The History of Weak Neutral Currents

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The Bubble Chamber **GARGAMELLE**

**Start**: 1970 at CERN

**End**: 1978

Famous for the discovery of weak neutral currents in 1973
Status : end 1950s

Two so far separate communities approach each other

- Electromagnetic interactions : QED gauge theory with photon=spin 1 gauge boson
- Weak interactions : V-A theory

Both have vector character : suggest intermediate vector boson (W) analogous to $\gamma$

Promising idea : Yang-Mills with nonabelian gauge groups, but...

**Problem #1**: YM-gauge boson must be massless

- $\gamma$ is massless $\rightarrow$ 2 helicity states
- W massive $\rightarrow$ 3 helicity states

relation between mass and helicity? (spontaneous symmetry breaking 1964)

Parity conserved in QED, but violated in Weak Interactions

**Problem #2**: why has $\mu \rightarrow e+\gamma$ negligible rate?

Feinberg (1958) : need W and 2 neutrinos

**Problem #3**: V-A successful at low energies, but bad at high energies

Need new ideas and higher energies
Beginning of High Energy ν Physics

- High energy proton synchrotrons at CERN and BNL
- Pontecorvo and Schwartz propose high energy neutrino beam
  2 new aspects:
  1. investigate weak interactions by direct ν-induced processes
  2. new energy range: 1-10 GeV
- Feasibility studies by Schwartz and Steinberger-Krienen-Salmeron
- Realization at CERN and BNL
- Bernardini is research director at CERN and pushes the project with strong motivation: W? and 2ν?
- 1959 CERN PS 24 GeV
  1960 BNL AGS 30 GeV
- Sketch by Schwartz

1. p-beam on fixed target: generate π⁺ — beam
2. Pion decay in flight generates neutrino-beam
3. Iron shielding stops all particles but neutrinos
4. Detect neutrino interactions in BC or SC
The Race between CERN and BNL

CERN project is ahead of time by half a year
Mid 1961 desaster: no events $\rightarrow$ CERN lost race
Steinberger leaves CERN and joins BNL crew with Schwartz, Lederman et al.
1962 BNL group discovers existence of 2 distinct neutrinos: $\nu_e \neq \nu_\mu$

CERN’s improved neutrino experiment

Stick to neutrino program and rebuild the beam line with 2 improvements:
- ejected proton beam
- Van der Meer’s magnetic horn:
Successful run 1963
Results presented at Siena Conference 1963
Total neutrino cross section rises linearly

Long range neutrino program at CERN

Further runs with Ramm chamber 1964 and 1967
1970 Gargamelle at PS with booster
1976 SPS: experiments with new detectors BEBC, CDHS, CHARM etc
  using various beams (WB, NB) and variety of targets
SIENA 1963 : no NC

- Ramm Bubble Chamber search for $\nu p \rightarrow \nu p$ and $\nu N \pi$

- CERN auditorium: Bernardini reports on SIENA conference

Energy Spectrum of Neutral Events

11 neutral current candidates

NC limit 5%

No evidence for NC
Community discouraged
Theoretical Progress

• Damp infinities with neutral weak boson Z (in addition to W)
• 1964 Higgs mechanism gives masses to W,Z
• 1967 Weinberg combines his work with Glashow, Salam, Higgs, Brout, Englert into model for leptons
• Problem with quarks: Cabibbo current $\bar{u} \gamma^\lambda (1-\gamma_5) (d \cos\theta_C + s \sin\theta_C)$ generates in GSW transitions $\Delta Q=0$ and $\Delta S \neq 0$
  But: flavour changing neutral currents are absent, since decay rate $K^0 \rightarrow \pi^+ \pi^-$ is negligible! Abandon hadron sector.
  Note: Solution of the problem had to wait until GIM 1970 and discovery of c-quark 1974 and in general QPM 1973.
• 1971 ‘t Hooft, Veltman show: model is renormalizable

Model including both electromagnetic and weak interactions postulating a new weak force
Experimental Progress

Gargamelle at CERN PS

Heavy Liquid Bubble Chamber
Magnet Coil and iron yoke
Thick iron Shielding

E-1A at NAL PS

Liquid Scintillation Calorimeter
Magnetic Iron Spectrometer
A Historic Moment

End of 1971: Theoreticians alert Gargamelle and HPW
Gargamelle: M.K.Gaillard, B.Zumino, J.Prentki, C.Bouchiat,
HPW: Weinberg

Great news:
1. GSW propose a model holding the promise to unify weak and electromagnetic interactions
2. ‘t Hooft: this model is renormalizable
3. The key element: weak neutral currents

Two detectors are ready to take up the challenge:
  search for $\nu \nu \rightarrow \nu + e$ and $\nu + N \rightarrow \nu + X$!
A Happy Circumstance

Scanning rules were setup before experiment started

- Class A: events with muon candidate
- Class B: events with identified hadrons
- Class C: one or more protons
- Class D: only electrons and positrons

ν-induced events are in class A.

n-induced events are in class A, if a charged final state hadron fakes a muon

n-induced events are in class B, if final state particles are identified as hadrons

Note: Class B serves to estimate the unavoidable neutron background in class A

The challenge: Are there ν-induced events without muon in the final state?

If so, they are already in class B: start NC search without delay
Searching for a New Effect

1. Define signature of candidates for the new effect
2. Investigate all processes simulating this signature
   all means in practice all known

Claim a discovery if
# signal $\gg$ # background
**Signal**

- Energy deposition
- Muon CC events with wide angle muon escaping

**Background**

- No energy deposition
- No wide angle muon escaping

Need two independent triggers: energy deposition and no muon

CC events with wide angle muon escaping
No worry about punch through
The first leptonic NC candidate

In $\bar{\nu}$-film: 360000 pictures scanned and found at Aachen in Dec 1972 an isolated forward electron

Explain as elastic $\nu_e$ $n \rightarrow e + p$?

1. Topology
   same kinematics as $\nu_\mu$ elastic scattering
   \[
   \frac{\mu^- (\theta_\mu < 5^\circ) + 0}{\mu^- + mp} = 1.3 \pm 7% \]

2. Rate
   observe 15 elastic $\nu_e$ - events in $\nu_\mu$ - film
   $\nu_e$ -flux in $\bar{\nu}$ -beam 10 % of $\nu$ -beam

Conclude: Observed 1 event with background: 0.03 ± 0.02

Interpret as leptonic neutral current candidate:

\[
\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e
\]

- **Identification**: unique by bremsstrahlung and curling
- **Energy**: 385±100 MeV
- **Angle**: 1.4 ± 1.4 degree
An early NC candidate

- 3-prong event
- very clean
- no muon
- total visible energy about 6 GeV
Euphory
- The unique $\bar{v}e$-candidate
- Many candidates without $\mu$
- Subsample of CC events ignoring the $\mu$ and imposing the same criteria on hadrons

**Expected** shape of distribution along chamber axis:
1. If NC candidates $n$-induced, then exponential falloff
2. If NC candidates $\nu$-induced, then flat distribution
3. The CC-subsample flat

**Distinctive features:**
- $n$: exponential falloff ($\lambda \ll L$)
- $\nu$: everywhere flat ($\lambda \gg L$)
The Data

• Compare hadron final state of NC with CC (no μ) and form NC/CC
  X=along beam direction
  R=radial

• NC = v- or n-induced?

• 3 arguments favour v-origin
  NC/CC is flat and big
  NC look v-like
  NC do not look n-like

• Oversimplified ORSAY Monte Carlo disfavours neutrons

A discovery at hand?
Damped Euphory

Doubts : Two critical arguments
• Neutrons make cascades
  → n-background ~ cascade length
  ORSAY MC underestimates neutrons
• Broad neutrino beam generates
  neutrons from sides → appearing as
  flat distribution (sensitive to energy
  and angular distribution of neutrons

Conclusion
• No distinctive feature left
• n-background may be dangerously big
• Dilemma : HPW may publish first
  ↔ n-background underestimated
• Decide for absolute prediction of
  neutron background including cascade
  and detailed geometry

The setup in terms of interaction lengths
• The chamber is embedded in heavy
  material
• #ν events ~ λ
• Huge number of ν-interactions outside
  the chamber

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Neutron Background Calculation

Ingredients

Matter distribution
Neutrino flux
Dynamics of final hadron state
Evolution of hadrons in matter

Complicated, but known
Measured
From ν-events
Need cascade model

Cascade Model: start March – ready beginning of July 1973
At first hopeless: short time and complexity
Breakthrough: cascade only transported by nucleon (>1 GeV)
Linear problem: need only the energy loss per collision
Elasticity distribution has been extracted from pp-data

Conclusion: Absolute prediction of neutron background
no free parameter
Appearance of neutron interactions

**B-event:**
ν-interaction upstream in shielding
Observe in chamber the **end** of the neutron-cascade

**AS-event:**
ν-interaction inside chamber
Observe in chamber the **beginning** of the neutron-cascade

**Predict B/AS:**
optimal use of data
model dependence reduced (except for cascade effect)
The Proof

Beginning of July 1973: 102 NC candidates in υ-film and 15 AS

Worst case hypothesis: All NC are background

\[
\frac{\text{#}B}{\text{#}AS} = \frac{\text{#}NC}{\text{#}AS} = \frac{102}{15}
\]

Cascade program predicts:

\[
\frac{B}{AS} = 1 \pm 0.3
\]

Similarly for antineutrino data

Hypothesis must be rejected: a new effect exists

The Hot Fall

- Prominent physicists disbelieve the Gargamelle analysis: "You have rediscovered the neutron!"
- GGM had anticipated all their arguments and rejected them firmly
- Bad stroke: HPW runs with modified detector: NC effect disappeared
- The CERN Directorate got worried
- Instead of doubting HPW Gargamelle was blamed to be wrong
- General attitude: GGM is wrong because of error in treating neutrons

Way out: YES or NO by special exposure of Gargamelle with proton pulses to test the neutron cascade by direct inspection

Modified HPW-detector

Introduce 13’ iron plate (red): increase muon acceptance
fatal consequence: punch through NC misidentified as CC thus: loose NC effect
July 17, 1973  
Rubbia informs Lagarrigue: **100 NC events**

August 3, 1973  
submitted tp PRL and Bonn Conference

September 14, 1973  
slightly revised

Collaboration decides to postpone and wait for more data with modified detector

November 13, 1973  
HPW informs Lagarrigue about **absence** of NC

February 25, 1974  
new paper submitted to PRL

April 1974  
Published in PRL 32 (1974) 800

**Existence** of neutral currents confirmed
Check the Background Calculation

- Special runs in Nov+Dec 1973 anticipate what should be observed
- Gargamelle exposed to fast extracted proton pulses of 4, 7, 12 and 19 GeV
- Measure **apparent** interaction length in chamber
- Measure **cascade** length
- Compare with prediction of neutron program (dotted lines)
- Reported to APS Meeting Washington (April 1974)

All aspects of the cascade program are confirmed
Example of a Cascade

- Event from the special exposure of Gargamelle in Nov/Dec 1973
- A proton of 7 GeV is entering and generating (event 3241 671 view2) a neutron cascade
- The measurement of the first interaction gives the \textit{apparent} interaction length of the chamber liquid
- Similarly the last interaction with energy deposition exceeding 1 GeV gives the effective \textit{cascade} length
Spring 1974 : Consensus

1. **Gargamelle**
   - Double statistics – good consistency
   - Neutron background accounts for only 10% of the candidates proven by absolute calculation and backed up by internal method
   - Cascade effect is experimentally confirmed

2. **ANL**: 12’ BC exclusive $n \pi^+$ and $p \pi^0$ production

3. **CITF**: new experiment at NAL in narrow band $\nu$ and $\bar{\nu}$
   - new method: event length

4. **HPW** confirms finally muonless events (the alternating currents)

The existence of weak neutral currents is finally accepted
The Electroweak Way

- Discover Higgs Boson
- Discover $\nu_\tau$
- Discover $t$-quark
- Predict mass of $t$
- $W$-propagator
- $Z$-resonance
- Discover $W$, $Z$ gauge bosons
- $GSW \rightarrow$ Standard Model
- $\tau$ b-quark $\rightarrow t$-quark
- Predict masses of $W,Z$
- Discover Weak Neutral Currents

CERN LHC
- Tevatron
- Tevatron
- Loop corrections
- HERA
- SLC/LEP
- CERN SppS
- Propose SppS
- CERN PS
The Weak Neutral Current

\[ J_f^\lambda = \bar{\psi}_f \gamma^\lambda \frac{1}{2} \{ f_L (1 - \gamma_5) + f_R (1 + \gamma_5) \} \psi_f \]

1. Measure the chiral couplings of the fermion \( f \) independent of a model
   Known flavours 1973: \((\nu_e, e), (\nu_\mu, \mu)\), beginning of QPM with u, d, s
2. GSW: \( f_{L,R} = I_{L,R}^3 - Q_f \sin^2 \theta_w \)
   First test: single parameter weak angle \( \theta_w \)

Initiate a worldwide effort

\textbf{Labs}: CERN (PS and SPS) FNAL, BNL, ANL, Serpuchov
\textbf{Beams}: Wide and narrow band neutrino and antineutrino covering 1 – 400 GeV
\textbf{Targets}: Bubble chamber liquids: CF3Br, C3H8, He, D2, H2
   Calorimeters: Fe, marble
\textbf{Detectors}: Gargamelle, BEBC, 12', 7', SKAT CDHS, CHARM, CITF, CCFR, CFFM, NuTev

Inclusive measurements NC/CC = \( fct(u_{L,R}, d_{L,R}) \), elastic e (\( e_{L,R} \)) and exclusive (elastic, 1\pi)

Extraction of the chiral couplings depends on nuclear structure

Poorly known in the 70s; beginning of QPM and QCD
The $Z u \bar{u}$ and $Z d \bar{d}$ couplings

<table>
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<th>exp</th>
<th>nucl.structure</th>
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<tr>
<td>$u^2_L$</td>
<td>0.1197</td>
<td>0.0116</td>
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<td>$d^2_L$</td>
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<td>$d^2_R$</td>
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</tbody>
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**Model independent** analysis of neutrino data: 1973-1987
All 41 experiments reanalysed with best nuclear structure functions
All correlations are determined

GSW is confirmed: $\sin^2 \theta_W = 0.2309 \pm 0.0029 \pm 0.0024$
Most precise value before LEP (1989)
The $Zu\bar{u}$ and $Zd\bar{d}$ couplings

\[ g_L^2 = u_L^2 + d_L^2 \]
\[ g_R^2 = u_R^2 + d_R^2 \]
\[ \delta_L^2 = u_L^2 - d_L^2 \]
\[ \delta_R^2 = u_R^2 - d_R^2 \]
The Virtue of Bubble Chambers

Study exclusive 1pion production in propane: \( \nu + N \rightarrow \nu + \pi + N \)

Note: propane has **free** protons

4 channels: \( p\pi^0 \)  \( p\pi^- n\pi^+ \)  \( n\pi^0 \)

\( \nu + n \rightarrow \nu + n + \pi^0 \): there are only **neutral** particles!

Excitation of resonance \( \Delta^+ (1236) \)
by the weak neutral current
Precision \( \nu - \) Physics

• Around 1980: calculate 1-loop corrections
  \[ (\sin^2 \theta_w)_{BORN} - (\sin^2 \theta_w)_{1\text{-}LOOP} \approx 0.01 \]

• Cogne 1981: SPS neutrino program
  Increase precision in NC/CC to a few per mil?
  Llewellyn-Smith: prediction for isoscalar
  \[ \text{NC}(\nu) = (\frac{1}{2} - \sin^2 \theta_w + \frac{5}{9} \sin^4 \theta_w) \text{CC}(\nu) + \frac{5}{9} \sin^4 \theta_w \text{CC}(\bar{\nu}) \]
  Correct for non-isoscalar contribution

• CDHS and CHARM succeed in 0.5 % measurement and verify 1-loop effect
NC as part of GSW

4-fermion processes: \( f+f' \rightarrow f+f' \)
- space like: \( \nu+f \rightarrow \nu+f \)
- time like: \( e^+ + e^- \rightarrow f + \bar{f} \)

\[
T_{ff'} = C_{ff'} J_f J_{f'}
\]

\[
C_{ff'} = \bar{e}^2(s) \frac{Q_f Q_{f'}}{s} + \bar{g}_Z^2(s) \frac{Q_w^w Q_{f'}^w}{s-M_Z^2+i\Gamma_Z M_Z}
\]

- e.m. known: \( \bar{e}^2(0) = 4\pi\alpha \)
- weak known: \( \bar{g}_W^2(0) = 4\sqrt{2} G M_W^2 \)

Physics at 1-loop level
1. The universal radiative corrections:

\[
\sim \bar{e}^2(q^2)
\]

\[
\sim \bar{s}^2(q^2)
\]

\[
\sim \bar{g}_Z^2(q^2)
\]

\[
\sim \bar{g}_W^2(q^2)
\]

2. Vertex and box corrections are process dependent
Summary of low energy data

The low $Q^2$ NC observables depend only on $\sin^2 \theta_W$ and $\rho$

1. Neutrino: $\nu_q$ and $\nu_e$
2. SLAC Yale experiment polarized e deuterium observe $(\gamma,Z)$ interference effect $10^{-4}$
3. Atomic parity violation very difficult experiments effect $10^{-7}$

$\bar{s}^2 = 0.2353 \pm 0.0044$
e-Experiments challenge QED

SLAC
High precision polarized electron on unpolarized deuterium
QED predicts $\sigma(e^\uparrow) - \sigma(e^\downarrow) = 0$, but observe parity conserving asymmetry
In agreement with GSW: $(\gamma,Z)$ – interference and parity violating NC

DESY
High energy collider $e^+e^-\rightarrow\mu^+\mu^-$
QED predicts $1+\cos^2\theta$
Observe angular asymmetry
Deviation $\sim \cos \theta$ agrees with GSW
\[ e^+ + e^- \rightarrow f + \bar{f} \]

\[ \frac{d\sigma_f}{d\Omega} = \frac{\alpha^2}{4s} N_f \left\{ F_1(s) \left[ 1 + \cos^2 \varphi \right] + F_0(s) 2 \cos \varphi \right\} \]

\[ F_1(s) = Q_e^2 Q_f^2 + 2 v_e v_f Q_e Q_f R e \chi(s) + (v_e^2 + a_e^2)(v_f^2 + a_f^2) |\chi(s)|^2 \]

\[ F_0(s) = 2 a_e a_f Q_e Q_f R e \chi(s) + 2 a_e v_e 2 a_f v_f |\chi(s)|^2 \]

\[ \chi(s) = \frac{s}{s - M_Z^2 + i M_Z \Gamma_Z} \frac{1}{\sin^2 2 \Theta_W} \]

\[ \Gamma_Z = \sum_f \Gamma_f \quad \Gamma_f = \frac{\alpha}{3} M_Z N_f \frac{v_f^2 + a_f^2}{\sin^2 2 \Theta_W} \]

Total cross section \[ \sigma_f(s) = \frac{4\pi\alpha^2}{3s} N_f F_1(s) \]

Asymmetry \[ A_f(s) = \frac{3 F_0}{4 F_1} \]
$(\gamma,Z)$-Interference

Time like

Space like

\[ e^+e^- \rightarrow \text{hadrons} \]

\[ W^+W^- \]

\[ Z \]

Centre-of-mass energy (GeV)

Cross-section (pb)

\[ Q^2 \text{ [GeV}^2\text{]} \]

HERA

\[ y < 0.9 \]

\[ P_e = 0 \]
From Current to Carrier

Aachen ν Conference 1976

1. GSW: $M_W$ and weak angle $\theta$ are related:
   $$M_W = \sqrt{\frac{\pi \alpha/\sqrt{2G}}{\sin \theta}} = \frac{37.3 \text{ GeV}}{\sin \theta}$$

2. ν NC/CC measurements
   $$\sin^2 \theta \approx 0.30 \pm 0.05$$

Predict: $M_W \approx 70 \text{ GeV}$
   $M_Z \approx 80 \text{ GeV}$

Conclusions:

1. Propagator method in ν-experiments hopeless
   $$<Q^2> = 0.1 E_\nu \ll M^2$$

2. Rubbia, Cline, MacIntyre propose $pp\bar{p}$ experiment
   → realized at CERN SPS

3. 1993 HERA ep collider
   with cm-energy = 300 GeV
   $Q^2$ large enough to see
   W-propagator
Discovery of $Z \rightarrow e^+ e^-$

**UA1**

**UA2**

Z-Mass: $95.2 \pm 2.5$ GeV

91.9 ± 1.3 ± 1.4 GeV
The Power of Loops

• SM is renormalizable depends on finite number of free parameters: \( \{p_1, \ldots, p_n\} \), i.e. masses, mixing angles and couplings

• An electroweak quantity \( Q \) is measured and predicted, once the free parameters are fixed by \( n \) independent measurements

• Test SM predictions:

\[
Q_{\text{exp}} \pm \Delta Q_{\text{exp}} = Q_{\text{th}} (\tilde{p} \pm \Delta \tilde{p})
\]

• Application: use precise Z-parameters and predict the top quark mass
Prediction and Discovery of the top-quark

- Discovery of $\tau$ (1975) and $b$ (1977)
  3\textsuperscript{rd} fermion family $\rightarrow$ isodoublets
  completed with $\nu_\tau$ and $t$-quark?
- Prejudice: $t$-mass = 3 $b$-mass
- 1978-86: toponium search at PETRA $: e^+e^- \rightarrow t\bar{t}$?
- Exploit radiative corrections
  a. 3 months before SLC/LEP start
    $90 < m_{top} < 170$ GeV
    two anecdotes
  b. Schaile 1994 Glasgow with precise data
    from SLC/LEP predicts
    $m_{top} = 173 \pm 12 \pm 19$ GeV
- Nobody anticipated a large $t$-mass

\textbf{Discovery 1995} by CDF $176 \pm 8 \pm 10$ GeV and D0 $199 \pm 20 \pm 22$ GeV
1995 : A Surprise

Precise vertex detectors: tag heavy flavours in events
Measure the partial Z-widths to c-, b-, hadrons: \( R_{c,b} = \frac{\Gamma_{c,b}}{\Gamma_h} \)
Sensitive to t-quark mass and sensitive to tagging method
Higgs Searches at $e^+e^-$

**LEP 1** (1989-1995) : Z-resonance

$e^+e^- \rightarrow H + f\bar{f}$

no effect : $m_H > 58$ GeV

**LEP 2** (1995-2000) energy up to 207 GeV

no effect : $m_H > 115$ GeV (95% CL)

**Electroweak fits**

Z-parameters + $\alpha$, G : constrain $(m_H, m_t)$-plane

uncertainty from $\alpha_s$ and $\alpha(m_Z)$

ew quantities $\sim \log m_H$

safe lower limit

weak upper limit from partial Z-width

$Z \rightarrow cc, bb$ \quad $R_{c,b} = \Gamma_{c,b} / \Gamma_h$

impact of top-mass

1987 : Ew fit + $m_{top}$ (Tevatron) :

\[ 80 < m_H < 350 \text{ GeV} \]

2003 : \[ 55 < m_H < 146 \text{ GeV} \]
The Higgs Sector

1964 spontaneous breaking of gauge symmetries introduced to particle physics by Brout, Englert, Higgs and Guralnik, Hagen, Kibble

1967 incorporated in GSW model

1971 proof of renormalizability by ‘t Hooft and Veltman makes GSW a predictive gauge theory

2003 searches at SLC/LEP and Tevatron leave energy gap between 115 and 130 GeV

2012 LHC: ATLAS and CMS discover Higgs boson at 125 GeV

2 recent measurements of the resonance:
Conclusions

• The **discovery** of weak neutral currents had a huge impact on all frontiers (energy, intensity, technology, formation of big collaborations ...)

• The GSW model evolved within 4 decades of intense interplay between theory and experiment step-by-step into the **electroweak gauge theory** embracing weak and electromagnetic phenomena:
  
  V-A theory appears as low energy approximation
  
  QED predictions remain valid if \( s, Q^2 \ll M_Z^2 \)

• **Agreement** between with theory and all data

We have a **solid** basis for future research