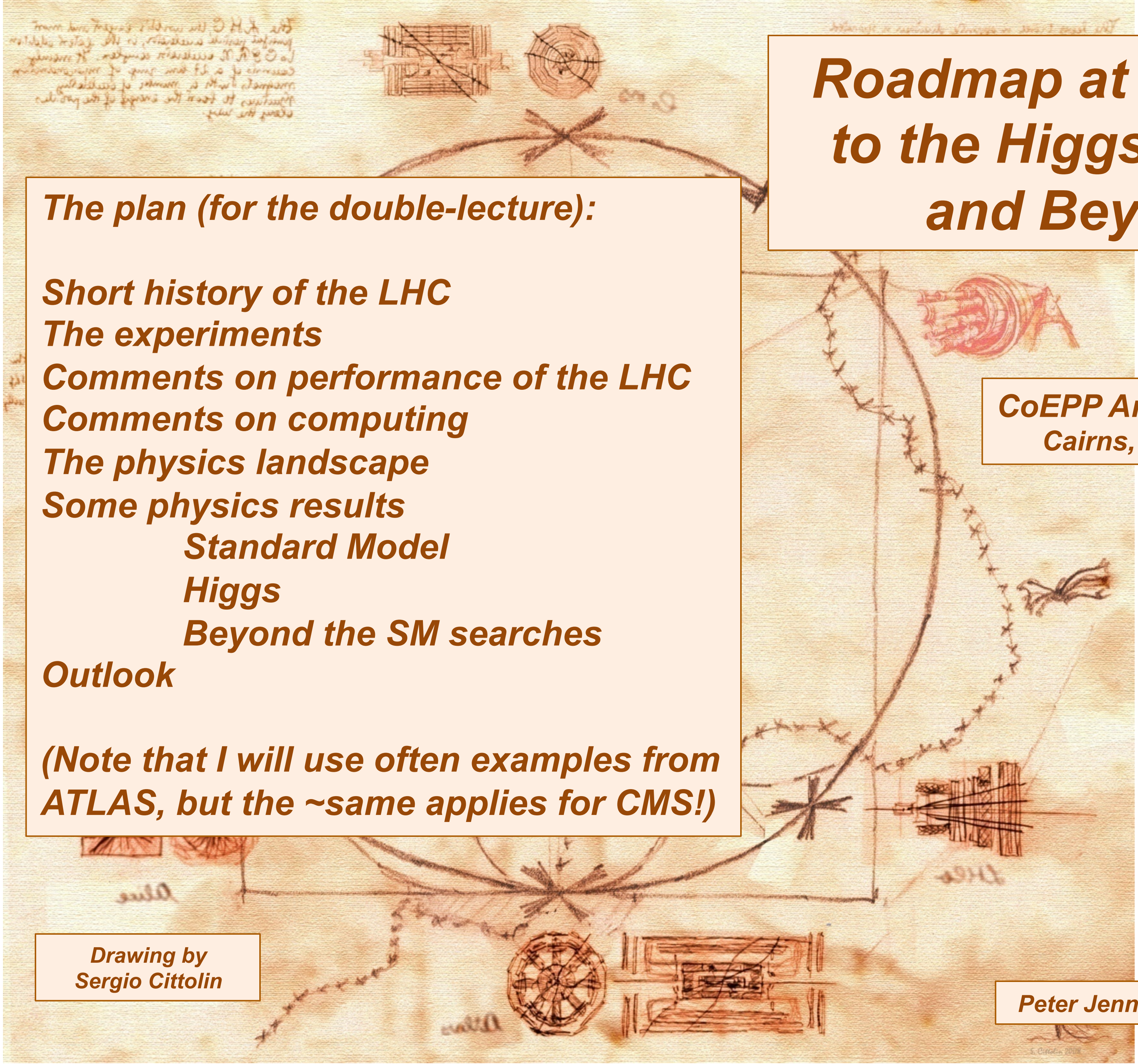
Roadmap at the LHC to the Higgs Boson and Beyond



The plan (for the double-lecture):

Short history of the LHC
The experiments
Comments on performance of the LHC
Comments on computing
The physics landscape
Some physics results
    Standard Model
    Higgs
    Beyond the SM searches
Outlook

(Note that I will use often examples from ATLAS, but the ~same applies for CMS!)

Drawing by
Sergio Cittolin

CoEPP Annual Workshop
Cairns, 7-12 July 2013

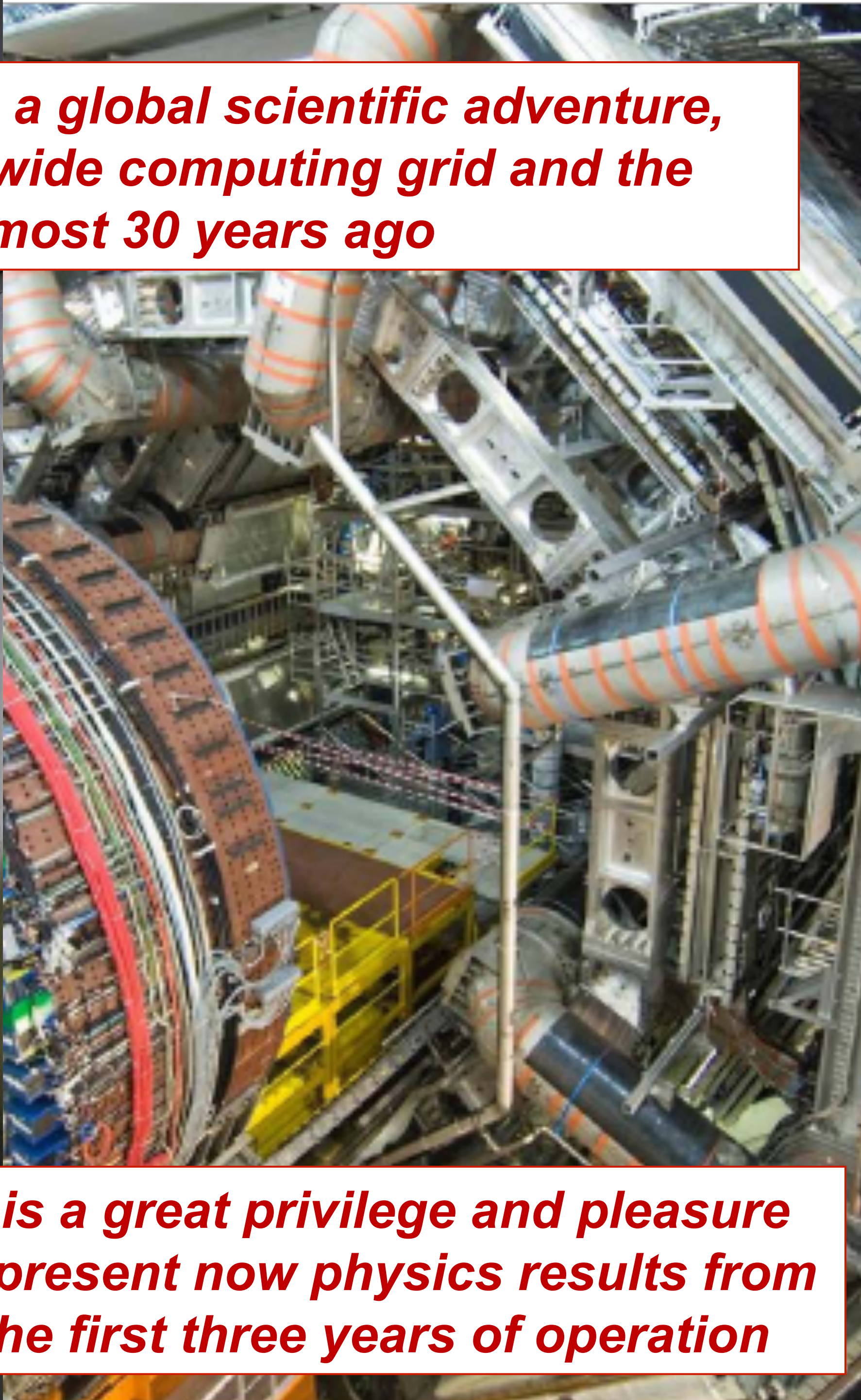
CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

UNI FREIBURG

CERN

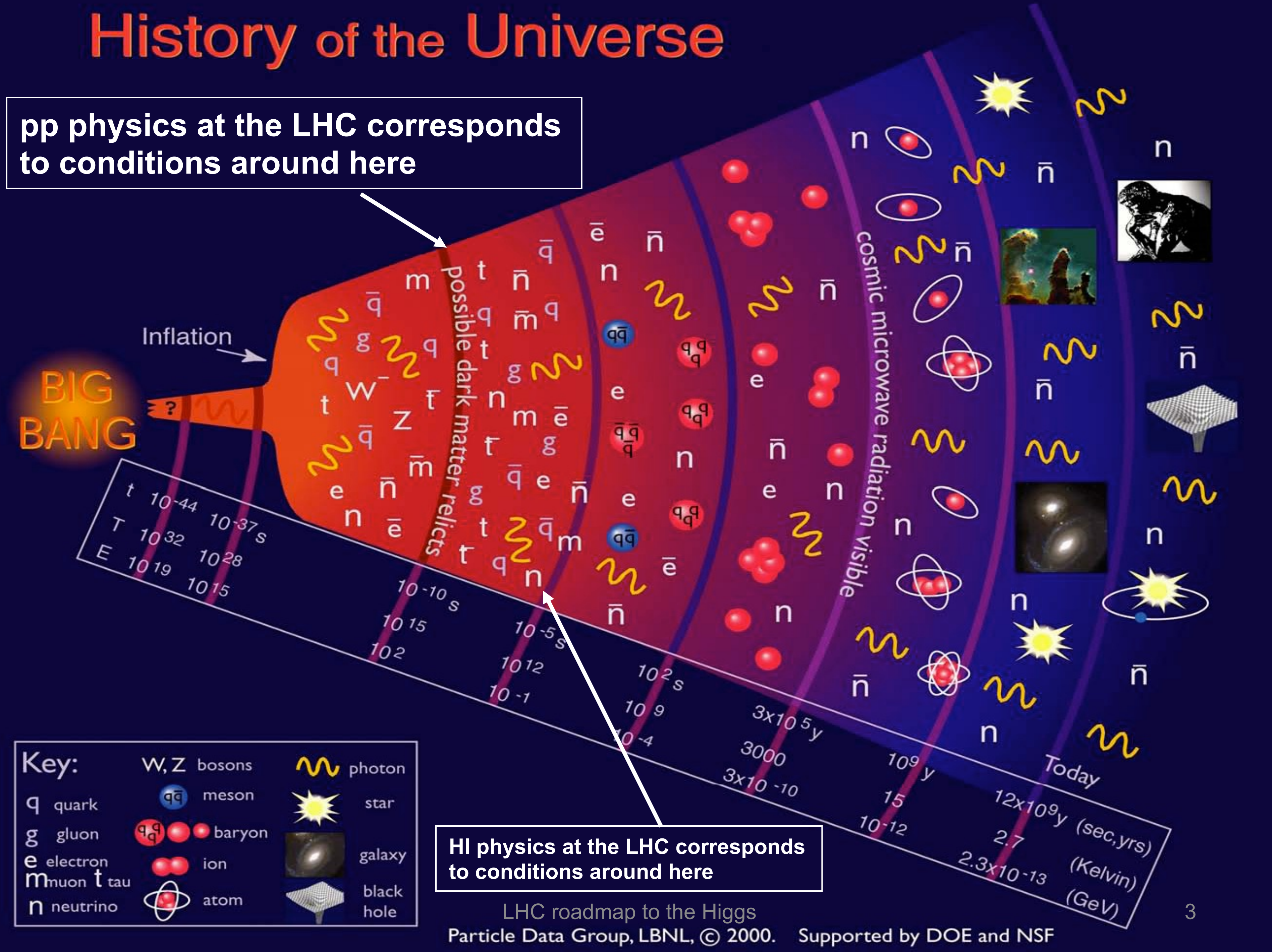
Peter Jenni, Freiburg and CERN

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

CoEPP, Cairns, 9.7.2013
P Jenni (Freiburg/CERN)



pp physics at the LHC corresponds to conditions around here

HI physics at the LHC corresponds to conditions around here

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

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 pri
present ~10 μs after the

What h
~ Universe

Ar ces in addition to the known four ?
Are 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 ~ 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)

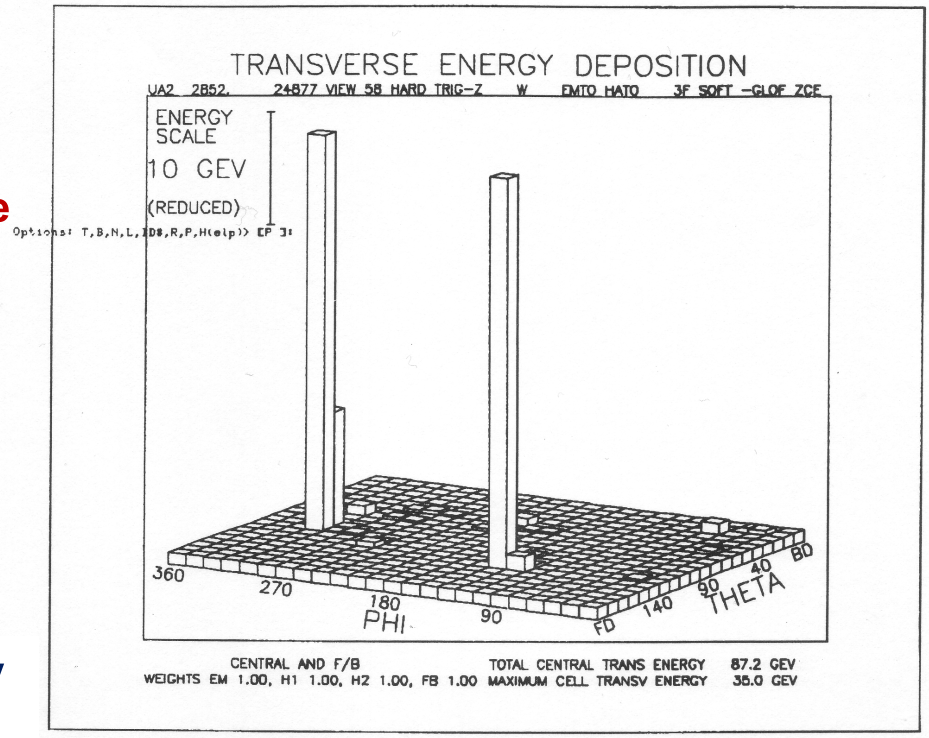
Some early key dates

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)

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

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

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

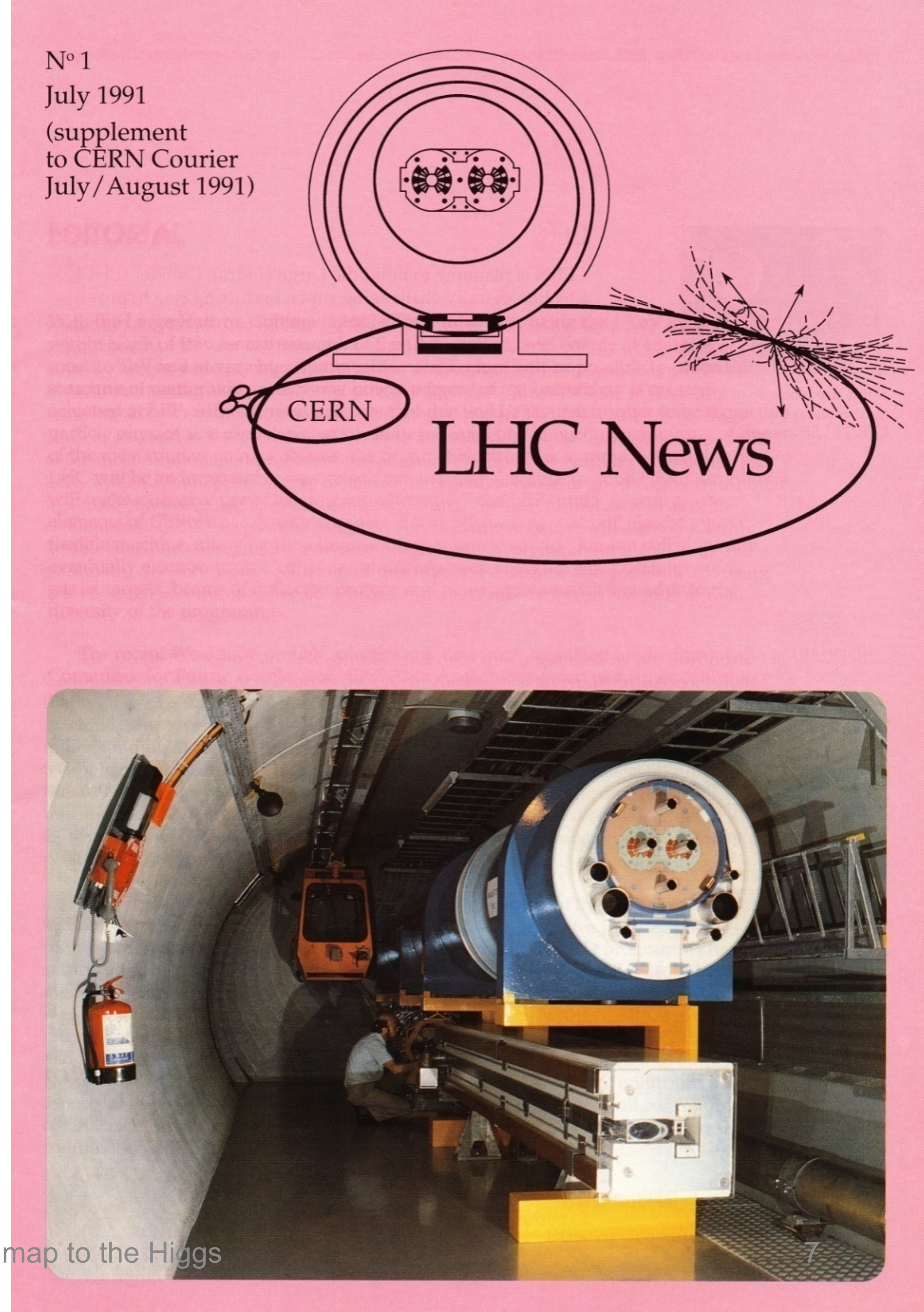
1993 December proposal of LHC
with commissioning in 2002

1994 June Council:

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



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

CERN

LHC News

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)

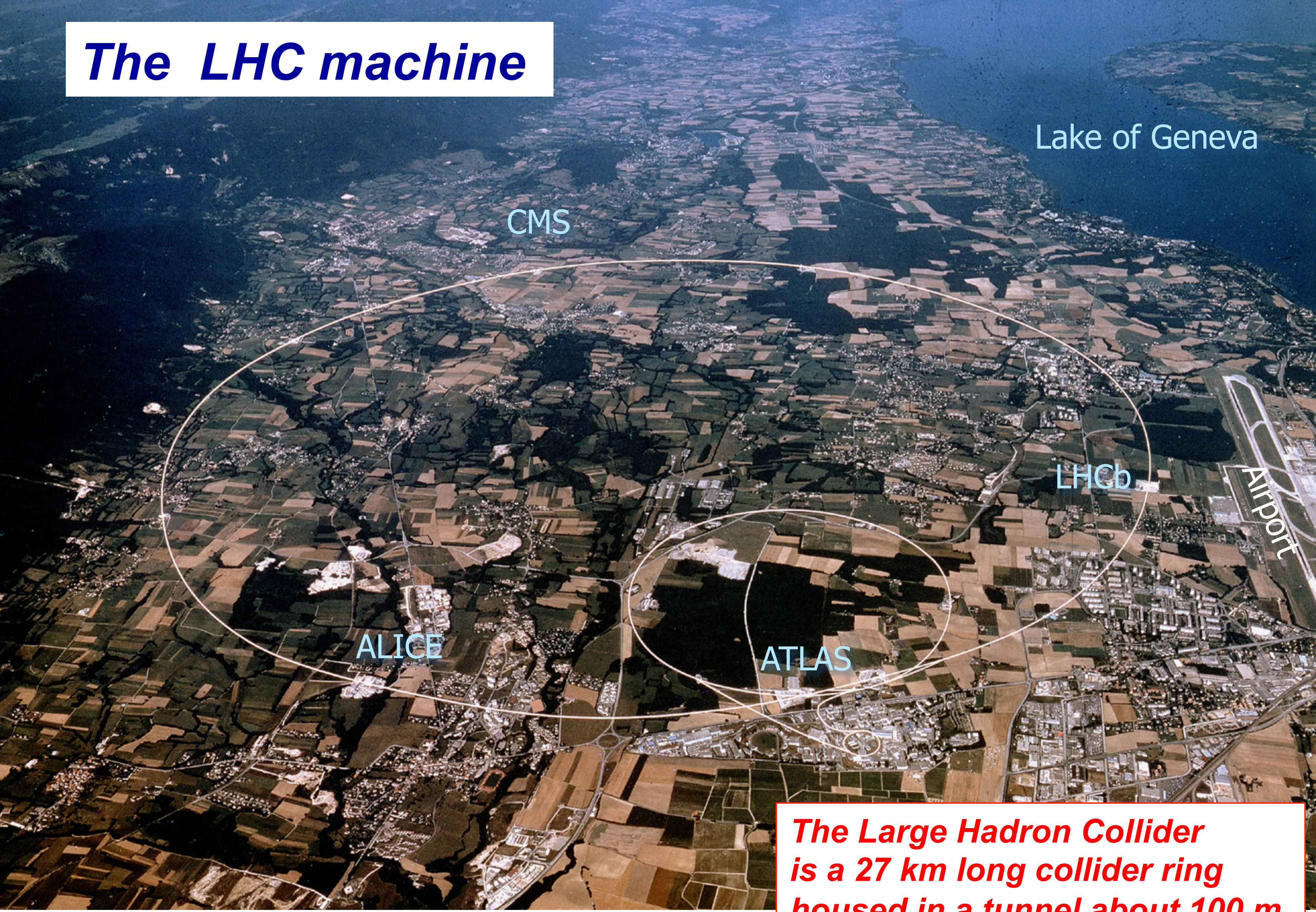
A CERN – Australia Cooperation Agreement from 1991 defines the fruitful collaboration since then

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



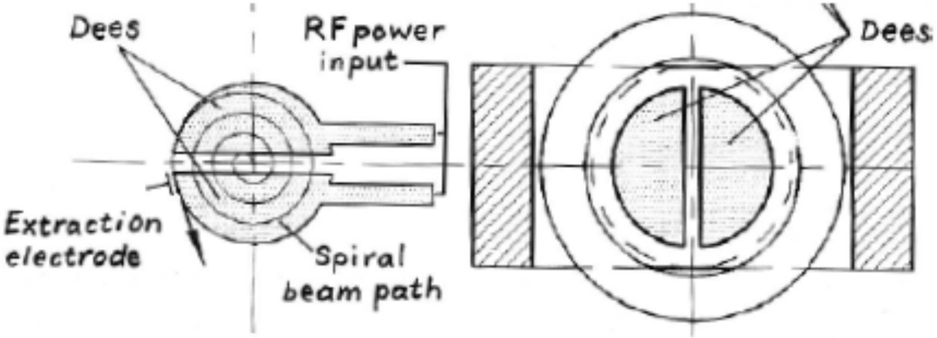
The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

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

Ernest Lawrence
(1901 - 1958)

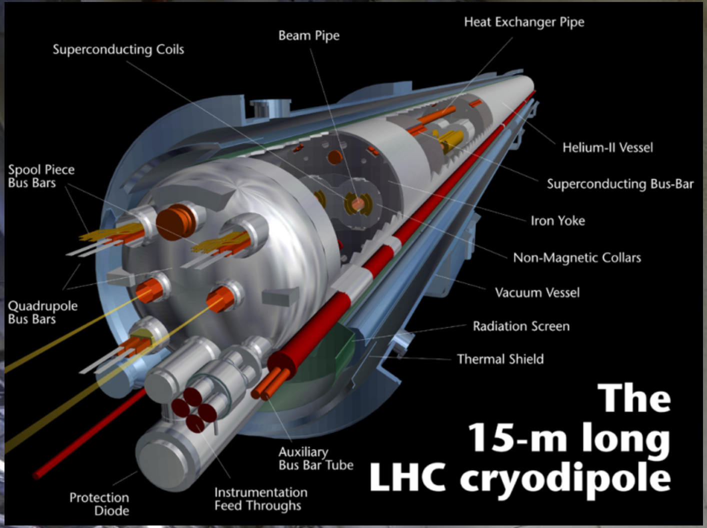
The first circular accelerator (Berkeley 1930)

184” 1946



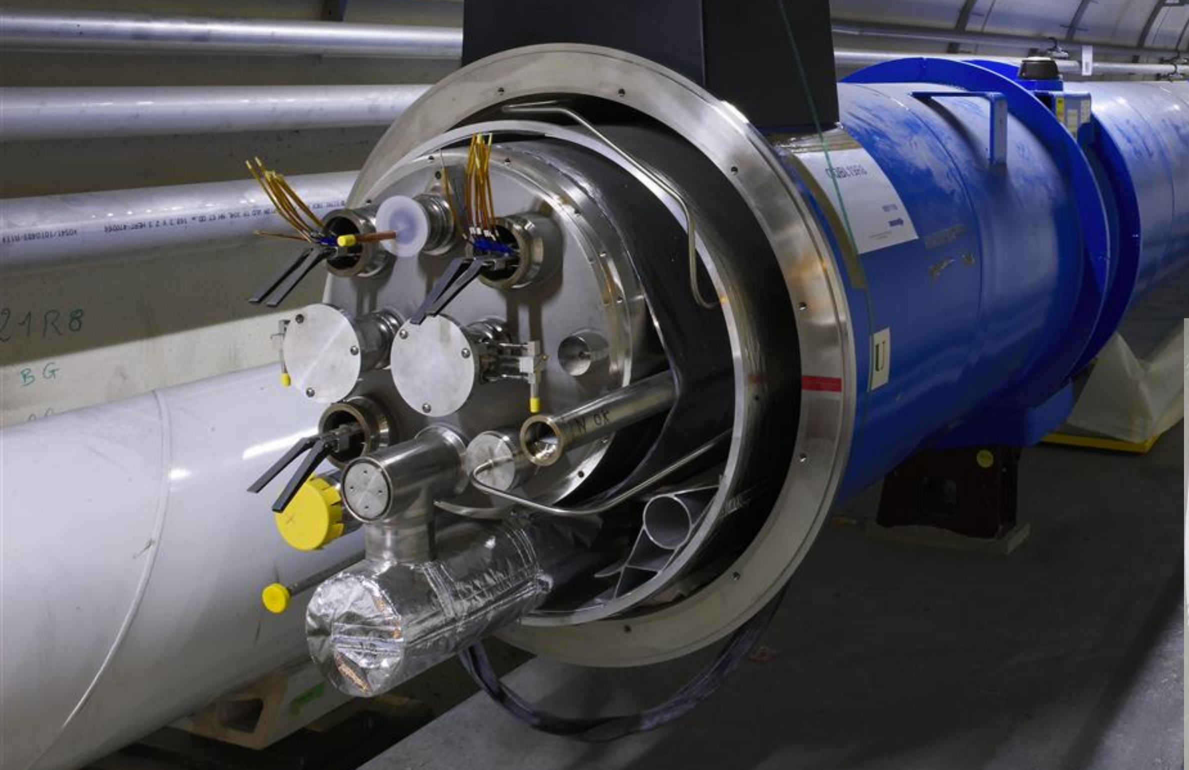
The most challenging components were the 1232 high-tech superconducting dipole magnets

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



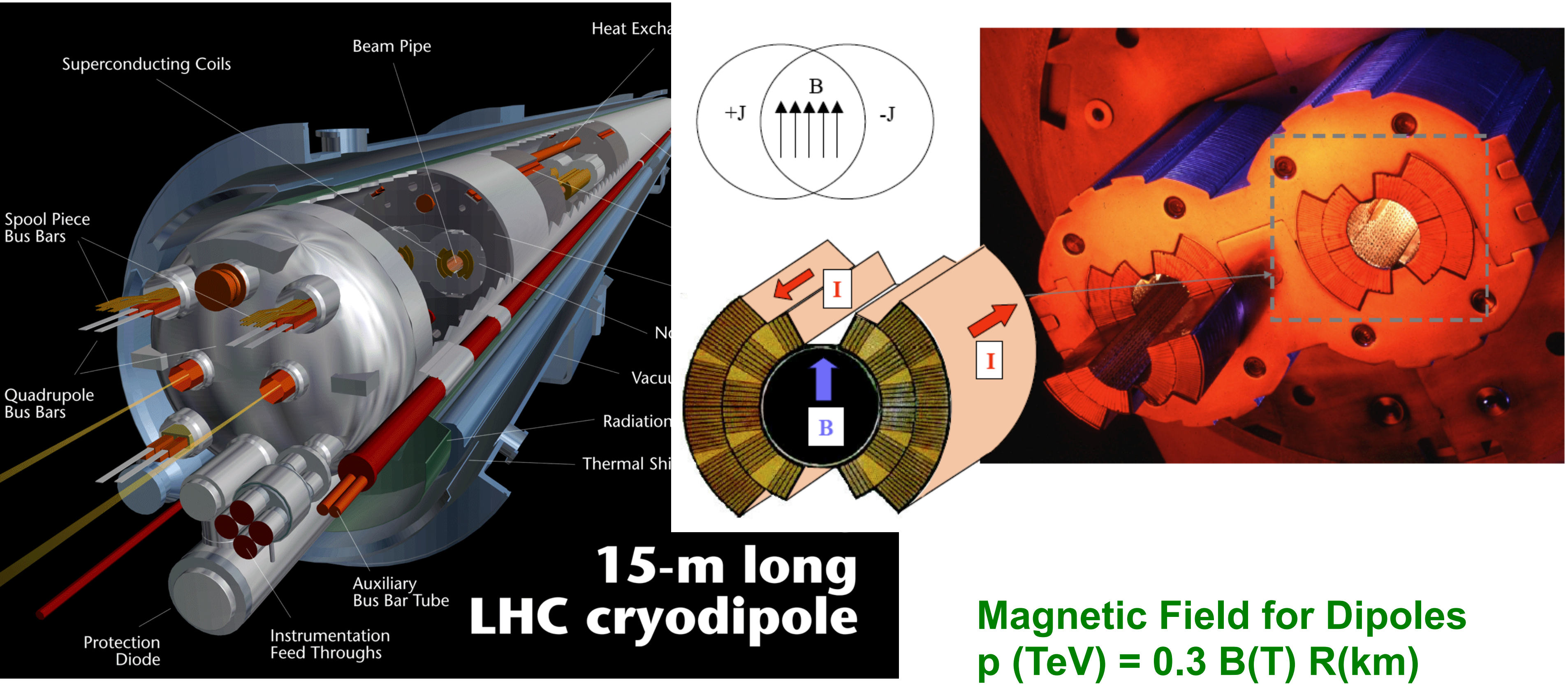
The 15-m long LHC cryodipole

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



LHC Construction Project Leader Lyndon Evans

LHC Accelerator Challenge: Dipole Magnets



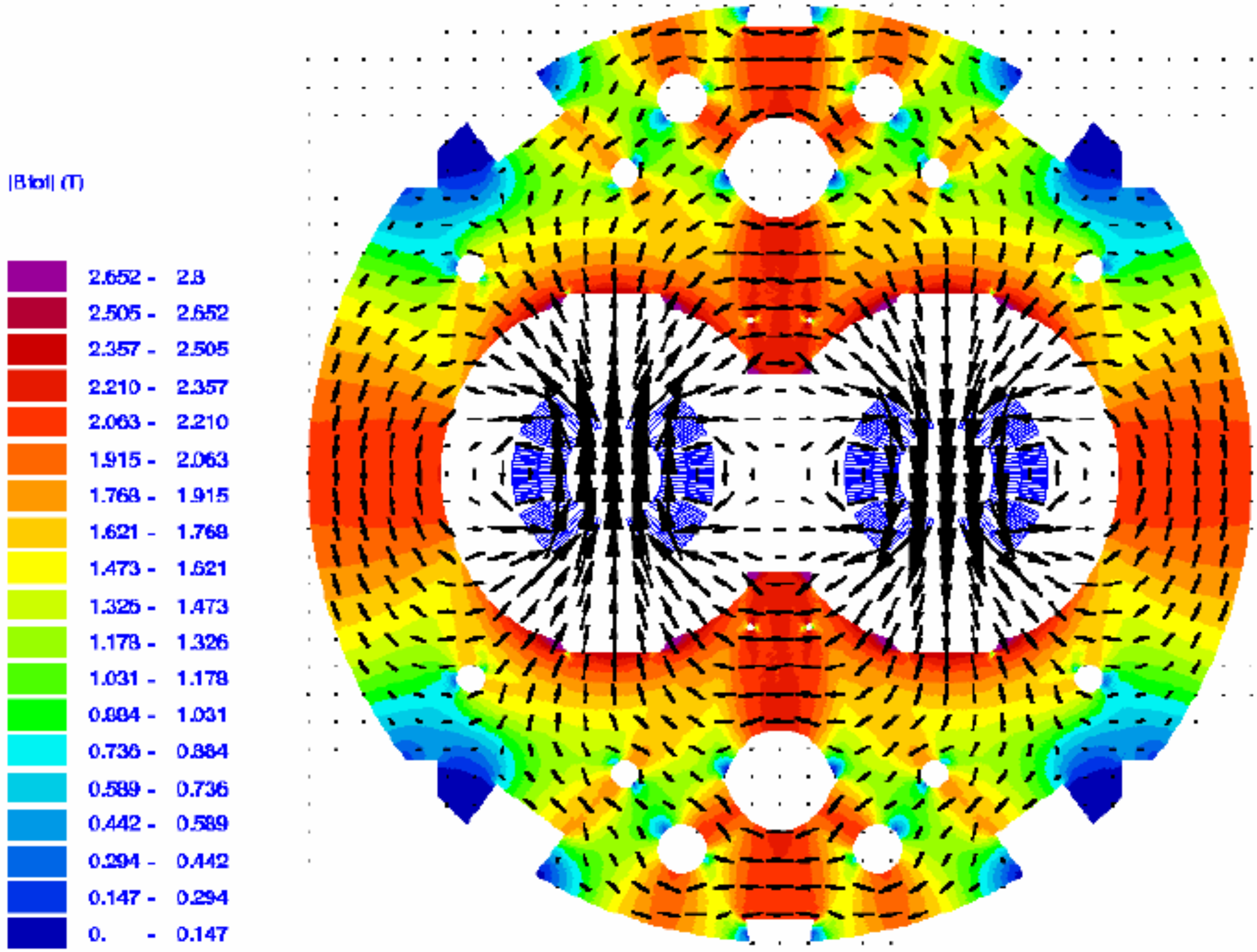
Magnetic Field for Dipoles
p (TeV) = 0.3 B(T) R(km)

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

Dipole magnetic flux plot



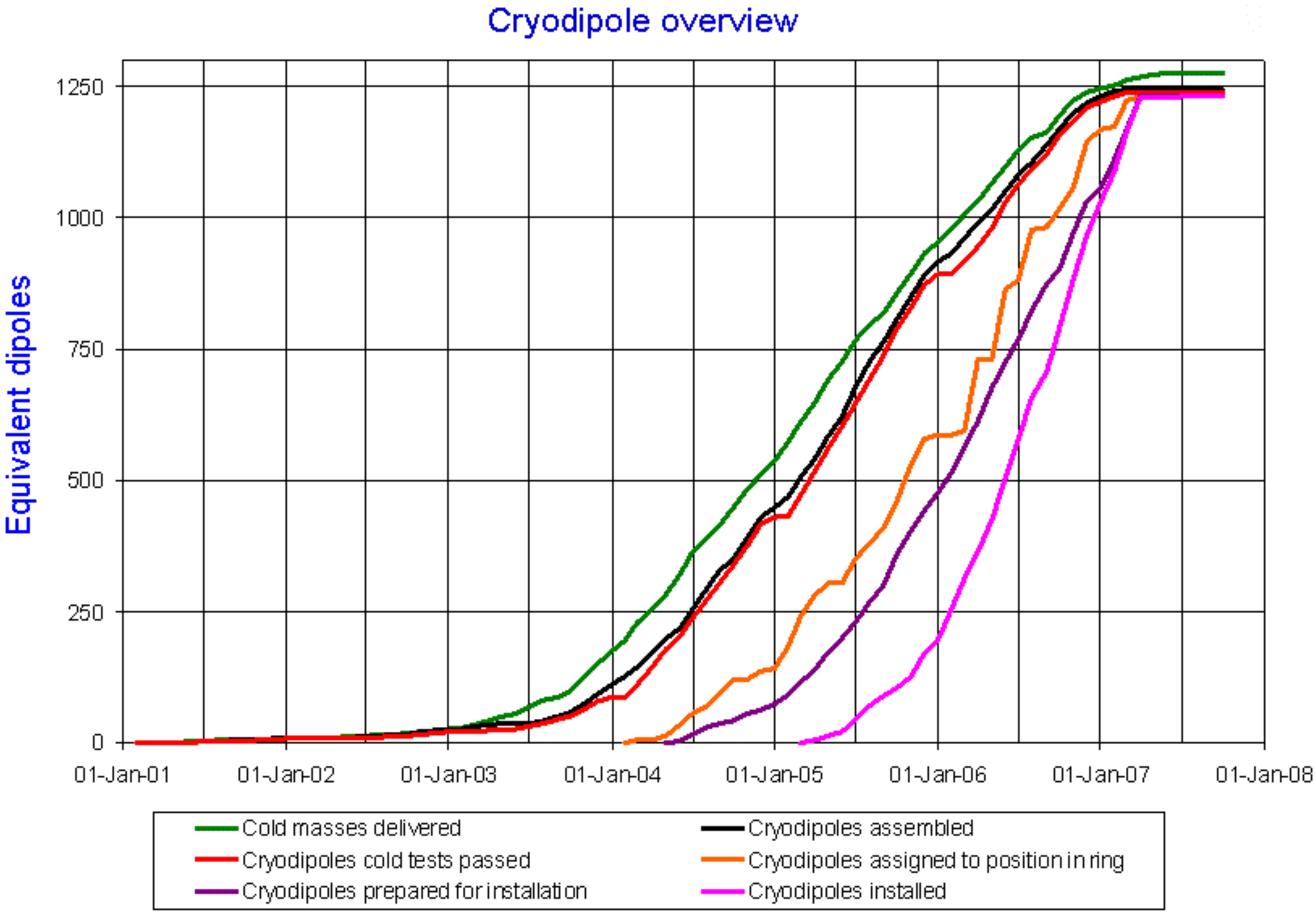
Descent of the last dipole magnet, 26 April 2007

30’000 km underground transports at a speed of 2 km/h!

LHC Progress Dashboard

History of the dipole magnet construction and installation

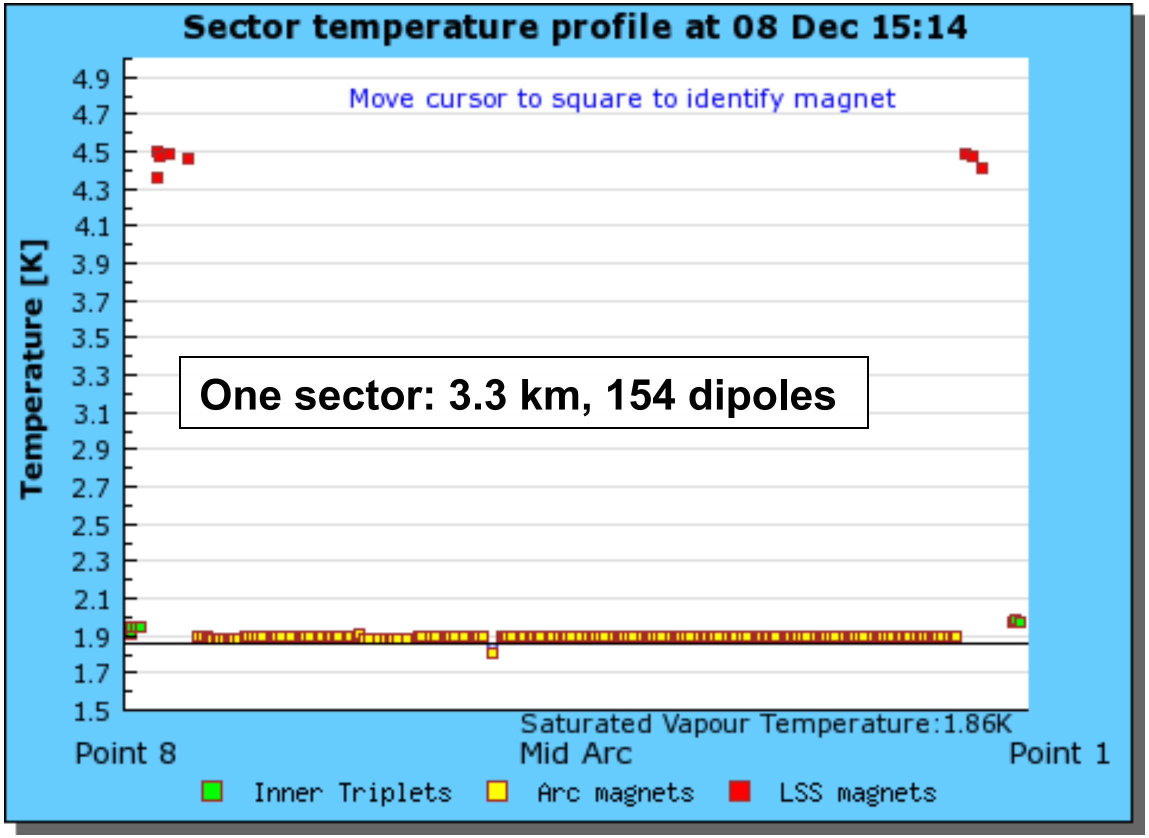
Accelerator Technology Department



Updated 30 September 2007

Data provided by D. Tommasini AT-MCS, L. Bottura AT-MTM

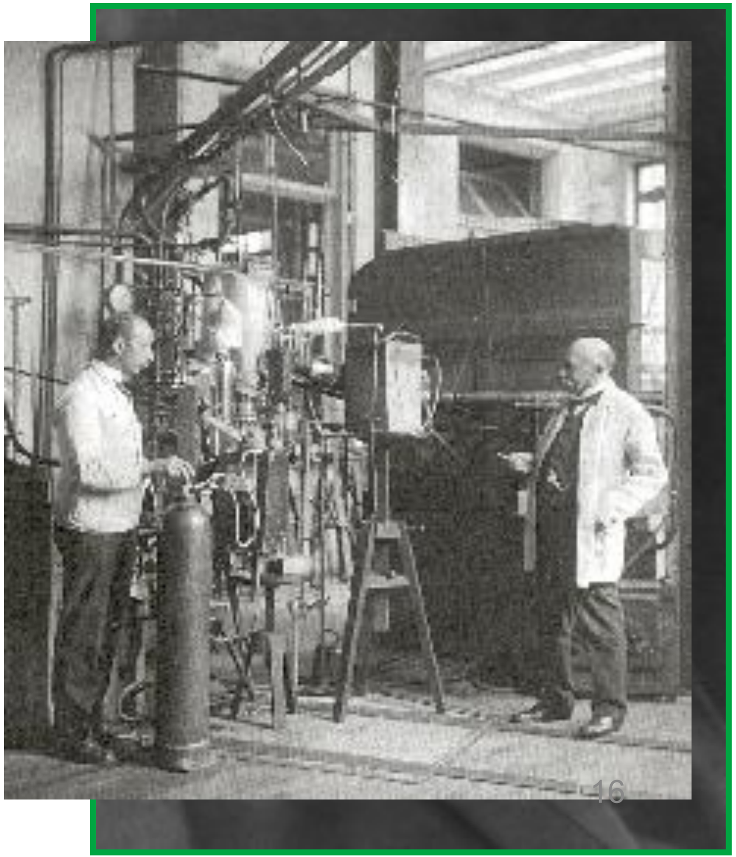
The LHC is the largest cryogenic system on earth, cooler than outer space



One sector: 3.3 km, 154 dipoles

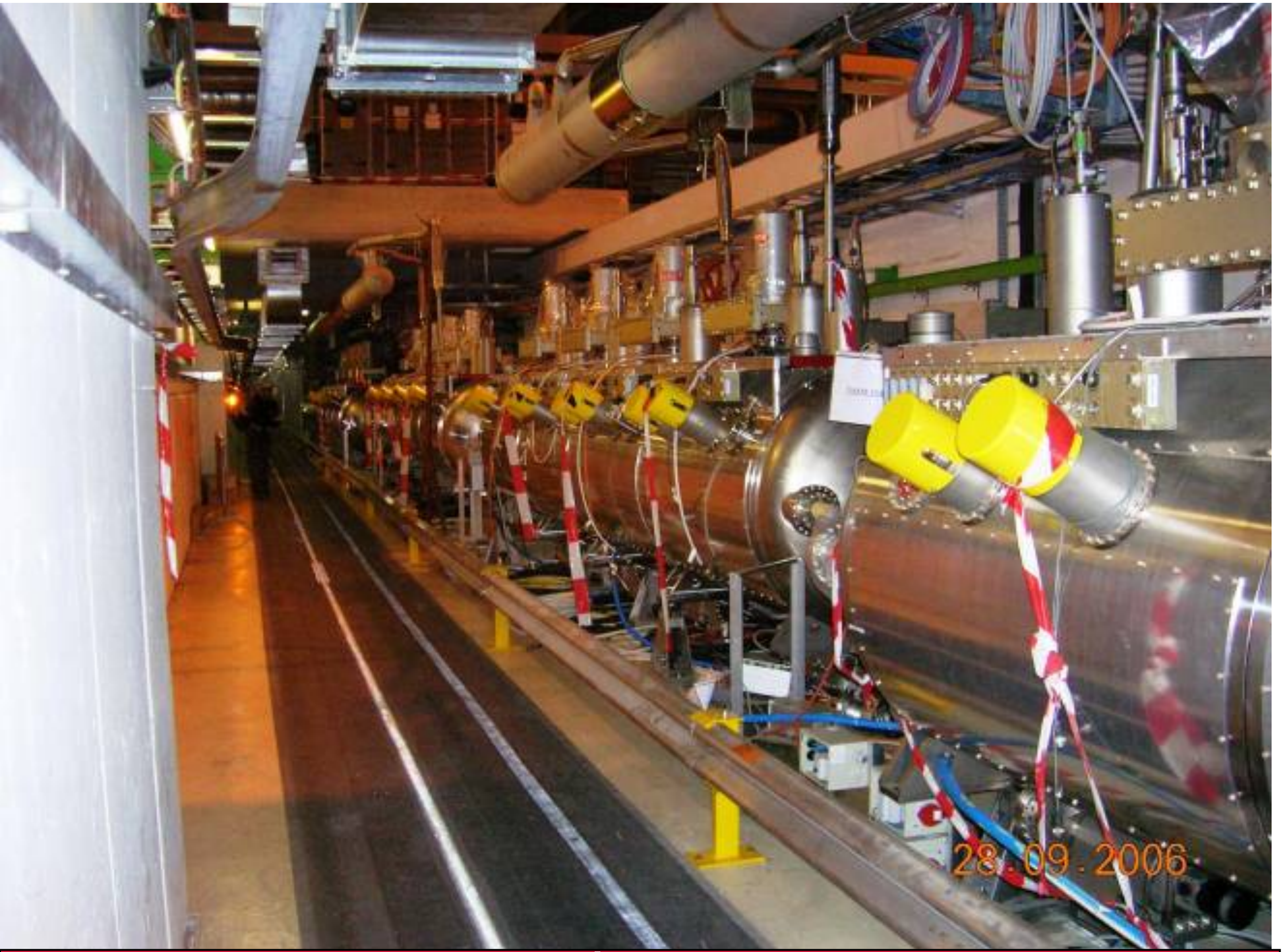
Magnets cooled down in a bath of ~120 tons of superfluid Helium (excellent thermal conductor)

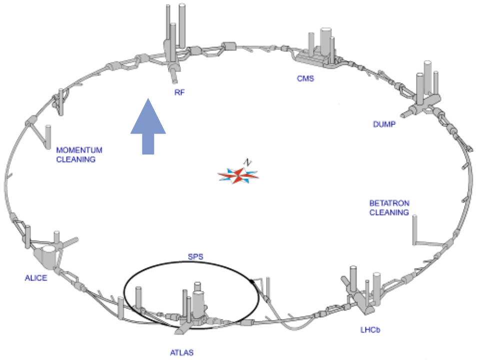
H K Onnes
Nobel Prize in Physics 1913



- 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

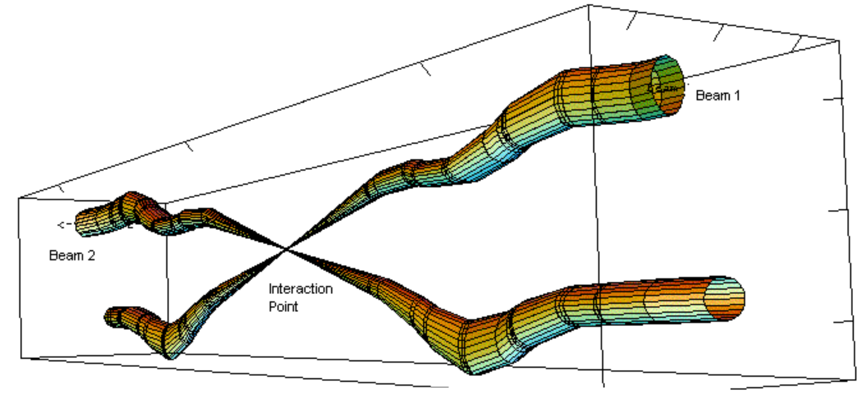




Note: The acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), because of the ~ $1/m^4$ behaviour of the synchrotron radiation energy losses [~ E^4_{beam}/Rm^4]

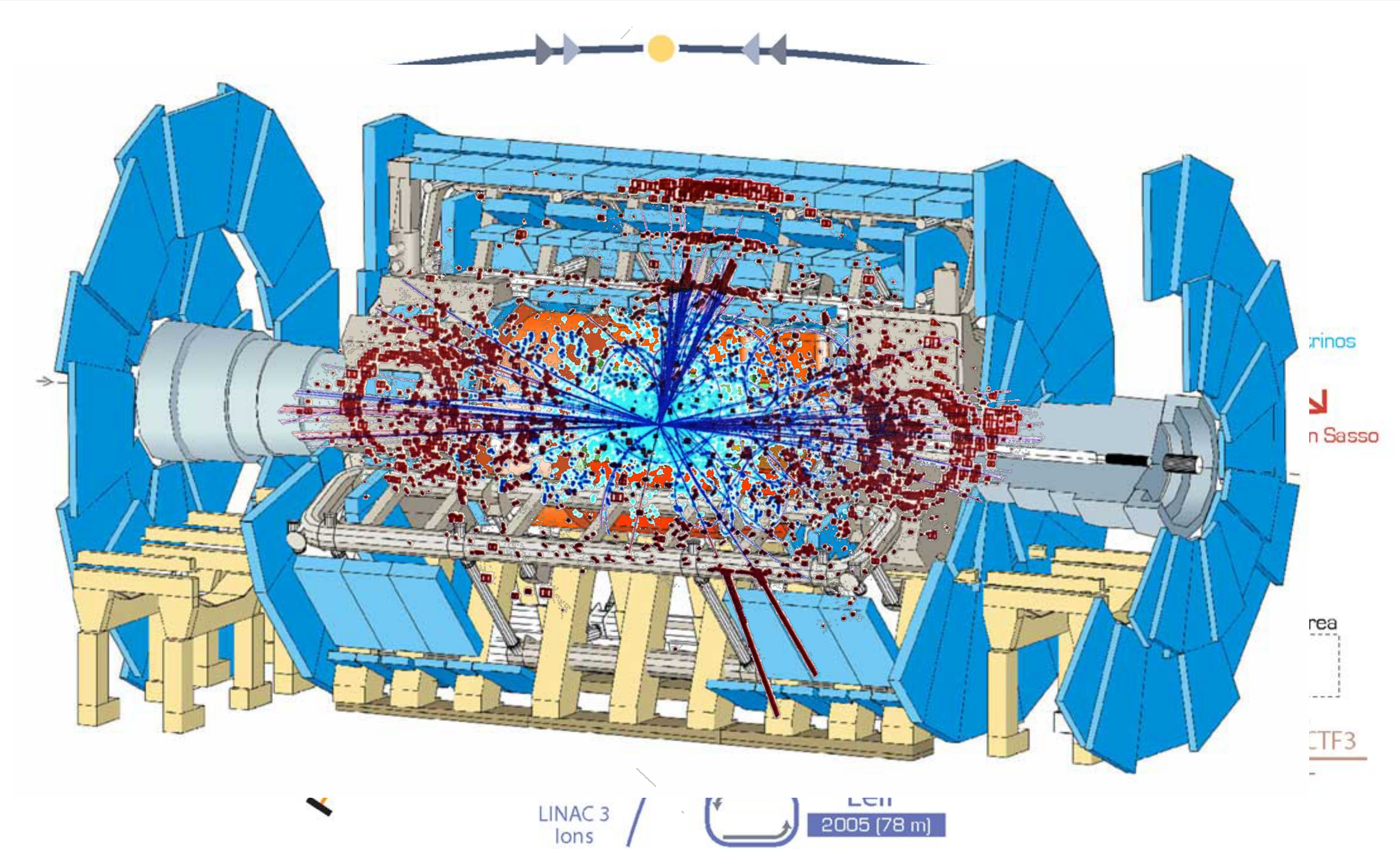
	LHC at 7 TeV	LEP at 100 GeV
Synchrotron radiation loss Peak accelerating voltage	6.7 keV/turn 16 MV/beam	3 GeV/turn 3600 MV/beam

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

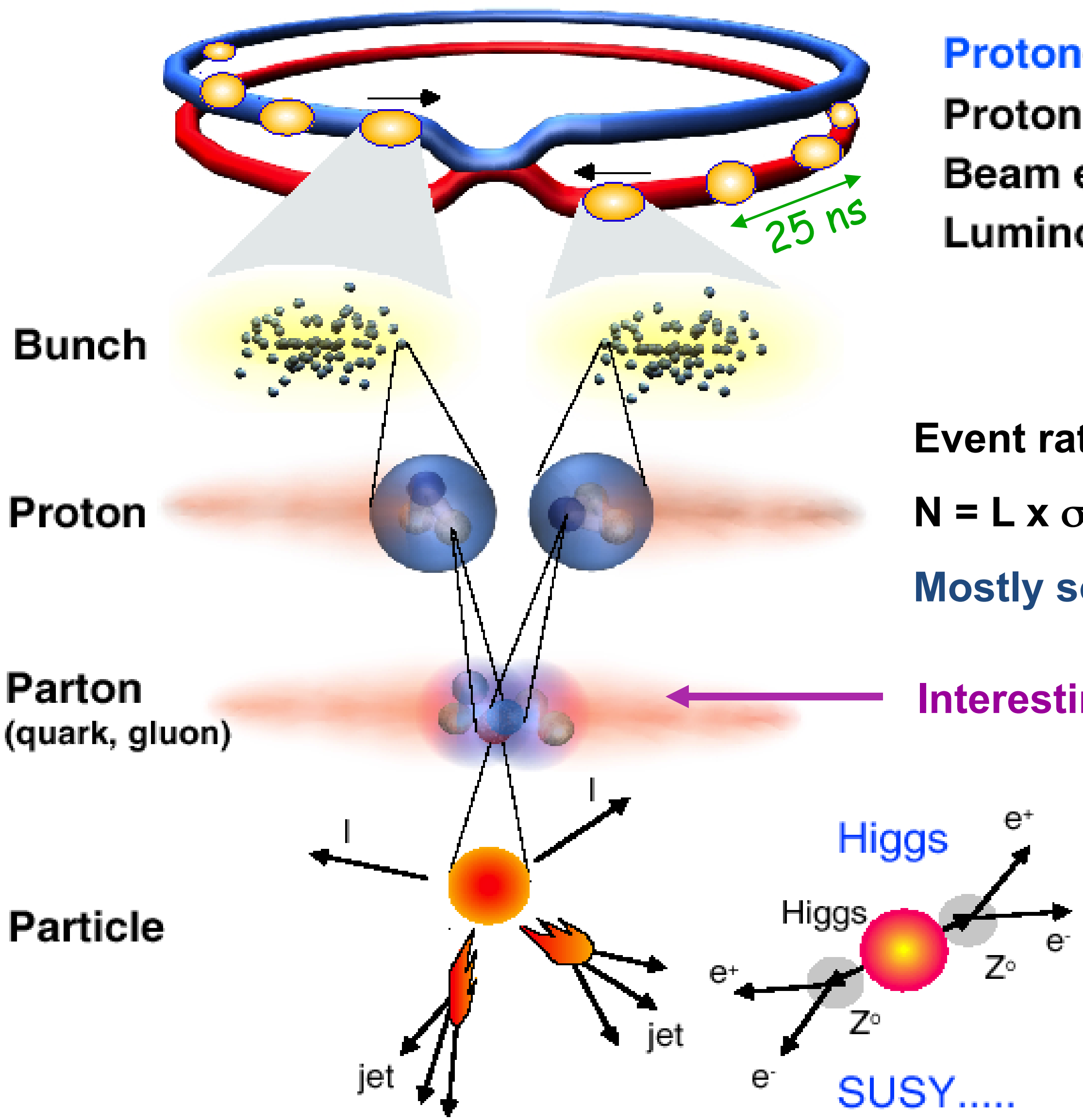


Relative beam sizes around the collision point

CERN’s particle accelerator chain



Collisions at LHC



Proton-Proton

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

Event rate:

N = L x σ (pp) ≈ 10^9 interactions/s

Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare

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

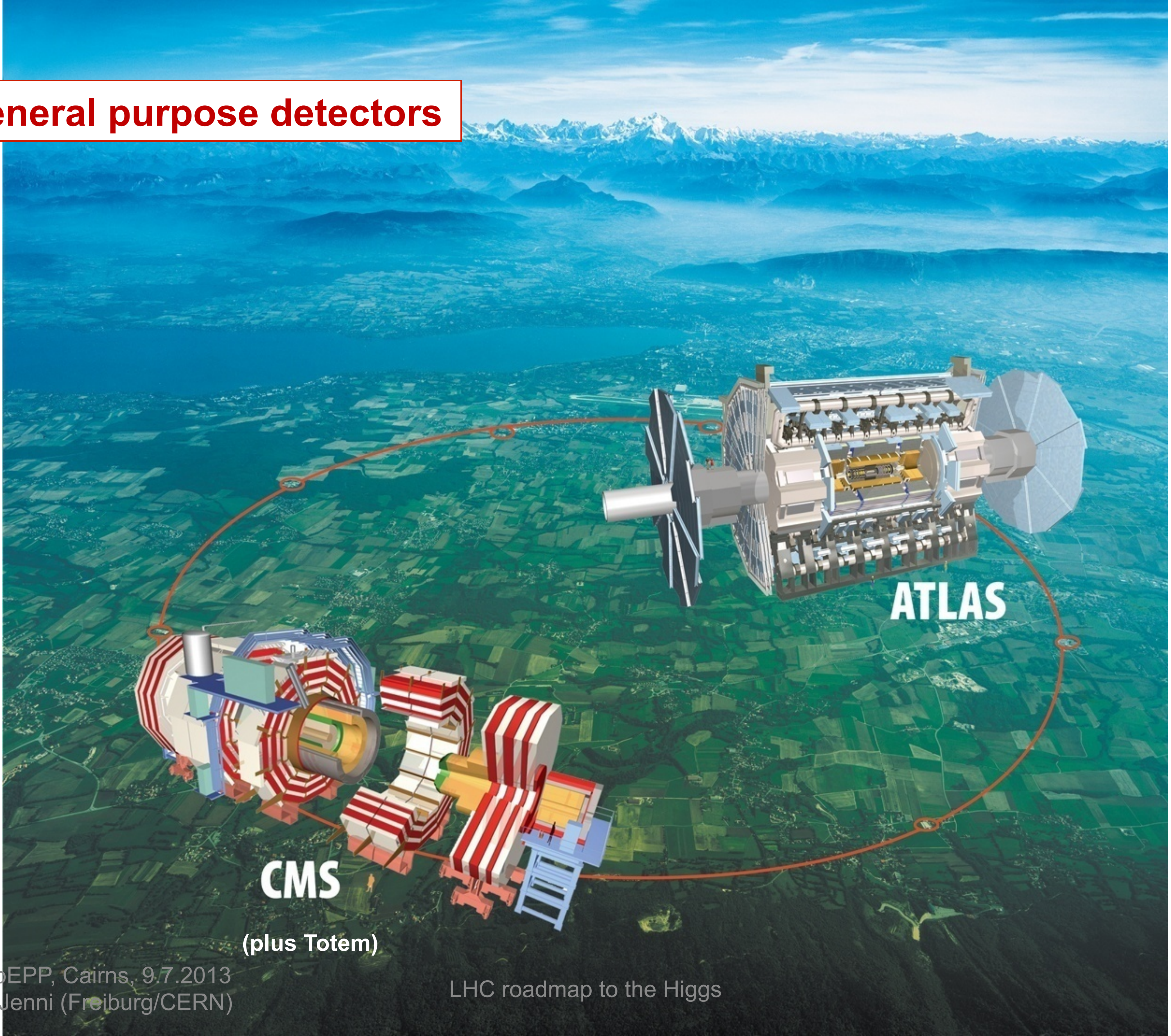
→ very powerful detectors needed

The SM is not a complete theory

Some of the outstanding questions in fundamental physics are

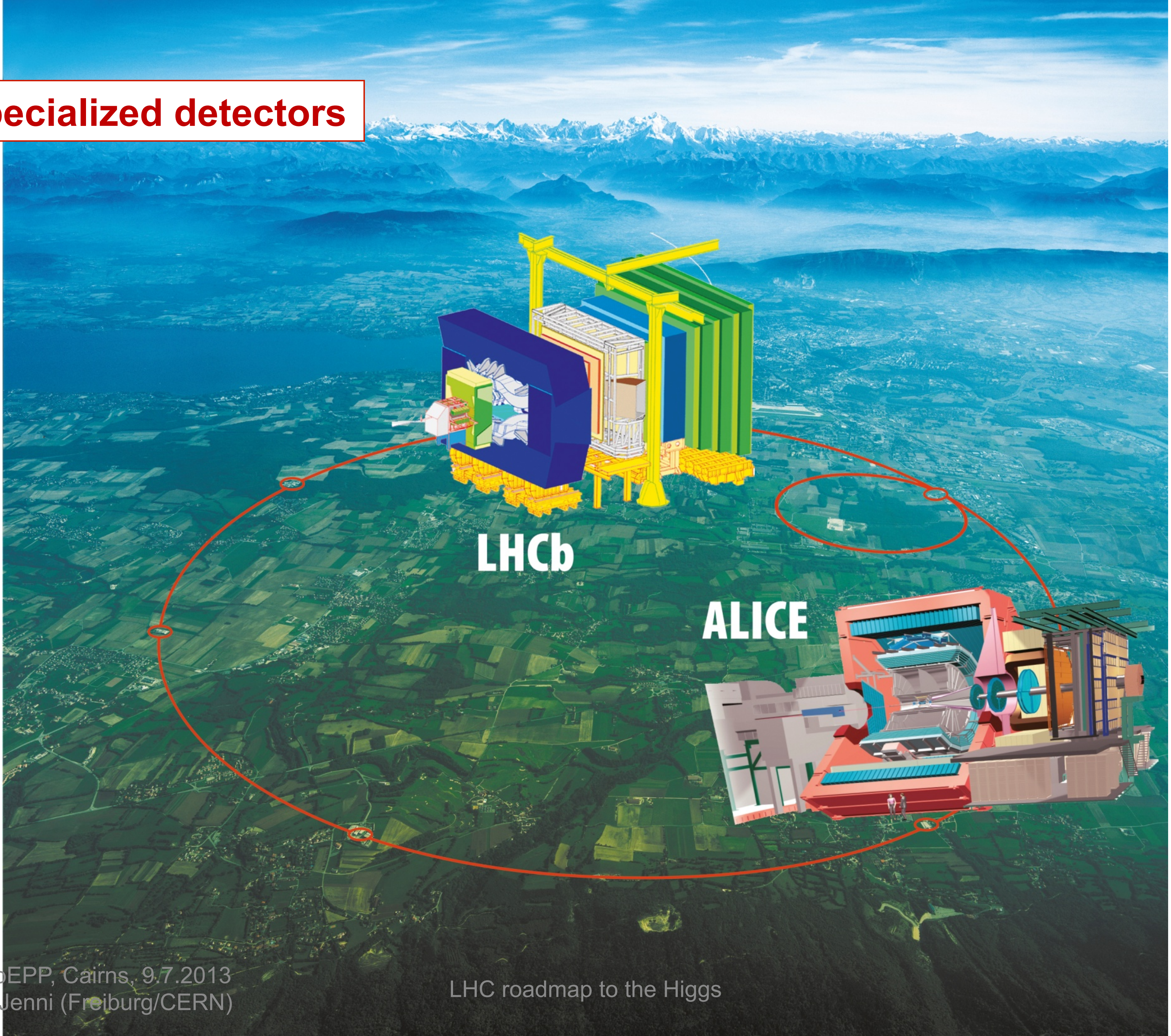
What is the origin of the elementary particle masses ?	ATLAS, CMS
What is the nature of the Universe dark matter ?	ATLAS, CMS
Why is only matter observed in the Universe as primary constituents and not anti-matter ?	LHCb
What are the features of the primordial plasma present ~10 μs after the Big Bang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

General purpose detectors



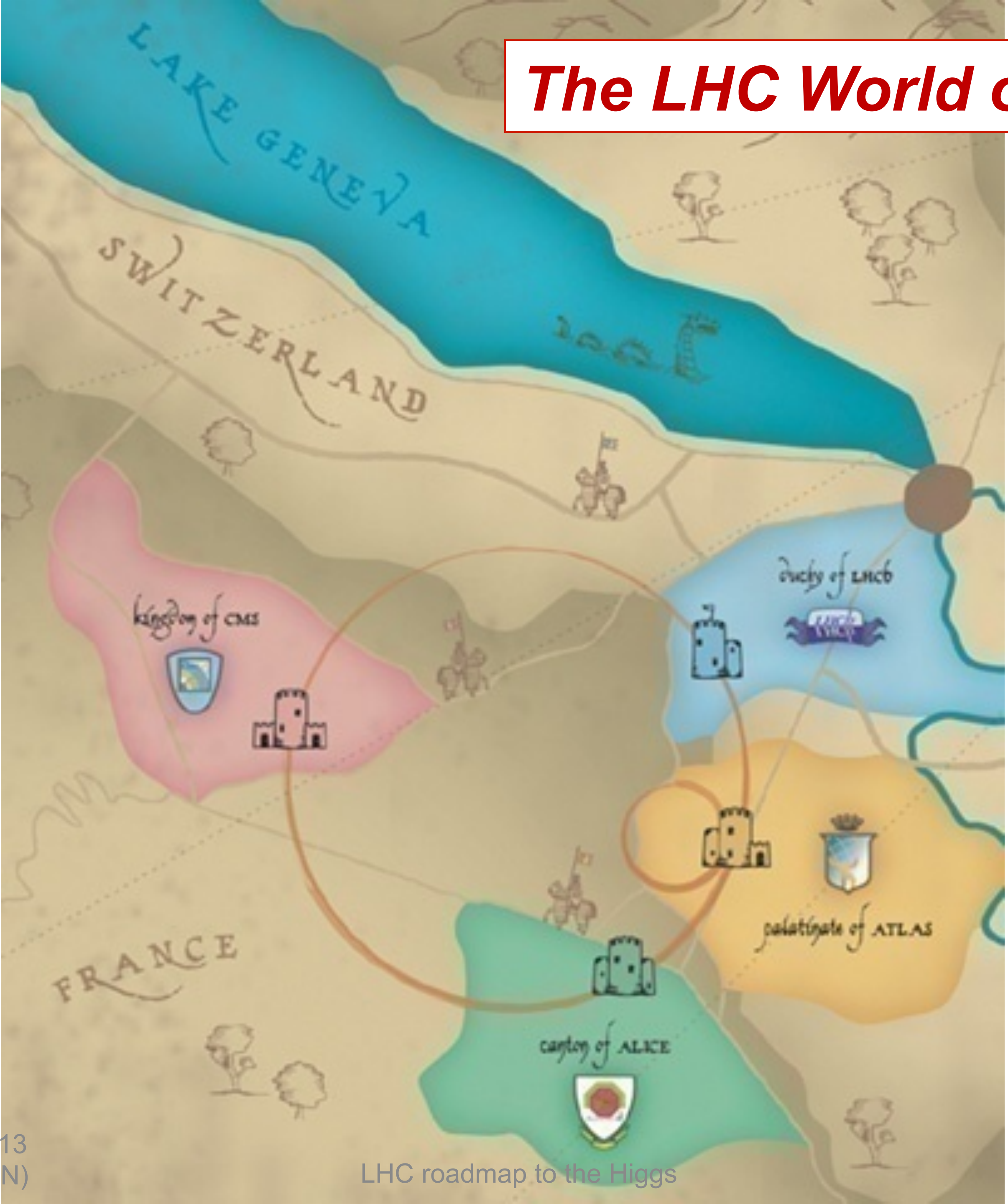
(plus Totem)

Specialized detectors



The LHC World of CERN

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

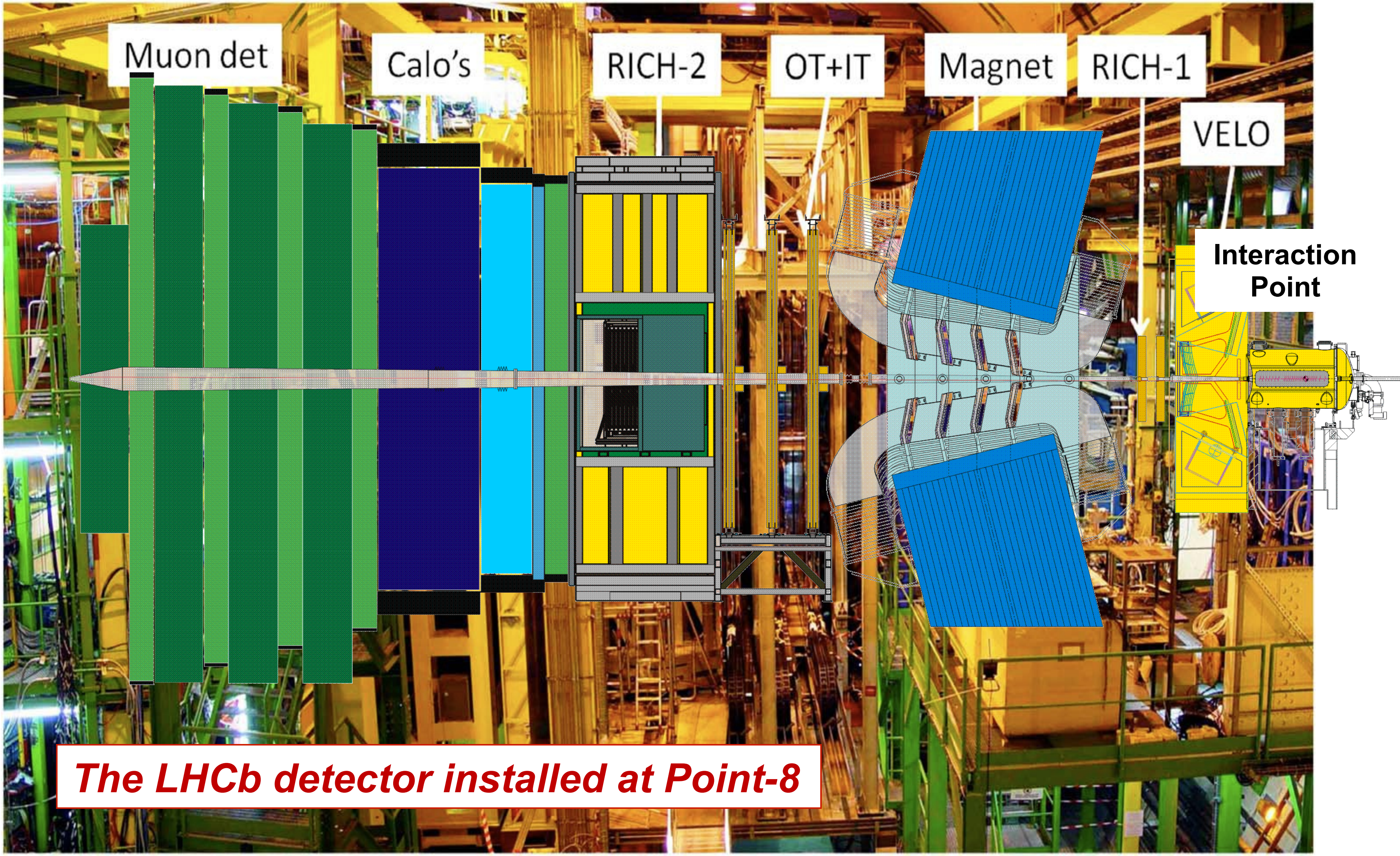


CMS
3000 Physicists
184 Institutions
38 countries
550 MCHF

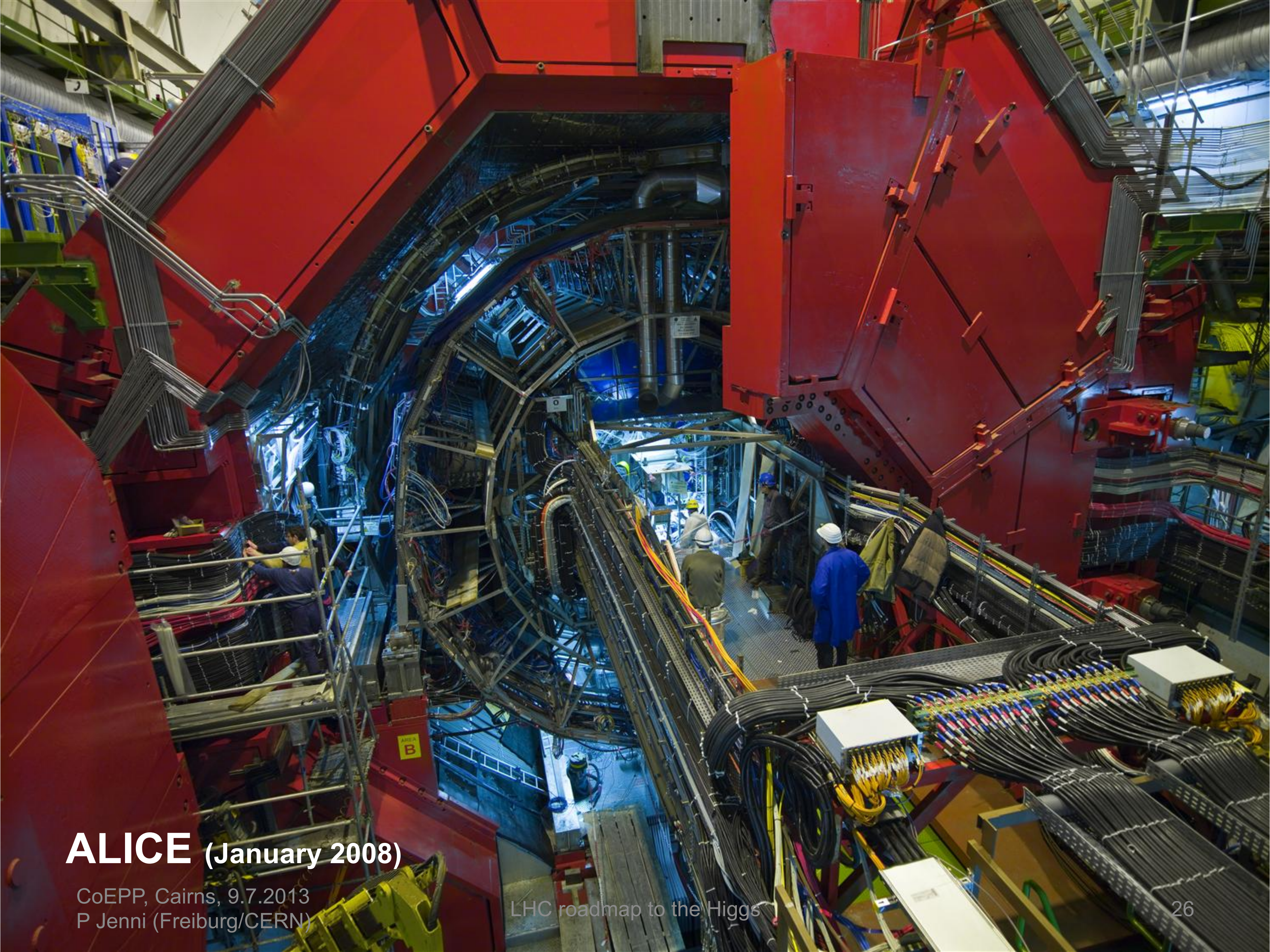
LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

ATLAS
3000 Physicists
177 Institutions
38 countries
550 MCHF

ALICE
1300 Physicists
130 Institutions
35 countries
160 MCHF

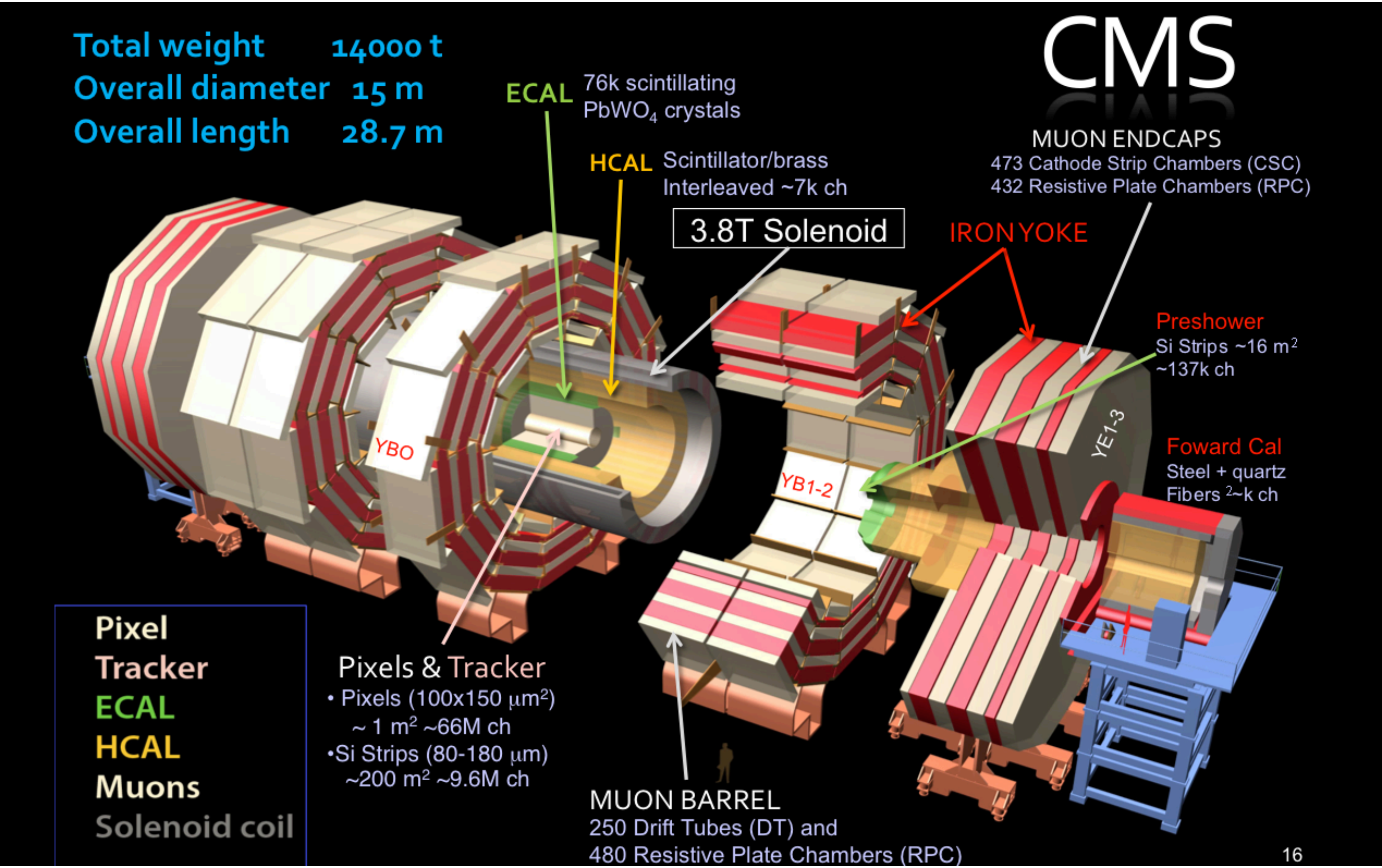


The LHCb detector installed at Point-8



ALICE **(January 2008)**

Exploded View of CMS



Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m

ECAL 76k scintillating PbWO$_4$ crystals

HCAL Scintillator/brass Interleaved ~7k ch

3.8T Solenoid

IRON YOKE

MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)

Preshower
Si Strips ~16 m^2
~137k ch

Foward Cal
Steel + quartz
Fibers ^{2}~k ch

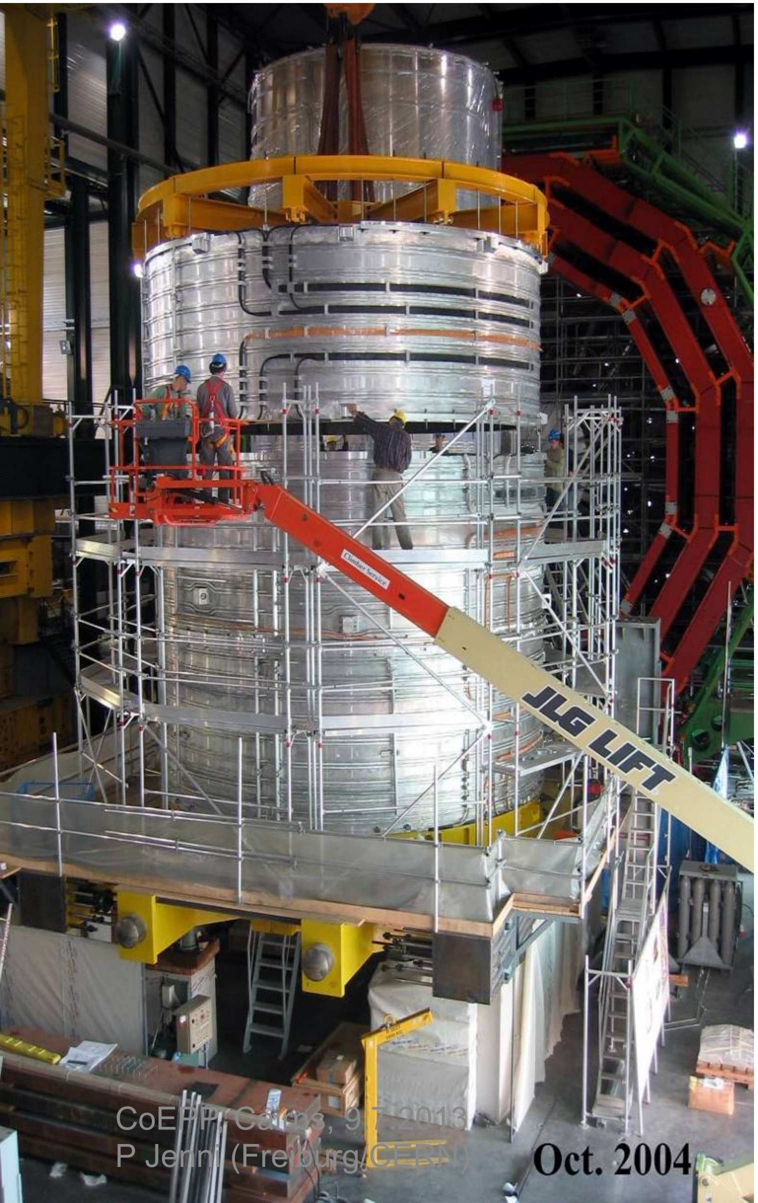
- Pixel
- Tracker
- ECAL
- HCAL
- Muons
- Solenoid coil

Pixels & Tracker
- Pixels (100x150 μm^2) ~ 1 m^2 ~66M ch
- Si Strips (80-180 μm) ~200 m^2 ~9.6M ch

MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

16

An Example of an Engineering Challenge: CMS Solenoid

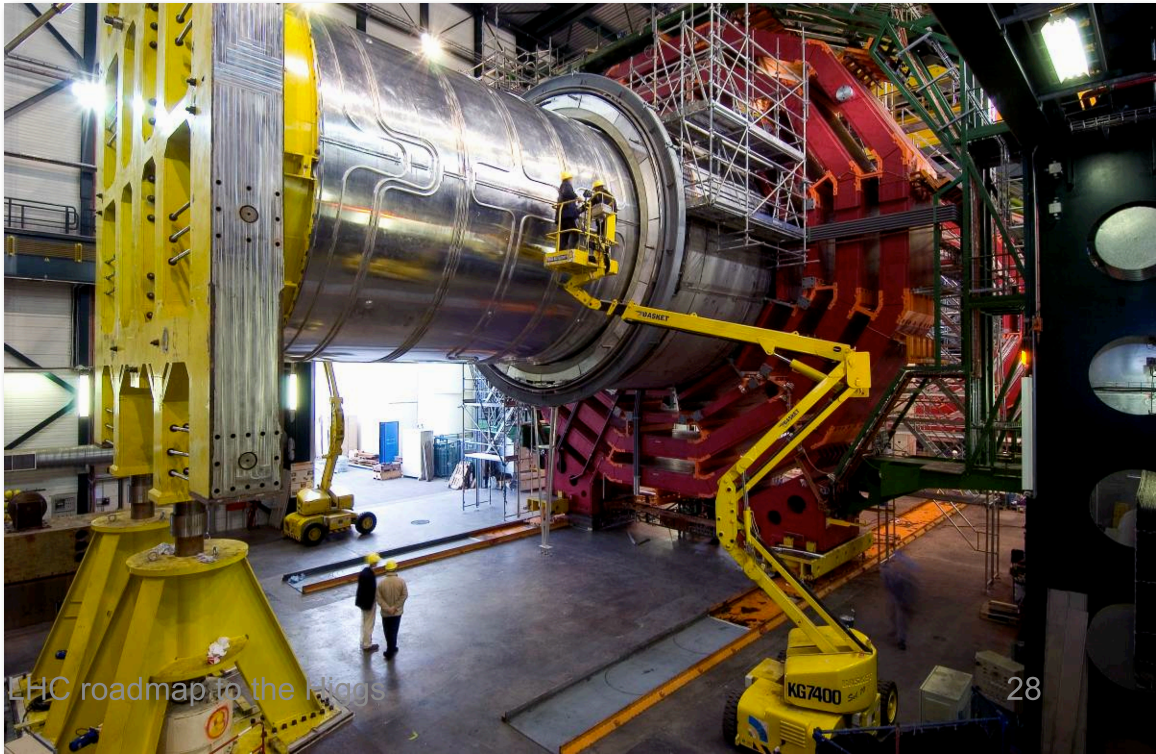


Oct. 2004

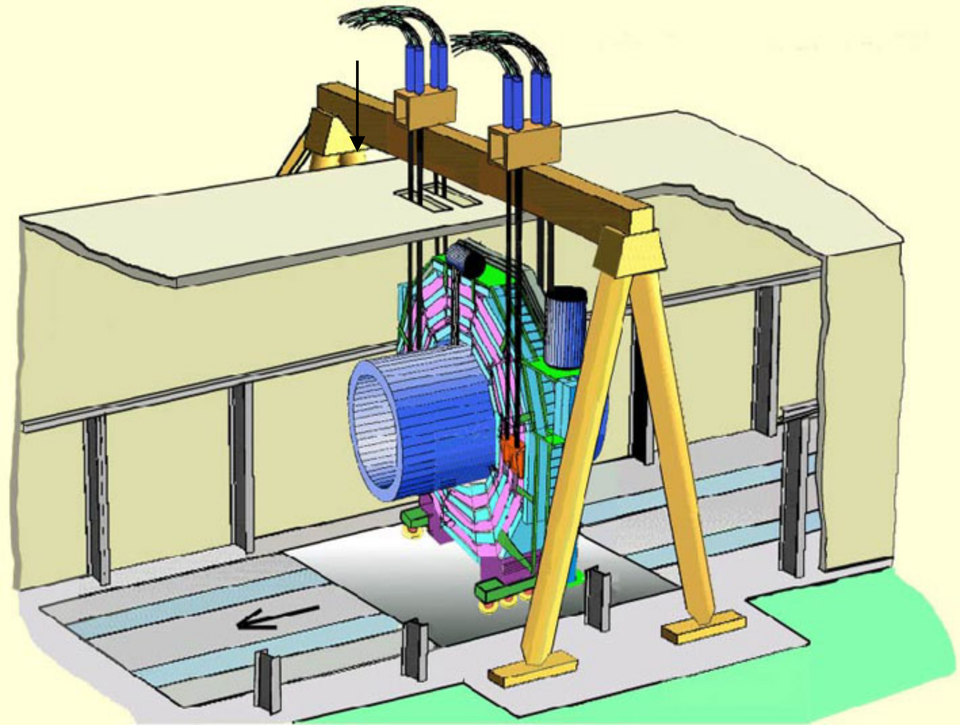
CMS solenoid:

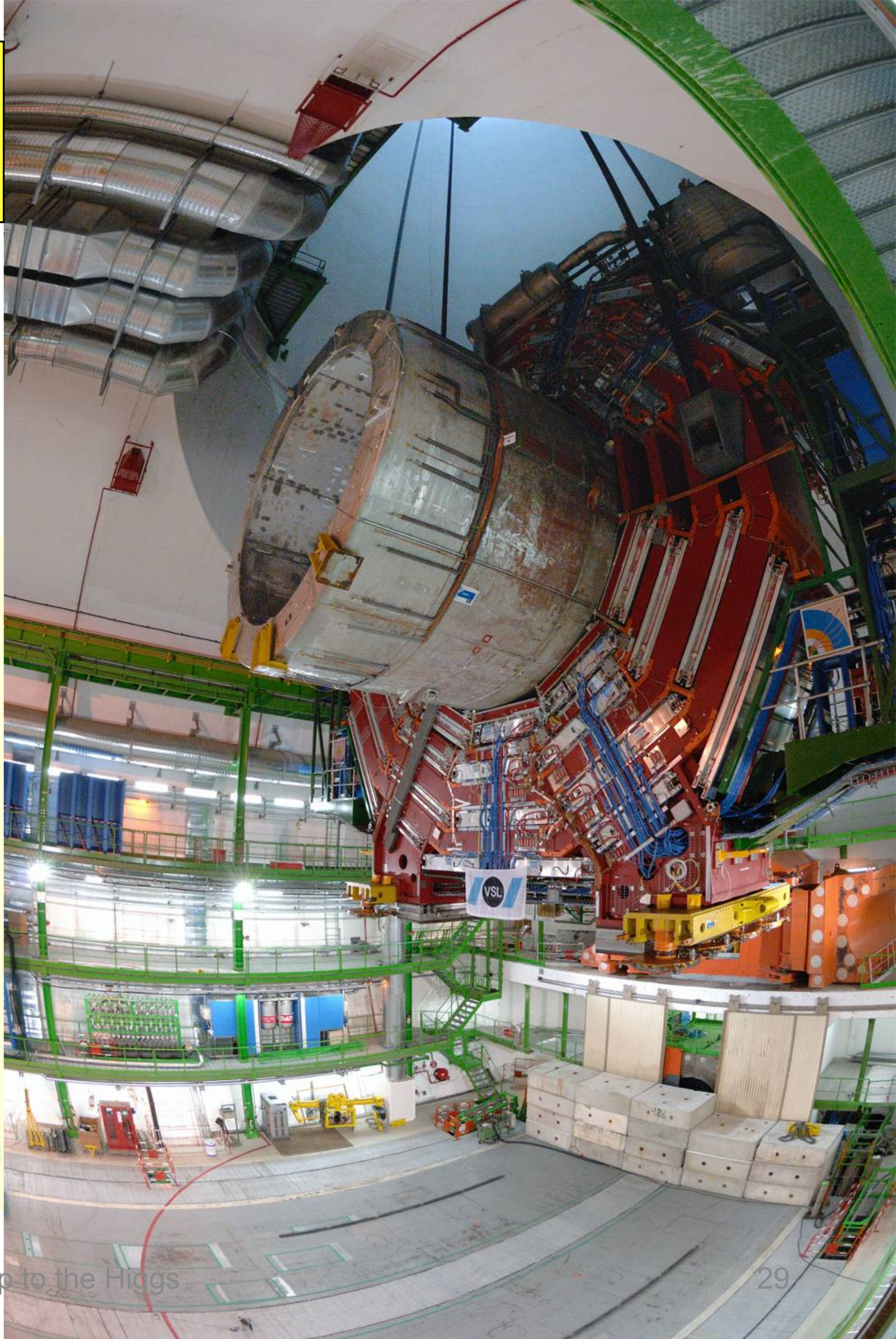
Magnetic length	12.5 m
Diameter	6 m
Magnetic field	4 T
Nominal current	20 kA
Stored energy	2.7 GJ

Tested at full current in Summer 2006



The central, heaviest slice (2000 tons) including the solenoid magnet lowered in the underground cavern in Feb. 2007





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, 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, 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

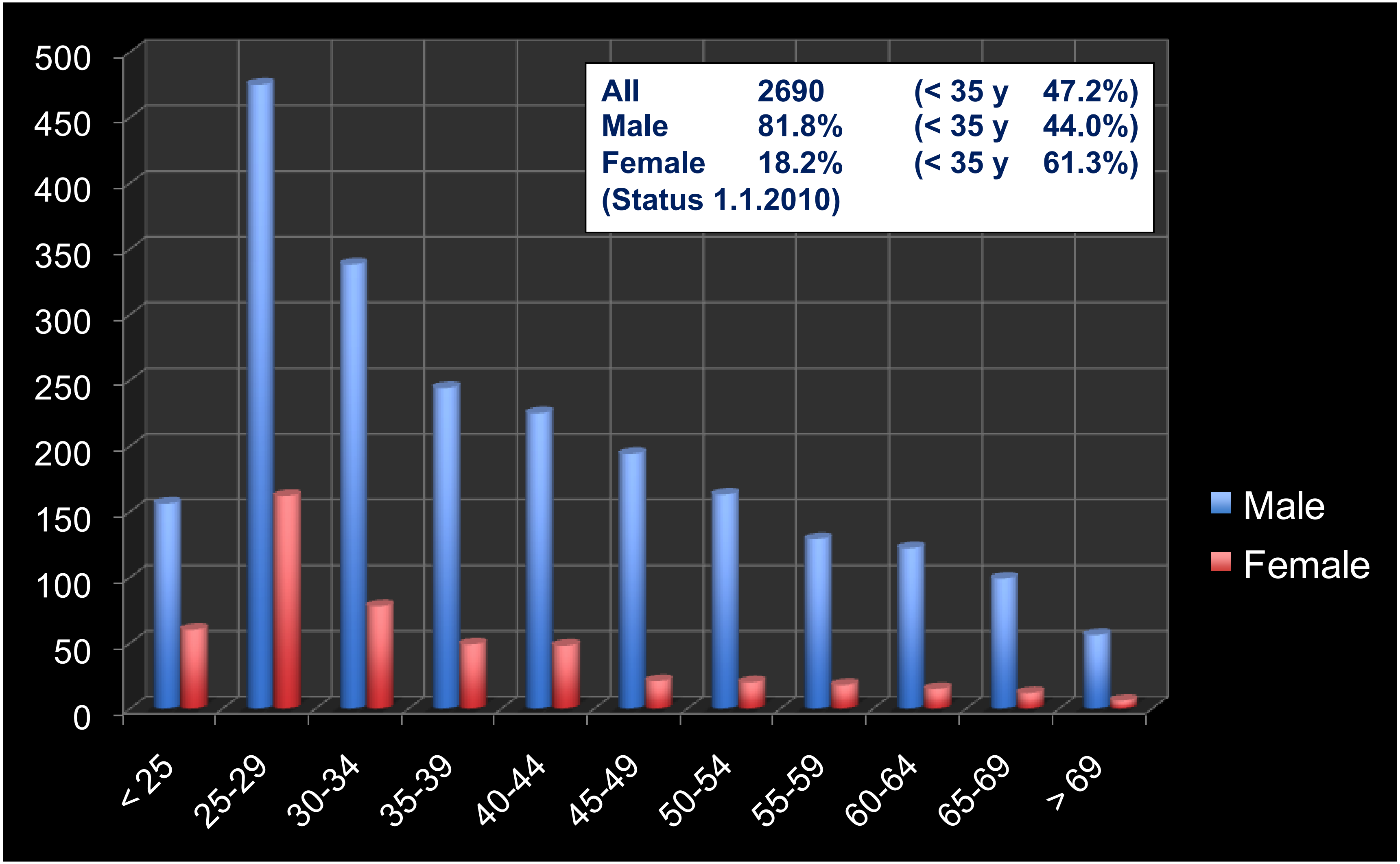
ATLAS Collaboration

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

It is a great pleasure to collaborate with ~30 colleagues, junior and senior, from the three Australian Universities since the very first days

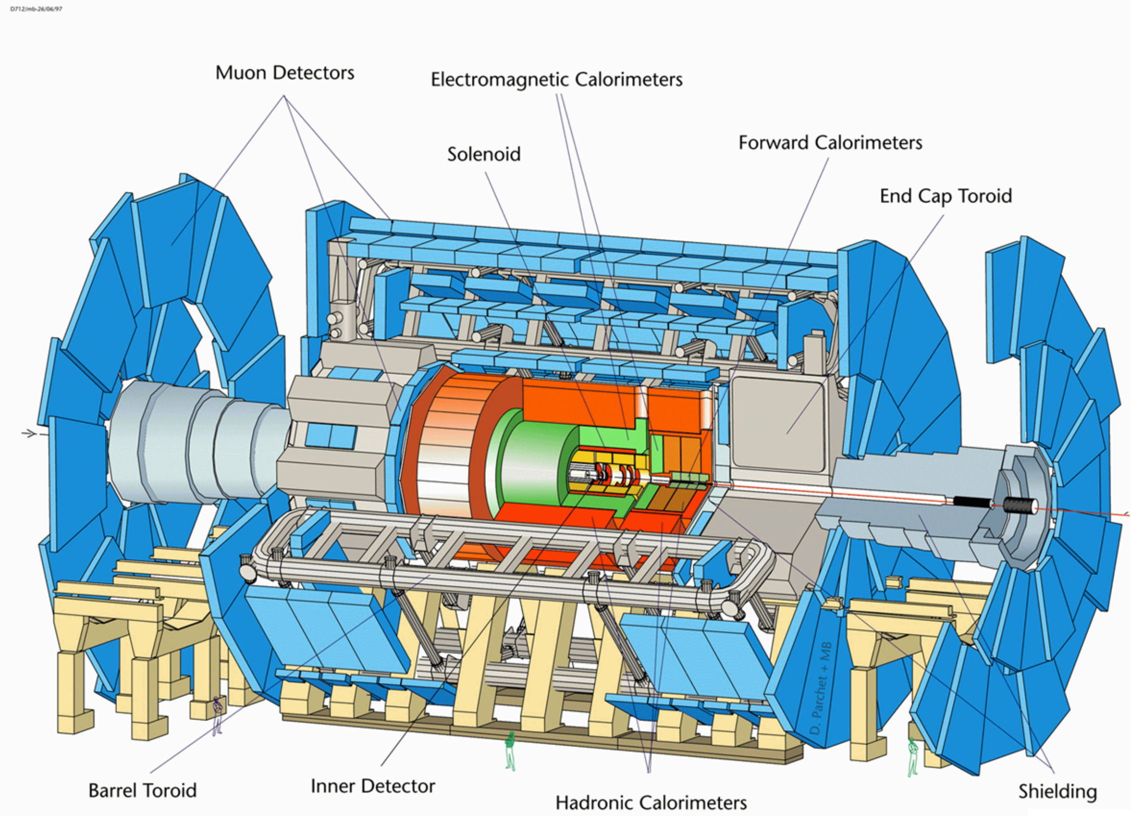
Adelaide, Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Brasil Cluster, Bratislava/SAS Kosice, Brookhaven 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, 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, 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

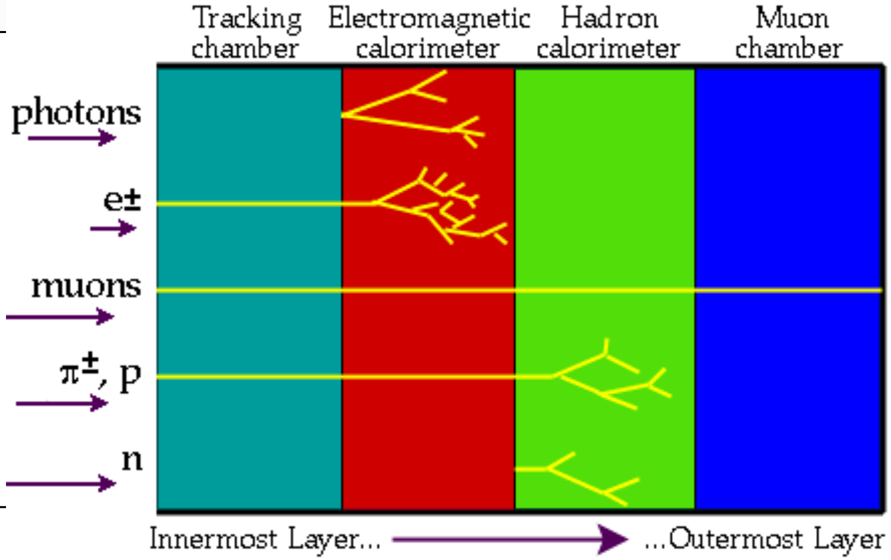


Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~ 10^8 electronic channels
~ 3000 km of cables

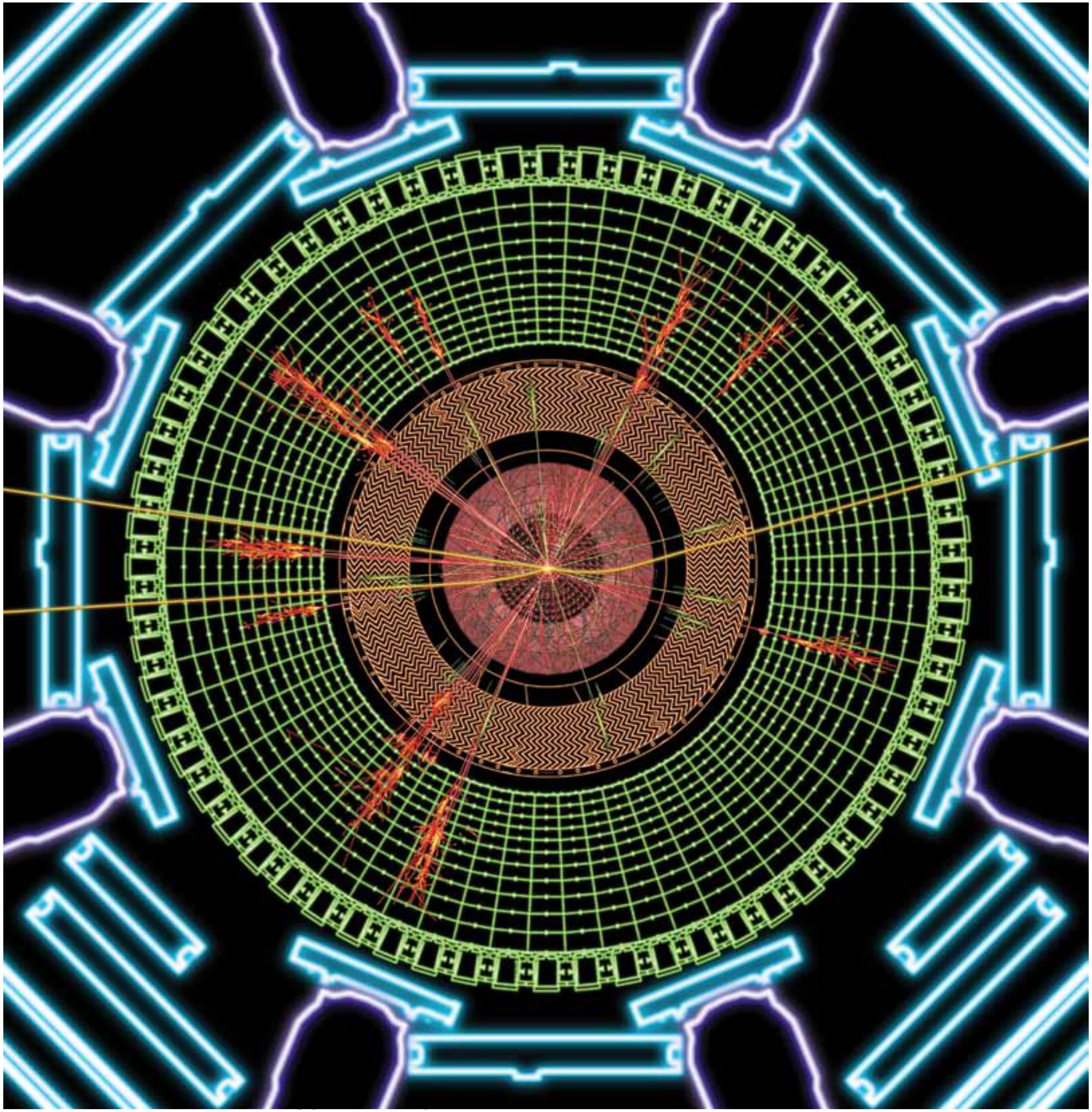
- **Tracking (|η|<2.5, B=2T) :**
  - **-- Si pixels and strips**
  - **-- Transition Radiation Detector (e/π separation)**

- **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



An artistic view of ATLAS



Front cover of the 2012 Annual Report

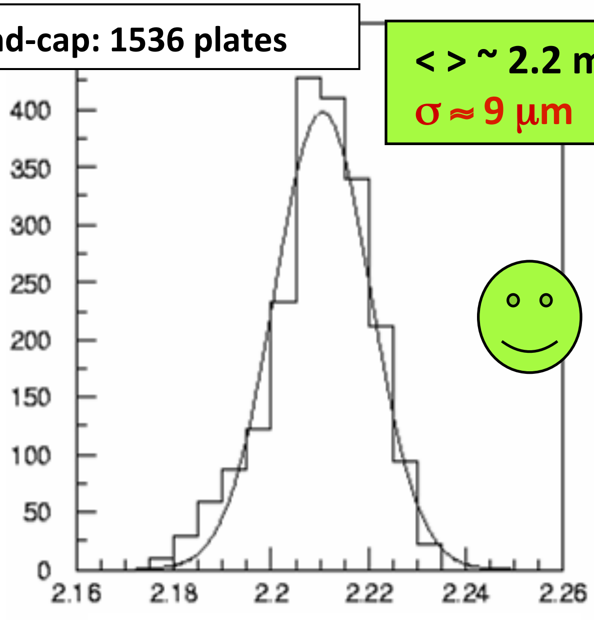
CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Construction example: ATLAS LAr em Accordion Calorimeter

Construction quality

Thickness of Pb plates must be uniform to 0.5% (~10 μm)

End-cap: 1536 plates



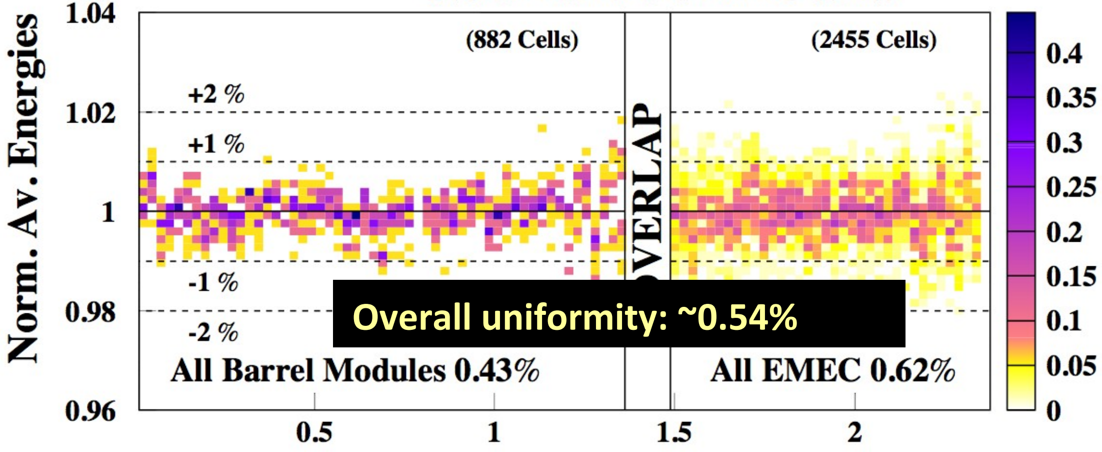
< > ~ 2.2 mm
σ ≈ 9 μm

Absorber thickness (mm)

Test-beam measurements

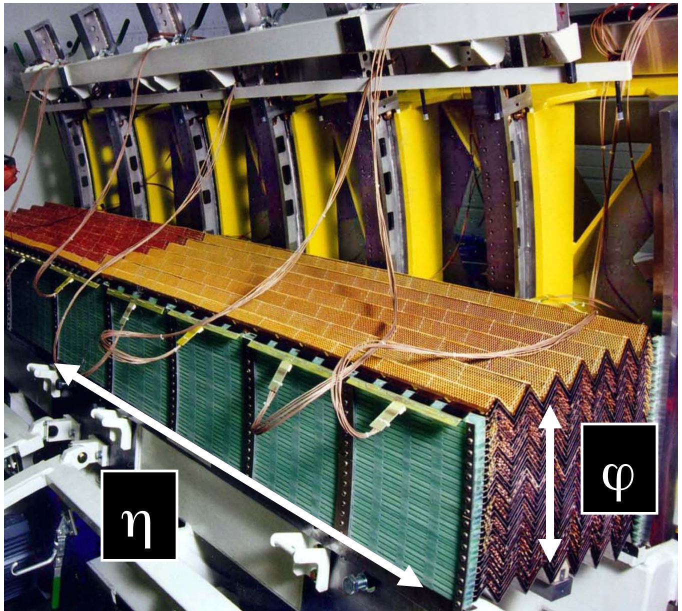
4 (out of 32) barrel modules and 3 (out of 16) end-cap (EMEC) modules tested with beams

Scans with 120-245 GeV electrons (all 7 tested modules)

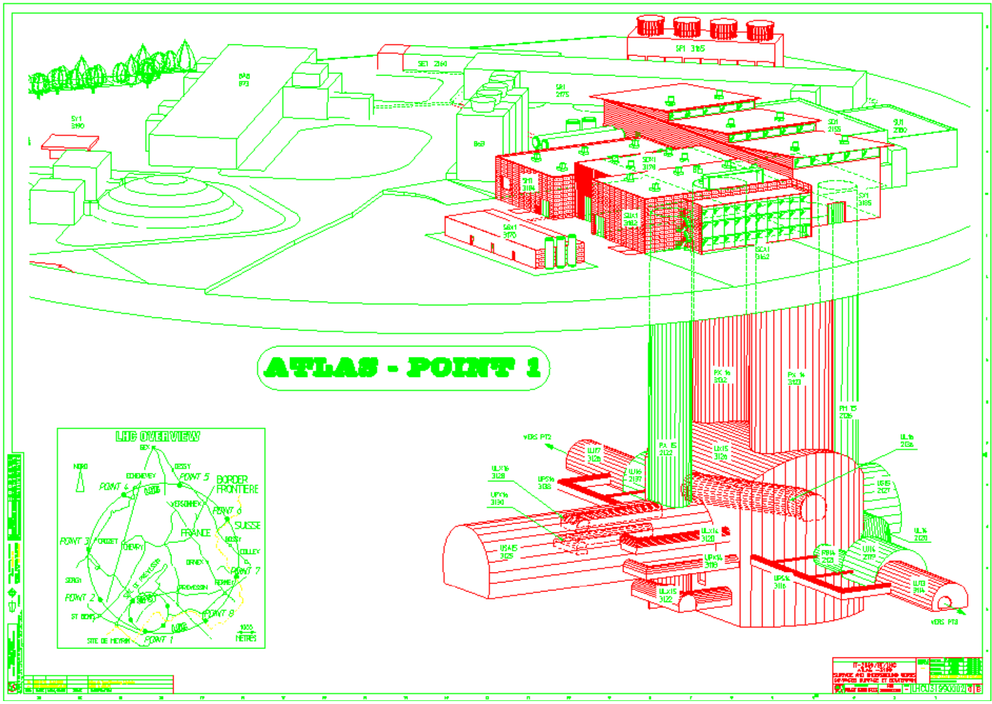


Overall uniformity: ~0.54%

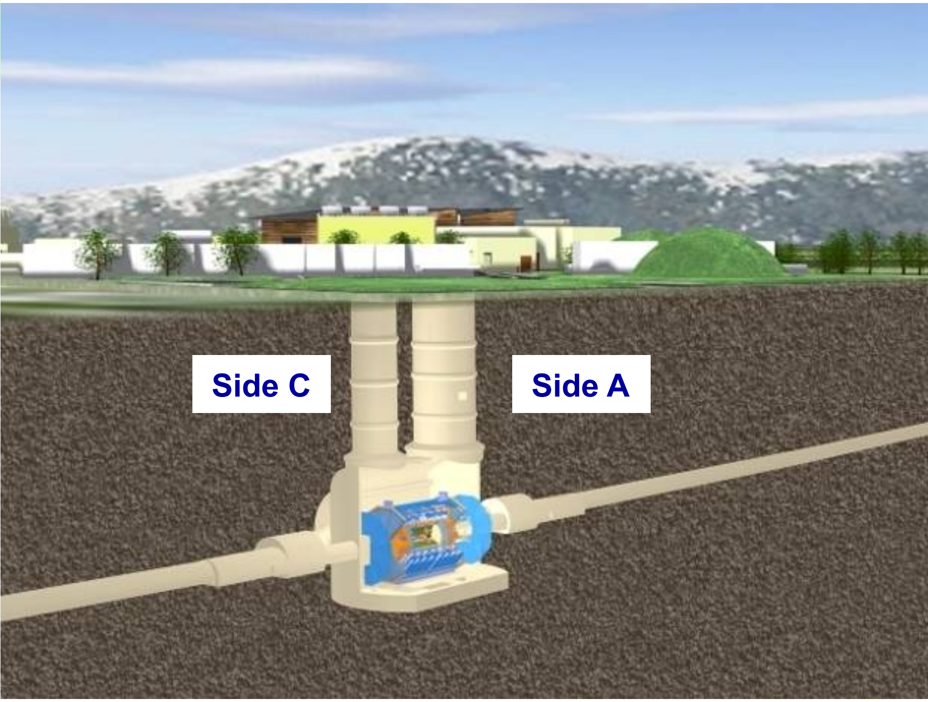
1 barrel module:
Δη x Δφ = 1.4 x 0.4
≈ 3000 channels



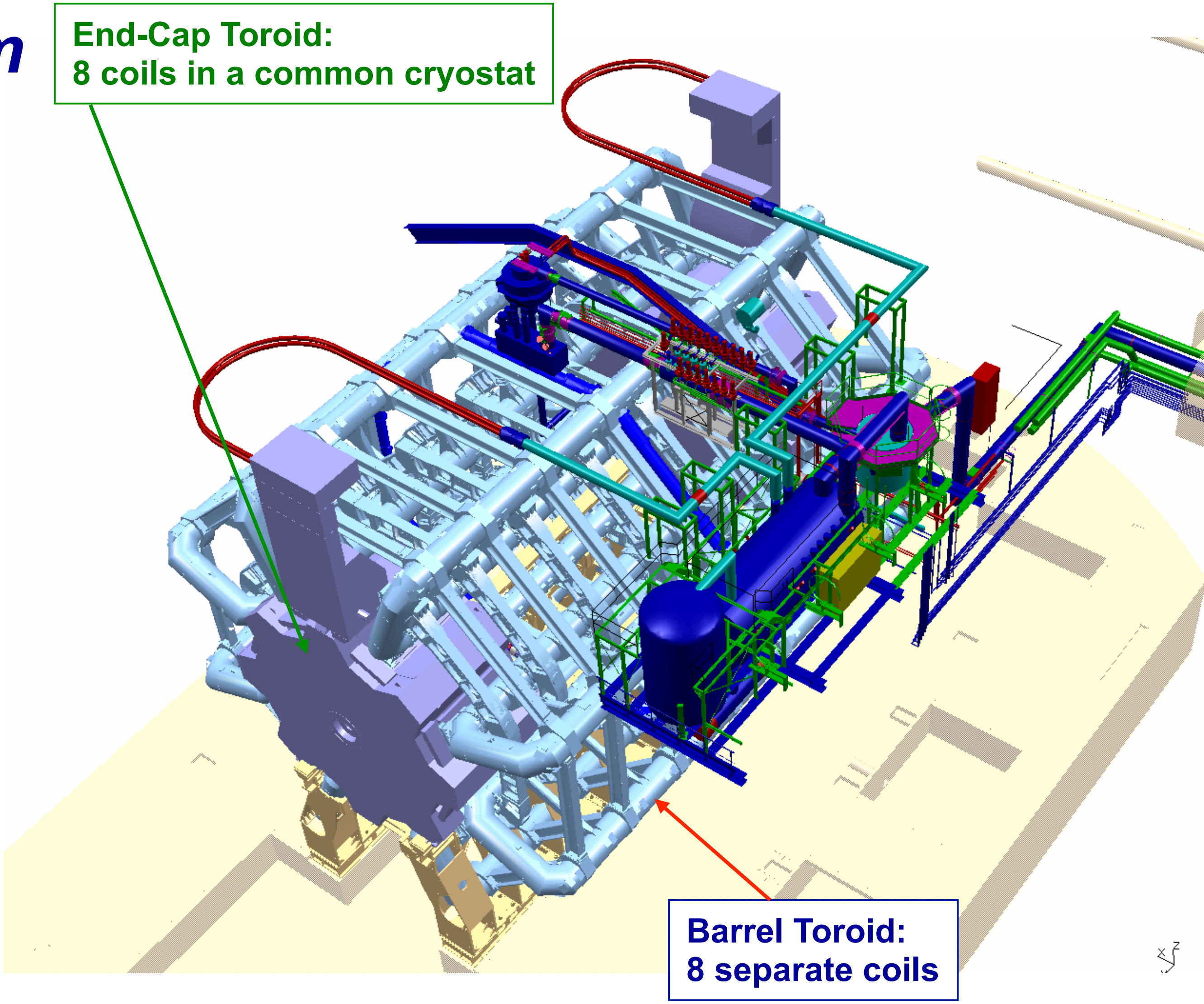
The Underground Cavern at Point-1 for the ATLAS Detector



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



ATLAS Toroid Magnet System



End-Cap Toroid:
8 coils in a common cryostat

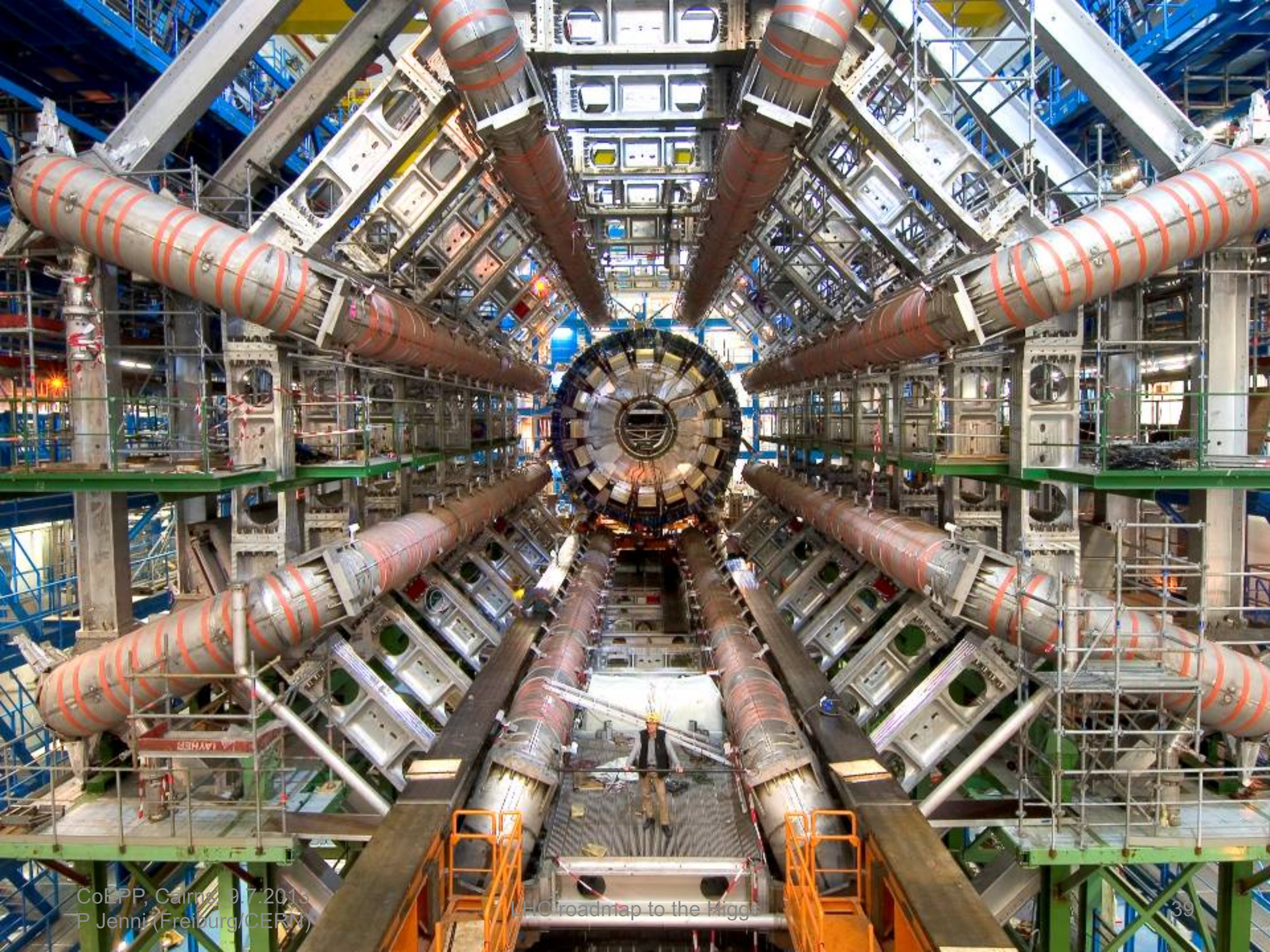
Barrel Toroid:
8 separate coils

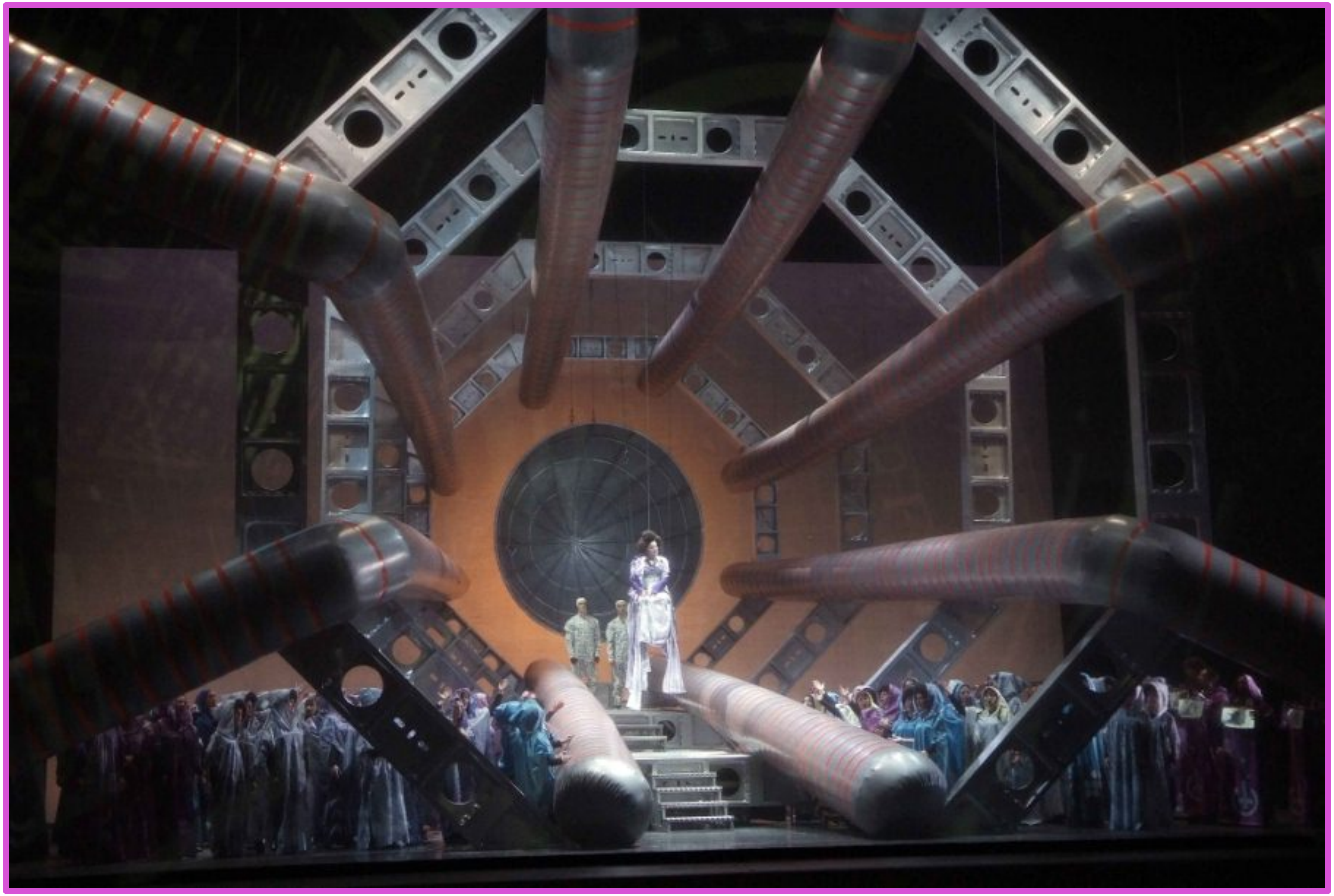
Barrel Toroid parameters

25.3 m length
20.1 m outer diameter
8 coils
1.08 GJ stored energy
370 tons cold mass
830 tons weight
4 T on superconductor
56 km Al/NbTi/Cu conductor
20.5 kA nominal current
4.7 K working point

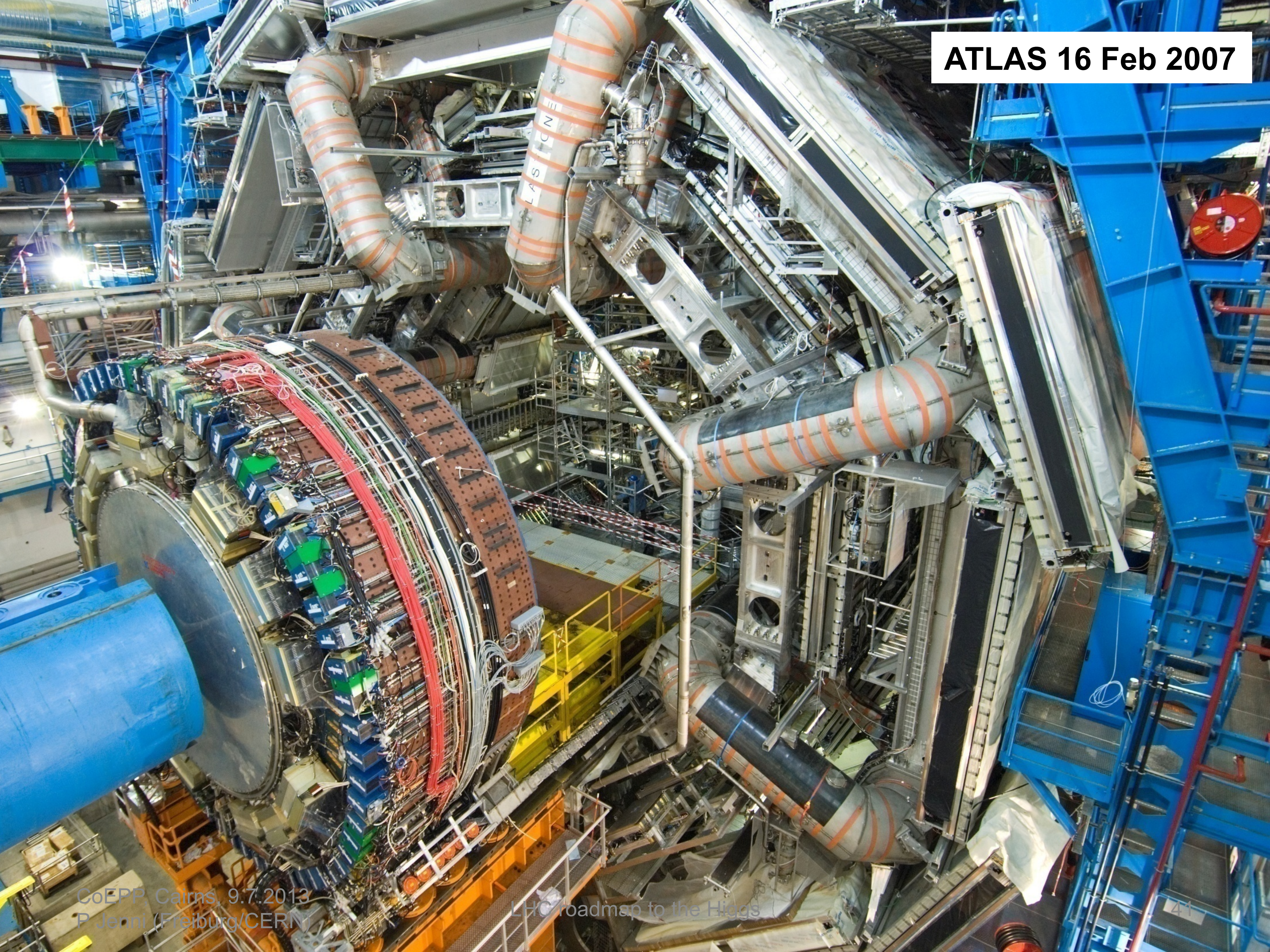
End-Cap Toroid parameters

5.0 m axial length
10.7 m outer diameter
2x8 coils
2x0.25 GJ stored energy
2x160 tons cold mass
2x240 tons weight
4 T on superconductor
2x13 km Al/NbTi/Cu conductor
20.5 kA nominal current
4.7 K working point





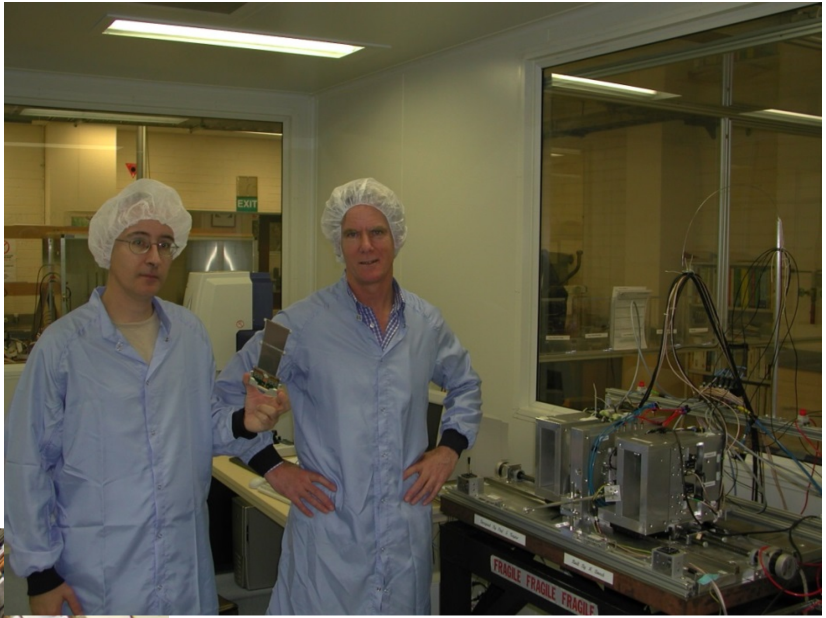
Hector Berlioz, “Les Troyens”, opera in five acts
Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009



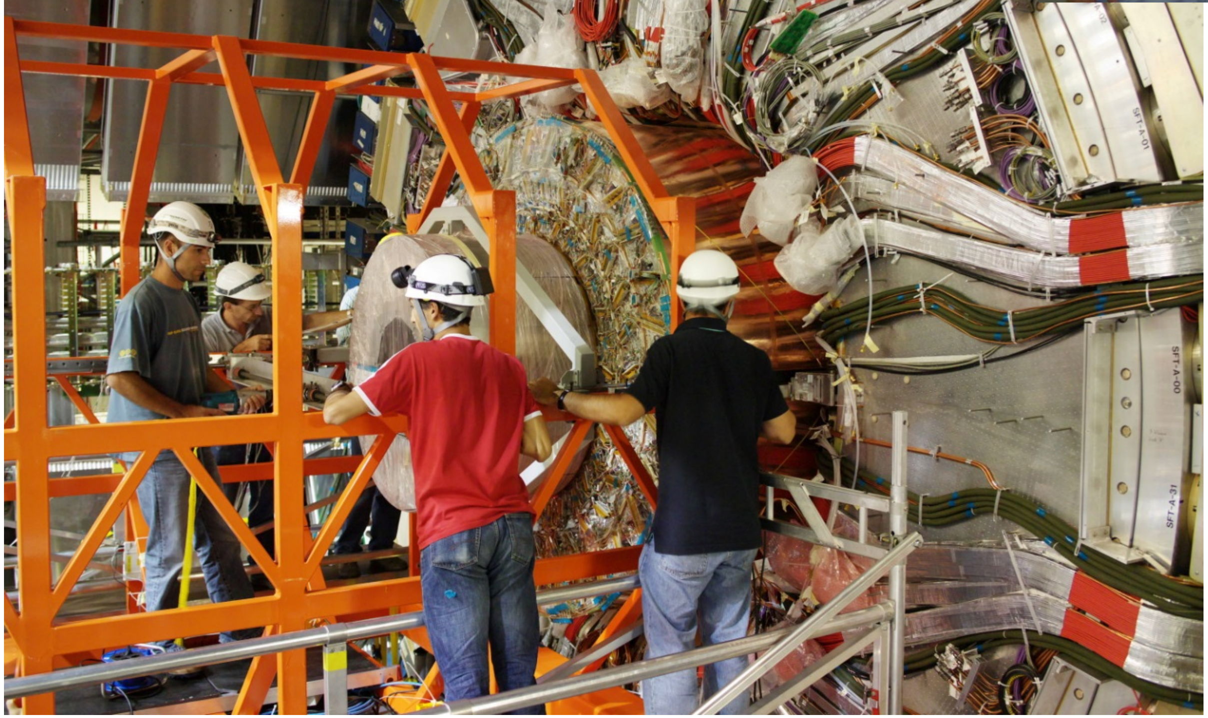
ATLAS 16 Feb 2007

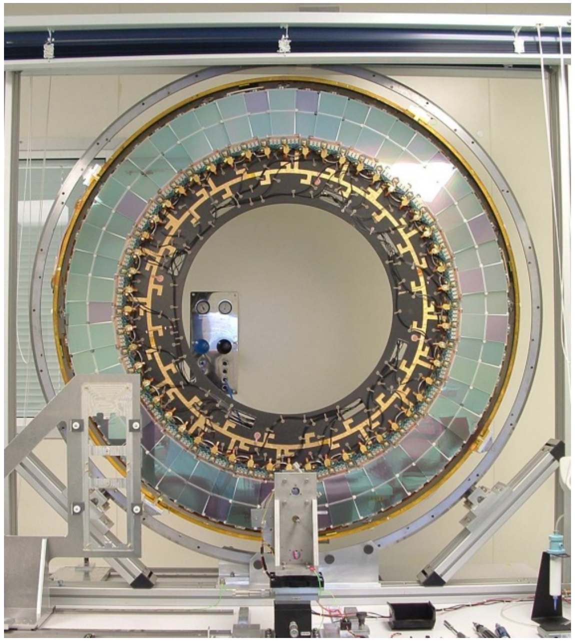
The Melbourne – Sydney team contributed to the high-tech silicon tracking detector

G Moorhead and G Taylor
in the Melbourne clean lab
in November 2004 during
one of my visits to Australia



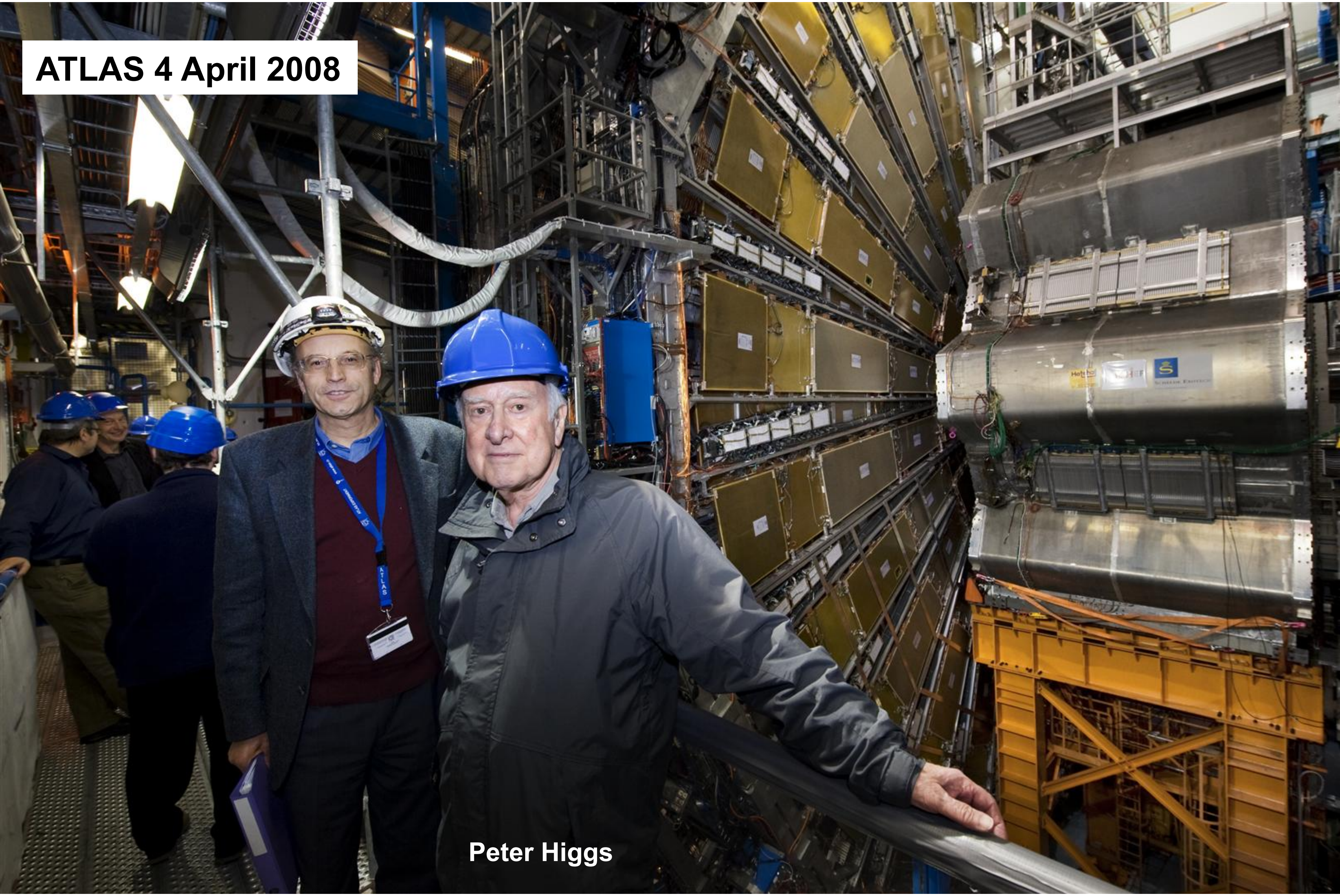
Insertion of the Silicon tracker
into the centre of the ATLAS
detector in August 2006





A forward Silicon Tracker disk

ATLAS 4 April 2008



Peter Higgs

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

Complementary Approaches in ATLAS and CMS

	ATLAS ≡ A Toroidal LHC ApparatuS	**CMS ≡ Compact Muon Solenoid**
MAGNET (S)	Air-core toroids + solenoid in inner cavity (4 magnets) Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 3.8x10^{-4}\ p_T \oplus 0.015$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5x10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 10$ % at 1 TeV standalone (~ 7% combined with tracker)	Fe → $\sigma/p_T \sim 15\text{-}30\%$ at 1 TeV standalone (5% with tracker)

Interconnections of two magnets

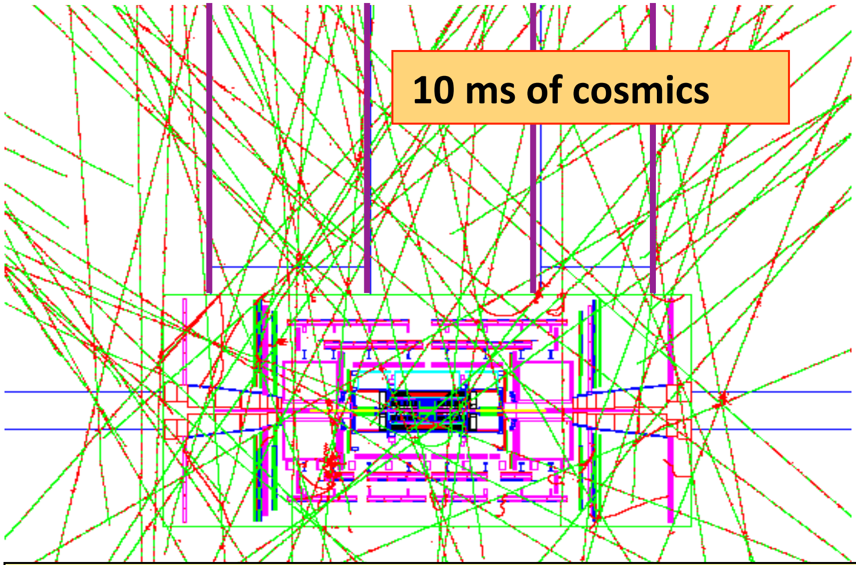
One (superconductor) joint failed on 19th September 2008, and it caused a catastrophic He-release that made serious collateral damage to sector 3-4 of the LHC machine

Commissioning with cosmics in the underground caverns

(the first real data in situ …)

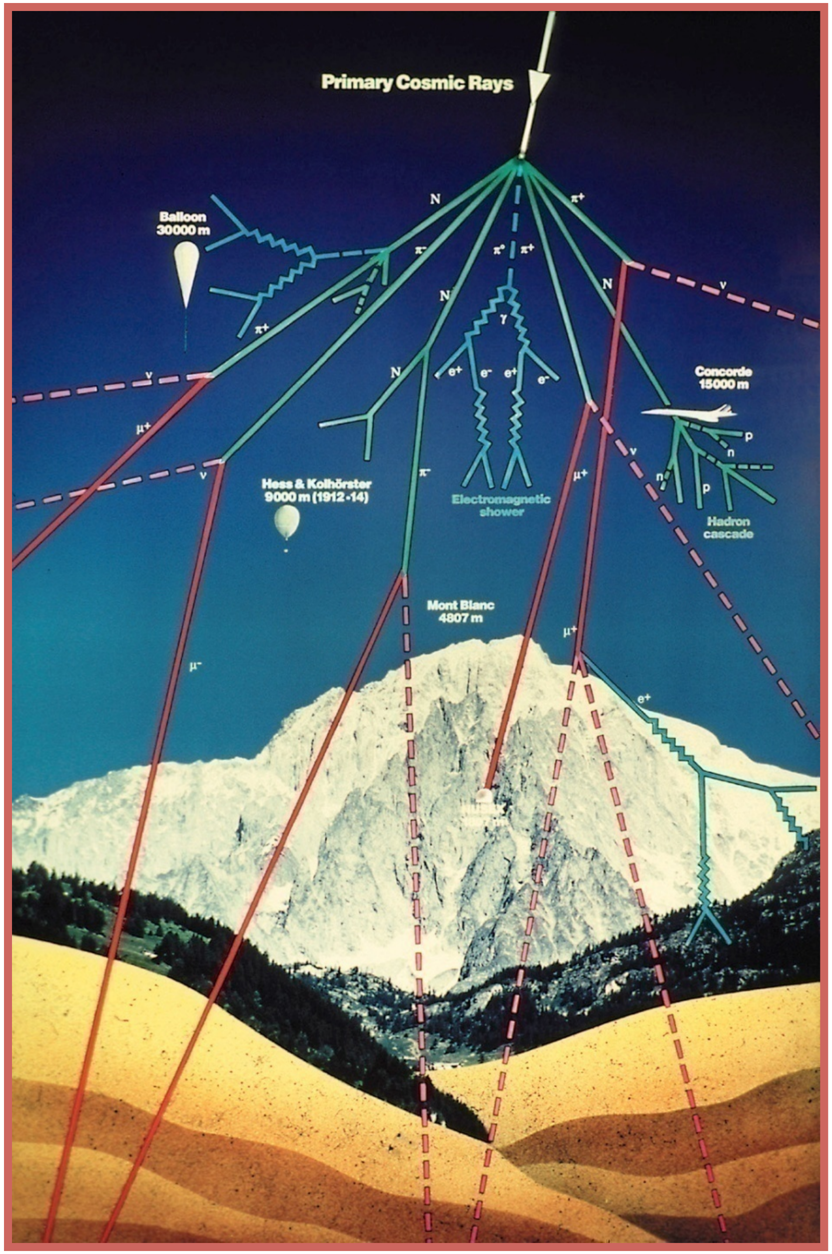
Started when the first components were installed.
Very useful to:

- Run an increasingly more complete detector with final trigger, data acquisition and monitoring systems. Data analyzed with final software
- Shake-down and debug the experiment in its final position → fix problems
- Perform first calibration and alignment studies
- Gain global operation experience in situ before collisions start

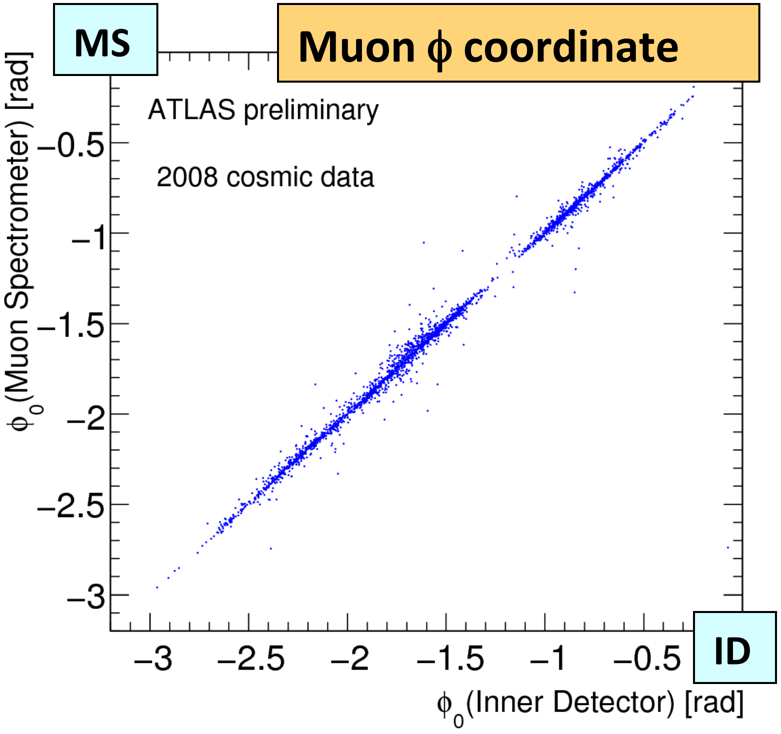


10 ms of cosmics

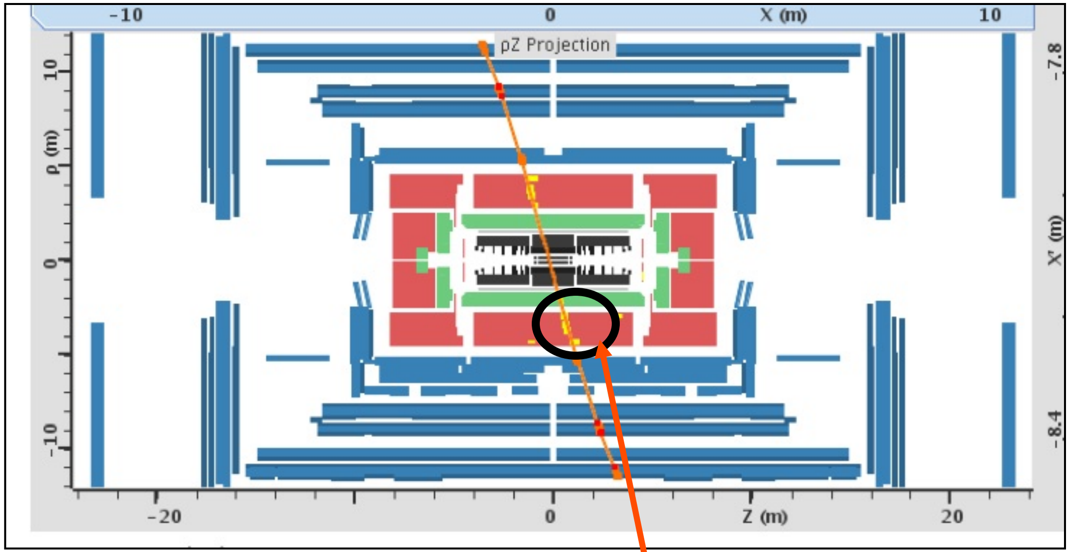
Rate of cosmics in ATLAS: 0.5-100 Hz
(depending on sub-detector size and location)



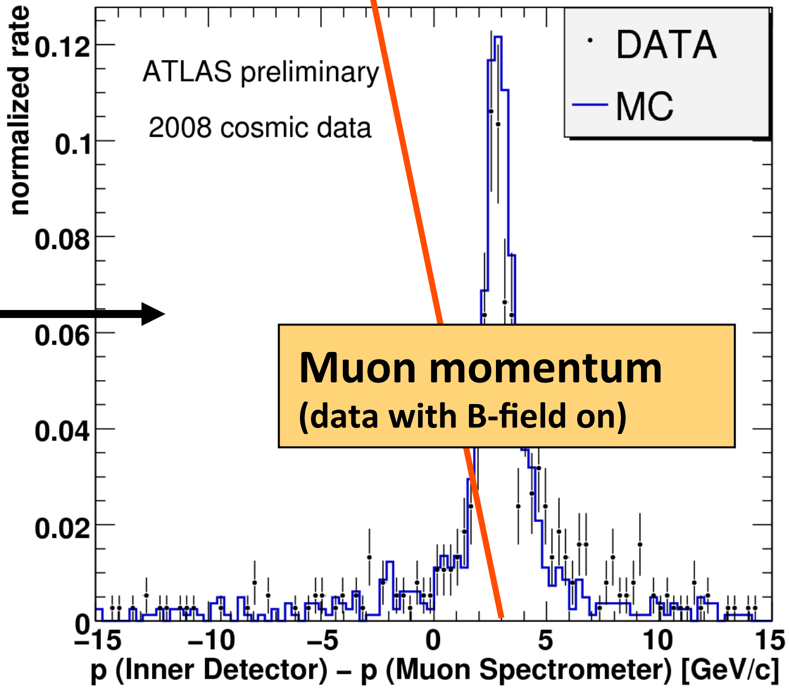
Correlation between measurements in the ATLAS Inner Detector and the Muon Spectrometer



Muon ϕ coordinate



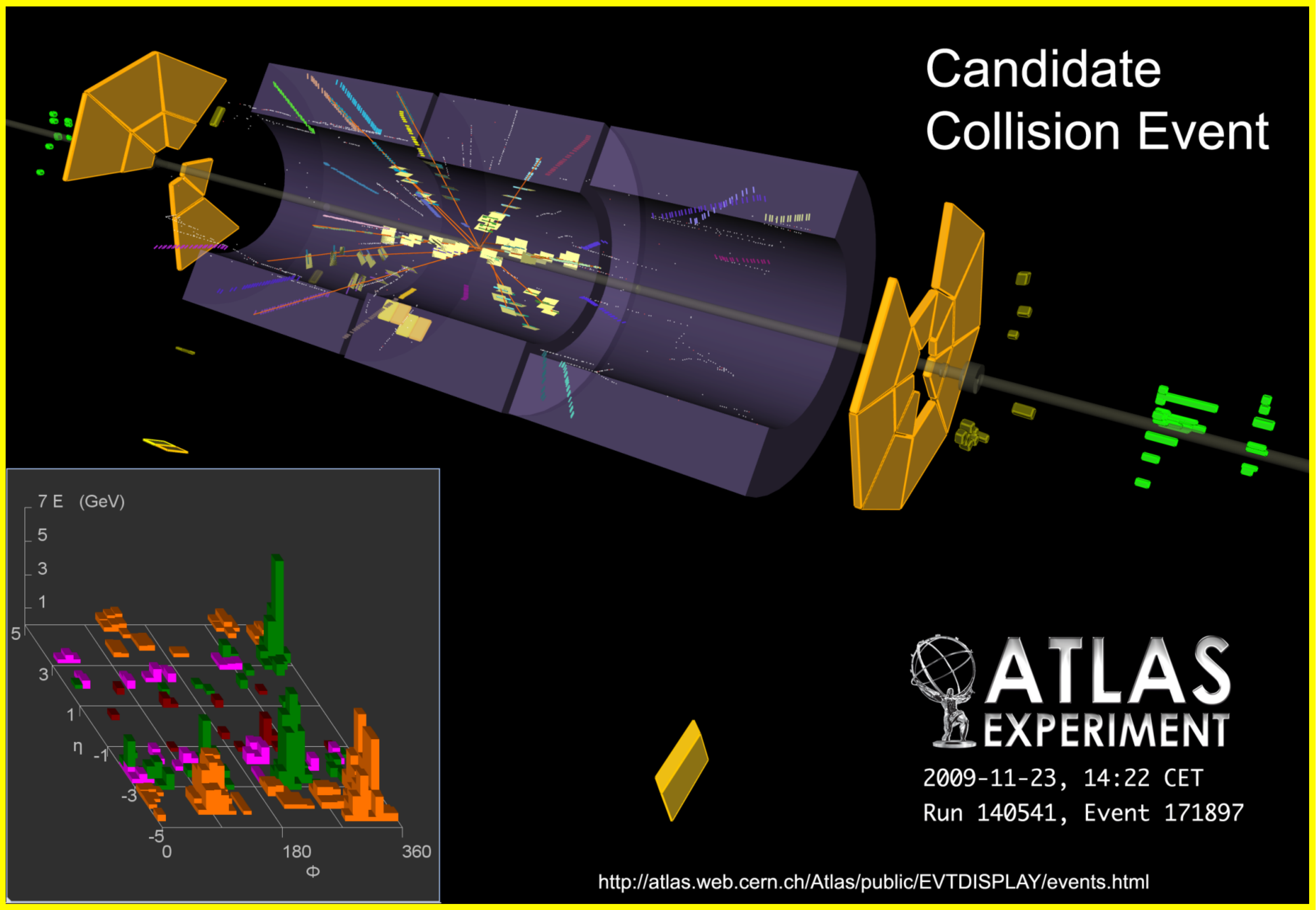
Difference between the muon momentum measured in the ID and in the MS for tracks in the bottom part of the detector (~ 3 GeV energy loss in the calorimeter)



Muon momentum
(data with B-field on)

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

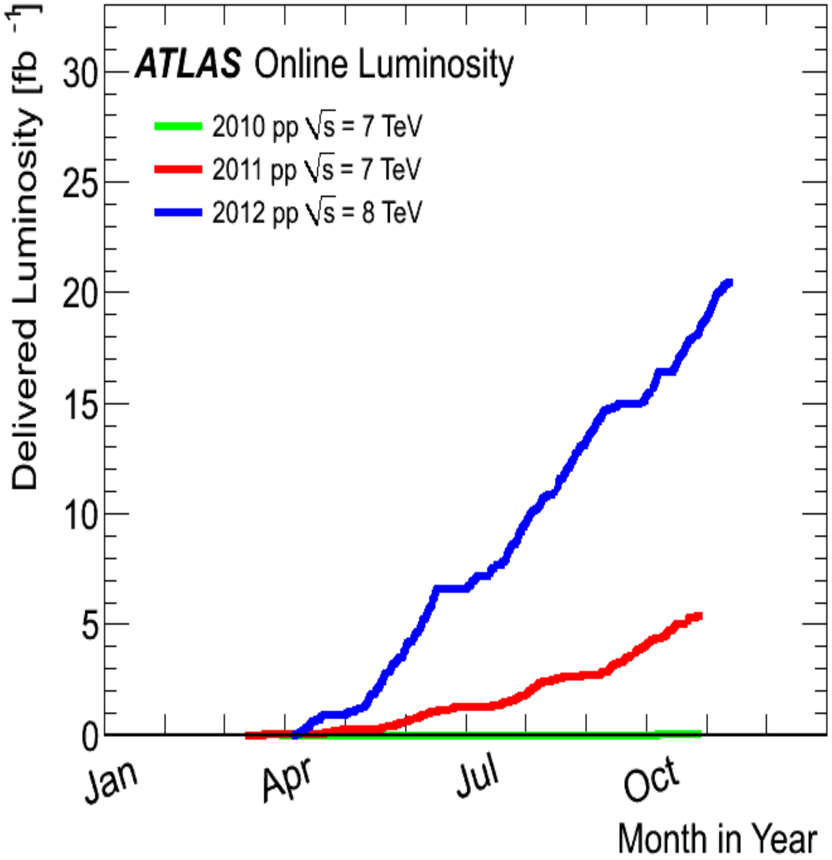
First collisions at the LHC end of November 2009 with beams at the injection energy of 450 GeV

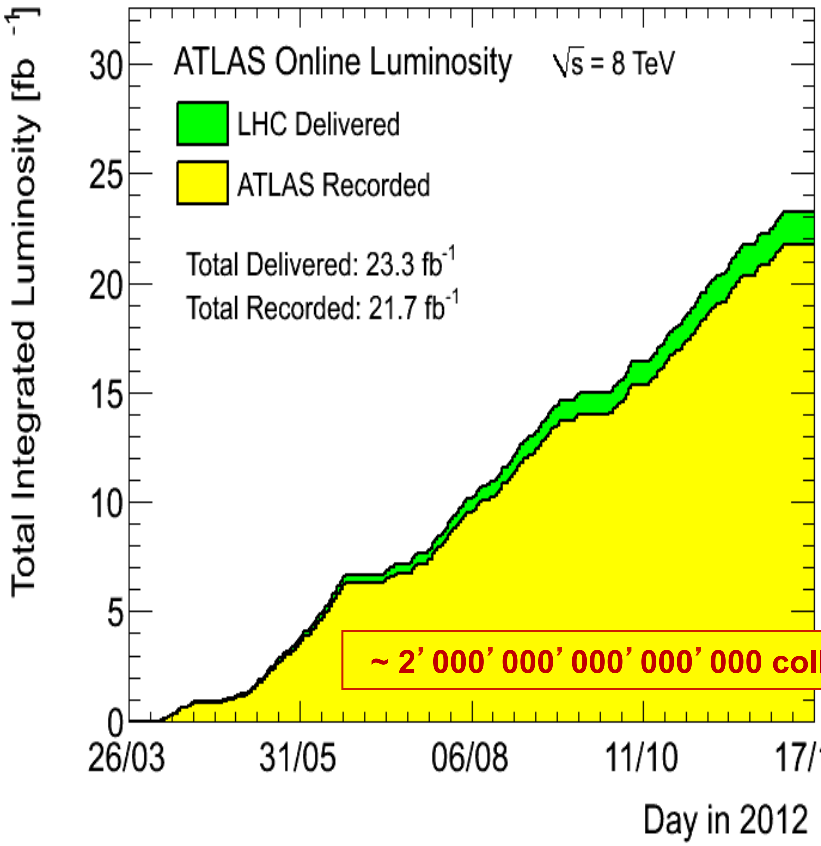


The LHC and experiments performances were simply fantastic over the last three years

Total integrated luminosity

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





~ 2’ 000’ 000’ 000’ 000’ 000 collisions

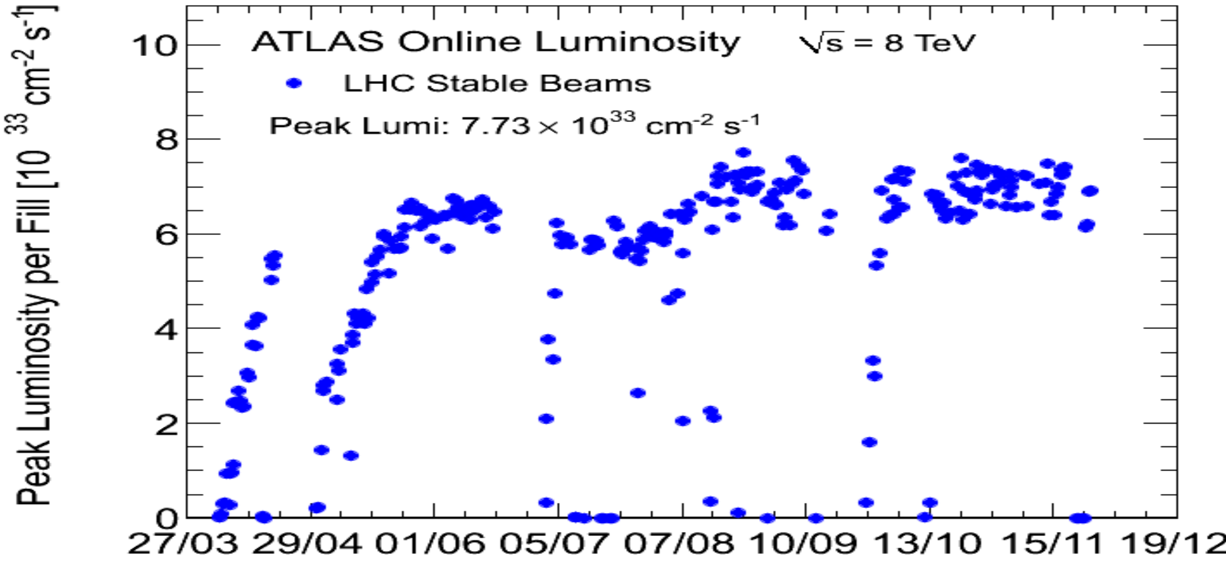
The experiment records typically 94% of the stably delivered luminosity, and uses up to 90% of the LHC luminosity in the final analyses!

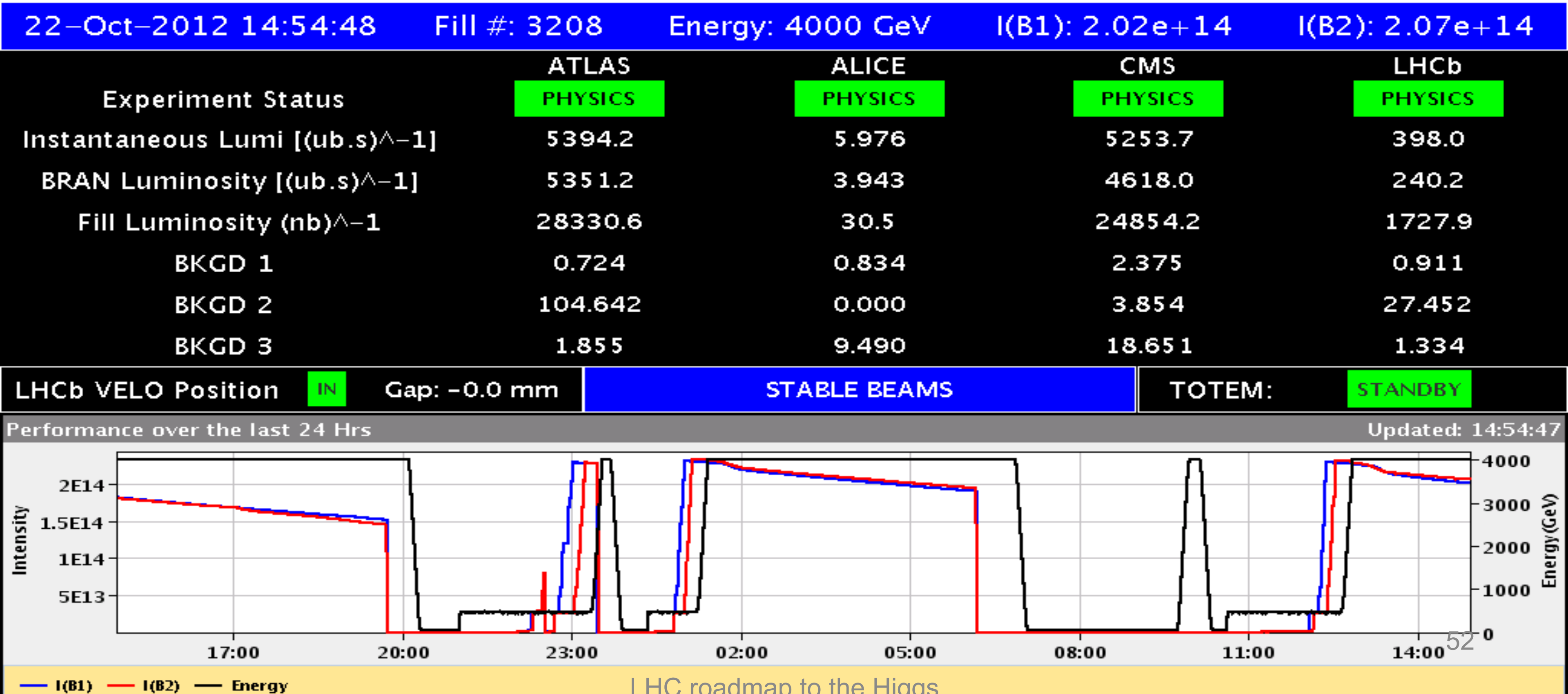
2012 LHC Operation:

1380 bunches per beam

50 ns bunch spacing

1.5 x 10^{11} protons / bunch





22-Oct-2012 14:54:48 Fill #: 3208 Energy: 4000 GeV I(B1): 2.02e+14 I(B2): 2.07e+14

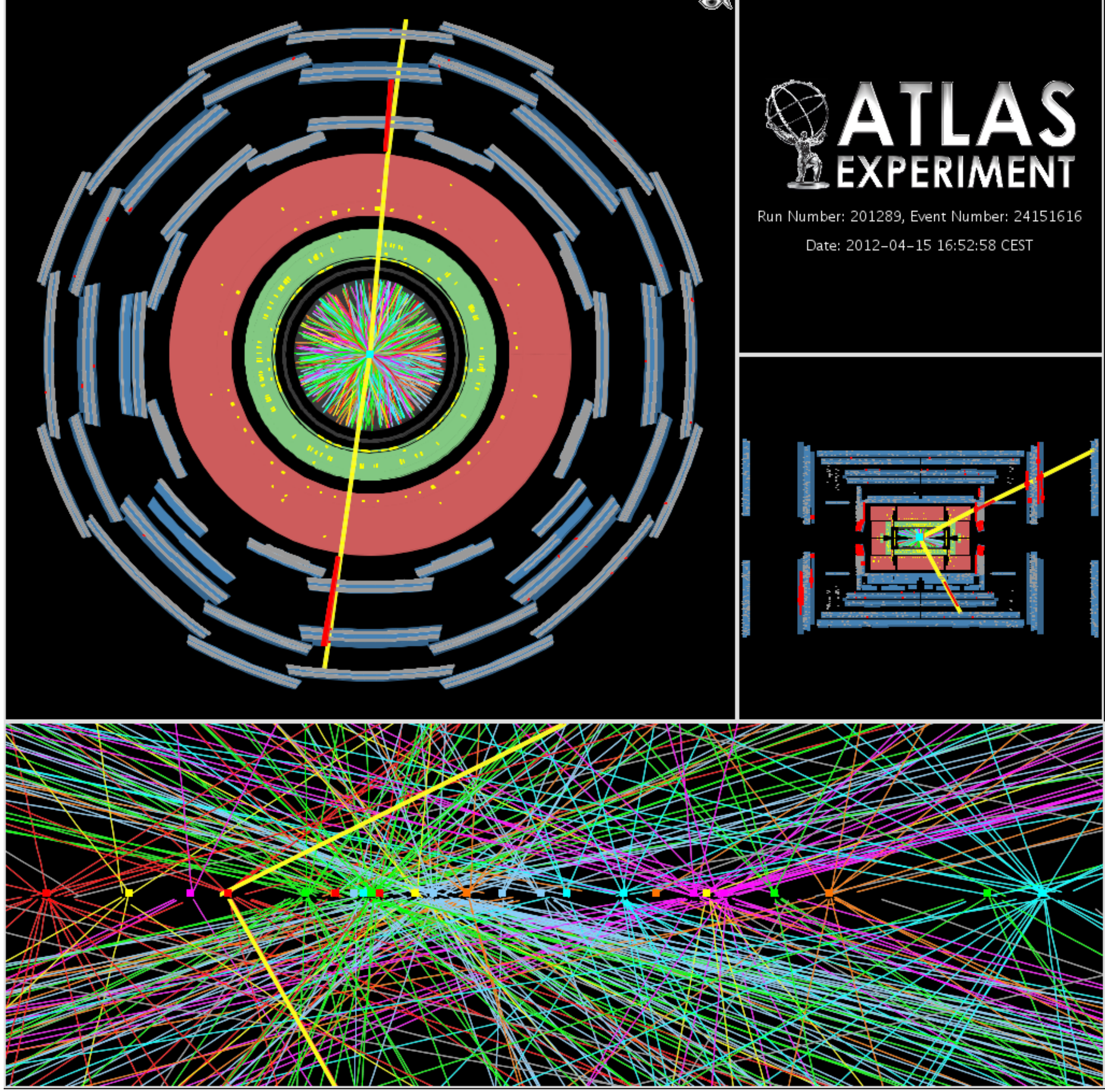
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi [(ub.s)^-1]	5394.2	5.976	5253.7	398.0
BRAN Luminosity [(ub.s)^-1]	5351.2	3.943	4618.0	240.2
Fill Luminosity (nb)^-1	28330.6	30.5	24854.2	1727.9
BKGD 1	0.724	0.834	2.375	0.911
BKGD 2	104.642	0.000	3.854	27.452
BKGD 3	1.855	9.490	18.651	1.334

LHCb VELO Position IN Gap: -0.0 mm STABLE BEAMS TOTEM: STANDBY

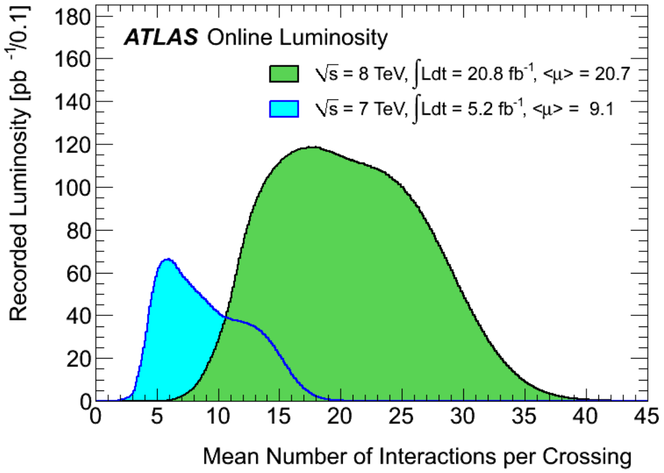
Performance over the last 24 Hrs Updated: 14:54:47

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

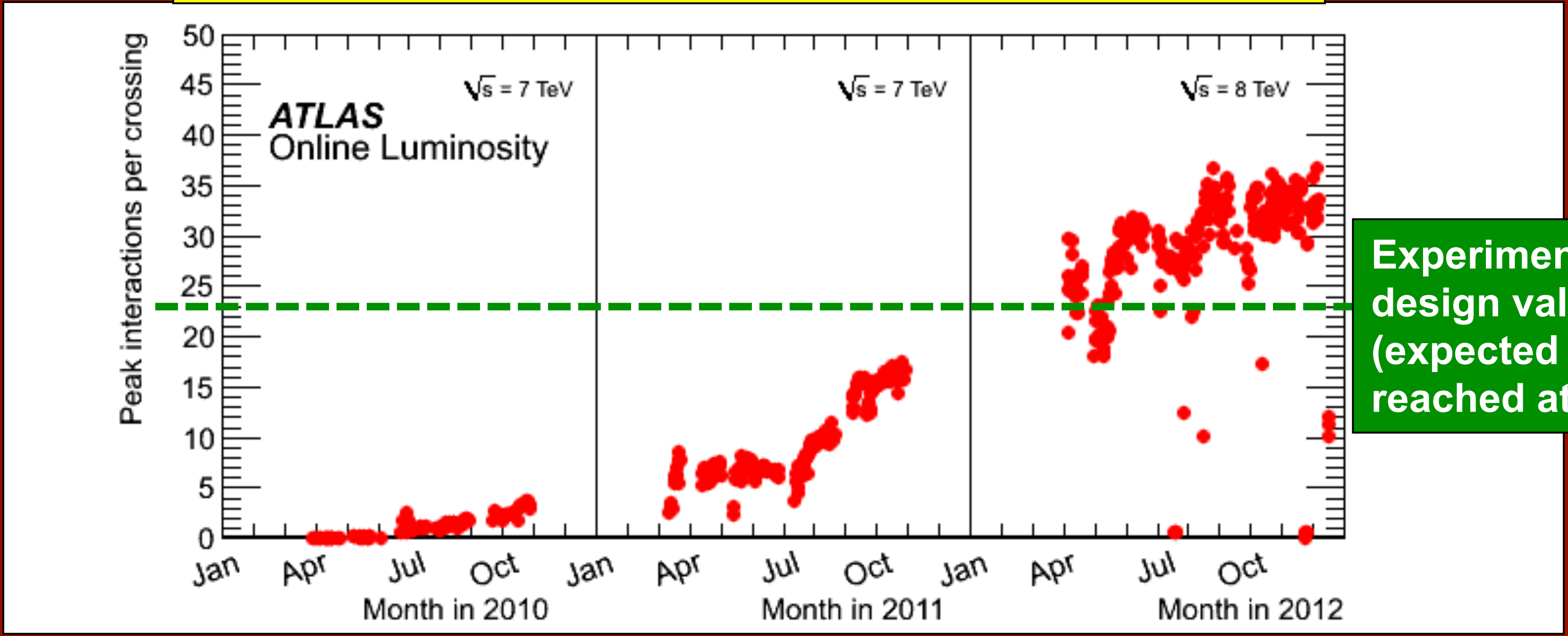
- **Trigger**
- **Pile-up**
- **Maintain accuracy of the the measurements in this environment**



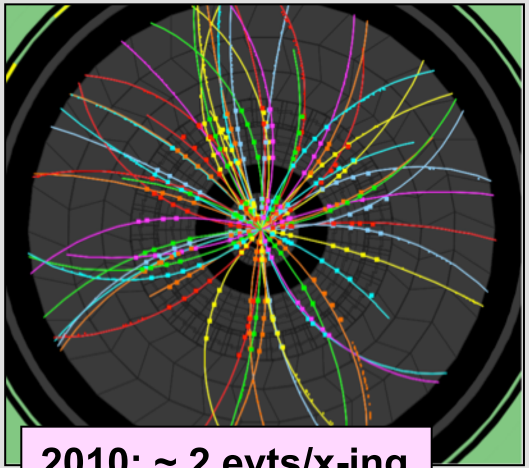
Inner Detector for a Z → μμ event with 25 primary vertices



The prize to pay for the high luminosity: pile-up
(number of simultaneous pp interactions per bunch crossing)



Experiment's design value (expected to be reached at $L=10^{34}$!)

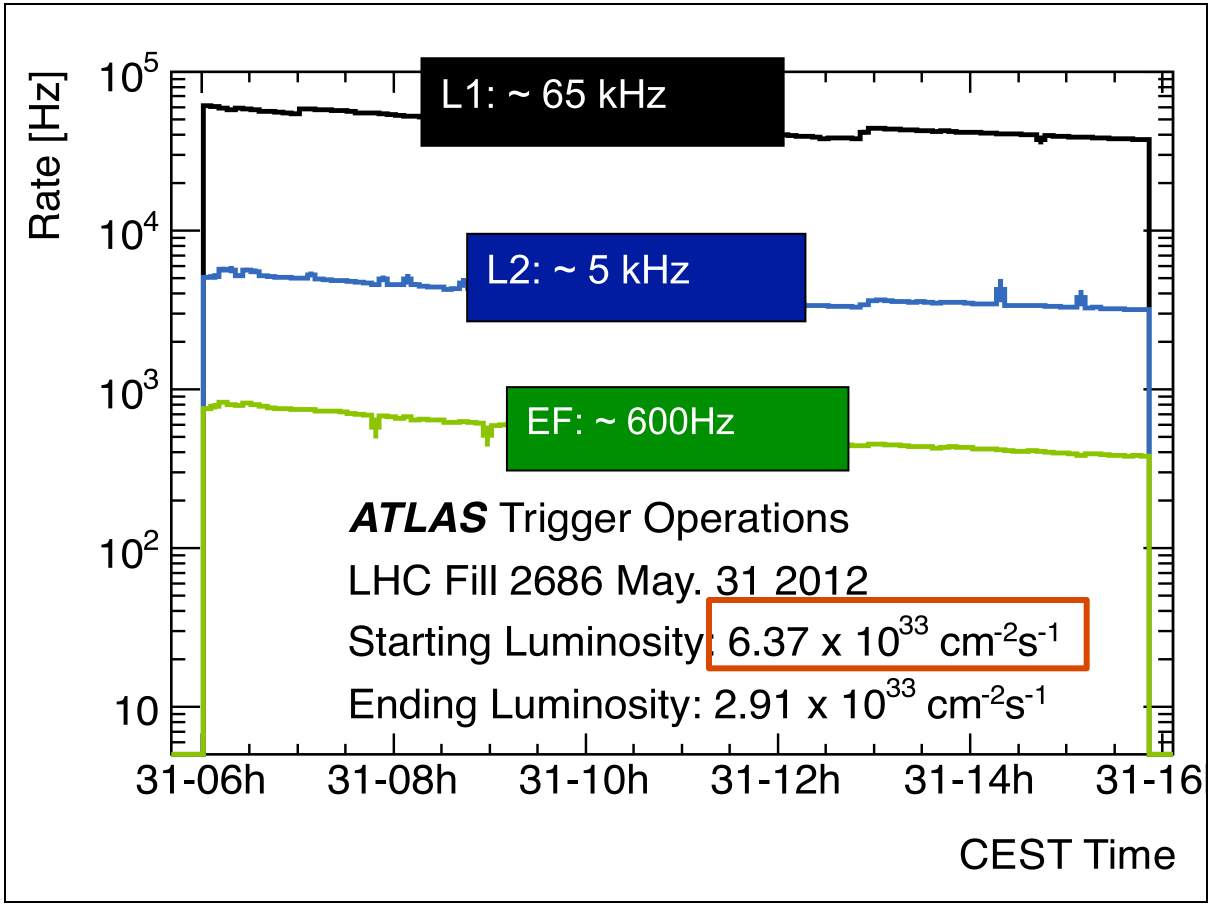


2010: ~ 2 evts/x-ing

2011: ~ 10 evts/x-ing

2012: ~ 20 evts/x-ing

Example for the typical trigger rates



Three levels of event selections:

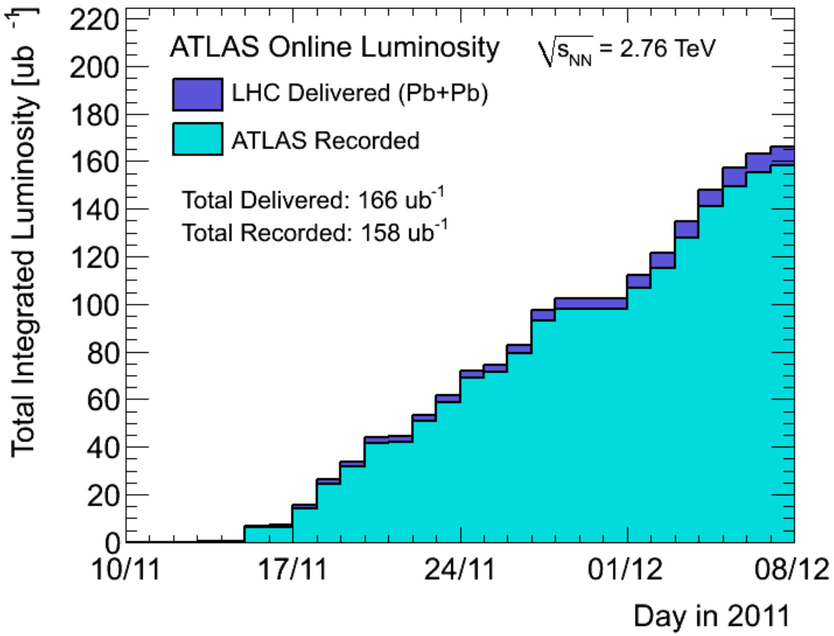
Level-1 underground with purpose-made electronics and processors

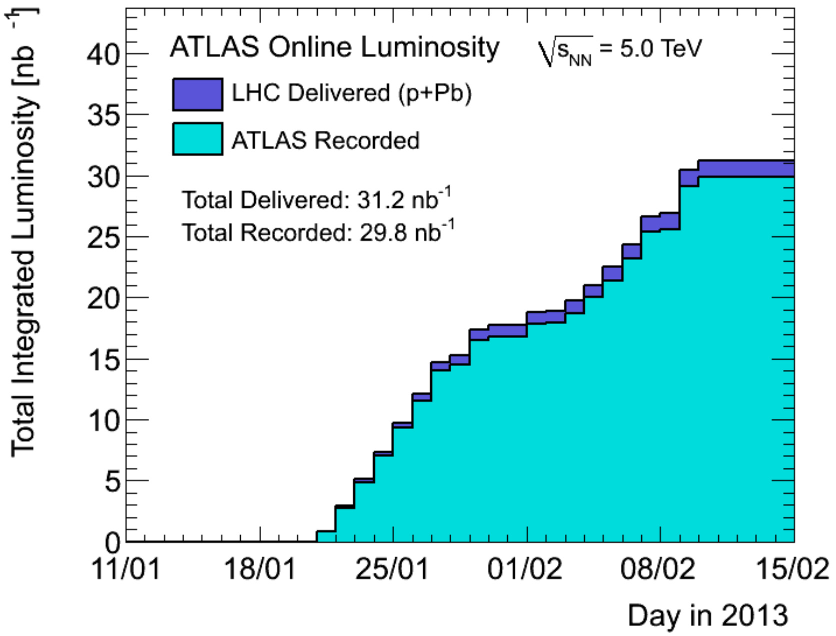
Level-2 and Event Filter in a large computer farm located at the surface of Point-1

(Noted in the plot are the output rates)

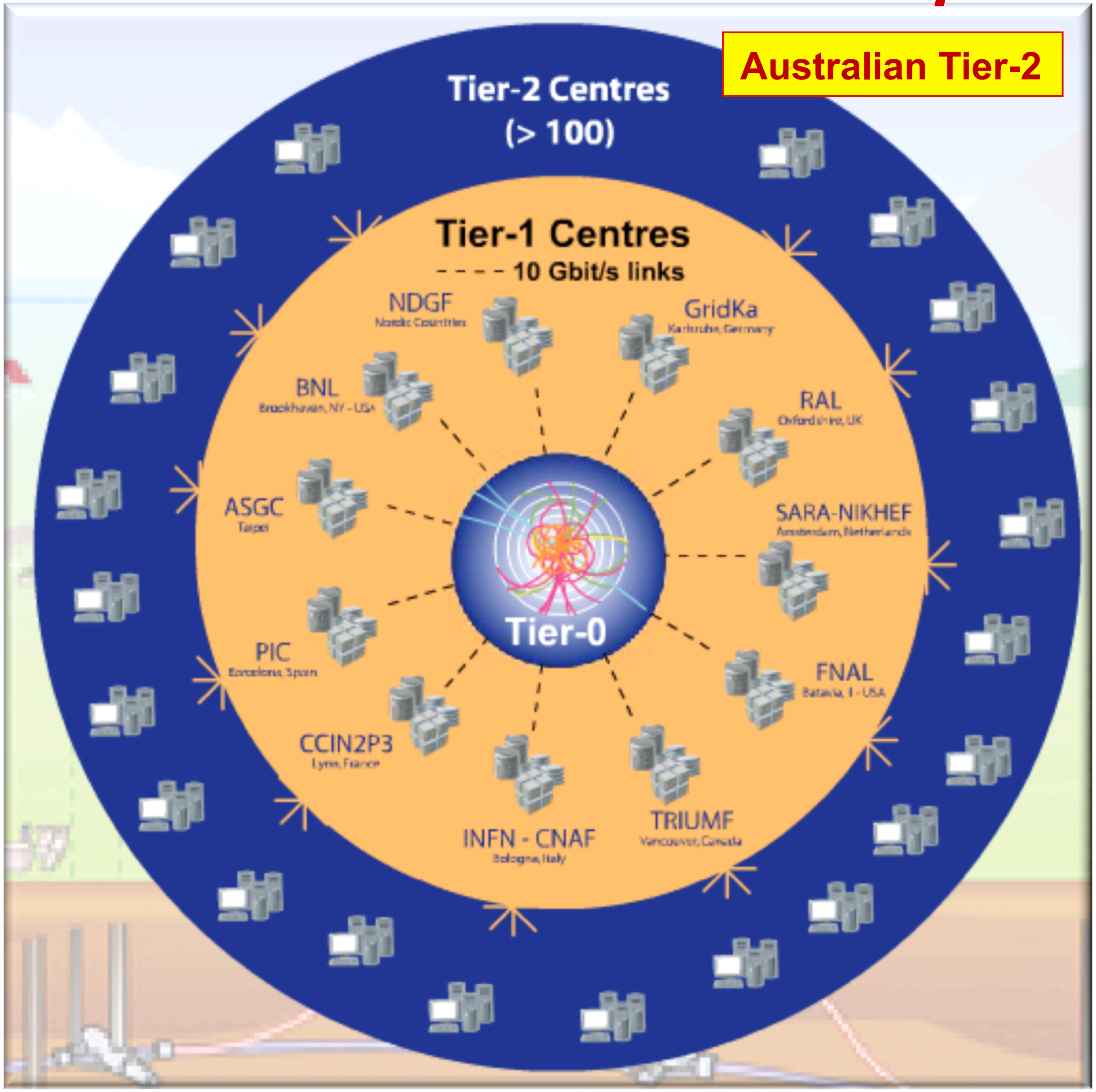
- ☐ **Typical recorded rates for main streams e/γ, Jets/τ/E_T^{miss} , Muons: ~ 100 Hz each**
- ☐ **Delayed stream (future Tier0 reconstruction): B-physics (~65 Hz) and Hadronic (~80 Hz)**
- ☐ **Note: 564 items in the trigger menu**

LHC (and ALICE, ATLAS and CMS) has also been operated very successfully as Pb-Pb and as p-Pb colliders





The Worldwide LHC Computing Grid (wLCG)



Australian Tier-2

WLCG
Worldwide LHC Computing Grid

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

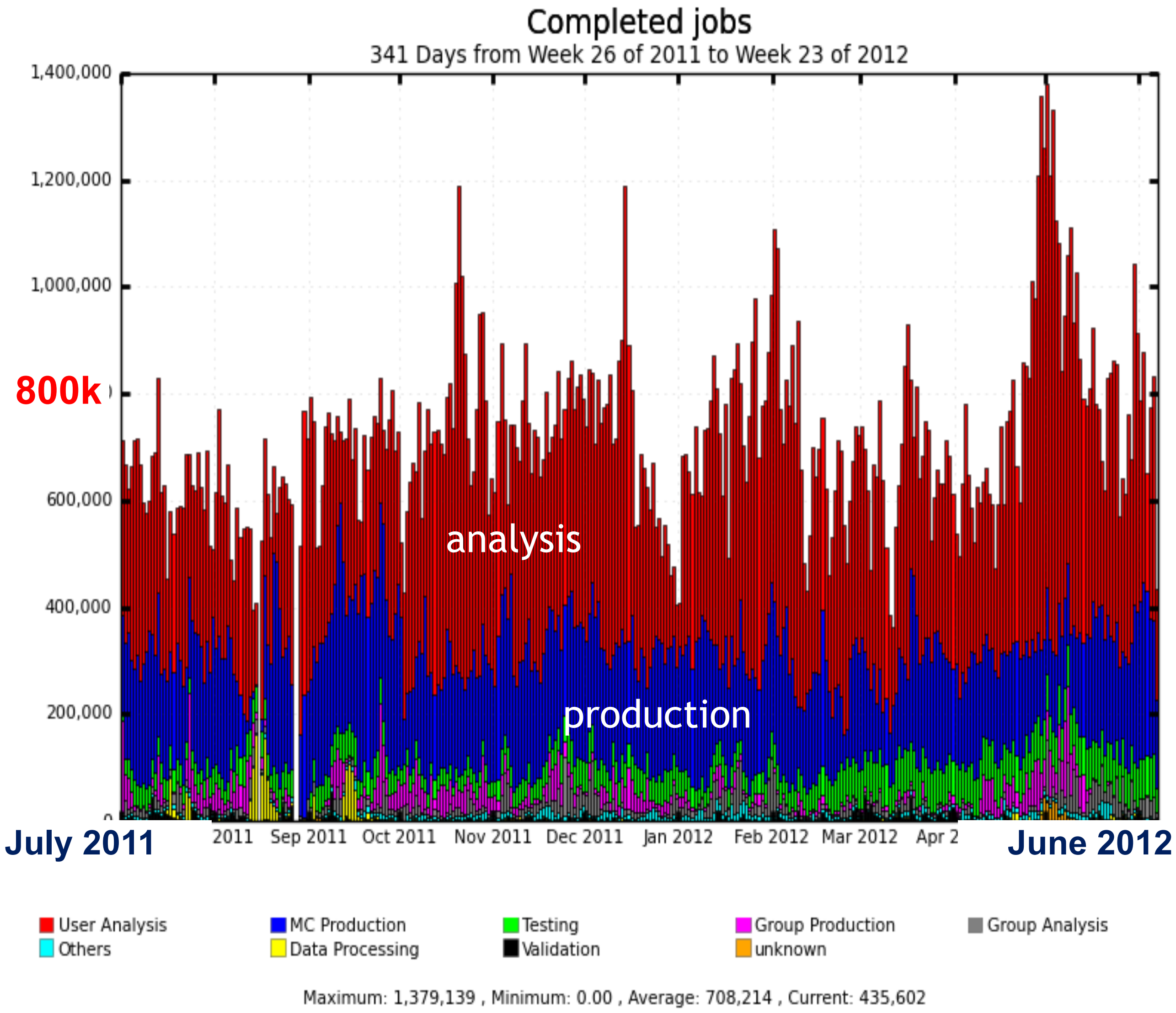
Computing Grid Delivers Physics

Data preparation:

First-pass reconstruction at Tier-0 within ~2 days

Calibration good for physics analysis on Grid within ~1 week

ATLAS jobs per day across all Tier-1 & Tier-2s



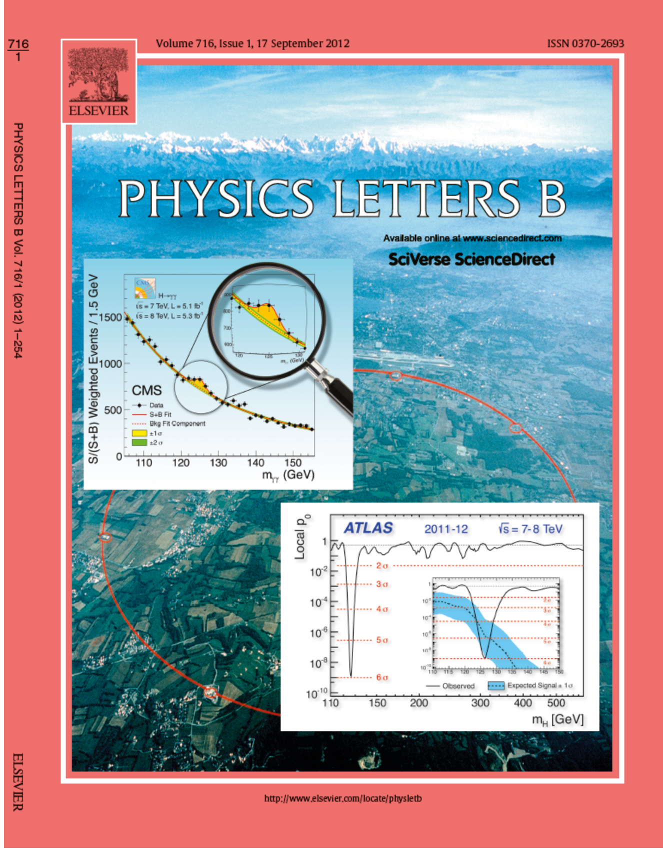
Physics Highlights

ATLAS and CMS have already published together more than 500 papers in scientific journals (and many more as public conference notes…)

The other experiments, ALICE, LHCb, LHCf, and TOTEM total another 200 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...



716 1

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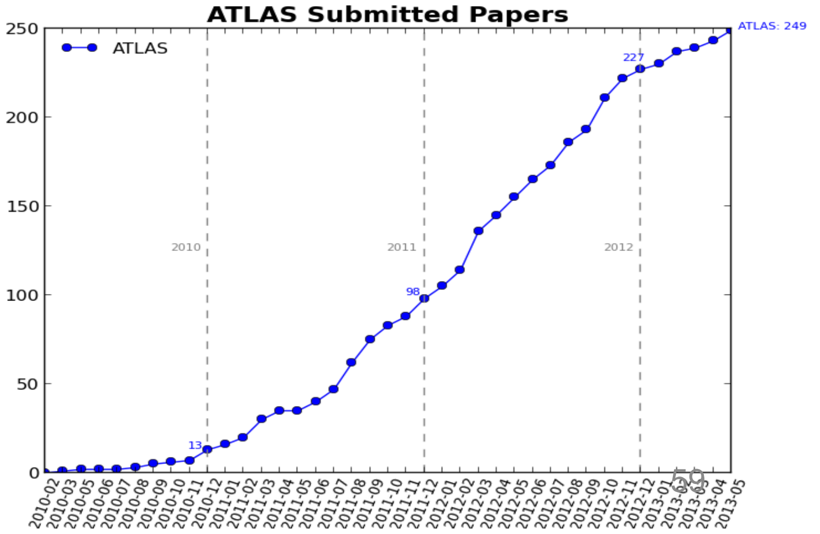
http://www.elsevier.com/locate/physletb

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

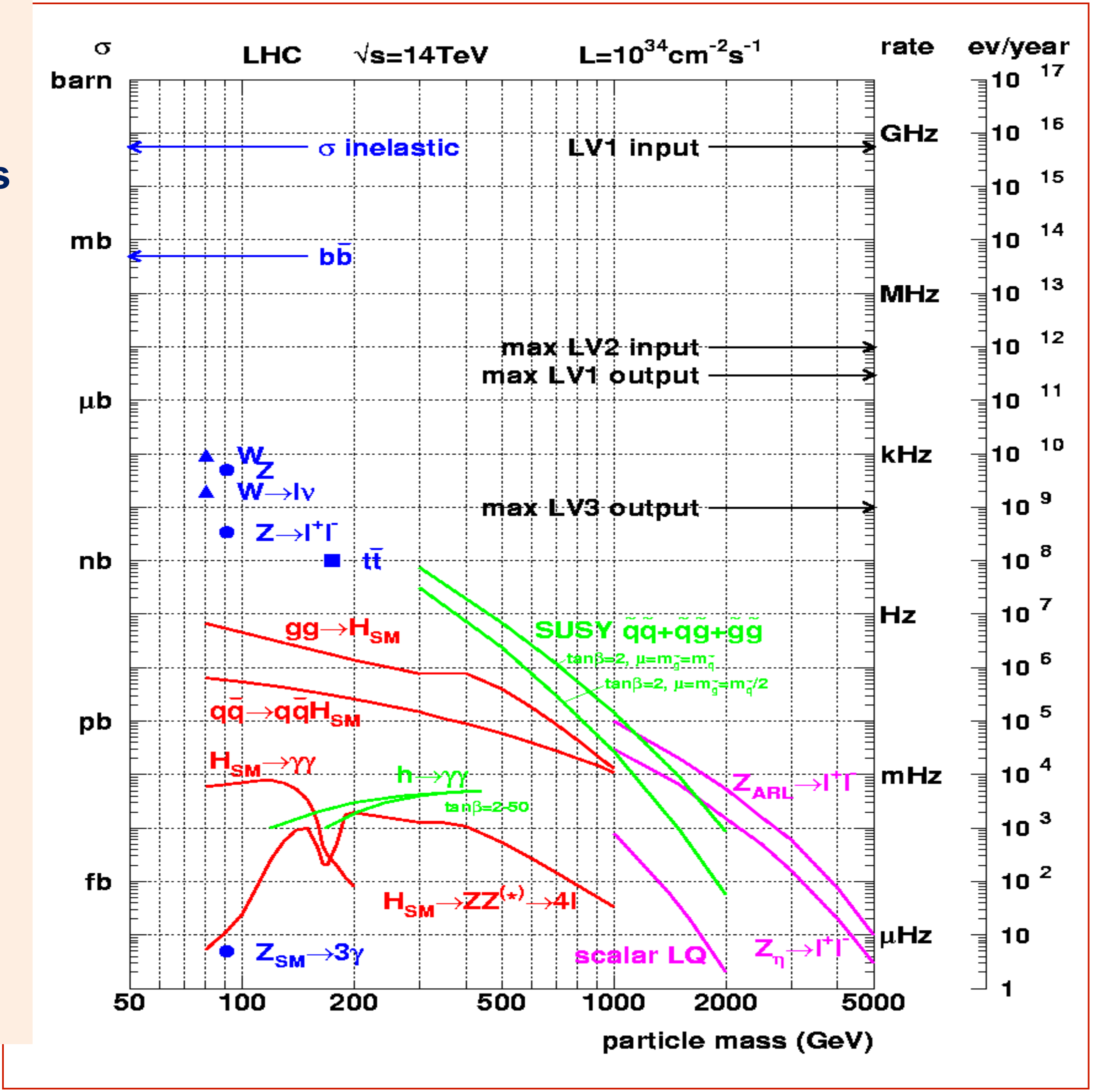
Heavy flavour physics

Standard Model physics including QCD jets

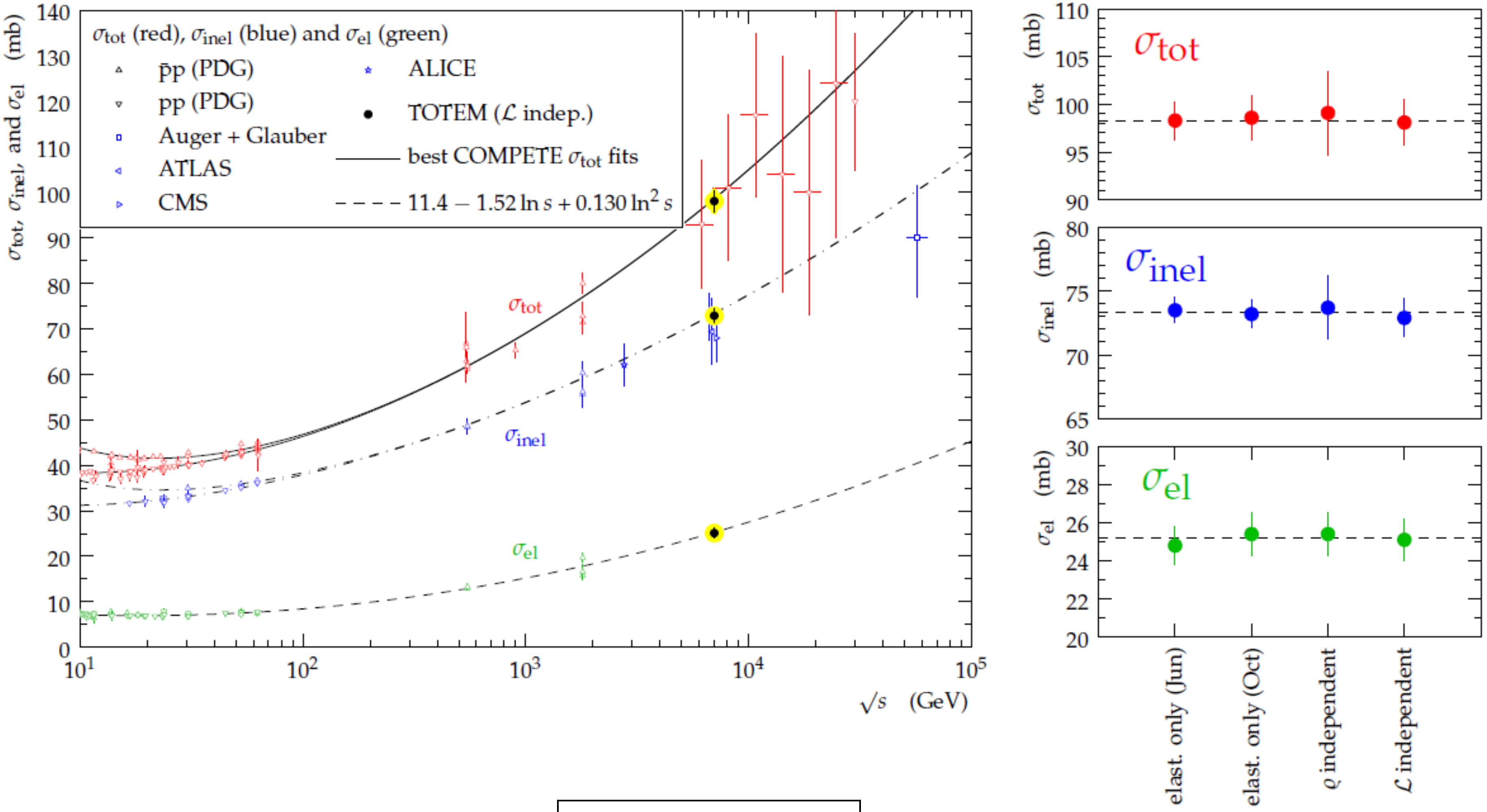
Higgs searches

Searches for SUSY

Searches for ‘exotic’ new physics

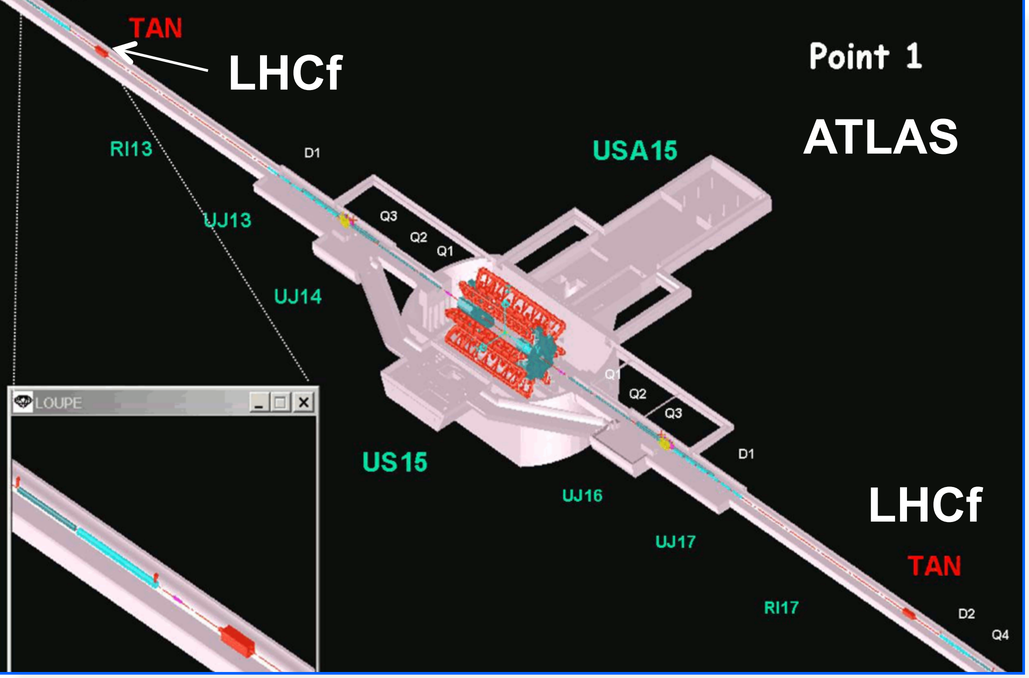


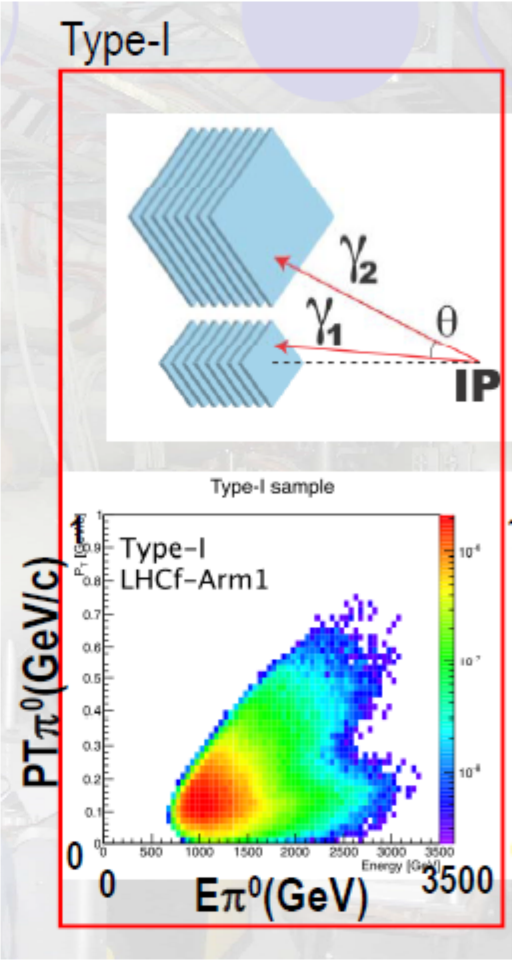
Total cross-section measurement by TOTEM

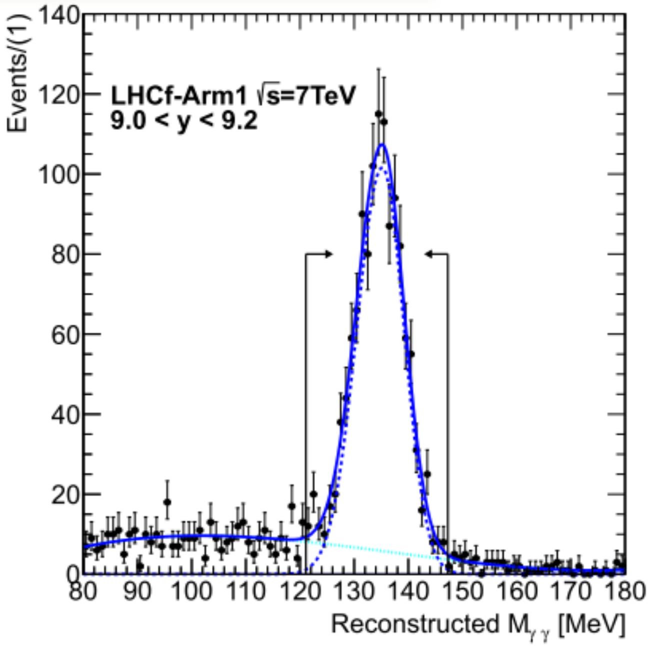


Presented at HCP2012

LHCf 7 TeV π^0 signal

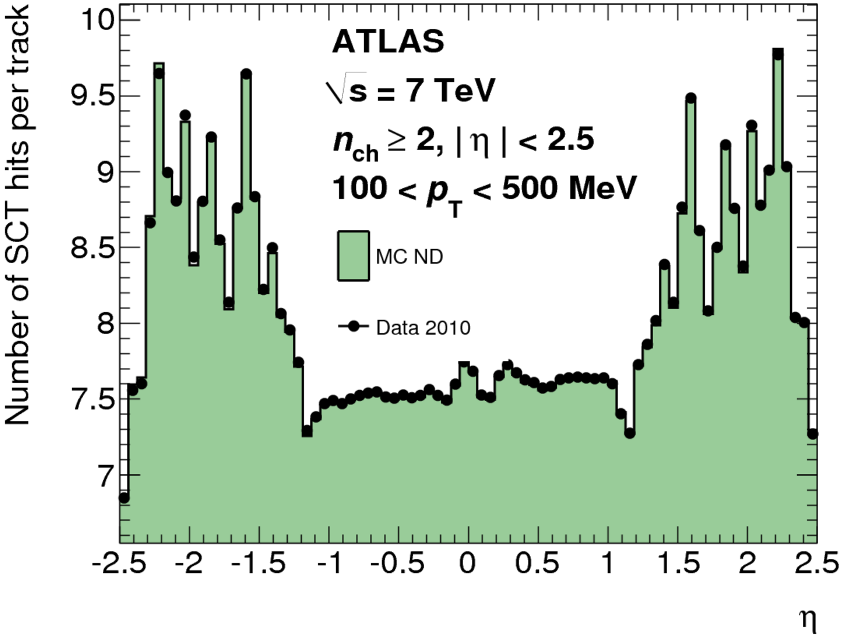






Feedback to modeling of Ultra High Energy Cosmic Rays (UHERCs)

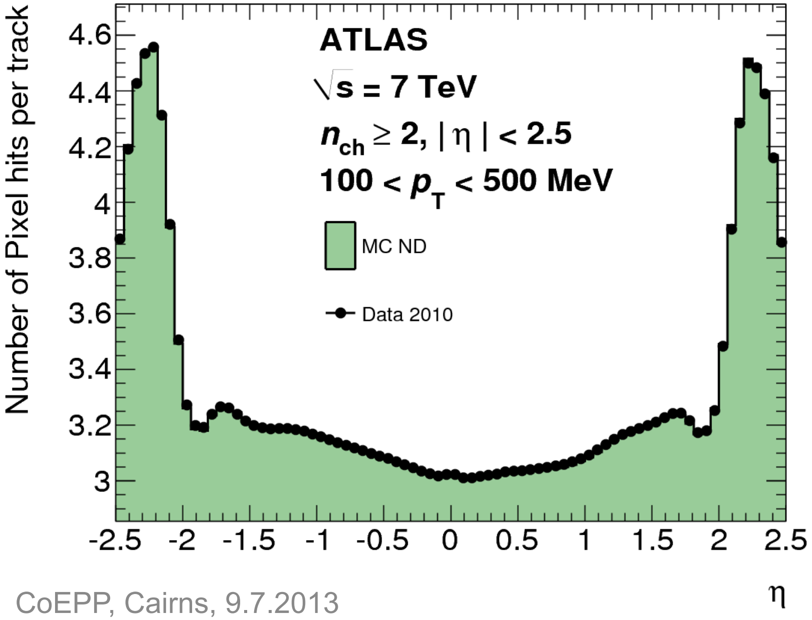
Presented at HCP2012

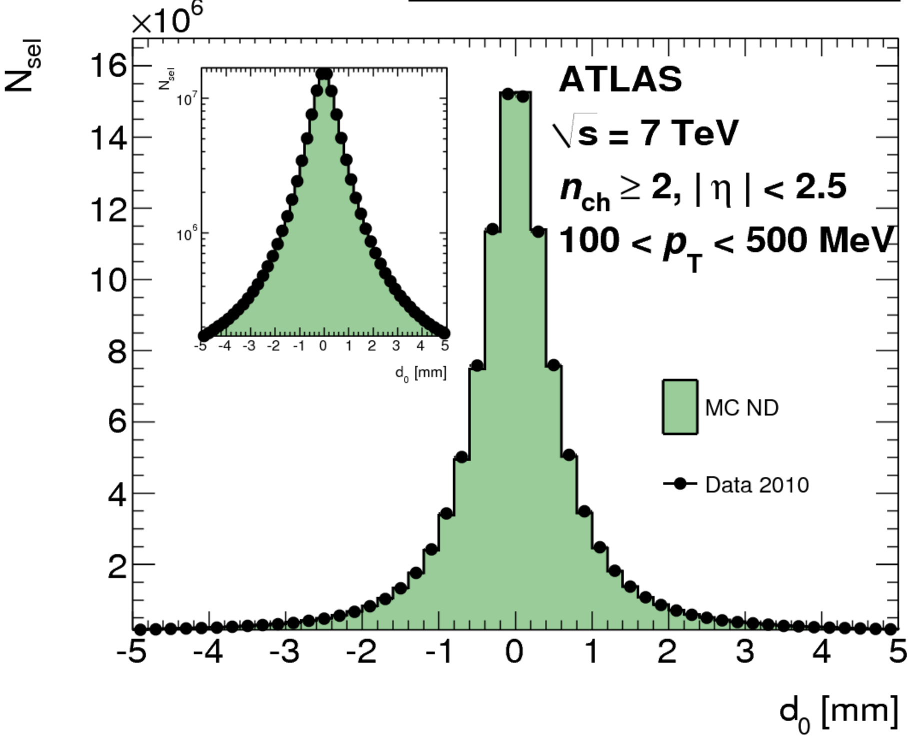


The tracking detector simulations are in a mature state, charged track measurements are well understood

Example shows the ATLAS description of minimum bias tracks (silicon and pixel hits, transverse impact parameter)

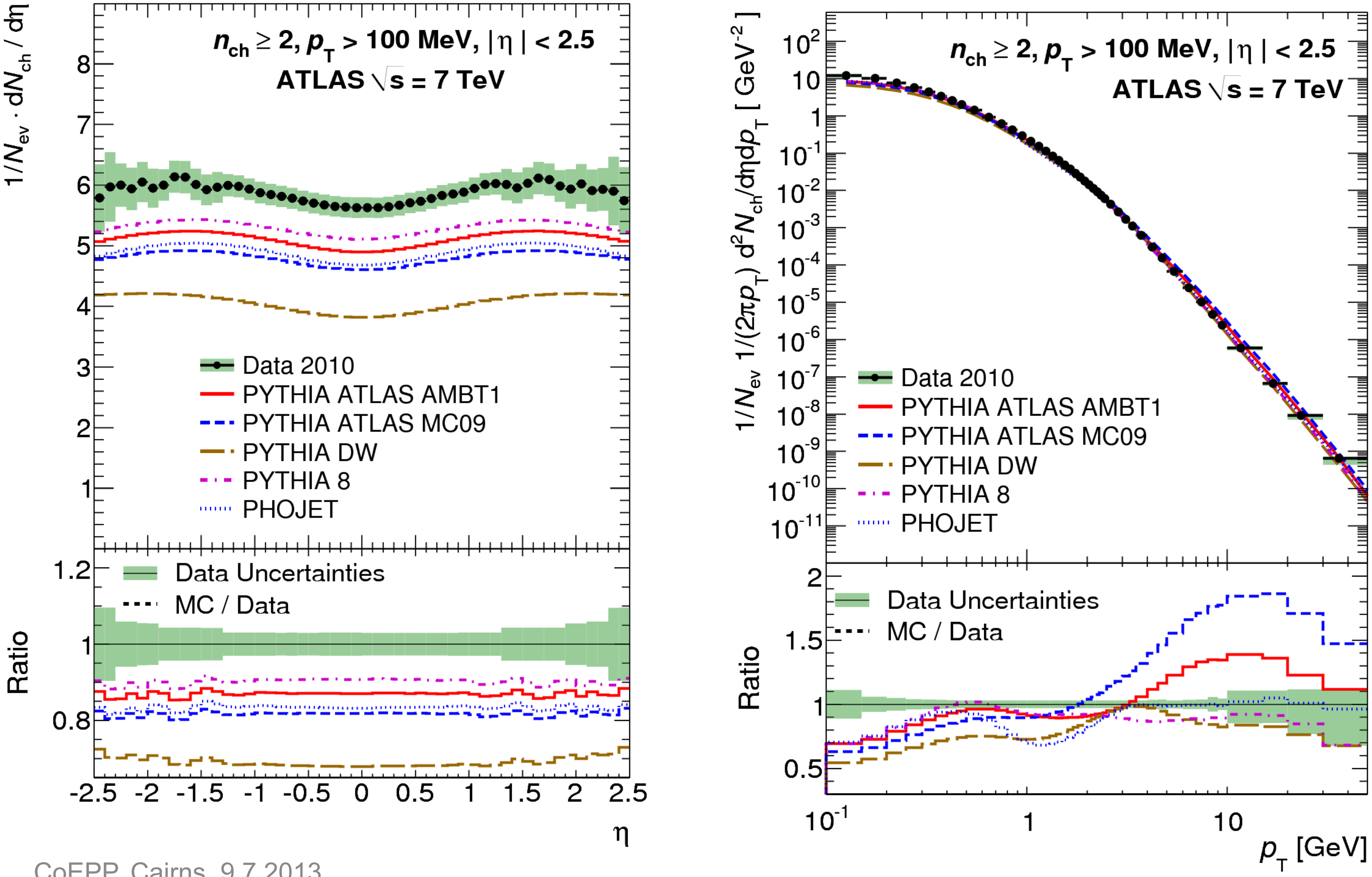
New J. Phys. 13 (2010) 053033



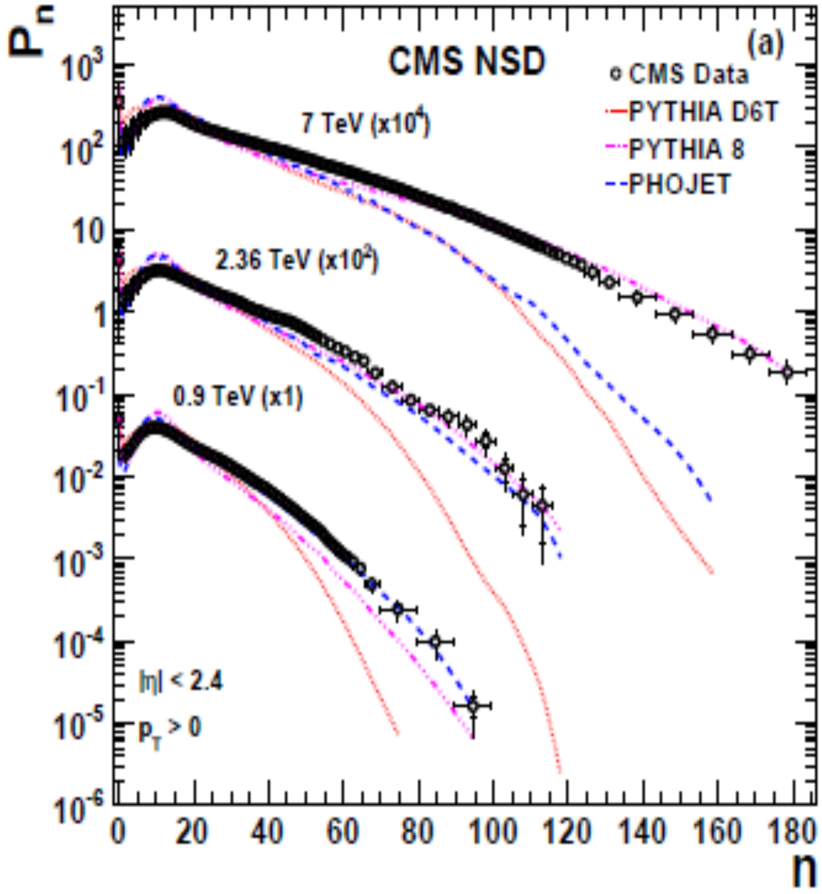


Charged-particle multiplicities as a function of pseudorapidity η and transverse momentum p_T for minimum bias events selected as specified, and compared to various Monte Carlo models

New J. Phys. 13 (2010) 053033

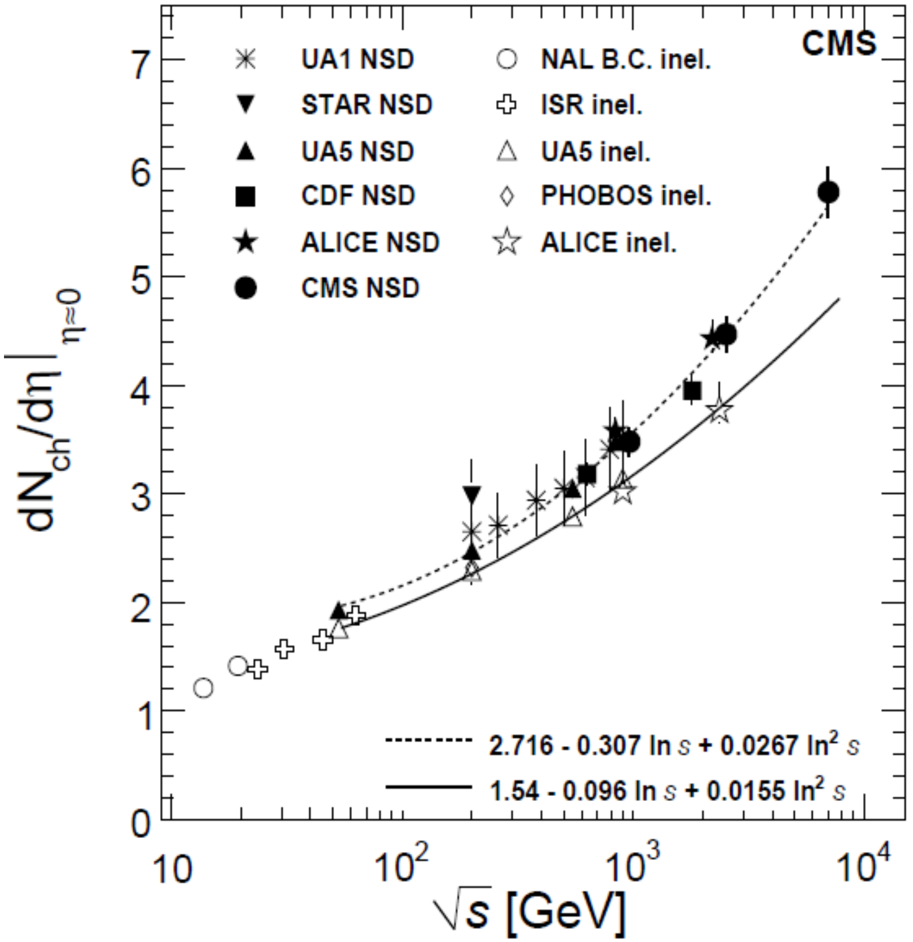


Charged hadron multiplicities at the three different √s



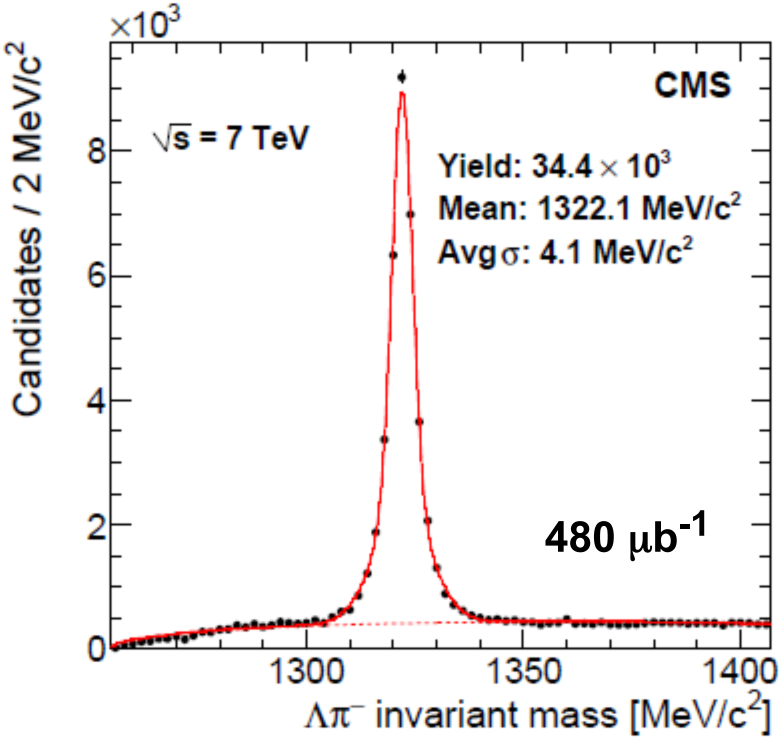
JHEP 01 (2011) 079

Average charged particle density for the central η region (pp and p$\bar{p}$)



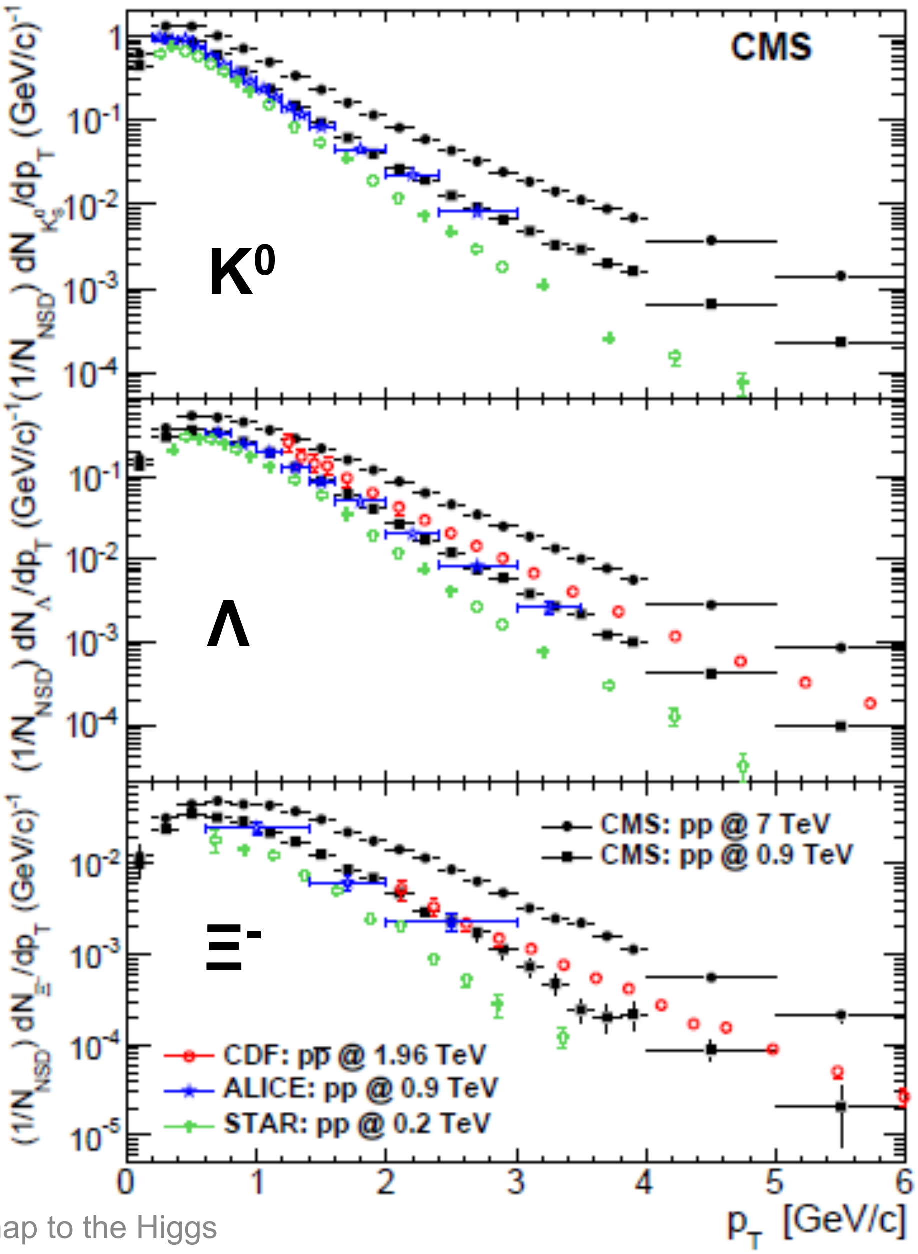
Phys. Rev. Lett. 105 (2010) 022002

Strange particle production spectra



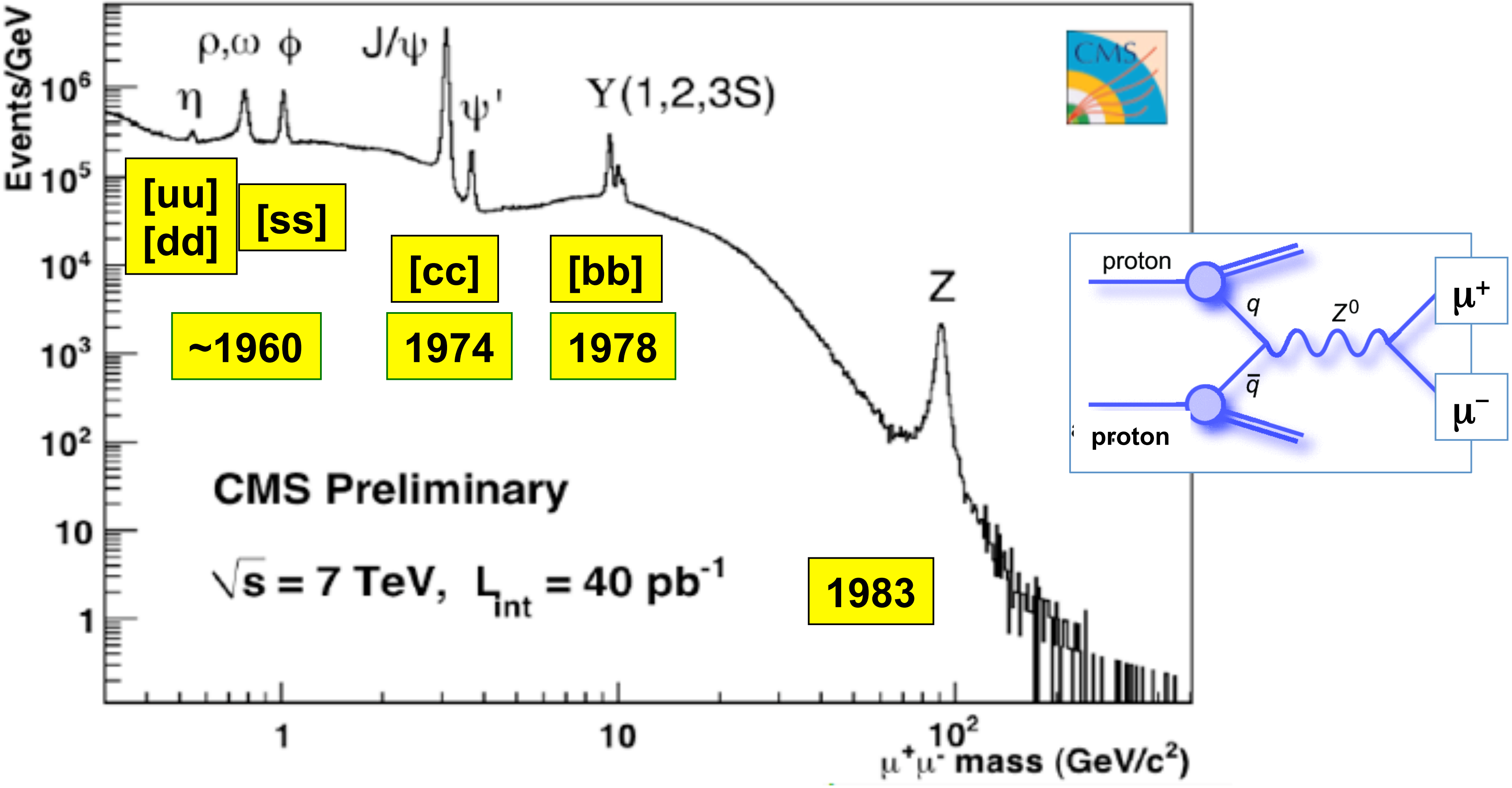
Example $\Xi^- \rightarrow \Lambda\pi^-$

JHEP 05 (2011) 064



2010

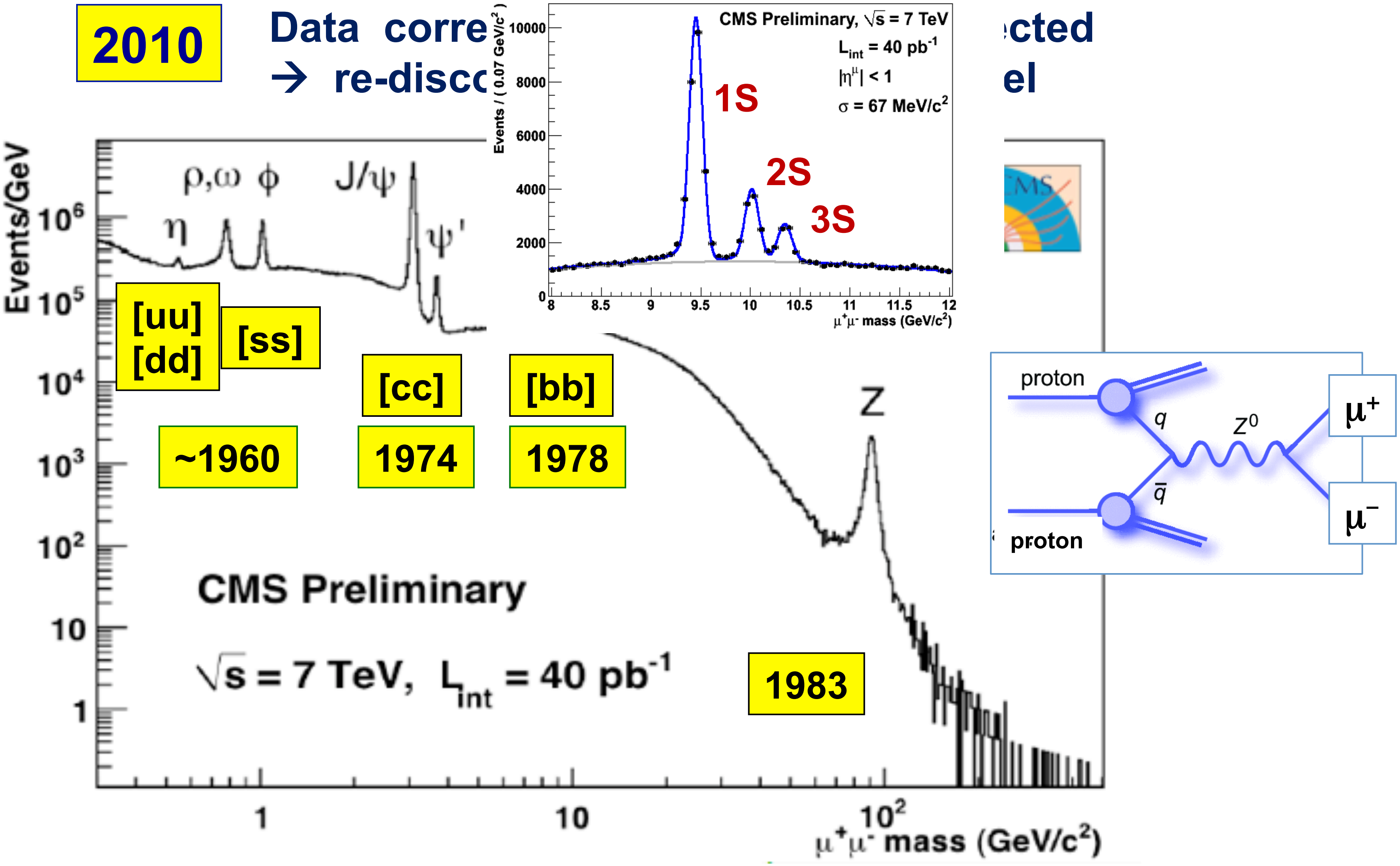
Data corresponding to ~40 pb^{-1} collected → re-discovery of the Standard Model



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

2010

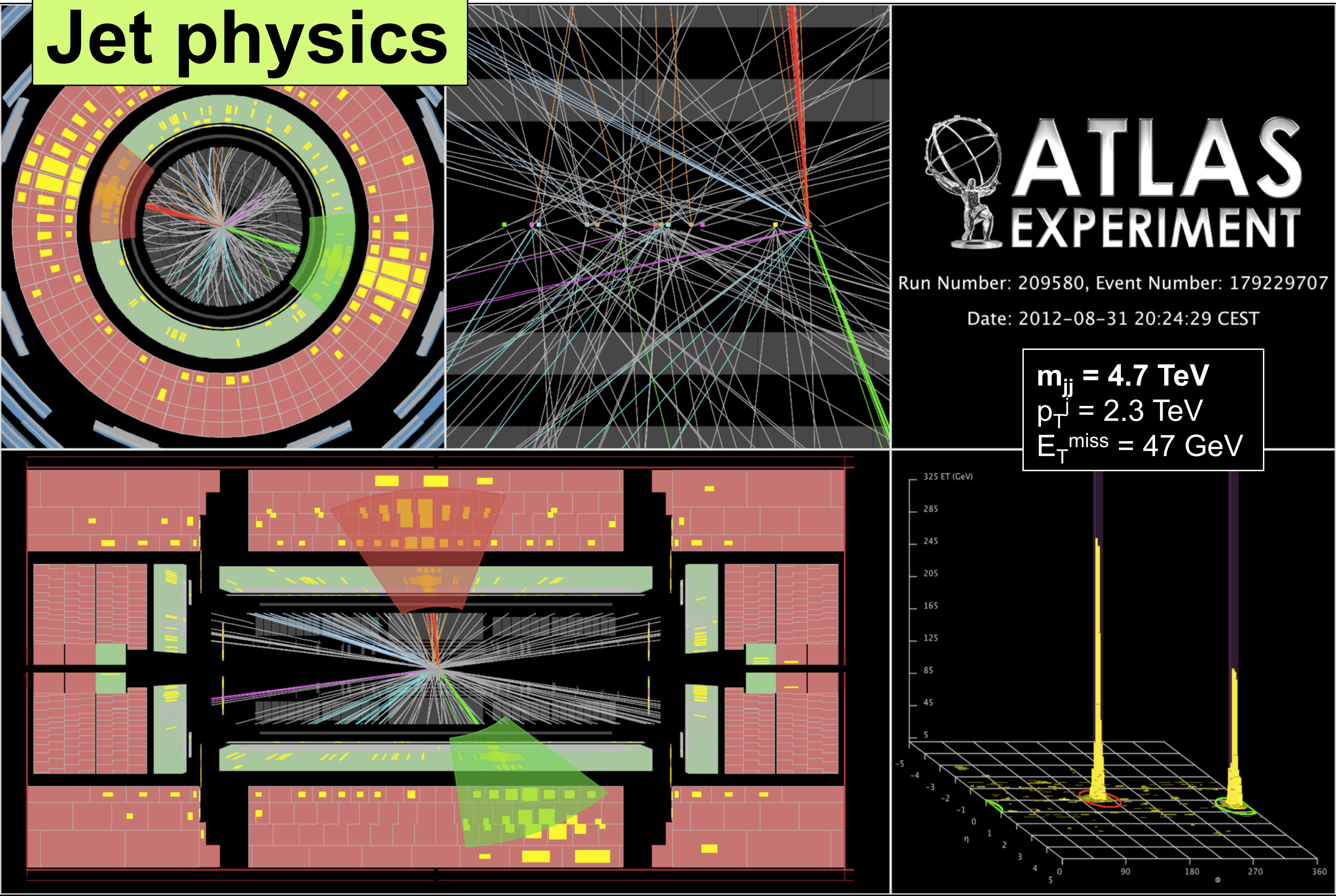
Data corre cted
→ re-discc el



The di-muon spectrum recalls a long period of particle physics:

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

Jet physics



Run Number: 209580, Event Number: 179229707

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

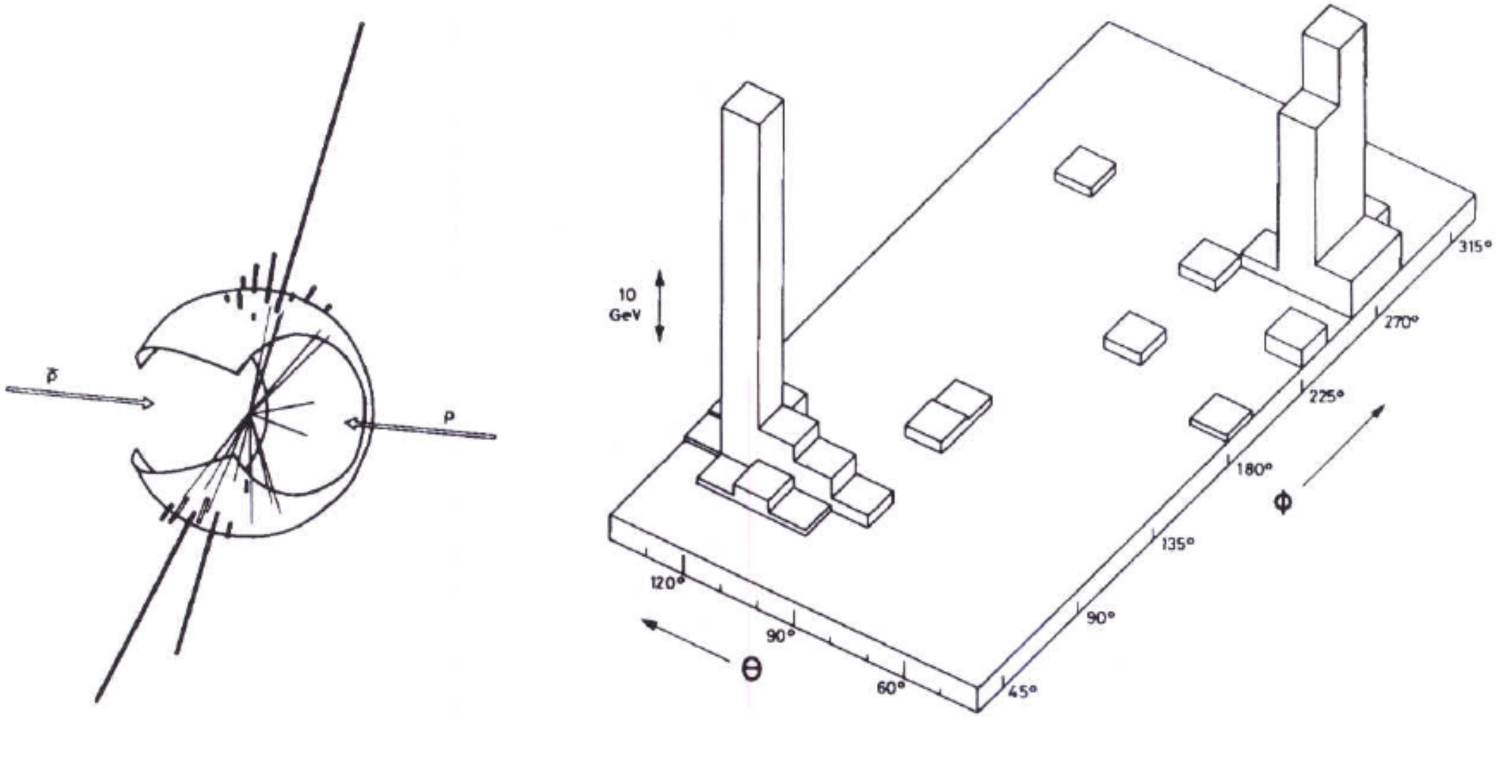
m_{jj} = 4.7 TeV

p_T^j = 2.3 TeV

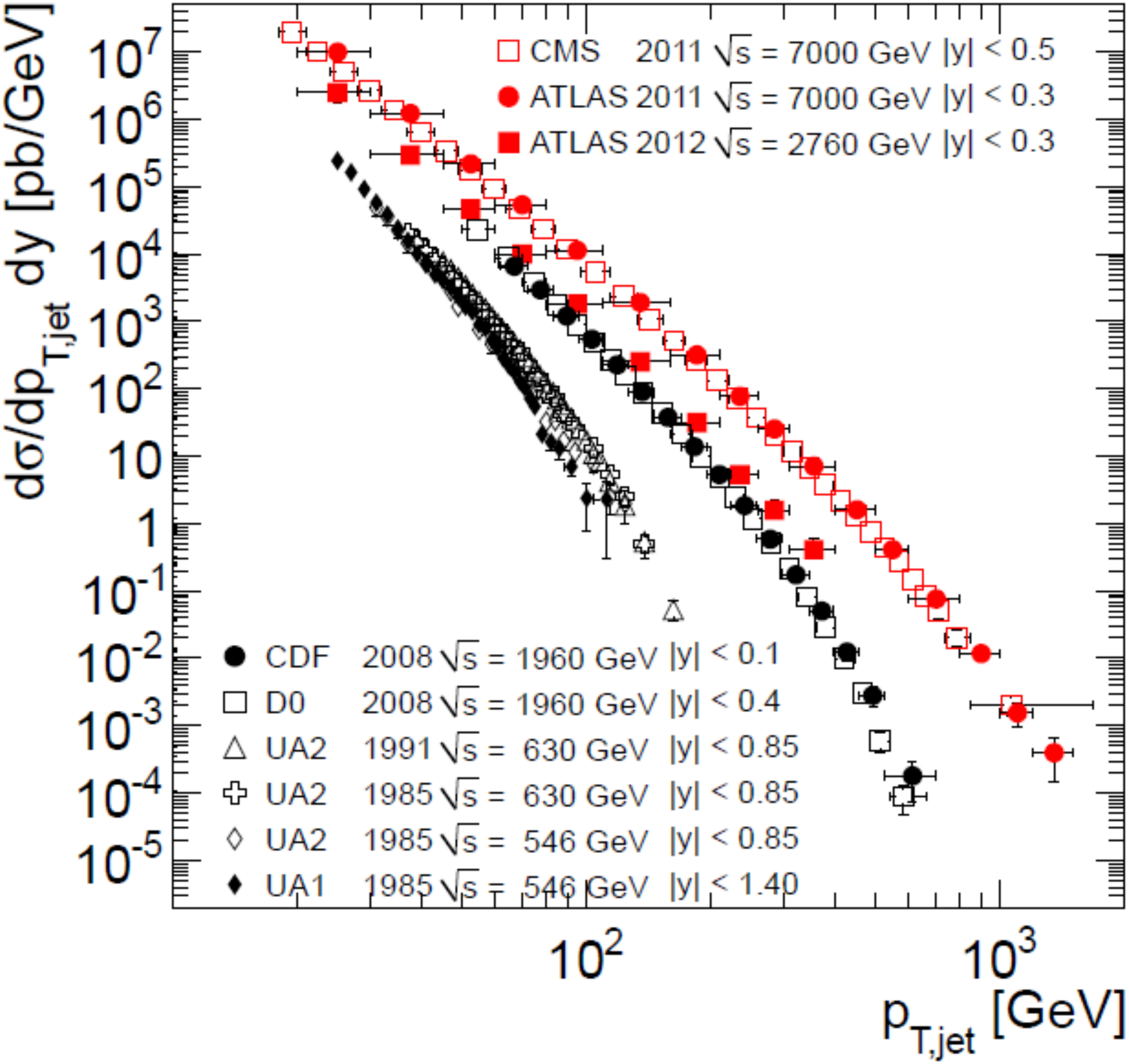
E_T^{miss} = 47 GeV

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

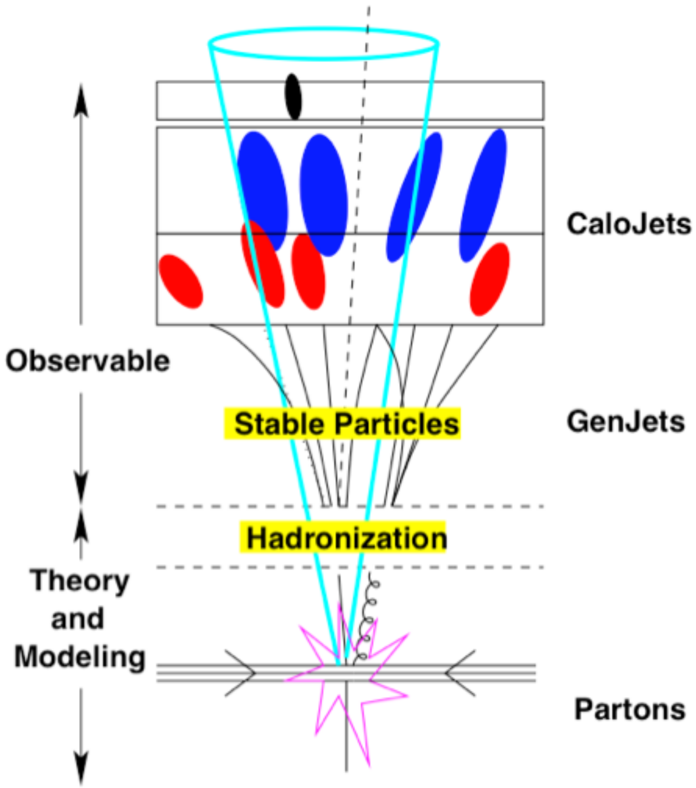
Volume 118B, number 1, 2, 3　　PHYSICS LETTERS　　2 December 1982

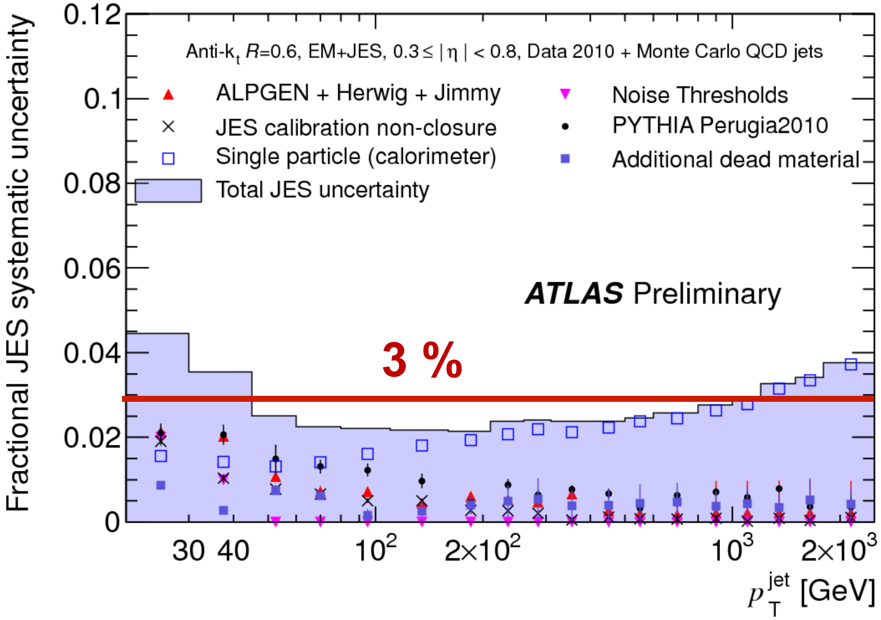


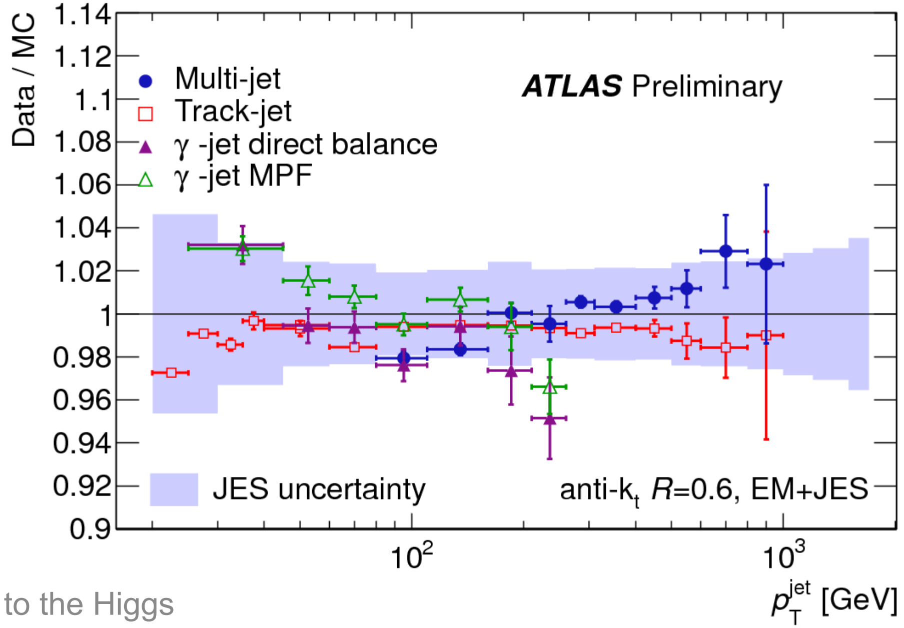
(a)　　(b)


dσ/dp_{T,jet} dy [pb/GeV]
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^2
10^3
p_{T,jet} [GeV]
□ CMS 2011 √s = 7000 GeV |y| < 0.5
● ATLAS 2011 √s = 7000 GeV |y| < 0.3
■ ATLAS 2012 √s = 2760 GeV |y| < 0.3
● CDF 2008 √s = 1960 GeV |y| < 0.1
□ D0 2008 √s = 1960 GeV |y| < 0.4
△ UA2 1991 √s = 630 GeV |y| < 0.85
✚ UA2 1985 √s = 630 GeV |y| < 0.85
◇ UA2 1985 √s = 546 GeV |y| < 0.85
♦ UA1 1985 √s = 546 GeV |y| < 1.40

A considerable effort went into understanding the Jet Energy Scale (JES), the dominant source of uncertainties for most jet measurements



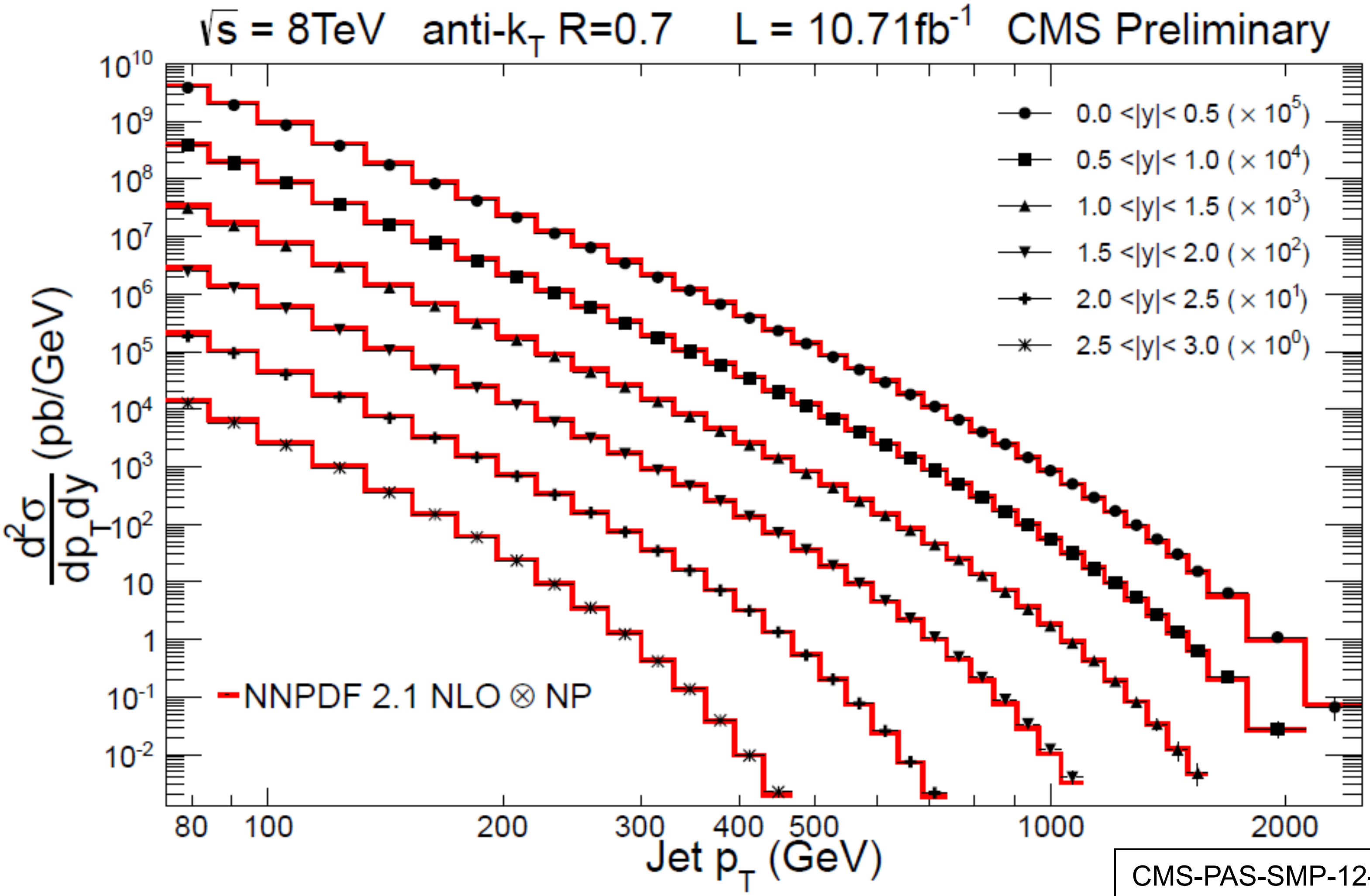




ATLAS-CONF-2011-032 and arXiv:1112.6426v1[hep-ex]

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

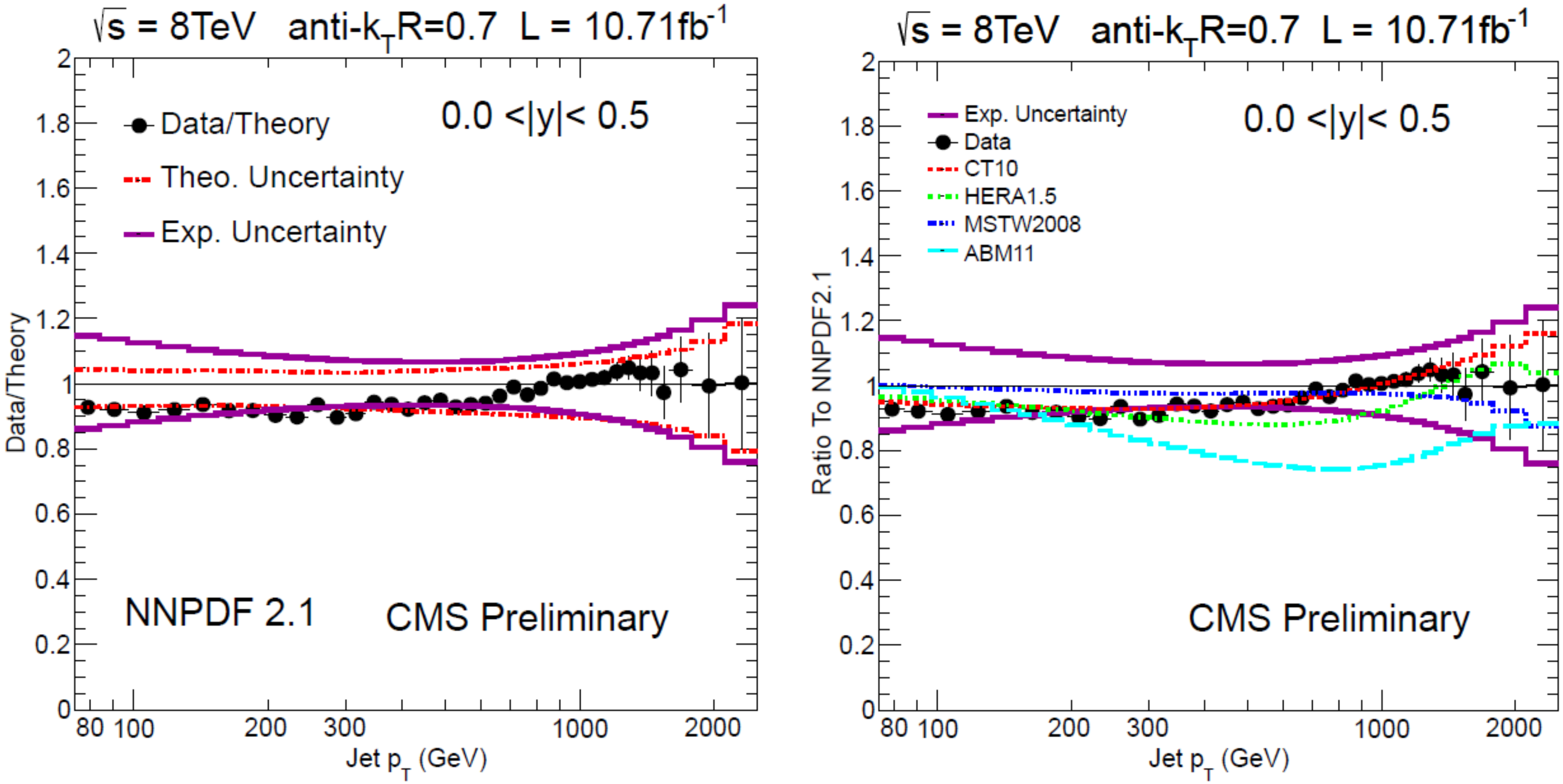
Example: The inclusive jet cross sections as a function of the jet P_T in rapidity bins



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

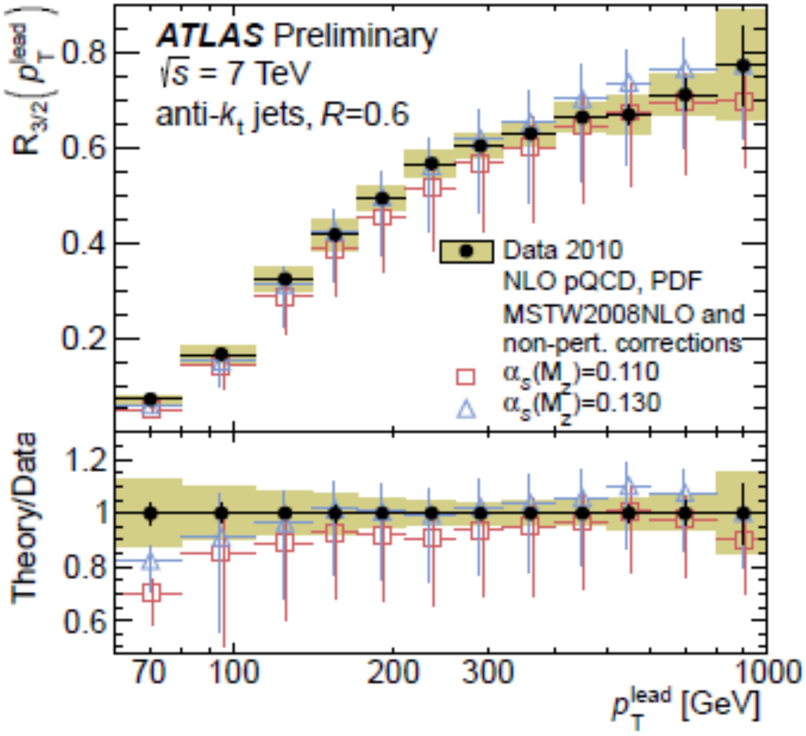


CMS-PAS-SMP-12-012

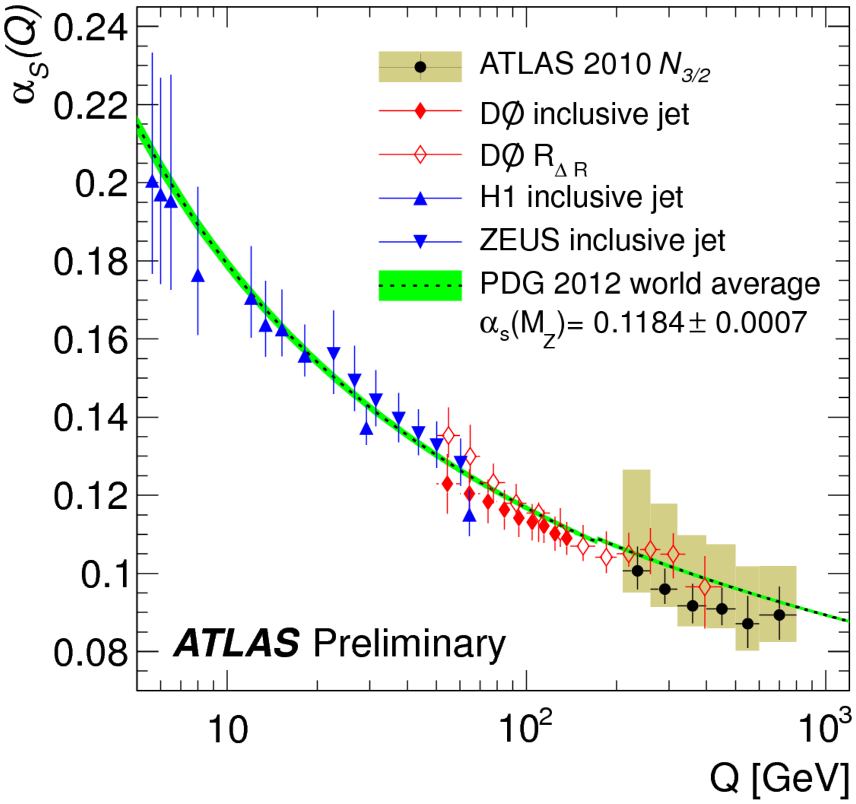
Cross-section ratios of multi-jets allow one to determine α_s

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

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



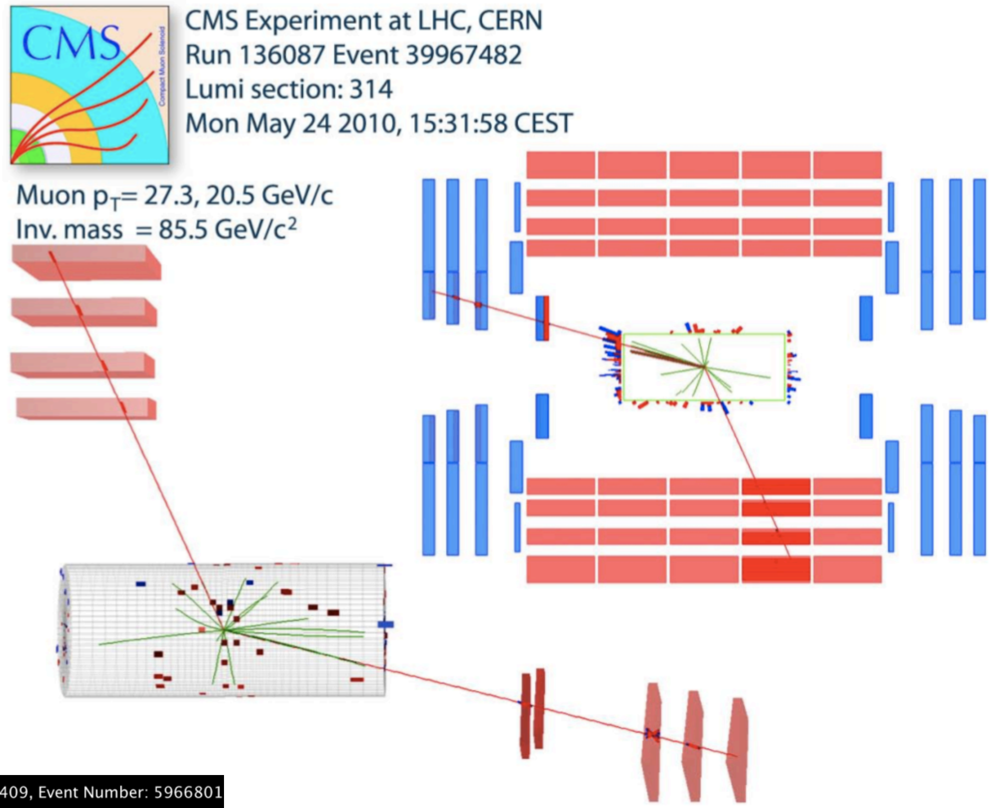
$\alpha_s(M_Z) = 0.111 \pm 0.006(\text{exp.}) ^{+0.016}_{-0.003}(\text{theory})$.



ATLAS-CONF-2013-041

Standard Model Physics

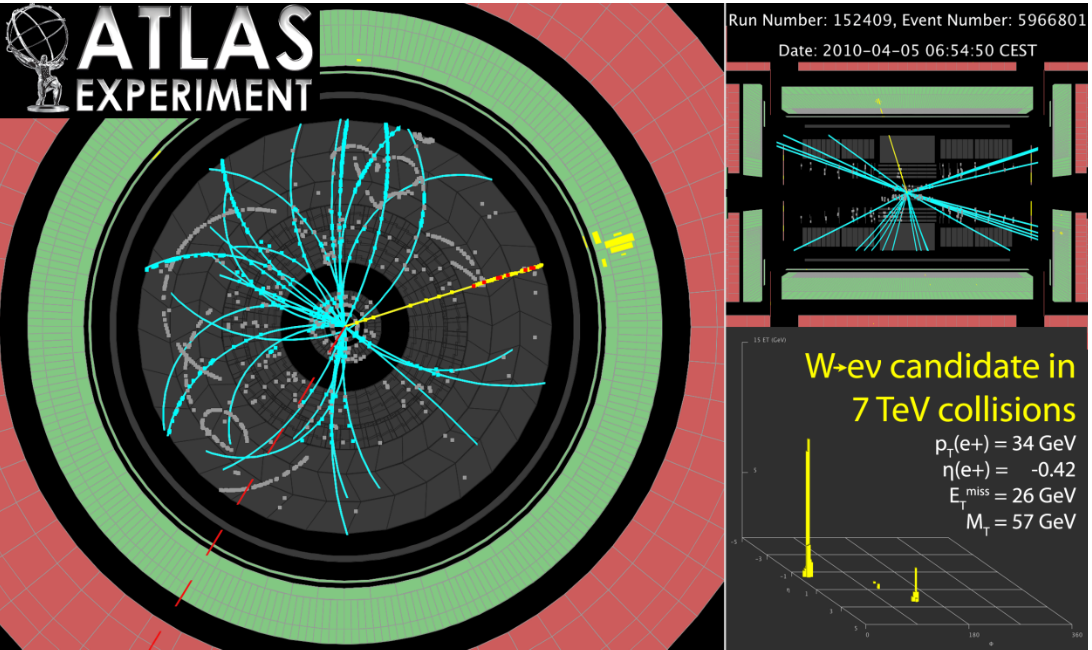
Candidate Z → $\mu^+\mu^-$



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 GeV/c
Inv. mass = 85.5 GeV/c^2

W → eν candidate



Run Number: 152409, Event Number: 5966801
Date: 2010-04-05 06:54:50 CEST

W→eν candidate in
7 TeV collisions
$p_T(e+)$ = 34 GeV
$\eta(e+)$ = -0.42
E_T^{miss} = 26 GeV
M_T = 57 GeV

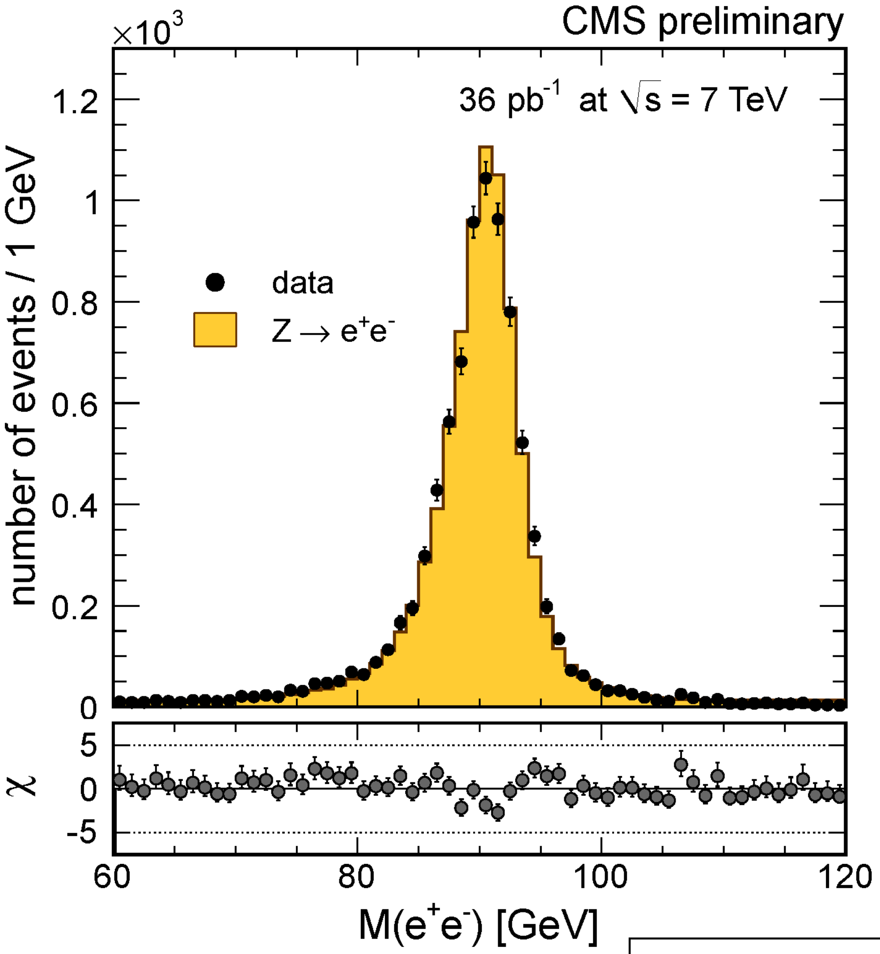
Today each ATLAS and CMS have in their data more than:

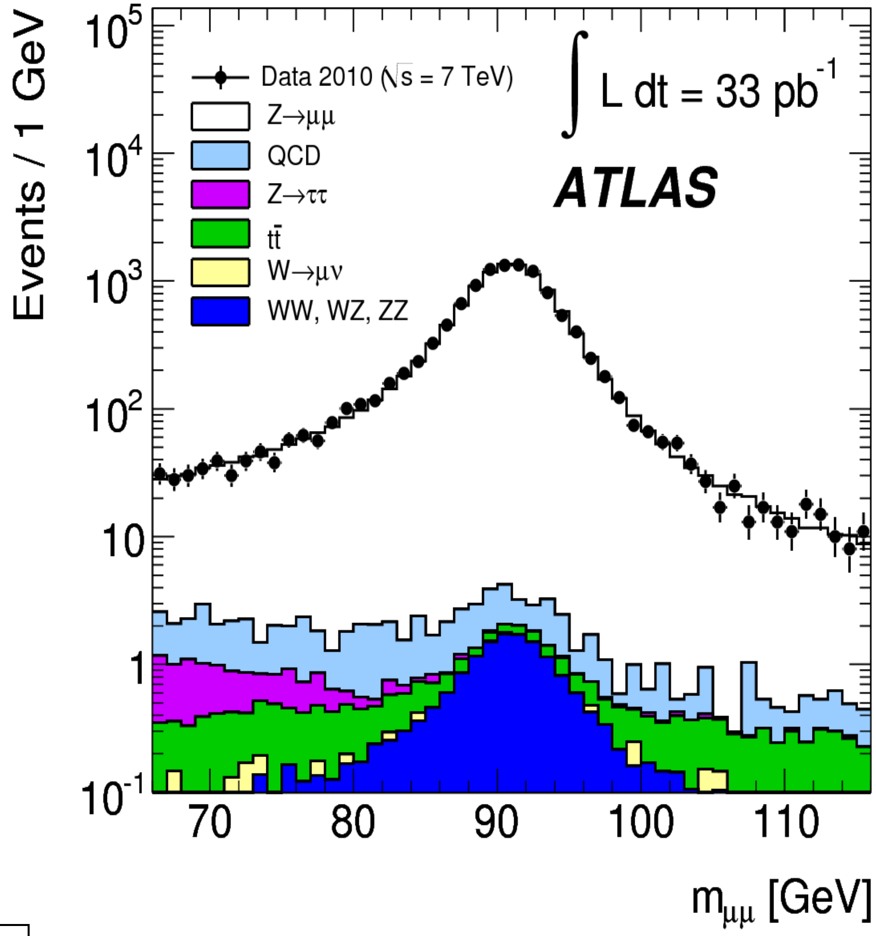
100 M W→ μν, eν events
10 M Z → μμ, ee events

after all selection cuts

Z and W production

Phys Rev D85 (2012) 072004





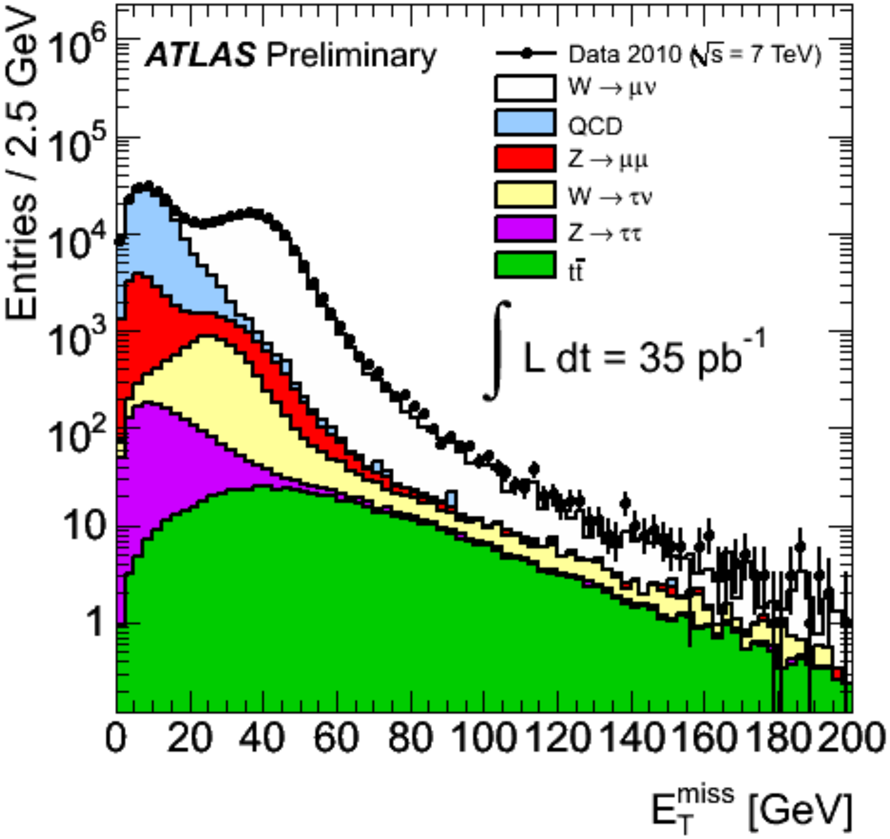
JHEP 10 (2011) 132

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

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

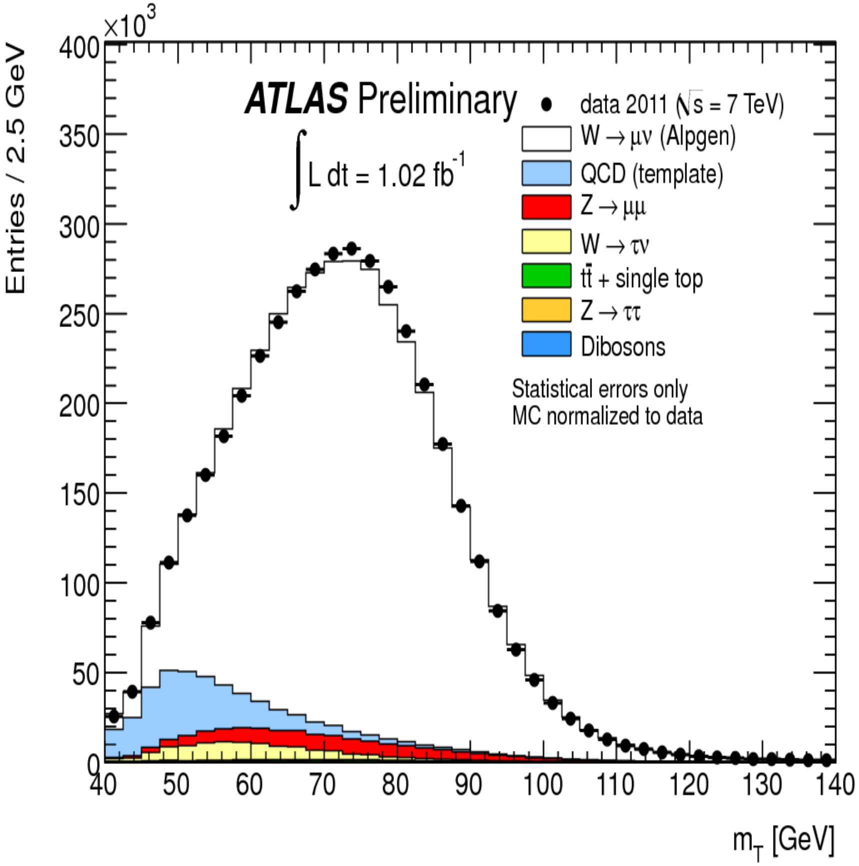
W transverse mass

μ with p_T>20 GeV, E_T^{miss}>25 GeV



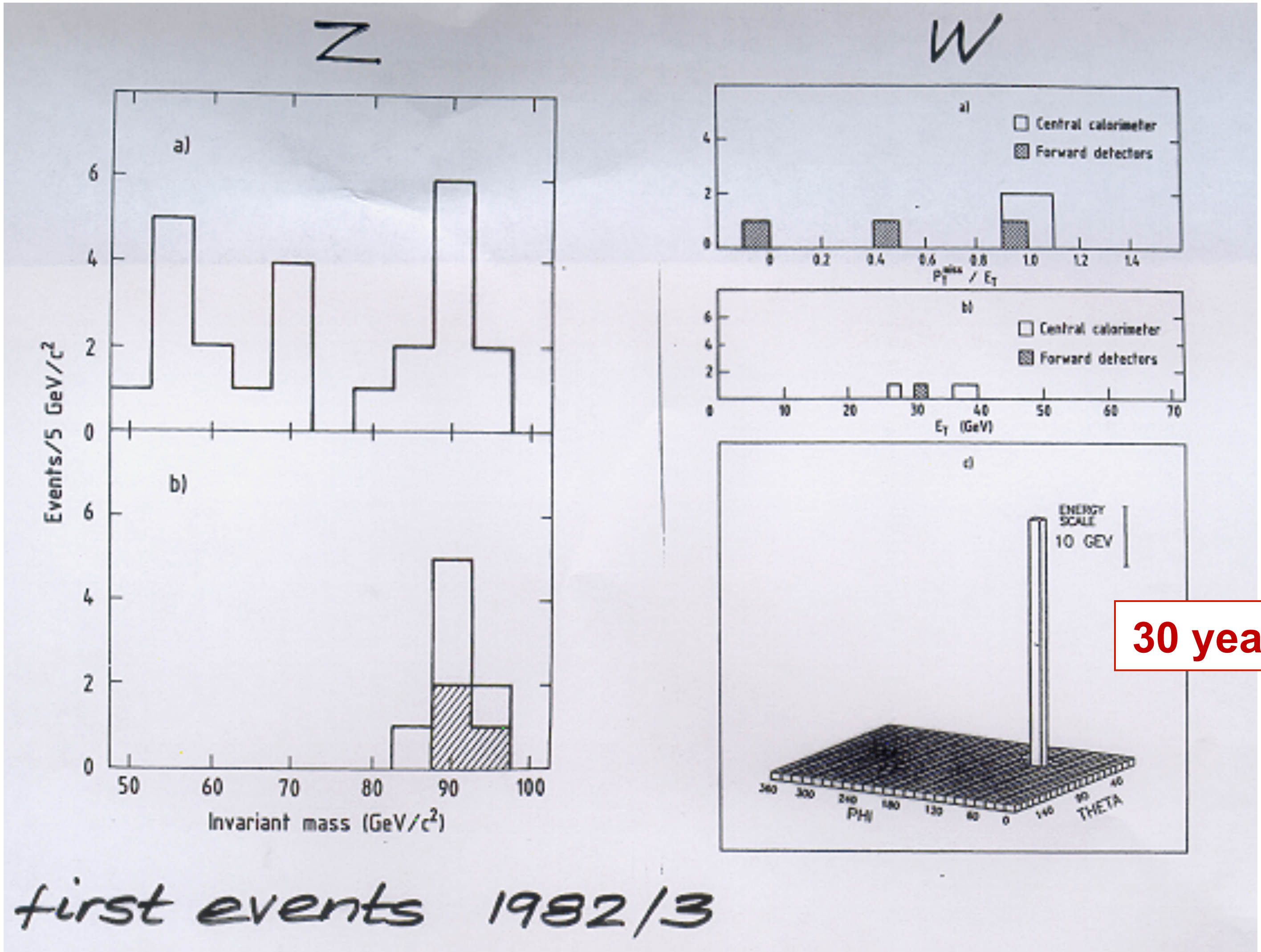
Missing transverse energy from the W → μ + ν decays

ATLAS-CONF-2011-041



$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\nu} (1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

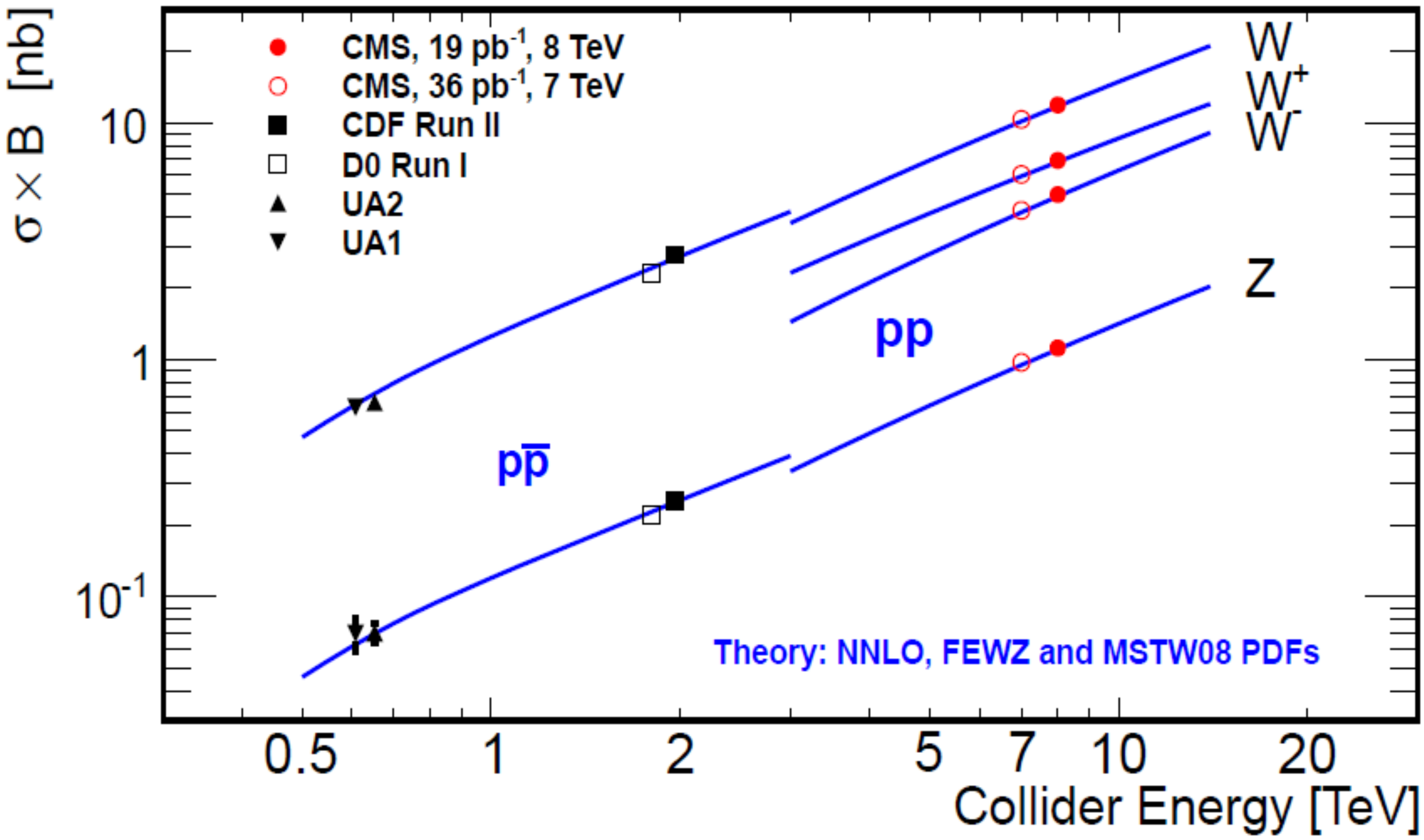
What a contrast to the Intermediate Vector Boson discovery distributions in 1982 and 1983 by UA1 and UA2 …



30 years ago!

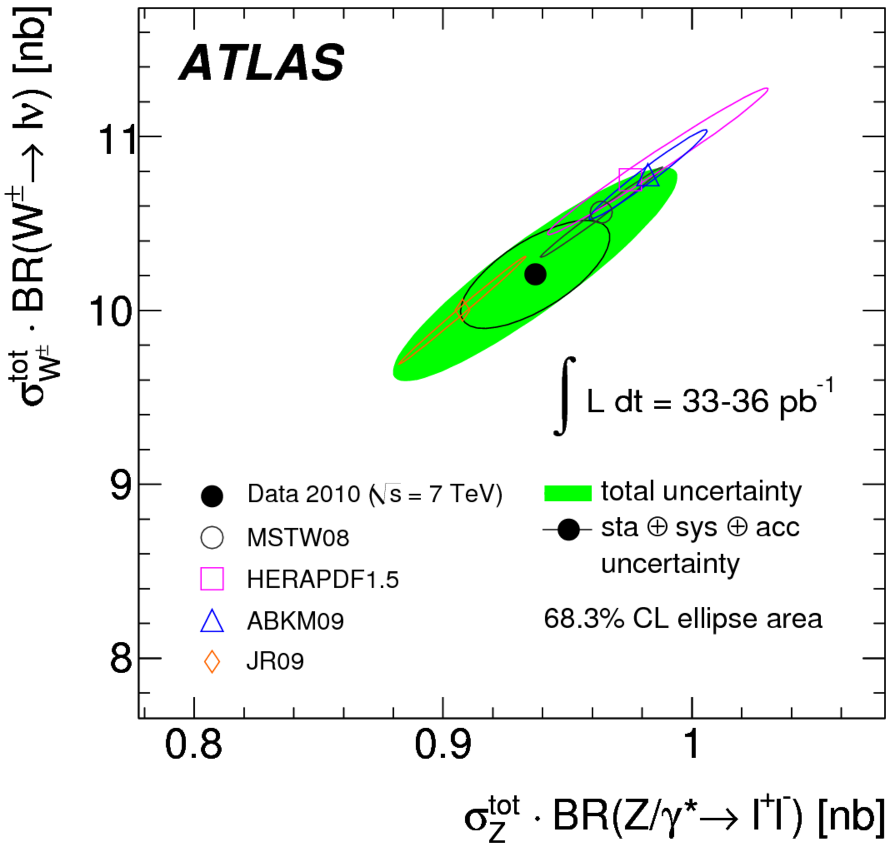
(here are shown the UA2 distributions)

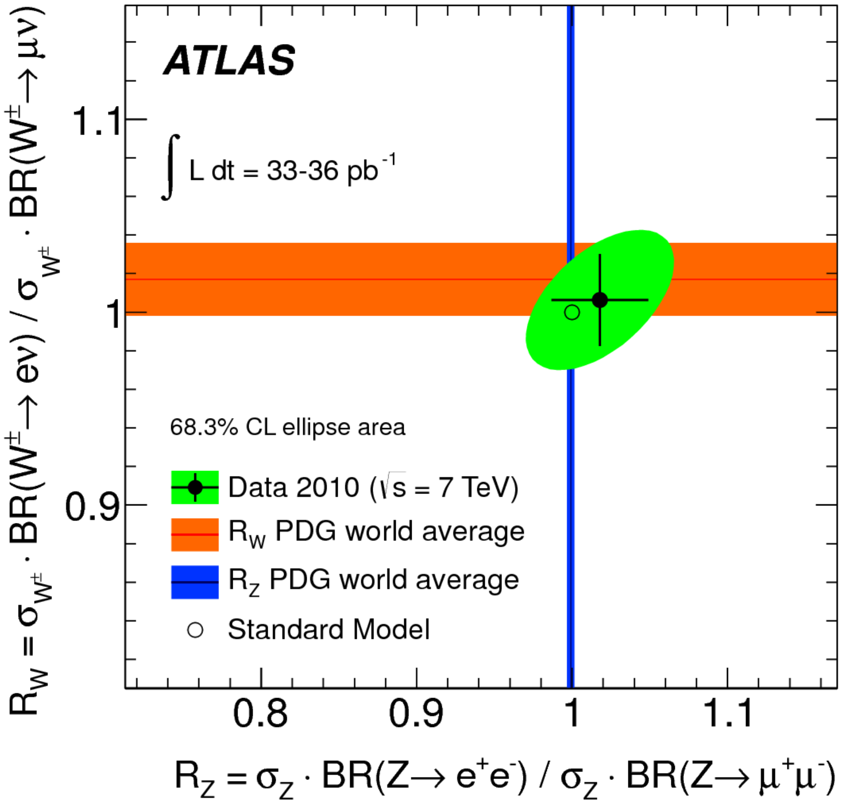
Cross section measurements



CMS-PAS-SMP-12-011

Two examples of confronting the 2010 data with SM theory

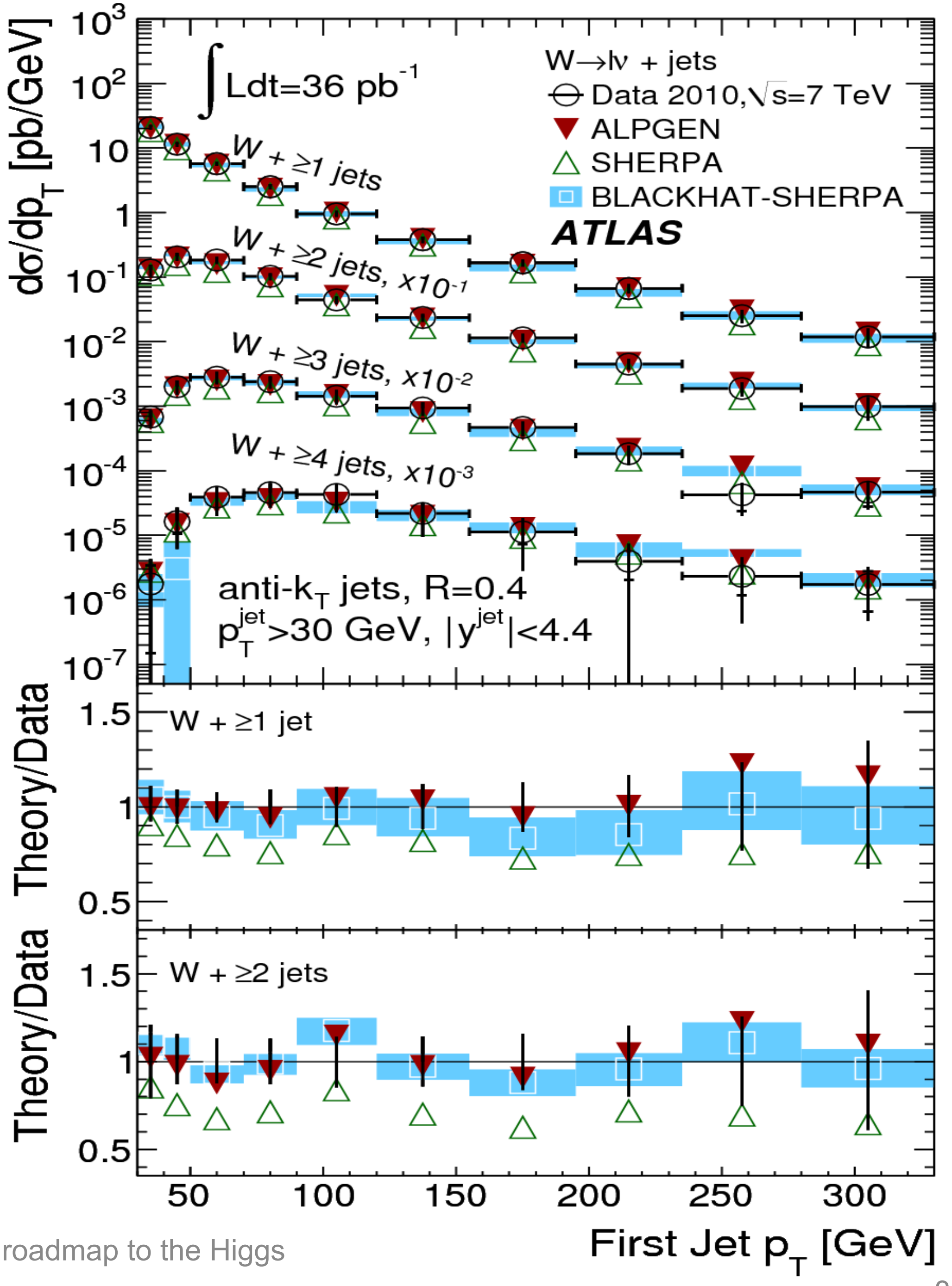




Phys Rev D85 (2012) 072004

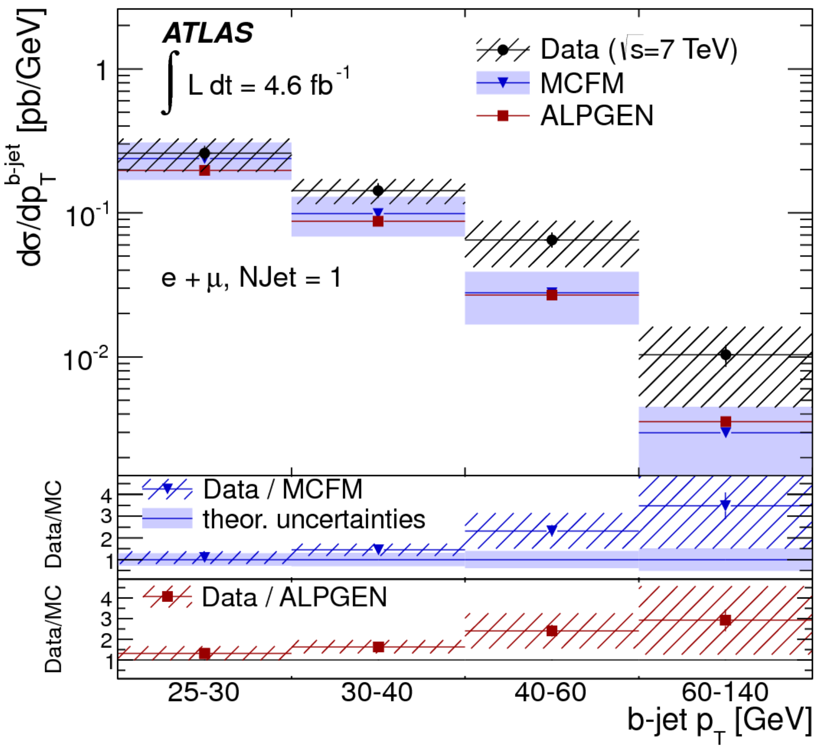
W + jet(s) production

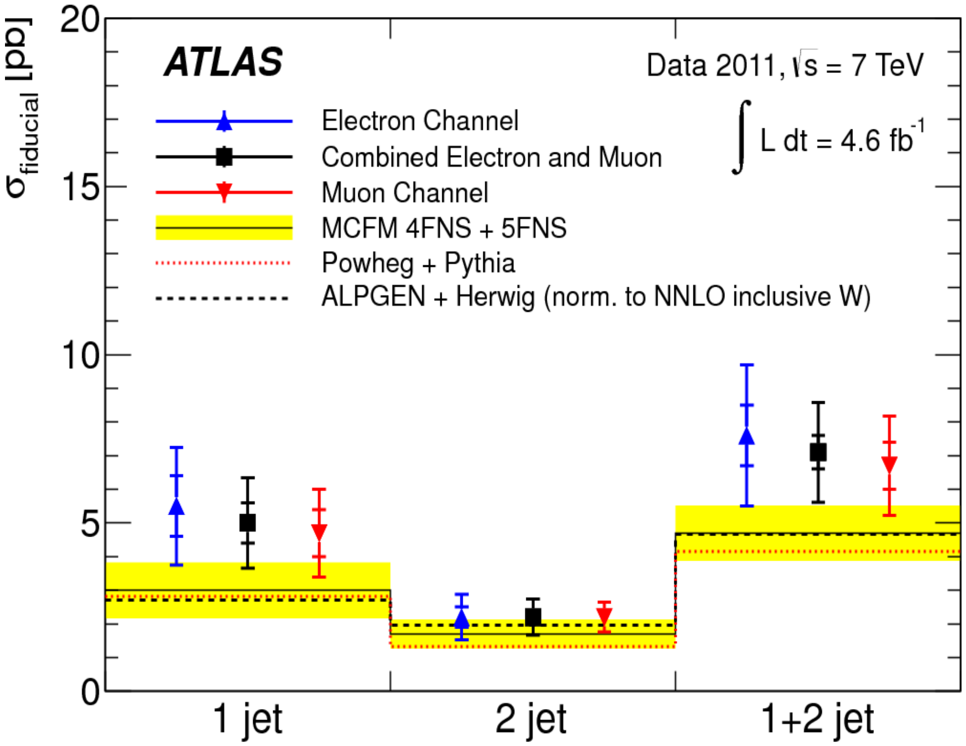
Both an interesting QCD measurement as well as a dominant background to many searches



Phys. Rev. D85 (2012) 092002

W + b-jet(s) production

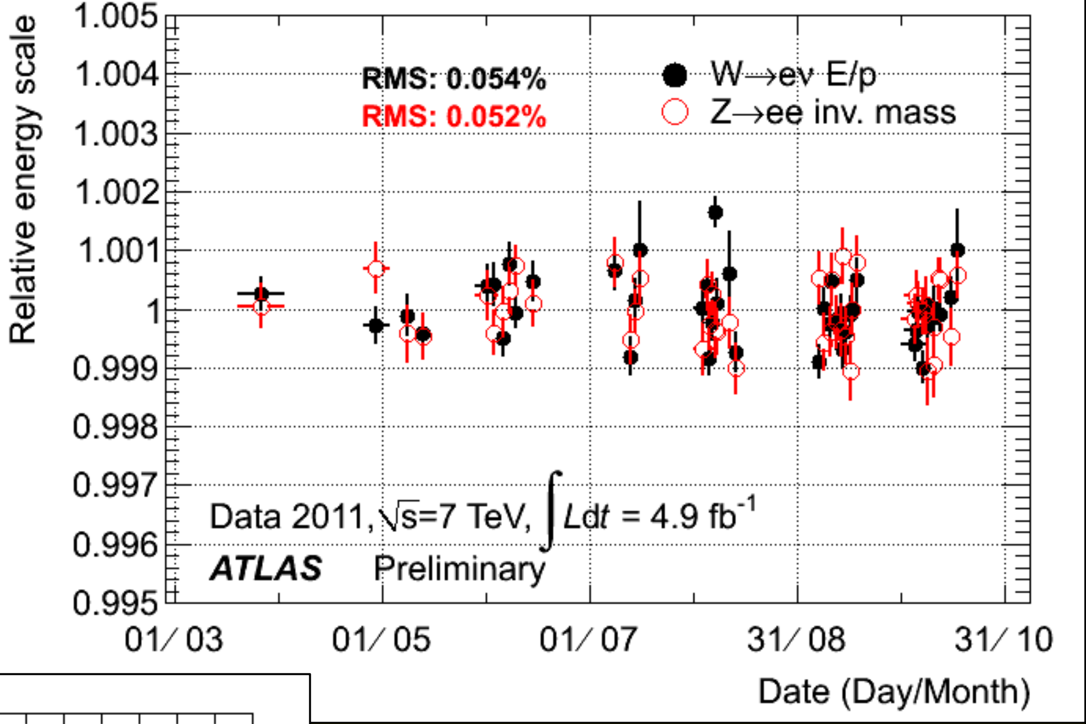




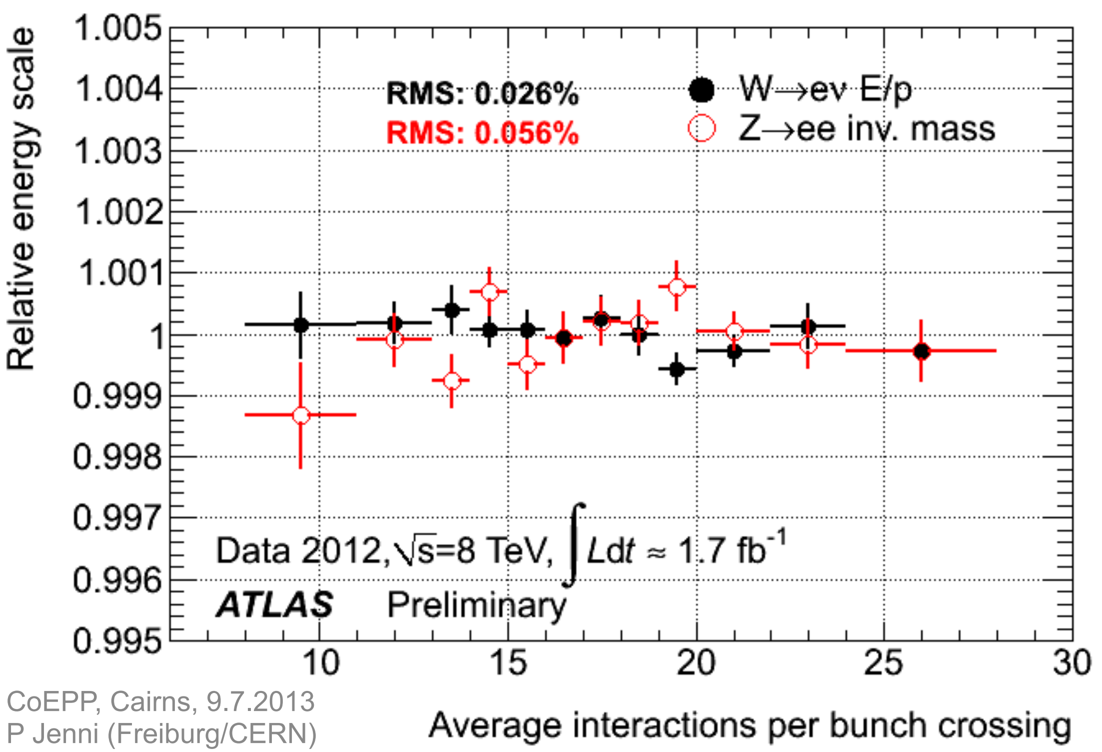
arXiv:1302.2929[hep-exp]

Example: W and Z as a ‘tool’ to assure the performance of the detector

vs time over the full 2011 run



vs pile-up in 2012



Stability of EM calorimeter E-scale: better than 0.1%

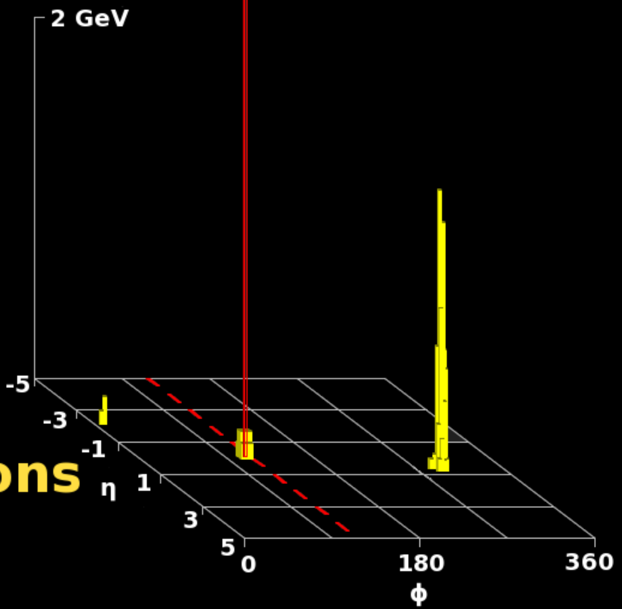
$p_T(\mu)$ = 18 GeV
$p_T^{vis}(\tau_h)$ = 26 GeV
m_{vis} (μ,τ_h) = 47 GeV
$m_T(\mu,E_T^{miss})$ = 8 GeV
E_T^{miss} = 7 GeV

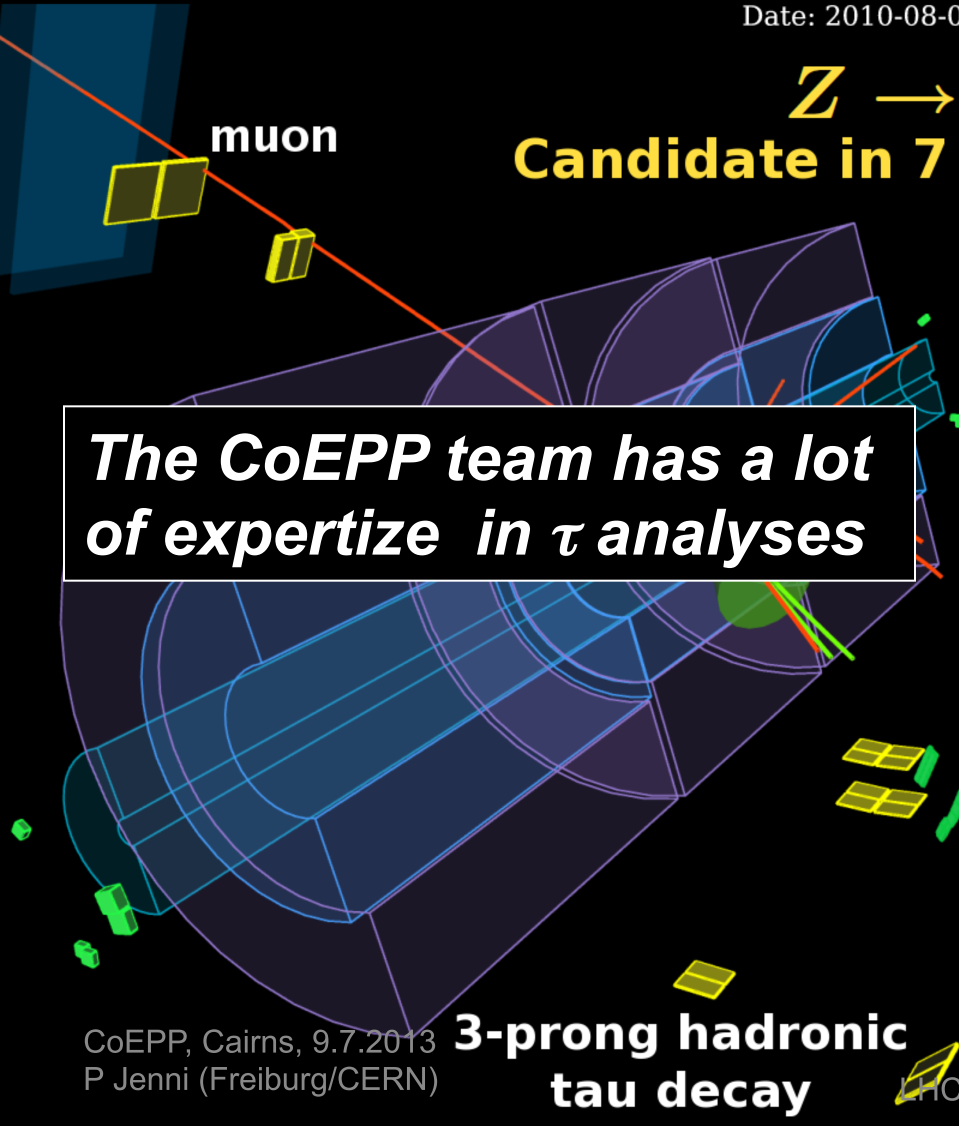
ATLAS EXPERIMENT

Run Number: 160613, Event Number: 9209492

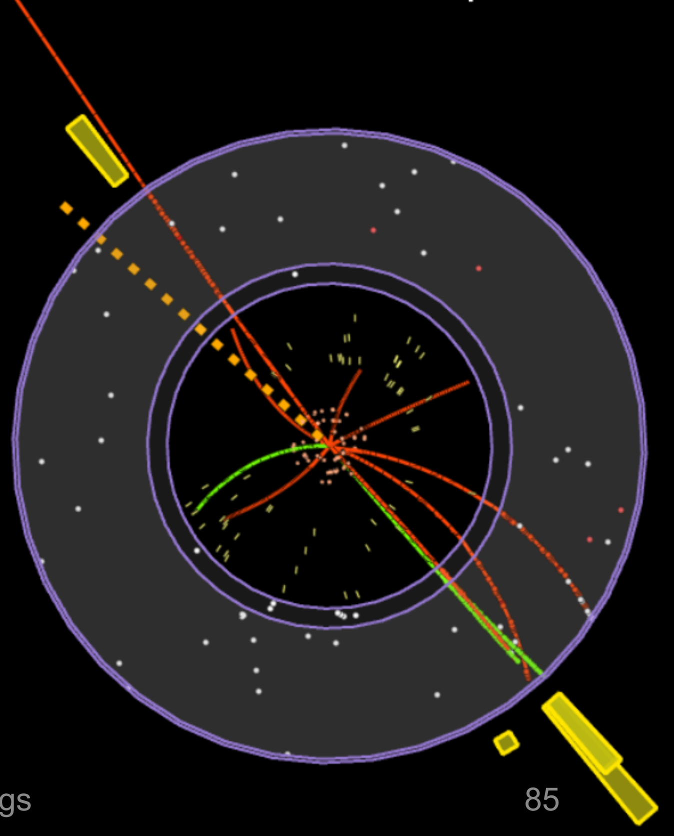
Date: 2010-08-03 02:12:37 CEST

$Z \rightarrow \tau\tau$ Candidate in 7 TeV Collisions

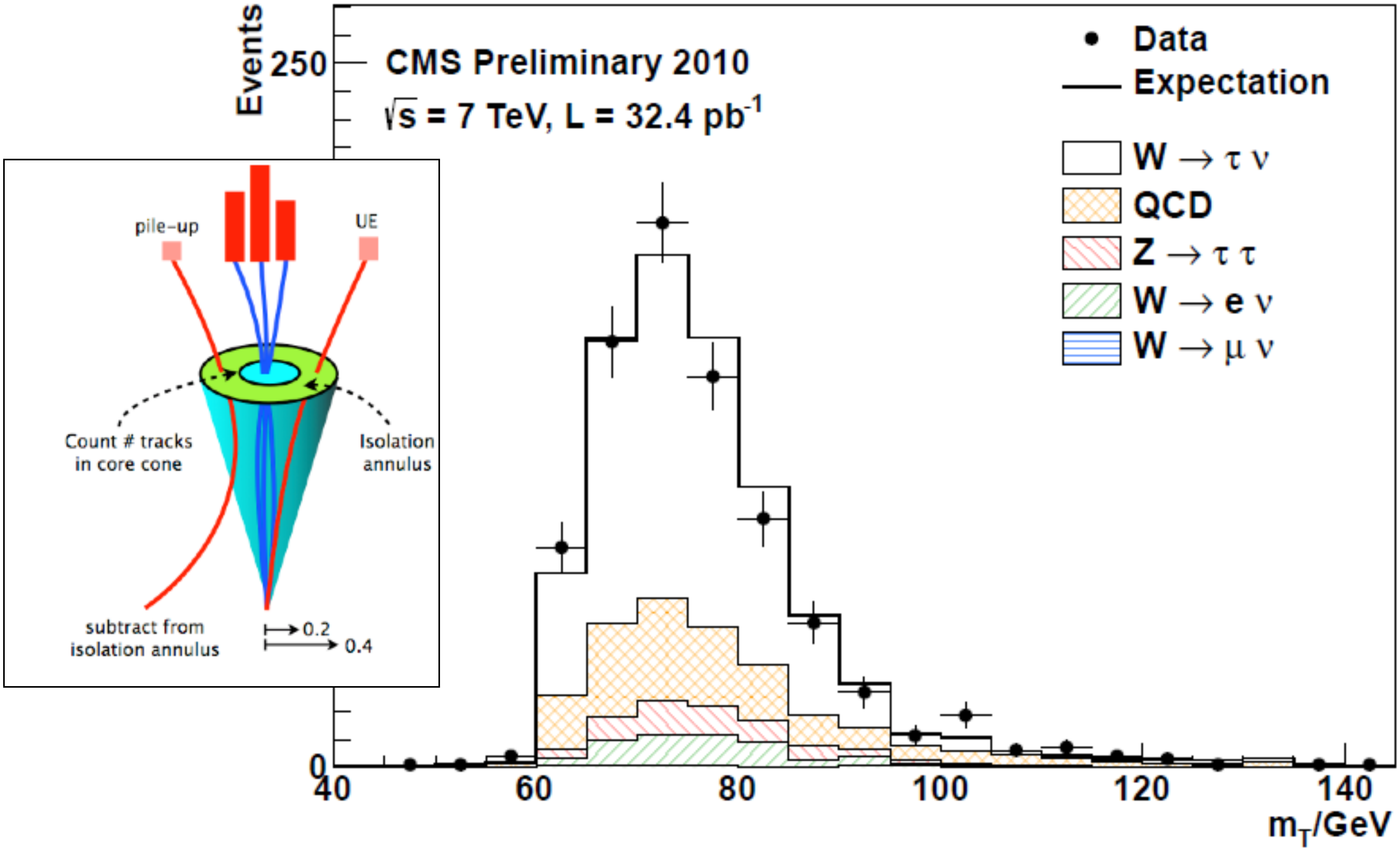




The CoEPP team has a lot of expertize in τ analyses



W → τν signal

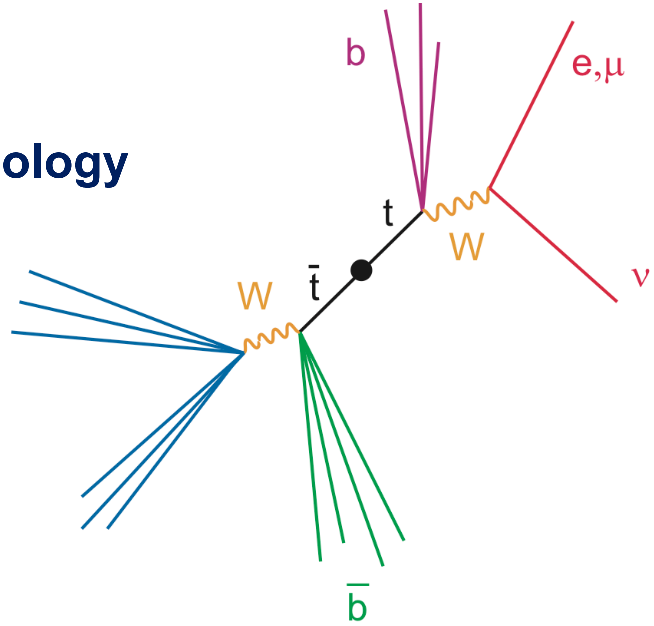


CMS-PAS-EWK-11-019

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**

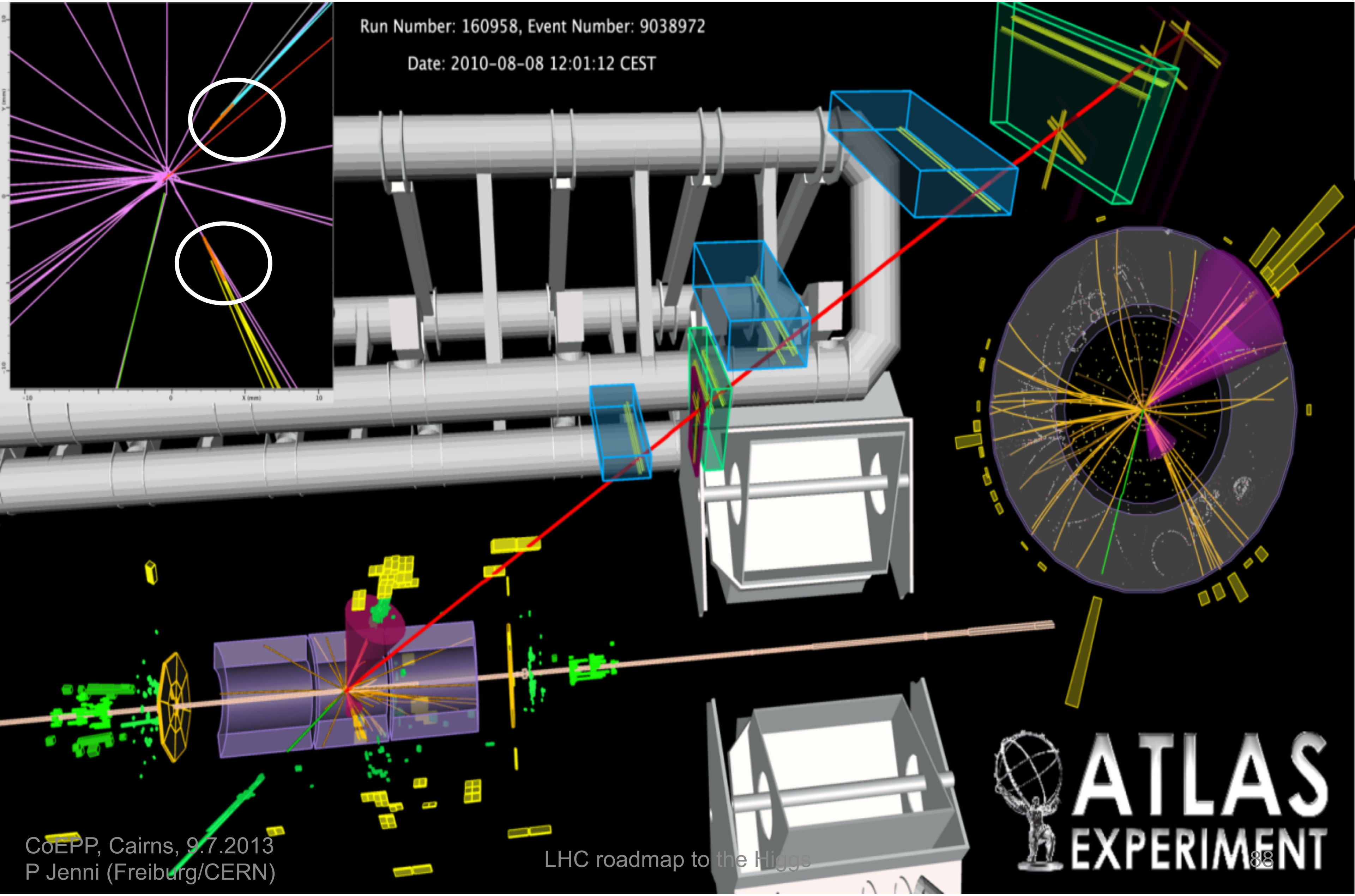
- **Assume all tops decay to Wb: event topology then depends on the W decays:**
    - **one lepton (e or μ), E_T^{miss}, jjbb (37.9%)**
    - **di-lepton (ee, μμ or eμ), E_T^{miss}, bb (6.5%)**



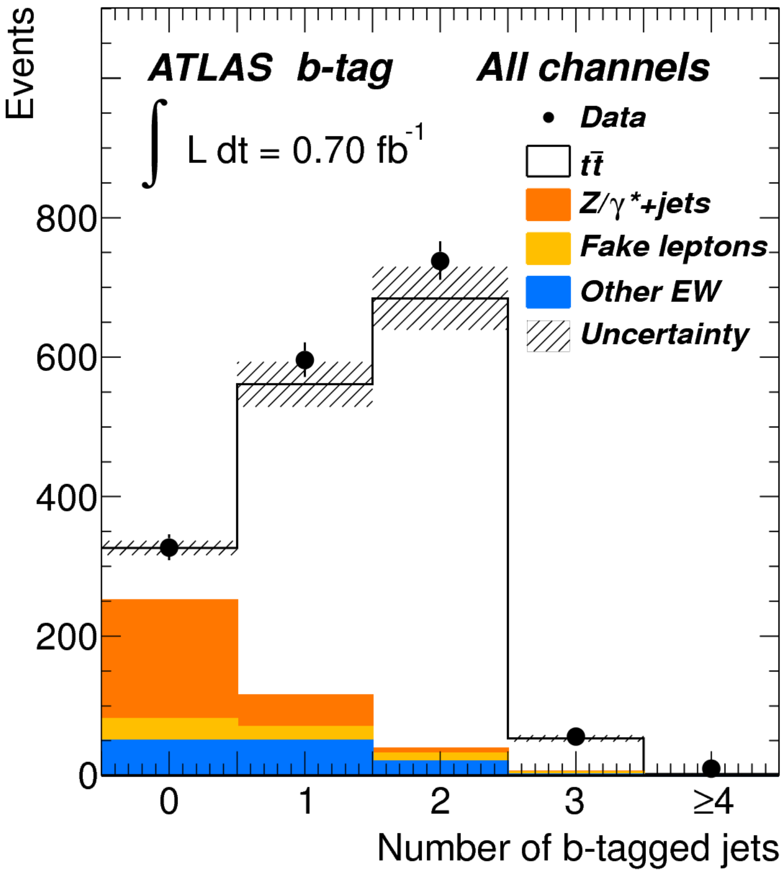
- **Data-driven methods to control QCD and W+jets backgrounds**

$t\bar{t}$ candidate event

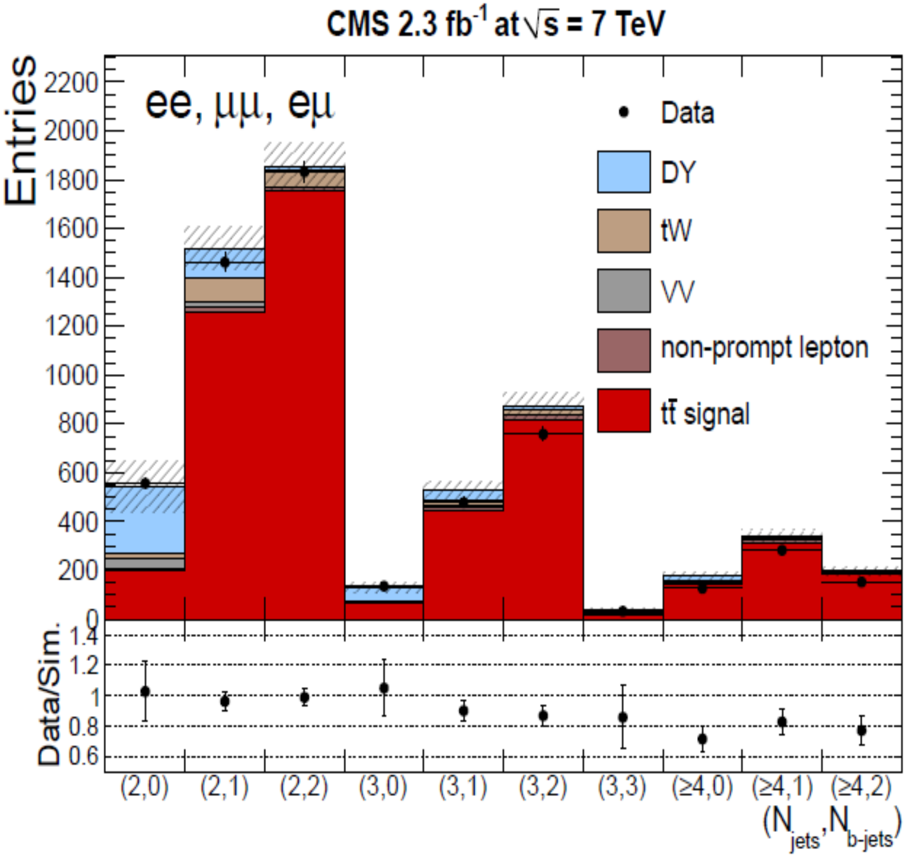
e + μ + 2 jets (b-tagged) +ETmiss



Example of top signals in the case of di-lepton channels

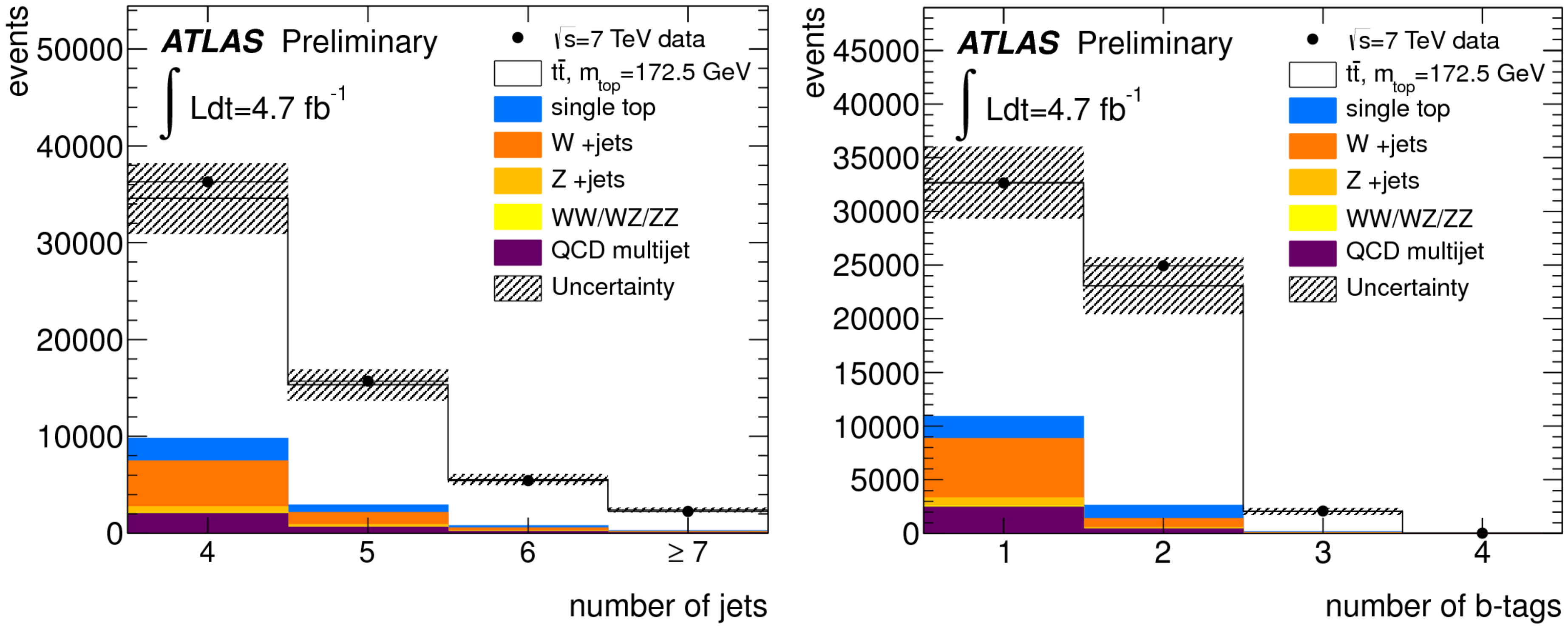


JHEP 1205 (2012) 059

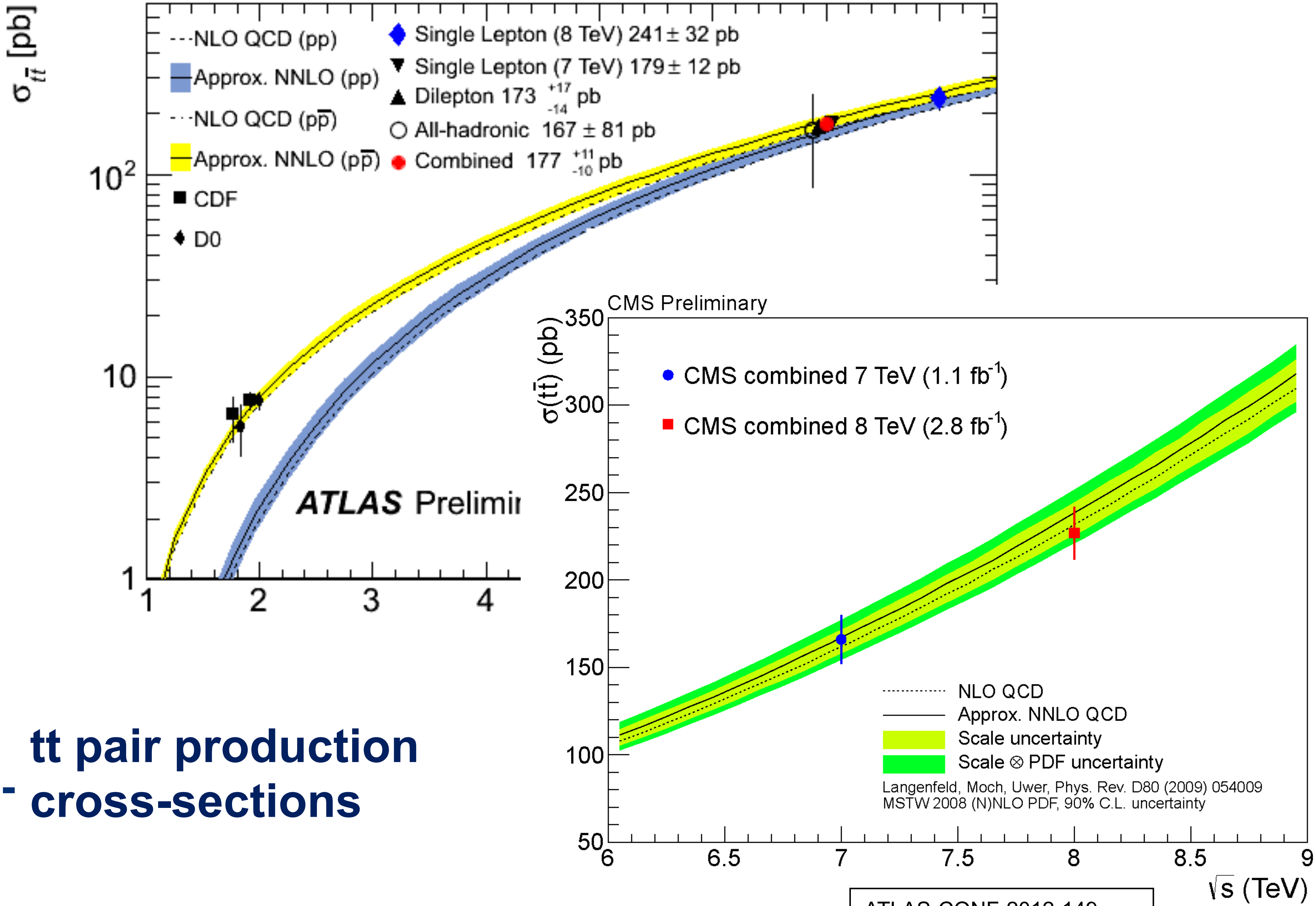


Example of top signals in the case of lepton-jet channels

ATLAS-CONF-2013-046



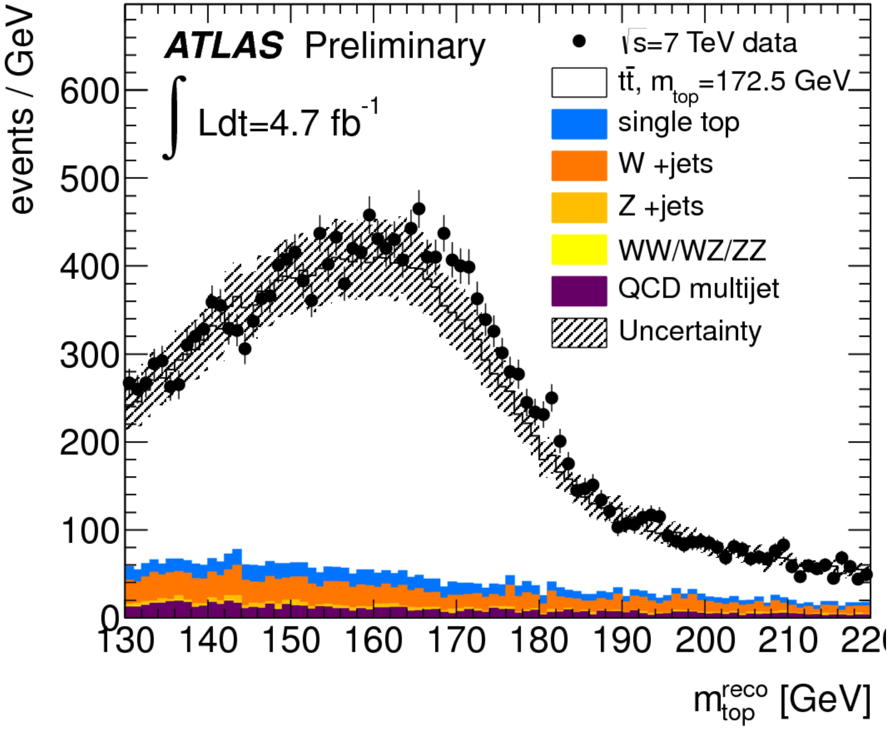
tt pair production - cross-sections

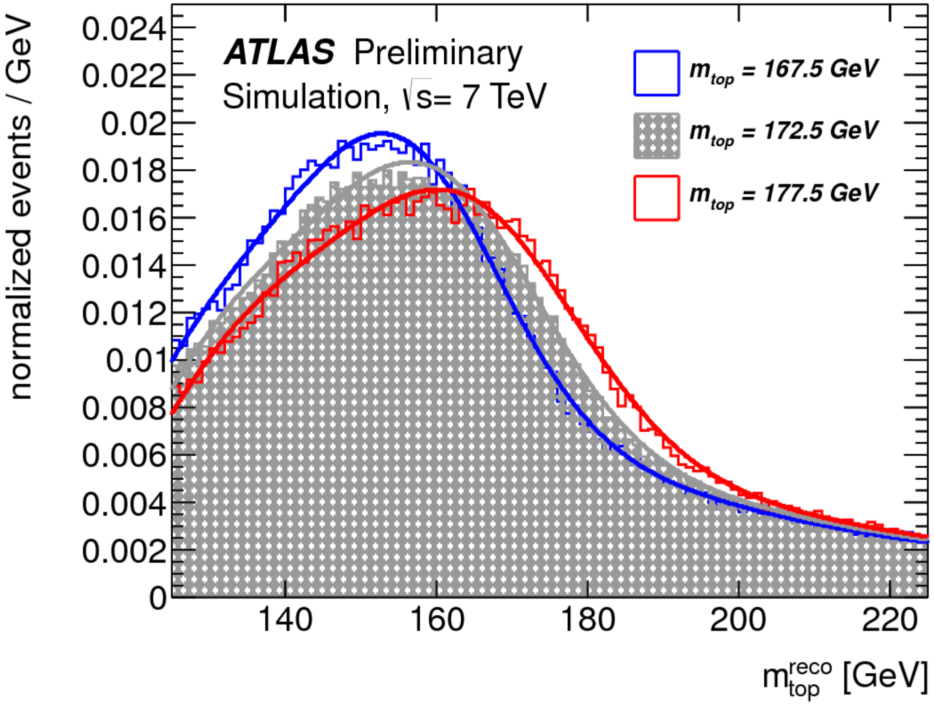


ATLAS-CONF-2012-149
CMS-PAS-TOP-12-006, 007

Example of top mass measurement: templates in the lepton-jet final state channel

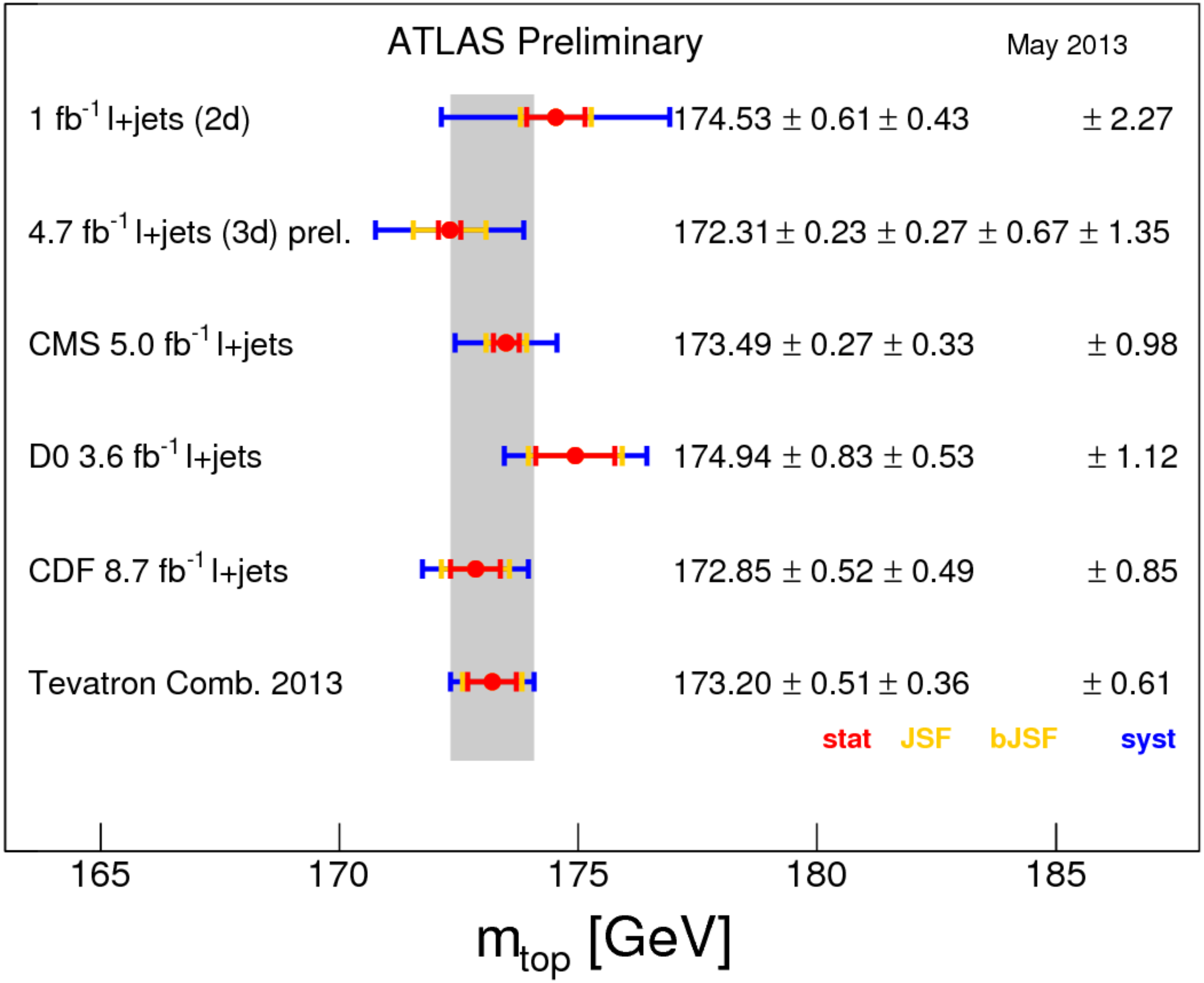
ATLAS-CONF-2013-046

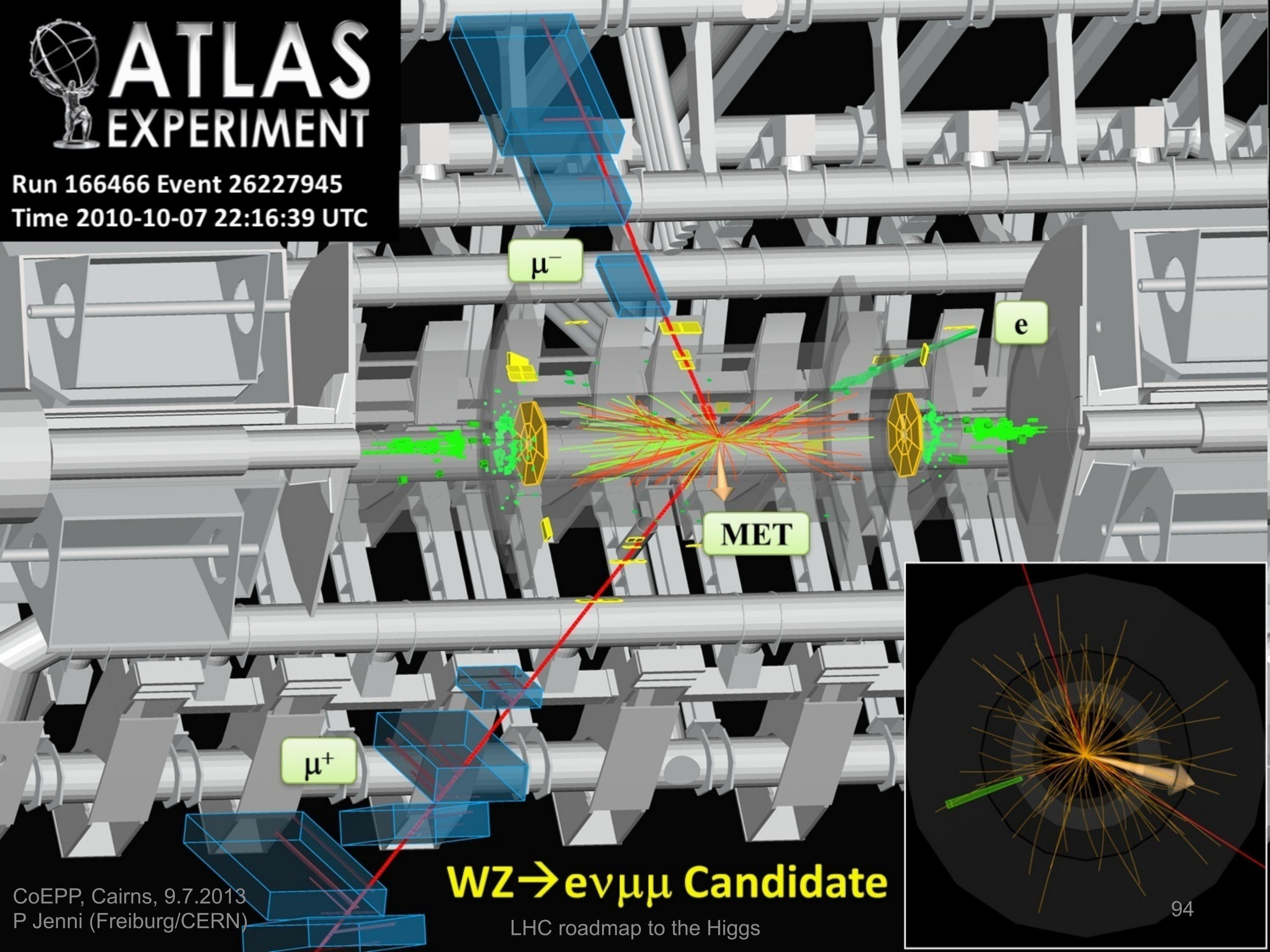




Mass is determined from a likelihood fit taking into account all measured kinematical variables

ATLAS-CONF-2013-046



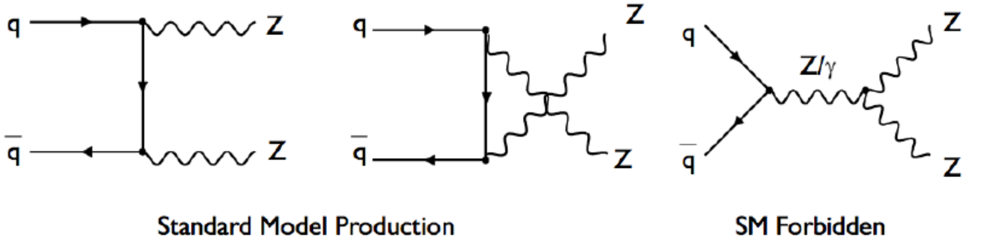


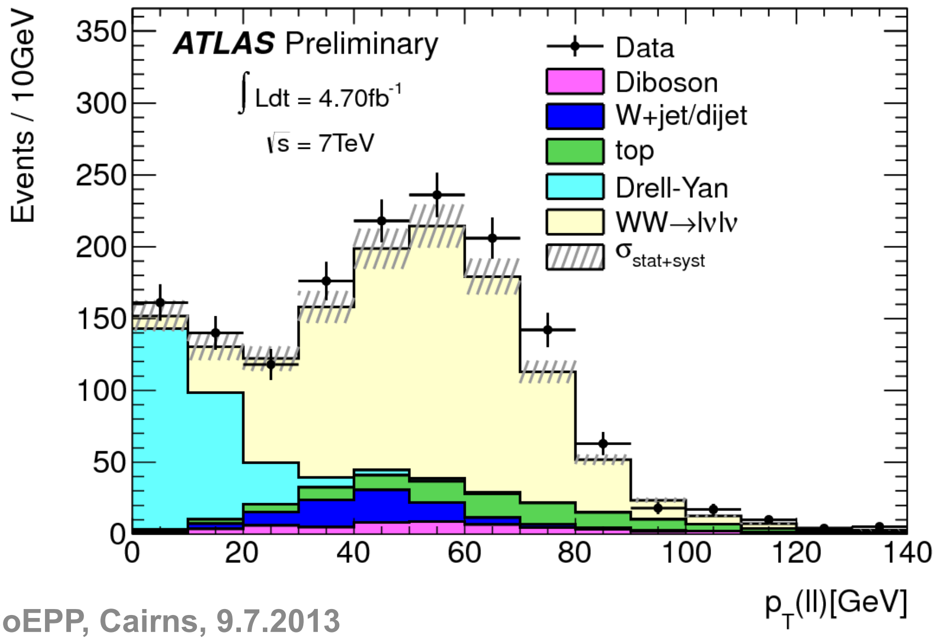
WZ→e$\nu\mu\mu$ Candidate

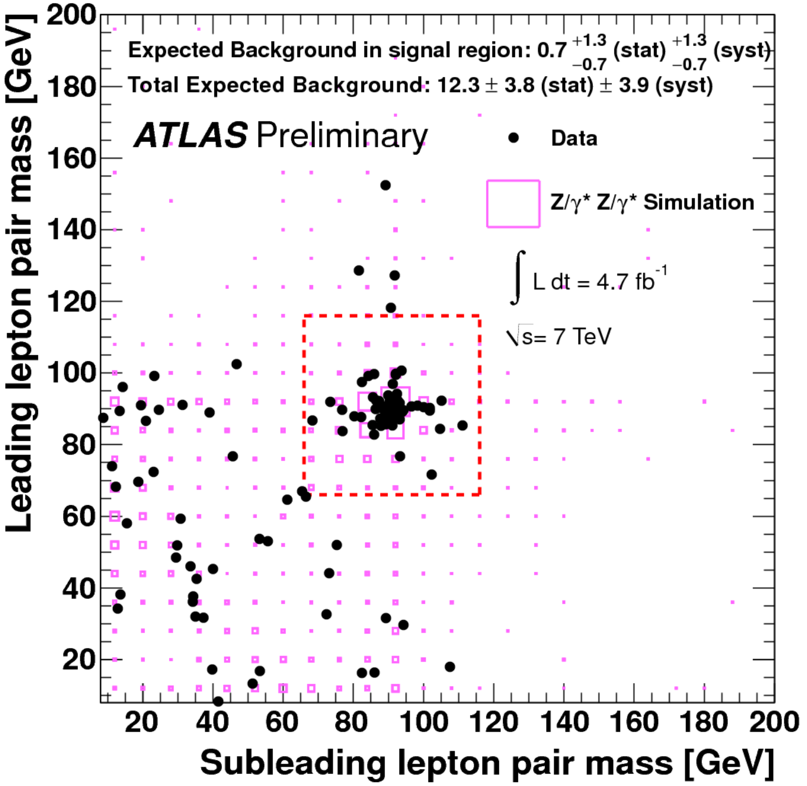
Electroweak di-boson production

Process	Final state	Measured total cross-section	Theory (NLO SM)
WW	**lνlν**	$\sigma^{tot}_{W^+W^-} = 53.4 \pm 2.1(\text{stat}) \pm 4.5(\text{syst}) \pm 2.1(\text{lumi})$ pb	45.1 ± 2.8 pb
ZZ	**4l**	$\sigma^{\text{tot}}_{ZZ} = 7.2^{+1.1}_{-0.9}$ (stat) $^{+0.4}_{-0.3}$ (syst) ± 0.3 (lumi) pb	$6.5^{+0.3}_{-0.2}$ pb
ZZ	**llνν**	$\sigma^{\text{tot}}_{ZZ} = 5.4^{+1.3}_{-1.2}(\text{stat.})^{+1.4}_{-1.0}(\text{syst.}) \pm 0.2(\text{lumi.})$ pb	$6.5^{+0.3}_{-0.2}$ pb

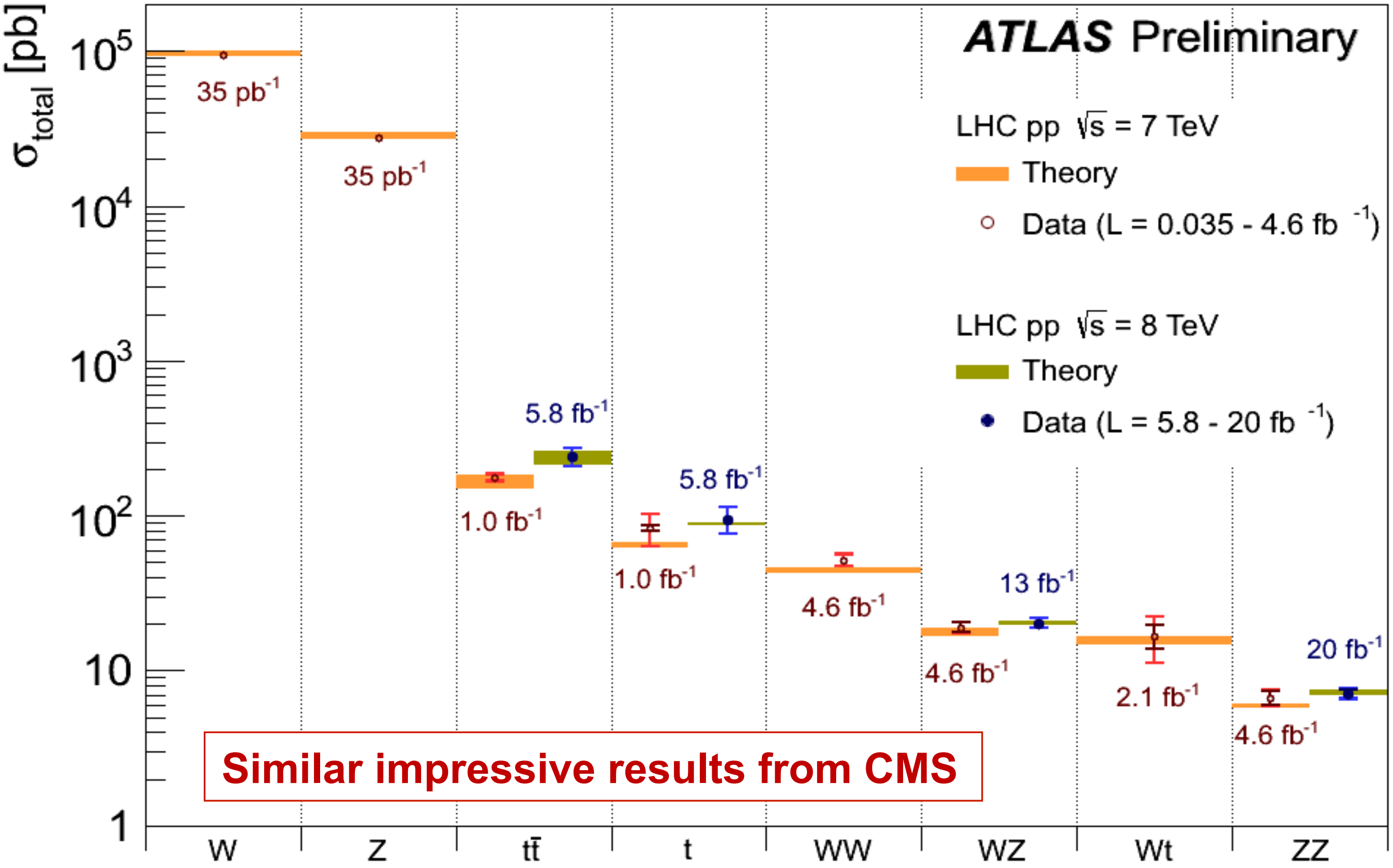
ATLAS-CONF-2012-025, 26, and 27







A summary of Standard Model measurements



Similar impressive results from CMS

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

Strategy toward physics

Before data taking starts:

- Strict quality controls of detector construction to meet physics requirements ✓
- Test beams (a 15-year activity culminating with a combined test beam in 2004) to understand and calibrate (part of) detector and validate/tune software tools ✓ (e.g. Geant4 simulation)
- Detailed simulations of realistic detector "as built and as installed" (including misalignments, material non-uniformities, dead channels, etc.)
  → test and validate calibration/alignment strategies ✓
- Experiment commissioning with cosmics in the underground cavern ✓

With the first data:

- Commission/calibrate detector/trigger in situ with physics (min.bias, $Z \to ll$, …) ✓
- "Rediscover" Standard Model, measure it at $\sqrt{s} = 7$ TeV (minimum bias, W, Z, tt, QCD jets, …)
- Validate and tune tools (e.g. MC generators) ✓
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)

↓

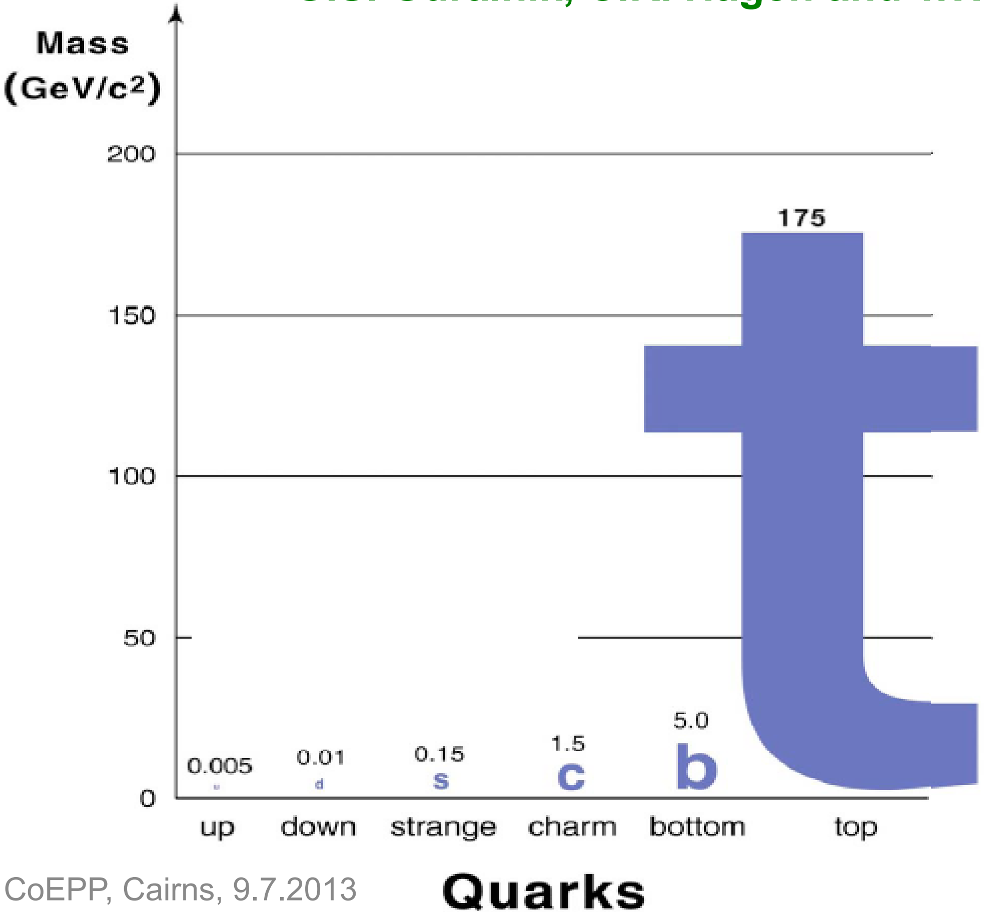
Prepare the road to discoveries …


HIGGS BOSON

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

Peter Higgs

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)



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

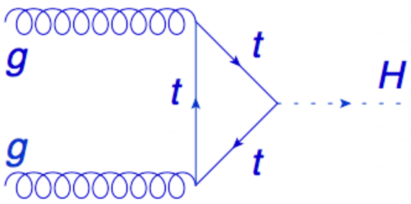
The LHC has sufficient energy to produce it for sure, if it exists

Francois Englert

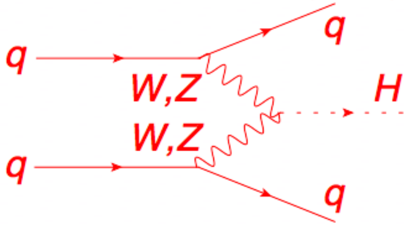
Search for the boson (H) of the EW symmetry breaking

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

gluon fusion

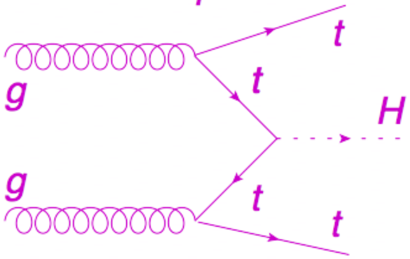


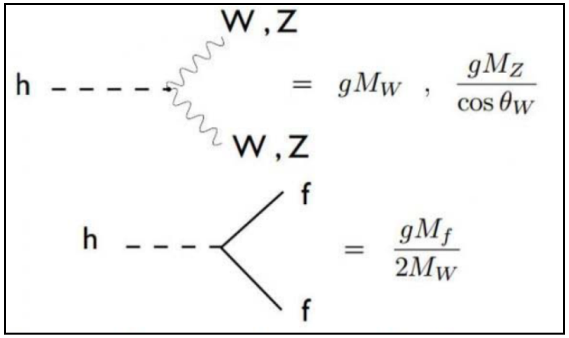
vector boson fusion (VBF)



associated prod. with W/Z

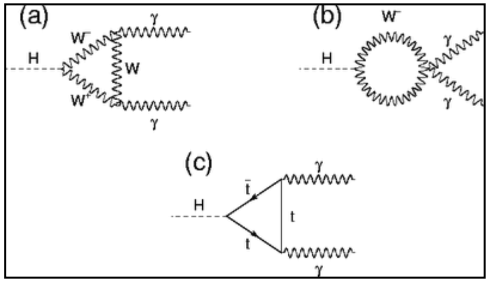
associated prod. with tt

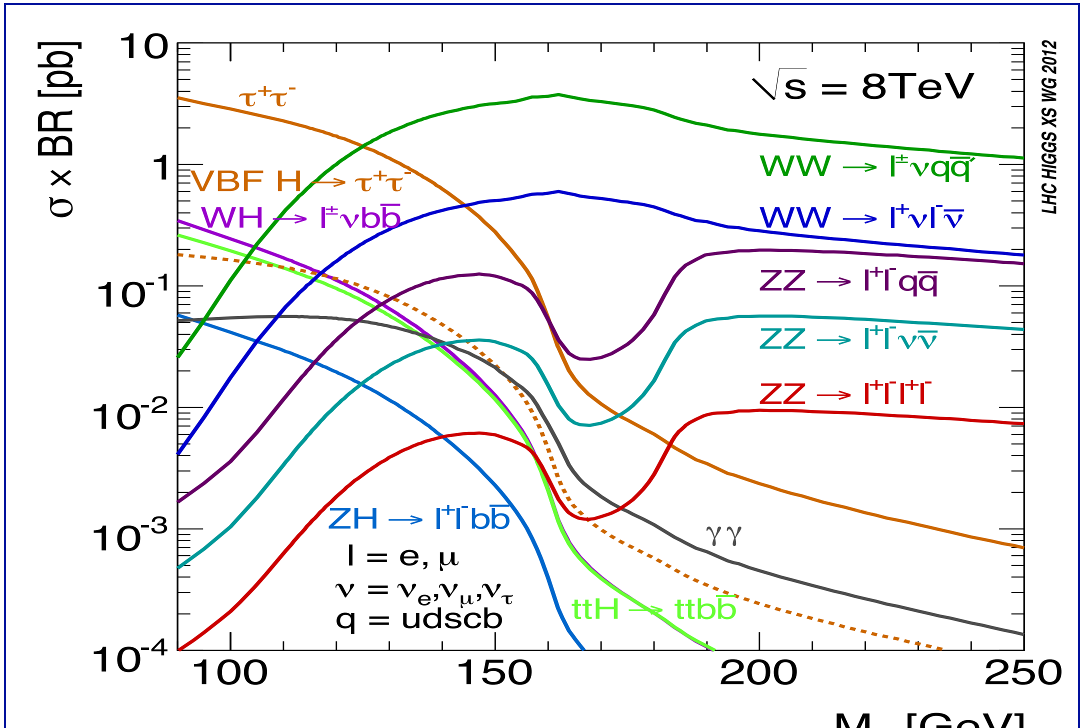




$$= gM_W \; , \; \frac{gM_Z}{\cos\theta_W}$$

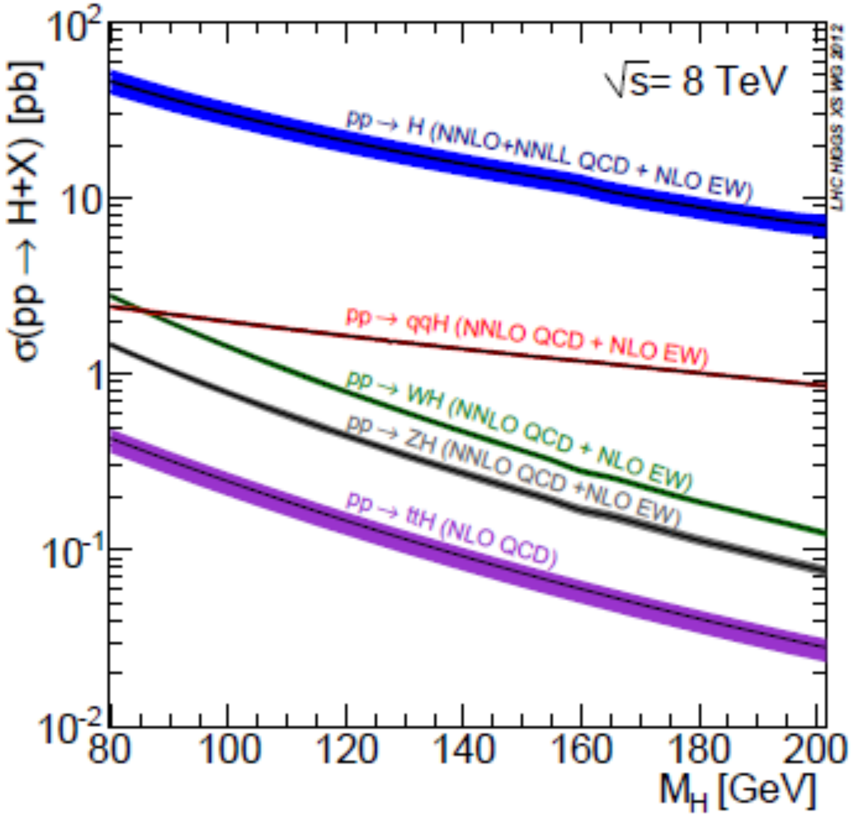
$$= \frac{gM_f}{2M_W}$$

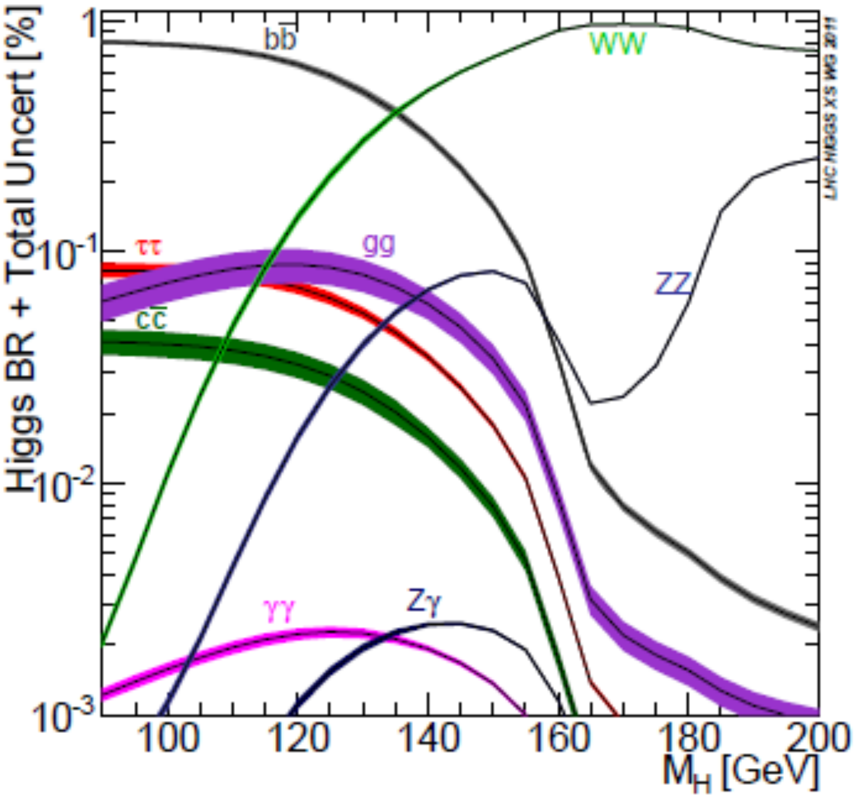




LHC roadmap to the Higgs

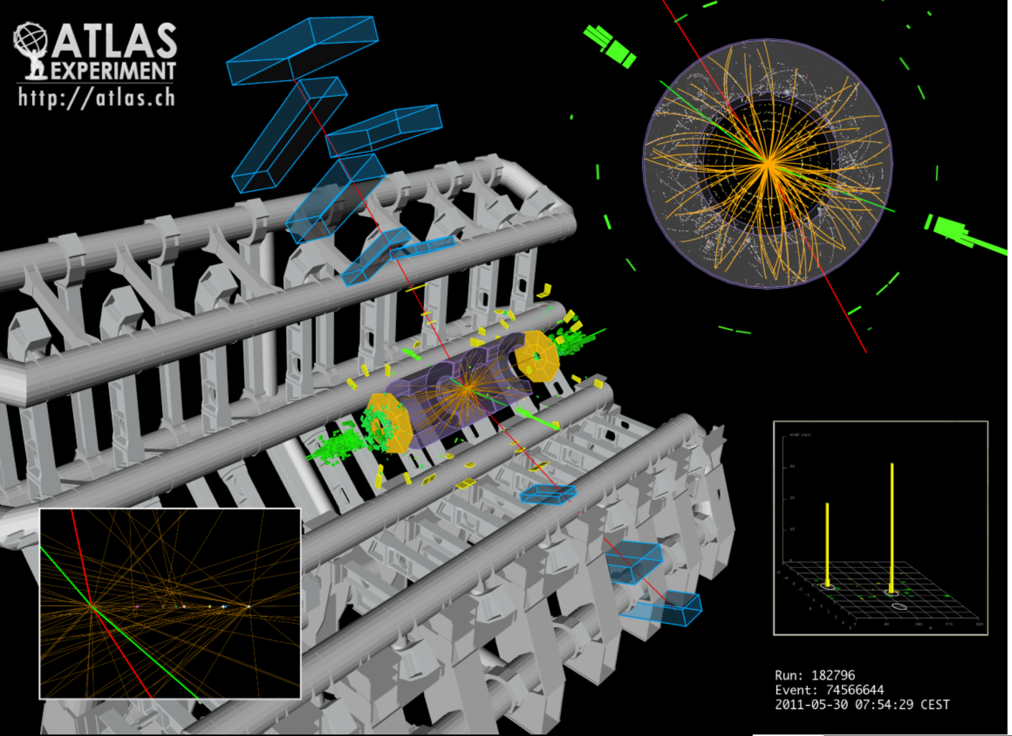
Higgs production cross-sections at 8 TeV, and branching fractions





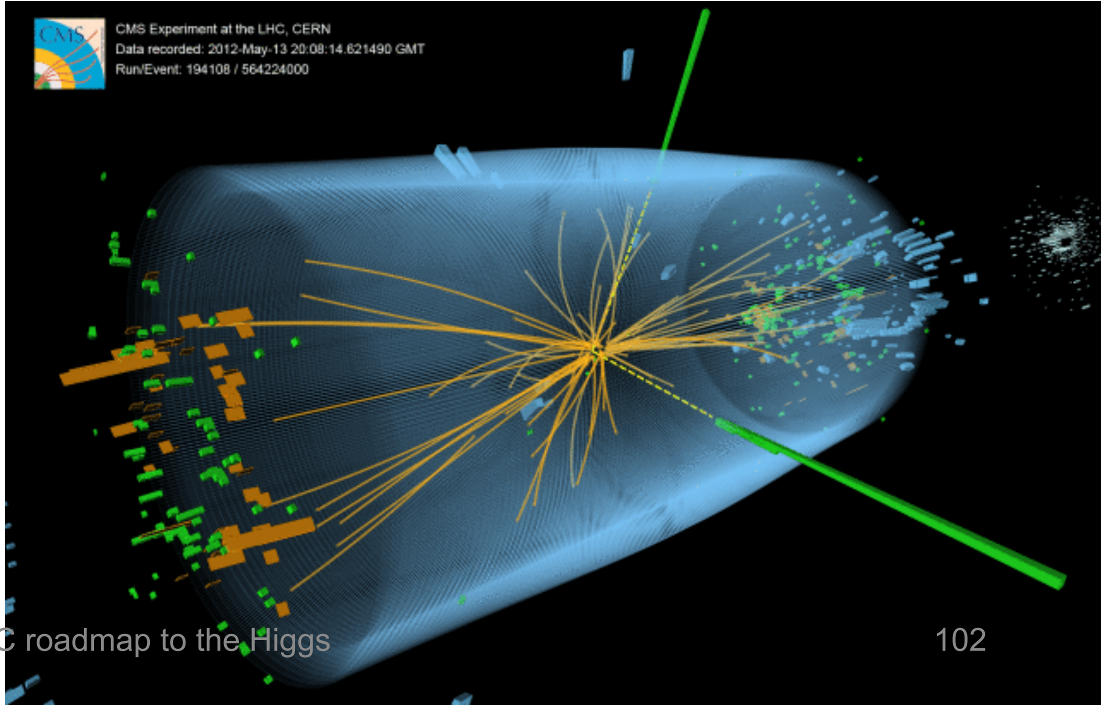
LHC Higgs cross-section working group, arXiv: 1101.0593 and 1201.3084
(the theoretical uncertainties are indicated by the width of the curves)

The Higgs(-~~like~~) boson

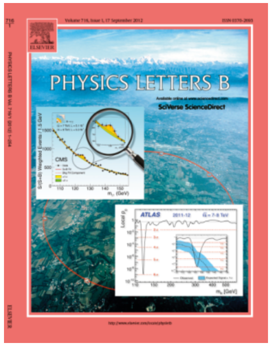


Candidate event for $H \rightarrow ZZ^* \rightarrow ee\,\mu\mu$

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



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



PHYSICS LETTERS B

Phys. Lett. B 716 (2012) 1

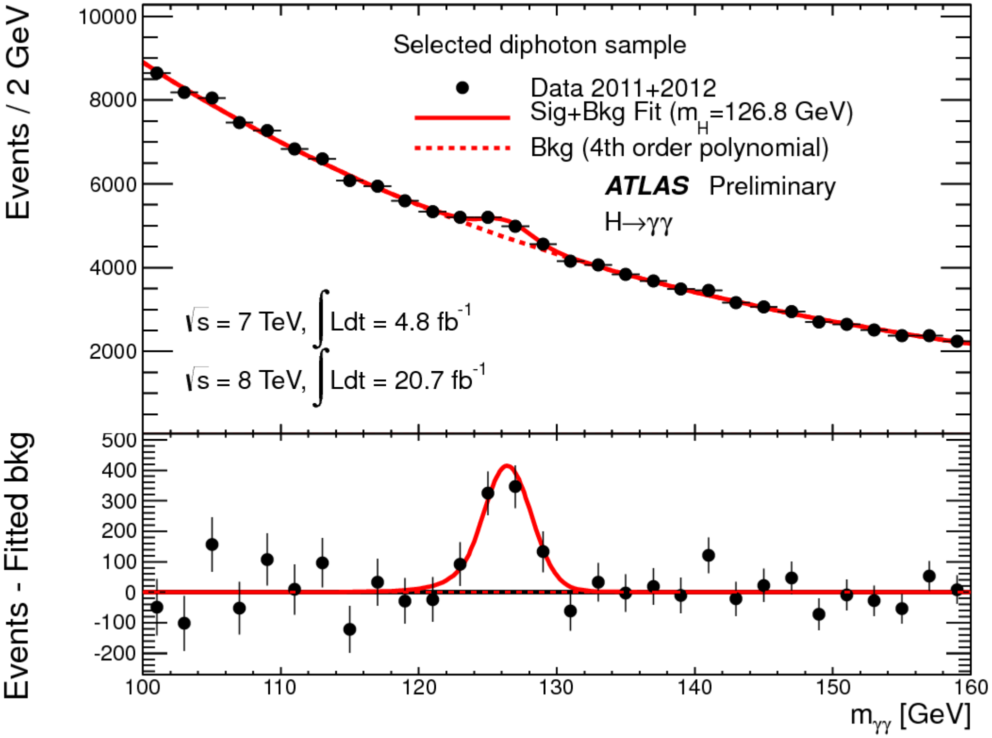
Phys. Lett. B 716 (2012) 30

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

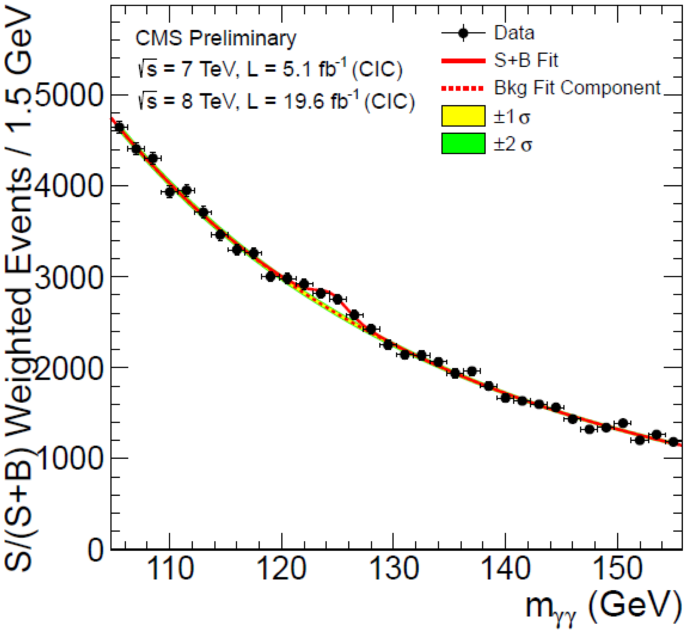
ICHEP2012
Melbourne

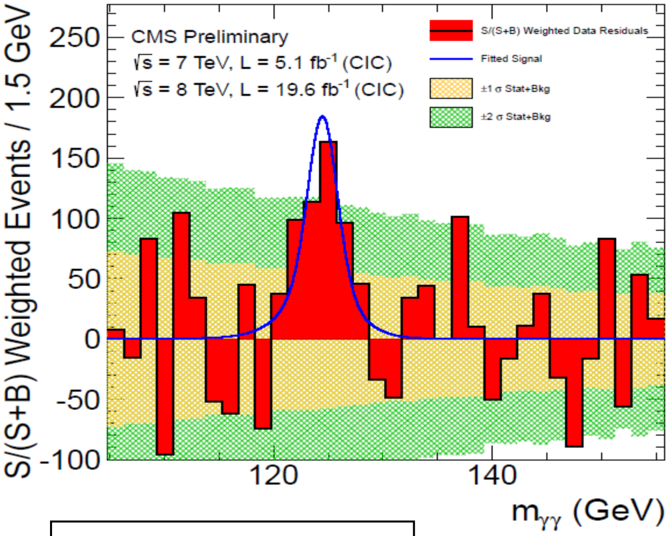
H → γγ

- 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 arXiv:1307.1427[hep.ex]





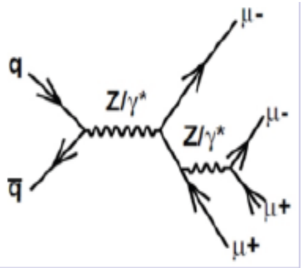
CMS-PAS-HIG-13-001

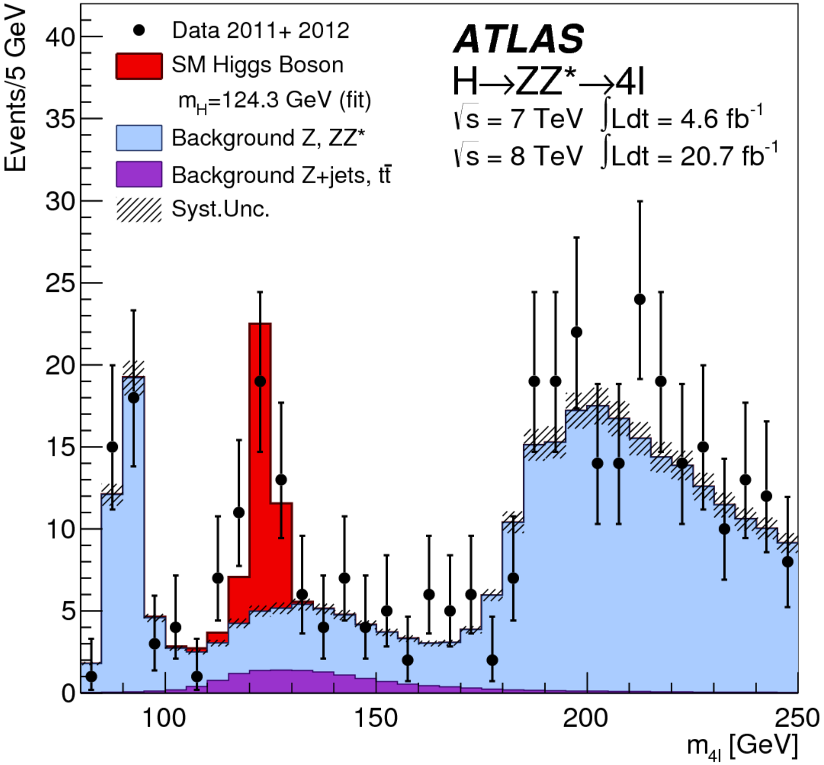
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (4e, 4μ, 2e2μ)

- **Rare process, small cross section: σ ~ 2-5 fb**
- **However: pure: S/B ~ 1**
- **4 leptons:**
- **Main background: $ZZ^{(*)}$ (irreducible)**

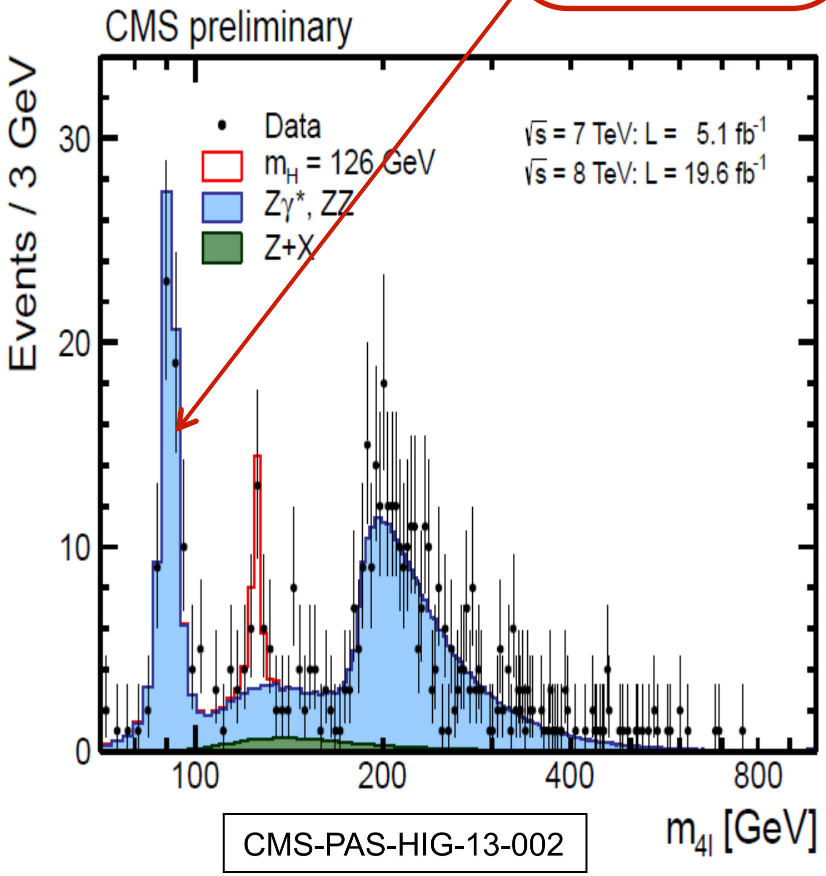
  In addition: Zbb, Z+jets, tt with two leptons from b-quarks or jets

Why a Z peak ?





ATLAS-CONF-2013-013 and arXiv:1307.1427[hep.ex]

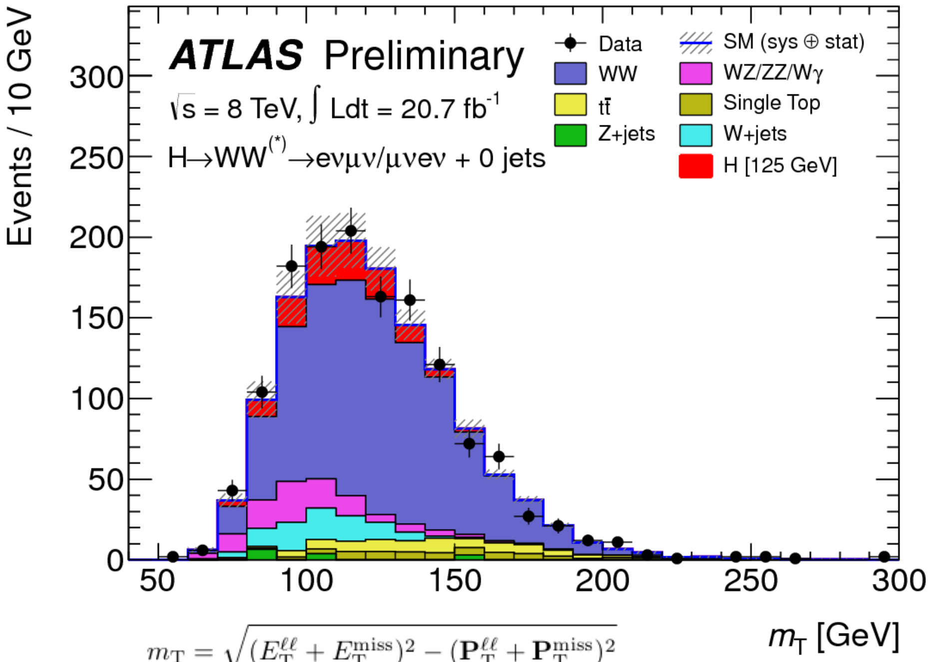


CMS-PAS-HIG-13-002

H → WW$^{(*)}$ → lνlν (eνeν, μνμν, eνμν)

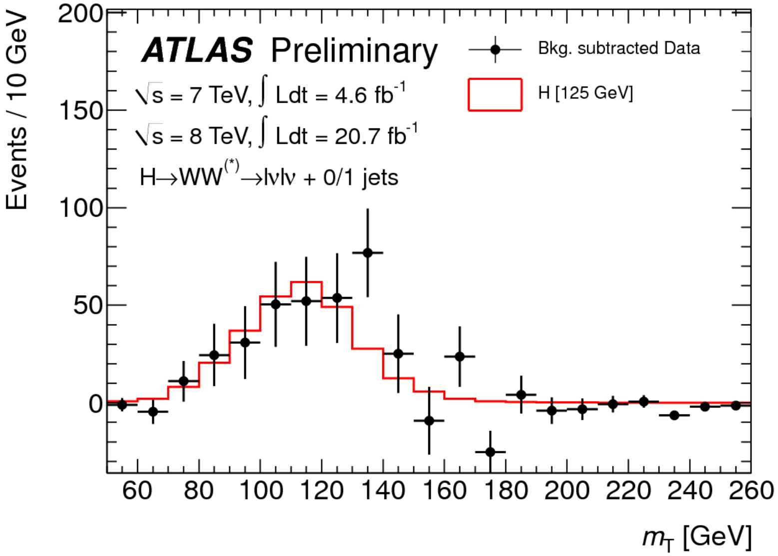
- Very sensitive channel over ~ 125-180 GeV (σ ~ 200 fb)
- Challenging: 2ν → no mass reconstruction/peak → "counting channel"
- 2 isolated opposite-sign leptons, use eνμν only for 2012 data, large E_T^{miss}
- Main backgrounds: WW, top, Z+jets, W+jets
- Topological cuts against "irreducible" WW background

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



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

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



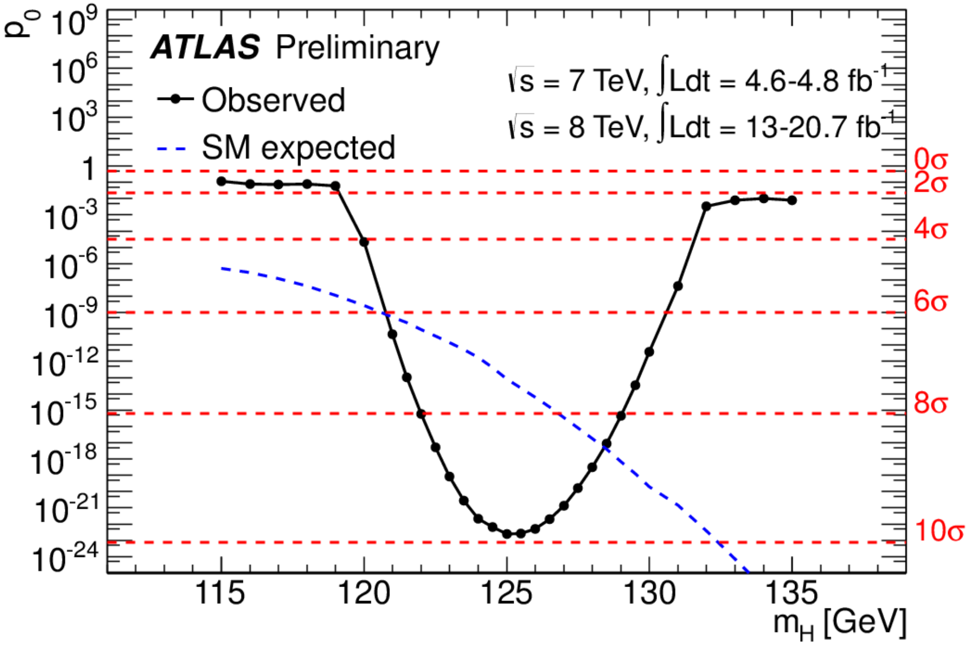
ATLAS-CONF-2013-030 and arXiv:1307.1427[hep.ex]

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]

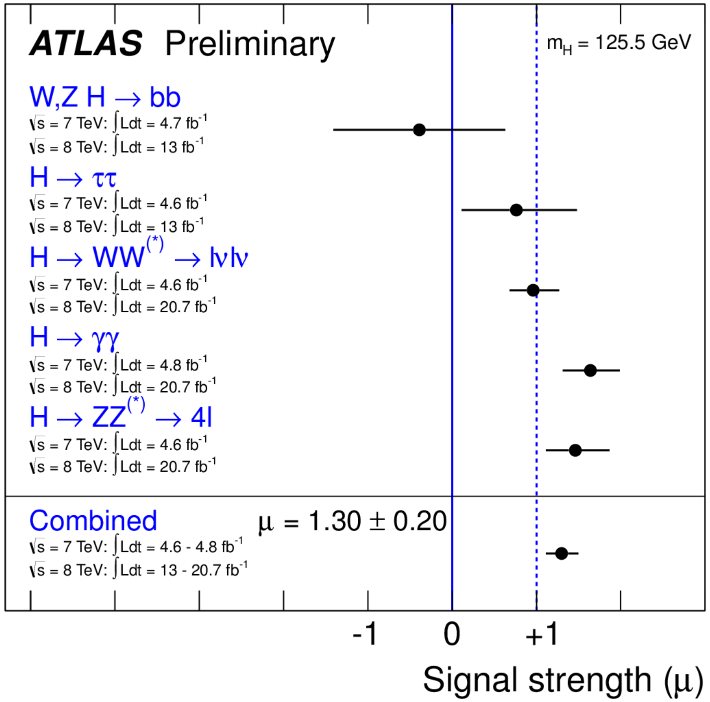
Observed data compared to the probability that the background fluctuates to fake the observed excess of events, and what is expected from a SM Higgs

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



ATLAS-CONF-2013-034

CMS-PAS-HIG-13-005



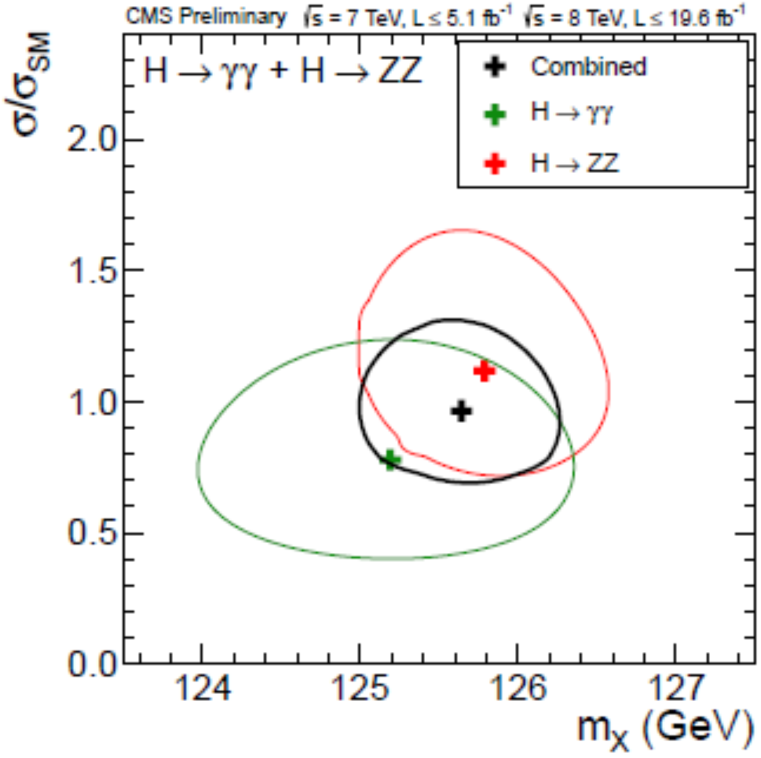
$\mu = 1.30 \pm 0.20$ [ATLAS]
$\mu = 0.80 \pm 0.14$ [CMS]

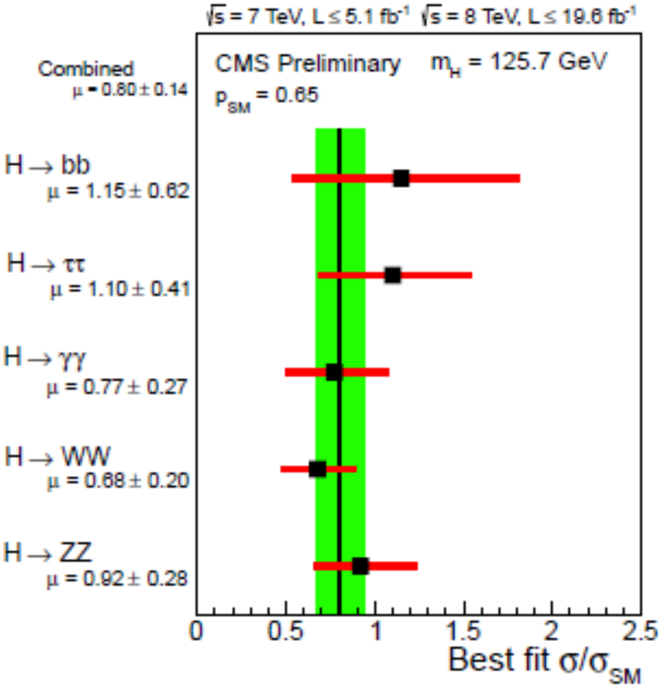
How significant is the signal for the new particle ?

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

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





ATLAS-CONF-2013-034

CMS-PAS-HIG-13-005

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

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

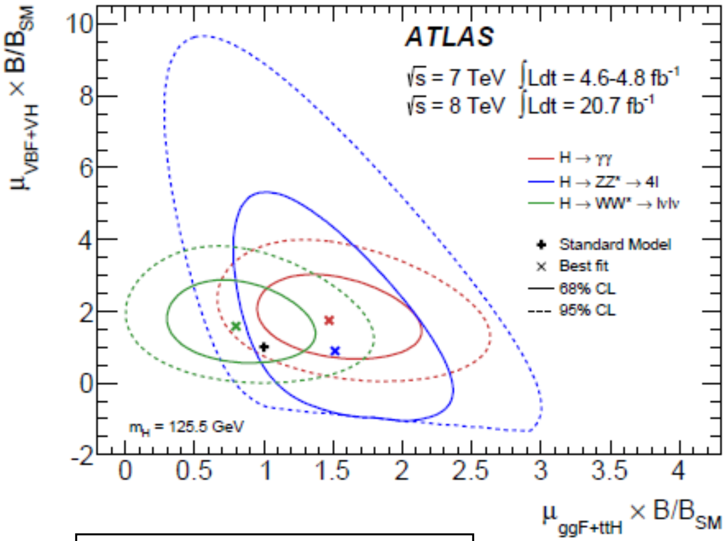
It will be important to understand with great precision if it is the only scalar boson of the Standard Model 'Brout-Englert-Higgs' mechanism to break the electroweak symmetry, or if it is only part of a broader physics picture going *Beyond the Standard Model*

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

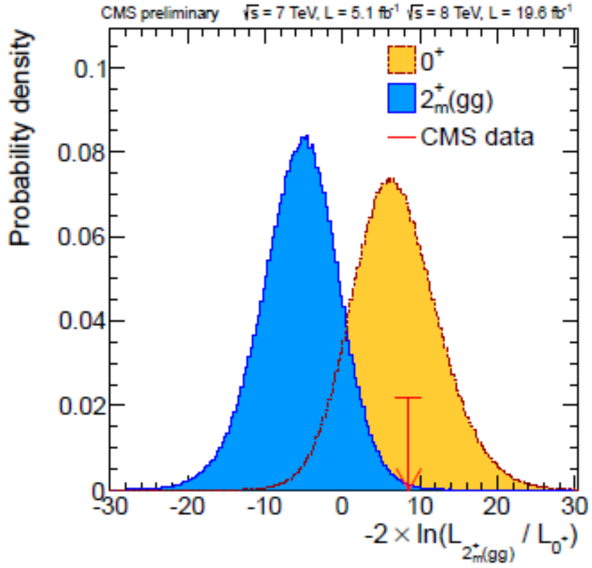
For the experts:

Couplings
Production modes
Spin-parity

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



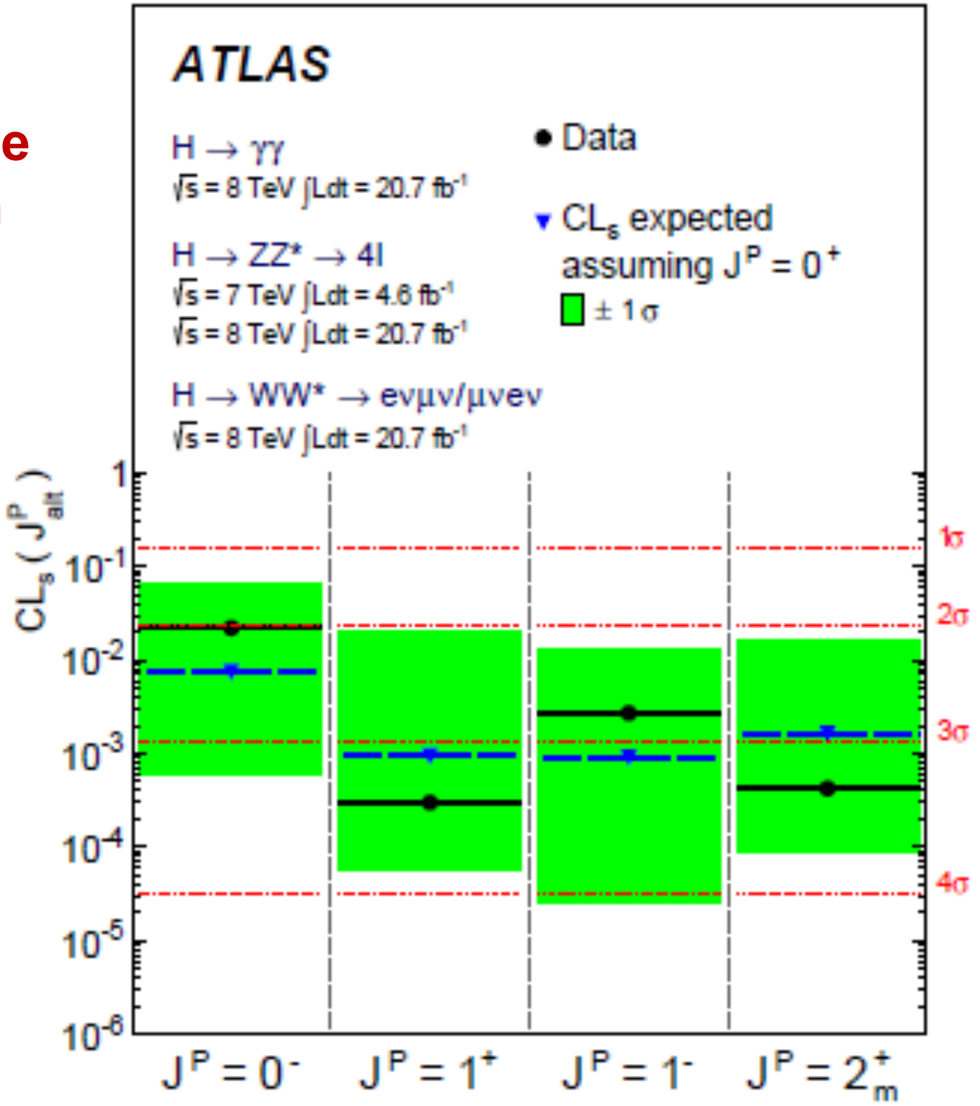
arXiv:1307.1427 [hep.ex]



CMS-PAS-HIG-13-005

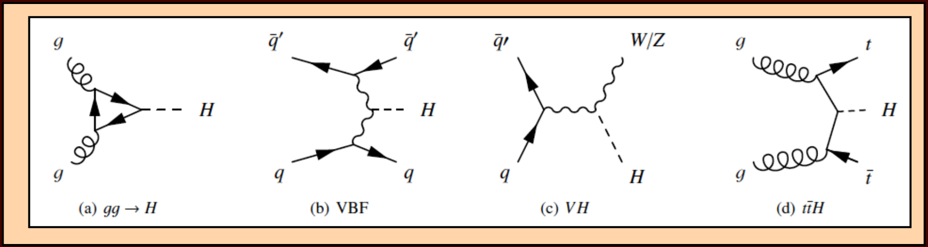
Hot off the press:

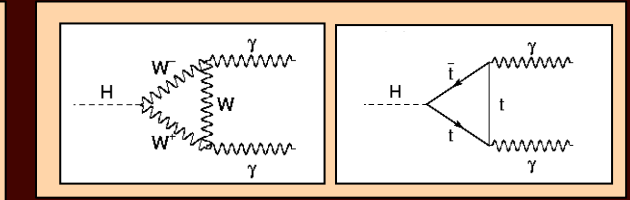
Confidence levels of alternative Spin-Parity assignments when assuming the SM expected 0^+



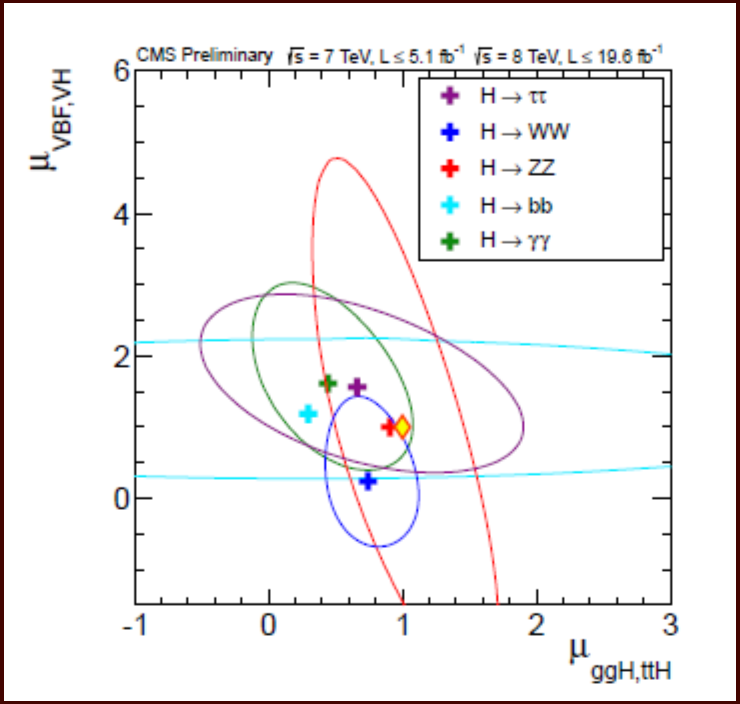
arXiv:1307.1432 [hep.ex]

Couplings



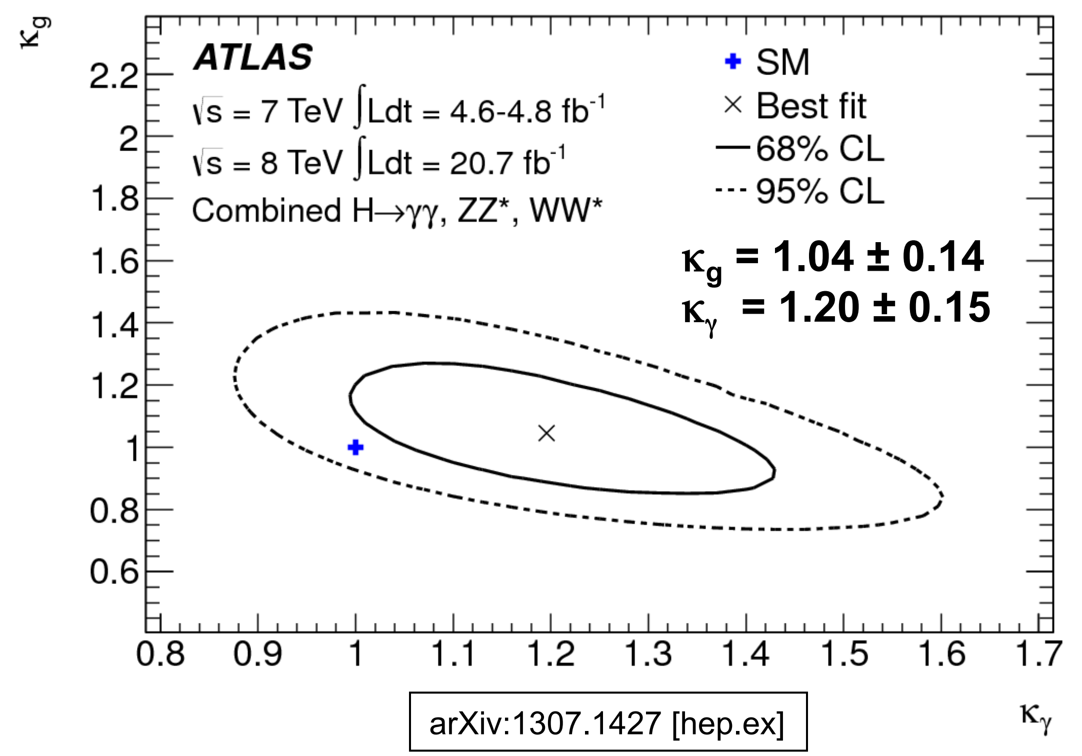


$$k_i^2 = \frac{\Gamma_i^{data}}{\Gamma_i^{SM}}$$



CMS-PAS-HIG-13-005

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

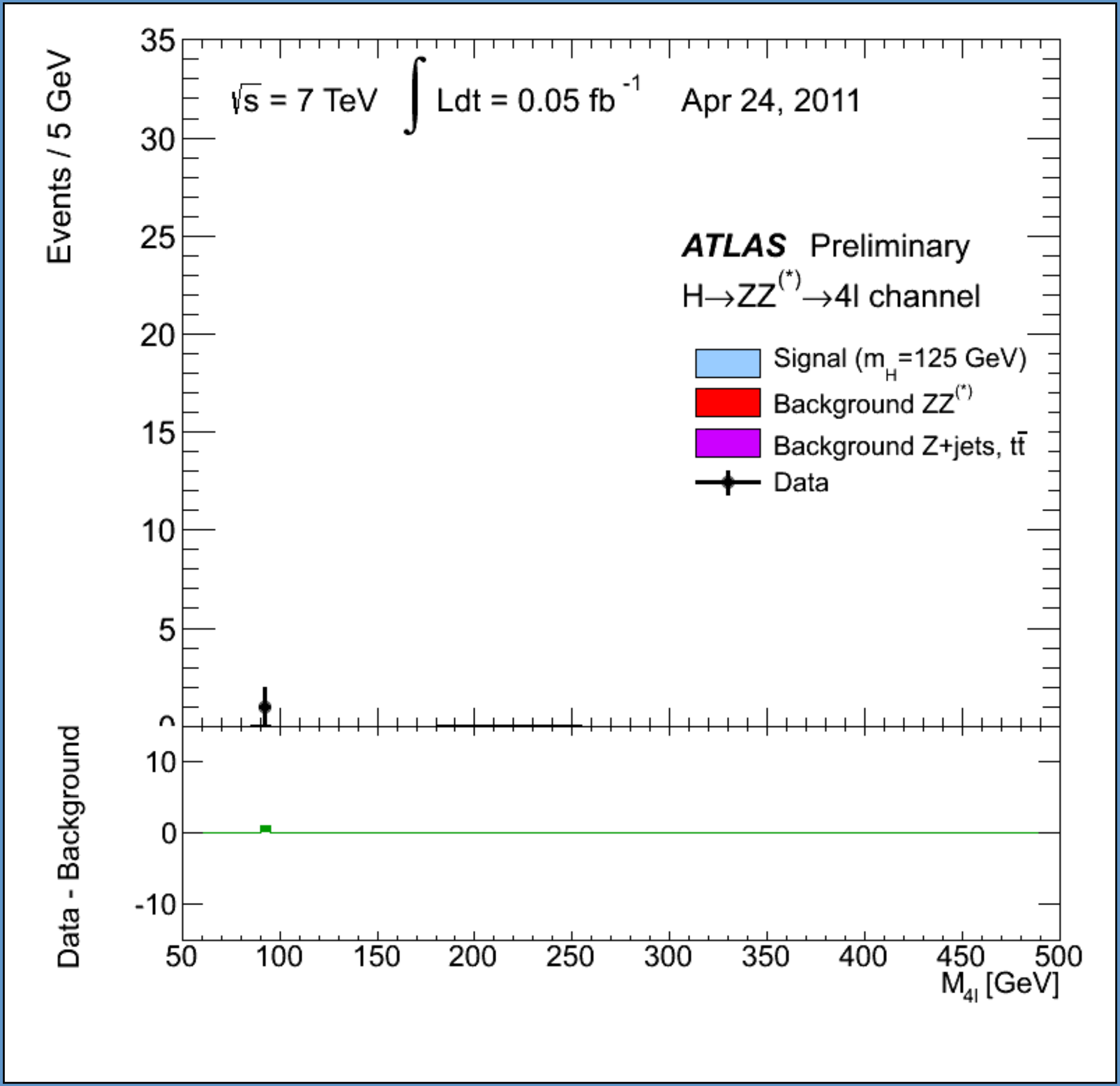


arXiv:1307.1427 [hep.ex]

→ New particle couples to other particles with strength proportional to their masses (to accomplish its job → Higgs mechanism) → 1st "fingerprint" of the Higgs boson

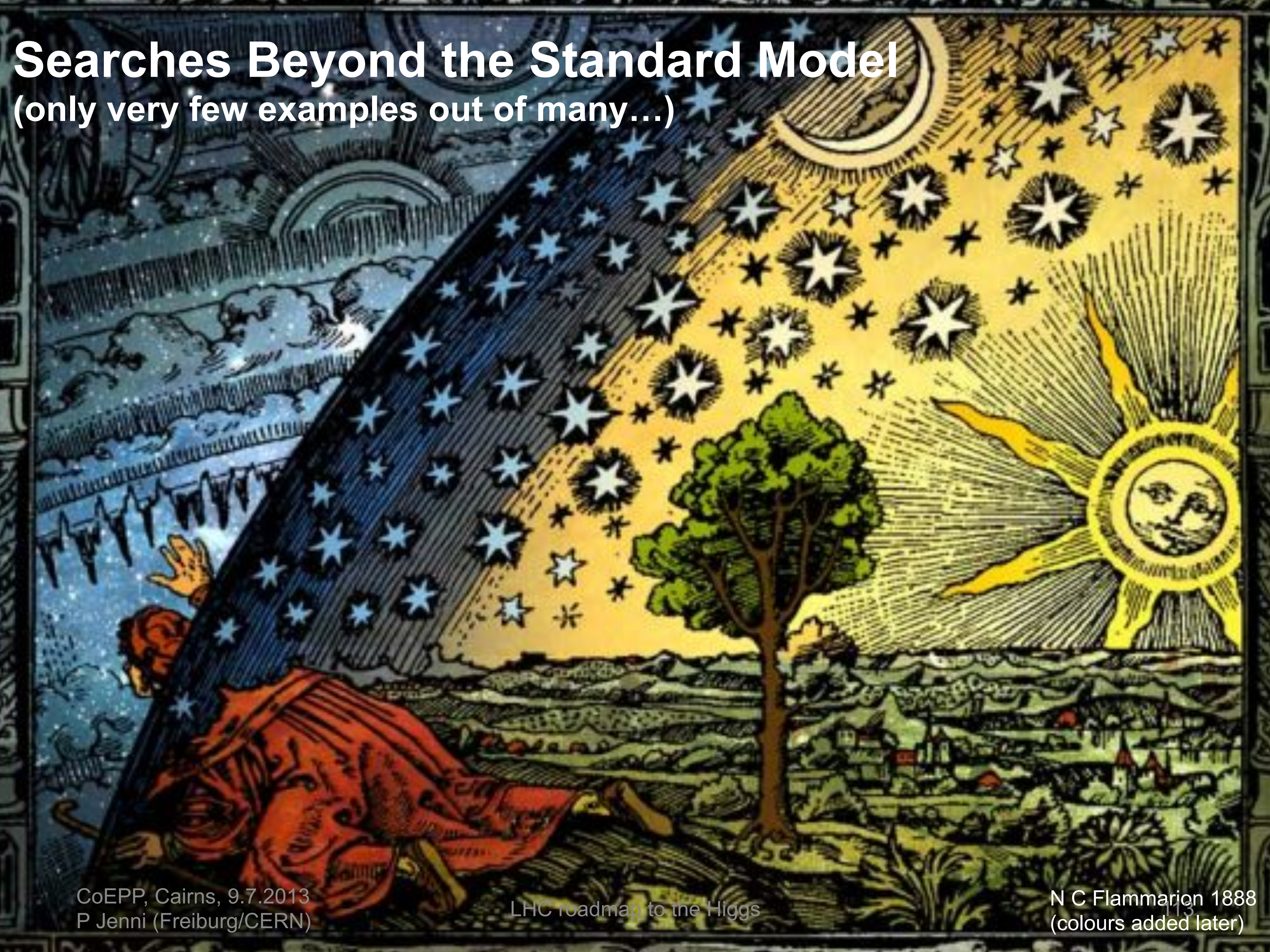
→ No significant New Physics contributions to its couplings (within present uncertainty)

Birth and evolution of a signal: H→ 4l



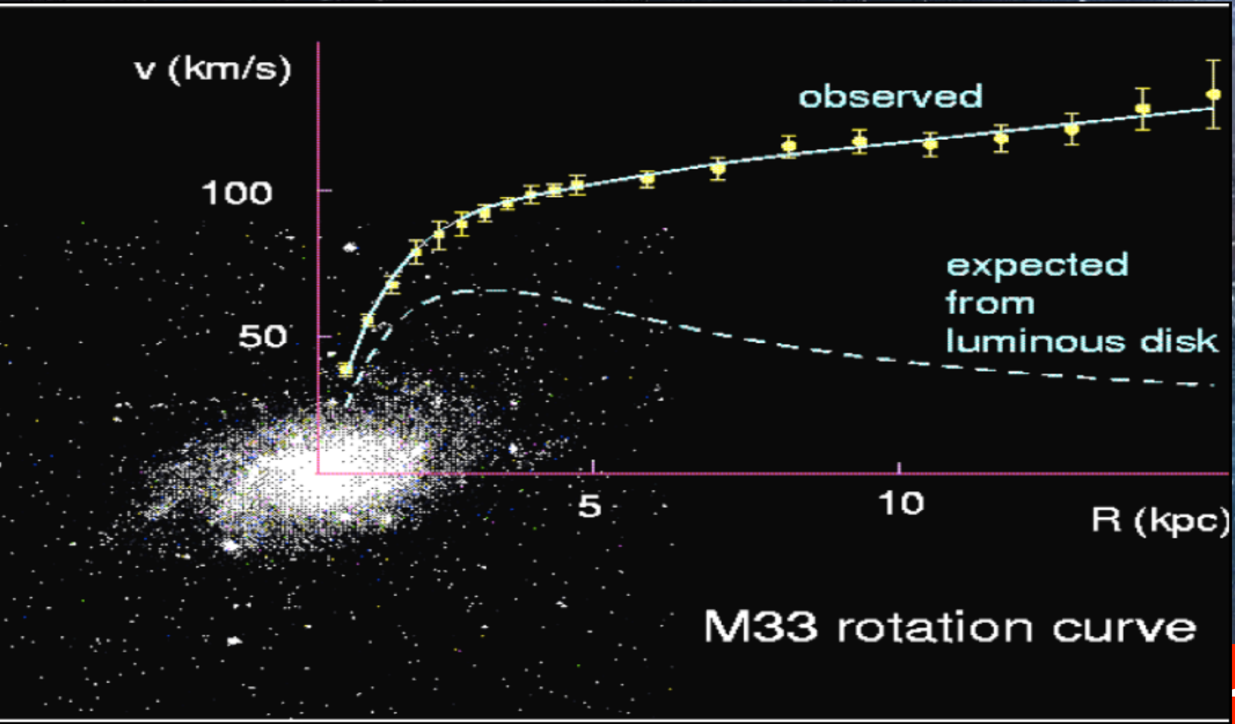
Searches Beyond the Standard Model

(only very few examples out of many…)



N C Flammarion 1888
(colours added later)

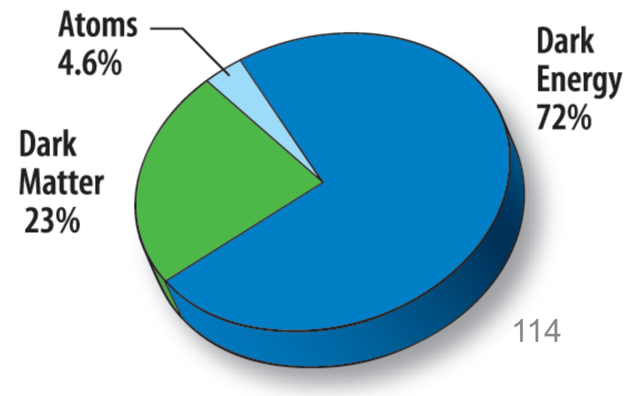
Dark Matter in the Universe



M33 rotation curve

Vera Rubin ~ 1970

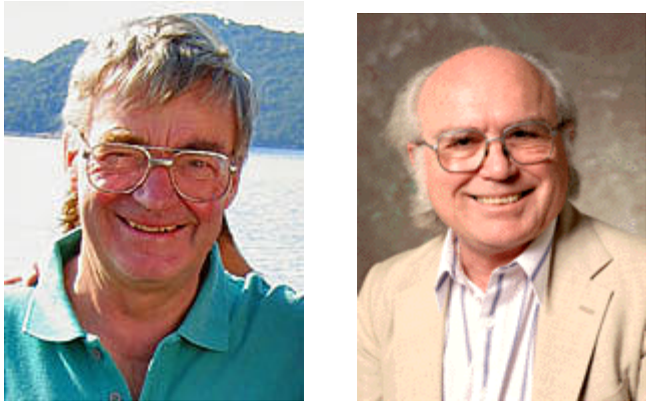
mmetric’ particles ?



F. Zwicky 1898-1974

Supersymmetry (SUSY)

(Julius Wess and Bruno Zumino, 1974)

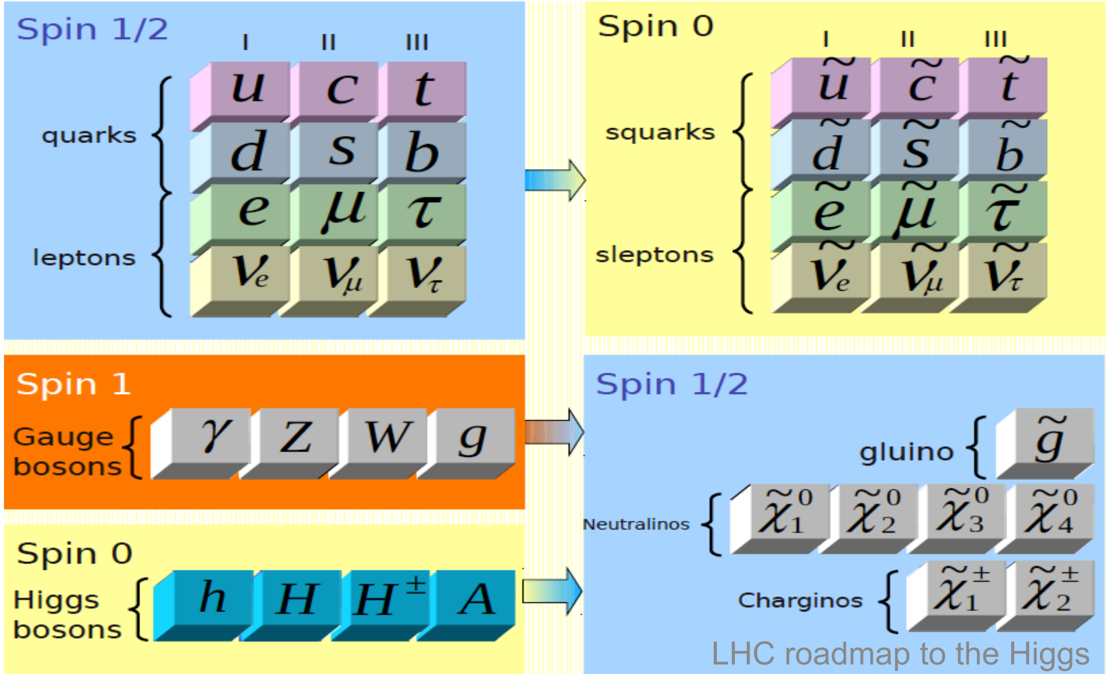


Establishes a symmetry between fermions (matter) and bosons (forces):

- 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?**



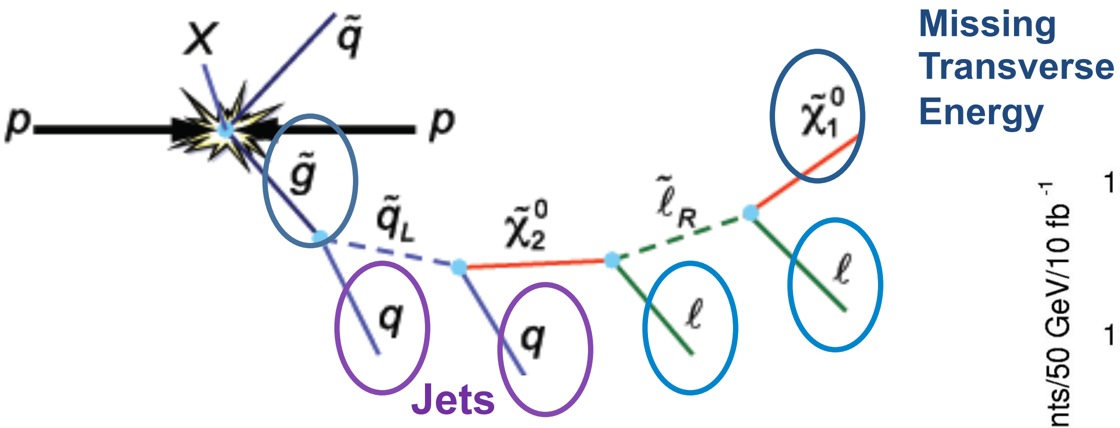
LHC roadmap to the Higgs

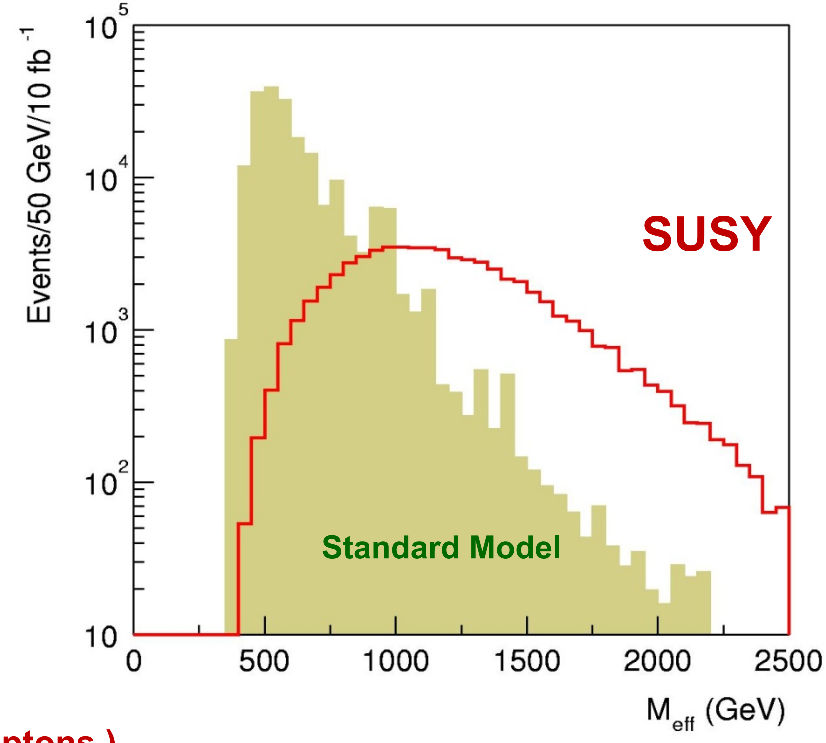
Motivation:

- ***Unification (fermions-bosons, matter-forces)***
- ***Solves some deep problems of the Standard Model (hierarchy, gauge couplings unification)***
- ***Dark matter candidate***

In practice SUSY searches at LHC are rather complicated

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





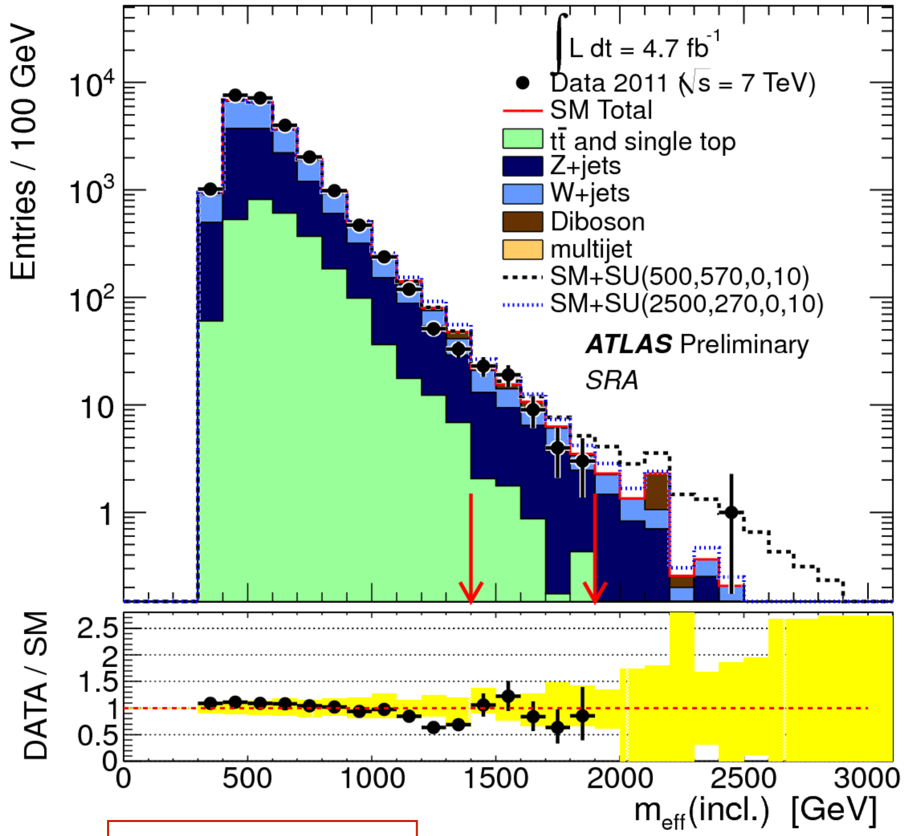
Meff = Etmiss + Σ pT(jets)

- **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**

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

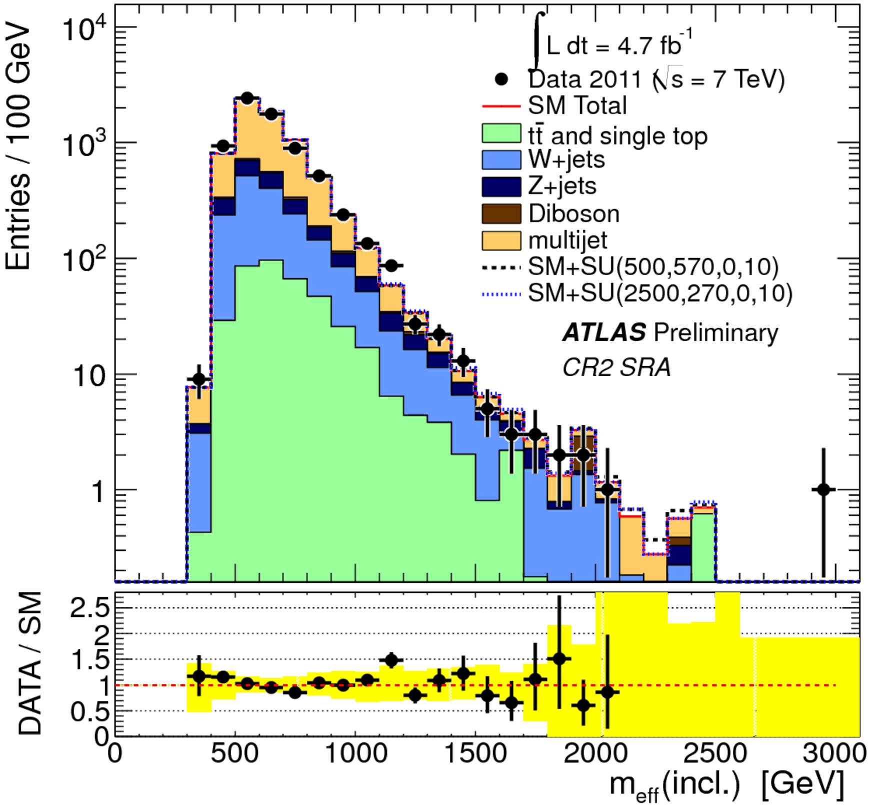
- **0-lepton + 2−6 jets + high MET (based on Et-miss+jet triggers)**
- **0-lepton + 6−9 (multi-)jets + MET (based on multi-jet triggers)**
- **1-lepton + 3,4 jets + high MET (based on lepton triggers)**

Example: O-leptons + 2-6 Jets analysis



A signal region

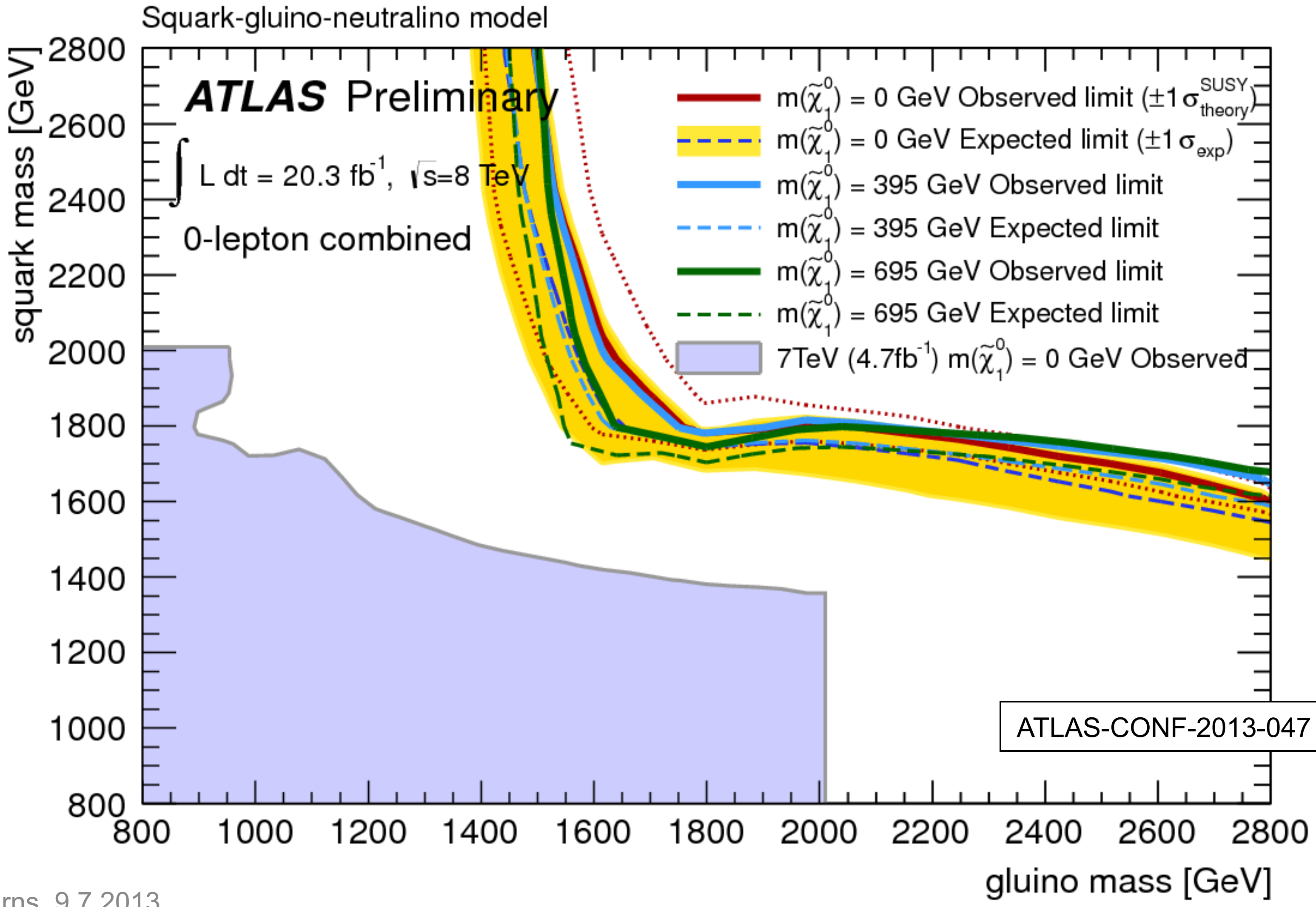
ATLAS-CONF-2012-033, 037, and 041



A control region where no signal is expected

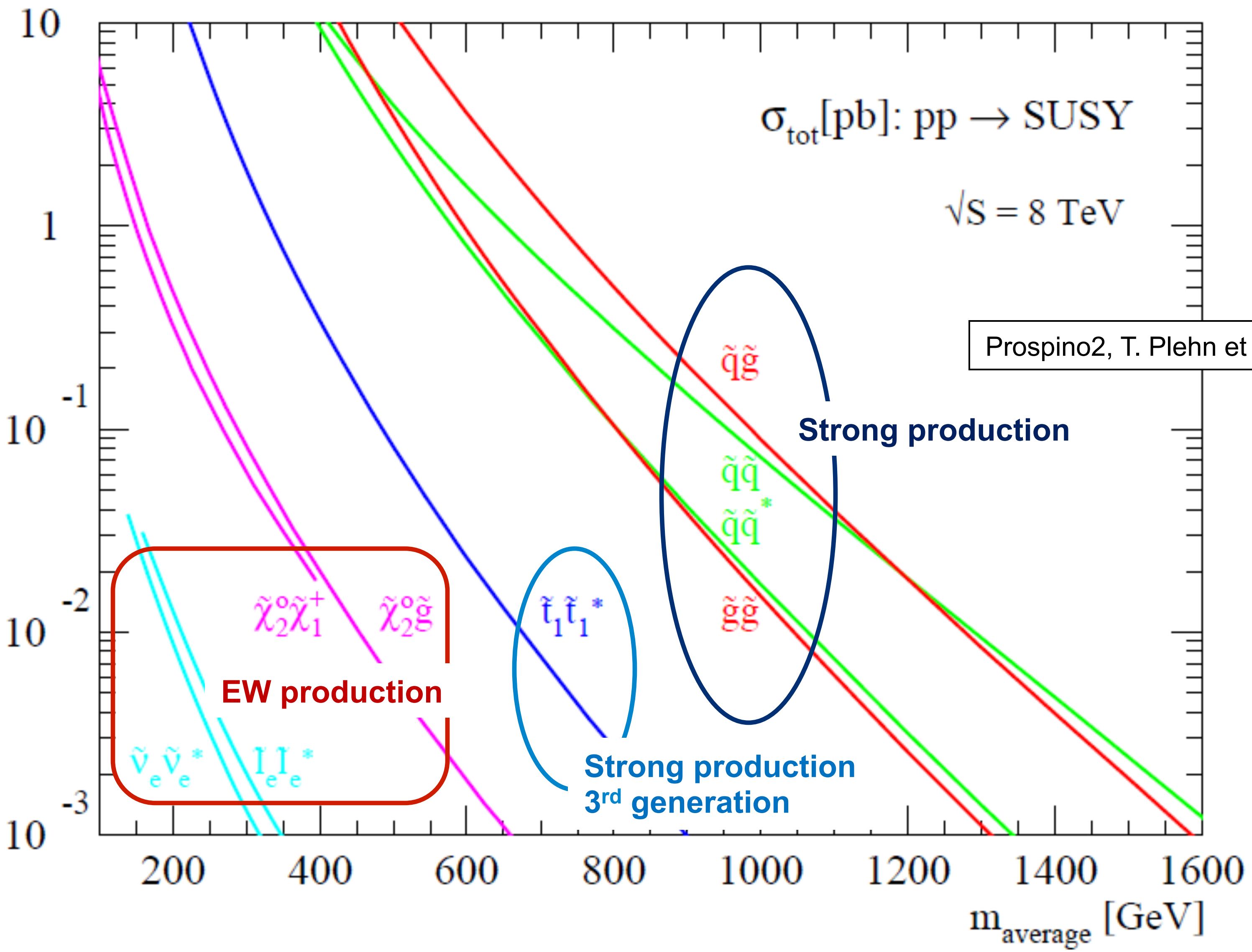
Interpretation of the results

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



ATLAS-CONF-2013-047

Expected production cross-sections at LHC



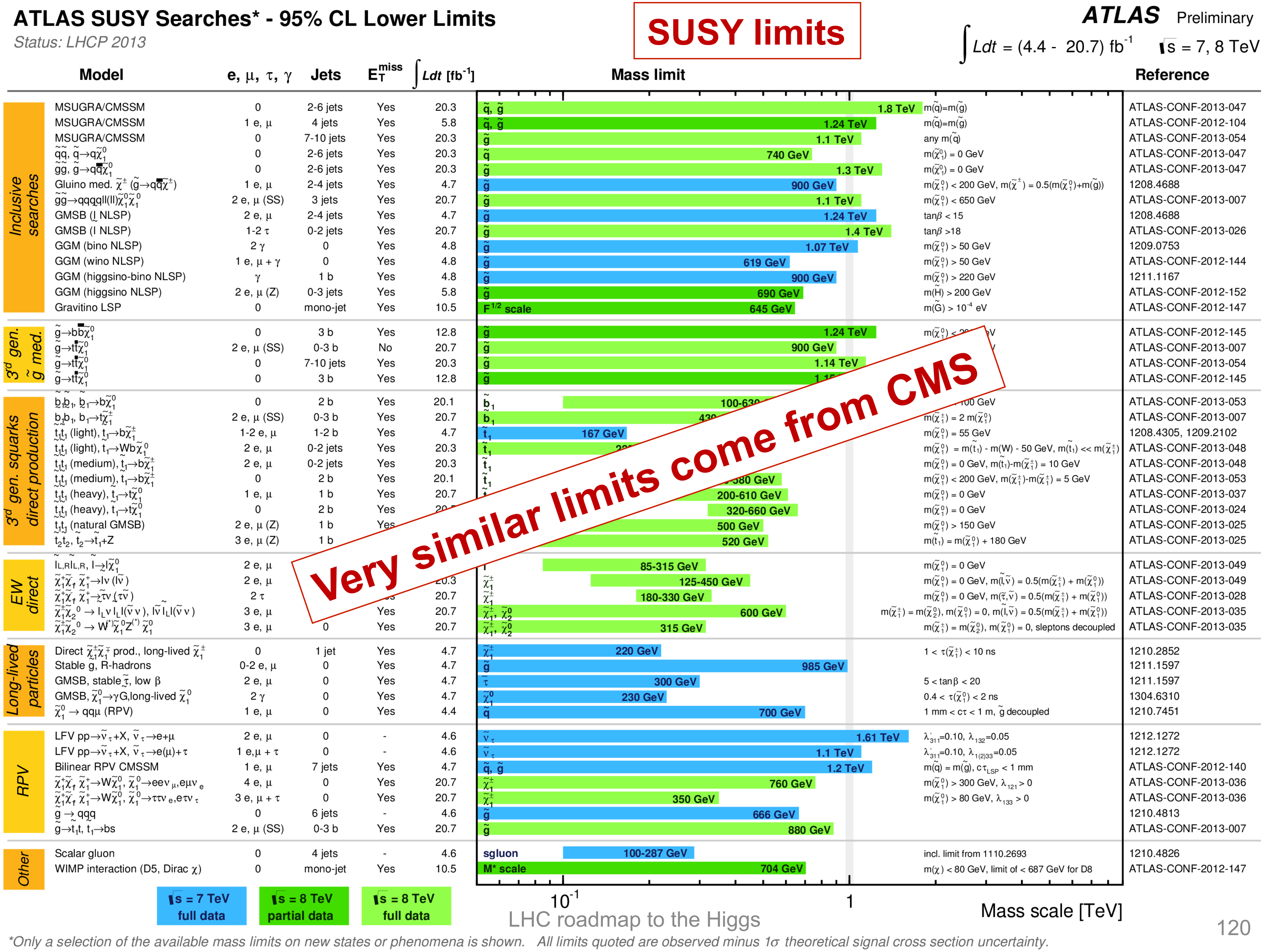
Prospino2, T. Plehn et al.

Strong production

EW production

Strong production
3^{rd} generation

SUSY limits



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: LHCP 2013

ATLAS Preliminary

$\int Ldt = (4.4 - 20.7)\ \mathrm{fb}^{-1}$ $\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int Ldt\ [\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.8 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	4 jets	Yes	5.8	$\tilde{q}, \tilde{g}$ 1.24 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2012-104
	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
	Gluino med. $\tilde{\chi}^\pm$ ($\tilde{g}\to q\bar{q}\tilde{\chi}^\pm$)	1 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$ < 200 GeV, $m(\tilde{\chi}^\pm) = 0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	1208.4688
	$\tilde{g}\tilde{g}\to qqqqll(ll)\tilde{\chi}_1^0\tilde{\chi}_1^0$	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 ($\tilde{l}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	tanβ < 15	1208.4688
	GMSB ($\tilde{\tau}$ 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	12.8	$\tilde{g}$ 1.24 TeV	$m(\tilde{\chi}_1^0)$ < 2[illegible]	ATLAS-CONF-2012-145
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 b	No	20.7	$\tilde{g}$ 900 GeV	[illegible]	ATLAS-CONF-2013-007
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.14 TeV	[illegible]	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	3 b	Yes	12.8	$\tilde{g}$ 1.1[illegible]	[illegible]	ATLAS-CONF-2012-145
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 [illegible]	[illegible]00 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 [illegible]	$m(\tilde{\chi}_1^\pm) = 2\ m(\tilde{\chi}_1^0)$	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	$\tilde{t}_1$ 22[illegible]	$m(\tilde{\chi}_1^0) = m(\tilde{t}_1) - m(W) - 50$ 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	$\tilde{t}_1$ [illegible]	$m(\tilde{\chi}_1^0)$ = 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	$\tilde{t}_1$ [illegible]-580 GeV	$m(\tilde{\chi}_1^0)$ < 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	200-610 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	[illegible]	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	[illegible]	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	[illegible]	[illegible]	520 GeV	$m(\tilde{t}_1) = m(\tilde{\chi}_1^0)$ + 180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{l}_{L,R}\tilde{l}_{L,R}, \tilde{l}\to l\tilde{\chi}_1^0$	2 e, μ	[illegible]	[illegible]	[illegible]	$\tilde{l}$ 85-315 GeV	$m(\tilde{\chi}_1^0)$ = 0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{l}\nu(l\tilde{\nu})$	2 e, μ	[illegible]	[illegible]	[illegible]	$\tilde{\chi}_1^\pm$ 125-450 GeV	$m(\tilde{\chi}_1^0)$ = 0 GeV, $m(\tilde{l},\tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	[illegible]	[illegible]	20.7	$\tilde{\chi}_1^\pm$ 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
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to \tilde{l}_L\nu\tilde{l}_Ll(\tilde{\nu}\nu), l\tilde{\nu}\tilde{l}_Ll(\tilde{\nu}\nu)$	3 e, μ	[illegible]	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{l},\tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to W^{(*)}\tilde{\chi}_1^0Z^{(*)}\tilde{\chi}_1^0$	3 e, μ	0	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 $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ prod., long-lived $\tilde{\chi}_1^\pm$	0	1 jet	Yes	4.7	$\tilde{\chi}_1^\pm$ 220 GeV	$1 < \tau(\tilde{\chi}_1^\pm) < 10$ ns	1210.2852
	Stable $\tilde{g}$, R-hadrons	0-2 e, μ	0	Yes	4.7	$\tilde{g}$ 985 GeV		1211.1597
	GMSB, stable $\tilde{\tau}$, low β	2 e, μ	0	Yes	4.7	$\tilde{\tau}$ 300 GeV	5 < tanβ < 20	1211.1597
	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	$0.4 < \tau(\tilde{\chi}_1^0) < 2$ ns	1304.6310
	$\tilde{\chi}_1^0 \to qq\mu$ (RPV)	1 e, 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
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\nu_\mu, e\mu\nu_e$	4 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	$m(\tilde{\chi}_1^0)$ > 300 GeV, $\lambda_{121} > 0$	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e, μ + τ	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	$m(\tilde{\chi}_1^0)$ > 80 GeV, $\lambda_{133} > 0$	ATLAS-CONF-2013-036
	$\tilde{g} \to qqq$	0	6 jets	-	4.6	$\tilde{g}$ 666 GeV		1210.4813
	$\tilde{g}\to\tilde{t}_1t, \tilde{t}_1\to bs$	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

🟦 $\sqrt{s}$ = 7 TeV full data

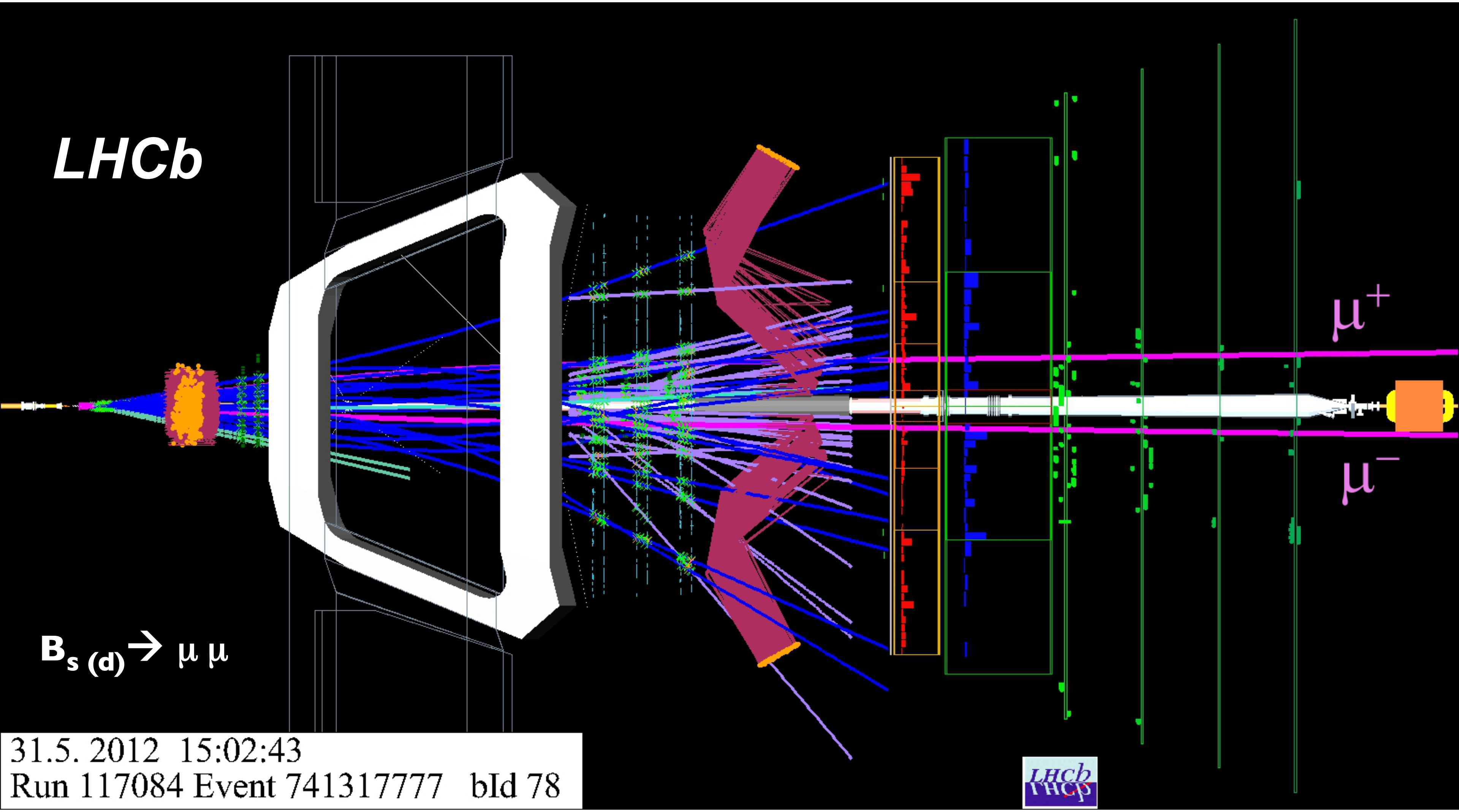
🟩 $\sqrt{s}$ = 8 TeV partial data

🟩 $\sqrt{s}$ = 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

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



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

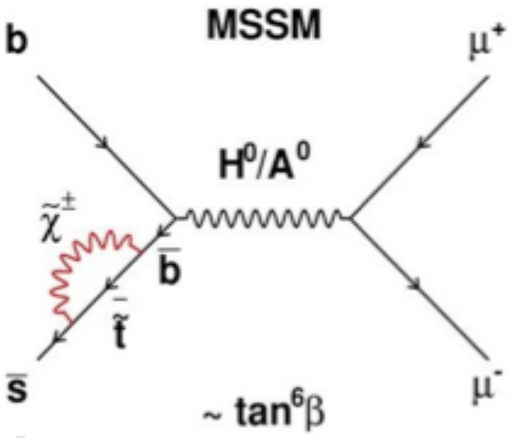
31.5. 2012 15:02:43
Run 117084 Event 741317777 bId 78

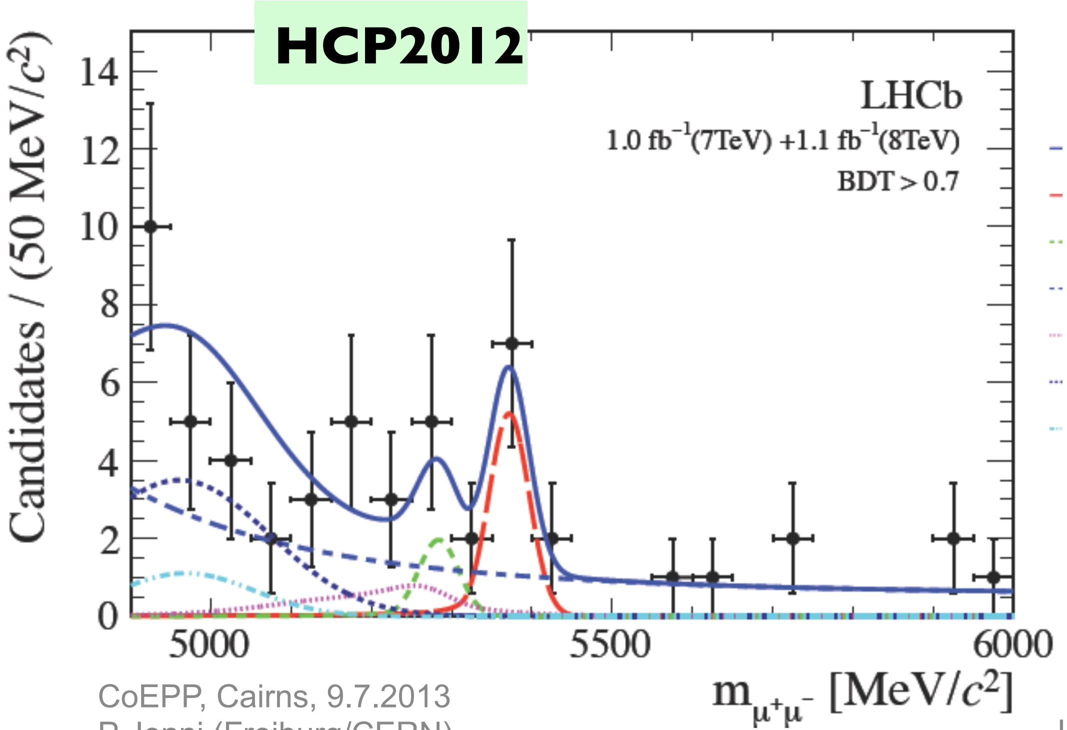
The search for $B_{s\,(d)} \rightarrow \mu\,\mu$

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





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 $B_d \rightarrow \mu\,\mu$

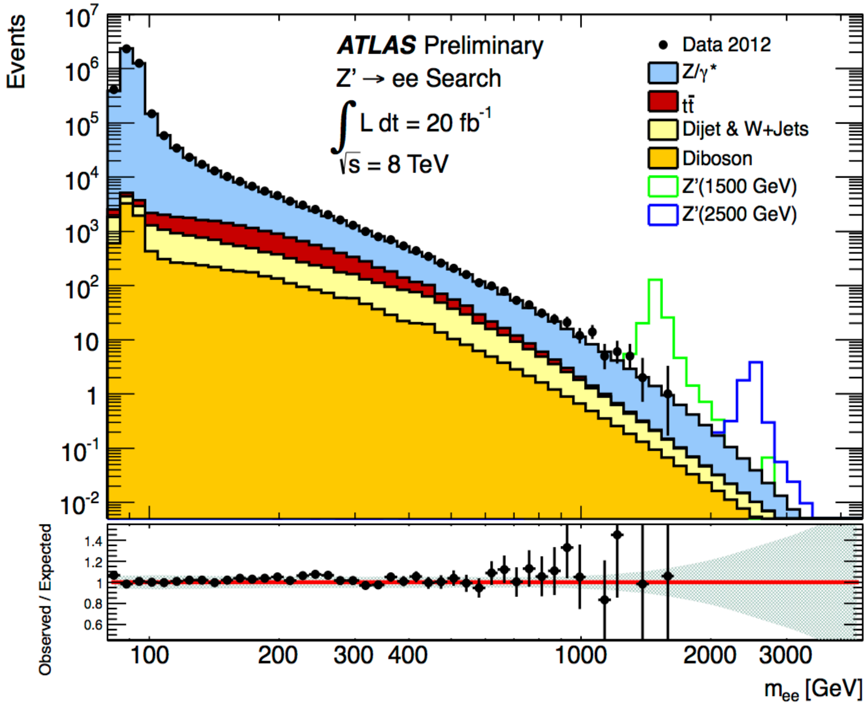
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 9.4\times 10^{-10}$ at 95% CL

Searches for heavy W and Z like particles

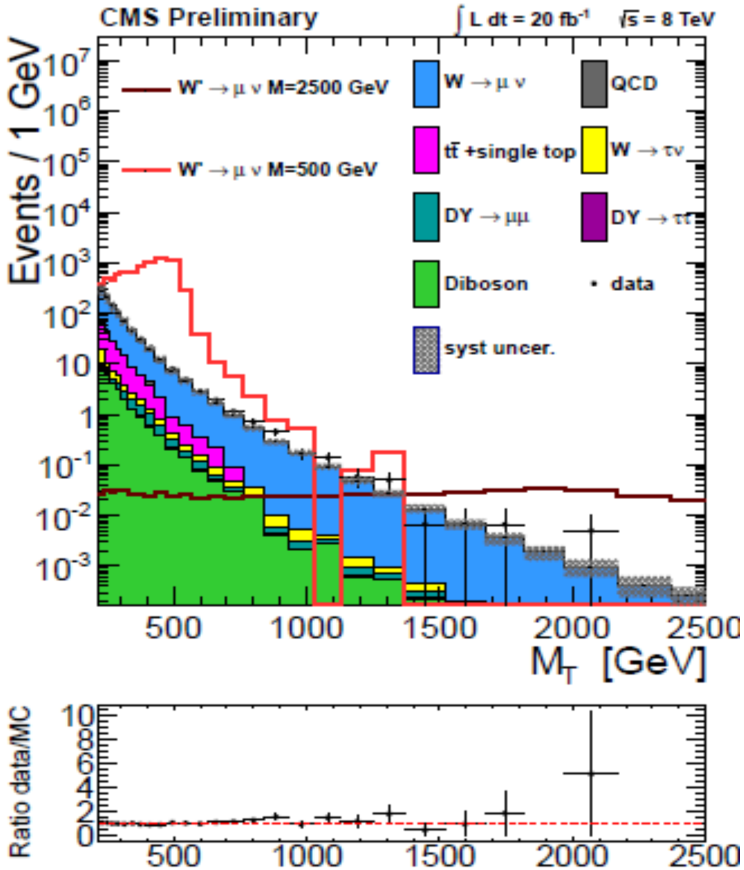
These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z' : Di-lepton pairs

W' : Lepton + ETmiss

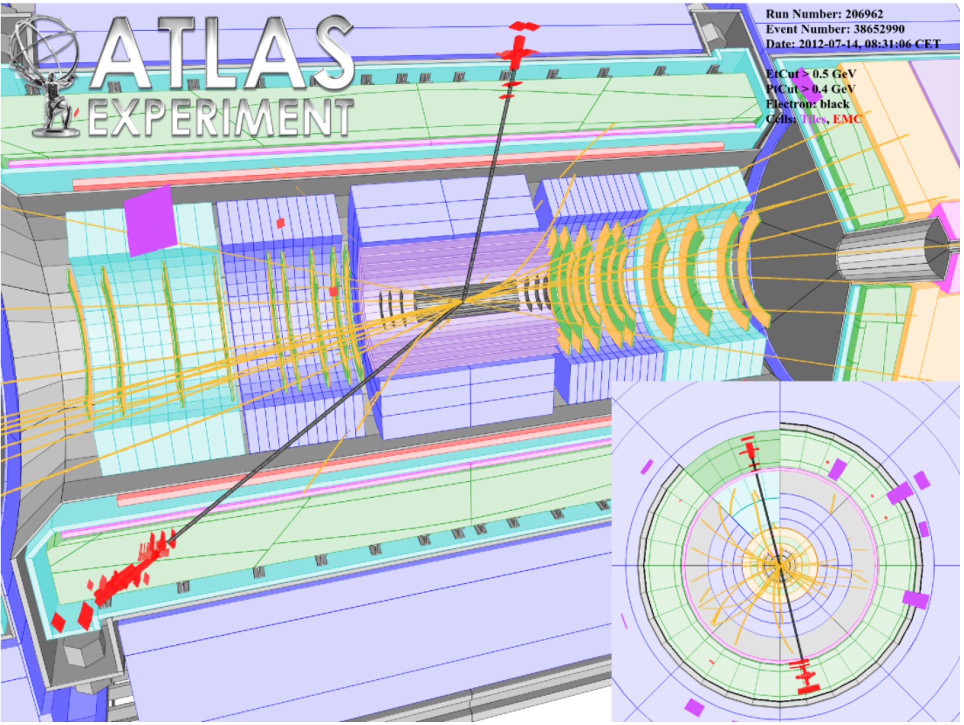


ATLAS-CONF-2013-017

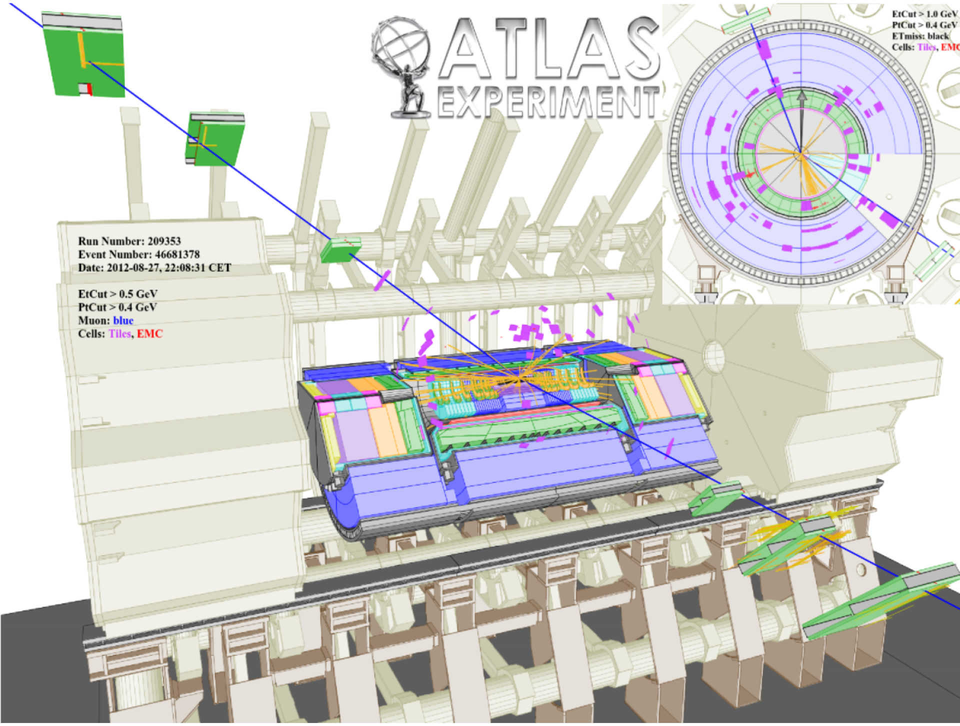


CMS-EXO-12-060

The highest mass di-lepton events from ATLAS

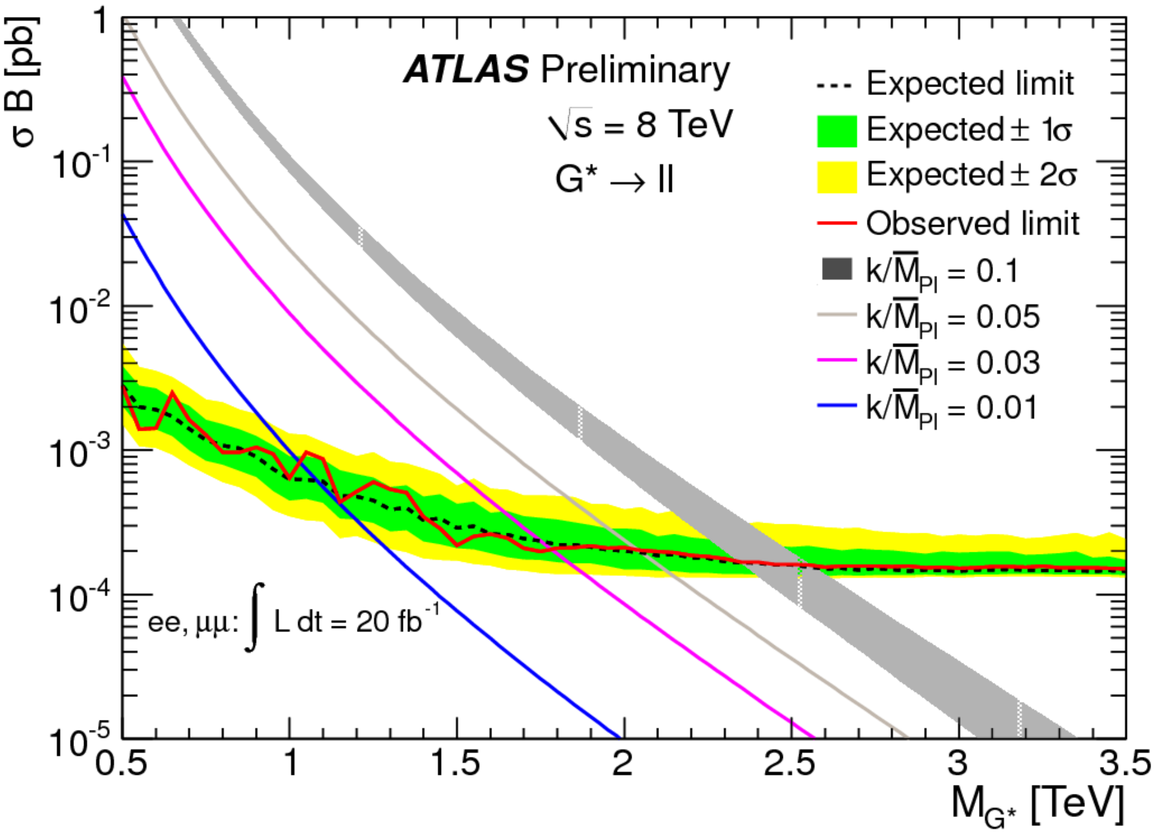


m (e^+e^-) = 1.54 TeV



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

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

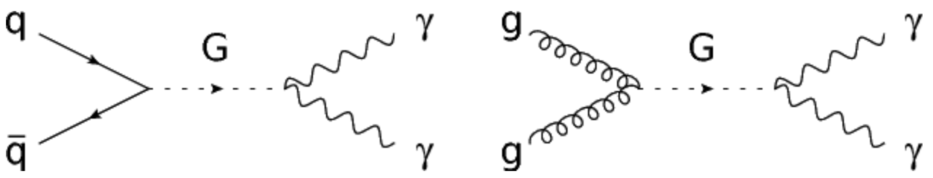


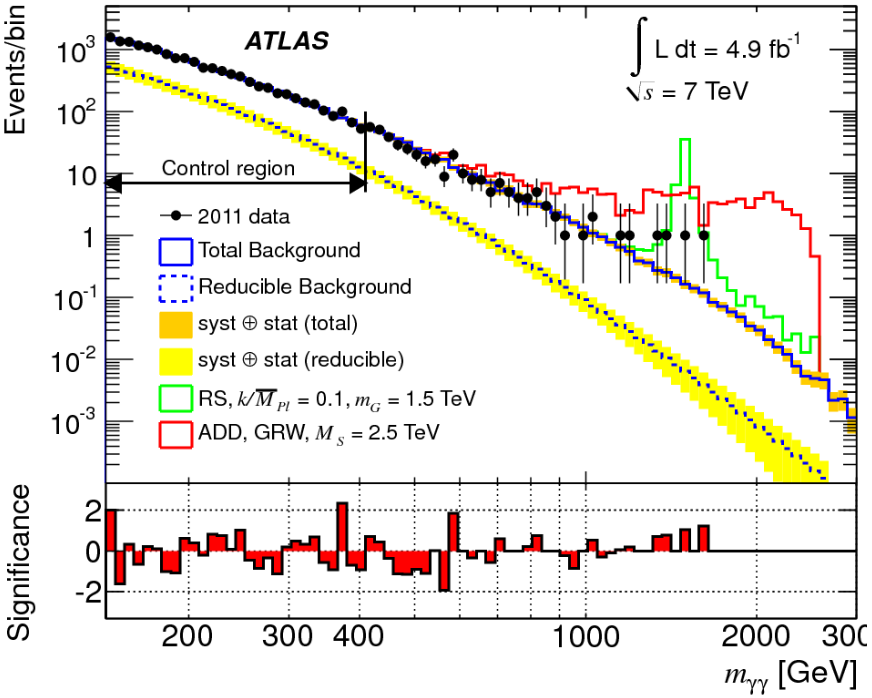
ATLAS-CONF-2013-017

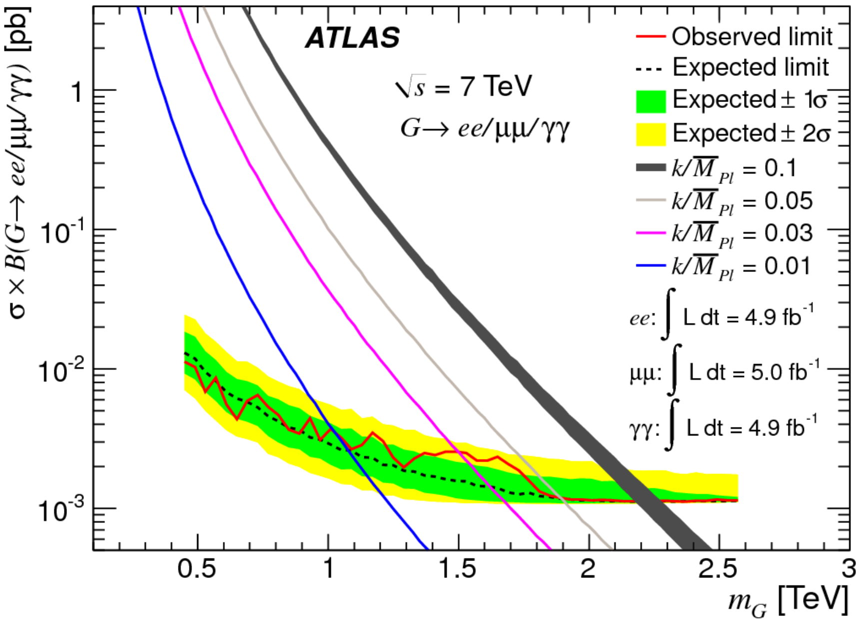
R Sundrum
L Randall
F Gianotti

New particles decaying into two photons

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



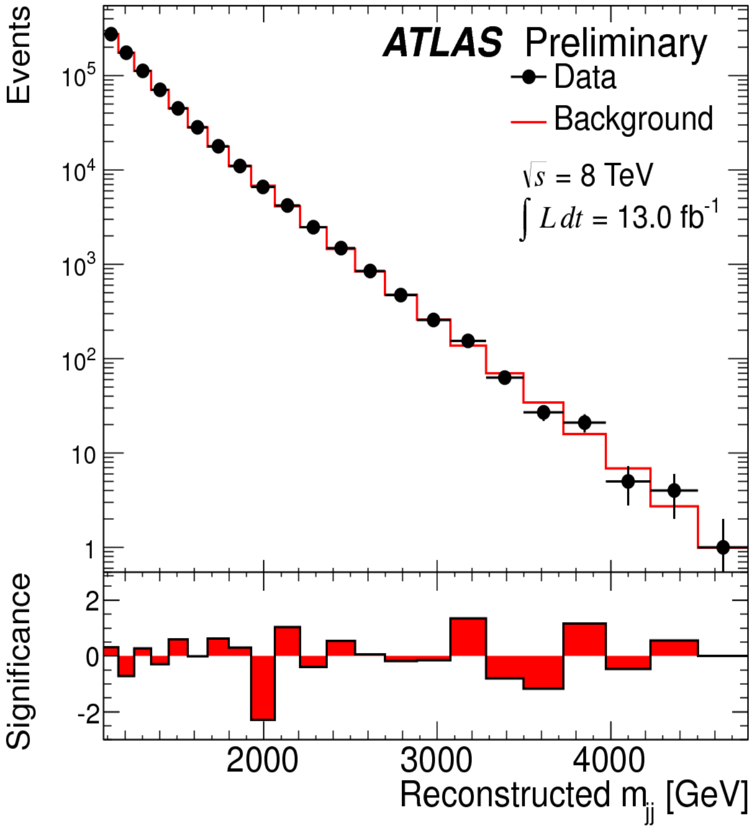




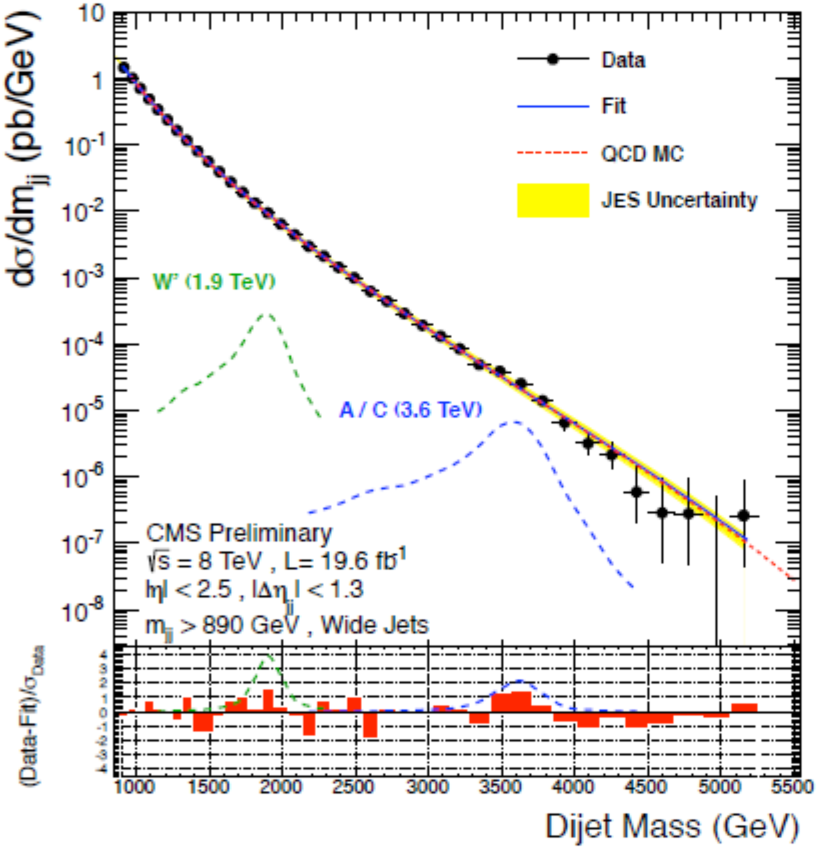
arXiv:1210.8389v12[hep-ex]

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

Search for resonances in the di-jet mass spectrum



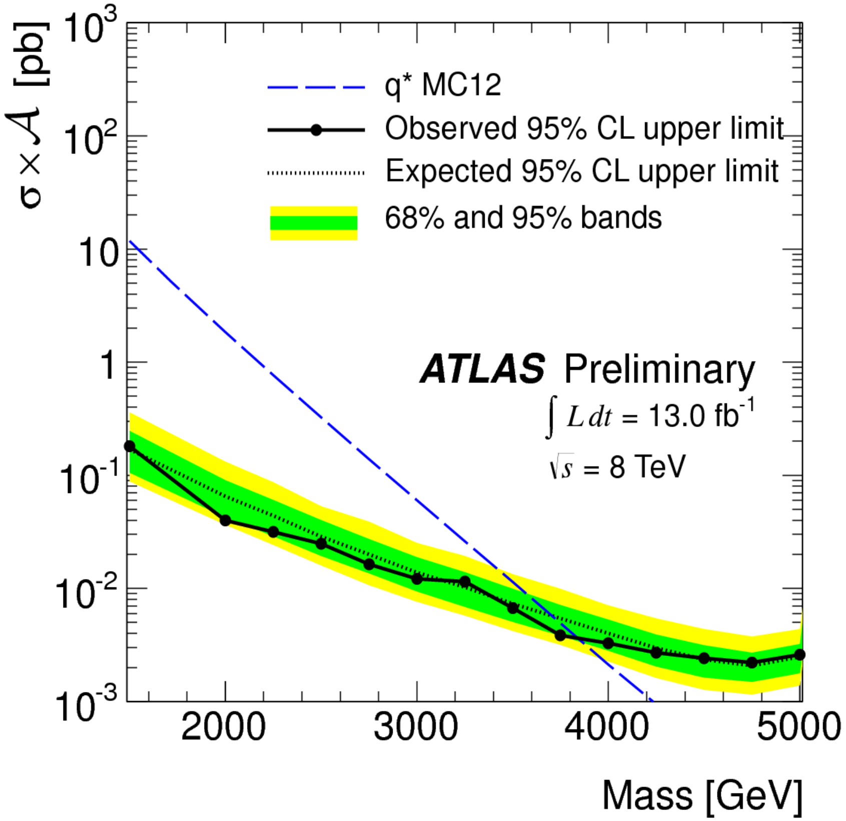
ATLAS-CONF-2012-148

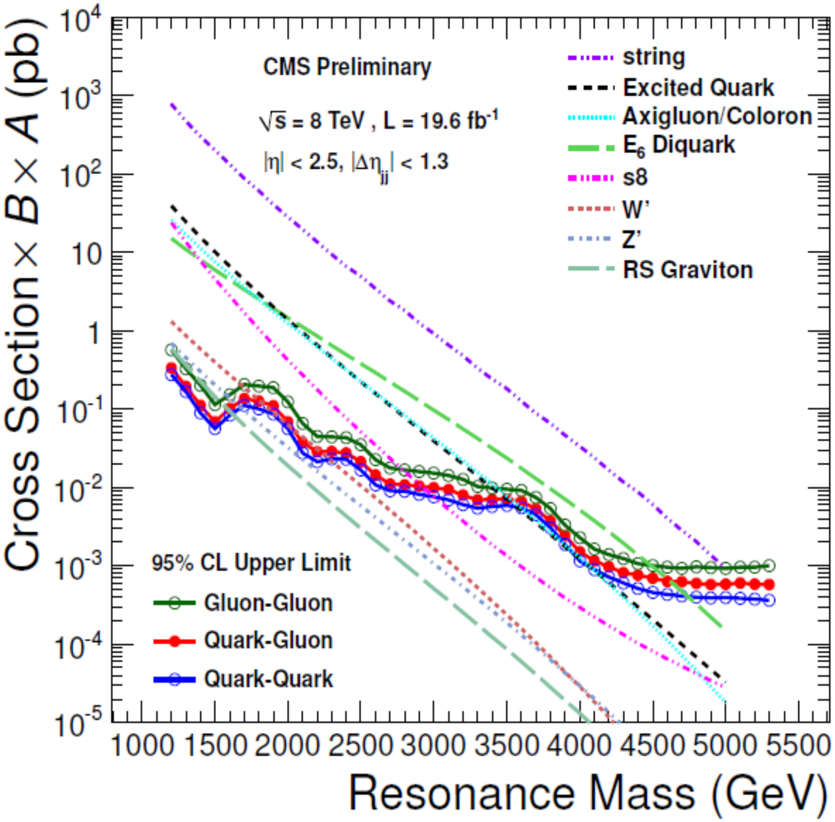


CMS-EXO-12-059

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

Search for resonances in the di-jet mass spectrum

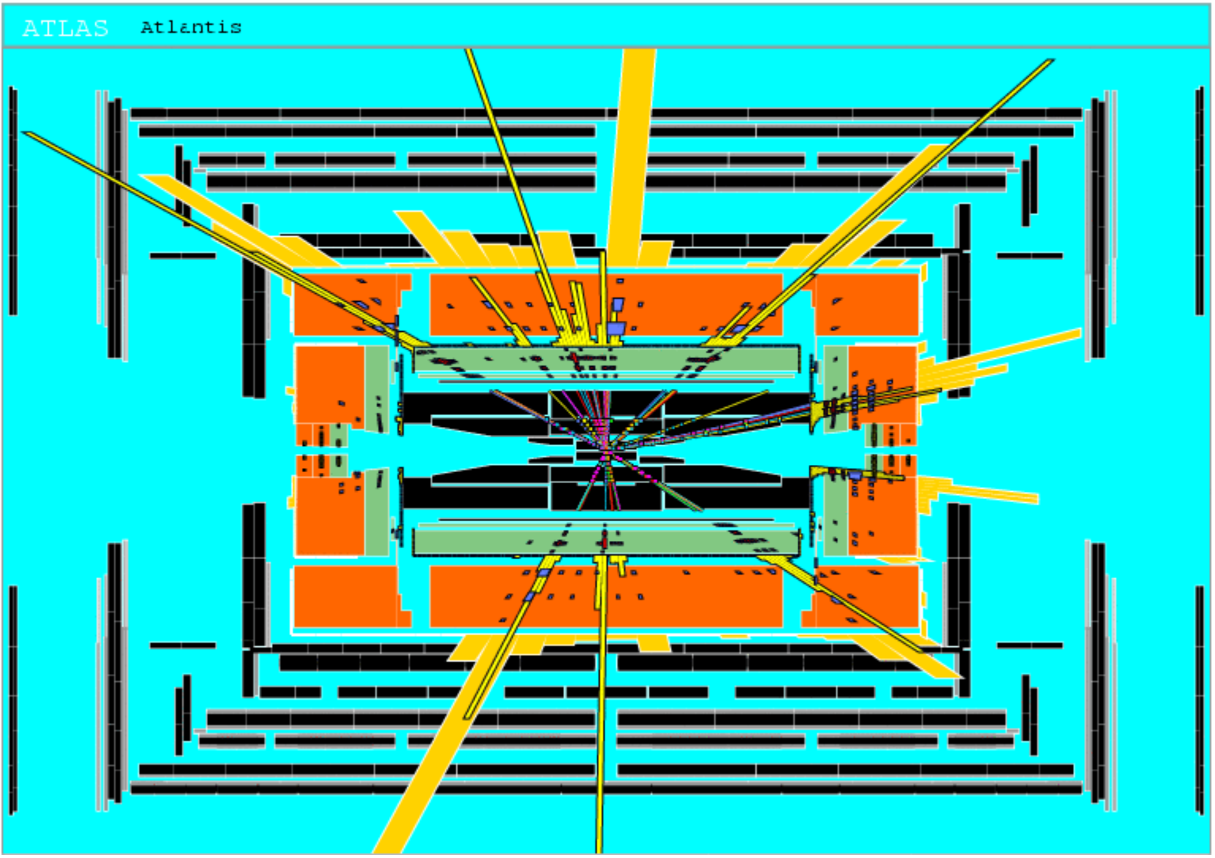




ATLAS-CONF-2012-148

CMS-EXO-12-059

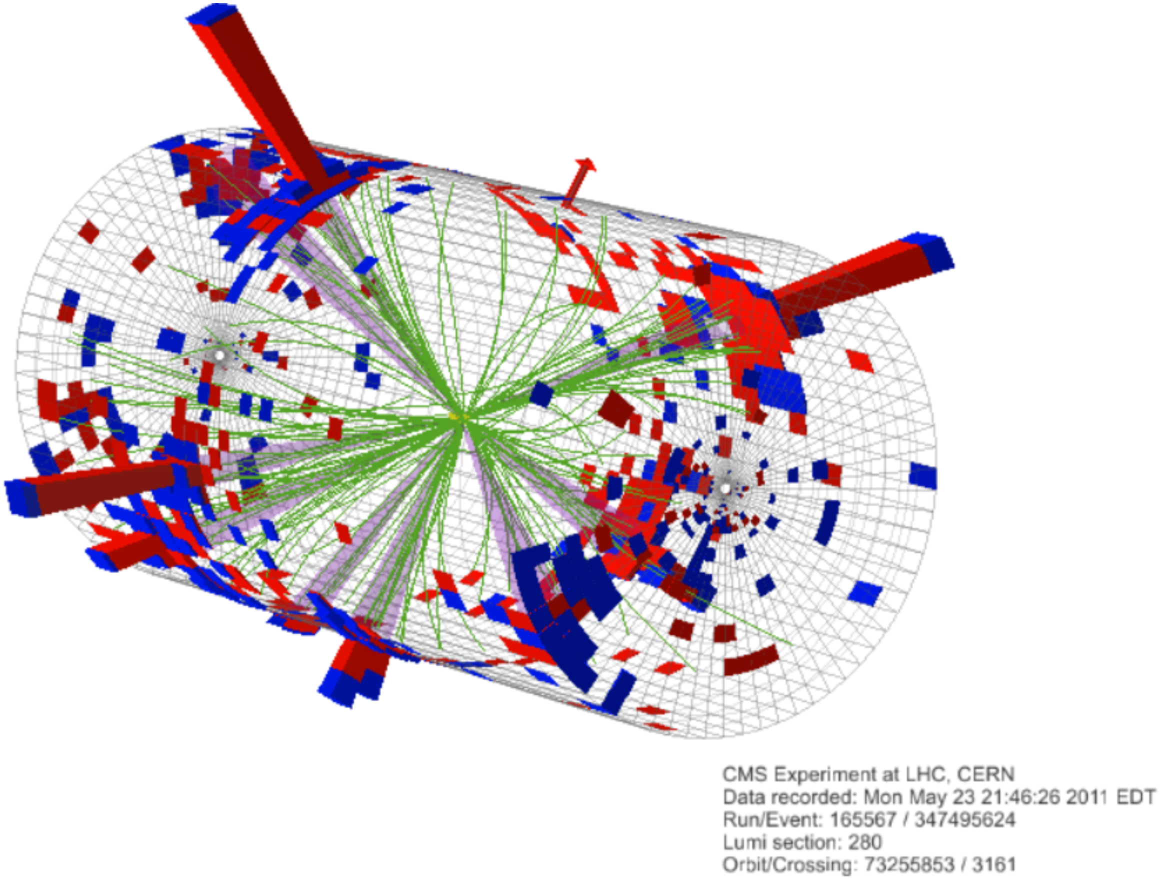
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



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



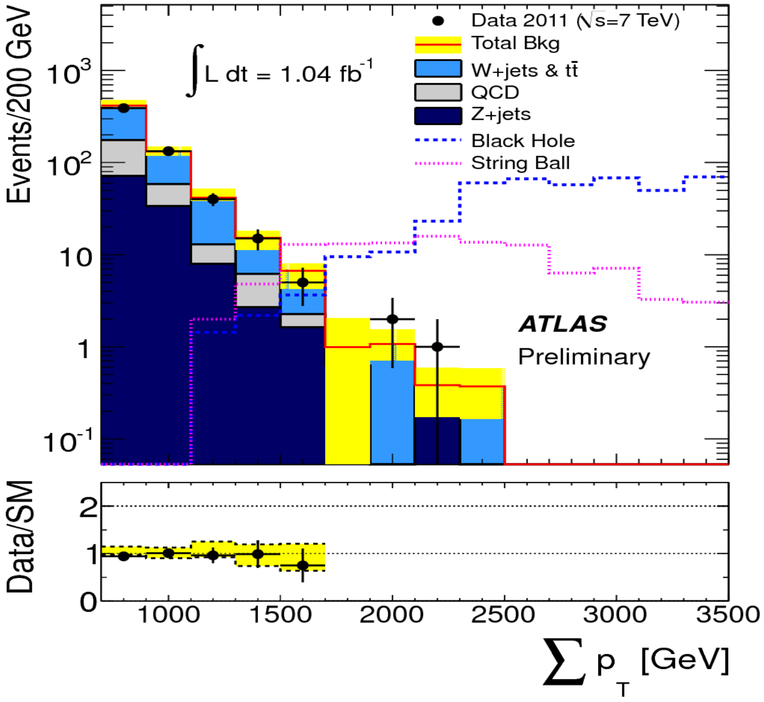
CMS Experiment at LHC, CERN
Data recorded: Mon May 23 21:46:26 2011 EDT
Run/Event: 165567 / 347495624
Lumi section: 280
Orbit/Crossing: 73255853 / 3161

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 wth large extra dimensions

(Arkani-Hamed, Dimopoulos, Dvali)

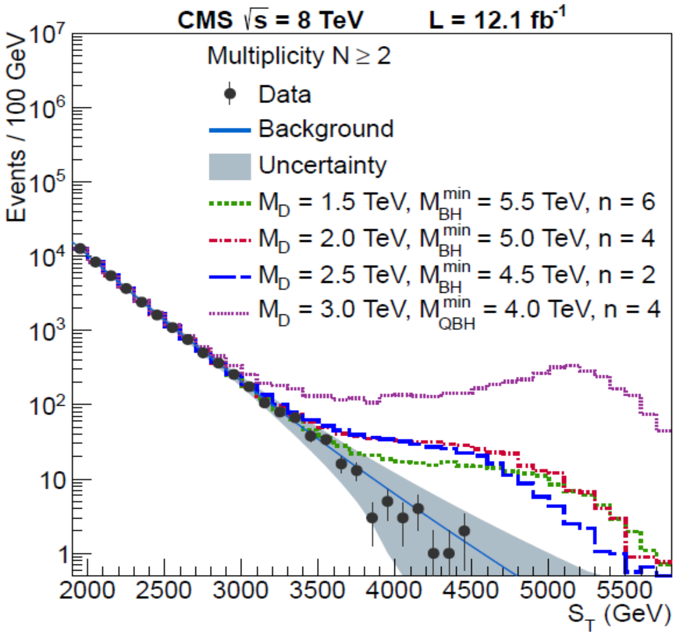


Decay into many objects (jets, leptons, photons)

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

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

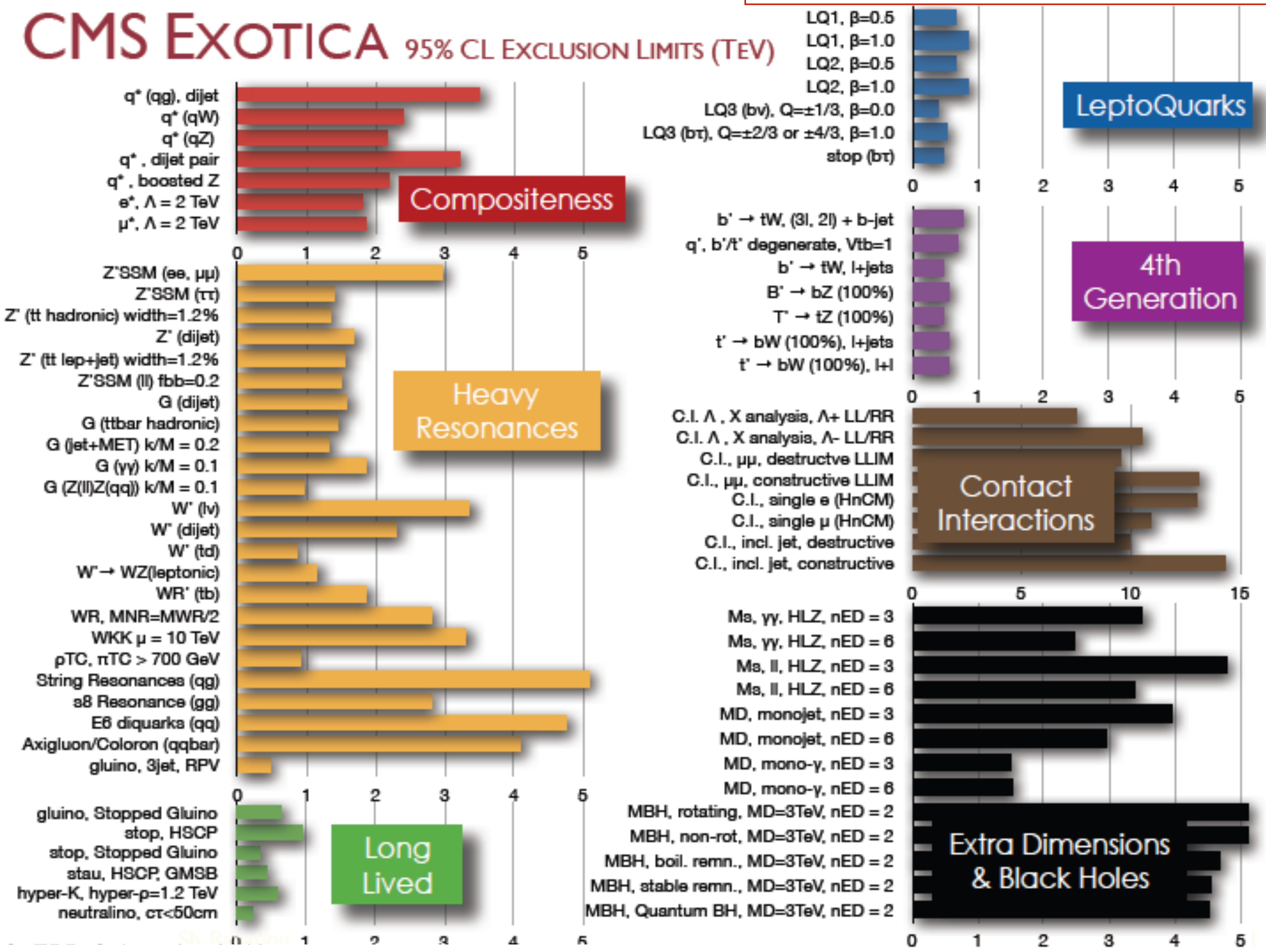
<u>Examples:</u> (ATLAS) at least one electron or muon and two or more jets, (CMS) any three objects



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

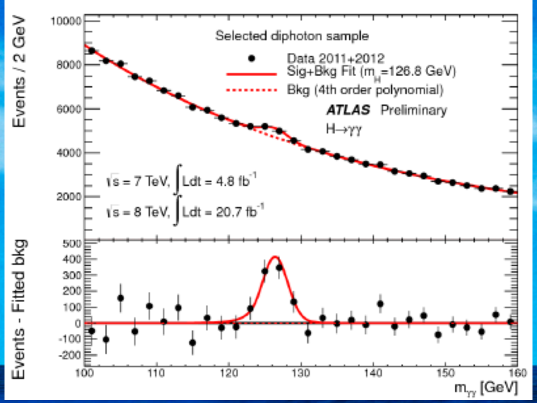
Submitted to JHEP
arXiv:1303.5338v1[hep-ex]

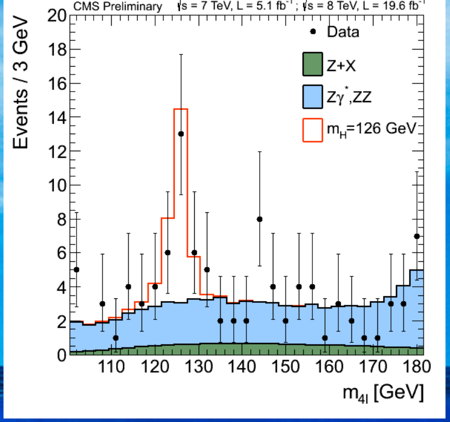
Similar results exist from ATLAS



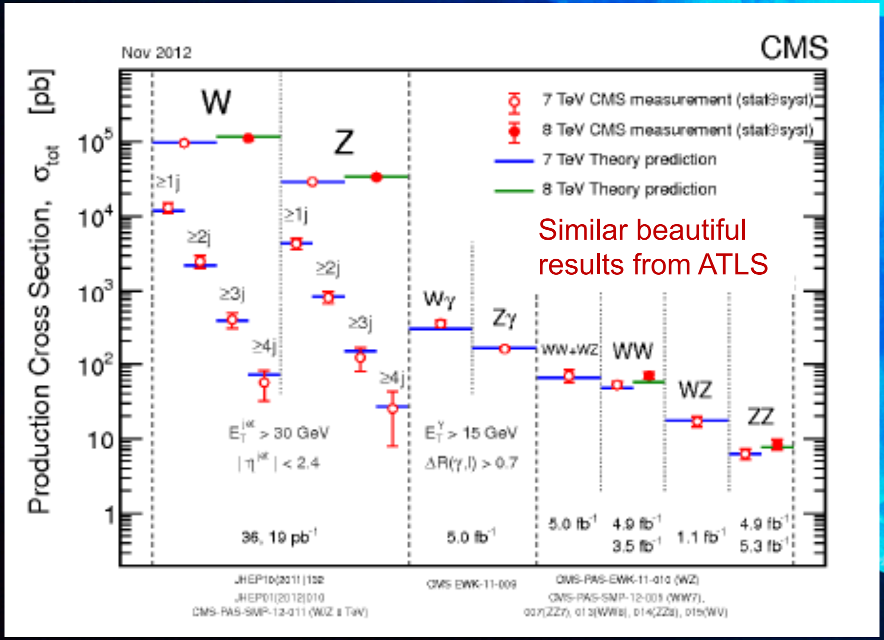
(TeV)

(TeV)

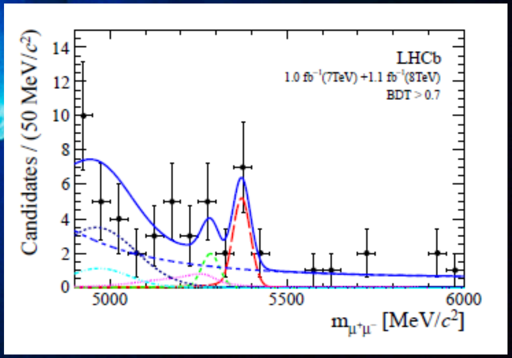




The High Energy Frontier

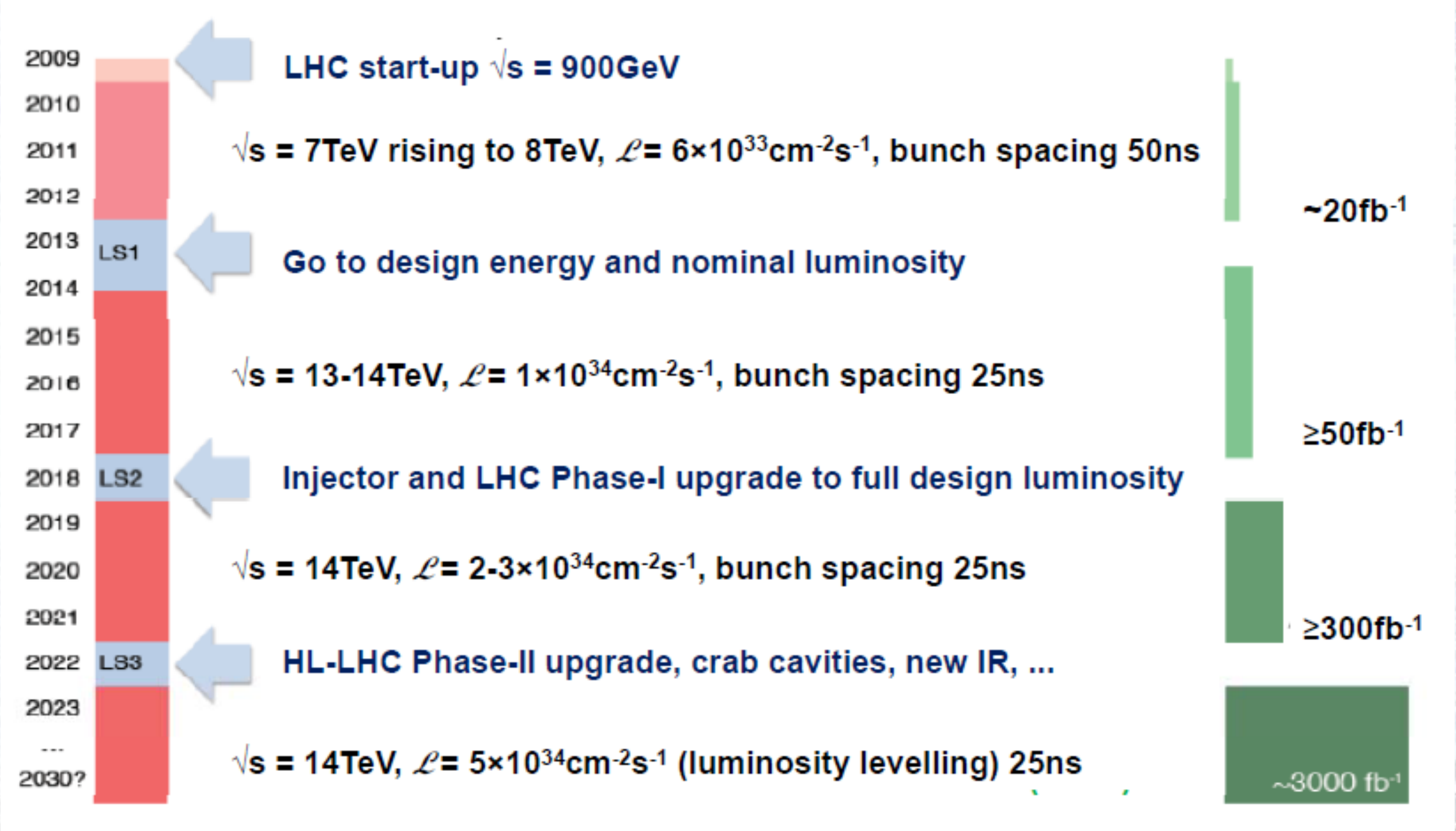


Similar beautiful results from ATLS



©Ralph A. Clevenger/CORBIS

LHC Schedule Assumptions



LHC start-up $\sqrt{s}$ = 900GeV

$\sqrt{s}$ = 7TeV rising to 8TeV, $\mathcal{L}$= 6×10^{33}cm^{-2}s^{-1}, bunch spacing 50ns

Go to design energy and nominal luminosity

$\sqrt{s}$ = 13-14TeV, $\mathcal{L}$= 1×10^{34}cm^{-2}s^{-1}, bunch spacing 25ns

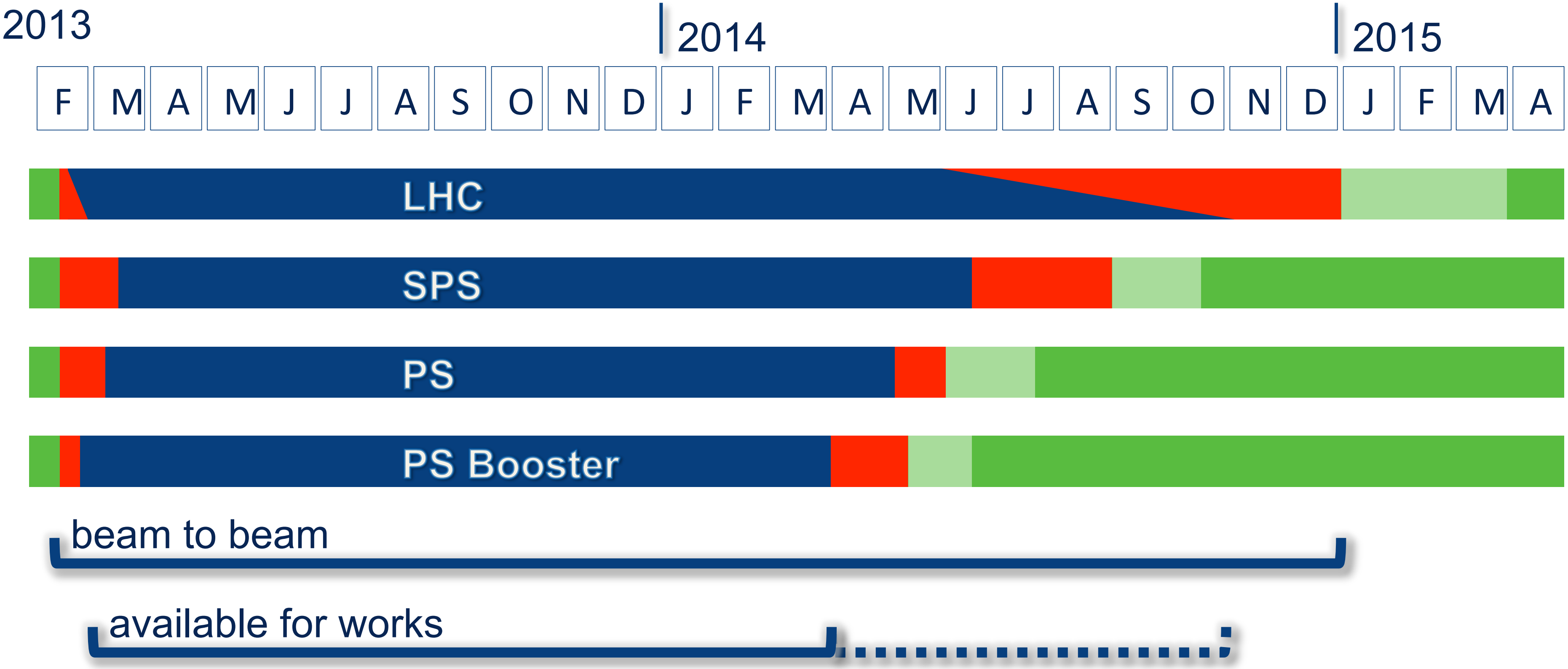
Injector and LHC Phase-I upgrade to full design luminosity

$\sqrt{s}$ = 14TeV, $\mathcal{L}$= 2-3×10^{34}cm^{-2}s^{-1}, bunch spacing 25ns

HL-LHC Phase-II upgrade, crab cavities, new IR, ...

$\sqrt{s}$ = 14TeV, $\mathcal{L}$= 5×10^{34}cm^{-2}s^{-1} (luminosity levelling) 25ns

LS1 - Accelerator complex

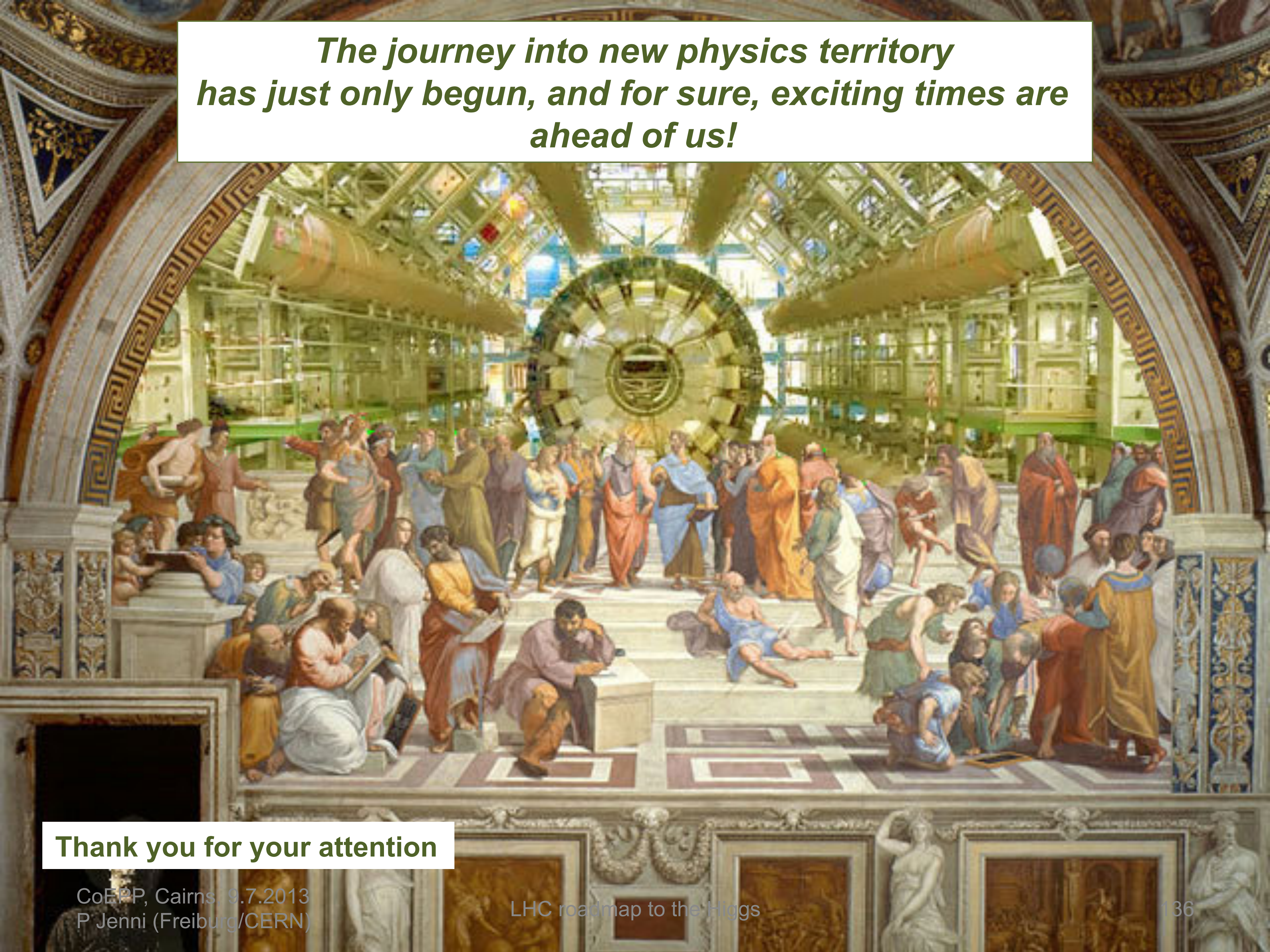


🟩 Physics

🟩 Beam commissioning

🟦 Shutdown

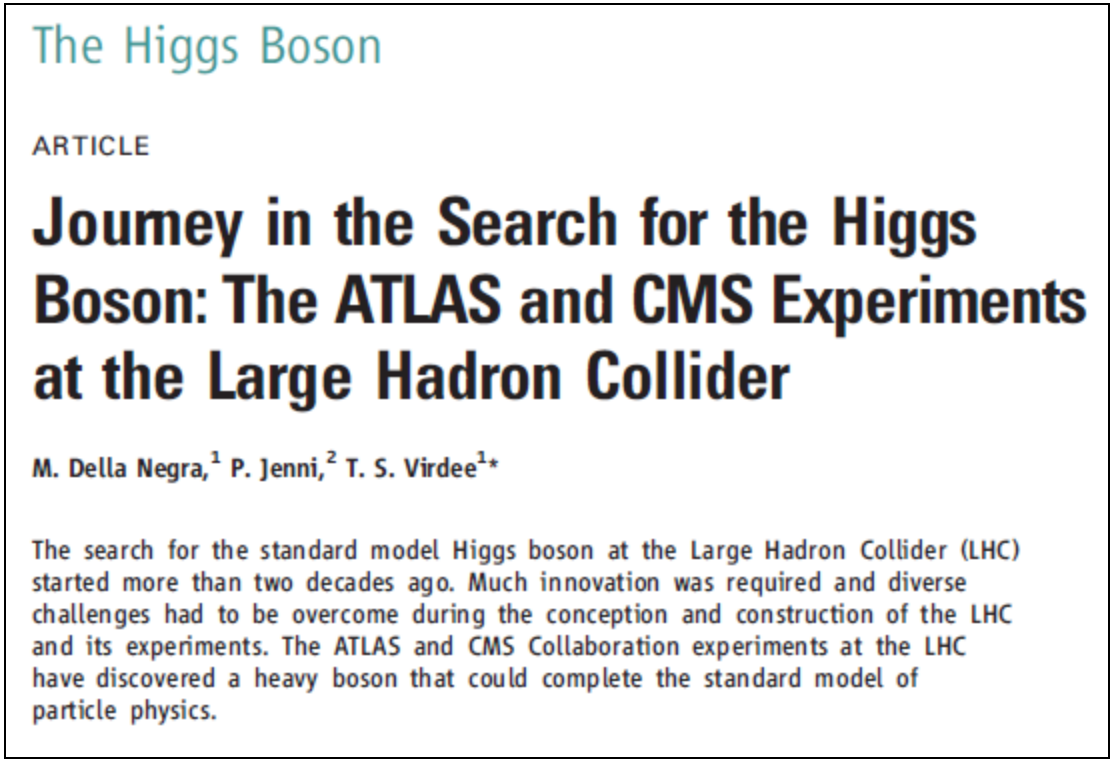
🟥 Powering tests



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 (1):



The Higgs Boson

ARTICLE

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

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

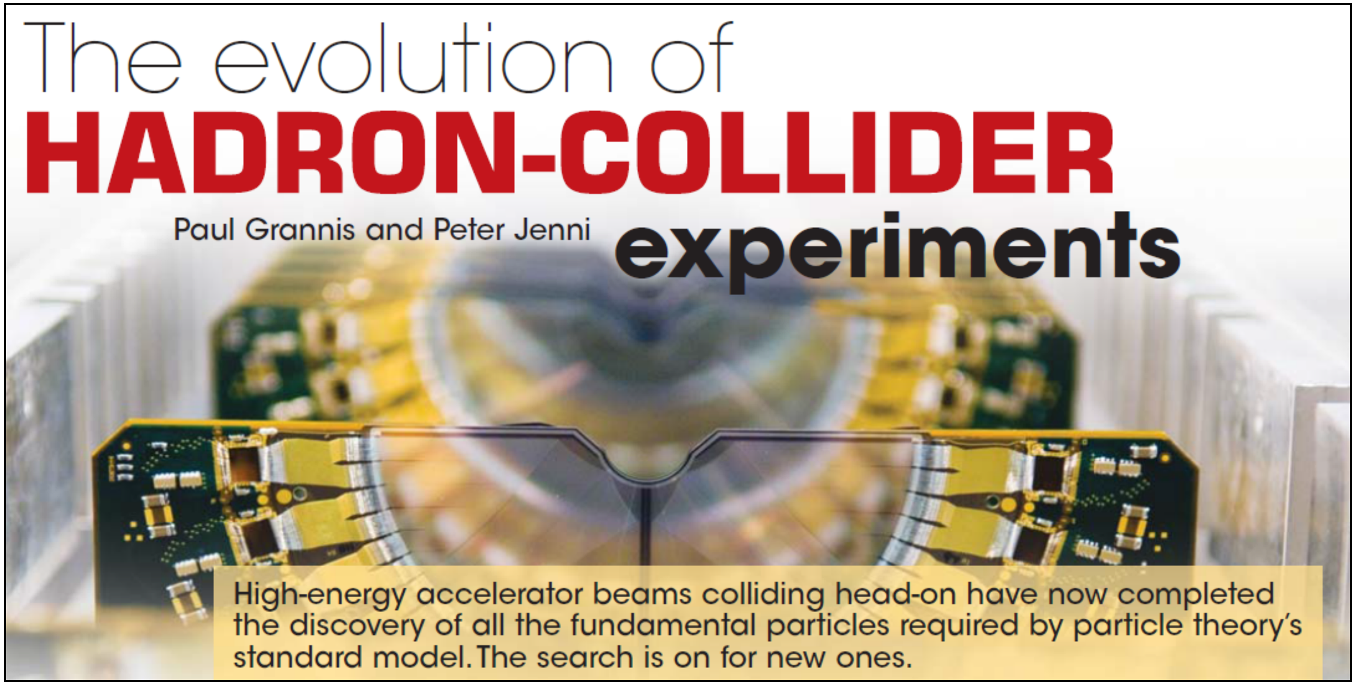
The search for the standard model Higgs boson at the Large Hadron Collider (LHC) started more than two decades ago. Much innovation was required and diverse challenges had to be overcome during the conception and construction of the LHC and its experiments. The ATLAS and CMS Collaboration experiments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

Science AAAS

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

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

Further reading (2):



The evolution of

HADRON-COLLIDER

experiments

Paul Grannis and Peter Jenni

High-energy accelerator beams colliding head-on have now completed the discovery of all the fundamental particles required by particle theory's standard model. The search is on for new ones.

The evolution of hadron-collider experiments

Paul Grannis and Peter Jenni

Citation: Phys. Today **66**(6), 38 (2013); doi: 10.1063/PT.3.2010
View online: http://dx.doi.org/10.1063/PT.3.2010
View Table of Contents: http://www.physicstoday.org/resource/1/PHTOAD/v66/i6
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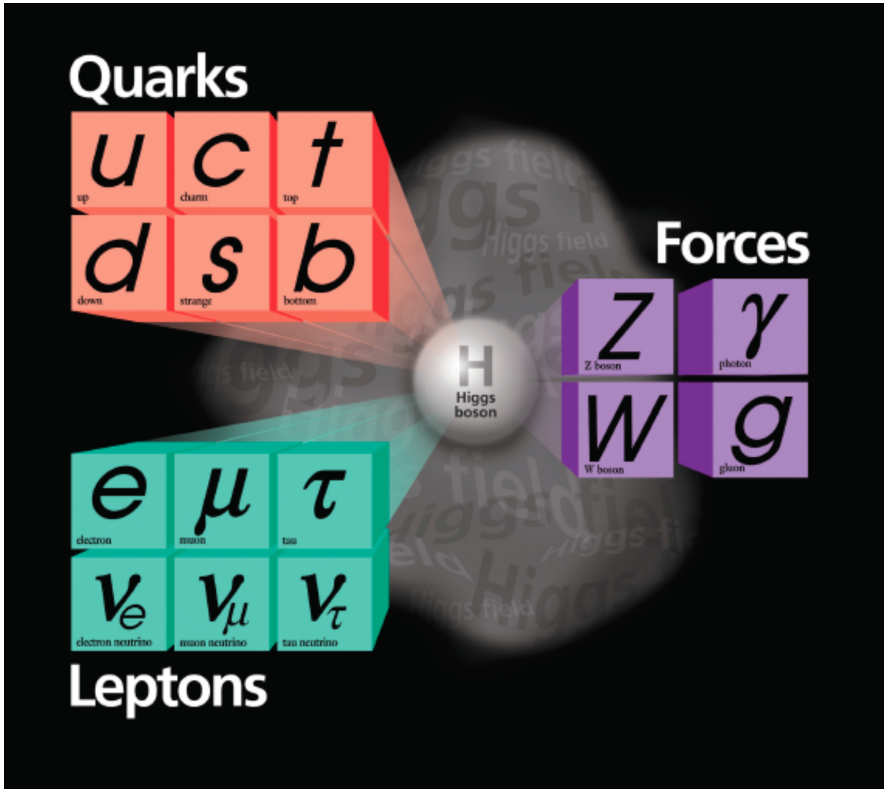
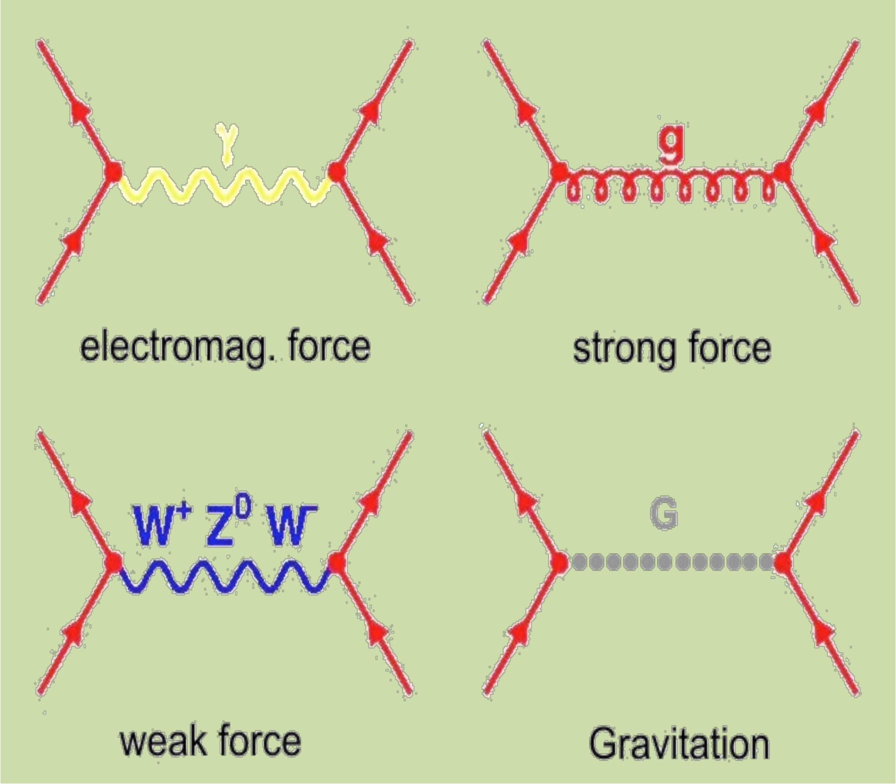
peter.jenni@cern.ch

Spares

The Standard Model of Particle Physics

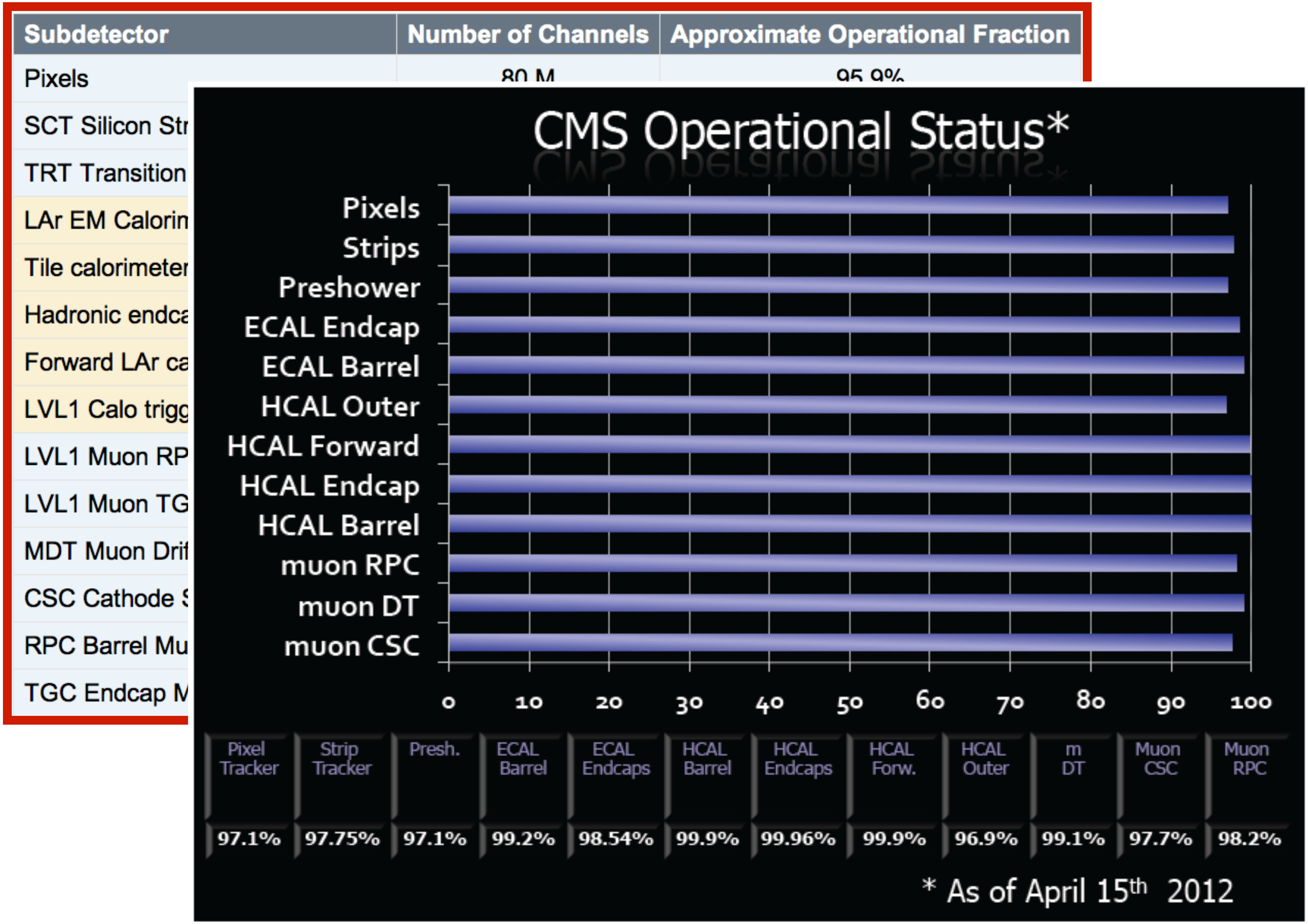




(i) Constituents of matter: quarks and leptons

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

(iii) The Higgs field (problem of mass)



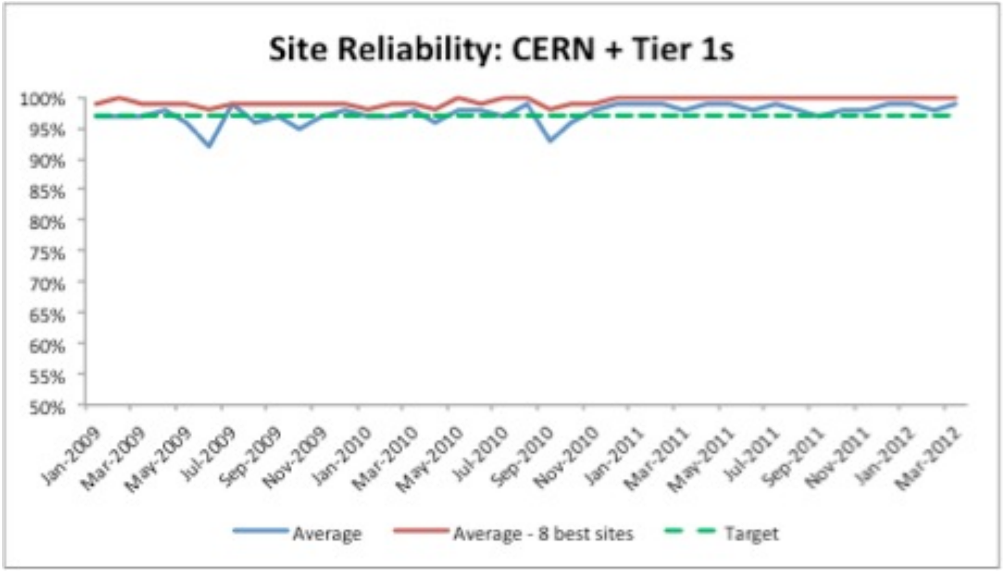
Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.9%
SCT Silicon Str		
TRT Transition		
LAr EM Calorin		
Tile calorimeter		
Hadronic endca		
Forward LAr ca		
LVL1 Calo trigg		
LVL1 Muon RP		
LVL1 Muon TG		
MDT Muon Drif		
CSC Cathode S		
RPC Barrel Mu		
TGC Endcap M		

CMS Operational Status*

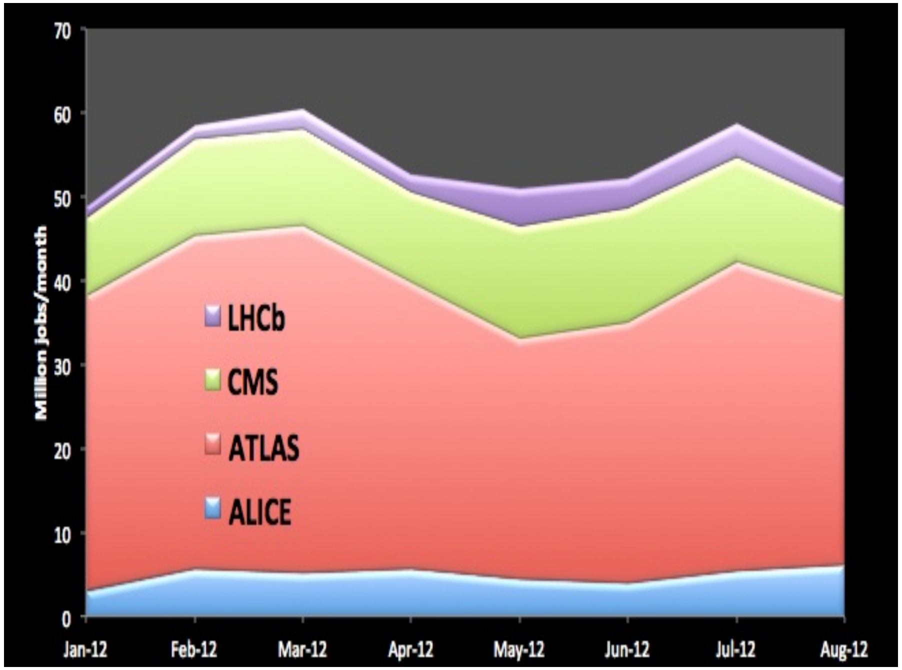
Pixel Tracker	Strip Tracker	Presh.	ECAL Barrel	ECAL Endcaps	HCAL Barrel	HCAL Endcaps	HCAL Forw.	HCAL Outer	m DT	Muon CSC	Muon RPC
97.1%	97.75%	97.1%	99.2%	98.54%	99.9%	99.96%	99.9%	96.9%	99.1%	97.7%	98.2%

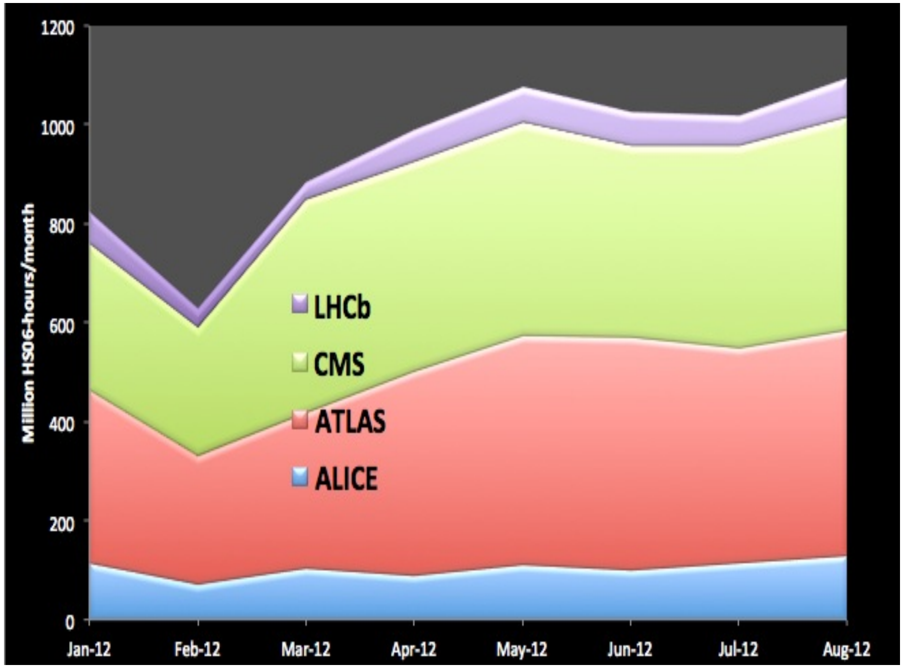
* As of April 15th 2012

wLCG Grid Operation



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





Physics Highlights:

General event properties

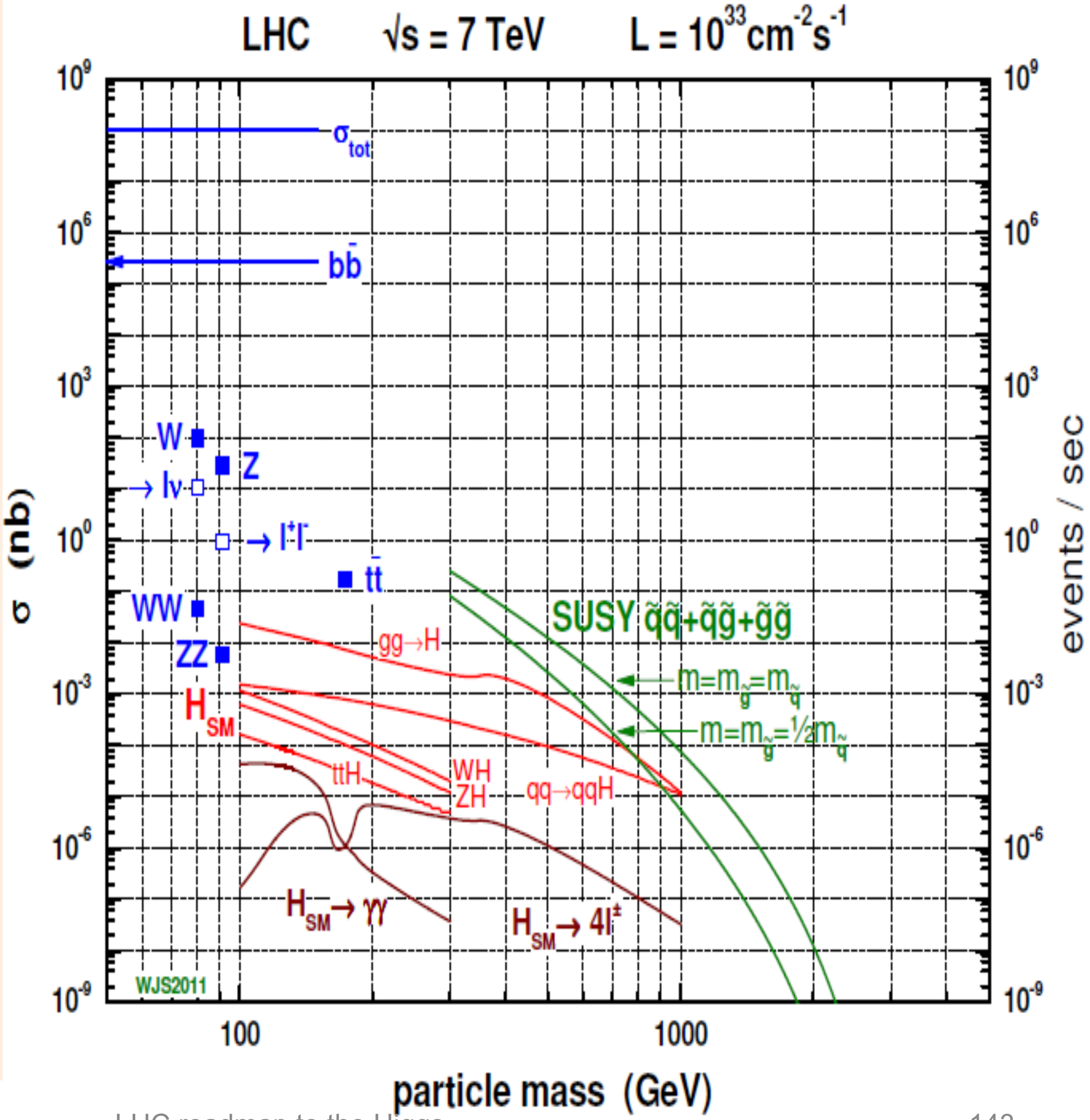
Heavy flavour physics

Standard Model physics including QCD jets

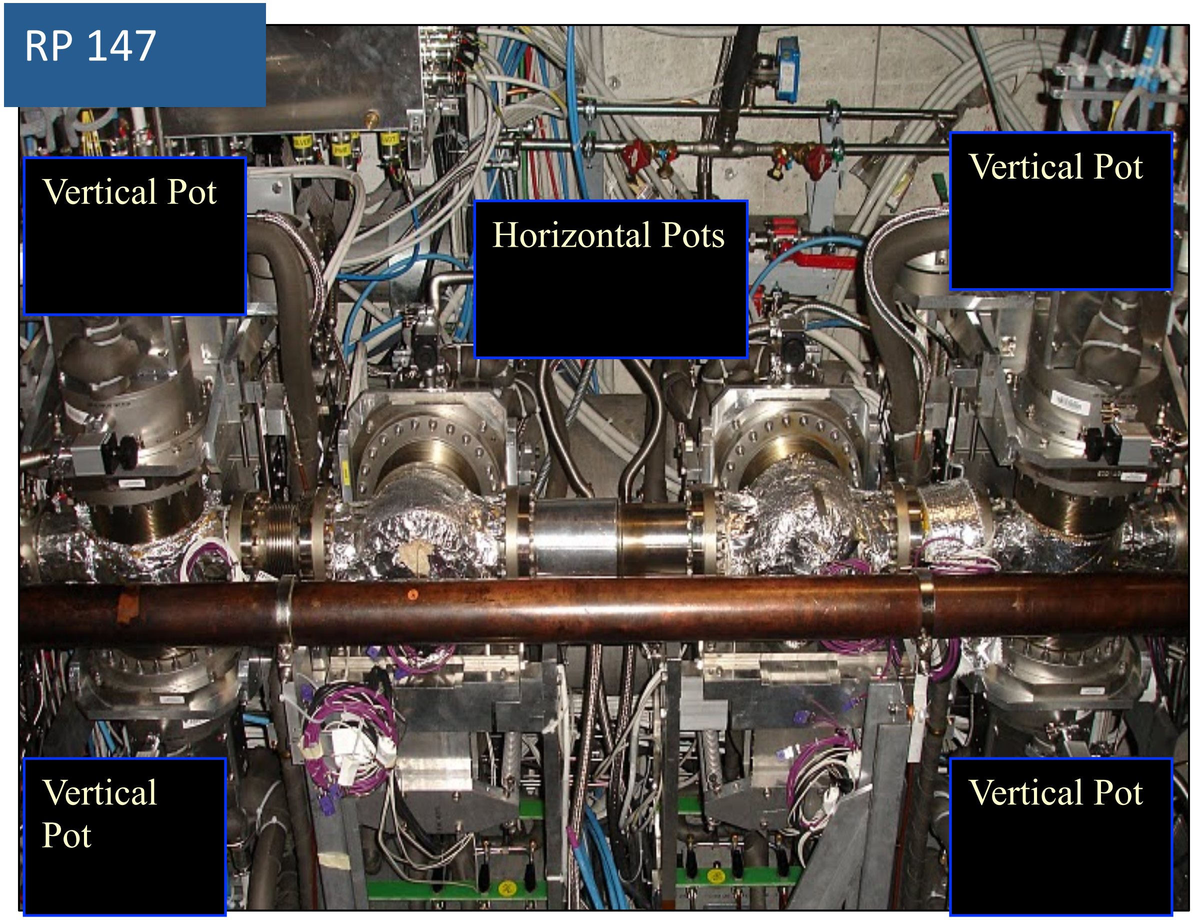
Higgs searches

Searches for SUSY

Searches for ‘exotic’ new physics



Total cross-section measurement by TOTEM

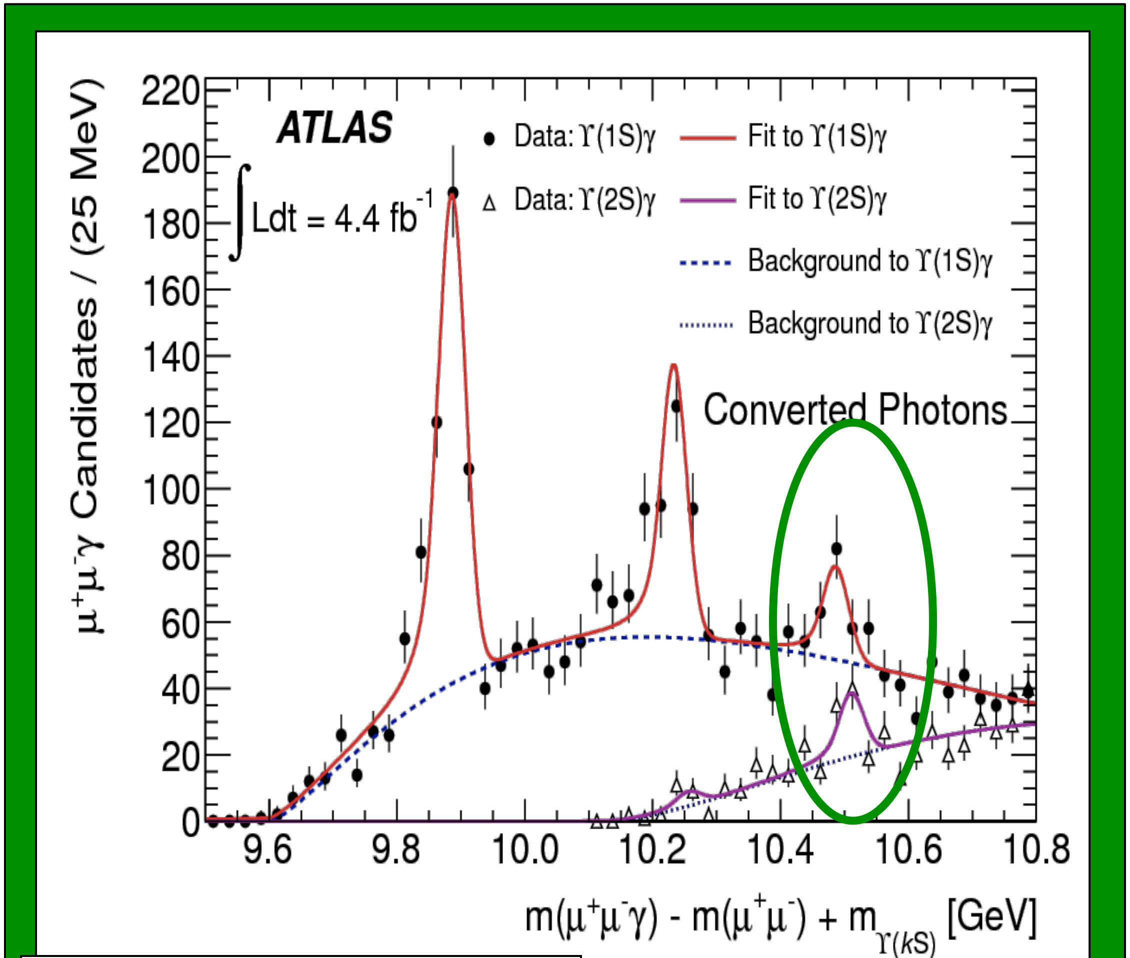


Example: Roman Pots at 147 m from interaction point

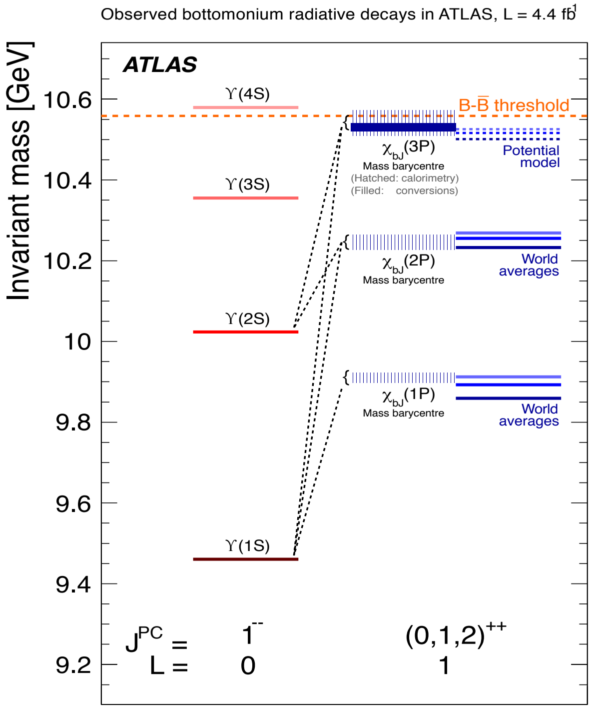
The first new particles 'discovered' at LHC, December 2011

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

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



Phys. Rev. Lett. 108 (2012) 152001



❑ $\chi_b(nP) \rightarrow \Upsilon(1s,2s)\ \gamma \rightarrow \mu\mu\ \gamma$

❑ $X_b(1P)$ m= 9.9 GeV and $X_b(2P)$ m= 10.2 GeV states clearly visible

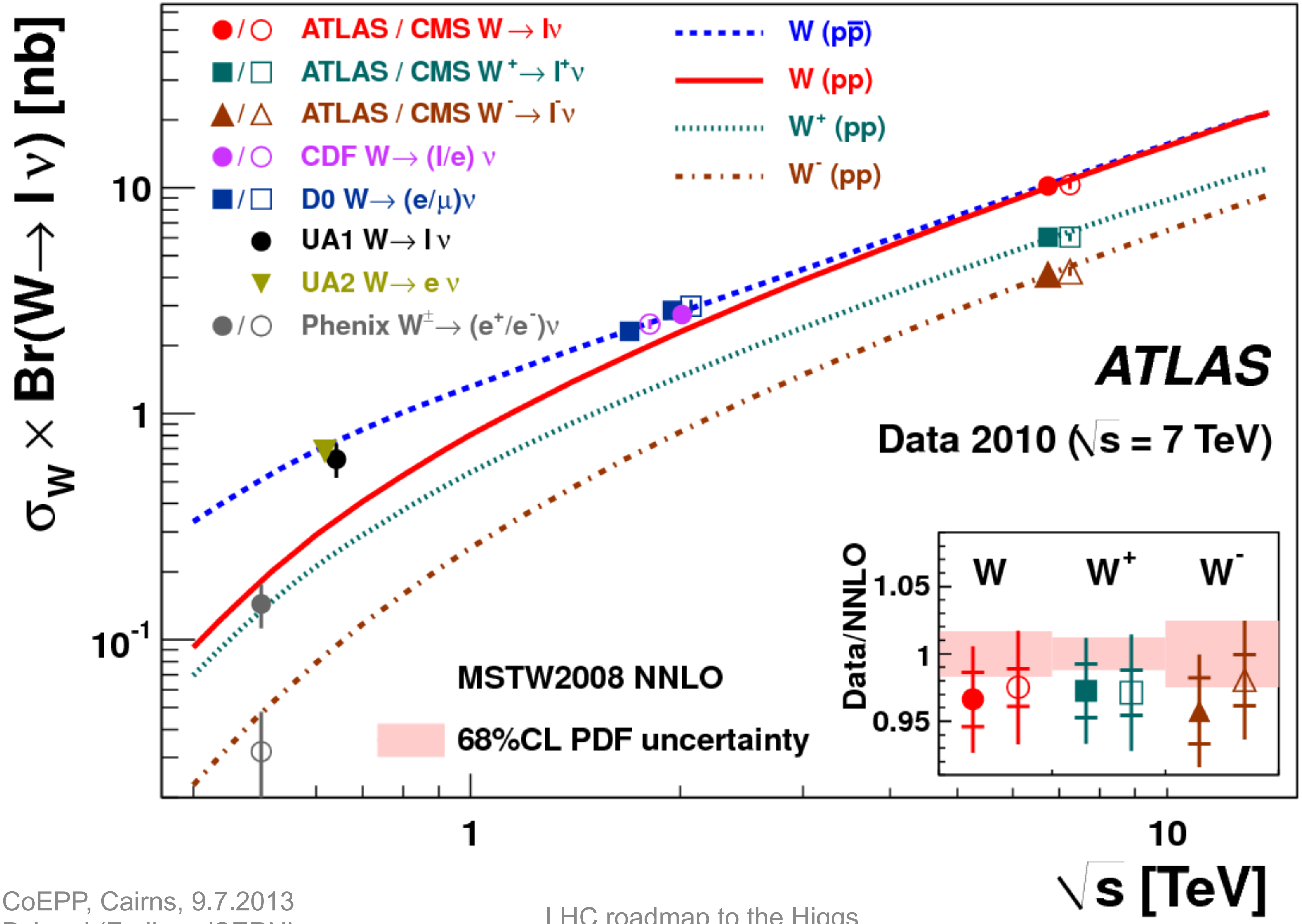
❑ New structure at 10.5 GeV → $X_b(3P)$

❑Significance > 6 σ

❑ As theoretically predicted

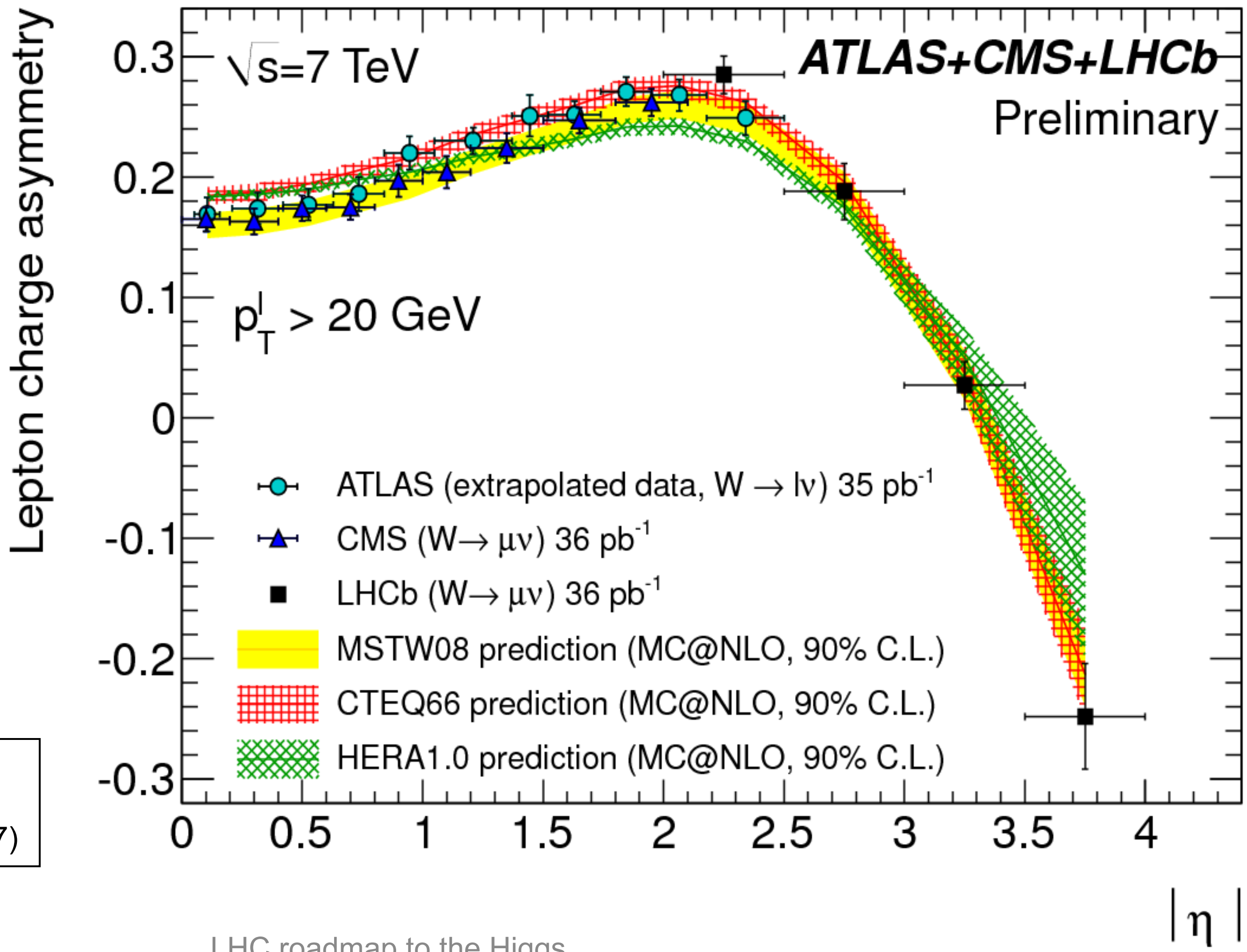
W cross section measurement with e and μ

Phys Rev D85 (2012) 072004



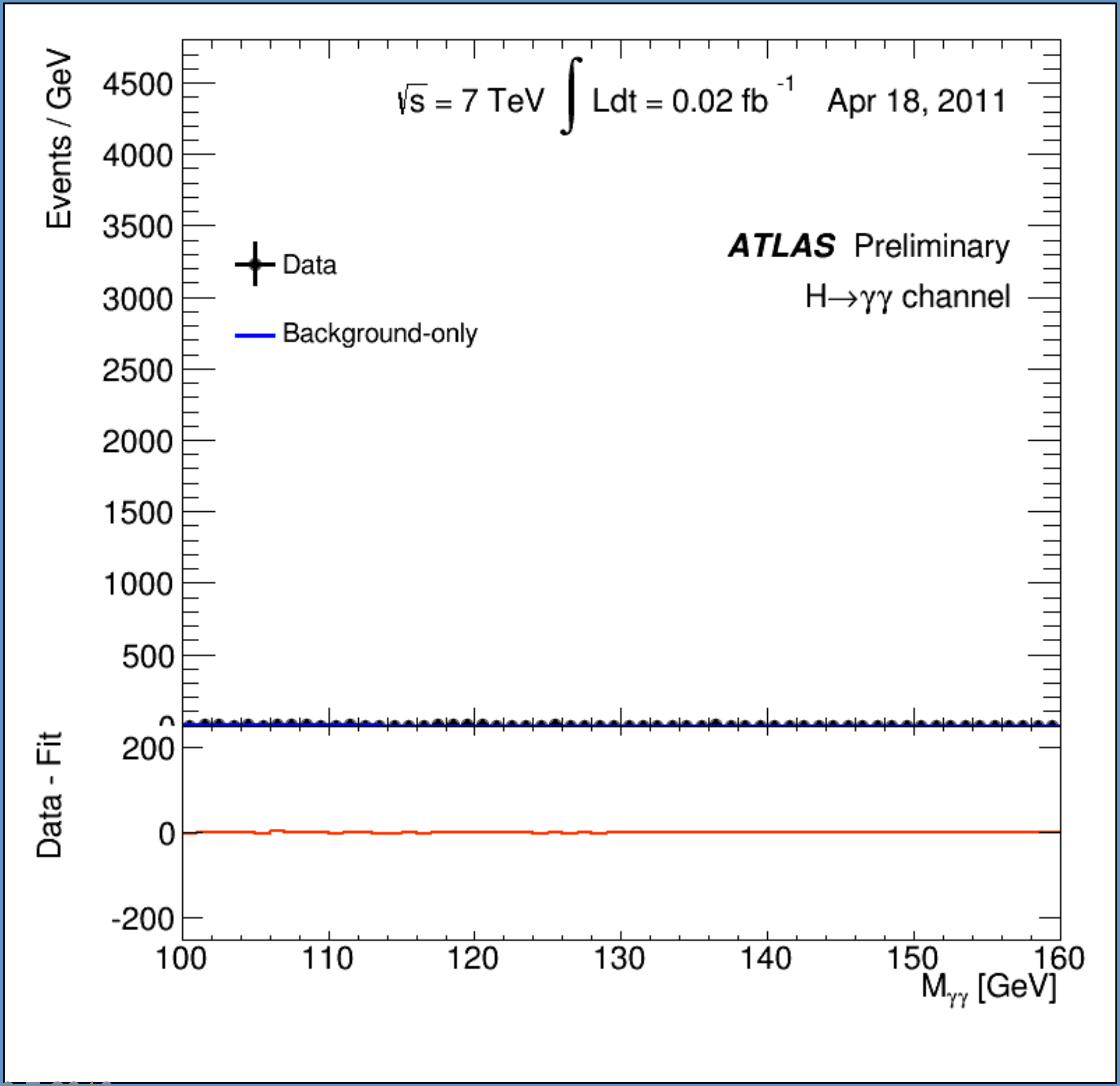
Lepton charge asymmetry from W decays in pp collisions at 7 TeV

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

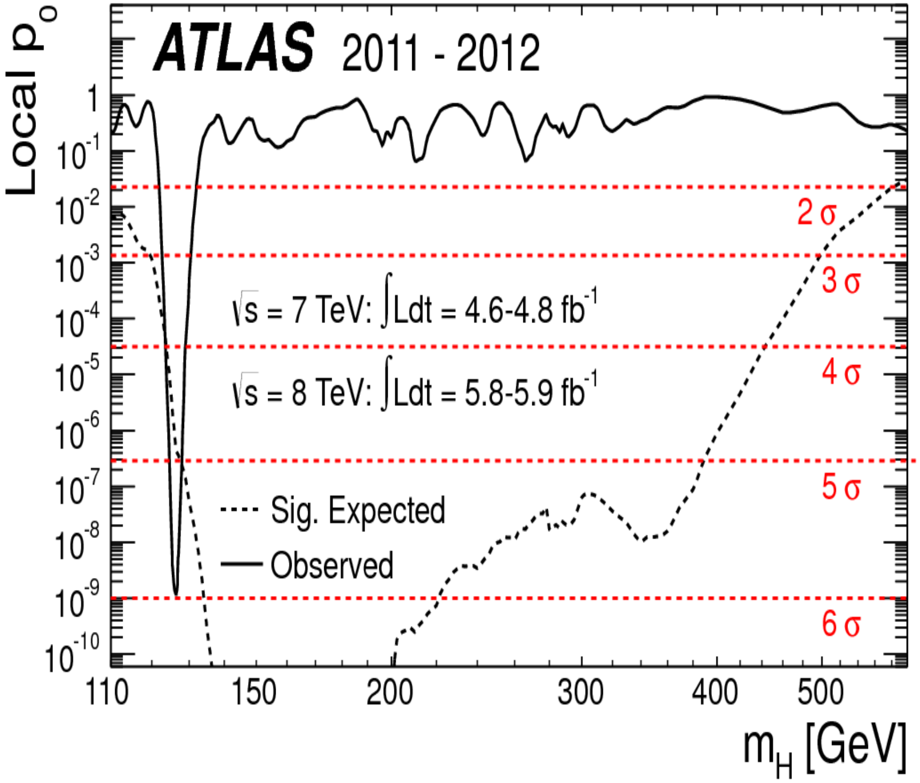


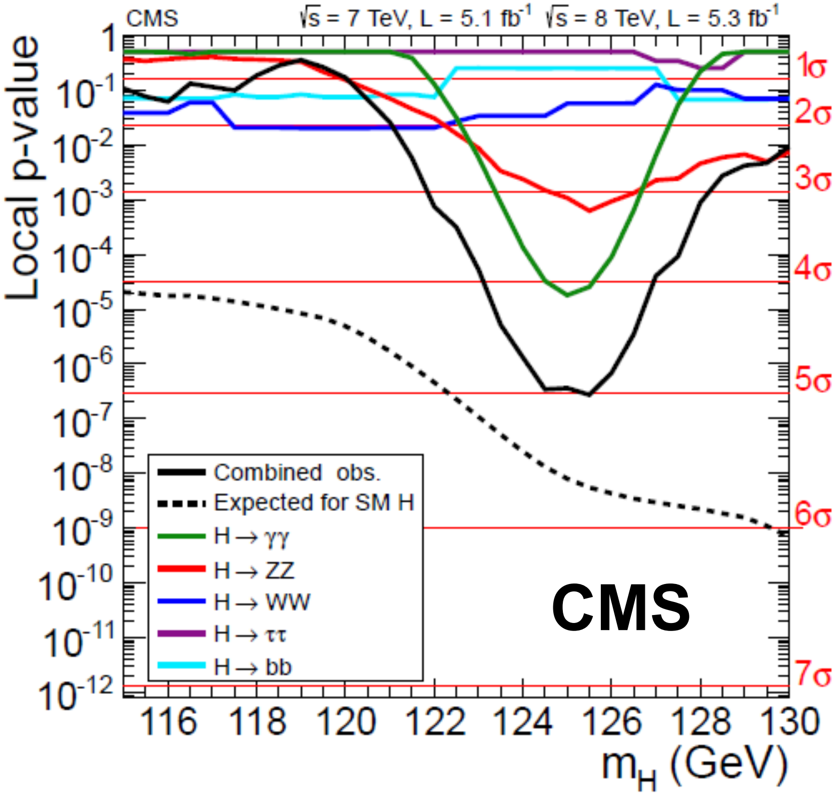
ATLAS-CONF-2011-129
LHCb-CONF-2011-039
CMS-EWK-10-006 (aXiv:1103.3407)

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

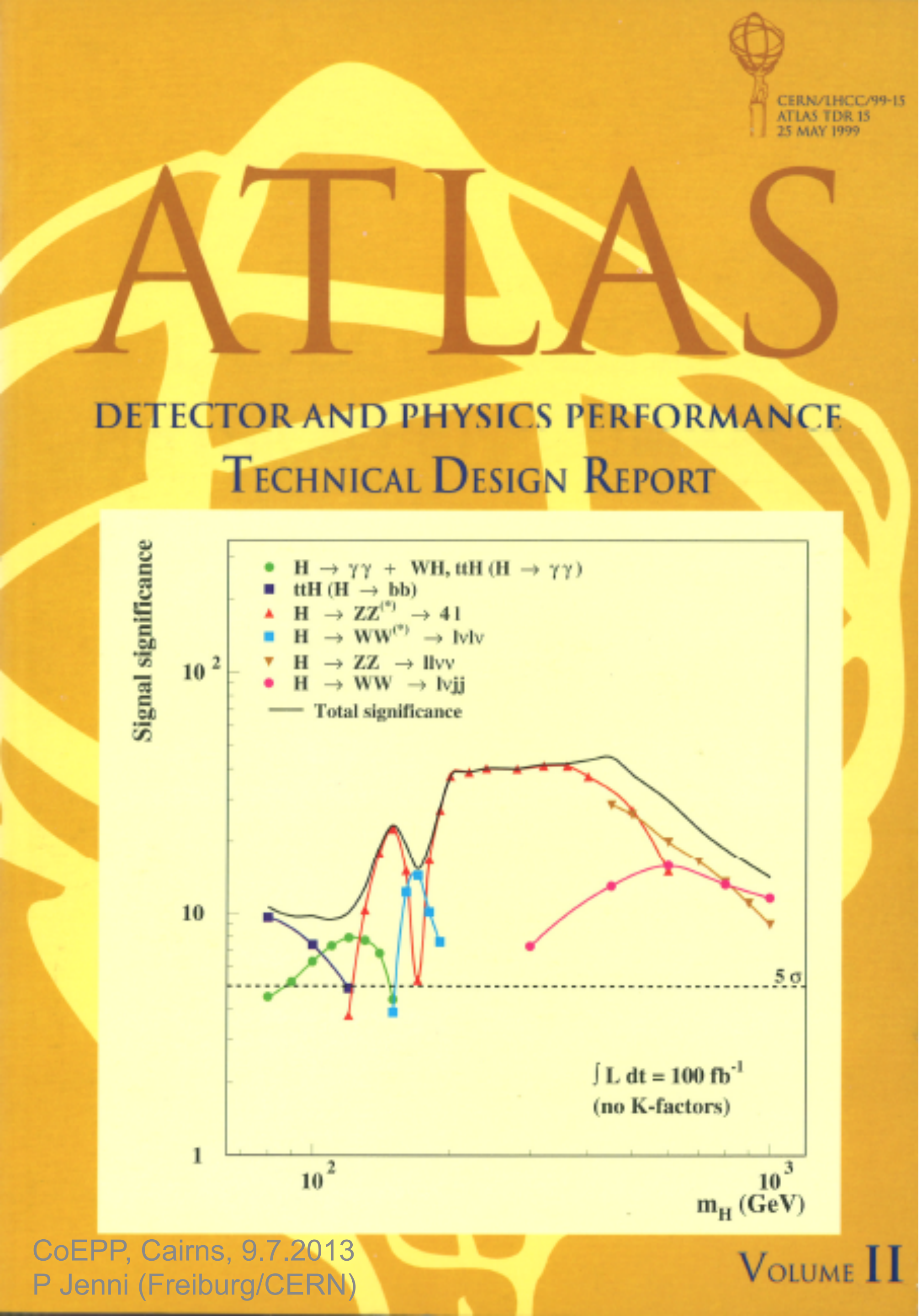


Two of the by now historical plots from the July 2012 discovery announcement





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



CERN/LHCC/99-15
ATLAS TDR 15
25 MAY 1999

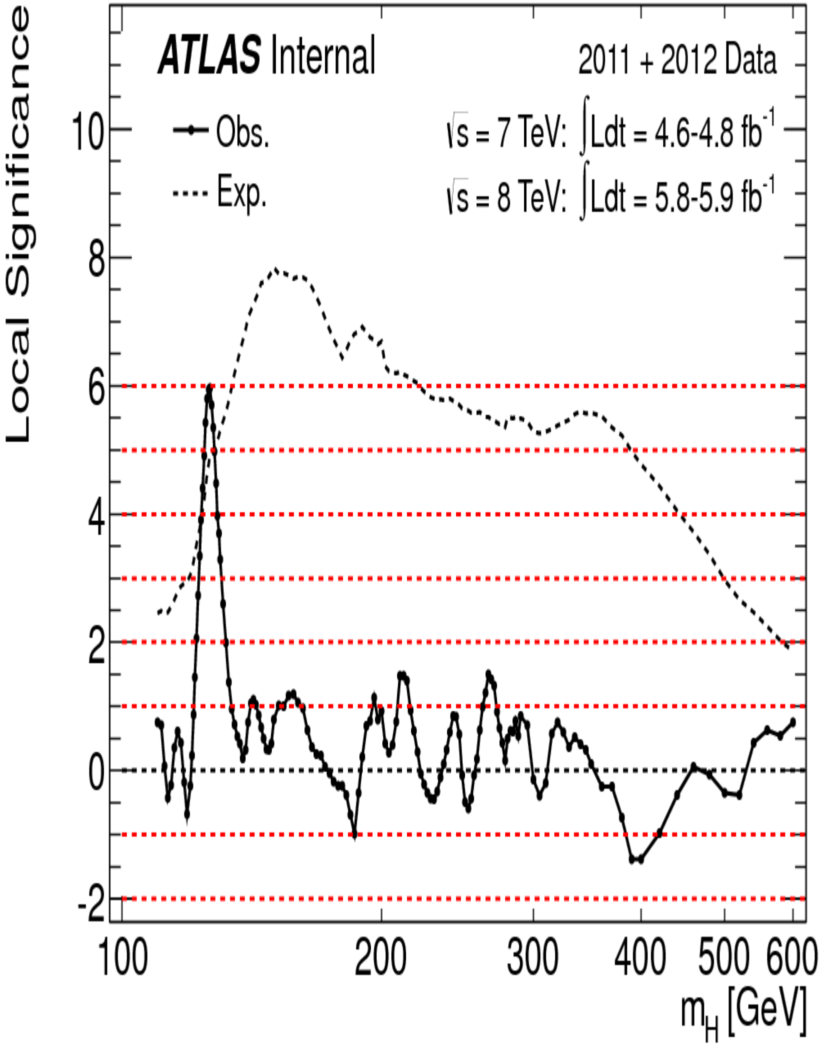
ATLAS

DETECTOR AND PHYSICS PERFORMANCE

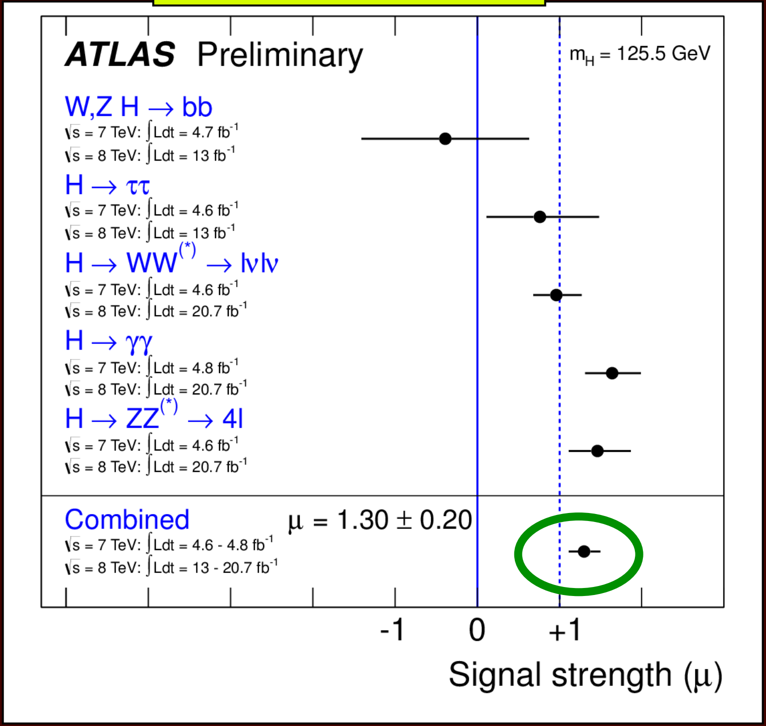
TECHNICAL DESIGN REPORT

VOLUME II

A dream becoming true much faster than anticipated long ago



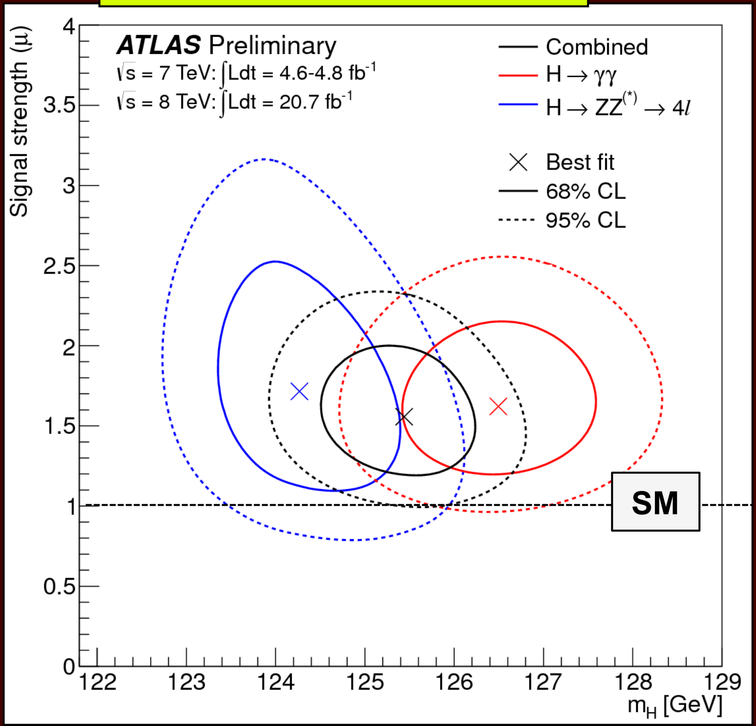
Signal strength



μ = signal strength normalized to SM Higgs expectation at m_H = 125.5 GeV

Best-fit value for m_H=125.5 GeV:
$\mu = 1.3 \pm 0.13$ (stat) $\pm$ 0.14 (syst)
→in agreement with SM expectation

Mass measurement



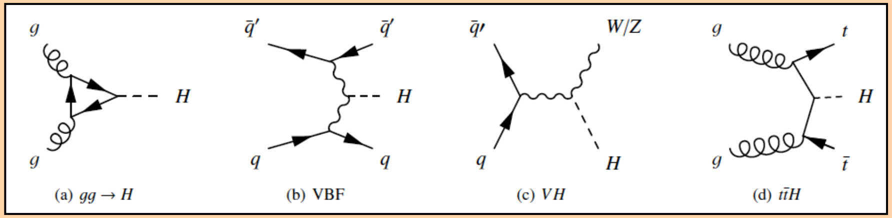
Estimated mass from high-resolution H→ γγ and H→ 4l channels:

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

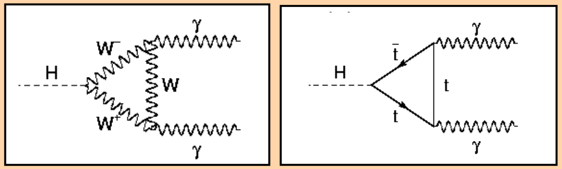
$$m_H(\gamma\gamma) = 126.8\ \text{GeV} \pm 0.2(\text{stat})\ \pm 0.7(\text{syst})\ \text{GeV}$$

$$m_H\ (4l) = 124.3\ \text{GeV}\ ^{+0.6}_{-0.5}(\text{stat})\ ^{+0.5}_{-0.3}(\text{syst})\ \text{GeV}$$

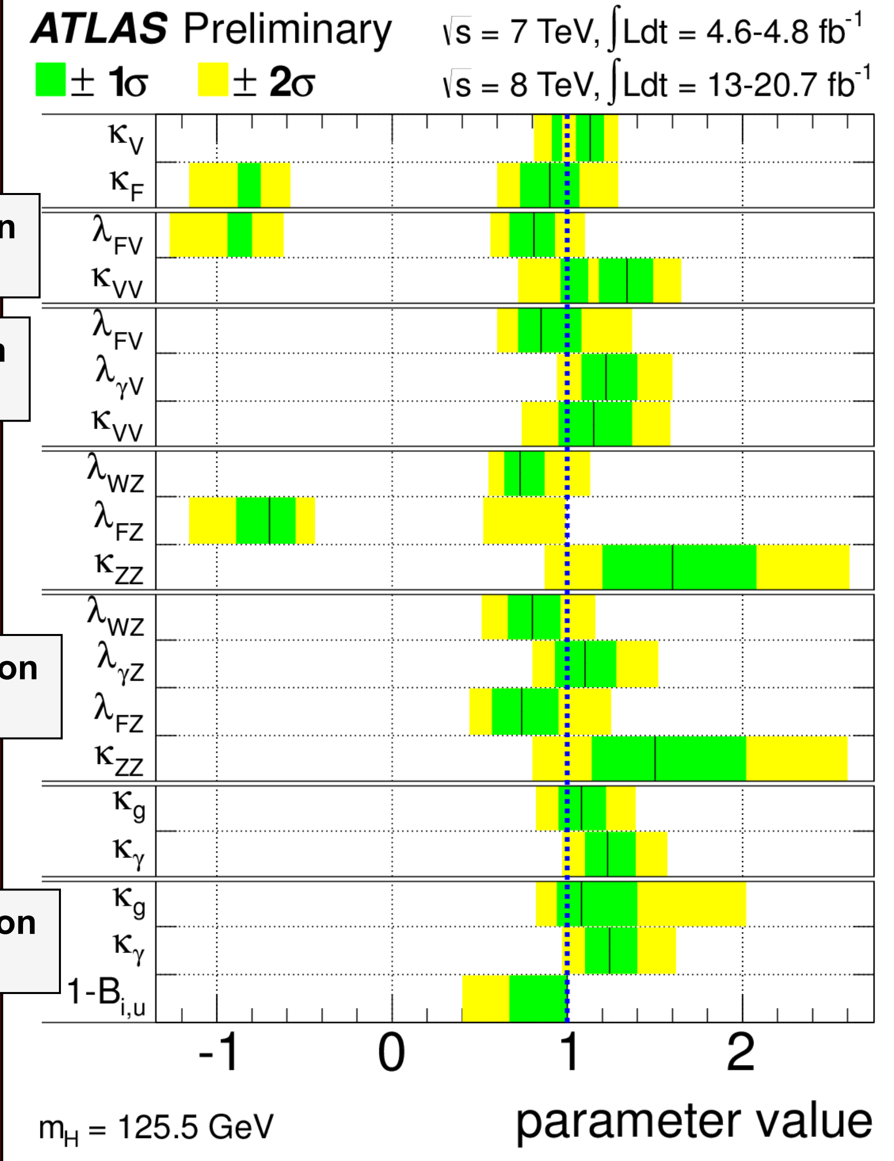
Probability from same particle: 1.5-8%



(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$



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



No assumption on Γ_H

No assumption on Γ_H, k_γ

No assumption on k_γ

No assumption on Γ_H

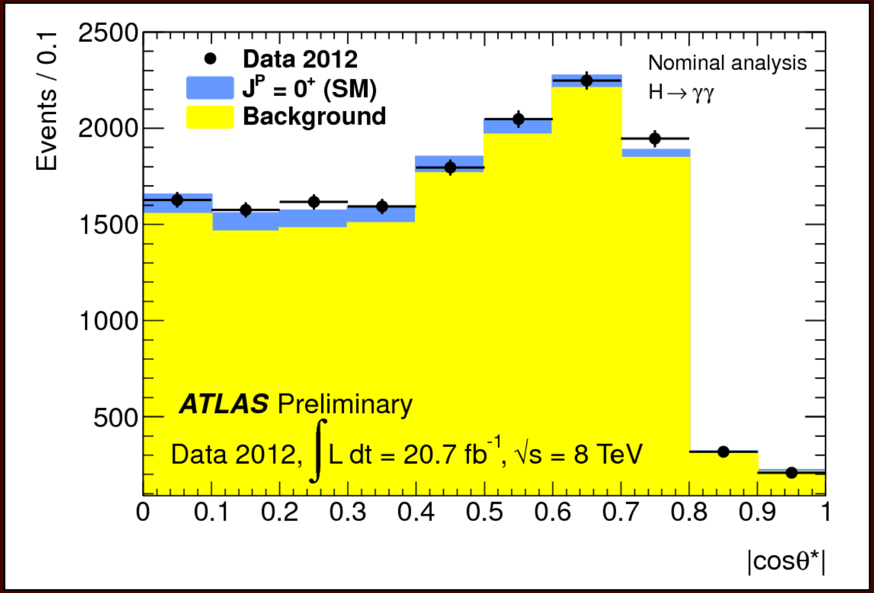
Is this new particle the first elementary scalar ? → Spin studies

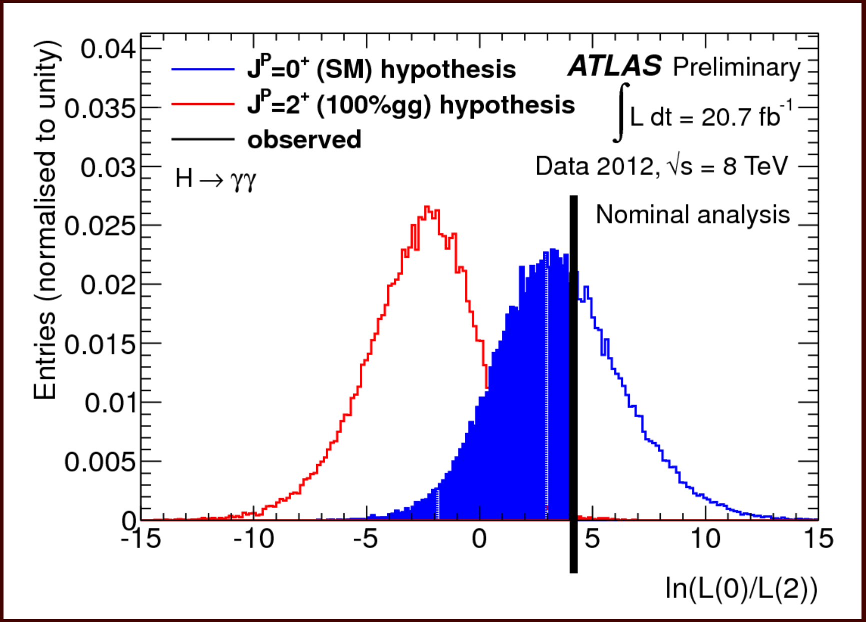
H→ γγ

Spin information from distribution of polar angle θ* of the di-photon system in the Higgs rest frame

Compare θ* distribution in the region of the peak for:

- ☐**spin-0 hypothesis: flat before cuts**
- ☐**spin-2 hypothesis: ~ $1+6\cos^2\theta^* + \cos^4\theta^*$ for Graviton-like (minimal models)**

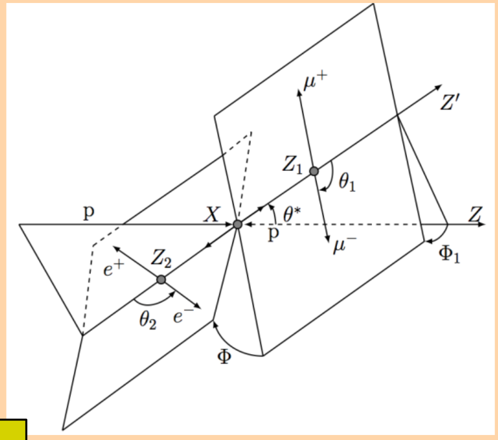




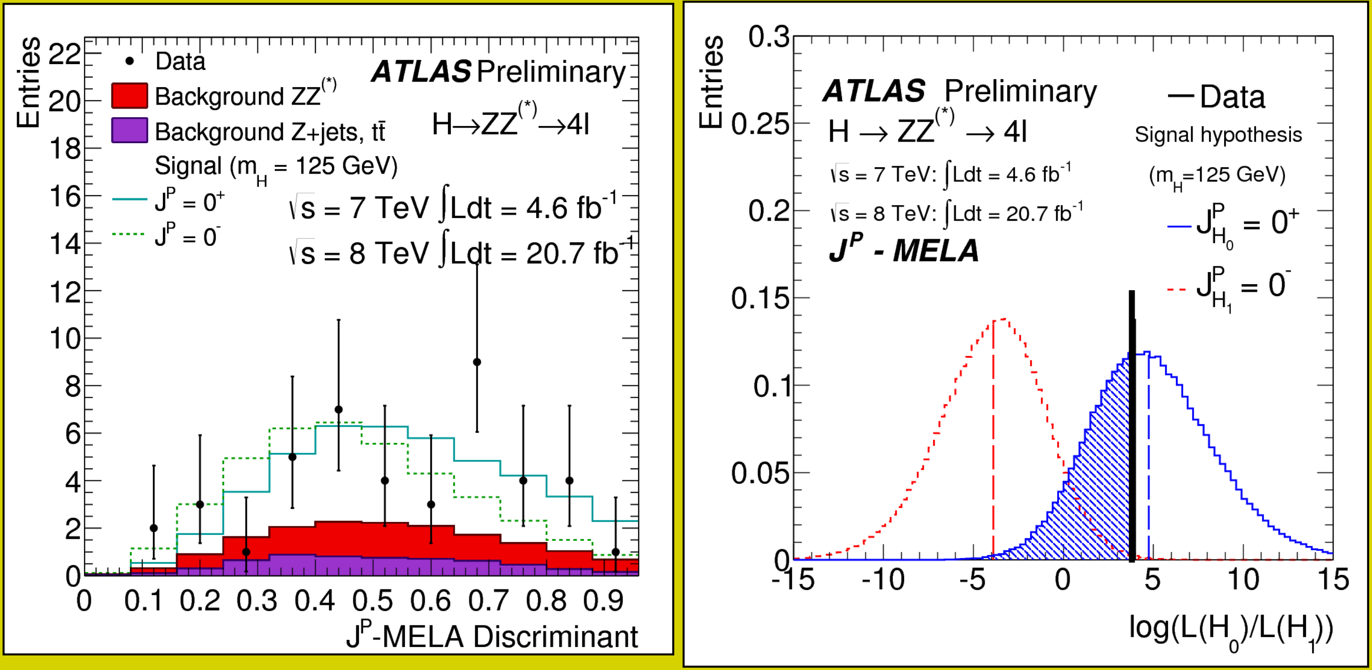
Fit to data disfavours 2^+ hypothesis at 99.3% CL. (66% CL) for pure gg → G (mixture of gg/qq → G) production (separation $0^+/2^+$ decreases with increasing qq contribution)

H→ 4l

Spin-parity information from distribution of 5 production and decay angles combined in BDT or Matrix Element (MELA) discriminants

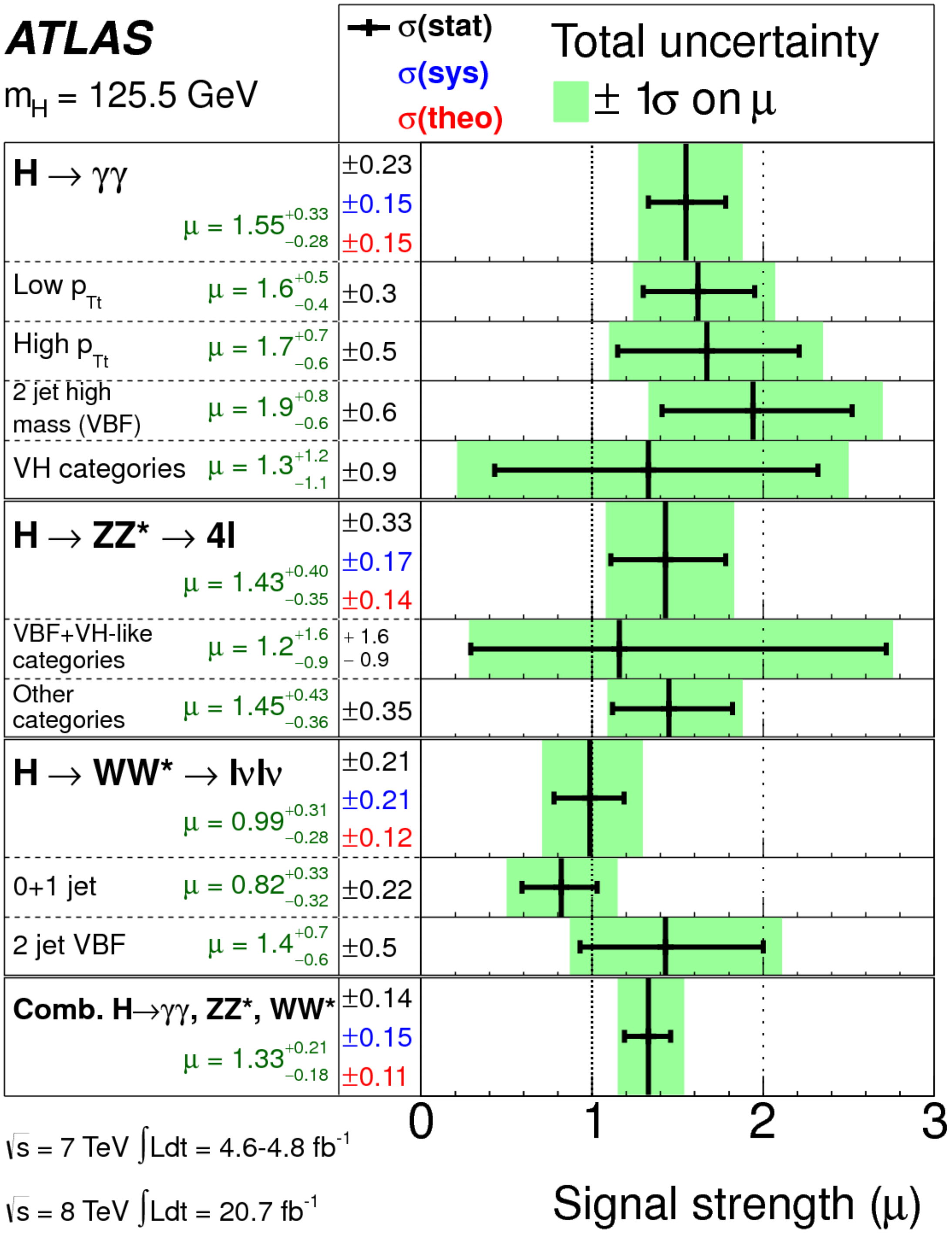


0^+ vs 0^- hypothesis

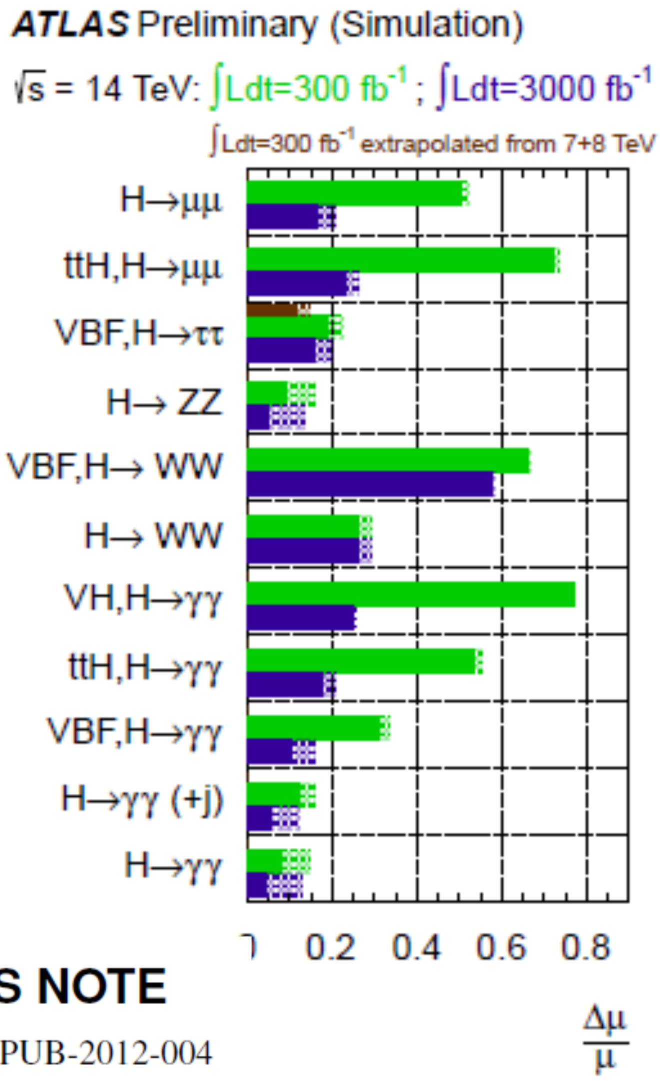


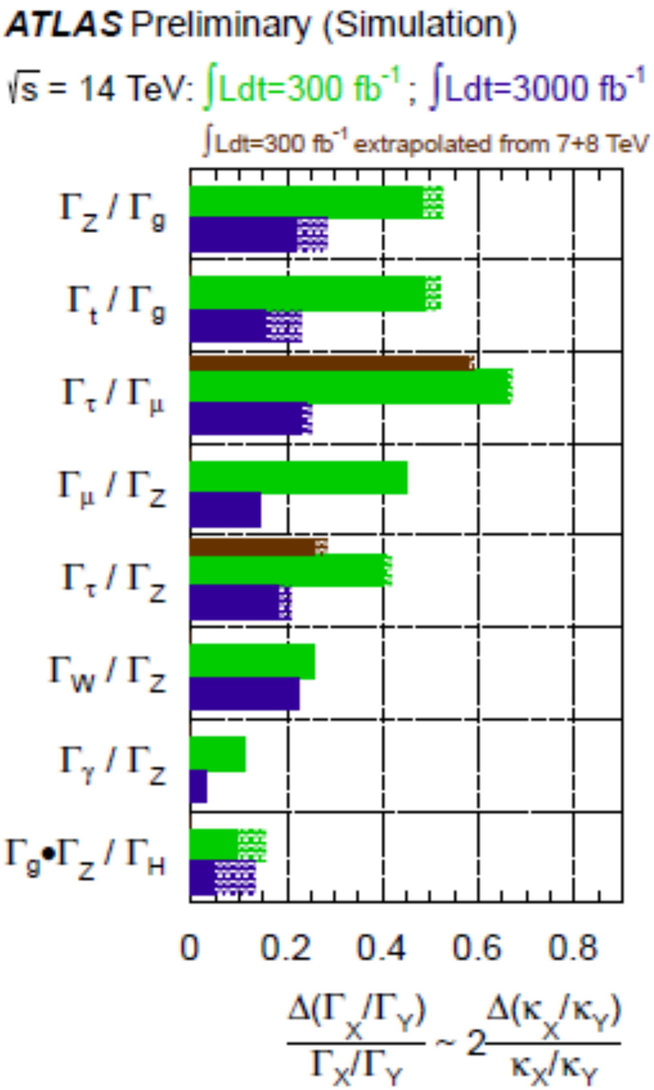
G-like spin-2 gg production

0^- excluded at 99.6% C.L. when compared to 0^+


ATLAS
m_H = 125.5 GeV
σ(stat)
σ(sys)
σ(theo)
Total uncertainty
± 1σ on μ
H → γγ
μ = $1.55^{+0.33}_{-0.28}$
±0.23
±0.15
±0.15
Low p_{Tt} μ = $1.6^{+0.5}_{-0.4}$
±0.3
High p_{Tt} μ = $1.7^{+0.7}_{-0.6}$
±0.5
2 jet high mass (VBF) μ = $1.9^{+0.8}_{-0.6}$
±0.6
VH categories μ = $1.3^{+1.2}_{-1.1}$
±0.9
H → ZZ* → 4l
μ = $1.43^{+0.40}_{-0.35}$
±0.33
±0.17
±0.14
VBF+VH-like categories μ = $1.2^{+1.6}_{-0.9}$
+ 1.6
− 0.9
Other categories μ = $1.45^{+0.43}_{-0.36}$
±0.35
H → WW* → lνlν
μ = $0.99^{+0.31}_{-0.28}$
±0.21
±0.21
±0.12
0+1 jet μ = $0.82^{+0.33}_{-0.32}$
±0.22
2 jet VBF μ = $1.4^{+0.7}_{-0.6}$
±0.5
Comb. H→γγ, ZZ*, WW*
μ = $1.33^{+0.21}_{-0.18}$
±0.14
±0.15
±0.11
0
1
2
3
$\sqrt{s}$ = 7 TeV $\int Ldt$ = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV $\int Ldt$ = 20.7 fb^{-1}
Signal strength (μ)

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



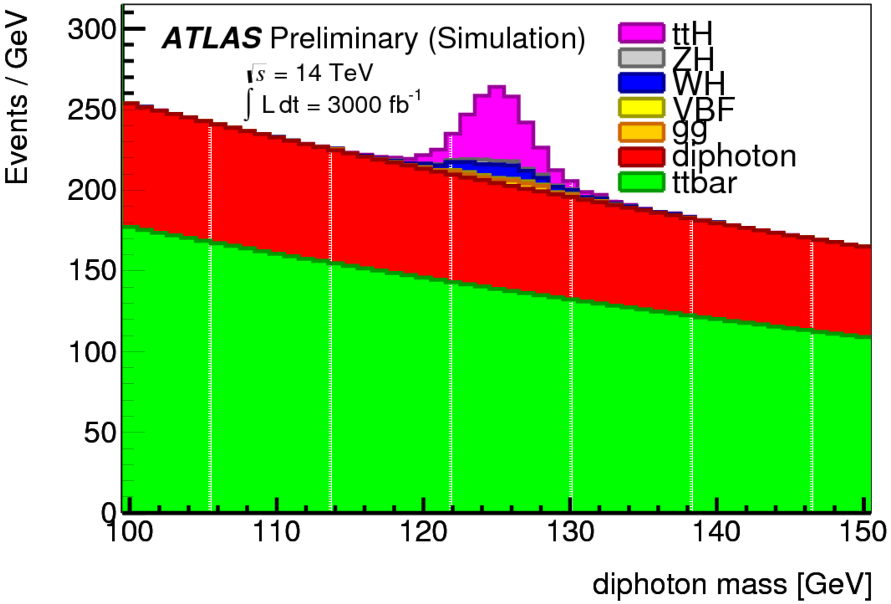


ATLAS NOTE

ATL-PHYS-PUB-2012-004

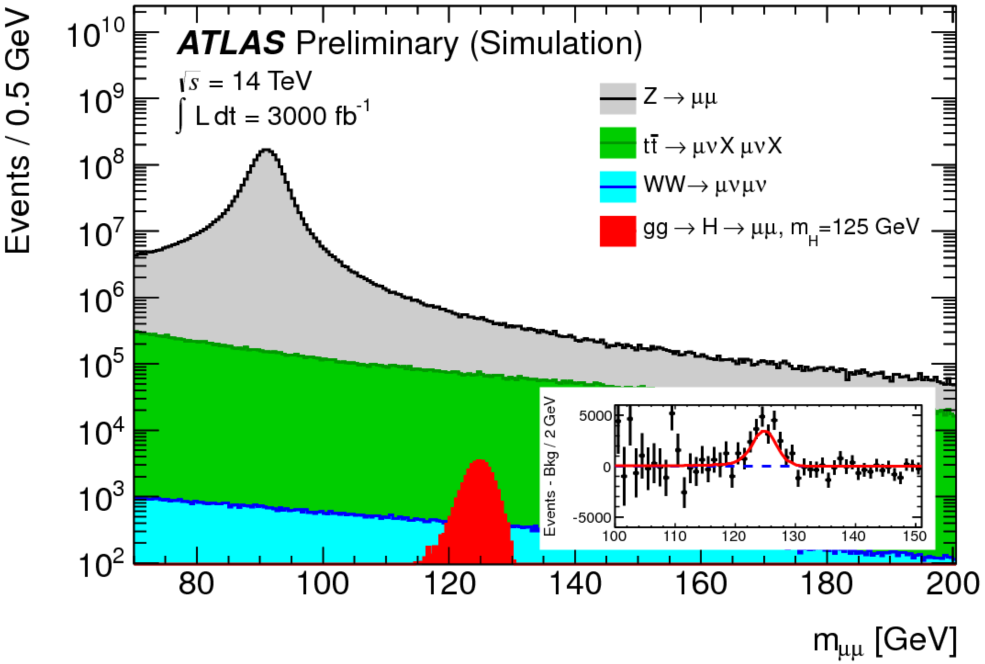
October 15, 2012

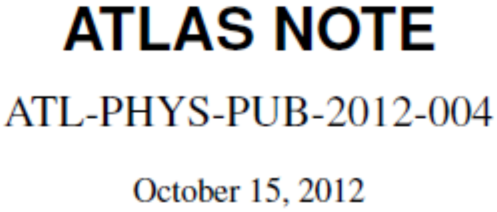
Outlook for HL-LHC on the Higgs physics (II)



ttH with H → γγ for 3000 fb^{-1}

H → μμ for 3000 fb^{-1}





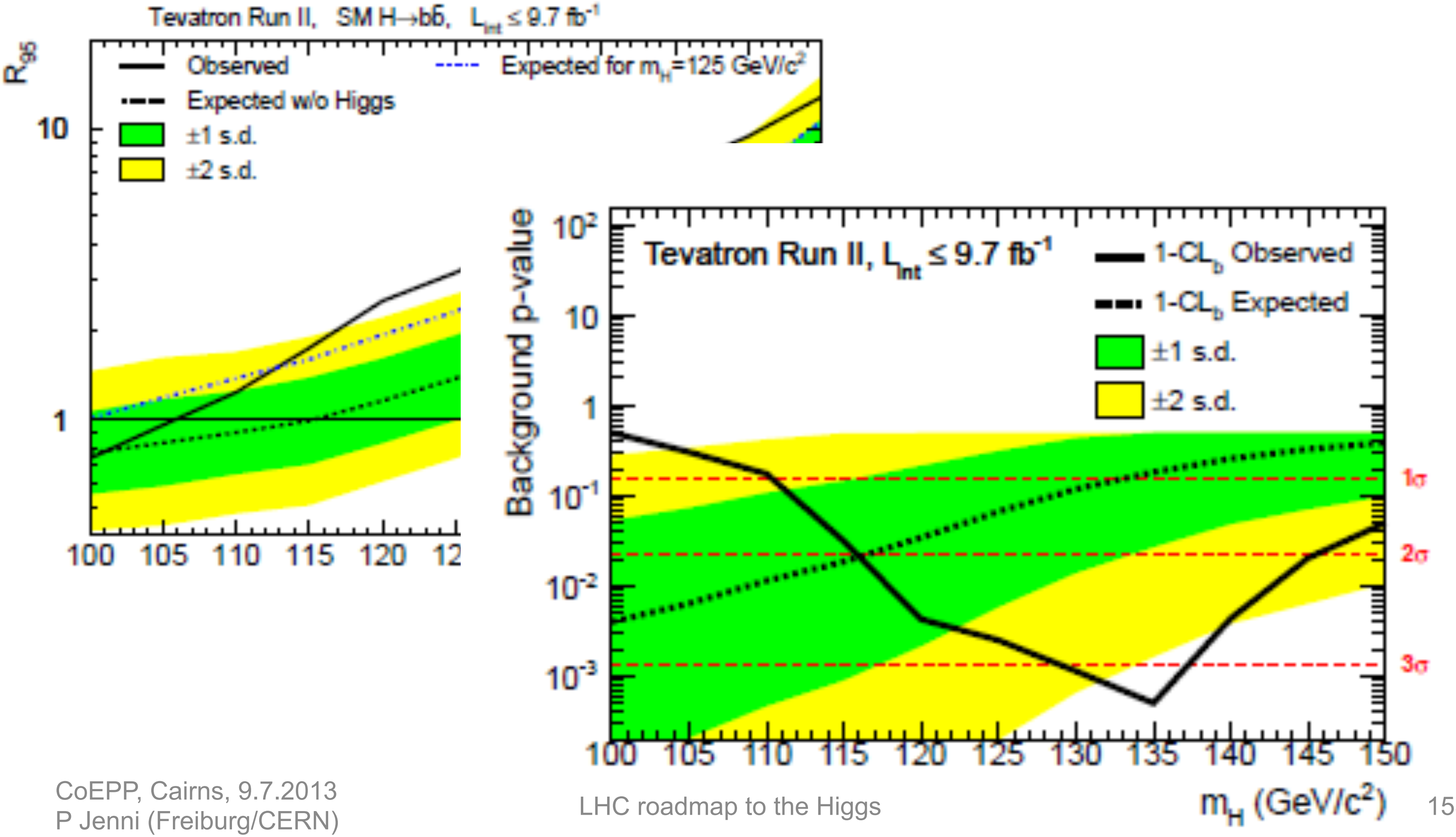
ATLAS NOTE

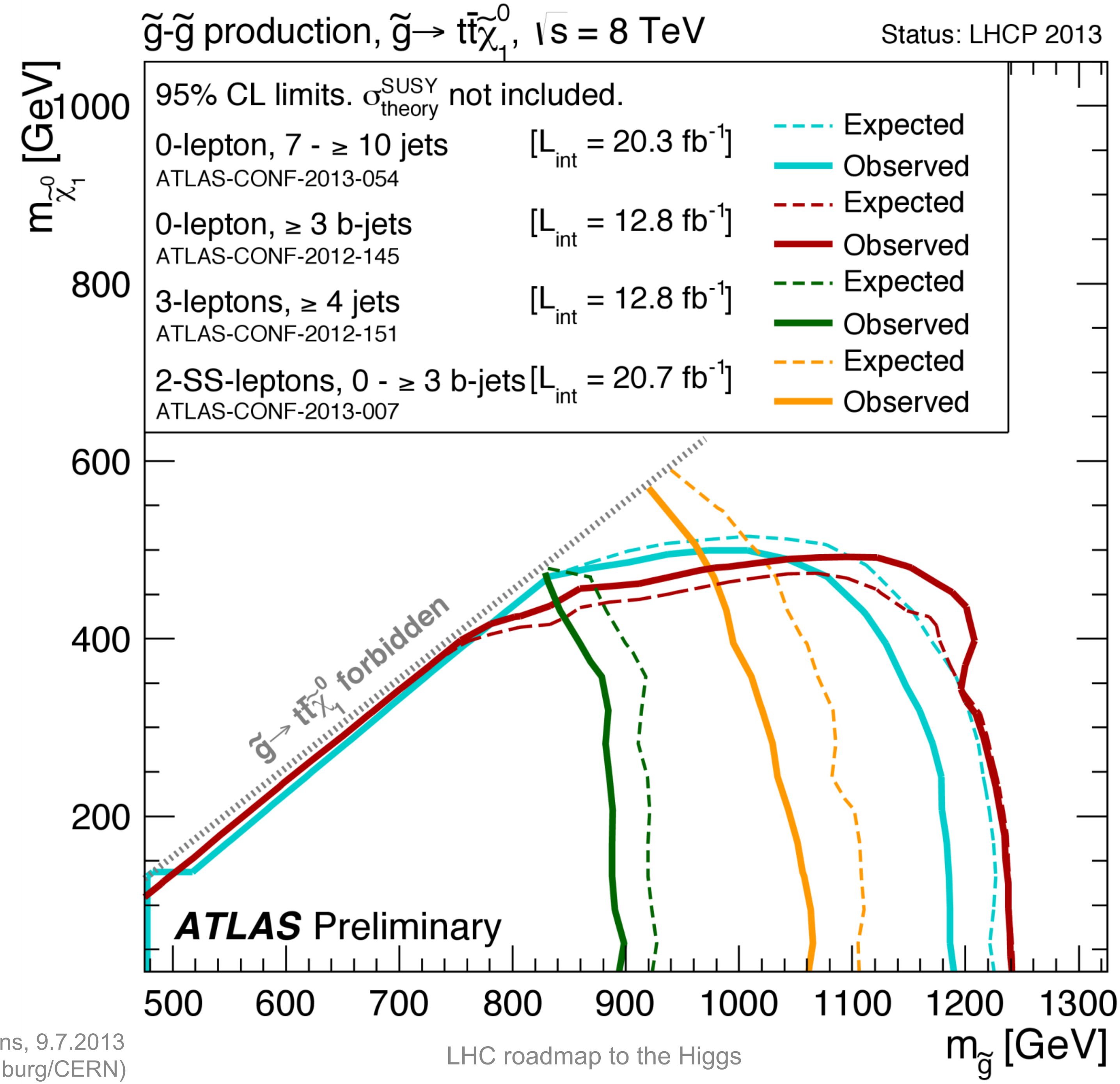
ATL-PHYS-PUB-2012-004

October 15, 2012

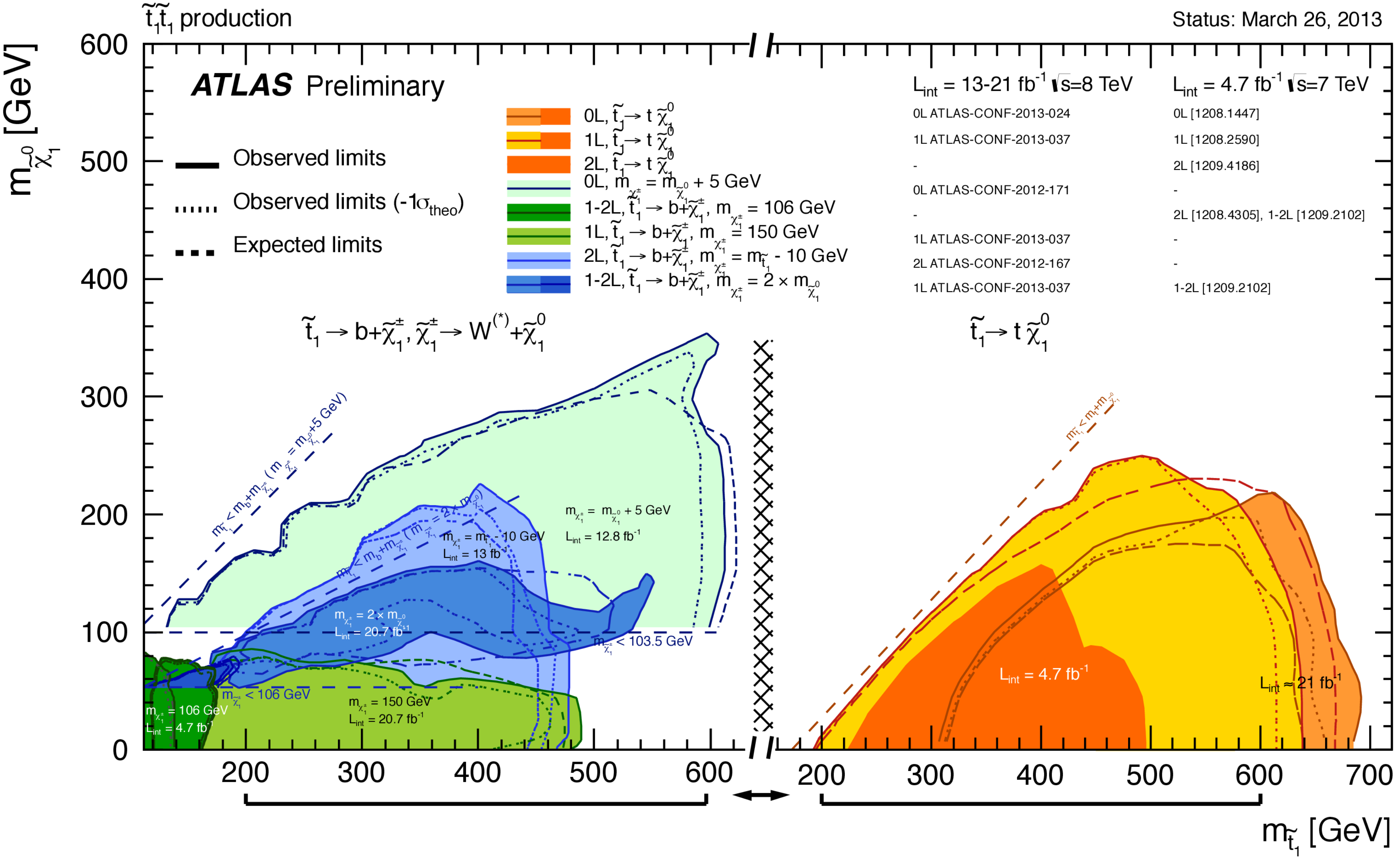
CDF and D0 Collaborations

Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom quark pair in Higgs boson search at the Tevatron, submitted to Phys. Rev. Lett. (2012), arXiv:1207.6436.




$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$, $\sqrt{s}$ = 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
$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ forbidden
ATLAS Preliminary
$m_{\tilde{\chi}_1^0}$ [GeV]
1000
800
600
400
200
500
600
700
800
900
1000
1100
1200
1300
$m_{\tilde{g}}$ [GeV]

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



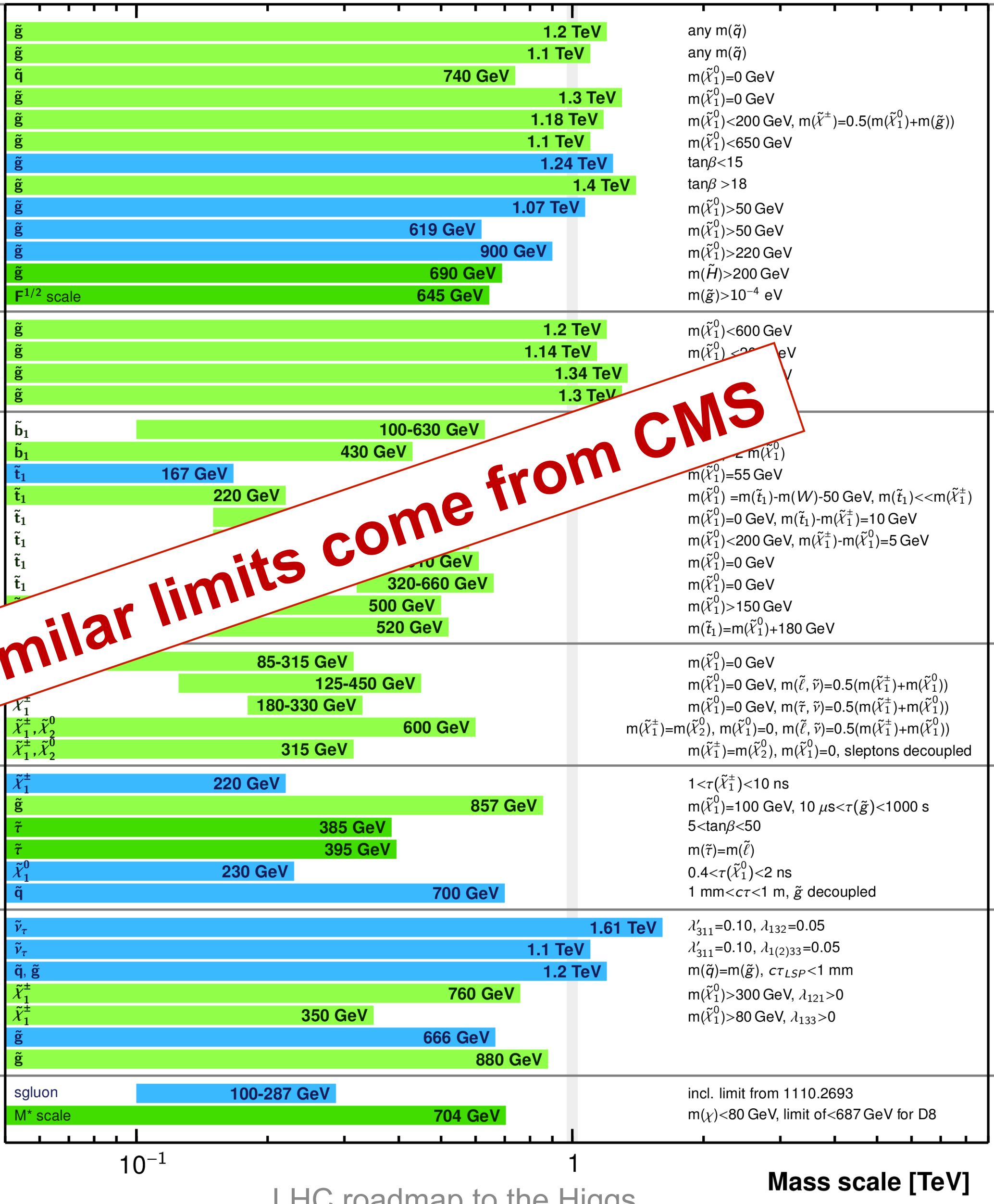
SUSY limits

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
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}^0_1\tilde{\chi}^0_1$	2 e, μ (SS)	3 jets	Yes	20.7	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}^0_1$)<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($\tilde{\chi}^0_1$)>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	0	Yes	4.8	$\tilde{g}$	619 GeV	m($\tilde{\chi}^0_1$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	m($\tilde{\chi}^0_1$)>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
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	m($\tilde{\chi}^0_1$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.14 TeV	m($\tilde{\chi}^0_1$) <2[illegible]eV	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	[illegible]	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	[illegible]	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-630 GeV	[illegible]	ATLAS-CONF-2013-053
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	430 GeV	[illegible] 2 m($\tilde{\chi}^0_1$)	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$	167 GeV	m($\tilde{\chi}^0_1$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	220 GeV	m($\tilde{\chi}^0_1$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}^\pm_1$)	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	[illegible]	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^\pm_1$)=10 GeV	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	0	2 b	Yes	20.1	$\tilde{t}_1$	[illegible]	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$	[illegible]10 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	[illegible]	500 GeV	m($\tilde{\chi}^0_1$)>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	[illegible]	[illegible]	520 GeV	m($\tilde{t}_1$)=m($\tilde{\chi}^0_1$)+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e, μ	0	[illegible]	[illegible]	[illegible]	85-315 GeV	m($\tilde{\chi}^0_1$)=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	[illegible]	[illegible]	[illegible]	[illegible]	125-450 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2013-049
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	[illegible]	[illegible]	[illegible]	$\tilde{\chi}^\pm_1$	180-330 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2013-028
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	[illegible]	[illegible]	20.7	$\tilde{\chi}^\pm_1, \tilde{\chi}^0_2$	600 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2013-035
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W^*\tilde{\chi}^0_1 Z^*\tilde{\chi}^0_1$	3 e, μ	[illegible]	Yes	20.7	$\tilde{\chi}^\pm_1, \tilde{\chi}^0_2$	315 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, sleptons decoupled	ATLAS-CONF-2013-035
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	0	1 jet	Yes	4.7	$\tilde{\chi}^\pm_1$	220 GeV	1<τ($\tilde{\chi}^\pm_1$)<10 ns	1210.2852
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	857 GeV	m($\tilde{\chi}^0_1$)=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, $\tilde{\chi}^0_1\to\gamma\tilde{g}$, long-lived $\tilde{\chi}^0_1$	2 γ	0	Yes	4.7	$\tilde{\chi}^0_1$	230 GeV	0.4<τ($\tilde{\chi}^0_1$)<2 ns	1304.6310
	$\tilde{\chi}^0_1\to qq\mu$ (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 $e, \mu + \tau$	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($\tilde{g}$), cτ_{LSP}<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e, μ	0	Yes	20.7	$\tilde{\chi}^\pm_1$	760 GeV	m($\tilde{\chi}^0_1$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	0	Yes	20.7	$\tilde{\chi}^\pm_1$	350 GeV	m($\tilde{\chi}^0_1$)>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

🟦 $\sqrt{s}$ = 7 TeV full data

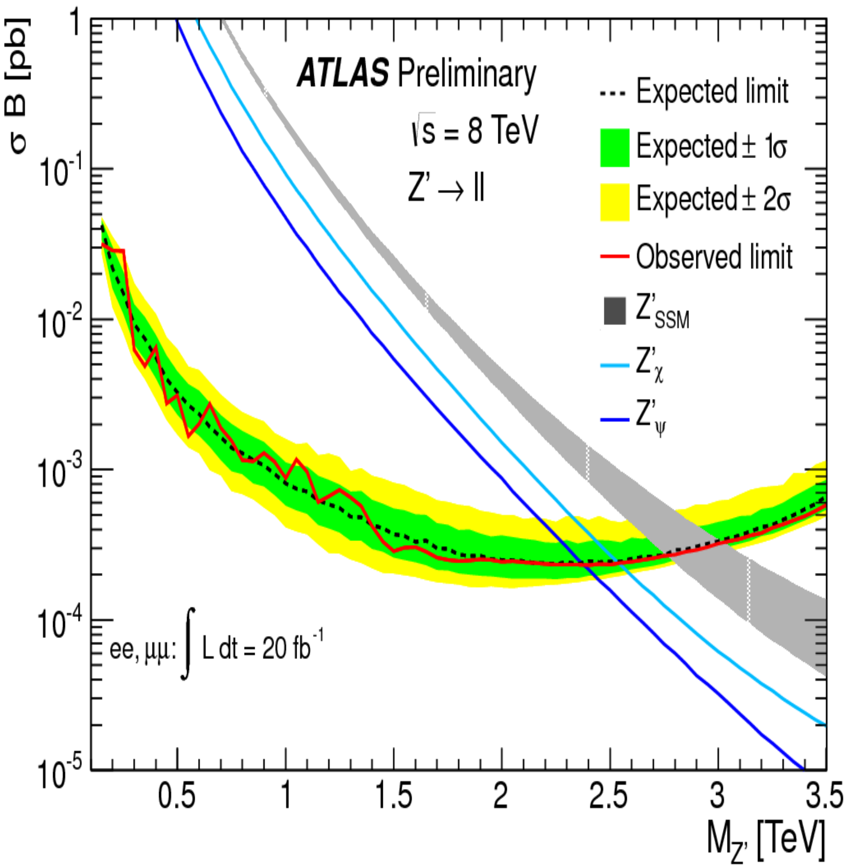
🟩 $\sqrt{s}$ = 8 TeV partial data

🟩 $\sqrt{s}$ = 8 TeV full data

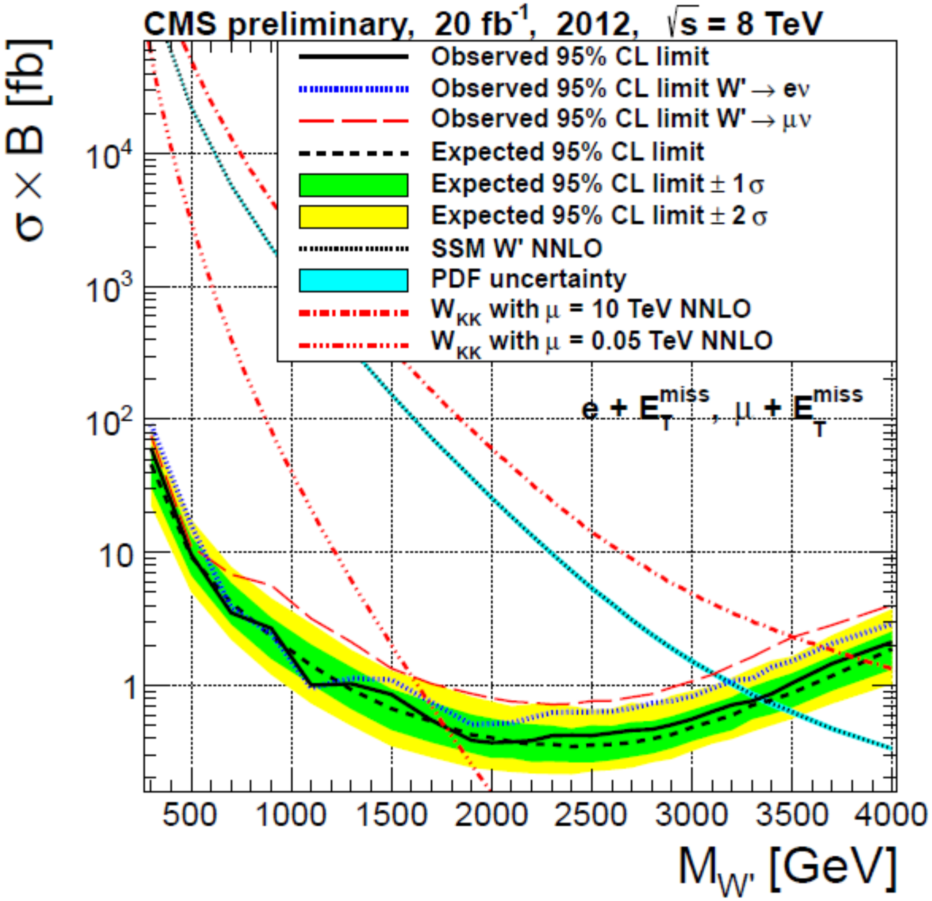
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Very similar limits come from CMS

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

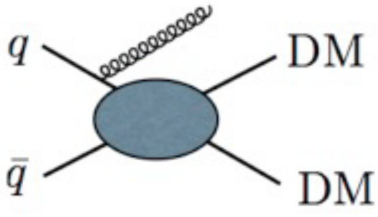


ATLAS-CONF-2013-017

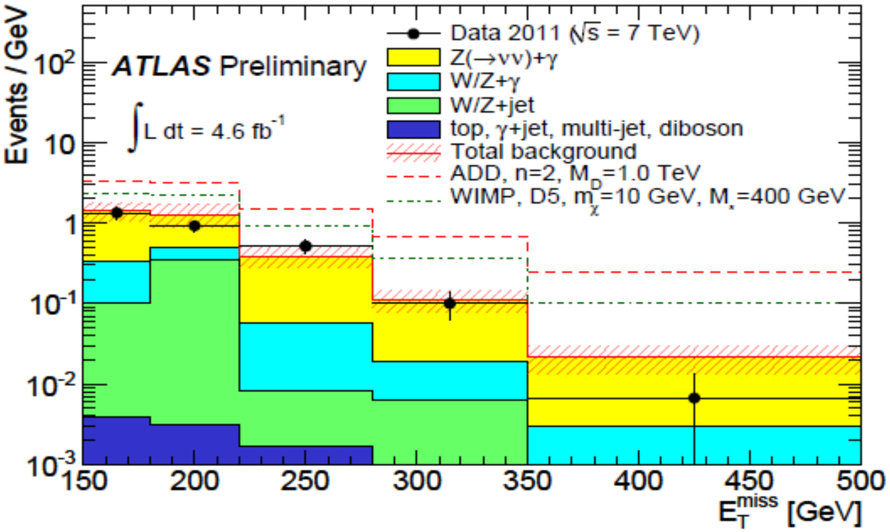


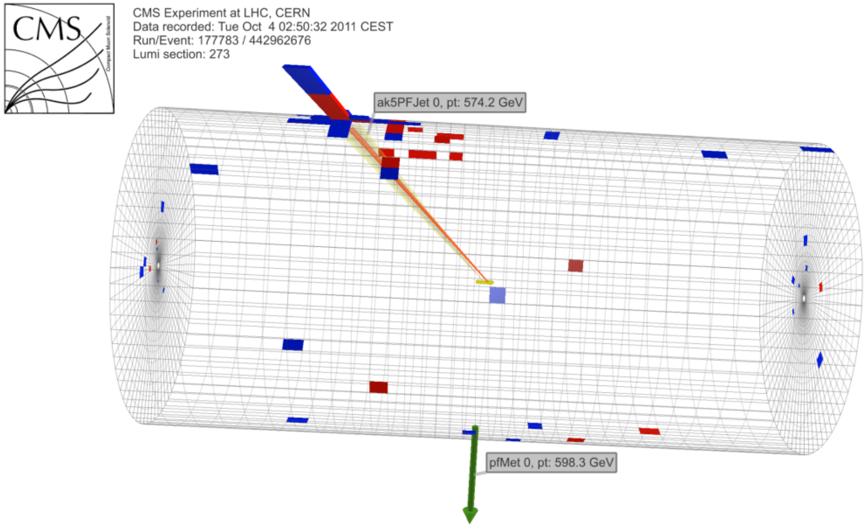
CMS-EXO-12-060

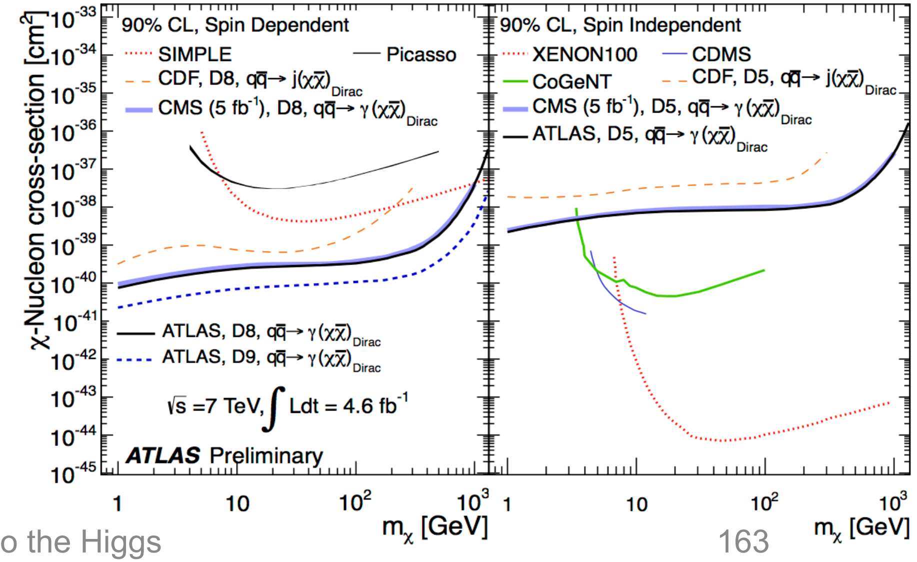
Search for direct Dark Matter (DM) particles in pair-production



A single photon (150 GeV) or jet plus ETmiss





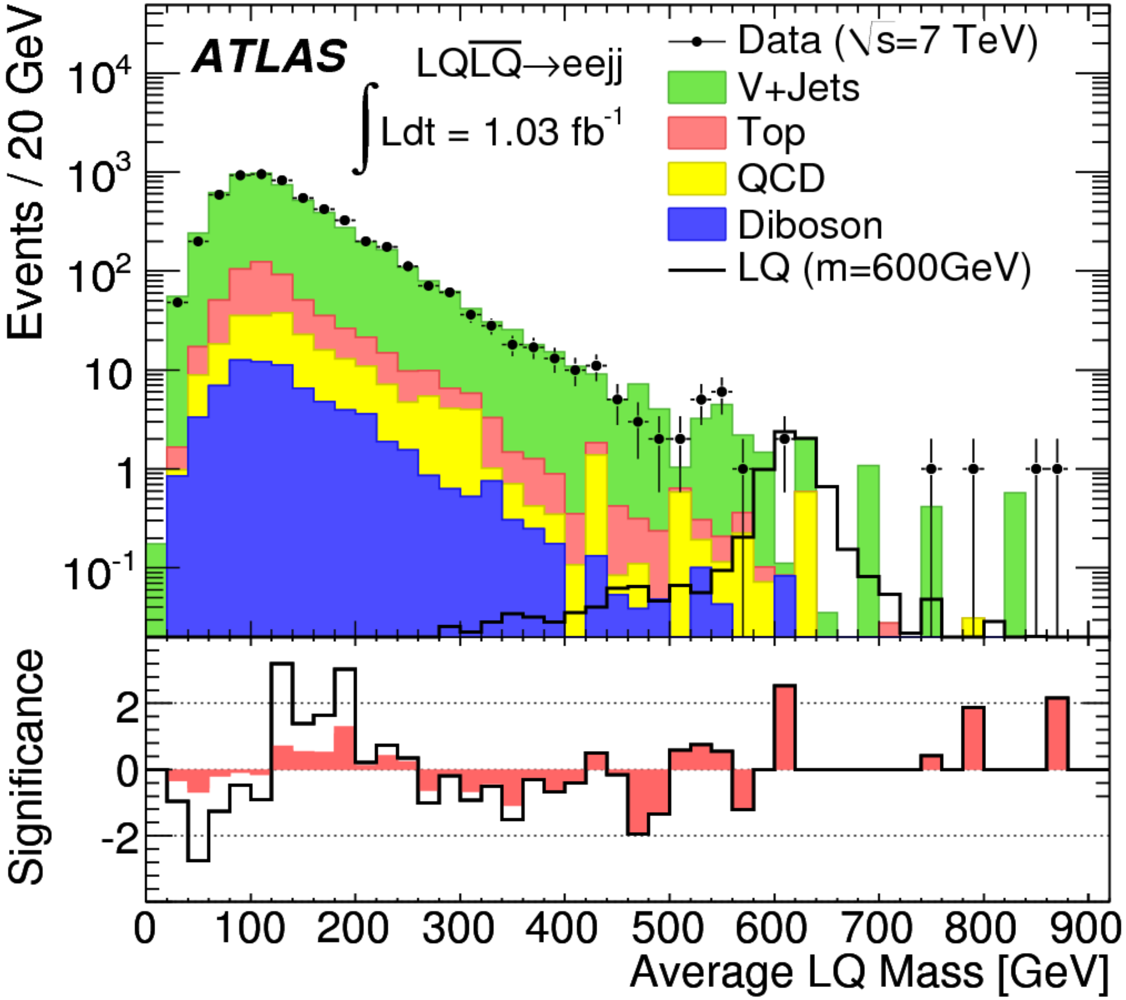


ATLAS-CONF-2012-085
arXiv:1210.4491v1[hep-ex]

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

Search for Lepto-Quarks (LQ)

$pp \rightarrow LQ\,\overline{LQ} \rightarrow lljj$ or $l\nu jj$ (l = e or μ)



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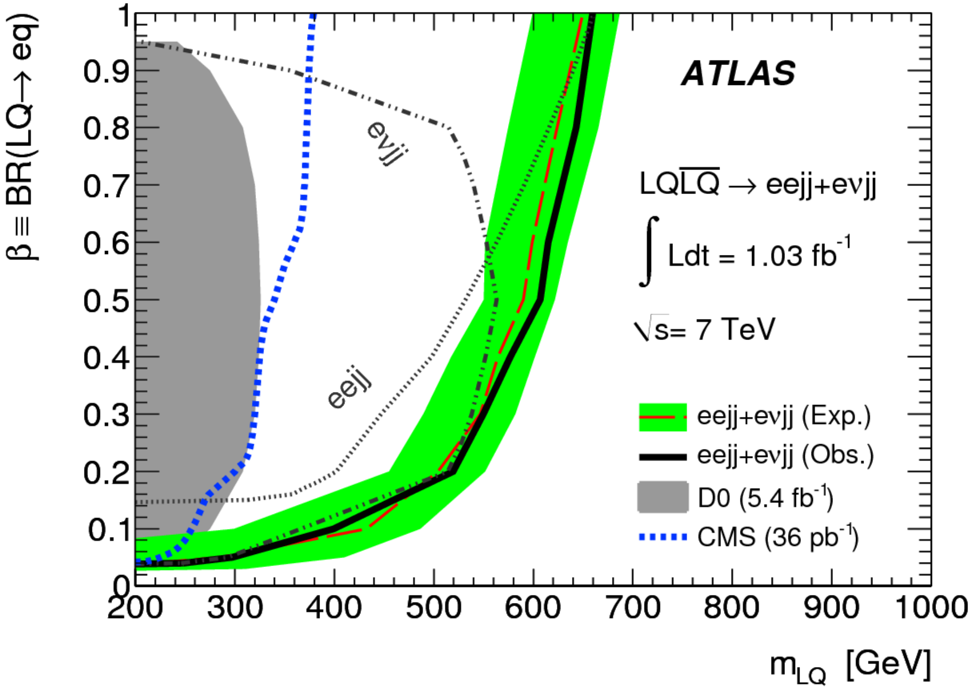
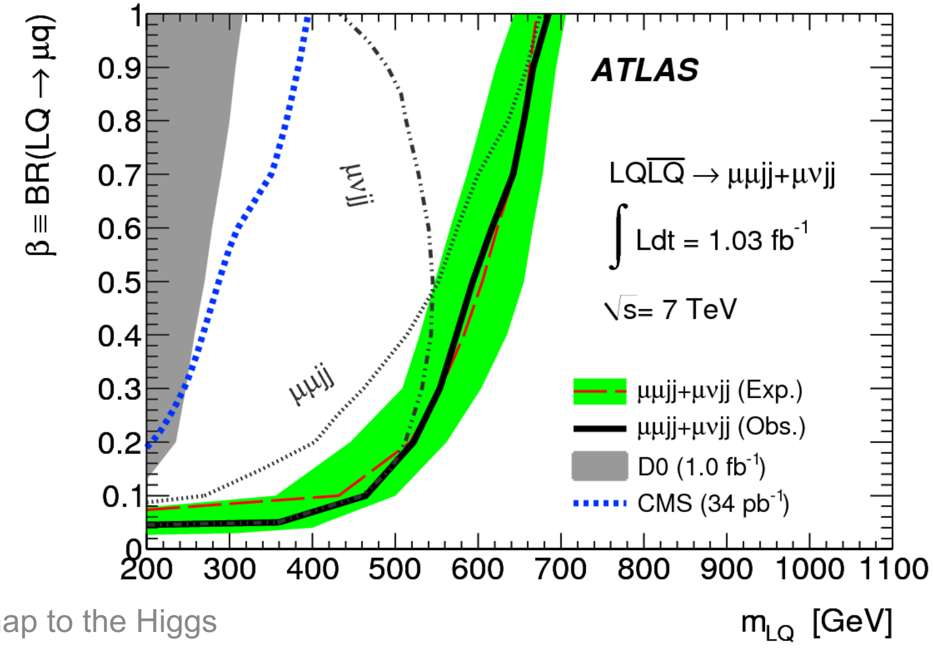
95% CL exclusion limits for Lepto-Quarks



1st generation LQ (electron-quark)

Phys. Lett. B709 (2012) 158

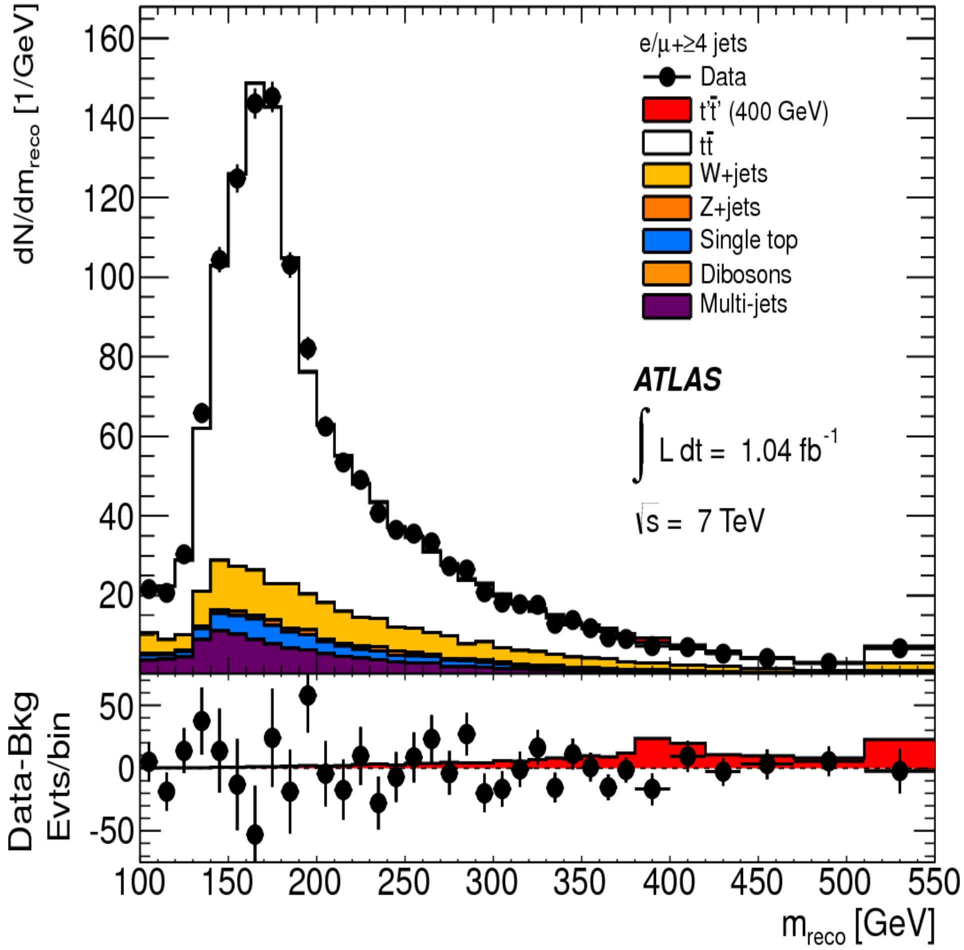
Sub. to European Physical Journal C
arXiv:1203.3172v1[hep-ex]

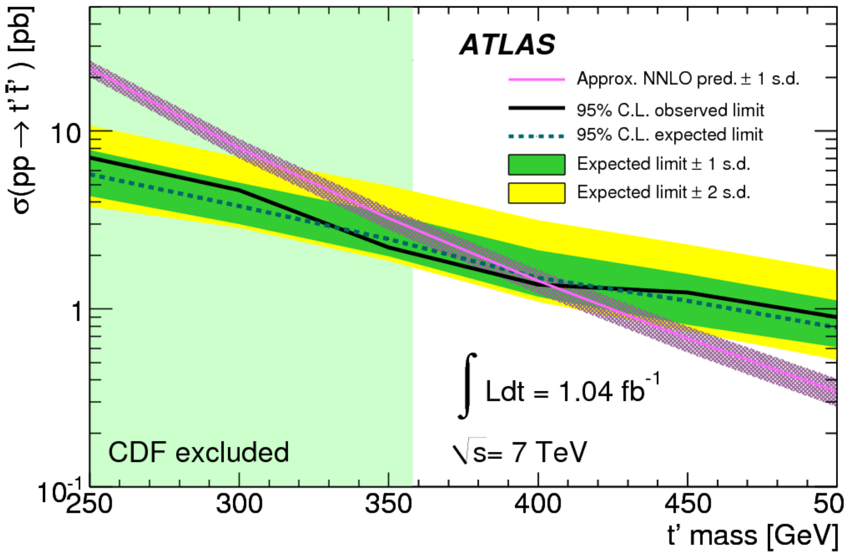


2nd generation LQ (muon-quark)

Search for New Heavy Quarks

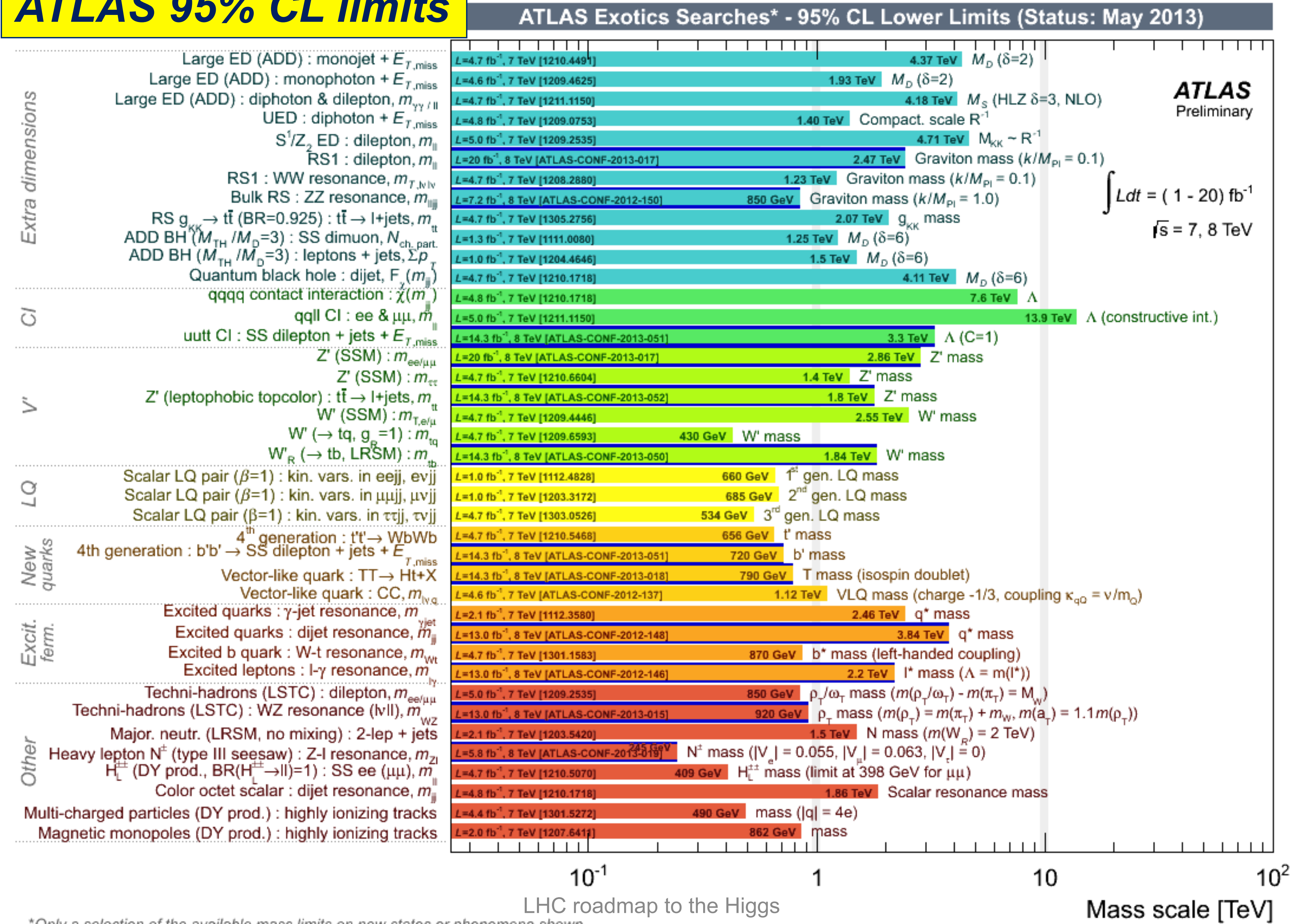
Example: pair-production of a heavy up-type quark (t’) decaying into W + b





Sub. to Phys. Rev. Letters
arXiv:1202.3076v1[hep-ex]

ATLAS 95% CL limits



*Only a selection of the available mass limits on new states or phenomena shown