The Discovery of Weak Neutral Currents

Dieter Haidt
DESY, Hamburg

Historic Neutrino Conference
Paris, 5-7 September 2018

GARGAMELLE

André Lagarrigue
- the father of
Gargamelle

Brief chronology

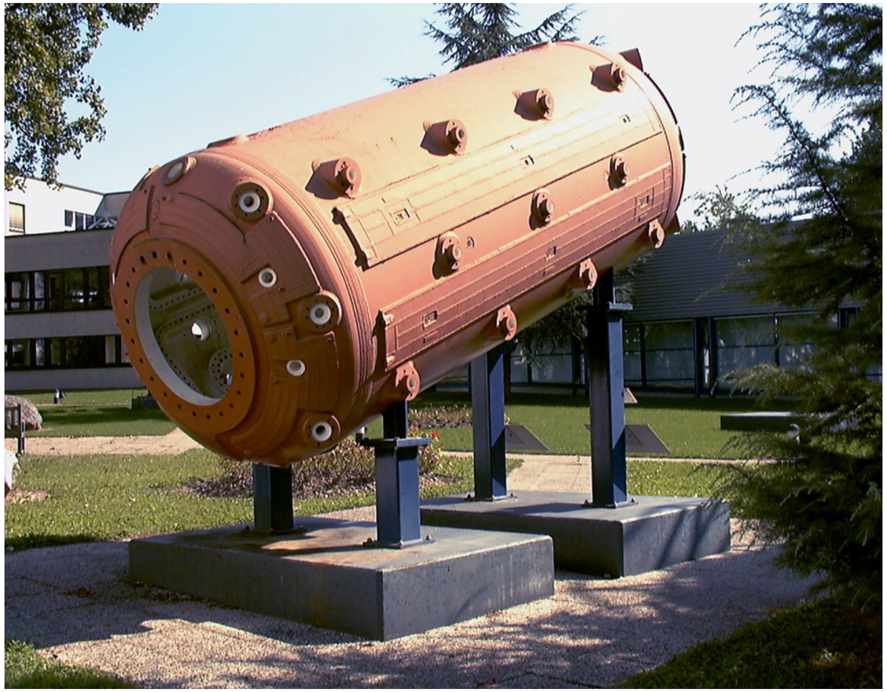
1963 conceived as large
2nd generation bubble chamber
geometry R=1m L=4.8m
heavy liquid (CF_3Br and C_3H_8)
good identification of final state

1970 installed at CERN

1971 first run in WB ν and ν̄-beams

1973 discovery of NC

1978 break down (crack)



Gargamelle emerita

Today exhibited on CERN ground

A Historic Moment

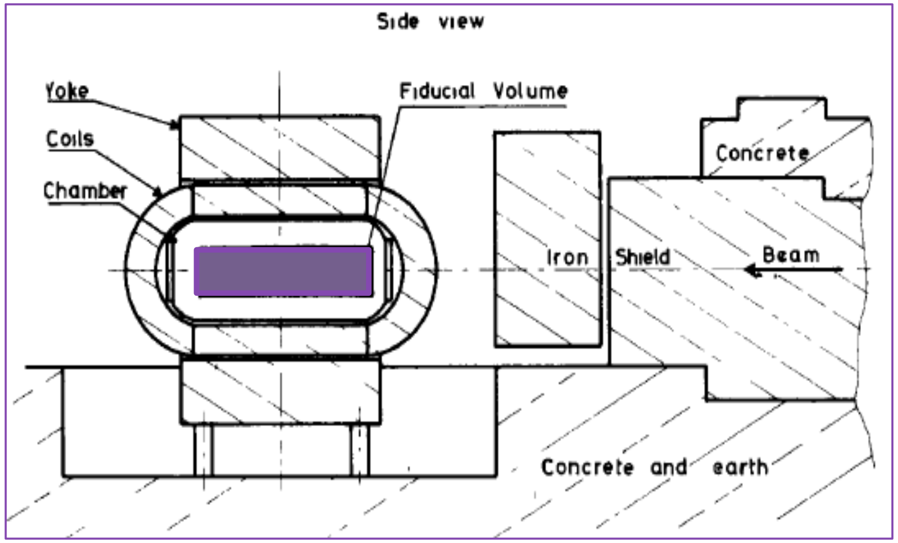
- End of 1971 : M.K.Gaillard, B.Zumino, J.Prentki, C.Bouchiat, M.Veltman approach Gargamelle and Weinberg HPW

1. Weinberg : There is a model combining leptonic weak and electromagnetic interactions based on the gauge symmetry $SU(2)\times U(1)$
2. 't Hooft : this model is renormalizable
3. The key element : **weak neutral currents**

Request : look for ν+e→ ν+e and ν+N→ ν+X !

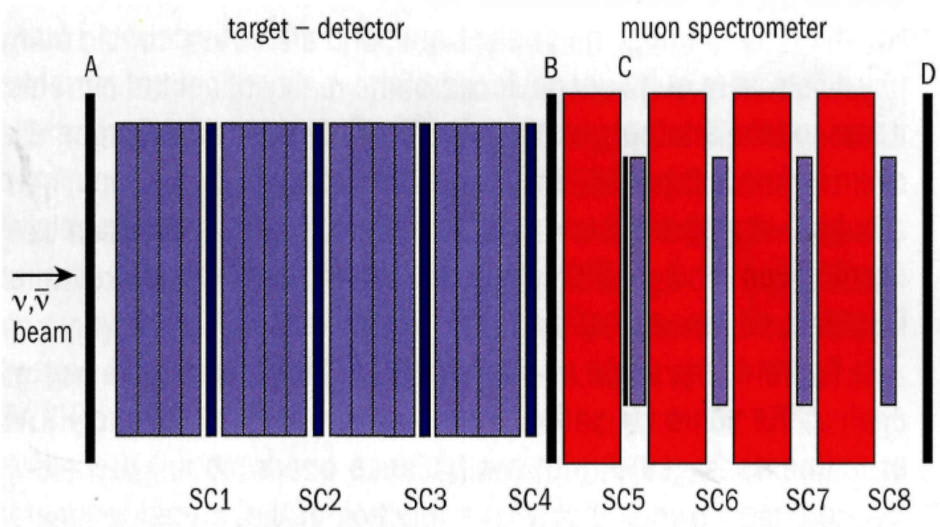
Two Detectors

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

GARGAMELLE

- Approved 1970
  priority : nucleon structure
- Data taking 1971/2
- Heavy liquid bubble chamber
  strong magnet coils, shielding
- CERN PS Booster 24 GeV
- WB hornfocussed ν and $\bar{\nu}$ beams 1-10 GeV
- Record everything

E-1A HPW

- Approved 1970
  priority : W search
- Data taking end 1972+spring 73
- Target calorimeter + muon spectrometer
- NAL PS 200/300 GeV
- WB beam mixed ν and $\bar{\nu}$
  10-200 GeV
- Set trigger to select interesting events

Note: Excellent research topics – but not Neutral Currents !
Sudden change of priority to NC search in 1972

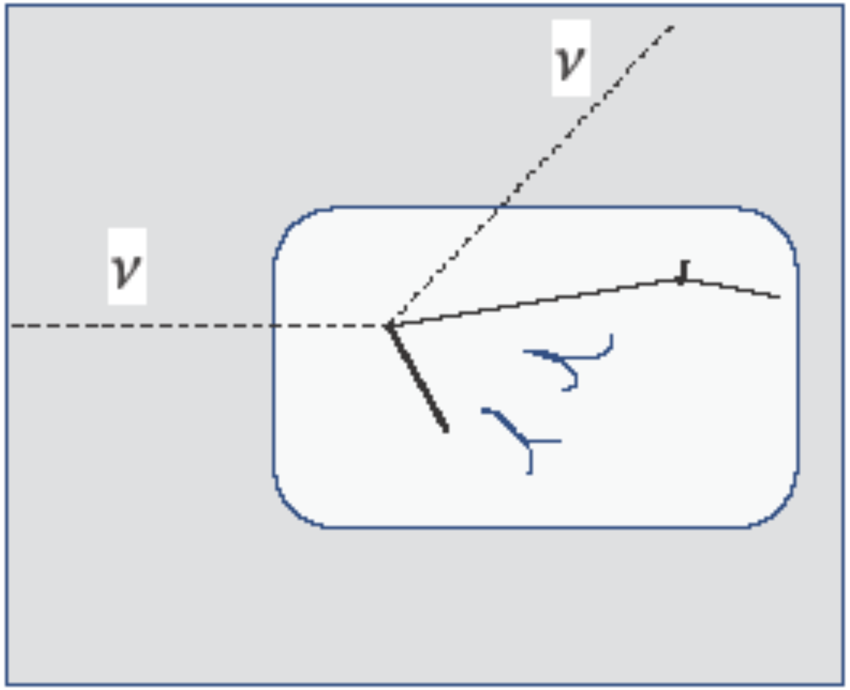
Searching for a new effect

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

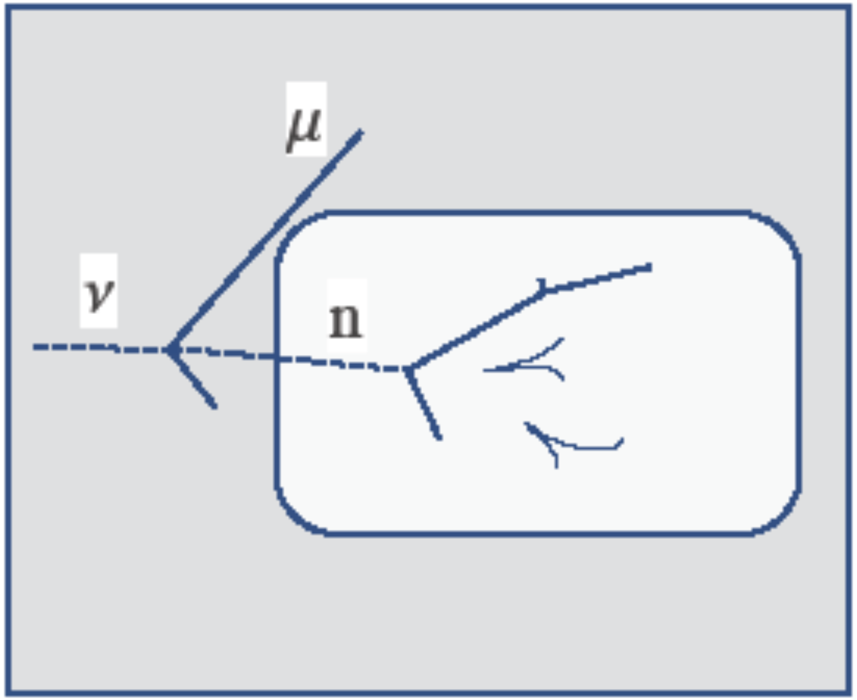
Claim a discovery if
$\#$ signal $\gg$ $\#$ background

Gargamelle

Signal

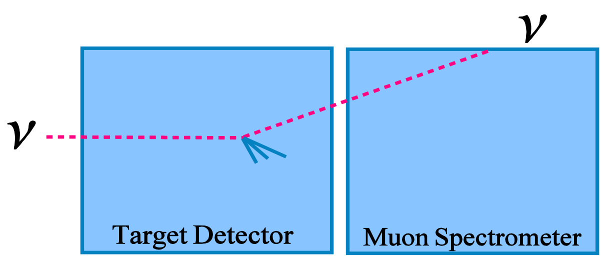


Background

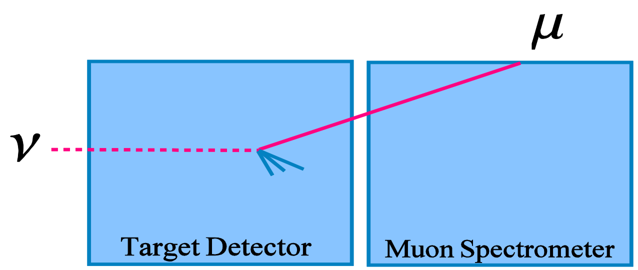


E-1A

Signal



Background



Need two independent triggers :
energy deposition and no muon

CC events with wide angle muon escaping
No worry about punch through

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

- 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

An exciting leptonic NC candidate

360000 pictures scanned
Isolated forward *e* found
at Aachen in Dec 1972.
Interpretation:

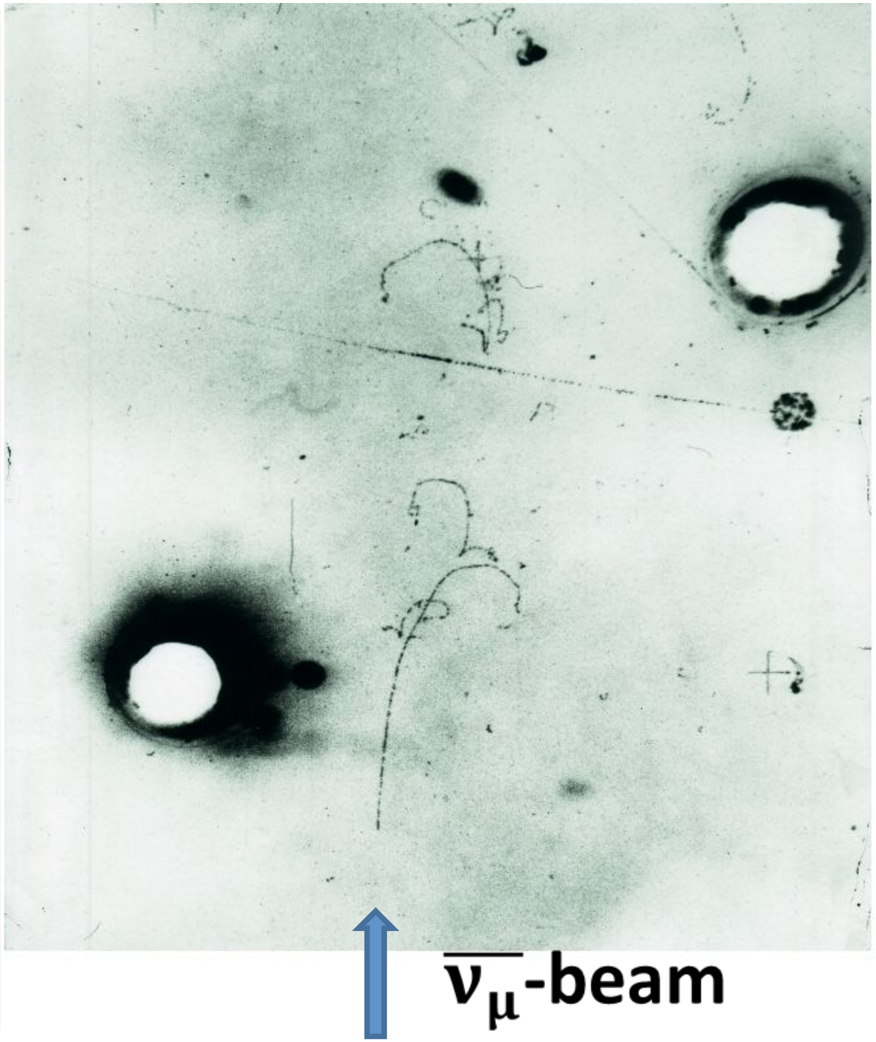
$$\overline{\nu_\mu} e \rightarrow \overline{\nu_\mu} e$$

Properties of electron :

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

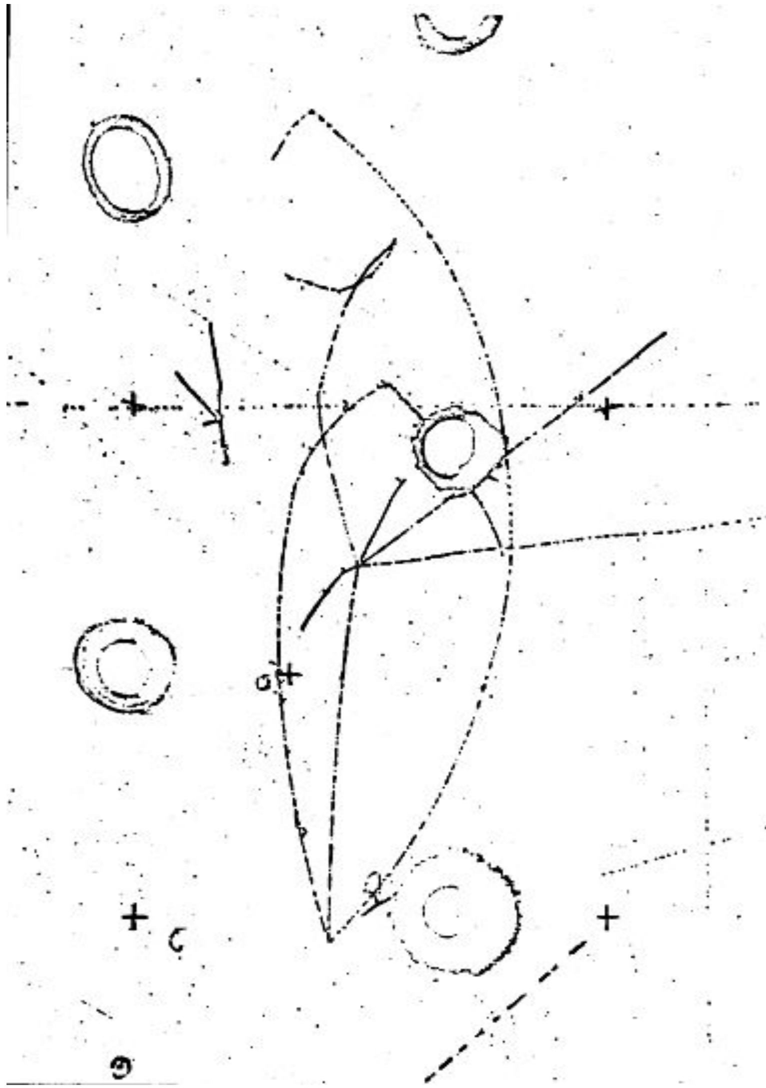
Background : 0.03 $\pm$0.02

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



An early NC candidate

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



The March 1973 Meeting
Euphory and Doubts

Euphory

- The unique $\bar{\nu}e$-candidate
- Many candidates without μ
- Subsample of CC events
  ignoring the μ and imposing the
  same criteria on hadrons

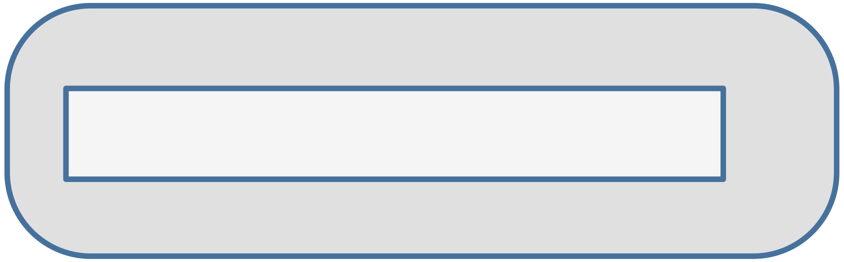
Expected shape of distribution along chamber axis:

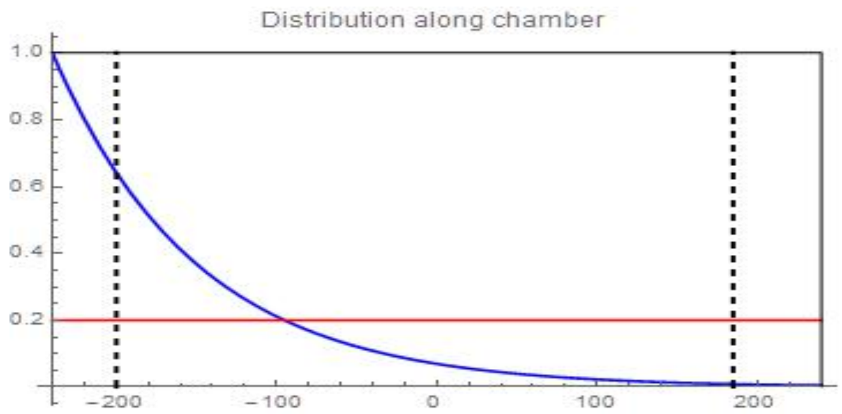
1. If NC candidates n-induced, then
   exponential falloff
2. If NC candidates ν-induced, then
   flat distribution
3. The CC-subsample flat

Distinctive features:

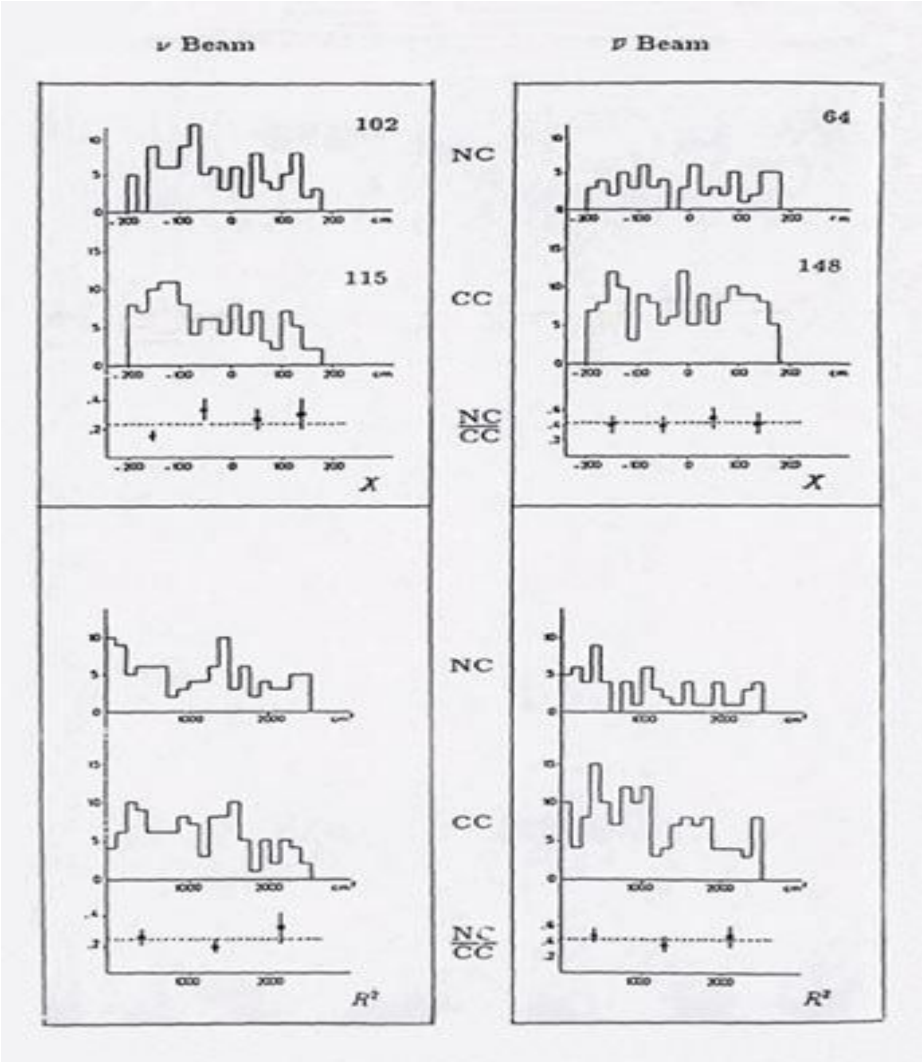
n : exponential falloff (λ≪L)

ν : everywhere flat (λ≫L)





The Data



- Compare hadron final state of NC with CC (no μ) and form NC/CC
  - X=along beam direction
  - R=radial
- **NC = ν- or n-induced ?**
- 3 arguments favour ν-origin
  - NC/CC is flat and big
  - NC look ν-like
  - NC do not look n-like
- Oversimplified ORSAY Monte Carlo disfavours neutrons

A discovery at hand ?

Damped Euphory

Two critical arguments

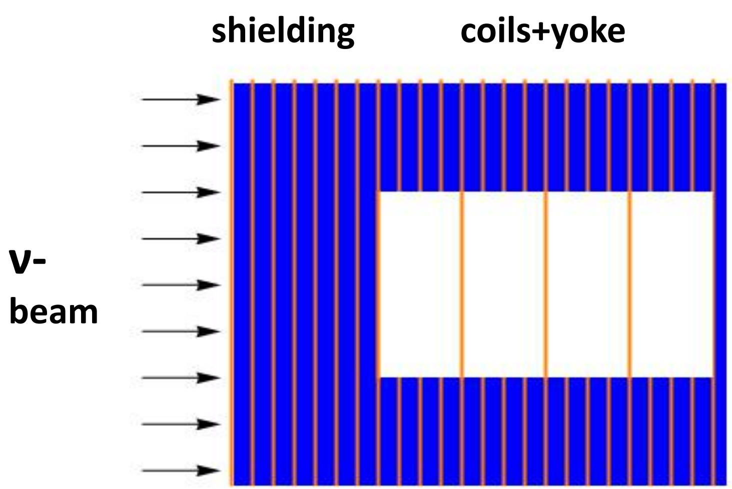
- Neutrons make cascades
  → n-background ~ cascade length
  ORSAY MC underestimates neutrons
- Broad neutrino beam generates neutrons from sides→ appearing as flat distribution (sensitive to energy and angular distribution of neutrons

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



Neutron Background Calculation

Ingredients

Matter distribution	Complicated, but known
Neutrino flux	Measured
Dynamics of final hadron state	From ν-events
Evolution of hadrons in matter	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

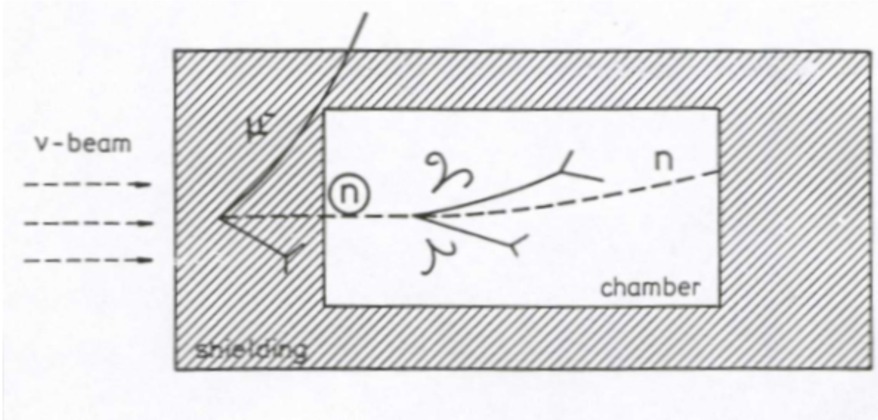
Elasticity distribution has been extracted from pp-data

Conclusion: Absolute prediction of neutron background

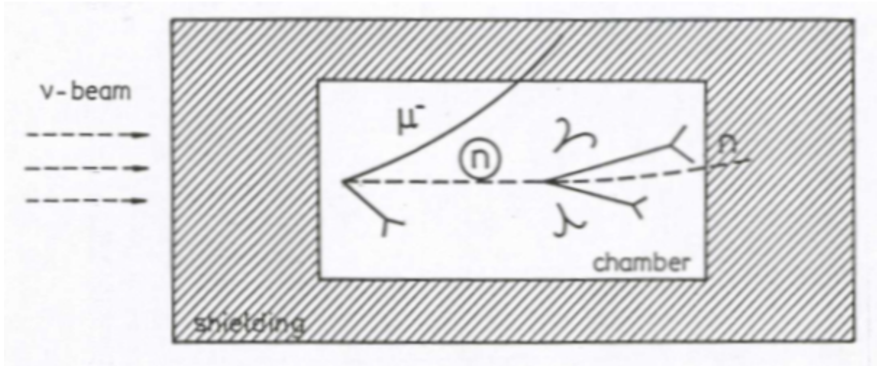
no free parameter

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 ν-film and 15 AS

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

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

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

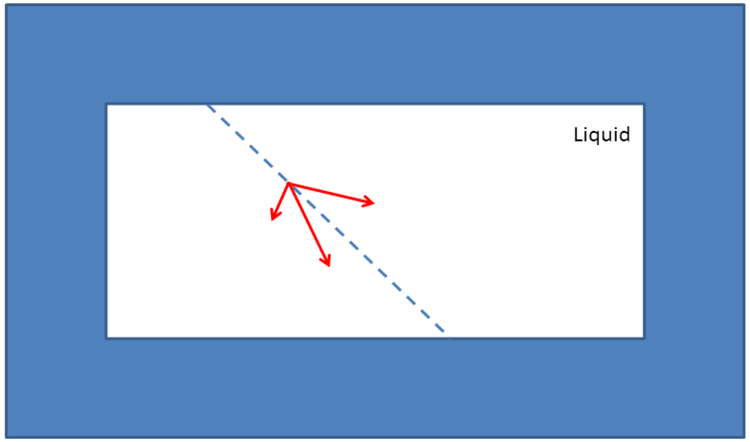
Similarly for antineutrino data

Hypothesis must be rejected : **a new effect exists**

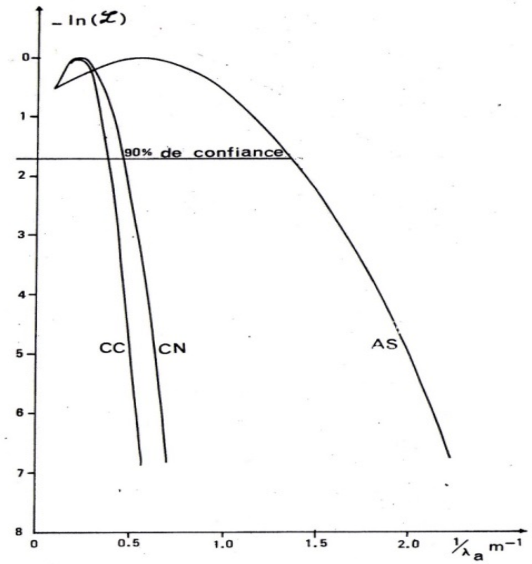
After hot and intense discussions submit paper July 25, 1973 to Phys.Lett.

Internal Method

Idea: Reconstruct for each event the flight direction from vector sum of final state hadrons
Then apply classical Bartlett method to obtain the apparent interaction length



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



Probability distribution :

$$\varphi(x)dx = \frac{e^{-x/\lambda}}{1-e^{-L/\lambda}} \frac{dx}{\lambda}$$

Measure : flight and potential paths x and L
for each event
Max Likelihood-fit to NC and CC samples

Conclusion : 1/λ(NC) ≪1/λ(n)

The Authors of the Discovery Papers

Volume 46B, number 1 PHYSICS LETTERS 3 September 1973

SEARCH FOR ELASTIC MUON-NEUTRINO ELECTRON SCATTERING

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Received 2 July 1973

Volume 46B, number 1 PHYSICS LETTERS 3 September 1973

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

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Received 25 July 1973

Deceased: Lagarrigue, Rousset, Musset, Rollier, Faissner, Schultze, Lanske, Nguyen-Khac, Camerini, Fry, Wachsmuth, Natali, Bullock, Violette Brisson

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

For the first time high energy **neutrino physics** included → from now on *Lepton-Photon* Conference

GGM presentation of results on weak neutral currents

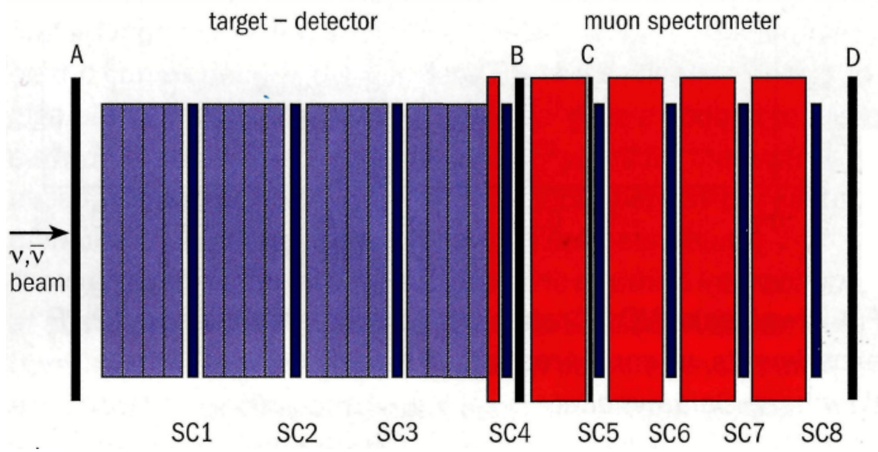
1. The published Gargamelle analysis
2. Include last minute contribution from HPW
   (based on analysis submitted to PRL in May 1973)
3. Contribution from Argonne 12 ft BC: exclusive 1-pion channel
4. First attempt to compare with theory : $sin^2\theta \approx 0.3$

C.N.Yang announces at the end of the conference : **NC exist**

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 I
- General suspicion: GGM is wrong because of error in treating neutrons
- Way out : YES or NO by special exposure of Gargamelle with proton pulses to test explicitly the neutron cascade

Modified HPW-detector



Introduce 13' iron plate (red) :
increase muon acceptance
fatal consequence : punchthrough
NC misidentified as CC
thus : loose NC effect

HPW Publication History

- July 17, 1973

  Rubbia informs Lagarrigue : 100 NC events
- August 3, 1973

  submitted tp PRL

  also submitted to 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
- Februar 25,1974

  new paper submitted to PRL
- April 1974

  Published in PRL 32 (1974) 800

  Existence of neutral currents confirmed

November 13, 1973

Professor A. Lagarrigue, Director
Linear Accelerator Laboratory
University of Paris - SUD
Centre D'Orsay
Batiment 200
91405 Orsay
France

Dear Professor Lagarrigue:

We write to inform you of the preliminary result of our recent experiment to search for neutrino interactions without final state muons. As you know, our apparatus was modified to provide a much larger detection efficiency for muons relative to the apparatus that was used in our earlier search for muonless events. We also improved our ability to locate accurately vertices of observed neutrino interactions, and lowered the threshold on the total energy of the hadrons in the final state.

From about one half of the data obtained in our recent run, we find the raw ratio $R_{raw} = 0.18 \pm 0.03$. We estimate the muon detection efficiency of the apparatus for the enriched antineutrino beam that was used in this experiment to be approximately 0.85. Taking into account small backgrounds produced by incident neutrons and by ν_e in the incident beam, the corrected ratio is $R_{corr} = 0.02 {}^{+0.05}_{-0.03}$, where the error includes an estimate of the uncertainty in the calculated detection efficiency. We are continuing to process the remainder of the data and to improve our understanding of the experiment.

We have written a paper intended for Physical Review Letters which will soon be submitted. A copy will, of course, be sent to you but for obvious reasons we wanted to convey our result informally to you before its publication.

With kindest regards

Yours sincerely,

D. Cline

A. K. Mann

D. D. Reeder

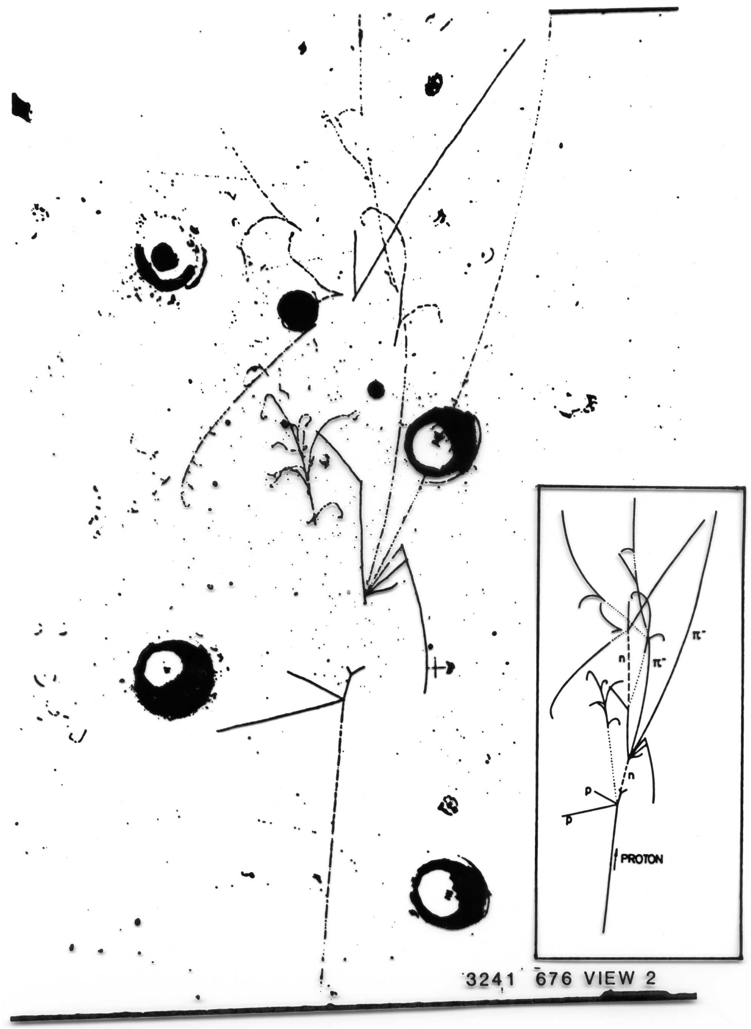
C. Rubbia

AKM/rs

Cascades really exist

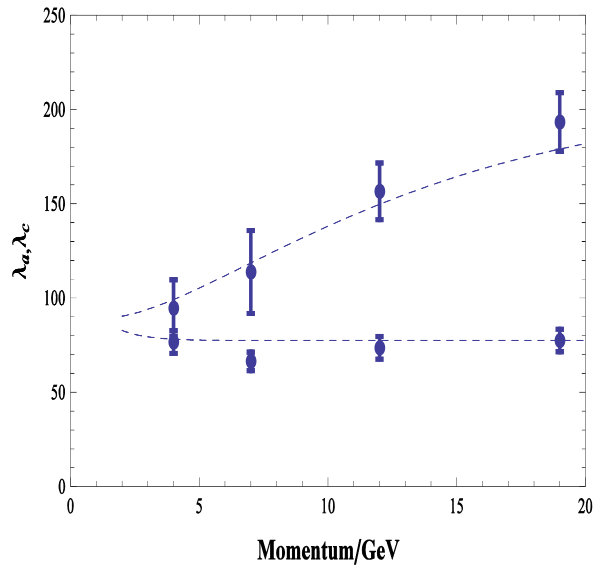
- Event from the special exposure of Gargamelle in Nov/Dec 1973
- A proton of 7 GeV is entering and generating (event 3241 671 view2)

  a neutron cascade
- The measurement of the first interaction gives the **apparent** interaction length of the chamber liquid
- Similarly the last interaction with energy deposition exceeding 1 GeV gives the effective **cascade** length



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 Wshington (April 1974)



All aspects of the cascade program are confirmed

Spring 1974 : The Happy End

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. HPW confirms finally muonless events (*the alternating currents*)
3. ANL : 12' BC exclusive n π^+ and p π^0 production
4. CITF : new experiment at NAL in narrow band ν and $\bar{\nu}$
   new method: event length

The existence of weak neutral currents is finally accepted

The Impact of the Discovery

- All major laboratories define a long range research program to explore the new force
- Two immediate applications

  1. Gravitational collapse

     W→ $e\nu$ also Z → νν (e,μ,τ)

  2. Predict W- and Z-masses

$$M_W = \frac{\sqrt{\frac{\pi\alpha}{\sqrt{2}G}}}{\sin\theta} = \frac{37.3 \text{ GeV}}{\sin\theta} \approx 70 \text{ GeV}$$

Propose $\bar{p}p$ experiment

CERN collider

- Start the electroweak way:

  weak and electromagnetic forces

  are on equal footing
- Breakthrough to gauge theories

  radiative effects

  nonabelian nature
- Develop and test models
- Push frontiers in

  energy → new colliders

  precision → large calorimeters
- Large collaborations
- Computing

Epilog

- Gargamelle was an excellent collaboration with an excellent pioneering spirit
- It was an exciting time seeing the huge progress of electroweak physics and QCD
- It was my first *large collaboration*, though small in today's standard
- It was a life without email, without ready-to-use computer codes, without laptop, but punching cards, handwritten slides,…

It was an honour for me to have been a member of Gargamelle and to feel the responsibility in a discovery situation