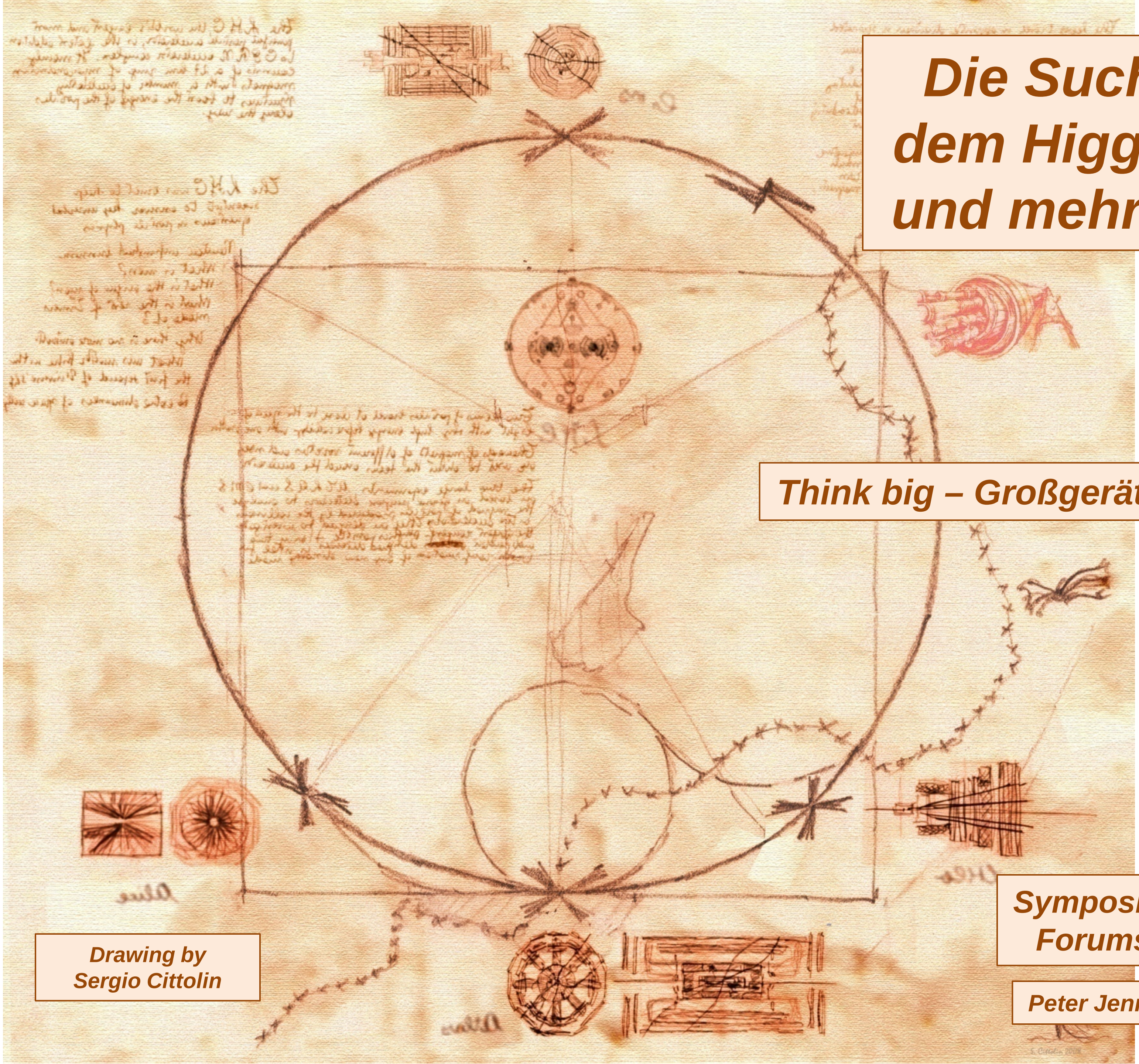
Die Suche nach dem Higgs-Boson und mehr am LHC

Think big – Großgeräte in der Physik

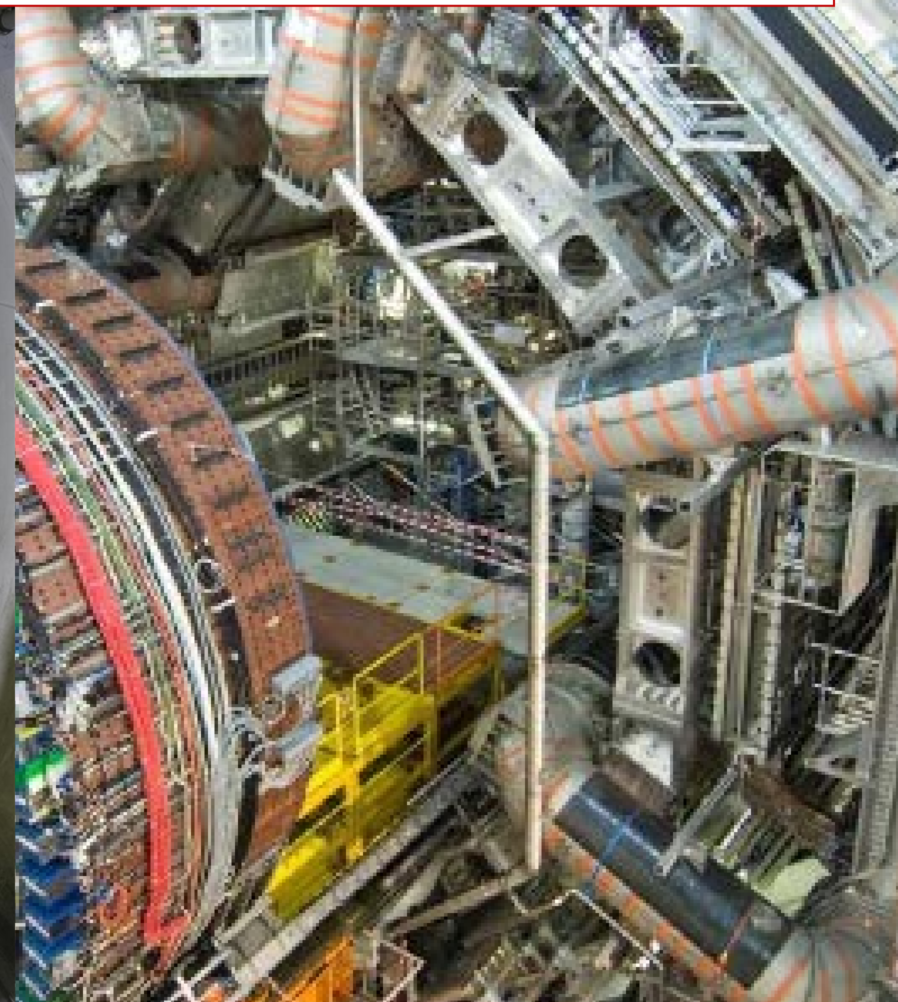


Drawing by Sergio Cittolin

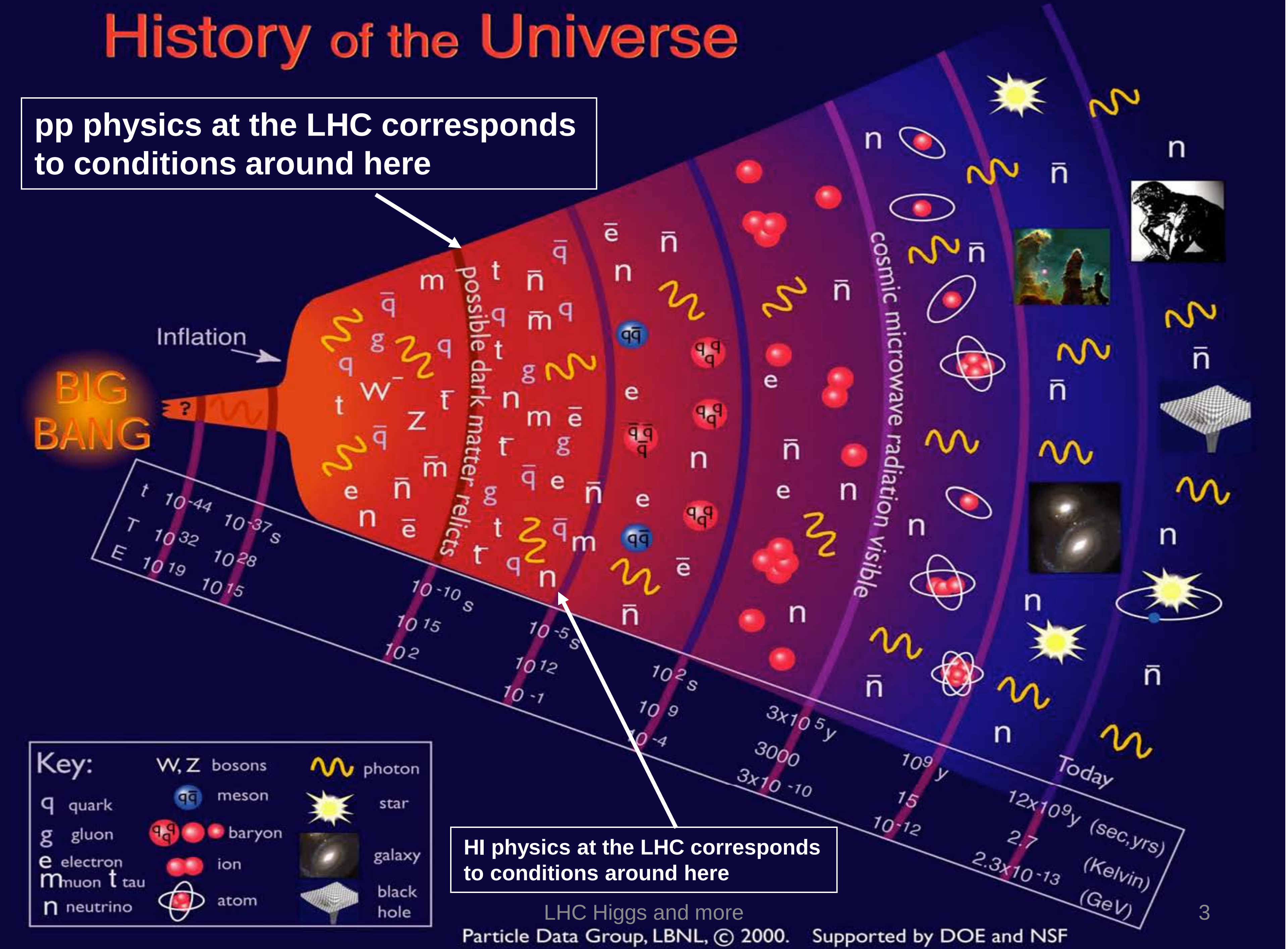
Symposium des BAdW Forums Technologie

Peter Jenni, CERN, 19.04.2013

The Large Hadron Collider project is a global scientific adventure, combining the accelerator, a worldwide computing grid and the experiments, initiated more almost 30 years ago



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

How the LHC came to be …

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

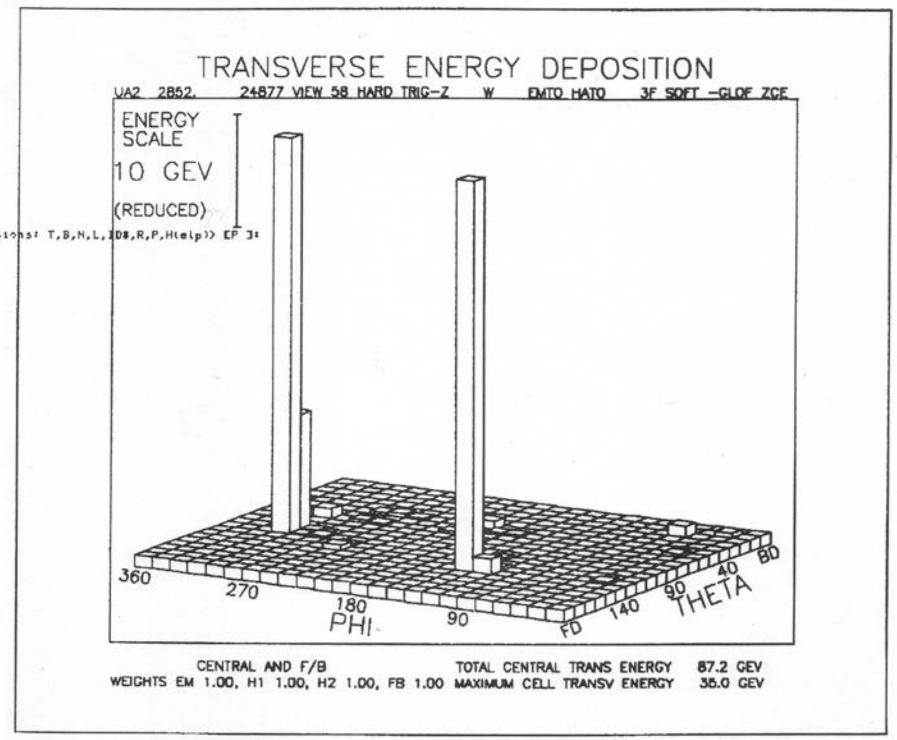
Some early key dates

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



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

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

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

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:

Staged construction was proposed by DG Chris Llewellyn Smith, but some 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

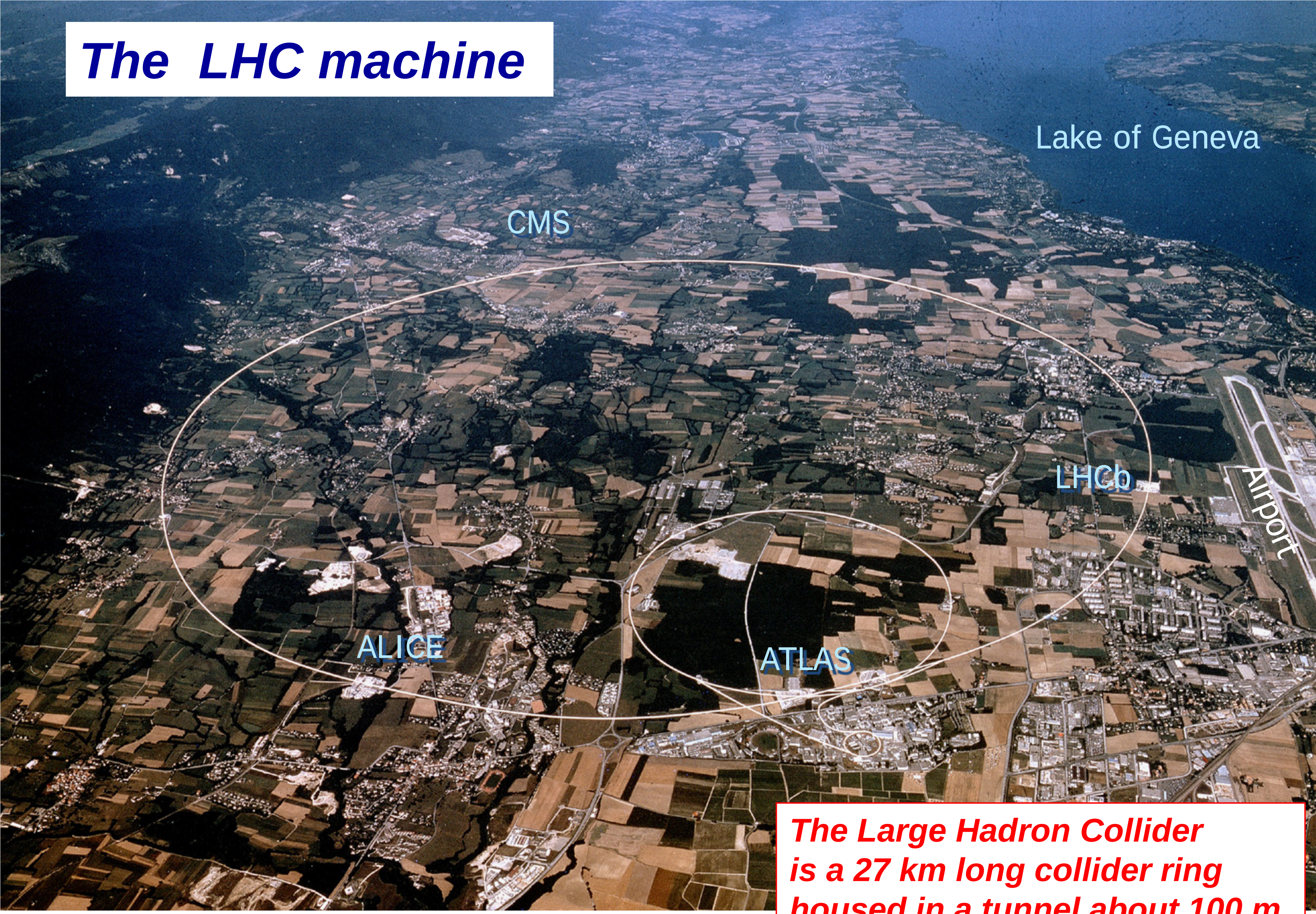
(Israel contributed all along to the full CERN programme and LHC)

1997

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 L Maiani and A Skrinsky in the centre

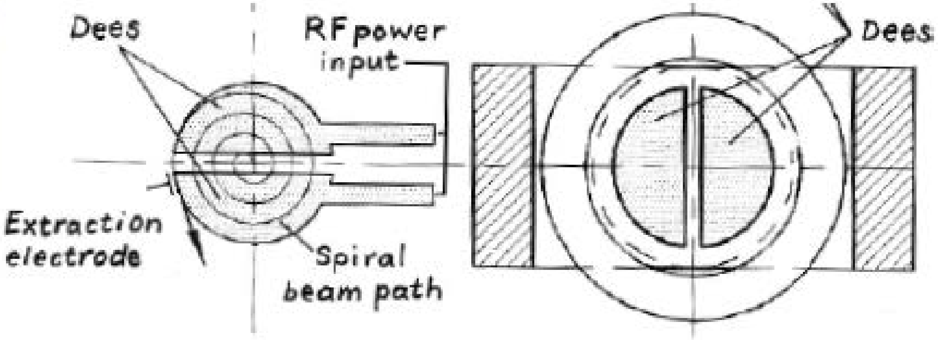
The LHC machine



The first cyclotron, and the famous 184” one of Berkeley

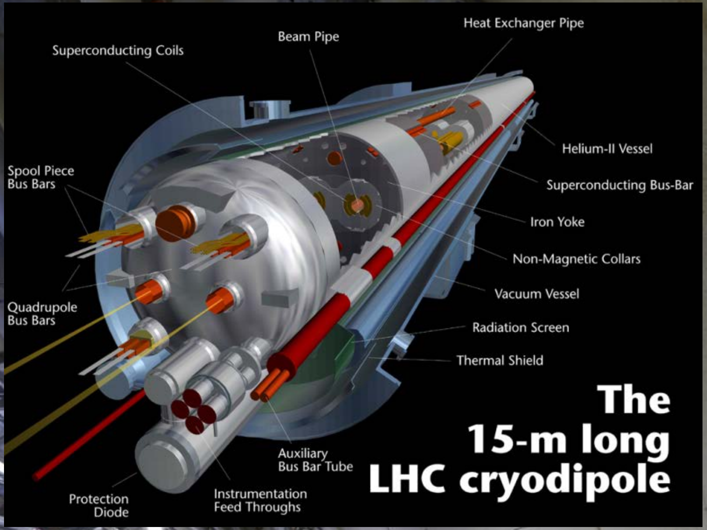
Ernest Lawrence
(1901 - 1958)

The first circular accelerator
(Berkeley 1930)



The most challenging components were the 1232 high-tech superconducting dipole magnets

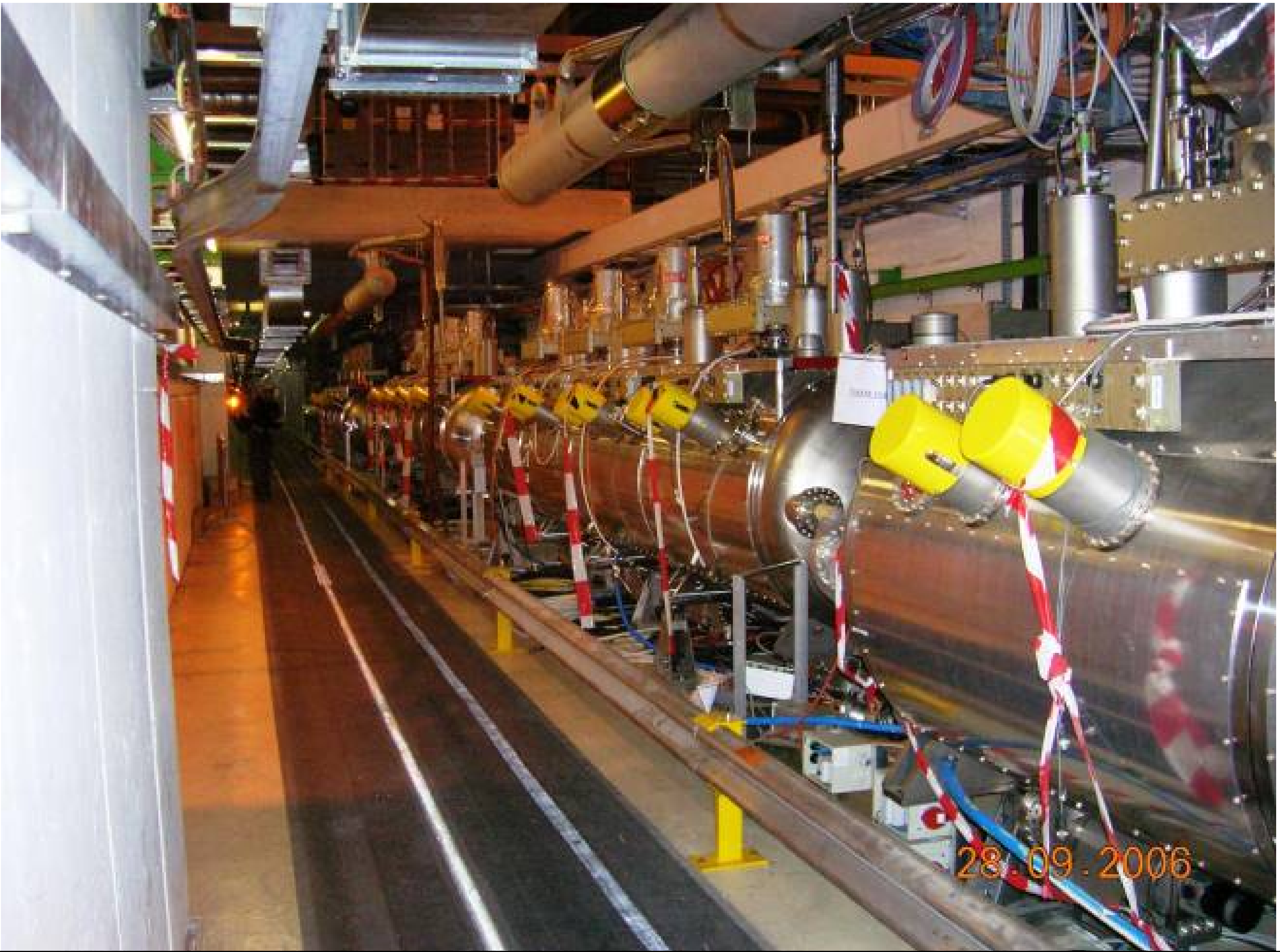
Magnetic field:	**8.4 T**
Operation temperature:	**1.9 K**
(120 tons of superfluid Helium)	
Dipole current:	**11700 A**
Stored energy:	**7 MJ**
Dipole weight:	**34 tons**
7600 km of Nb-Ti superconducting cable	

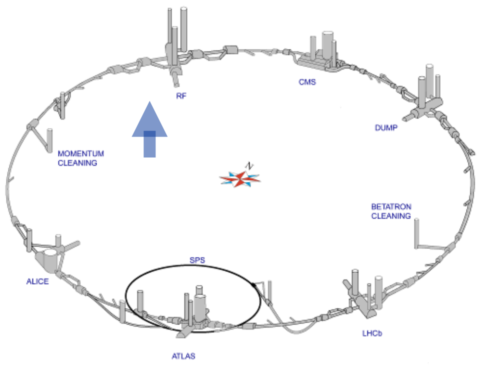


p(TeV) = 0.3 B(T) R(km)

LHC Construction Project Leader Lyndon Evans

The particle beams are accelerated by superconducting Radio-Frequency (RF) cavities

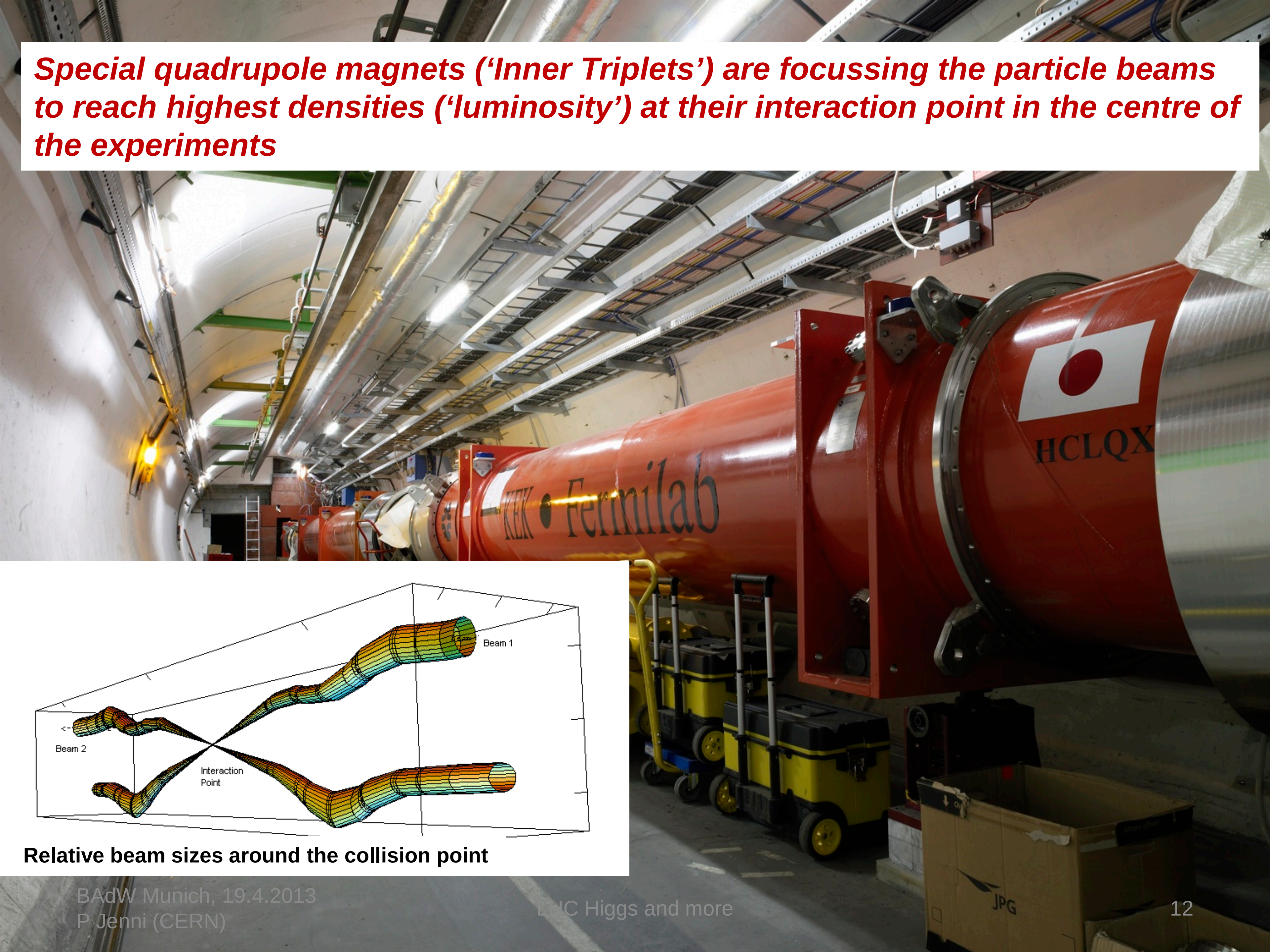




Note: The acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), because of the $\sim 1/m^4$ behaviour of the synchrotron radiation energy losses $[\sim E^4_{beam}/Rm^4]$

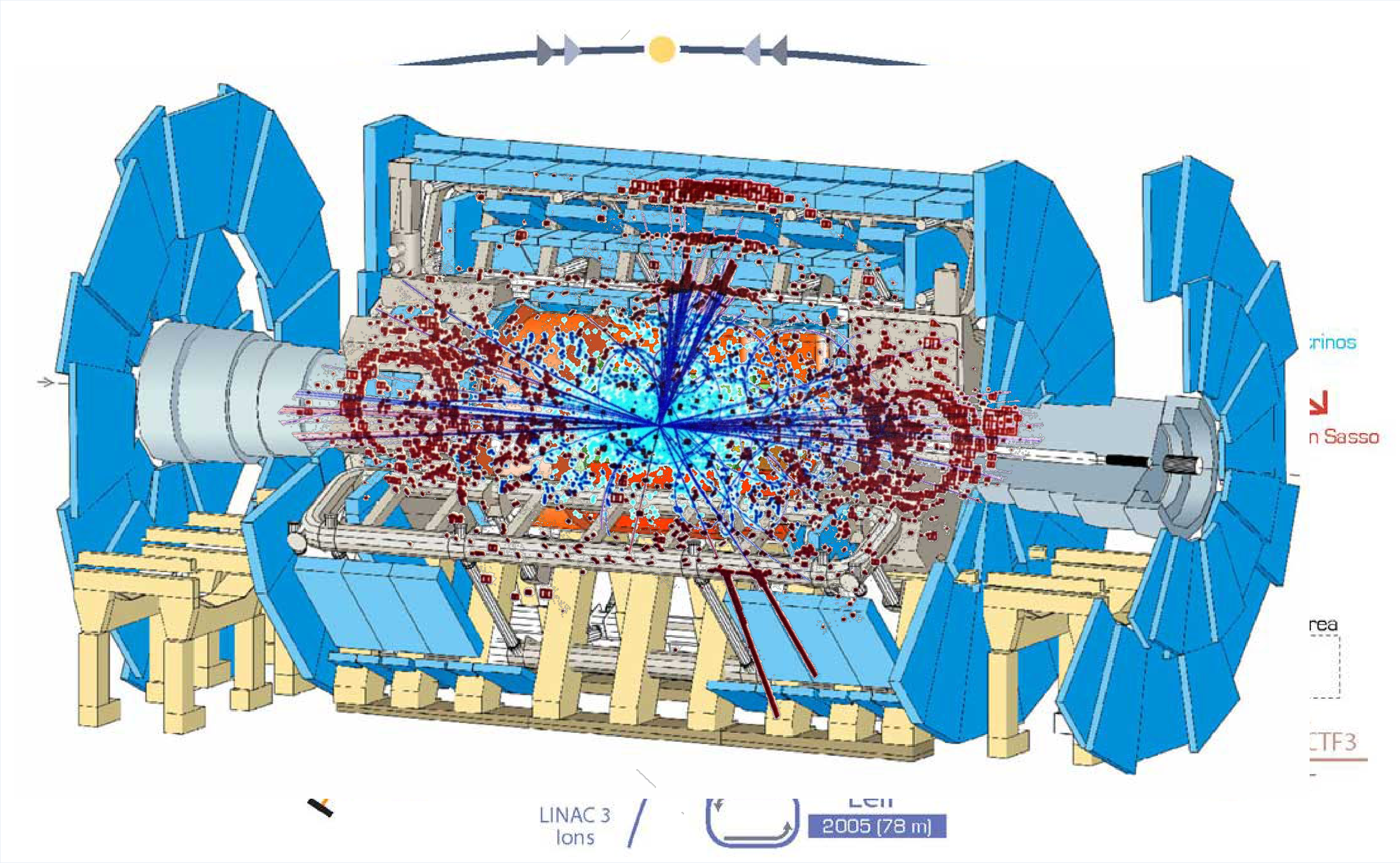
	LHC at 7 TeV	LEP at 100 GeV
Synchrotron radiation loss	6.7 keV/turn	3 GeV/turn
Peak accelerating voltage	16 MV/beam	3600 MV/beam

Special quadrupole magnets (‘Inner Triplets’) are focussing the particle beams to reach highest densities (‘luminosity’) at their interaction point in the centre of the experiments

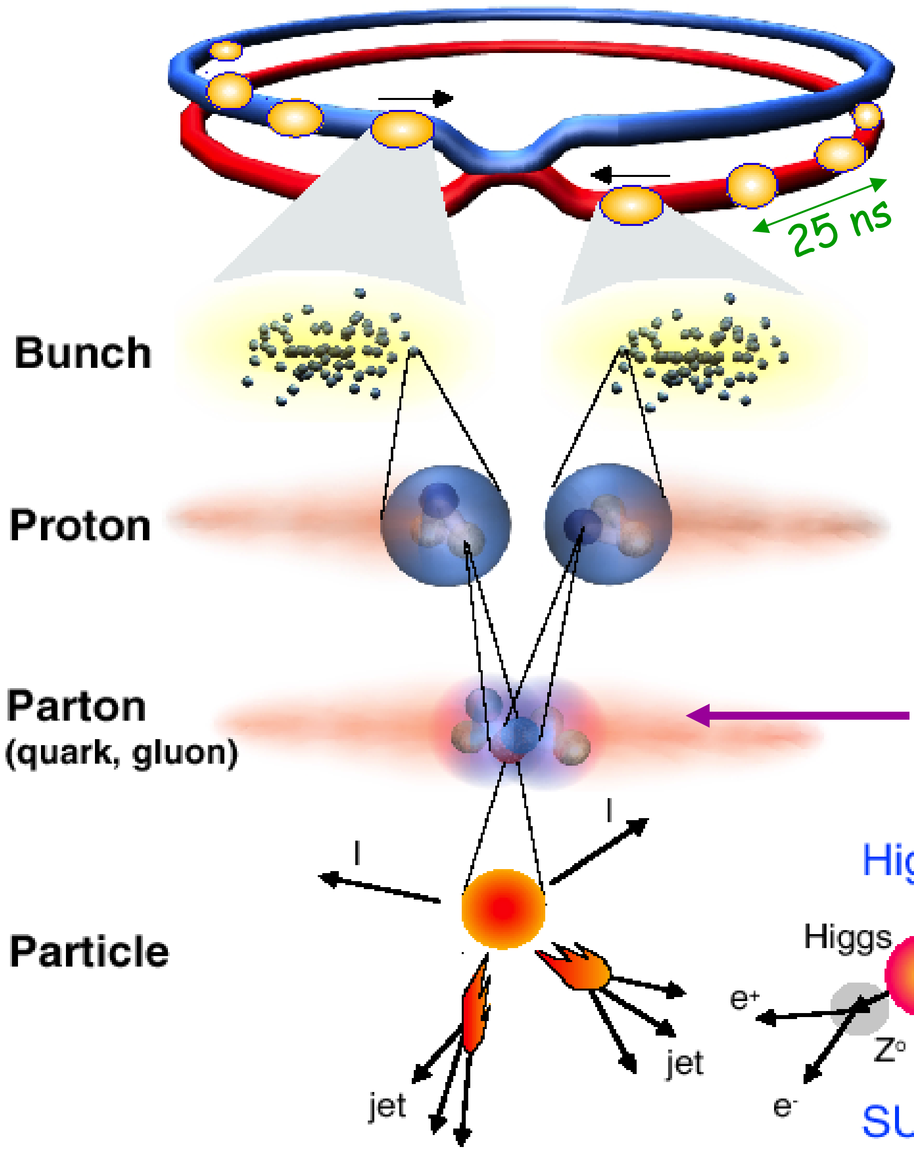


Relative beam sizes around the collision point

CERN’s particle accelerator chain



Collisions at LHC



Proton-**Proton**

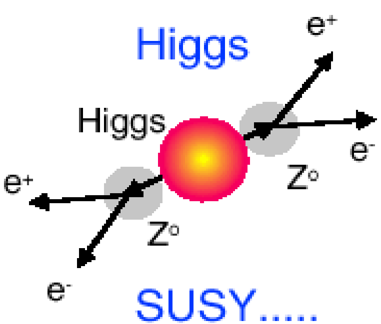
Protons/bunch	**10^{11}**
Beam energy	**7 TeV (7×10^{12} eV)**
Luminosity	**10^{34} cm^{-2} s^{-1}**

Event rate:

$N = L \times \sigma$ (pp) ≈ 10^9 interactions/s

Mostly soft (low p_T) events

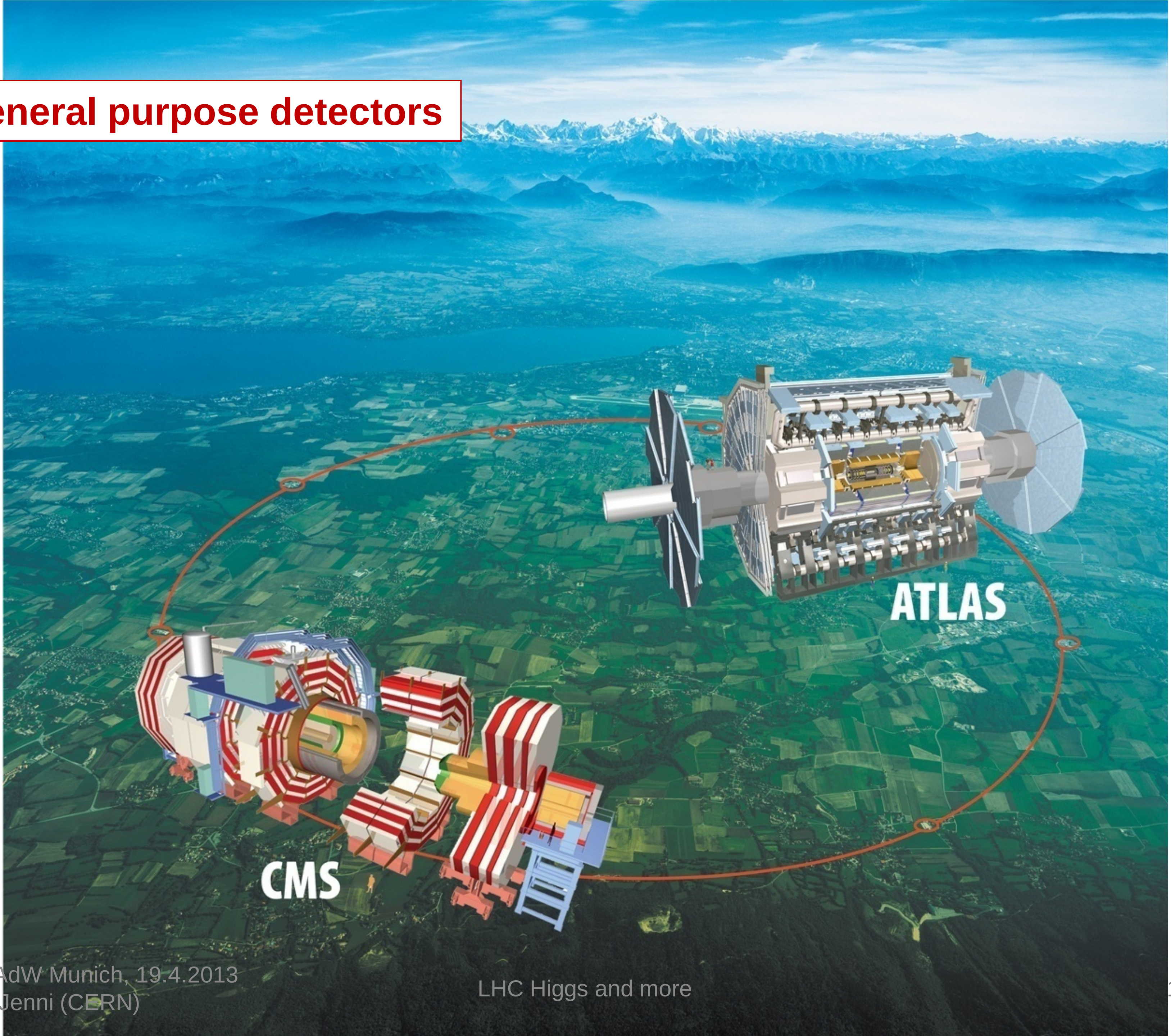
Interesting hard (high-p_T) events are rare



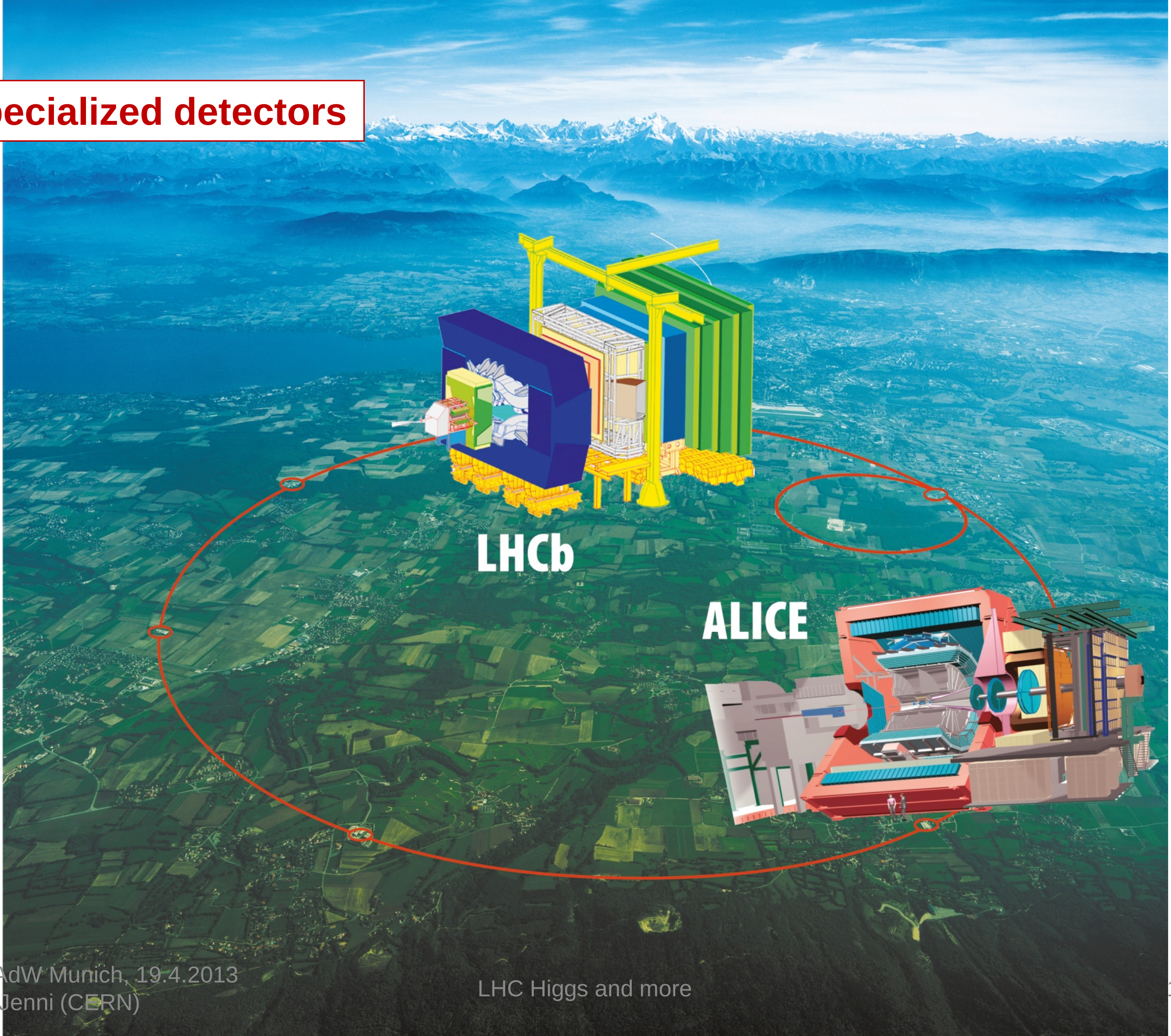
Selection of 1 in 10,000,000,000,000

→ very powerful detectors needed

General purpose detectors



Specialized detectors



The LHC World of CERN

Plus smaller local earldoms
LHCf (point-1)
TOTEM (point-5)
Moedal (point-8)

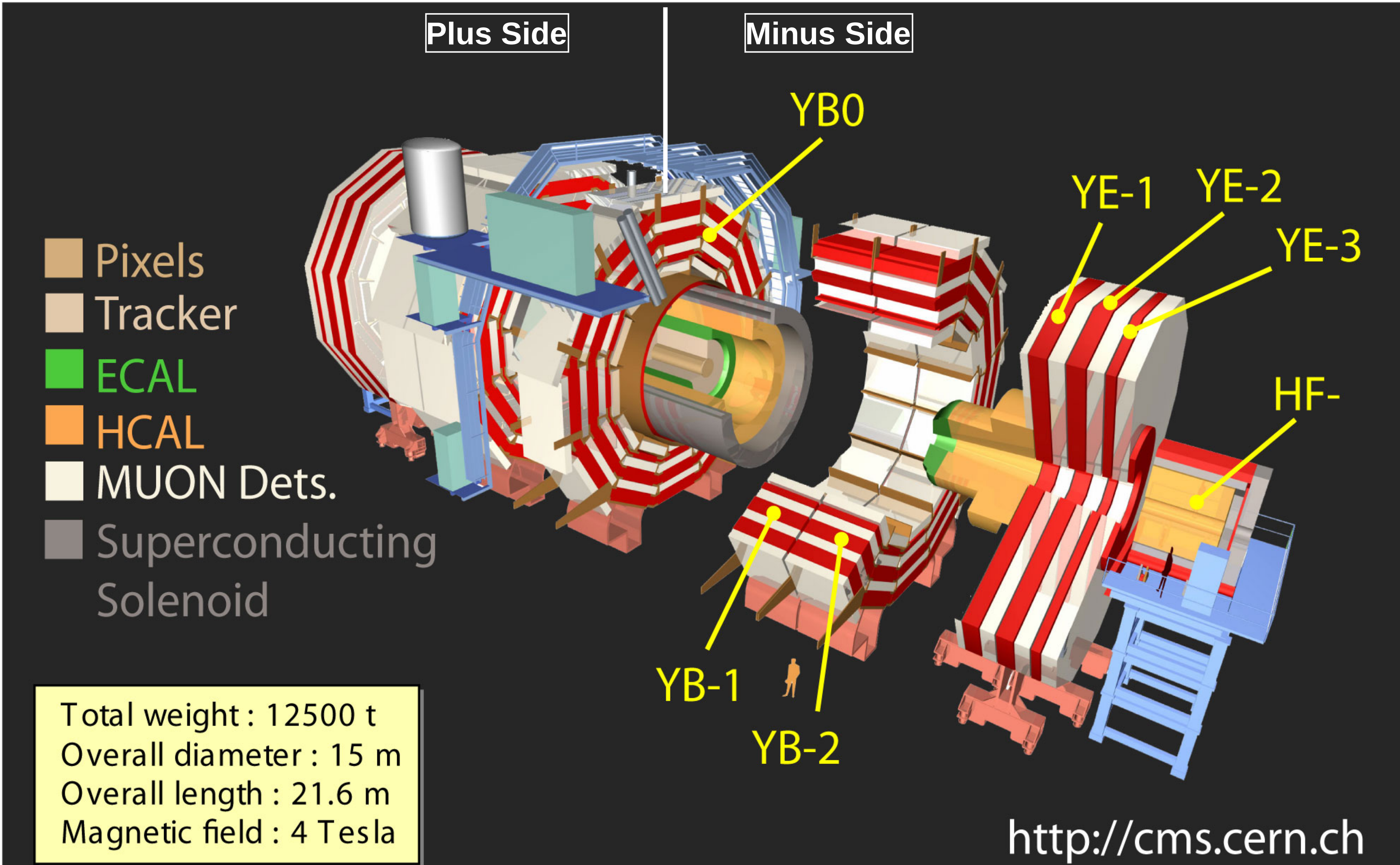
CMS
3000 Physicists
184 Institutions
38 countries
550 MCHF

ALICE
1300 Physicists
130 Institutions
35 countries
160 MCHF

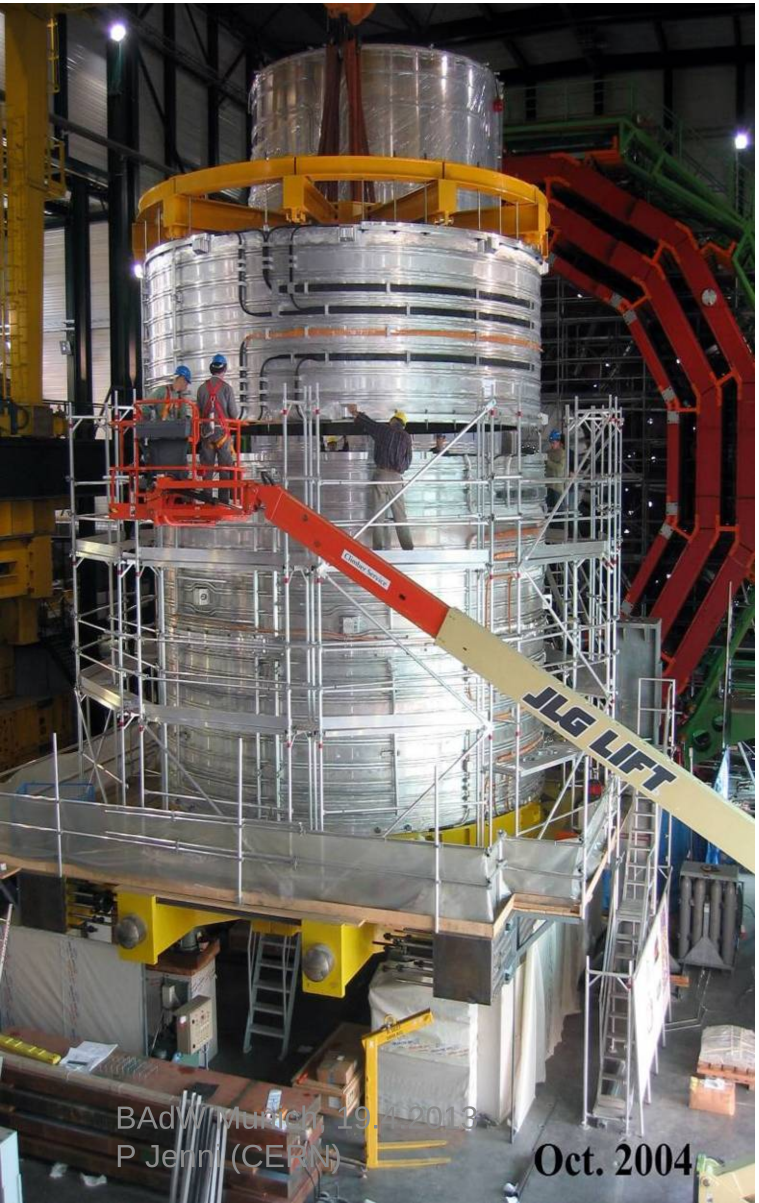
LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

ATLAS
3000 Physicists
176 Institutions
38 countries
550 MCHF

Exploded View of CMS



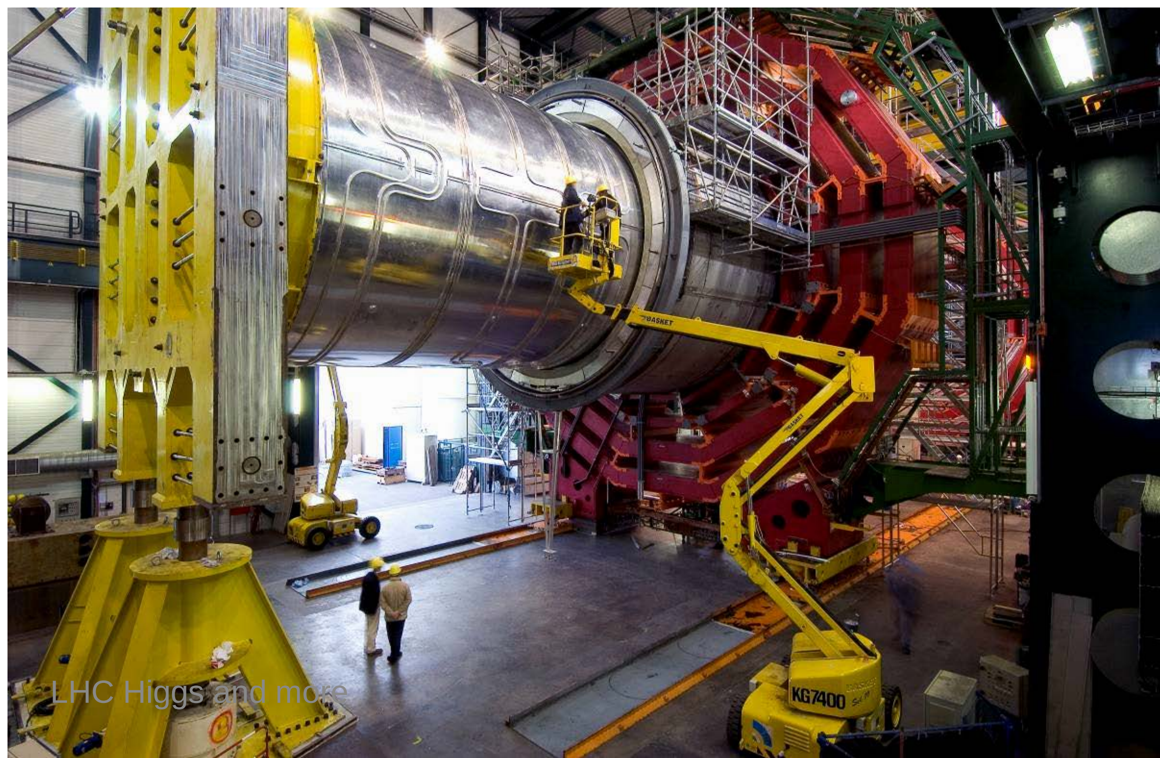
An Example of an Engineering Challenge: CMS Solenoid



<u>CMS solenoid:</u>

Magnetic length	**12.5 m**
Diameter	**6 m**
Magnetic field	**4 T**
Nominal current	**20 kA**
Stored energy	**2.7 GJ**

Tested at full current in Summer 2006



CMS before closure 2008

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

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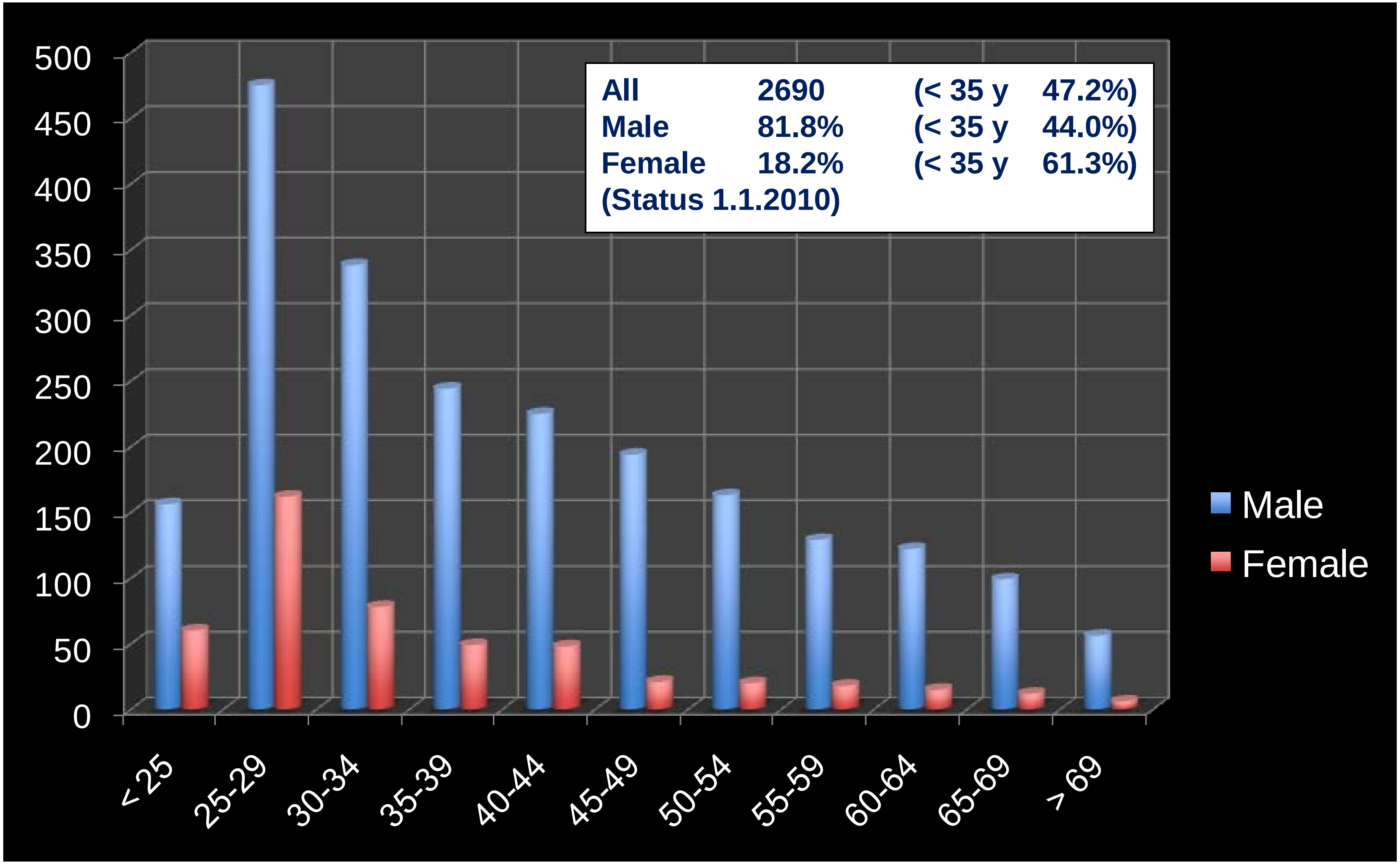
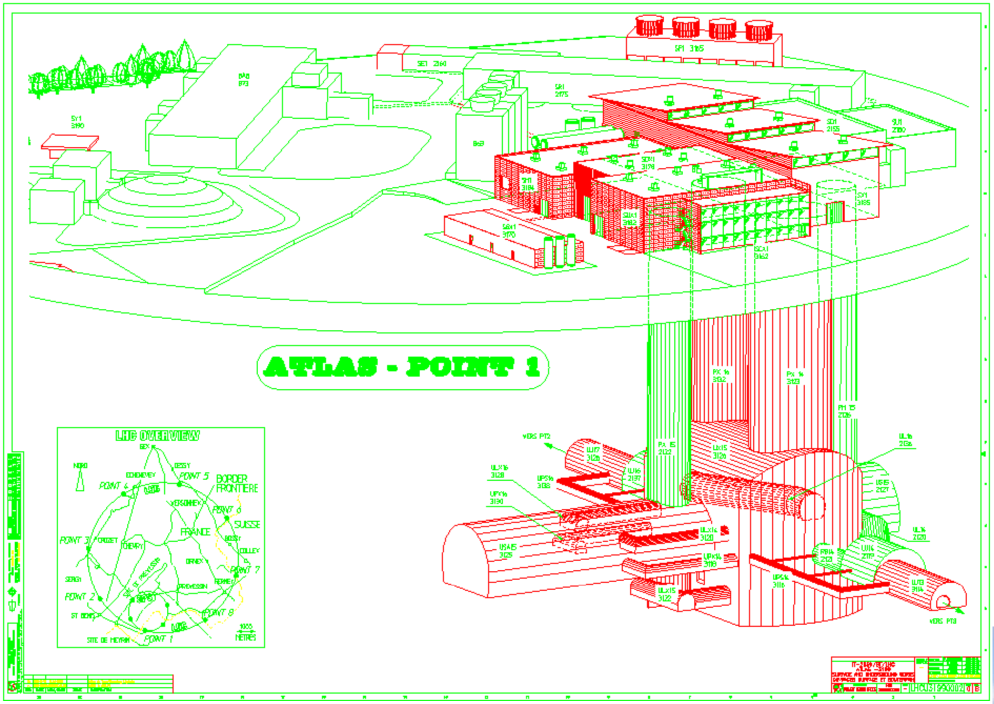
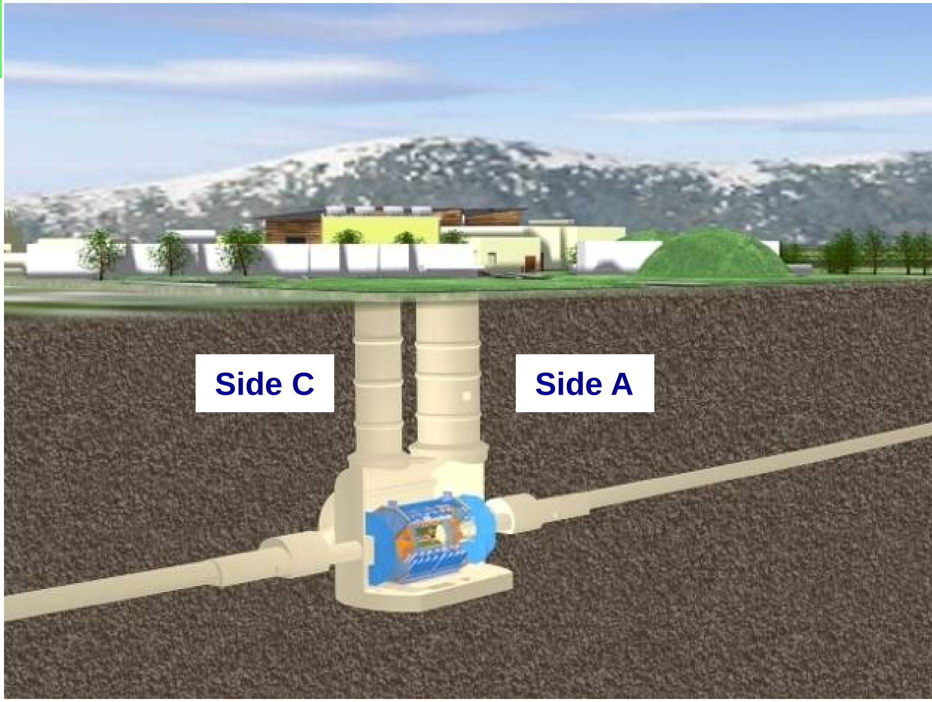
Age distribution of the ATLAS population

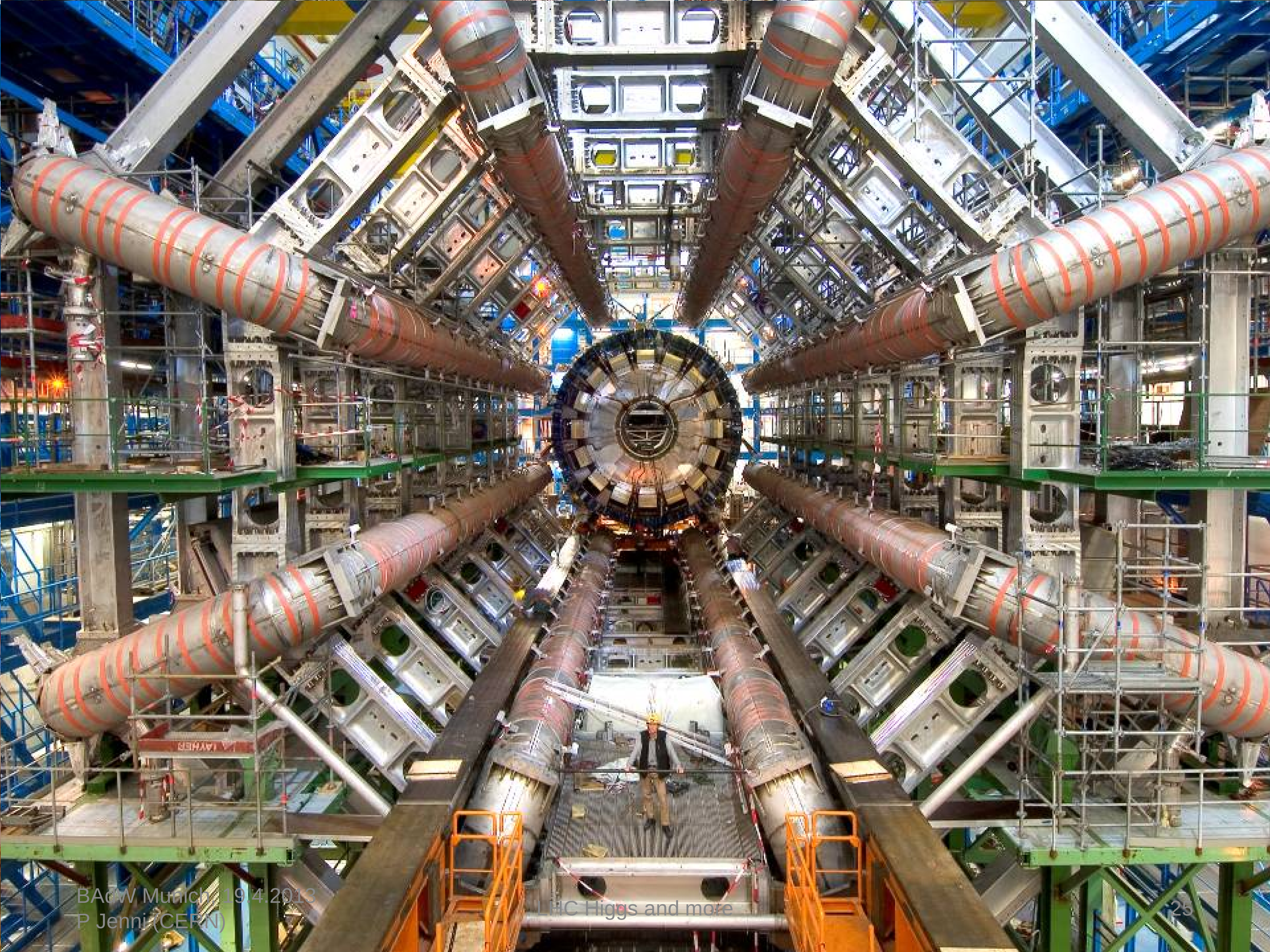


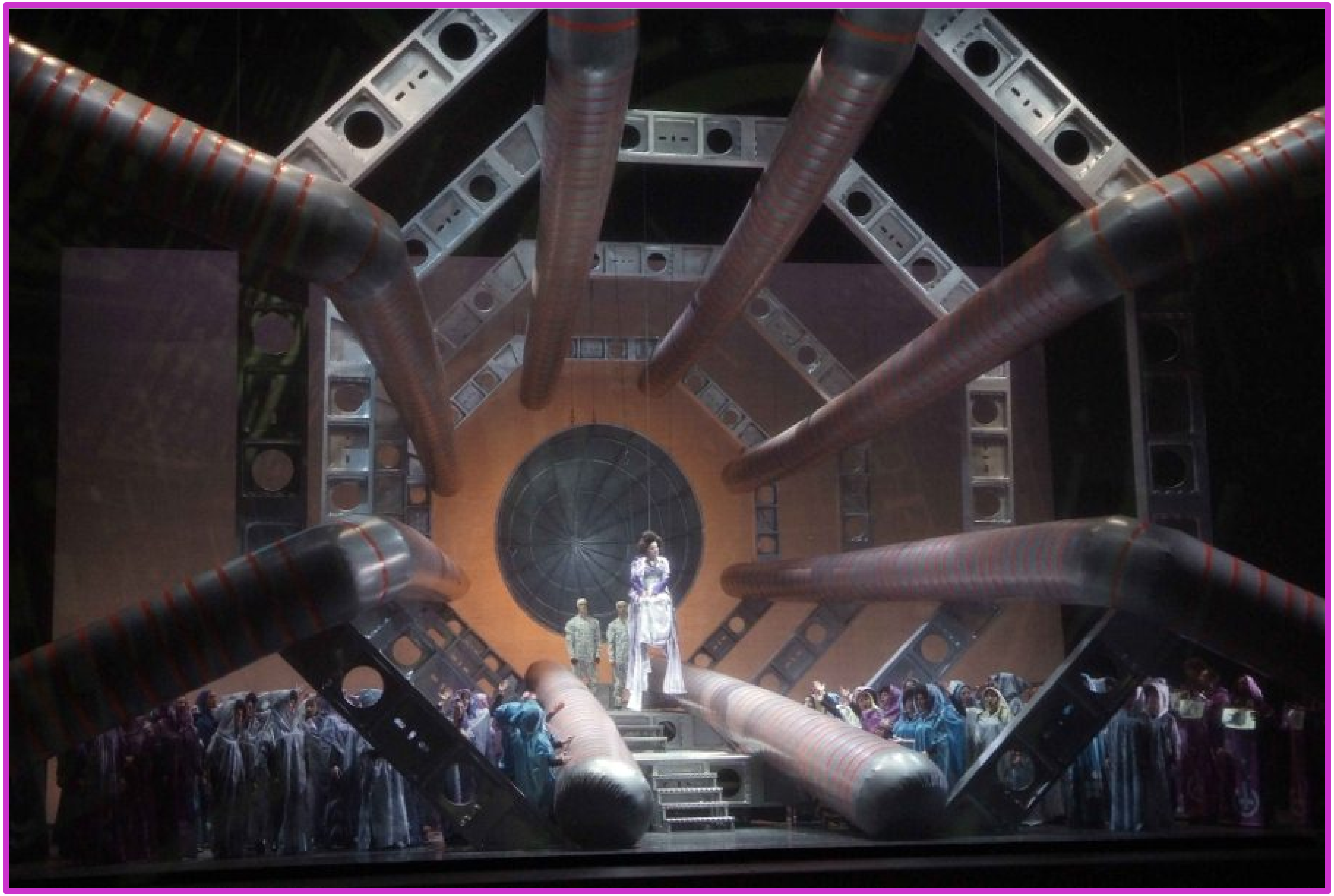


The Underground Cavern at Point-1 for the ATLAS Detector

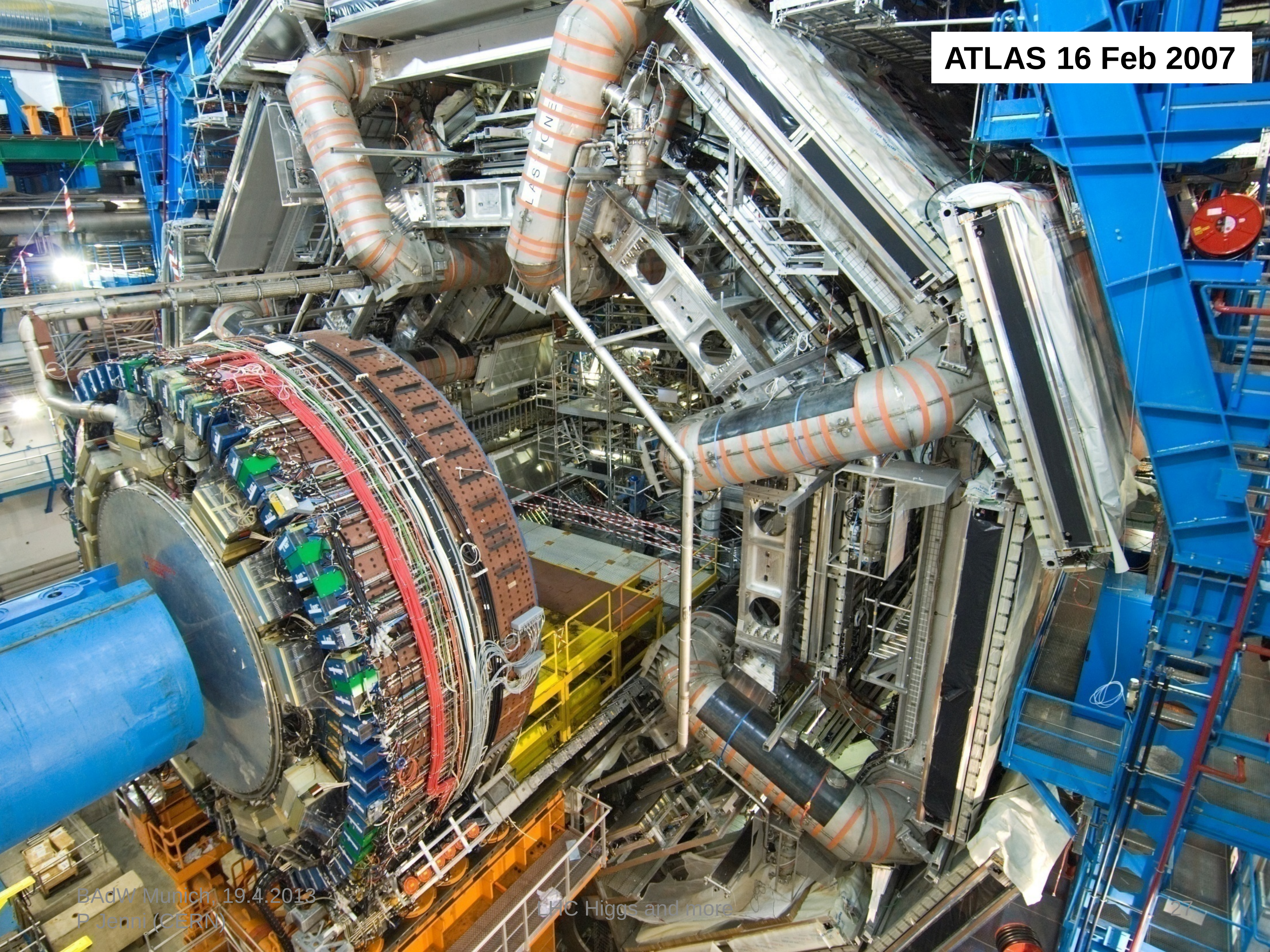
Length = 55 m
Width = 32 m
Height = 35 m

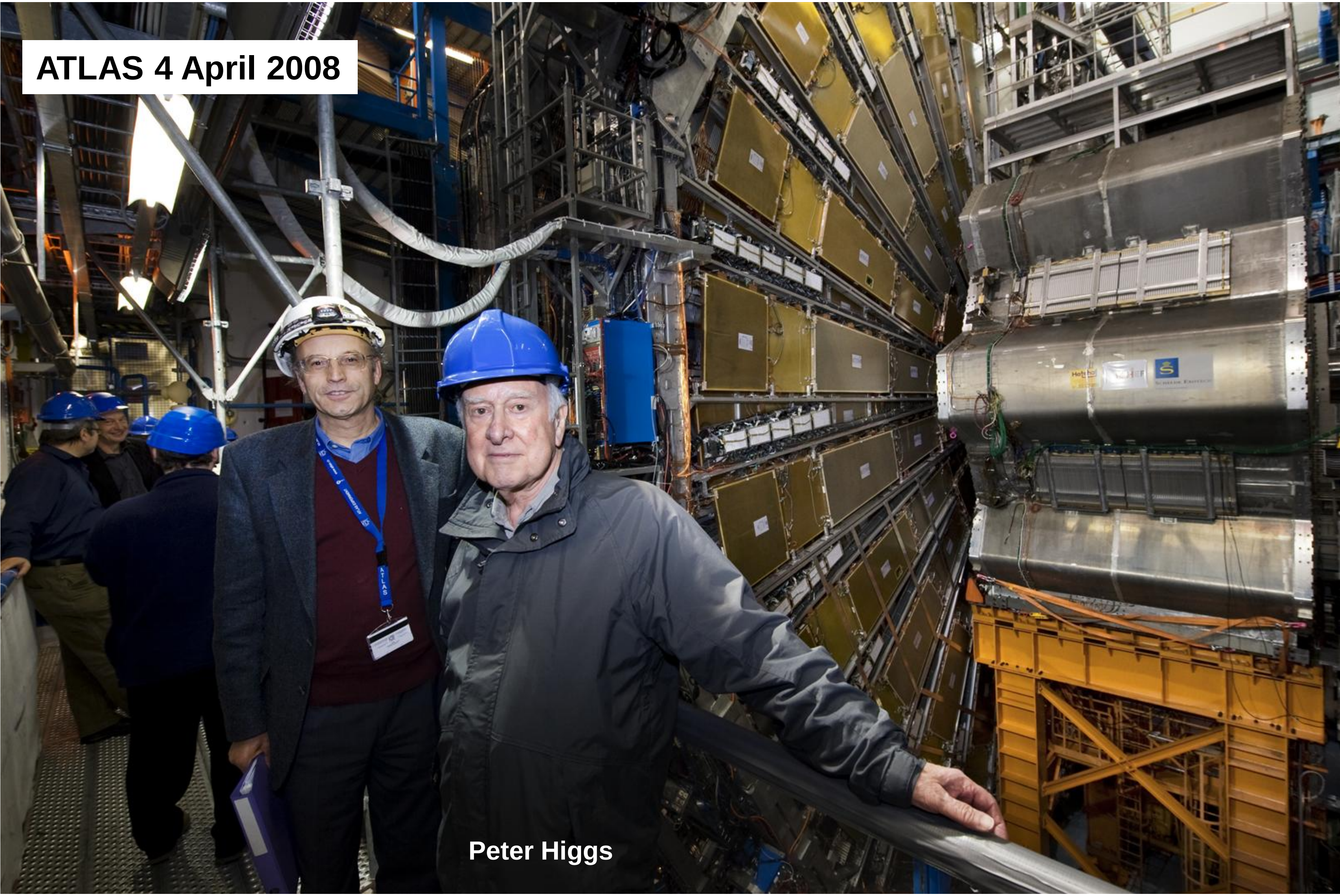






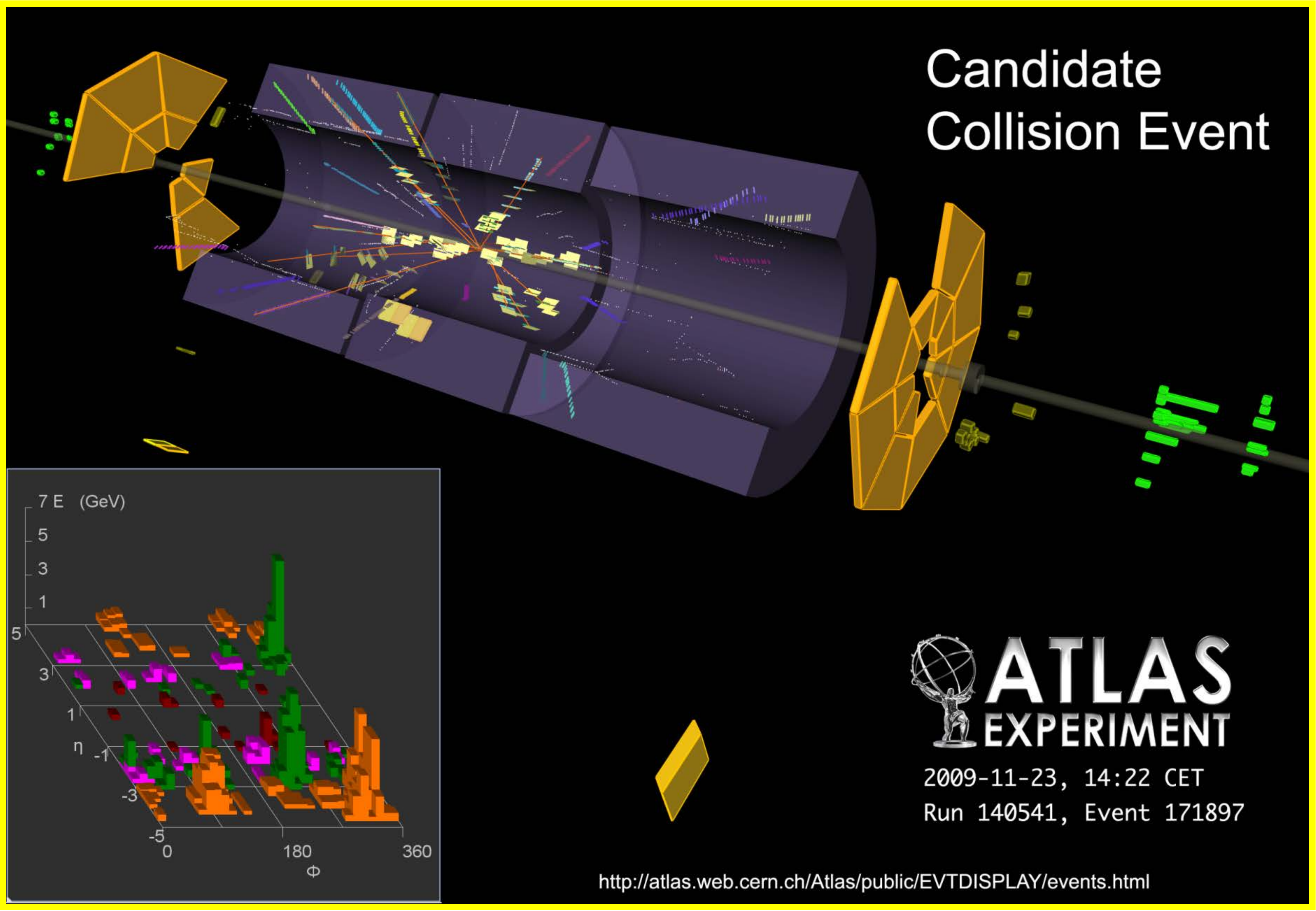
Hector Berlioz, “Les Troyens”, opera in five acts
Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009


ATLAS 16 Feb 2007


ATLAS 4 April 2008
Peter Higgs

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

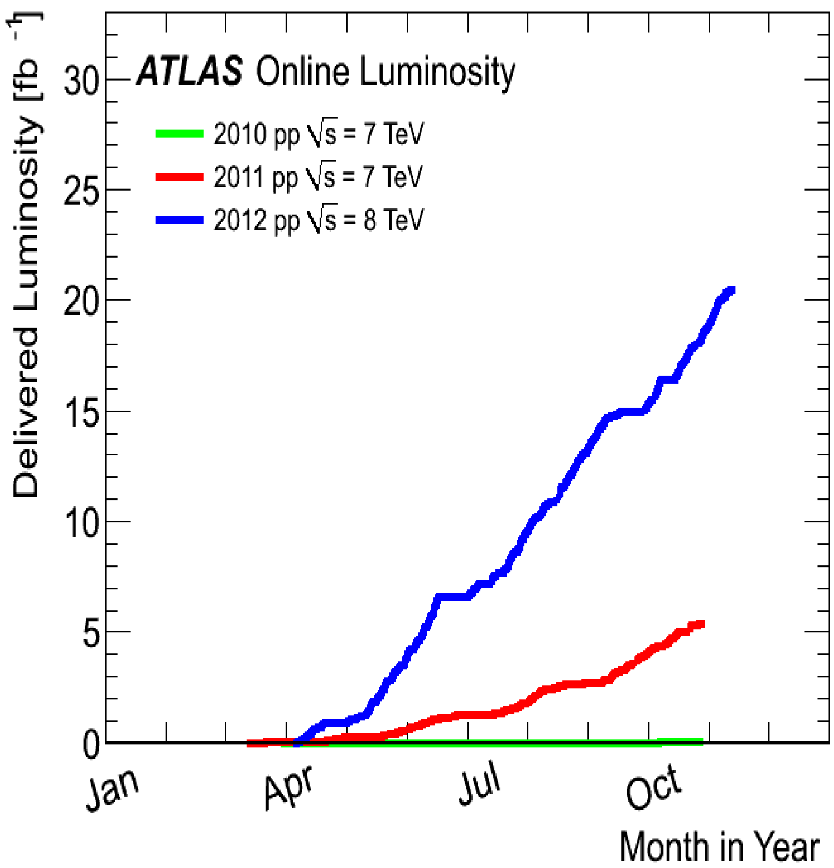
First collisions at the LHC end of November 2009 with beams at the injection energy of 450 GeV

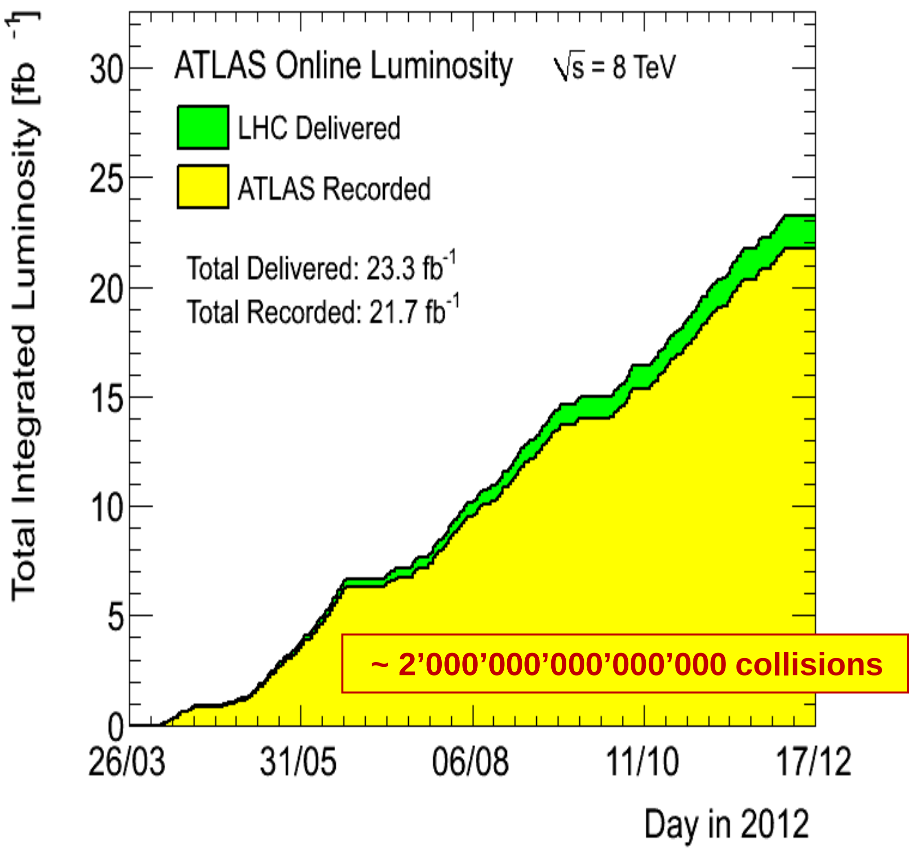


The LHC and experiments performances were simply fantastic over the last three years

Total integrated luminosity

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

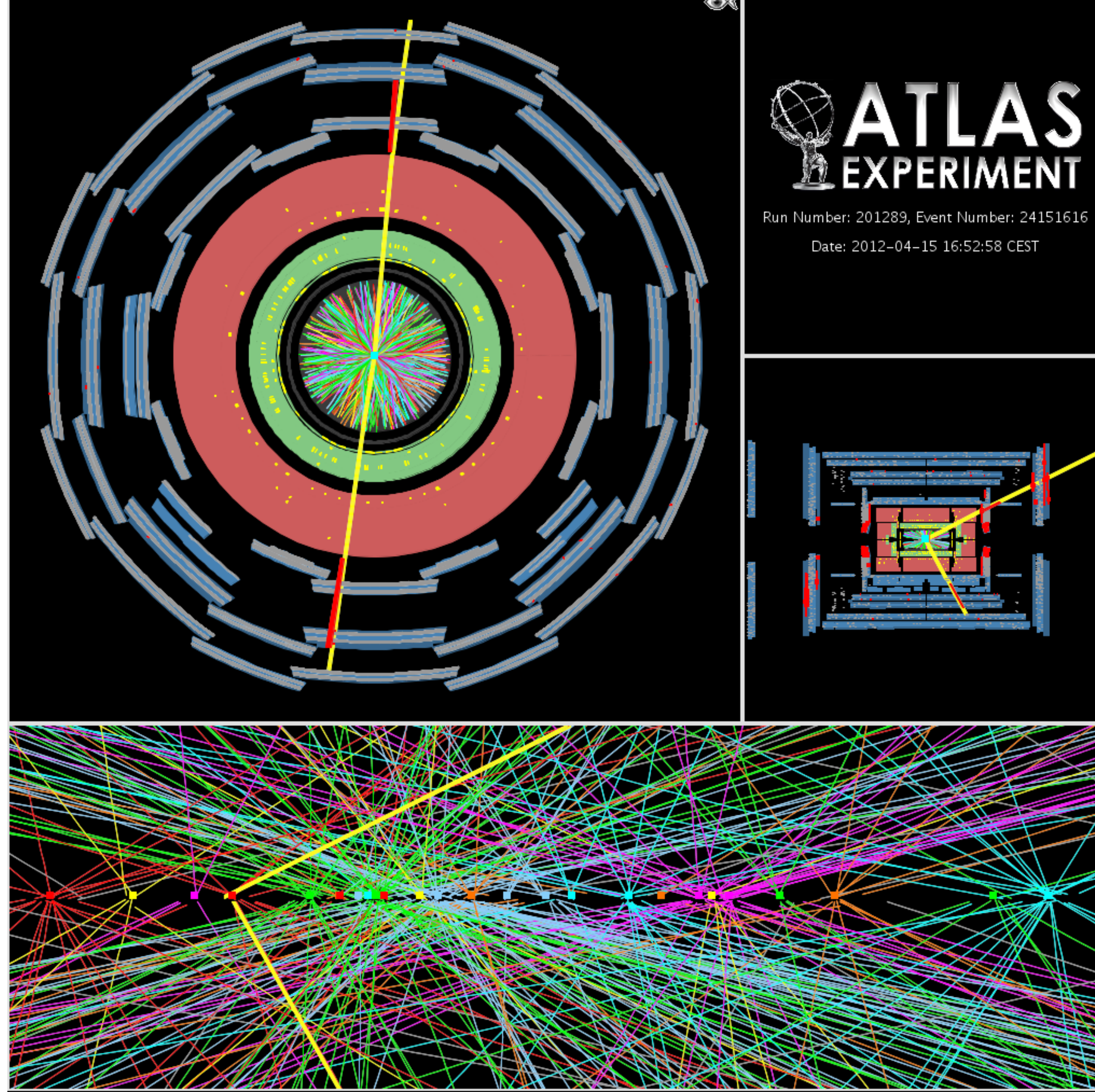




The experiment records typically 94% of the stably delivered luminosity, and uses up to 90% of the LHC luminosity in the final analyses!

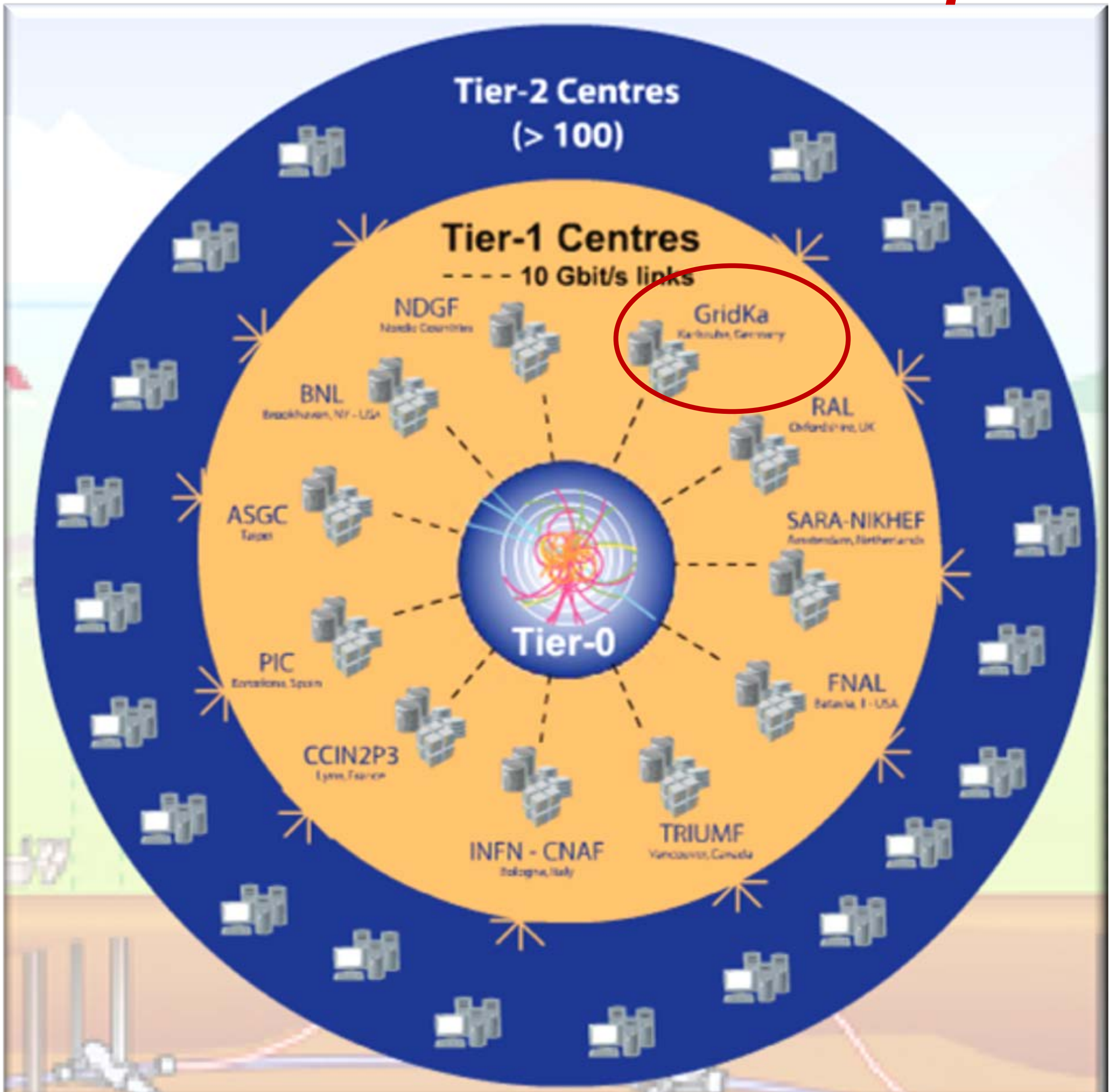
Excellent LHC performance is a (nice) challenge for the experiment:

- **Trigger**
- **Pile-up**
- **Maintain accuracy of the the measurements in this environment**



Inner Detector for a Z → μμ event with 25 primary vertices

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

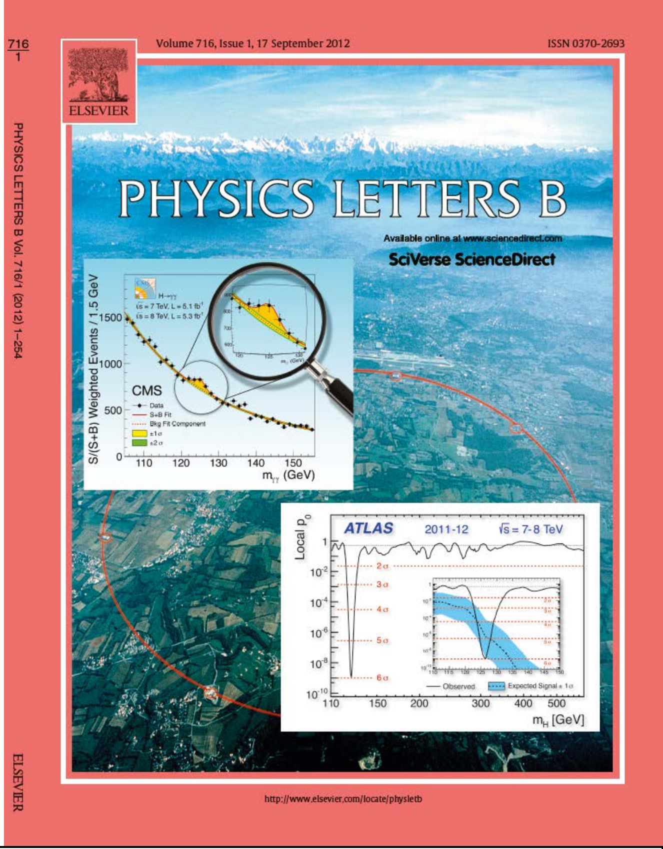
Physics Highlights

ATLAS and CMS have already published together more than 400 papers in scientific journals (and many more as public conference notes…)

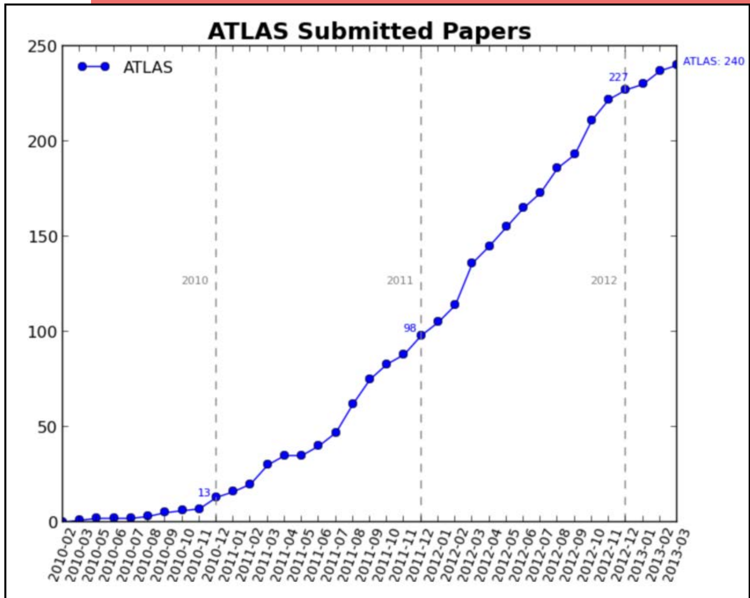
The other experiments, ALICE, LHCb, LHCf, and TOTEM total another 150 journal publications together

It is clearly not possible to cover all these results…

No attempt is made to show in a democratic way, for example, CMS and ATLAS results, but examples are given that are meant to represent the others as well where applicable...



Note that all public results are available from the experiments Web pages, and from the CERN Document Server
http://cdsweb.cern.ch/collection/LHC%20Experiments?ln=en



Physics Highlights:

General event properties

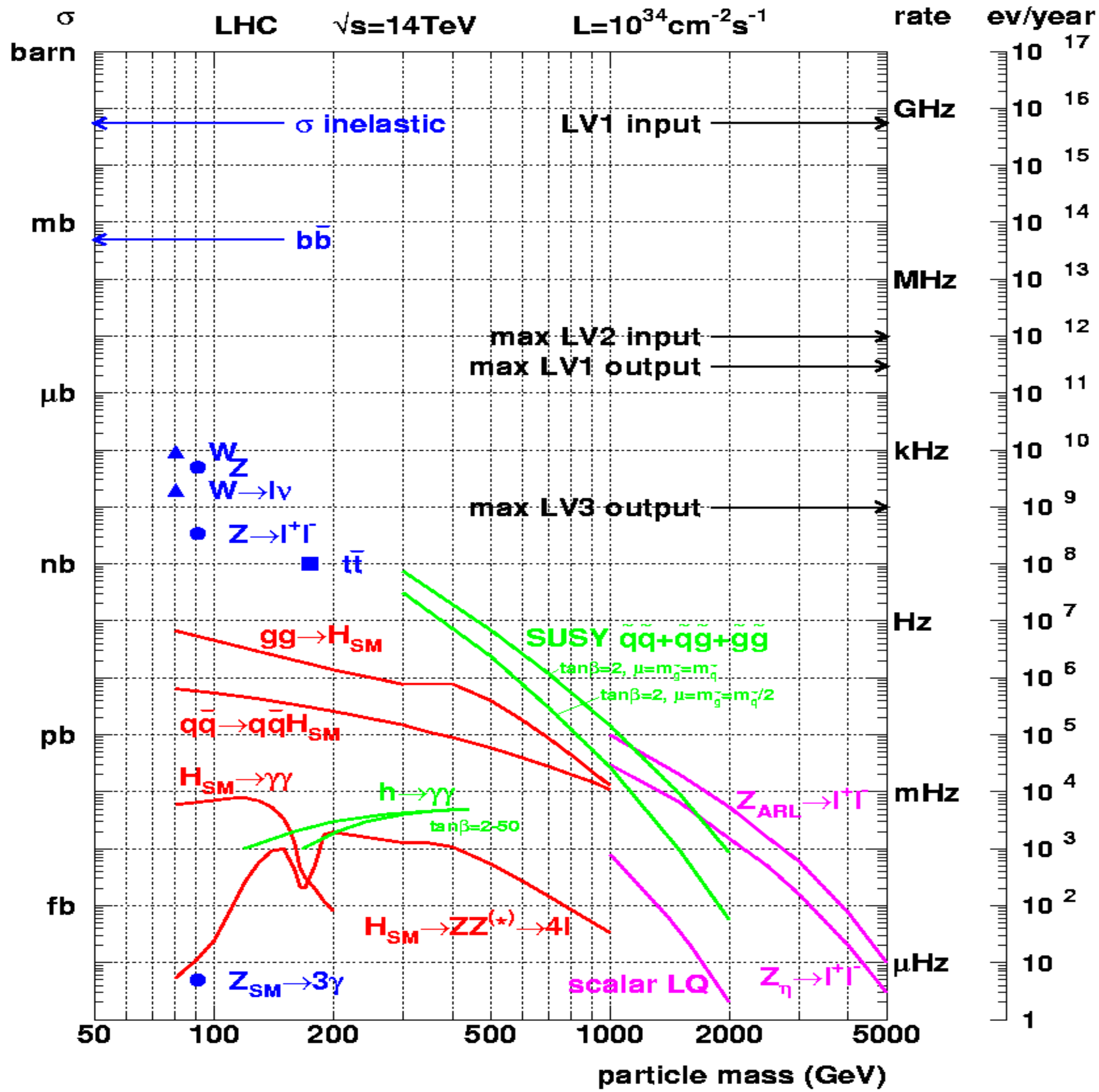
Heavy flavour physics

Standard Model physics including QCD jets

Higgs searches

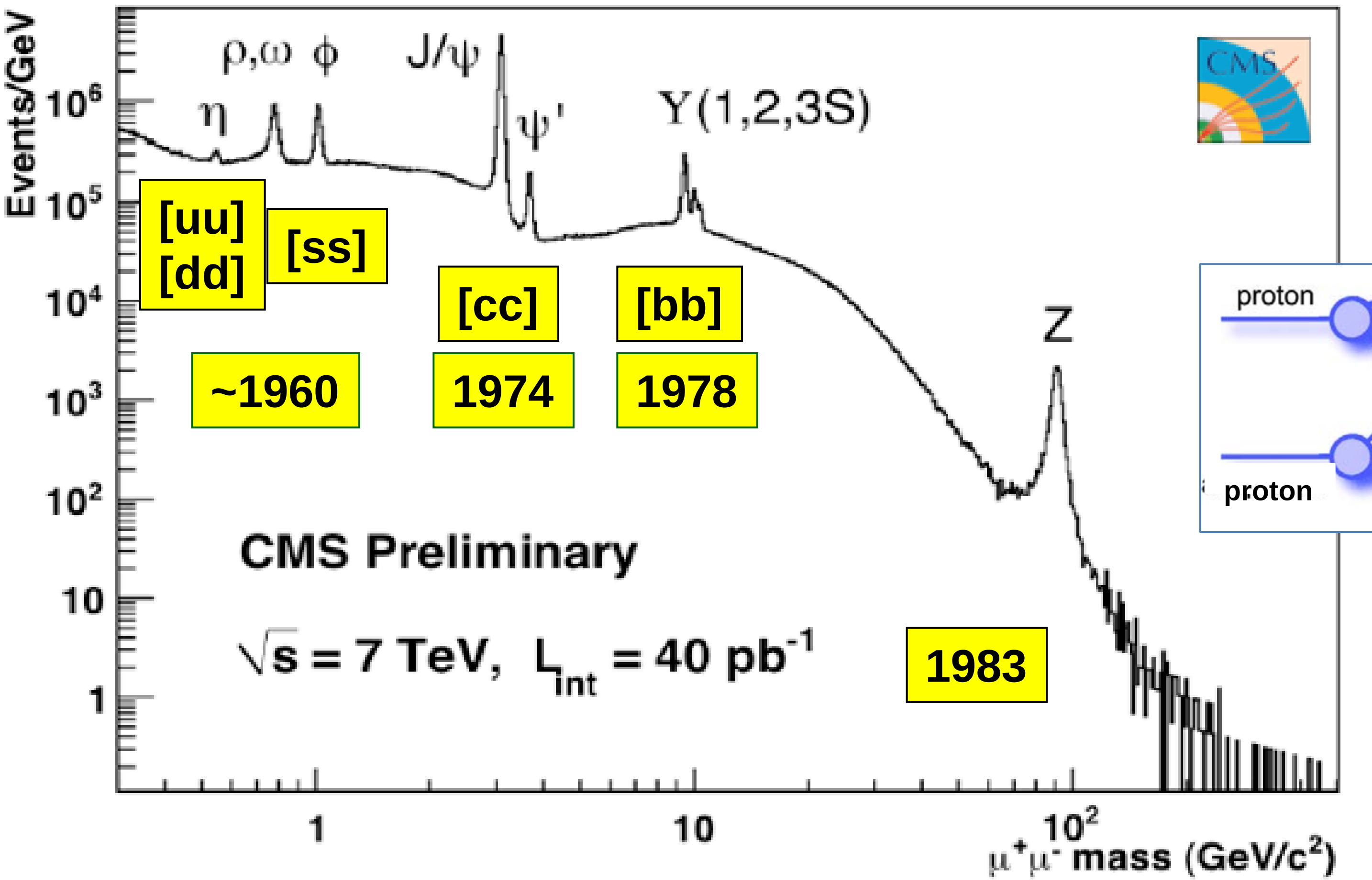
Searches for SUSY

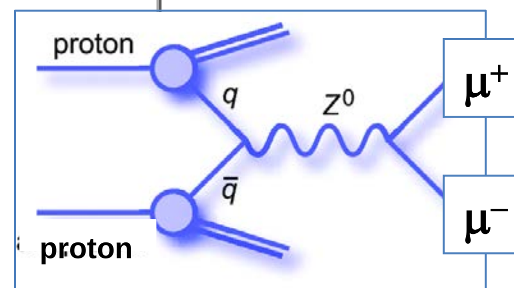
Examples of searches for ‘exotic’ new physics



2010

Data corresponding to ~40 pb^{-1} collected
→ re-discovery of the Standard Model

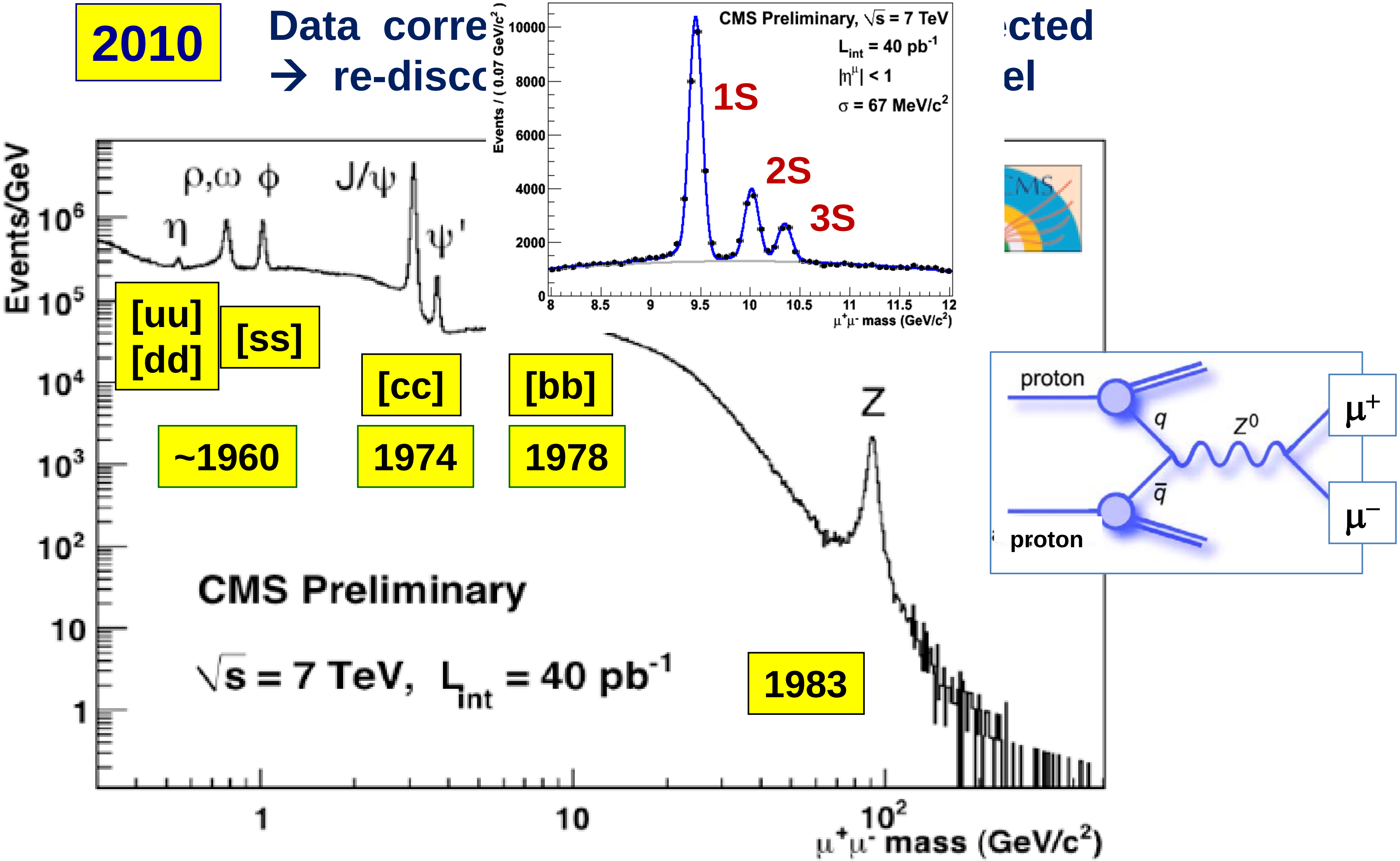




The di-muon spectrum recalls a long period of particle physics:
Well known quark-antiquark resonances (bound states) appear "online"

2010

Data corre... cted
→ re-discc... el



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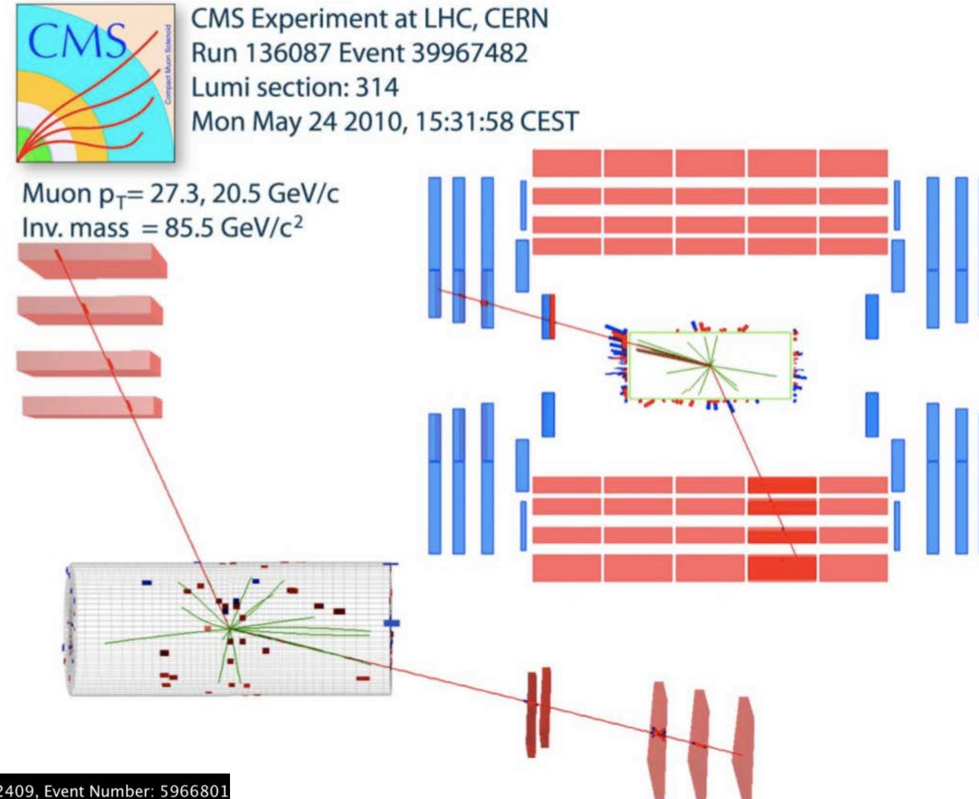
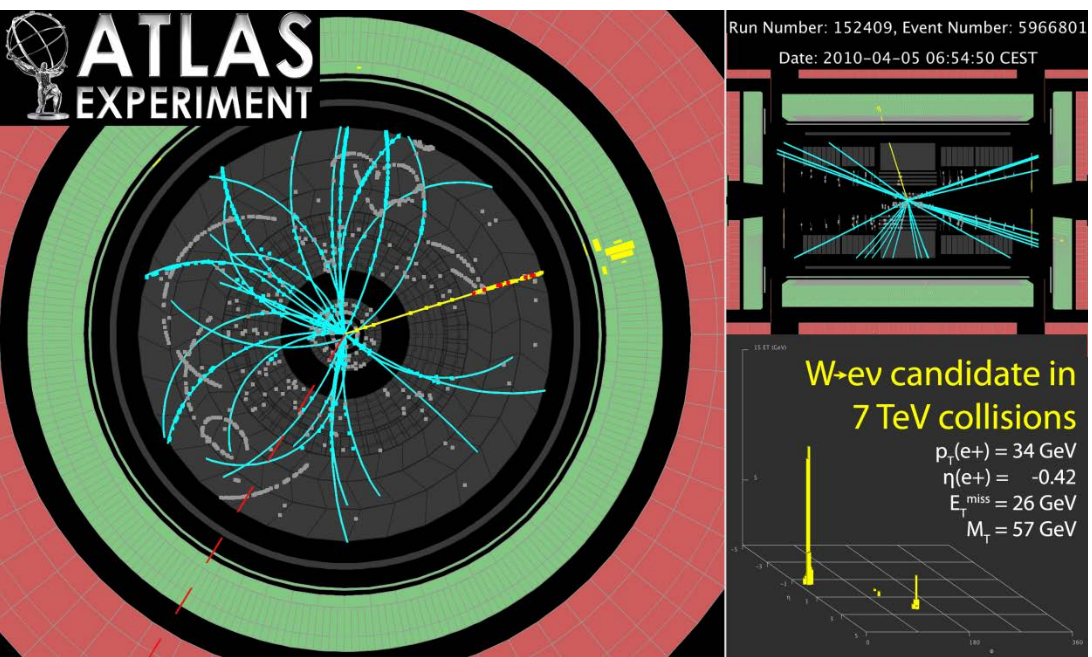
Well known quark-antiquark resonances (bound states) appear "online"

Standard Model Physics

Candidate Z → $\mu^+\mu^-$



W → eν candidate



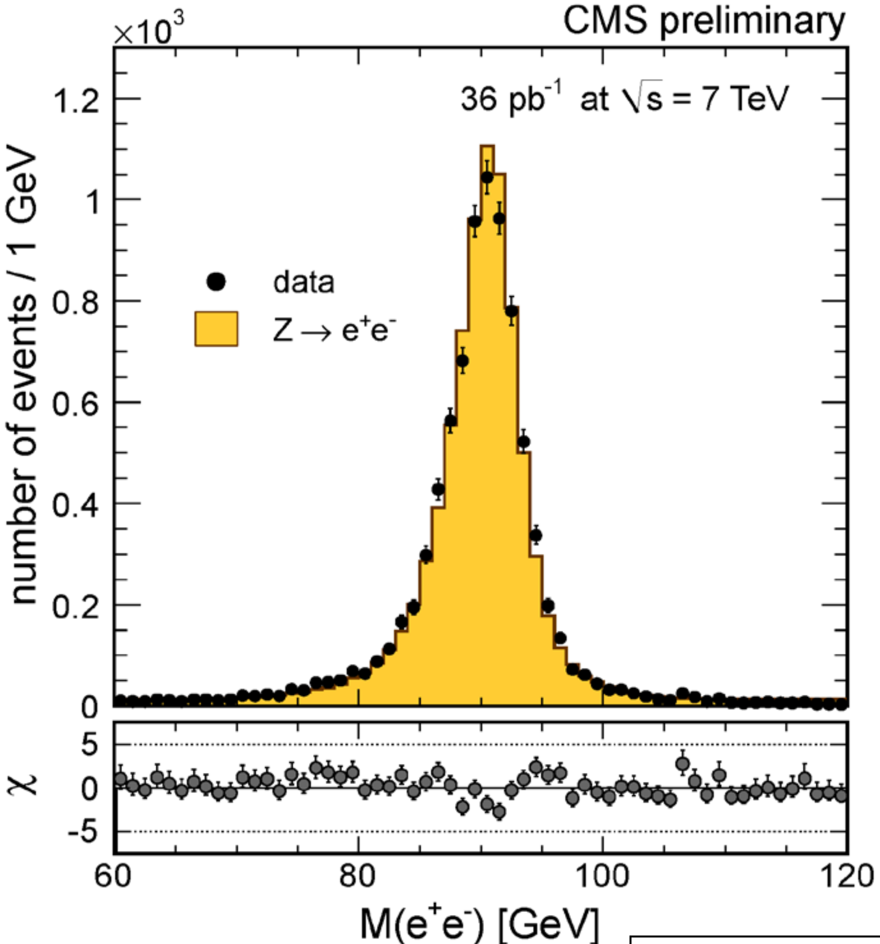
Today each ATLAS and CMS have in their data more than:

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

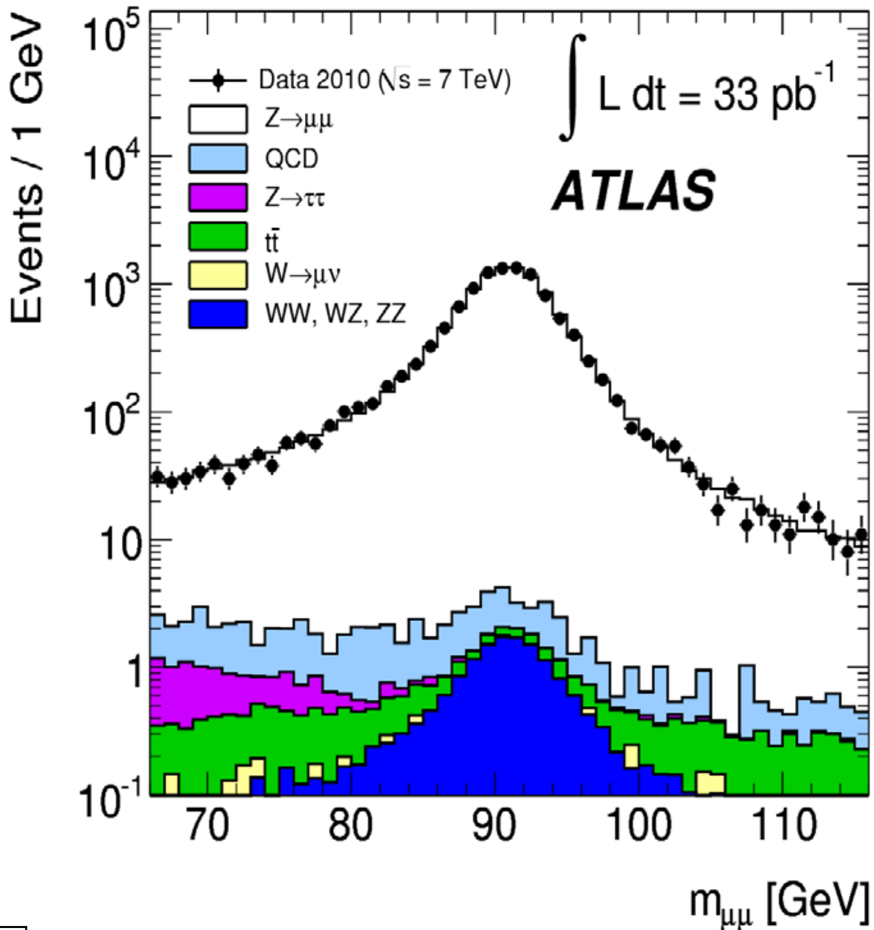
after all selection cuts

Z and W production

Phys Rev D85 (2012) 072004



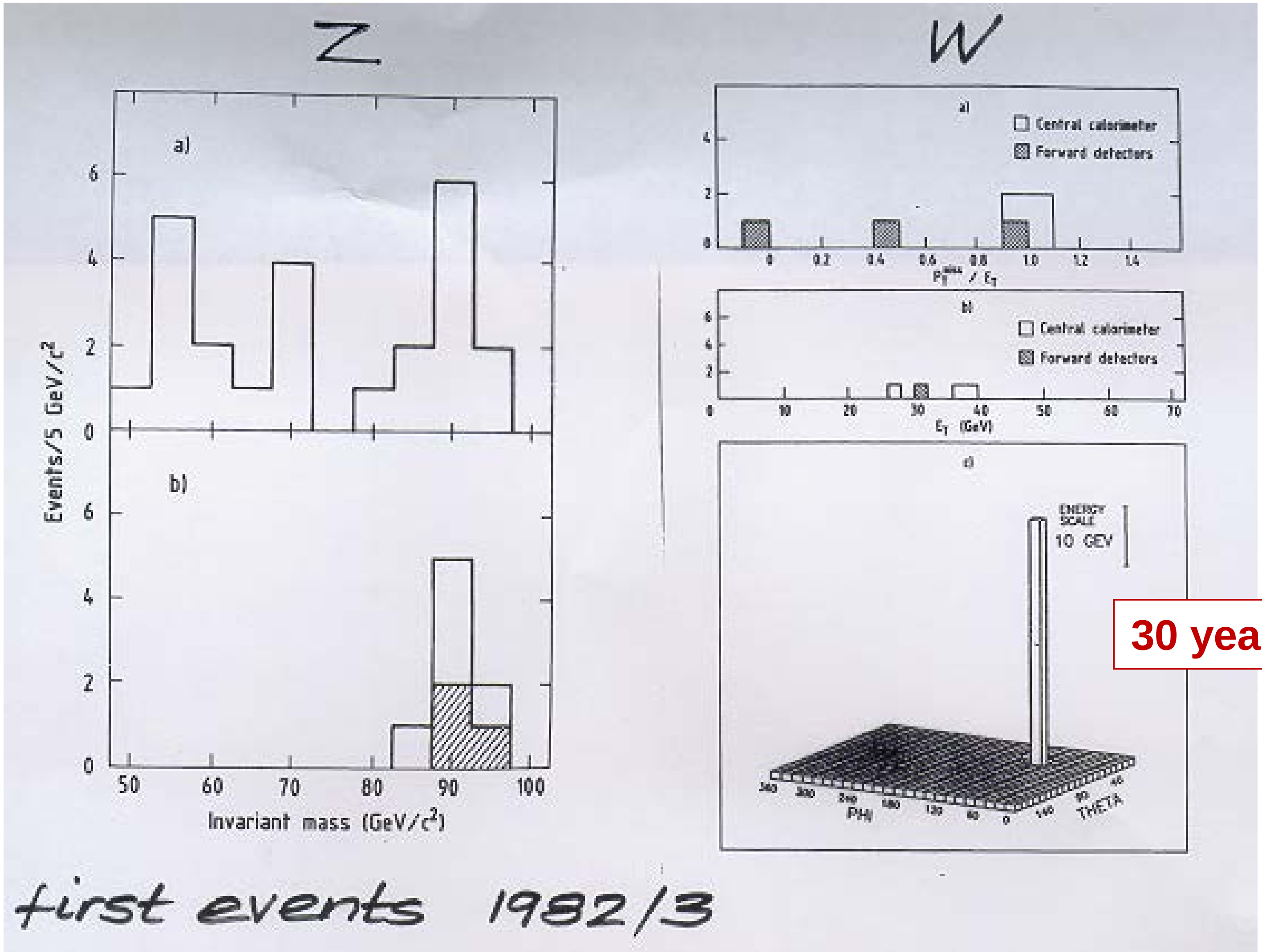
JHEP 10 (2011) 132



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

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

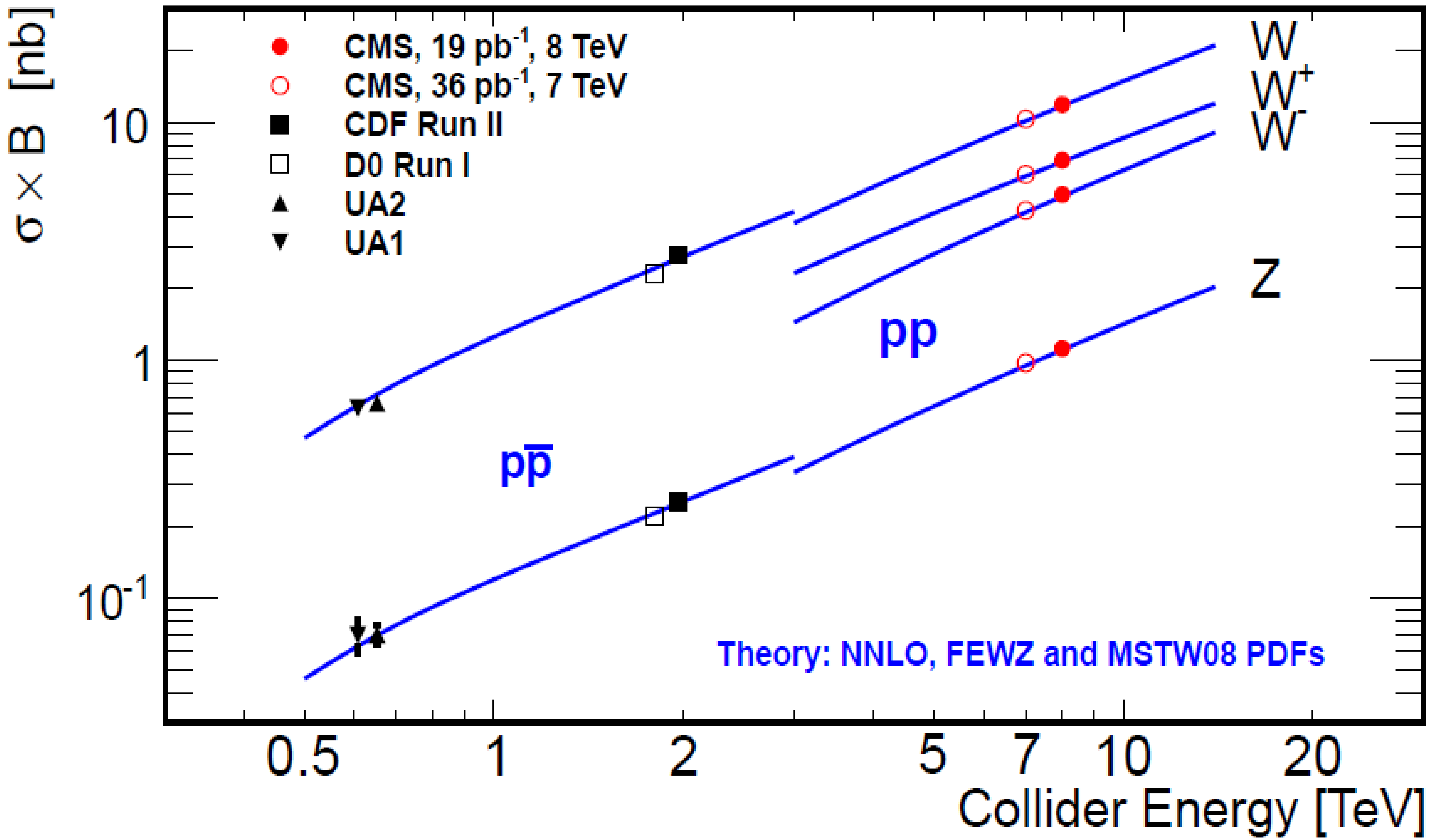
What a contrast to the Intermediate Vector Boson discovery distributions in 1982 and 1983 by UA1 and UA2 …



30 years ago!

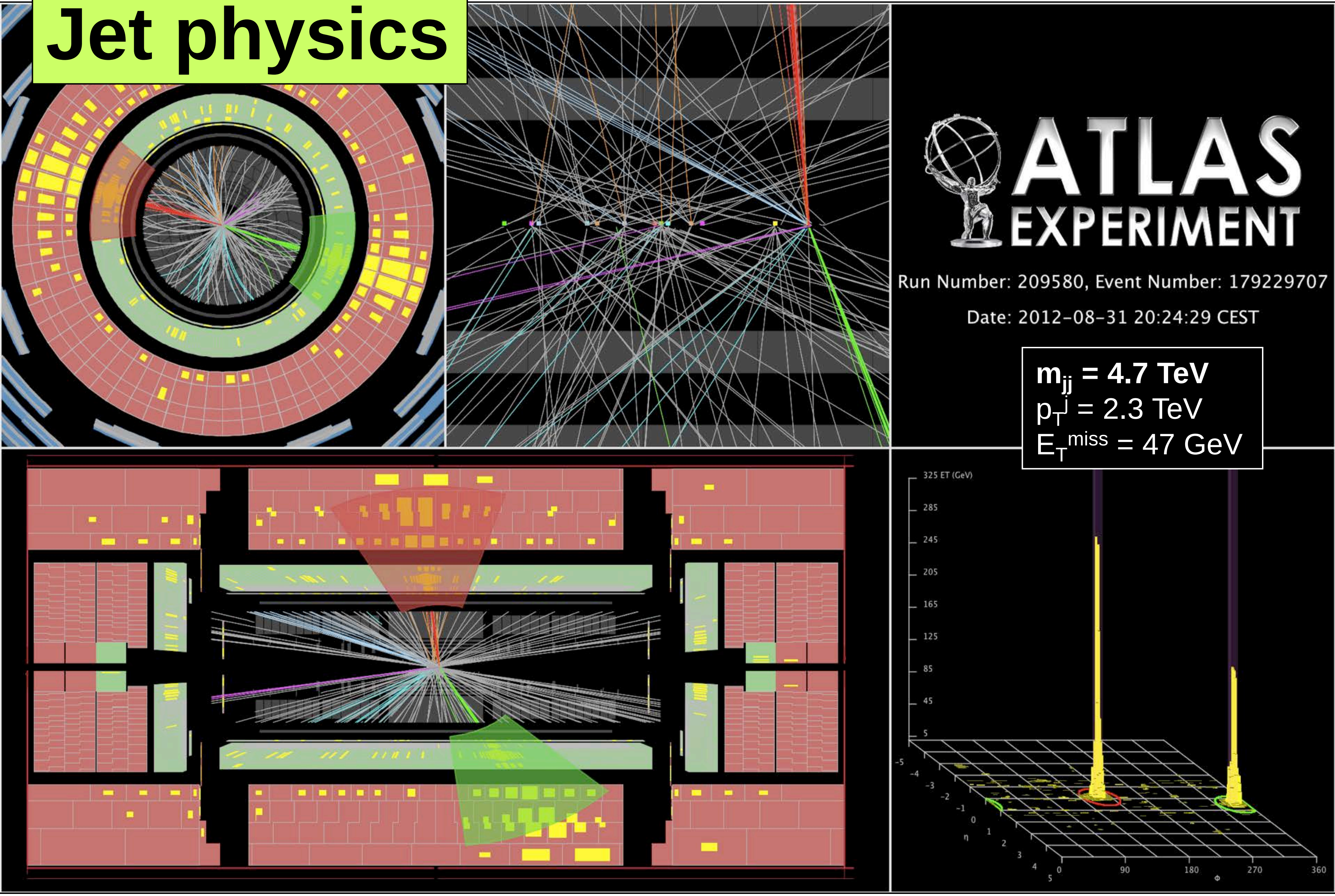
(here are shown the UA2 distributions)

Cross section measurements

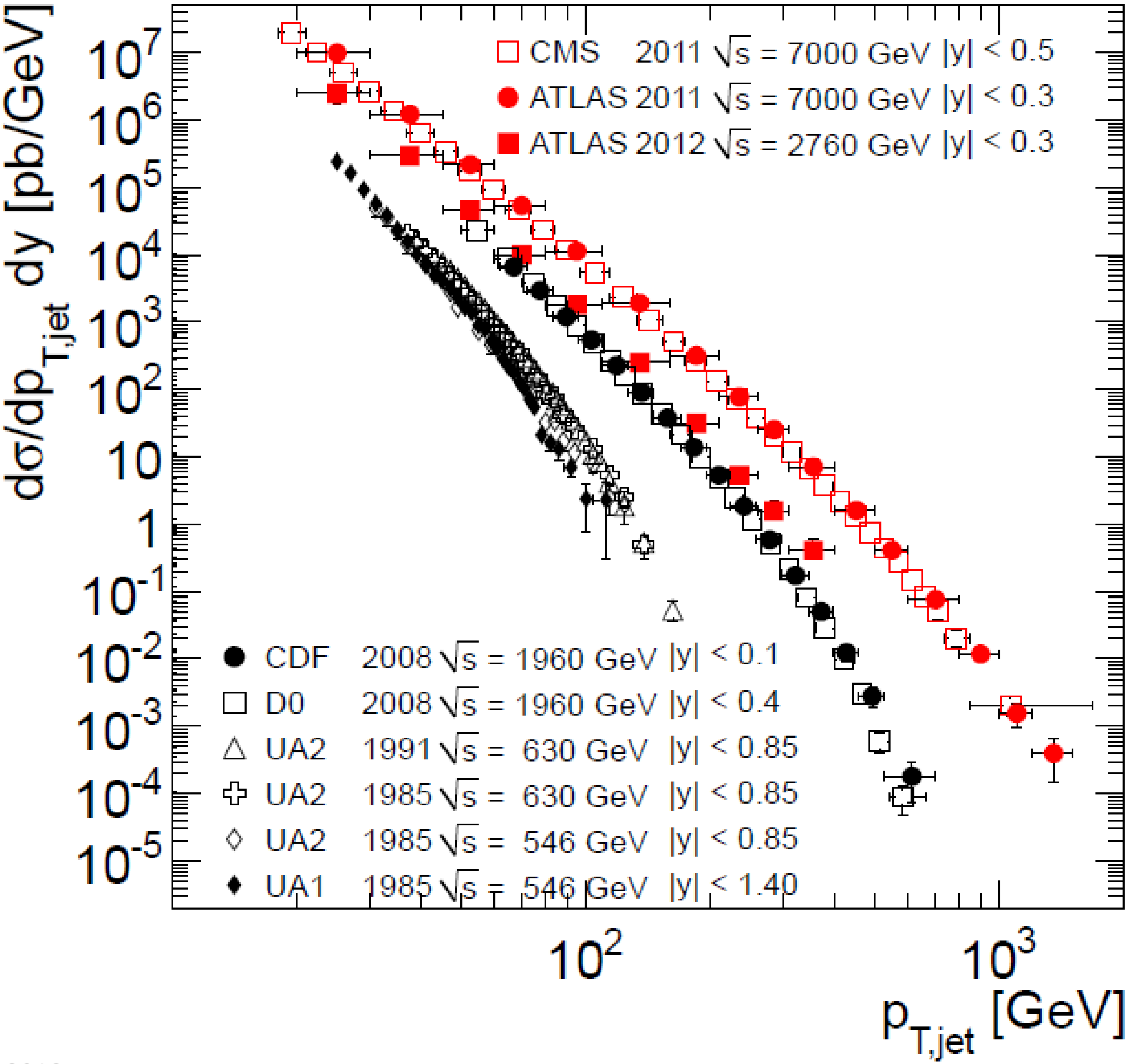


CMS-PAS-SMP-12-011

Jet physics



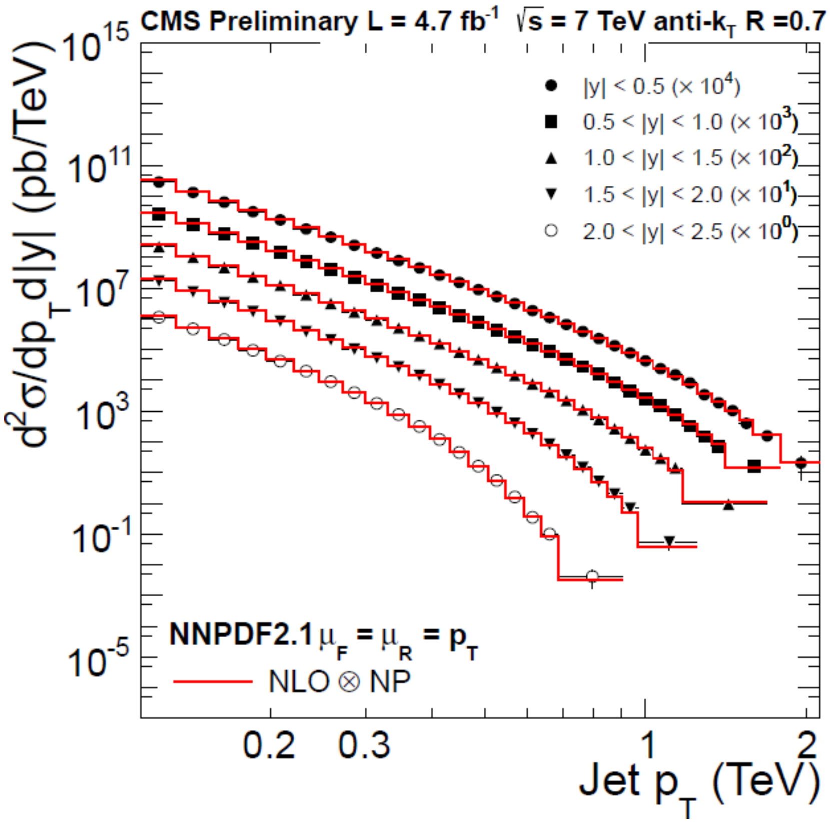
m_{jj} = 4.7 TeV
p_T^j = 2.3 TeV
E_T^{miss} = 47 GeV

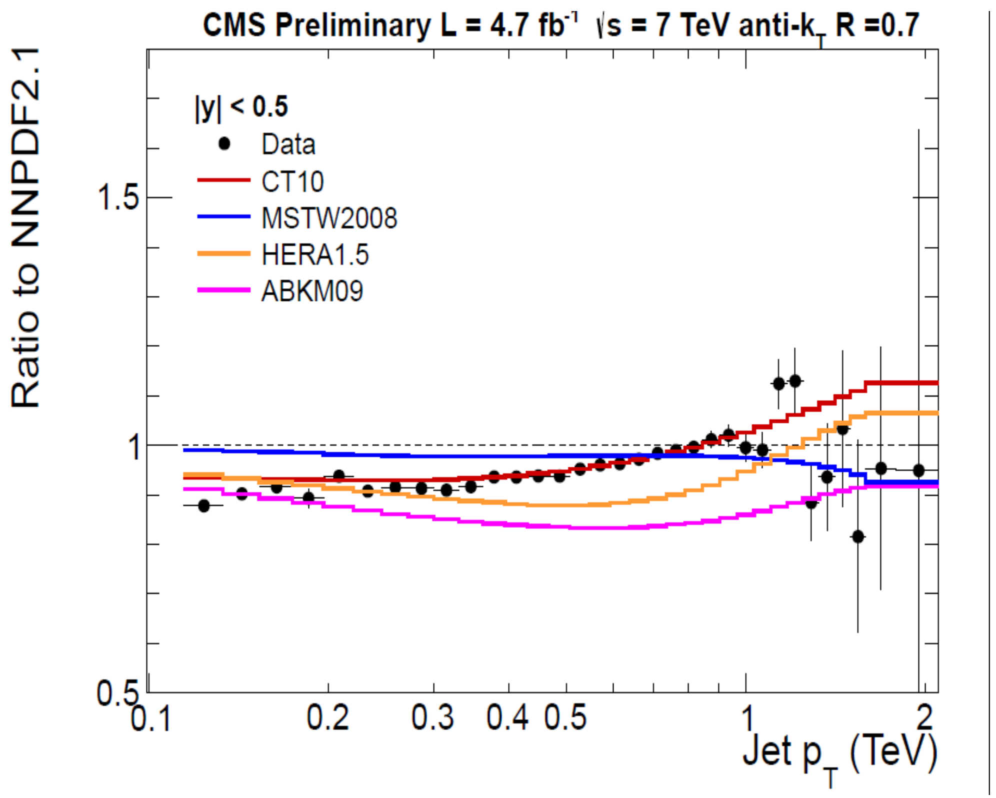


$d\sigma/dp_{T,jet}\,dy$ [pb/GeV]
$p_{T,jet}$ [GeV]
CMS 2011 $\sqrt{s}$ = 7000 GeV |y| < 0.5
ATLAS 2011 $\sqrt{s}$ = 7000 GeV |y| < 0.3
ATLAS 2012 $\sqrt{s}$ = 2760 GeV |y| < 0.3
CDF 2008 $\sqrt{s}$ = 1960 GeV |y| < 0.1
D0 2008 $\sqrt{s}$ = 1960 GeV |y| < 0.4
UA2 1991 $\sqrt{s}$ = 630 GeV |y| < 0.85
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 jet cross sections as a function of the jet P_T in rapidity bins



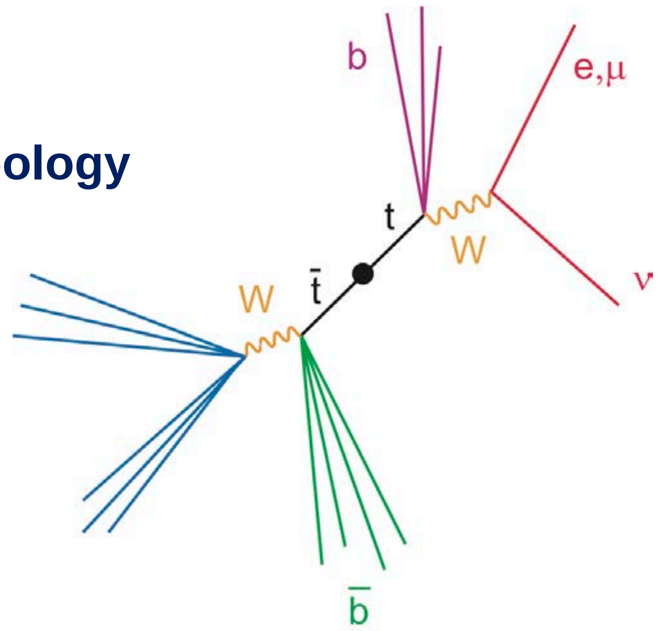


CMS-PAS-QCD-11-004

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**

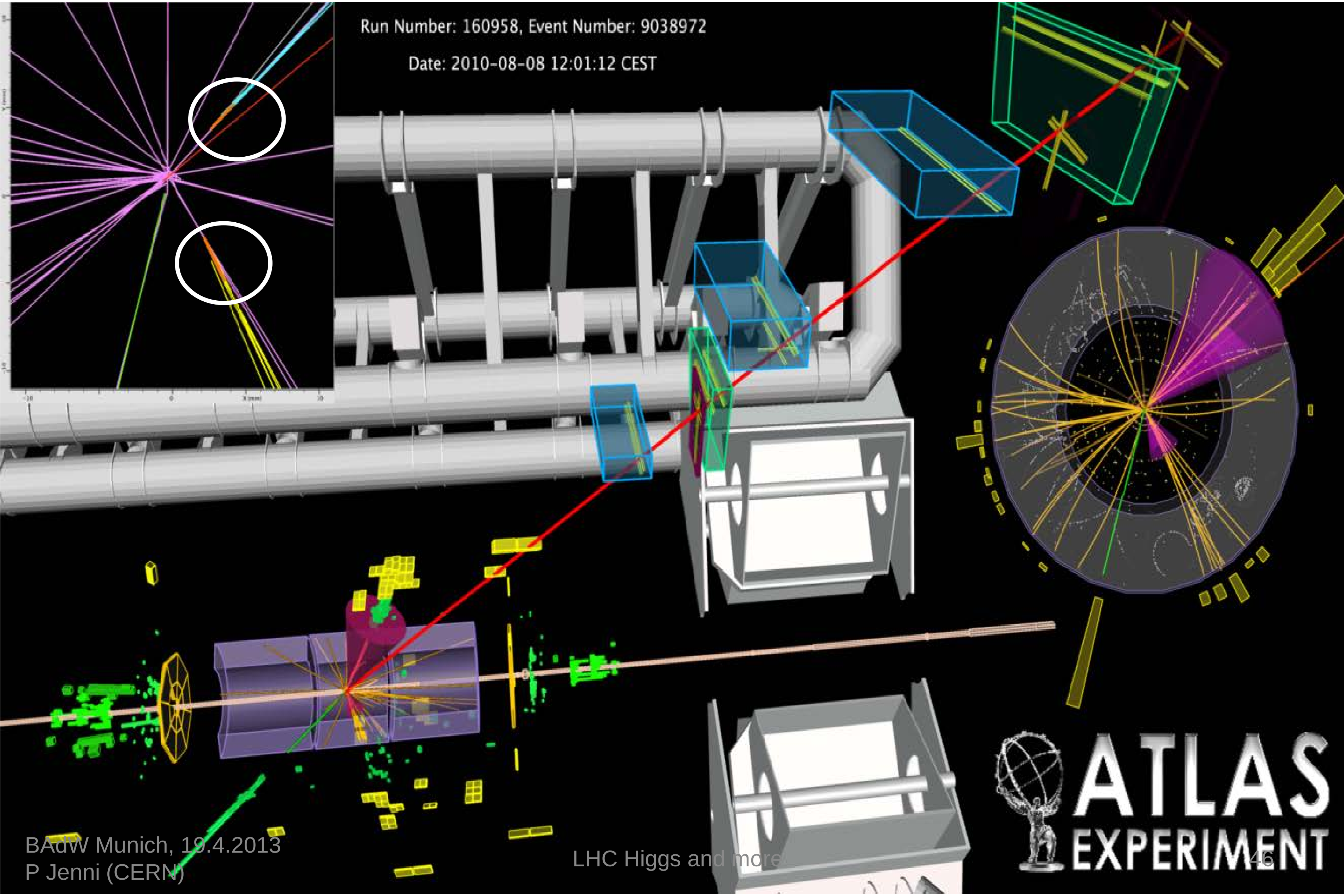
- **Assume all tops decay to Wb: event topology then depends on the W decays:**
  - **one lepton (e or μ), E_T^{miss}, jjbb (37.9%)**
  - **di-lepton (ee, $\mu\mu$ or eμ), E_T^{miss}, bb (6.5%)**

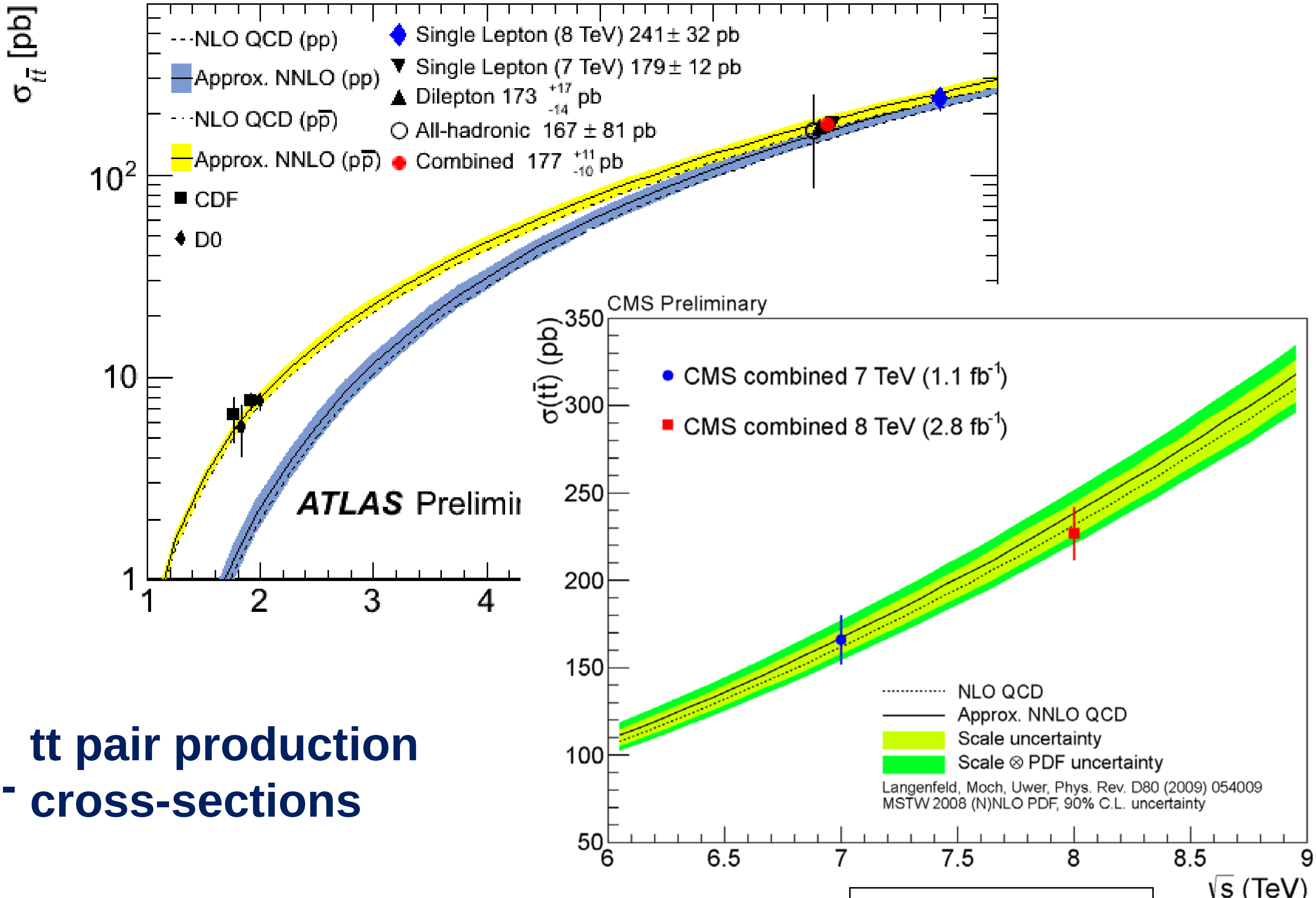


- **Data-driven methods to control QCD and W+jets backgrounds**

$t\bar{t}$ candidate event

e + μ + 2 jets (b-tagged) +ETmiss

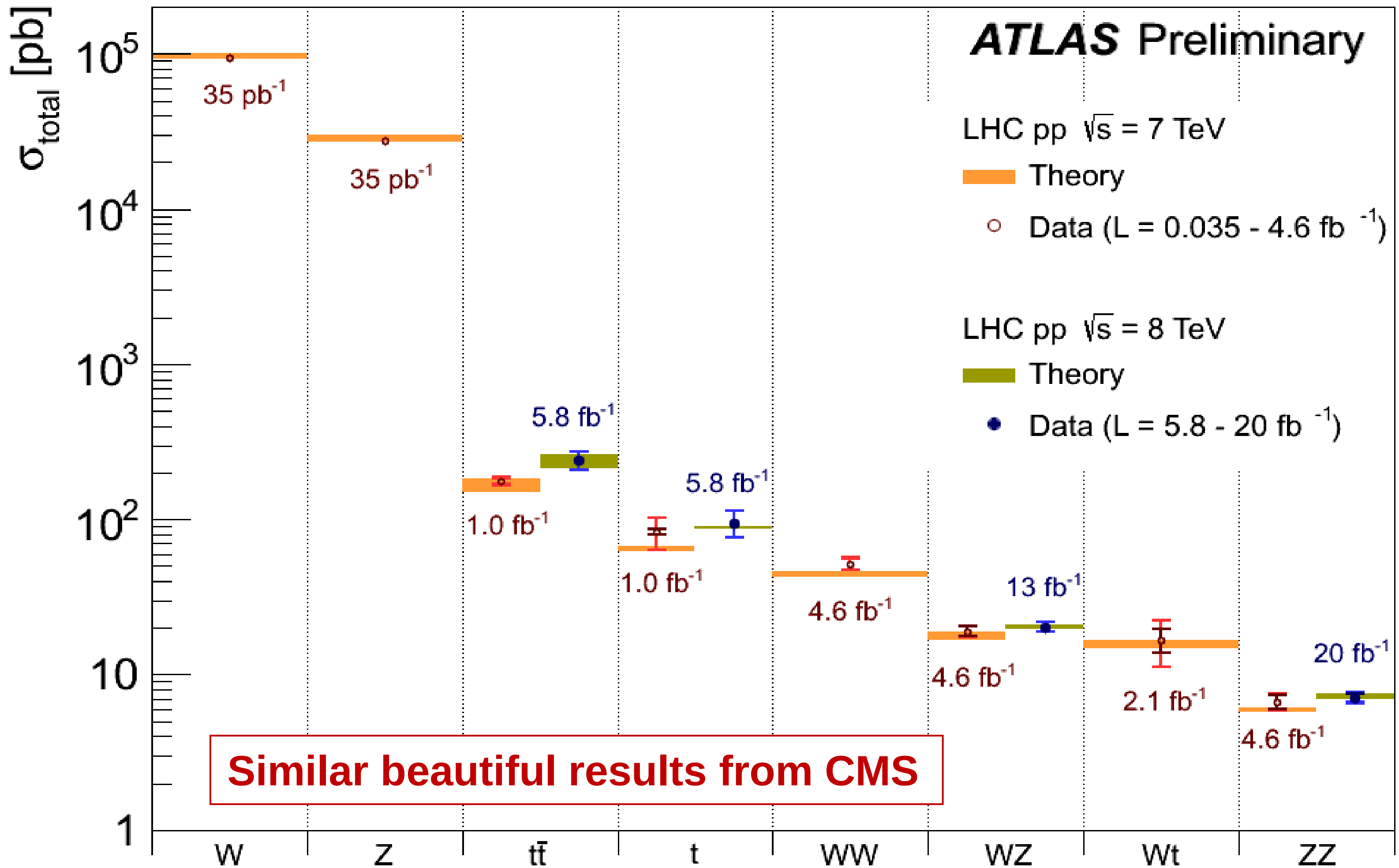




tt pair production - cross-sections

ATLAS-CONF-2012-149
CMS-PAS-TOP-12-006, 007

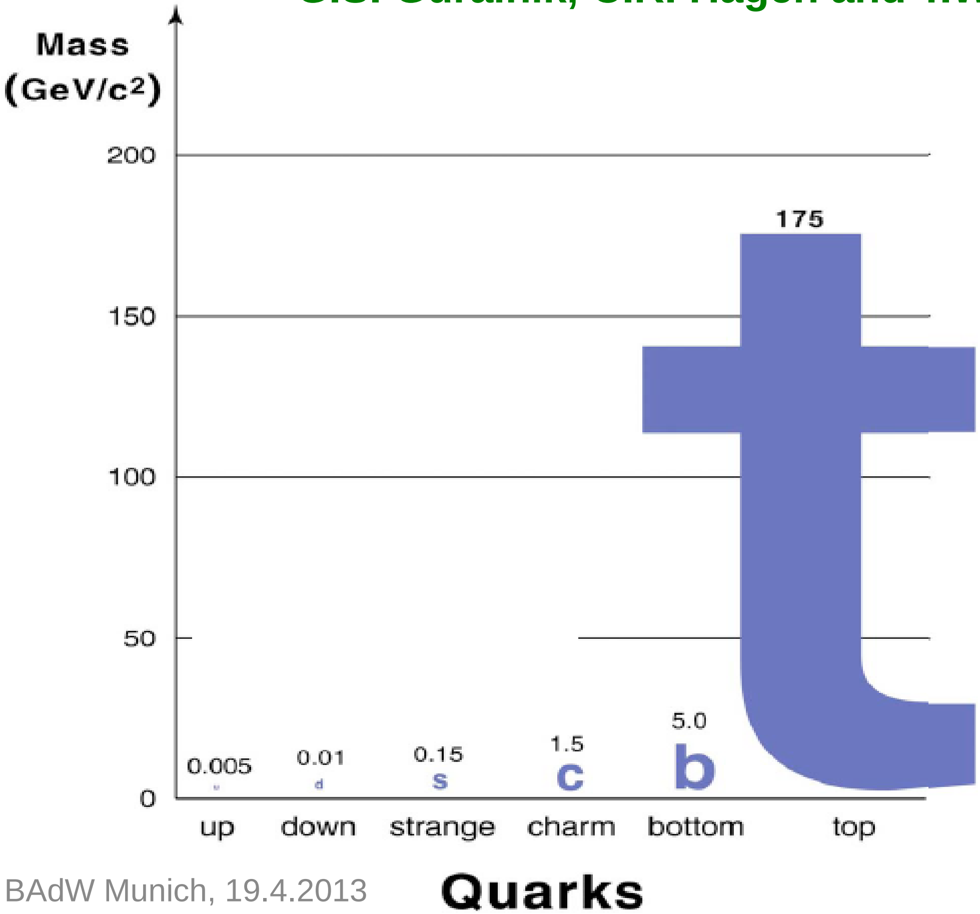
A summary of Standard Model measurements



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

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

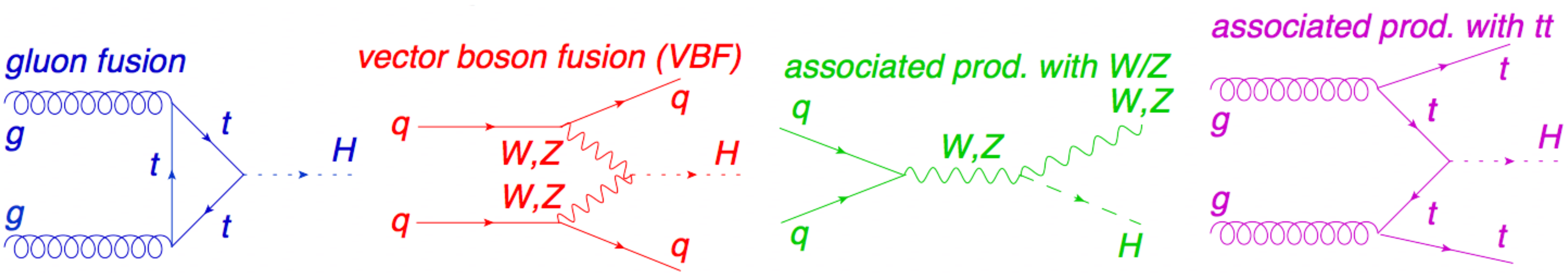
The Higgs (H) particle has been searched for since decades at accelerators …

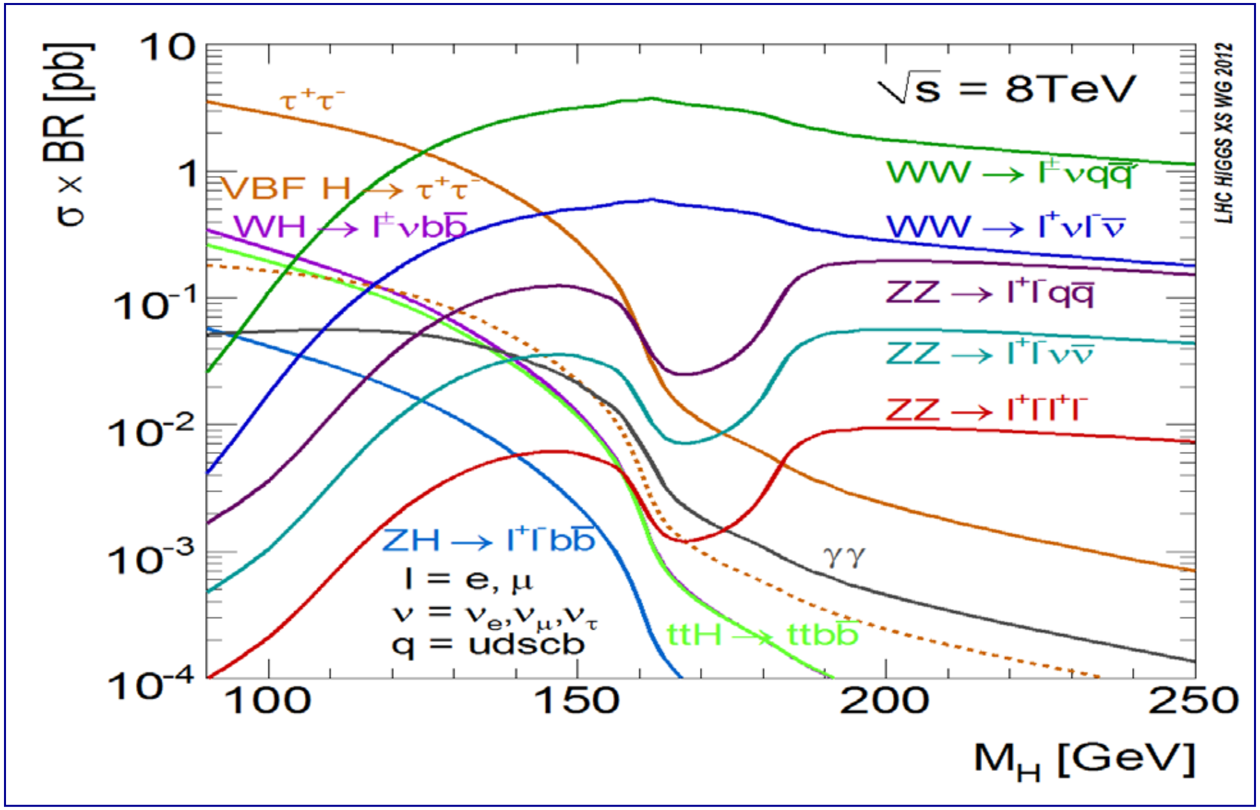
The LHC has sufficient energy to produce it for sure, if it exists

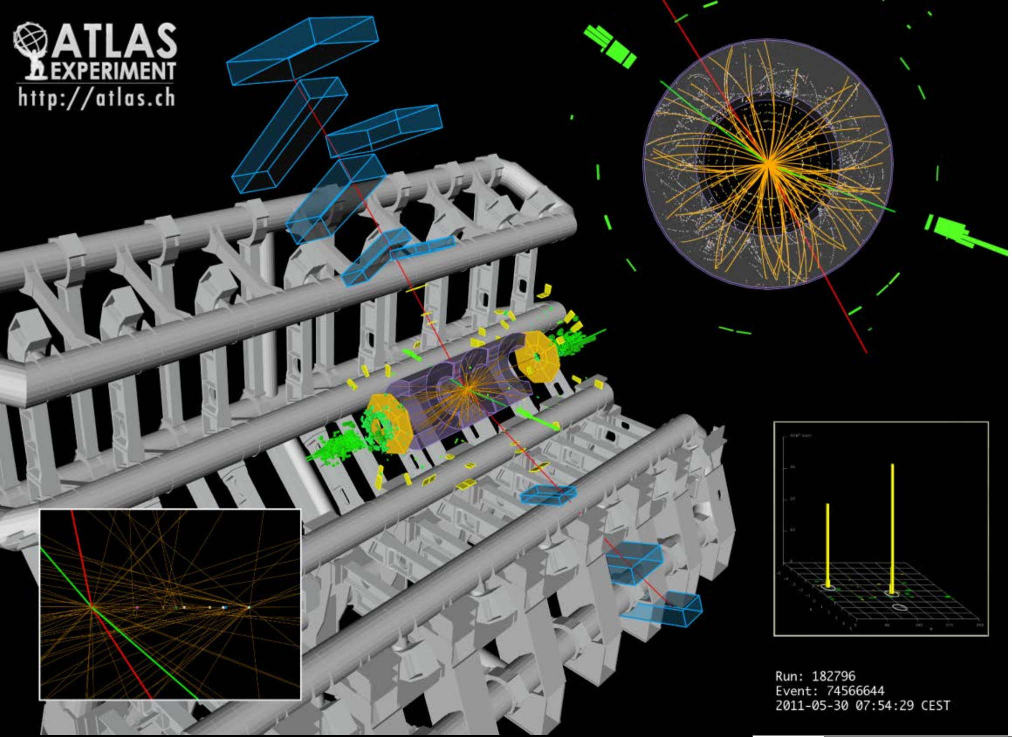
Francois Englert

Search for the boson (H) of the EW symmetry breaking

SM H boson production cross sections times observable decay branching ratios at 8 TeV



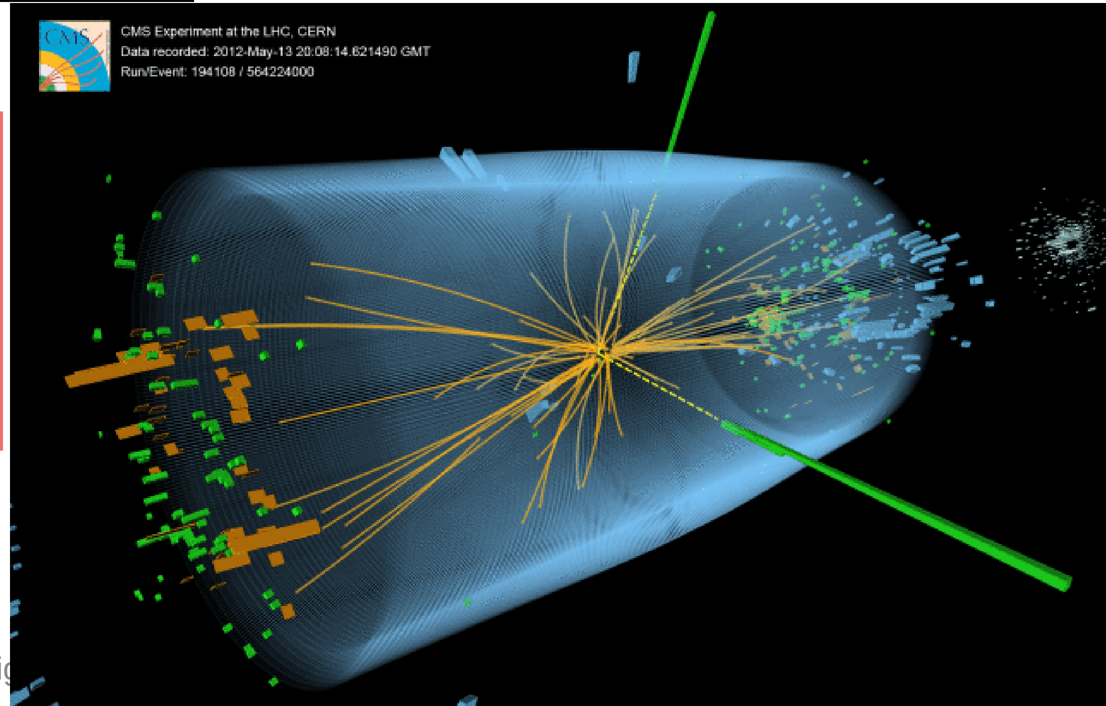




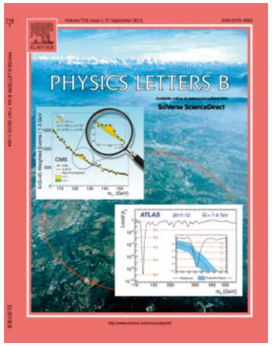
The Higgs(-~~like~~) boson

Candidate event for H → $\gamma\gamma$

Candidate event for H → ZZ* → ee $\mu\mu$



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

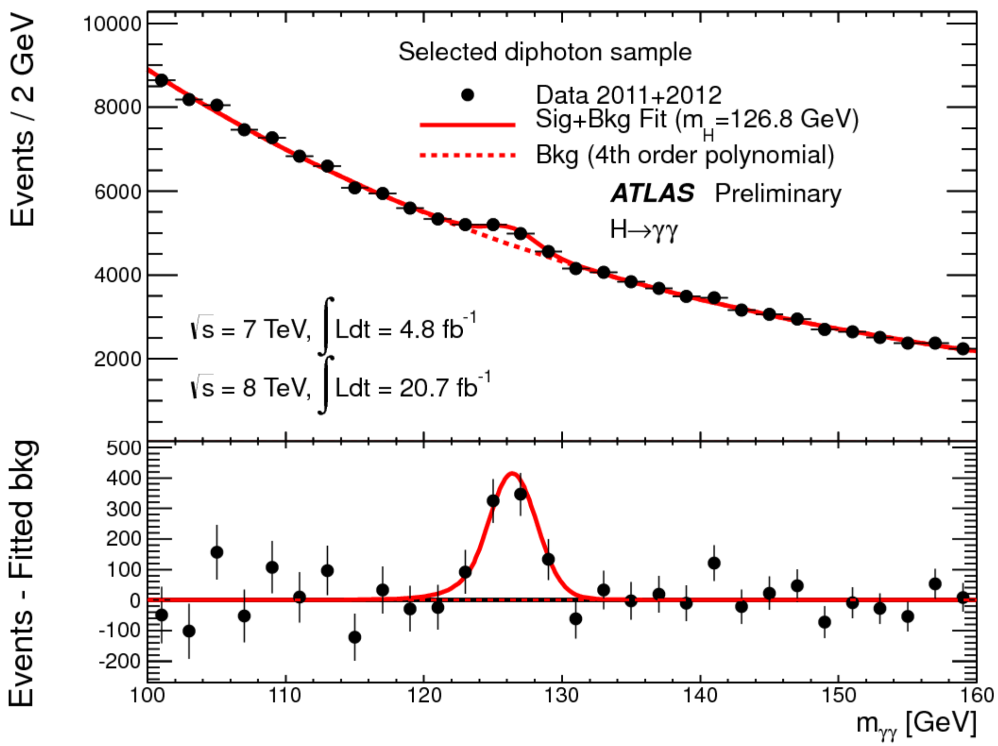


Phys. Lett. B 716 (2012) 1

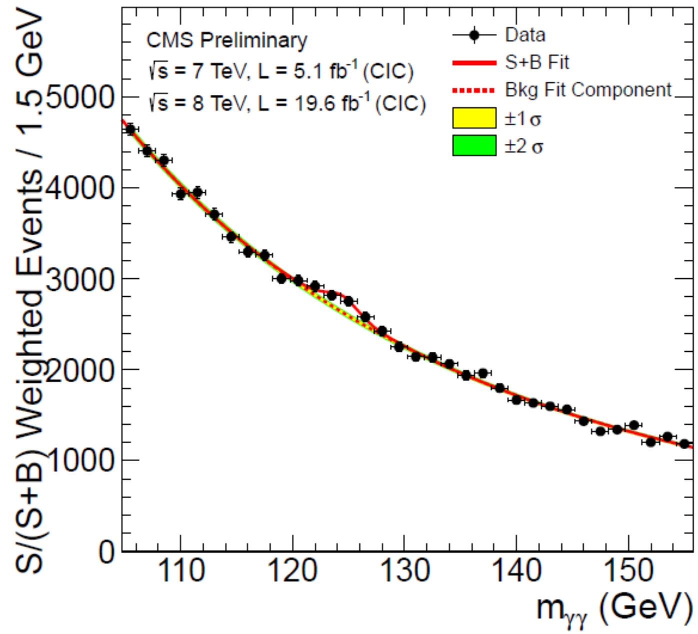
Phys. Lett. B 716 (2012) 30

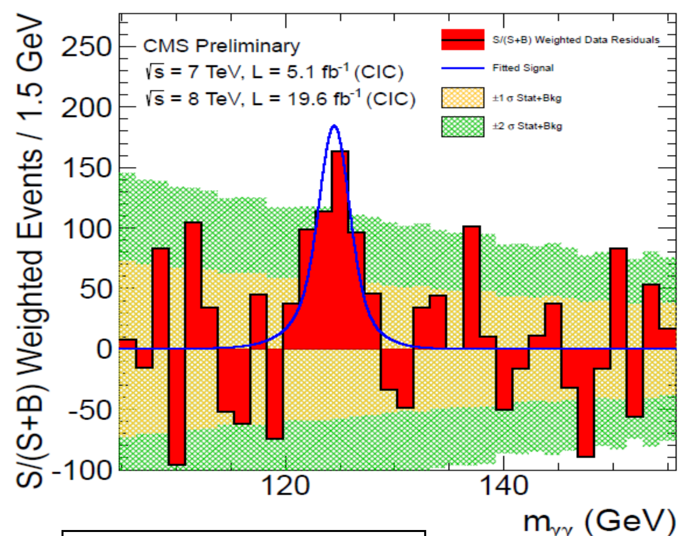
H → γγ

- Small cross-section: σ ~ 40 fb
- Expected S/B ~ 0.02
- Simple final state: two high-p_T isolated photons
- Main background: γγ continuum (irreducible) and fake γ from γj and jj events (reducible)



ATLAS-CONF-2013-012

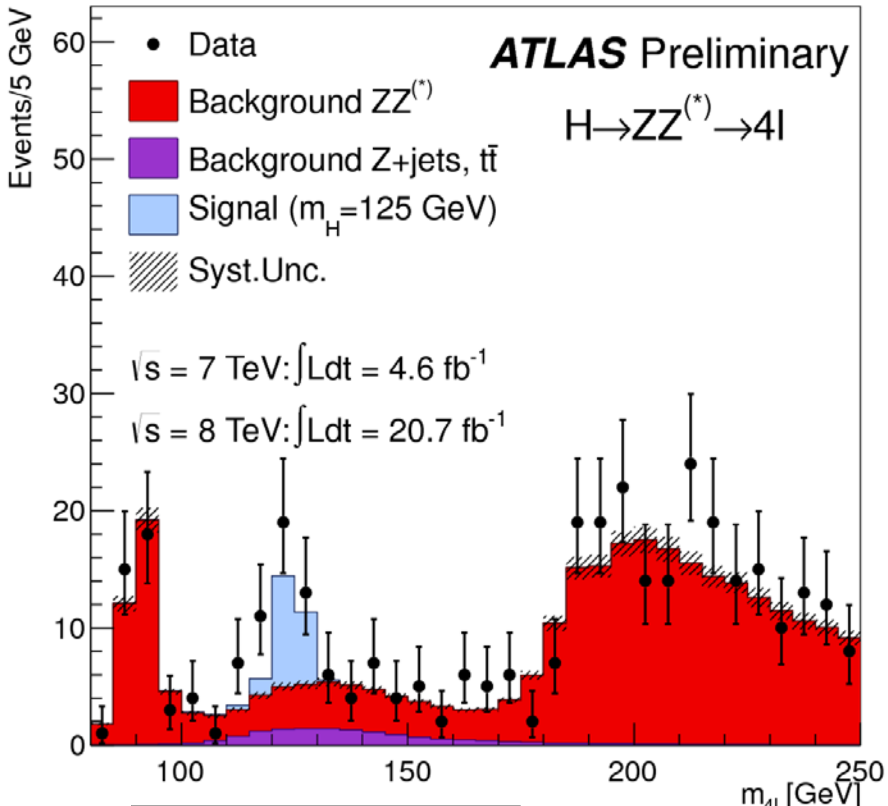




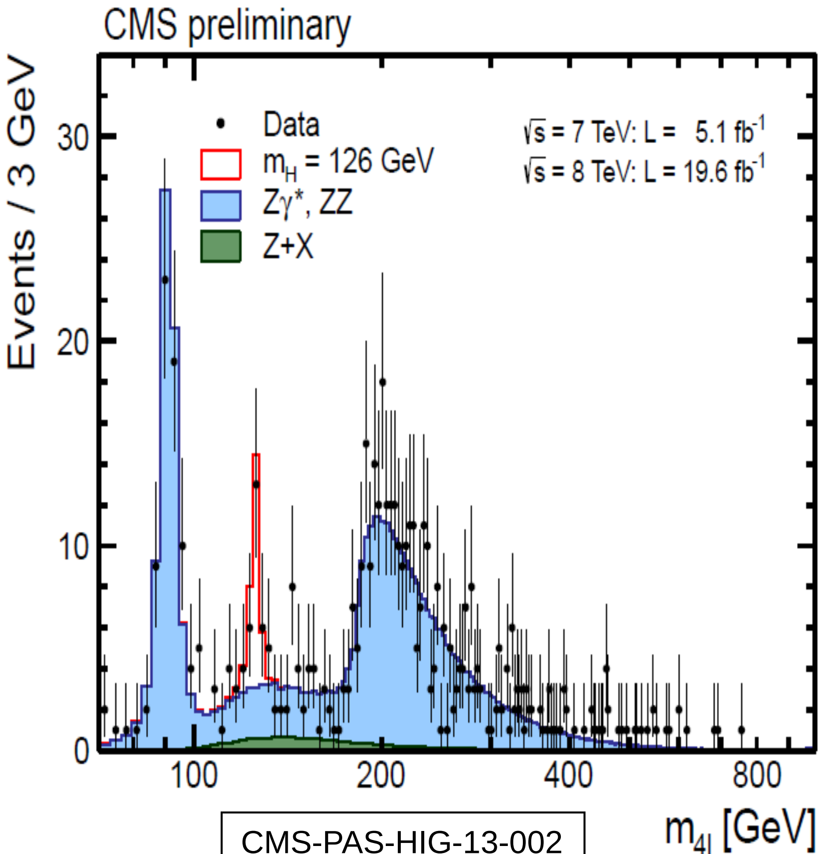
CMS-PAS-HIG-13-001

H → ZZ$^{(*)}$ → 4l (4e, 4μ, 2e2μ)

- Rare process, small cross section: σ ~ 2-5 fb
- However: pure: S/B ~ 1
- 4 leptons:
- Main background: ZZ$^{(*)}$ (irreducible)
  In addition: Zbb, Z+jets, tt with two leptons from b-quarks or jets



ATLAS-CONF-2013-013



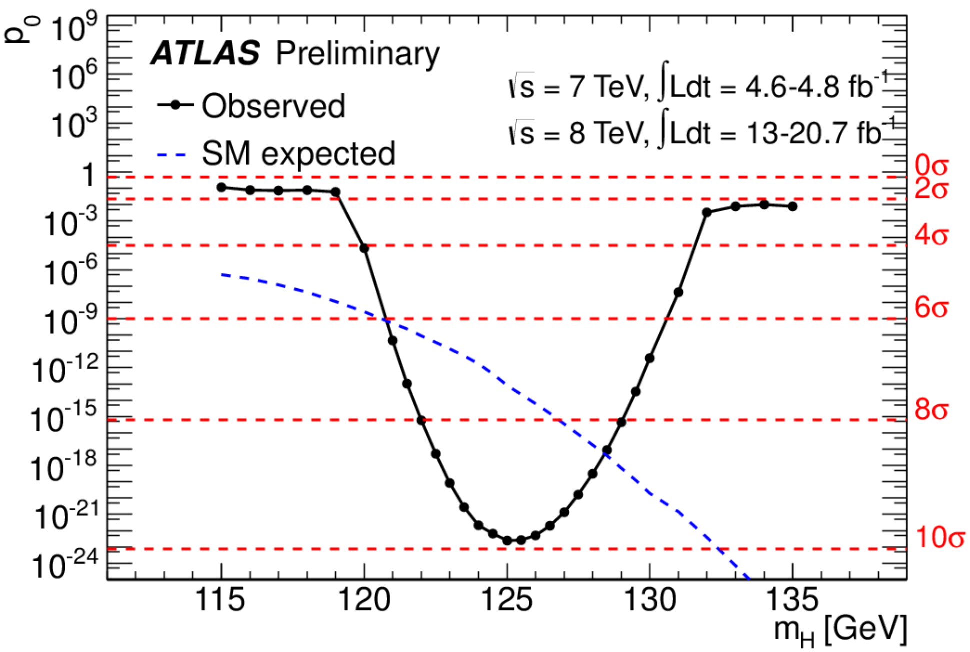
CMS-PAS-HIG-13-002

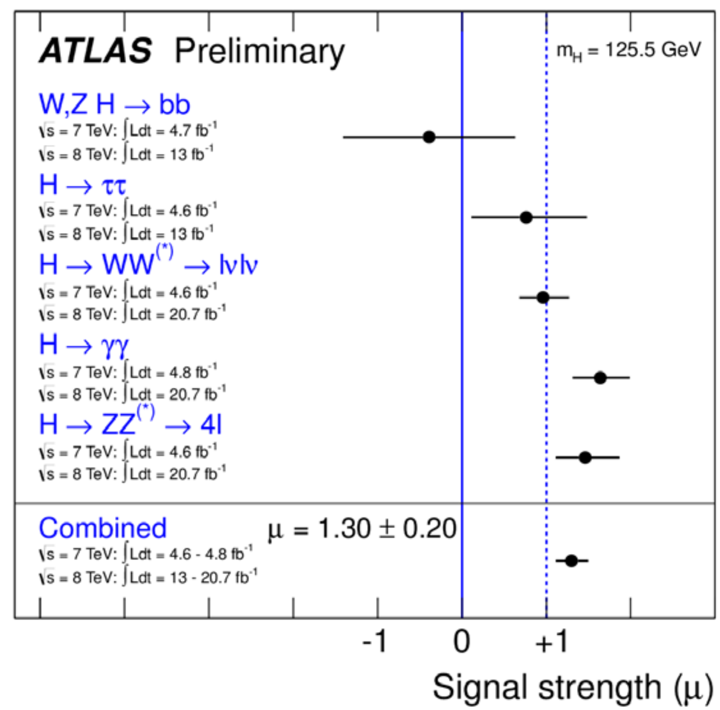
How significant is the signal for the new particle ?

Mass = 125.5 ± 0.2 (stat) ± 0.6 (syst) GeV [ATLAS]
125.8 ± 0.4 (stat) ± 0.4 (syst) GeV [CMS]

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

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





ATLAS-CONF-2013-034

CMS: Moriond QCD presentation

$\mu = 1.30 \pm 0.20$ [ATLAS]
$\mu = 0.88 \pm 0.21$ [CMS]

Detailed studies of the production and decay properties have started in order to characterize the new particle

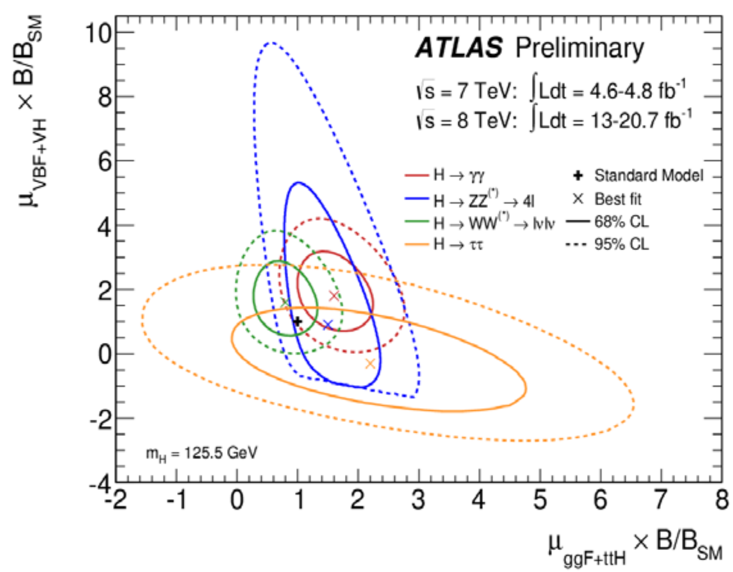
It will be important to understand with great precision if it is the only scalar boson of the Standard Model 'Brout-Englert-Higgs' mechanism to break the electroweak symmetry, or if it is only part of a broader physics picture going *Beyond the Standard Model*

These studies will be among the most central ones in the decades to come both at the LHC and at possible other future colliders

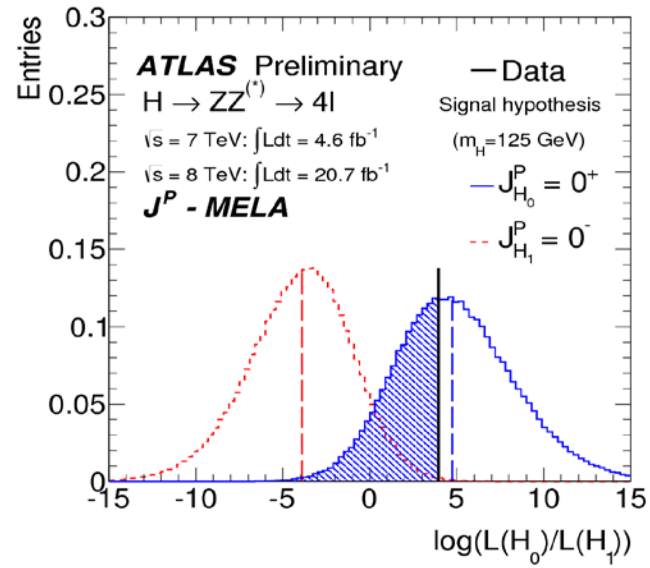
For the experts:

Couplings
Production modes
Spin-parity

all support at the 2-3 σ level the SM Higgs with present limited statistics

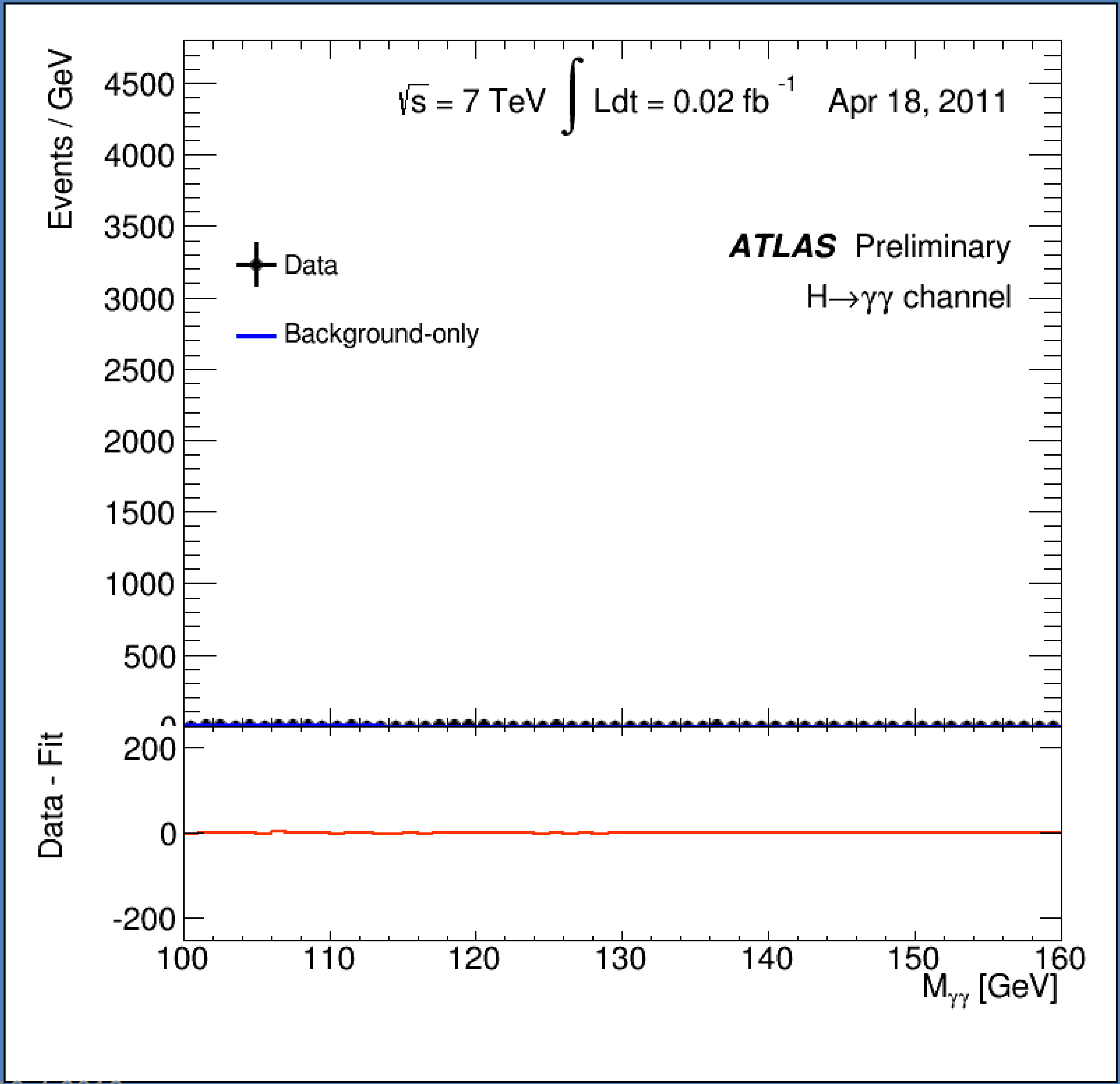


ATLAS-CONF-2013-034

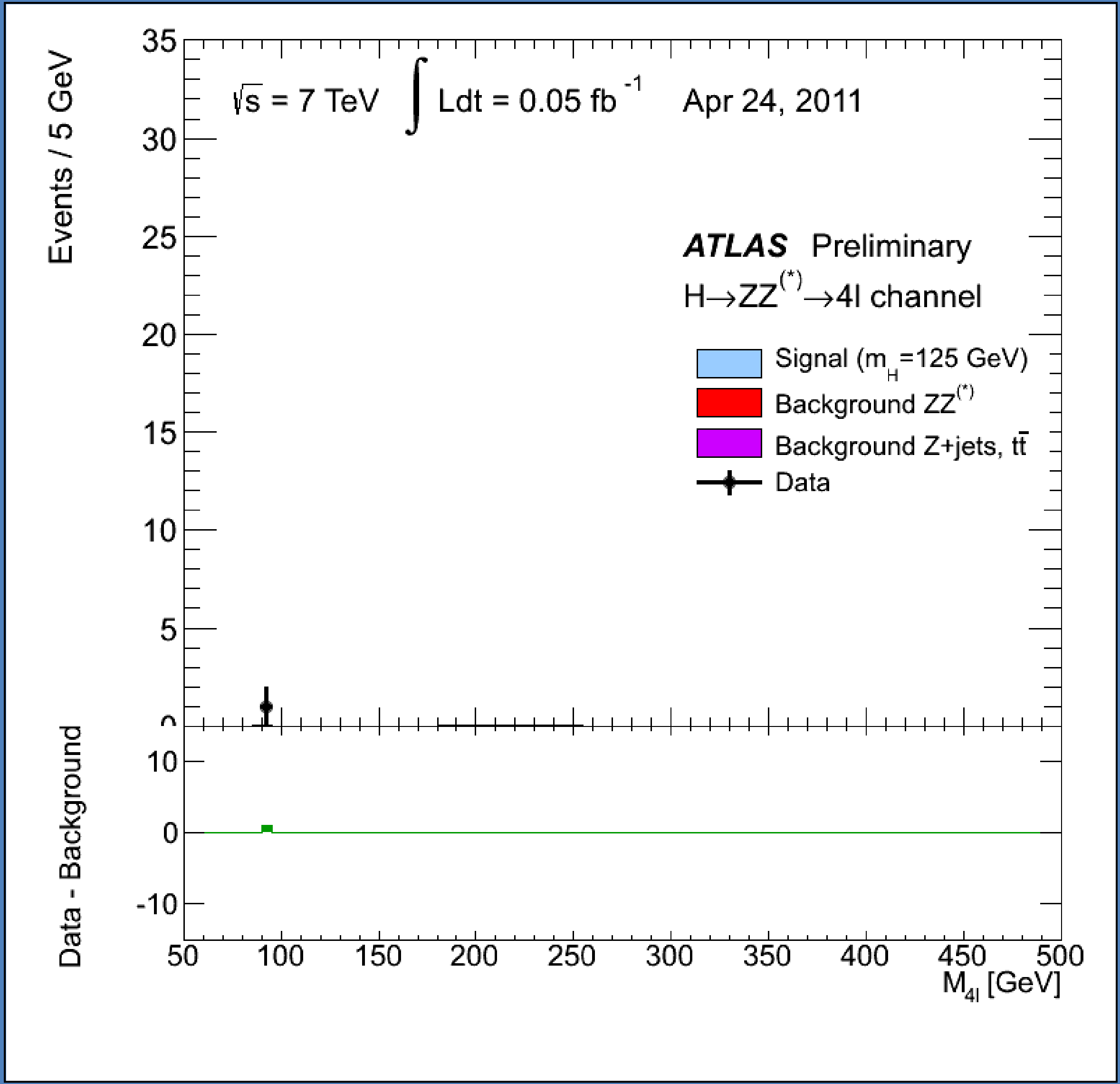


ATLAS-CONF-2013-013

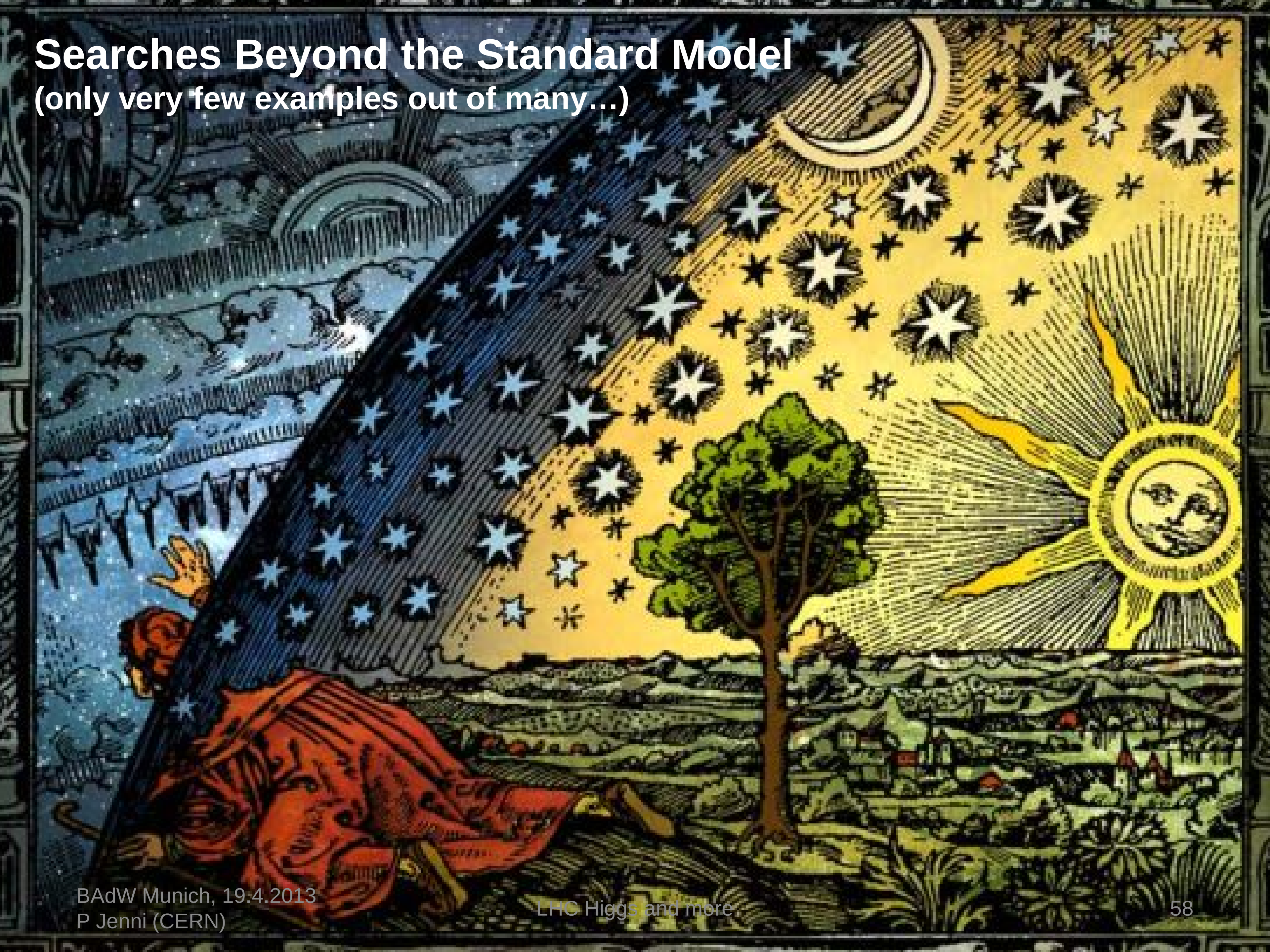
Birth and evolution of a signal: H→ $\gamma\gamma$



Birth and evolution of a signal: H→ 4l



Searches Beyond the Standard Model
(only very few examples out of many…)

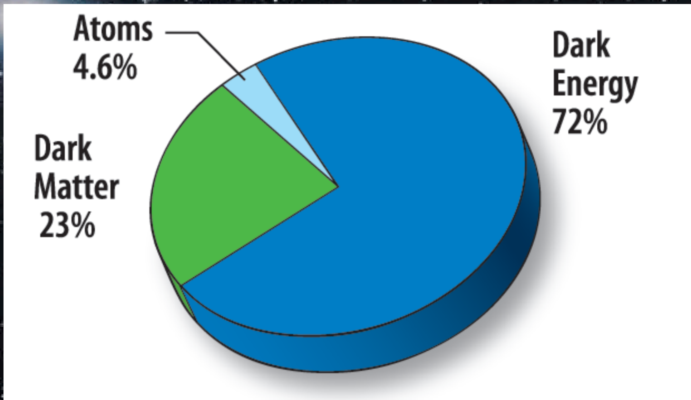


Dark Matter in the Universe

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

Vera Rubin ~ 1970

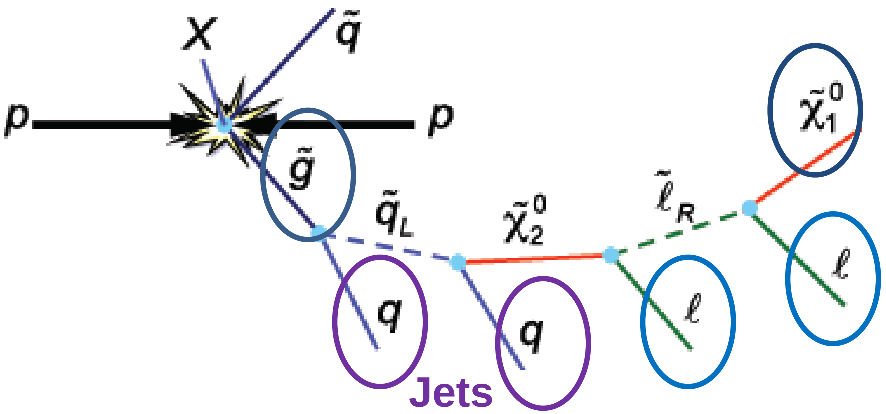
'Supersymmetric' particles ?

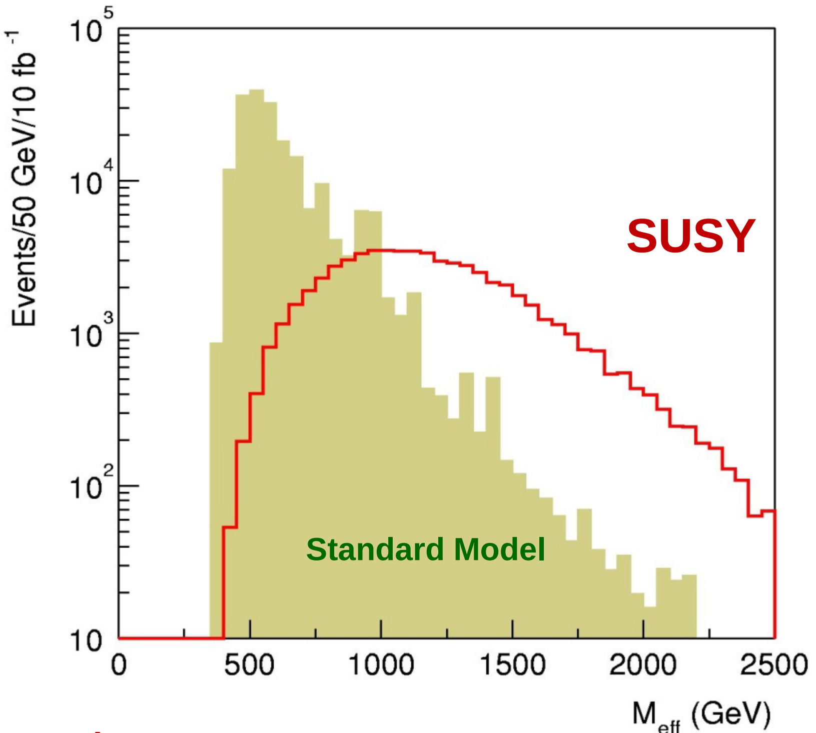


F. Zwicky 1898-1974

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**

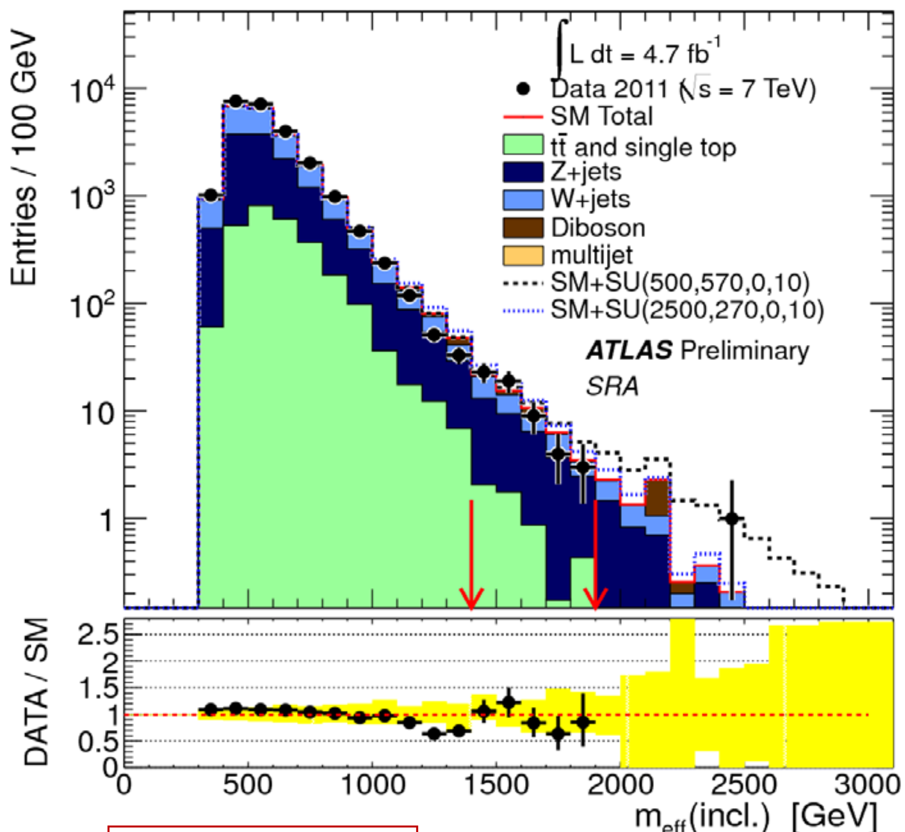
Meff = Etmiss + Σ pT(jets)

An example from the 2011 data, to show the principle, final results will be quoted for updated analyses including 2012 data

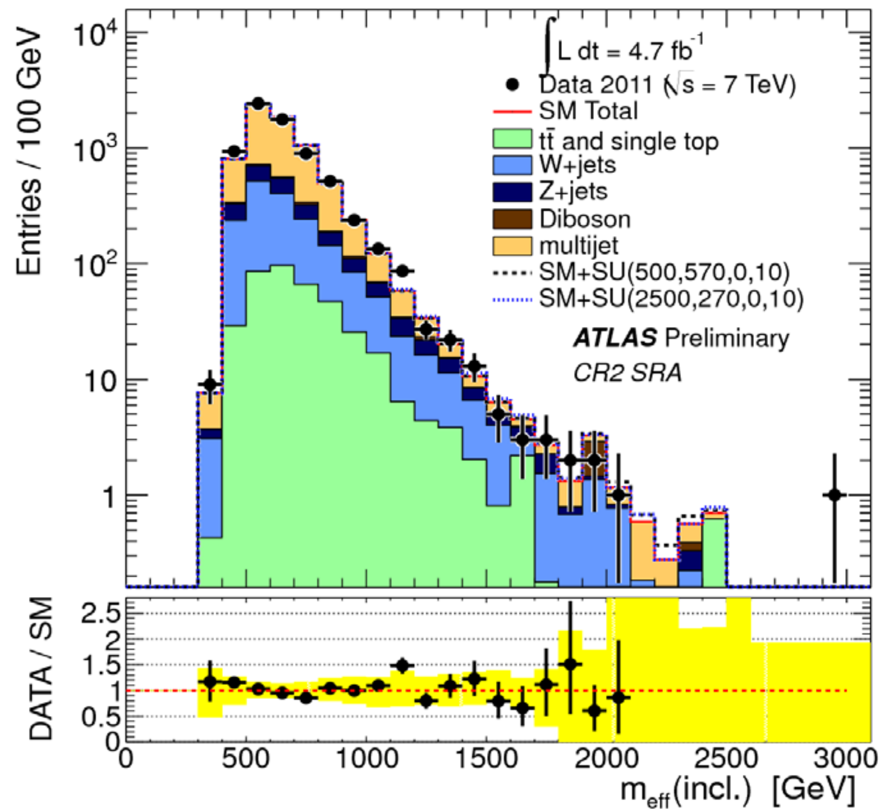
- **0-lepton + 2−6 jets + high MET (based on Et-miss+jet triggers)**
- **0-lepton + 6−9 (multi-)jets + MET (based on multi-jet triggers)**
- **1-lepton + 3,4 jets + high MET (based on lepton triggers)**

Example: O-leptons + 2-6 Jets analysis

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



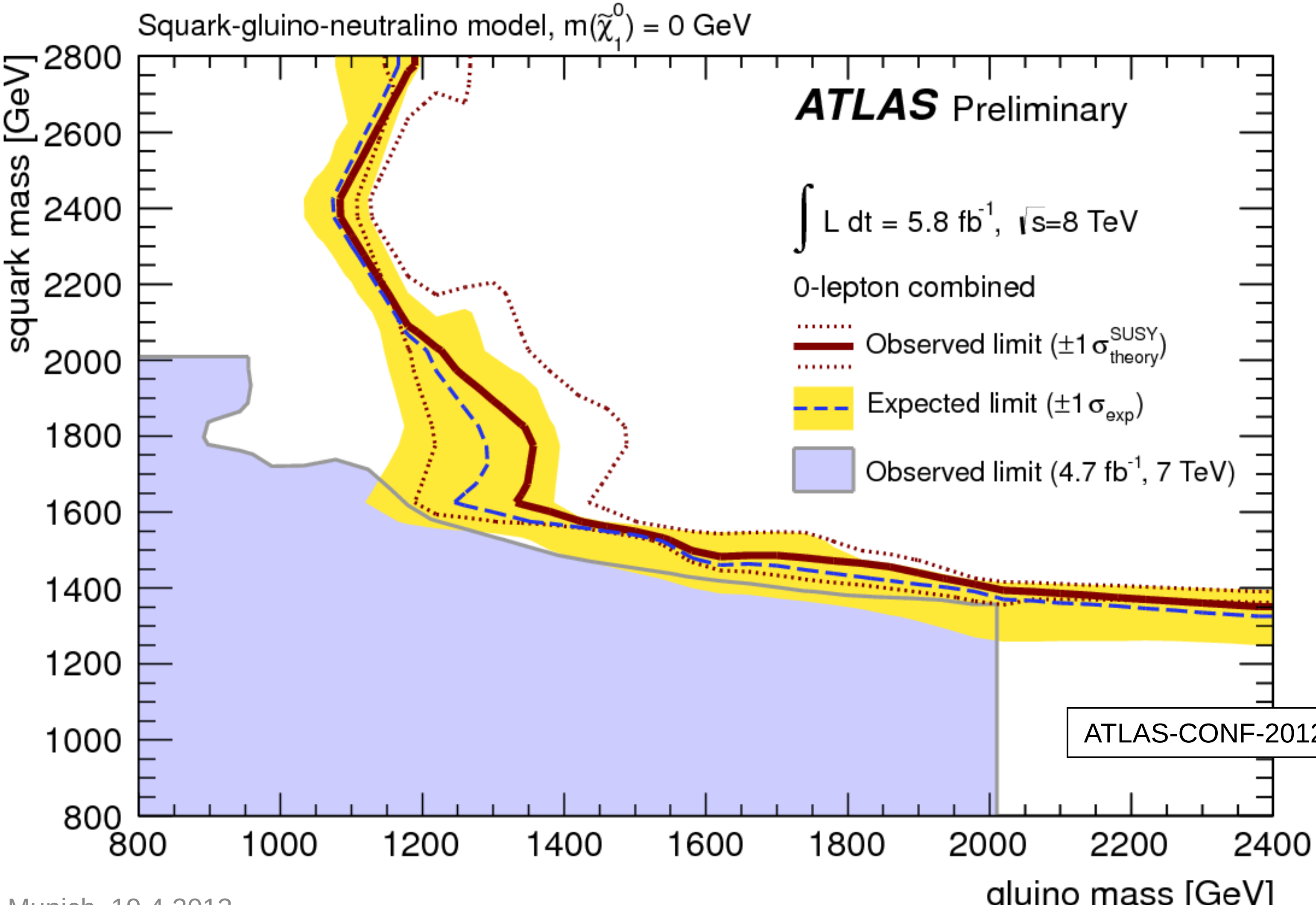
A signal region



A control region where no signal is expected

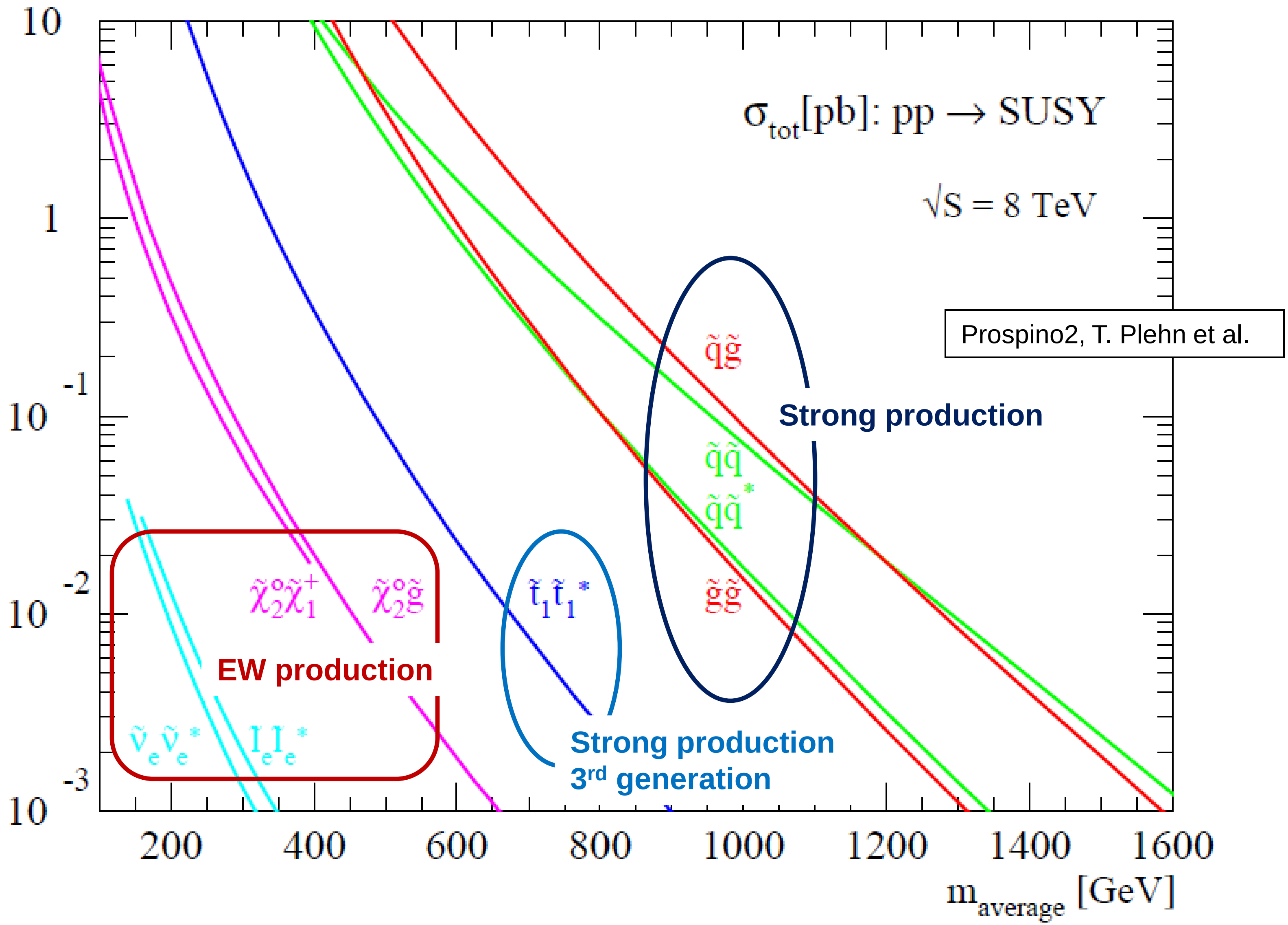
Interpretation of the results

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

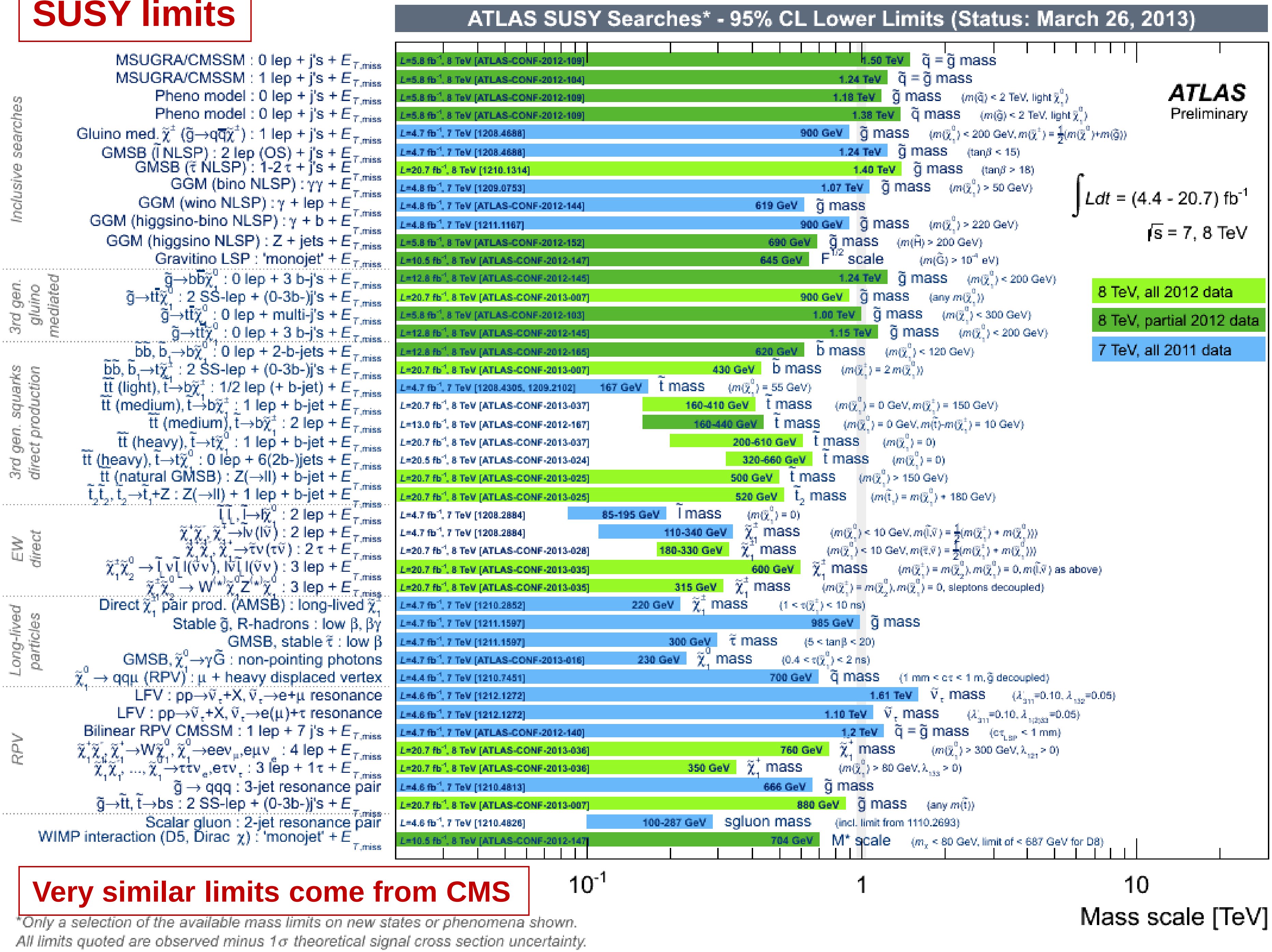


ATLAS-CONF-2012-0109

Expected production cross-sections at LHC



SUSY limits

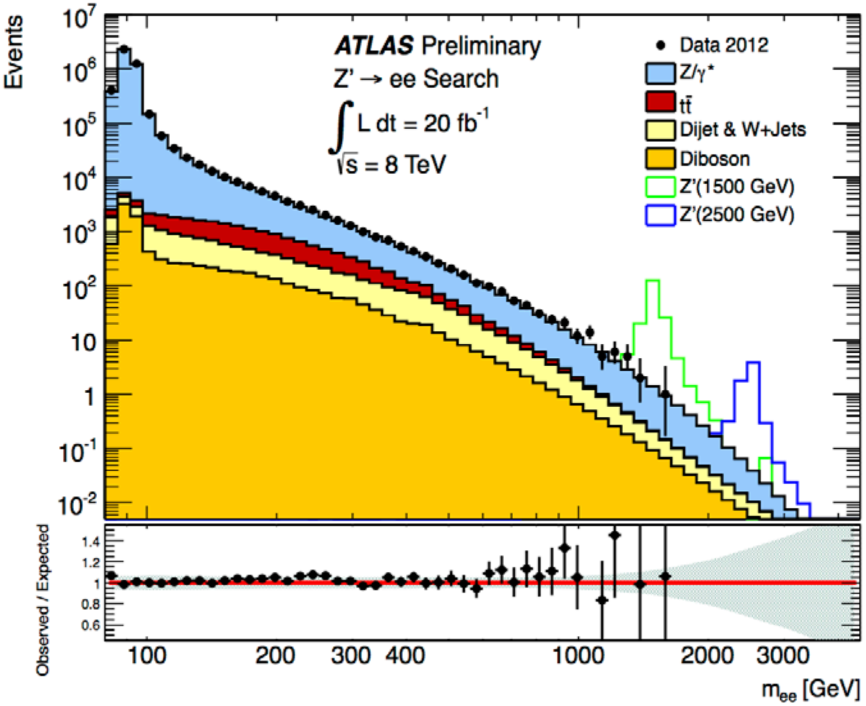


Very similar limits come from CMS

Searches for heavy W and Z like particles

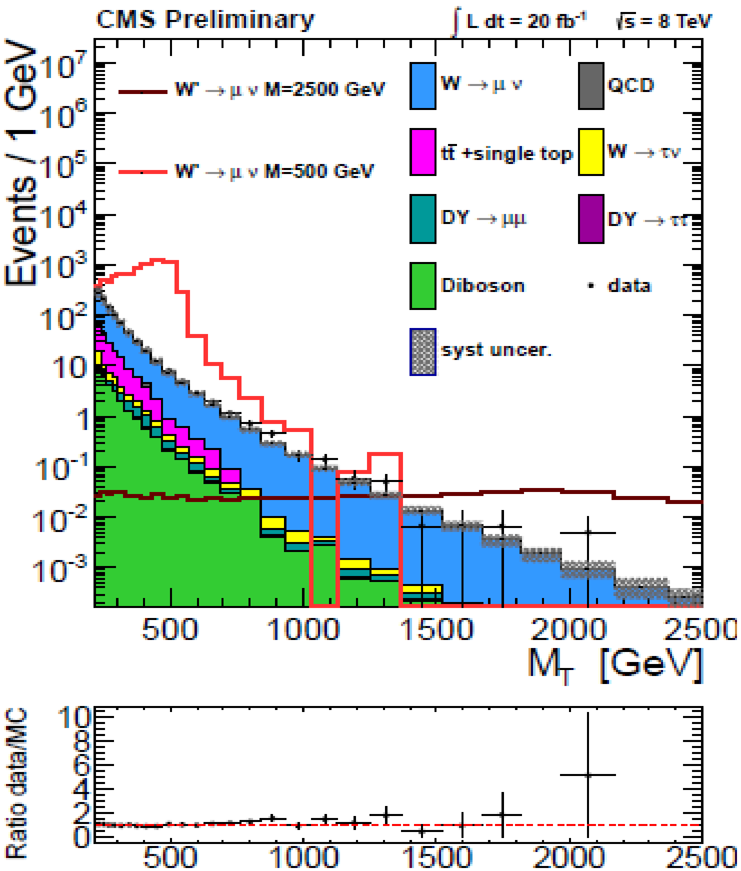
These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z': Di-lepton pairs

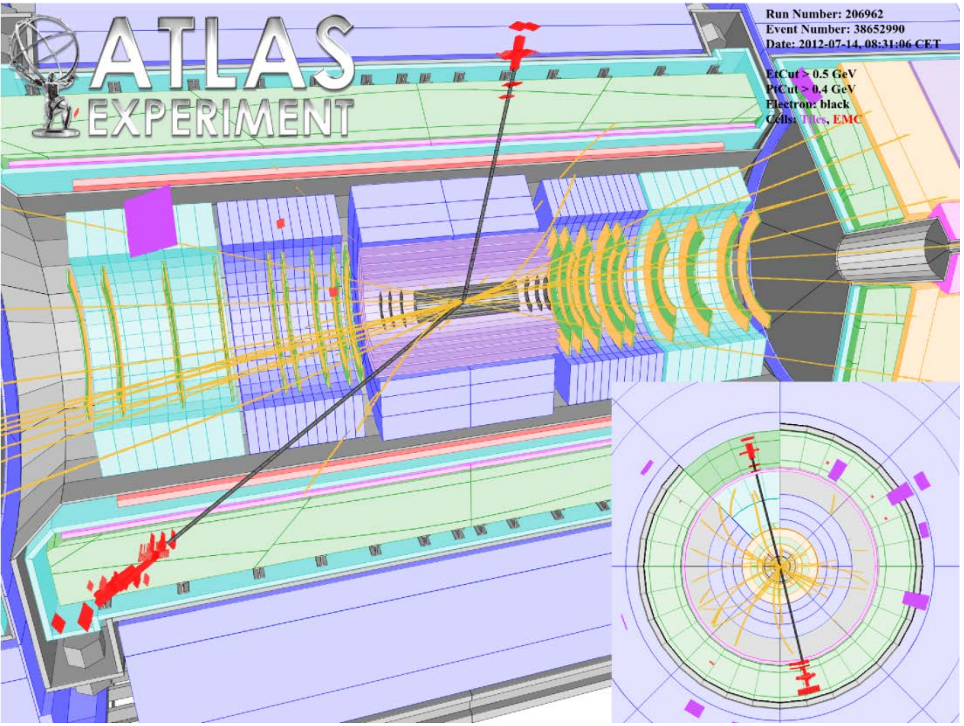


ATLAS-CONF-2013-017

W': Lepton + ETmiss

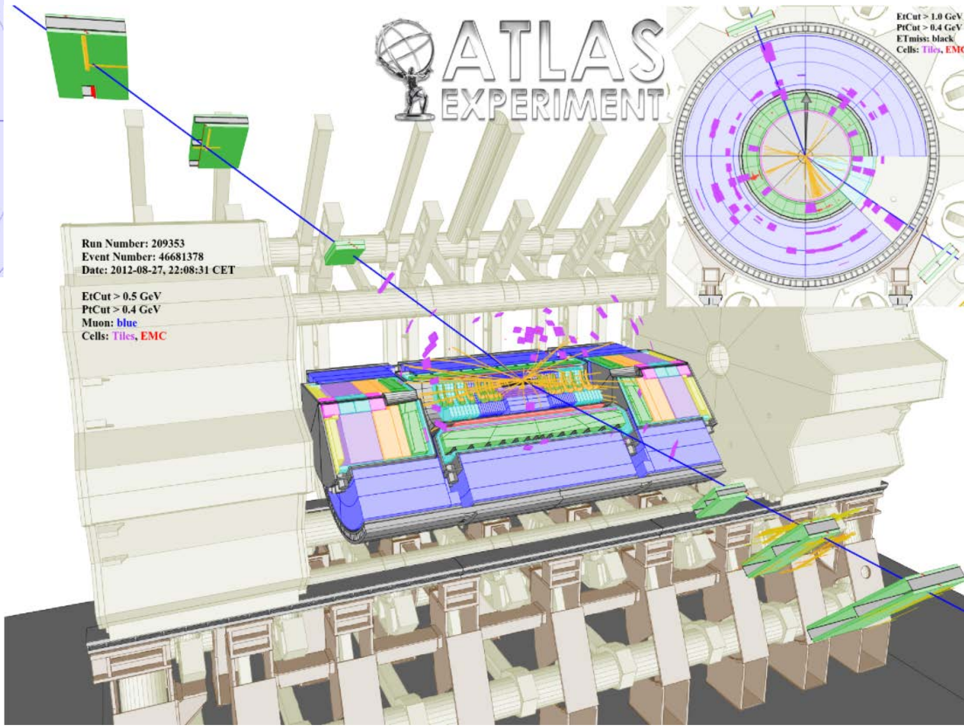


CMS-EXO-12-060



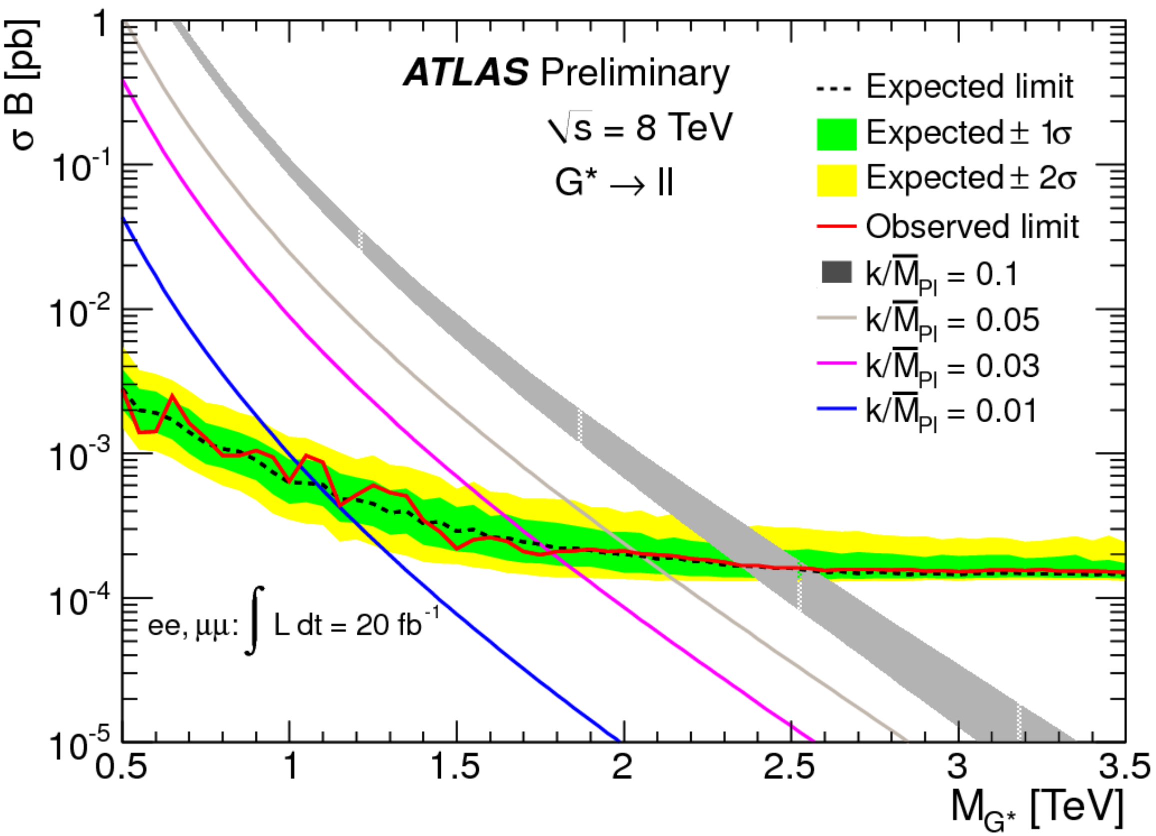
The highest mass di-lepton events from ATLAS

m (e^+e^-) = 1.54 TeV



m ($\mu^+\mu^-$) = 1.84 TeV

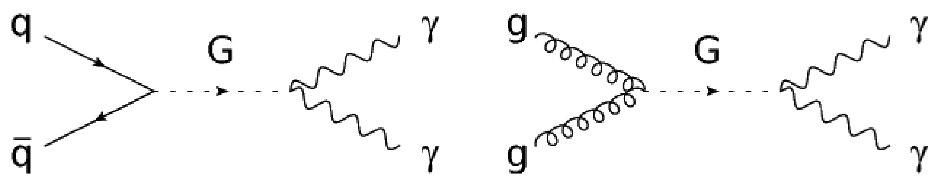
Lower mass limits, at 95% CL, for spin-2 Randall-Sundrum Gravitons



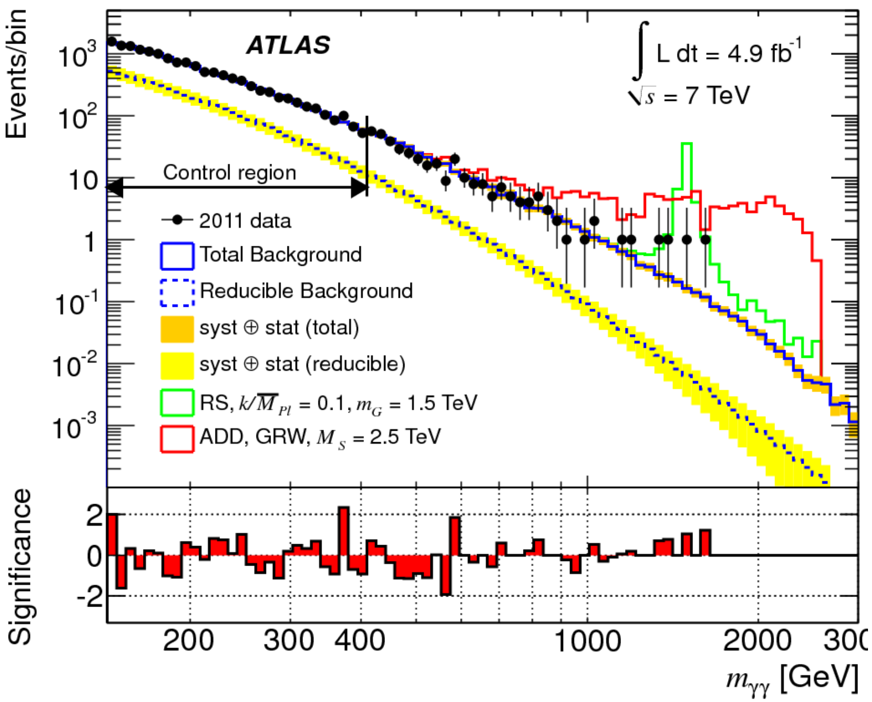
ATLAS-CONF-2013-017

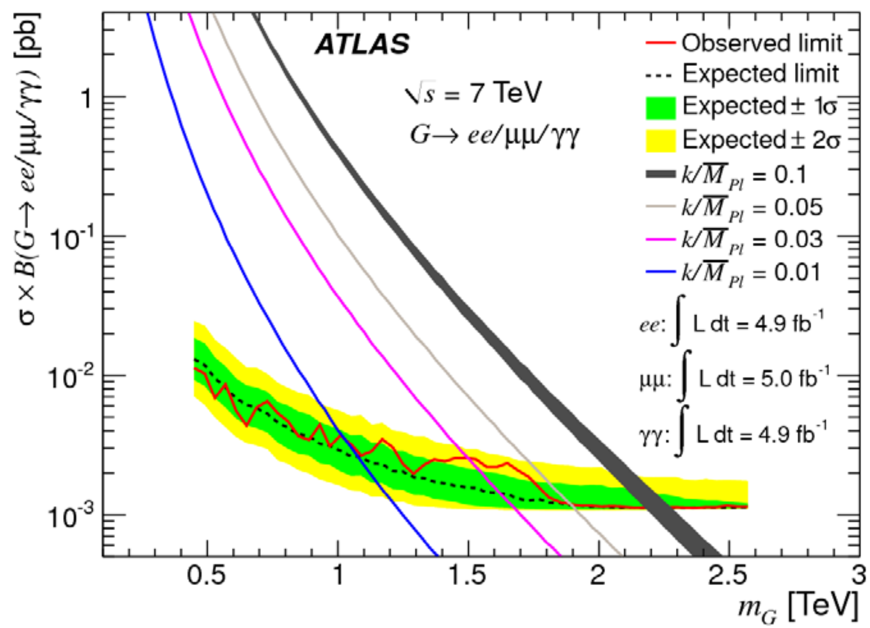
R Sundrum
L Randall
F Gianotti

New particles decaying into two photons



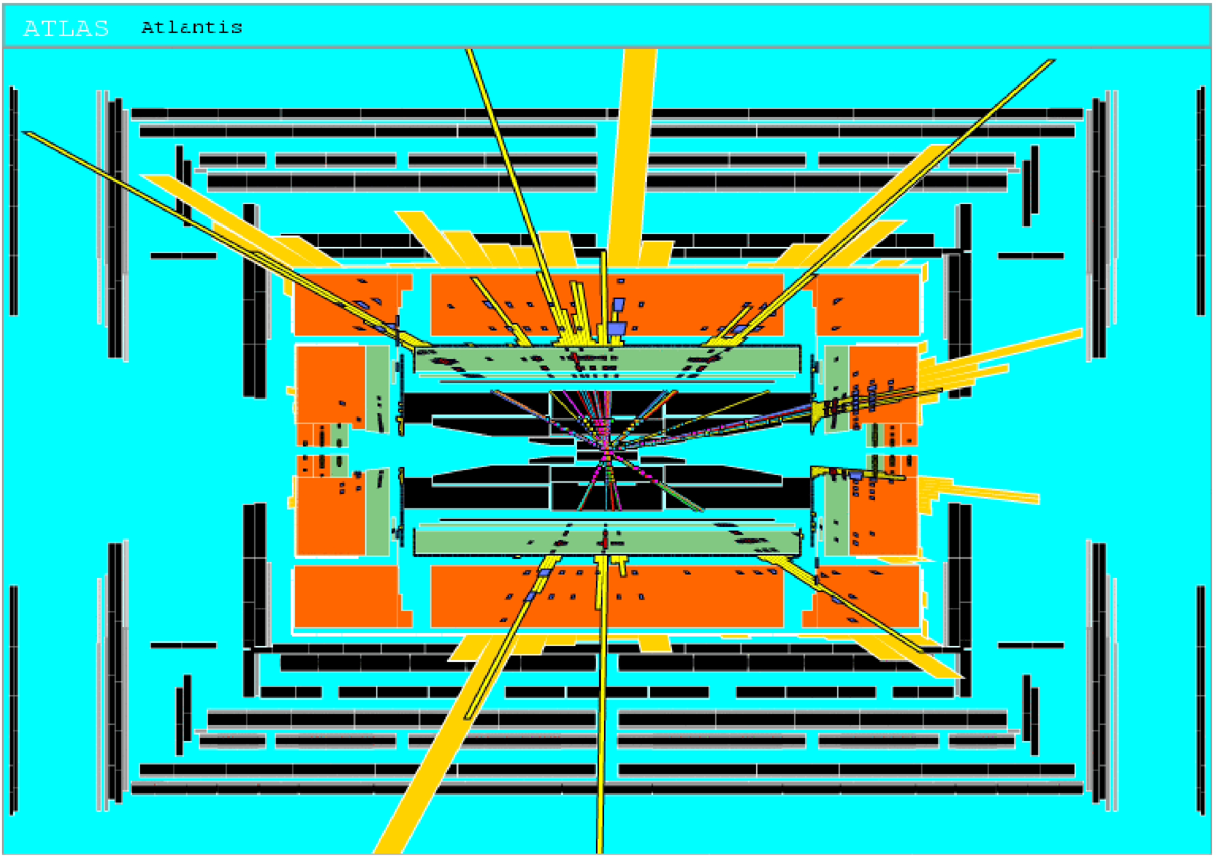
Example for a search of extra dimension signals (Kaluza-Klein Graviton in the Randall-Sundrum and Arkani-Hamed, Dimopoulos and Dvali models)





arXiv:1210.8389v12[hep-ex]

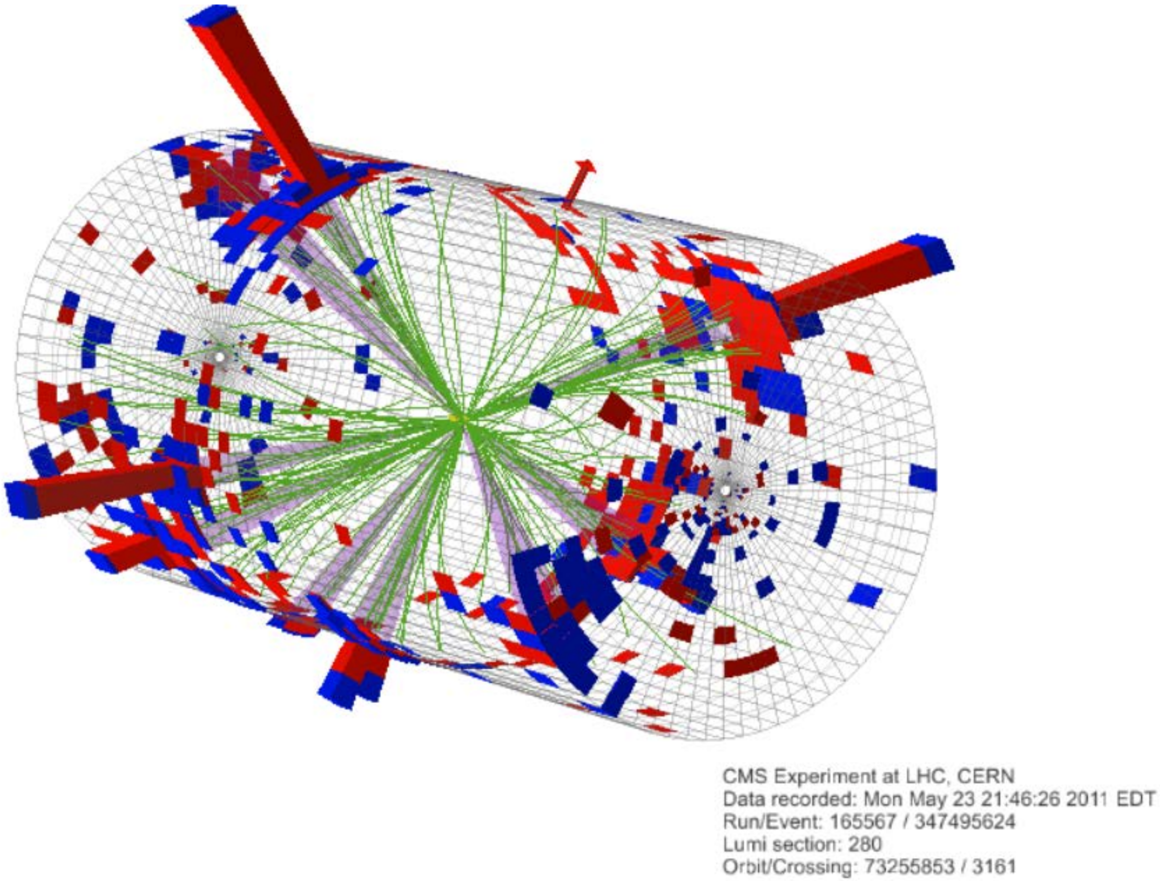
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



Simulation of a black hole event with M_{BH} ~ 8 TeV in ATLAS

They decay immediately through Stephen Hawking radiation

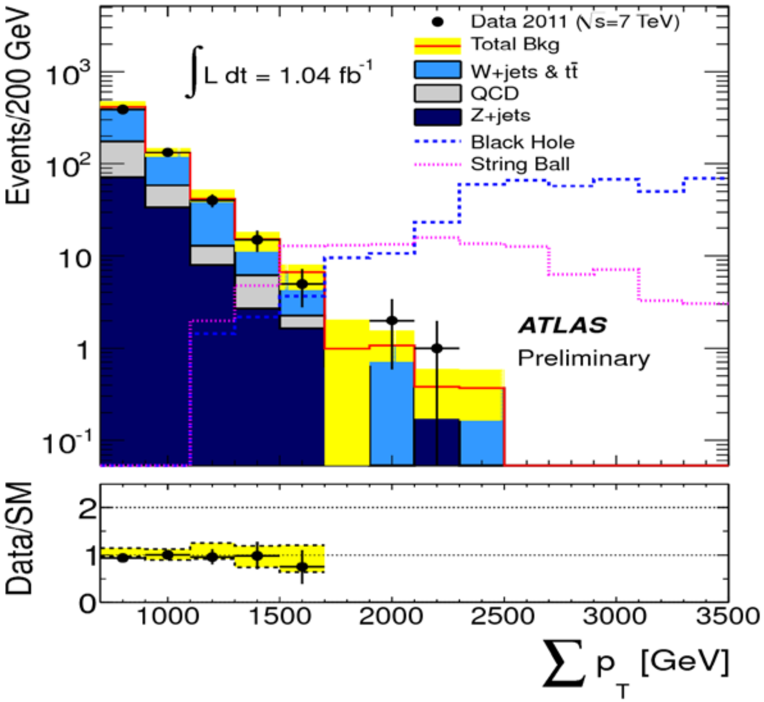
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



A real 'candidate' event of a 'black hole' in CMS with 9 jets and ST = 2.6 TeV

They decay immediately through Stephen Hawking radiation

Search for Microscopic Black Hole production in models wth large extra dimensions
(Arkani-Hamed, Dimopoulos, Dvali)

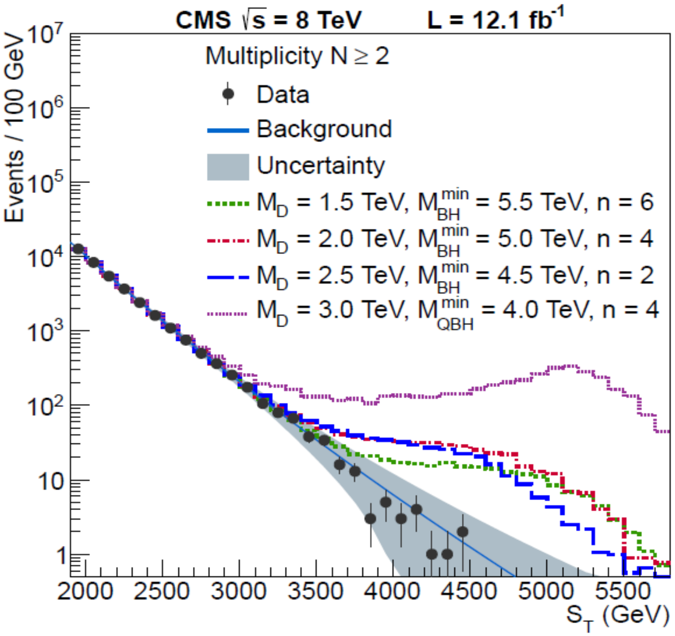


Decay into many objects (jets, leptons, photons)

ATLAS-CONF-2011-147
arXiv:1204.4646v1[hep-ex]

ΣP_T : scalar sum of the E_T of the N objects in the event

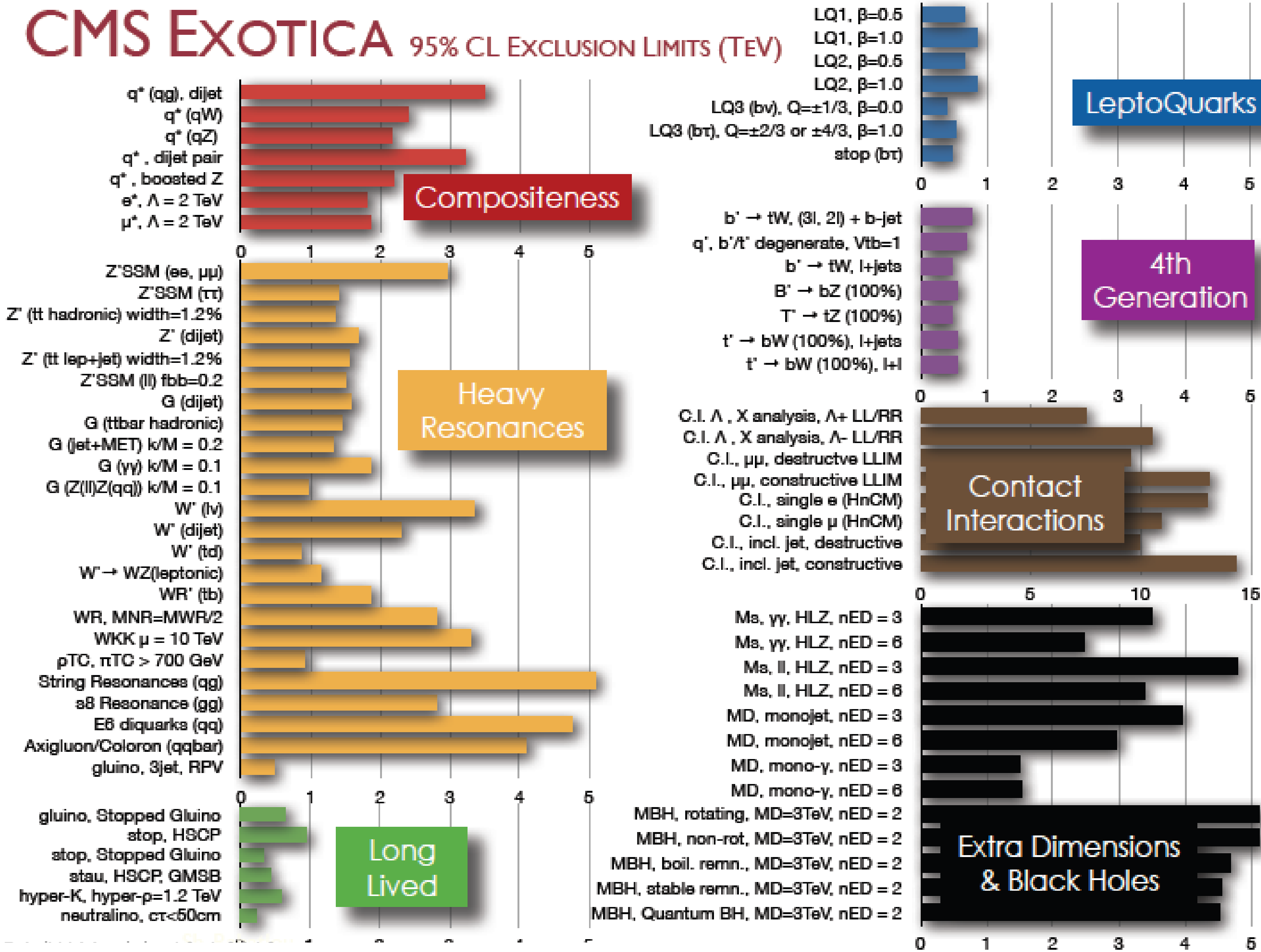
<u>Examples:</u> (ATLAS) at least one electron or muon and two or more jets, (CMS) any three objects



No deviation is seen for events with at least 3 objects with > 50 GeV pT

Submitted to JHEP
arXiv:1303.5338v1[hep-ex]

Similar results exist from ATLAS



(TeV) **(TeV)**

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

Thank you for your attention

J Blaeu 1664