V4 – Theoretical basics II, W mass

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Classical mechanics

- **All information of a physical system is contained in the action**

$$S = \int \mathrm{d}t \, L(\vec{q}, \dot{\vec{q}}, t)$$

$\vec{q}$ generalised coordinates

Lagrange function L: $L = T - U = (E_{\mathrm{kin}} - E_{\mathrm{pot}})$

- **Equations of motion from principle of stationary action, dS = 0:**

$$\frac{d}{\mathrm{d}t} \frac{\partial L}{\partial(\partial \dot{q}_i)} - \frac{\partial L}{\partial q_i} = 0$$

Euler-Lagrange equations

Lagrange formalism

Relativistic quantum mechanics

- **All information is contained in the action integral**

$$\mathrm{S} = \int \mathrm{dt} \int \mathrm{d}^3 x \mathcal{L}(\phi(x), \partial_\mu \phi(x))$$

Field $\phi(x)$ here scalar:
Separate coordinate at each x
(generalisation of canonical coords.)

Lagrange density ('Lagrangian') : $\mathcal{L}$ $\quad T - U\|_{\delta x} \equiv (E_{\mathrm{kin}} - E_{\mathrm{pot}})|_{\delta x}$

- **Equations of motion from principle of stationary action, dS = 0:**

$$\partial_\mu \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi(x))} - \frac{\partial \mathcal{L}}{\partial \phi(x)} = 0$$

Euler-Lagrange equations

Lagrangian: Examples

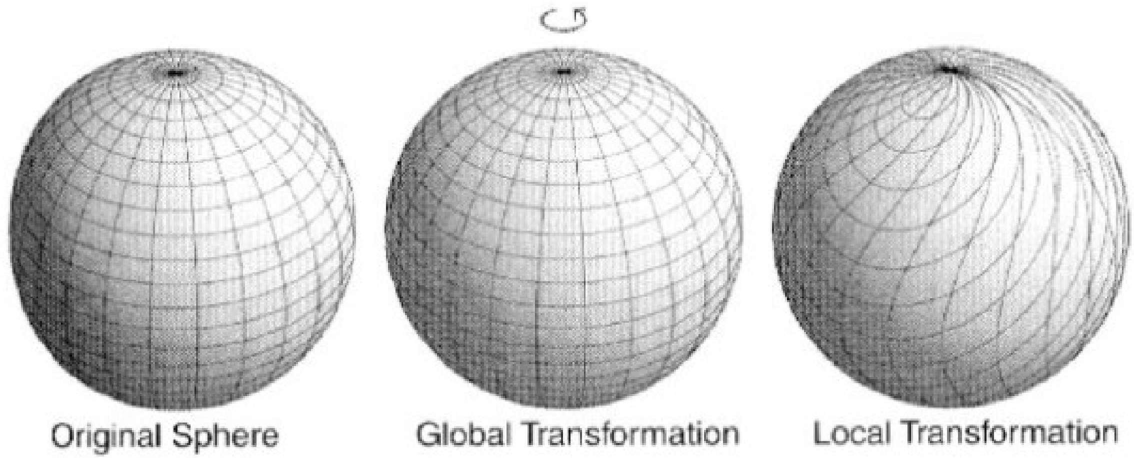
- **Lagrange densities for various fields of particles with mass m**

field	Lagrange density $\mathcal{L}$	equation of motion
scalar field $\phi(x)$ $(S = 0)$	$\frac{1}{2}\left[(\partial_\mu\phi)(\partial^\mu\phi)^* - m^2\phi^2\right]$	Klein-Gordon eq.
fermion field $\psi(x)$ $(S = \frac{1}{2})$	$\overline{\psi}(i\gamma^\mu\partial_\mu - m)\psi$	Dirac eq.
vector field $A_\mu(x)$ $(S = 1)$	$-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m^2 A_\mu A^\mu$	Proca eq.

- $\mathcal{L}$ **has dimension GeV^{-1}**
- $\mathcal{L}$ **is a Lorentz scalar: Lorentz-invariant without 'free' indices μ**

Symmetries

- **Global and local symmetries**
  - **Global:** same everywhere
  - **Local:** varies with x



universe-review.ca

- **Example: quantum-mechanical phase**
  - **Global:** physics unchanged for $\psi(x) \to U\,\psi(x) = \exp[i\alpha]\,\psi(x)$
  - **Local:** physics unchanged for $\psi(x) \to U(x)\,\psi(x) = \exp[i\alpha(x)]\,\psi(x)$
- **Connection to group theory**
  - Continuous transformations $\psi(x) \to U\psi(x)$ form Abelian group U(1) under multiplication: Group of unitary transformations
  - Abelian group: U commute, i.e. $[U_i, U_j] = 0$

Global phase transformations

- **Lagrangians of fermions and bosons are invariant**
  - **Global: The phase α = const is the same for any space-time point x**

- **Example: Lagrangian of free fermions**

$$\psi(x) \rightarrow \psi^{'}(x) = e^{i\alpha}\psi(x)$$
$$\overline{\psi}(x) \rightarrow \overline{\psi}^{'}(x) = \overline{\psi}(x)e^{-i\alpha}$$

- **Proof**

$$\mathcal{L}^{'} = \overline{\psi}^{'}(i\gamma^{\mu}\partial_{\mu} - m)\psi^{'}$$
$$= \overline{\psi}e^{-i\alpha}(i\gamma^{\mu}\partial_{\mu} - m)e^{i\alpha}\psi$$
$$= \overline{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi = \mathcal{L}$$

Local phase transformations

- **Let's allow different phases at each point in space-time … α = α(x)?**

  → physics still should stay invariant!

taken from A. Quandt

Local phase transformations

- **But: Lagrangian is NOT invariant under local phase transformations α = α(x)!**

$$\psi(x) \rightarrow \psi'(x) = e^{i\alpha(x)}\psi(x)$$

$$\overline{\psi}(x) \rightarrow \overline{\psi}'(x) = \overline{\psi}(x)e^{-i\alpha(x)}$$

- **Proof:**

$$\mathcal{L}' = \overline{\psi}'(i\gamma^\mu\partial_\mu - m)\psi'$$

$$= \overline{\psi}e^{-i\alpha(x)}(i\gamma^\mu\partial_\mu - m)e^{i\alpha(x)}\psi$$

$$= \overline{\psi}(i\gamma^\mu(\partial_\mu + i\partial_\mu\alpha(x)) - m)\psi \neq \mathcal{L}$$

Covariant derivative

- **Invariance can be restored at the cost of introducing artificially the covariant derivative $\partial_\mu \rightarrow D_\mu = \partial_\mu + iqA_\mu$ and an additional gauge field A_μ with transformation behaviour:**

$$\psi(x) \rightarrow \psi^{'}(x) = e^{i\alpha(x)}\psi(x)$$

$$\overline{\psi}(x) \rightarrow \overline{\psi}^{'}(x) = \overline{\psi}(x)e^{-i\alpha(x)}$$

$$A_\mu(x) \rightarrow A^{'}_\mu(x) = A_\mu(x) - \frac{1}{q}\partial_\mu\alpha(x)$$

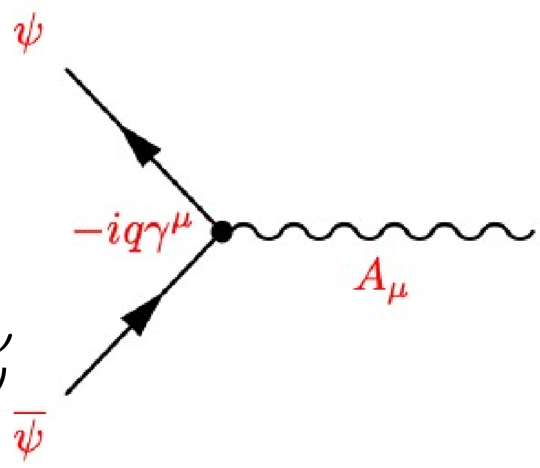
- **Proof:**

$$\begin{aligned}
\mathcal{L}^{'} &= \overline{\psi}^{'}(i\gamma^\mu D^{'}_\mu - m)\psi^{'} \\
&= \overline{\psi}^{'}(i\gamma^\mu \left(\partial_\mu + iqA^{'}_\mu\right) - m)\psi^{'} \\
&= \overline{\psi}e^{-i\alpha(x)}(i\gamma^\mu (\partial_\mu + iqA_\mu - i\partial_\mu\alpha(x)) - m)e^{i\alpha(x)}\psi \\
&= \overline{\psi}(i\gamma^\mu (\partial_\mu + i\partial_\mu\alpha(x) + iqA_\mu - i\partial_\mu\alpha(x)) - m)\psi \\
&= \overline{\psi}(i\gamma^\mu D_\mu - m)\psi = \mathcal{L}
\end{aligned}$$

The “artificial” gauge field

- Covariant derivative introduces gauge field A_μ
- Allows arbitrary phase α(x) of ψ(x)
  - Gauge field transports phase information from x to x’ (no instantaneous information exchange)
- A_μ couples to property q of spinor field ψ(x)
  - q can be identified with electric charge

$$\mathcal{L} = \overline{\psi}(i\gamma^\mu D_\mu - m)\psi$$
$$\rightarrow \underbrace{\overline{\psi}(i\gamma^\mu \partial_\mu - m)\psi}_{\text{free fermion}} - \underbrace{q(\overline{\psi}\gamma^\mu\psi)A_\mu}_{\text{interaction}} - \underbrace{\tfrac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\text{photon}}$$



- A_μ can be identified with photon field
- Dynamics of A_μ given by $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu = \frac{i}{q}[D_\mu, D_\nu]$

$\mathrm{L_{kin}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$ → Proca equation for massless vector boson

Lagrange density of QED

- **Postulation of local U(1) gauge symmetry → Lagrangian of QED**

$$\mathcal{L}_{\text{QED}} = \overline{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$= \underbrace{\overline{\psi}(i\gamma^\mu \partial_\mu - m)\psi}_{\text{free fermion}} - \underbrace{q(\overline{\psi}\gamma^\mu\psi)A_\mu}_{\text{interaction}} - \underbrace{\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\text{photon gauge field}}$$

- **Euler-Lagrange eq. for $\overline{\psi}$:** $\partial_\mu \frac{\partial\mathcal{L}}{\partial(\partial_\mu\overline{\psi})} - \frac{\partial\mathcal{L}}{\partial\overline{\psi}} = 0$

  - **Dirac equation for interacting fermion**

$$\rightarrow (i\gamma^\mu\partial_\mu - m)\psi = q\gamma^\mu A_\mu \psi$$

Lagrange density of QED

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- **Euler-Lagrange eq. for A_ν** $\quad \partial_\mu \frac{\partial\mathcal{L}}{\partial(\partial_\mu A_\nu)} - \frac{\partial\mathcal{L}}{\partial A_\nu} = 0$

$$\partial_\mu \frac{\partial\mathcal{L}}{\partial(\partial_\mu A_\nu)} = \partial_\mu F^{\mu\nu} = 0$$

$$\partial_\mu\left(\partial^\mu A^\nu - \partial^\nu A^\mu\right) = \left(\partial_\mu\partial^\mu A^\nu - \partial^\nu\partial_\mu A^\mu\right) = 0$$

$$\partial_\mu A^\mu = 0$$

Lorenz gauge

- **Proca equation for massless vector boson**

$$\to \left(\partial_\mu\partial^\mu - 0\right)A^\nu = 0$$

Lagrange density of QED

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- Electromagnetic interaction derived as a consequence of local gauge invariance
- Lagrangian must not have boson mass term $m^2 A_\mu A^\mu$
  - ➔ massive gauge bosons break local gauge invariance

Lagrange density $\rightarrow$ Observable?

- ***Process rate*** given by (cf. Fermi's gold rule)

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{|\text{matrix element}|^2}{\text{flux of incoming particles}} \cdot \text{phase space}$$

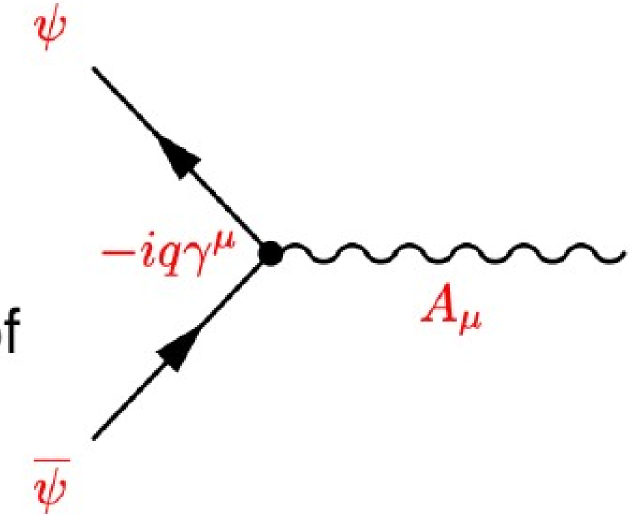
- ***Dynamics*** of process encoded in ***matrix element***
  - Element of scattering matrix that transforms initial state into outgoing state ('scattered wave')
- From Lagrange density: rules how to compute matrix element in perturbation theory $\rightarrow$ ***Feynman rules***
  - Graphical representation: ***Feynman graphs***

Perturbative series

- Process dynamics given by ***matrix element***

$$\mathcal{M}_{fi} = \psi_f^\dagger \psi_{\text{scat}} = \psi_f^\dagger \mathcal{S} \psi_i$$

  - ψ_f: final state after scattering of initial state ψ_i



- E.g. fermion scattering: ψ_{scat} given by solution of inhomogeneous Dirac equation

$$(i\gamma^\mu \partial_\mu - m)\psi_{\text{scat}} = -e\gamma^\mu A_\mu \psi_{\text{scat}}$$

  Cannot be solved analytically!

- Possible to ***expand solution*** in orders of coupling constant $\alpha \equiv e^2 \ll 1$

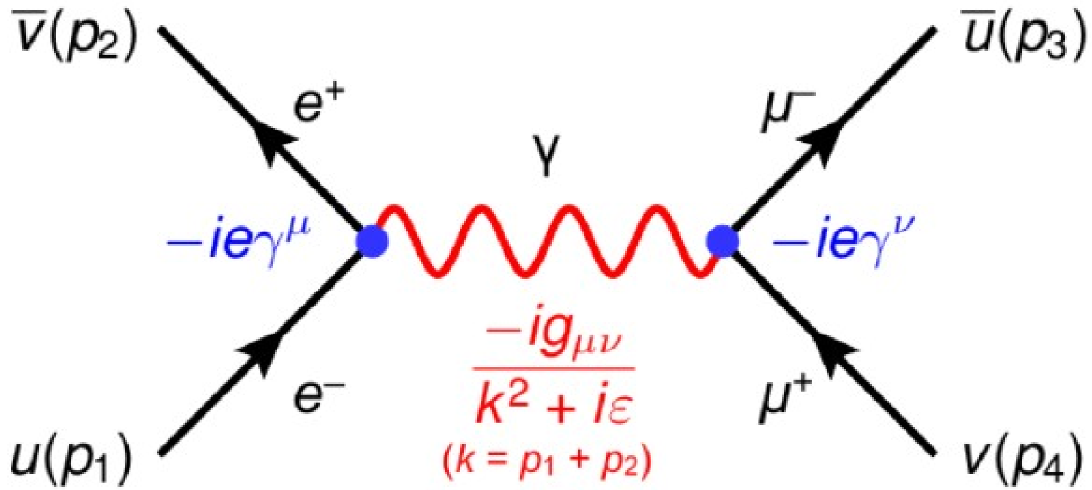
$$\psi_{\text{scat}} = \mathcal{S}\psi_i = \left[\sum_{n=0}^{\infty} \alpha^n S_n\right] \psi_i$$

  - Each term in ***perturbation series*** associated with distinct process
  - S_n can be computed with ***Feynman rules***

Feynman rules

- Elements of Feynman rules
  - External lines: incoming/outgoing particles
  - Vertices: coupling between particles
  - Propagators (=internal lines): exchange of virtual particles during scattering process (Green's function of free field equation in momentum space)

- For example, $e^+e^- \to \mu^+\mu^-$ scattering



$$\mathcal{M} = \overline{v}(p_2)(-ie\gamma^\mu)u(p_1)\frac{-ig_{\mu\nu}}{(p_1+p_2)^2+i\varepsilon}\overline{u}(p_3)(-ie\gamma^\nu)v(p_4)$$

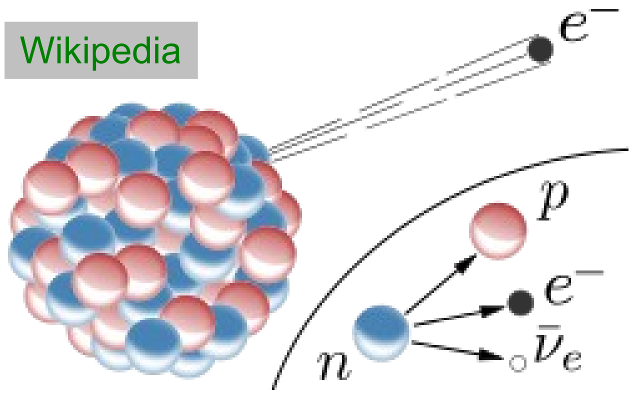
Summary

- Symmetries are a basic principle of physics
- Principle of local gauge invariance
  - Postulate of local gauge invariance of the Lagrange density
    → leads to interaction terms with gauge bosons as mediators
- QED: Symmetry under U(1) gauge transformation → photon exchange
- Cross section from Lagrange density
  - Fermi's golden rule:
    matrix element squared X phase space → cross section
  - Feynman rules:
    - set of rules how to calculate matrix elements
    - can be read off Lagrange density (at leading order …)
    - represented by Feynman graphs

Fermi's four-fermion coupling

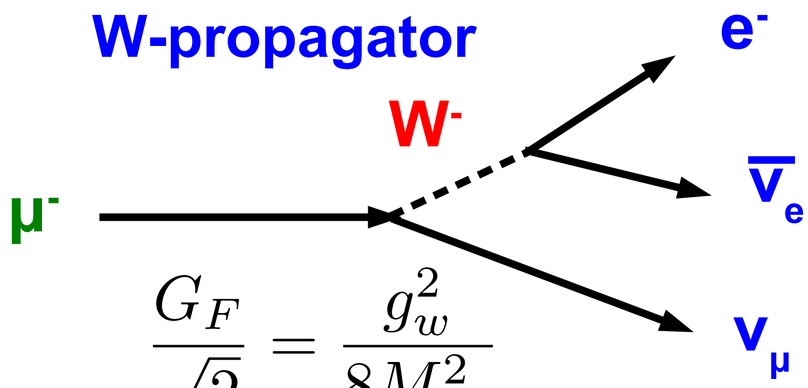
β-decay

Wikipedia



μ-decay

W-propagator



$$\frac{G_F}{\sqrt{2}} = \frac{g_w^2}{8M_W^2}$$

Modern interpretation as weak decays!

Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

Fermi, Z. Phys., 1934, 88, 16; Nuovo Cim., 1934, 11, 1

Weak interaction divergencies

Divergence #1: From Fermi's 4-fermion point-coupling

- **Coupling constant G_F has dimensions of 1/GeV^2** $G_F = 1.16639(2) \cdot 10^{-5} \mathrm{GeV}^{-2}$
- **Predicted cross section grows as** $\sigma \propto G_F^2 E_{\mathrm{cms}}^2 = G_F^2 \cdot s$
- **Violation of Froissart bound** $\sigma < \mathrm{const} \cdot \ln^2(s/[s])$

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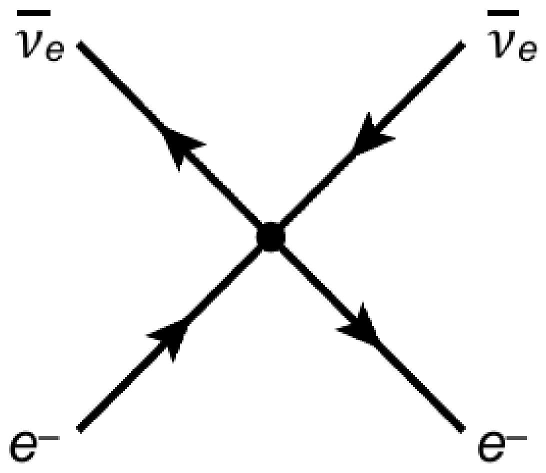
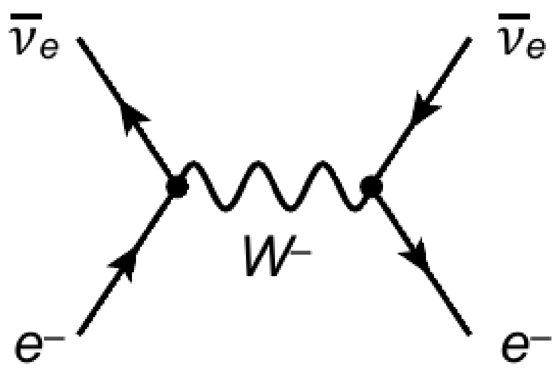
Solution: Exchange of massive vector bosons

$$m_V = O\left(1/\sqrt{G_F}\right) \approx 100\,\mathrm{GeV}$$



ev scattering as contact interaction



ev scattering with W propagator

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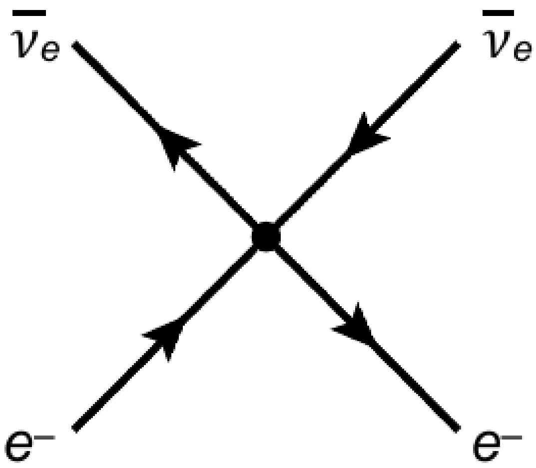

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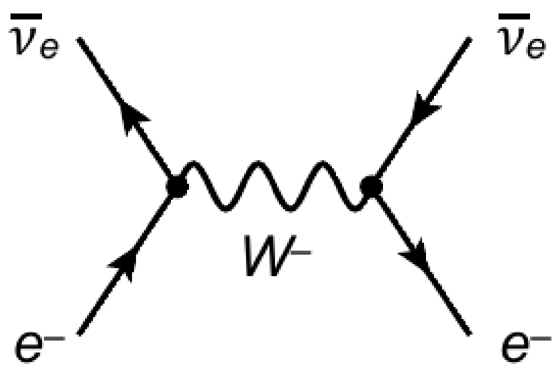

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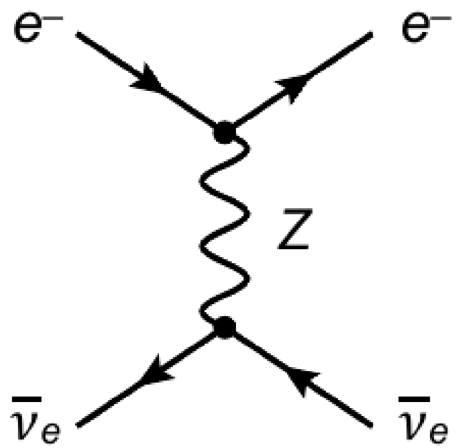
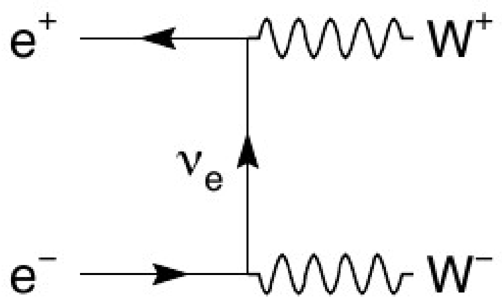


Attention: weak neutral currents!

Weak interaction divergencies

- **Divergence #2: WW pair production in V-A theory**
  - **Again predicted cross section grows too fast**
  - **Violation of unitarity (more WW produced than incoming ee flux)**



t-channel ν exchange

Weak interaction divergencies

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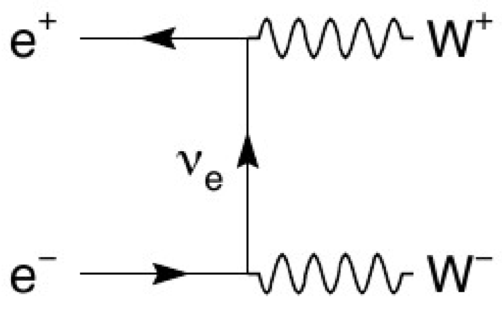
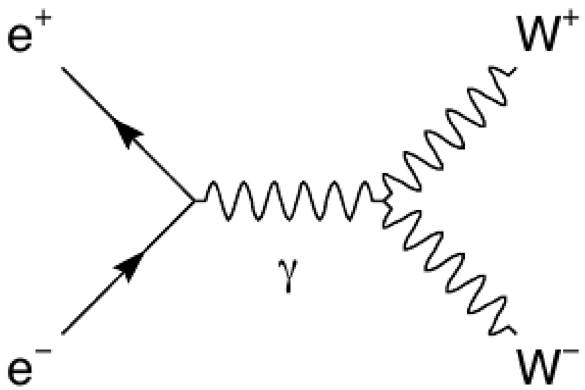
- **Solution 1: Trilinear coupling among W+, W-, and photon γ**
  - **Triple gauge coupling (TGC) γW^+W^-**
  - **But not sufficient!**



t-channel ν exchange



s-channel γWW TGC

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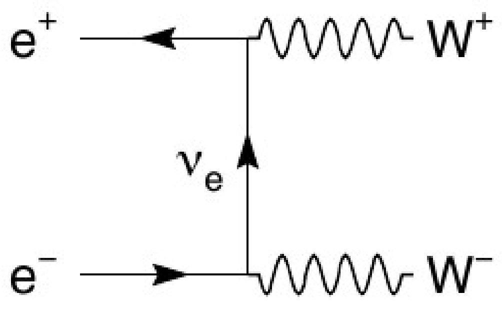
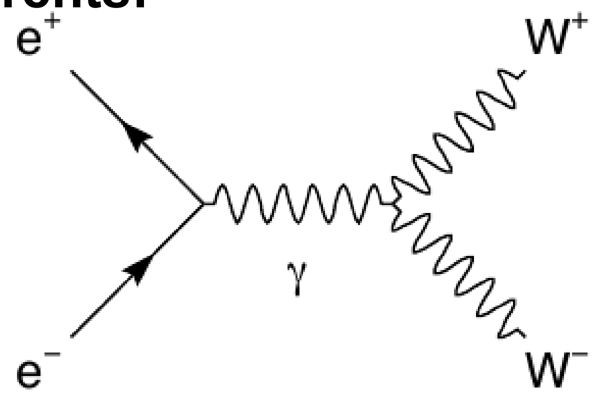
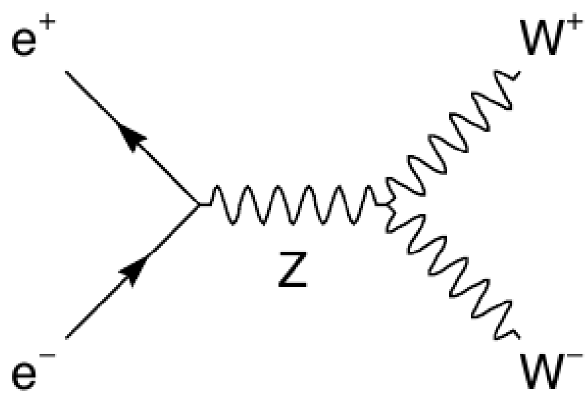
- **Solution 1: Trilinear coupling among W+, W-, and photon γ**
  - **Triple gauge coupling (TGC) γW^+W^-**
  - **But not sufficient!**
- **Solution 2: Trilinear coupling also with neutral massive boson Z**
  - **Triple gauge coupling ZW^+W^-**
  - **Again weak neutral currents!**



t-channel ν exchange



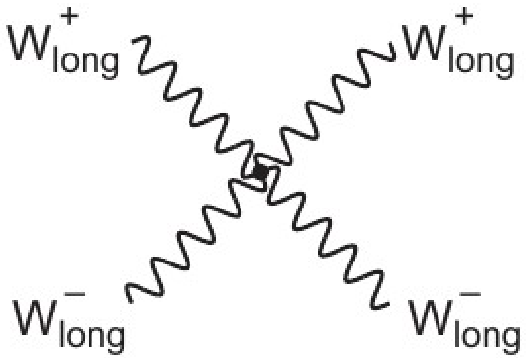
s-channel γWW TGC

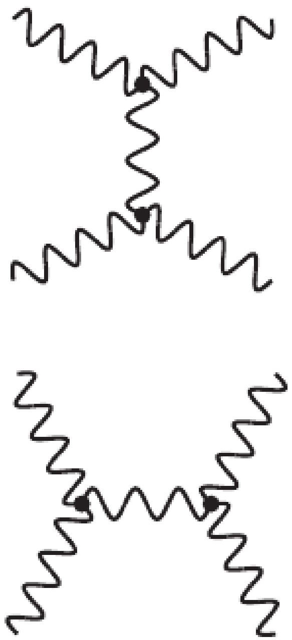


s-channel ZWW TGC

Divergence #3: Longitudinal scattering $W_L W_L \rightarrow W_L W_L$

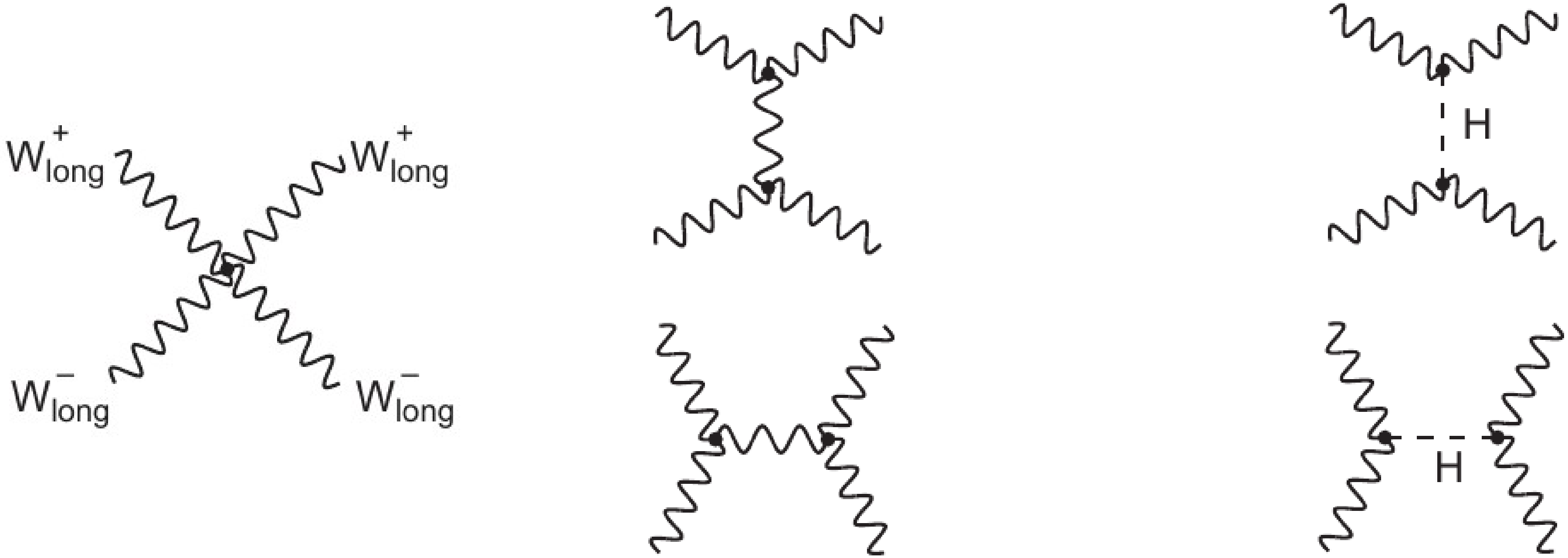
- **Again cross section grows too fast ...**





WW quartic and triple gauge boson couplings

- **Divergence #3: Longitudinal scattering $W_L W_L \rightarrow W_L W_L$**
  - **Again cross section grows too fast ...**
- **Solution: Additional scattering amplitudes with SCALAR boson**
  - **Indirect hint to existence of Higgs boson**

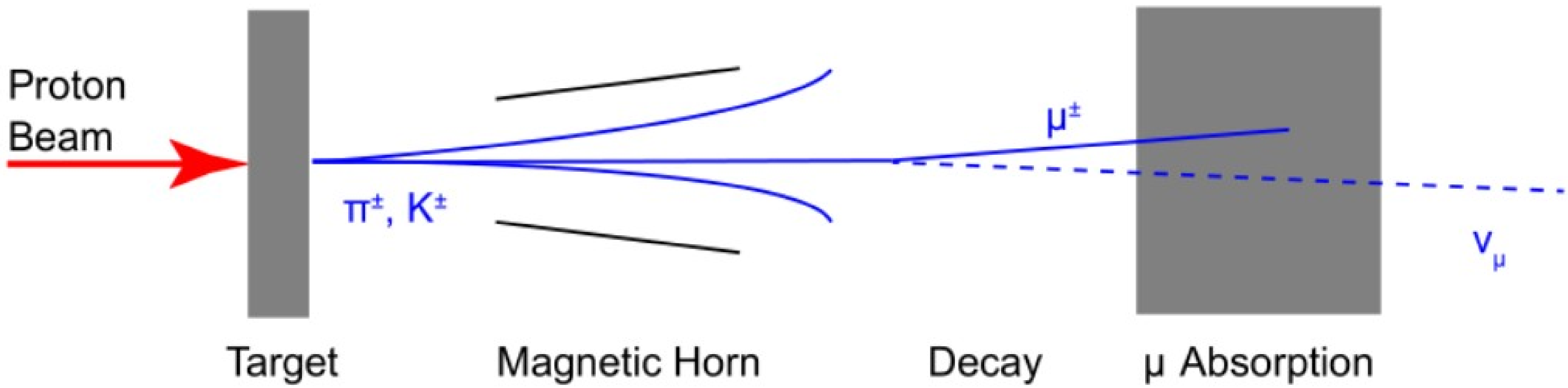


WW quartic and triple gauge boson couplings

Scalar boson exchanges

Search for neutral currents (NC)

- Strategy: interactions of neutrinos
  - No electromagnetic processes
  - Charged-particle scattering: huge background of electromagnetic processes $\rightarrow$ impossible
- CERN **neutrino beam** (since 1970)
  - Protons from CERN PS on target: **muon neutrinos**, e. g. $\pi^+ \rightarrow \mu^+ \nu_\mu$
  - Detection: **bubble chamber** experiment Gargamelle



Search for neutral currents (NC)

- **Historical perspective nicely described in article to celebrate the 50th anniversary of CERN**
  - **Theory developments until 1972: Great theory candidate for electroweak interactions → weak neutral currents (NC) must exist!**
  - **Previous ν experiments → no weak neutral currents!**
  - **Two ν experiments active but unprepared for NC:**
    - **Gargamelle at CERN (7 european labs incl. Aachen)**
    - **HPWF at Fermilab**
  - **Major challenge: Not designed for NC, events to be found in "background" category B of original measurement plan**
    - **Upstream ν reactions create neutrons entering chamber**
    - **Versus ν entering directly creating NC reaction**
  - **Discovery reported in 1973**
  - **HPWF: Disappearance of their signal after changing setup**
  - **Months of hard work to prove n background estimation ...**

D. Haidt in CERN Courier Vol. 44 no. 8, October 2004.

Gargamelle bubble chamber

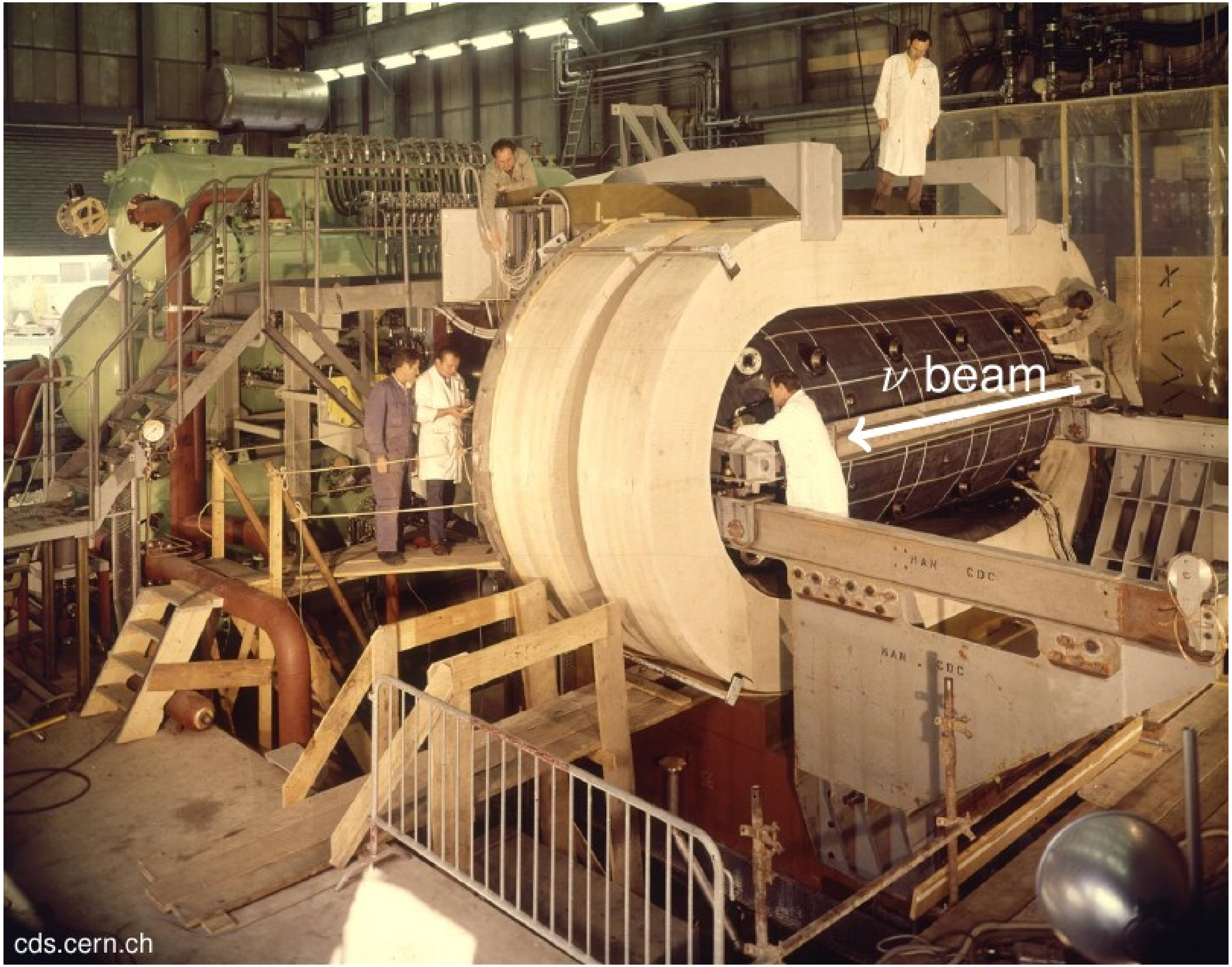


Table 1

	ν-exposure	$\bar{\nu}$-exposure
No. of neutral-current candidates	102	64
No. of charged-current candidates	428	148

Background modeling of neutron-initiated hadronic cascade tested with incident proton beam
→ proton-initiated hadronic cascades
→ established overshoot of NC events

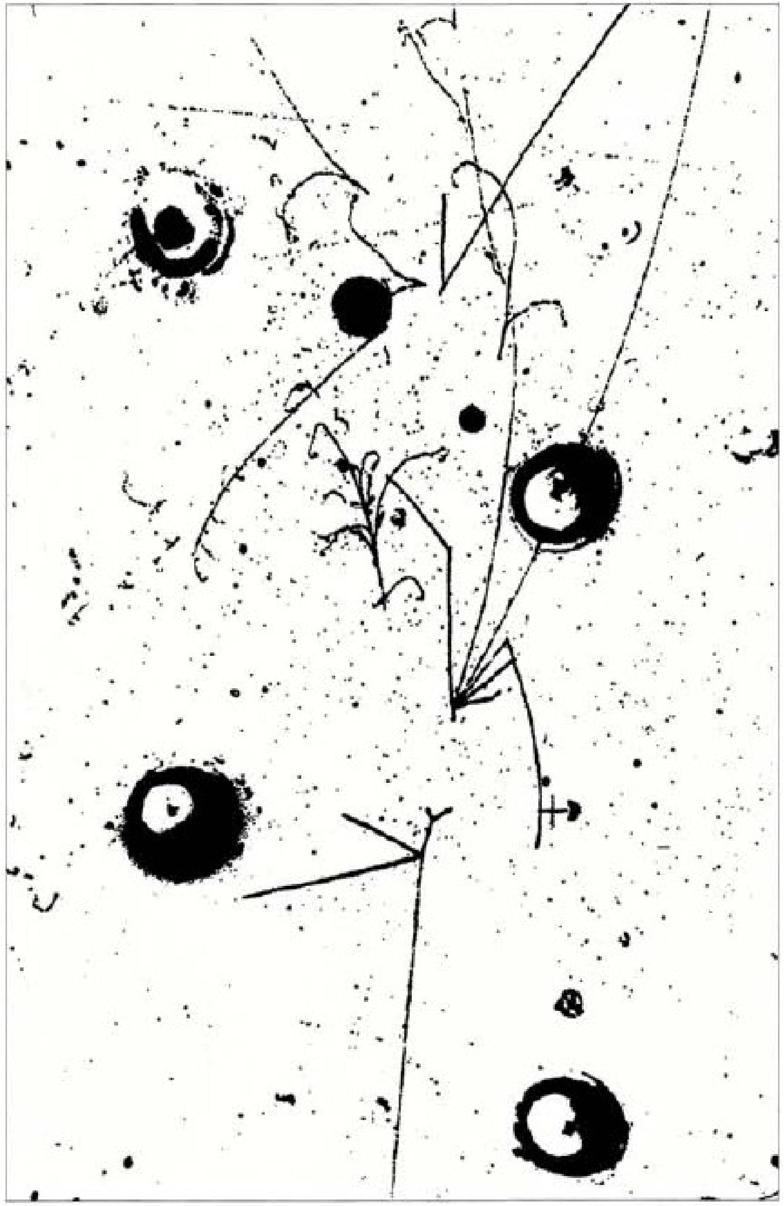
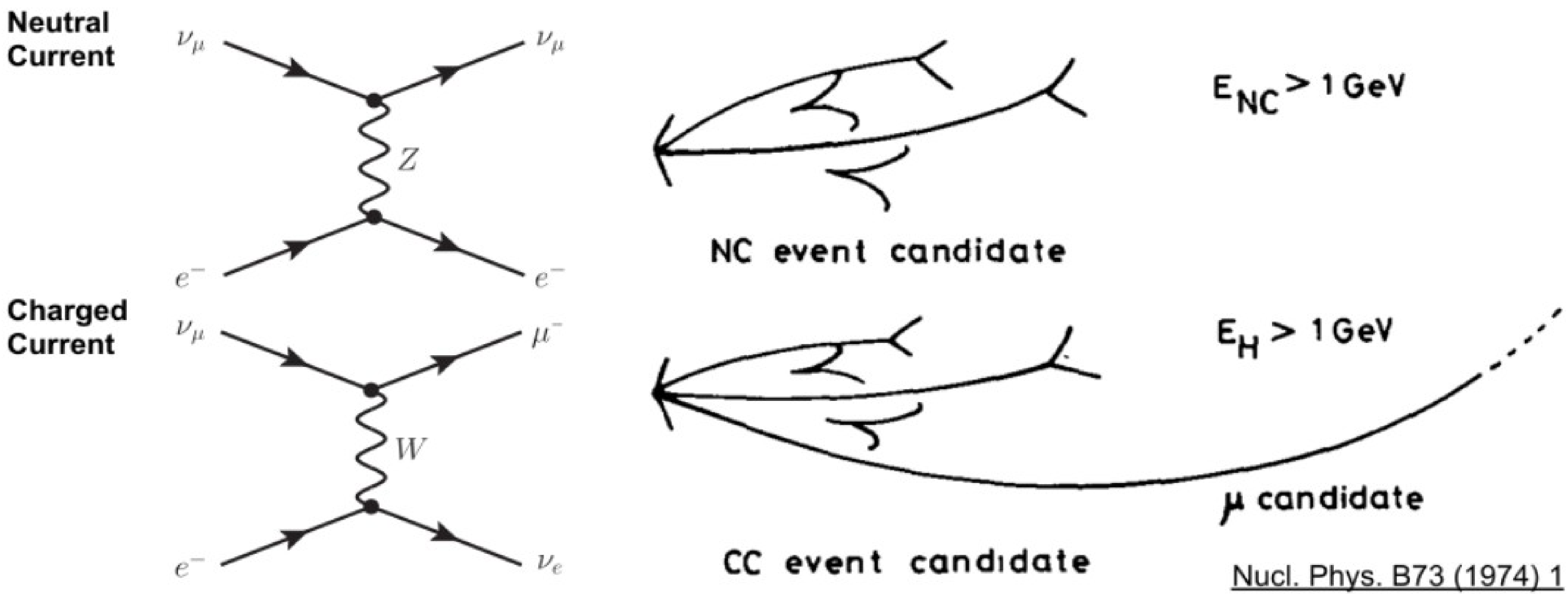


Fig. 3. A 7 GeV proton enters the Gargamelle bubble chamber from below and induces a three-step neutron cascade.

D. Haidt in CERN Courier Vol. 44 no. 8, October 2004.

Discovery of neutral currents

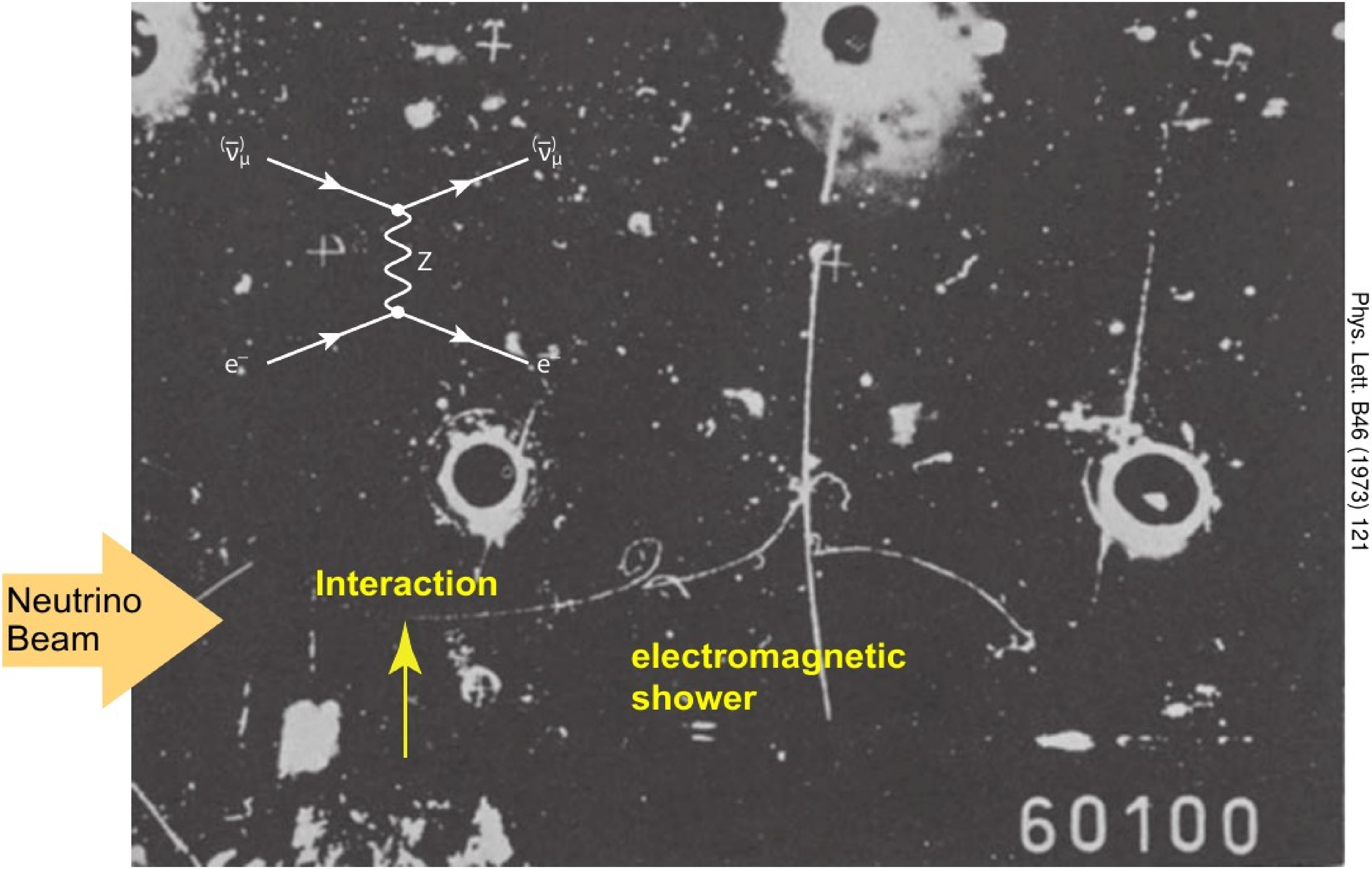
- Gargamelle: neutrino beam hits **heavy liquid** (freon)
- Neutrinos interact with **electrons** and atomic **nuclei**



Nucl. Phys. B73 (1974) 1

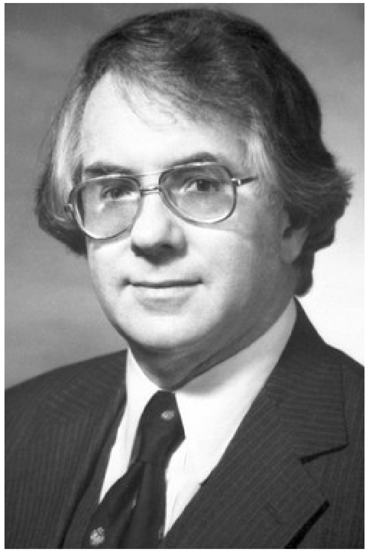
- **Neutral-current** interaction: scattered electron → electromagnetic shower (bremsstrahlung and e^+e^- production)
- **Charged-current** interaction: muon in final state → long track

νe neutral currents



No Nobel prize for experiment

But for theory: 1979



S. Glashow

A. Salam

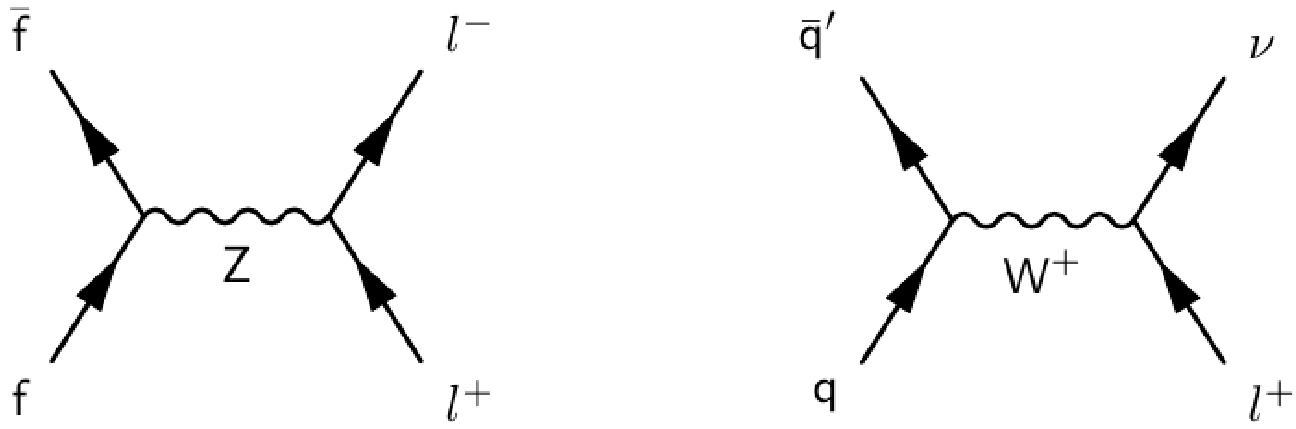
S. Weinberg

"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"

[nobelprize.org]

W and Z boson production

- **Production process**: lepton production in hadronic interactions ("Drell–Yan process")
- Requirement to produce **real W and Z bosons** at accelerators: E_{cms} of initial-state fermions at expected boson mass ($\approx 100\,\text{GeV}$)



- **Fixed-target** setup: $\sqrt{s} = \sqrt{2m_p E} \to E = 5\,\text{TeV} \to$ unrealistic
- **Electron-positron collider**: $\sqrt{s} = E_1 + E_2 \to 50\,\text{GeV}$ beam energy $\to$ technically feasible only from the 1990s, only Z production
- **Proton-antiproton collider**: W/Z production by annihilation of valence quark in proton and valence antiquark in antiproton

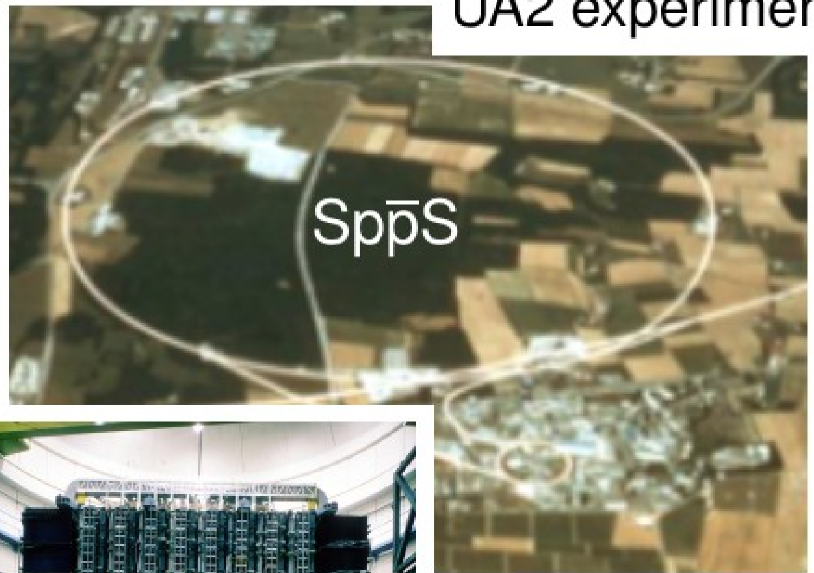
SppS collider at CERN

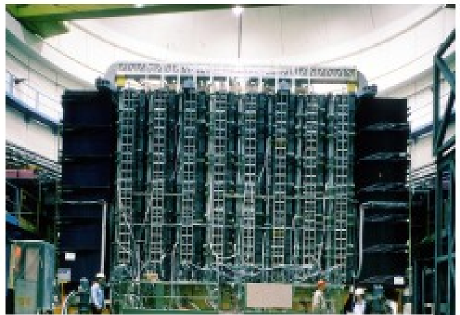
- $p\bar{p}$ collider reach
  - Momentum fractions of colliding valence (anti)quarks $x_1 \approx x_2 \approx 0.2$

  $\rightarrow$ estimated E_{cms}: $\sqrt{\hat{s}} \approx \sqrt{x_1 x_2 s} \stackrel{!}{=} 100\,\text{GeV} \rightarrow \sqrt{s} = 500\,\text{GeV}$
- SPS (Super Proton Synchrotron) at CERN
  - 6.9 km circumference
  - 400 GeV protons

  Idea (C. Rubbia, 1976): upgrade to a $p\bar{p}$ collider


UA2 experiment



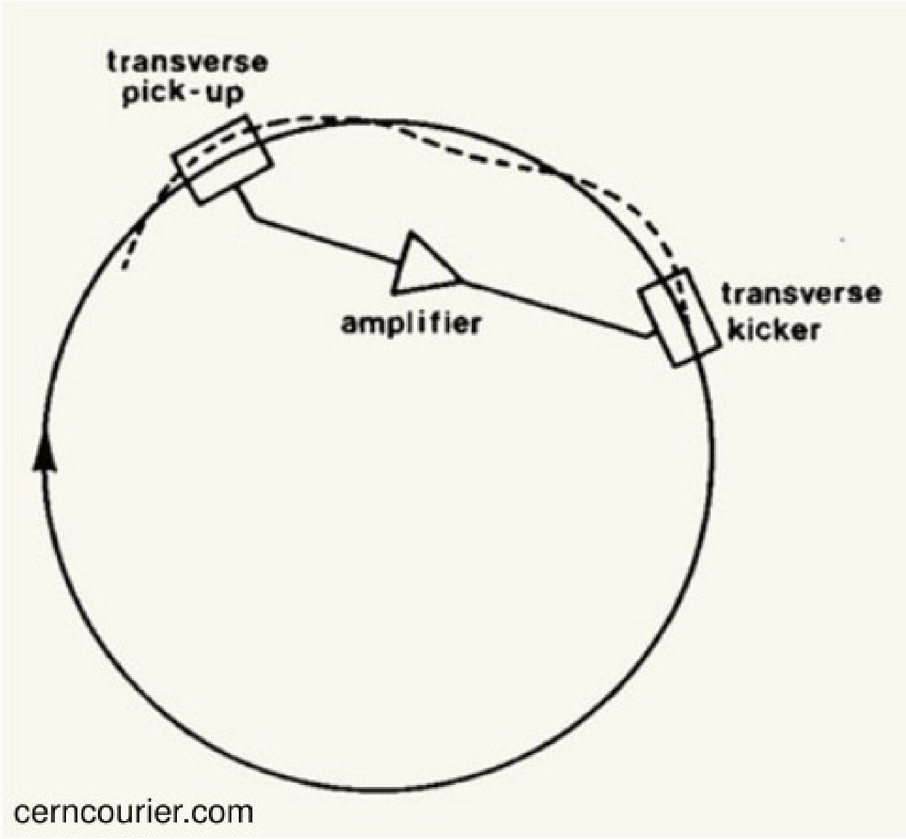

UA1 experiment

Sp$\bar{p}$S

- $E_{\text{cms}} = 540\,\text{GeV}$ initially, later upgrade to 630 GeV
- UA1 and UA2 experiments, data taking from 1981

SppS collider at CERN

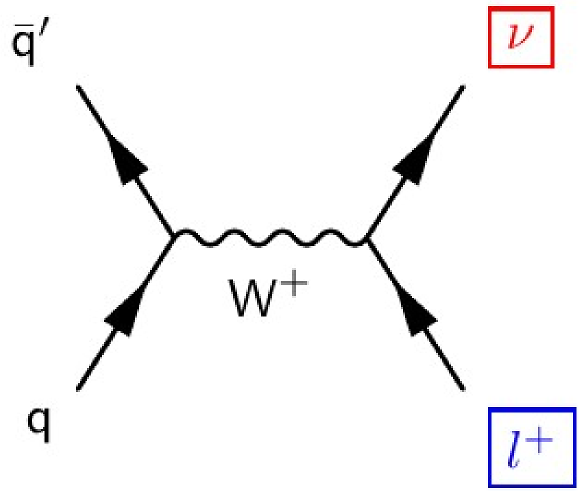
- **Antiprotons**
  - p beam on target: approximately 1 $\bar{p}$ in 10^9 final-state particles
  - Very large **emittance** of $\bar{p}$ beam: reduction without violating Liouville's theorem?
  - Solution (S. van der Meer, 1968): **stochastic cooling**[1] with pick-up and kicker
- Further challenges
  - p and $\bar{p}$ share **same beam pipe**
  - **Hermetic** 4π **detectors** for the first time at hadron colliders

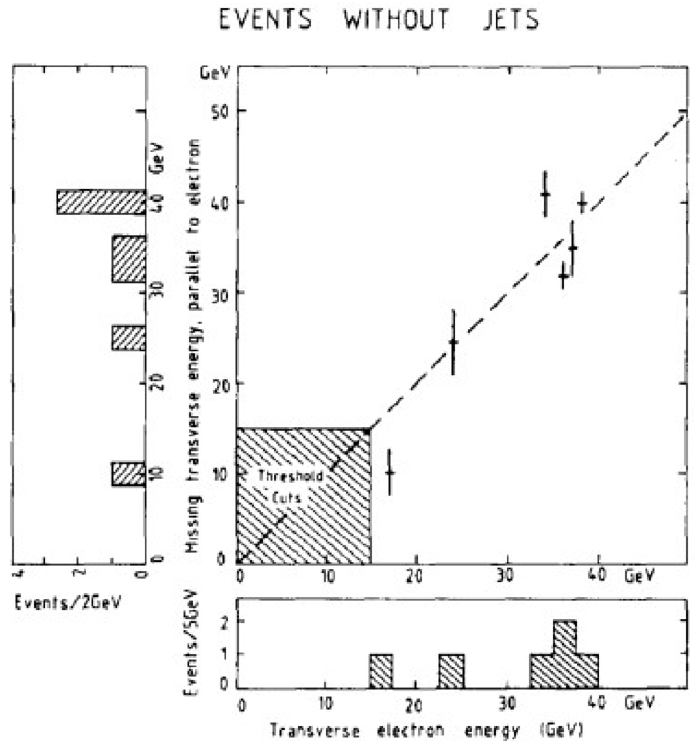


[1] Details e. g. Nucl. Instrum. Meth. A532 (2004) 11

Discovery of the W boson (1983)

- Process $p\bar{p} \to W \to l\nu$ ($l = e, \mu$)





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- Analysis strategy: charged lepton + $\not{E}_T$
  - **Charged lepton**: clean detector signature
  - Neutrino: **missing transverse momentum**

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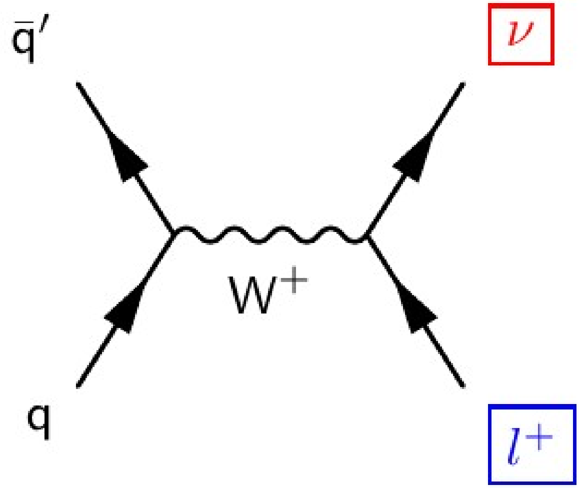

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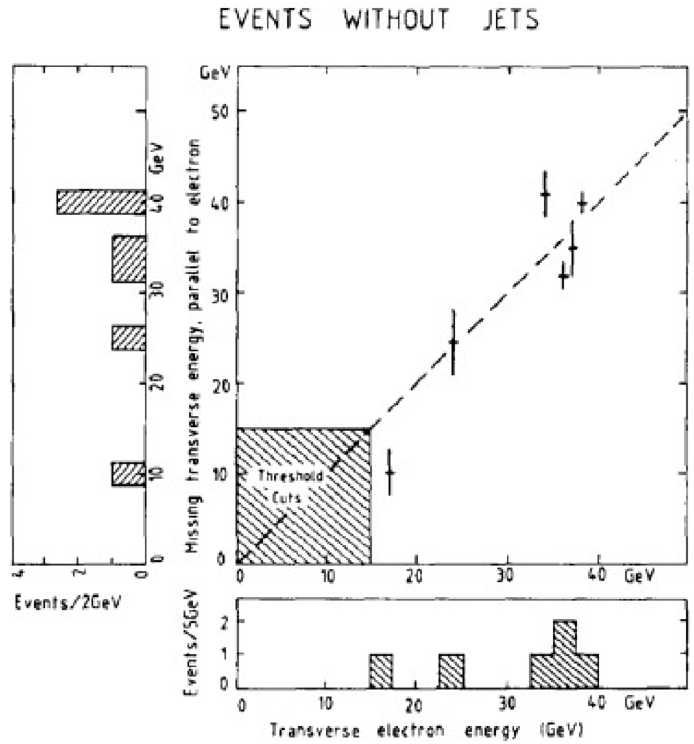
  - QCD jet production **background**: no preferred relative directions of lepton and $\not{E}_T$



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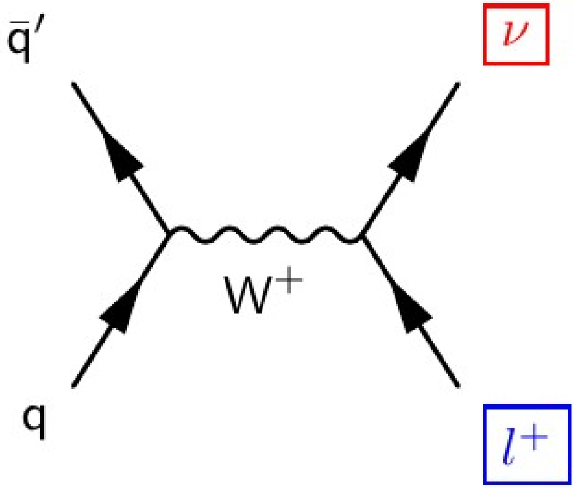

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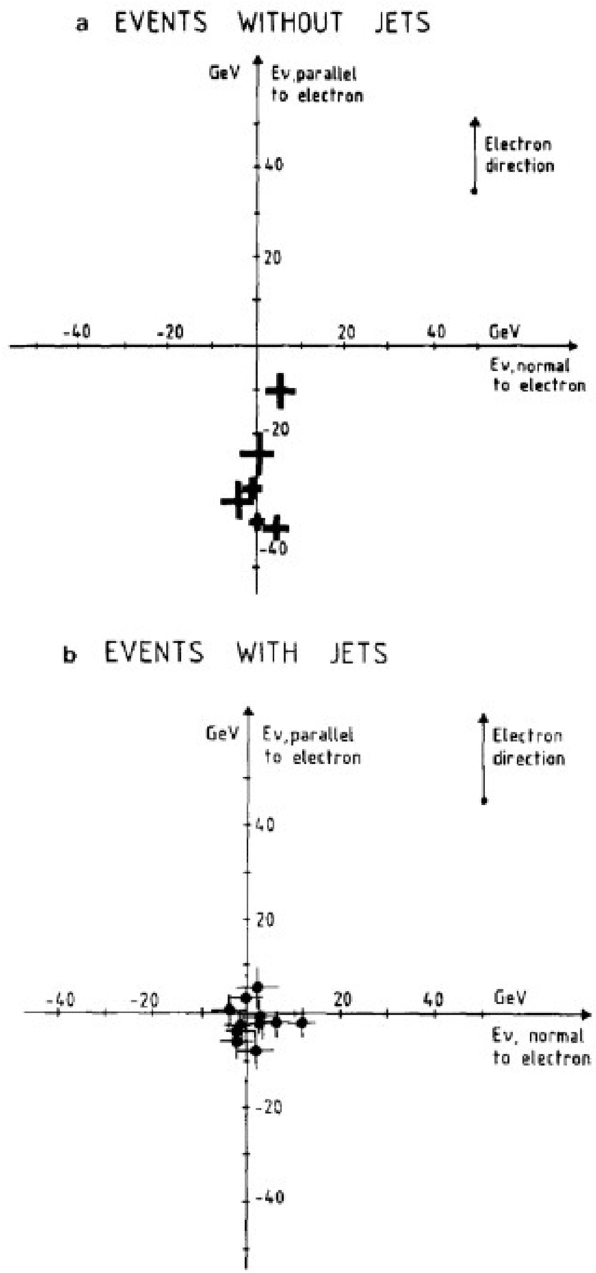

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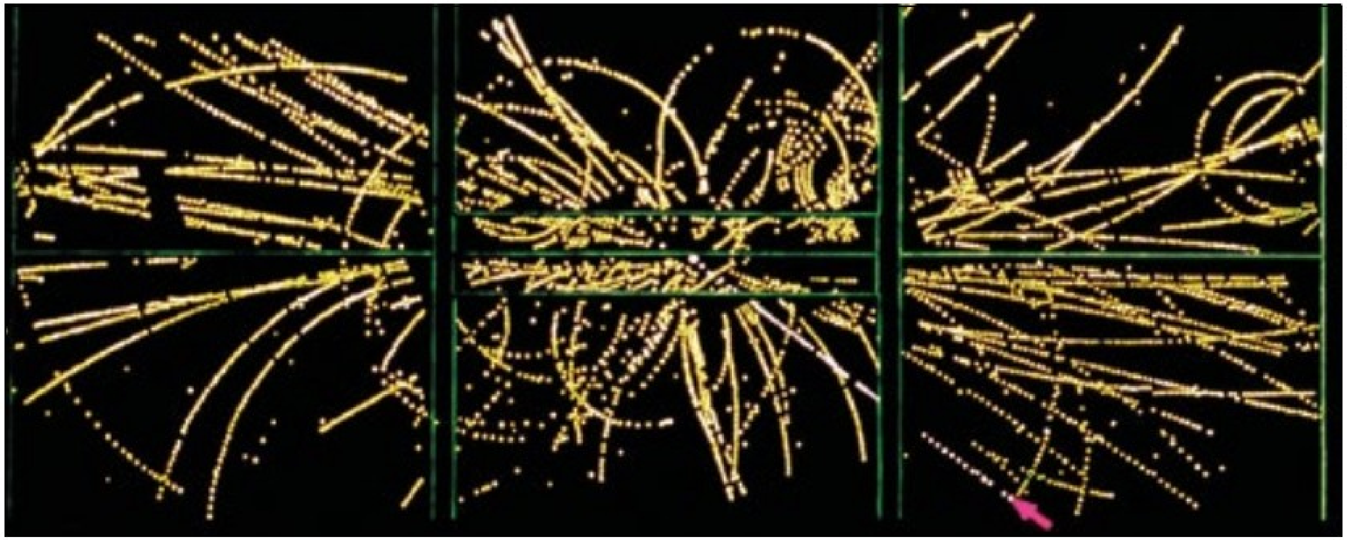
40th anniversary of W discovery

- **Again nice nistorical perspective in article to celebrate this year the 40th anniversary of W discovery at CERN**
  - **Must find charged and neutral weak bosons**
  - **C. Rubbia initiated SppS with second “p” really an anti-proton!**
  - **Two experiments: UA1 and UA2; January 1983: 4 and 6 candidates**
  - **No imaginable background**

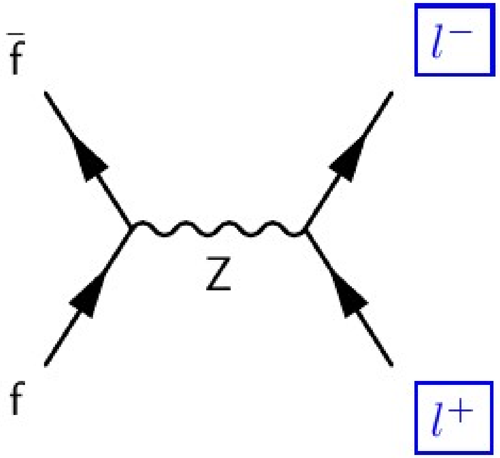


Striking *A W event recorded by UA1 in late 1982, with a high transverse-momentum electron (pink arrow) and only soft particles in opposite directions to it, as expected if an undetected neutrino balances the electron's transverse momentum.*

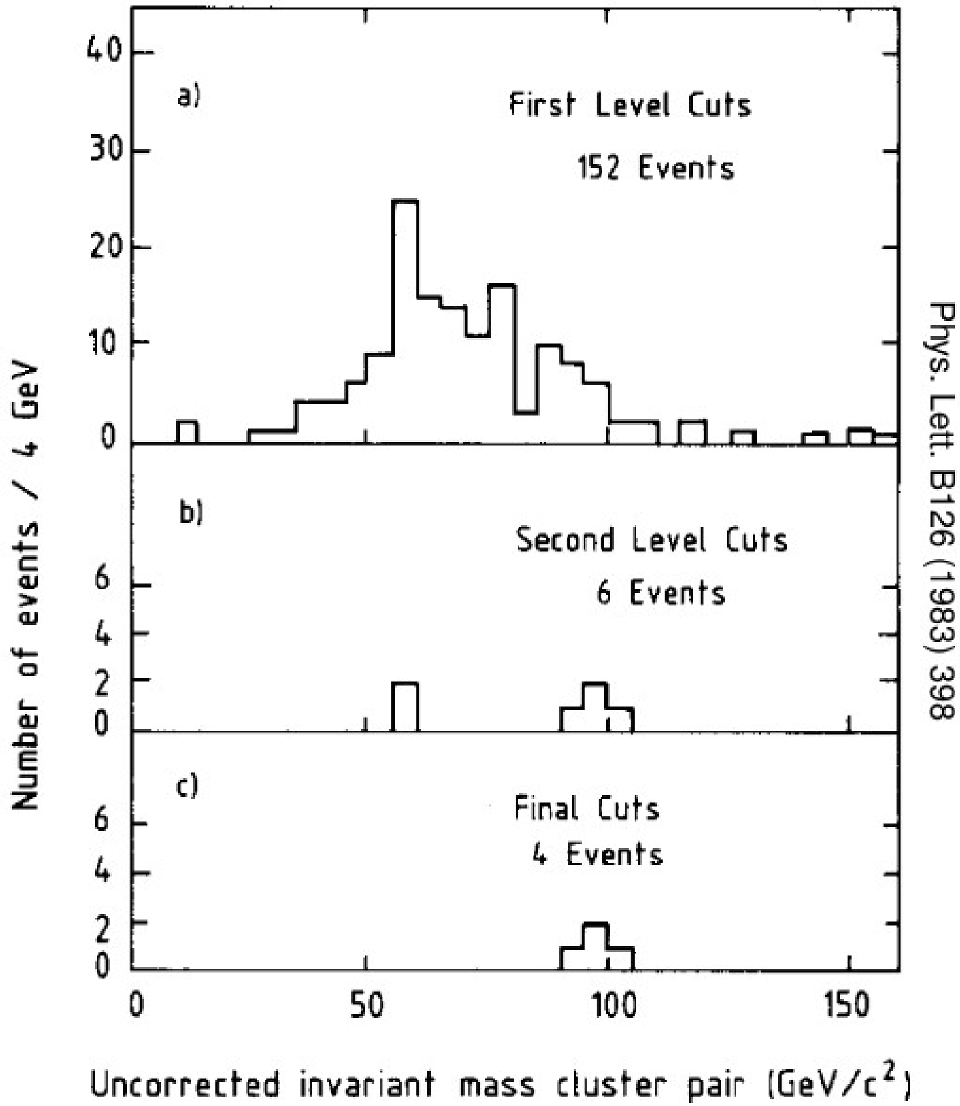
L. Di Lella in CERN Courier Vol. 63 no. 1, Jan/Feb 2023.

Discovery of the Z boson (1983)

- Process $p\bar{p} \to Z \to l^+ l^- \; (l = e, \mu)$

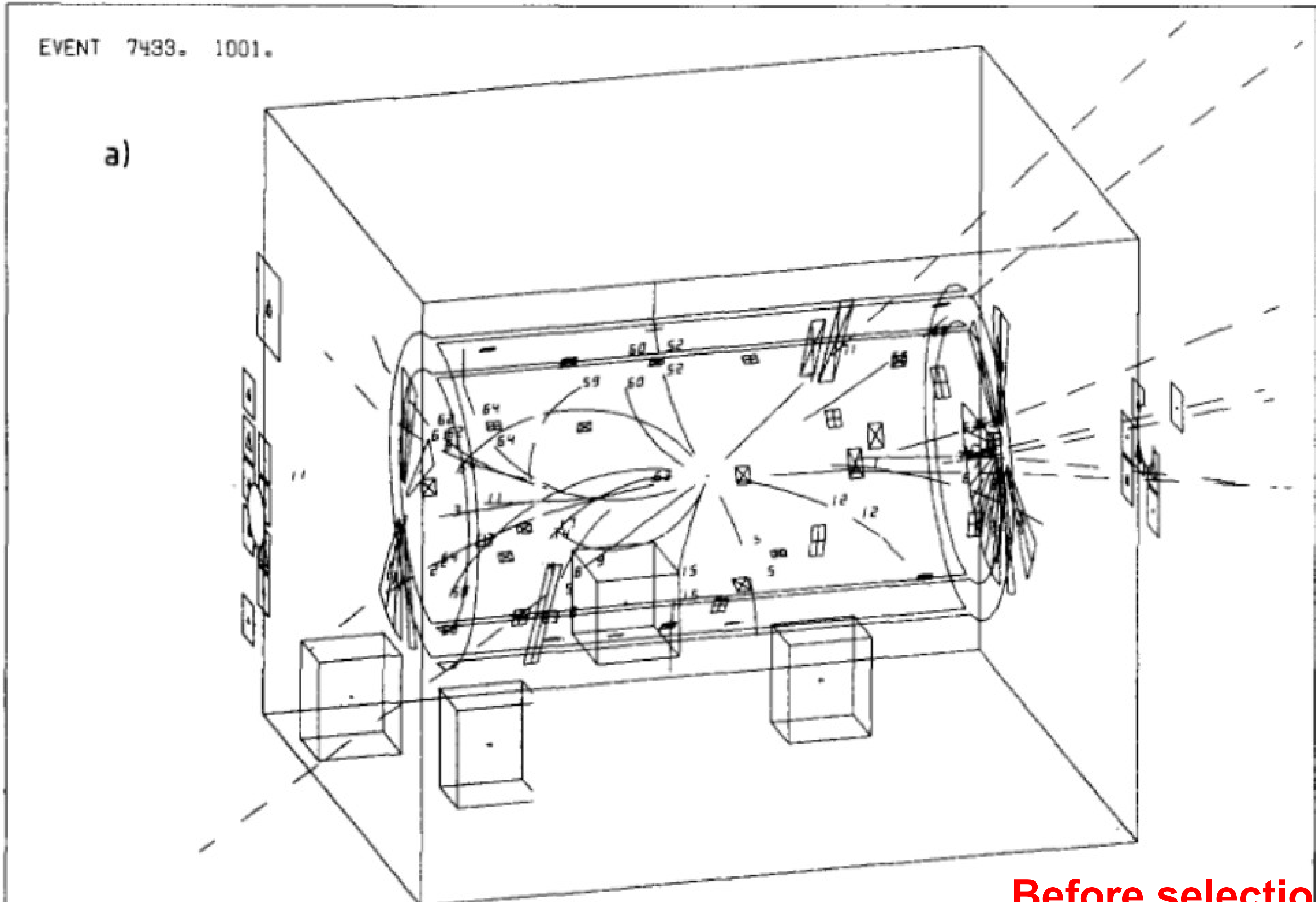


- Analysis strategy: **charged leptons**
  - **Invariant mass** of lepton pair
  - Depends on lepton momenta and opening angle (lepton masses neglected)



$$m_Z^2 \approx 2 \cdot |\vec{p}_{l^+}| \cdot |\vec{p}_{l^-}| \cdot (1 - \cos\phi_{l^+l^-})$$

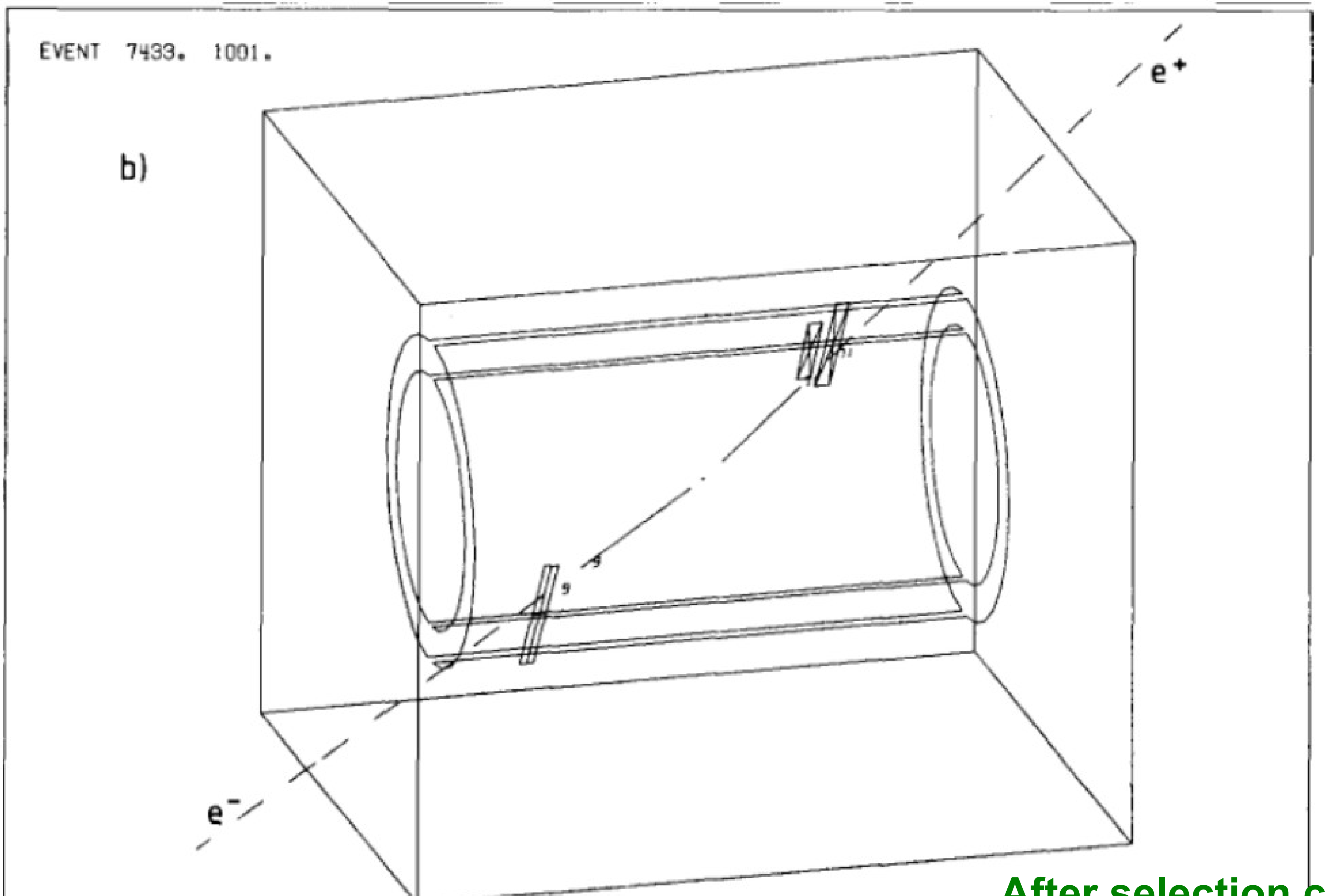
Candidate event with e^+e^-



Phys. Lett. B126 (1983) 398

Before selection cuts

Candidate event with e^+e^-



Phys. Lett. B126 (1983) 398

After selection cuts

Nobel prize 1984

C. Rubbia

S. van der Meer

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

[nobelprize.org]

Summary

- The predicted neutral weak currents have been found in myon-neutrino scattering on electrons in the Gargamelle bubble chamber at CERN (1973)
- The discovery of the weak bosons $W^\pm$ and Z at the SppS proton-antiproton collider at CERN by the UA1 and UA2 experiments has been crowned with a Nobel prize for S. van der Meer and C. Rubbia
- Their masses still need to be explained …