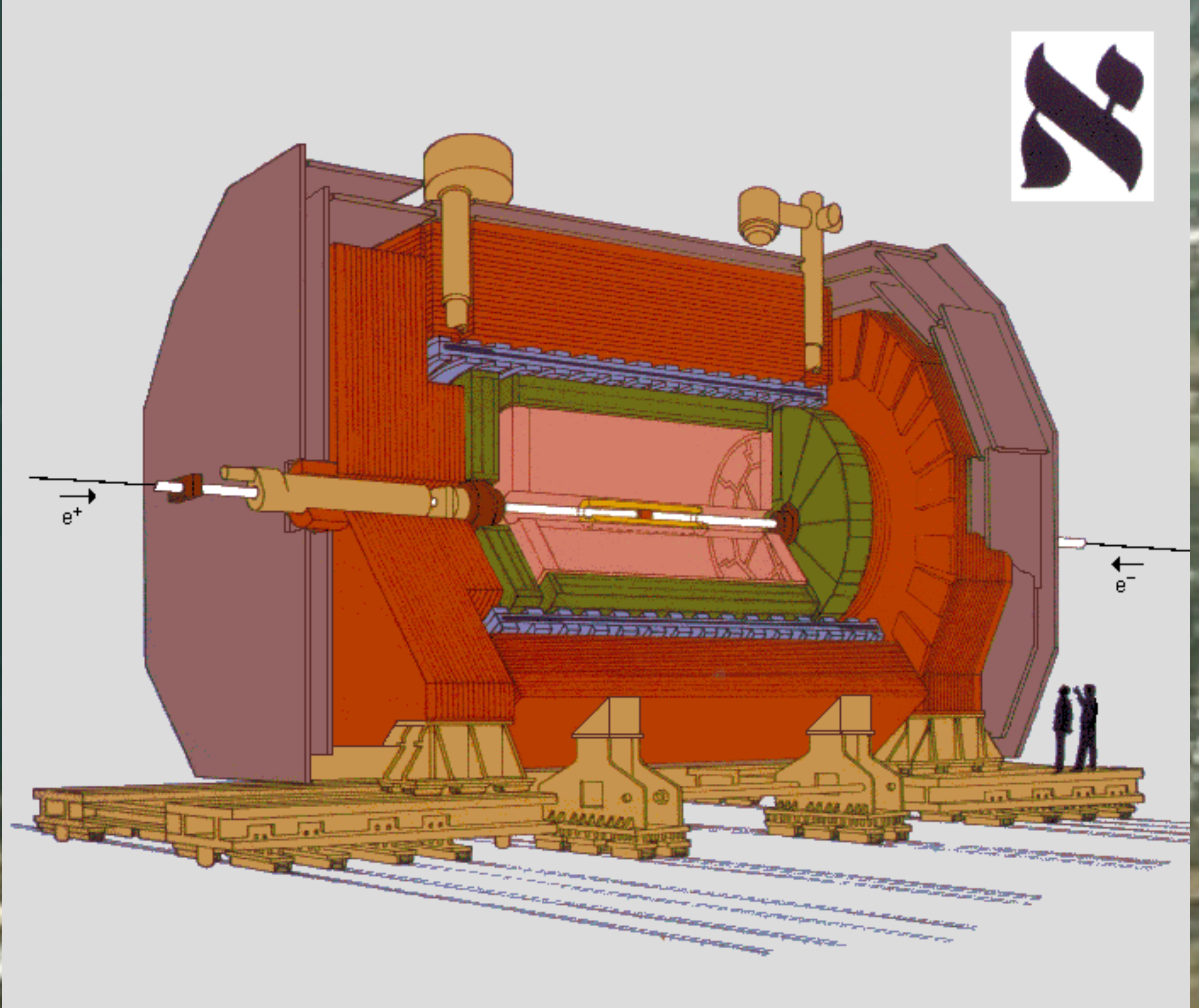
Z factories

- 2 projects to produce Z bosons in **large amounts:** ("Z factories"):
- e^+e^- collider with $\sqrt{s} = m_Z \approx 91$ GeV („at the Z pole")
- 5 experiments: hermetic 4π detectors

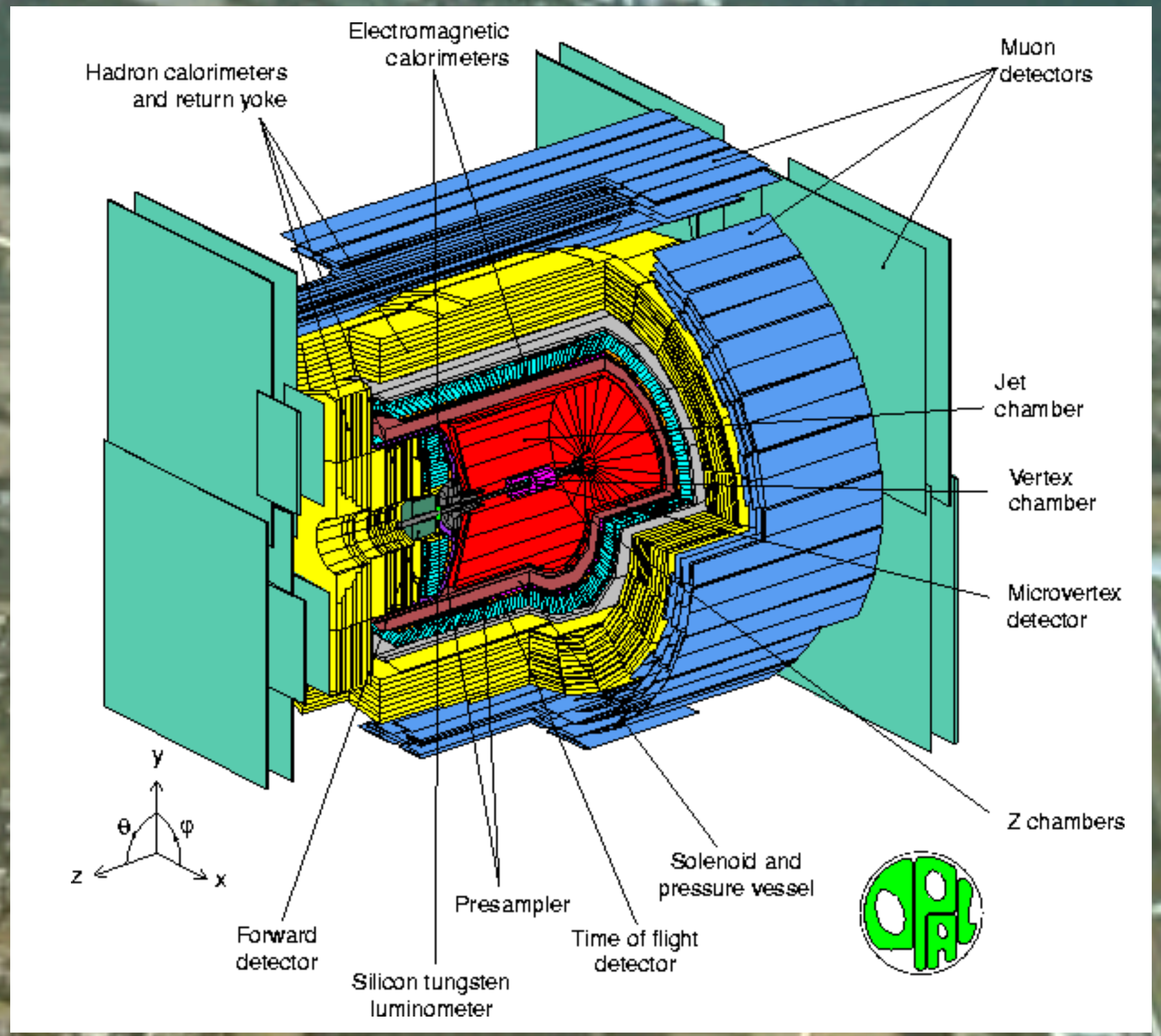
	LEP	**SLC**
data taking	LEP 1(1989-1995) 91 GeV	Unpolarized (1989-1991)
	LEP 2 (1996-2000) 160-207 GeV	Polarized (1989-1998)
accelerator	circular	linear
experiments	ALPEH, OPAL, DELPHI, L3	Mark II (until 1991) SLD (1992-1998)
# of Z-bosons	17M	0.6M

LEP: Large electron positron collider at CERN

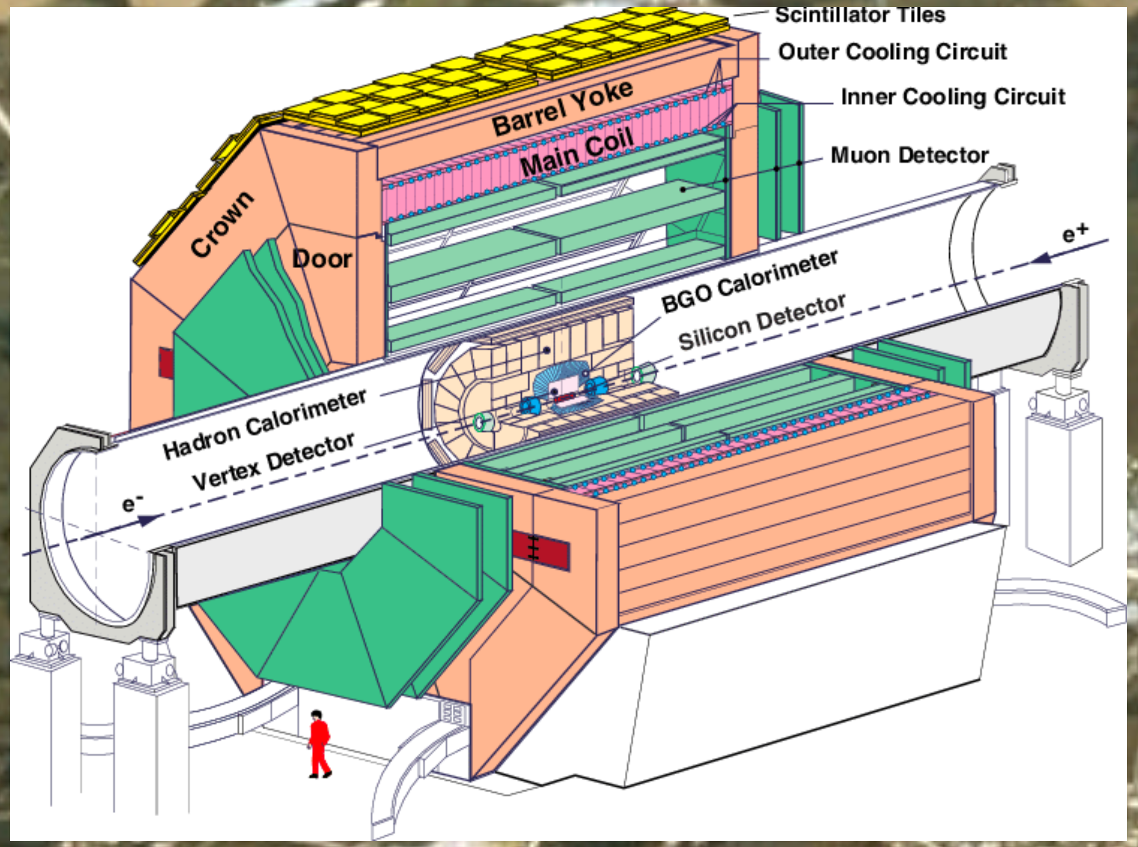
ALEPH Experiment



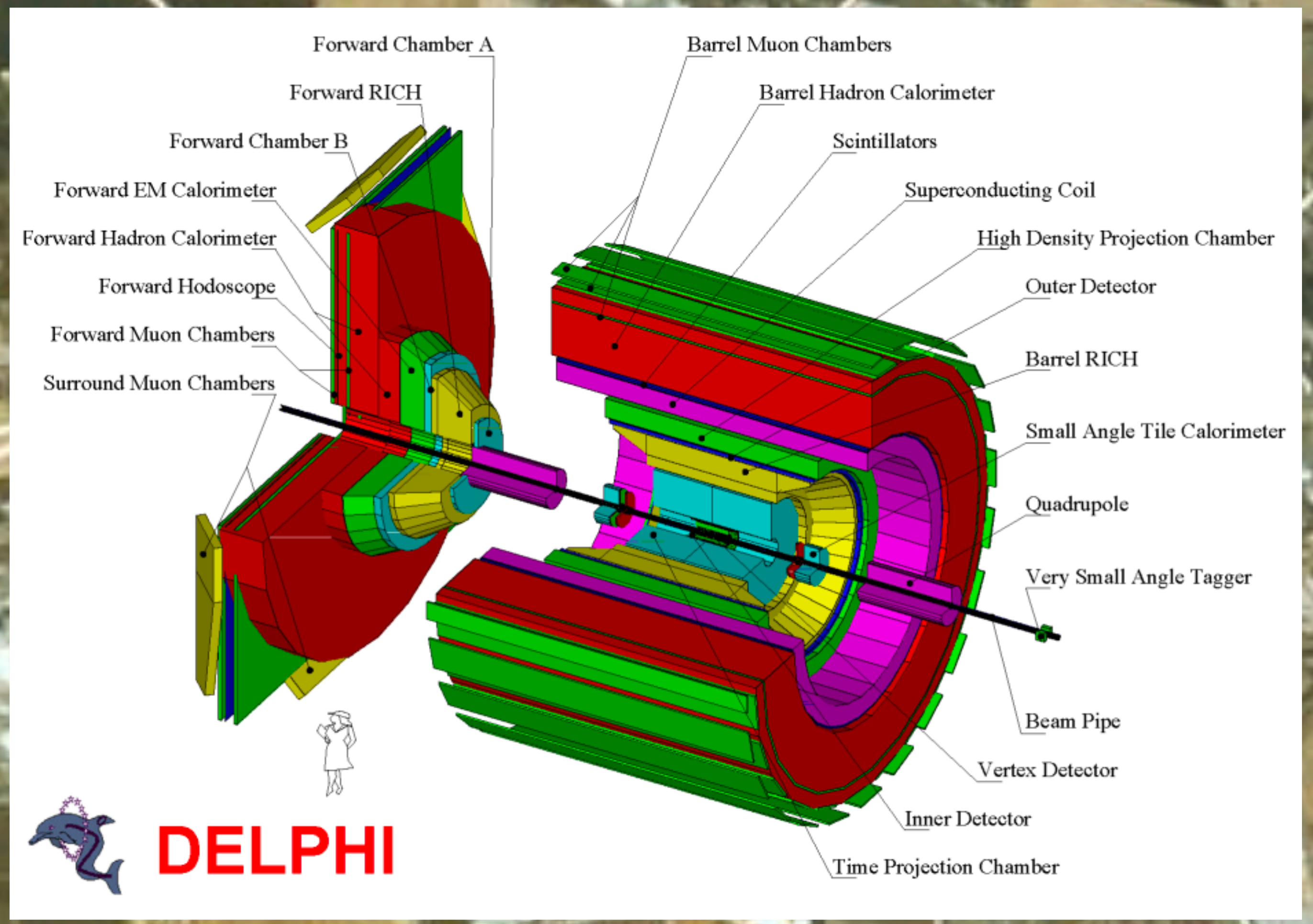
OPAL Experiment



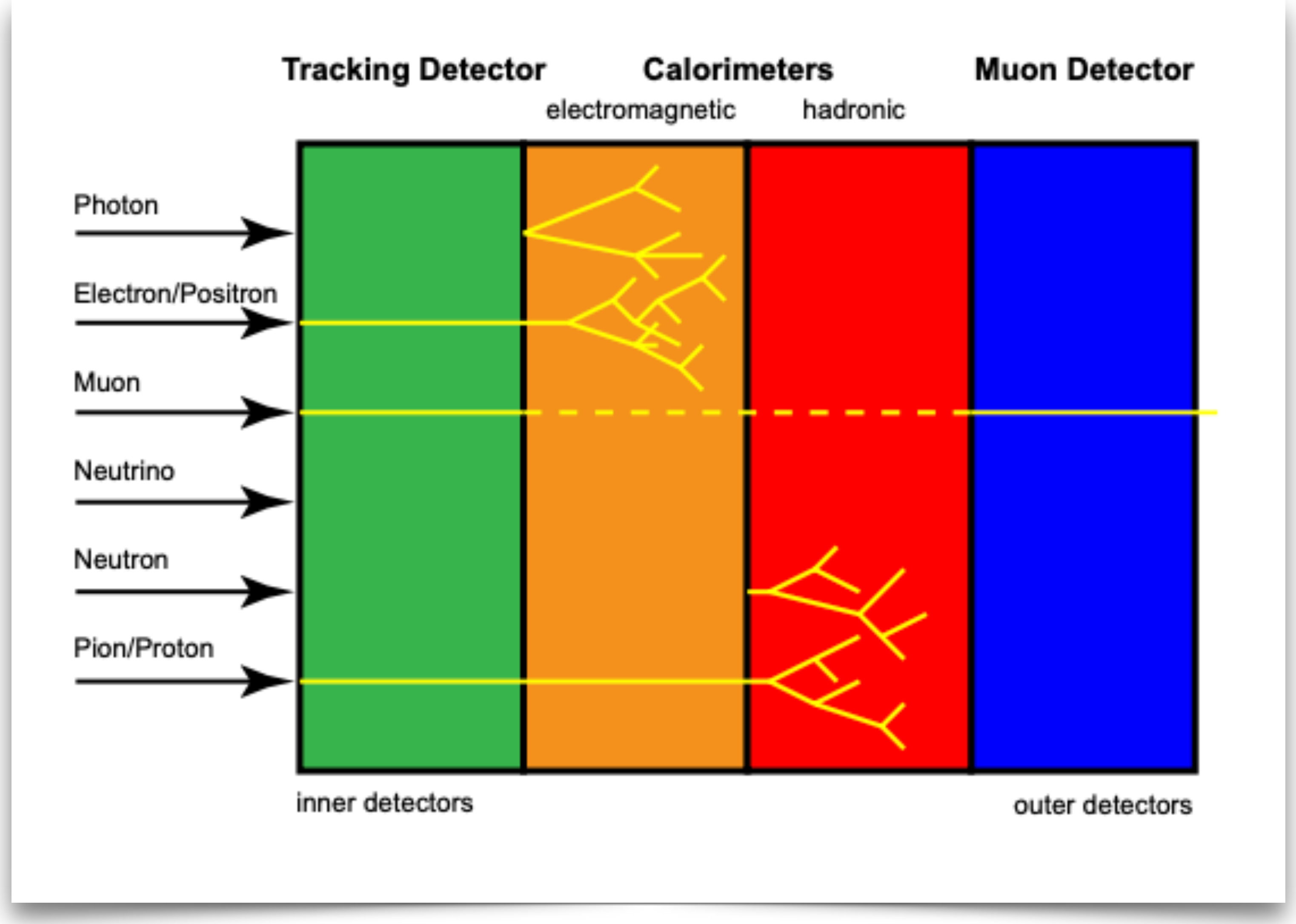
L3 Experiment

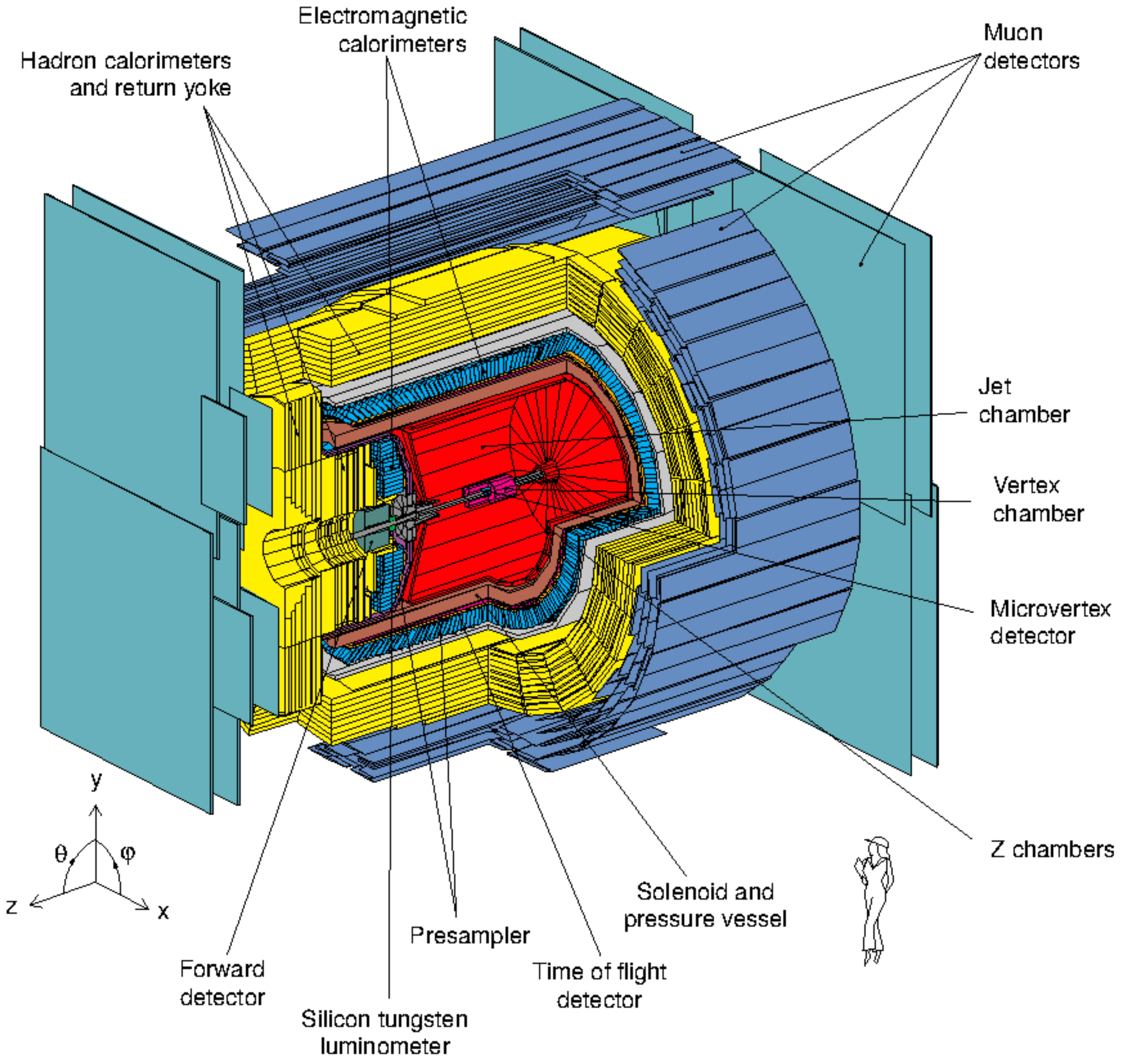


DELPHI Experiment

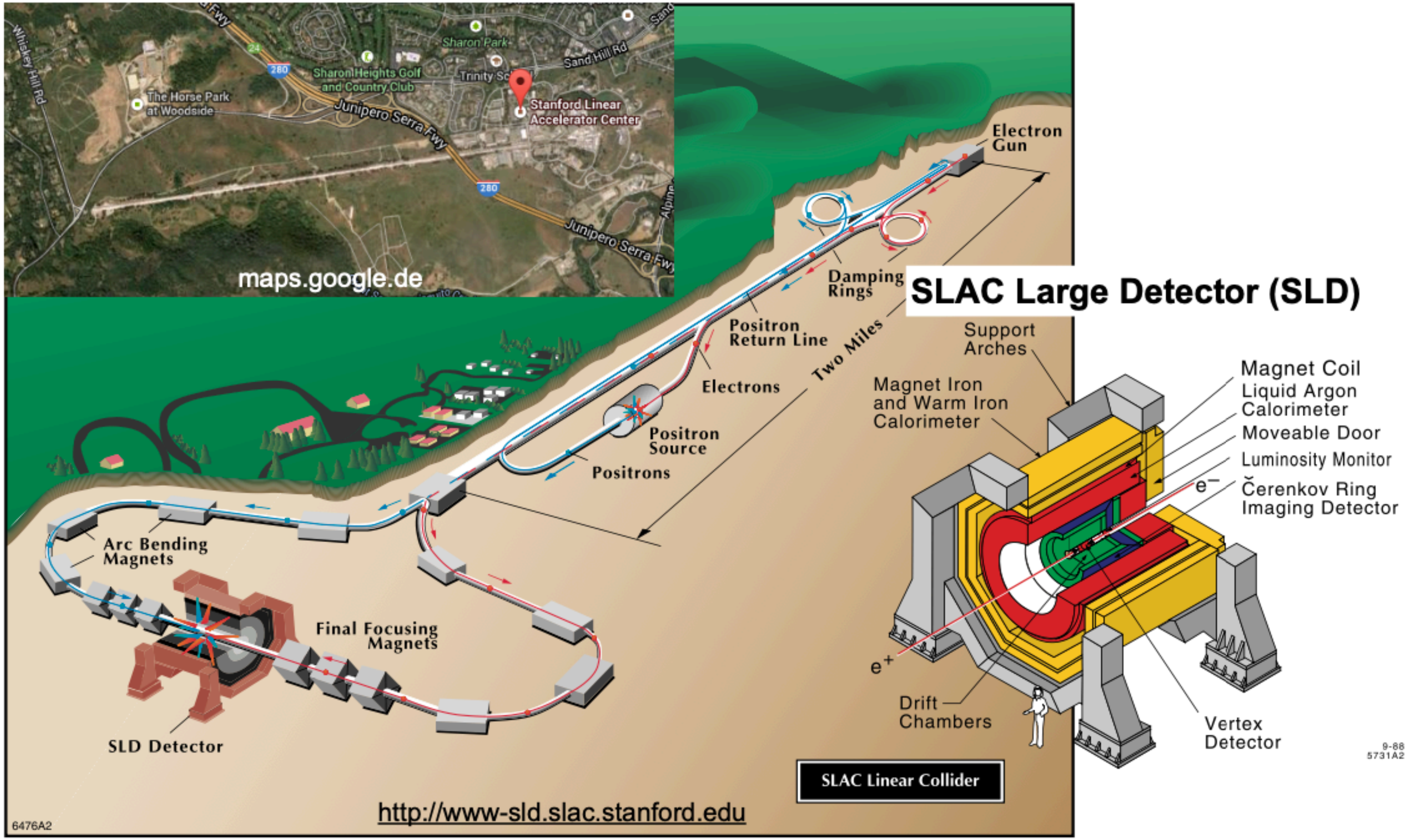


Example: OPAL





SLC: Stanford linear collider at SLAC



What questions do you have?