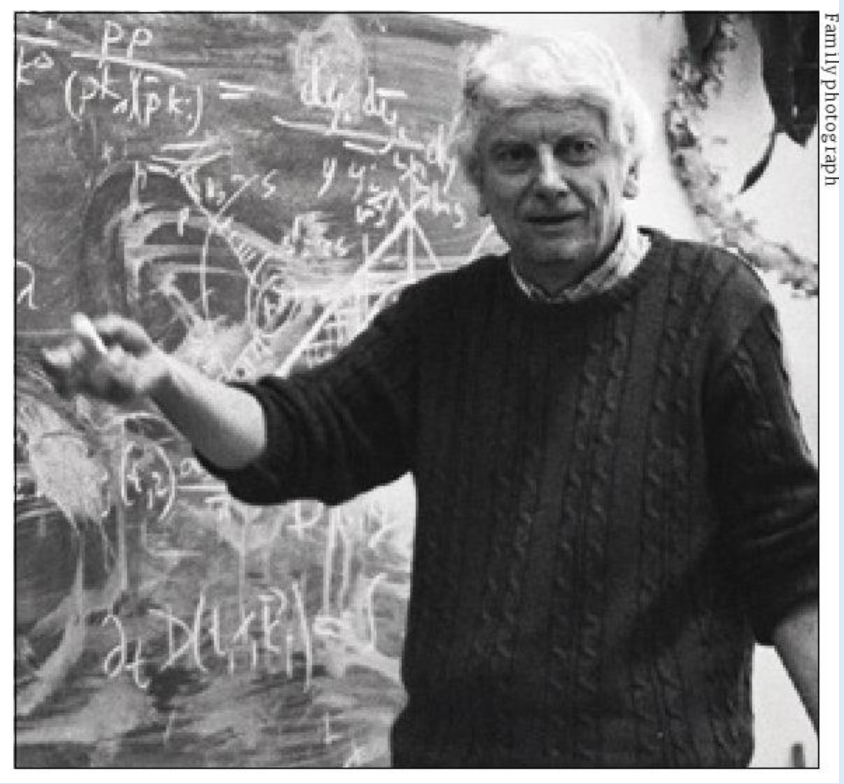
The Discovery of the Standard Model

\-\-\-

A subjective stroll

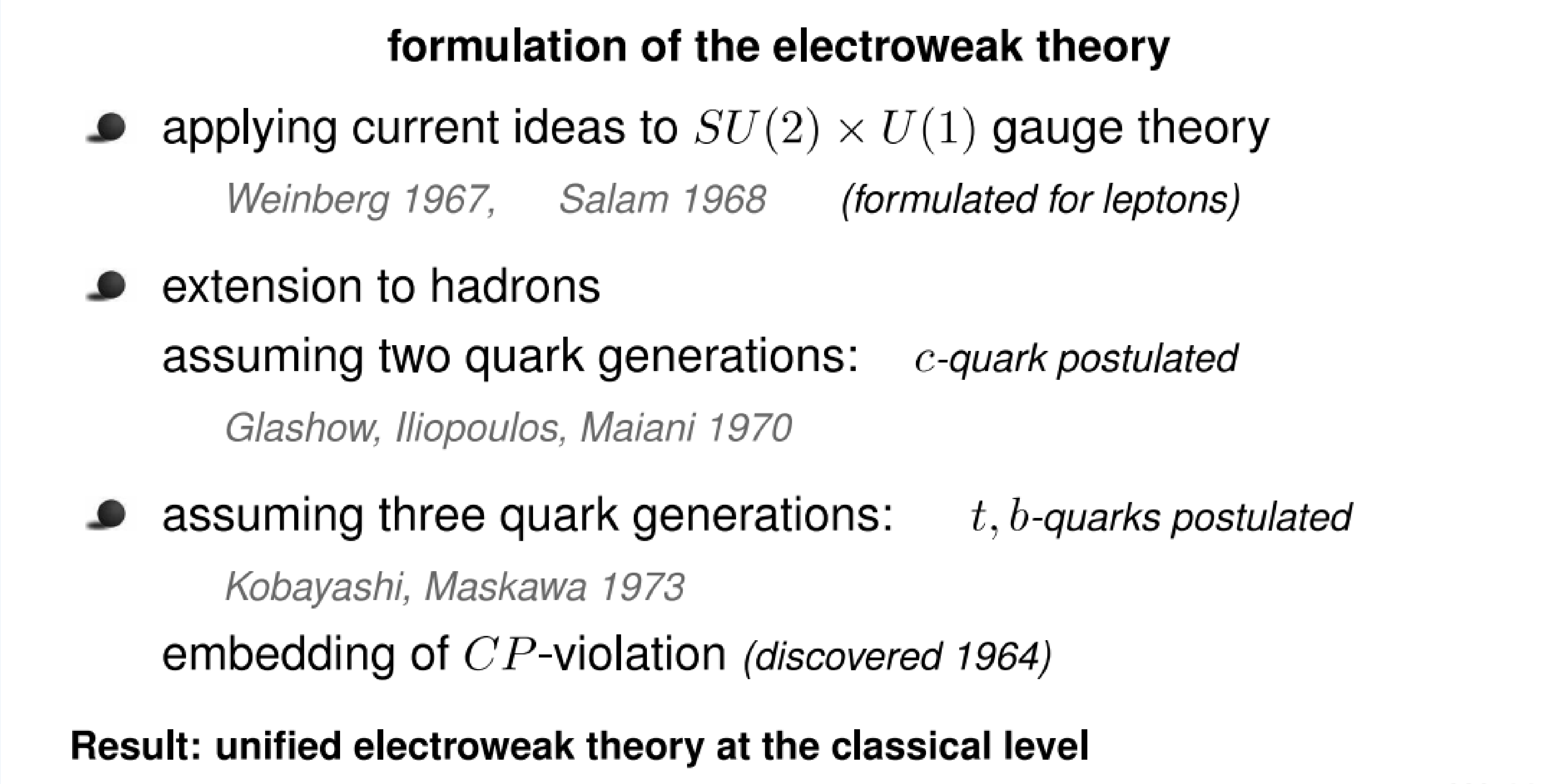
From PETRA to the LHC and beyond

Precision matters



Family photograph

late 60ies, early 70ies



formulation of the electroweak theory

- applying current ideas to $SU(2) \times U(1)$ gauge theory

  Weinberg 1967, *Salam 1968* *(formulated for leptons)*

- extension to hadrons

  assuming two quark generations: c*-quark postulated*

  Glashow, Iliopoulos, Maiani 1970

- assuming three quark generations: t, b*-quarks postulated*

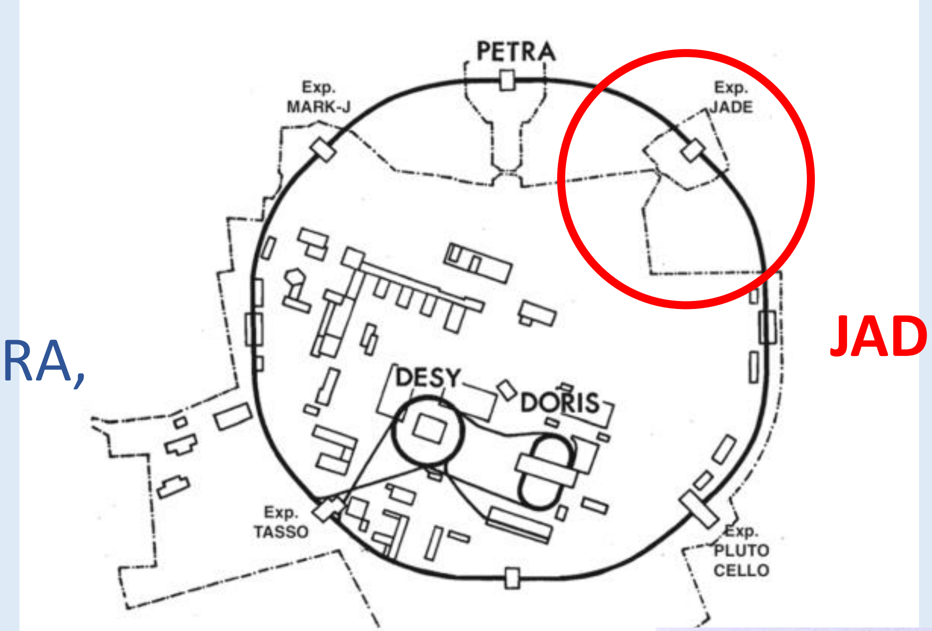
  Kobayashi, Maskawa 1973

  embedding of CP-violation *(discovered 1964)*

Result: unified electroweak theory at the classical level

W. HOLLIK

1978 at DESY

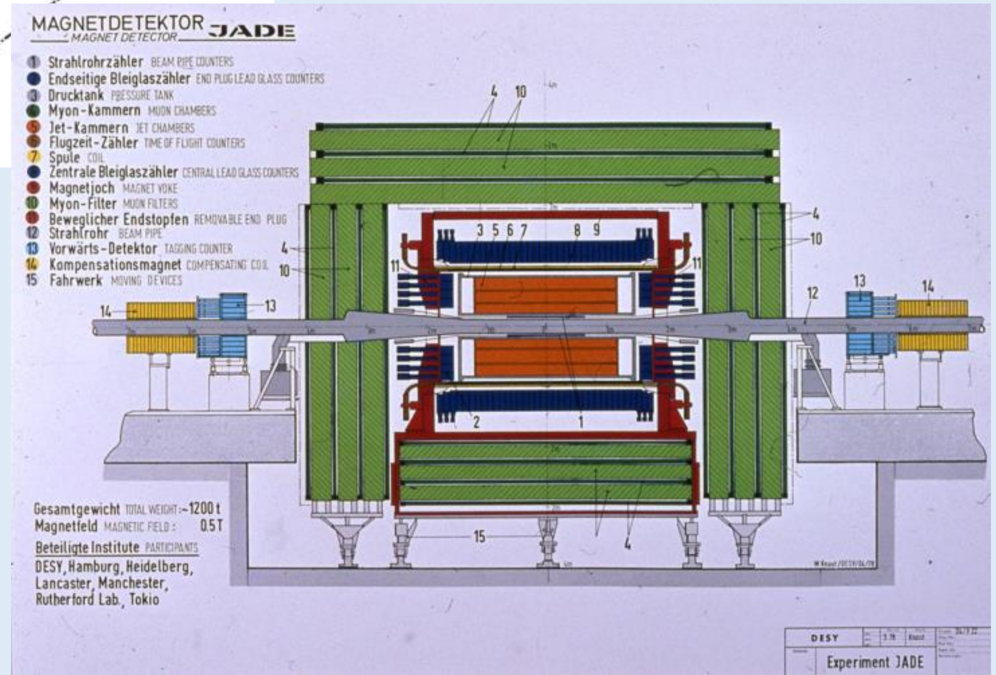


JADE

First beams were stored in PETRA, the new e+e- storage ring

Max Energy PETRA: 47 GeV

4 experiments had been installed JADE, MARK-J, PLUTO (Cello), TASSO



JADE: Carefully selected typical events

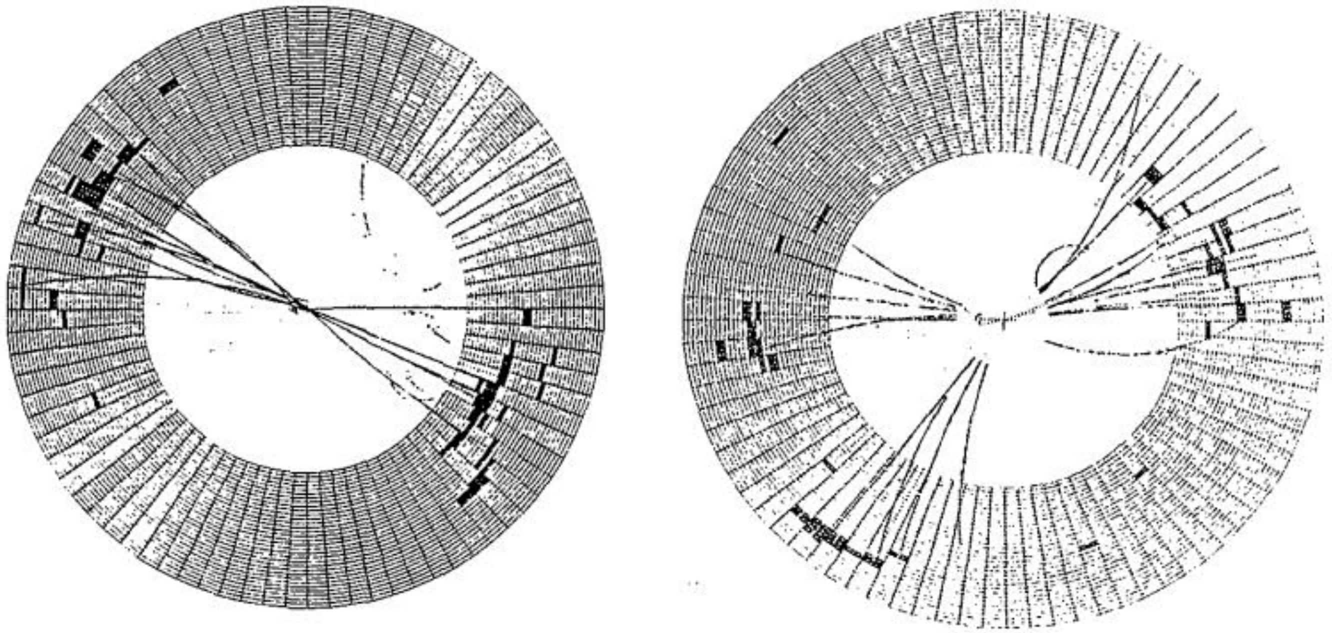


Figure 5.1: Examples of a two jet and a three jet event in the JADE detector

“nicest” event displays available at that time

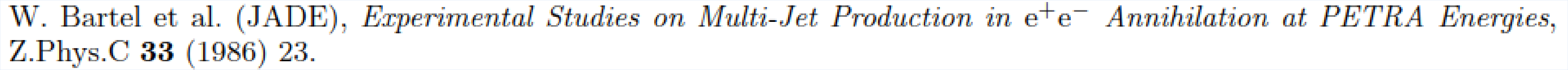
Planar events are the signature for gluon radiation

Discovery of the gluon

A jet is simply a highly collimated bunch of particles (calorimeter cells, tracks, etc.) that can (easily) be found after a visual analysis of events.

But to compare observables based on jet momenta with a theory, one needs an objective and unambiguous jet definition to be used by experimentalists and theorists on an equal footing.

Most used algorithm for jet definitions at the time



W. Bartel et al. (JADE), *Experimental Studies on Multi-Jet Production in* e^+e^- *Annihilation at PETRA Energies*, Z.Phys.C **33** (1986) 23.

optimal for α_S determination studies, setting the standard for a long time

Thrust distributions for different √s

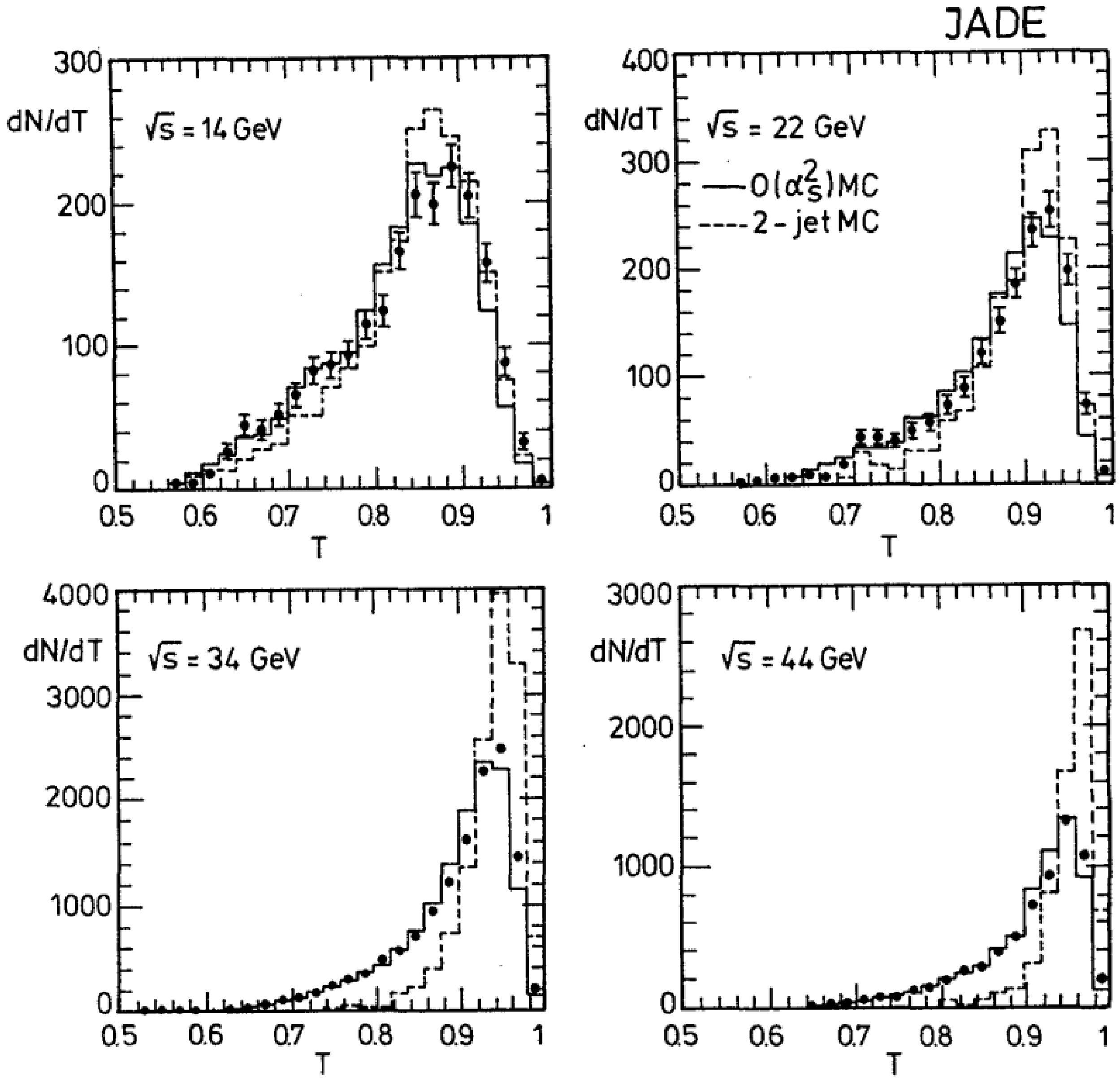
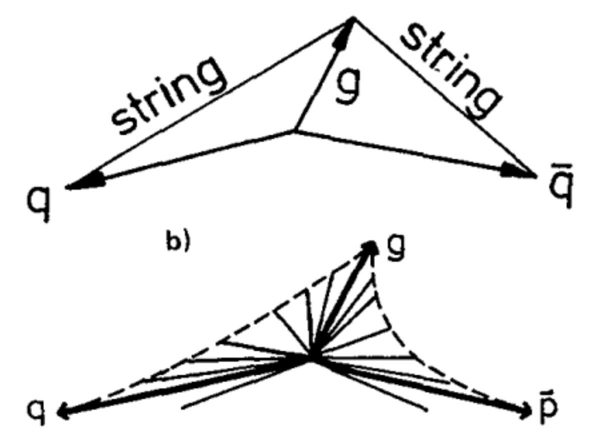


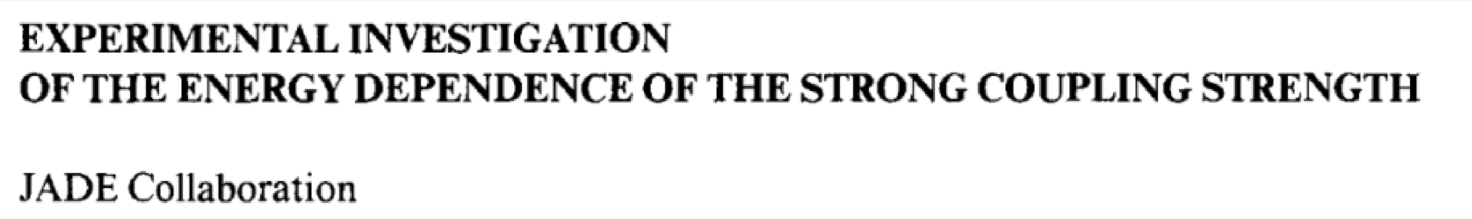
Figure 5.2: Thrust Distributions at four centre-of-mass energies compared with two models: The dotted line was calculated for two jet events and σ_q=265 MeV, the full line is from a model (Lund) which contains gluon emission.



Excellent agreement with the Lund Model

1988

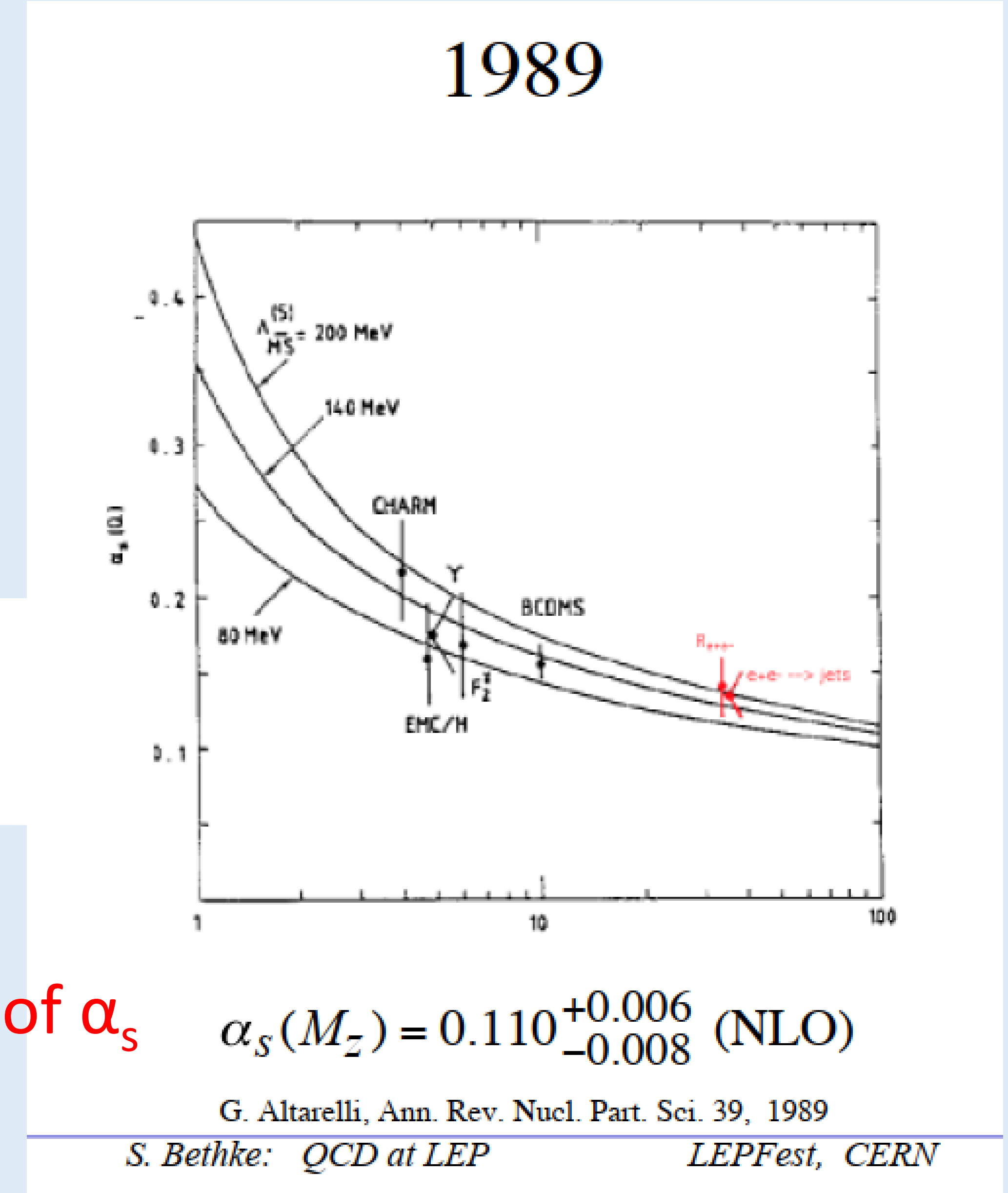
JADE published its studies of jet production rates in the energy range from 22 to 46.7 GeV, and published the first



EXPERIMENTAL INVESTIGATION
OF THE ENERGY DEPENDENCE OF THE STRONG COUPLING STRENGTH

JADE Collaboration

Energy dependence of α_s



1989

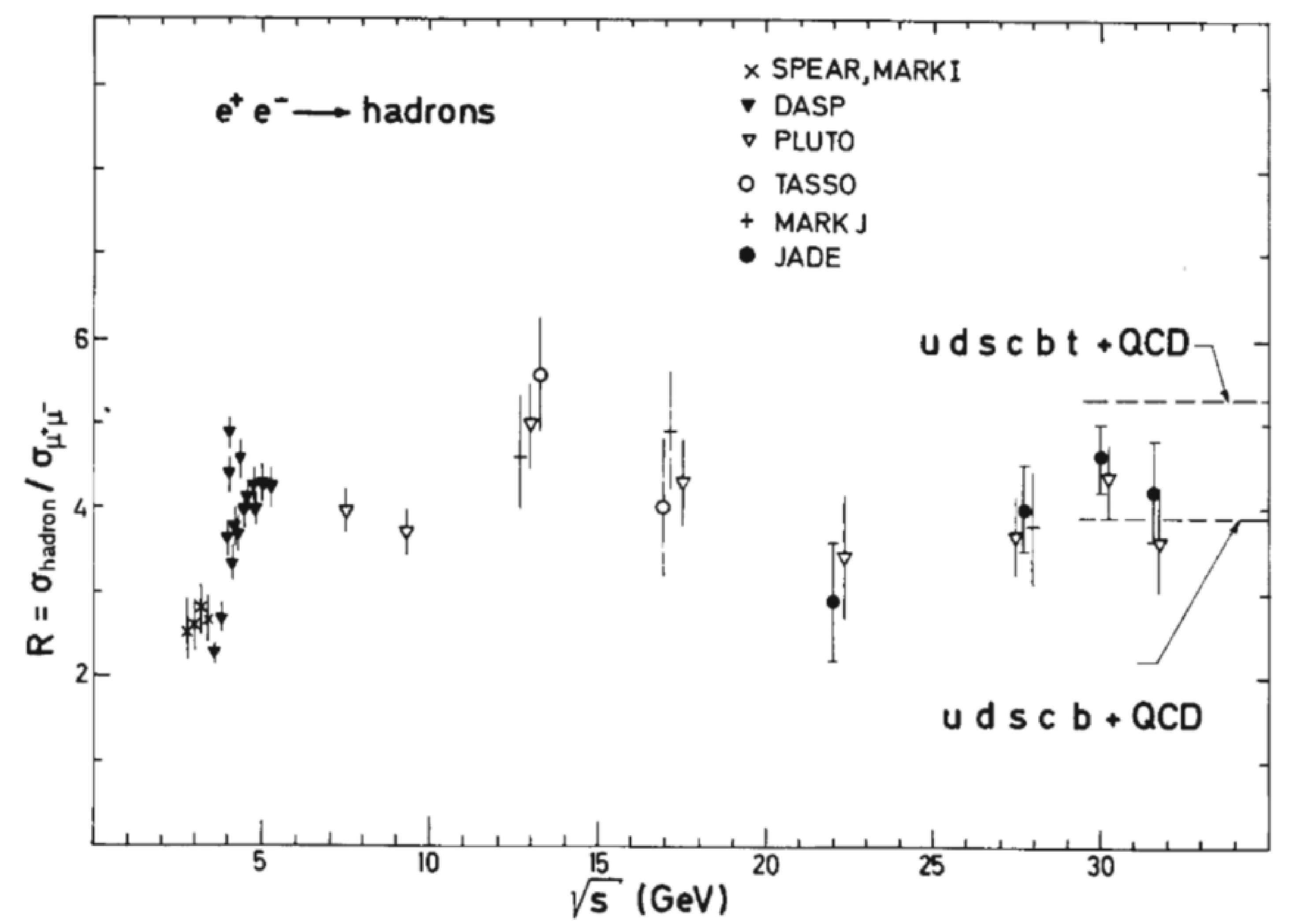
$$\alpha_S(M_Z) = 0.110^{+0.006}_{-0.008} \text{ (NLO)}$$

G. Altarelli, Ann. Rev. Nucl. Part. Sci. 39, 1989

S. Bethke: QCD at LEP *LEPFest, CERN*

But we expected more:

All experiments at PETRA were searching for the top quark



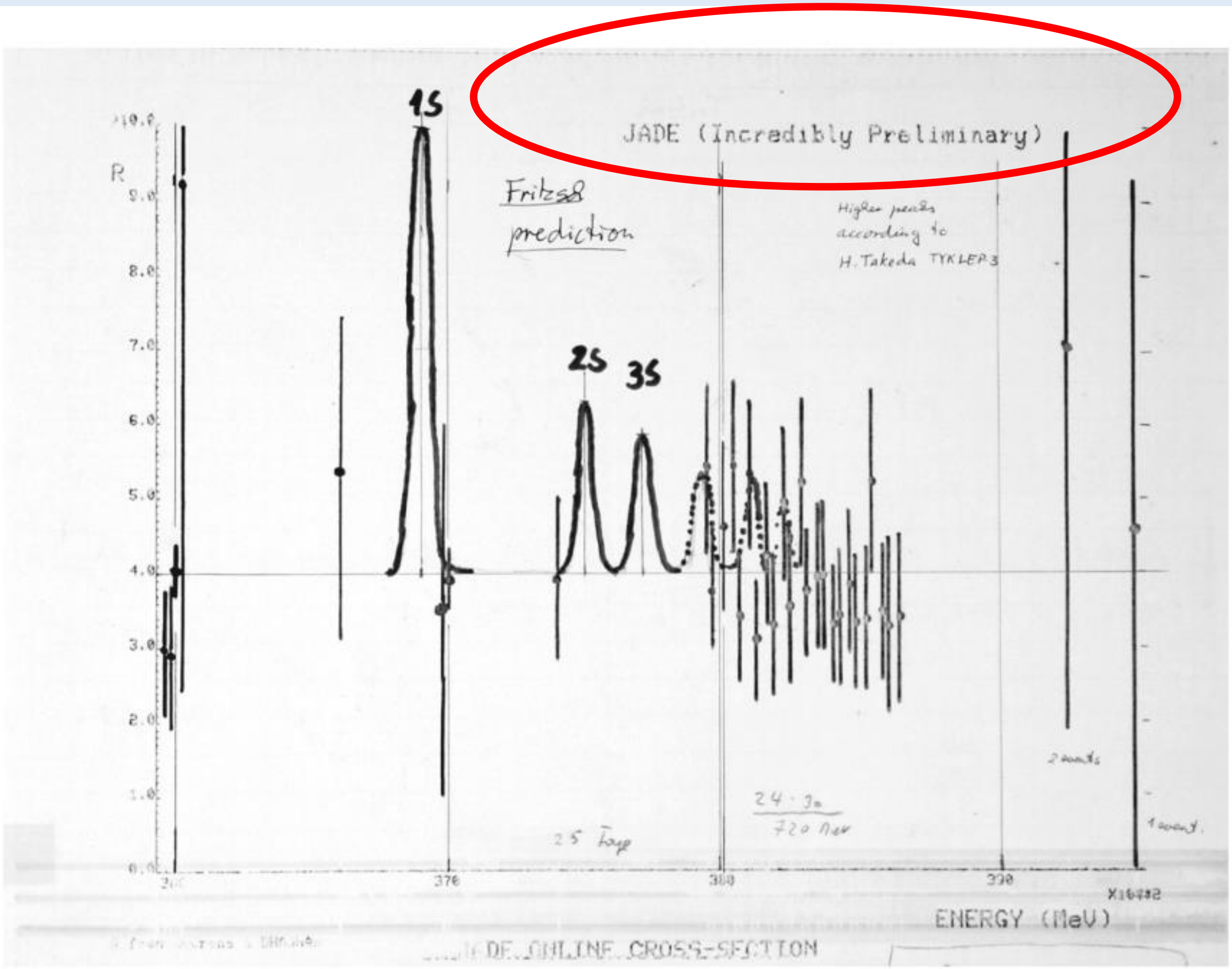
Theoretical prediction for its mass were rather variable

Energy scan

JADE (of course) had
already
an online analysis program

and
a new classification of results

new JADE classification



Online version of the R-plot

Fig. 8 Online version of the "R-plot", the normalised hadronic cross section as function of the c.m. energy, from 36 to 39.5 GeV, as plotted on 21 December, at the end of the 1982 energy scan to search for the top quark (JADE online logbook #10, page 73 [45]). Drawn-in by hand is a sketch of the expectation for the ground state and higher $t\bar{t}$ resonances according to a then actual theoretical prediction. The expectation for R in case of 5 quark flavours, without the top-quark, is 3.8, and for 6 quarks, including the top-quark in the continuum, about 5.2. The horizontal line at $R = 4$ is drawn to guide the eye

Beyond the strong interaction:

Study of the electro-weak interference

Beate Naroska 1986 Physics Report

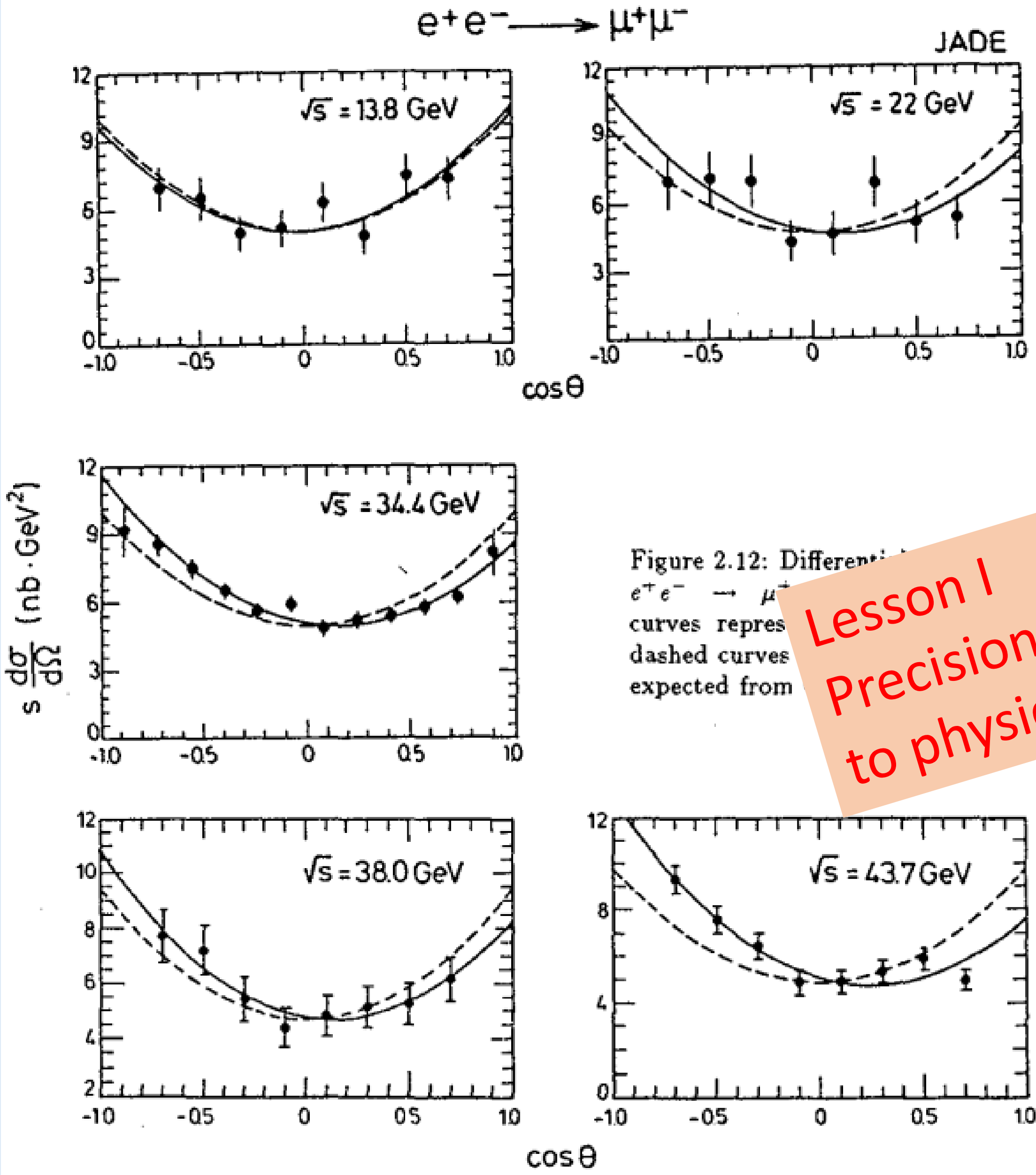


Figure 2.12: Differenti
$e^+e^- \rightarrow \mu^+$
curves repres
dashed curves
expected from

Lesson I

Precision measurements indicate the path to physics beyond present energy reach

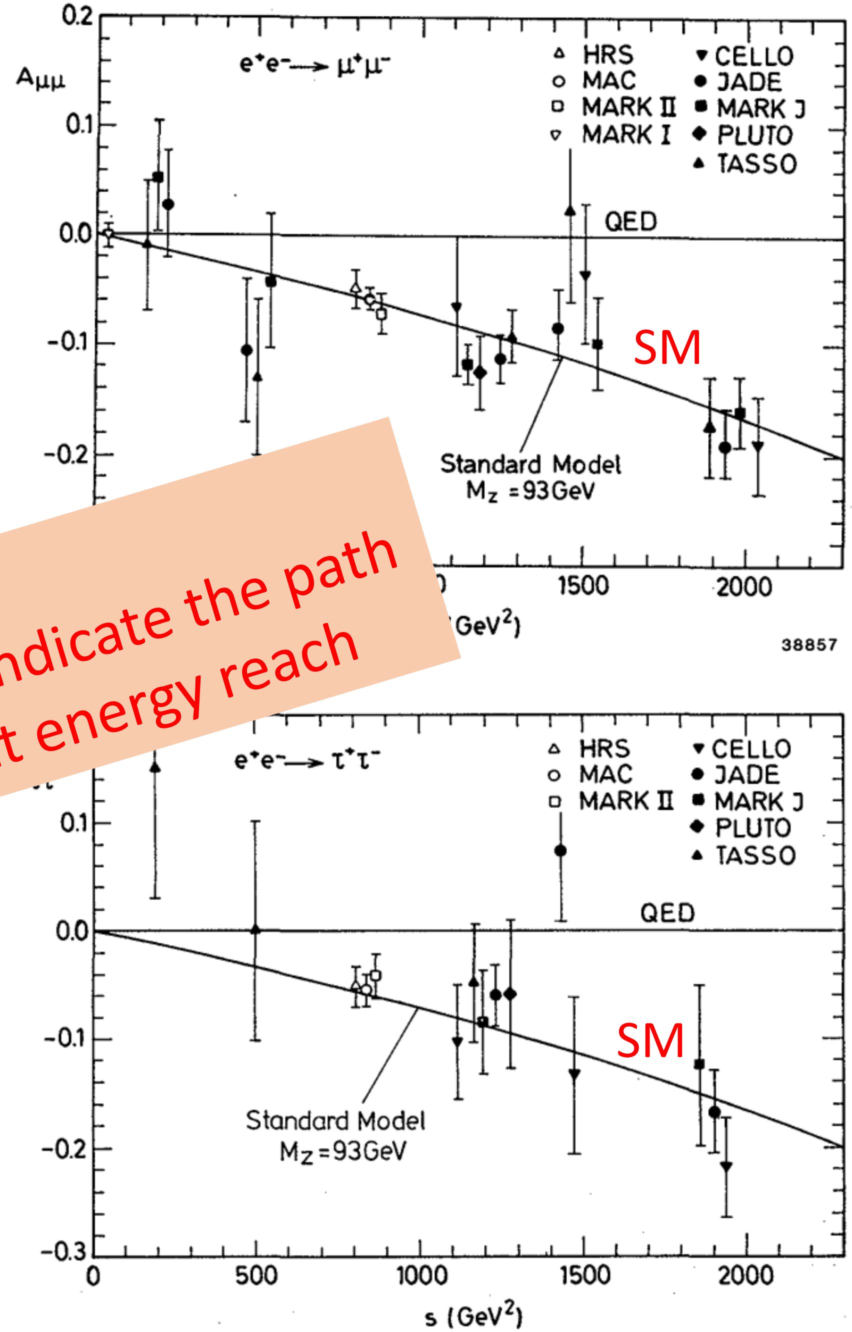
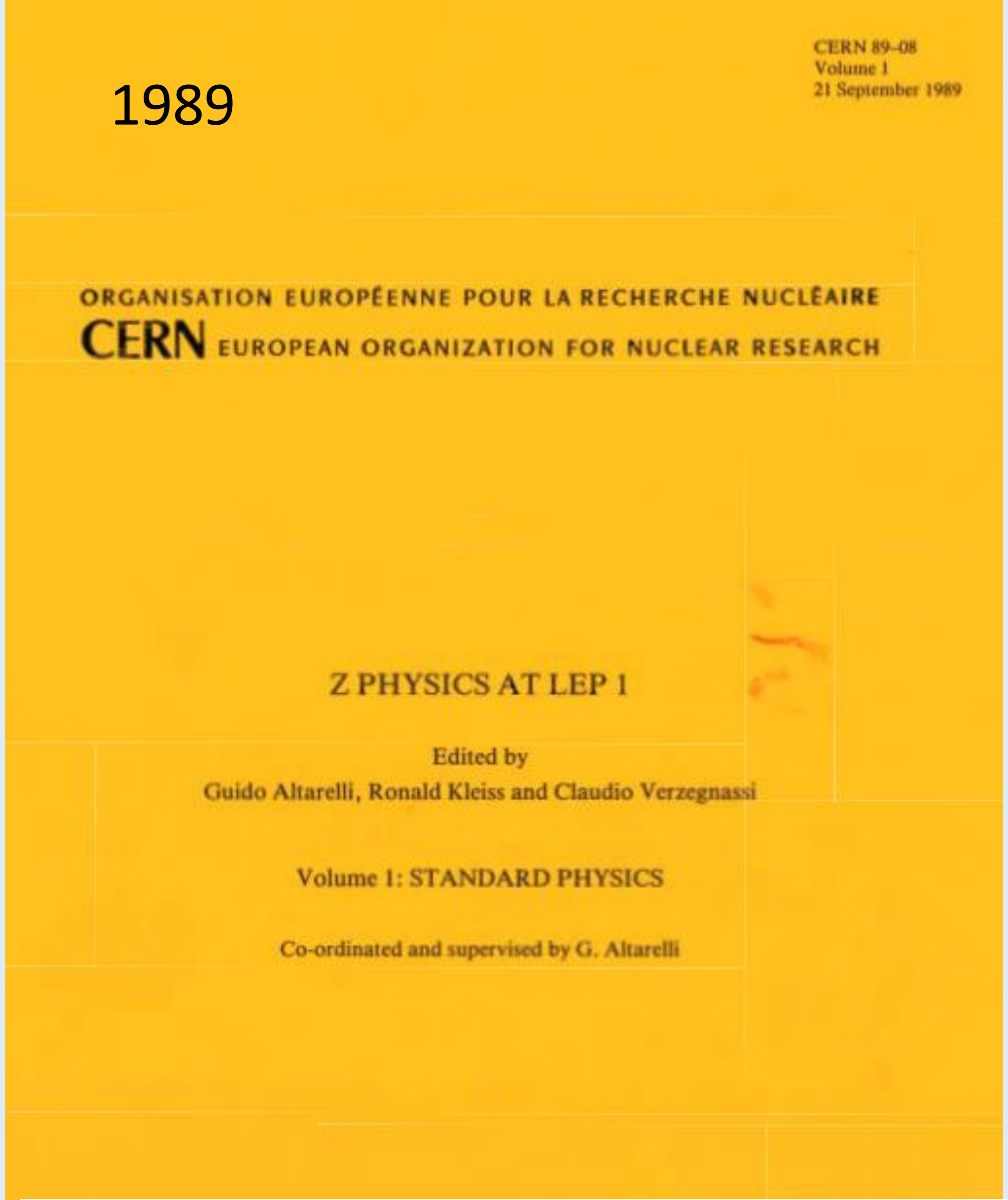


Figure 2.14: Asymmetry as a function of s for $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$

Further progress needs progress in
experimental techniques
as well as
in theory

1989 Looking to LEP

1989



CERN 89-08
Volume 1
21 September 1989

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Z PHYSICS AT LEP 1

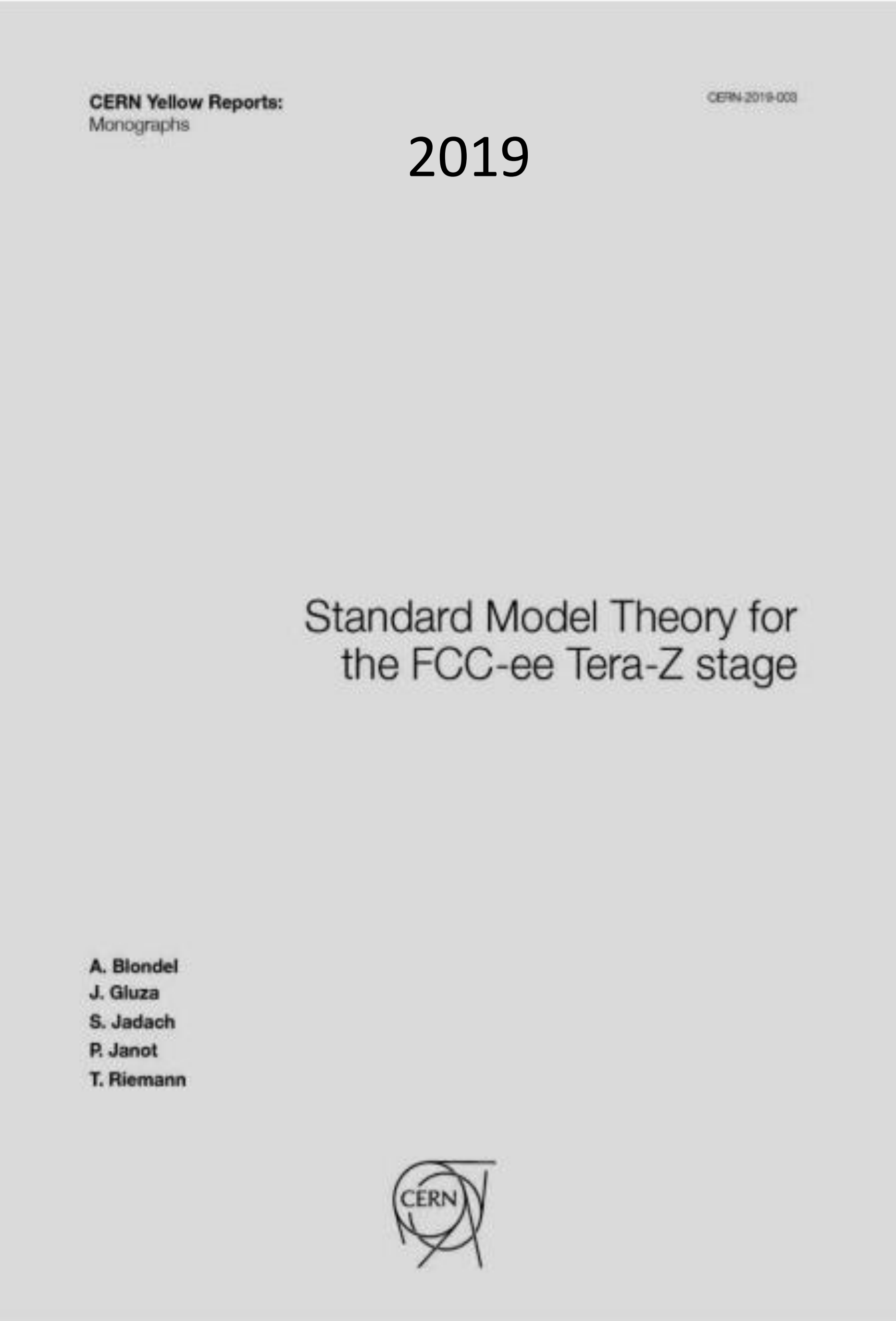
Edited by
Guido Altarelli, Ronald Kleiss and Claudio Verzegnassi

Volume 1: STANDARD PHYSICS

Co-ordinated and supervised by G. Altarelli

The τ polarization measurement *S. Jadach and Z. Wąs* 235

2019 Looking forward
to FCC-ee



2019

CERN Yellow Reports:
Monographs

CERN-2019-003

Standard Model Theory for the FCC-ee Tera-Z stage

A. Blondel
J. Gluza
S. Jadach
P. Janot
T. Riemann

OPAL Detector

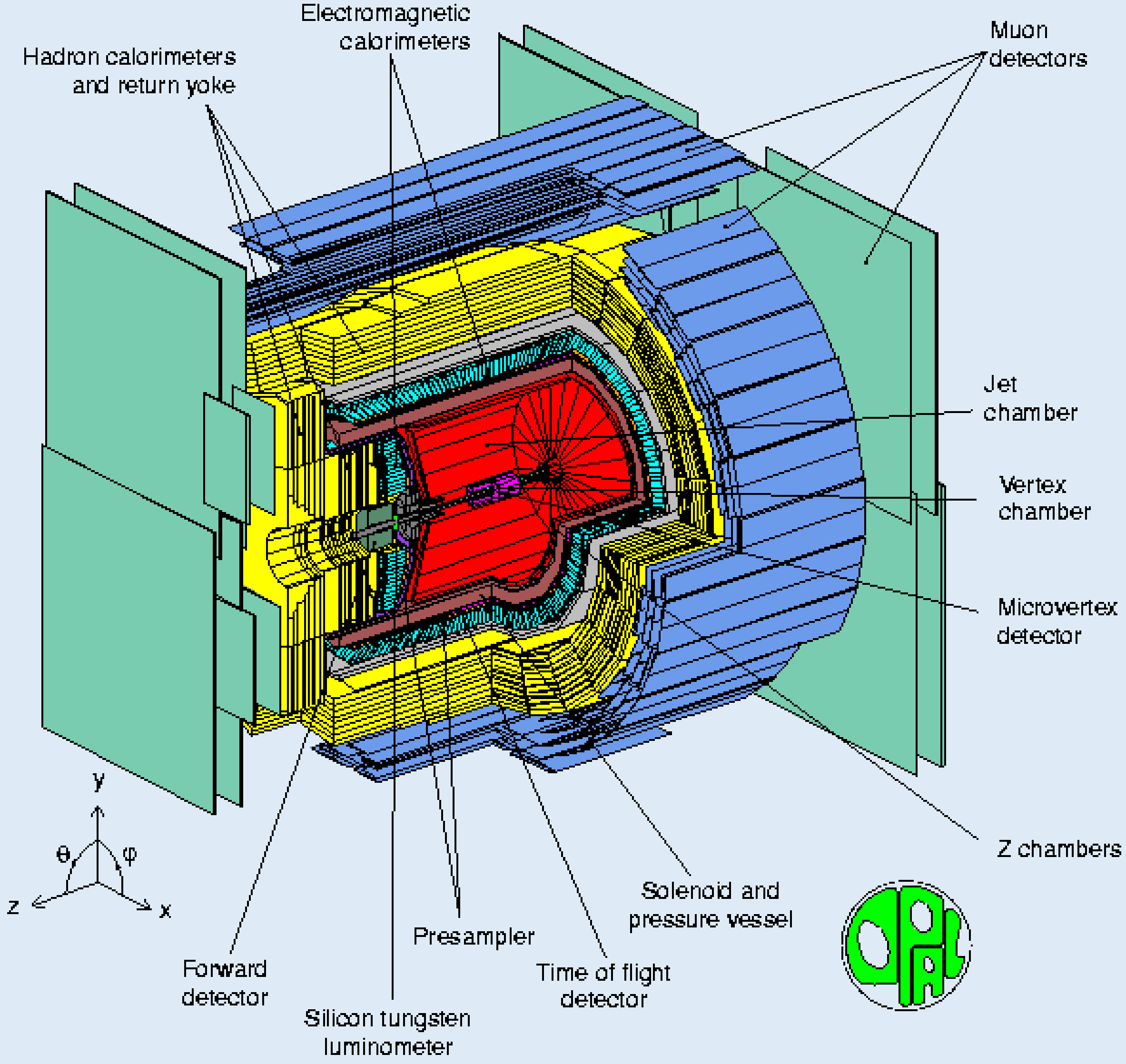
(back to)

LEP

Max Energy 209 GeV

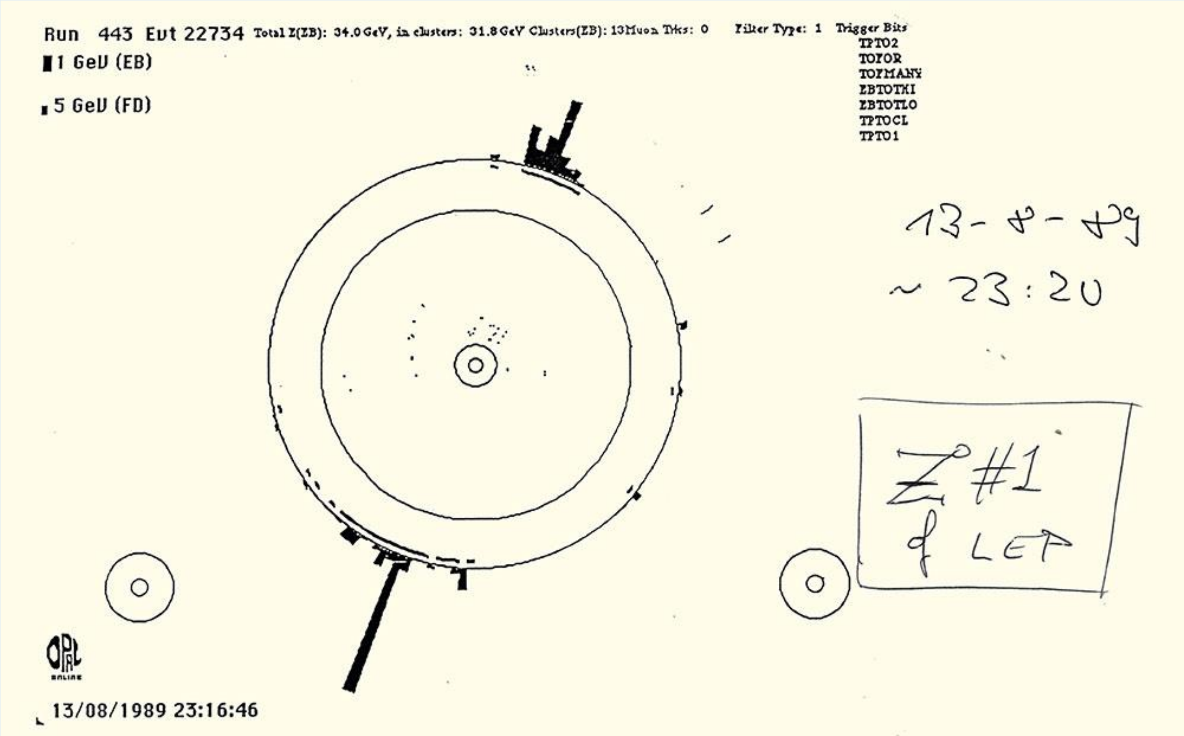
Data delivery 1989-2000

ALEPH-DELPHI-L3-OPAL



OPAL logbook entries:

first Z seen at LEP



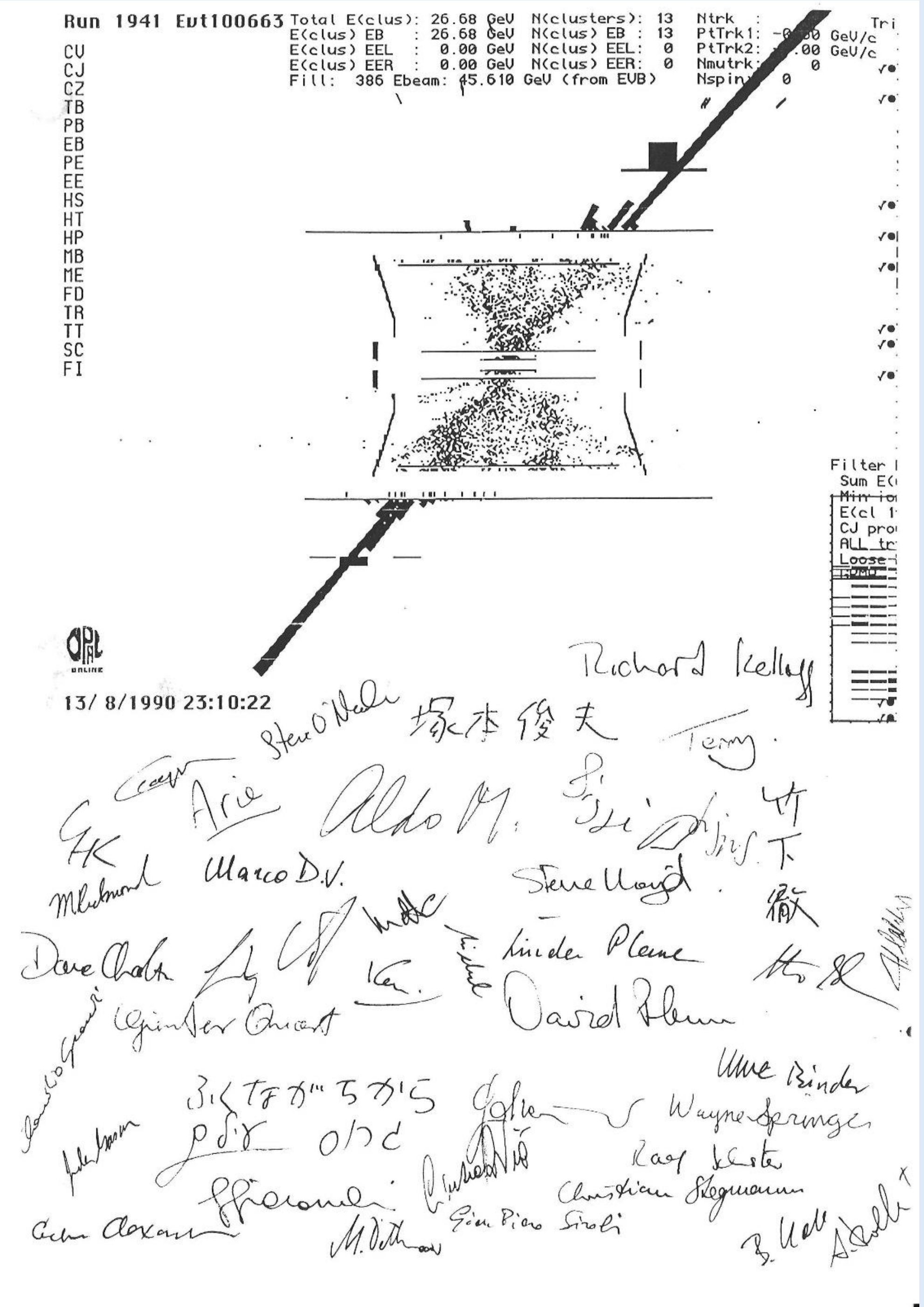
```
Run  443  Evt 22734  Total E(EB): 34.0GeV, in clusters: 31.8GeV Clusters(EB): 13Muon Trks: 0    Filter Type: 1  Trigger Bits
                                                                                                                  TPTO2
                                                                                                                  TOFOR
                                                                                                                  TOFMANY
                                                                                                                  EBTOTHI
                                                                                                                  EBTOTLO
                                                                                                                  TPTOCL
                                                                                                                  TPTO1
```

13-8-89
~ 23:20

Z #1 of LEP

13/08/1989 23:16:46

last event seen (at OPAL) 1990



```
Run  1941  Evt100663 Total E(clus): 26.68 GeV  N(clusters): 13   Ntrk   :
                     E(clus) EB   : 26.68 GeV  N(clus) EB  : 13   PtTrk1:
                     E(clus) EEL  :  0.00 GeV  N(clus) EEL:   0   PtTrk2:
                     E(clus) EER  :  0.00 GeV  N(clus) EER:   0   Nmutrk:
                     Fill:  386 Ebeam: 45.610 GeV (from EVB)      Nspin
```

13/ 8/1990 23:10:22

Richard Kellogg
Steve O'Neale
塚本俊夫
Terry
Arie
Aldo M.
Marco D.V.
Steve Lloyd
Dave Charlton
Ken
Linda Plane
Günter Quast
David Plane
Uwe Binder
ふくながちから
Wayne Springer
Christian Stegmann
Gian Piero Siroli
M. Dittmar

Z metrology: original expectations

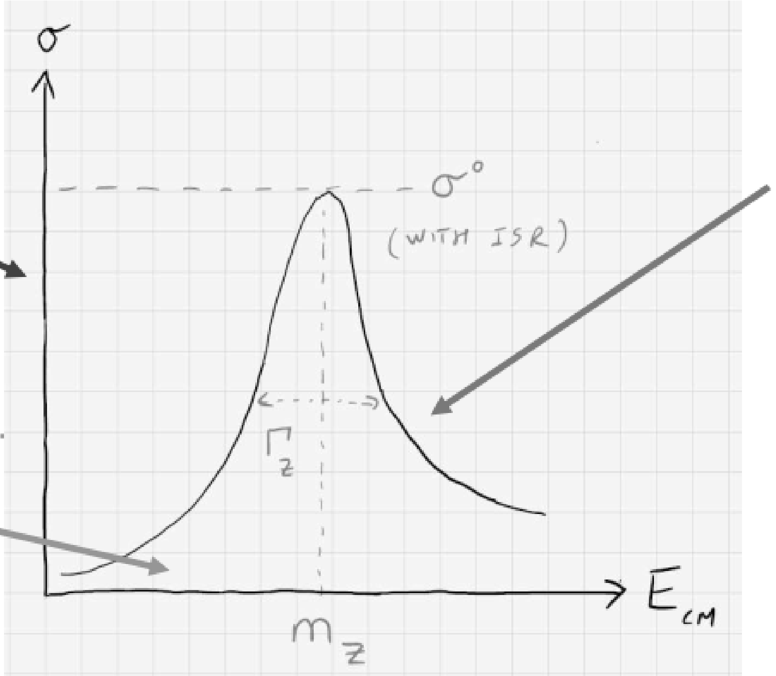
Outlook shortly before LEP turn on: *“The overall conclusion is that at LEP the Z^0 mass and width can be measured with relative ease down to … +/- 50 MeV. A factor of 2-3 improvement can be reached with a determined effort…”*
CERN 86-02 ‘Physics at LEP’, ed. Ellis and Peccei.

Vertical-scale uncertainty dominated by luminosity, largely correlated between experiments.

It was assumed this could be done to ~2%.

Horizontal-scale uncertainty set by knowledge of collision energy, also common between experiments.

It was guessed that ~10 MeV uncertainty *might* be possible.



Also vital Is understanding of shape, in particular effect of QED radiative corrections.

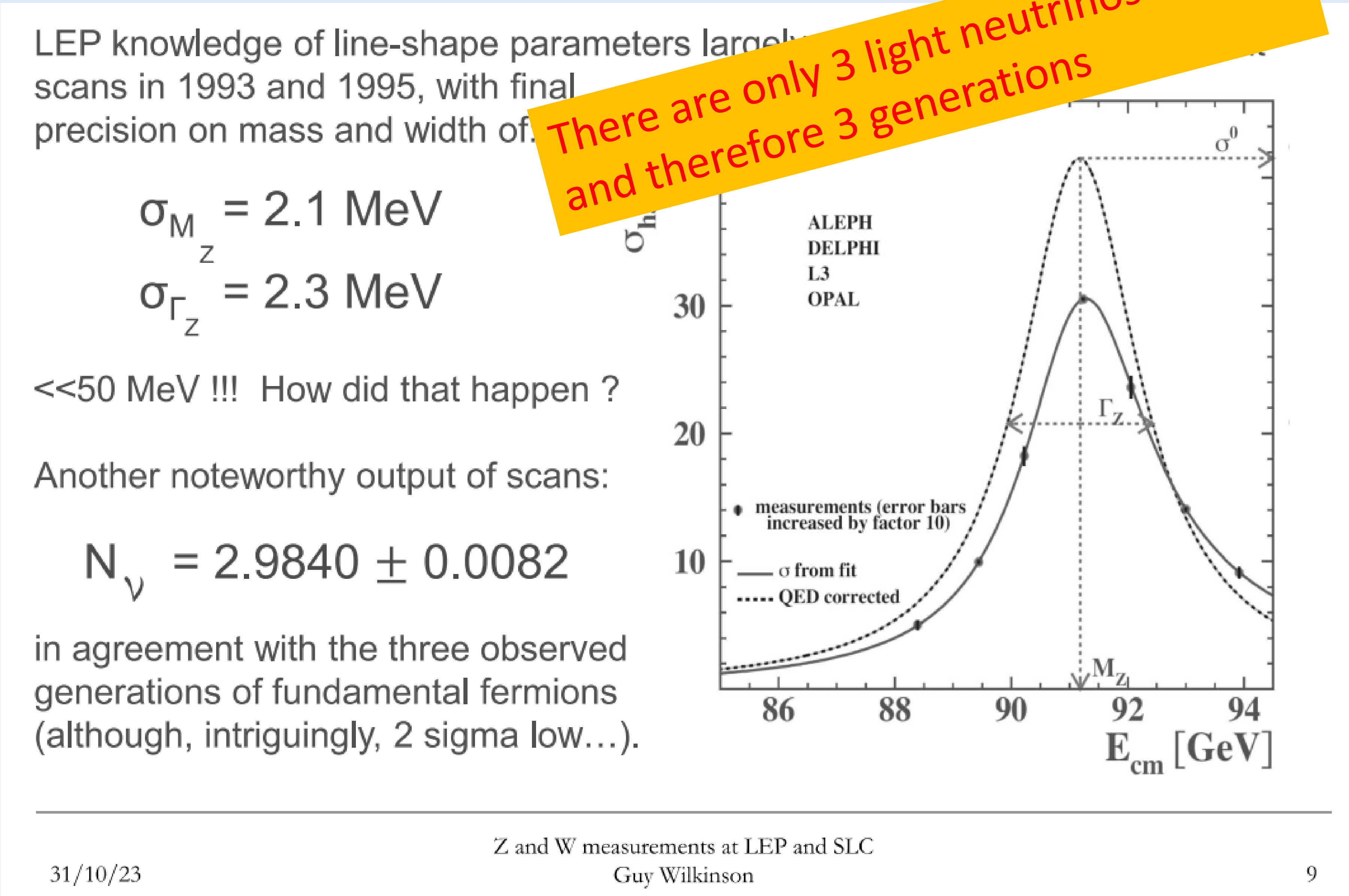
Important, but not discussed further today.

Prior to LEP, all calculations of radiative corrections were based on first- and, later, partially second-order results. This limited the theoretical precision to the 1% level, which was unacceptable for experiments. In 1987 S. Jadach solved that problem in a single-author report, inspired by the classic work of Yennie, Frautschi and Suura, featuring a new calculational method for any number of photons……

Most of the analysis of LEP data was based exclusively on the novel calculations provided by Jadach and his colleagues. The most important concerned the LEP luminosity measurement via Bhabha scattering, the production of lepton and quark pairs, and the production and decay of W and Z boson pairs……

CERN Courier

There are only 3 light neutrinos and therefore 3 generations



LEP knowledge of line-shape parameters largel
scans in 1993 and 1995, with final
precision on mass and width of:

$$\sigma_{M_Z} = 2.1 \text{ MeV}$$
$$\sigma_{\Gamma_Z} = 2.3 \text{ MeV}$$

<<50 MeV !!! How did that happen ?

Another noteworthy output of scans:

$$N_\nu = 2.9840 \pm 0.0082$$

in agreement with the three observed generations of fundamental fermions (although, intriguingly, 2 sigma low…).

Luminosity measurement

Lumi measured in QED-dominated low-angle $e^+e^- \rightarrow e^+e^-$.

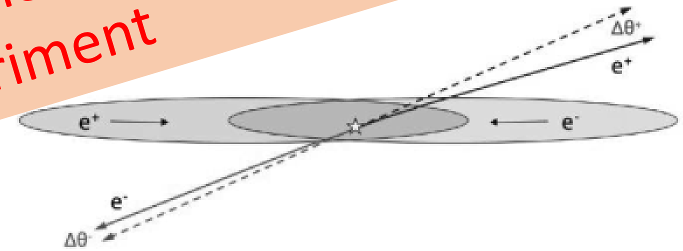
LEP was expected to measure lumi to ~2%, but in fact did better than 0.1% !

Two ingredients: Enormous theoretical work, resulting in a LEP-wide correlated error of 0.06% + Precision luminometers, with 5 μm tolerances & excellent understanding of acceptance

e.g. OPAL achieved 3 x 10^{-4}

There is an amusing epilogue. Reviews of t ith the FCC-ee in mind has discover

beam-beam effects modifyi
[Voutsinas *et al.*, PLB 800 (2020) 13



plus updates to the LEP-era ca ulations with current knowledge [Janot & Jadach, PLB 803 (2020) 135319].

$$N_\nu = 2.9840 \pm 0.0082 \quad ➡ \quad N_\nu = 2.9963 \pm 0.0074$$

"The 20-years-old
2σ tension…
is gone" !

Lesson II
Precision Physics needs progress in
Theory and Experiment

Remember the electro-weak results at PETRA?

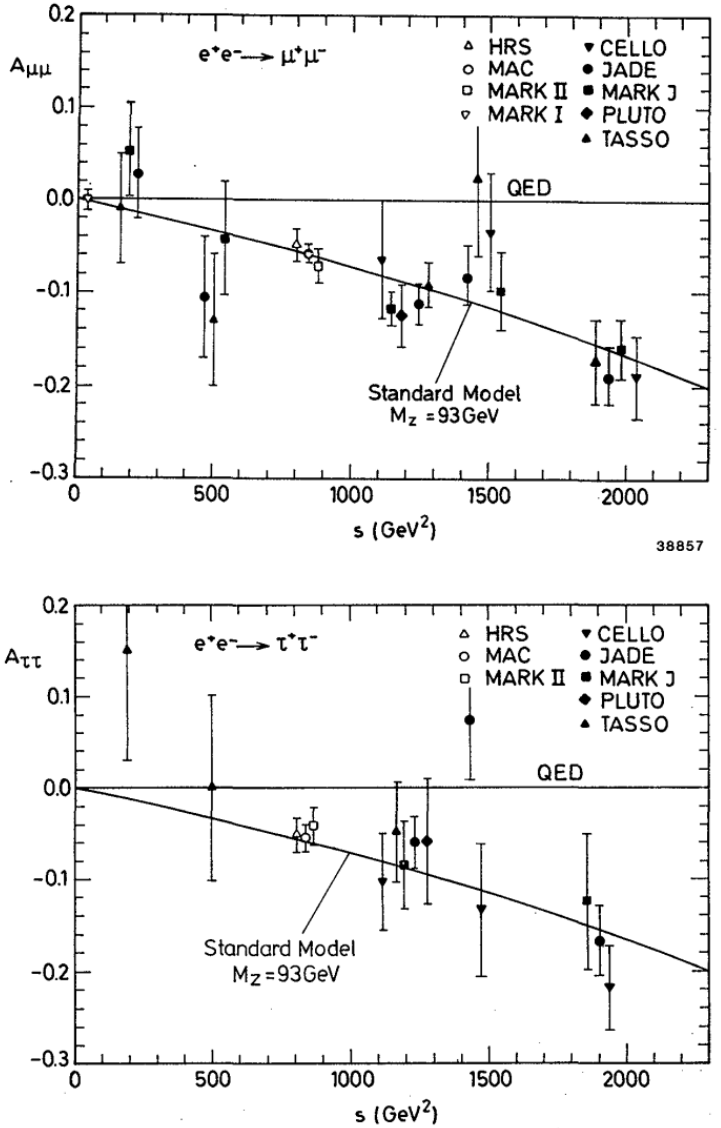
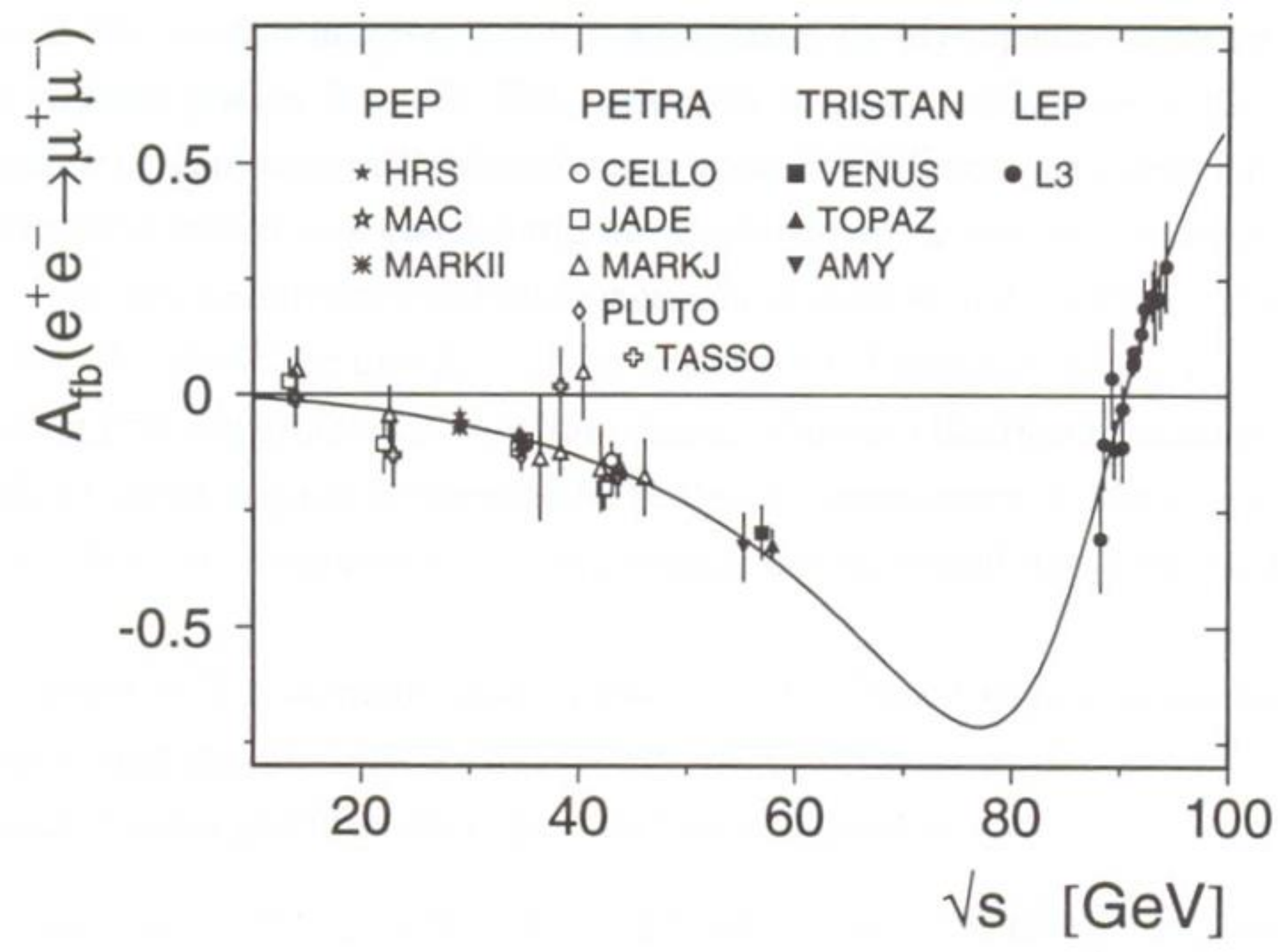


Figure 2.14: Asymmetry as a function of s for $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$

From PETRA to LEP

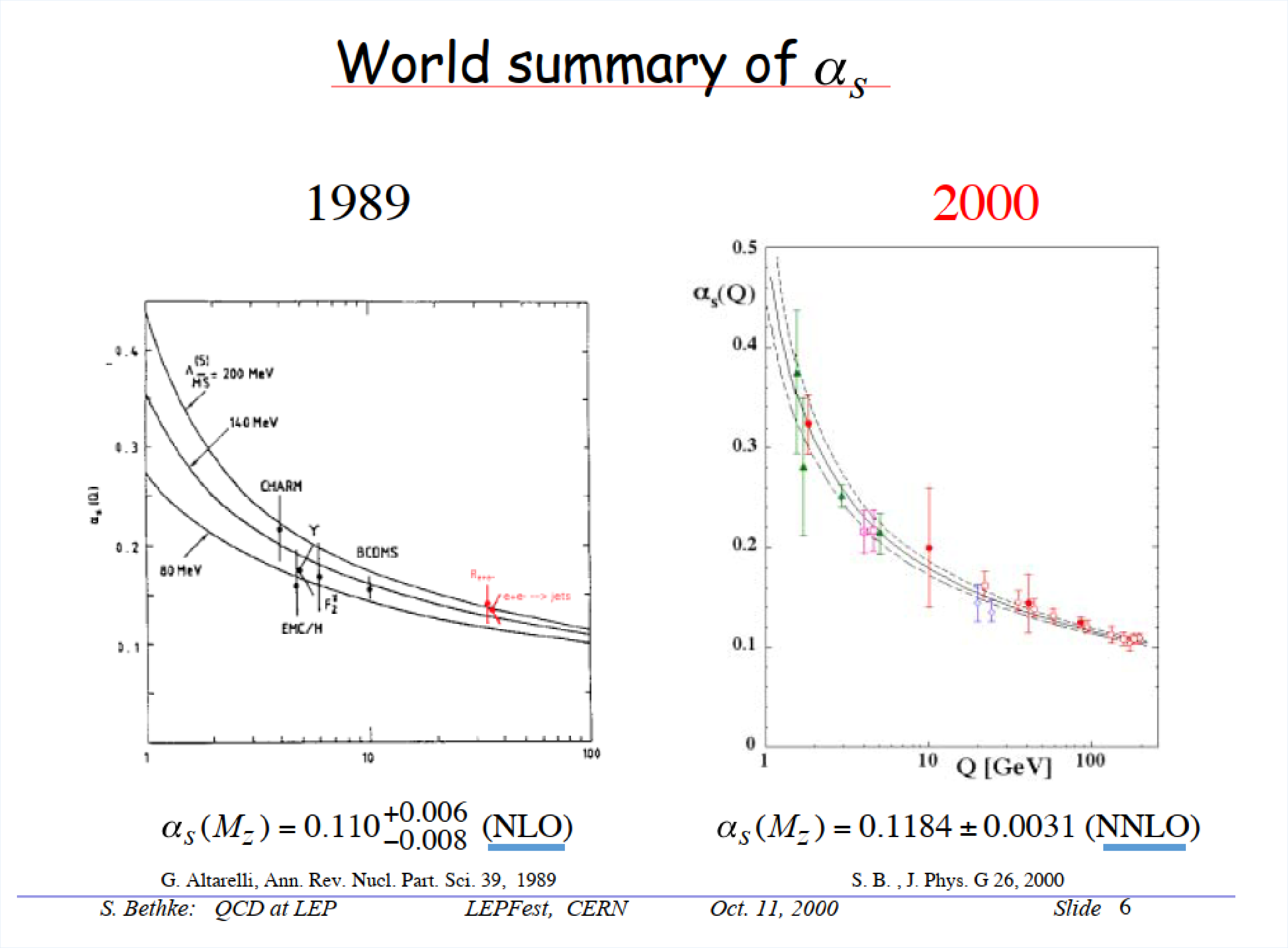


Lesson I:
Precision measurements can guide the way to the next discovery

LEP beyond the e-w interaction:

Study of the strong interaction (QCD)

Progress within 10 years



World summary of α_s

1989

2000

$\alpha_s(M_z) = 0.110^{+0.006}_{-0.008}$ (NLO)

$\alpha_s(M_z) = 0.1184 \pm 0.0031$ (NNLO)

G. Altarelli, Ann. Rev. Nucl. Part. Sci. 39, 1989

S. B. , J. Phys. G 26, 2000

S. Bethke: QCD at LEP *LEPFest, CERN* *Oct. 11, 2000* *Slide* 6

Going beyond three jets

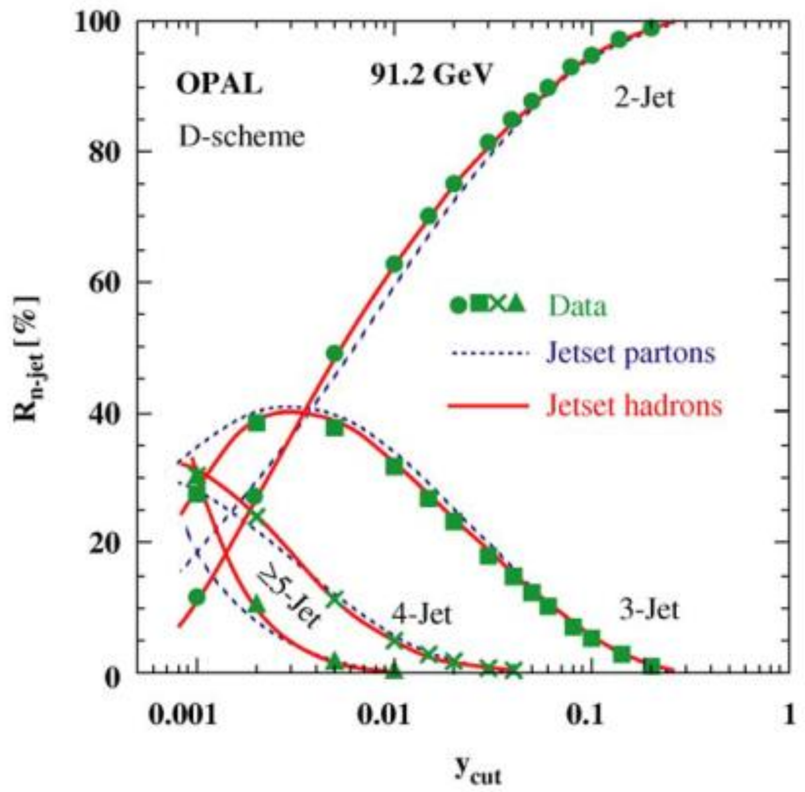
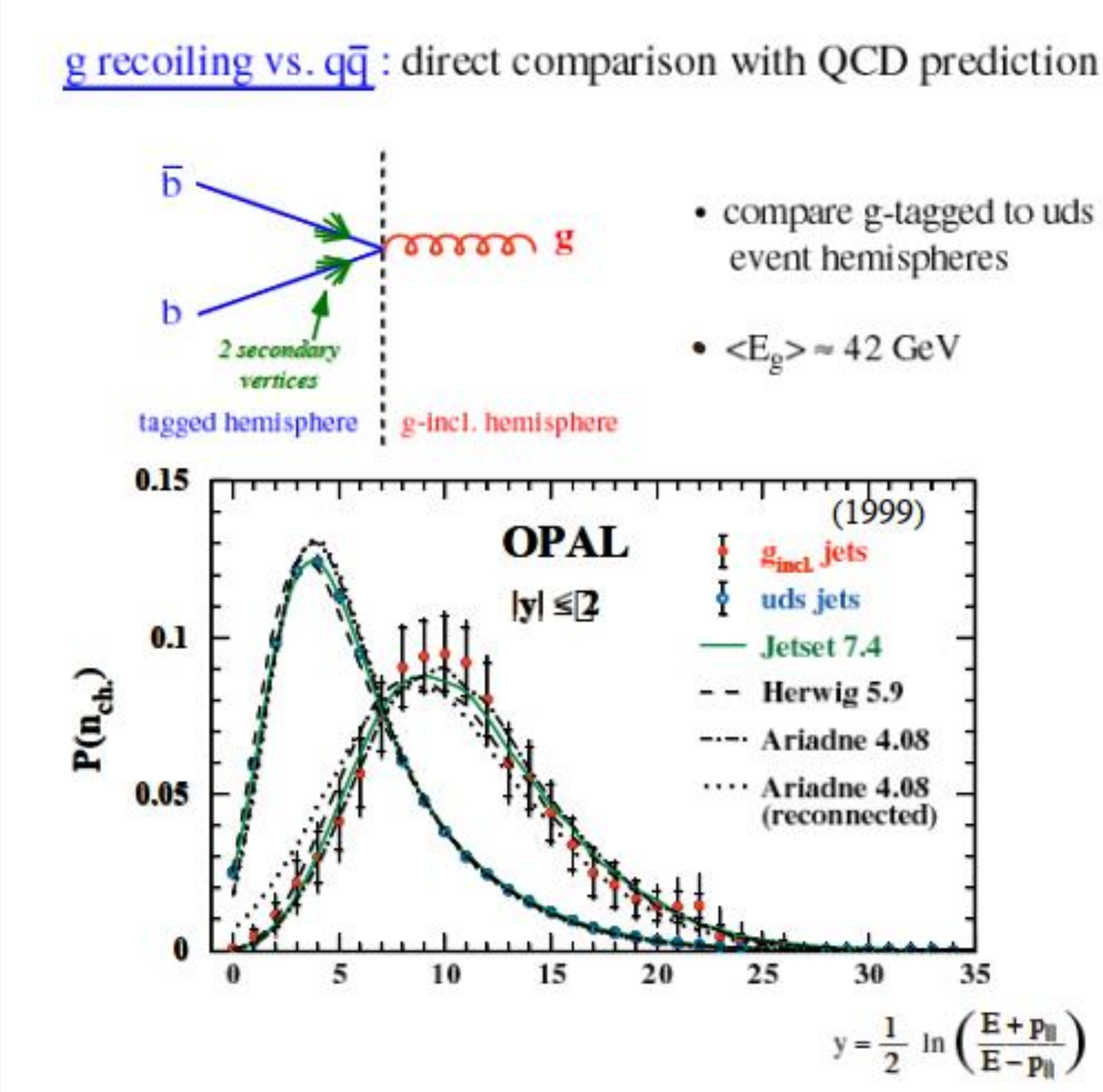


Fig. 2. Relative production rates of *n*-jet events ($n = 2$–5) for different values of the jet resolution parameter y_{cut}, measured at the Z^0 resonance at LEP [29]. The data are compared to predictions of the JETSET QCD shower and hadronisation model (*hadrons*). The predictions for *partons*, before hadronisation, are also given in order to illustrate the size of the hadronisation effect.

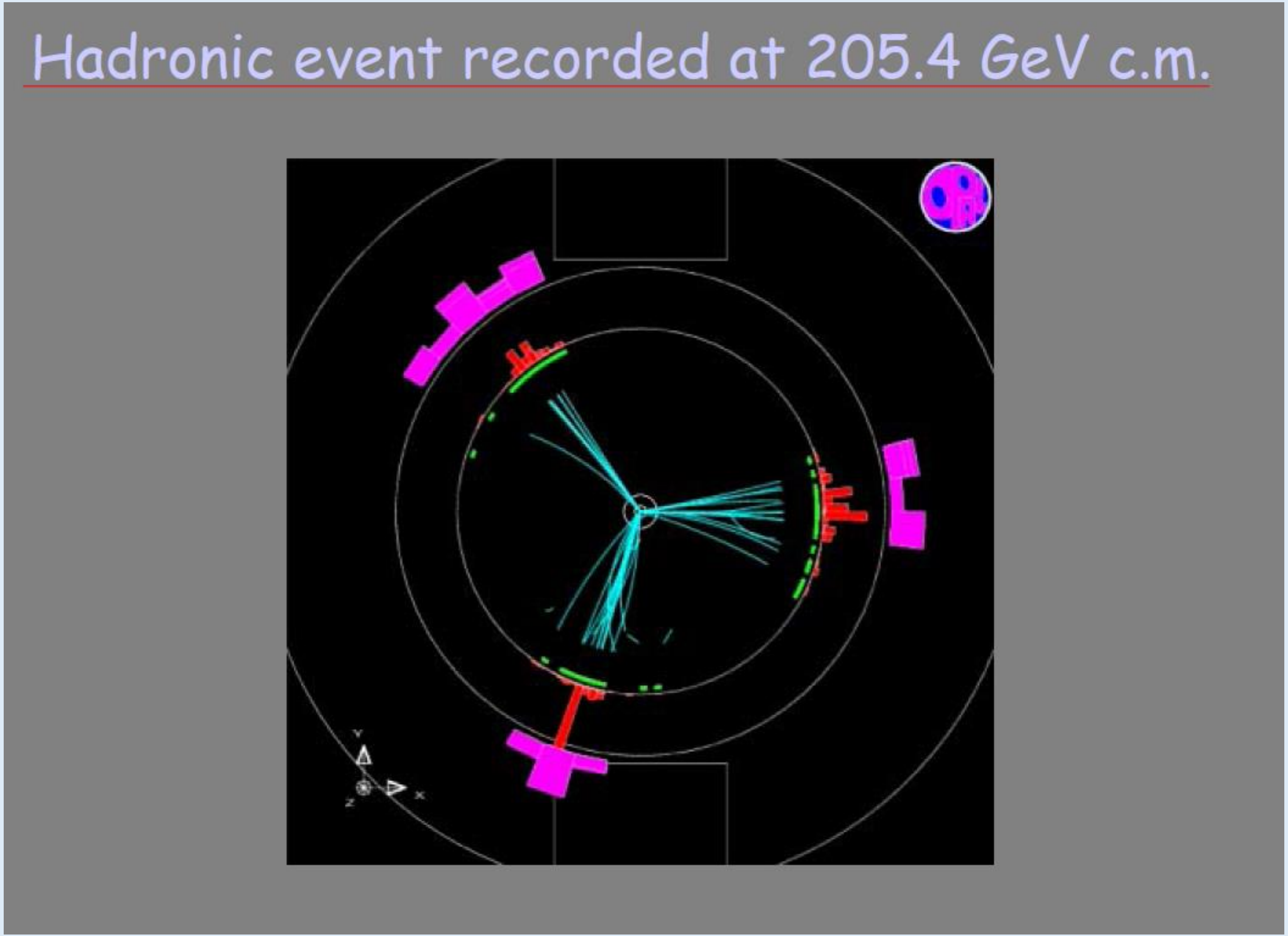
Properties of jets



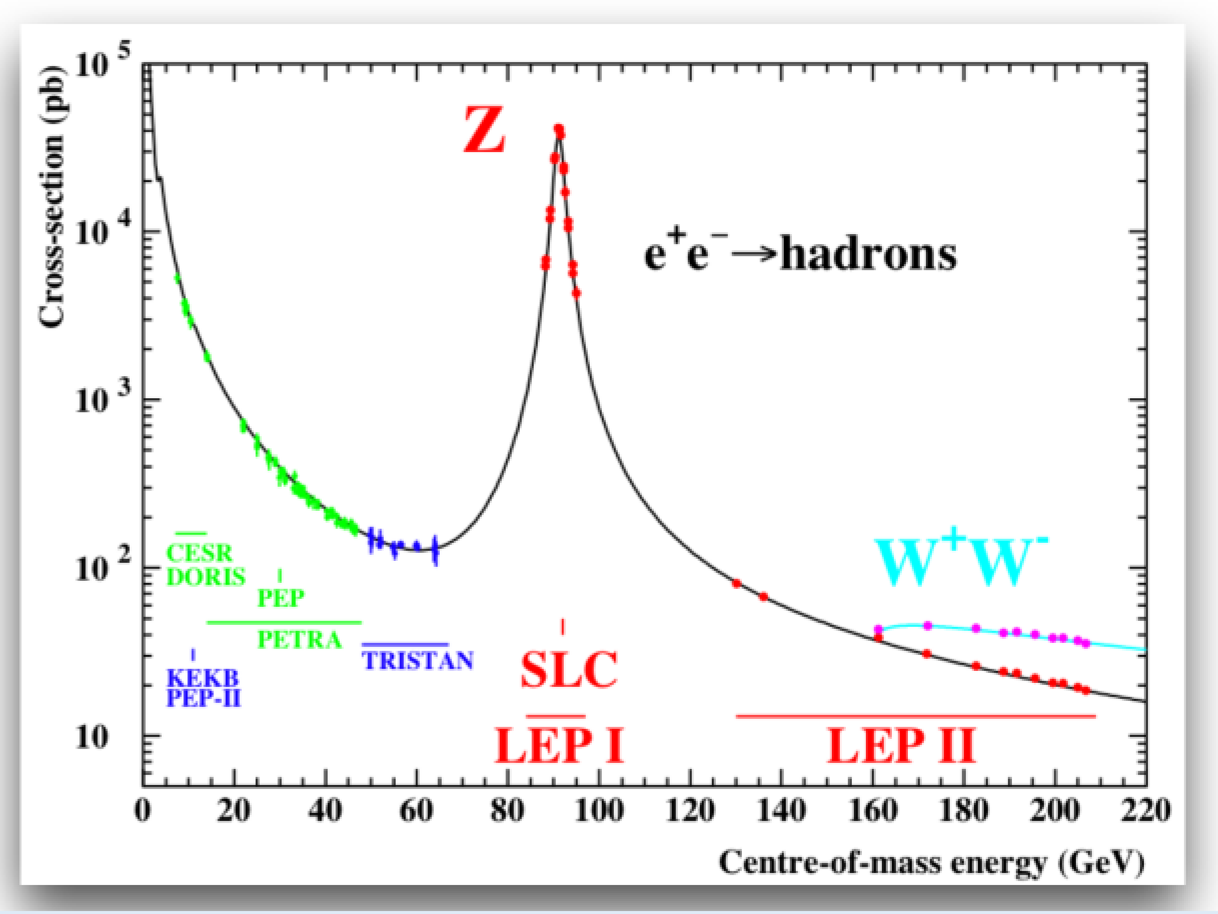
g recoiling vs. $q\bar{q}$: direct comparison with QCD prediction

- compare g-tagged to uds event hemispheres
- $\langle E_g \rangle \approx 42$ GeV

Energy increase beyond W-pair production threshold

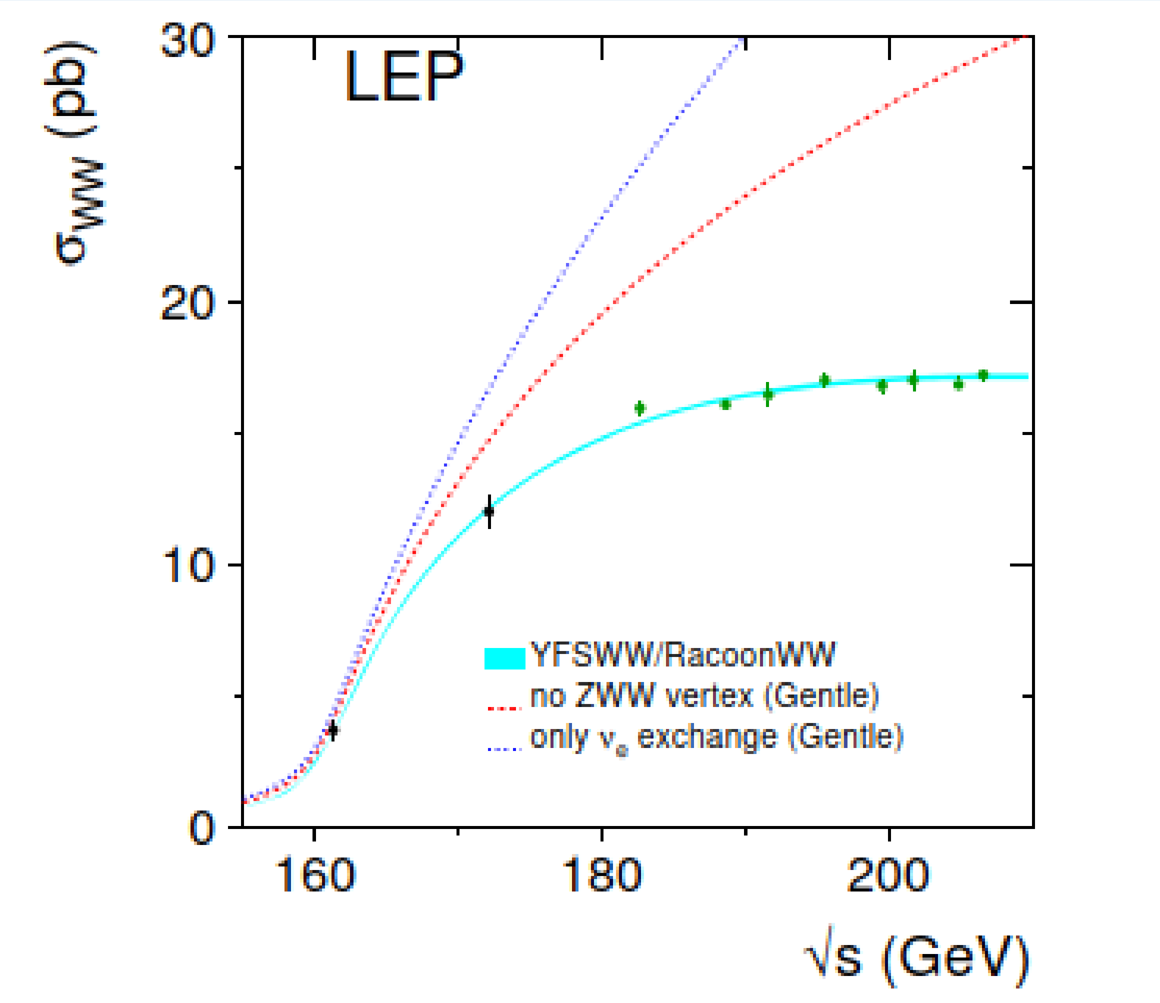

Hadronic event recorded at 205.4 GeV c.m.

Energy increase beyond W-pair production threshold



Energy increase beyond
W-pair production threshold
allowed

Confirmation of the
Gauge Boson self-coupling



What should we do with the data once the experiment is switched off?

Very often, data are unique achievements in many respects like energy range, process dynamics and experimental techniques. New, improved and refined scientific questions may require (re-)analysis of such data sets. Investments necessary to repeat past experiments would exceed the efforts of data preservation by far.
Long-term preservation of data from large-scale high-energy physics (HEP) experiments is imperative to preserve the ability of addressing scientific questions at times long after the completion of those experiments.

The scientific motivation for re-using and re-analysing data from past experiments is given by:

- the availability of new theoretical input in terms of increased precision, advanced models or new predictions;
- new and improved analysis techniques;
- the desire to perform cross-checks between different experiments.

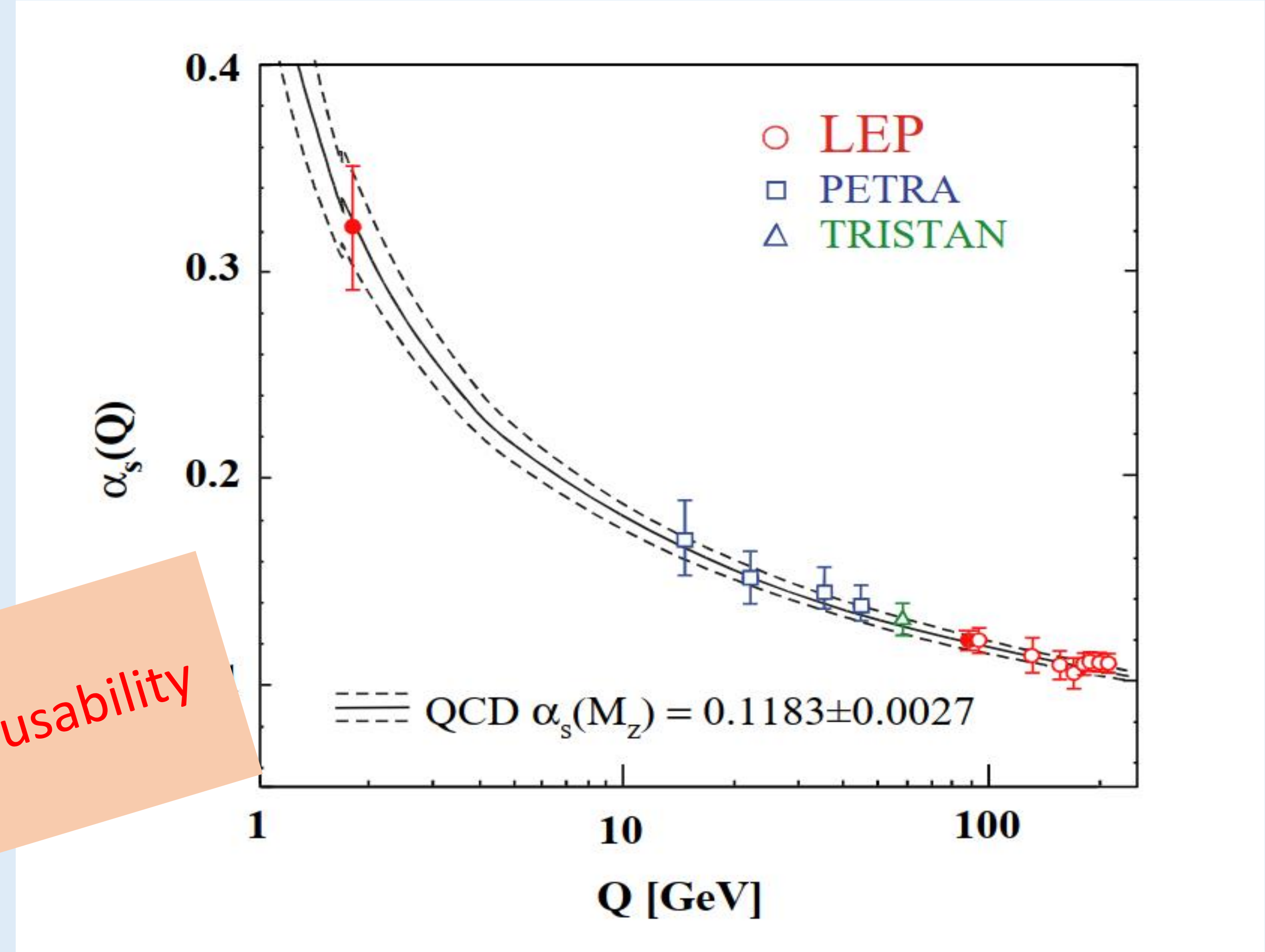
The JADE collaboration had no plan for further data preservation and future use of their data. Private initiatives for long-term preservation started in 1995/1996 at DESY, when Jan Olsson at DESY organised to copy the JADE data to modern and more efficient data carriers, and to preserve the JADE software libraries.

Driven by the desire to re-analyse JADE data in terms of much advanced QCD calculations and Monte Carlo models, the resurrection of the JADE software and its usability on modern computer platforms was initiated in 1996/1997, by Siggi Bethke.

Until 2013, the revived software was actively used for new analyses of the JADE data, resulting in 3 further PhD theses, 10 journal publications and several contributions to international conferences and workshops.

The recovery and reusability of JADE data
can be seen as a precursor of today's FAIR principle

Result of the re-analysis of JADE data



Lesson III
Data preservation and reusability
are important

Data from JADE and OPAL analyzed with the same algorithm and most recent theoretical input

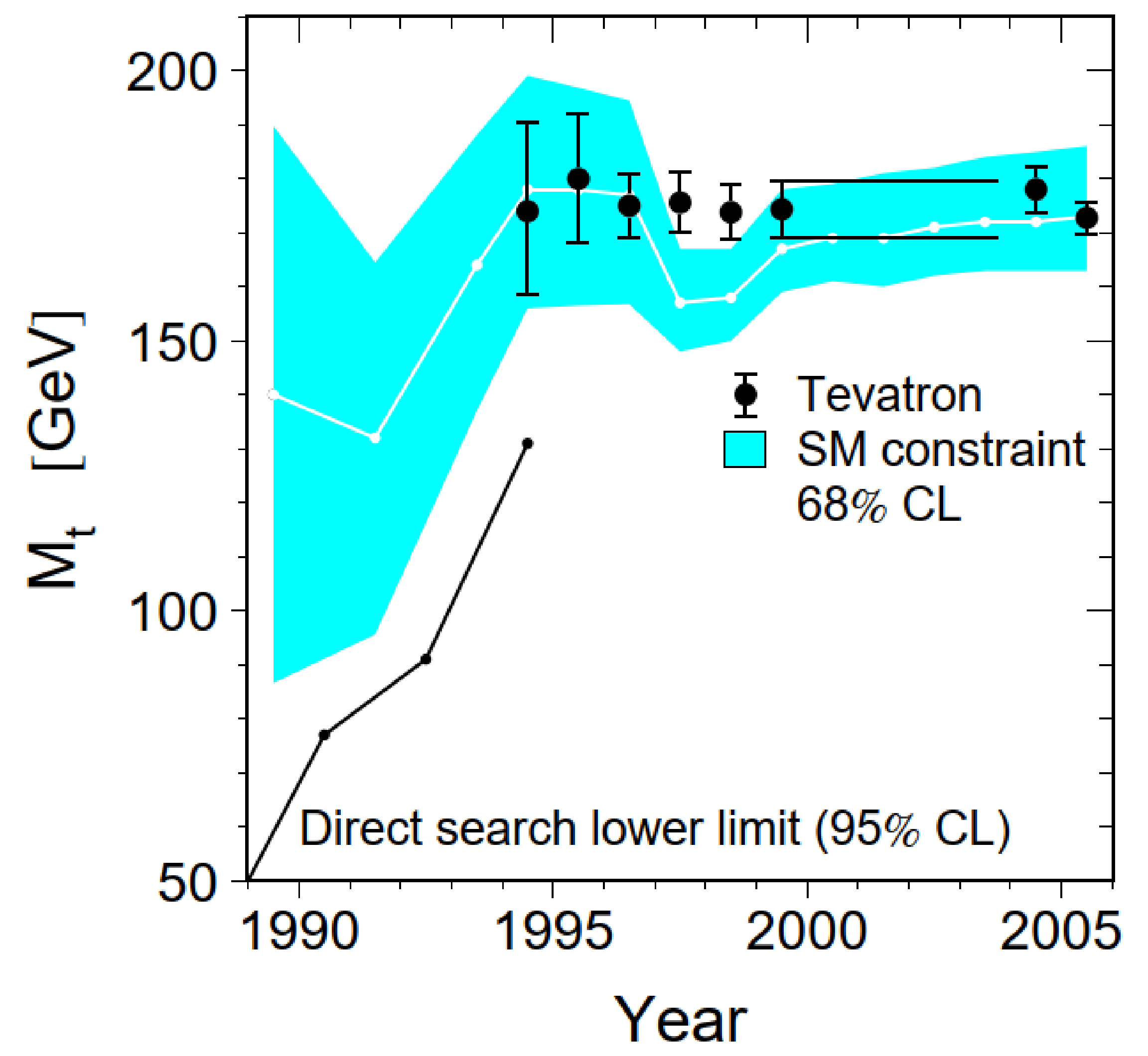
But is there also life beyond all this?

→ Searches at LEP

Pointing the way to the top and the Higgs

Electroweak corrections present in the EW observables have a quadratic dependence on the top mass, and a logarithmic dependence on the Higgs.

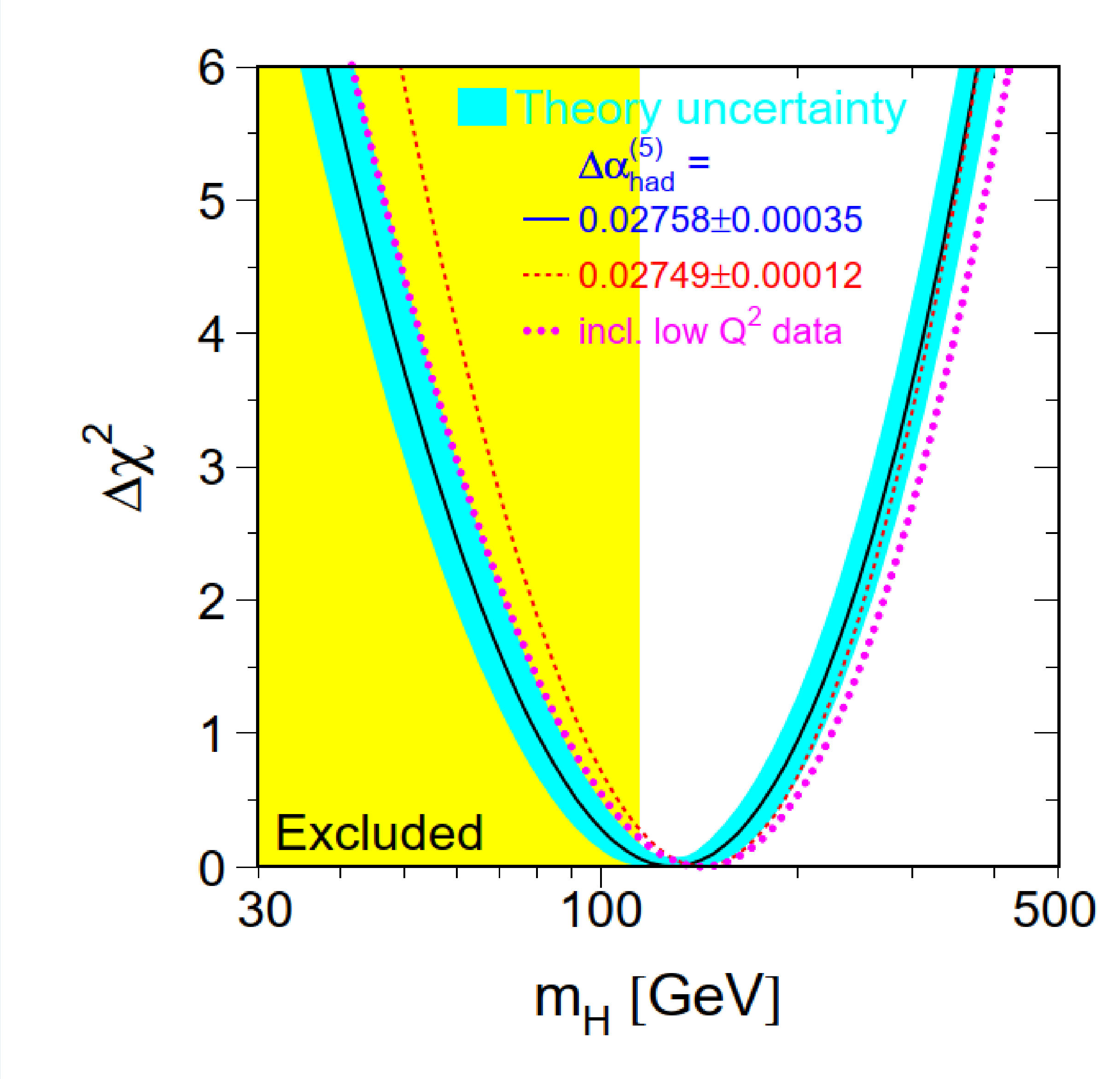
Search for the Top quark



LEP and SLD data indicated
the value of the top mass
well before discovery

Precision measurements (SM constraints)
and direct measurements agree and
complement each other well

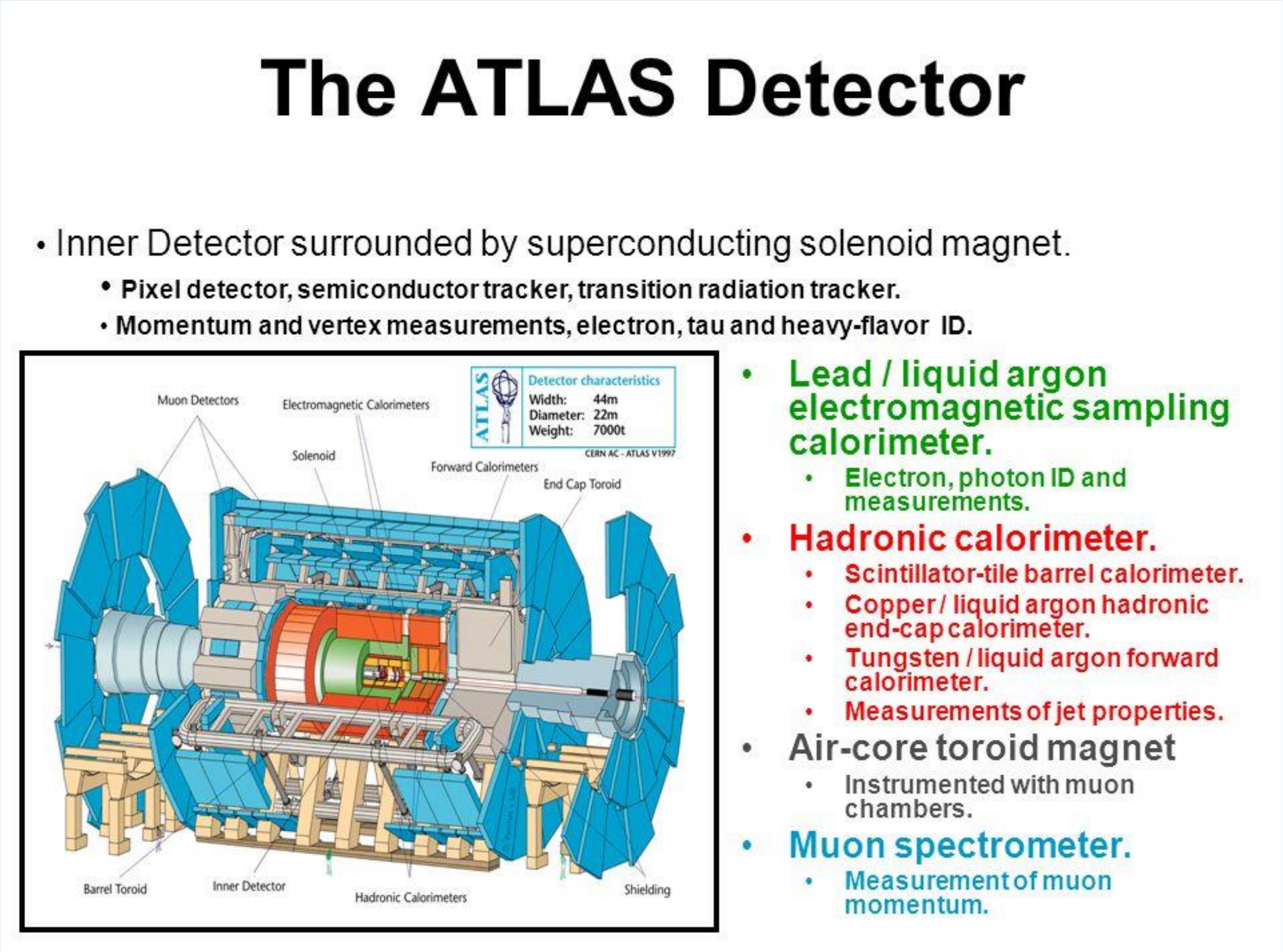
Search for the Higgs-Boson (at that time the last missing ingredient to the SM)



LEP1 data and SM require something Higgs-like and within LHC reach

Lesson 1 repeated:
Precision measurements can guide the way to the next discovery

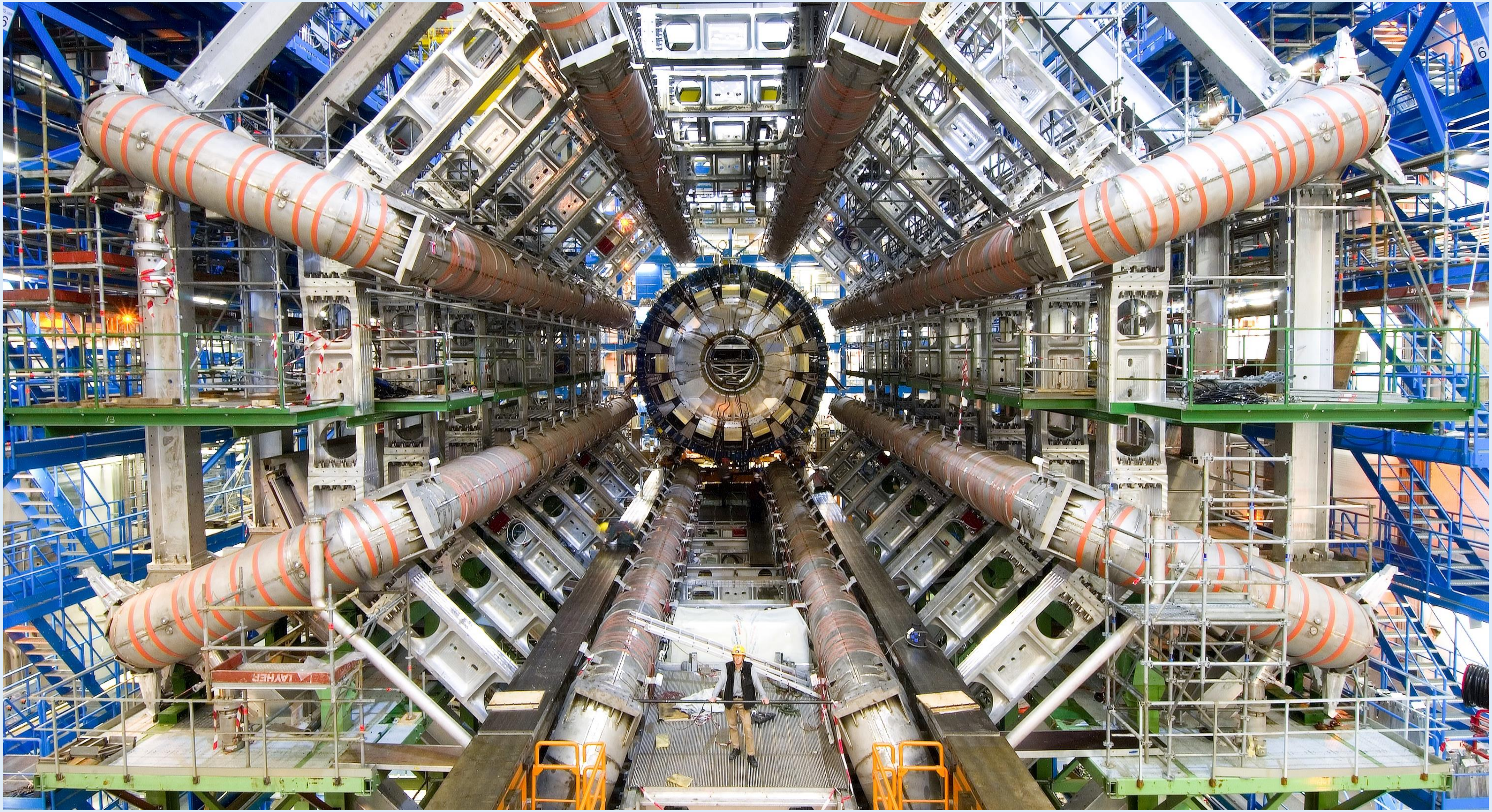
After LEP: Towards the LHC



The ATLAS Detector

- Inner Detector surrounded by superconducting solenoid magnet.
  - **Pixel detector, semiconductor tracker, transition radiation tracker.**
  - **Momentum and vertex measurements, electron, tau and heavy-flavor ID.**
- **Lead / liquid argon electromagnetic sampling calorimeter.**
  - **Electron, photon ID and measurements.**
- **Hadronic calorimeter.**
  - **Scintillator-tile barrel calorimeter.**
  - **Copper / liquid argon hadronic end-cap calorimeter.**
  - **Tungsten / liquid argon forward calorimeter.**
  - **Measurements of jet properties.**
- **Air-core toroid magnet**
  - **Instrumented with muon chambers.**
- **Muon spectrometer.**
  - **Measurement of muon momentum.**

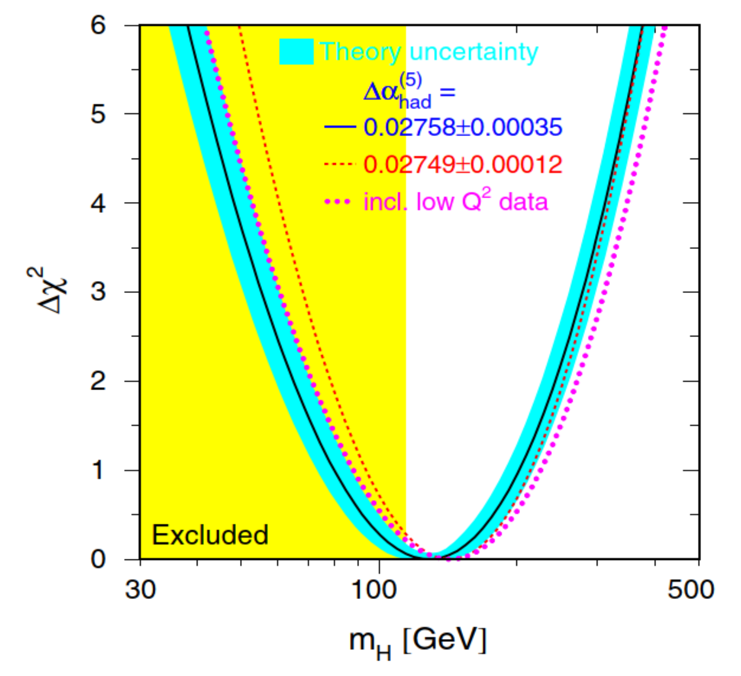
Data taking since 2009

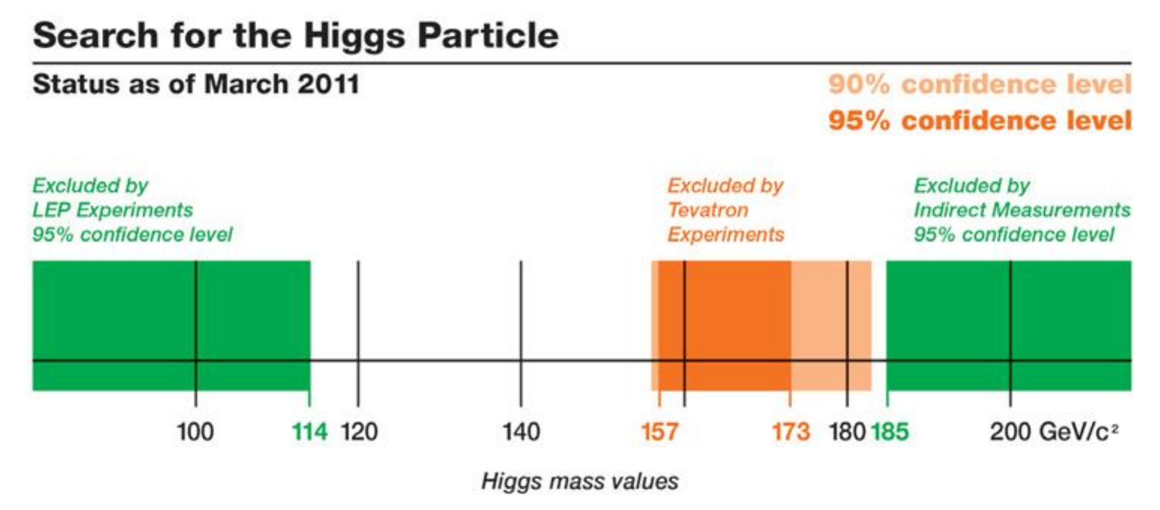


Status of the search for the Higgs-Boson March 2011

LEP1 1989 - 2000

Precision tests of the Standard Model

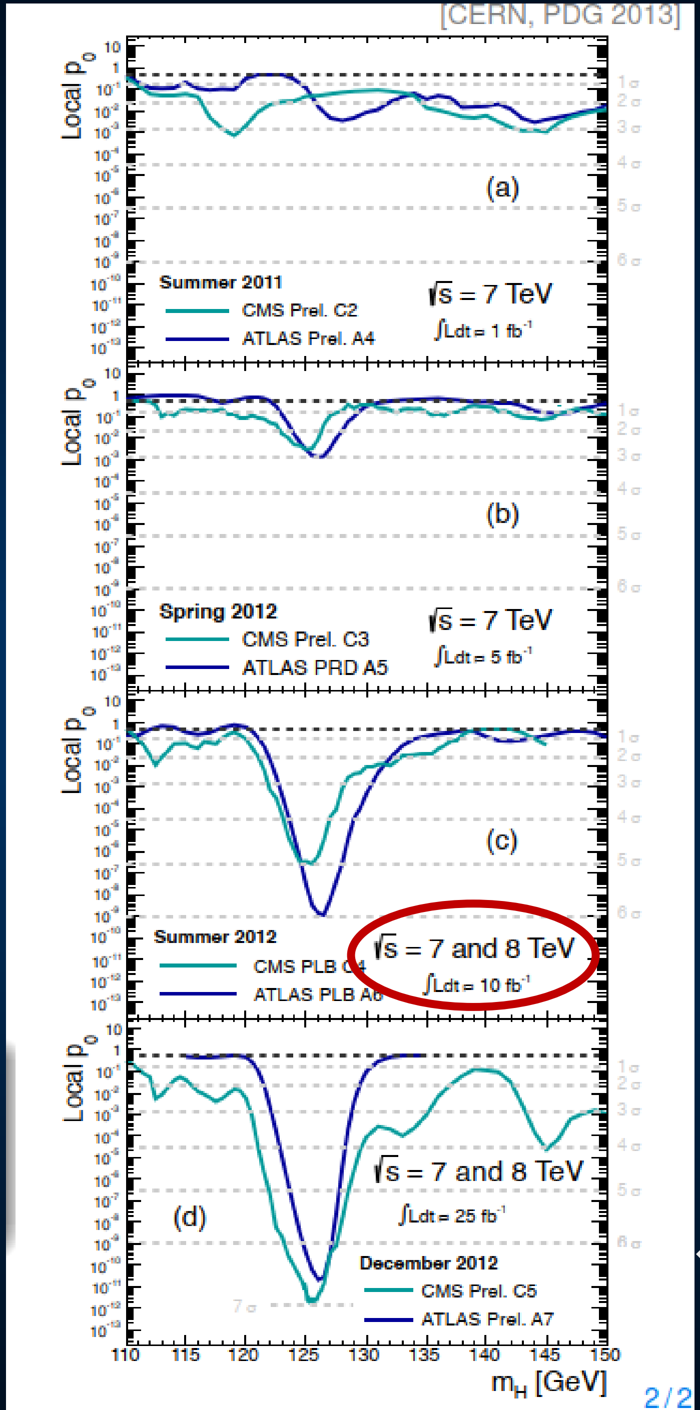




LEP1 + LEP2 and Tevatron

Signal Development

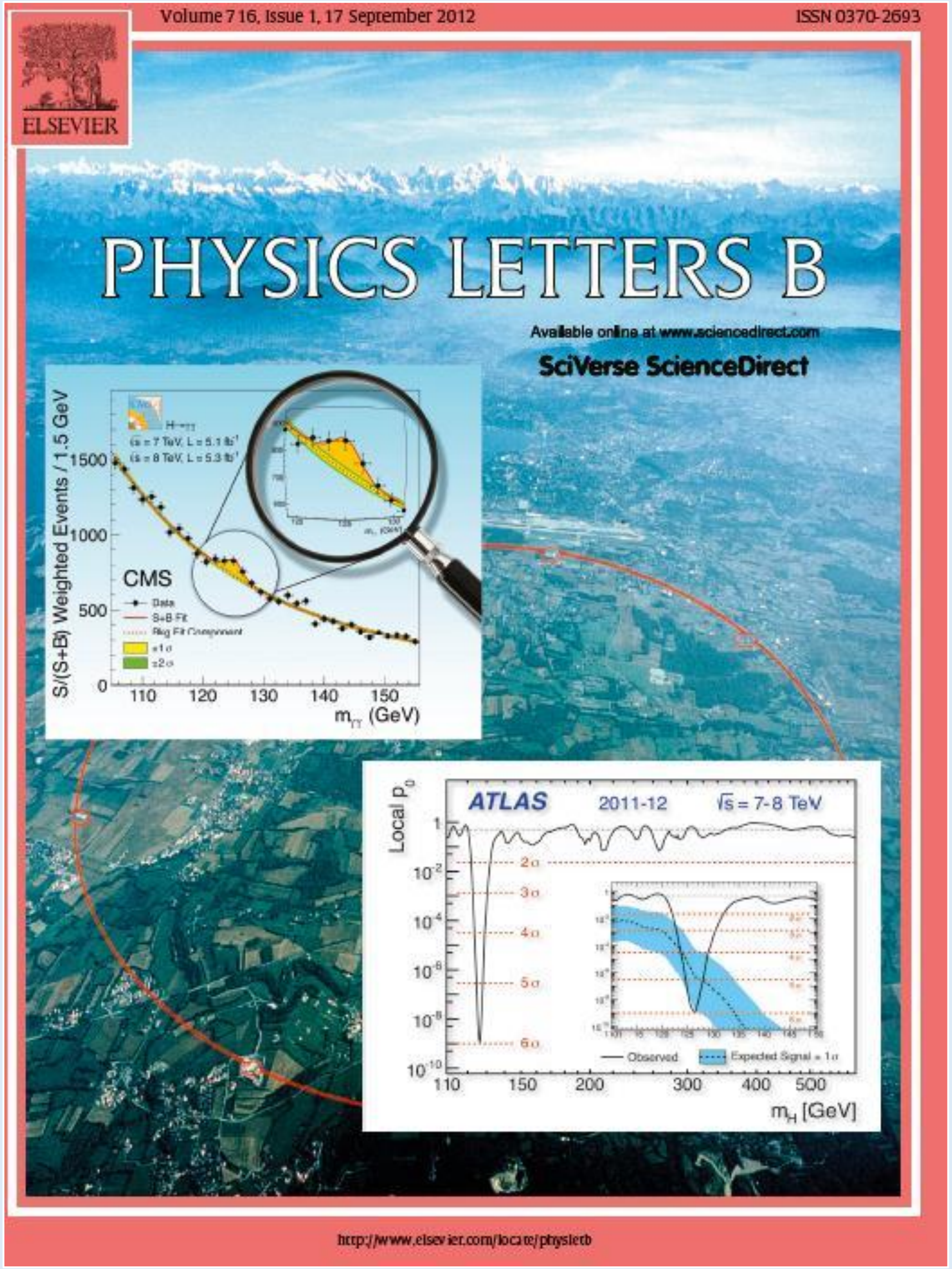
during the 12 months before the announcement



← 3 sigma

← 5 sigma

← 6 sigma



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SciVerse ScienceDirect

http://www.elsevier.com/locate/physletb

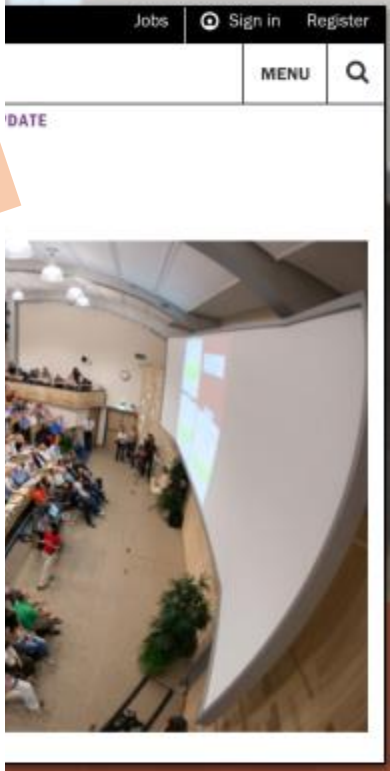
DESTAQUE

Maior acelerador de p
bosão de Higgs

Ana Gerschenfeld 5 de Julho de 2012, 0:00

SCIENCES

Les physiciens ont découv



Broadly, particle physics is to the universe what DNA is to life: the hidden principle underlying so much else. Like the uncovering of DNA's structure by Francis Crick and James Watson in 1953, the discovery Higgs makes sense of what wou otherwise be incomprehensible. significance is massive. Literally. Without the Higgs there would be mass. And without mass, there would be no stars, no planets and no atoms. And certainly no human beings. Indeed, there would be no history.

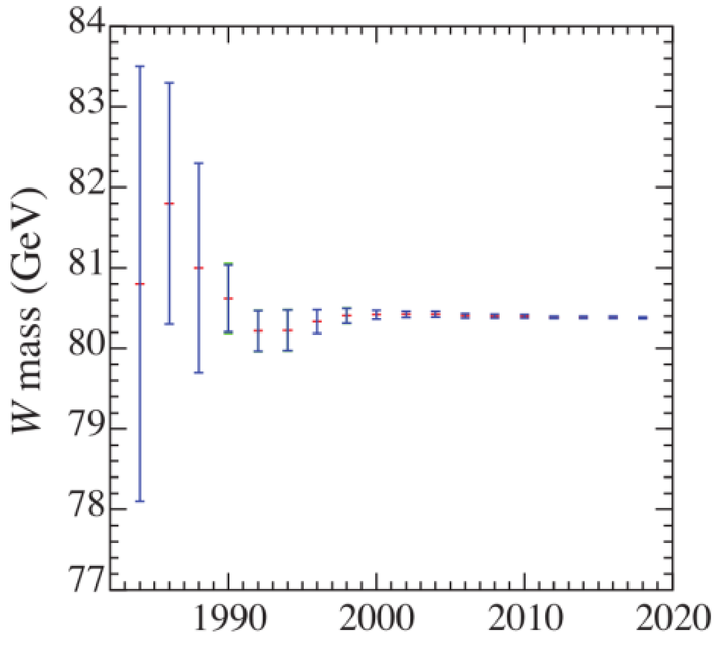
Science's great leap forward
After decades of searc
mysteries of t

Today it still triggers much interest in society

Lesson IV

Good communication to society is mandatory


NASA/masterfile



Precision measurements

M_W : present experimental situation

- At hadron colliders :

D0 (4.3+1.1 fb^{-1}) [*Phys. Rev.* ***D89*** *(2014) 012005*]

m_W = 80375 ± 11 (stat.) ± 20 (sys.) MeV

CDF (8.8 fb^{-1}) [*Science* ***376*** *(2022) 170*]

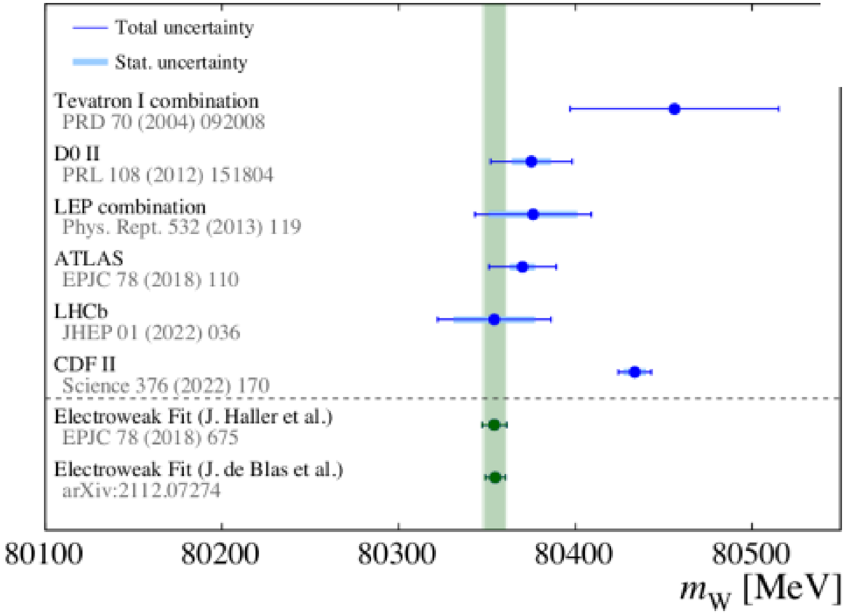
m_W = 80433.5 ± 6.4 (stat.) ± 6.9 (sys.) MeV

ATLAS (4.6 fb^{-1}) [*Eur. Phys. J.* ***C78*** *(2018) 110*]

m_W = 80370 ± 7 (stat.) ± 18 (sys.) MeV

LHCb (1.7 fb^{-1}) [*JHEP* ***01*** *(2022) 036*]

m_W = 80354 ± 23 (stat.) ± 22 (sys.) MeV

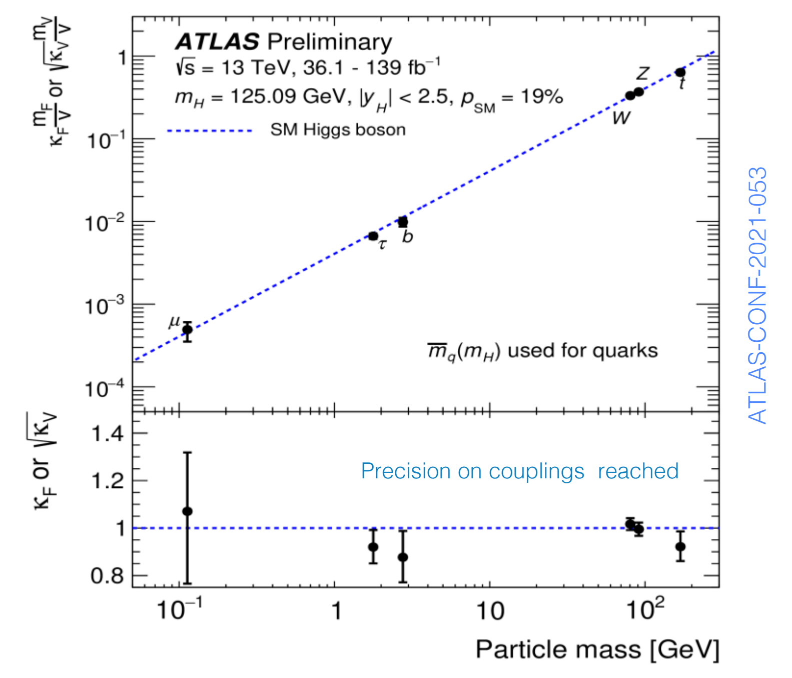


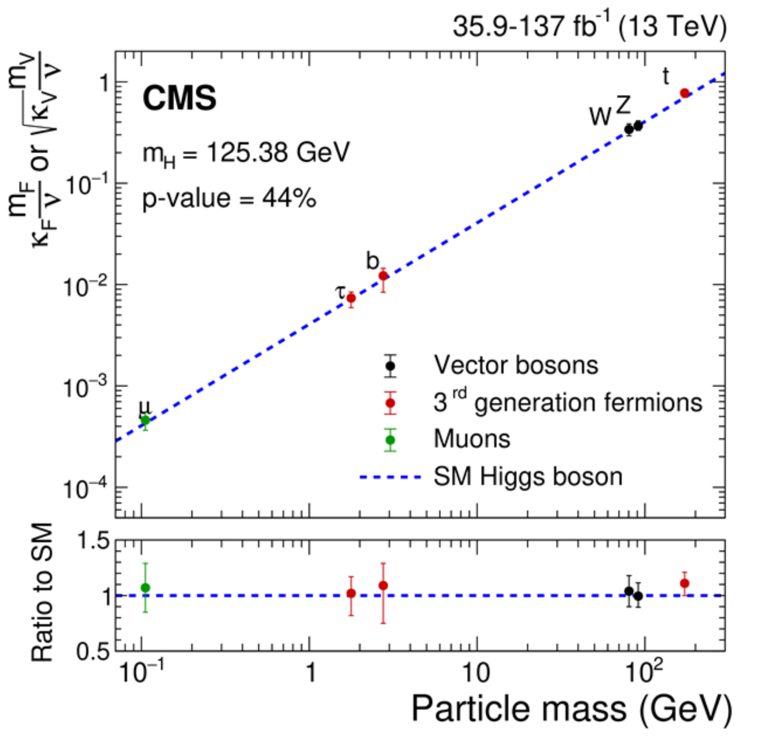
- LEP legacy : m_W = 80376 ± 33 MeV

Achievements since the Higgs Boson Discovery

- Example: measurement of the Higgs couplings to fundamental particles
- ATLAS result based on the full data set (Run 2)
- Key prediction of the Standard Model:

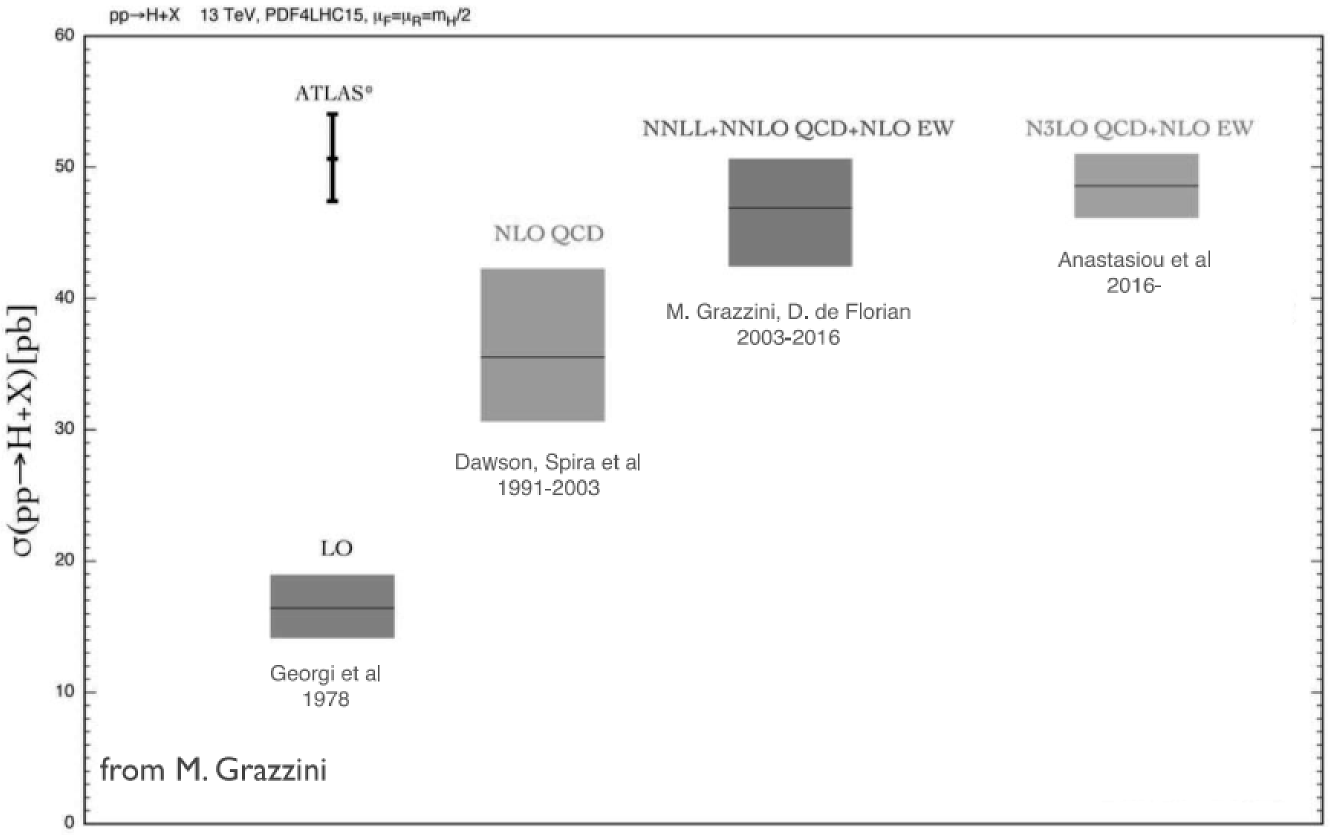
  Higgs coupling to particles is proportional to their mass





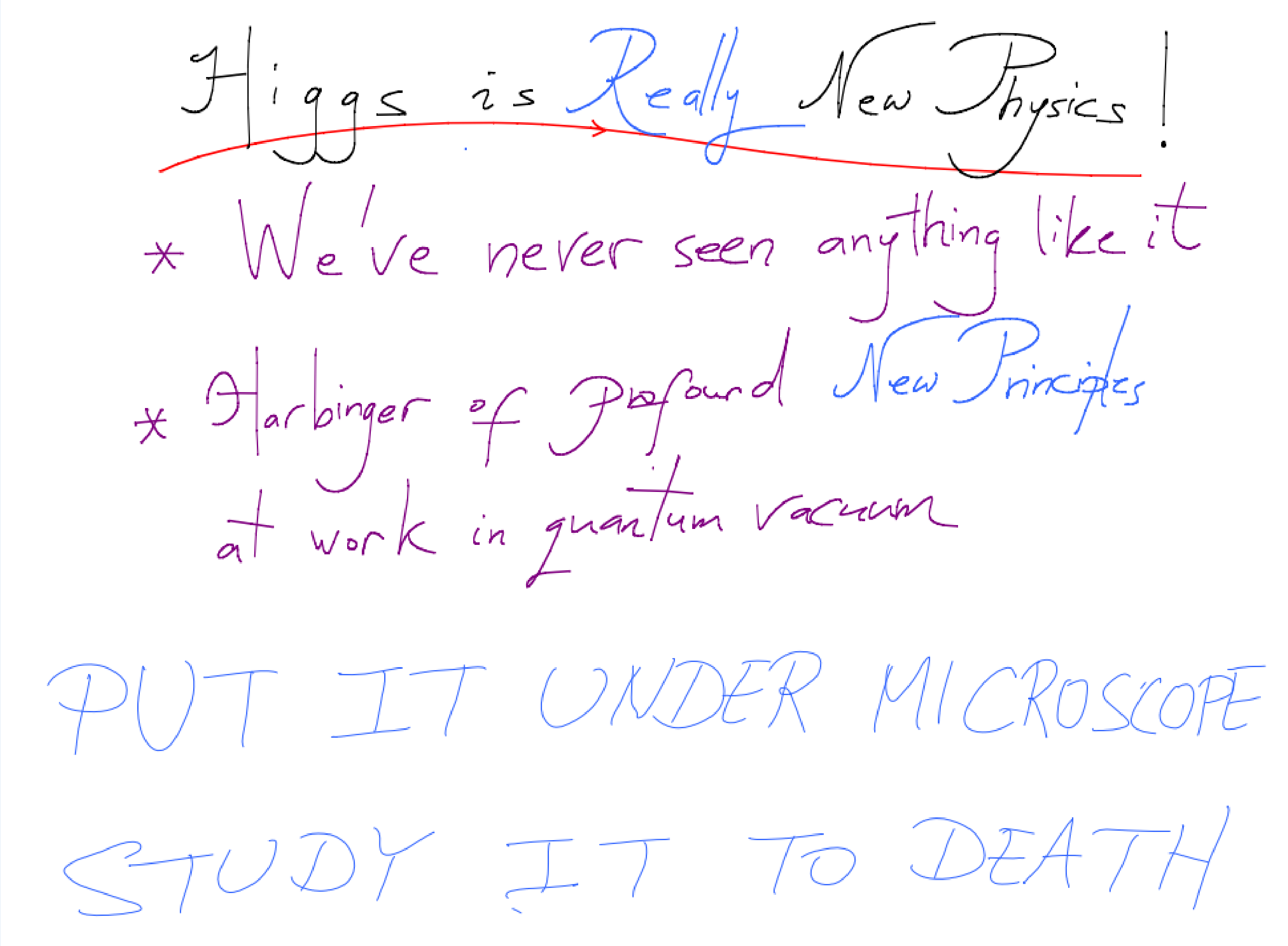
Impressive verification with an accuracy often better than 10%

Progress in experiments has to be accompanied by progress in theory and vice versa



from M. Grazzini

incomplete higher-order calculations provoke wrong conclusions!



Higgs is Really New Physics!

- * We've never seen anything like it
- * Harbinger of Profound New Principles at work in quantum vacuum

PUT IT UNDER MICROSCOPE

STUDY IT TO DEATH

Nima Arkani-Hamed

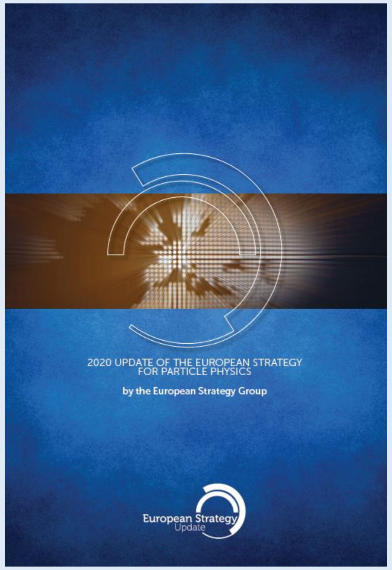
The path forward:

Update European Strategy for Particle Physics

CERN Council updated the European Strategy for Particle Physics in June 2020

Scientific recommendations

- **Full exploitation of the LHC and HL-LHC**
- **Highest-priority next collider: e+e- Higgs factory**
- Increased R&D on accelerator technologies
- Investigation of the technical and financial feasibility of a future ≥ 100 TeV hadron collider
- Long-baseline neutrino projects in US and Japan
- High-impact scientific diversity programme complementary to high-energy colliders
- R&D on detector and computing
- Theory


2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

Other high priority items:

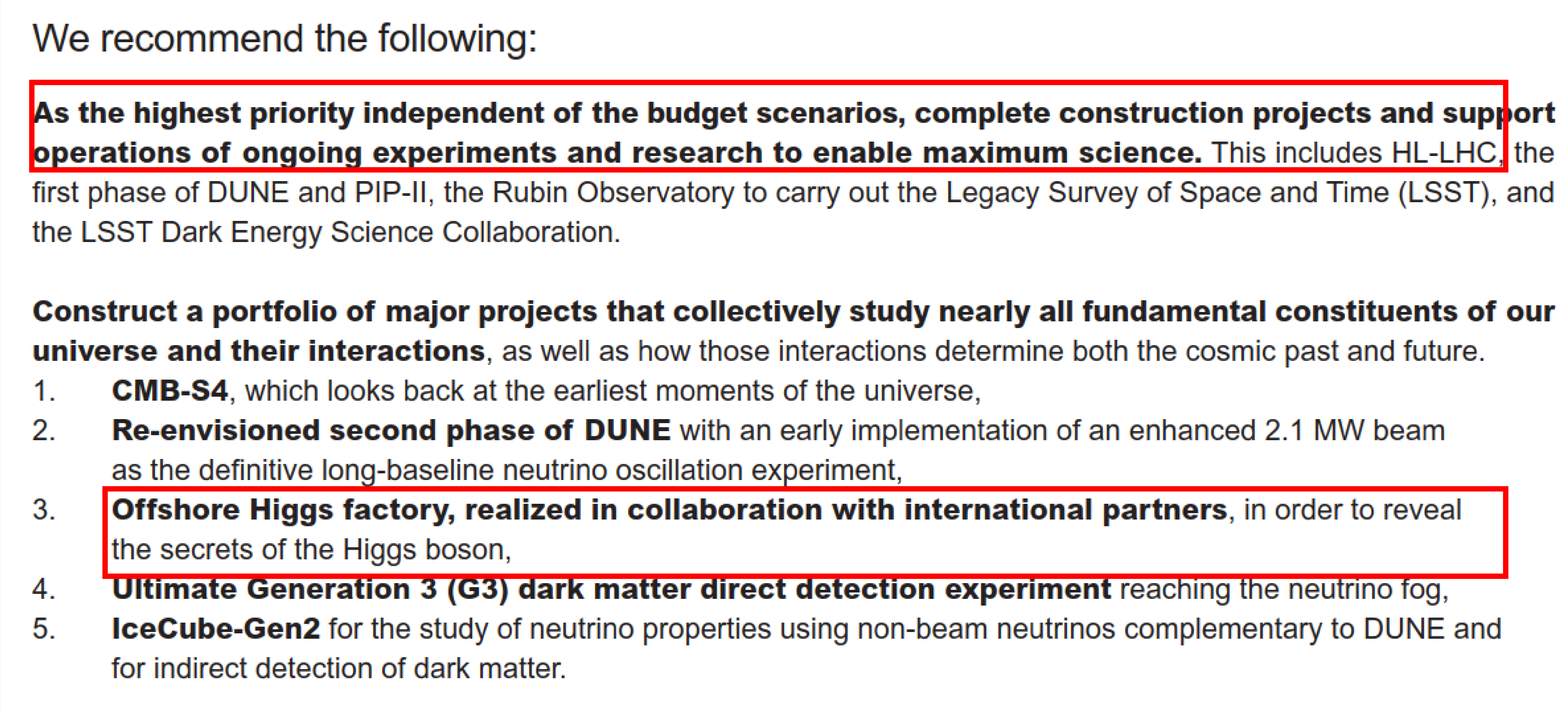
- Exploit synergies with neighboring field, in particular nuclear and astroparticle physics
- Mitigate environmental impact of particle physics
- Invest in next generation of researchers
- Support knowledge and technology transfer
- Public engagement, education and communication

Importance of collaboration between CERN and national labs highlighted

ESPPU provides guidelines for the coming years/decades to the particle physics community in general and to CERN

The path forward:

P5 Report



We recommend the following:

As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science. This includes HL-LHC, the first phase of DUNE and PIP-II, the Rubin Observatory to carry out the Legacy Survey of Space and Time (LSST), and the LSST Dark Energy Science Collaboration.

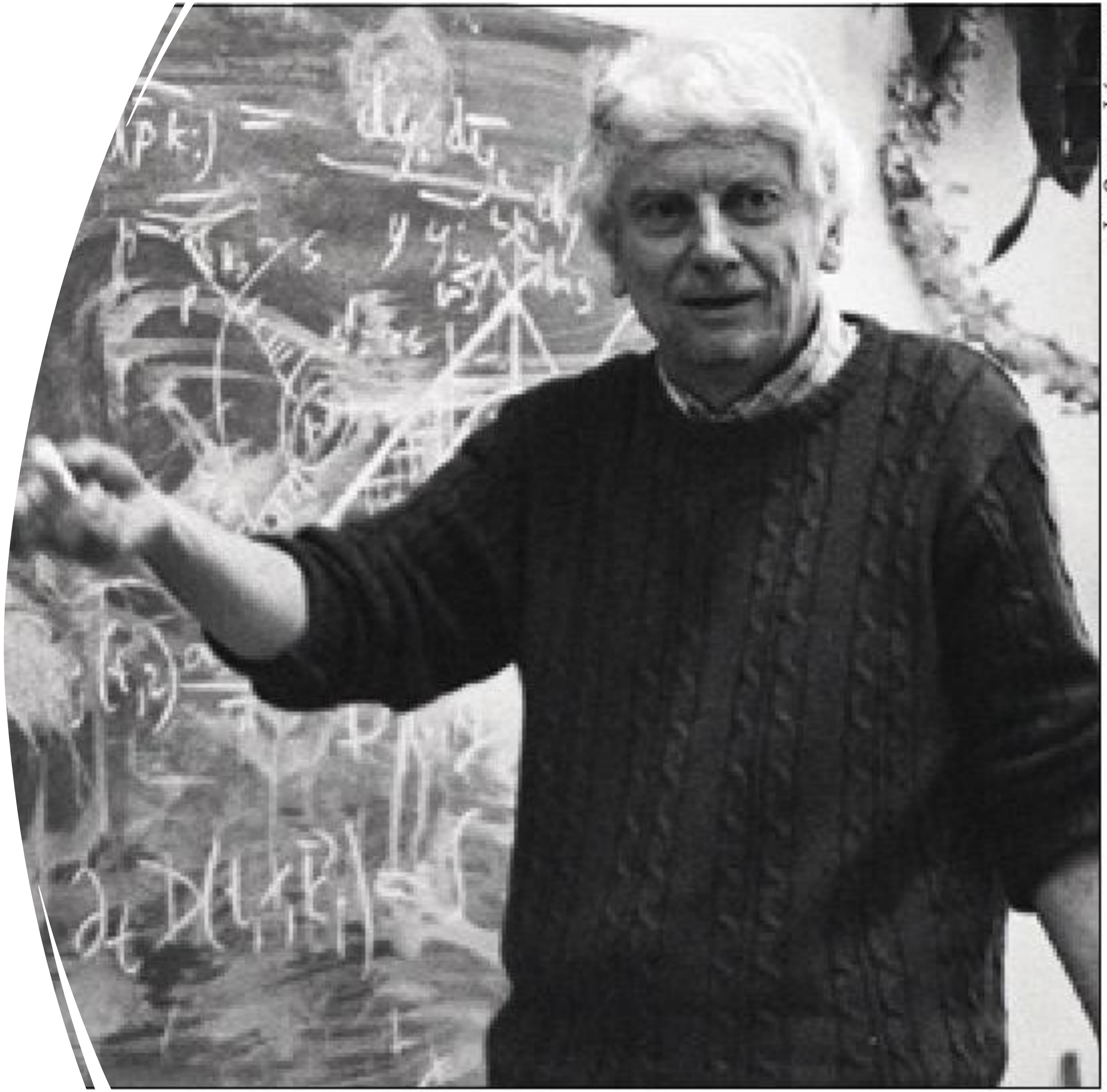
Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

1. **CMB-S4**, which looks back at the earliest moments of the universe,
2. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam as the definitive long-baseline neutrino oscillation experiment,
3. **Offshore Higgs factory, realized in collaboration with international partners**, in order to reveal the secrets of the Higgs boson,
4. **Ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog,
5. **IceCube-Gen2** for the study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter.

Concluding Remarks

Steady progress in theory and experiment over more than fifty years established the Standard Model

Stanislaw Jadach played a key role during the whole journey


Family photograph