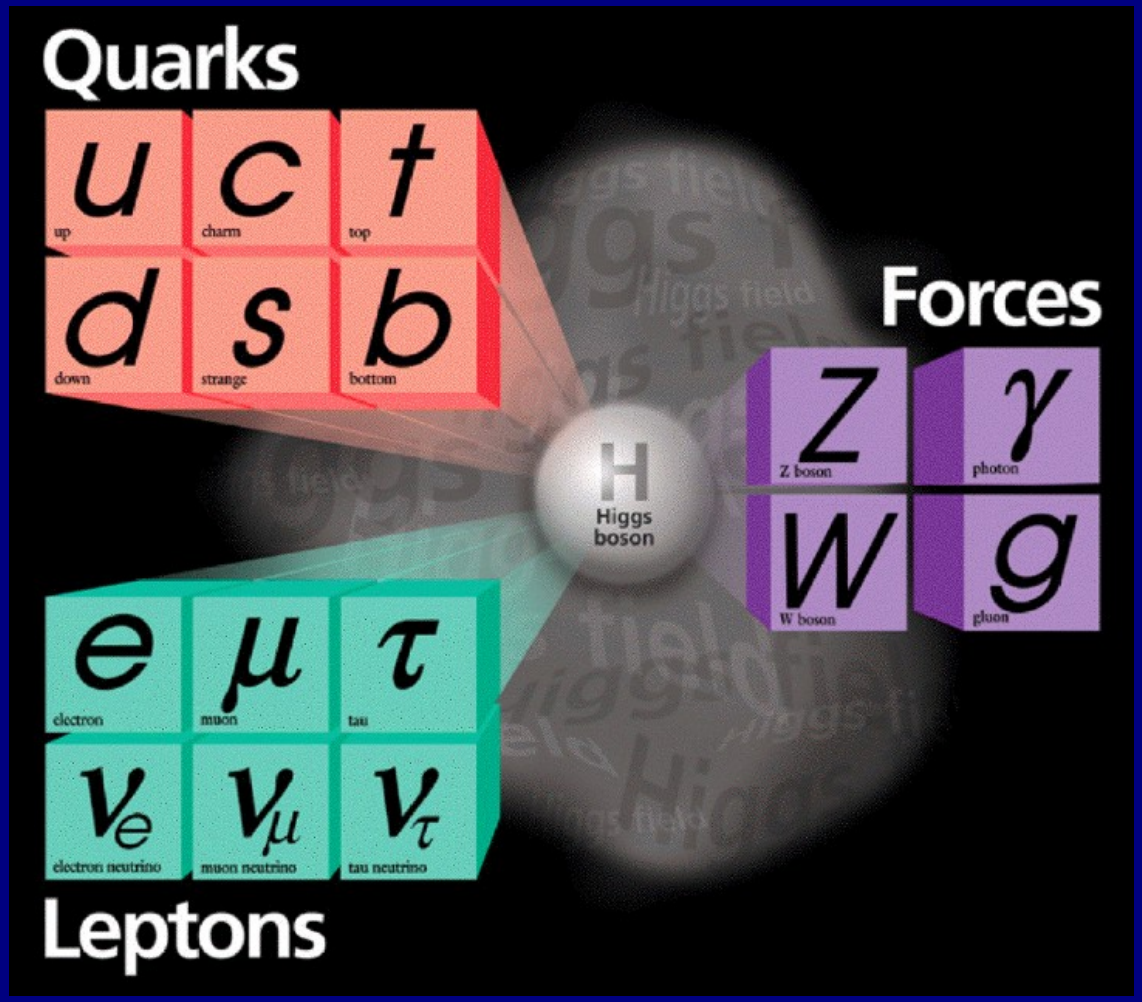
Exploring the Broken Symmetry of the Electroweak Theory

"Before and Since the Higgs Discovery"

Dave Charlton
School of Physics & Astronomy, University of Birmingham, and the ATLAS Collaboration

The Standard Model



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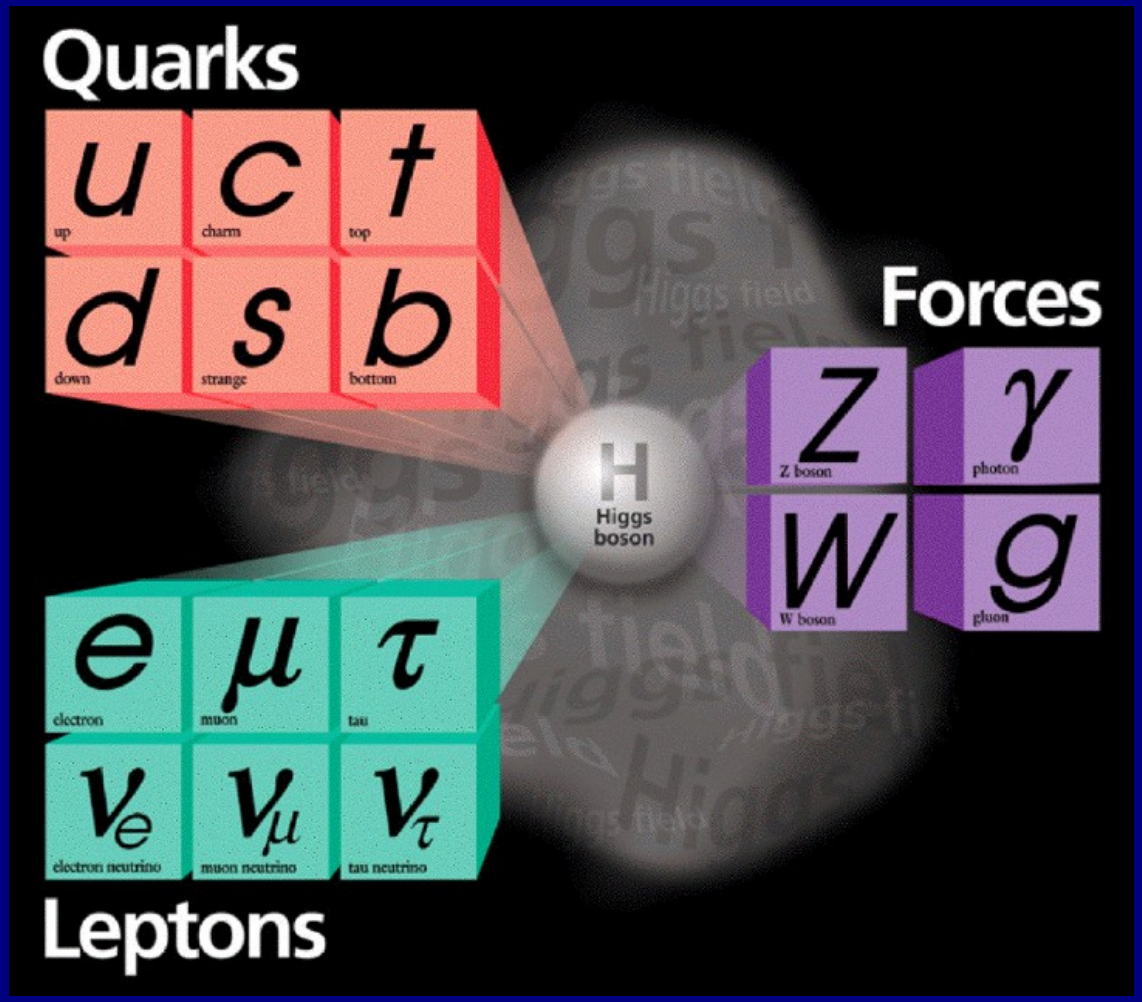


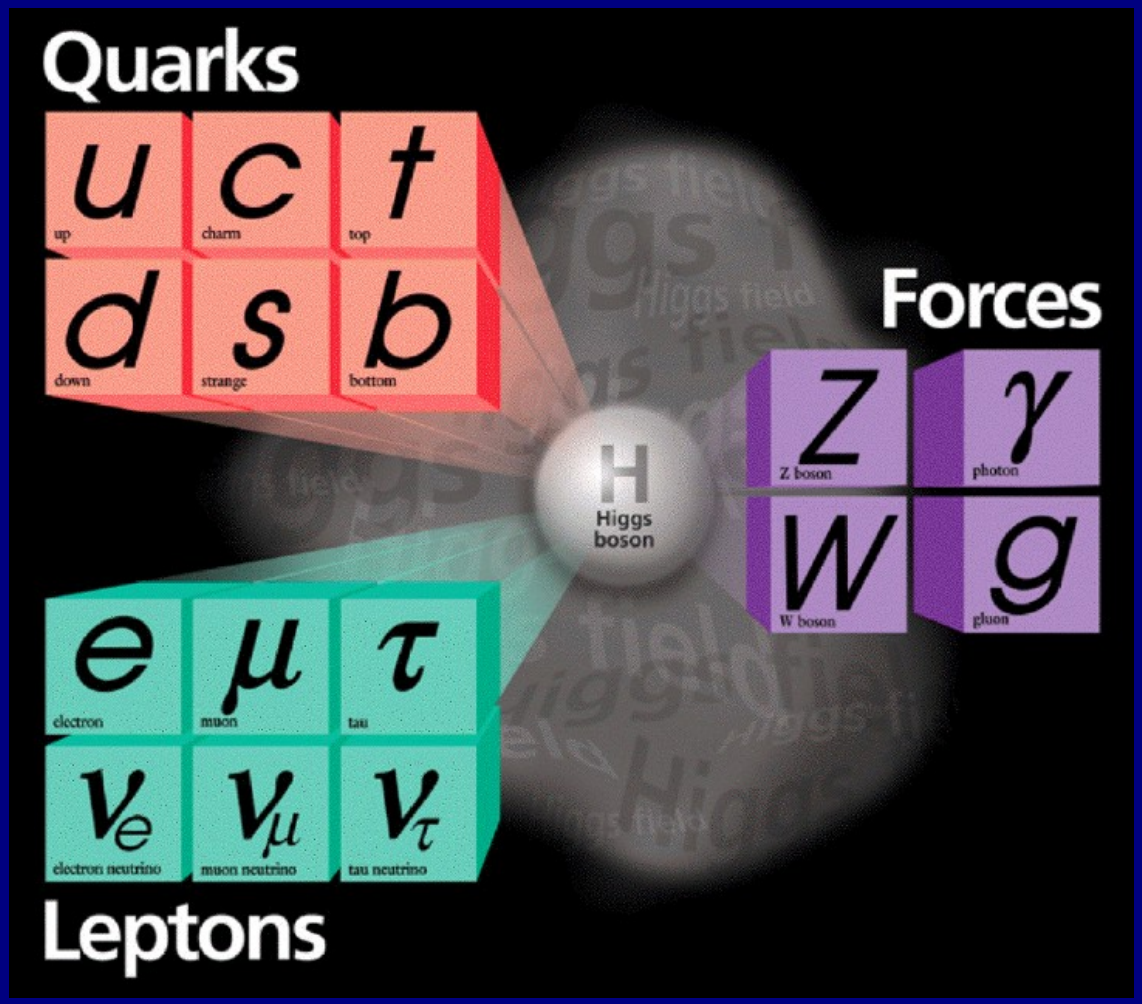
Is much more than this...

The Lorentz structures of the interactions are fully included in the Standard Model lagrangian

Some interactions – e.g the interactions of the gauge bosons with each other – are *fully predicted* by the gauge symmetry group of the Standard Model

$$SU(2)_L \times U(1)_Y \times SU(3)_c$$

The Standard Model



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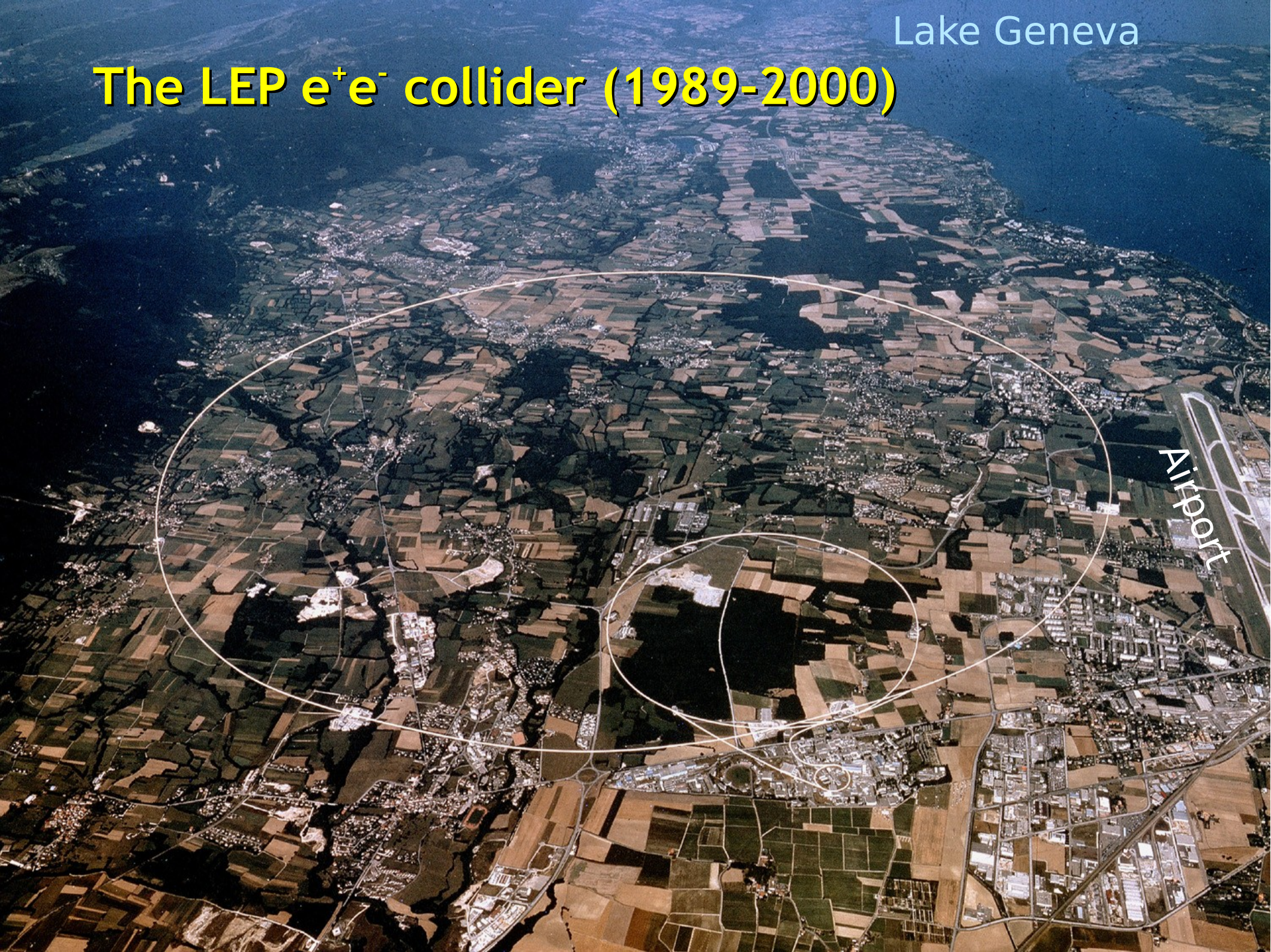
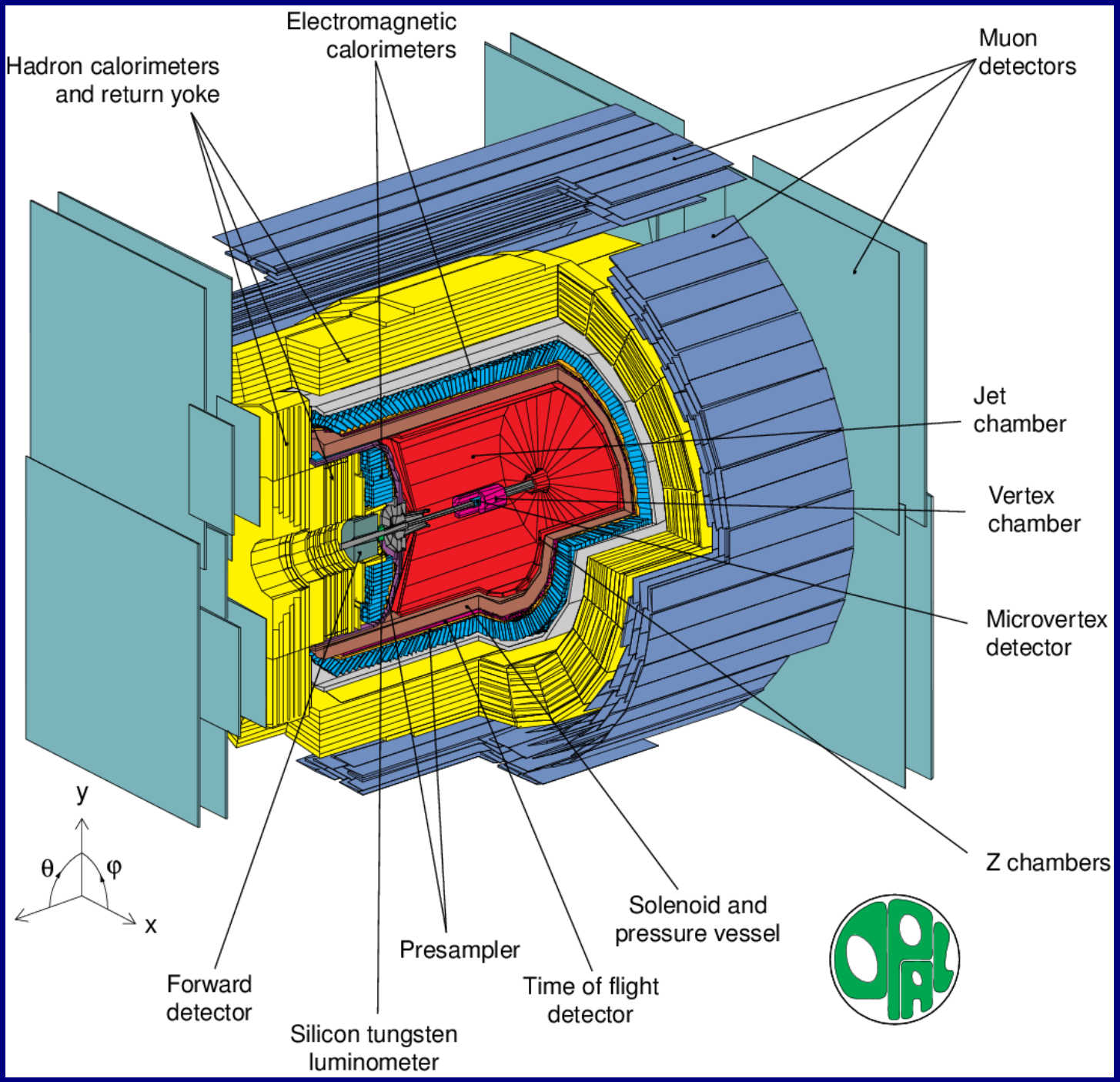
$$SU(2)_L \times U(1)_Y \times SU(3)_c$$

The triple-interactions of the gauge bosons were measured directly at the LEP collider at CERN in the late 90's, and also at Fermilab

The LEP e^+e^- collider (1989-2000)





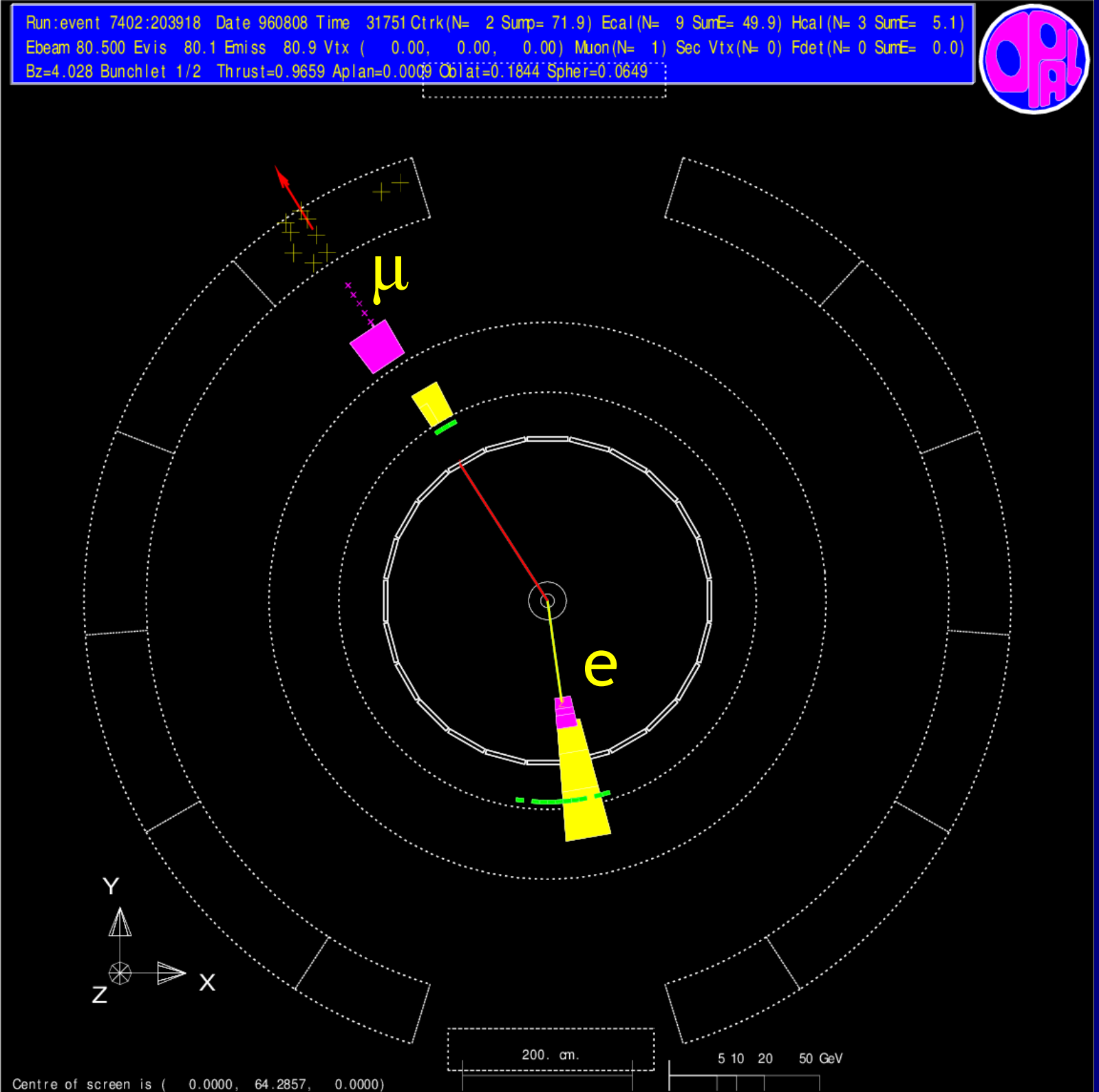
OPAL

One of the four detectors at LEP

~11m-cube

Collaboration of ~350 physicists and engineers from 8 countries

e^+e^- collisions → simple event topologies, collect "every" collision event



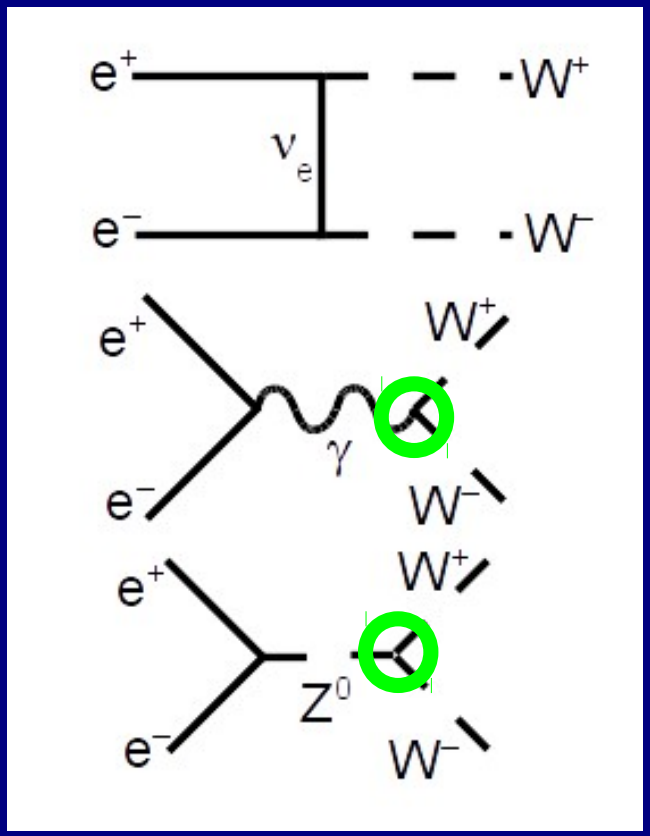
Candidate for

$e^+e^- \rightarrow WW$

$\rightarrow e\nu\mu\nu$

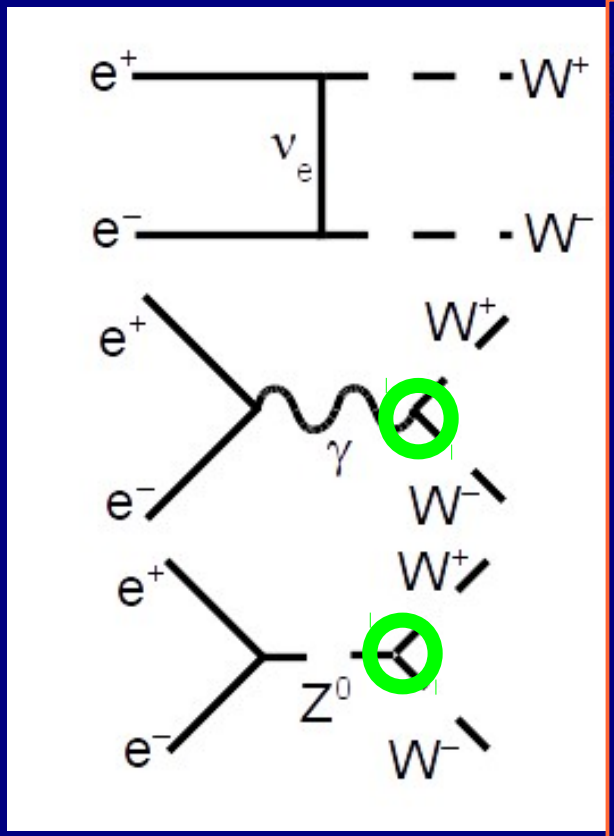
Beautifully simple events

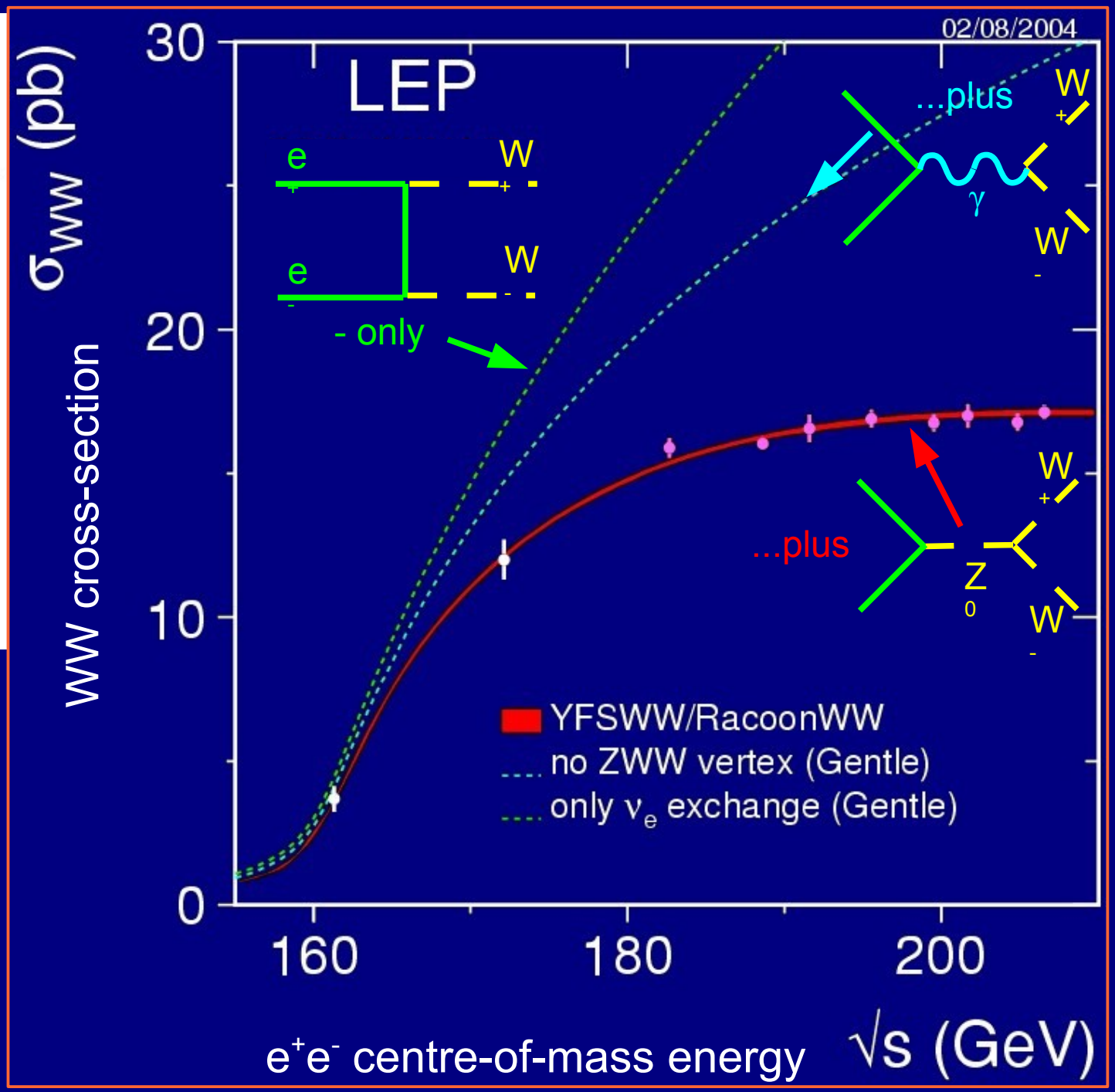
LEP operated above the W-pair production threshold energy during 1996-2000

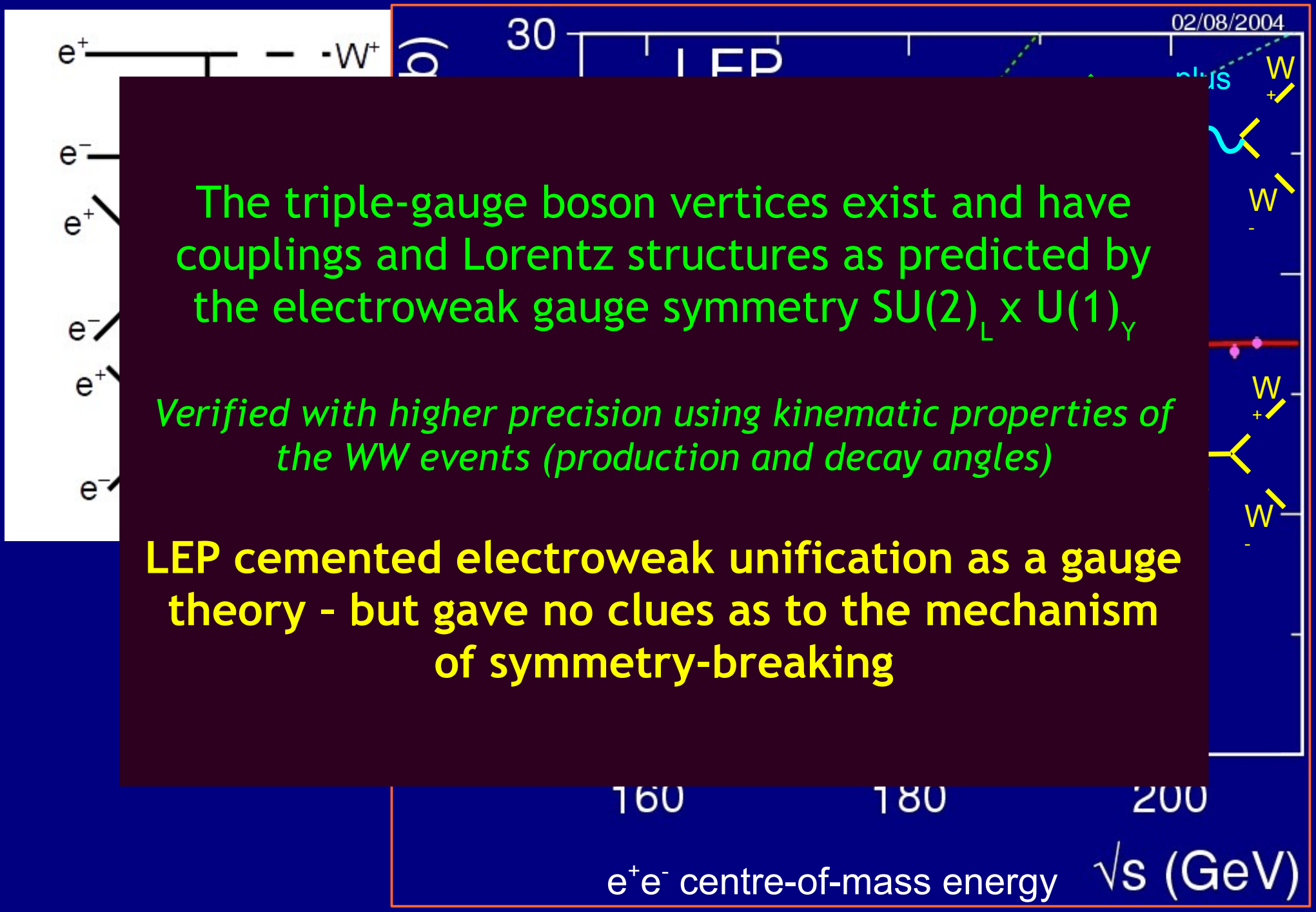


W-pair production at LEP

Three tree-level Feynman diagrams
Two contain a triple vector boson vertex


e+
e−
νe
W+
W−
γ
Z0

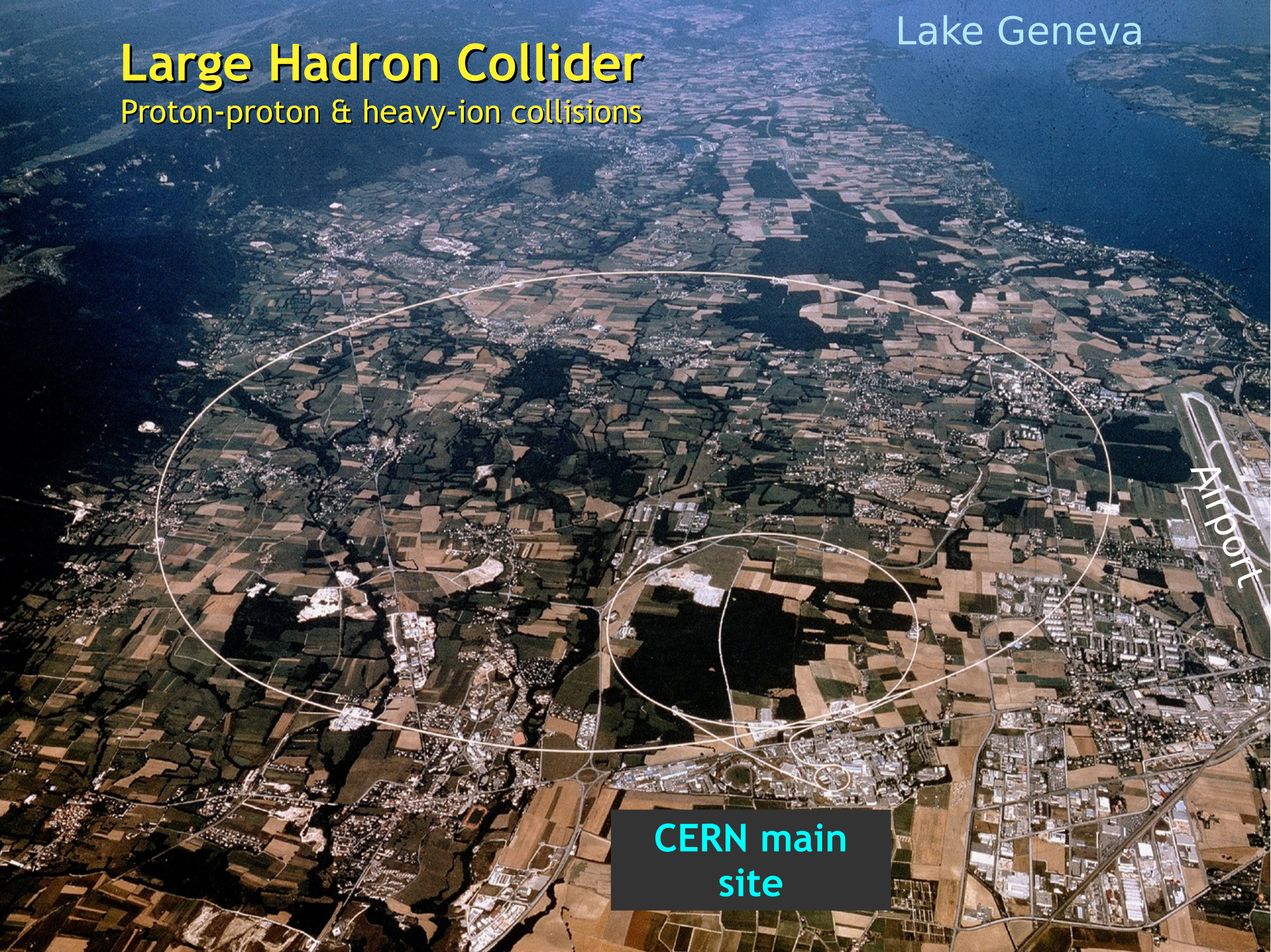

02/08/2004
LEP
σWW (pb)
WW cross-section
30
20
10
0
160
180
200
√s (GeV)
e+e- centre-of-mass energy
e+
e-
W+
W-
- only
...plus
γ
Z0
YFSWW/RacoonWW
no ZWW vertex (Gentle)
only νe exchange (Gentle)



The triple-gauge boson vertices exist and have couplings and Lorentz structures as predicted by the electroweak gauge symmetry $SU(2)_L \times U(1)_Y$

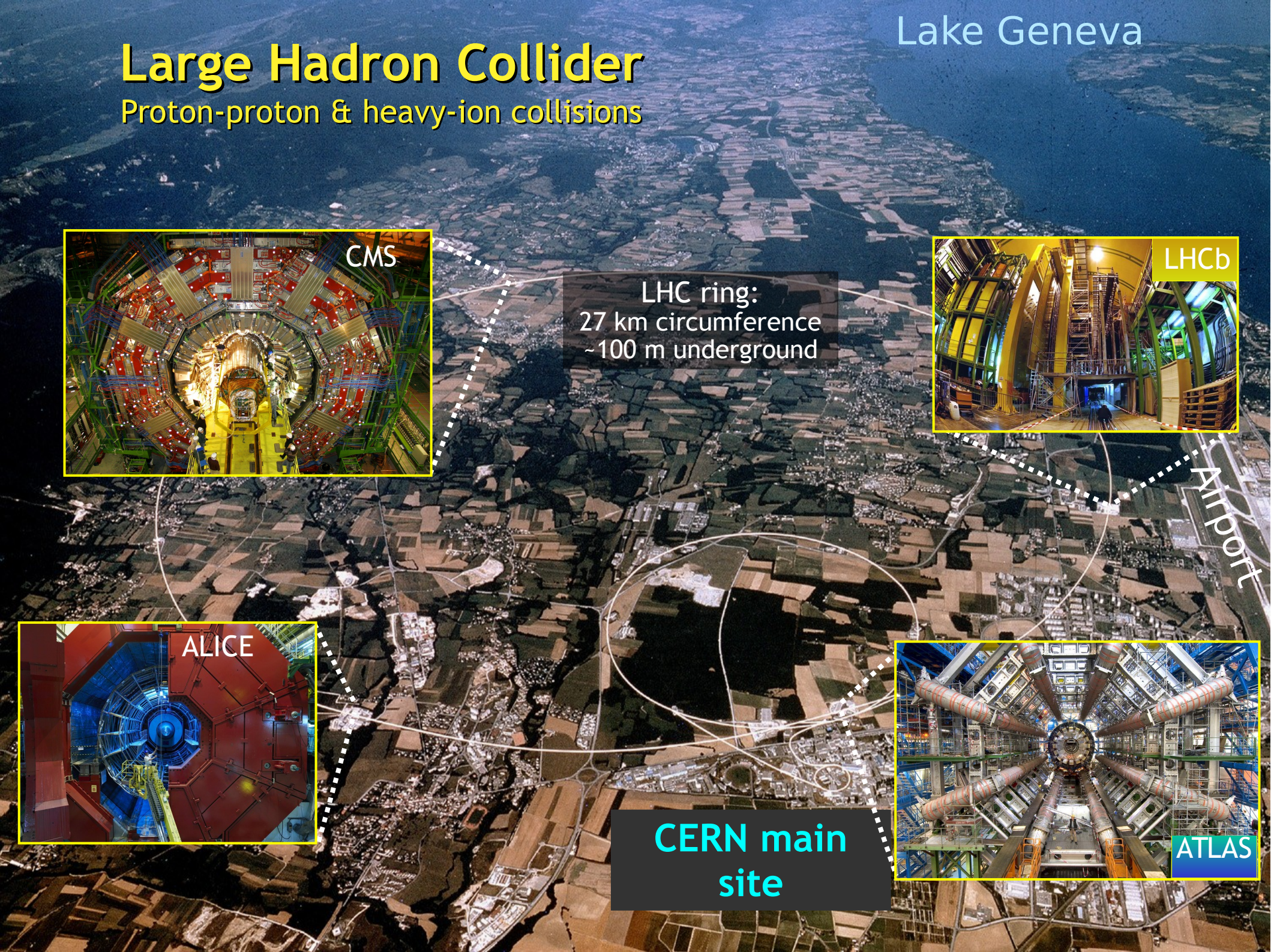
Verified with higher precision using kinematic properties of the WW events (production and decay angles)

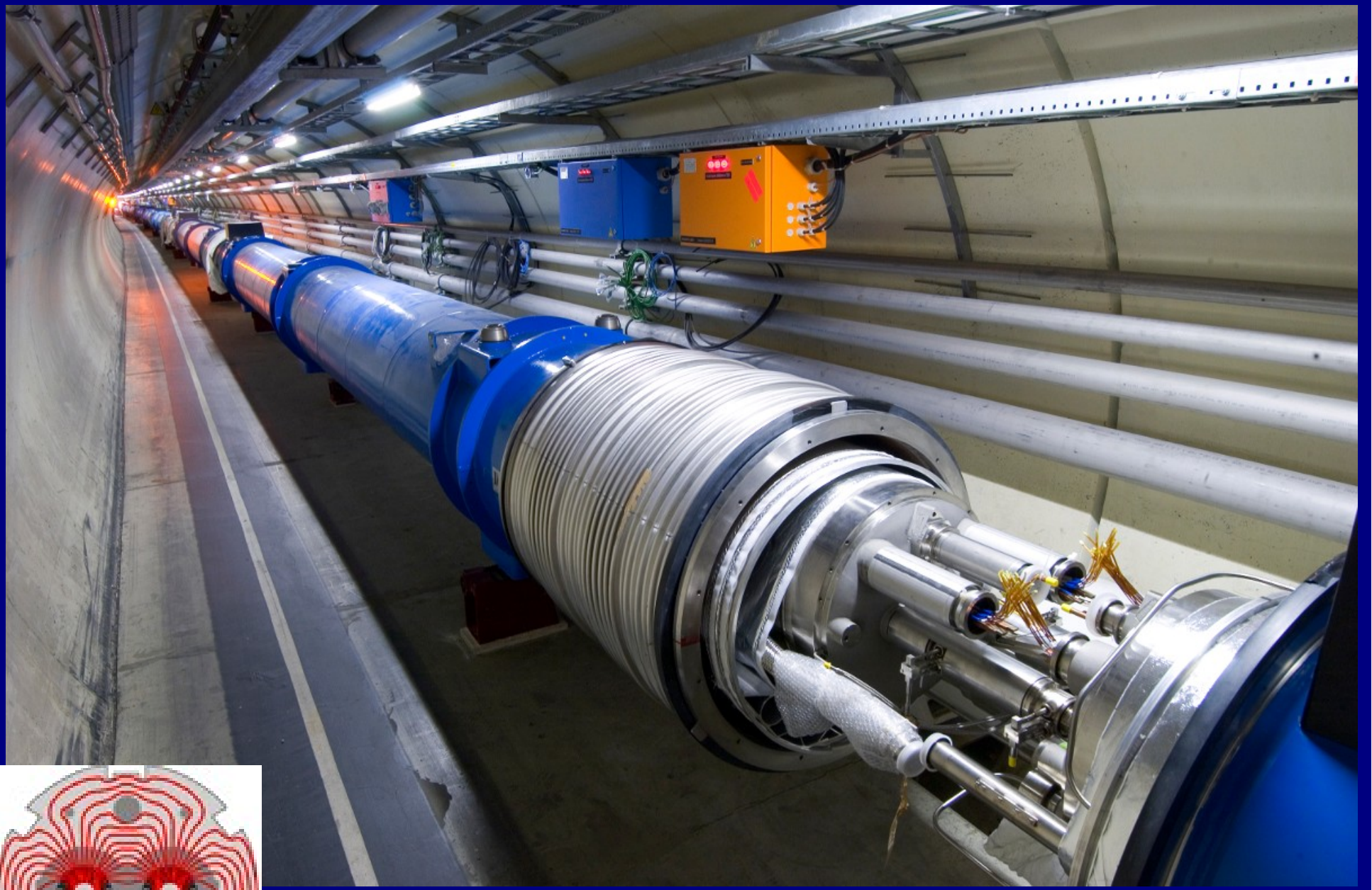
LEP cemented electroweak unification as a gauge theory - but gave no clues as to the mechanism of symmetry-breaking

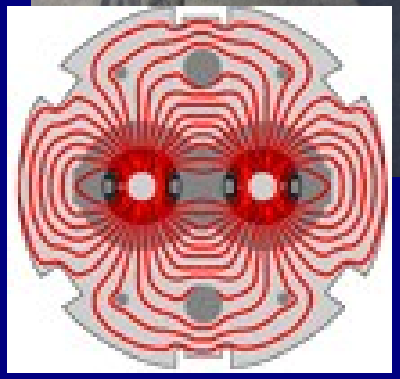

Large Hadron Collider
Proton-proton & heavy-ion collisions
Lake Geneva
Airport
CERN main site

Large Hadron Collider

Proton-proton & heavy-ion collisions

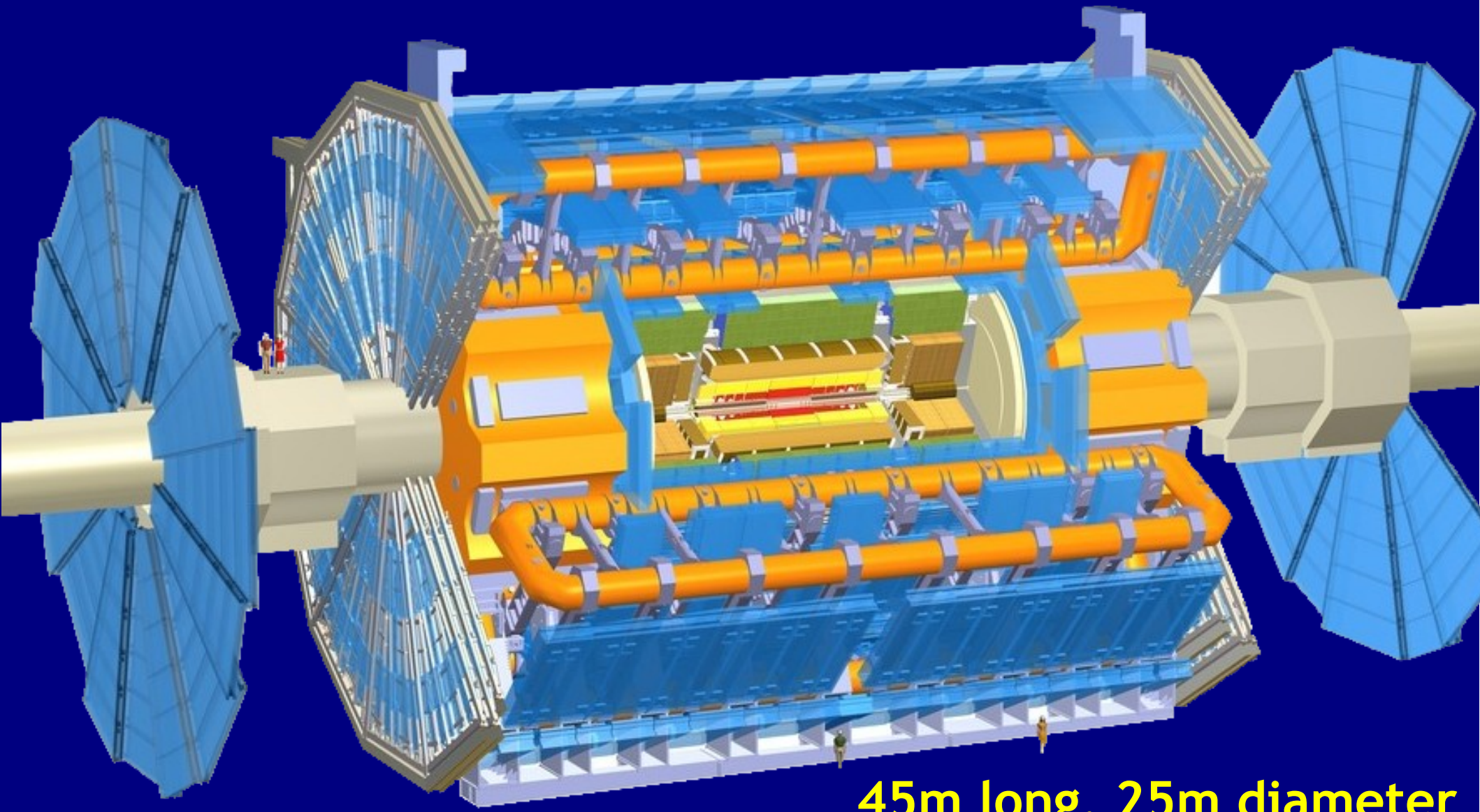






- 1232 14m-long superconducting main dipoles
- Two-in-one coil design
- Maximum field 8.4 T
- Cooled to 1.9K with 90t on LHe

The ATLAS Detector



45m long, 25m diameter
7000 tons

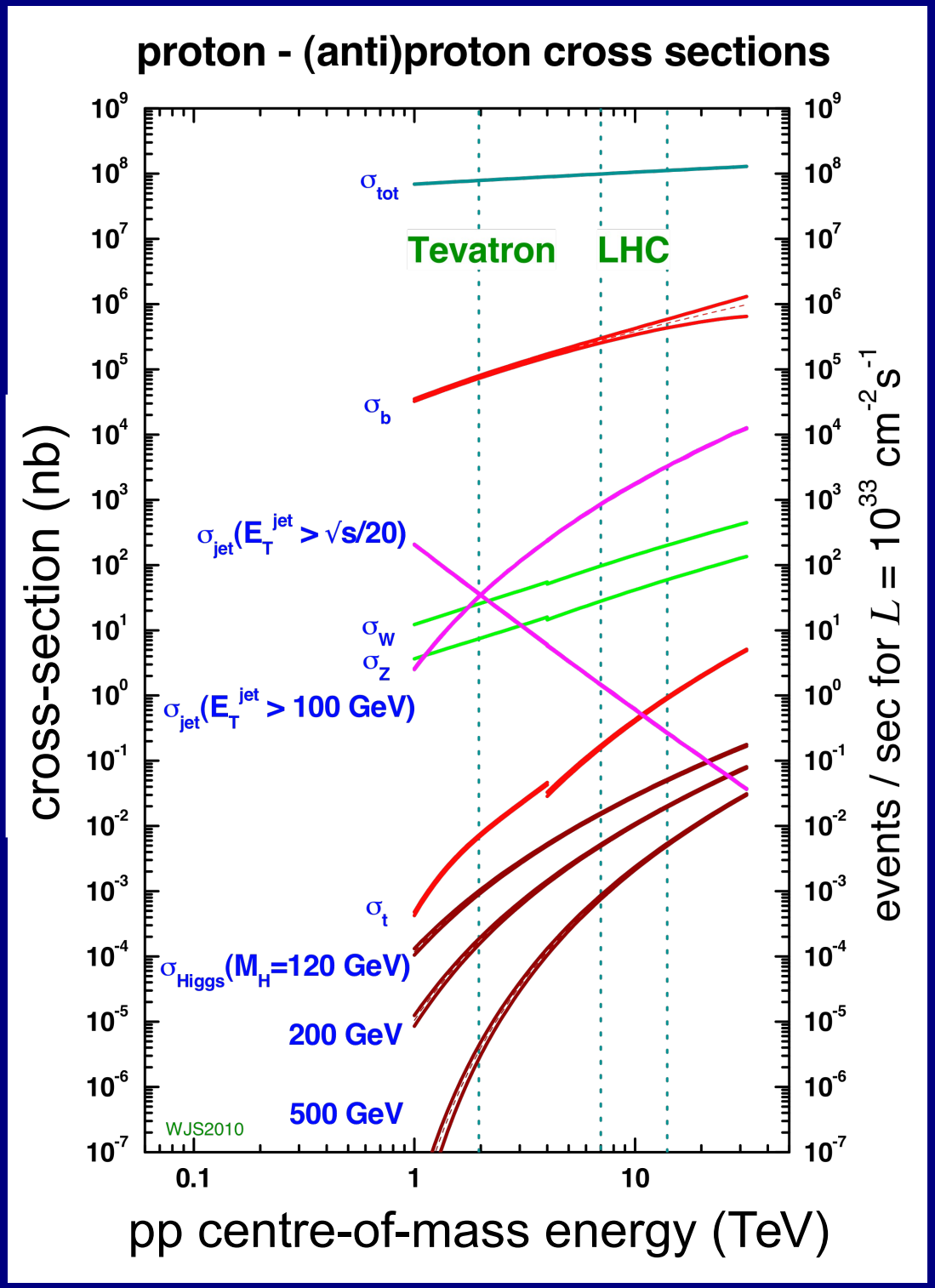
100 million channels: track ~1000 particles per event with precision ~10's μm over 10's m

ATLAS collaboration

178 institutions from 38 countries

2900 scientific authors, including 1000 students

Adelaide, Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brazil Cluster, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Hong Kong, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QM London, RH London, UC London, Louisiana Tech, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois University, BINP Novosibirsk, NPI Petersburg, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, RAL-STFC, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa Cluster, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Warwick, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan



Challenges

So far LHC has run at pp centre-of-mass energy of 7-8 TeV

At the luminosities achieved so far, maximum collision rate
~10^9 events / sec

Production rate of
H → any ~ 0.1 Hz
H → γγ ~ 1 / hour

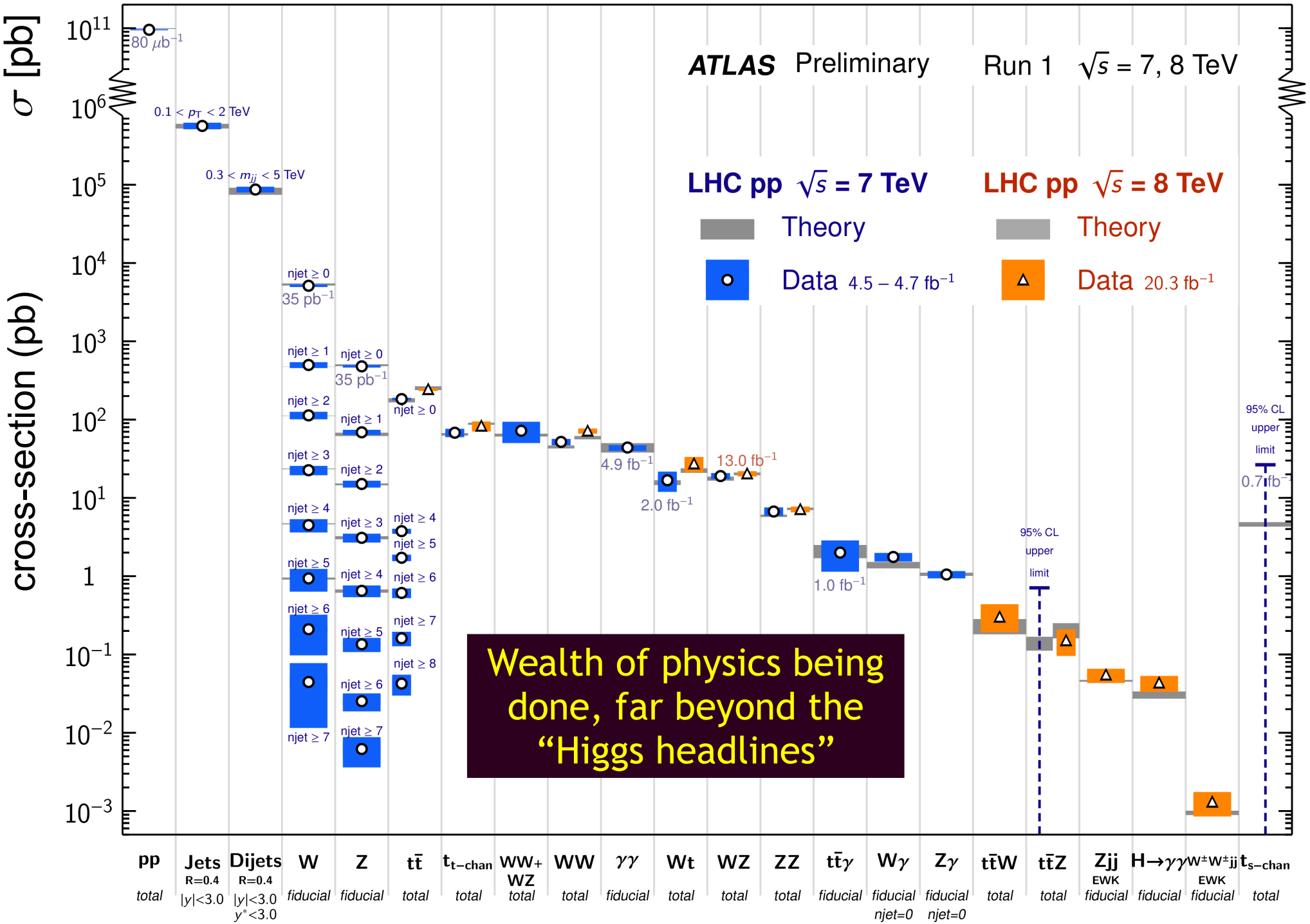
Huge online data rejection ("trigger") ~10^{-5}

Huge offline data volumes

Radiation hard electronics

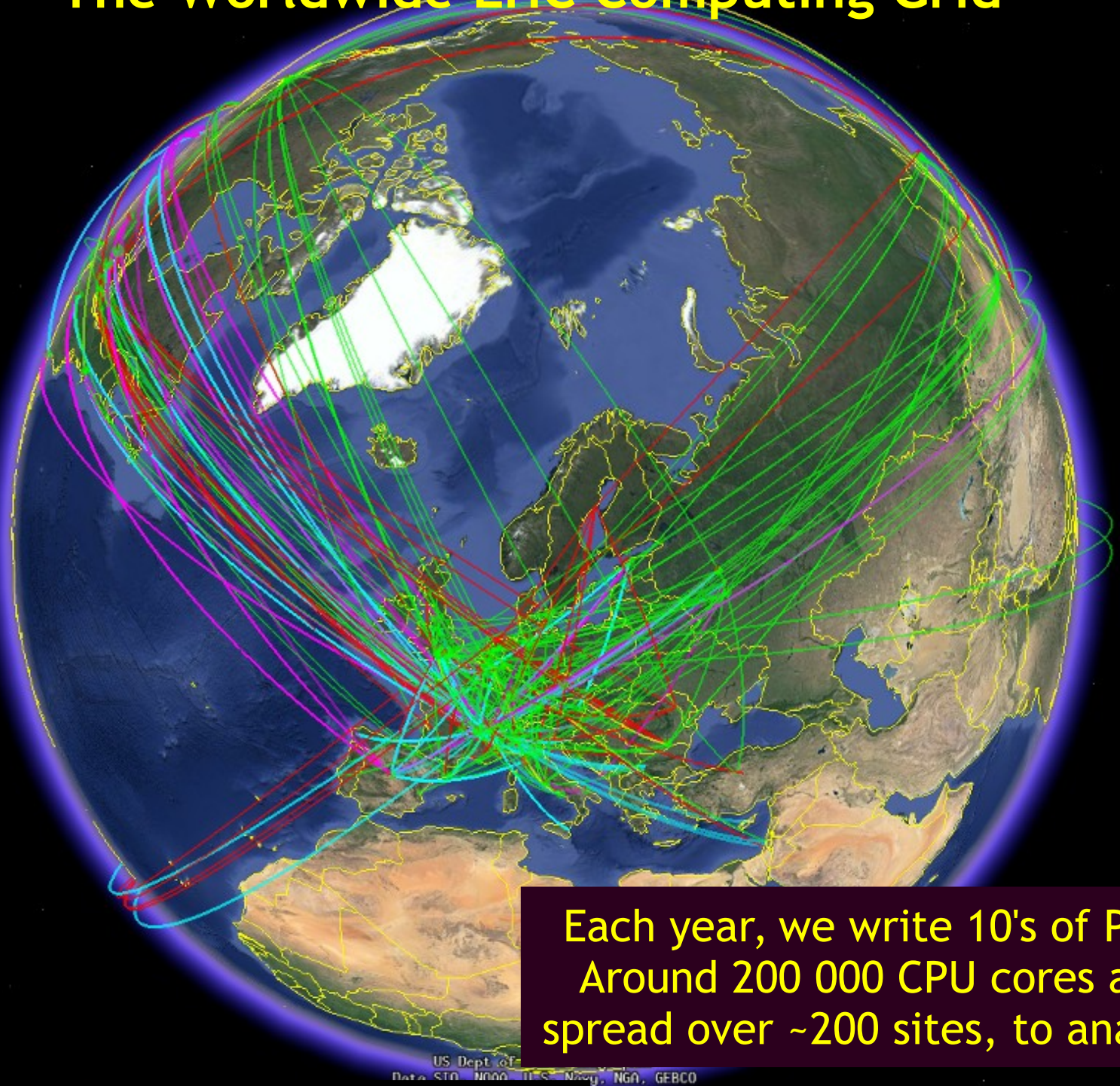
Standard Model Production Cross Section Measurements

Status: July 2014



Wealth of physics being done, far beyond the "Higgs headlines"

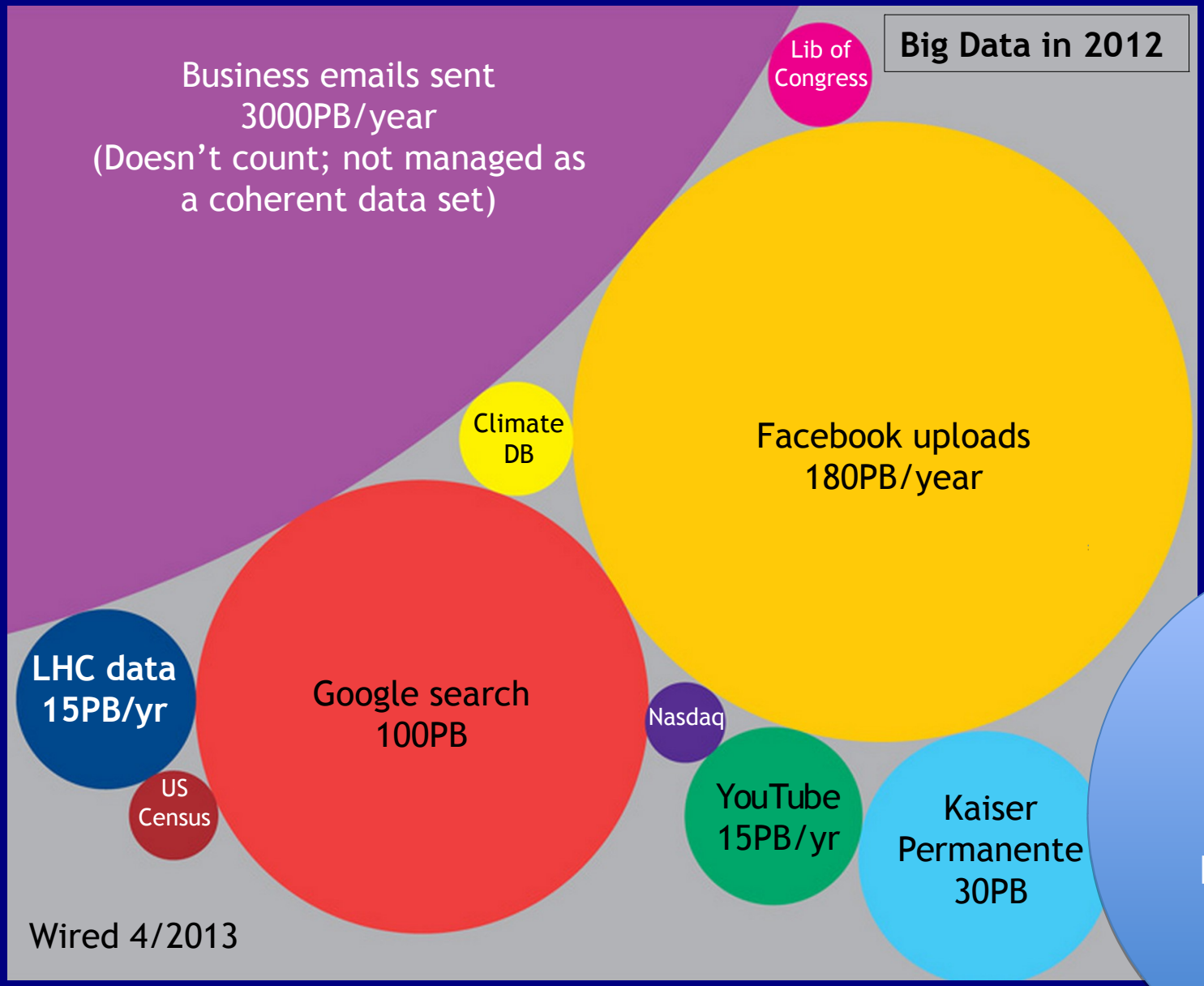
The Worldwide LHC Computing Grid



Each year, we write 10's of PB of data
Around 200 000 CPU cores are used,
spread over ~200 sites, to analyse them

http://dashb-earth.cern.ch/dashboard/dashb-earth-all.kmz

The Worldwide LHC Computing Grid – Big Data

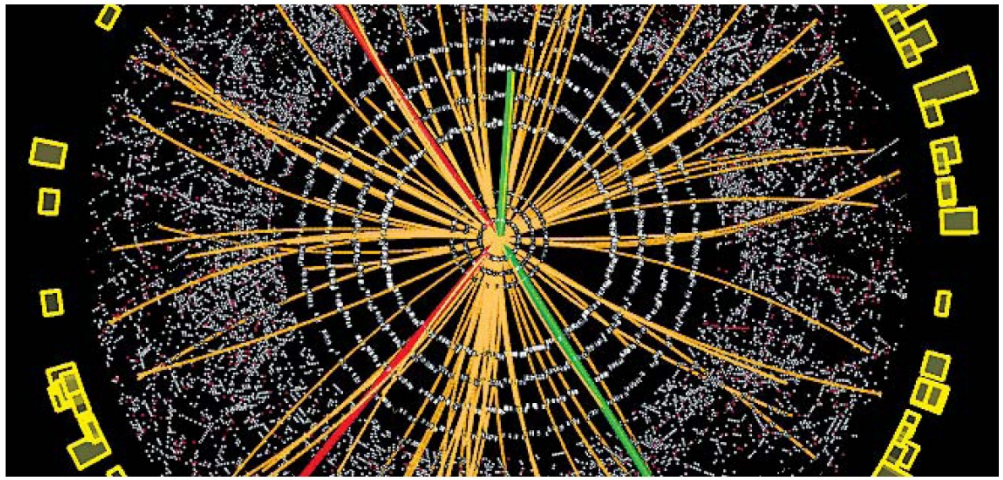


Current ATLAS data set, all data products: 140 PB

http://www.wired.com/magazine/2013/04/bigdata/

July 4th 2012 (CERN and Melbourne)

Higgs was right Picture that changes the way we see the universe for ever



Ian Sample Geneva

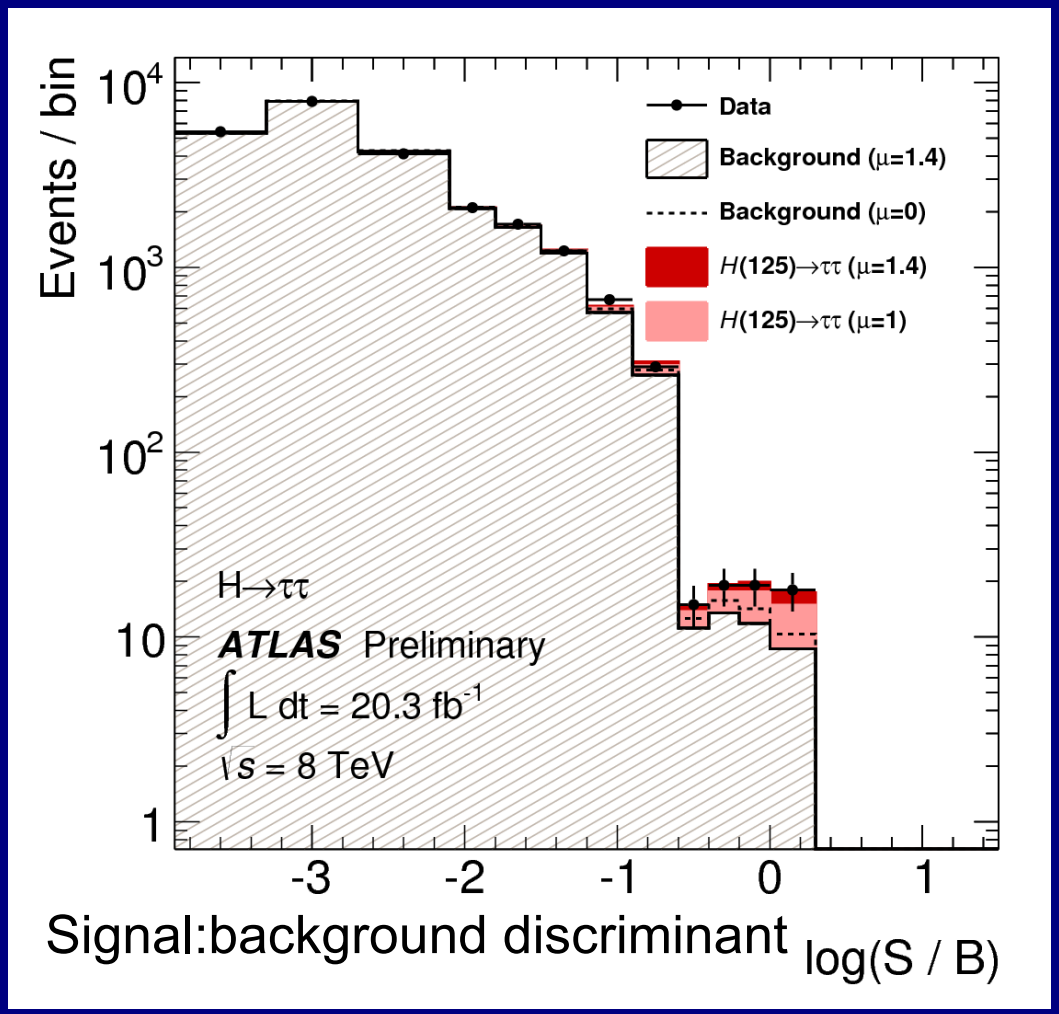
Since July 2012

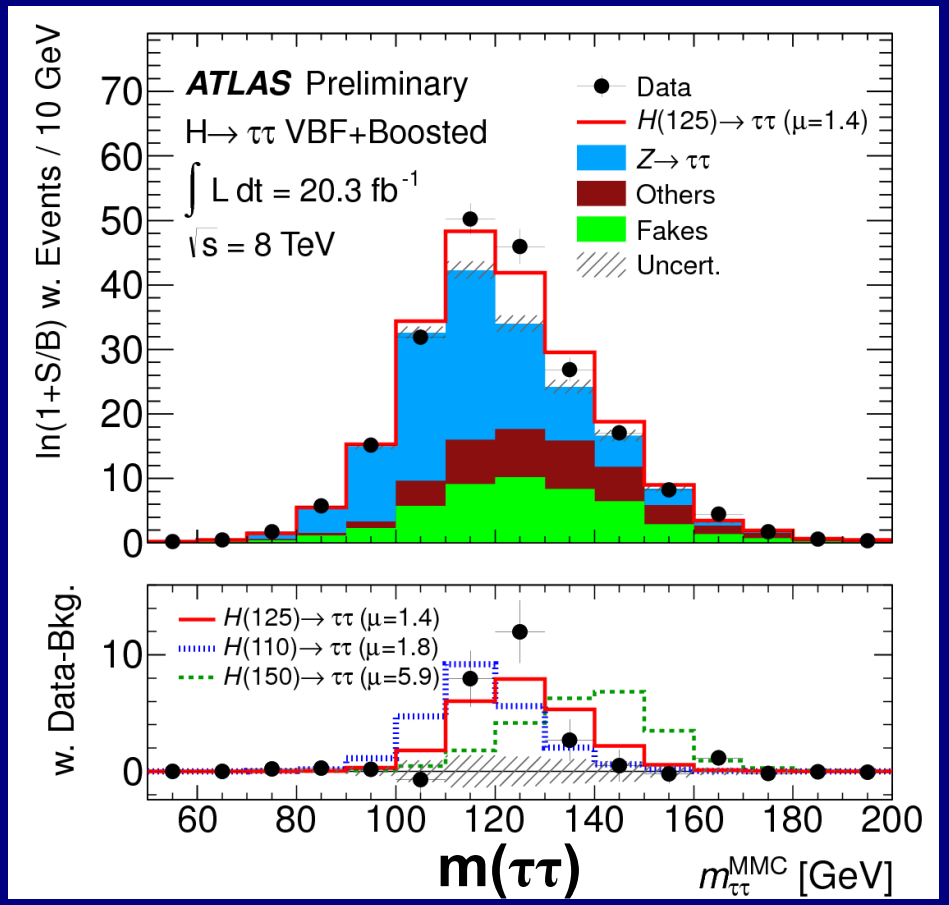
About 2.5 times more data analysed
Signals continued to strengthen
Declared "a Higgs boson" in March 2013 (no longer "Higgs-like")

Many studies of the new H(125) boson – spin-parity, production mechanisms, couplings to bosons, searches for new particles decaying into H(125), precision mass measurements, fully corrected cross-sections … …

These will continue, with substantially higher statistics, when the LHC restarts in 2015

H(125) decays to fermions



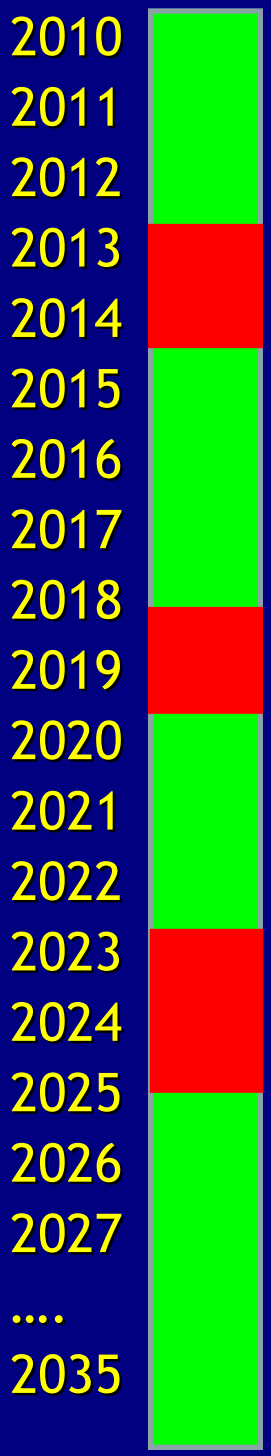


Recently established (Nov 2013)

- Original Brout-Englert-Higgs mechanism gave mass to gauge bosons
- Standard Model uses *same* scalar fields to give mass to fermions

Now established experimentally – for one fermion species so far (τ)

LHC Roadmap



Run 1: energy 7-8 TeV, 25 fb^{-1} of data

Shutdown 1: phase 0 upgrade

Run 2: energy 13+ TeV, ~120 fb^{-1} of data

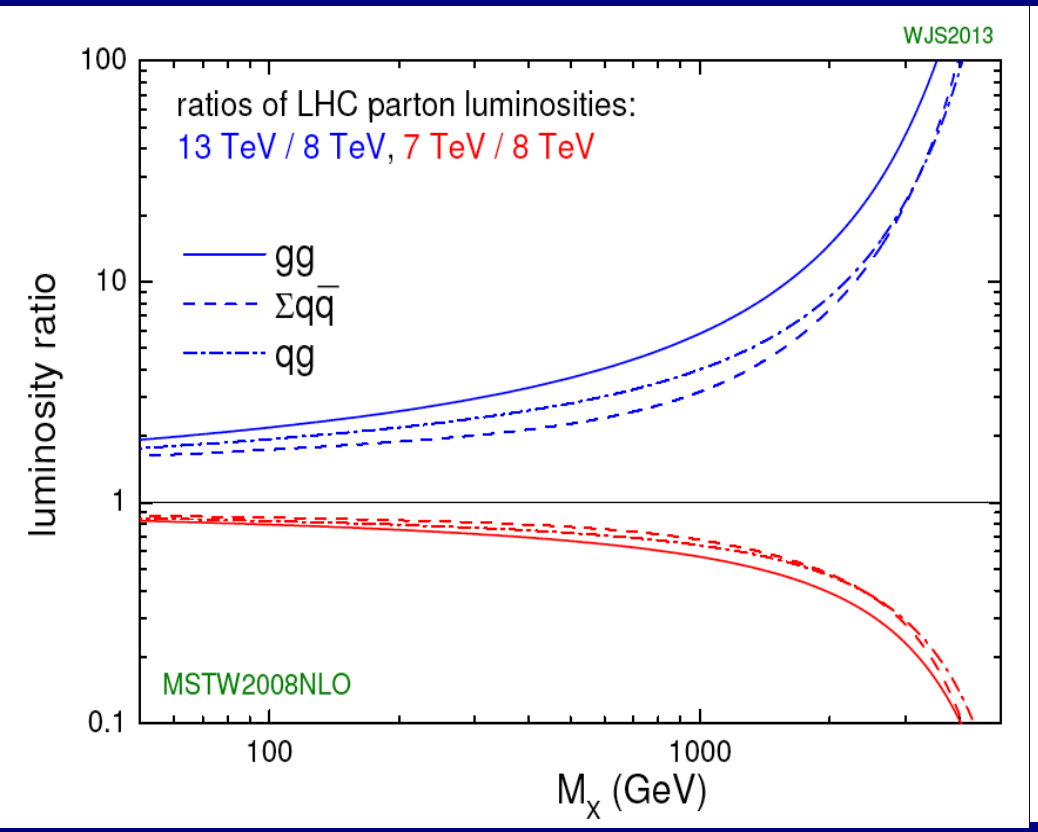
Shutdown 2: phase 1 upgrade

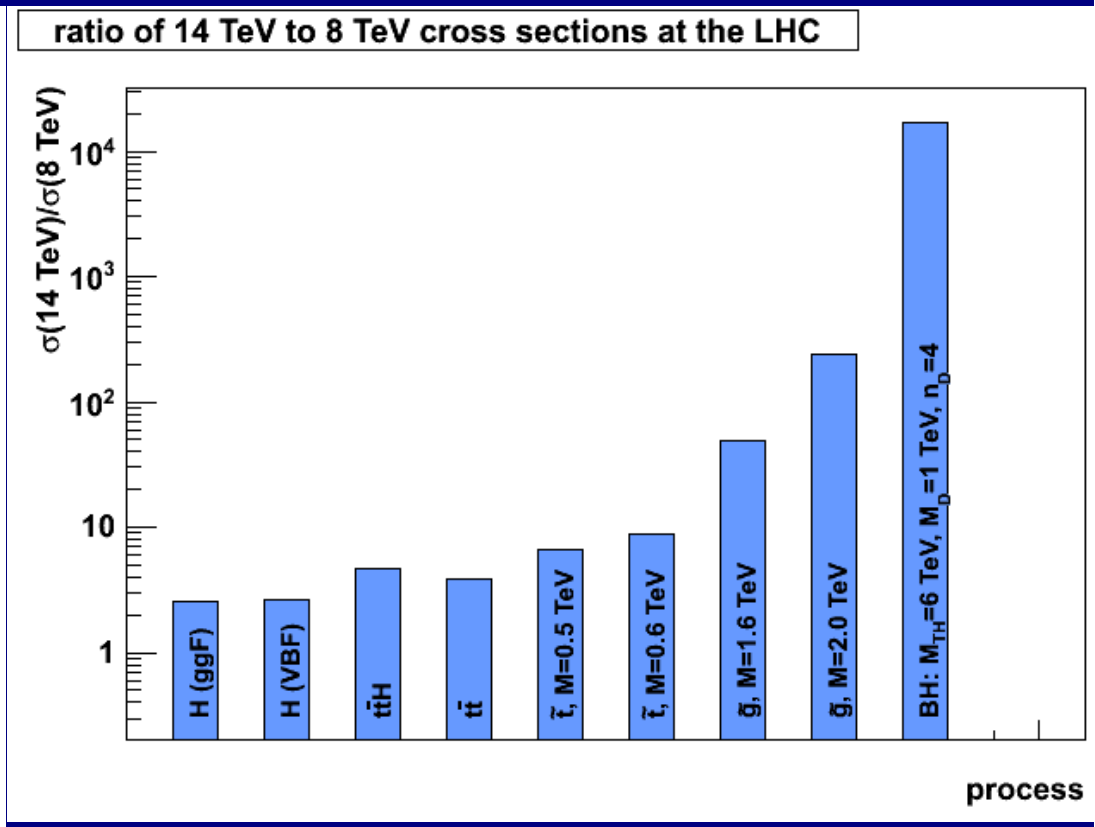
Run 3: energy 14 TeV, ~350 fb^{-1} of data

Shutdown 3: phase 2 upgrade

HL-LHC: energy 14 TeV, ~3000 fb^{-1} of data

Prospects for 2015+





Run-2 will begin in Spring 2015 and is planned to run to mid-2018

Increase in cross-sections by a factor ~10 for m(system) ~ 2 TeV

Within a few months, discovery of new TeV-scale particles is possible

Concluding Remarks

The huge LHC experiments & global collaborations pose challenges

Technically:

- Detector construction over 10 years
- Hundreds of people involved in operation
- Operation until mid 2030's

Organisationally:

- Scientific results are the responsibility of the whole collaboration
- Management based around finding common goals, and agreed procedures to find consensus
- Global scope & diverse collaboration does bring strengths

There *are* challenges (e.g.) in the sharing and recognition of work - specialisation within the experiment is essential – external parties (universities, labs, funders) must understand the need for diverse skills and expertise

The collaborations succeed in delivering fundamental science