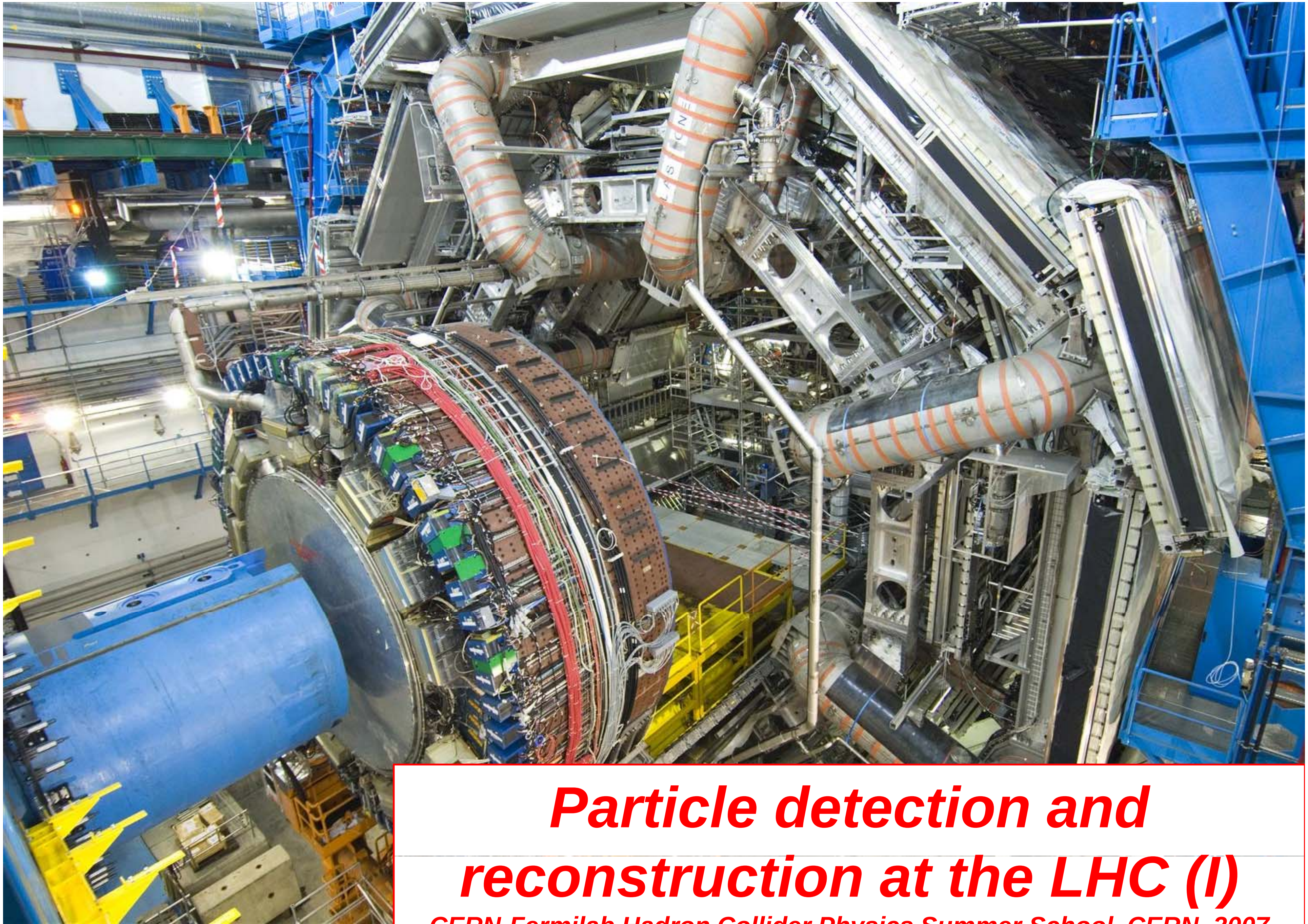


Particle detection and reconstruction at the LHC (I)

CERN-Fermilab Hadron Collider Physics Summer School, CERN, 2007

11^{th} to 14^{th} of August 2007 (D. Froidevaux, CERN)

Particle detection and reconstruction at the LHC (and Tevatron)

Lecture 1

- Historical introduction: from UA1/UA2 to ATLAS/CMS

Lecture 2

- Experimental environment, main design choices and intrinsic performance

Lecture 3

- Electrons, photons, muons, τ-leptons and particle-ID

Lecture 4

- Hadronic jets and neutrinos

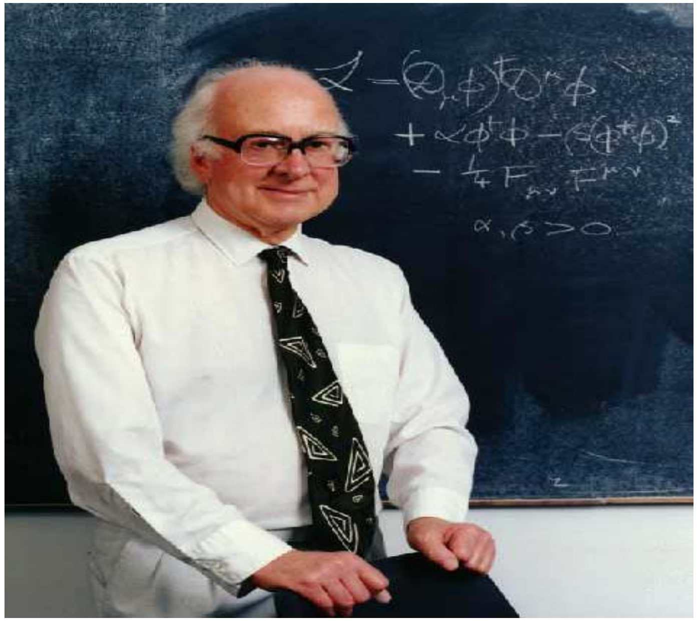
Not covered here

- Trigger, data acquisition and offline (see lectures by A. Yagil)
- Calibration, alignment and commissioning (see lectures by D. Acosta)

Historical introduction

Higgs boson has been with us for several decades as:

1. a theoretical concept,
2. a scalar field linked to the vacuum,
3. the 'dark' corner of the Standard Model,
4. an incarnation of the Communist Party, since it controls the masses (L. Alvarez-Gaumé in lectures for CERN summer school in Alushta),
5. a painful part of the first chapter of our Ph. D. thesis



P.W. Higgs, Phys. Lett. 12 (1964) 132

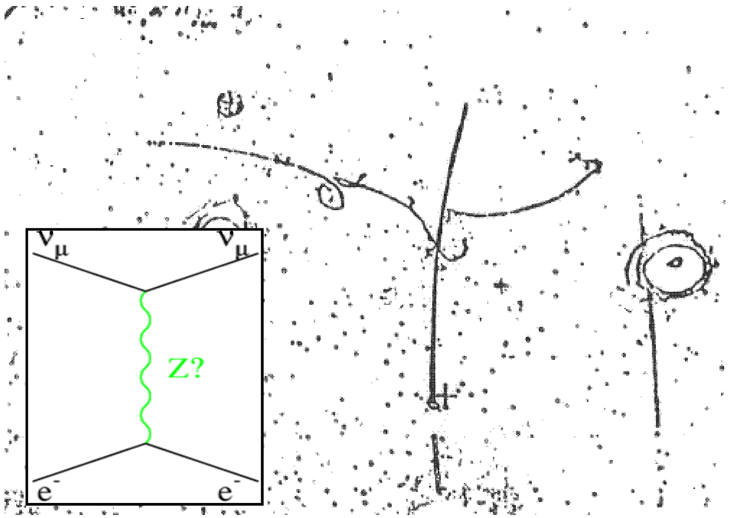
Only unambiguous example of observed Higgs (apologies to ALEPH collab.)

Historical introduction

1964: First formulation of Higgs mechanism (P.W.Higgs)

1967: Electroweak unification, with W, Z and H (Glashow, Weinberg, Salam)

1973: Discovery of neutral currents in $\nu_\mu e$ scattering (Gargamelle, CERN)



1974: Complete formulation of the standard model with $SU(2)_W \times U(1)_Y$ (Iliopoulos)

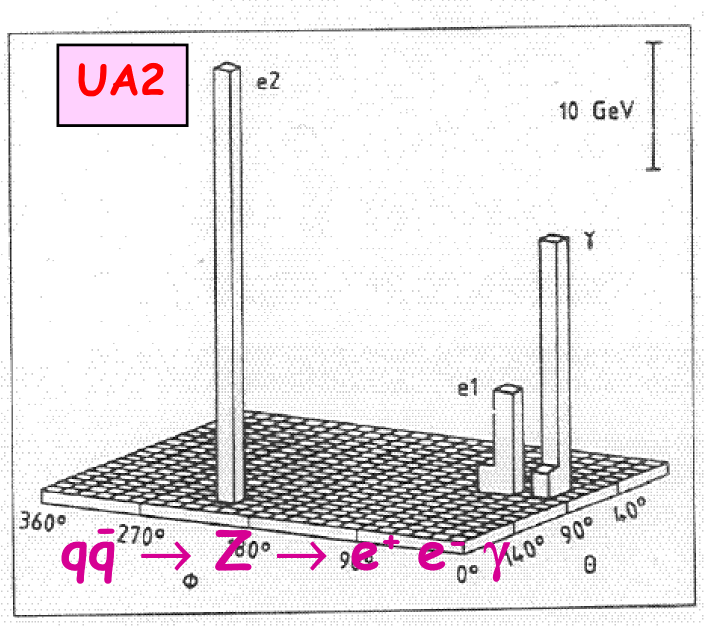
1981: The CERN SpS becomes a proton-antiproton collider

LEP and SLC are approved before W/Z boson discovery

1983: LEP and SLC construction starts

W and Z discovery (UA1, UA2)

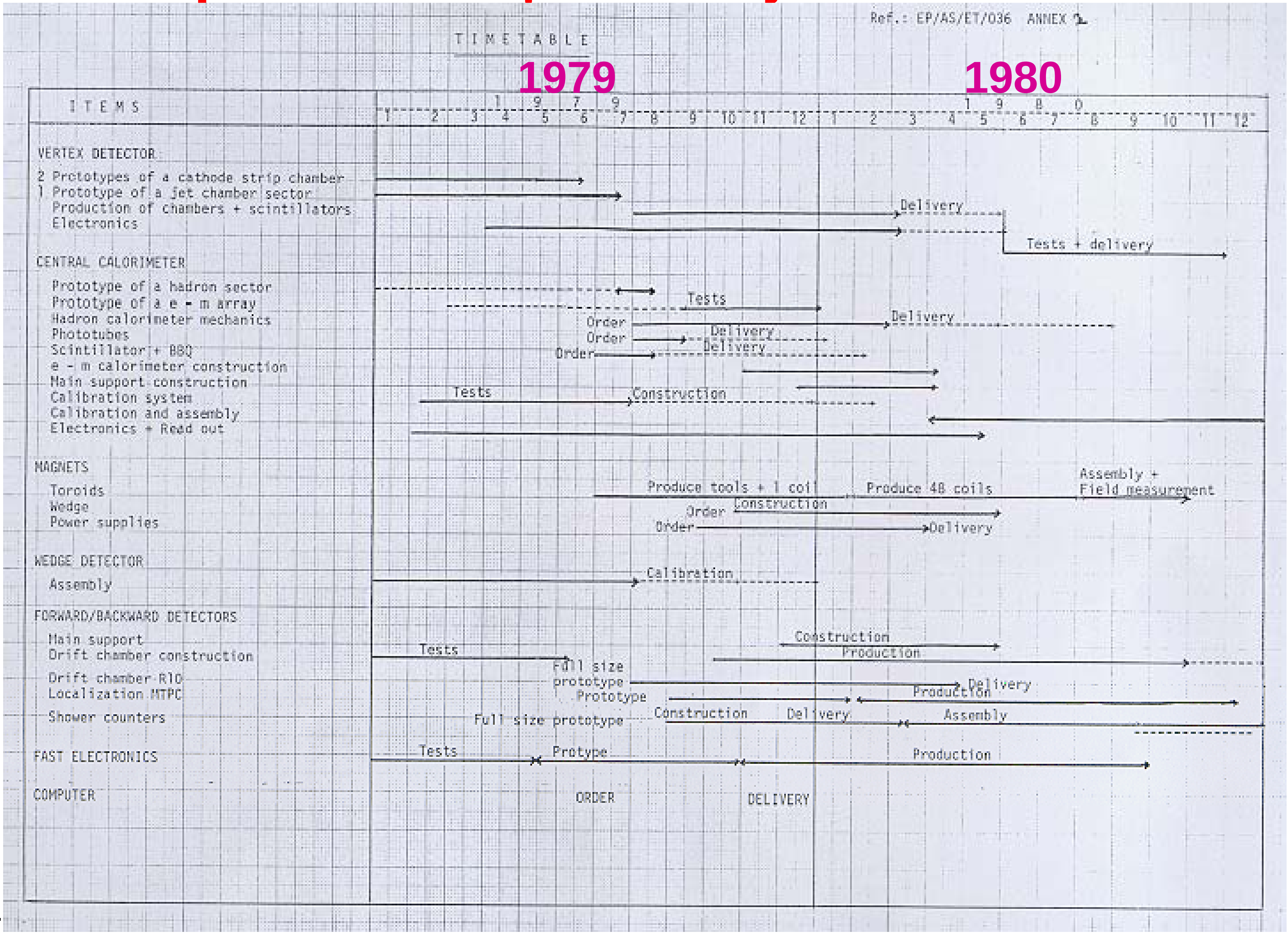
One of the first Z-bosons detected in the world



UA2 at the SppS collider

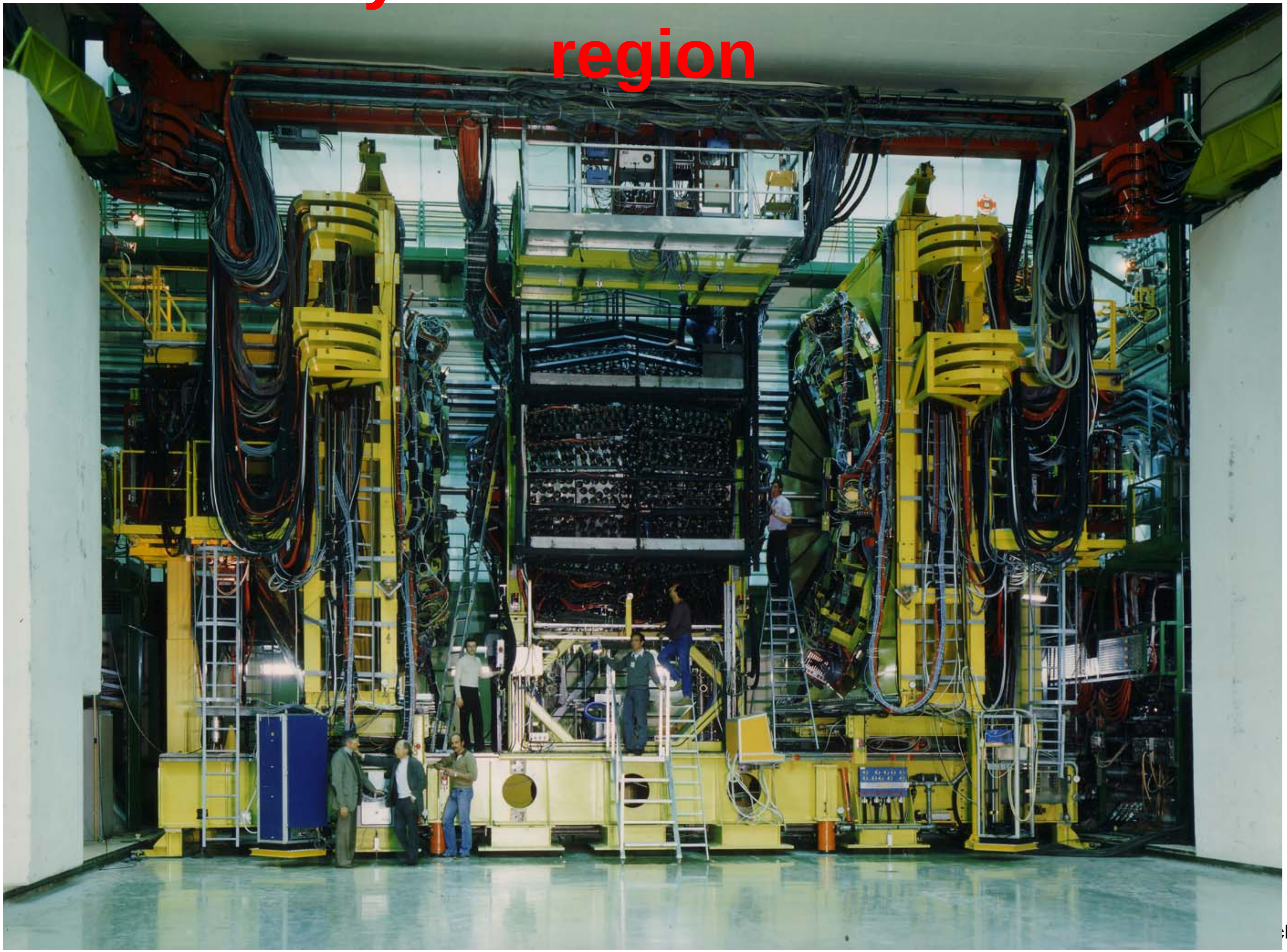
- UA2 proposed and approved in 1978
- UA2 constructed in 1979-1980
- First proton-antiproton run in 1981
- Discovery of W and Z in 1983
- Upgrade of UA2 to UA2’ from 1984 to 1987
- Data taking with UA2’ from 1987 to 1990 (at which point CDF at the Tevatron took over for ppbar physics)

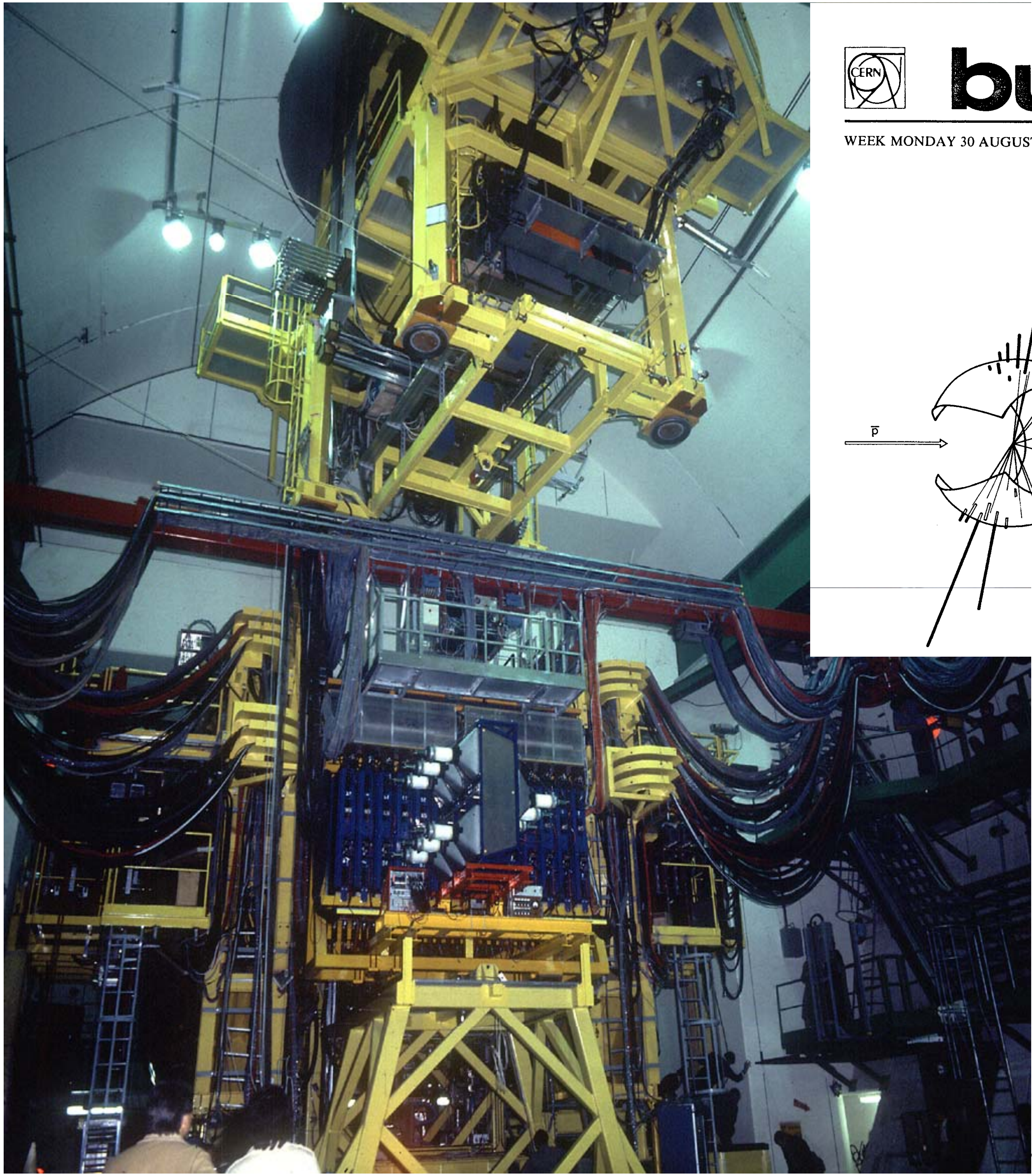
Equivalent of µsoftProject for UA2

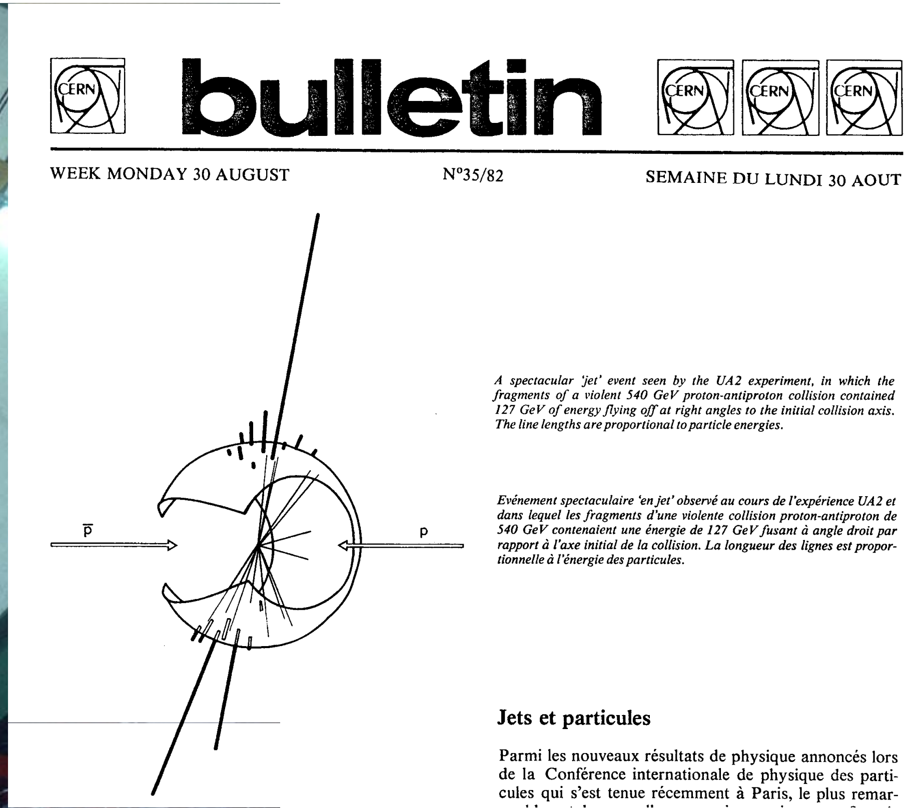


D.

UA2 ready to roll into the interaction region







bulletin

WEEK MONDAY 30 AUGUST N°35/82 SEMAINE DU LUNDI 30 AOUT

A spectacular 'jet' event seen by the UA2 experiment, in which the fragments of a violent 540 GeV proton-antiproton collision contained 127 GeV of energy flying off at right angles to the initial collision axis. The line lengths are proportional to particle energies.

Evénement spectaculaire 'en jet' observé au cours de l'expérience UA2 et dans lequel les fragments d'une violente collision proton-antiproton de 540 GeV contenaient une énergie de 127 GeV fusant à angle droit par rapport à l'axe initial de la collision. La longueur des lignes est proportionnelle à l'énergie des particules.

Jets et particules

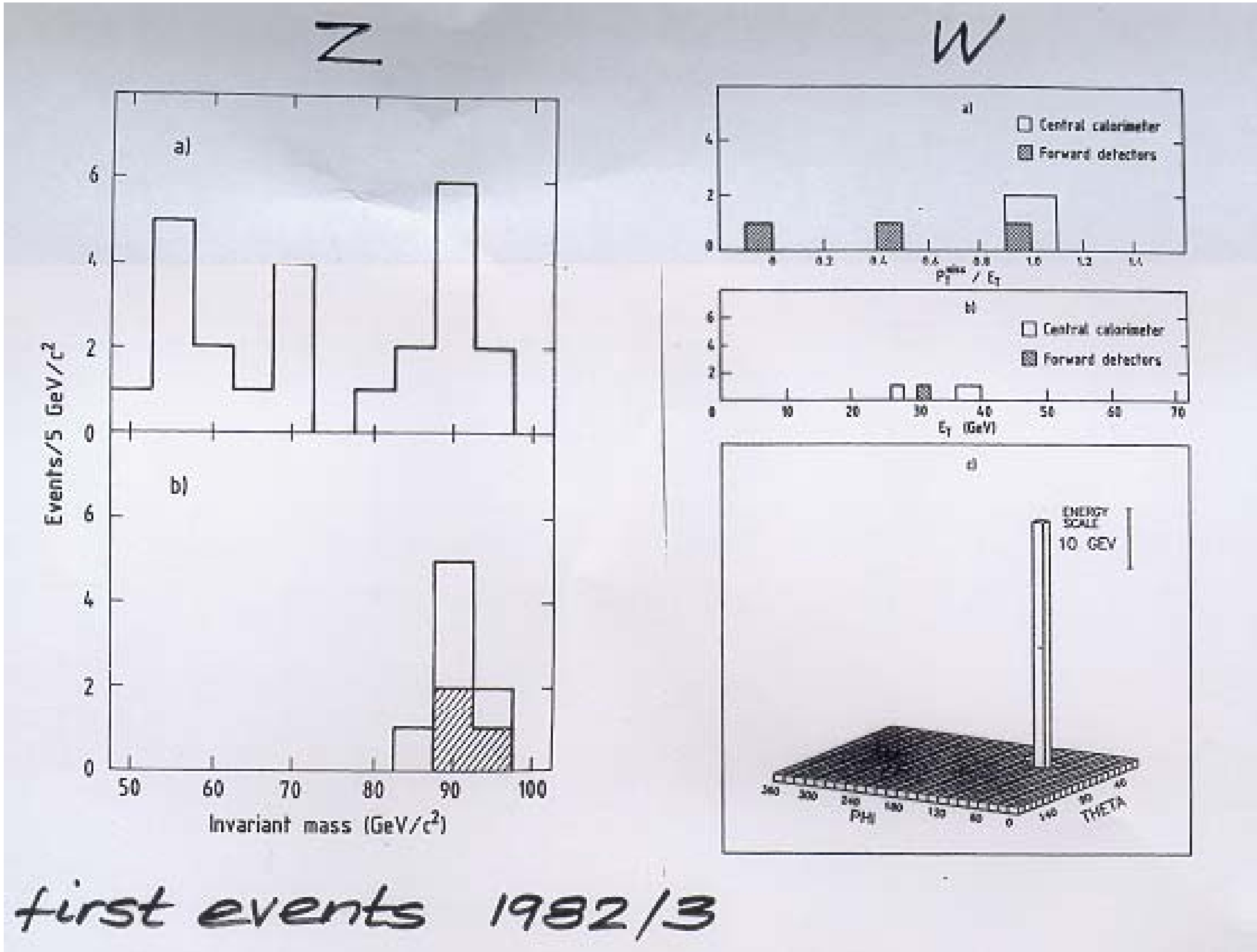
Parmi les nouveaux résultats de physique annoncés lors de la Conférence internationale de physique des particules qui s'est tenue récemment à Paris, le plus remar-

September 1981: first (small) run for UA2

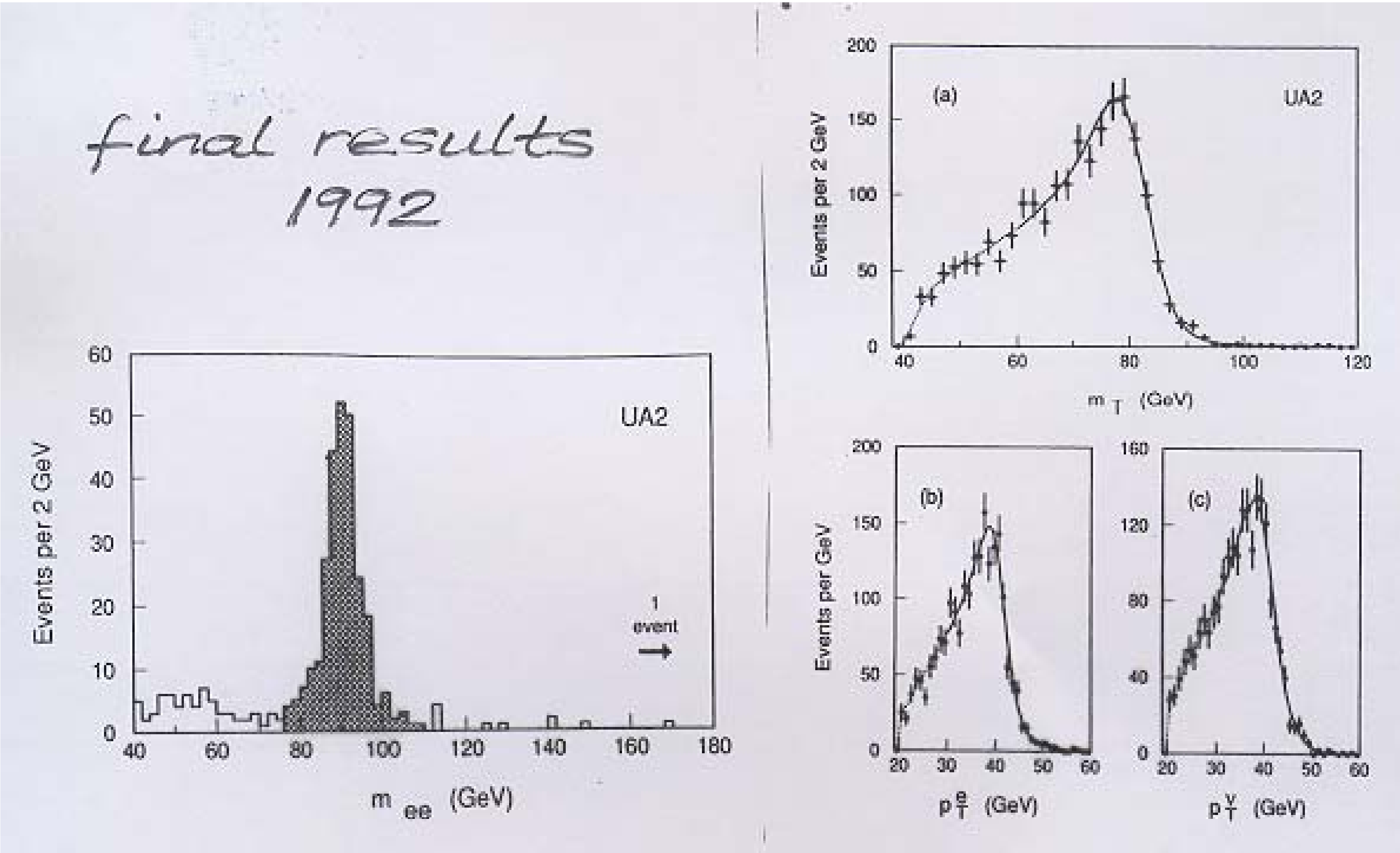
↓

First observation of jets in hadronic collisions

rom the beginning, with the observation of two-jet dominance and of 4 W $\rightarrow$ eν and 8 Z $\rightarrow$ e$^+$e$^-$ decays



› the end, with first accurate measurements of the W/Z masses and the search for the top quark and for supersymmetry



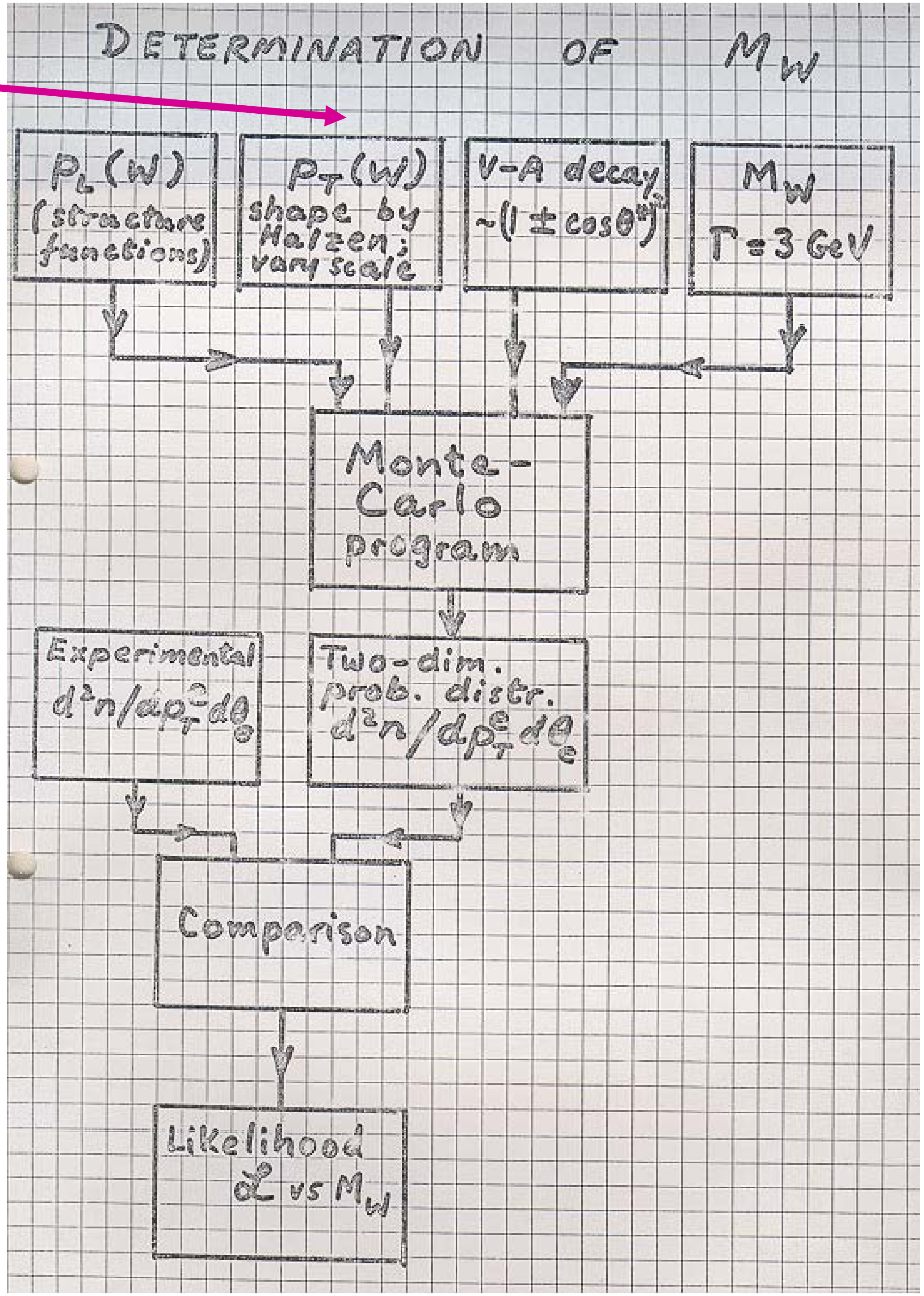
Software design in 1984

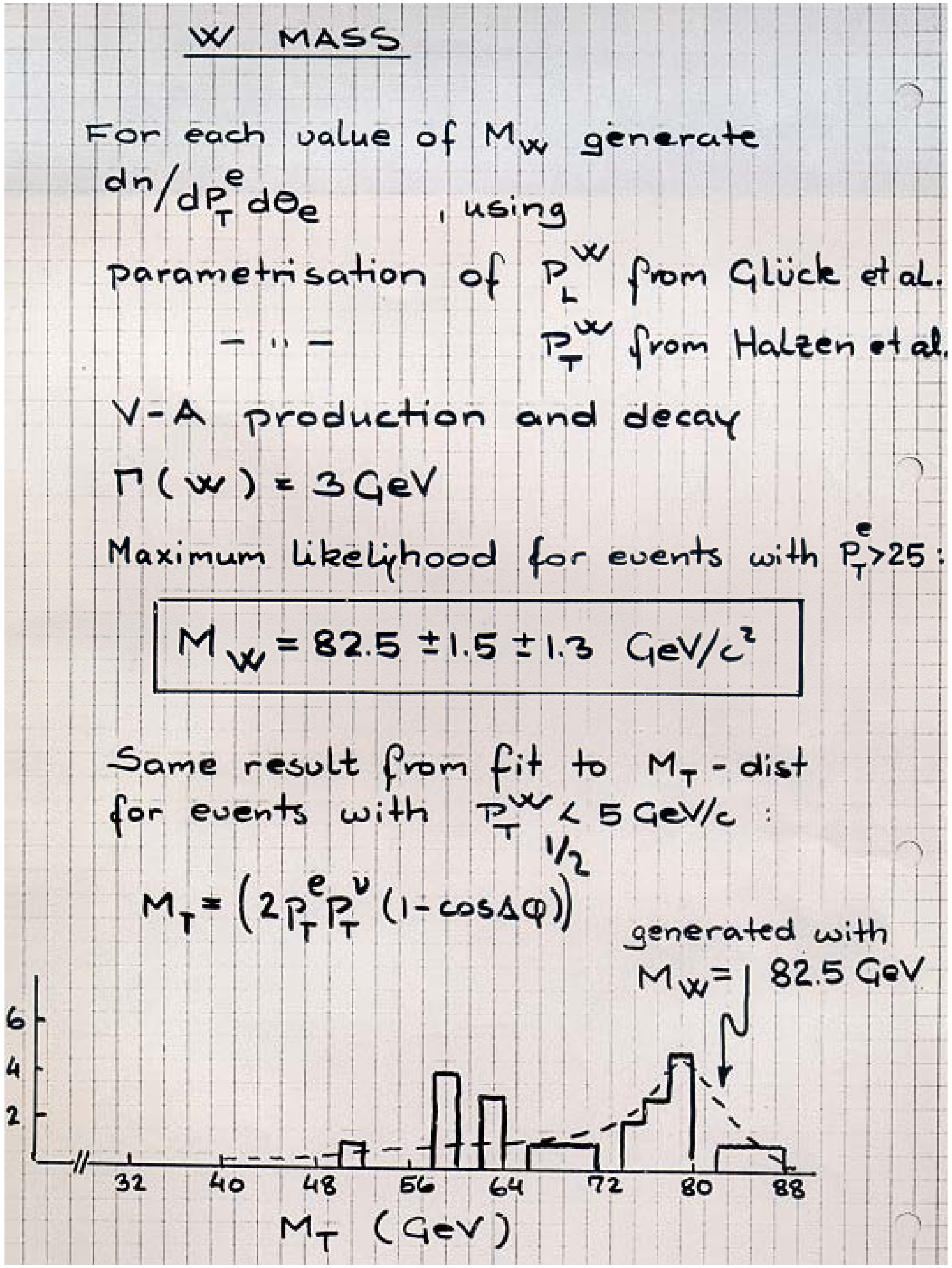
UA2 was perceived as large at the time:

- ✦ 10-12 institutes
- ✦ from 50 to 100 authors
- ✦ cost ~ 10 MCHF
- ✦ duration 1980 to 1990

Physics analysis was organised in two groups:

1. Electrons → electroweak
2. Jets → QCD





W MASS

For each value of M_W generate $dn/dP_T^e d\theta_e$, using parametrisation of P_L^W from Glück et al.

— " — P_T^W from Halzen et al.

V-A production and decay

$\Gamma(W) = 3$ GeV

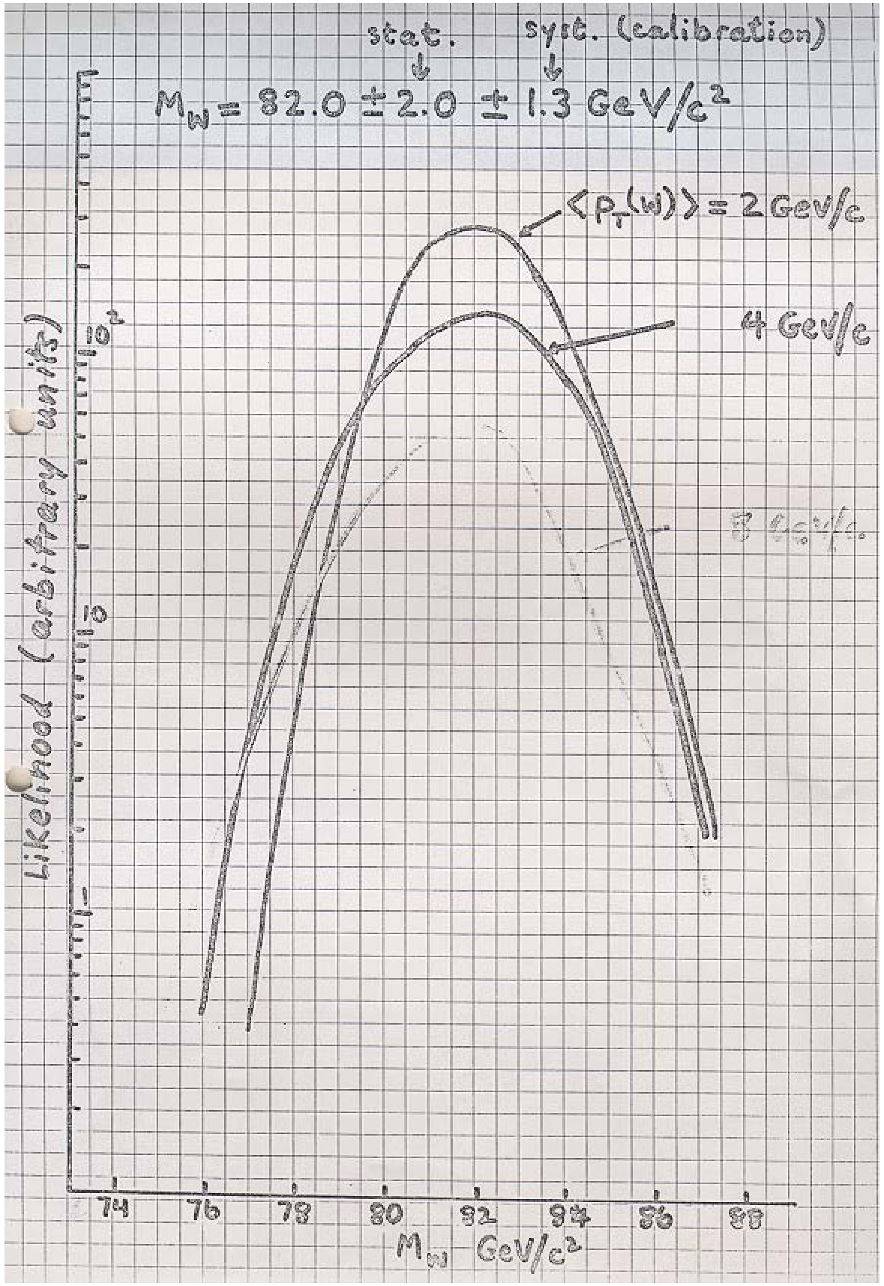
Maximum likelihood for events with $P_T^e > 25$:

$M_W = 82.5 \pm 1.5 \pm 1.3$ GeV/c^2

Same result from fit to M_T - dist for events with $P_T^W < 5$ GeV/c :

$M_T = \left(2 P_T^e P_T^\nu (1-\cos\Delta\varphi)\right)^{1/2}$

Software documentation in 1984



Analysis results in 1984

84-1985 were exciting (and confusing) time

Many lessons learned by young physicists in UA1/UA2 collaborations from our more experienced colleagues

- **take care with statistics!**
- **bizarre events are usely unforeseen manifestations of SM physics**
- **constrain background estimates as much as feasible using data**

"Over-abundance" of $Z \rightarrow ee\gamma$ events

Monojets

Dijets with missing E_T

High-p_T electrons with jets and missing E_T

Top quark "discovery"

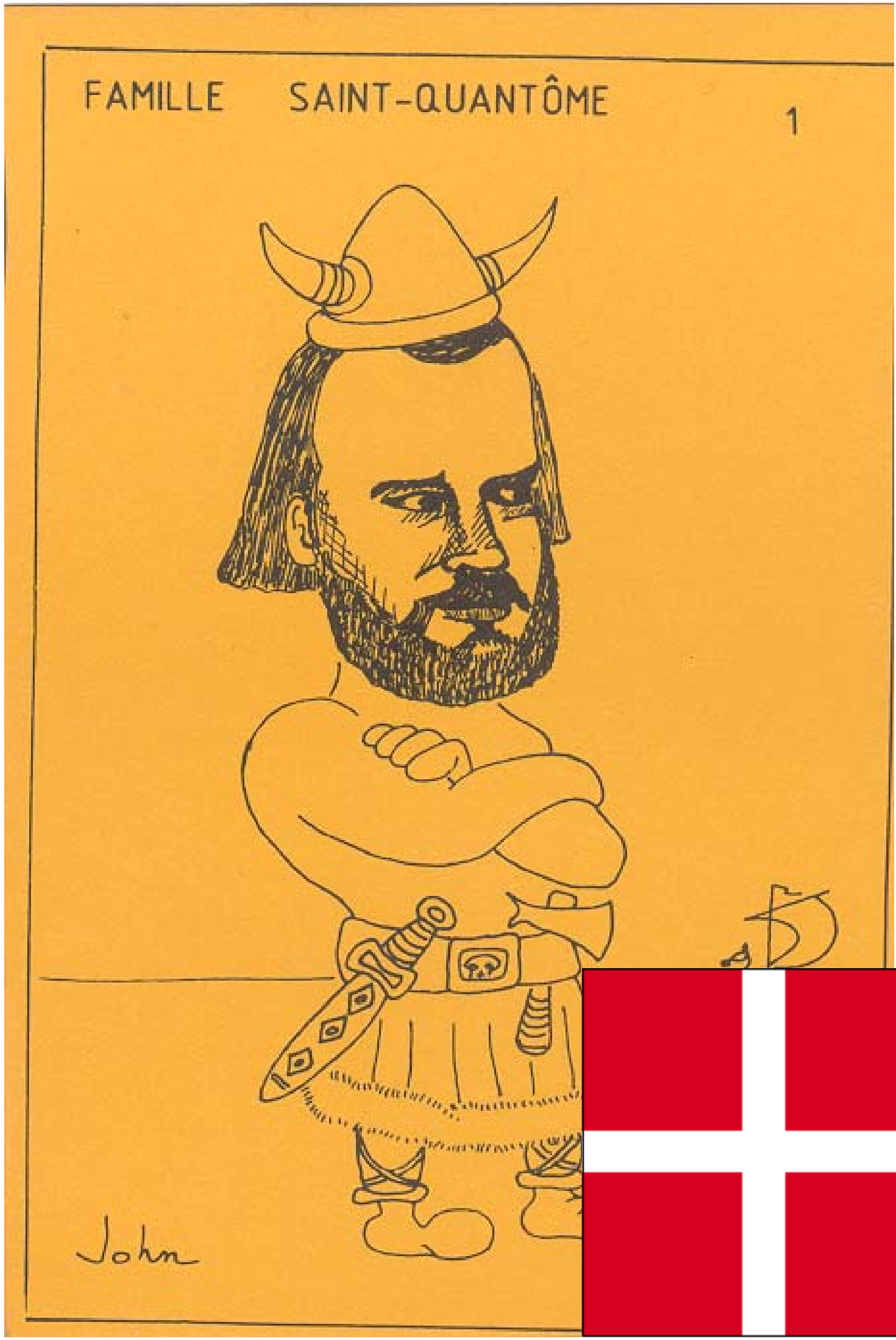
Bumps in distributions (jet-jet mass in UA2, W decay electron spectrum in

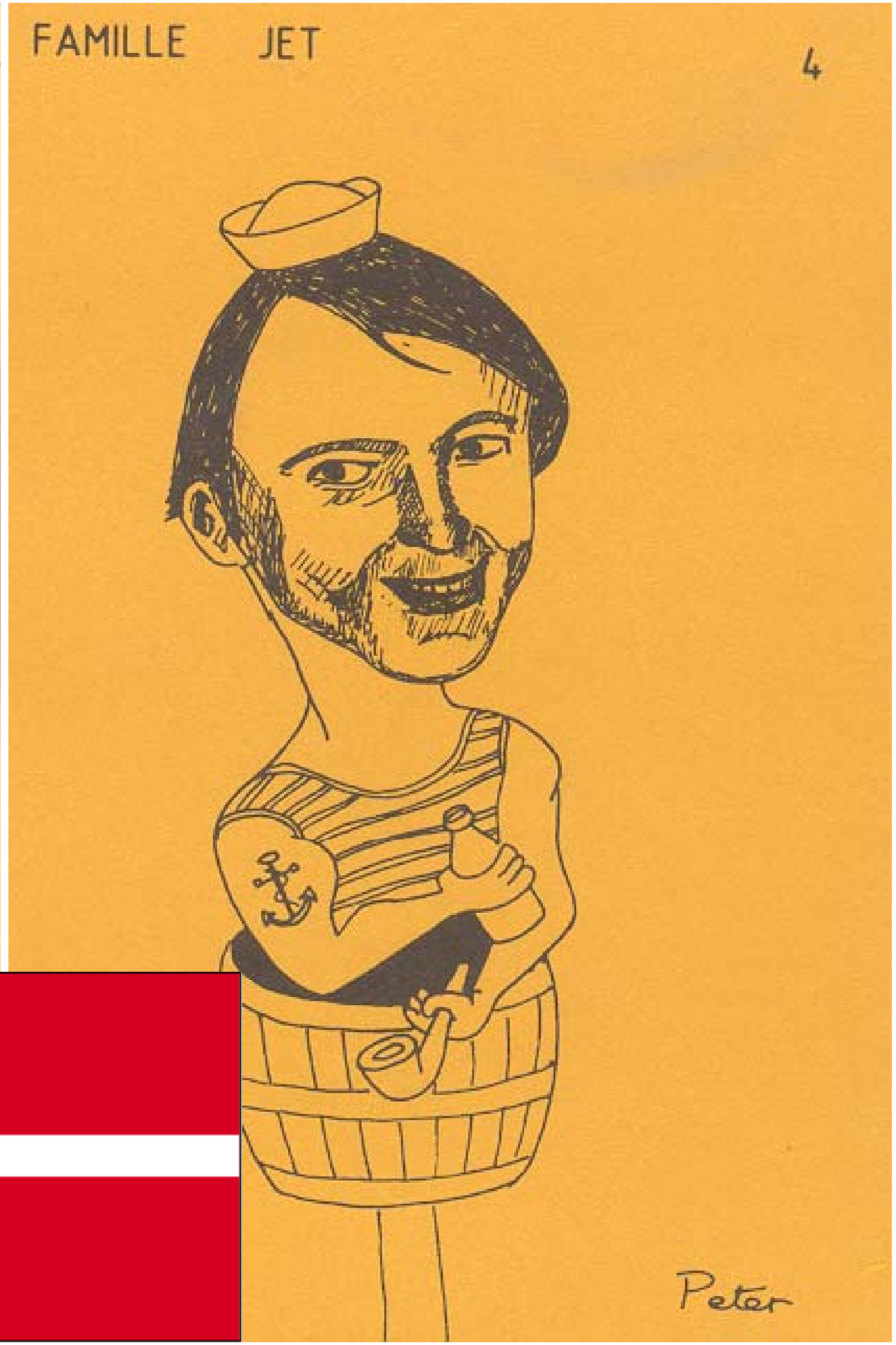
42 authors could make it into a deck of playing car

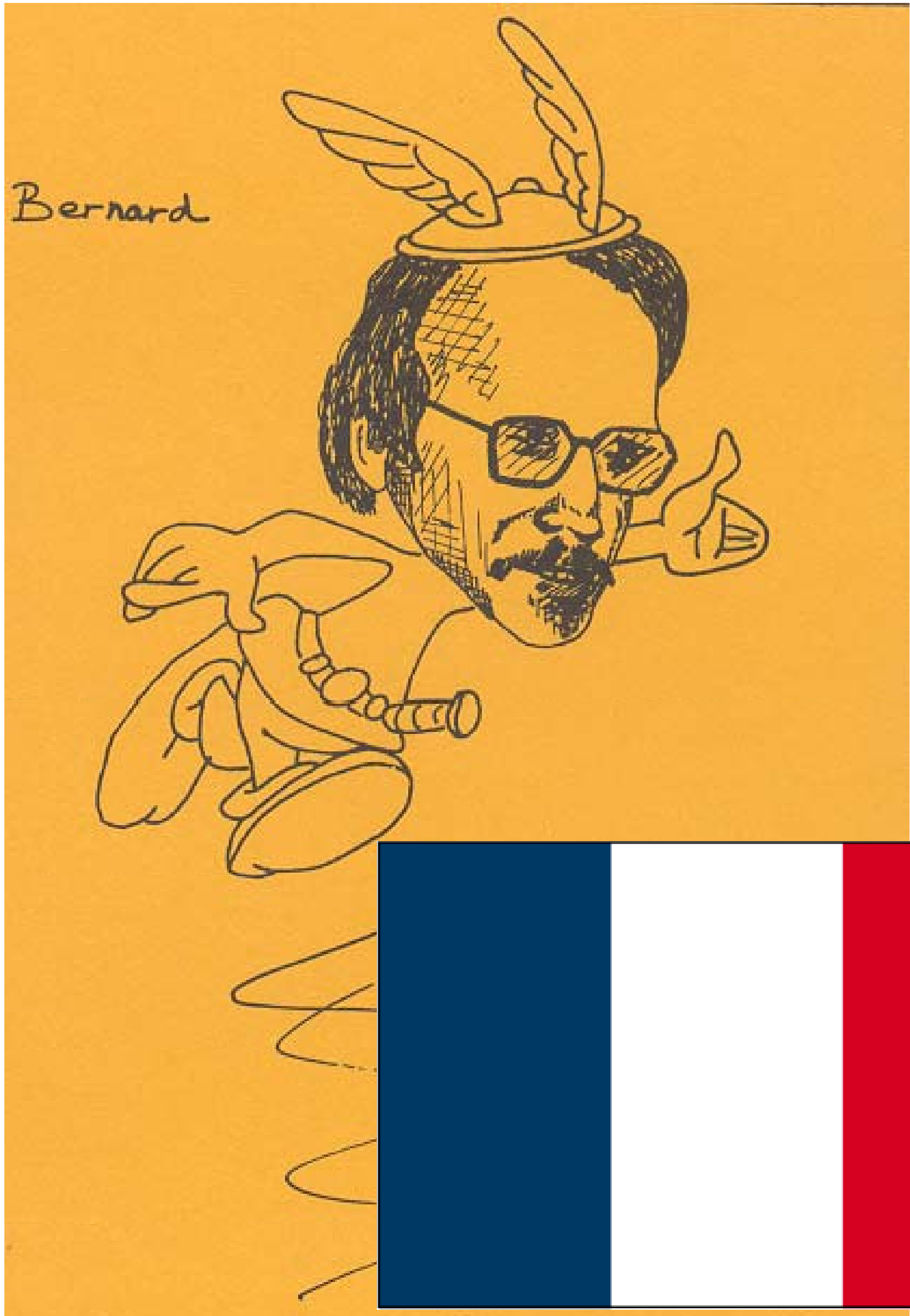
Pictures courtesy of Pierre Darriulat

Règle du jeu

Un joueur distribue les 42 cartes (le joker est une carte parfaitement inutile qui n'est pas distribuée). Si le nombre des joueurs n'est pas un diviseur de 42, certains d'entre eux auront une carte de moins que les autres. Le but du jeu est de rassembler le plus possible de familles complètes (il y a 7 familles de 6 cartes chacune).


FAMILLE SAINT-QUANTÔME
1
John


FAMILLE JET
4
Peter

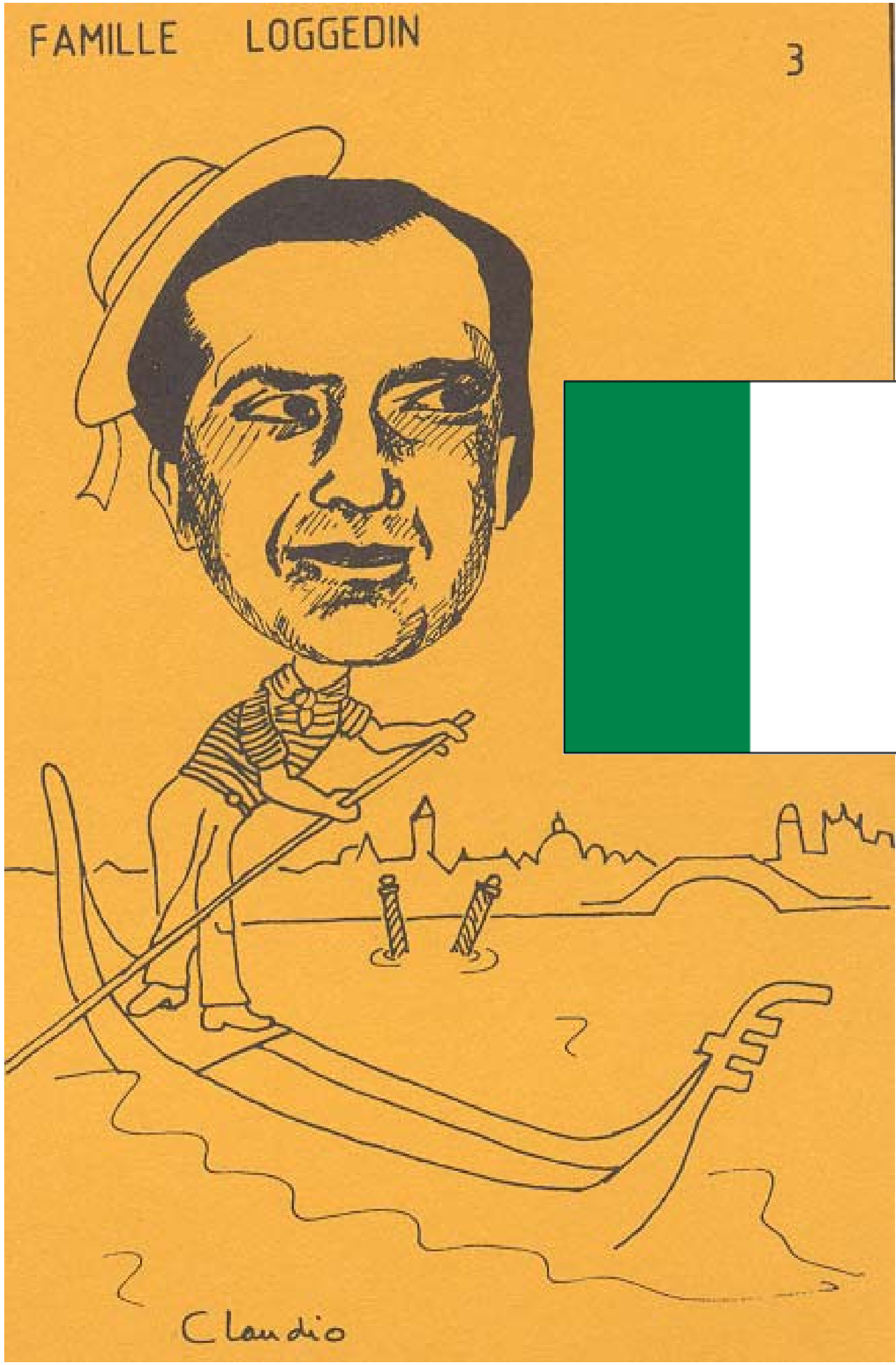


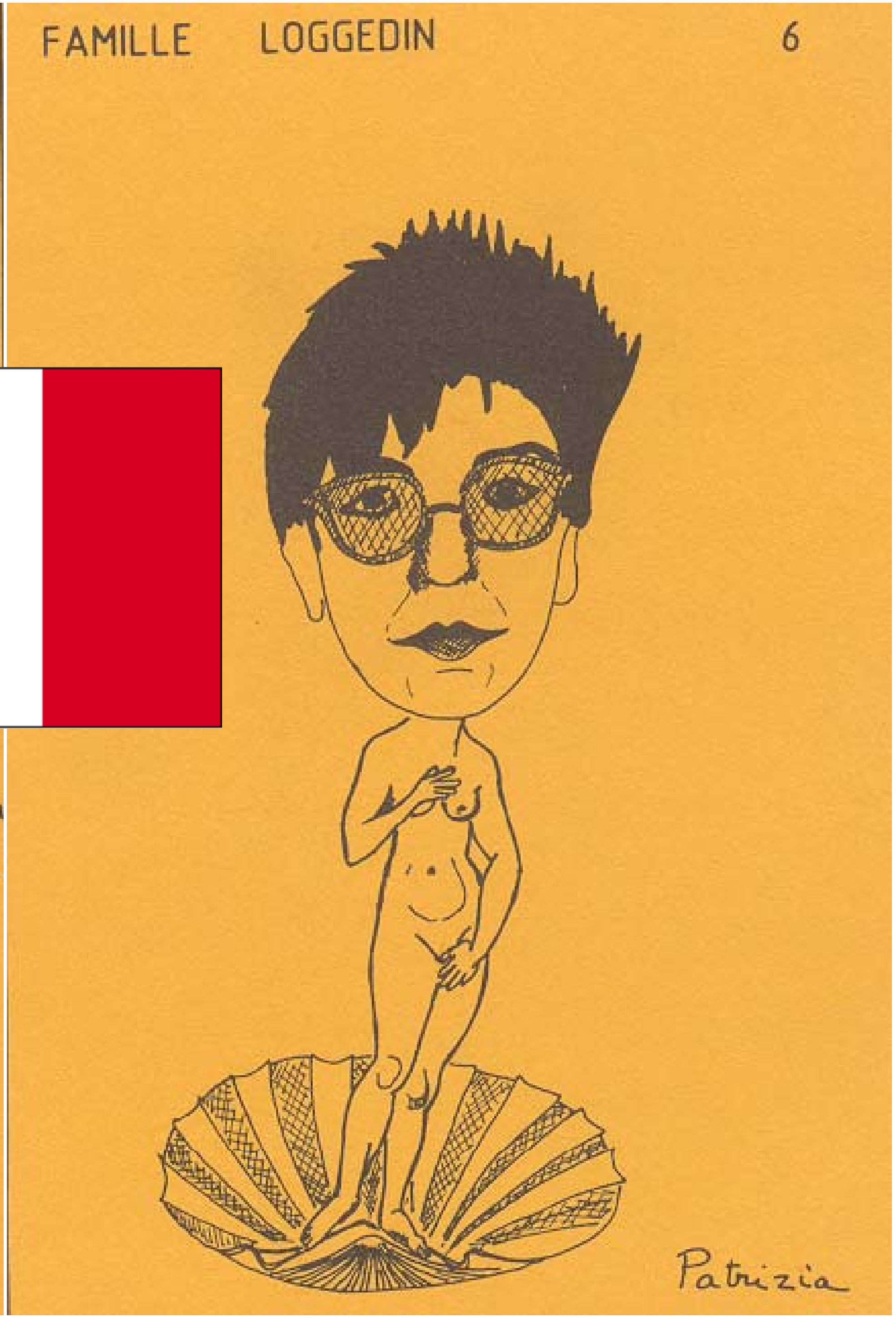
FAMILLE NUTSNBOLTS

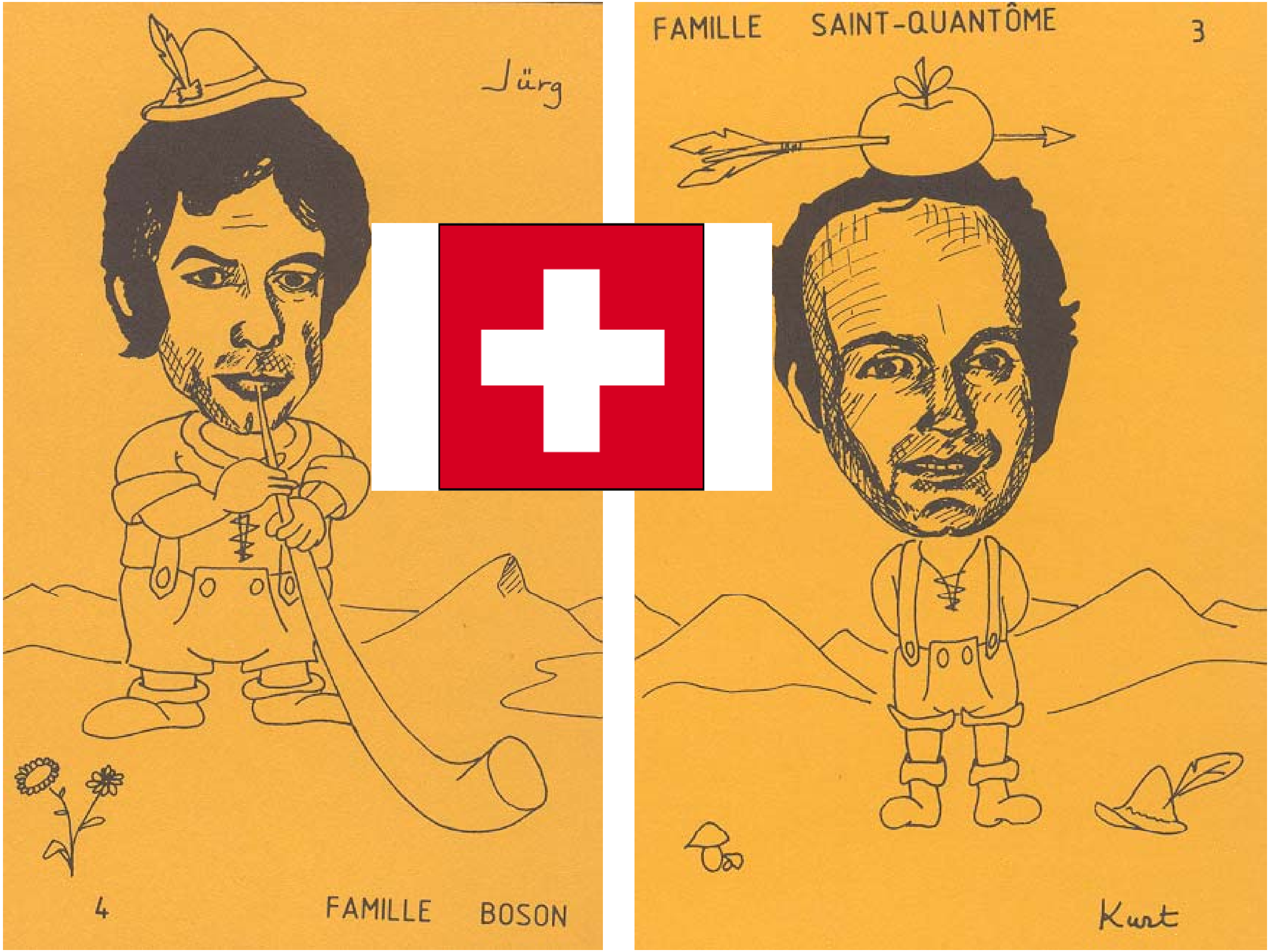
FAMILLE JET


FAMILLE TOURNEBANDE
3
Andy


6
FAMILLE JET
Tony


FAMILLE LOGGEDIN
3
Claudio


FAMILLE LOGGEDIN
6
Patrizia


Jürg
4
FAMILLE BOSON
FAMILLE SAINT-QUANTÔME
3
Kurt

Historical introduction

1984: Glimmerings of LHC and SSC

1987: First comparative studies of physics potential of hadron colliders (LHC/SSC) and e^+e^- linear colliders (CLIC)

1989: First collisions in LEP and SLC

Precision tests of the SM and search for the Higgs boson begin in earnest

R&D for LHC detectors begins

1993: Demise of the SSC

1994: LHC machine is approved (start in 2005)

1995: Discovery of the top quark at Fermilab by CDF (and D0)

Precision tests of the SM and search for the Higgs boson continue at LEP2

Approval of ATLAS and CMS

2000: End of LEP running

2001: LHC schedule delayed by two more years

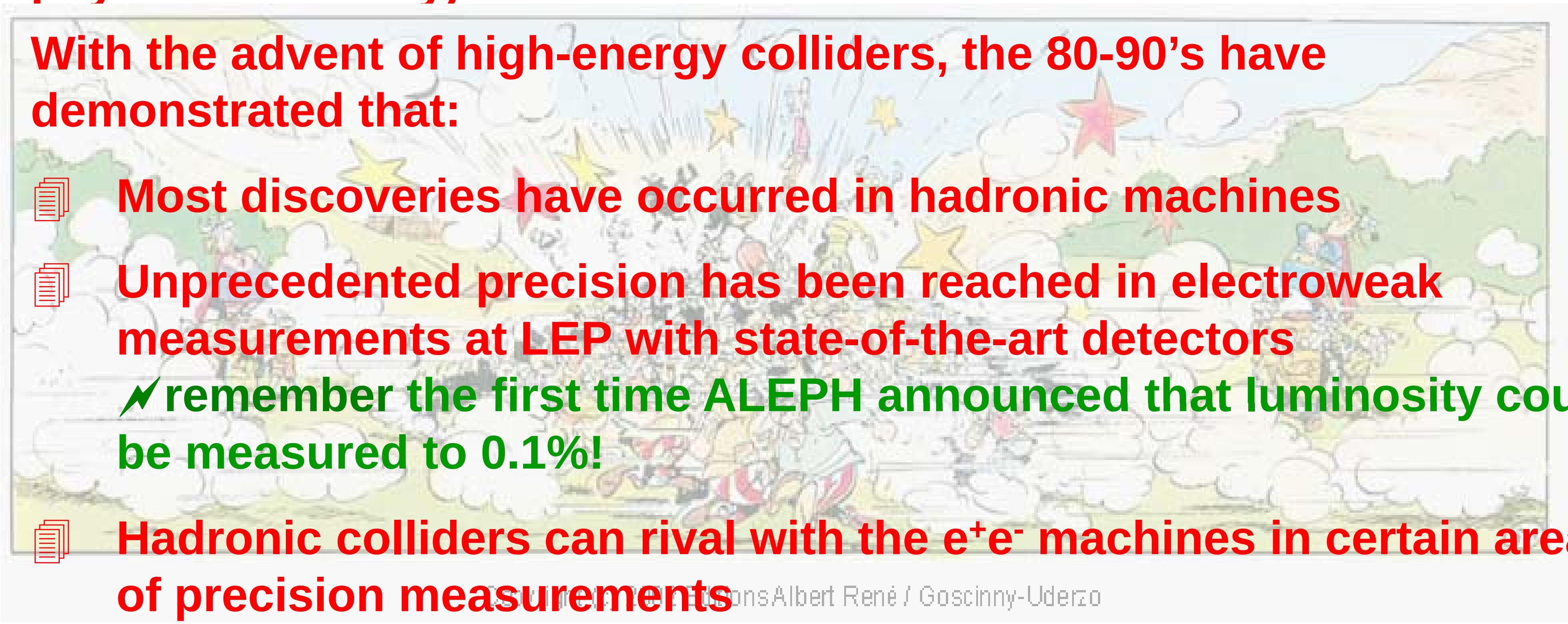
During the last 13 years, three parallel activities have been ongoing, all with impressive results:

1) Physics at LEP with a wonderful machine
2) Construction of the LHC machine
3) Construction of the LHC detectors after an initial very long R&D period

Historical introduction

What has been the evolution of our HEP culture over these past 30 years?

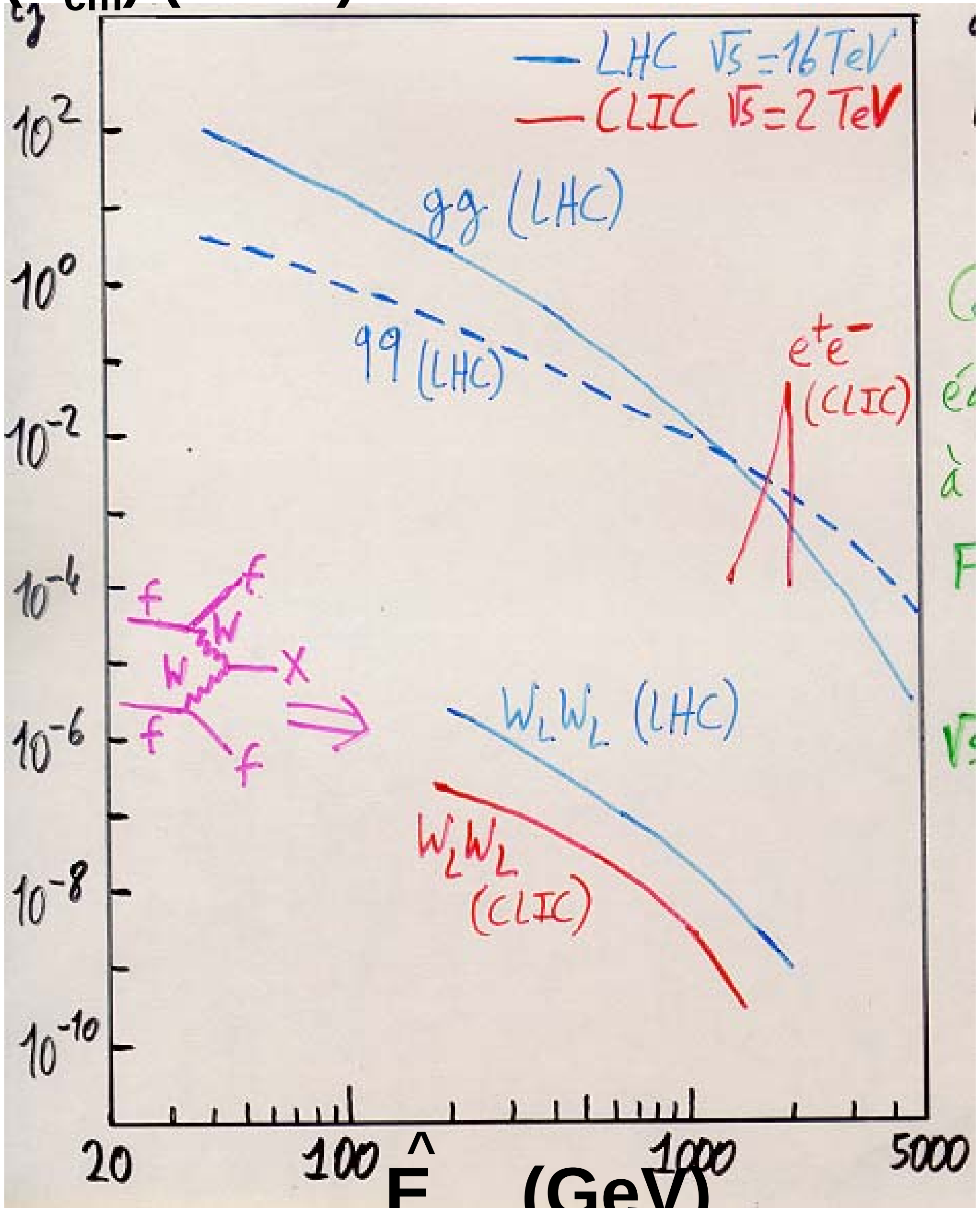
1. **In the 70-80's, the dogma was that e^+e^- physics was the only way to do clean and precise measurements and even discoveries (hadron physics were dirty).**
2. **With the advent of high-energy colliders, the 80-90's have demonstrated that:**



- **Most discoveries have occurred in hadronic machines**
- **Unprecedented precision has been reached in electroweak measurements at LEP with state-of-the-art detectors**
  - **remember the first time ALEPH announced that luminosity could be measured to 0.1%!**
- **Hadronic colliders can rival with the e^+e^- machines in certain areas of precision measurements**
  - **remember the almost simultaneous publication of the Z-mass measurements from CDF and SLC with comparable precision (200 MeV!)**
  - **even with Run I (100 pb^{-1}), CDF has been able to compete with LEP in the field of B-physics**

Historical introduction

$F_{ij}(\hat{E}_{cm})$ (GeV^{-1})



$\hat{E}_{cm}$ (GeV)

Parton luminosities $F_{ij}(\hat{E}_{cm})$

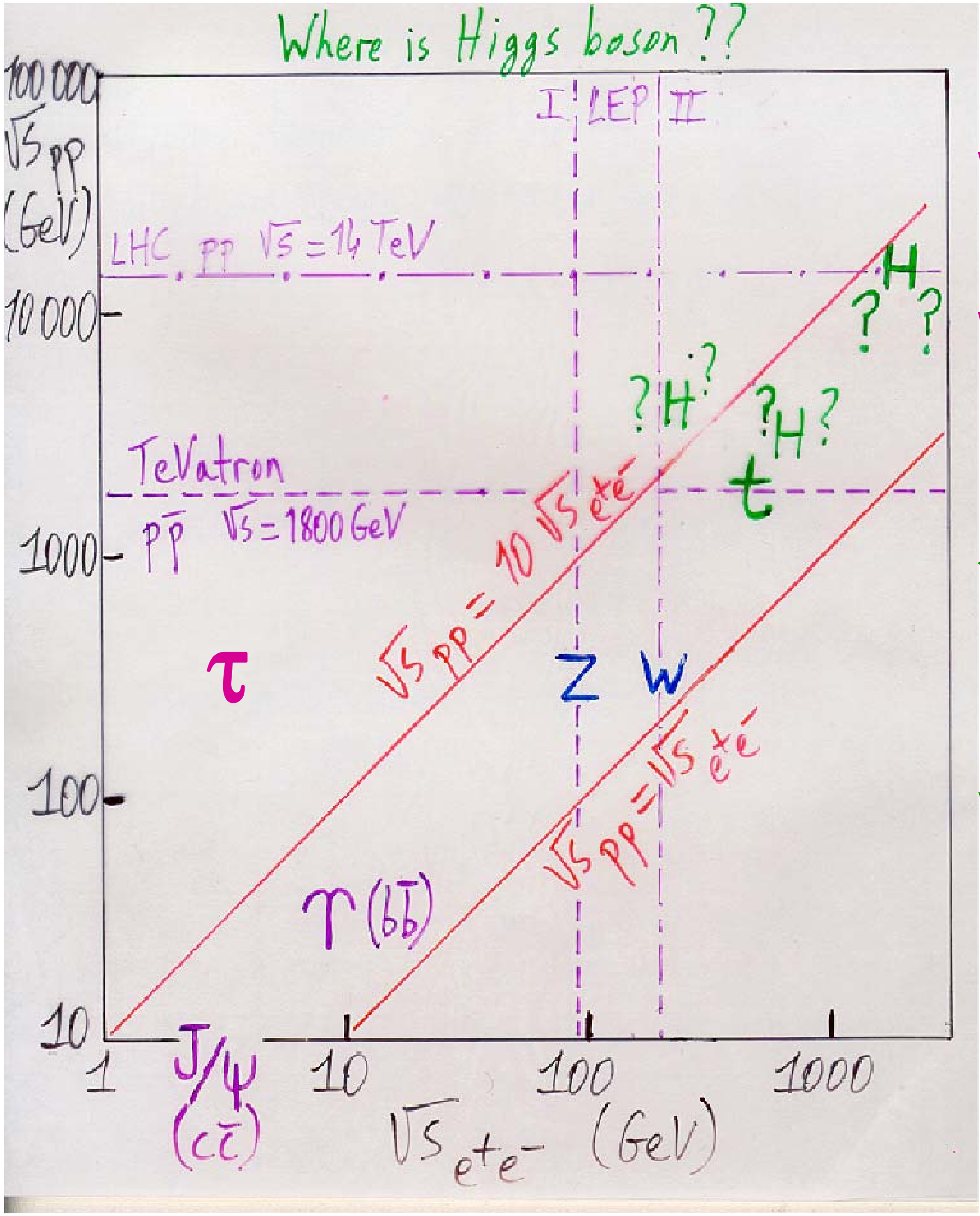
where $\hat{E}$cm is the centre-of-mass energy of two "partons" i and j,

are useful to compare intrinsic potential of different machines

Important to note that:

1. **as centre-of-mass energy grows, processes without beam-energy constraint such as vector-boson fusion become also important at e^+e^- machines;**
2. **Proton-proton collisions are equivalent to e^+e^- collisions for $\sqrt{s_{pp}} \approx 5\sqrt{s_{e+e-}}$**

Historical introduction



All particles in plot were discovered first at hadron machines with one notable exception:

- **the τ-lepton was (and could have been) observed only in vector-boson decays at the CERN proton-antiproton collider.**

Historical introduction

What has been the evolution of our HEP culture over these past 30 years?

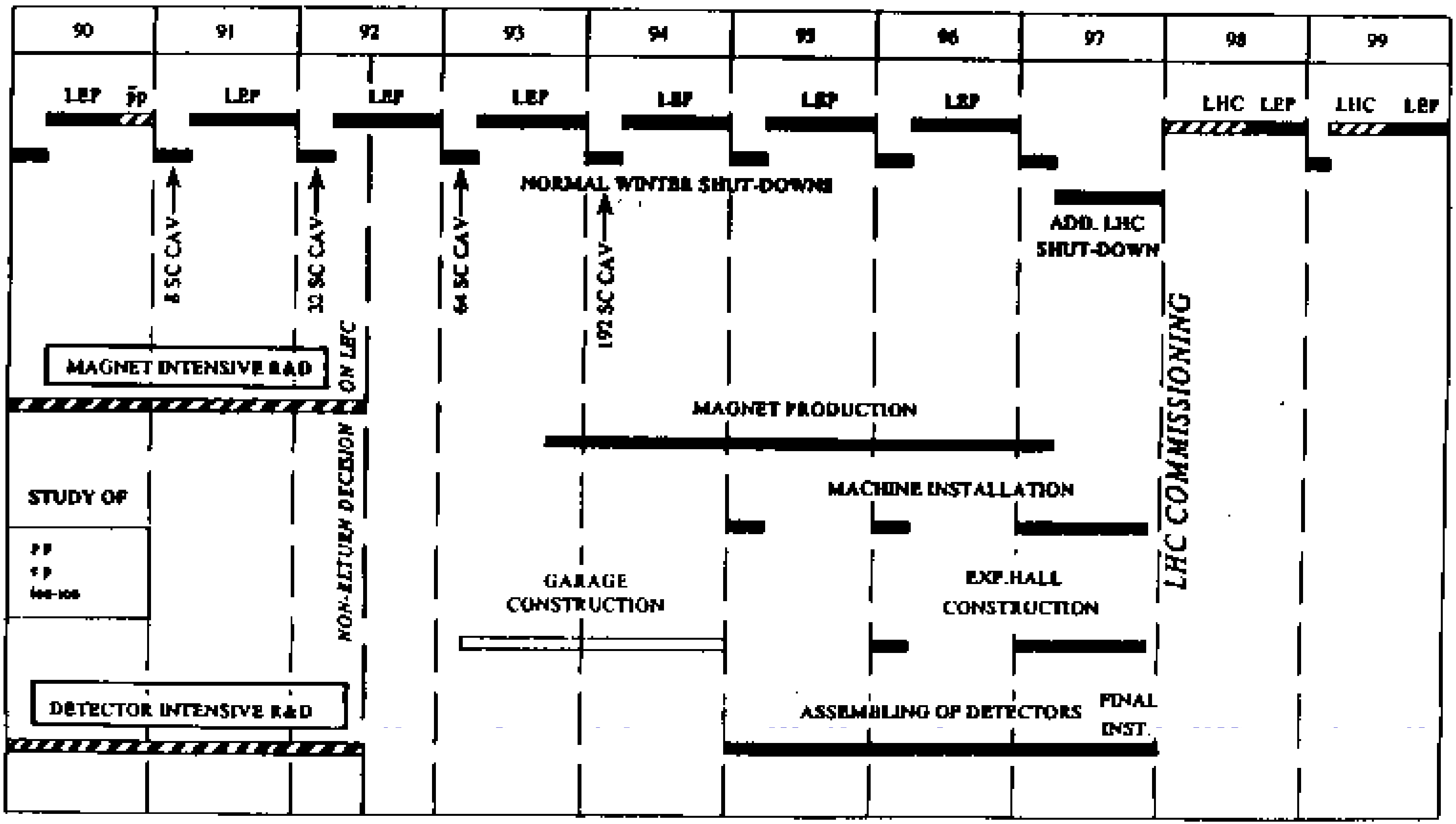
3. **Today's culture is the result of the experience gathered over the past years, which has displayed the nice feature, at least to experimentalists, of being largely unpredictable in terms of future measurements:**

- There is no doubt that Tevatron and LHC will do precision physics
  - ➚ see Lectures by A. Parker
- There is also no doubt that the ultimate precision physics on e.g. the lightest supersymmetric Higgs boson (h) cannot be done at the LHC but could be done at a future e^+e^- linear collider
- The ultimate precision which one needs can however be debated:
  - What would one really learn by measuring e.g. the $H \to cc$ branching ratio to 1% or m_{top} to 0.3 GeV in a machine like the ILC?
  - Measuring self-coupling of Higgs boson is a far more important task, which is unlikely to be fulfilled with good

Historical introduction

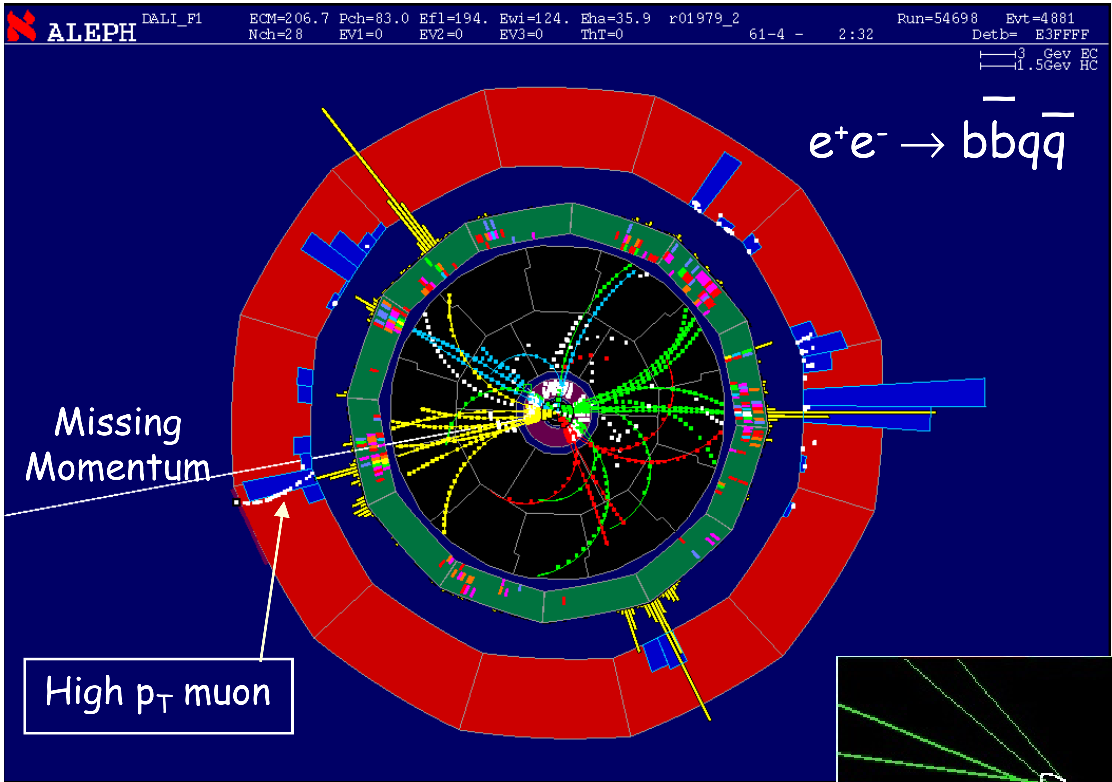
Possible LHC Schedule (as imagined in 1990)

LEP I: 1989 to 1993 **LEP II: 1994 to 1997** **LHC starts 1**



a better understanding of the fundamental aspects of high-energy

SM Higgs: direct searches at LEP2

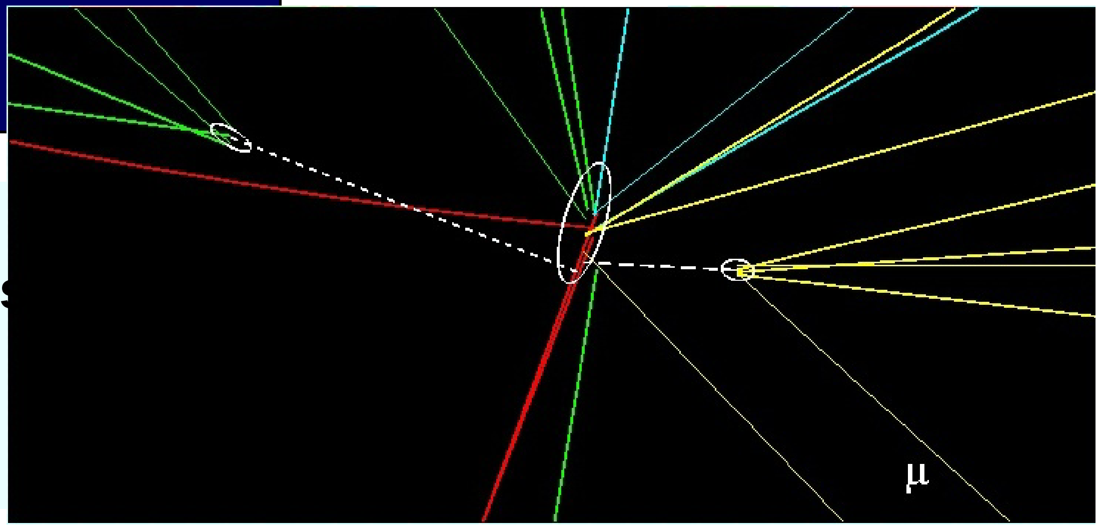


Golden 4-jet event
(ALEPH, 14/06/00, 206.7 GeV)

- **Mass 114 ± 3 GeV**
- **Good HZ fit**
- **Poor WW and ZZ fits**
- **P(Background) ≈ 2%**
- **s/b(115) = 4.6**

b-tagging
(0 = light quarks, 1 = b quarks

- **Higgs jets: 0.99 and 0.99;**
- **Z jets: 0.14 and 0.01.**



Higgs at LEP/SLD: conclusions

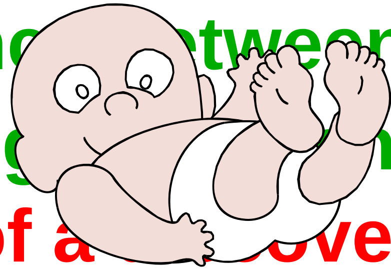
- SM Higgs-boson mass now quite constrained:

  $114.4 < m_H < \sim 200$ GeV at 95% C.L.

  from beautiful precision measurements and

  direct searches

- But some 2-3σ effects mar the beauty of the landscape:



...anc... etween A_{fb} and A_{LR}

...trig... nts at $m_H \approx 114$ GeV:

... of a ... overy or a statistical fluctuation ?

Baby HIGGS left by CERN in LEP
Size: 7σ
Weight: 115 GeV

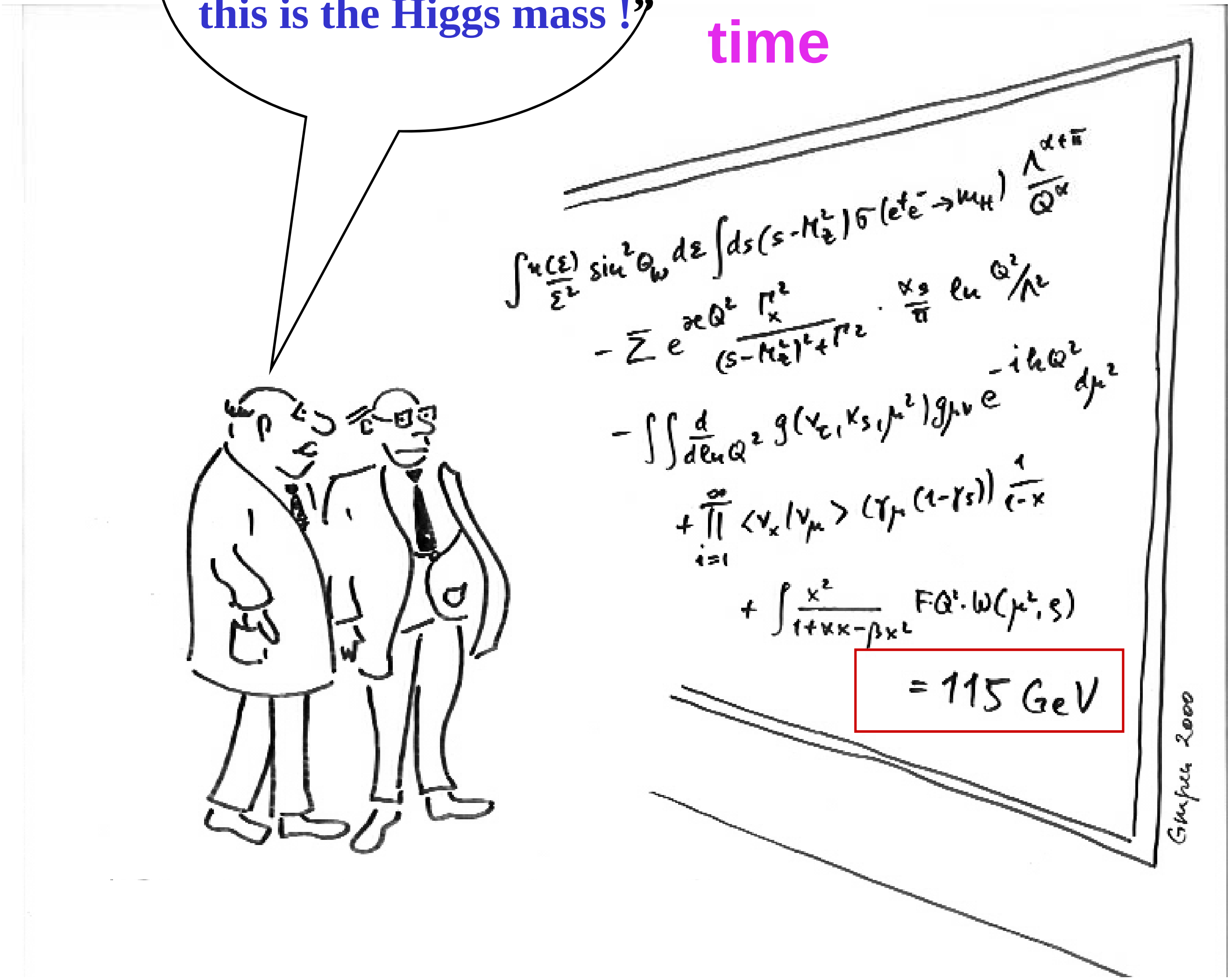
Dream of a few?? or Underlying reality??

Courtesy of P. Janot

Higgs at LEP: conclusions

"This does not necessarily mean that this is the Higgs mass !"

The number 115 GeV will remain stuck in our heads for quite some time



Tevatron ??
LHC ?
2010 (±1 year)?

How huge are ATLAS and CMS?

- **Size of detectors**
  - **Volume: 20 000 m^3 for ATLAS**
  - **Weight: 12 500 tons for CMS**
  - **66 to 80 million pixel readout channels near vertex**
  - **200 m^2 of active Silicon for CMS tracker**
  - **175 000 readout channels for ATLAS LAr EM calorimeter**
  - **1 million channels and 10 000 m^2 area of muon chambers**
  - **Very selective trigger/DAQ system (see lectures by A. Yagil)**
  - **Large-scale offline software and worldwide computing (GRID)**
- **Time-scale will have been about 25 years from first conceptual studies (Lausanne 1984) to solid physics results confirming that LHC will have taken over the high-energy frontier from Tevatron (early 2009?)**
- **Size of collaboration**
- **Number of meetings and Powerpoint slides to browse**

ATLAS Collaboration

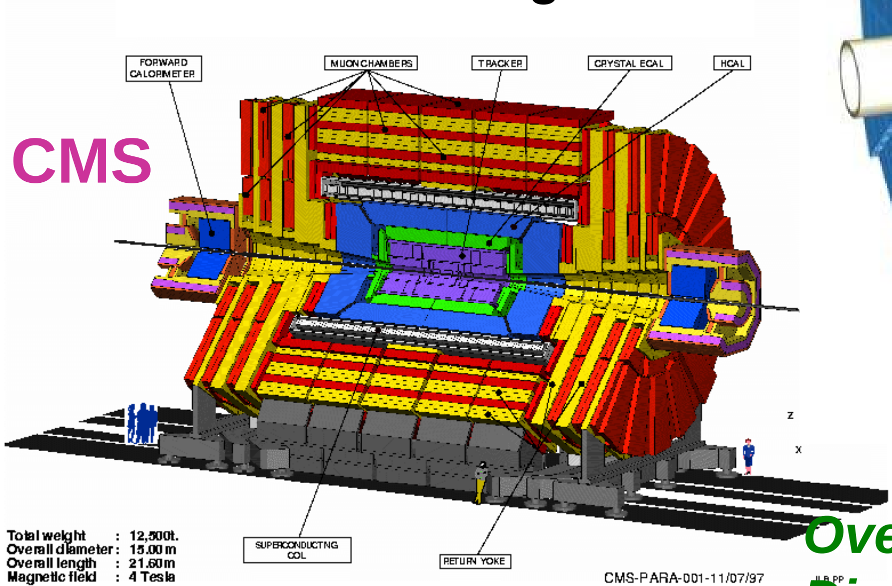
(As of July 2006)

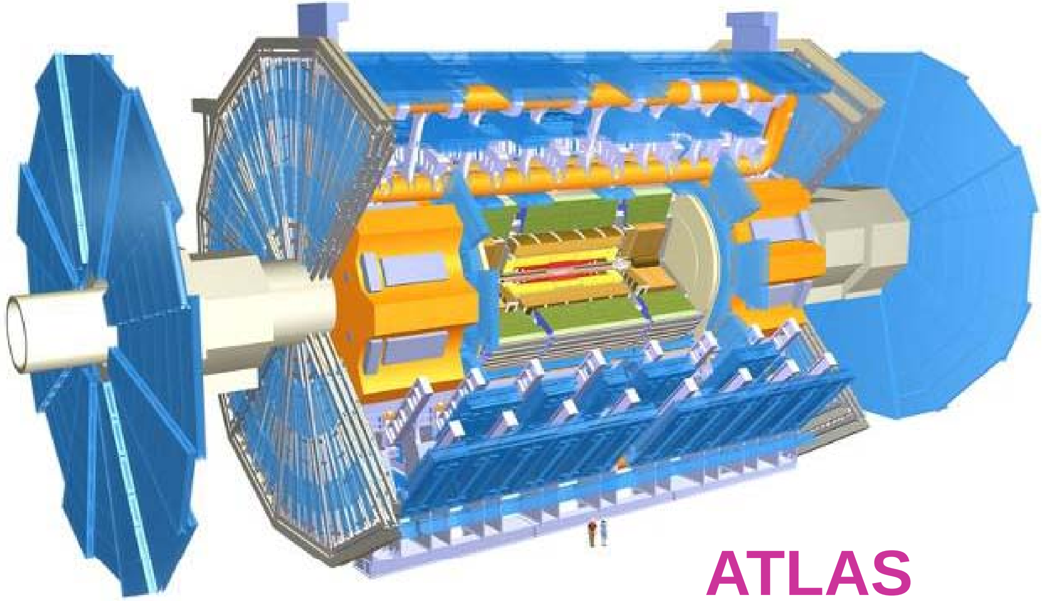
35 Countries
162 Institutions
1650 Scientific Authors
(1300 with a PhD)

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku,
IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, Bern, Birmingham, Bologna, Bonn, Boston, Brandeis,
Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, Casablanca/Rabat, CERN, Chinese Cluster, Chicago, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, DESY, Dortmund,
TU Dresden, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima, Hiroshima IT, Humboldt U Berlin, Indiana, Innsbruck, Iowa SU, Irvine UC, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, UN
La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, FIAN Moscow,
ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Naples, Naruto UE, New Mexico, New York U, Nijmegen, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa,
Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Ritsumeikan, UFRJ Rio de Janeiro, Rochester, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby,
Southern Methodist Dallas, NPI Petersburg, SLAC, Stockholm, KTH Stockholm, Stony Brook, Sydney, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Toronto, TRIUMF, Tsukuba, Tufts, Udine, Uppsala, Urbana UI, Valencia, UBC Vancouver, Victoria, Washington, Weizmann Rehovot,
Wisconsin, Wuppertal, Yale, Yerevan

How huge are ATLAS and CMS?

ATLAS superimposed to the 5 floors of building 40

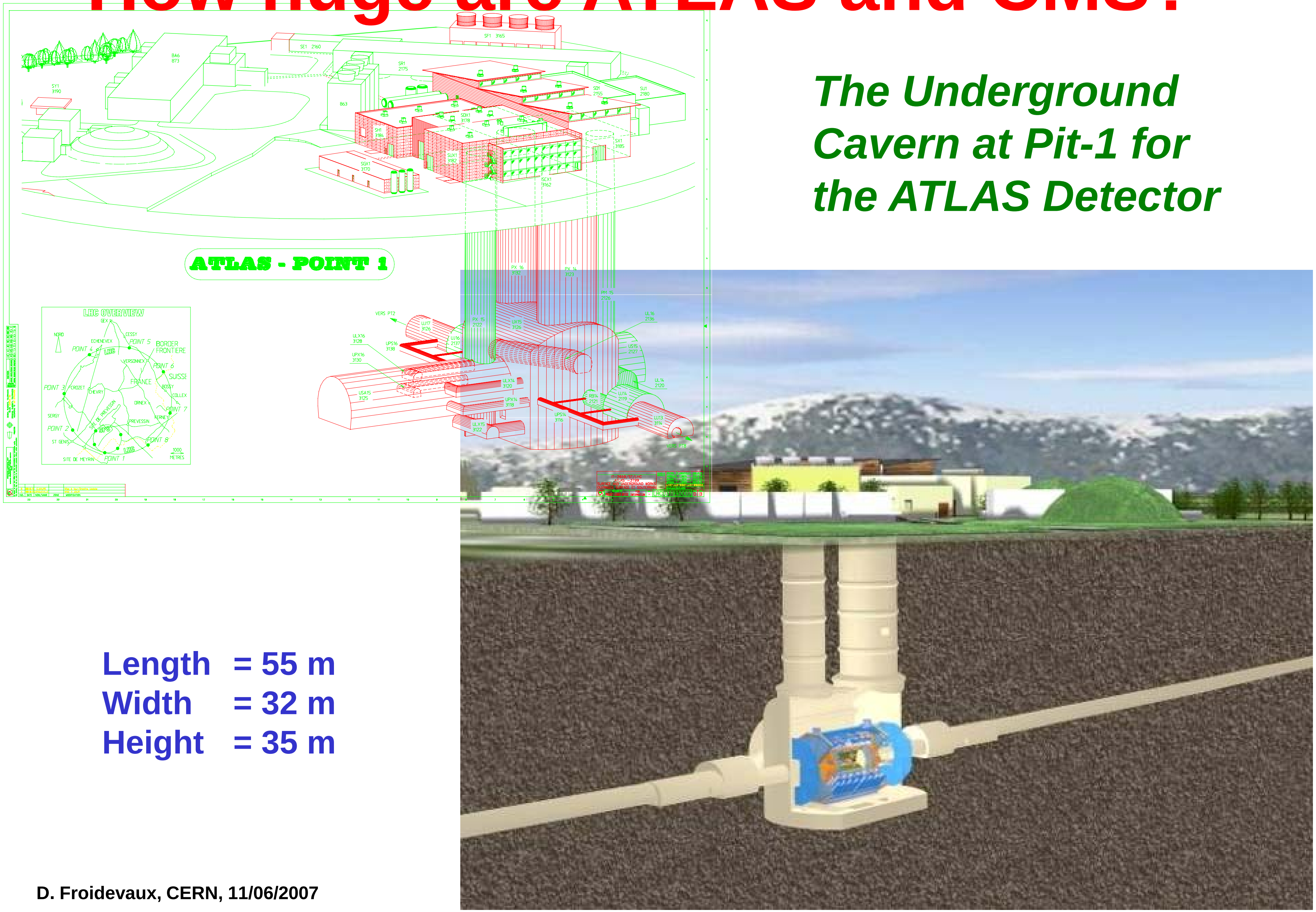




ATLAS

	ATLAS	CMS
Overall weight (tons)	*7000*	*12500*
Diameter	*22 m*	*15 m*
Length	*46 m*	*22 m*
Solenoid field	*2 T*	*4 T*

How huge are ATLAS and CMS?



The Underground Cavern at Pit-1 for the ATLAS Detector

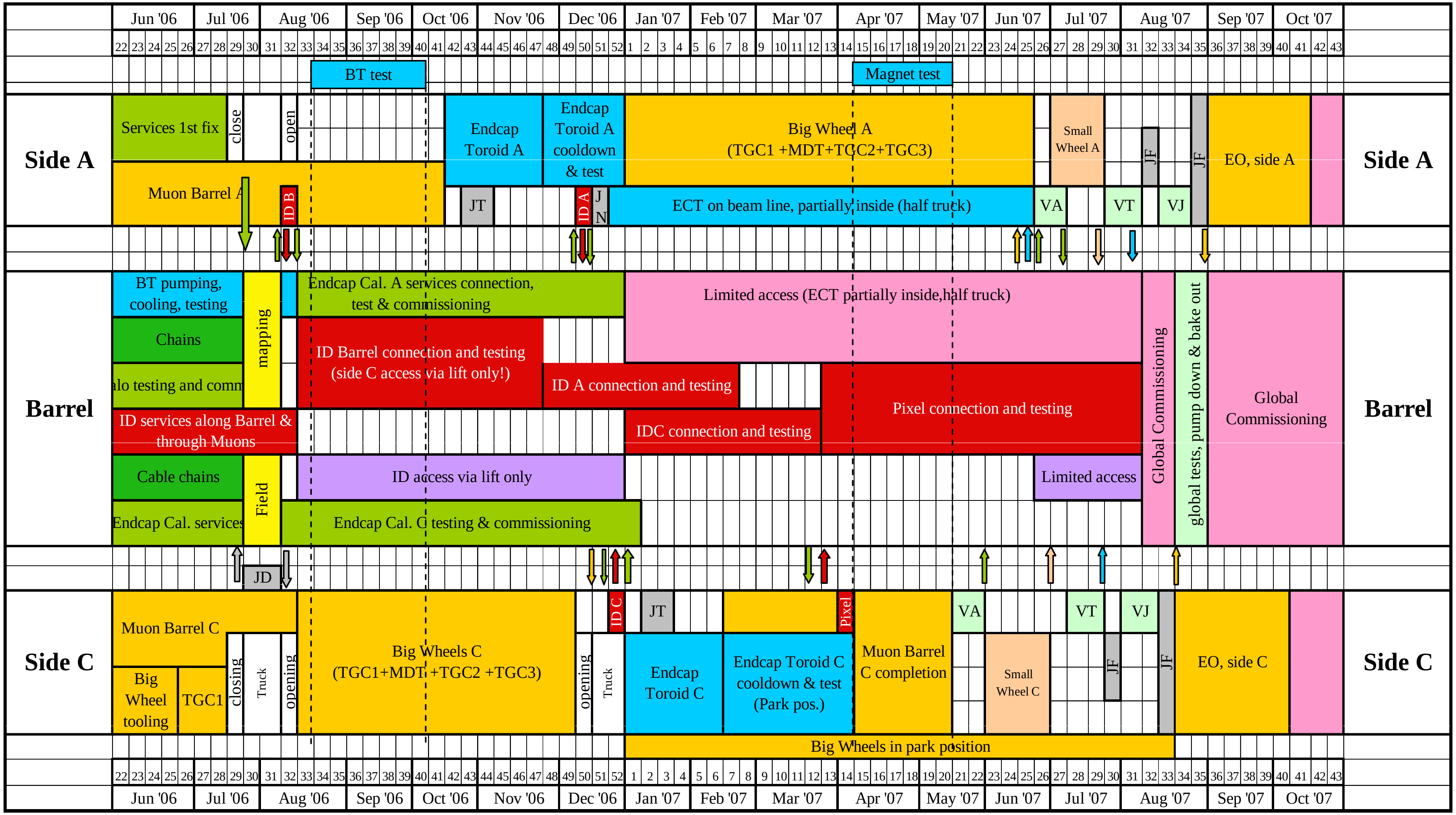
Length = 55 m
Width = 32 m
Height = 35 m

How huge are ATLAS and CMS?

An Aerial View of Point-1

(Across the street from the CERN main entrance)

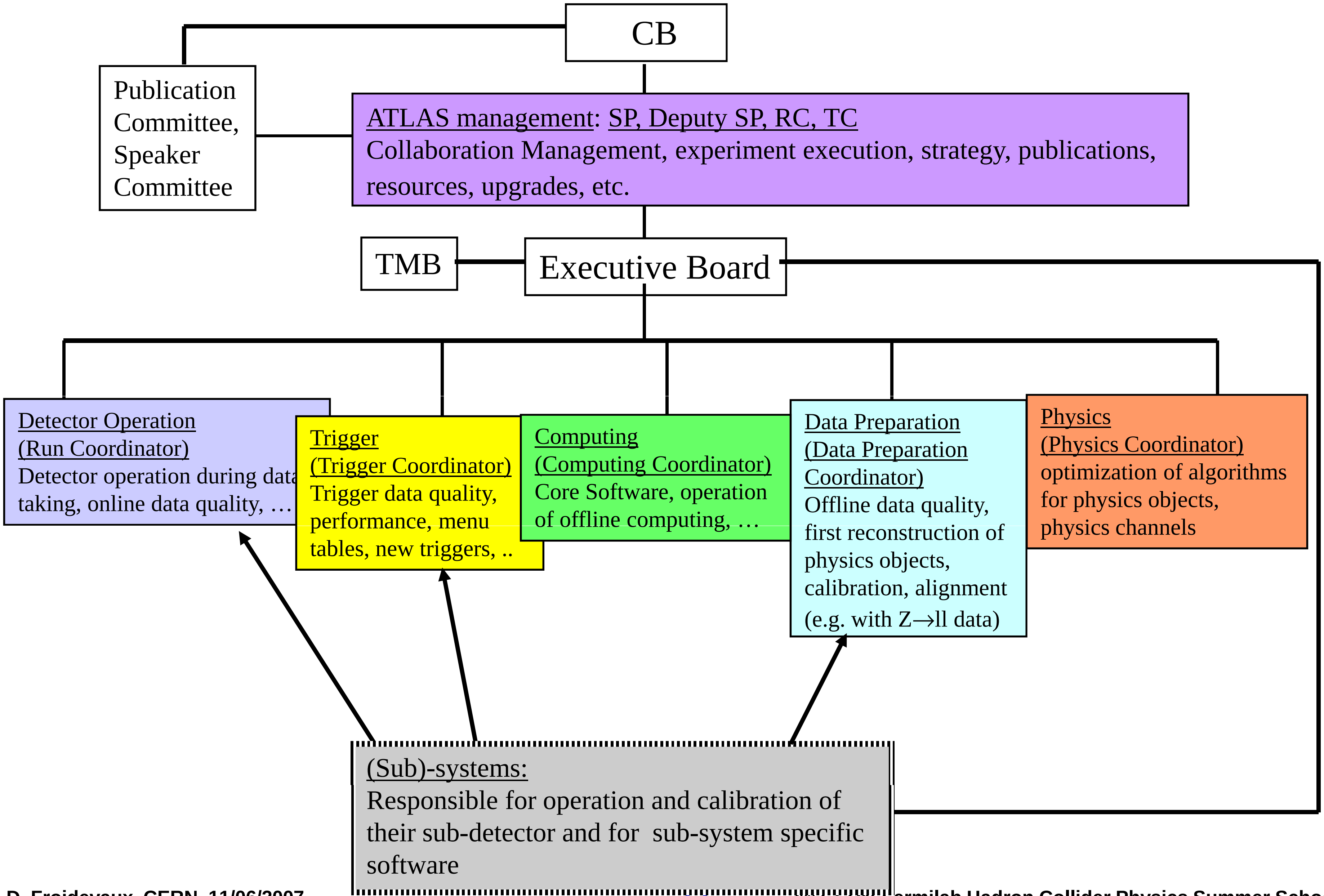
ATLAS Installation Schedule Version 8.0



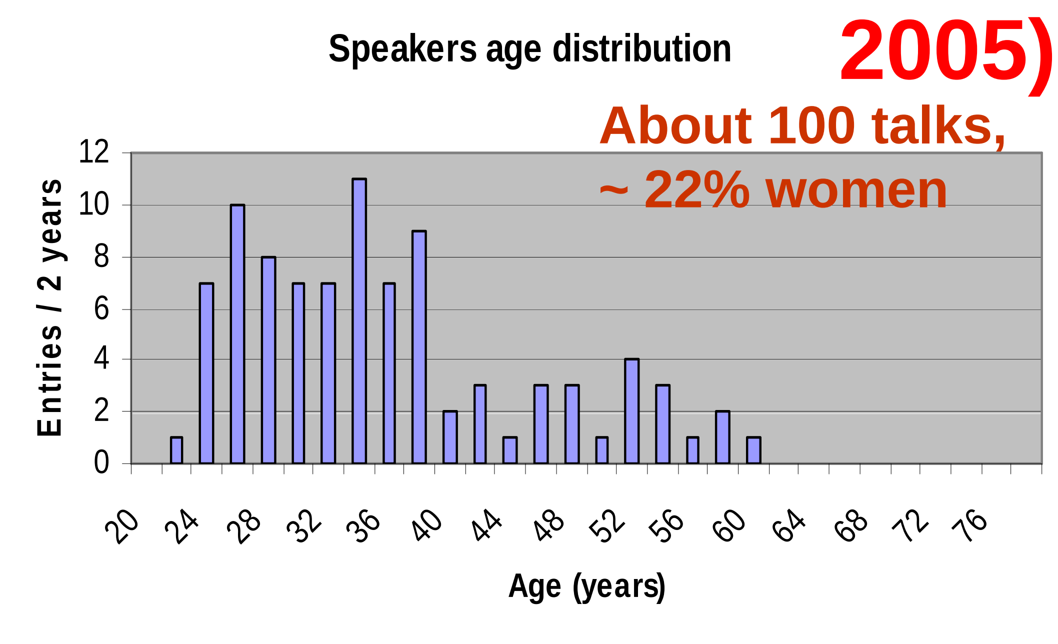
- Beam pipe in place end of August 2007
- Restricted access to complete end-wall muon chambers and global commissioning until mid-Oct 2007
- Ready for collisions from mid-October 2007

Operation Model (Organization for LHC Exploitation)

(Details can be found at http://uimon.cern.ch/twiki//bin/view/Main/OperationModel)



ATLAS physics workshop in Rome (June 2005)



About 100 talks, ~ 22% women

~ 450 participants

Generic features required of ATLAS and CMS

- **Detectors must survive for 10 years or so of operation**
  - **Radiation damage to materials and electronics components**
  - **Problem pervades whole experimental area (neutrons): NEW!**

- **Detectors must provide precise timing and be as fast as feasible**
  - **25 ns is the time interval to consider: NEW!**

- **Detectors must have excellent spatial granularity**
  - **Need to minimise pile-up effects: NEW!**

- **Detectors must identify extremely rare events, mostly in real time**
  - **Lepton identification above huge QCD backgrounds (e.g. e/jet ratio at the LHC is ~ 10^{-5}, i.e. ~ 100 worse than at Tevatron)**
  - **Signal X-sections as low as 10^{-14} of total X-section: NEW!**

Generic features required of ATLAS and CMS

- Detectors must measure and identify according to certain specs
  - Tracking and vertexing: ttH with H $\rightarrow$ bb
  - Electromagnetic calorimetry: H $\rightarrow \gamma\gamma$ and H $\rightarrow$ ZZ $\rightarrow$ eeee
  - Muon spectrometer: H $\rightarrow$ ZZ $\rightarrow \mu\mu\mu\mu$
  - Missing transverse energy: supersymmetry, H $\rightarrow \tau\tau$
- Detectors must please
  - Collaboration: physics optimisation, technology choices
  - Funding agencies: affordable cost (originally set to 475 MCHF per experiment by CERN Council and management)
  - Young physicists who will provide the main thrust to the scientific output of the collaborations: how to minimise formal aspects? How to recognise individual contributions?

Review article on ATLAS and CMS as built (DF and P. Sphicas) at

Higgs at the LHC: the challenge