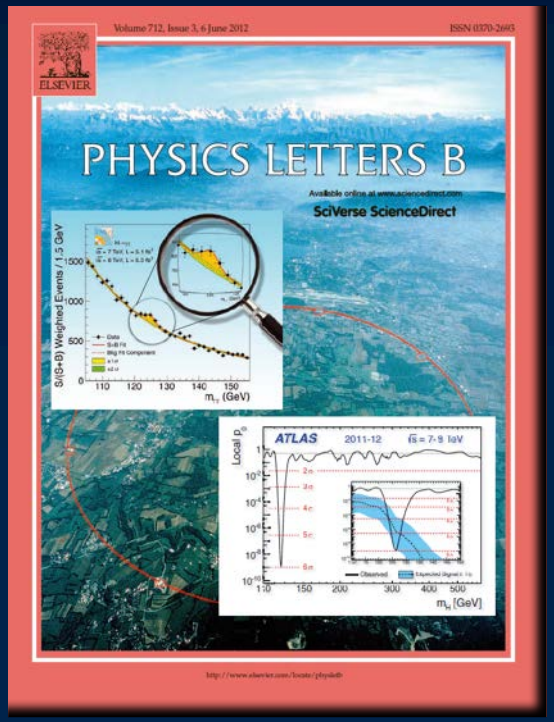
The LHC: challenges on the way to the Higgs discovery

3rd International Conference on New Frontiers in Physics (ICNFP 2014)
28 July – 6 August 2014
Crete, Greece

ETH Institute for Particle Physics
Felicitas Pauss
ETH Zurich

4 July 2012: CERN press conference

"CERN experiments observe particle consistent with long-sought Higgs boson"



"The highlight of a remarkable year 2012"

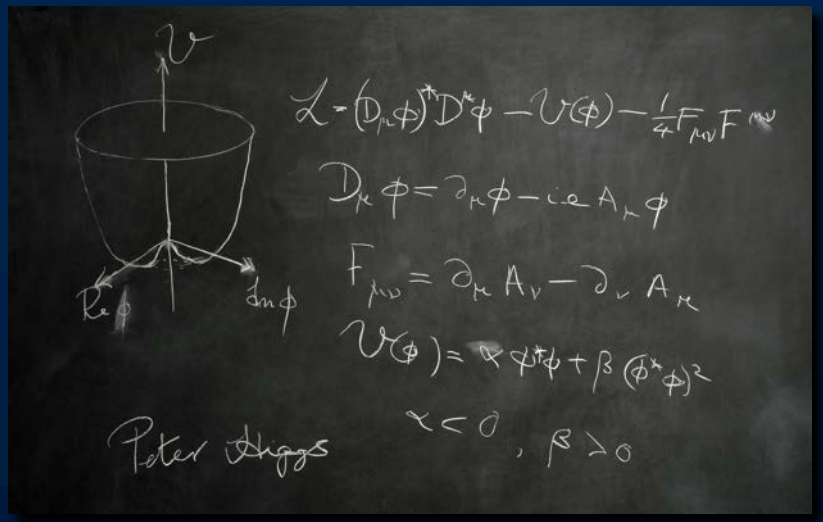
A historic milestone – but only beginning of a full exploitation of LHC physics potential

2013 Nobel Prize in Physics

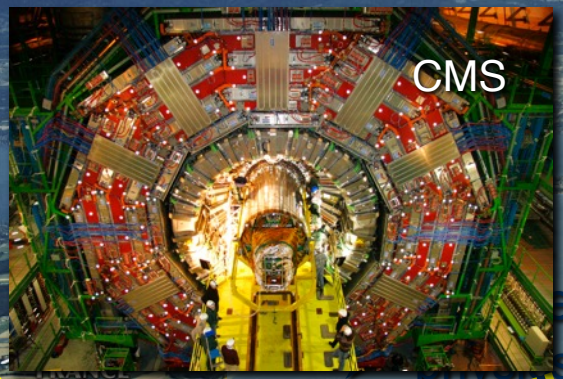
to François Englert & Peter Higgs

"For the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

CERN, July 2012



The LHC: challenges on the way to the Higgs discovery



- all start?
- e the challenges?
  - s motivation / goals
  - choice of technologies
  - time schedule and milestones
  - financing, upper limit of costs ("design-to-co
  - management (number of institutes and colla increasing)
  - .....
- What is next?

.... will focus on ATLAS and CMS .....

The LHC Project: how it all started ….

1984 Lausanne workshop official starting point for work at the LHC:

E_{cm} = 18 TeV ?, L = 10^{33} cm^{-2} s^{-1} ?

1987 La Thuile workshop: comparison of LHC, CLIC (e^+e^-), e-p option

LHC: E_{cm} = 16 TeV, L = 10^{33} cm^{-2} s^{-1} → 10^{34} cm^{-2} s^{-1} (D. Treille)

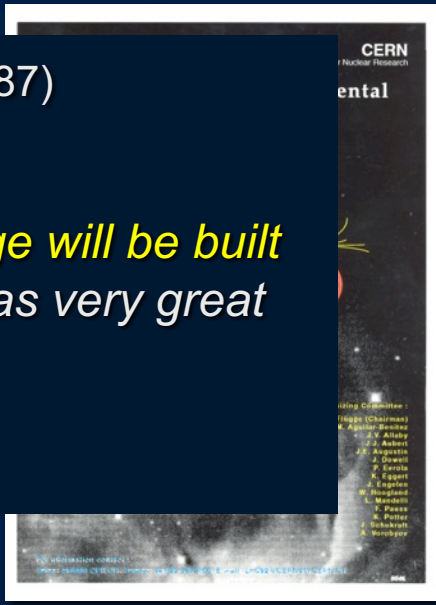
e-p: 1.3 - 1.8 TeV, CLIC: 2 TeV

Conclusion: La Thuile workshop (CERN-TH.4682/87; March 1987)

J. Ellis, F. Pauss (convener of WG beyond SM)

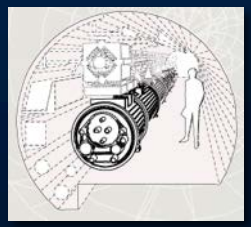
"It seems to us inevitable that a pp collider in the LHC/SSC range will be built in Europe and/or the United States. Such a machine certainly has very great physics capabilities .....

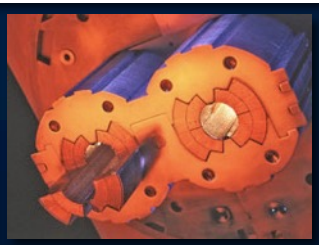
(also strongly encouraged R&D for CLIC)



1995 LHC conceptual design: 14 TeV, L = 10^{34} cm^{-2} s^{-1}

1993 SSC cancelled (87 km, 40TeV)

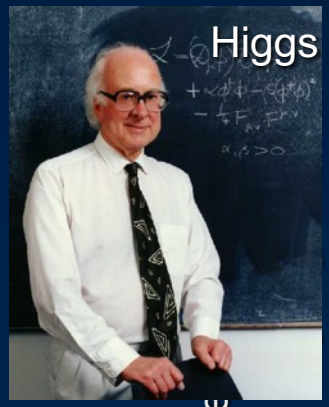


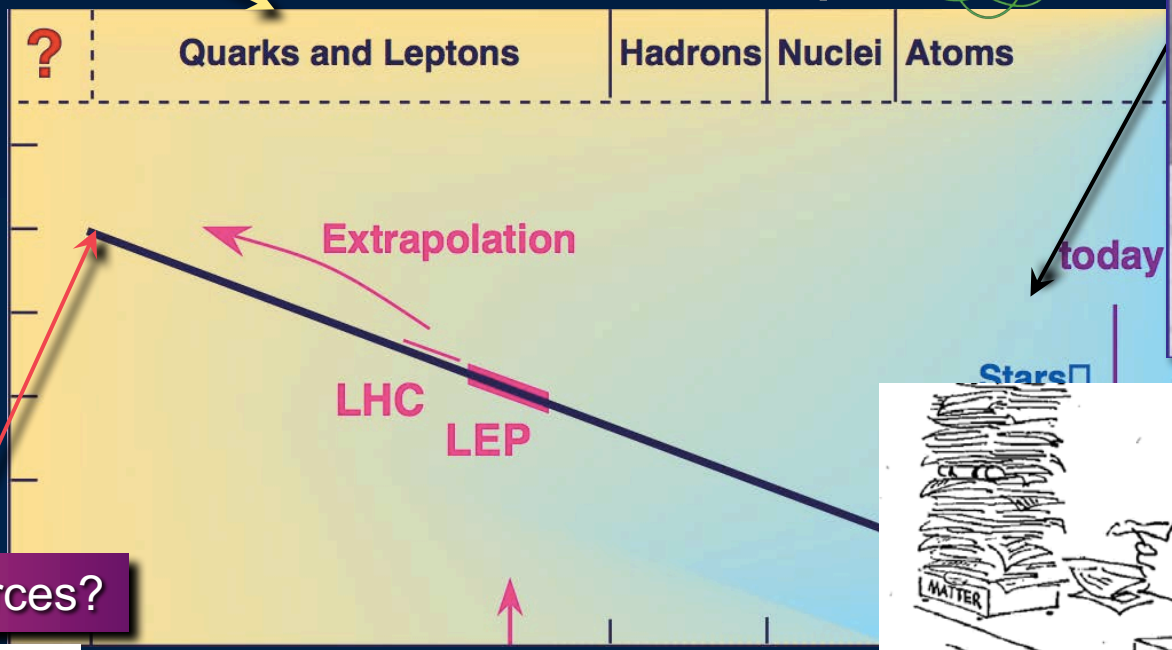


Physics motivation / goals – as in the late 1980's

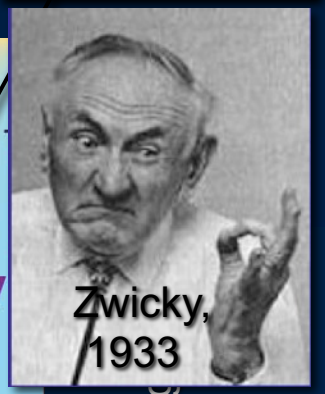
before the start of LEP

Particle masses?

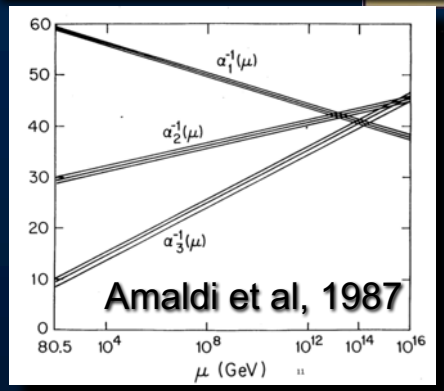


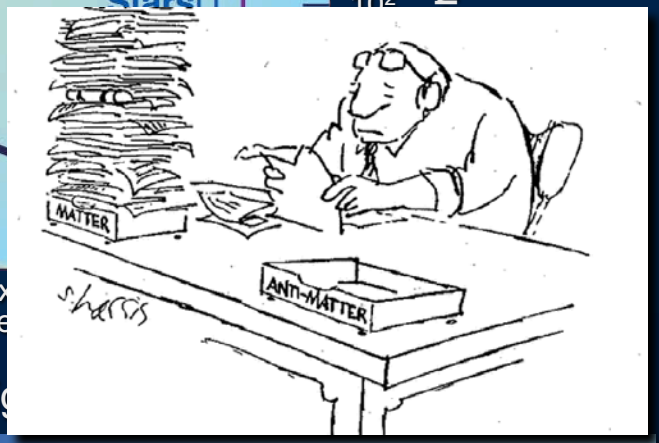


Dark Matter?



Unification of forces?





Matter-Antimatter Asymmetry?

LHC ➪ Answers to open questions

..... some (theoretical) Higgs history .....

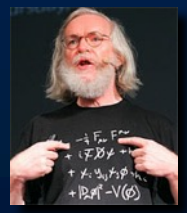
Back in 1964: 3 important publications

1) F. Englert and R. Brout, June1964: *Broken Symmetry and the Mass of Gauge Vector Mesons*
2) P. Higgs, August 1964: *Broken Symmetries and the Masses of Gauge Bosons*
3) G. Guralnik, T. Kibble, C. Hagen, October 1964*:* *Global Conservation Laws and Massless Particles*

Back in 1975: first comprehensive phenomenological investigations ....

J. Ellis, M.K. Gaillard, D.V. Nanopoulos: *A Phenomenological Profile of the Higgs Boson*

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.



Open Questions in SM and Possible Solutions (late 80's)

Higgs sector: is Higgs mechanism in SM correct description? m_H = ?

- Hierarchy problem: elw scale ~ 10^2 GeV; Planck scale ~ 10^{19} GeV
- Naturalness problem/fine tuning: Rad. correct.: $m_{Higgs} \sim \Lambda$ (Higgs is scalar !!)

Standard Model

successful for ever?

Open Questions in SM and Possible Solutions (late 80's)

La Thuile 1987
Conveners: J.Ellis, F.Pauss

Supersymmetry
new particles at ~ TeV scale; light Higgs; unification of Forces, DM candidate

Standard Model

Z'
concentrated on novel/speculative Z', which mixes with Z

Composite Models
new contact interactions

Leptoquarks
studied J=0, Q=-1/3 LQs

successful for ever?

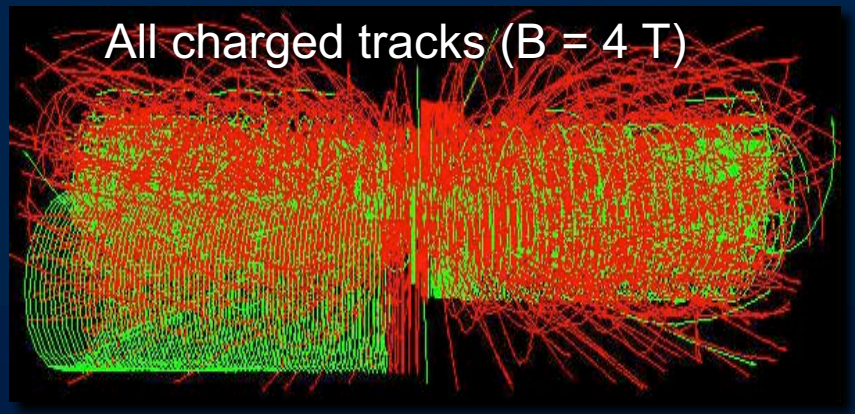
For all proposed solutions: new particles should appear at **TeV** scale or below

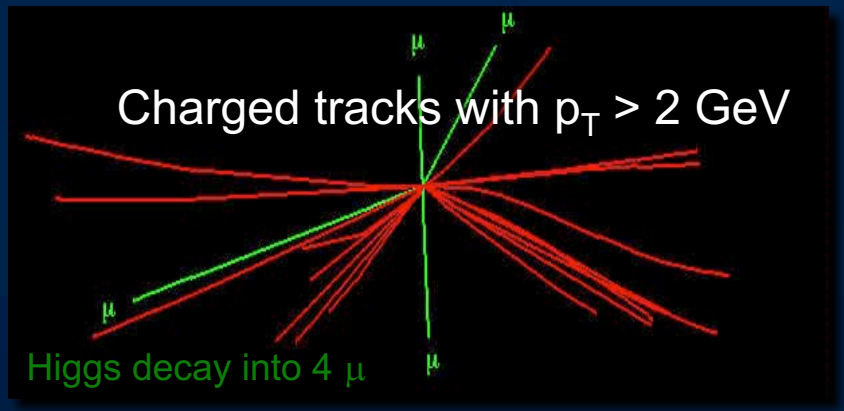
Experimental Challenges at LHC

LHC: E_{cm} = **14 TeV**, Luminosity $\mathcal{L}_{Design}$ = **10^{34} cm^{-2}s^{-1}**

Every 25 ns on average about 1000 charged particles produced in $\eta < 3$
($\theta \sim 4^{\circ}$ w.r.t. beam axis)

- Require high granularity, i.e. many channels $\mathcal{O}(10^7)$ (no pixel detector)
- Require fast (25 ns!) , radiation hard detectors and electronics

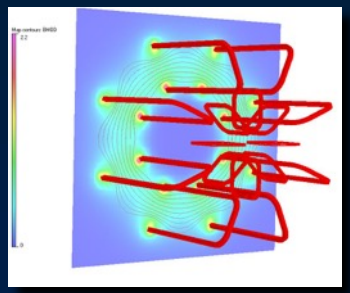


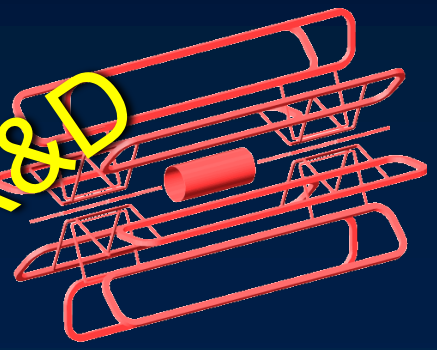


- Trigger: 40 MHz collision rate → $\mathcal{O}$(100 Hz)
- Data volume per year: **10 Petabytes → GRID** computing

Which technology? ←→ R&D

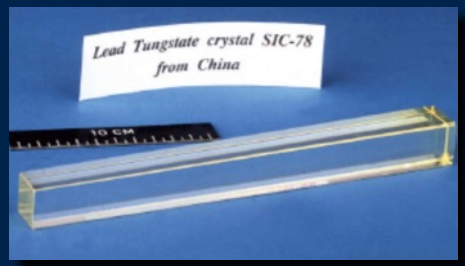
Magnet:
- toroid
- solenoid
- or both?



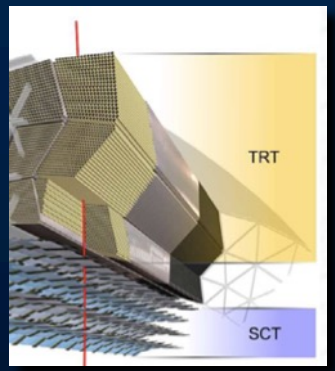


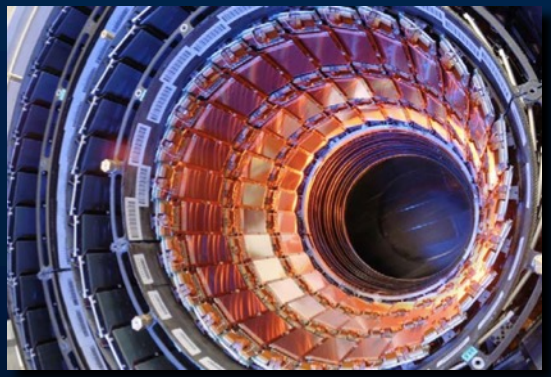
Many years of intense R&D

Calorimetry:
- sampling
- scintillating crystals

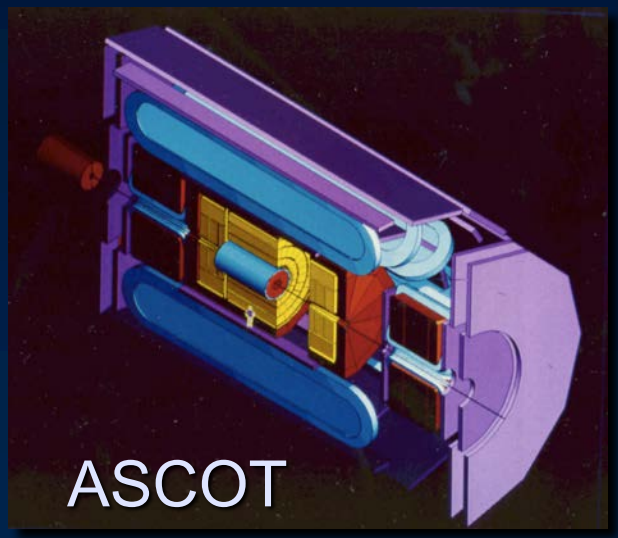


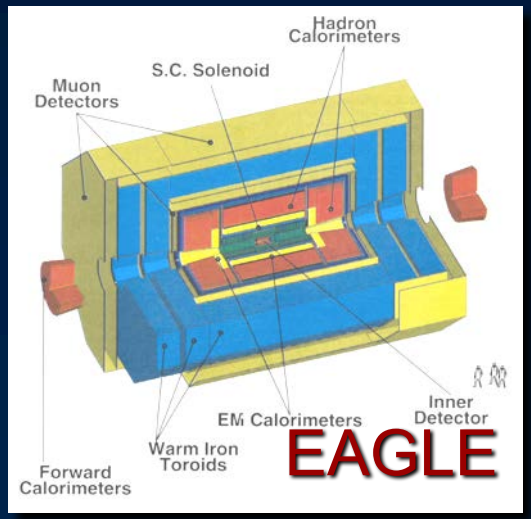
Tracking:
- gas (MSGC)
- TRT
- silicon

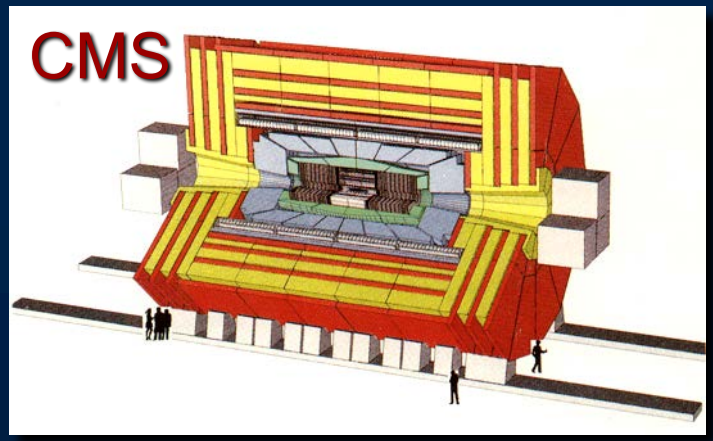


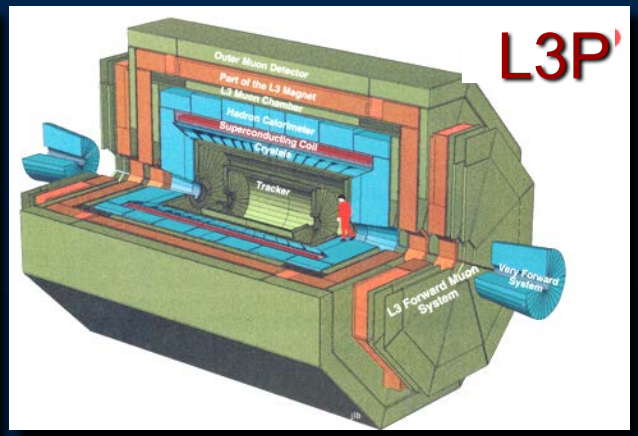


1992: EoI (Evian workshop) ⇨ LoI (CERN)





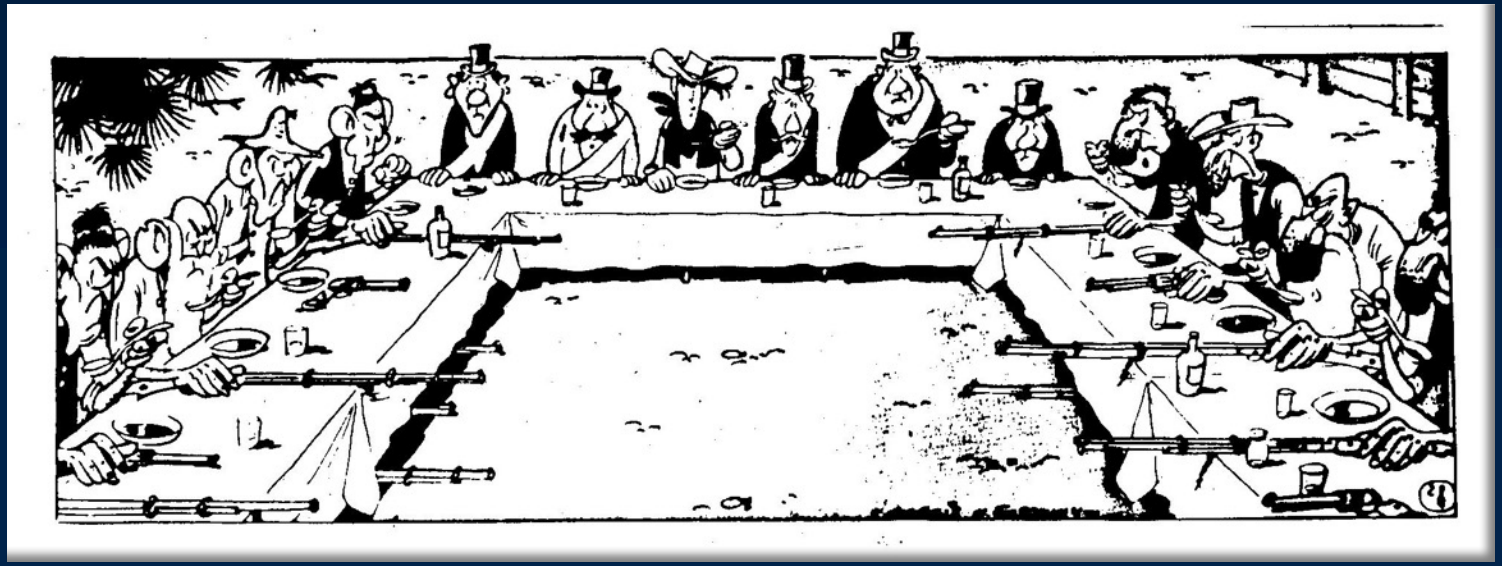


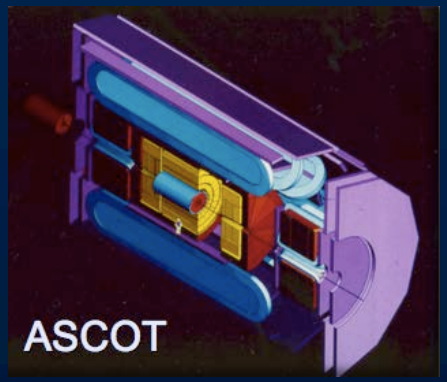


Evian meeting: also first ideas about b-physics and heavy ion physics

…. from 4 to 2 experiments …

Period of negotiations ….





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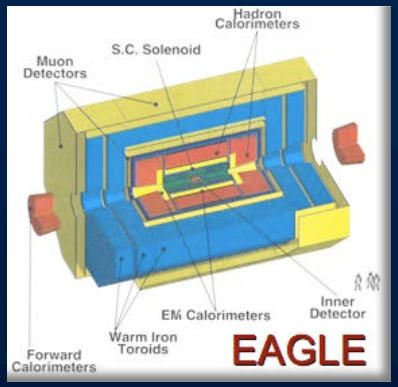

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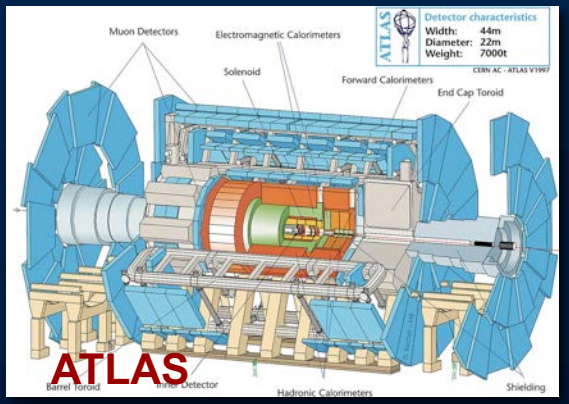
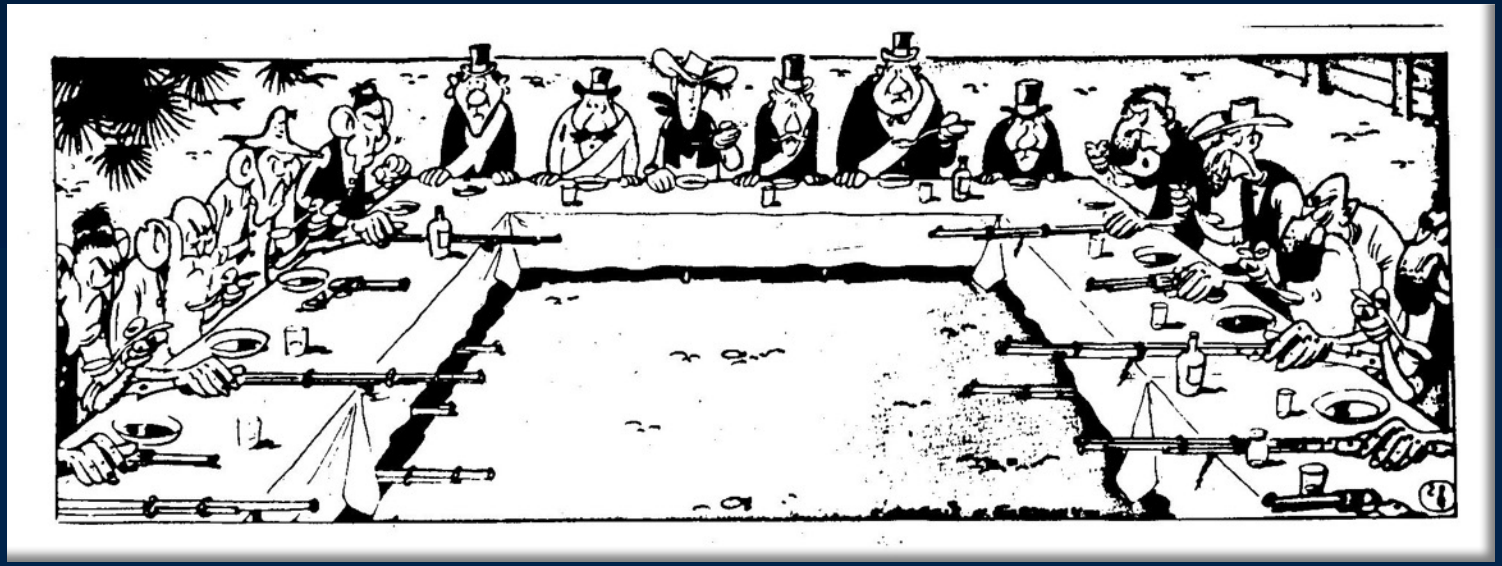
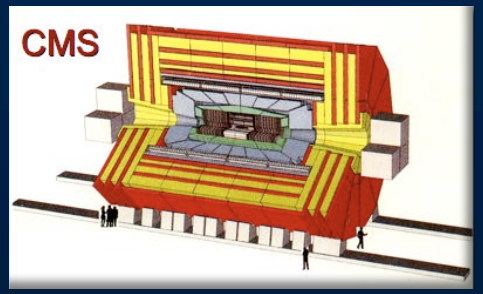


…. from 4 to 2 experiments …

Period of negotiations ….





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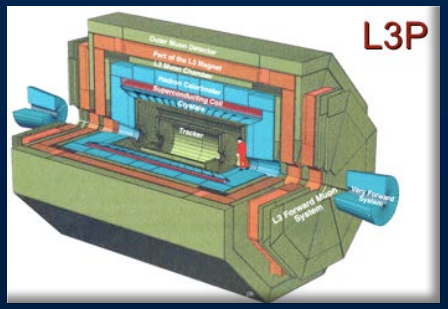

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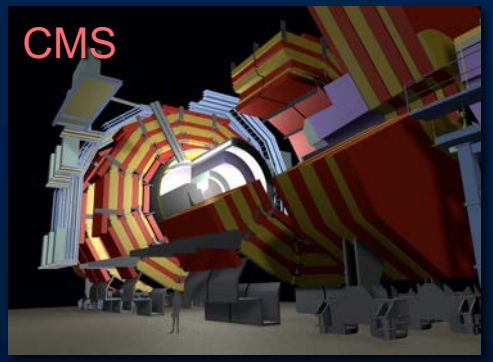
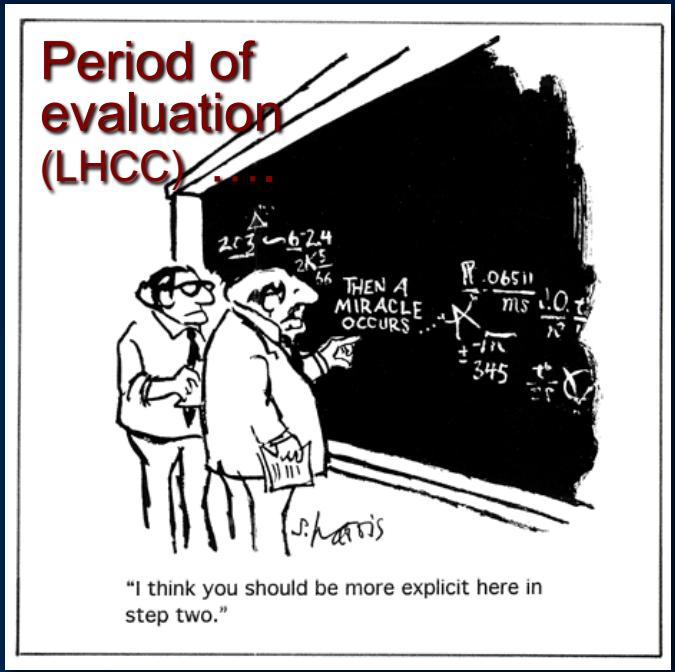


EoI ➪ LoI ➪ TP ➪ approval ➪ TDR (subsystems)

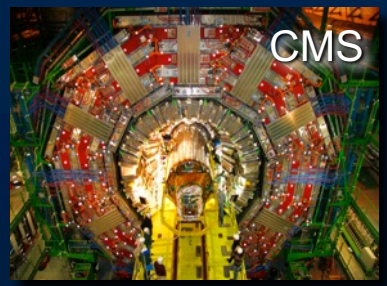


- Dec 1994: Council approves LHC project, initially for construction in two stages 'missing magnet machine'
- 1996: single-stage construction approved

- Technical Proposals (TPs):
  - 1994: ATLAS and CMS
  - 1995: ALICE
  - 1998: LHCb

Approval of experiments:

February 1996



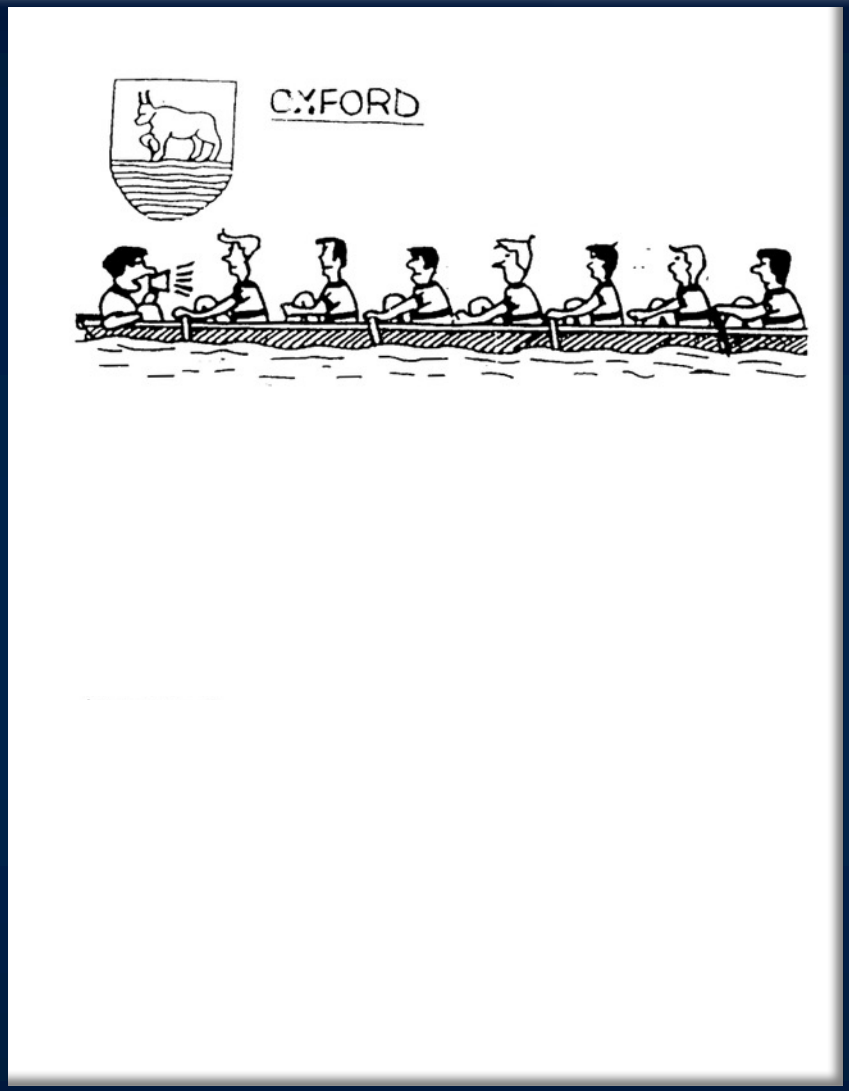
February 1996

February 1997

September 1998

" We are ready for an unforeseen event that may or may not occur" (A. Gore)

Big Collaborations …. Management duties …



Construction starts ……..

1998

Civil engineering work for the ATLAS experiment

About 10 years later ….

Construction starts ……..

1998

Gallo-Roman ruins and coins discovered at CMS dig site → 6 months delay

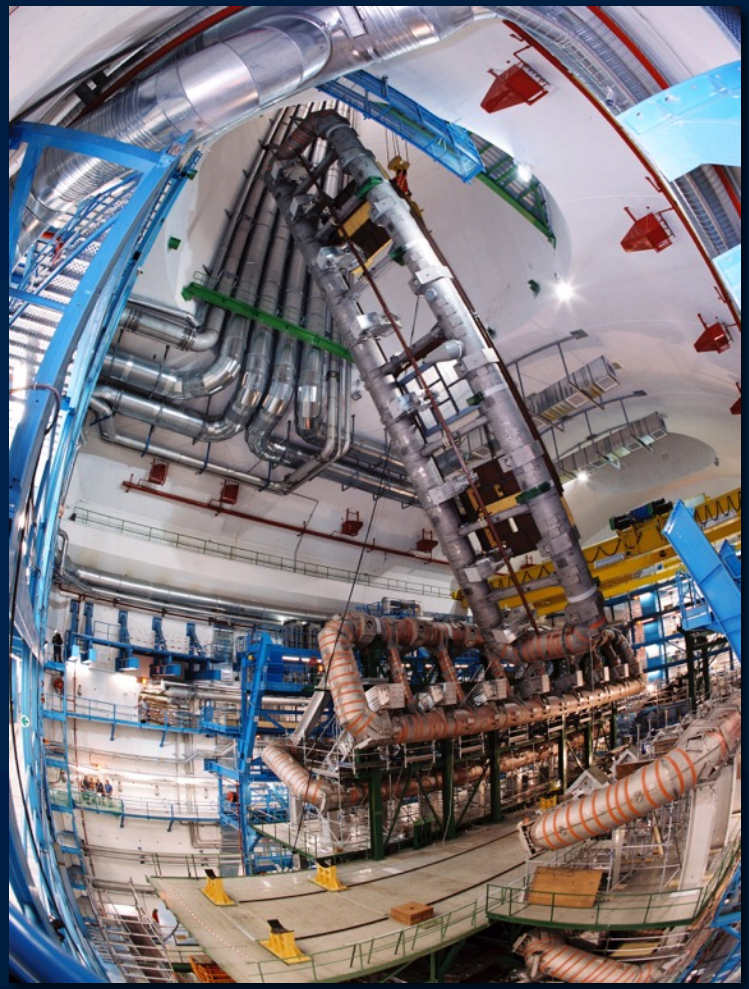
2006

Construction starts ……..

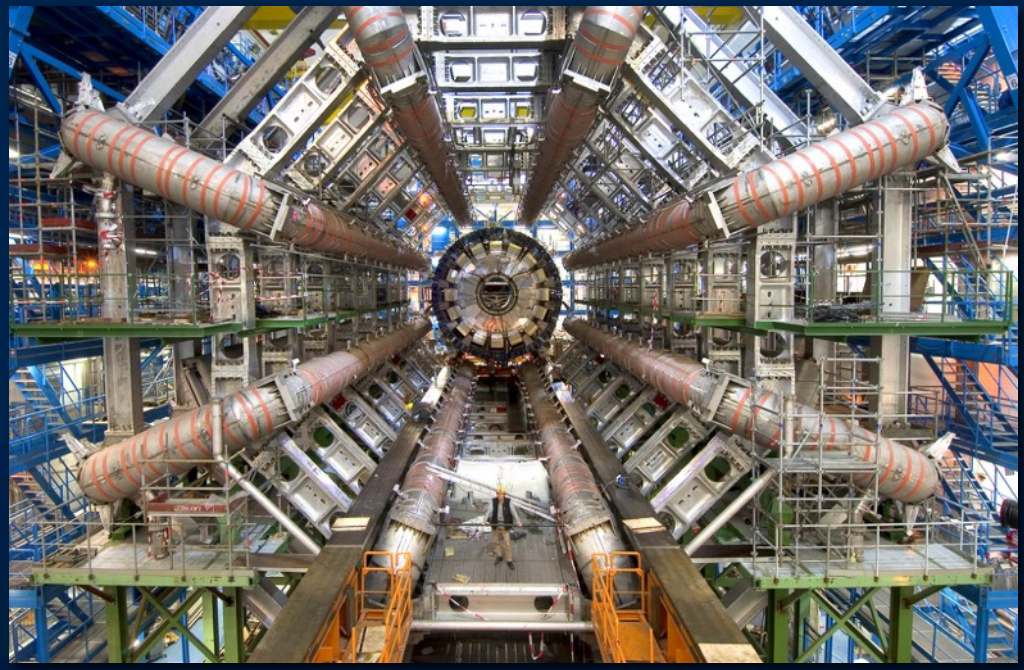
Civil Engineering at ATLAS (Point 1):
Cavern delivered in April 2003

Civil Engineering at CMS (Point 5):
Cavern delivery in July 2004

ATLAS: assembly in cavern



Barrel toroid system: eight 25m-long, 5m-wide, 100 ton superconducting coils
Field ~0.5 T; ~1GJ stored energy

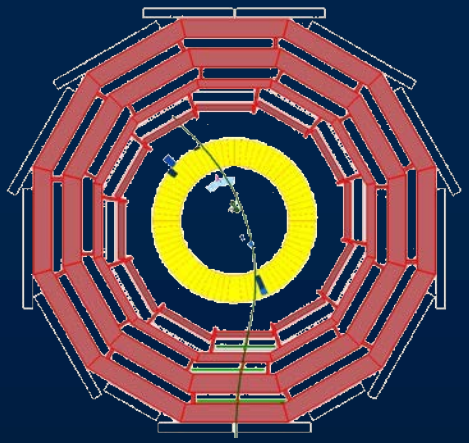


The famous ATLAS picture

Closing CMS for the first time in July 2006

28. August: CMS SC Solenoid: stable magnet operation at 4 Tesla !
19.14 kA, 2.5 GJ stored energy, sufficient to melt 18 t of gold

~ 25 million cosmic events recorded



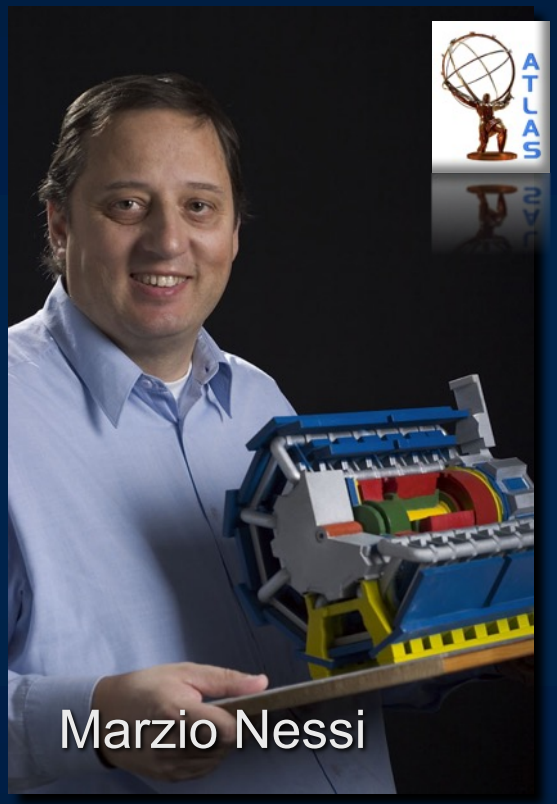
SC Magnet: 4 Tesla, l = 13 m, Ø = 6 m, weight > 10’000 tons

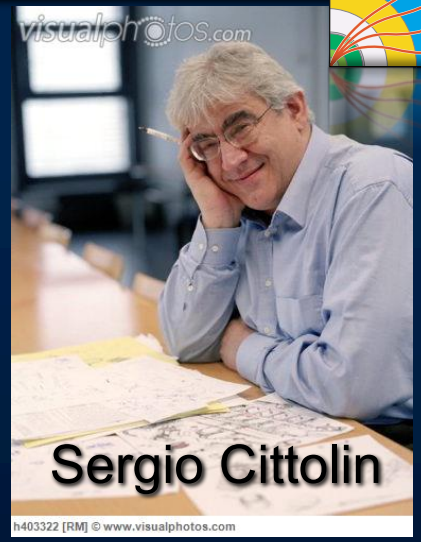
Lowering of heavy elements into cavern

Lowering of central and heaviest element (~ 2000 t) on 28 February 2007 ……

Lowering of the last heavy element on 22 January 2008

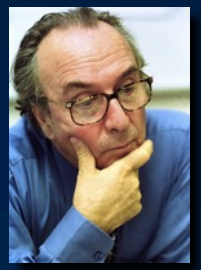
Technical Coordination, TriDAS, ...





Schedule: towards first collisions at the LHC

- Schedule (Aachen workshop 1990): start civil engineering in 1992; commissioning in 1998; LEP + LHC concurrent operation
- 1995: start LHC project, duration 10 years (2005 first collisions)
- 2003: DG (LM) confirms LHC start-up in 2007



2007: DG (RA) confirms LHC start-up in May 2008:
2008: E_{cm} = 10 TeV: 40 physics days, L_{peak}= $5 \cdot 10^{31}$ cm^{-2} s^{-1}, L_{deliv} ~ 20 pb^{-1}
2009: E_{cm} = 14TeV: 150 physics days, L_{peak}= 10^{33} cm^{-2} s^{-1}, L_{delive}~ 2.5 fb^{-1}

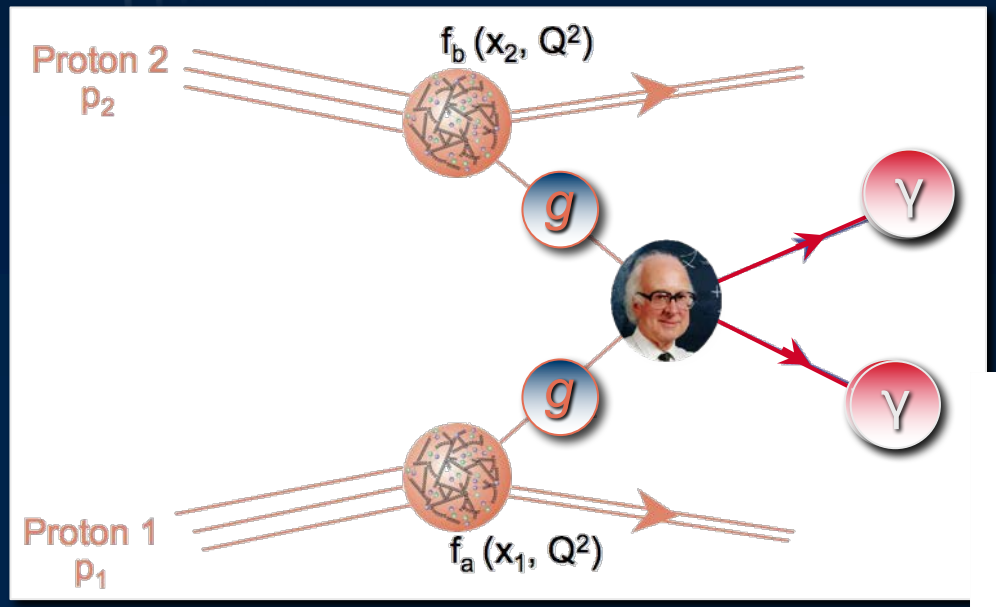
10 Sept 2008: first protons circulating in the LHC ring

- 19 Sept 2008: incident in sector 3-4
- Nov 2009: 2 beams circulating
- March 2010: collisions at E_{cm} = 7 TeV

See talk by L. Evans

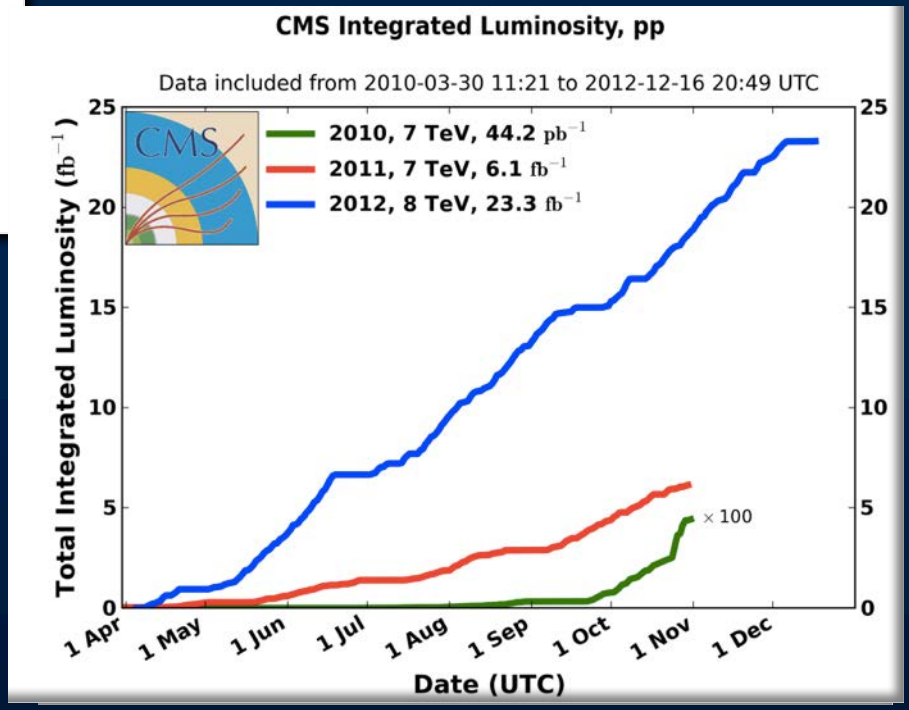
Film: first protons injected into LHC

The Higgs success story



December 2011 (run @ 7 TeV: ~5 fb^{-1})

ATLAS und CMS see “hints” in 120 - 130 GeV mass region



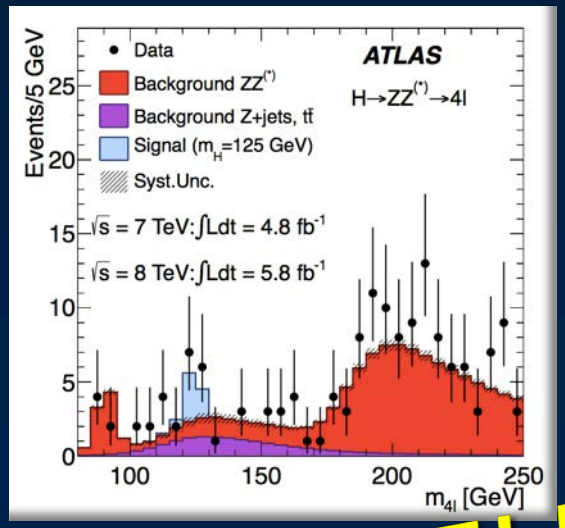
2012 run @ 8 TeV:
December 2012: ~25 fb^{-1}

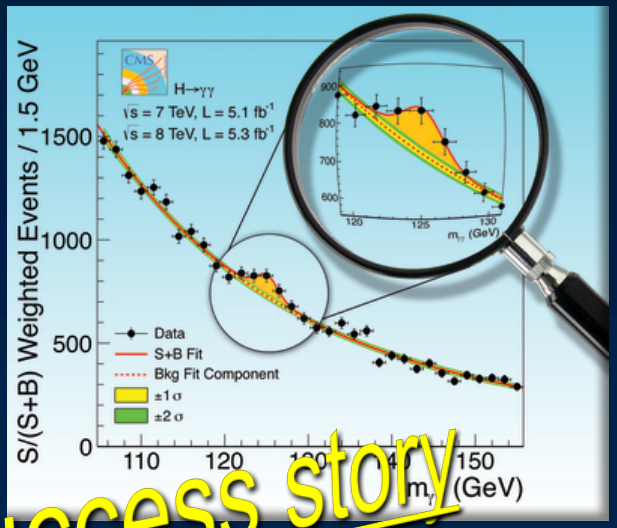
The Higgs success story

4 July 2012:
Discovery

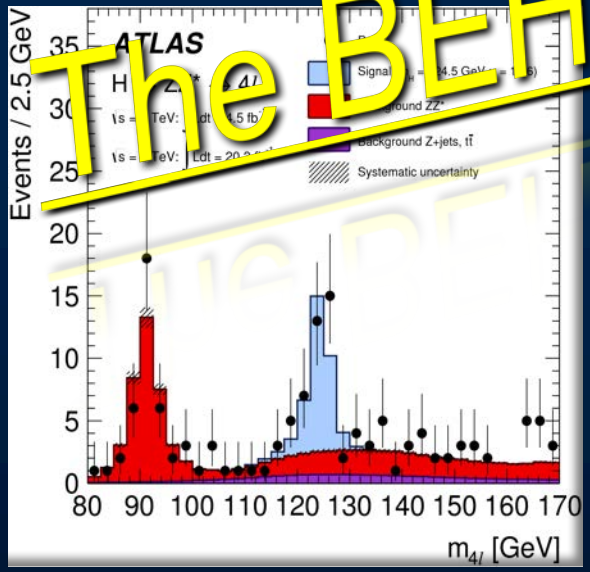
July 2014:
ICHEP 2014

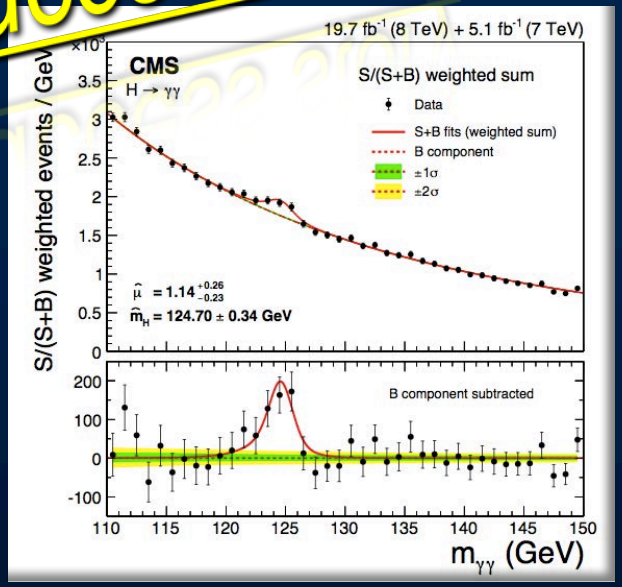
one Higgs → 4e
produced in 10^{13} pp
collisions



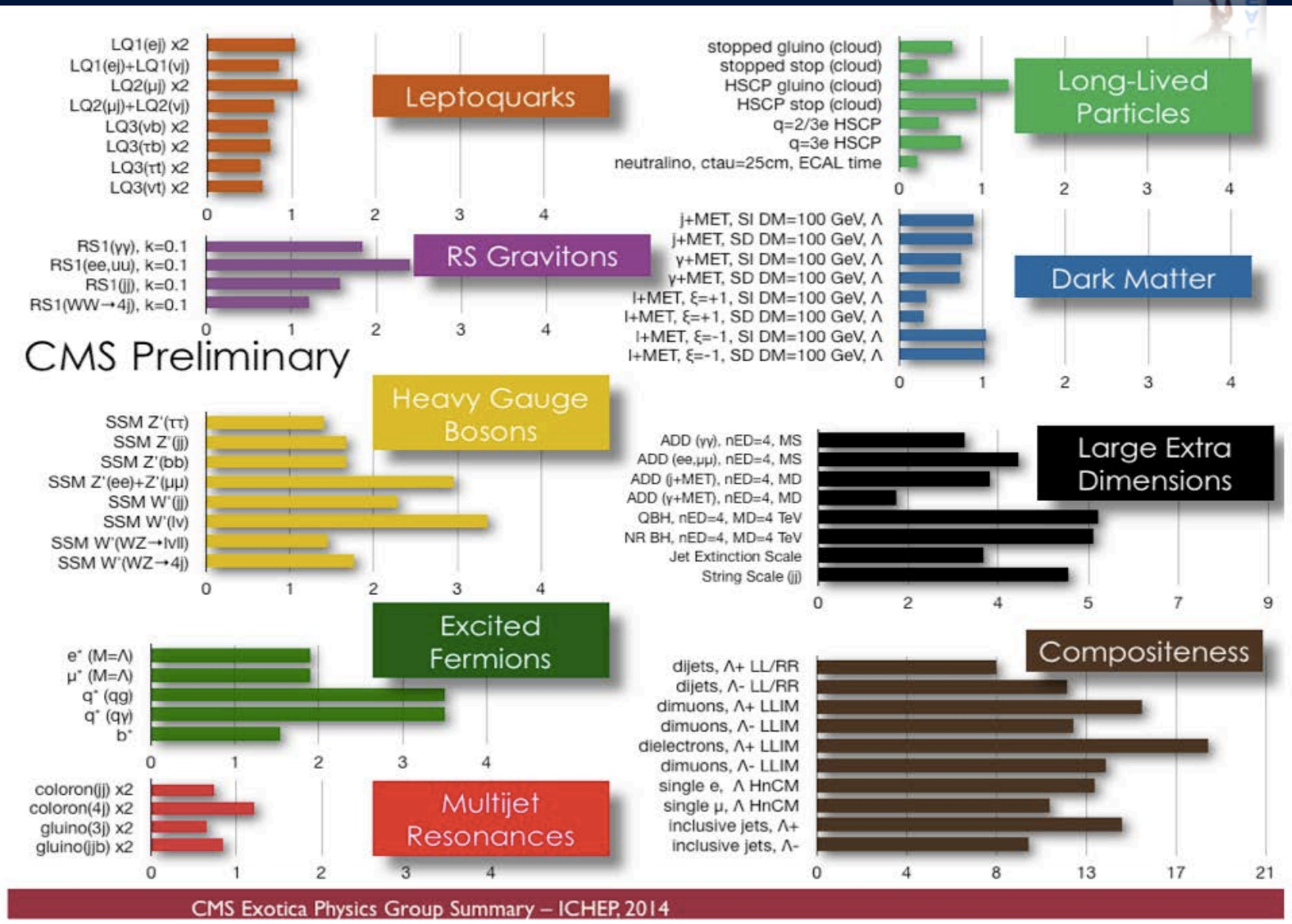


The BEH success story



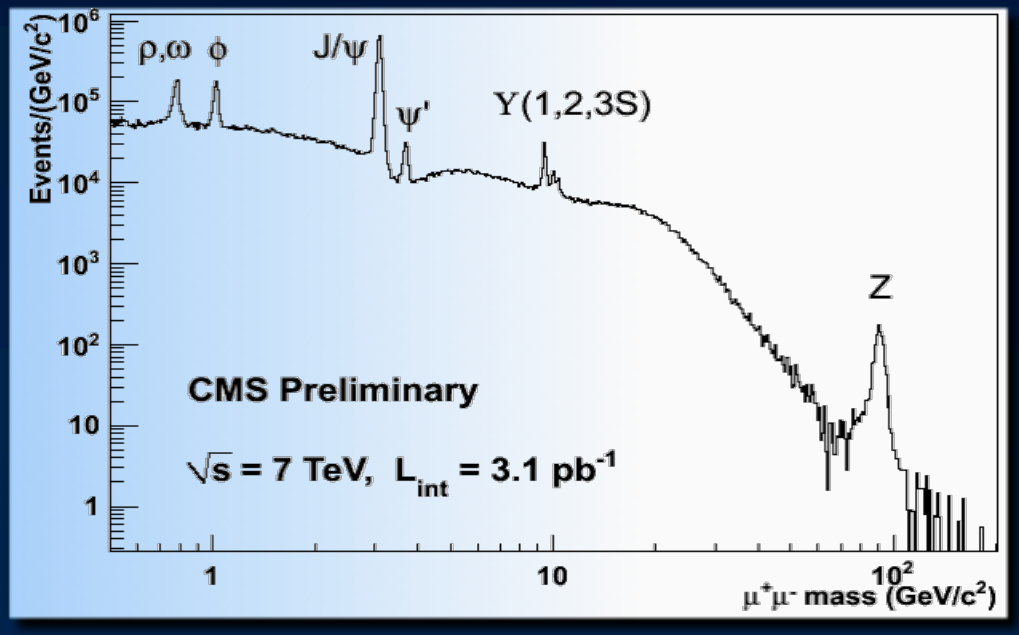


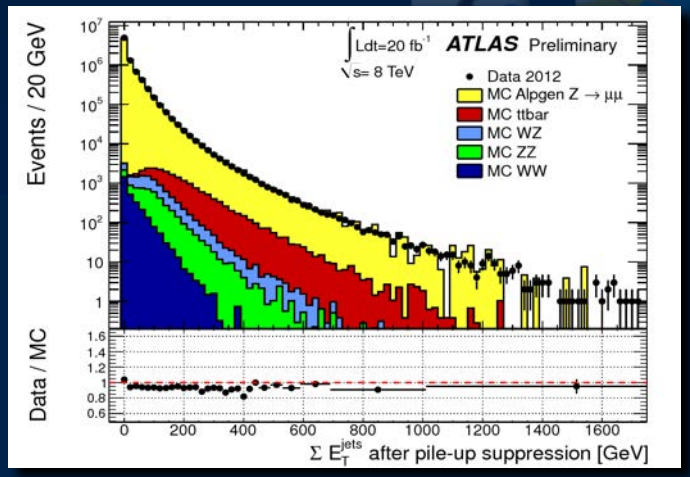
Impressive scientific output from Run1@LHC

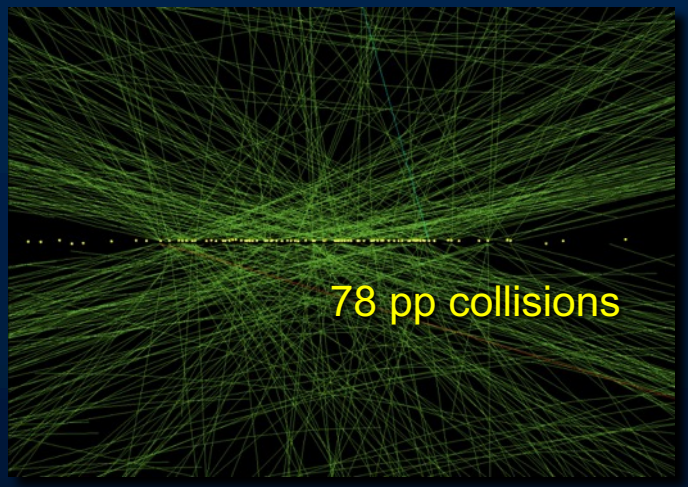


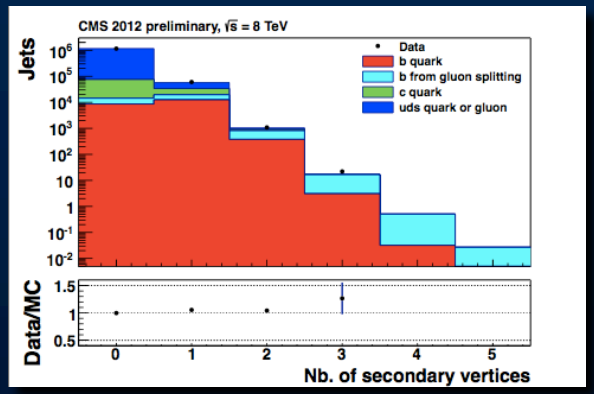
Impressive scientific output ←→impressive detector performance

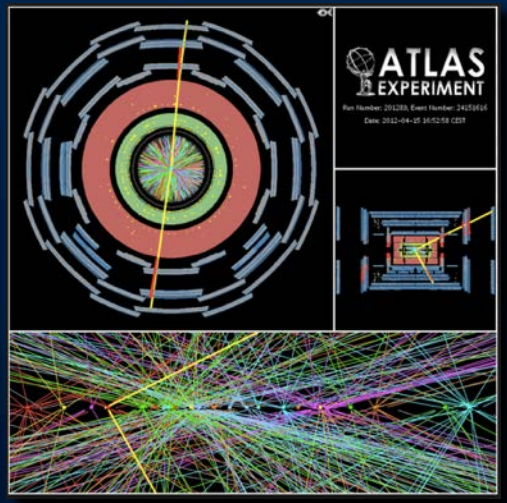
Examples











Physics motivation / goals – in 2014

Particle masses?

Higgs

Actually, the Brout-Englert ... boson...

BEH discovered

Dark Matter?

Zwicky, 1933

Quarks and Leptons | Hadrons | Nuclei | Atoms

Temperature

10^{13}

10^{7}

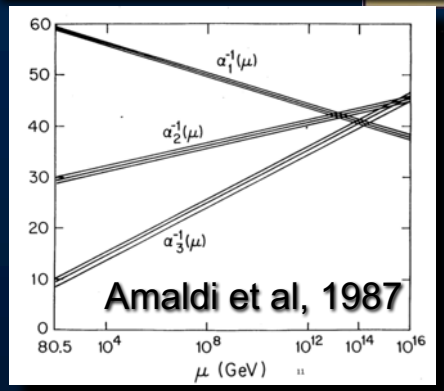
33 s

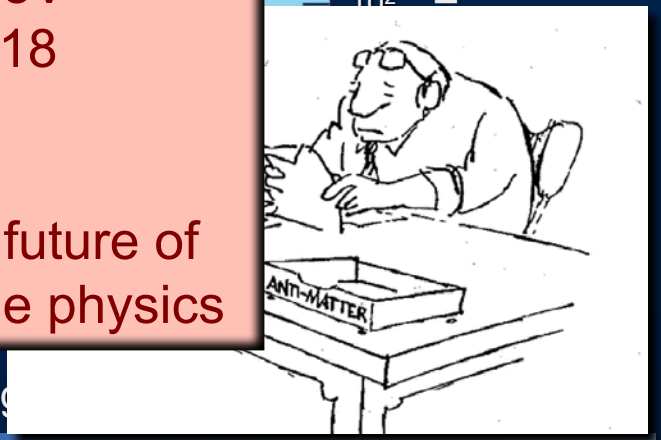
Time after Big

After long shut-down - start in 2015
with an essentially new machine!
E_{CM} ~ 13 TeV → 14 TeV
Data taking till Q2 2018

Important for the long term future of
LHC / CERN – and of particle physics

Unification of forces?



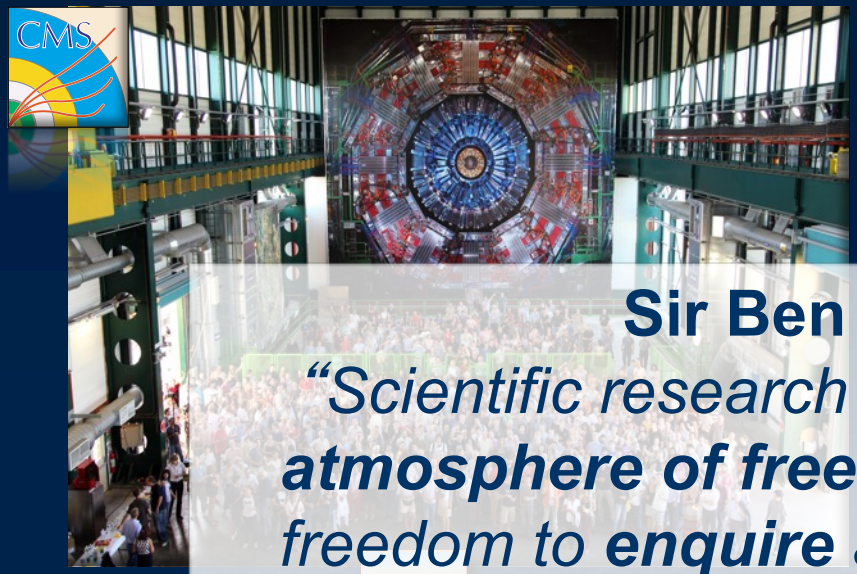


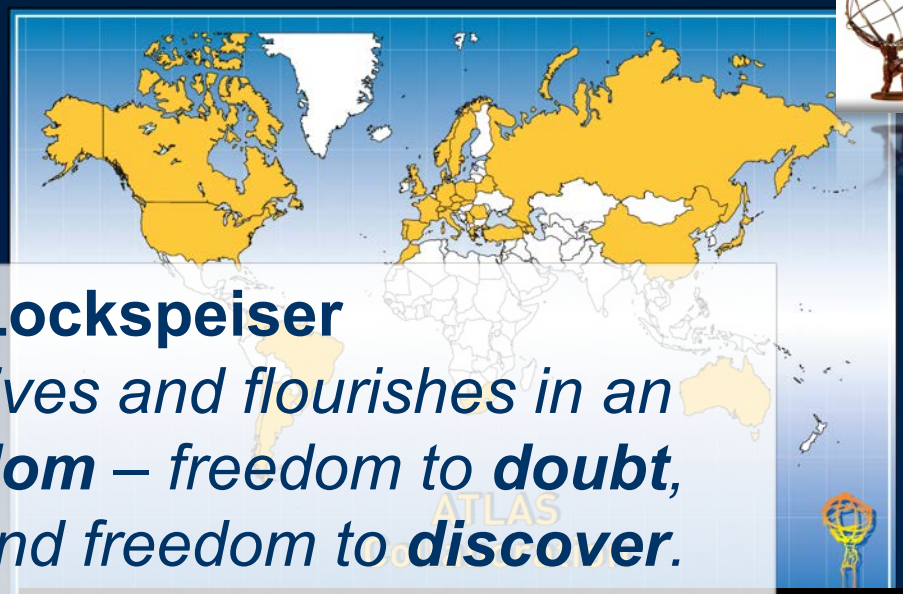
Matter-Antimatter Asymmetry?

LHC ➪ Answers to open question → still valid!

Success of a truly global scientific project

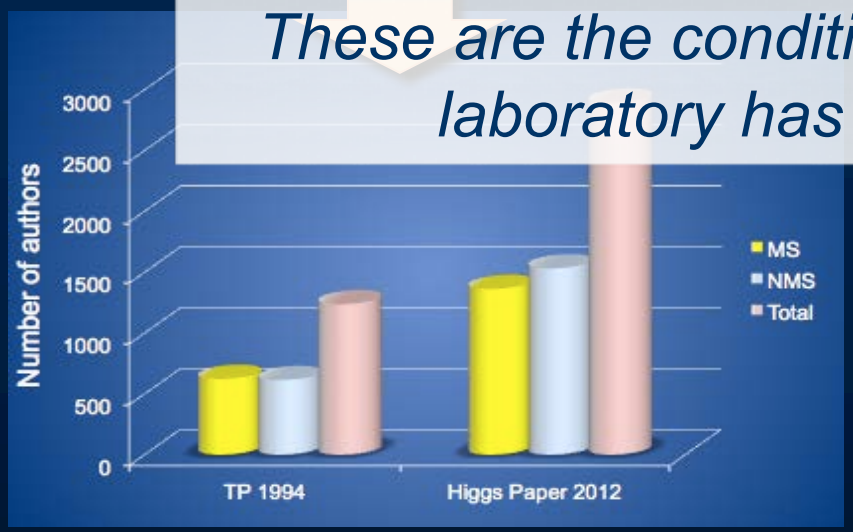
Collaborations: ~3000 scientists, ~40 countries, ~200 institutes

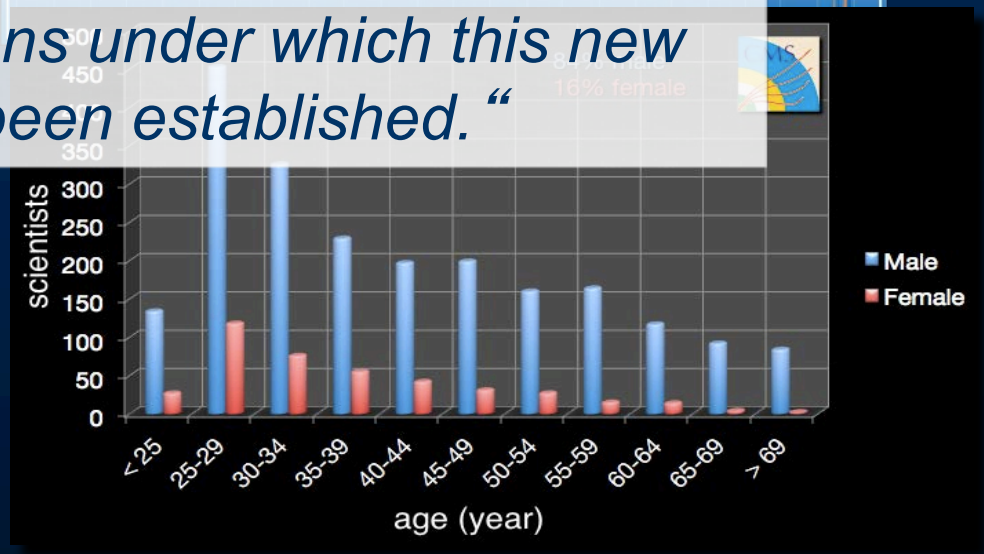




Sir Ben Lockspeiser

"Scientific research lives and flourishes in an ***atmosphere of freedom*** *– freedom to* ***doubt****, freedom to* ***enquire*** *and freedom to* ***discover****. These are the conditions under which this new laboratory has been established."*





The foundations for CERN's success

- European scientists and political leaders with visionary minds created CERN 60 years ago:
  - Building strong links between scientists of large and small countries
  - Tying together human and financial resources for a common scientific goal
  - Realization of long-term goals with strong support from all Member States

Start of construction in Meyrin

- To meet the challenges posed by the increasing global (and competitive) nature of frontier facilities, a clear scientific vision and strong political support is needed for a bright future of CERN

Thank you !!!

Felicitas Pauss
ETH Institute for Particle Physics