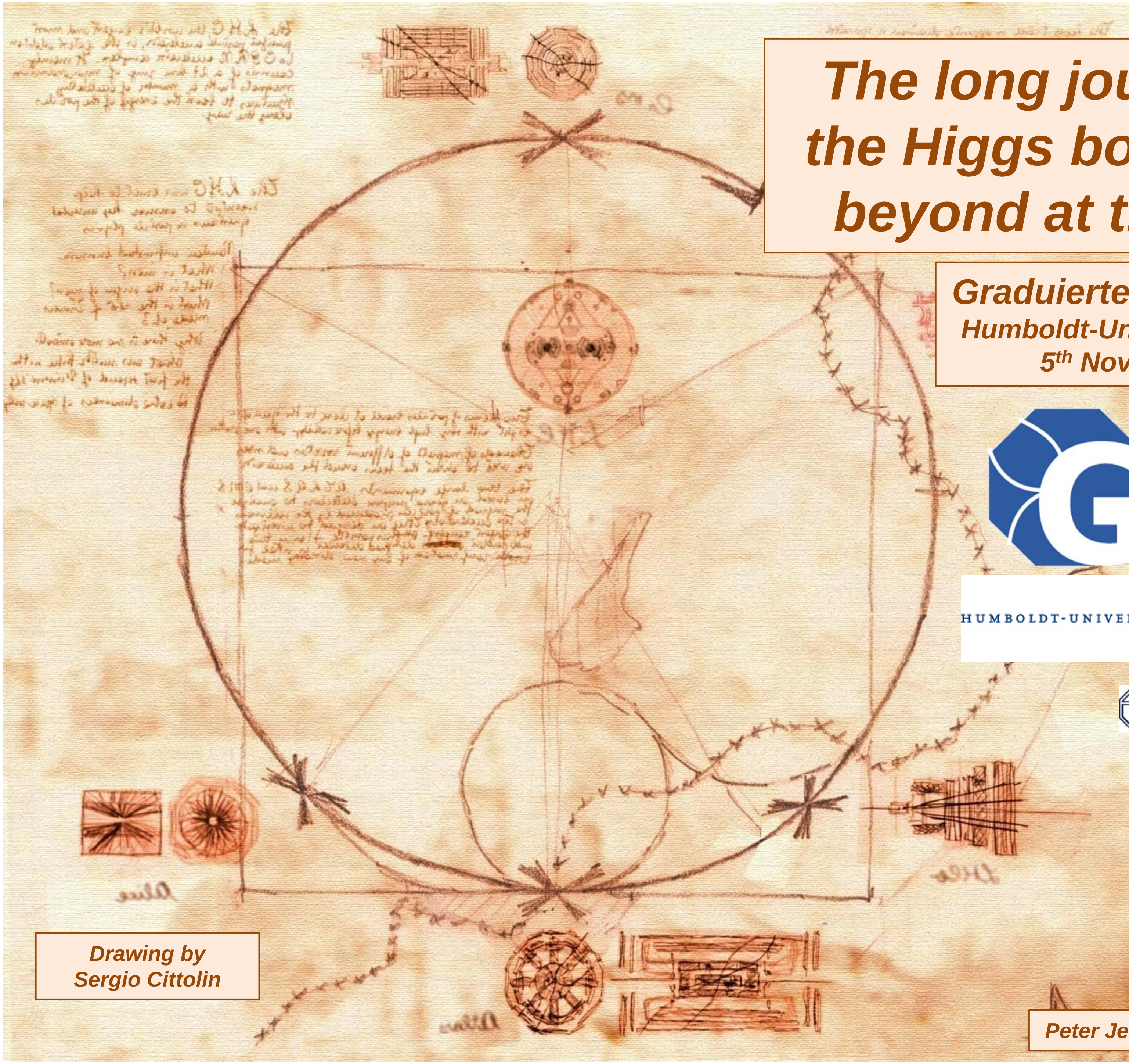
The long journey to the Higgs boson and beyond at the LHC

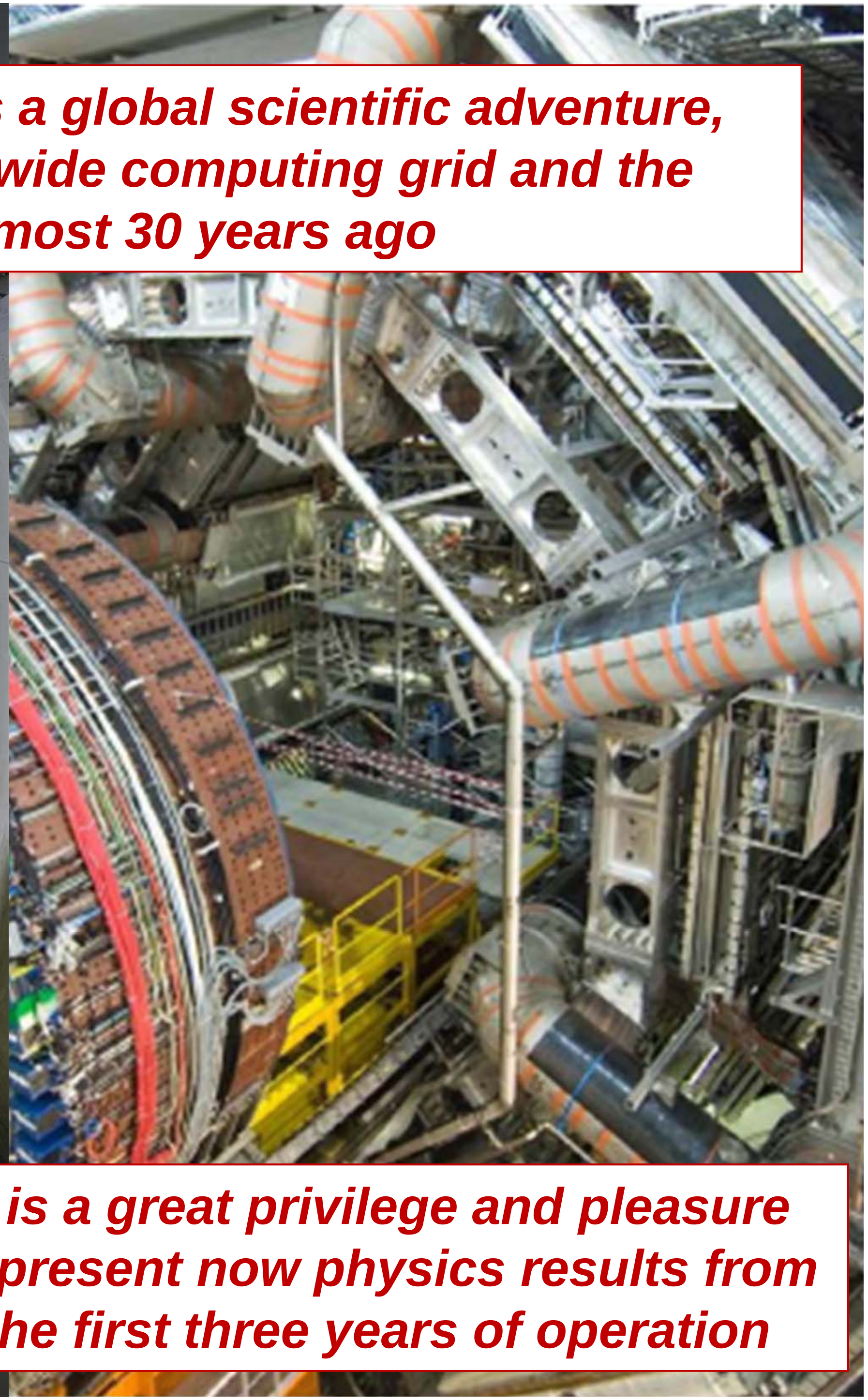
Graduiertenkolleg 1504/2
Humboldt-Universität zu Berlin
5th November 2013



Drawing by Sergio Cittolin

Peter Jenni, Freiburg and CERN

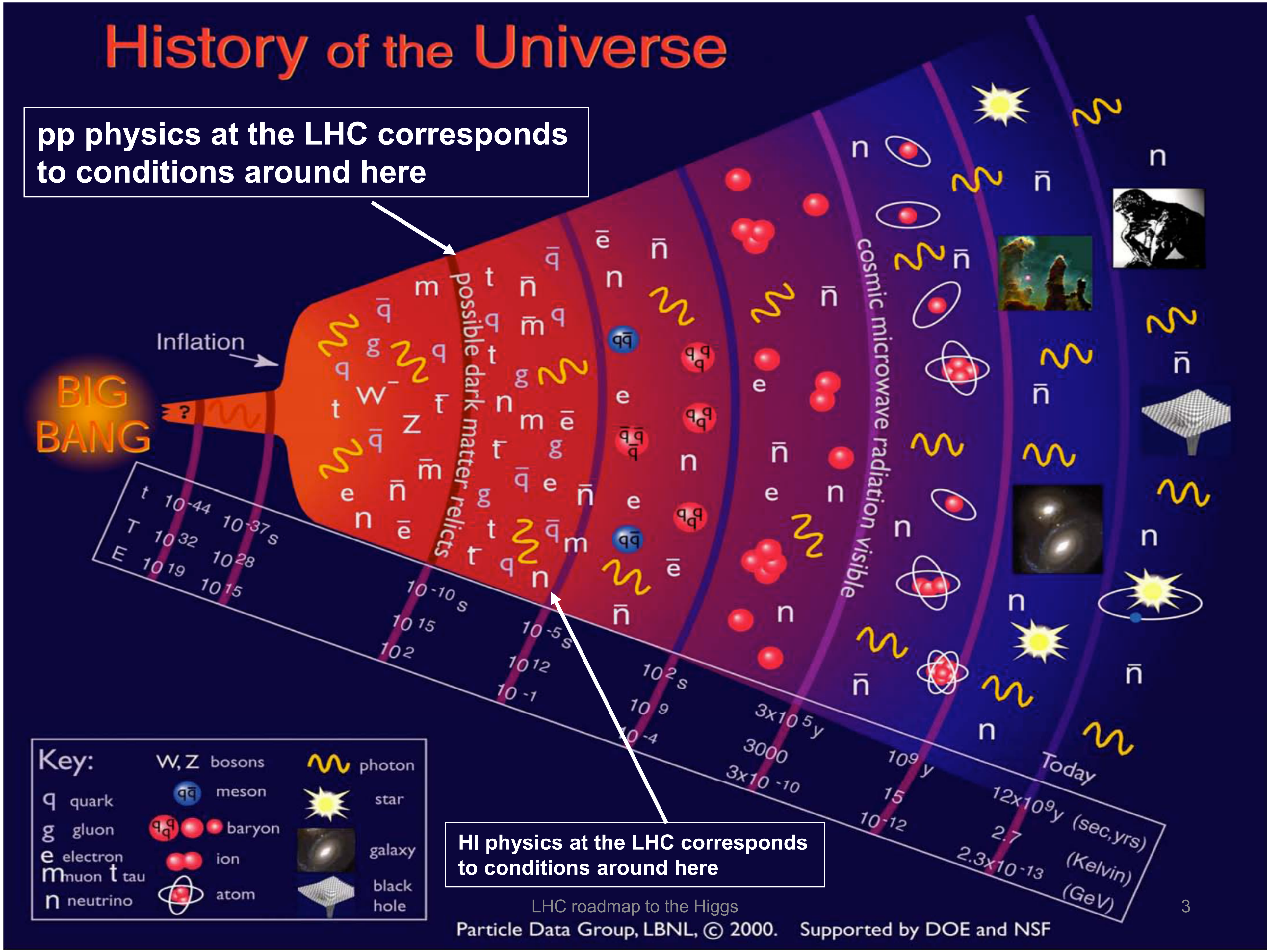
The Large Hadron Collider project is a global scientific adventure, combining the accelerator, a worldwide computing grid and the experiments, initiated almost 30 years ago

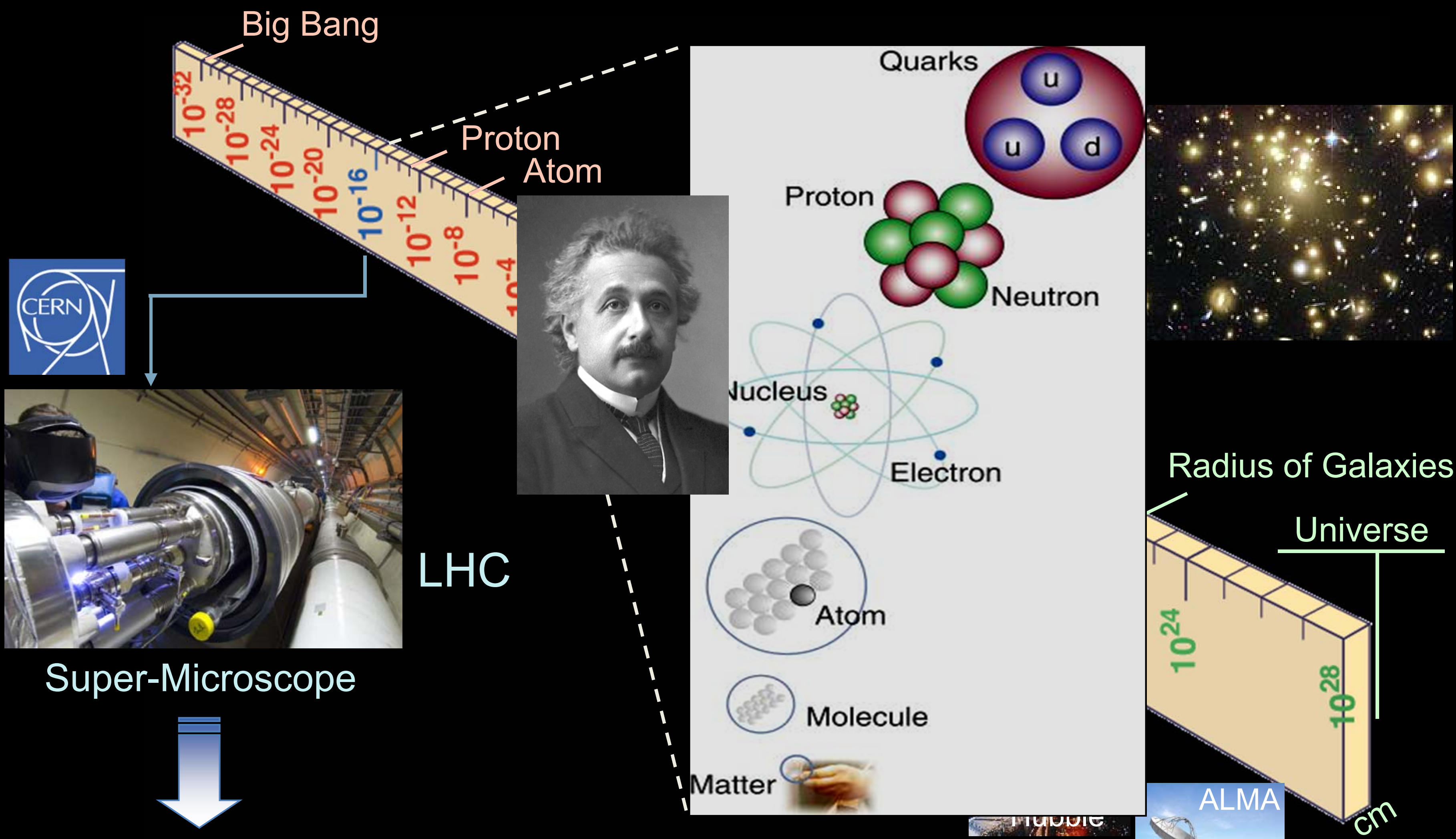


It is a great privilege and pleasure to present now physics results from the first three years of operation

pp physics at the LHC corresponds to conditions around here

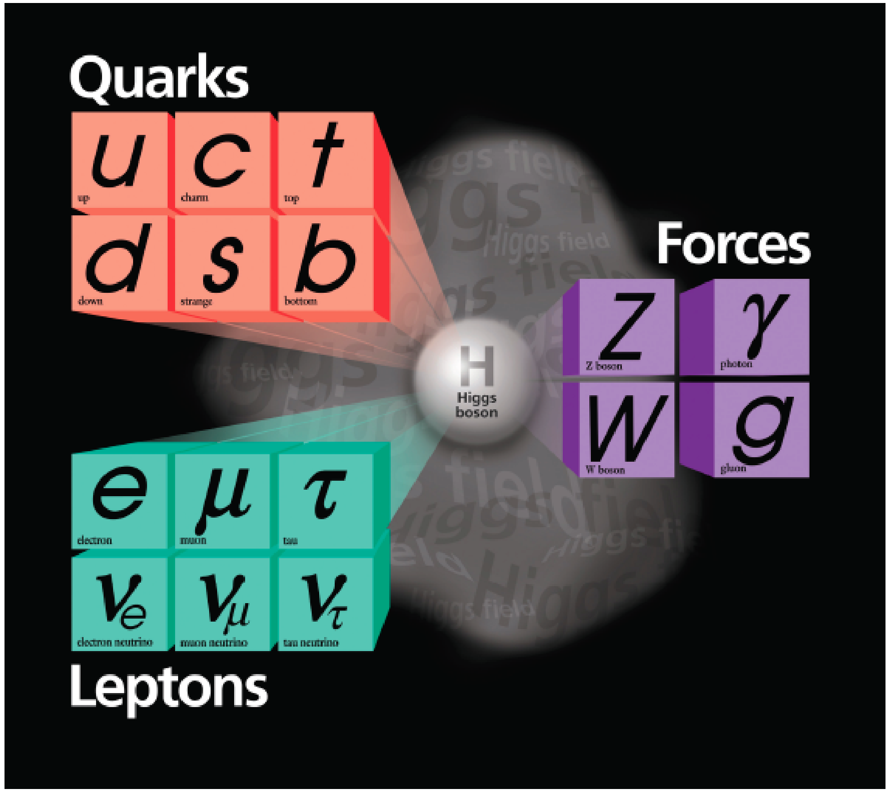
HI physics at the LHC corresponds to conditions around here

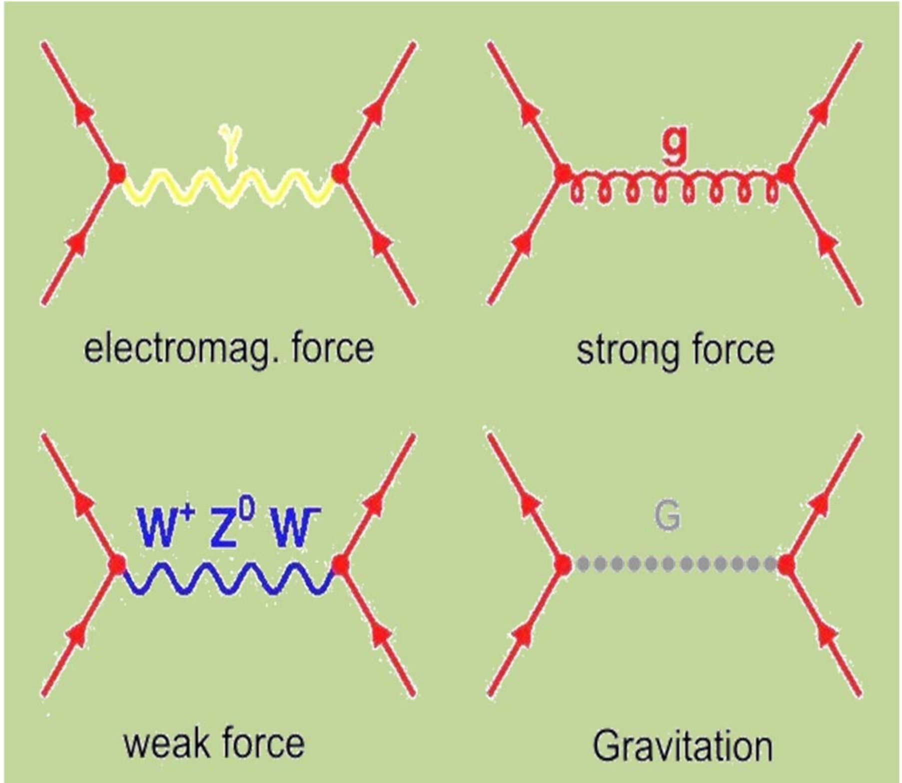




Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology

The Standard Model of Particle Physics



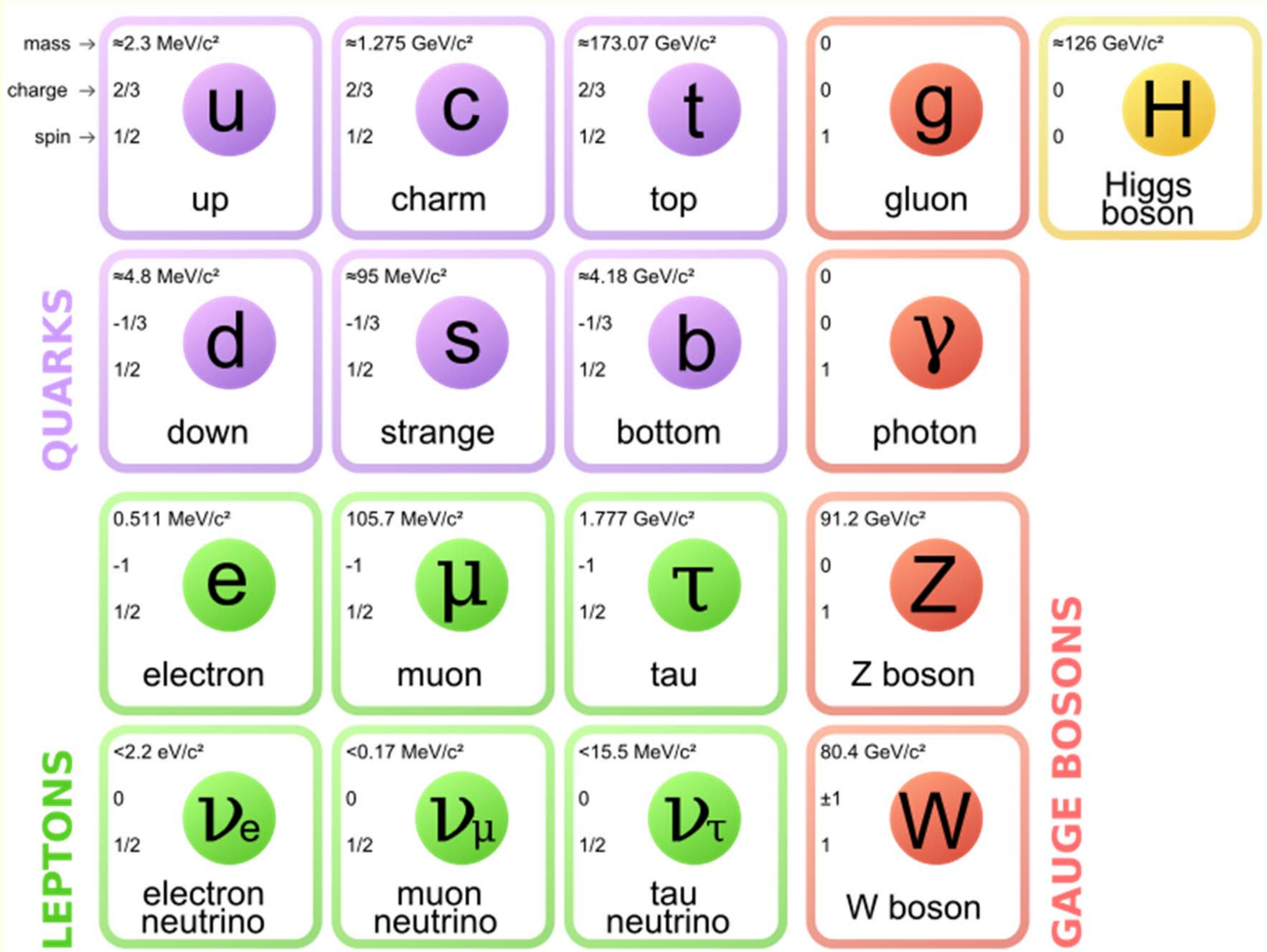


(i) Constituents of matter: quarks and leptons

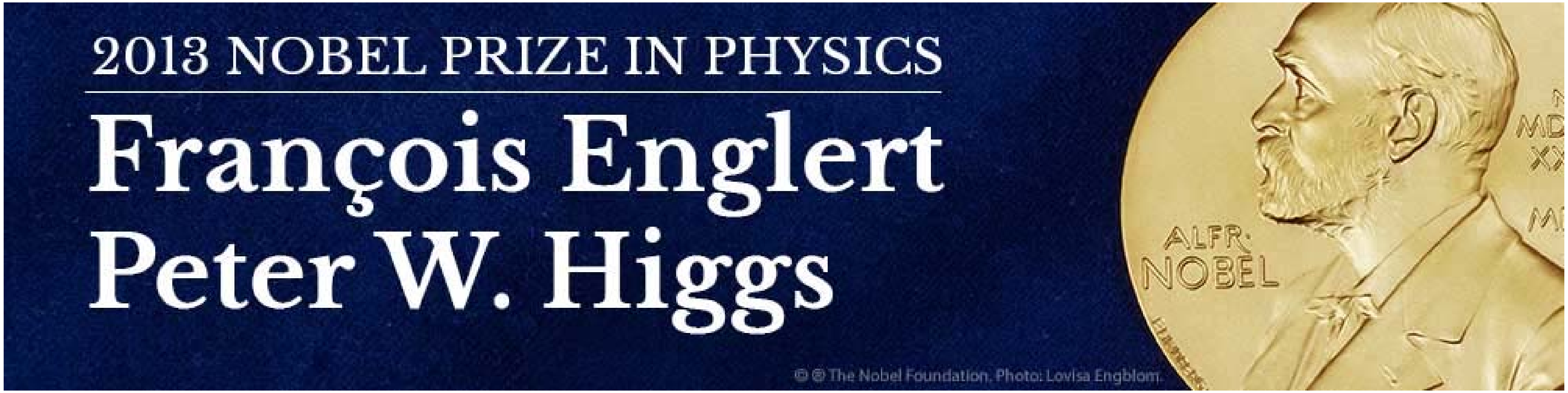
(ii) Four fundamental forces
(described by quantum field theories, except gravitation)

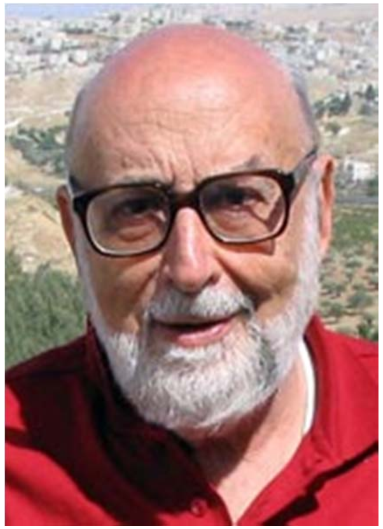
(iii) The Higgs field (problem of mass)

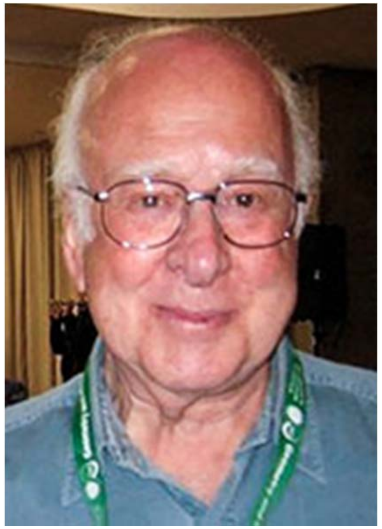
Standard Model of Elementary Particles



On Tuesday 8th October 2013:

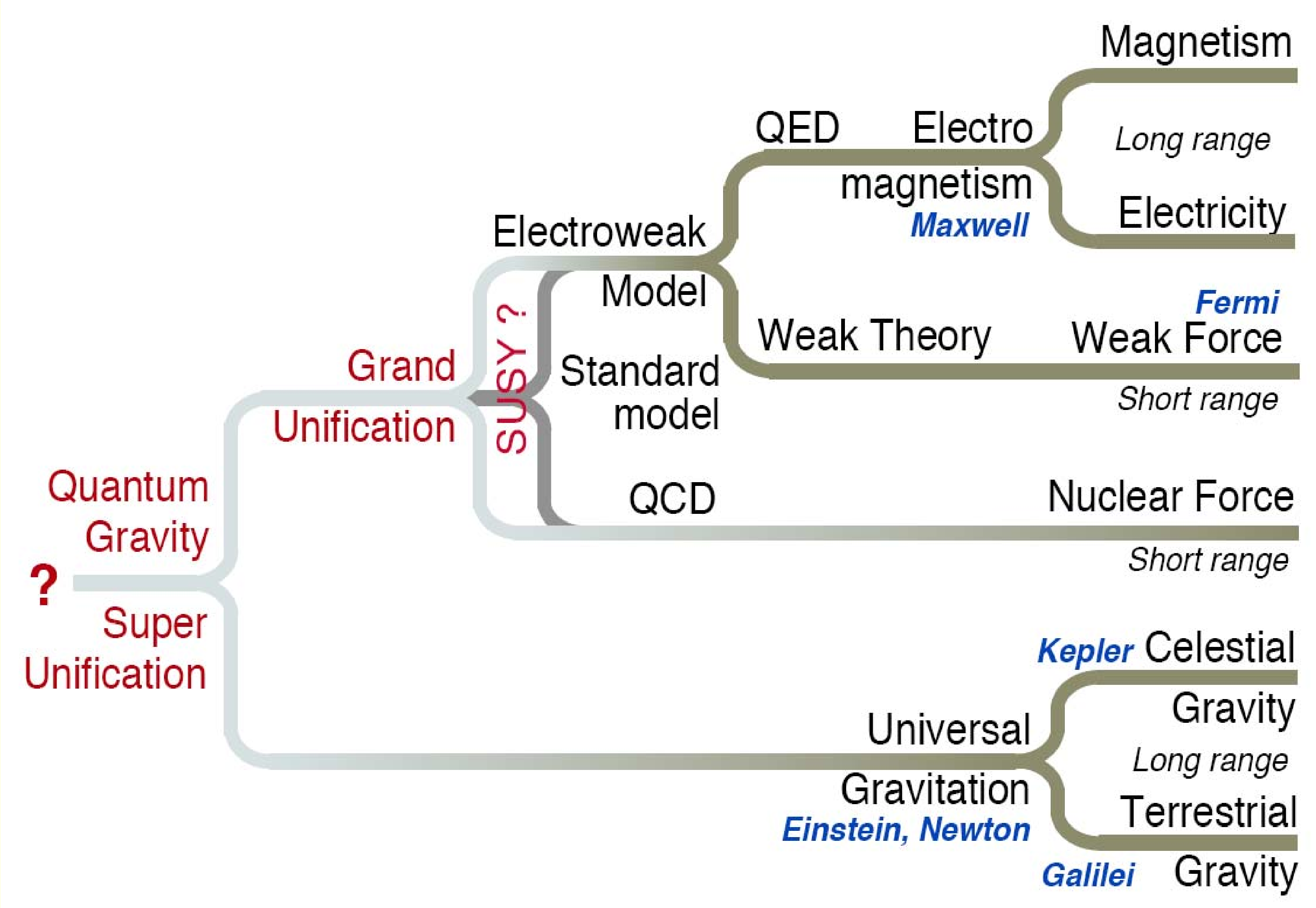






"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Unification of Forces



The SM is not a complete theory

Some of the outstanding questions in fundamental physics addressed, at least in part, with the LHC are:

What is the origin of the elementary particle masses ? (~✔)

What is the nature of the Universe dark matter ?

Why is only matter observed in the Universe as primary constituents and not anti-matter ?

What are the features of the primordial plasma present ~10 μs after the Big Bang ?

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

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

The SM is not a complete theory

Some of the outstanding questions in fundamental physics addressed, at least in part, with the LHC are:

What is the origin of the elementary particle masses ? (~✔)

What is the nature of the Universe dark matter ?

Why is only matter observed in the Universe as primary constituents and not anti-matter ?

What are the features of the primord…
present ~10 μs after the Big B…

What happ… the Universe
~10…

Are th… forces in addition to the known four ?
Are there additional (microscopic) space dimensions ?
….

New Physics beyond the Standard Model is needed to answer these and other questions. This New Physics could manifest itself at the ~ 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)

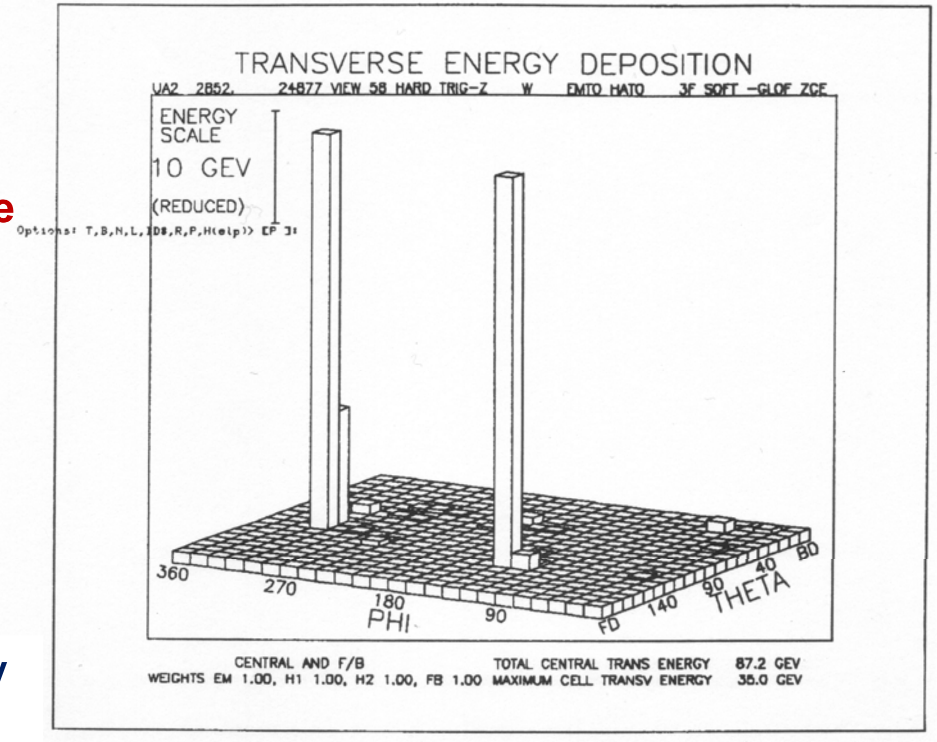
Some early key dates

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 → ee online display from one of the detectors (UA2)

1984 For the community it all started with the CERN - ECFA Workshop in Lausanne on the feasibility of a hadron collider in the future LEP tunnel

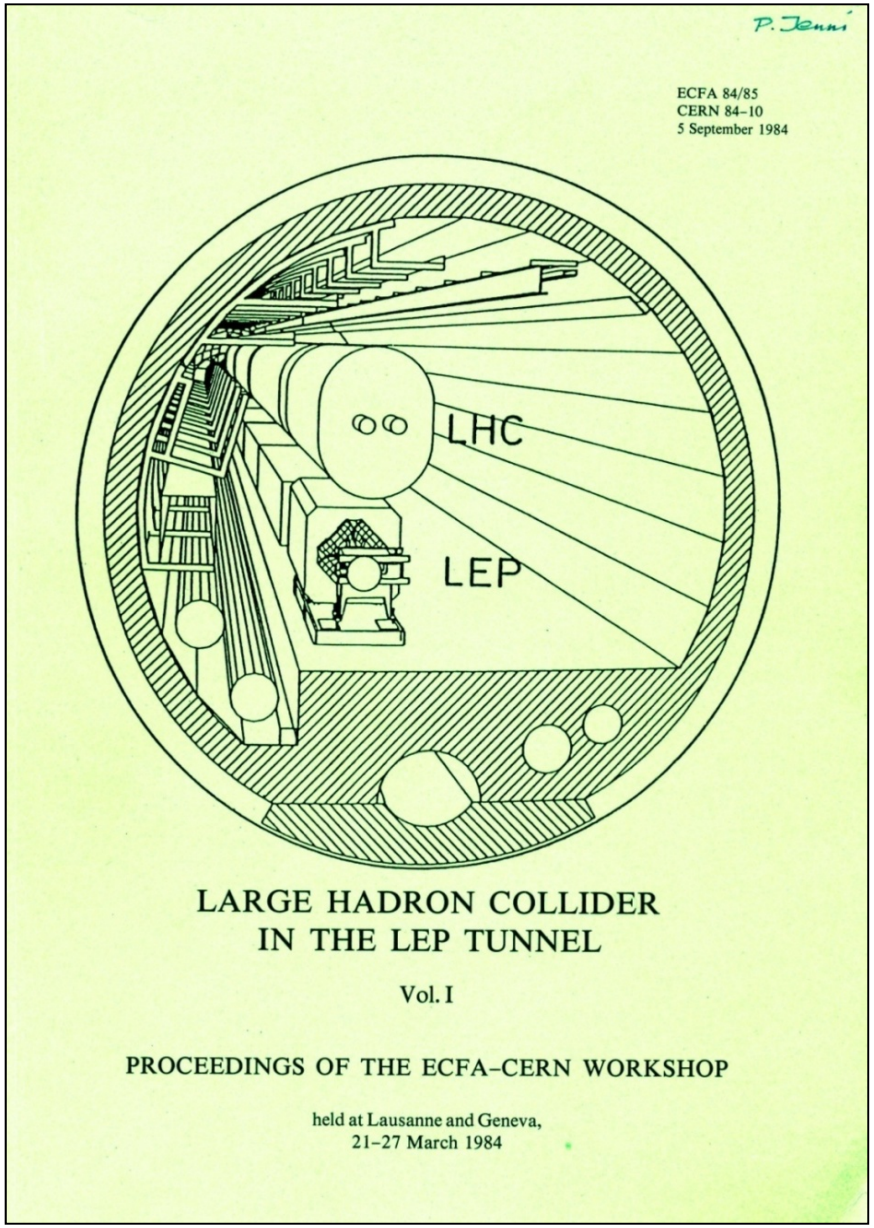
1987 La Thuile Workshop

Many LHC colleagues were already involved in this WS set up by Carlo Rubbia as part of the Long Range Planning Committee

1989 ECFA Study Week in Barcelona for LHC instrumentation

1990 Large Hadron Collider Workshop Aachen (CERN - ECFA)

1992 CERN – ECFA meeting 'Towards the LHC Experimental Programme' in Evian



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

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)

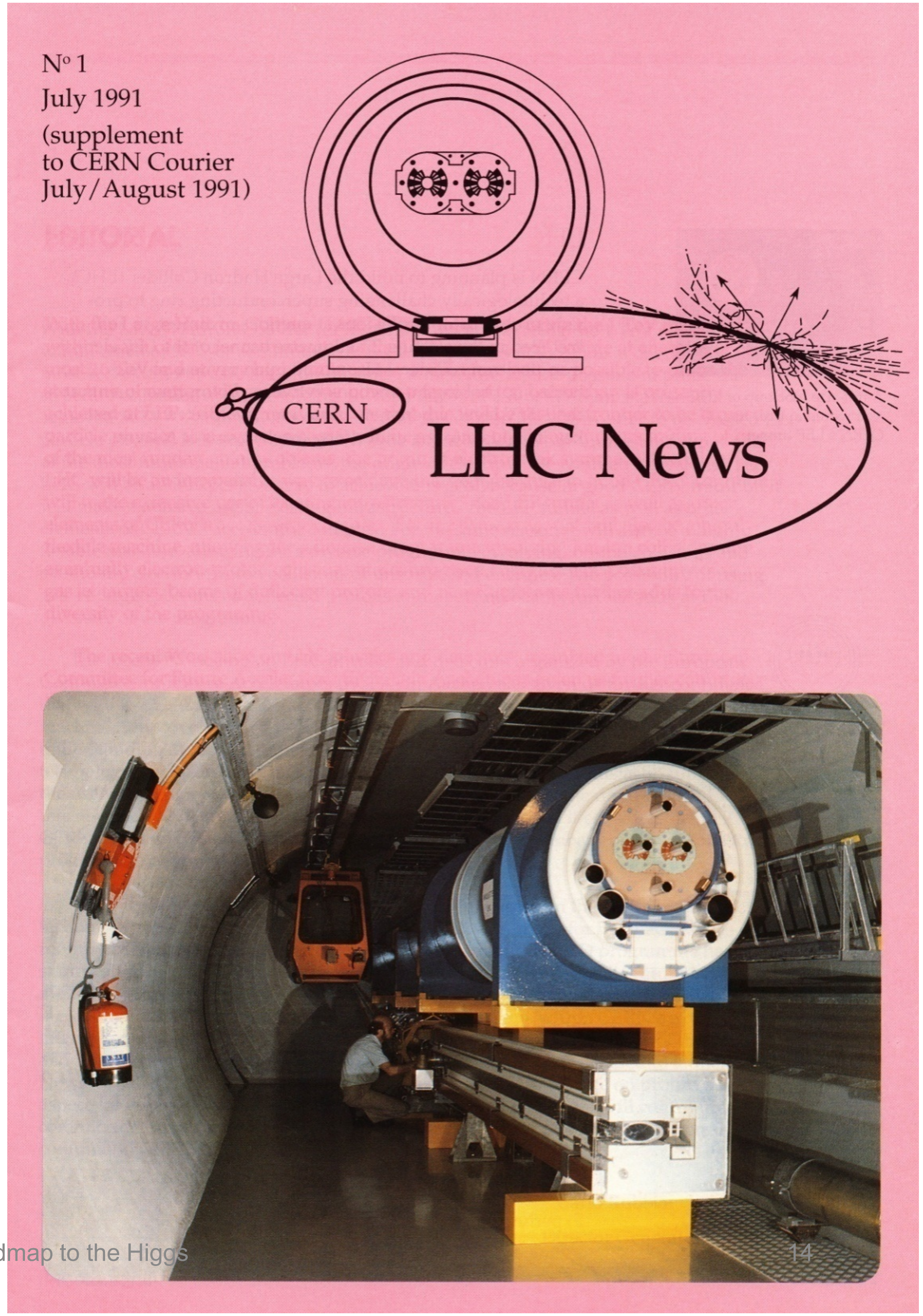
1993 December proposal of LHC with commissioning in 2002

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

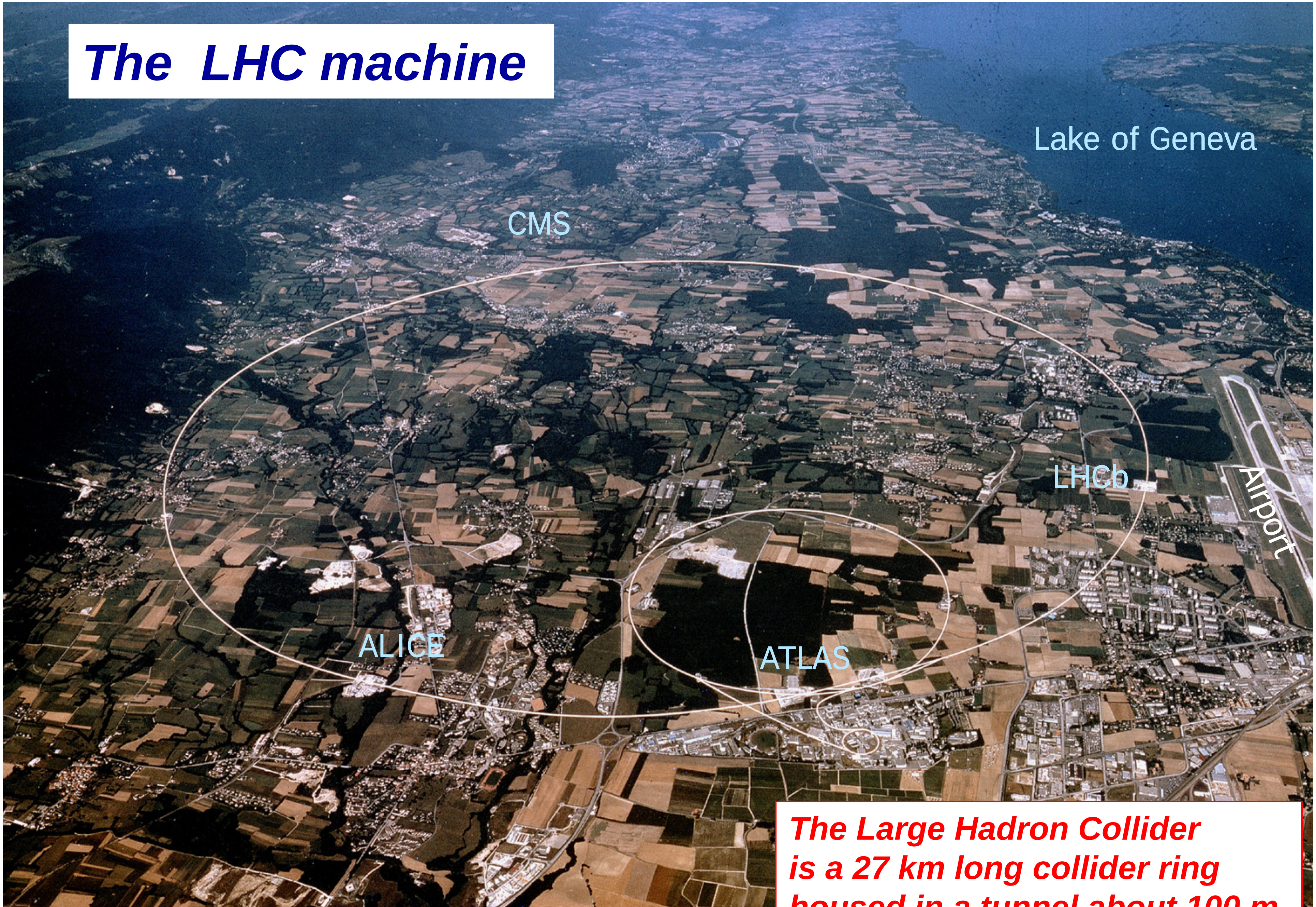
(Israel contributed all along to the full CERN programme and LHC)

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



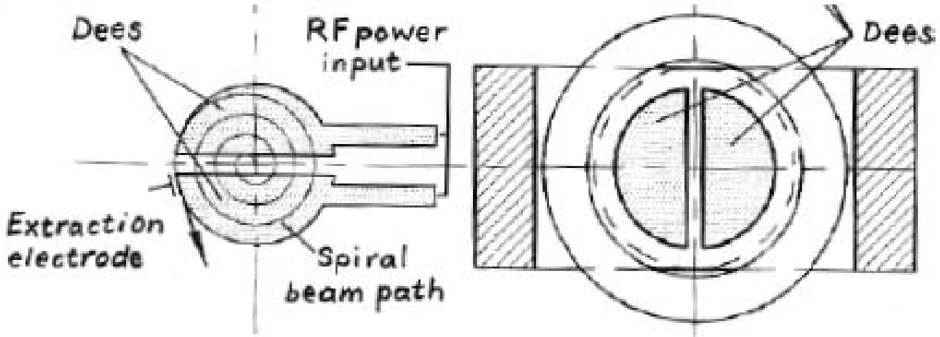
The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

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

Ernest Lawrence
(1901 - 1958)

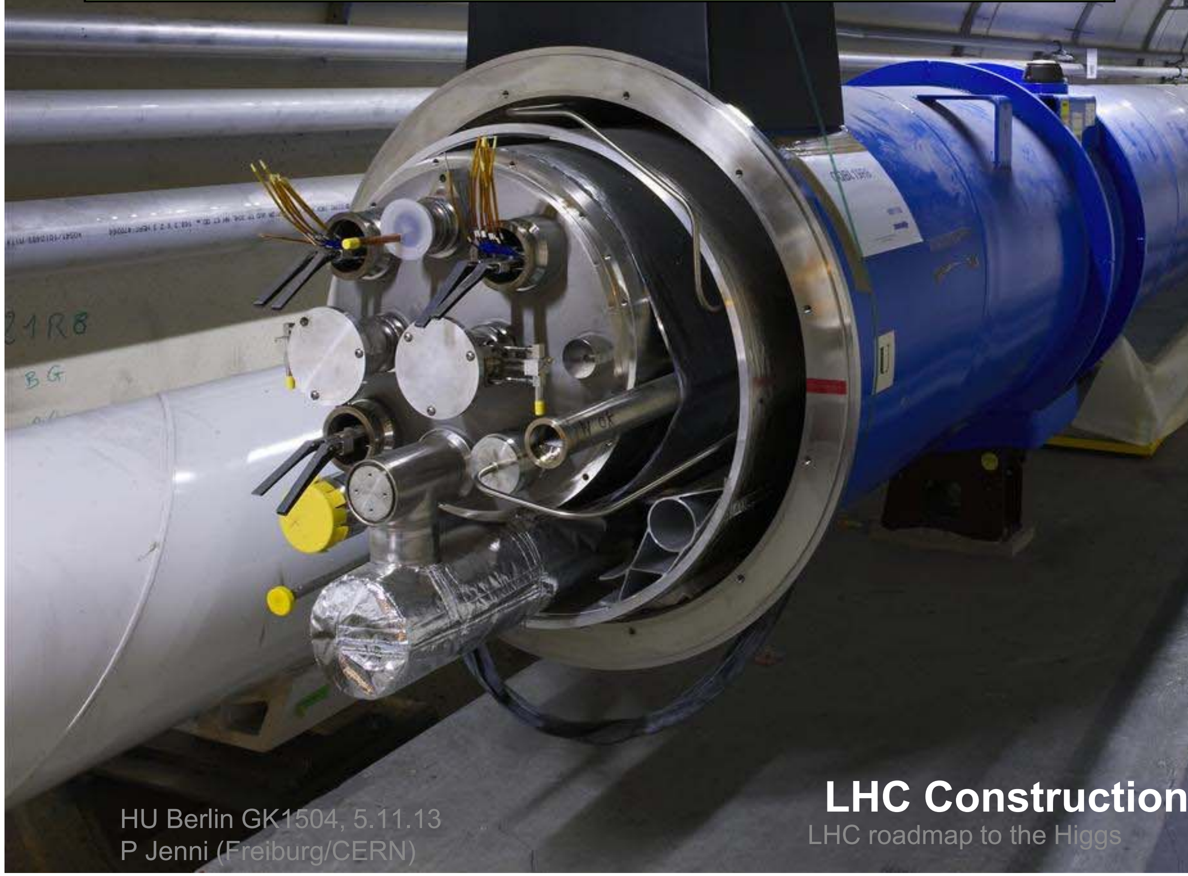
The first circular accelerator
(Berkeley 1930)

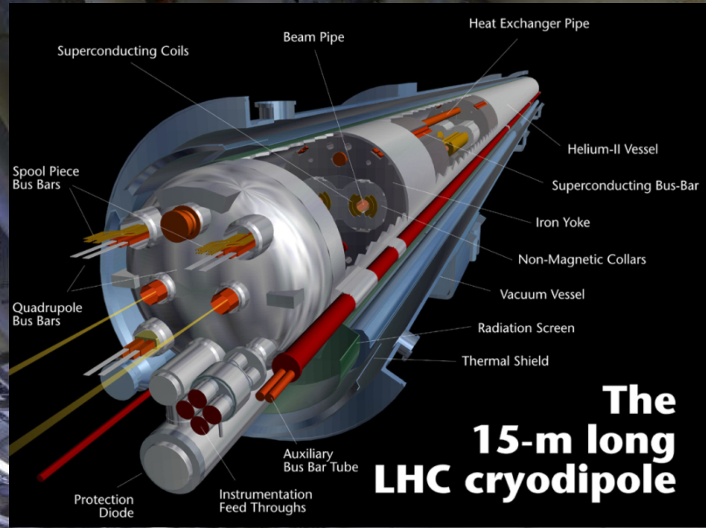
184" 1946



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	

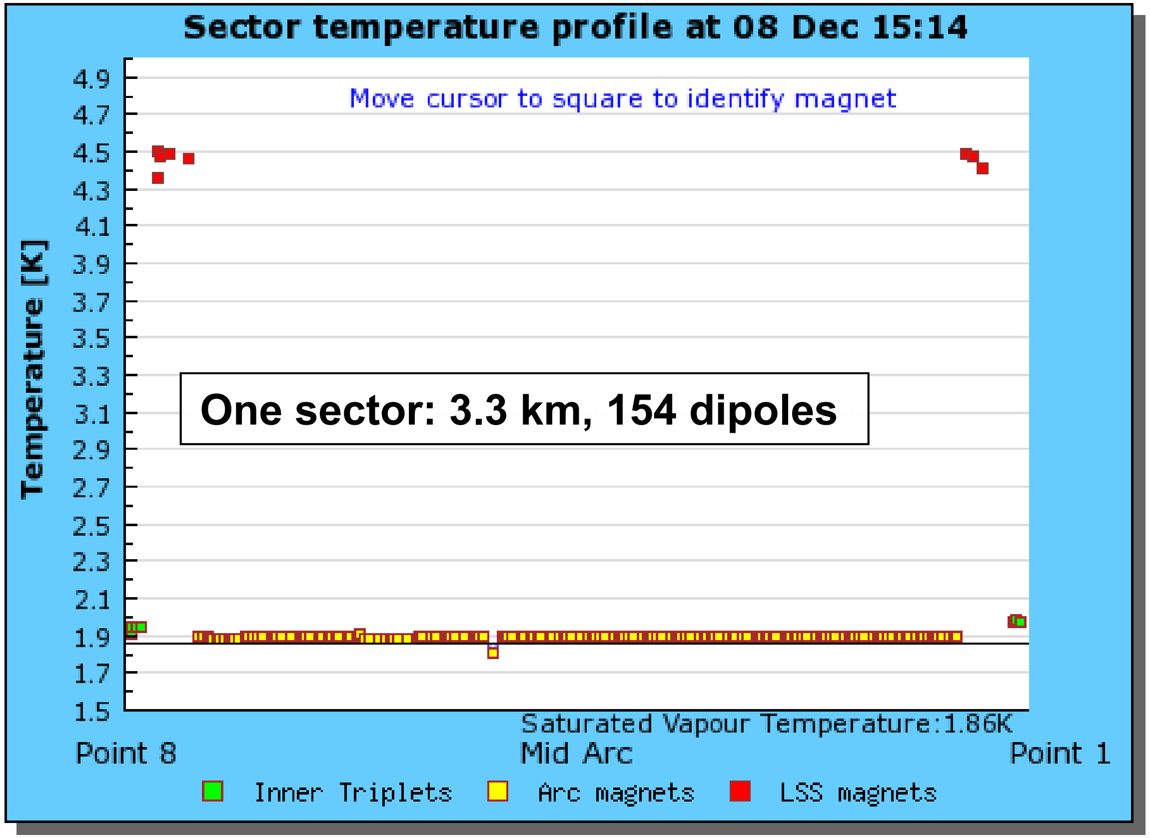




$p(\text{TeV}) = 0.3\ B(\text{T})\ R(\text{km})$

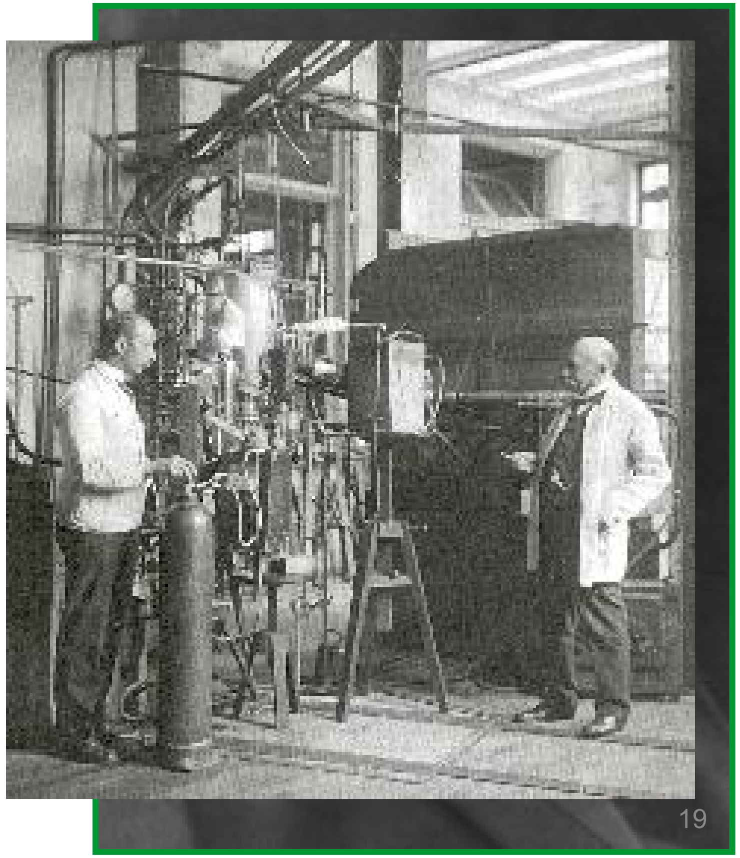
LHC Construction Project Leader Lyndon Evans

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



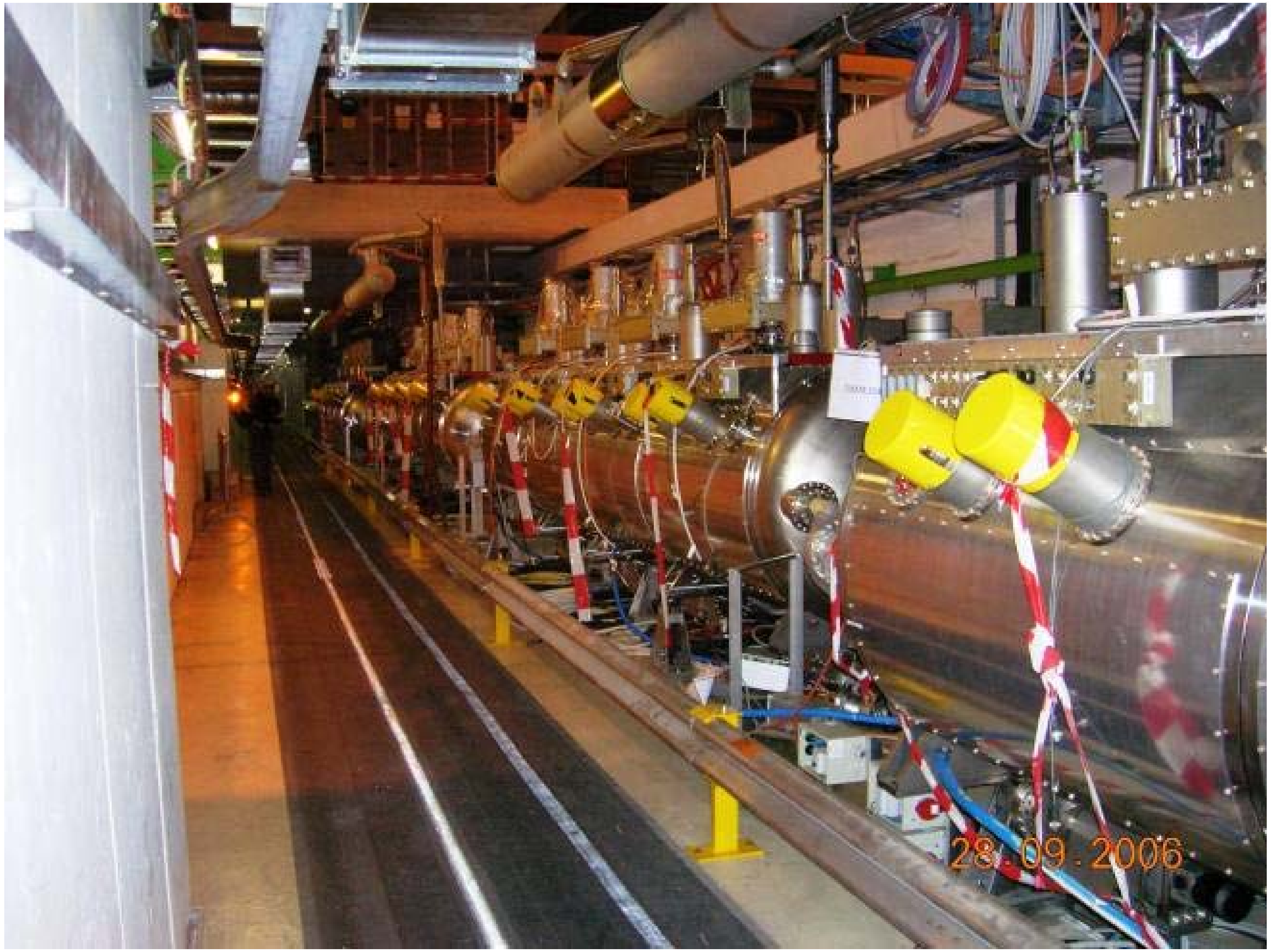
Magnets cooled down in a bath of ~120 tons of superfluid Helium (excellent thermal conductor)

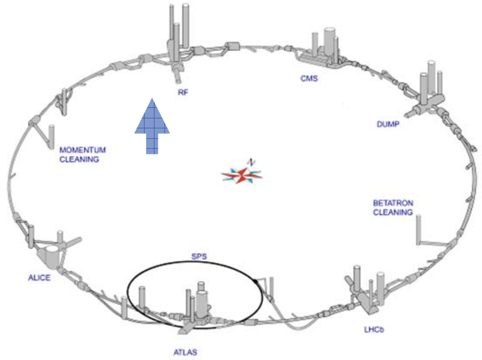
H K Onnes
Nobel Prize in Physics 1913



- **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)**

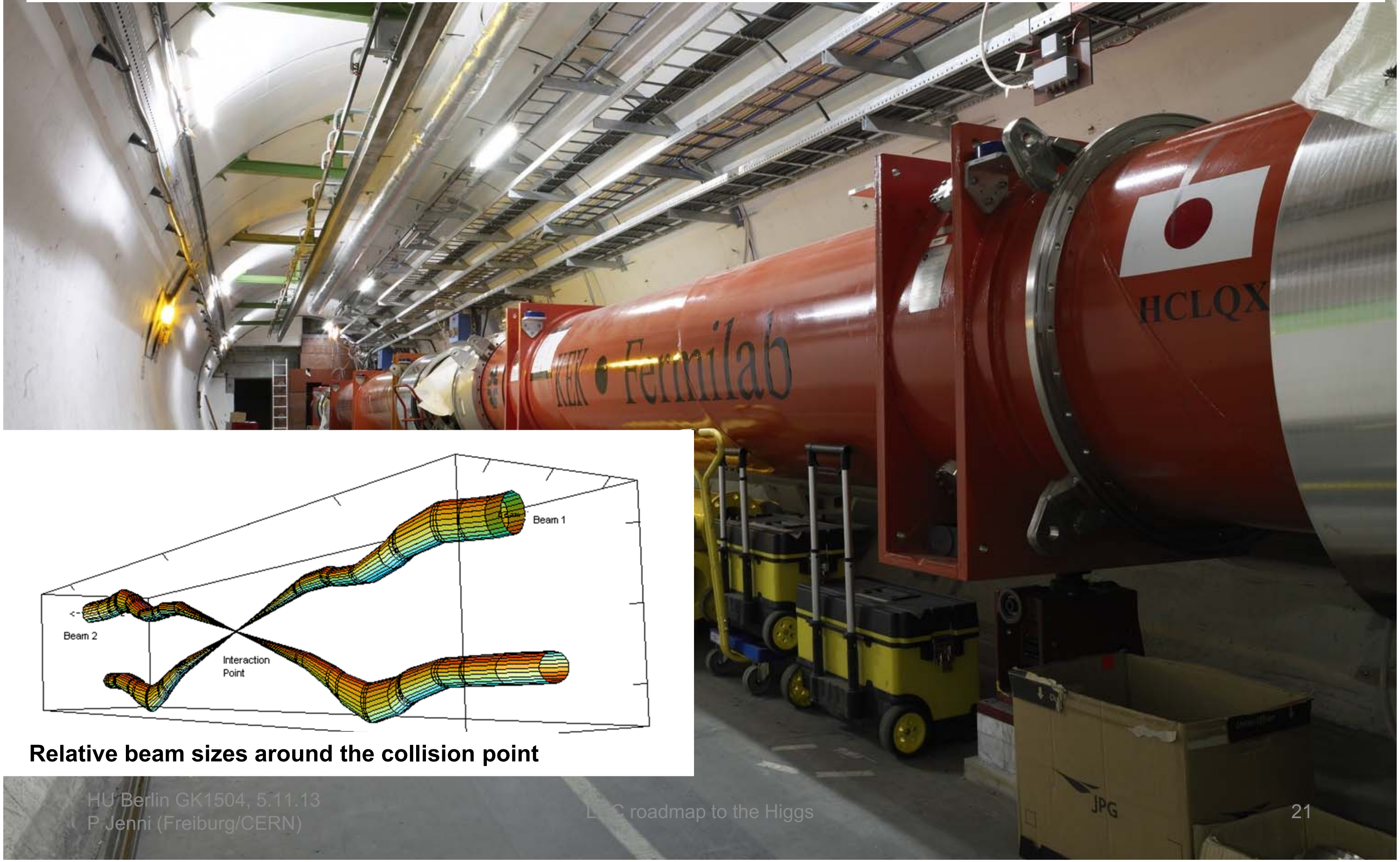
The particle beams are accelerated by superconducting Radio-Frequency (RF) cavities





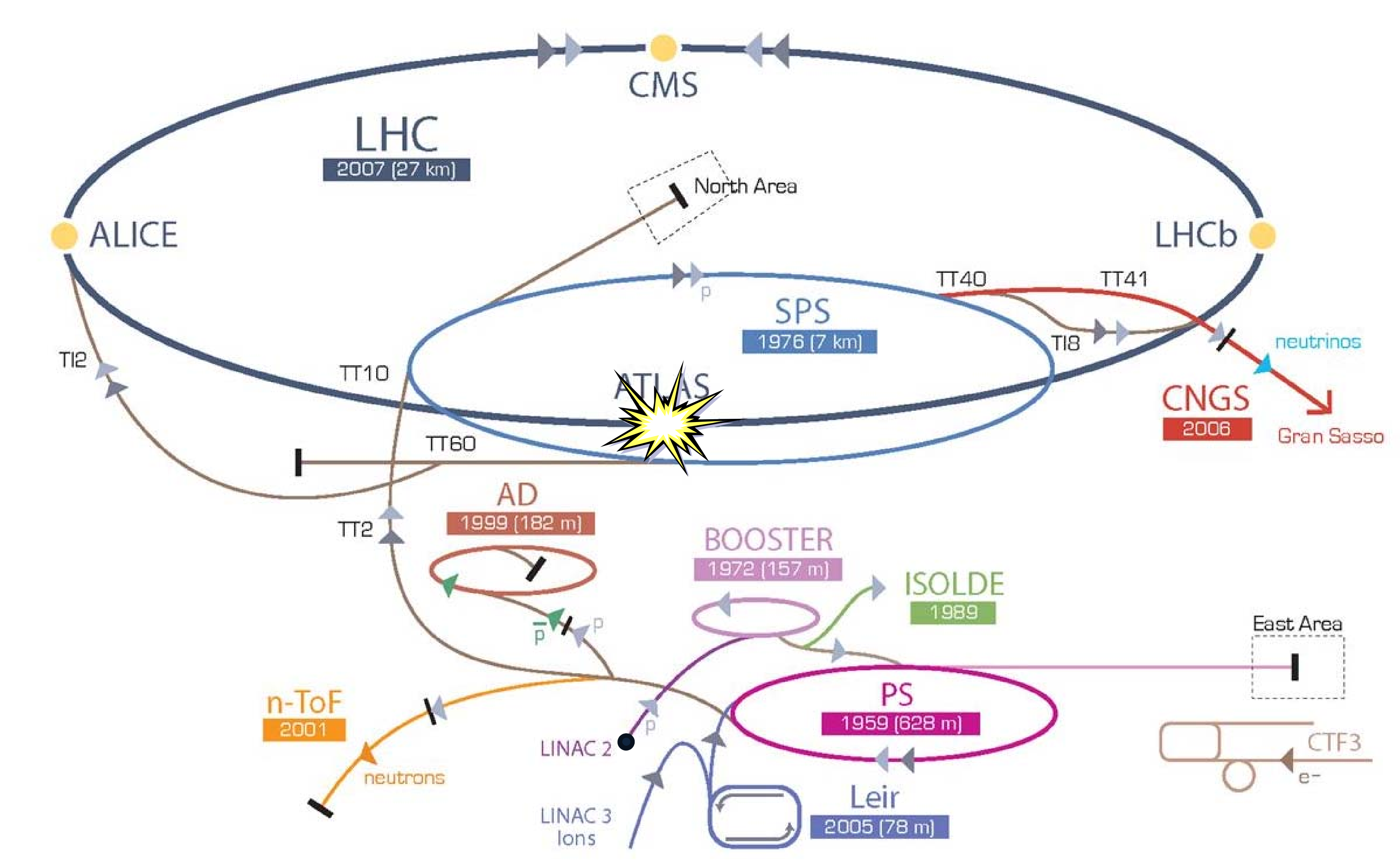
Note: The acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), because of the ~ $1/m^4$ behaviour of the synchrotron radiation energy losses [~ E^4_{beam}/Rm^4]

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



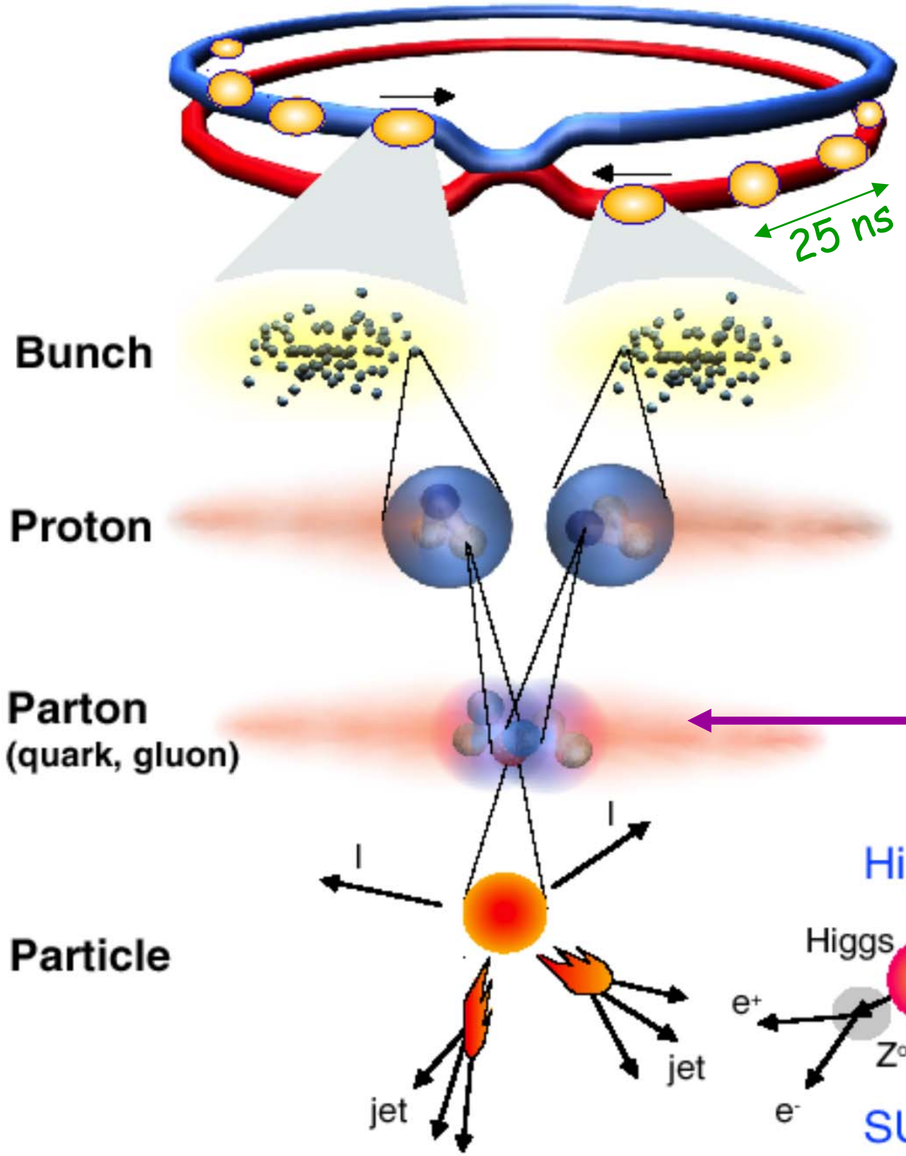
Relative beam sizes around the collision point

CERN's particle accelerator chain



Eine am 30. März 2010 aufgezeichnete Teilchenkollision in LHC

Collisions at LHC



Proton-Proton

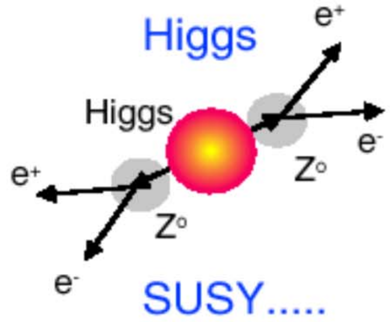
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate:

$N = L \times \sigma\,(pp) \approx$ **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

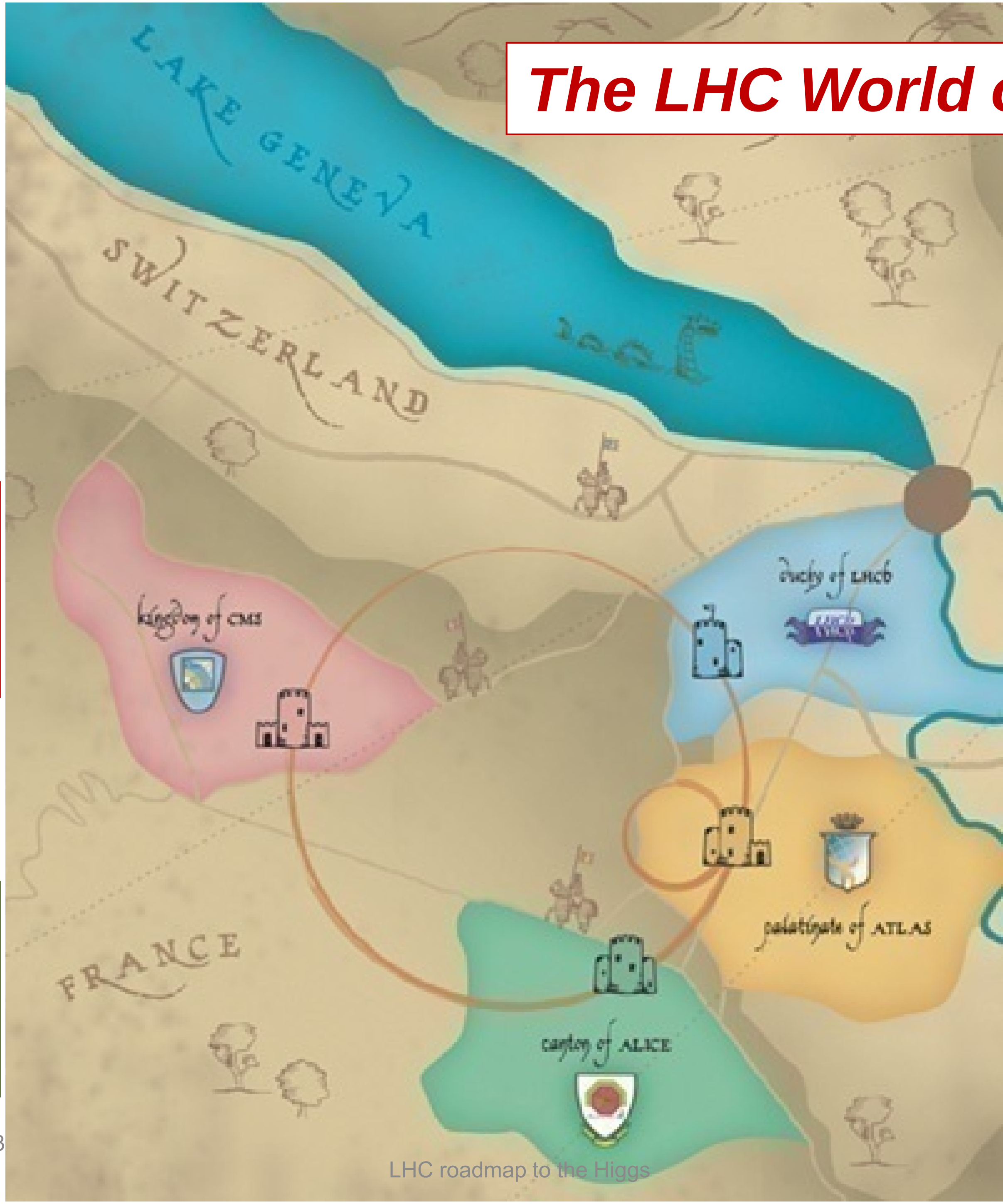
The SM is not a complete theory

Some of the outstanding questions in fundamental physics are

Question	Experiment
What is the origin of the elementary particle masses ?	ATLAS, CMS
What is the nature of the Universe dark matter ?	ATLAS, CMS
Why is only matter observed in the Universe as primary constituents and not anti-matter ?	LHCb
What are the features of the primordial plasma present ~10 μs after the Big Bang ?	ALICE
What happened in the first moments of the Universe ~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
….	

The LHC World of CERN

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



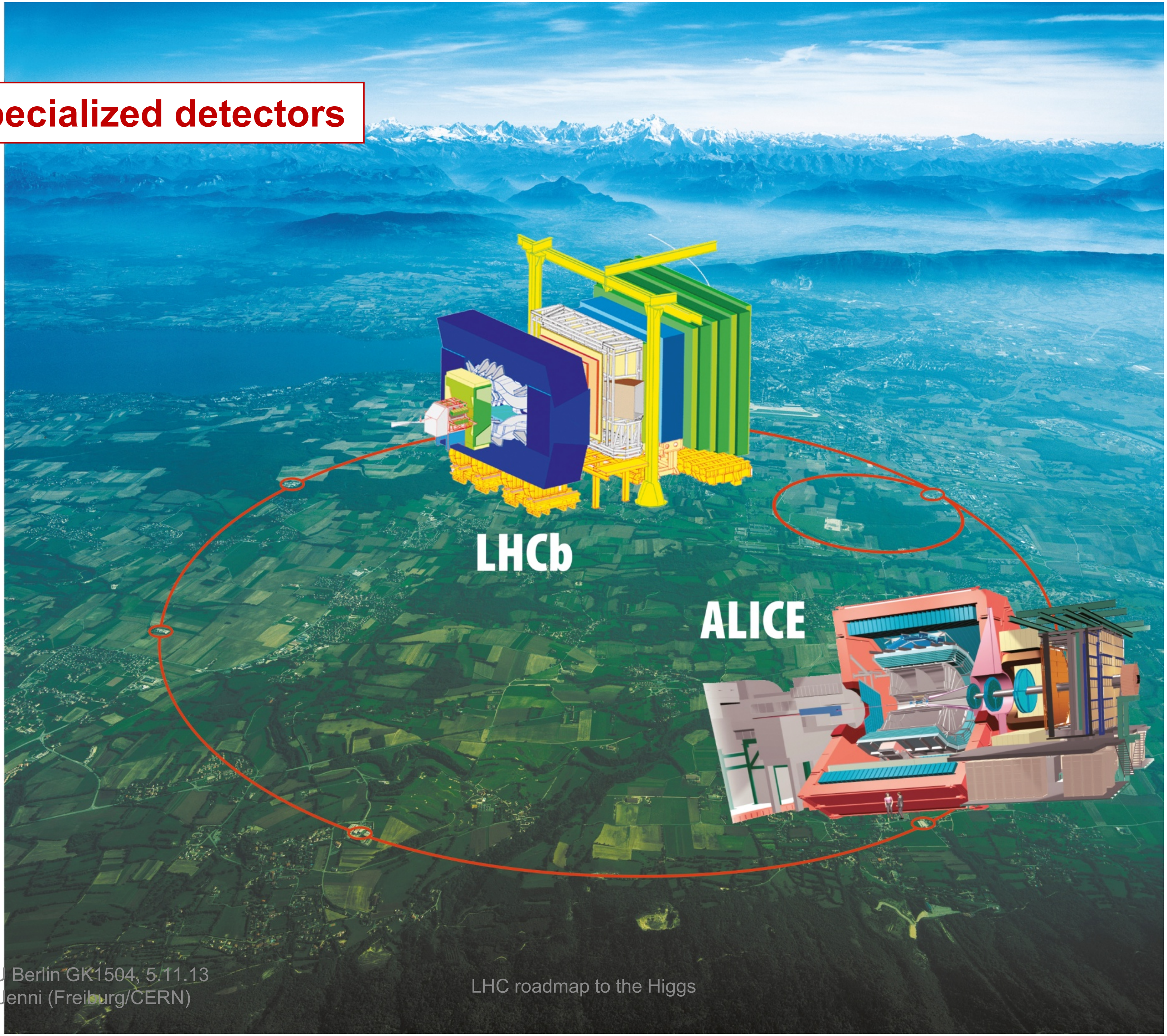
CMS
3000 Physicists
184 Institutions
38 countries
550 MCHF

ALICE
1300 Physicists
130 Institutions
35 countries
160 MCHF

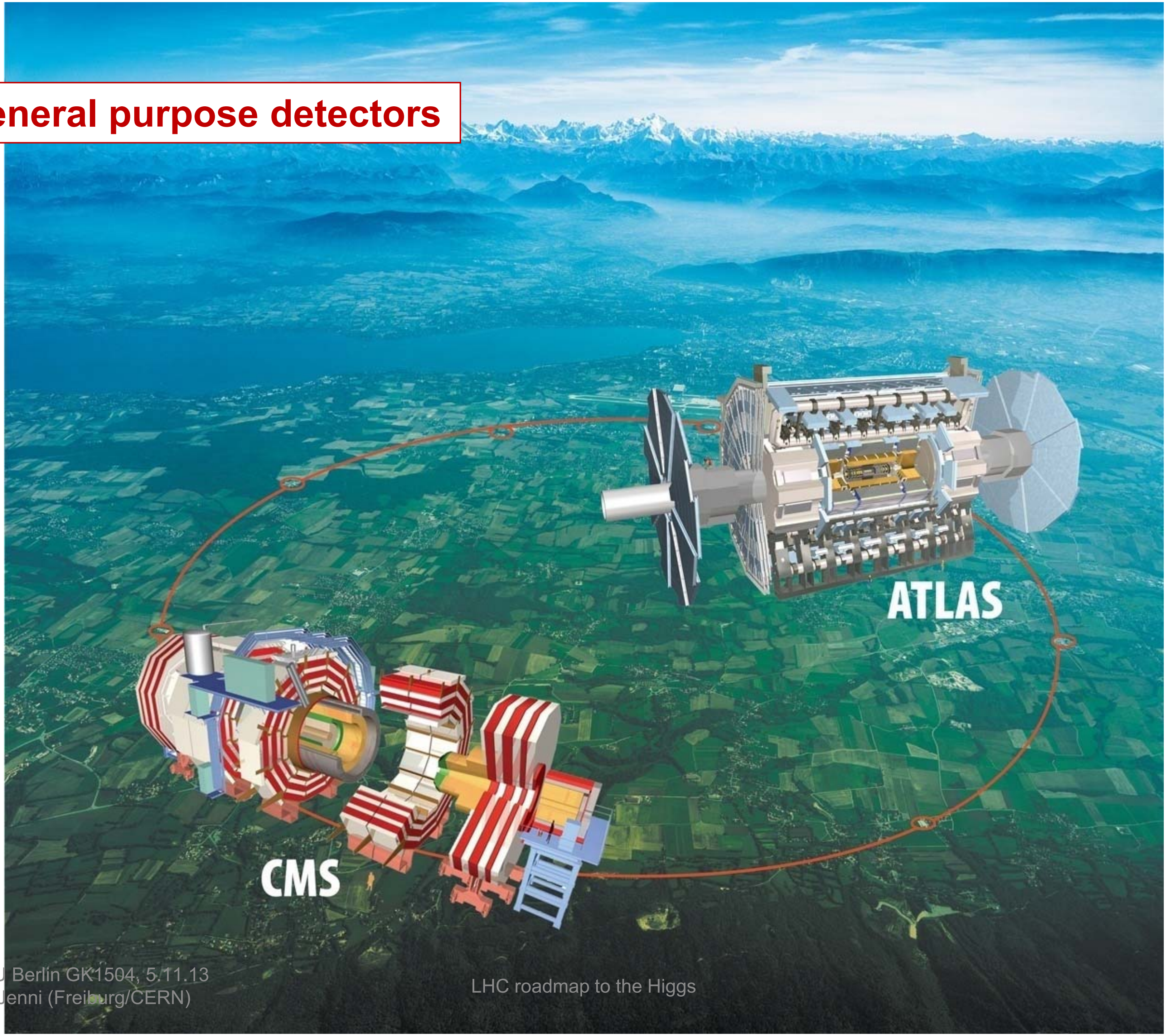
LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

ATLAS
3000 Physicists
177 Institutions
38 countries
550 MCHF

Specialized detectors

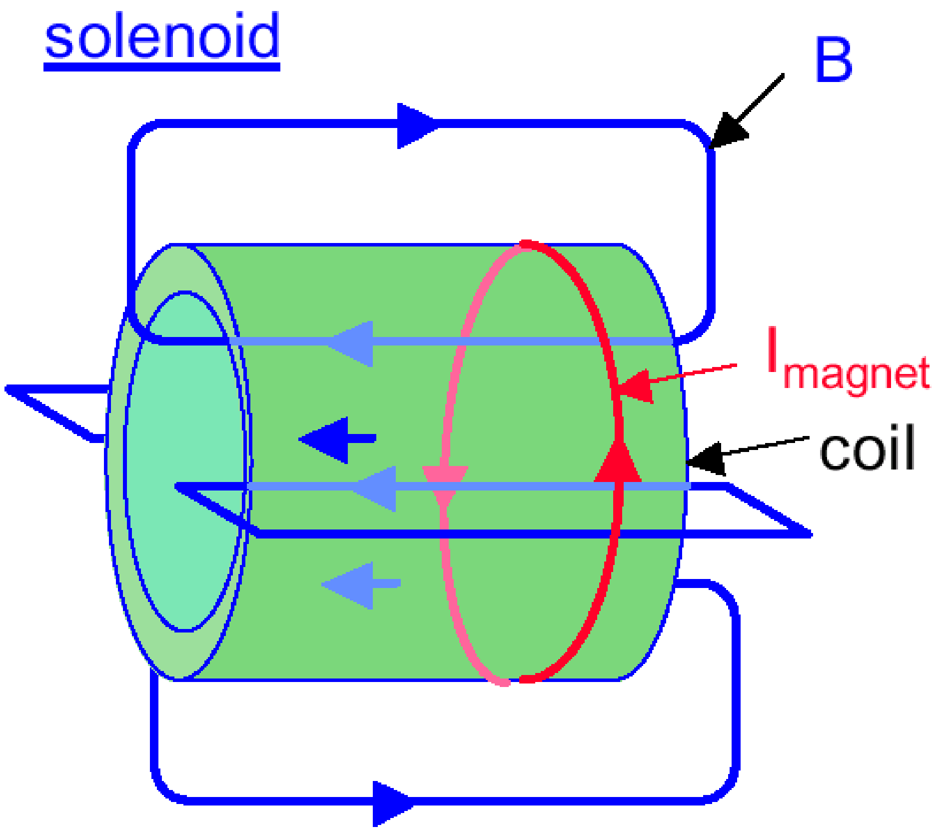


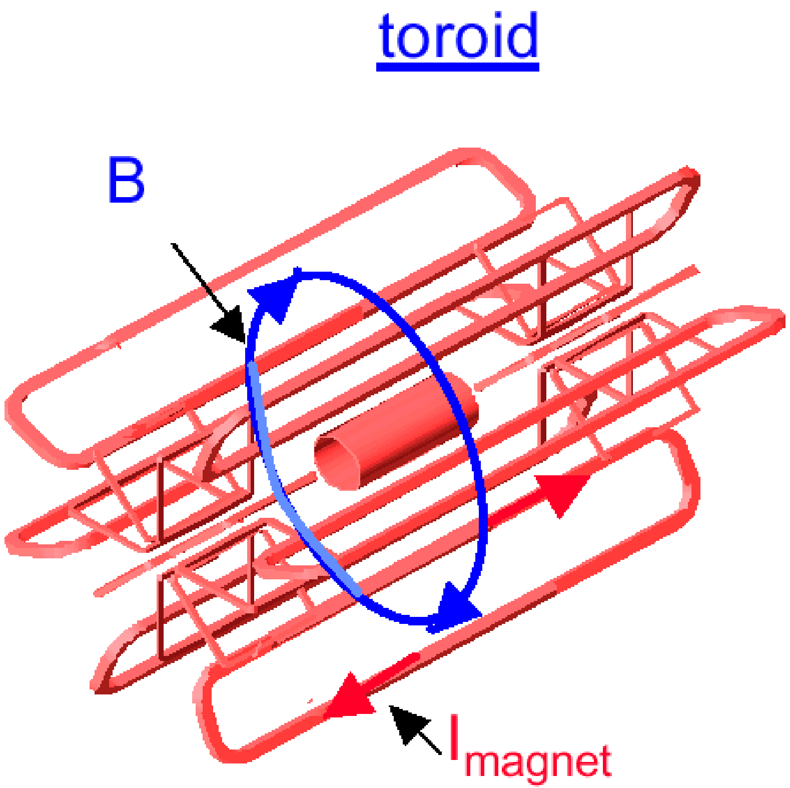
General purpose detectors



Magnetic fields

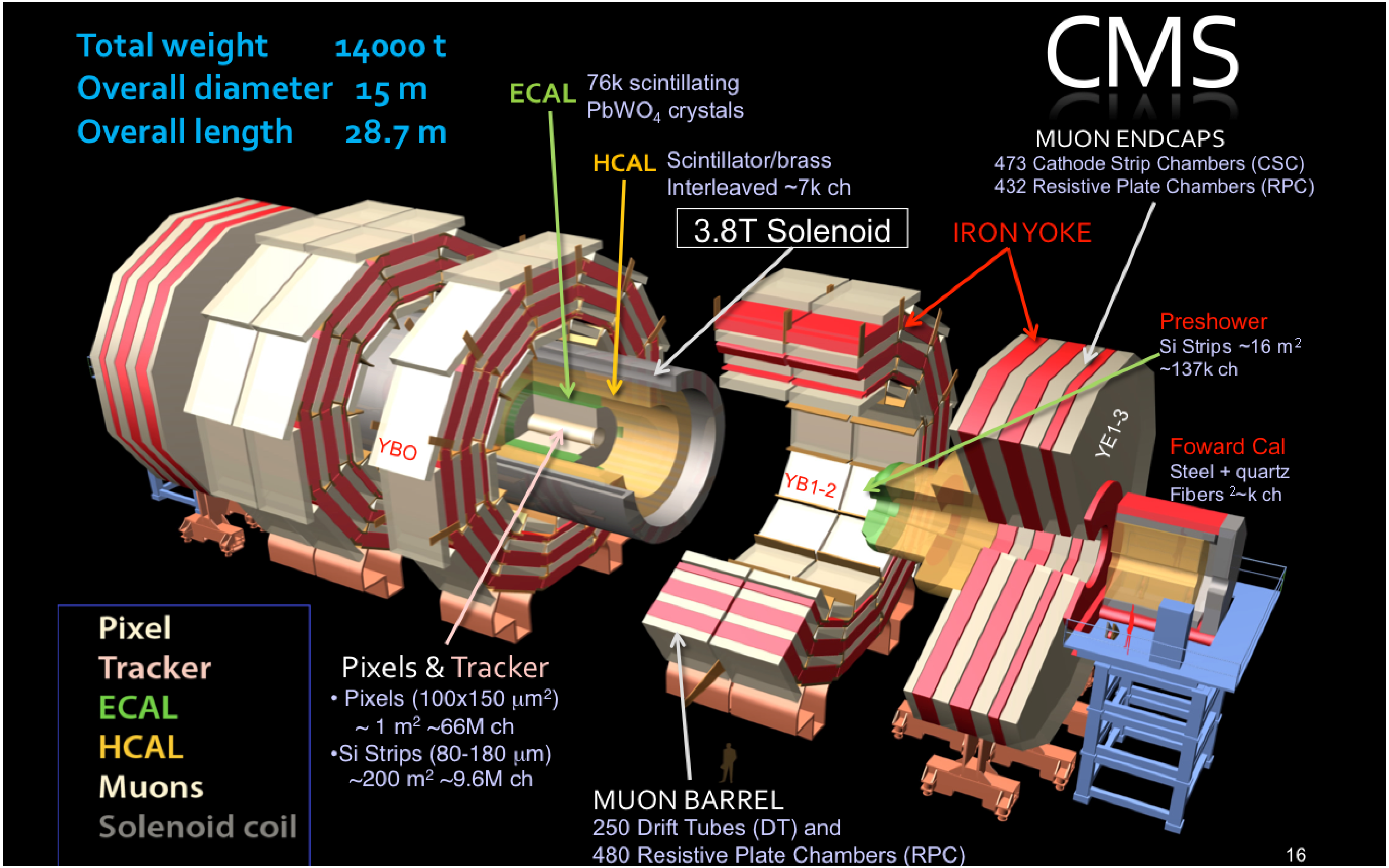
Magnetic field configurations:



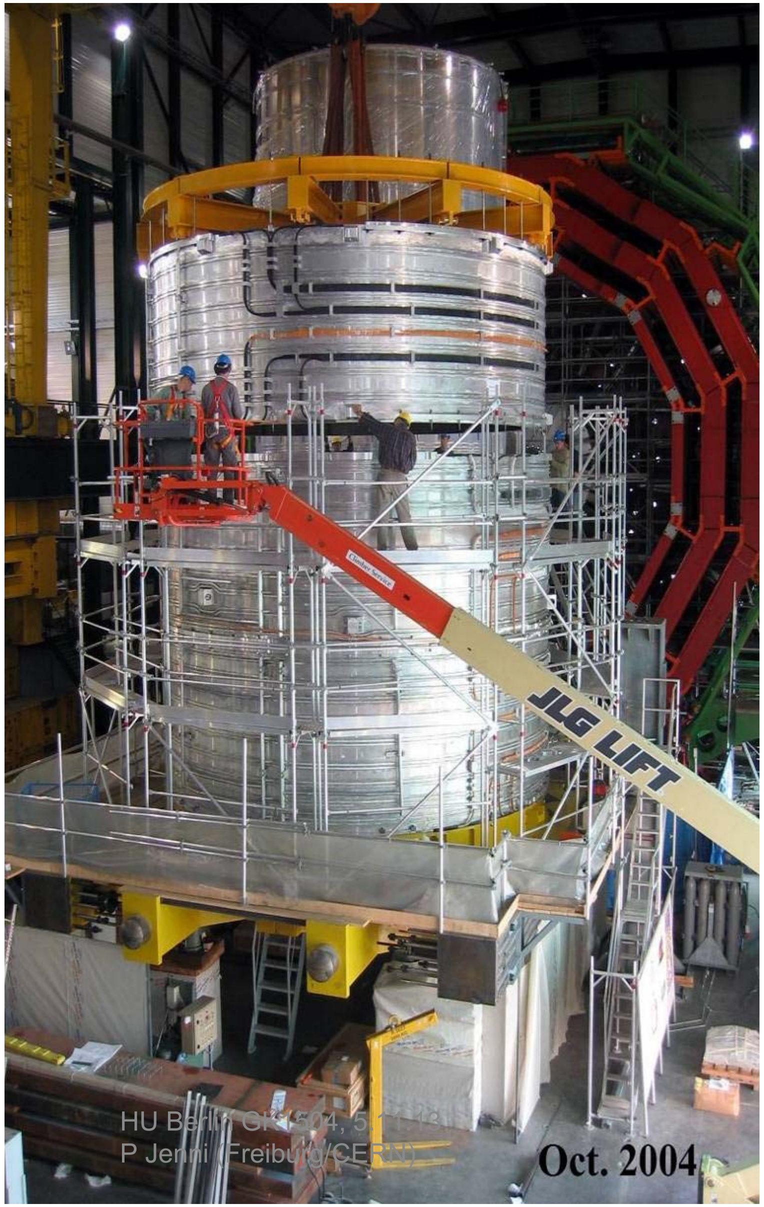


From C.Joram

Exploded View of CMS



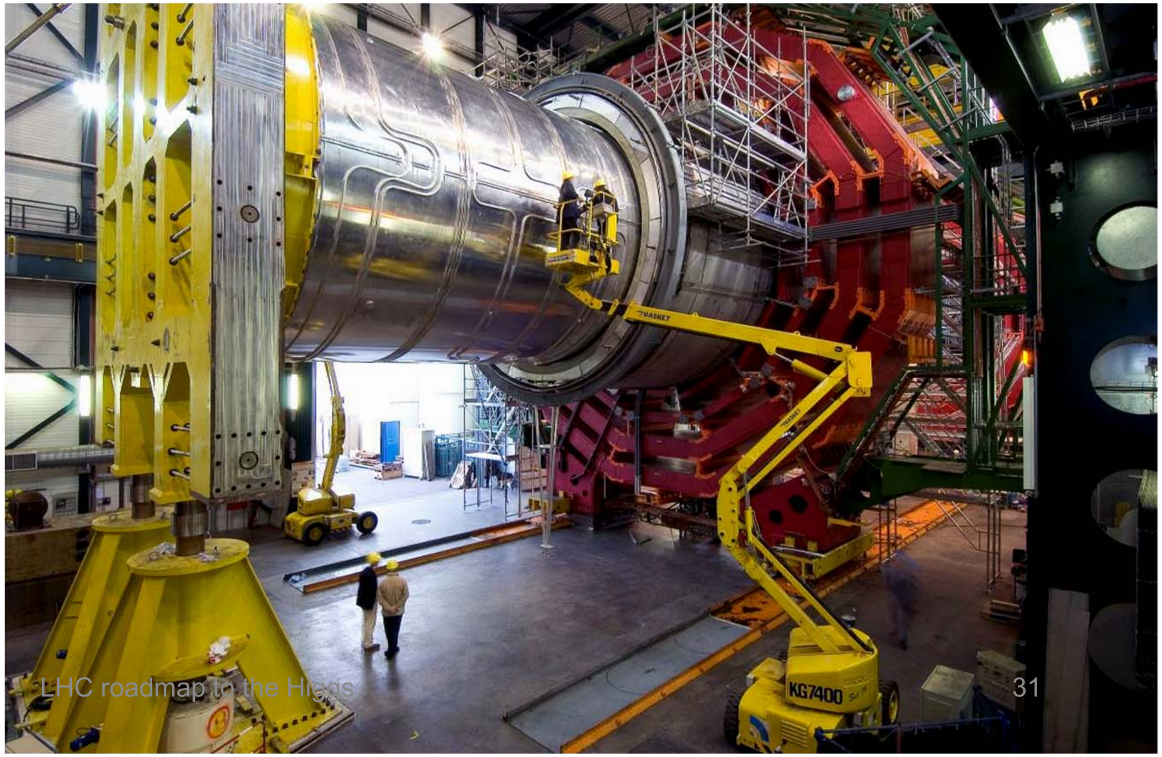
An Example of an Engineering Challenge: CMS Solenoid



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



CMS before closure 2008

ATLAS Collaboration

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

Adelaide, Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, 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, 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, Louisiana Tech, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, 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

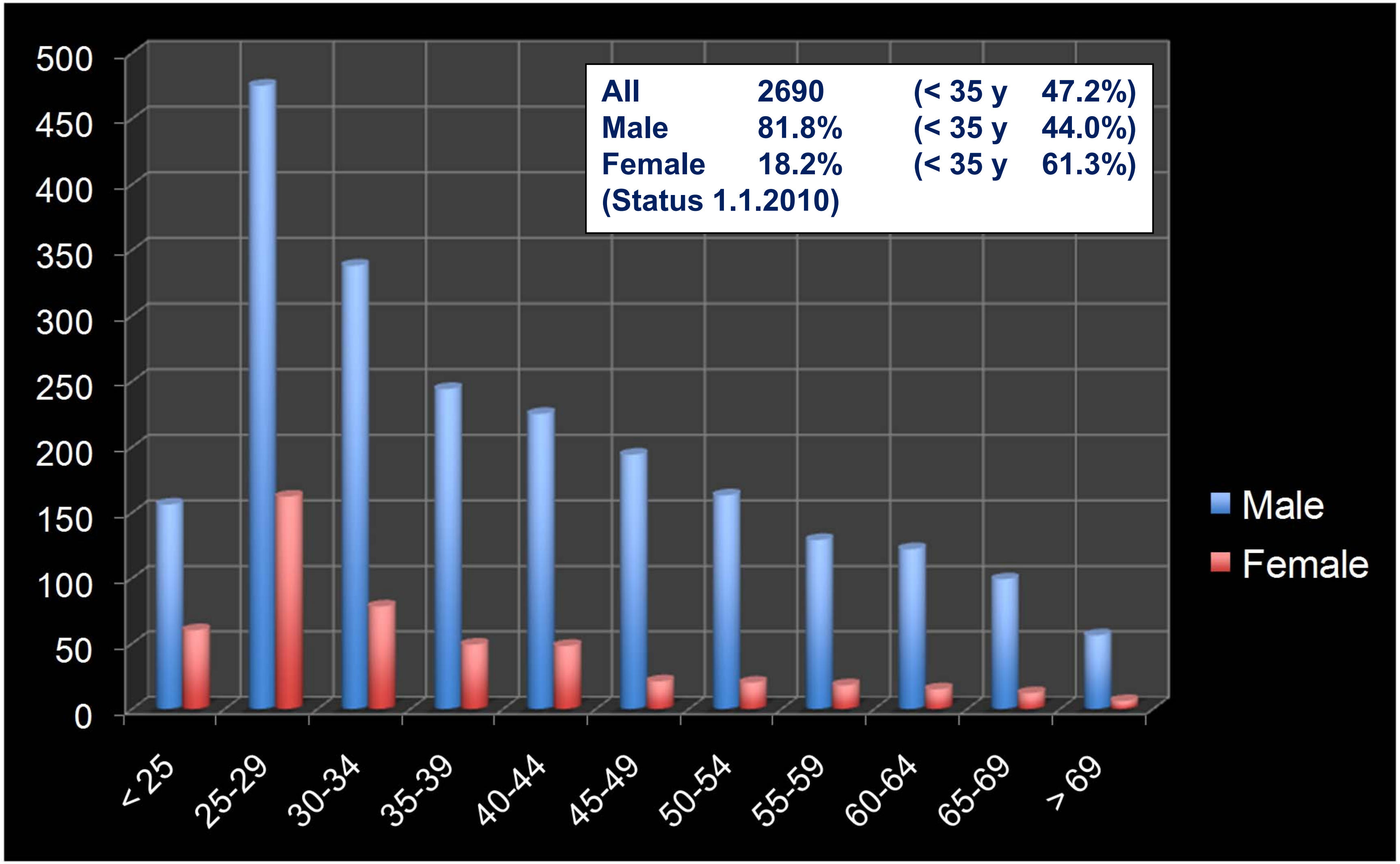
38 Countries
177 Institutions
3000 Scientific participants total
(1000 Students)

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

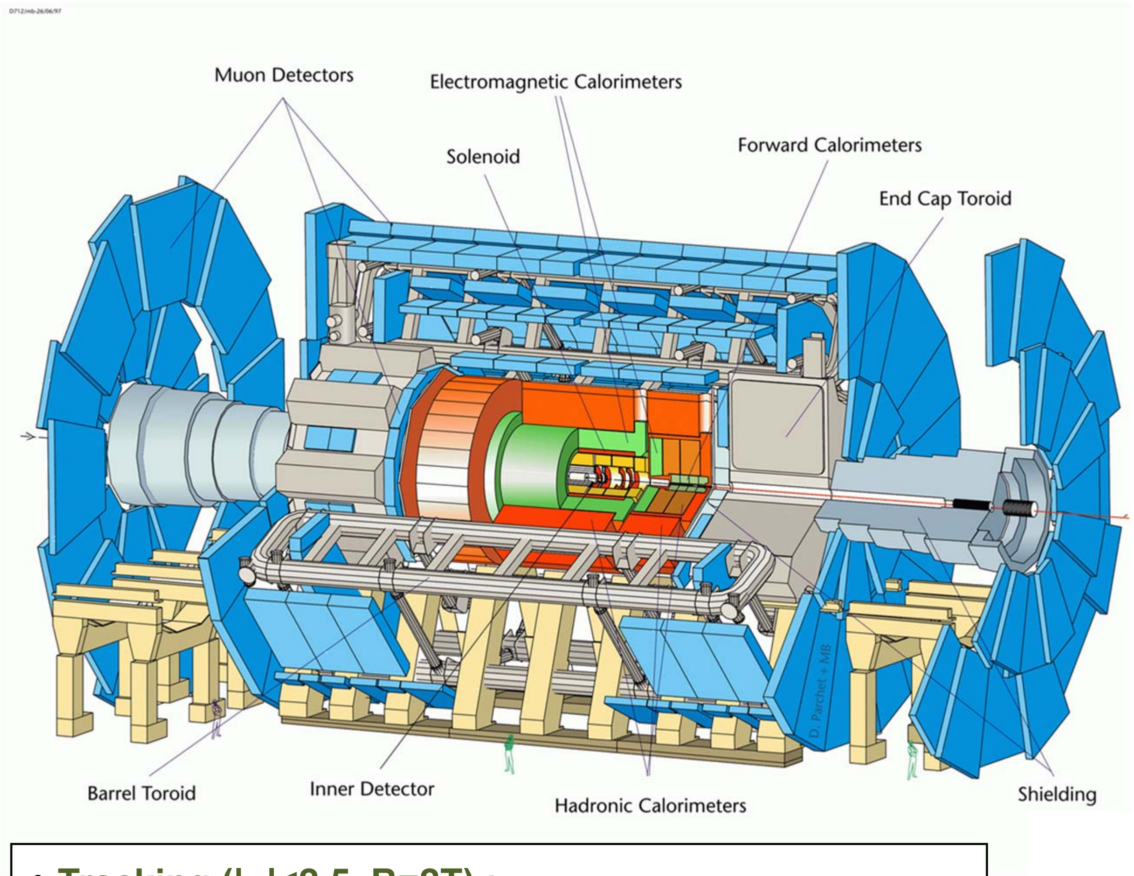
(GK1504/2 teams in red)

Adelaide, Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, **HU Berlin**, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, 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**, 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, Louisiana Tech, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, LMU Munich, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, NPI Petersburg, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Warwick, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

Age distribution of the ATLAS population



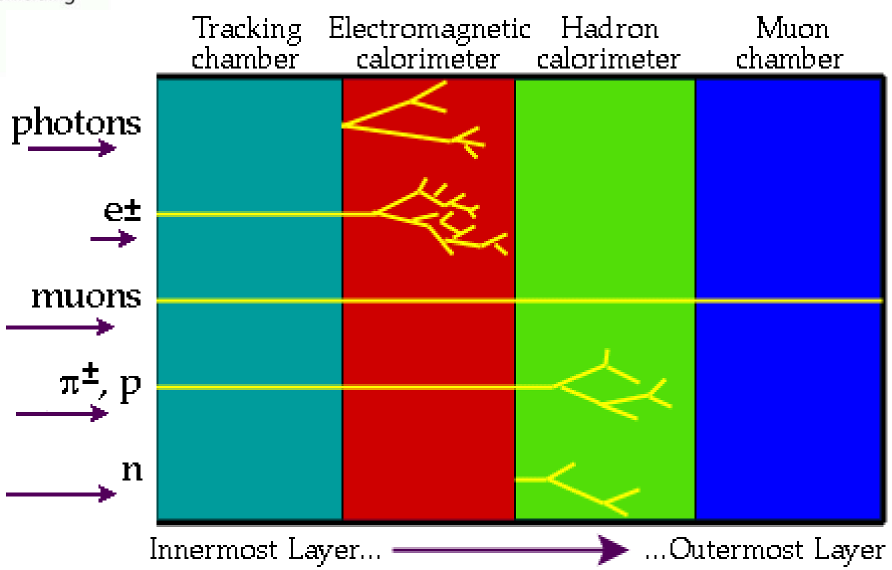
All	2690	(< 35 y	47.2%)
Male	81.8%	(< 35 y	44.0%)
Female	18.2%	(< 35 y	61.3%)
(Status 1.1.2010)			



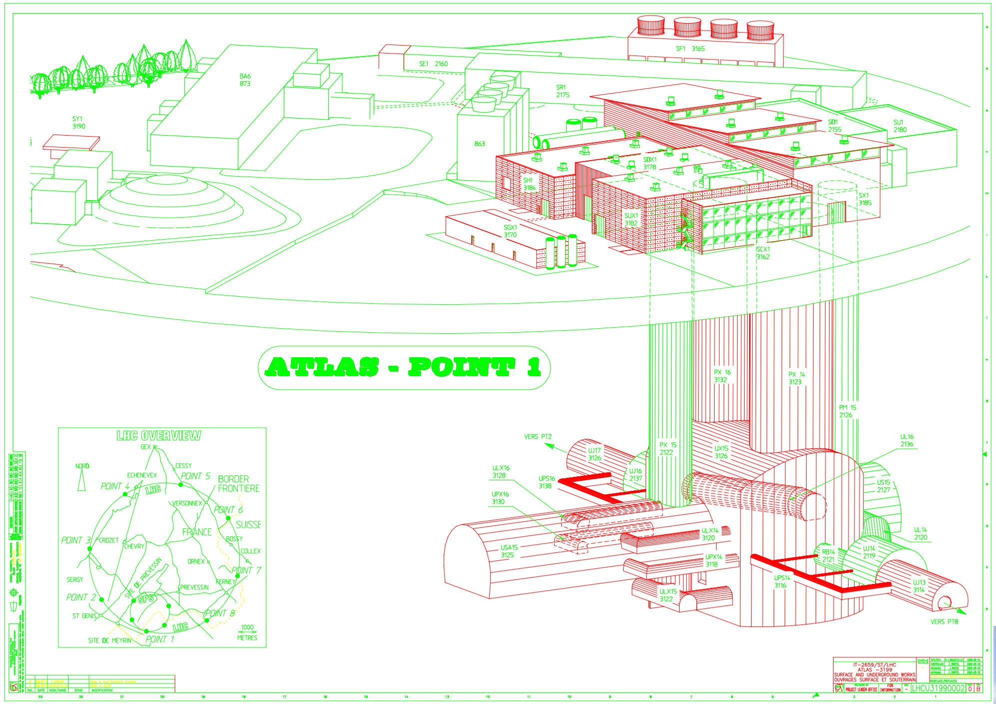
ATLAS

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~ 10^8 electronic channels
~ 3000 km of cables

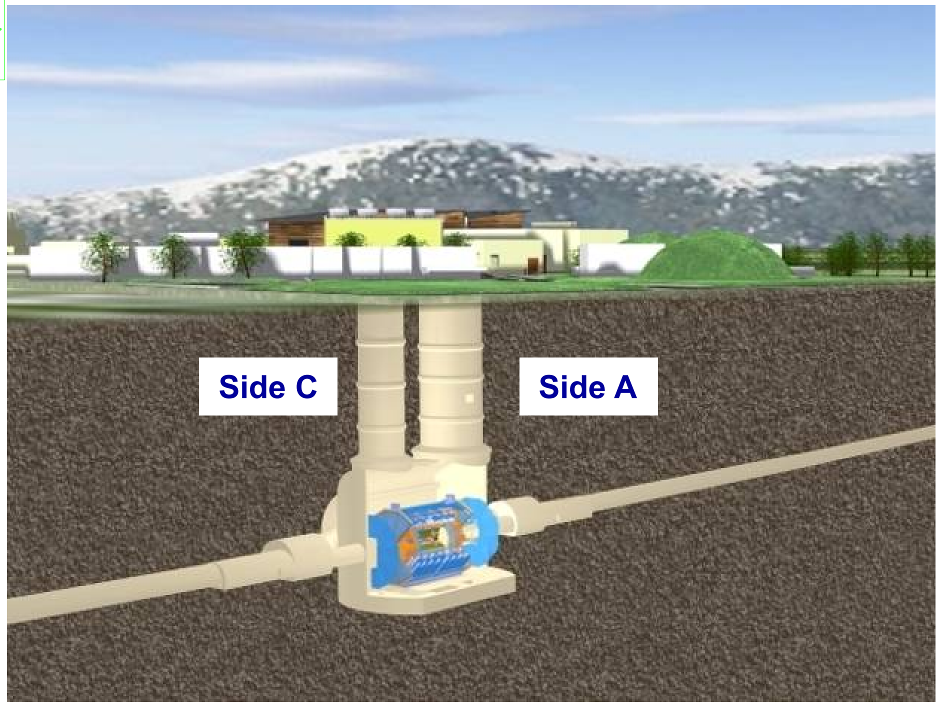
- **Tracking (|η|<2.5, B=2T) :**
  - **-- Si pixels and strips**
  - **-- Transition Radiation Detector (e/π separation)**
- **Calorimetry (|η|<5) :**
  - **-- EM : Pb-LAr**
  - **-- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)**
- **Muon Spectrometer (|η|<2.7) :**
  - **-- air-core toroids with muon chambers**



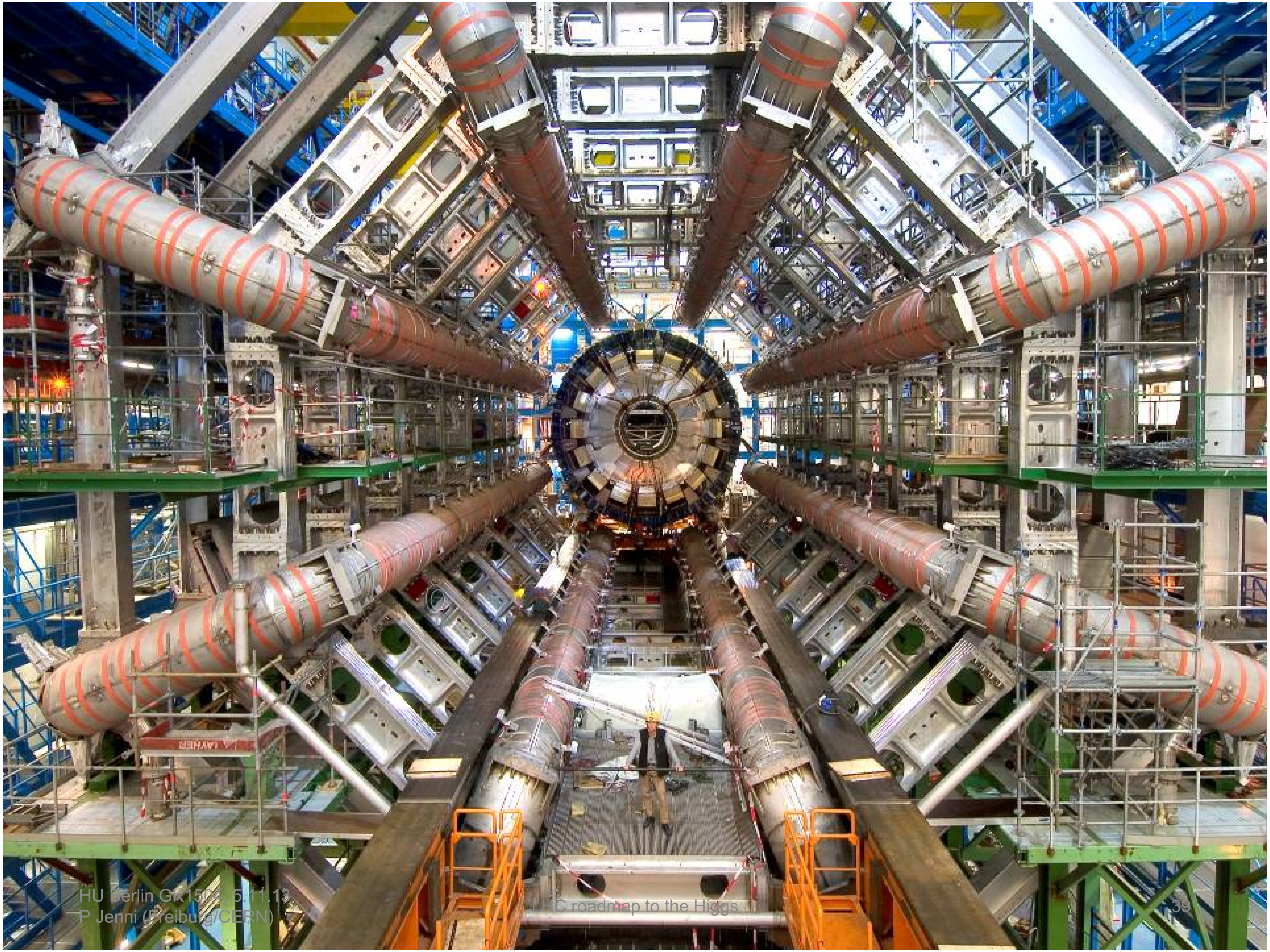
The Underground Cavern at Point-1 for the ATLAS Detector

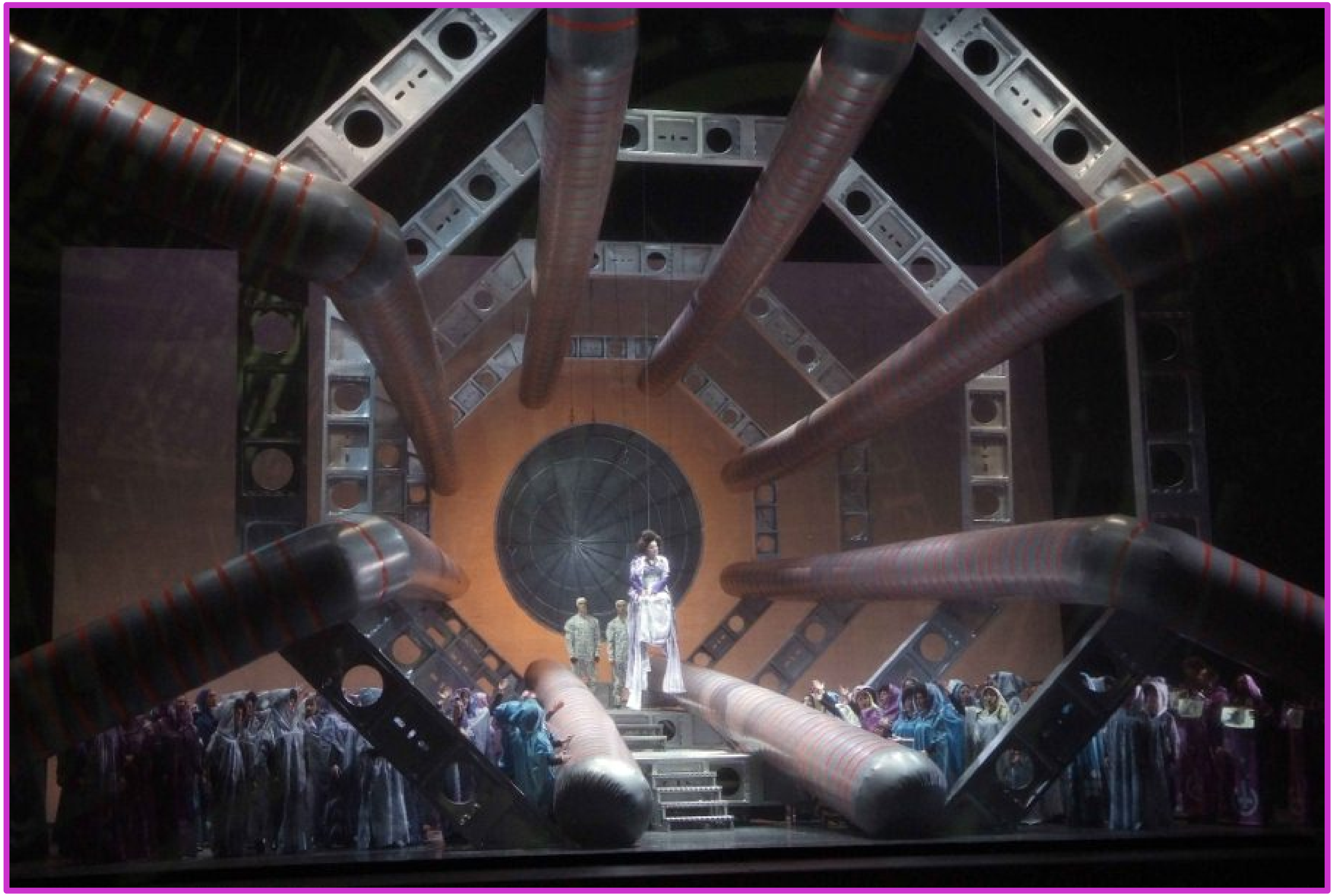


Length = 55 m
Width = 32 m
Height = 35 m

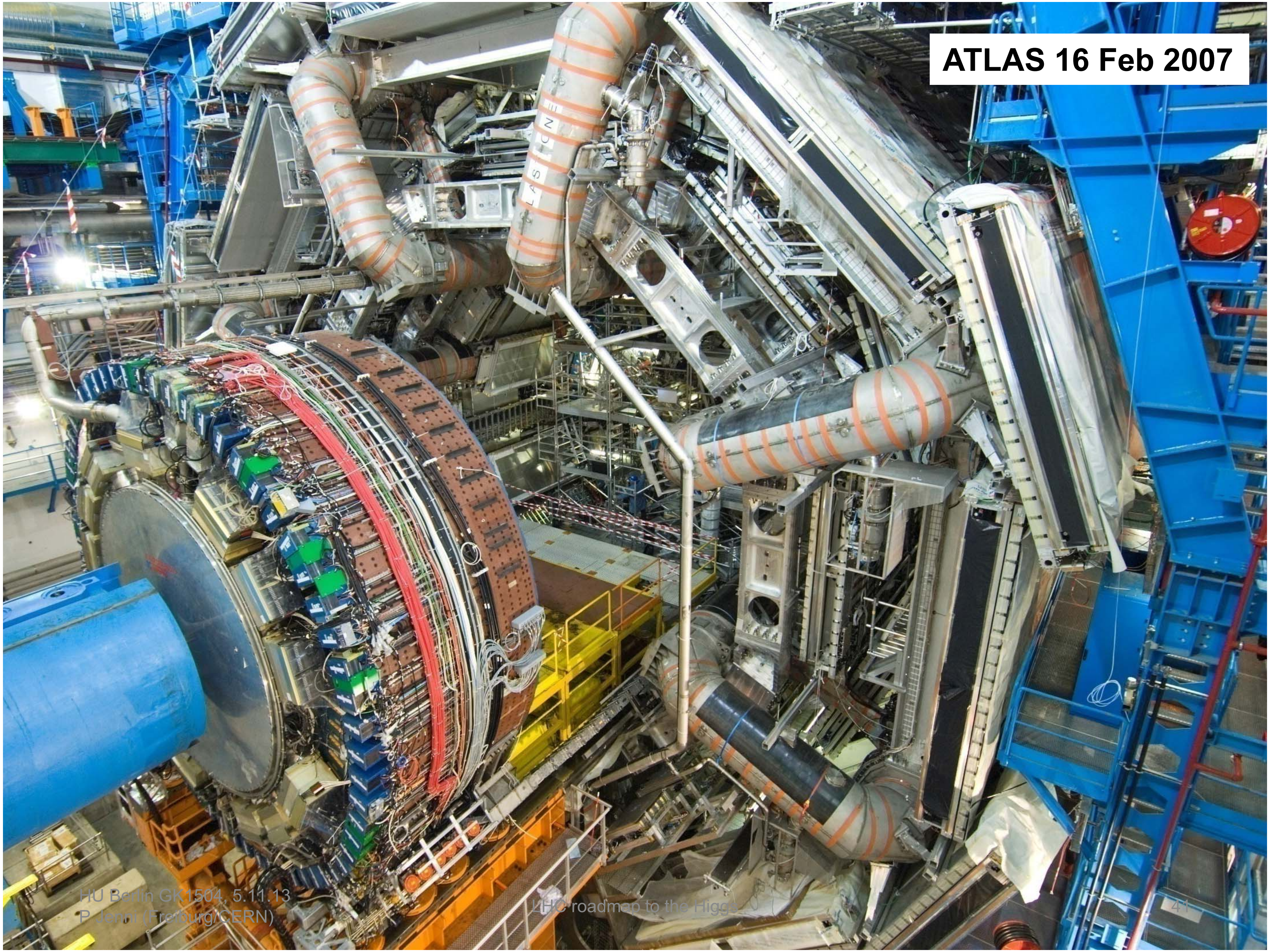


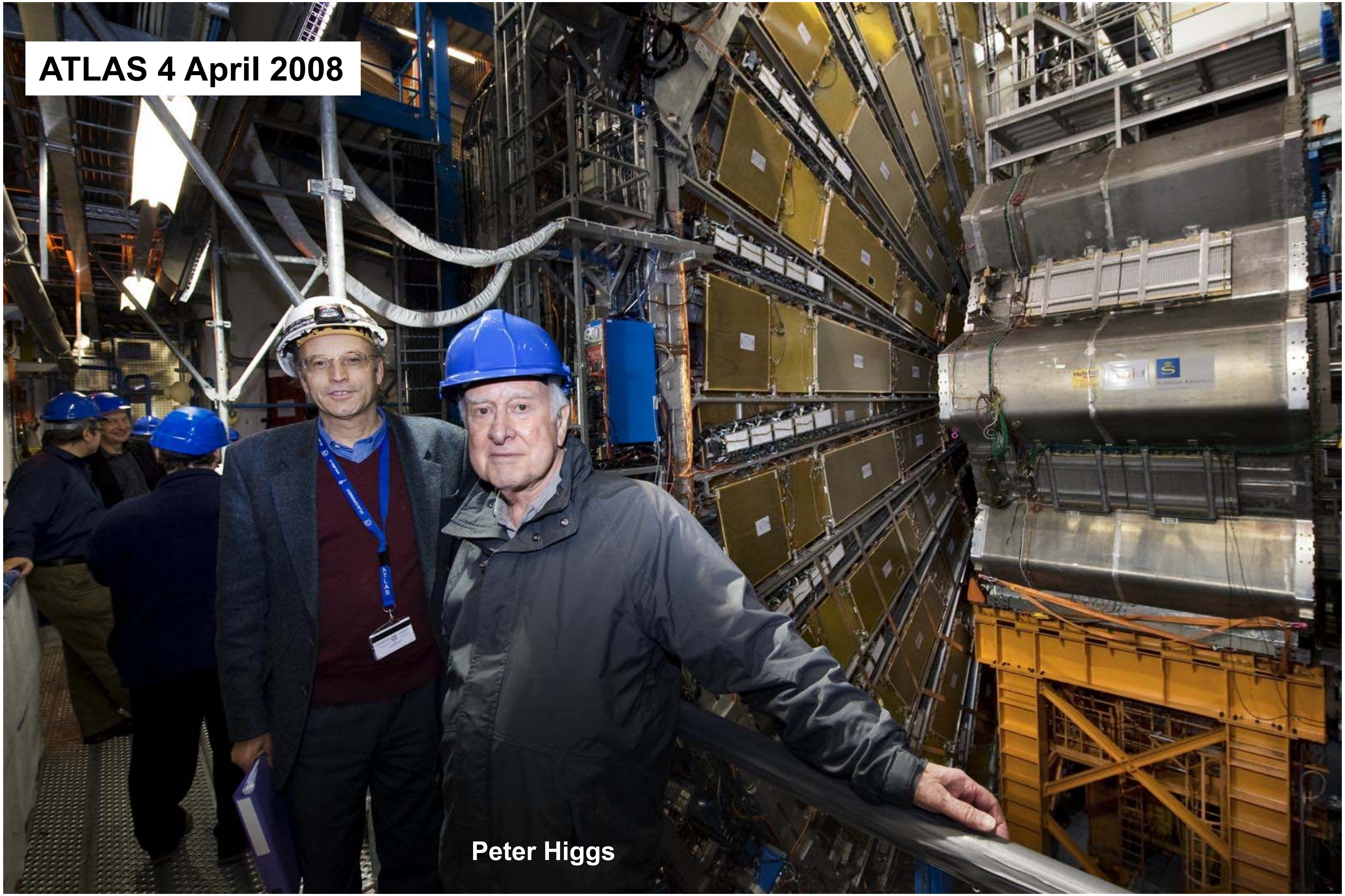
LHC Point 1 - UX 15 Cavern - Concrete walls 6th lift - 20-02-2003 - CERN ST-CE





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


ATLAS 16 Feb 2007

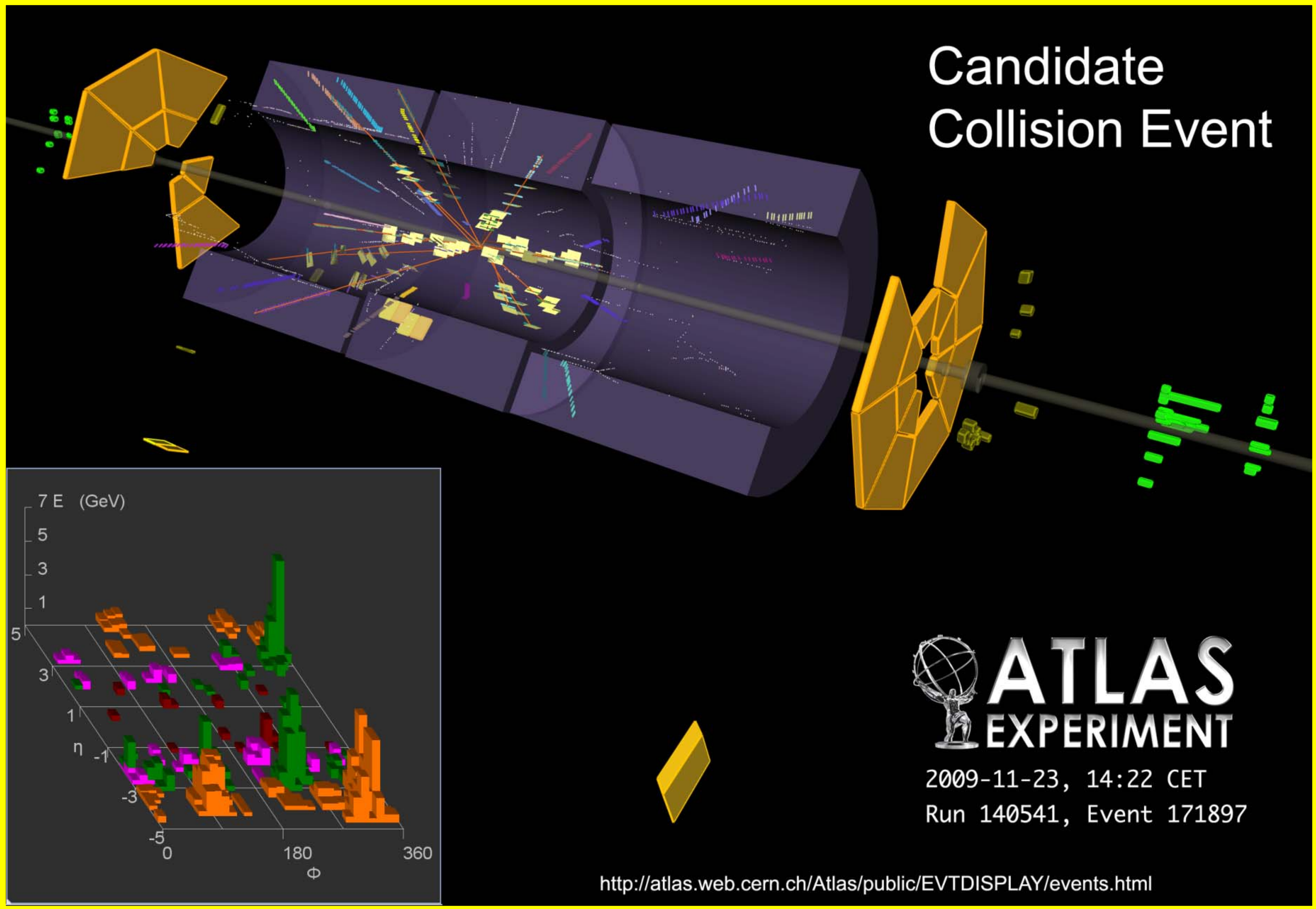

ATLAS 4 April 2008
Peter Higgs
ATLAS

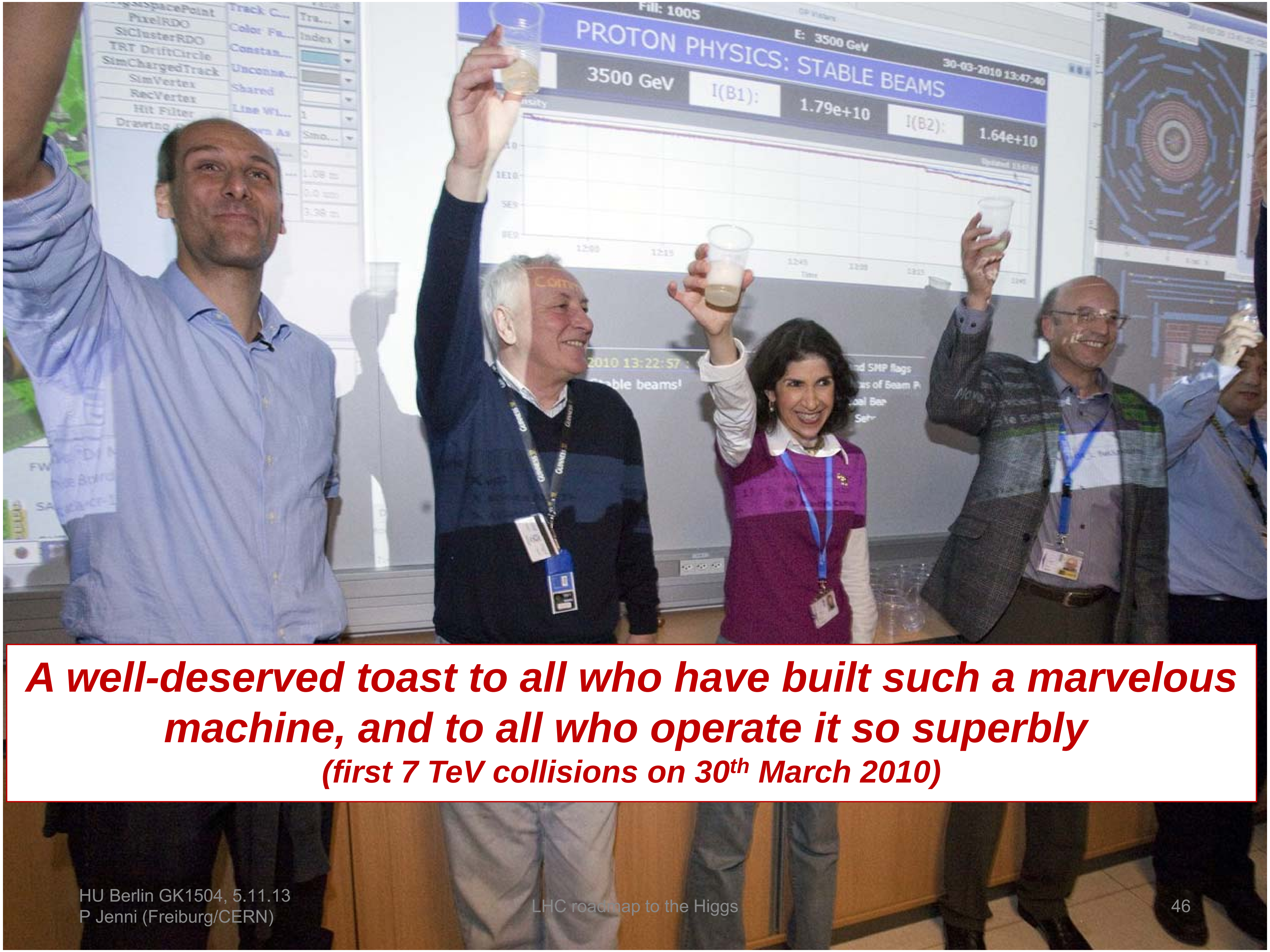
Interconnections of two magnets

One (superconductor) joint failed on 19th September 2008, and it caused a catastrophic He-release that made serious collateral damage to sector 3-4 of the LHC machine

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





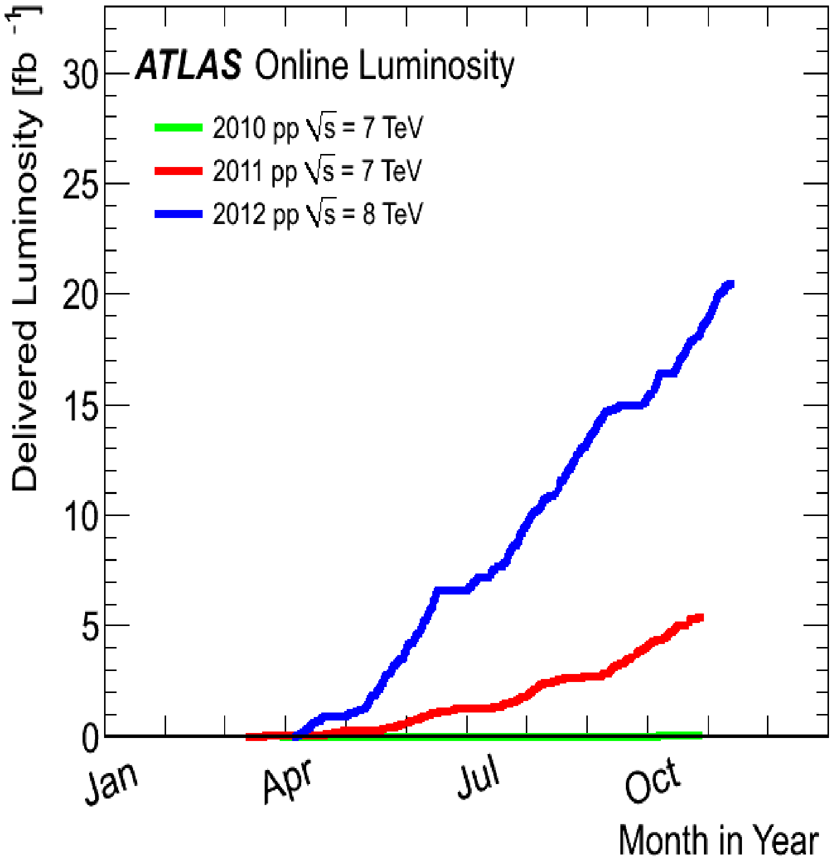
A well-deserved toast to all who have built such a marvelous machine, and to all who operate it so superbly

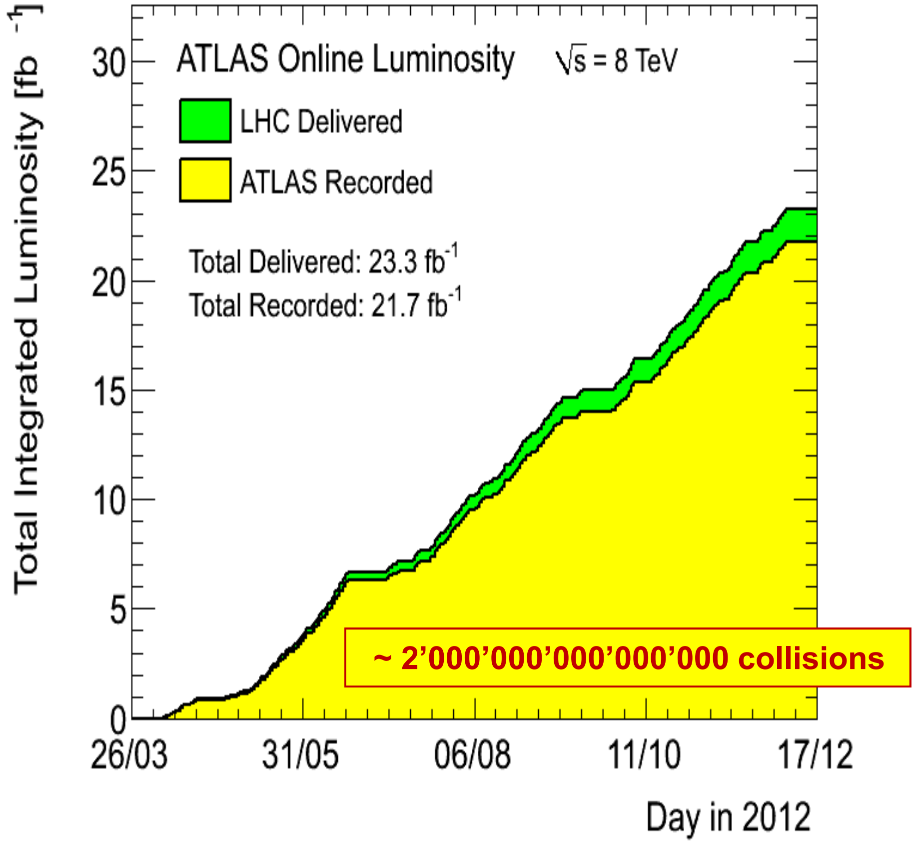
(first 7 TeV collisions on 30th March 2010)

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

Total integrated luminosity

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

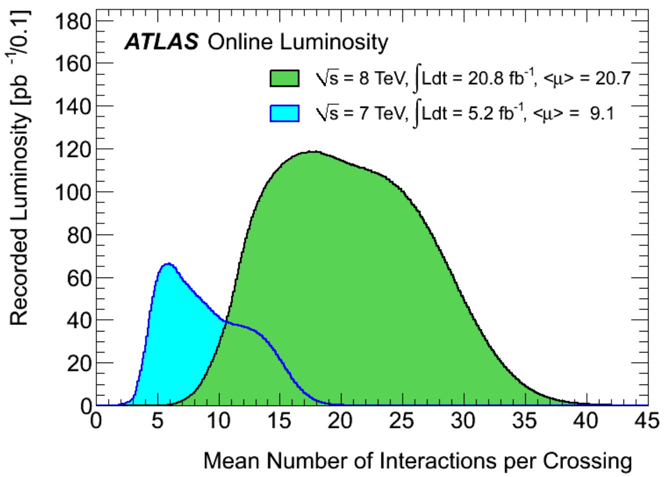


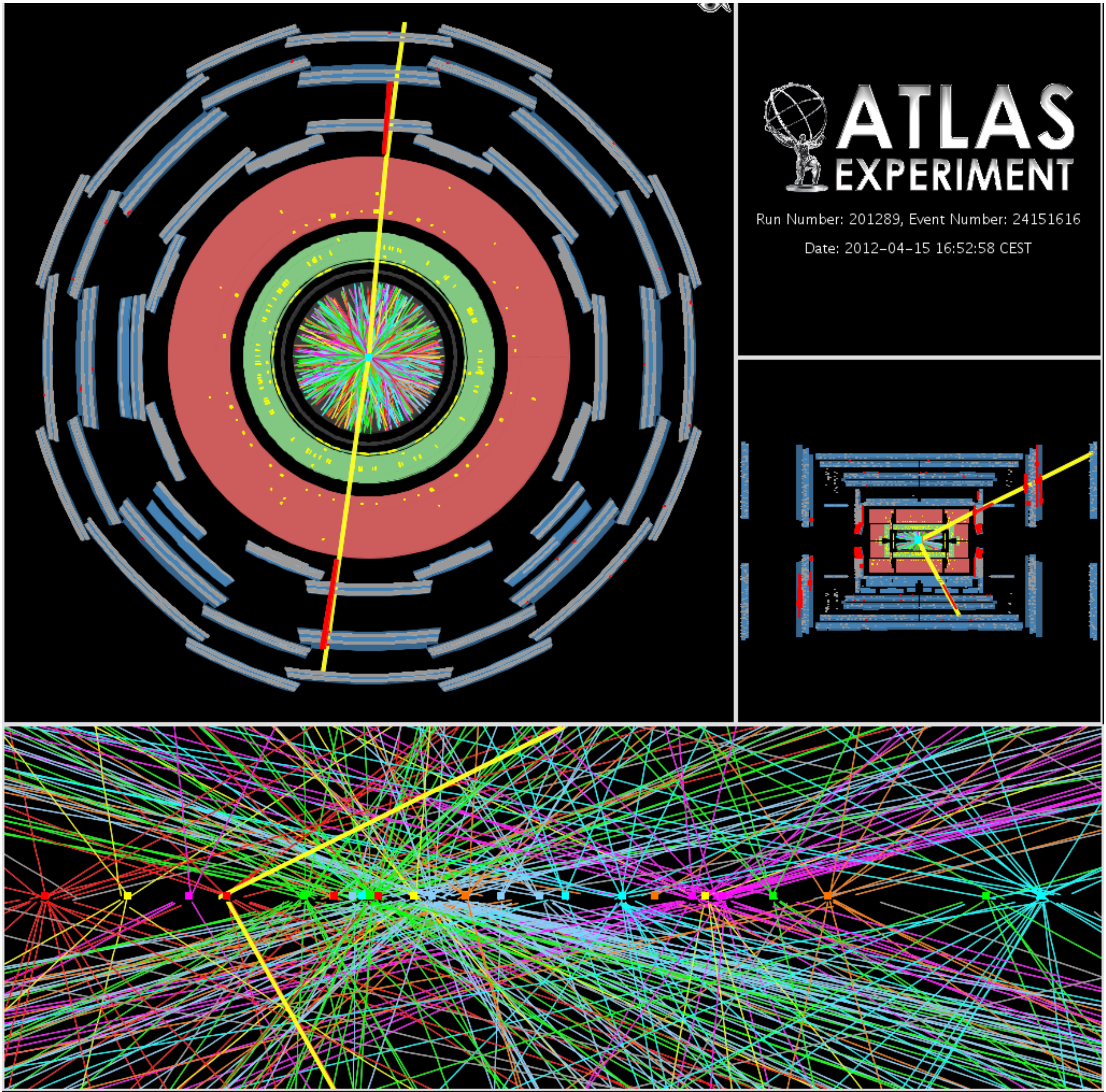


The experiment records typically 94% of the stably delivered luminosity, and uses up to 90% of the LHC luminosity in the final analyses!

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

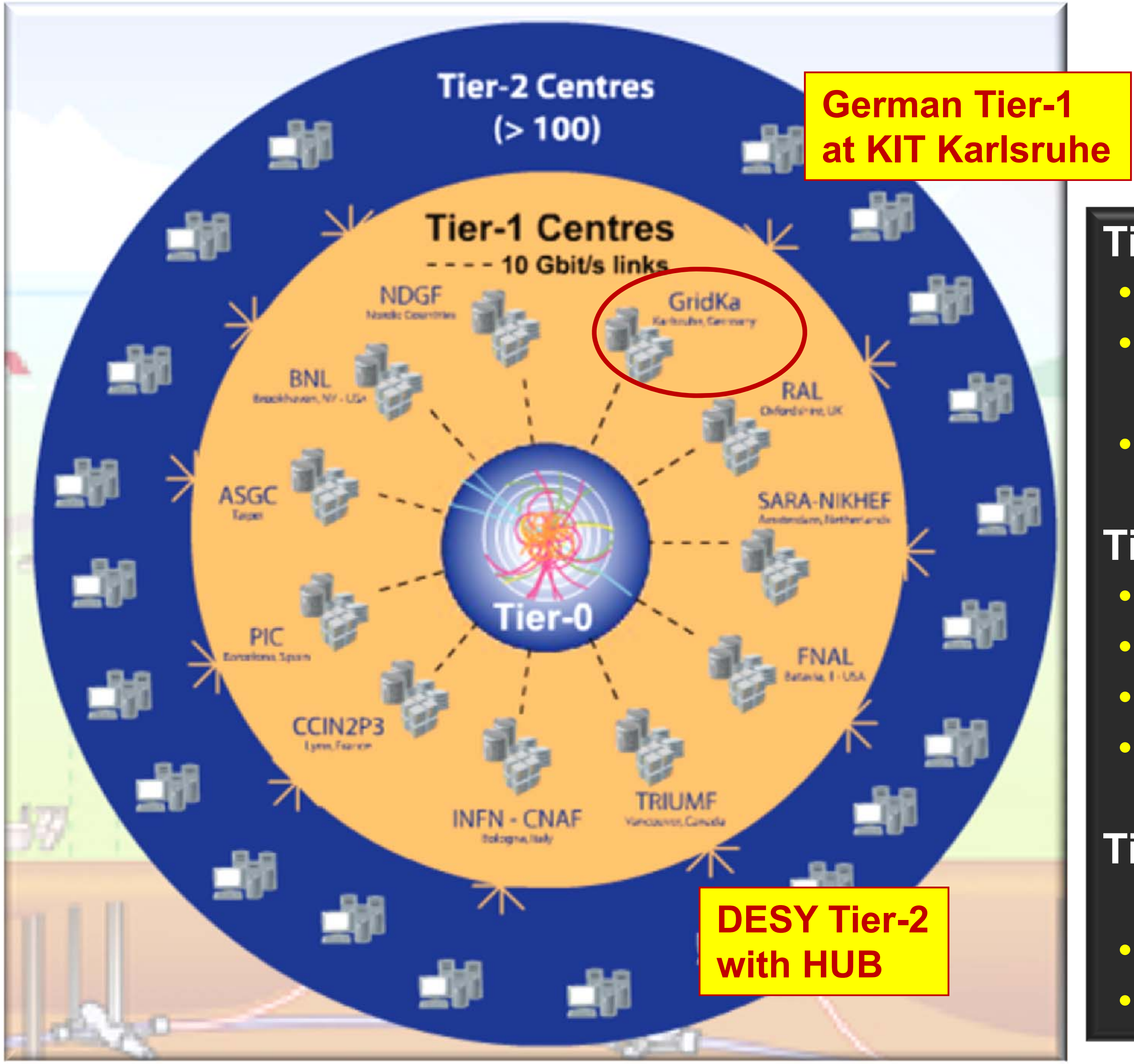
- **Trigger** *(GK1504 expertize!)*
- **Pile-up**
- **Maintain accuracy of the the measurements in this environment**





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

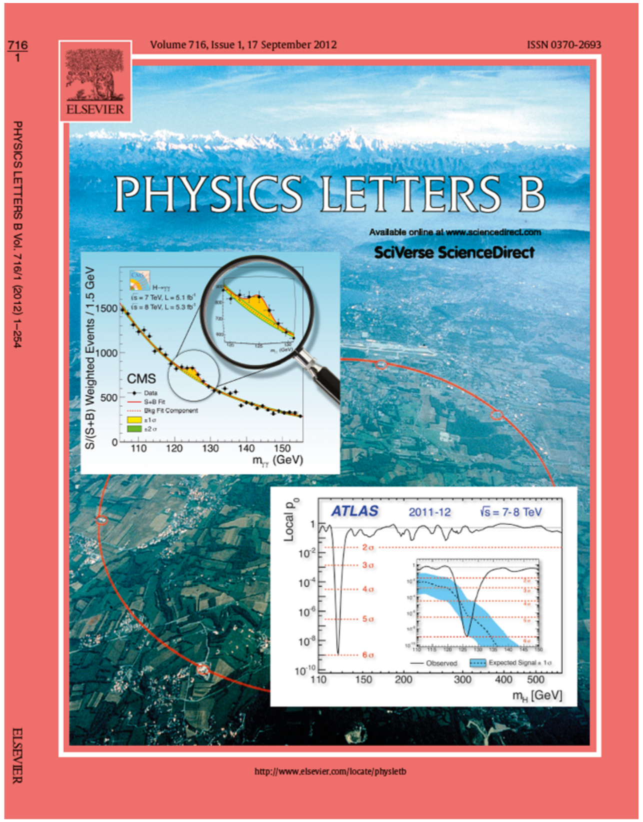
Physics Highlights

ATLAS and CMS have already published together about 550 papers in scientific journals (and many more as public conference notes…)

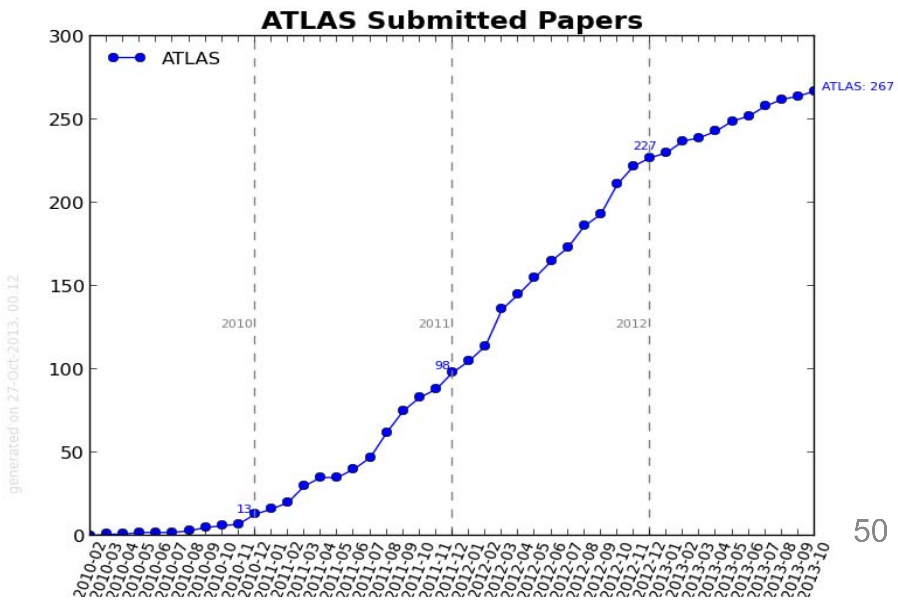
The other experiments, ALICE, LHCb, LHCf, and TOTEM total another 220 journal publications together

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, only 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

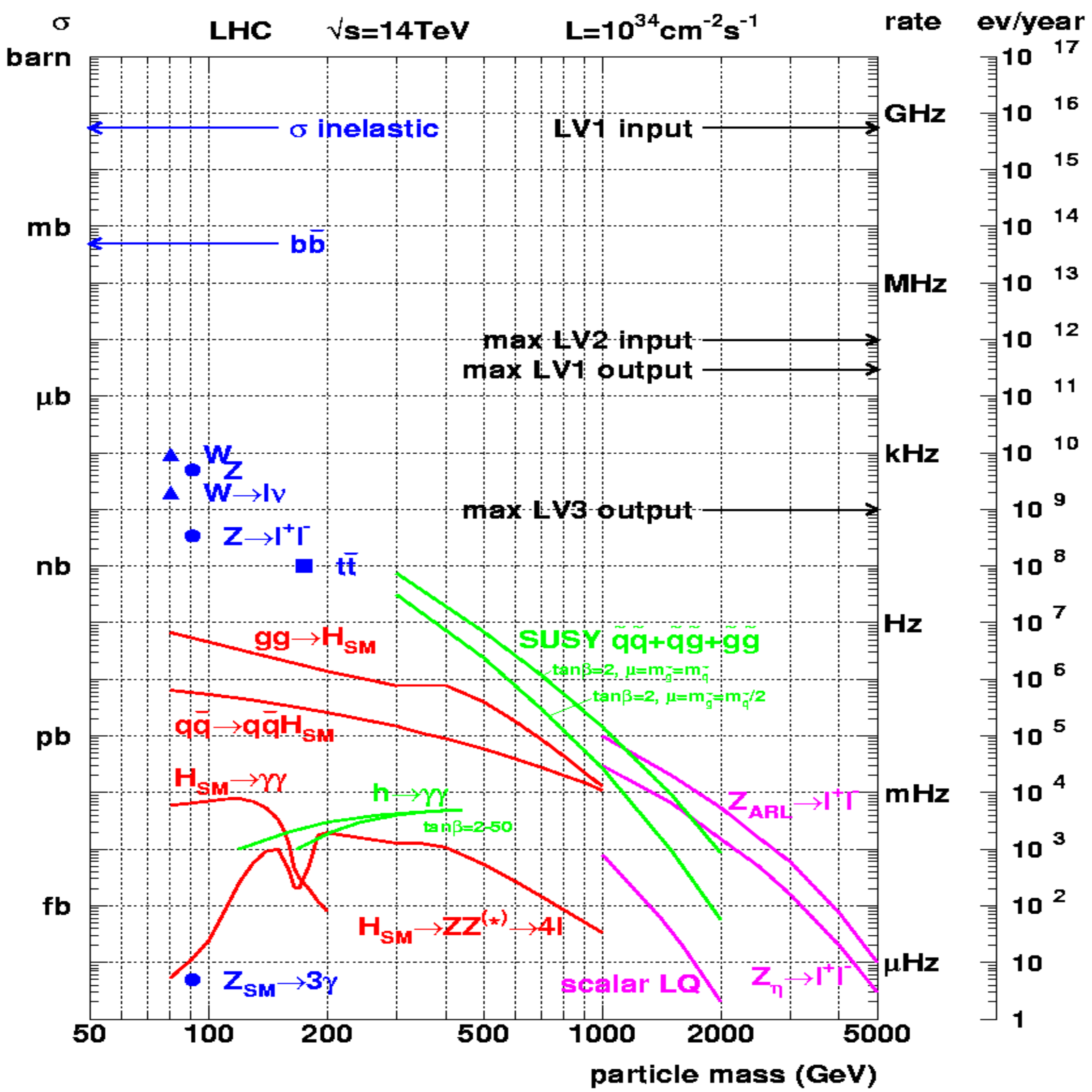
Heavy flavour physics

Standard Model physics including QCD jets

Higgs searches

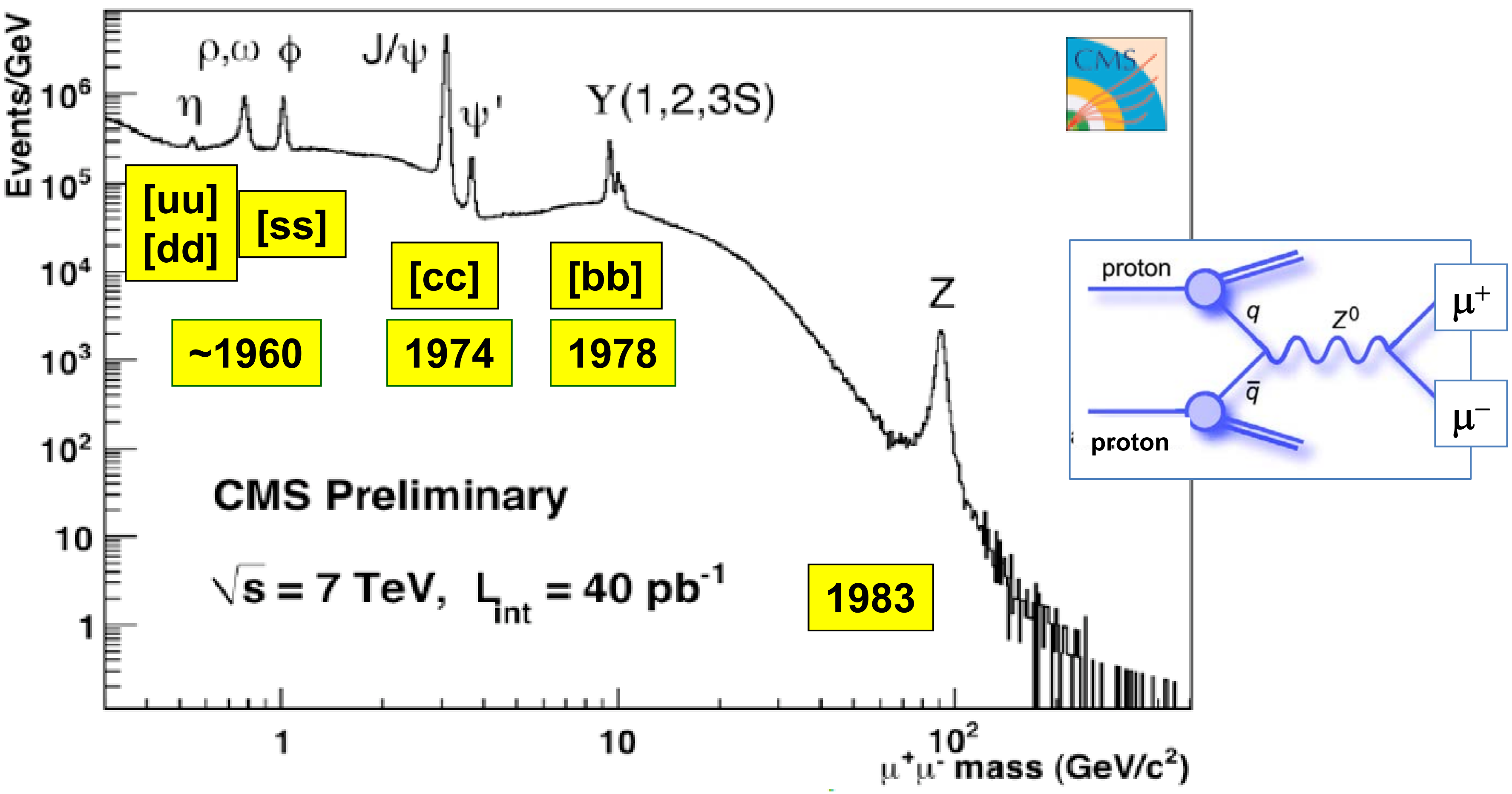
Searches for SUSY

Searches for 'exotic' new physics



2010

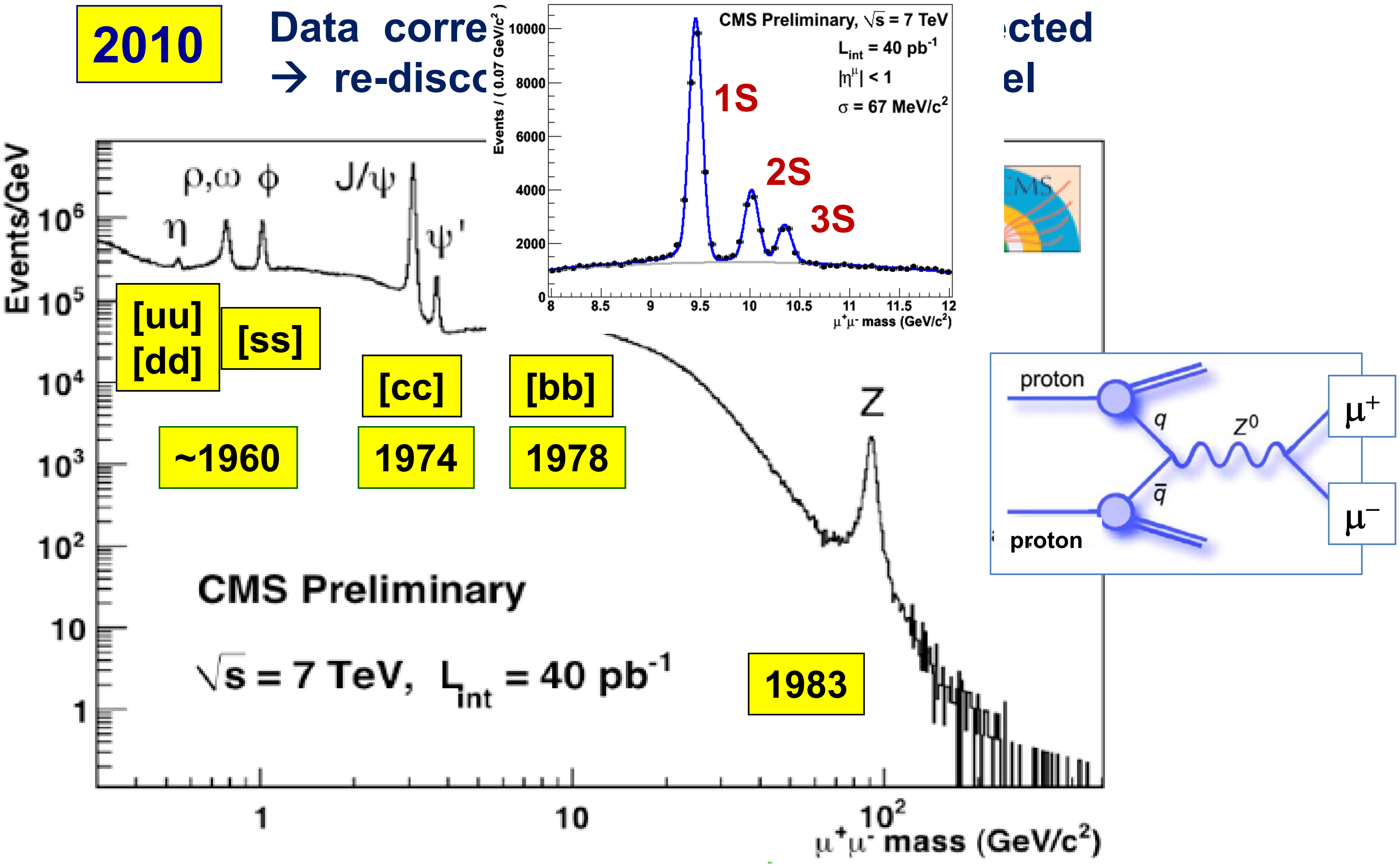
Data corresponding to ~40 pb^{-1} collected
→ re-discovery of the Standard Model



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

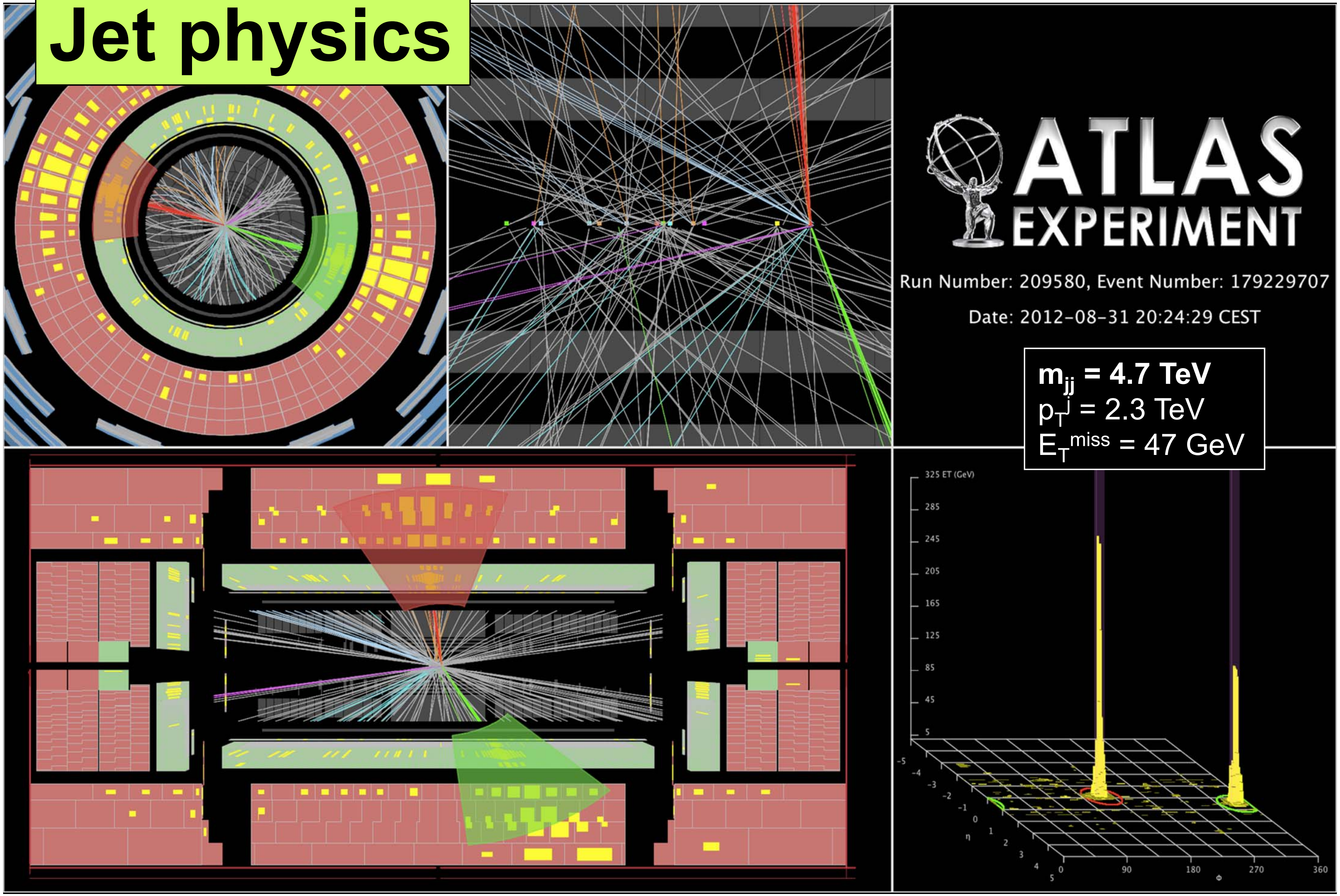
2010

Data corre… …cted
→ re-disco… …el



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

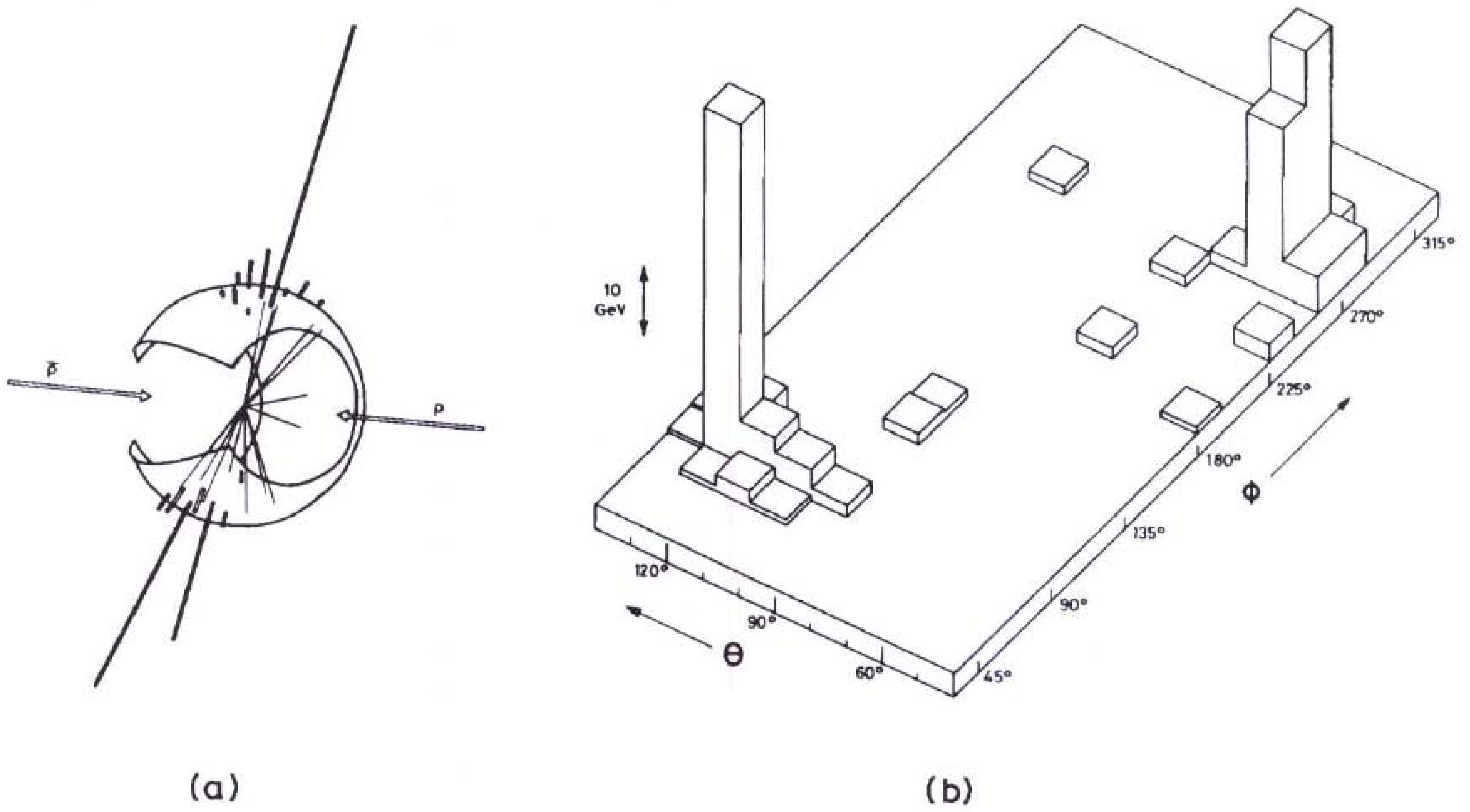
Jet physics

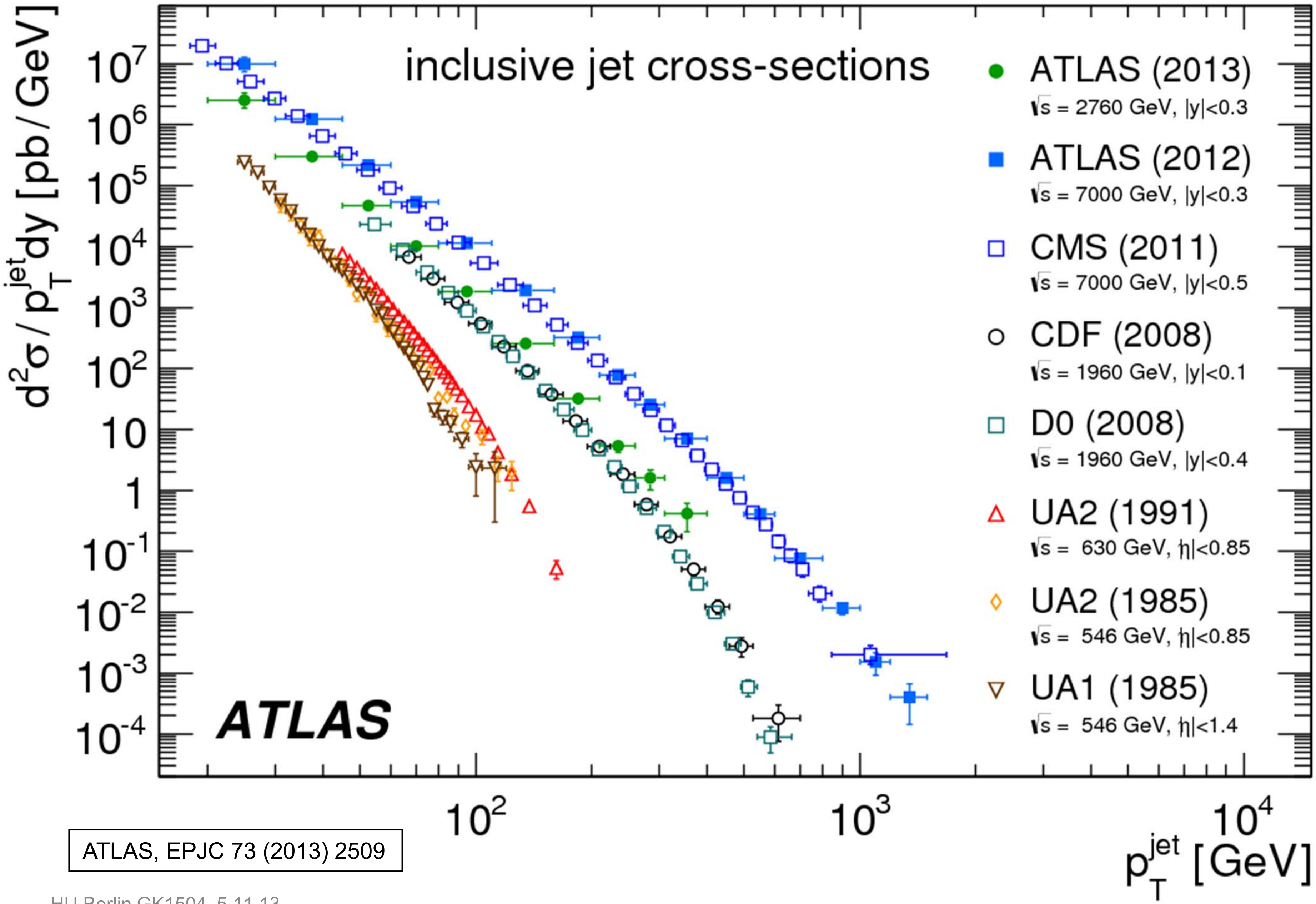


ATLAS
EXPERIMENT
Run Number: 209580, Event Number: 179229707
Date: 2012-08-31 20:24:29 CEST
m_{jj} = 4.7 TeV
p_T^j = 2.3 TeV
E_T^{miss} = 47 GeV
325 ET (GeV)
η
φ

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

Volume 118B, number 1, 2, 3 PHYSICS LETTERS 2 December 1982

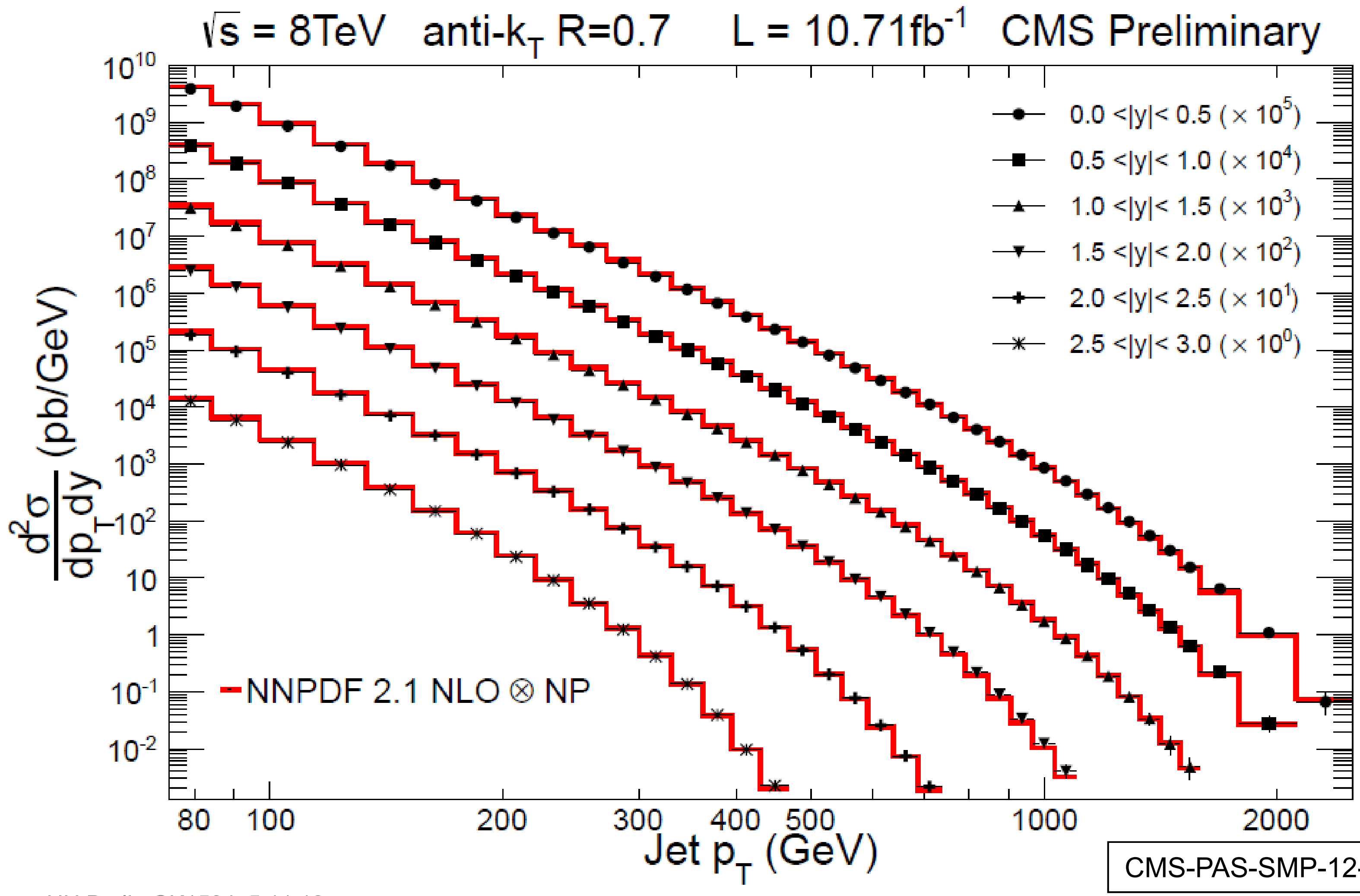




ATLAS, EPJC 73 (2013) 2509

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

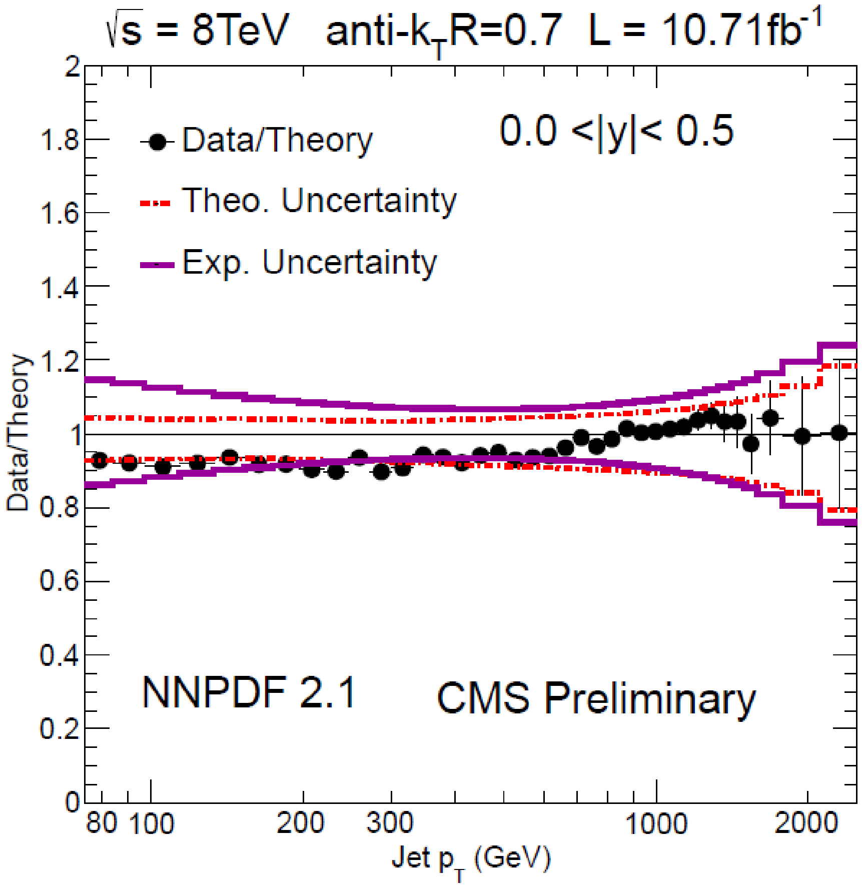
Example: The inclusive jet cross sections as a function of the jet P_T in rapidity bins

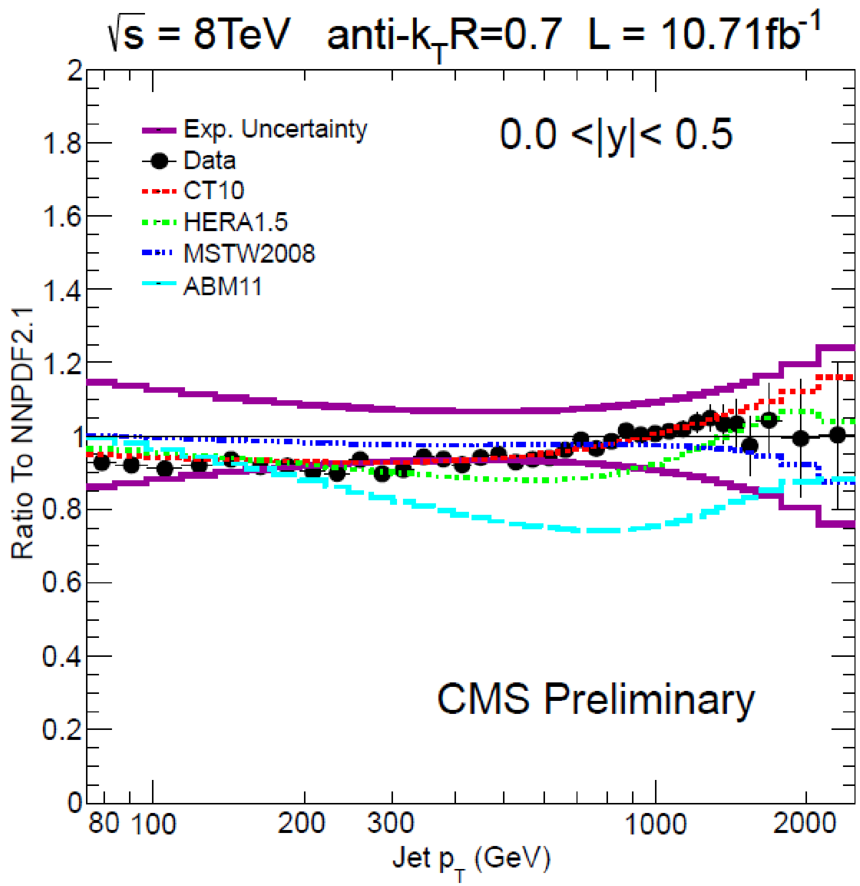


CMS-PAS-SMP-12-012

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



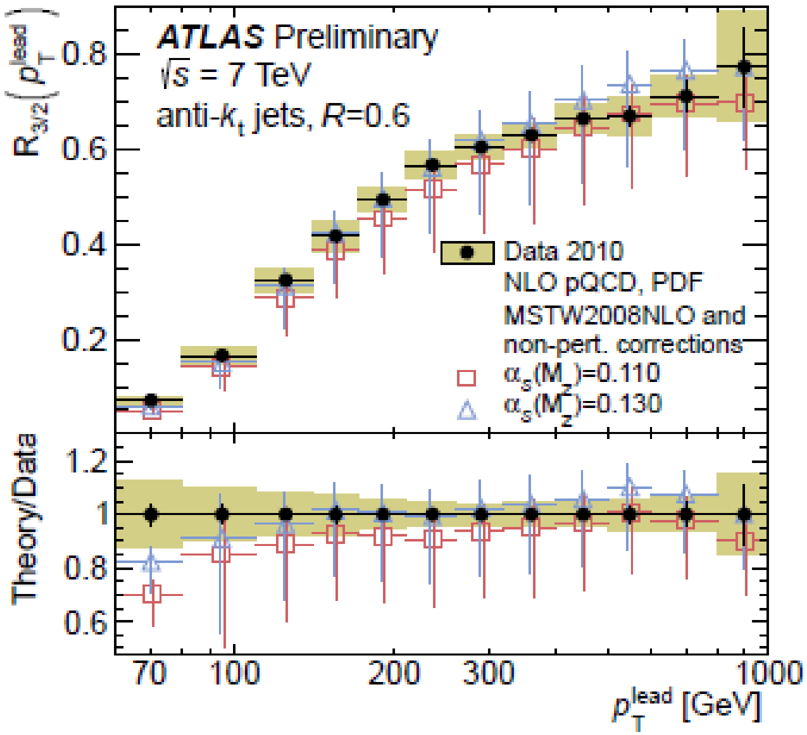


CMS-PAS-SMP-12-012

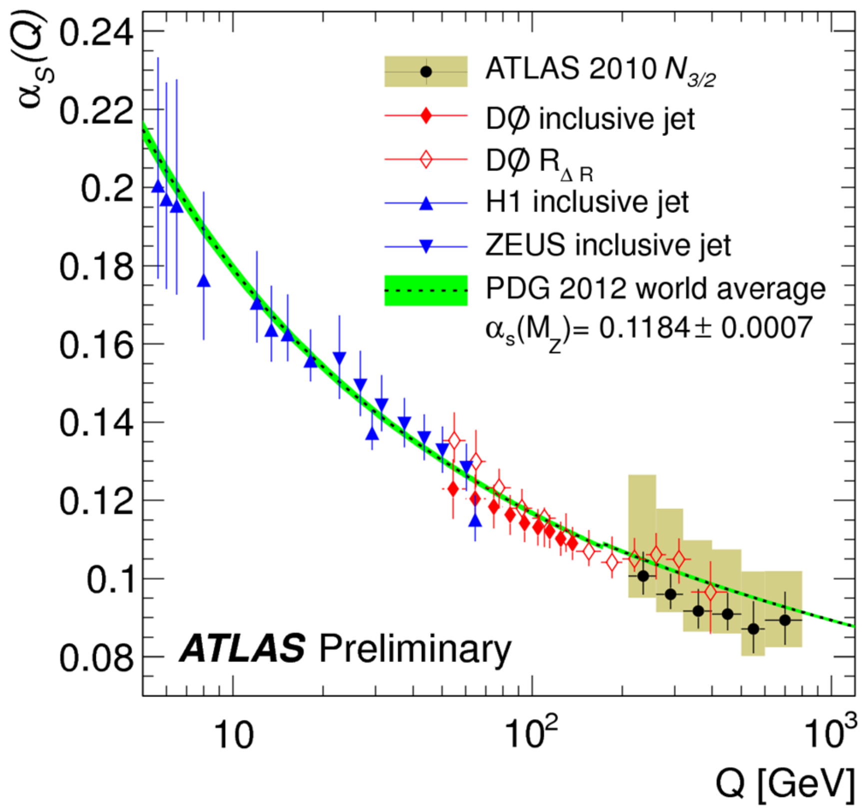
Cross-section ratios of multi-jets allow one to determine α_s

$$R_{3/2}(p_T^{\text{lead}}) = \frac{d\sigma_{N_{\text{jet}}\geq 3}/dp_T^{\text{lead}}}{d\sigma_{N_{\text{jet}}\geq 2}/dp_T^{\text{lead}}}$$

$p_T > 40$ GeV and $|y| < 2.8$.



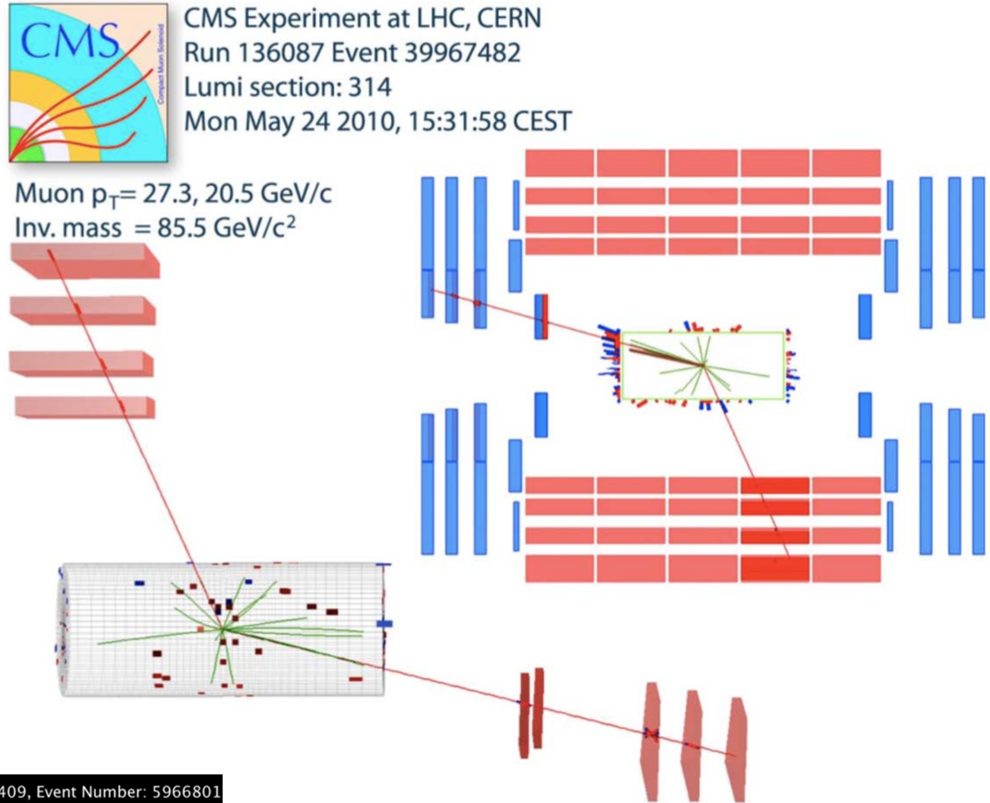
$$\alpha_s(M_Z) = 0.111 \pm 0.006(\text{exp.})\,^{+0.016}_{-0.003}(\text{theory}).$$



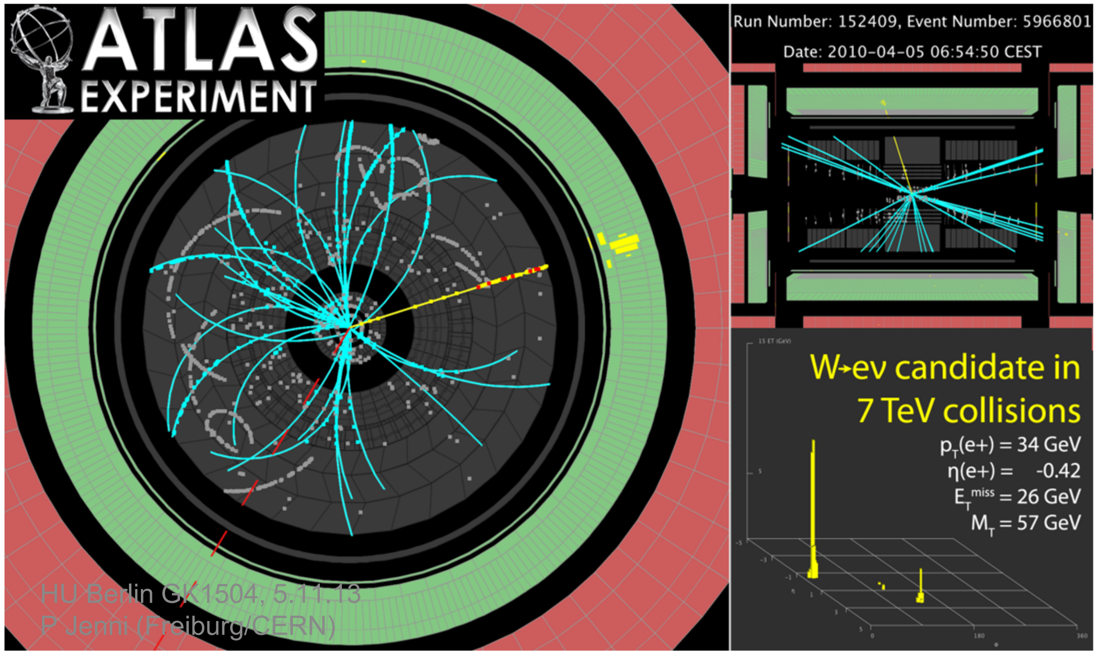
ATLAS-CONF-2013-041

Standard Model Physics

Candidate Z → $\mu^+\mu^-$



W → eν candidate



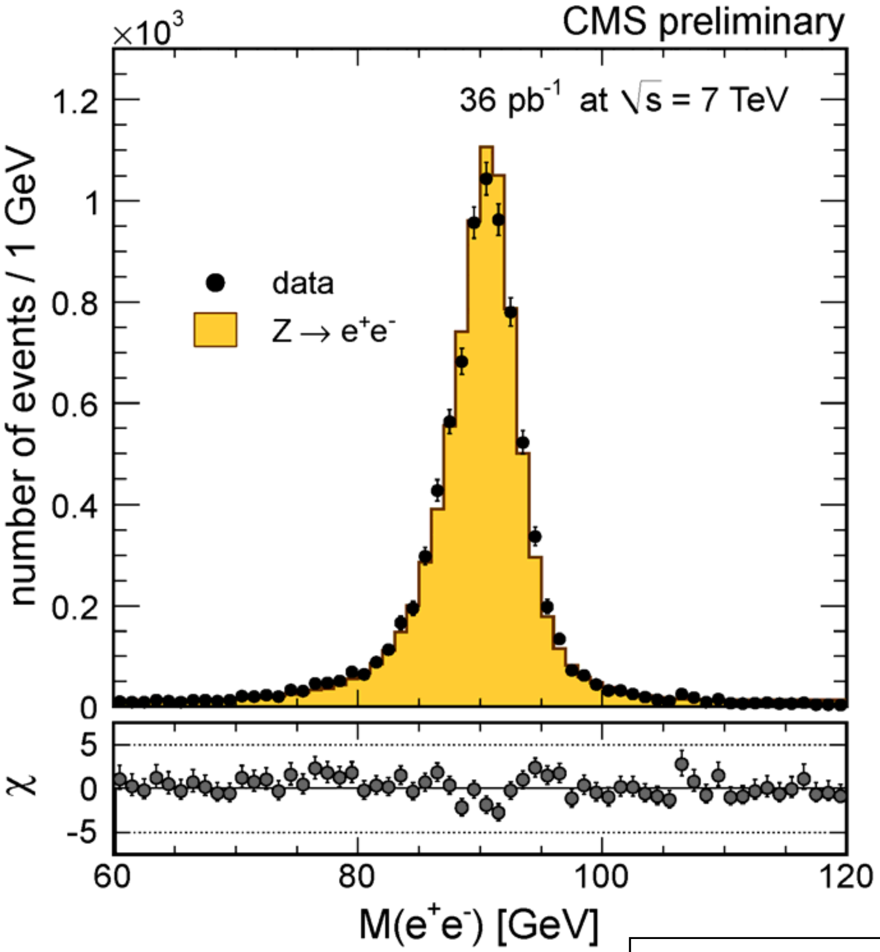
Today each ATLAS and CMS have in their data more than:

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

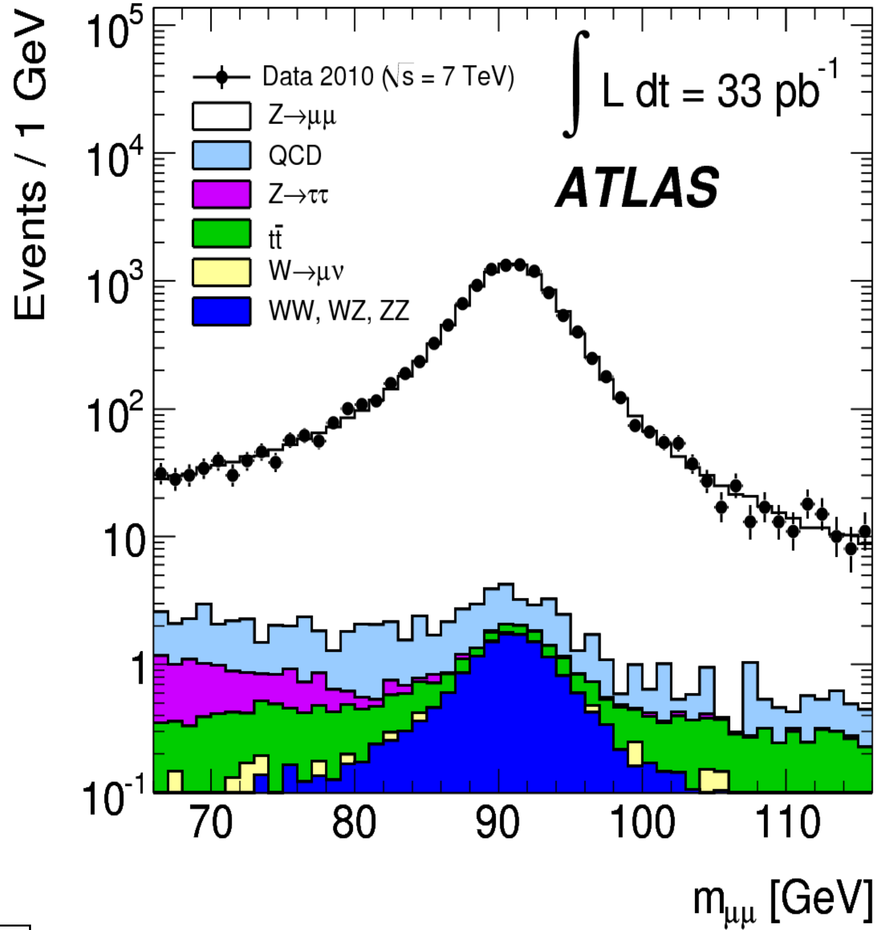
after all selection cuts

Z and W production

Phys Rev D85 (2012) 072004



JHEP 10 (2011) 132

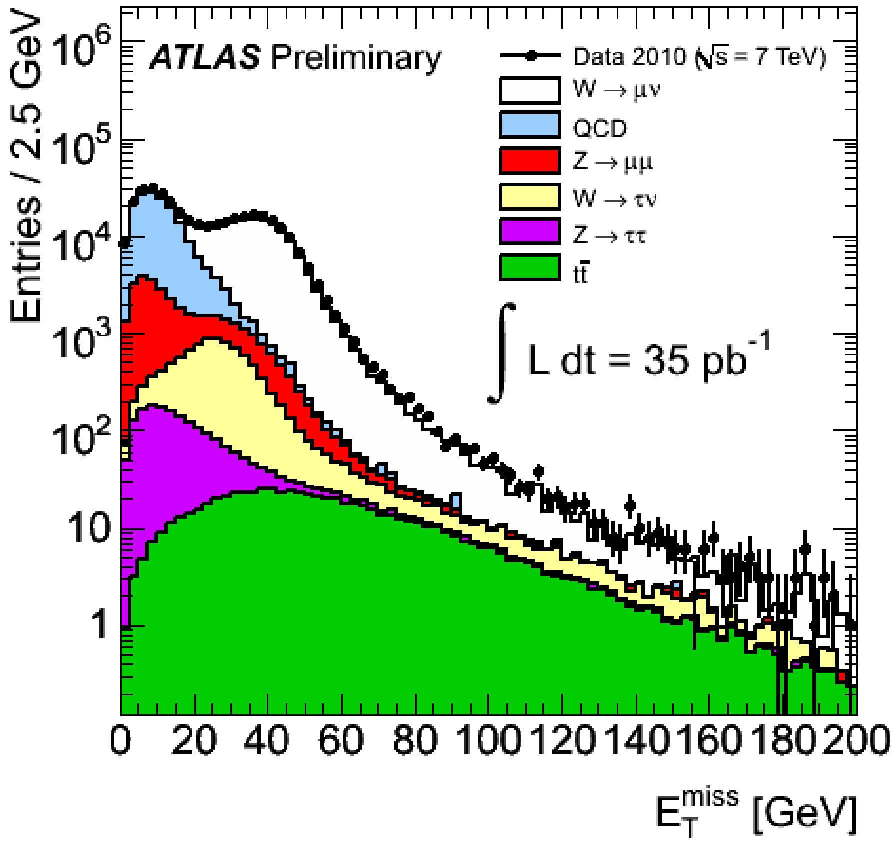


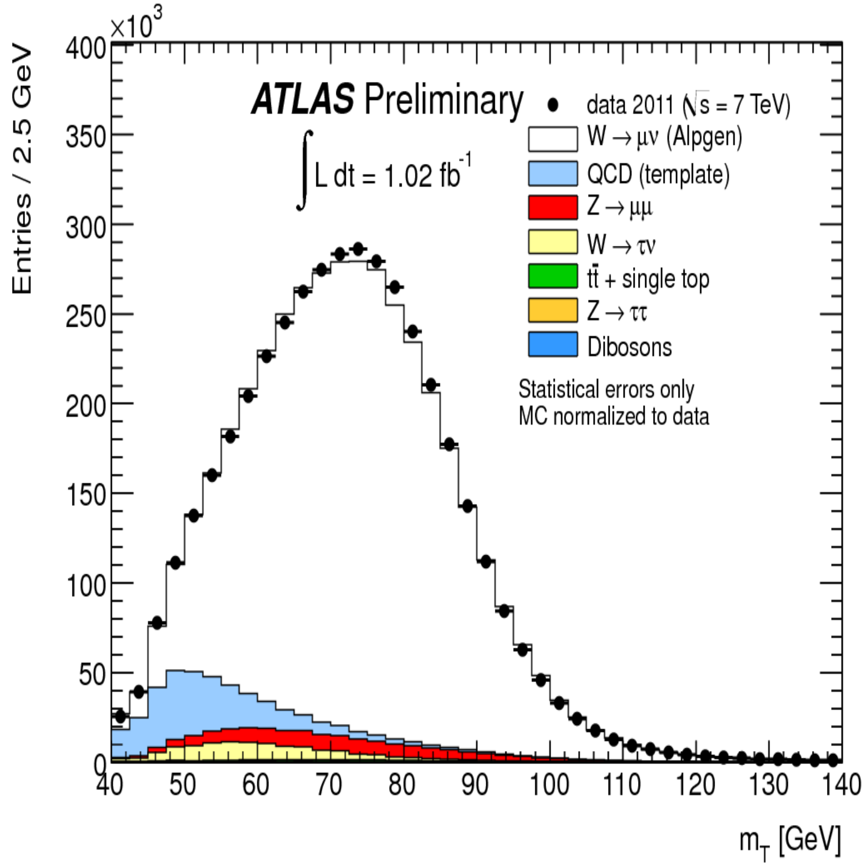
Z peak (di-lepton pair mass distributions, can be extracted essentially background-free)

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

W transverse mass

μ with p_T>20 GeV, E_T^{miss}>25 GeV



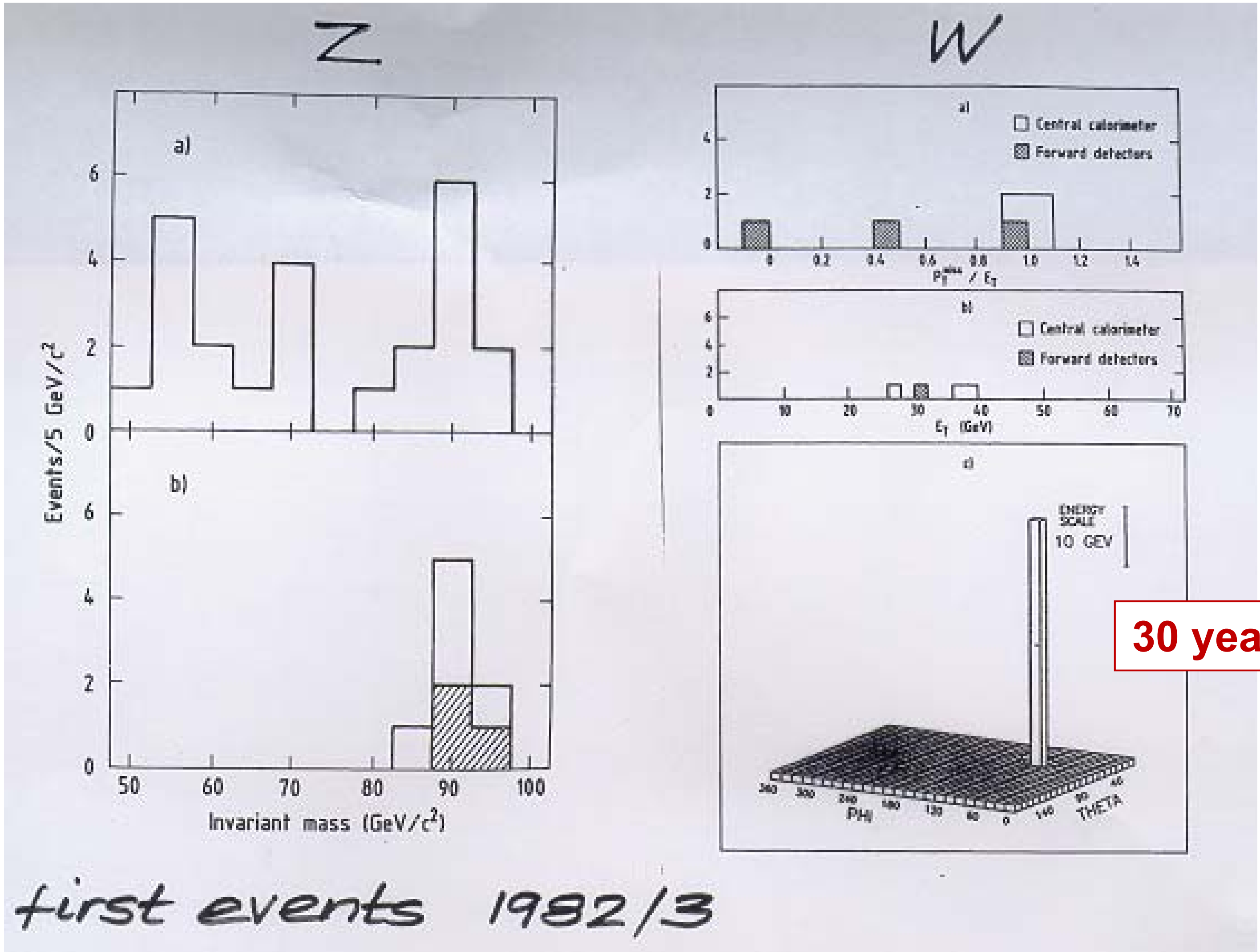


Missing transverse energy from the W → μ + ν decays

ATLAS-CONF-2011-041

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

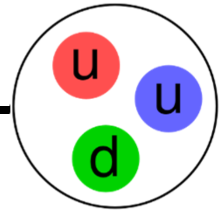
What a contrast to the Intermediate Vector Boson discovery distributions in 1982 and 1983 by UA1 and UA2 …

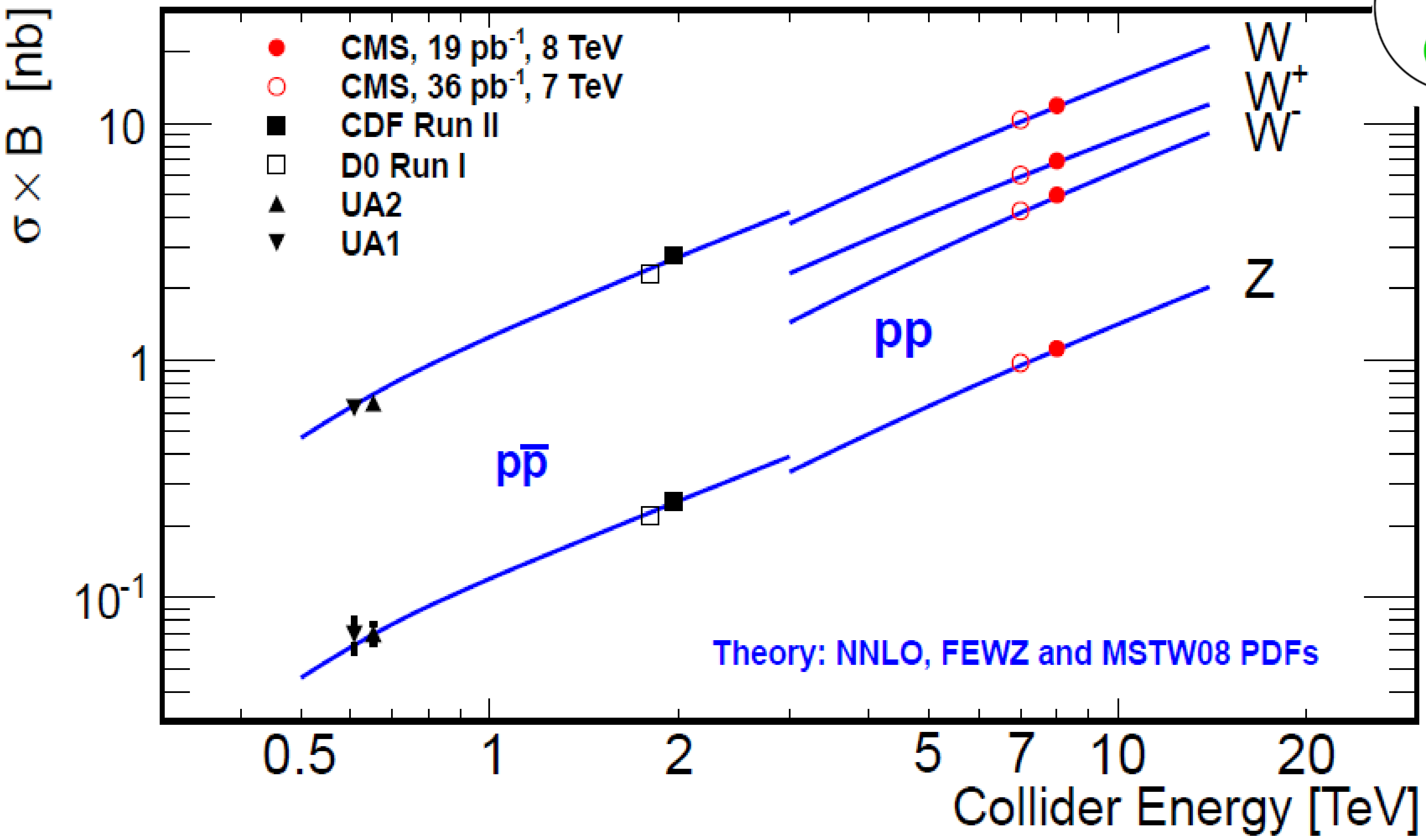


30 years ago!

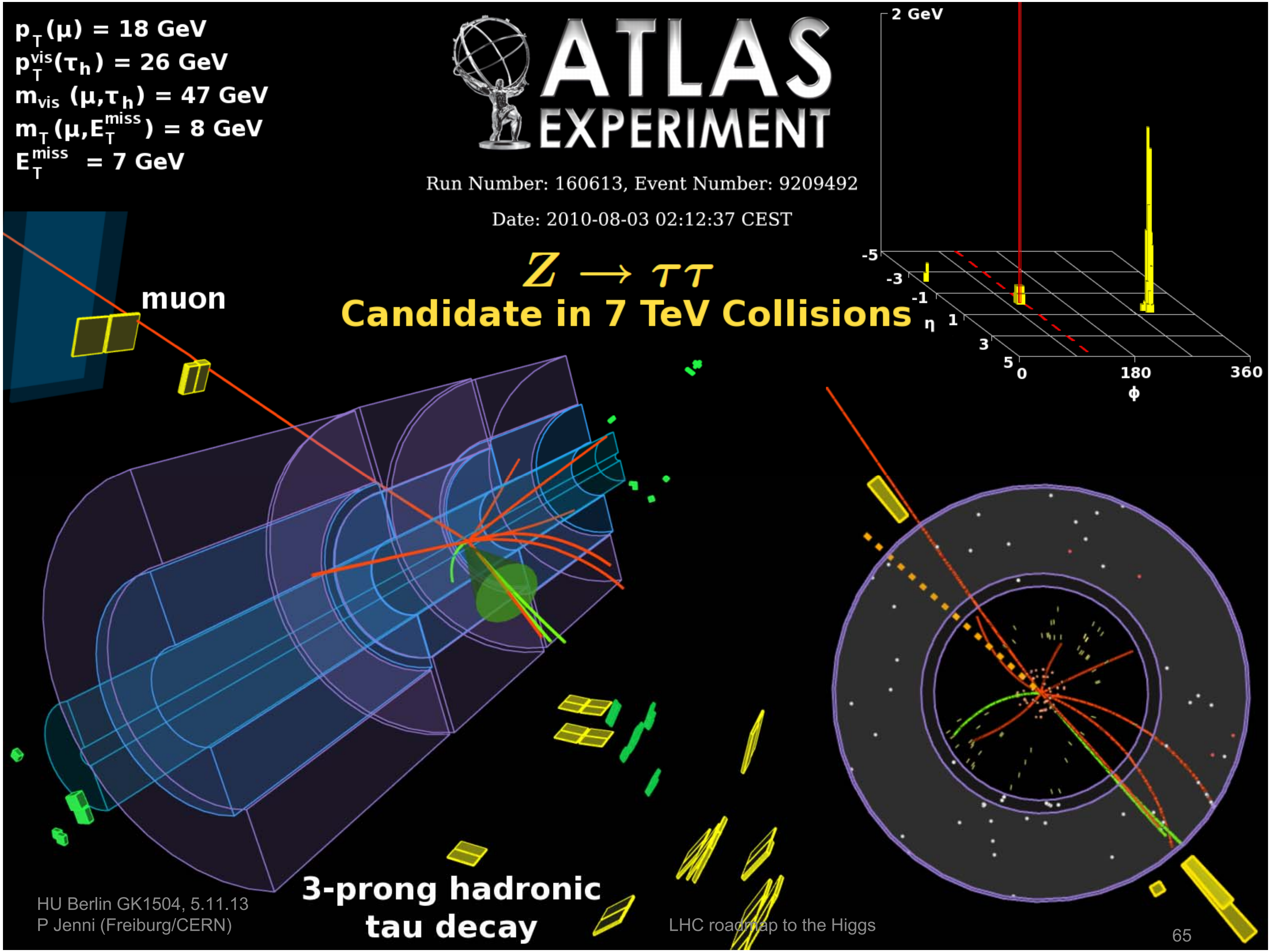
(here are shown the UA2 distributions)

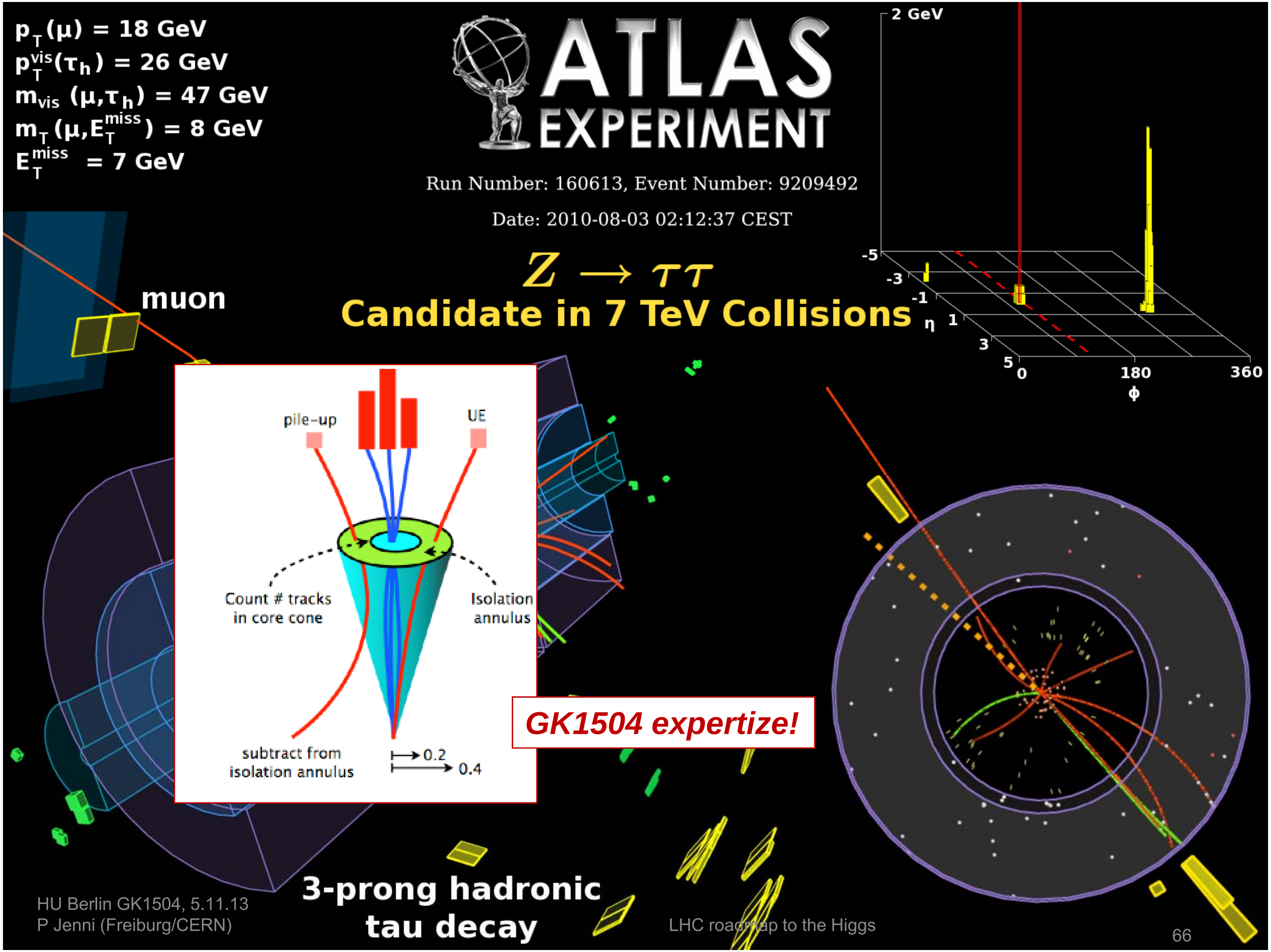
Cross section measurements





CMS-PAS-SMP-12-011

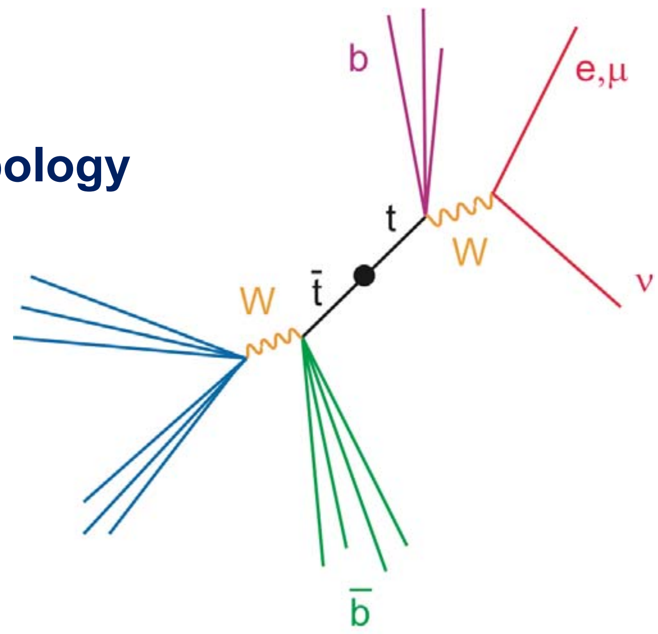

$p_T(\mu)$ = 18 GeV
$p_T^{vis}(\tau_h)$ = 26 GeV
m_{vis} (μ,τ_h) = 47 GeV
m_T (μ, E_T^{miss}) = 8 GeV
E_T^{miss} = 7 GeV
ATLAS EXPERIMENT
Run Number: 160613, Event Number: 9209492
Date: 2010-08-03 02:12:37 CEST
$Z \rightarrow \tau\tau$
Candidate in 7 TeV Collisions
muon
3-prong hadronic tau decay
2 GeV
-5
-3
-1
1
3
5
η
0
180
360
ϕ



p_T(μ) = 18 GeV
p_T^vis(τ_h) = 26 GeV
m_vis (μ,τ_h) = 47 GeV
m_T (μ,E_T^miss) = 8 GeV
E_T^miss = 7 GeV
ATLAS EXPERIMENT
Run Number: 160613, Event Number: 9209492
Date: 2010-08-03 02:12:37 CEST
Z → ττ
Candidate in 7 TeV Collisions
2 GeV
-5
-3
-1
1
3
5
η
0
180
360
φ
muon
pile-up
UE
Count # tracks
in core cone
Isolation
annulus
subtract from
isolation annulus
0.2
0.4
GK1504 expertize!
3-prong hadronic
tau decay
HU Berlin GK1504, 5.11.13
P Jenni (Freiburg/CERN)
LHC roadmap to the Higgs
66

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

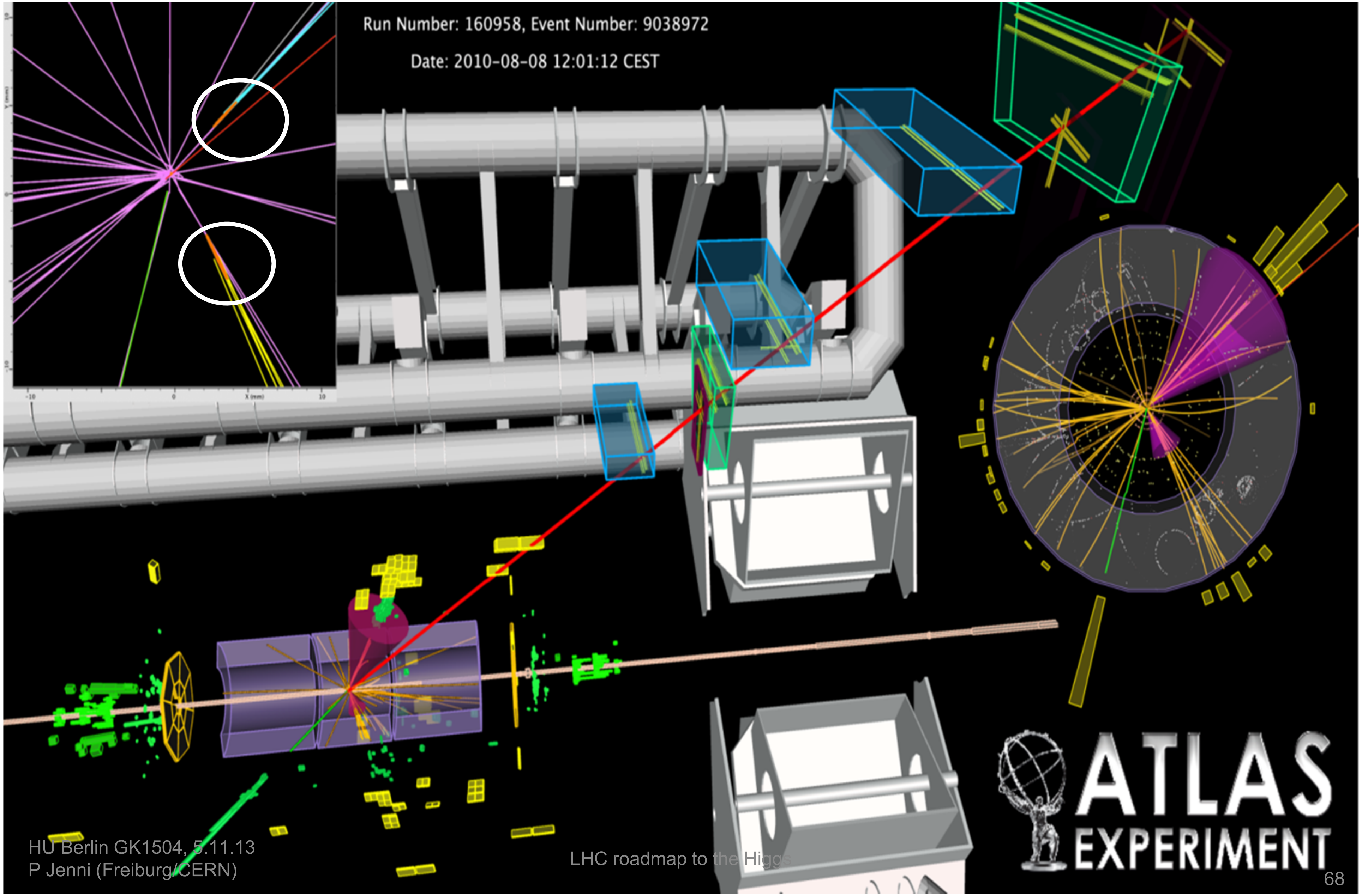


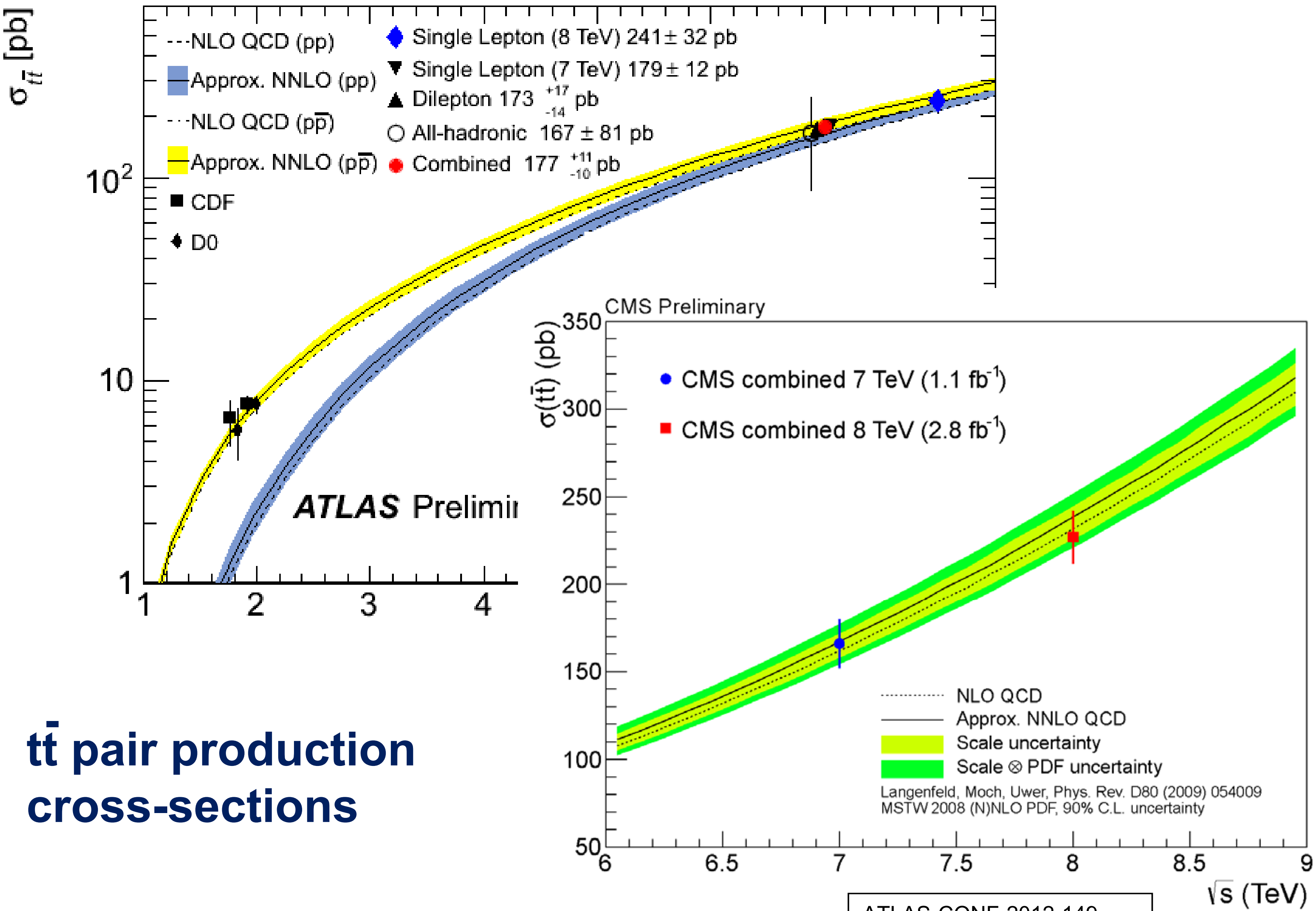
- Assume all tops decay to Wb: event topology then depends on the W decays:
  - one lepton (e or μ), E_T^{miss}, jjbb (37.9%)
  - di-lepton (ee, $\mu\mu$ or eμ), E_T^{miss}, bb (6.5%)

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

$t\bar{t}$ candidate event

e + μ + 2 jets (b-tagged) +ETmiss



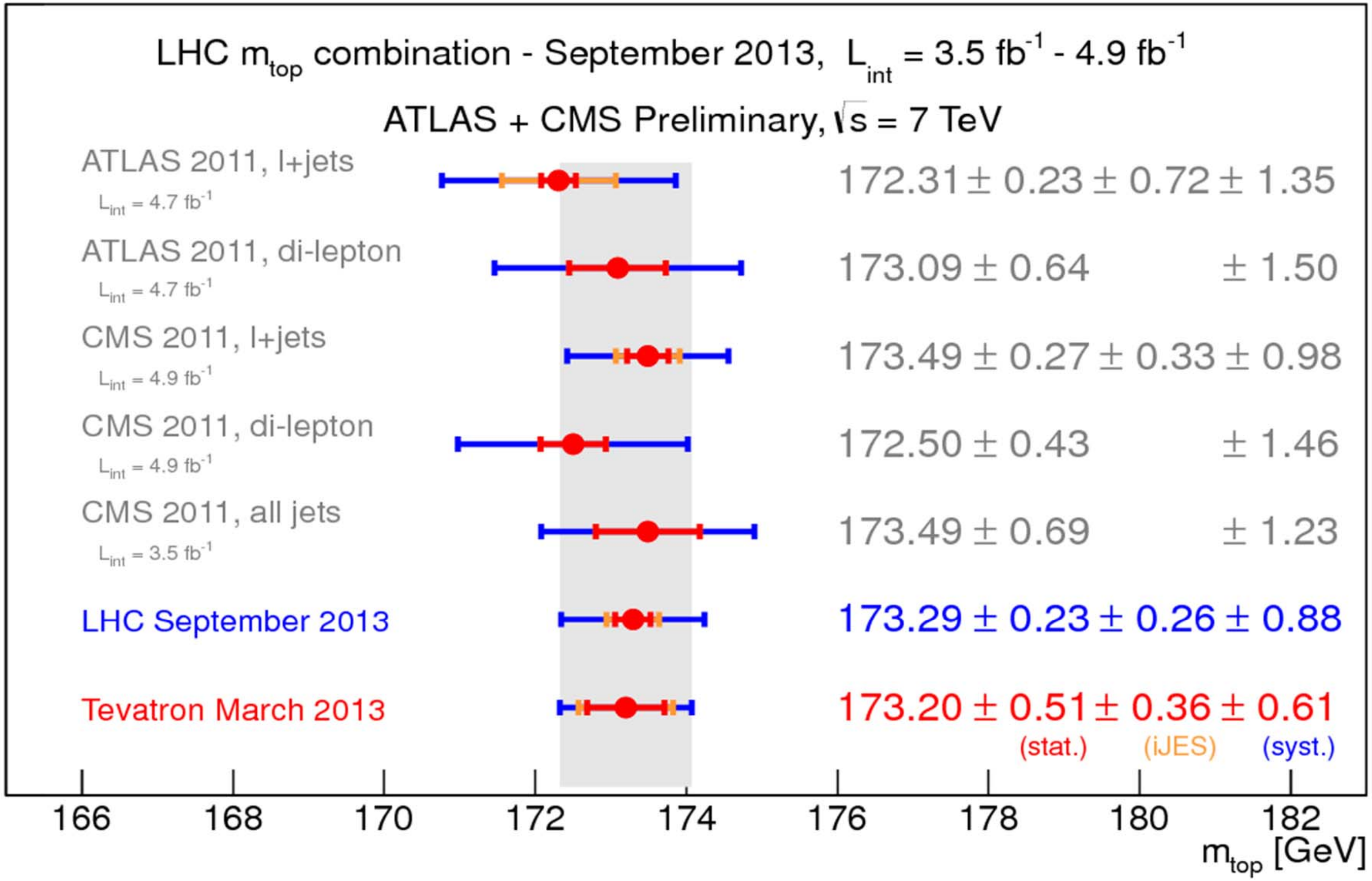


tt̄ pair production cross-sections

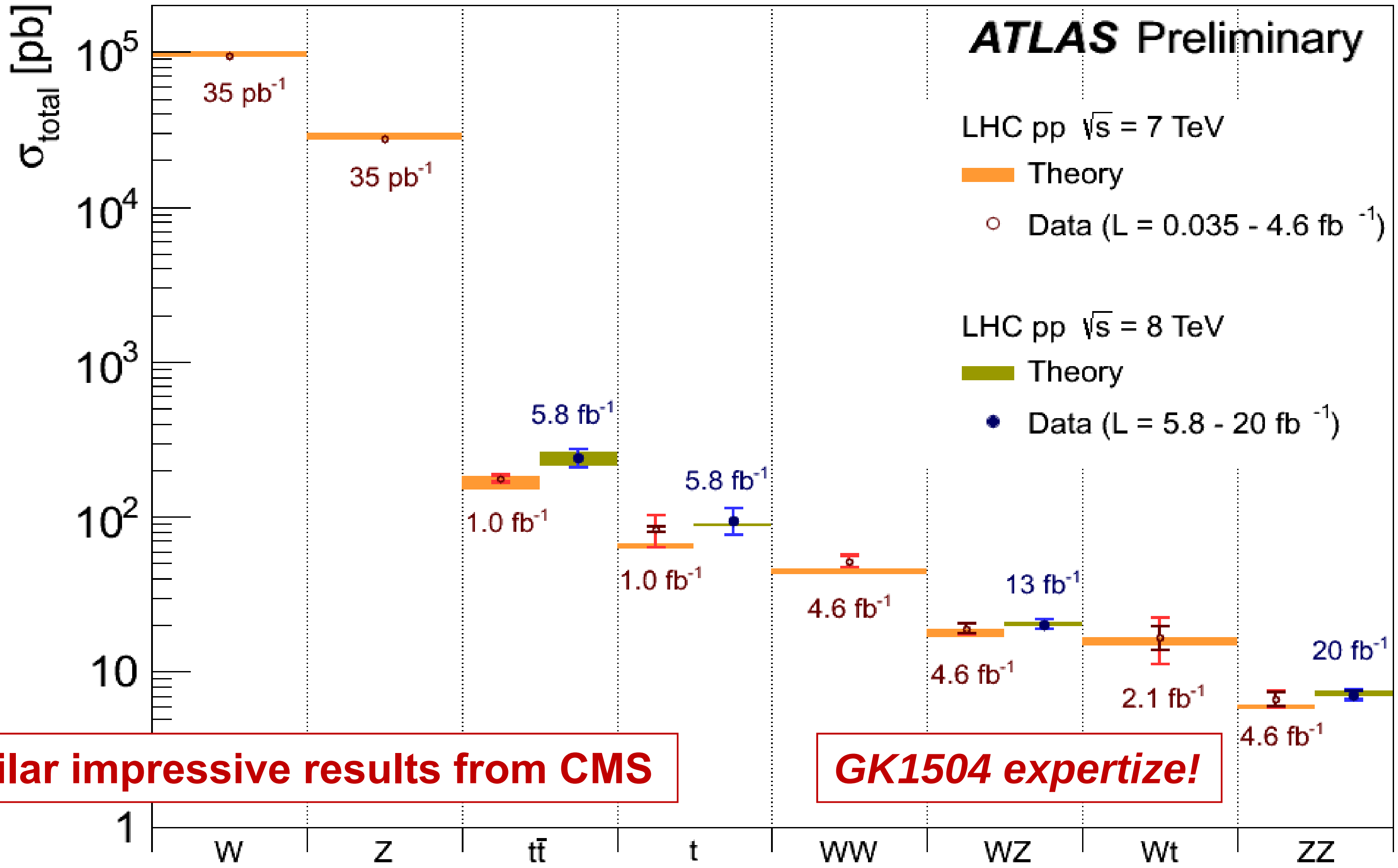
ATLAS-CONF-2012-149
CMS-PAS-TOP-12-006, 007

ATLAS-CONF-2013-102
CMS-PAS-TOP-13-005

Top quark mass measurements



A summary of Standard Model measurements



Similar impressive results from CMS

GK1504 expertize!

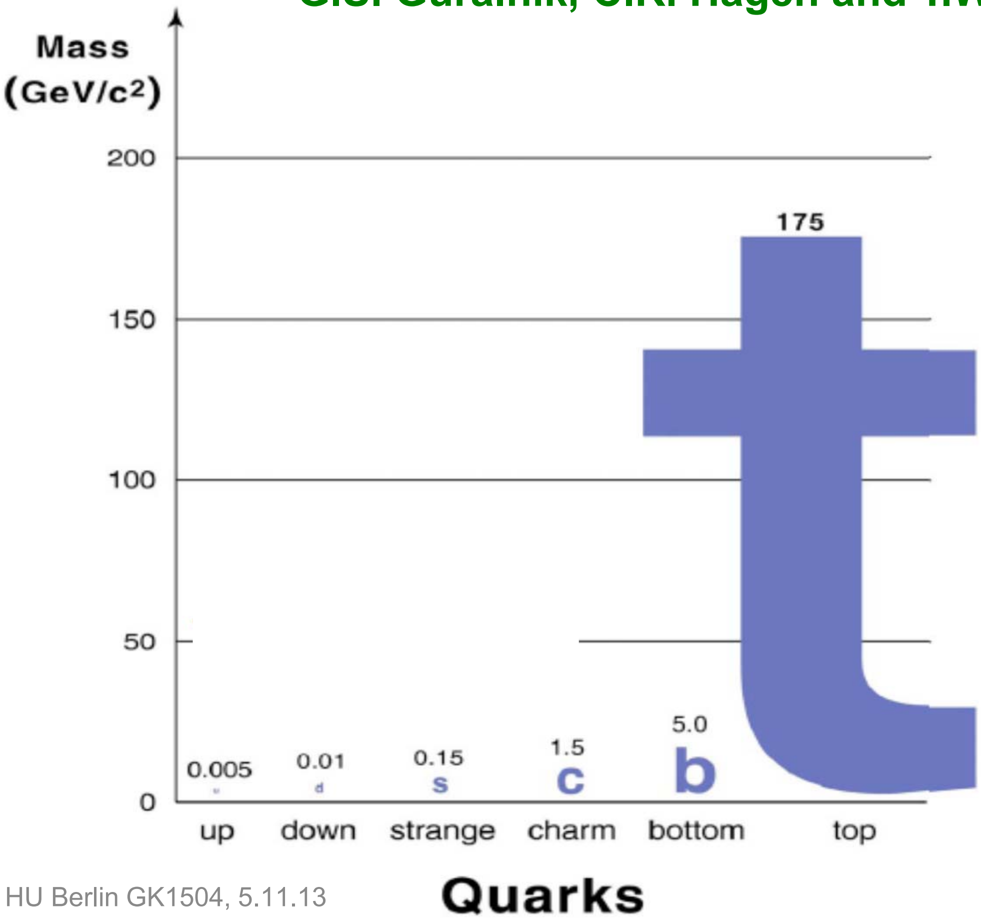
The excellent performance in measuring Standard Model physics gives confidence for the readiness of the two experiments to search for New Physics


HIGGS BOSON

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

The mass mystery for fundamental particles 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

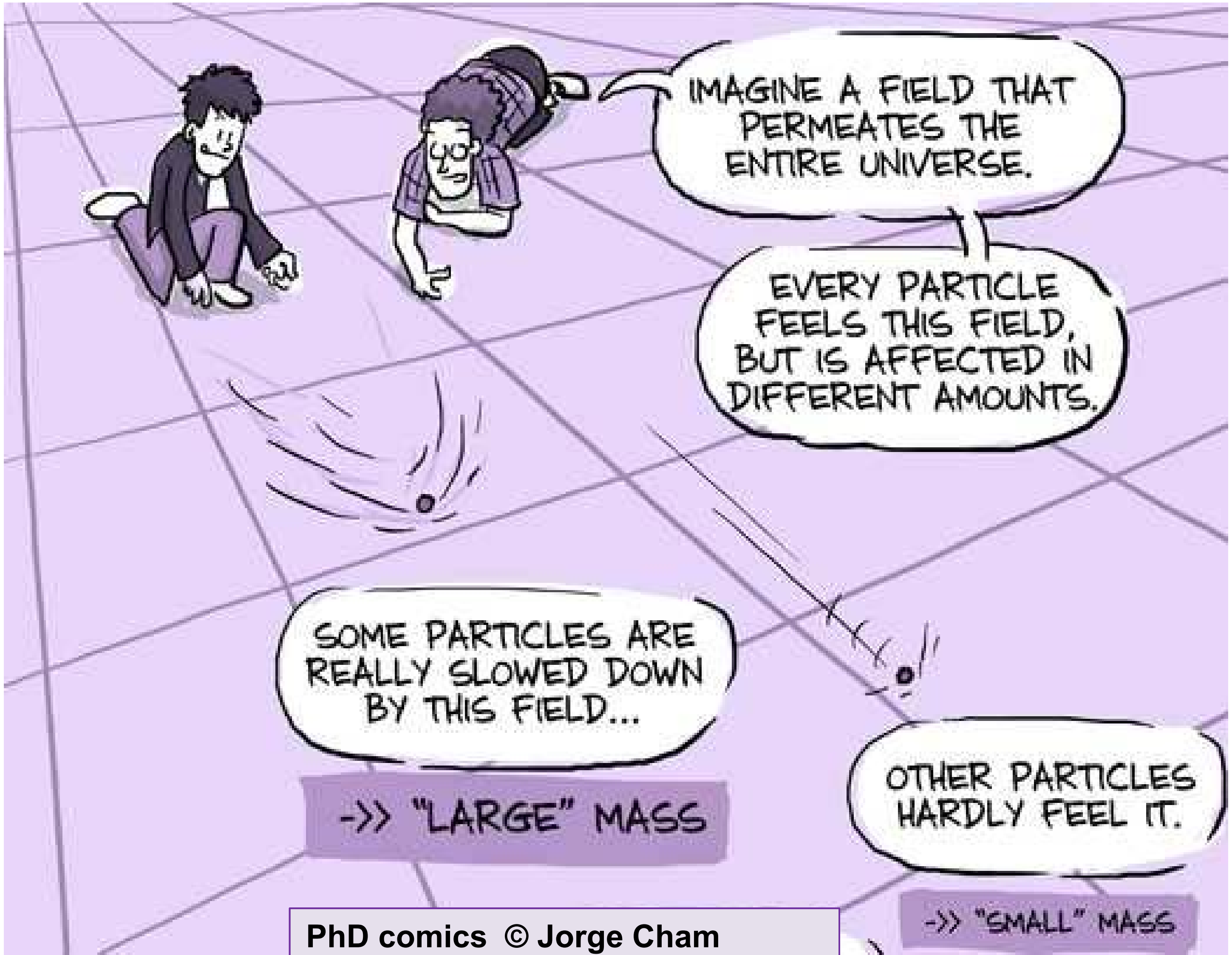


The Higgs (H) particle has been searched for since decades at accelerators …

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

Francois Englert

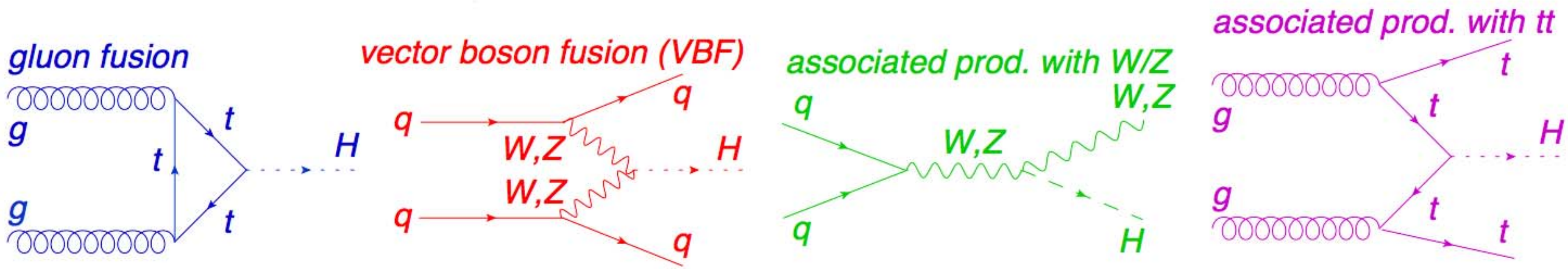
A cartoon ‘illustrating’ the scalar Brout-Englert-Higgs field filling all space that affects elementary particles, and ‘gives’ them their mass by interacting with them

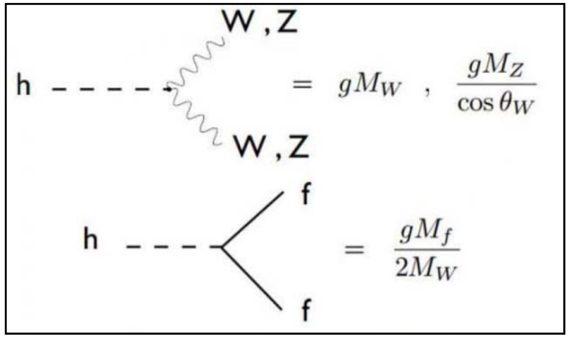


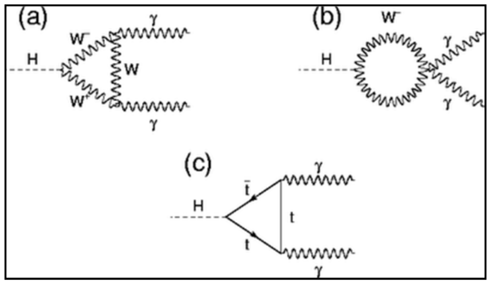
PhD comics © Jorge Cham
http://www.phdcomics.com/higgs/

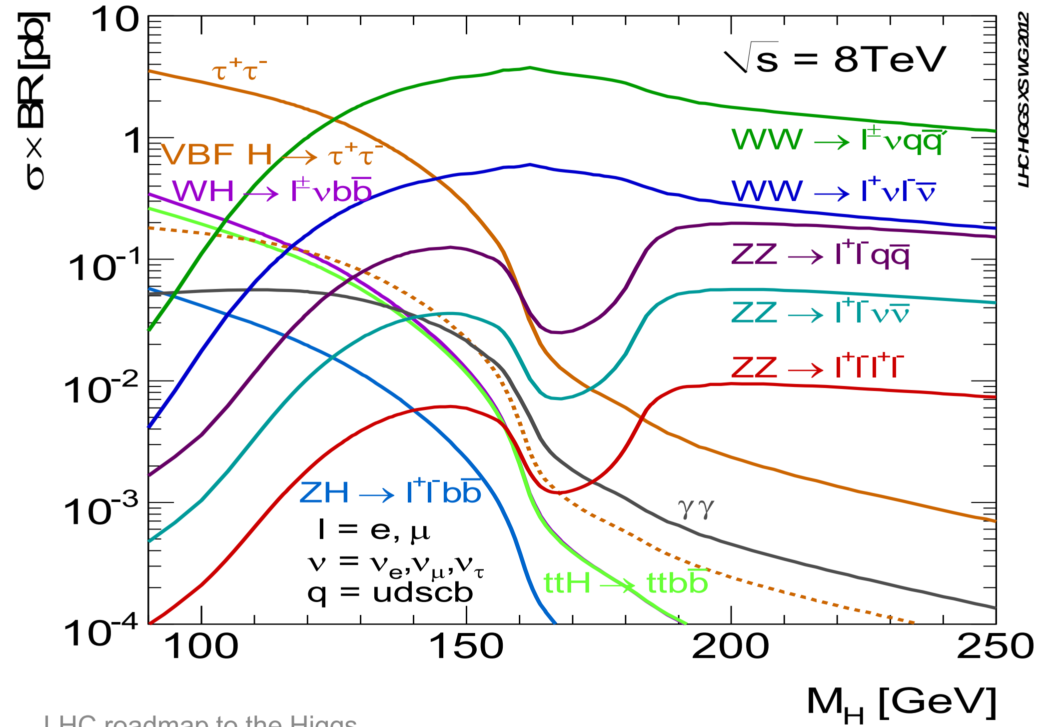
Search for the boson (H) of the EW symmetry breaking

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



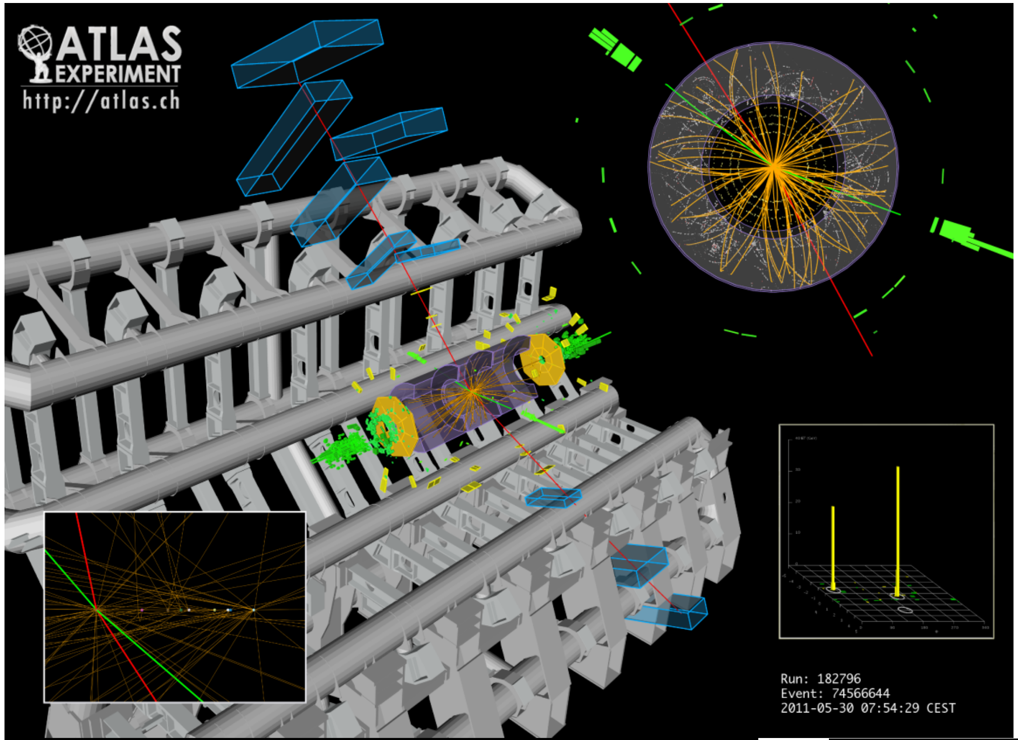






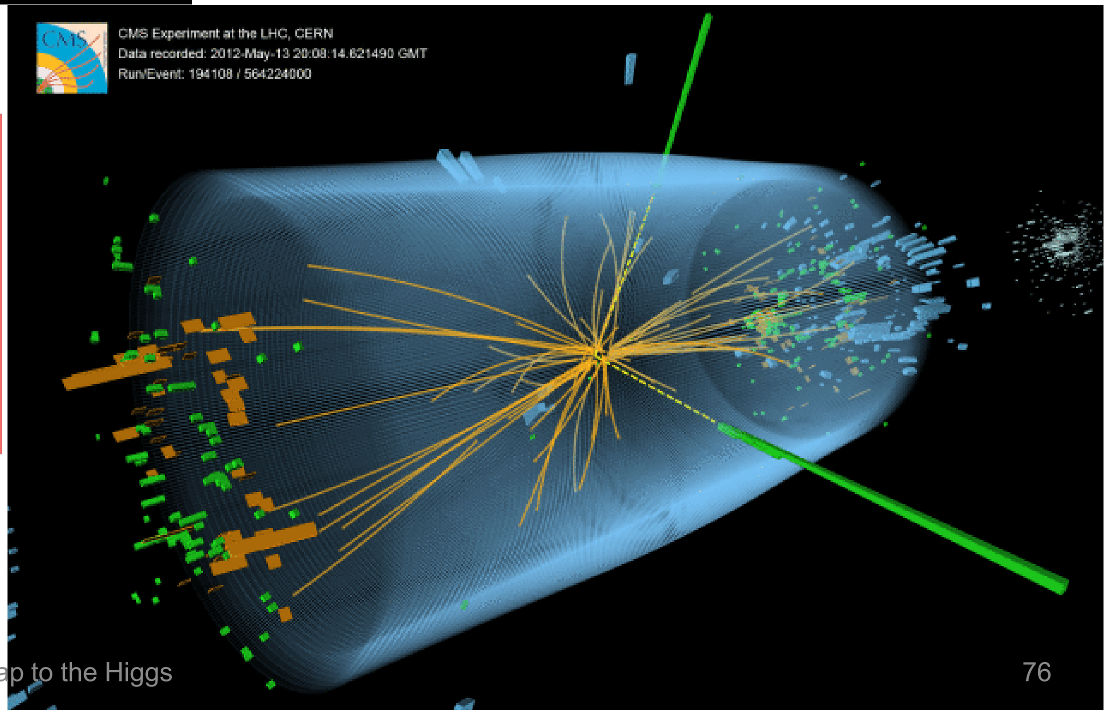
LHC roadmap to the Higgs

Discovery of the Higgs boson

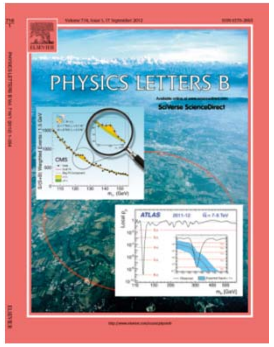


Candidate event for H → ZZ^* → ee $\mu\mu$

Candidate event for H → $\gamma\gamma$



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

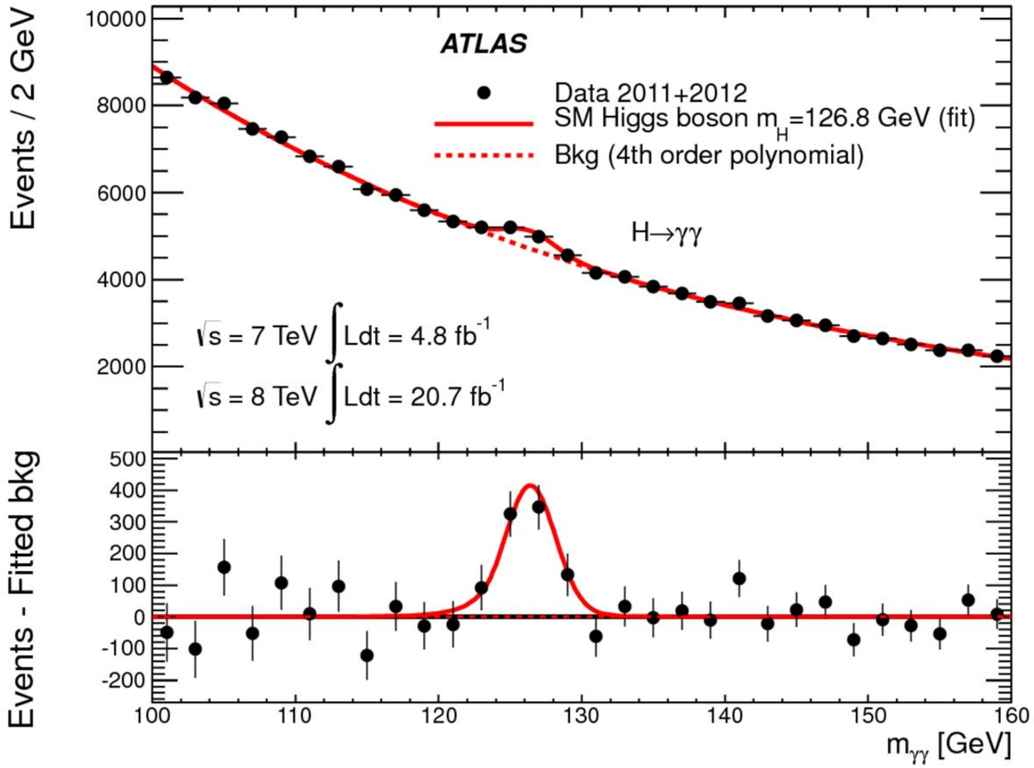
Phys. Lett. B 716 (2012) 30

Very happy faces after the announcement of the discovery on 4th July 2012 at CERN and at ICHEP Melbourne

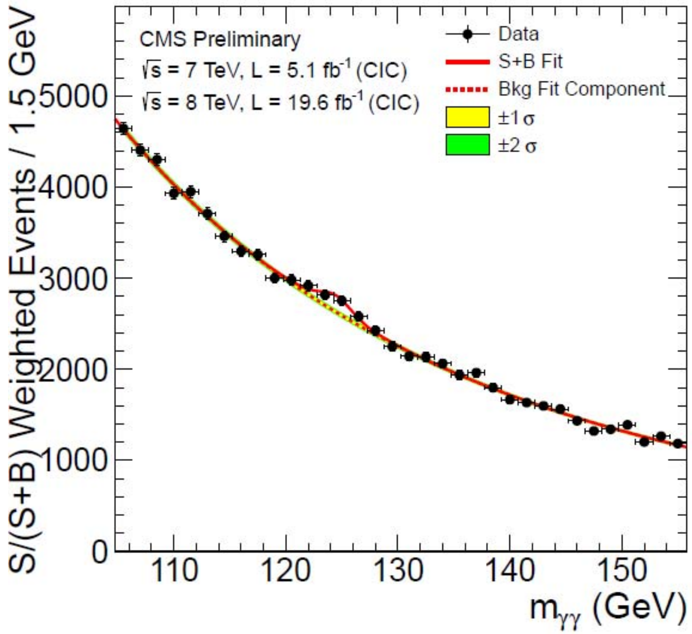
ICHEP2012
Melbourne

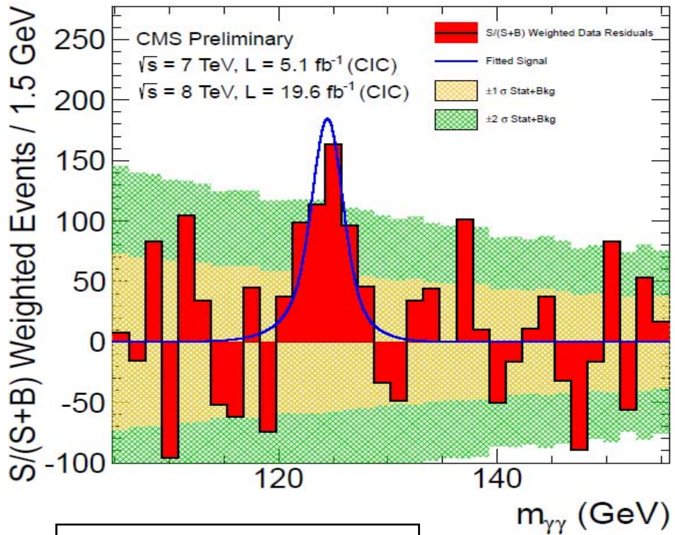
H → γγ

- 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 and Phys. Lett. B 726 (2013) 88-119

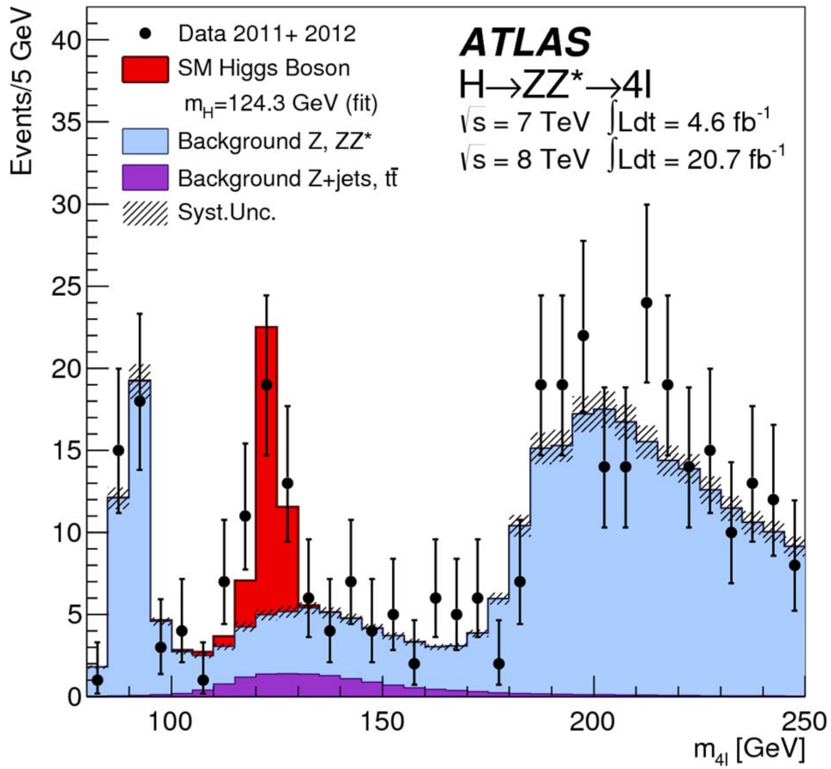




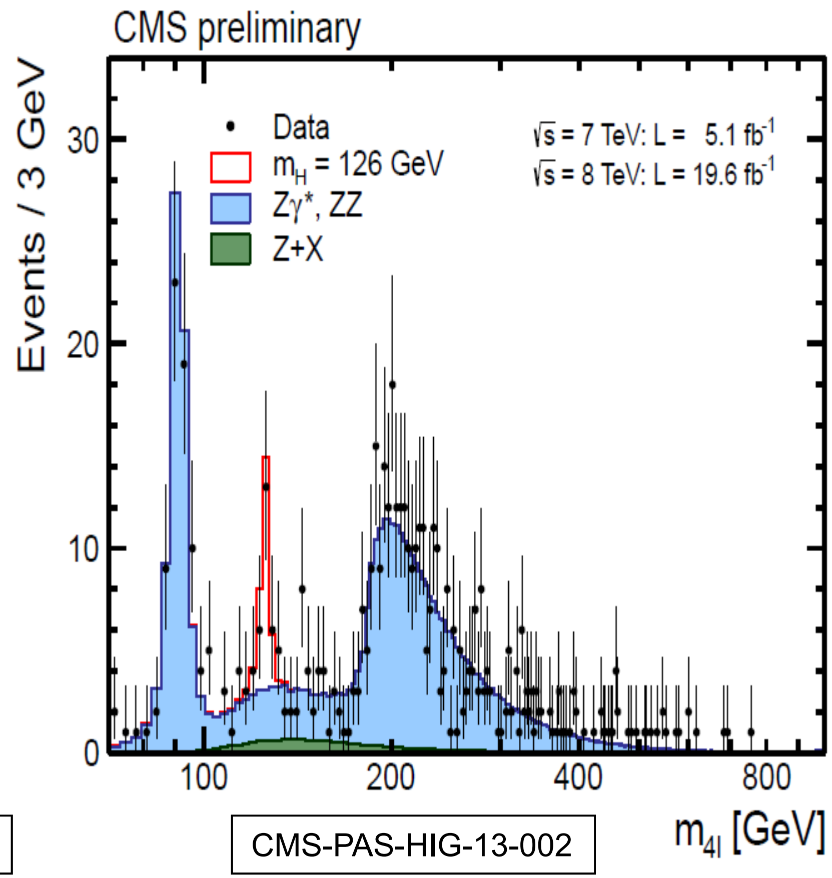
CMS-PAS-HIG-13-001

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (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 and Phys. Lett. B 726 (2013) 88-119

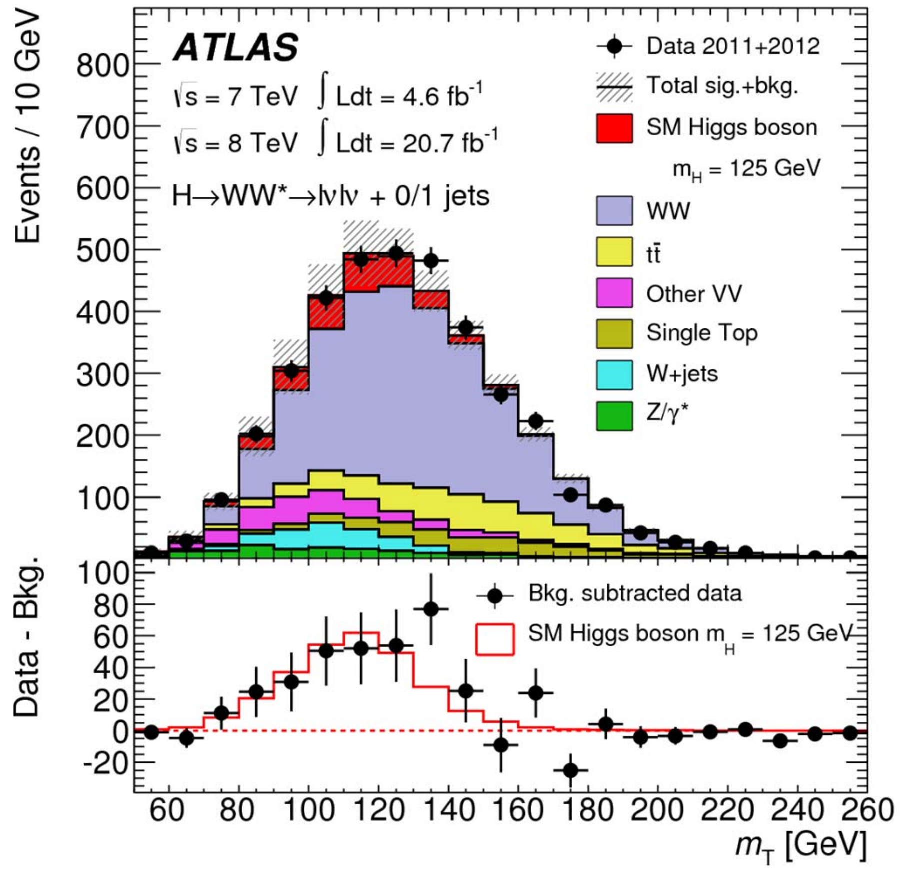


CMS-PAS-HIG-13-002

H → WW(*) → lνlν (eνeν, μνμν, eνμν)

- Very sensitive channel over ~ 125-180 GeV (σ ~ 200 fb)
- Challenging: 2ν → no mass reconstruction/peak → “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)



ATLAS-CONF-2013-030 and Phys. Lett. B 726 (2013) 88-119

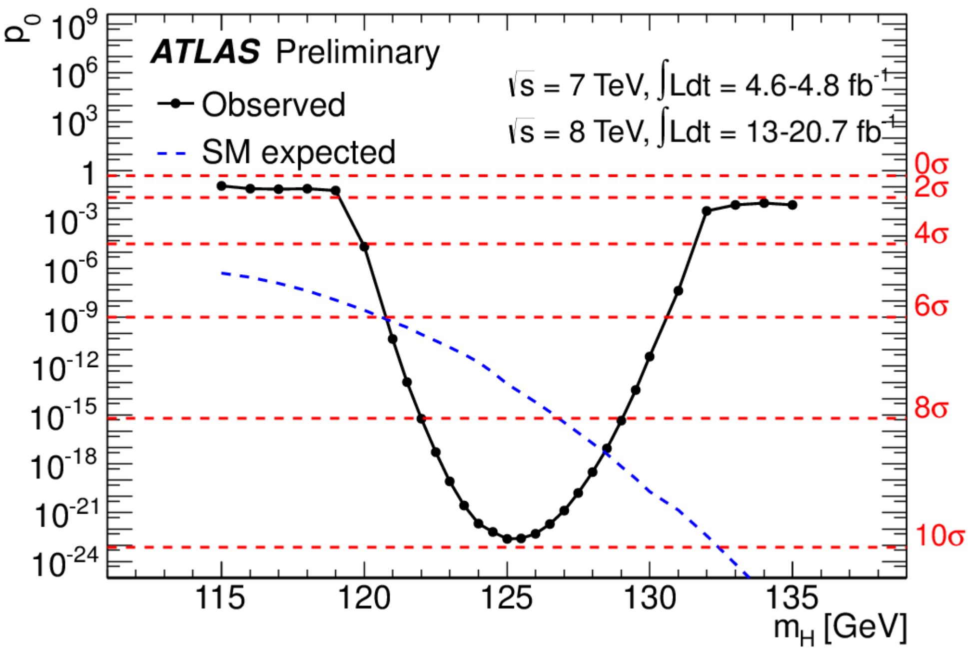
$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$

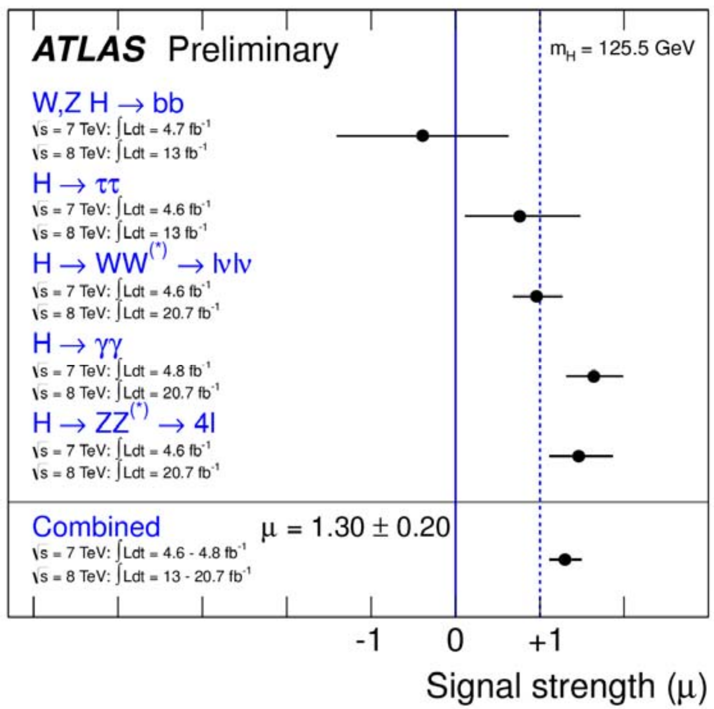
How significant is the signal for the new particle ?

Mass = 125.5 ± 0.2 (stat) ± 0.6 (syst) GeV [ATLAS]
125.7 ± 0.3 (stat) ± 0.3 (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
μ = 0 background only hypothesis
μ = 1 SM Higgs hypothesis





ATLAS-CONF-2013-034

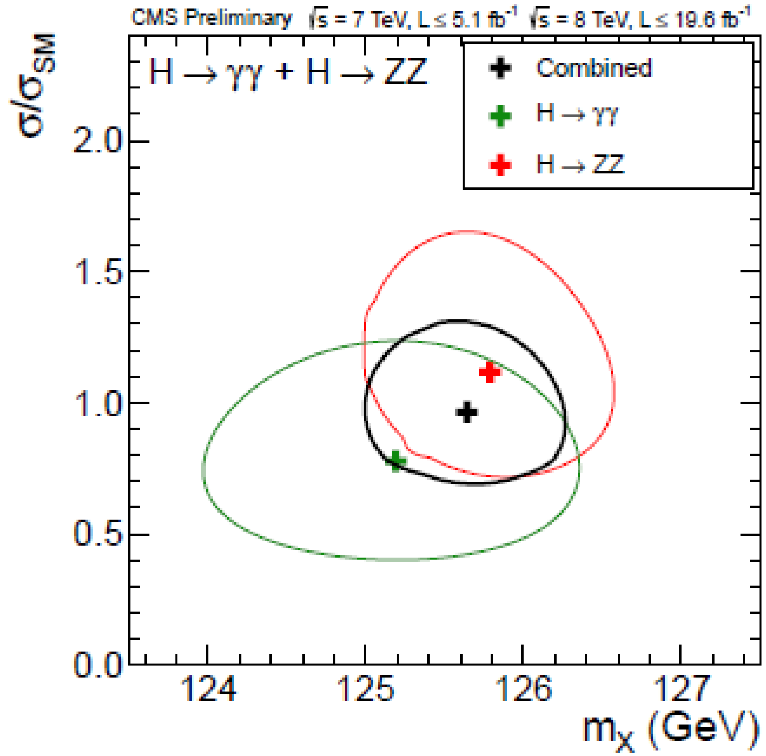
CMS-PAS-HIG-13-005

μ = 1.30 ± 0.20 [ATLAS]
μ = 0.80 ± 0.14 [CMS]

How significant is the signal for the new particle ?

Mass = 125.5 ± 0.2 (stat) ± 0.6 (syst) GeV [ATLAS]
125.7 ± 0.3 (stat) ± 0.3 (syst) GeV [CMS]

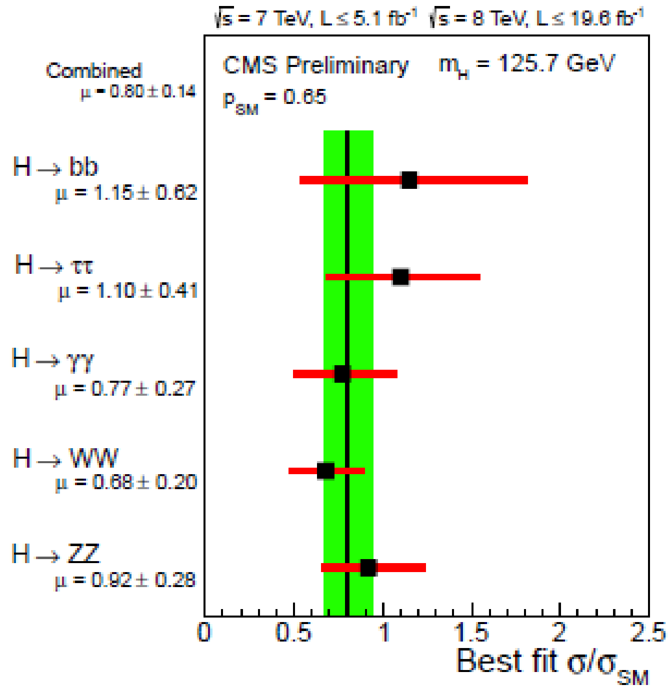
Mass measurements in the two high-resolution channels from CMS



ATLAS-CONF-2013-034

CMS-PAS-HIG-13-005

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

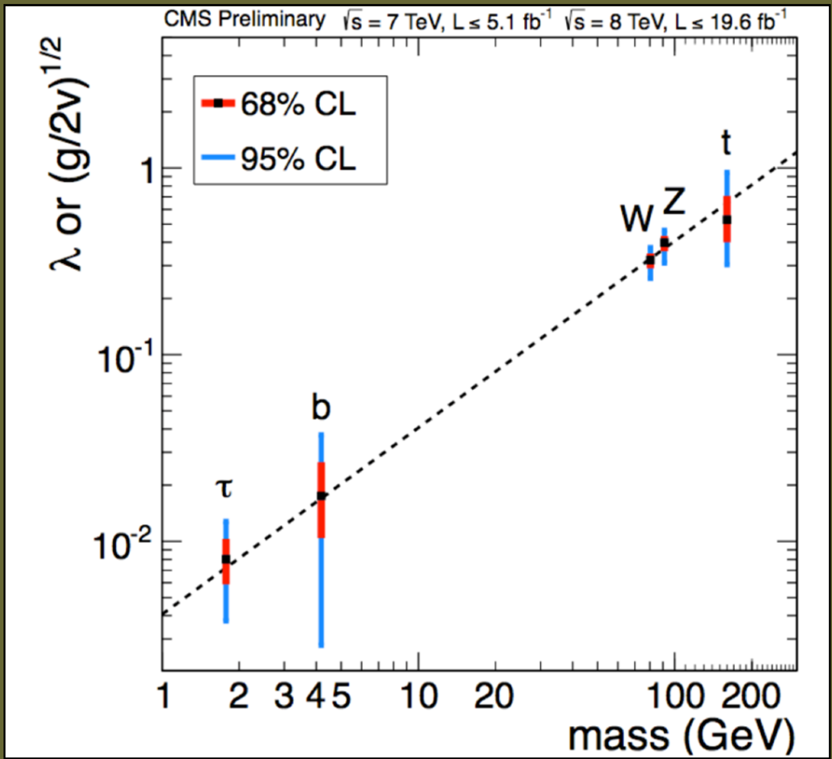


$\mu = 1.30 \pm 0.20$ [ATLAS]
$\mu = 0.80 \pm 0.14$ [CMS]

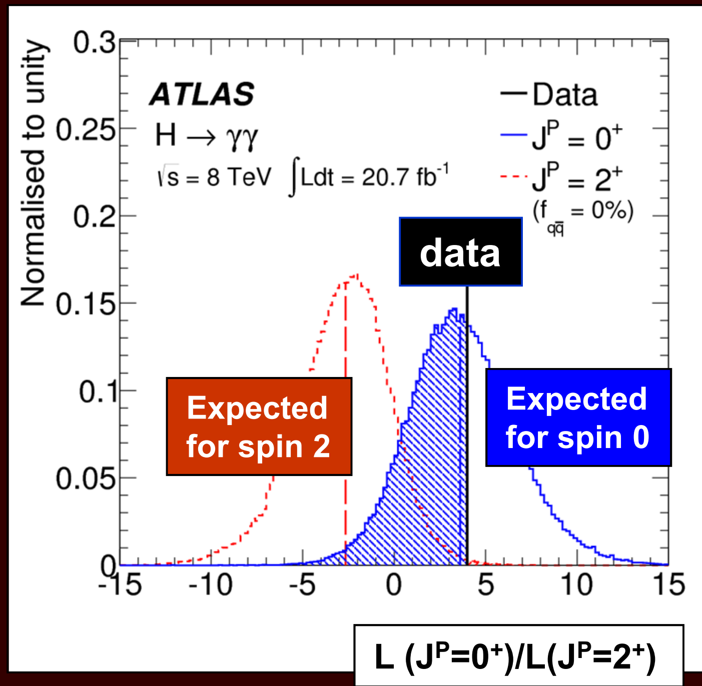
Is the new particle a Higgs boson ?

ATLAS and CMS have verified the two "fingerprints"

1) To accomplish its job (providing mass) it interacts with other particles (in particular W, Z) with strength proportional to their masses



2) It has spin zero (scalar)



Hypothesis	Rejection (C.L.)
0^-	97.8%
1^+	99.97%
1^-	99.7%
2^+	99.9%

From F Gianotti

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*

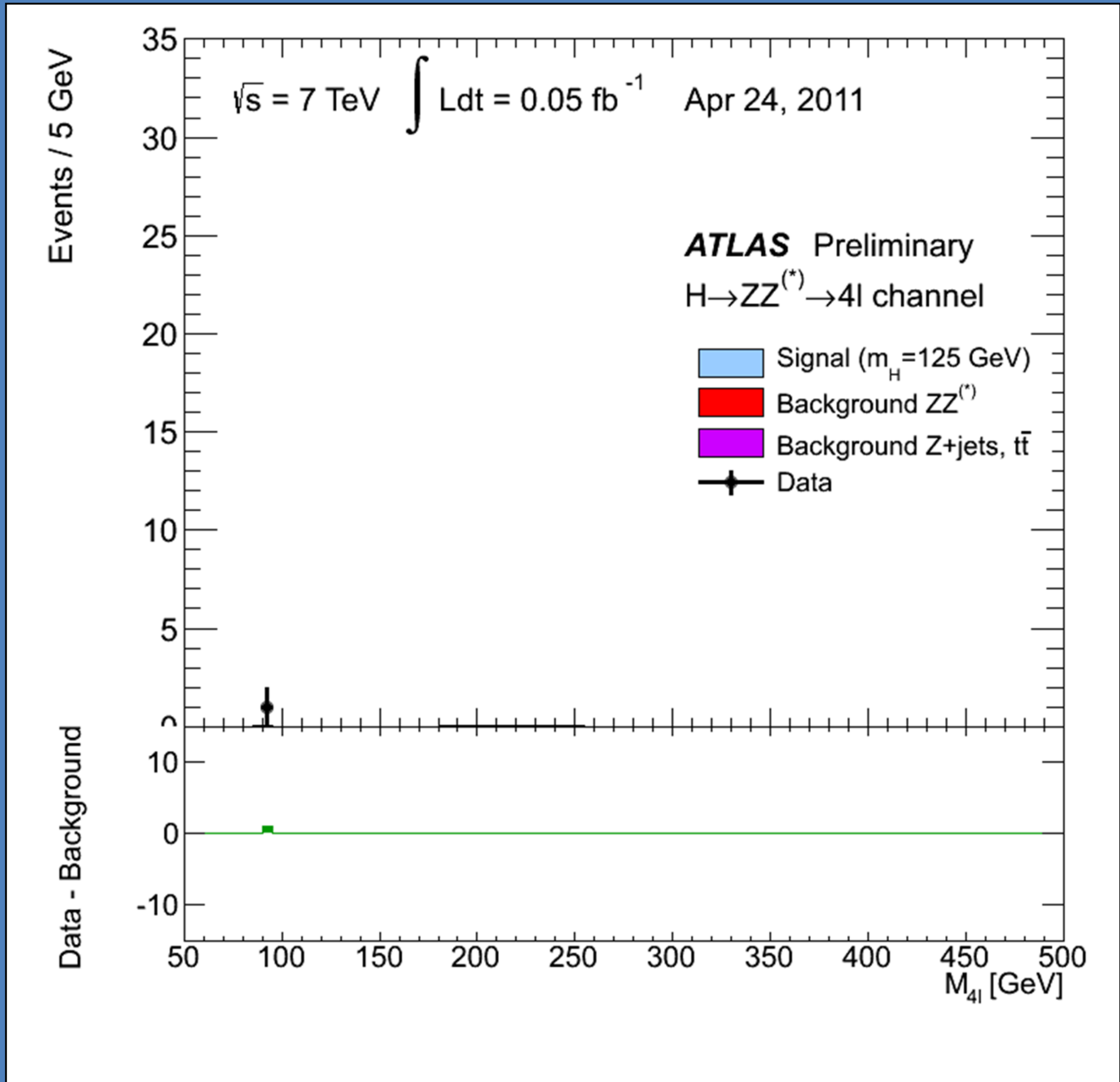
These studies will be among the most central ones in the decades to come both at the LHC and at possible other future colliders

For the experts:

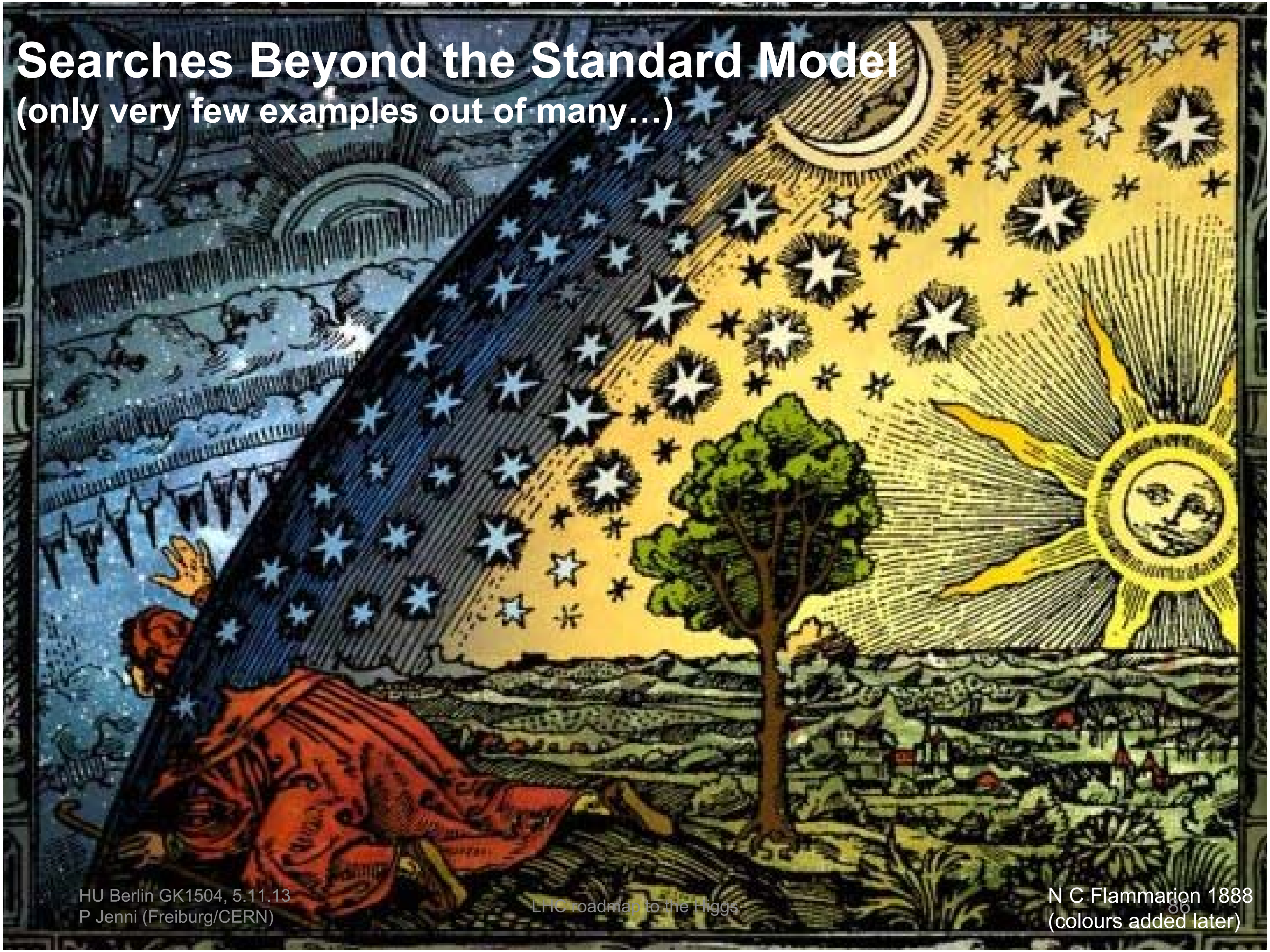
Couplings
Production modes
Spin-parity

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

Birth and evolution of a signal: H→ 4l



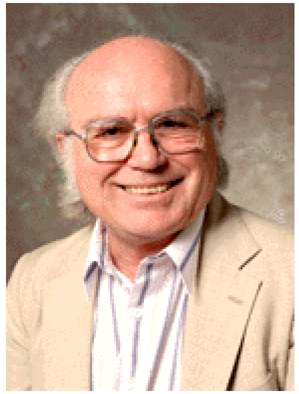
Searches Beyond the Standard Model
(only very few examples out of many…)



N C Flammarion 1888
(colours added later)

Supersymmetry (SUSY)

(Julius Wess and Bruno Zumino, 1974)

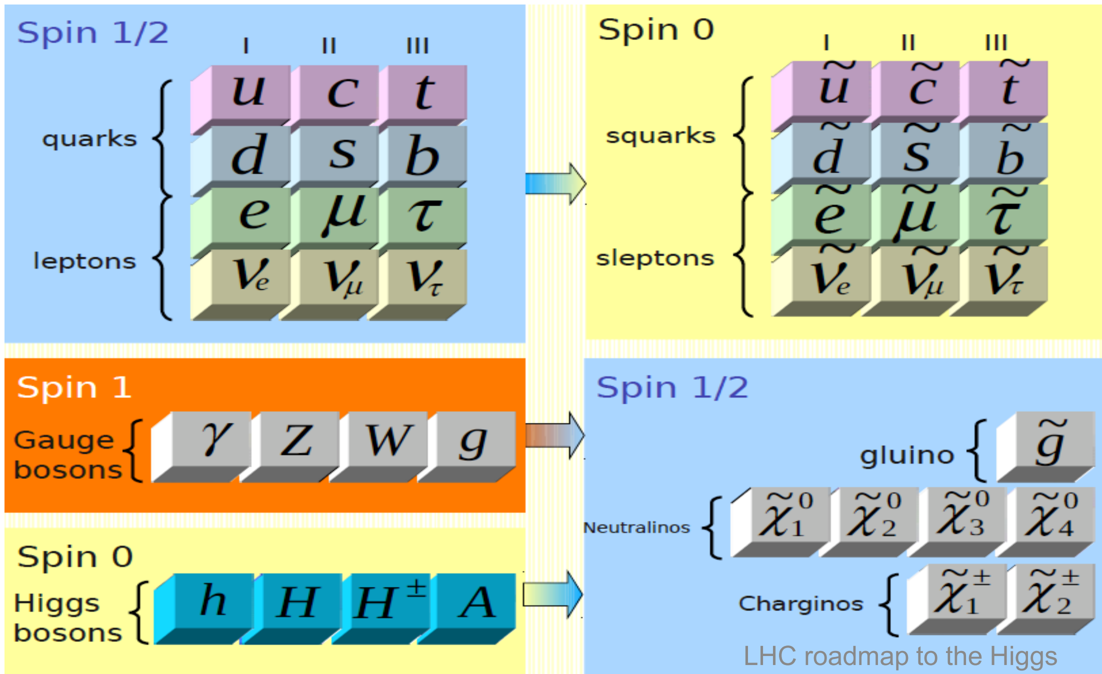


Establishes a symmetry between fermions (matter) and bosons (forces):

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

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

Our known world… **Maybe a new world?**



Motivation:

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

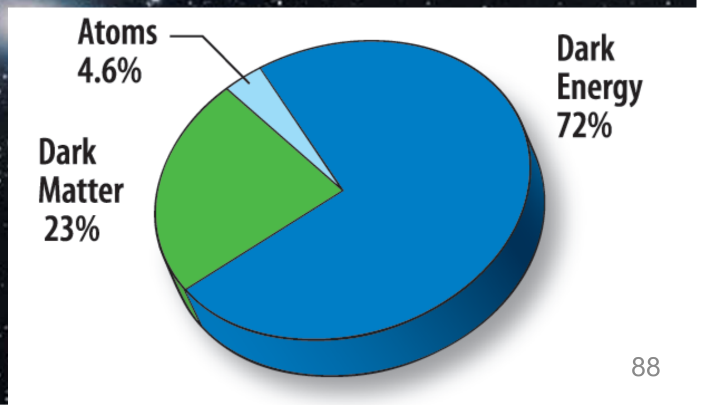
Dark Matter in the Universe

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

Vera Rubin ~ 1970

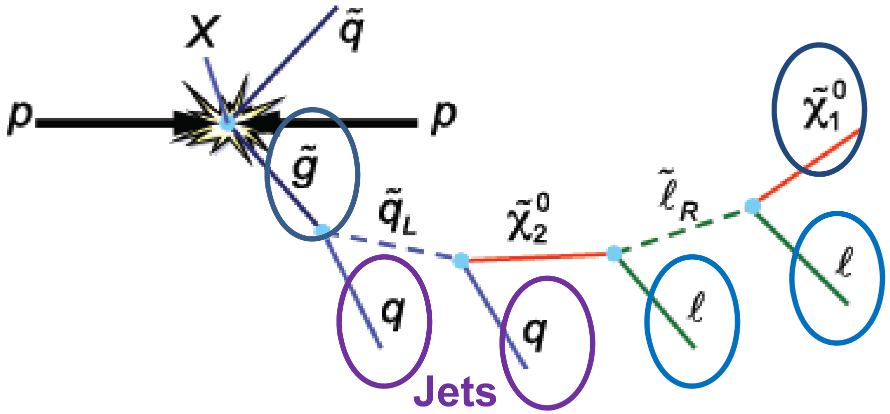
'Supersymmetric' particles ?

F. Zwicky 1898-1974

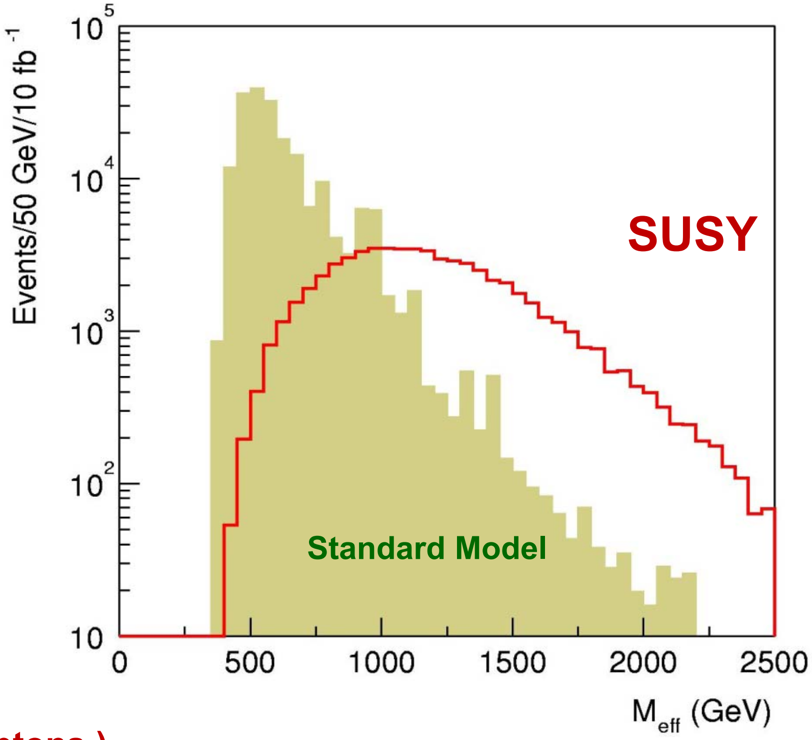


In practice SUSY searches at LHC are rather complicated

- **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**



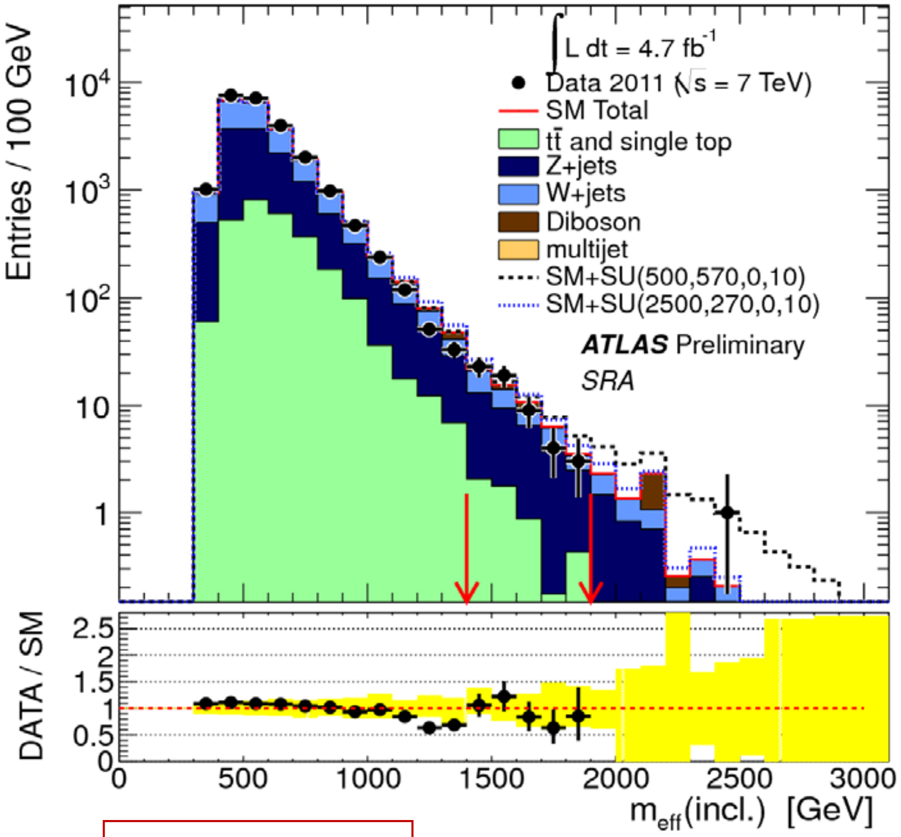
Meff = Etmiss + Σ pT(jets)

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

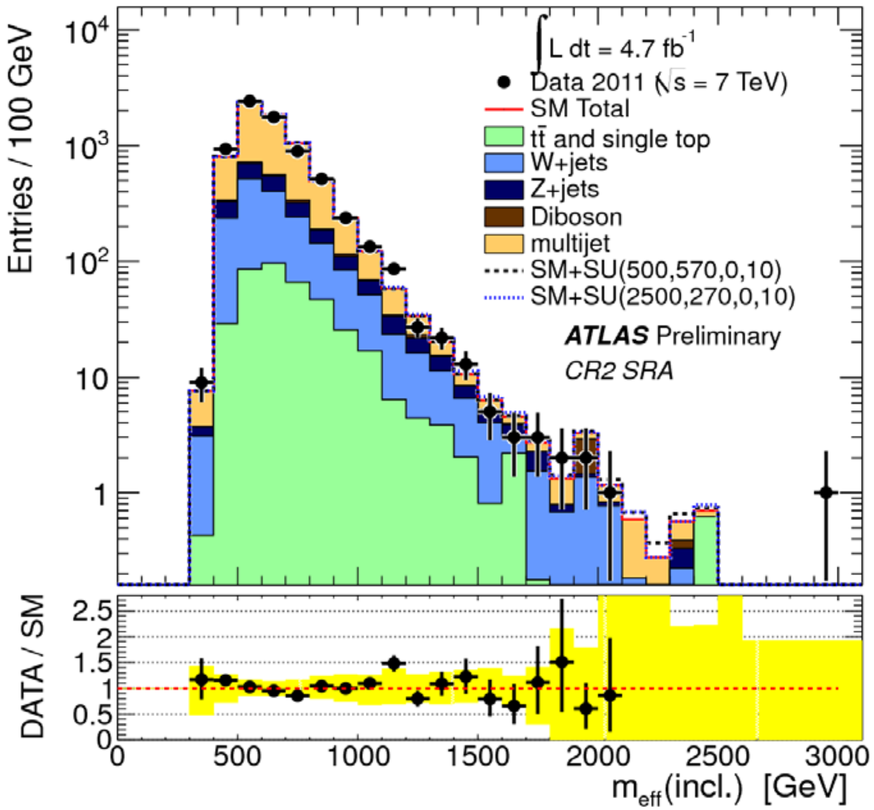
- **0-lepton + 2−6 jets + high MET (based on Et-miss+jet triggers)**
- **0-lepton + 6−9 (multi-)jets + MET (based on multi-jet triggers)**
- **1-lepton + 3,4 jets + high MET (based on lepton triggers)**

Example: O-leptons + 2-6 Jets analysis

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



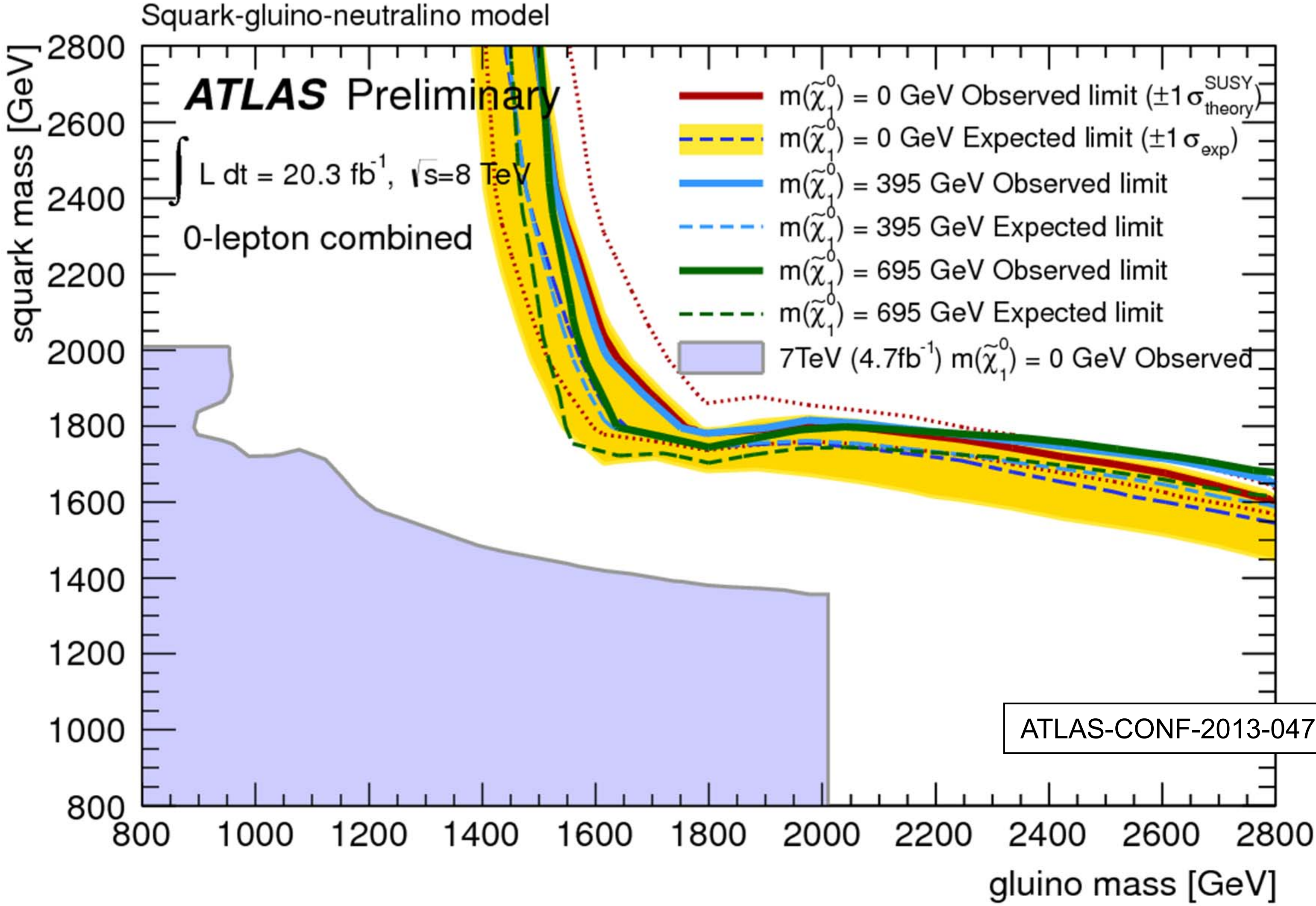
A signal region



A control region where no signal is expected

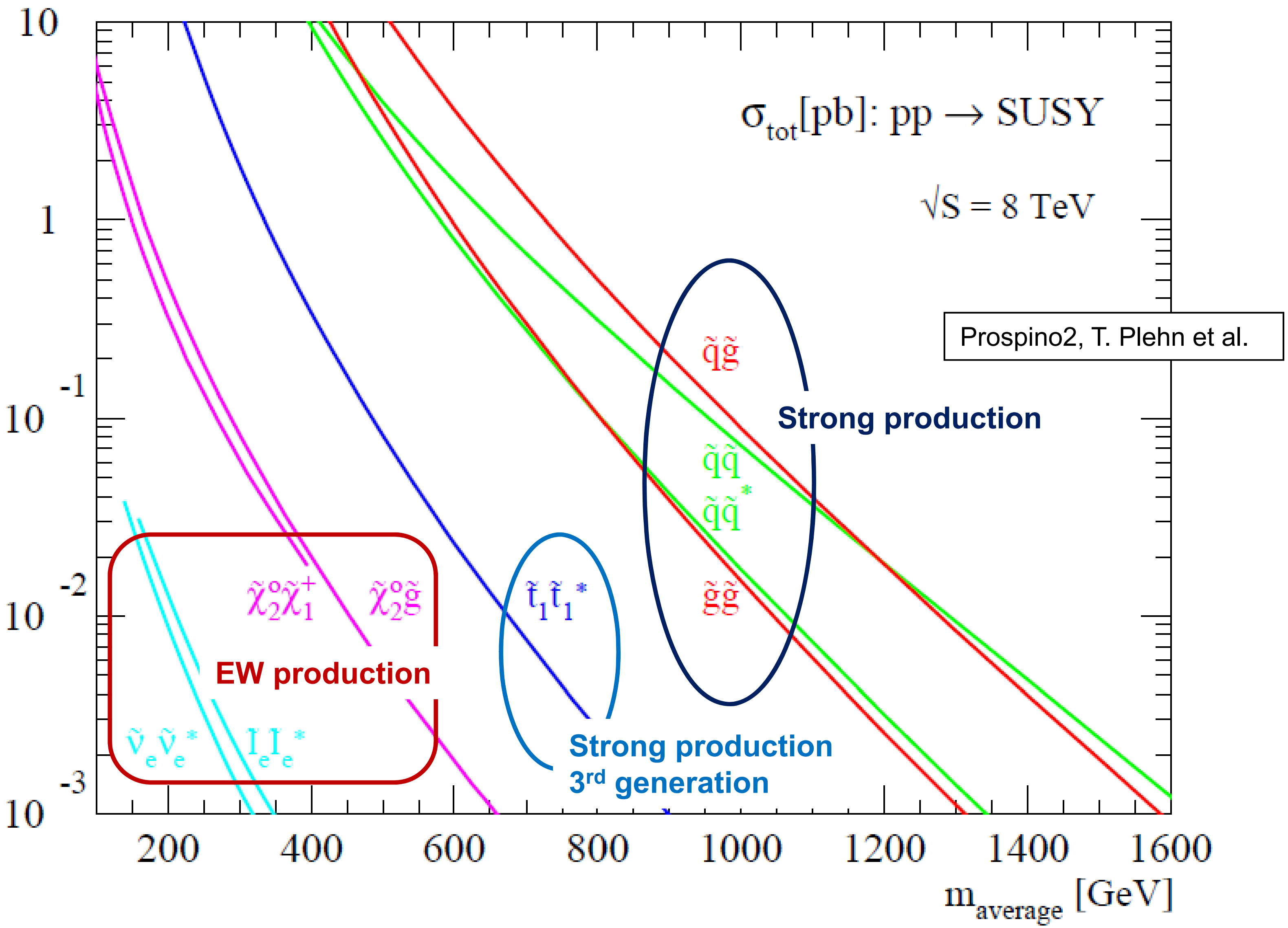
Interpretation of the results

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

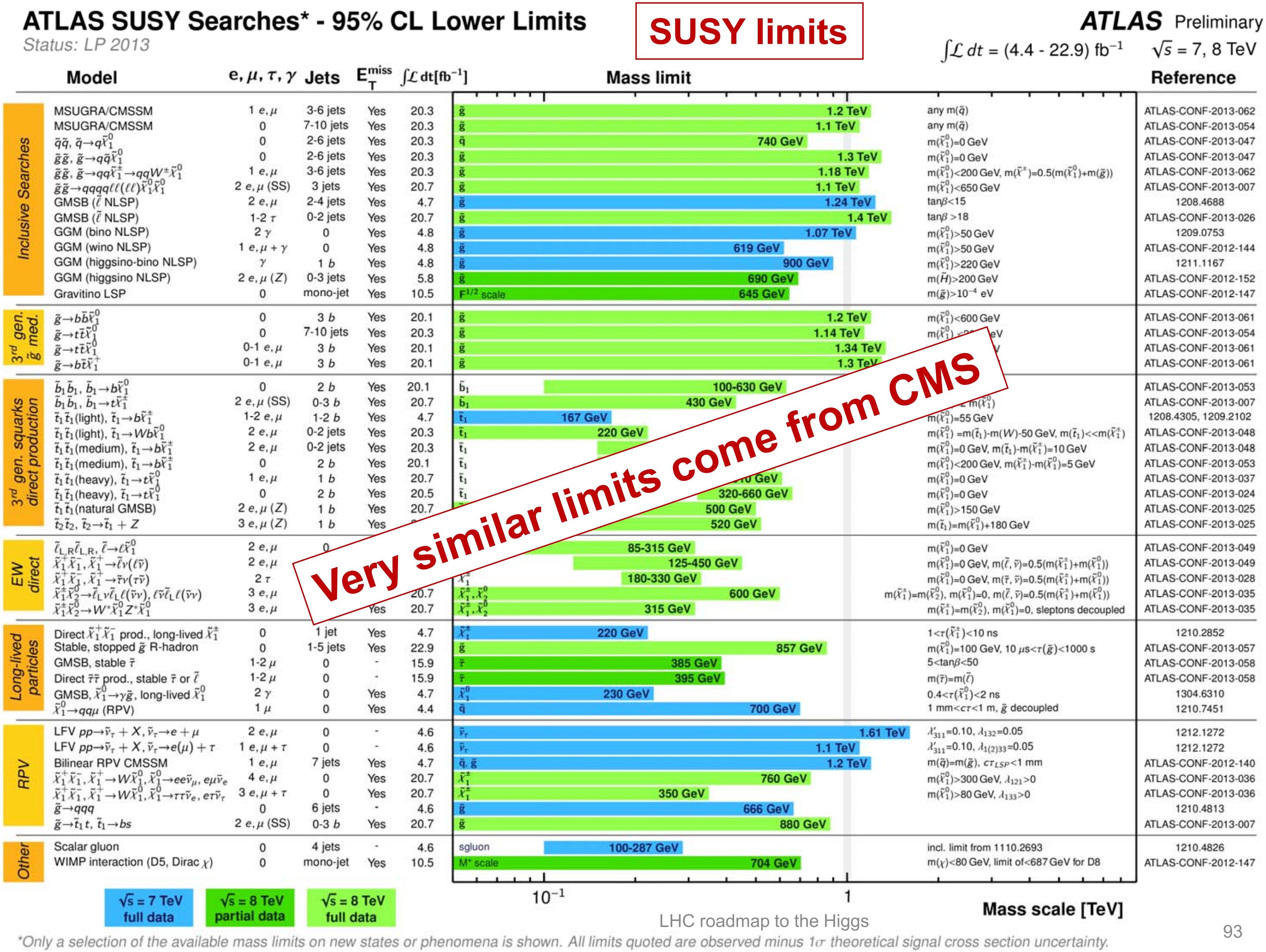


ATLAS-CONF-2013-047

Expected production cross-sections at LHC



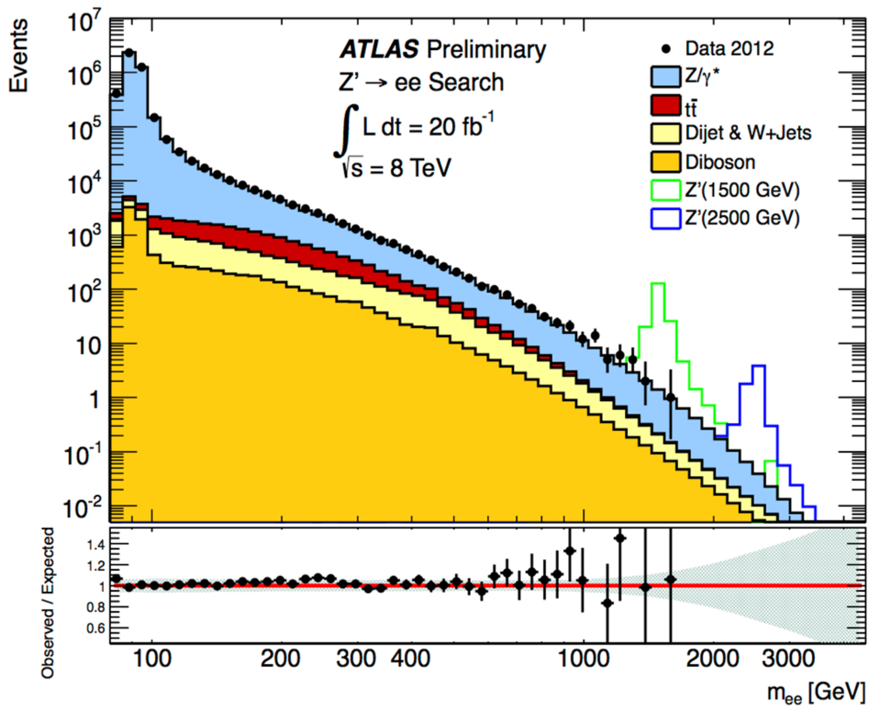
SUSY limits


ATLAS SUSY Searches* - 95% CL Lower Limits
Status: LP 2013
ATLAS Preliminary
$\int \mathcal{L}\,dt = (4.4 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s}$ = 7, 8 TeV
Model | e, μ, τ, γ | Jets | E_T^{miss} | $\int \mathcal{L}\,dt[\mathrm{fb}^{-1}]$ | Mass limit | Reference
Inclusive Searches
MSUGRA/CMSSM | 1 e, μ | 3-6 jets | Yes | 20.3 | $\tilde{g}$ 1.2 TeV | any m($\tilde{q}$) | ATLAS-CONF-2013-062
MSUGRA/CMSSM | 0 | 7-10 jets | Yes | 20.3 | $\tilde{g}$ 1.1 TeV | any m($\tilde{q}$) | ATLAS-CONF-2013-054
$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | $\tilde{q}$ 740 GeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2013-047
$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | $\tilde{g}$ 1.3 TeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2013-047
$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$ | 1 e, μ | 3-6 jets | Yes | 20.3 | $\tilde{g}$ 1.18 TeV | m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$)) | ATLAS-CONF-2013-062
$\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}_1^0\tilde{\chi}_1^0$ | 2 e, μ (SS) | 3 jets | Yes | 20.7 | $\tilde{g}$ 1.1 TeV | m($\tilde{\chi}_1^0$)<650 GeV | ATLAS-CONF-2013-007
GMSB ($\tilde{\ell}$ NLSP) | 2 e, μ | 2-4 jets | Yes | 4.7 | $\tilde{g}$ 1.24 TeV | tanβ<15 | 1208.4688
GMSB ($\tilde{\ell}$ NLSP) | 1-2 τ | 0-2 jets | Yes | 20.7 | $\tilde{g}$ 1.4 TeV | tanβ >18 | ATLAS-CONF-2013-026
GGM (bino NLSP) | 2 γ | 0 | Yes | 4.8 | $\tilde{g}$ 1.07 TeV | m($\tilde{\chi}_1^0$)>50 GeV | 1209.0753
GGM (wino NLSP) | 1 e, μ + γ | 0 | Yes | 4.8 | $\tilde{g}$ 619 GeV | m($\tilde{\chi}_1^0$)>50 GeV | ATLAS-CONF-2012-144
GGM (higgsino-bino NLSP) | γ | 1 b | Yes | 4.8 | $\tilde{g}$ 900 GeV | m($\tilde{\chi}_1^0$)>220 GeV | 1211.1167
GGM (higgsino NLSP) | 2 e, μ (Z) | 0-3 jets | Yes | 5.8 | $\tilde{g}$ 690 GeV | m($\tilde{H}$)>200 GeV | ATLAS-CONF-2012-152
Gravitino LSP | 0 | mono-jet | Yes | 10.5 | $F^{1/2}$ scale 645 GeV | m($\tilde{g}$)>10^{-4} eV | ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.
$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ | 0 | 3 b | Yes | 20.1 | $\tilde{g}$ 1.2 TeV | m($\tilde{\chi}_1^0$)<600 GeV | ATLAS-CONF-2013-061
$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0 | 7-10 jets | Yes | 20.3 | $\tilde{g}$ 1.14 TeV | ATLAS-CONF-2013-054
$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 e, μ | 3 b | Yes | 20.1 | $\tilde{g}$ 1.34 TeV | ATLAS-CONF-2013-061
$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$ | 0-1 e, μ | 3 b | Yes | 20.1 | $\tilde{g}$ 1.3 TeV | ATLAS-CONF-2013-061
3rd gen. squarks direct production
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$ | 0 | 2 b | Yes | 20.1 | $\tilde{b}_1$ 100-630 GeV | ATLAS-CONF-2013-053
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$ | 2 e, μ (SS) | 0-3 b | Yes | 20.7 | $\tilde{b}_1$ 430 GeV | ATLAS-CONF-2013-007
$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$ | 1-2 e, μ | 1-2 b | Yes | 4.7 | $\tilde{t}_1$ 167 GeV | m($\tilde{\chi}_1^0$)=55 GeV | 1208.4305, 1209.2102
$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ | 2 e, μ | 0-2 jets | Yes | 20.3 | $\tilde{t}_1$ 220 GeV | m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^\pm$) | ATLAS-CONF-2013-048
$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$ | 2 e, μ | 0-2 jets | Yes | 20.3 | $\tilde{t}_1$ | m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^\pm$)=10 GeV | ATLAS-CONF-2013-048
$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$ | 0 | 2 b | Yes | 20.1 | $\tilde{t}_1$ | m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV | ATLAS-CONF-2013-053
$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$ | 1 e, μ | 1 b | Yes | 20.7 | $\tilde{t}_1$ GeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2013-037
$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$ | 0 | 2 b | Yes | 20.5 | $\tilde{t}_1$ 320-660 GeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2013-024
$\tilde{t}_1\tilde{t}_1$(natural GMSB) | 2 e, μ (Z) | 1 b | Yes | 20.7 | 500 GeV | m($\tilde{\chi}_1^0$)>150 GeV | ATLAS-CONF-2013-025
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$ | 3 e, μ (Z) | 1 b | Yes | 520 GeV | m($\tilde{t}_1$)=m($\tilde{\chi}_1^0$)+180 GeV | ATLAS-CONF-2013-025
EW direct
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 e, μ | 0 | 85-315 GeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2013-049
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$ | 2 e, μ | 125-450 GeV | m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | ATLAS-CONF-2013-049
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$ | 2 τ | 180-330 GeV | m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | ATLAS-CONF-2013-028
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$ | 3 e, μ | 20.7 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 600 GeV | m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | ATLAS-CONF-2013-035
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W^*\tilde{\chi}_1^0 Z^*\tilde{\chi}_1^0$ | 3 e, μ | Yes | 20.7 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 315 GeV | m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled | ATLAS-CONF-2013-035
Long-lived particles
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | 0 | 1 jet | Yes | 4.7 | $\tilde{\chi}_1^\pm$ 220 GeV | 1<τ($\tilde{\chi}_1^\pm$)<10 ns | 1210.2852
Stable, stopped $\tilde{g}$ R-hadron | 0 | 1-5 jets | Yes | 22.9 | $\tilde{g}$ 857 GeV | m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s | ATLAS-CONF-2013-057
GMSB, stable $\tilde{\tau}$ | 1-2 μ | 0 | - | 15.9 | $\tilde{\tau}$ 385 GeV | 5<tanβ<50 | ATLAS-CONF-2013-058
Direct $\tilde{\tau}\tilde{\tau}$ prod., stable $\tilde{\tau}$ or $\tilde{\ell}$ | 1-2 μ | 0 | - | 15.9 | $\tilde{\tau}$ 395 GeV | m($\tilde{\tau}$)=m($\tilde{\ell}$) | ATLAS-CONF-2013-058
GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 γ | 0 | Yes | 4.7 | $\tilde{\chi}_1^0$ 230 GeV | 0.4<τ($\tilde{\chi}_1^0$)<2 ns | 1304.6310
$\tilde{\chi}_1^0\to qq\mu$ (RPV) | 1 μ | 0 | Yes | 4.4 | $\tilde{q}$ 700 GeV | 1 mm<cτ<1 m, $\tilde{g}$ decoupled | 1210.7451
RPV
LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e+\mu$ | 2 e, μ | 0 | - | 4.6 | $\tilde{\nu}_\tau$ 1.61 TeV | λ'_{311}=0.10, λ_{132}=0.05 | 1212.1272
LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu)+\tau$ | 1 e, μ + τ | 0 | - | 4.6 | $\tilde{\nu}_\tau$ 1.1 TeV | λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05 | 1212.1272
Bilinear RPV CMSSM | 1 e, μ | 7 jets | Yes | 4.7 | $\tilde{q}, \tilde{g}$ 1.2 TeV | m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm | ATLAS-CONF-2012-140
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$ | 4 e, μ | 0 | Yes | 20.7 | $\tilde{\chi}_1^\pm$ 760 GeV | m($\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0 | ATLAS-CONF-2013-036
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$ | 3 e, μ + τ | 0 | Yes | 20.7 | $\tilde{\chi}_1^\pm$ 350 GeV | m($\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0 | ATLAS-CONF-2013-036
$\tilde{g}\to qqq$ | 0 | 6 jets | - | 4.6 | $\tilde{g}$ 666 GeV | 1210.4813
$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$ | 2 e, μ (SS) | 0-3 b | Yes | 20.7 | $\tilde{g}$ 880 GeV | ATLAS-CONF-2013-007
Other
Scalar gluon | 0 | 4 jets | - | 4.6 | sgluon 100-287 GeV | incl. limit from 1110.2693 | 1210.4826
WIMP interaction (D5, Dirac χ) | 0 | mono-jet | Yes | 10.5 | M* scale 704 GeV | m(χ)<80 GeV, limit of<687 GeV for D8 | ATLAS-CONF-2012-147
10^{-1}
1
Mass scale [TeV]
$\sqrt{s}$ = 7 TeV full data
$\sqrt{s}$ = 8 TeV partial data
$\sqrt{s}$ = 8 TeV full data
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.
Very similar limits come from CMS

Searches for heavy W and Z like particles

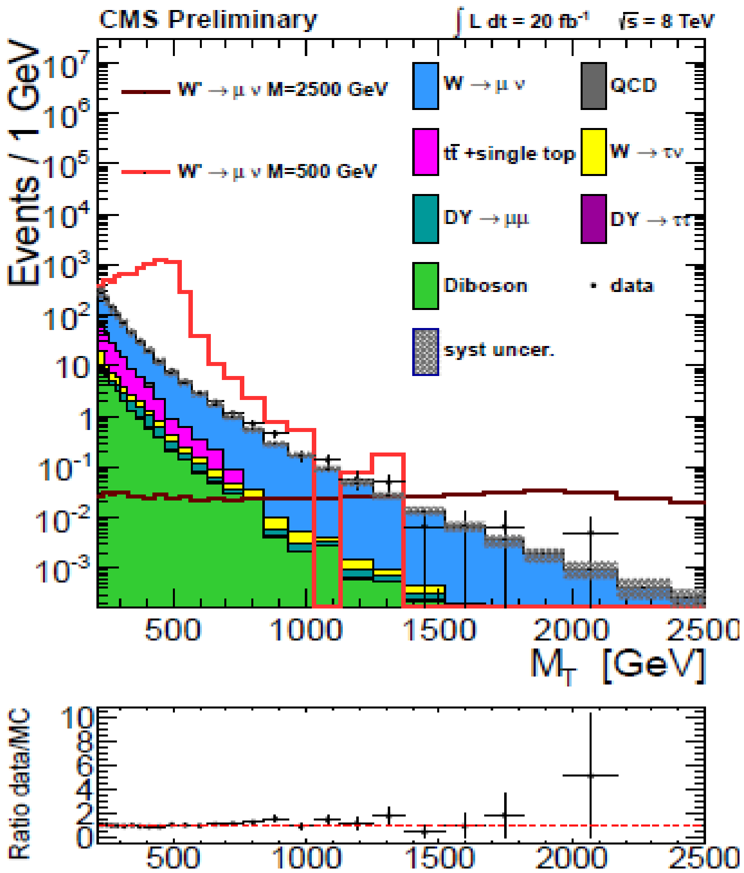
These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z': Di-lepton pairs

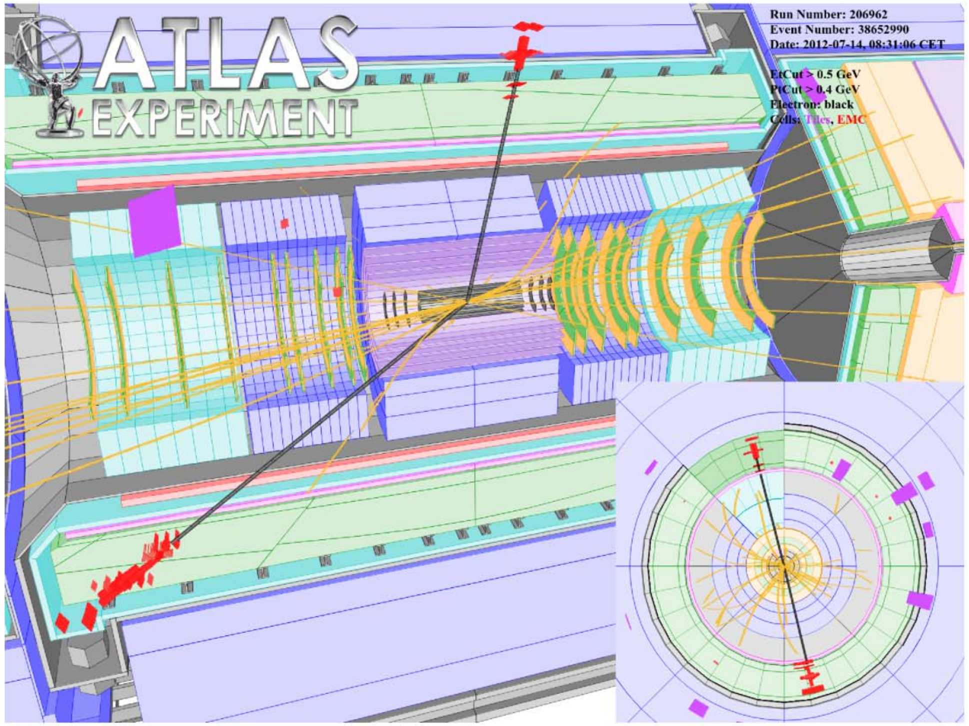


ATLAS-CONF-2013-017

W': Lepton + ETmiss

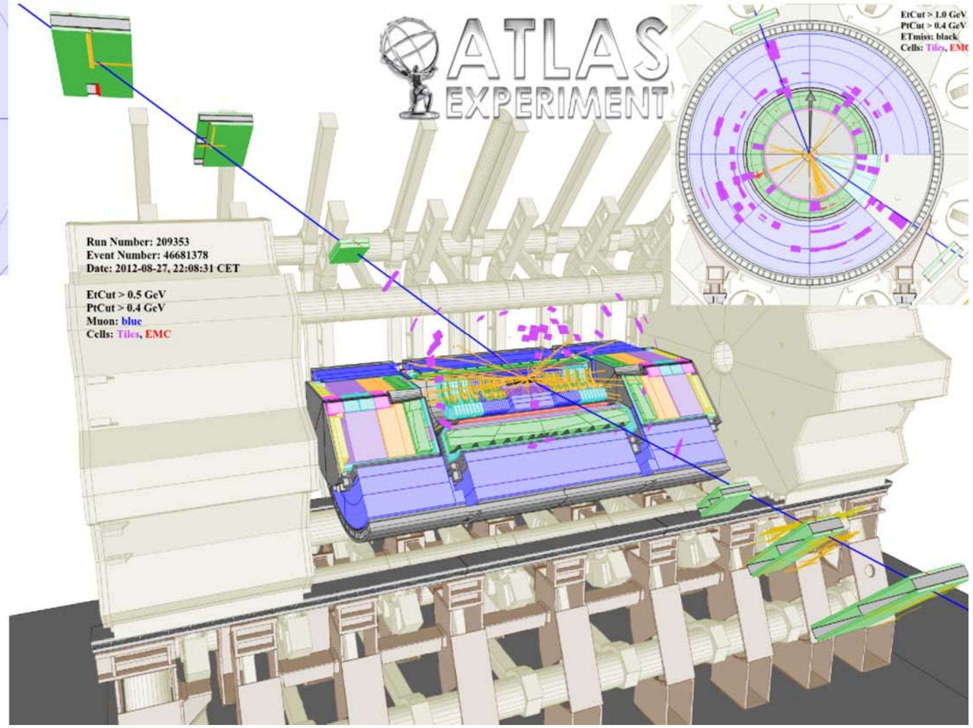


CMS-EXO-12-060



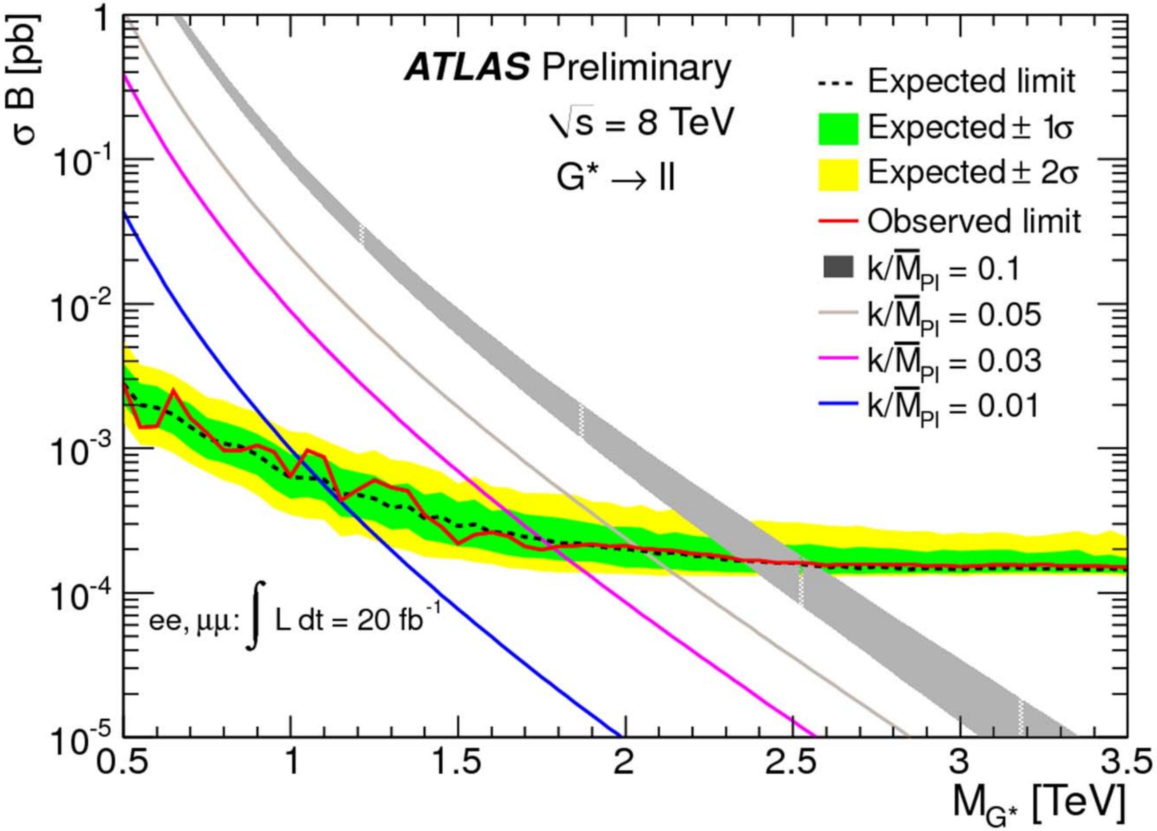
The highest mass di-lepton events from ATLAS

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



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

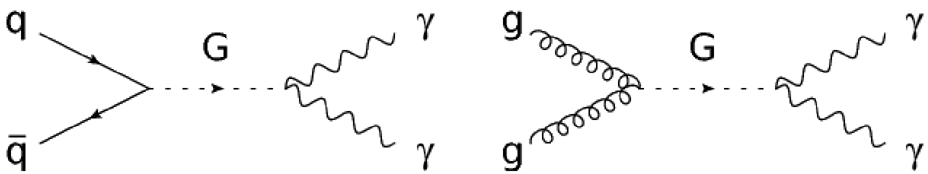
Lower mass limits, at 95% CL, for spin-2 Randall-Sundrum Gravitons



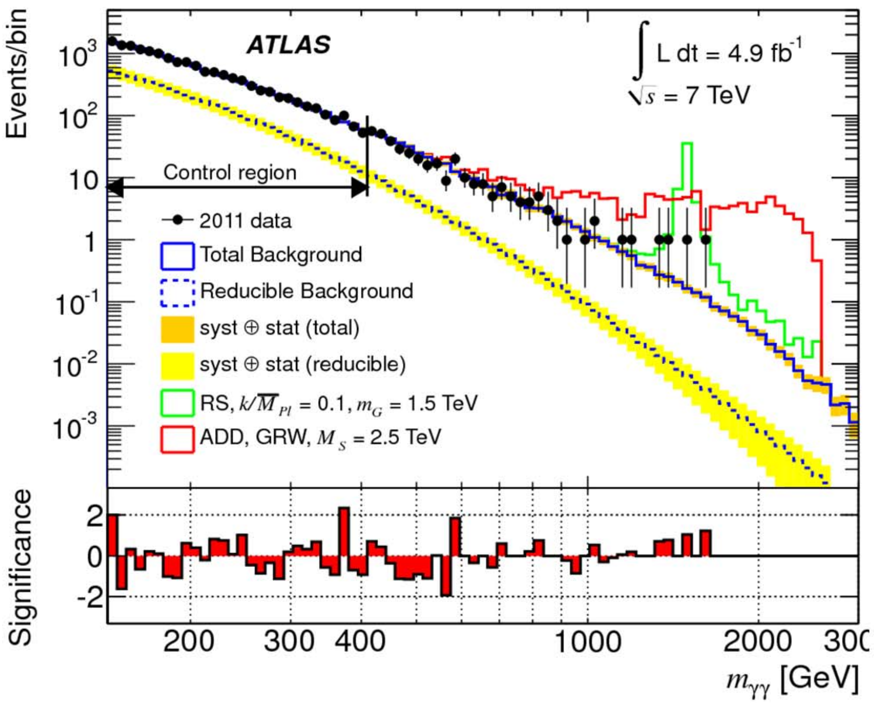
ATLAS-CONF-2013-017

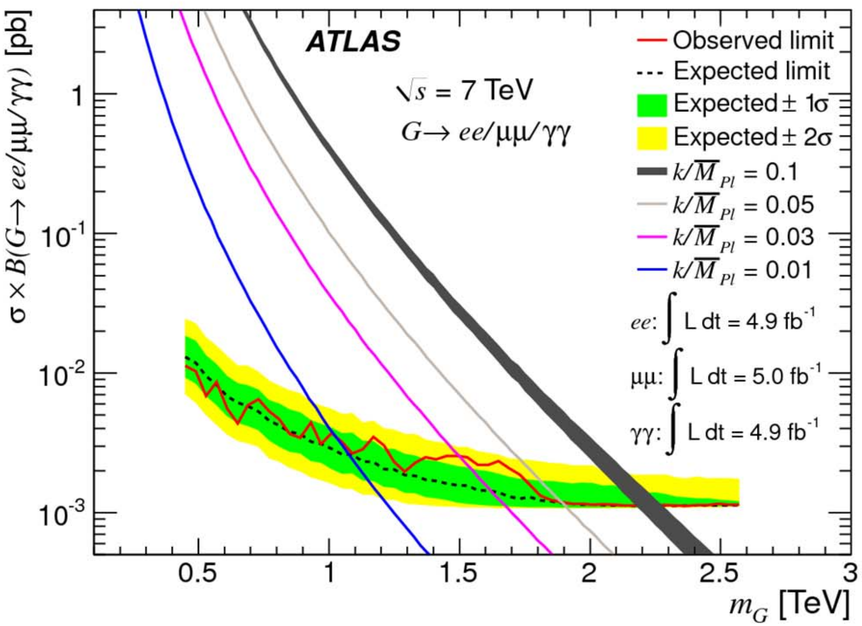
R Sundrum
L Randall
F Gianotti

New particles decaying into two photons



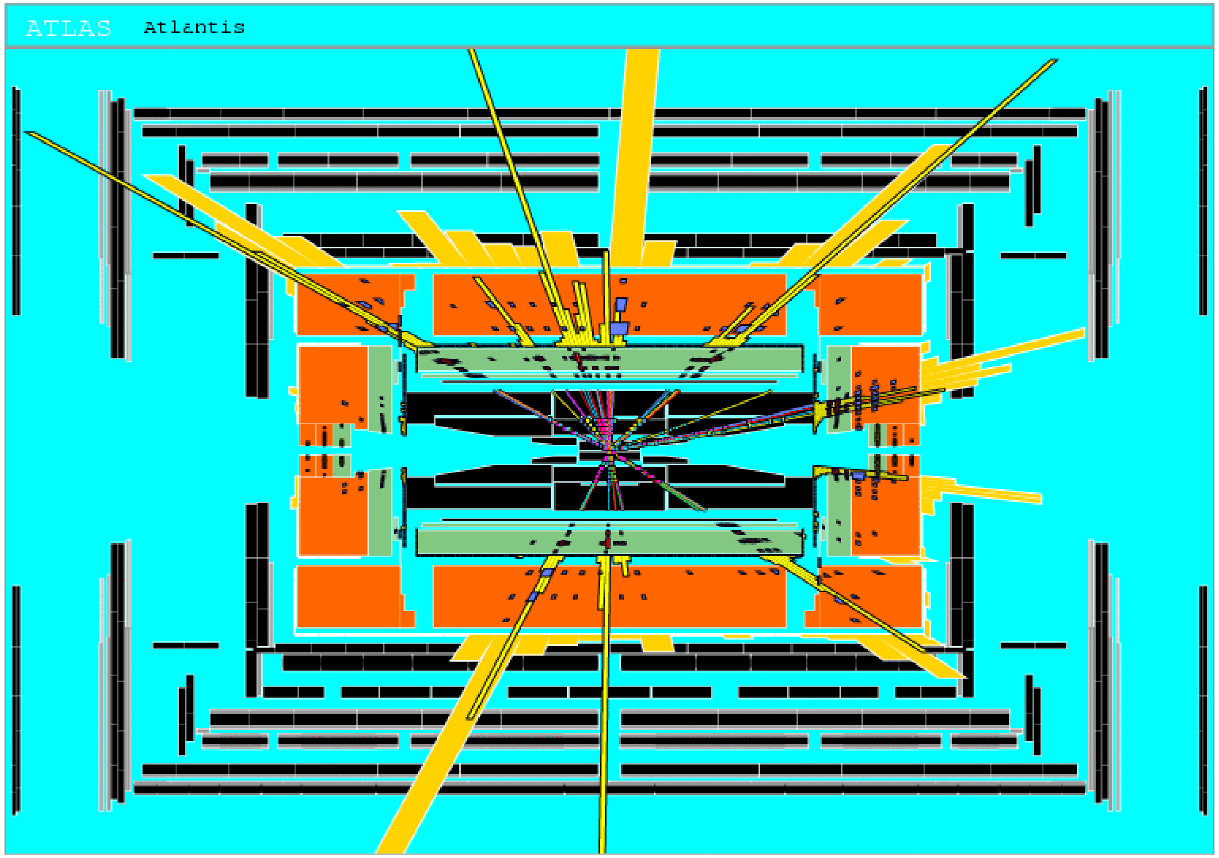
Example for a search of extra dimension signals (Kaluza-Klein Graviton in the Randall-Sundrum and Arkani-Hamed, Dimopoulos and Dvali models)





New J Phys 15 (2013) 043007

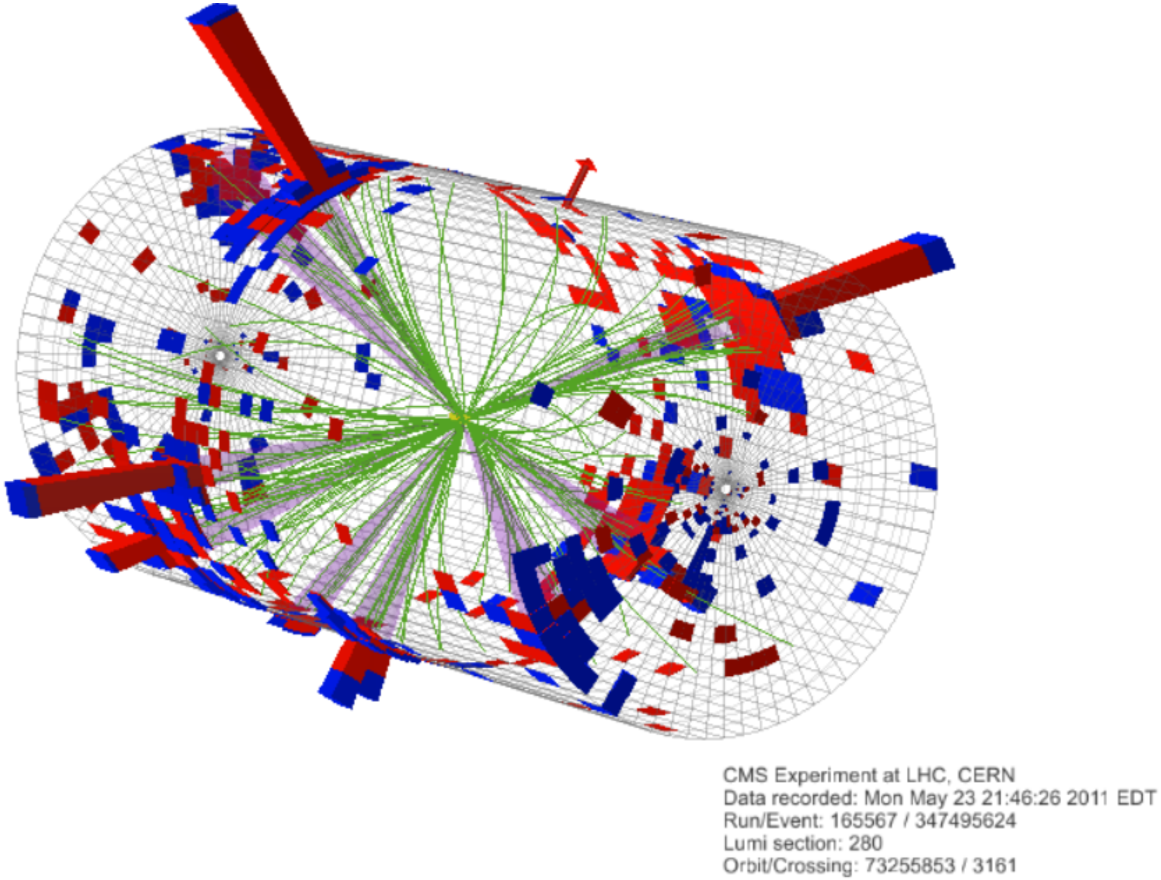
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



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

They decay immediately through Stephen Hawking radiation

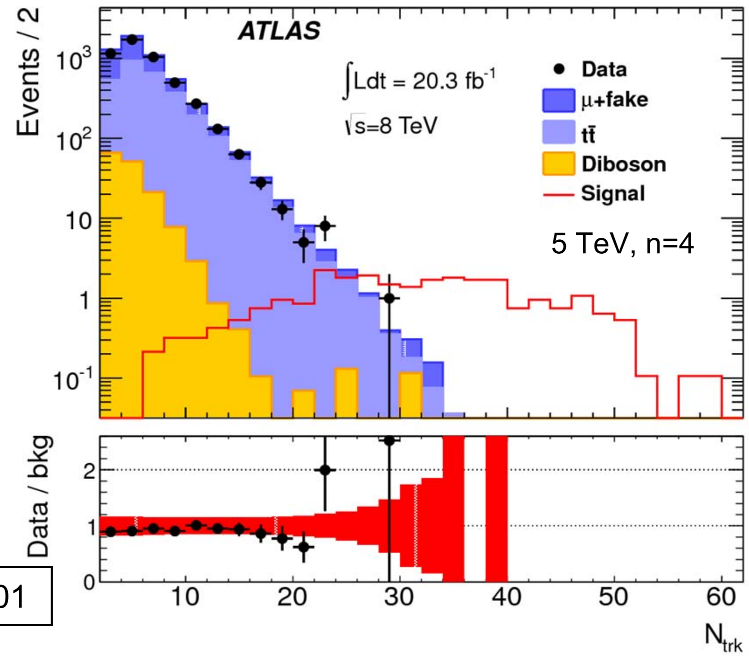
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



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)



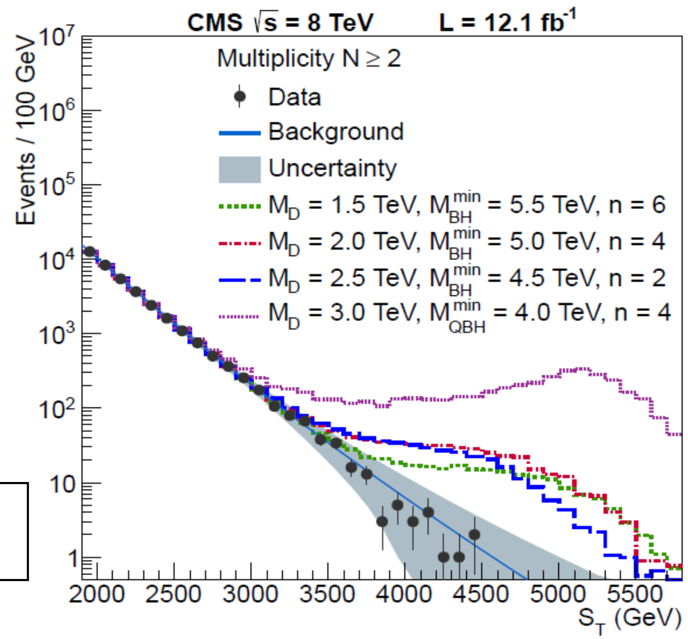
Phys Rev D88 (2013) 072001

Decay into many objects (jets, leptons, photons)

<u>Examples:</u> (ATLAS) two same sign muons and large multiplicity, (CMS) any three objects

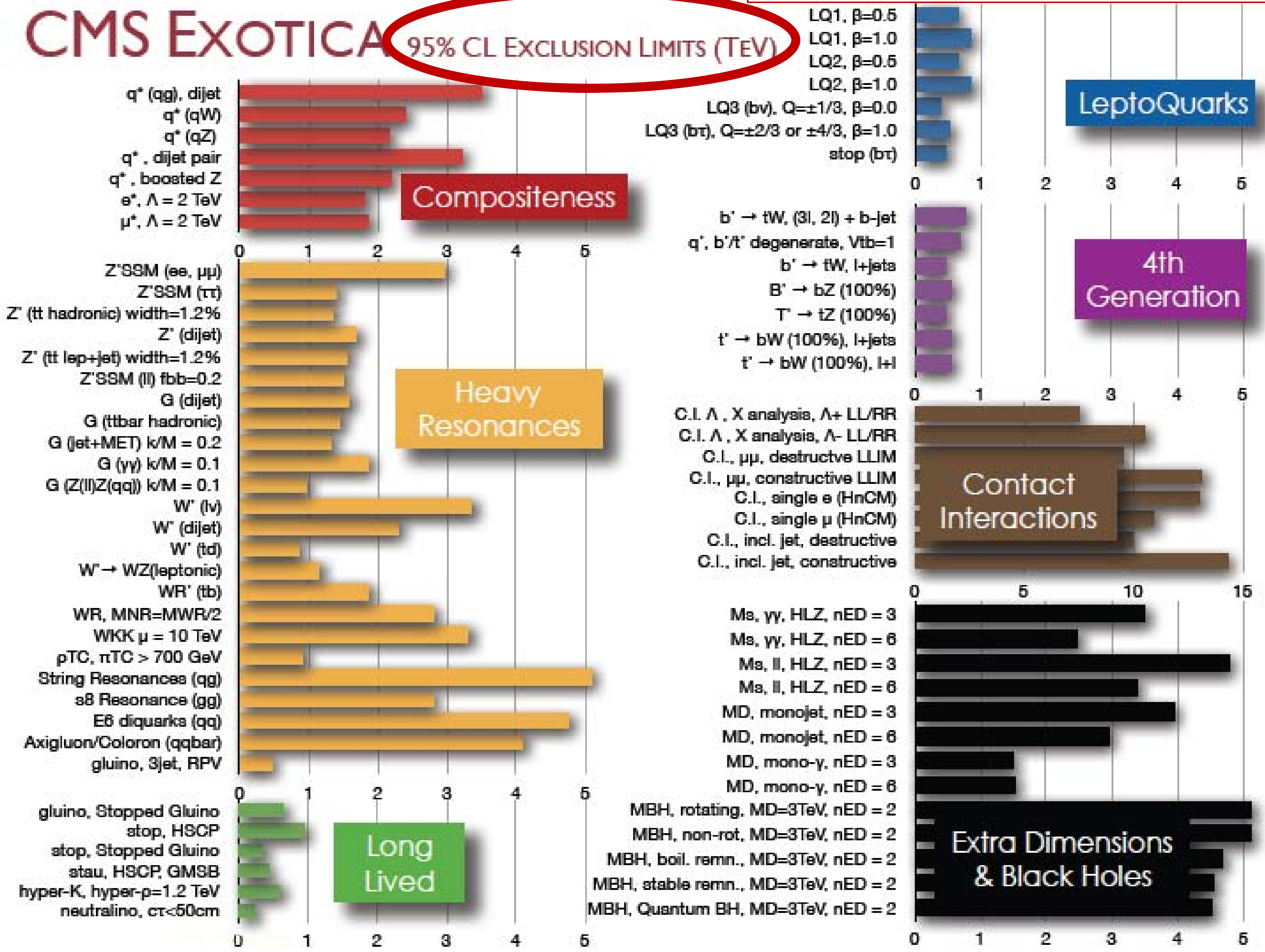
($S_T = \Sigma P_T$: scalar sum of the E_T of the N objects in the event)

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



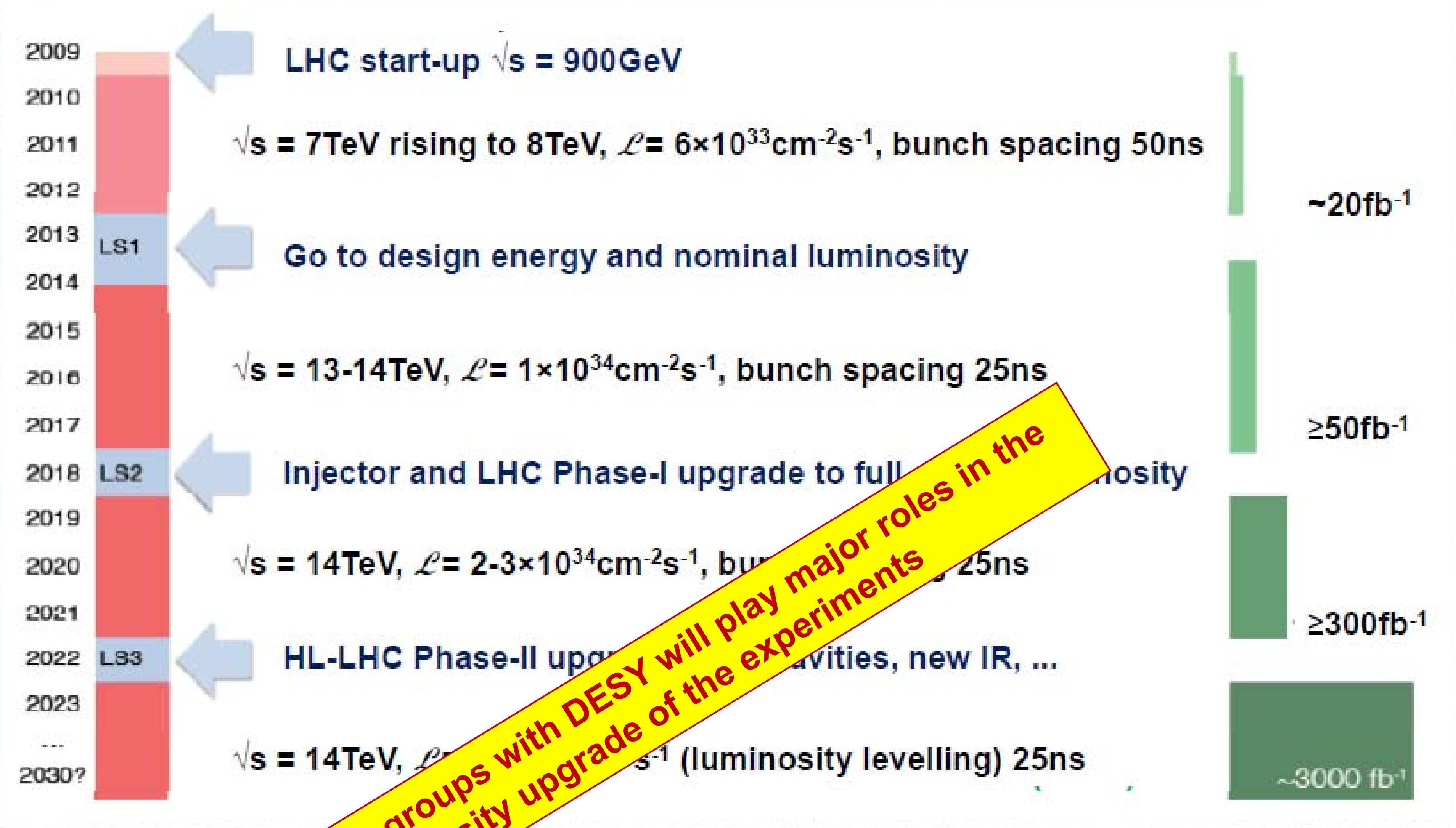
Submitted to JHEP
arXiv:1303.5338v1[hep-ex]

Similar results exist from ATLAS

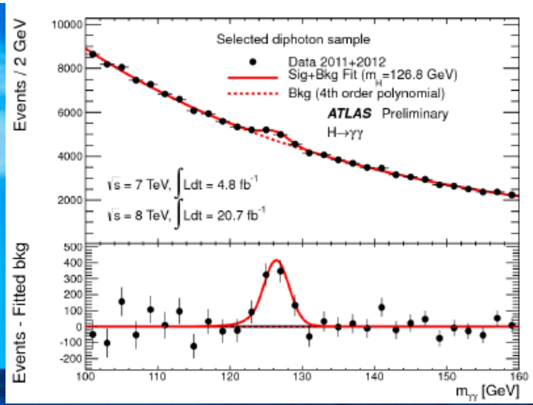


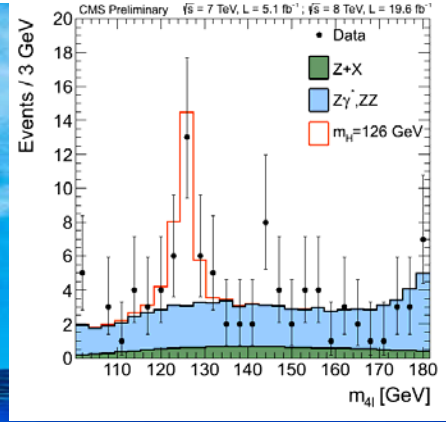
(TeV) **(TeV)**

LHC Schedule and Upgrade

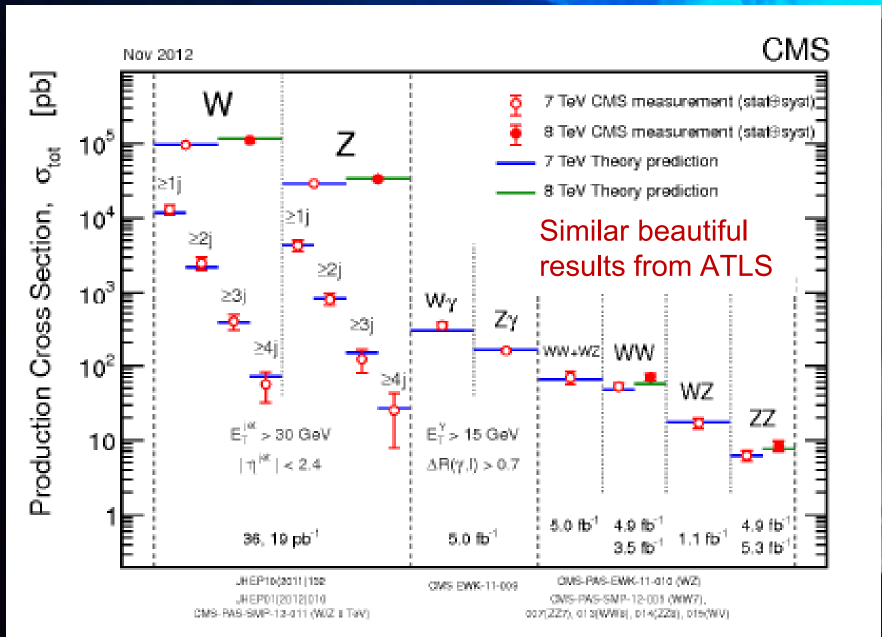


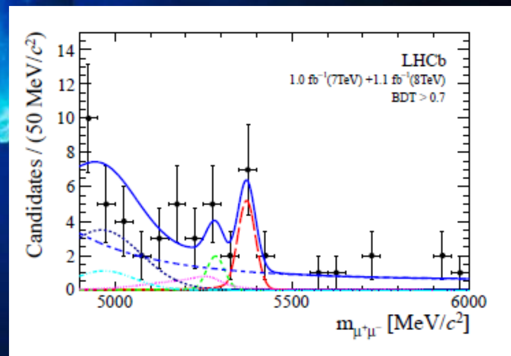
German groups with DESY will play major roles in the high-luminosity upgrade of the experiments





The High Energy Frontier





Collider options for the high energy frontier

pp colliders

	Years	E_{cm} TeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Int. Luminosity fb^{-1}
Design LHC	2014-21	14	1-2	300
HL-LHC	2024-30	14	5	3000
HE-LHC	>2035	26-33*	2	100-300/y
V-LHC**	>2035	42-100		

* 16-20 T dipole field
** 80 km Tunnel

e+e- colliders

	Years	E_{cm} GeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Tunnel length km
ILC 250	<2030	250	0.75	
ILC 500		500	1.8	~30
ILC 1000		1000		~50
CLIC 500	>2030	500	2.3(1.3)	~13
CLIC 1400		1400(1500)	3.2(3.7)	~27
CLIC 3000		3000	5.9	~48
LEP3	>2024	240	1	LEP/LHC ring
TLEP	>2030	240	5	80 (ring)
TLEP		350	0.65	80 (ring)

Other options:

$\mu^+\mu^-$ and $\gamma\gamma$ colliders with similar physics as e^+e^- colliders

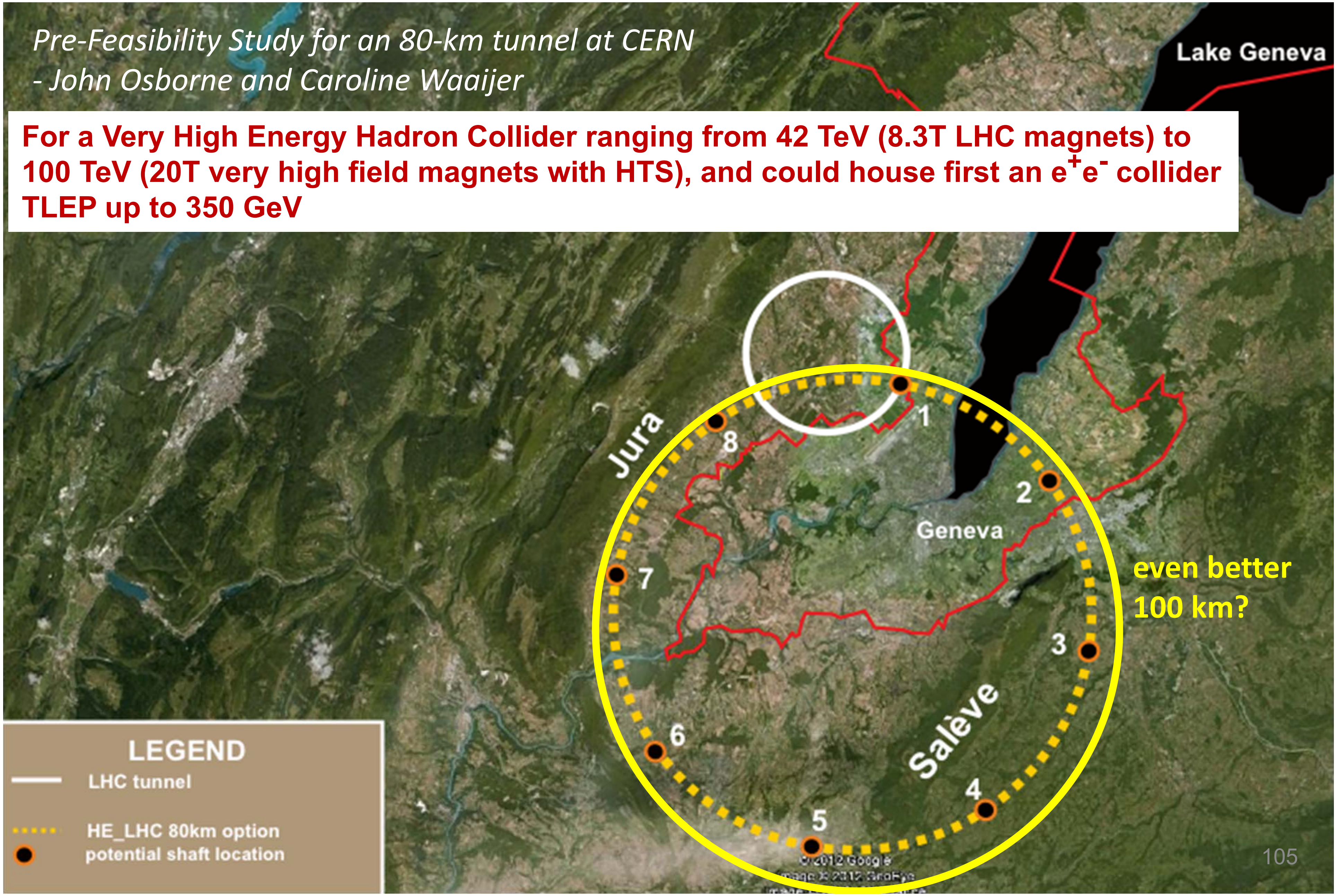
LHeC for ep collisions

See European Strategy Briefing Book for references

Options for preliminary studies at CERN

Pre-Feasibility Study for an 80-km tunnel at CERN
- John Osborne and Caroline Waaijer

For a Very High Energy Hadron Collider ranging from 42 TeV (8.3T LHC magnets) to 100 TeV (20T very high field magnets with HTS), and could house first an e^+e^- collider TLEP up to 350 GeV



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

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]*

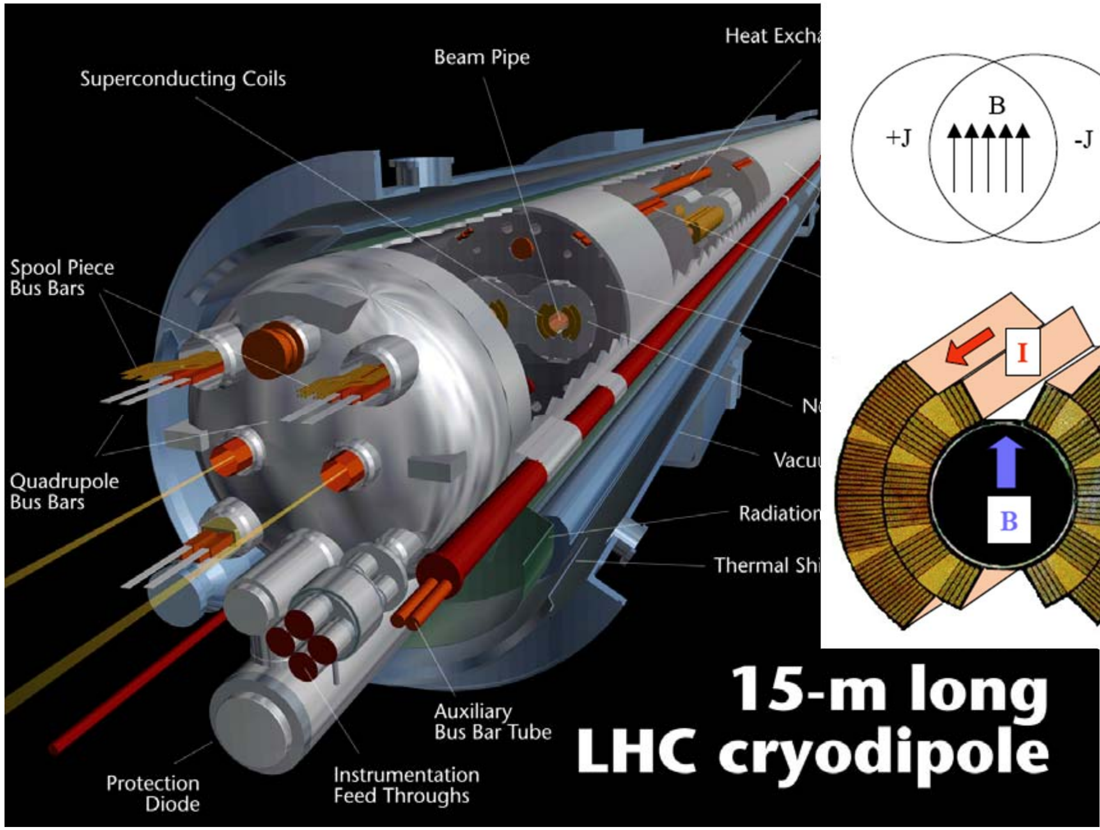
The search for the standard model Higgs boson at the Large Hadron Collider (LHC) started more than two decades ago. Much innovation was required and diverse challenges had to be overcome during the conception and construction of the LHC and its experiments. The ATLAS and CMS Collaboration experiments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

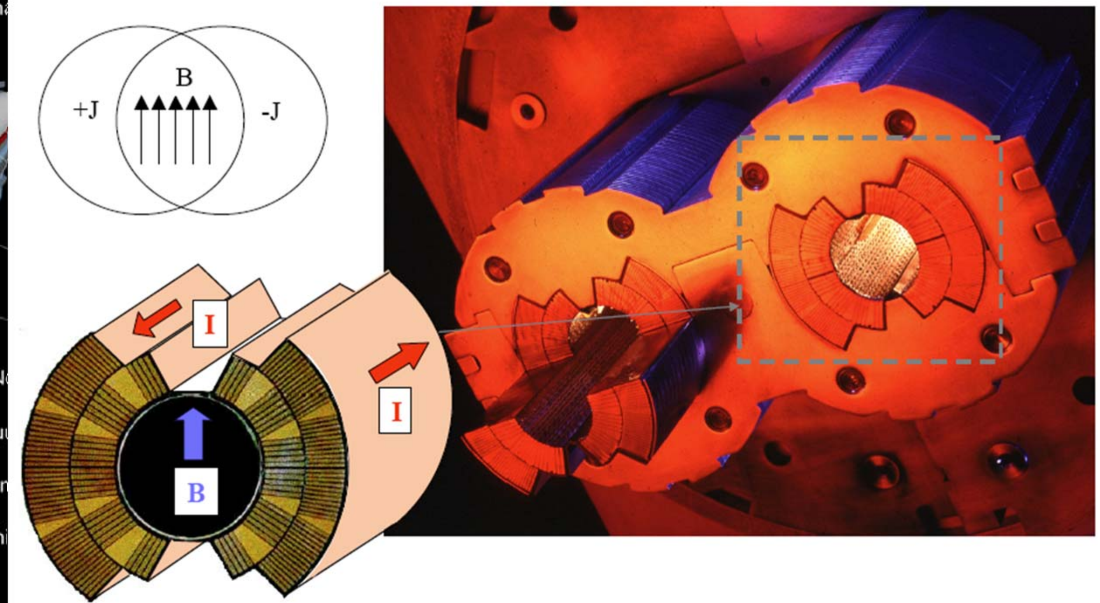
Journey in the Search for the Higgs Boson: The ATLAS and CMS Experiments at the Large Hadron Collider
M. Della Negra *et al.*
Science **338**, 1560 (2012);
DOI: 10.1126/science.1230827

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

Spares

LHC Accelerator Challenge: Dipole Magnets



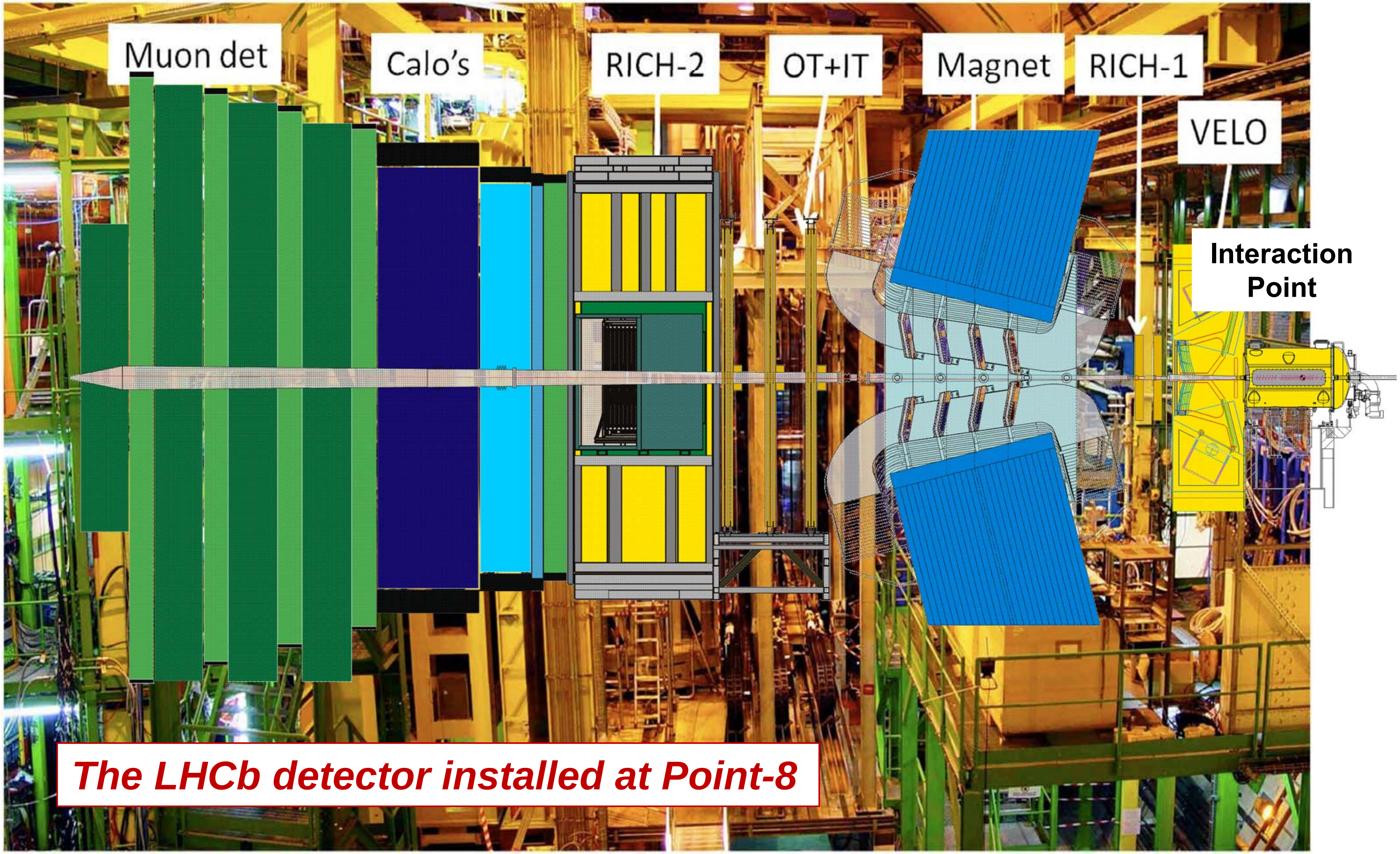


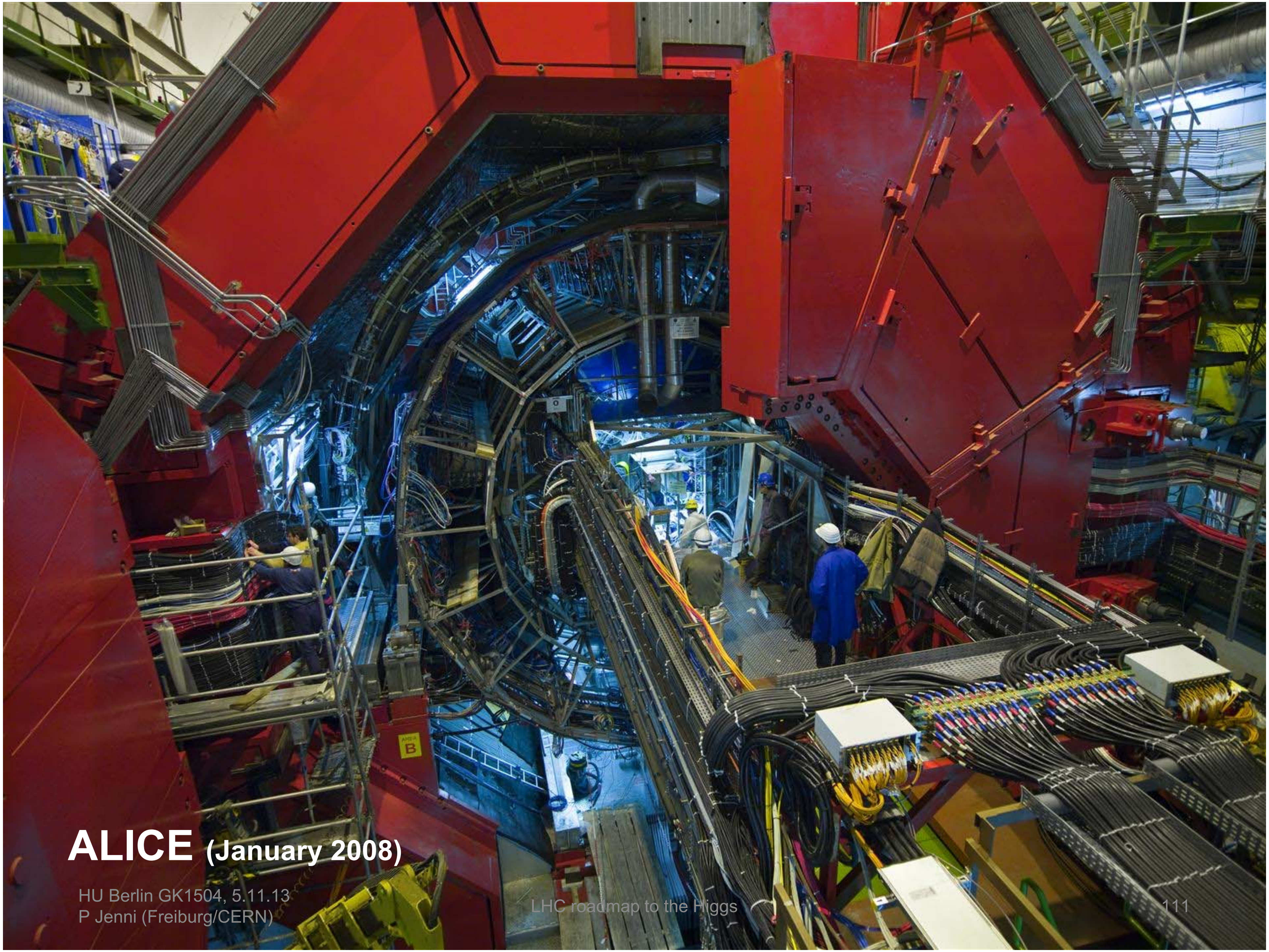
Magnetic Field for Dipoles
p (TeV) = 0.3 B(T) x R(km)

For p = 7 TeV and R = 4.3 km
⇨ B = 8.4 T
⇨ Current 12 kA

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

LHC magnets are cooled with pressurized superfluid Helium

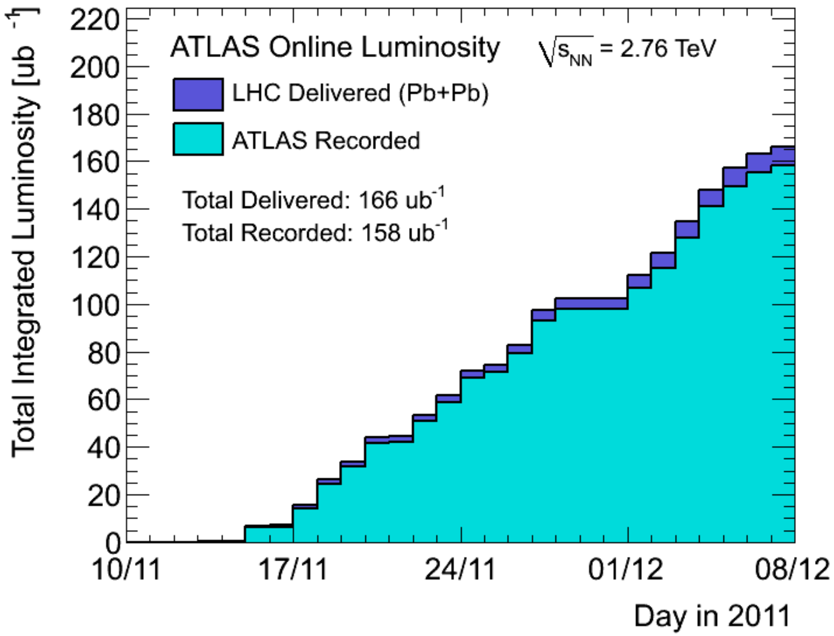

Muon det
Calo's
RICH-2
OT+IT
Magnet
RICH-1
VELO
Interaction Point
The LHCb detector installed at Point-8

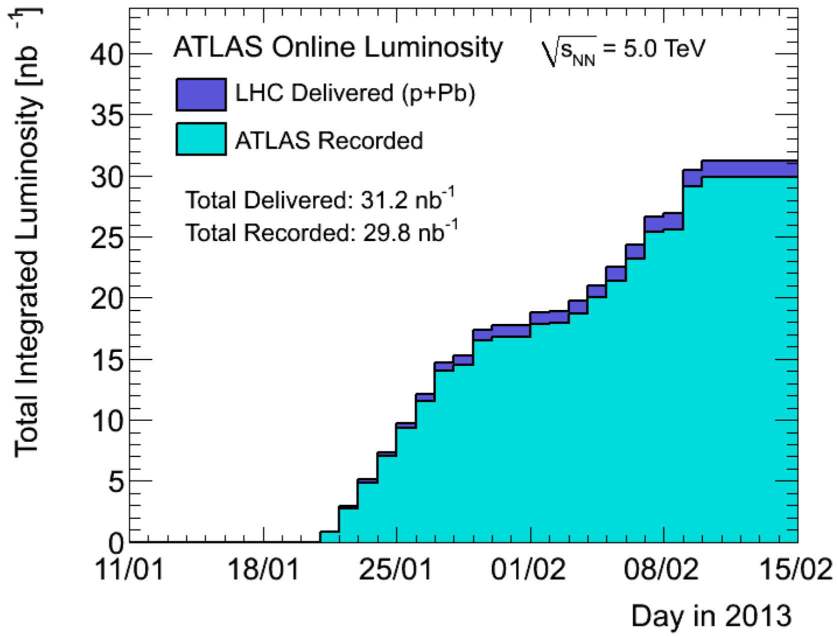


ALICE (January 2008)

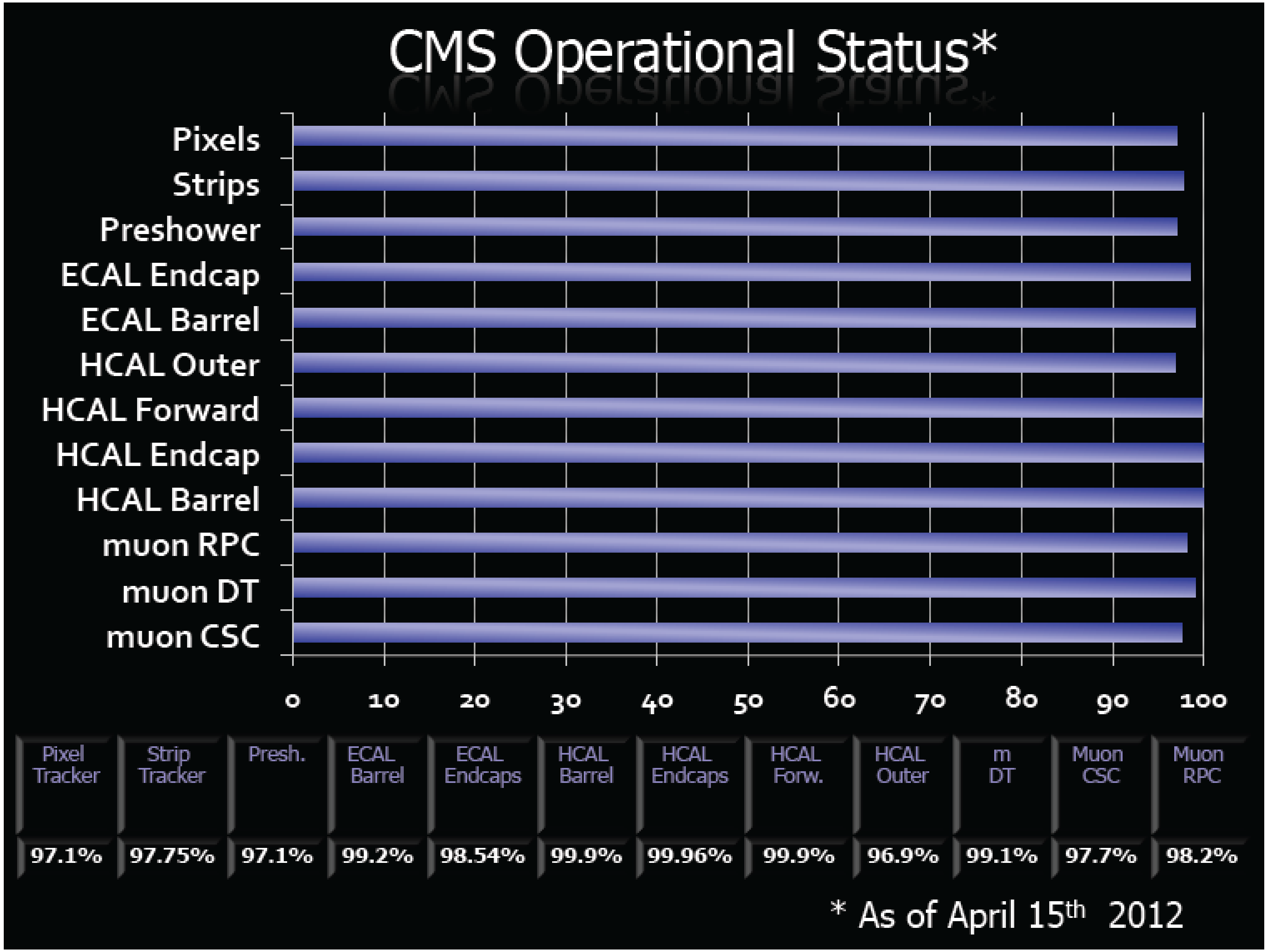
A historical moment:
Closure of the LHC beam pipe ring on 16th June 2008

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

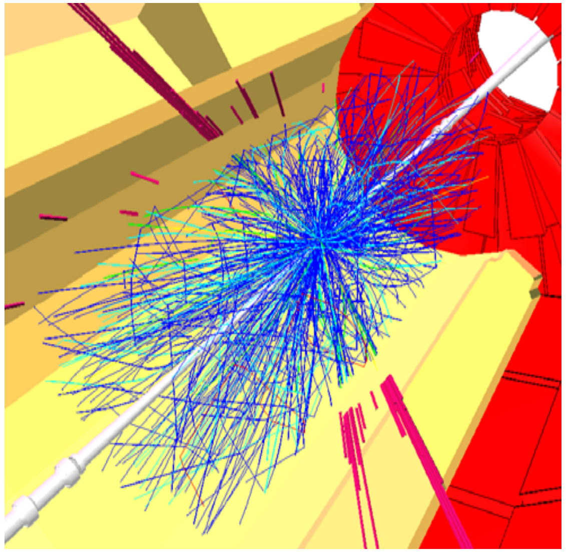




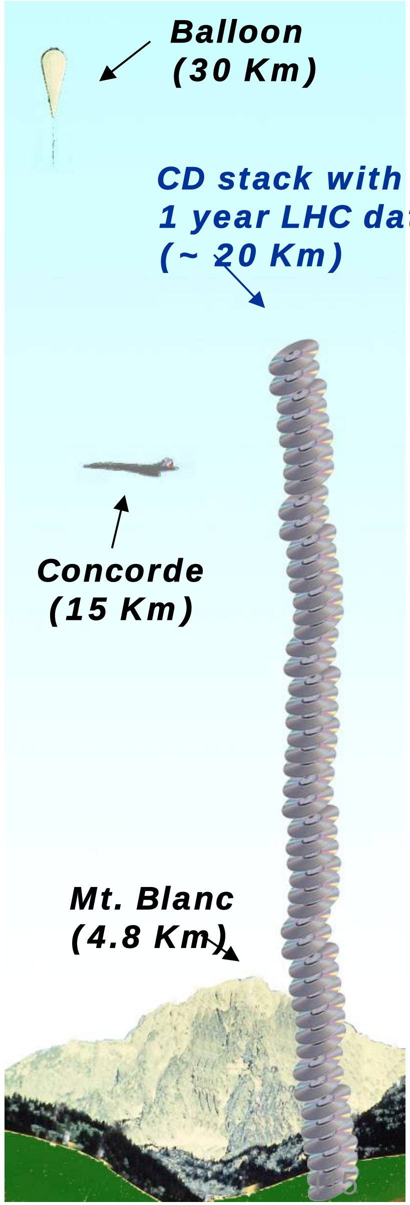
Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.9%
SCT Silicon Str		
TRT Transition		
LAr EM Calorin		
Tile calorimeter		
Hadronic endca		
Forward LAr ca		
LVL1 Calo trigg		
LVL1 Muon RP		
LVL1 Muon TG		
MDT Muon Drif		
CSC Cathode S		
RPC Barrel Mu		
TGC Endcap M		



Worldwide LHC Computing Grid (wLCG)



WLCG is a worldwide collaborative effort on an unprecedented scale in terms of storage and CPU requirements, as well as the software project's size

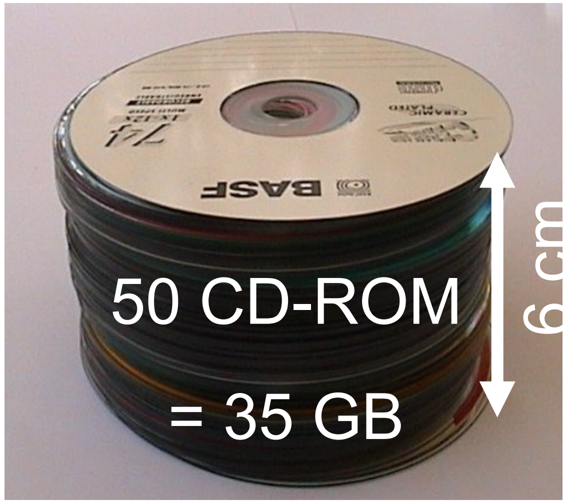


GRID computing developed to solve problem of data storage and analysis

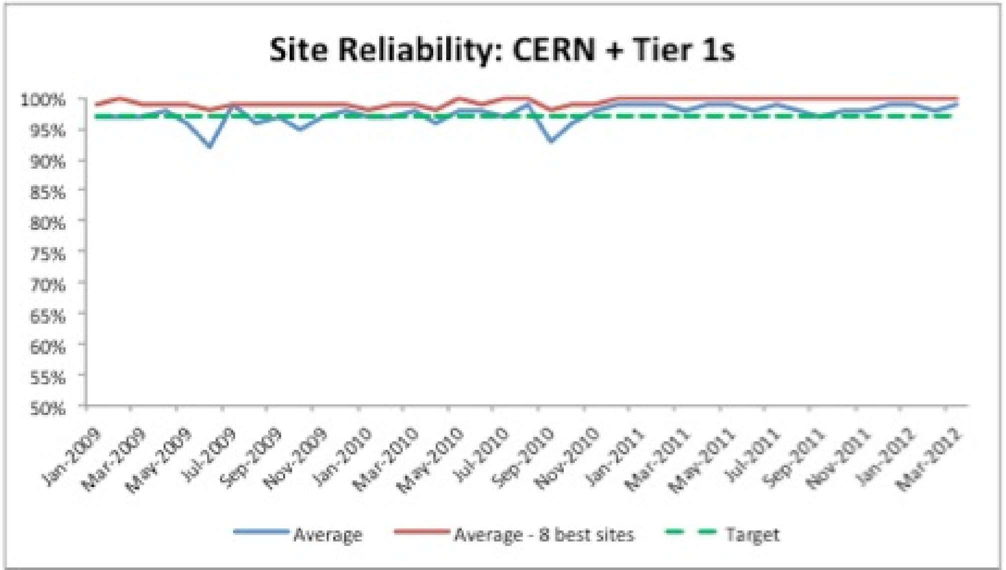
LHC data volume per year: 10-15 Petabytes

One CD has ~ 600 Megabytes
1 Petabyte = 10^9 MB = 10^{15} Byte

(Note: the WWW is from CERN...)

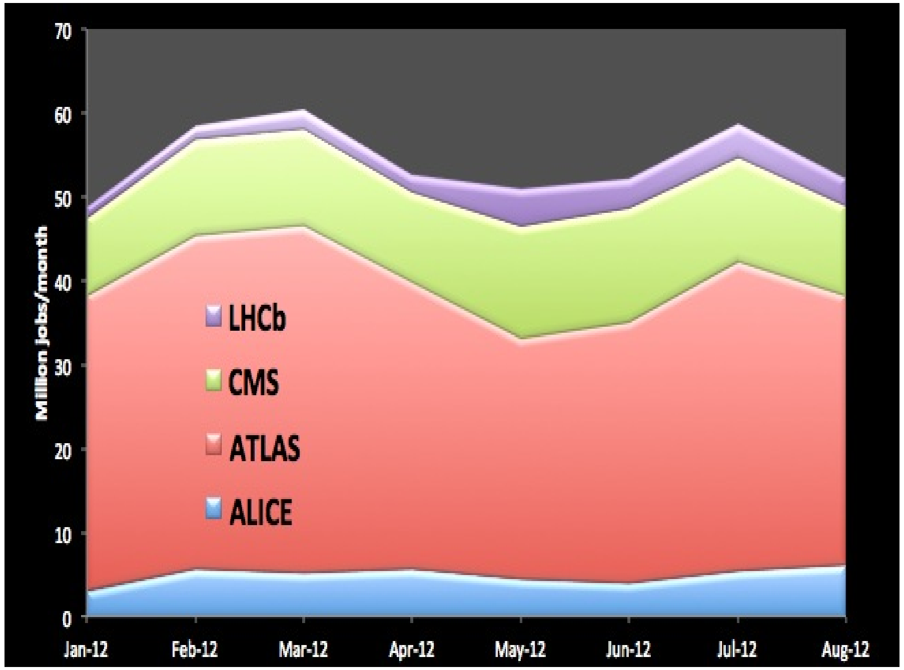


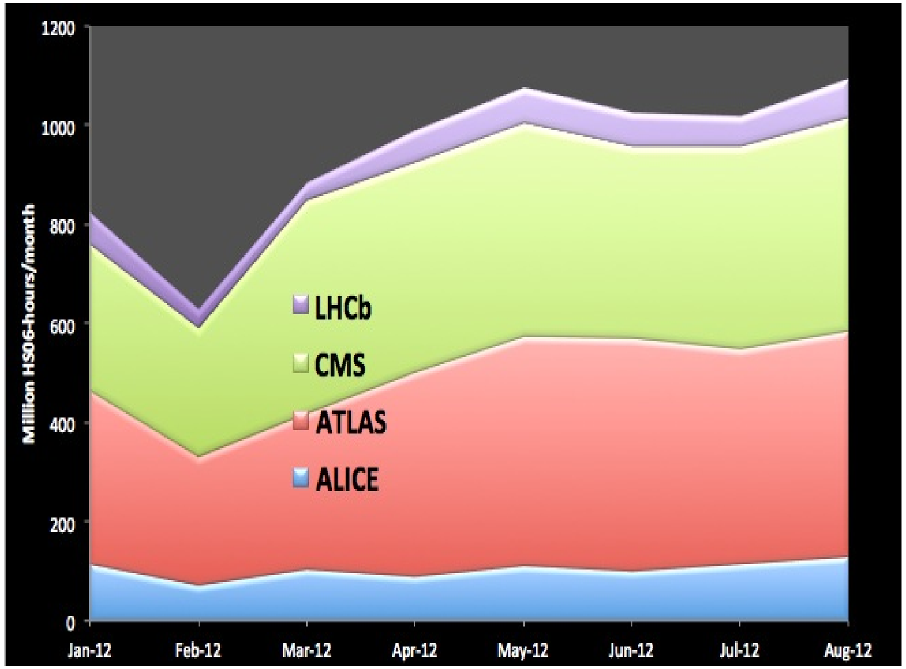
The high quality of the WLCG computing system allows LHC experiments to show results from data taken just few weeks before



Data preparation (ATLAS):

- **First-pass reconstruction at Tier-0 within ~2 days**
- **Calibration good for physics analysis on Grid within ~1 week**





Physics Highlights:

General event properties

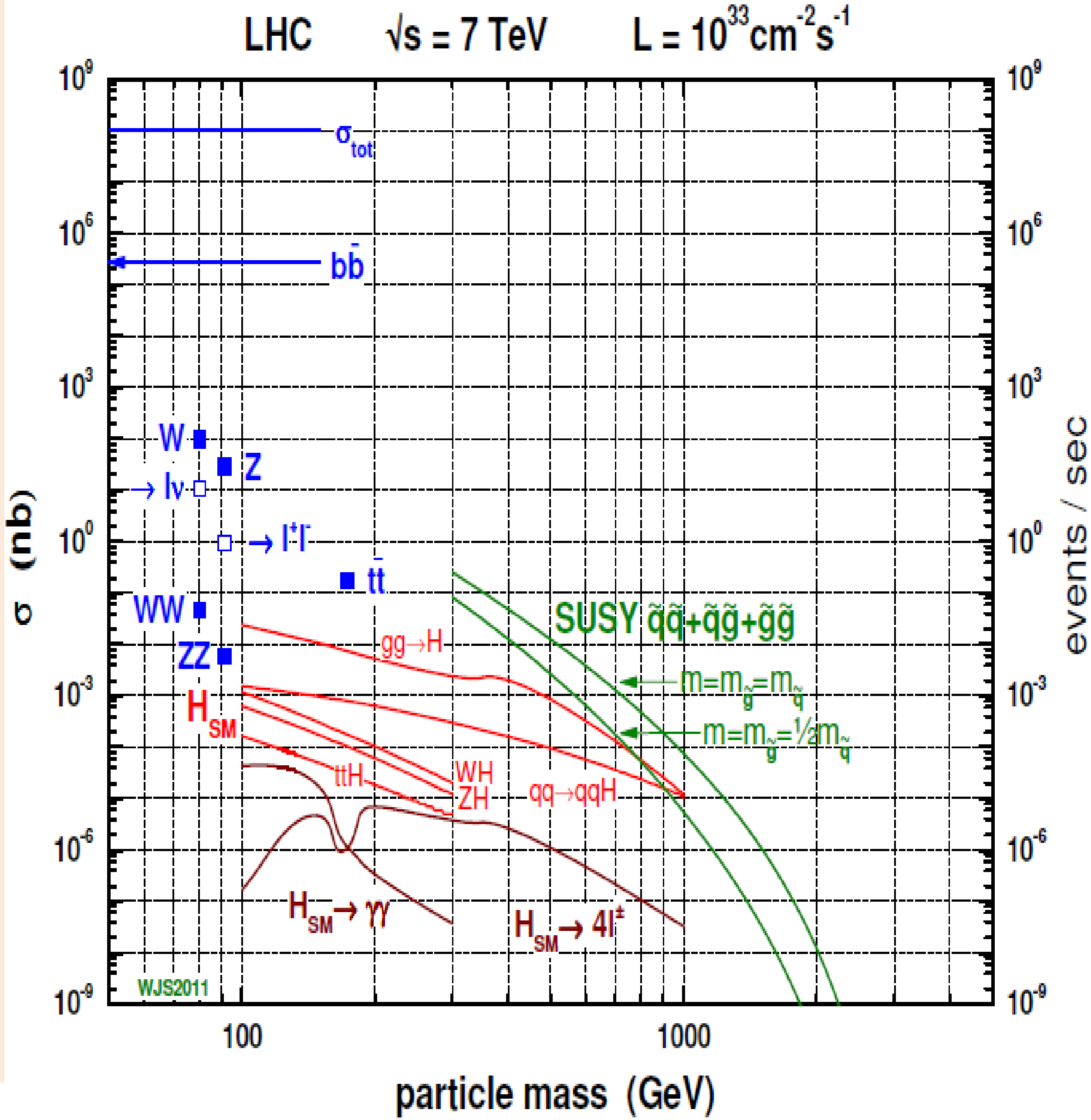
Heavy flavour physics

Standard Model physics including QCD jets

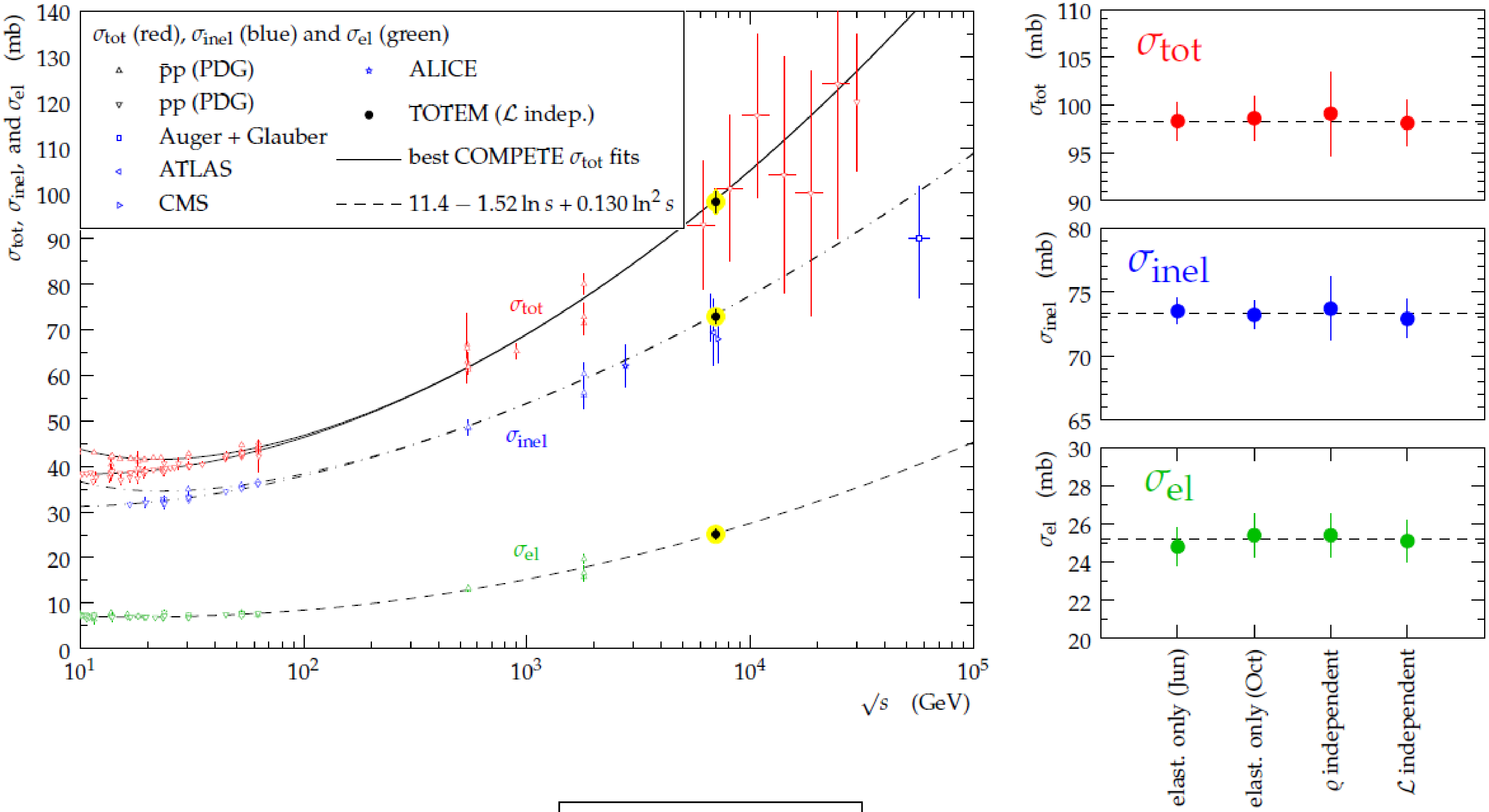
Higgs searches

Searches for SUSY

Searches for 'exotic' new physics



Total cross-section measurement by TOTEM

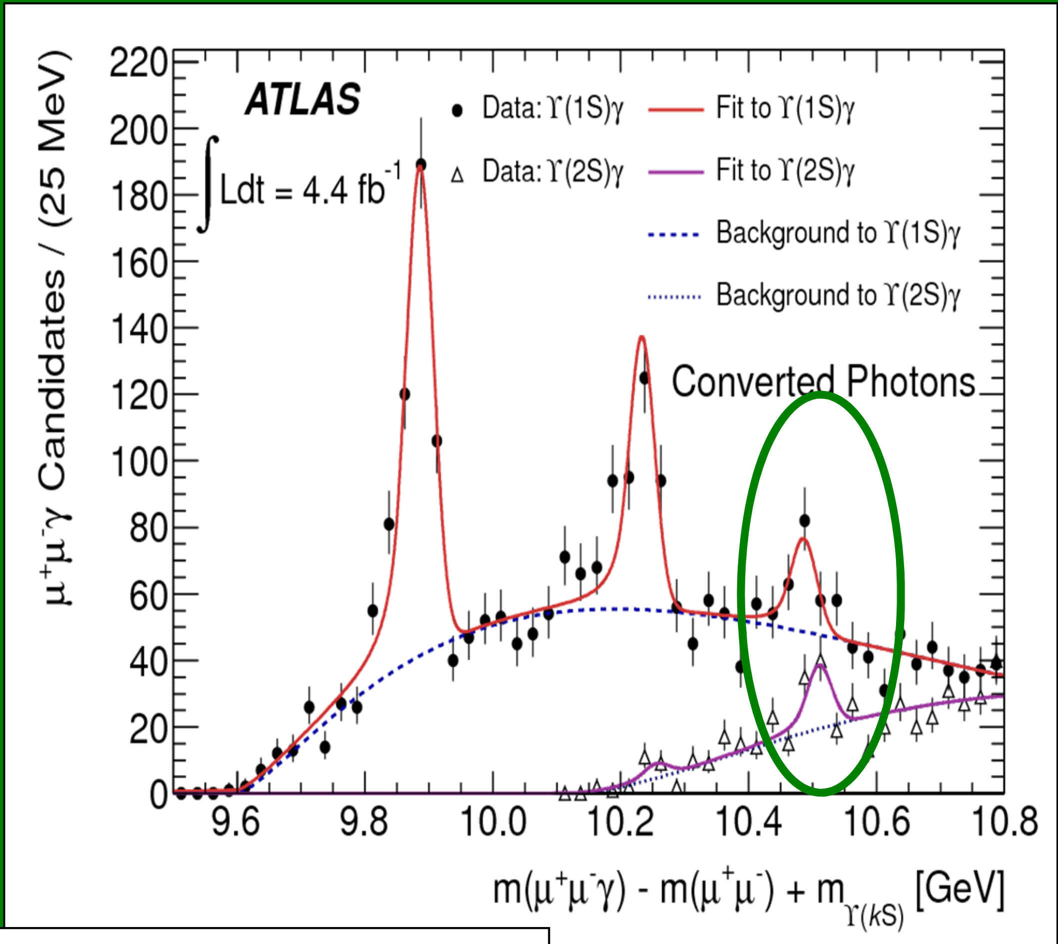


Presented at HCP2012

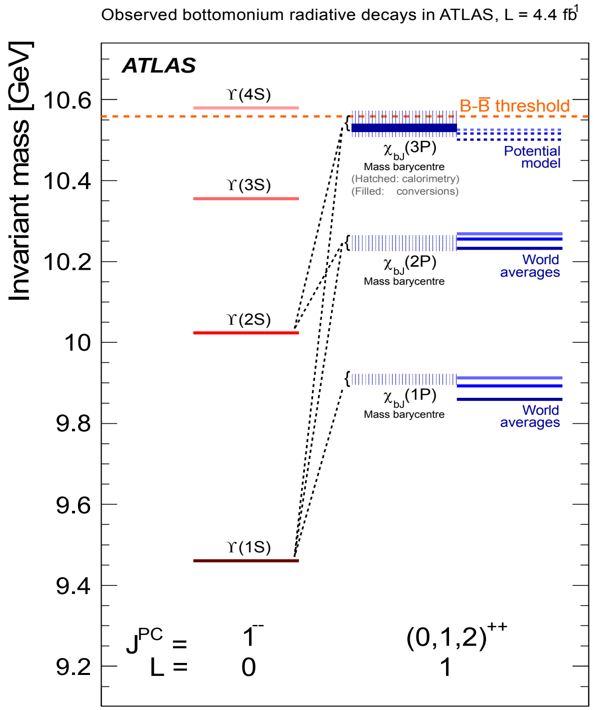
The first new particles 'discovered' at LHC, December 2011

$\chi_b(3P) \rightarrow Y(1s,2s)\,\gamma$

$m\,[\chi_b(3P)] = 10.530 \pm 0.005\,(stat) \pm 0.009\,(syst)$ GeV

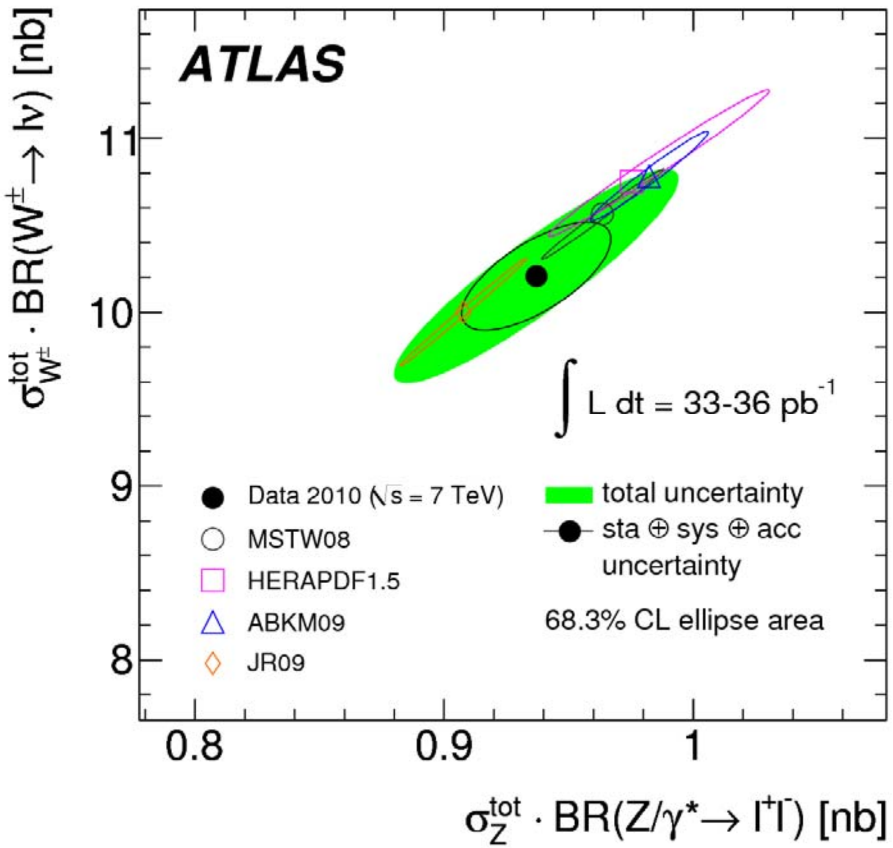


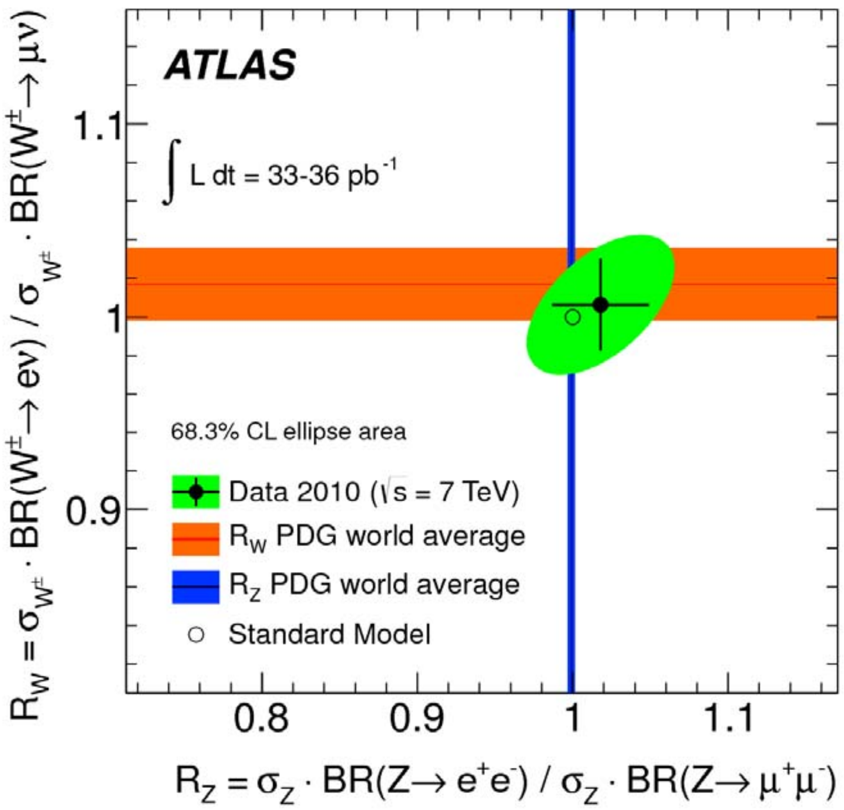
Phys. Rev. Lett. 108 (2012) 152001



- ❑ $\chi_b(nP) \rightarrow Y(1s,2s)\,\gamma \rightarrow \mu\mu\,\gamma$
- ❑ $X_b(1P)$ m= 9.9 GeV and $X_b(2P)$ m= 10.2 GeV states clearly visible
- ❑ New structure at 10.5 GeV → $X_b(3P)$
- ❑ Significance > 6 σ
- ❑ As theoretically predicted

Two examples of confronting the 2010 data with SM theory

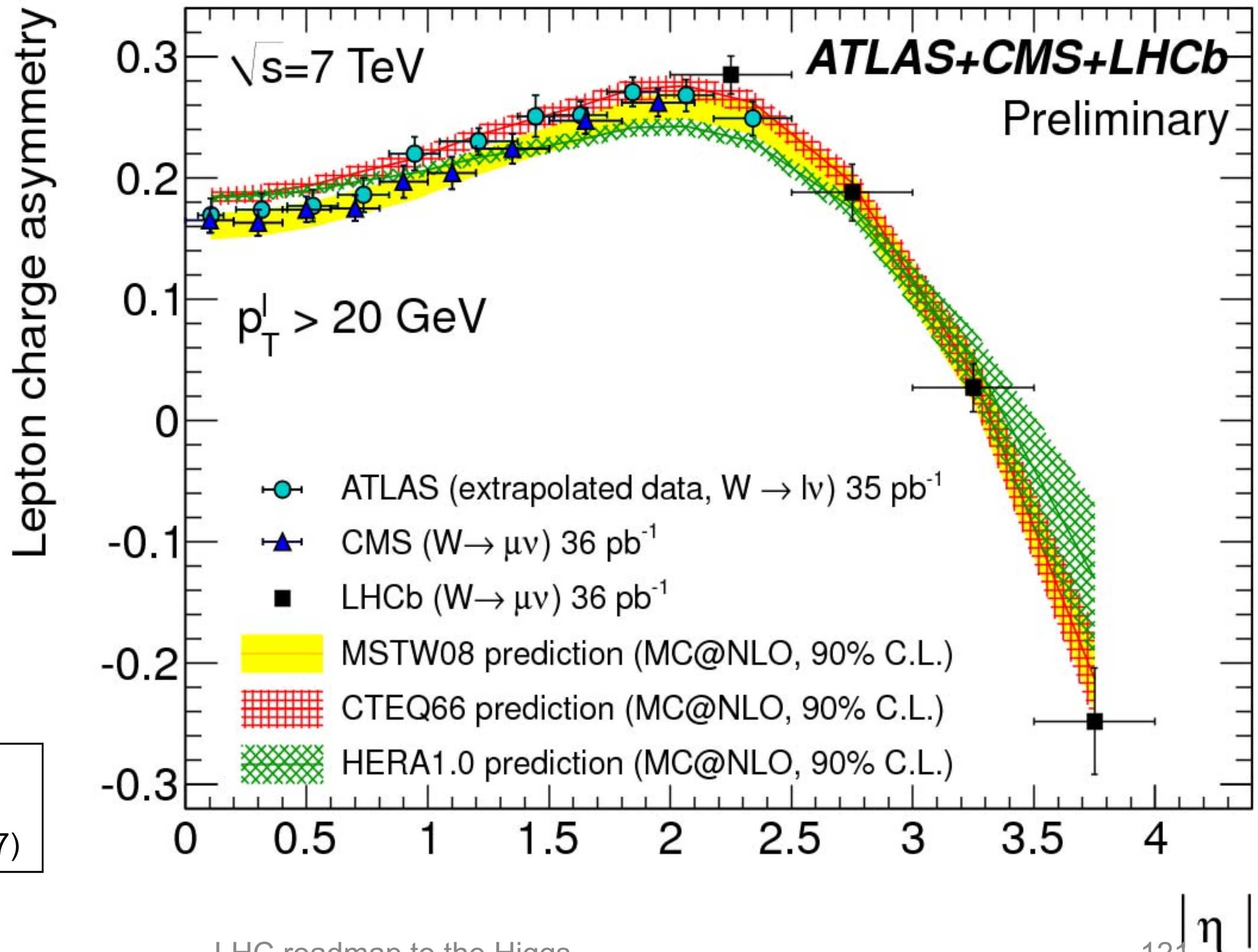




Phys Rev D85 (2012) 072004

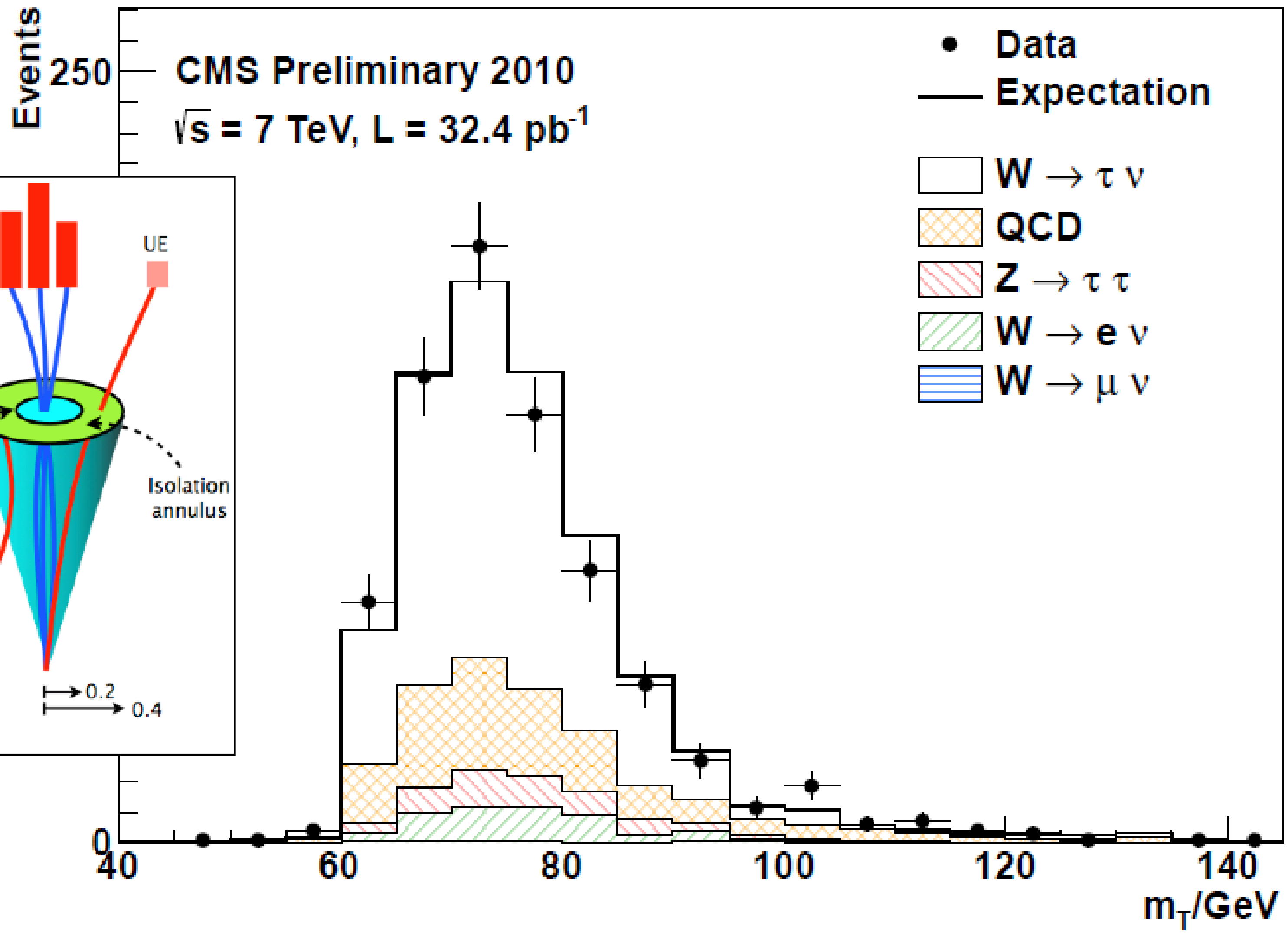
Lepton charge asymmetry from W decays in pp collisions at 7 TeV

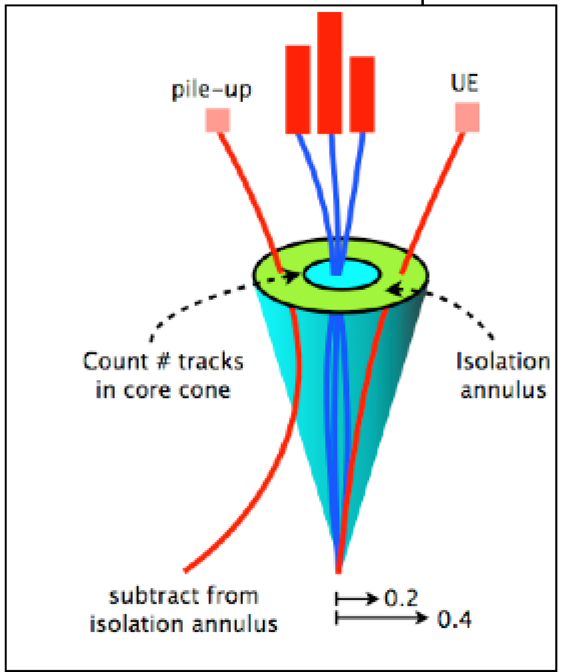
$$A(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})},$$



ATLAS-CONF-2011-129
LHCb-CONF-2011-039
CMS-EWK-10-006 (aXiv:1103.3407)

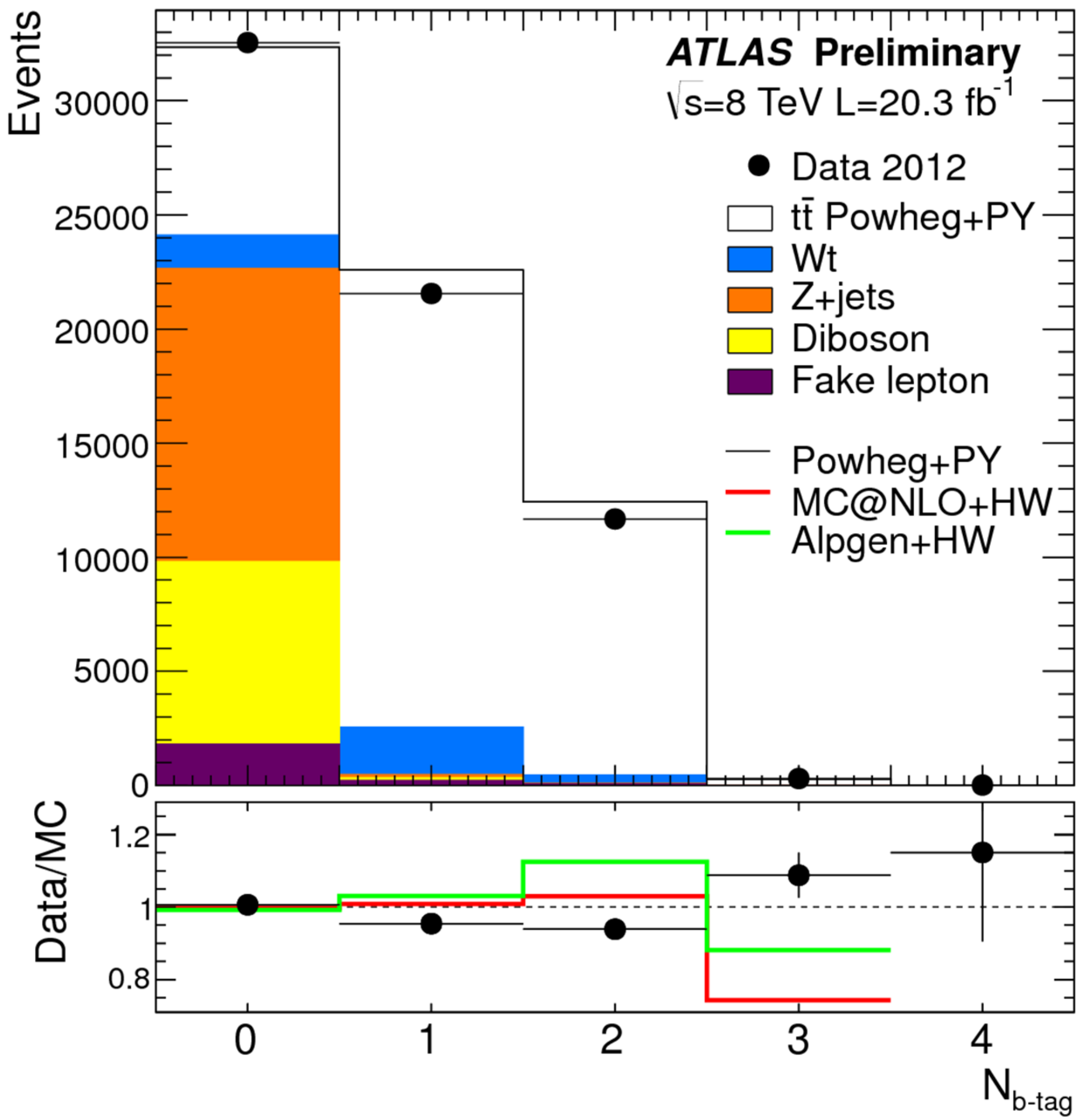
W → τν signal



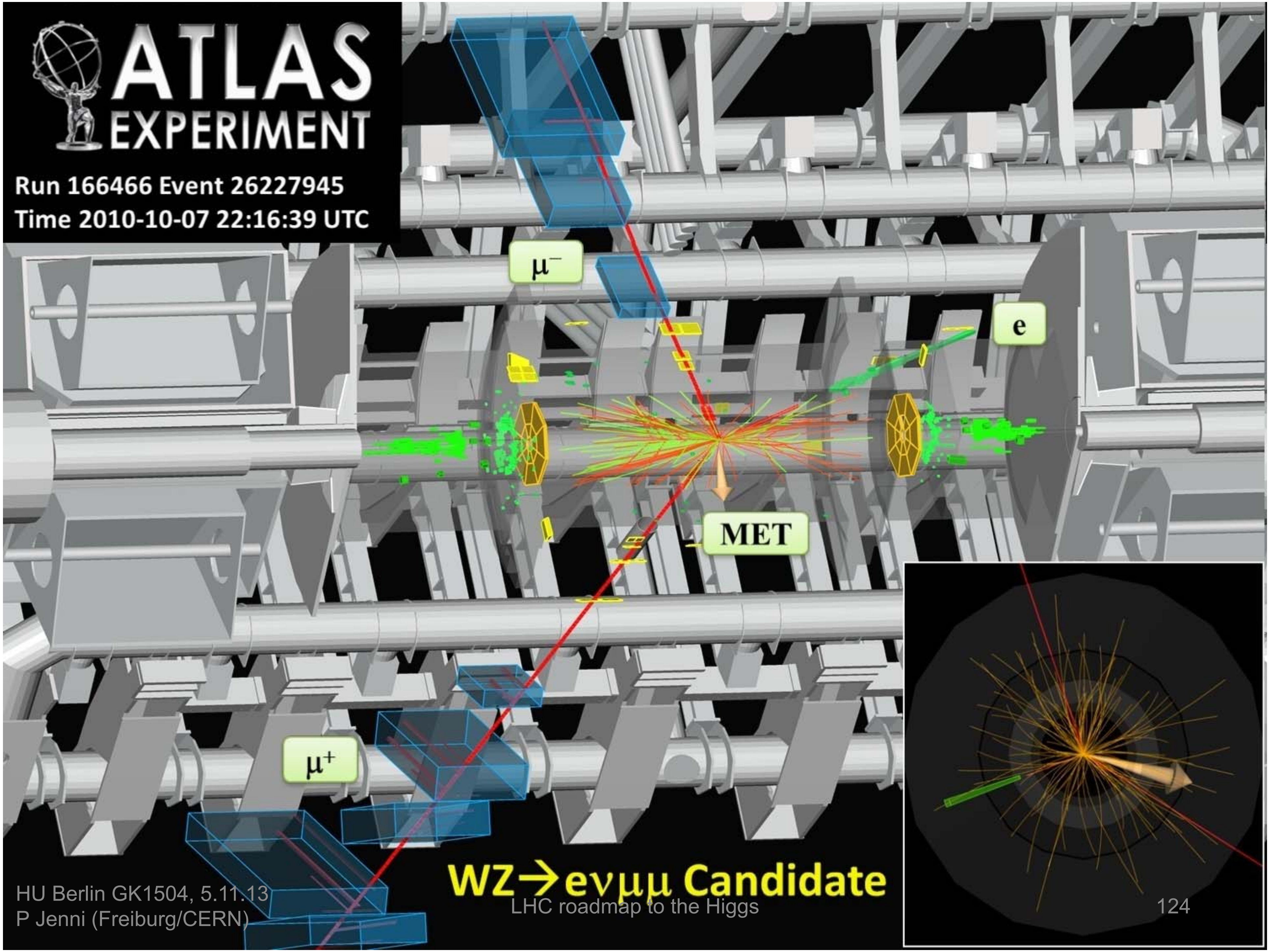


CMS-PAS-EWK-11-019

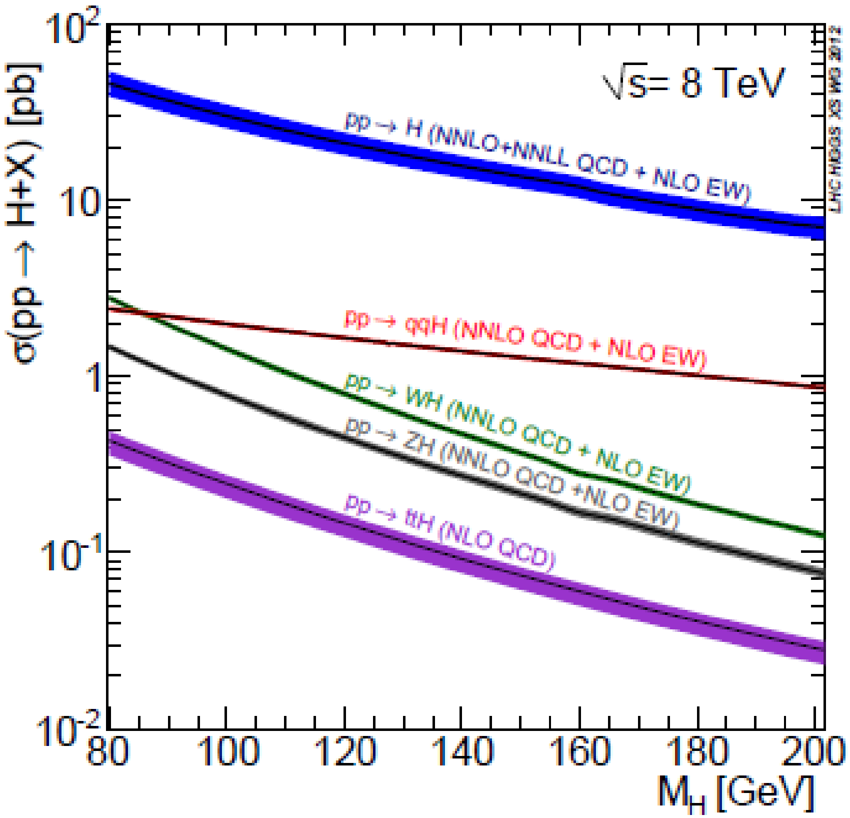
tt – production with b-tagged e-μ events

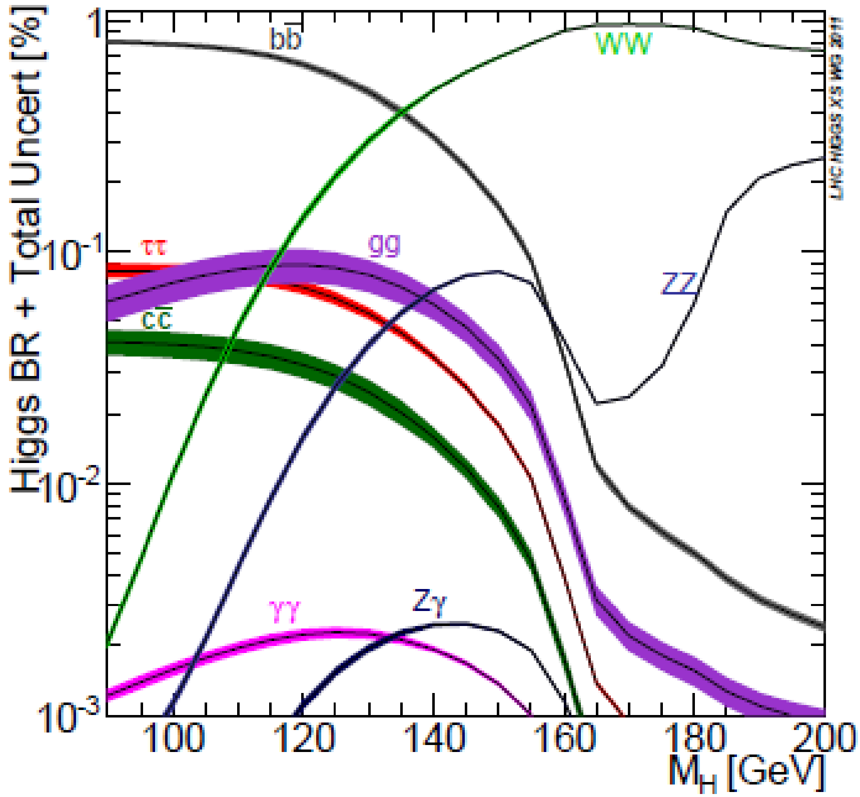


ATLAS-CONF-2013-097


ATLAS
EXPERIMENT
Run 166466 Event 26227945
Time 2010-10-07 22:16:39 UTC
μ⁻
e
MET
μ⁺
WZ→eνμμ Candidate

Higgs production cross-sections at 8 TeV, and branching fractions



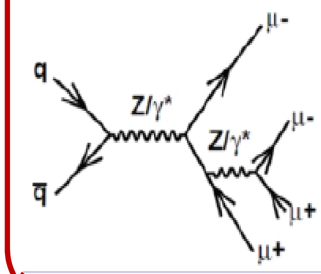


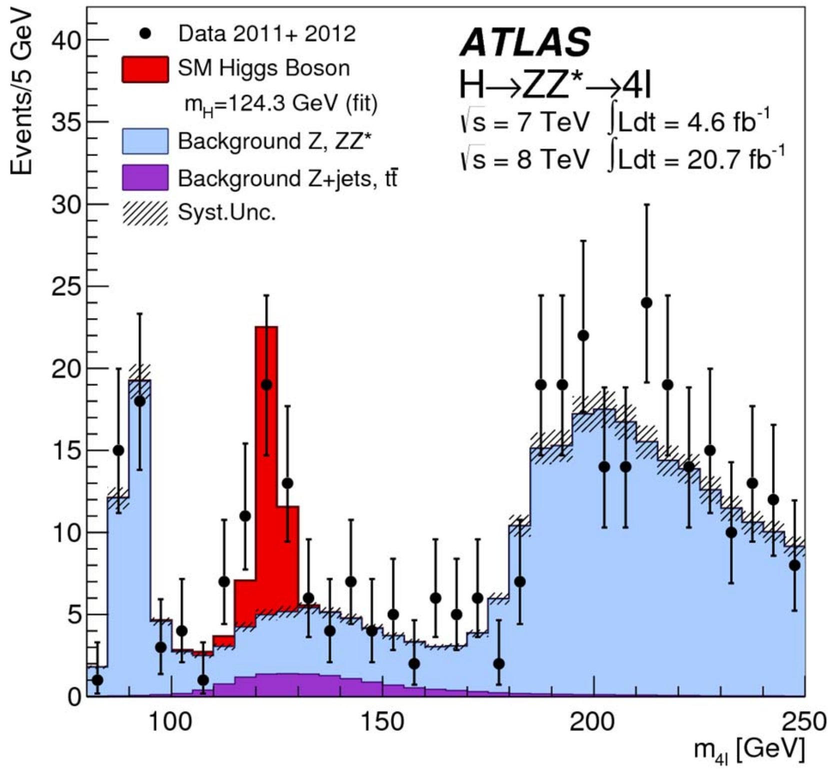
LHC Higgs cross-section working group, arXiv: 1101.0593 and 1201.3084
(the theoretical uncertainties are indicated by the width of the curves)

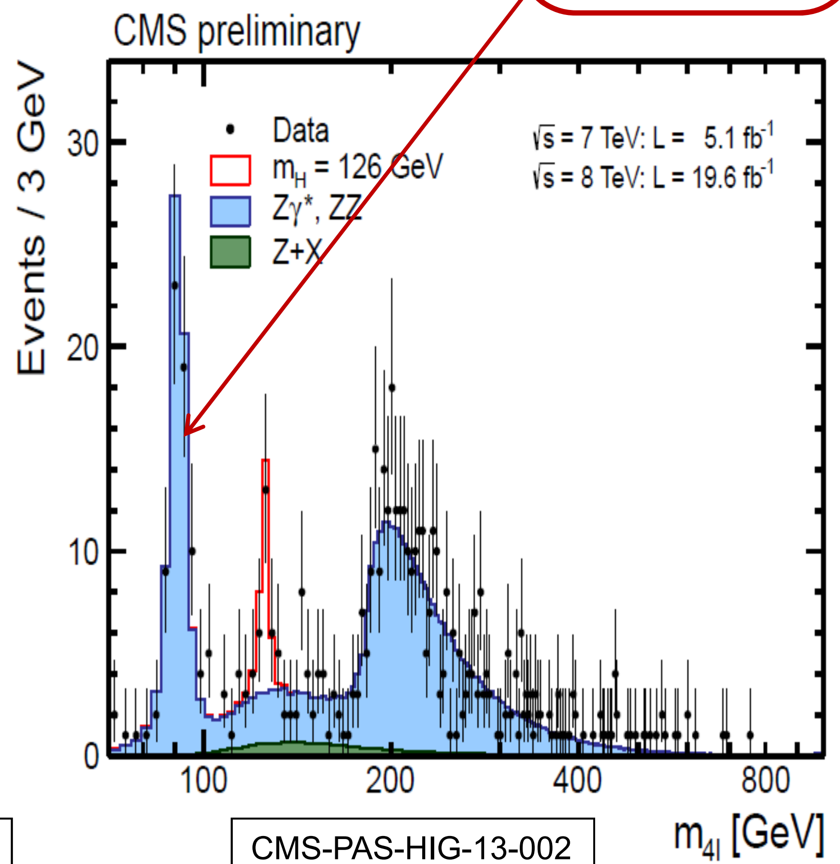
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (4e, 4μ, 2e2μ)

- ❑ **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

Why a Z peak ?



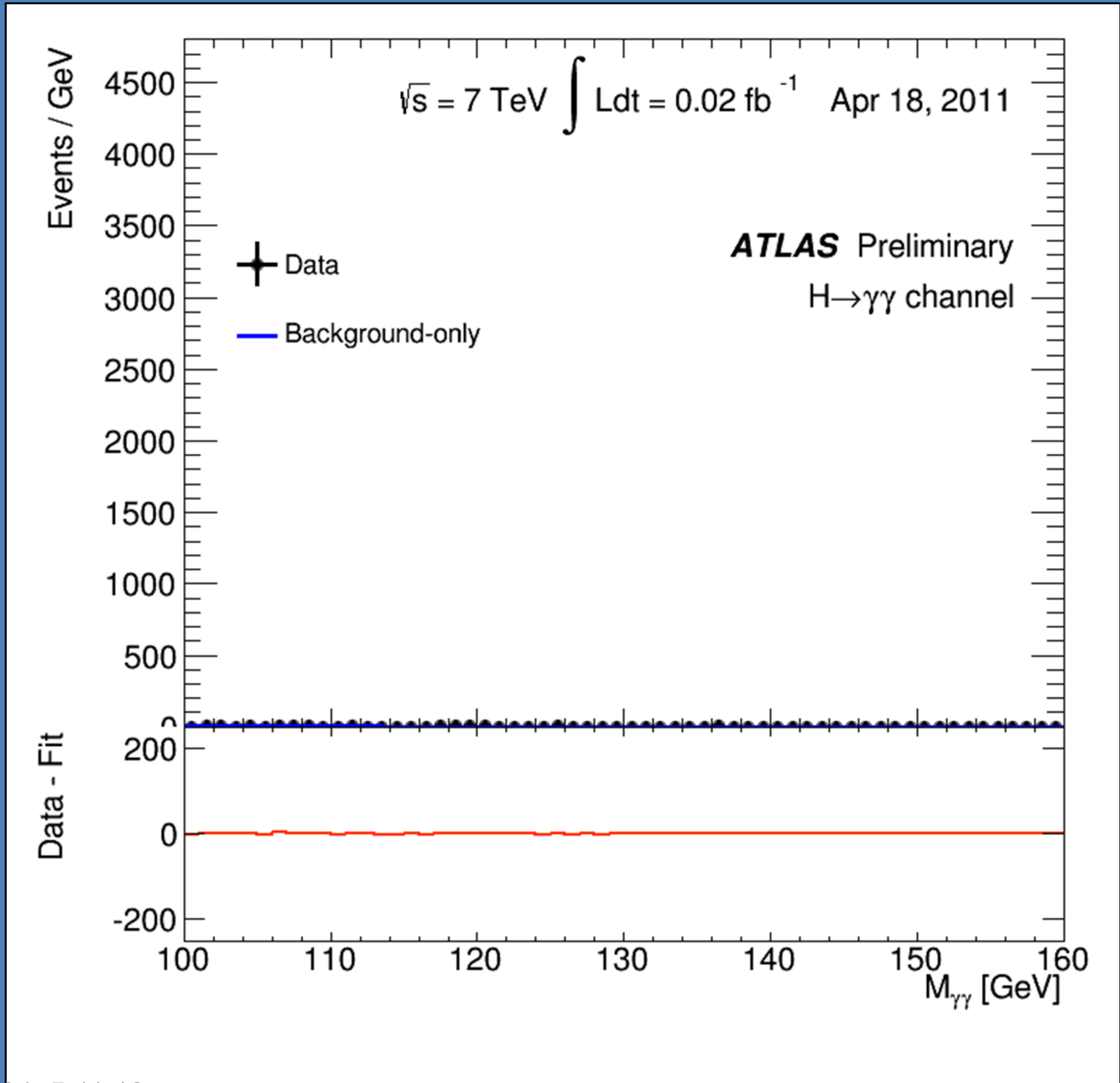




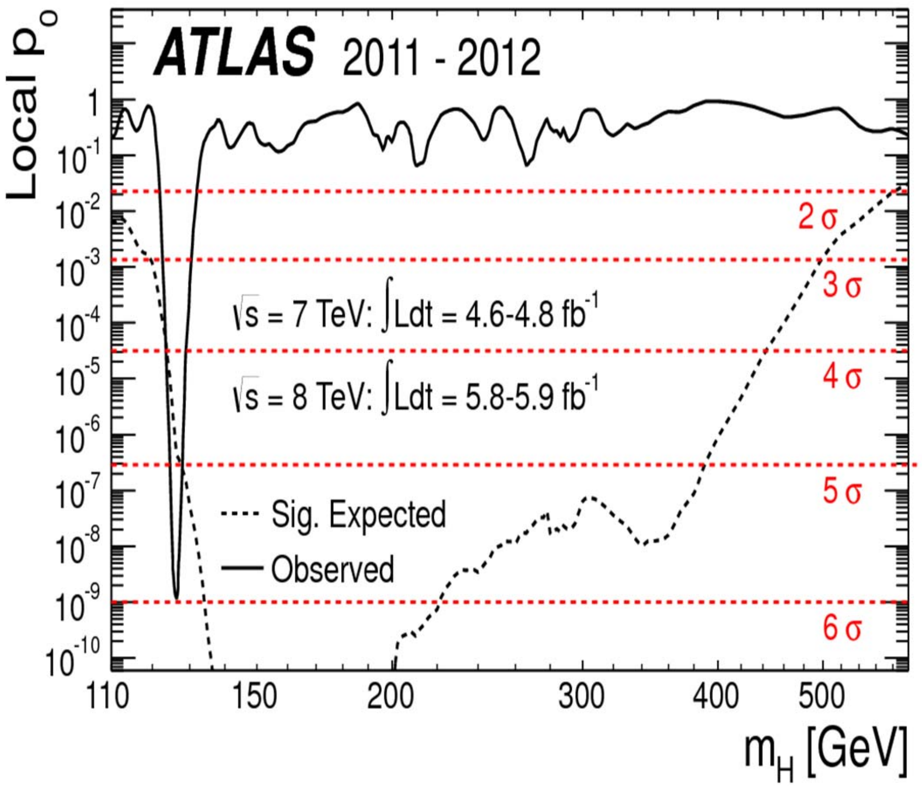
ATLAS-CONF-2013-013 and Phys. Lett. B 726 (2013) 88-119

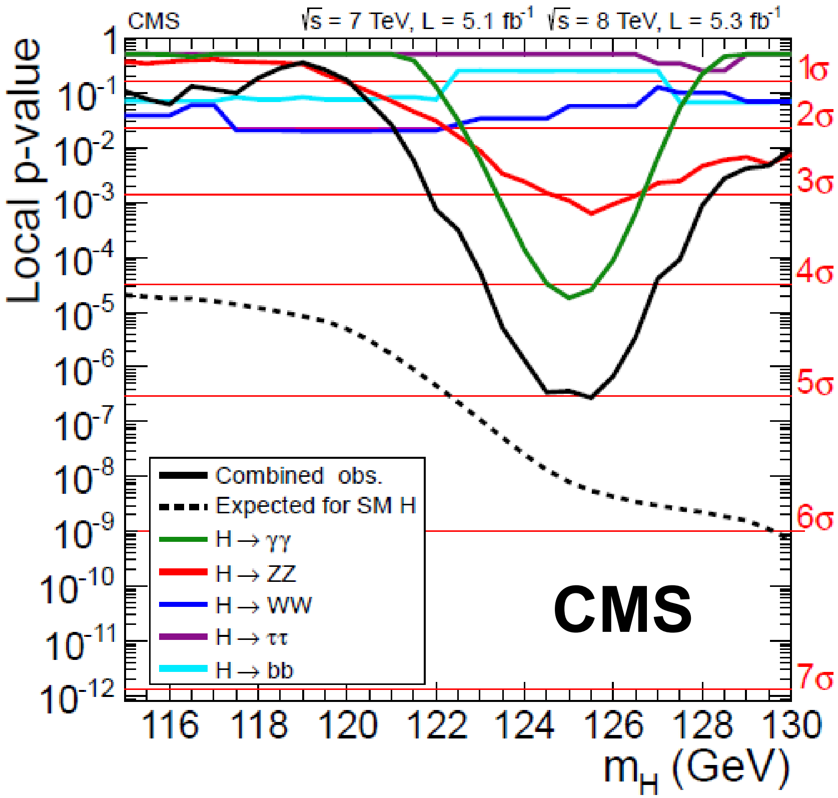
CMS-PAS-HIG-13-002

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

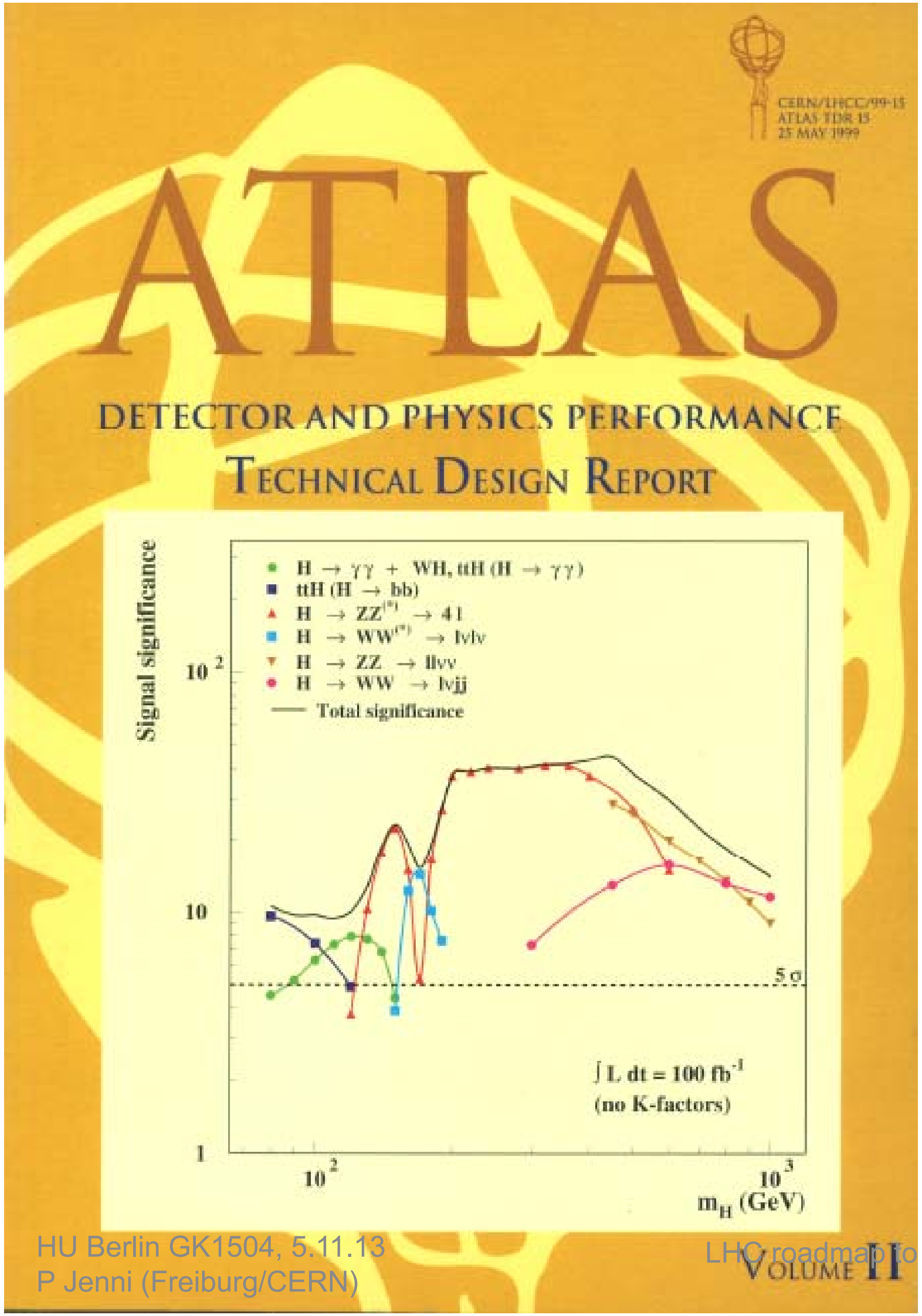


Two of the by now historical plots from the July 2012 discovery announcement

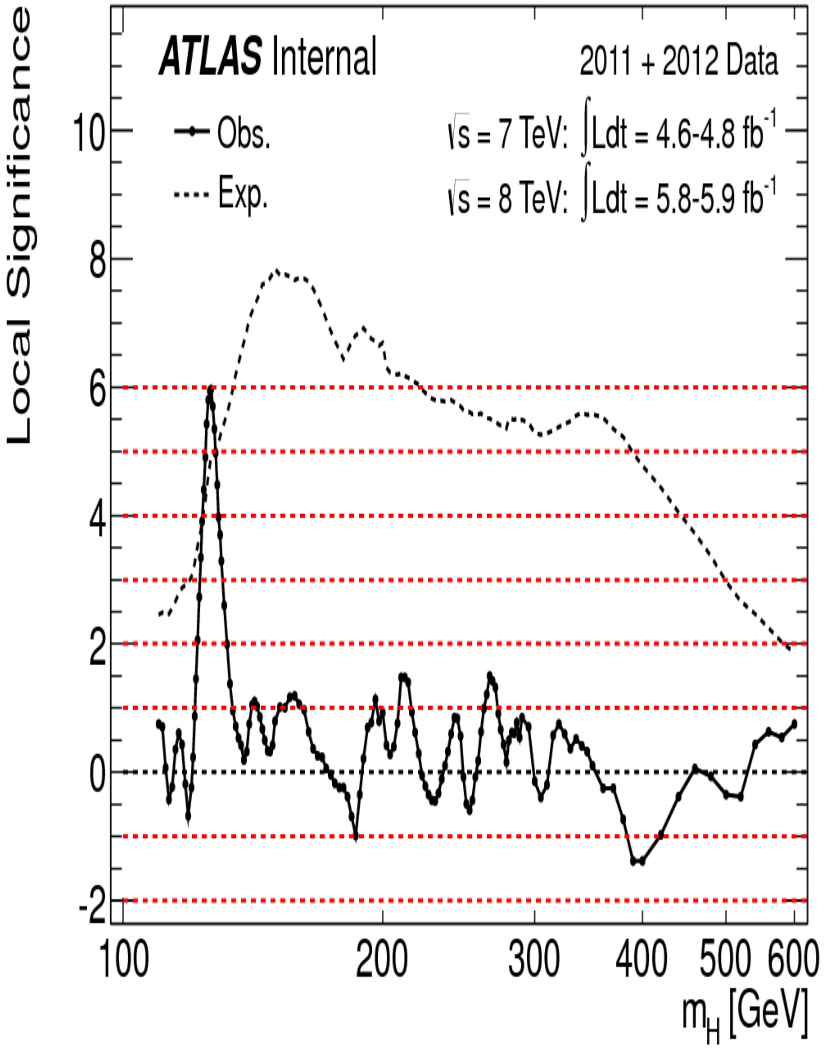




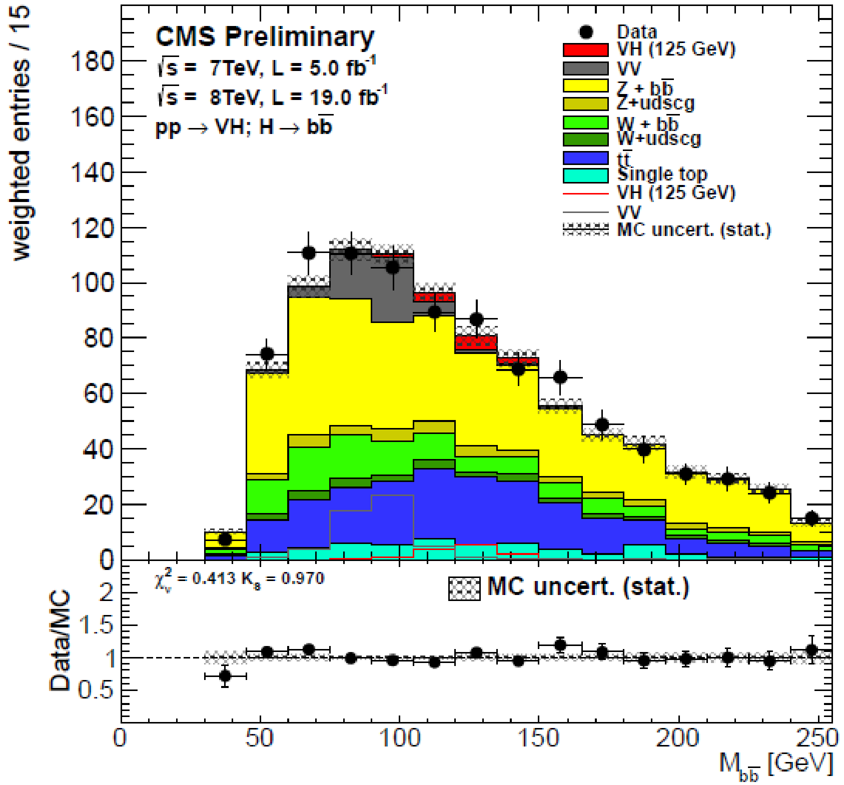
Observed data compared to the probability that the background fluctuates to fake the observed excess of events, and what is expected from a SM Higgs

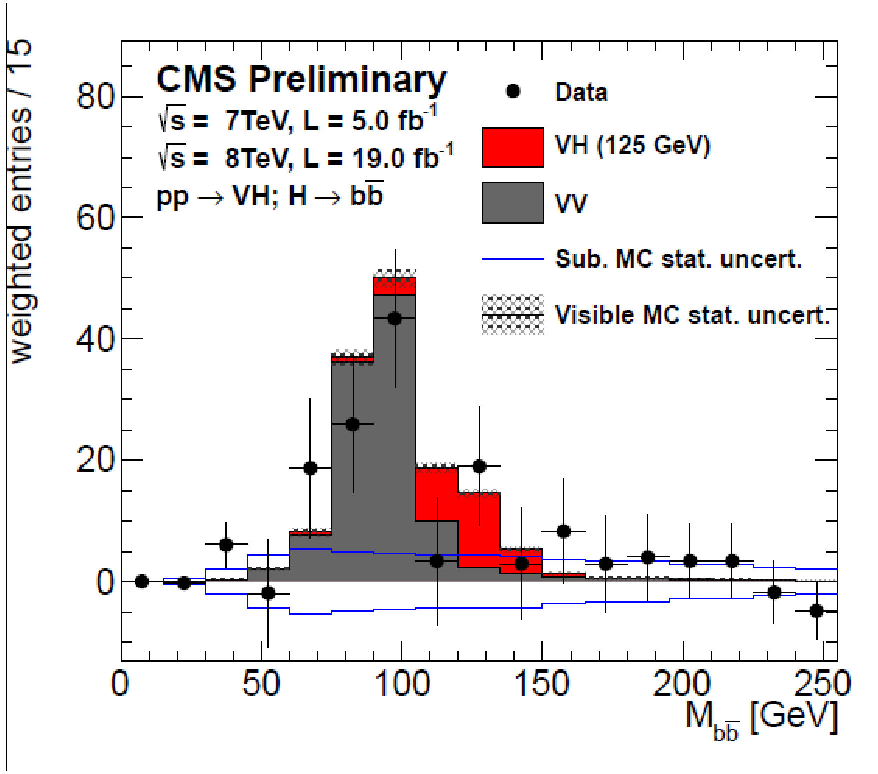


A dream becoming true much faster than anticipated long ago



H search in the bb channel



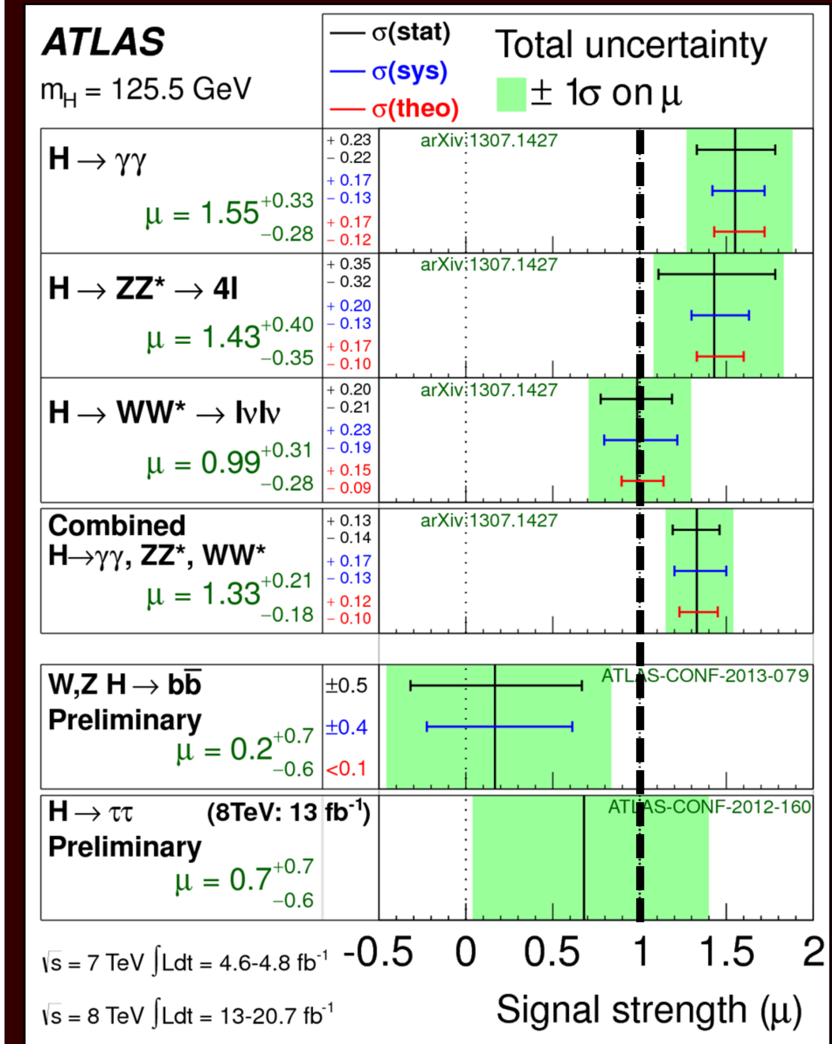


From F Gianotti

Mass measurement

From high-resolution
H→ $\gamma\gamma$ and H→ 4l channels

$$m_H(\text{combined}) = 125.5\ \text{GeV} \pm 0.2\ (\text{stat})\ ^{+0.5}_{-0.6}(\text{syst})\ \text{GeV}$$



Signal production strength

μ = measured signal production rate in a given final state normalized to SM Higgs expectation

From di-boson final states ($\gamma\gamma$, 4l, WW) :
μ = 1.33 ± 0.20

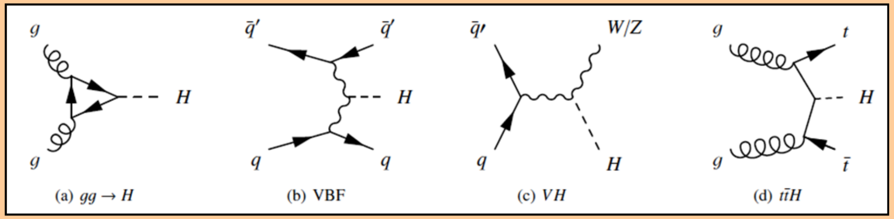
Including preliminary results from fermionic final states (bb, $\tau\tau$):
μ = 1.23 ± 0.18

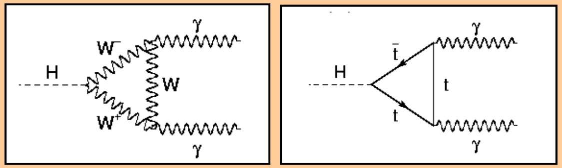
→in agreement with SM expectation

Note: similar contributions from statistical and systematic uncertainties to total error and from theory and experimental uncertainties to total systematic error

Constraining production modes and couplings (examples …)

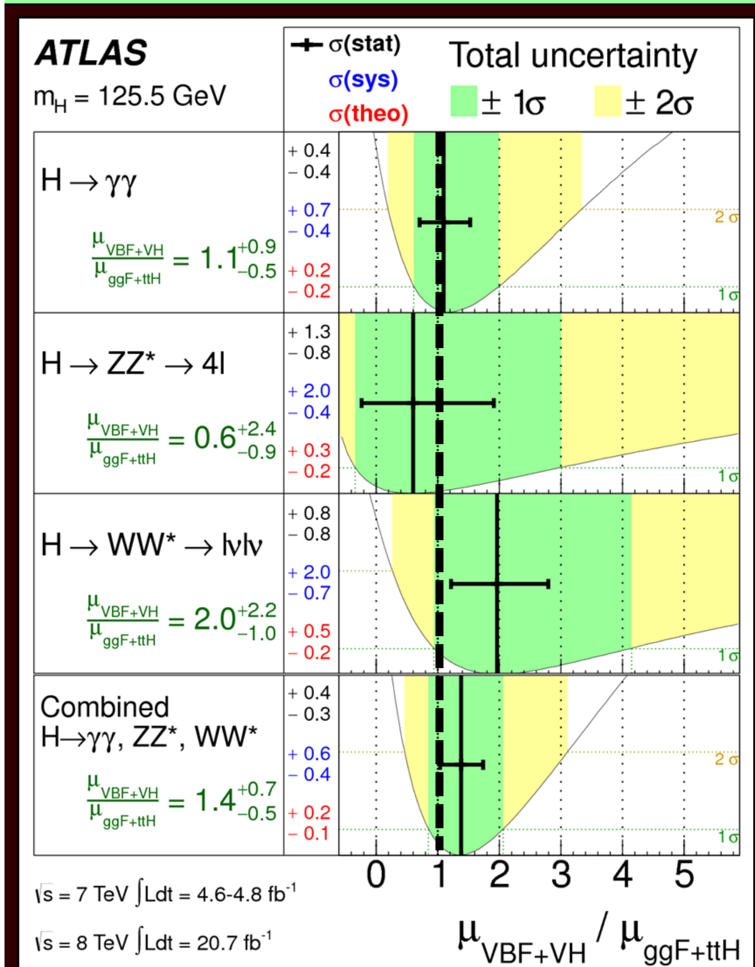
From F Gianotti



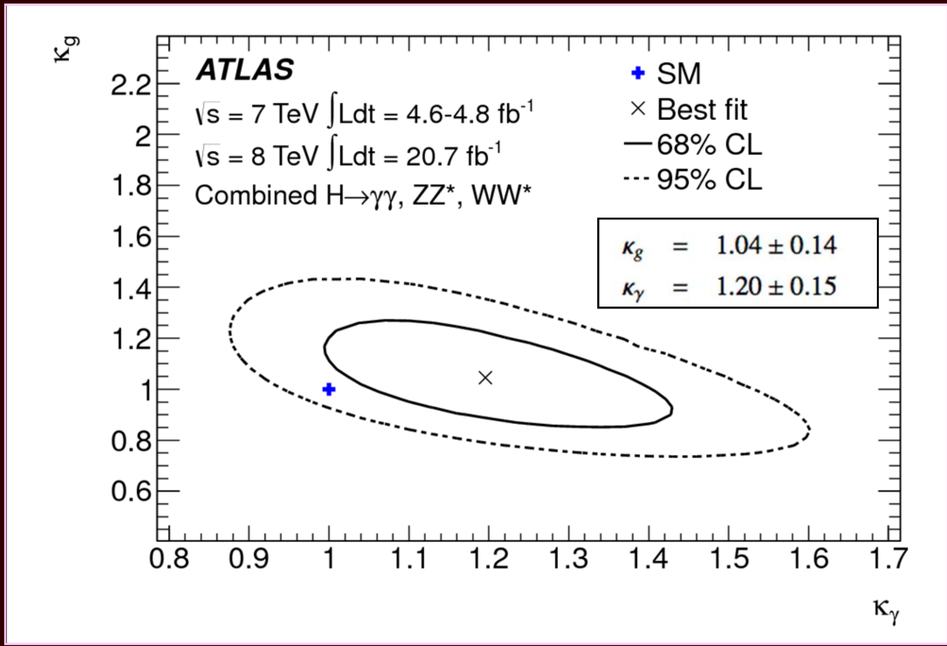


$$k_i^2 = \frac{\Gamma_i^{data}}{\Gamma_i^{SM}}$$

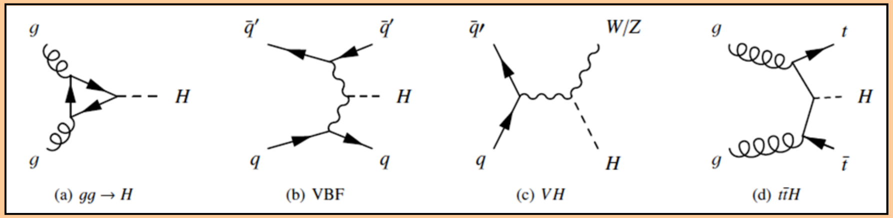
Ratios of vector-boson (VBH, VH) to top-quark (ggF, ttH) induced processes

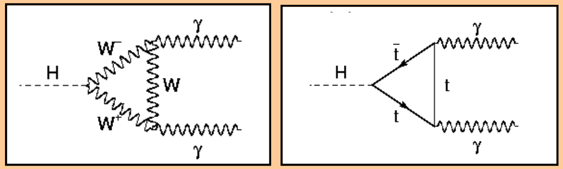


New particles in the gg → H and H→ γγ loops ?

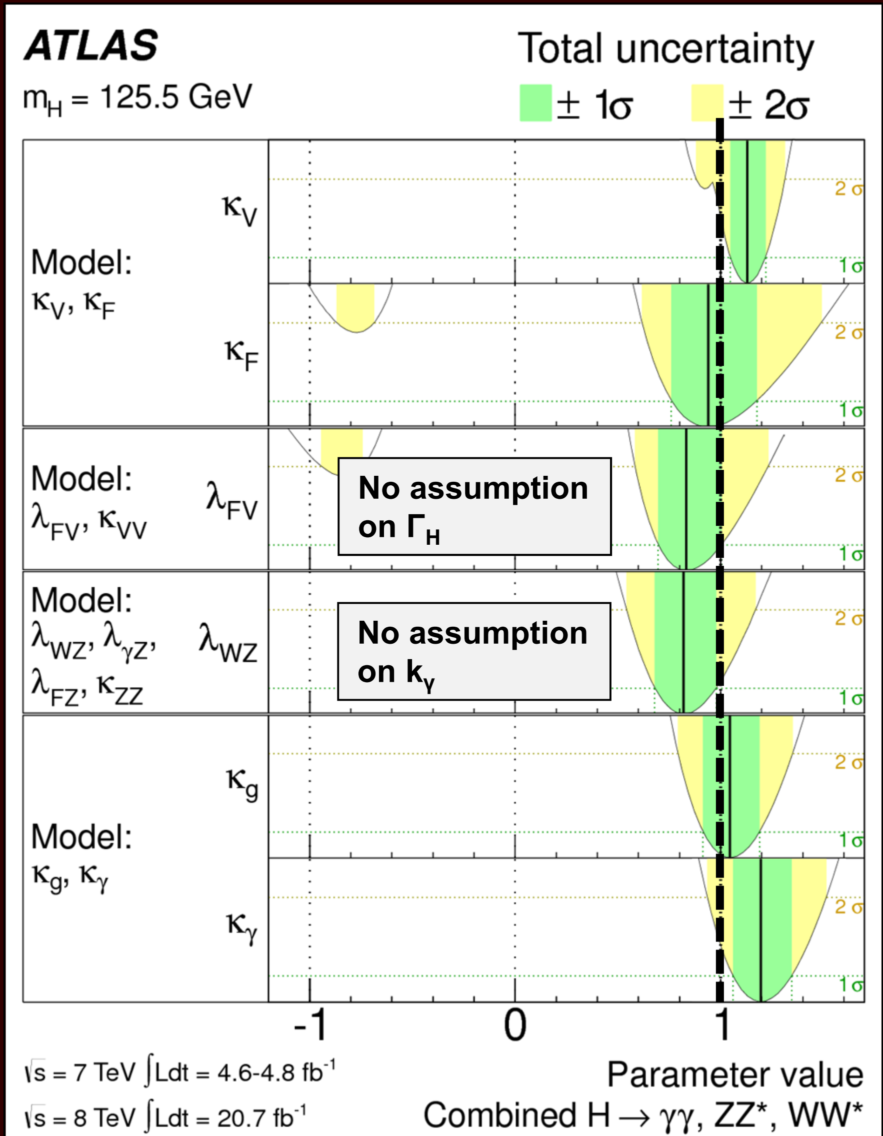


- ❑ > 3σ significance for non-vanishing VBF
- ❑ new particle couples to W and Z as expected
- → first "fingerprint" of a Higgs boson (to do its job → EWSB/Higgs mechanism)
- ❑ No significant New Physics contributions (within present uncertainty)





$$k_i^2 = \frac{\Gamma_i^{data}}{\Gamma_i^{SM}}$$



… and many others …

Main conclusions:

- ❑ **measurements at the 10-20% level**
- ❑ **couplings to W, Z as expected from EWSB mechanism**
- ❑ **couplings to fermions at > 5σ observed indirectly (mainly through ggF loop)**
- ❑ **no evidence for new physics within present uncertainty**

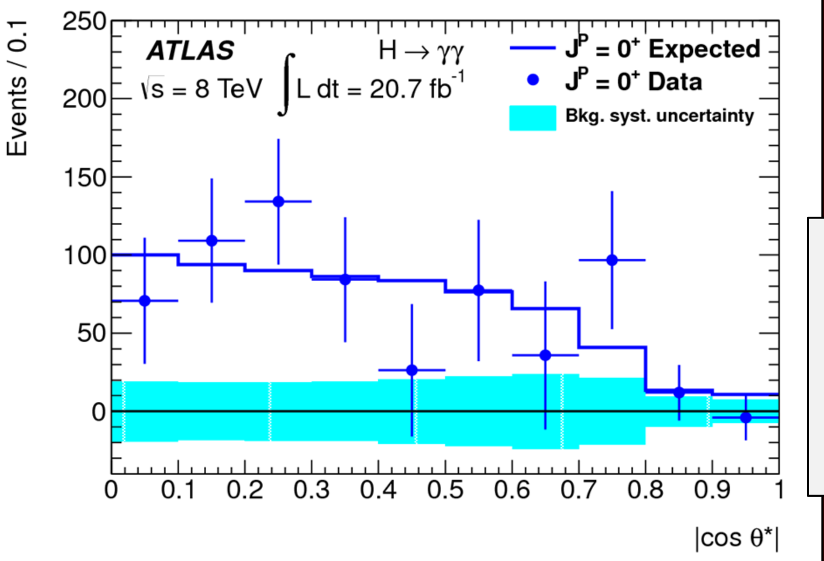
From F Gianotti

From F Gianotti

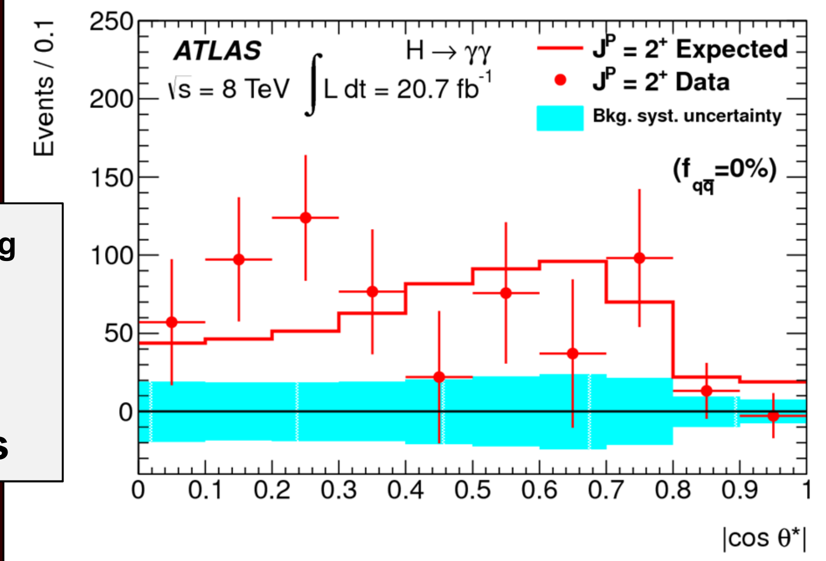
2^{nd} "fingerprint" of a Higgs boson: spin zero

- Spin information from angular and kinematic distributions of decay products
- H→ γγ, H→ 4l and H→ lνlν channels combined
- Fits to data test $J^P=0^+$ hypothesis (SM) against $J^P= 0^-, 1^+, 1^-, 2^+$

H→ γγ: distribution of polar angle θ* of γγ system for events in signal peak region



Data (after bckg subtraction) **vs**
$J^P=0^+$ (left)
$J^P=2^+$ (right)
expectations



Hypothesis	Rejection (C.L.)
0^-	97.8%
1^+	99.97%
1^-	99.7%
2^+	99.9%

First elementary (likely) scalar observed
→ consequences also for Universe evolution (inflation triggered by a scalar field)

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

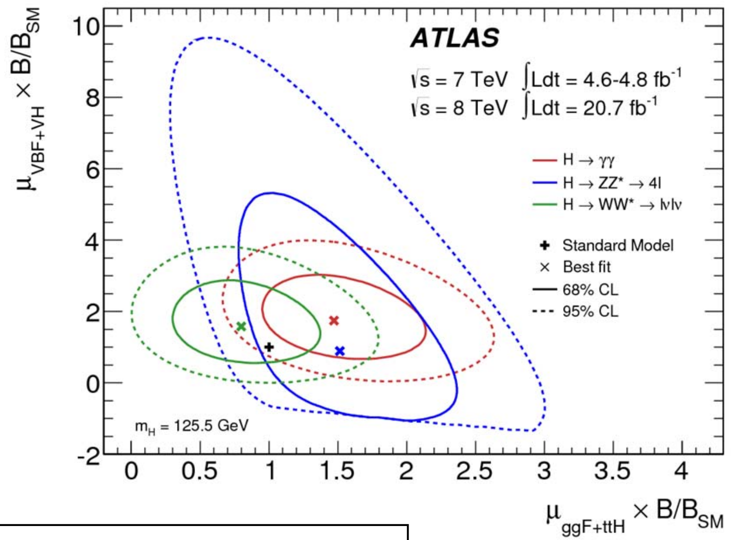
It will be important to understand with great precision if it is the only scalar boson of the Standard Model 'Brout-Englert-Higgs' mechanism to break the electroweak symmetry, or if it is only part of a broader physics picture going *Beyond the Standard Model*

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

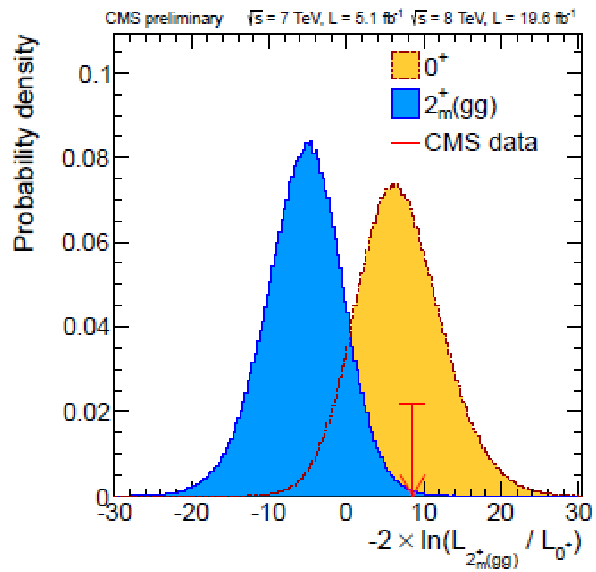
For the experts:

Couplings
Production modes
Spin-parity

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

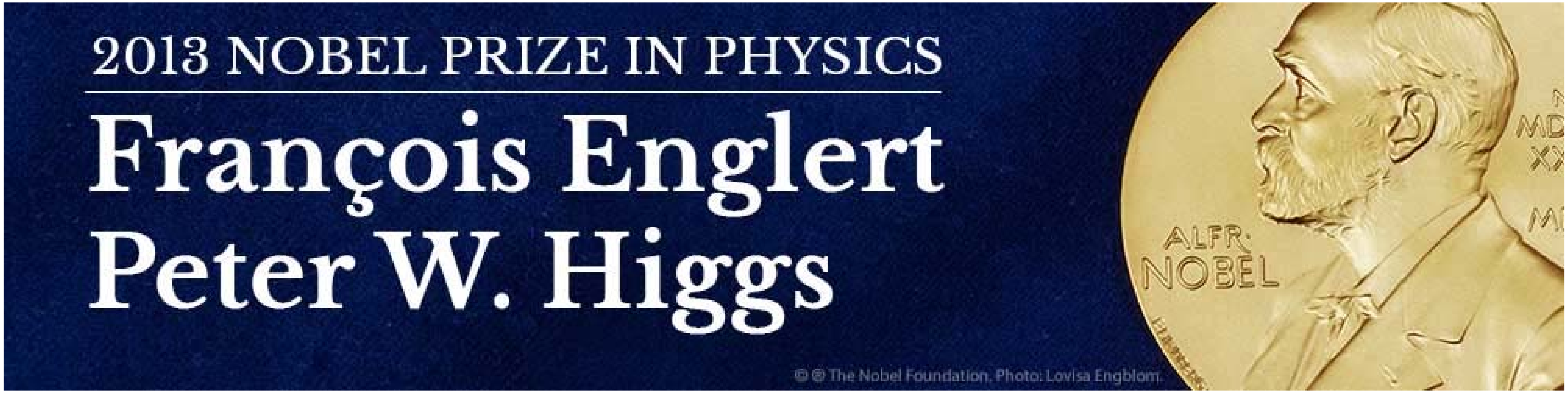


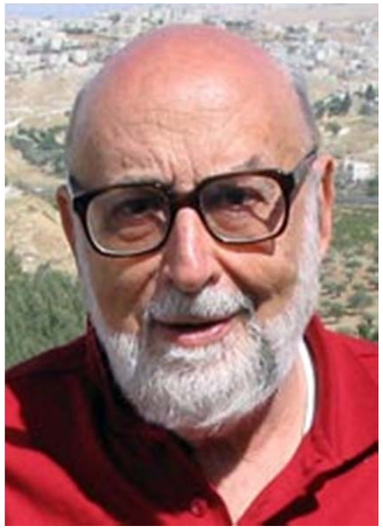
ATLAS, Phys. Lett. B 726 (2013) 88-119 and 120-144

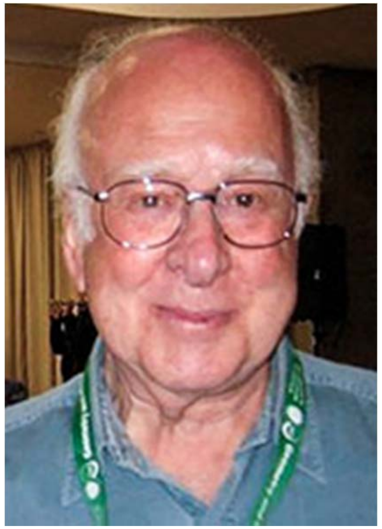


CMS-PAS-HIG-13-005

Recall the Happy End of Higgs-Chapter-1 from last month …

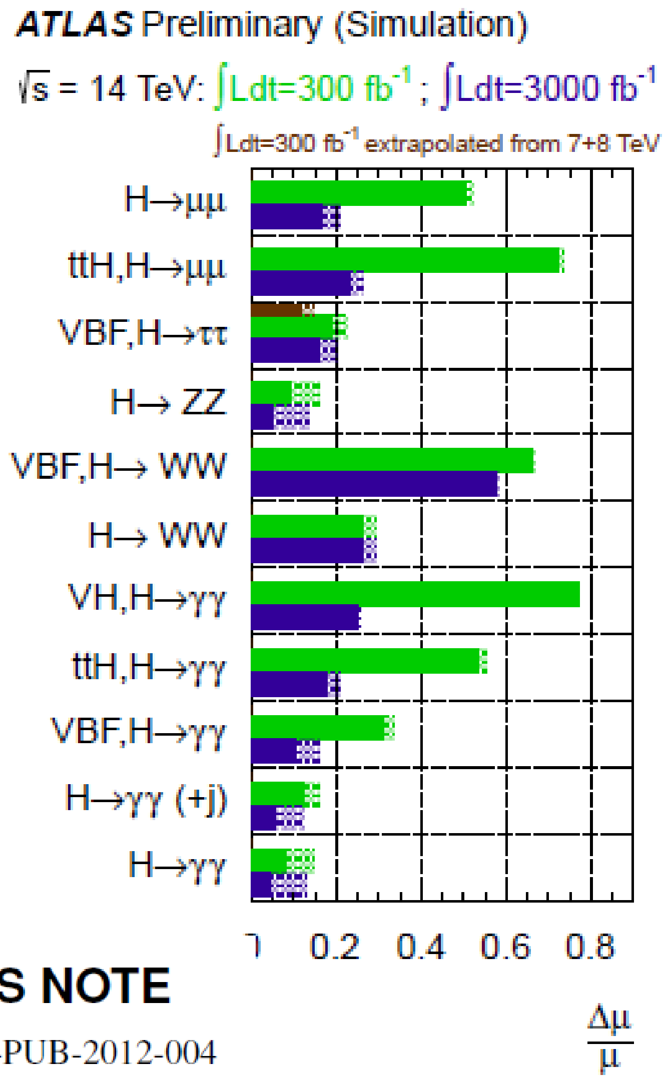


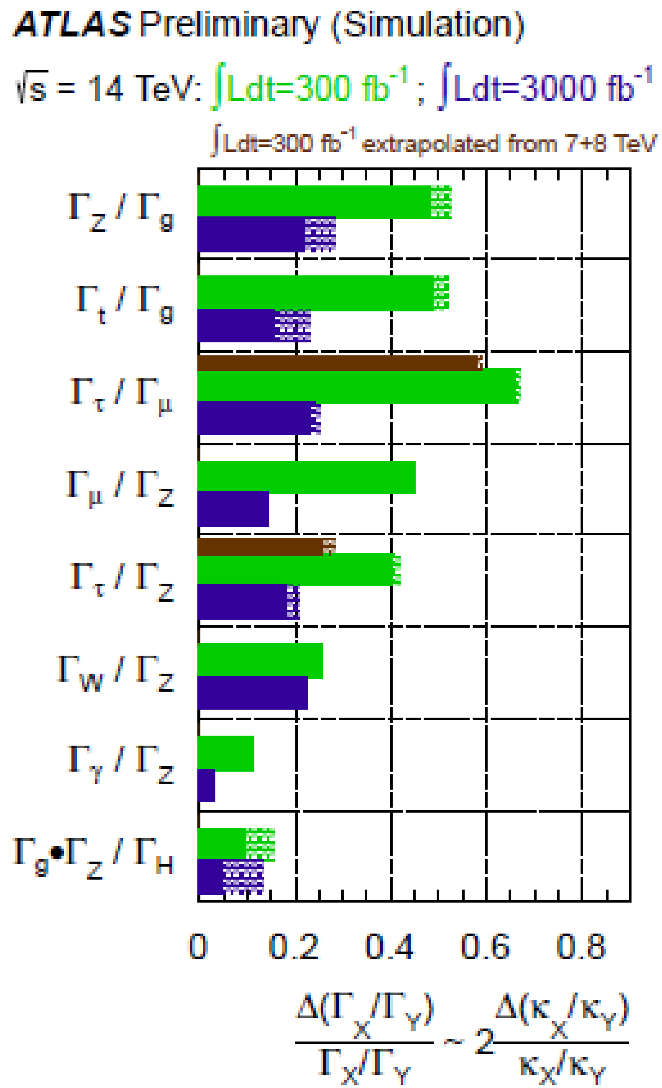




"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Outlook for HL-LHC on the Higgs physics (I)



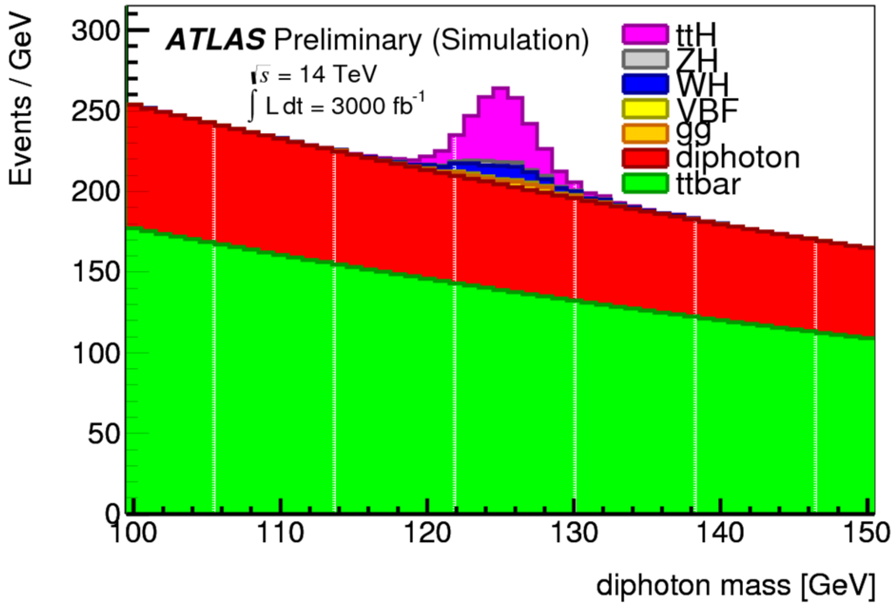


ATLAS NOTE

ATL-PHYS-PUB-2012-004

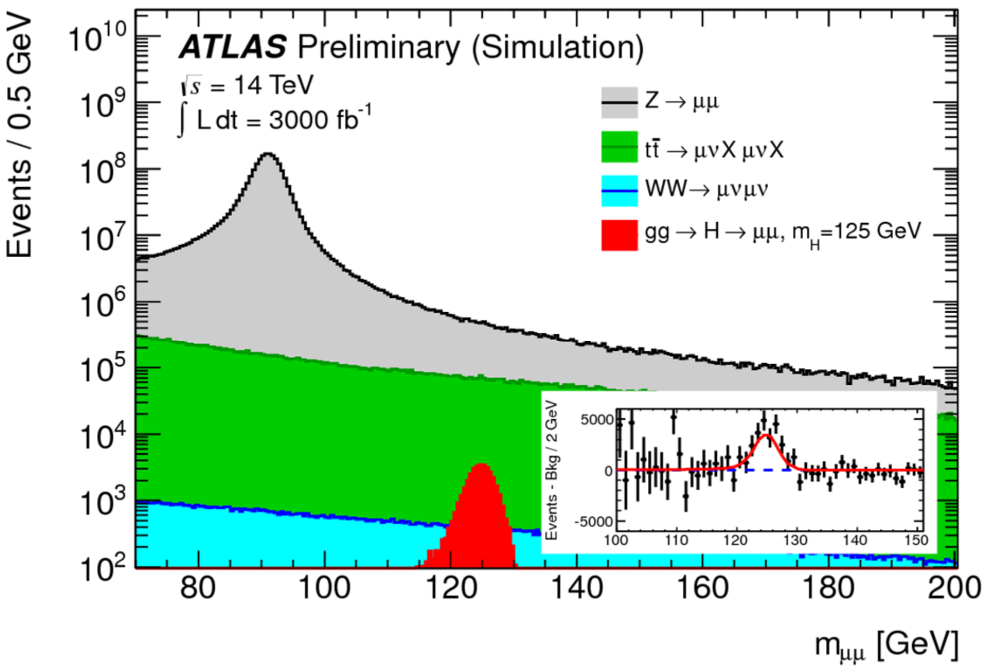
October 15, 2012

Outlook for HL-LHC on the Higgs physics (II)



ttH with H → γγ for 3000 fb^{-1}

H → μμ for 3000 fb^{-1}

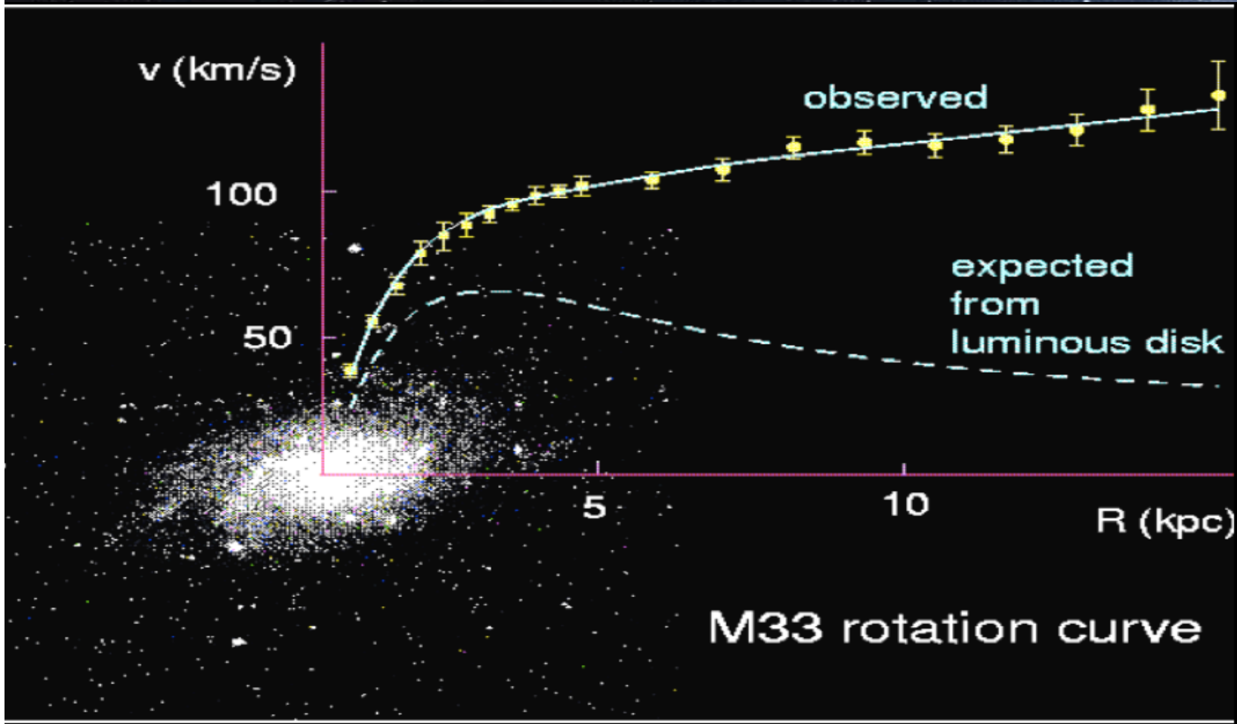


ATLAS NOTE

ATL-PHYS-PUB-2012-004

October 15, 2012

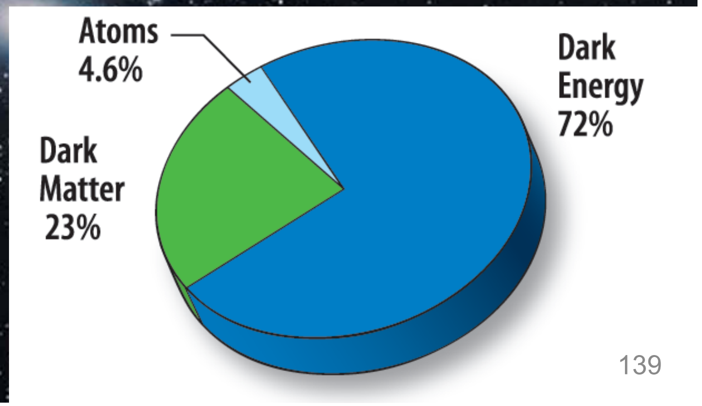
Dark Matter in the Universe

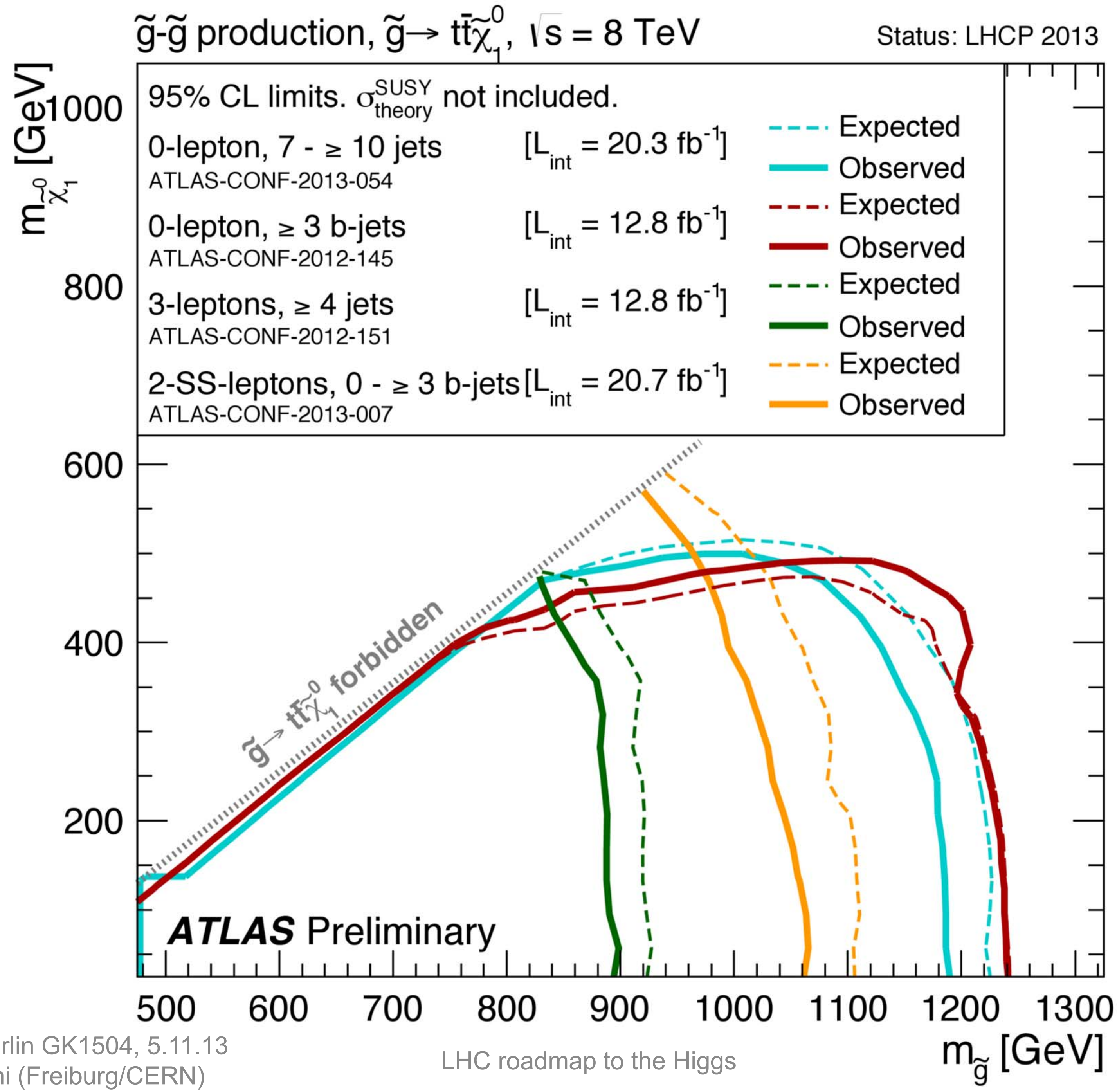


Vera Rubin ~ 1970

metric' particles ?

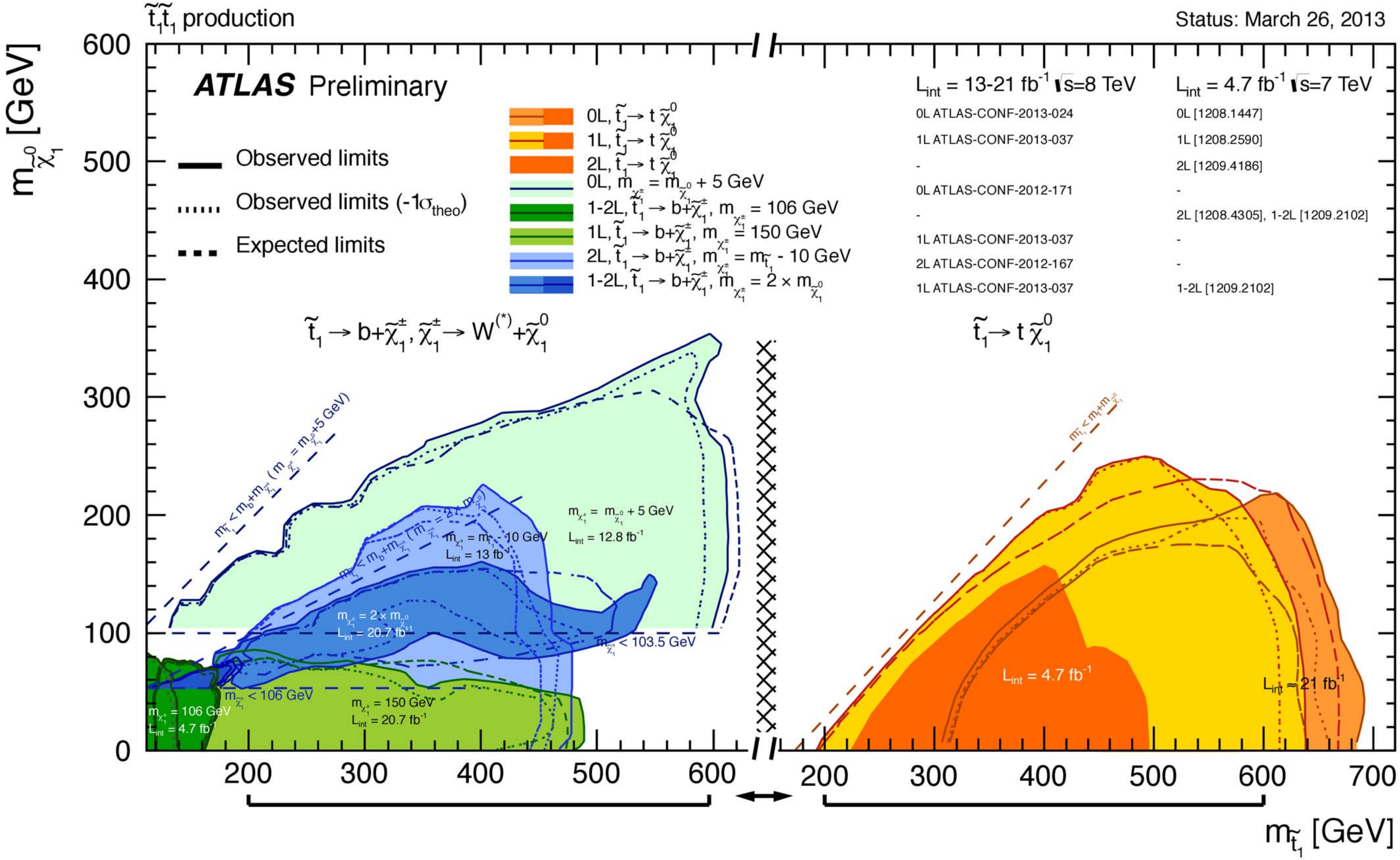
F. Zwicky 1898-1974



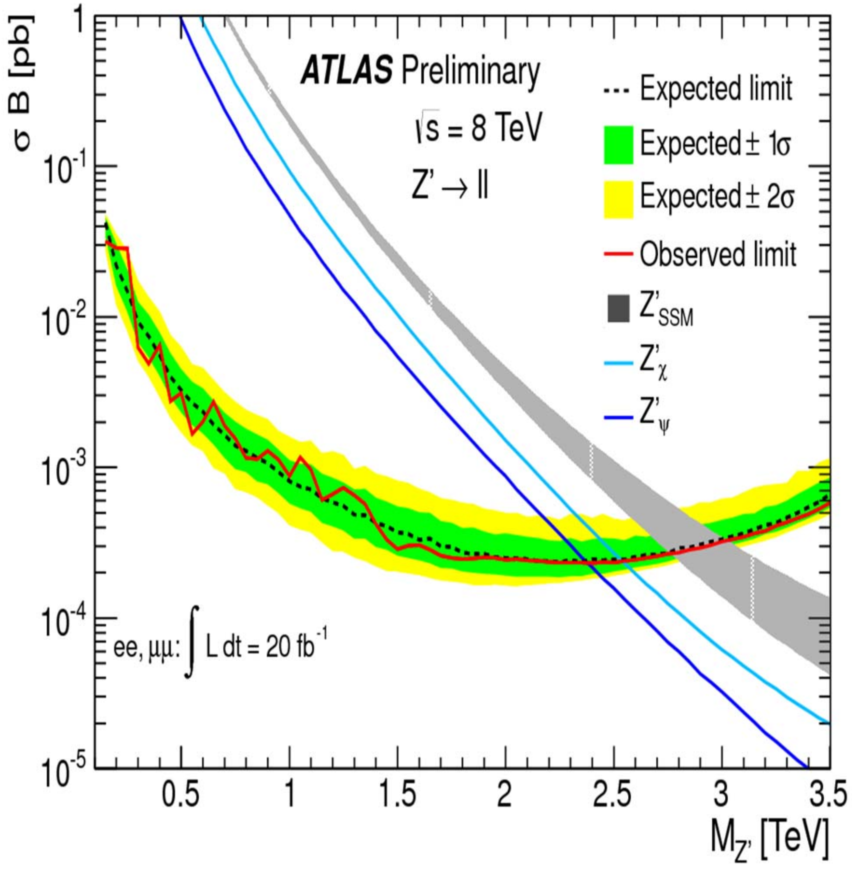


g̃-g̃ production, g̃→ tt̄χ̃₁⁰, √s = 8 TeV
Status: LHCP 2013
95% CL limits. σ theory SUSY not included.
0-lepton, 7 - ≥ 10 jets [L int = 20.3 fb-1]
ATLAS-CONF-2013-054
0-lepton, ≥ 3 b-jets [L int = 12.8 fb-1]
ATLAS-CONF-2012-145
3-leptons, ≥ 4 jets [L int = 12.8 fb-1]
ATLAS-CONF-2012-151
2-SS-leptons, 0 - ≥ 3 b-jets [L int = 20.7 fb-1]
ATLAS-CONF-2013-007
Expected
Observed
Expected
Observed
Expected
Observed
Expected
Observed
g̃→ tt̄χ̃₁⁰ forbidden
ATLAS Preliminary
m χ̃₁⁰ [GeV]
m g̃ [GeV]
200
400
600
800
1000
500
600
700
800
900
1000
1100
1200
1300

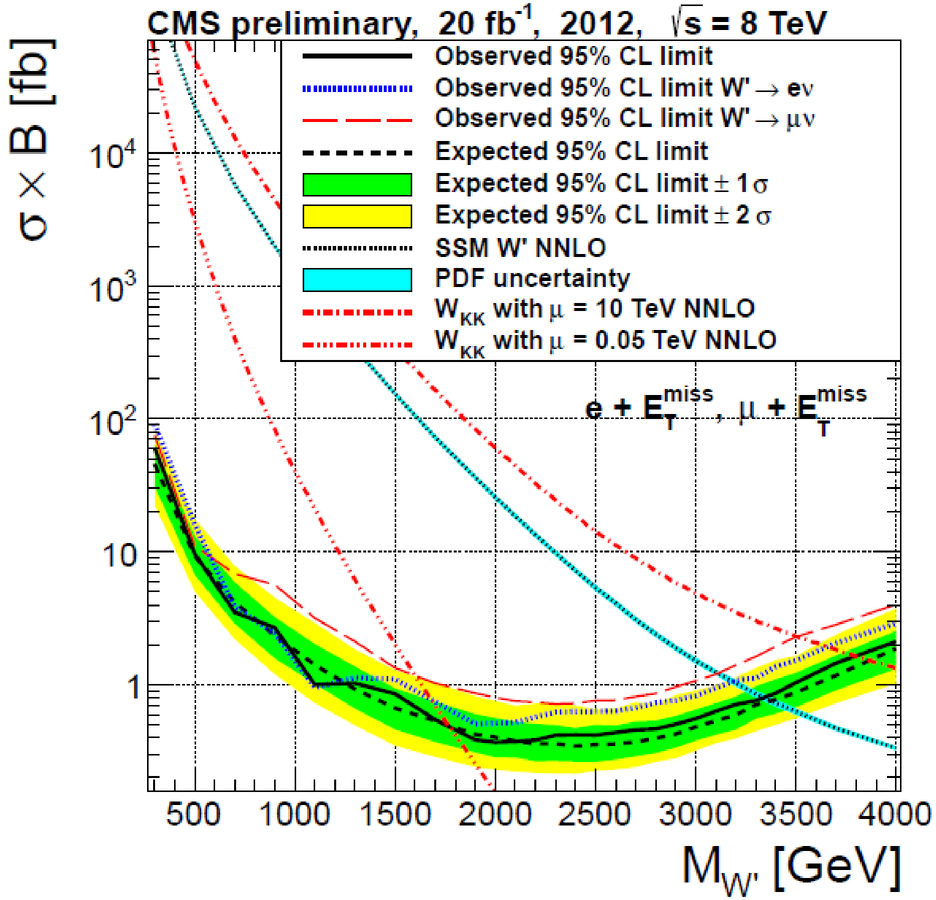
Summary of dedicated searches for top squark pair production for some theoretically preferred models with relatively light 3rd generation squarks



Lower mass limits, at 95% CL, for various Z' and W' like objects



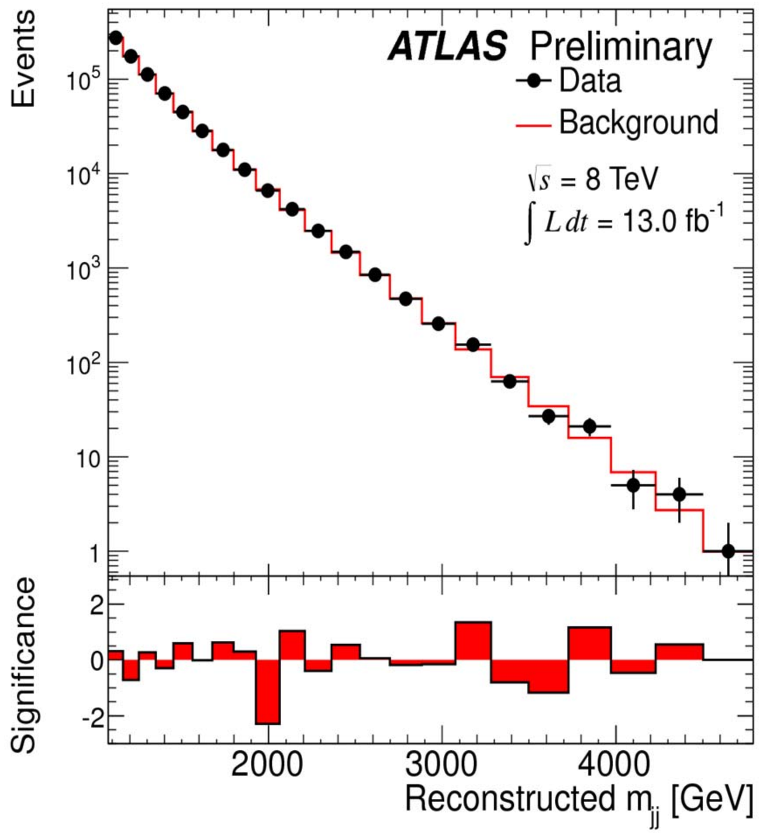
ATLAS-CONF-2013-017



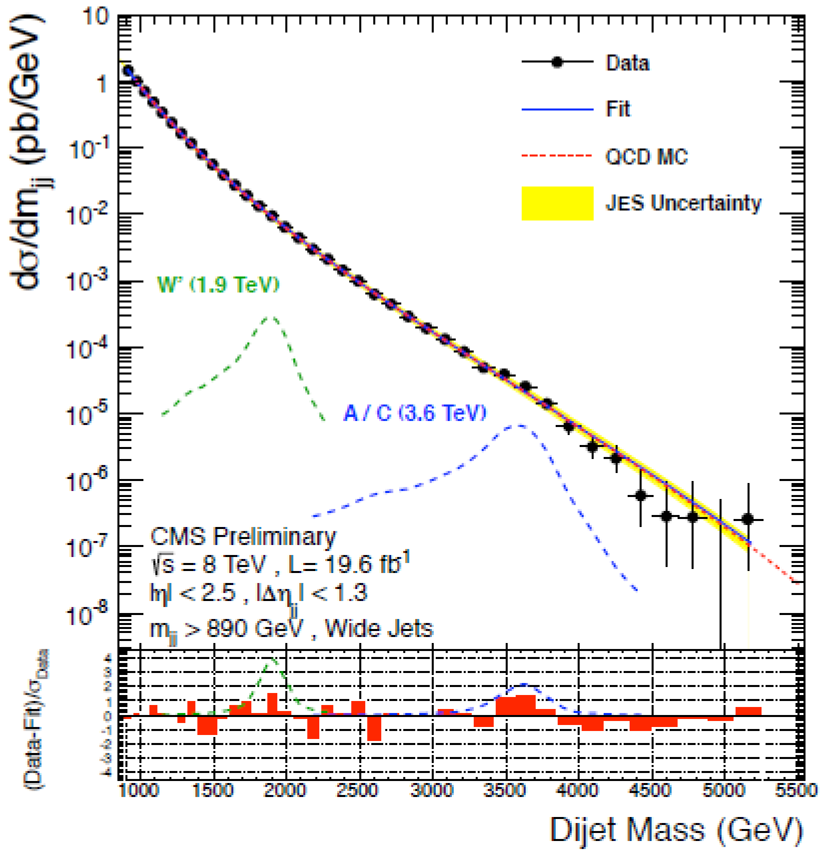
CMS-EXO-12-060

Example of searches for New Physics as deviations from QCD behaviour of hadronic jet distributions

Search for resonances in the di-jet mass spectrum



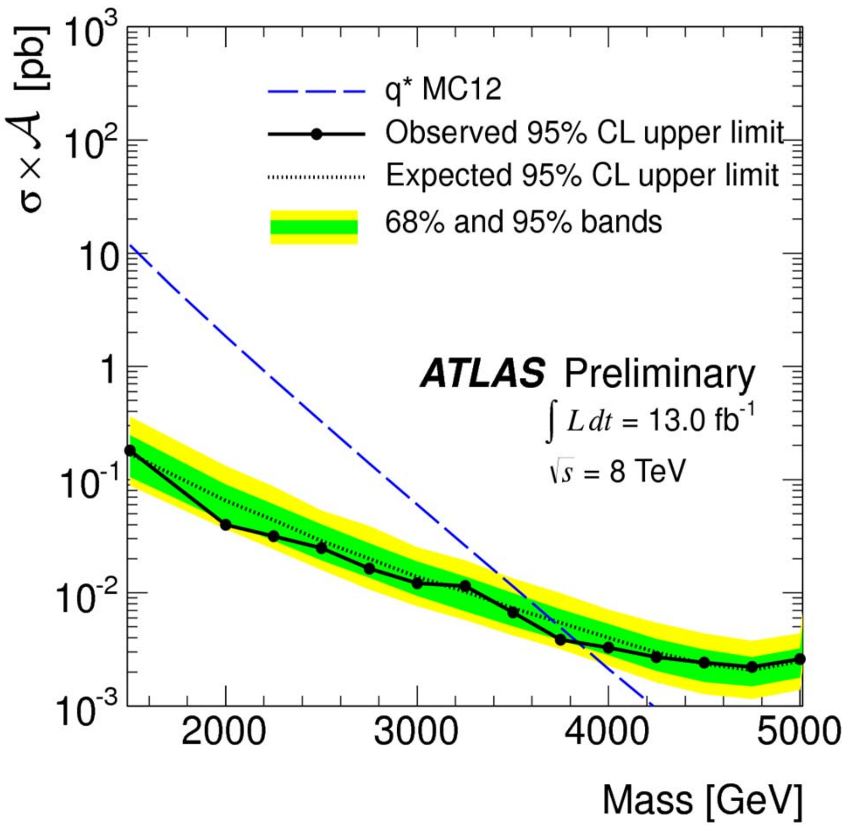
ATLAS-CONF-2012-148



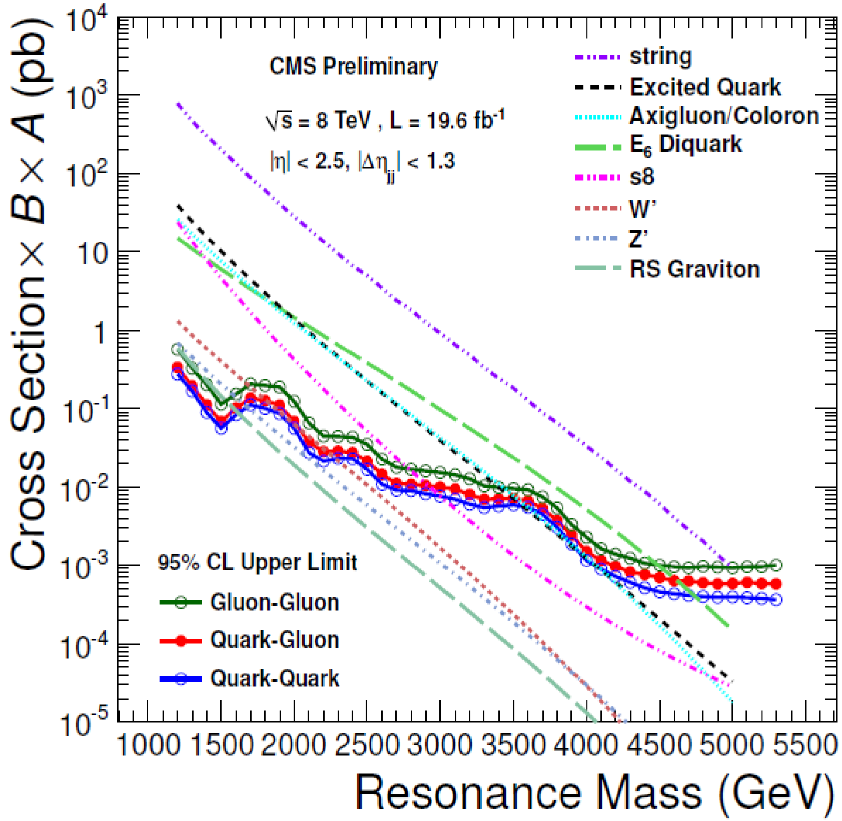
CMS-EXO-12-059

Example of searches for New Physics as deviations from QCD behaviour of hadronic jet distributions

Search for resonances in the di-jet mass spectrum

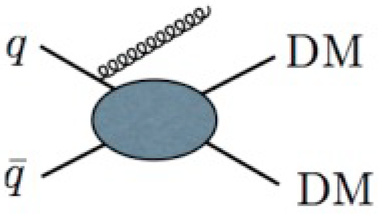


ATLAS-CONF-2012-148

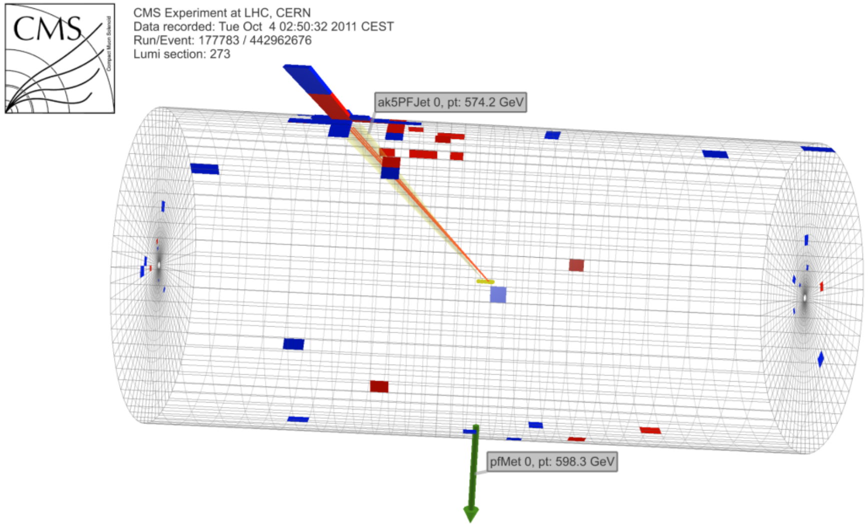


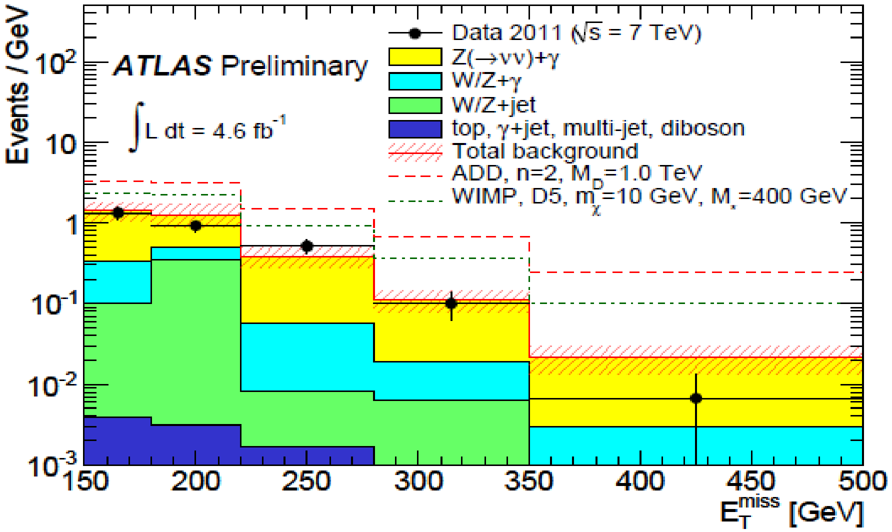
CMS-EXO-12-059

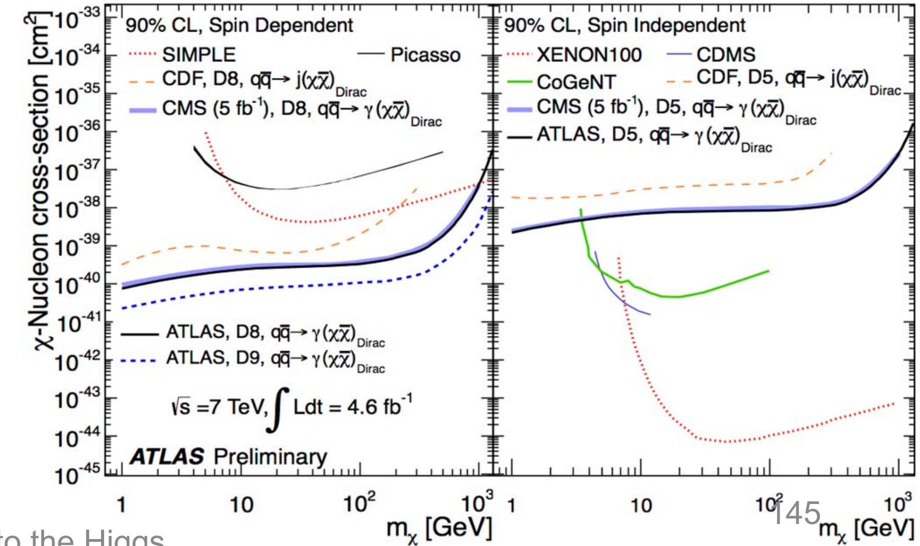
Search for direct Dark Matter (DM) particles in pair-production



A single photon (150 GeV) or jet plus ETmiss



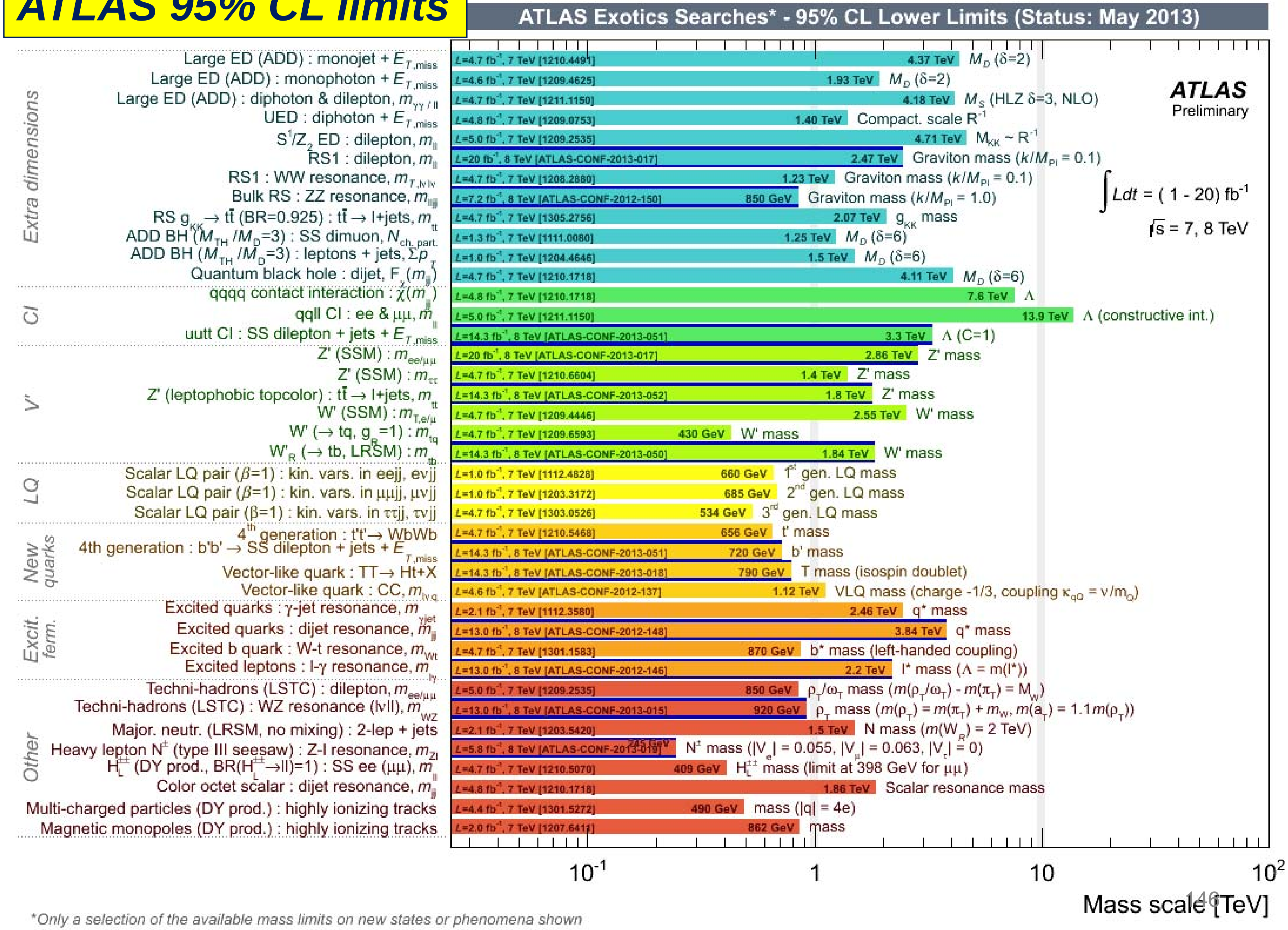




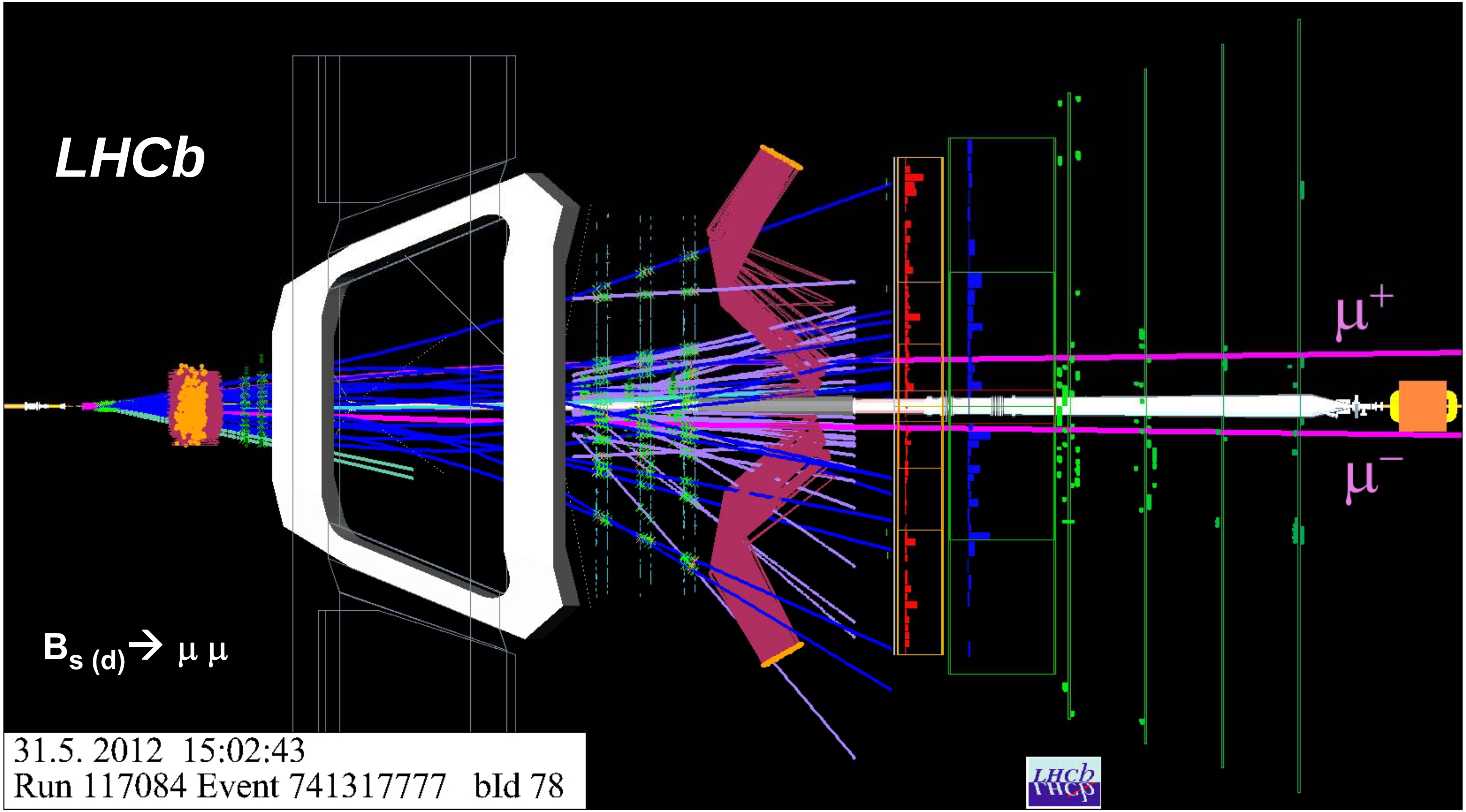
ATLAS-CONF-2012-085
arXiv:1210.4491v1[hep-ex]

CMS: Sub. to Phys. Rev. Lett.
arXiv:1204.0821v1[hep-ex]
arXiv:1206.5663[hep-ex]

ATLAS 95% CL limits



Indirect indications for physics BSM, like SUSY, could come from rare decays showing rates deviating from the SM expectations



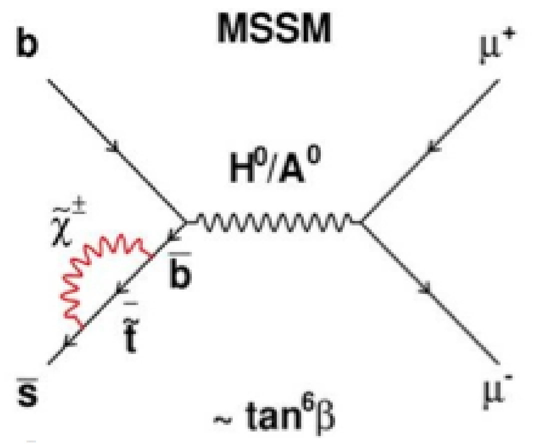
The search for $B_{s\,(d)} \rightarrow \mu\,\mu$

Submitted to Phys. Rev. Lett.
arXiv:1211.2674v1[hep-ex]

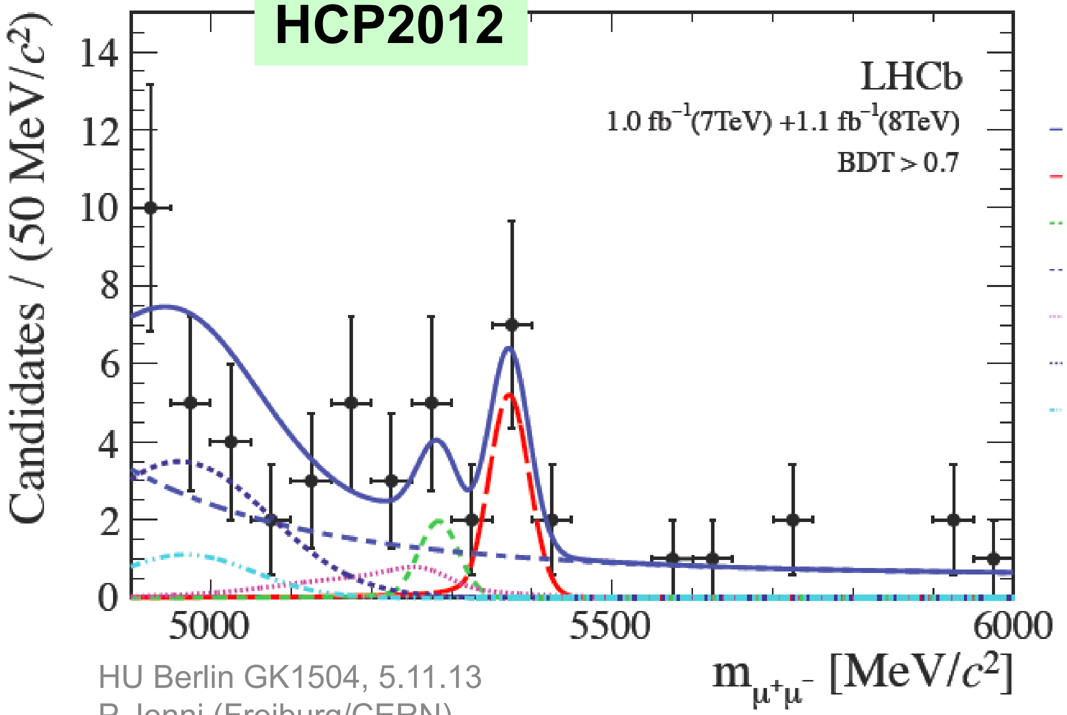
Very rare decay sensitive to New Physics (in particular to models with high *tan β*)

Precise predictions in SM:
BR($B_s \rightarrow \mu\,\mu$) = $3.5 \pm 0.2\ 10^{-9}$
BR($B_d \rightarrow \mu\,\mu$) = $1.1 \pm 0.2\ 10^{-10}$

Very clean experimental signature



HCP2012



With 2011+2012 data (2.1/fb) first evidence of $B_s \rightarrow \mu\,\mu$ decay at ~ 3.5 σ

$$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

in agreement with SM.
Potential impact on models

Also best limit on $B_d \rightarrow \mu\,\mu$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 9.4 \times 10^{-10} \text{ at 95\% CL}$$

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	...	2030
	Phase 0			LS1		Phase I,II			LS2	Phase II			LS3			

Consolidation | **Upgrades**

ATLAS has devised a 3 stages program to optimise the physics reach at each Phase

- New Insertable pixel b-layer (IBL)
- New Al beam pipe
- New pixel services
- New evaporative cooling plant
- Consolidation of detector elements (e.g. calorimeter power supplies)
- Add specific neutron shielding
- Finish installation of EE muon chambers staged in 2003
- Upgrade magnet cryogenics

- New Small Wheel (nSW) for the forward muon Spectrometer
- High Precision Calorimeter Trigger at Level-1
- Fast TracKing (FTK) for the Level-2 trigger
- Topological Level-1 trigger processors
- New forward diffractive physics detectors (AFP)

- All new Tracking Detector
- Calorimeter electronics upgrades
- Upgrade part of the muon system
- Possible Level-1 track trigger
- Possible changes to the forward calorimeters