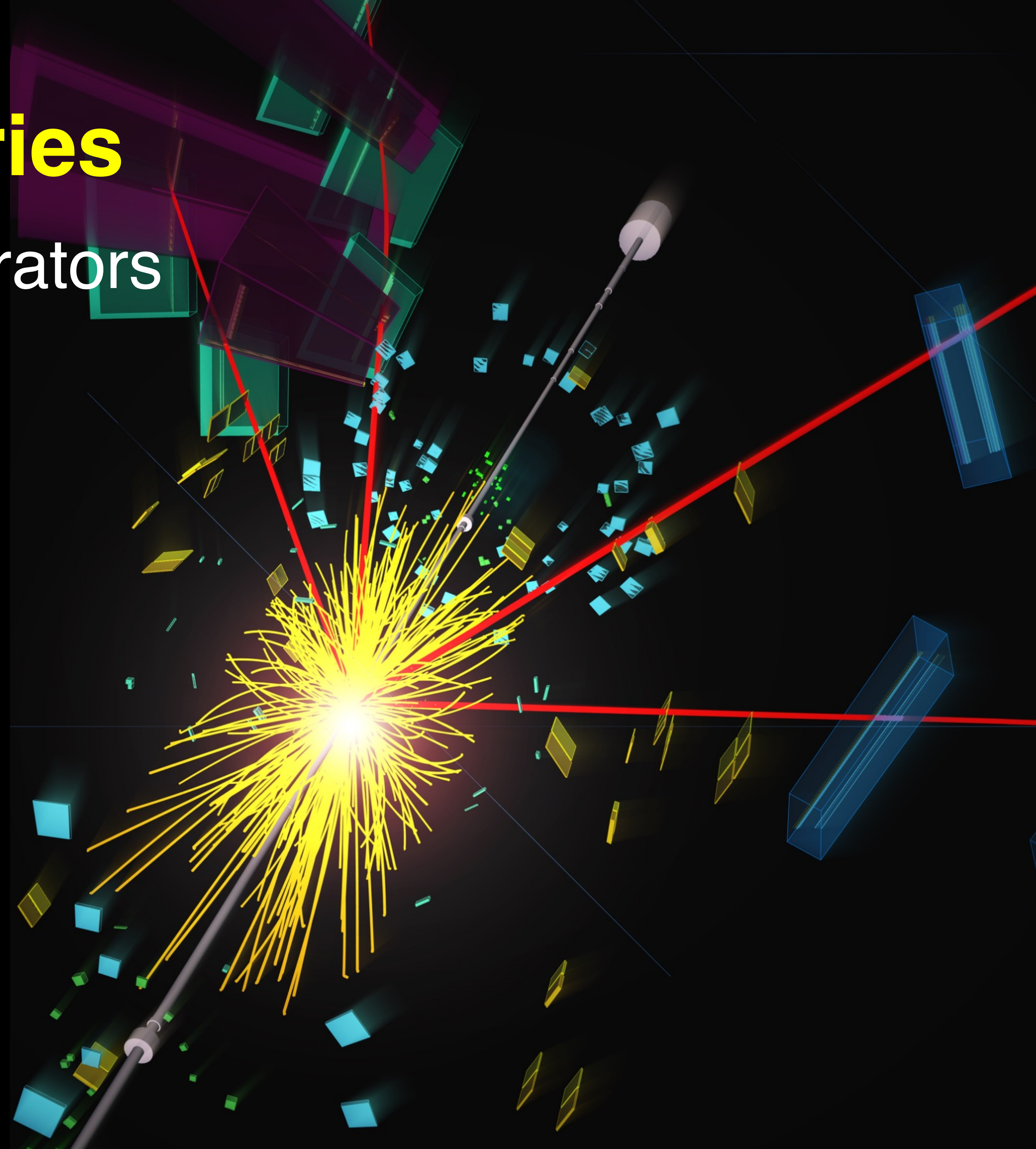
Smashing discoveries

Particle physics at accelerators

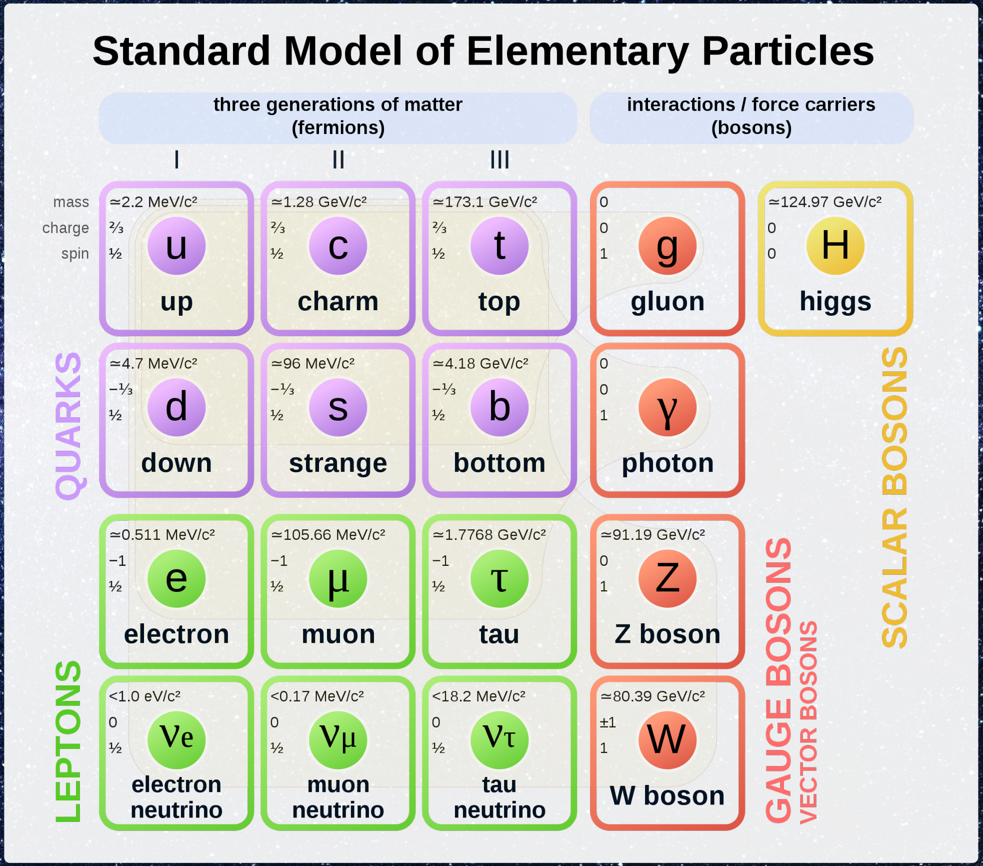
Andreas Hoecker (CERN)

50 years of physics — from particles to the universe
Symposium to honour 50 years IN2P3



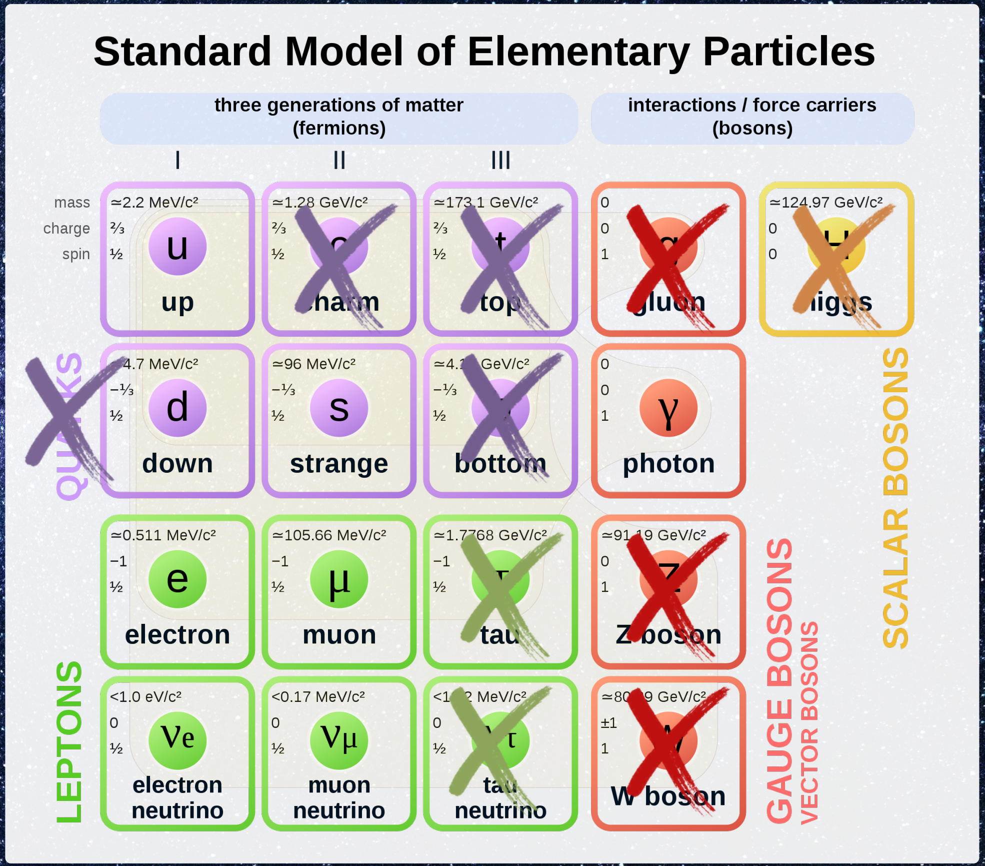

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE
LABORATOIRE ACCÉLÉRATEUR LINÉAIRE

It’s all made of a handful of particles and forces

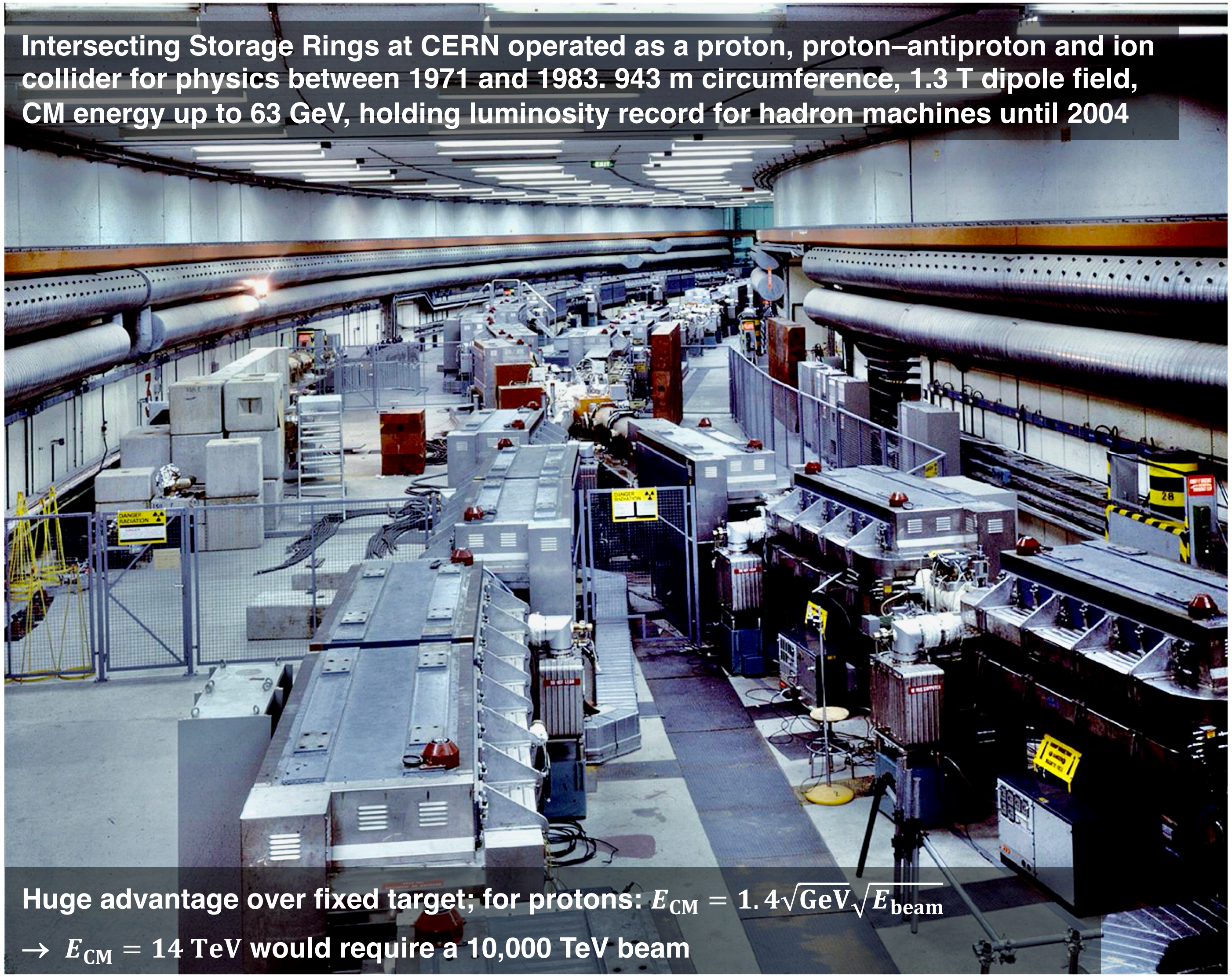


It's all made of a handful of particles and forces

What was particle physics alike in 1971?



1971 — the *(almost forgotten* — Steve Myers) first ever hadron collider

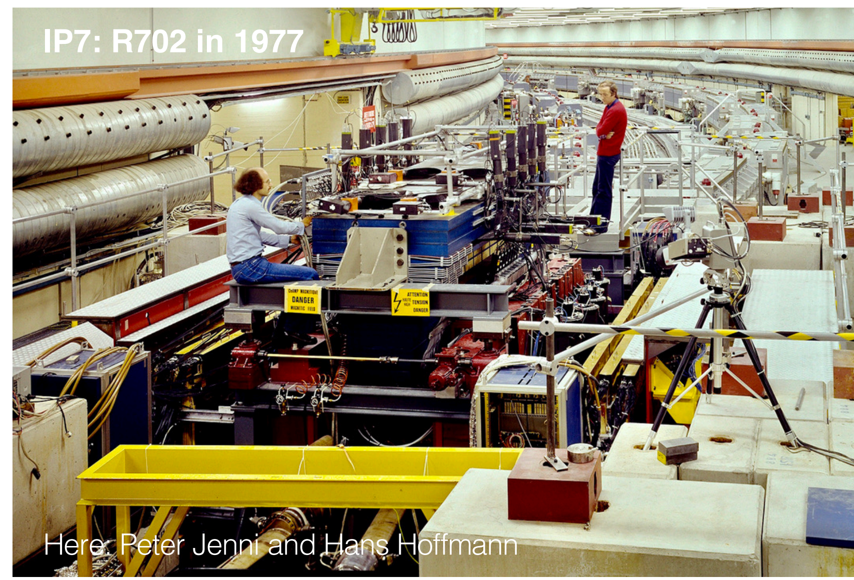


Intersecting Storage Rings at CERN operated as a proton, proton–antiproton and ion collider for physics between 1971 and 1983. 943 m circumference, 1.3 T dipole field, CM energy up to 63 GeV, holding luminosity record for hadron machines until 2004

Huge advantage over fixed target; for protons: $E_{\mathrm{CM}} = 1.4\sqrt{\mathrm{GeV}}\sqrt{E_{\mathrm{beam}}}$

$\rightarrow E_{\mathrm{CM}} = 14\ \mathrm{TeV}$ would require a 10,000 TeV beam

IP5



IP7: R702 in 1977

Here: Peter Jenni and Hans Hoffmann

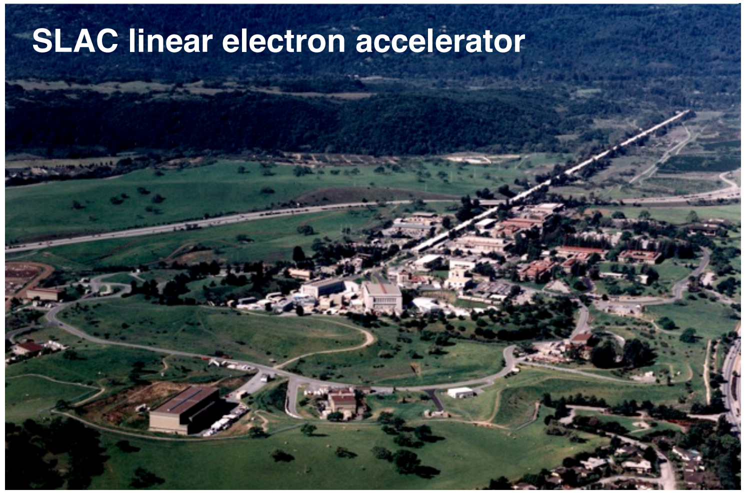
ISR Control Room (early 70s)

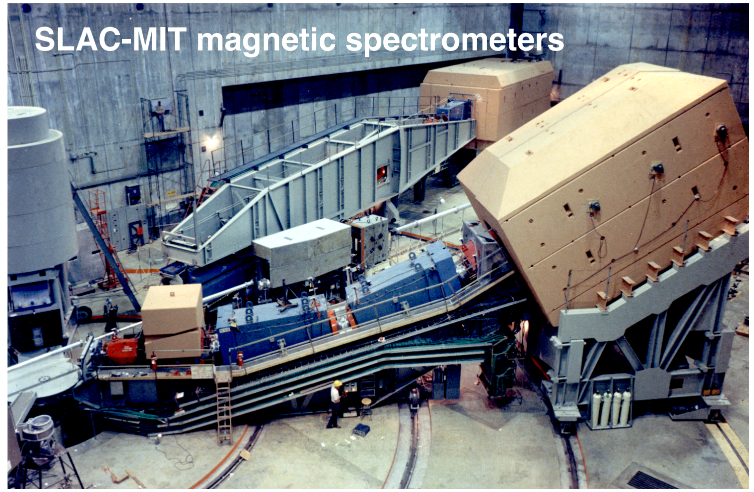
Ugo Amaldi at 50 years hadron collider symposium, CERN, Oct 2021

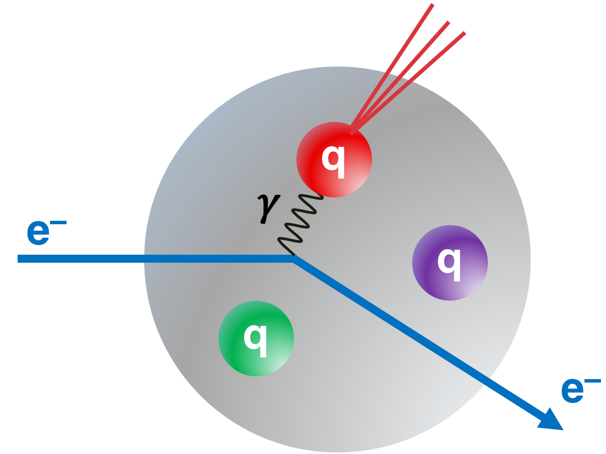
- The ISR was the only CERN collider built without a specific physics goal
- The program was shaped by the dominant view at the time: proton–proton collisions are soft processes
- The ISR Committee favoured many experiments performed by small teams

→ ***Complete change of paradigms for future colliders***

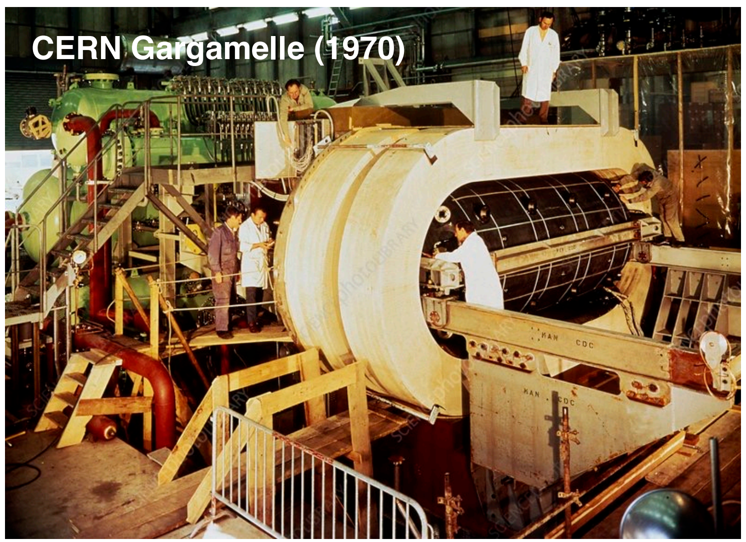
SLAC-MIT & Gargamelle proved proton substructure

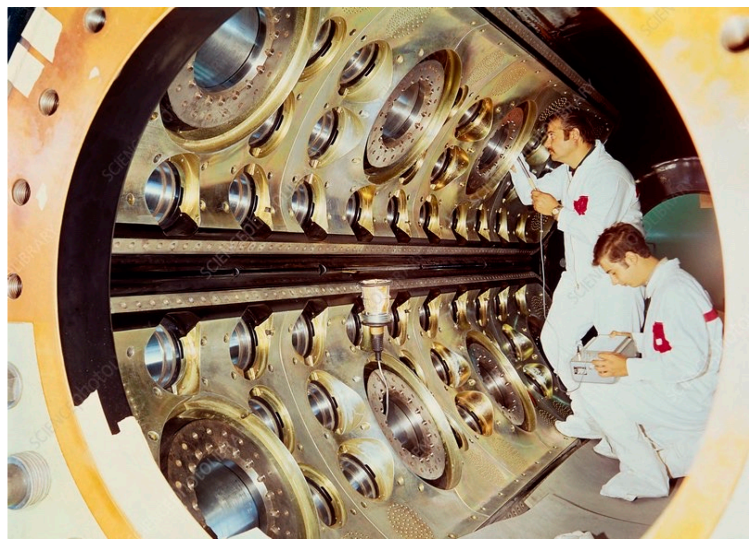


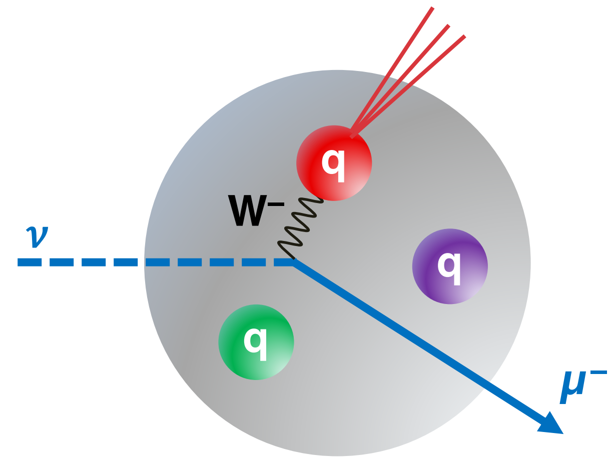




1972: electron deep-inelastic scattering: "partons" (probably quarks) exist within protons

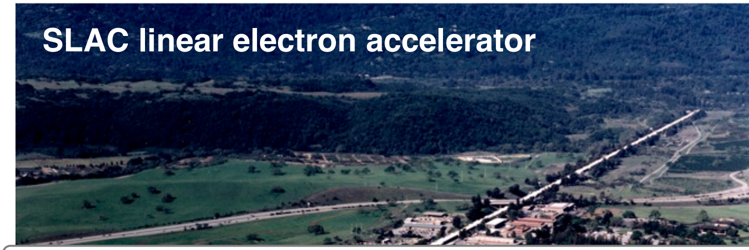


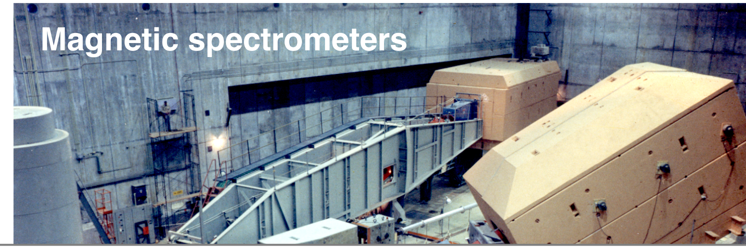


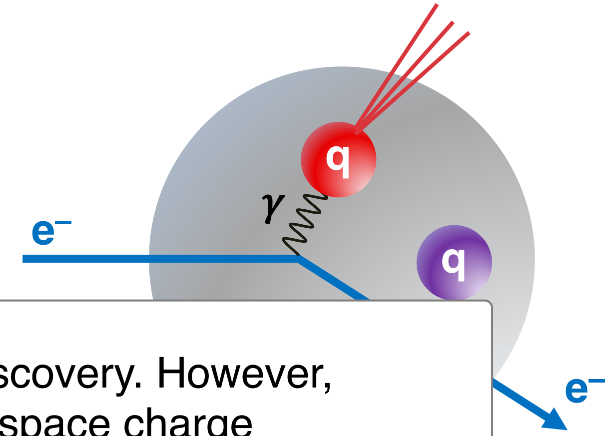


1972: neutrino deep-inelastic scattering: confirmation that partons are quarks

SLAC-MIT & Gargamelle proved proton substructure

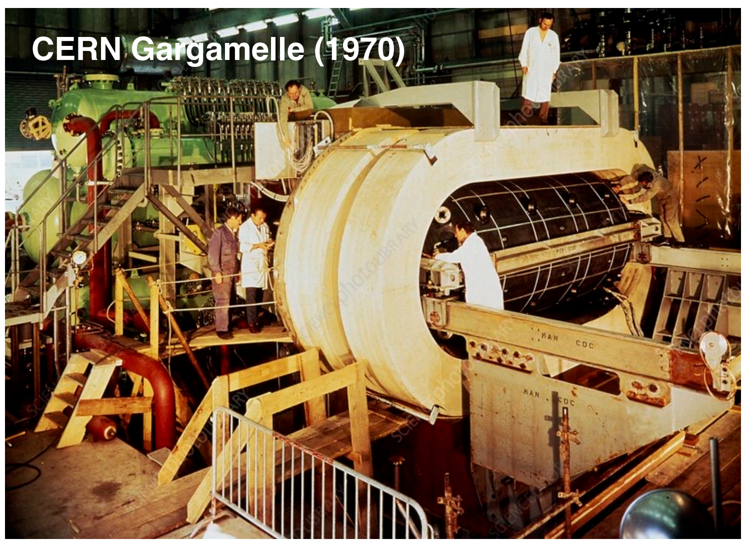


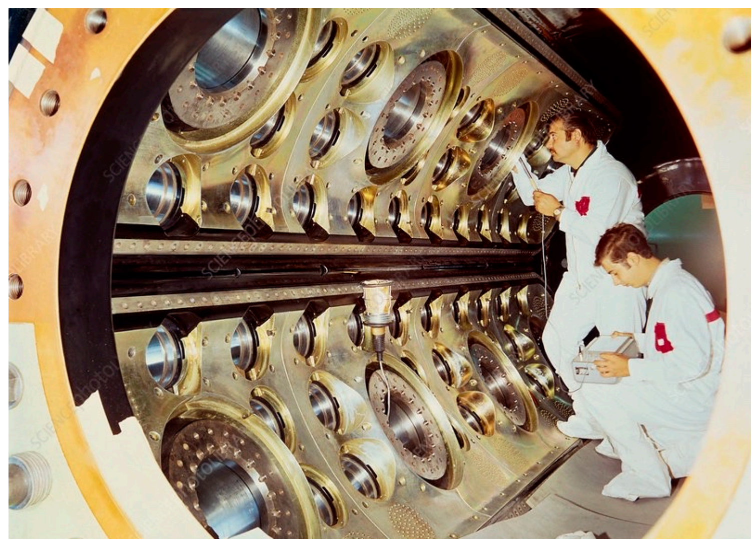


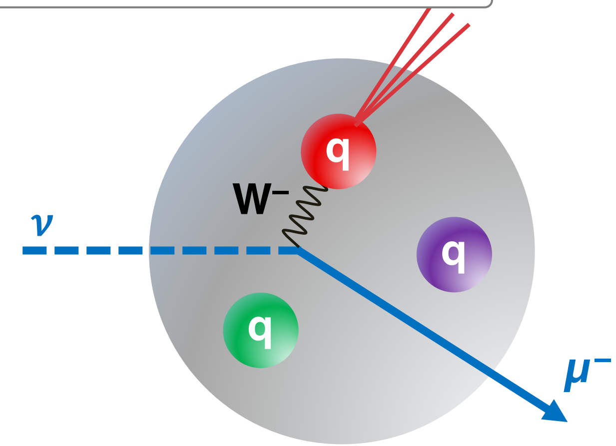


tering:
within protons

The ISR missed the 1974 November revolution and also the bottom quark discovery. However, its legacy enabled the next generation collider experiments: proton stacking, space charge compensation, beam diagnostics, stochastic cooling, van-der-Meer luminosity scans, importance of efficient triggers and large-angle coverage, jets, etc.

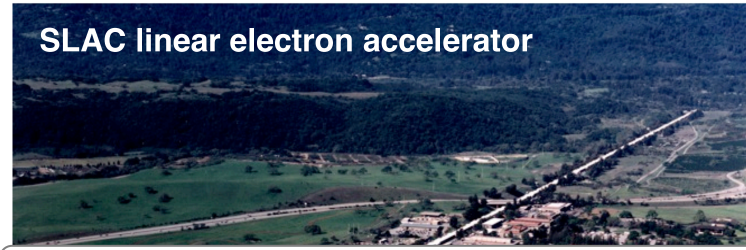


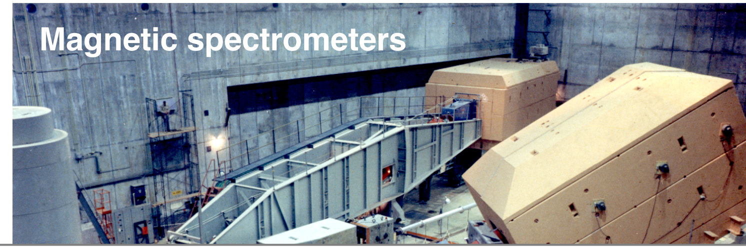


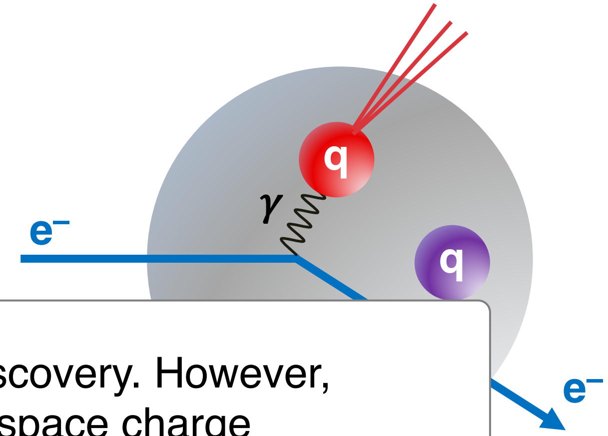


1972: neutrino deep-inelastic scattering: confirmation that partons are quarks

SLAC-MIT & Gargamelle proved proton substructure



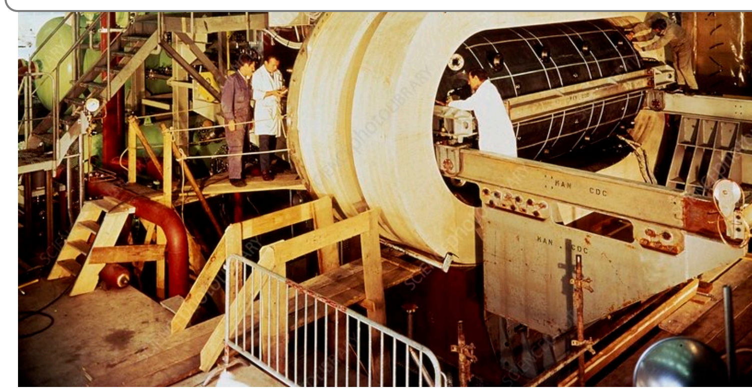


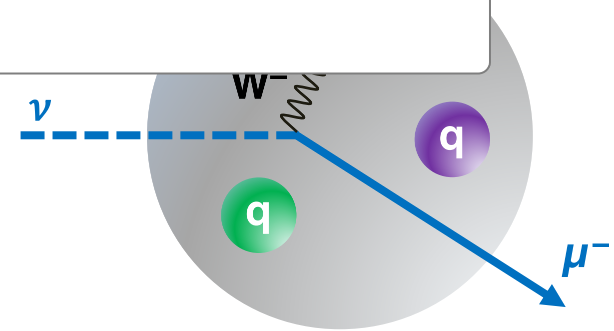


The ISR missed the 1974 November revolution and also the bottom quark discovery. However, its legacy enabled the next generation collider experiments: proton stacking, space charge compensation, beam diagnostics, stochastic cooling, van-der-Meer luminosity scans, importance of efficient triggers and large-angle coverage, jets, etc.

Pierre Darriulat wrote: “*We, who worked at the ISR… tend to see [it] and the proton–antiproton colliders, both at CERN and at the Tevatron, as a lineage, father and sons, the success of the latter being indissociable from the achievements of the former.*”

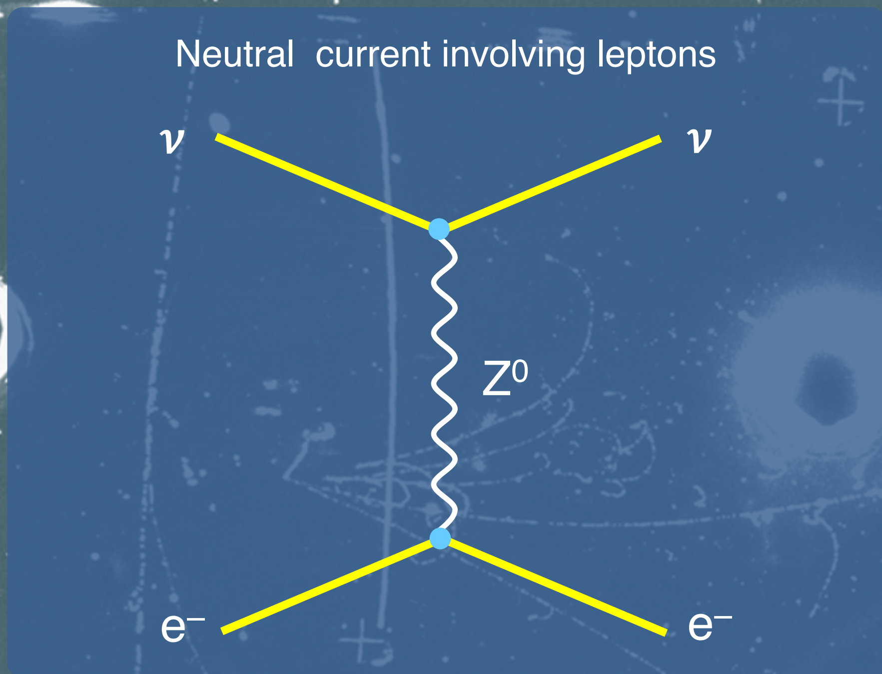
tering:
within protons





1972: neutrino deep-inelastic scattering: confirmation that partons are quarks

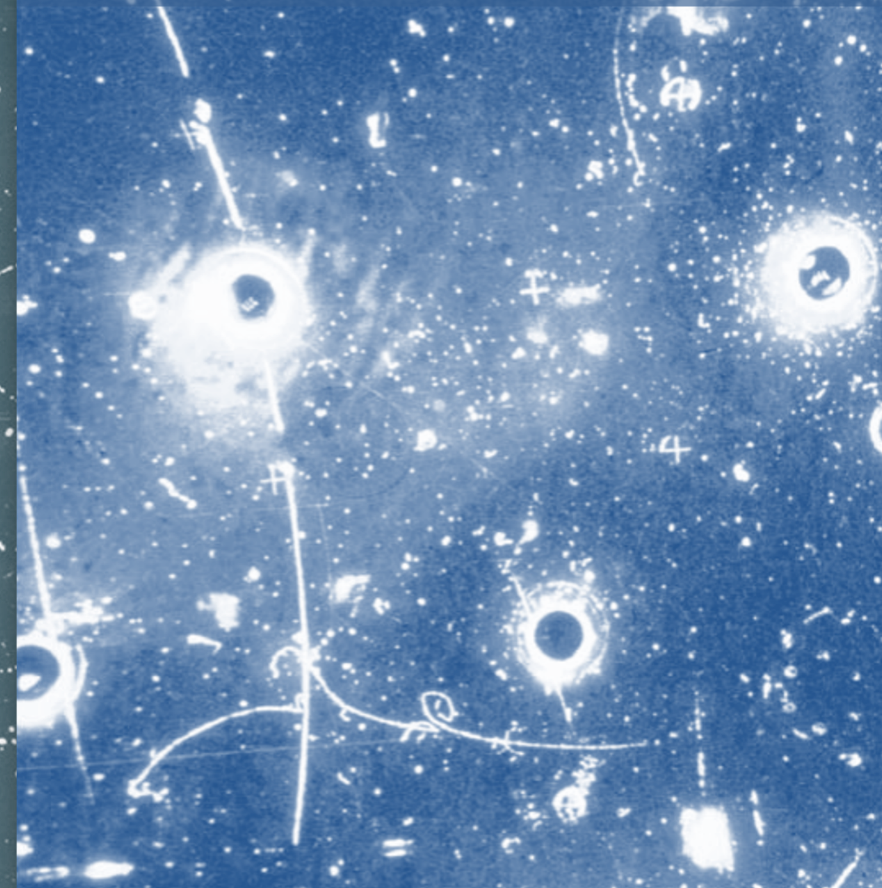
Gargamelle’s other breakthrough



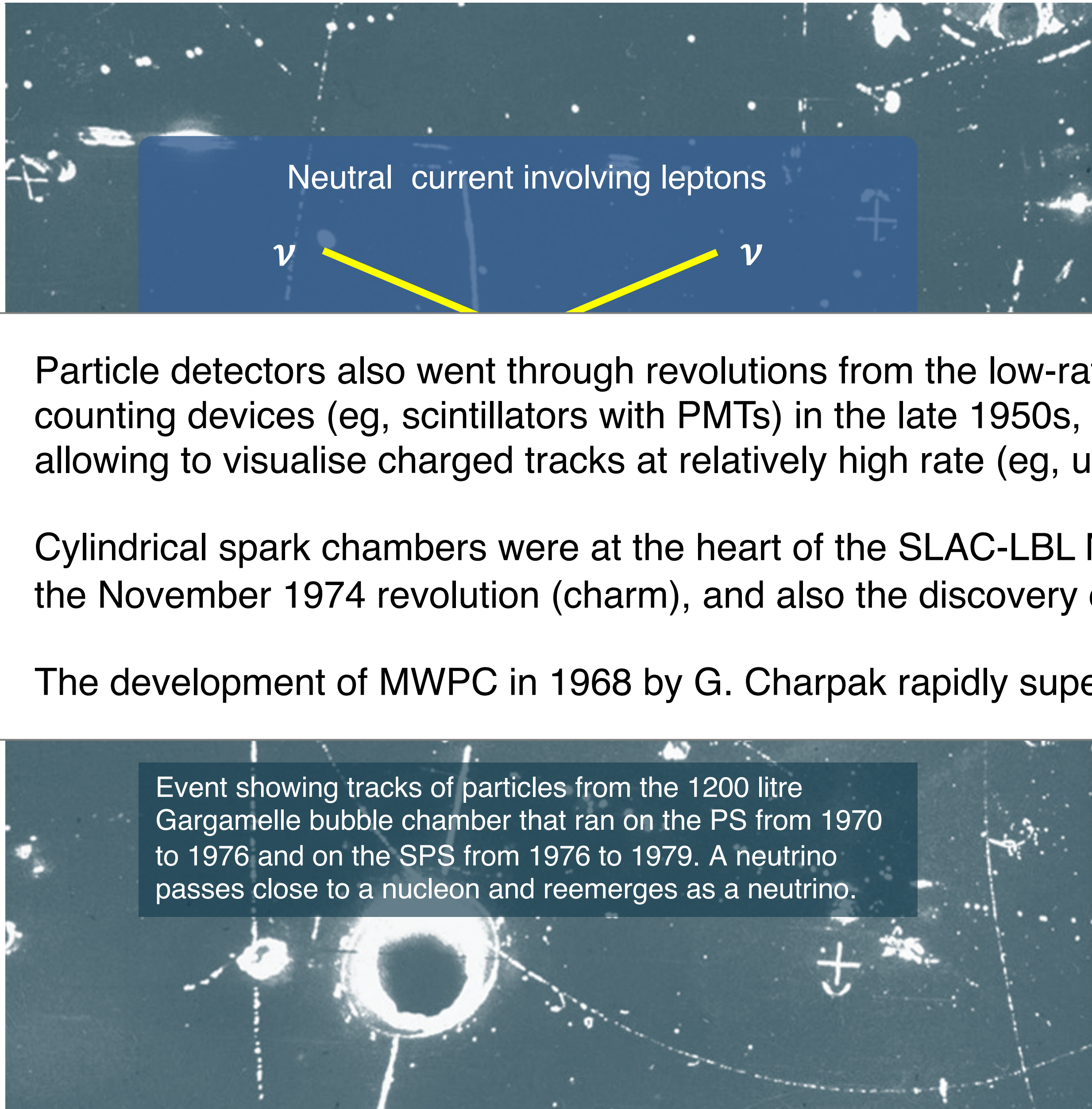
Event showing tracks of particles from the 1200 litre Gargamelle bubble chamber that ran on the PS from 1970 to 1976 and on the SPS from 1976 to 1979. A neutrino passes close to a nucleon and reemerges as a neutrino.

The first example of the leptonic neutral current (Sep 1973). An incoming muon-antineutrino (from the lower right) knocks an electron forwards, creating a characteristic electronic shower with electron-positron pairs.

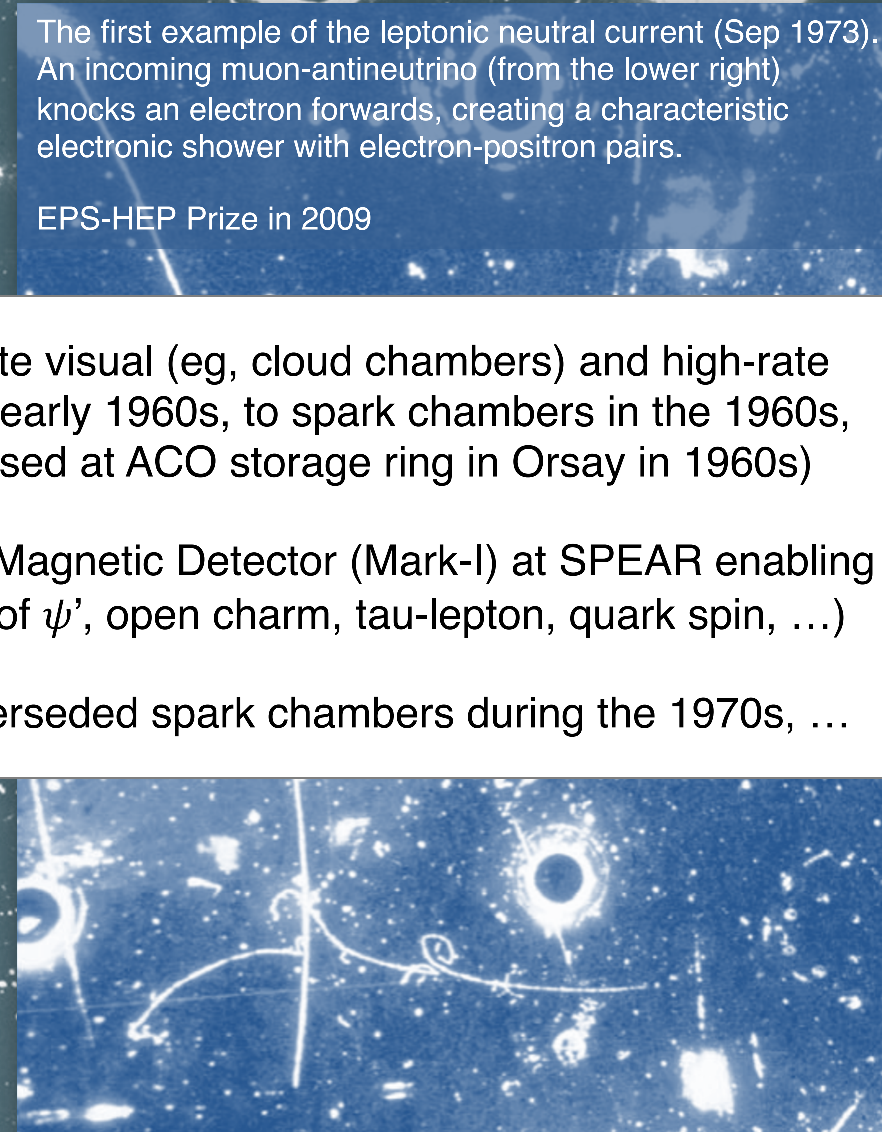
EPS-HEP Prize in 2009



Gargamelle’s biggest breakthrough



Event showing tracks of particles from the 1200 litre Gargamelle bubble chamber that ran on the PS from 1970 to 1976 and on the SPS from 1976 to 1979. A neutrino passes close to a nucleon and reemerges as a neutrino.



The first example of the leptonic neutral current (Sep 1973). An incoming muon-antineutrino (from the lower right) knocks an electron forwards, creating a characteristic electronic shower with electron-positron pairs.

EPS-HEP Prize in 2009

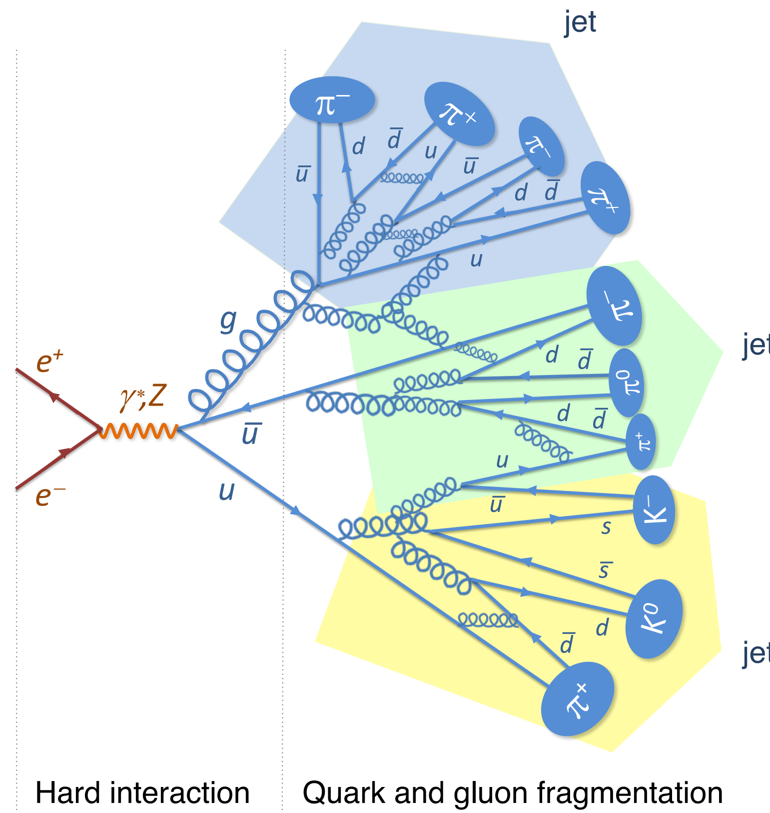
Particle detectors also went through revolutions from the low-rate visual (eg, cloud chambers) and high-rate counting devices (eg, scintillators with PMTs) in the late 1950s, early 1960s, to spark chambers in the 1960s, allowing to visualise charged tracks at relatively high rate (eg, used at ACO storage ring in Orsay in 1960s)

Cylindrical spark chambers were at the heart of the SLAC-LBL Magnetic Detector (Mark-I) at SPEAR enabling the November 1974 revolution (charm), and also the discovery of ψ’, open charm, tau-lepton, quark spin, …)

The development of MWPC in 1968 by G. Charpak rapidly superseded spark chambers during the 1970s, …

Protons were thus made of quarks but was QCD right?

In 1979, the existence of gluons was proven with the observation of hard-scattering three-jet events at the PETRA, a 2.3 km e^+e^- storage ring (13–46 GeV between 1979 and 1986) at DESY



A 6.9-km circumference Super Proton Synchrotron

Approval in Feb 1971, press release (left). SPS inauguration in 1977 (right)

300 GeV PROJECT APPROVED

15

Meyrin-Geneva : At its resumed meeting today the Council of CERN approved the construction of CERN II, a new European nuclear particle physics laboratory centred on a proton synchrotron at least ten times larger than the existing CERN 20-30 GeV accelerator which has been operating now for nearly 12 years. The Director-General of the new laboratory is Dr. J.B. Adams. The accelerator will be built deep underground on a site adjacent to the present CERN laboratory partly in France and partly in Switzerland. Five zones have been designated the first three of which will be put progressively at the disposal of CERN by the host countries as the programme develops. Approximately 412 ha are in France and 68 ha in Switzerland. The buildings on the ground surface will be limited to a central group of laboratories and assembling halls and some experimental halls along the beam lines from the machine. The programme of construction will last eight years and will cost 1150 MSwFr (at 1970 prices) of which some 250 MSwFr will be absorbed by the previously forecast budgets of the existing CERN I.

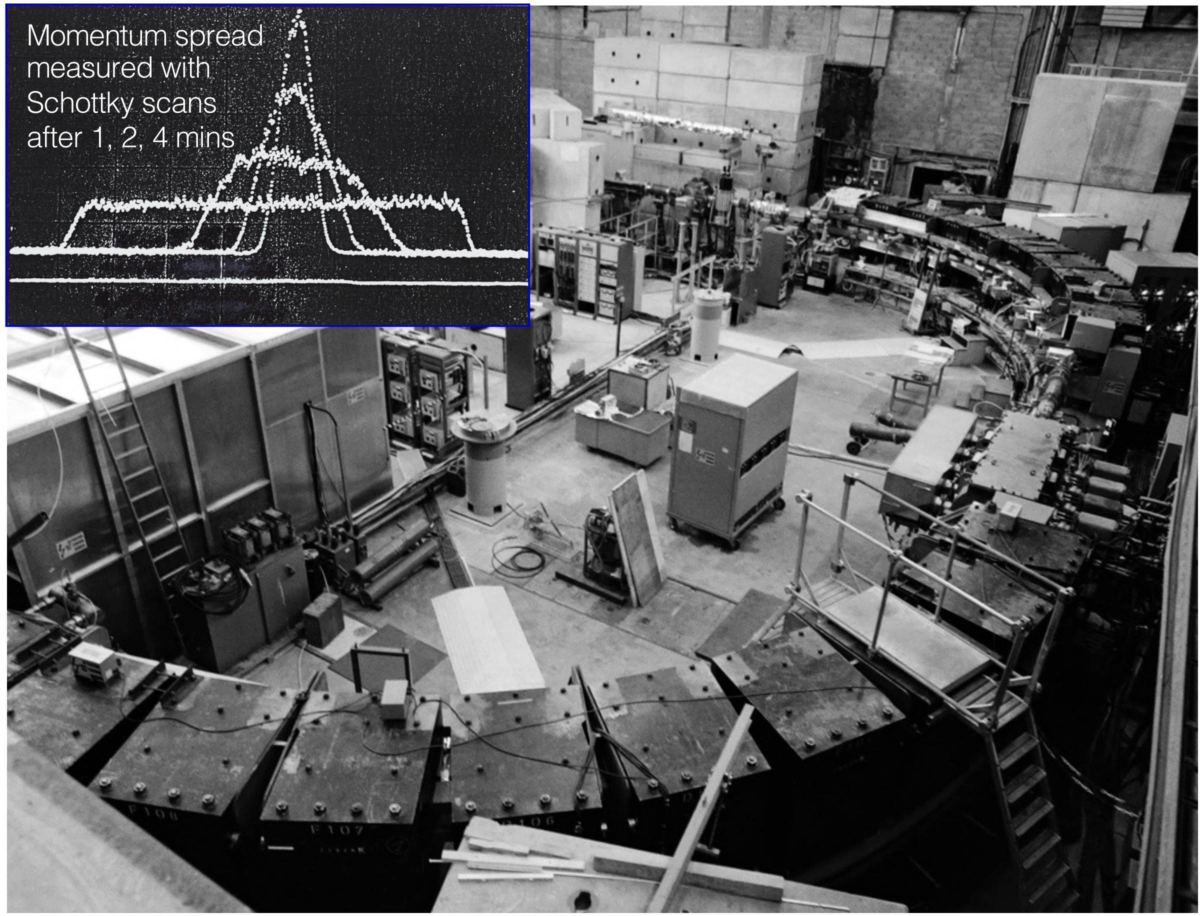
Ten countries will participate in the programme sharing the cost as follows: Austria 2.01 % , Belgium 3.88 % , France 20.48 % , Fed. Rep. Germany 23.96 %, Italy 13.27 %, Netherlands 4.56 % , Norway 1.57 % , Sweden 4.72 % , Switzerland 3.30 %, U.K. 22.25 %.

Total cost, corrected for inflation, not so different from LHC

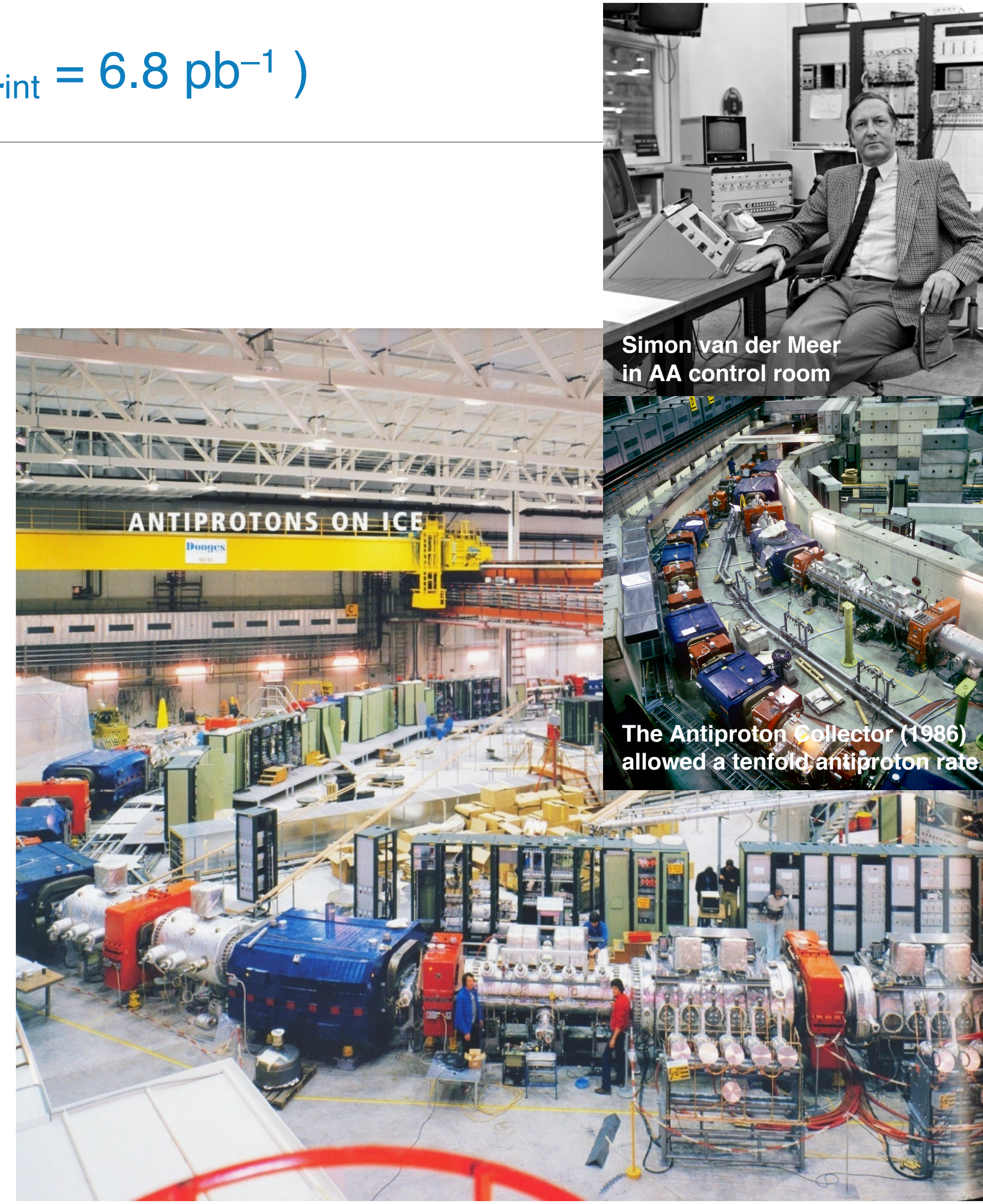
Lyn Evans at 50 years hadron collider symposium

The Sp$\bar{p}$S (1981—1991, E_{CM} up to 900 GeV, $L_{\mathrm{int}} = 6.8\ \mathrm{pb}^{-1}$)

Antiprotons had to be accumulated and cooled

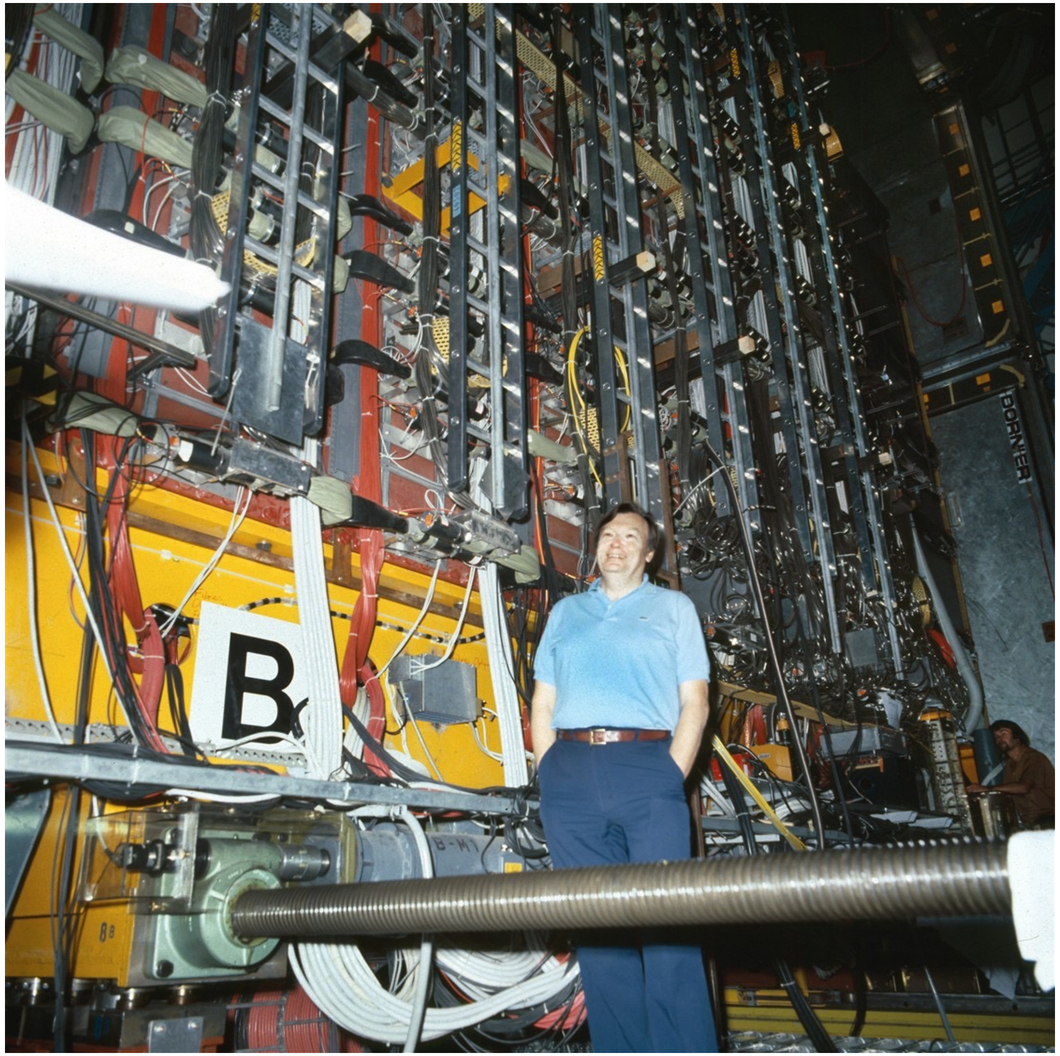


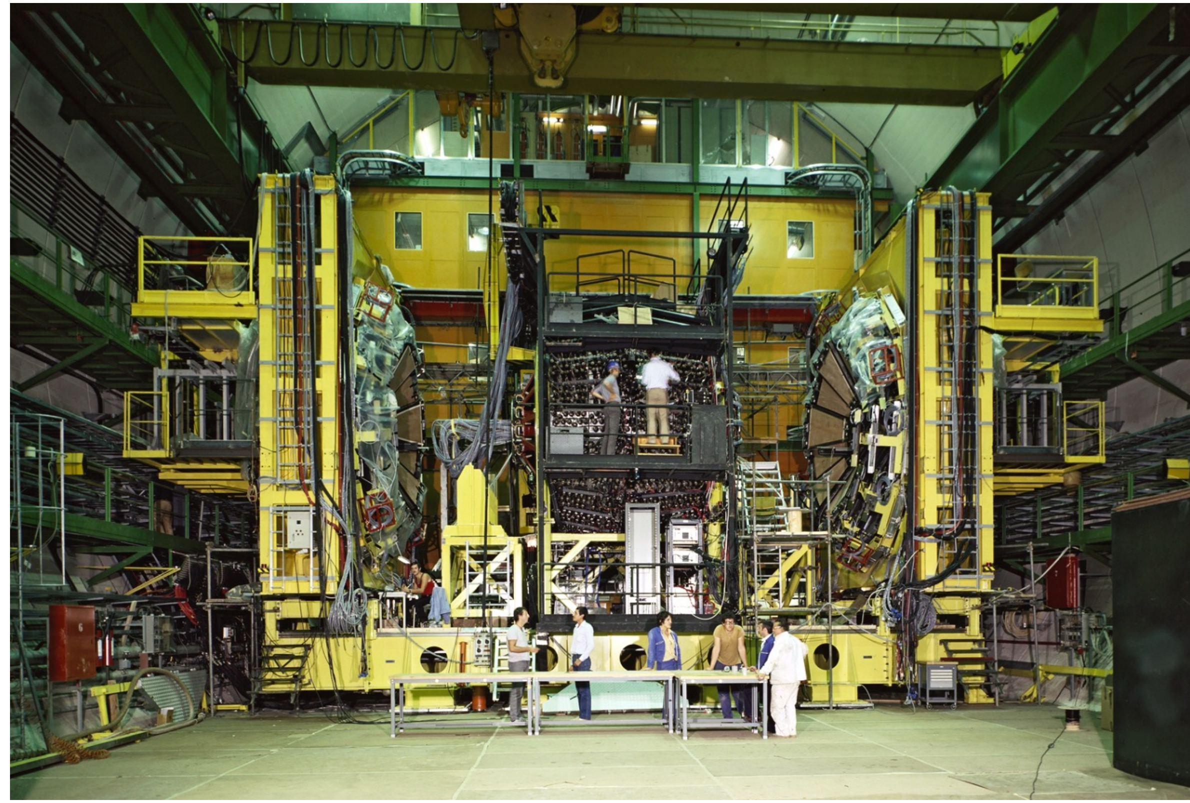
Initial Cooling Experiment (protons), ICE (1978) — built from first g–2 magnets



Antiproton Accumulator (antiprotons produced in PS at ~3.5 GeV; it took about 20 hours of stacking and cooling to produce a sufficiently dense antiproton stack for transfer to SPS)

The S$p\bar{p}$S and its experiments Underground Areas 1 & 2



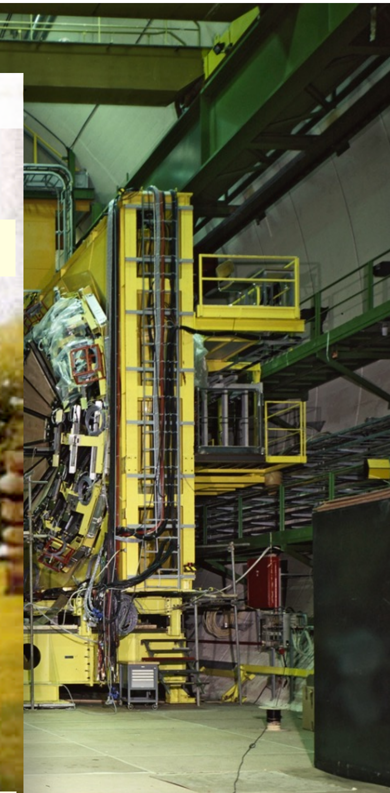


UA1: hermetic (4π) detector with drift chamber, calorimeters, large muon system, and 0.7 T dipole magnet

UA2: optimized for W and Z detection in electron channel, no central magnetic field, no muon system, high-granular projective calorimeter, first silicon pad vertex tracker (after upgrade, not on picture)

Both experiments were approved in 1978, first data taking in 1981

The Sp$\bar{p}$S and its experiments Underground Areas 1 & 2

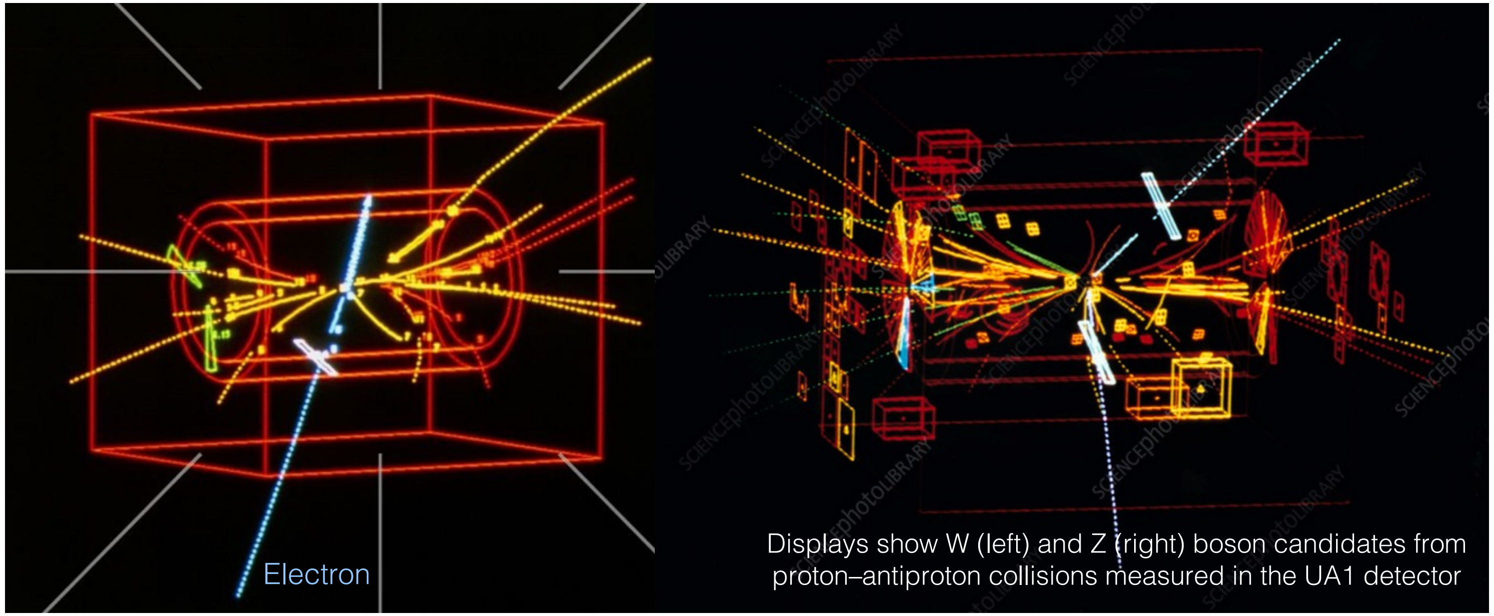


meters, large muon

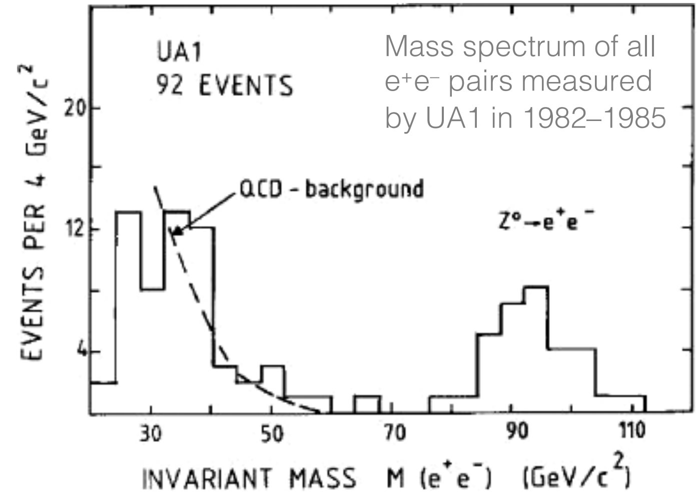
nnel, no central
projective calorimeter,

Both experiments were approved in 1978, first data taking in 1981

The W and Z boson discovery by UA1 & UA2



Displays show W (left) and Z (right) boson candidates from proton–antiproton collisions measured in the UA1 detector

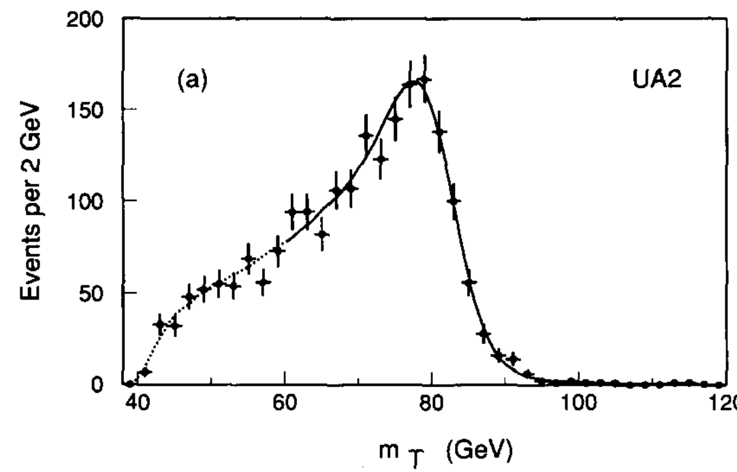


Mass spectrum of all e^+e^- pairs measured by UA1 in 1982–1985

25 Jan 1983: CERN press conference announcing W discovery
Nobel Prize in 1984 for C. Rubbia and S. van der Meer

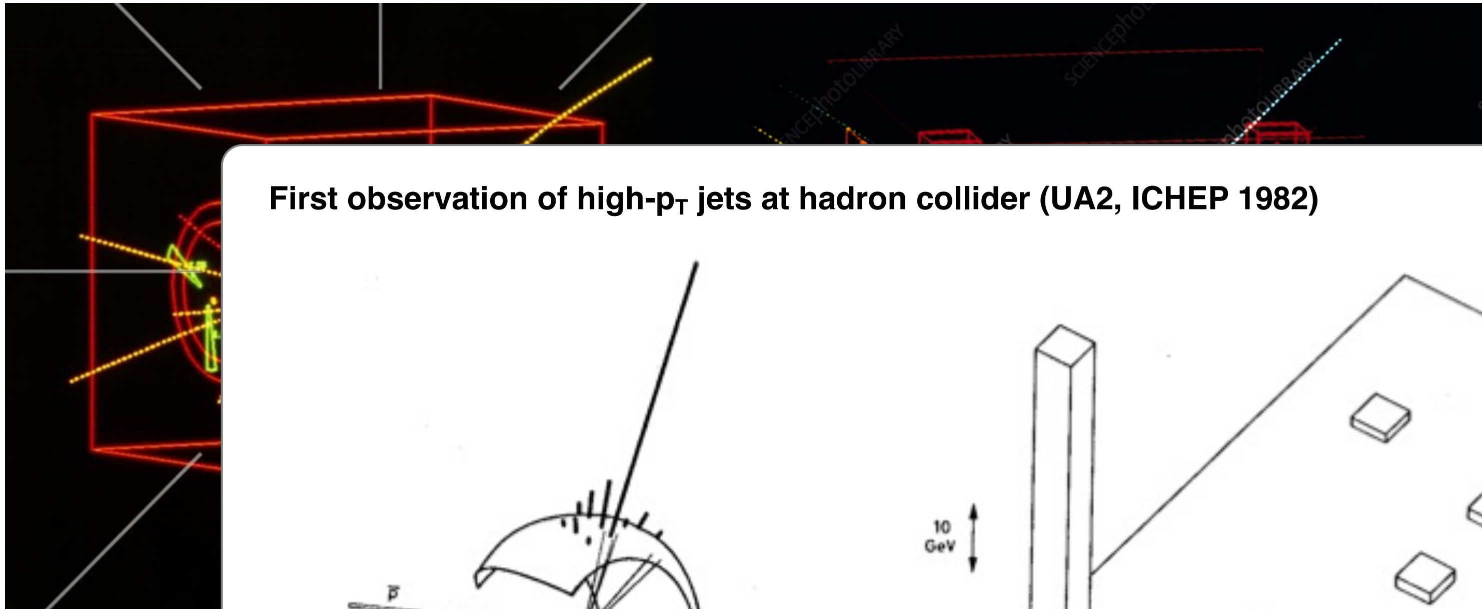
Lessons learned (F. Pauss, Oct 2021):

- Machine background much less than feared
- Hermetic detector with magnetic field is essential
- Be aware of statistical fluctuations and of tails in distributions
- Think carefully about upgrade projects
- High-granular calorimeter for jet measurement [*my addition*]



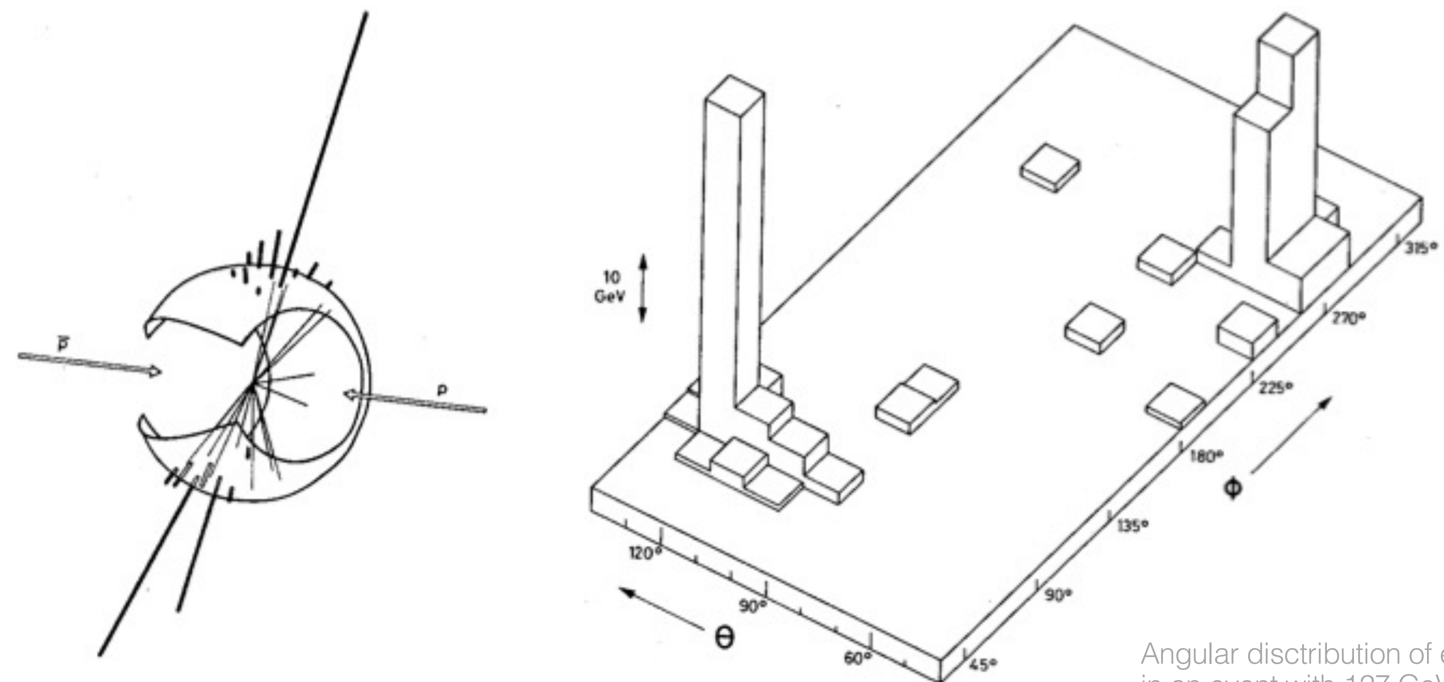
Jacobian peak with full UA2 dataset (1992):
$m_W = 80.84 \pm 0.22$ GeV

The W and Z boson discovery by UA1 & UA2



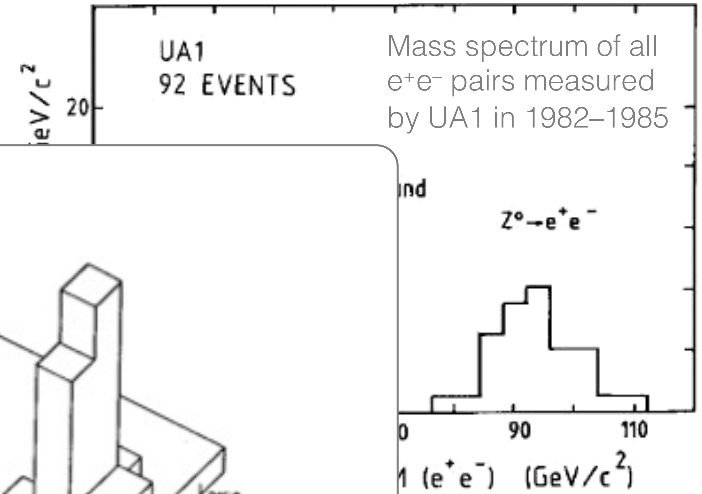
25 Jan 1983: CERN press conference announcing W discovery
Nobel Prize in 1984 for C. Rubbia and S. van der Meer

First observation of high-p_T jets at hadron collider (UA2, ICHEP 1982)

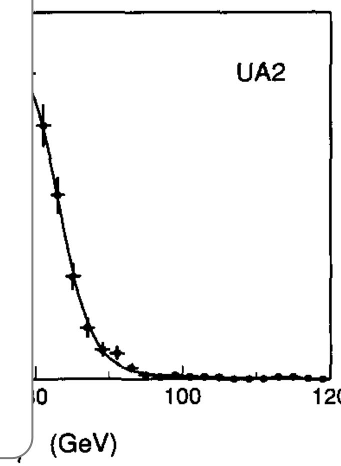


Angular disctribution of energy in an event with 127 GeV E_T sum

- and of tails in distributions
- Think carefully about upgrade projects
- High-granular calorimeter for jet measurement [*my addition*]



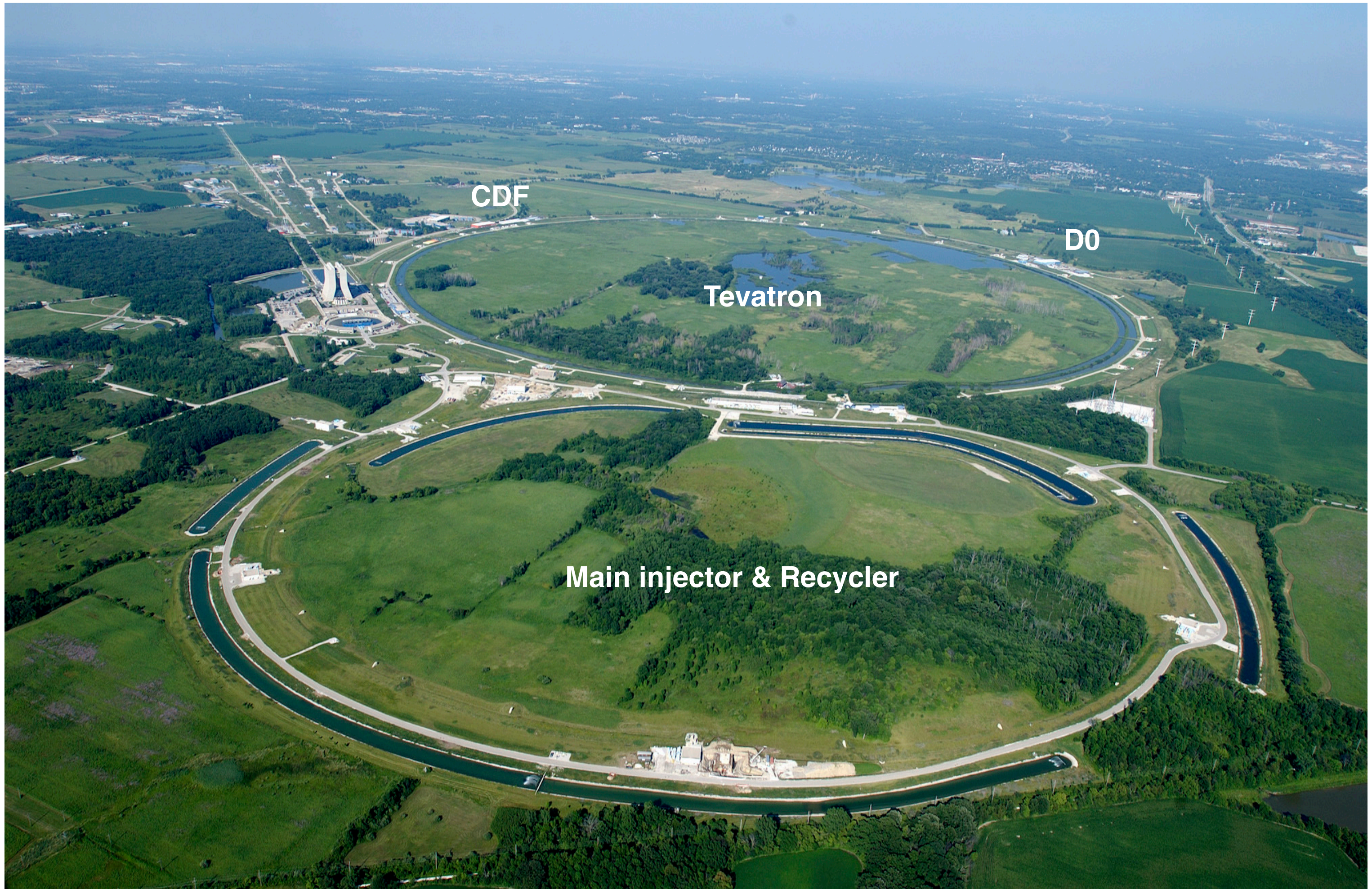
Mass spectrum of all e+e− pairs measured by UA1 in 1982–1985



Jacobian peak with full UA2 dataset (1992): $m_W = 80.84 \pm 0.22$ GeV

The Tevatron at Fermilab climbed at the energy frontier

Thanks to 4.4 T superconducting dipole magnets, the 6.3-km circumference Tevatron reached 1.8 TeV proton–antiproton collision energy (later up to 1.98 TeV) and quickly overtook the Sp$\bar{p}$S after physics operation started in 1987 (the antiproton cooling was based on Gersh Budker's *electron cooling* method during Run 2)

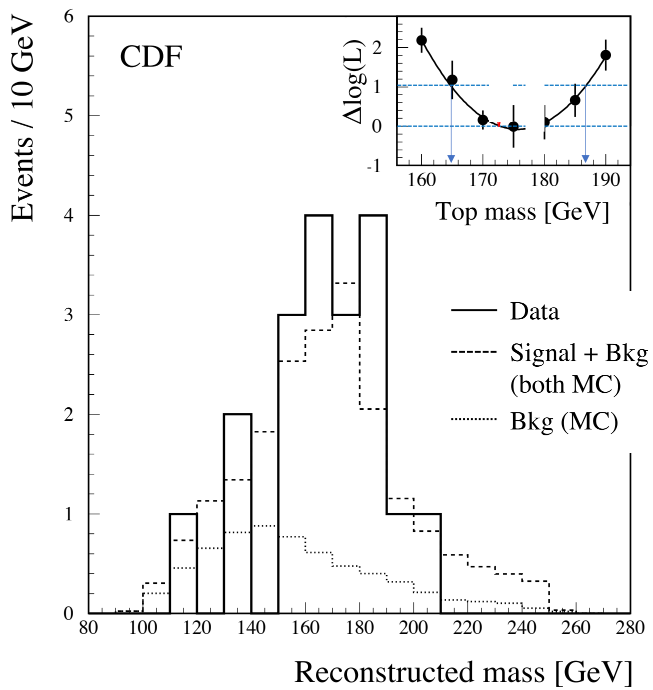


Aerial view of Fermilab's proton--antiproton accelerator and collider complex towards the closure of its operation in 2011. The Main Injector and Recycler ring is seen in front and the 6.3-kilometre circumference Tevatron collider ring in the background. On the left the iconic Wilson Hall, Fermilab's central laboratory building. Close-by are the proton source and the Booster. Tevatron's main detectors CDF and D0 are placed to the left and right along the ring, respectively.

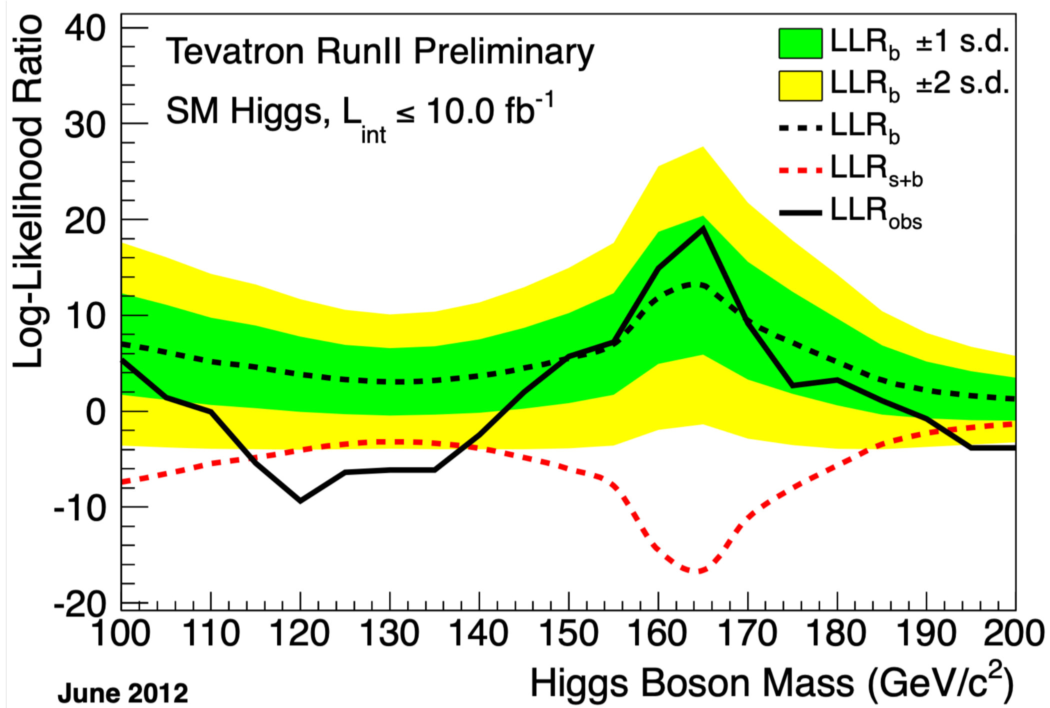
The Tevatron at Fermilab climbed at the energy frontier

Among the Tevatron legacies:

Top-quark discovery by CDF & D0 in 1995



Final combined CDF & D0 Higgs boson search result (2012)



- Also: first observation of neutral B_s oscillation by CDF in 2006
- High-precision top and W mass measurements, $\sigma(m_{top})$ = 0.65 GeV (0.4%), $\sigma(m_W)$ = 16 MeV (0.02%)

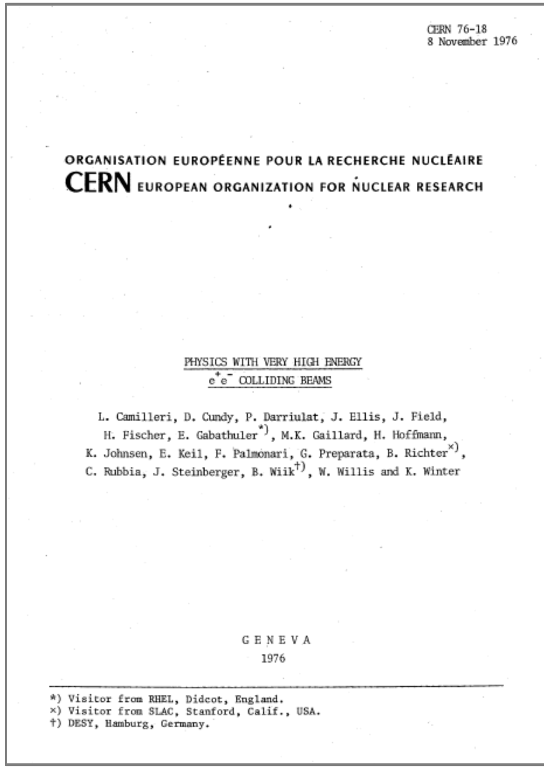
A *Future Circular Collider*

Visionary people prepared a bright future of particle physics and CERN

- A Nobel on sabbatical at CERN proposed a very **high-energy electron–positron collider** to study weak interactions, which was followed by a first physics study
- Several proposals discussed, main issue: **circumference of tunnel**
- Strong arguments in favour of smaller tunnel to avoid delays and budget over cost ("Reduce size and move out of Jura, or let others build the tunnel", "I believe however that one should go further and avoid the mountain completely … I would strongly advocate that one takes the fastest and safest solution of remaining under flat land.")
- The wise decision made considered the next-after project: **a very high-energy hadron collider**
- Complex budget discussions, compromise foresaw staged machine, reduction of interaction regions (4 instead of 8 !), constant core budget with no contingency other than time, no budget for experiments, stop of ongoing projects (tough decisions had to be taken)

A *Future Circular Collider*

The birth of LEP and the LHC: **a 26.7 km tunnel facility**



CERN 76-18
8 November 1976

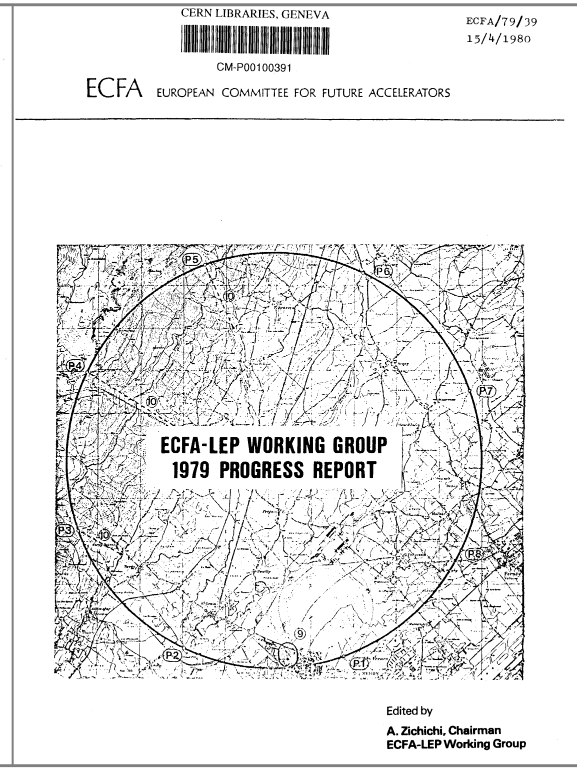
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS WITH VERY HIGH ENERGY
e^+e^- COLLIDING BEAMS

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, E. Gabathuler*), M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter×),
C. Rubbia, J. Steinberger, B. Wiik†), W. Willis and K. Winter

GENEVA
1976

*) Visitor from RHEL, Didcot, England.
×) Visitor from SLAC, Stanford, Calif., USA.
†) DESY, Hamburg, Germany.



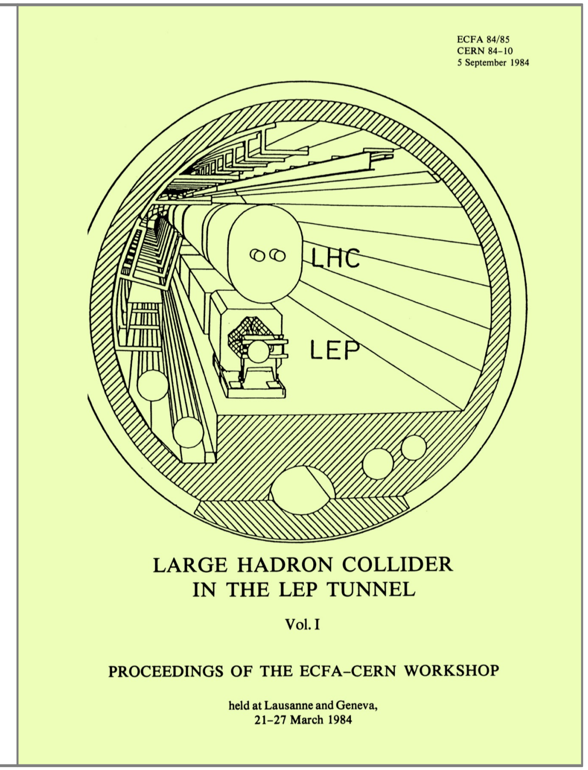
CERN LIBRARIES, GENEVA
CM-P00100391

ECFA/79/39
15/4/1980

ECFA EUROPEAN COMMITTEE FOR FUTURE ACCELERATORS

ECFA-LEP WORKING GROUP
1979 PROGRESS REPORT

Edited by
A. Zichichi, Chairman
ECFA-LEP Working Group



ECFA 84/85
CERN 84-10
5 September 1984

LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

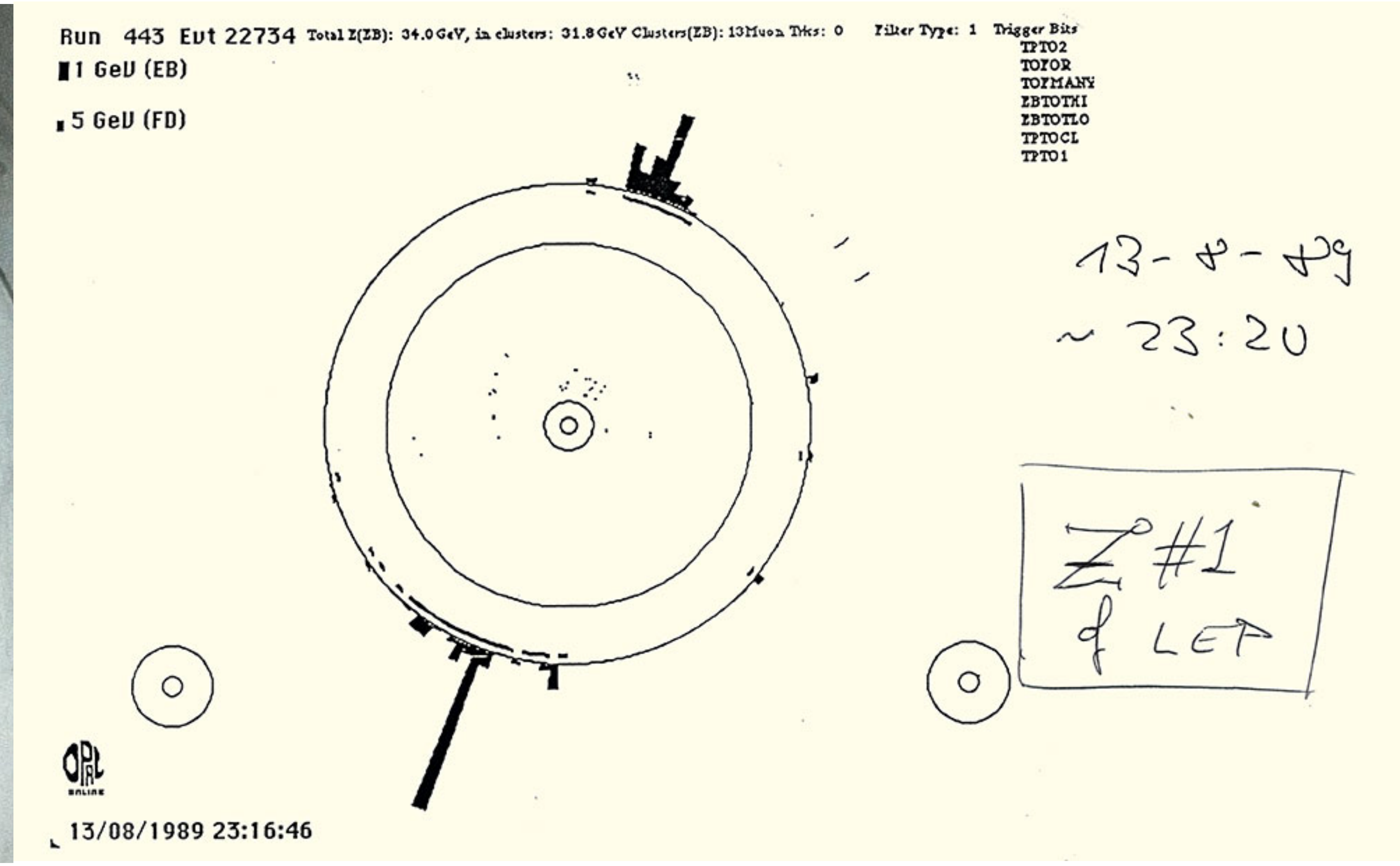
PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21-27 March 1984

The Large Electron–Positron Collider

LEP was formally approved in 1981, tunnel construction 1983–1988, first beam on 14 July 1989

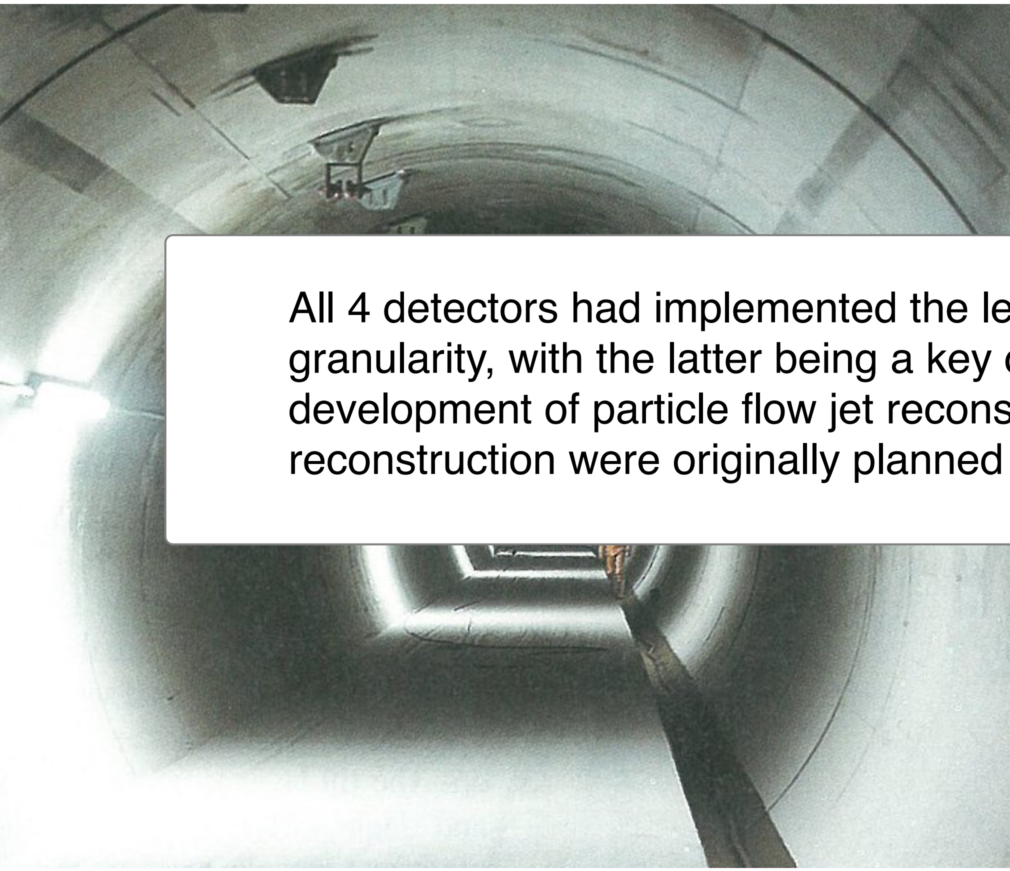
LEP tunnel before installation of bending magnets

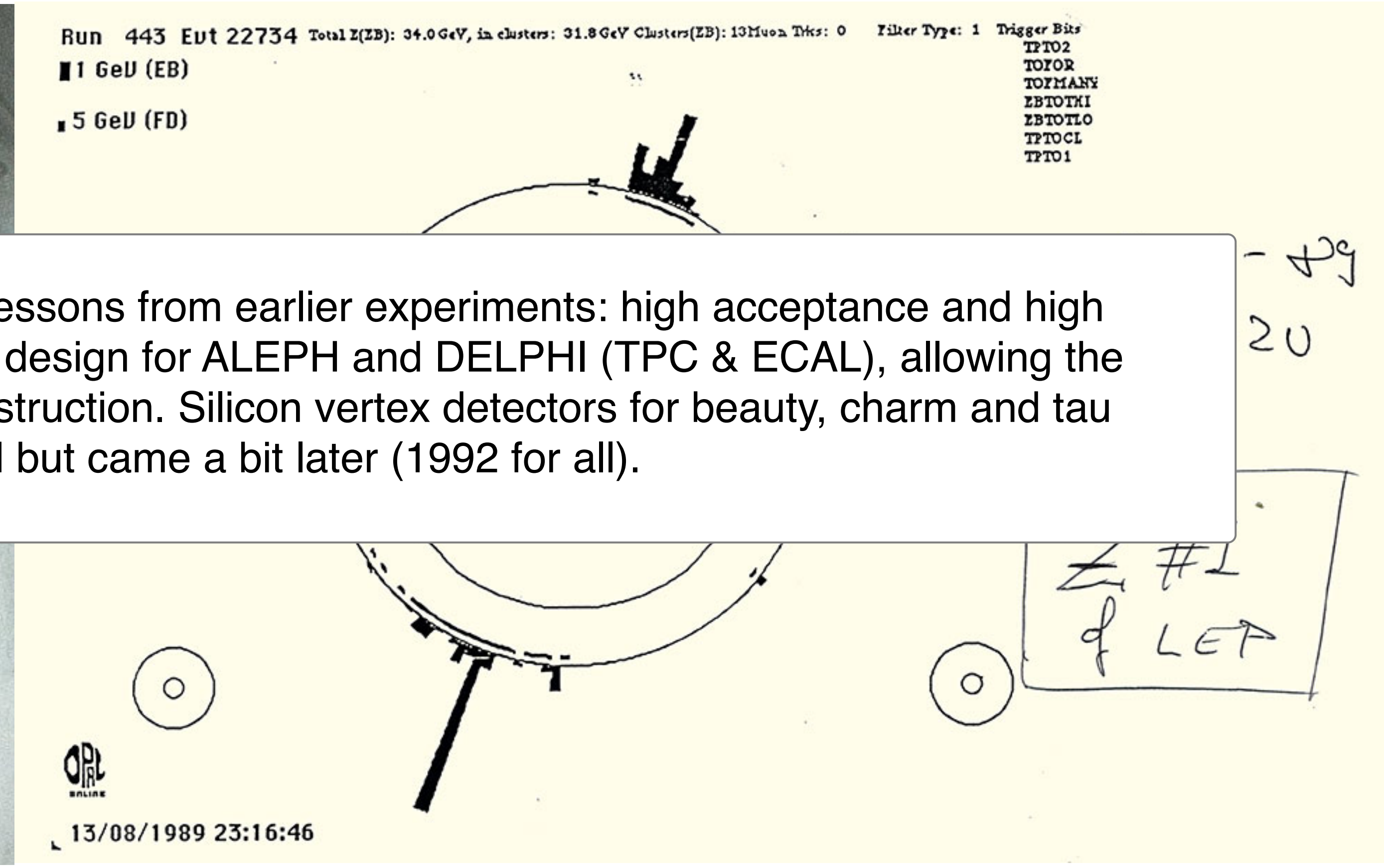


OPAL logbook entry on 13 Aug 1989 with the first Z-boson candidate

The Large Electron–Positron Collider

LEP was formally approved in 1981, tunnel construction 1983–1988, first beam on 14 July 1989





All 4 detectors had implemented the lessons from earlier experiments: high acceptance and high granularity, with the latter being a key design for ALEPH and DELPHI (TPC & ECAL), allowing the development of particle flow jet reconstruction. Silicon vertex detectors for beauty, charm and tau reconstruction were originally planned but came a bit later (1992 for all).

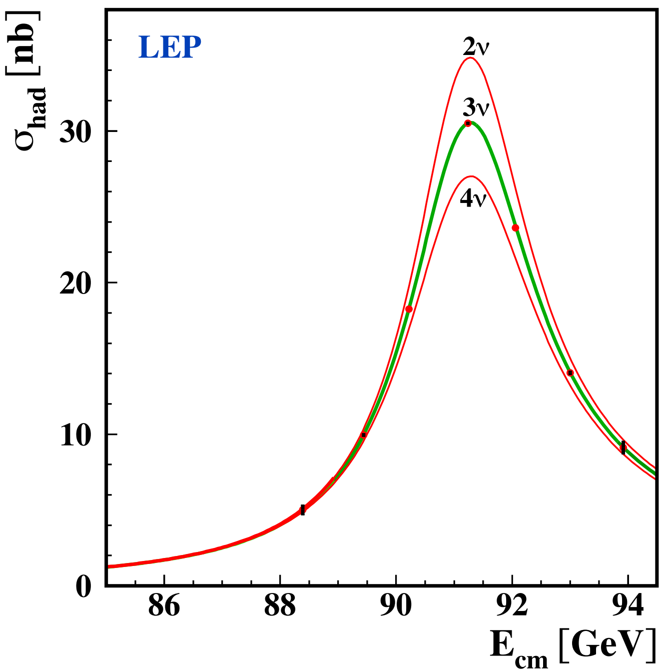
LEP tunnel before installation of bending magnets

OPAL logbook entry on 13 Aug 1989 with the first Z-boson candidate

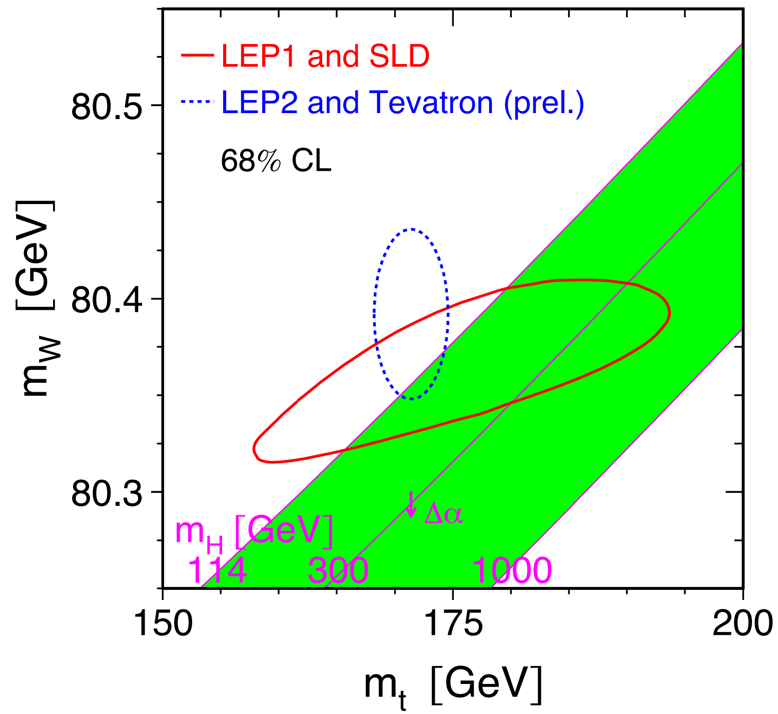
With LEP, the Standard Model entered the precision era

Huge amount of experimental and theoretical developments during LEP years, pioneering era of high-precision physics in HEP

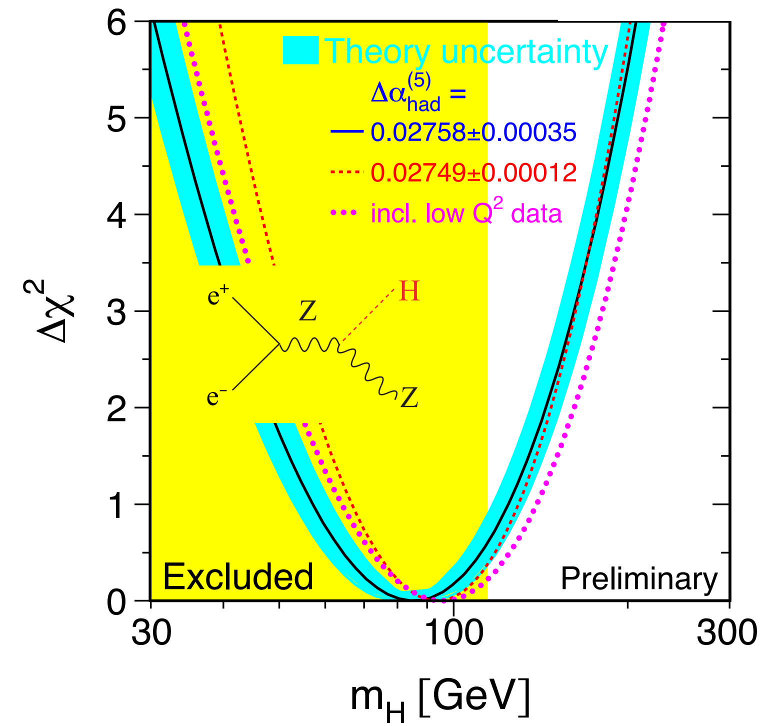
There are 3 light neutrino families



The top quark is heavy



The Higgs boson is light, but > m_Z

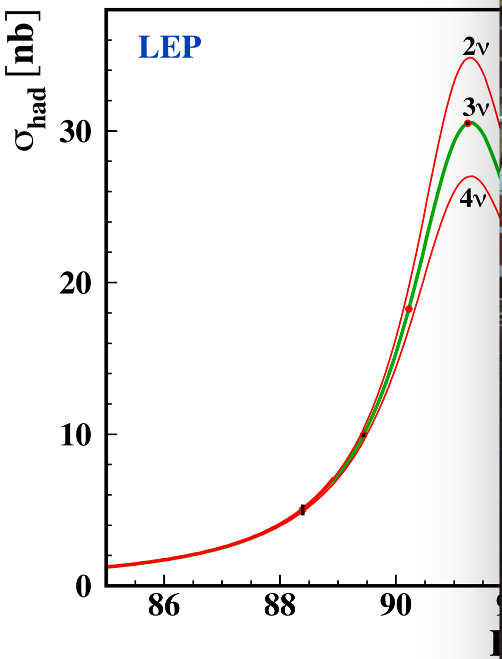


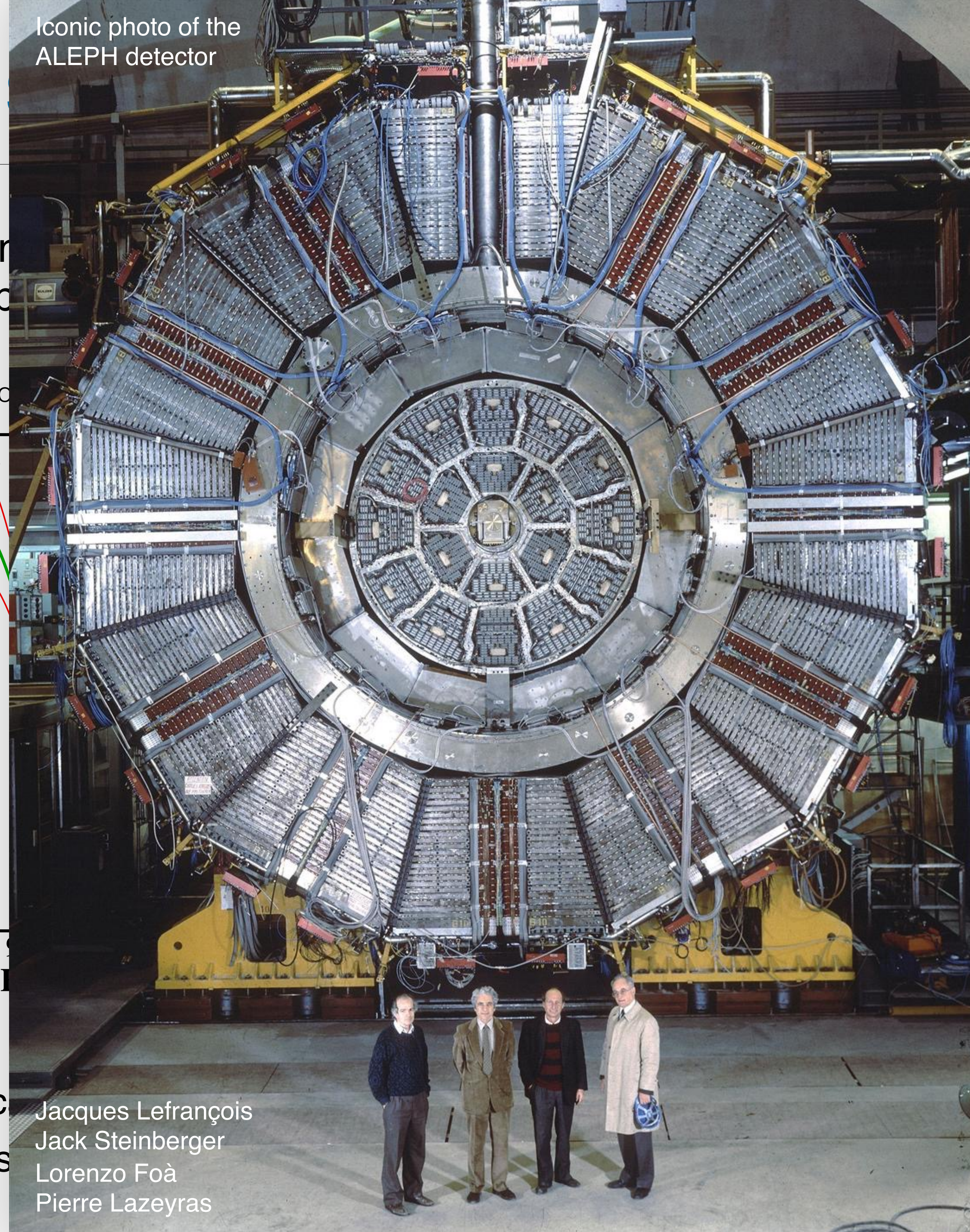
- Precise beam energy calibration allowed to measure m_Z with 2.1 MeV (0.0023%) precision
- Lepton universality was tested to per-mil level, deep tests of QCD and tau-lepton properties

With LEP, the … cision era

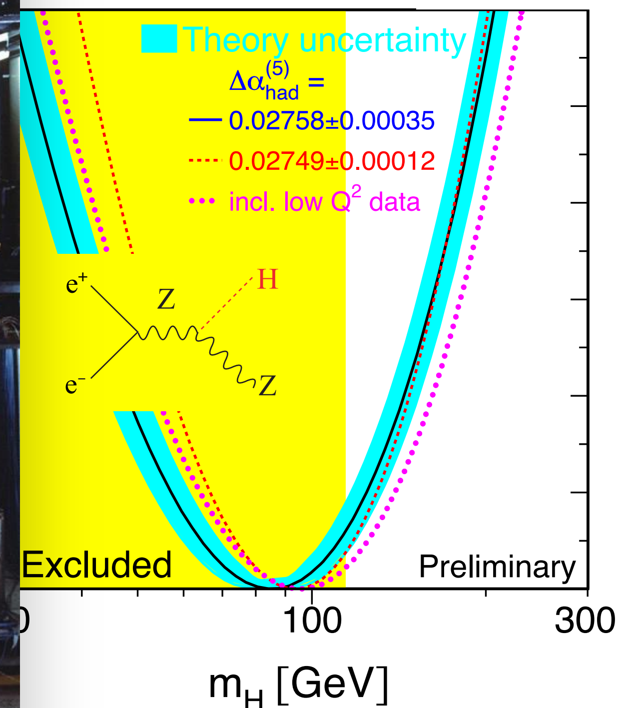
Huge amount of experi… …s,
pioneering era of high-p…

There are 3 light neutrino…



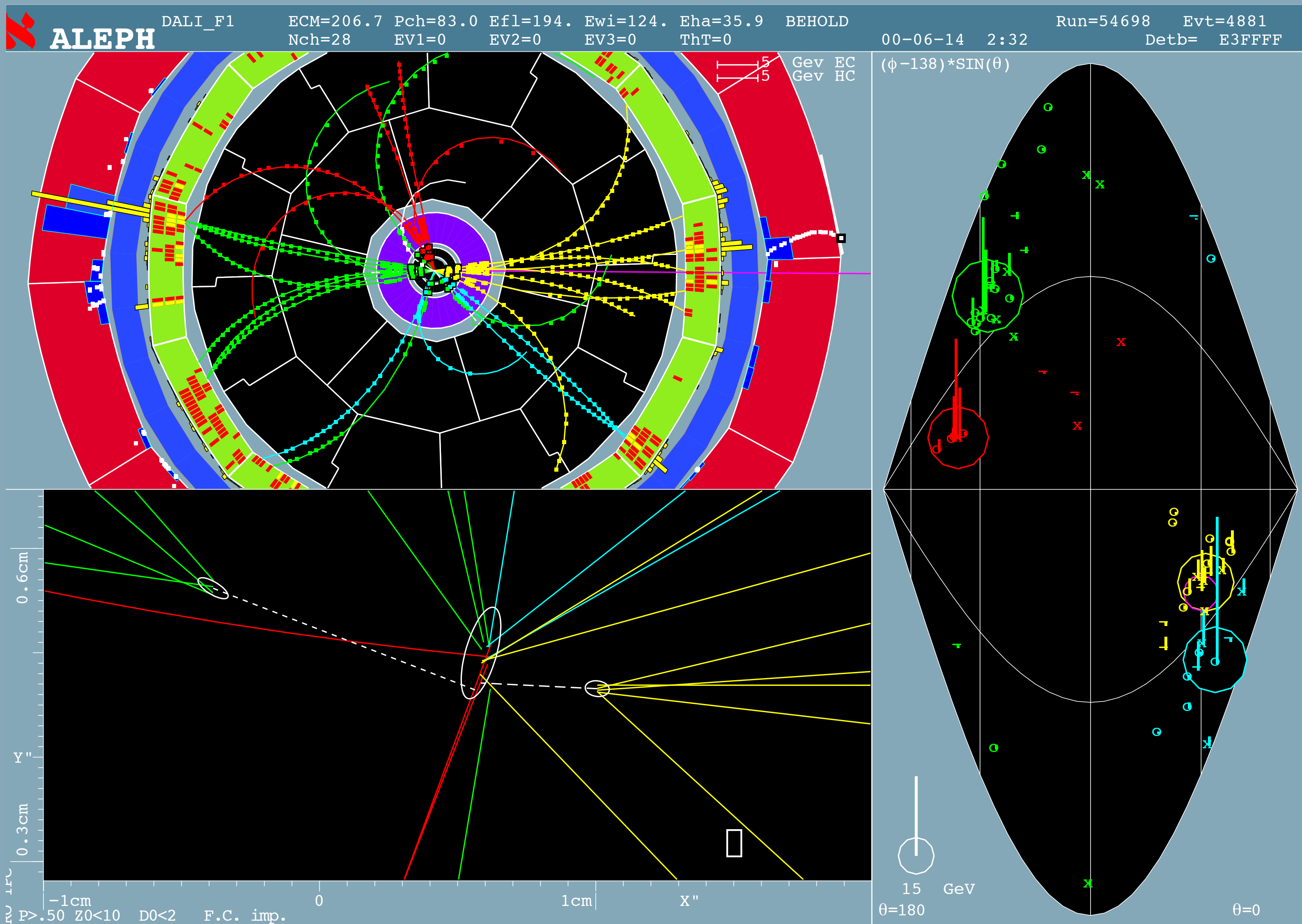


The Higgs boson is light, but > m_Z



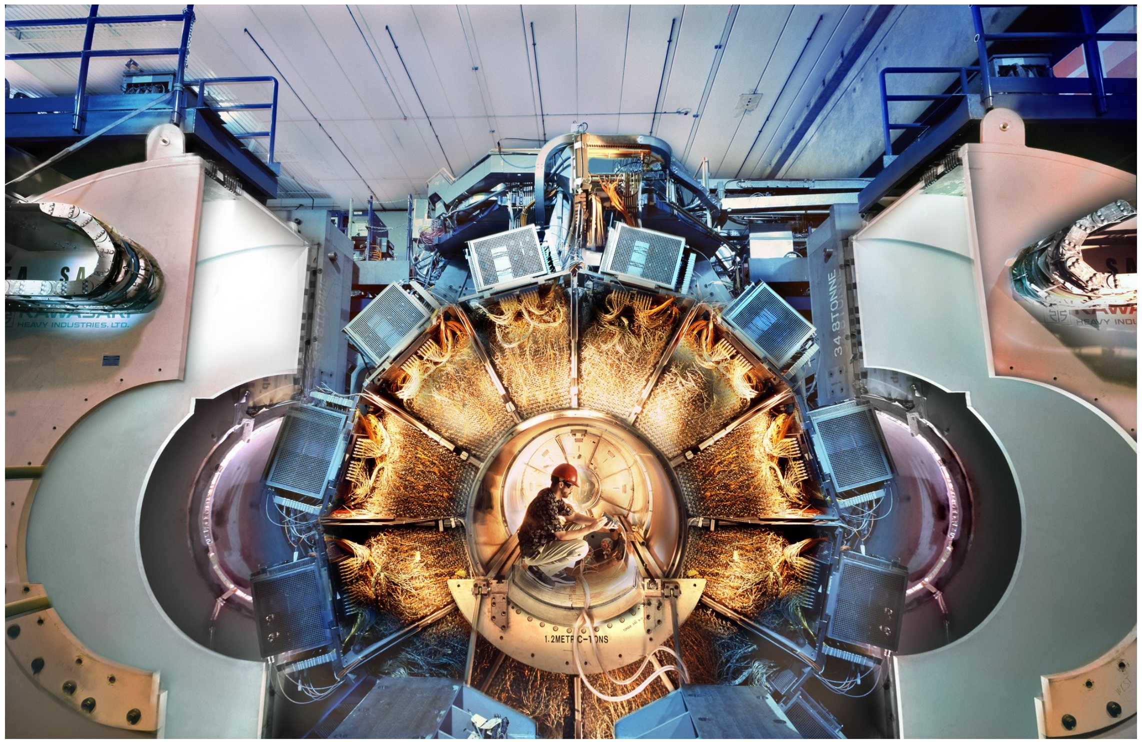
- Precise beam energy c… …ecision
- Lepton universality was… …roperties

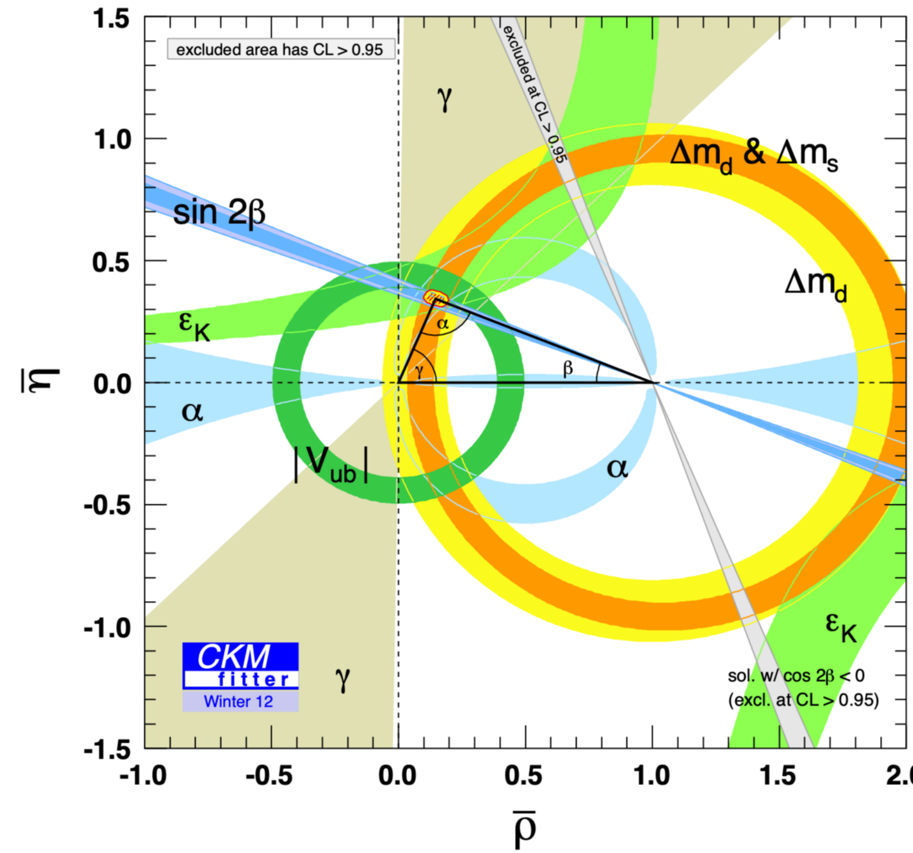
Despite hints and hopes, the Higgs boson was not found at LEP



Beyond the energy frontier

Asymmetric B-factories began data taking at KEK and SLAC in 1998 and observed CP violation in the B sector, a highly successful programme which is continued at KEK with the SuperKEKB project





Left: DIRC — novel particle ID detector at the BABAR experiment

Right: legacy of the B factories (2012) — the Standard Model holds

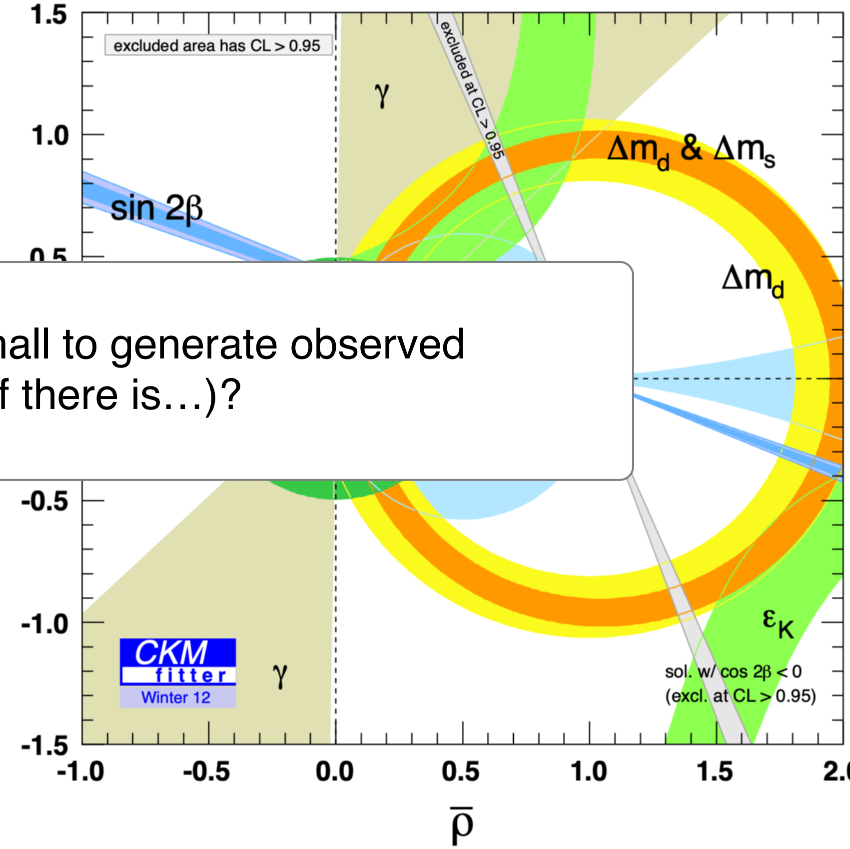
Also: start of an all new heavy-hadron spectroscopy field leading to the discovery of tetra and pentaquarks by LHCb

Note: direct CP violation was first discovered in the kaon sector by NA48 at CERN

Beyond the energy frontier

Asymmetric B-factories began data taking at KEK and SLAC in 1998 and observed CP violation in the B sector, a highly successful programme which is continued at KEK with the SuperKEKB project

But: CP violation in Standard Model far too small to generate observed baryon asymmetry — so what is its purpose (if there is…)?



Left: DIRC — novel particle ID detector at the BABAR experiment

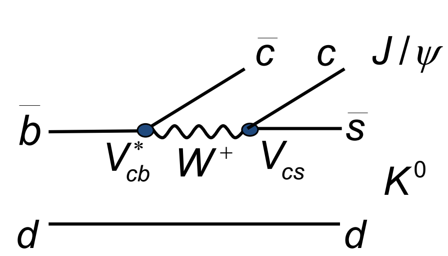
Right: legacy of the B factories (2012) — the Standard Model holds

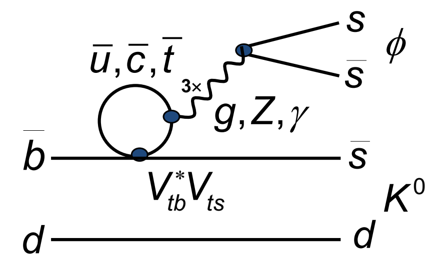
Also: start of an all new heavy-hadron spectroscopy field leading to the discovery of tetra and pentaquarks by LHCb

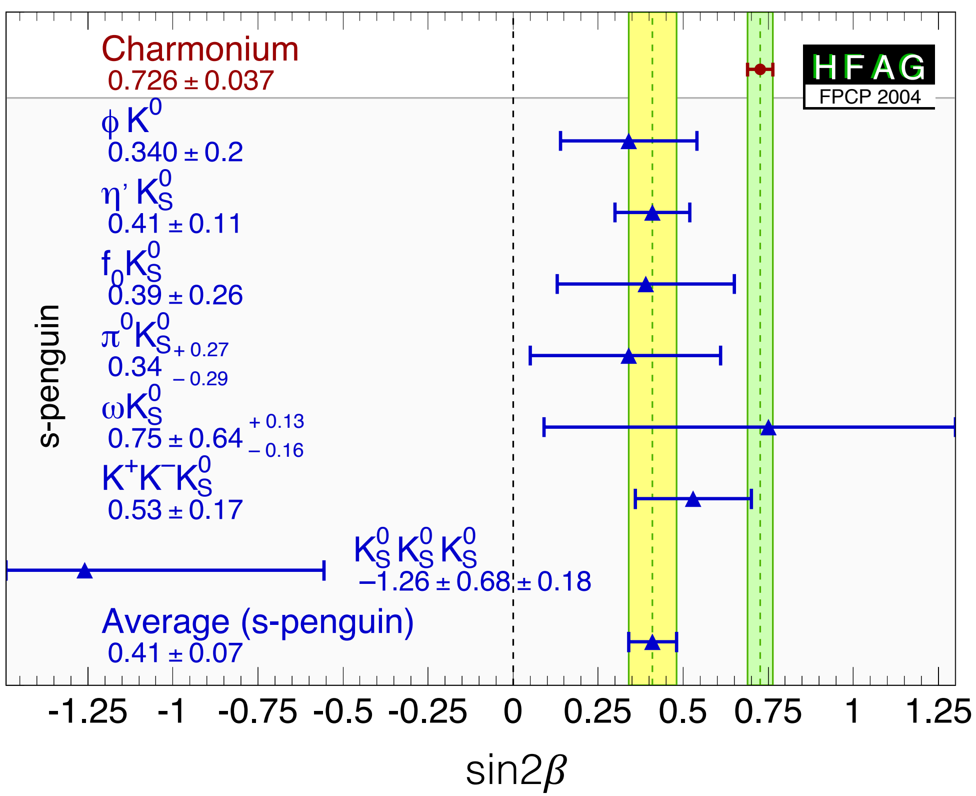
Note: direct CP violation was first discovered in the kaon sector by NA48 at CERN

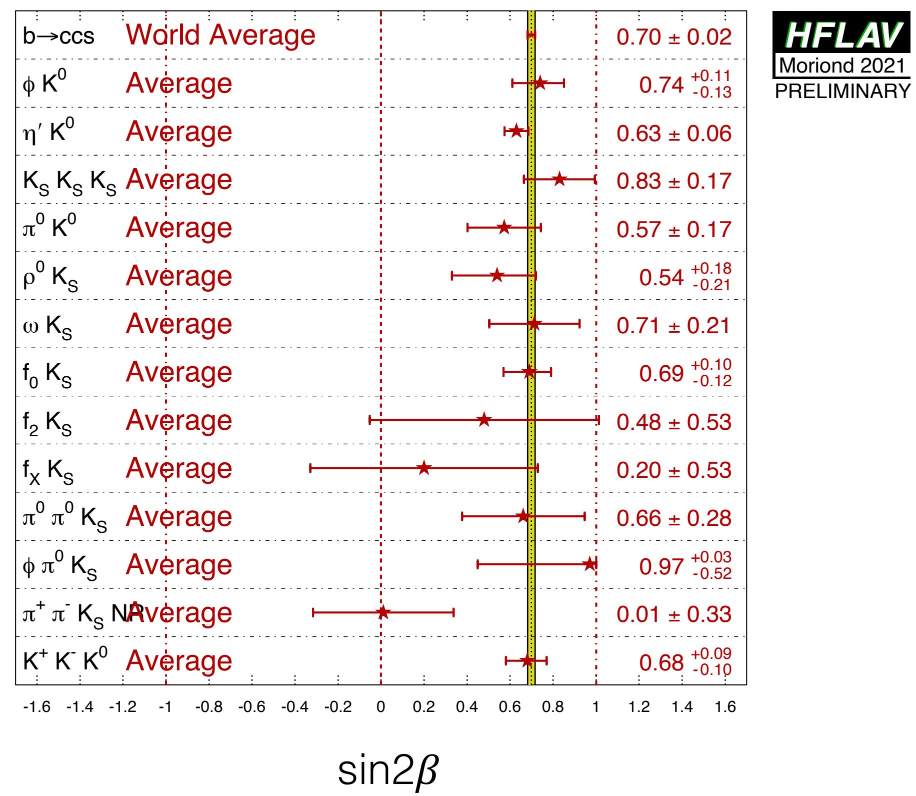
Beyond the energy frontier

The penguin lesson

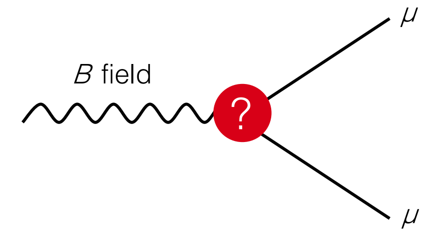






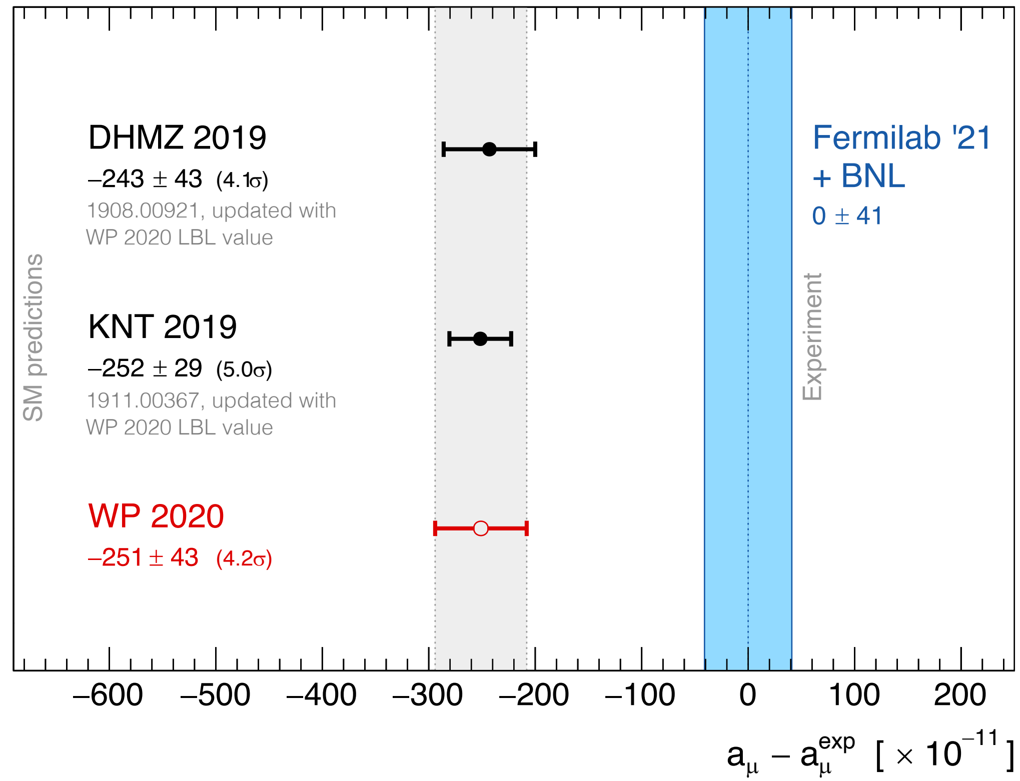


Beyond the energy frontier



High-precision measurements of the muon g–2 continued at BNL (1997–2001) and Fermilab (2020–2022), after a successful series at CERN (1961–1979), leaving a puzzle

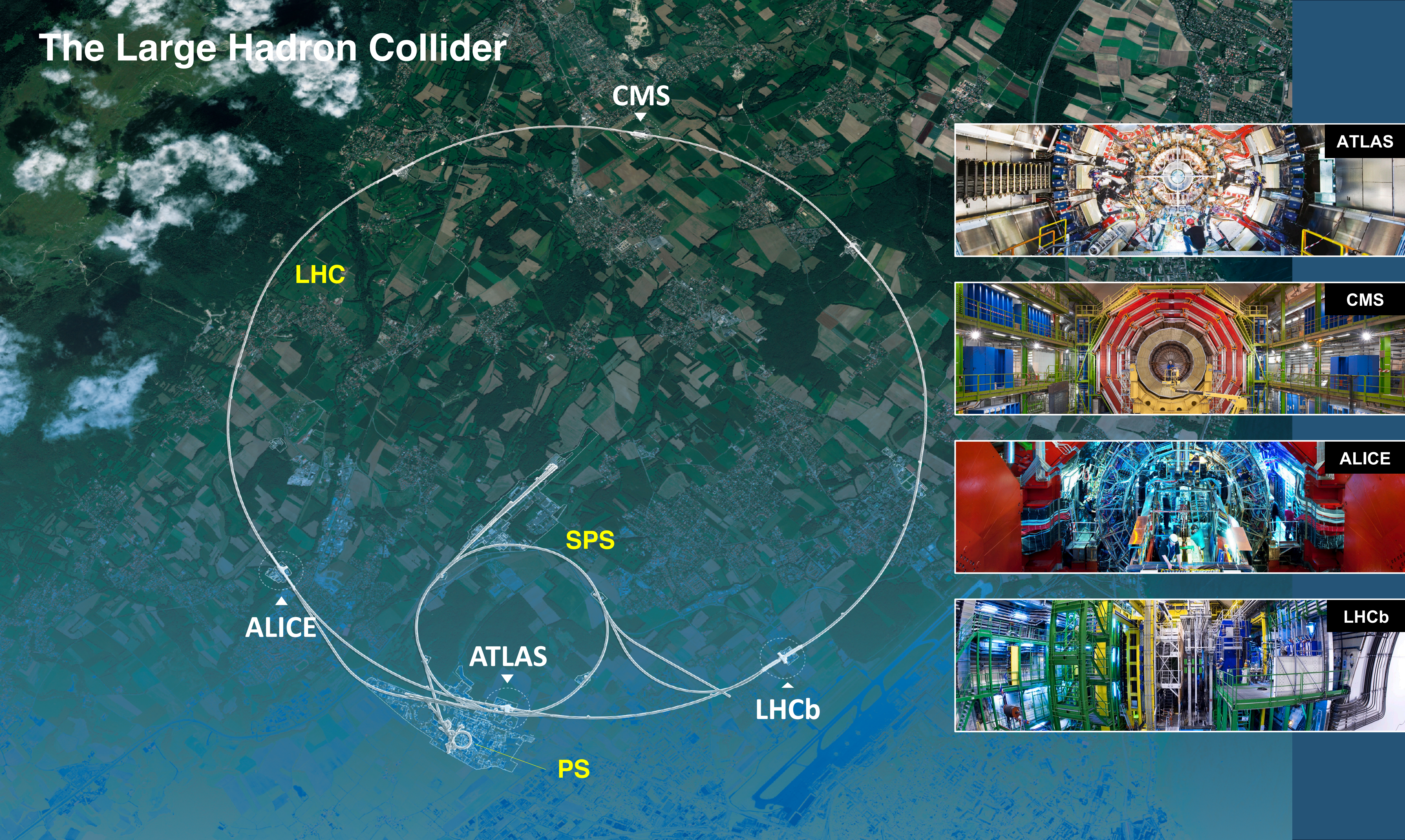
Fermilab g–2 Experiment



- Theory uncertainty (dominated by hadronic contributions) ~ experimental one
- More data currently being analysed


The Large Hadron Collider

The Large Hadron Collider



The Large Hadron Collider

The LHC and its experiments are projects of superlatives

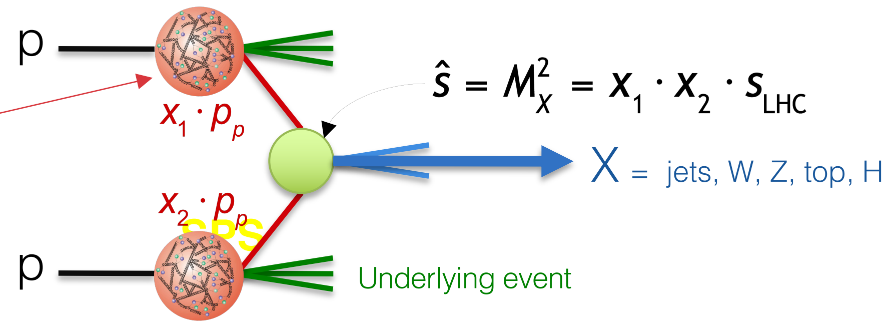
- Factors of 7 / 50 larger energy / luminosity, almost twice larger dipole fields, 16 times narrower bunch spacing than the Tevatron
- Compact two-in-one accelerating scheme
- Detectors as technological masterpieces, incorporating everything learned from previous experiments, and designed and optimised from scratch using detailed simulation
- Their physics performance exceeds the design expectations in all aspects
- World-wide distributed computing organised as its own collaboration
- Experimental collaborations count several thousand scientists and span entire careers between proposal and exploitation

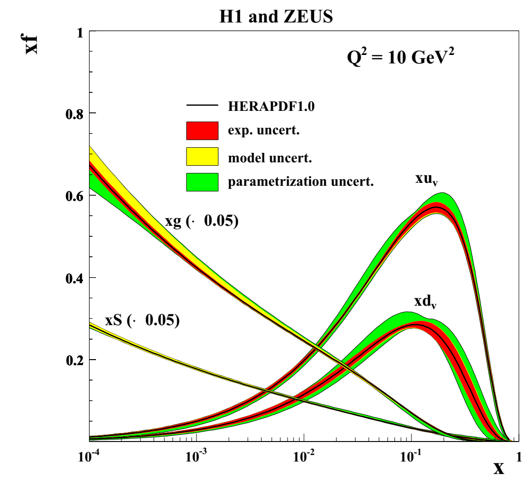
A major ingredient

In proton–proton collisions, cross section is convolution of parton distribution functions (PDF) with parton scattering matrix element

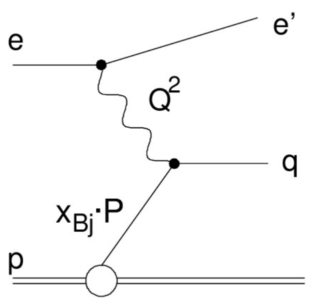
Parton distribution functions

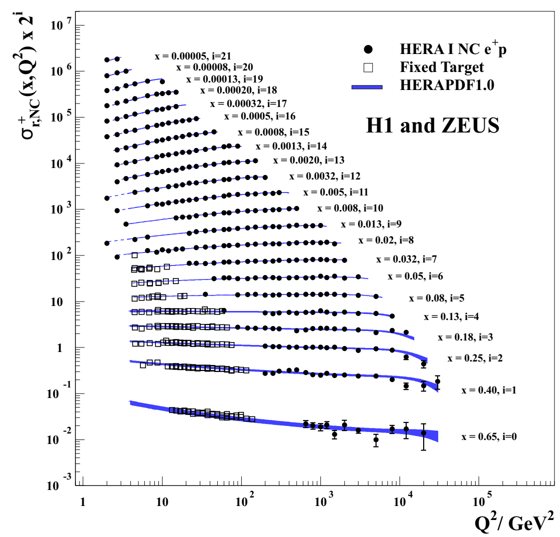
Representing structure of proton, extracted using experimental data and QCD properties





PDFs were measured precisely at the 6.3 km superconducting ep collider HERA at DESY (1992–2007)

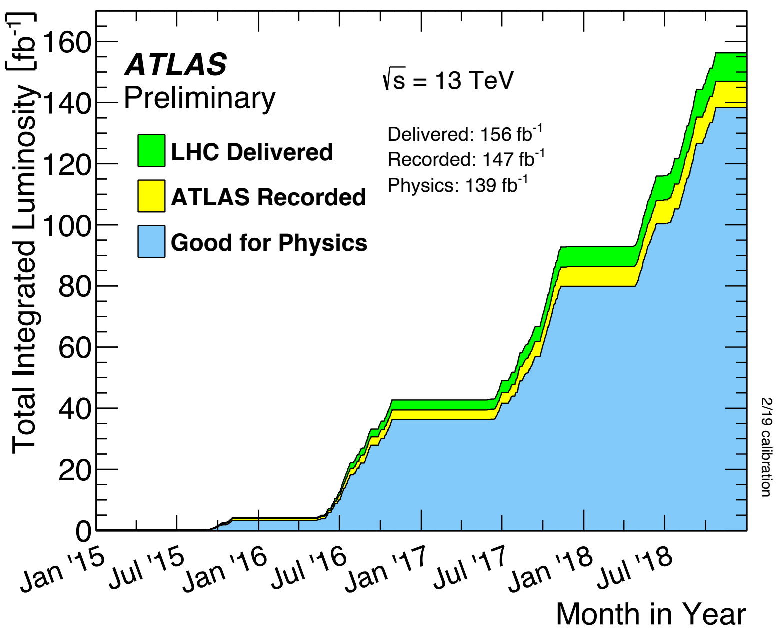




Extremely successful LHC runs between 2010 and 2018

Run-2 dataset (2015–2018) at 13 TeV

Excellent data-taking (94.2%) and data quality (94.6%) efficiency

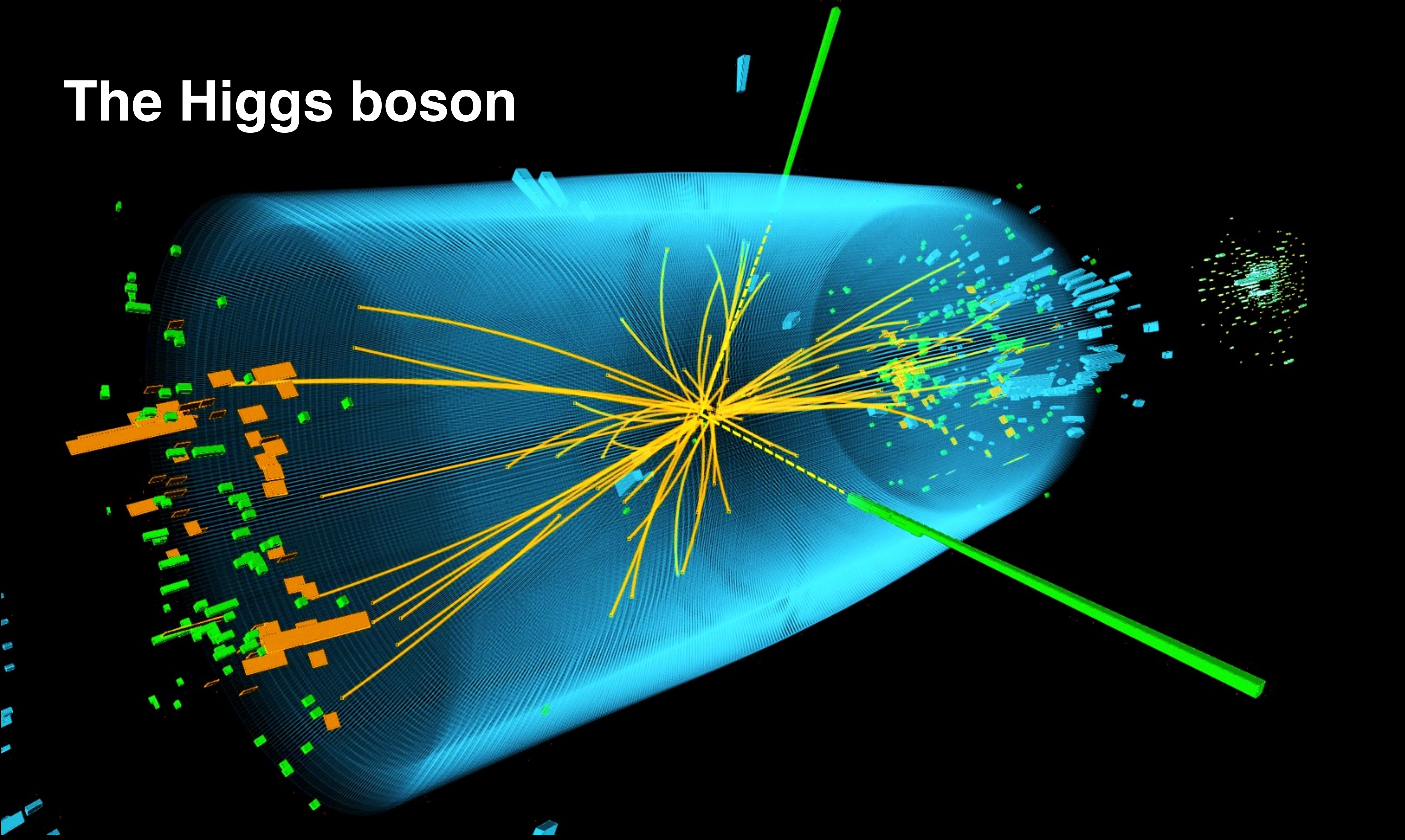


Particle	Produced in 140 fb^{-1} pp at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.8 million	
Top quark	275 million	(115 million tt)
Z boson	8 billion	($\rightarrow \ell\ell$, 270 million per flavour)
W boson	26 billion	($\rightarrow \ell\nu$, 2.8 billion per flavour)
Bottom quark	~160 trillion	(significantly reduced by acceptance)

The LHC experiments have in their hands the richest and best understood hadron collision data sample ever recorded

ATLAS & CMS published each > 1000 papers

The Higgs boson

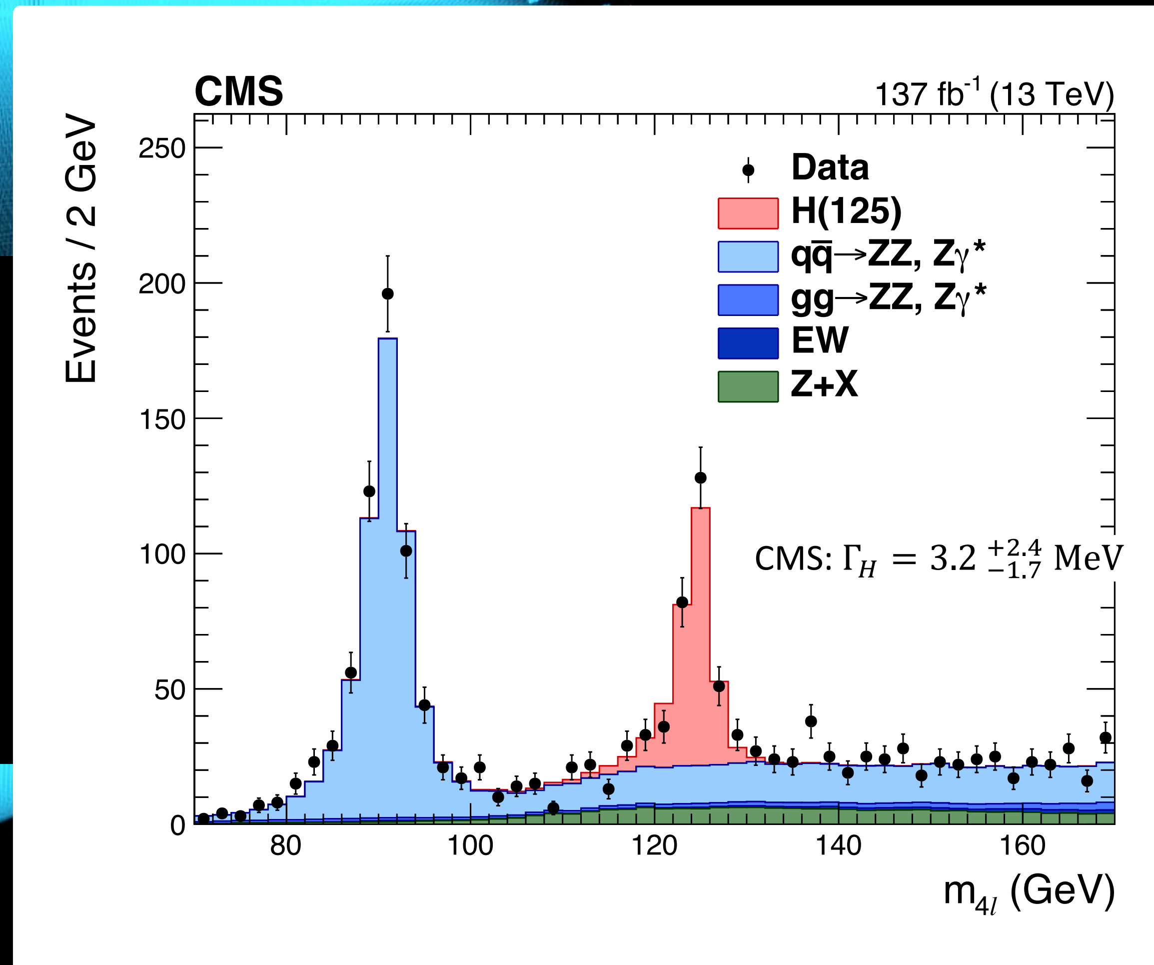


The Higgs boson

The LHC’s magnum opus

The discovery allows us to access a new sector of the SM Lagrangian:

- Yukawa couplings
- Gauge–scalar boson interactions
- Higgs potential (incl. self coupling)

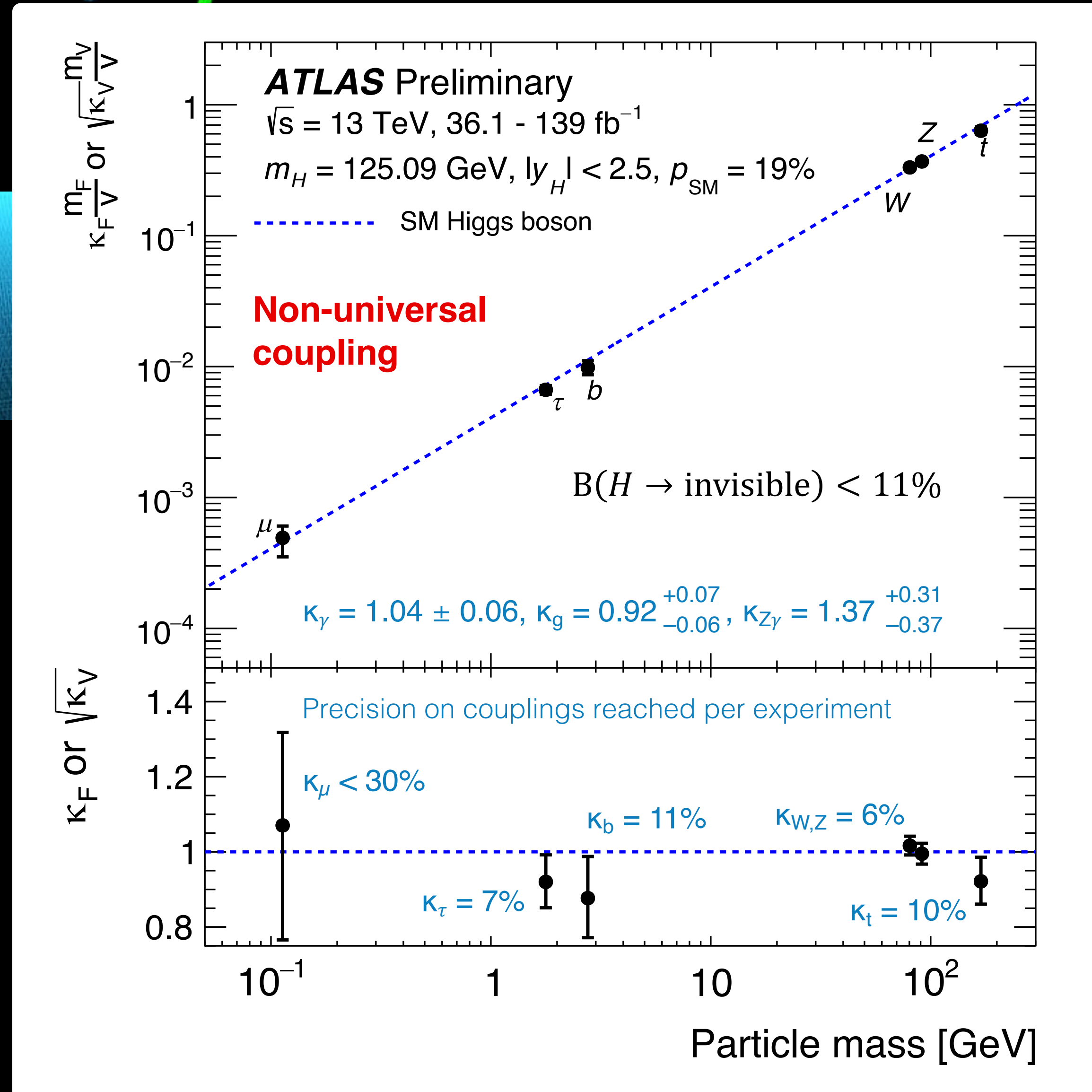


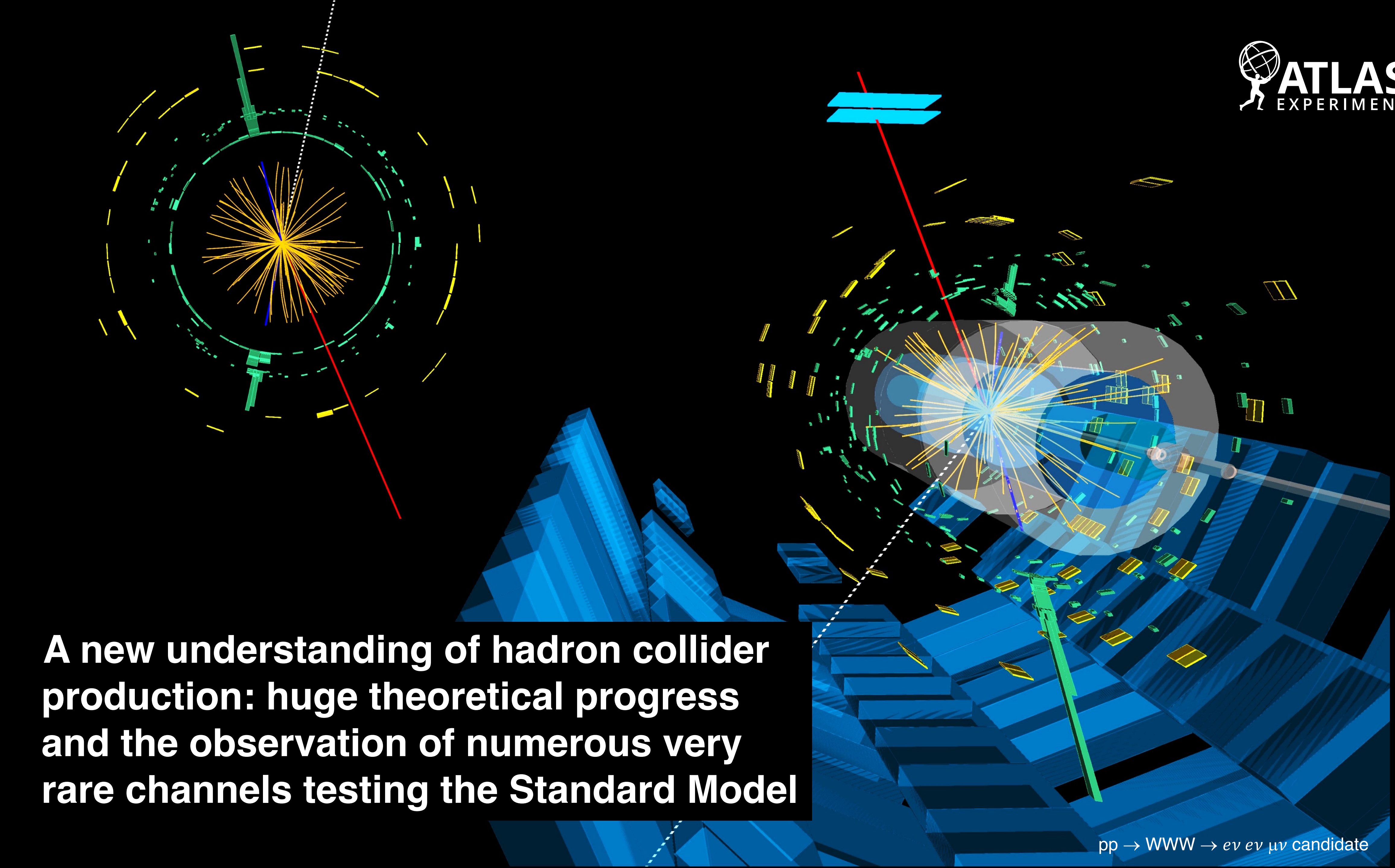
The BEH mechanism is real !

The Higgs sector is directly connected with very profound questions: naturalness, vacuum stability & energy, flavour

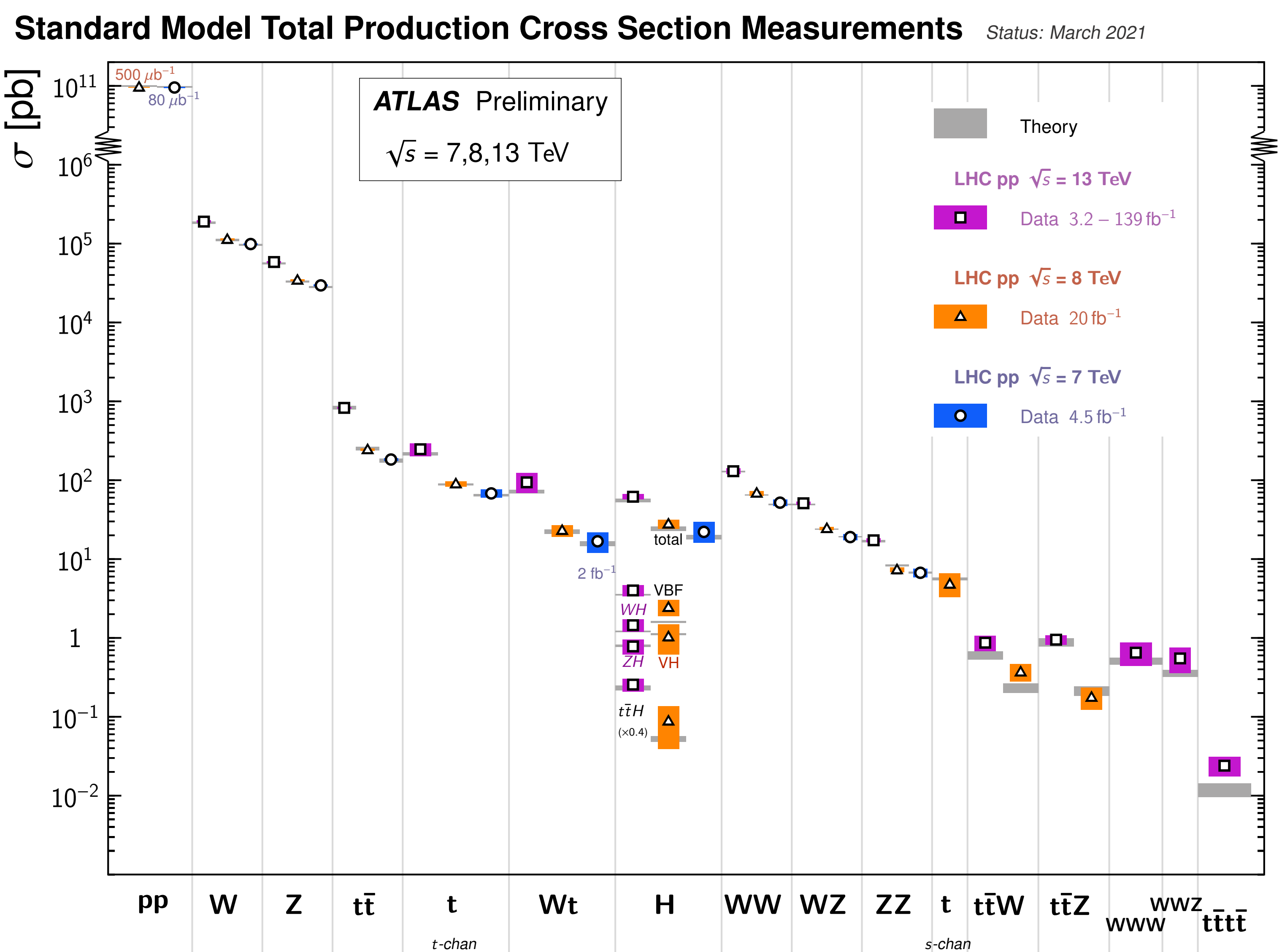
The Higgs boson discovery allows us to directly study this sector, requiring a broad experimental programme that will extend over decades (incl. the measurement of Higgs self coupling)

The discovery of an (apparently) fundamental scalar particle, resulting from spontaneous symmetry breaking, fuels renewed interest in other fundamental (pseudo)scalars, such as the axion…





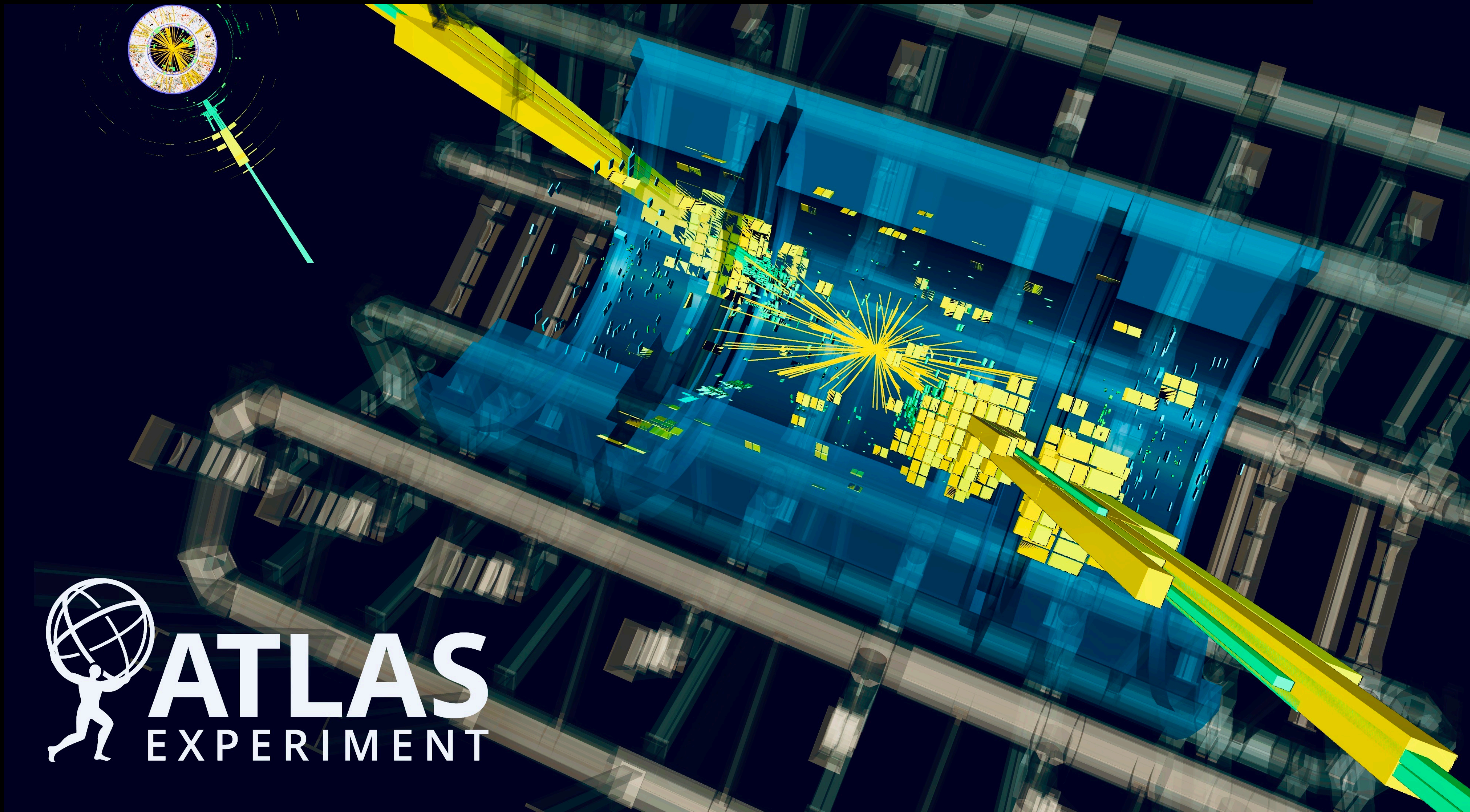
A new understanding of hadron collider production: huge theoretical progress and the observation of numerous very rare channels testing the Standard Model



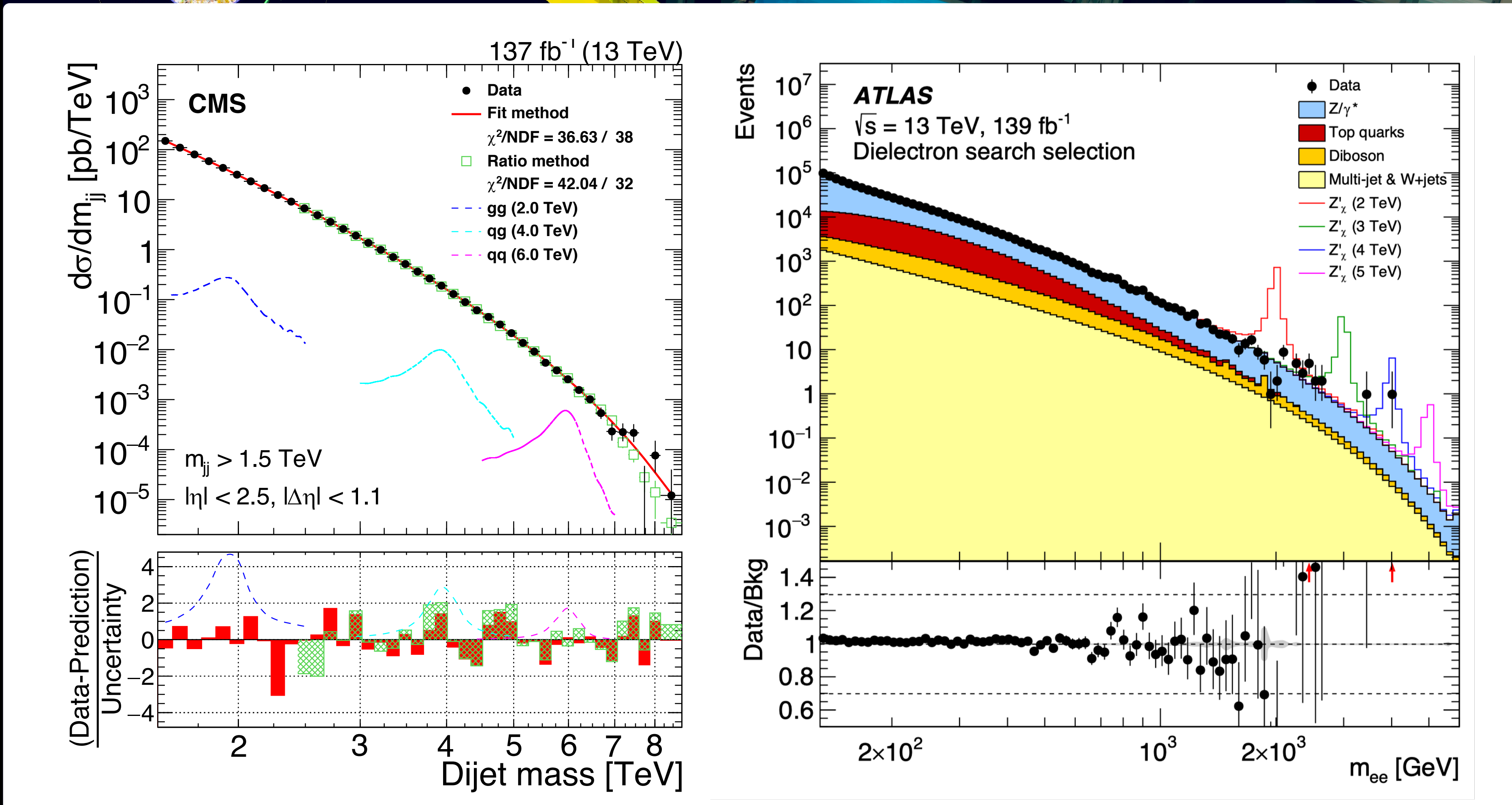
ATLAS EXPERIMENT

pp → WWW → eν eν μν candidate

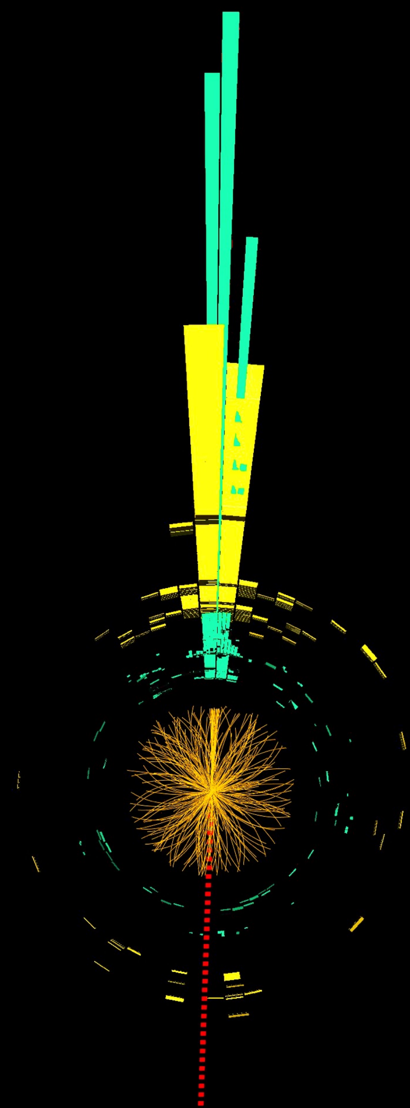
Deep and broad searches for new physics

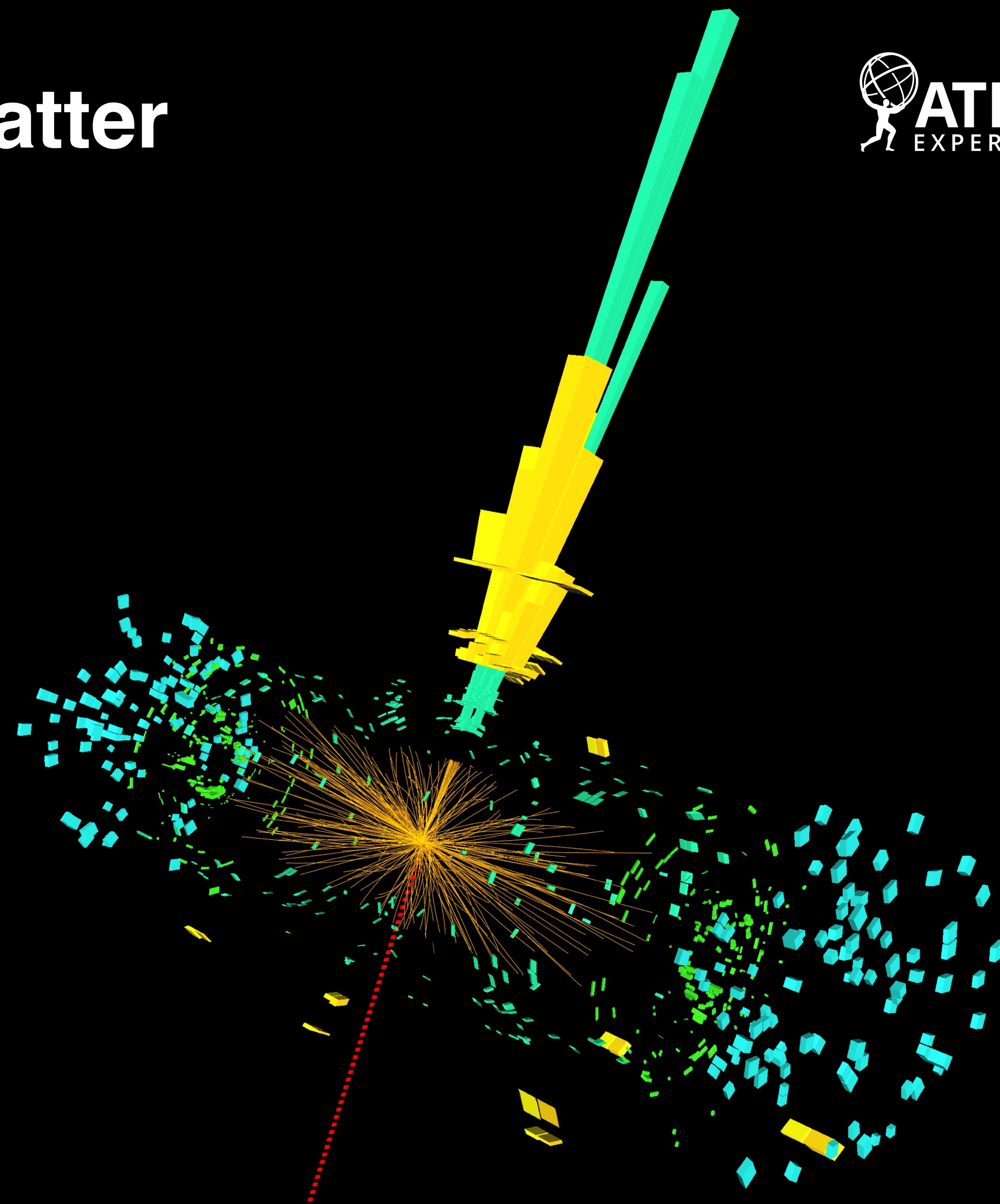


Deep and broad searches for new physics

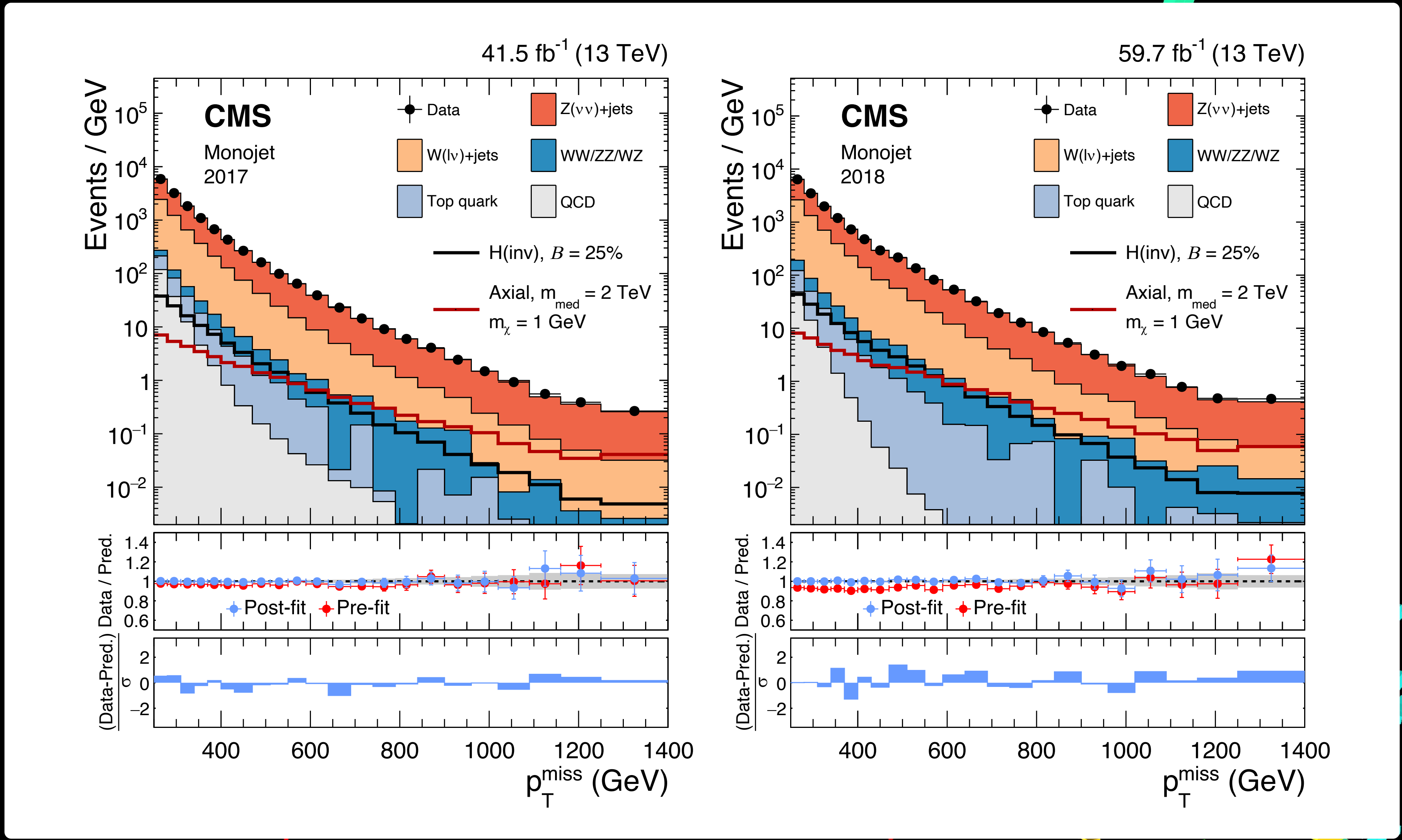


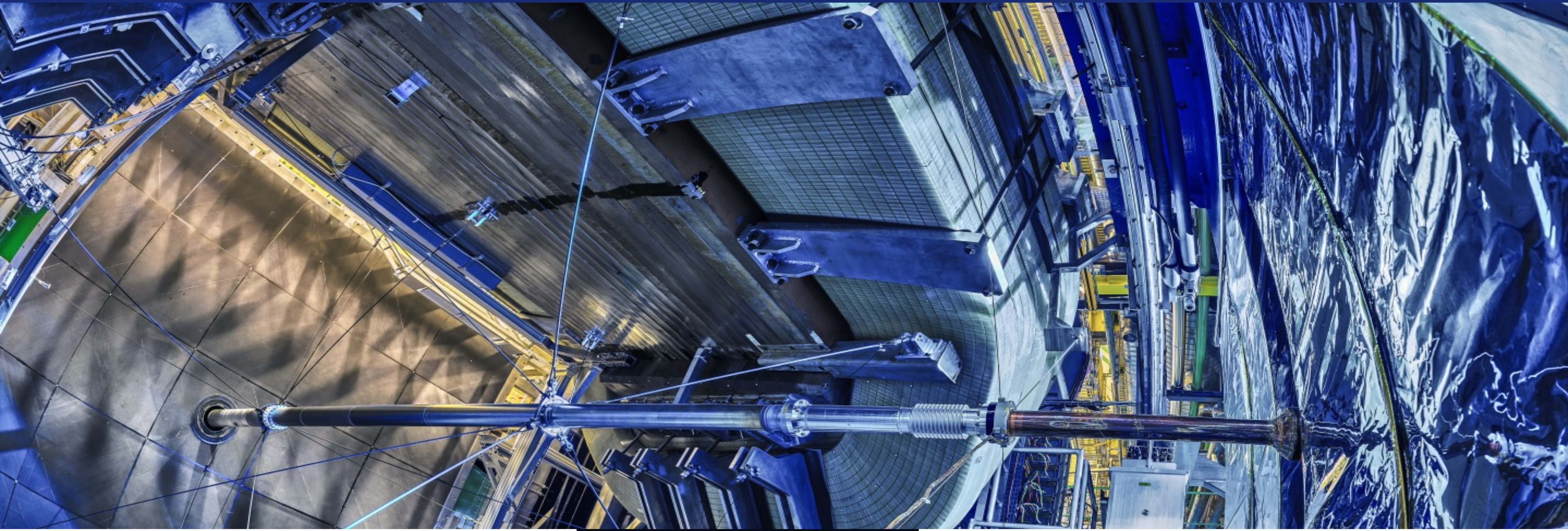
Searches for Dark Matter



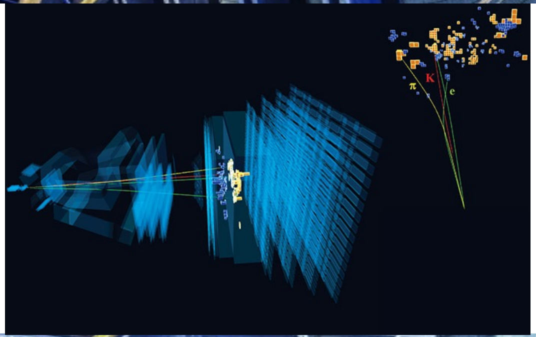


Searches for Dark Matter



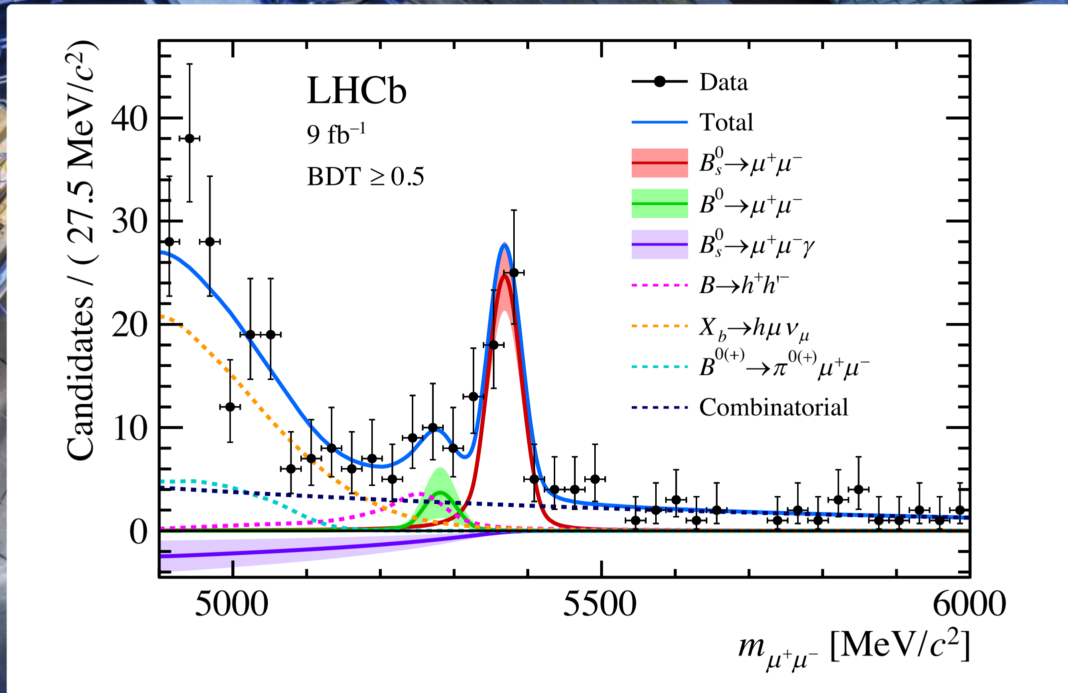


Flavour physics

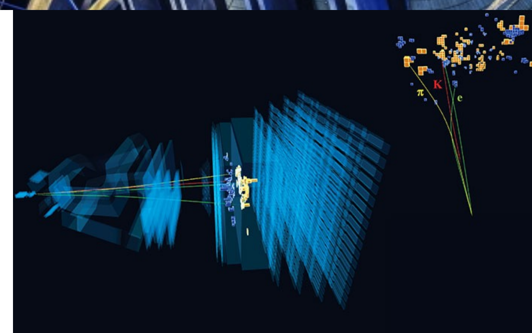


Success of SM flavour structure is since long a source of discomfort for BSM physics…

LHCb's dipole magnet at 2018 detector opening

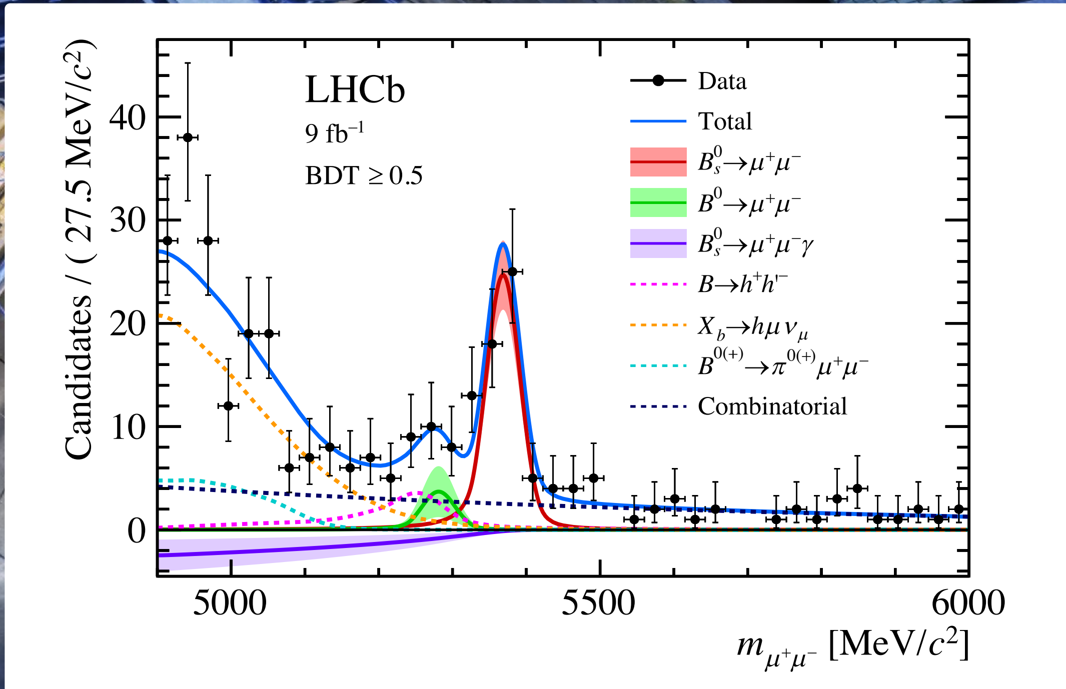


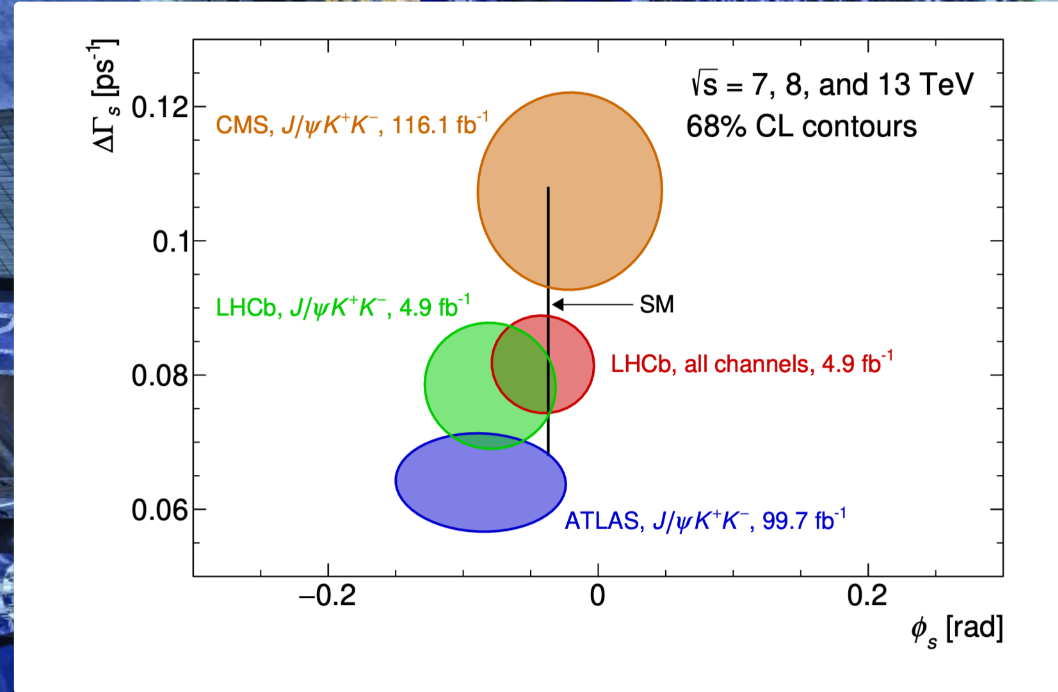
Flavour physics



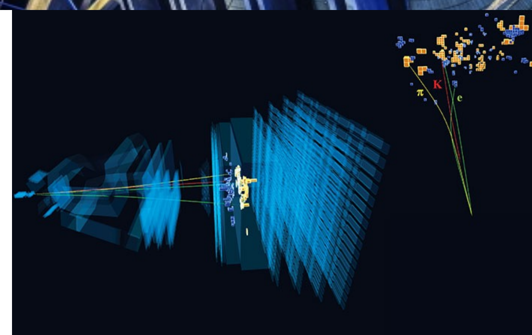
Success of SM flavour structure is since long a source of discomfort for BSM physics…

LHCb's dipole magnet at 2018 detector opening



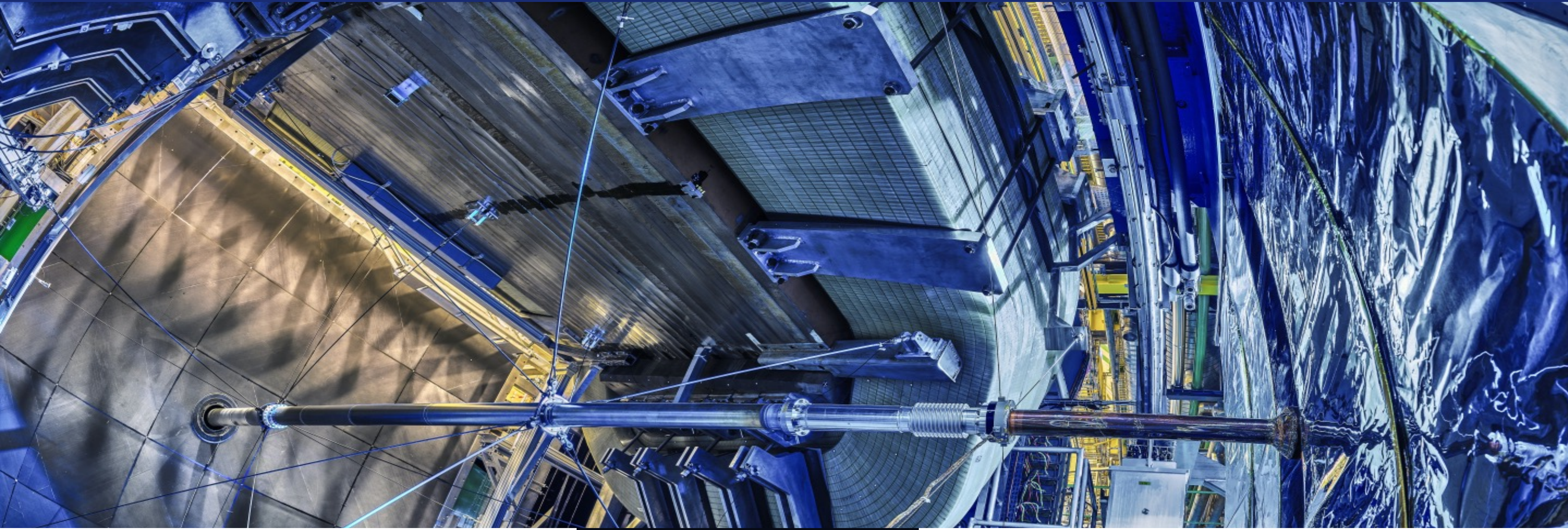


Flavour physics

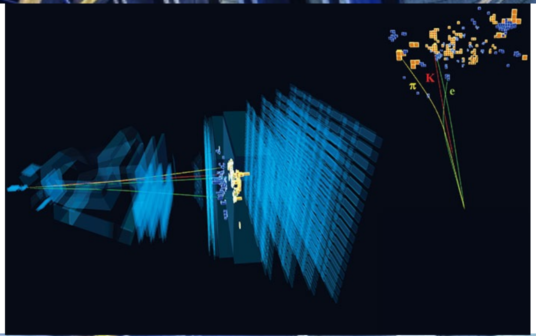


Success of SM flavour structure is since long a source of discomfort for BSM physics…

LHCb's dipole magnet at 2018 detector opening

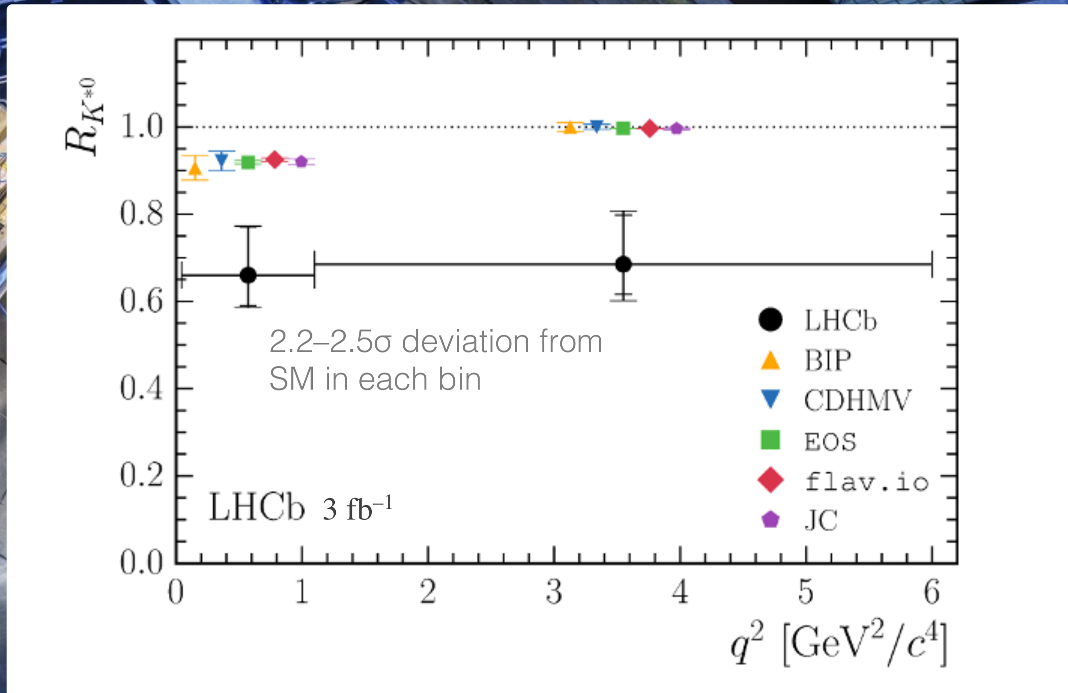


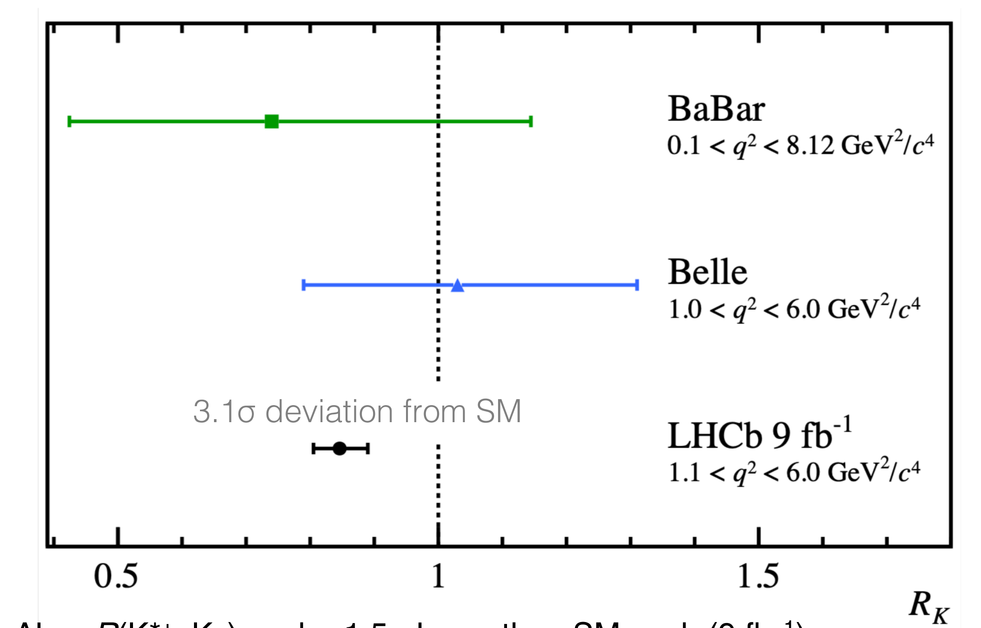
Flavour physics



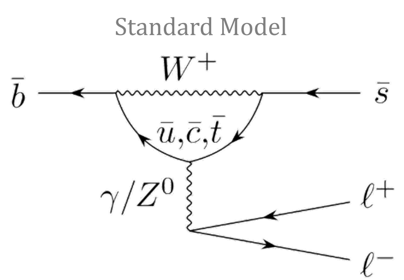
Success of SM flavour structure is since long a source of discomfort for BSM physics…
as are anomalies a source of excitement

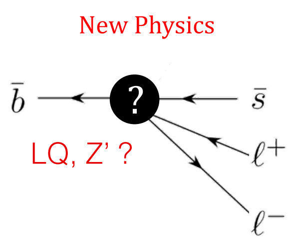
LHCb's dipole magnet at 2018 detector opening

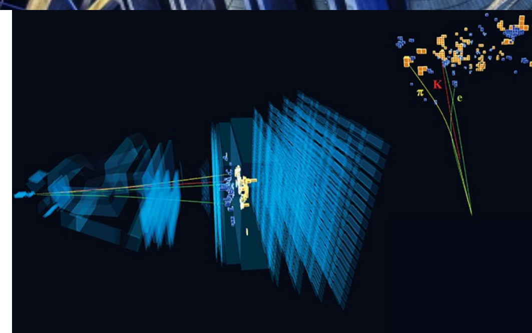




Also: $R(K^{*+}, K_S)$ each ~1.5σ lower than SM each (9 fb^{-1})







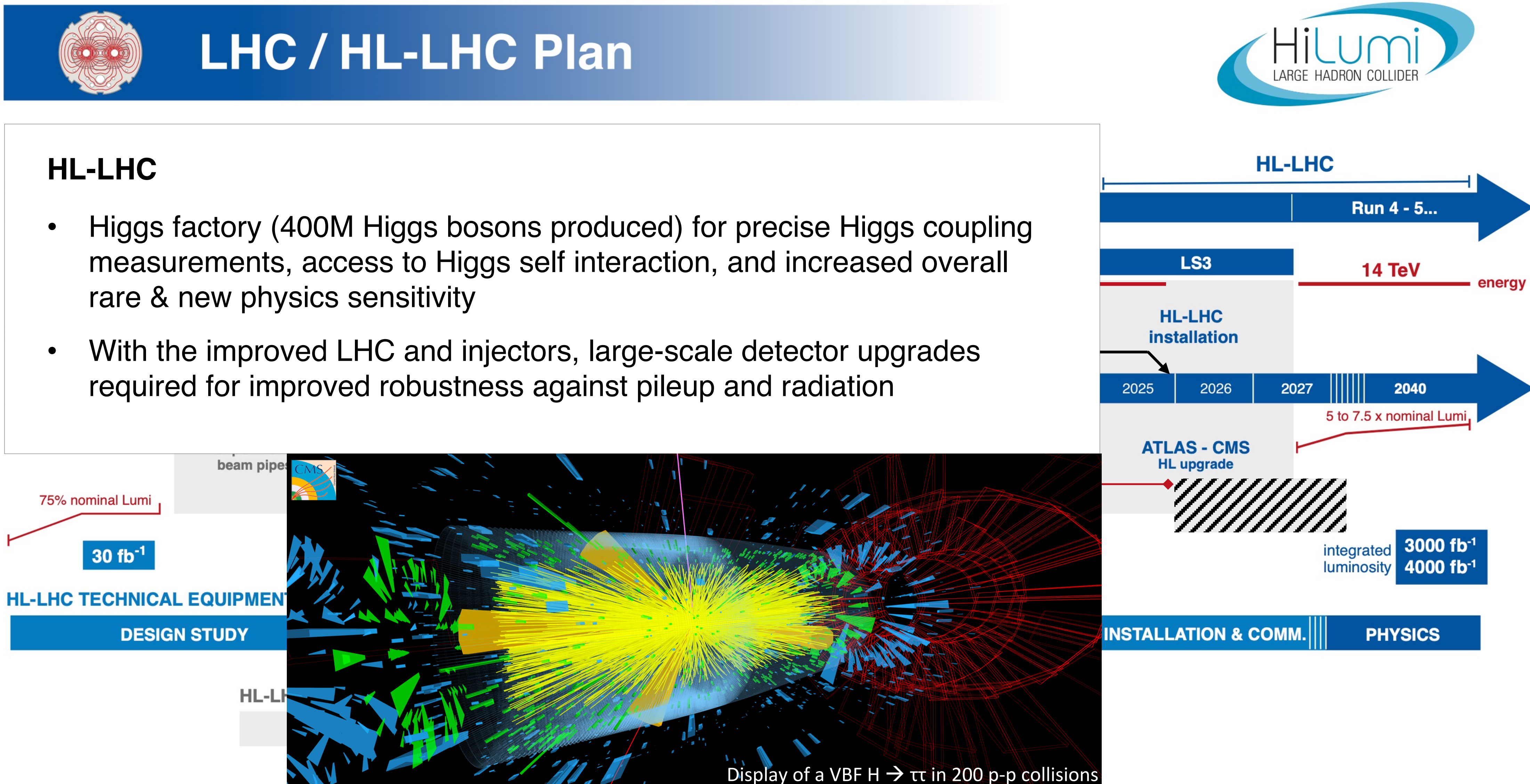
Success of SM flavour structure is since long a source of discomfort for BSM physics…
as are anomalies a source of excitement

LHCb's dipole magnet at 2018 detector opening

The next steps

Preparing the future — the grand plan

Preparing the future — the grand plan



HL-LHC

- Higgs factory (400M Higgs bosons produced) for precise Higgs coupling measurements, access to Higgs self interaction, and increased overall rare & new physics sensitivity
- With the improved LHC and injectors, large-scale detector upgrades required for improved robustness against pileup and radiation

Display of a VBF H → ττ in 200 p-p collisions

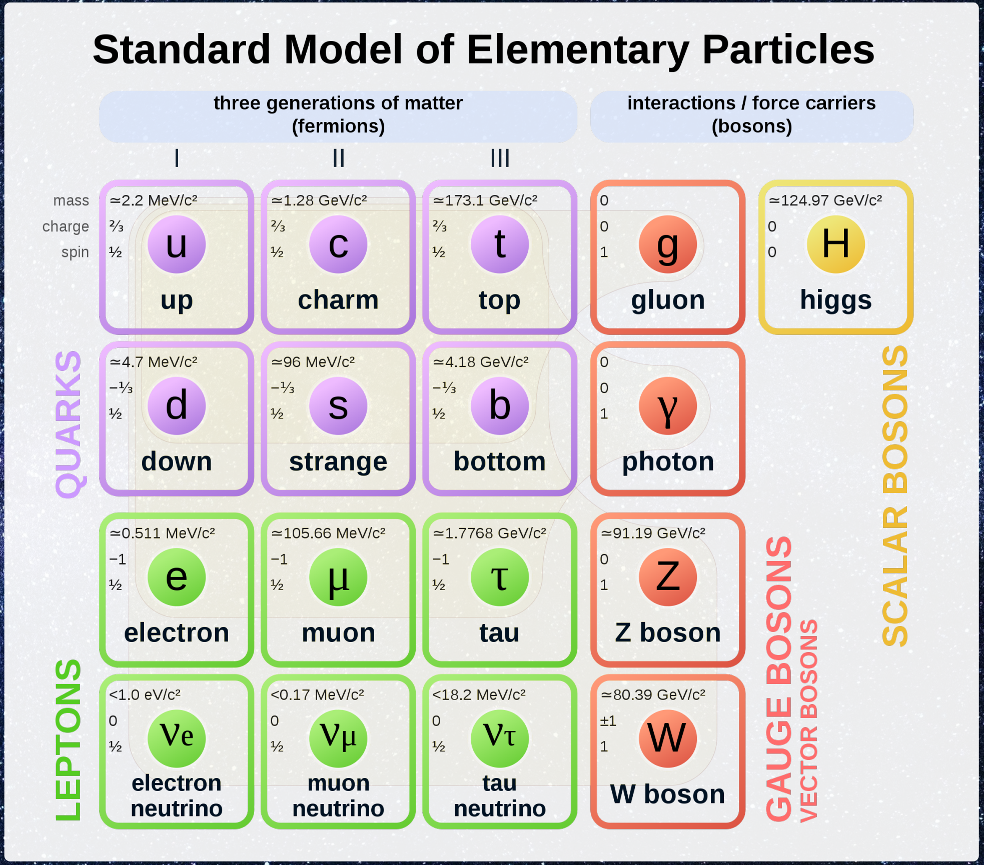
Preparing for the High-Luminosity LHC

Preparing for the High-Luminosity LHC

ATLAS EXPERIMENT

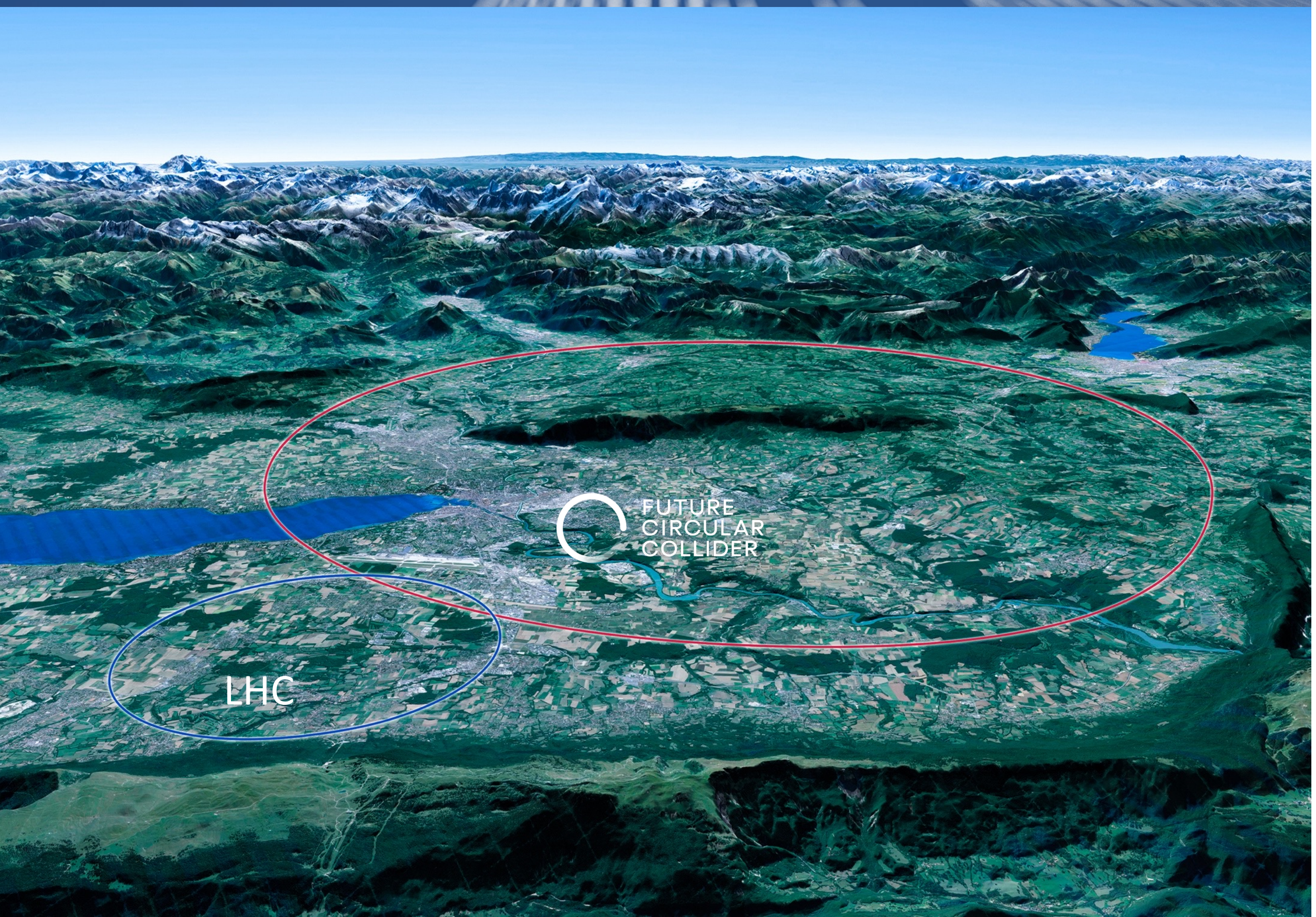
July 12, 2021, lowering the NSW-A into the ATLAS cavern

The Standard Model is complete



The eighteen arbitrary parameters of the SM in your everyday life, Bob Cahn (1996)

Many deep questions remain, many of which require energy frontier experiments



Scientific priorities for the future

Implementation of the recommendations of the 2020 Update of the European Strategy for Particle Physics:

- Fully exploit the HL-LHC
- Build a Higgs factory to further understand this unique particle
- Investigate the technical and financial feasibility of a future 100 TeV energy-frontier collider at CERN
- Ramp up relevant R&D
- Continue supporting other projects around the world

A phenomenal machine

A phenomenal machine

A high-luminosity 100 TeV hadron collider offers huge physics potential

- 5σ discovery potential for new phenomena: q* up to 40 TeV, Z'_{SSM} up to 43 TeV, gluino / stop up to 16 / 10 TeV, …
- Precision probes of Higgs self coupling and rare Higgs processes (400 times larger HH cross section than at LHC)
- Studies of SM processes such high-mass longitudinal vector boson scattering (3%), Drell-Yan up to 15 TeV mass (10%)
- WIMP dark matter sensitivity between 1 and 3 TeV
- Heavy-ion physics program with $\sqrt{s_{NN}}$ = 39 TeV for PbPb and 63 TeV for pPb

The timescale, size, cost and technical challenges of this facility are daunting, **can we do it?**

Were LEP & LHC so different? With the expected completion of the HL-LHC around 2040, the full programme will have taken 57 years since the start of the civil engineering work in 1983

The e^+e^- Higgs factory gives time to develop the high-field magnets required for the new high-energy frontier. This R&D must be pursued with full strength & conviction: without a realistic hadron collider option the tunnel facility will have a difficult standing

Progress in particle physics crucially relies on energy frontier experiments

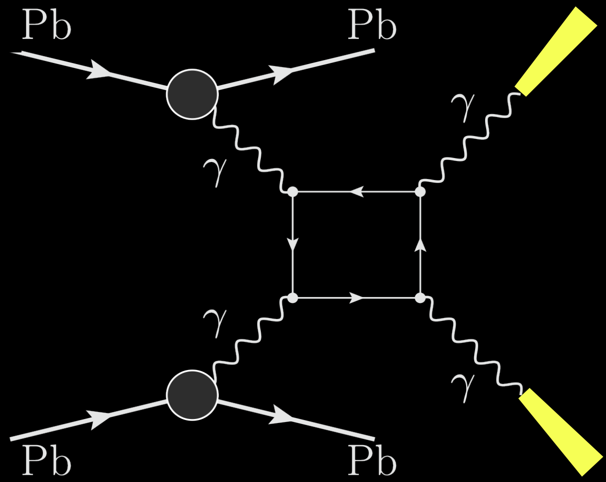

We’ve come a long way
The adventure continues

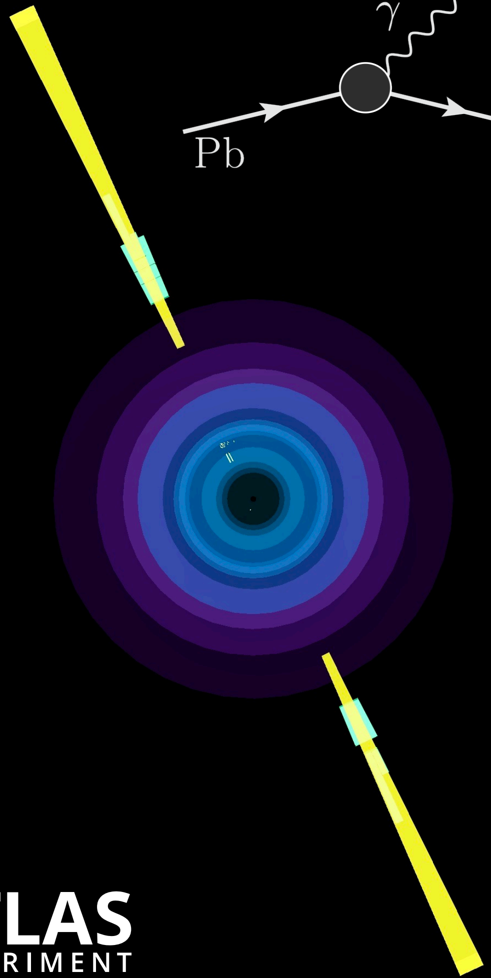

We've come a long way
Congratulations
IN2P3
50 ANS DE PHYSIQUE
DES DEUX INFINIS
The adventure continues

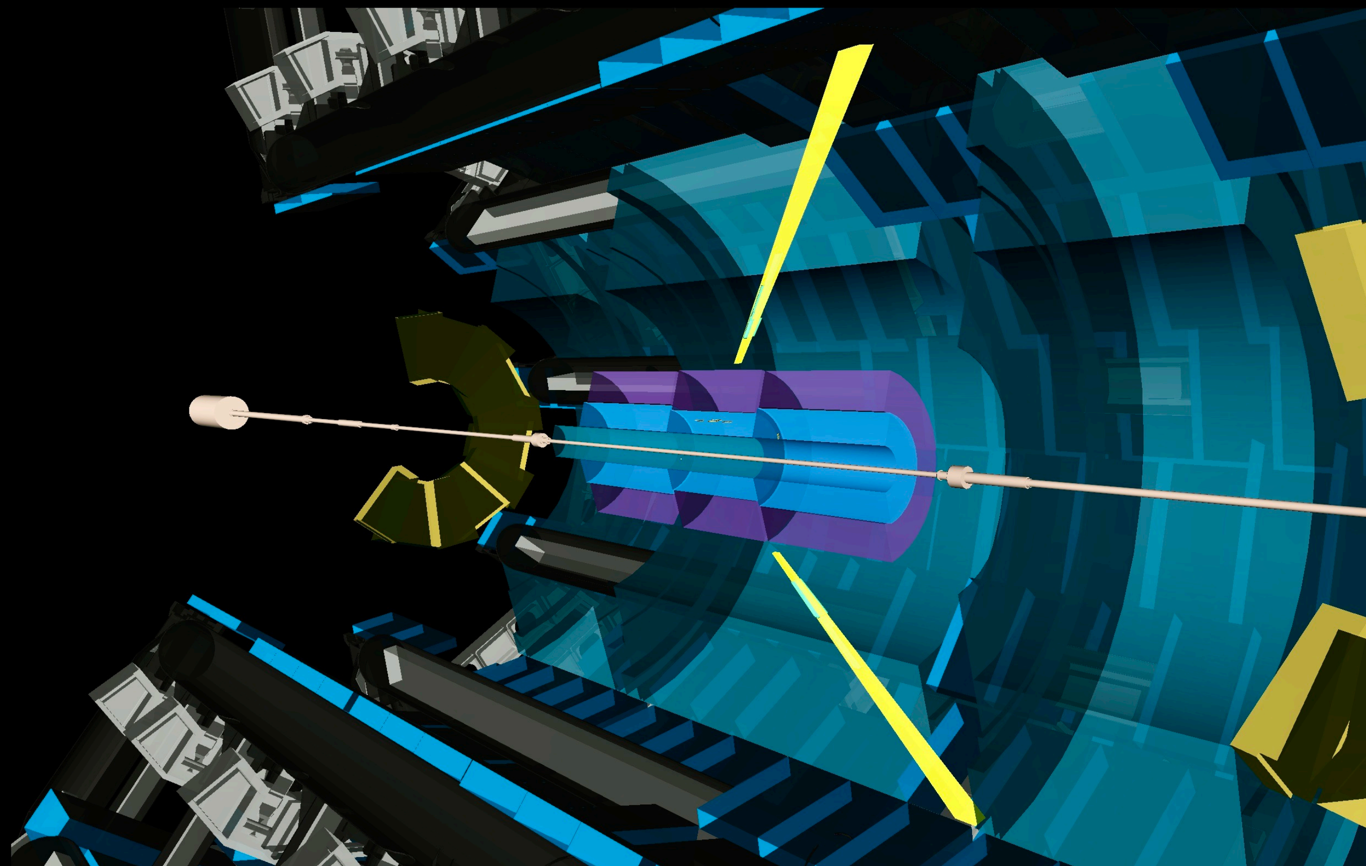
Congratulations

Extra slides

Studies of physics in extreme electromagnetic fields ?

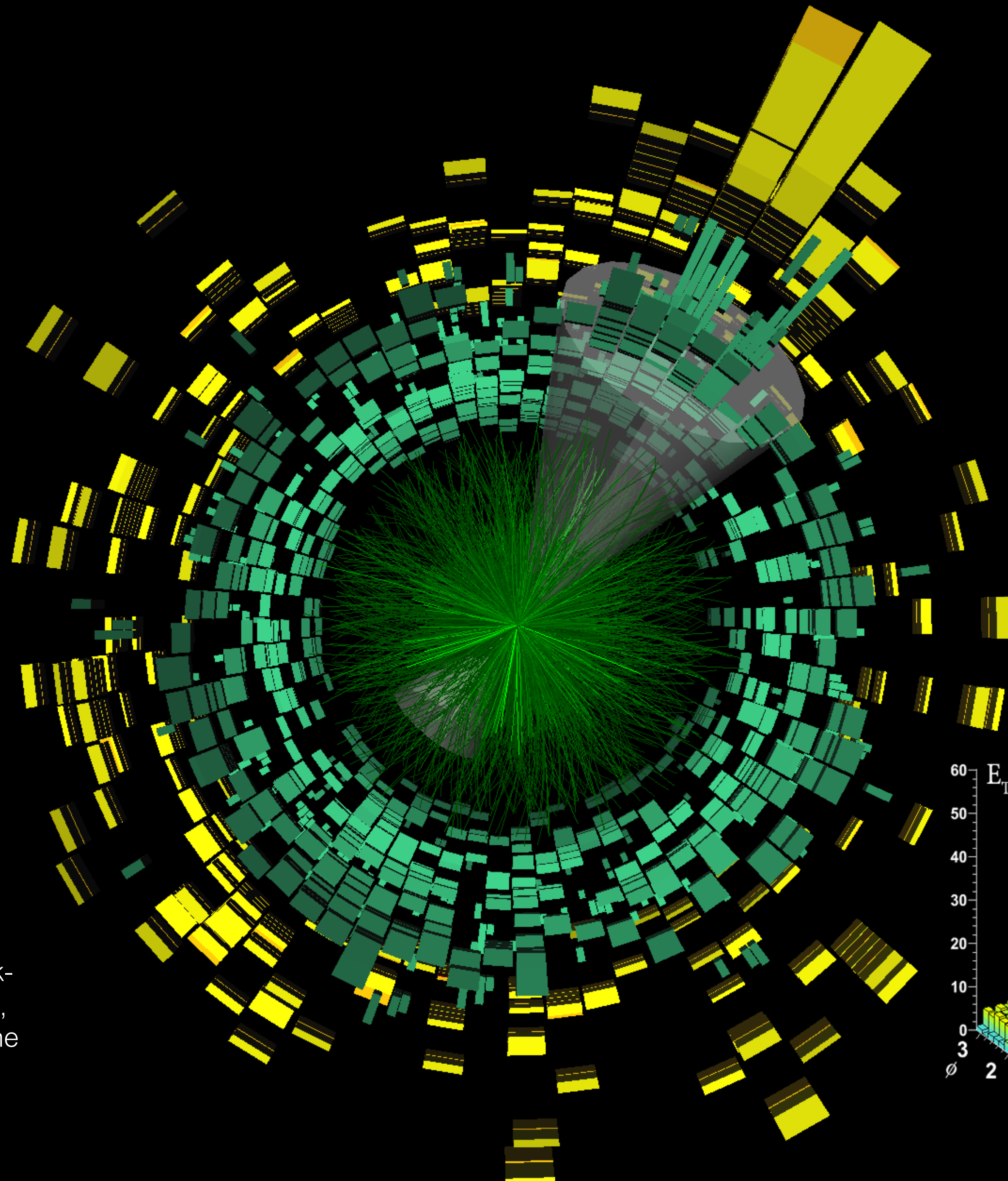




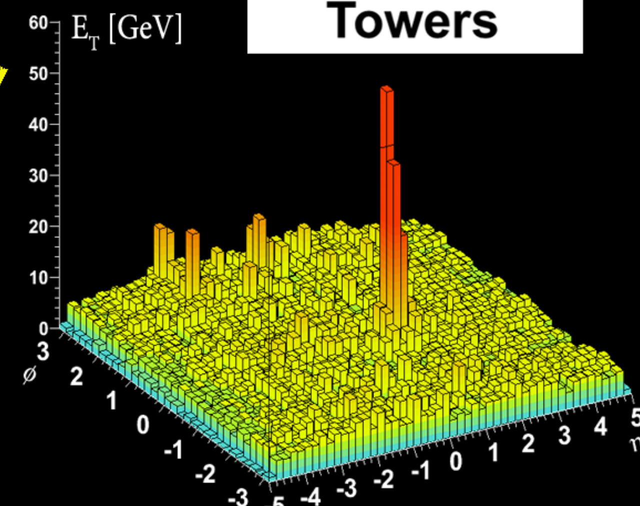


ATLAS
EXPERIMENT

And a detailed mapping of the properties of the quark-gluon plasma with soft and hard probes



Calorimeter Towers



In collisions of heavy ions, the LHC creates for a very brief moment a quark-gluon plasma of up to 6 trillion degrees, almost half a million times hotter than the core of the sun