The History of Weak Neutral Currents

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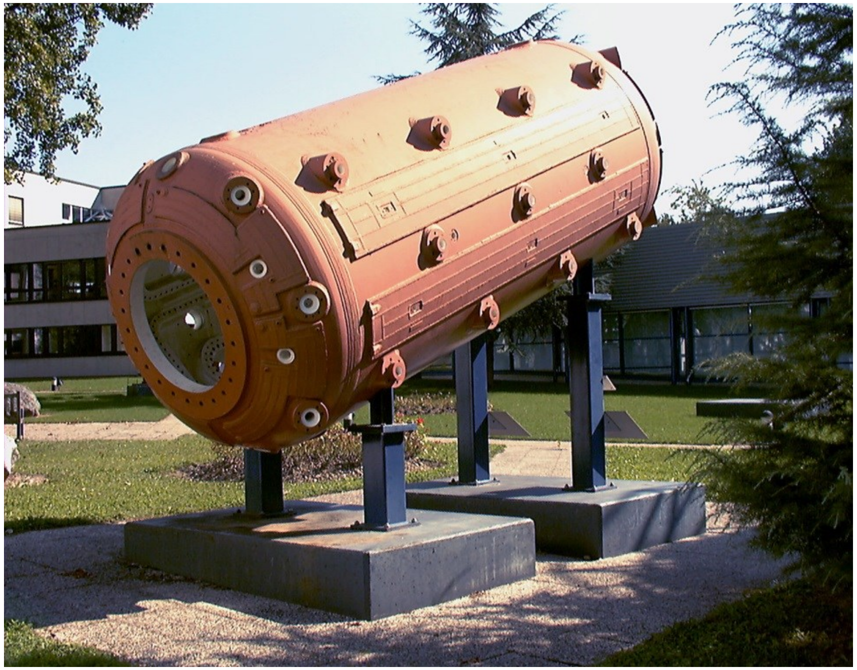
The Bubble Chamber **GARGAMELLE**

Start: 1970 at CERN

End : 1978



Famous for the discovery of weak neutral currents in 1973

Status : end 1950s

Two sofar 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 γ

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

Problem #1: YM-gauge boson must be massless

γ 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

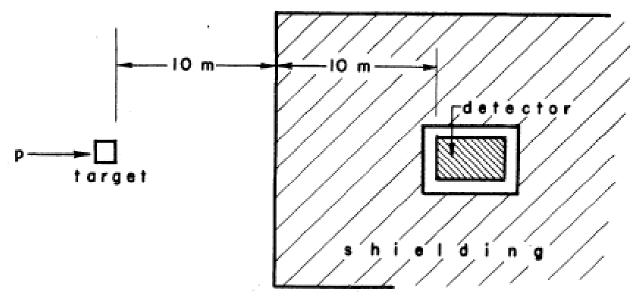
- High energy proton synchrotrons at CERN and BNL
- Pontecorvo and Schwartz propose high energy neutrino beam

  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 $\pi^+ -$ 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 → 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

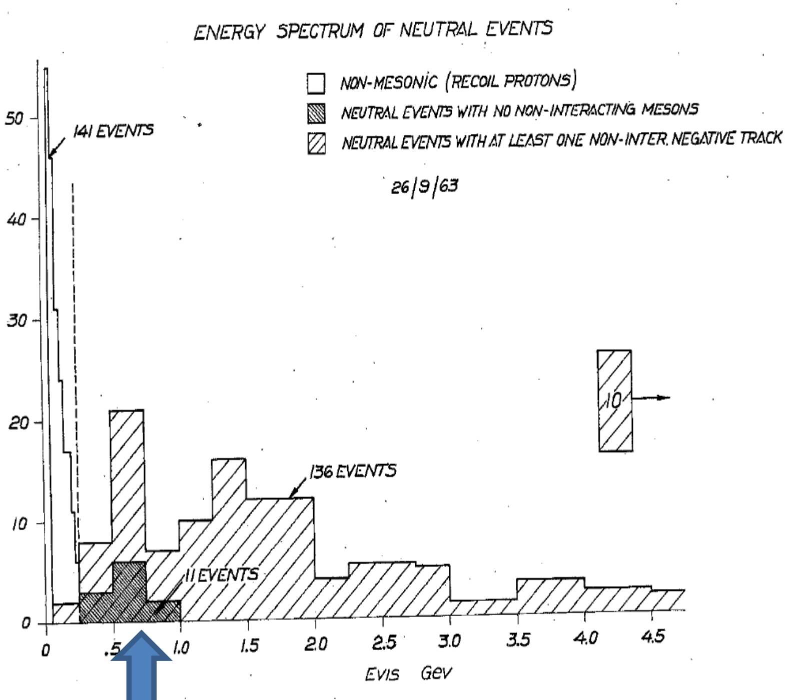
Long range neutrino program at CERN

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

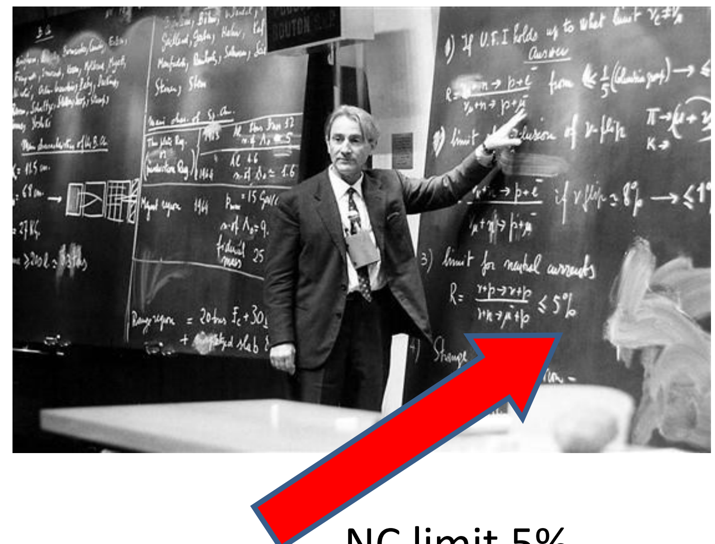
- Ramm Bubble Chamber

  search for $\nu + p \rightarrow \nu p$ and $\nu N \pi$



11 neutral current candidates

- CERN auditorium : Bernardini reports on SIENA conference



NC limit 5%

No evidence for NC

Community discouraged

Theoretical Progress

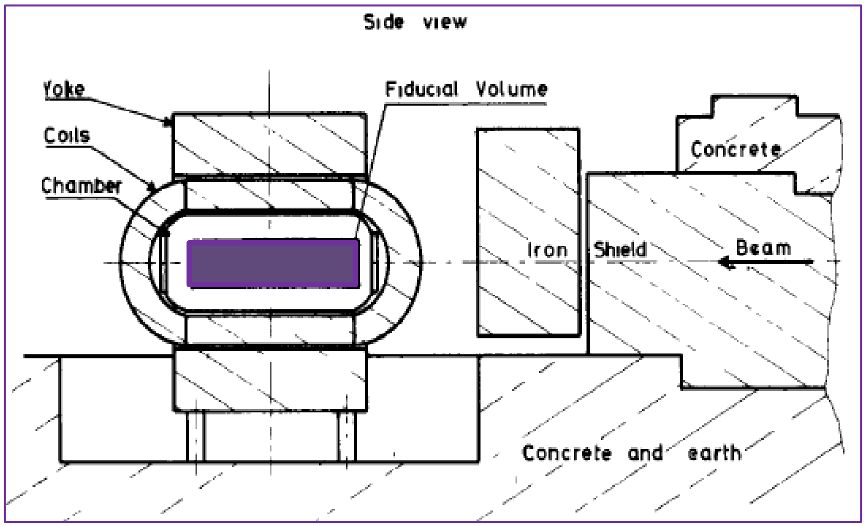
- Damp infinities with neutral weak boson Z (in addition to W)
- 1964 Higgs mechanism gives masses to W,Z
- 1967 Weinberg combines his work with Glashow, Salam, Higgs, Brout, Englert into model for leptons
- Problem with quarks : Cabibbo current $\bar{u}\ \gamma^{\lambda}$ (1-γ_5) (d cosϑ_C + s sinϑ_C)
  generates in GSW transitions ΔQ=0 and ΔS$\neq$ 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 'ṭ Hooft, Veltman show : model is renormalizable

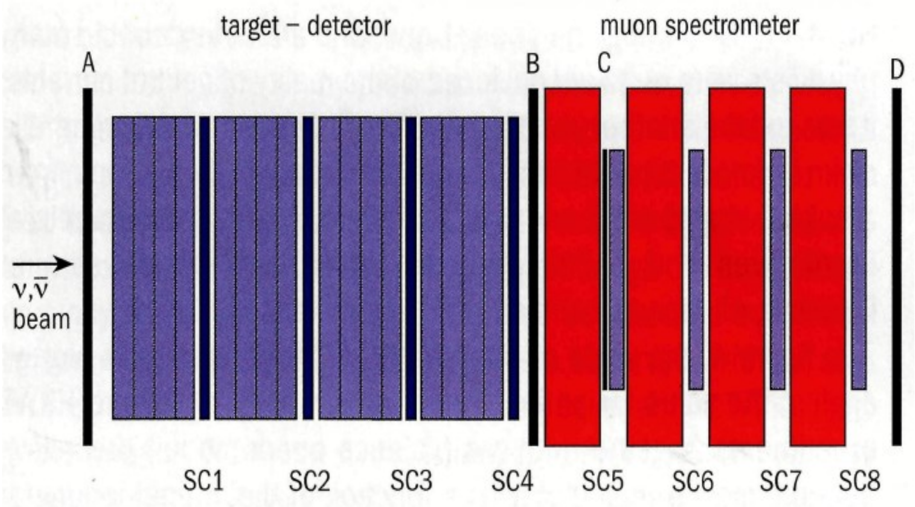
Model including both electromagnetic and weak interactions postulating a **new weak force**

Experimental Progress

Gargamelle at CERN PS

E-1A at NAL PS





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

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 **ν+e**→ ν**+e** and **ν+N**→ ν**+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

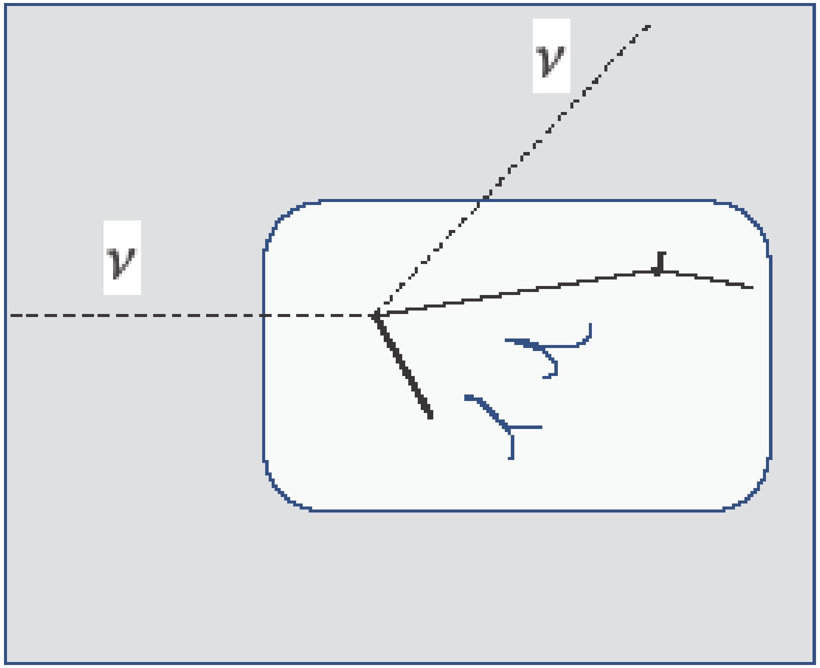
Searching for a New Effect

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

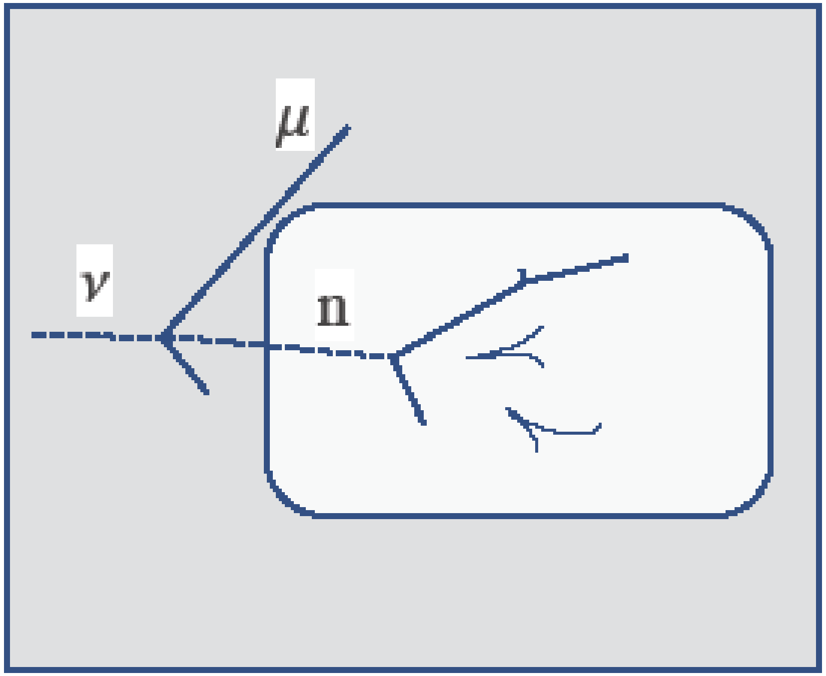
Claim a discovery if
signal $\gg$ # background

Gargamelle

Signal

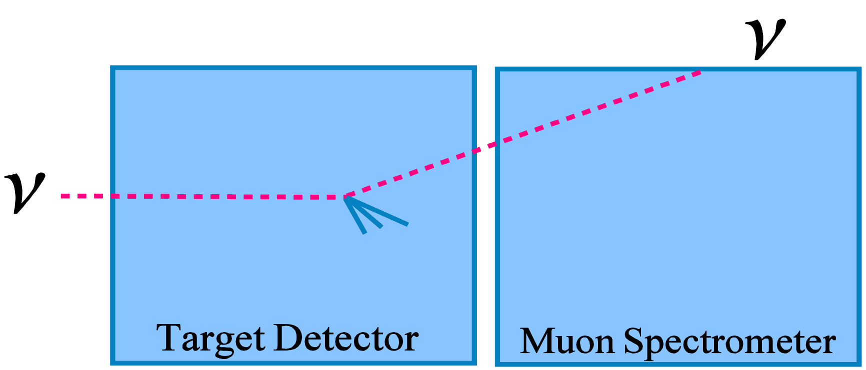


Background

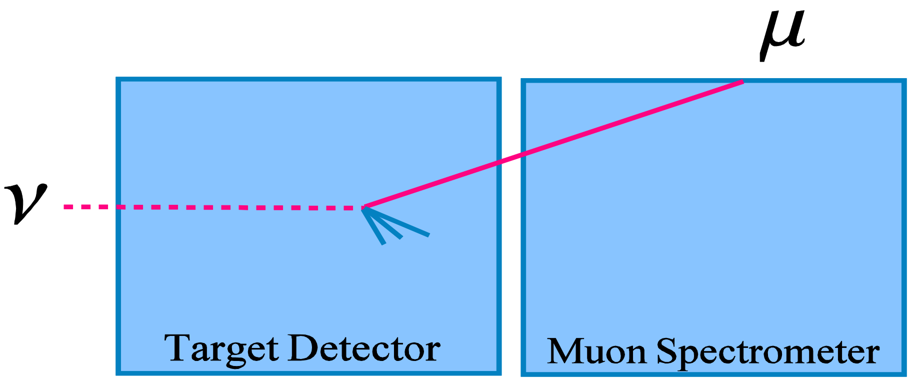


E-1A

Signal



Background



Need two independent triggers :
energy deposition and no muon

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

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 ν_μ elastic scattering

   $$\frac{\mu^-(\theta_\mu < 5°) + 0_p}{\mu^- + mp} = 1.3 \pm 7\%$$

2. Rate

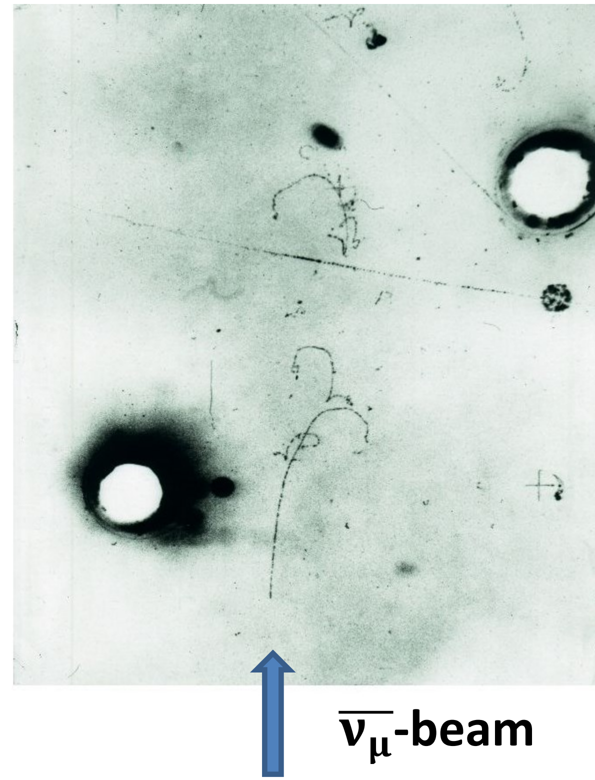
   observe 15 elastic ν_e - events in ν_μ - film

   ν_e -flux in $\bar{\nu}$ -beam 10 % of ν -beam

Conclude : Observed 1 event with background : 0.03 $\pm$0.02

Interpret as leptonic neutral current candidate :

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

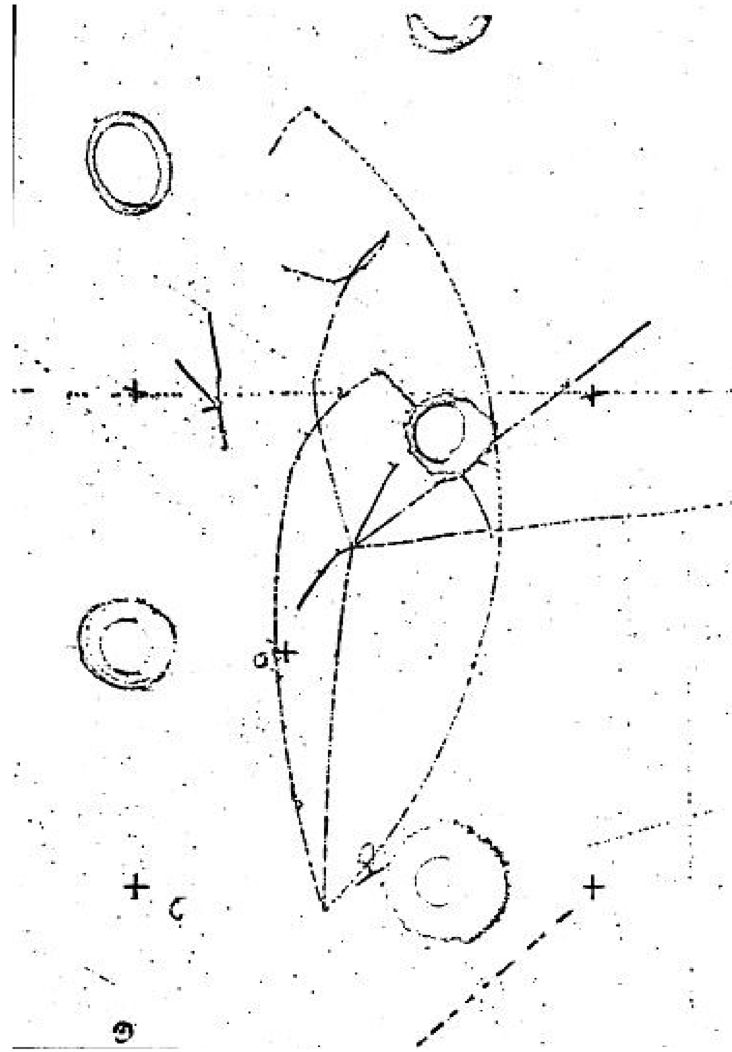


$\overline{\nu_\mu}$-beam

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

An early NC candidate

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



The March 1973 Meeting

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

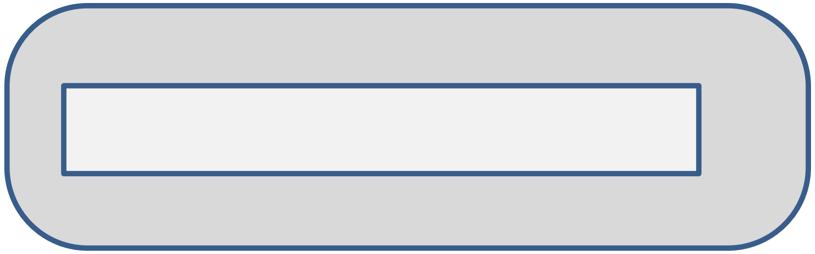
Expected shape of distribution along chamber axis:

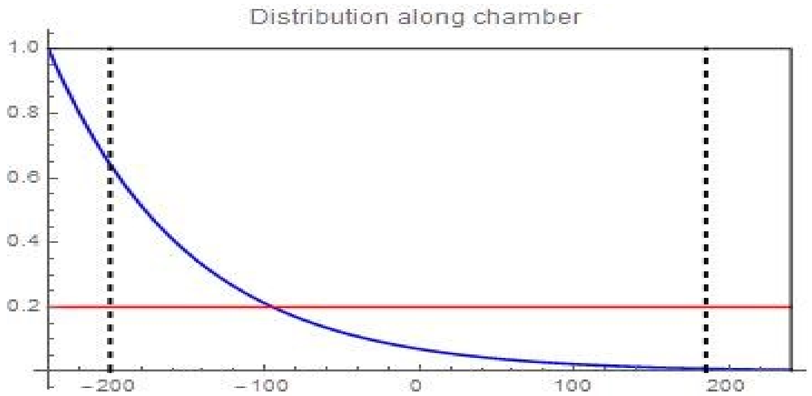
1. If NC candidates n-induced, then exponential falloff
2. If NC candidates ν-induced, then flat distribution
3. The CC-subsample flat

Distinctive features:

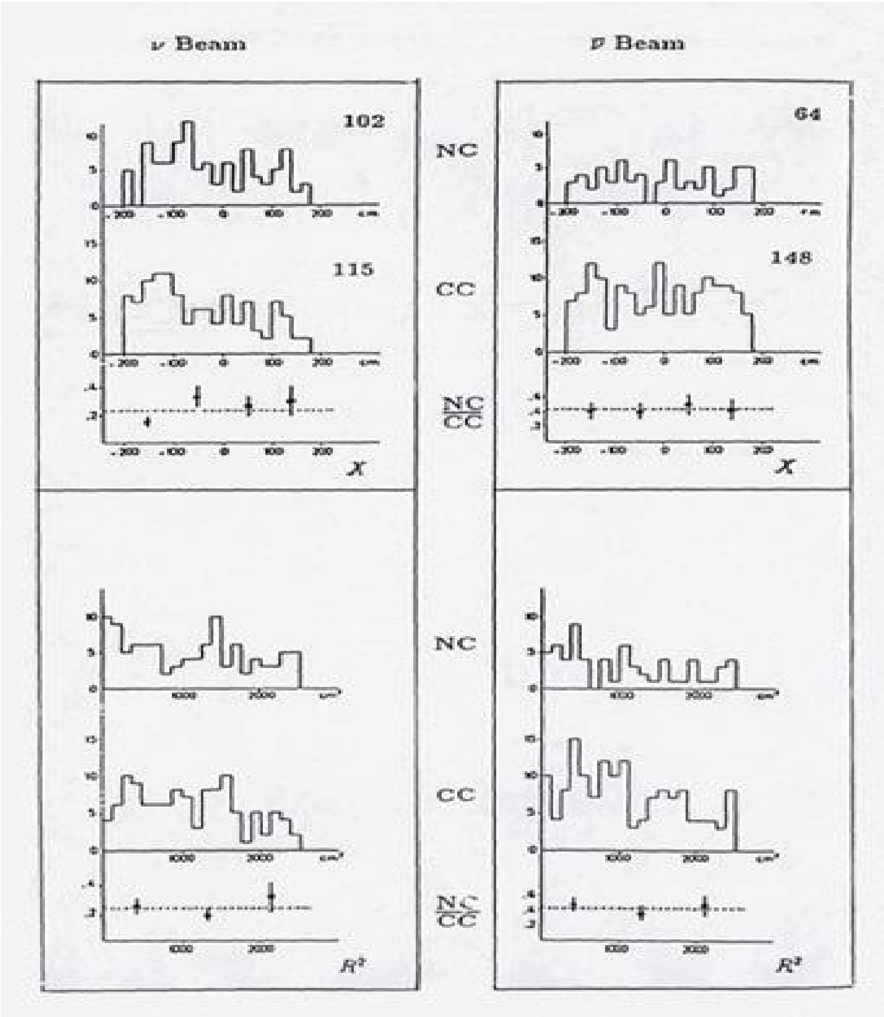
n : exponential falloff ($\lambda \ll L$)

ν : 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 = 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

Doubts : Two critical arguments

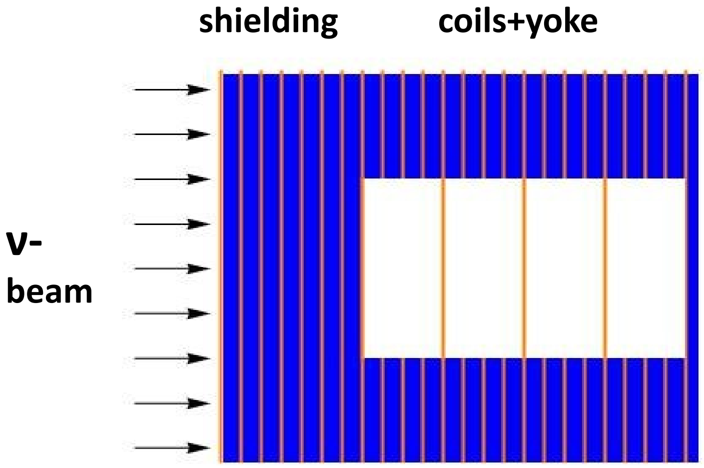
- Neutrons make cascades
  → n-background ∼ cascade length
  ORSAY MC underestimates neutrons
- Broad neutrino beam generates neutrons from sides→ appearing as flat distribution (sensitive to energy and angular distribution of neutrons

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



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

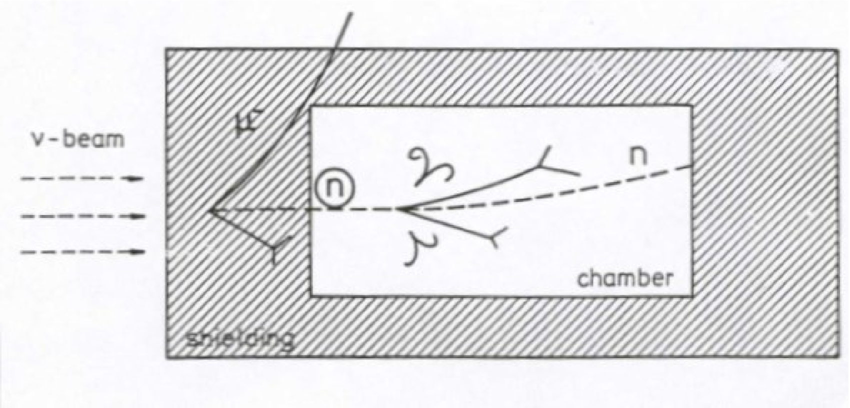
Elasticity distribution has been extracted from pp-data

Conclusion: Absolute prediction of neutron background

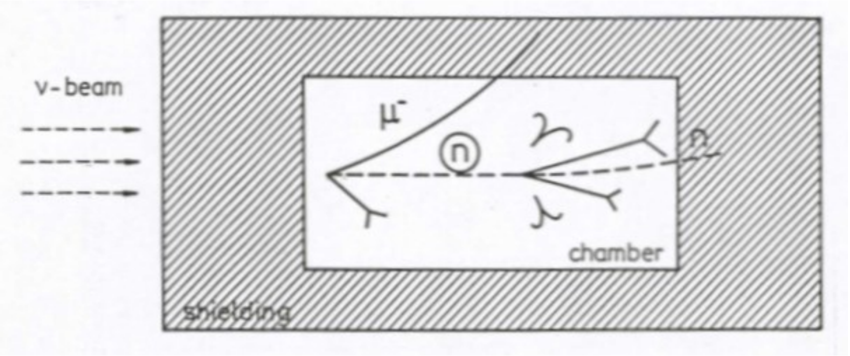
no free parameter

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**

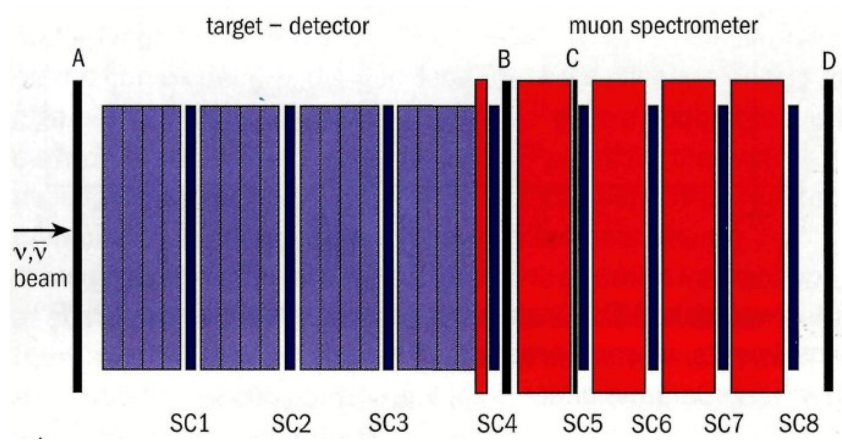
After hot and intense discussions submit paper July 25, 1973 to Phys.Lett.

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 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

HPW Publication History

- 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
- 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 $R_{corr} = 0.02 {+0.05 \atop -0.03}$, 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

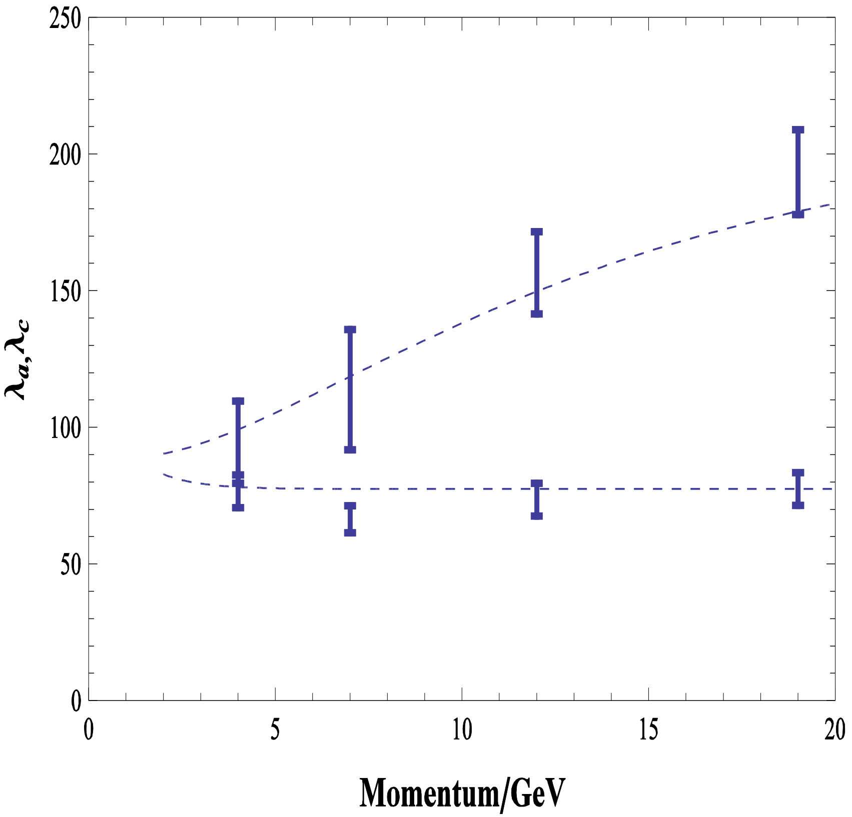
D. D. Reeder

C. Rubbia

AKM/rs

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)

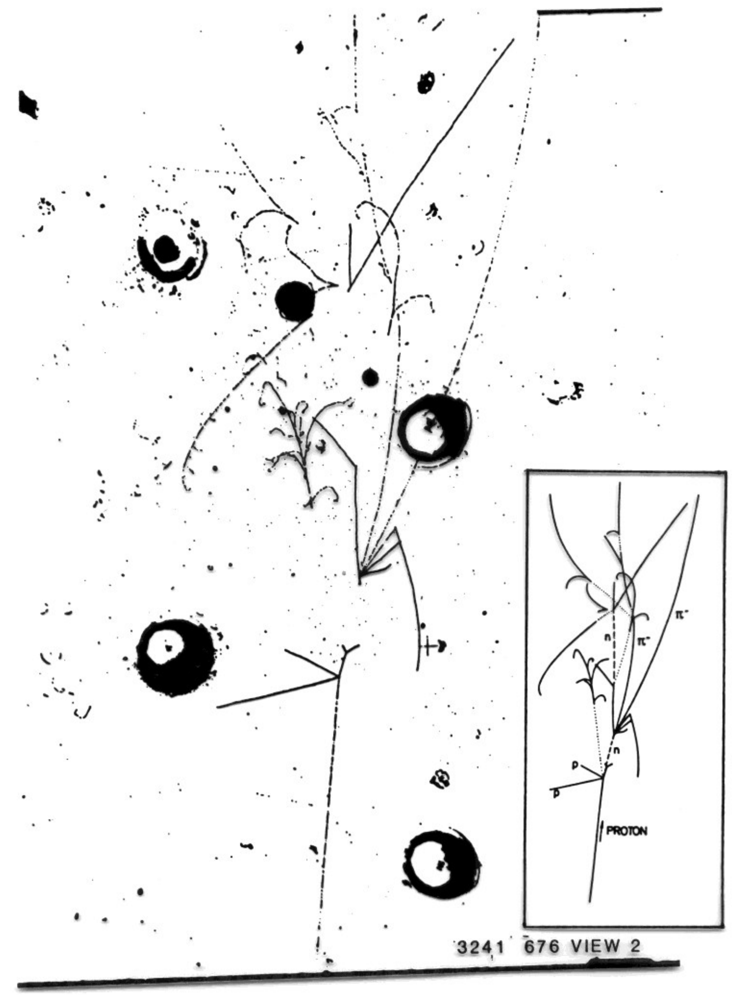


All aspects of the cascade program are confirmed

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 **apparent** interaction length of the chamber liquid
- Similarly the last interaction with energy deposition exceeding 1 GeV gives the effective **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 ν 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

2010	**Discover Higgs Boson**	CERN LHC
2000	ν_τ	Tevatron
	Discover t-quark	Tevatron
	Predict mass of t	Loop corrections
	W-propagator	HERA
1990	Z-resonance	SLC/LEP
	Discover W, Z gauge bosons	CERN SppS
1980	GSW → Standard Model	
	τ b-quark → t-quark	
	Predict masses of W,Z	Propose SppS
1970	**Discover Weak Neutral Currents**	CERN PS

The Weak Neutral Current

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

1. Measure the chiral couplings of the fermion f independent of a model
   Known flavours 1973 : (ν_e, e) , (ν_μ, μ), beginning of QPM with u, d, s
2. GSW : $f_{L,R} = I^3_{L,R} - Q_f \sin^2\Theta_w$
   First test : **single** parameter weak angle Θ_w

Initiate a worldwide effort
Labs : CERN (PS and SPS) FNAL , BNL , ANL Serpuchov
Beams : Wide and narrow band neutrino and antineutrino covering 1 – 400 GeV
Targets : Bubble chamber liquids : CF3Br, C3H8, He, D2, H2
Calorimeters : Fe, marble
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, 1π)
Extraction of the chiral couplings depends on nuclear structure
Poorly known in the 70s; beginning of QPM and QCD

The $Zu\bar{u}$ and $Zd\bar{d}$ couplings

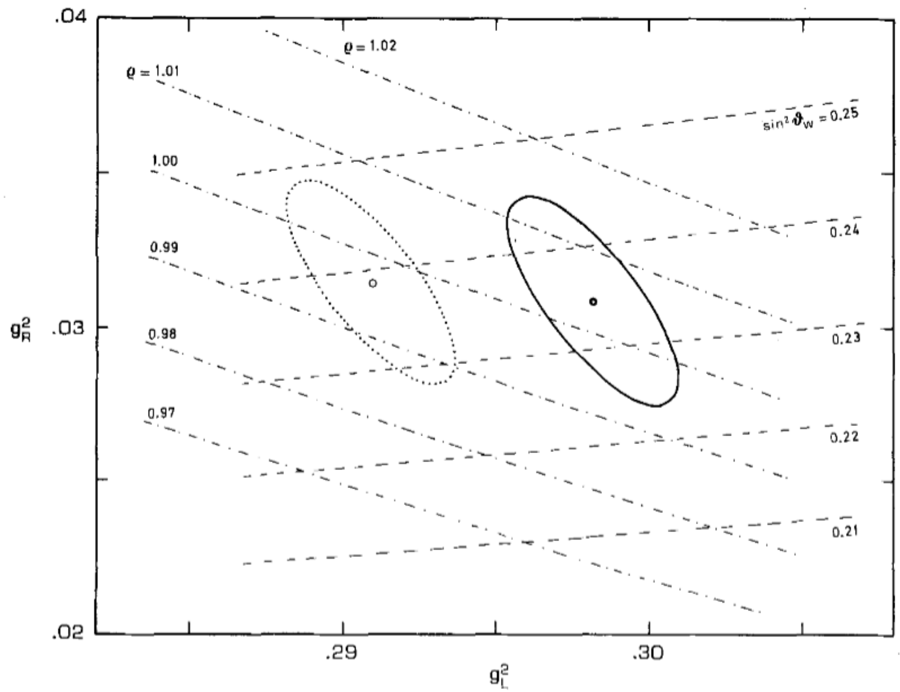
u_L^2	0.1197	0.0116	0.0008
d_L^2	0.1785	0.0119	0.0035
u_R^2	0.0257	0.0081	0.0014
d_R^2	0.0052	0.0078	0.0030

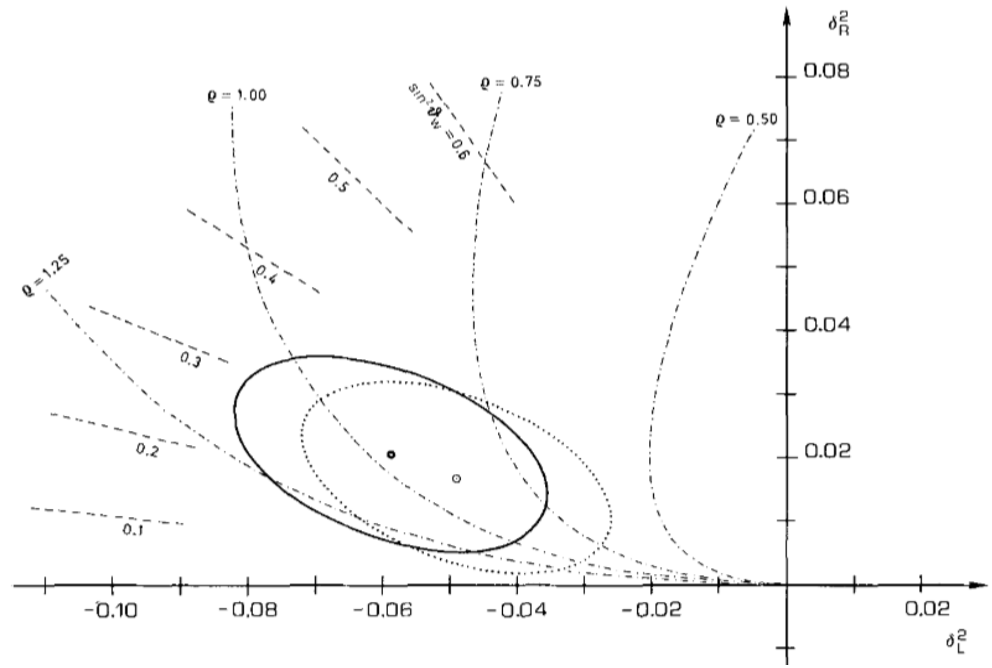
exp nucl.structure

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





$g_L^2 = u_L^2 + d_L^2$

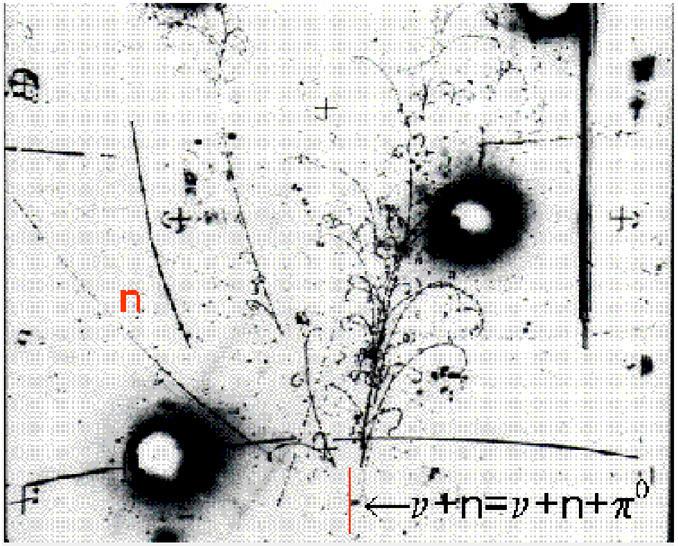
$g_R^2 = u_R^2 + d_R^2$

$\delta_L^2 = u_L^2 - d_L^2$

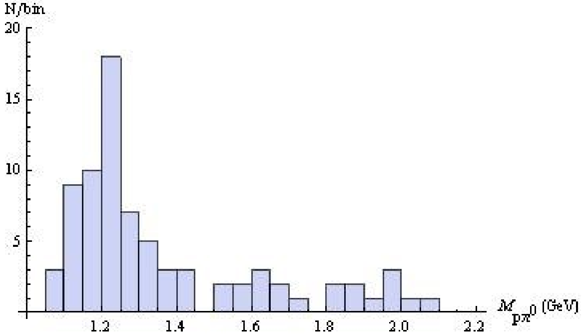
$\delta_R^2 = u_R^2 - d_R^2$

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 Δ^+ (1236) by the weak neutral current



Precision ν - Physics

- Around 1980 : calculate 1-loop corrections

  $(sin^2\theta_w)_{BORN}$- $(sin^2\theta_w)_{1-LOOP}$ ≈ 0.01
- Cogne 1981 : SPS neutrino program

  Increase precision in NC/CC to a few per mil ?

  Llewellyn-Smith : prediction for isoscalar

  $$NC(\nu) = (\frac{1}{2} - sin^2\theta_w + \frac{5}{9} sin^4\theta_w)\, CC(\nu) + \frac{5}{9} sin^4\theta_w\, CC(\overline{\nu})$$

  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' → f+f'

- space like   ν+f → ν+f
- time like $e^{+} + e^{-} \to f + \bar{f}$

$T_{ff'} = C_{ff'}\ J_f\ J_{f'}$

$C_{ff'} = \bar{e}^2(\mathrm{s})\,\frac{Q_f Q_{f'}}{s} + \bar{g}_Z^2(\mathrm{s})\,\frac{Q_f^W Q_{f'}^W}{s - M_Z^2 + i\Gamma_Z M_Z}$

e.m.   weak

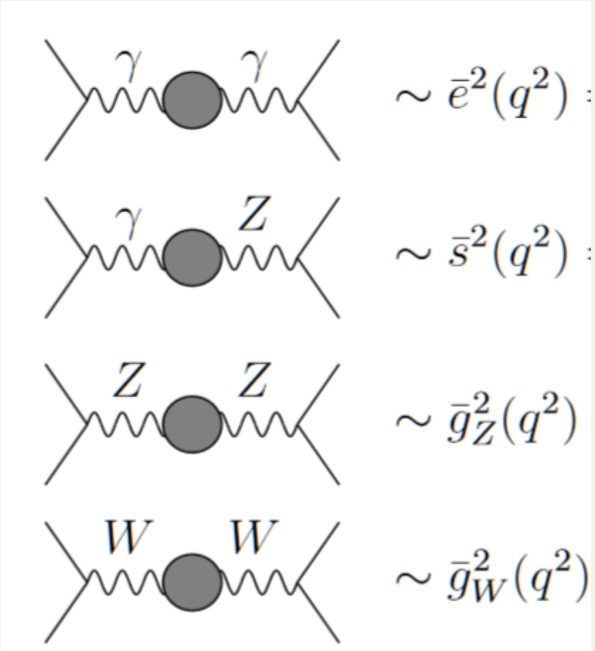
known :

$\bar{e}^2(0) = 4\pi\alpha$

$\bar{g}_W^2(0) = 4\sqrt{2}\ G\ M_W^2$

Physics at 1-loop level

1. The universal radiative corrections :

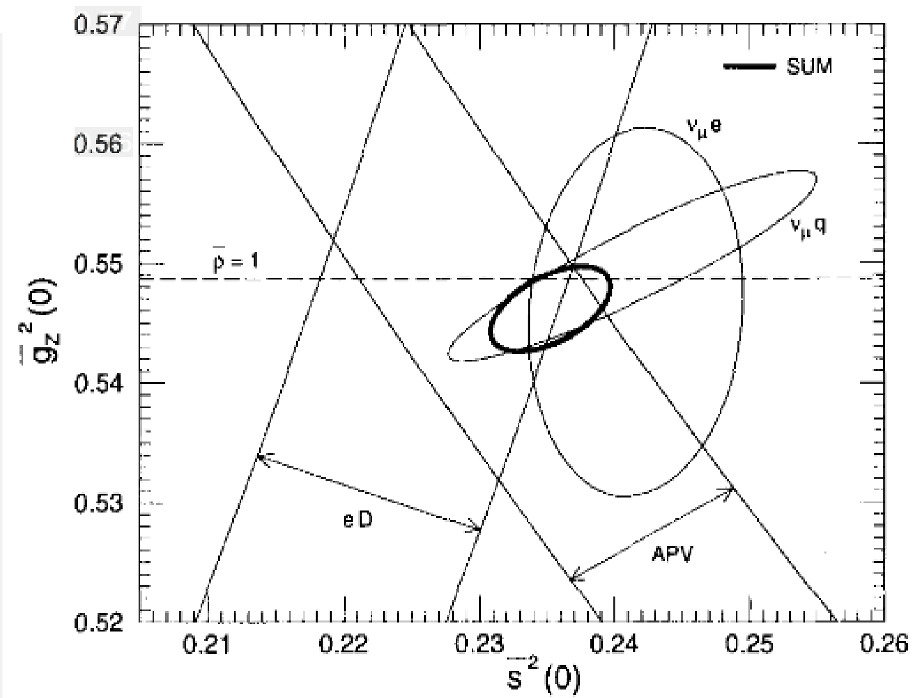


2. Vertex and box corrections are process dependent

Summary of low energy data

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

1. Neutrino : νq and νe
2. SLAC Yale experiment polarized e deuterium
   observe (γ,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 σ(e↑) – σ(e↓) = 0, but observe parity conserving asymmetry

In agreement with GSW : (γ,Z) – interference and parity violating NC

DESY

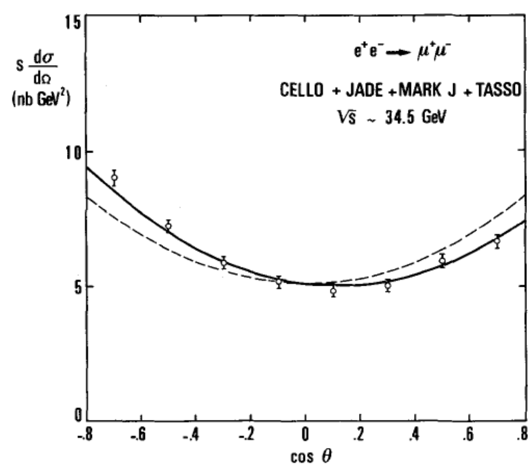
High energy collider e^+e^- PETRA

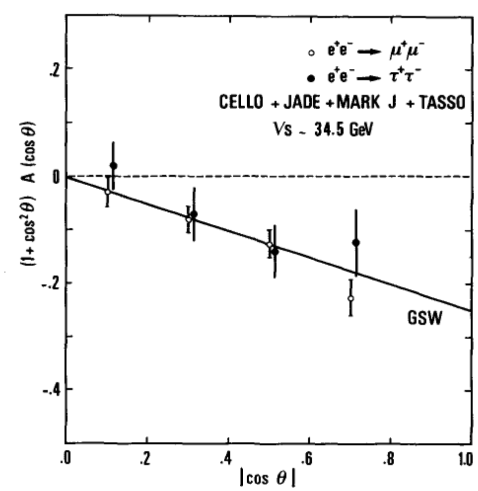
Measure $e^+e^- \rightarrow \mu^+\mu^-$

QED predicts $1+cos^2\theta$

Observe angular asymmetry

Deviation ~ cos Θ agrees with GSW





$e^+ + e^- \to f + \bar{f}$

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

$$F_1(s) = Q_e^2 Q_f^2 + 2v_e v_f Q_e Q_f Re\chi(s) + (v_e^2 + a_e^2)(v_f^2 + a_f^2)\,|\chi(s)|^2$$

$$F_0(s) = 2a_e a_f Q_e Q_f Re\chi(s) + 2a_e v_e 2a_f v_f\,|\chi(s)|^2$$

$$\chi(s) = \frac{s}{s - M_Z^2 + iM_Z\Gamma_Z}\,\frac{1}{\sin^2 2\Theta_W}$$

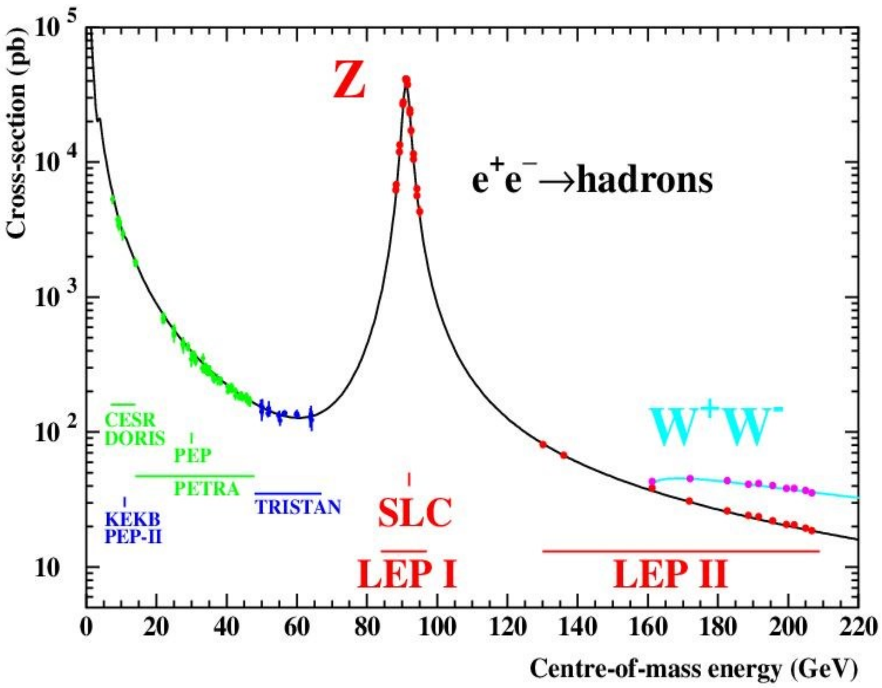
$$\Gamma_Z = \sum_f \Gamma_f \qquad \Gamma_f = \frac{\alpha}{3} M_Z N_f \frac{v_f^2 + a_f^2}{\sin^2 2\Theta_W}$$

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

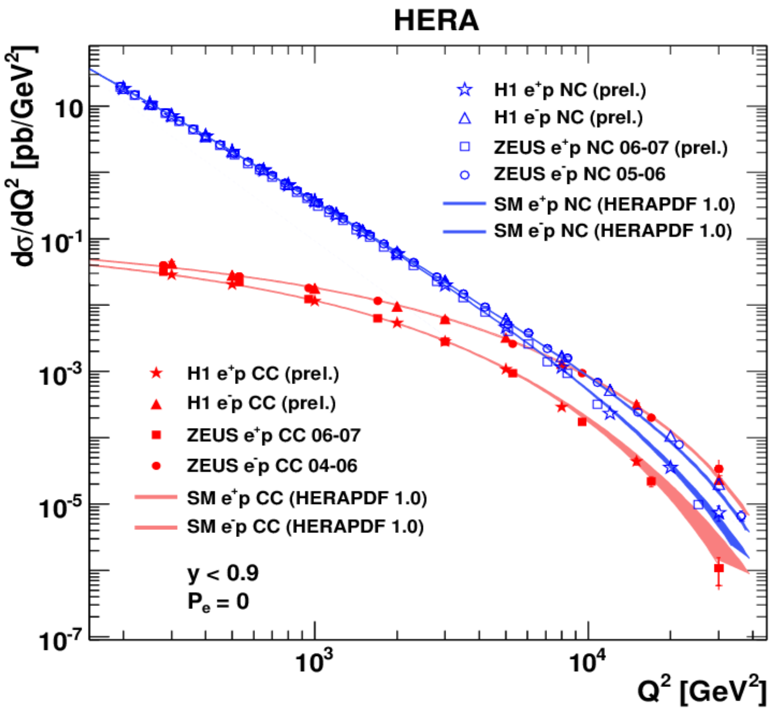
Asymmetry $A_f(s) = \frac{3}{4}\frac{F_0}{F_1}$

(γ,Z)-Interference

Time like



Space like



From Current to Carrier

Aachen ν Conference 1976

1. GSW : M_W and weak angle θ are related :

$$M_W = \frac{\sqrt{\pi\alpha/\sqrt{2}G}}{\sin\Theta} = \frac{37.3\ GeV}{\sin\theta}$$

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

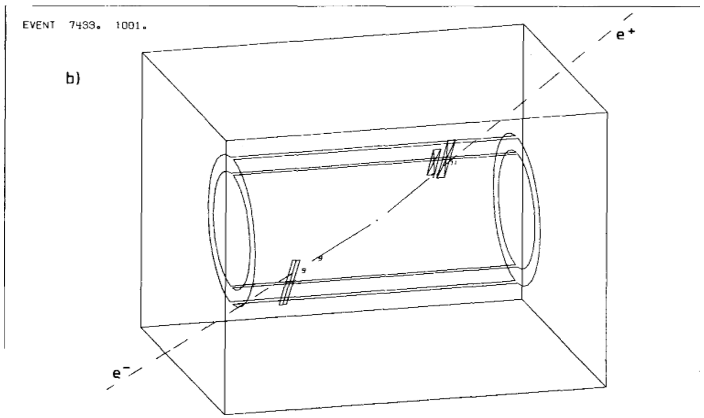
Predict : $M_W \approx 70$ GeV
$M_Z \approx 80$ GeV

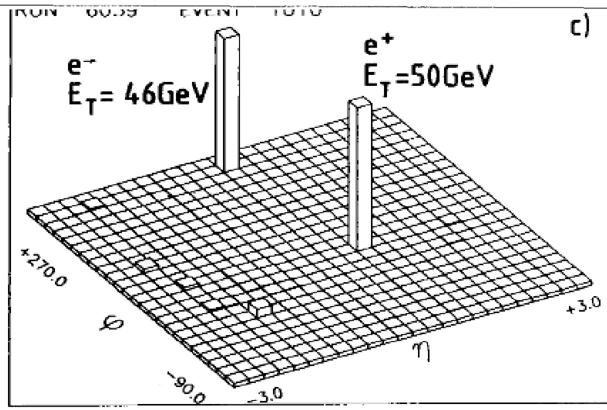
Conclusions :

1. Propagator method in ν-experiments hopeless
$<Q^2> = 0.1\ E_\nu \ll M^2$
2. Rubbia, Cline, MacIntyre propose $p\bar{p}$ 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 → e^+e^-

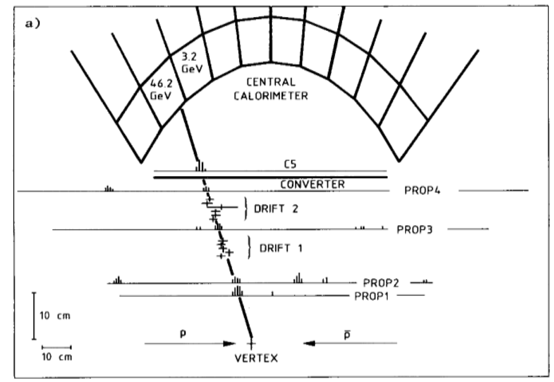
UA1

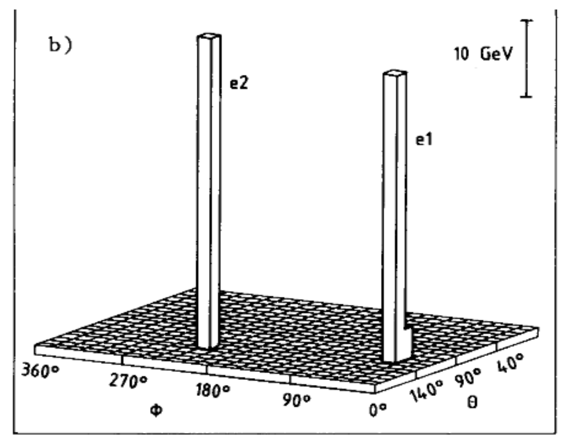




Z-Mass : 95.2 ± 2.5 GeV

UA2





$91.9 \pm 1.3 \pm 1.4$ GeV

The Power of Loops

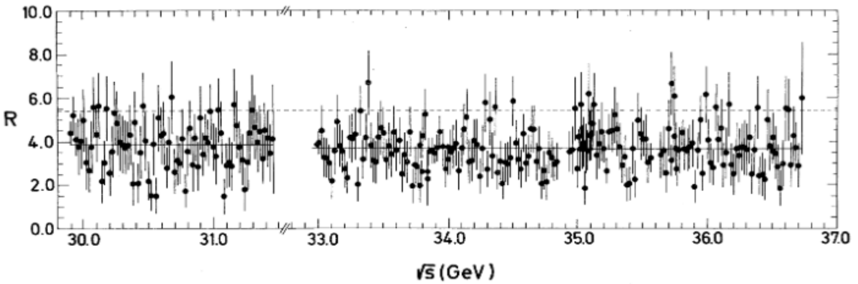
- SM is renormalizable ⟹ depends on finite number of free parameters : $\{p_1, ..., p_n\}$, i.e. masses, mixing angles and couplings
- An electroweak quantity Q is measured and predicted, once the free parameters are fixed by n independent measurements
- Test SM predictions :

$$Q_{exp} \pm \Delta Q_{exp} = Q_{th}(\vec{p} \pm \Delta\vec{p})$$

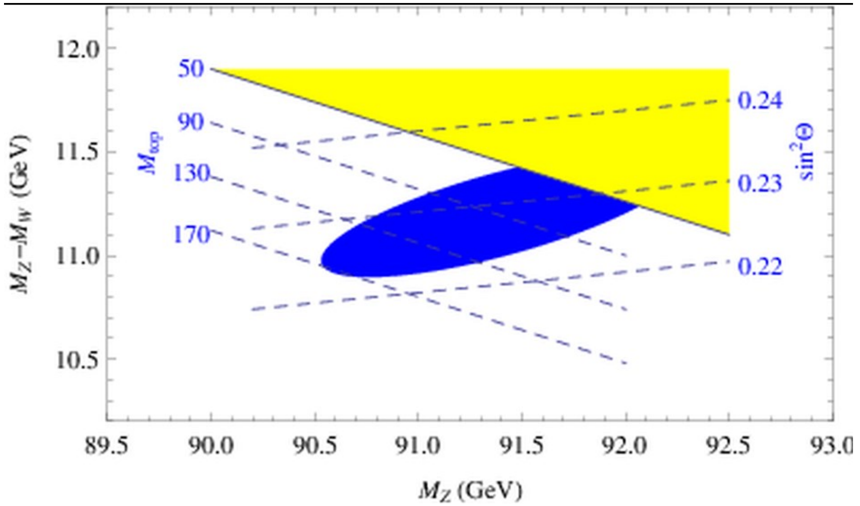
- Application : use precise Z-parameters and predict the top quark mass

Prediction and Discovery of the top-quark

- Discovery of τ (1975) and b (1977)
  3rd fermion family → isodoublets
  completed with $\boldsymbol{\nu_\tau}$ 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



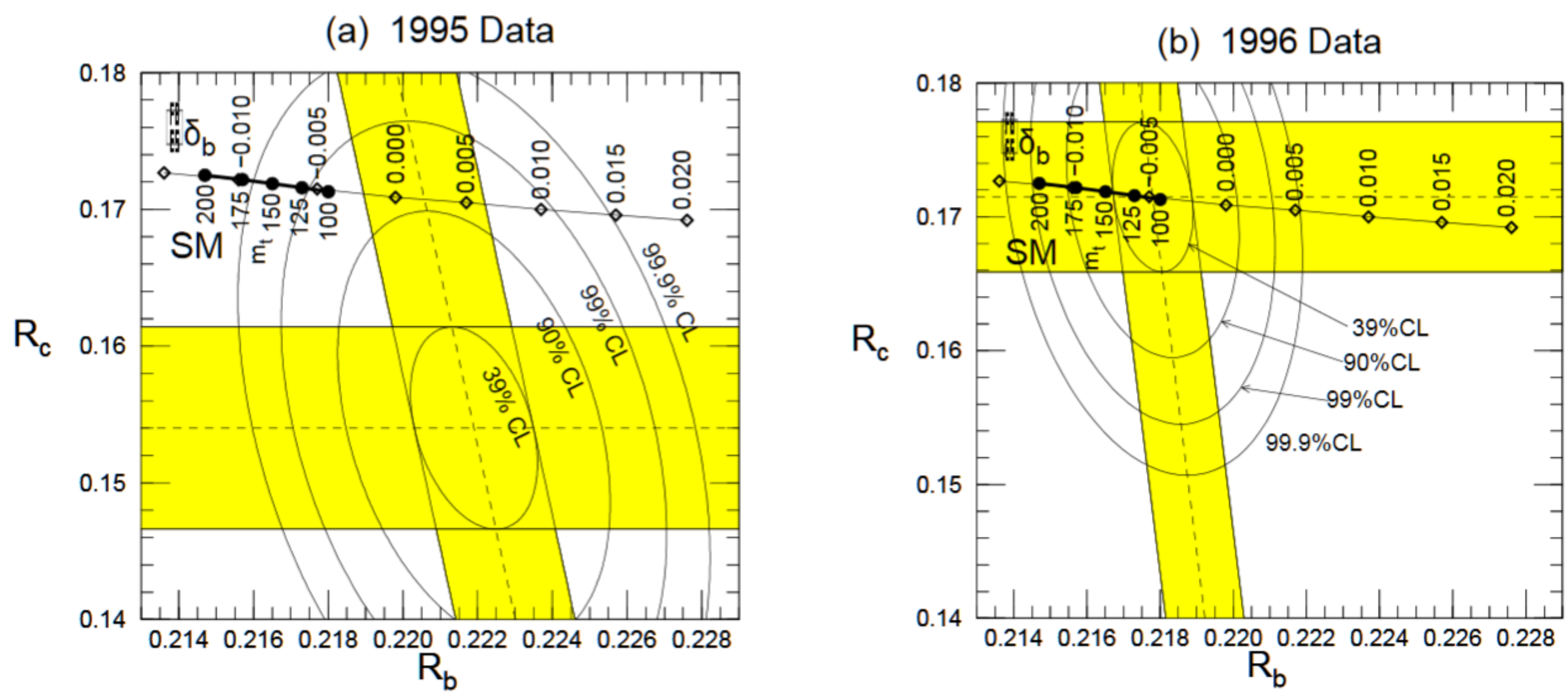
No deviation → m_{top} > 23 GeV



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 : $R_{c,b} = \Gamma_{c,b} / \Gamma_h$
Sensitive to t-quark mass and sensitive to tagging method



Higgs Searches at e^+e^-

LEP 1 (1989-1995) : Z-resonance

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

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 + α, G : constrain (m_H, m_t)-plane

uncertainty from α_s and $\alpha(m_Z)$

ew quantities ~ log m_H

safe lower limit

weak upper limit from partial Z-width

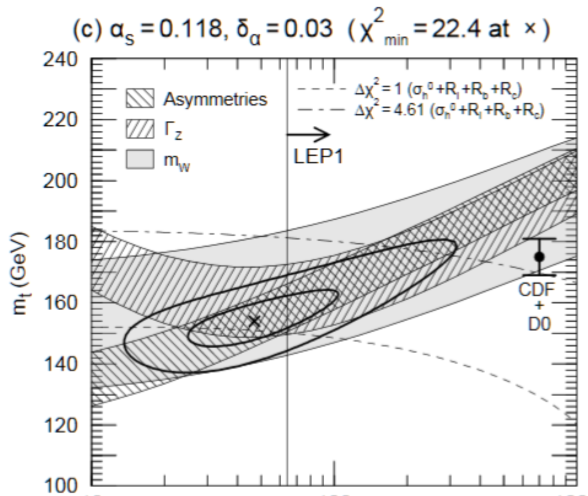
Z→ cc, bb $R_{c,b} = \Gamma_{c,b} / \Gamma_h$

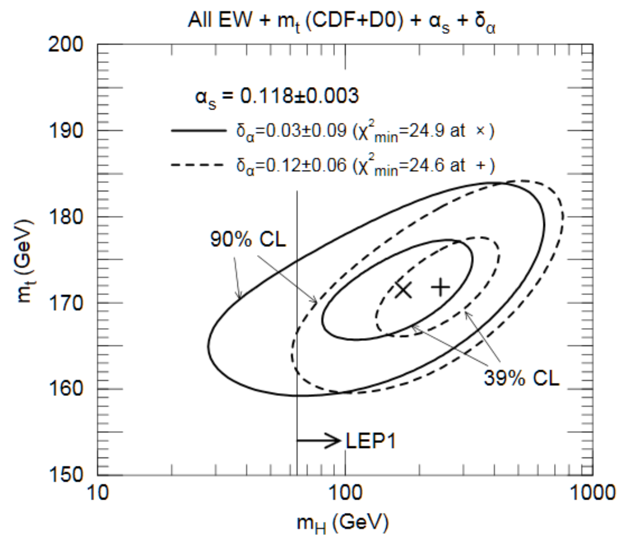
impact of top-mass

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

80 < m_H < 350 GeV

2003 : 55 < m_H < 146 GeV





The Higgs Sector

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

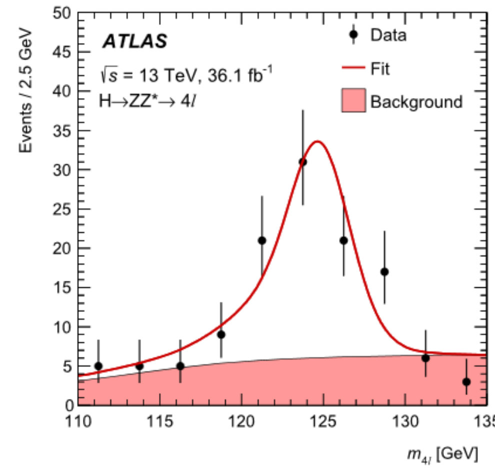
1967 incorporated in GSW model

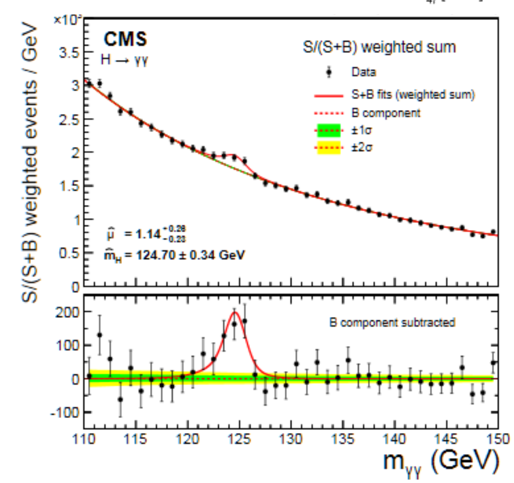
1971 proof of renormalizability by ‘t Hooft and Veltman makes GSW a predictive gauge theory

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