Workshop on the Standard Model and Beyond

AUGUST 28 - SEPTEMBER 8, 2022

(B-E)-H bosons between <~ 1964 and ~2012

Louis FAYARD (IJCLab Orsay)

Historical short description related to the (B-E)-H bosons
before the discovery ***(*** circa 4th july 2012 ***)***
with emphasis on the LHC

- **Theory**
- **Experimental developments, including**
  detectors, magnets
- **Searches**
- **Discovery**

Rien n'est cru si fermement que ce
que l'on sait le moins
Nothing is believed more strongly that which we know the least

Montaigne, Essais

Giving an historical talk is difficult !

If I have seen further it is by standing on the shoulders of giants

Isaac Newton, Letter to Robert Hooke, February 5, 1675

You can have a look at historical talks at the Higgs Hunting Workshop

see also various CERN jamborees

Spontaneous Symmetry breaking *(Baker-Glashow)*

The Electroweak Theory *(Salam)*

The Brout-Englert-Higgs mechanism

The LHC

in a

1950 Ginzburg-Landau (Meissner-Ochsenfeld effect → London penetration length ~ W mass

1959 Nambu

1960 Goldstone, Gell-Mann Levy, NJL

1961Schwinger

1962 Anderson

1964 Brout, Englert, Higgs, Guralnik, Hagen,

1967 Weinberg, Salam Faddeev, Popov

1970 Glashow, Iliopoulos,

Maiani, 't Hooft, Veltman, BRST…..

1973 Neutral Currents dis

particles of m

1983 Rubbia, van der Mee

1984 Spiro. Repellin. …

1989 August 198

beginning o

The 10 metre long prototype bending magnet for LHC, which has reached a field of 8,73 Tesla on 14 April 1994

1998 approval o

1999 ATLAS Ph

2006 CMS Physi

2008 ATLAS Ex

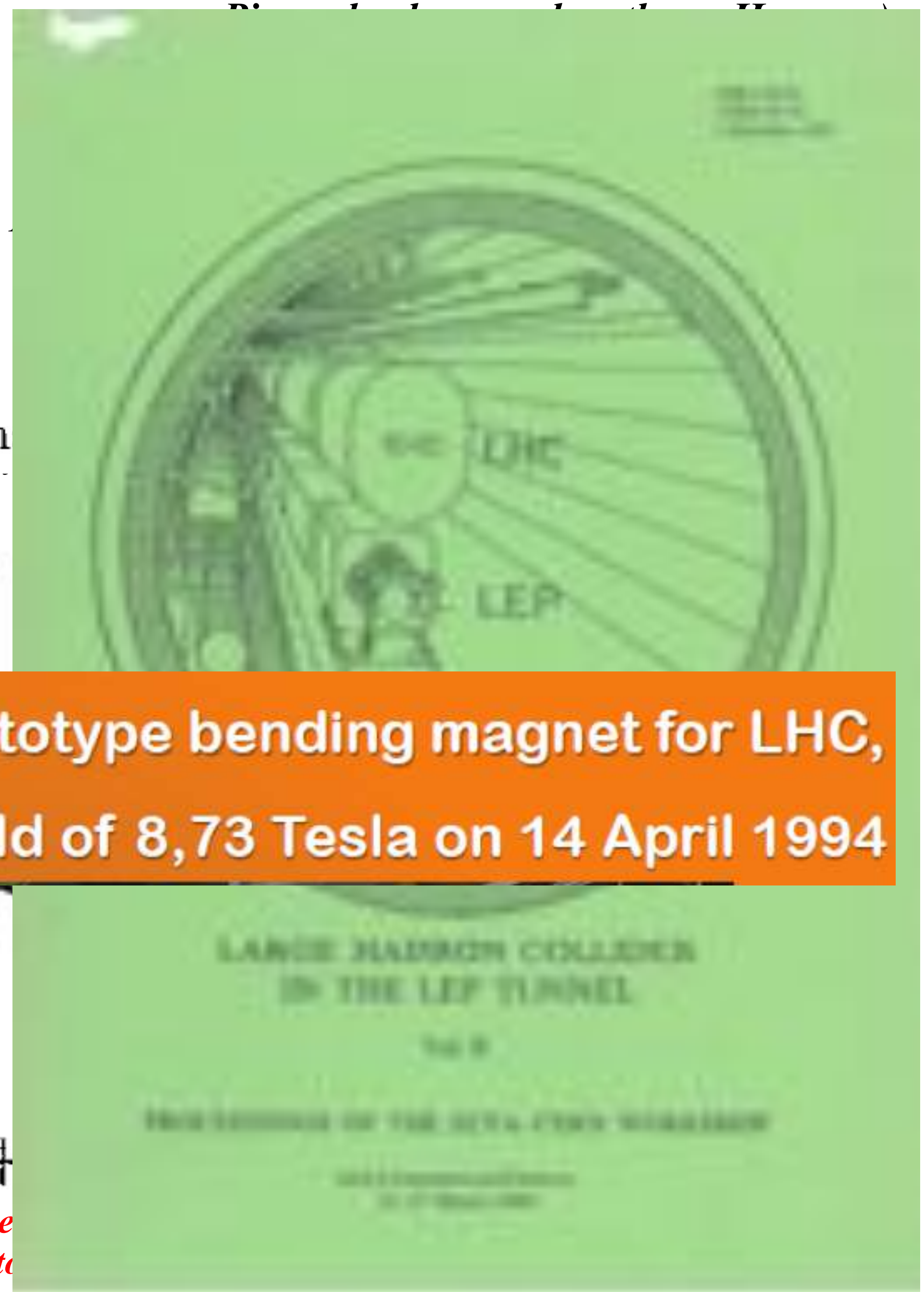
2010 start-up at

2012 4th July discovery of boson (m ~ 125 Ge

2013 boson like properties Nobel prize t

2014

$$\frac{\mu_0^2}{2}\varphi^2 +$$



2008

10th september 2008 : first beams around
19th september 2008 : incident

2009

14 months of major repairs and consolidation
New Quench Protection system


20th november 2009 : first beams around (again)
december 2009 : collisions at 2.36 TeV cms

2010

January 2010 : decided scenario 2010-11 7 TeV cms
instead of 14 TeV

30th march 2010 : first collisions at 7 TeV cms
august 2010 : luminosity of 10^{31} cm^{-2} s^{-1}

2011

September 2011 : end of Tevatron data taking

may 2011 : luminosity > 10^{33} cm^{-2} s^{-1}
november 2011 : 7 TeV integrated luminosity ~ 5 fb^{-1}
13th december 2011 : first 'signal' around 126 GeV

2012

march 2012 : start again at 8 TeV
(50 ns between bunches)
4th July 2012 : evidence for a new boson
(8 TeV integrated luminosity ~ 6 fb^{-1})

2013

(Standard-Model) boson-like properties
peak luminosity 7 10^{33} cm^{-2} s^{-1}
integrated luminosity ~ 5+ 20 fb^{-1}

end of Run-1

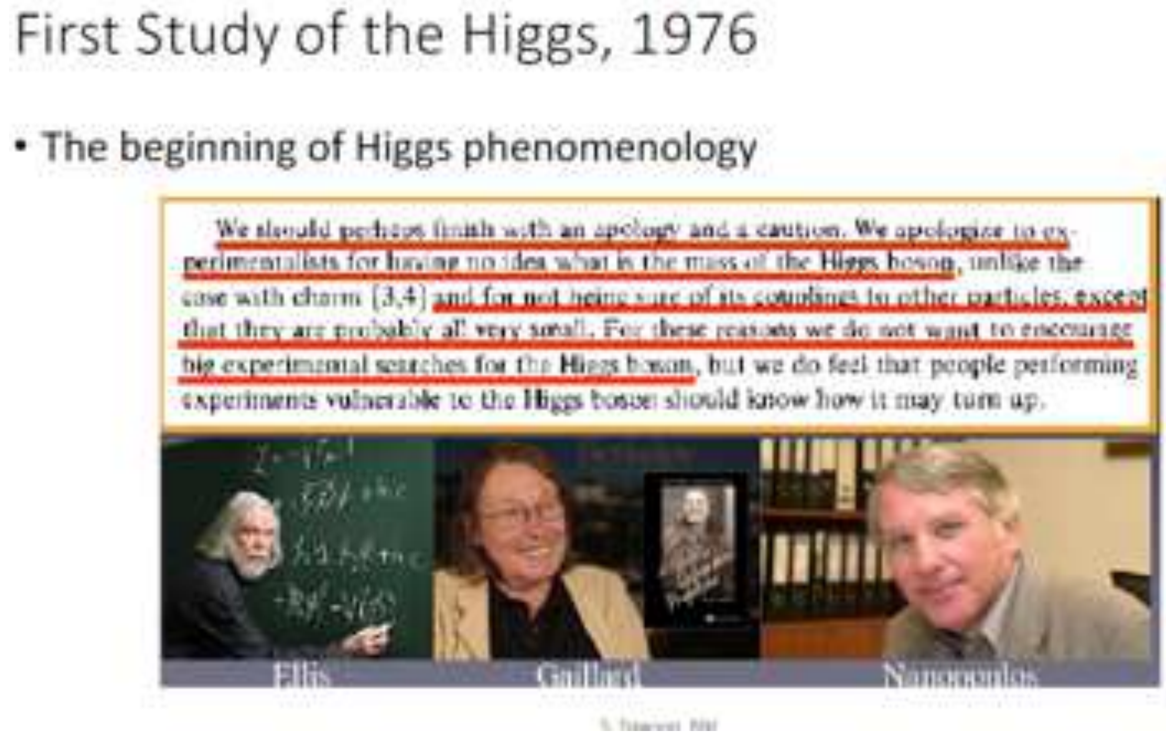
Englert –Higgs Nobel prize

now

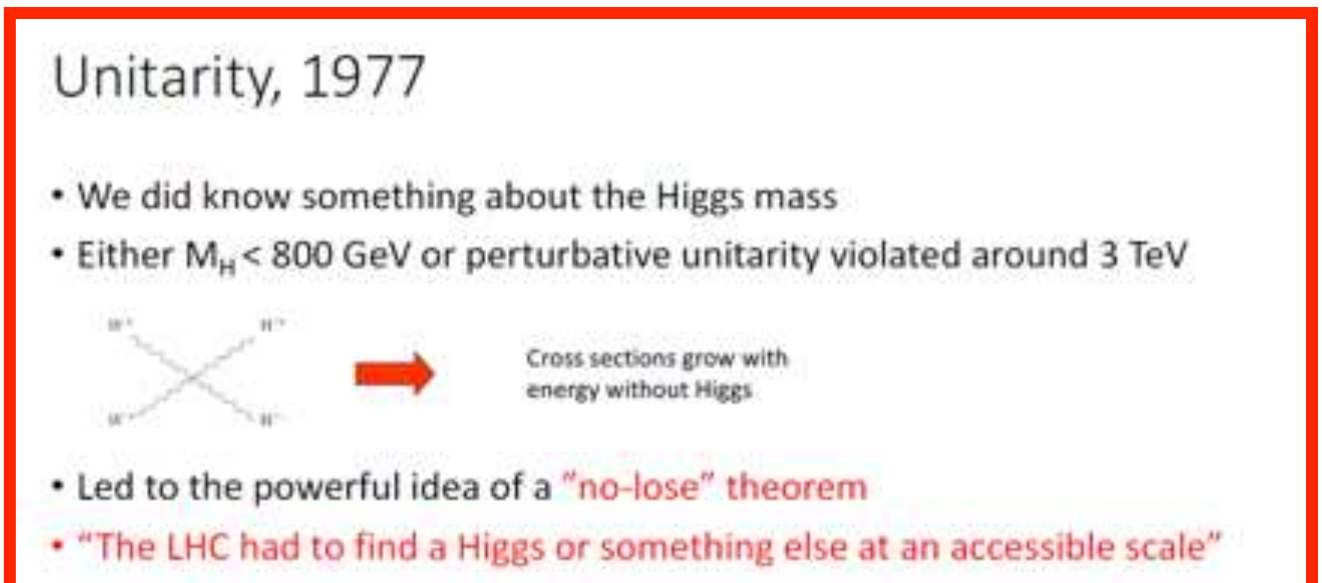
(B-E)-H boson discovery

- **Theory**
- **Experimental developments, including detectors, magnets**
- **Searches**
- **Discovery**

S.Dawson 4th July 2022



A Phenomenological Profile of the Higgs Boson
John R. Ellis (CERN), Mary K. Gaillard (CERN and Orsay, LPT), Dimitri V. Nanopoulos (CERN) (Oct, 1975)
Published in: *Nucl.Phys.B* 106 (1976) 292



Weak Interactions at Very High-Energies: The Role of the Higgs Boson Mass
Benjamin W. Lee (Fermilab), C. Quigg (Fermilab), H.B. Thacker (Fermilab) (Mar, 1977)
Published in: *Phys.Rev.D* 16 (1977) 1519

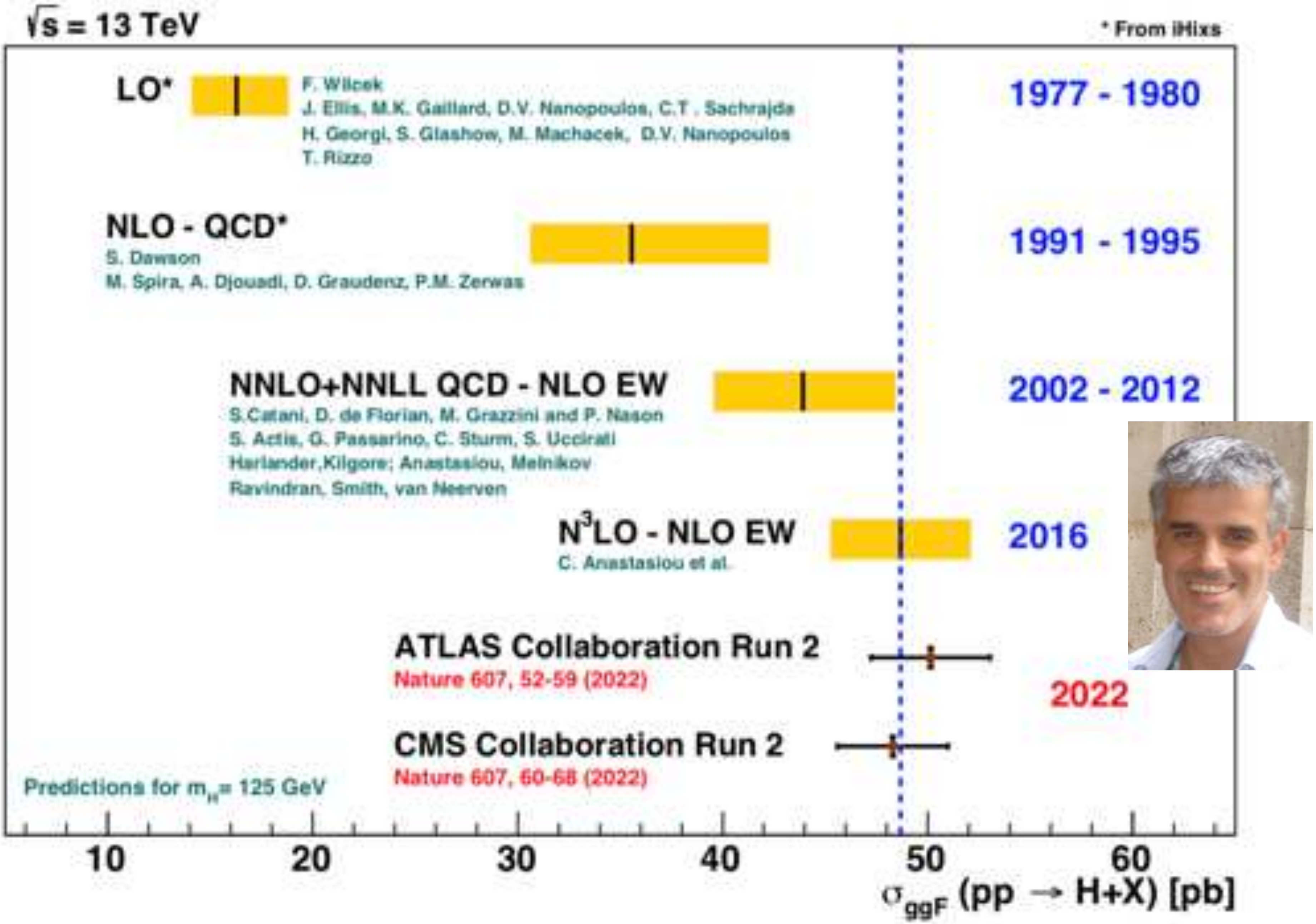
The Strength of Weak Interactions at Very High-Energies and the Higgs Boson Mass
Benjamin W. Lee (Fermilab), C. Quigg (Fermilab), H.B. Thacker (Fermilab) (Feb, 1977)
Published in: *Phys.Rev.Lett.* 38 (1977) 883-885

Theorists and SUSY prefer low mass boson

$m_h < m_Z$ at lowest order . But was realized that this prediction is subject to important radiative corrections that could push m_h up to ~130 GeV in simple supersymmetric models

Y. Okada, M. Yamaguchi and T. Yanagida, *Upper bound of the lightest Higgs boson mass in the minimal supersymmetric standard model*, Prog. Theor. Phys. **85** (1991) 1.

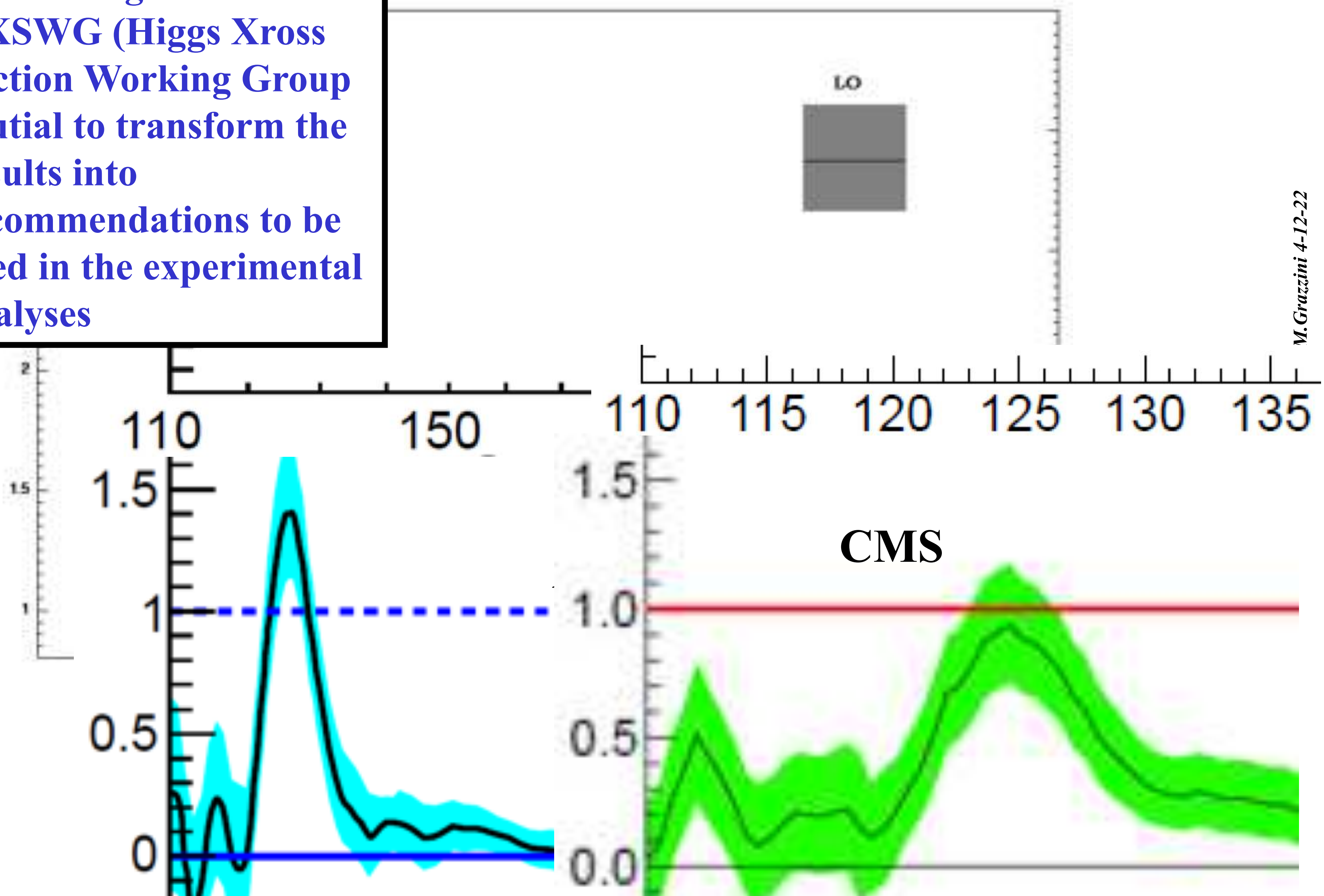
J. R. Ellis, G. Ridolfi and F. Zwirner, *Radiative corrections to the masses of supersymmetric Higgs bosons*, Phys. Lett. B **257** (1991) 83; H. E. Haber and R. Hempfling, *Can the mass of the lightest Higgs boson of the minimal supersymmetric model be larger than m(Z)?*


√s = 13 TeV
* From iHixs
LO*
F. Wilcek
J. Ellis, M.K. Gaillard, D.V. Nanopoulos, C.T . Sachrajda
H. Georgi, S. Glashow, M. Machacek, D.V. Nanopoulos
T. Rizzo
1977 - 1980
NLO - QCD*
S. Dawson
M. Spira, A. Djouadi, D. Graudenz, P.M. Zerwas
1991 - 1995
NNLO+NNLL QCD - NLO EW
S.Catani, D. de Florian, M. Grazzini and P. Nason
S. Actis, G. Passarino, C. Sturm, S. Uccirati
Harlander,Kilgore; Anastasiou, Melnikov
Ravindran, Smith, van Neerven
2002 - 2012
N3LO - NLO EW
C. Anastasiou et al.
2016
ATLAS Collaboration Run 2
Nature 607, 52-59 (2022)
2022
CMS Collaboration Run 2
Nature 607, 60-68 (2022)
Predictions for mH= 125 GeV
10
20
30
40
50
60
σggF (pp → H+X) [pb]

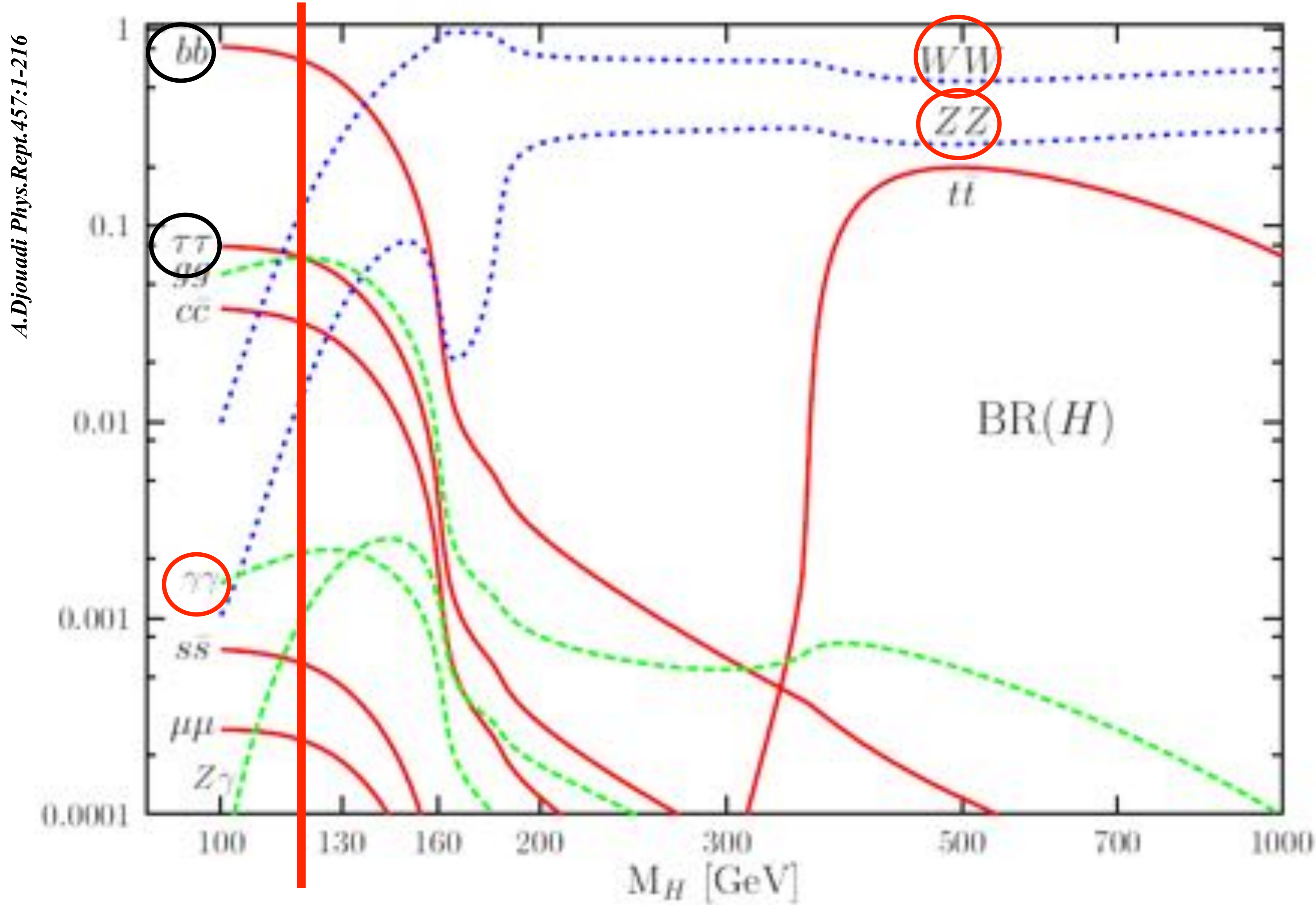
…or signal strength

discovery papers (2012)

Do not forget the HXSWG (Higgs Xross Section Working Group crutial to transform the results into recommendations to be used in the experimental analyses



M.Grazzini 4-12-22



In addition , at the time of the discovery a small use was made of the different production modes

- **Theory**
- **Experimental developments, including detectors, magnets**
- **Searches**
- **Discovery**

The construction of the machine and of the experiments went very well

.. But not without problems

LEP : approved in Oct 1981   starts operation in August 1989

ECFA-79-039

ECFA-LEP working group : 1979 progress report

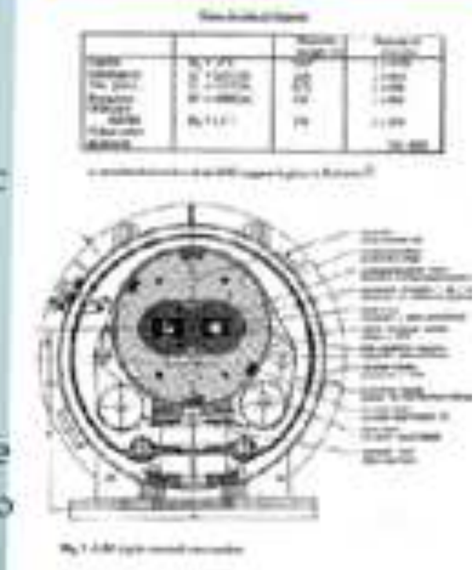
The LEP-White Book

Zichichi, Antonino (ed.) (CERN)

1. Prologue: the LEP tunnel

- Physicists had thought to make the tunnel wider than what was strictly needed so as to be able to install later a proton machine with superconducting magnets
- The ECFA study (Roma 1978, chaired by A. Zichichi) had made a recommendation in this direction, nothwitstanding the resistence of those afraid that the implied cost increase would put the LEP project at risk
- As a compromise, a tunnel of 4 meters diameter was accepted. However, this was not enough for a cryogenic system with two independent magnets (such as was designed for the SSC).
- CERN was forced to develop a new advanced design: "two-in-one", more compact and less expensive
- The choice of tunnel's dimensions, all in all, is a positive story: an admirable compromise that made it possible to prolong the lifetime of CERN well above 20 years.

Two-in-one Dipole Superconducting Magnets



SSC approved in November 1988 Cancelled in October 1993

(ISABELLE was cancelled in July 1983)

Countries that contributed to SSC(US , Japan, India , …) will contribute to LHC

L.Maiani Higgs Hunting 2021

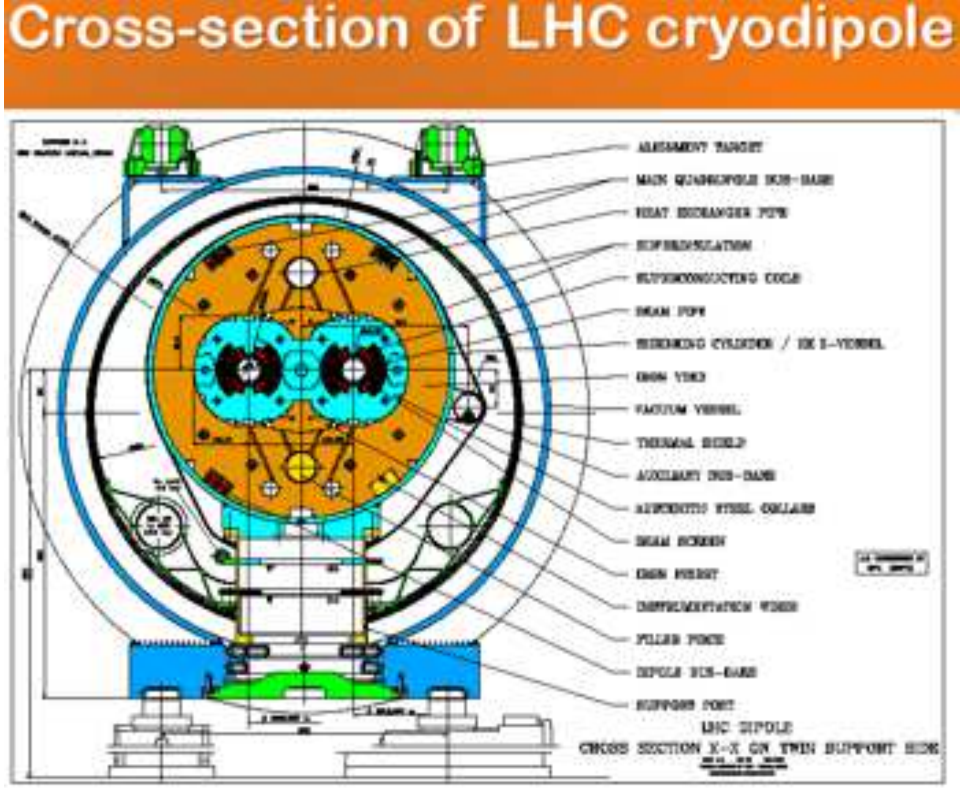
1989 ECFA Study Week in Barcelona

2. Early LHC chronology

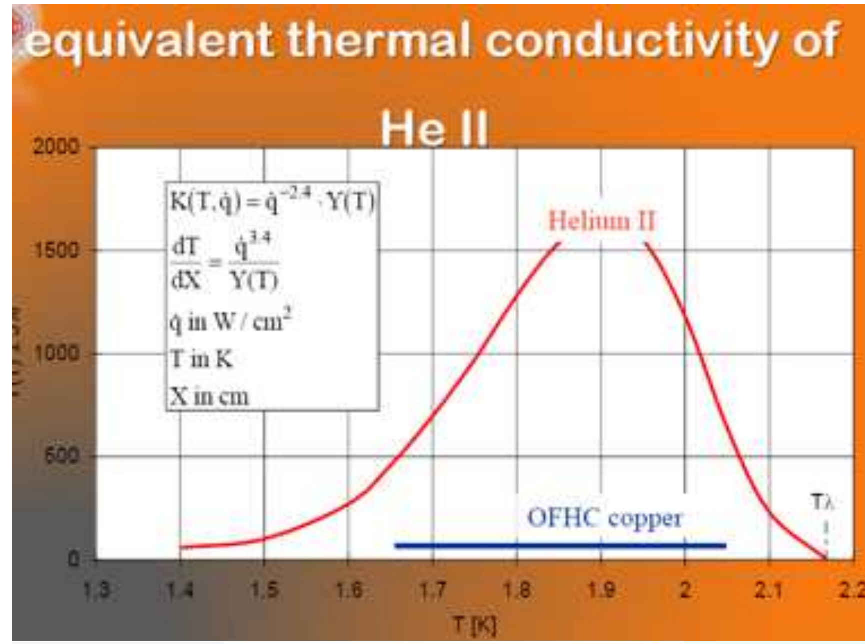
$L = 10^{33}\ cm^{-2}\ s^{-1}$

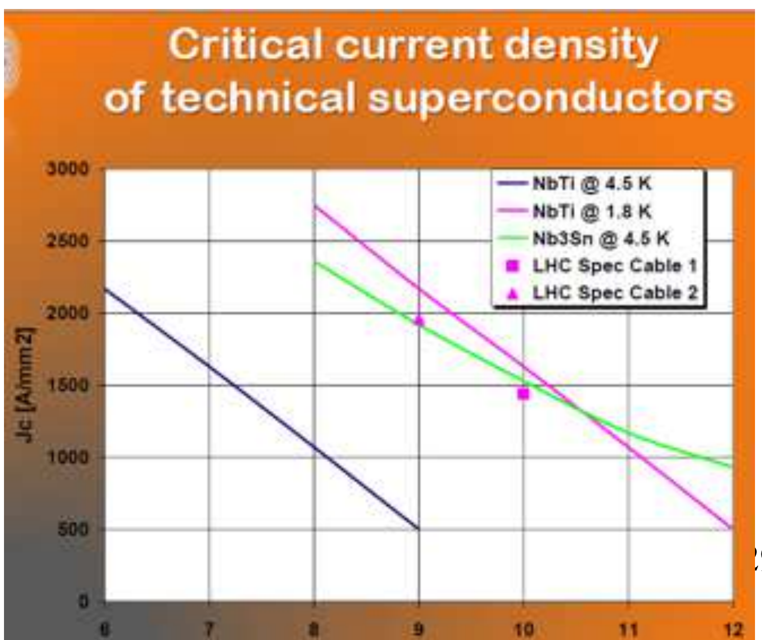
- **1984** Lausanne ECFA workshop: LHC in LEP tunnel
- **1987** La -Thuile workshop: first design (G. Brianti)
- **1988** Feasibility of High Luminosity expts at LHC, Geneve meeting
- **1990** ***Aachen meeting***: main lines are delineated.
- ***G. Kalmus*** closing remarks: (The Aachen meeting) has marked a watershed, the time, when the LHC project… ***graduated*** ..***to being the way forward for European particle physics.***
- ***C. Rubbia: high luminosity makes LHC competitive with the SSC (compensating for an energy ratio 40/16)***
- A lot of wishful thinking:
  - schedule: start civil engineering in 1992, commissioning in 1998 (6 years).
  - ***In reality***….start civil engin. in 1997(+5), commiss. in 2008 (11 years).
  - It was still considered possible to install in the tunnel LHC together with LEP and run LEP and LHC concurrently.
  - The possibility was kept alive until 1995. The need to dismantle LEP was announced by C. Llewellyn Smith in Beijing… I. Mannelli asked me to protest formally, on behalf of INFN.
  - no cost mentioned.
- **1992** Council declares that the LHC ***"will be CERN's next facility"***.
- **1992** Expressions of Interest for experiments are presented in Evian; the LHC experiments Committe is created.

$L = 10^{34}\ cm^{-2}\ s^{-1}$



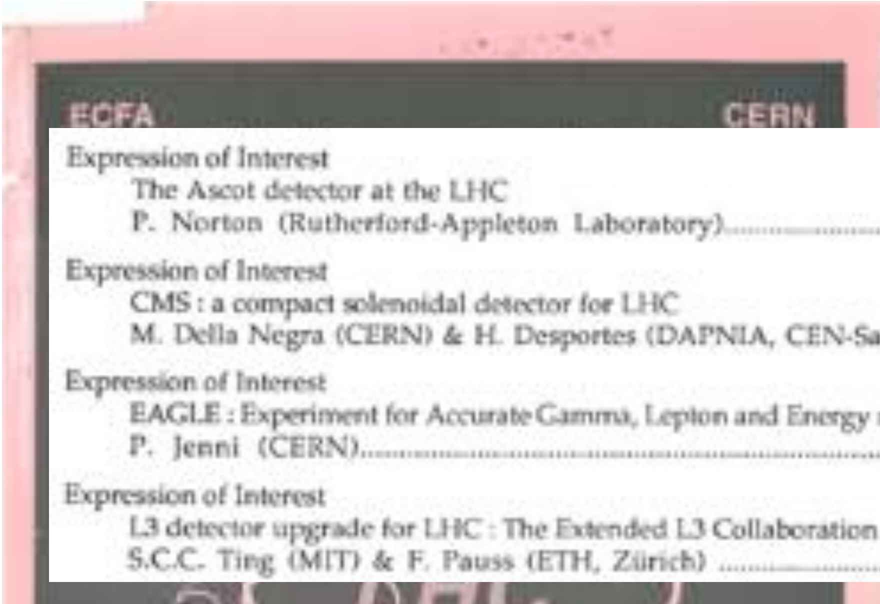
superfluid Helium (1.9 K)
which permeates
through the conductor



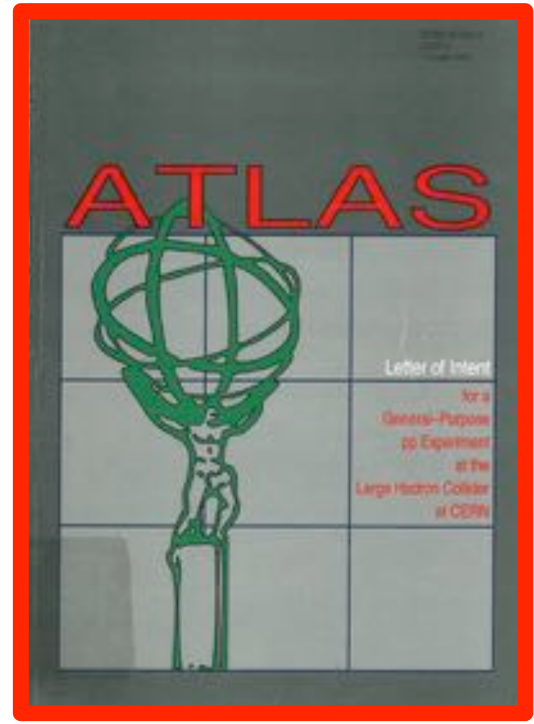


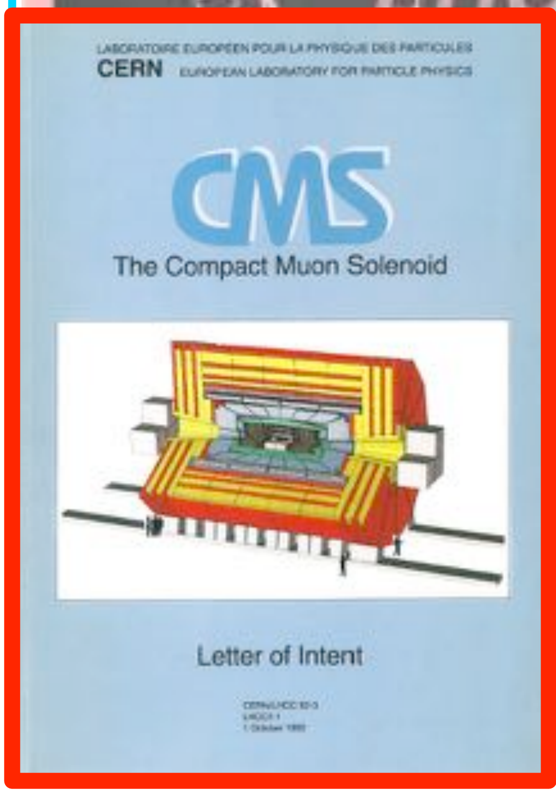
→ Very good thermal stability of the machine

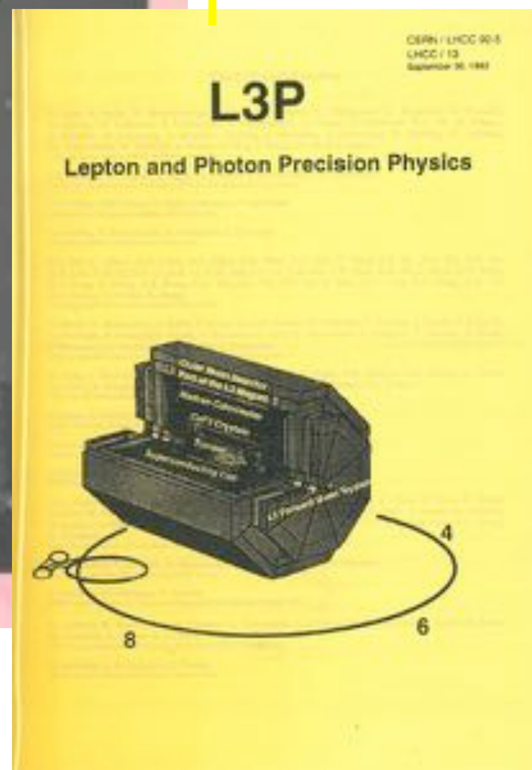
© L...Evans 4-12-22


ECFA
CERN

♥

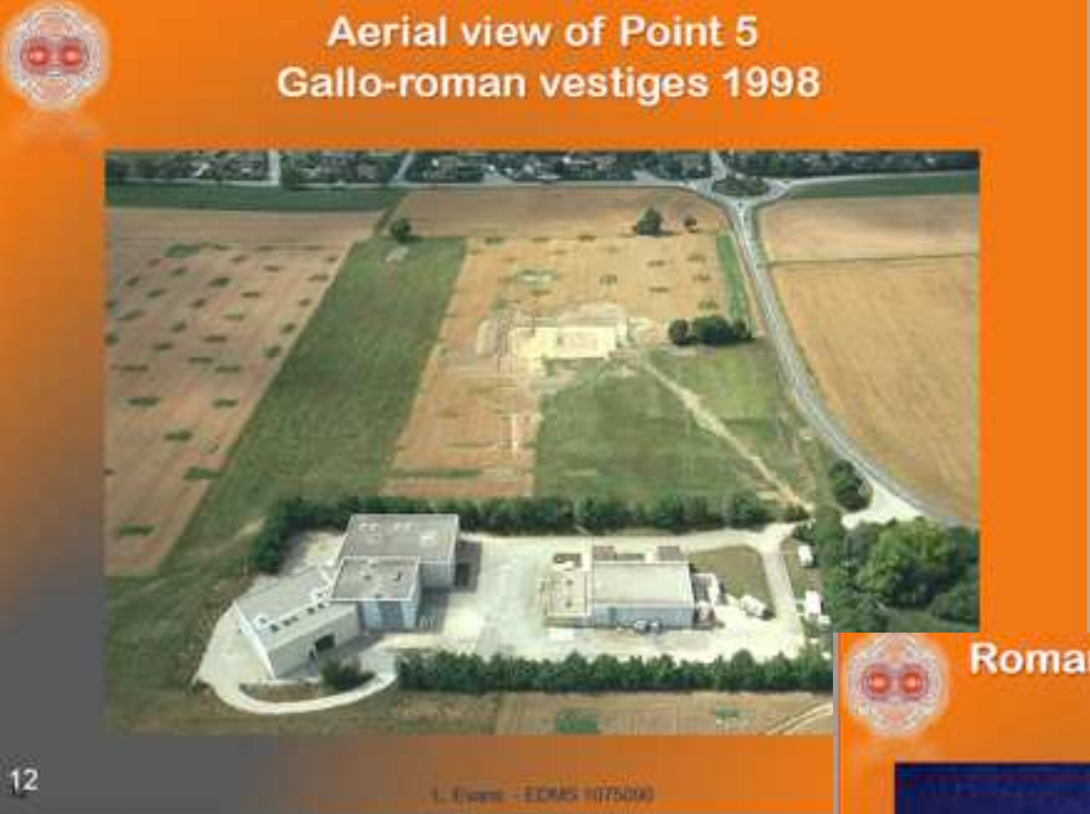

ATLAS
Letter of Intent
for a
General-Purpose
pp Experiment
at the
Large Hadron Collider
at CERN


LABORATOIRE EUROPEEN POUR LA PHYSIQUE DES PARTICULES
CERN
EUROPEAN LABORATORY FOR PARTICLE PHYSICS
CMS
The Compact Muon Solenoid
Letter of Intent


L3P
Lepton and Photon Precision Physics
4
6
8

chosen

Point 5 = CMS


Aerial view of Point 5
Gallo-roman vestiges 1998
12


Roman coins found during archeological
excavations at Point 5

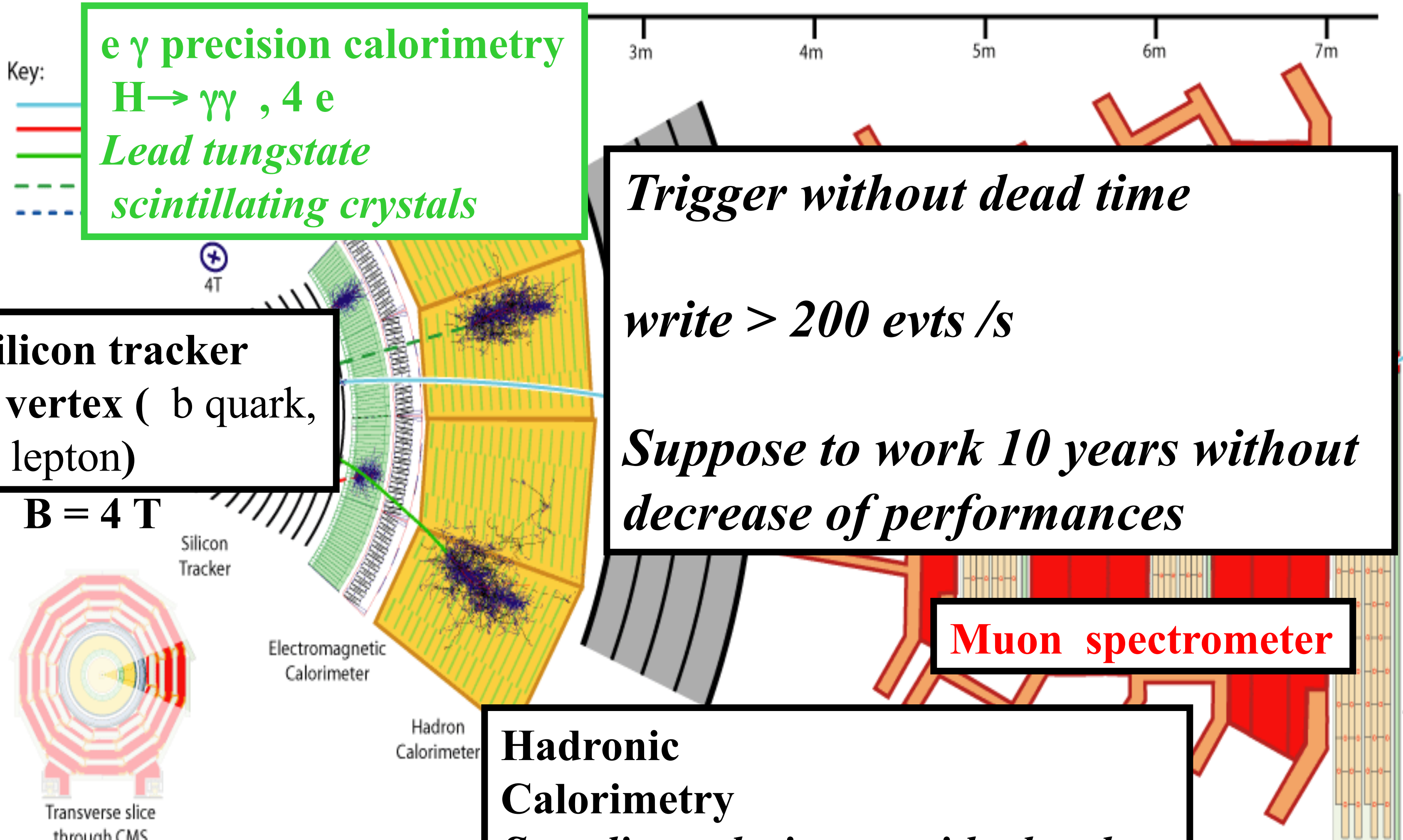
..and major crises: LEP

LEP in the year 2000

- LEP has obtained important results in the last months of operation in the year 2000
- evidence for a Higgs particle at about 115 GeV/c^2.
- LEP Collaborations requested a further run in 2001(from May to October) in order to consolidate the data.

Pulling out – on 2 November 2000, CERN SPS/LEP division head Steve Myers ceremonially switched off LEP for the last time.

CMS = (*Compact Muon Solenoid*)



e γ precision calorimetry
H→ γγ , 4 e
Lead tungstate scintillating crystals

Trigger without dead time

write > 200 evts /s

Suppose to work 10 years without decrease of performances

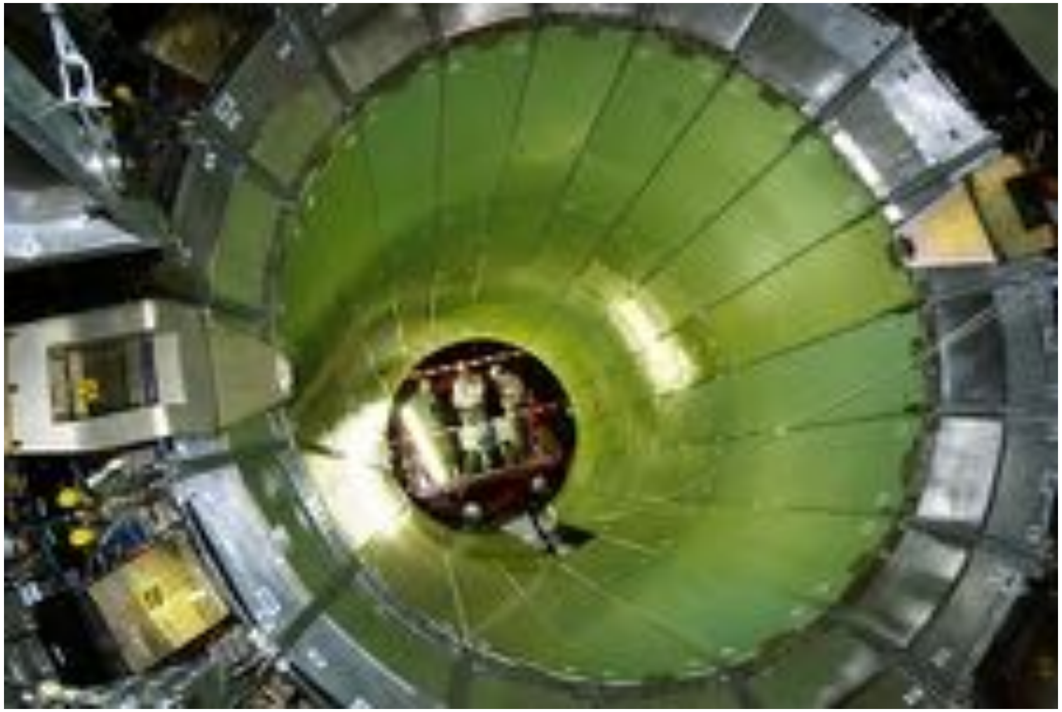
Silicon tracker
+ vertex (b quark, τ lepton)

B = 4 T

Muon spectrometer

« 4 π » detector
up to η=5
(from θ = 1.35°)

Hadronic Calorimetry
Sampling calorimeter with absorber (brass) and plastic scintillators
Jets and $E_T$miss



CMS EM calorimeter
more than 75000
cristals of $PbW0_4$

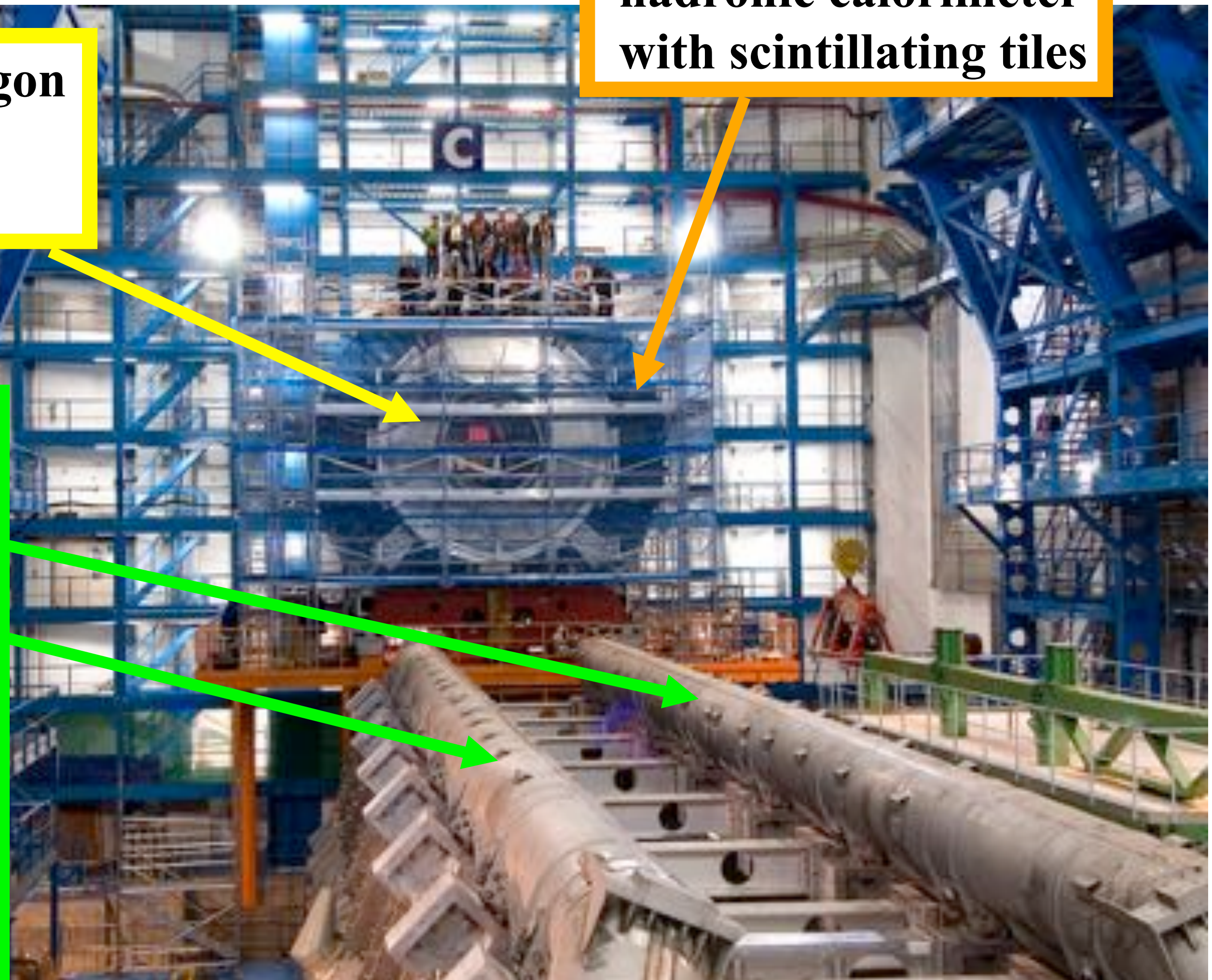
$$\sigma(E)/E = 3\%/\sqrt{E_{GeV}} \oplus 0.7\ \%$$

High level quality control !

ATLAS end of 2004

hadronic calorimeter
with scintillating tiles

barrel Liquid Argon
electromagnetic
calorimeter



two of the
eight coils of
the toroid

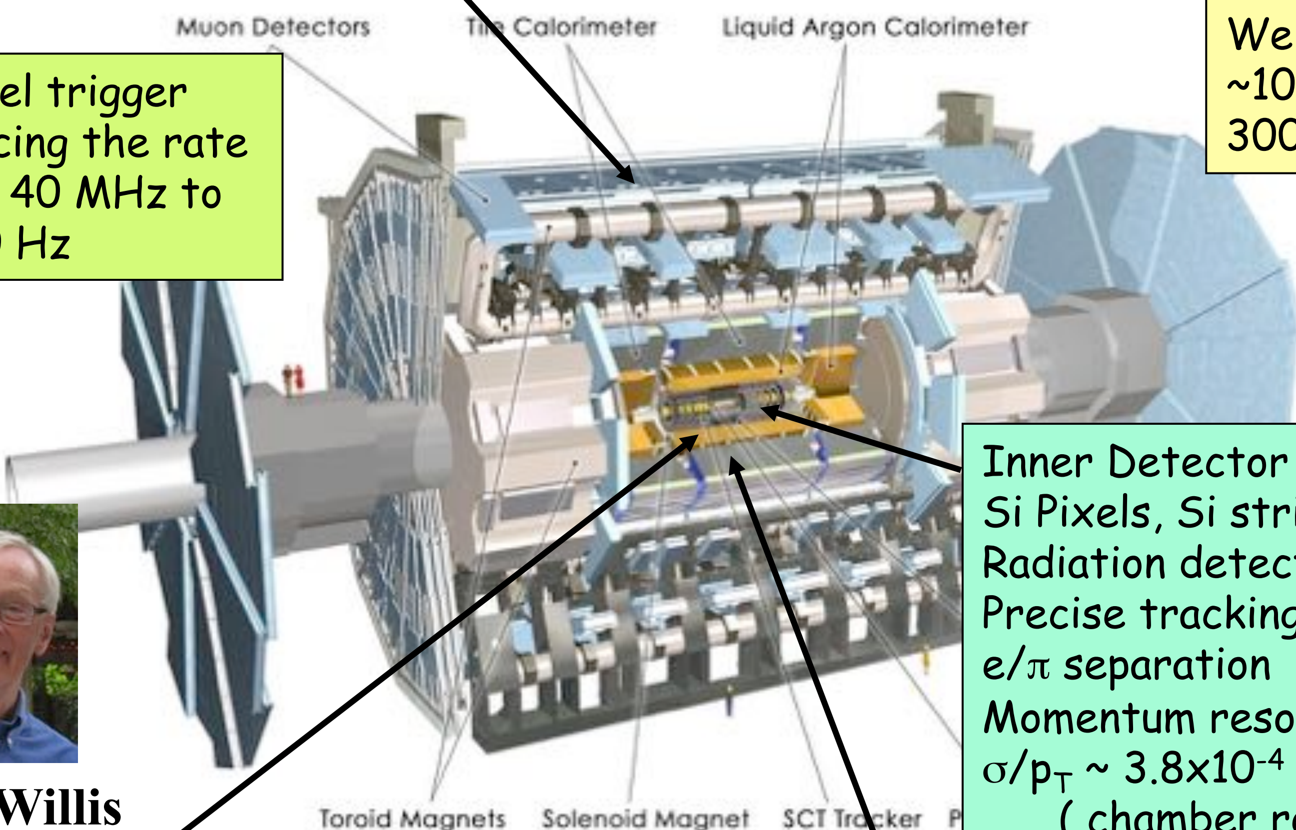
MarcVirchaux
(1953-2004)

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids (B ~ 0.5 / 1T in barrel/ end-cap) with gas-based muon chambers Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

ATLAS detector

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz



Boris Dolgoshein

Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\text{GeV}) \oplus 0.015$
(chamber resolution ⊕ MS)

Bill Willis

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

Daniel Fournier

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

vacuum leak in the cryogenic distribution line → 1.5 year delay

a fault occurs in the electrical bus connection in the region between a dipole and a quadrupole, resulting in mechanical damage and release of helium from the magnet cold mass into the tunnel (1.5 year delay)

- Theory
- Experimental developments, including detectors, magnets
- **Searches**
- Discovery

Search for the Standard Model Higgs Boson at LEP

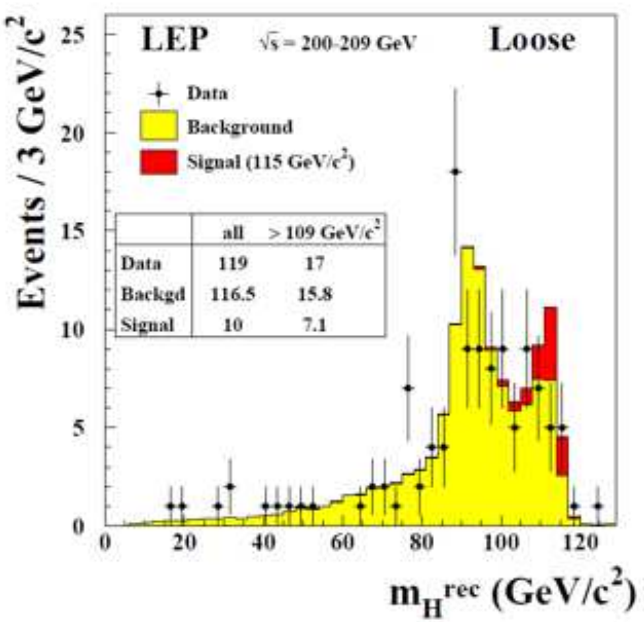
Phys.Lett.B 565 (2003) 61-75

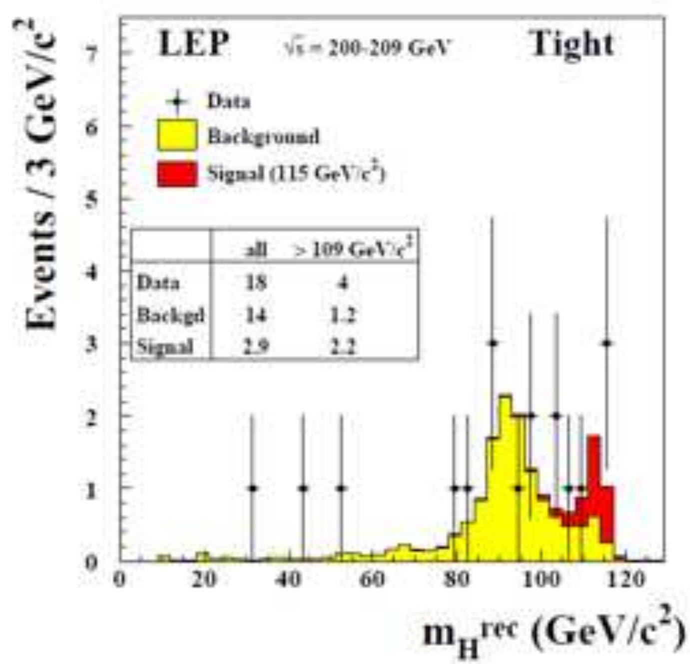
LEP Working Group for Higgs boson searches and ALEPH and DELPHI and L3 and OPAL Collaborations

2461 pb^{-1} of e^+e^- collision data at centre-of-mass energies between 189 and 209 GeV

$$e^+e^- \rightarrow HZ$$

A lower bound of 114.4 GeV/c^2 is established, at the 95% confidence level



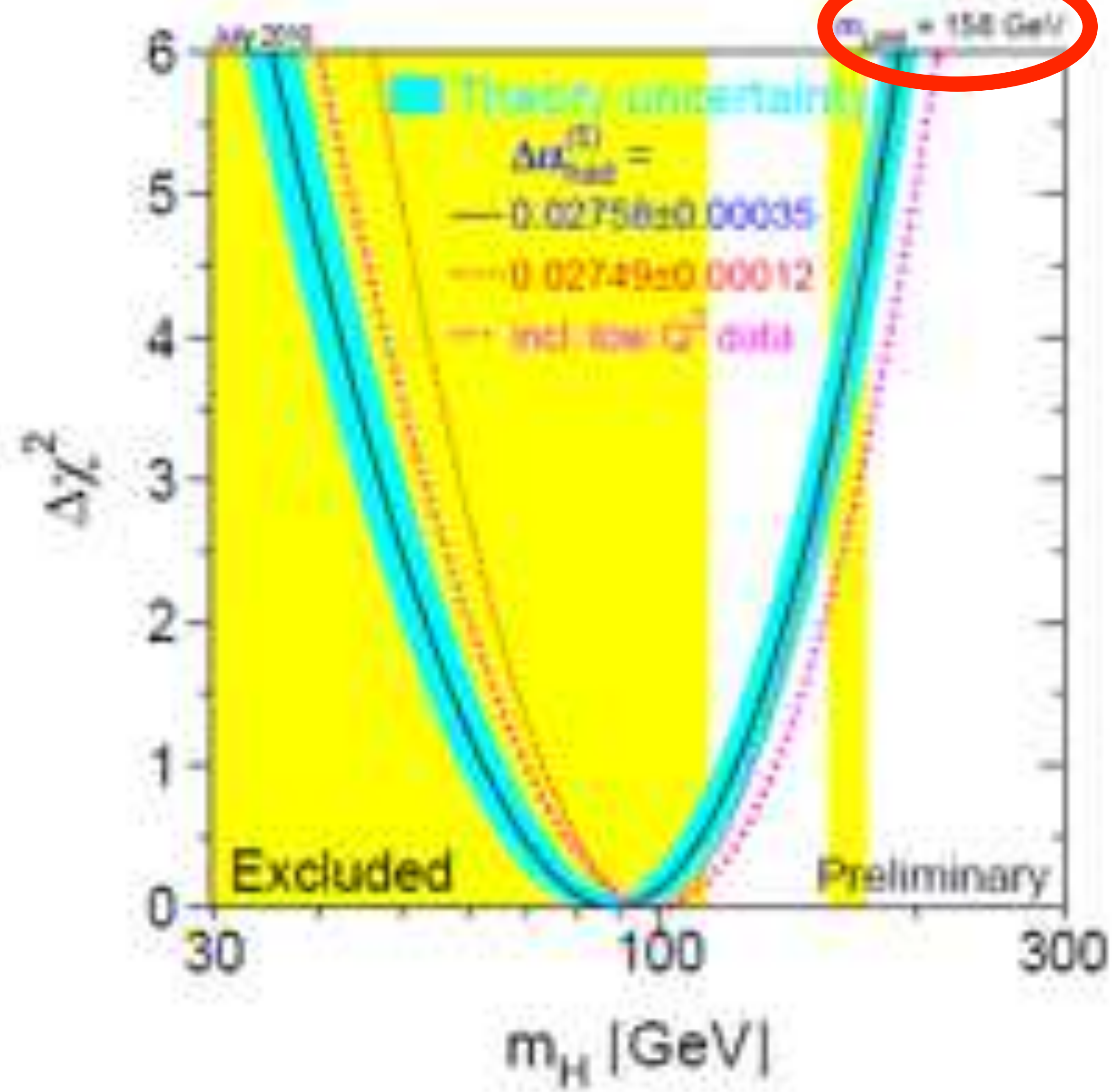


Precision Electroweak Measurements and Constraints on the Standard Model

#1

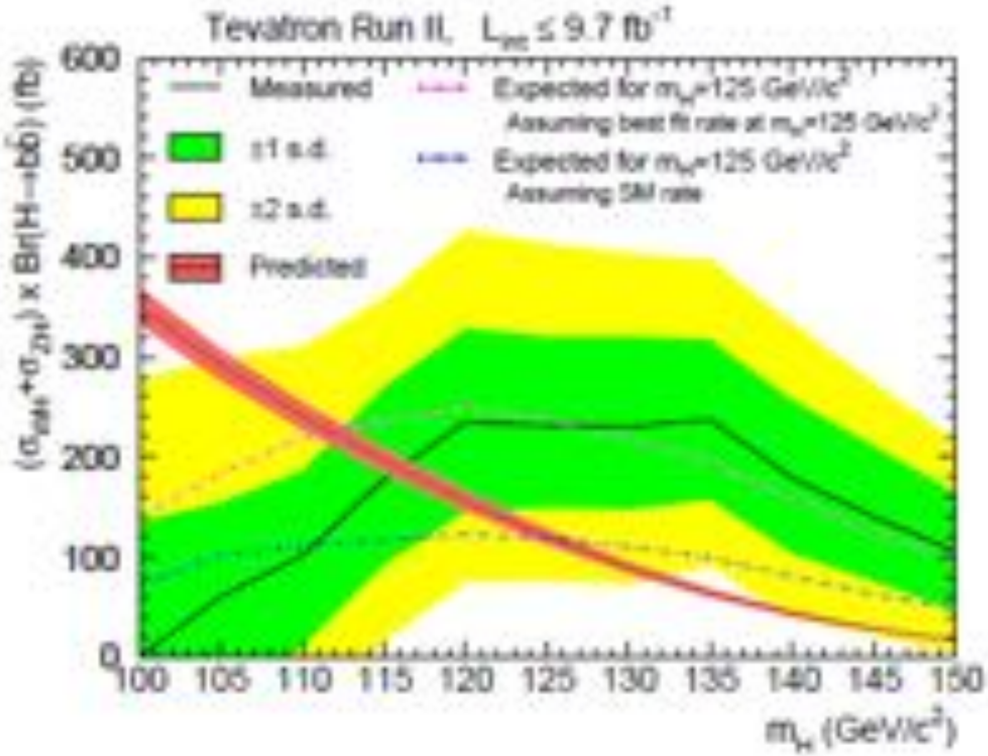
ALEPH and CDF and D0 and DELPHI and L3 and OPAL and SLD and SLD Electroweak Collaborations and LEP Electroweak Working Group and Tevatron Electroweak Working Group and Heavy Flavour Groups (Dec, 2010)

e-Print: 1012.2367 [hep-ex]



(*Tevatron data (proton –antiproton √s =1.96 TeV) ended in september 2011*)

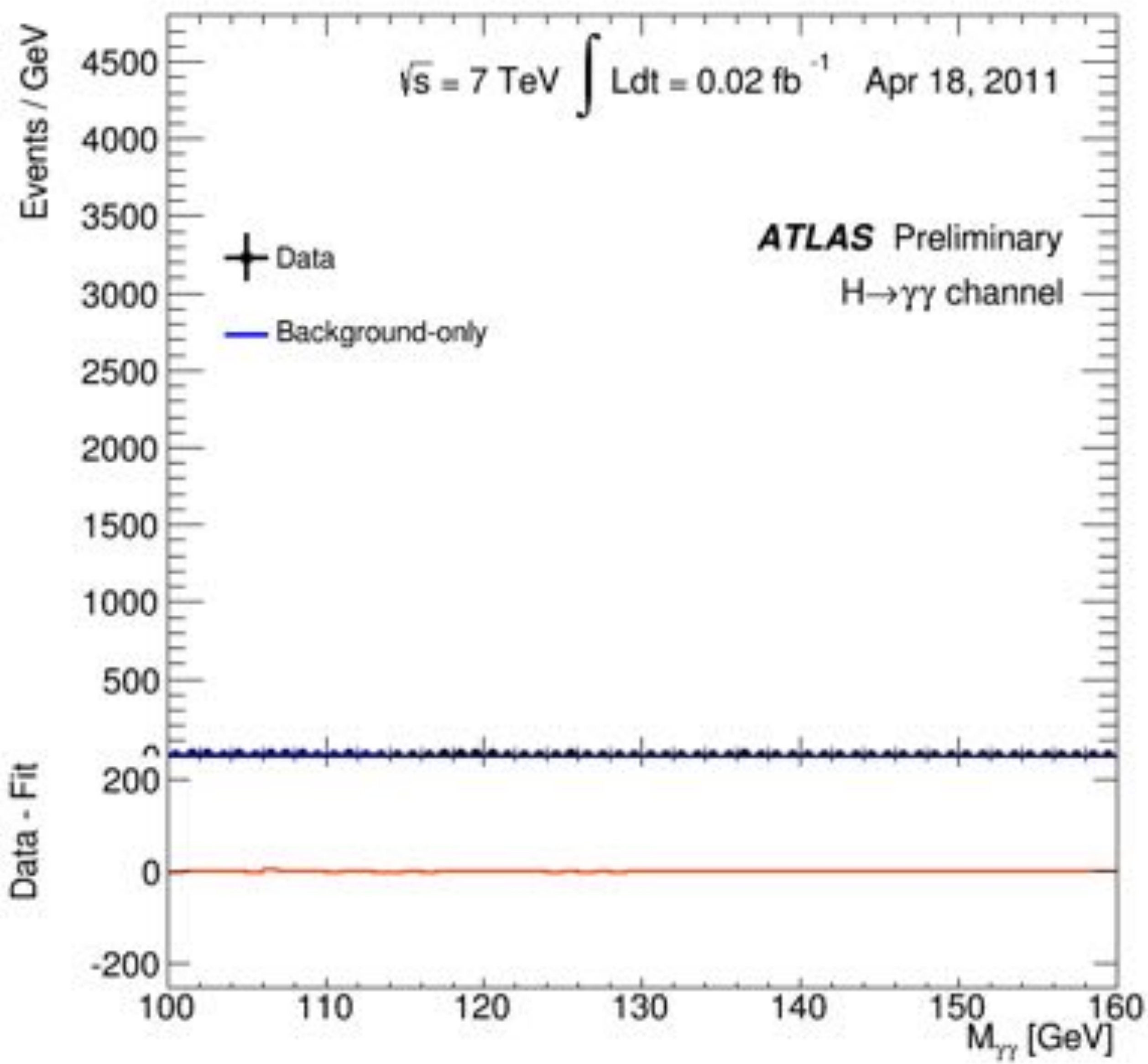
CDF and D0
(at Tevatron**) have paved the way and brought sophistication and maturity into Higgs boson searches at hadron colliders**

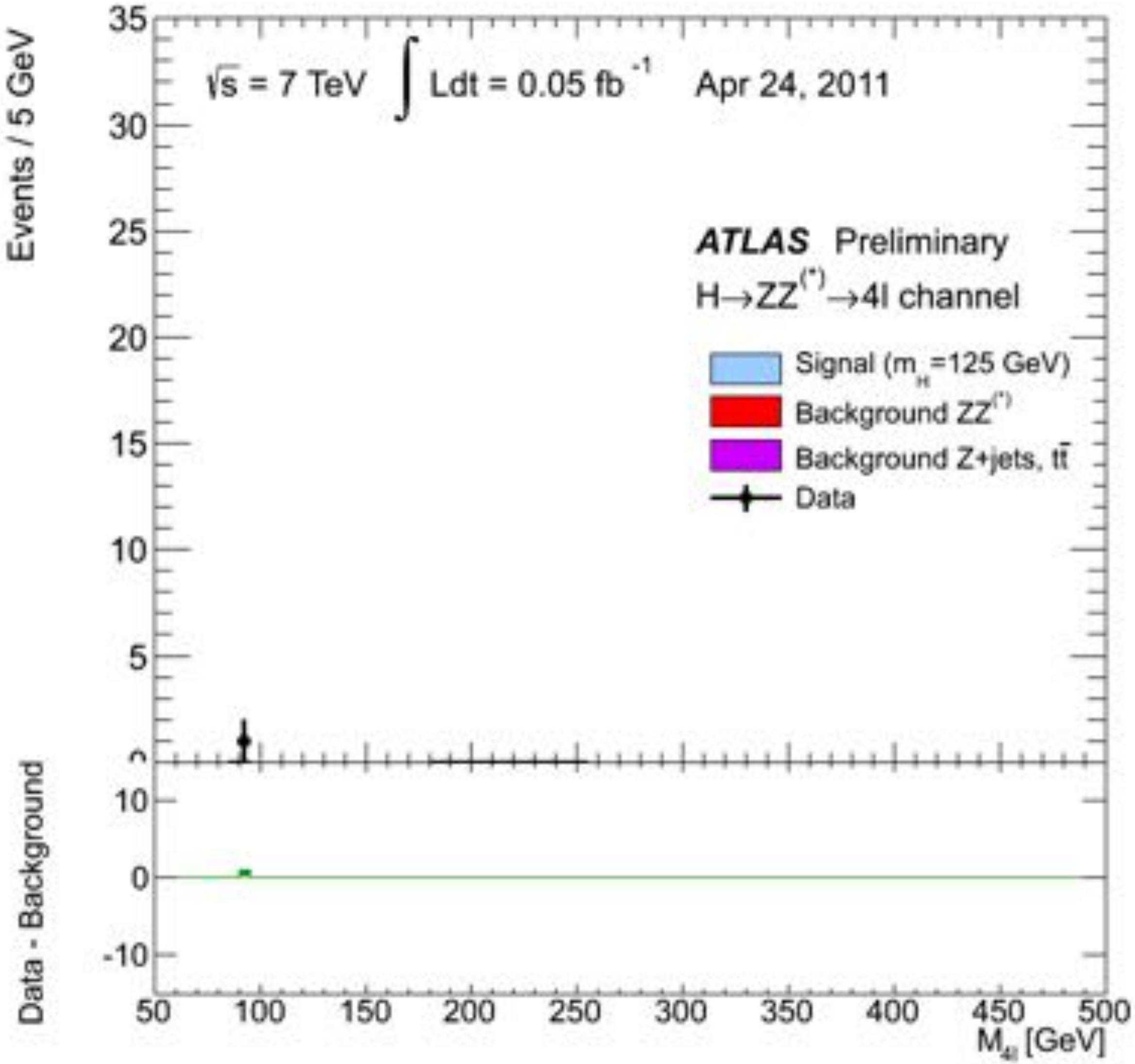


Phys.Rev.Lett. 109 (2012) 071804

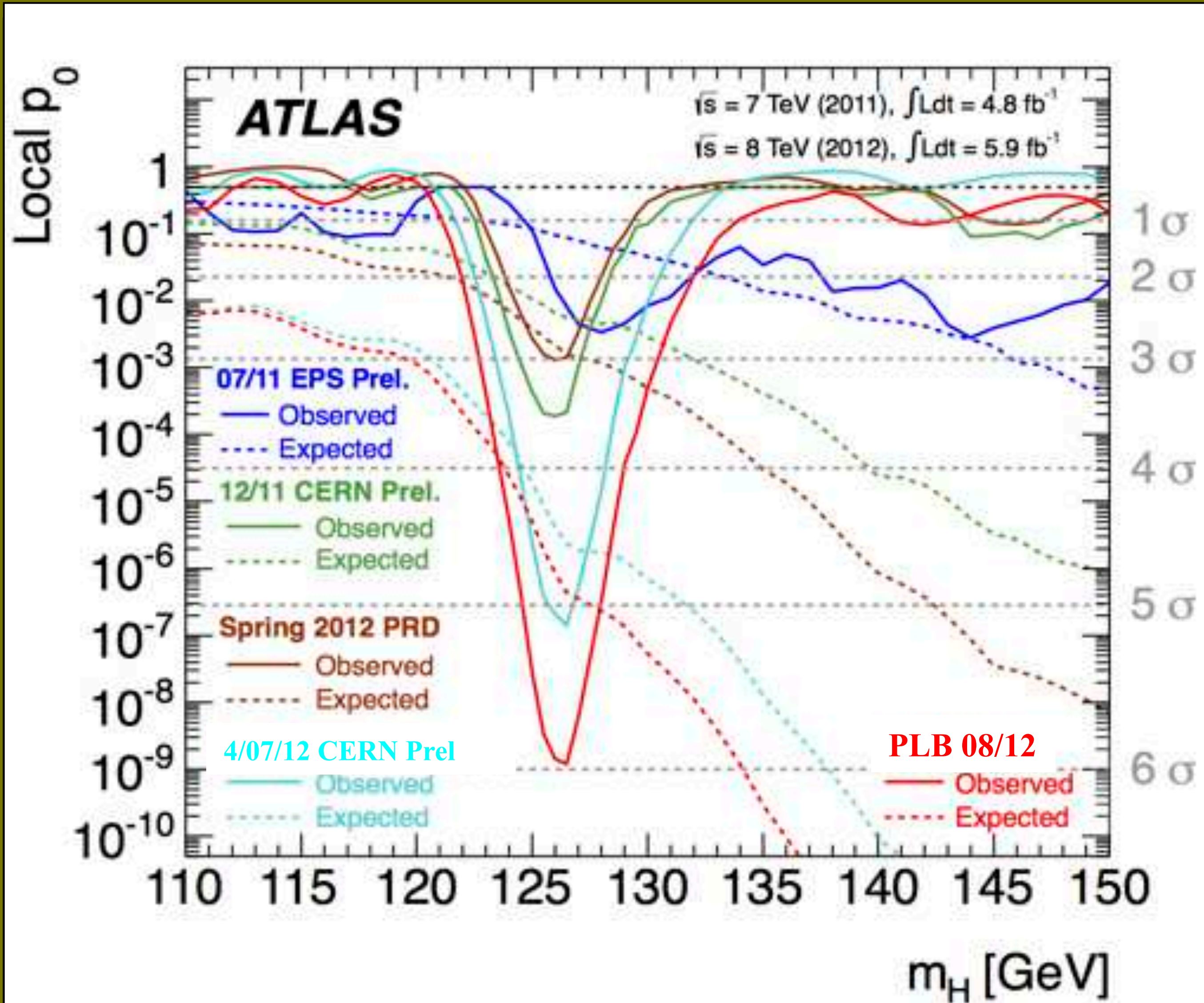
We combine searches by the CDF and D0 Collaborations for the associated production of a Higgs boson with a W or Z boson and subsequent decay of the Higgs boson to a bottom-antibottom quark pair. The data, originating from Fermilab Tevatron $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, correspond to integrated luminosities of up to 9.7 fb^{-1}. The searches are conducted for a Higgs boson with mass in the range 100–150 GeV/c^2. We observe an excess of events in the data compared with the background predictions, which is most significant in the mass range between 120 and 135 GeV/c^2. The largest local significance is 3.3 standard deviations, corresponding to a global significance of 3.1 standard deviations. We interpret this as evidence for the presence of a new particle consistent with the standard model Higgs boson, which is produced in association with a weak vector boson and decays to a bottom-antibottom quark pair.

- Theory
- Experimental developments, including detectors, magnets
- Searches
- **Discovery**


Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
√s = 7 TeV ∫ Ldt = 0.02 fb^-1 Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Data - Fit
200
0
-200
100
110
120
130
140
150
160
M_γγ [GeV]


√s = 7 TeV ∫ Ldt = 0.05 fb -1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M4l [GeV]

Evolution of the excess with time



p_0= probability that the background fluctuates more than the observed excess

Thank you for your attention

all the technicians, engineers and physicists who have contributed to the machine and to the experiments at CERN and elsewhere have to be congratulated

(without forgetting the theorists ..)

After 2012 , precision physics with the boson at LHC ..

another story .. which will last still 20 years

see talks from *M.Cristinziani ,D.Pyatiizbyantseva, S.M.Tkaczyk,D.Varouchas, M.Zerlauth,L.Morvaj, ….*

BACKUP

CHAPTER XII: NEW PARTICLES AND THEIR EXPERIMENTAL SIGNATURES, *J. Ellis et al.*

CONTENTS

I. INTRODUCTION

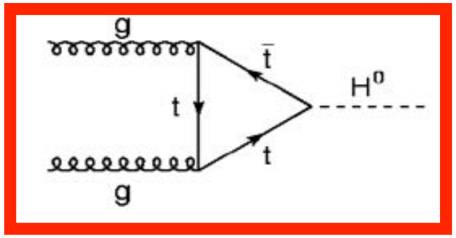
The phy… undergone a remark… …st decade. A host of … accessible by a new gen… …tors and the accompanying ra… …eoretical ideas have brought to the … …erence. Our current outlook has been … …e identification of quarks and leptons as fun… …al constituents of matter and by the gauge theory … …nthesis of the fundamental interactions.[1] These developments represent an important simplification of

…gy scale in elementary … beam energies between … …umber of conventional … …rounds to more exotic … for several new phe… …oint for the choice of

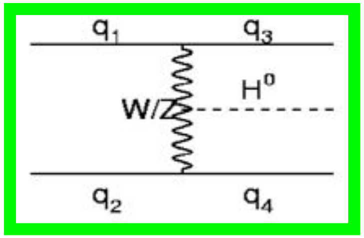
cancellation of Superconducting SuperCollider by US congress in 1993

- **Theory**
- **Experimental developments, including detectors, magnets**
- **Searches**
- **Discovery**

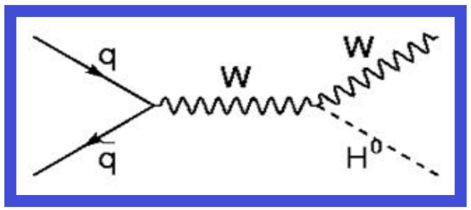
A.Djouadi Phys.Rept.457:1-216



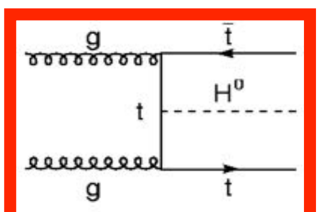
GF **$H \rightarrow WW , ZZ , \gamma\gamma , (bb),\tau\tau$**



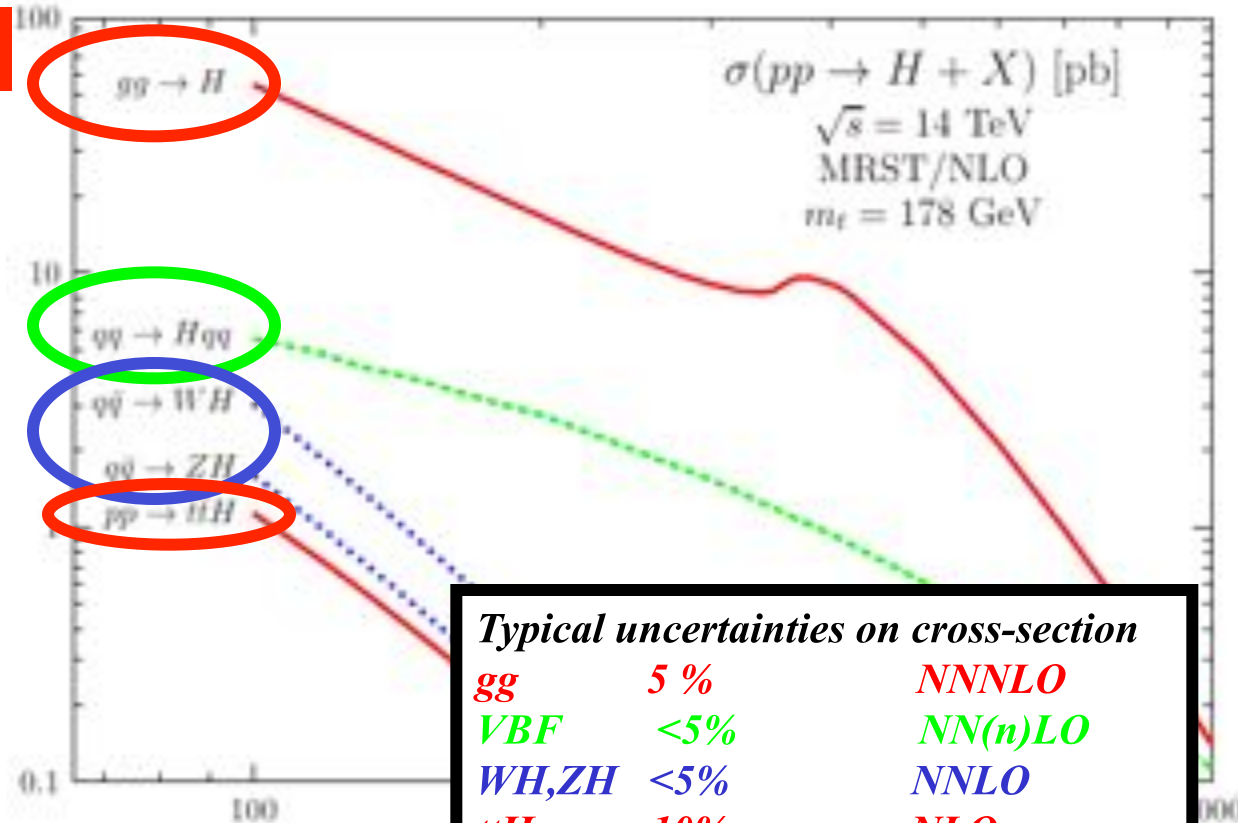
VBF **$H \rightarrow WW, ZZ , \gamma\gamma , bb, \tau\tau$**



WH, ZH **$H \rightarrow WW, \gamma\gamma, bb$**



ttH **$H \rightarrow WW, \gamma\gamma, \tau\tau, ZZ, bb$**



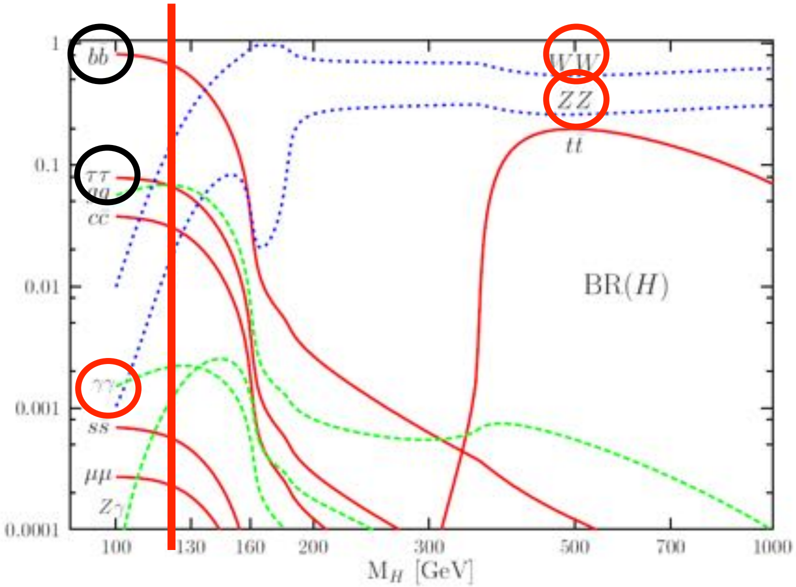
Typical uncertainties on cross-section

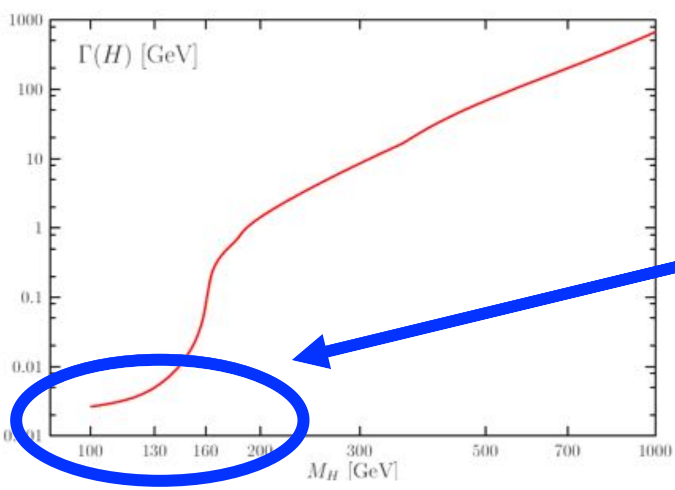
gg	*5 %*	*NNNLO*
VBF	*<5%*	*NN(n)LO*
WH,ZH	*<5%*	*NNLO*
ttH	*10%*	*NLO*

These production cross sections have to be used with the decays **bb , ττ , WW , ZZ , γγ**

channels with good mass resolution

A.Djouadi Phys.Rept.457:1-216





Width smaller than ‘leptonic/γ resolution’

zone favored by *(pre-LHC)* data

For $m_H \sim 125$ GeV the width is about 4 MeV corresponding to $\sim 10^{-22}$ s and ~100 fm

On the Theory of superconductivity

V.L. Ginzburg (Lebedev Inst.), L.D. Landau (Lebedev Inst.) (1950)

Published in: *Zh.Eksp.Teor.Fiz.* 20 (1950) 1064-1082

$$F_{s0} = F_{n0} + \alpha |\Psi|^2 + \frac{\beta}{2} |\Psi|^4. \quad (6)$$

Superconductivity and Elementary Particles

D.A. Kirzhnits (Lebedev Inst.) (1978)

Published in: *Usp.Fiz.Nauk* 125 (1978) 169-194

From Superconductors to supercolliders

Lance J. Dixon (SLAC) (1996)

Published in: *SLAC Beam Line* 26N1 (1996) 23-30

Quasi-Particles and Gauge Invariance in the Theory of Superconductivity*

Yoichiro Nambu
The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois
(Received July 23, 1959)

The Axial Vector Current in Beta Decay (*).

M. Gell-Mann (**)
Collège de France and Ecole Normale Supérieure - Paris (***)
M. Lévy
Faculté des Sciences, Orsay, and Ecole Normale Supérieure - Paris (*.*)
(ricevuto il 19 Febbraio 1960)

AXIAL VECTOR CURRENT CONSERVATION IN WEAK INTERACTIONS*

Yoichiro Nambu
Enrico Fermi Institute for Nuclear Studies and Department of Physics
University of Chicago, Chicago, Illinois
(Received February 23, 1960)

Field Theories with «Superconductor» Solutions.

J. Goldstone
CERN - Geneva
(ricevuto l'8 Settembre 1960)

Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity. I*

Y. Nambu and G. Jona-Lasinio†
The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois
(Received October 27, 1960)

Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity. II*

Y. Nambu and G. Jona-Lasinio†
Enrico Fermi Institute for Nuclear Studies and Department of Physics, University of Chicago, Chicago, Illinois
(Received May 10, 1961)

Broken Symmetries*

Jeffrey Goldstone
Trinity College, Cambridge University, Cambridge, England
and
Abdus Salam and Steven Weinberg†
Imperial College of Science and Technology, London, England
(Received March 16, 1962)

Coherent Excited States in the Theory of Superconductivity: Gauge Invariance and the Meissner Effect

P. W. Anderson
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received January 27, 1958)

Random-Phase Approximation in the Theory of Superconductivity*

P. W. Anderson
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received July 28, 1958)

Plasmons, Gauge Invariance, and Mass

P. W. Anderson
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 8 November 1962)

PARTIAL-SYMMETRIES OF WEAK INTERACTIONS

SHELDON L. GLASHOW †
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

Received 9 September 1960

ELECTROMAGNETIC AND WEAK INTERACTIONS

A. SALAM and J. C. WARD *
Imperial College, London

Received 24 September 1964

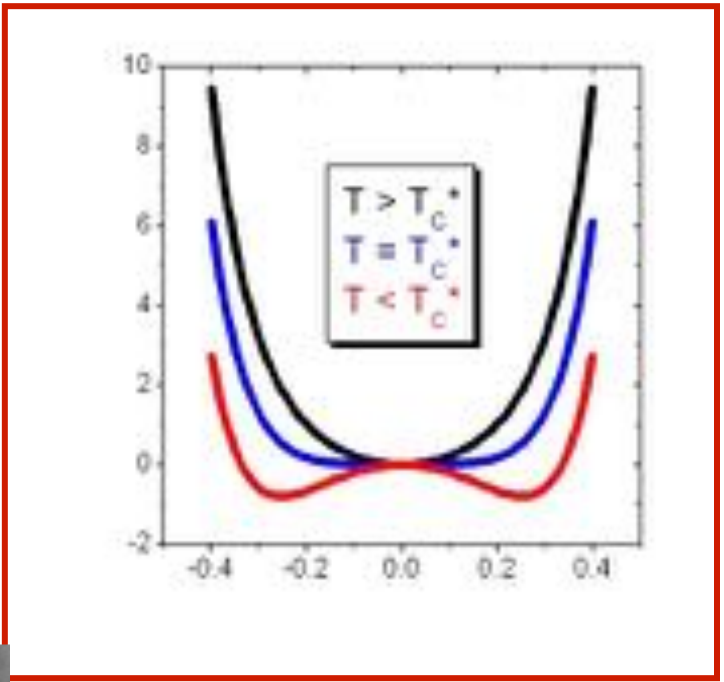
Condensed matter physics

SSB = Spontaneous Symmetry Breaking :There are symmetries of the Lagrangian that are not symmetries of the fundamental state (vacuum)

1928 (Heisenberg) For $T<T_C$ dipoles are aligned in some arbitrary direction

1950 (Ginzburg Landau) : phase transition in superconductivity

1957 (Bardeen, Cooper, Schrieffer) SSB of EM gauge invariance



Particle physics - strong interaction (global symmetry)

1959 (Nambu** Jona-Lasinio)* ***: SSB transmitted from condensed matter to particle physics

SSB of (global) chiral symmetry → pseudoscalar boson π^0

massless boson if exact symmetry

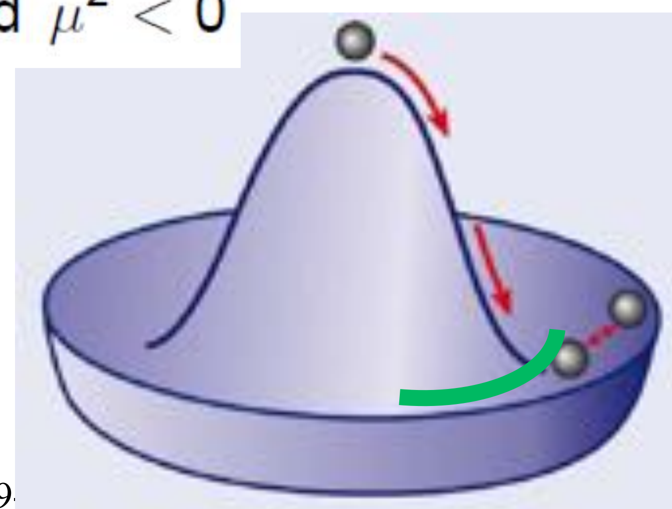
1960 (Goldstone) : generalization : SSB of continuous global symmetry → massless (Nambu-Goldstone) bosons

$$L = \partial^\mu \phi^\dagger \partial_\mu \phi - V(\phi^\dagger \phi)$$

$$V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2; \ \lambda > 0 \text{ and } \mu^2 < 0$$

and massive boson mass $\sqrt{(-2\mu^2)}$

$\sigma = f_0(600)$



Particle physics - strong interaction (local symmetry)

1964 (Brout,Englert, Higgs, Guralnik, Hagen,Kibble)

SSB of gauge symmetries

The BEH mechanism : no massless particles
massive gauge bosons

mass of gauge boson acquired by 'eating' the N-G boson

one massive particle $\sqrt{(-2 \mu^2)}$: BEH boson (or Higgs boson)



BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

The interaction between the φ and the A_μ fields is

$$H_{\mathrm{int}} = ieA_\mu \varphi^* \overleftrightarrow{\partial}_\mu \varphi - e^2 \varphi^* \varphi A_\mu A_\mu,$$

where $\varphi = (\varphi_1 + i\varphi_2)/\sqrt{2}$. We shall break the symmetry by fixing $\langle\varphi\rangle \neq 0$ in the vacuum, with the phase chosen for convenience such that $\langle\varphi\rangle = \langle\varphi^*\rangle = \langle\varphi_1\rangle/\sqrt{2}$.

and causes the A_μ field to acquire a mass

$$\mu^2 = e^2 \langle\varphi_1\rangle^2.$$

Field Theories with «Superconductor» Solutions.

J. GOLDSTONE
CERN - Geneva

(ricevuto l'8 Settembre 1960)

Plasmons, Gauge Invariance, and Mass

P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 8 November 1962)

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

Spontaneous Symmetry Breakdown without Massless Bosons*

PETER W. HIGGS†
Department of Physics, University of North Carolina, Chapel Hill, North Carolina
(Received 27 December 1965)

Symmetry Breaking in Non-Abelian Gauge Theories*

T. W. B. KIBBLE
Department of Physics, Imperial College, London, England
(Received 24 October 1966)

Weak and Electromagnetic Interactions

Abdus Salam (Imperial Coll., London and ICTP, Trieste) (May, 1968)

Published in: *Conf.Proc.C* 680519 (1968) 367-377 • Contribution to: 8th Nobel Symposium, 367-377

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Particle physics - weak interaction (local symmetry)

1967 (Weinberg Salam) Electroweak theory of leptons

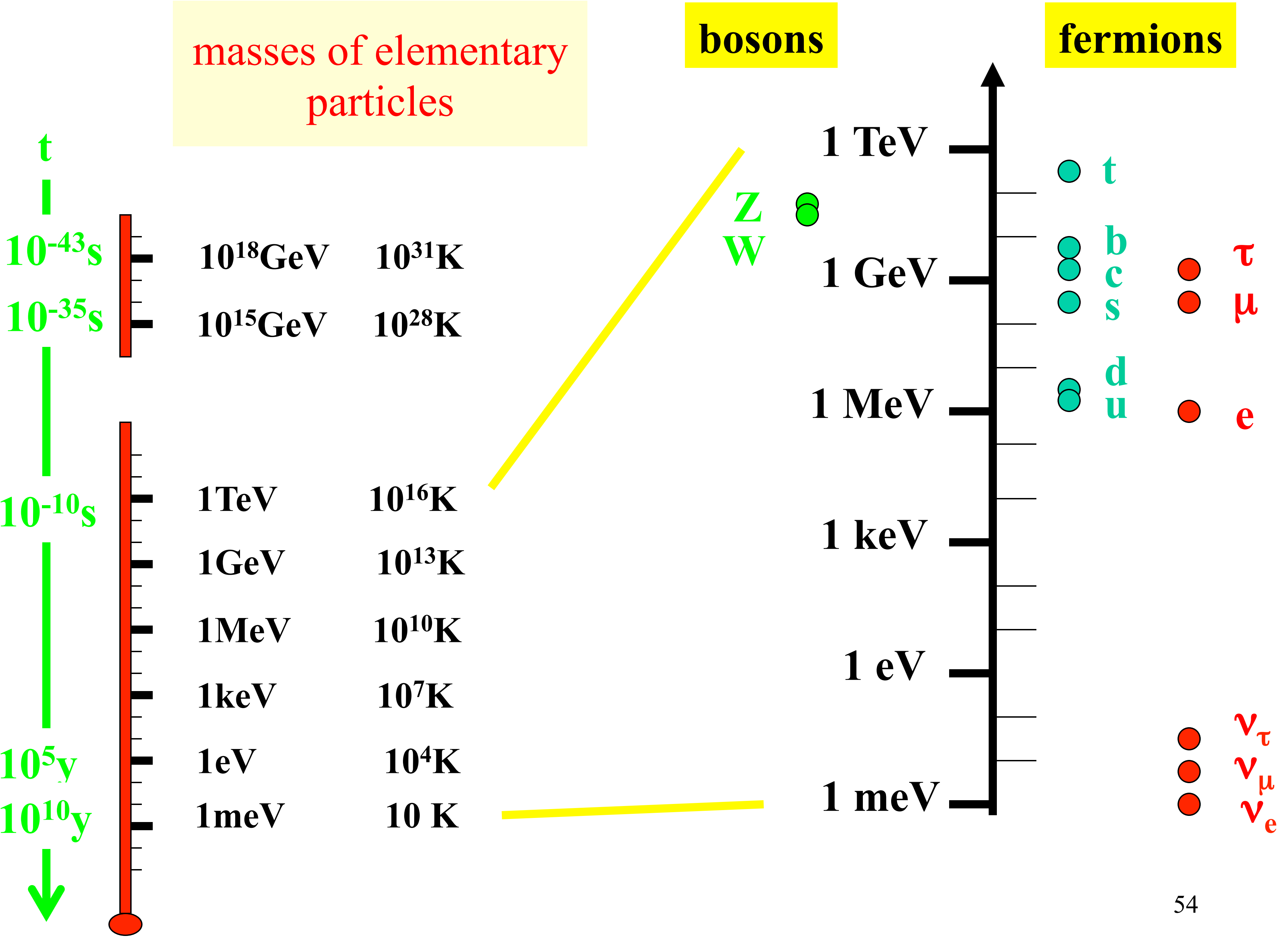
$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

- ***Three massive bosons : W and Z***
- ***One massless vector boson : photon γ***
- ***One massive scalar boson : BEH boson H***
- ***massive leptons by Yukawa couplings to BEH boson***

1970 (Glashow, Iliopoulos, Maiani) introduction of quarks in theory

Faddeev,Popov,’t Hooft,Veltman,Lee,Zinn-Justin,Becchi, Rouet,Stora,Tyutin : renormalizable theory

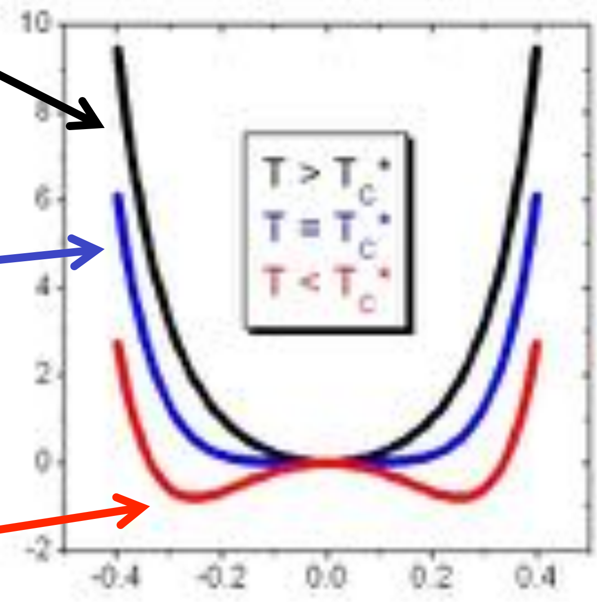
masses of elementary particles



Mass of the 4 scalar bosons positive
W and Z mass = 0
fermion masses =0

10^{-10} s

Mass of one scalar (BEH) boson positive
W and Z mass positive
fermion have their masses



Early Phenomenological Bounds

- Emission from stars:

  $M_H > 0.7\ m_e$ (Sato & Sato, 1975)

- Neutron-electron scattering:

  $M_H > 0.7$ MeV (Rafelski, Muller, Soff & Greiner; Watson & Sundaresan; Adler, Dashen & Treiman; 1974)

- Neutron-nucleus scattering:

  $M_H > 13$ MeV (Barbieri & Ericson, 1975)

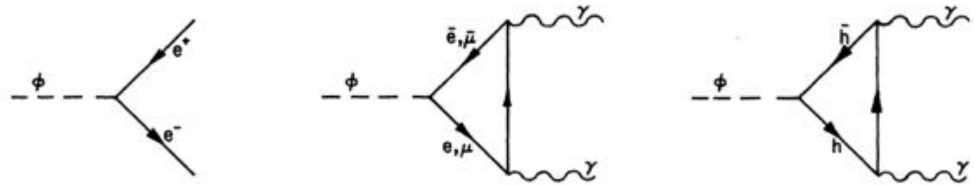
- Nuclear $0^+ - 0^+$ transitions:

  $M_H > 18$ MeV (Kohler, Watson & Becker, 1974)

Phenomenology of scalar boson (theory)

Is There a Light Scalar Boson?

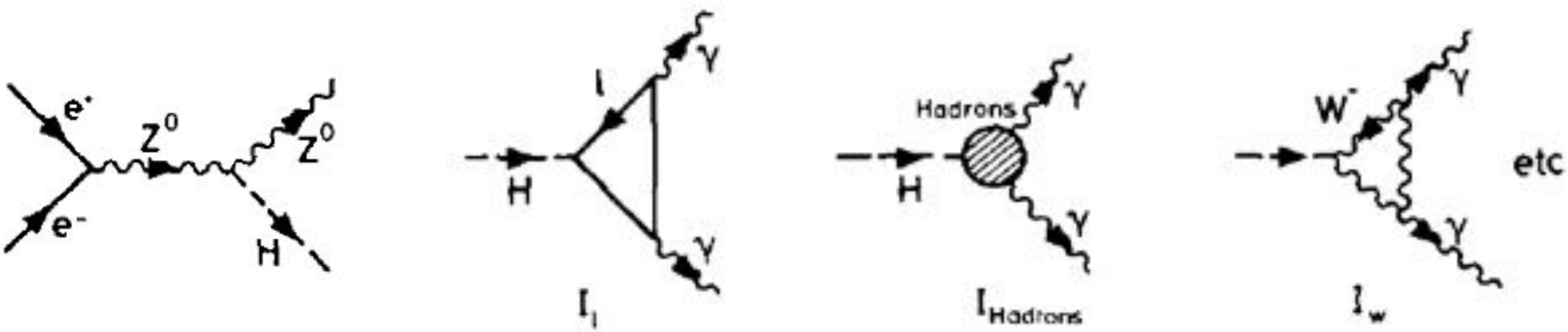
L. Resnick, M. K. Sundaresan, and P. J. S. Watson
Department of Physics, Carleton University, Ottawa, Canada
(Received 28 July 1972; revised manuscript received 2 January 1973)



A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975



Higgs Boson on the Experimental Agenda

- Searches at LEP:

  (EG, Yellow report 76-18)
- $e^+e^- \rightarrow Z + H$

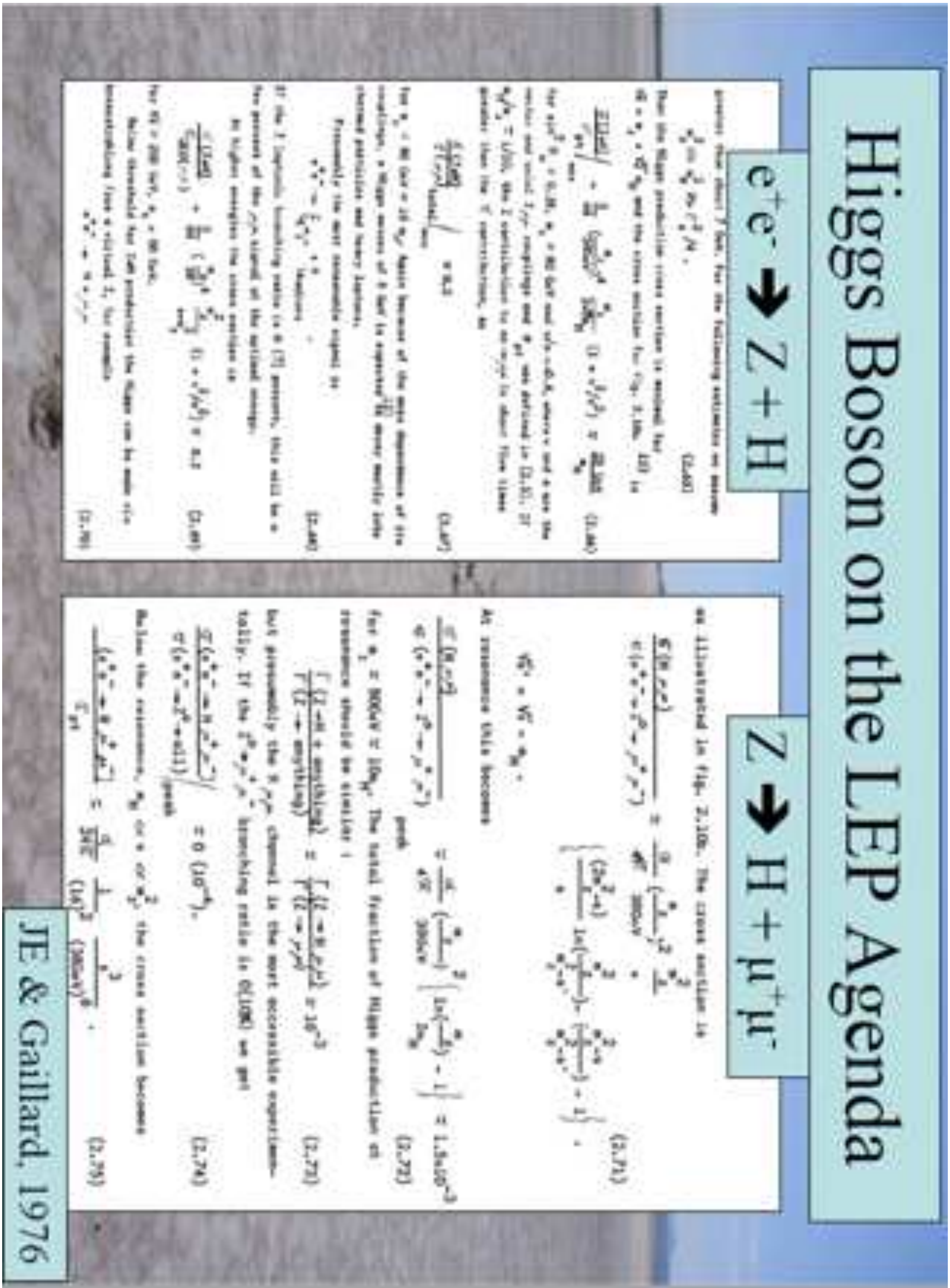
  (EGN 76, Ioffe & Khoze 78, Lee, Quigg & Thacker 77)
- $Z \rightarrow H + \mu^+\mu^-$

  (EG 76, Bjorken 1978)
- $M_H > 114.4$ GeV

III- THEORETICAL REMARKS

J. Ellis, M.K. Gaillard

Contents :


Higgs Boson on the LEP Agenda
$e^+e^- \rightarrow Z + H$
$Z \rightarrow H + \mu^+\mu^-$
JE & Gaillard, 1976

J. D. Bjorken, in Proceedings of the 1976 SLAC Summer Institute on Particle Physics, ed. M. Zipf (SLAC Report No. 198, 1976) p. 22;

B.L. Ioffe and V.A. Khoze, Sov. J. Part. Nucl. 9 (1978) 50;

D.R.T. Jones and S.T. Petcov, Phys. Lett. 84B (1979) 440;

J. Finjord, Physica Scripta 21 (1980) 143.

HEAVY HIGGS BOSONS AT LEP

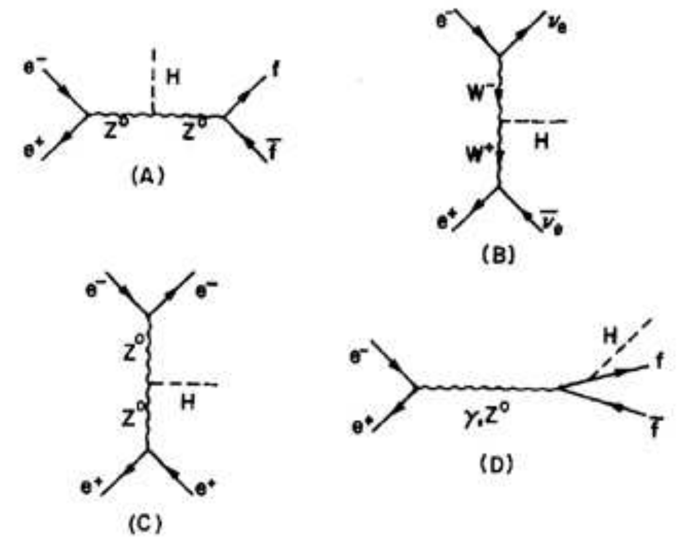
D.R.T. JONES
CERN, Geneva, Switzerland

and

S.T. PETCOV
CERN, Geneva, Switzerland
and Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

Received 30 April 1979

VBF process



Phenomenology of scalar boson (theory)

Higgs Bosons from Two-Gluon Annihilation in Proton-Proton Collisions

H. M. Georgi, S. L. Glashow, M. E. Machacek, and D. V. Nanopoulos
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 27 December 1977)

We estimate the cross section for Higgs-boson production in proton-proton collisions. We find that most of the cross section comes from a two-gluon annihilation process, in which the gluons couple to Higgs bosons via heavy-quark loops.

Low-energy theorems for Higgs meson interaction with photons

A. I. Vaĭnshteĭn, M. B. Voloshin, V. I. Zakharov, and M. A. Shifman
Institute of Theoretical and Experimental Physics of the State Committee on Atomic Energy
(Submitted 21 May 1979)
Yad. Fiz. 30, 1368–1378 (November 1979)

Searching for the intermediate-mass Higgs boson

John F. Gunion
Physics Department, University of California, Davis, California 95616

Pat Kalyniak
Physics Department, Carleton University, Ottawa, Ontario, Canada K1S 5B6

M. Soldate
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

Peter Galison
Physics Department, Stanford University, Stanford, California 94305

(Received 30 September 1985)

We study the feasibility of detecting a neutral Higgs boson H^0, with mass between $2m_t \simeq 80$ GeV (by assumption) and $2m_W$ at an e^+e^- machine or the Superconducting Super Collider (SSC). Backgrounds to the production at an e^+e^- machine of H^0 in association with a Z are calculated with particular emphasis on the case when $m_H \simeq m_Z$. We present a detailed survey of the signals for and backgrounds to the inclusive or associated production at the SSC of H^0 followed by the decay of H^0 into one of the available channels. There is no signature which is established to be identifiable at the SSC. Only a few signatures remain to be studied, and the further calculations of most immediate interest are pointed out.

SEARCH TECHNIQUES FOR CHARGED AND NEUTRAL INTERMEDIATE-MASS HIGGS BOSONS*

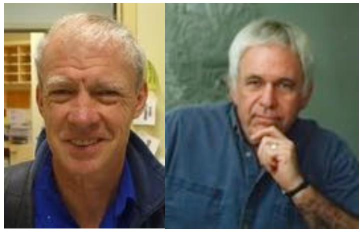
J.F. GUNION

Department of Physics, U.C. Davis, Davis, CA 95616, USA

G.L. KANE and Jose WUDKA

Randall Laboratory of Physics, University of Michigan, Ann Arbor, MI 48104, USA

Received 12 October 1987



J.Gunion **G.Kane**

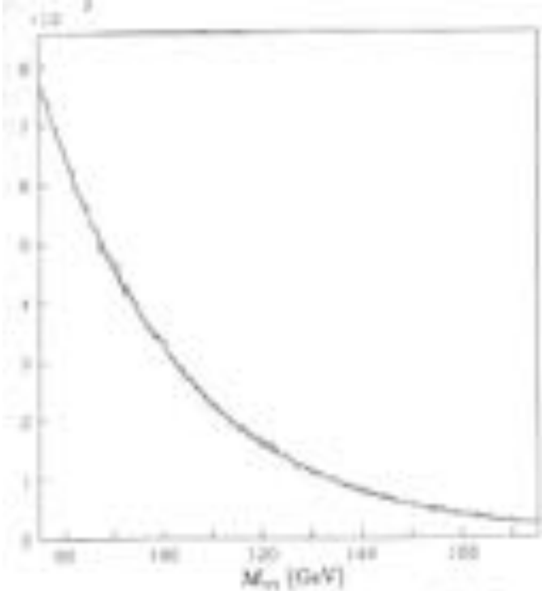


FIG. 6. Simulated mass distribution for 100 GeV Higgs in detector with extraordinary resolution.

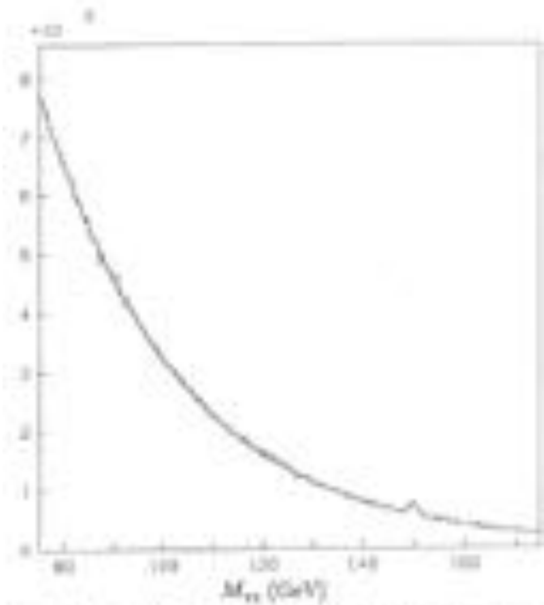


FIG. 7. Simulated mass distribution for 150 GeV Higgs in detector with extraordinary resolution.

DETECTION OF $H^0 \to \gamma\gamma$ AT THE SSC

C. Barter and R. Partridge
Brown University, Providence, Rhode Island 02912

A. Bay and A. Spadafora
Lawrence Berkeley Laboratory, Berkeley, California 94720

S. Whitaker
Boston University, Boston, Massachusetts 02215

A. Abashian
University of Virginia, Chalottesville, Virginia 22901

R. Kass
Ohio State University, Columbus, Ohio 43210

Proceedings of the Summer Study on High Energy Physics in the 1990s

June 27 – July 15, 1988
Snowmass, Colorado

Editor
Sharon Jensen

SSC-SDC-90-00113

PRODUCTION OF $WH \to W\gamma\gamma \to e/\mu\gamma\gamma$

Michelangelo L. MANGANO

Istituto Nazionaledi FisicaNucleare
Scuola NormaleSuperioreand
Dipartimento di Fisica,Pisa, ITALY

- Theory
- **Experimental developments, including detectors, magnets**
- Searches
- Discovery

November 1988.
SSC approved at a new site: Waxahachie, Texas, Fermilab loses the competition for hosting the SSC

- **1988** **SSC approved,** proton-proton, 20 TeV/beam, 87 km tunnel, cost 4-5 B US$.
  1989 SSC construction starts.
- **1993** SSC discontinued by the US Congress after a bitter discussion which invested all the scientific community (projected cost >10 B US$, 2 B US$ spent).

10 November 1988. Leon Lederman, wearing a Stetson hat, annoounces to the Laboratory that Fermilab has not been chosen as the SSC site. FNAL Visual Media Service.

Shaft to the SSC tunnel di SSC, located at about10 meters underground. The planned tunnel had a circumference of 87 km.

1994: LHC is approved

- the cancellation of the SSC programme (1993) made a real shock-wave in Europe, firing back on particle physics and CERN.
- Top quark discovery (1994) had a very good balancing effect (as seen from Italy)
- the first prototype of the 11 m superconducting LHC magnets was deliverd to CERN in Dec. 1993 and presented to CERN Council in March 1994, with a very positive effect
- ***On the basis of the SppbarS and LEP successes, CERN project was approved in December 1994***.

First prototype of 15 m superconducting LHC dipole by CERN-INFN-Ansaldo Energia collaboration,1998.

from LEP to LHC in the same tunnel

LEP, July 1989-
December 2000

LHC, January
2010-

LHC agreements: 1995 to 1997

Chris Llewellyn Smith (right), with Hubert Curien, President of Council (center) receives a Daruma Doll from Kaoru Yosano, Japan Minister of Education, Science and Culture, June 1st 1995 at the signature of the Japan-CERN agreement for Japan participation in LHC (machine and experiments.

Signature of the USA-CERN agreement for the US participation in LHC (machine and experiments), Washington 8 december 1997. From left: Neil Lane, Director NSF, Federico Peña, Secretary for Energiy, Luciano Maiani, President of Council, Chris Llewellyn Smith, Director General of CERN.

Agreements were made with several other countries, among them:

- Russia: warm magnets for the beam transfer line from SPS to the LHC (over 150 MCHF)
- India: hardware, software and skilled superconductor manpower
- Pakistan: detector construction (RPC); barrel yoke (35 tons) for the CMS detector

The December 1996 resolution

- CERN Council came back to LHC in december 1996
- The new resolution approved to start LHC construction in 1997, in the final stage of full magnets
- At the same time, Council accepted the request of Germany ***to reduce the annual CERN budget by some 8%, a total of about 700 MCHF over the construction period***
- CERN, accepted the cut, to be reabsorbed by a general reduction of the Laboratory expenses, within 2009.
- ***The starting of LHC was fixed to 2005***.
- LHC had no more contingency and no resources for magnet R&D
- Chris had fulfilled his goal to obtain the approval, at the expense of moving the problems forward in time.

Was to fire back in 2001

- ***The community, myself included, was anyway satisfied for the approval. Physicists of all countries started preparing the detectors, leaving to CERN the problem to make the machine under financial severe conditions.***

CERN personnel protest against budget cuts requested by CERN Council to approve LHC construction. December 1996

To prolong LEP running for one year, required to stop the LHC civil works for the connection of SPS to the LHC tunnel, with an estimated cost of ~ 120 MCHF, to be added to the overall LHC budget.

Letter to G. Kalmus, Chair Scientific Policy Committee
November 4th, 2000

…an interesting evidence for the Higgs boson in LEP data. However, I am much more sceptical that a year running may allow us to get any better.
….Indeed, even the more optimistic analyses conclude that there are no golden plated events to be seen, all relying on small statistical effects accumulating here and there. This may well be the case, by the way, of LHC experiments, but when we shall be there we shall have all the time and the energy to improve the statistics as much as we want, a much more comfortable situation.

The idea that we may find ourselves in September 2001 with 3.5-4 sigmas, CERN's financial position aggravated, LHC delayed and LHC people disbanded is not very encouraging. I am not going to go along this way.

4. The cost-to-completion crisis

- In summer 2001 we received the replies to the call for making the 1232 magnetic dipoles, the biggest contract, and the cost of the escavation of the ATLAS and CMS halls could be made with good approximation
- A conference of the groups dedicated to LHC construction was made and a cost to completion could be estimated reliably
- at the same time, we could make a cost estimate for the upgrading of CERN infrastructures needed to host the LHC, obtaining a realistic cost-to-completion of the whole project.
- We presented the result to the Finance Committe, 19 Sept. 2001.
- A shortfall of money was found, with respect to the projected budget, and a big crisis started, which lasted until the end of 2002

The LHC extra cost to completion: main figures

Presented to the Finance Committe March 2002

The model following the cost review and the assumptions above are:

Sept.19 talk		
480	LHC machine and areas construction	+ 475.0
150	Prototyping	+ 143.0
50	CERN share of detector construction and M&O	+ 56.0
	LHC Injectors	+ 26.0
120	LHC computing Phase II	+ 120.0
	LHC infrastructure and support(*) (machine & detectors)	+ 53.2
	Radioactive waste management	+ 14.0
		+ 887.2
	Cut for LHC prototyping (over 2001-2008)	- 143.0
	Cut in R&D	- 25.8
	Cut in consolidation	- 10.0
		- 178.8
	Balance	+ 708.4
40	Missing in-kind contributions	+ 40.0
	Total	748.4

(*) Corresponds to the [illegible] not allocated to the [illegible] Review (CERN/FC/4360/corr.) distributed so as to increase the support provided to the LHC project and the related CERN infrastructure.

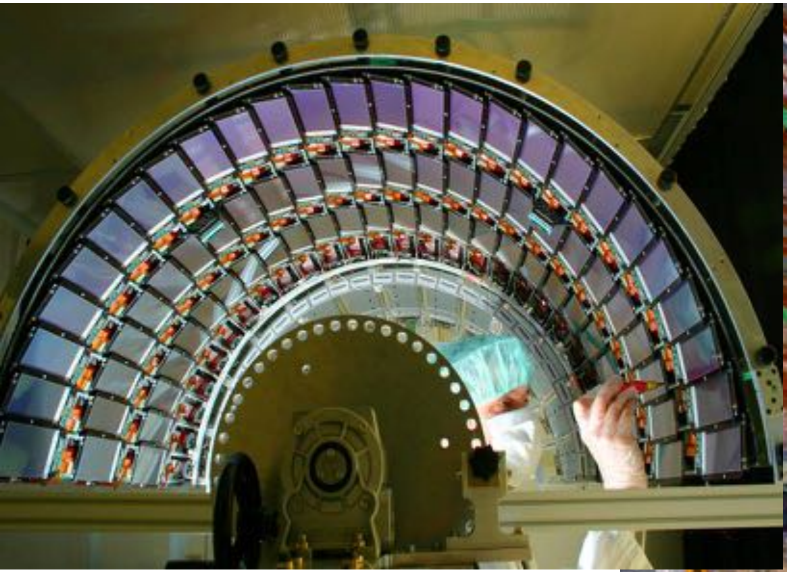
≈10	**Further Assumptions:** Special Indexation of Host States stops after 2005. From 2006 onwards indexation keeps purchasing power

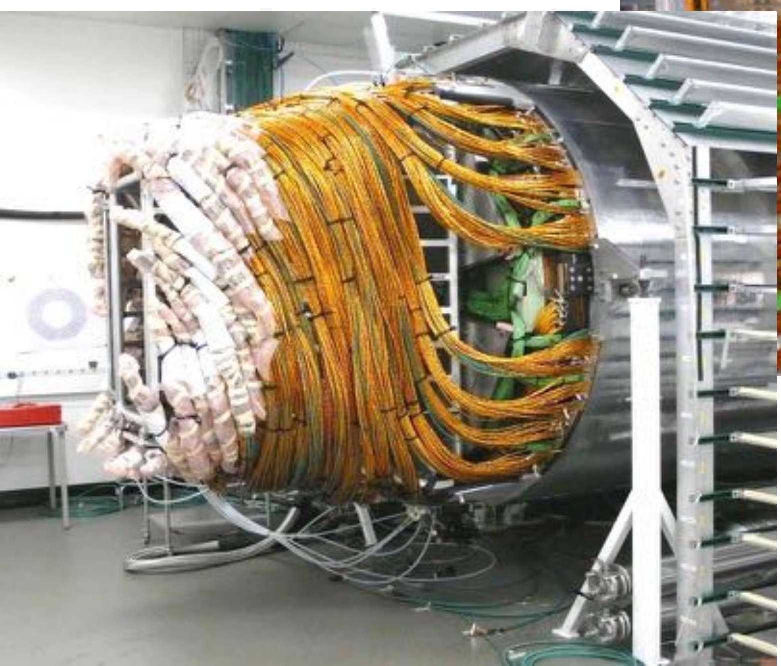
... a tough cure, a balanced package

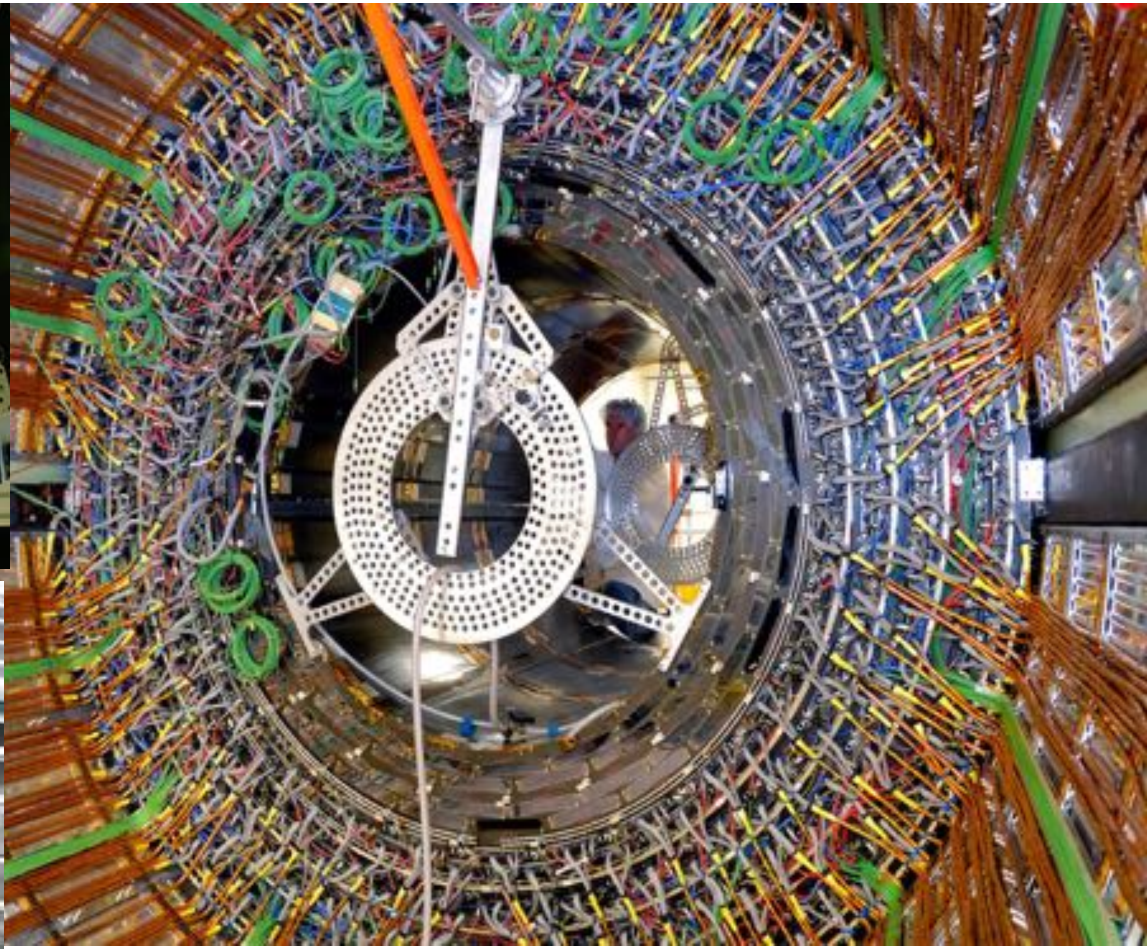
In very rough figures:

- savings: ***reduction in science programme*** with recuperation of manpower, ***rescheduling*** (required anyway by cable production rate) ...more ***spending control***...(about 300 MCHF)
- extending repayment period from 2007 to 2010 (about 400 MCHF)
- CERN came out leaner but more focussed....

CMS Silicon Tracker







The Silicon tracker ($200m^2$) has 10 M channels
Operating temperature -15°C

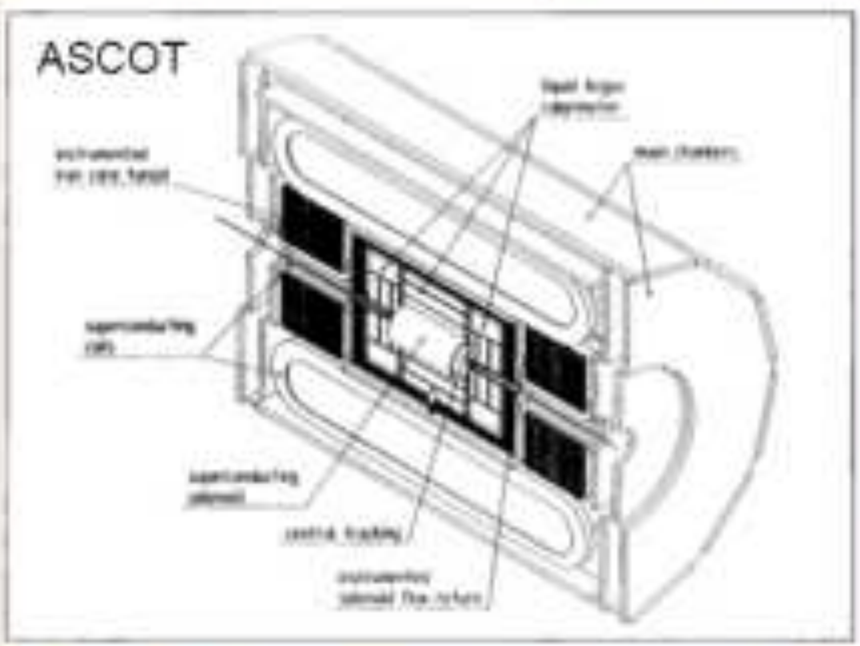
CMS solenoid

B= 3.8 T
Diameter = 6m
Stored energy = 2.6 GJ
Magnetic length = 12.5 m

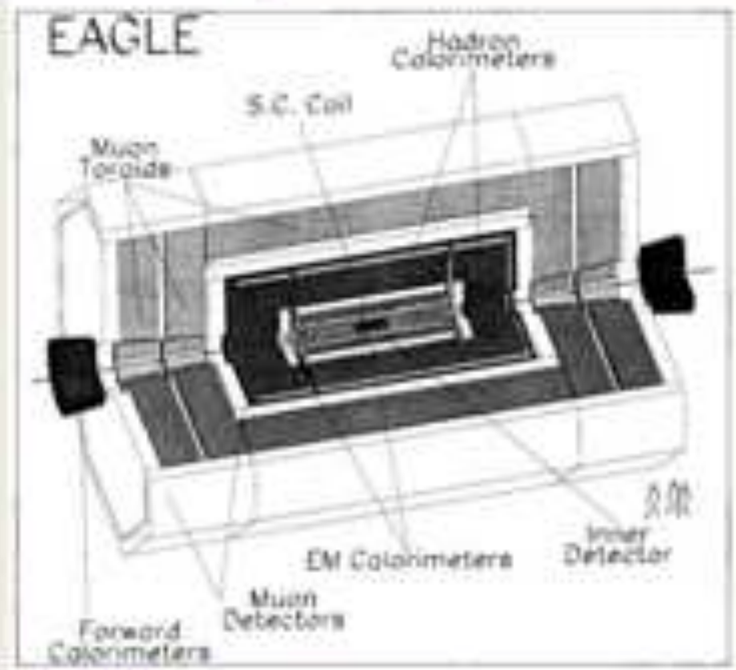
Forward CMS hadronic calorimeter going down

The ASCOT and EAGLE proto-collaborations both presented detector concepts with a toroid magnet configuration for the muon spectrometer at the Evian meeting

From their Expressions of Interest

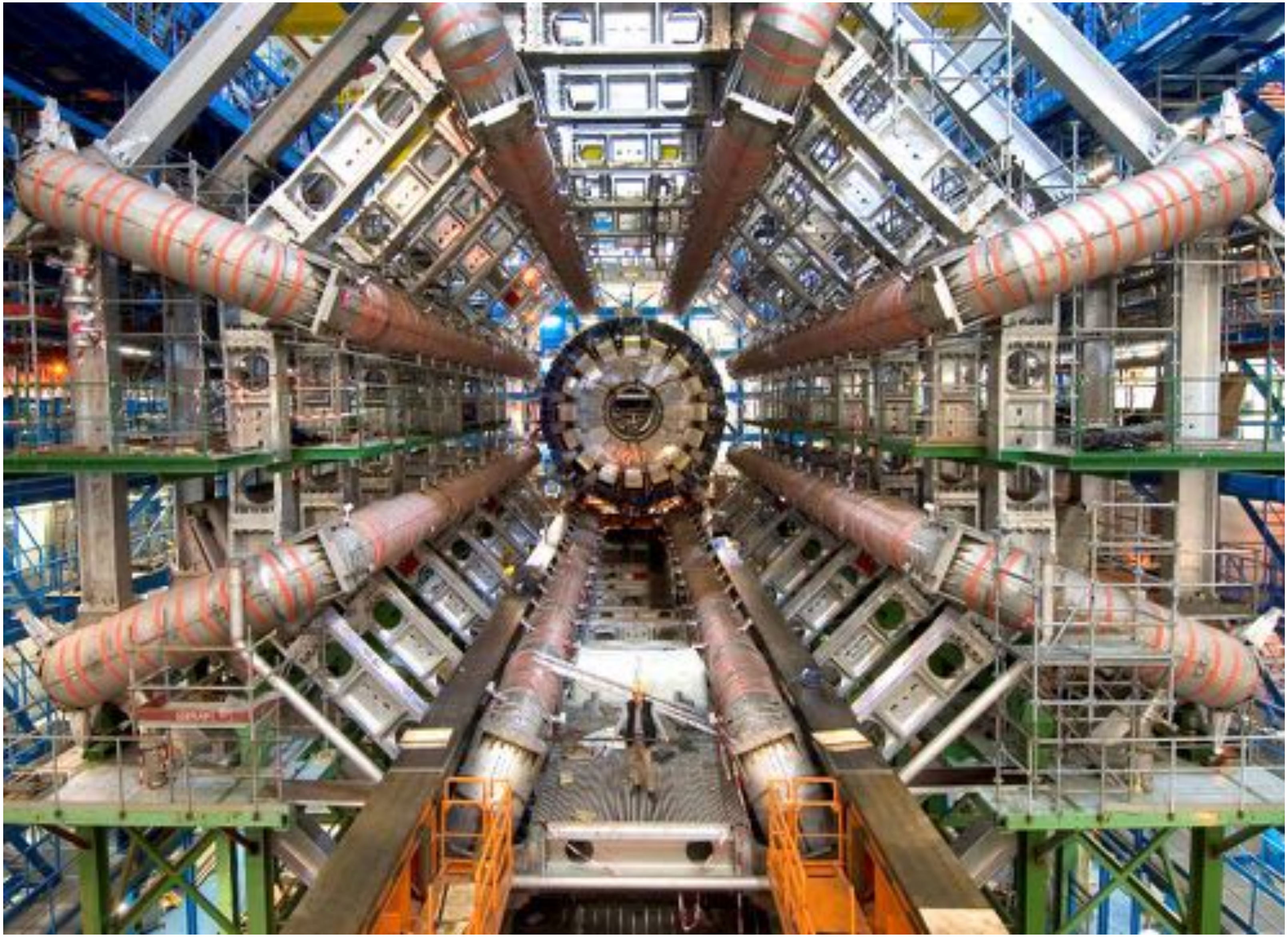


ASCOT with a superconducting air-core barrel and warm iron end cap toroids



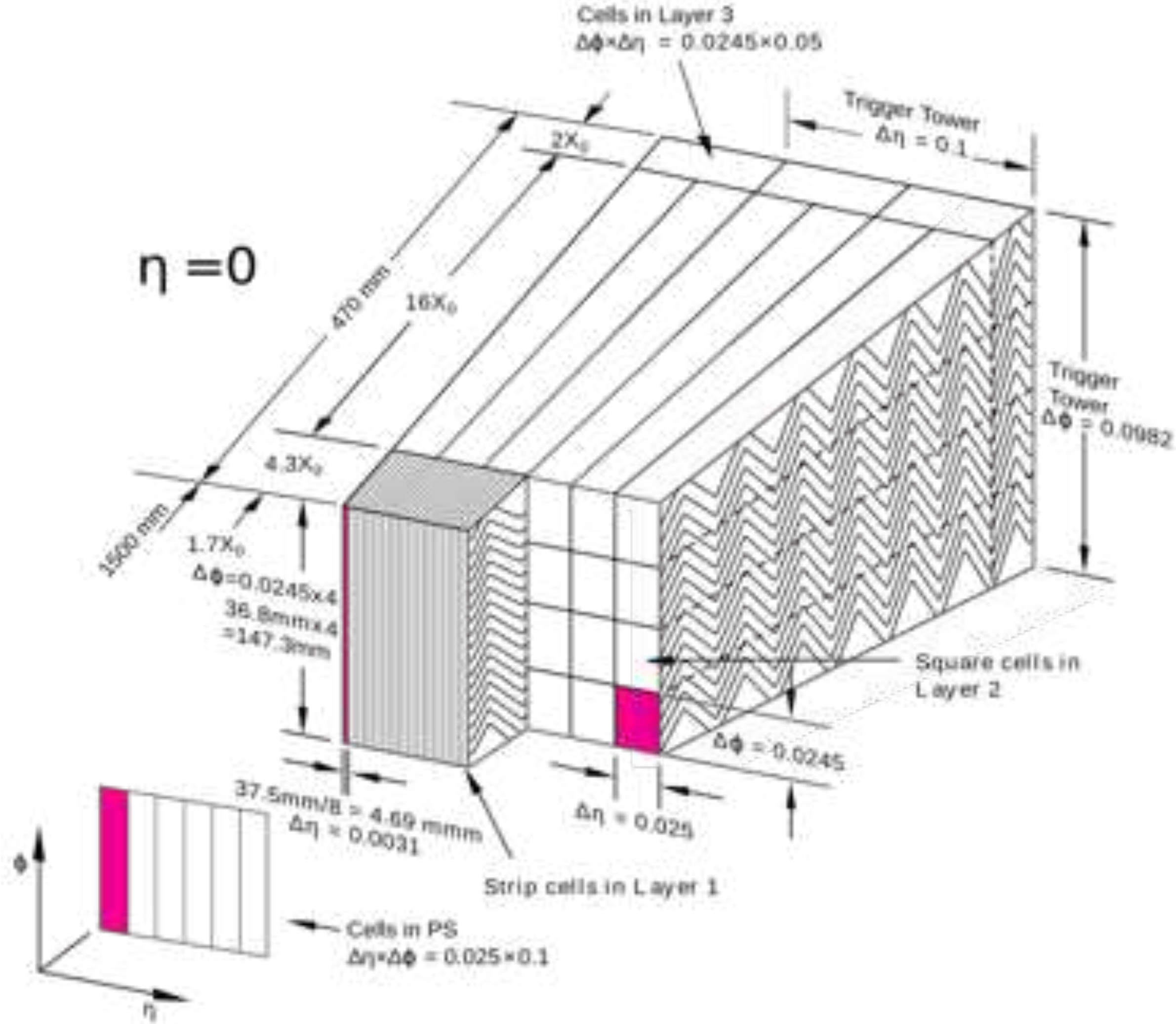
EAGLE with warm iron barrel and end cap toroids

The barrel superconducting toroid of ATLAS
(A Toroidal LHC ApparatuS)



First prototype of a novel LAr concept ('accordion' 1990)

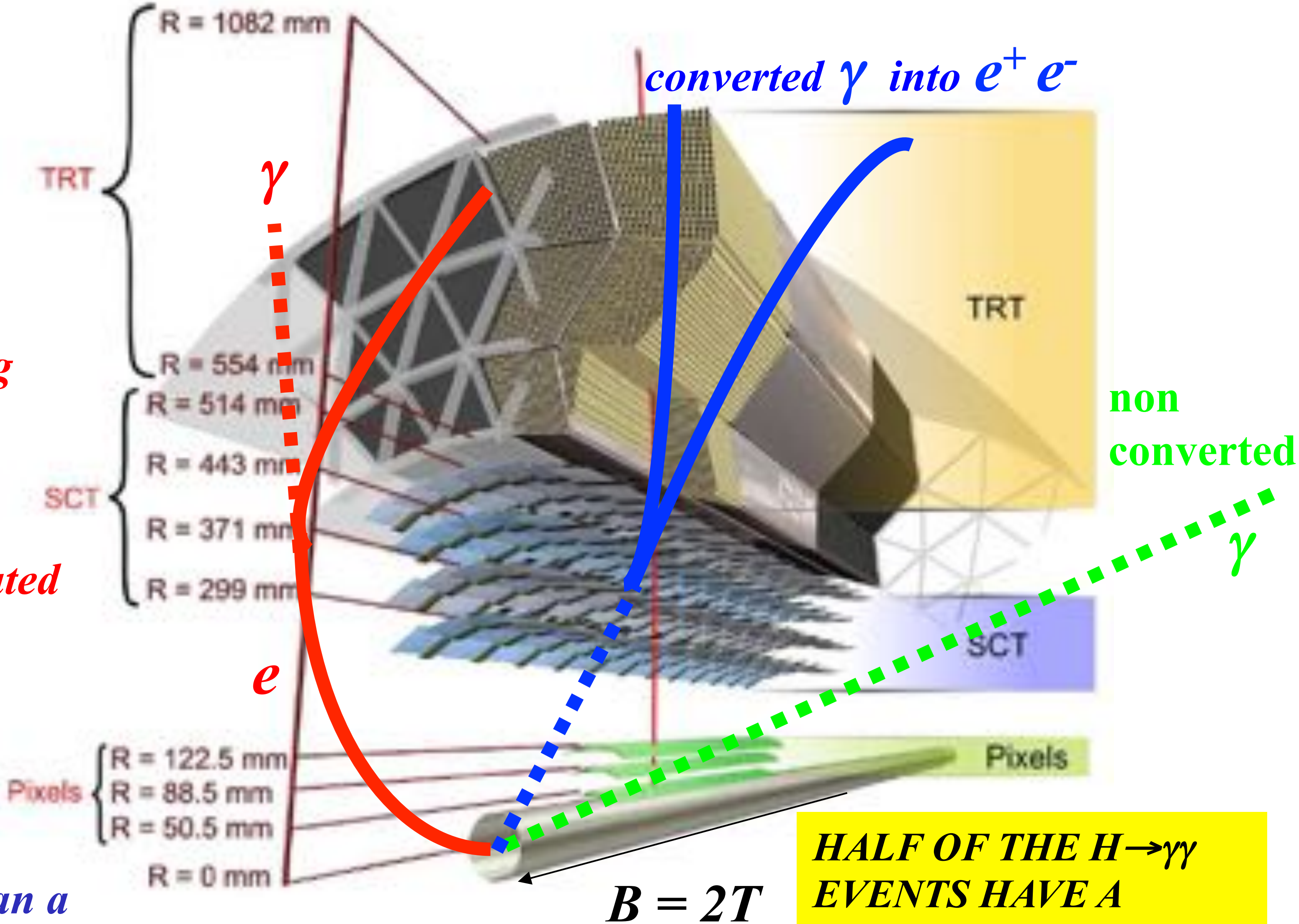
LAr EM calorimeter construction 1999 - 2004



presampler and longitudinal segmentation of the EM
ATLAS (*Liquid Argon* ***) accordion calorimeter***

ATLAS inner detector

Outside are installed the calorimeters and the muon detector

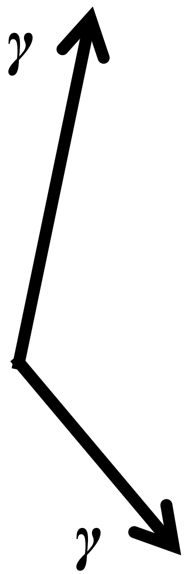


electrons can do some bremsstrahlung in the Inner Detector ⇒ response more complicated

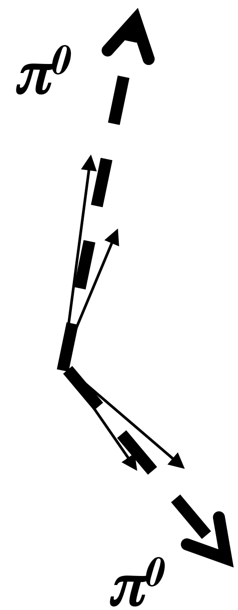
photons can convert ⇒ more complicated than a non converted photon

HALF OF THE H→γγ EVENTS HAVE A CONVERTED PHOTON

Example of H → γγ



signal

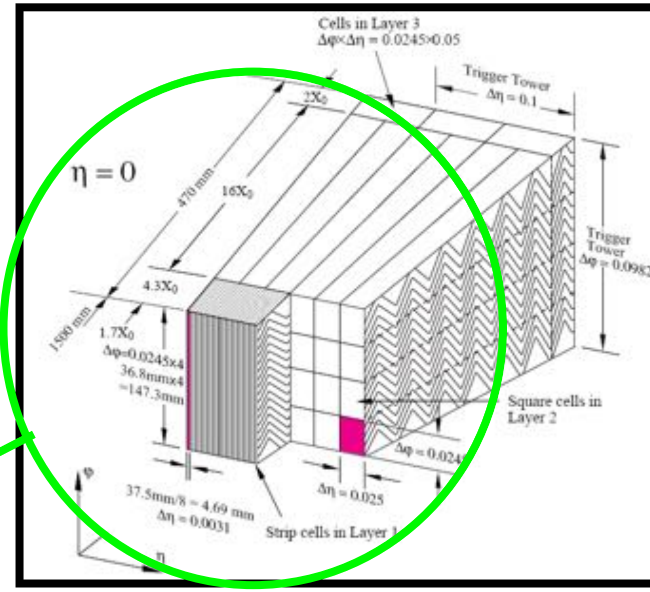


background

angle between the 2 γ of a π^0 $\sim \dfrac{2\ m(\pi^0)}{p_T(\pi^0)}$

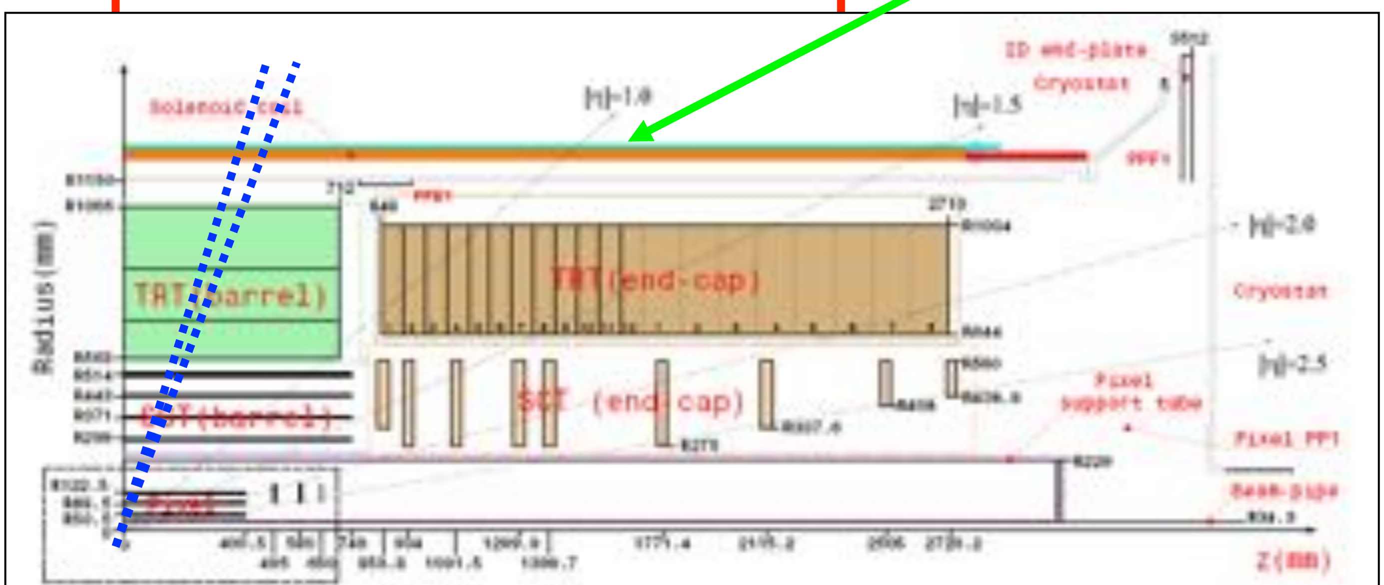
♦ *good jet rejection essential (to reduce γj and jj backgrounds)*

The granularity of the electromagnetic ATLAS detector is very useful to reject the π^0 bakground



opening of photons coming from a π^0 (p_T = 50 GeV)

$\Delta R > .006 \sim 2\, m(\pi^0)/p_T(\pi^0)$

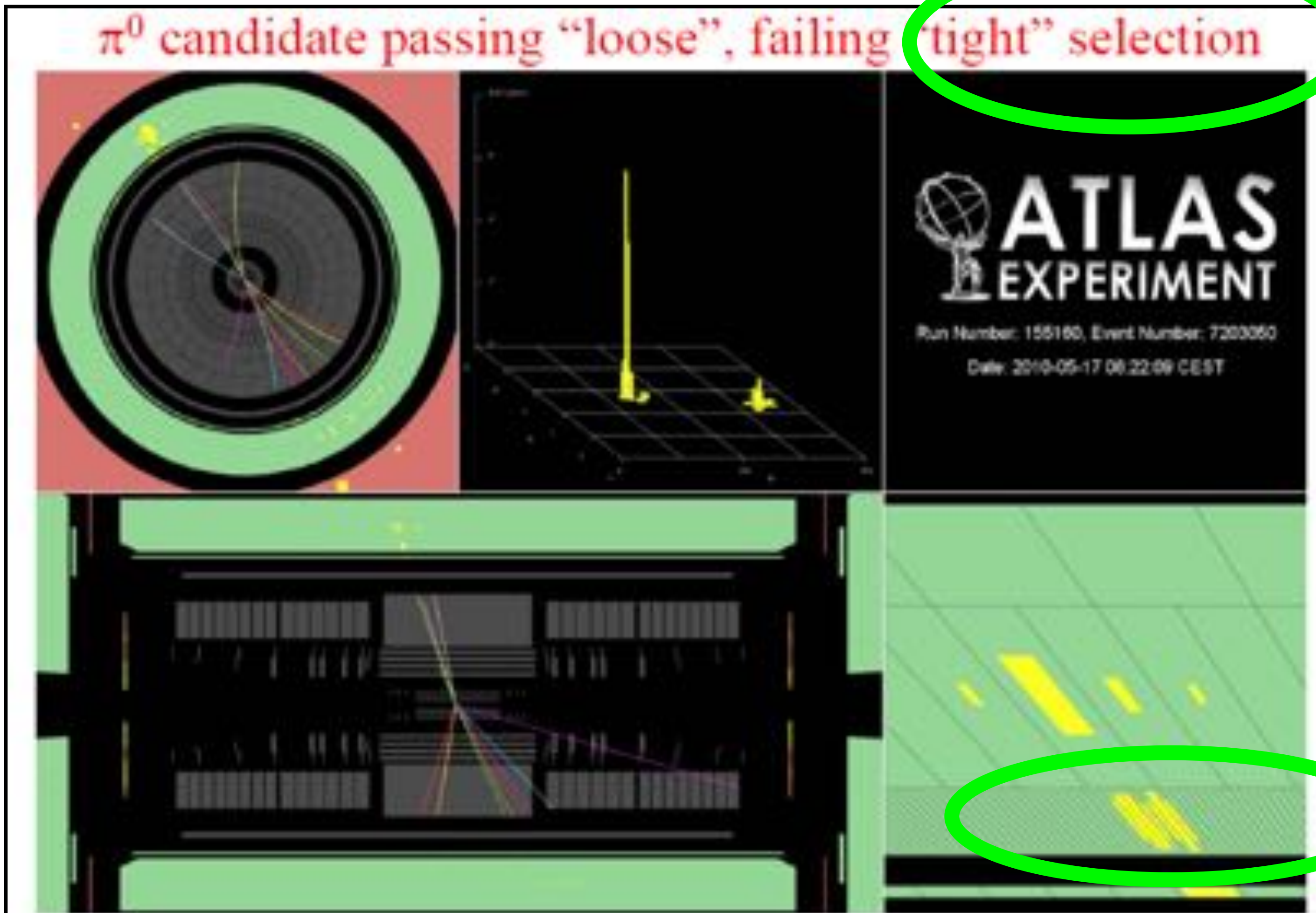


granularity of 1st sampling of calorimeter

$\Delta\eta \sim .003$

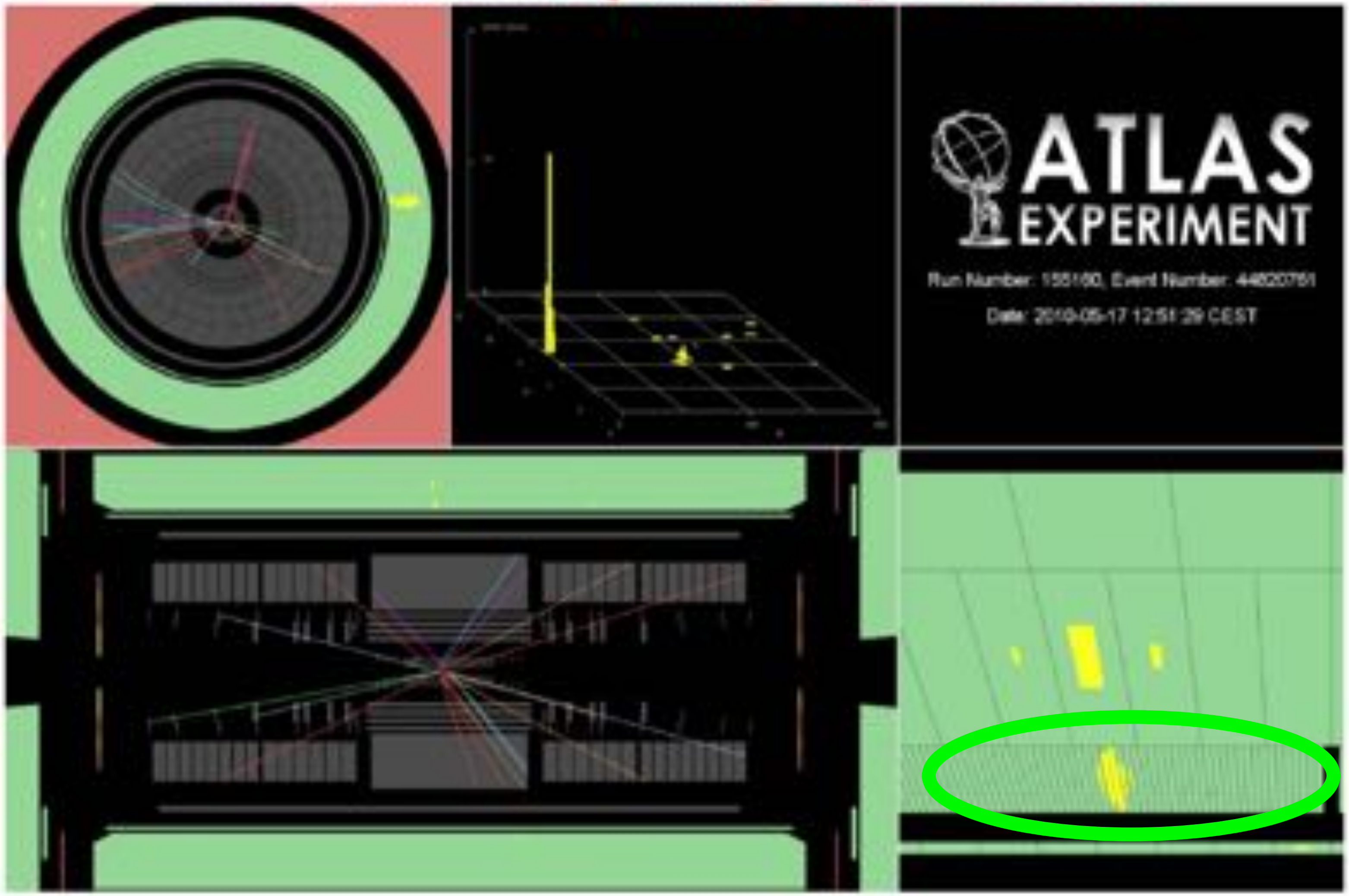
Photon identification with shower shapes

reminder: opening angle between the two photons of a π^0 of p_T =50 GeV is > 0.006 to be compared with size of strip calo 1st sampling ~0.003

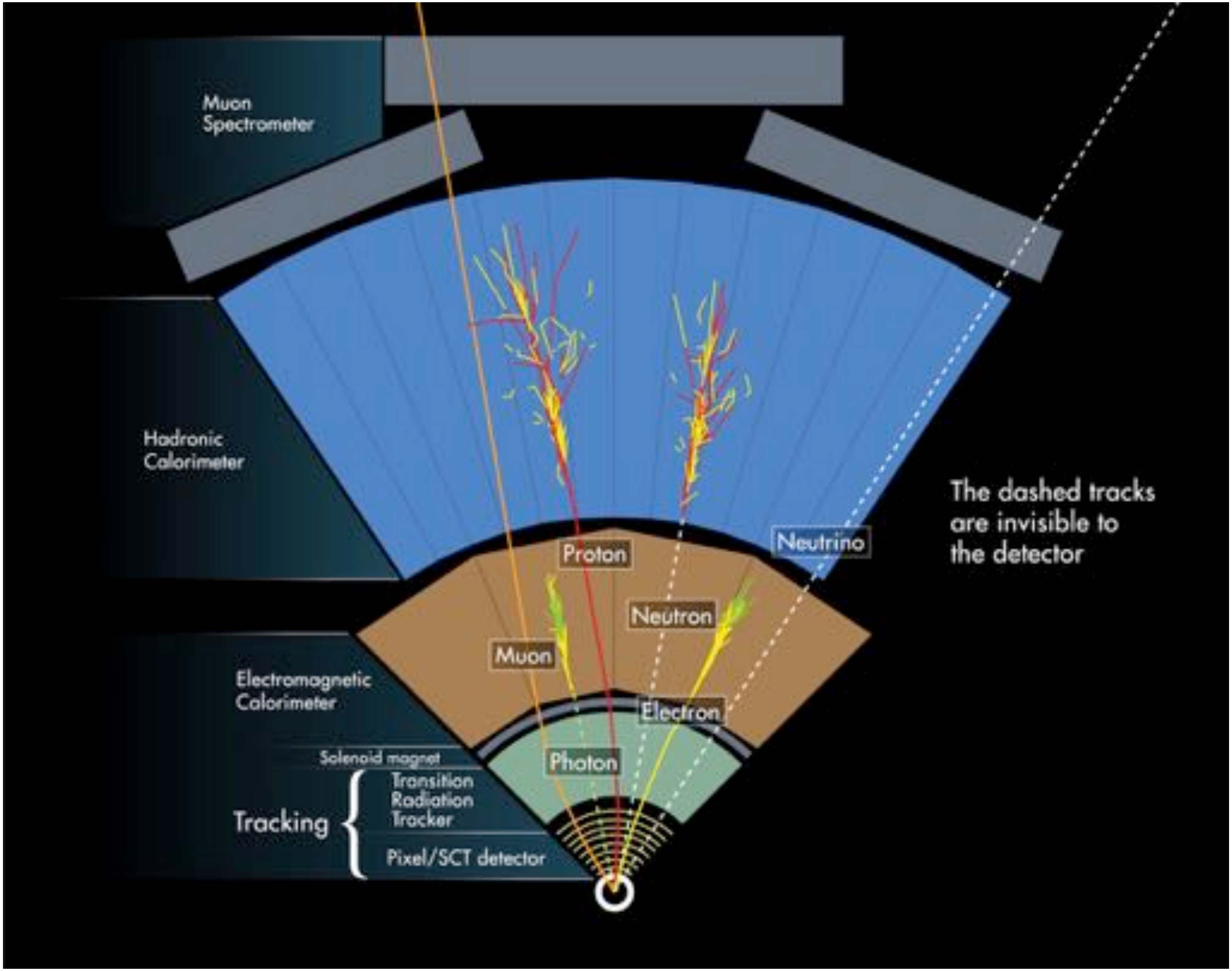


tight selection uses mainly calo 1st sampling

Photon candidate passing “tight” selection

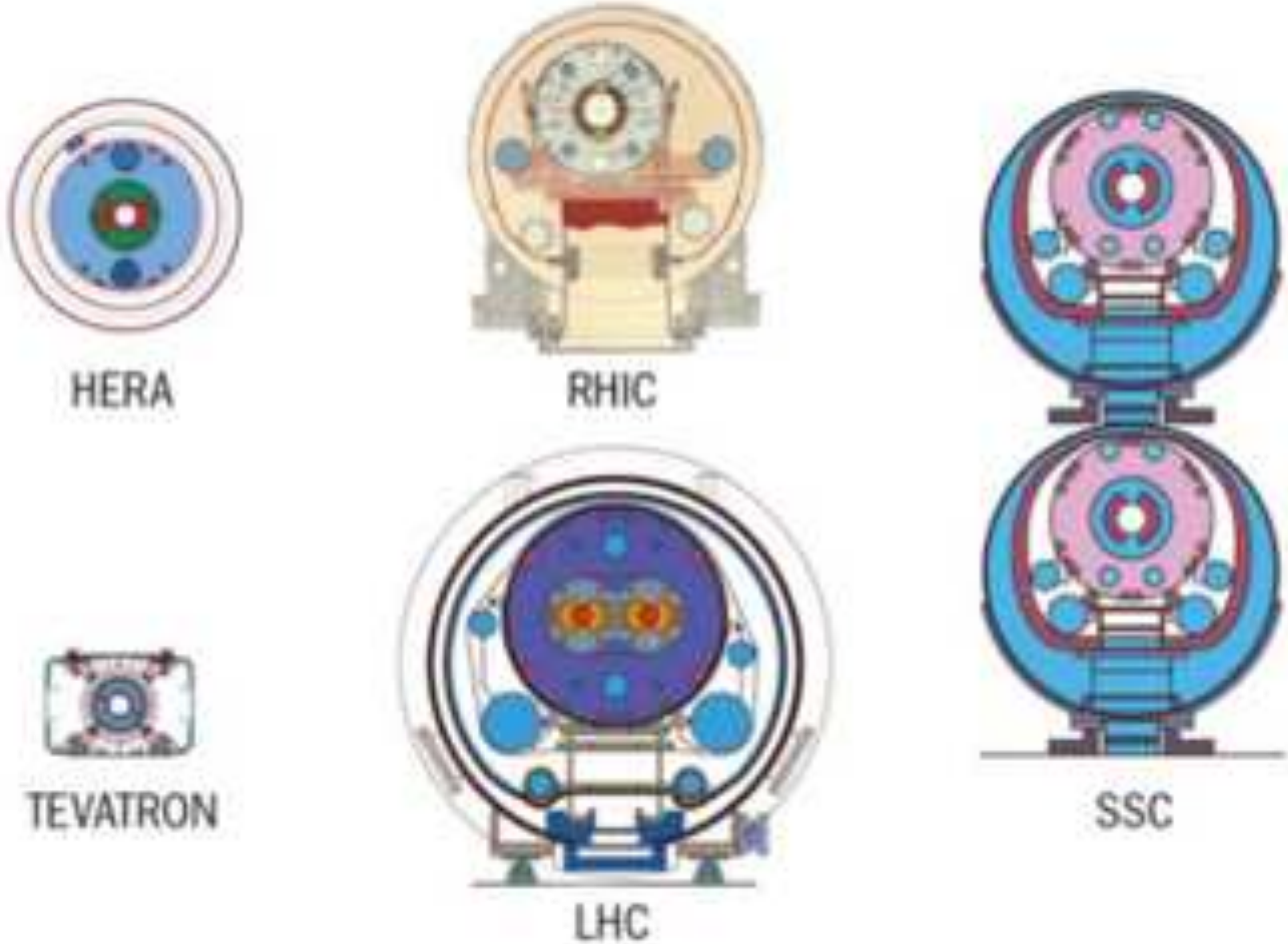


Nice shape in first sampling of EM calormeter


Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks
are invisible to
the detector

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid 4 magnets Calorimeters in field-free region	Solenoid 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\times10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeVstandalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

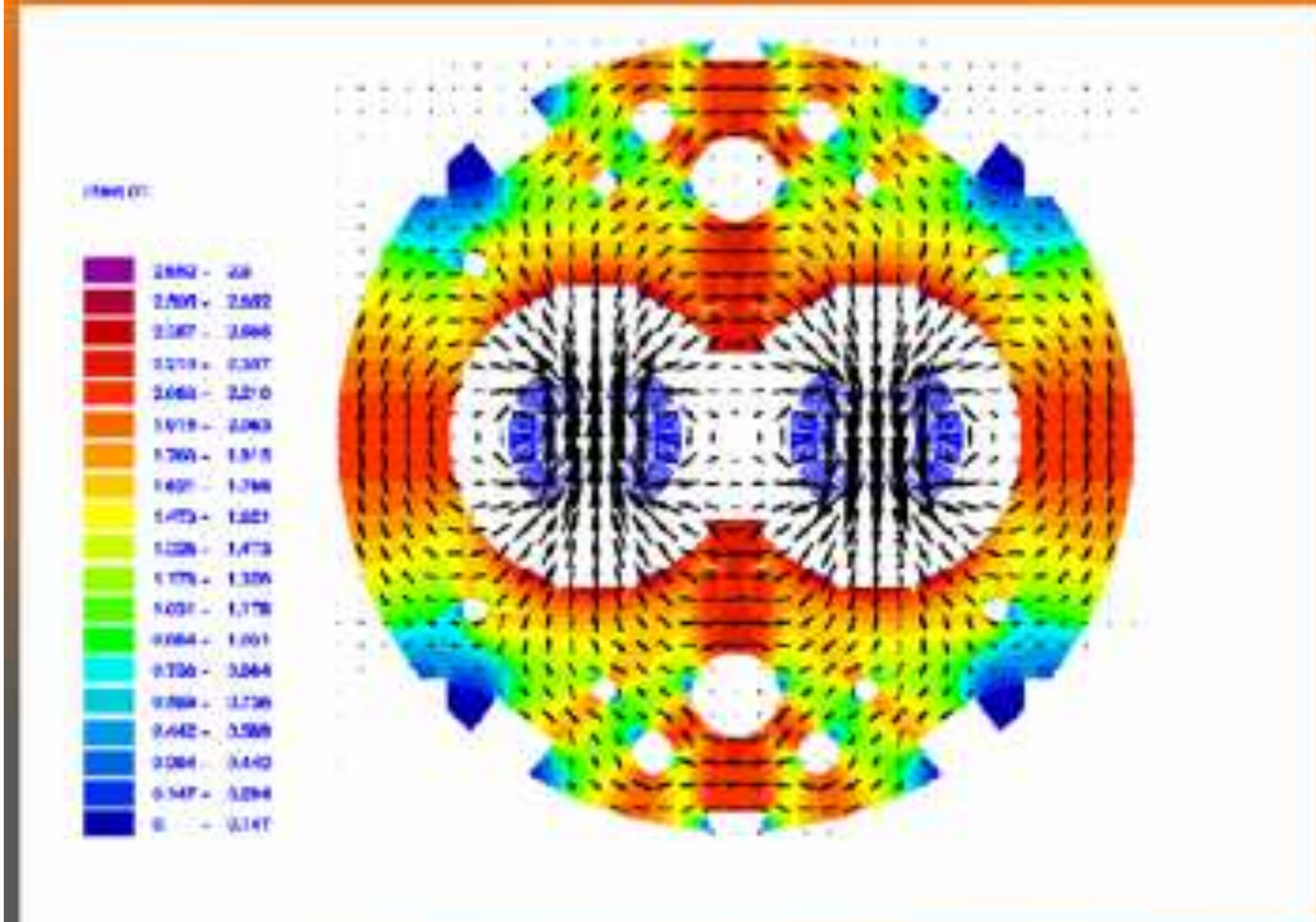
3. Normal sufferings...ground freezing at the CMS shaft

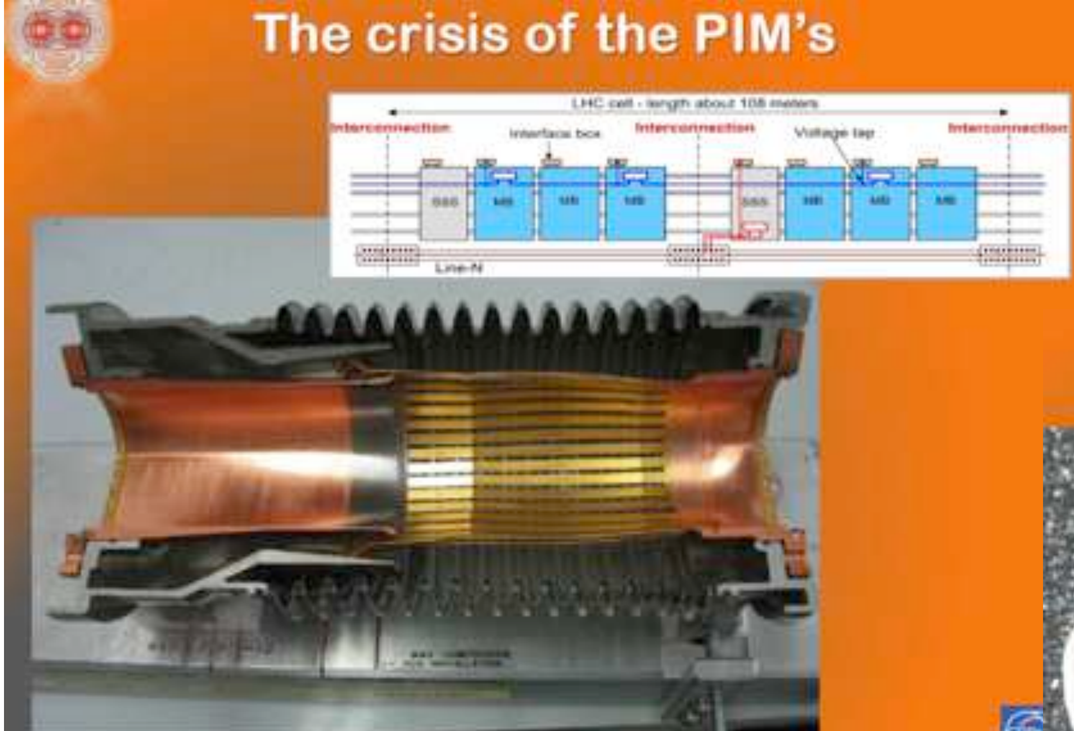


Comparison of dipoles from the Tevatron to the LHC.

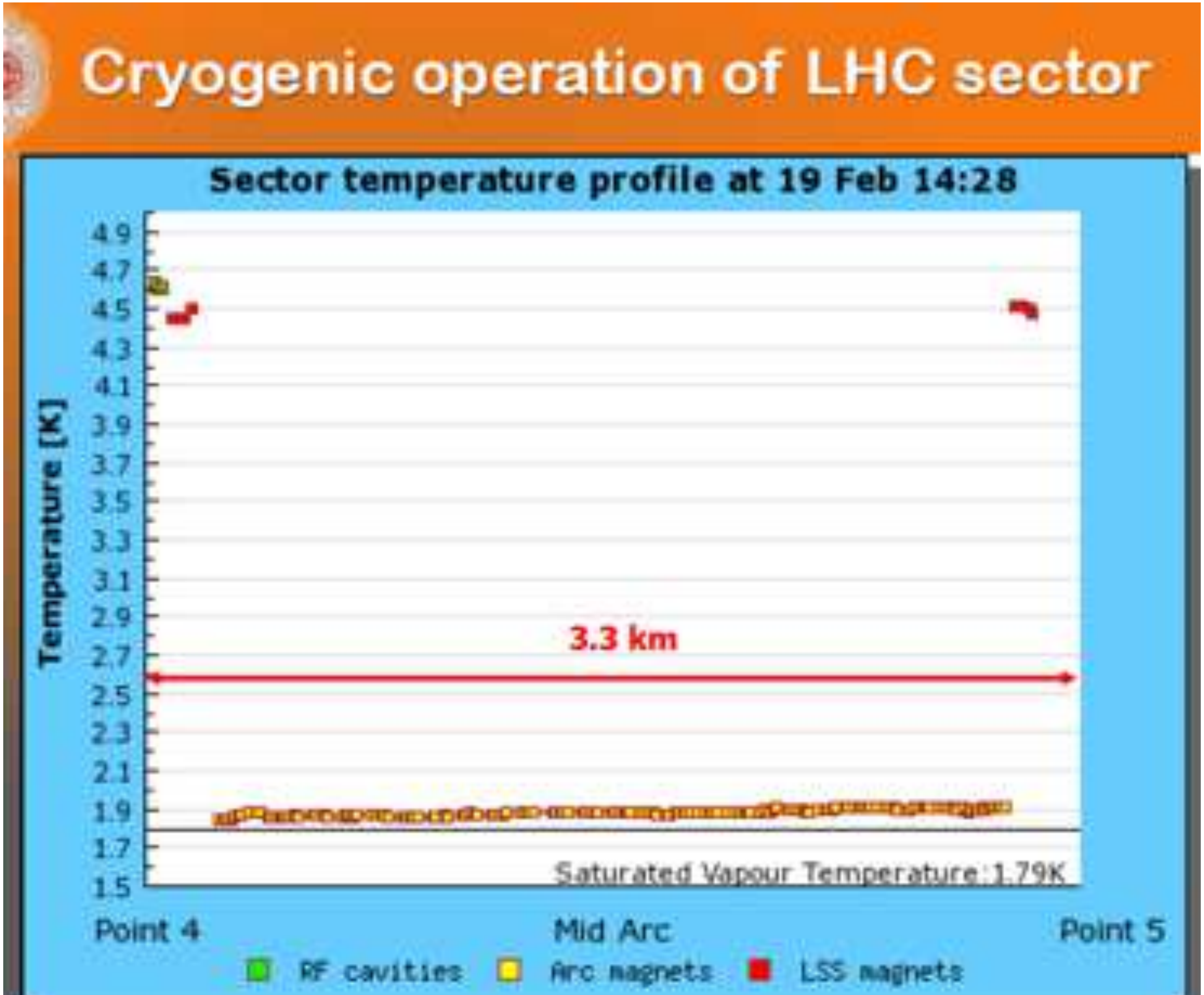
Taken from: **Lucio Rossi** (2011): *Superconductivity and the LHC: the early days*

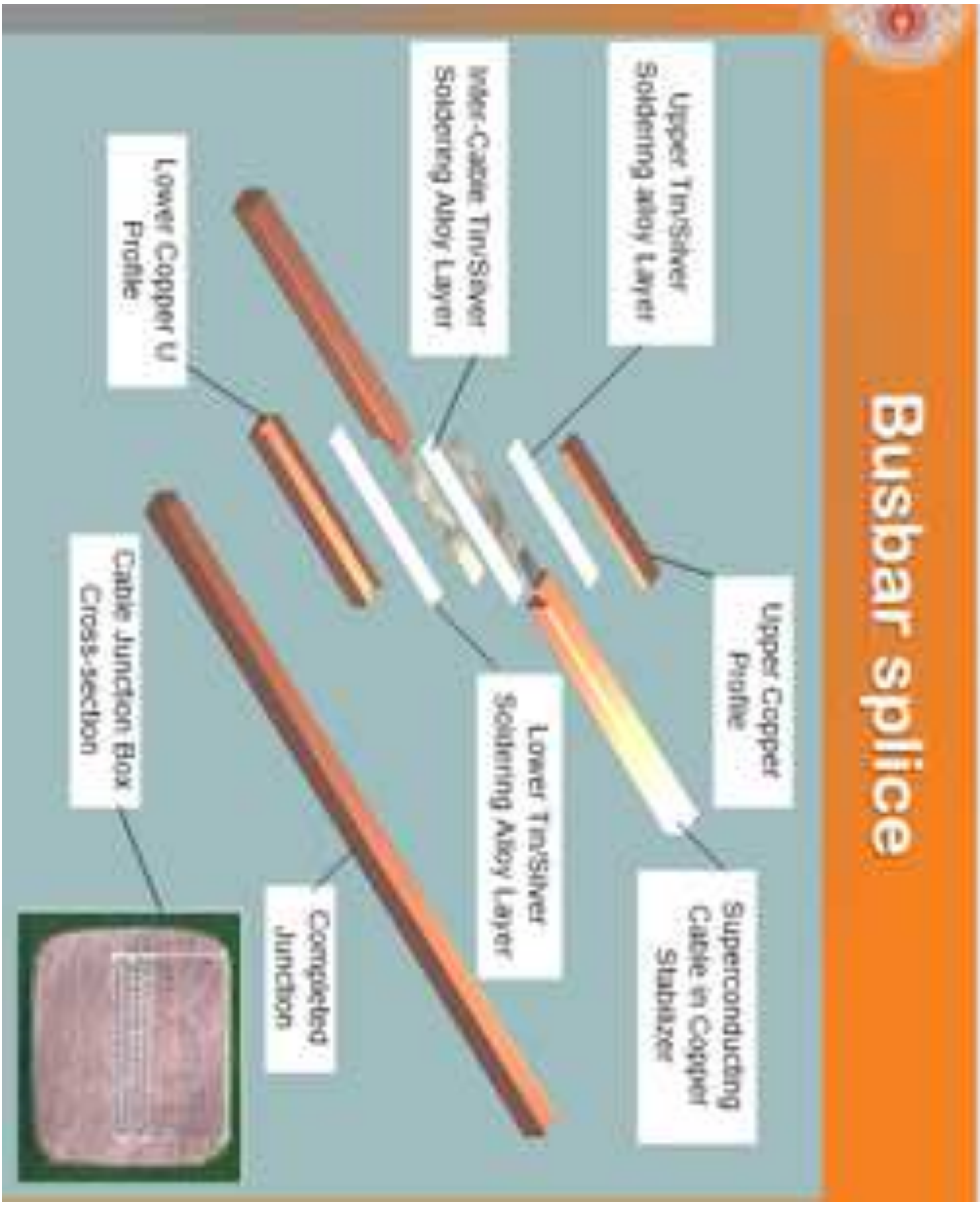
Dipole magnetic flux plot





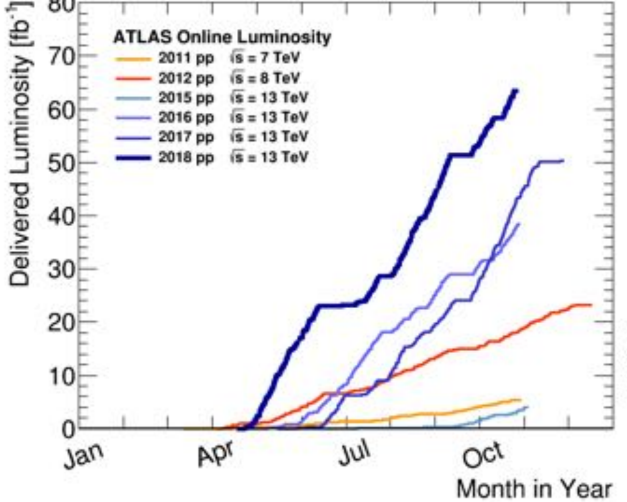
PIM = Plugged In Module

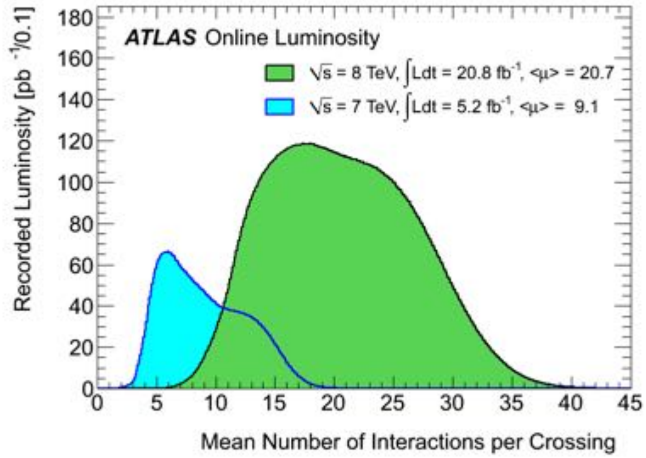

Cryogenic operation of LHC sector
Sector temperature profile at 19 Feb 14:28
Temperature [K]
4.9
4.7
4.5
4.3
4.1
3.9
3.7
3.5
3.3
3.1
2.9
2.7
2.5
2.3
2.1
1.9
1.7
1.5
3.3 km
Saturated Vapour Temperature:1.79K
Point 4
Mid Arc
Point 5
RF cavities
Arc magnets
LSS magnets

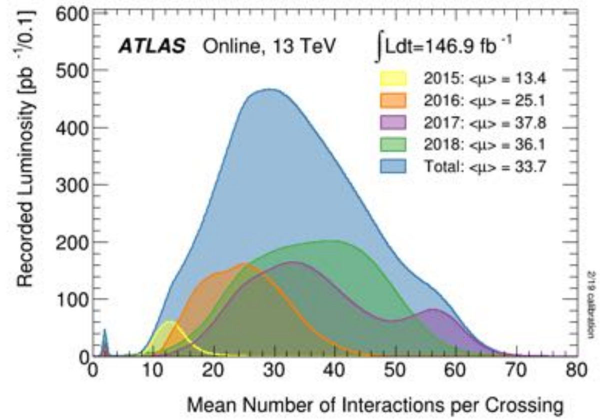

Busbar splice
Upper Tin/Silver Soldering alloy Layer
Inter-Cable Tin/Silver Soldering Alloy Layer
Lower Copper U Profile
Upper Copper Profile
Lower Tin/Silver Soldering Alloy Layer
Superconducting Cable in Copper Stabilizer
Cable Junction Box Cross-section
Completed Junction

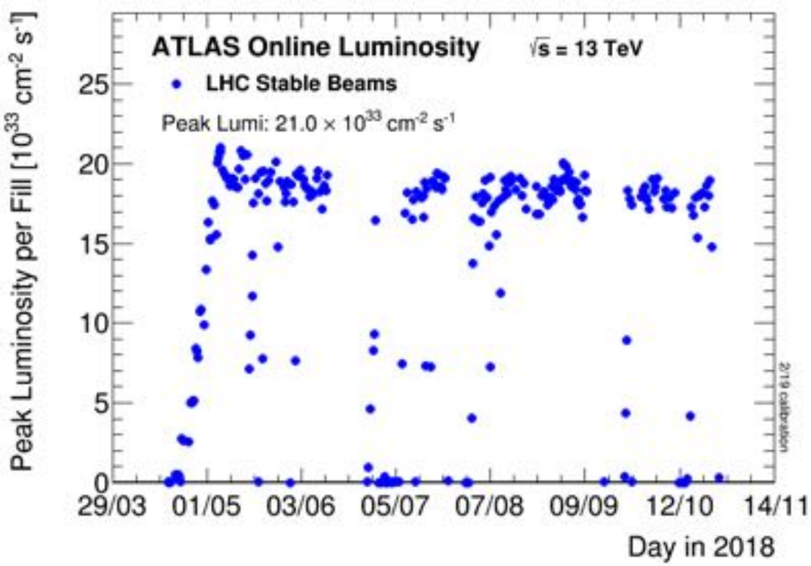

Interconnection of 2 magnets

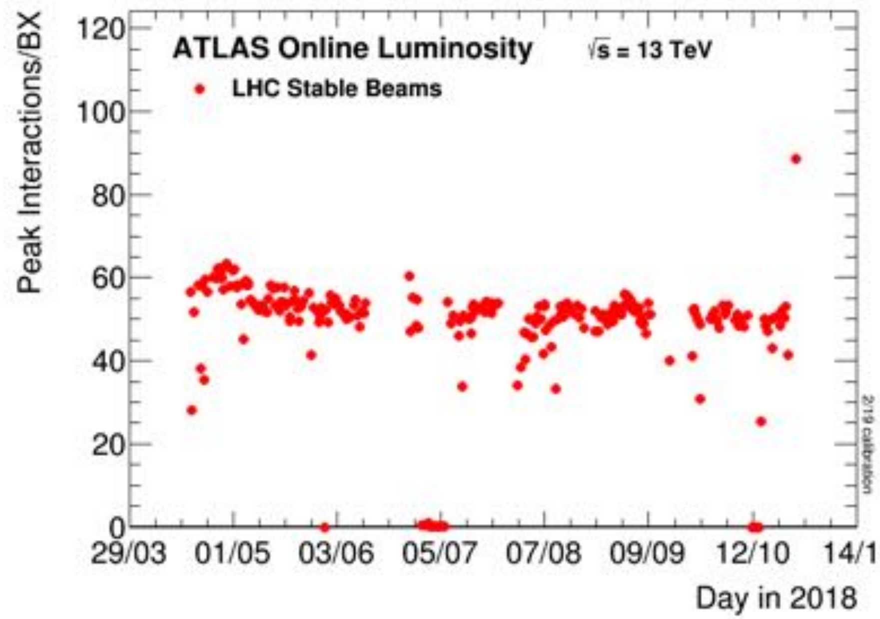
Collateral problems : movements of magnets


ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
2017 pp √s = 13 TeV
2018 pp √s = 13 TeV
Delivered Luminosity [fb⁻¹]
Jan
Apr
Jul
Oct
Month in Year


ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 20.8 fb⁻¹, <μ> = 20.7
√s = 7 TeV, ∫Ldt = 5.2 fb⁻¹, <μ> = 9.1
Recorded Luminosity [pb⁻¹/0.1]
Mean Number of Interactions per Crossing


ATLAS Online, 13 TeV
∫Ldt=146.9 fb⁻¹
2015: <μ> = 13.4
2016: <μ> = 25.1
2017: <μ> = 37.8
2018: <μ> = 36.1
Total: <μ> = 33.7
Recorded Luminosity [pb⁻¹/0.1]
Mean Number of Interactions per Crossing


ATLAS Online Luminosity
√s = 13 TeV
LHC Stable Beams
Peak Lumi: 21.0 × 10³³ cm⁻² s⁻¹
Peak Luminosity per Fill [10³³ cm⁻² s⁻¹]
29/03
01/05
03/06
05/07
07/08
09/09
12/10
14/11
Day in 2018


ATLAS Online Luminosity
√s = 13 TeV
LHC Stable Beams
Peak Interactions/BX
29/03
01/05
03/06
05/07
07/08
09/09
12/10
14/11
Day in 2018

- Theory
- Experimental developments, including detectors, magnets
- **Searches**
- Discovery

First experimental note on scalar boson search at LEP

DESY 79/27
May 1979

THE PRODUCTION AND DETECTION OF HIGGS PARTICLES AT LEP

ECFA/LEP Specialised Study Group 9 "Exotic Particles"

G. Barbiellini - *INFN, Frascati and CERN*
G. Bonneaud - *Strasbourg and CERN*
G. Coignet - *LAPP, Annecy-le-vieux*
J. Ellis - *CERN*
M. K. Gaillard - *LAPP, Annecy-le-vieux*
J. F. Grivaz - *LAL, Orsay*
C. Matteuzzi - *CERN*
B. H. Wiik - *DESY*

$H \rightarrow \gamma\gamma$ (historical mode)

Photon decay modes of the intermediate mass Higgs
ECFA Higgs working group
C.Seez and T. Virdee
L. DiLella, R. Kleiss, Z. Kunszt and W. J.Stirling

Presented at the LHC Workshop, Aachen, 4 - 9 October 1990
by C. Seez, Imperial College, London.

CERN 90-10
ECFA 90-133
Volume II
3 December 1990

A report is given of studies of:
(a) $H \to \gamma\gamma$ (work done by C. Seez and T. Virdee)
(b) $W H \to \gamma\gamma$ (work done by L. DiLella, R. Kleiss, Z. Kunszt and W. J. Stirling)
for Higgs bosons in the intermediate mass range ($90 < m_H < 150$ GeV/c^2).
The study of the two photon decay mode is described in detail.

L. Fayard
G. Unal
EAGLE Note
PHYSICS-NO-001
december 1991

SEARCH FOR HIGGS DECAY INTO PHOTONS WITH EAGLE

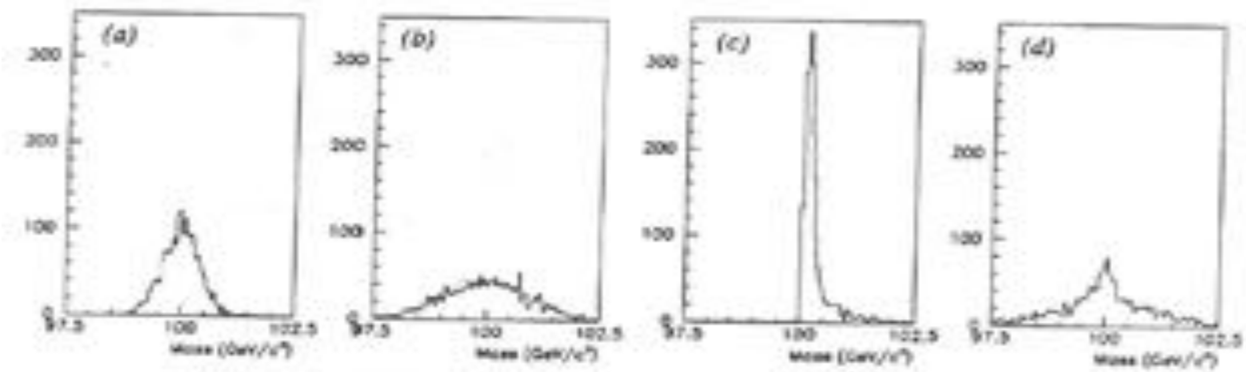
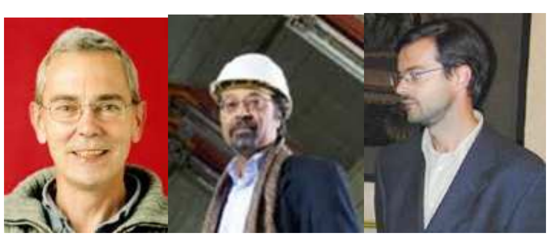


Figure 4: Reconstructed mass plots for Higgs boson, m_H=100GeV/c²
(a) smeared by: calorimeter energy resolution of $\Delta E/E = 2\%/\sqrt{E} \oplus 0.5\%$
(b) smeared by: calorimeter energy resolution of $\Delta E/E = 7\%/\sqrt{E} \oplus 1.0\%$
(c) smeared by: pileup energy from, on average, 10 interactions
(d) smeared by: loss of knowledge of the vertex position (σ_{vtx}=5.5 cm)



C.Seez **J.Virdee** **G.Unal**

was studied at the LHC
for more than 20 years
(and even before at the SSC)

H → 4l (gold plated mode)

Proceedings of the Summer Study on High Energy Physics in the 1990s

June 27 – July 15, 1988
Snowmass, Colorado

Editor
Sharon Jensen

SEARCH FOR H → Z*Z* → 4 LEPTONS AT LHC

Higgs Study Group

M. Della Negra, D. Froidevaux, K. Jakobs, R. Kinnunen,
R. Kleiss, A. Nisati and T. Sjöstrand

CERN 90-10
ECFA 90-133
Volume II
3 December 1990

In Section 2, we discuss the simulation of the Higgs signal, and we study the backgrounds from $t\bar{t}$, $Zb\bar{b}$ and Z^*Z^*, γ^*Z^*, in Section 3. Finally, in Section 4, we present and discuss the results, and we conclude in Section 5.

Effect of Lepton Energy Resolution on Higgs Searches at the SSC.*

Ian Hinchliffe
Edward M. Wang
Lawrence Berkeley Laboratory
University of California
1 Cyclotron Road
Berkeley, California 94720

Abstract

We discuss the effects of realistic detector resolution on the processes $H \to ZZ \to e^+e^-e^+e^-$ and $H \to ZZ \to e^+e^-\mu^+\mu^-$ at the SSC. The background from $t\bar{t}$ where the $t\bar{t}$ system produces two isolated leptons in its decays is discussed.

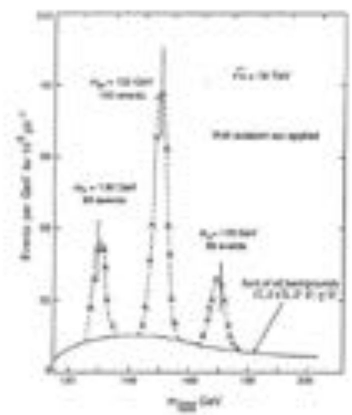


Fig. 10

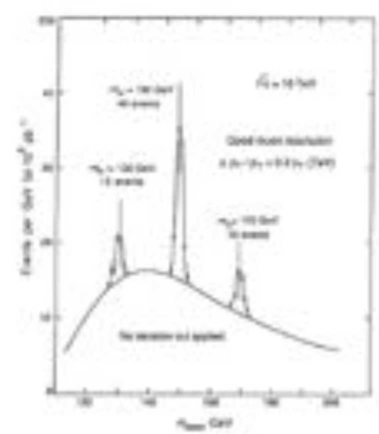
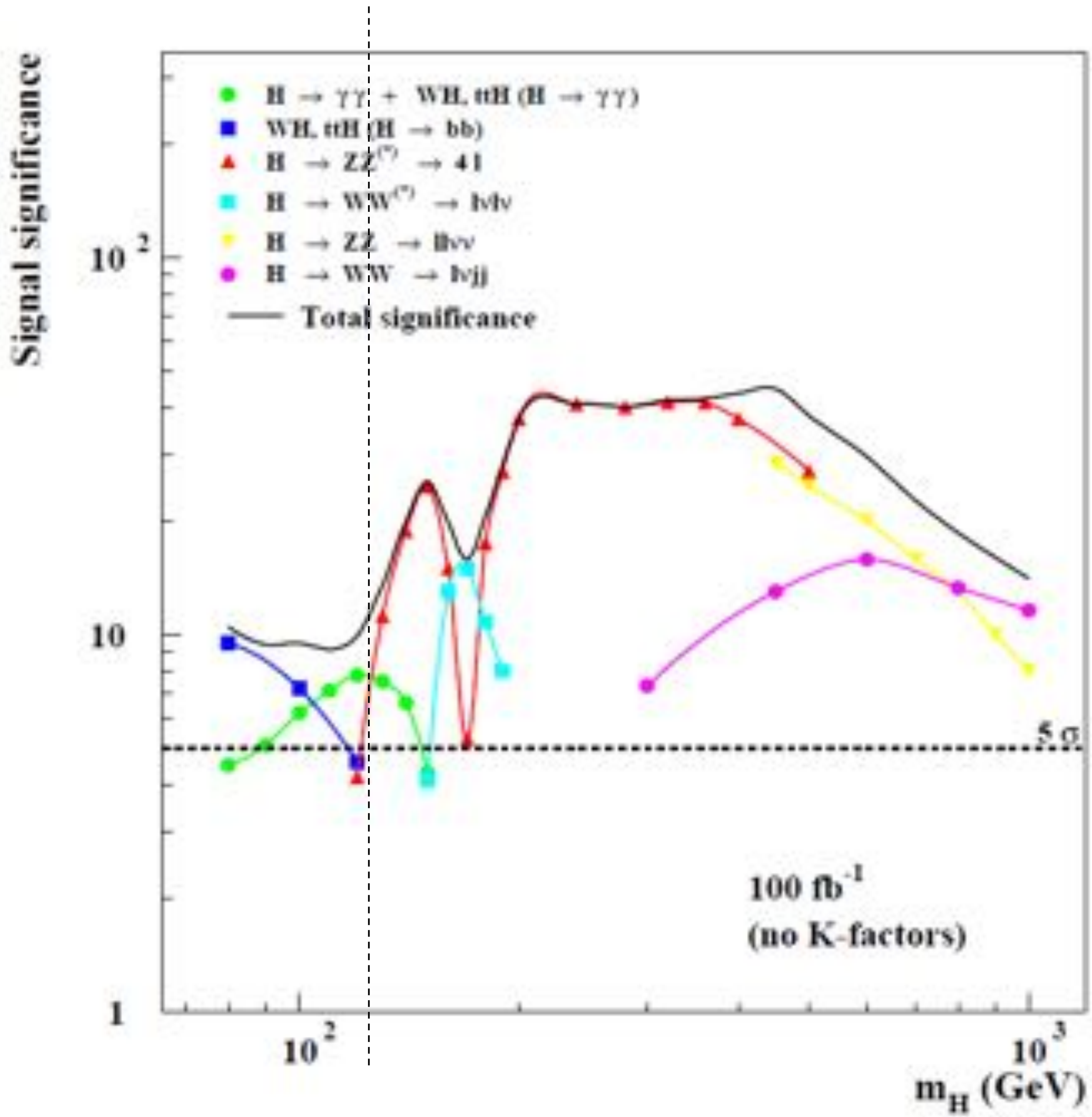
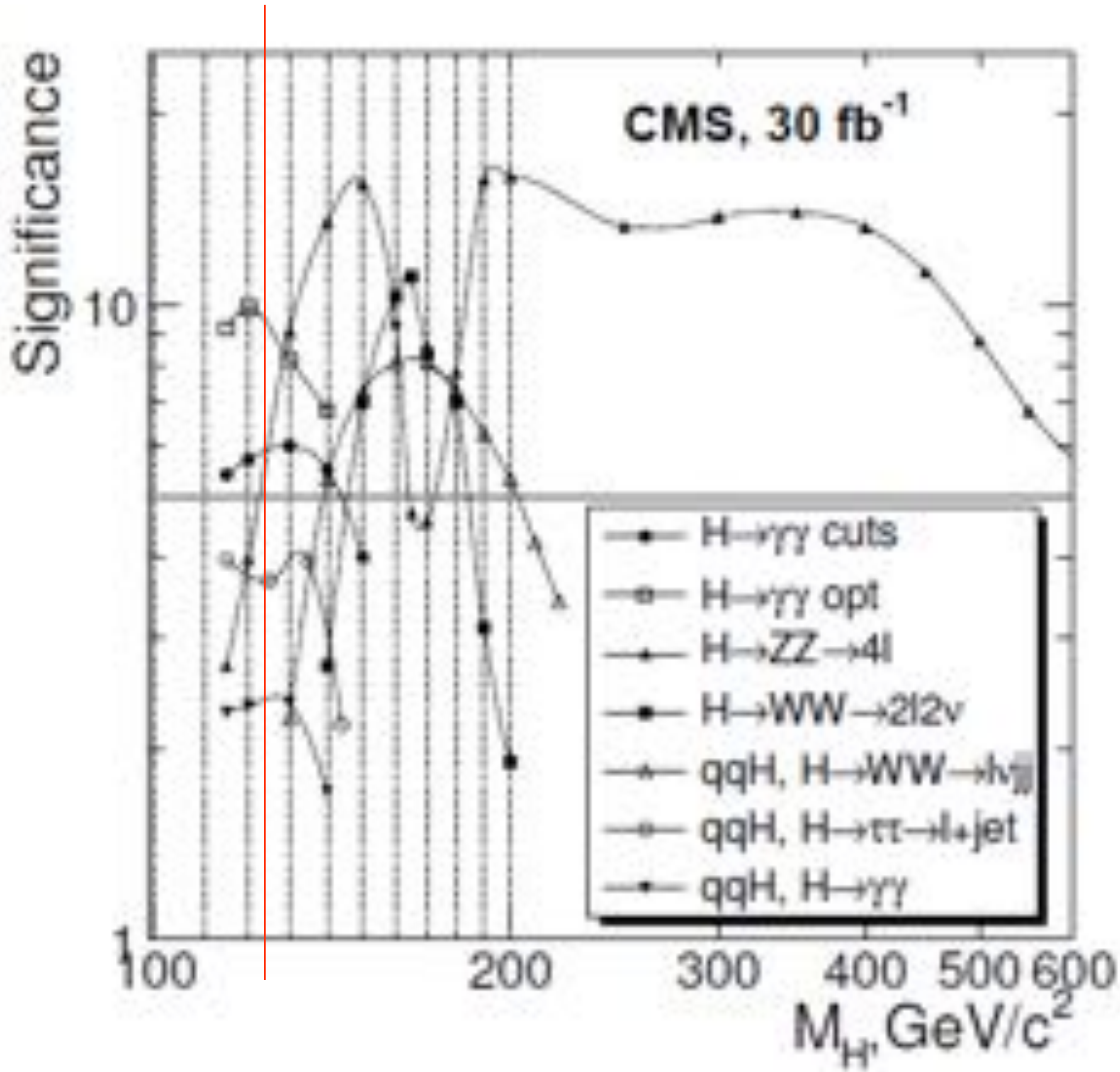


Fig. 11



ATLAS TDR 15, CERN/LHCC 99-15
25 May 1999



CERN/LHCC 2006-021
CMS TDR 8.2
26 June 2006

Testing the Higgs sector of the
supersymmetric standard mode
hadron colliders

Z. Kunszt
Institute of Theoretical Physics, ETH, Zurich, Swit

F. Zwirner *
Theory Division, CERN, Geneva, Switzerlan

Received 31 March 1992
Accepted for publication 8 July 1992

m_A tan(β) plane

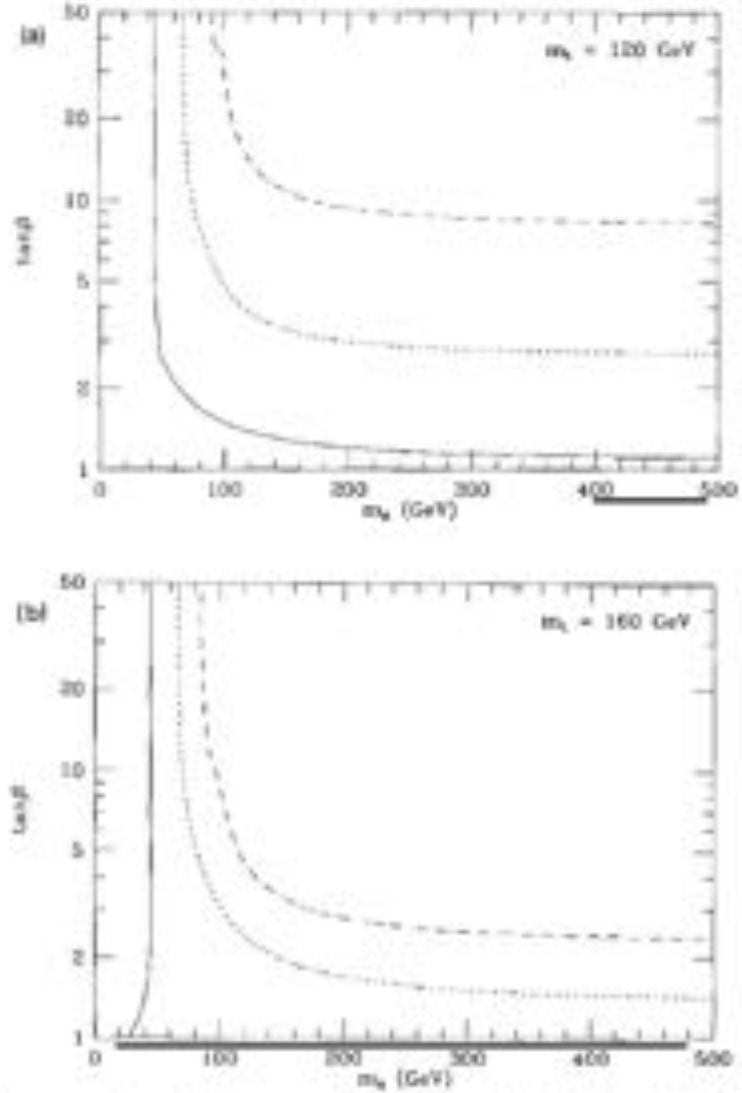


Fig. 8. Schematic representation of the present LEP I limits and of the future LEP II sensitivity in the (m_A, tan β) plane, for $m_{\tilde{q}}$ = 1 TeV and (a) m_t = 120 GeV, (b) m_t = 160 GeV. The solid lines correspond to the present LEP I limits. The dashed lines correspond to $\sigma(e^+e^- \to hZ, HZ, hA, HA)$ = 0.2 pb at $\sqrt{s}$ = 175 GeV, which could be seen as a rather conservative estimate of the LEP II sensitivity. The dash-dotted lines correspond to $\sigma(e^+e^- \to hZ, HZ, hA, HA)$ = 0.05 pb at $\sqrt{s}$ = 190 GeV, which could be seen as a rather optimistic estimate of the LEP II sensitivity.

Estimating the Mass of the Higgs

- Electroweak radiative corrections are sensitive to massive particles:

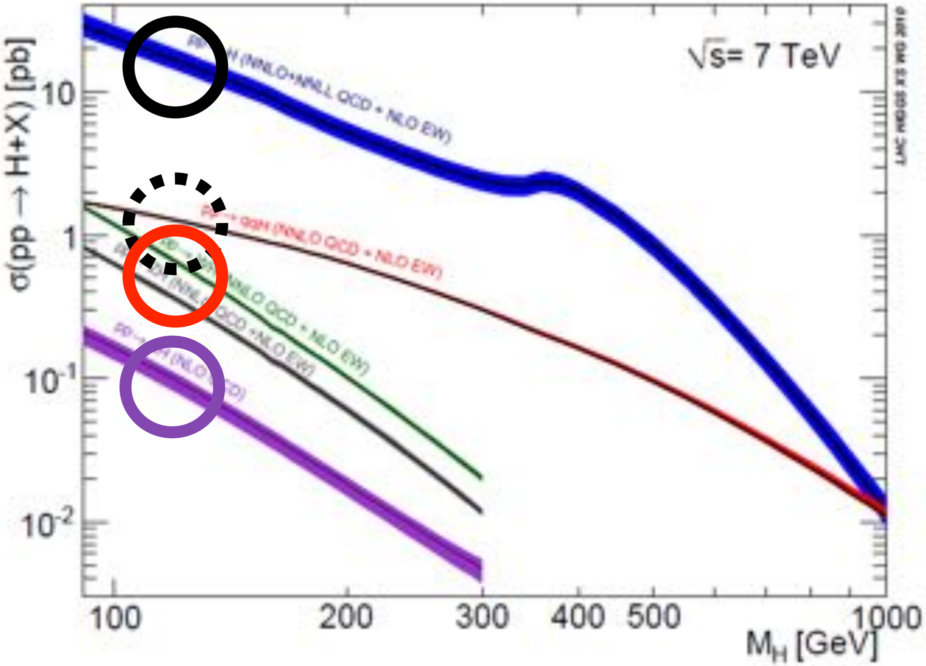
$$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

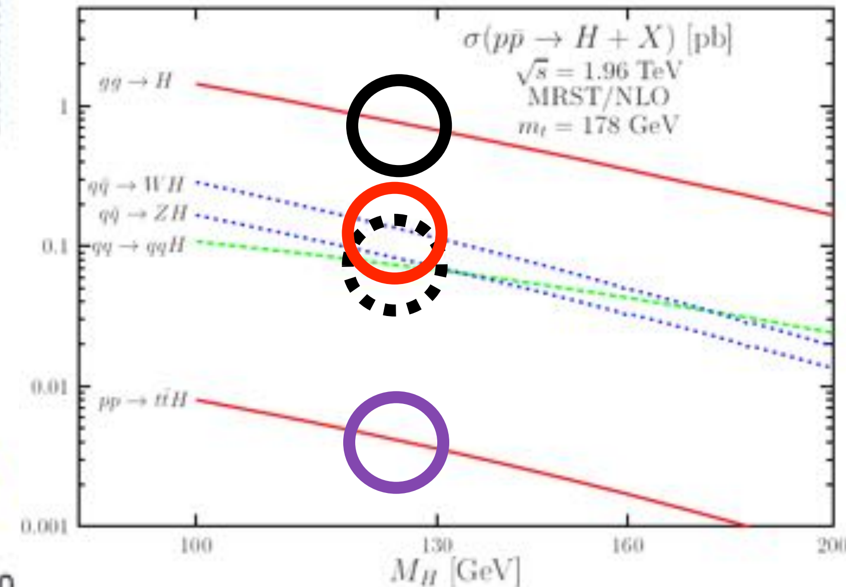
- Sensitivity to the top quark mass >> sensitivity to Higgs mass:

$$\frac{3G_F}{8\pi^2\sqrt{2}}m_t^2 \qquad \frac{\sqrt{2}G_F}{16\pi^2}m_W^2\left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2}+\ldots\right),\ M_H >> m_W$$

- But LEP measurements gave an indication for a light Higgs even before the top discovery

JE, Fogli & Lisi: 1990/1





comparison between LHC and Tevatron :

gg cross section at least 10 × higher at LHC

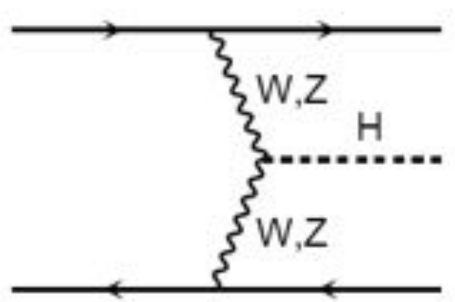
backgrounds to WW , ZZ , γγ are q qbar annihilation

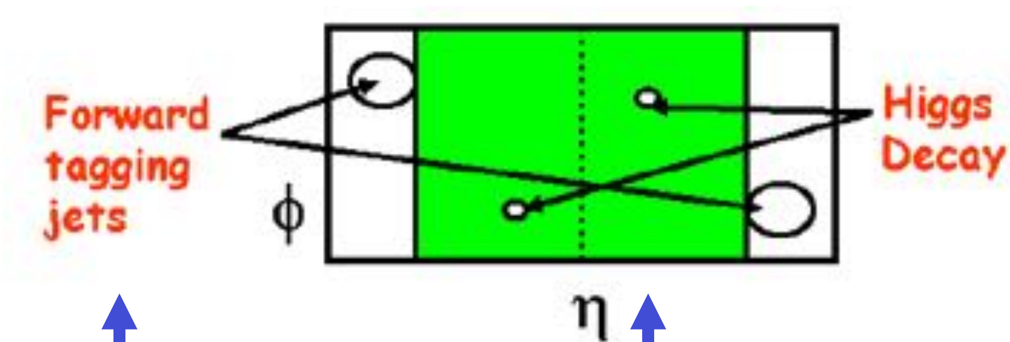
(Remember Tevatron was a p pbar collider)

→ S/B better in these channels at LHC than at Tevatron

however it is worse in associated modes ⚠

Low mass VBF





2 high p_T tag jets at large rapidity

no color flow between tag jets ⇒ rapidity gap

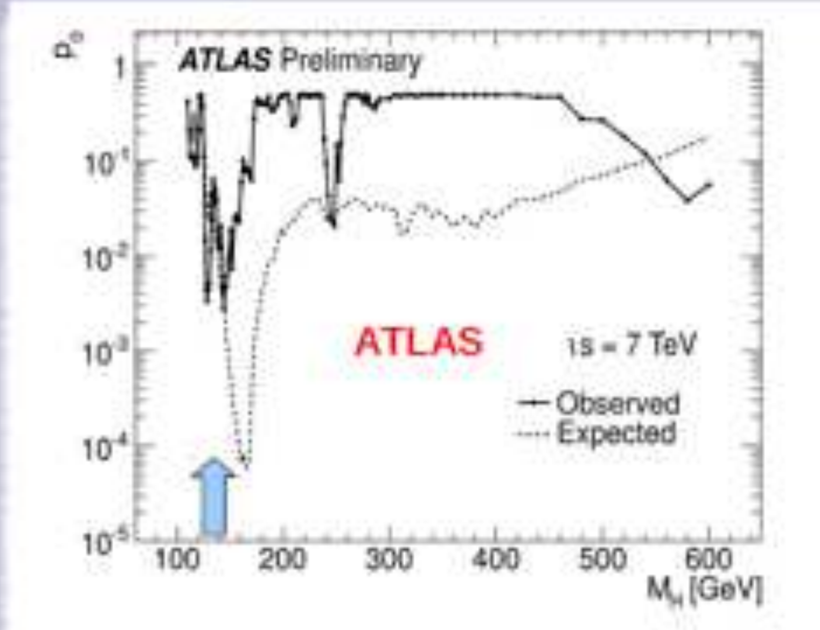
central jet veto effective to reduce backgrounds

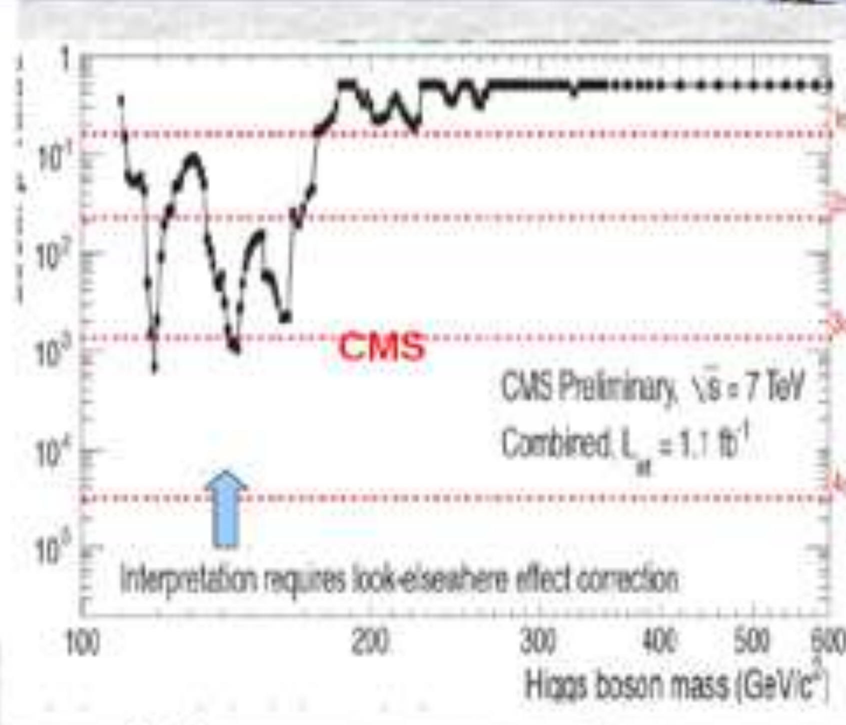
VBF was used for high mass searches but was used (on Monte-Carlos) at low mass at the end of the 90's

D.Rainwater and D.Zeppenfeld JHEP 9712 (1997) 005

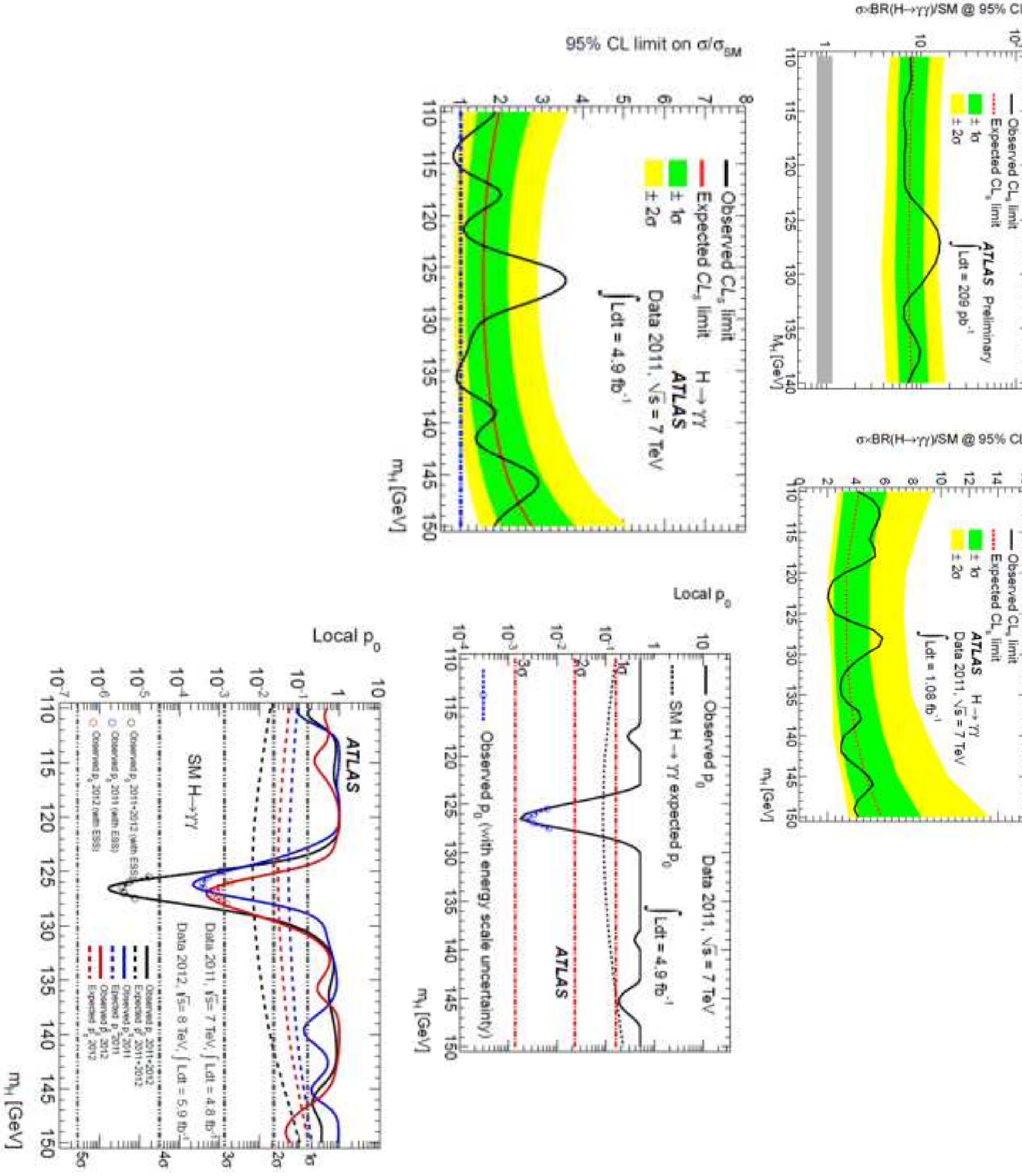
- Theory
- Experimental developments, including detectors, magnets
- Searches
- **Discovery**

Combined p-value





- Fraction of time background fluctuates so far
  - Beware: there is a look 'elsewhere effect'
- Both experiments have excess at low mass



Observation of a BEH-like boson decaying into two photons with the ATLAS detector at the LHC
Nansi Andari(Orsay, LAL) (Sep 26, 2012)