

The long journey to the Higgs boson and beyond at the LHC



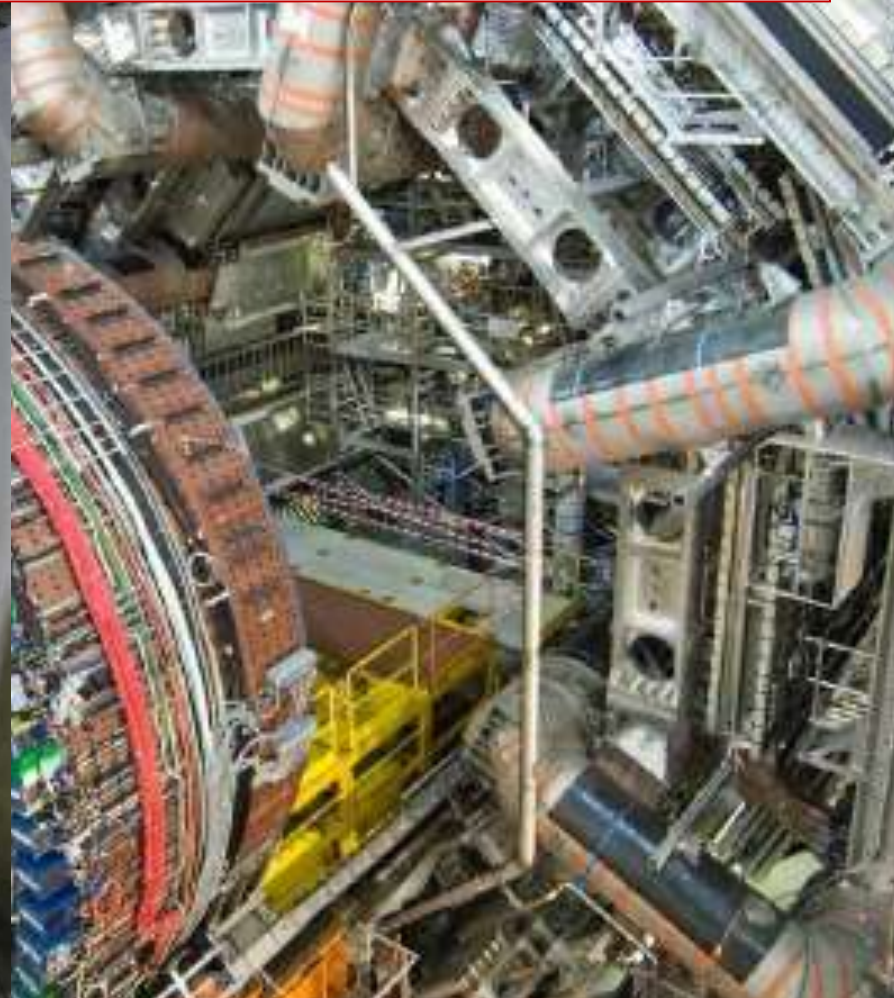
5th Dvořák Lecture
Institute of Physics of the AS CR
Prague, 12th June 2013



Drawing by Sergio Cittolin

Peter Jenni, Freiburg and CERN

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



AS CR, Praha, 12.6.2013
P Jenni (Freiburg/CERN)

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

History of the Universe

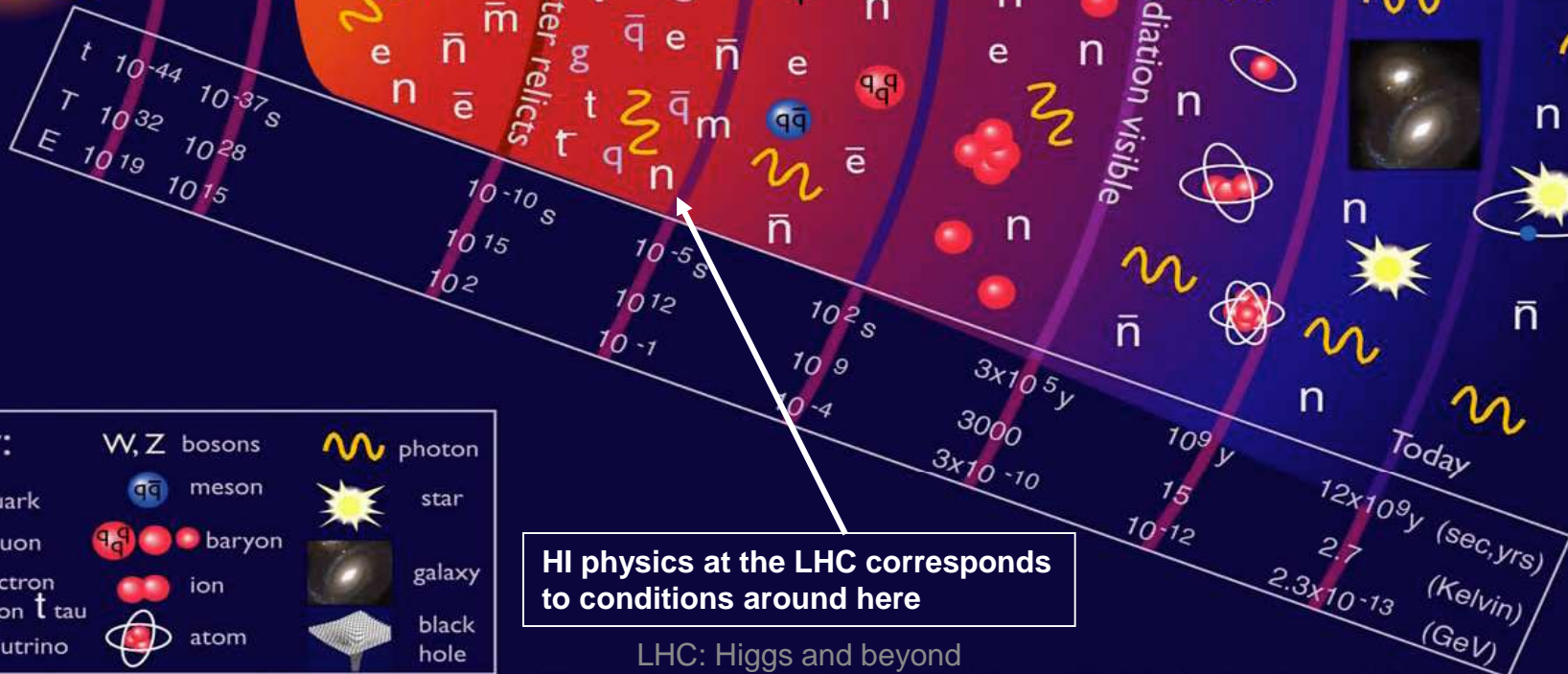
pp physics at the LHC corresponds to conditions around here

BIG BANG

Inflation

possible dark matter relicts

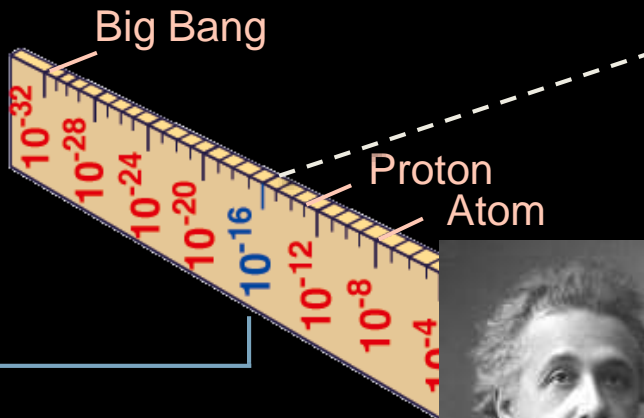
cosmic microwave radiation visible



Key:

- W, Z bosons
- q quark
- g gluon
- e electron
- m muon
- n neutrino
- meson
- baryon
- ion
- atom
- photon
- star
- galaxy
- black hole

HI physics at the LHC corresponds to conditions around here

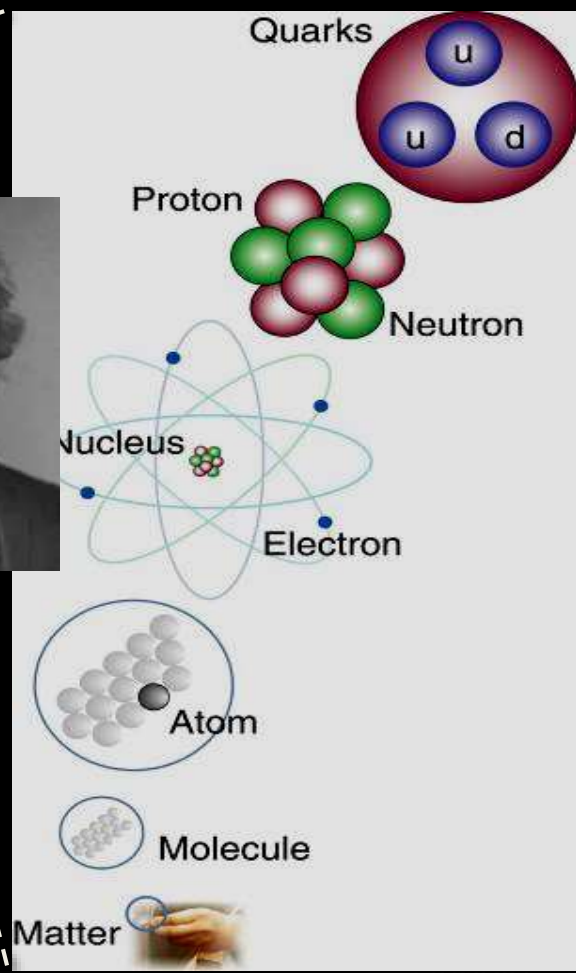
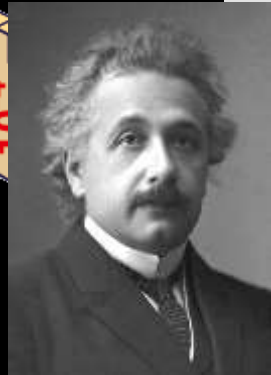


LHC

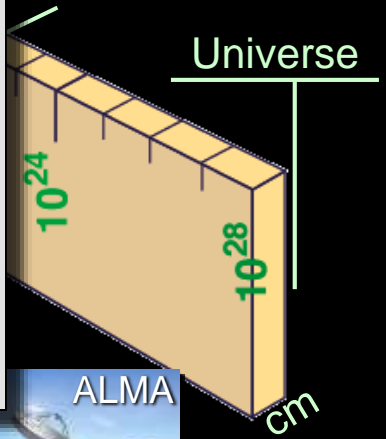
Super-Microscope



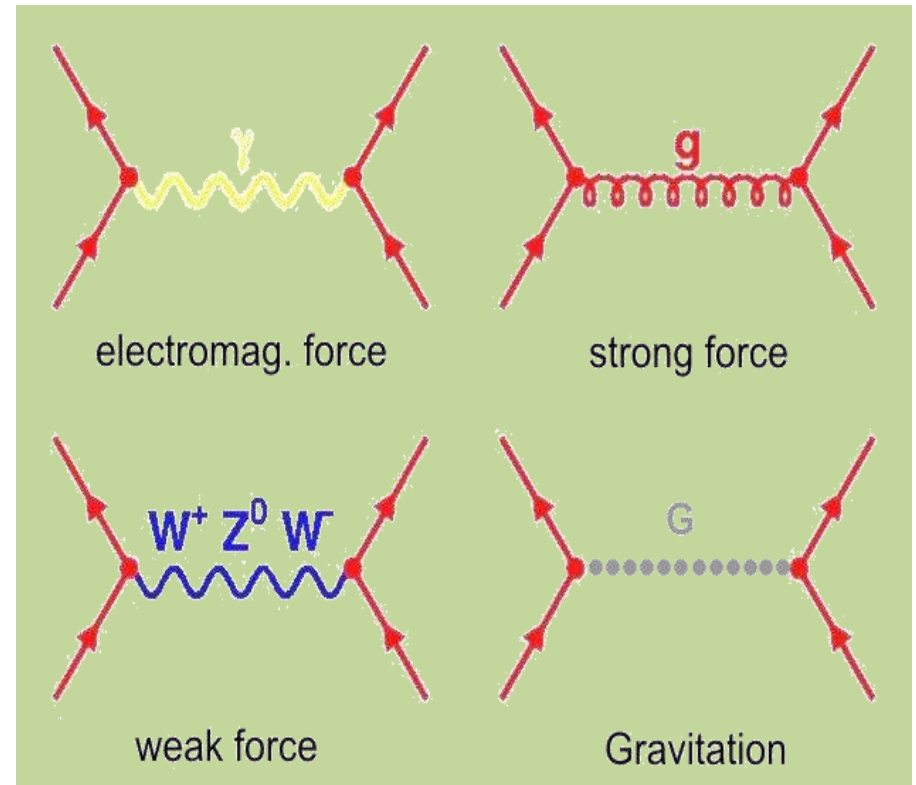
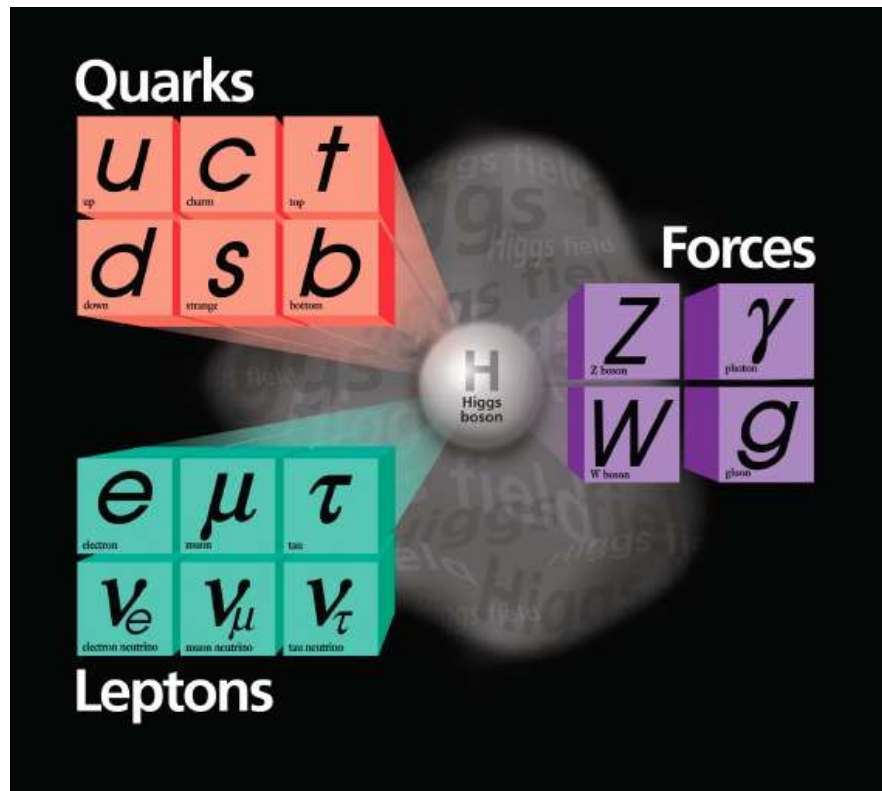
Study physics laws of first moments after Big Bang
 increasing Symbiosis between Particle Physics,
 Astrophysics and Cosmology



Radius of Galaxies



The Standard Model of Particle Physics



- (i) **Constituents of matter: quarks and leptons**
- (ii) **Four fundamental forces**
(described by quantum field theories, except gravitation)
- (iii) **The Higgs field (problem of mass)**

However: the SM is not a complete theory

Some of the outstanding questions in fundamental physics are

What is the origin of the elementary particle masses ?

(~✓)

What is the nature of the Universe dark matter ?

Why is there so much less antimatter than matter in the Universe ?

What are the features of the primordial Universe present $\sim 10 \mu\text{s}$ after the Big Bang ?

What happens at the $\sim 10^{-12}$ s scale ?

Are there additional (microscopic) space dimensions ?

.....

New Physics beyond the Standard Model is needed to answer these and other questions. The huge amount of precise experimental data collected so far indicate that this New Physics could manifest itself at the $\sim \text{TeV}$ energy scale being explored by the LHC

How the LHC came to be ...

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

Some early key dates

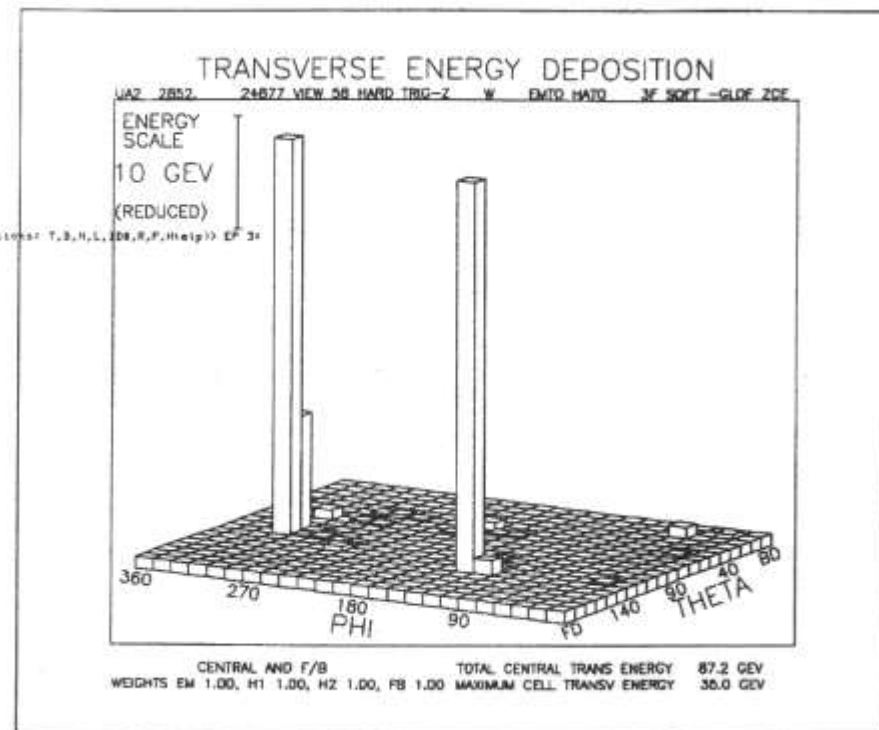
1977 The community talked about the LEP project, and it was already mentioned that a new tunnel could also house a hadron collider in the far future

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 $Z \rightarrow ee$ 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***

AS CR, Praha, 12.6.2013
P Jenni (Freiburg/CERN)

N° 1
July 1991
(supplement
to CERN Courier
July / August 1991)



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)

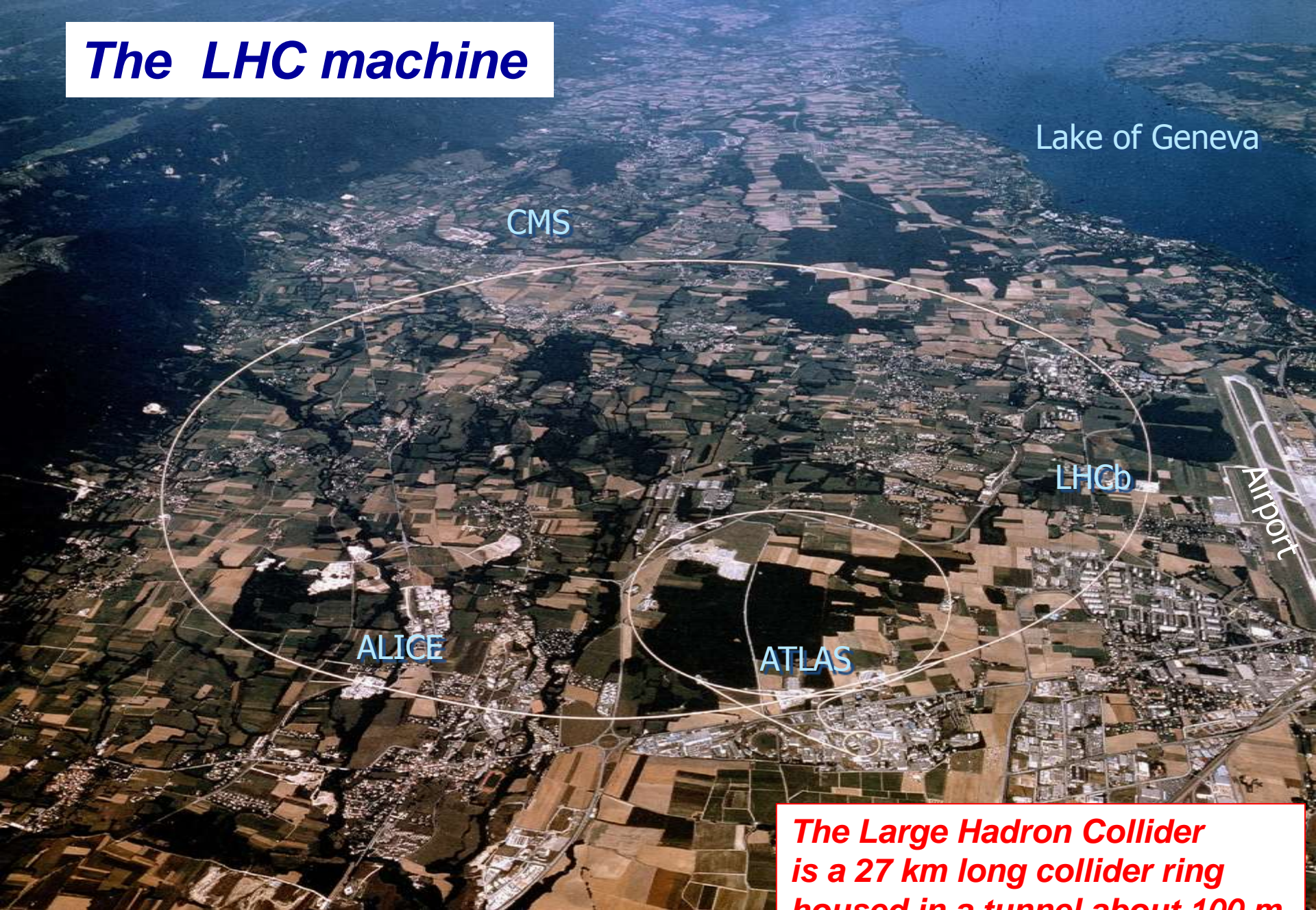
1997

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



Lake of Geneva

CMS

LHCb

ALICE

ATLAS

Airport

The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

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



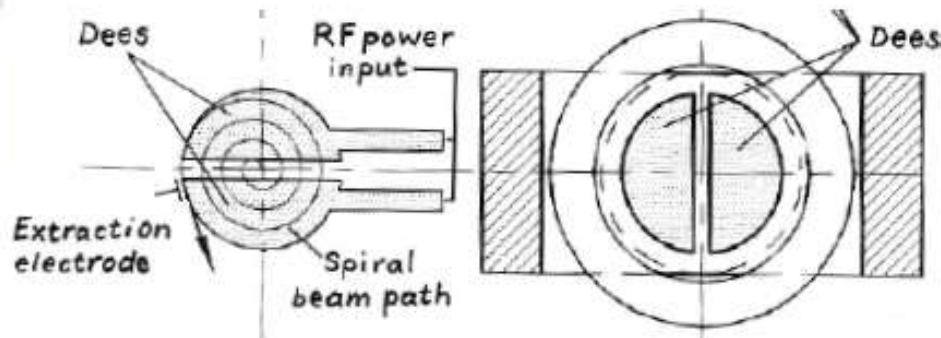
Ernest Lawrence
(1901 - 1958)



**The first circular accelerator
(Berkeley 1930)**

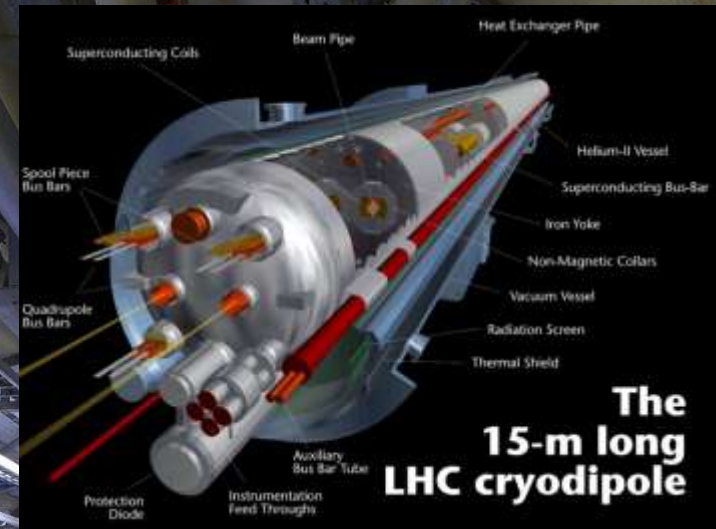


184" 1946



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



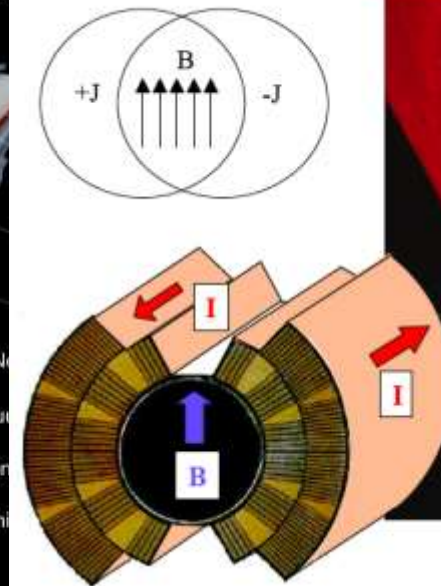
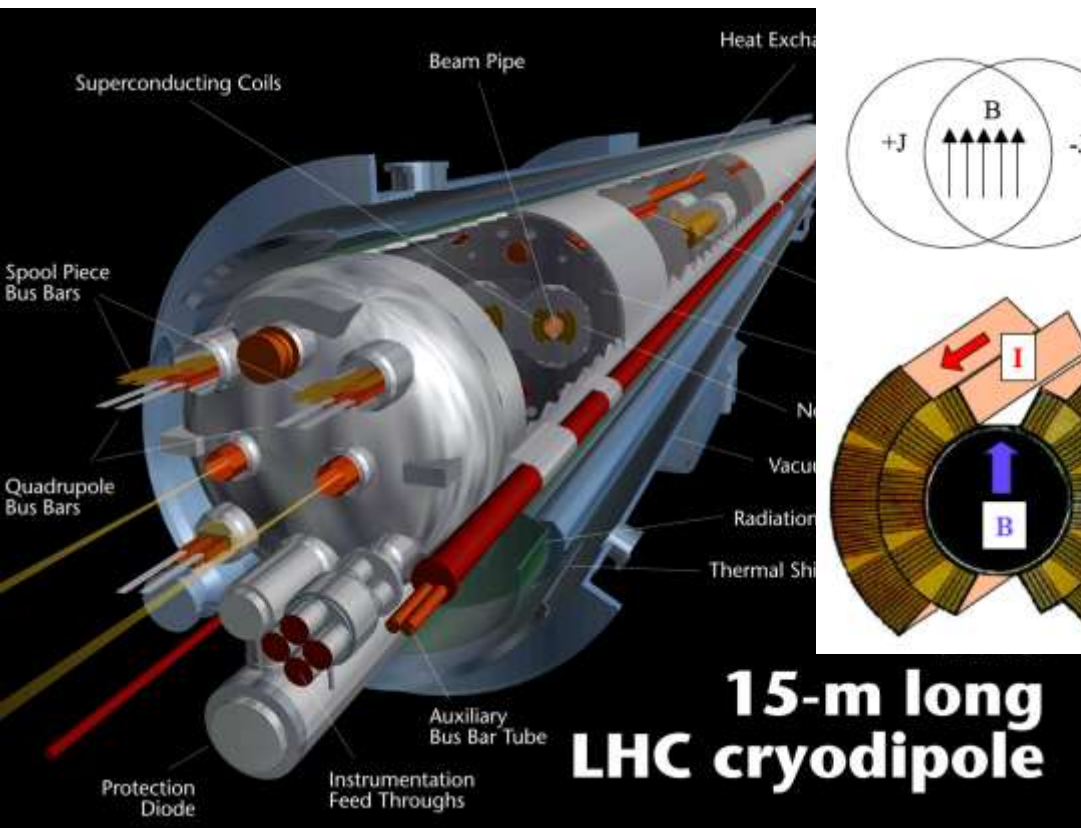
$$p(\text{TeV}) = 0.3 \text{ B(T)} R(\text{km})$$



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P Jenni (Freiburg/CERN)

LHC Construction Project Leader Lyndon Evans

LHC Accelerator Challenge: Dipole Magnets



Magnetic Field for Dipoles
 $p \text{ (TeV)} = 0.3 \text{ B(T)} R(\text{km})$

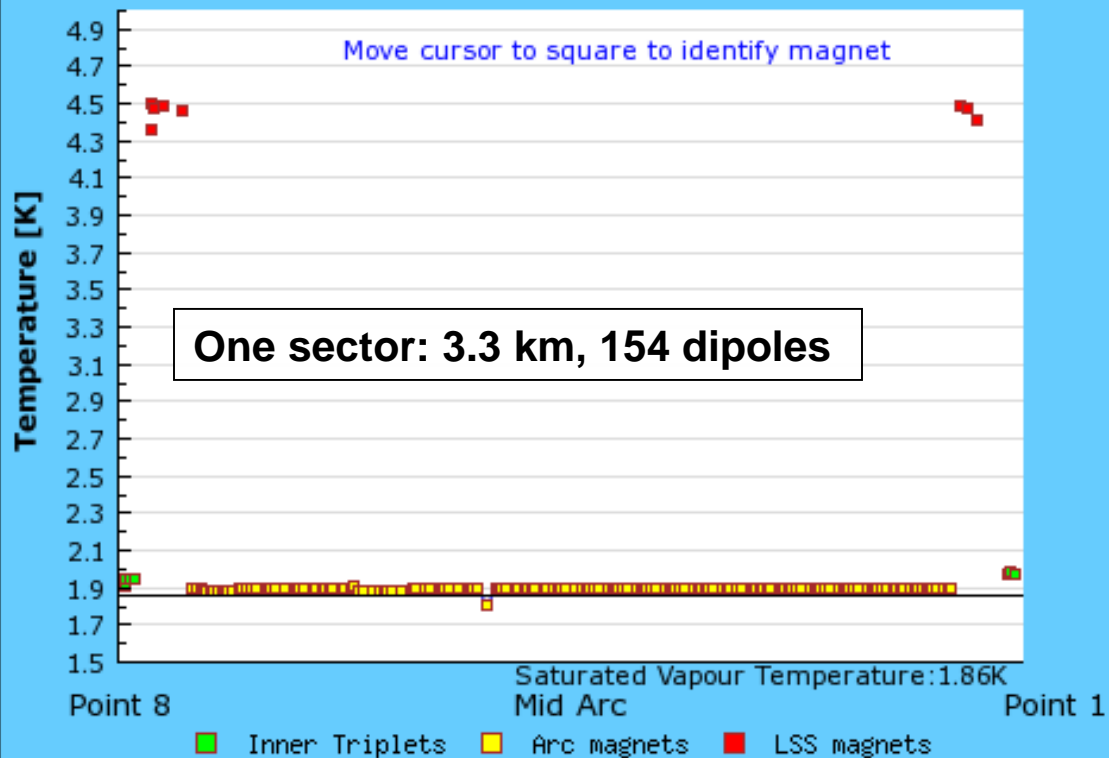
Coldest Ring in the Universe ?
1.9 K (CMBR is about 2.7 K)

LHC magnets are cooled with pressurized
superfluid helium

For $p = 7 \text{ TeV}$ and $R = 4.3 \text{ km}$
 $\Rightarrow B = 8.4 \text{ T}$
 $\Rightarrow \text{Current } 12 \text{ kA}$

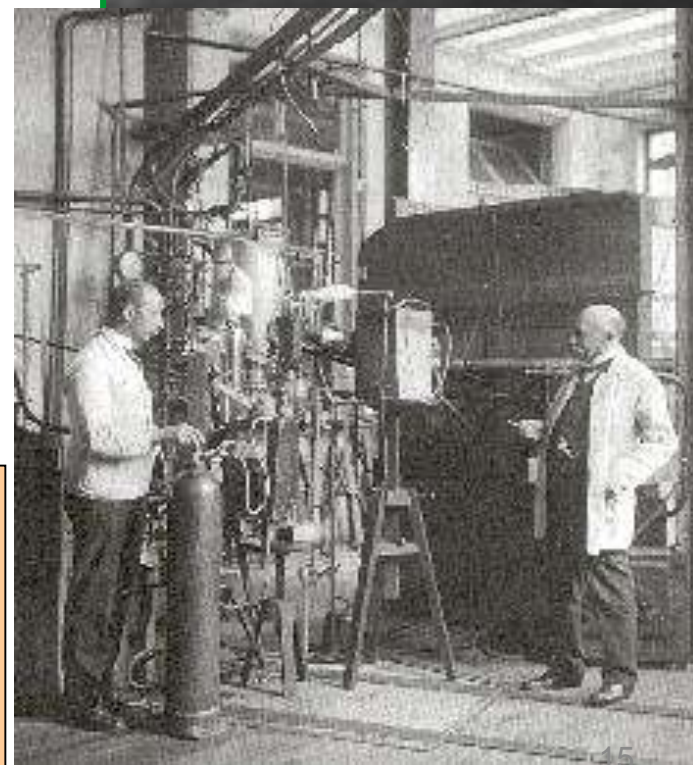
The LHC is the largest cryogenic system on earth, cooler than outer space

Sector temperature profile at 08 Dec 15:14



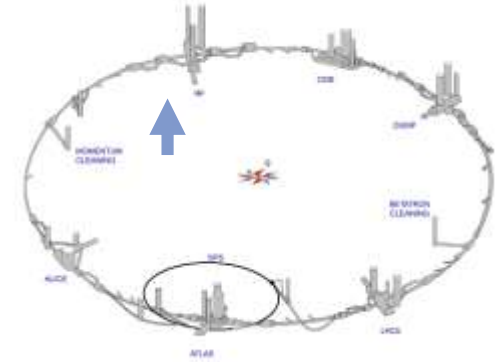
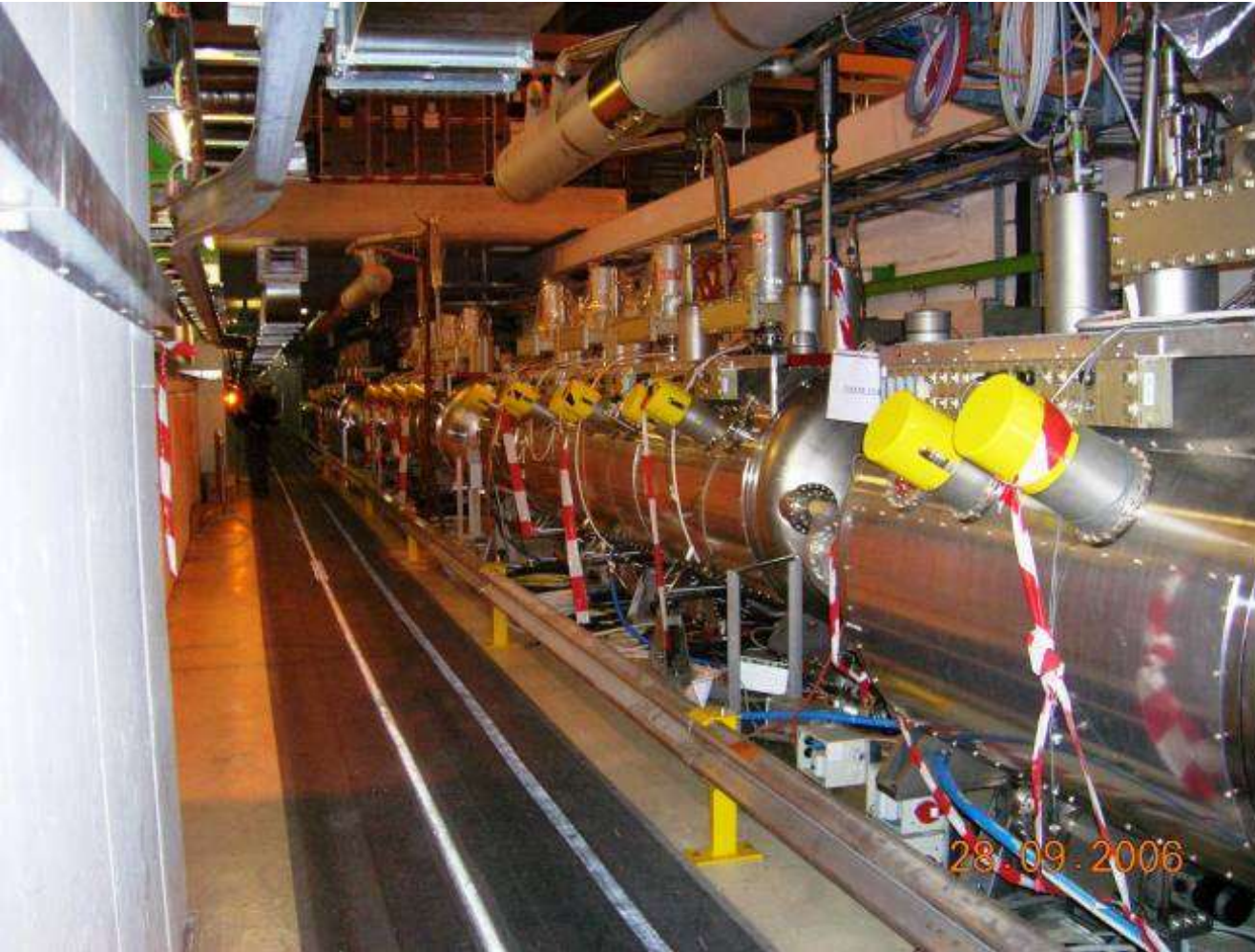
Magnets cooled down in a bath of ~120 tons of superfluid Helium (excellent thermal conductor)

H K Onnes
Nobel Prize in Physics 1913



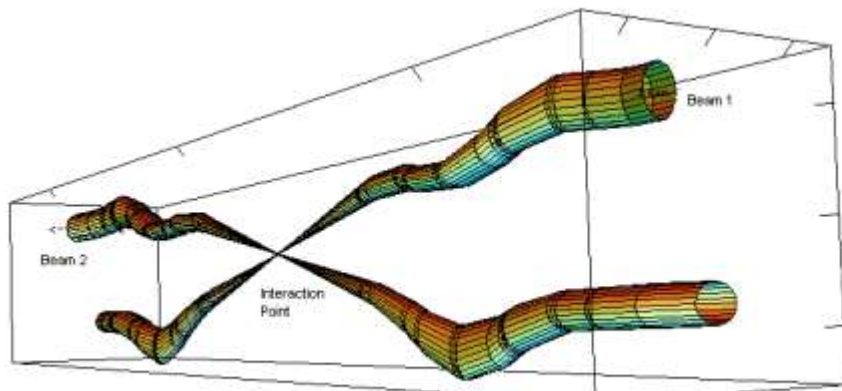
- 105 years ago, on 10 July 1908: Heike K Onnes first liquefied Helium (60 ml in 1 hour) in Leiden
- LHC today: 32000 He liters liquefied per hour by eight big cryogenic plants (the largest refrigerator in the world)

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



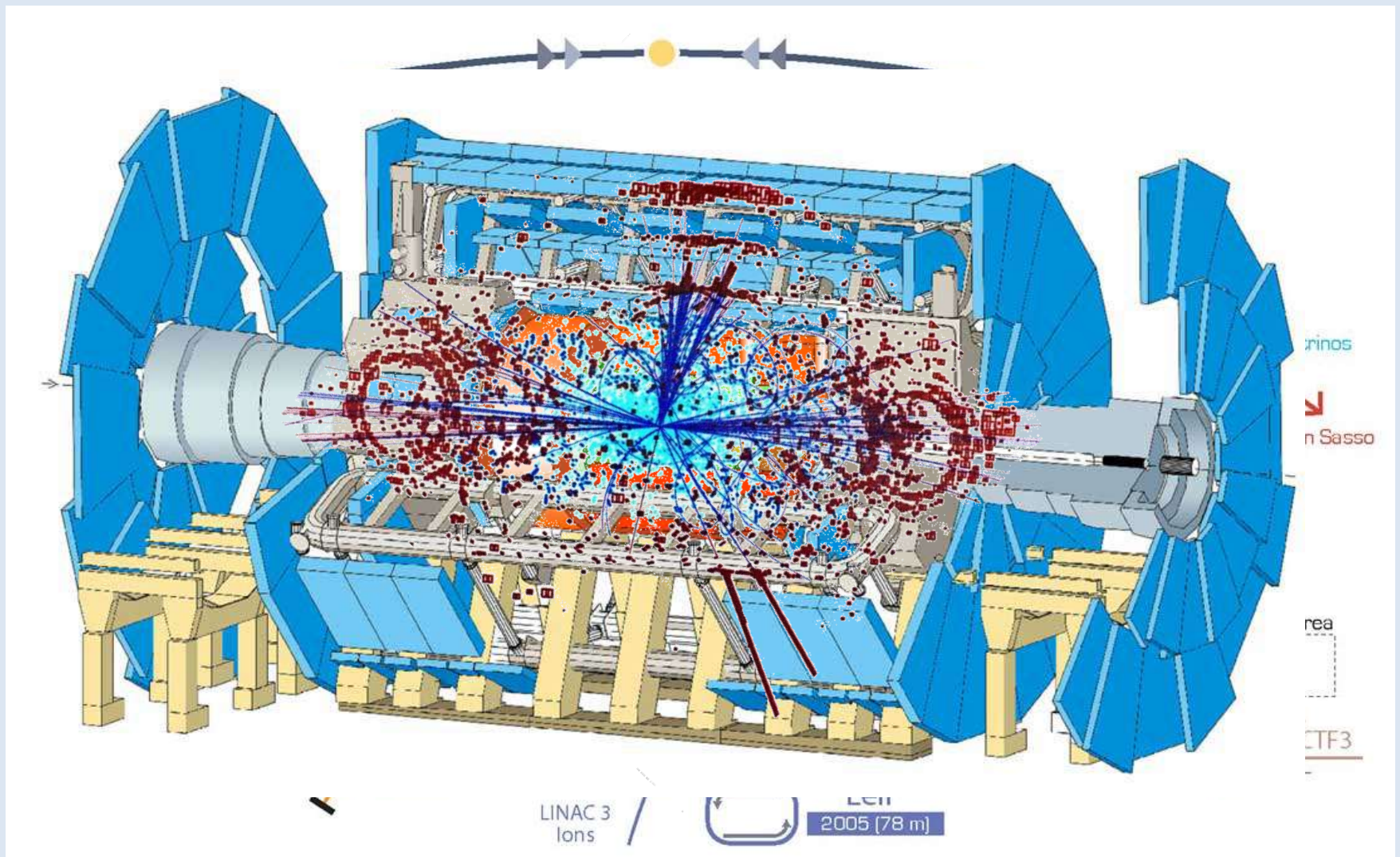
Note: The acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), because of the $\sim 1/m^4$ behaviour of the synchrotron radiation energy losses [$\sim E_{\text{beam}}^4/Rm^4$]

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

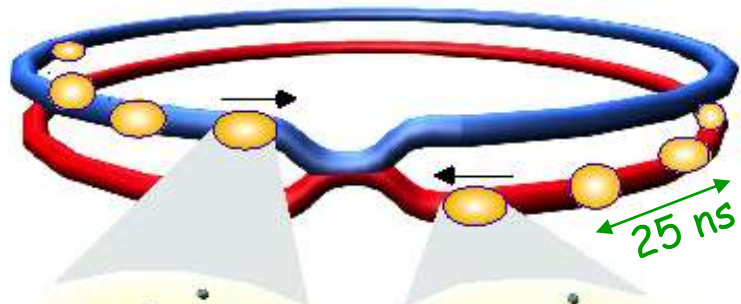


Relative beam sizes around the collision point

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

Bunch



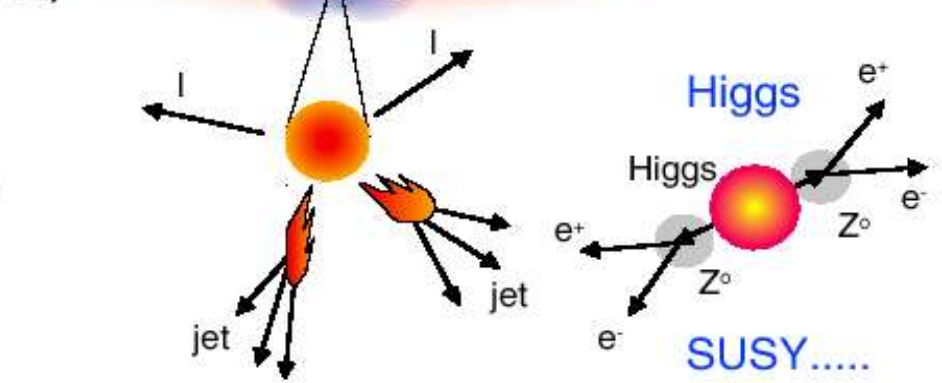
Proton



Parton
(quark, gluon)



Particle



Event rate:

$$N = L \times \sigma (pp) \approx 10^9 \text{ interactions/s}$$

Mostly soft (low p_T) events

Interesting hard (high- p_T) events are rare

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

However: the SM is not a complete theory

Some of the outstanding questions in fundamental physics are

What is the origin of the elementary particle masses ?

ATLAS, CMS

What is the nature of the Universe dark matter ?

ATLAS, CMS

Why is there so much less antimatter than matter in the Universe ?

LHCb

What are the features of the primordial plasma present $\sim 10 \mu\text{s}$ after the Big Bang ?

ALICE

What happened in the first moments of the Universe $\sim 10^{-11}$ s after the Big Bang ?

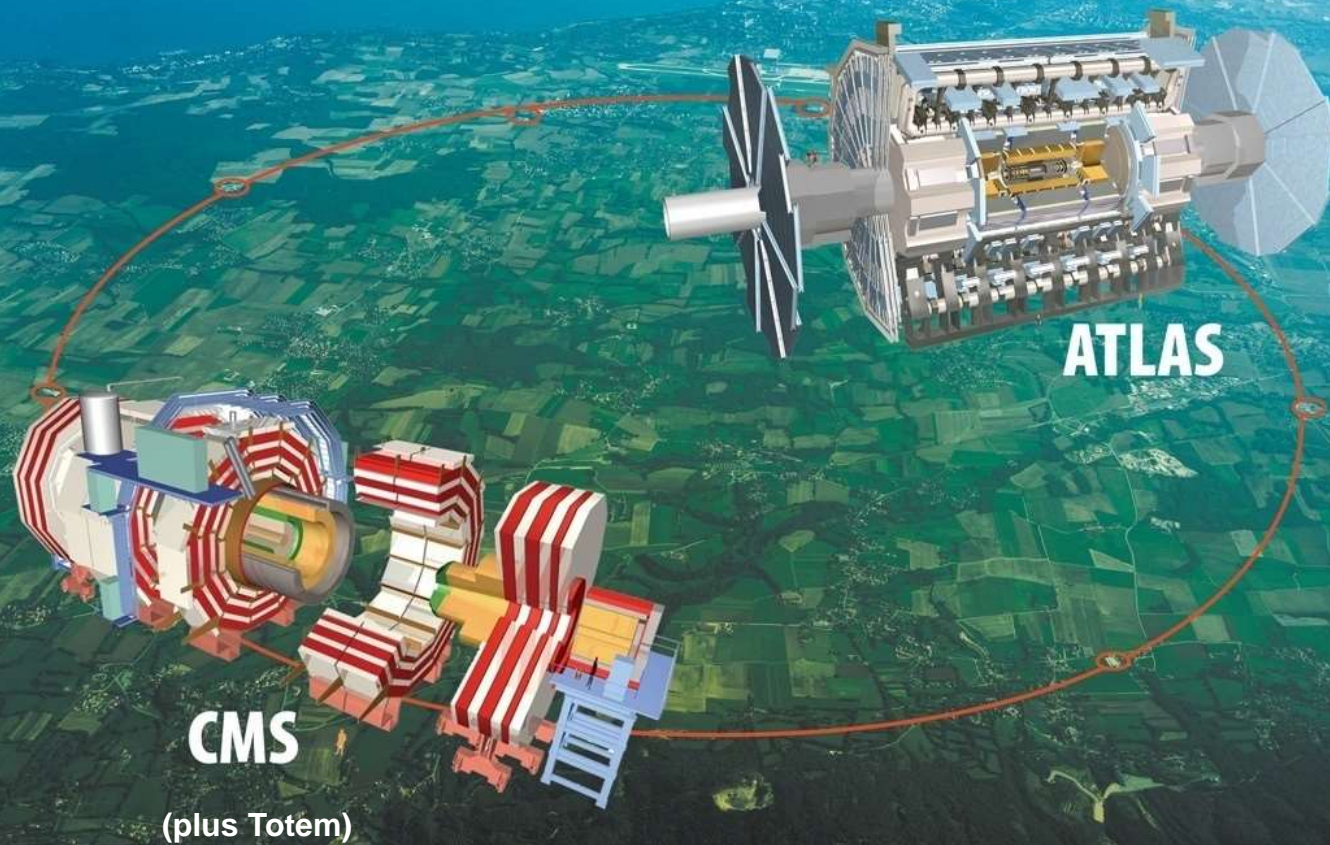
ATLAS, CMS

**Are there other forces in addition to the known four ?
Are there additional (microscopic) space dimensions ?**

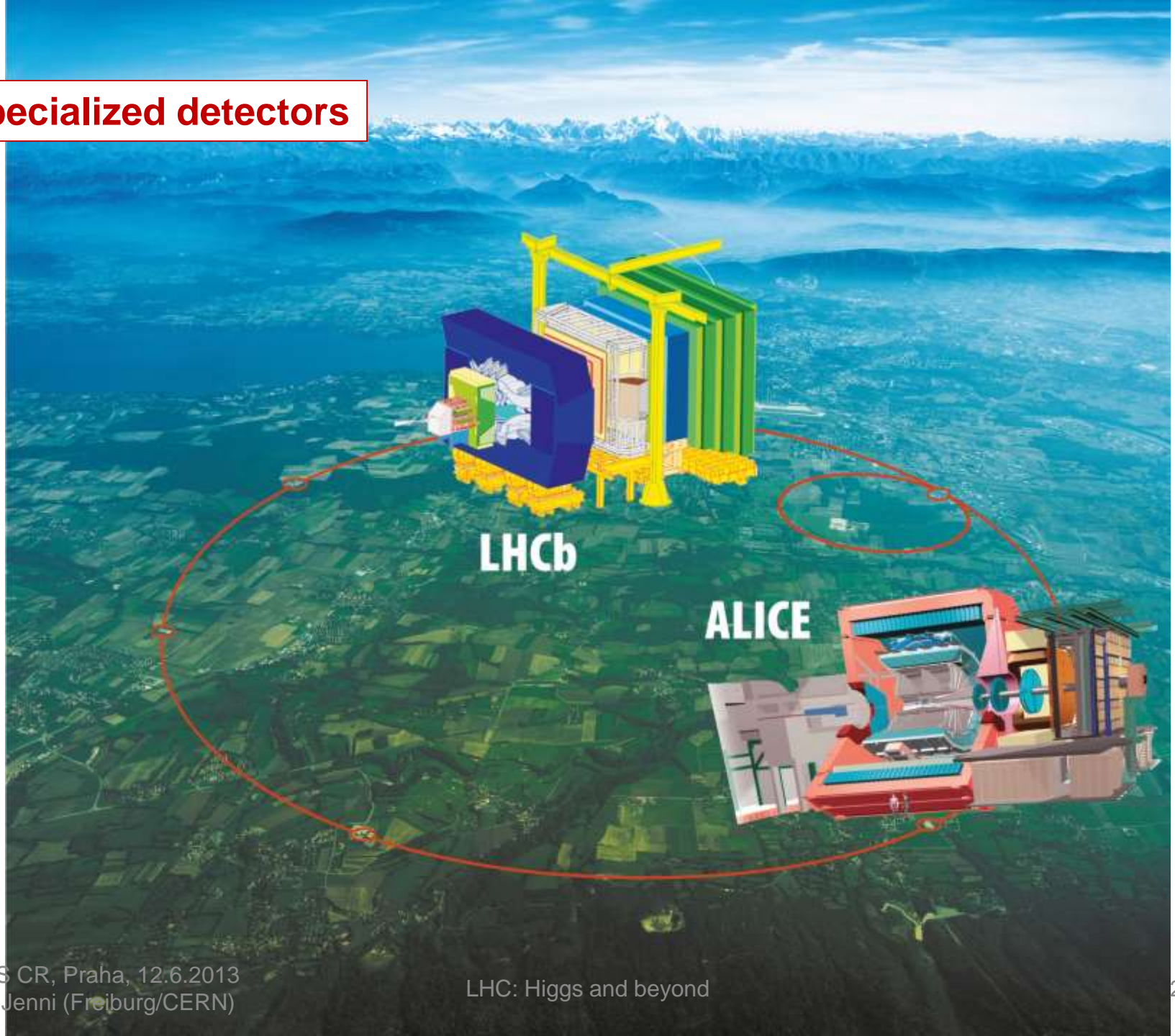
ATLAS, CMS

....

General purpose detectors



Specialized detectors



LHCb

ALICE

The LHC World of CERN

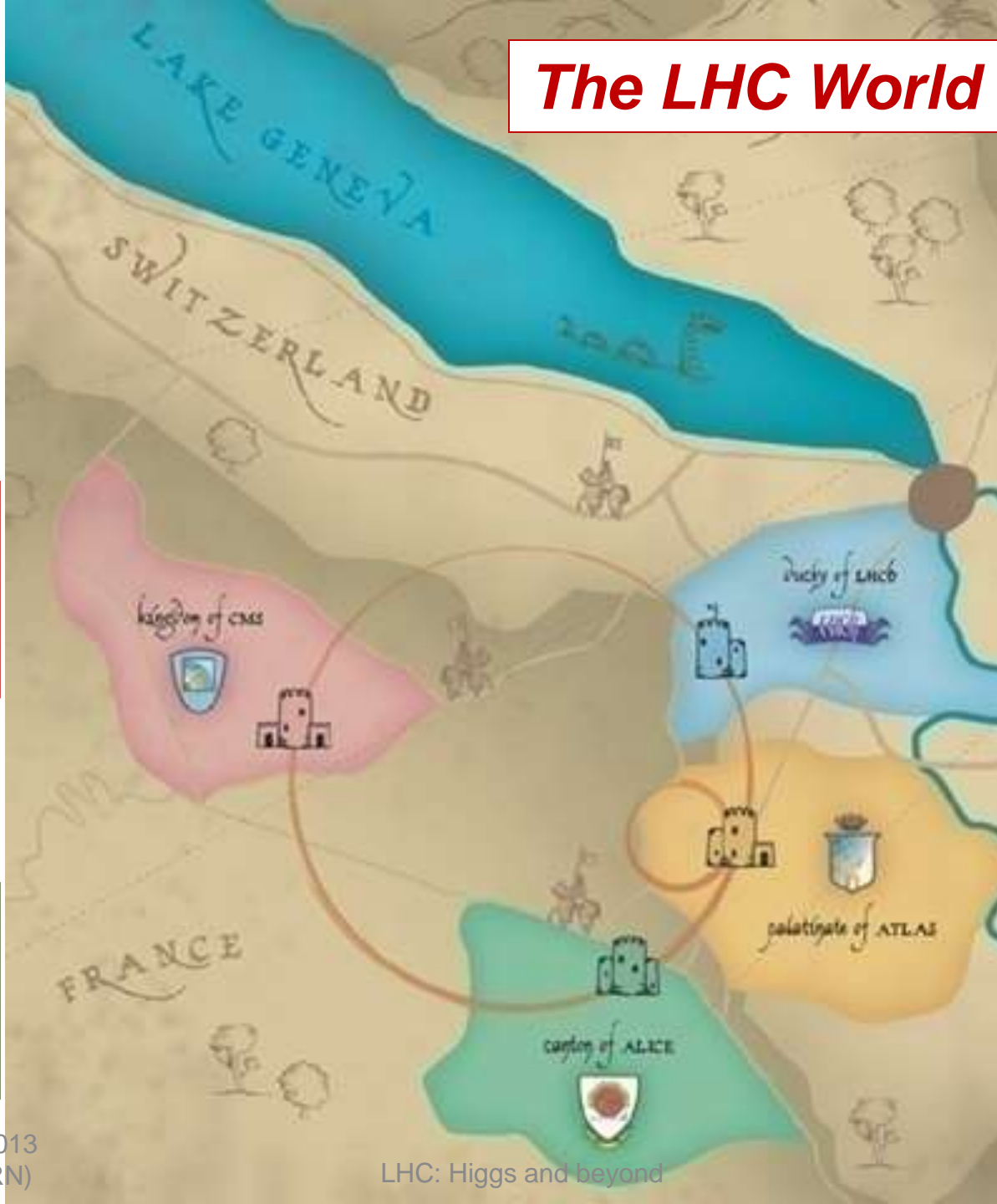
Plus smaller
local earldoms
LHCf (point-1)
TOTEM (point-5)
Moedal (point-8)

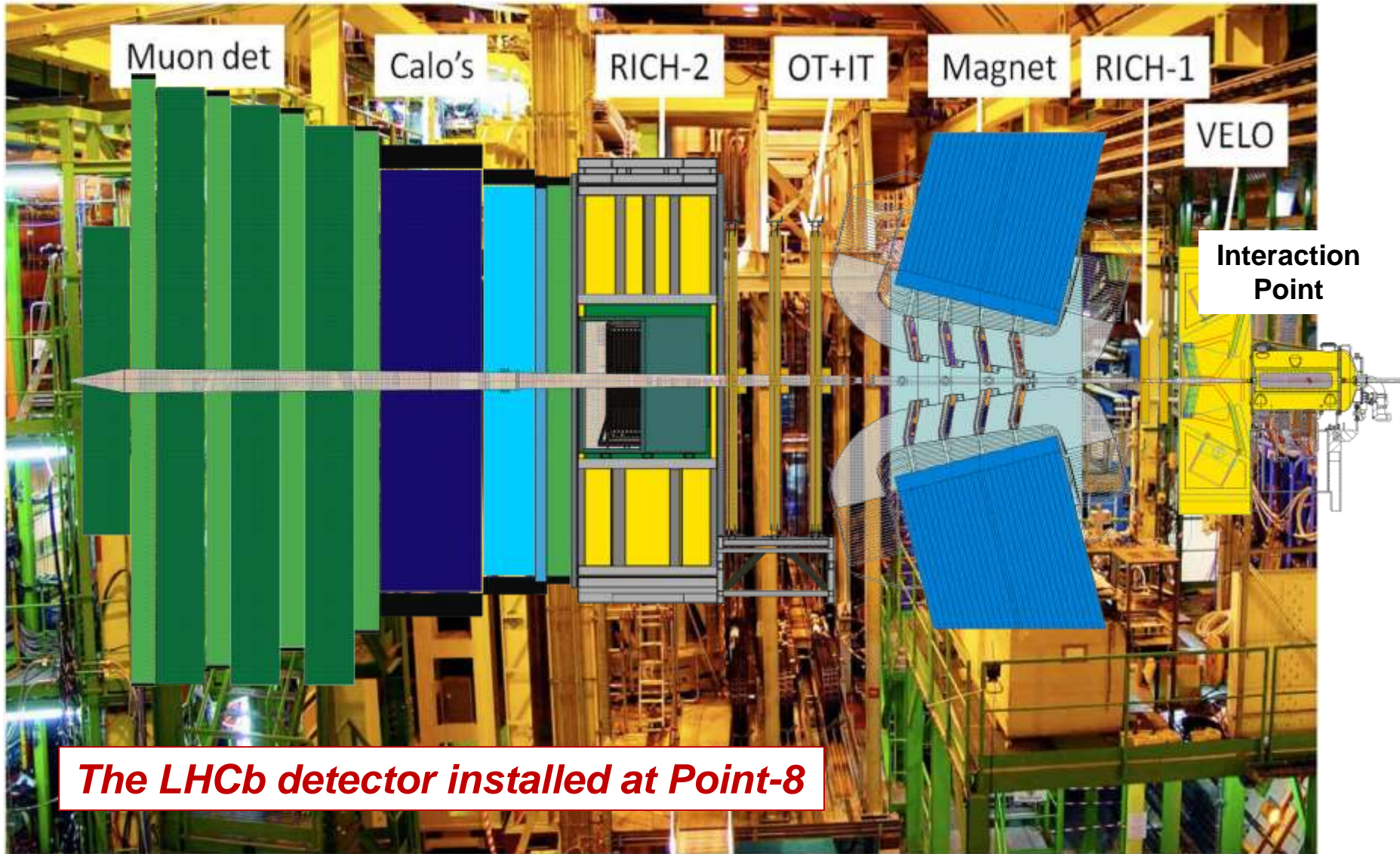
CMS
3000 Physicists
184 Institutions
38 countries
550 MCHF

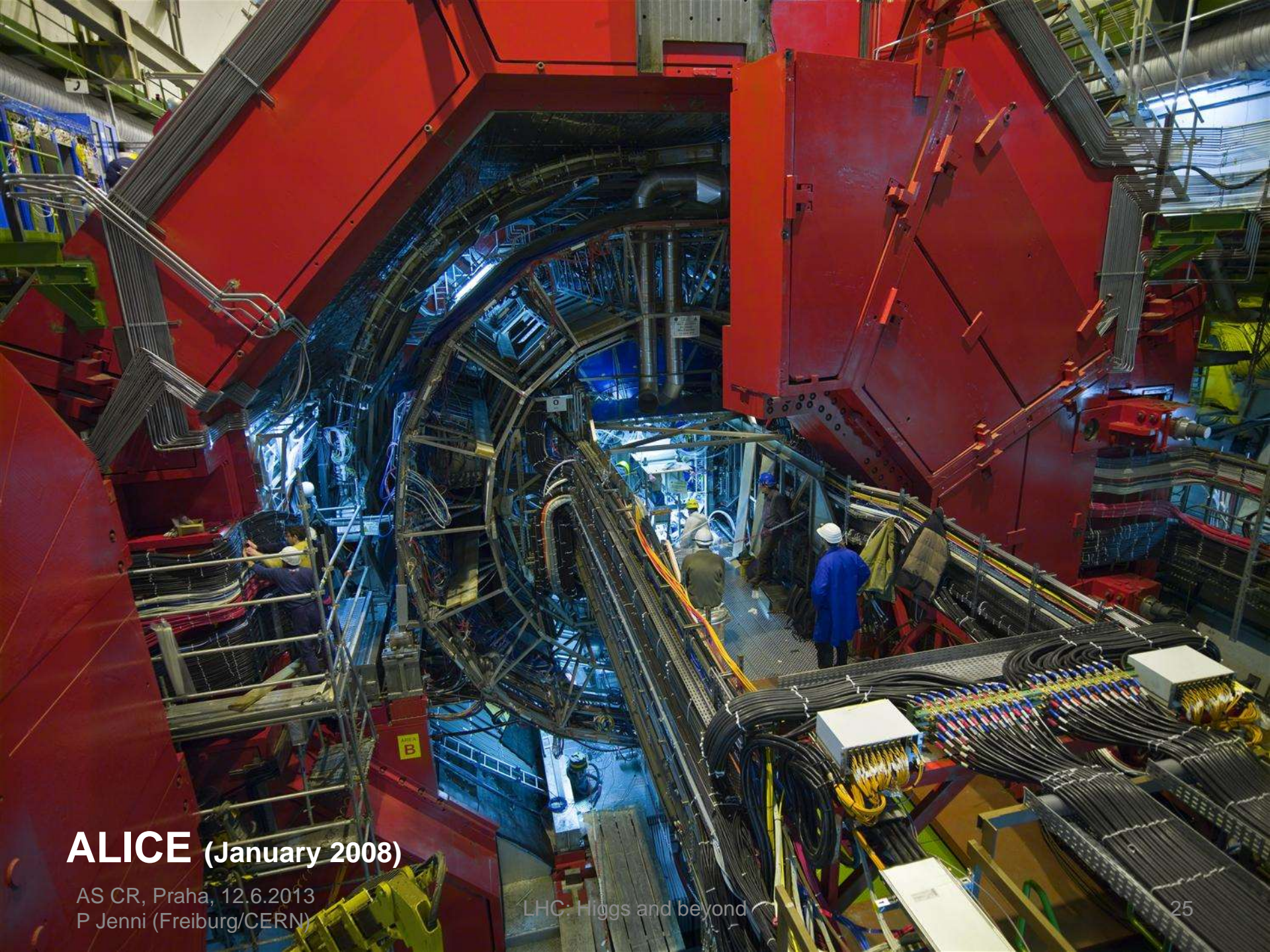
ALICE
1300 Physicists
130 Institutions
35 countries
160 MCHF

LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

ATLAS
3000 Physicists
176 Institutions
38 countries
550 MCHF







ALICE (January 2008)

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P Jenni (Freiburg/CERN)

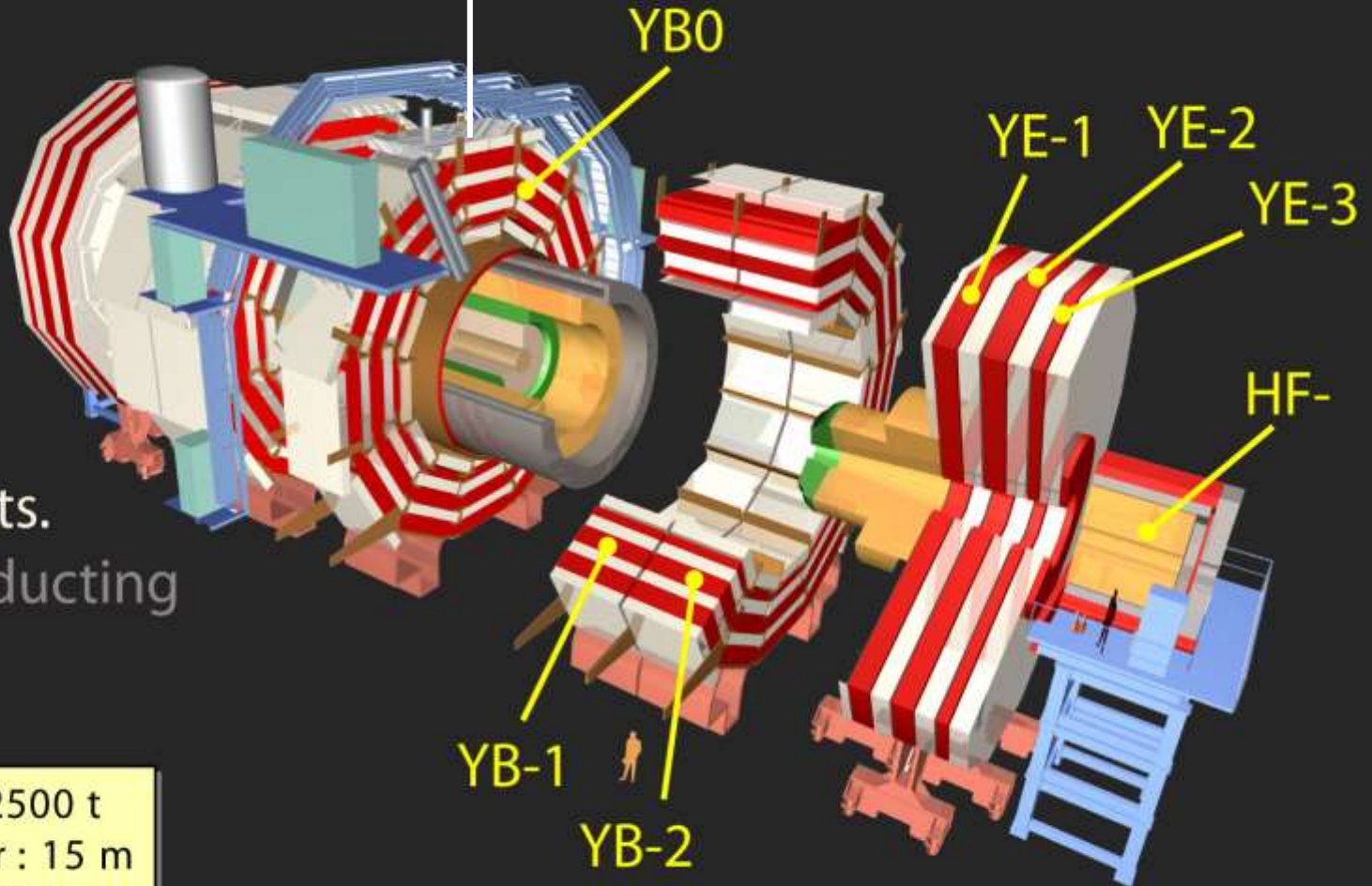
LHC: Higgs and beyond

Exploded View of CMS

Plus Side

Minus Side

- Pixels
- Tracker
- ECAL
- HCAL
- MUON Dets.
- Superconducting Solenoid



Total weight : 12500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

<http://cms.cern.ch>

An Example of an Engineering Challenge: CMS Solenoid



AS CR, Praha, 12.6.2013
P Jenni (Freiburg/CERN)

Oct. 2004

CMS solenoid:

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



LHC: Higgs and beyond

CMS before closure 2008



ATLAS Collaboration

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



Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Ancecy, 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

ATLAS Collaboration

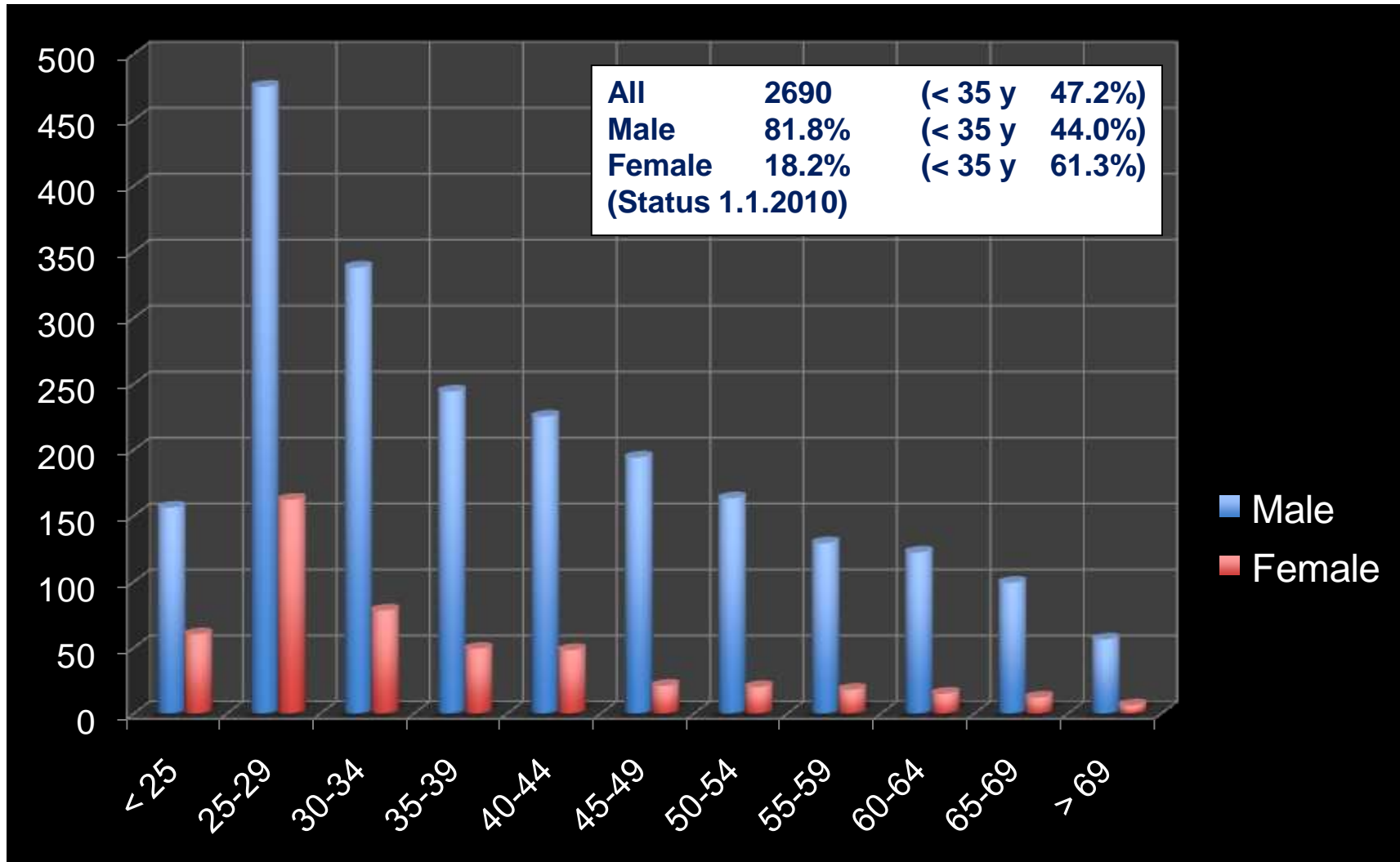
38 Countries
176 Institutions
3000 Scientific participants total
(1000 Students)

It is a great pleasure to collaborate with ~75 colleagues, junior and senior, from the four Czech Universities since the very first days



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, **ASCR 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





ATLAS Overview Week

A meeting of the world-wide ATLAS Collaboration building a detector for the near future of particle physics at the Large Hadron Collider at CERN. 13 –19 September 2003, Prague, Czech Republic

ATLAS has a long-standing, excellent, cooperation with the Czech teams, since the official start of the project in 1992

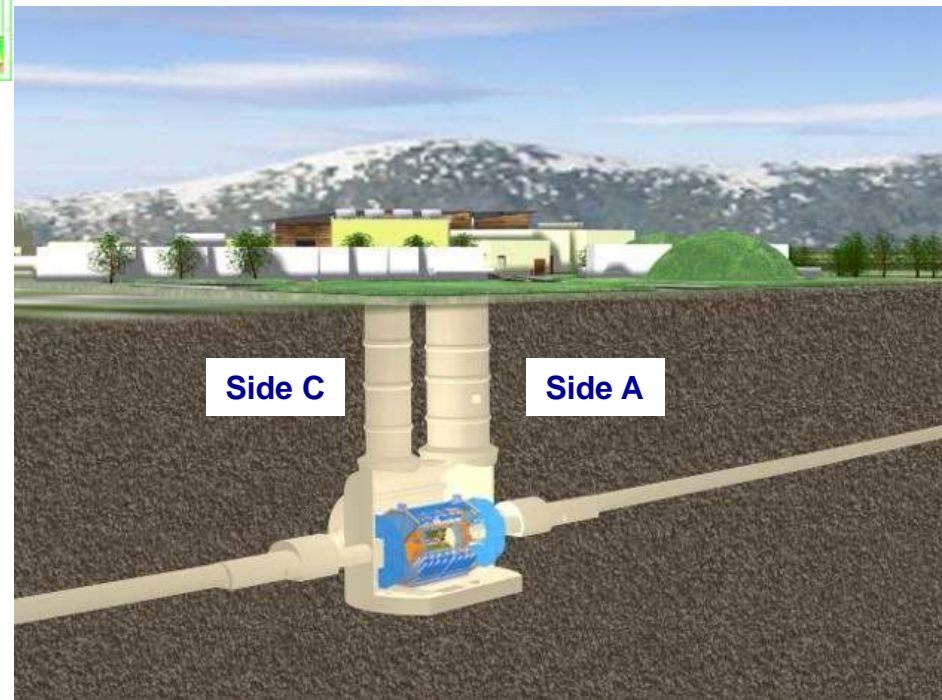
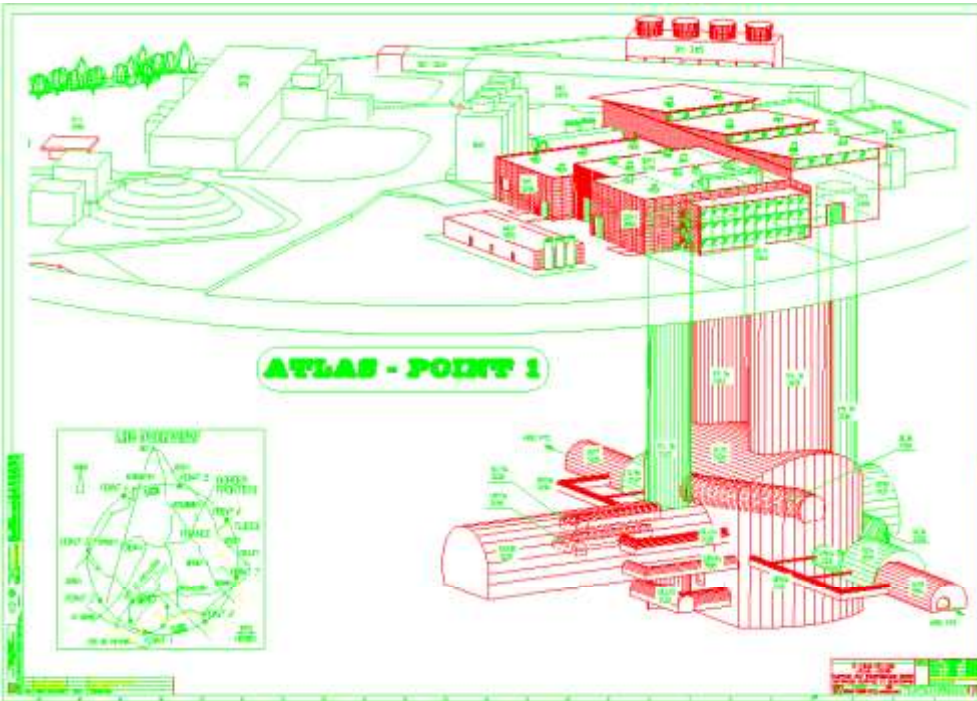
An important milestone was the ATLAS Collaboration meeting in Prague 2003, just before we started installing the detector

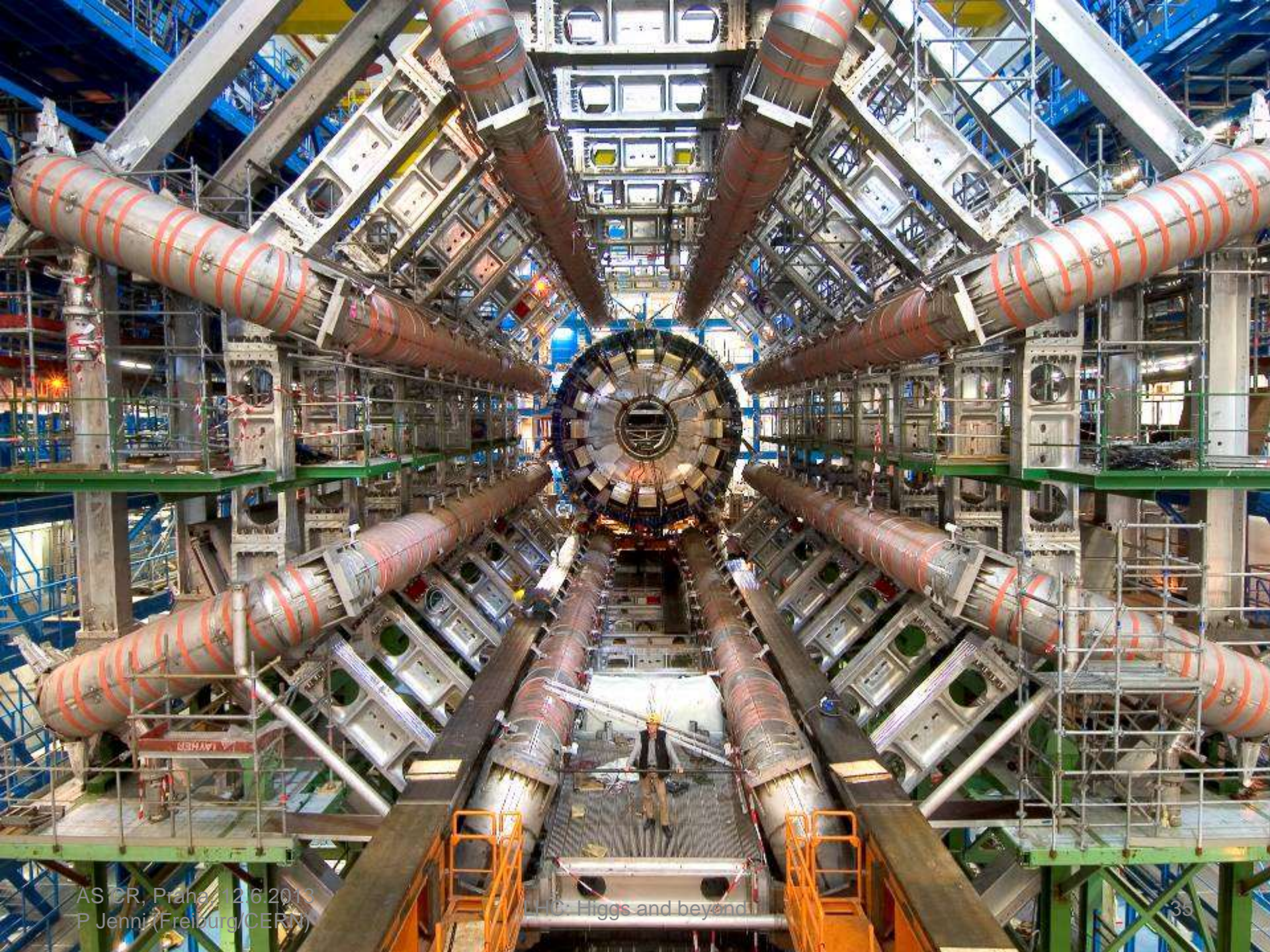


Professor J Niederle (1939-2010) opening the ATLAS Overview Week in Prague

The Underground Cavern at Point-1 for the ATLAS Detector

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







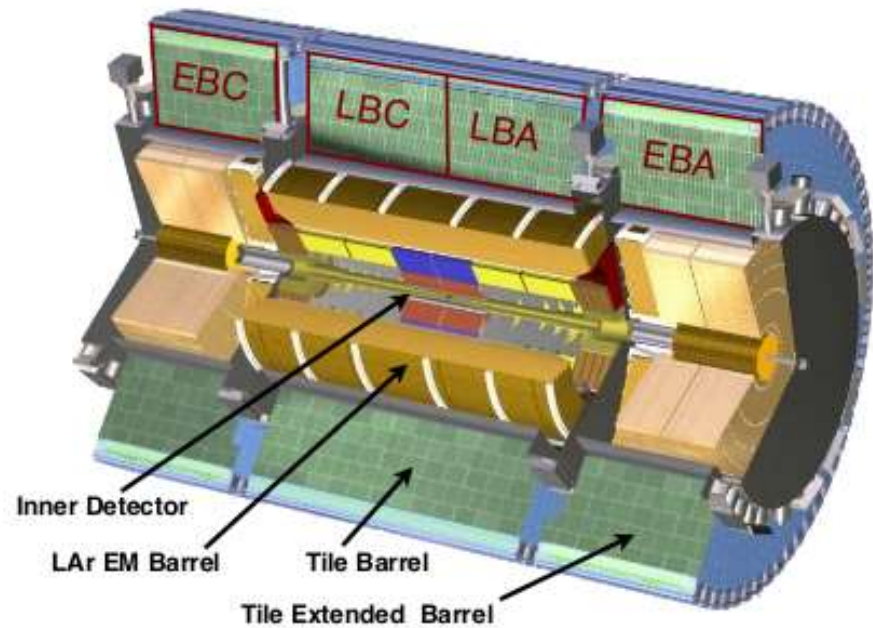
**Hector Berlioz, “Les Troyens”, opera in five acts
Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009**

Tile Calorimeter

EBC pre-assembly on the surface, April 2003

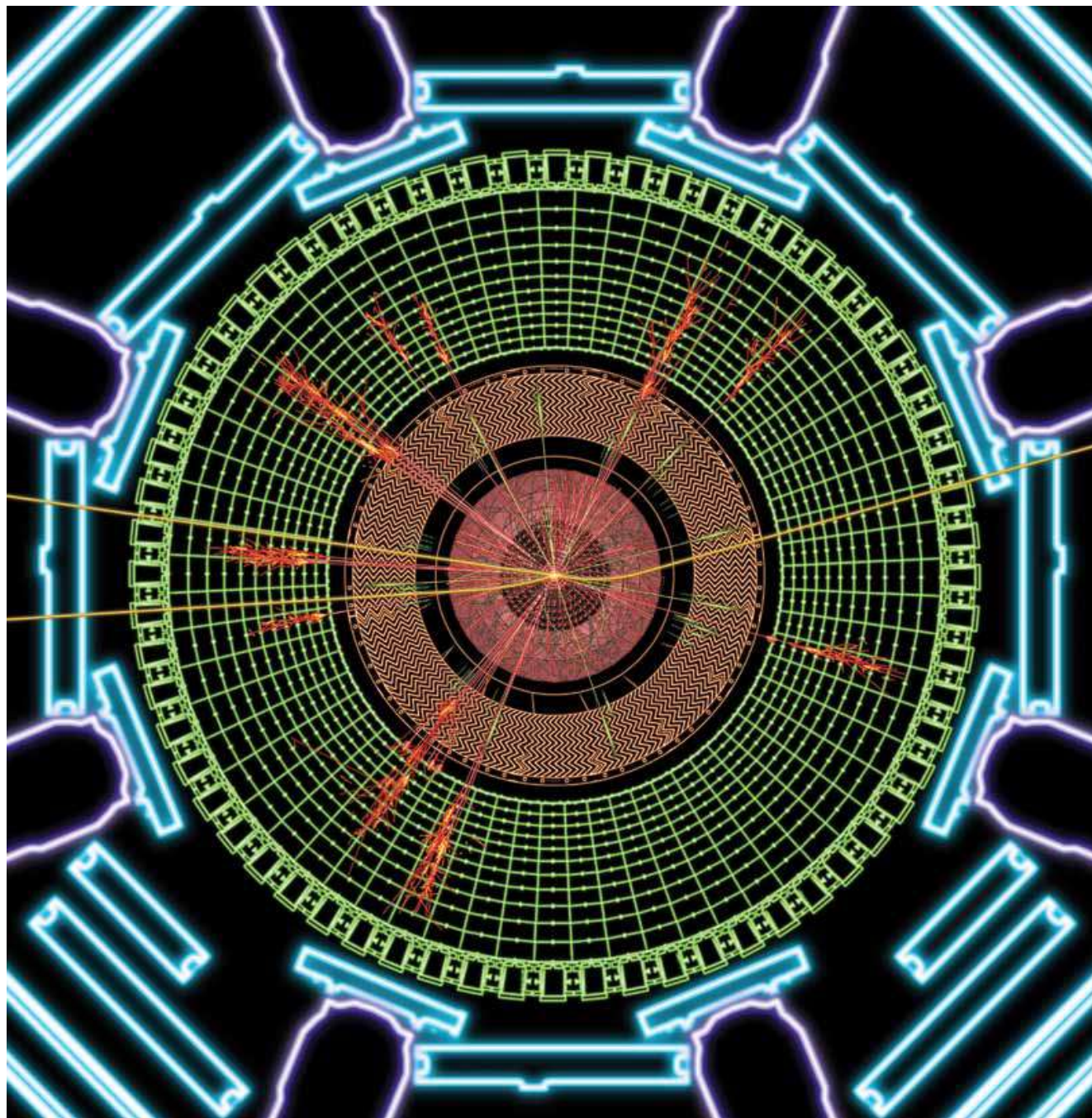


AS CR, Praha, 12.6.2013
P Jenni (Freiburg/CERN)



Rupert Leitner Project Leader 2001-2004

*An artistic view
of the ATLAS Tile
Calorimeter with
simulated em and
hadronic showers*



©



AS CR, Praha, 12.6.2013
P Jenni (Freiburg/CERN)



Tile Calorimeter sub-module construction in Prague 1999



Czech Deputy Prime Minister Petr Mares visiting the Tile Calorimeter pre-assembly (Dec 2003)



AS CR, P
P Jenni (F

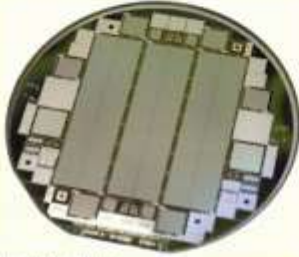
Transport of part of the Barrel Tile Calorimeter to the experimental area Point-1 (Sep 2004)

ATLAS Supplier Award

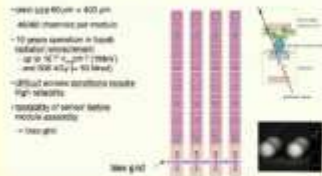
In recognition of excellent supplier performance

ATLAS Supplier Award for ON Semiconductor

Supplier of Silicon Sensors for the ATLAS Pixel Detector



Design of the sensor

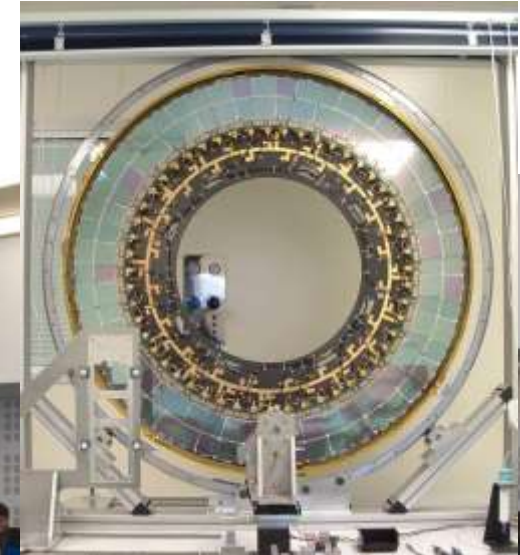


The ON Semiconductor Czech Republic branch of Brno, Czech Republic has supplied a total of 513 production sensor modules containing a total of 1177 production sensor chips within the technical specifications for the ATLAS Pixel Detector. These sensors were delivered on schedule and within budget.

The requirements of the ATLAS Pixel Detector were very demanding. It is the first large-scale silicon detector to combine such a complex sensor layer (40000 individual pixel modules arranged in a two-dimensional array within a 10 cm^2 active area) with extreme radiation requirements (stable operation to a total dose of 10^{14} cm^{-2} neutron-equivalent, roughly ten times higher than for typical strip sensors). Achieving these requirements led to the first commercial implementation of several new sensor technologies. The high-dose sensor requirement led to the use of a low-dose beam implantation (so called "p-spray" isolation) which allowed breakdown-free operation of the sensors at bias voltages above 600V after the full isolation dose. The silicon bulk material was specially processed using the DCEZ technique (diffusion oxygenation) at very high temperature to embed significant Oxygen in the Silicon lattice and improve the depletion behavior of the material after high radiation doses. In addition, the need to achieve high quality and yield in volume production required a new testing capability, implemented as a "bias grid" which allows a complete IV characterization of the sensor tile with a single set of measurements.

ON Semiconductor, in its Brno branch, has produced modules satisfying all of these requirements with excellent yield. As there are three sensor tiles per module, and the full order mass production, this work was essential to the success of the ATLAS experiment.

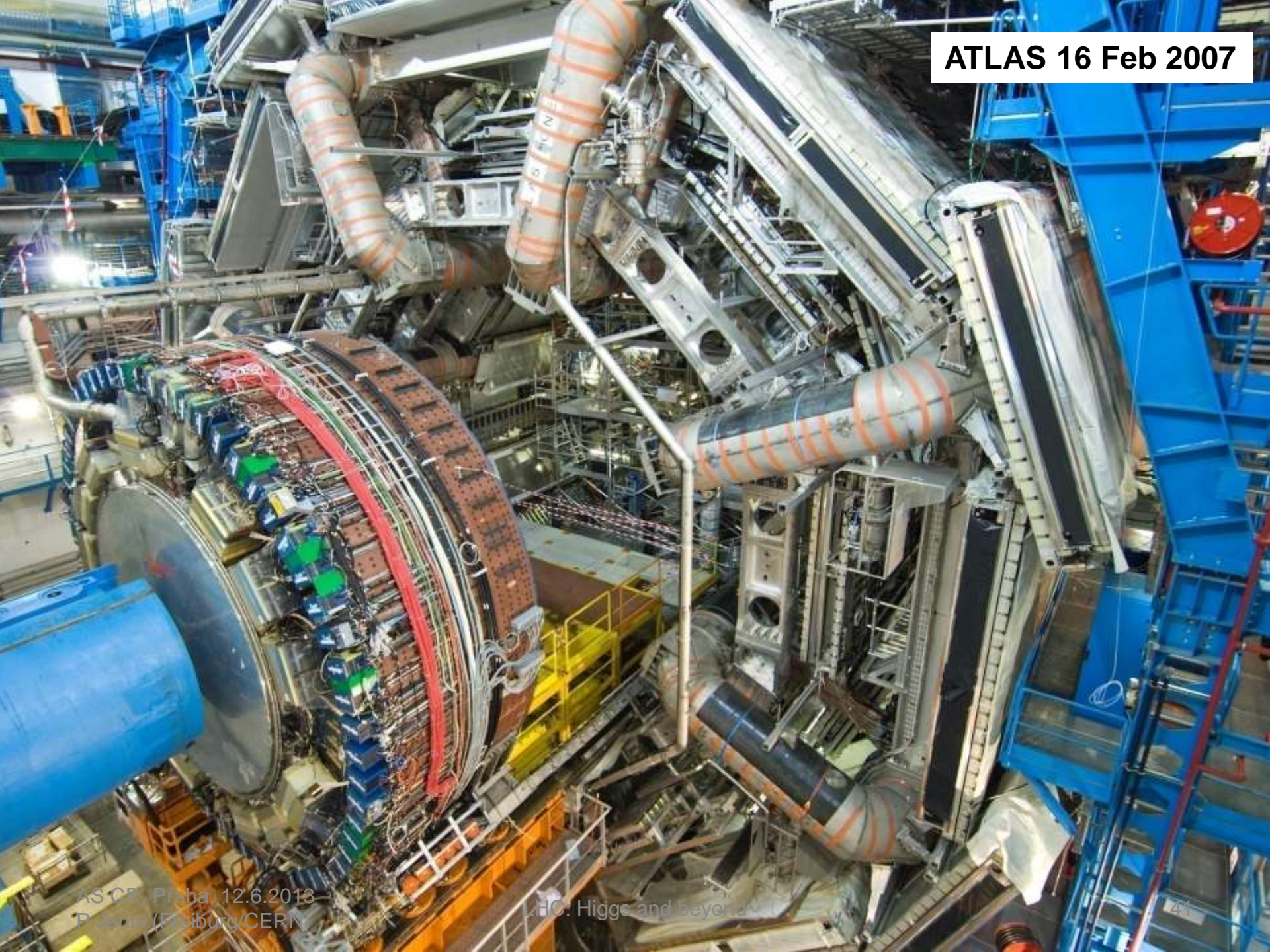
The Prague groups (and Czech industry) are also important collaborators on the semiconductor tracking system (SCT and Pixels)



ATLAS Supplier Award ceremony for 'On Semiconductor' (ex 'Tesla') in 2007

Also 'Skoda Hute' received the same award in 2004 for their shielding work, another important expertise of Czech groups in radiation matters

ATLAS 16 Feb 2007



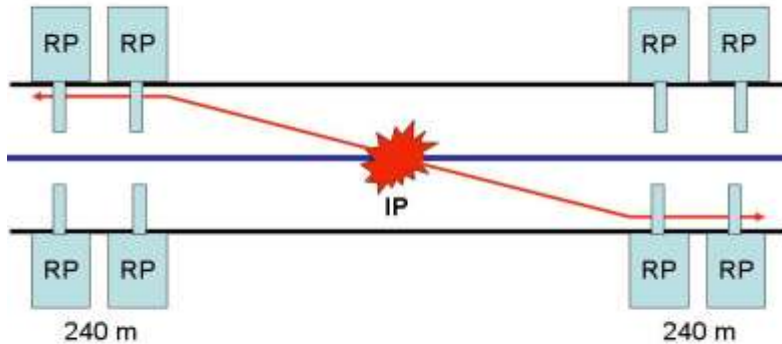
ATLAS 4 April 2008



Peter Higgs

ATLAS Roman Pots (ALFA)

There is also a strong involvement of Czech colleagues and industry in ALFA since the Palacky University in Olomouc joined ATLAS in 2008



**Absolute
Luminosity
For
ATLAS**



**Roman Pots mechanics,
based on Czech work in
the Totem experiment**

AS CR, Praha, 12.6.2013
P Jenni (Freiburg/CERN)

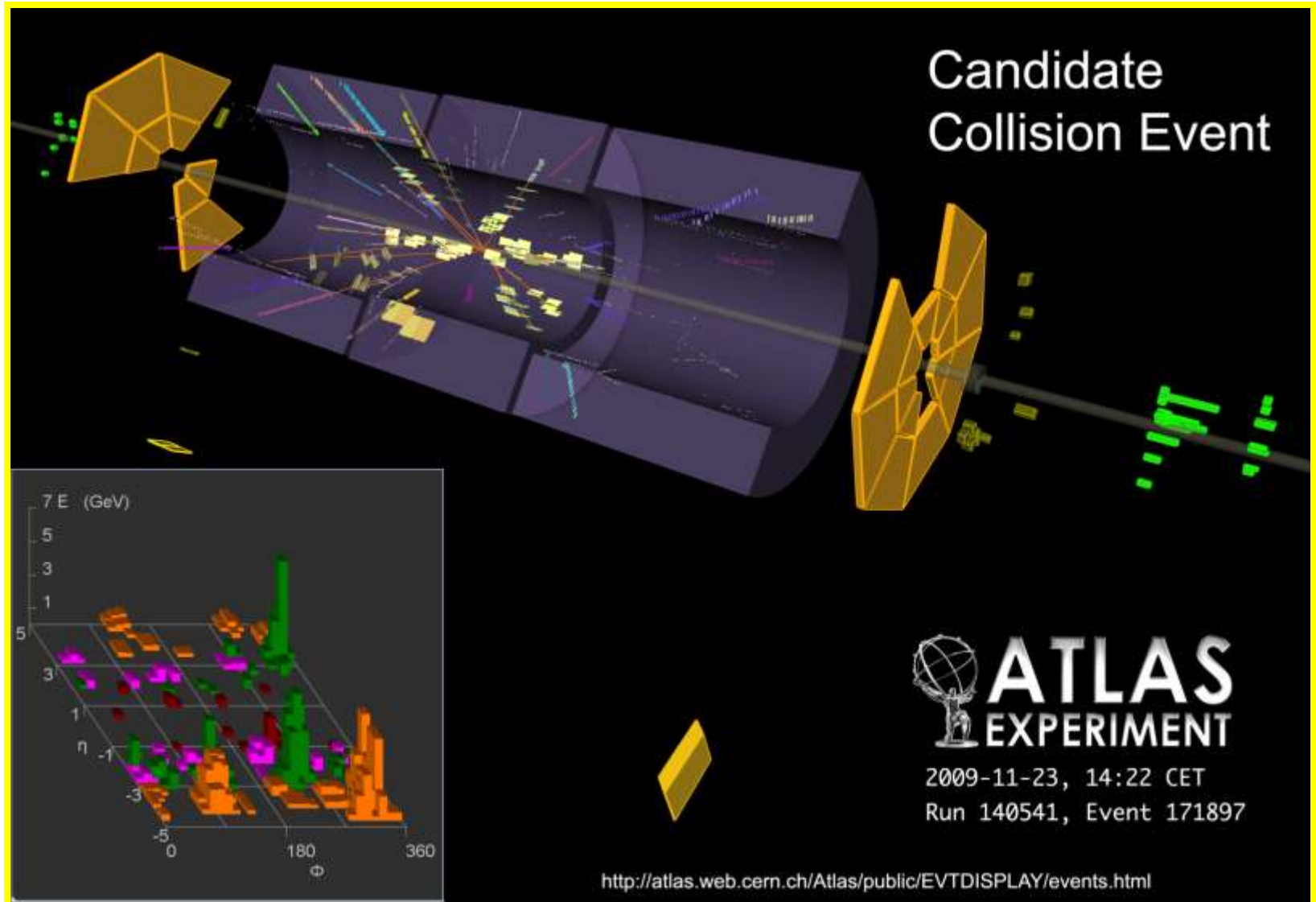
LHC: Higgs and beyond



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



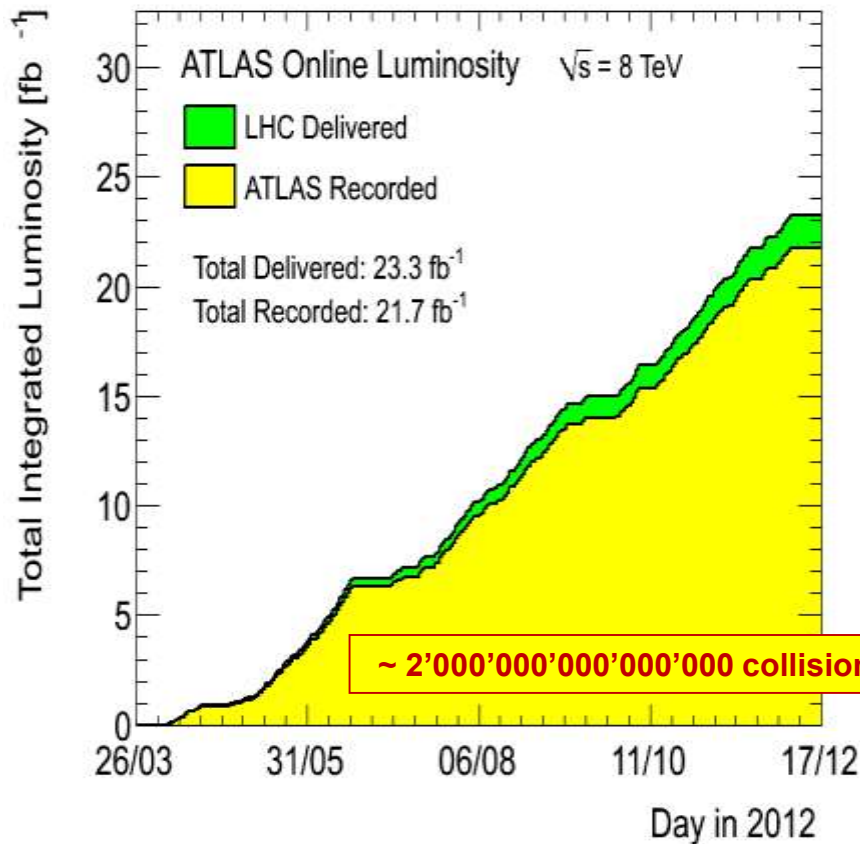
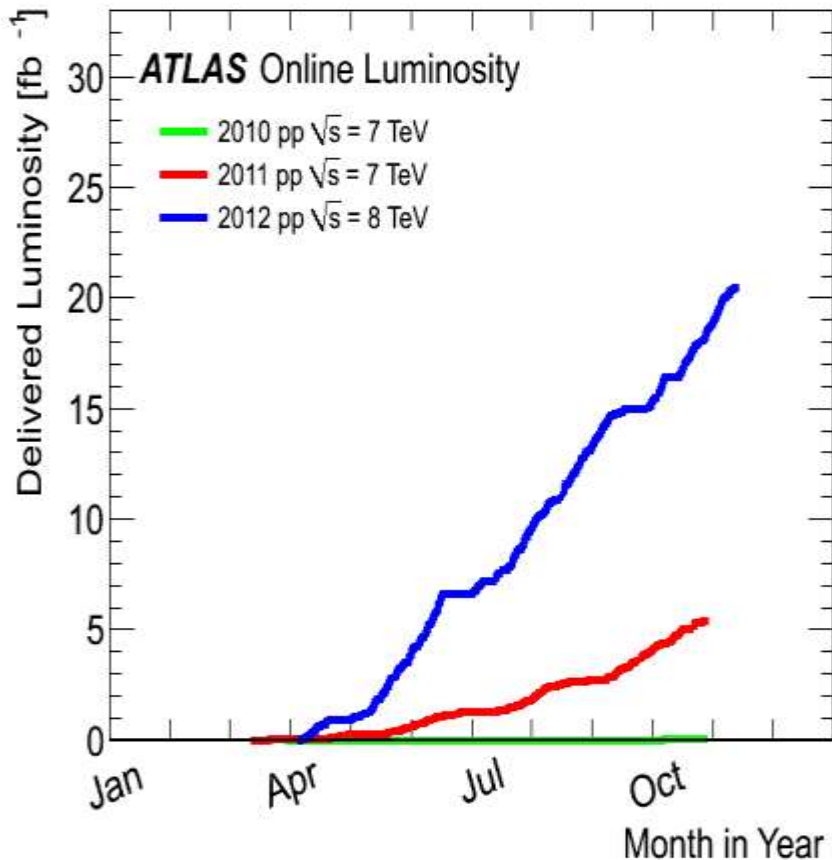
First collisions at the LHC end of November 2009 with beams at the injection energy of 450 GeV



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

Total integrated luminosity

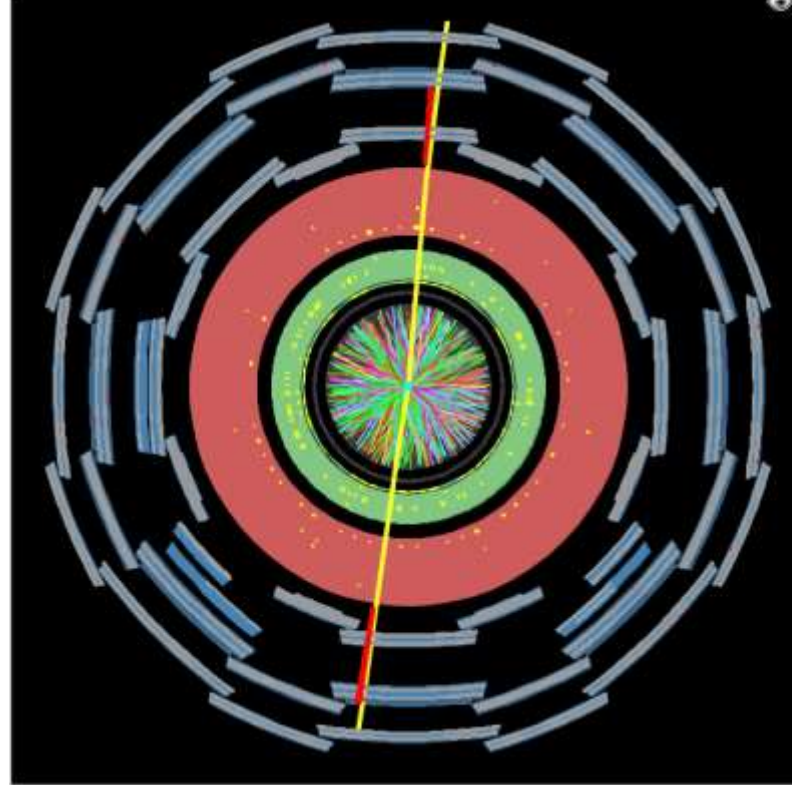
$$N_{\text{events}} = \sigma \int L dt$$



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:

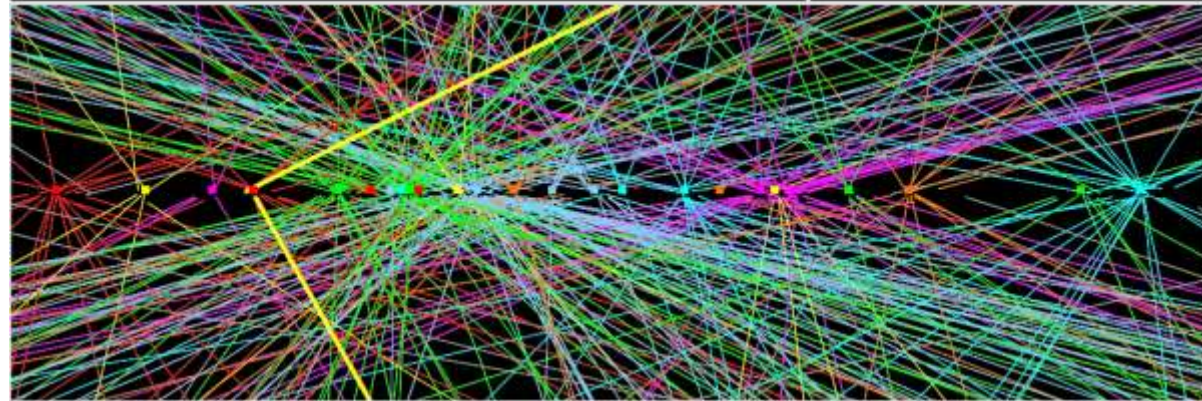
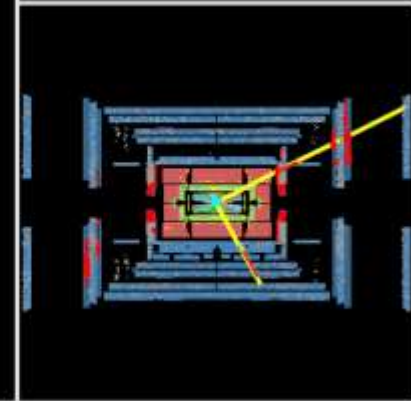
- Trigger
- Pile-up
- Maintain accuracy of the the measurements in this environment



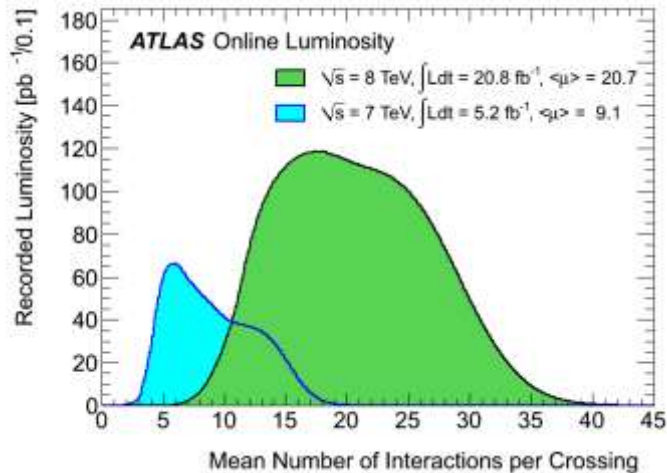
ATLAS
EXPERIMENT

Run Number: 201289, Event Number: 24151616

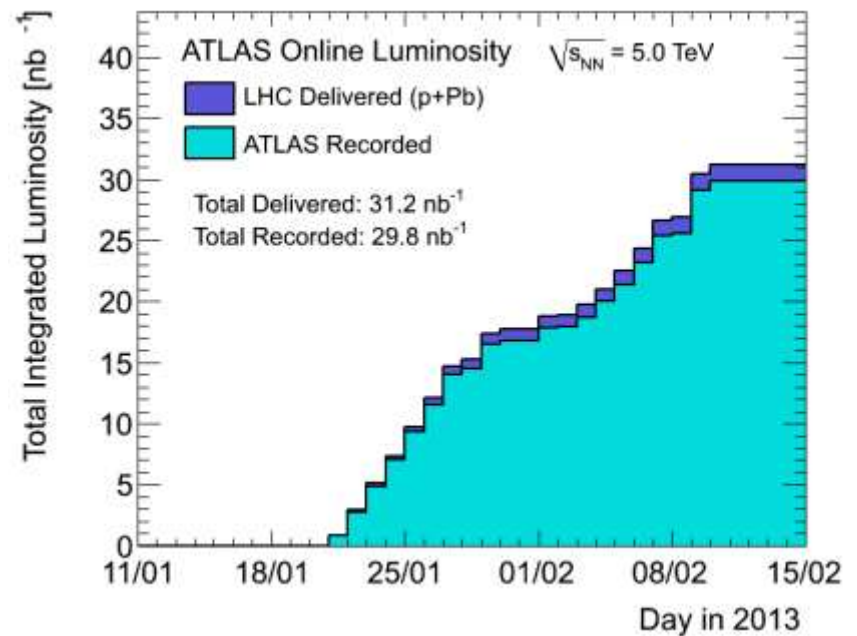
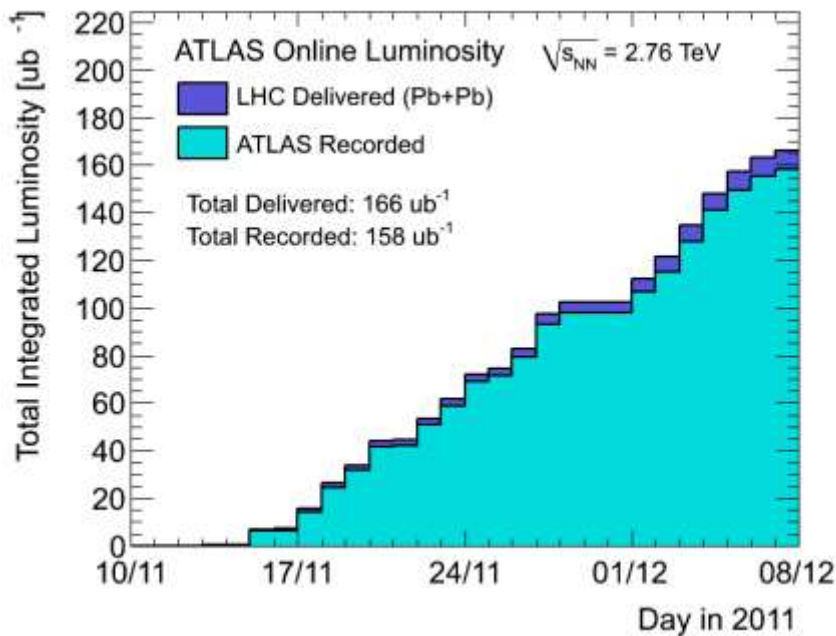
Date: 2012-04-15 16:52:58 CEST



Inner Detector for a $Z \rightarrow \mu\mu$ event with 25 primary vertices

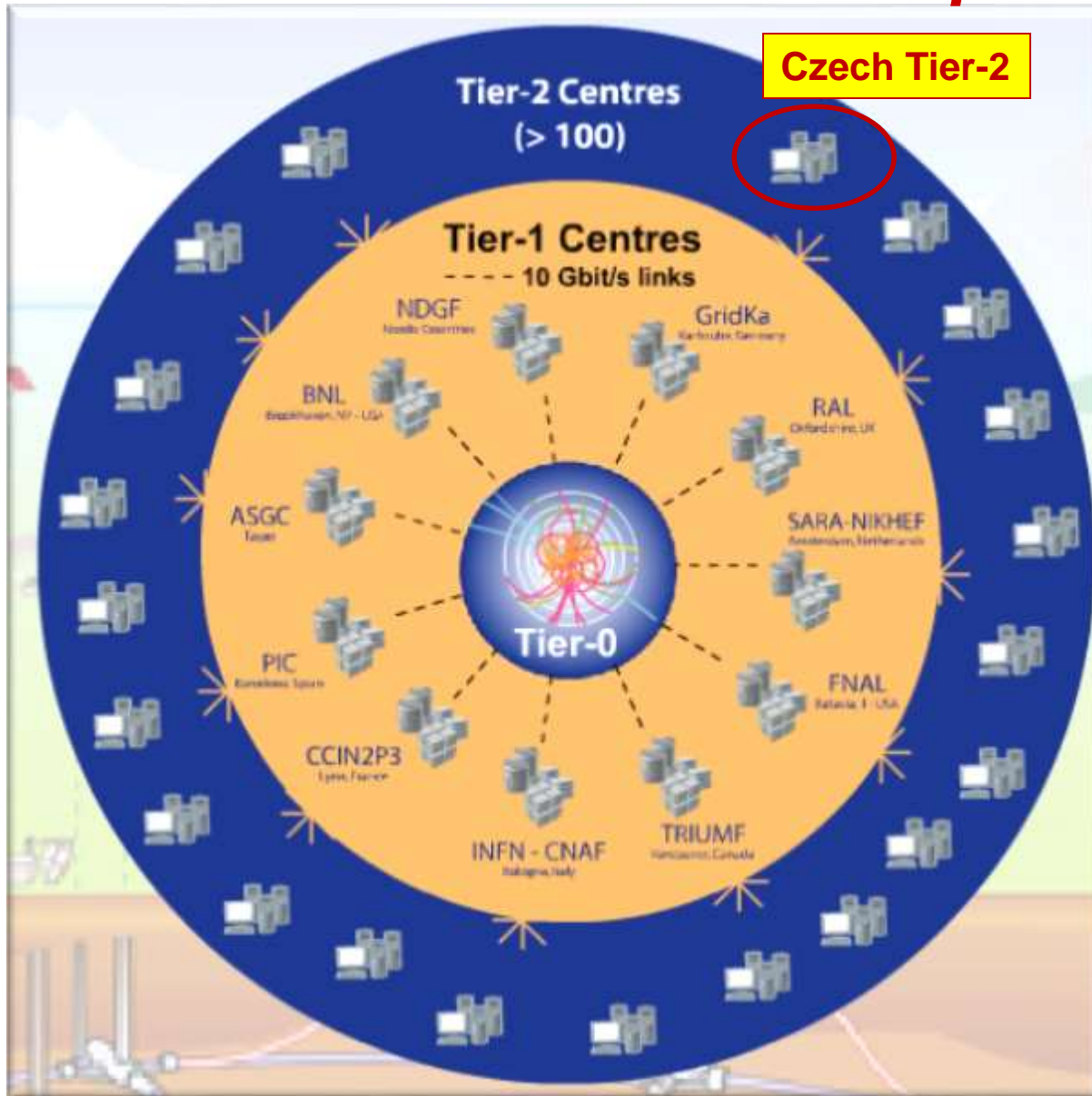


LHC and ATLAS have also been operated very successfully as Pb-Pb and as p-Pb colliders



Czech ATLAS scientists are very active in this rich field of quark-gluon plasma physics

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...)

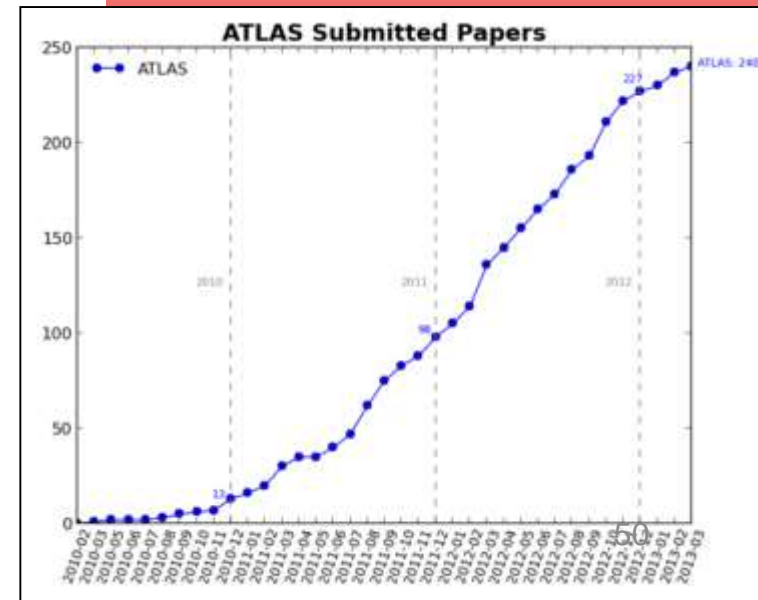
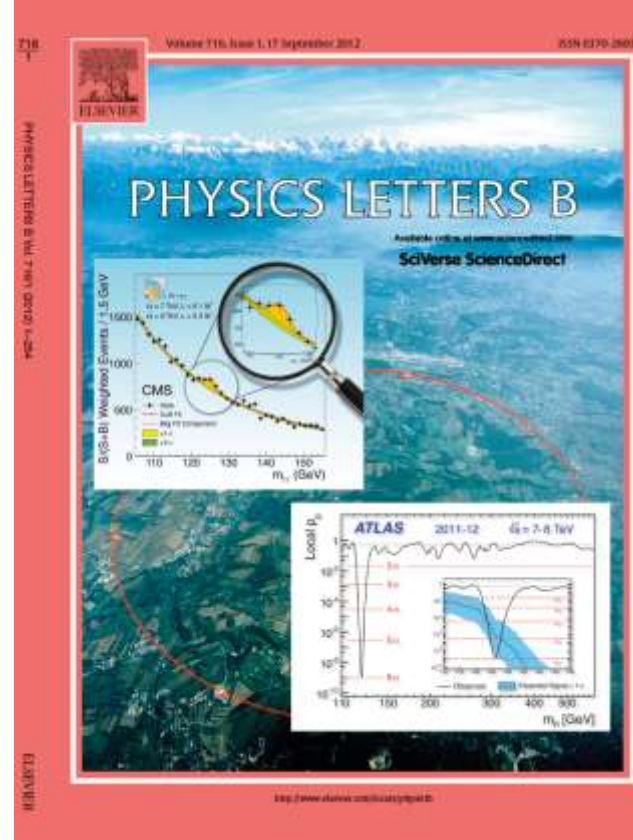
The other experiments, ALICE, LHCb, LHCf, and TOTEM total another 150 journal publications together

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

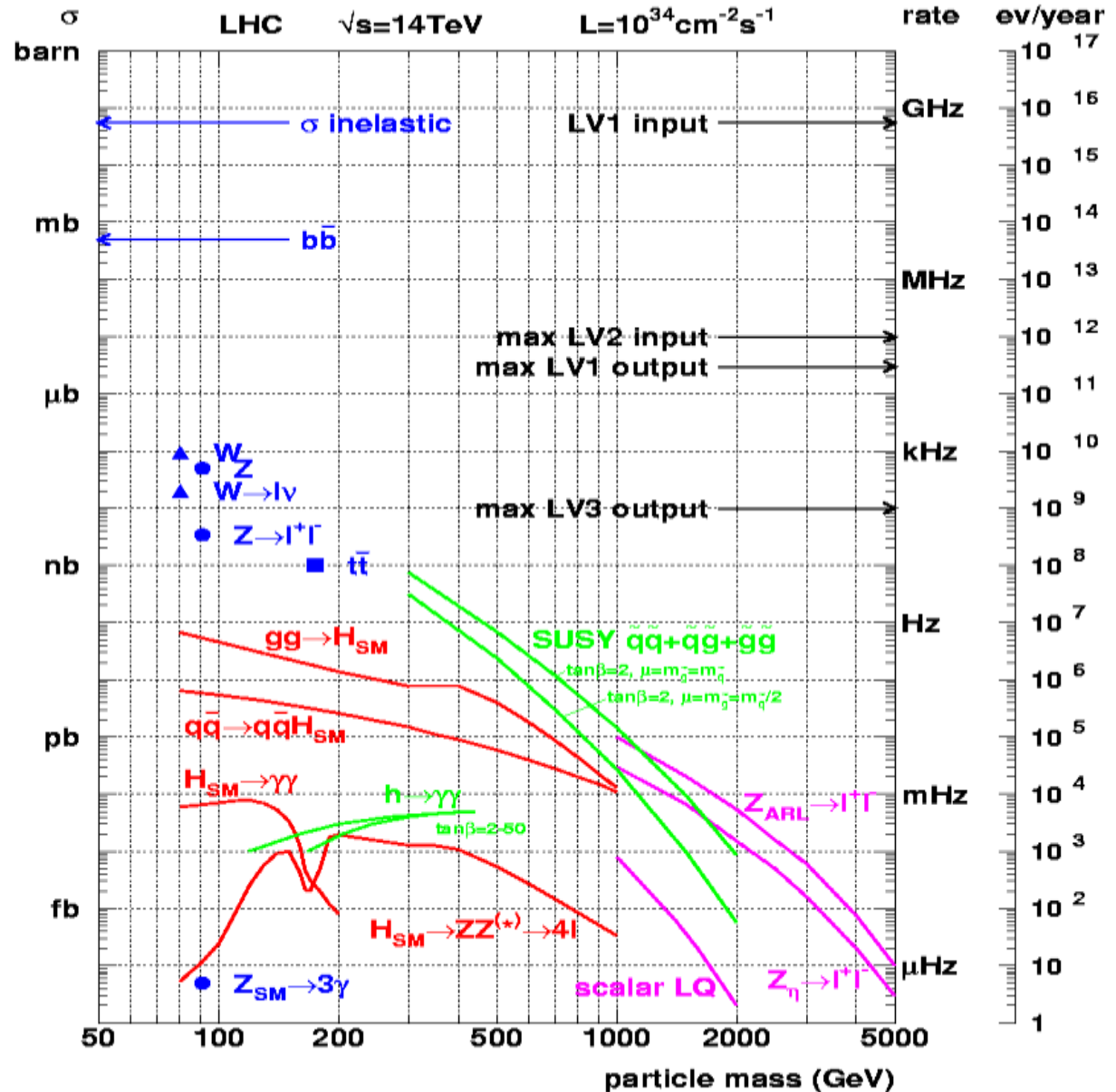
Heavy flavour physics

Standard Model physics including QCD jets

Higgs searches

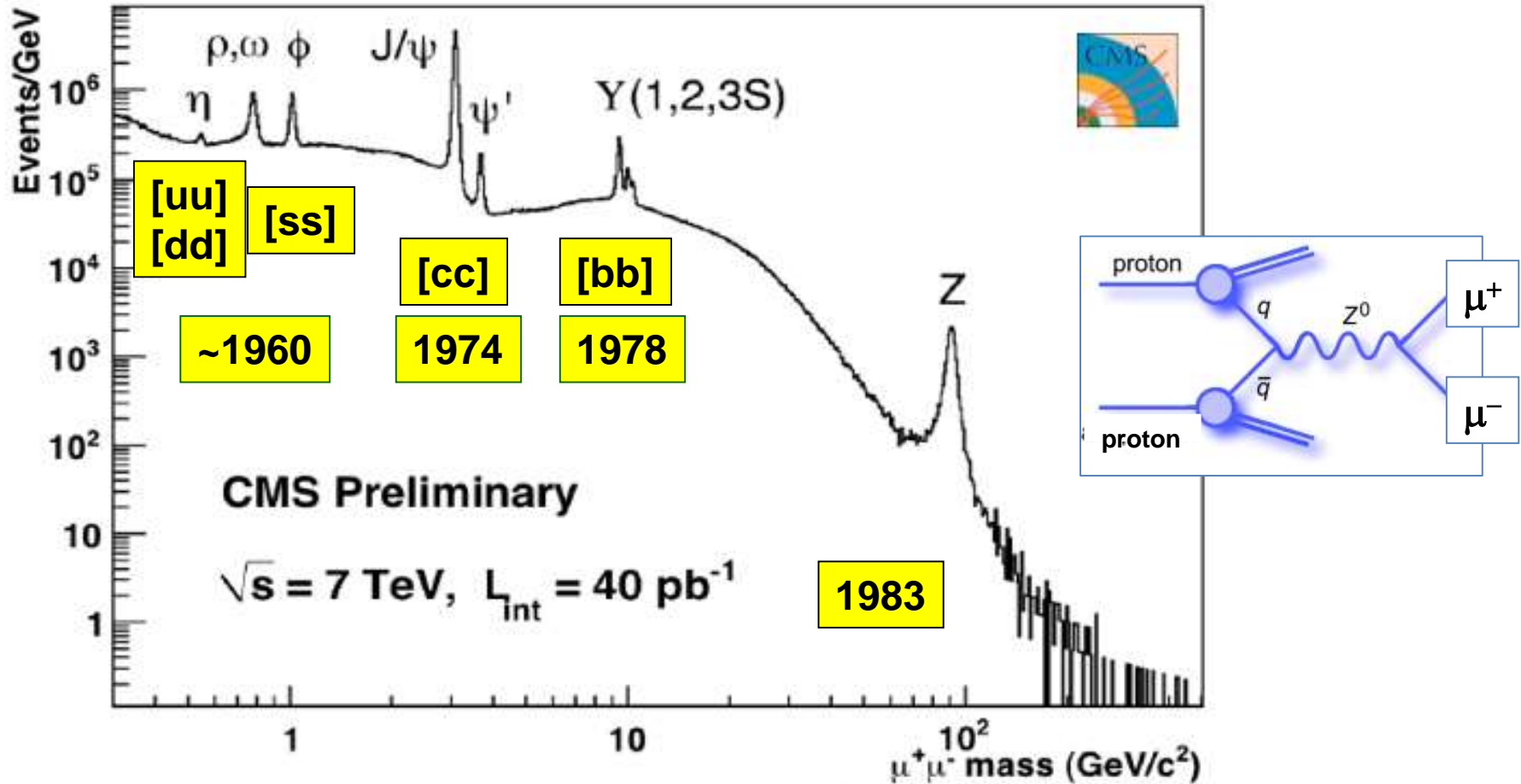
Searches for SUSY

Searches for 'exotic' new physics



2010

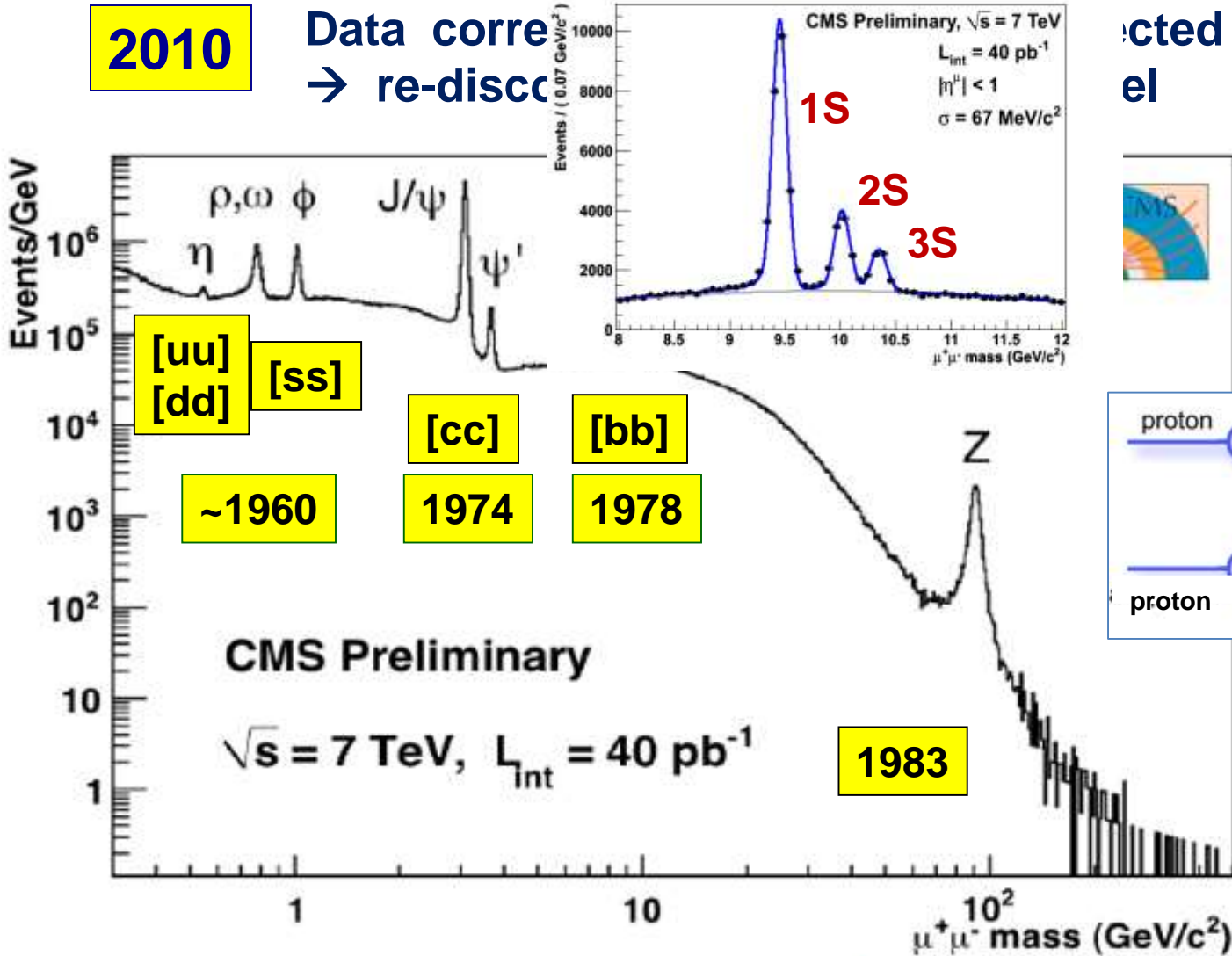
Data corresponding to $\sim 40 \text{ pb}^{-1}$ collected
→ re-discovery of the Standard Model



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

2010

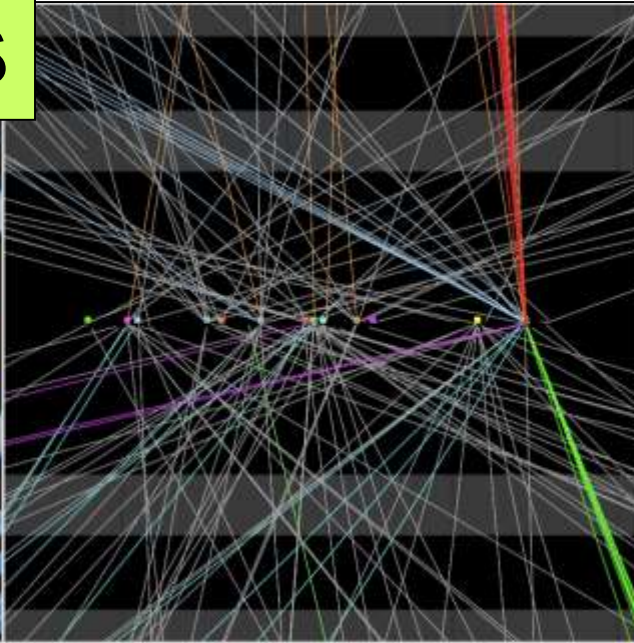
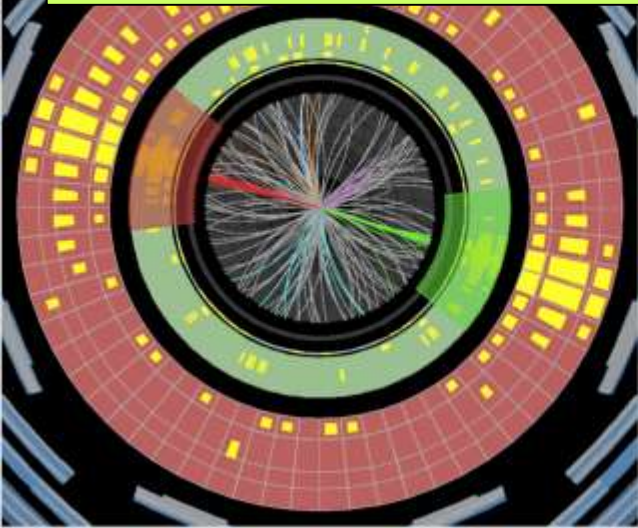
Data corrected
→ re-discussed



corrected
re-discussed

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

Jet physics

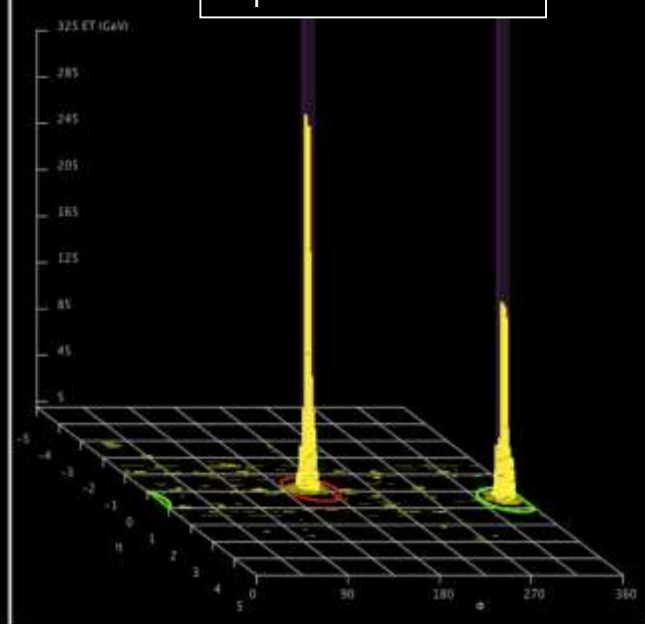
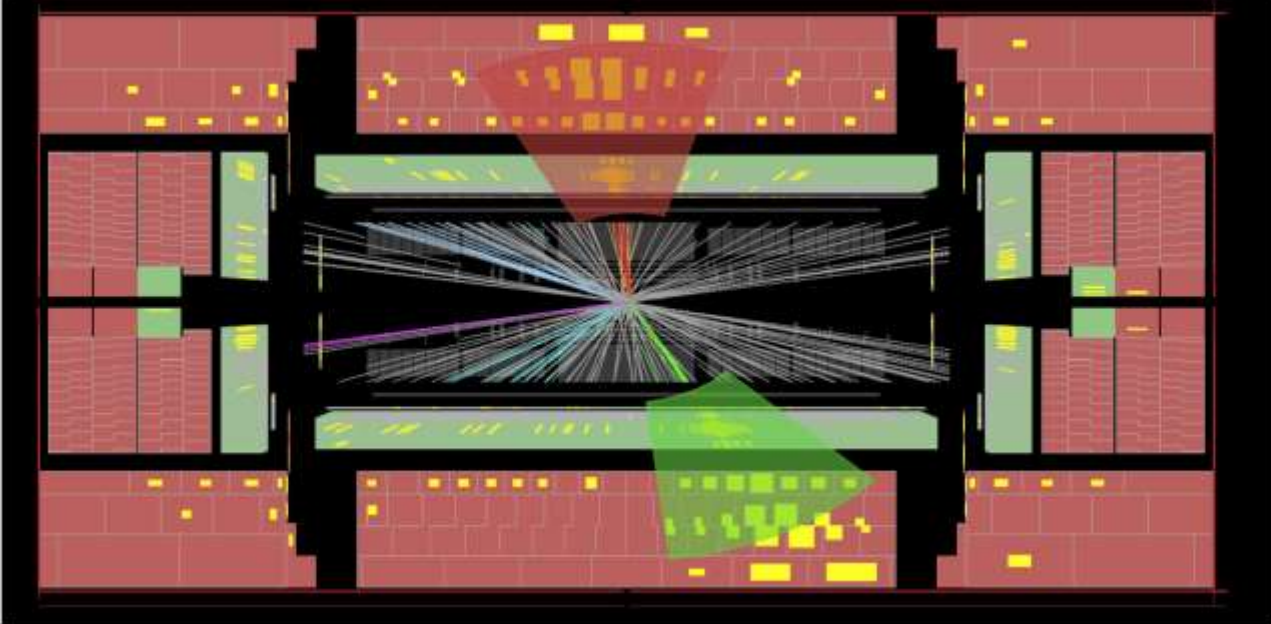


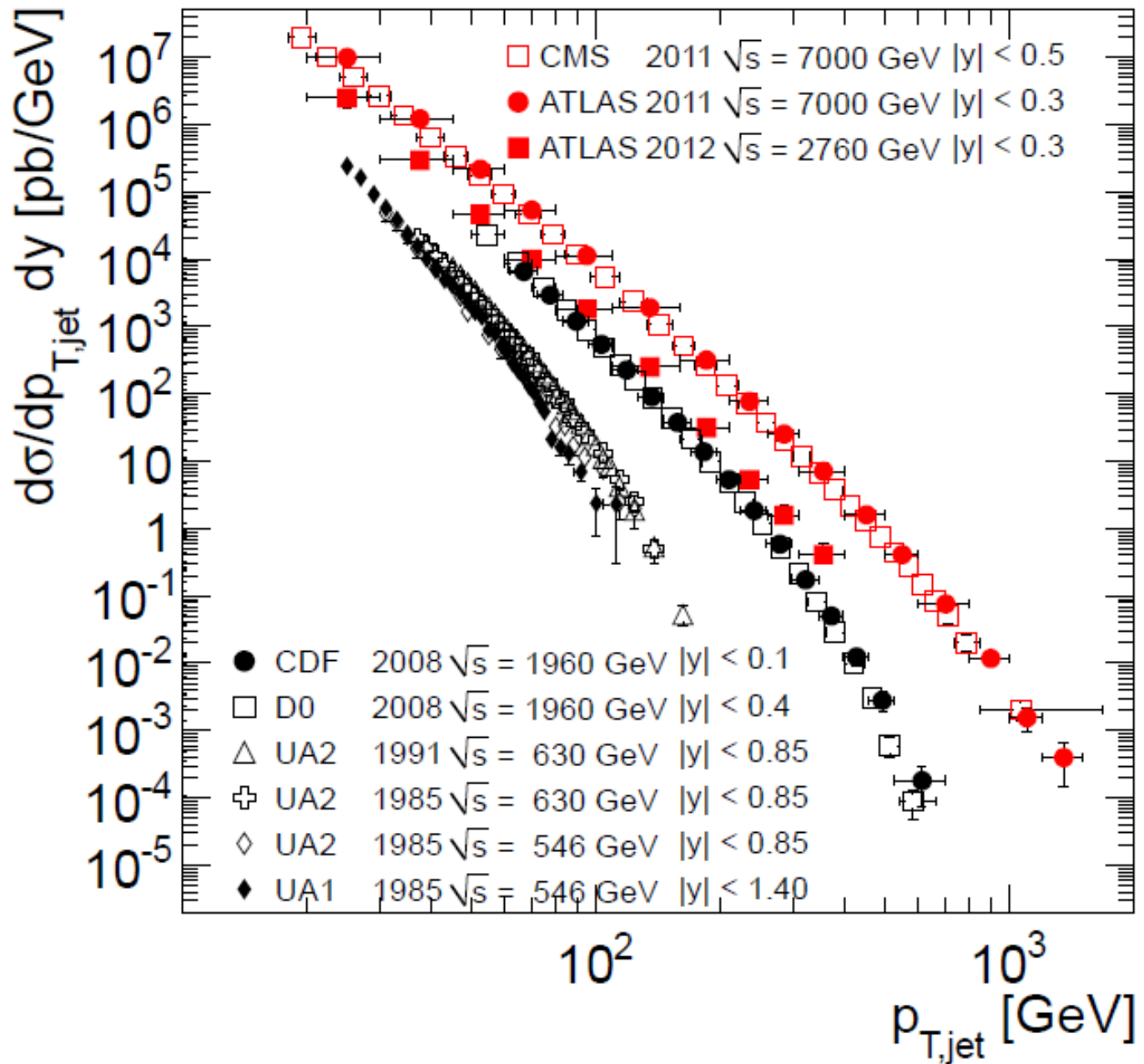
ATLAS EXPERIMENT

Run Number: 209580, Event Number: 179229707

Date: 2012-08-31 20:24:29 CEST

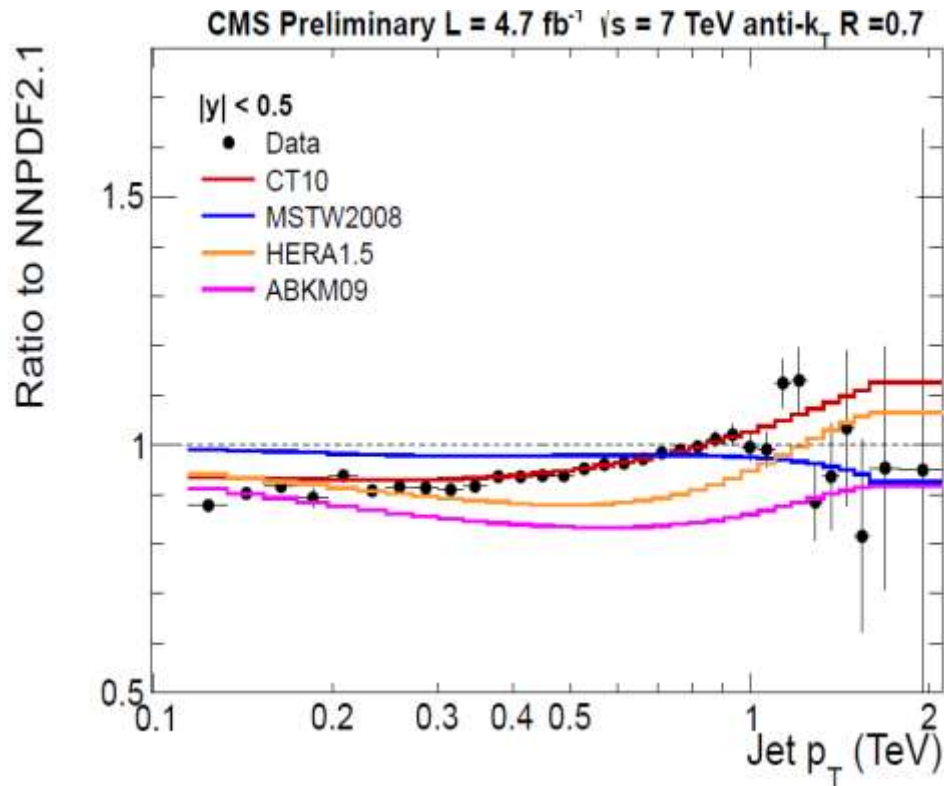
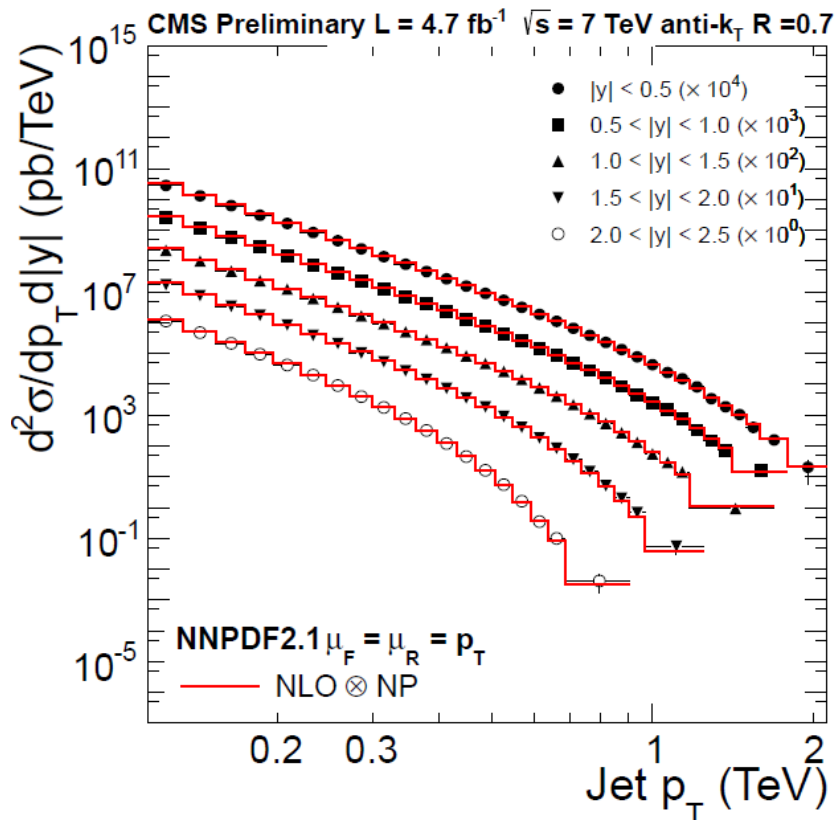
$m_{jj} = 4.7 \text{ TeV}$
 $p_T^j = 2.3 \text{ TeV}$
 $E_T^{\text{miss}} = 47 \text{ GeV}$





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



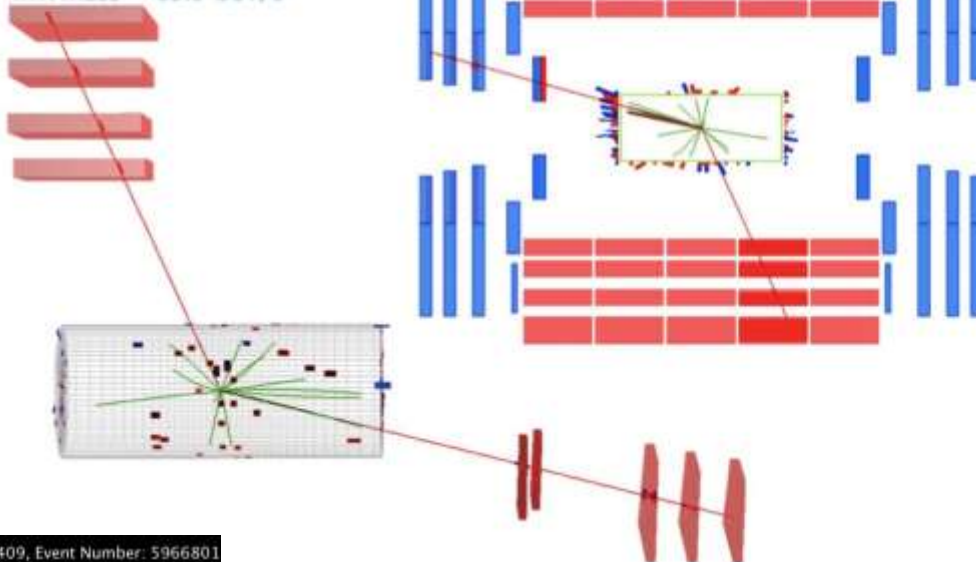
CMS-PAS-QCD-11-004

Standard Model Physics



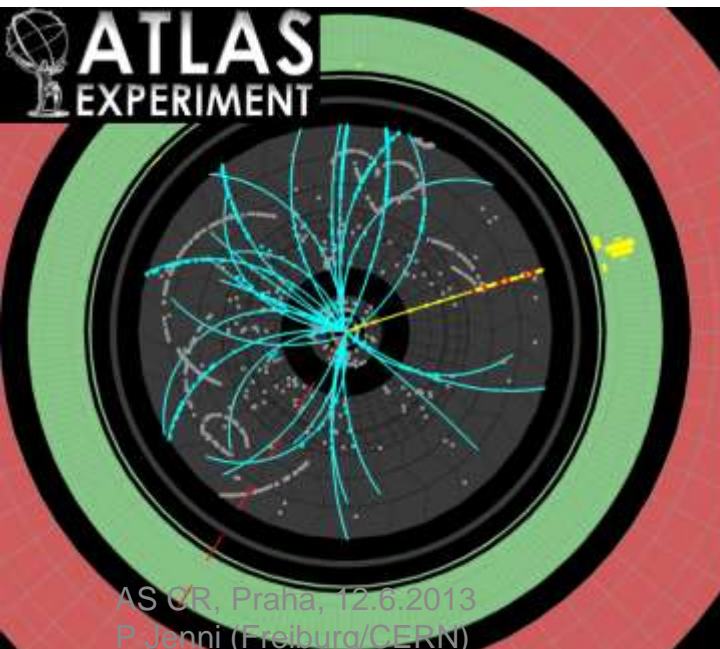
CMS Experiment at LHC, CERN
Run 136087 Event 39967482
Lumi section: 314
Mon May 24 2010, 15:31:58 CEST

Muon $p_T = 27.3, 20.5 \text{ GeV}/c$
Inv. mass = $85.5 \text{ GeV}/c^2$



Candidate $Z \rightarrow \mu^+\mu^-$

$W \rightarrow e\nu$ candidate



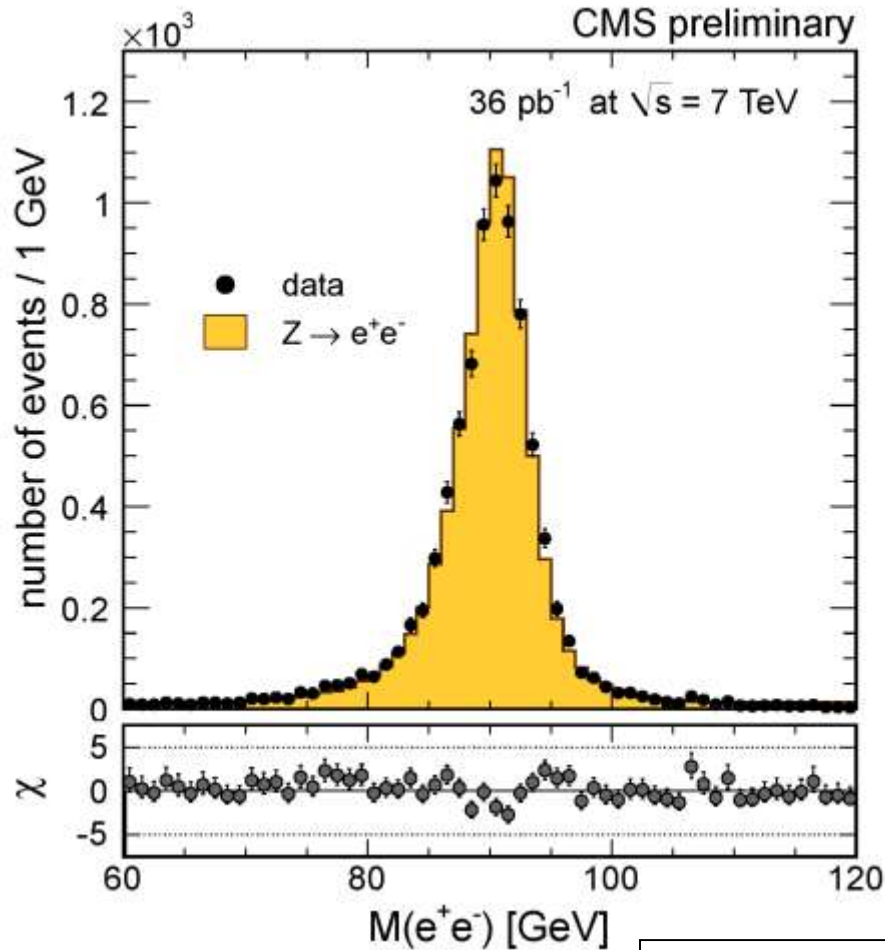
Today each ATLAS and CMS have in their data more than:

100 M $W \rightarrow \mu\nu, e\nu$ events
10 M $Z \rightarrow \mu\mu, ee$ events

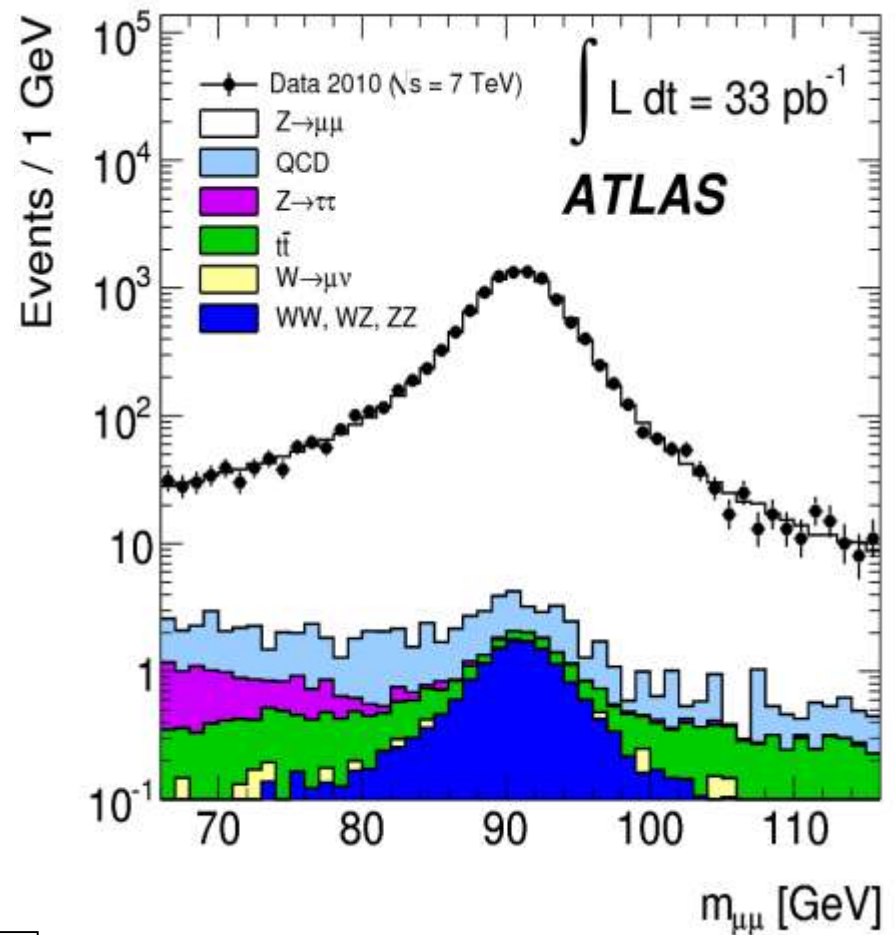
after all selection cuts

Z and W production

Phys Rev D85 (2012) 072004



JHEP 10 (2011) 132

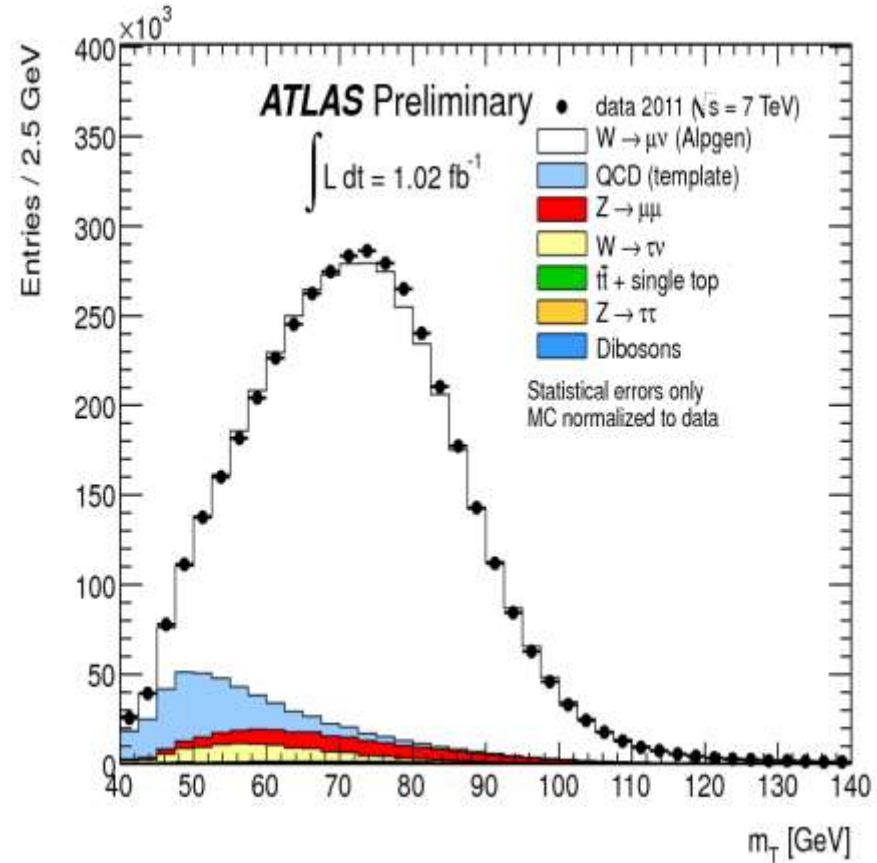
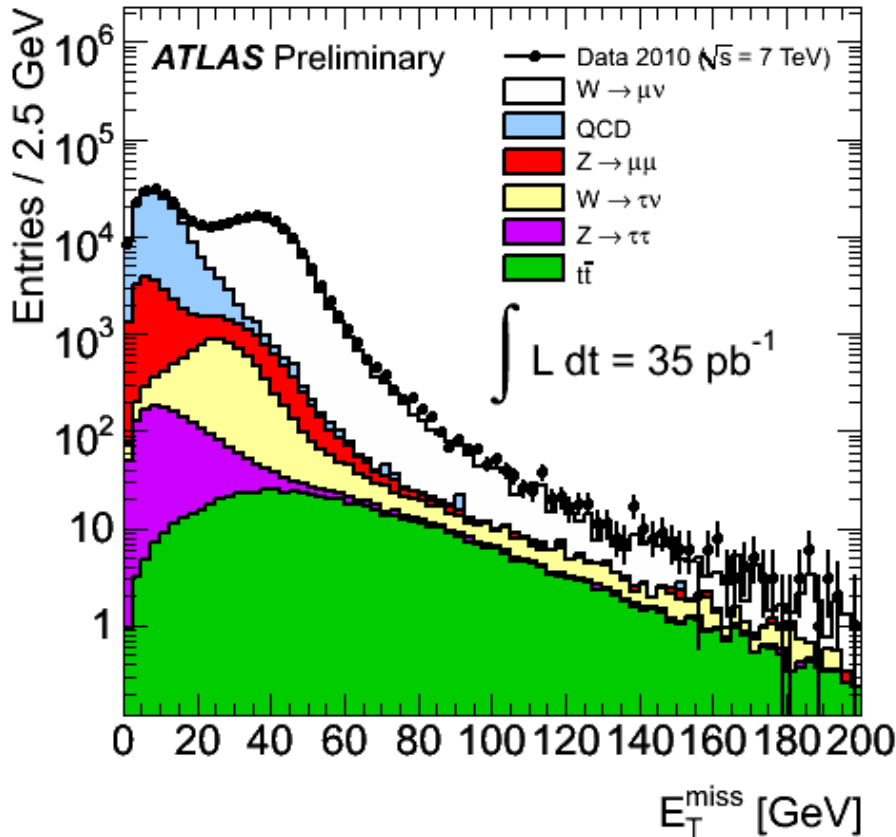


Z peak (di-lepton pair mass distributions, can be extracted essentially background-free)

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

W transverse mass

μ with $p_T > 20$ GeV, $E_T^{\text{miss}} > 25$ GeV

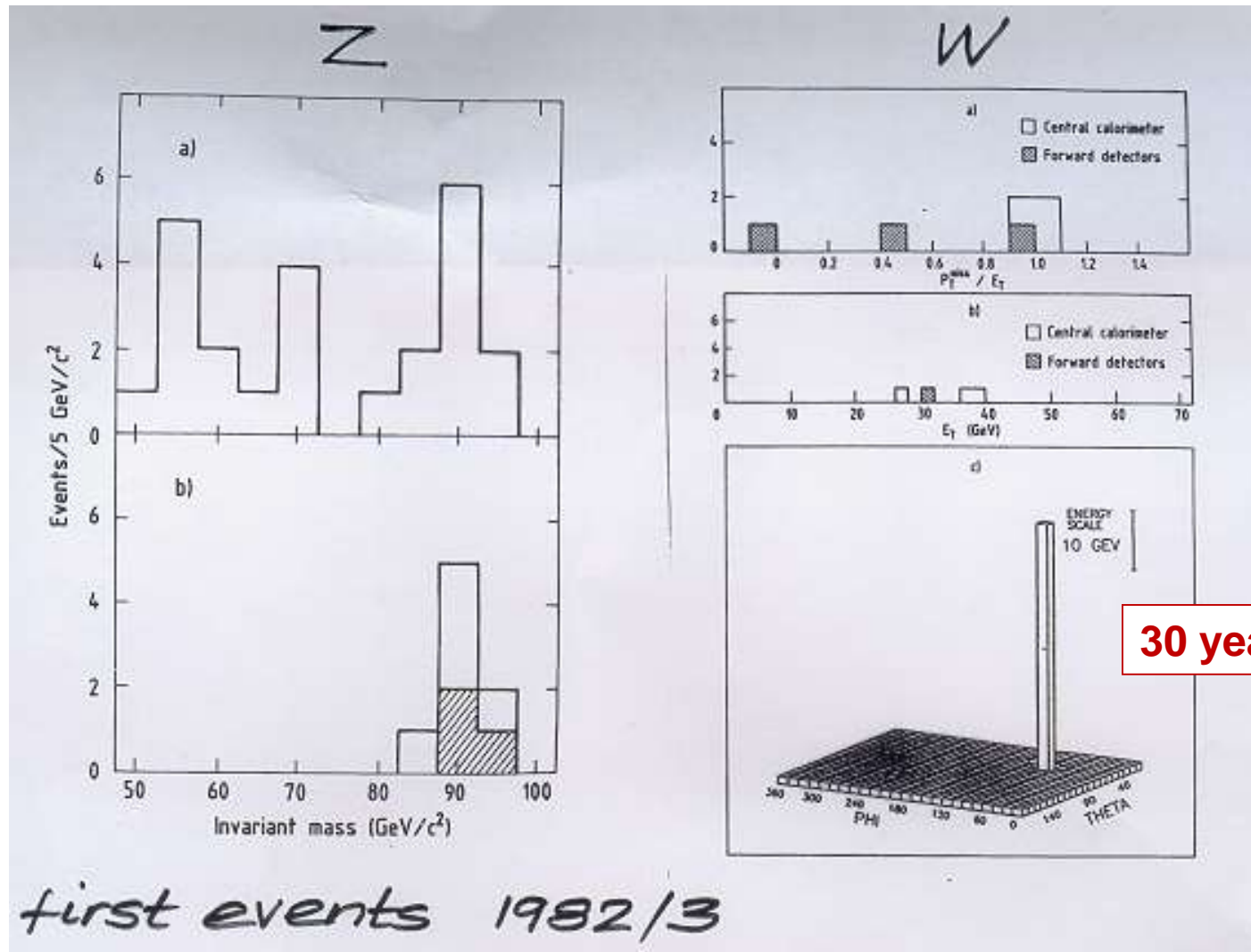


Missing transverse energy
from the $W \rightarrow \mu + \nu$ decays

ATLAS-CONF-2011-041

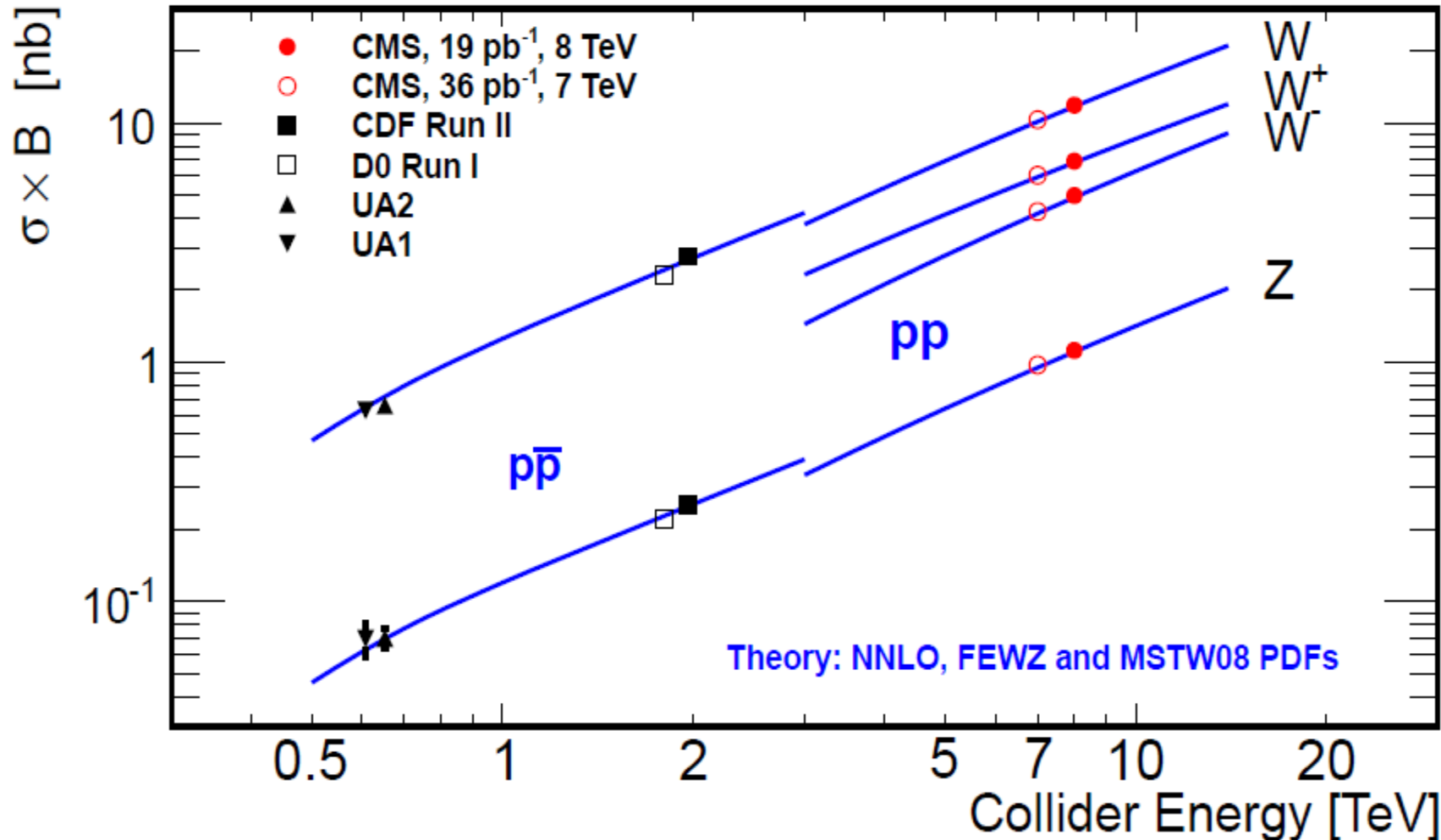
$$m_T = \sqrt{2p_T^\ell p_T^\nu (1 - \cos(\phi^\ell - \phi^\nu))}$$

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



(here are shown the UA2 distributions)

Cross section measurements



CMS-PAS-SMP-12-011

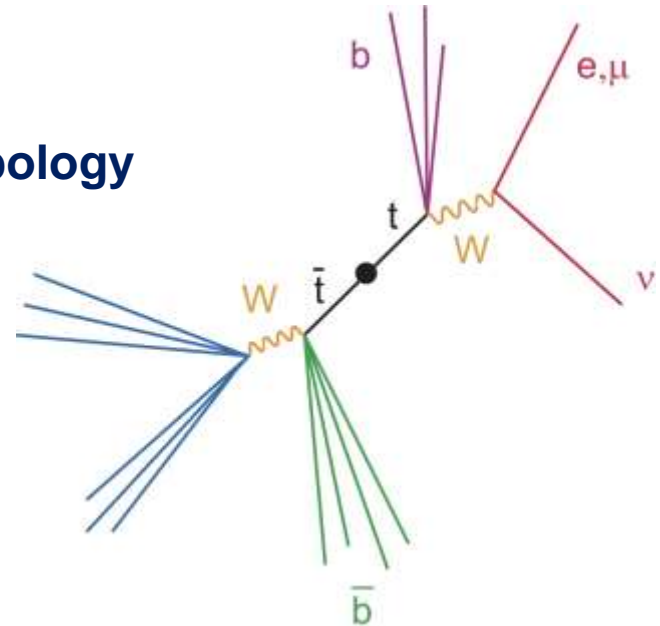
Top measurements

- Complete set of ingredients to investigate production of $t\bar{t}$, which is the next step in verifying the SM at the LHC:

- $e, \mu, E_T^{\text{miss}}, \text{jets}, \text{b-tag}$

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

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

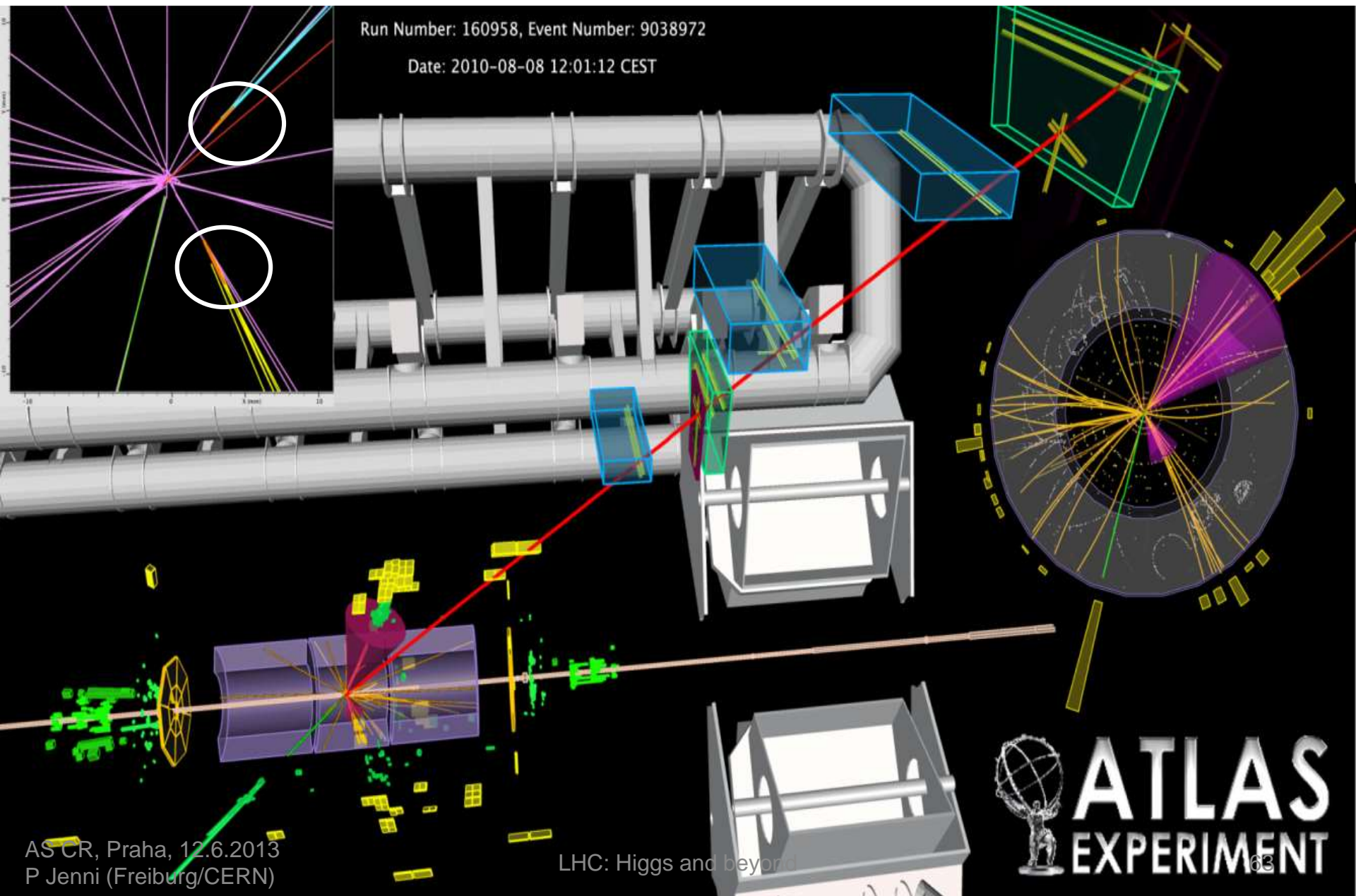


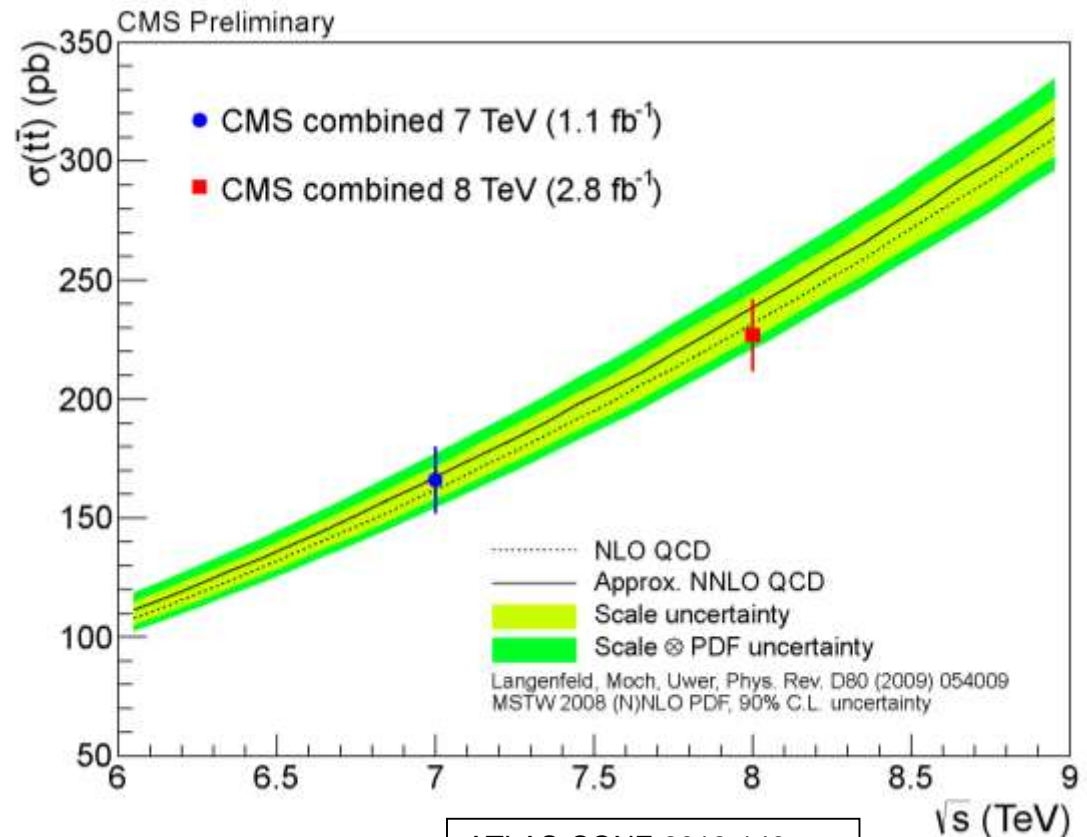
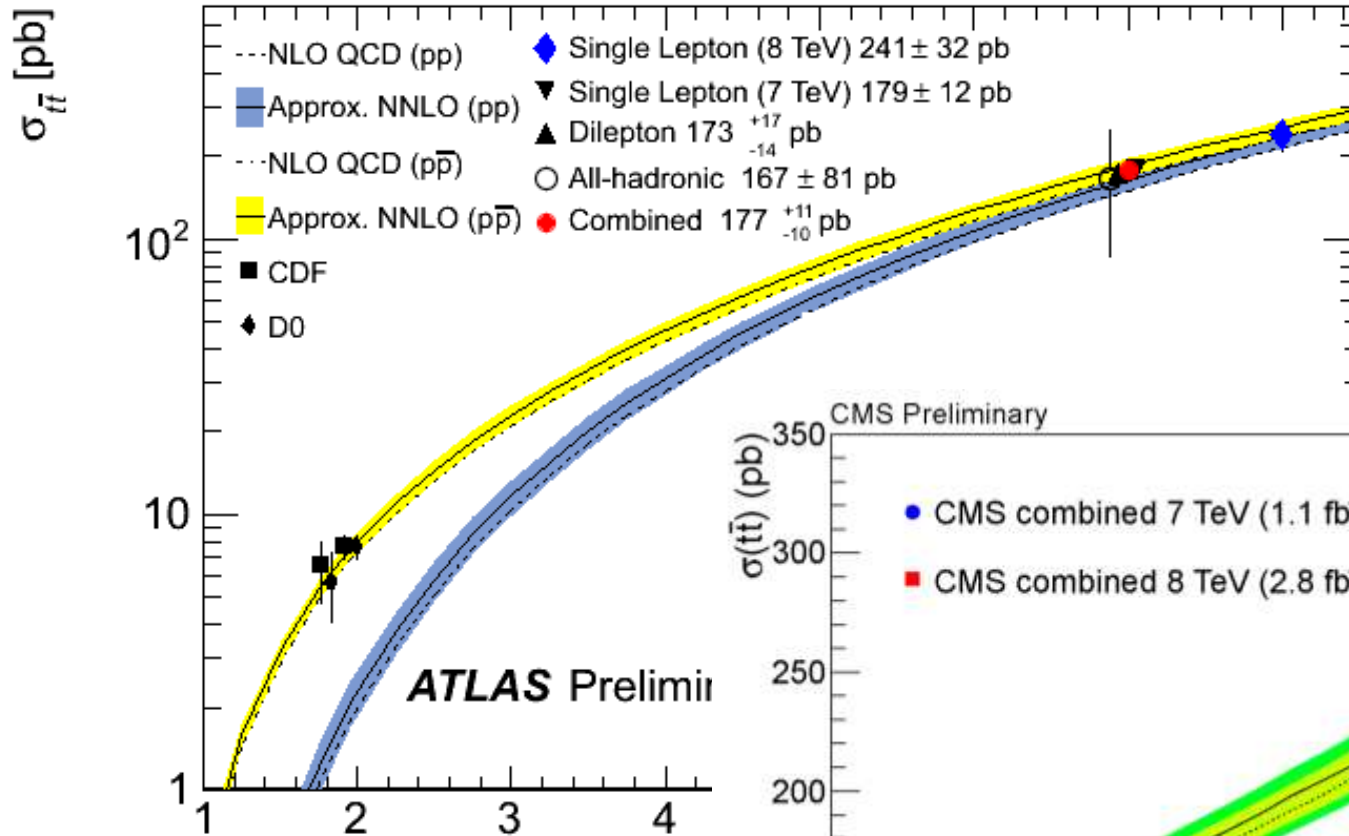
- Data-driven methods to control QCD and W +jets backgrounds

Czech ATLAS colleagues are experts in top physics

$t\bar{t}$ candidate event

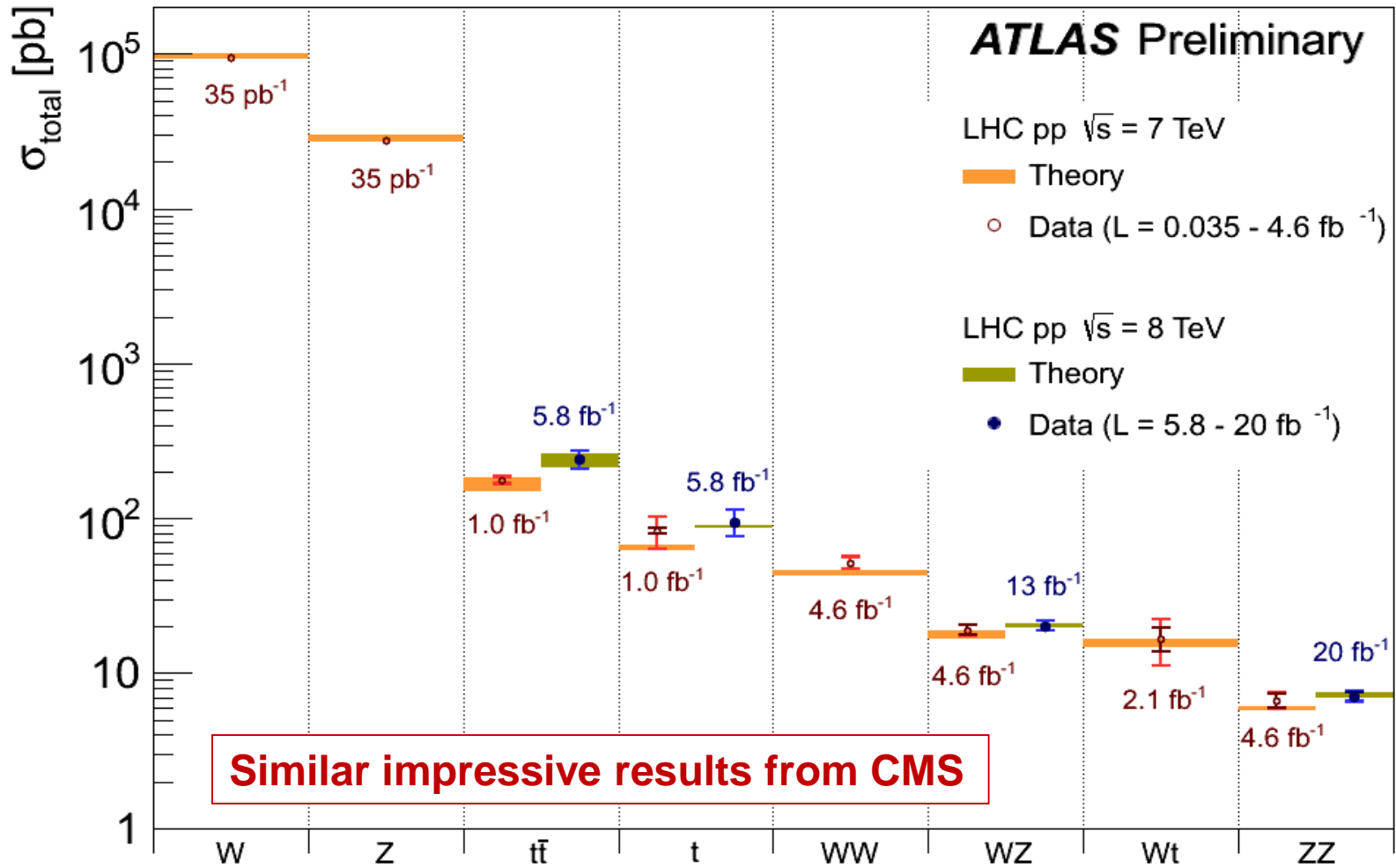
$e + \mu + 2 \text{ jets (b-tagged)} + E_T^{\text{miss}}$





tt pair production cross-sections

A summary of Standard Model measurements



Similar impressive results from CMS

Czech ATLAS colleagues contributed strongly to the di-boson analyses

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

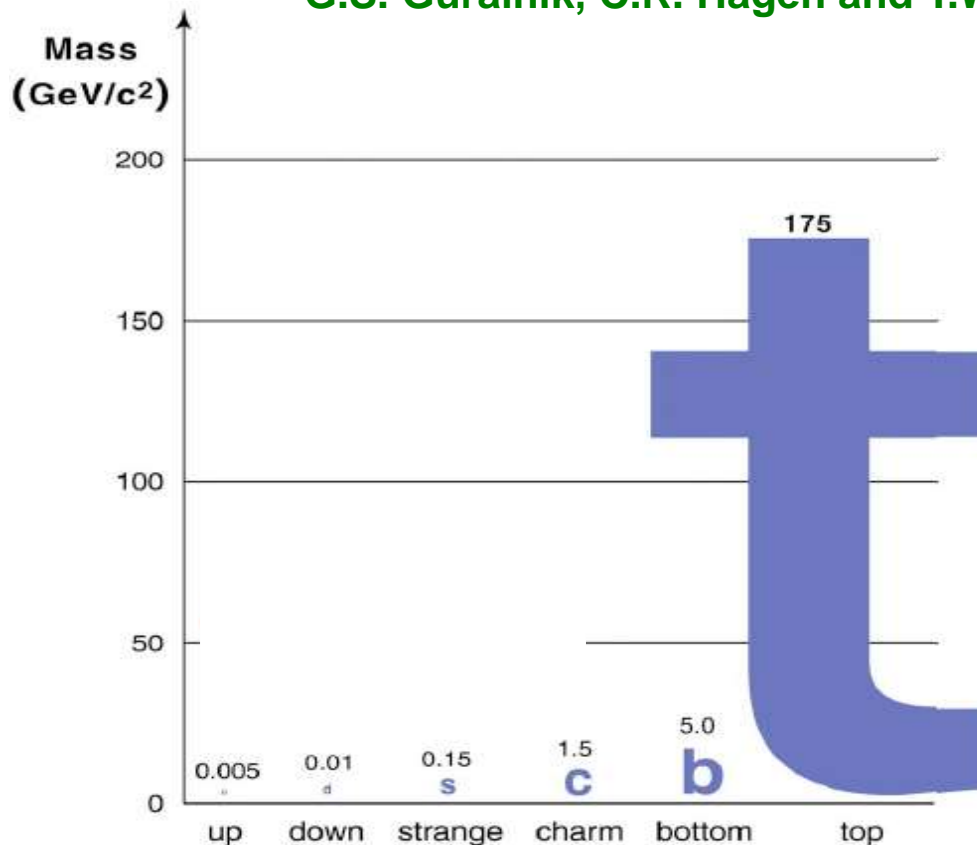


A most basic question is why particles (and matter) have masses (and so different masses)

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



Quarks

LHC: Higgs and beyond

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

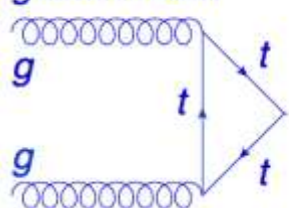
Francois Englert



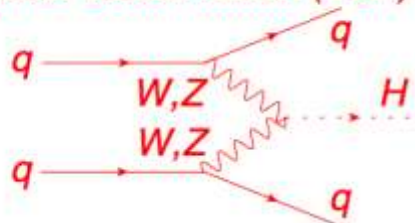
Search for the boson (H) of the EW symmetry breaking

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

gluon fusion



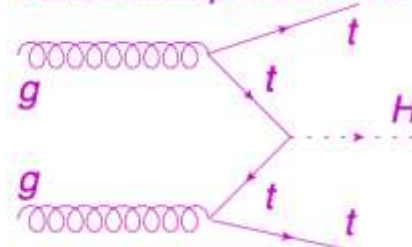
vector boson fusion (VBF)



associated prod. with W/Z

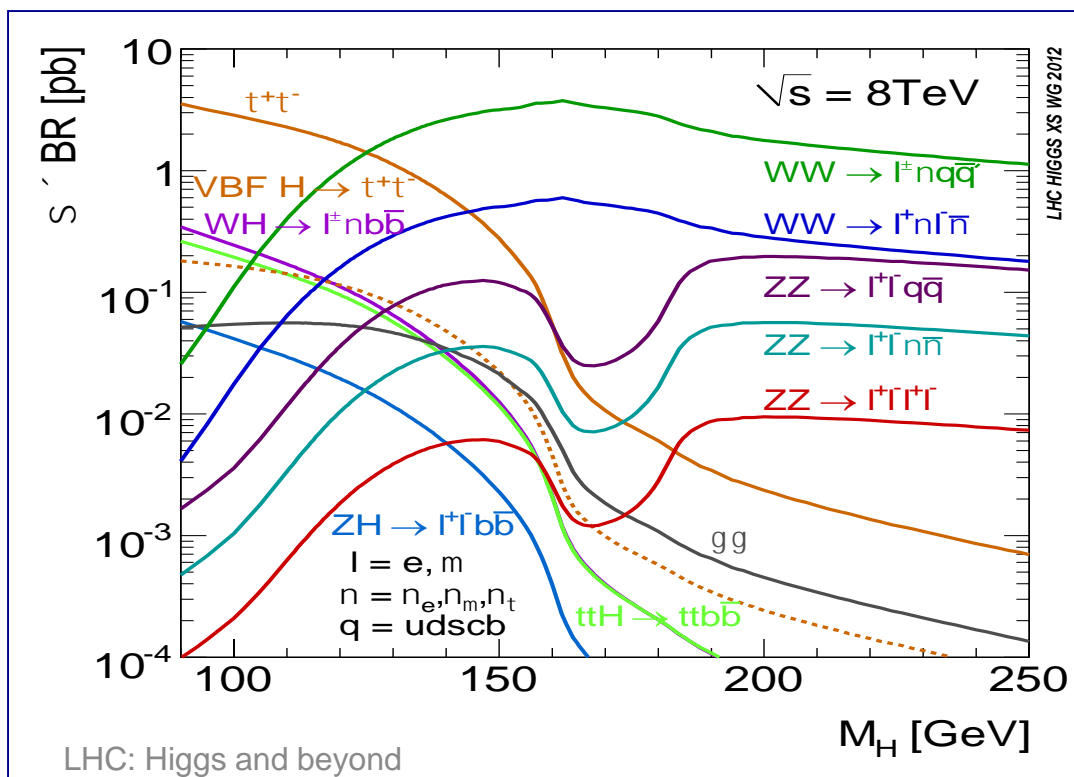
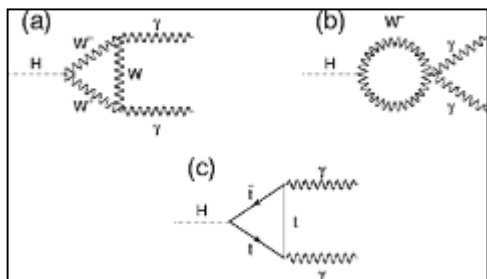


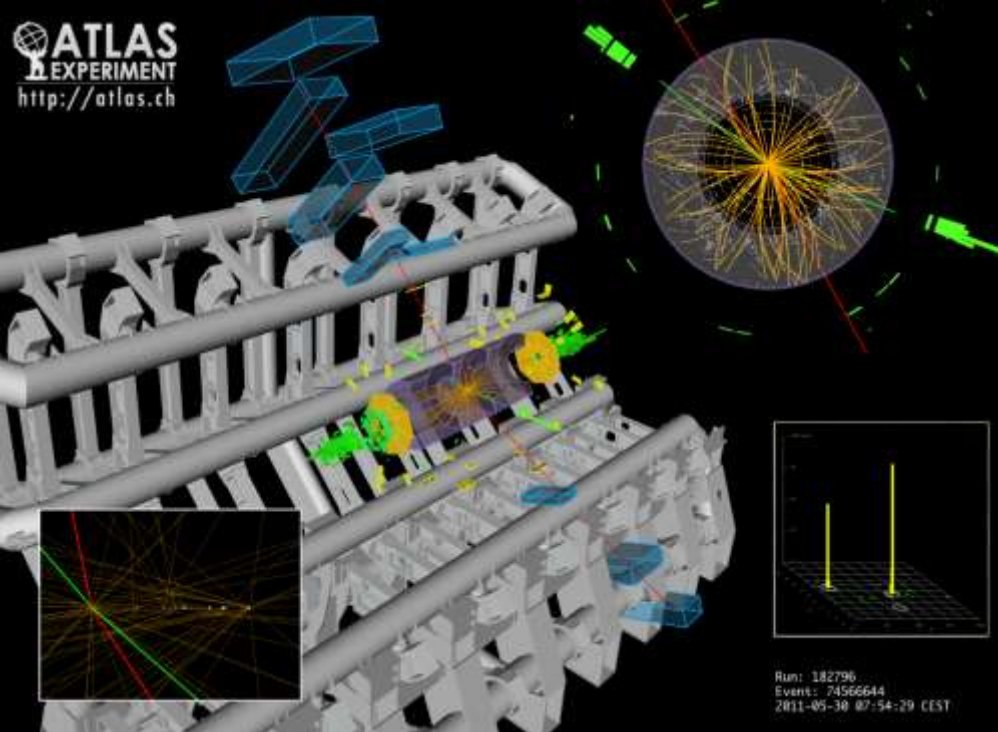
associated prod. with tt



$$h \text{---} W, Z = gM_W, \frac{gM_Z}{\cos\theta_W}$$

$$h \text{---} f = \frac{gM_f}{2M_W}$$





Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

The Higgs(-like) boson

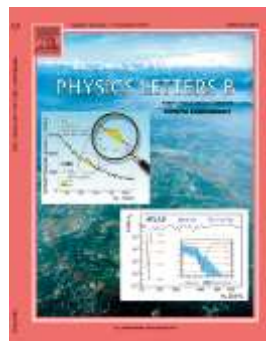
Candidate event for $H \rightarrow \gamma\gamma$

Candidate event for $H \rightarrow ZZ^* \rightarrow ee\mu\mu$



CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564234000

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

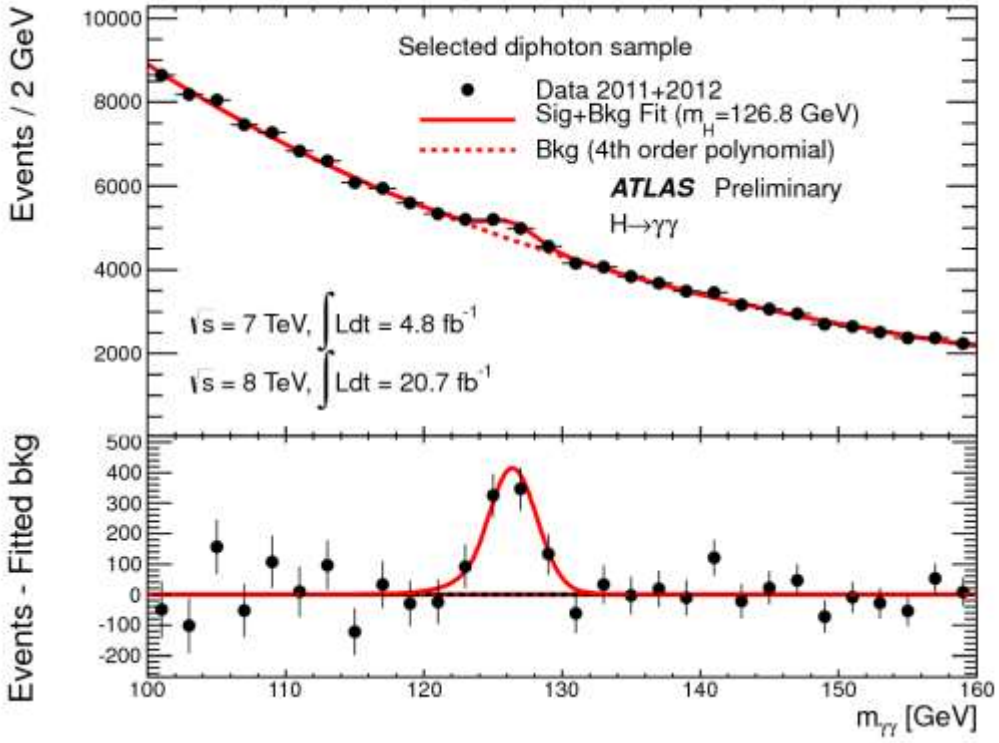


Phys. Lett. B 716 (2012) 1

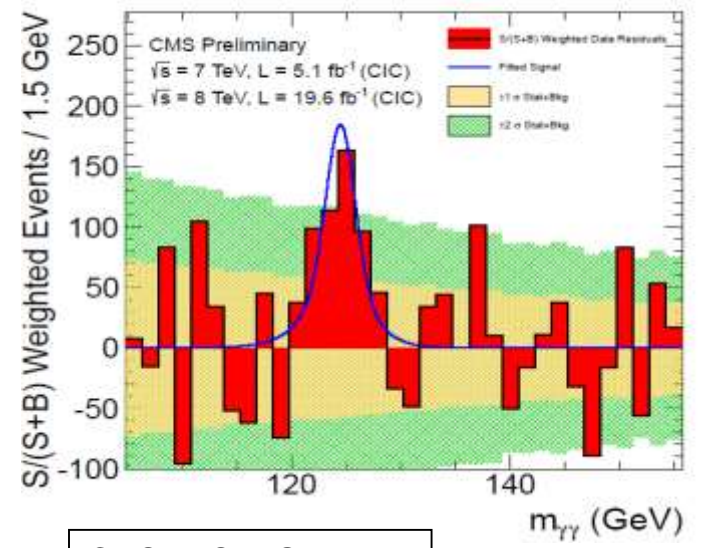
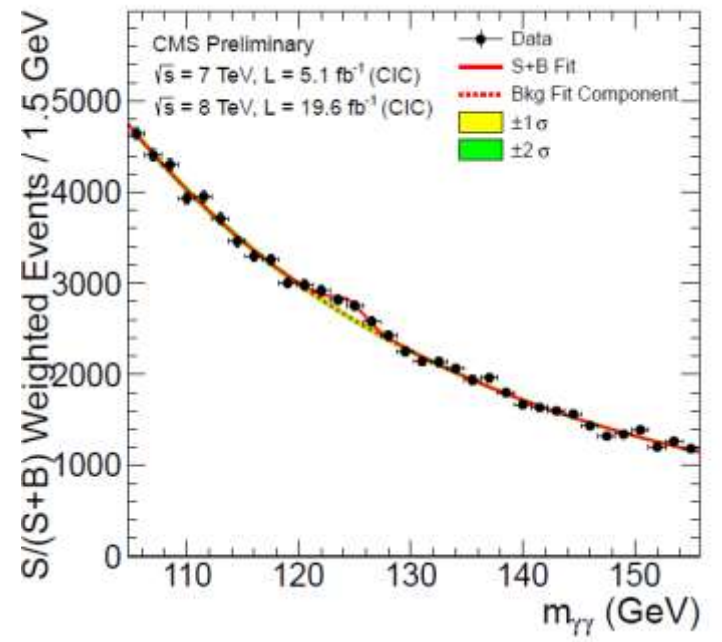
Phys. Lett. B 716 (2012) 30

H \rightarrow $\gamma\gamma$

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



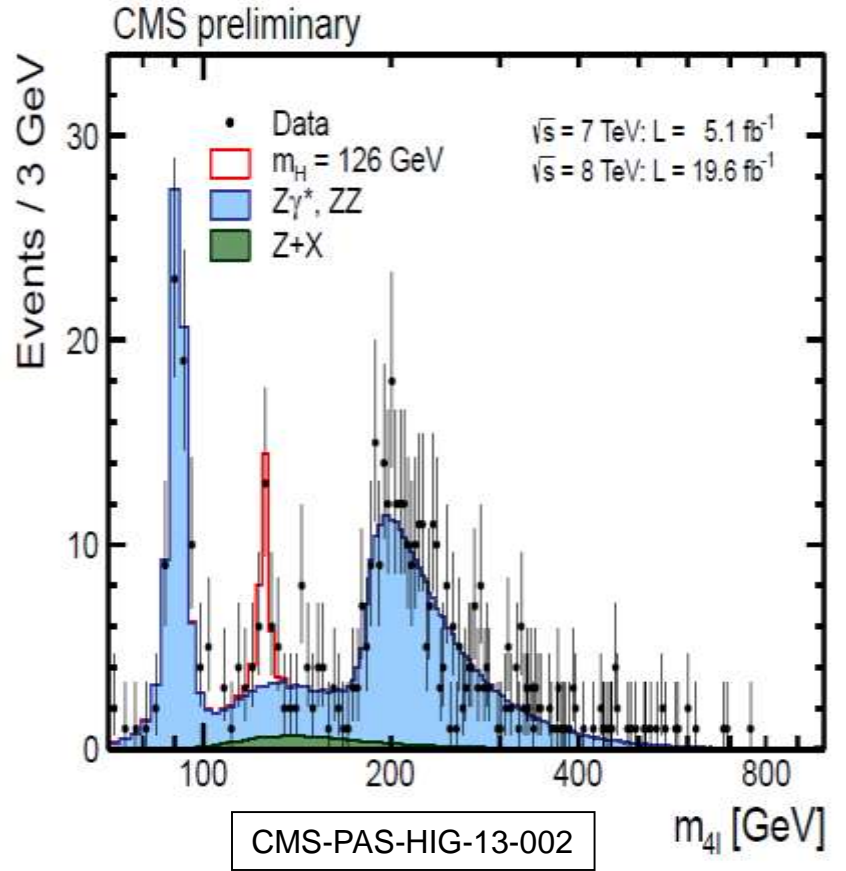
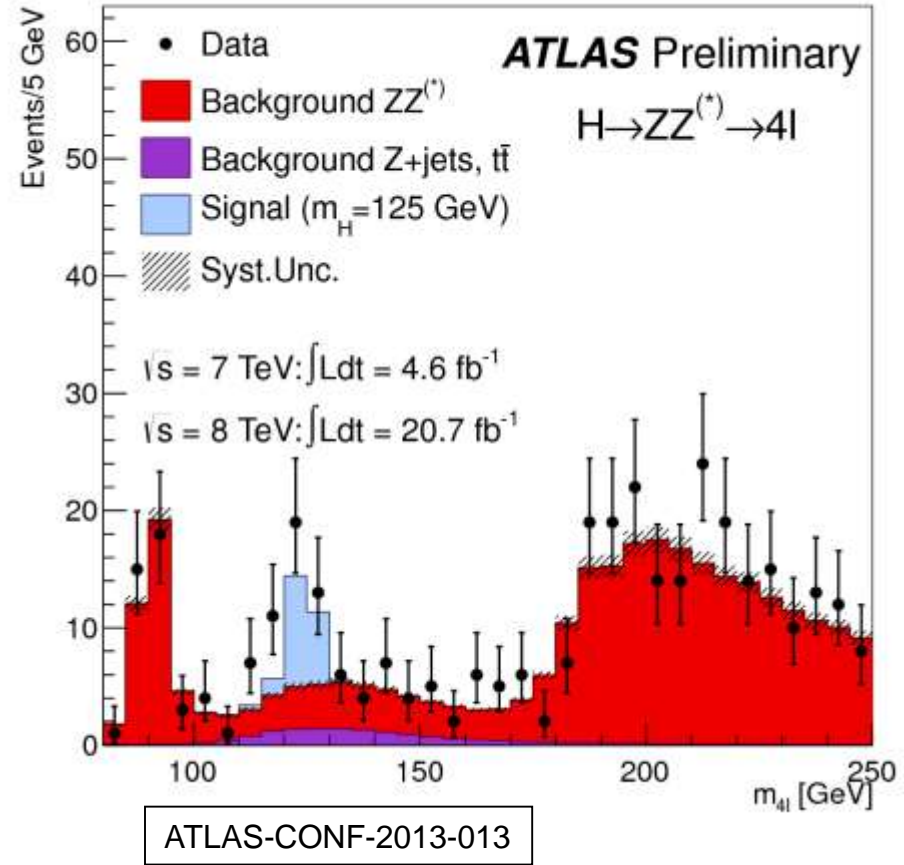
ATLAS-CONF-2013-012



CMS-PAS-HIG-13-001

H \rightarrow ZZ^(*) \rightarrow 4l (4e, 4μ, 2e2μ)

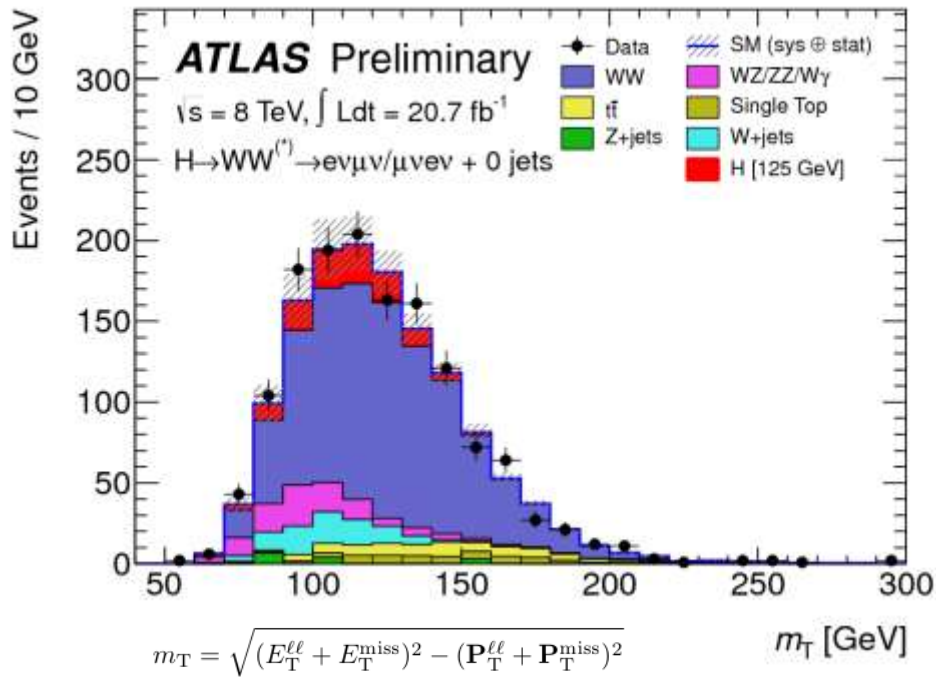
- Rare process, small cross section: $\sigma \sim 2\text{-}5 \text{ fb}$
 - However: pure: S/B ~ 1
 - 4 leptons:
 - Main background: ZZ^(*) (irreducible)
- In addition: Zbb, Z+jets, tt with two leptons from b-quarks or jets



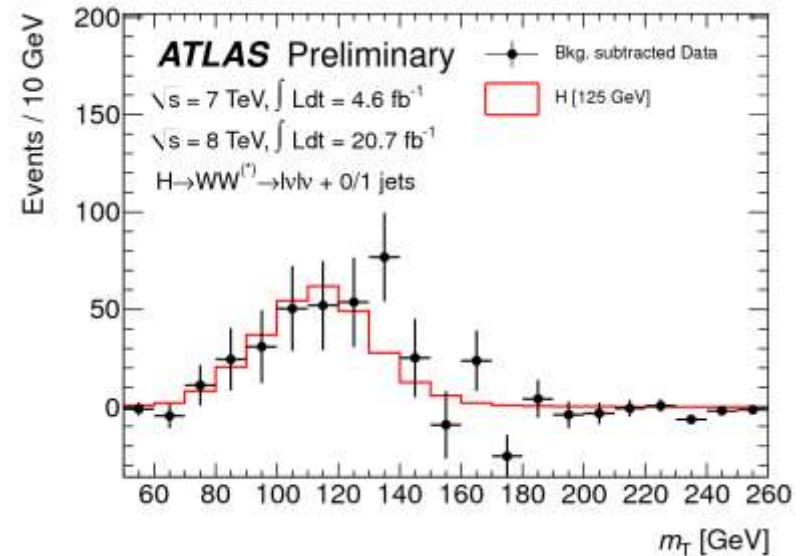
$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ (eνeν, μνμν, eνμν)

- ❑ Very sensitive channel over ~ 125-180 GeV ($\sigma \sim 200$ fb)
- ❑ Challenging: $2\nu \rightarrow$ no mass reconstruction/peak \rightarrow “counting channel”
- ❑ 2 isolated opposite-sign leptons, use eνμν only for 2012 data, large E_T^{miss}
- ❑ Main backgrounds: WW, top, Z+jets, W+jets
- ❑ Topological cuts against “irreducible” WW background

(Just an example distributions from several categories used in both experiments)



To get a feeling for the number of events, this is for all categories the summed, background-subtracted distributions



ATLAS-CONF-2013-030

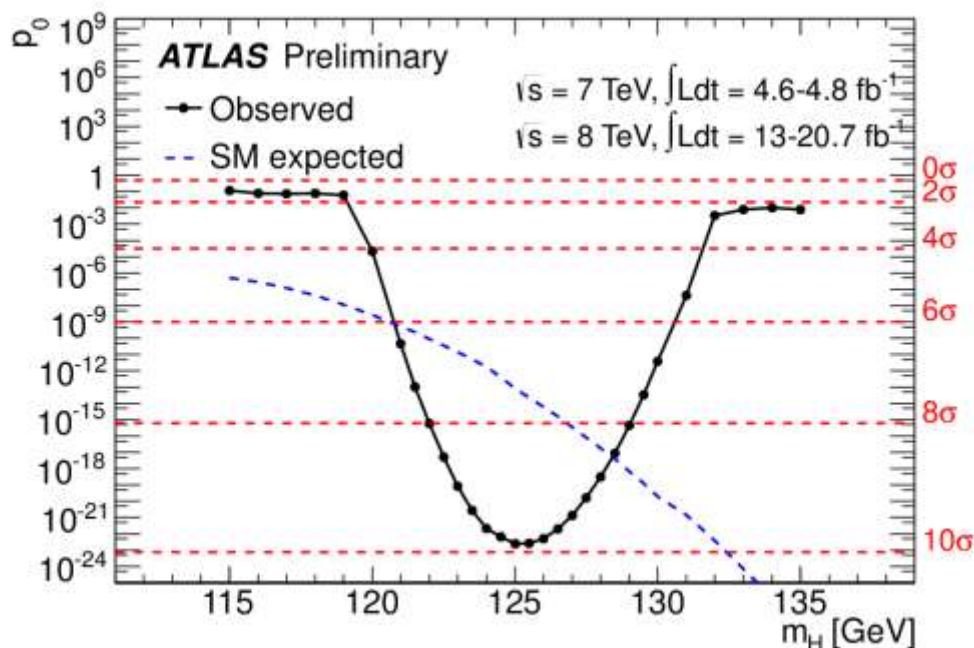
How significant is the signal for the new particle ?

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

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

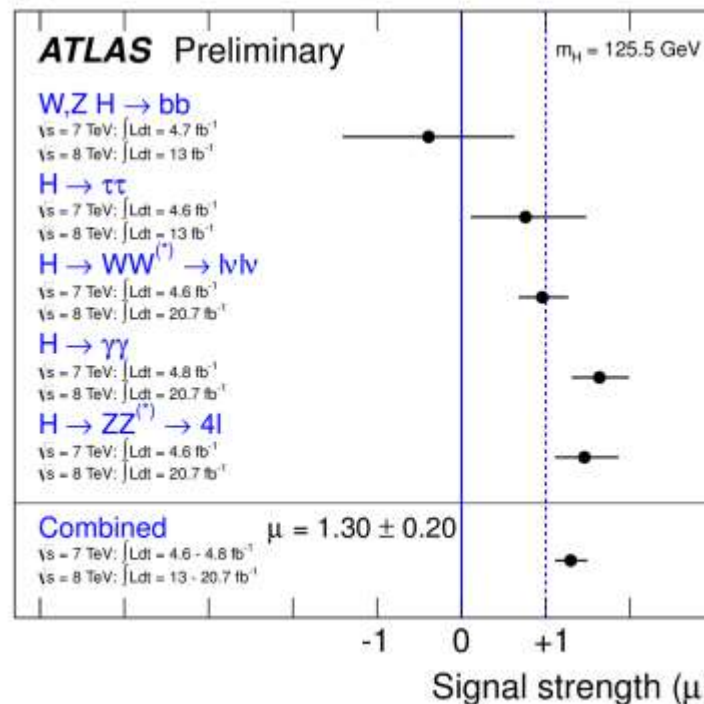
Signal strength

$\mu = 0$ 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

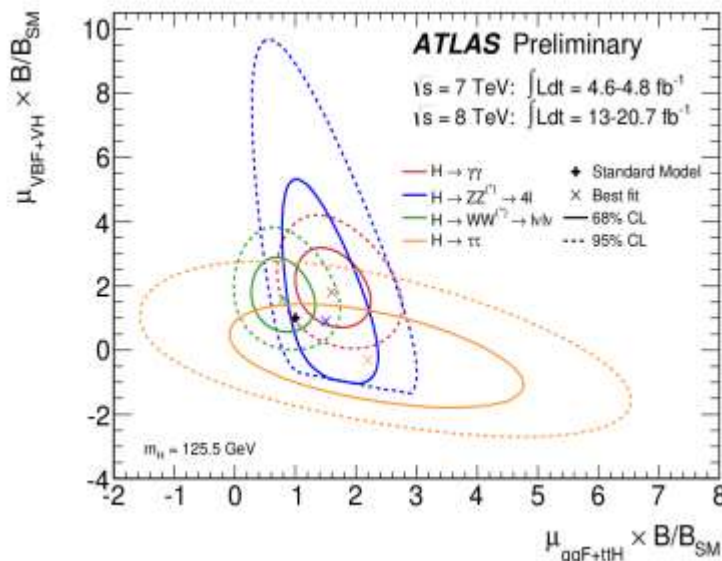
It will be important to understand with great precision if it is the only scalar boson of the Standard Model 'Brout-Englert-Higgs' mechanism to break the electroweak symmetry, or if it is only part of a broader physics picture going *Beyond the Standard Model*

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

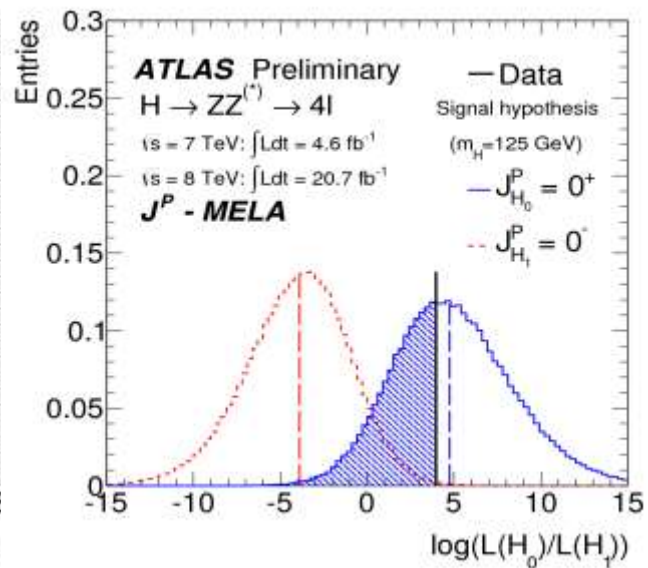
For the experts:

Couplings
Production modes
Spin-parity

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

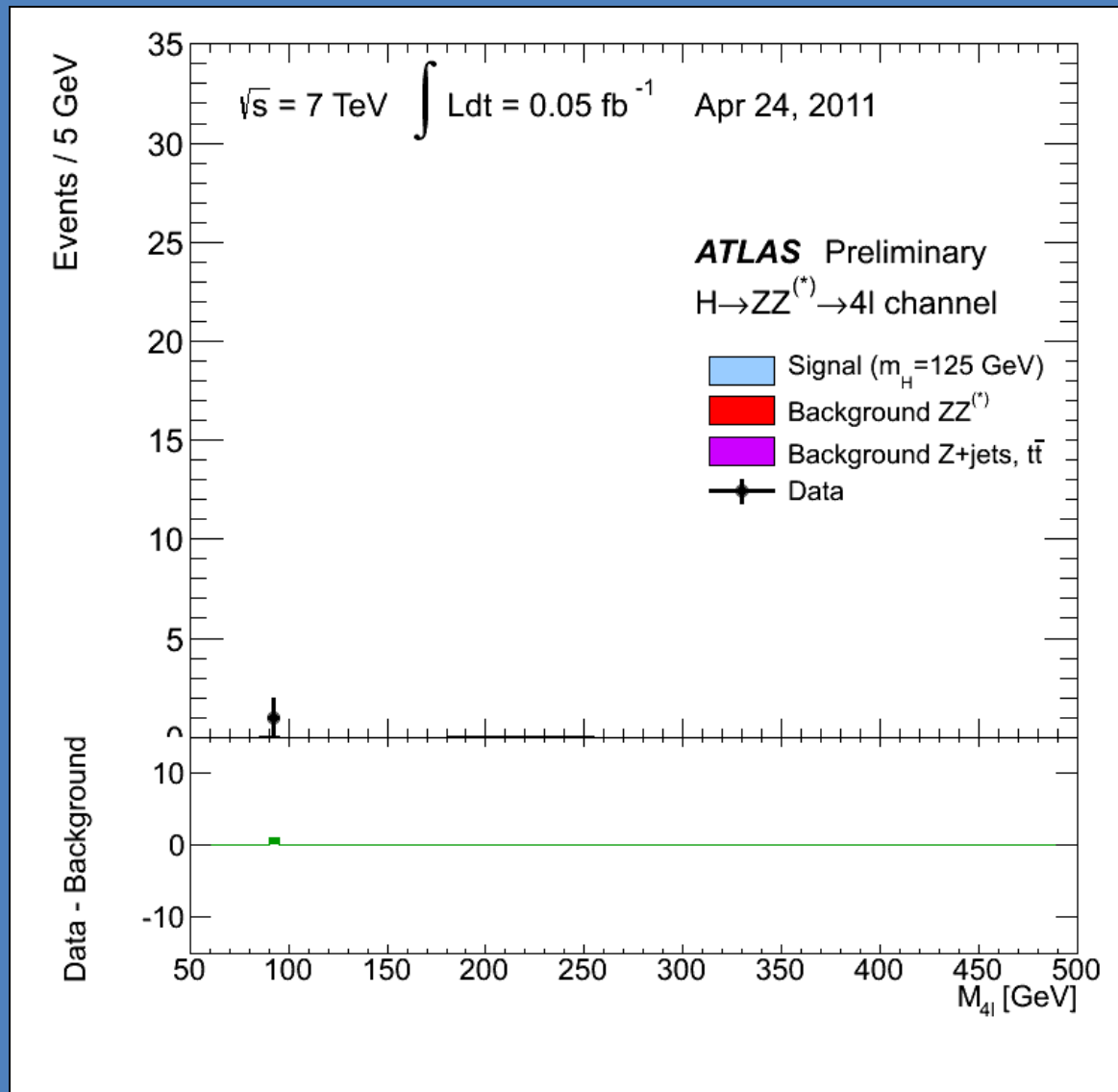


ATLAS-CONF-2013-034



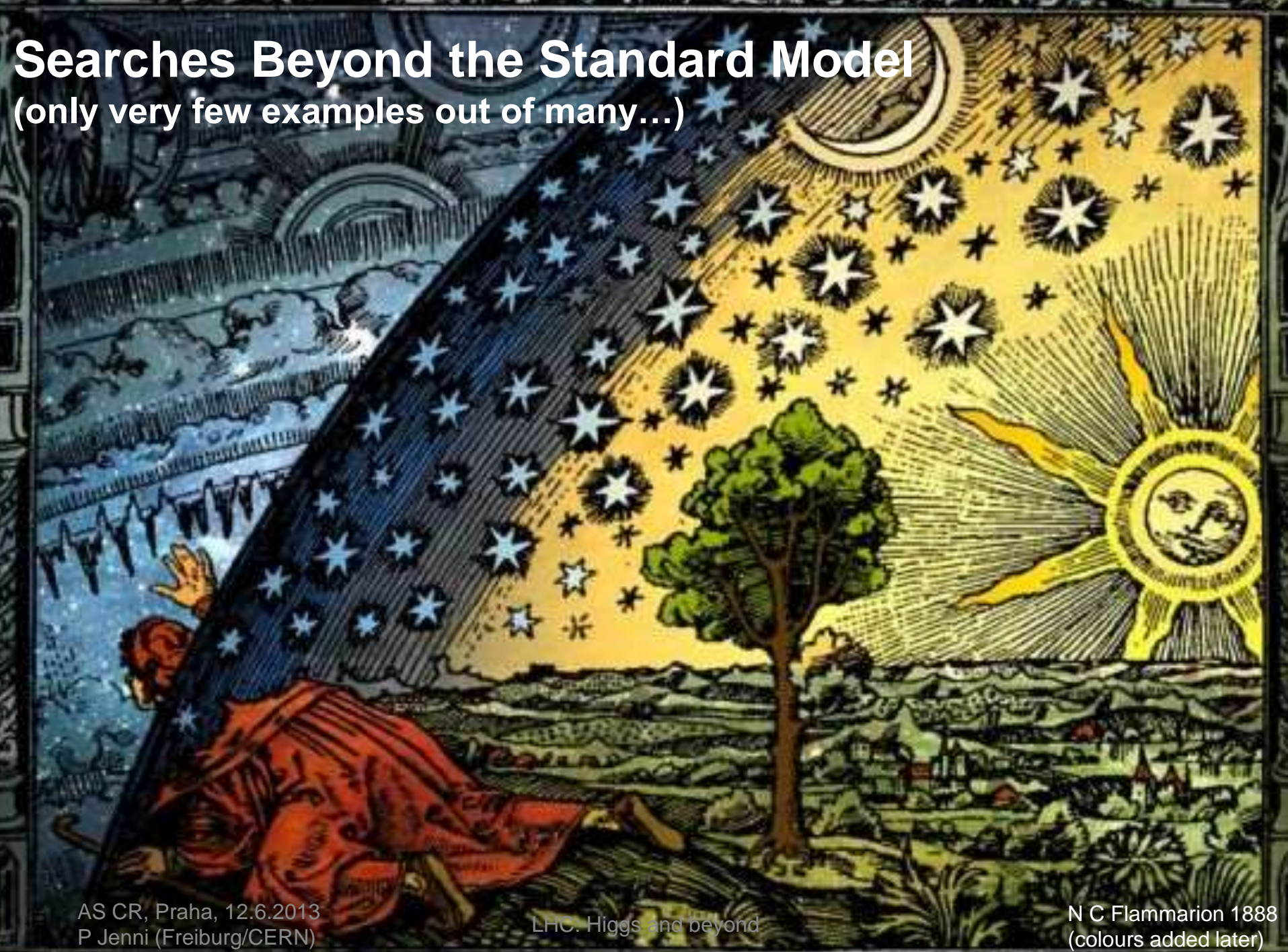
ATLAS-CONF-2013-013

Birth and evolution of a signal: $H \rightarrow 4l$



Searches Beyond the Standard Model

(only very few examples out of many...)



Supersymmetry (SUSY)

(Julius Wess and Bruno Zumino, 1974)

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

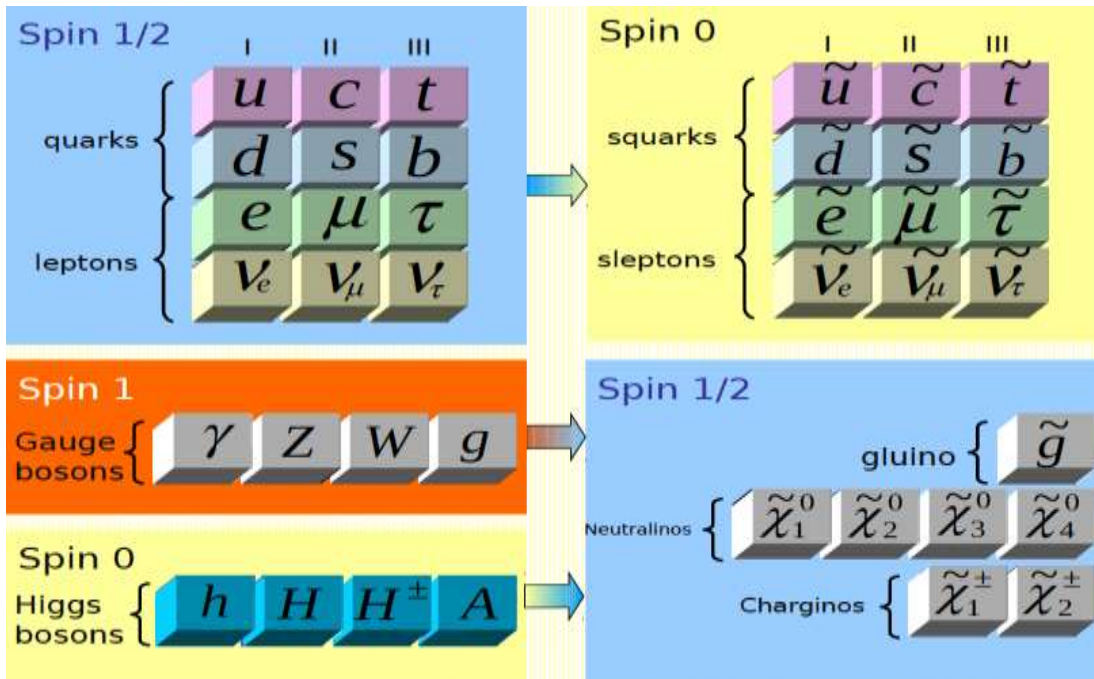
- Each particle p with spin s has a SUSY partner \tilde{p} with spin $s - 1/2$

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



Our known world...

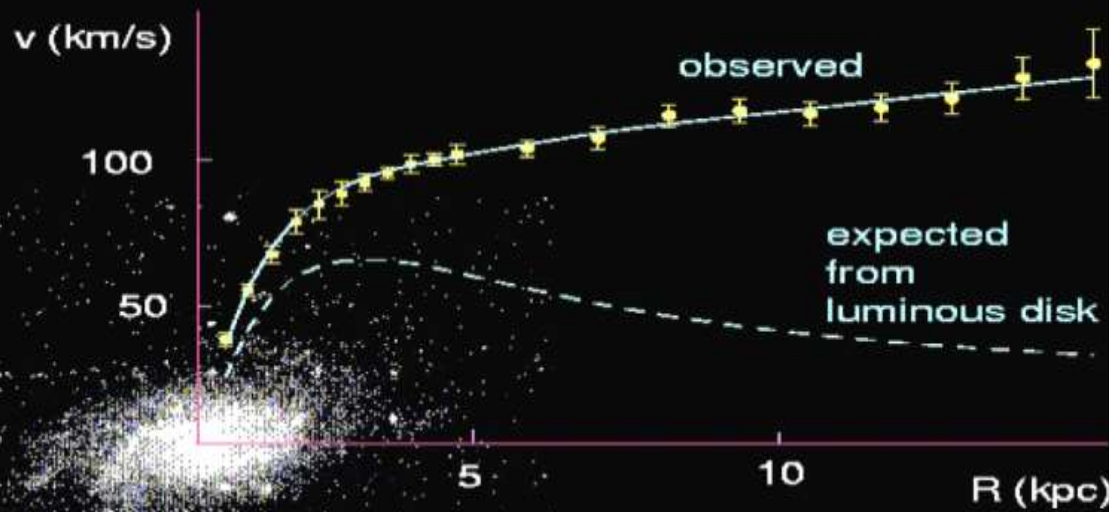
Maybe a new world?



Motivation:

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

Dark Matter in the Universe



M33 rotation curve



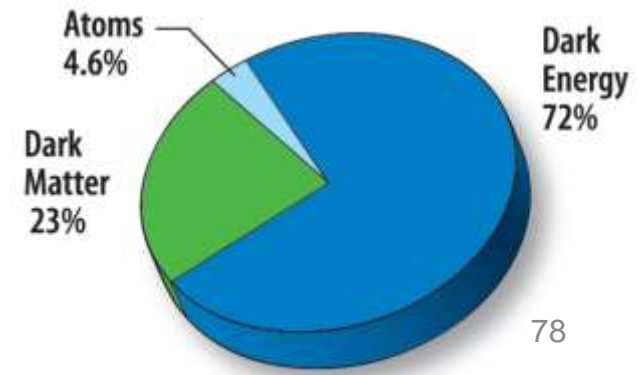
Vera Rubin ~ 1970

symmetric' particles ?



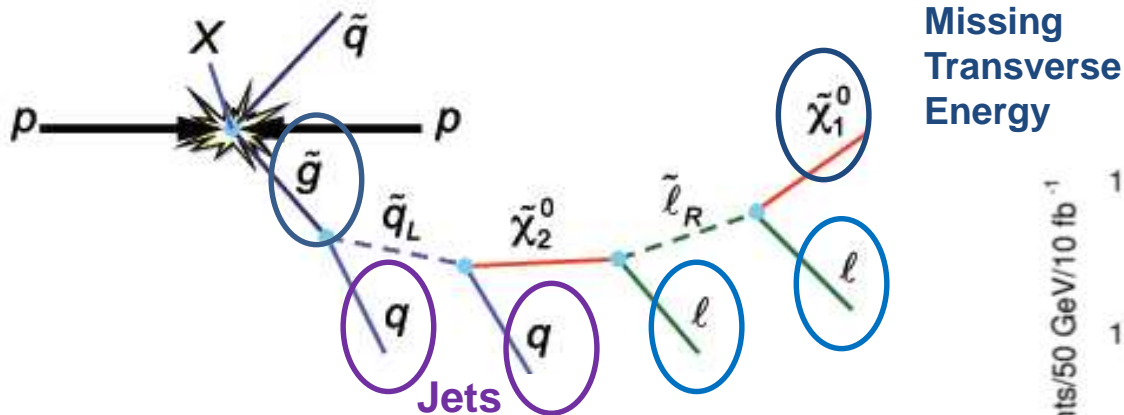
F. Zwicky 1898-1974

LHC: Higgs and beyond



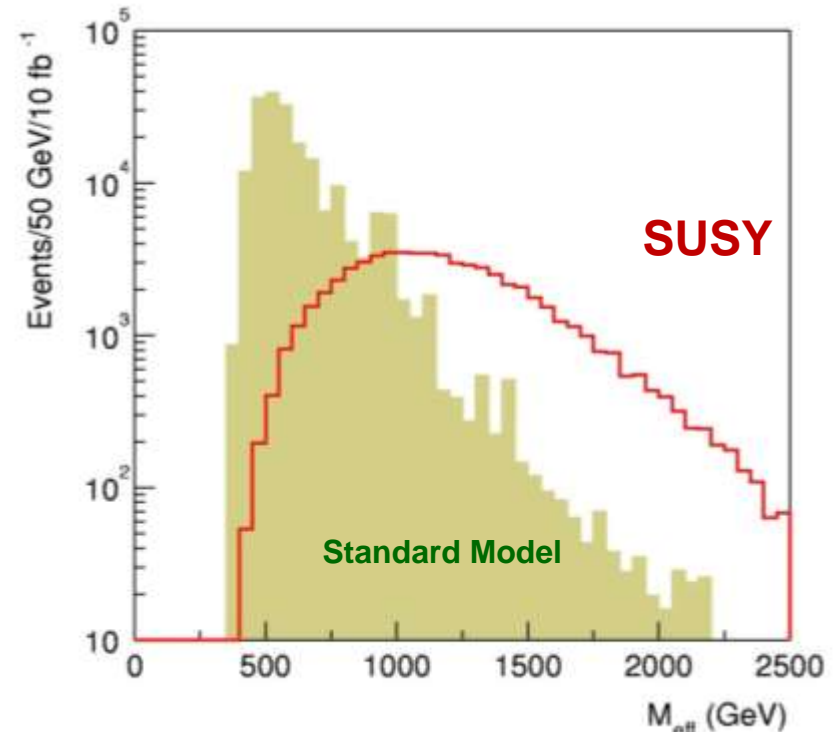
In practice SUSY searches at LHC are rather complicated

- 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

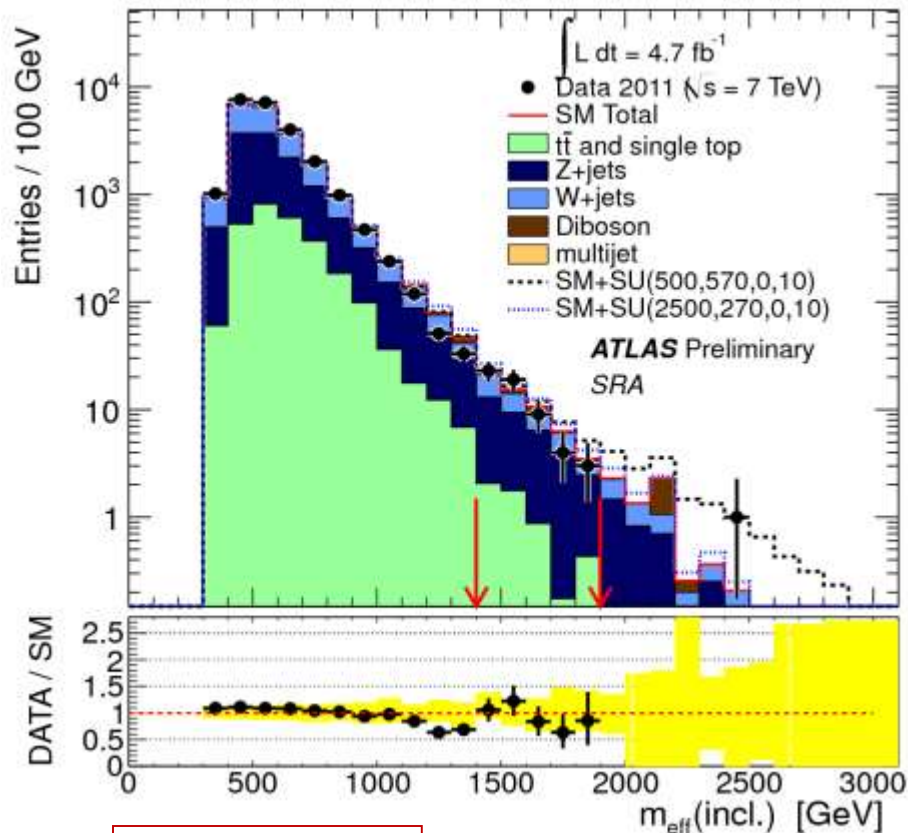


$$M_{\text{eff}} = E_{\text{miss}} + \sum p_T(\text{jets})$$

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

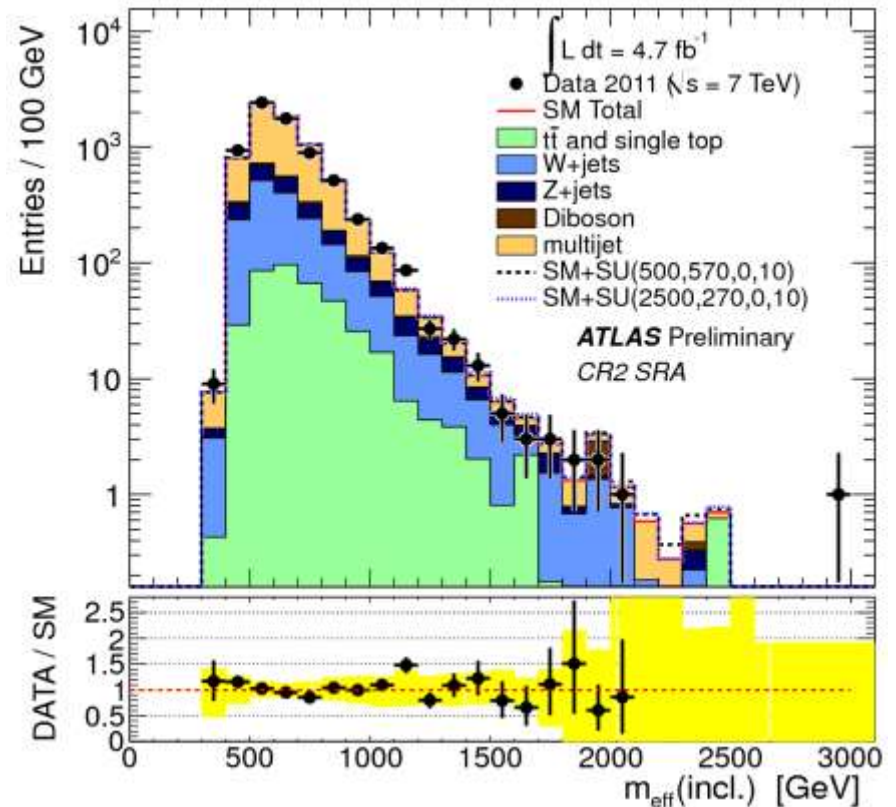
- 0-lepton + 2–6 jets + high MET (based on Et-miss+jet triggers)
- 0-lepton + 6–9 (multi-)jets + MET (based on multi-jet triggers)
- 1-lepton + 3,4 jets + high MET (based on lepton triggers)

Example: 0-leptons + 2-6 Jets analysis



A signal region

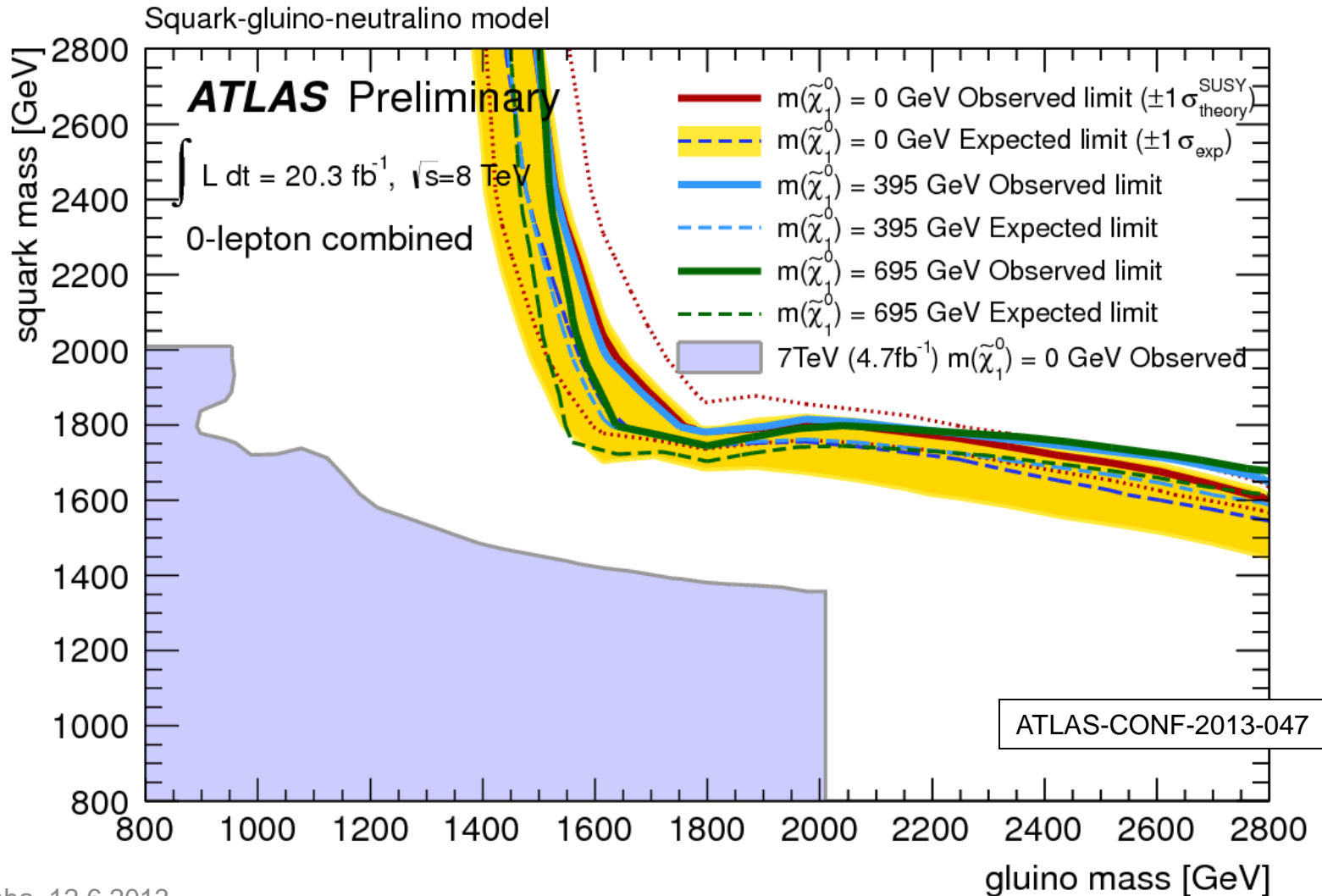
ATLAS-CONF-2012-033, 037, and 041



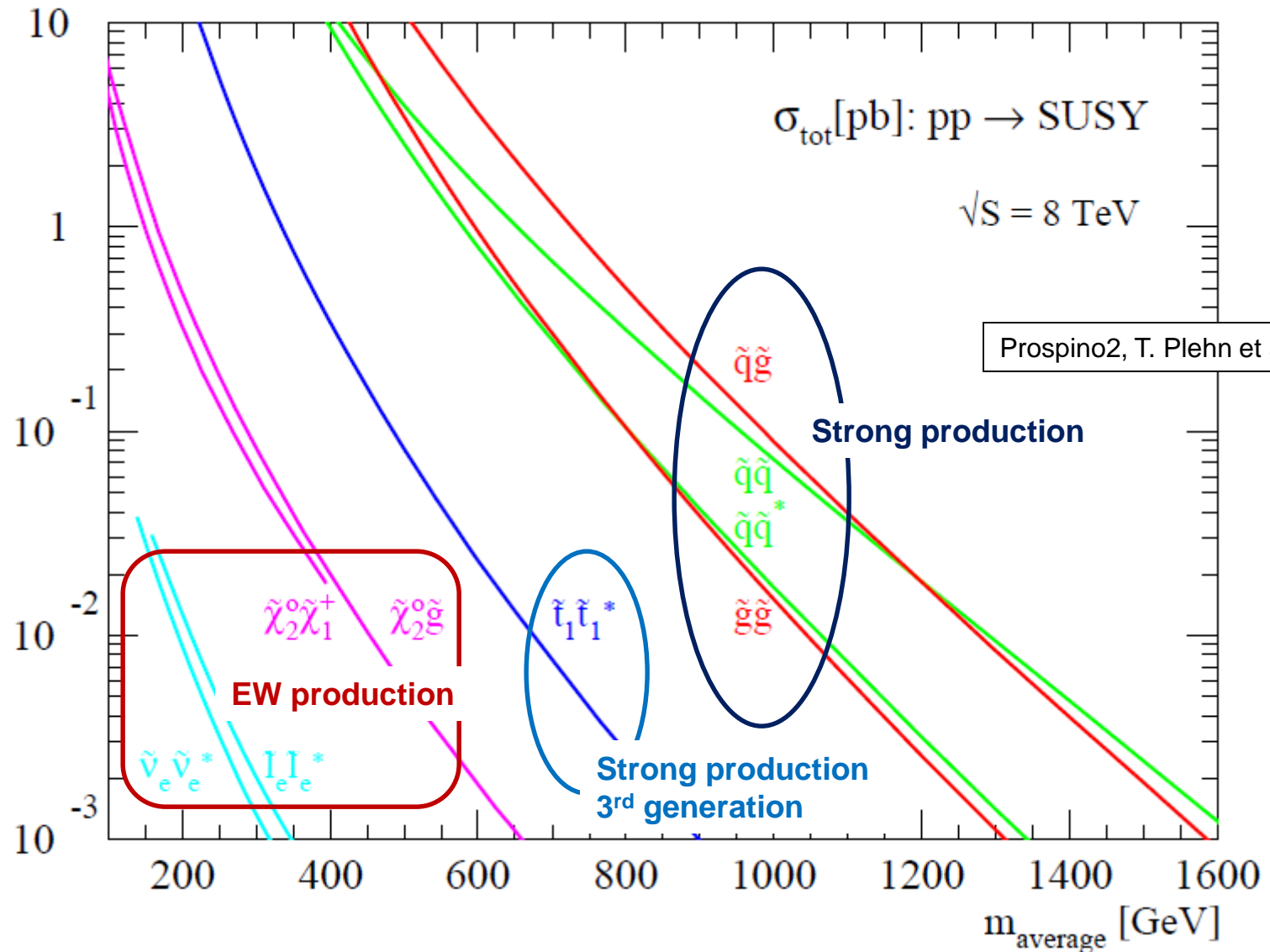
A control region where no signal is expected

Interpretation of the results

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

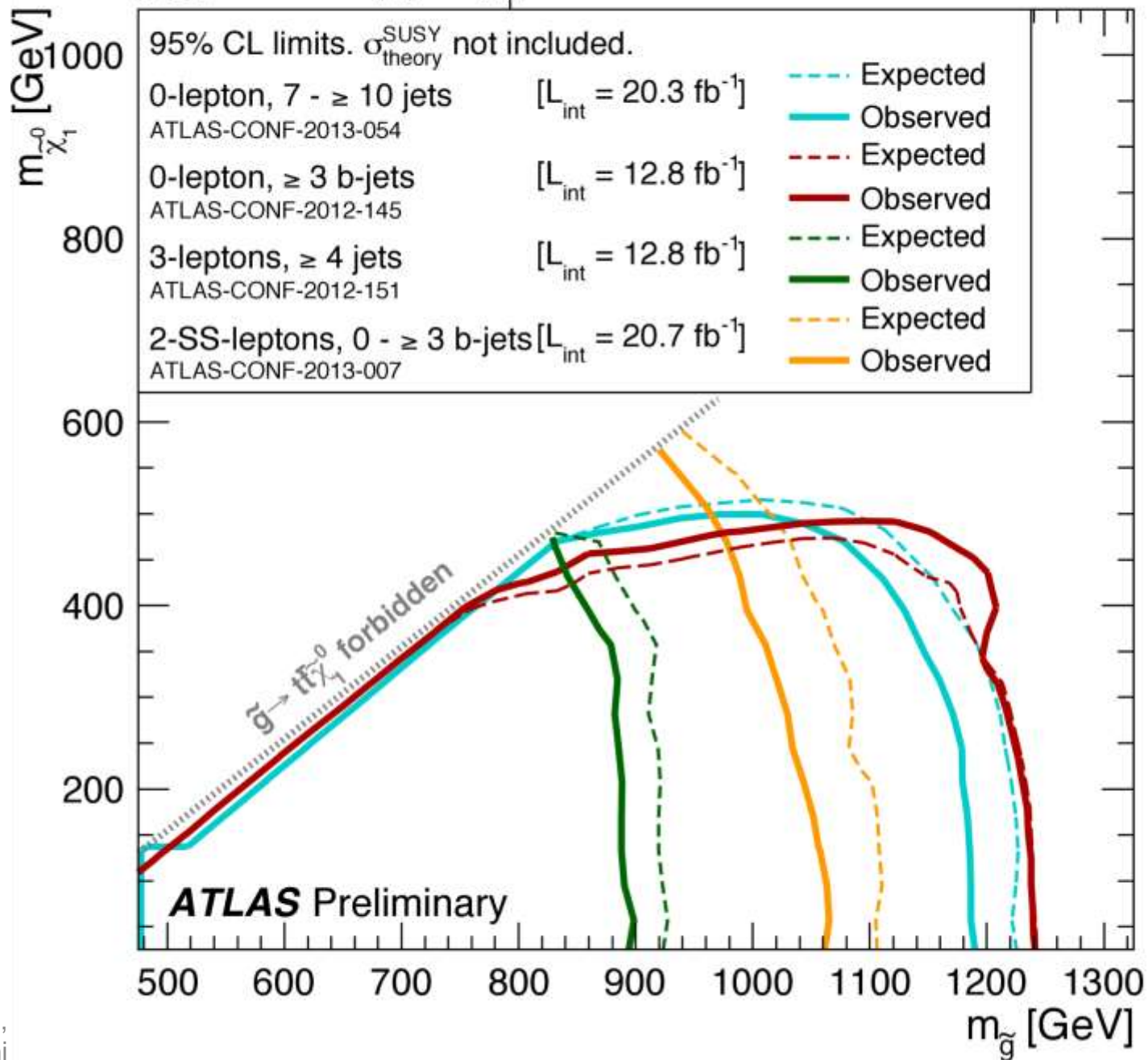


Expected production cross-sections at LHC



$\tilde{g}\text{-}\tilde{g}$ production, $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$, $\sqrt{s} = 8$ TeV

Status: LHCP 2013



SUSY limits

$$\int L dt = (4.4 - 20.7) \text{ fb}^{-1} \quad \sqrt{s} = 7, 8 \text{ TeV}$$

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int L dt [\text{fb}^{-1}]$	Mass limit	Reference		
Inclusive searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	q, \bar{q} 1.8 TeV	ATLAS-CONF-2013-047	
	MSUGRA/CMSSM	1 e, μ	4 jets	Yes	5.8	q, \bar{q} 1.24 TeV	ATLAS-CONF-2012-104	
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	q, \bar{q} 1.1 TeV	ATLAS-CONF-2013-054	
	$q\bar{q} \rightarrow q\bar{q}Z^0$	0	2-6 jets	Yes	20.3	q, \bar{q} 740 GeV	ATLAS-CONF-2013-047	
	$g\bar{g} \rightarrow g\bar{g}Z^0$	0	2-6 jets	Yes	20.3	q, \bar{q} 1.3 TeV	ATLAS-CONF-2013-047	
	Gluino med. $\tilde{\chi}^0 \rightarrow q\bar{q}\tilde{\chi}^0$	1 e, μ	2-4 jets	Yes	4.7	g 900 GeV	1208.4688	
	$g\bar{g} \rightarrow qq\bar{q}\bar{q}\chi^0_{1,2}$	2 e, μ (SS)	3 jets	Yes	20.7	g 1.1 TeV	ATLAS-CONF-2013-007	
	GMSB (NLSP)	2 e, μ	2-4 jets	Yes	4.7	g 1.24 TeV	1208.4688	
	GMSB (NLSP)	1-2 τ	0-2 jets	Yes	20.7	g 1.4 TeV	ATLAS-CONF-2013-026	
	GGM (bino NLSP)	2 γ	0	Yes	4.8	g 1.07 TeV	1209.0753	
	GGM (wino NLSP)	1 $e, \mu + \gamma$	0	Yes	4.8	g 619 GeV	ATLAS-CONF-2012-144	
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	g 900 GeV	1211.1167	
GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	g 590 GeV	ATLAS-CONF-2012-152		
Gravitino LSP	0	mono-jet	Yes	10.5	M^2 scale 645 GeV	ATLAS-CONF-2012-147		
3 rd gen. g med.	$g \rightarrow b\bar{b}\tilde{\chi}^0_{1,2}$	0	3 b	Yes	12.8	g 1.24 TeV	ATLAS-CONF-2012-145	
	$g \rightarrow t\bar{t}\tilde{\chi}^0_{1,2}$	2 e, μ (SS)	0-3 b	No	20.7	g 900 GeV	ATLAS-CONF-2013-007	
	$g \rightarrow d\bar{d}\tilde{\chi}^0_{1,2}$	0	7-10 jets	Yes	20.3	g 1.14 TeV	ATLAS-CONF-2013-054	
	$g \rightarrow u\bar{u}\tilde{\chi}^0_{1,2}$	0	3 b	Yes	12.8	g 1.14 TeV	ATLAS-CONF-2012-145	
	3 rd gen. squarks direct production	$b\bar{b}, \bar{b} \rightarrow b\tilde{\chi}^0_{1,2}$	0	2 b	Yes	20.1	b, \bar{b} 100-630 GeV	ATLAS-CONF-2013-053
$b\bar{b}, \bar{b} \rightarrow \tilde{\chi}^0_{1,2}$		2 e, μ (SS)	0-3 b	Yes	20.7	b, \bar{b} 430 GeV	ATLAS-CONF-2013-007	
$l_1\bar{l}_1$ (light), $l_1 \rightarrow b\tilde{\chi}^0_{1,2}$		1-2 e, μ	1-2 b	Yes	4.7	l_1, \bar{l}_1 167 GeV	1208.4305, 1209.2102	
$l_1\bar{l}_1$ (light), $l_1 \rightarrow Wb\tilde{\chi}^0_{1,2}$		2 e, μ	0-2 jets	Yes	20.3	l_1, \bar{l}_1 230 GeV	ATLAS-CONF-2013-048	
$l_1\bar{l}_1$ (medium), $l_1 \rightarrow b\tilde{\chi}^0_{1,2}$		2 e, μ	0-2 jets	Yes	20.3	l_1, \bar{l}_1 230 GeV	ATLAS-CONF-2013-048	
$l_1\bar{l}_1$ (medium), $l_1 \rightarrow b\tilde{\chi}^0_{1,2}$		0	2 b	Yes	20.1	l_1, \bar{l}_1 380 GeV	ATLAS-CONF-2013-053	
$l_1\bar{l}_1$ (heavy), $l_1 \rightarrow b\tilde{\chi}^0_{1,2}$		1 e, μ	1 b	Yes	20.7	l_1, \bar{l}_1 200-610 GeV	ATLAS-CONF-2013-037	
$l_1\bar{l}_1$ (heavy), $l_1 \rightarrow t\tilde{\chi}^0_{1,2}$		0	2 b	Yes	20.7	l_1, \bar{l}_1 320-660 GeV	ATLAS-CONF-2013-024	
$l_1\bar{l}_1$ (natural GMSB)		2 e, μ (Z)	1 b	Yes	20.7	l_1, \bar{l}_1 500 GeV	ATLAS-CONF-2013-025	
$l_2\bar{l}_2, l_2 \rightarrow l_1 + Z$		3 e, μ (Z)	1 b	Yes	20.7	l_2, \bar{l}_2 520 GeV	ATLAS-CONF-2013-025	
EW direct		$l_1\bar{l}_1, l_1 \rightarrow l_2\tilde{\chi}^0_{1,2}$	2 e, μ	0	Yes	20.7	l_1, \bar{l}_1 85-315 GeV	ATLAS-CONF-2013-049
		$Z\tilde{\chi}^0_{1,2}, \tilde{\chi}^0_{1,2} \rightarrow l_1\bar{l}_1(\nu\bar{\nu})$	2 e, μ	0	Yes	20.3	$Z, \tilde{\chi}^0_{1,2}$ 125-450 GeV	ATLAS-CONF-2013-049
	$Z\tilde{\chi}^0_{1,2}, \tilde{\chi}^0_{1,2} \rightarrow \tau\bar{\tau}(\nu\bar{\nu})$	2 τ	0	Yes	20.7	$Z, \tilde{\chi}^0_{1,2}$ 180-330 GeV	ATLAS-CONF-2013-028	
	$Z\tilde{\chi}^0_{1,2} \rightarrow l_1\nu l_1(\nu\bar{\nu}), \bar{l}_1\nu l_1(\nu\bar{\nu})$	3 e, μ	0	Yes	20.7	$Z, \tilde{\chi}^0_{1,2}$ 600 GeV	ATLAS-CONF-2013-035	
	$Z\tilde{\chi}^0_{1,2} \rightarrow W\tilde{\chi}^0_{1,2}\tilde{\chi}^0_{1,2}$	3 e, μ	0	Yes	20.7	$Z, \tilde{\chi}^0_{1,2}$ 315 GeV	ATLAS-CONF-2013-035	
Long-lived particles	Direct $\tilde{\chi}^0_{1,2}\tilde{\chi}^0_{1,2}$ prod., long-lived $\tilde{\chi}^0_{1,2}$	0	1 jet	Yes	4.7	$\tilde{\chi}^0_{1,2}$ 220 GeV	1210.2852	
	Stable g, R-hadrons	0-2 e, μ	0	Yes	4.7	g 985 GeV	1211.1597	
	GMSB, stable $\tilde{\chi}^0_{1,2}$, low β	2 e, μ	0	Yes	4.7	$\tilde{\chi}^0_{1,2}$ 300 GeV	1211.1597	
	GMSB, $\tilde{\chi}^0_{1,2} \rightarrow \gamma$ Long-lived $\tilde{\chi}^0_{1,2}$	2 γ	0	Yes	4.7	$\tilde{\chi}^0_{1,2}$ 230 GeV	1304.6310	
	$\tilde{\chi}^0_{1,2} \rightarrow qq\mu$ (RPV)	1 e, μ	0	Yes	4.4	q, \bar{q} 700 GeV	1210.7451	
RPV	LFV $pp \rightarrow \bar{\nu}_i + X, \bar{\nu}_i \rightarrow e + \mu$	2 e, μ	0	-	4.6	$\tilde{\nu}_i, \bar{\nu}_i$ 1.51 TeV	1212.1272	
	LFV $pp \rightarrow \bar{\nu}_i + X, \bar{\nu}_i \rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	0	-	4.6	$\tilde{\nu}_i, \bar{\nu}_i$ 1.1 TeV	1212.1272	
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	q, \bar{q} 1.2 TeV	ATLAS-CONF-2012-140	
	$\tilde{\chi}^0_{1,2}\tilde{\chi}^0_{1,2} \rightarrow W\tilde{\chi}^0_{1,2}, \tilde{\chi}^0_{1,2} \rightarrow e\nu, \mu\nu$	4 e, μ	0	Yes	20.7	$\tilde{\chi}^0_{1,2}$ 760 GeV	ATLAS-CONF-2013-036	
	$\tilde{\chi}^0_{1,2}\tilde{\chi}^0_{1,2} \rightarrow W\tilde{\chi}^0_{1,2}, \tilde{\chi}^0_{1,2} \rightarrow \tau\nu, e\nu$	3 $e, \mu + \tau$	0	Yes	20.7	$\tilde{\chi}^0_{1,2}$ 350 GeV	ATLAS-CONF-2013-036	
	$g \rightarrow qqg$	0	6 jets	-	4.6	g 665 GeV	1210.4813	
Other	Scalar gluon	0	4 jets	-	4.6	sgluon 100-287 GeV	1210.4826	
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M^2 scale 704 GeV	ATLAS-CONF-2012-147	

Very similar limits come from CMS

$\sqrt{s} = 7 \text{ TeV}$ full data
 $\sqrt{s} = 8 \text{ TeV}$ partial data
 $\sqrt{s} = 8 \text{ TeV}$ full data

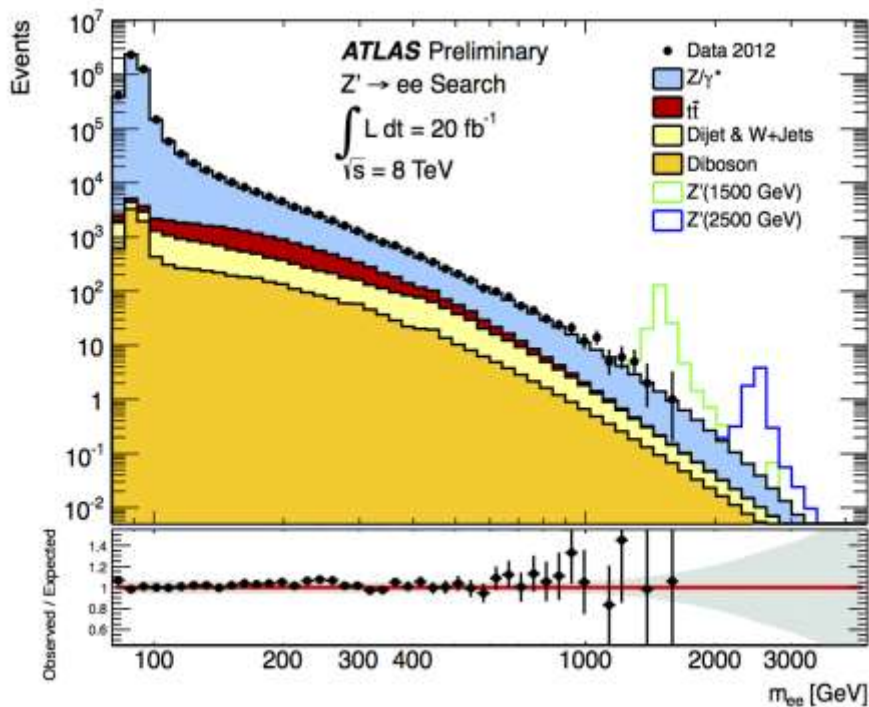
10⁻¹ 1 Mass scale [TeV]
 LHC: Higgs and beyond

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

Searches for heavy W and Z like particles

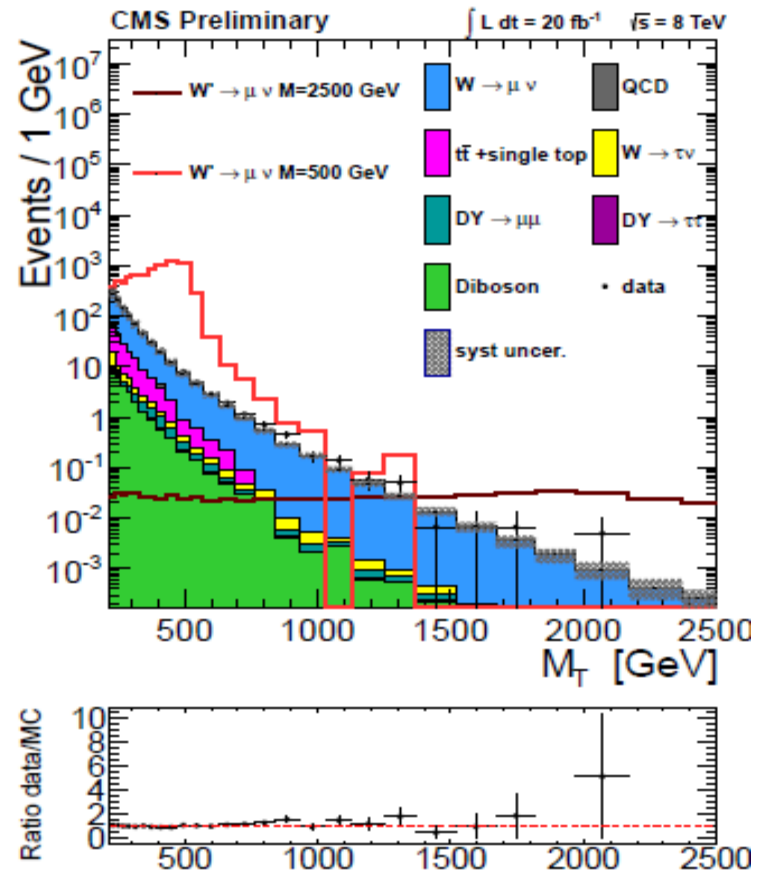
These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z' : Di-lepton pairs

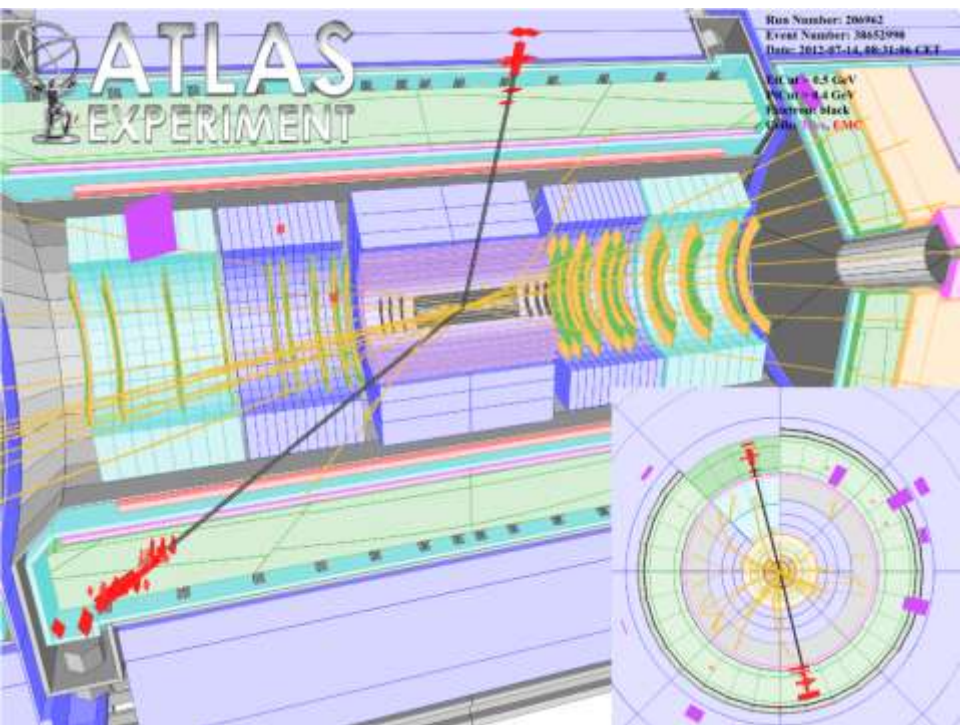


ATLAS-CONF-2013-017

W' : Lepton + ETmiss



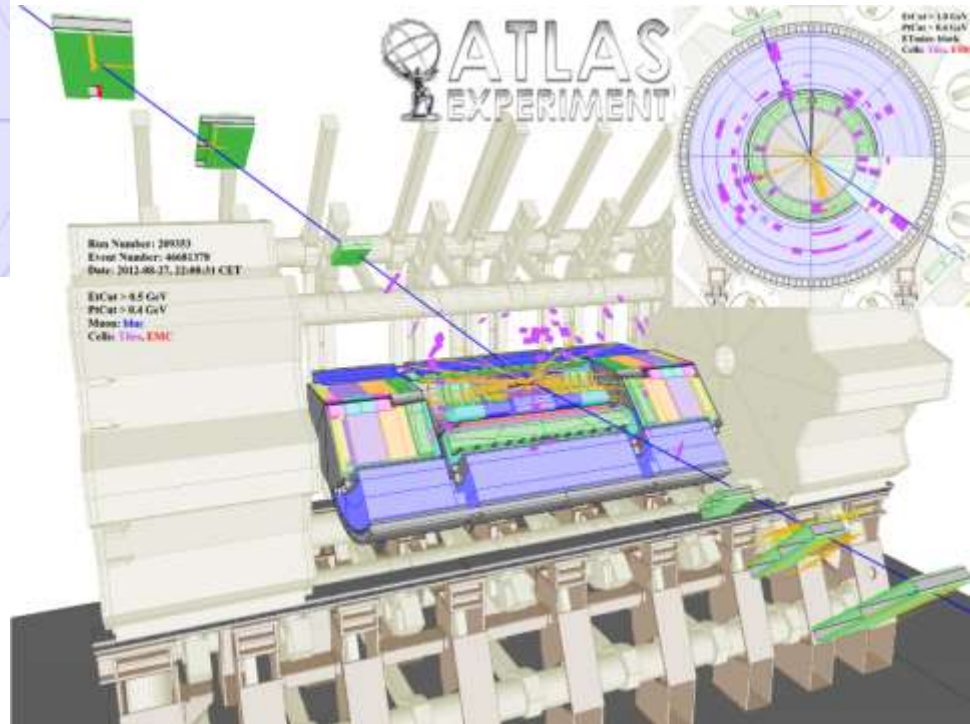
CMS-EXO-12-060



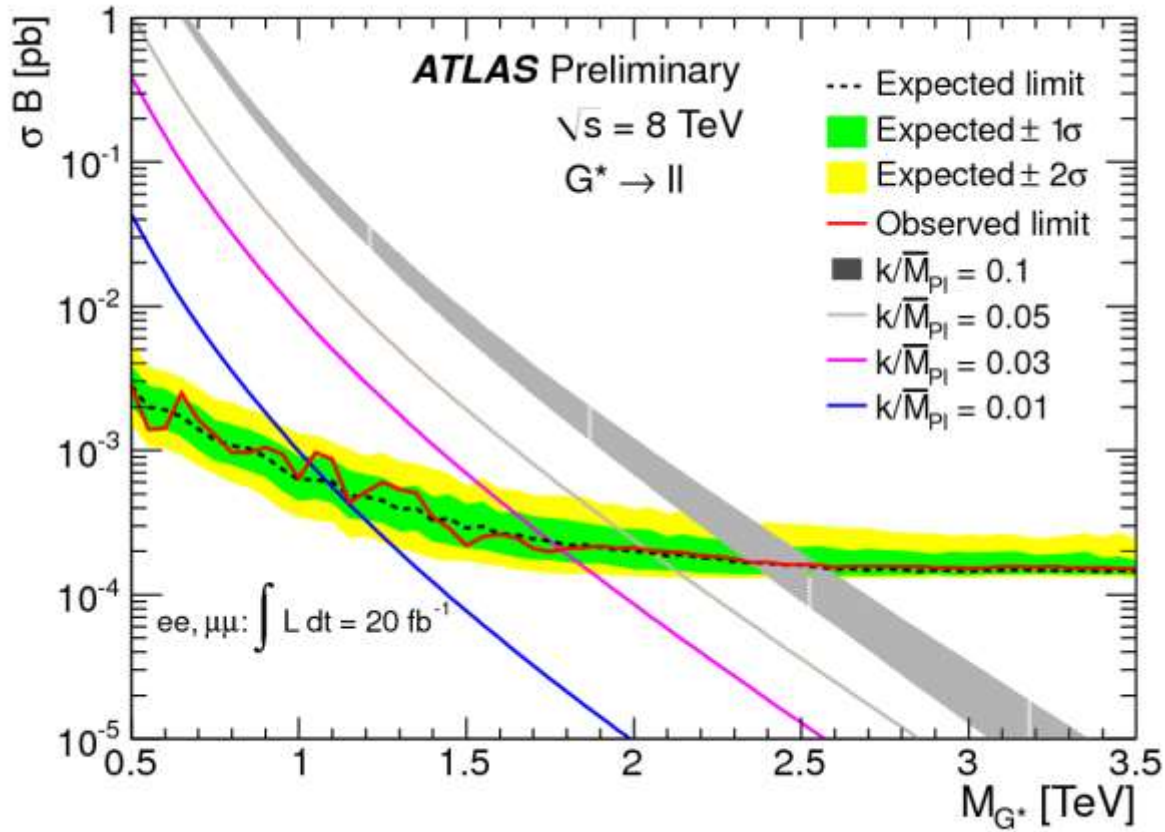
$m (e^+e^-) = 1.54 \text{ TeV}$

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

The highest mass di-lepton events from ATLAS



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



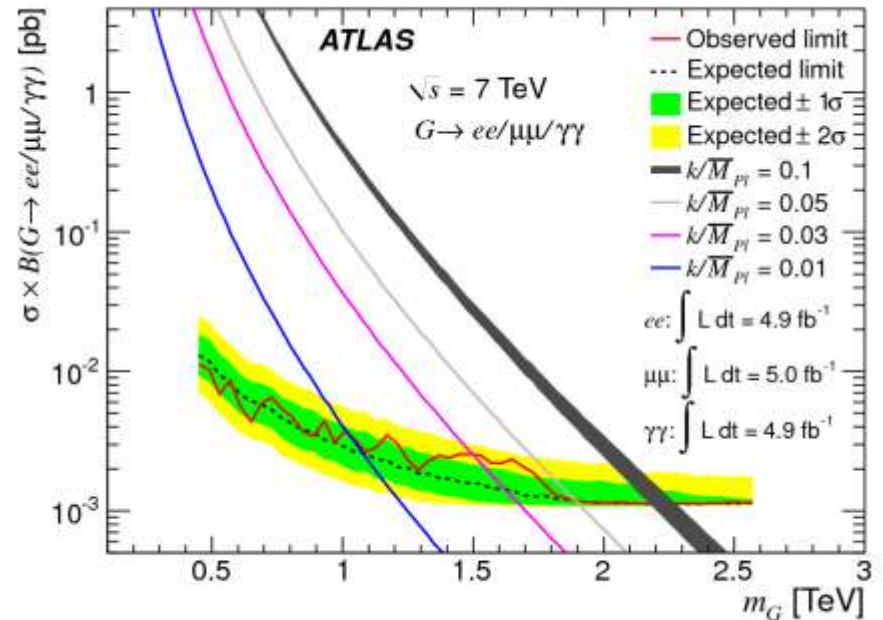
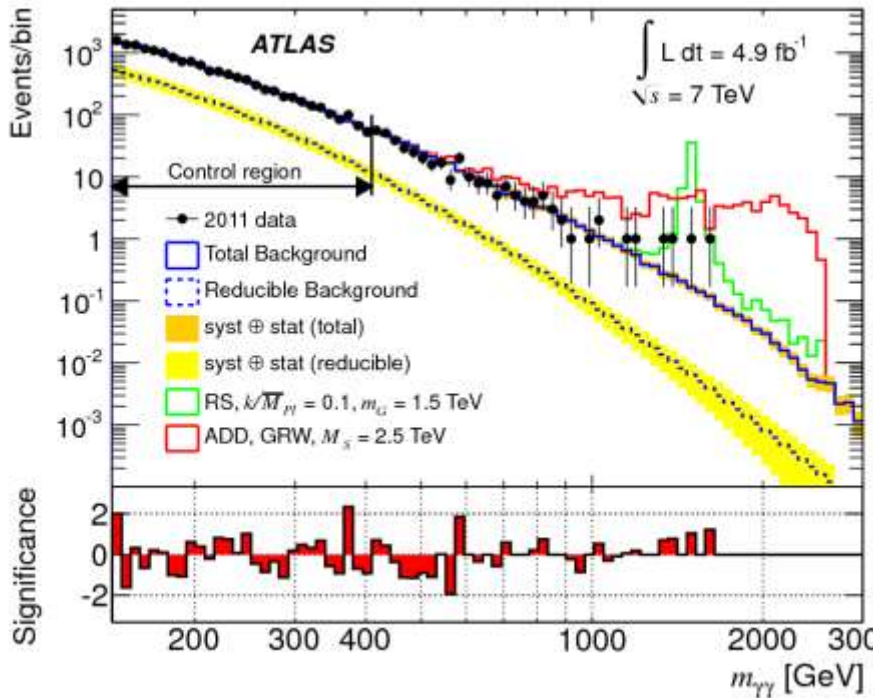
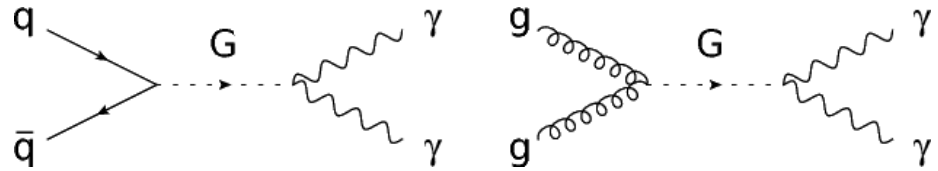
ATLAS-CONF-2013-017



R Sundrum
L Randall
F Gianotti

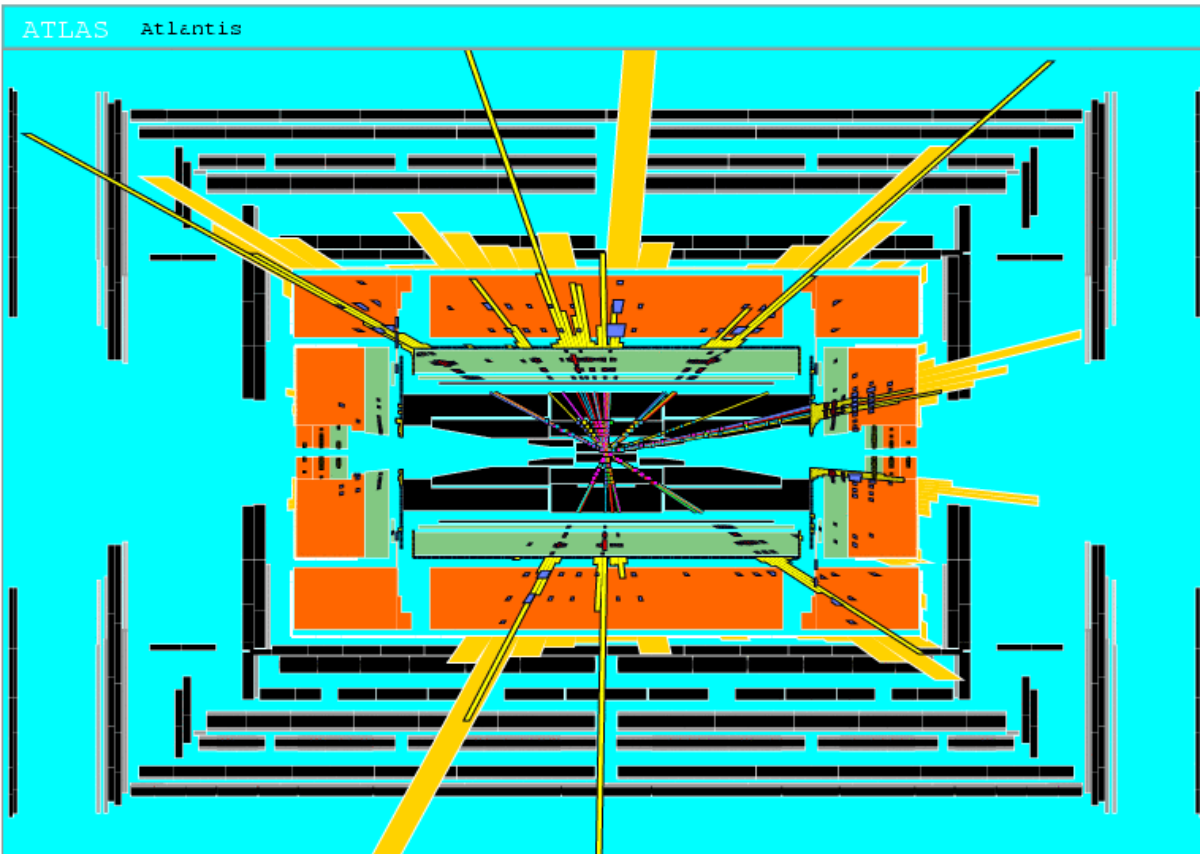
New particles decaying into two photons

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

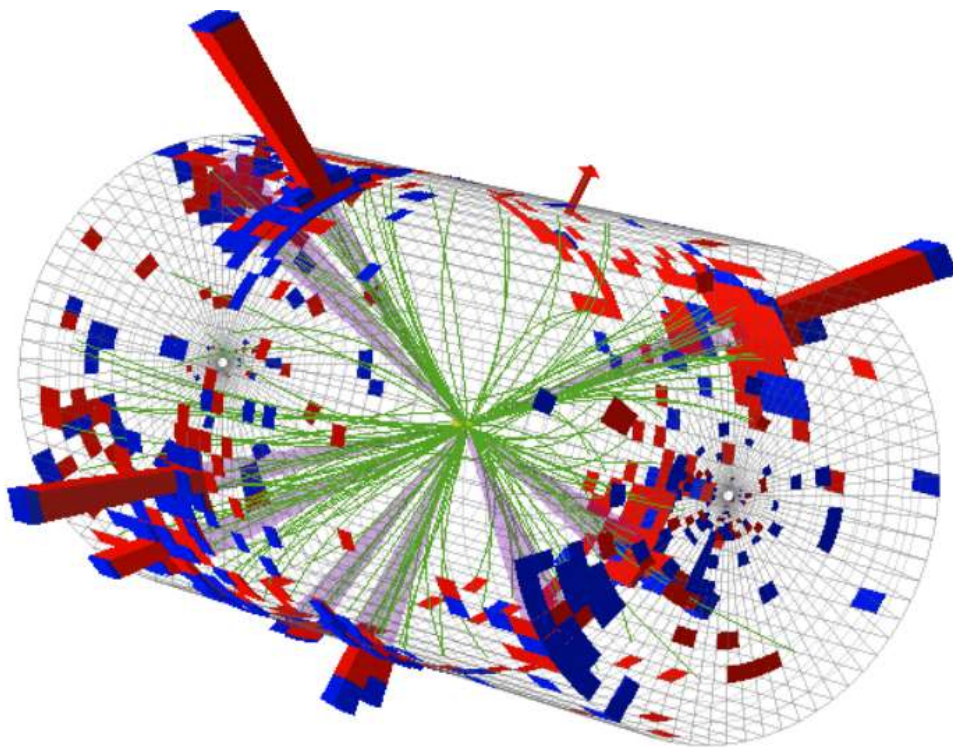


Simulation of a black hole event with $M_{\text{BH}} \sim 8 \text{ TeV}$ in ATLAS



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



CMS Experiment at LHC, CERN
Data recorded: Mon May 23 21:46:26 2011 EDT
Run/Event: 165567 / 347495624
Lumi section: 280
Orbit/Crossing: 73255853 / 3161

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 with large extra dimensions

(Arkani-Hamed, Dimopoulos, Dvali)

Decay into many objects (jets, leptons, photons)

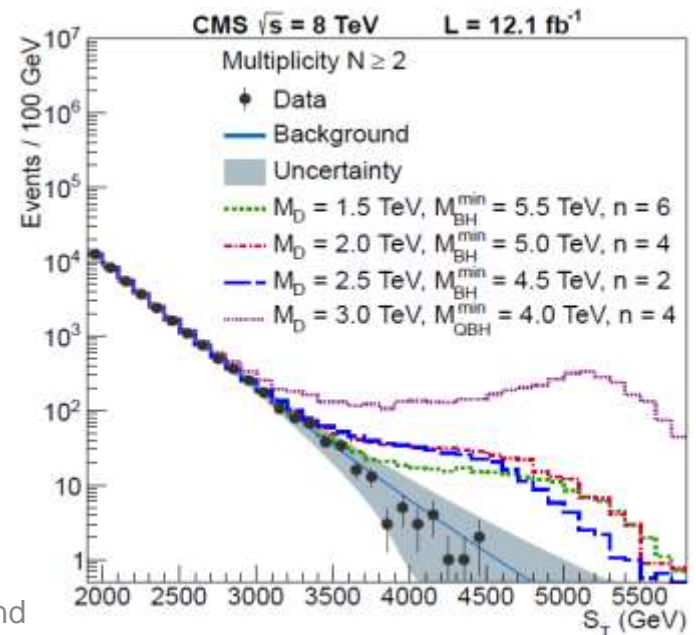
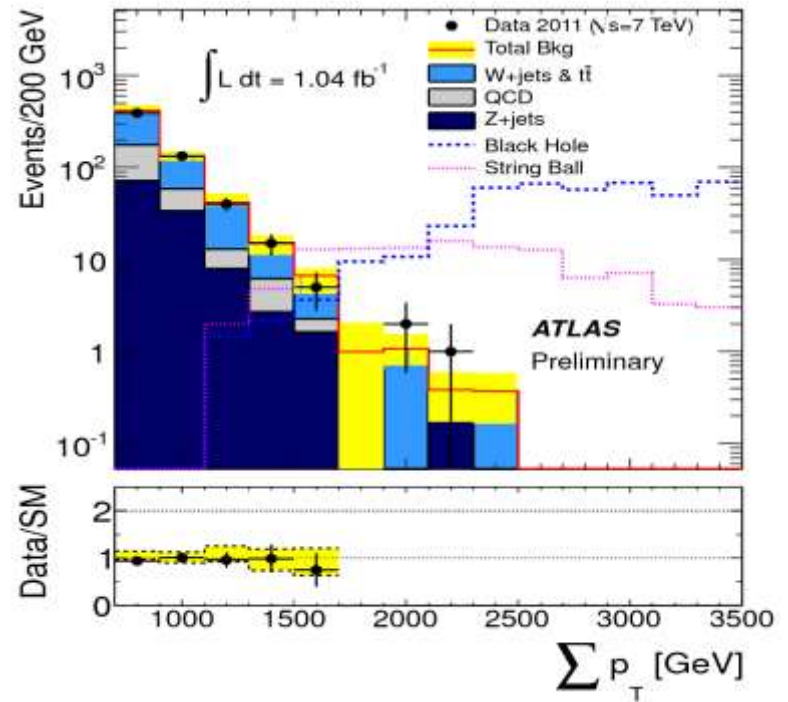
ATLAS-CONF-2011-147
arXiv:1204.4646v1[hep-ex]

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

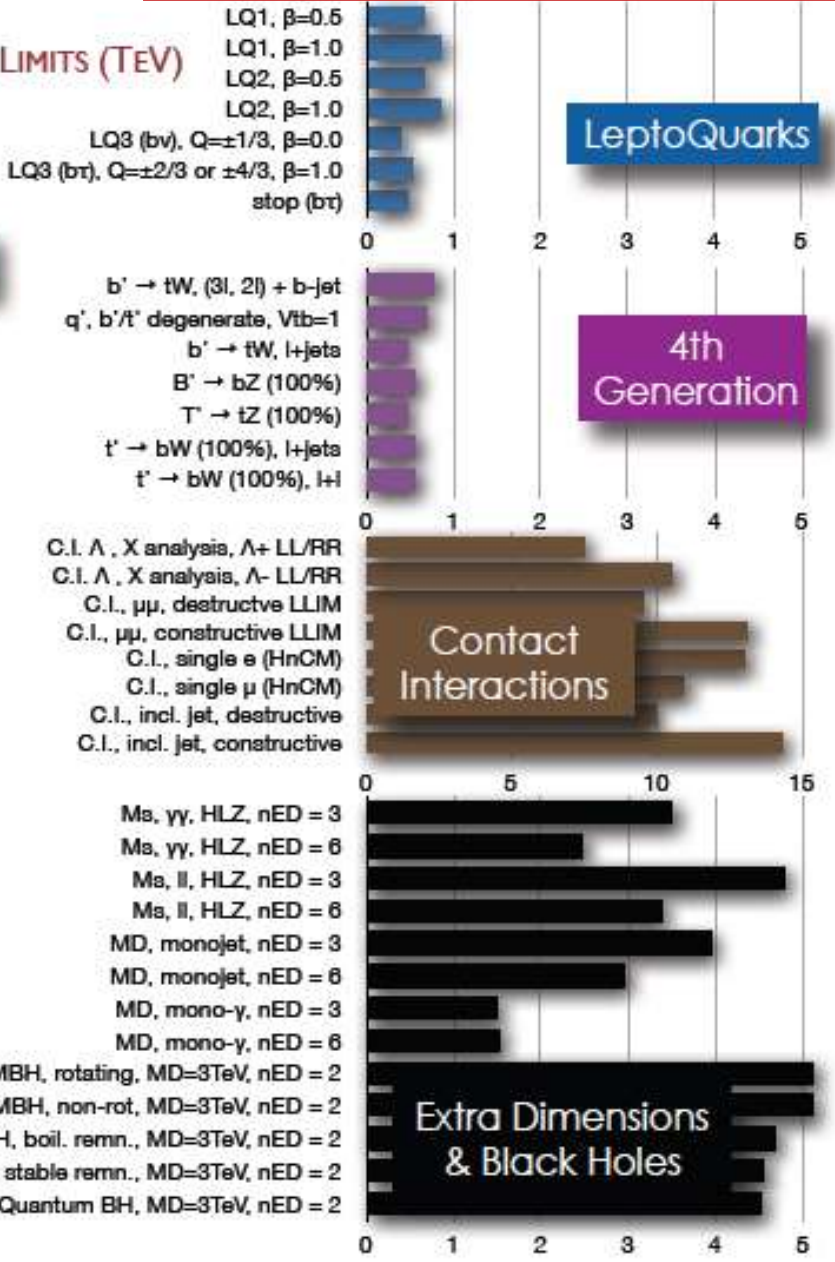
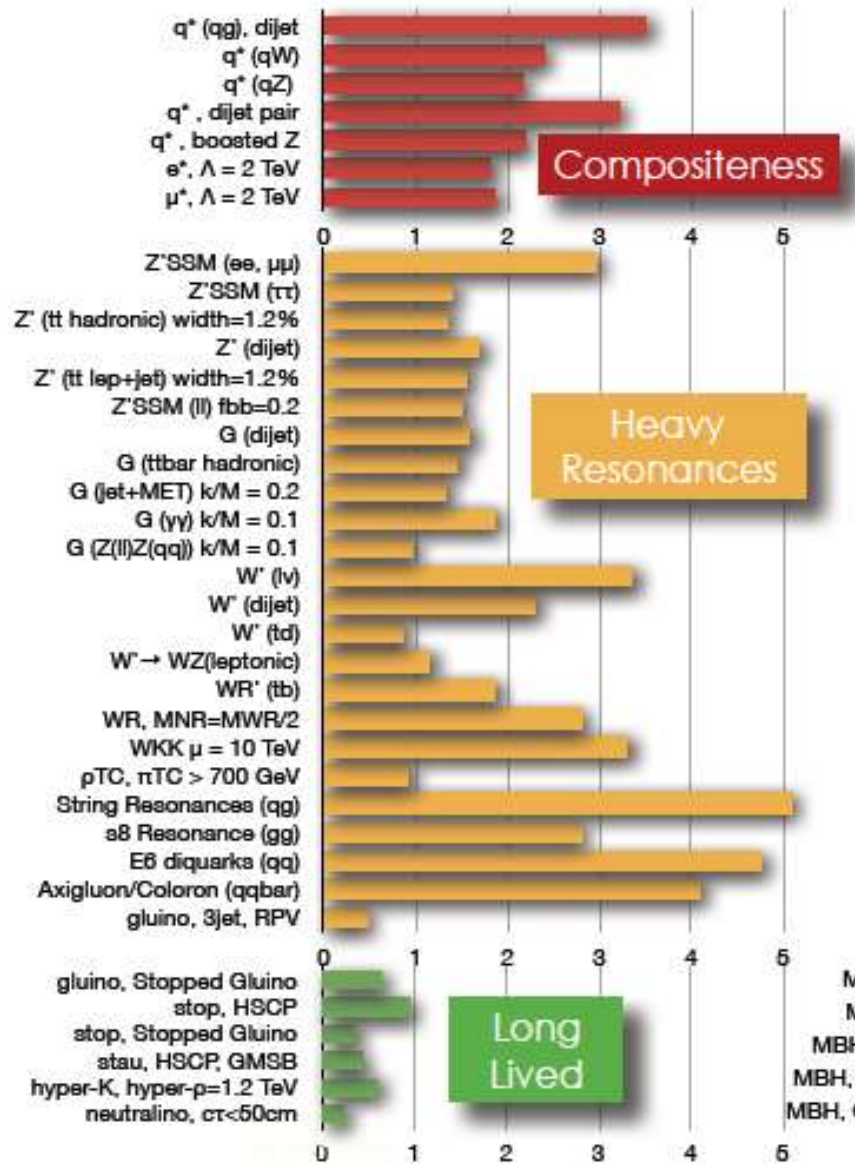
Examples: (ATLAS) at least one electron or muon and two or more jets, (CMS) any three objects

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

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



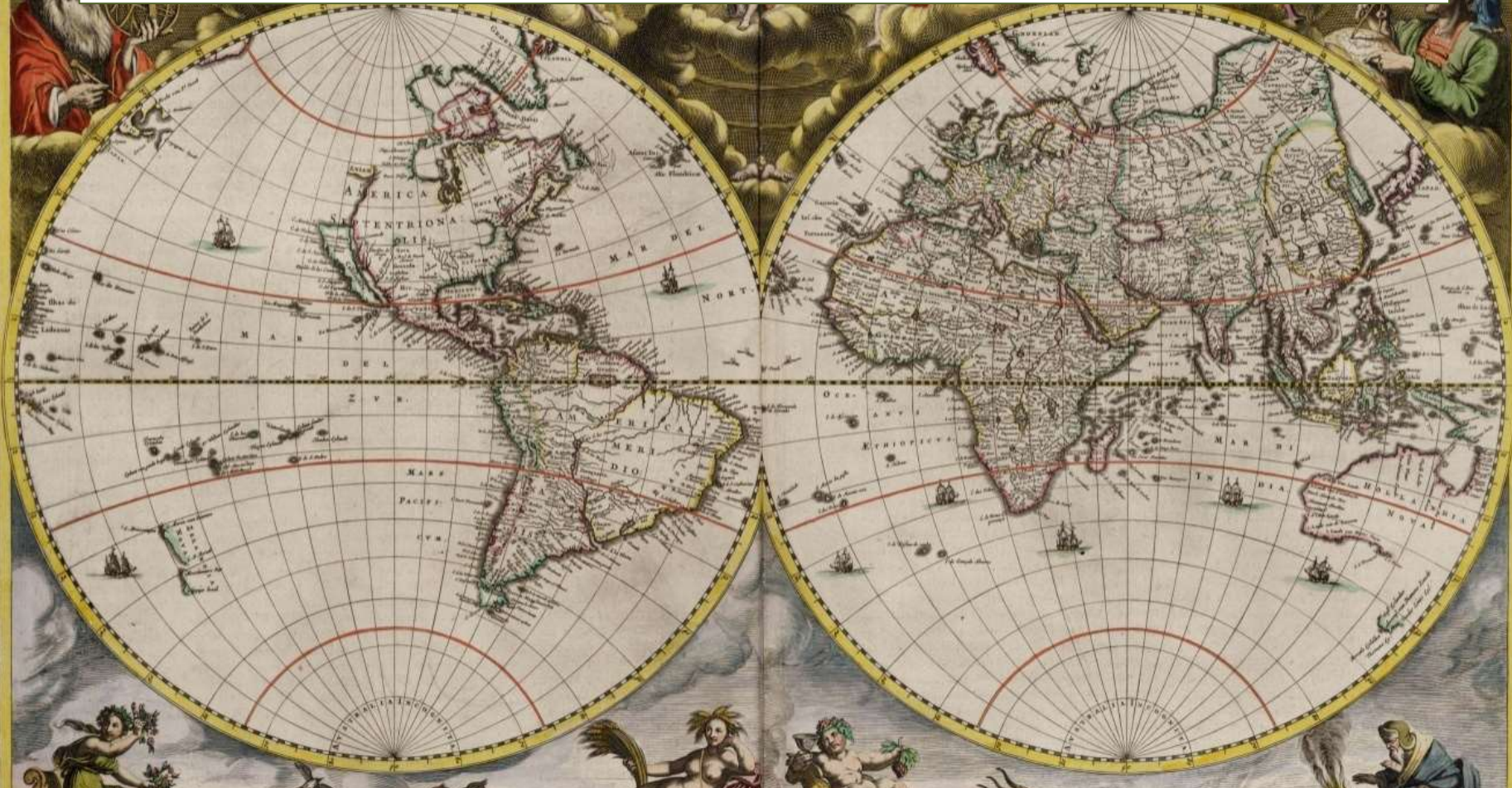
CMS EXOTICA 95% CL EXCLUSION LIMITS (TeV)



(TeV) LHC: Higgs and beyond

(TeV) 92

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



Thank you for your attention

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.



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>