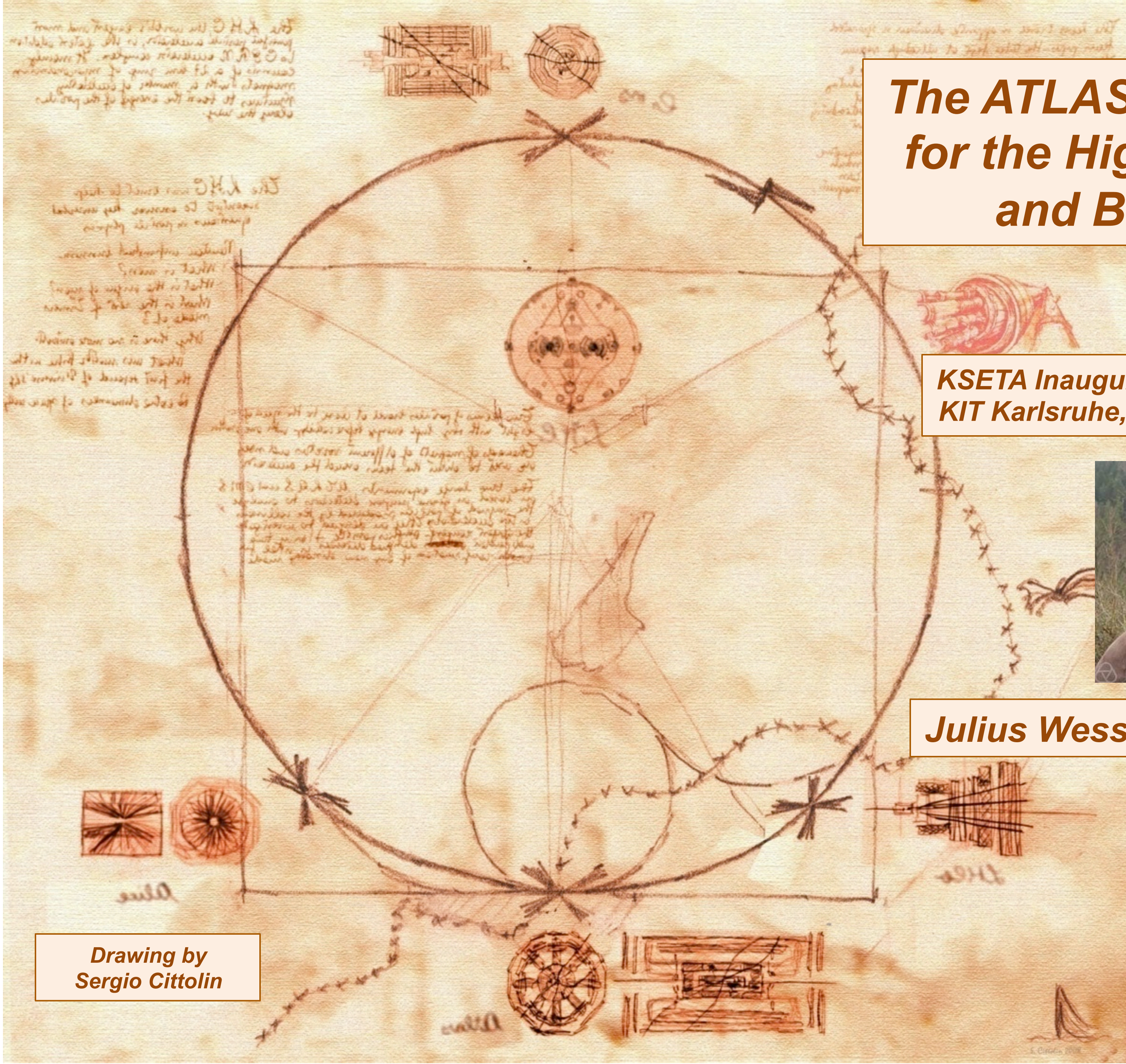
The ATLAS Road Map for the Higgs Boson and Beyond



KSETA Inauguration Symposium
KIT Karlsruhe, 1st February 2013

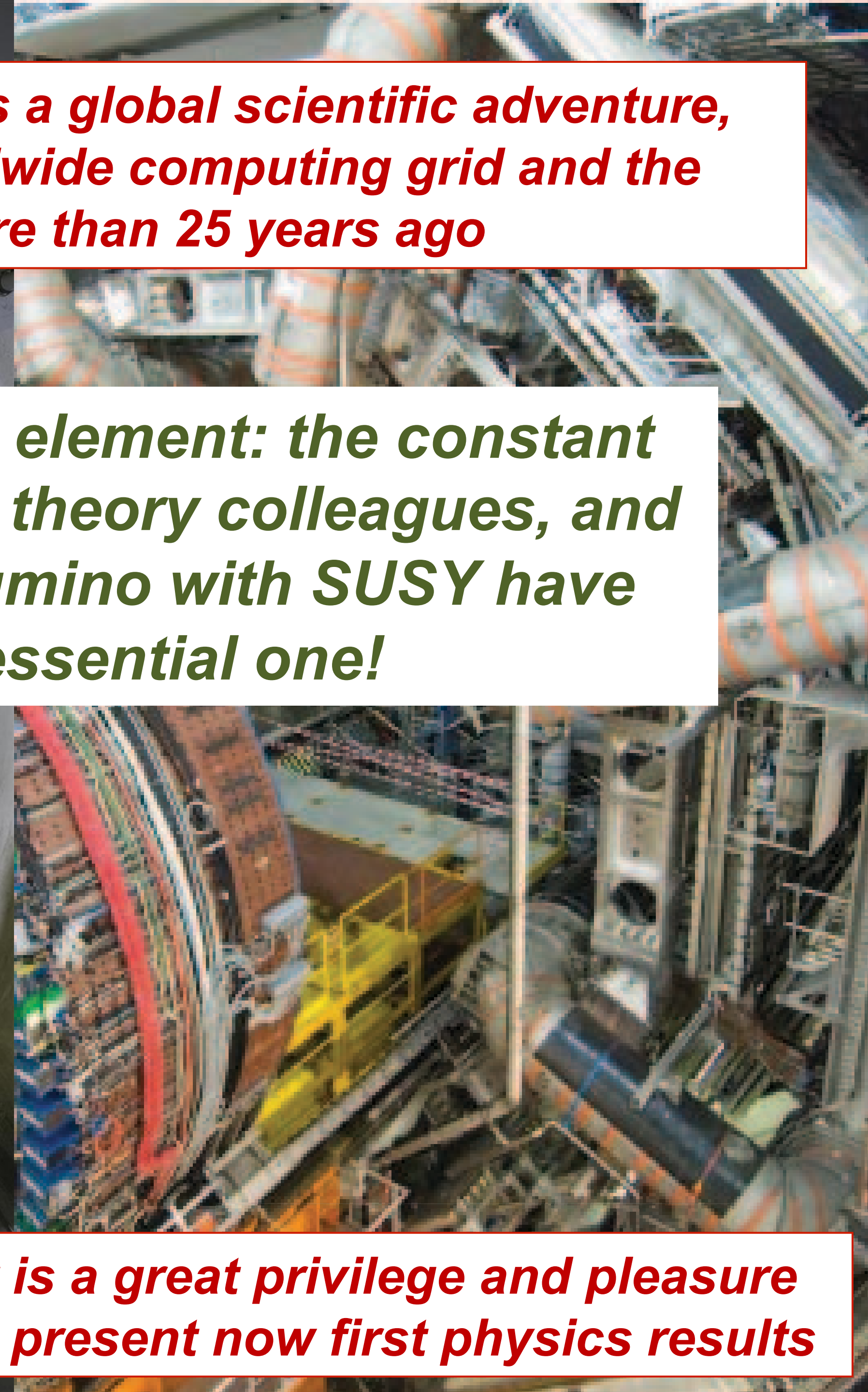
Julius Wess Award lecture

Drawing by Sergio Cittolin

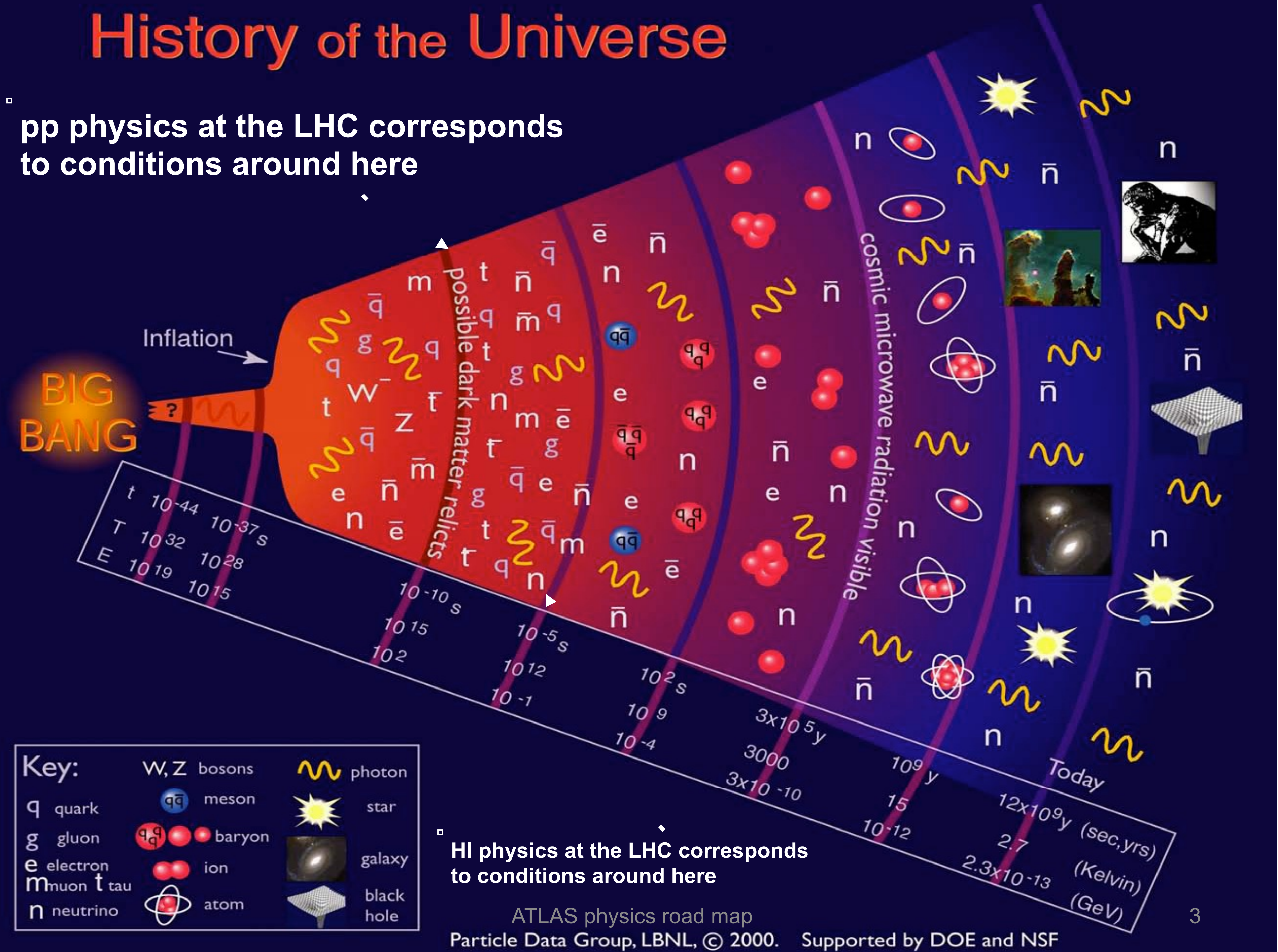
Peter Jenni, CERN

The Large Hadron Collider project is a global scientific adventure, combining the accelerator, a worldwide computing grid and the experiments, initiated more than 25 years ago

There is a fourth, essential element: the constant driving motivation from our theory colleagues, and Julius Wess and Bruno Zumino with SUSY have created such an essential one!



It is a great privilege and pleasure to present now first physics results



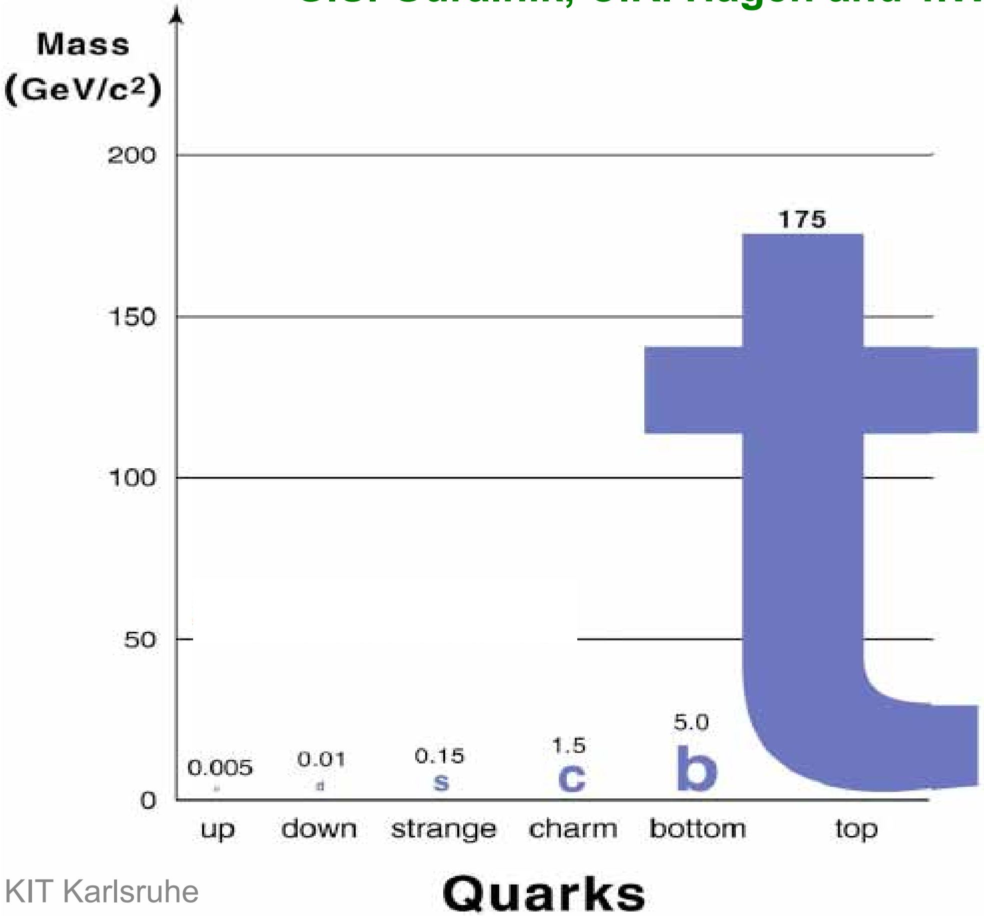
pp physics at the LHC corresponds to conditions around here

HI physics at the LHC corresponds to conditions around here

A most basic question is why particles (and matter) have masses (and so different masses)

The mass mystery could be solved with the 'EW symmetry breaking mechanism' which predicts the existence of a new elementary particle, the 'Higgs' particle
(theory 1964: R. Brout and F. Englert; P.W. Higgs;
G.S. Guralnik, C.R. Hagen and T.W.B. Kibble)

Peter Higgs



The Higgs (H) particle has been searched for since decades at accelerators …

The LHC has sufficient energy to produce it for sure, if it exists

Francois Englert

Supersymmetry (SUSY)

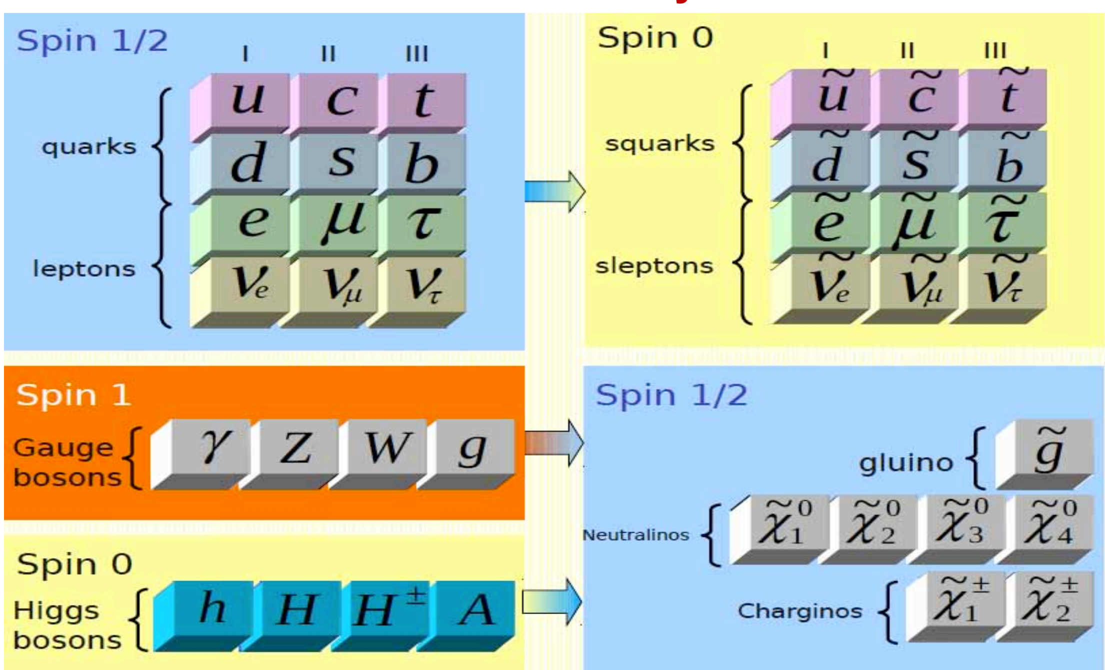
(Julius Wess and Bruno Zumino, 1974)

Establishes a symmetry between fermions (matter) and bosons (forces):

- Each particle p with spin s has a SUSY partner $\tilde{p}$ with spin s -1/2

- Examples q (s=1/2) → $\tilde{q}$ (s=0) squark
  g (s=1) → $\tilde{g}$ (s=1/2) gluino

Our known world… Maybe a new world?



Motivation:

- *Unification (fermions-bosons, matter-forces)*
- *Solves some deep problems of the Standard Model*

How the LHC came to be …

(see a nice article by Chris Llewellyn Smith in Nature 448, p281)

Some early key dates

1977 **The community talked about the LEP project, and it was already mentioned that a new tunnel could also house a hadron collider in the far future**

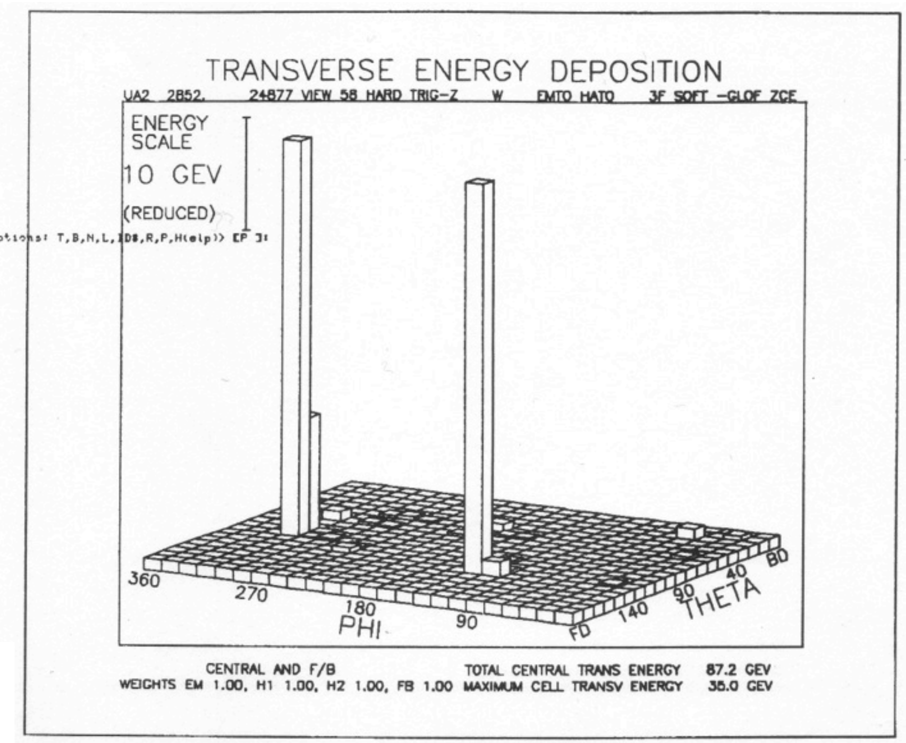
1981 **LEP was approved with a large and long (27 km) tunnel**

1983 **The early 1980s were crucial:**

The real belief that a 'dirty' hadron collider can actually do great discovery physics came from UA1 and UA2 with their W and Z boson discoveries at CERN

This also triggered a famous quote from a 1983 New York Times editorial:

'Europe: 3 - US Not Even Z-Zero'



A very early Z → ee online display from one of the detectors (UA2)

Spokesperson Fabiola Gianotti, celebrating 20 years of ATLAS on 1st October 2012

ATLAS and CMS were born with Letters of Intent (LoI), submitted on 1st October 1992, 20 years ago

1991 December CERN Council:
'LHC is the right machine for advance of the subject and the future of CERN' (thanks to the great push by DG C Rubbia)

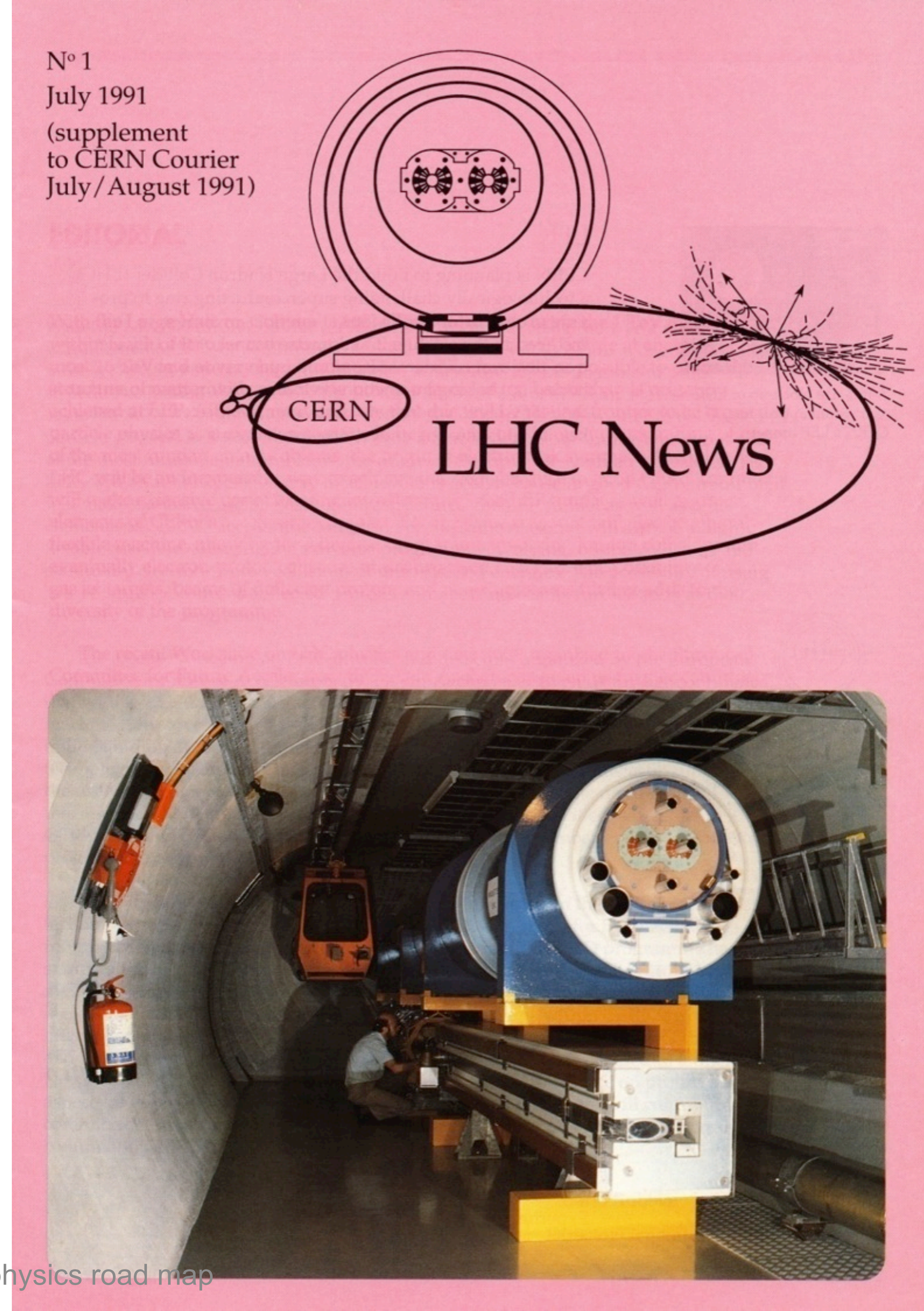
1993 December proposal of LHC with commissioning in 2002

1994 June Council:

Construction was formally proposed by DG Chris Llewellyn Smith, but few countries could not yet agree, so the Council session vote was suspended until

16 December 1994 Council:

(Two-stage) construction of LHC was approved



The two-stage approval of LHC was understood to be modified in case sufficient CERN non-member state contributions would become available

A lot of LHC campaigns and negotiations took place in the years 1995 - 1997, including also the experiments

Japan, Russia, India, Canada and the USA were agreeing in that phase to contribute to the LHC

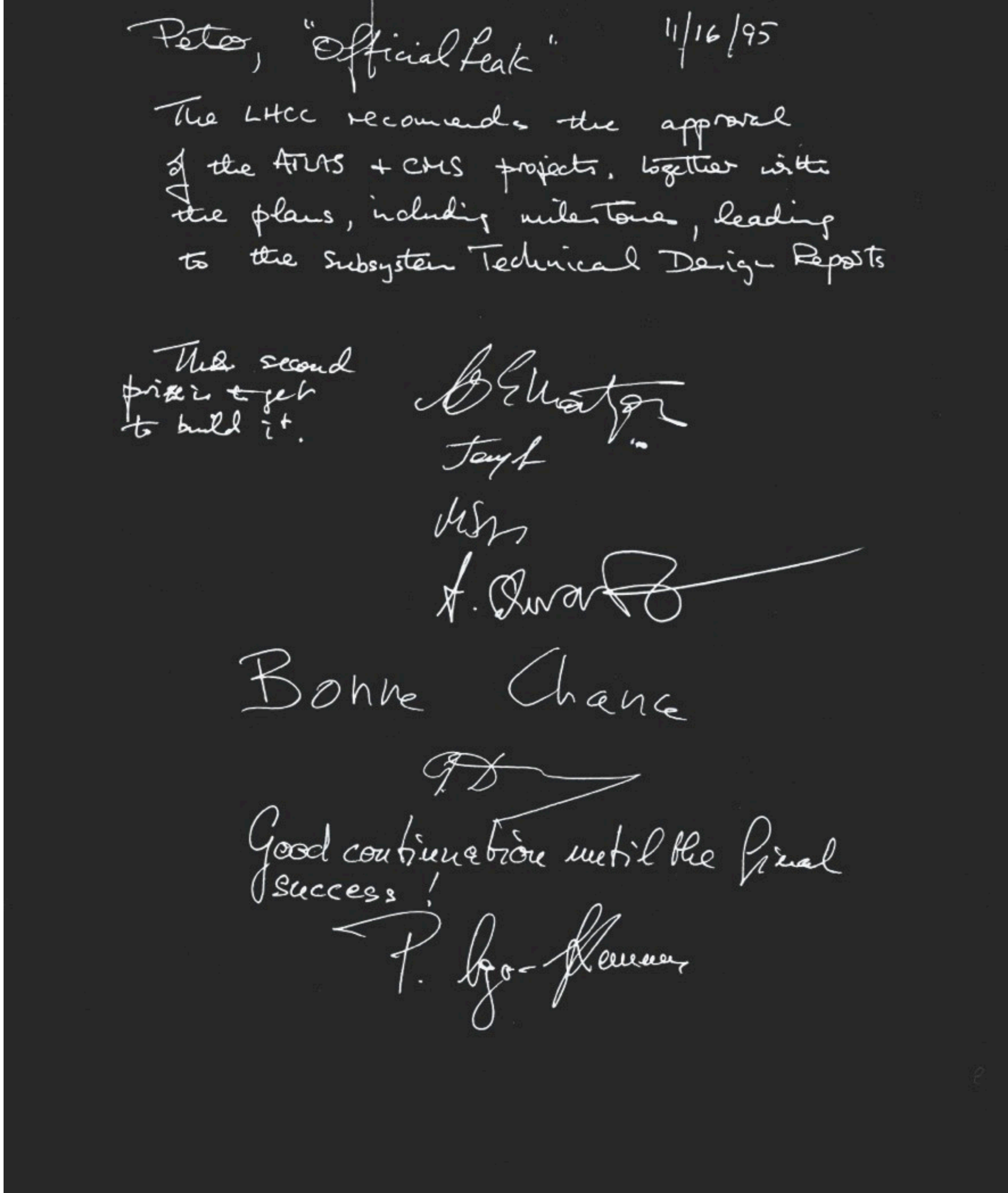
(Israel contributed all along to the full CERN programme and LHC)

1996

December Council approved finally the single-stage 14 TeV LHC for completion in 2005

Delivery of the last dipole for the LHC injection lines from Russia (15th June 2001), with DG L Maiani and A Skrinsky in the centre

For the experiments it was a long way convincing the LHCC, but finally, on 16th November 1995, our referees were happy, and Hugh Montgomery, ATLAS main referee at that time, gave us the following 'official leak' from the committee…


Peter, "Official Leak" 11/16/95

The LHCC recommends the approval of the ATLAS + CMS projects, together with the plans, including milestones, leading to the Subsystem Technical Design Reports

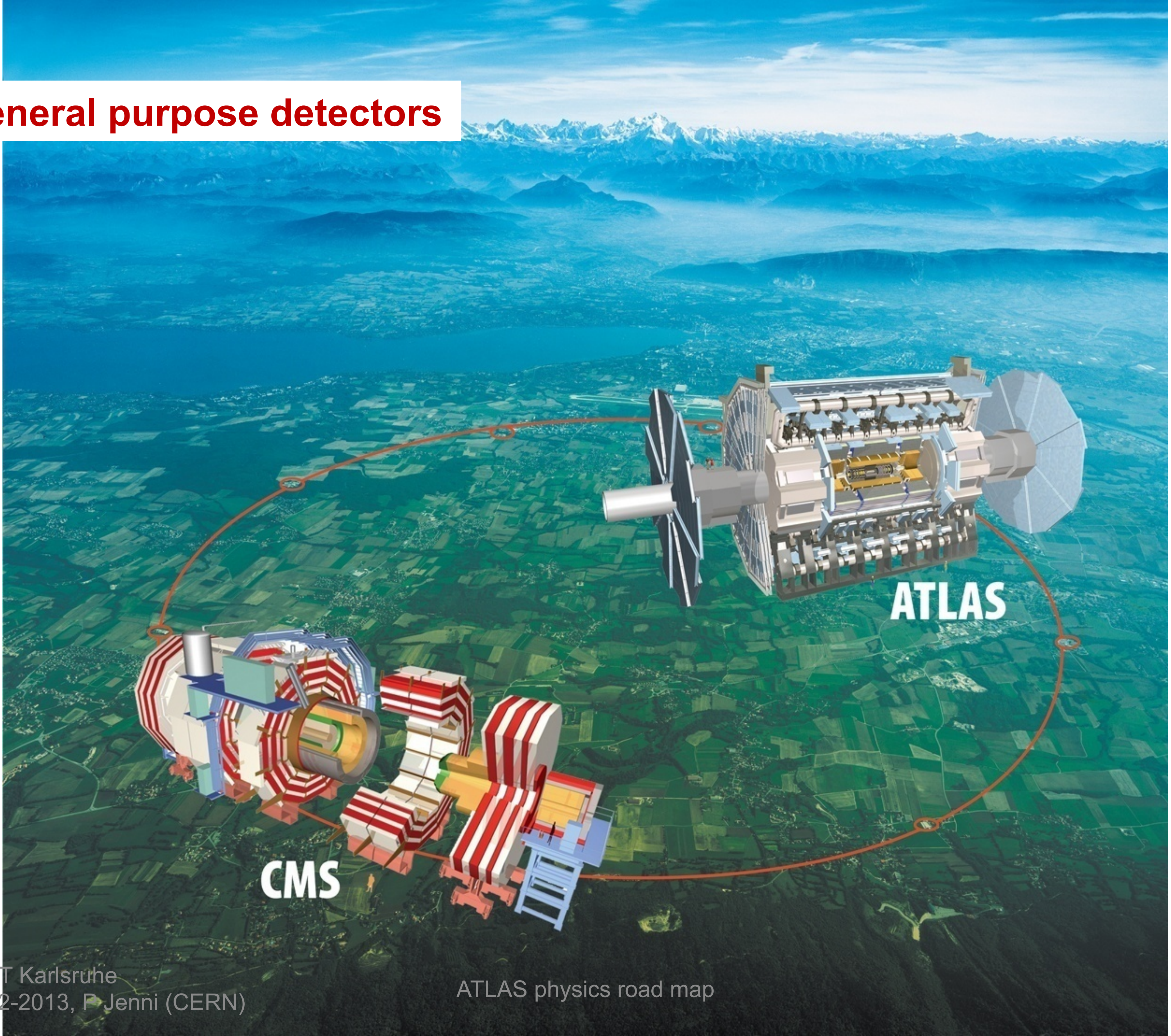
The second prize is to get to build it.

Bonne Chance

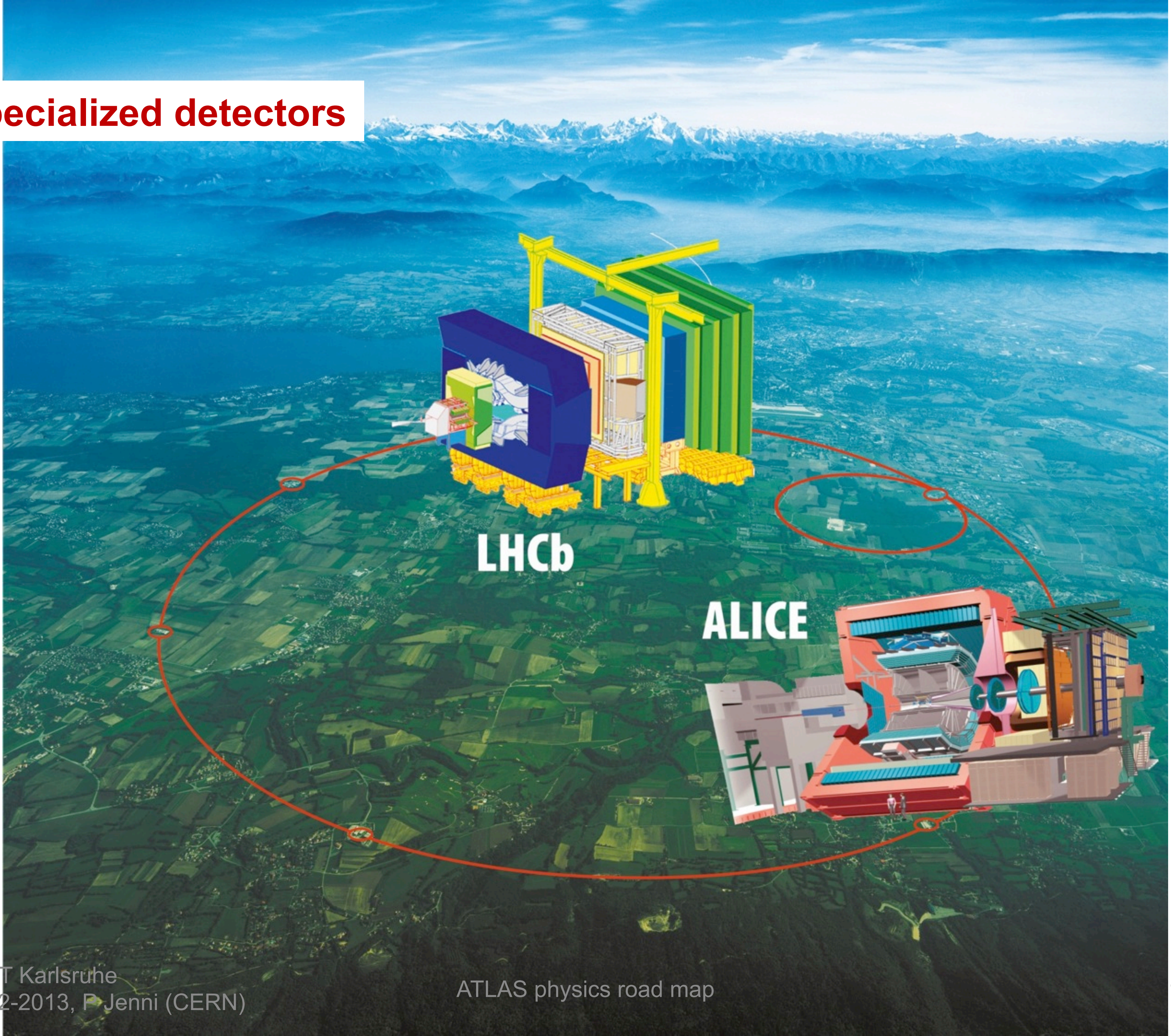
Good continuation until the final success!

The LHCC recommendations meant in particular that ATLAS and CMS could now proceed in developing their series of Technical Design Reports

General purpose detectors



Specialized detectors



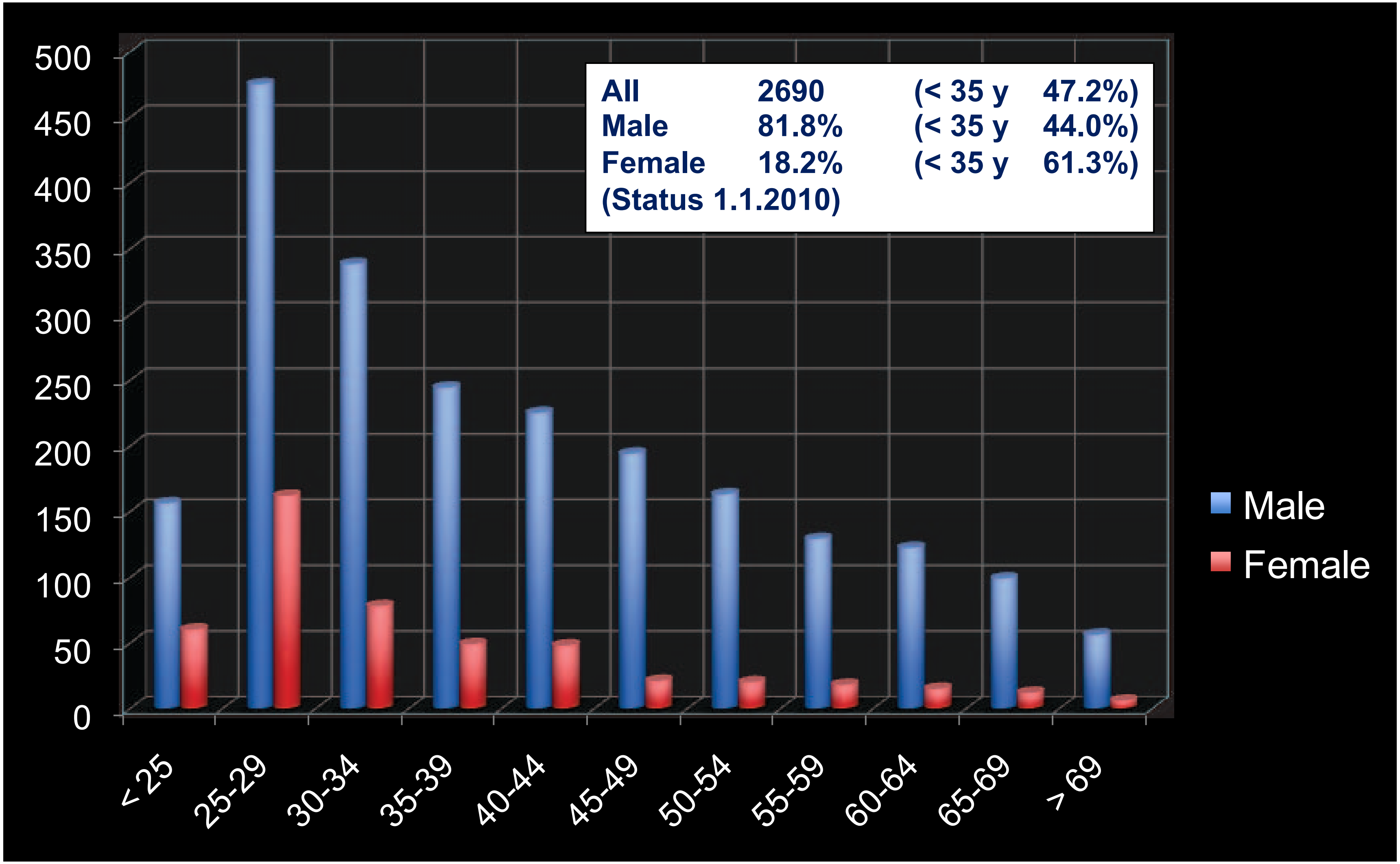
ATLAS Collaboration

38 Countries
176 Institutions
3000 Scientific participants total
(1000 Students)

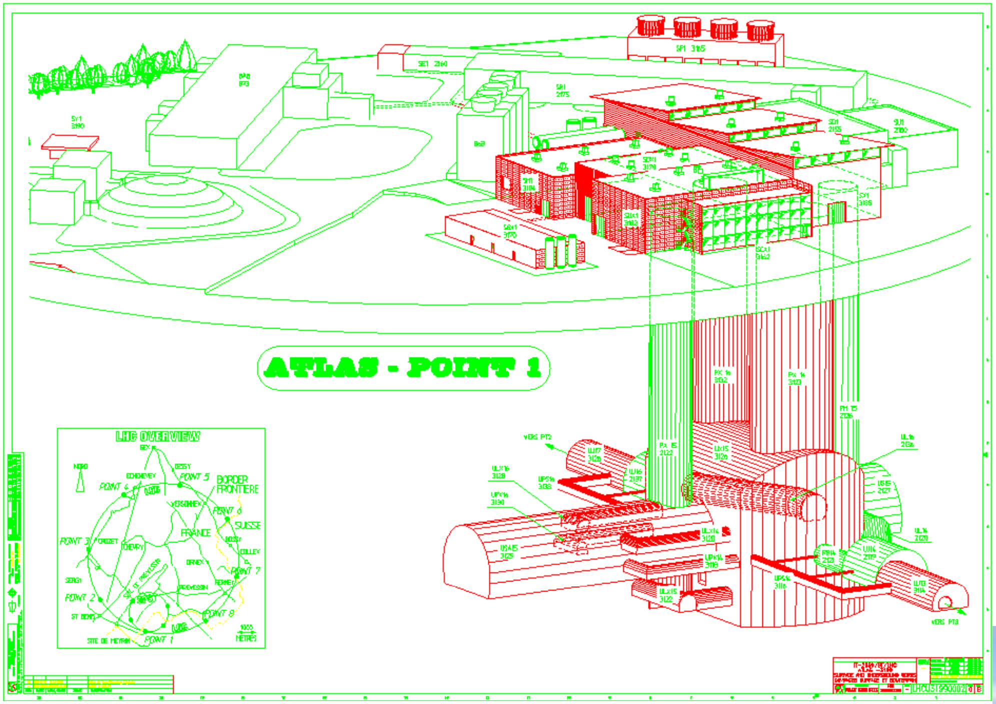
It is a pleasure to collaborate with 425 colleagues, senior and junior, from 13 Universities, DESY and MPI Munich from Germany

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, Brasil Cluster, Bratislava/SAS Kosice, 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, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, 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, LMU Munich, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, NPI Petersburg, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa, 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

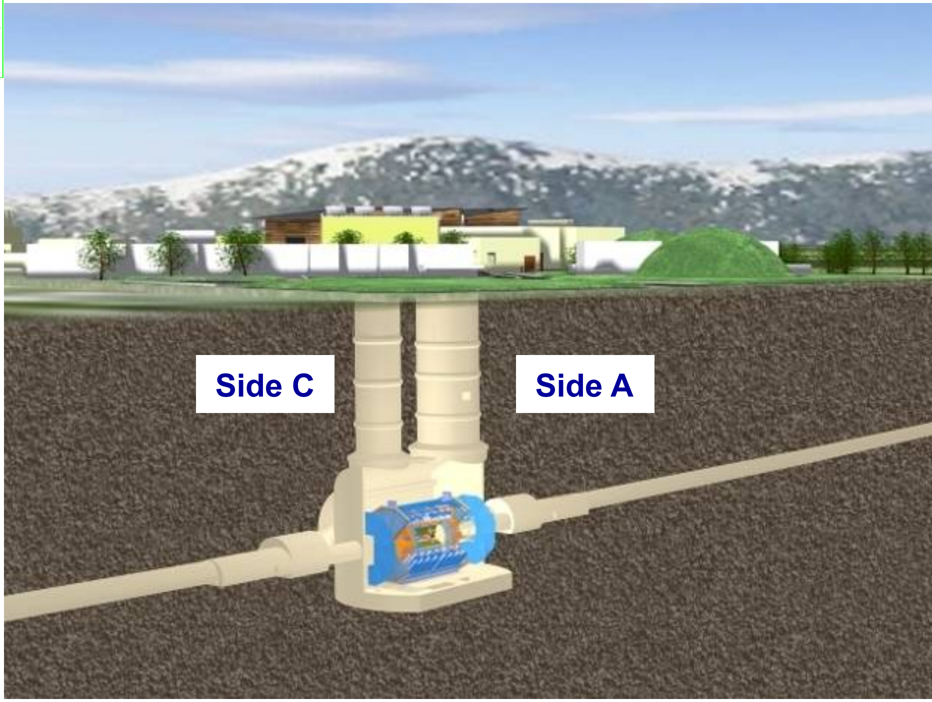
Age distribution of the ATLAS population

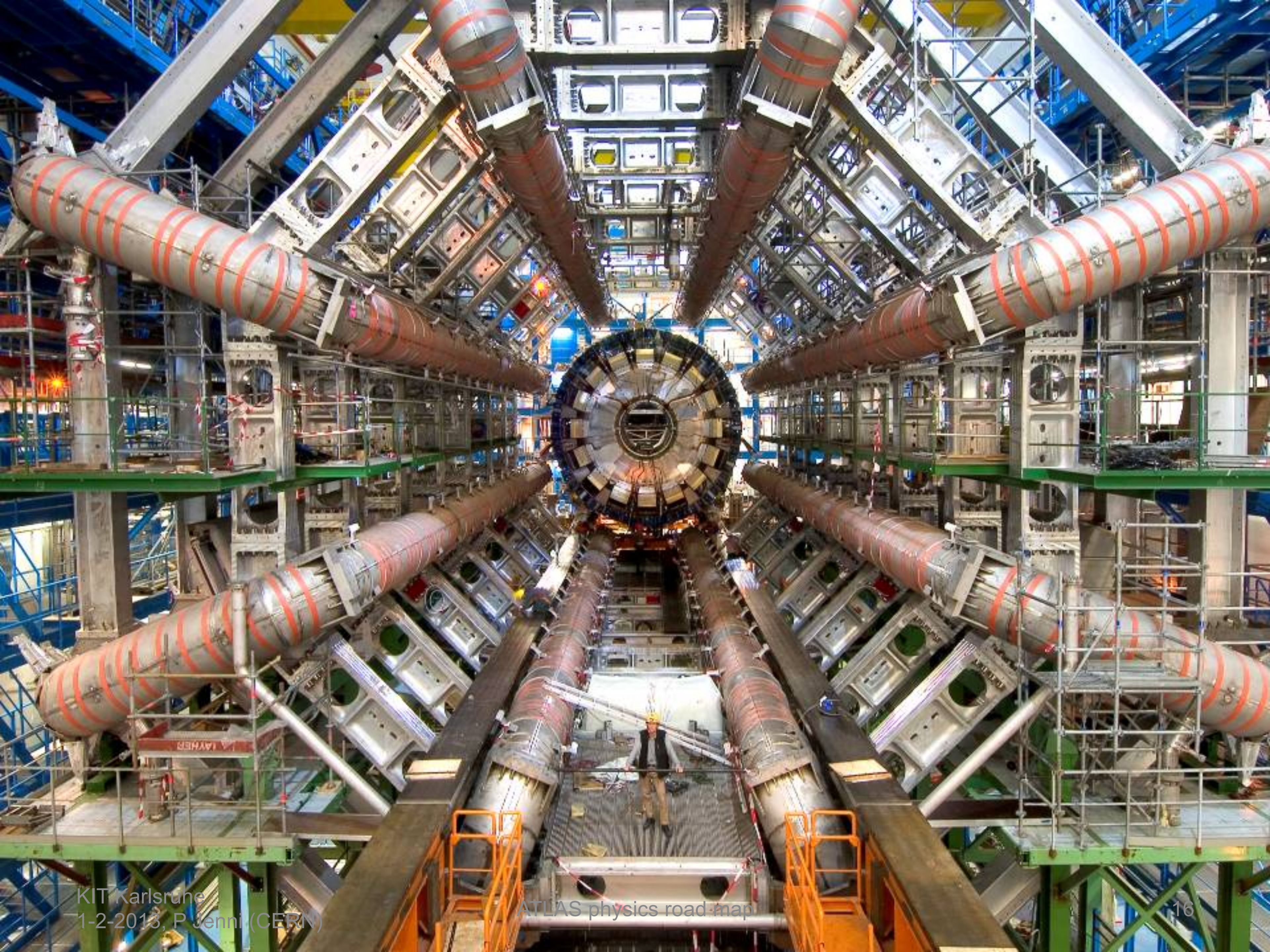


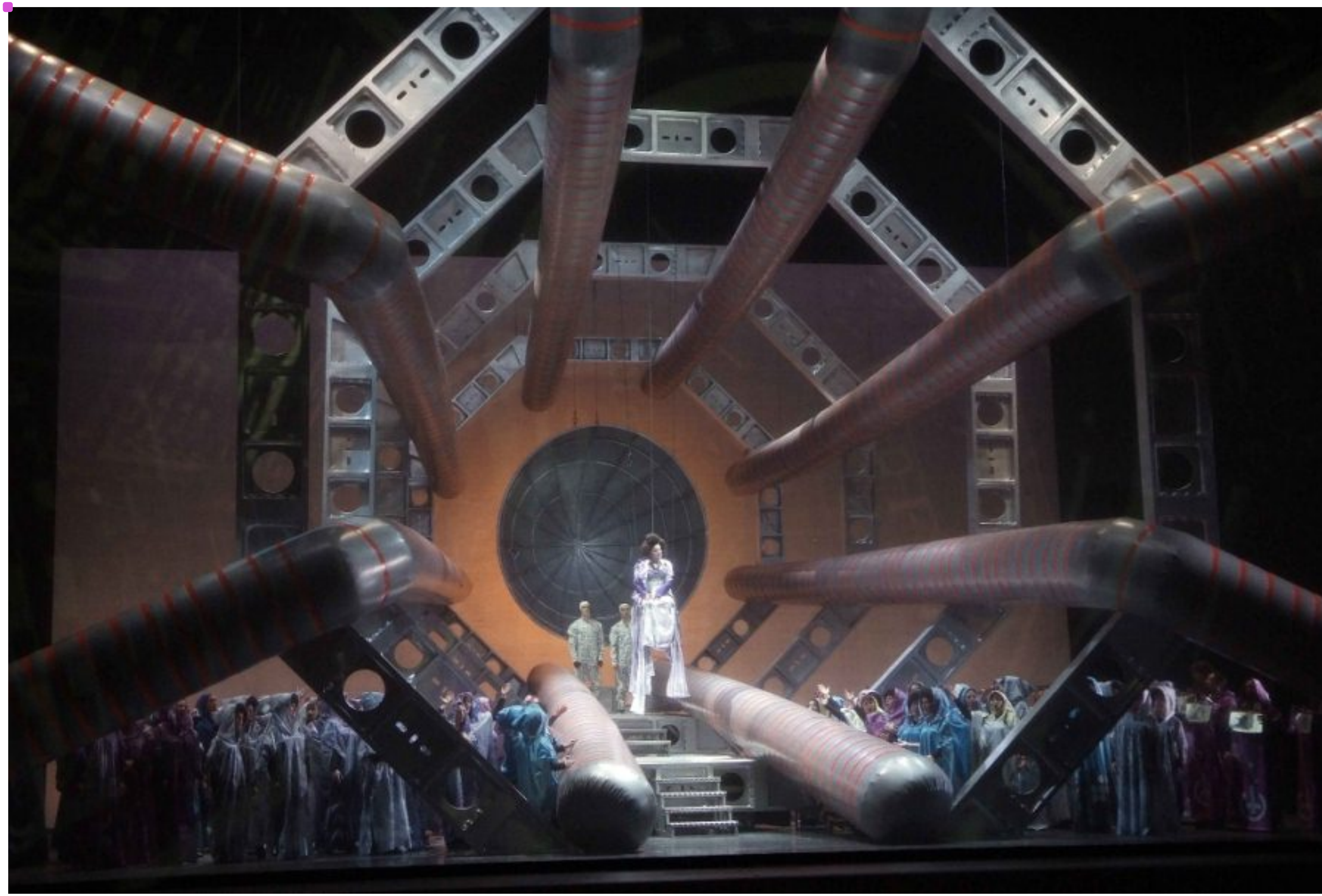
The Underground Cavern at Point-1 for the ATLAS Detector



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

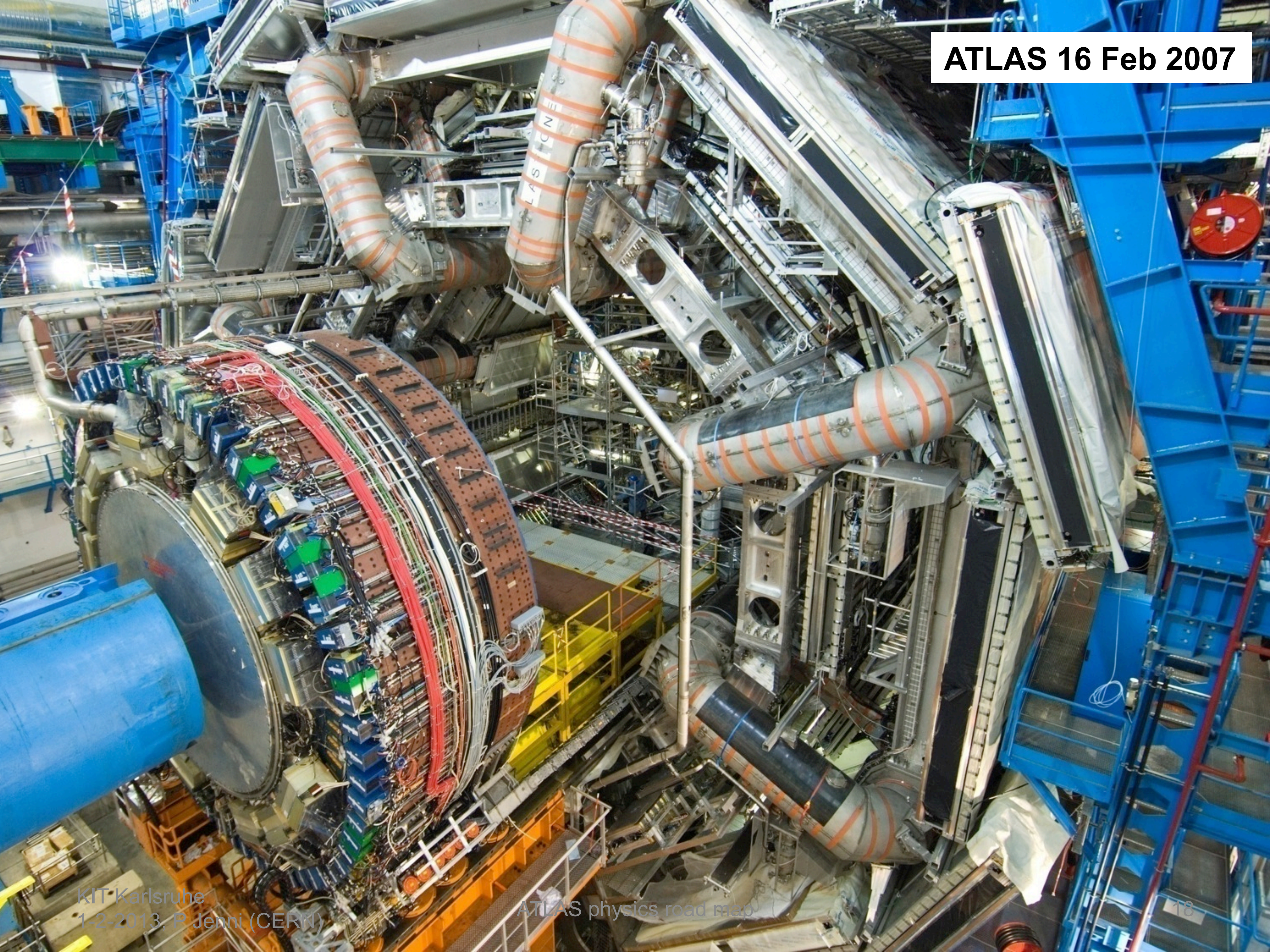






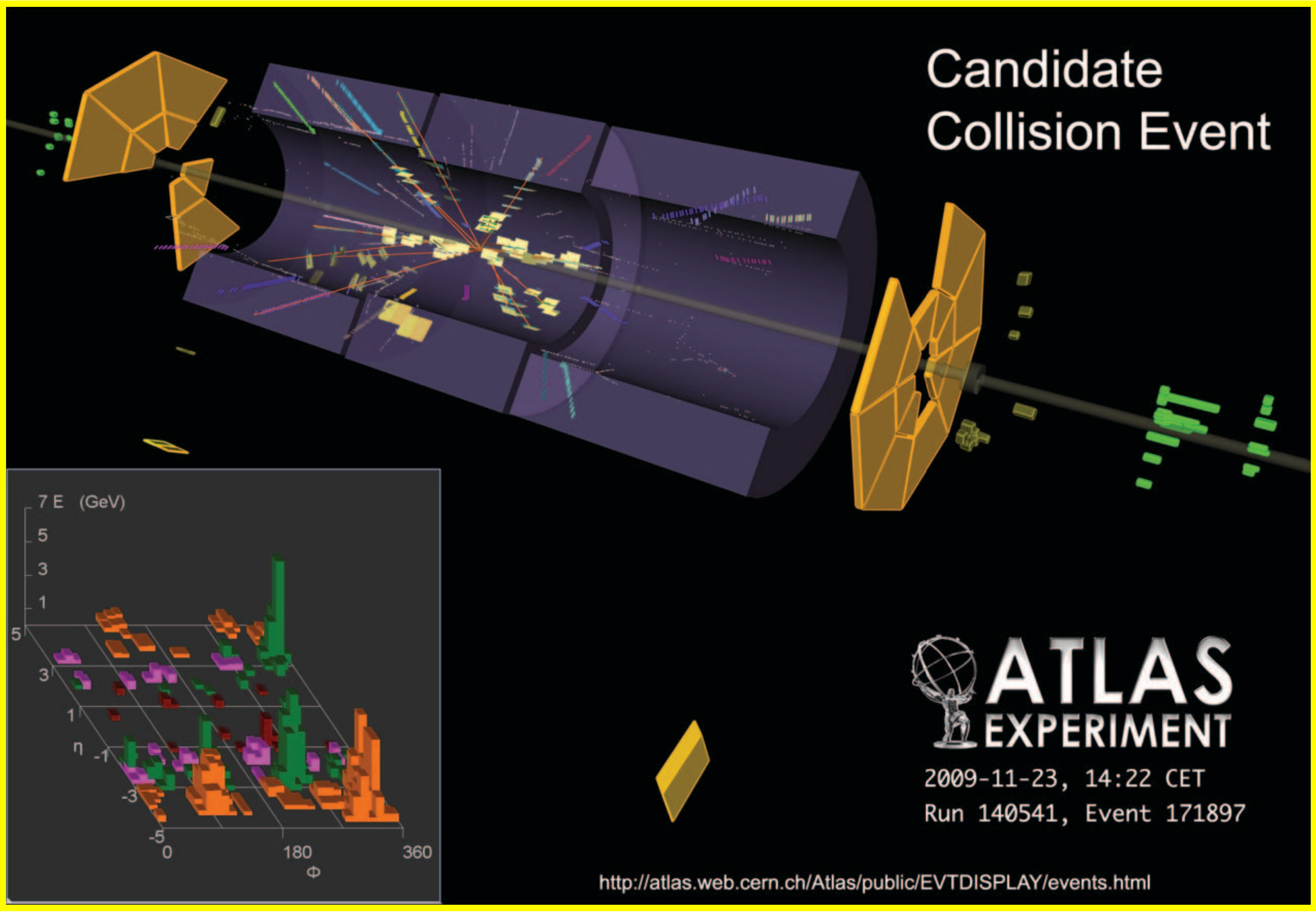
Hector Berlioz, “Les Troyens”, opera in five acts
Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009

ATLAS 16 Feb 2007



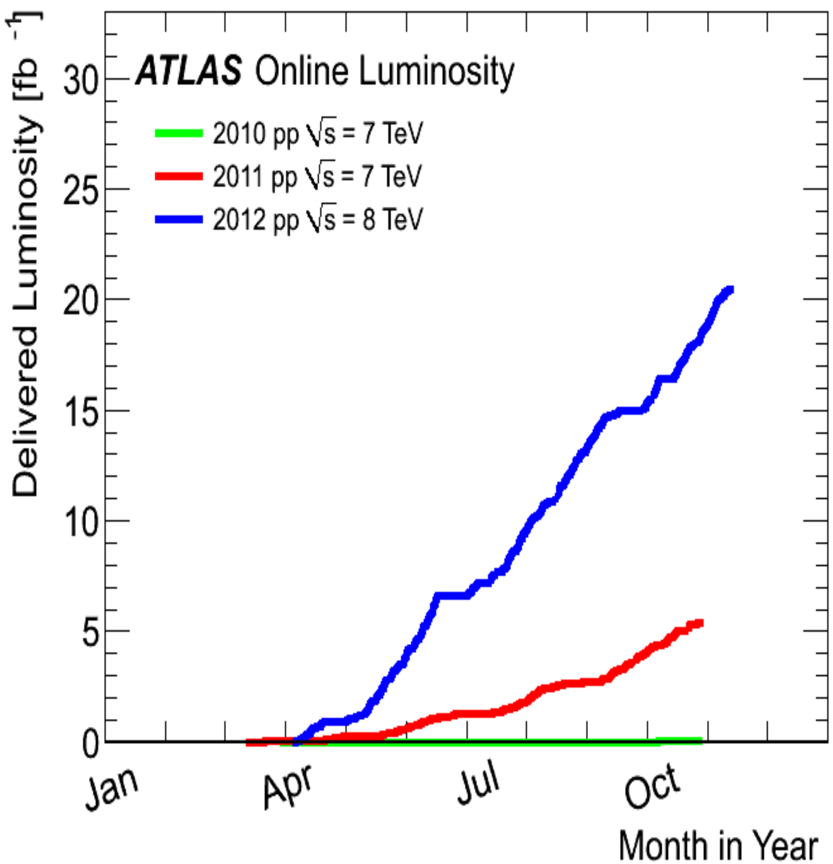
The joy in the ATLAS Control Room when the first LHC beam collided on November 23rd, 2009....

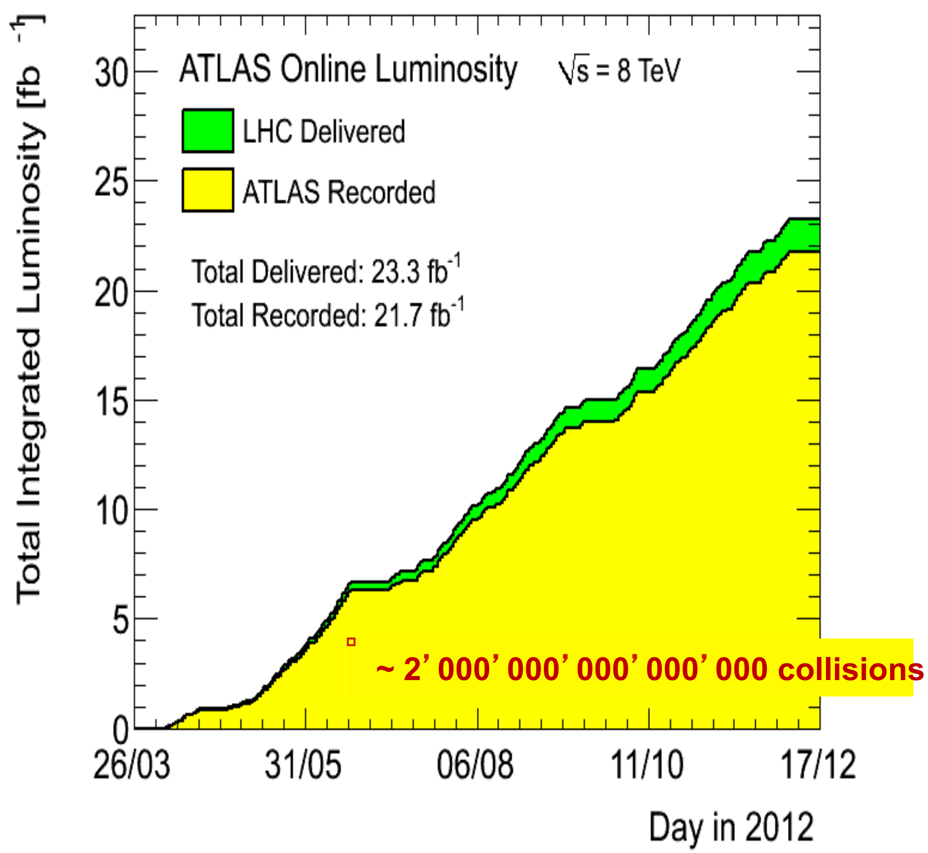
First collisions at the LHC end of November 2009 with beams at the injection energy of 450 GeV



Total integrated luminosity

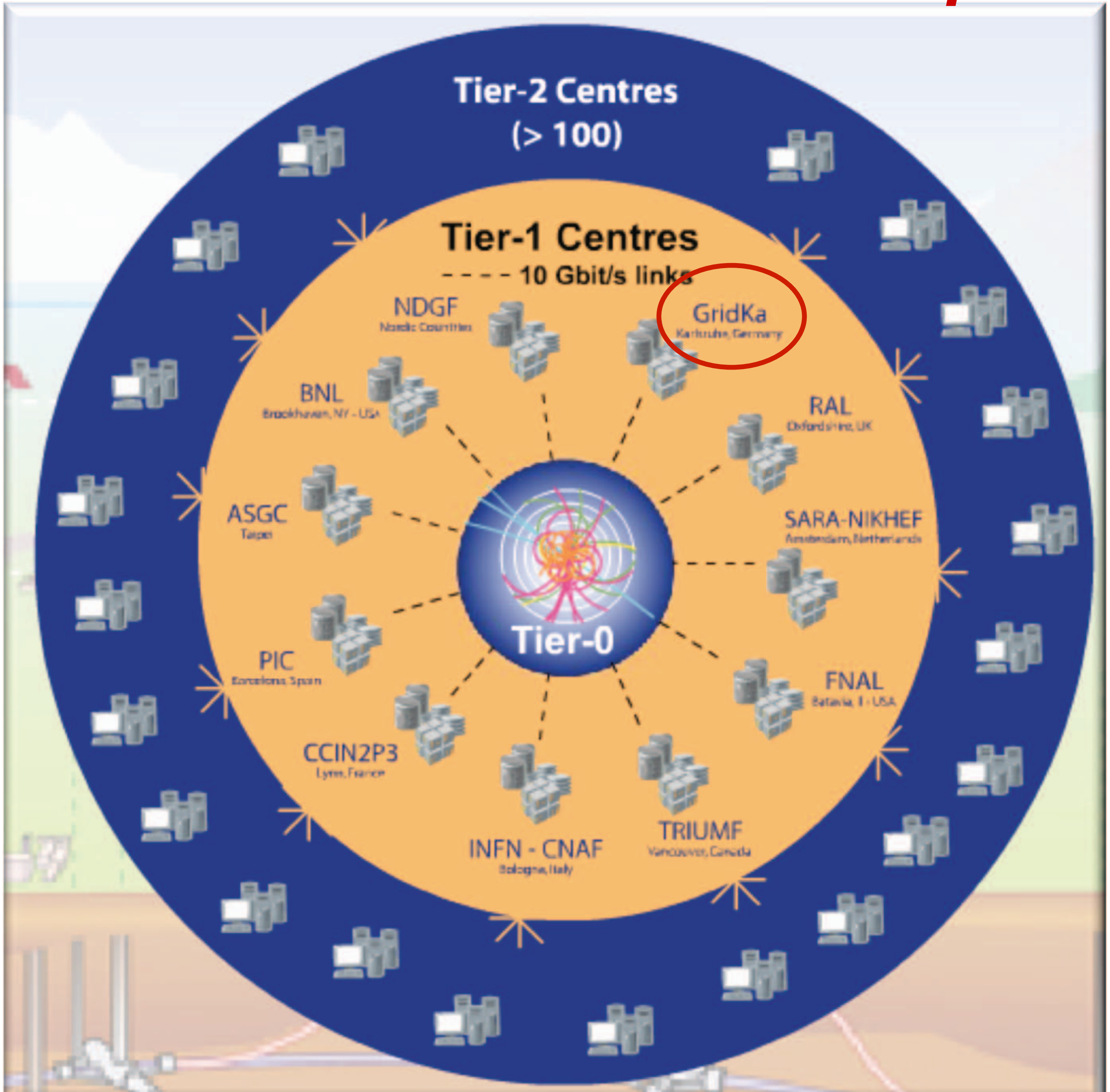
$N_{events} = \sigma \int L\, dt$





The experiment records typically 94% of the stably delivered luminosity, and uses up to 90% of the LHC luminosity in the final analyses!

The Worldwide LHC Computing Grid (wLCG)



Tier-0 (CERN):
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (12 centres):
- Permanent storage
- Re-processing
- Analysis
- Simulation

Tier-2 (68 federations of >100 centres):
- Simulation
- End-user analysis

Physics Highlights:

General event properties

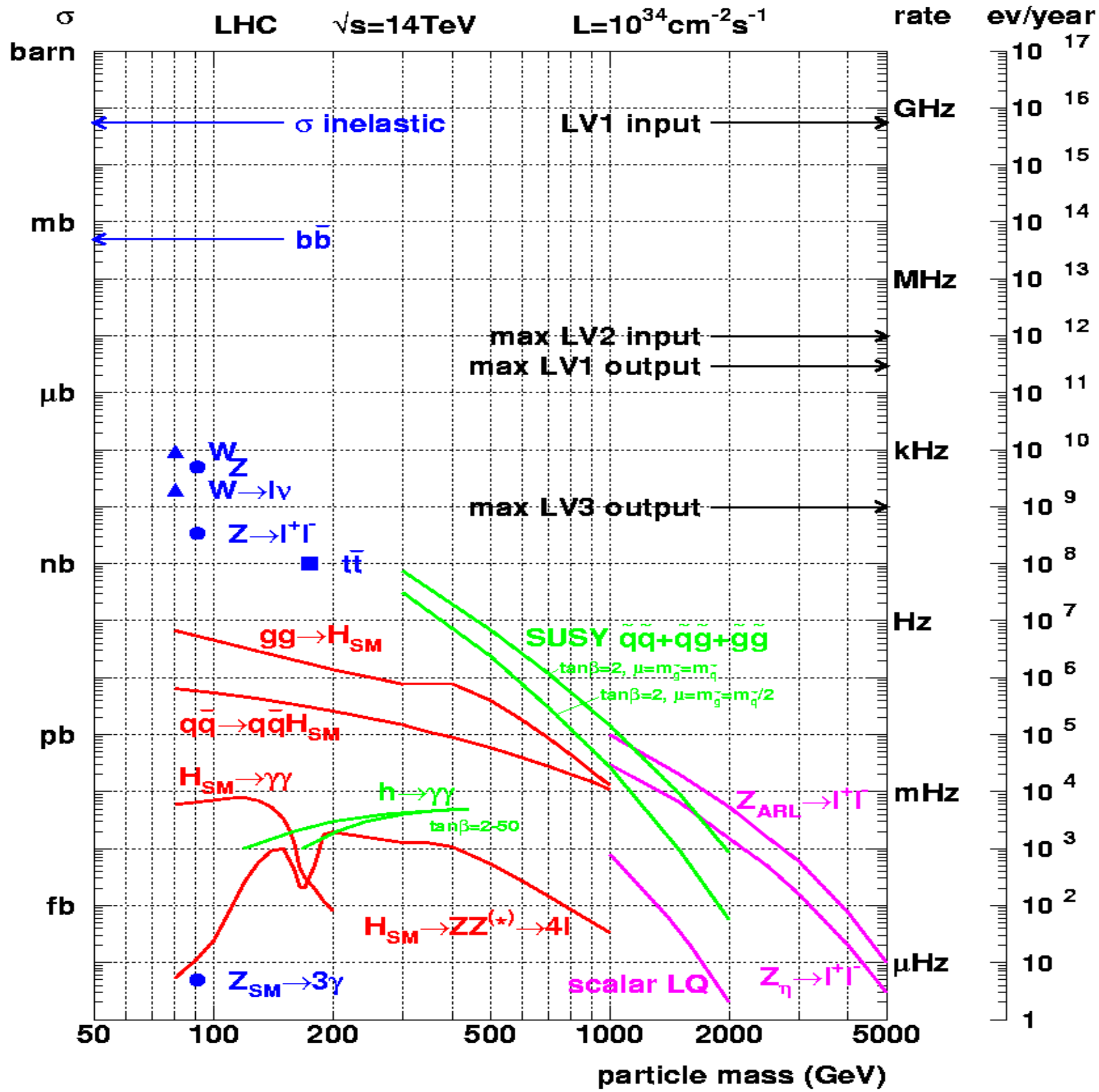
Heavy flavour physics

Standard Model physics including QCD jets

Higgs searches

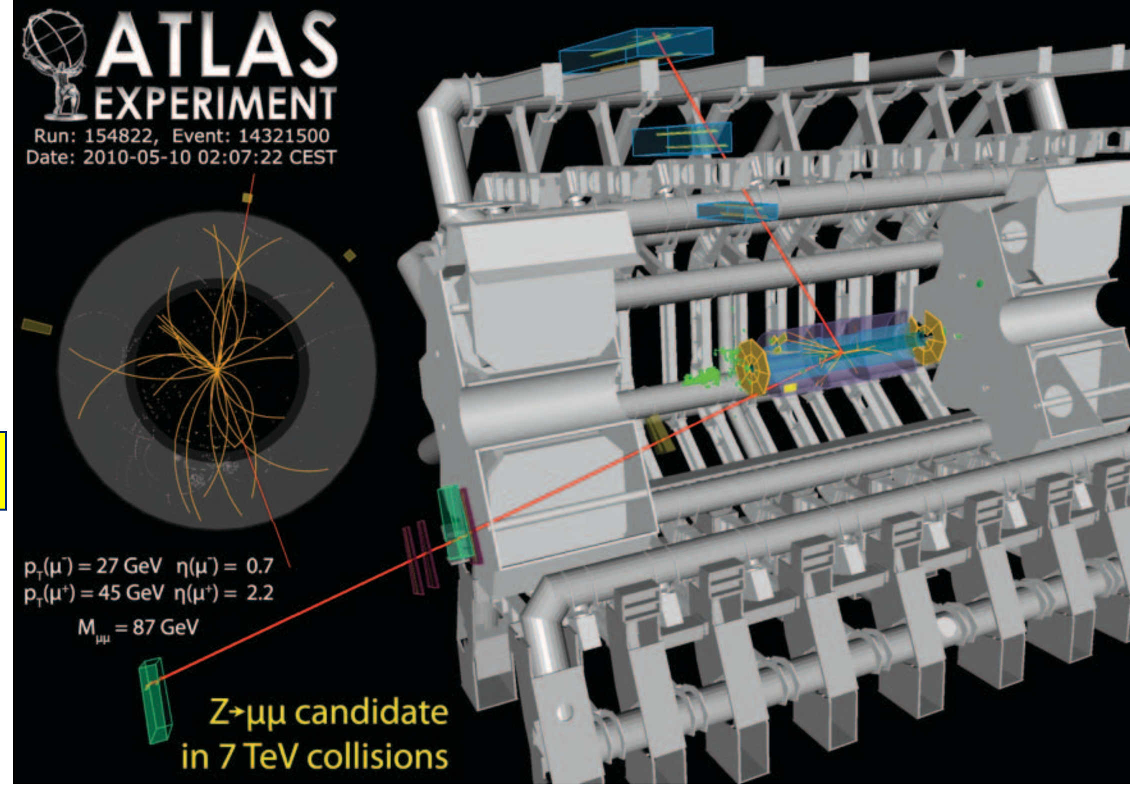
Searches for SUSY

Examples of searches for 'exotic' new physics

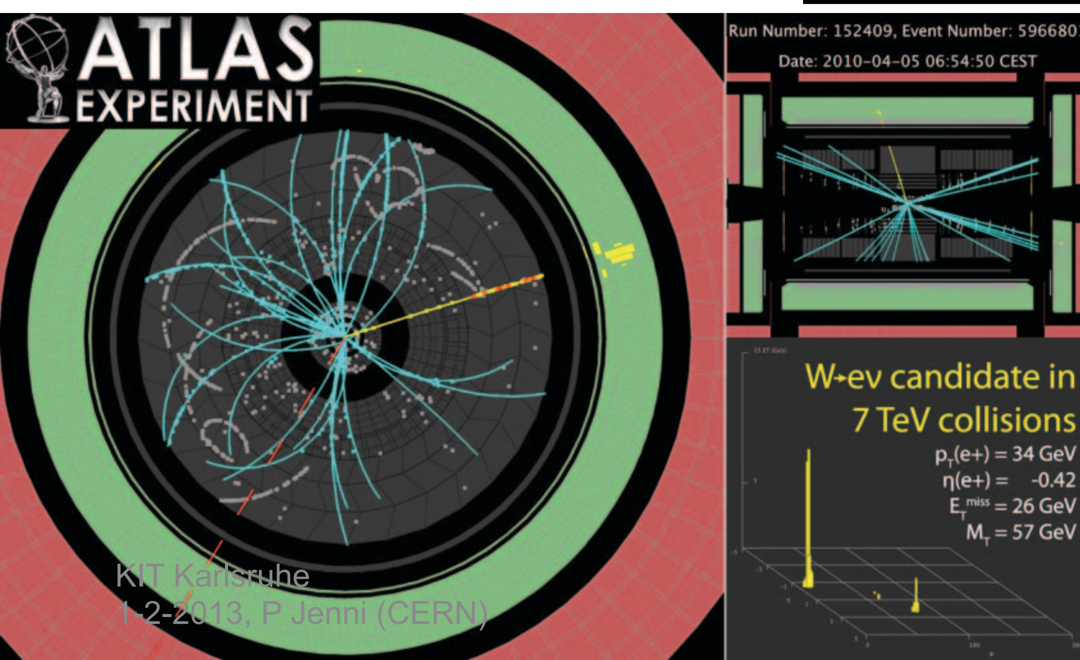


Standard Model Physics

Candidate Z → $\mu^+\mu^-$



W → eν candidate



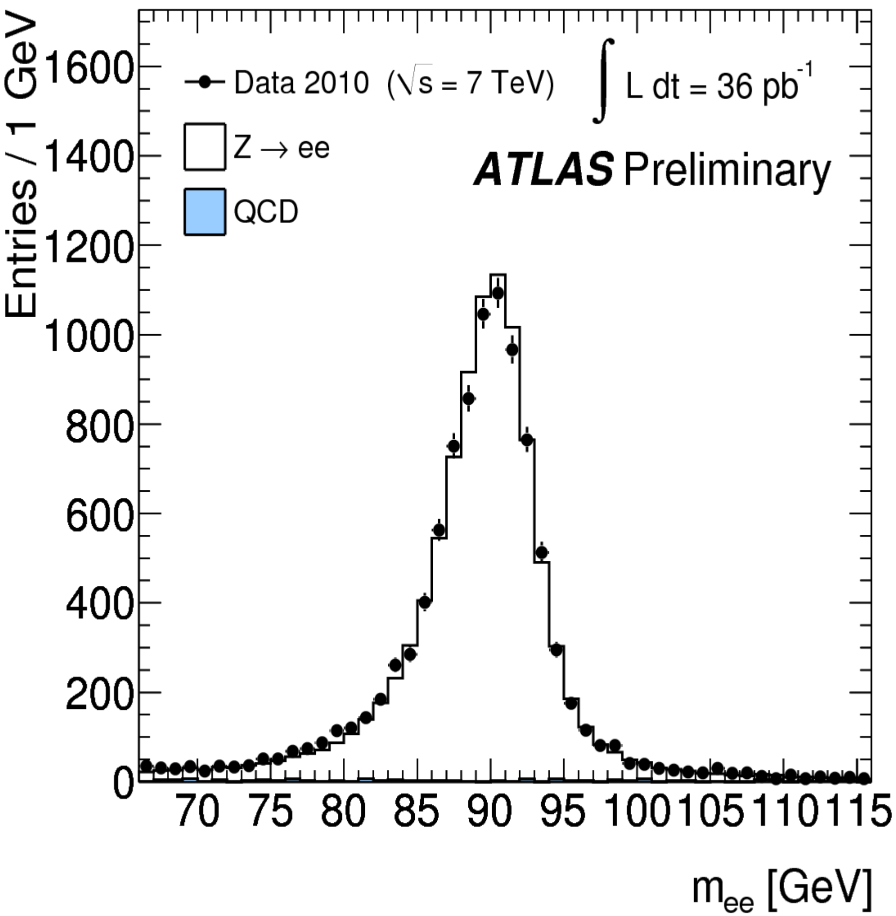
Today ATLAS has in the data more than:

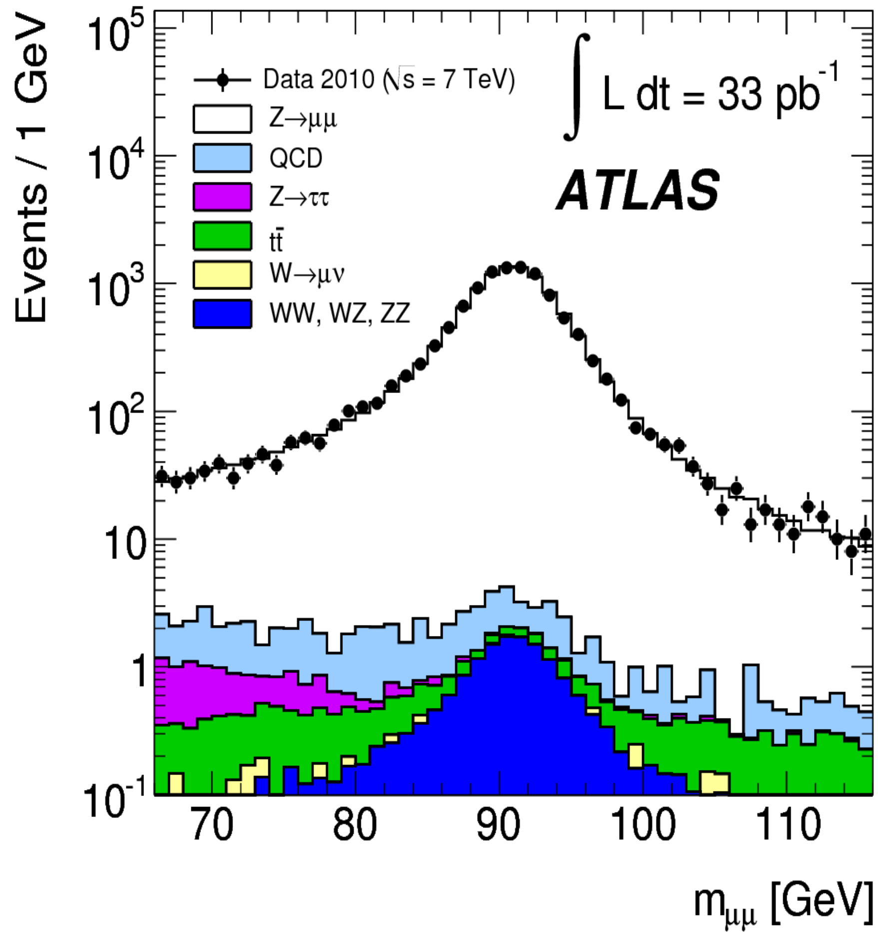
100 M W→ μν, eν events
10 M Z → μμ, ee events

after all selection cuts

Z and W production

Phys Rev D85 (2012) 072004

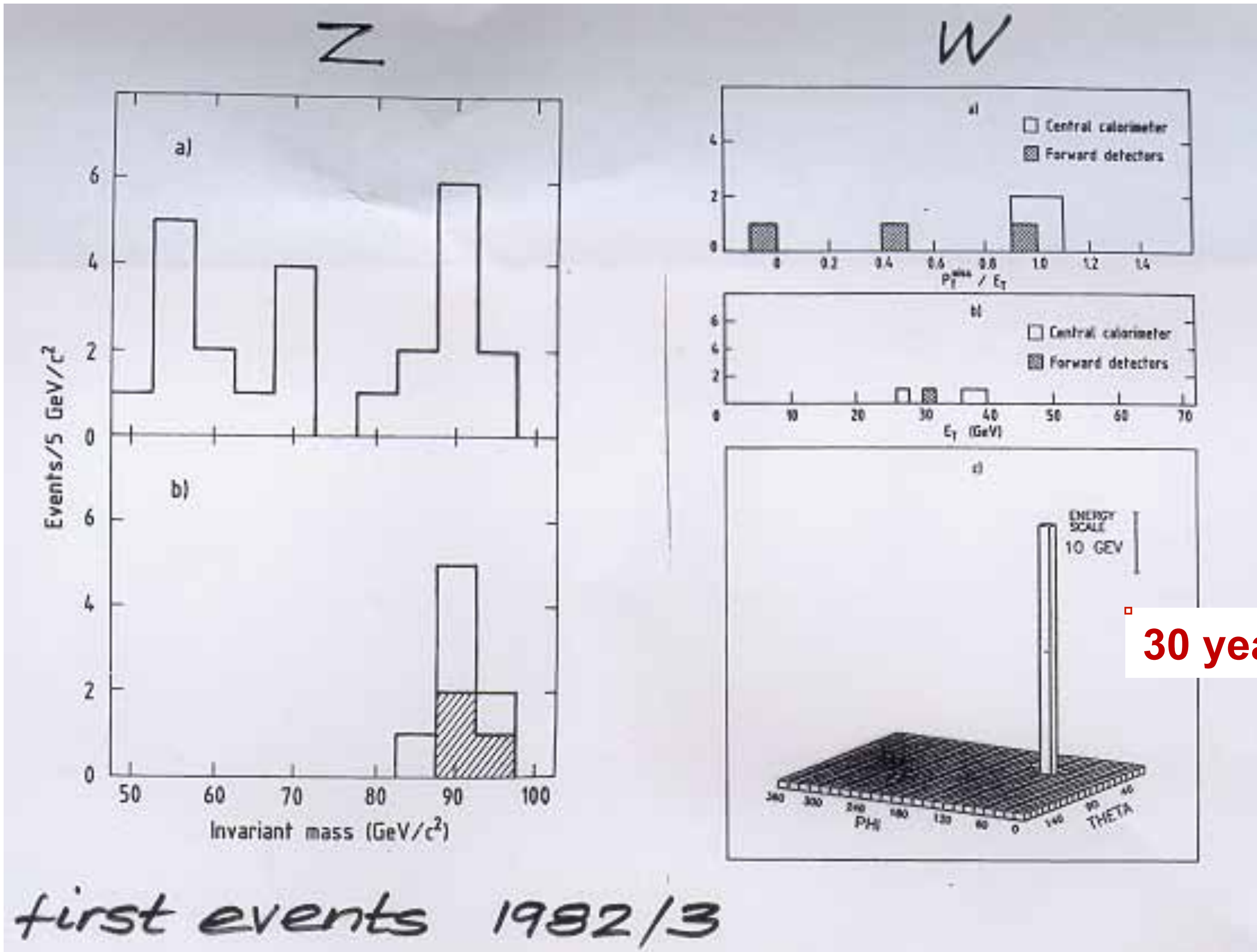




Z peak (di-lepton pair mass distributions, can be extracted essentially background-free)

$$\boxed{m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}}$$

What a contrast to the Intermediate Vector Boson discovery distributions in 1982 and 1983 by UA1 and UA2 …

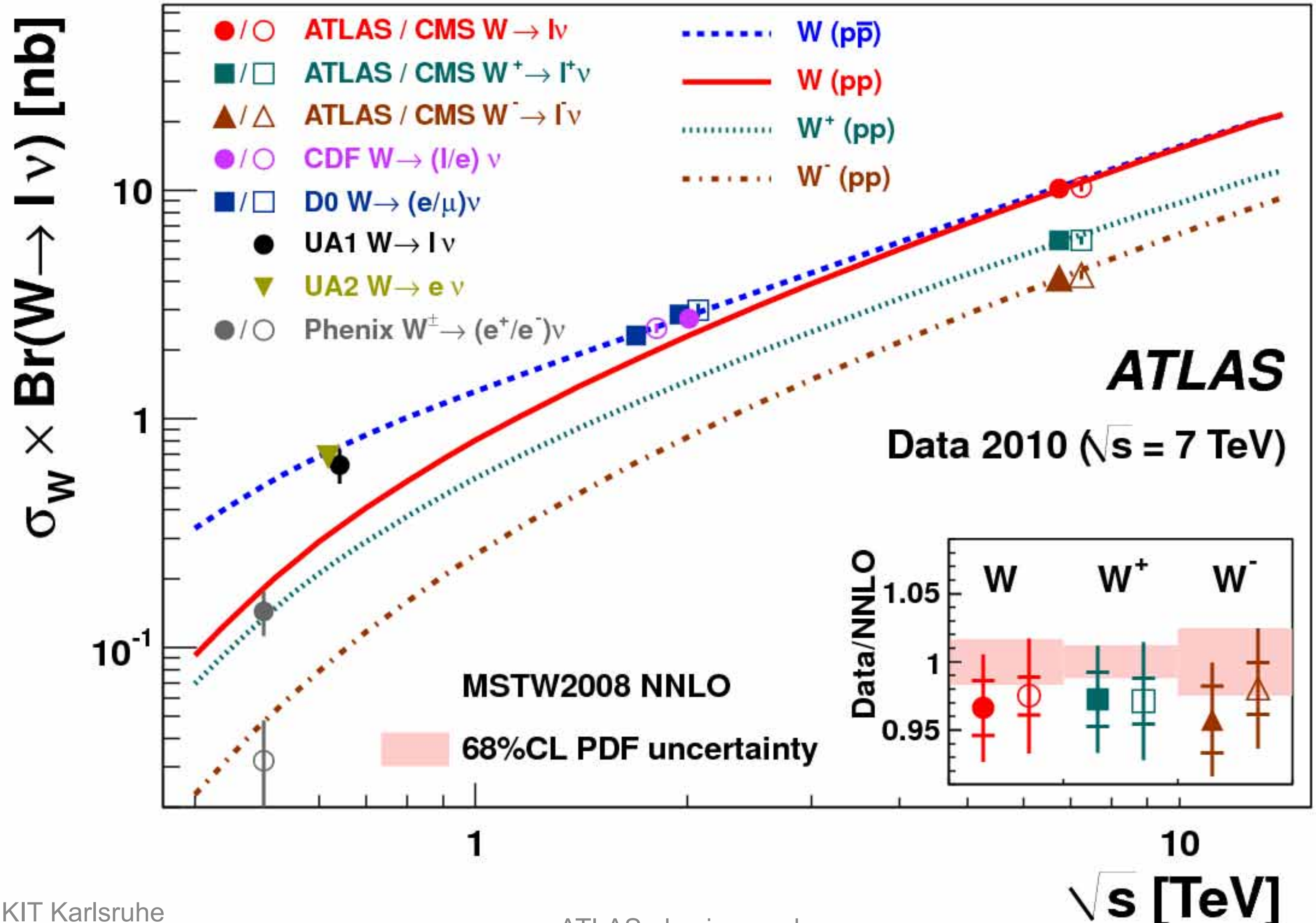


30 years ago!

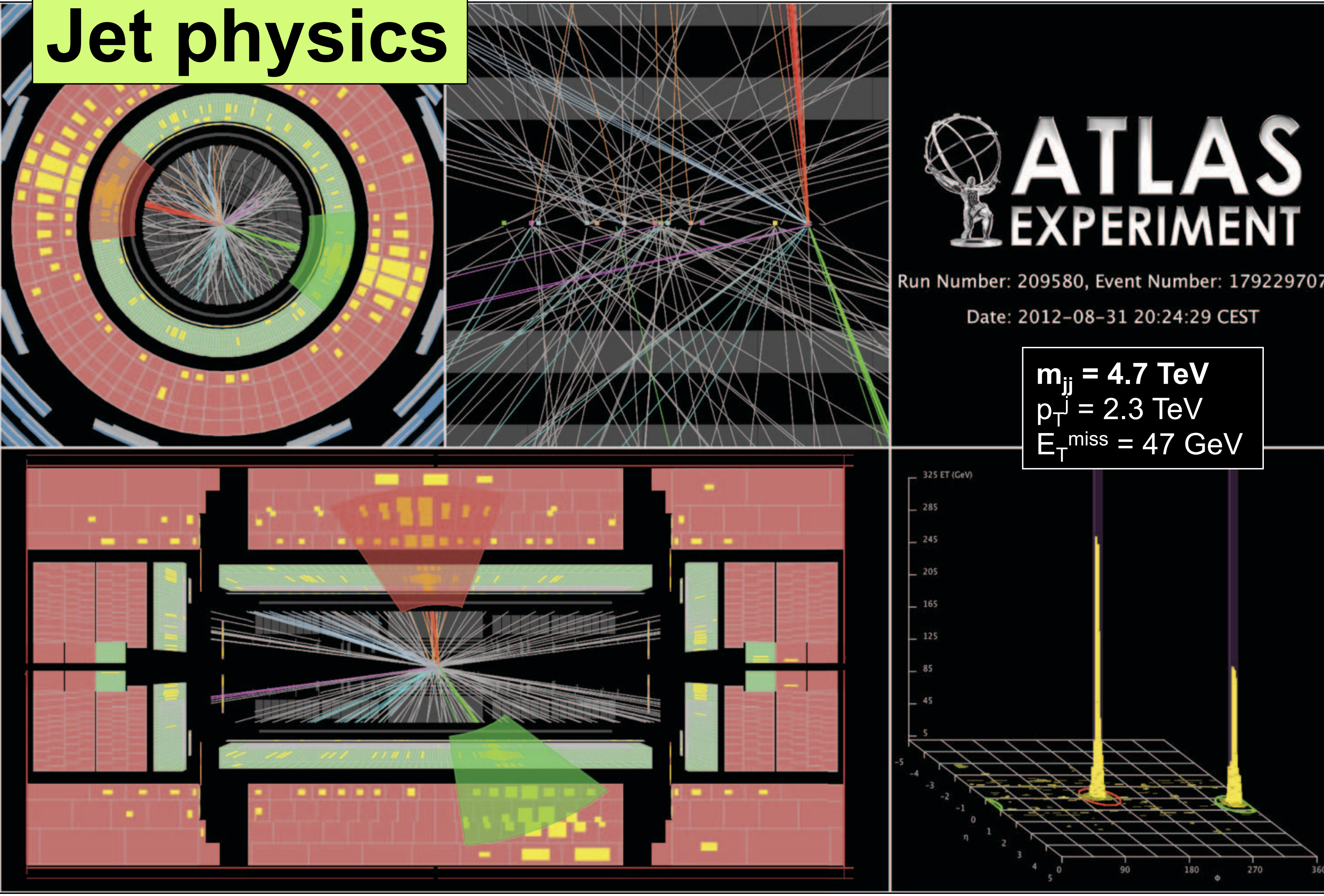
(here are shown the UA2 distributions)

W cross section measurement with e and μ

Phys Rev D85 (2012) 072004

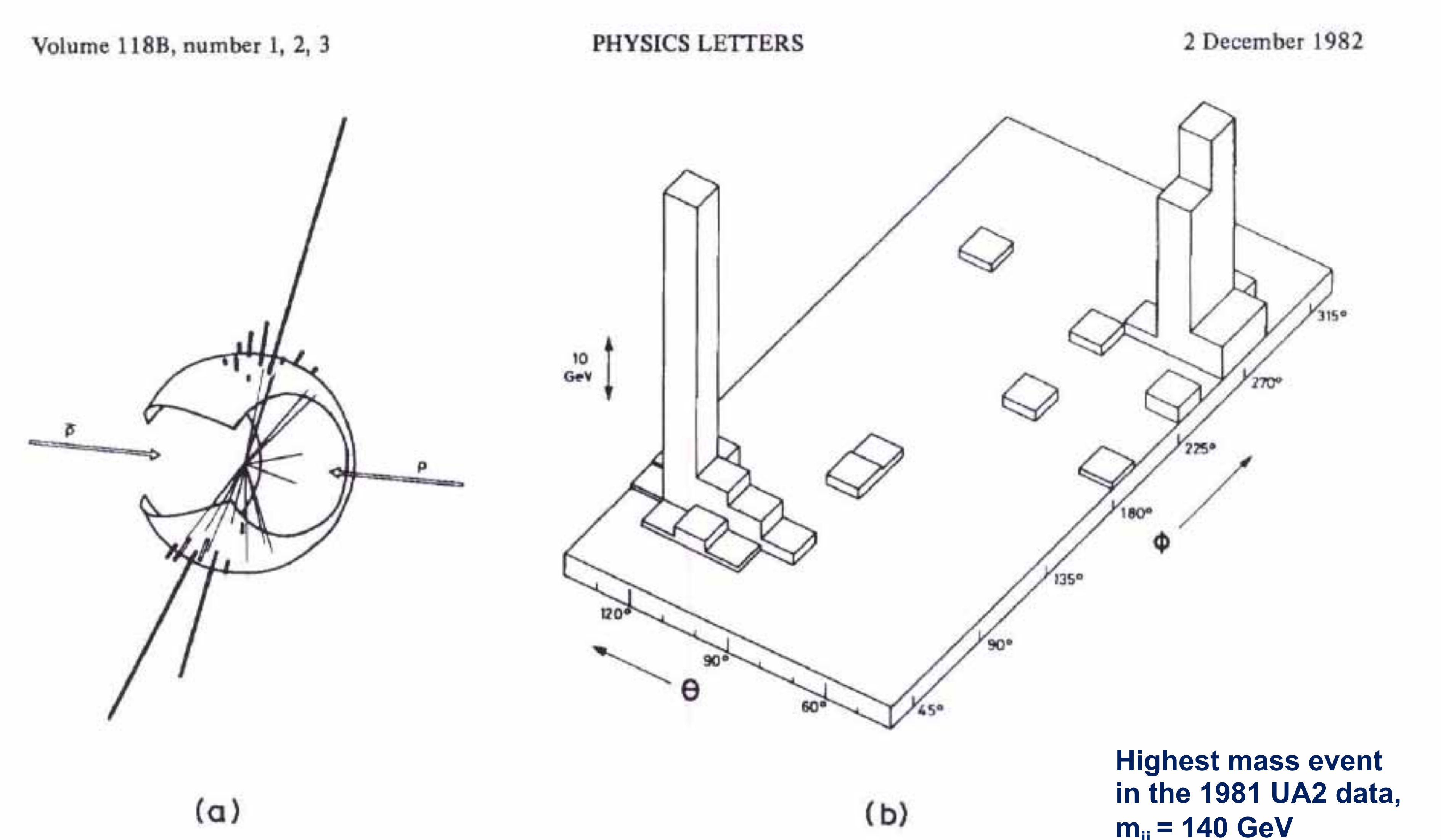


Jet physics

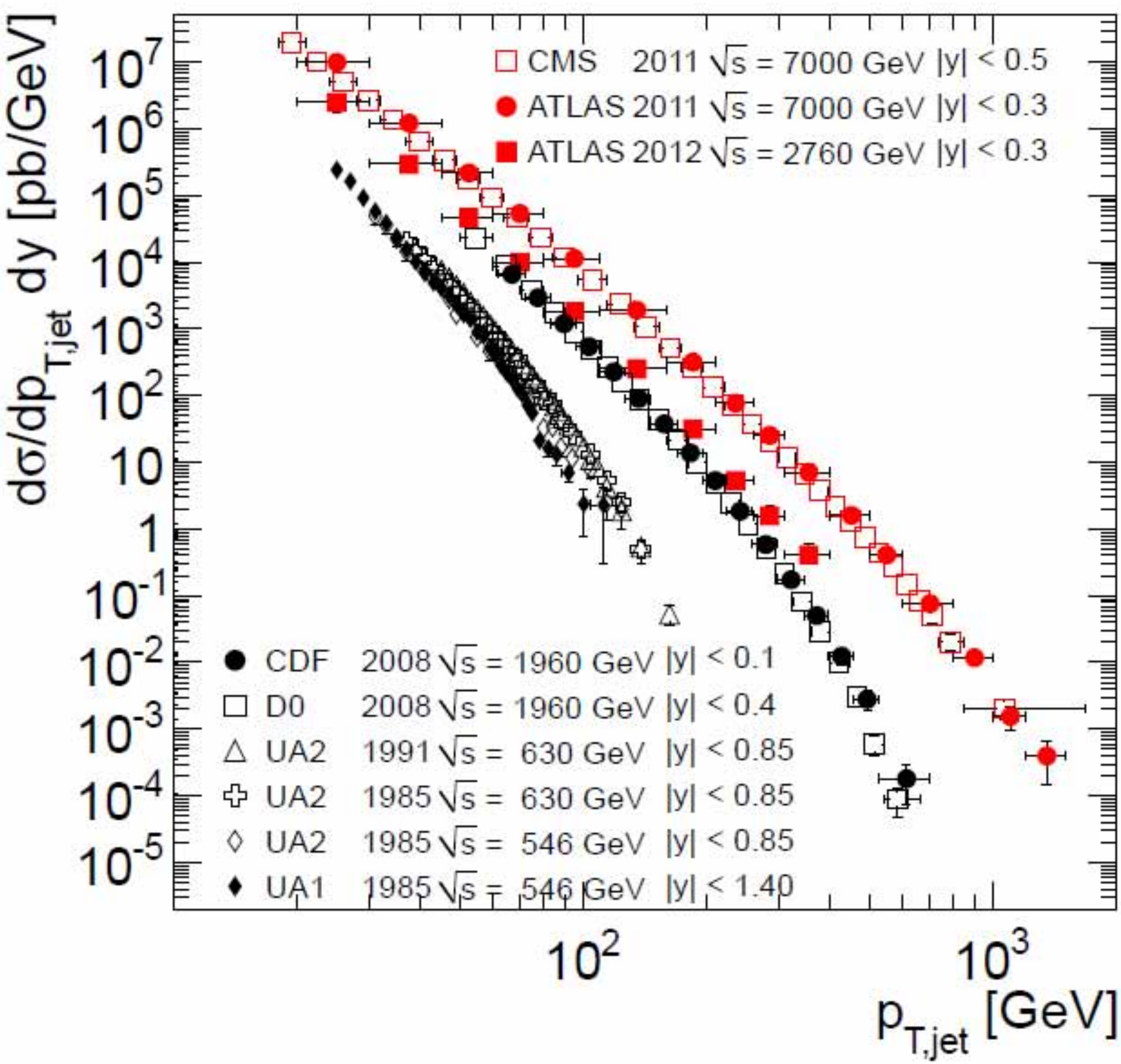


ATLAS EXPERIMENT
Run Number: 209580, Event Number: 179229707
Date: 2012-08-31 20:24:29 CEST
m_{jj} = 4.7 TeV
p_T^j = 2.3 TeV
E_T^{miss} = 47 GeV
325 ET (GeV)

Note also that the event displays have become more sophisticated since the first spectacular events, hand-drawn, at a hadron collider …



Highest mass event in the 1981 UA2 data, m_{jj} = 140 GeV



$d\sigma/dp_{T,jet}\, dy$ [pb/GeV]
$p_{T,jet}$ [GeV]
CMS 2011 $\sqrt{s}$ = 7000 GeV |y| < 0.5
ATLAS 2011 $\sqrt{s}$ = 7000 GeV |y| < 0.3
ATLAS 2012 $\sqrt{s}$ = 2760 GeV |y| < 0.3
CDF 2008 $\sqrt{s}$ = 1960 GeV |y| < 0.1
D0 2008 $\sqrt{s}$ = 1960 GeV |y| < 0.4
UA2 1991 $\sqrt{s}$ = 630 GeV |y| < 0.85
UA2 1985 $\sqrt{s}$ = 630 GeV |y| < 0.85
UA2 1985 $\sqrt{s}$ = 546 GeV |y| < 0.85
UA1 1985 $\sqrt{s}$ = 546 GeV |y| < 1.40

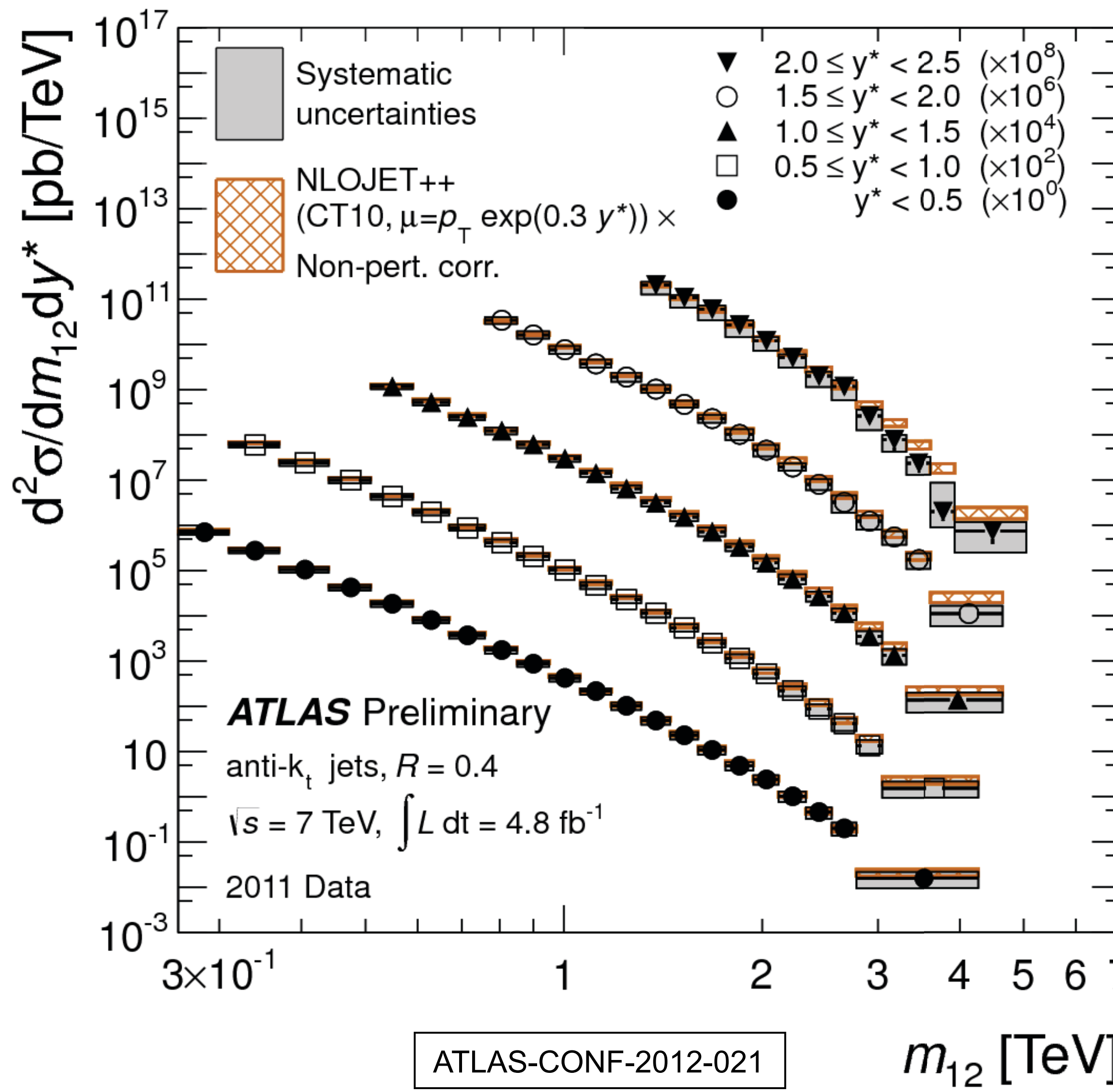
Very detailed jet measurements are now available from LHC that can be compared with QCD calculations …

Example:
The inclusive di-jet cross sections as a function of the di-jet mass for various rapidity separations

The data are spanning jets over a large phase space:

- **20 GeV < p_T < 2 TeV**
- **$|\eta|$ < 4.4**

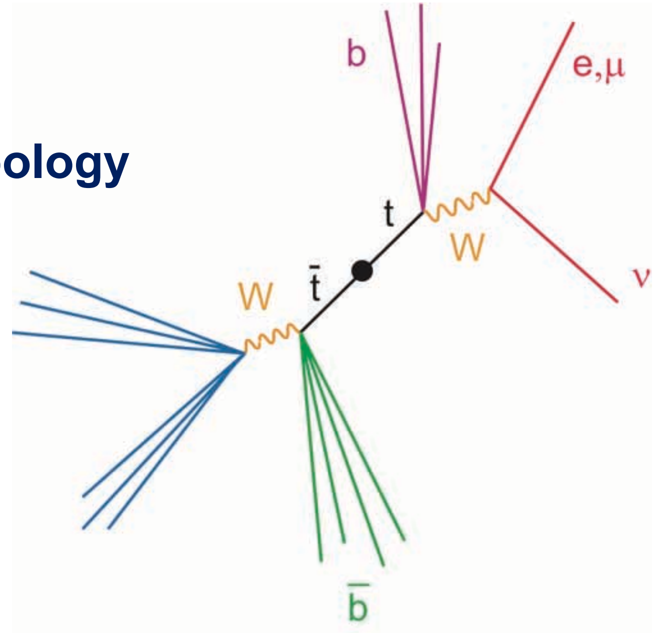
($y^* = 0.5\,|\eta_1 - \eta_2|$)



Top measurements

- Complete set of ingredients to investigate production of ttbar, which is the next step in verifying the SM at the LHC:
  - e, μ, E_T^{miss}, jets, b-tag

- Assume all tops decay to Wb: event topology then depends on the W decays:

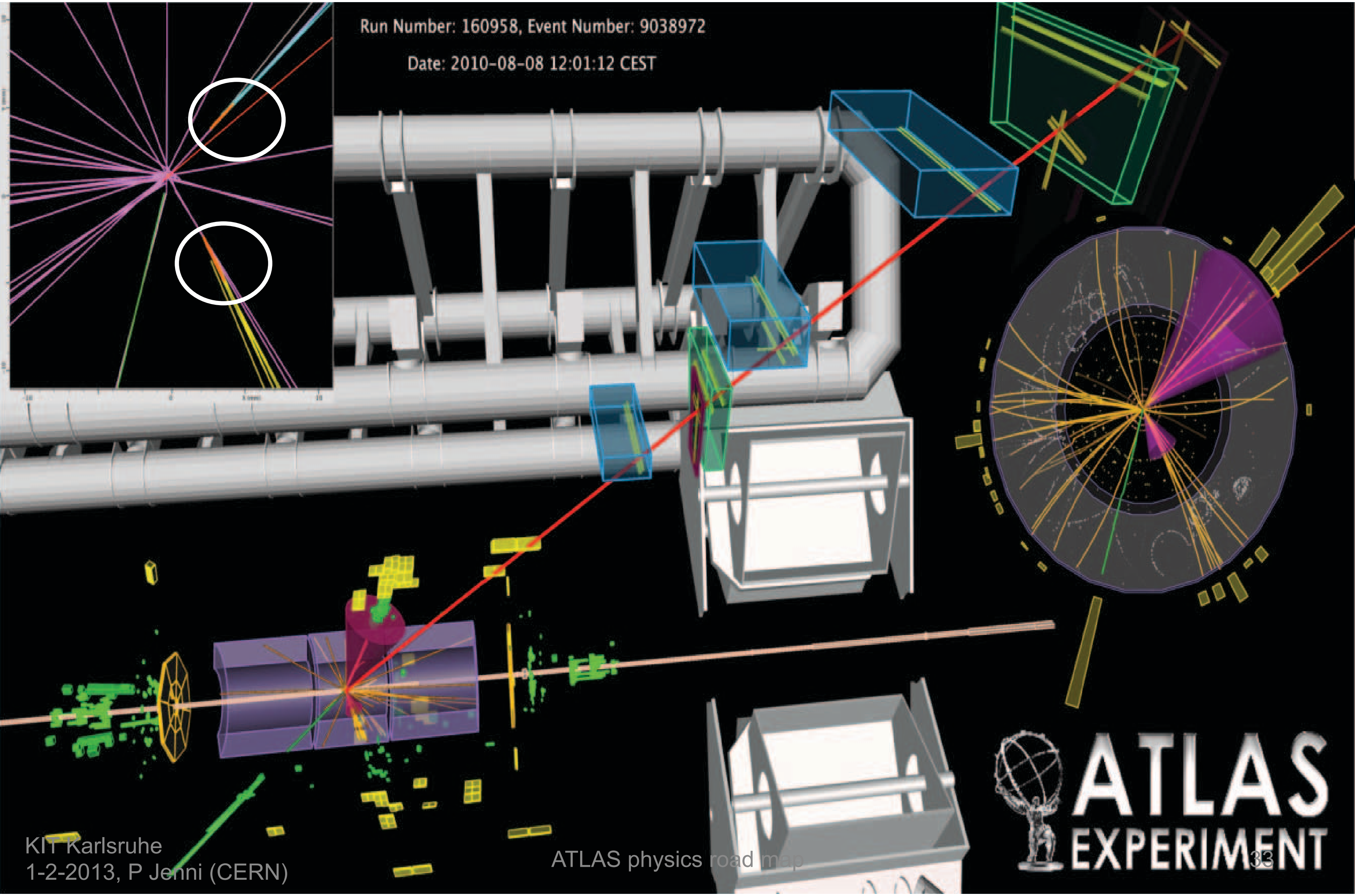


  - one lepton (e or μ), E_T^{miss}, jjbb (37.9%)
  - di-lepton (ee, $\mu\mu$ or eμ), E_T^{miss}, bb (6.5%)

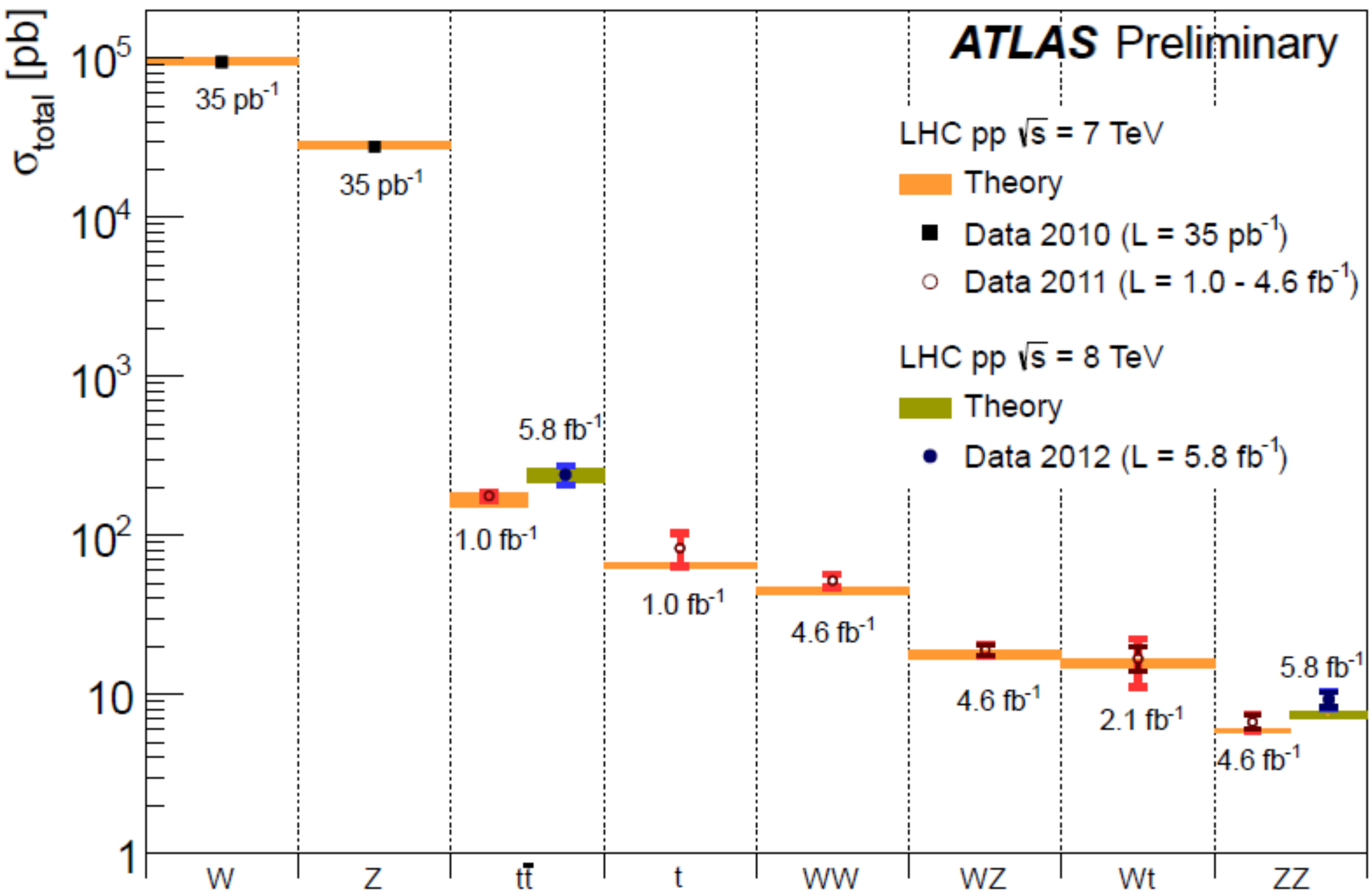
- Data-driven methods to control QCD and W+jets backgrounds

$t\bar{t}$ candidate event

e + μ + 2 jets (b-tagged) +ETmiss

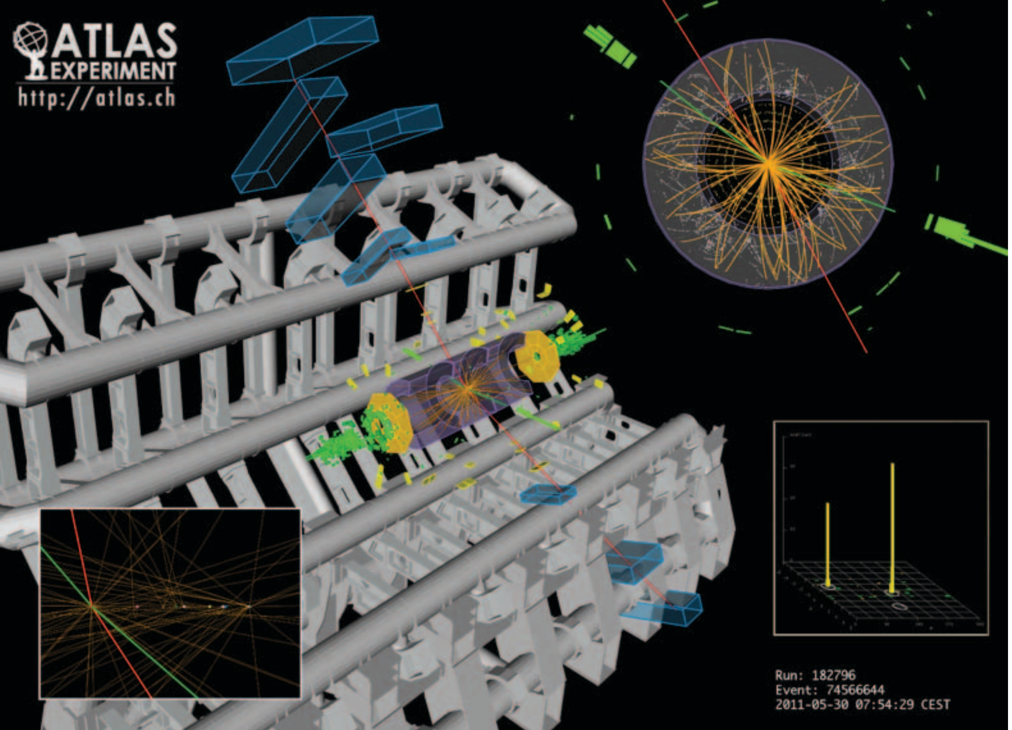


A summary of Standard Model measurements



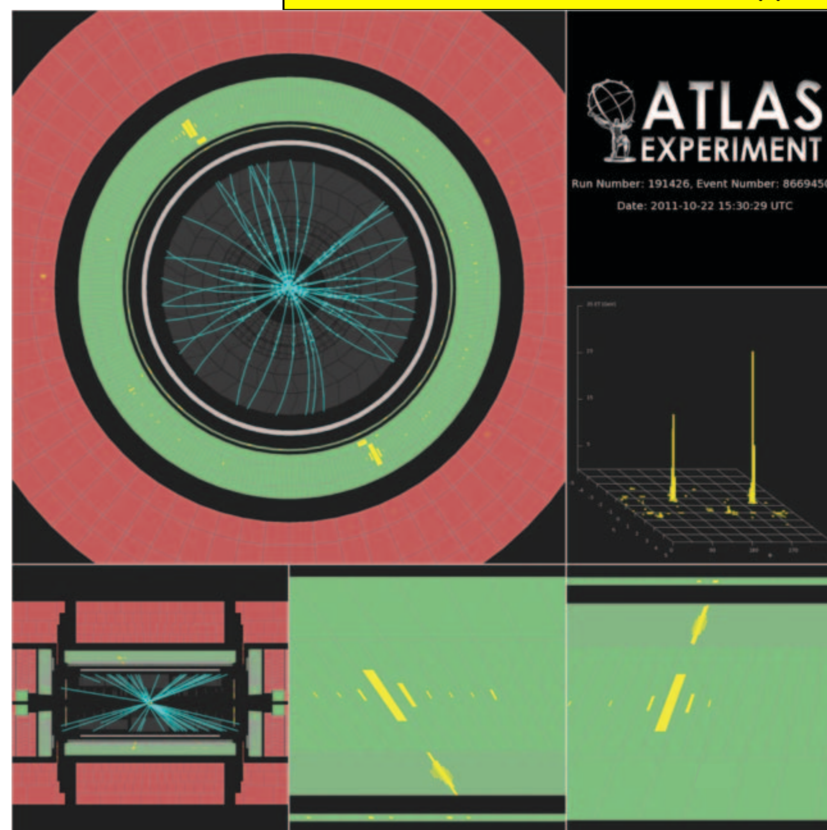
The excellent performance in measuring Standard Model physics gives confidence for the readiness of the two experiments to search for New Physics

The Higgs(-~~like~~) boson



d v d a → : → μμ

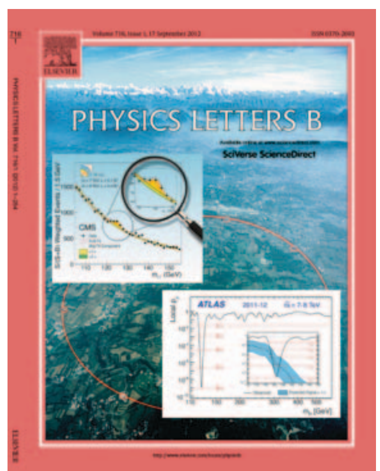
d v d a → γγ



ATLAS and CMS have announced the discovery of a new boson together on 4th July 2012, published in a special issue of Physics Letter B

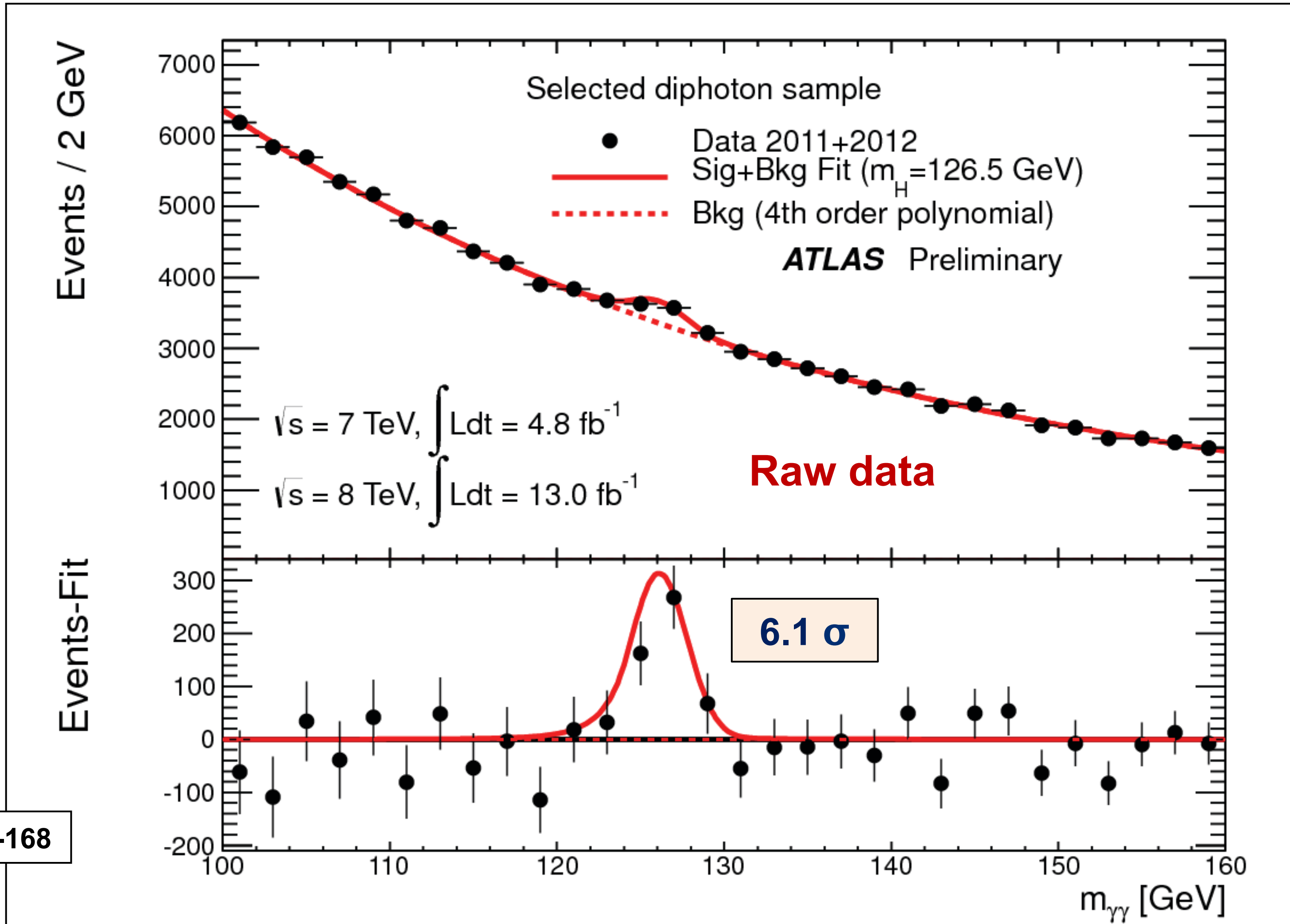
Phys. Lett. B 716 (2012) 1

Phys. Lett. B 716 (2012) 30



? ?→?γγ

- ?? ????a?msn??i ??m*?σ?E4?? ?
- ?o????d????c??σ?4l4fb?
- ??? ??????????nd?d?mdf ???????s?,??n???d?????????d??n?
- ? ??????????a? ??mγγ????i ? ? ??aa??? ?????ti?
  ????????γ??a?? ?γ????????v???dh?a?? ?????ti?

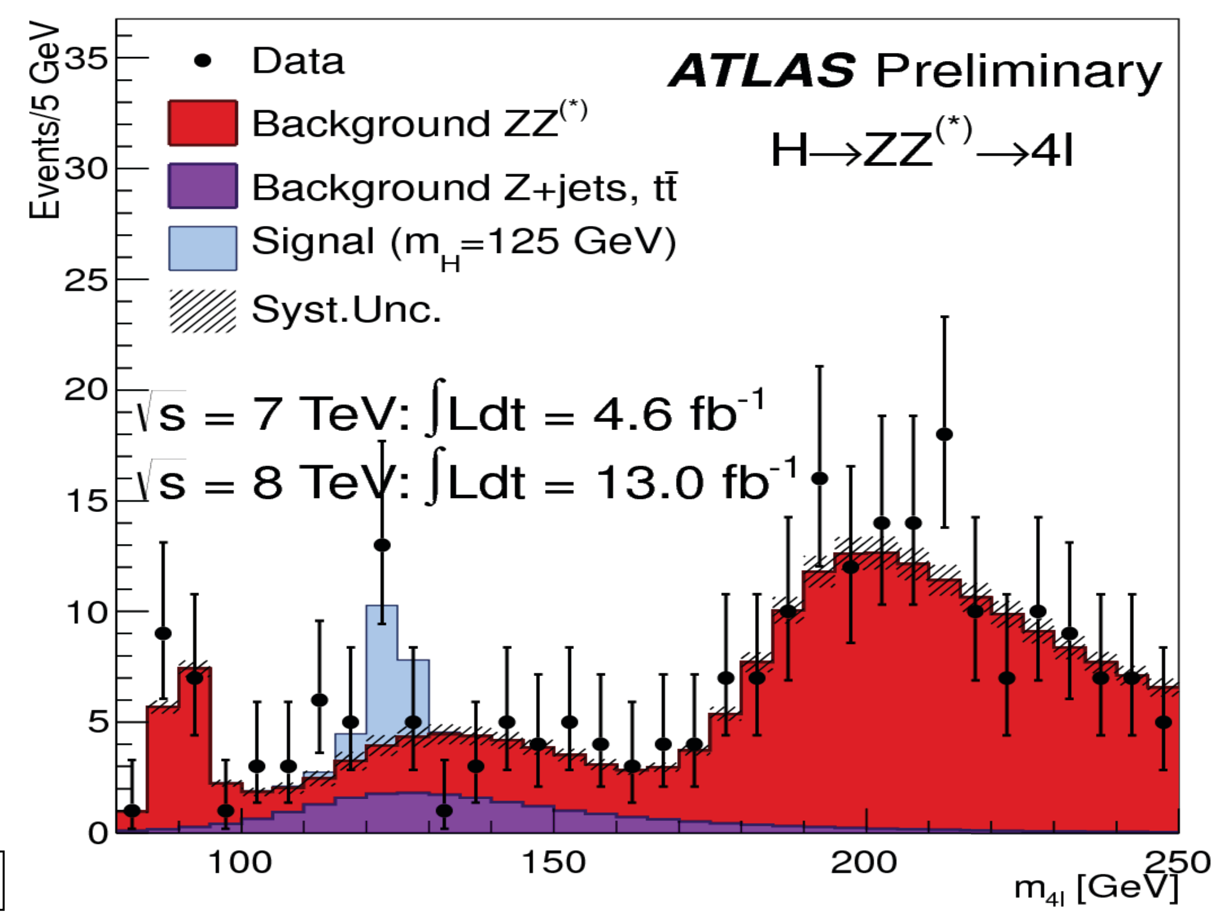


ATLAS-CONF-2012-168

? ?→ ??-: t? → ?E ??-E?SEZ Sfbflz t?

- ??a??a???mSh? ???a?mh??i ??m* ?b?flsx? ?
- ??f ?v?am? a?m?c??b0?
- E???d??m?
- ? ??????a? ??m??-: t?-?a?? ???t?

???????????i ??m???S?/??dhSe ?f ?d?df ????d??n?
???????a?? ?sC ?a?n??a??dh?

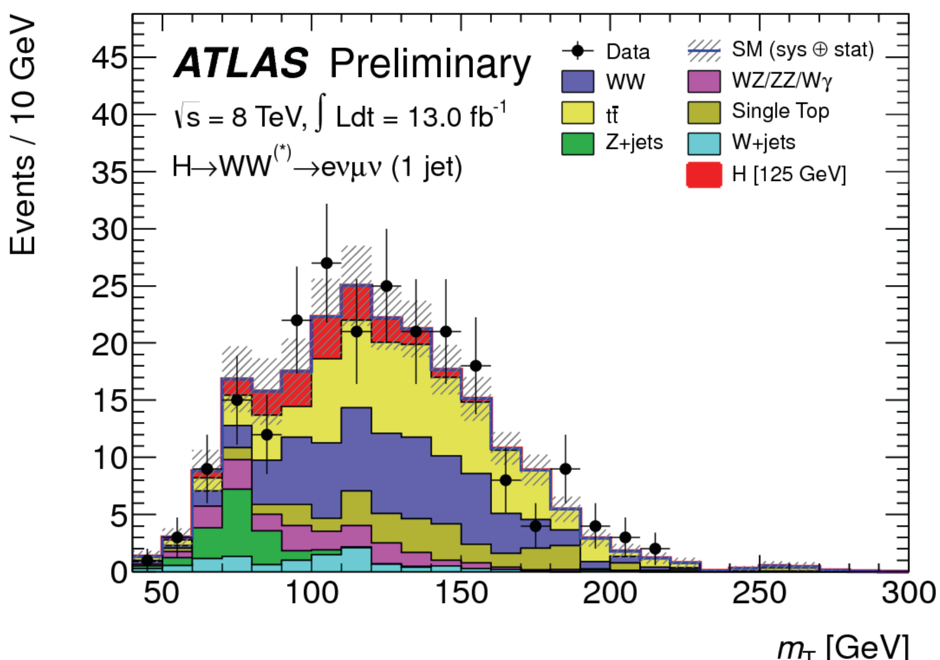


ATLAS-CONF-2012-169

? ?→?? ? -: t?→??ν?ν??ν?νS?ZνZνS?νZνt?

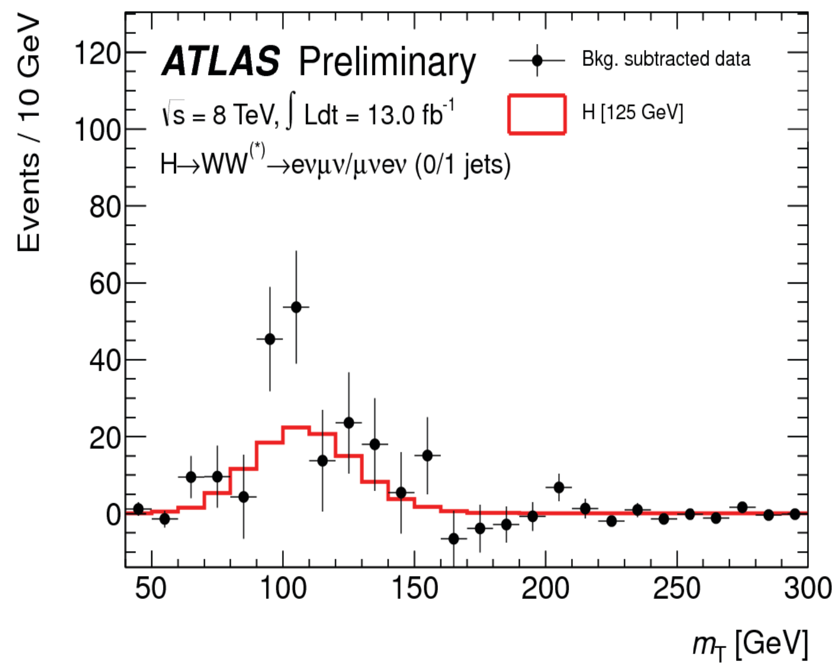
- ??ar h???n? v?????????????v??a?b?0fb s0p4?? ??? ?*?b?f?44?? t?
- ????????????????nfb?→???? ?mn?a??????nda ?i ???c??????→?“?? ?i ???????????’?
- fb?h???d????????nd?sn???????d???nS? n???νZν ????r ???a?f?40fb????d?S???a????,? ?n???
- ? ??????????a? ??m?? ? S?d???S?/???dnS? /??dn?
- ???????????? dh??????nd?“??a??? ?????”?? ? ??????a? ????

(Just as an example of several subsamples)



$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\rm miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{\rm miss})^2}$$

(All subsamples, background subtracted)



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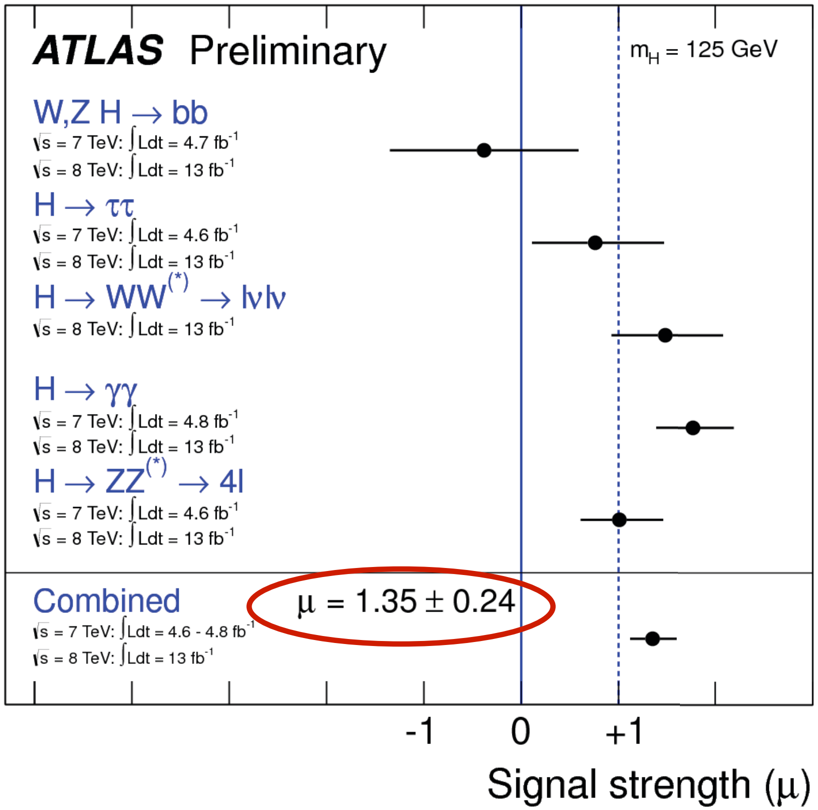
Summary and combination

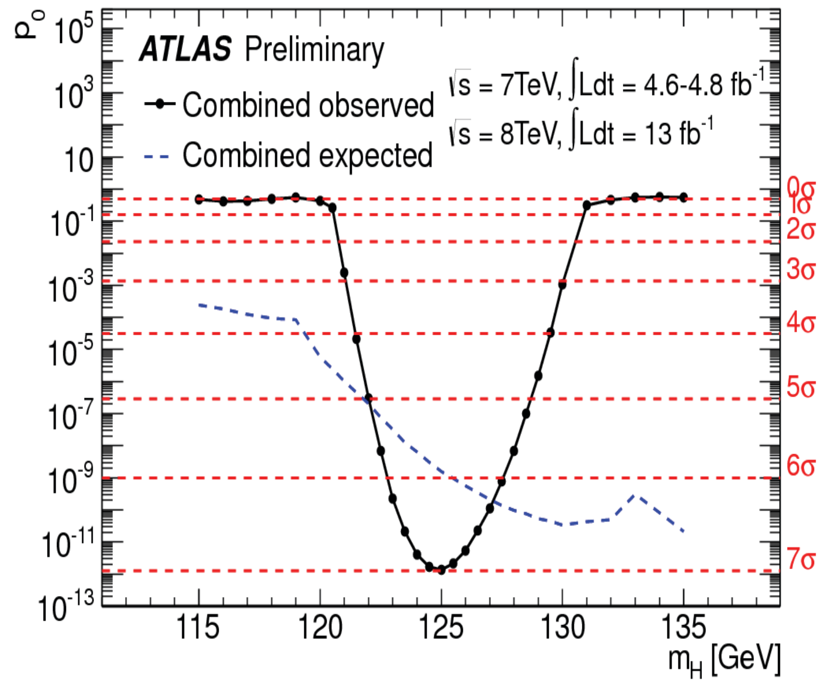
m = 125.2 ± 0.3 (stat) ± 0.6 (syst) GeV

$\mu = 0$ background only hypothesis
$\mu = 1$ SM Higgs hypothesis



ATLAS-CONF-2012-170

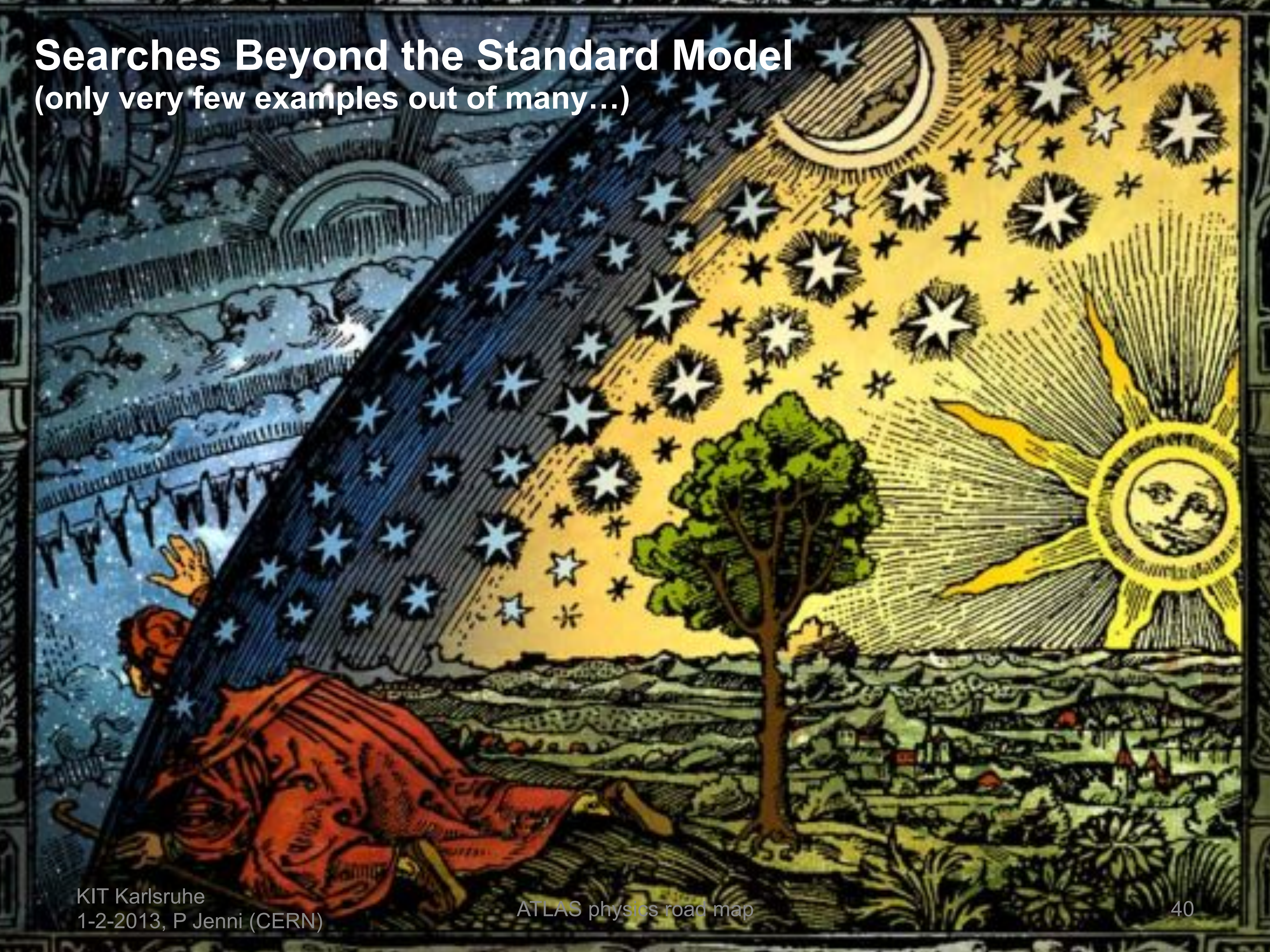
Observed data compared to the probability that the background fluctuates to fake the observed excess of events, and what is expected from a SM Higgs ("local p_0")



(First analyses and fits for the Higgs couplings and spin have been made as well which are still very much limited by statistics, albeit well compatible with the Standard Model)

Searches Beyond the Standard Model

(only very few examples out of many…)

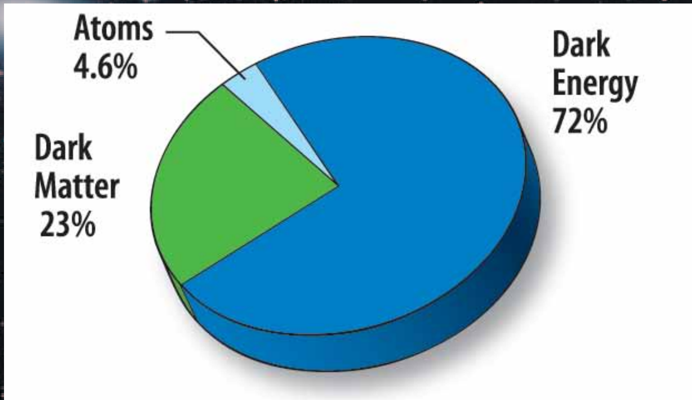


Dark Matter in the Universe

Astronomers found that most of the matter in the Universe must be invisible Dark Matter

Vera Rubin ~ 1970

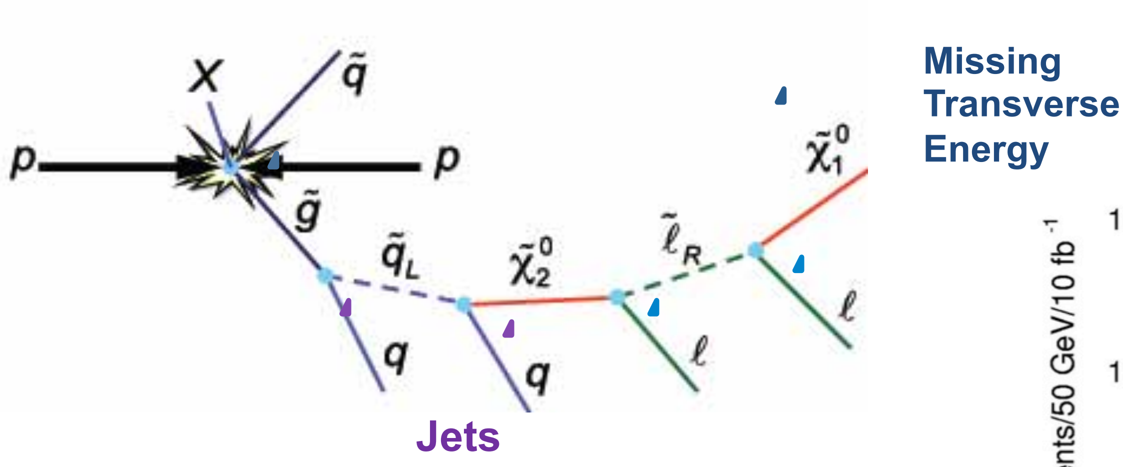
Supersymmetric particles ?

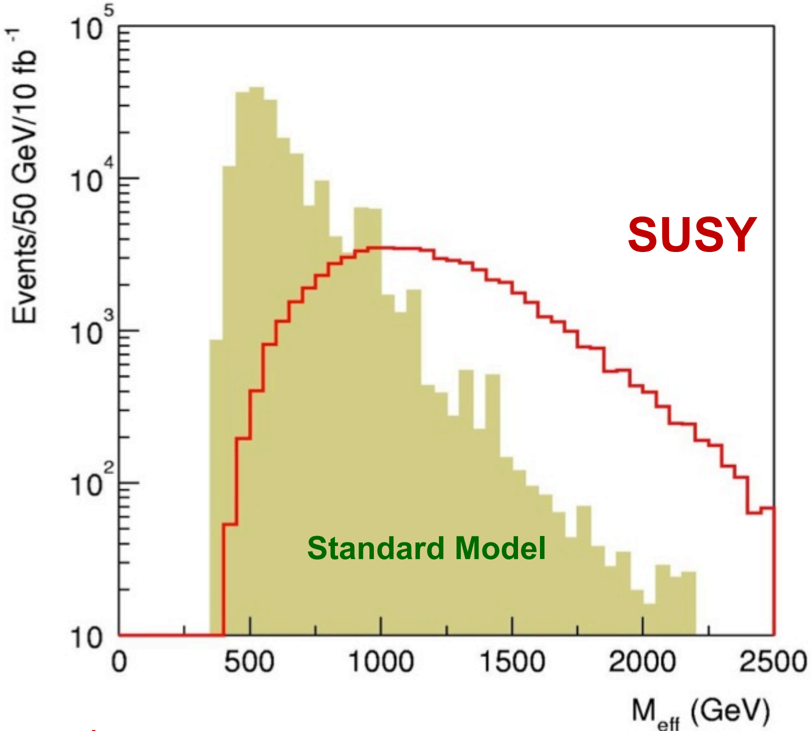


F. Zwicky 1898-1974

In practice SUSY searches at LHC are rather complicated

- **Complex (and model-dependent) squark/gluino cascades**





- **Focus on signatures covering large classes of models while strongly rejecting SM background**
  - large missing E_T
  - High transverse momentum jets
  - Leptons
    - Perform separate analyses with and without lepton veto (0-lepton / 1-lepton / 2-leptons)
  - B-jets: to enhance sensitivity to third-generation squarks
  - Photons: typically for models with the gravitino as LSP

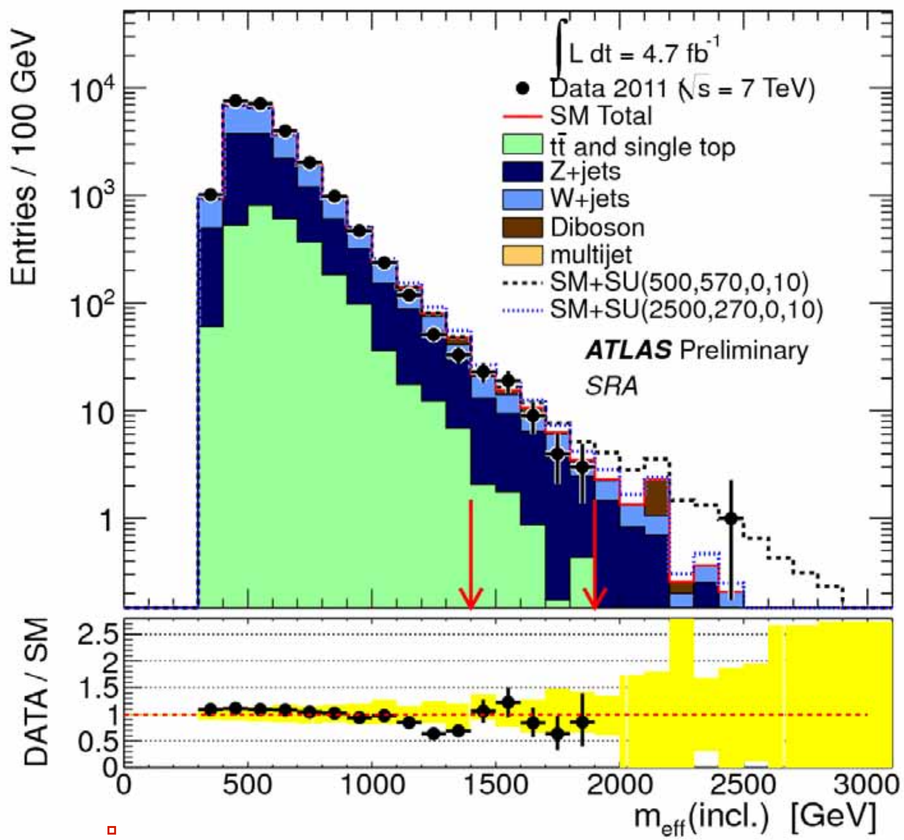
Meff = Etmiss + Σ pT(jets)

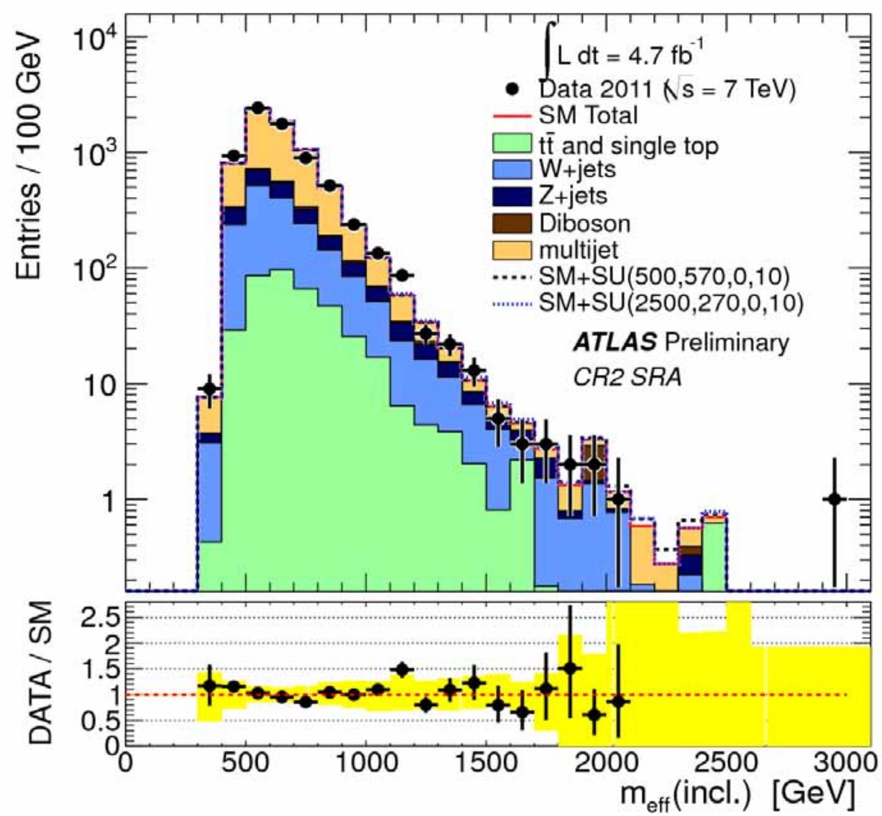
Analyses re-optimized and updated with full 2011 Luminosity

- 0-lepton + 2−6 jets + high MET (based on Et-miss+jet triggers)
- 0-lepton + 6−9 (multi-)jets + MET (based on multi-jet triggers)
- 1-lepton + 3,4 jets + high MET (based on lepton triggers)

Example: O-leptons + 2-6 Jets analysis

ATLAS-CONF-2012-033, 037, and 041



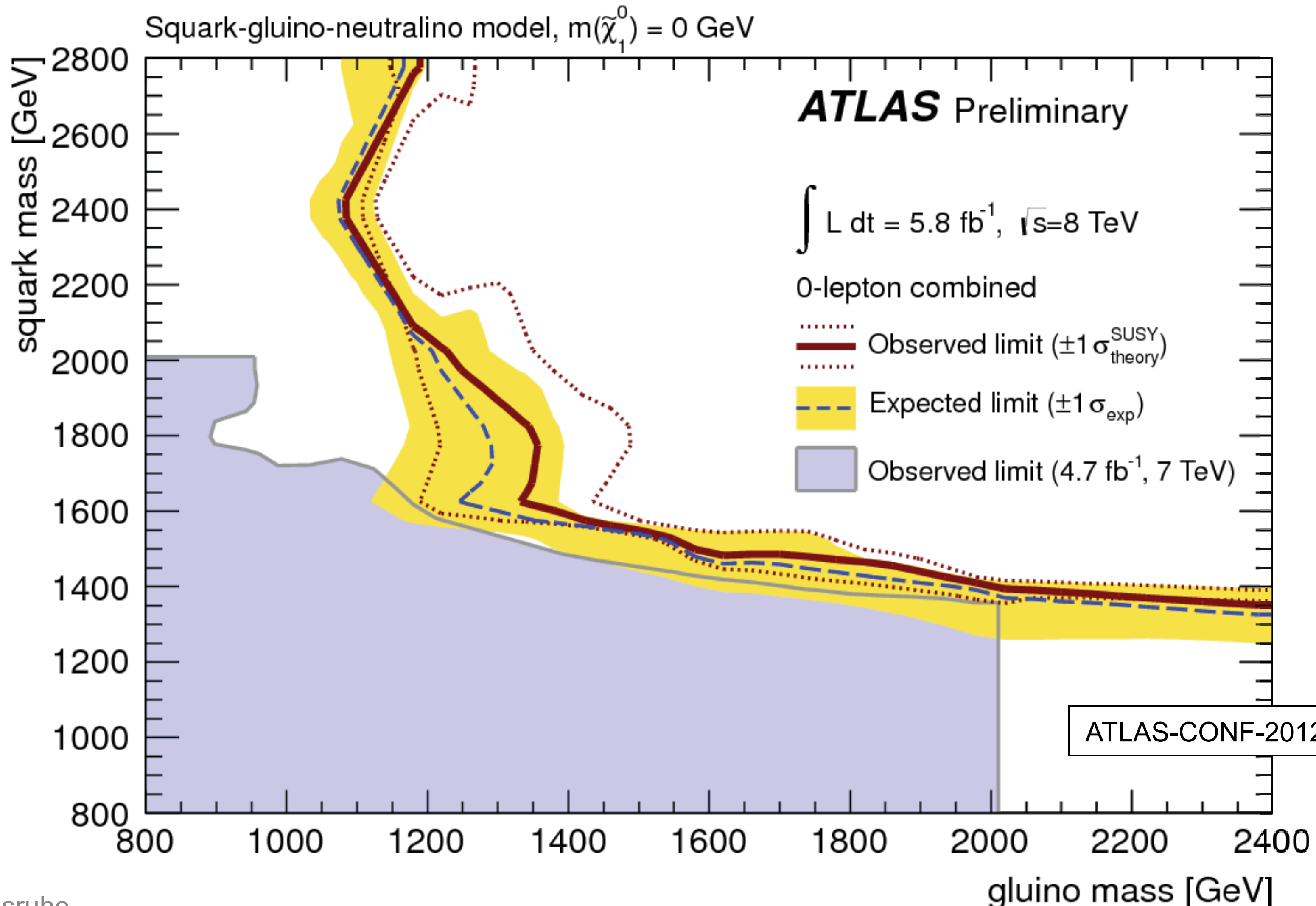


A signal region

A control region where no signal is expected

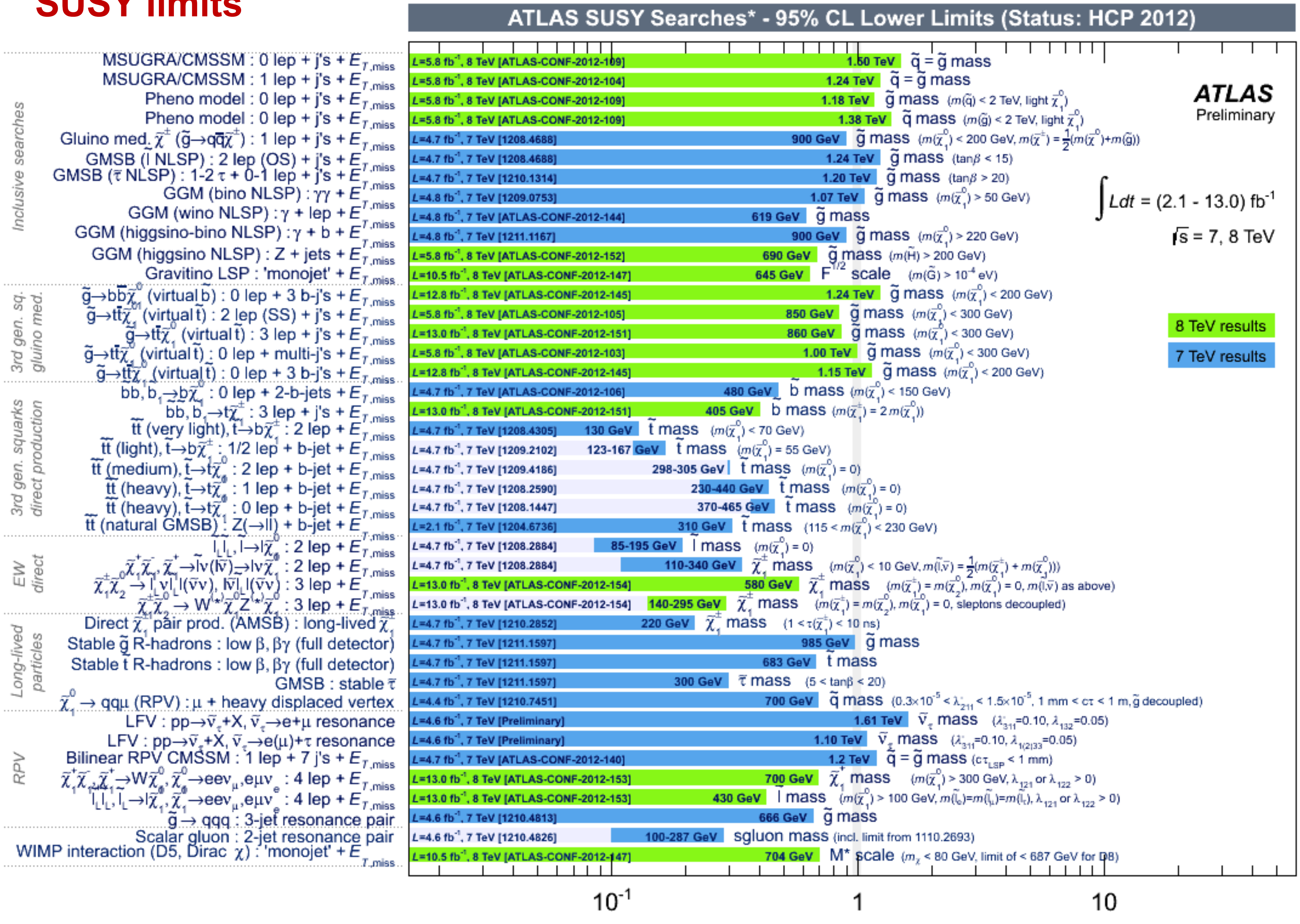
Interpretation of the results

Consider phenomenological MSSM models containing only squarks of 1st and 2nd generation, gluino and light neutralinos



ATLAS-CONF-2012-0109

SUSY limits

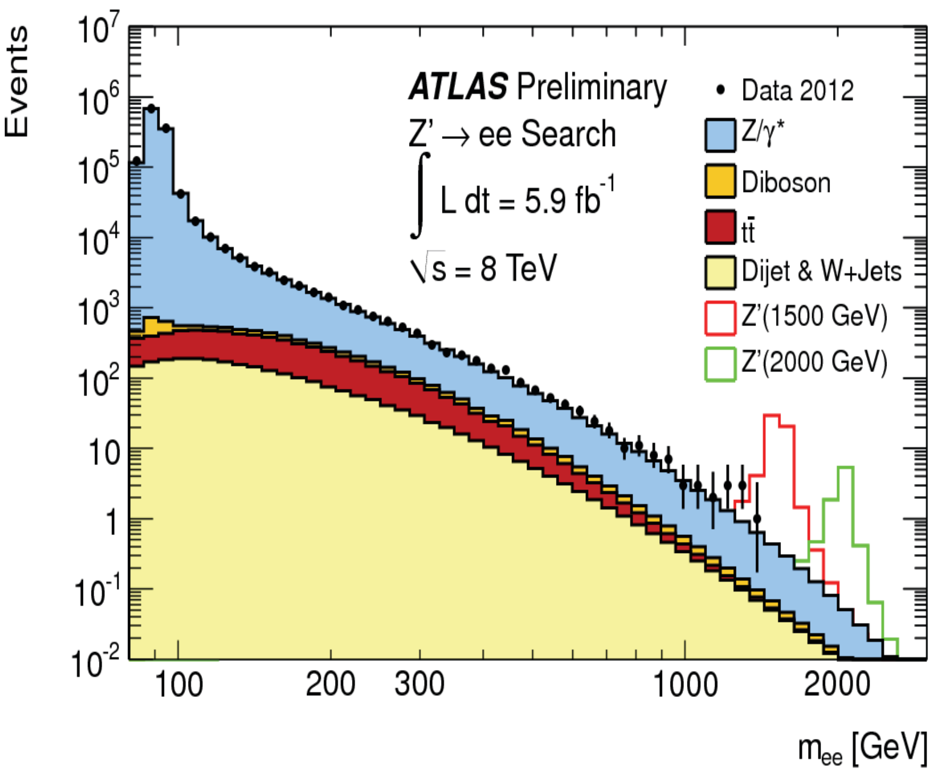


*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Searches for heavy W and Z like particles

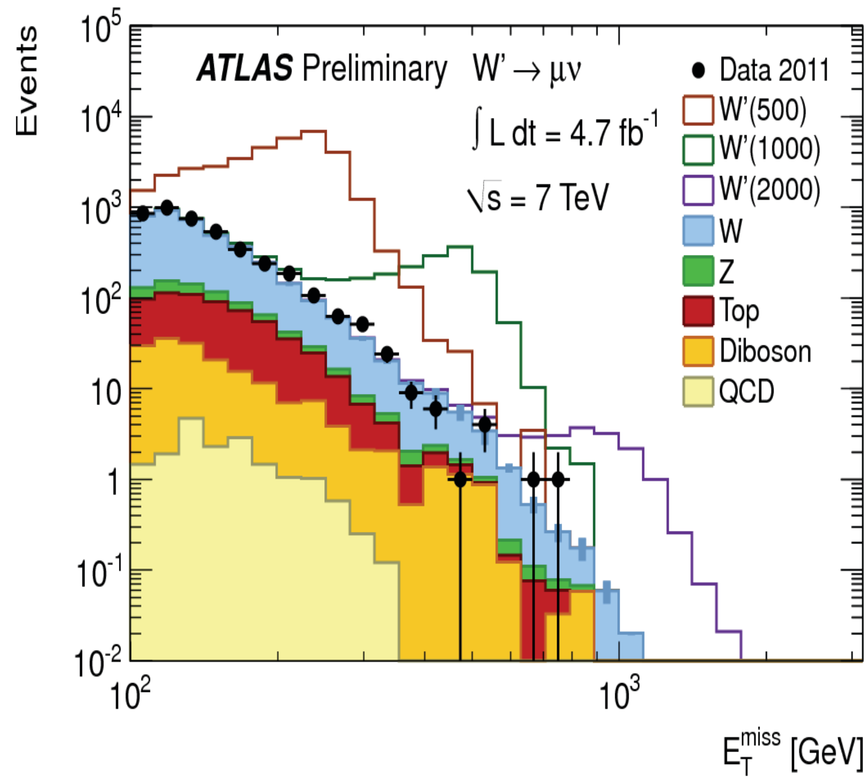
These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z□ Di-lepton pairs

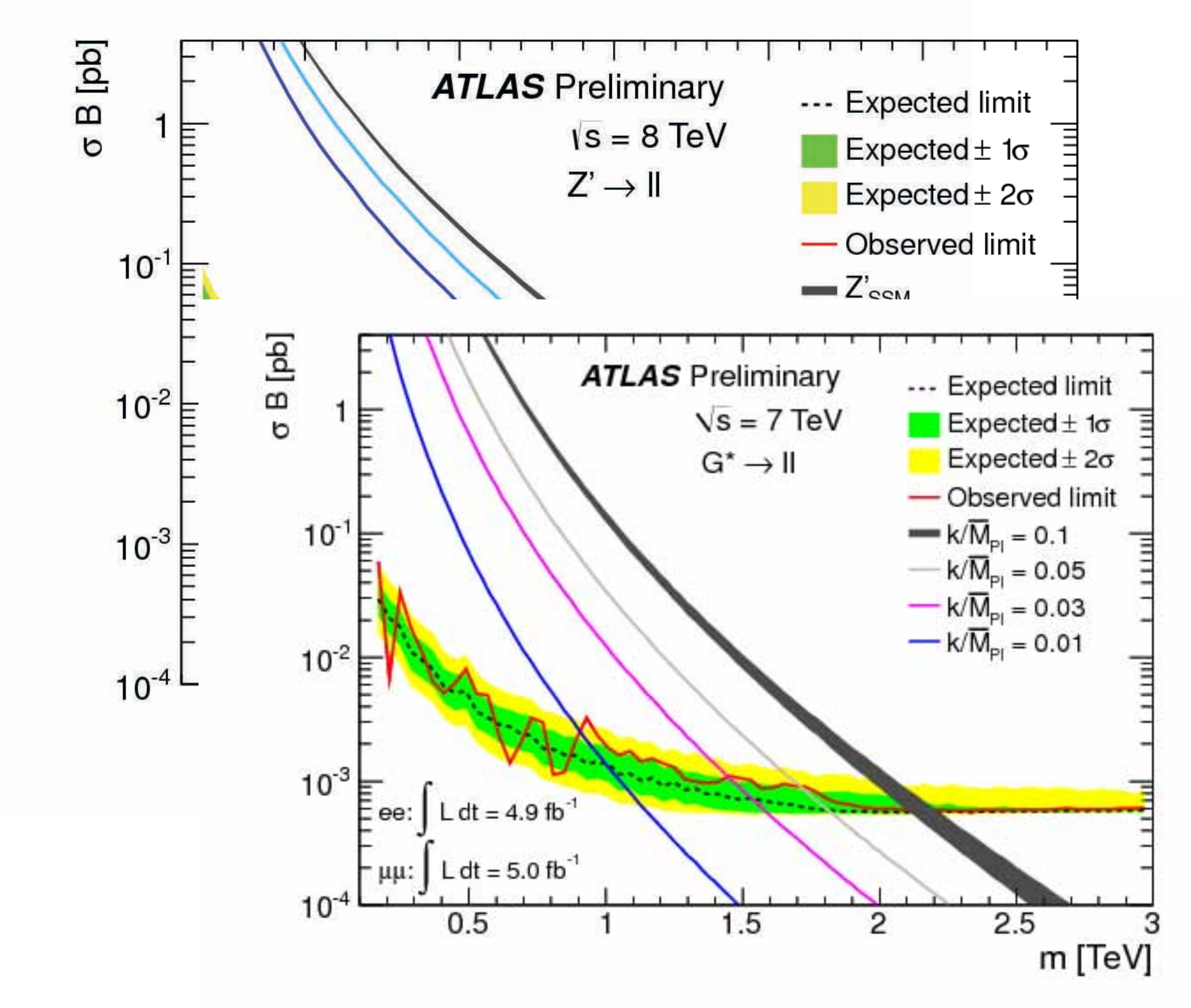


ATLAS-CONF-2012-129

W□ Lepton + ETmiss



ATLAS-CONF-2012-086



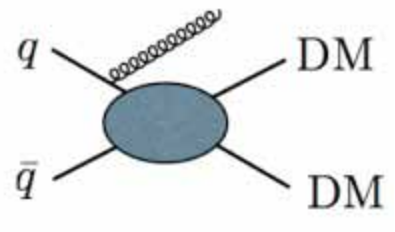
R Sundrum
L Randall
F Gianotti

ATLAS-CONF-2012-129

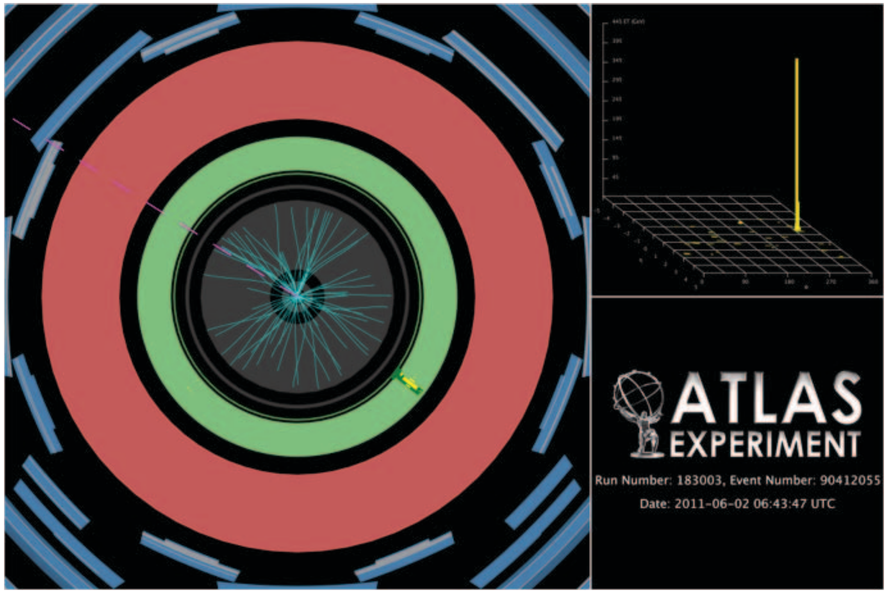
ATLAS-CONF-2012-007

Randall-Sundrum Graviton

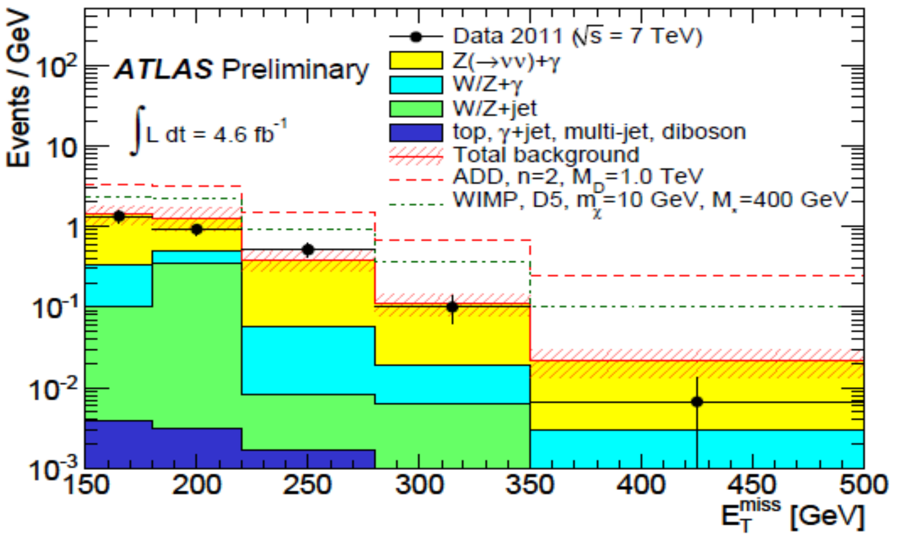
Search for direct Dark Matter (DM) particles in pair-production

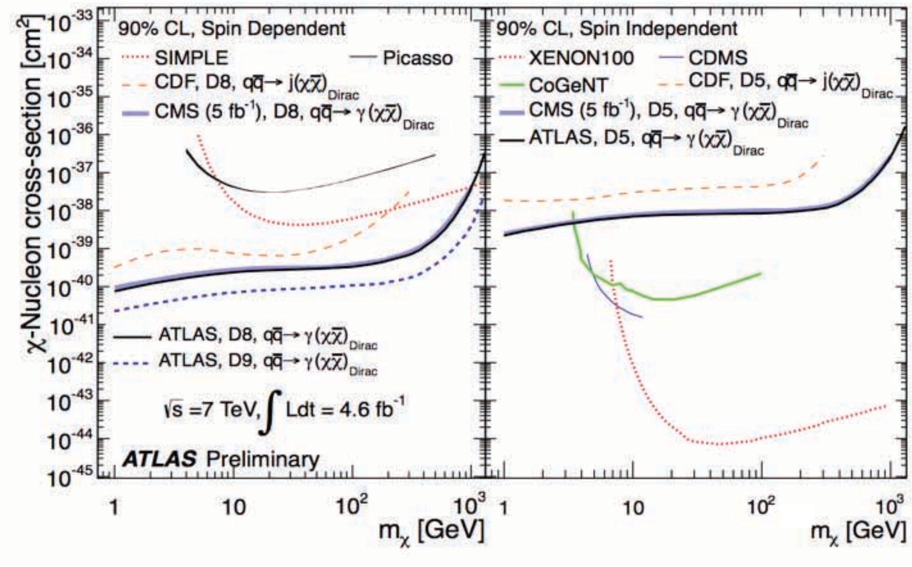


A single photon (150 GeV) or jet plus ETmiss

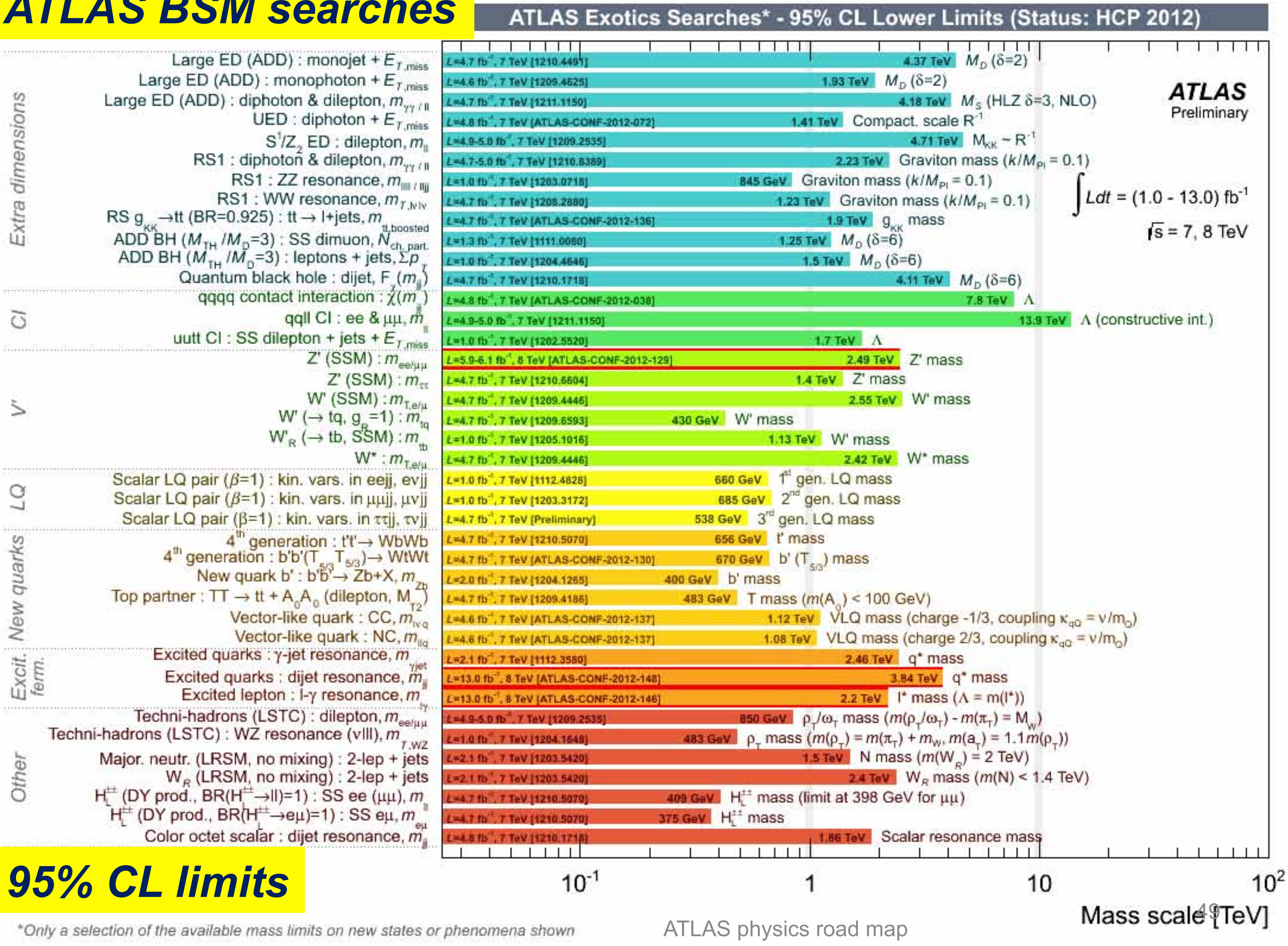


ATLAS-CONF-2012-085
arXiv:1210.4491v1[hep-ex]

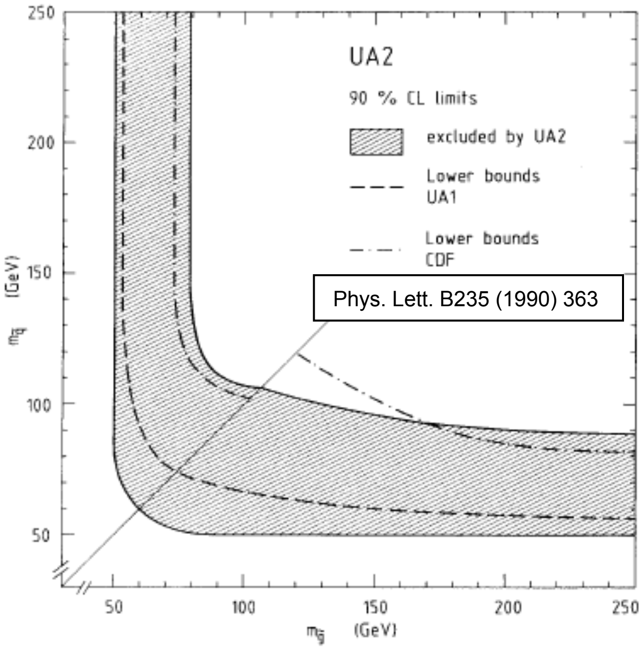


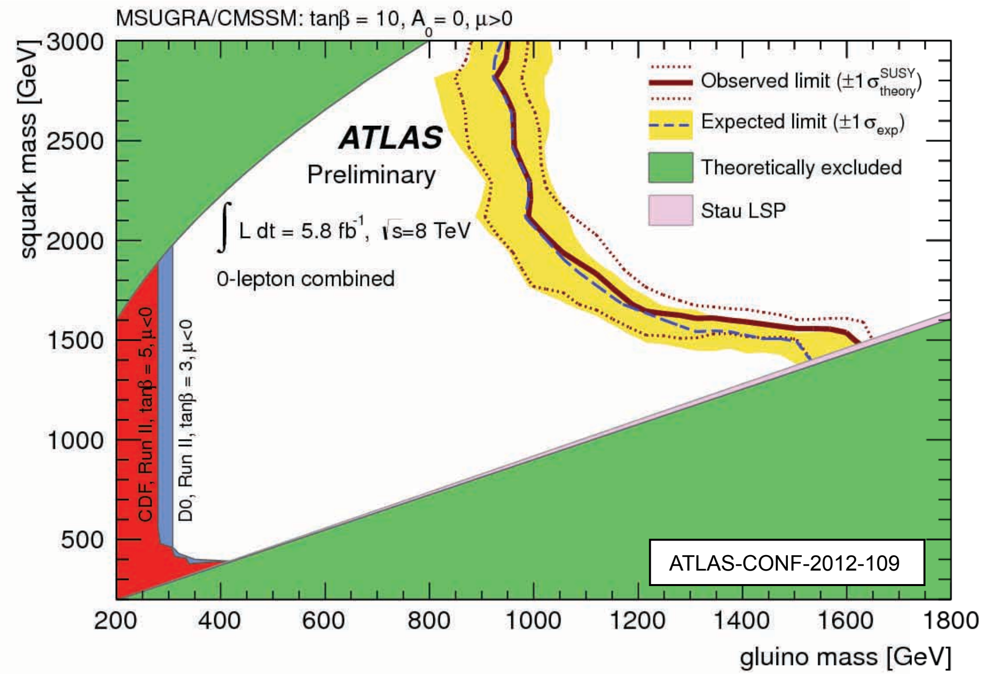


ATLAS BSM searches



95% CL limits

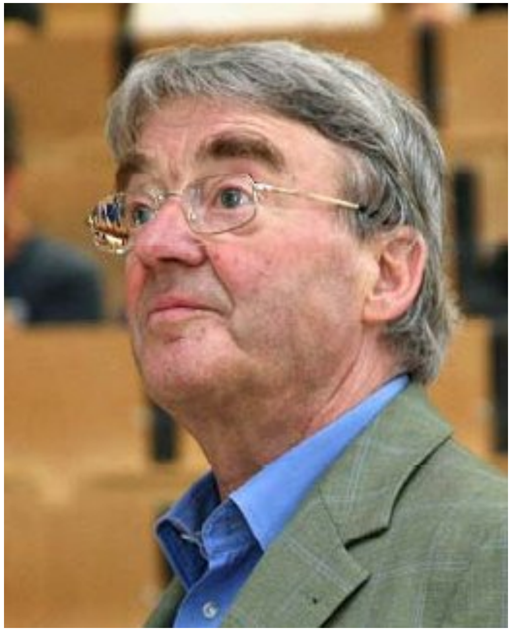




On a personal note:

The search for SUSY has been a motivation for me for 30 years, and in spite of exclusion limits only so far I have not given up yet!

I am therefore particularly happy and grateful to be honoured with the Julius Wess Award



The journey with LHC into new physics territory has only just begun, and for sure, further exciting times are ahead of us!

Thank you for your attention

J Blaeu 1664

Further reading:

The Higgs Boson

ARTICLE

Journey in the Search for the Higgs Boson: The ATLAS and CMS Experiments at the Large Hadron Collider

M. Della Negra,[1] P. Jenni,[2] T. S. Virdee[1]*

The search for the standard model Higgs boson at the Large Hadron Collider (LHC) started more than two decades ago. Much innovation was required and diverse challenges had to be overcome during the conception and construction of the LHC and its experiments. The ATLAS and CMS Collaboration experiments at the LHC have discovered a heavy boson that could complete the standard model of particle physics.

Science
AAAS

Journey in the Search for the Higgs Boson: The ATLAS and CMS Experiments at the Large Hadron Collider
M. Della Negra *et al.*
Science **338**, 1560 (2012);
DOI: 10.1126/science.1230827

http://www.sciencemag.org/content/338/6114/1560.full.html