Six lectures in the Standard Theory of Elementary Particle Physics

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BuijingUniversity,
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Beijing 30 October 2026

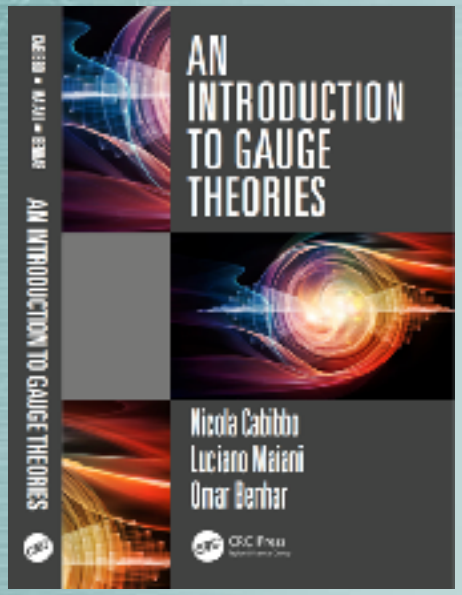


Lecture 6
Higgs boson search, future

We are getting close to the end of my lectures
For questions or clarifications:
write to me !!!

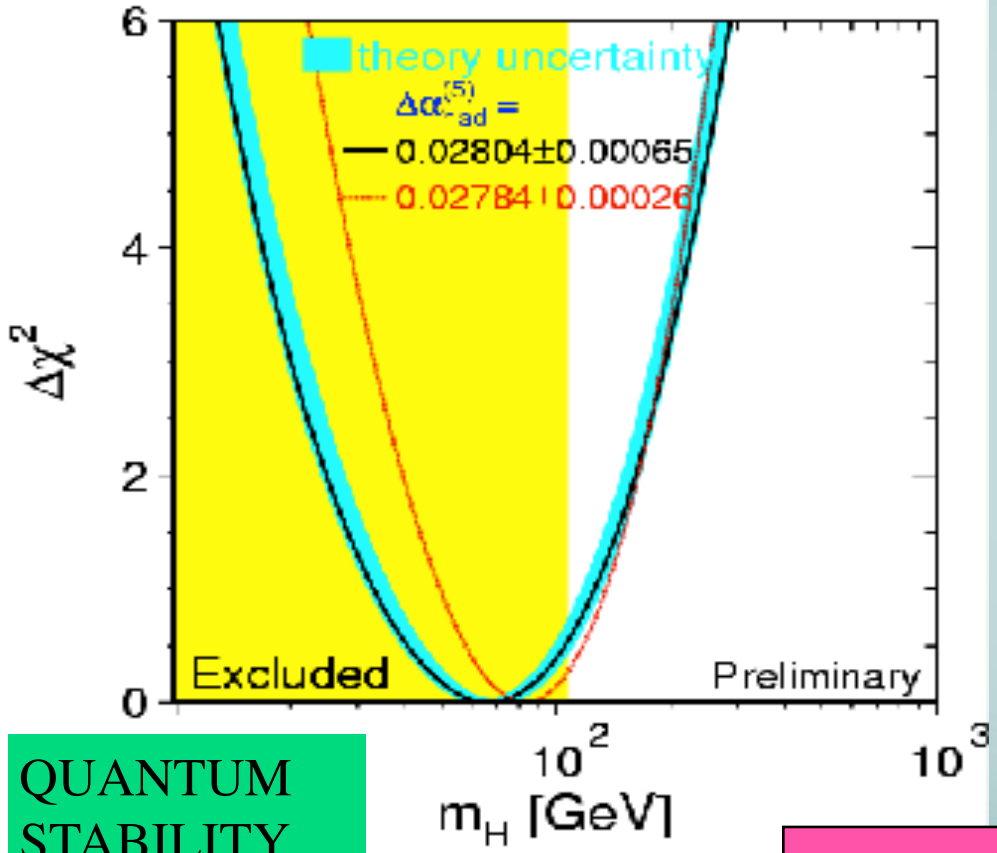
- luciano.maiani@cern.ch
- My office is in B1, from 11 a.m. to (not too late) afternoon.

I wll reply by e-mail or in person



N. Cabibbo, L. Maiani and O. Benhar
An Introduction to Gauge Theories,
CRC Press, 2017,
ISBN 978-1-315-36972-3

1. Precision Electroweak Measurements at LEP and Fermilab give informations about the Higgs Boson mass (year 2000)



- Includes all electroweak precision measurements;
- Constrained by direct m_W and m_{top} determinations;

$$m_H = (77^{+69}_{-39}) \text{ GeV/c}^2$$

QUANTUM STABILITY

135-170 GeV $\Lambda = 10^{19}$

$m_H < 188$ GeV/c² at 95%C.L.

The Higgs boson was searched at LEP II up to M=115 GeV with the following production and decay channels:

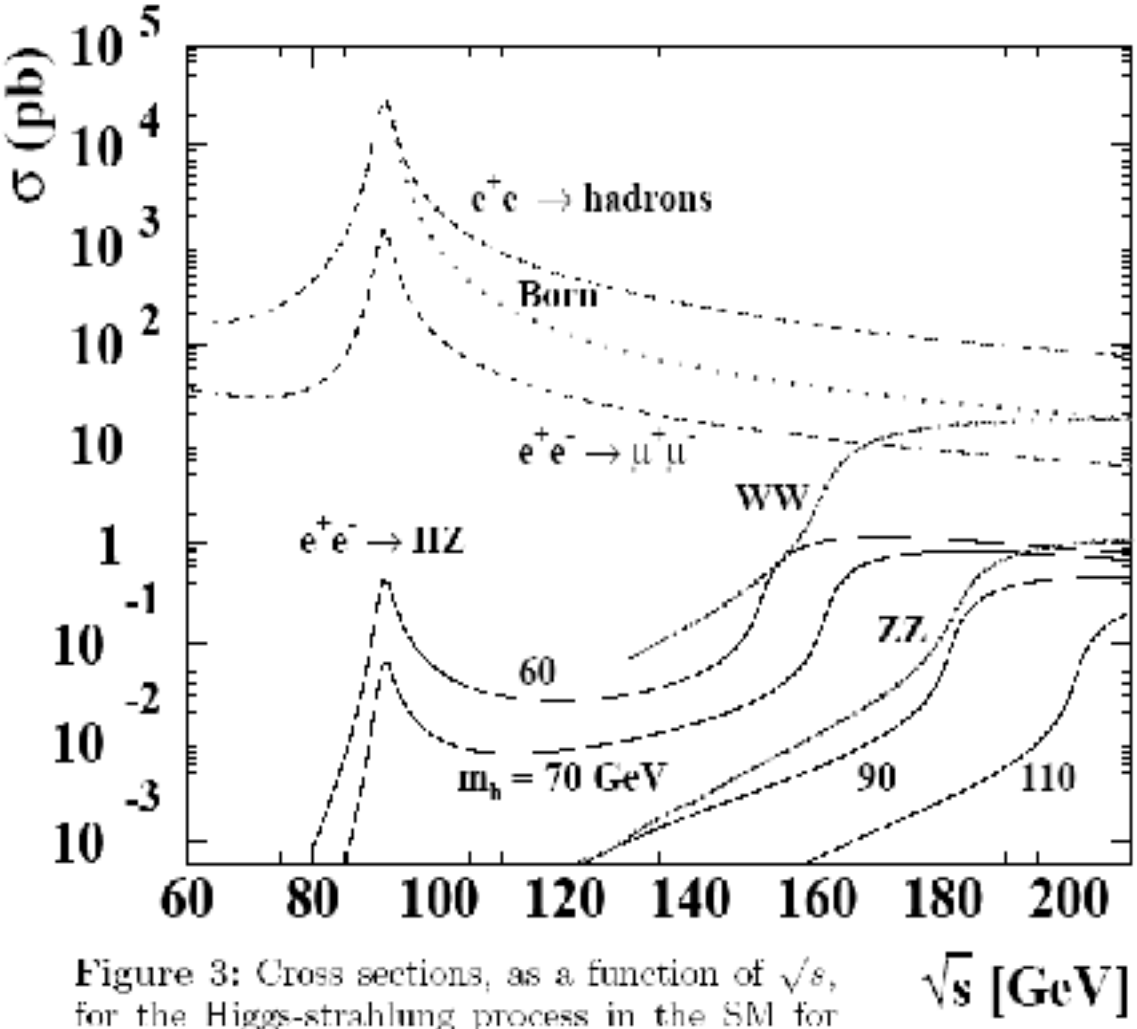


Figure 3: Cross sections, as a function of $\sqrt{s}$, for the Higgs-strahlung process in the SM for fixed values of m_{H^0} (full lines), and for other SM processes which contribute to the background.

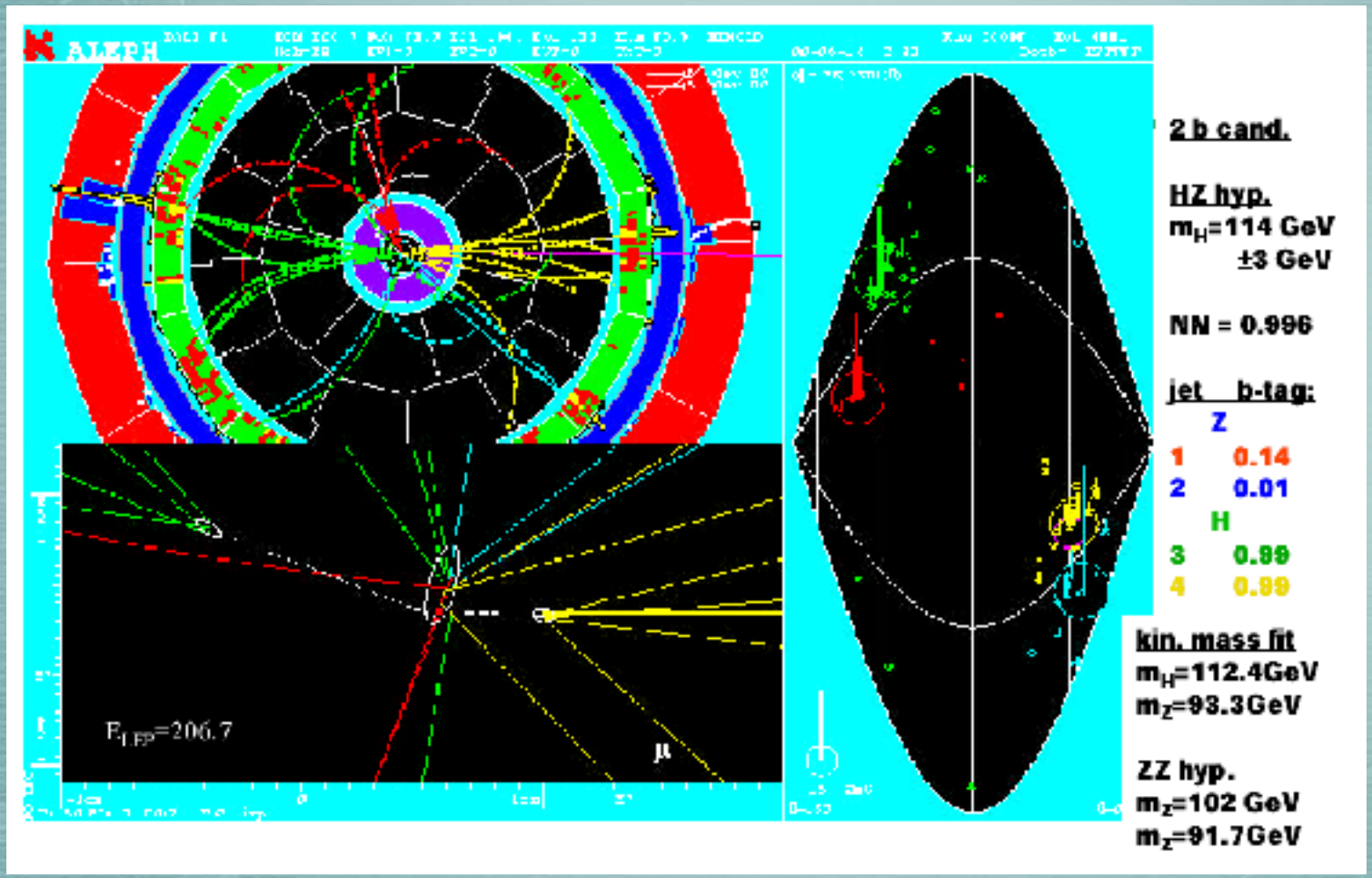
$$e^+e^- \to Z + H$$

followed by:

$H \to b\bar{b}$,

$Z \to q\bar{q},\ l^+l^-,\ \nu\bar{\nu}$.

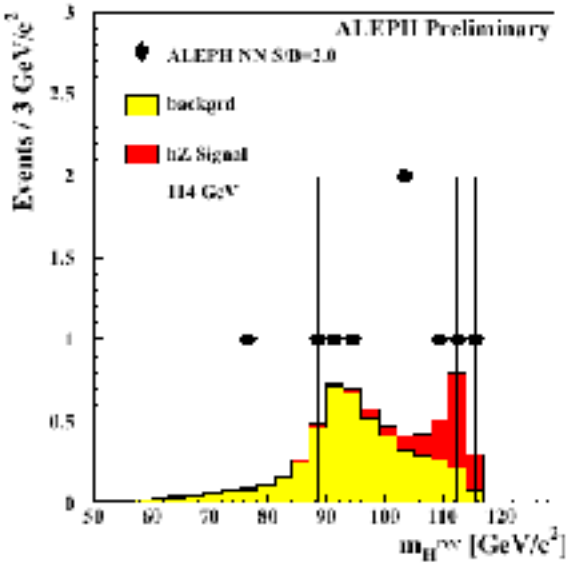
ALEPH:
Candidate for e+e-→Z+H (Summer 2000)



Mass plot by ALEPH (Sept. 2000)

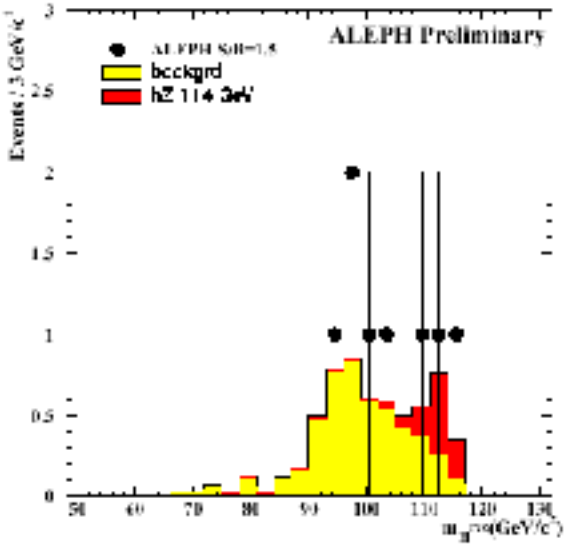
Mass Plot - Tight Cuts

NN Analysis



When cuts are tightened, both accept the same three four jet events with M_H >109 GeV/c^2

CUT Analysis



The survival of these three candidates indicates that they are indeed quite signal-like

The future of CERN is in the LHC !!!

CC Statement

"*On 17th November 2000, the CERN Committee of Council held a meeting to examine a proposal by the Director-General concerning the continuation of the existing CERN programme, which foresees the decommissioning of the LEP accelerator at the end of the year 2000.*

The Committee has expressed its recognition and gratitude for the outstanding work done by the LEP accelerator and experimental teams.

It has taken note of the request by many members of the CERN Scientific Community to continue LEP running into 2001 and also noted the divided views expressed in the Scientific Committees consulted on this subject.

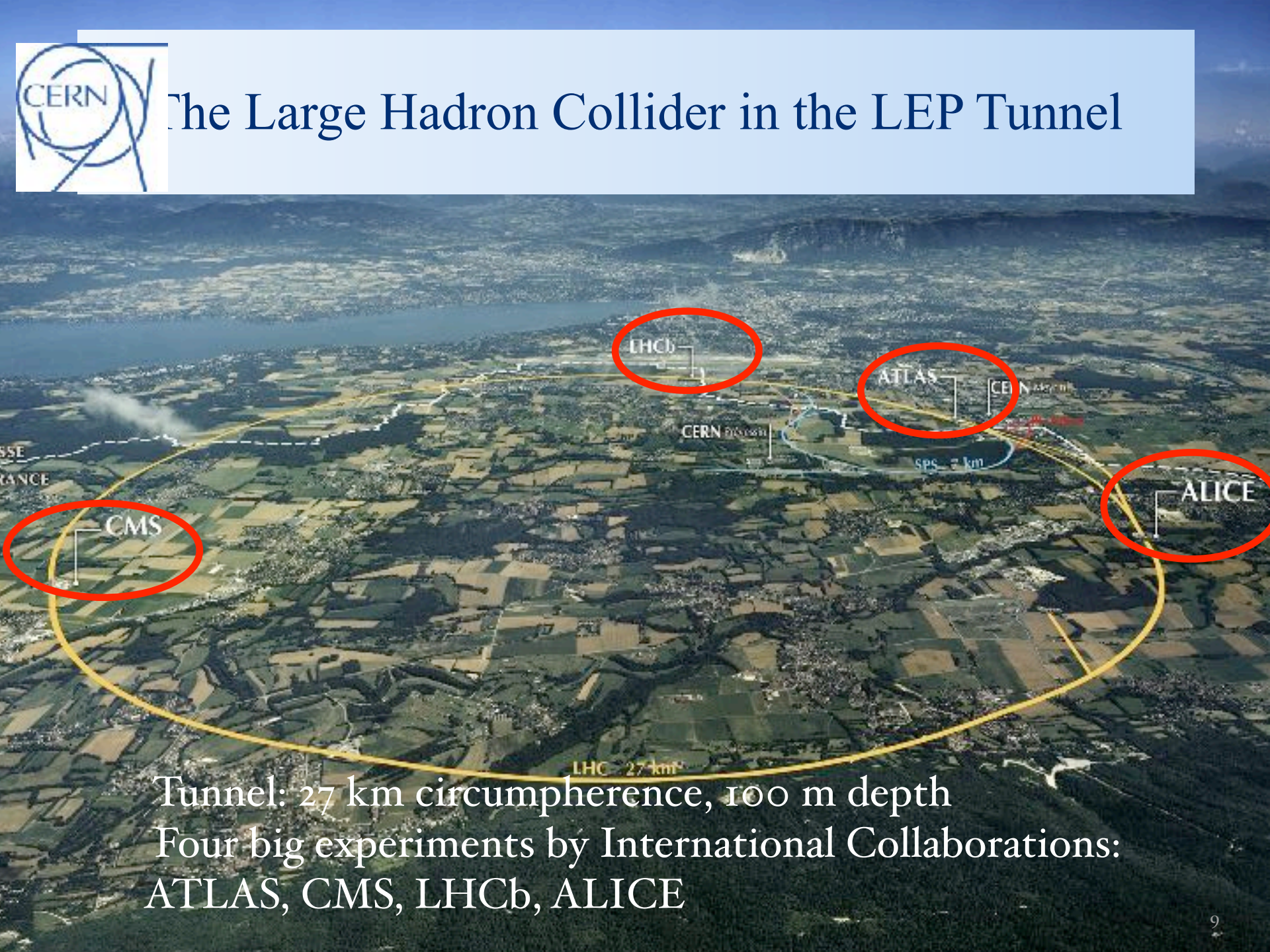
On the basis of these considerations and in the absence of a consensus to change the existing programme, the Committee of Council supports the Director-General in pursuing the existing CERN programme."

This decision moves us definitely into the LHC era

A powerful complex, machine and detectors, to fully explore the Higgs and SUSY region

Le Roi est mort
Vive le Roi !!

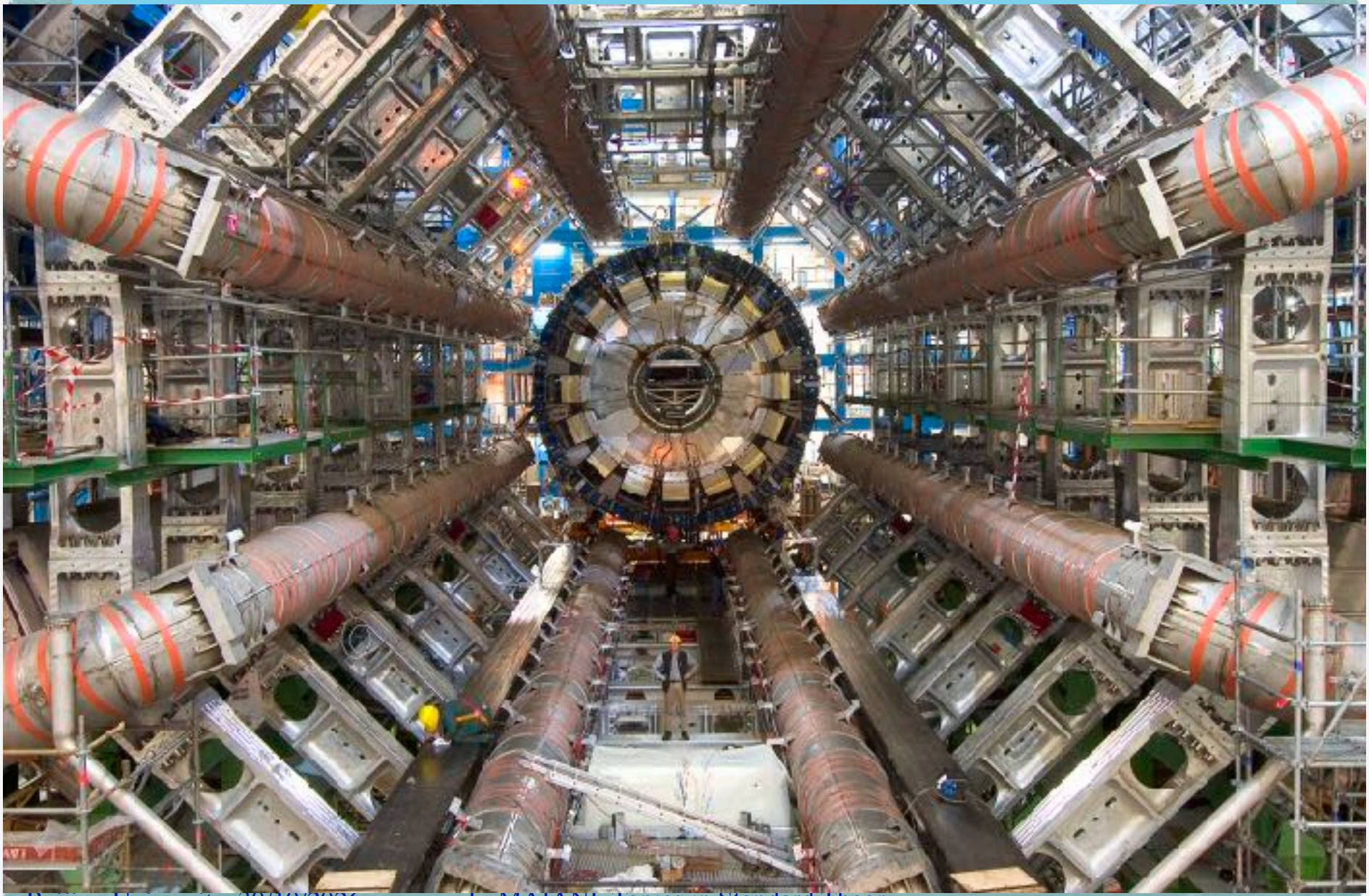
The Large Hadron Collider in the LEP Tunnel



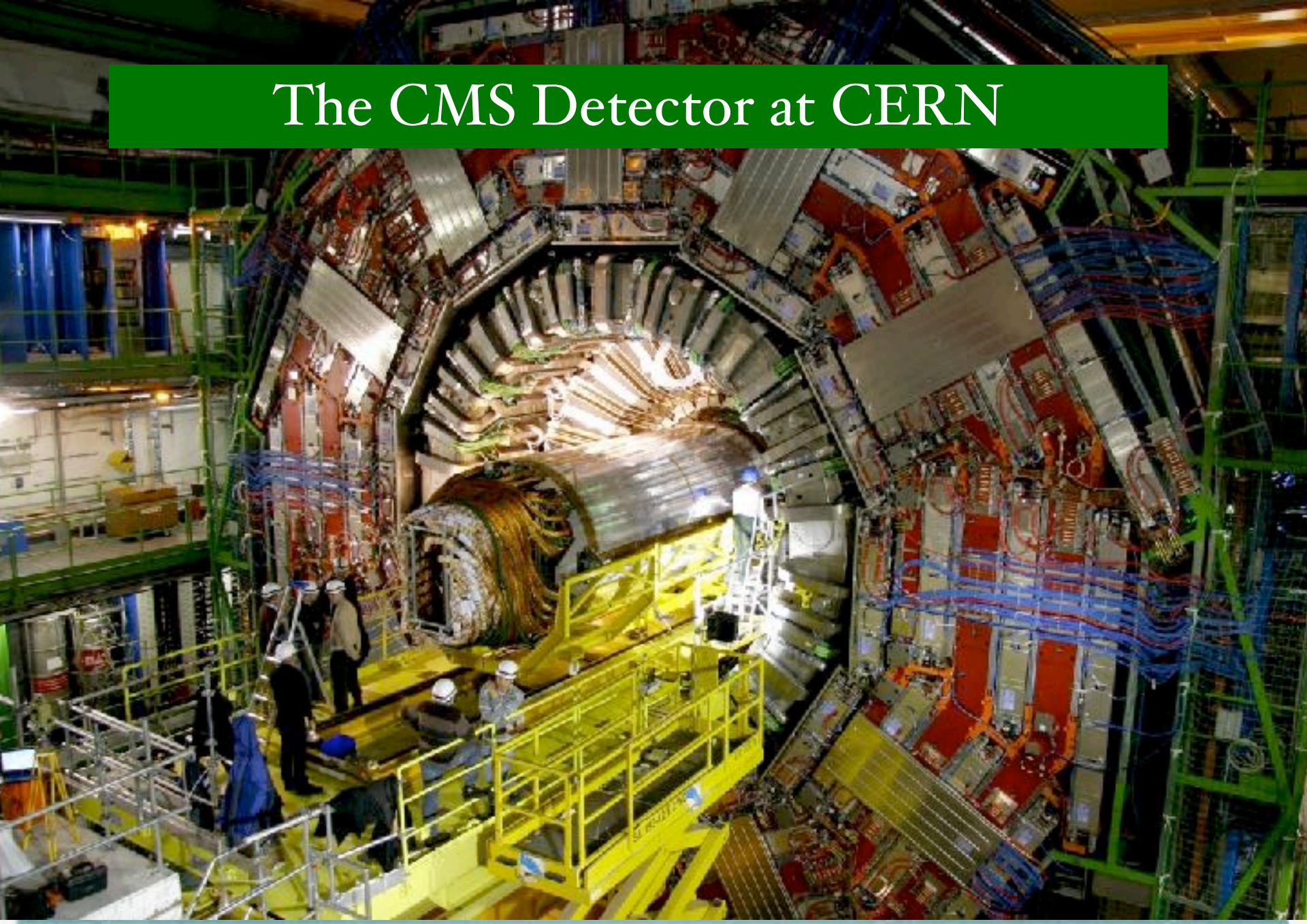
Tunnel: 27 km circumpherence, 100 m depth
Four big experiments by International Collaborations:
ATLAS, CMS, LHCb, ALICE



The ATLAS Detector at CERN



The CMS Detector at CERN



2. Announcing the boson:
ATLAS and CMS, CERN Seminar, July 4th, 2012

- People arrived 4 o'clock in the morning to find a seat
- a completely full conference room
- talks by Joe Incandelas, CMS, and Fabiola Gianotti, ATLAS



- François Englert (Left) and Peter Higgs (Right) at CERN seminar..
- and Fabiola Gianotti, John Ellis..and many others

In the coming years, we will recognize a clear discontinuity in physics: BEFORE and AFTER the 4th of July talks by CMS and ATLAS.

ATLAS final statement (Fabiola Gianotti)

We observe an excess of events at $m_H \sim 126.5$ GeV with local significance **5.0 σ**

CMS final statement (Joe Incandelas)

We have observed a new boson with a mass of
125.3 ± 0.6 GeV
at
4.9 σ significance !

Papers available (July 31, 2012):
ATLAS: ArXiv 1207.7214
CMS: ArXiv 1207.7235

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

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

H must appear as a peak in the mass distribution of 2 gammas: H-> γγ or 4 muons: H-> $\mu^+\mu^+\mu^-\mu^-$

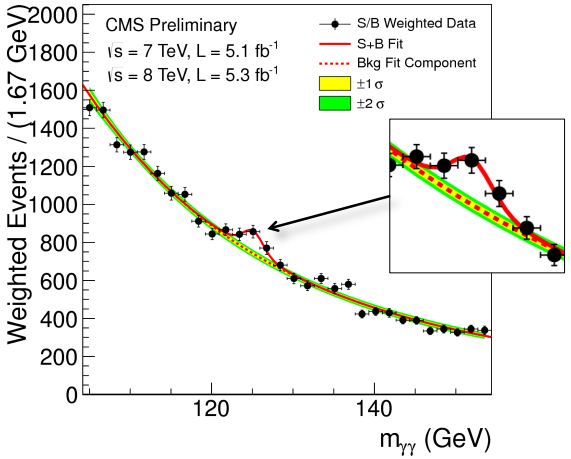
J. Incandelas

CMS data

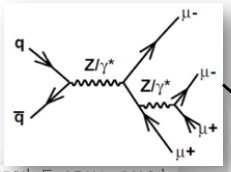
S/B Weighted Mass Distribution

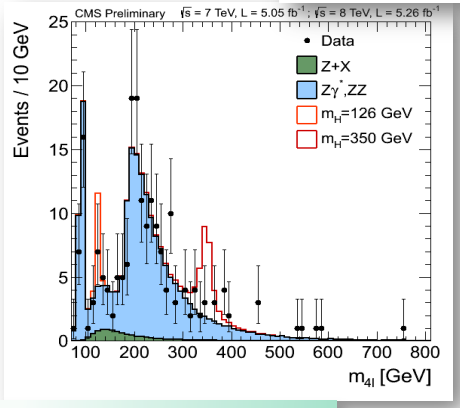
Sum of mass distributions for each event class, weighted by S/B

- B is integral of background model over a constant signal fraction i









J. Incandela for the CMS COLLABORATION

's of the Higgs Search

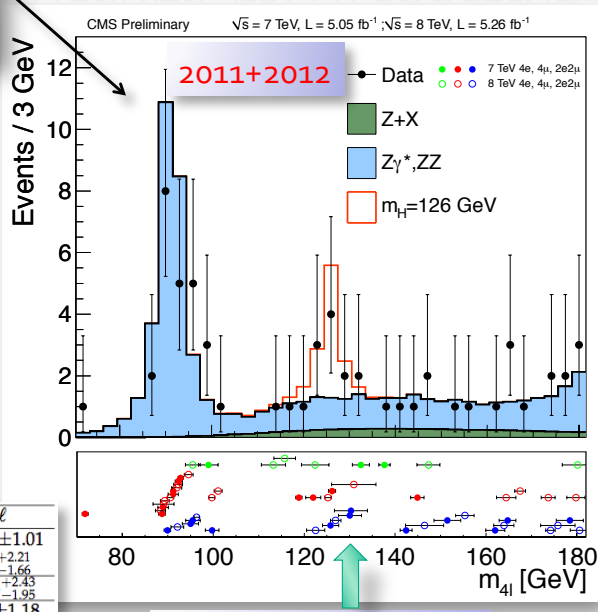
July 4

Yields for m(4l)=110..160 GeV

Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.65 ±0.31	5.65 ±0.59	7.17 ±0.76	15.48 ±1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126$ GeV	1.51 ±0.48	2.99 ±0.60	3.81 ±0.89	8.31 ±1.18

164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

Results: m(4l) spectrum



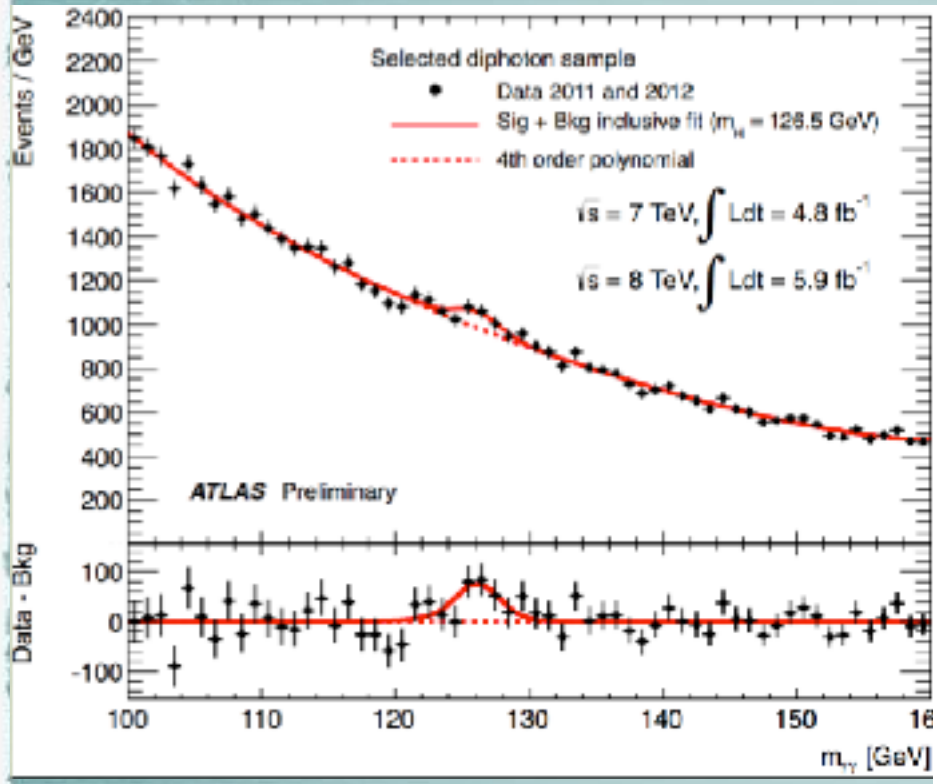
Event-by-event errors

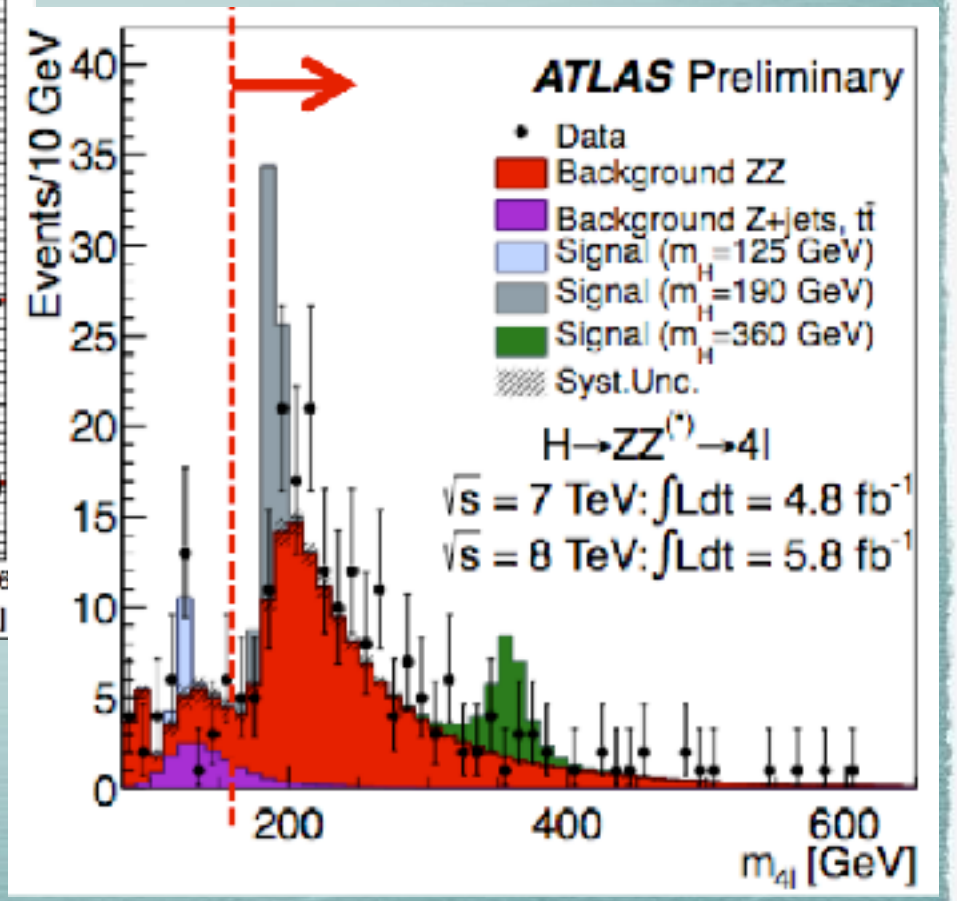
ATLAS

2 gammas: H-> γγ

4 muons: H-> $\mu^+\mu^+\mu^-\mu^-$

F. Gianotti

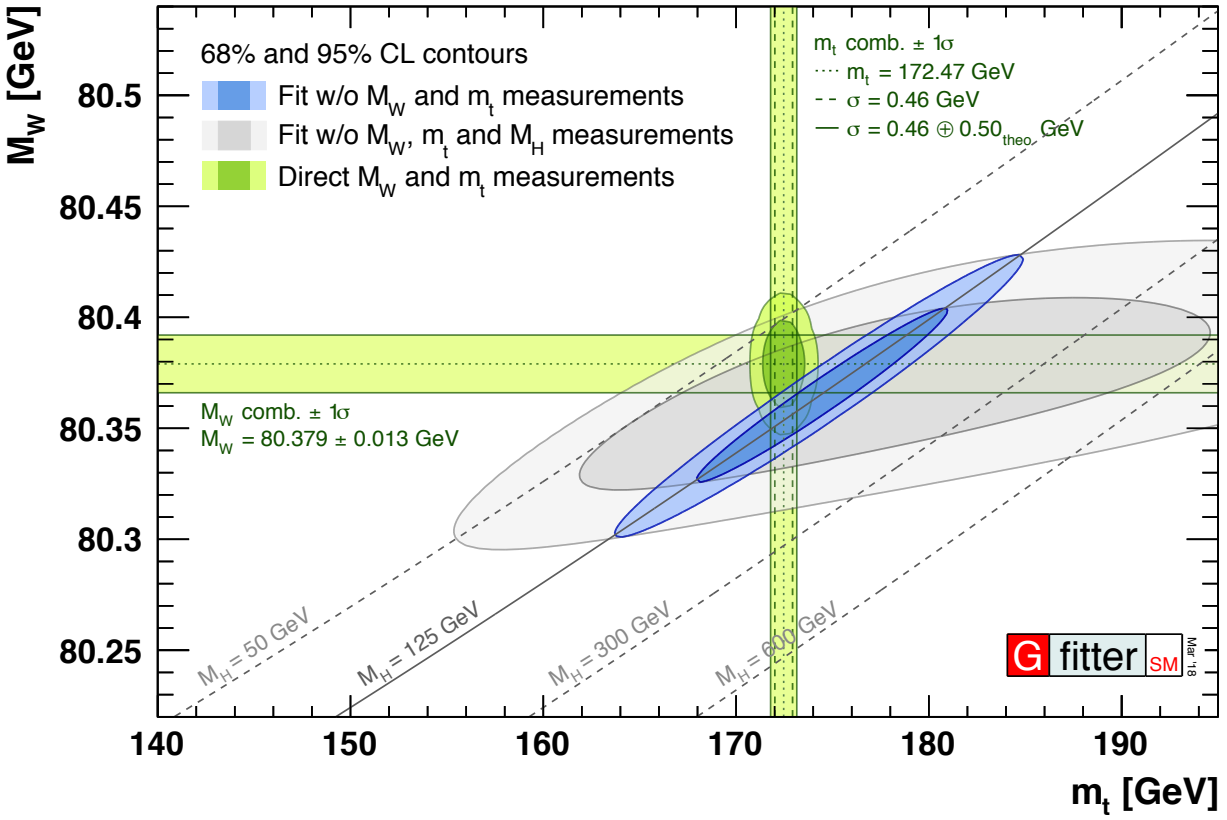




Roman Kogler (with the Gfitter group and C. Englert, H. Schulz, M. Spannowsky) Moriond ElectroWeak 2018

SM: Incredibly Healthy!

[Gfitter, 1803.01853]

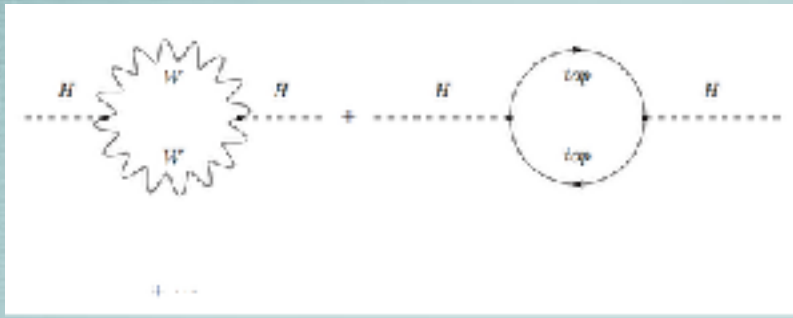


4. Unnatural: what is it?

- The Standard Theory is incomplete: missing parts imply mass scale >> W mass
  - Gravity: regulated by the Planck mass $M_P = 1/\sqrt{G_{Newton}} = 10^{19}$ GeV
  - Unification of the three gauge interactions of ST, Grand Unification mass $M_{GUT} = 10^{14}$ GeV
- How is it possible to have a low energy sector almost decoupled from the high energy scales? (ths is called ***the hierarchy problem***)
- Spin 1/2 and 1 particles: in the zero mass limit a new symmetry is gained (chiral symmetry for spin 1/2, gauge symmetry for spin 1)
- higher order corrections to the mass do vanish in the limit where the bare mass vanishes
- thus, e.g. for the electron mass: $m_e(q^2)=m_0\ \mathrm{Log}(q^2/M_{GUT})$ and the large mass is locked into Logs.
- ***In the Standard Model, no increased symmetry is gained by letting the mass of the elementary scalar to vanish: ST is "unnatural"*** ('t-Hooft, 1979). This happens with supersymmetry,
-

Quadratic divergences

- Sometime unnaturalness of the Higgs is tyed to quadratic divergences and unnatural tuning between bare mass and rad corrections



$$\mu^2 = \mu_0^2 + \frac{\alpha}{\pi} \times Cost \times \Lambda^2 + \cdots$$

- Quadratic divergences to the Higgs potential do vanish in softly broken Supersymmetric models: supersymmetry is restored in the limit of zero mass.

L. Maiani, Proc. of the Summer School on Particle Physics, Gif-sur-Yvette, (1979).
see e.g. L. Girardello, M.T. Grisaru, Nucl. Phys. B (1982) 65;
N. Cabibbo, L. Maiani and O. Benhar, *An Introduction to Gauge Theories*, CRC Press, 2017, p. 292;.

$$V^{(2)} = \frac{1}{2}\, m_0^2\phi^2 + \frac{\Lambda^2}{32\pi^2} \sum_J (-1)^{2J}(2J+1)\, M_J(\phi)^2$$

$=0$ in softly broken Susy

Alternative possibilties

- ***Low energy supersymmetry*** relates scalars and fermions, whose mass is protected by chiral symmetry, and reduces the cutoff scale to M_{SUSY}, needed to be O(1TeV) for not too unnatural tuning, ... or
- ***No elementary scalars***, the Higgs boson is composite by fermion fields, tied together by forces at a scale O(1 TeV), called generically Technicolor forces.
- H could be much lighter than the high energy strong interactions scale, if it is the ***would-be-Goldstone boson*** of some symmetry.
- New strong-interactions at high energy: not indicated by electroweak precision data (which are becoming high-precision data).
- The value found for the Higgs boson mass speaks in favour of SUSY
- but we should keep ***both options*** open...for the time being.
- Important: it is not a matter of a factor of 2 or 4…
- A third option, which is becoming popular, is to ignore the problem… Physical constants are such as to give thenUniverse enough time to develop human life…an ***anthropic solution***?

If this is the answer...what was the question? (Financial Times)

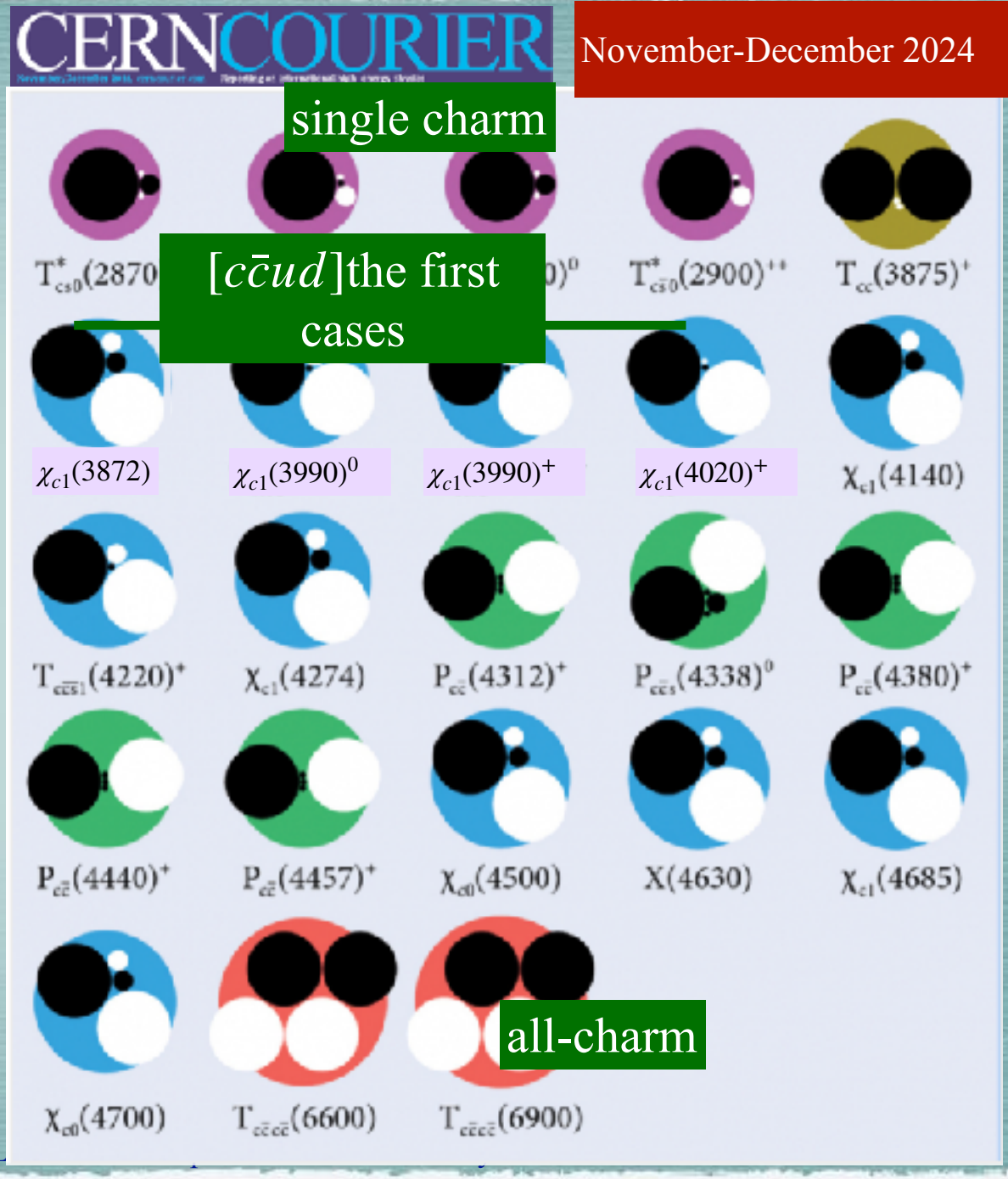
Unexpected Exotic Hadrons

The first unexpected hadron , the $X(3872)$, was discovered by BELLE in 2003, confirmed by BABAR and seen in many other High Energy experiments.

Since then, a wealth of Exotic Hadrons have been observed, mesons and baryons that cannot be described by the classical Gell-Mann configurations ($q\bar{q}$) and (qqq).

First observed:

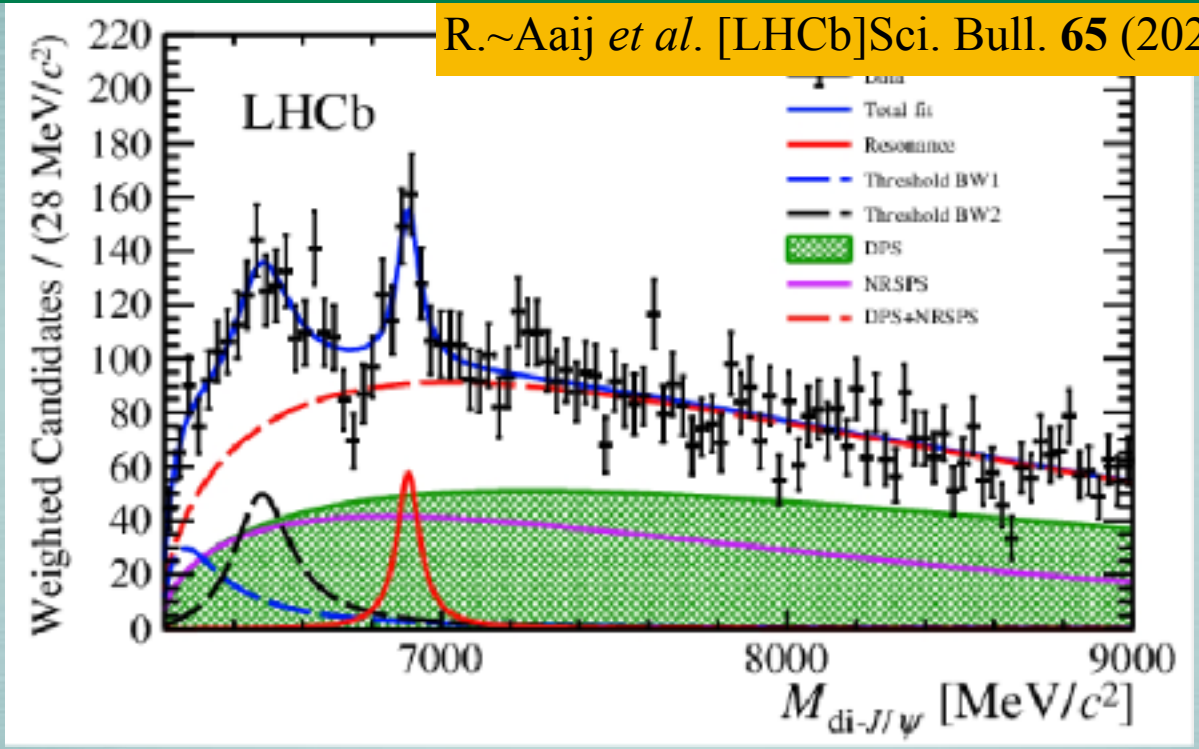
$X(3872)$, $Z(3990)$, $Z(4020)$



All-charm tetraquarks: the new frontier

Nov. 10, 2020: First observation: 2 J/Ψ resonances $\rightarrow 4\mu$

R.~Aaij *et al*. [LHCb]Sci. Bull. **65** (2020) 1983



- flavour composition: $(cc)^{\bar{3}}(\bar{c}\bar{c})^{3}$ (cc in color **6**: repulsive QCD interaction)
- Fermi statistics requires simmetric spin: $(cc)^{\bar{3}}_{s=1}(\bar{c}\bar{c})^{3}_{s=1}$
- for S-wave tetraquarks, total $J^{PC} = 0^{++},\ 1^{+-},\ 2^{++}$

Conclusions (very personal)

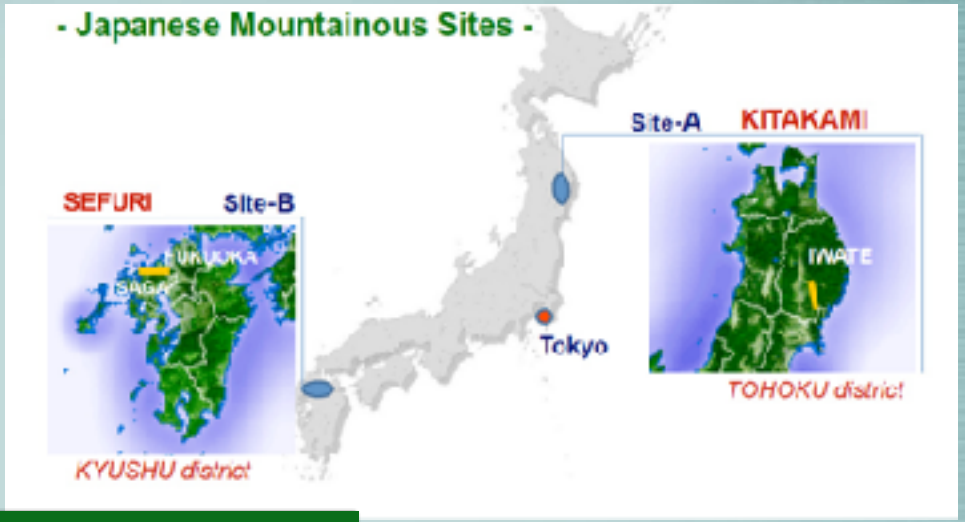
- Vast non-accelerator, low energy, physics program to continue: 0νββ, Wimps, microlensing, axions…,
- Supposed "discrepancies" at low energy require new experiments (g-2, lepton universality violations…) and new theoretical developments (lattice QCD)
- Exotic hadrons: a vigorous experimental effort is called in
  - production in deep inelastic collisions or annihilations
  - higher resolution
  - study of doubly or fully heavy tetraquarks
  - exotics, stable under strong and e.m. decays?
- theoretical non perturbative methods:
  - lattice,
  - Born-Oppenheimer,
  - QCD sum rules
- … not botanics… may be the key to understand low-energy QCD…who knows…

5. High Enerfy: what's next?

An electron-positron step ?

LHC extensions will remain anyway at the border of the interesting energy region.

An $e^+ e^-$ Higgs boson factory, could aim at high precision, to probe Higgs physics at high energies



Repeat the LEP-LHC strategy

- go for a circular e^+e^- @ 250-300 GeV in a large tunnel (Higgs factory)
- 70-100 km to make radiation losses acceptable,
- the same tunnel may host later a p-p collider @ 80-100 TeV, to explore the region left by LHC, 3 to 10 TeV
- projects are being made at CERN, (FCC-ee), and in China at IHEP (CepC)

Physics Beyond the Standard Model: the High Energy Way



The large European Project:
Future Circular Collider
at CERN

Kick-off Meeting of the
Future Circular Collider Design Study
University of Geneva, 2014



Strategic planning for U.S. particle physics

SCAC Facilities Subcommittee from the Division of Particles and Fields of the American Physical Society

Breaking News!!!! August 2026

The FCC-ee [4] is a proposed 91 km circularcollider at CERN, costing approximately 15 BCHF, includes tunnel cost.

Cost of LHC (excluding detectors, no tunnel excavation): 5 BCHF

The 2026 update of the European Strategy for Particle Physics [5], endorsed by the CERN Council, selected it as CERN's recommended future flagship collider.

The proposed ~ $1000M U.S. contribution is not inconsistent with P5's call for funding commensurate with U.S. participation in the LHC and HL-LHC.

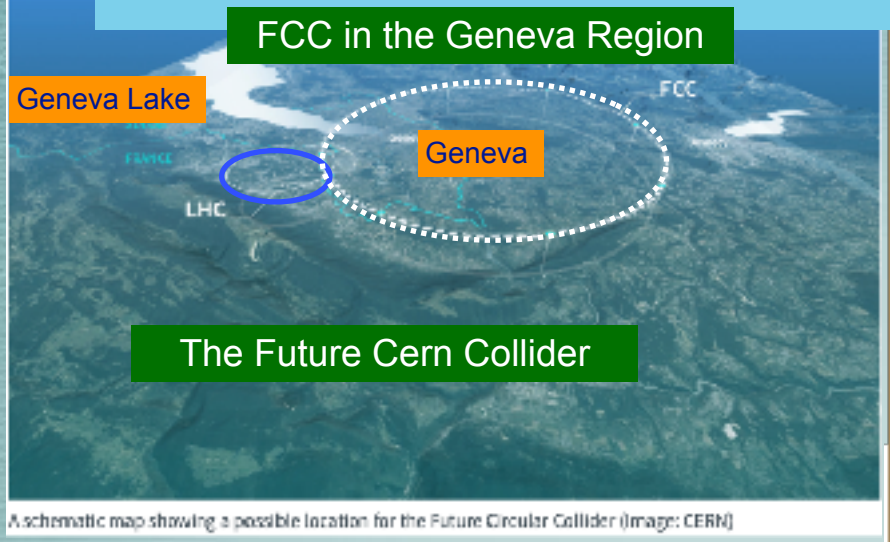
As the cost of the FCC-ee is twice that of LHC/HL-LHC, a proportional contribution would be $2 B.

APS: Strategic planning for U.S. particle physics
FCC-ee

- FCC-ee is designed to study the Higgs boson:
- Is it composite, connected to new forces or symmetries, or influenced by extra dimensions?
- Does it interact with dark matter?
- How did the Higgs field freeze throughout the Universe when it was a trillionth of a second old, and was this connected to the matter-antimatter asymmetry?
- The Higgs enables atoms to exist if, as predicted by the Standard Model (SM), it is responsible for the generation of the electron mass.
- Does it couple to electrons?
- Are there new particles to be discovered in its decays?

These are examples of the unanswered questions about this newest of the fundamental particles.

Physics Beyond the Standard Model: the High Energy Way





- A new generation of TeV Colliders is a fantastic challenge
- new innovative technologies: material science, low temperatures, electronics, computing, big data
- an attraction for new physics ideas and young talents to solve the hardest scientific problems which we have been confronted in the last 100 year (Dark matter, SUSY..).



Future High-Energy Collider. For decades, U.S. scientists have contributed significantly to large international high energy physics projects. That leadership is expected to continue with possible future colliders, such as the Higgs Factory proposed for CERN. Shown here is the envisioned 90.7-km underground

US possible contribution ***Under consideration***
$ 1-2 B ***DOE, august 2026 !!***
Timescale: R&D phase, completion after 2030