The Discovery of Weak Neutral Currents

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Now and Then

- Table with laptop
- Email, handy, www
- Electronic programming
- Slides with Power point
- Omnipurpose detectors
- Thousands of physicists
- Use facilities (Pythia, PDF…)
- Theory at TeV scale

- Table with pad, pencil and slide rule
- Telephone, Post Office
- Punching cards
- Hand written transparencies
- Specific detectors
- Small collaborations
- Use the data
- Models at GeV scale

Down the electroweak way

	Higgs Boson	CERN LHC
2010		
2000	ν_τ	Tevatron
	ν-oscillation	Kamioka
	t-quark	Tevatron
	Z-resonance	SLC LEP
1990	W- propagator	HERA
	SN1987A	Kamioka
	W , Z gauge bosons	CERN SppS
1980	γZ interference	PETRA
	τ b-quark	SPEAR FNAL
	c-quark	SPEAR BNL
	Weak Neutral Currents	CERN PS
1970		

Dream : theory for electromagnetic and weak phenomena

QED

- Pure vector
- Parity conserving
- Mediated by photon:
  neutral, massless and
  infinite range
- Gauge theory

V-A

- Vector and axial vector
- Maximal parity violation
- Intermediate Vector boson ?
  charged, massive and
  short range
- Higher orders diverge

Conclusion: common features and serious differences

The Glashow-Salam-Weinberg Model

- See Steve Weinberg's talk at the CERN Symposium 2003 (cf. EPJC 34 2004)
- Essential ingredients

> - Extend gauge principle to groups larger than U(1)
> - In addition to charged IVB (W) introduction of a neutral IVB (Z) , implying weak neutral currents
> - Spontaneous symmetry breaking
> - GIM mechanism for quark sector (avoid FCNC)
> - 't Hooft-Veltman : the GSW Model is renormalizable

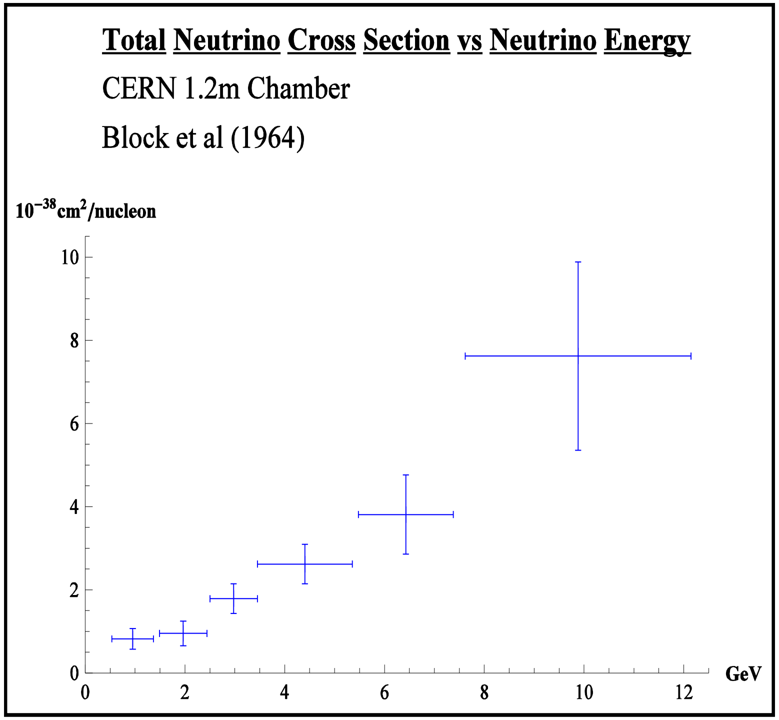
The Accelerator Era

- Absence of $\mu \rightarrow e + \gamma$
  1958 Feinberg : two neutrinos ? W ?
- Pontecorvo and Schwartz propose ν-beam
  realized at CERN and BNL
  weak interactions in GeV-regime expecting
  two discoveries
- 1960 T.D.Lee and C.N.Yang set up catalog of
  9 important questions including NC

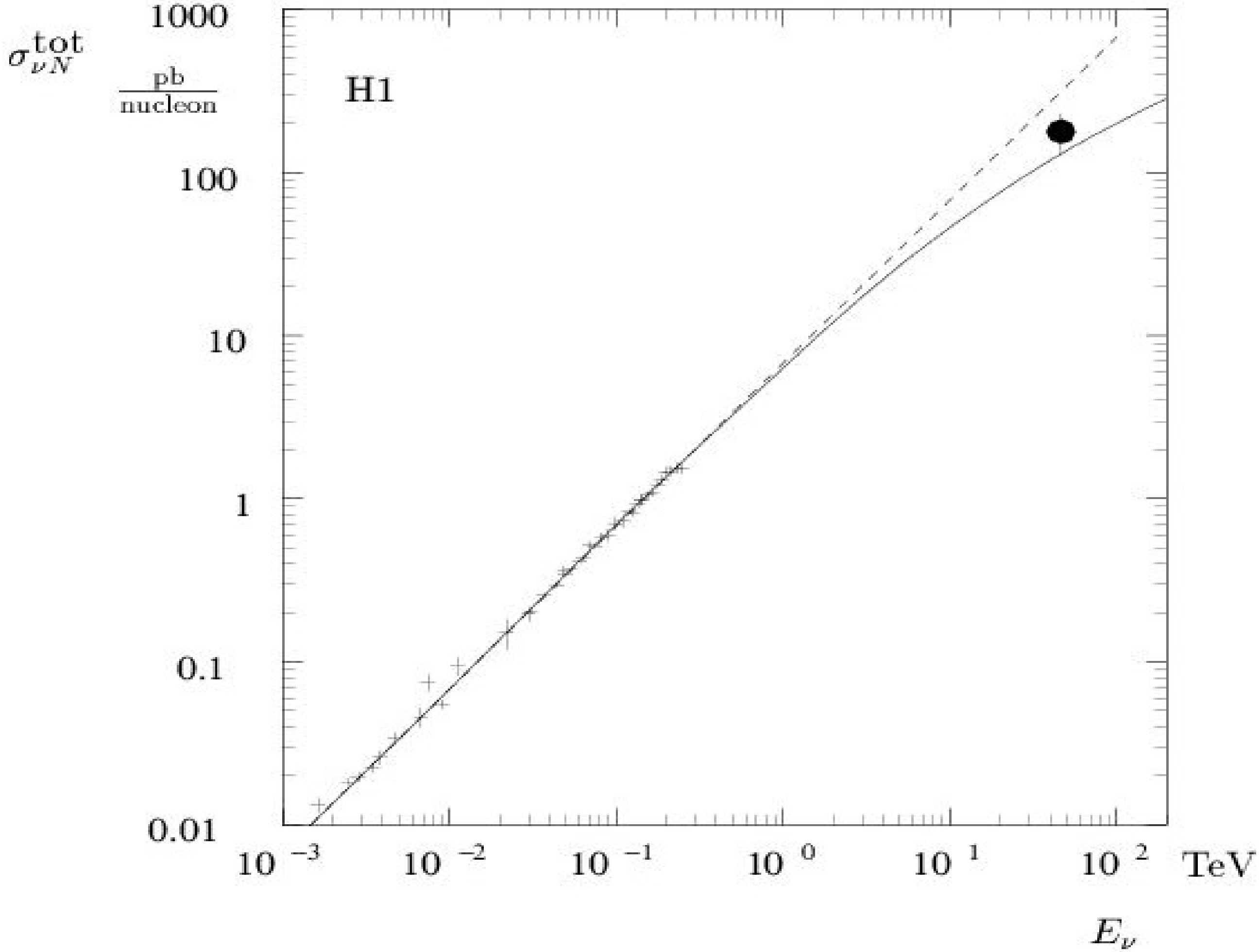
First Results

- 1962 BNL discovers
  $\nu_\mu \neq \nu_e$
- Siena Conference 1963

> ➢ BC and SC confirm 2ν
> ➢ Where is the W ?
> ν N→ $\mu + e + X$
> $\sigma \sim E$ (linear !)
> W-propagator ⇨ M_W
> ➢ Neutral currents ?

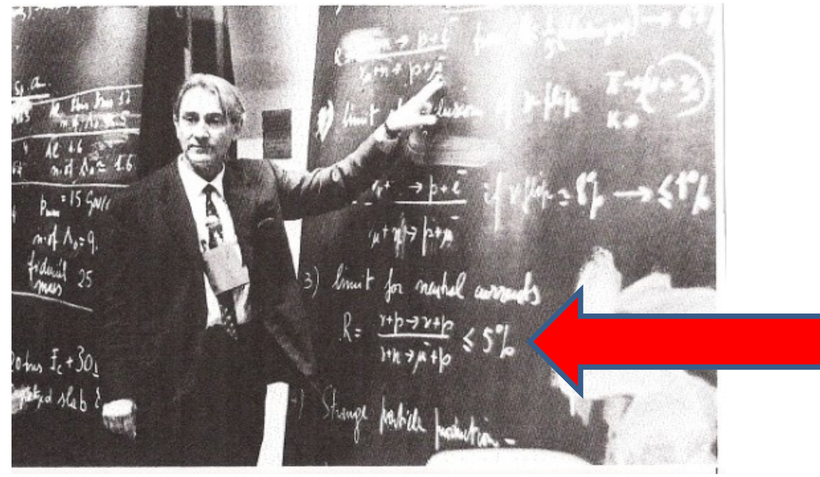


20 years later



The first NC-searches

1. Decays : $\Delta Q = 0$ and $\Delta S \neq 0$ absent
2. Ramm Bubble Chamber
   $\nu + p \rightarrow \nu + p$
   look for events without muon
   problem : neutron background
   small upper limit of 5%
   (1970 corrected to (12 ± 6)%)
3. No results from Spark Chamber
   need trigger without μ



Gilberto Bernardini reports results from Siena 1963

Conclusion : community discouraged

Gargamelle

- 1963 Lagarrigue's vision for next generation bubble chamber
  - ➢ Two main requirements :
    10-times more events
    details of final state
  - ➢ Solution :
    cylindrical bubble chamber with
    1m diameter and 5m long
    filled with heavy liquid
- 1970 installed in CERN PS ν-beamline
- 1971 start running : ν and anti-ν
- 1978 break down

Lagarrigue
the father of Gargamelle

The Physics Program

- 2-day meeting at Milan 1968
- The highlight : SLAC discovered substructure of proton
- Gargamelle looks at partons with W instead of photon
- Search for W remains at highest priority
- Search for NC was not discussed, but included in proposal with low priority
- Proposal submitted 1970

The Gargamelle Collaboration

- 7 european laboratories: Aachen Brussels CERN Ecole Polytechnique Milan Orsay UC London
  and guests from USA
- Scanning and measuring must be strictly organized in advance
- Scan rules : event classes
  A. events with muon candidate
  B. events without muon candidate
  C. events consisting of protons only
  D. events with isolated electron, positron or gamma

Installing Gargamelle 1970

CERN and NAL

- Gargamelle
- Approved 1970
- Data taking 1971
- Heavy liquid bubble chamber
- CERN PS Booster 24 GeV
- Wide band ν and $\bar{\nu}$ beams 1-10 GeV
- Record everything

- E-1A HPW
- Approved 1970
- Data taking 1972
- Target calorimeter + muon spectrometer
- NAL PS 400 GeV
- WB beam mixed ν and $\bar{\nu}$ 10-200 GeV
- Set trigger to select interesting events

Note: Interest in neutral currents started only in 1972

Status of Theory 1971

Promising renormalizable gauge theory exists

1. For $Q^2 \ll M_W{}^2$ reproduce QED and V-A
2. Missing experimental evidence in all sectors

   - Fermion sector : no GIM current (c-quark)
   - Gauge sector : no W and Z
   - Higgs sector : no spin 0 boson

3. Predict weak neutral currents ➡ expect ν_μ-interactions without final state μ : challenge Gargamelle and HPW (E-1A)

1972: Change Priority

- Theoreticians alert and urge Gargamelle and E-A1 to look for weak neutral currents
- Both collaborations took up immediately the challenge
- **Gargamelle** was lucky :

  If NC, then already included in category B

  setup selection criteria (1 GeV)

  worry about neutron background
- **E-A1** had to setup a new trigger

  worry about lost muons and hadron punch through

The first leptonic NC candidate

Scanned 360000 pictures

Isolated forward e observed at Aachen Dec 1972.

Interpretation:

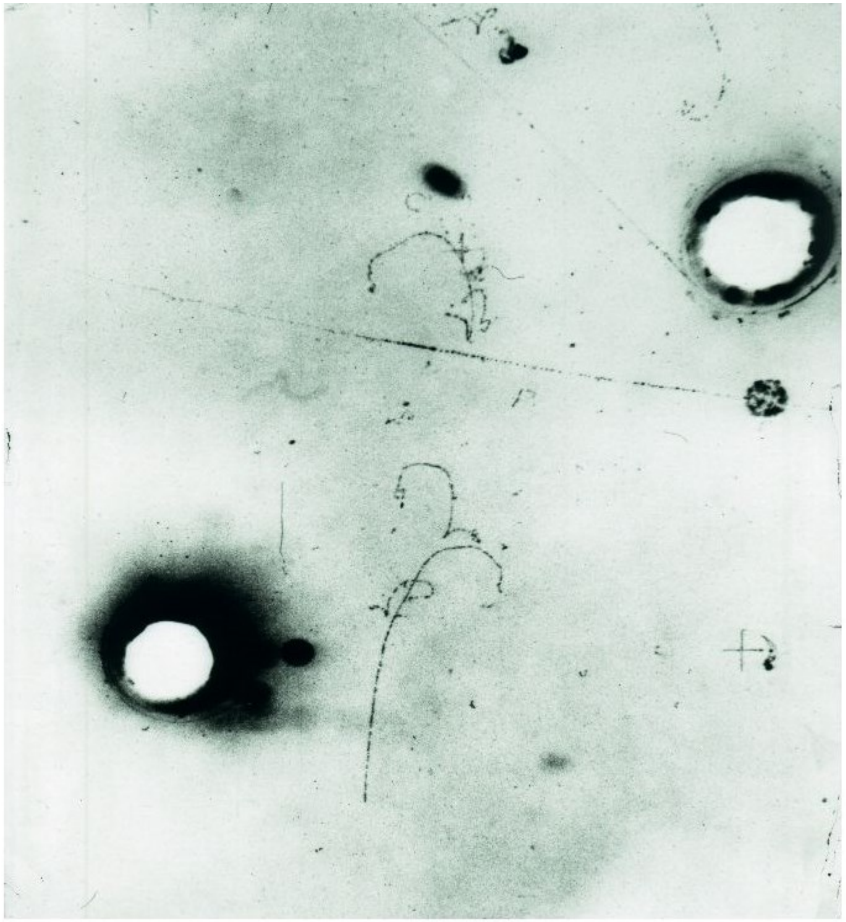
$$\overline{\nu_\mu} e \rightarrow \overline{\nu_\mu} e$$

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

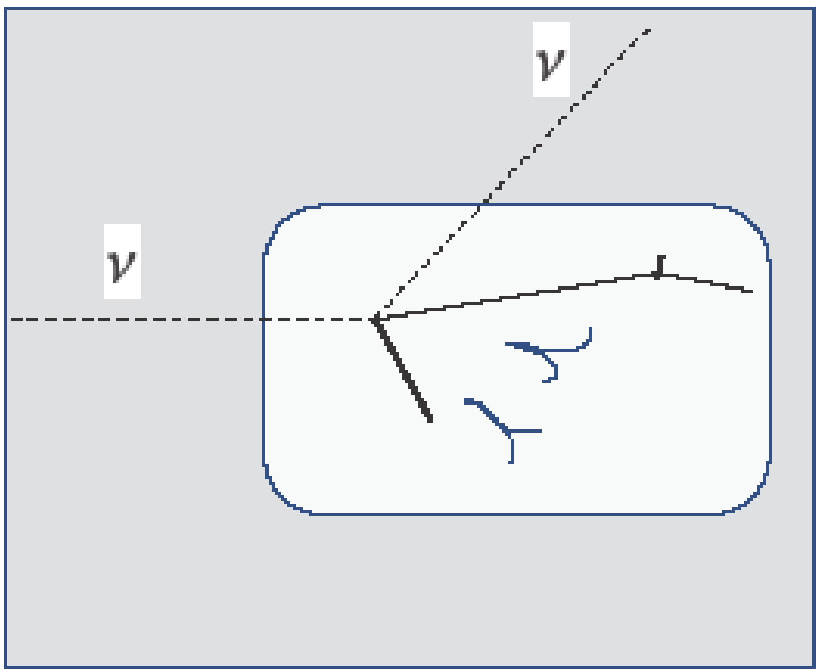
$\nu_e\, n \rightarrow e + p\ (invisible)$



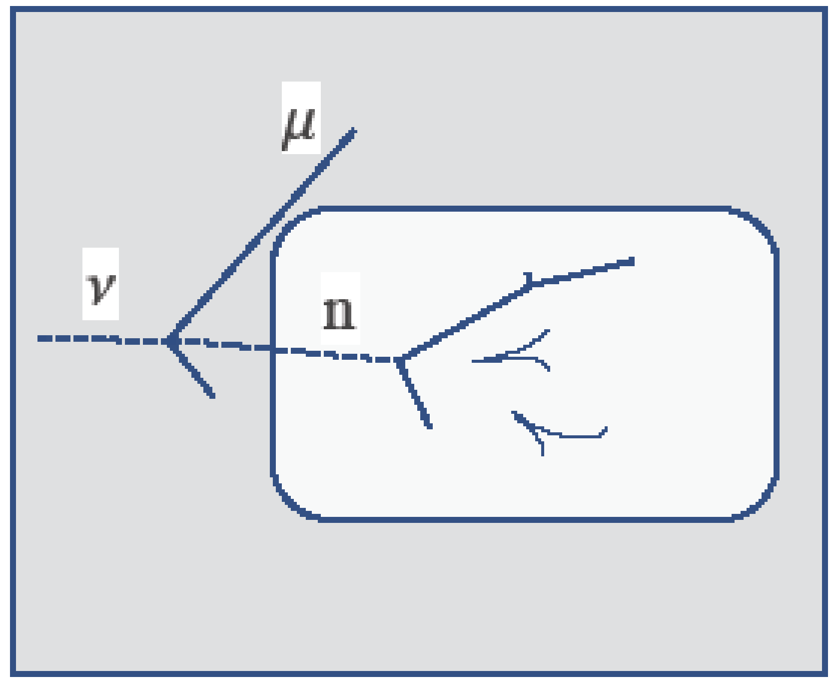
$\overline{\nu_\mu}$-beam

Signal and Background

ν+N → ν +hadrons

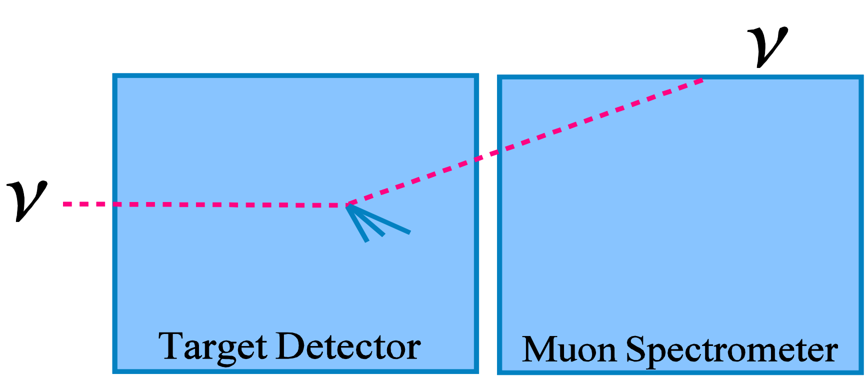


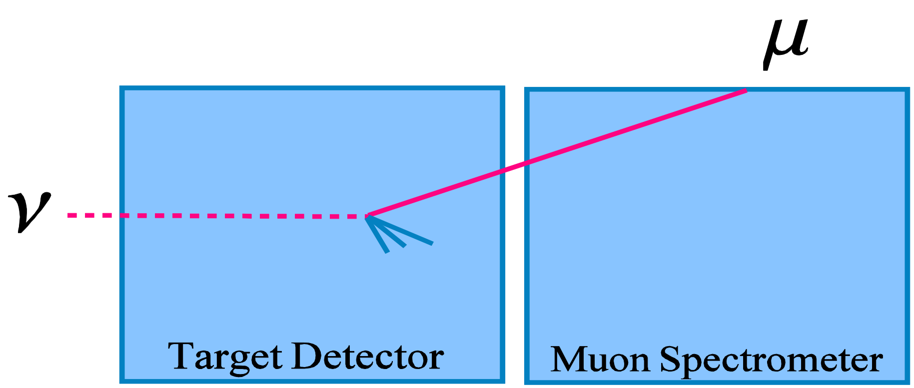
ν+N → μ + n +mesons
n+N → hadrons



E-1A Experiment

signal | **background**



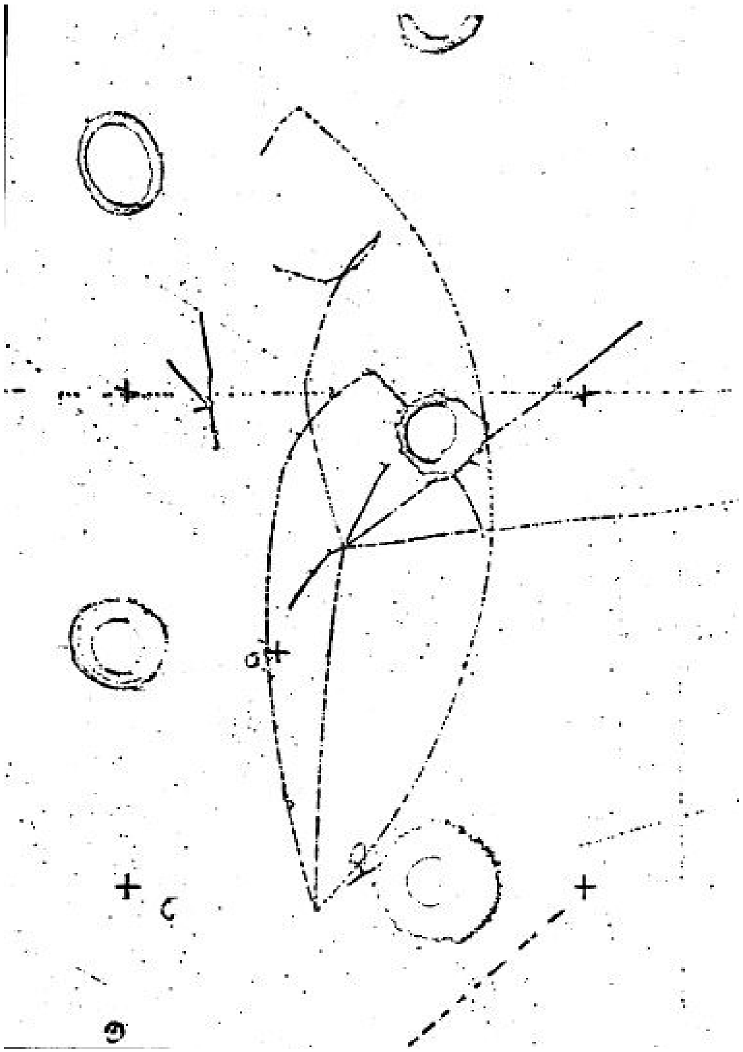


Loose NC if hadron punches through

CC → NC candidate if μ escapes

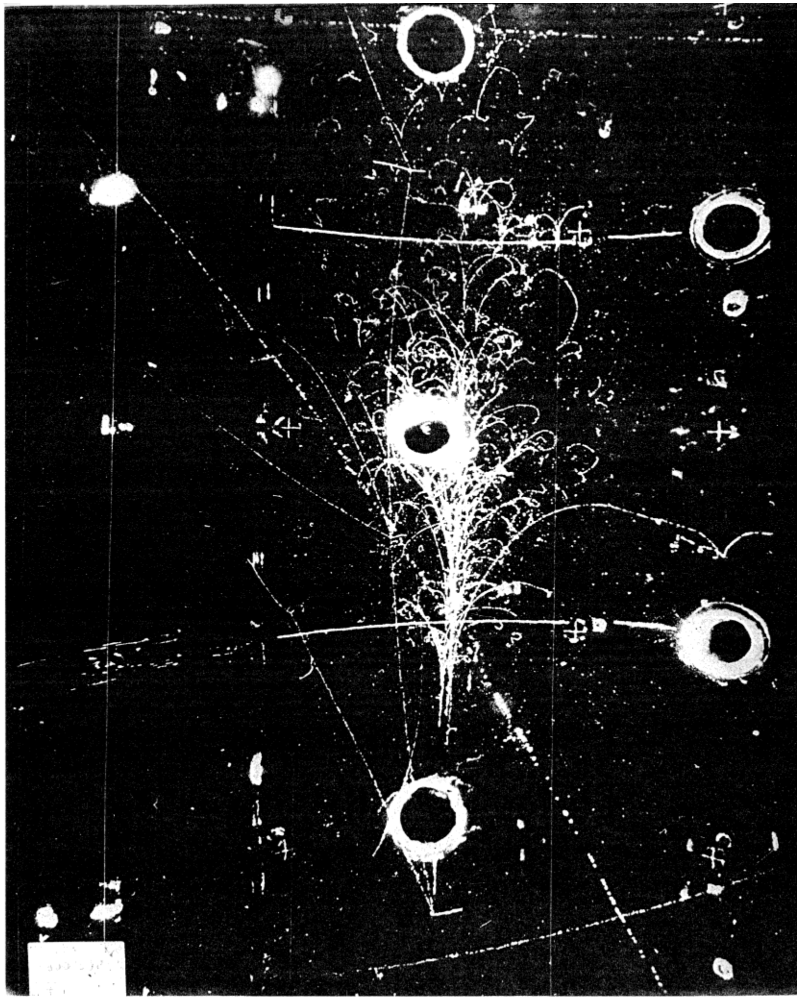
An early NC candidate

- 3-prong event
- very clean
- no muon
- total visible energy about 6 GeV

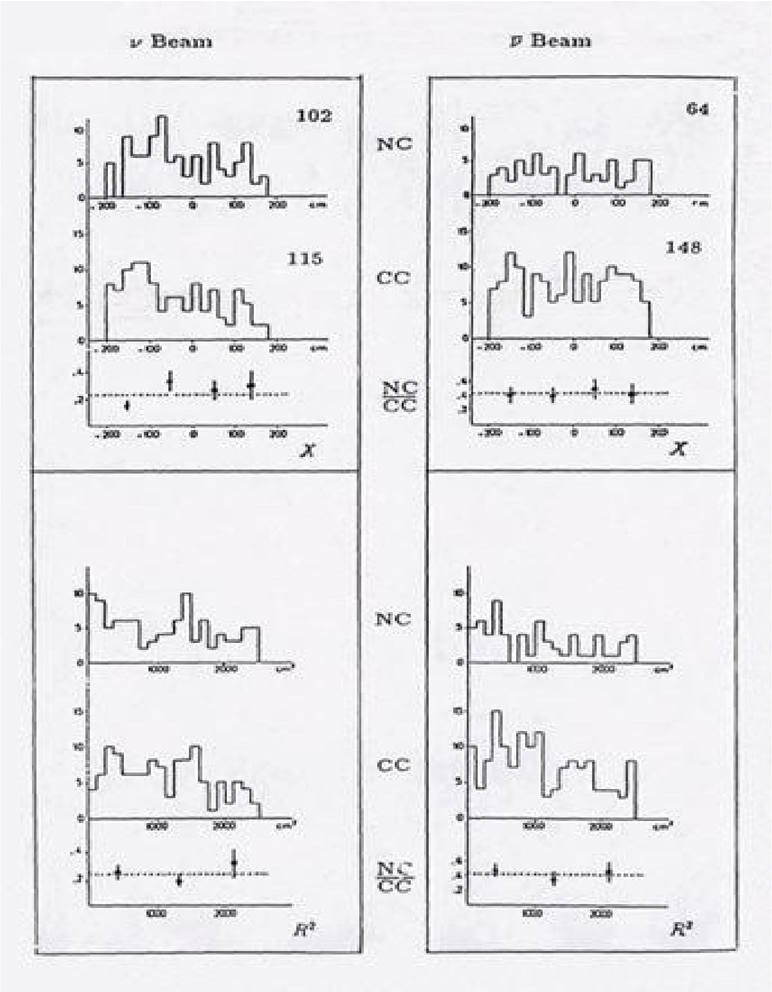


A spectacular NC-candidate

- Event found in Brussels
- All final state particles interact
- High energy neutral pion producing a huge electromagnetic shower



Status March 1973



- Compare hadron final state of NC with CC(=ν):

  X=along beam direction

  R=radial

- NC = ν- or n-induced ?
- 3 arguments for ν-origin

  NC/CC is flat and big

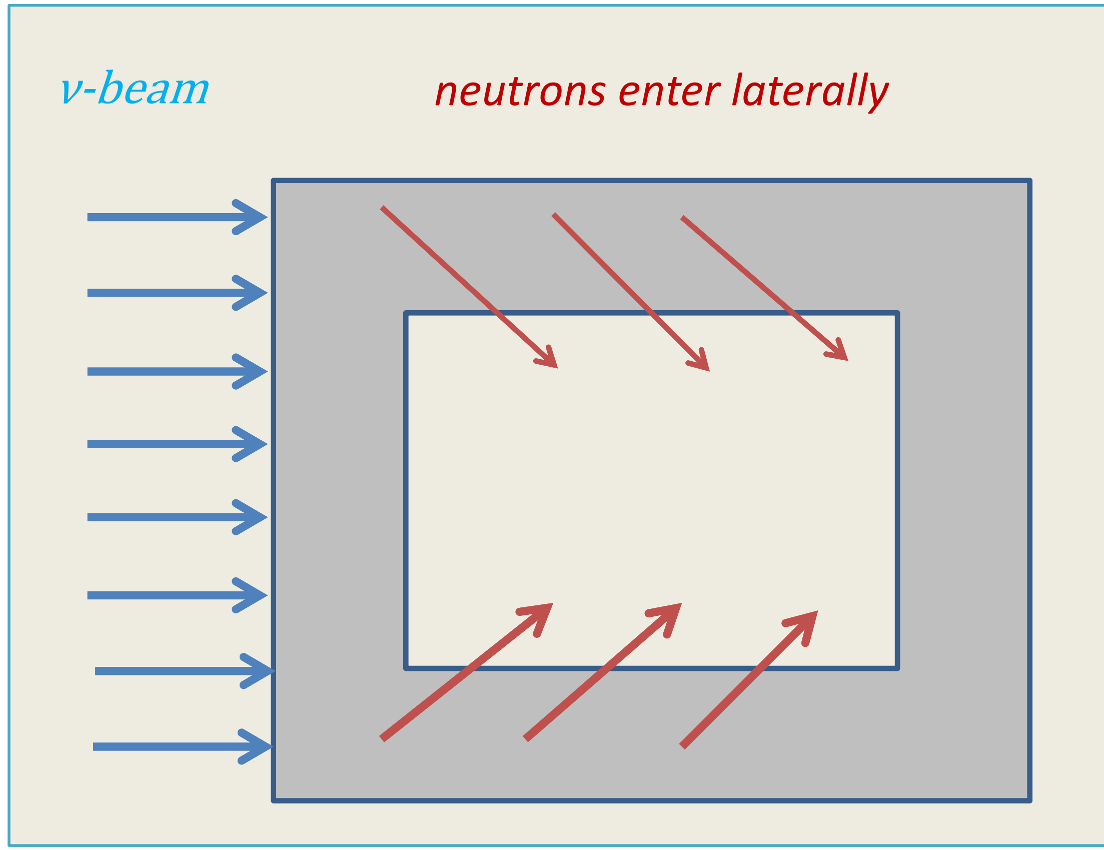
  NC look ν-like

  NC do not look n-like

Counter Argument #1

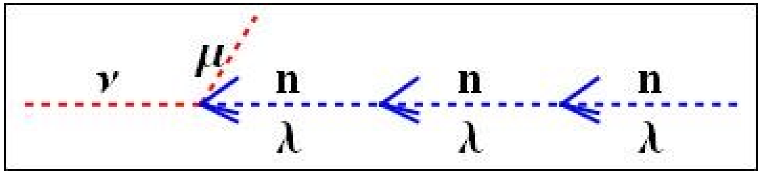
- Broad ν-beam
- Dense matter around chamber (coils)

→ neutrons enter sideways and generate a flat X-distribution



Counter Argument #2

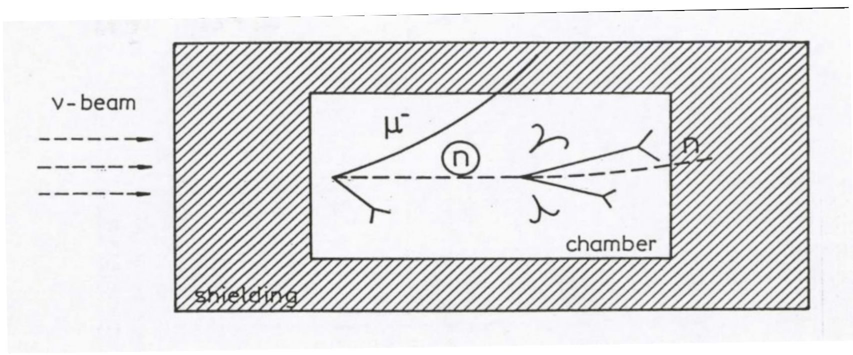
The neutron cascade :



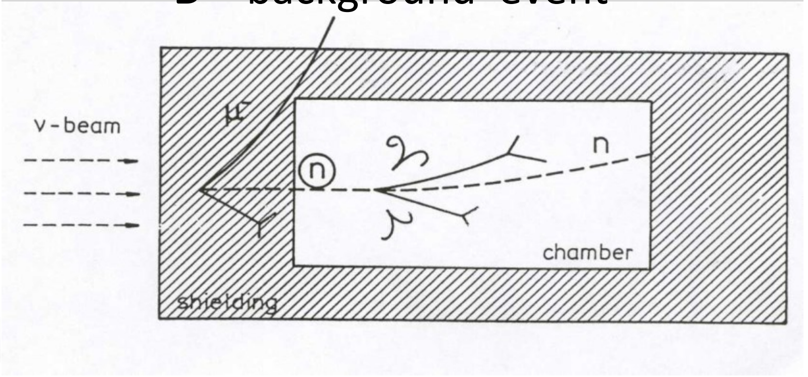
Jack Fry

Observe in the chamber :

beginning of cascade
AS = associated event



end of cascade
B = background event



Conclusion : Background proportional to cascade length
need quantitative calculation of n-background

Background Calculation

Discovery only if $\#n \ll \# NC$

Need quantitative estimate of n-background

Ingredients

Matter distribution	Known
Neutrino flux	Measured
Dynamics of final hadron state	From ν-events
Evolution of hadrons in matter	Need cascade model

Breakthrough : cascade only transported by nucleon
extract elasticity from pp-data

Predict neutron background : no free parameter

The Proof

D.Haidt

Given : 102 NC candidates in ν-film and 15 AS

Worst case : **All NC are background**

$$\frac{\#B}{\#AS} = \frac{\#NC}{\#AS} = \frac{102}{15}$$

Cascade program predicts : $\frac{B}{AS} = 1 \pm 0.3$

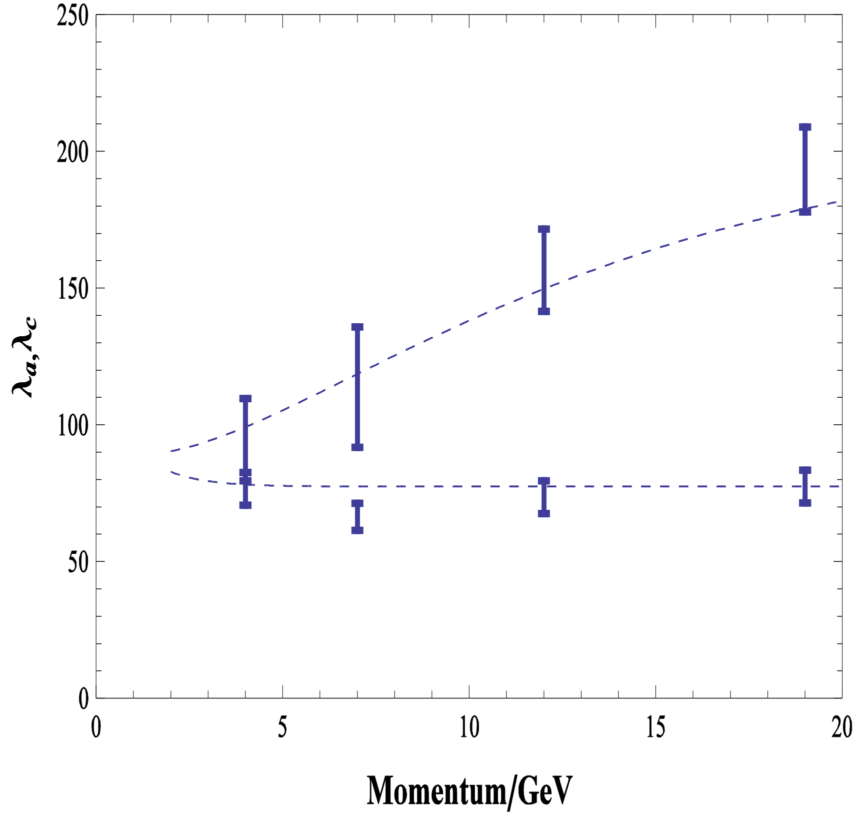
Hypothesis wrong : **a new effect exists**

The Hot Fall 1973

Cronology of events	
July	Gargamelle Publication
End August	Electron Photon Conference at Bonn CN Yang : NC by Gargamelle and HPW The highlight of the conference
Sep/Oct	HPW modified setup NC effect disappeared Is Gargamelle wrong ? Neutron background underestimated ?
Nov/Dec	CERN Directorate inquires Special exposure to Gargamelle Observe p-induced cascade

Check the Background Calculation

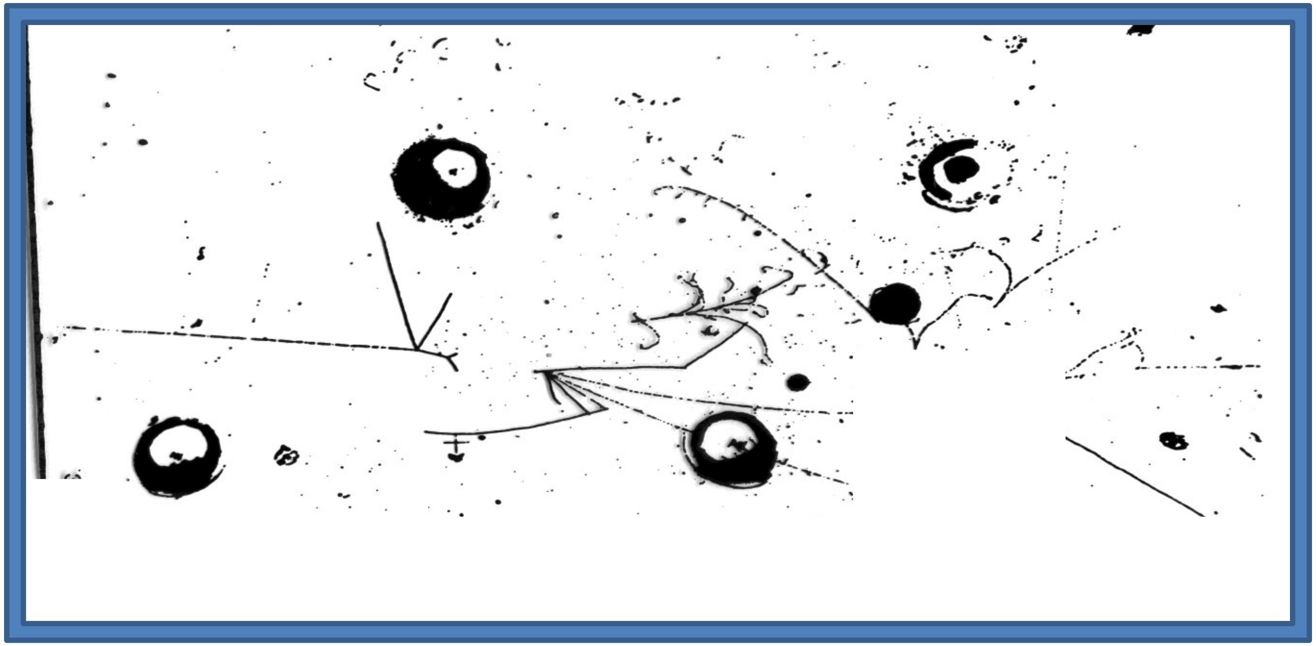
- Special runs in Nov+Dec 1973
- Gargamelle exposed to fast extracted proton pulses of 4, 7, 12 and 19 GeV
- Measure interaction length in chamber
- Measure cascade length



The cascade program is confirmed

A proton cascade in Gargamelle

Proton 7 GeV
enters Gargamelle



Event : 3241 671 view 2

Gargamelle : upgrade

Presented to APS-meeting Washington in April 1974

#events/film	BONN (8/1973)	WASHINGTON (4/1974)
#NC/film ν	$\frac{102}{111} = 0.92 \pm 0.13$	$\frac{102}{111} = 0.92 \pm 0.13$
#NC/film $\overline{\nu}$	$\frac{63}{276} = 0.23 \pm 0.03$	$\frac{70}{298} = 0.23 \pm 0.10$
#AS/film ν	$\frac{15}{111} = 0.14 \pm 0.04$	$\frac{40}{277} = 0.14 \pm 0.03$
#AS/film $\overline{\nu}$	$\frac{12}{276} = 0.04 \pm 0.01$	$\frac{14}{328} = 0.04 \pm 0.01$

Internal Method

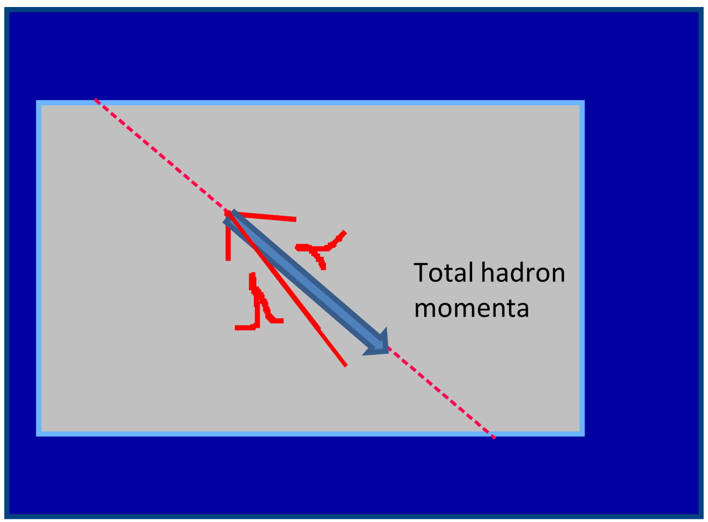
A.Pullia

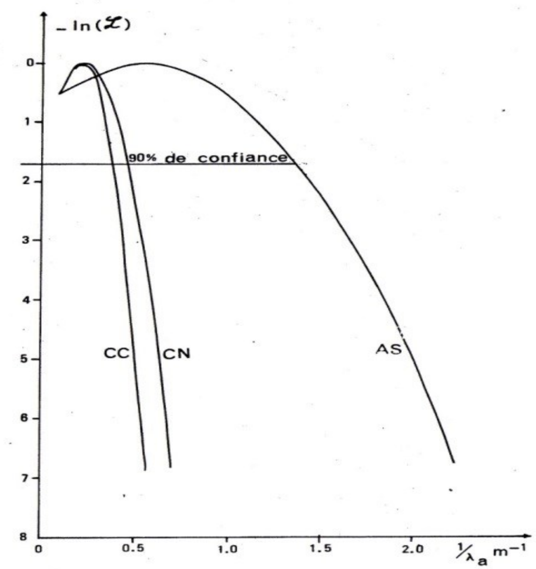
Idea: Interaction lengths of neutrinos and neutrons in chamber liquid are very different

Beam	1/λ for NC	1/λ for CC
ν	$0.16 \pm 0.10\ \mathrm{m}^{-1}$	$0.15 \pm 0.10\ \mathrm{m}^{-1}$
$\bar{\nu}$	$0.27 \pm 0.13\ \mathrm{m}^{-1}$	$0.10 \pm 0.10\ \mathrm{m}^{-1}$

$$\frac{1 - e^{-l/\lambda}}{1 - e^{-L/\lambda}}$$

l=flight path
L=potential path
λ=interaction length





Spring 1974 : The Happy End

1. Gargamelle
   - Double statistics
   - confirm background calculation
   - new method
2. HPW confirms muonless events
3. ANL : 12' BC exclusive n π^+ and p π^0 production
4. CITF: narrow band ν and $\overline{\nu}$

   new method: event length

The existence of weak neutral currents is finally accepted