The Discovery of Weak Neutral Currents in Gargamelle

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Symposium celebrating the 50^{th} anniversary
CERN, October 31, 2023

50 years paving the Electroweak Way

The crown					
Higgs	2012	LHC	ATLAS and CMS	2 x 5500	Standard Model Full SU(2)⊗U(1) gauge theory
The pillars					
W and Z	1983	SPS SppS	UA1 and UA2	150 + 50	GSW Model with parameter $sin^2\theta_W$
The fundament					
Neutral Currents	1973	PS ν-beam	Gargamelle Bubble chamber	60	QED + Weak Interactions Weinberg's model of leptons QPM

Beginning of High Energy Neutrino Physics

- The first ν beams at CERN (*Bernardini*) and BNL (*Schwartz*) : 1-10 GeV
- Strong motivation : where is the W ? catch word "the Intermediate Vector Boson, if it exists"

  1 or 2 ν species ?

  new processes : neutral currents (e.g. ν+p → $\boldsymbol{\nu}$+X)
- CERN beam was a flop → BNL's chance to discover the ν_μ Veltman : snatched away
- 2nd attempt : results from HLBC and Spark Chamber presented in SIENA 1963

  Thanks to Don Cundy, a contemporaneous witness

  First measurements of exclusive processes : quasielastic, 1238 Δ^{++} resonance, multi-π events (DIS), di-leptons

  Surprise : σ_{total}(ν N) vs E_ν compatible with **linear rise** --- Don Perkins asks Veltman & Bell why ?

  nobody anticipated ν-scattering off pointlike constituents Veltman (1993) -> Don Perkins

  Important topic : the search for W Alvarez intervention

  First NC search

The first NC Search : νN→νX

Perkins presented at SIENA

11 events with identified hadrons

all of low energy

Problem : the neutron background

νN→ μ + n + X

n* in chamber simulates NC

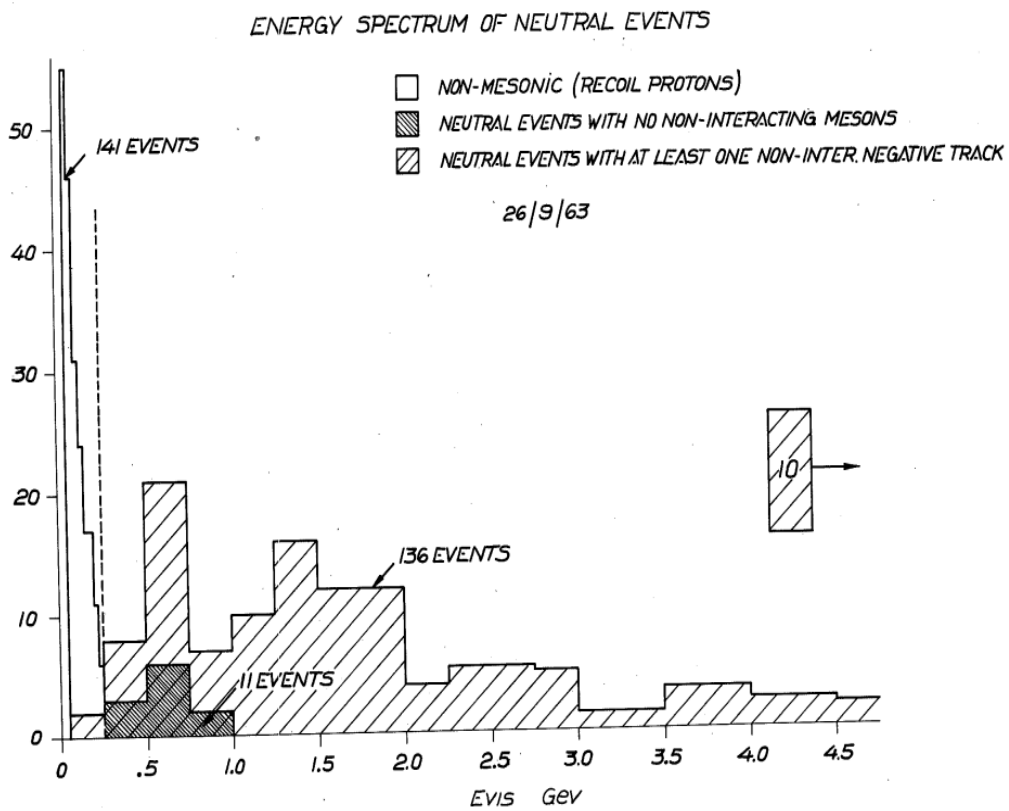
$L_{chamber} \approx \lambda_n$ (neutron interaction length)

result : upper limit $\frac{\nu p \to \nu p}{\nu n \to \mu p}$ < 5 %

A posteriori (1970) : ratio was underestimated

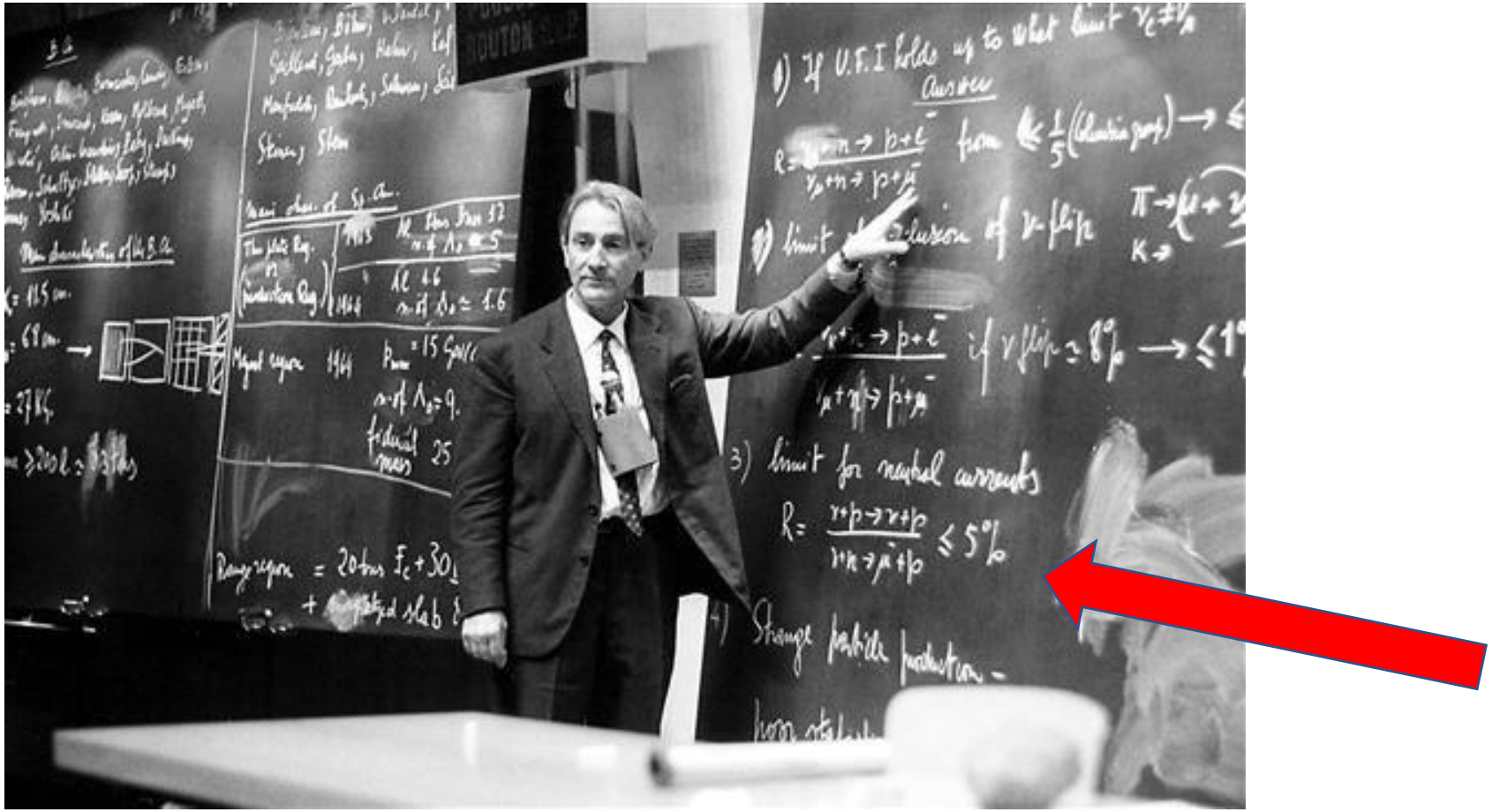
single unidentified positive tracks assumed to be pions

new analysis (propane) < 12±6 %



NPA Int 63-23

Bernardini reporting ν-Results



Lagarrigue's Dream at Siena 1963

- Neutrino physics has a great potential
- Need an order of magnitude more events
- Build a giant bubble chamber ->

  Leprince-Ringuet : Gargamelle named after mother of giant Gargantua
- The chamber was financed and built by France, operated by CERN

The Meeting at Milan 1968

- The Gargamelle Collaboration

  Lagarrigue formed collaboration of 7 european laboratories :

  Aachen, Brussels, CERN, École Polytechnique, Milan, Orsay and UC London

- Discuss Physics Program in CERN PS neutrino beam

  Highlight : SLAC discovered 1967 proton substructure

  Probe : SLAC : em current ⟷ GGM : charged weak current

  New insight : electric charge (distinguish quark and antiquark), parity

  Setup priorities for proposal :

  #1 W search #2 DIS … way down #8 NC search

  since no experimental hint of NC

Historic Moment

- Breakthrough in theory

  Weinberg's *model of leptons* (1967) attracted little attention until 1971

  't Hooft/Veltman's proof : it is renormalizable

  Unified theory of electromagnetic and weak phenomena

  No experimental support : no W, no Z, no H

  Theory predicts processes mediated by the new Z-boson (analogous to W)

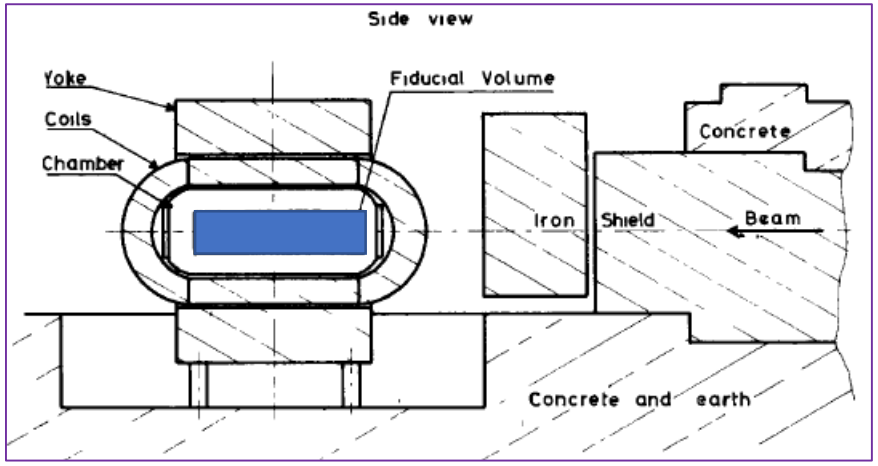
- The Milan group of Gargamelle : first hint from events with only hadrons anecdote
- Collaboration Meeting : Paris 2-3 March 1972

  Pullia presents their vertex distribution (31 events) – excitement : it is flat

  Decision : Start NC search in both channels : ve → $\nu + e$ and vN → $\nu + hadrons$

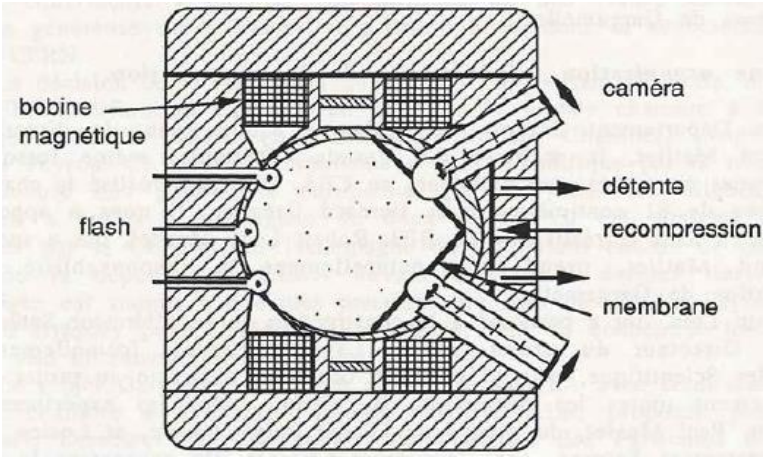
Some technical Details

The setup : longitudinal section



The body is inside magnet coil and iron yoke
Muon shield : 22m iron
Length 4.8 m and diameter 1.8 m $(\ll \lambda_{int})$
Filling : heavy liquid freon density 1.5 g/ cm^3
Fiducial volume 3 m^3 → big target mass
High detection efficiency for the final state particles

The optical system



Tracks illuminated by flashlight
Recorded by 2 rows of 4 cameras (fisheye optics)
Images are transported through 2m iron yoke

Development of special scan tables

Evaluation

- Data recorded on film and distributed to 7 laboratories
- Rules for scanning and measuring established before start in 1971
- 4 event categories :

  A. Events with muon candidate : the regular ν+N -> μ+anything

  B. Events with only identified hadrons : needed for neutron background

  C. Events consisting of 1 or more protons

  D. Events with isolated electron or photon

- Data taking started in March 1971 in ν_μ- and $\bar{\nu}_\mu$- wide band beam
  emphasis on total cross section and nucleon structure
- March 1972 : **Are there weak neutral currents ?**

  If so, they are already included in class B → Start dedicated search

Search for a new Effect

Signal : neutrino induced interaction without a lepton in the final state

Background : dominated by neutron interactions

must prove : #background events $\ll$ #candidates

Competition:

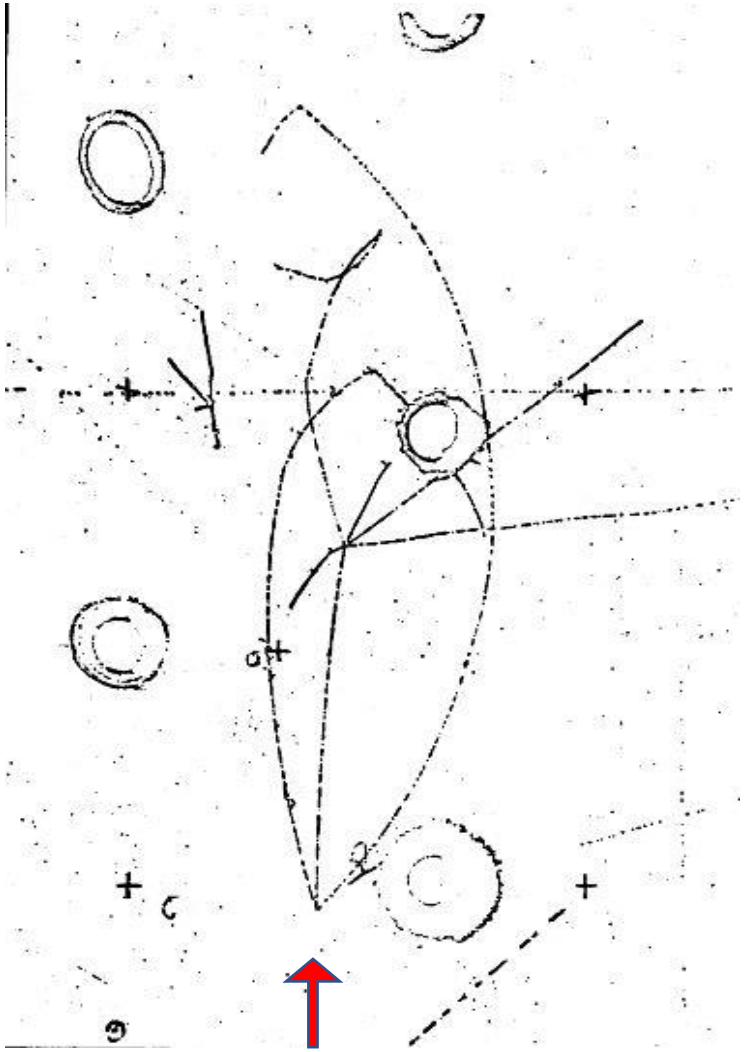
Gargamelle $\longleftrightarrow$ HPW = Harward-Pennsylvania-Wisconsin

Feel the tension between

being first and being right

An early NC Candidate

- Clean 3-prong event
- Final state has only identified hadrons
- total visible energy about 6 GeV



A welcome Event : great Excitement

360.000 pictures scanned
Isolated forward *electron* found
at Aachen in Dec 1972. anecdote

Interpretation:

$\bar{\nu}_\mu$ e $\rightarrow$ $\bar{\nu}_\mu$ e

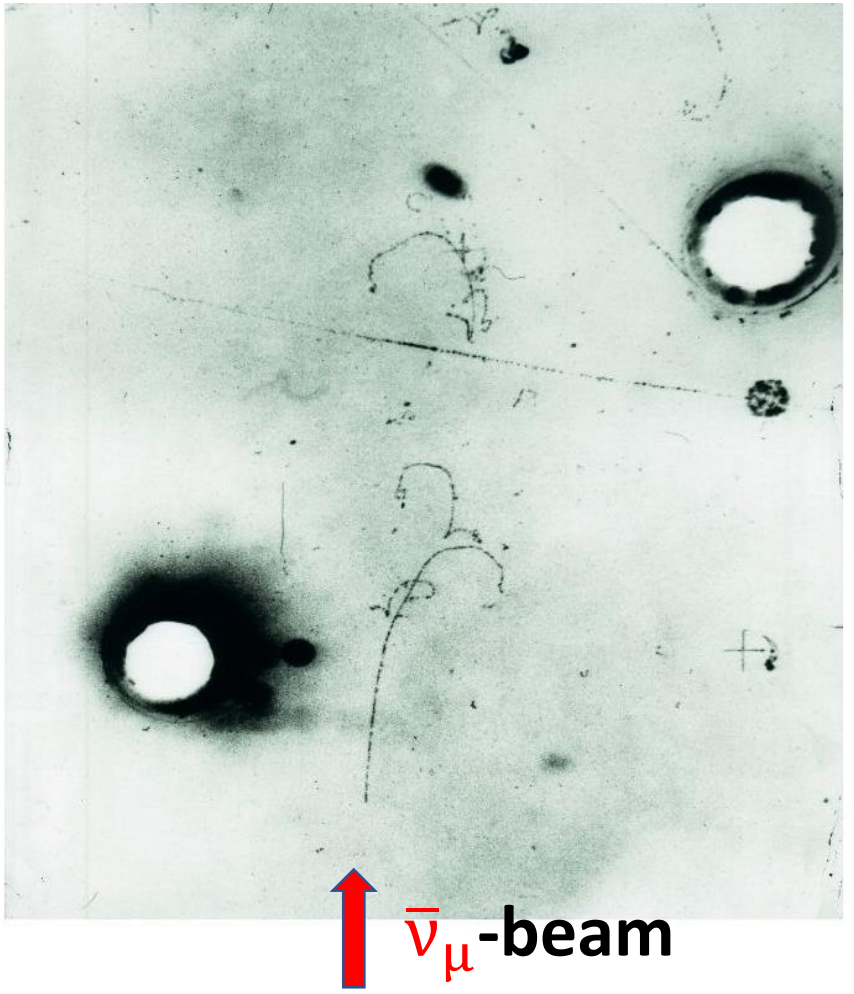
Properties of electron :

- **Identification** : unique by bremsstrahlung and curling
- **Energy** 385$\pm$100 MeV
- **Angle** 1.4 $\pm$ 1.4 degree

Background : 0.03 $\pm$0.02

$\nu_e\, n \rightarrow e + p$
$(proton\ invisible)$

Submitted to Phys Lett : 2/7/1973



Collaboration Meeting in March 1973

- Analysis based on : 83(ν)+207($\bar{\nu}$) kpix
- **NC** sample

  leptonic channel : one

  hadronic channel : 102 in ν and 64 in $\bar{\nu}$ film
- **CC** sample for comparison

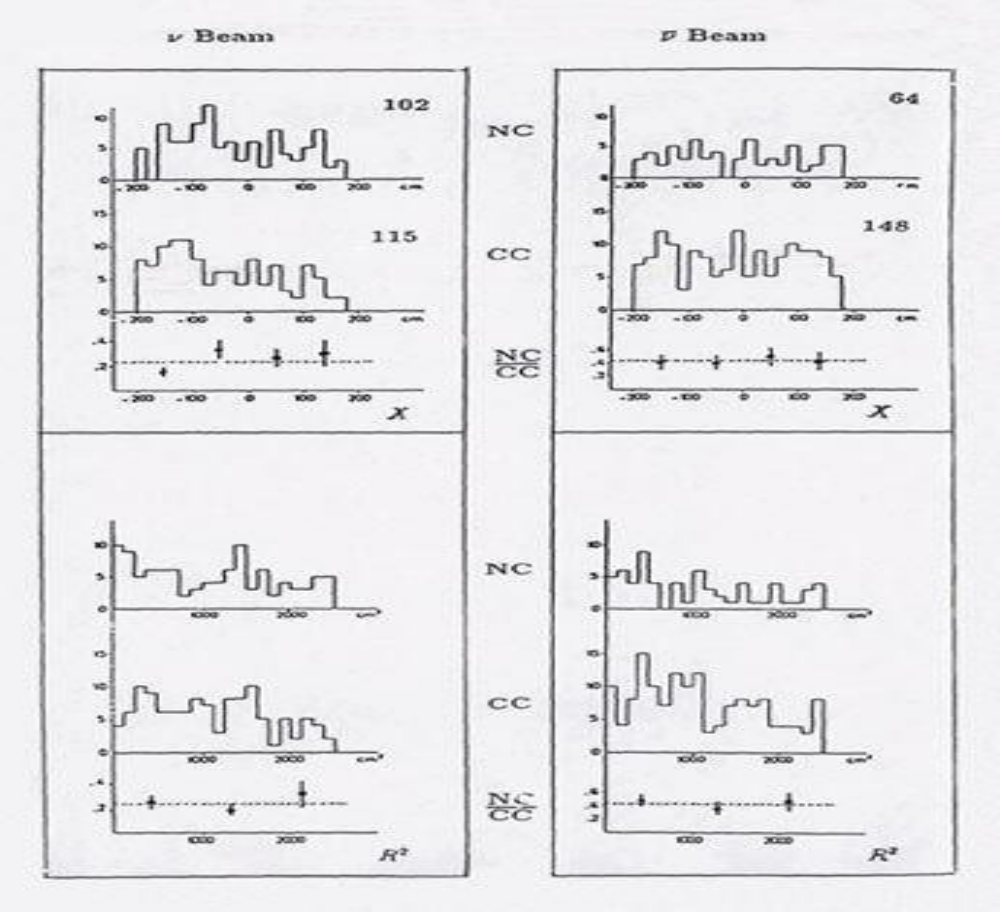
  ignore μ, criteria for hadron final state as for NC
- Expectation for **NC/CC**

  ν → NC/CC flat along chamber axis

  n → exponential fall off (λ≪ L_{GGM})

  ORSAY Monte Carlo

Intriguing result : discovery ?



BUT …

- Neutrons make cascades

  #n* ~ cascade length

- ν-flux is broad

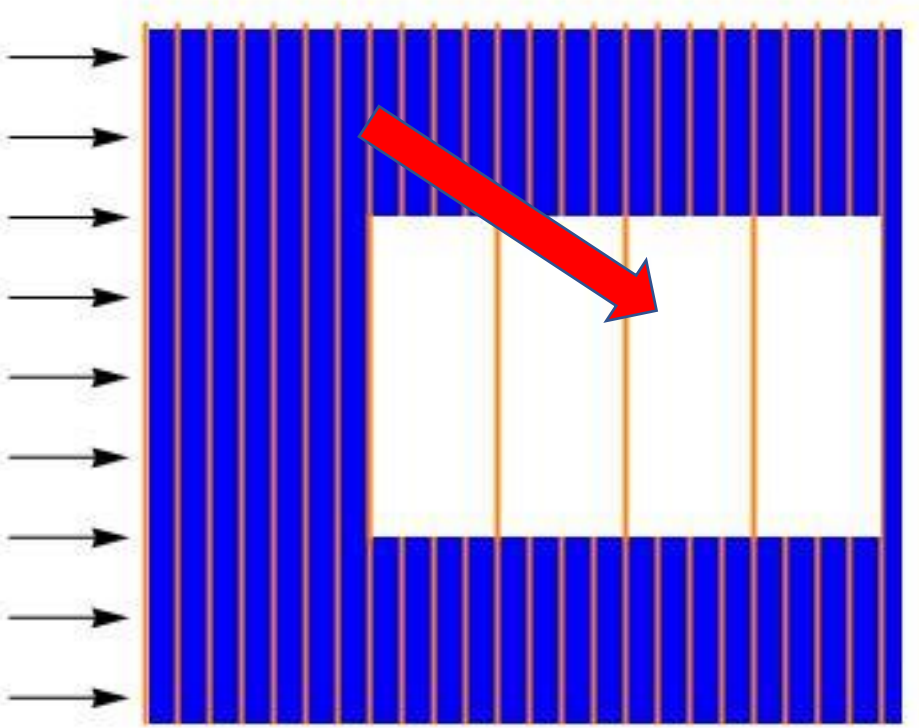
  huge amount of ν-interactions outside

  chamber (i.e. sources of neutrons)

Damped euphoria :

No distinctive feature left

back to prove #n ≪ #NC



Predicting the Neutron Background became my preoccupation

- The Monte Carlo method : only way to cope with the complexity of the experiment
- Predicting the neutron flux requires

1. Geometry of the setup	known
2. Matter distribution	known
3. Neutrino flux	measured
4. Dynamics of ν-interaction	measured
5. Propagation of final state hadrons	unknown – need a model

- A solution within a few weeks seemed hopeless until breakthrough

  meson component inactive → need only model for **linear nucleon cascade**

  elasticity at each interaction : $E_{out} = \lambda E_{in}$ get λ from NN-data (Fry, DH)

  cascade stops, when the entering neutron cannot produce a star with **E > 1 GeV**

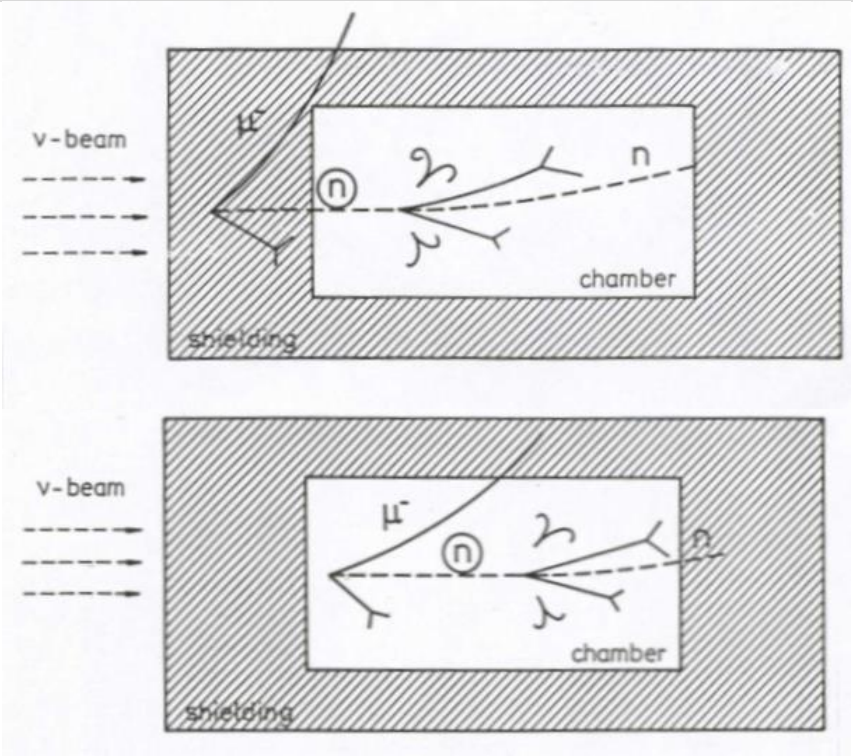
- Result : Absolute prediction of neutron background

  No free parameters

Configuration 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 ratio B/AS: safe prediction
remaining model dependence : cascade effect

The Moment of Truth

- Beginning of July 1973

  Pullia：The final AS events sample is ready : 15 (ν) and 11 ($\bar{\nu}$)

  The neutron background program is ready and predicts : B/AS = 1.0 ± 0.3

  A simple model : equilibrium neutral hadrons ↔ neutrinos in infinite homogeneous medium and uniform flux

  B/AS = 1/<p>-1 with single parameter <p>=mean neutron interaction probability

- Worst case hypothesis : **All NC candidates are background**

$$\left(\frac{B}{AS}\right)_{meas} = \frac{\#NC}{\#AS} = \frac{102}{15} = \mathbf{6.8 \pm 0.3} \quad \Longleftrightarrow \quad \left(\frac{B}{AS}\right)_{calc} = \mathbf{1.0 \pm 0.3}$$

- Reject hypothesis (both ν and $\bar{\nu}$): **new effect exists**
- Flaws ? No doubts anymore after 2 weeks of very hot discussions :

  July 19 presentation in CERN Auditorium by Musset

  July 25 submit paper to Phys.Lett

The Authors of the Discovery

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OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

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SEARCH FOR ELASTIC MUON-NEUTRINO ELECTRON SCATTERING

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Received 2 July 1973

The Electron-Photon Symposium at BONN August 27-31, 1973

- First time that results from Weak Interaction are included.

  Since then the title was changed to **Lepton**-Photon Symposium

- Plenary session : G.Myatt presented the Gargamelle Discovery

  He included a last minute contribution by HPWF

  Data of both experiments agree

- Parallel session : talk by F. Bullock.

  Detailed discussion of the experiment and neutron background

  Intervention by Rubbia (HPW) with critical questions – we were quick to reply anecdote

  The epithany of C.N.Yang : he stood up at the end and said *weak neutral currents have been discovered*

The Crisis

Autumn 1973 :

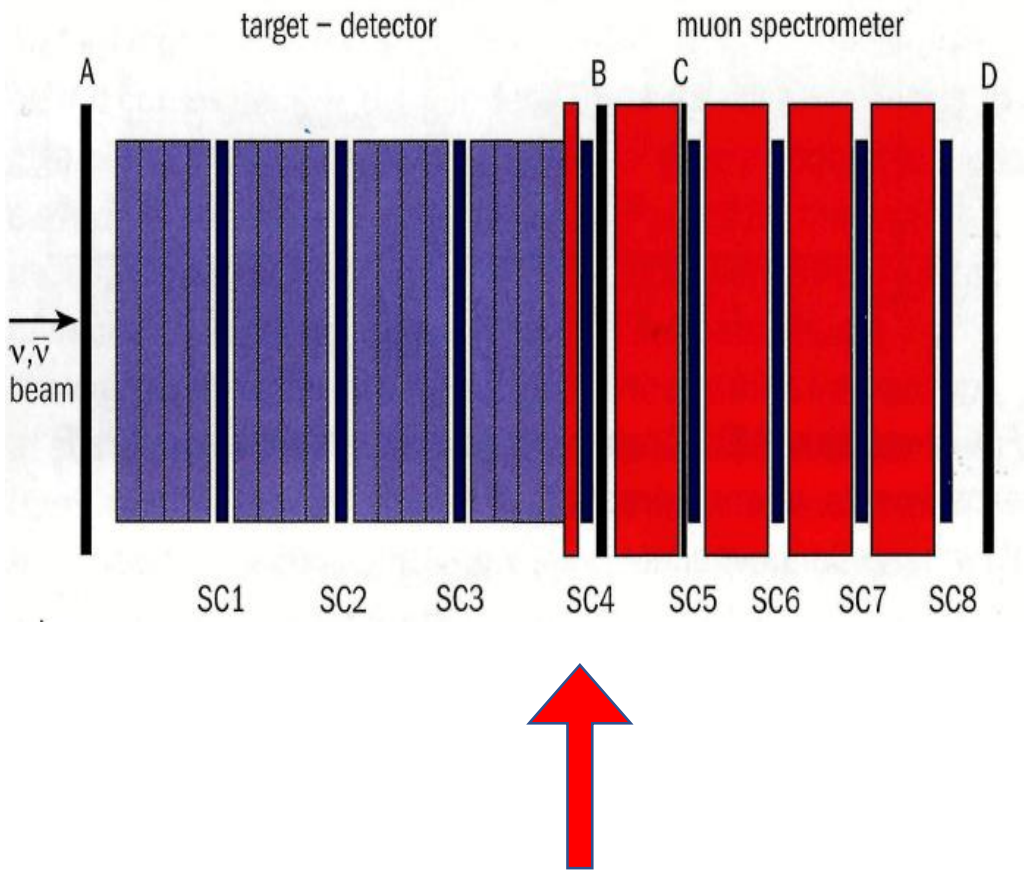
HPWF postpone publication for more statistics : introduce 13’ iron plate

Increase muon acceptance

fatal consequence : punchthrough

NC misidentified as CC : loose NC effect

Gargamelle treated with derision and critics



Voices by prominent Physicists

Steinberger	You have rediscovered the neutron What can come out of a cigar ?
Adams (CERN DG)	The Gargamelle claim is the worst thing that ever happened to CERN
T.D.Lee	Disbelief : experiments have to be done right
C.N.Yang	Neutral currents are discovered (Bonn Conference)
Feynman	Wait for our boys in CalTech
Faissner	Cascade programs are notoriously wrong – yours too

Perkins meets the DG Jentschke

CERN Courier : May 31, 2003

When the claim to have found neutral currents in Gargamelle was followed by the report from Fermilab that the NC/CC ratio they found was consistent with zero, many physicists … believed that the Gargamelle result must be wrong. Indeed, one senior CERN physicist bet so heavily against Gargamelle that he lost half his wine cellar. But Jentschke himself was always very supportive of the experiment … I did meet him on one occasion in the CERN lift. He told me he was worried about the Gargamelle result, because some people had told him that it could be wrong … and [that] would be very bad for CERN. My response was that, coming after the "split A2" affair, it would be an absolute disaster. However, I knew the group had gone through the event analysis many times and for almost a year we had searched intensively for some other explanation for the effects observed, without success. So I thought the result was absolutely solid, and he should just ignore rumours from across the Atlantic. I don't know if my words reassured him, but he got out of the lift with a smile on his face.

Checking the Neutron Cascade

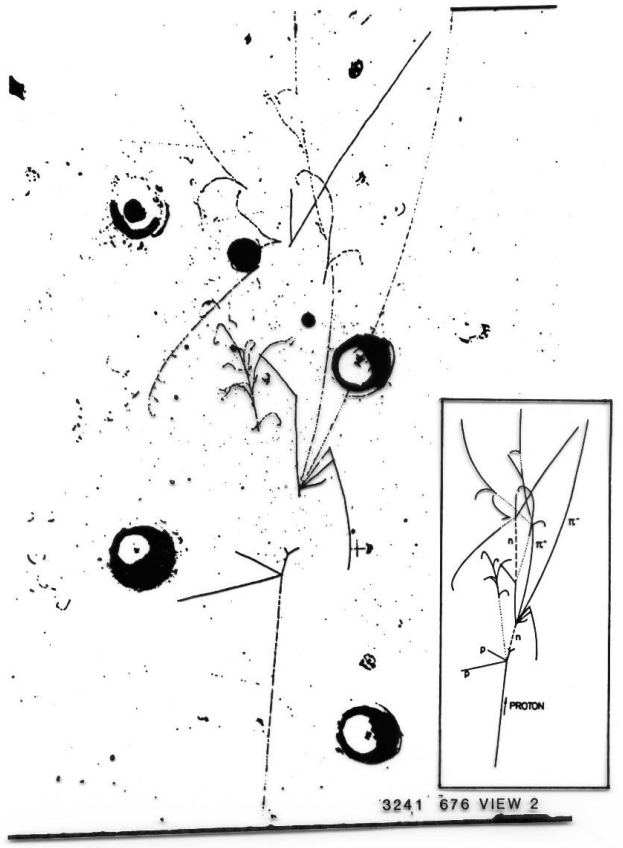
Urgent question :

Is the cascade program right or wrong ?

Expose Gargamelle to fast extracted proton pulses of 4,7,12,19 GeV from the PS and observe directly the induced cascade. 2 runs in Nov/Dec 1973

Example : A proton of 7 GeV is entering and generating a neutron cascade (event 3241 676 view2)

Predict beforehand the properties of the proton-induced cascades with the neutron background program



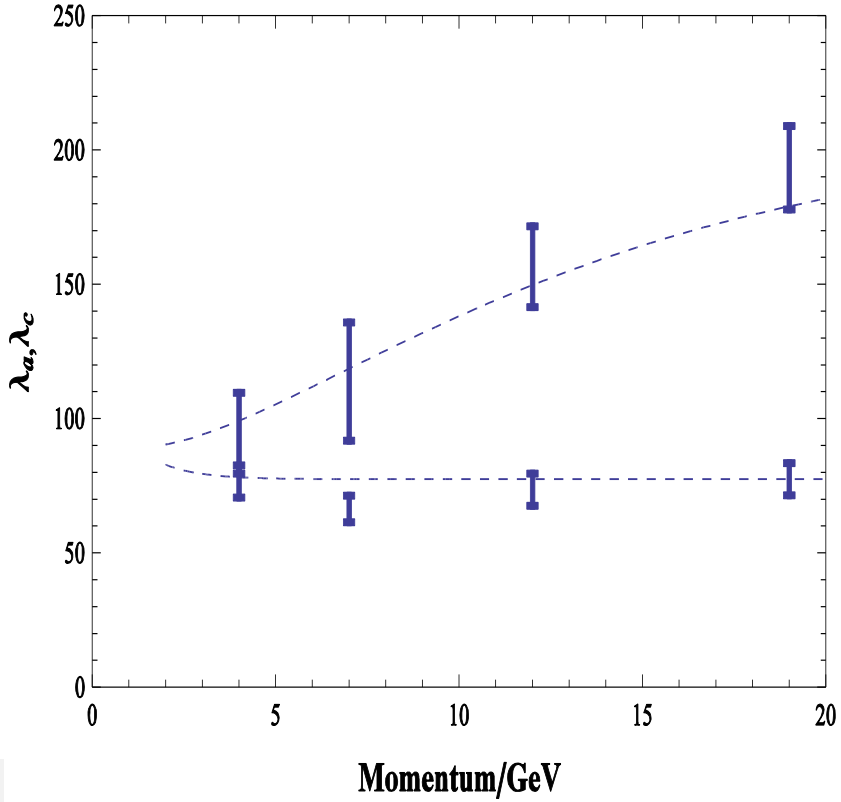
Results

Measurements

1. apparent interaction length in chamber
2. cascade length

Comparison with prediction of the cascade program (dotted lines)

Reported to APS Meeting Washington (April 1974)



All aspects of the cascade are confirmed

Conclusions

- Gargamelle was right
- Overwhelming evidence in Spring 1974

  Gargamelle doubled statistics in agreement with previous results

  New experiment in narrow band ν-beam by Berry Barish et al

  Single pion production in ANL 12 foot bubble chamber

  HPWF confirms the NC signal Joke : discovery of alternating currents
- The discovery of weak neutral currents by the Gargamelle collaboration stands out as a significant contribution to High Energy Physics
- CERN gained a leading role with the discovery of weak neutral currents

Steinberger's Hindsight

The history of Neutrinos, 1930-1985

Quote from :
Talk prepared for "25th International Conference On Neutrino Physics and Astrophysics", Kyoto (Japan), June 2012

In 1973 the Gargamelle team published results which demonstrated the existence of muon-less events and so confirmed the E-W theory. For me, although I was slow to accept it, this is the most important discovery at CERN, ever. It established the electroweak unified theory