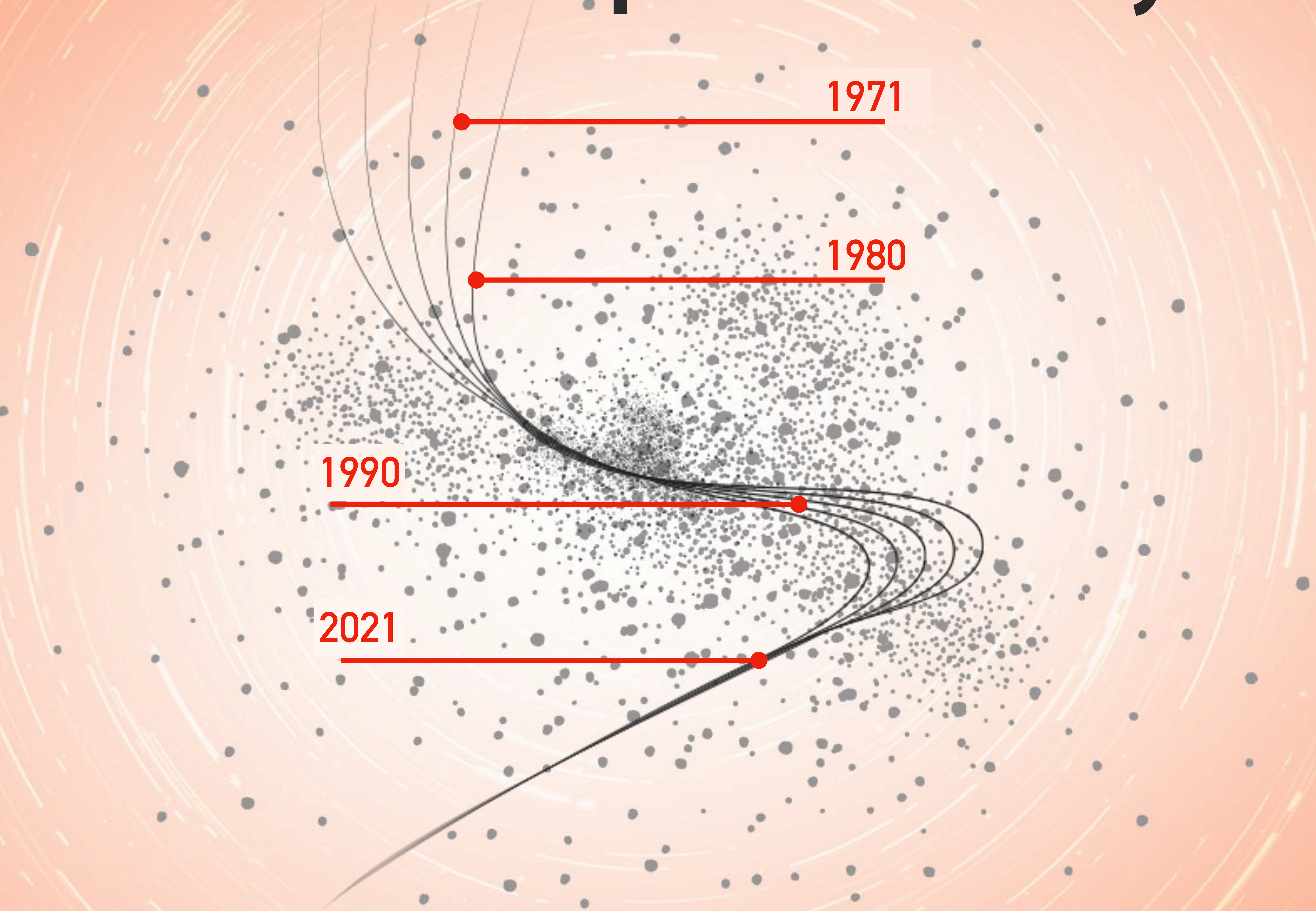
Symétrie et brisure spontanée de symétrie



Le 50 ans de l'IN2P3 avec le

Roberto Salerno

Avant-propos

"The Fabulous '60"

Impressive sequence of **theoretical discoveries** that have completely changed the vision we had of the world.

1961 *Goldstone*: prediction of unavoidable massless bosons if global symmetry of the Lagrangian is spontaneously broken

1961 *Salam and Ward*: invention of the gauge principle

1962 *Glashow*: first introduction of the neutral intermediate weak boson

1963 *Cabibbo*: introduction of the Cabibbo angle and hadronic weak currents.

1964 *Bjorken and Glashow*: proposal for the existence of a charmed fundamental fermion

1964 *Higgs, Englert, and Brout*: field theory with spontaneous symmetry breakdown, no massless Goldstone boson, and massive vector boson

1964 *Salam and Ward*: Lagrangian for the electroweak synthesis, estimation of the W mass

1967 *Weinberg*: Lagrangian for the electroweak synthesis and estimation of W and Z masses

1968 *Salam*: Lagrangian for the electroweak synthesis.

1970 *Glashow, Iliopoulos and Maiani*: lepton–quark symmetry and the proposal of charmed quark

1971 *'t Hooft*: rigorous proof of renormalizability of the mass-less and massive Yang– Mills quantum field theory with spontaneously broken gauge invariance.

1973 : *Kobayashi and Maskawa*: CP violation is accommodated in the Standard Model with six favours.

Avant-propos

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1964 *Bjorken and Gl*… n

1964 *Higgs, Engler*… massless Goldstone boson, and massive vector…

1964 *Salam and W*… mass

In the last 50 years LLR with IN2P3 played a fundamental role in the experimental proofs of these theories

1967 *Weinberg*: Lagrangian for the electroweak synthesis and estimation of W and Z masses

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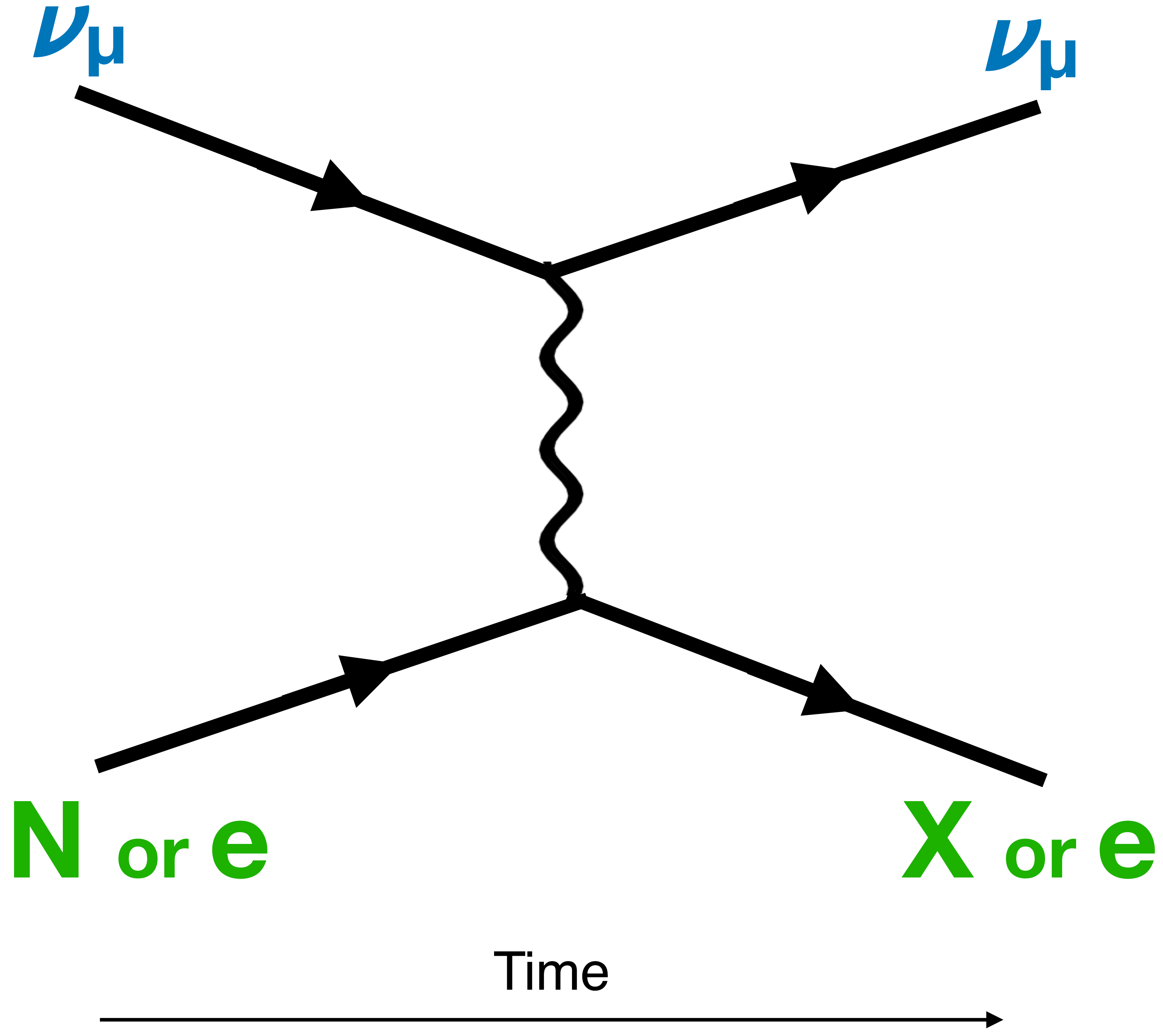
The weak neutral current

An essential part of the electroweak unification: a neutral particle (Z^0 boson) should exist to carry the weak fundamental force.

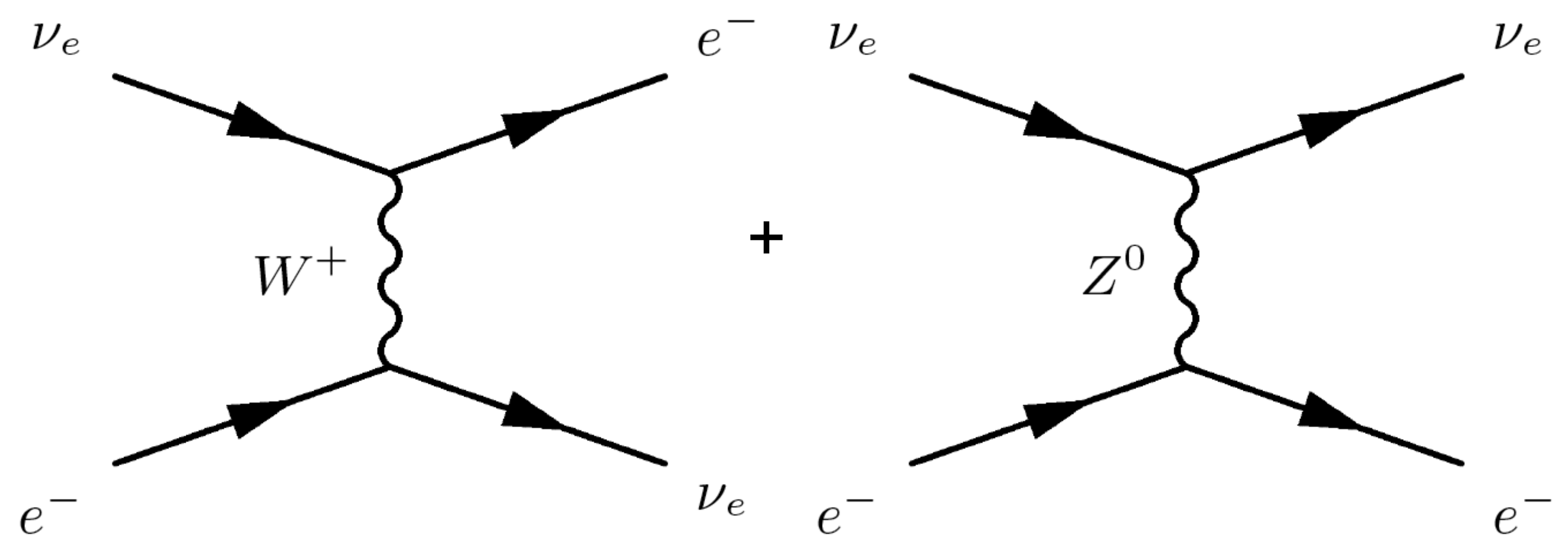
Its existence can be probed with "elastic neutrino interaction"



A muon neutrino (ν_μ) and hadron (N) or electron (e) change energy.

Flavors are unaffected(*)

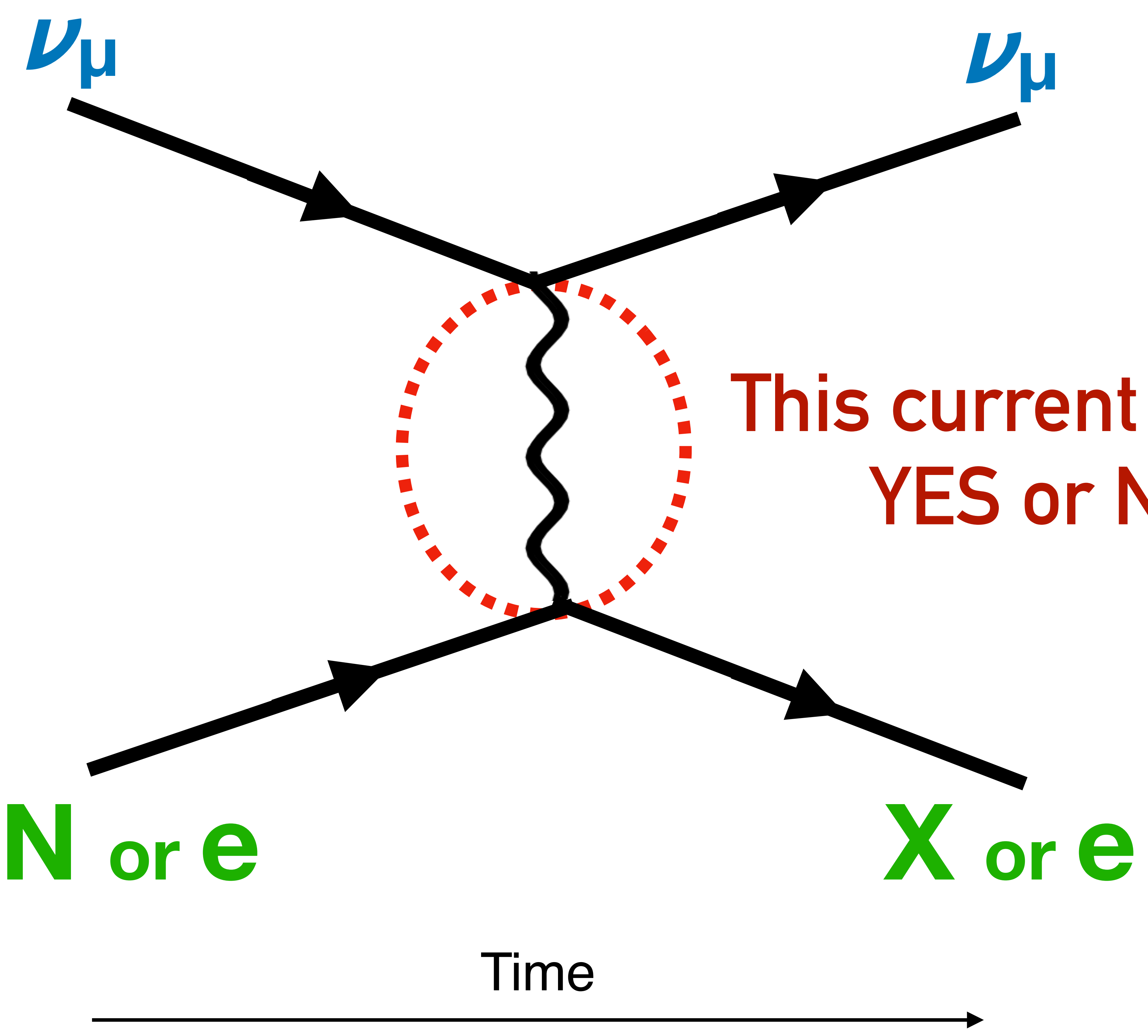
(*) Scattering with same flavour involved as well charged currents



The weak neutral current

An essential part of the electroweak unification: a neutral particle (Z^0 boson) should exist to carry the weak fundamental force.

An experiment was prompted to answer this fundamental question



This current exists?
YES or NO?

PROPOSAL FOR A NEUTRINO EXPERIMENT IN GARGAMELLE

Aachen, Brussels, CERN, Ecole Polytechnique,
Milan, Orsay, University College

1970

1. INTRODUCTION

Among the many problems posed in weak interactions, it appears that neutrino experiments in Gargamelle would be especially suitable to investigate the following : *)

i) Total cross-sections in the high energy region, for ν and $\bar{\nu}$;

ii) Inelastic continuum excitation of the hadronic amplitude-structure factors and "partons";

iii) Existence of the intermediate W-boson;

iv) Coupling constants for diagonal and non-diagonal weak interactions;

v) Neutral currents.

The Gargamelle(*) experiment

(*) named it by Leprince-Ringuet
after the giantess created
400 years earlier by Rabelais

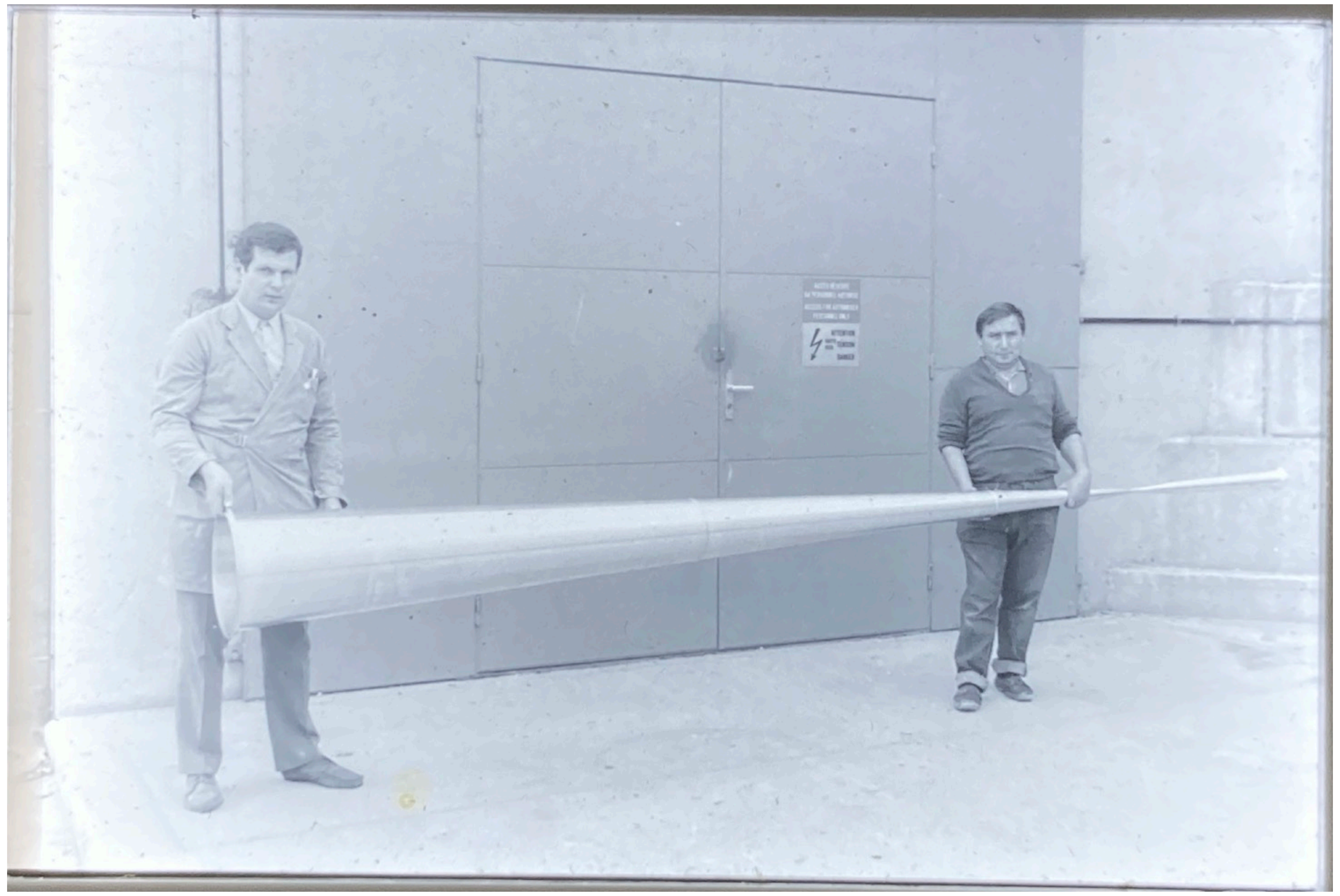
The key characteristics of the success

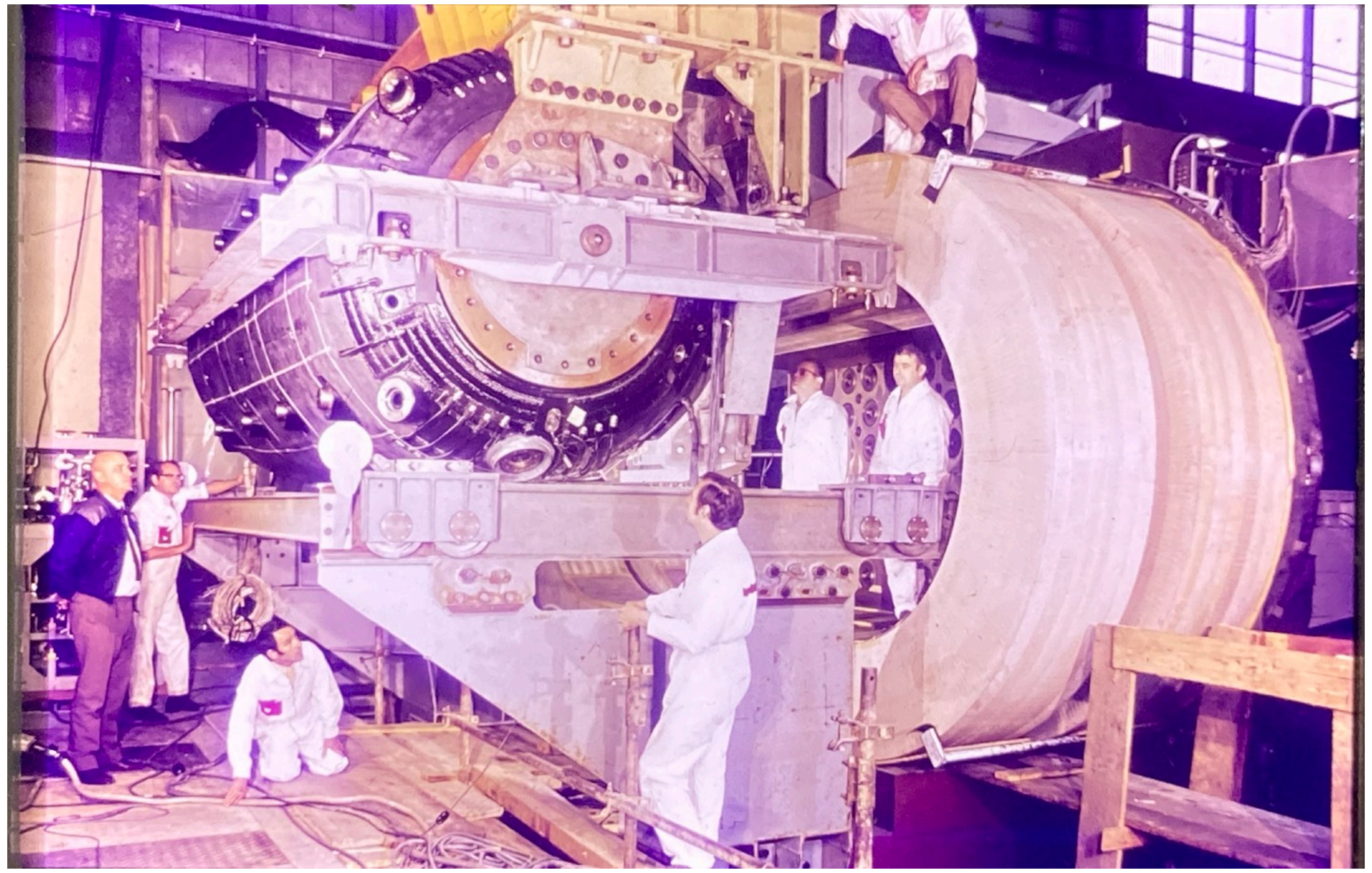
1. An intense and well measured muon (anti)neutrino flux

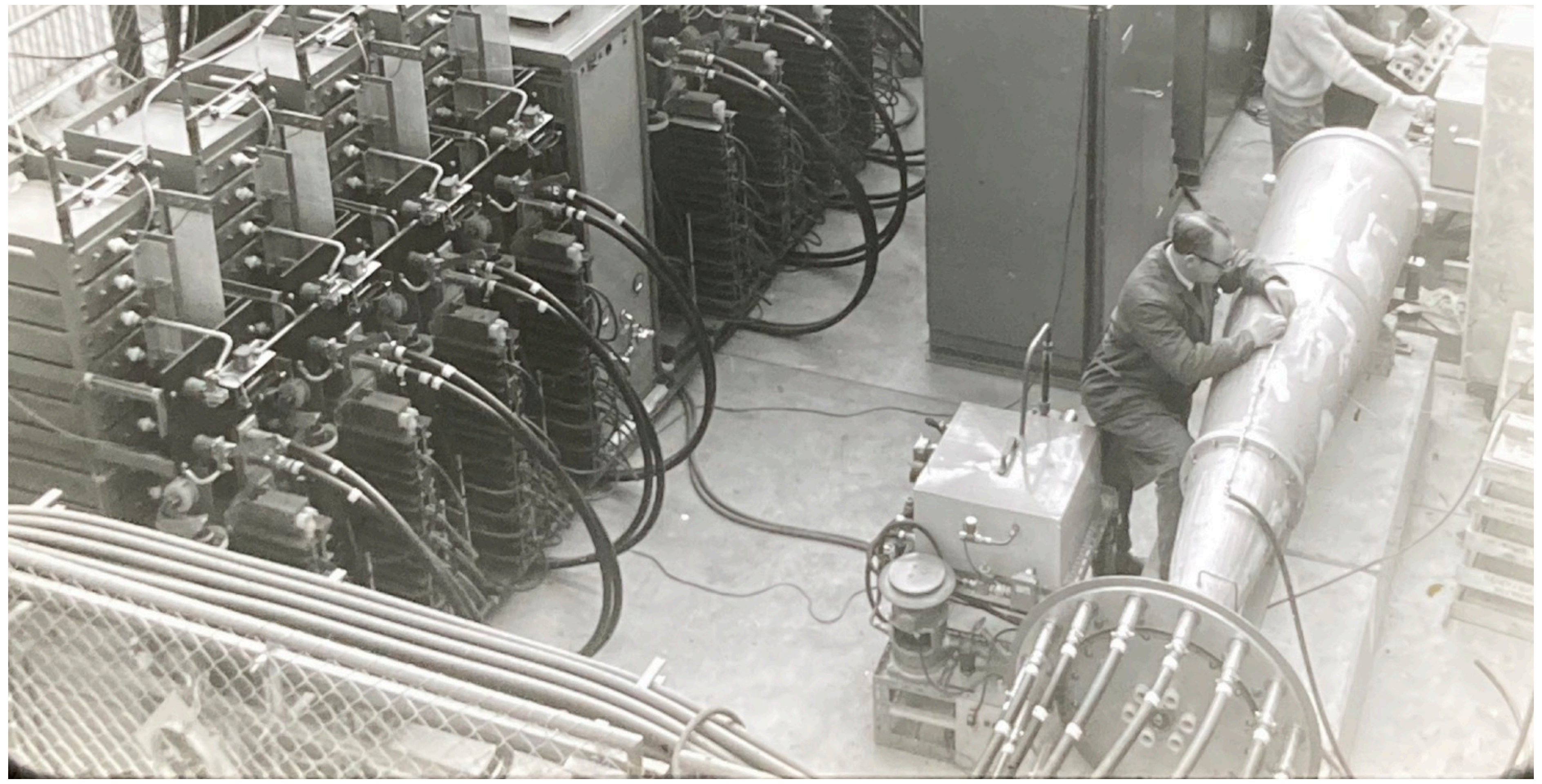
2. A gigantic bubble chamber with very large target mass

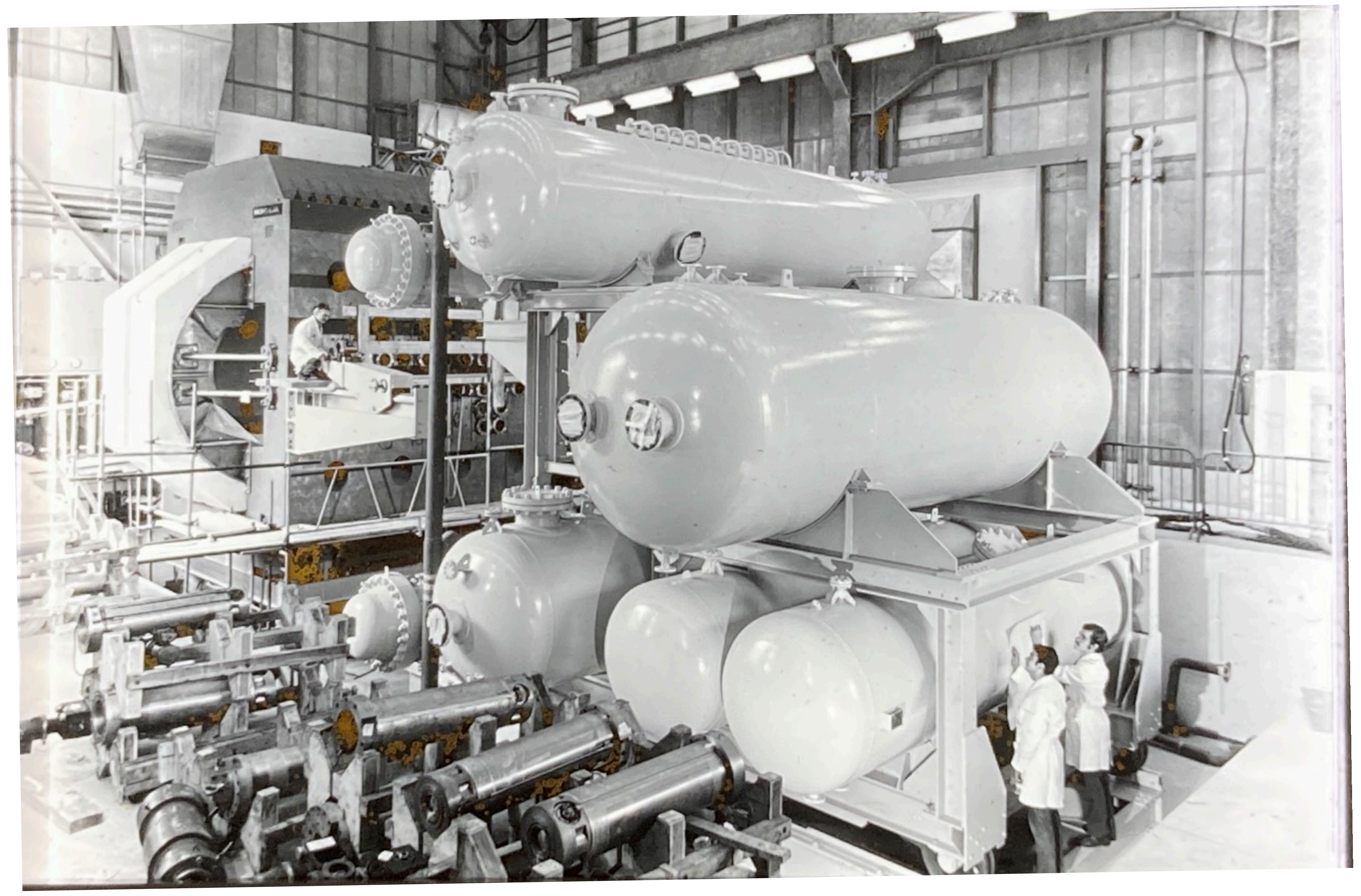
3. Good identification of muons/electrons and detailed knowledge about final states

Pictures







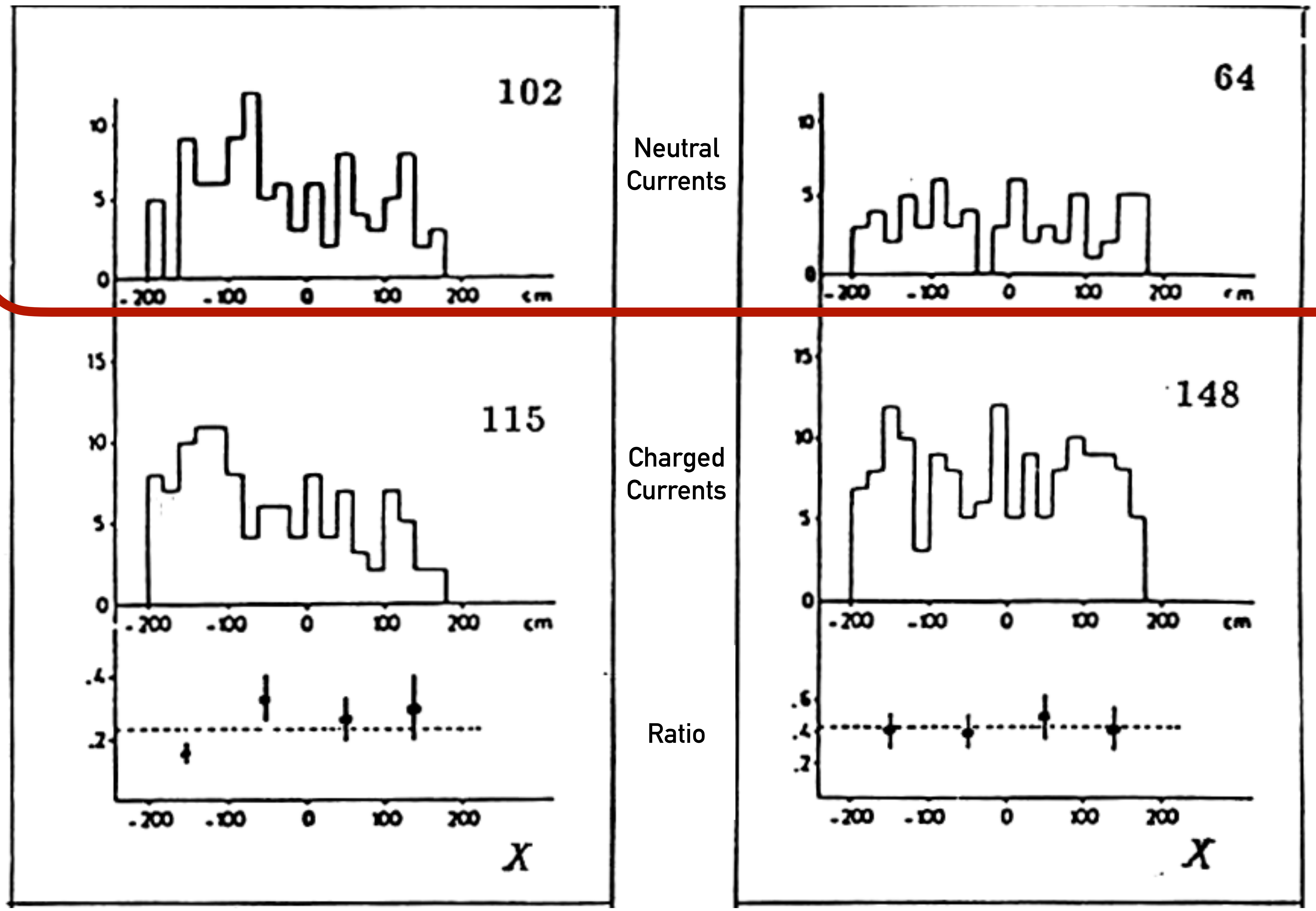


The discovery

1973

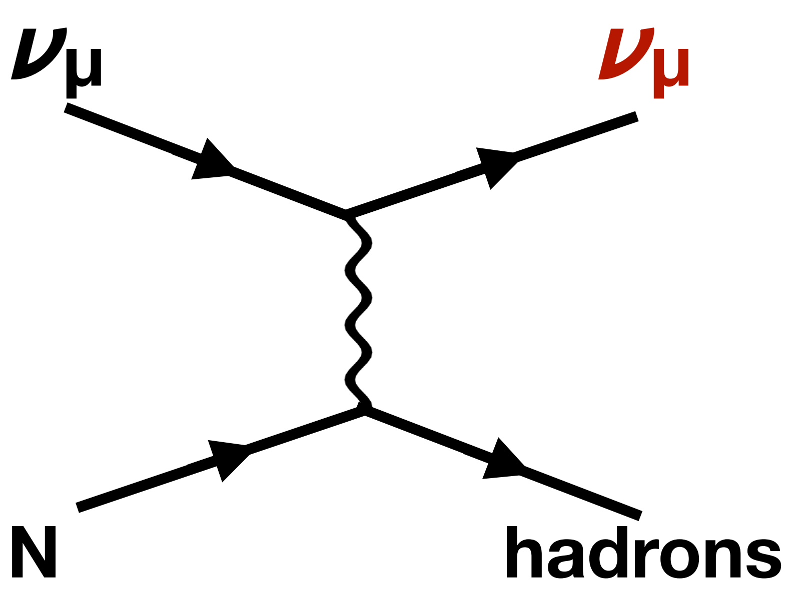
The analysis was based on $O(10^5)$ ν_μ and $\bar{\nu}_\mu$ pictures manually scanned

After the selection 166 hadronical Neutral Currents events observed

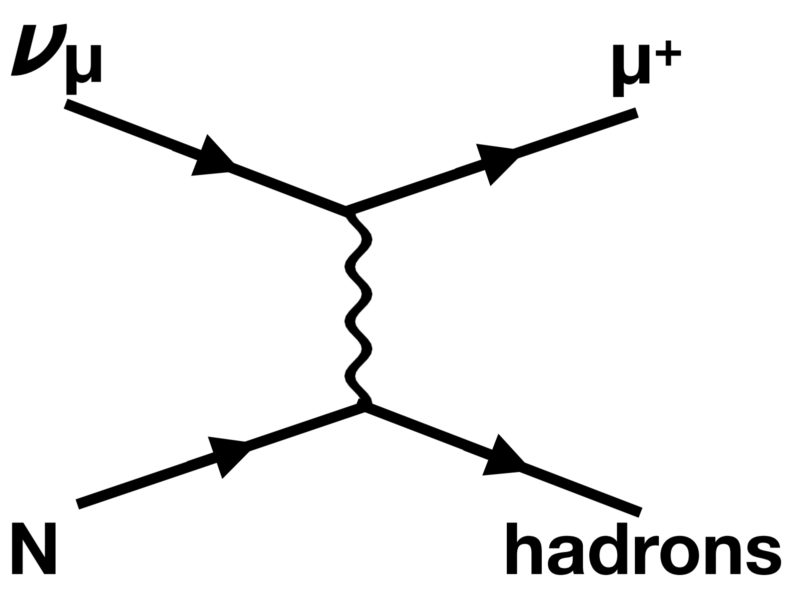


Neutrino beam

Antineutrino beam



No charged leptons in the final states



Similar spatial distributions of Neutral and Charged Currents

The discovery

The analysis was based on $O(10^5)$ ν_μ and $\bar{\nu}_\mu$ pictures manually scanned

A hadronic Neutral Currents event

$\bar{\nu}_\mu$

3 secondary particles, all clearly identifiable as hadrons,

The discovery papers

1973

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

F.J. HASERT, S. KABE, W. KRENZ, J. Von KROGH, D. LANSKE, J. MORFIN, K. SCHULTZE and H. WEERTS

III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany

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CERN, Geneva, Switzerland

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Istituto di Fisica dell'Università, Milano and I.N.F.N. Milano, Italy

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Laboratoire de l'Accélérateur Linéaire, Orsay, France

F.W. BULLOCK, M.J. ESTEN, T.W. JONES, J. McKENZIE, A.G. MICHETTE*[9] G. MYATT* and W.G. SCOTT*[6,*9]

University College, London, England

Received 25 July 1973

Events induced by neutral particles and producing hadrons, but no muon or electron, have been observed in the CERN neutrino experiment. These events behave as expected if they arise from neutral current induced processes. The rates relative to the corresponding charged current processes are evaluated.

SEARCH FOR ELASTIC MUON-NEUTRINO ELECTRON SCATTERING

F.J. HASERT, H. FAISSNER, W. KRENZ, J. Von KROGH, D. LANSKE, J. MORFIN, K. SCHULTZE and H. WEERTS

III Physikalisches Institut der technischen Hochschule, Aachen, Germany

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and

F.W. BULLOCK, M.J. ESTEN, T. JONES, J. McKENZIE, A.G. MICHETTE*[8] G. MYATT*[5], J. PINFOLD and W.G. SCOTT*[5], *[8]

University College, University of London, England

Received 2 July 1973

First event ever of this type!

One possible event of the process $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$ has been observed. The various background processes are discussed and the event interpreted in terms of the Weinberg theory. The 90% confidence limits on the Weinberg parameter are $0.1 < \sin^2\theta_W < 0.6$.

Gargamelle aftermath

The discovery of Neutral Currents was major step in HEP bringing to

the first experimental support for the electroweak theory

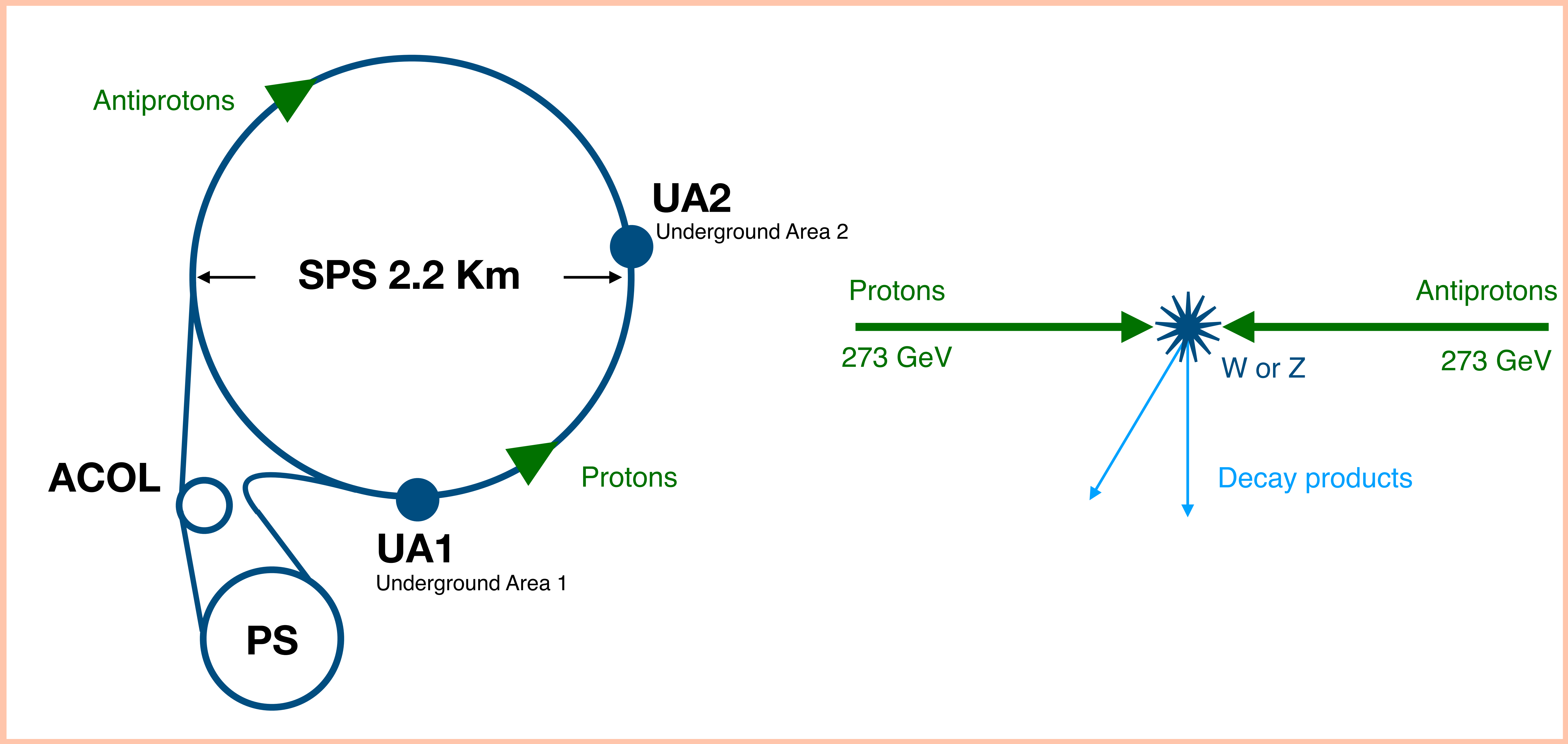
the first reliable value of the weak mixing angle ($\sin^2\theta_W$)
a fundamental parameter of the electroweak theory

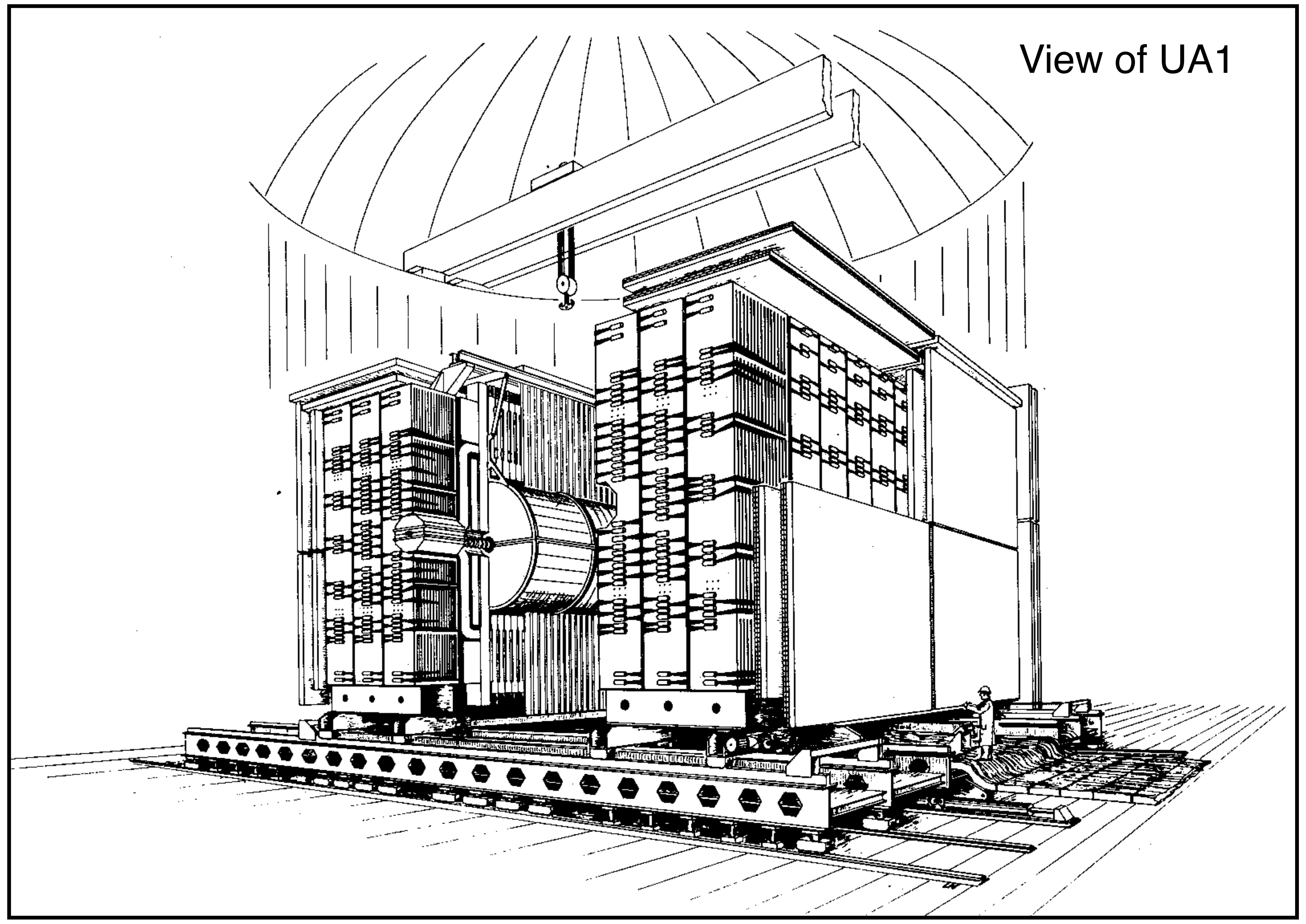
the first estimations of the expected masses of $W^{\pm}$ and Z^0 vector bosons several years before their discovery
(predicted in theory in terms of the parameter $\sin^2\theta_W$)

The next natural step is the direct search of $W^{\pm}$ and Z^0 vector bosons…

Search of $W^{\pm}$ and Z^0 bosons

The CERN proton-antiproton SPS ($\sqrt{s}$ = 546 GeV), the first protons and antiprotons collider, designed to discover the bosons during LEP construction





Two detectors/experiments approved in late '70 in the collision points : **UA1** and **UA2**

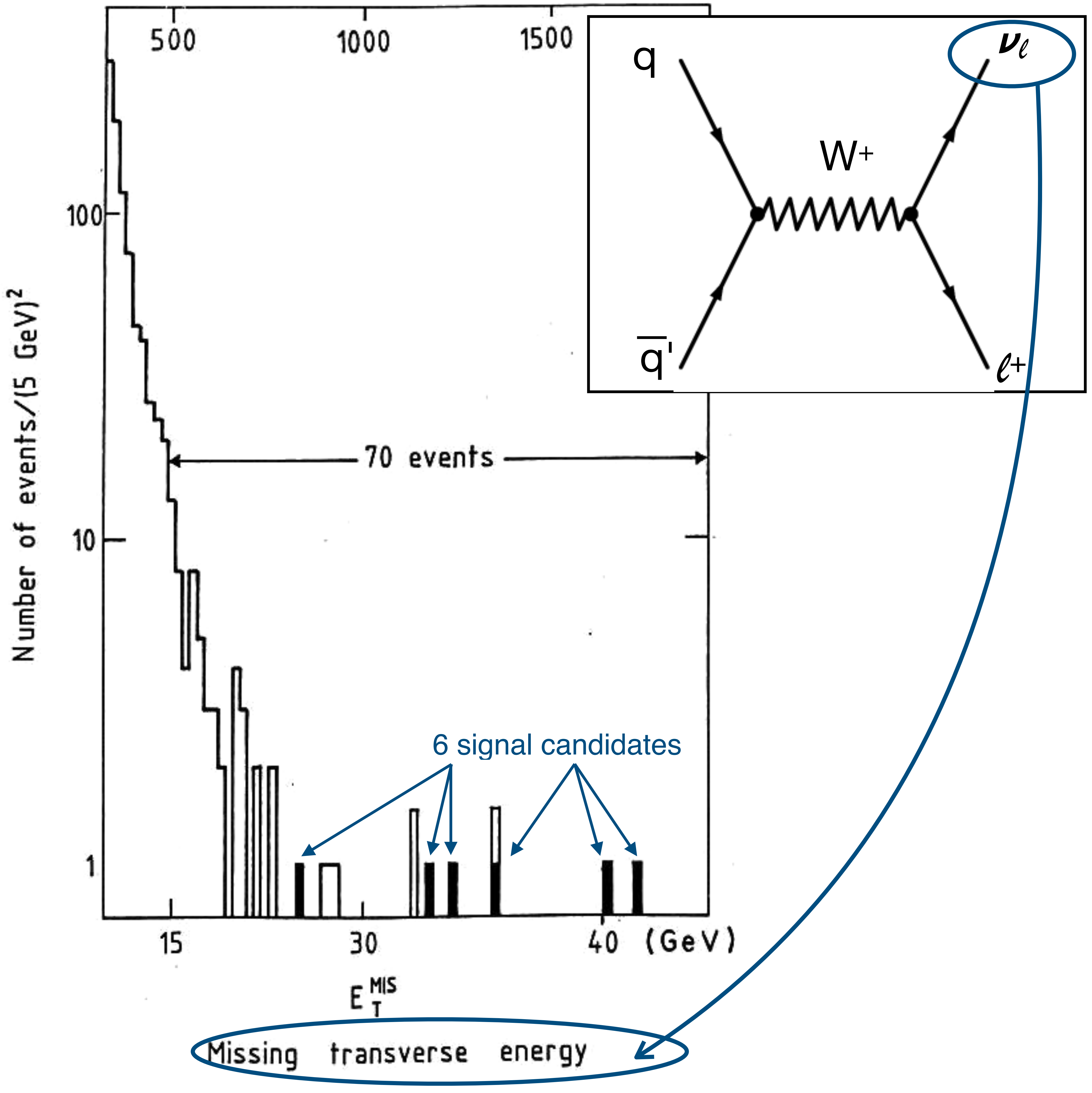
The UA1 was at cutting edge of technology those days and the key feature was the "hermeticity" → it becomes the basic of all future general-purpose

The discovery of $W^{\pm}$ and Z^0 bosons

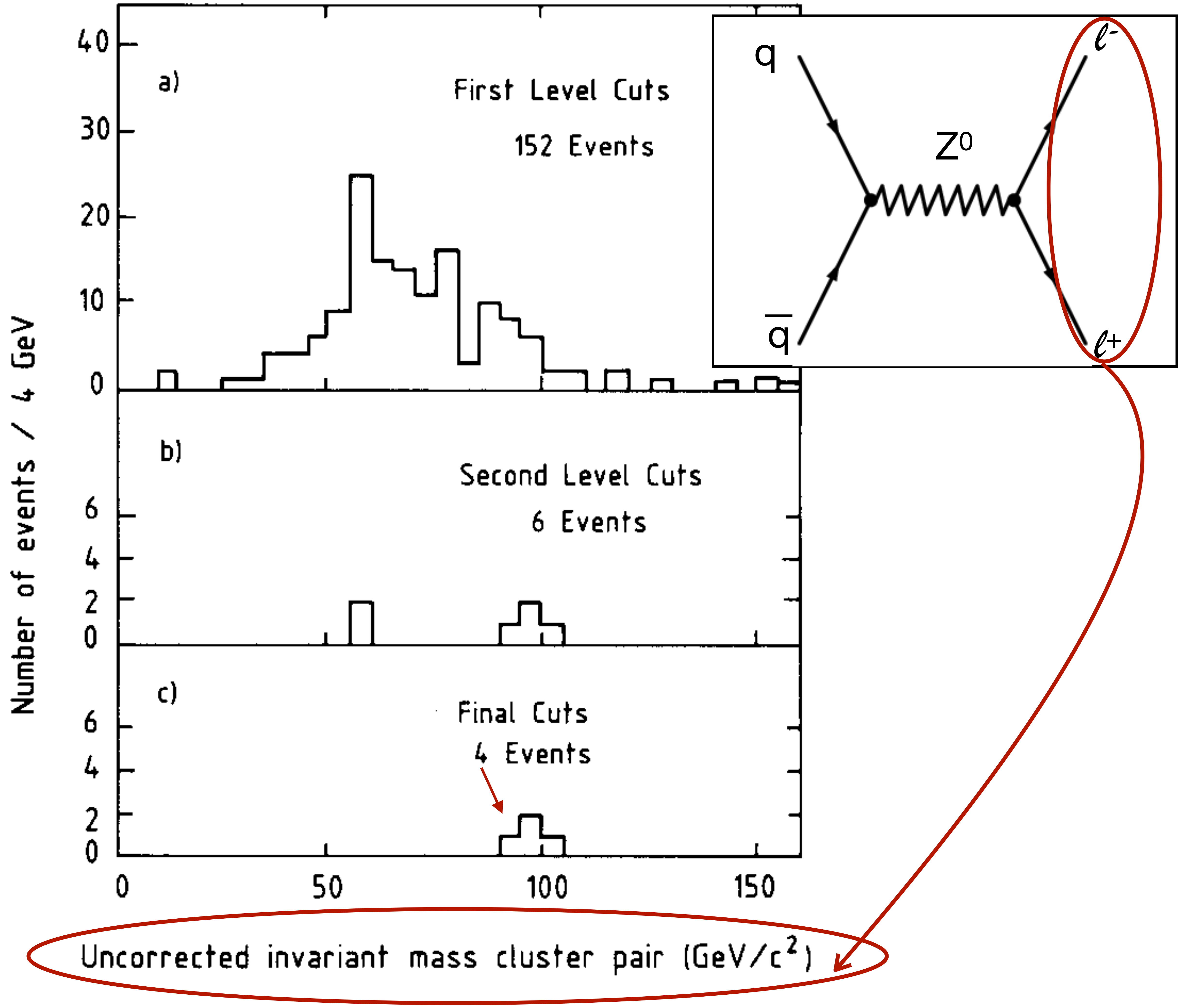
1983

Focus on leptonic decays

$W^{\pm}$ decay : high transverse momentum isolated lepton
high missing transverse momentum



Z^0 decay : 2 high transverse momentum isolated leptons
their invariant mass consistent with the detector resolution



The discovery papers

1983

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland

G. ARNISON[j], A. ASTBURY[j], B. AUBERT[b], C. BACCI[i], G. BAUER[1], A. BÉZAGUET[d], R. BÖCK[d], T.J.V. BOWCOCK[f], M. CALVETTI[d], T. CARROLL[d], P. CATZ[b], P. CENNINI[d], S. CENTRO[d], F. CERADINI[d], S. CITTOLIN[d], D. CLINE[1], C. COCHET[k], J. COLAS[b], M. CORDEN[c], D. DALLMAN[d], M. DeBEER[k], M. DELLA NEGRA[b], M. DEMOULIN[d], D. DENEGRI[k], A. Di CIACCIO[i], D. DiBITONTO[d], L. DOBRZYNSKI[g], J.D. DOWELL[c], M. EDWARDS[c], K. EGGERT[a], E. EISENHANDLER[f], N. ELLIS[d], P. ERHARD[a], H. FAISSNER[a], G. FONTAINE[g], R. FREY[h], R. FRÜHWIRTH[1], J. GARVEY[c], S. GEER[g], C. GHESQUIÈRE[g], P. GHEZ[b], K.L. GIBONI[a], W.R. GIBSON[f], Y. GIRAUD-HÉRAUD[g], A. GIVERNAUD[k], A. GONIDEC[b], G. GRAYER[j], P. GUTIERREZ[h], T. HANSL-KOZANECKA[a], W.J. HAYNES[j], L.O. HERTZBERGER[2], C. HODGES[h], D. HOFFMANN[a], H. HOFFMANN[d], D.J. HOLTHUIZEN[2], R.J. HOMER[c], A. HONMA[f], W. JANK[d], G. JORAT[d], P.I.P. KALMUS[f], V. KARIMÄKI[e], R. KEELER[f], I. KENYON[c], A. KERNAN[h], R. KINNUNEN[e], H. KOWALSKI[d], W. KOZANECKI[h], D. KRYN[d], F. LACAVA[d], J.-P. LAUGIER[k], J.-P. LEES[b], H. LEHMANN[a], K. LEUCHS[a], A. LÉVÊQUE[k], D. LINGLIN[b], E. LOCCI[k], M. LORET[k], J.-J. MALOSSE[k], T. MARKIEWICZ[d], G. MAURIN[d], T. McMAHON[c], J.-P. MENDIBURU[g], M.-N. MINARD[b], M. MORICCA[i], H. MUIRHEAD[d], F. MULLER[d], A.K. NANDI[j], L. NAUMANN[d], A. NORTON[d], A. ORKIN-LECOURTOIS[g], L. PAOLUZI[i], G. PETRUCCI[d], G. PIANO MORTARI[i], M. PIMIÄ[e], A. PLACCI[d], E. RADERMACHER[a], J. RANSDELL[h], H. REITHLER[a], J.-P. REVOL[d], J. RICH[k], M. RIJSSENBEEK[d], C. ROBERTS[j], J. ROHLF[d], P. ROSSI[d], C. RUBBIA[d], B. SADOULET[d], G. SAJOT[g], G. SALVI[f], G. SALVINI[i], J. SASS[k], J. SAUDRAIX[k], A. SAVOY-NAVARRO[k], D. SCHINZEL[f], W. SCOTT[j], T.P. SHAH[j], M. SPIRO[k], J. STRAUSS[1], K. SUMOROK[c], F. SZONCSO[1], D. SMITH[h], C. TAO[d], G. THOMPSON[f], J. TIMMER[d], E. TSCHESLOG[a], J. TUOMINIEMI[e], S. Van der MEER[d], J.-P. VIALLE[d], J. VRANA[g], V. VUILLEMIN[d], H.D. WAHL[1], P. WATKINS[c], J. WILSON[c], Y.G. XIE[d], M. YVERT[b] and E. ZURFLUH[d]

Aachen [a]–Annecy (LAPP) [b]–Birmingham [c]–CERN [d]–Helsinki [e]–Queen Mary College, London [f]–Paris (Coll. de France) [g]–Riverside [h]–Rome [i]–Rutherford Appleton Lab. [j]–Saclay (CEN) [k]–Vienna [1] Collaboration

Received 23 January 1983

EXPERIMENTAL OBSERVATION OF LEPTON PAIRS OF INVARIANT MASS AROUND 95 GeV/c^2 AT THE CERN SPS COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

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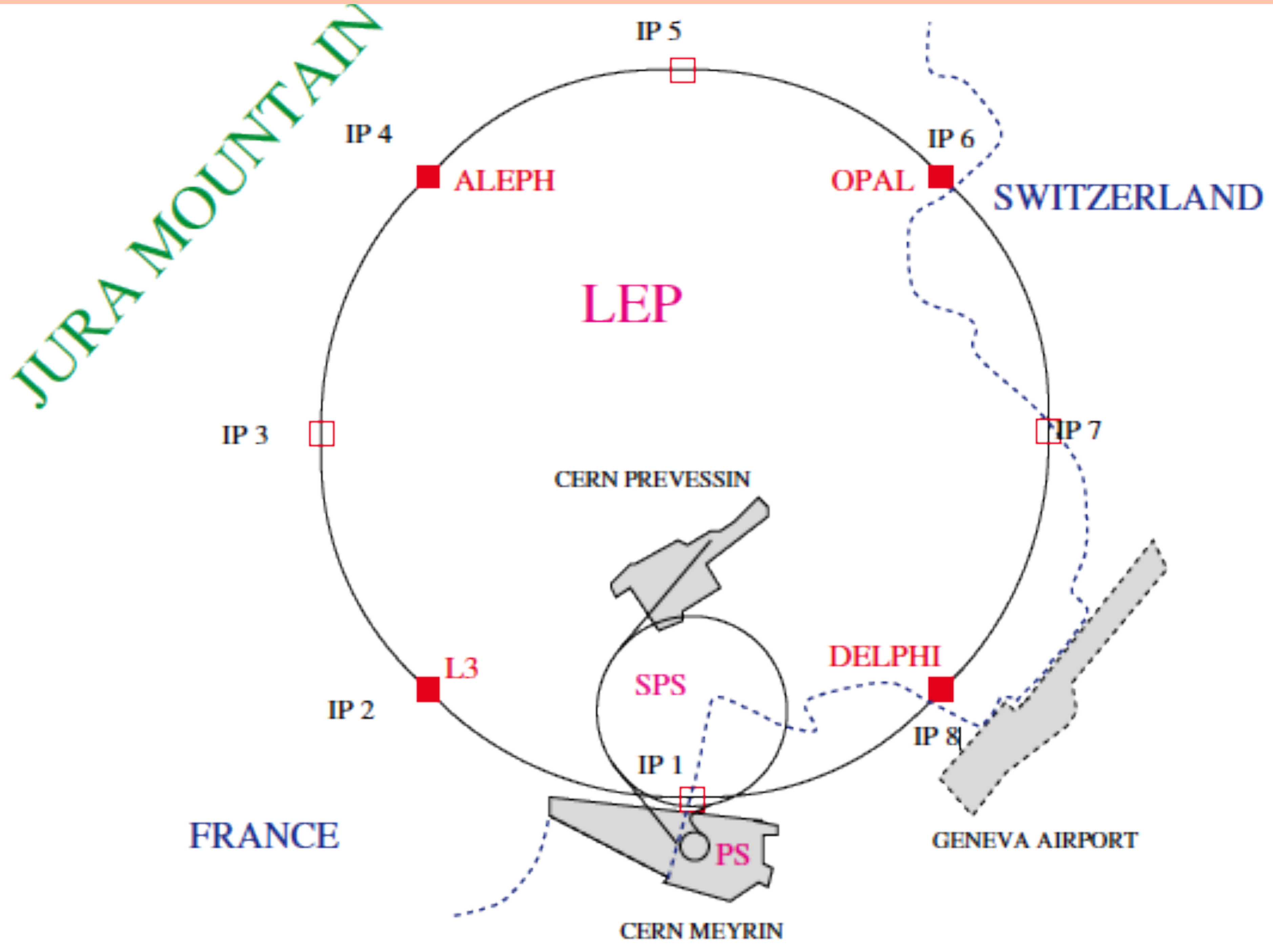
Received 6 June 1983

Participation of LLR members

LEP : the Large Electron-Positron Collider

A collider 4 times bigger than anything before it

To push the frontiers of knowledge and understand the electroweak interactions, with high-precision measurements of the properties of the Z^0 and $W^{\pm}$ bosons



- ✓ 27-kilometre circumference
- ✓ The largest electron-positron collider ever built
- ✓ 4 enormous detectors: **ALEPH**, DELPHI, L3 and OPAL
- ✓ 11 years of operational life : 1989 → 2000
- ✓ Energy stages (LEP1/LEP2) from 90 GeV to 210 GeV

LEP Changed the high-energy physics from a 10% to a 1% science

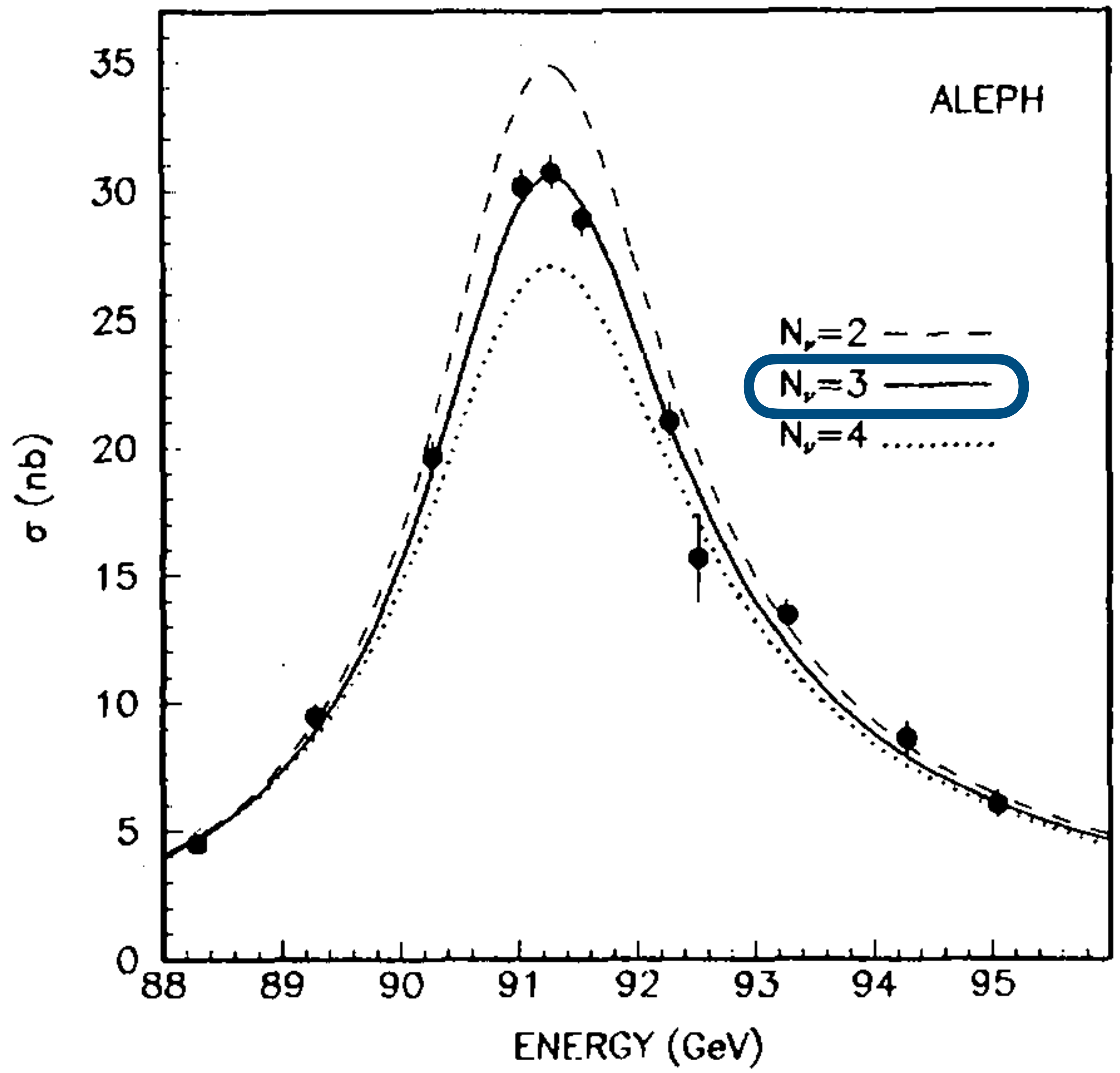
The existence of 3 neutrino flavours

1989

A cornerstone the physics program is the study of the Z-boson "lineshape" to measure the parameters of the electroweak interactions

The 'invisible' width ($\Gamma_{\nu\nu}$) of the Z-boson is related to its decay into neutrinos and gives access to the number of neutrino (N_ν)

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + N_\nu \Gamma_{\nu\nu}$$



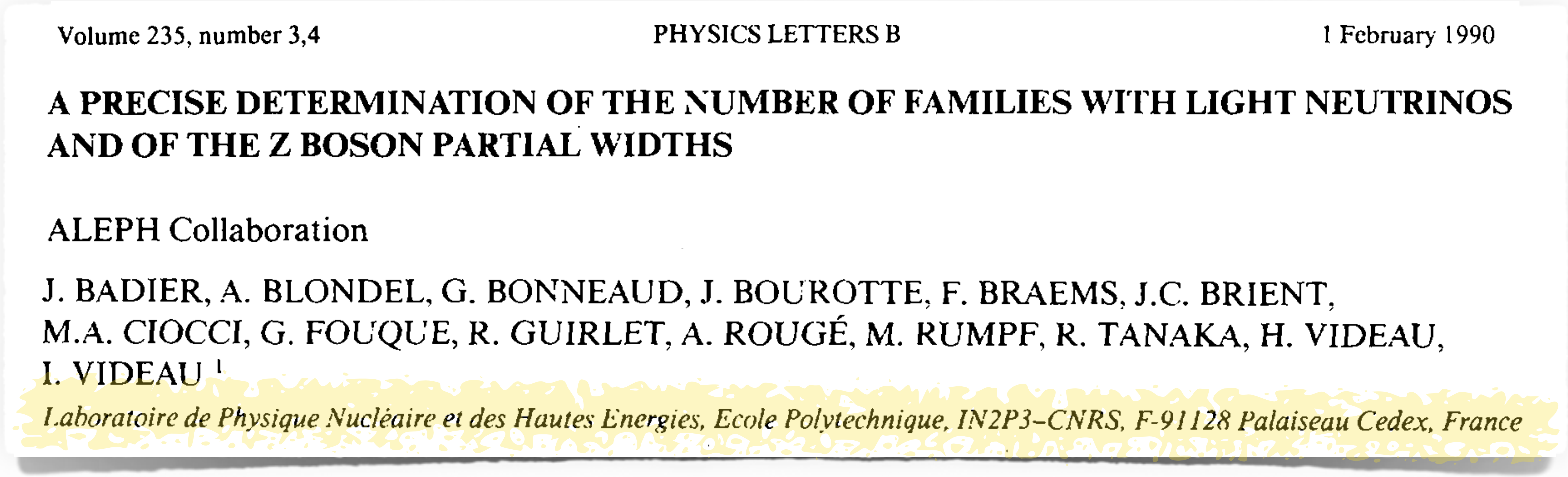
The first Z^0 pole cross section measured by **ALEPH**

Analysis done with **3** weeks of data… and there were only **3** neutrinos

The existence of 3 neutrino flavours

1989

A cornerstone the physics program is the study of the Z-boson "lineshape" to measure the parameters of the electroweak interactions



Volume 235, number 3,4 — PHYSICS LETTERS B — 1 February 1990

A PRECISE DETERMINATION OF THE NUMBER OF FAMILIES WITH LIGHT NEUTRINOS AND OF THE Z BOSON PARTIAL WIDTHS

ALEPH Collaboration

J. BADIER, A. BLONDEL, G. BONNEAUD, J. BOUROTTE, F. BRAEMS, J.C. BRIENT, M.A. CIOCCI, G. FOUQUE, R. GUIRLET, A. ROUGÉ, M. RUMPF, R. TANAKA, H. VIDEAU, I. VIDEAU [1]

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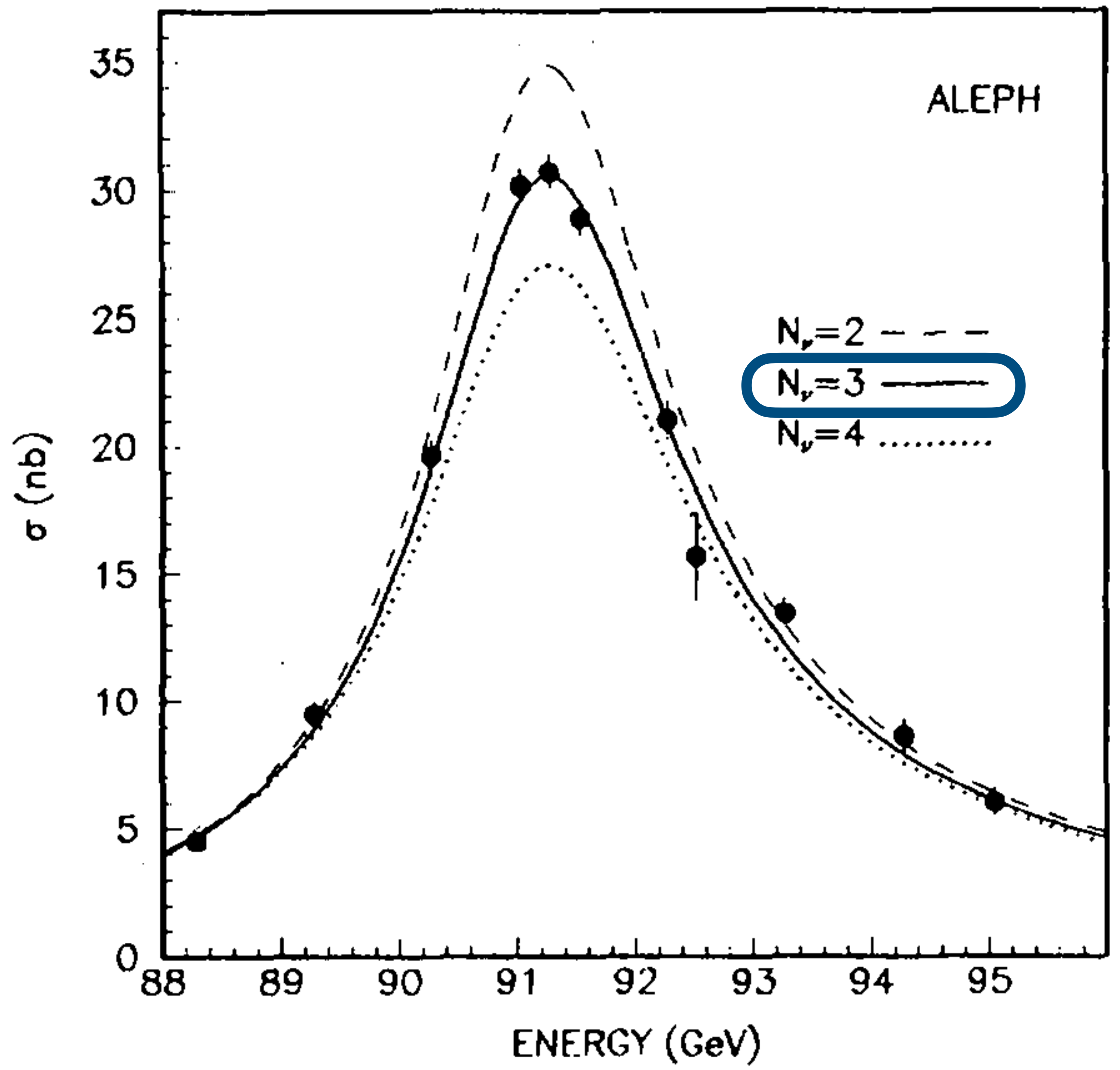


The first Z^0 pole cross section measured by **ALEPH**

Analysis done with **3** weeks of data… and there were only **3** neutrinos

Lessons from LEP

2000

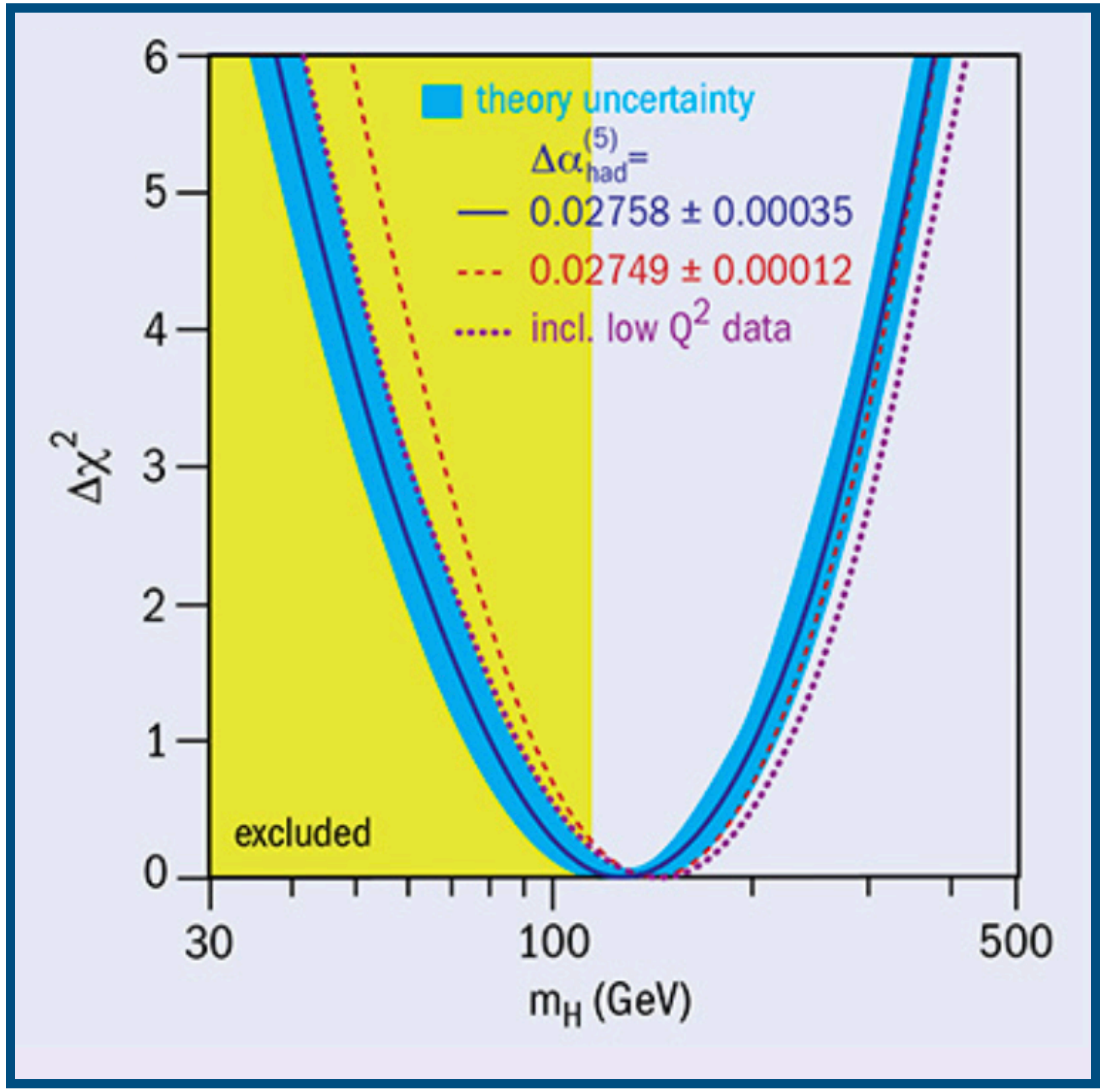
Spectacular agreement of data with the prediction of the Standard Model

Measured the radiative corrections, the essential element showing that the Standard Model is a renormalisable theory.

Enabled predictions of the top-quark mass, later confirmed at Tevatron

Showed that the strong coupling constant, α_S, runs with energy

Used the combined electroweak measurements to make prediction of the Higgs boson mass



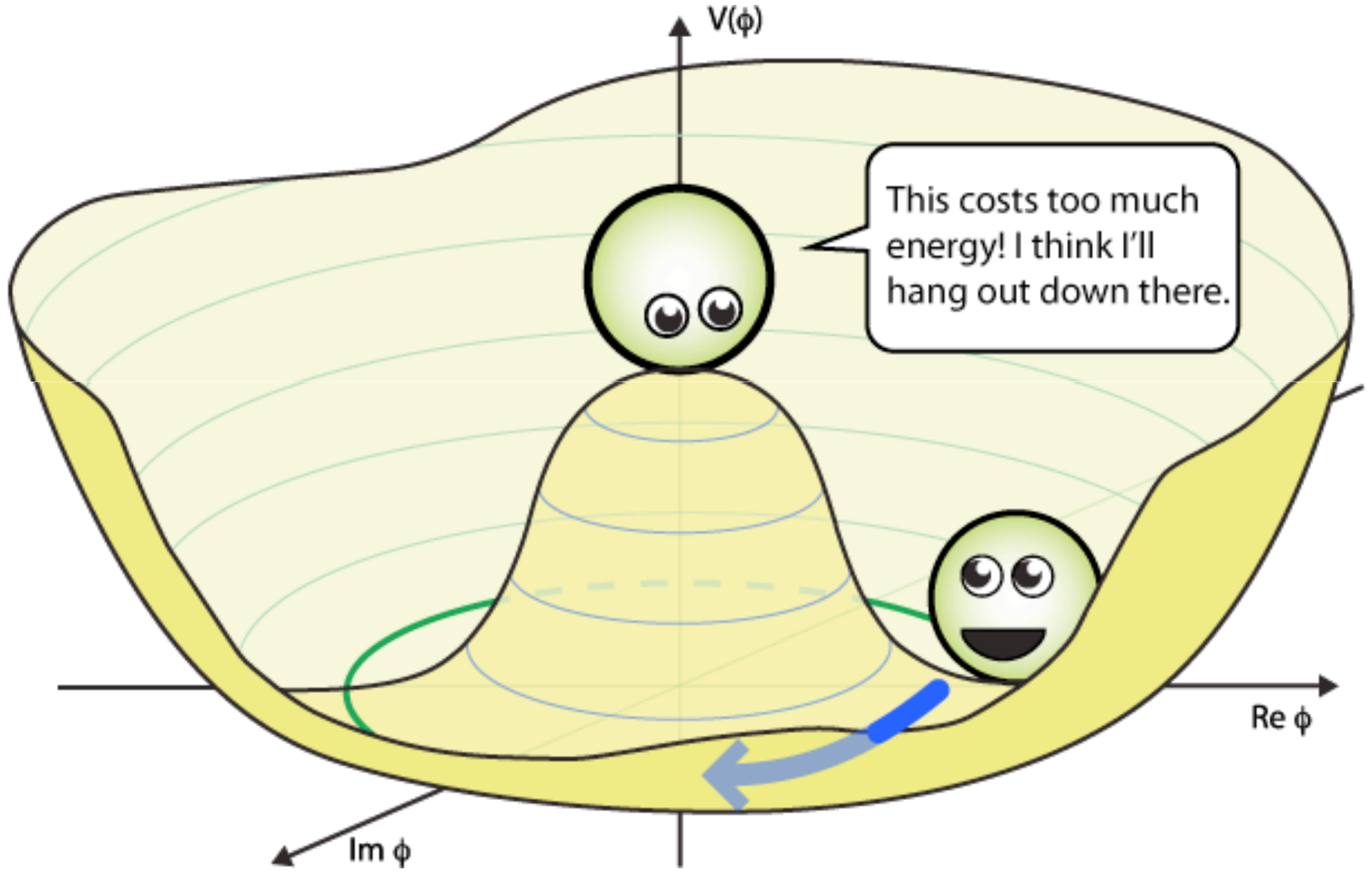
But the Higgs boson still has to be discovered

The Higgs boson

The Brout-Englert-Higgs (BEH) mechanism

The economical way to endow fundamental particles with mass while keeping the theory gauge invariant and predictive

The field is responsible for the spontaneous breaking of electroweak symmetry

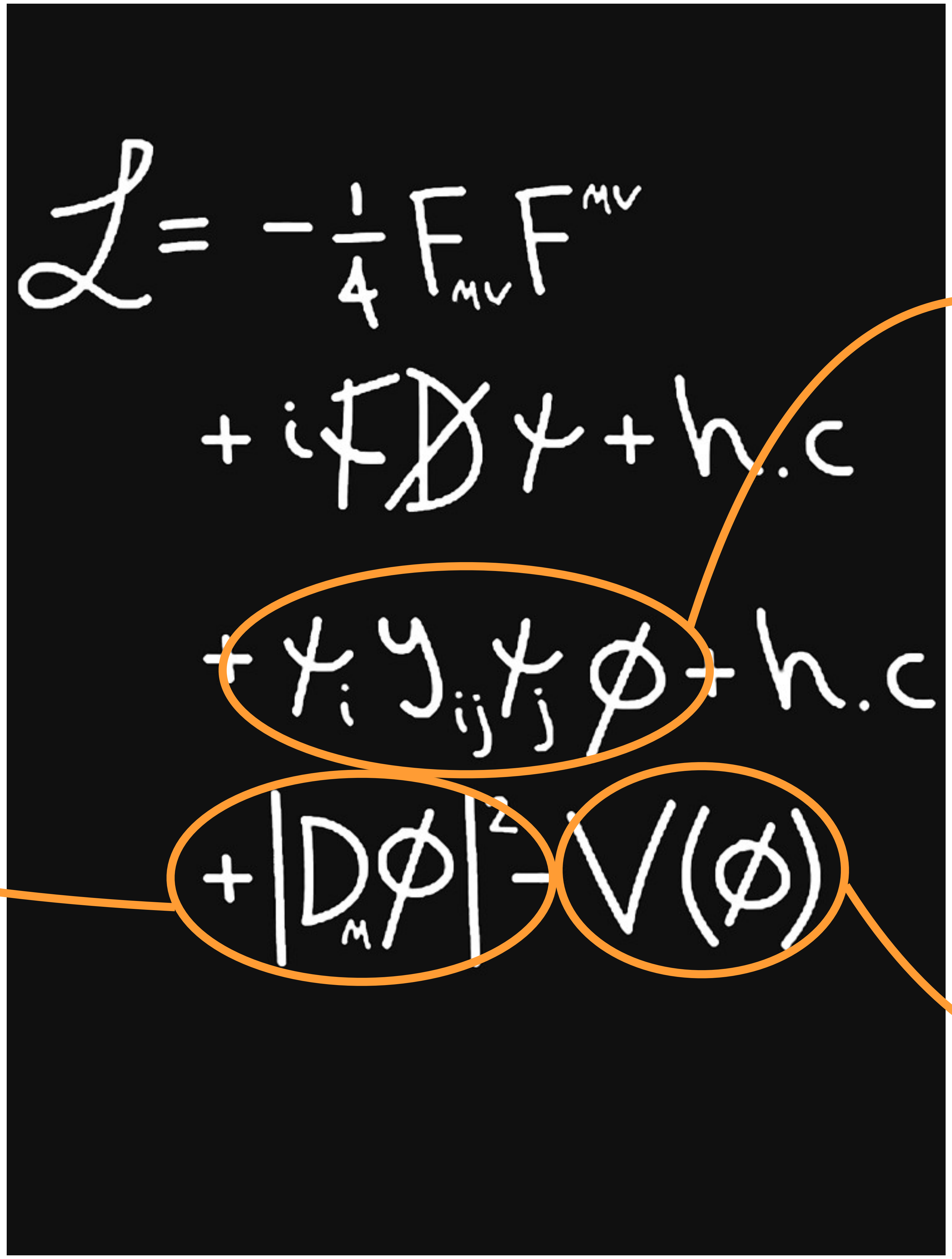


"**Only**" requires one new particle: the Higgs boson **(H)**
"**Only**" one unknown: the Higgs boson mass **(m_H)**

The Higgs boson is special

It is a fundamental scalar particle (spin 0) and
its theory is unlike anything else has been seen in Nature!

A gauge interaction
with vector bosons

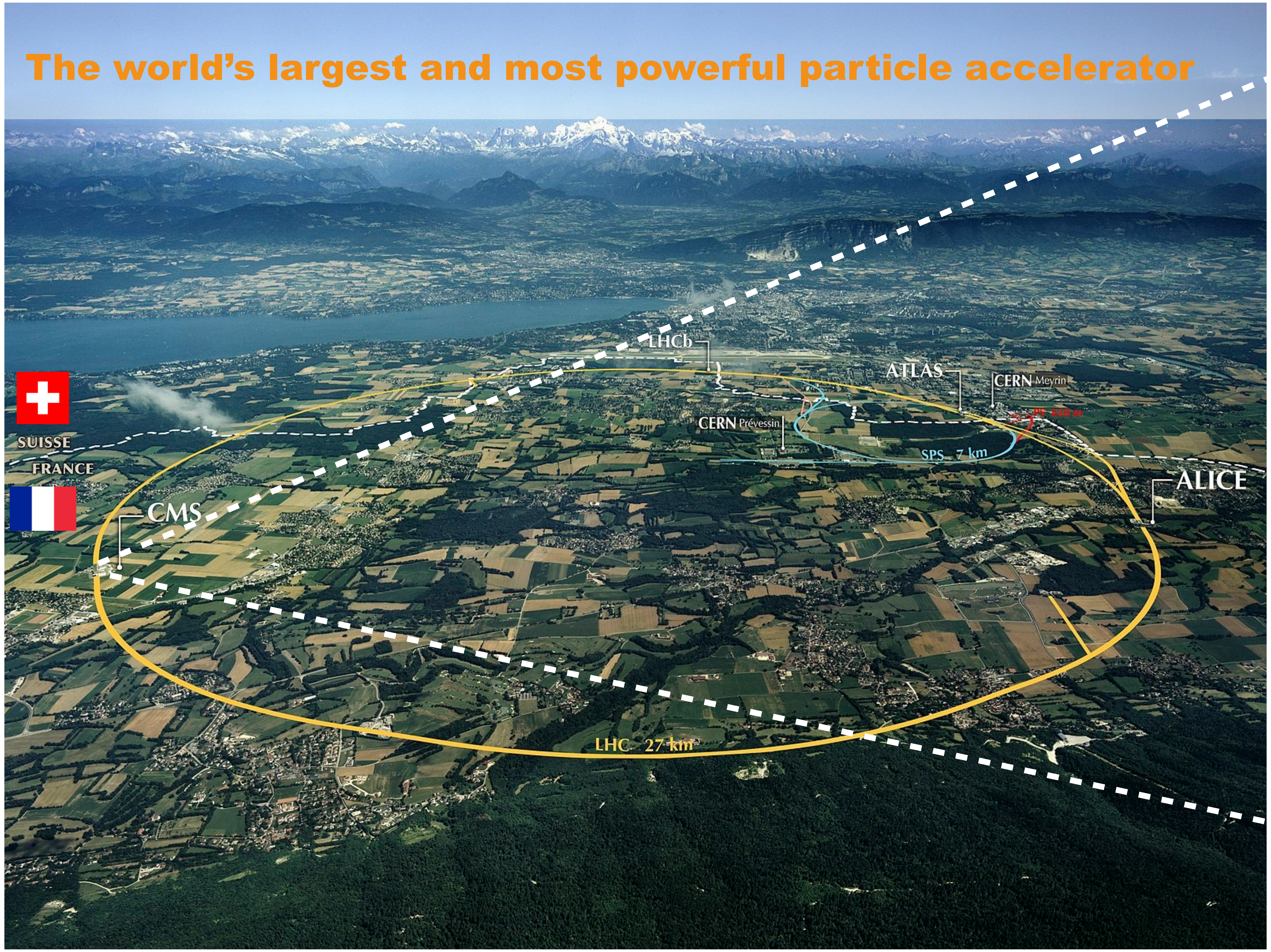


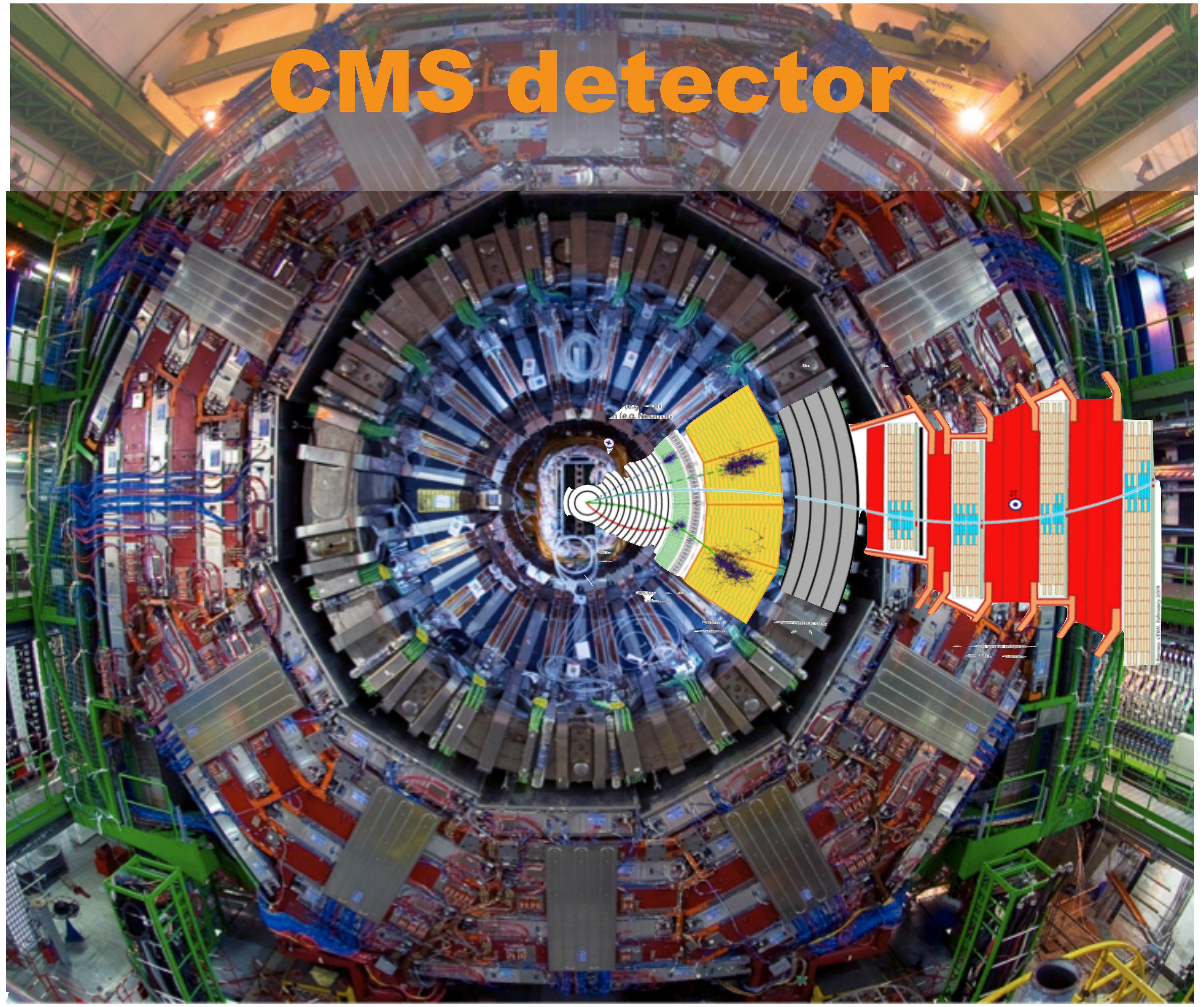
A Yukawa interaction
with the fermions

A potential $V(\phi) \sim -\mu^2(\phi\phi^\dagger) + \lambda(\phi\phi^\dagger)^2$
the keystone of the BEH mechanism and SM

Inspired by G. Salam's LHCP2018 talk

LHC : a new dimension in particle physics



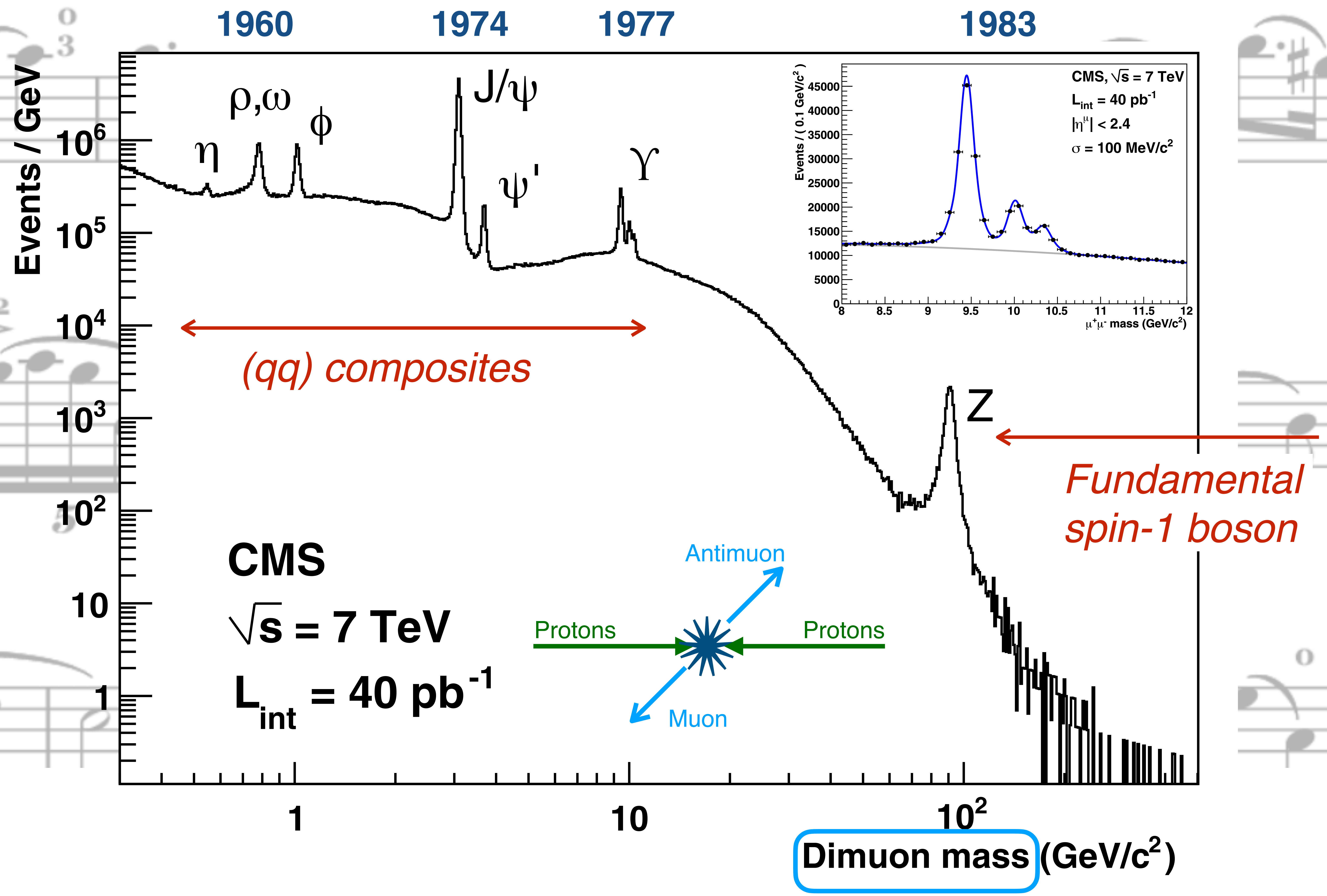


14000-tonne weight
21 metres long, 15 metres wide and 15 metres high
4 Tesla field (~10^6 times the magnetic field of the Earth)

“Intermezzo”

2010

50 years of particle physics … in few weeks of data taking



The Higgs boson timeline at LHC

Years of unprecedented moments in HEP

Few highlights

Higgs boson searches

Higgs boson observation

LHC combination

Towards the precision physics era

HH searches

Observation 3rd-generation couplings

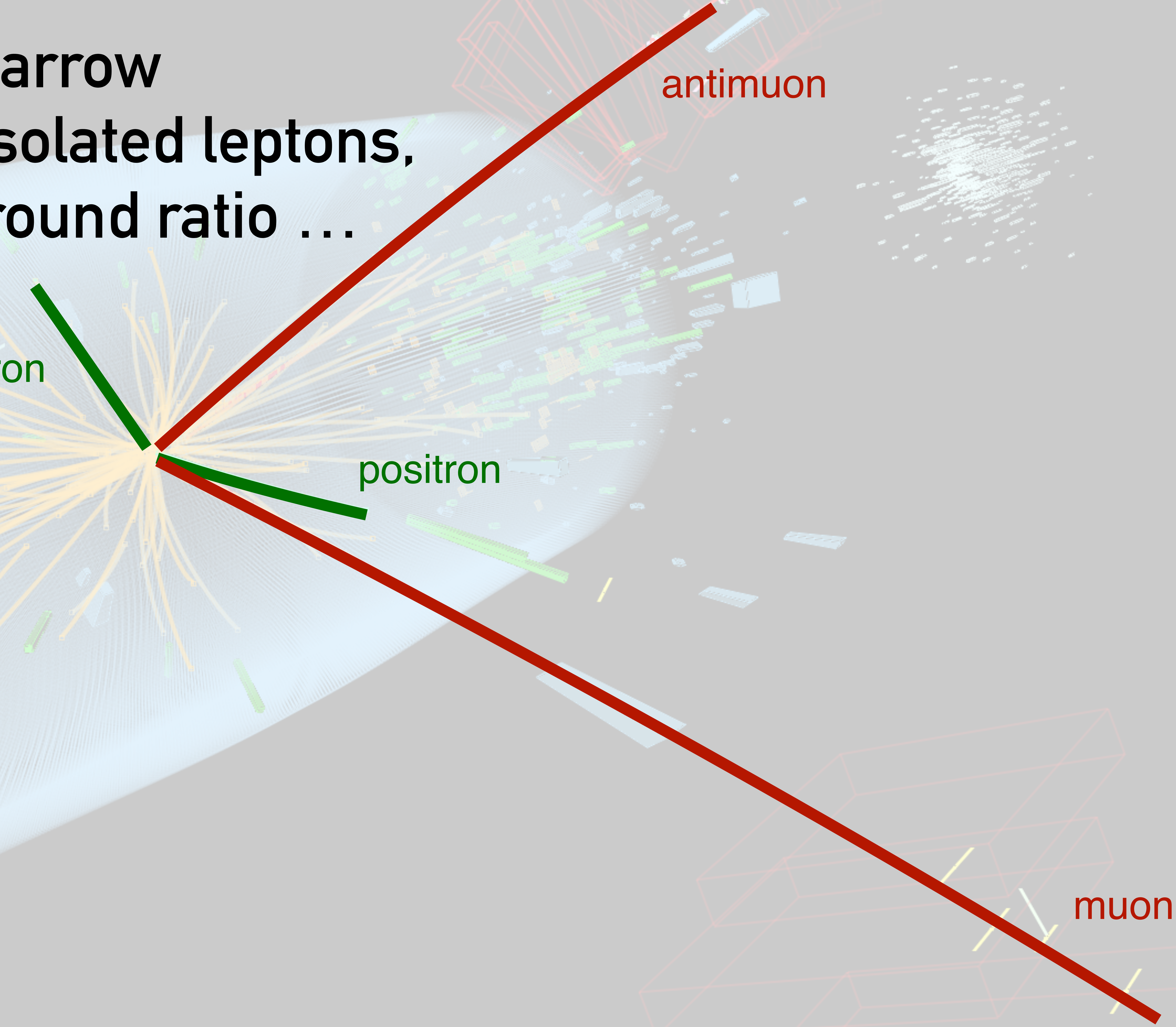
Evidence 2nd-generation coupling

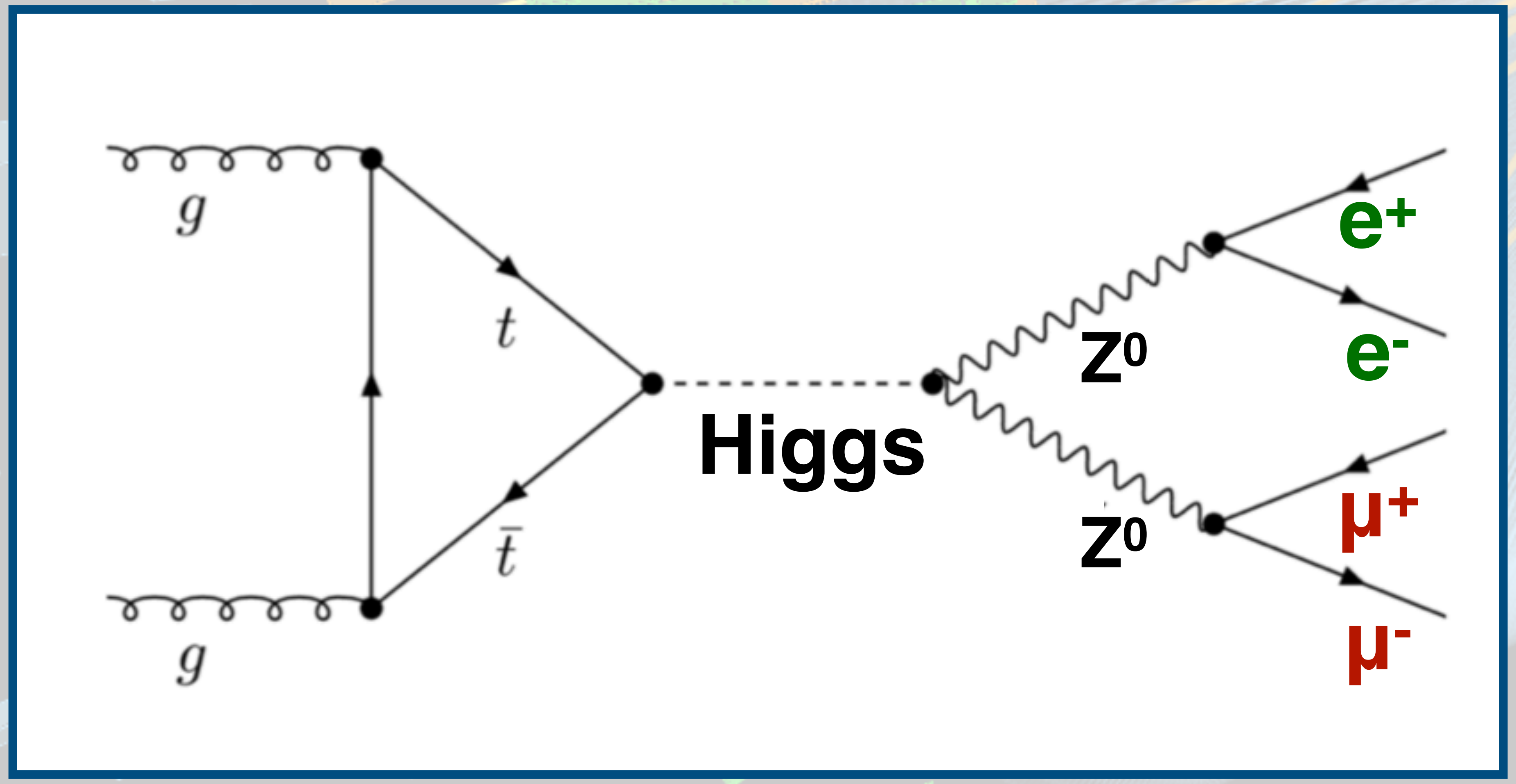
Key channel : H→ZZ→4ℓ

"LHC a world leader"

Key channel : H→ZZ→4ℓ

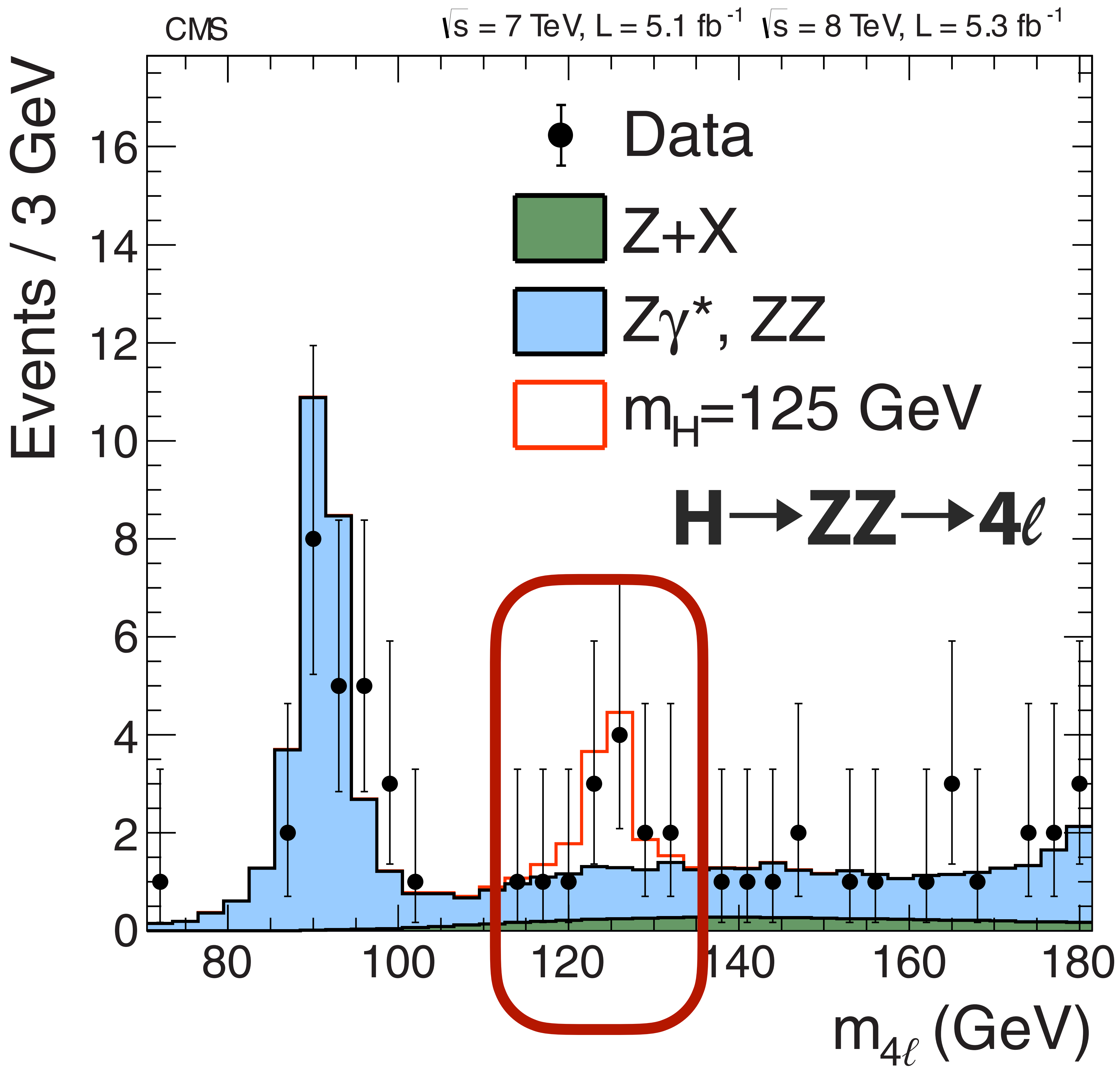
Clean experimental signature: narrow resonance of four primary and isolated leptons, with very large signal-to-background ratio …





The Higgs boson discovery day

2012



A new boson with mass close to 125 GeV was discovered

The fantastic outcome of a long experimental journey and a new start

The discovery paper

2012

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

A R T I C L E   I N F O

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A B S T R A C T

Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

J. Badier, S. Baffioni, F. Beaudette, E. Becheva, L. Benhabib, L. Bianchini, M. Bluj [13], C. Broutin, P. Busson, M. Cerutti, D. Chamont, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, Y. Geerebaert, R. Granier de Cassagnac, M. Haguenauer, P. Hennion, G. Milleret, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, T. Romanteau, D. Sabes, R. Salerno, A. Sartirana, Y. Sirois, C. Thiebaux, C. Veelken, A. Zabi

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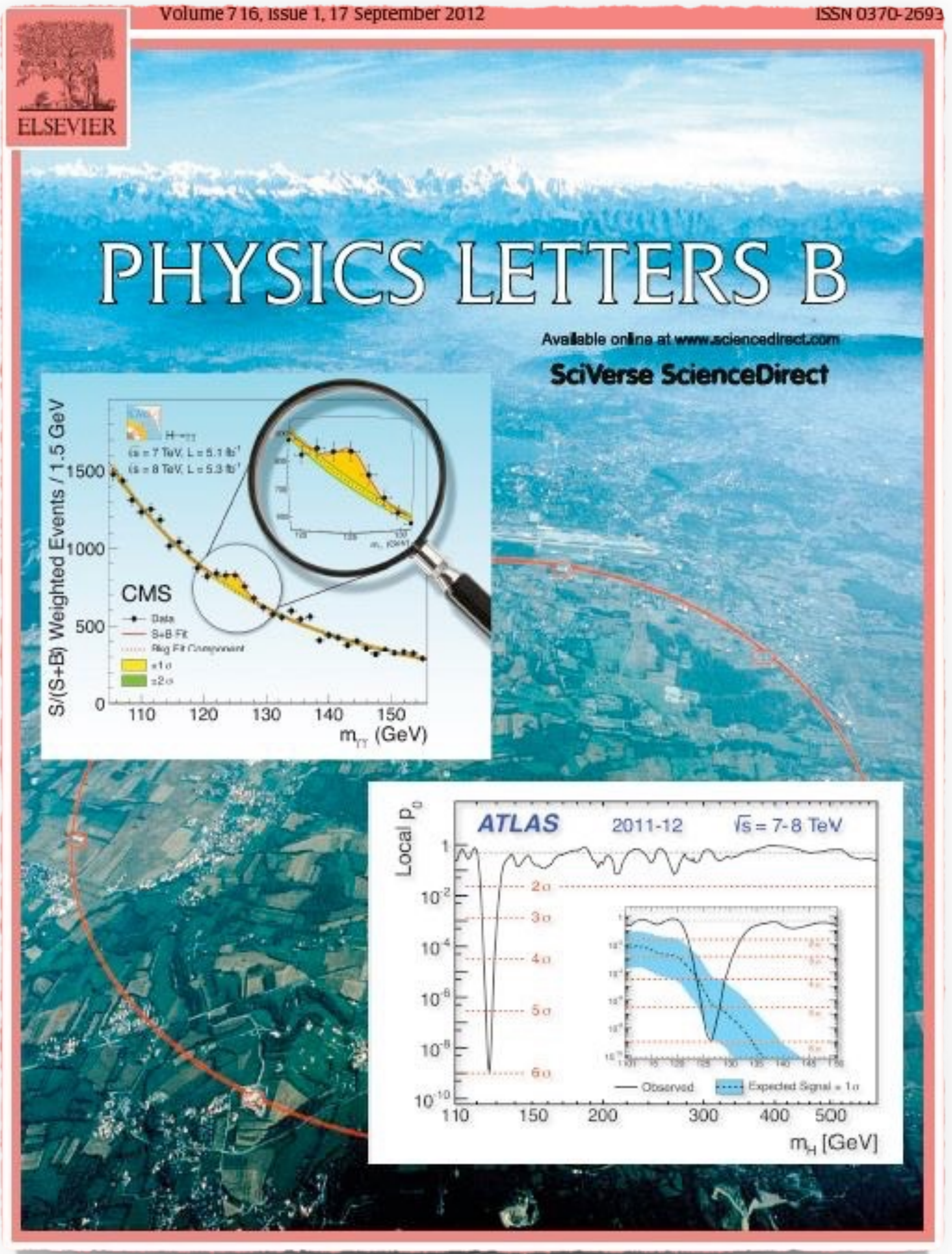


The birth of a "nobel" Higgs boson

2013

CERNCOURIER

Results from ATLAS and CMS now provide enough evidence to identify the new particle of 2012 as 'a Higgs boson'.

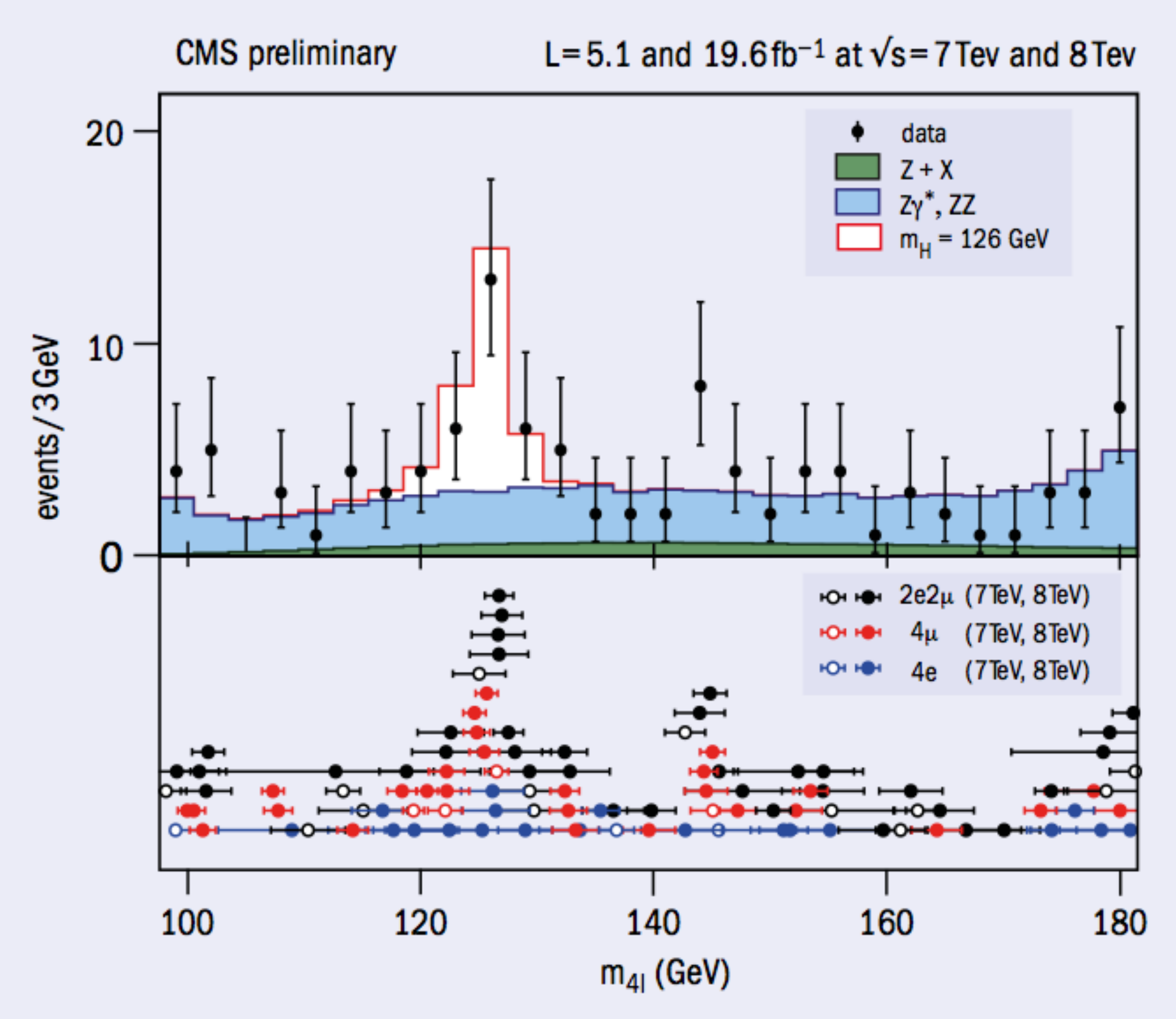
In the history of particle physics, July 2012 will feature prominently as the date when the ATLAS and CMS collaborations announced that they had discovered a new particle with a mass near 125 GeV in studies of proton–proton collisions at the LHC. The discovery followed just over a year of dedicated searches for the Higgs boson, the particle linked to the Brout-Englert-Higgs mechanism that endows elementary particles with mass. At this early stage, the phrase "Higgs-like boson" was the recognized shorthand for a boson whose properties were yet to be fully investigated (*CERN Courier* September 2012 p43 and p49). The outstanding performance of the LHC in the second half of 2012 delivered four times as much data at 8 TeV in the centre of mass as were used in the "discovery" analyses. Thus equipped, the experiments were able to present new results at the 2013 Rencontres de Moriond in March, giving the particle-physics community enough evidence to name this new boson "a Higgs boson".

At the Moriond meeting, in addition to a suite of final results from the experiments at Fermilab's Tevatron on the same subject, the ATLAS and CMS collaborations presented preliminary new results that further elucidate the nature of the particle discovered just eight months earlier. The collaborations find that the new particle is looking more and more like a Higgs boson. However, it remains an open question whether this is *the* Higgs boson of the Standard Model of particle physics, or one of several such bosons predicted in theories that go beyond the Standard Model. Finding the answer to this question will require more time and data.

This brief summary provides an update of the measurements

Observed CL_s compared with $J^P=0^+$		0^- (gg) pseudo-scalar	2^+_m (gg) minimal couplings	2^+_m ($q\bar{q}$) minimal couplings	1^- ($q\bar{q}$) exotic vector	1^+ ($q\bar{q}$) exotic pseudo-vector
$ZZ^{(*)}$	ATLAS	2.2%	6.8%	16.8%	6.0%	0.2%
	CMS	0.16%	1.5%	<0.1%	<0.1%	<0.1%
$WW^{(*)}$	ATLAS	–	5.1%	1.1%	–	–
	CMS	–	14%	–	–	–
$\gamma\gamma$	ATLAS	–	0.7%	12.4%	–	–

Table 1. Summary of preliminary results of the hypothesis tests compared with the Standard Model hypothesis of no spin, positive parity ($J^P=0^+$). All alternatives are disfavoured using the CL_s ratio of probabilities that takes into account how the observation relates to both the Standard Model and the alternative hypotheses.



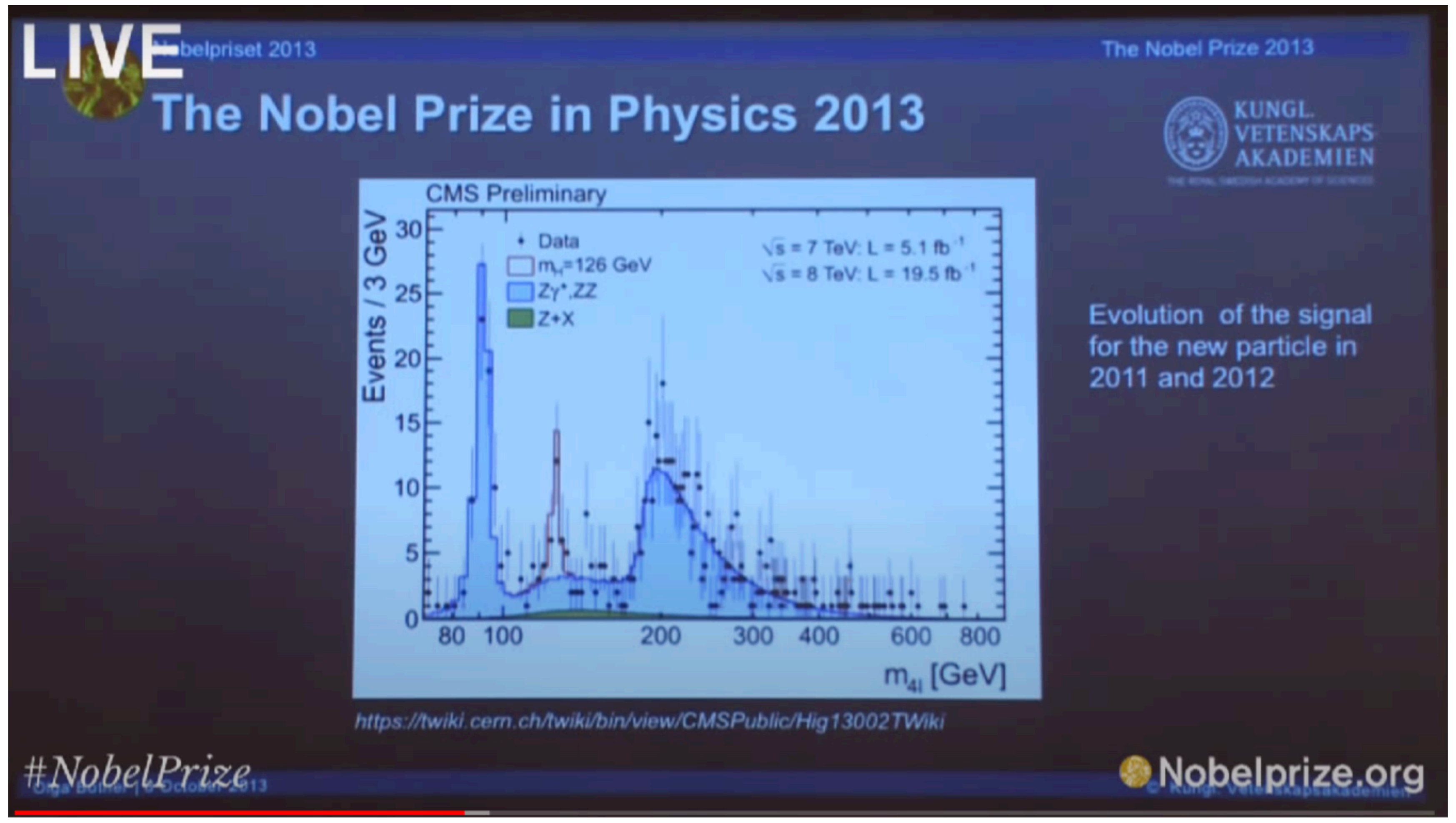
The Nobel Prize in Physics 2013

Photo: A. Mahmoud

François Englert

Photo: A. Mahmoud

Peter W. Higgs



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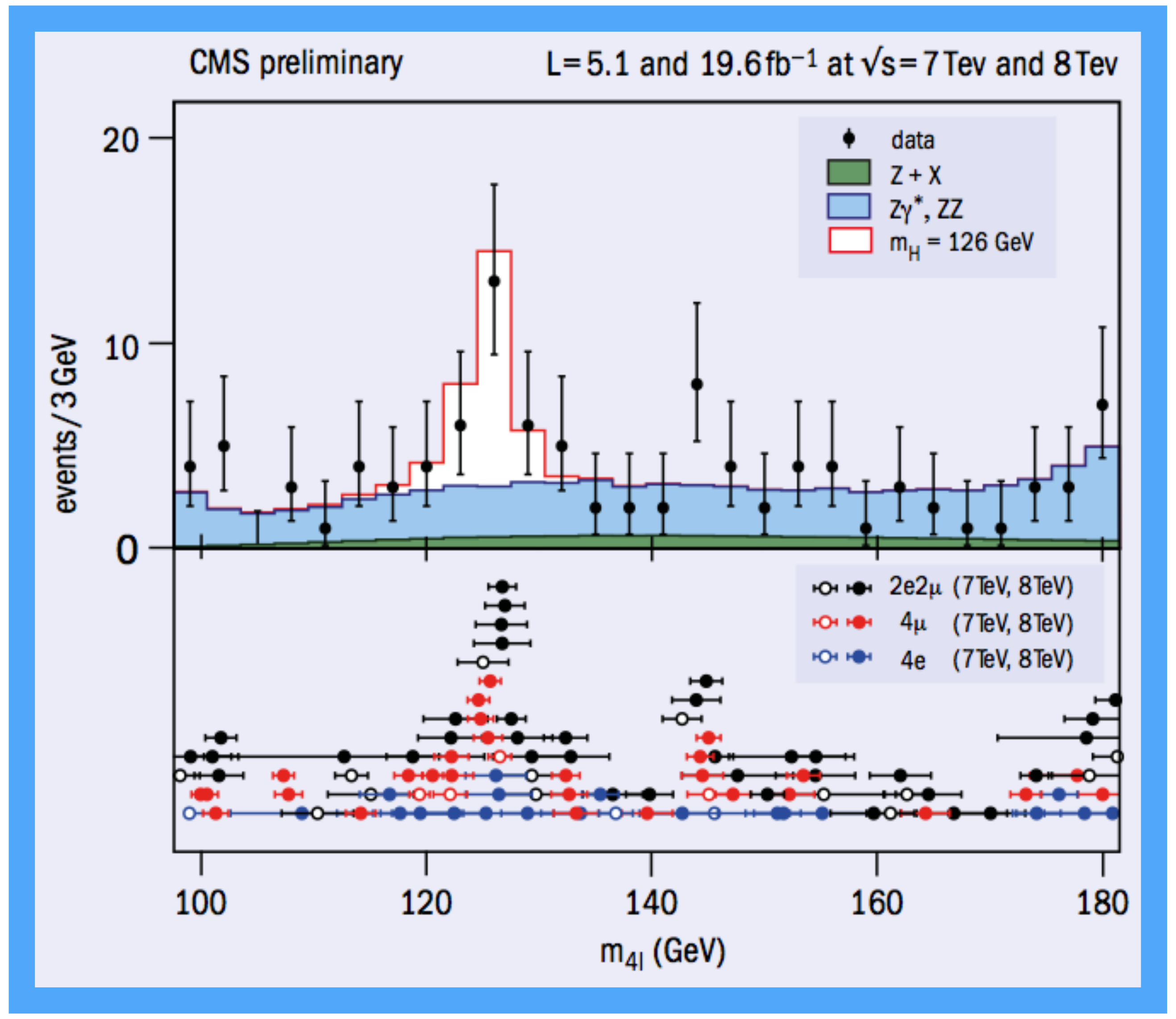

(*)

The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert

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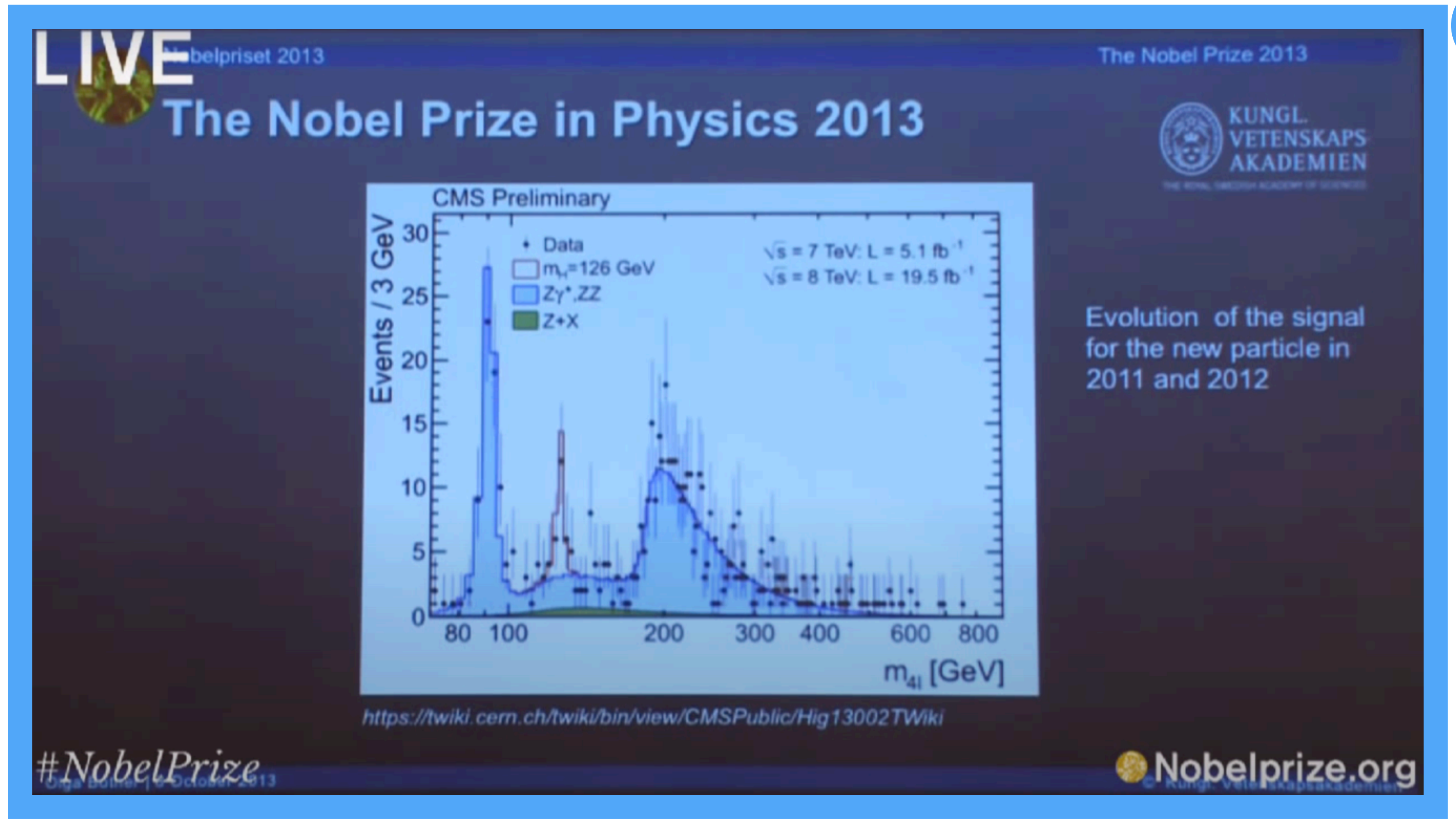
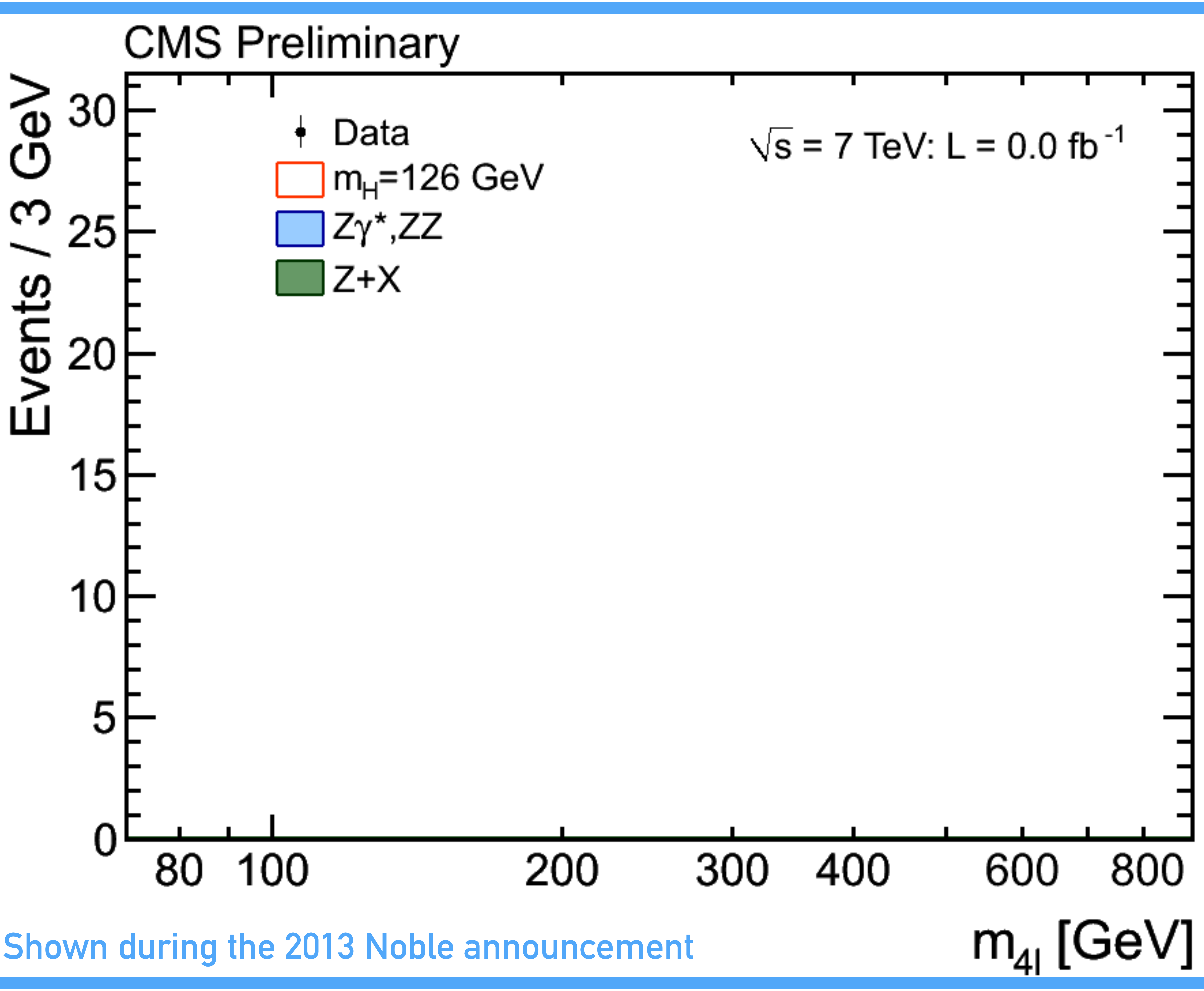
Peter W. Higgs



(*)

(*) LLR H→ZZ→4ℓ on the front line

The birth of a "nobel" Higgs boson



Shown during the 2013 Noble announcement

LHC Run2, LHC Run3, HL-LHC, …

..with the Higgs boson discovery a huge landscape of possibilities opens

Complete study of the strength and tensor structure of the Higgs-boson

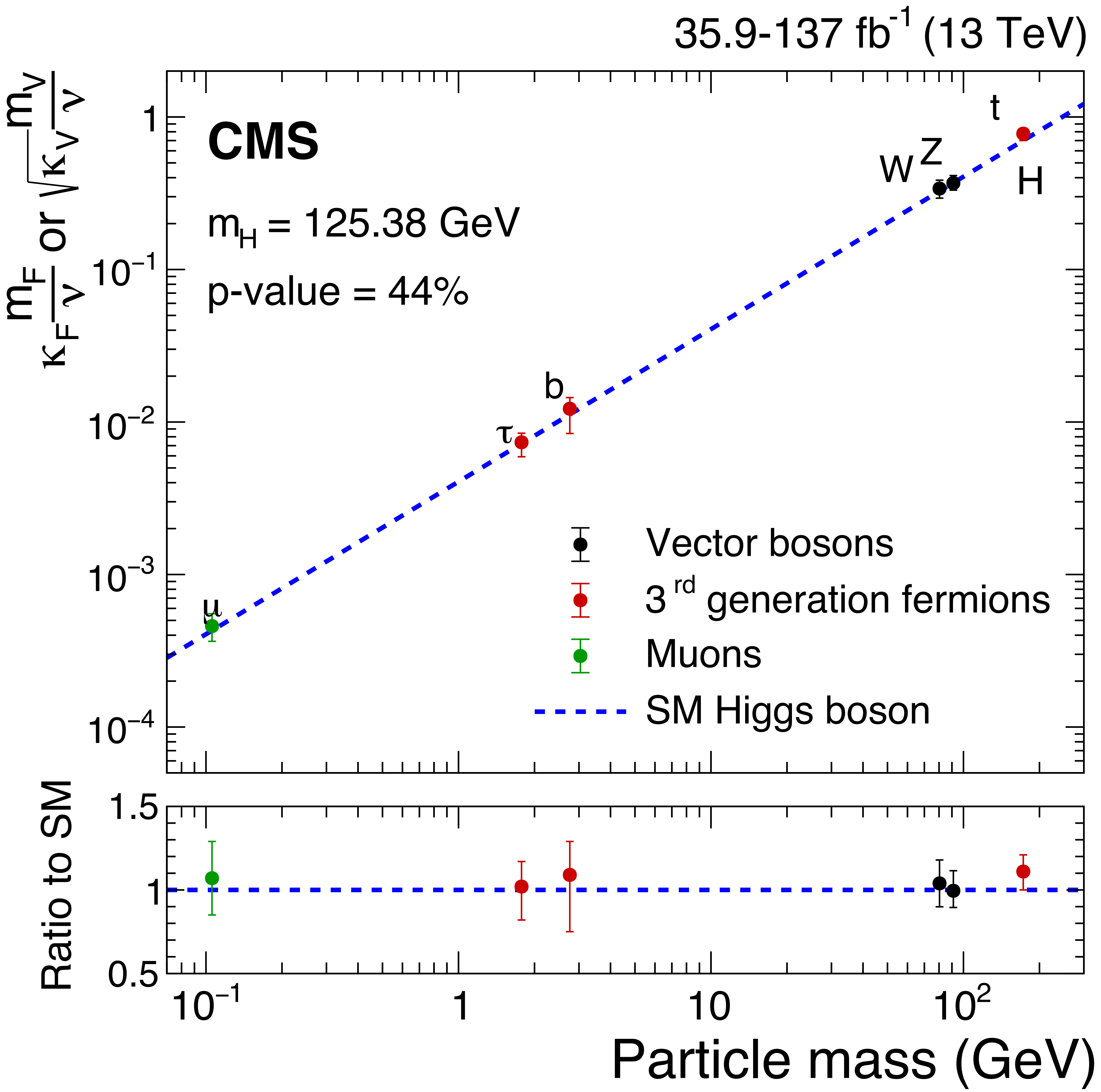
Study of the Higgs Boson self-coupling

The Higgs boson as a tool to reveal the mysteries of Universe (Dark matter, BSM, ….)

The Higgs boson profile

2020

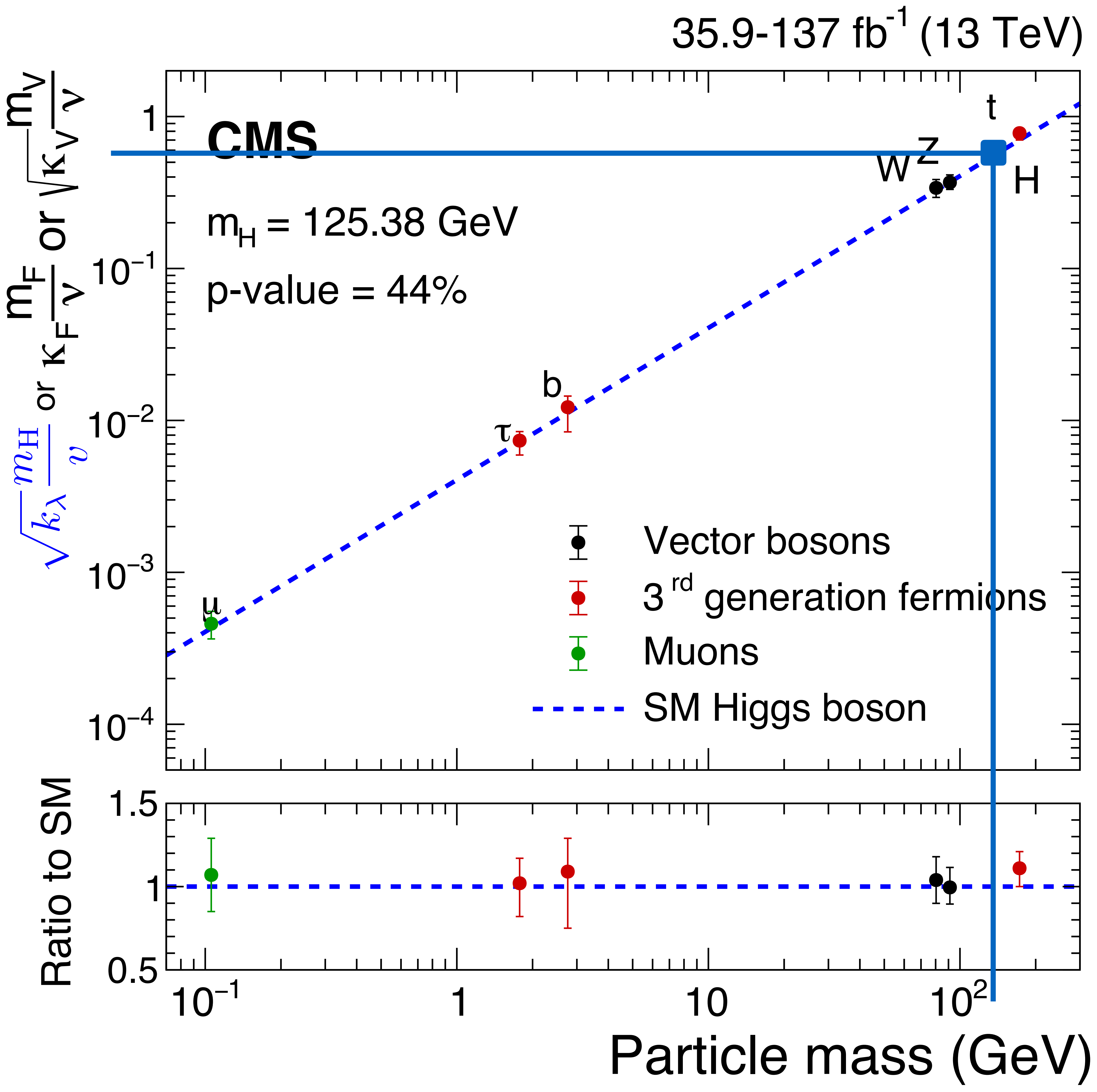
Today : The Higgs boson coupling with gauge bosons, 3rd and 2nd generation fermions is probed!

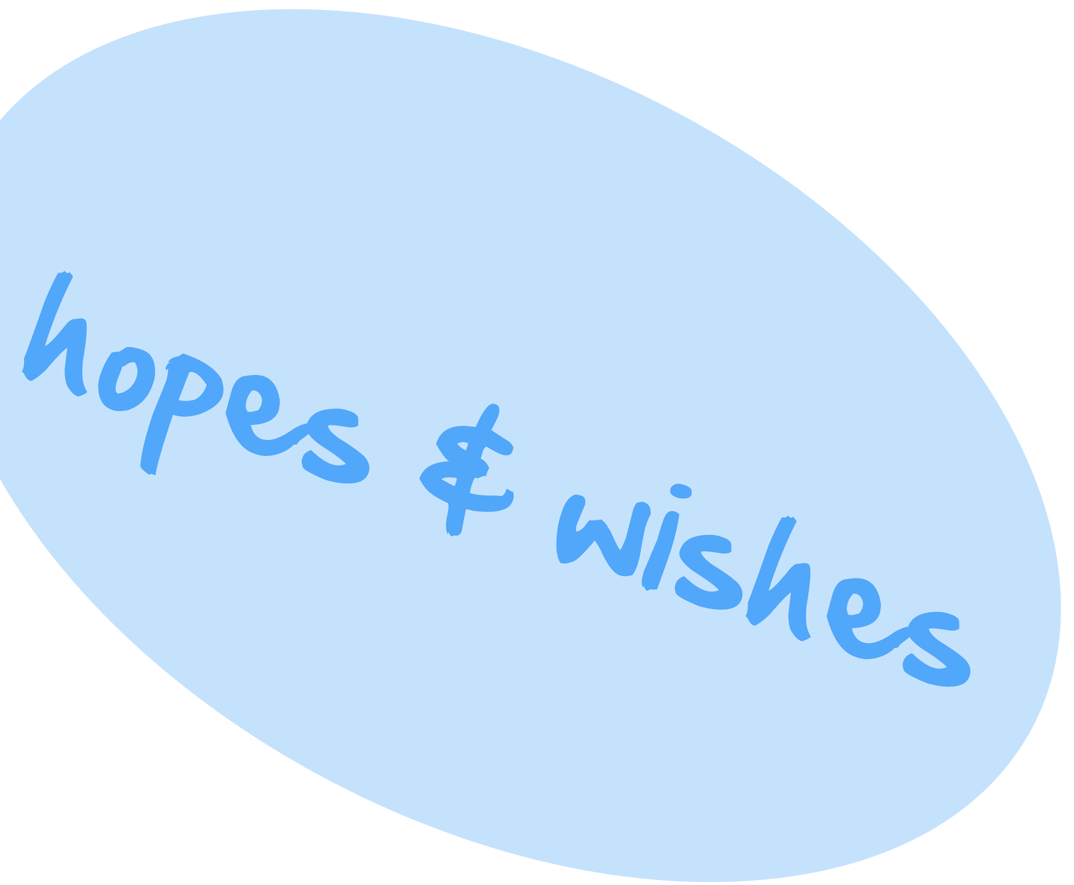


The Higgs boson profile

>2030

HL-LHC : first measurement of
the Higgs boson self-interactions

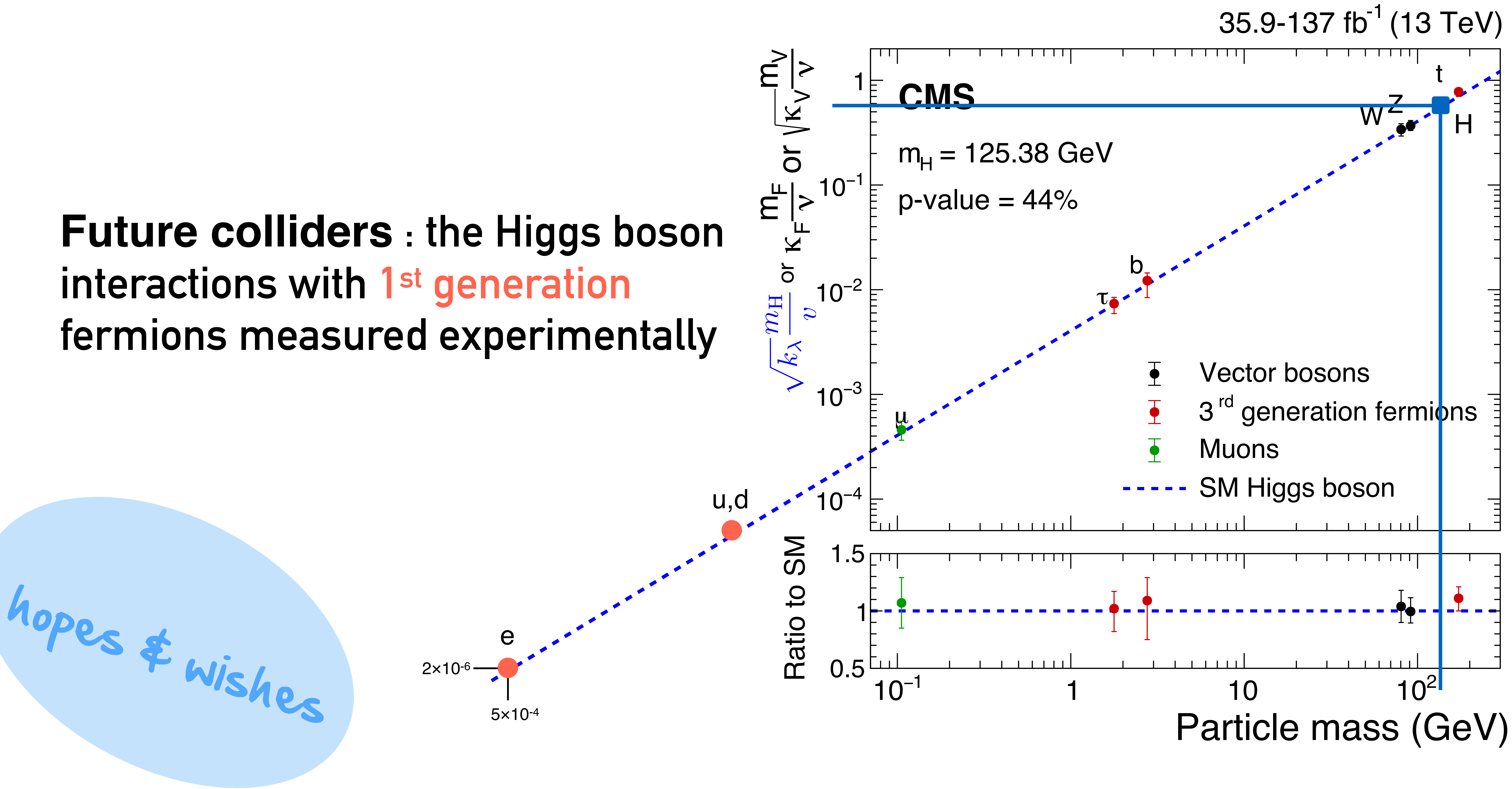




The Higgs boson profile

>2050

Future colliders : the Higgs boson interactions with 1st generation fermions measured experimentally



Outlook

The last 50 years was an historical period for HEP
LLR and IN2P3 were there as main players!

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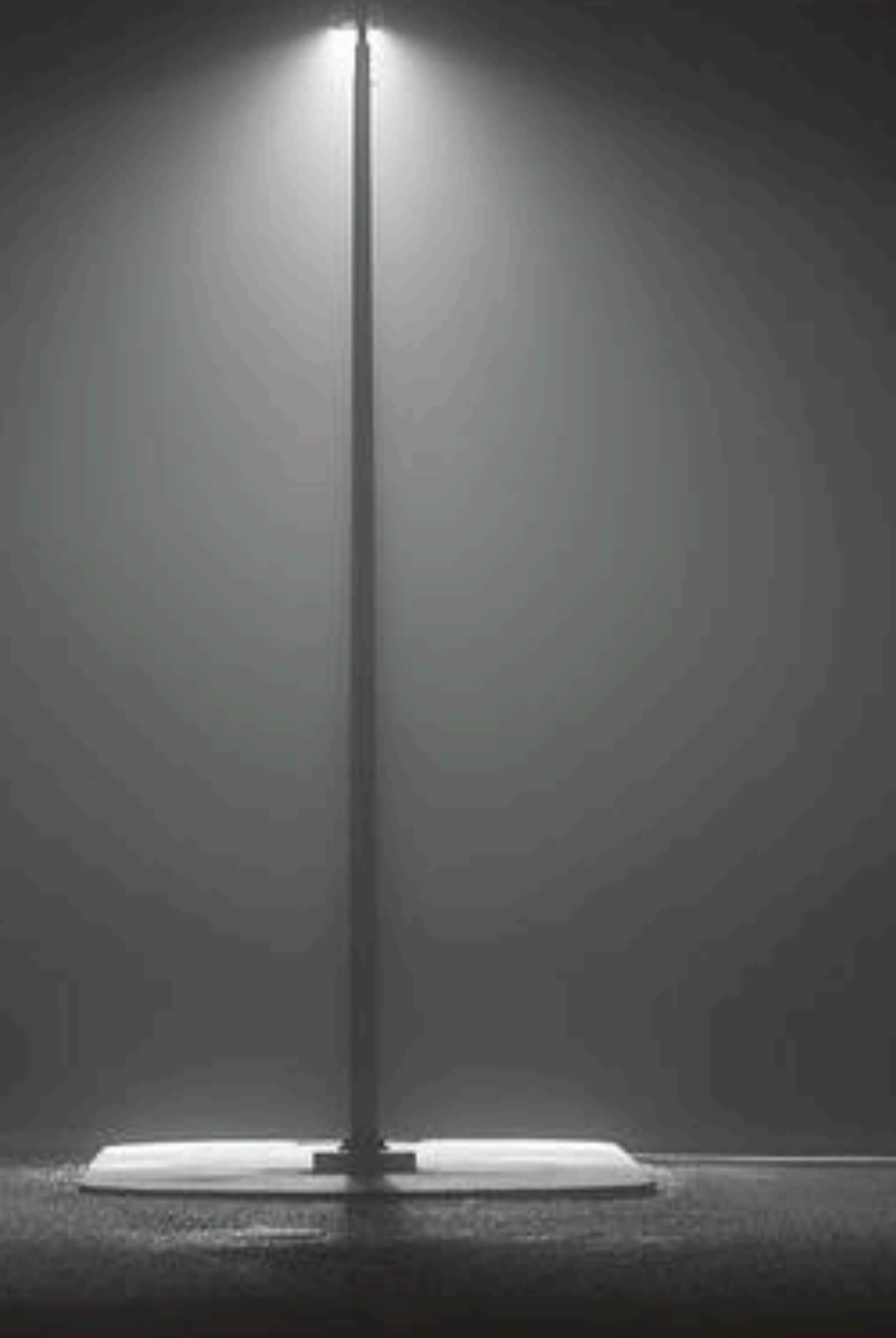

Looking forward to the bright future that will increase our knowledge of the Universe and, if not enable a new discovery, point us to the best street lamp under which to look for it.