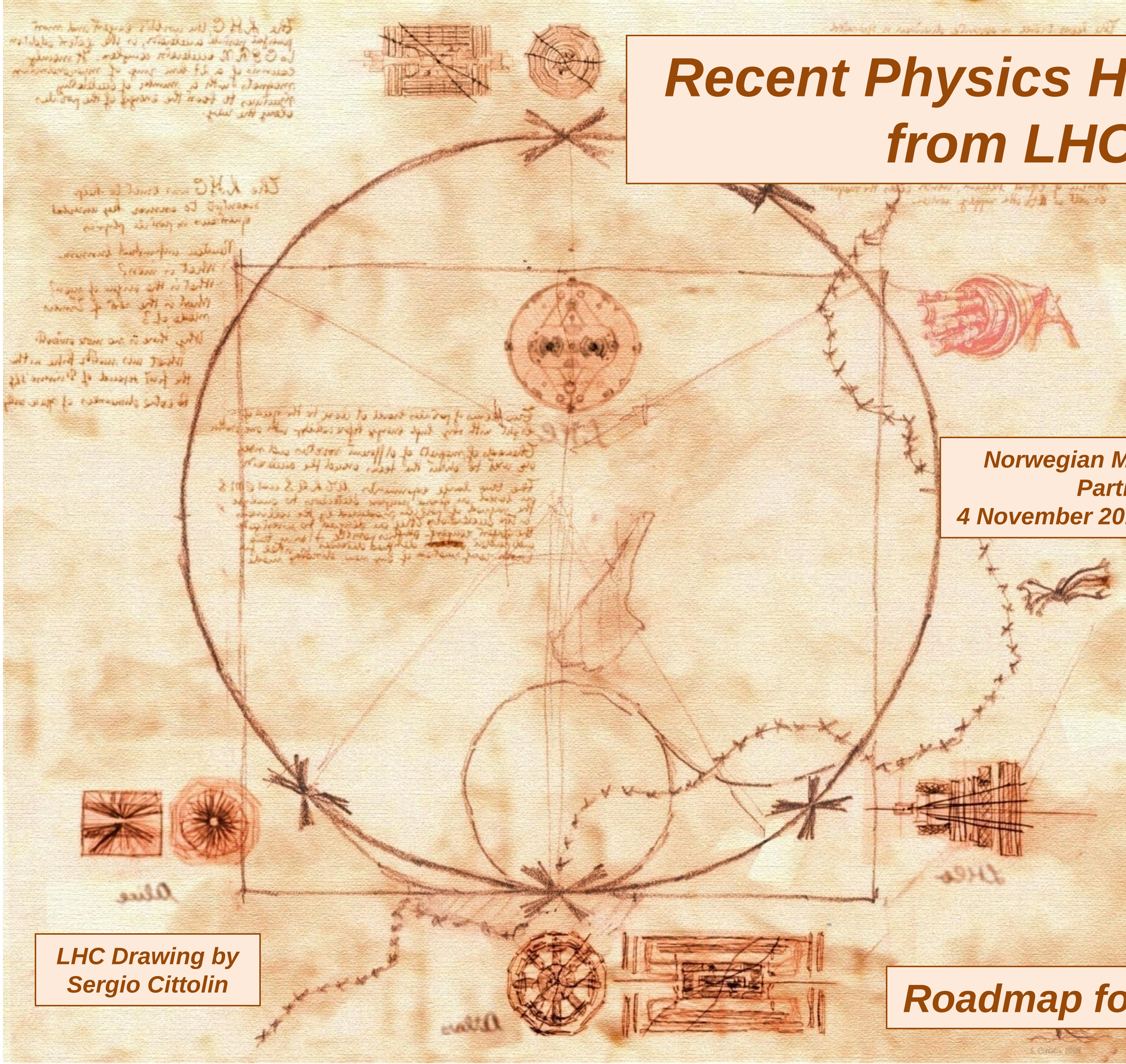
Recent Physics Highlights from LHC



LHC Drawing by Sergio Cittolin

Norwegian Mini-Winterschool on Particle Physics
4 November 2011, Peter Jenni (CERN)

Roadmap for Discoveries

The Large Hadron Collider project has to be seen as a global scientific adventure, combining the accelerator, the experiments and computing

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

How the LHC came to be …

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

Some early key dates

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

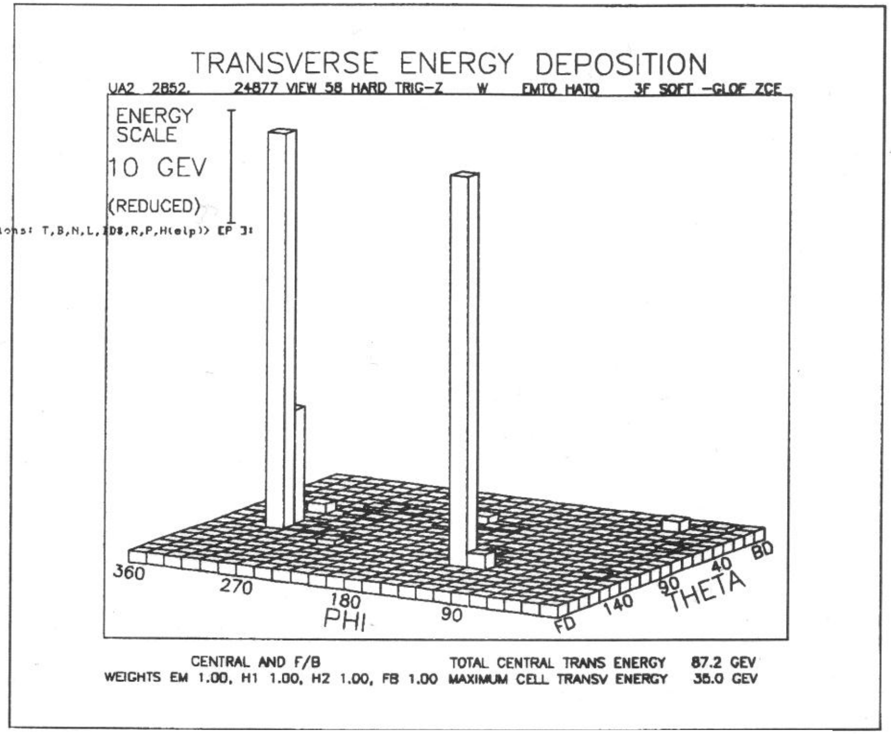
1981 **LEP was approved with a large and long (27 km) tunnel**

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

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

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

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



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

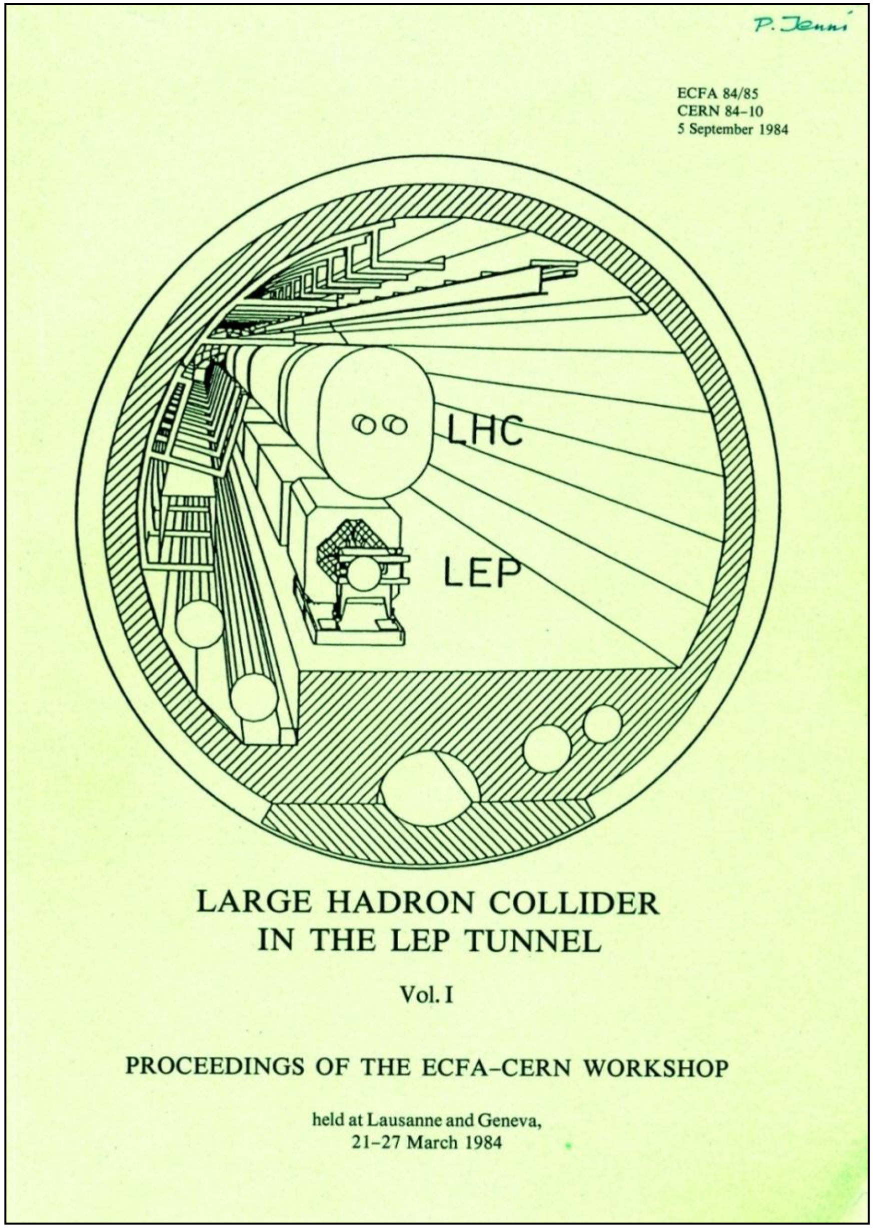
1984 For the community it all started in a way with the 1st CERN – ECFA Workshop Lausanne on the feasibility of a hadron collider in the future LEP tunnel

1987 La Thuile LHC Workshop

Many LHC colleagues were already involved in this, a clear evolution started for detectors away from a 4μ iron-ball experiment (C Rubbia) towards multi-purpose detectors…)

1989 ECFA Study Week in Barcelona for LHC instrumentation

At this conference a few decided to start setting up a structure for an LHC proto-Collaboration….



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)

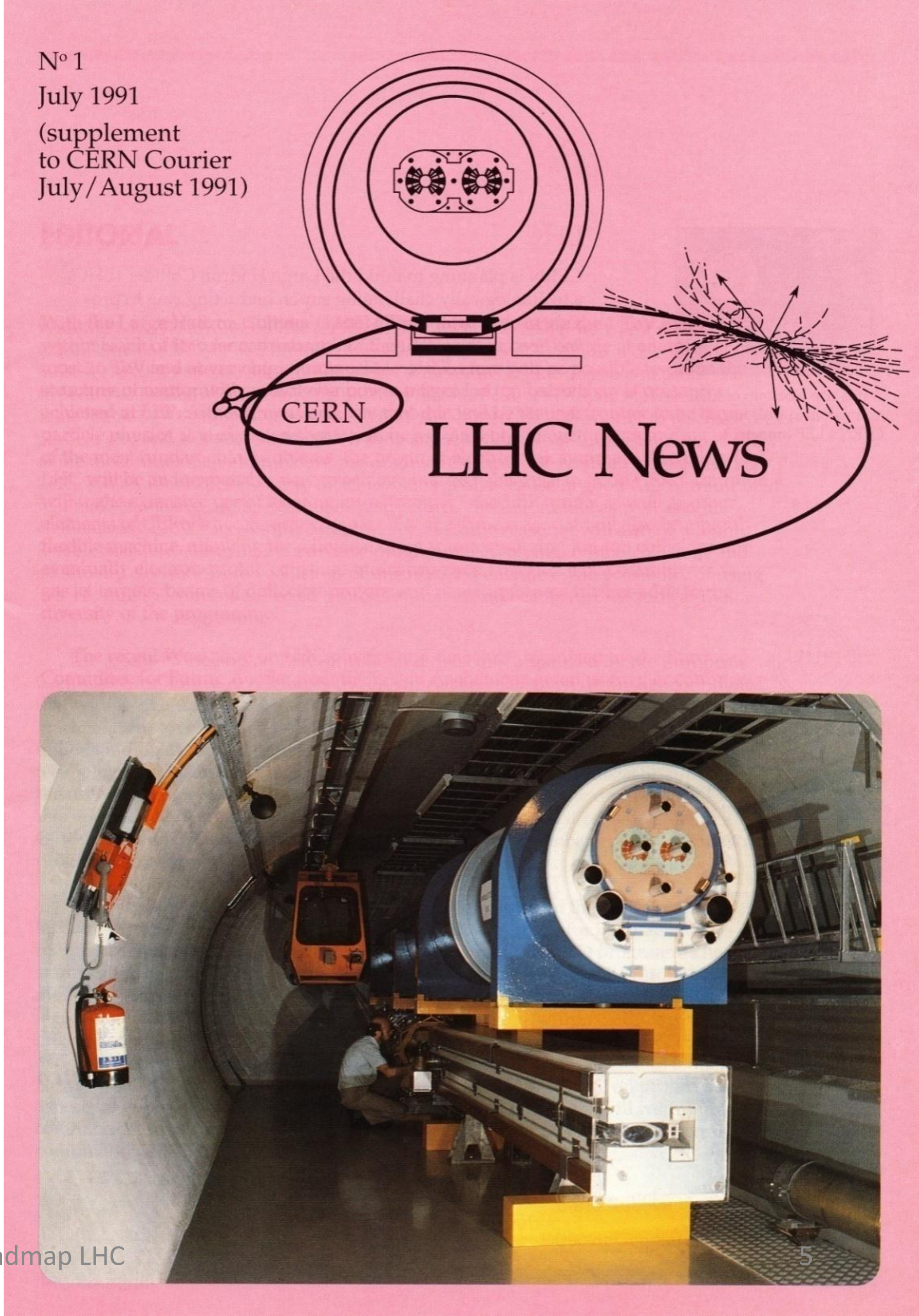
1993 December proposal of LHC with commissioning in 2002

1994 June Council:

Staged construction was proposed, but some countries could not yet agree, so the Council session vote was suspended until

16 December 1994 Council:

(Two-stage) construction of LHC was approved



The two-stage approval 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 coming years, including also the experiments

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

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

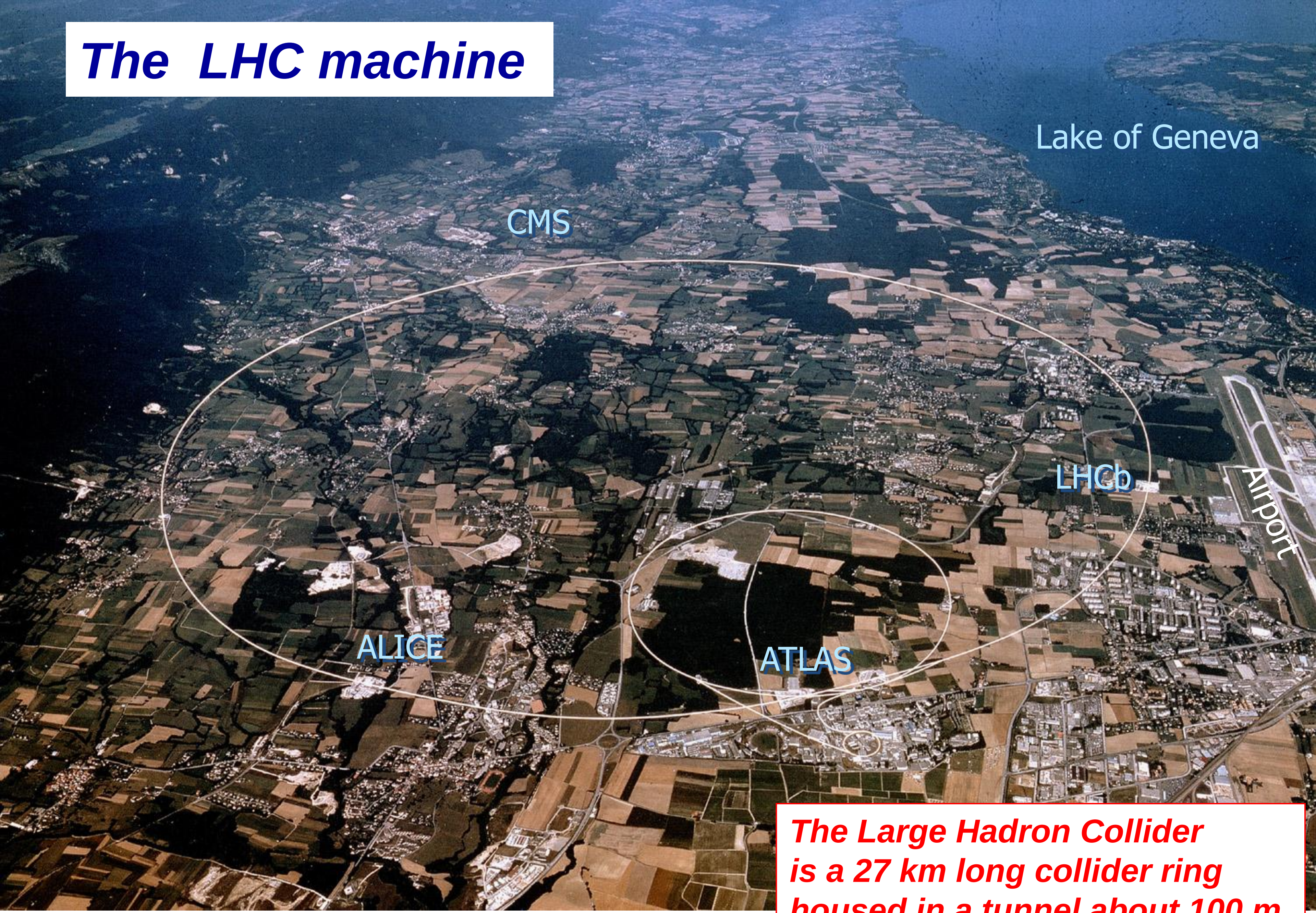
1997

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

Delivery of the last dipole for the LHC injection lines from Russia (15th June 2001)

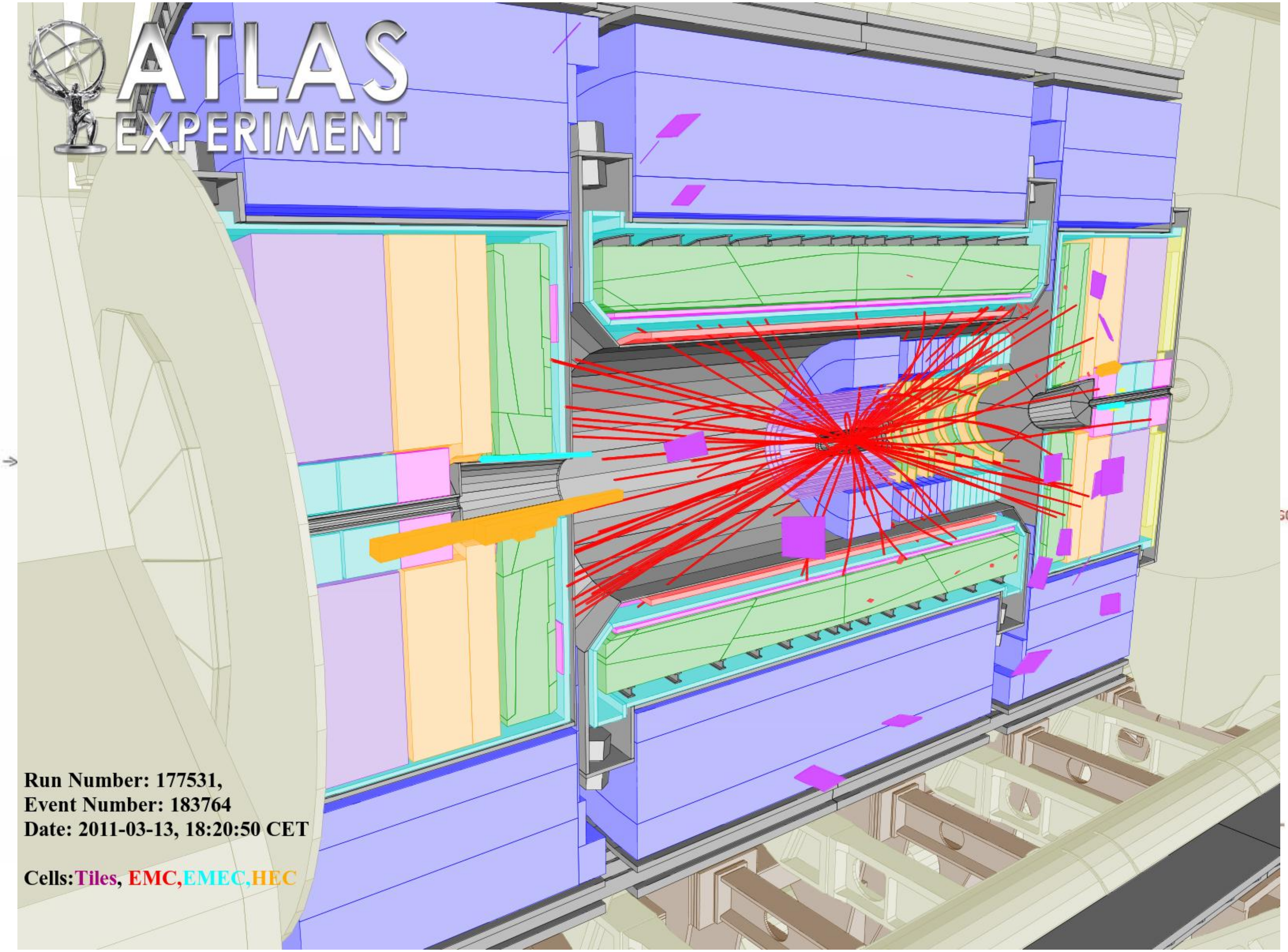
The first picture on the Web in 1992 !

The LHC machine



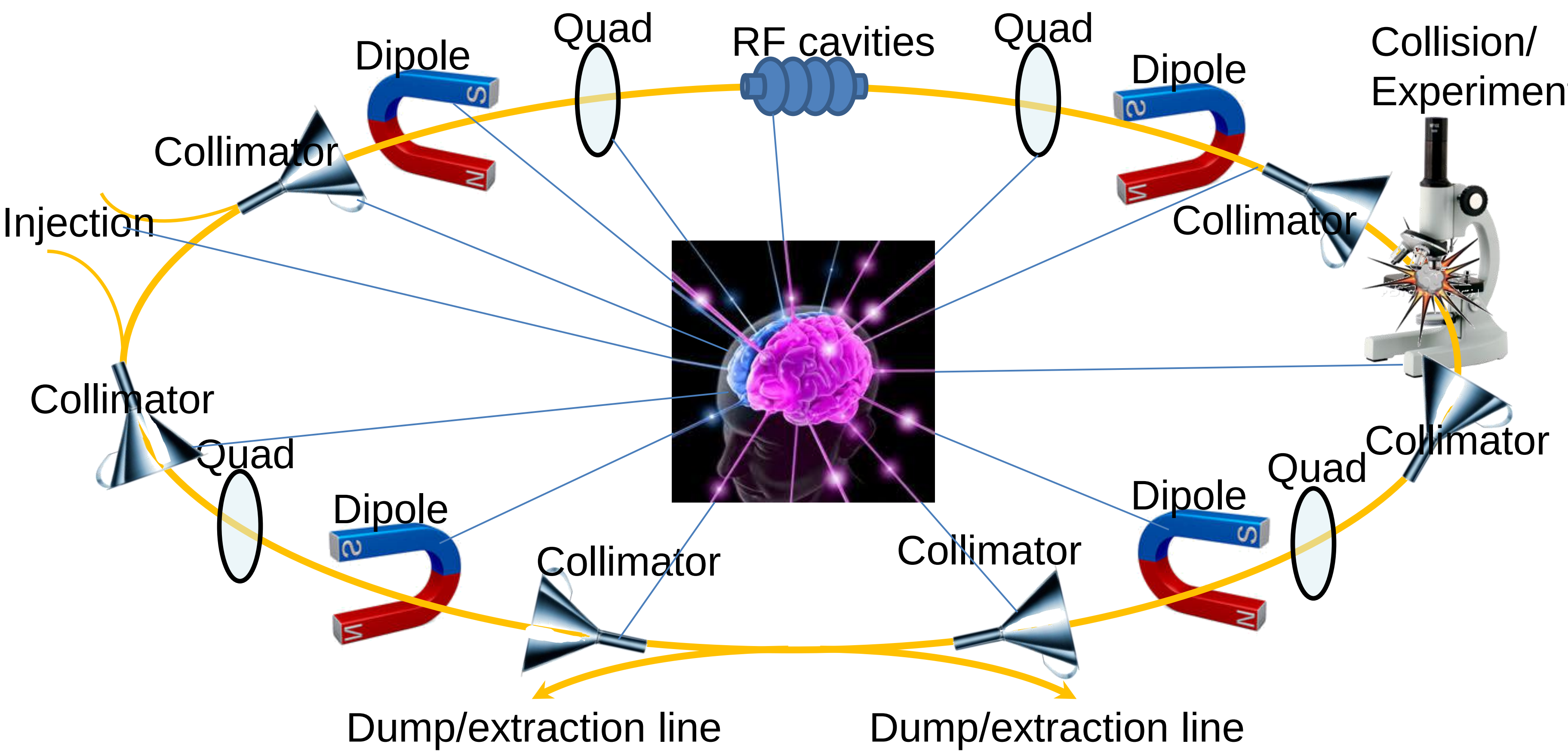
The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

CERN's particle accelerator chain



LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron
AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

Pedagogical sketch of a hadron machines



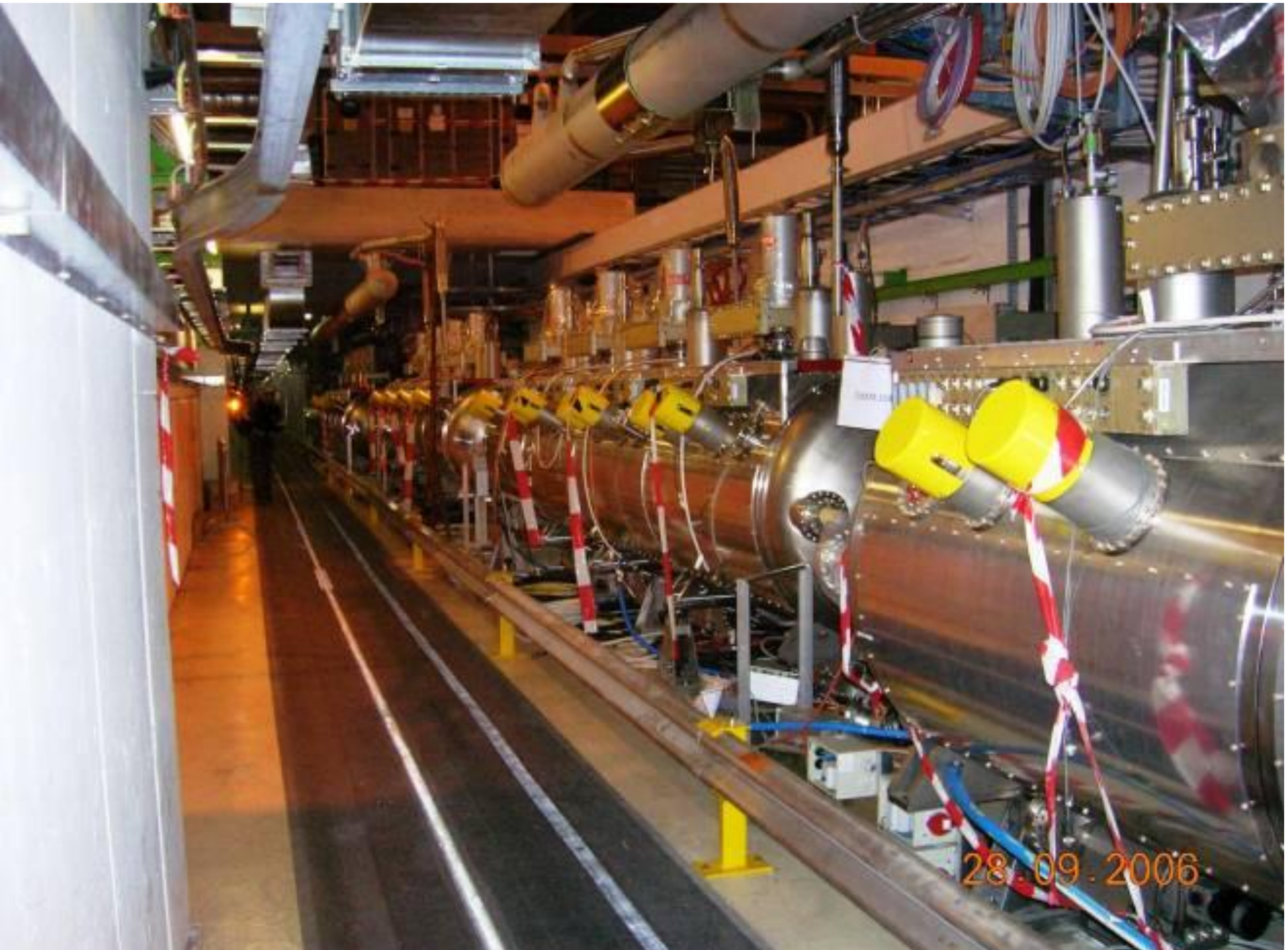
Goal: producing the highest number of collisions at the highest energy, in the safest way…

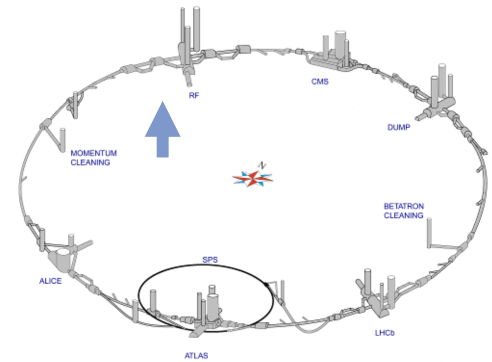
The most challenging components are the 1232 high-tech superconducting dipole magnets

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

LHC Construction Project Leader Lyndon Evans

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

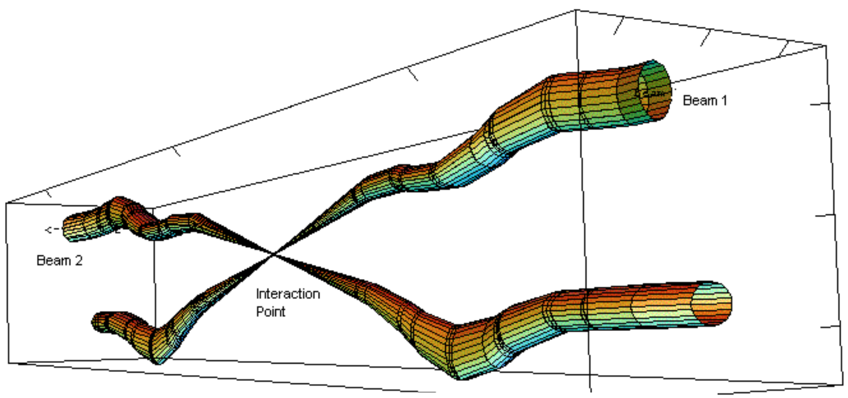




Note: The acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), because of the ~ $1/m^4$ behaviour of the synchrotron radiation energy losses [~ E^4_{beam}/Rm^4]

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

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

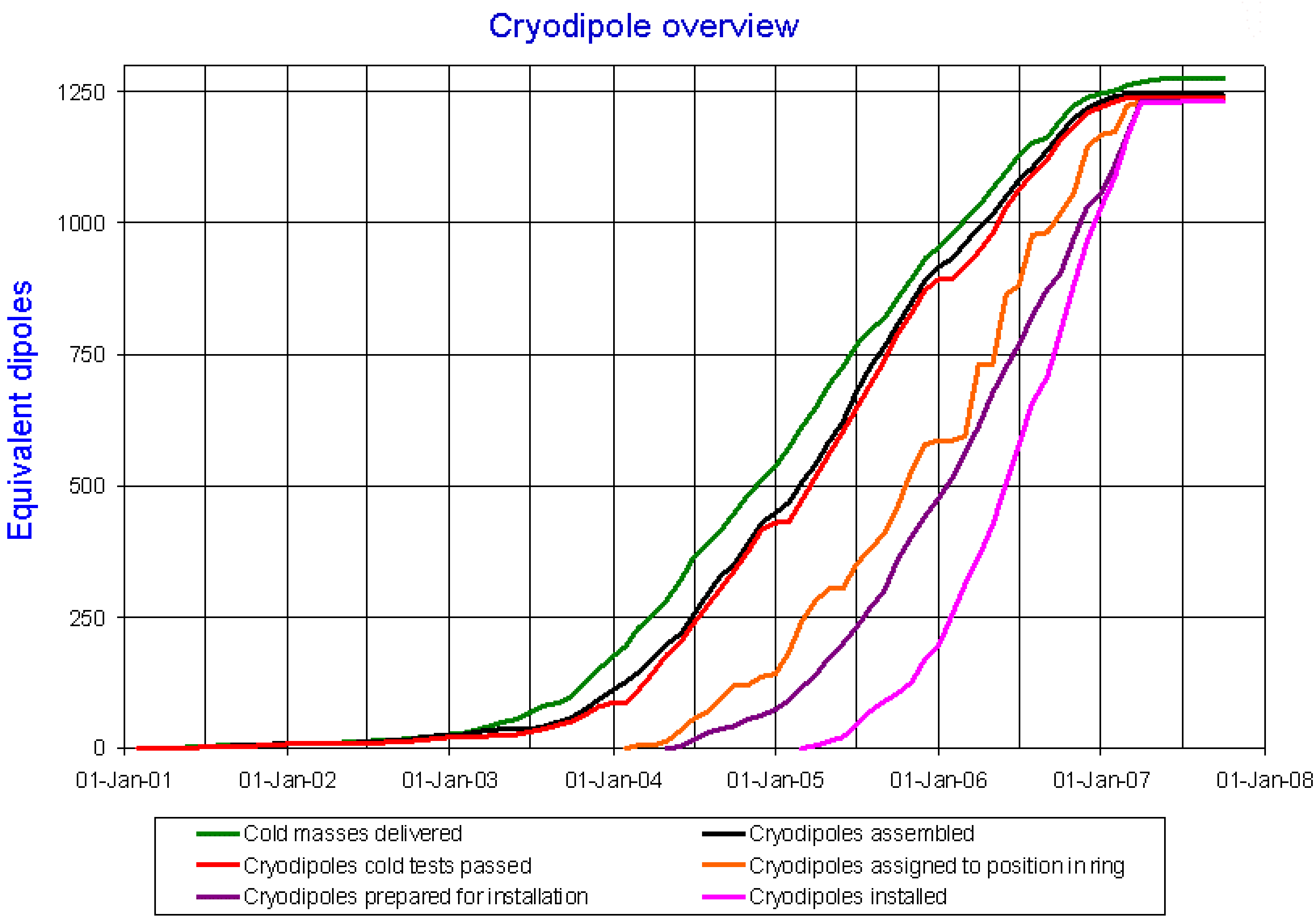


Relative beam sizes around the collision point

LHC Progress Dashboard

History of the dipole magnet construction and installation

Accelerator Technology Department

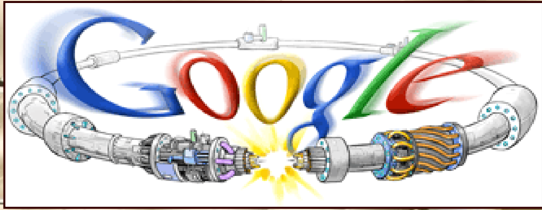


Updated 30 September 2007

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

10 September 2008: LHC inauguration day

First (single) beams circulating in the machine



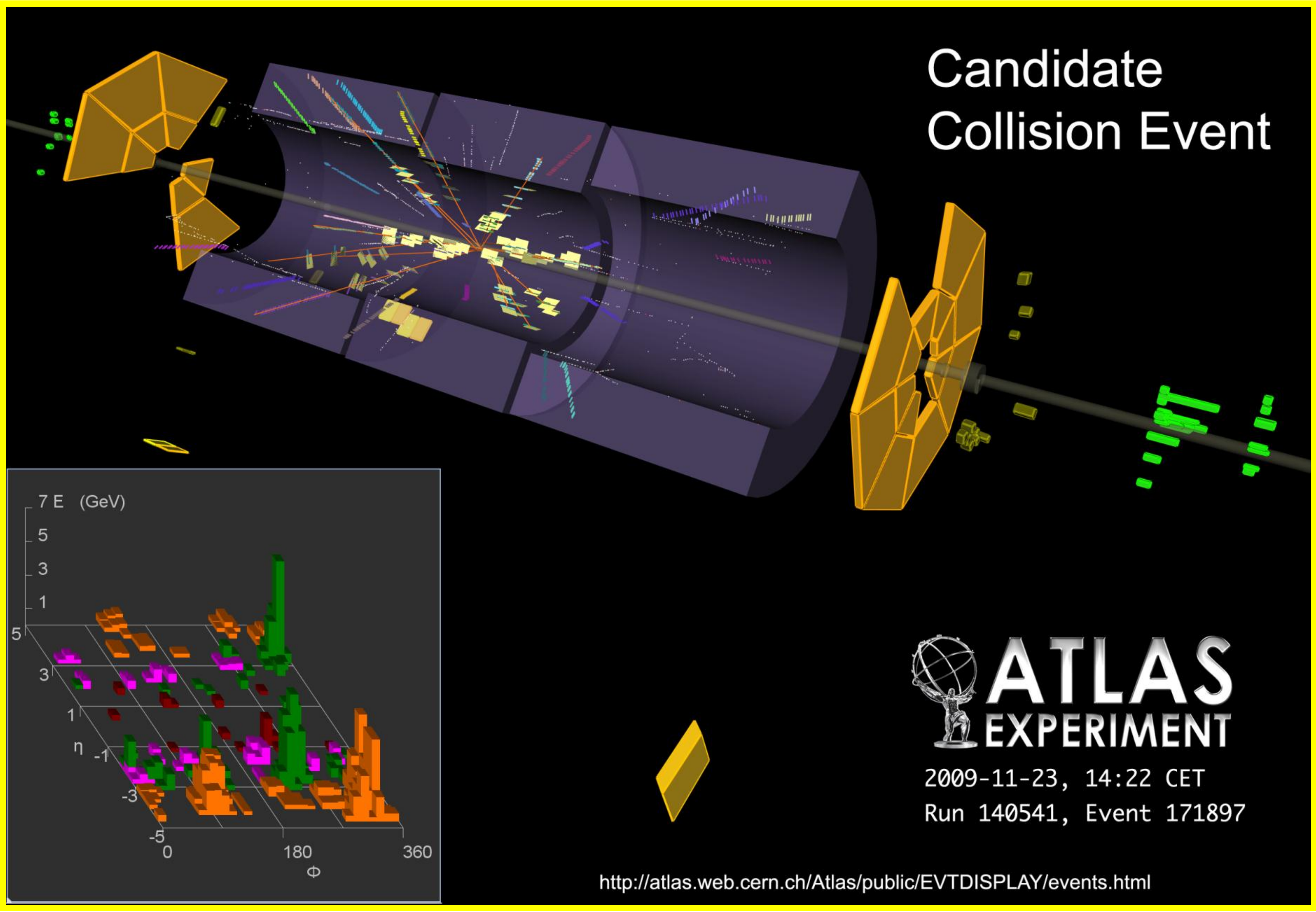
Five CERN DGs, from conception to realization: Schopper, Rubbia, Llewellyn Smith, Maiani, Aymar (from right to left)

Interconnections of two magnets

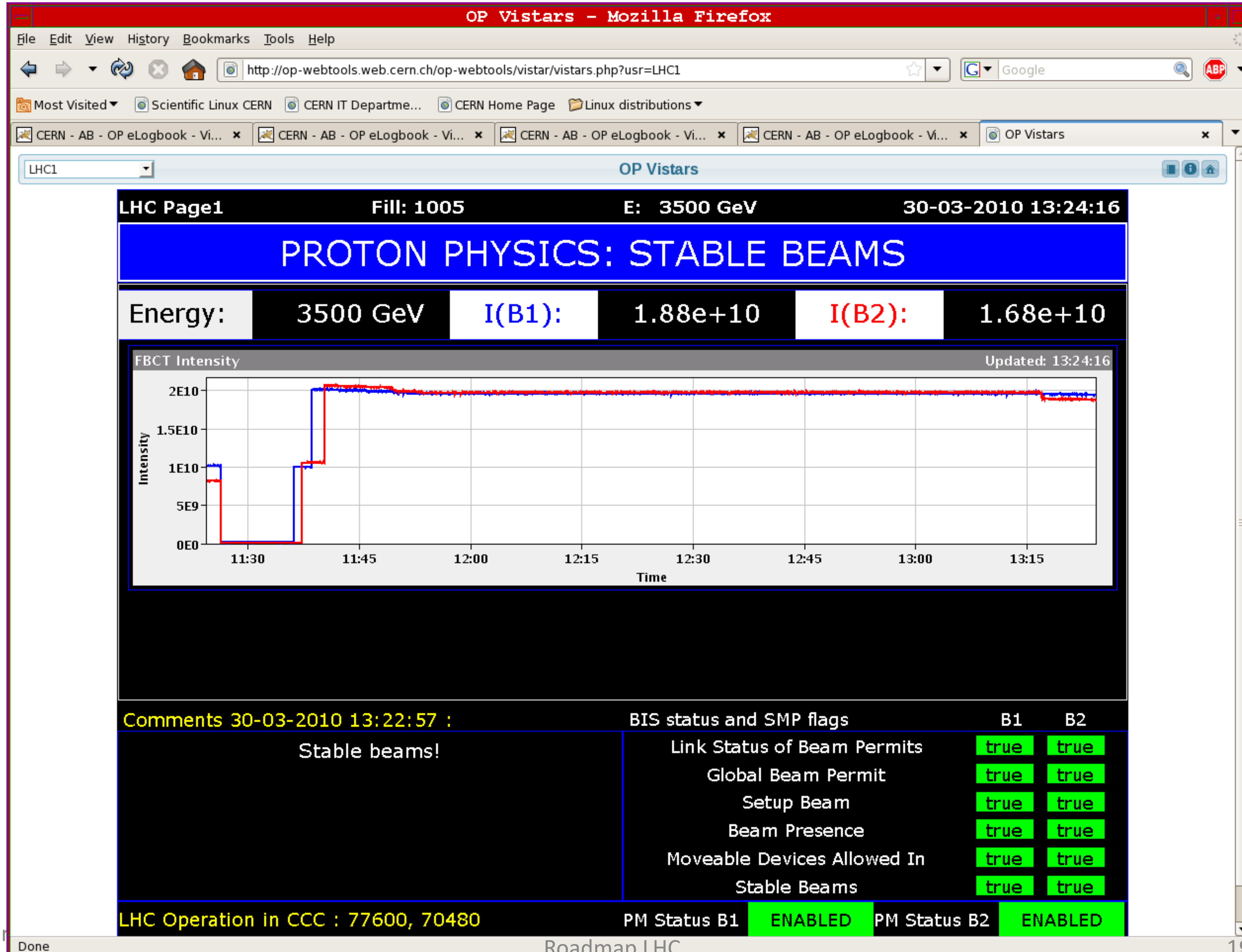
One (superconductor) joint failed on 19th September 2008, and it caused a catastrophic He-release that made serious collateral damage to sector 3-4 of the LHC machine

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

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

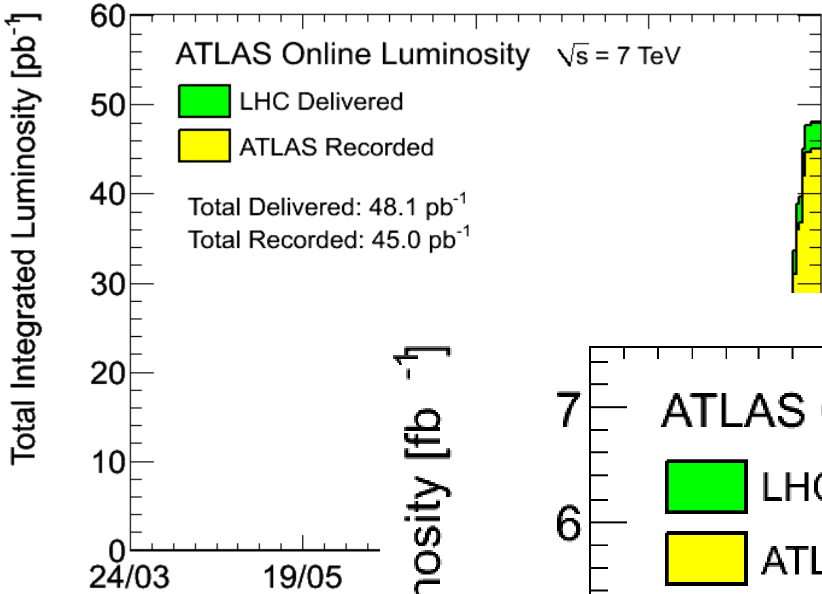


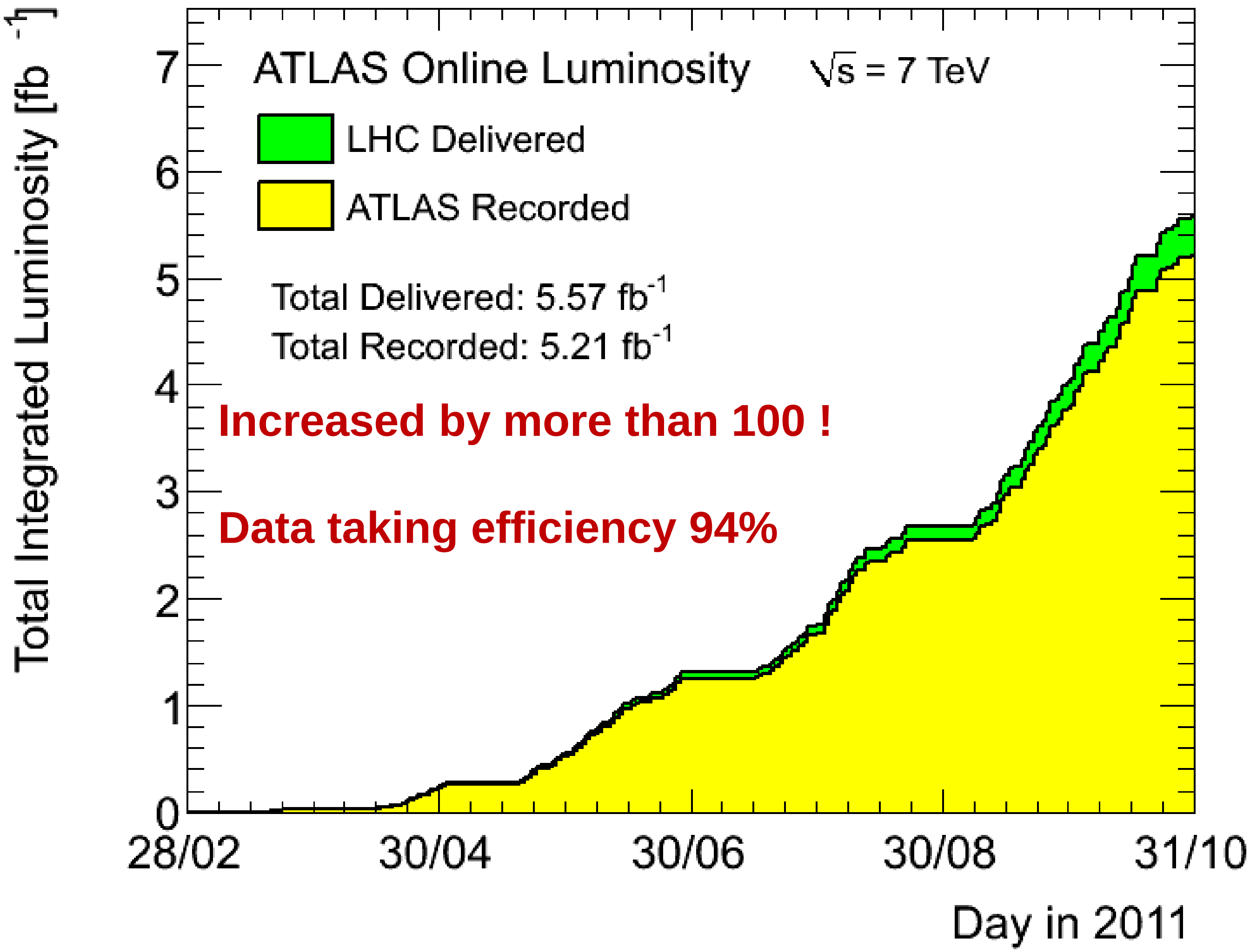
High-energy operation with 3.5 TeV beams started on 30th March 2010




Fill: 1005
PROTON PHYSICS: STABLE BEAMS
E: 3500 GeV
30-03-2010 13:47:40
3500 GeV
I(B1):
1.79e+10
I(B2):
1.64e+10
2010 13:22:57
Stable beams!

A lot of exciting physics results are already possible thanks to the superb performance of the LHC





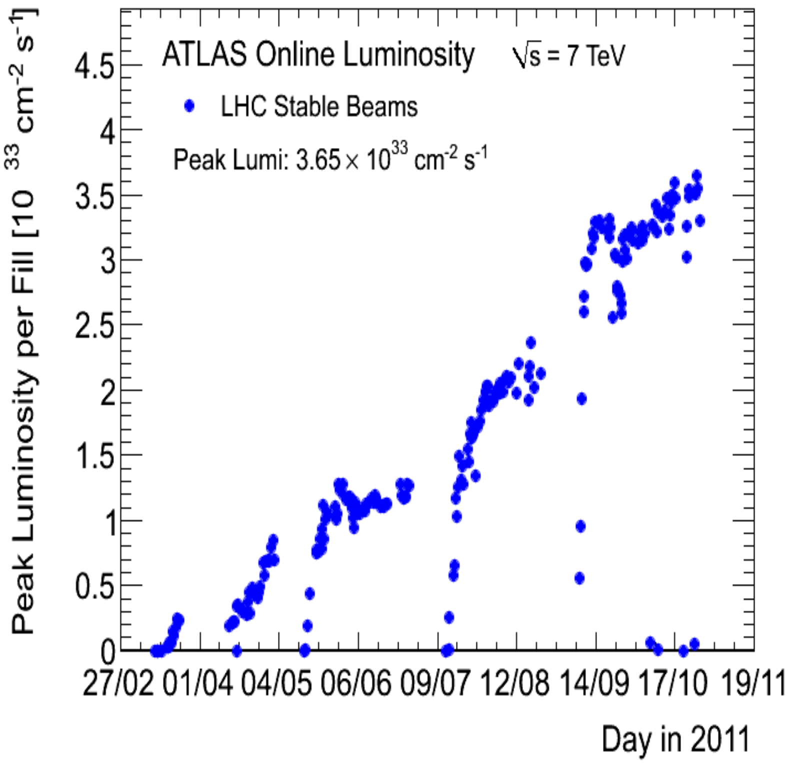
$$N_{events} = \sigma \int L\, dt$$

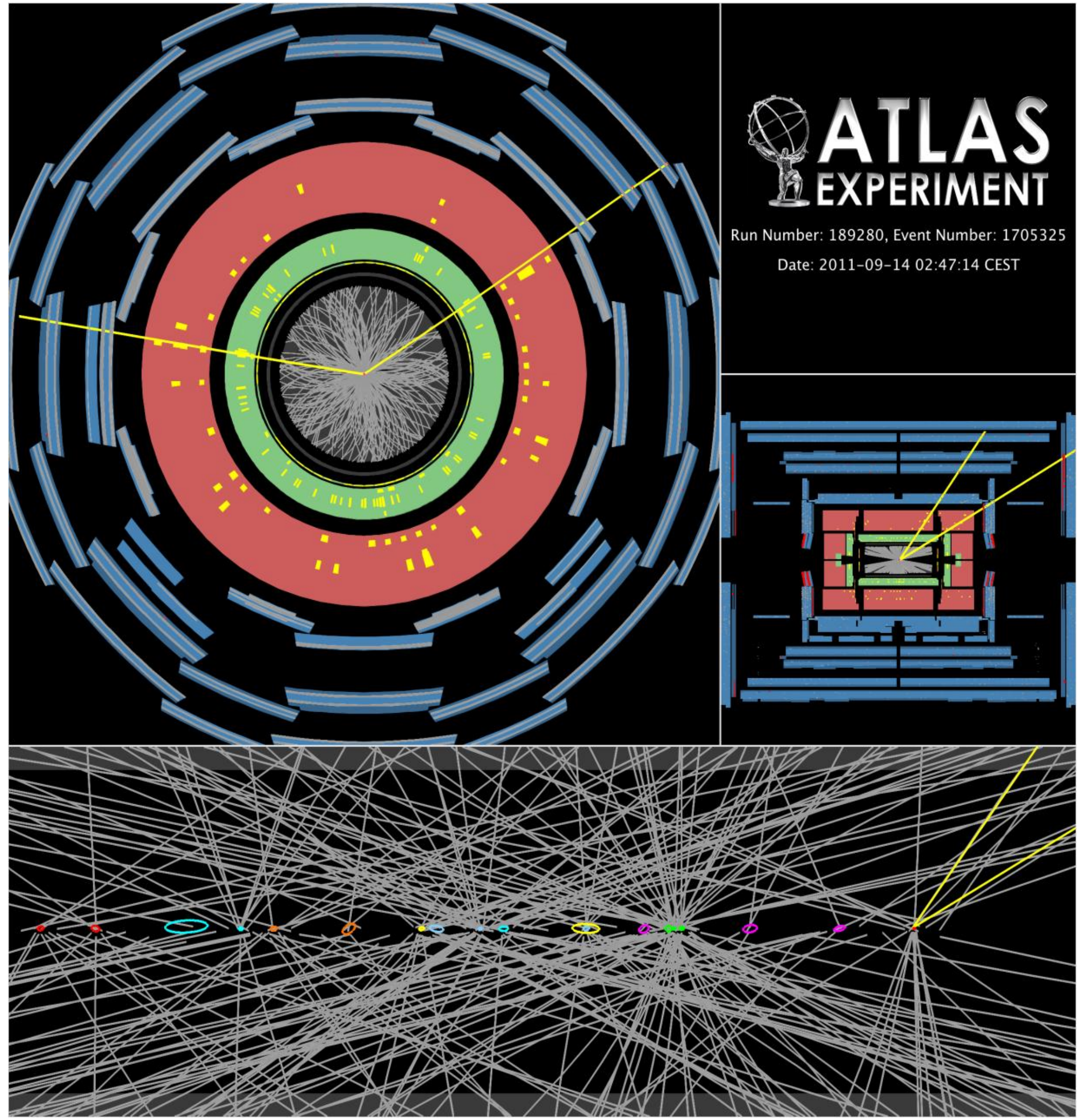
Current LHC Operation:

1380 bunches per beam

50 ns bunch spacing

up to 1.5 x 10^{11} protons / bunch





Z → μμ event with 20 primary vertices

(Typical peak pile-up per bunch crossing: 12)

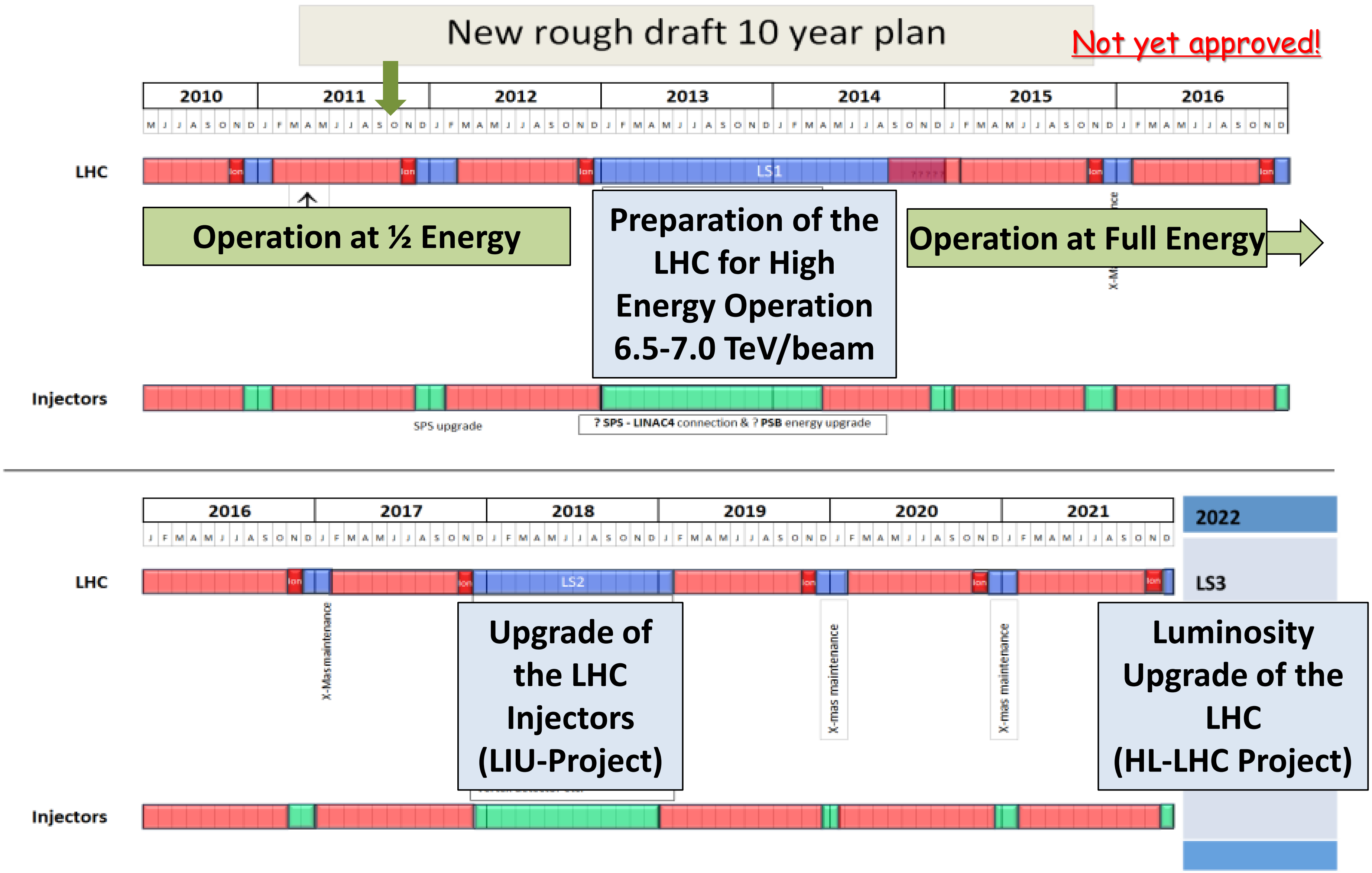
Road Map of Expected Hadron Collider Performances

End 2010	**Tevatron**	**2 TeV**	**7 fb^{-1} (analysed)**
	LHC	**7 TeV**	**45 pb^{-1}**
End 2011	**Tevatron**	**2 TeV**	**10 fb^{-1} (analysed)**
	LHC	**7 TeV**	**5 fb^{-1}**
End 2012	**LHC**	**7 TeV**	**15 fb^{-1}**
End 2015	**LHC**	**14 TeV**	**30 fb^{-1}**
End 2017	**LHC**	**14 TeV**	**100 fb^{-1}**
Early 2020s	**LHC**	**14 TeV**	**500 fb^{-1}**
2030	**(s)LHC**	**14 TeV**	**3000 fb^{-1} (ultimately…)**

(These are round numbers and estimates, just to give a rough idea…)

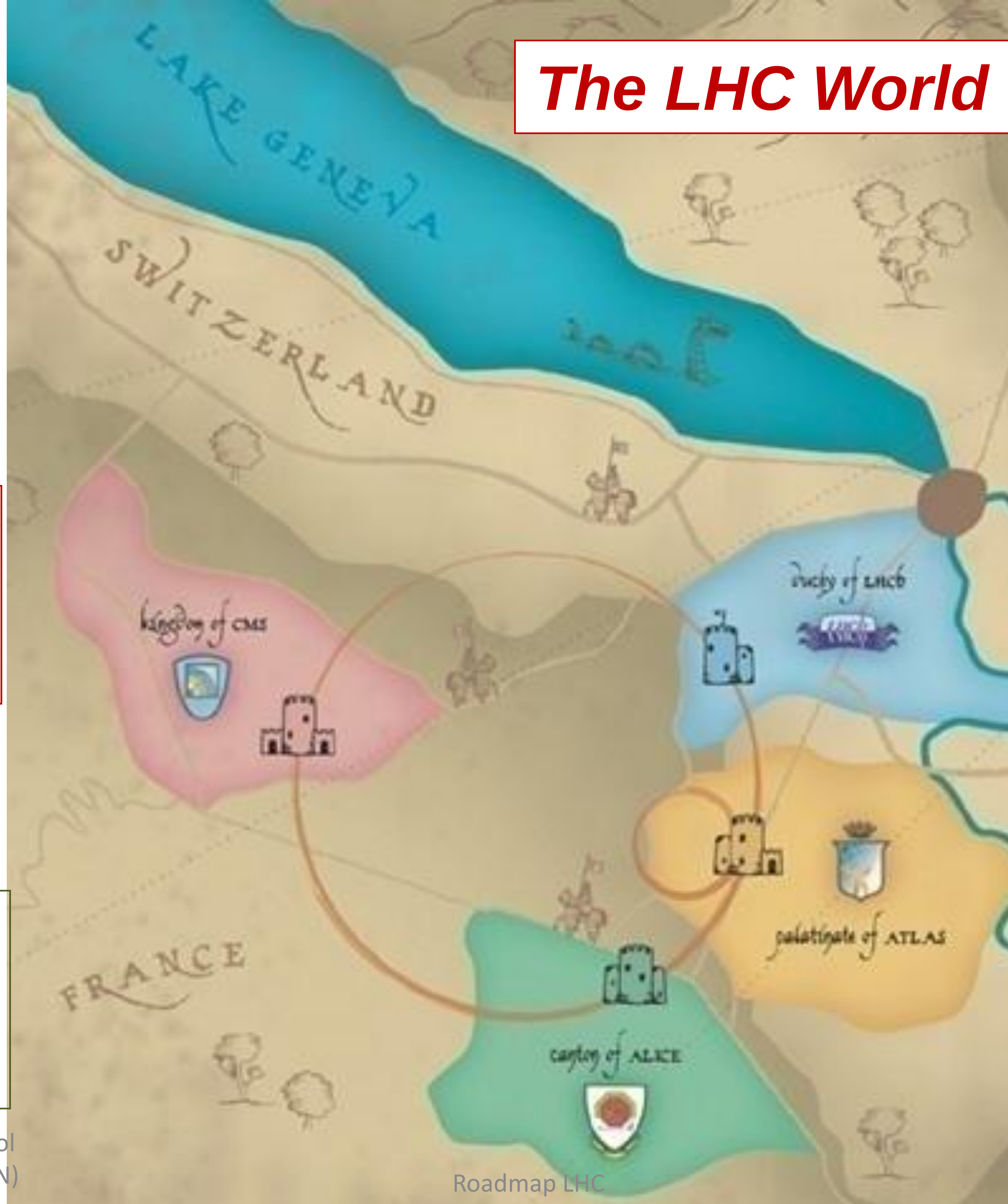
(1 fb^{-1} = 1000 pb^{-1})

Long Term Planning



The LHC World of CERN

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



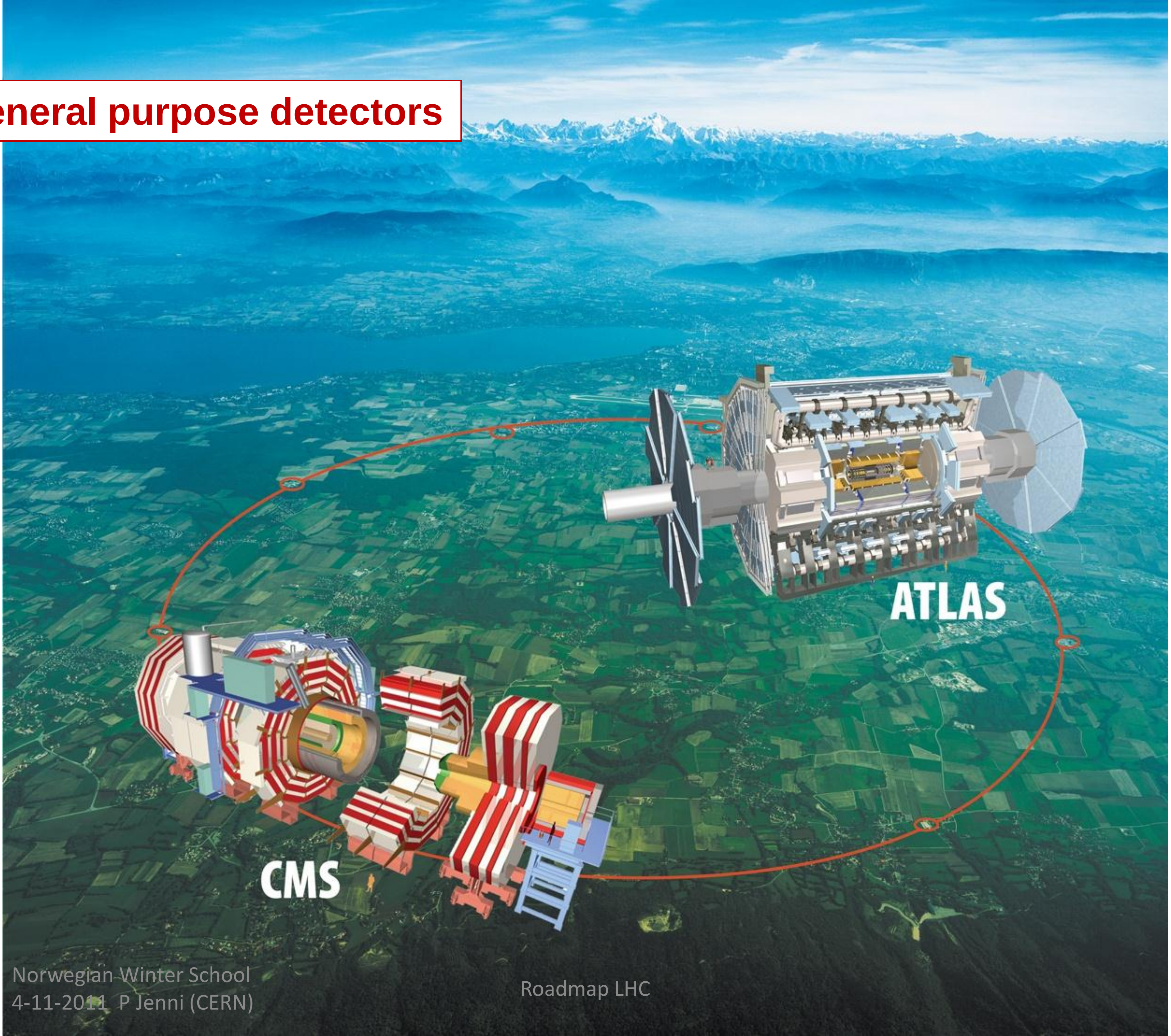
CMS
2900 Physicists
184 Institutions
38 countries
550 MCHF

LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

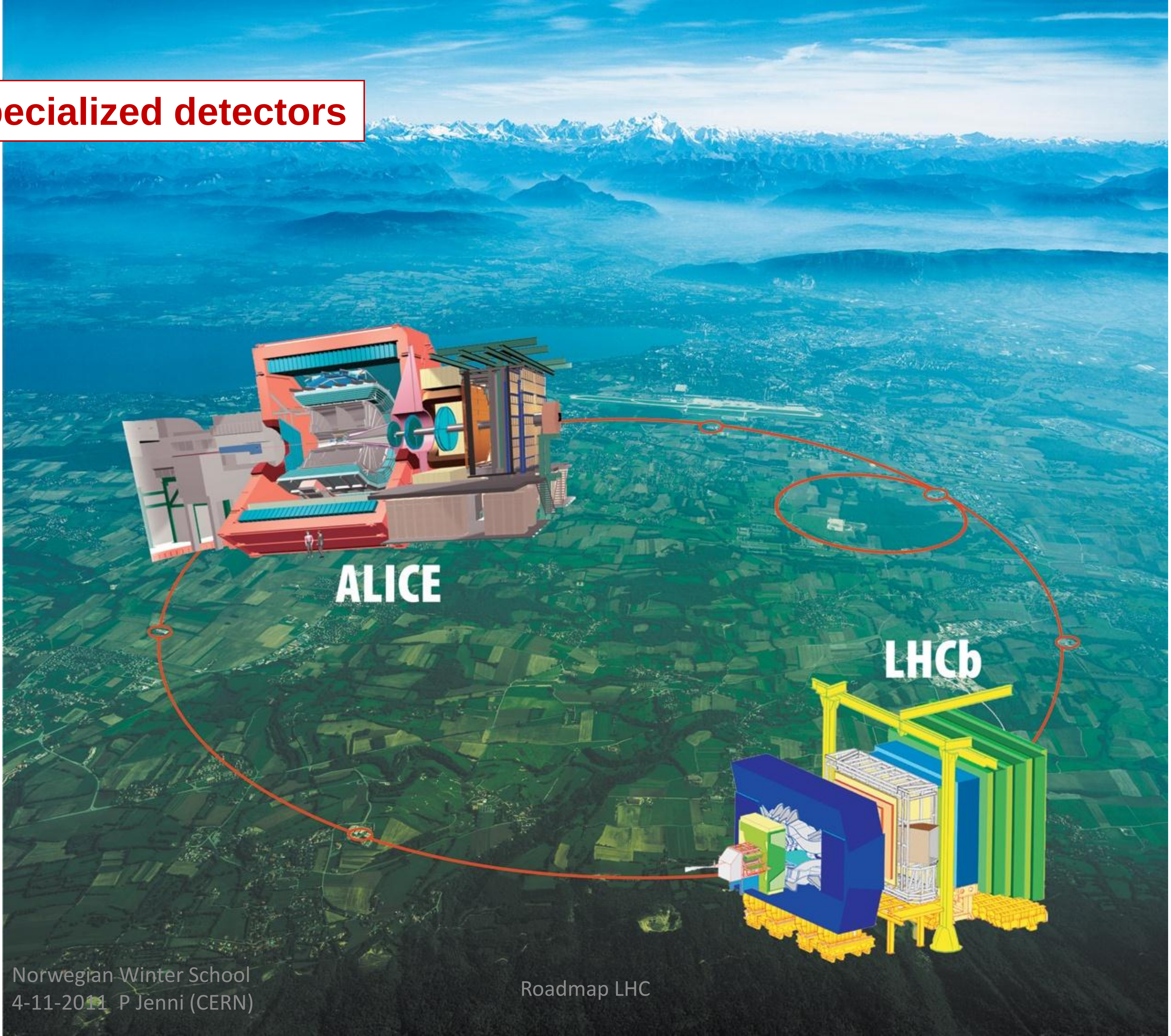
ATLAS
3000 Physicists
174 Institutions
38 countries
550 MCHF

ALICE
1000 Physicists
105 Institutions
30 countries
150 MCHF

General purpose detectors

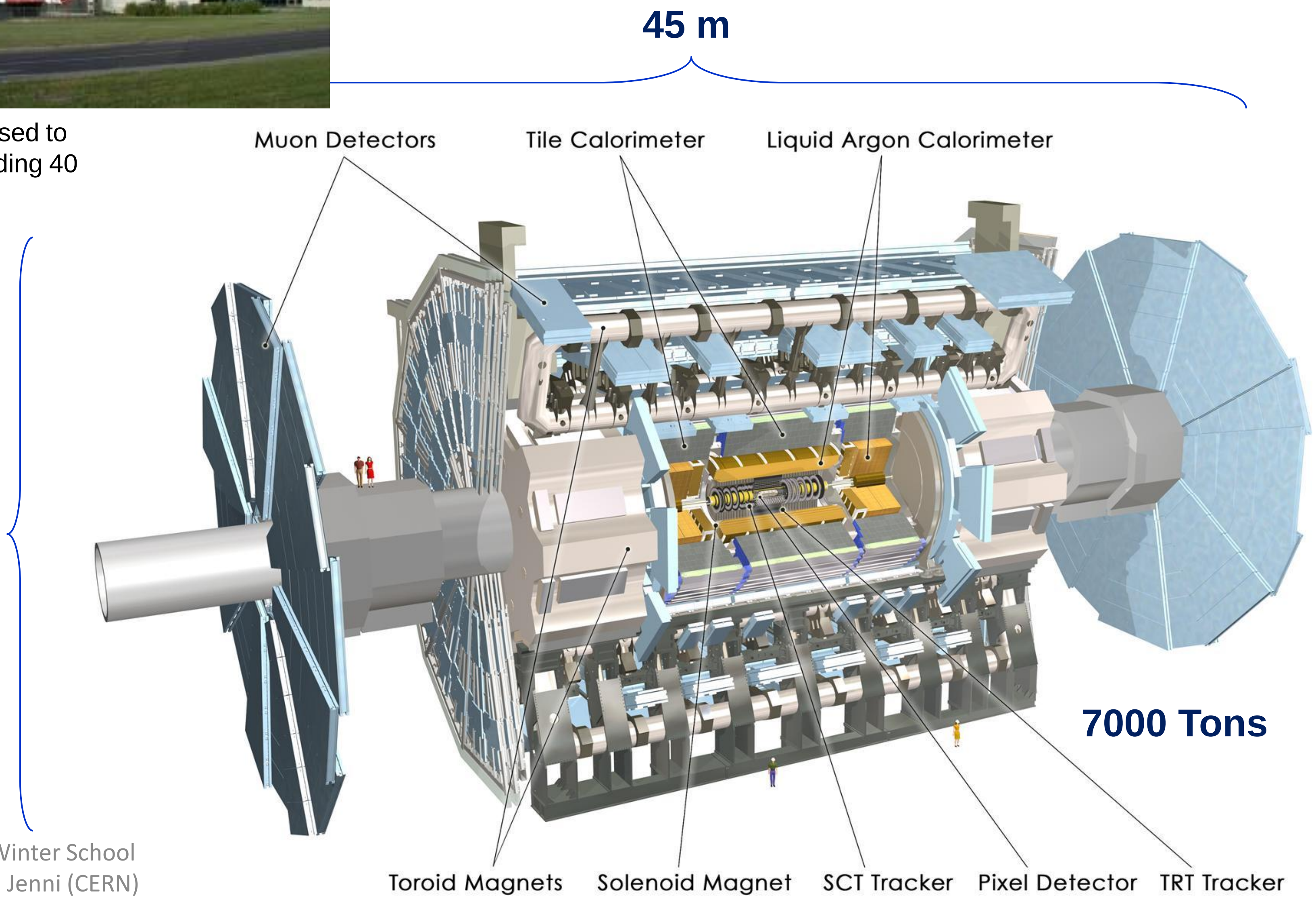


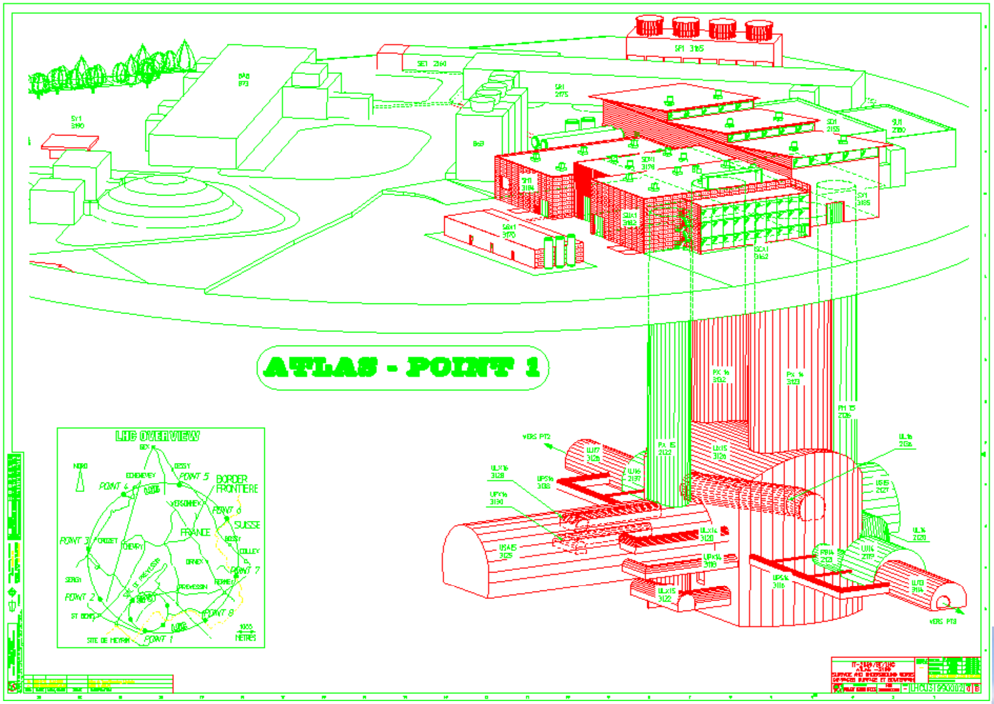
Specialized detectors



ATLAS Detector

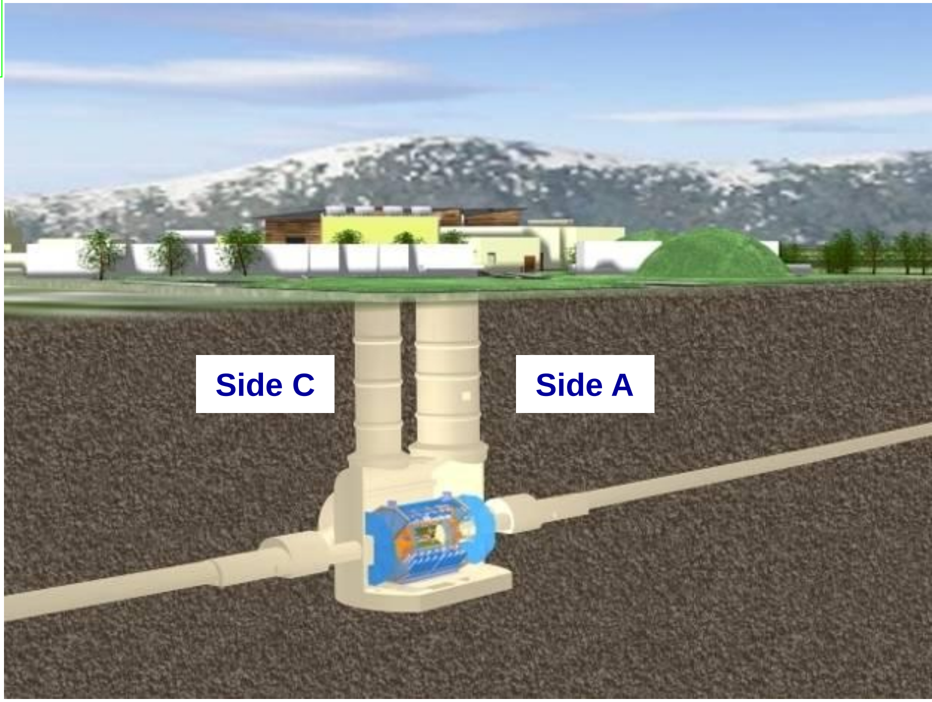
ATLAS superimposed to the 5 floors of building 40

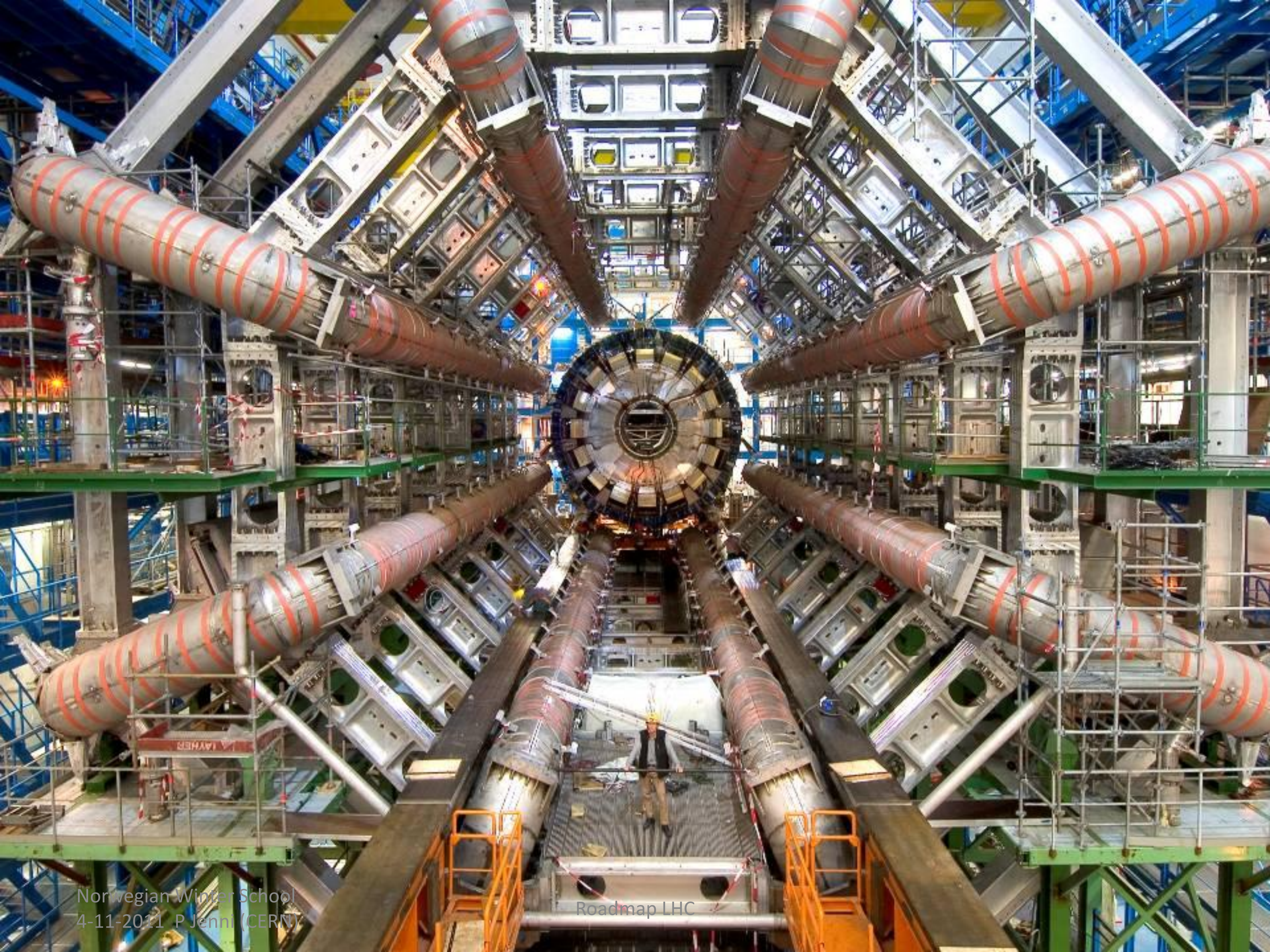


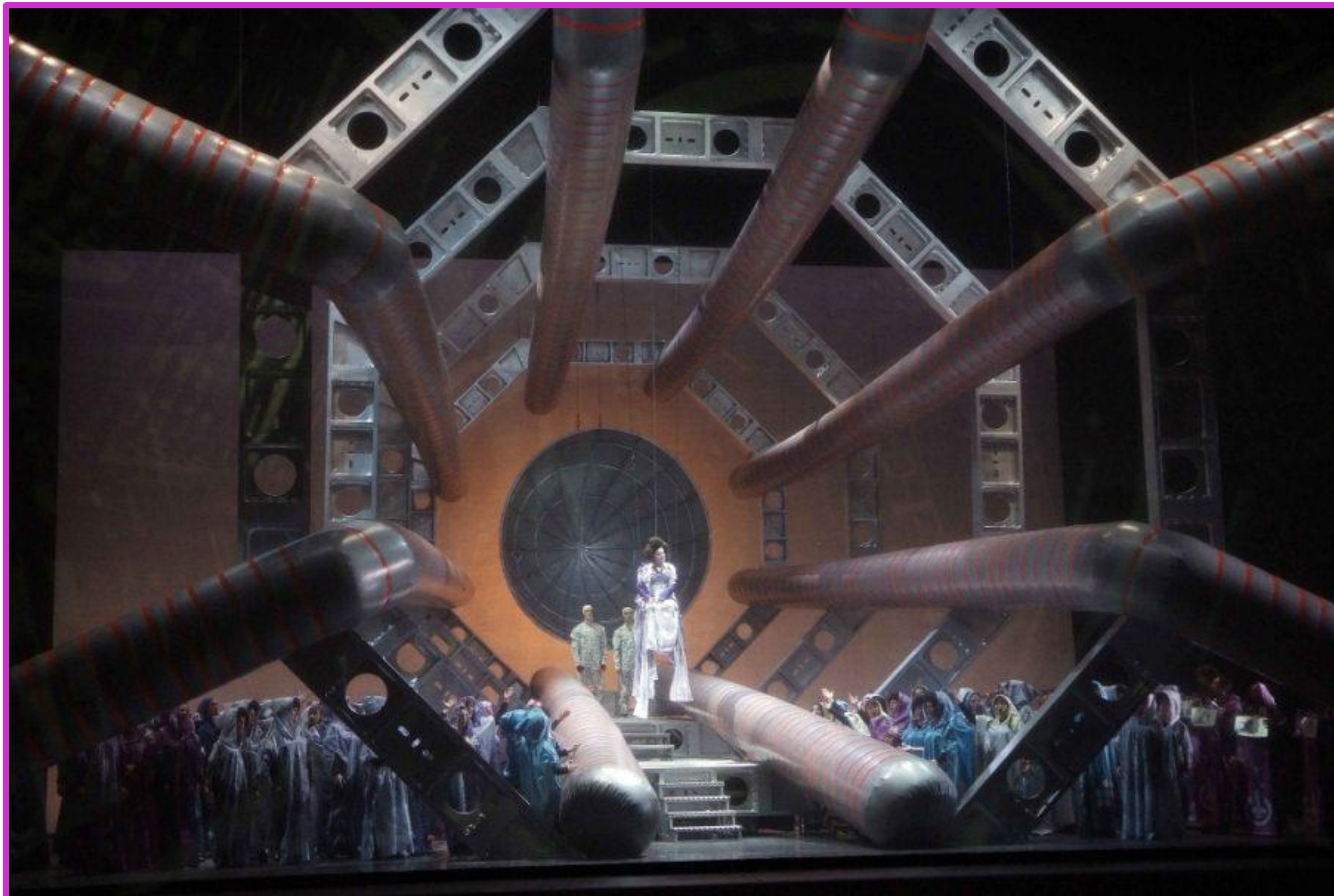


The Underground Cavern at Point-1 for the ATLAS Detector

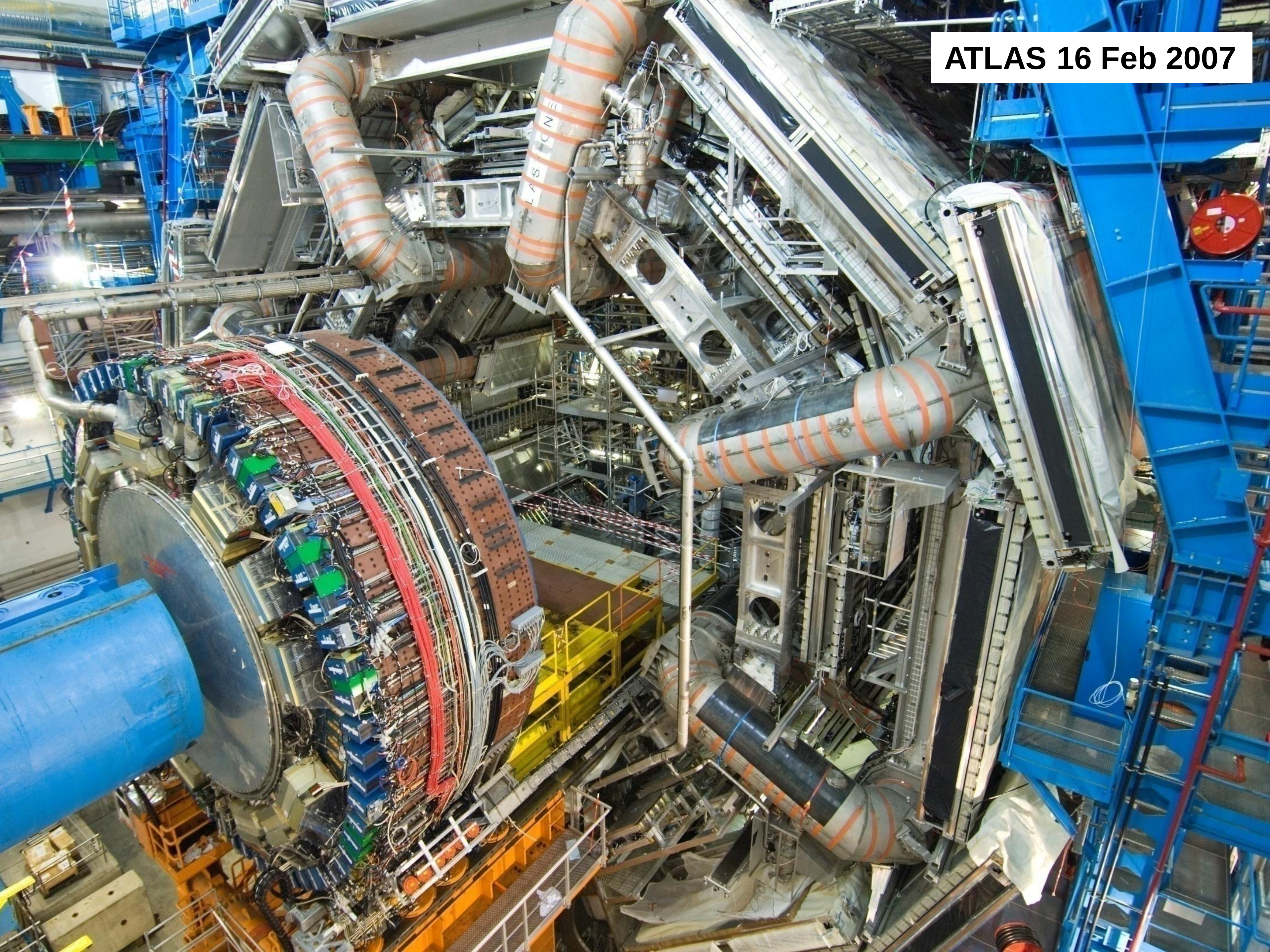
Length = 55 m
Width = 32 m
Height = 35 m







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


ATLAS 16 Feb 2007

CMS before closure

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

ATLAS operational status February 2011

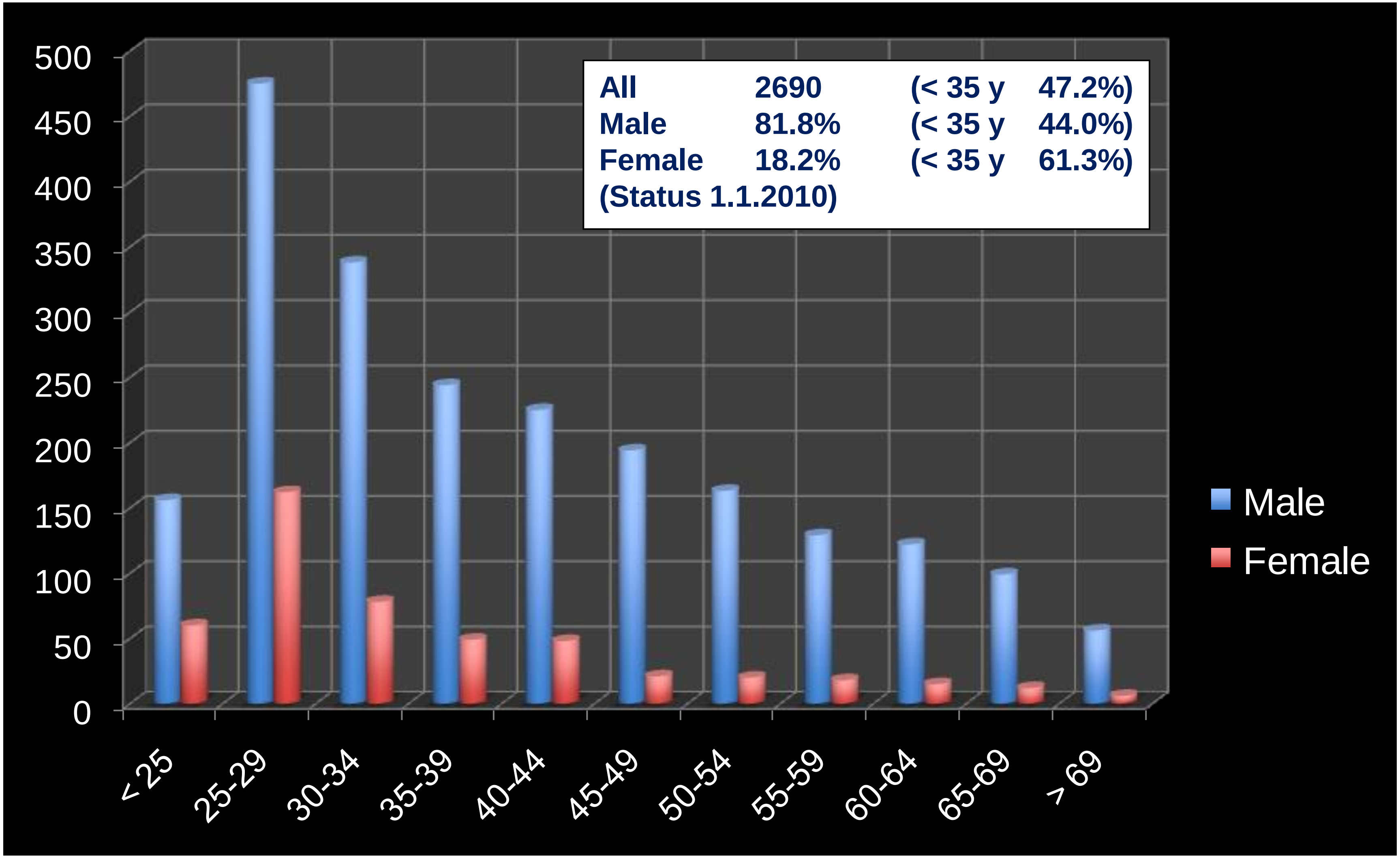
Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	97.2%
SCT Silicon Strips	6.3 M	99.2%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.9%
Tile calorimeter	9800	98.8%
Hadronic endcap LAr calorimeter	5600	99.8%
Forward LAr calorimeter	3500	99.9%
LVL1 Calo trigger	7160	99.9%
LVL1 Muon RPC trigger	370 k	99.5%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.8%
CSC Cathode Strip Chambers	31 k	98.5%
RPC Barrel Muon Chambers	370 k	97.0%
TGC Endcap Muon Chambers	320 k	99.1%

ATLAS Collaboration

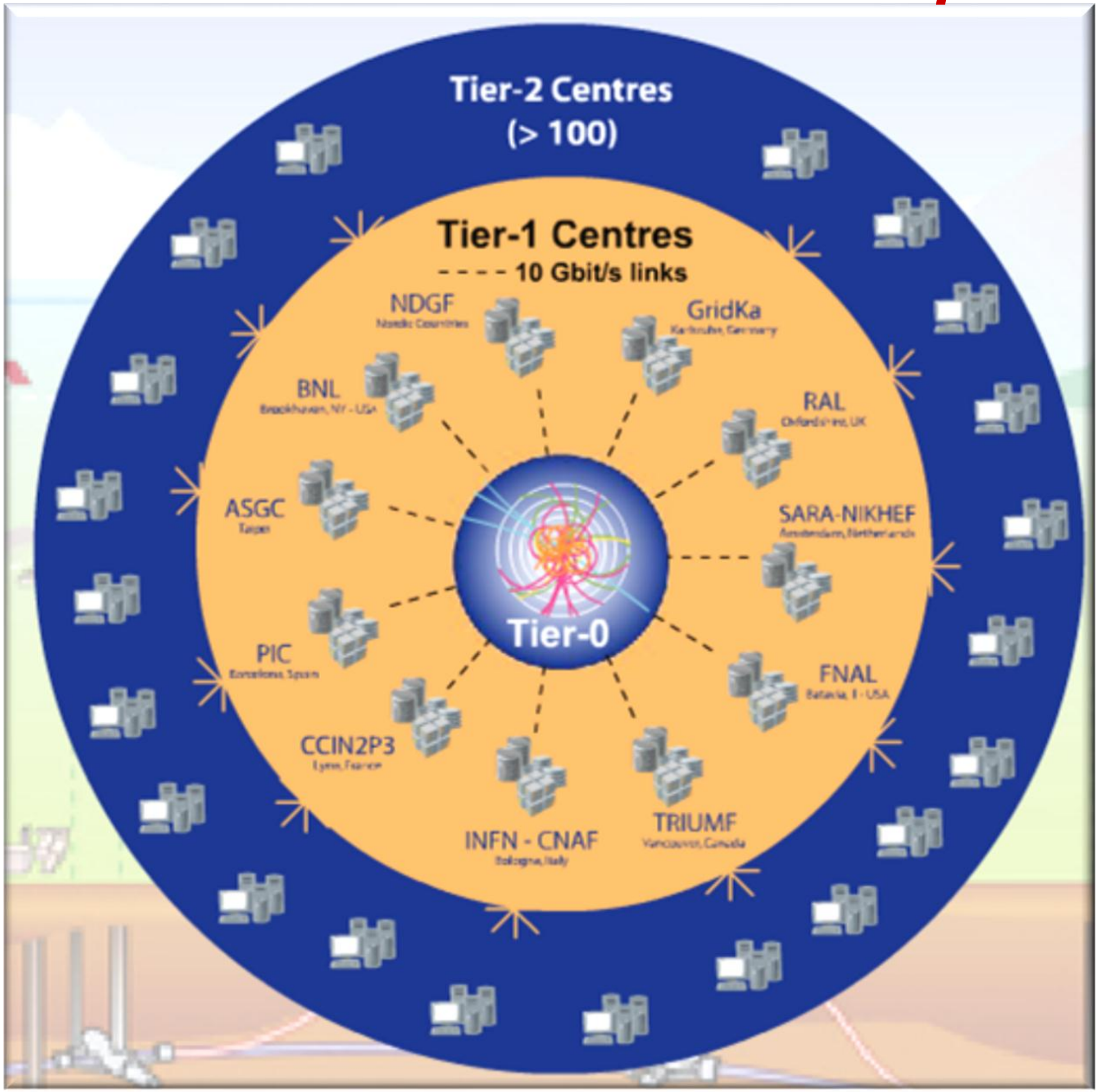
38 Countries
173 Institutions
3000 Scientific participants total
(1000 Students)

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, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, LMU Munich, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, NPI Petersburg, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

Age distribution of the ATLAS population



The Worldwide LHC Computing Grid (wLCG)



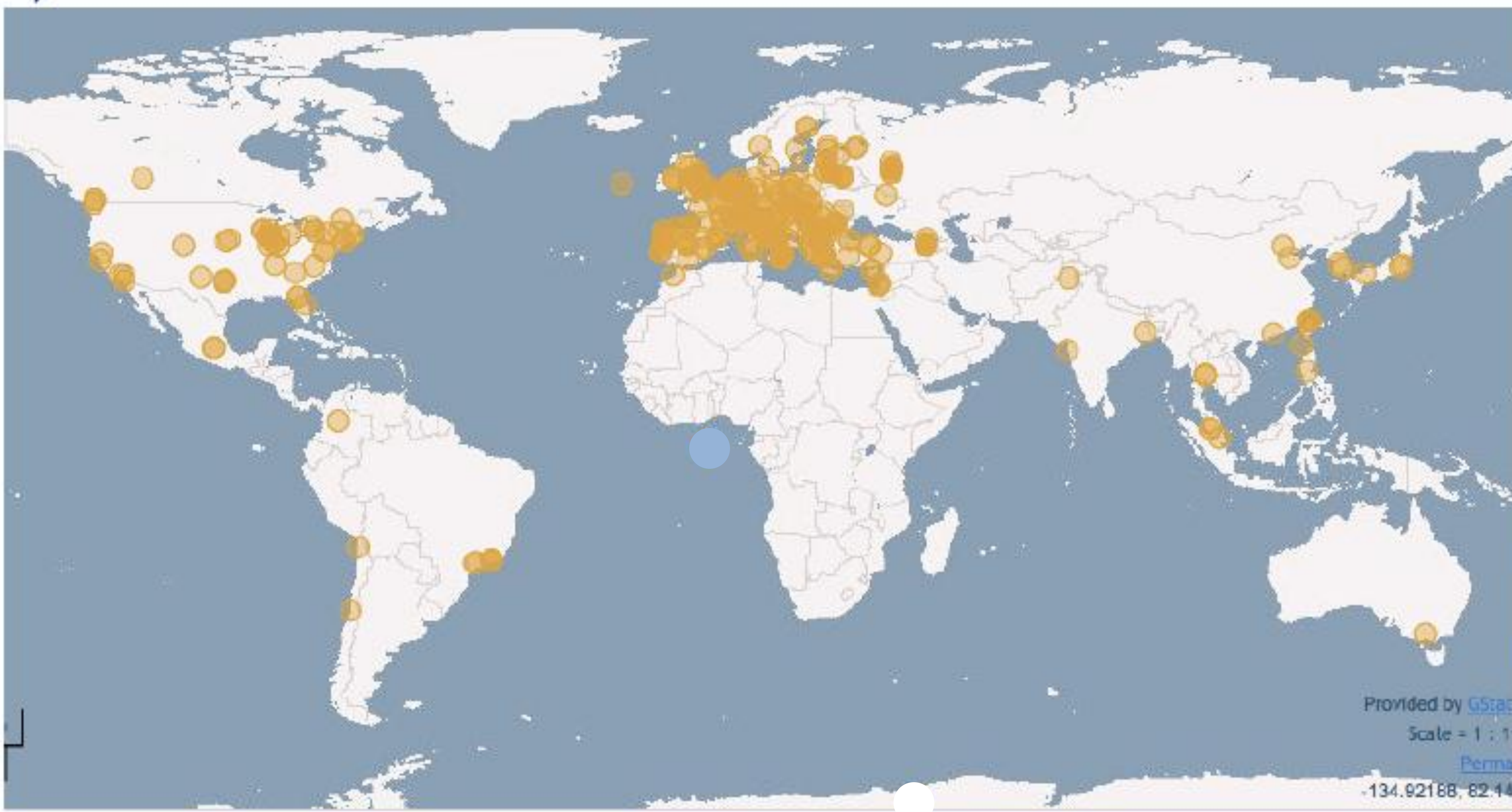
Tier-0 (CERN):
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (11 centres):
- Permanent storage
- Re-processing
- Analysis
- Simulation

Tier-2 (federations of ~130 centres):
- Simulation
- End-user analysis

Today's WLCG

- More than 170 computing facilities in 34 countries
  - More than 100k Processing Cores
  - More than 50PB of disk



Computing Grid Delivers Physics

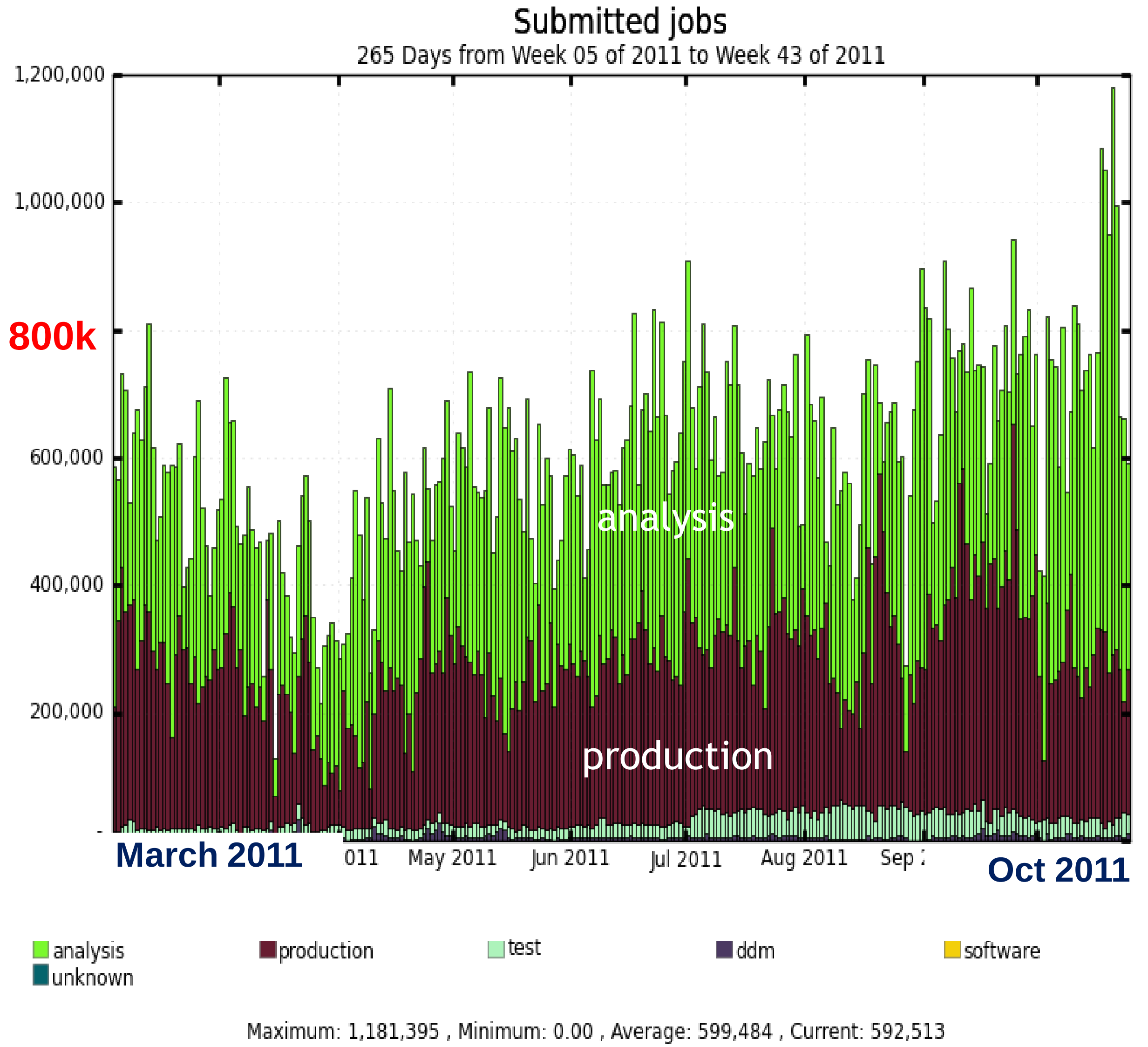
Data preparation:

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

Calibration good for physics analysis on Grid within ~1 week

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

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



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

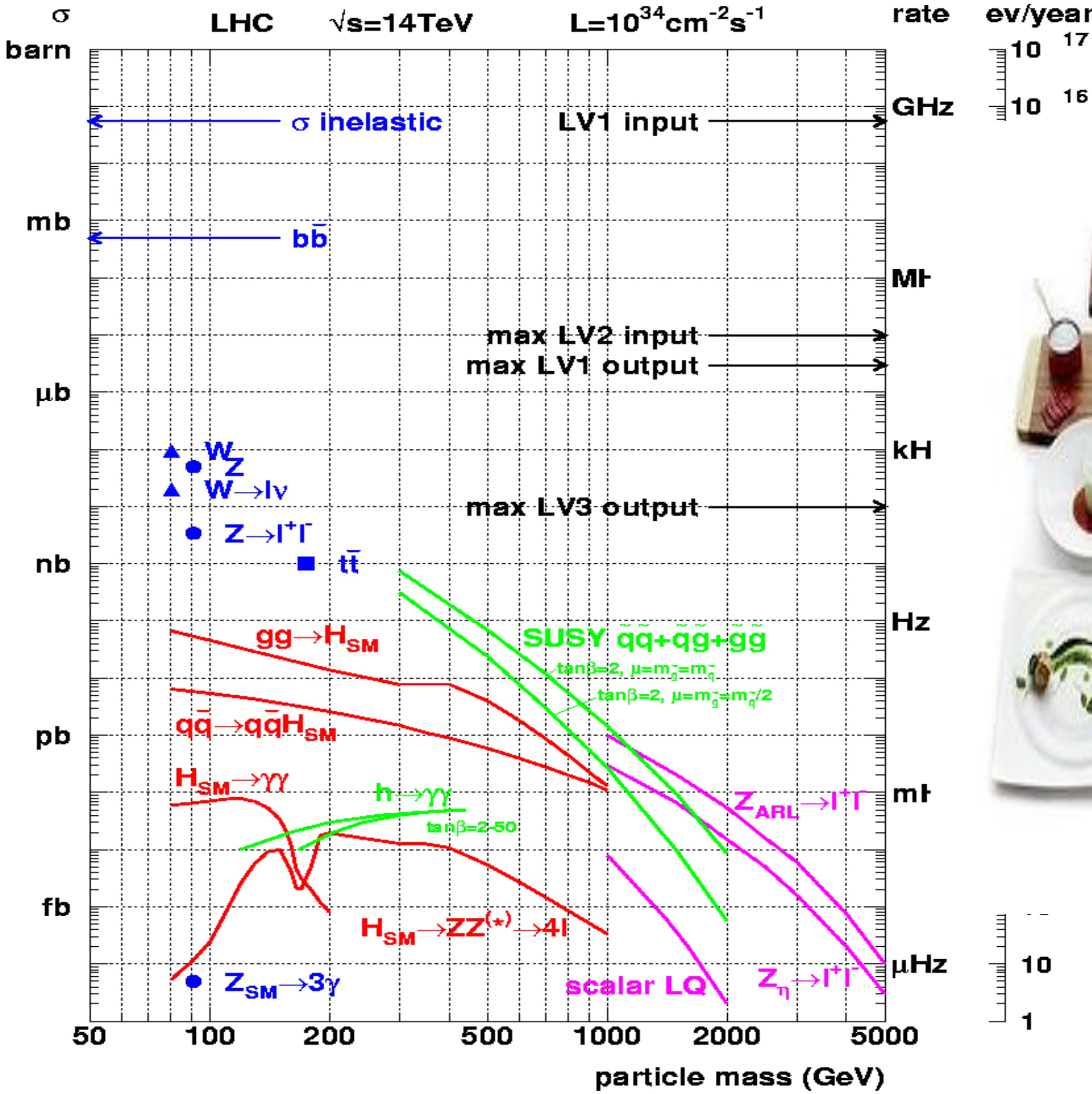
With the first data:

- Commission/calibrate detector/trigger in situ with physics (min.bias, Z→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 …

Menu Degustation



Menu Degustation

Gastronomical Tour through the
Award-Winning Cuisine of "La Mer"

Carpaccio of Tuna
with Lemon Curd and Marcona Almonds
Marinated Salmon, Aquitaine Caviar,
and Beetroot Mostarda
Carpaccio de Thon, Crème au Citron et Amandes de Marcona
Saumon Mariné, Caviar d'Aquitaine, et Betterave Mostarda

Duo of Foie Gras
with Rice Flake, Candied Rhubarb,
Maraschino Cherries, and Pistachio
Duo de Foie Gras
Flocon de Riz, Rhubarbe Confit,
Cerises de Maraschino, et Pistache

Poached Lobster Tail
Served with Watercress Velouté and Fine Herbs
Queue de Langoustine Pochée
Cresson Velouté et Fines Herbes

Fillet of Opakapaka
Heirloom Tomato and Basil Tartare,
Black Olives and Artichoke à la Barigoule
Filet d'Opakapaka
Tartare de Tomate "Heirloom" et de Basilic,
Olives Noires et Artichaut à la Barigoule

Veal Cheek Braised in Red Wine
with Sweetbreads, Mushroom Duxelles
and Ravioli Niçoise
Joue de Veau Braisée au Vin Rouge,
Ris de Veau, Champignon Duxelles, et Ravioli Niçoise

Lime Gelée with Roquette
Grape Must and Olive Oil
Gelée de Citron Vert, Salade de Roquette
Moût de Raisin et Huile d'Olive

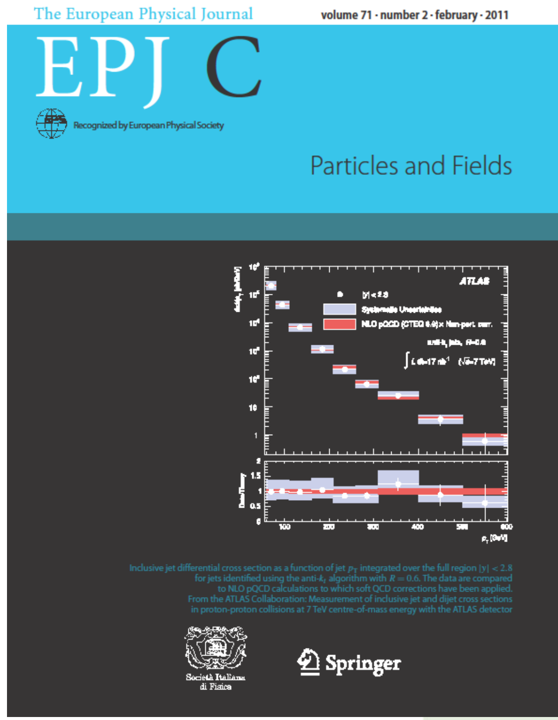
Selection of French Cheese
Sélection de Fromages Français

Chocolate and Wild Hibiscus
with Hot Cocoa Butter and Champagne Sauce
Chocolat et Hibiscus Sauvage
au Beurre de Cacao Chaud et Sauce Champagne

Mignardises
Frivolitées Gourmandes

The extent of this report is very limited in scope

ATLAS has already published more than 80 papers in scientific journals (and many more results are public conference notes…)



It is obviously not possible to cover all these results…

Note that all public results from ATLAS are available at: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Content

General event properties

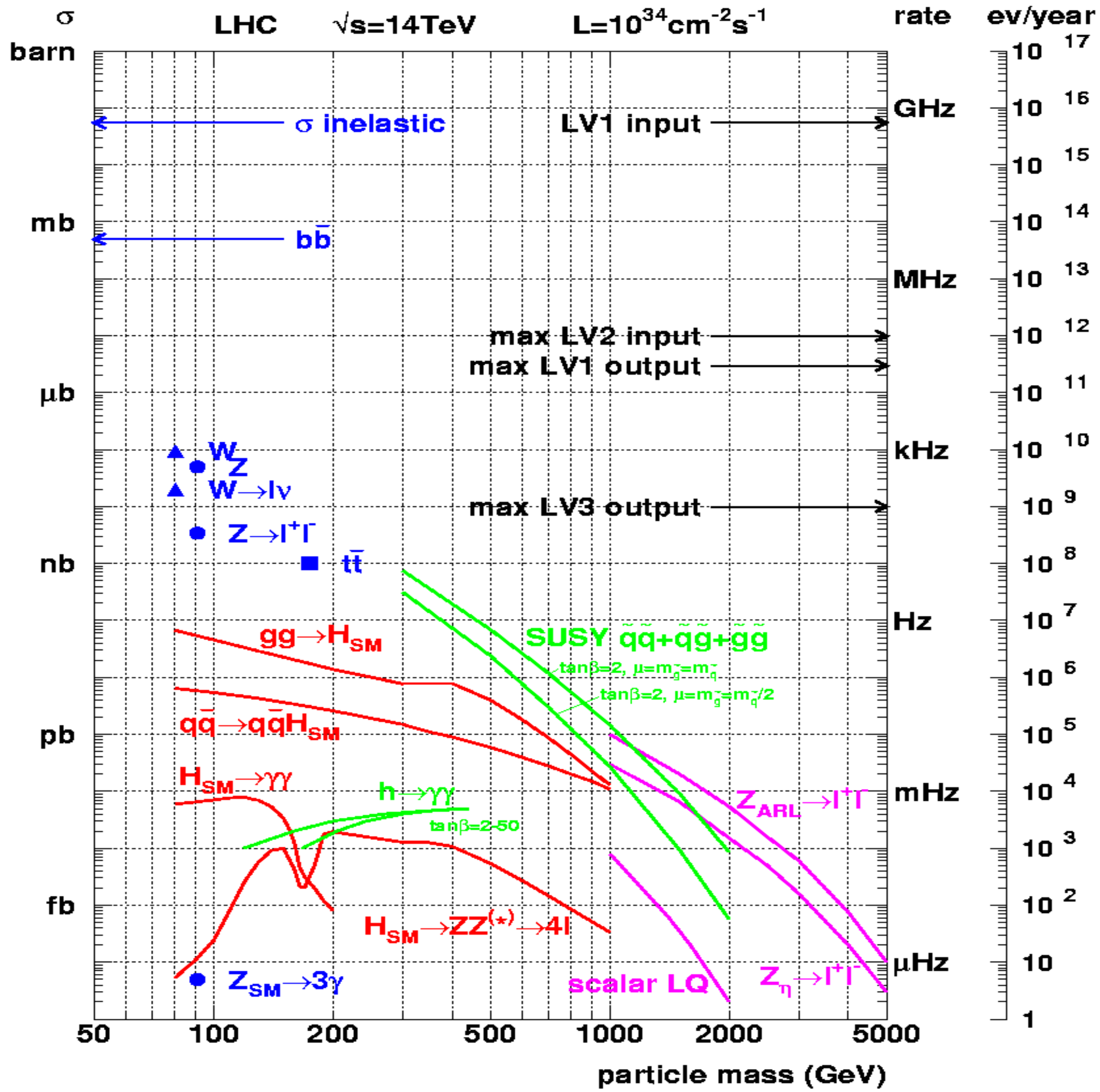
Heavy flavour physics

Standard Model physics
including QCD jets

Higgs searches

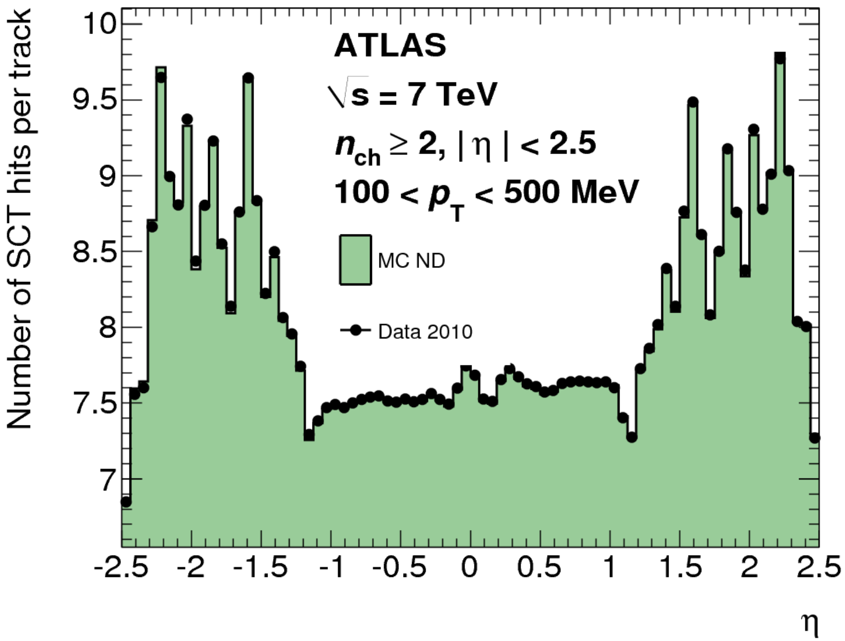
Searches for SUSY

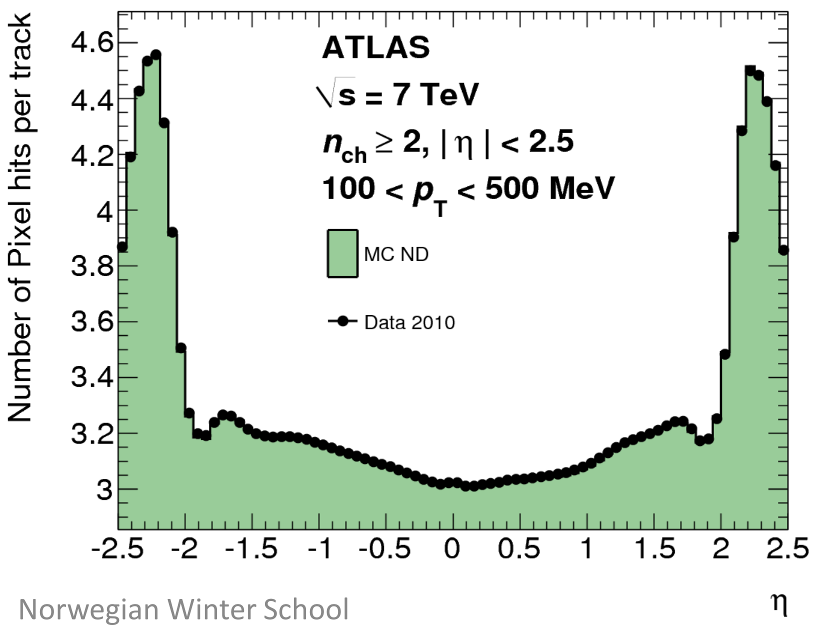
Examples of searches
for 'exotic' new physics



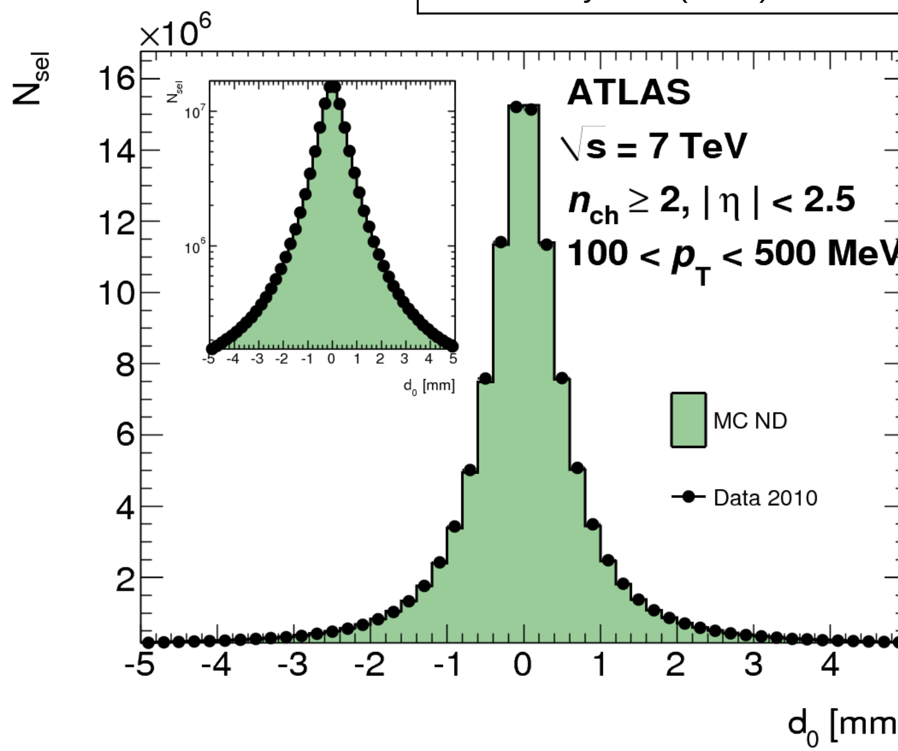
The tracking detector simulations are in a mature state, charged track measurements are well understood

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



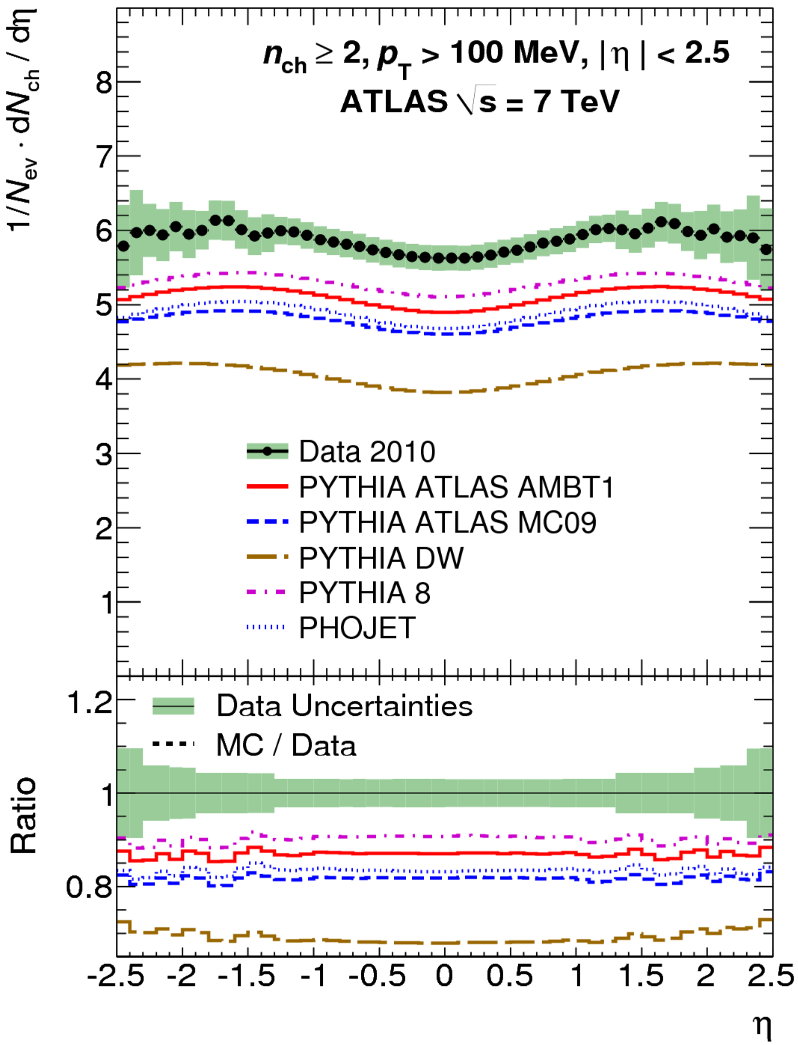


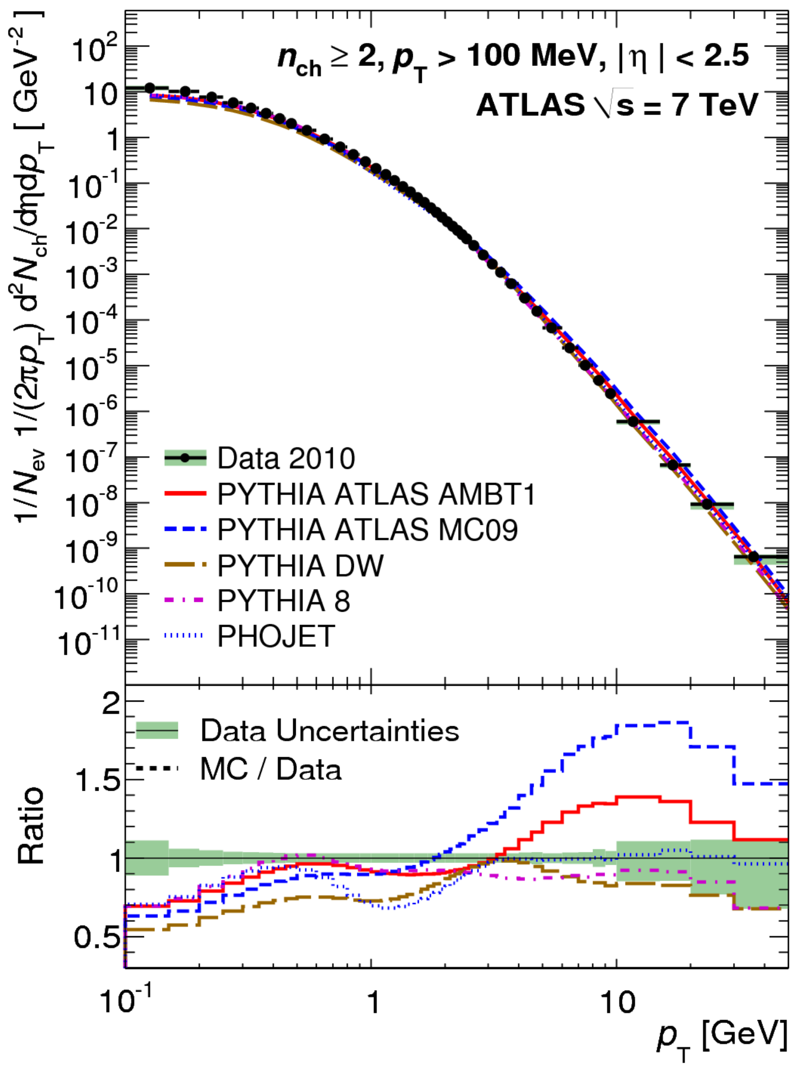
New J. Phys. 13 (2010) 053033



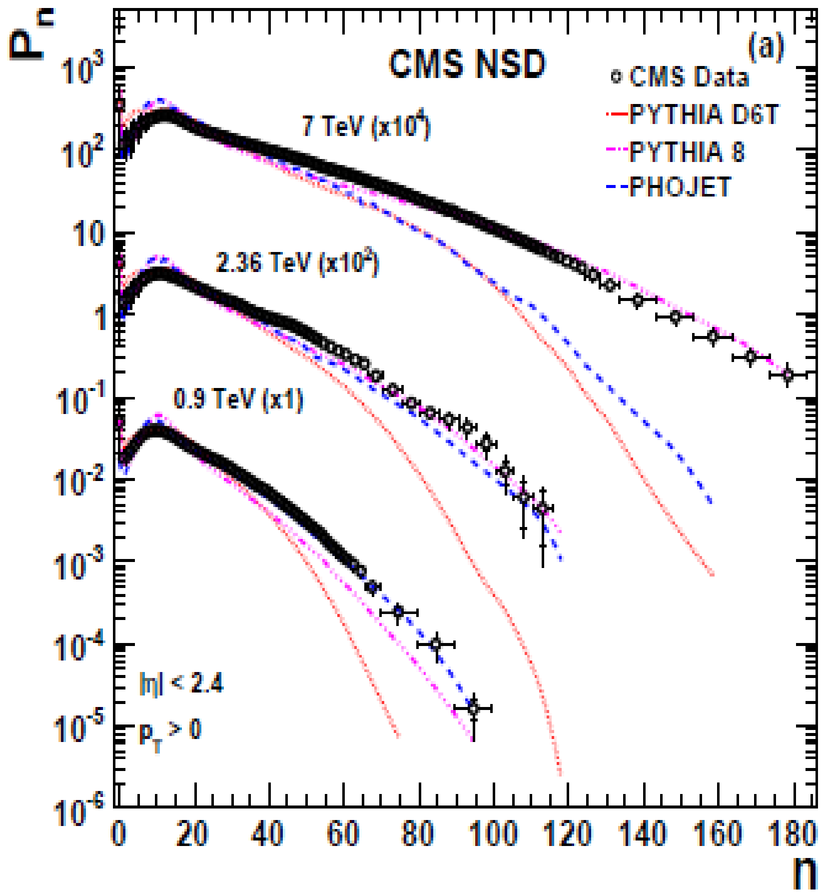
Charged-particle multiplicities as a function of pseudorapidity η and transverse momentum p_T for minimum bias events selected as specified, and compared to various Monte Carlo models

New J. Phys. 13 (2010) 053033



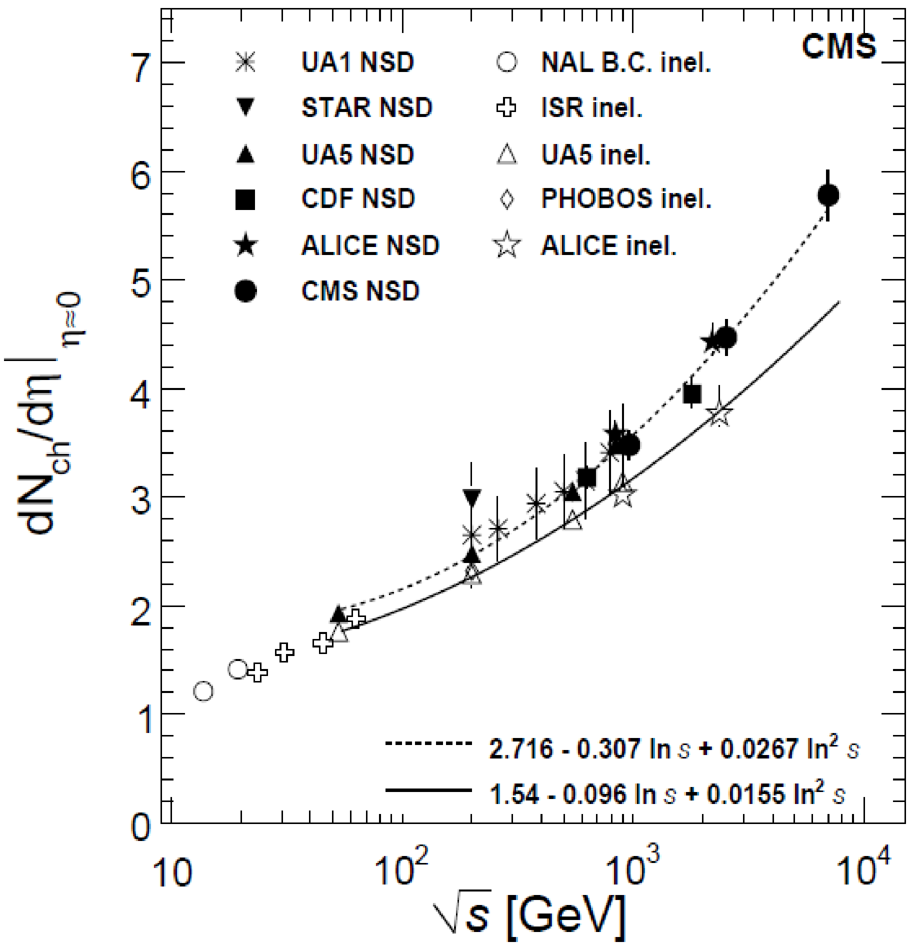


Charged hadron multiplicities at the three different √s



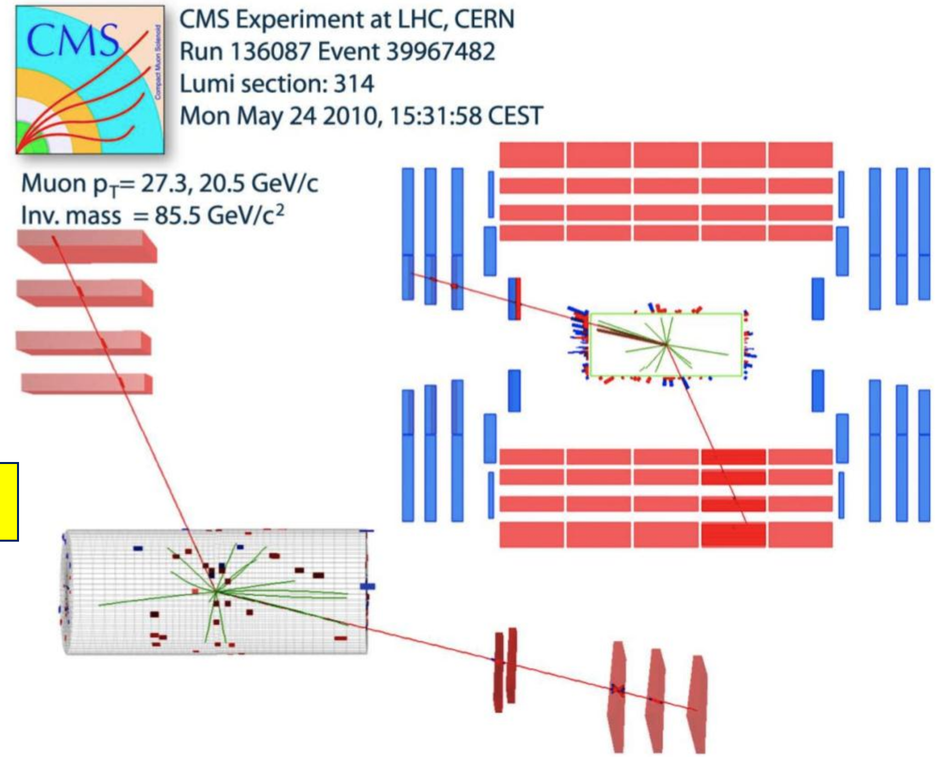
JHEP 01 (2011)079

Average charged particle density for the central η region (pp and p̄p)

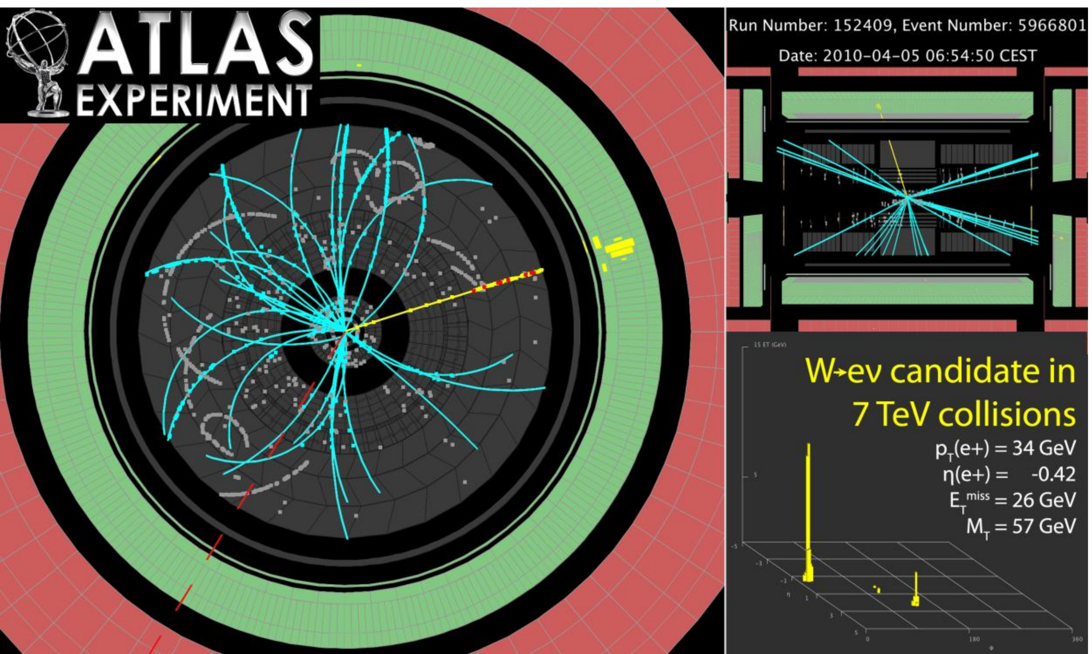


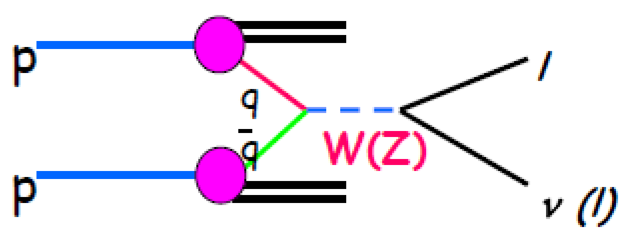
Phys. Rev. Lett. 105 (2010) 022002

Standard Model Physics



CMS candidate Z → $\mu^+\mu^-$

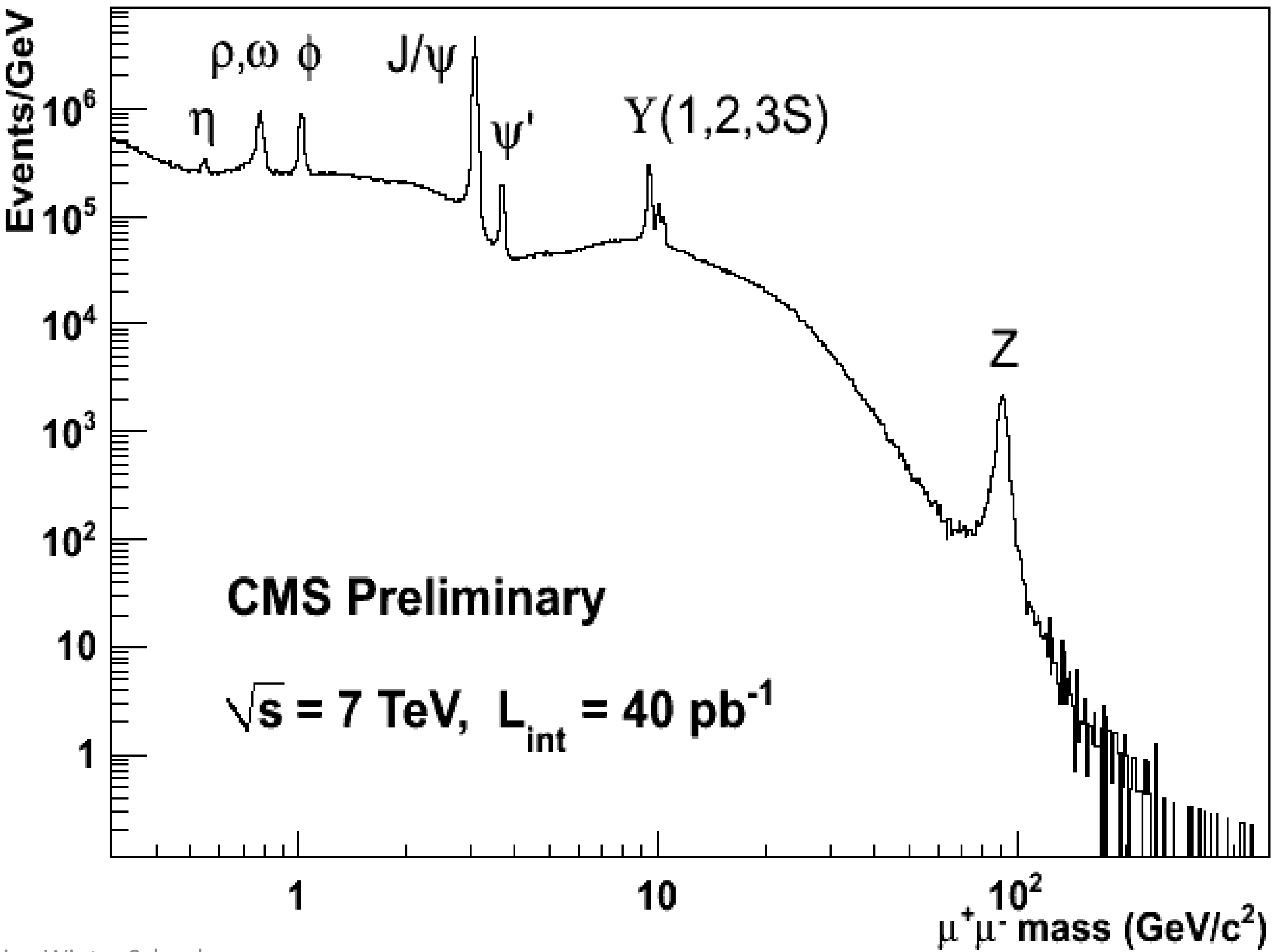




ATLAS W → eν candidate

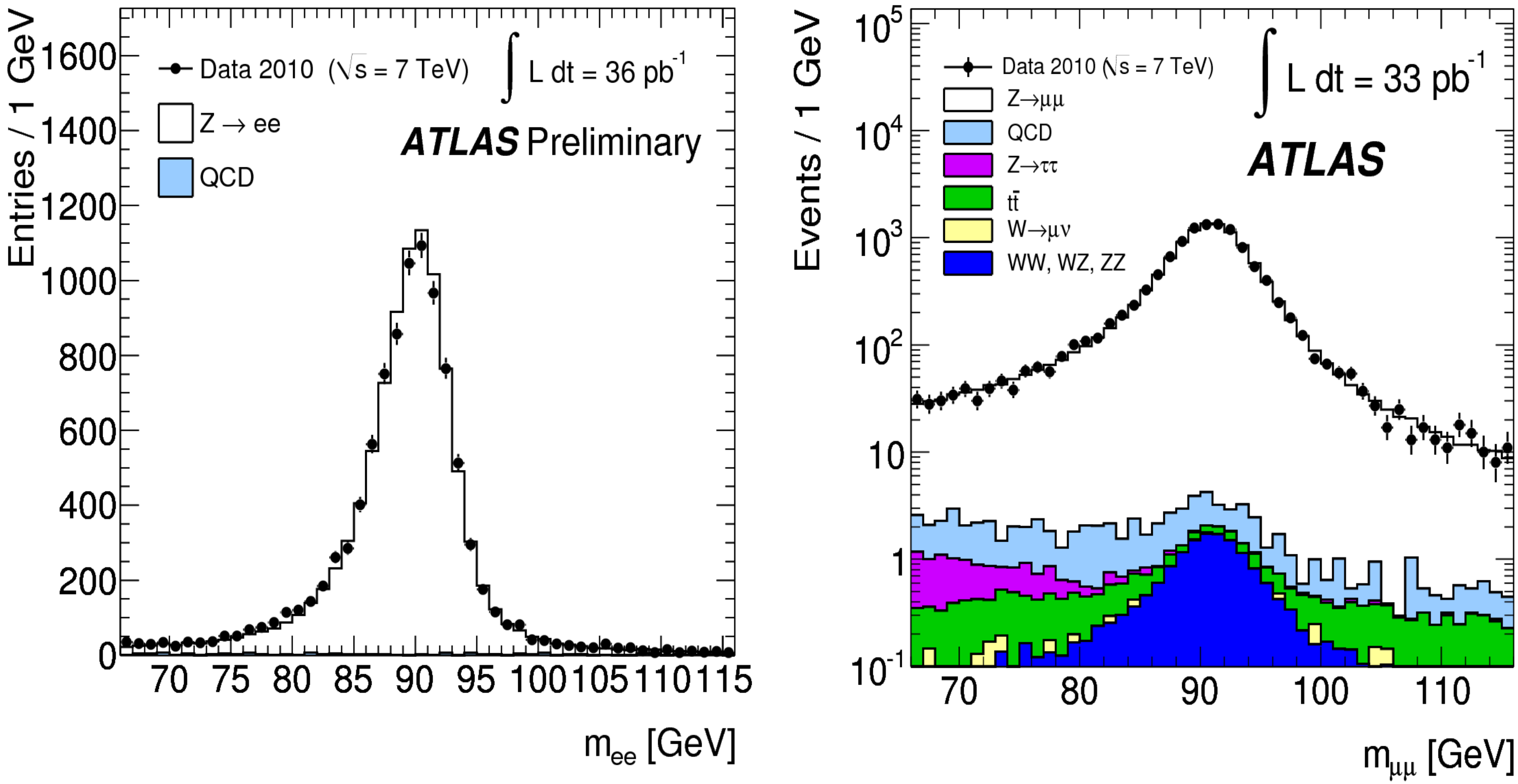
Di-lepton invariant mass spectra

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



Z and W production

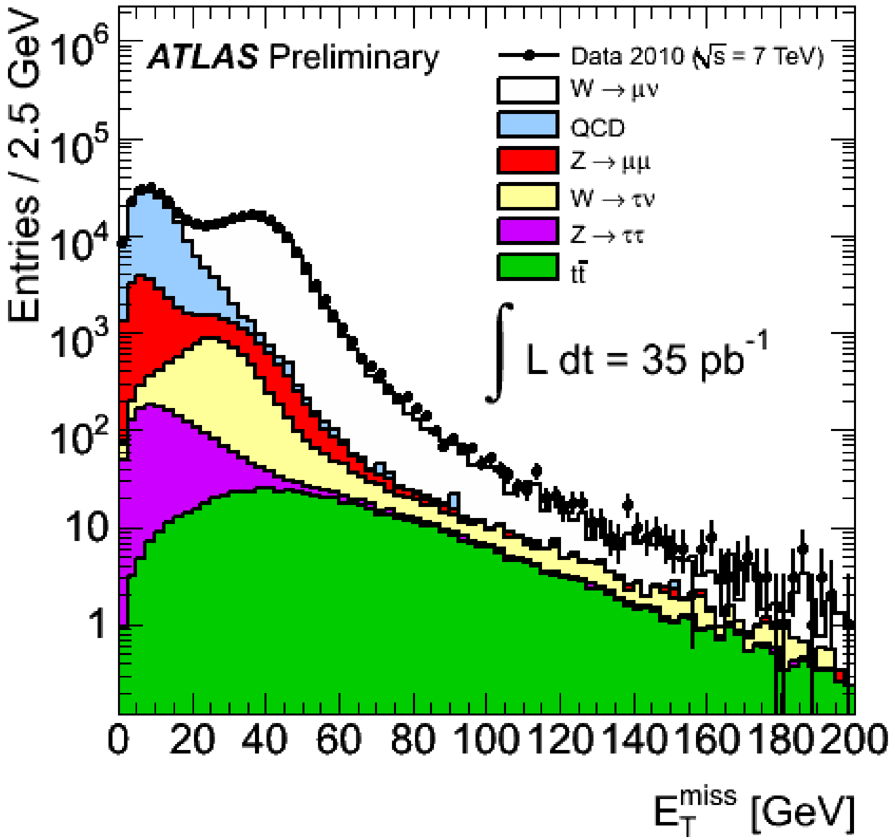
Sub. to Phys Rev D
arXiv:1109.5141hep-ex]



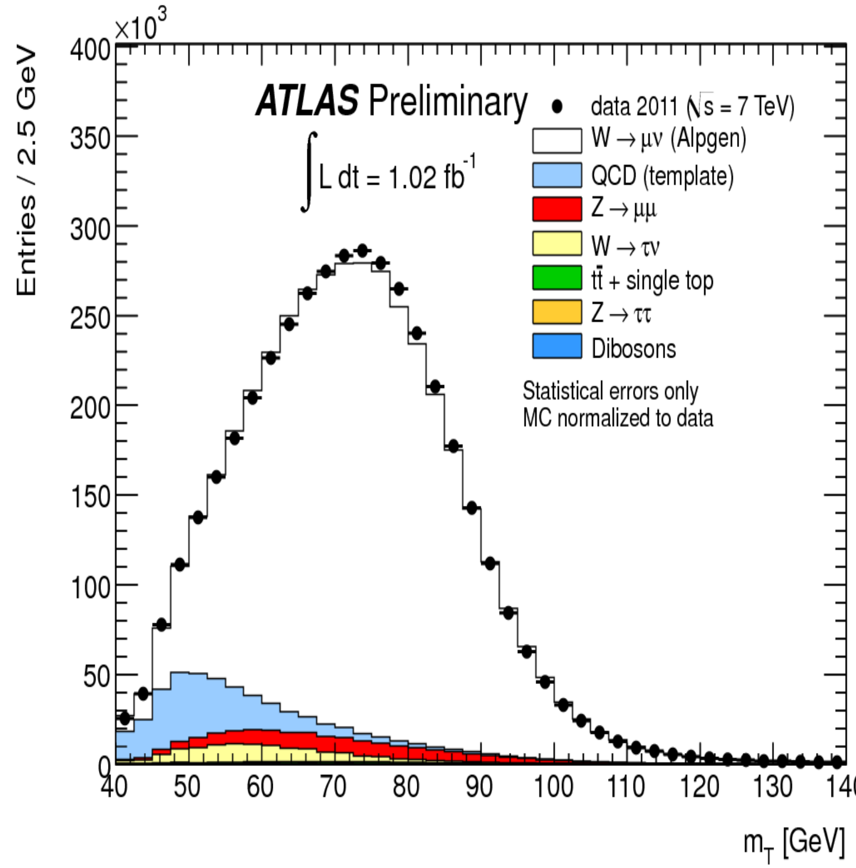
Z peak (di-lepton pair mass distributions, can be extracted essentially background-free)

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

W transverse mass



μ with p_T>20 GeV, E_T^{miss}>25 GeV



Missing transverse energy from the W → μ + ν decays

ATLAS-CONF-2011-041

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

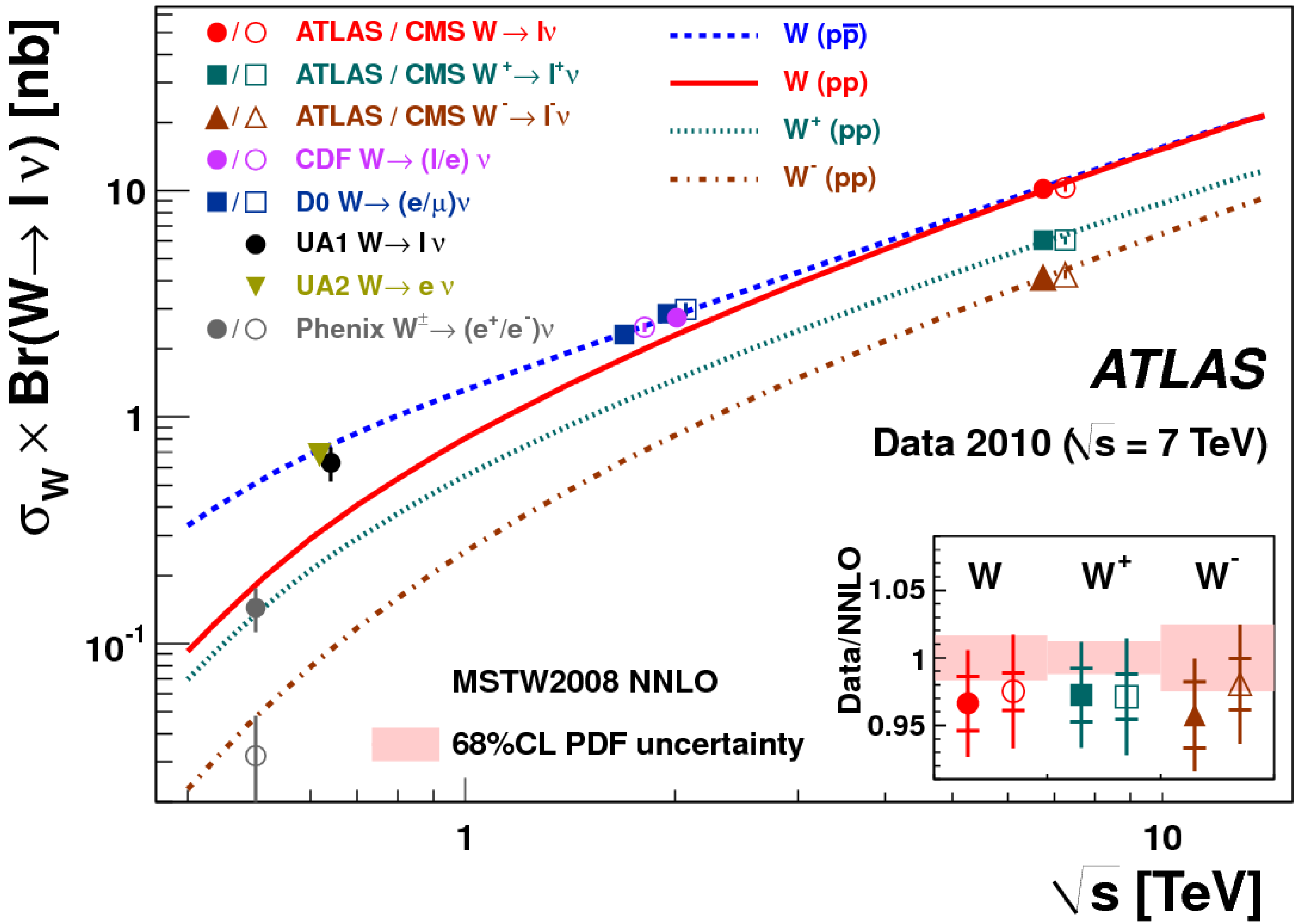
What is a Cross Section?

- Differential cross section: $d\sigma/d\Omega$:
  - Probability of a scattered particle in a given quantum state per solid angle $d\Omega$
    - E.g. Rutherford scattering experiment
- Other differential cross sections: $d\sigma/dE_T$(jet)
  - Probability of a jet with given E_T
- Integrated cross section
  - Integral: $\sigma = \int d\sigma/d\Omega \, d\Omega$

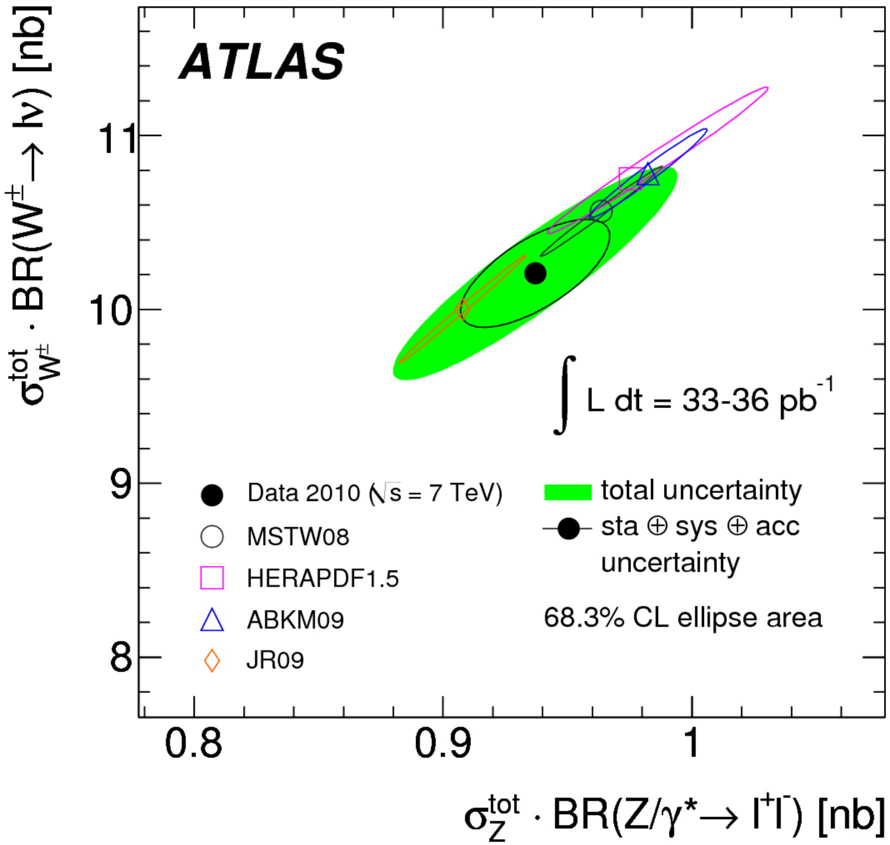
Measurement: $\sigma=(N_{obs}-N_{bg})/(\varepsilon L)$

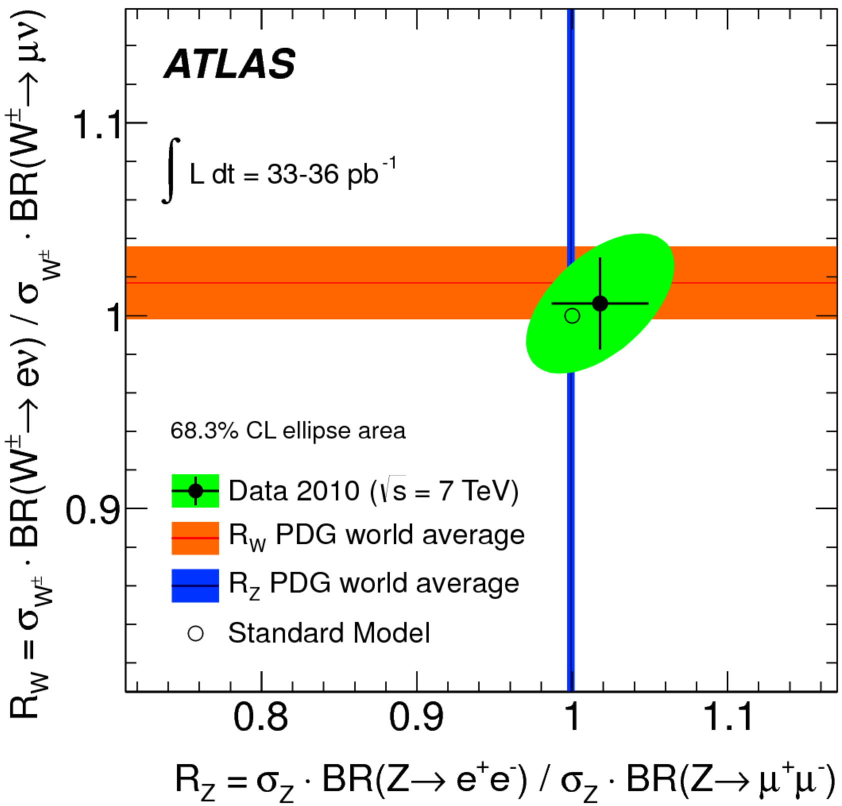
4

W cross section measurement with e and μ



Two examples of confronting the 2010 ATLAS data with SM theory

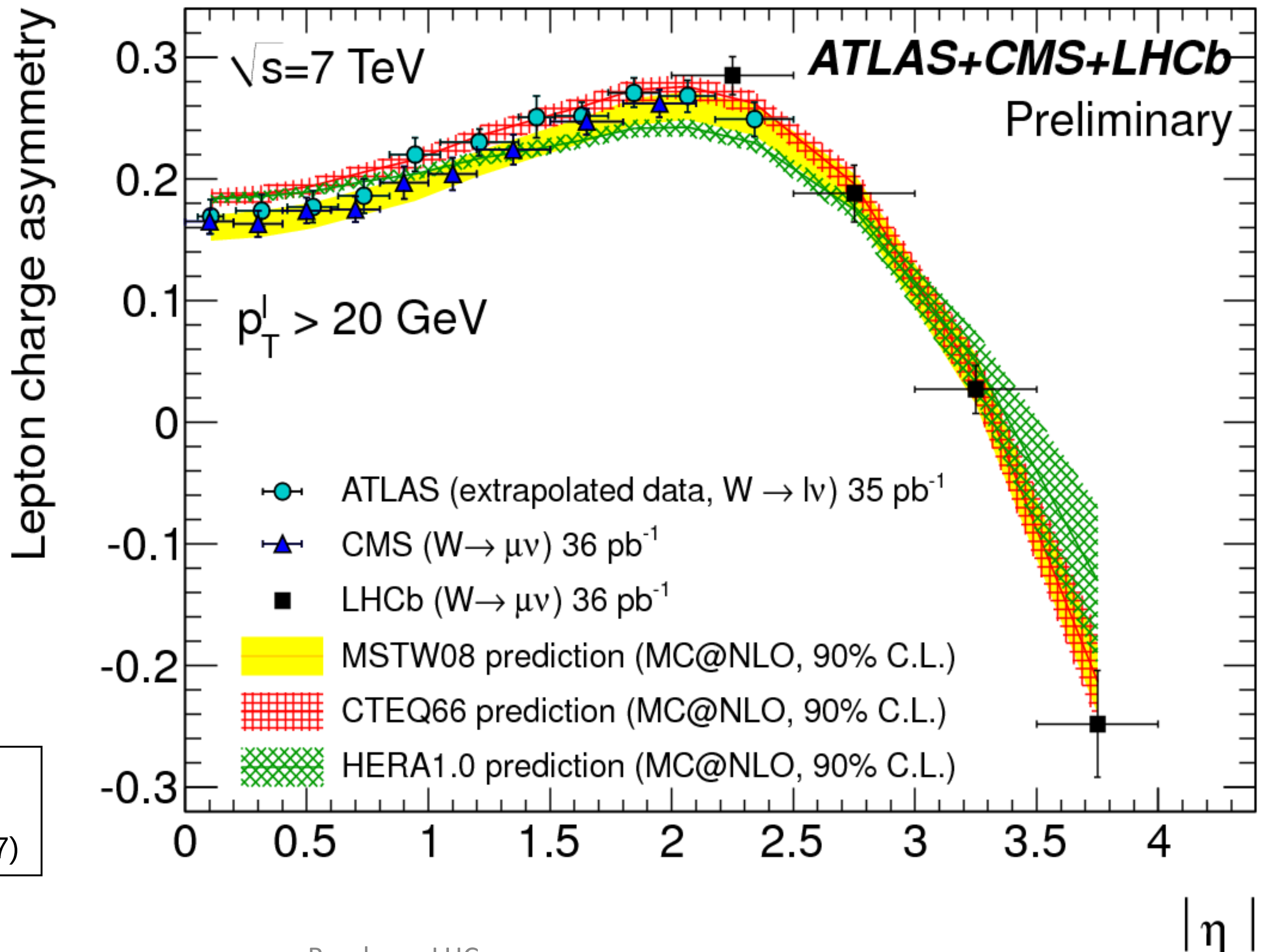




Sub. to Phys Rev D
arXiv:1109.5141hep-ex]

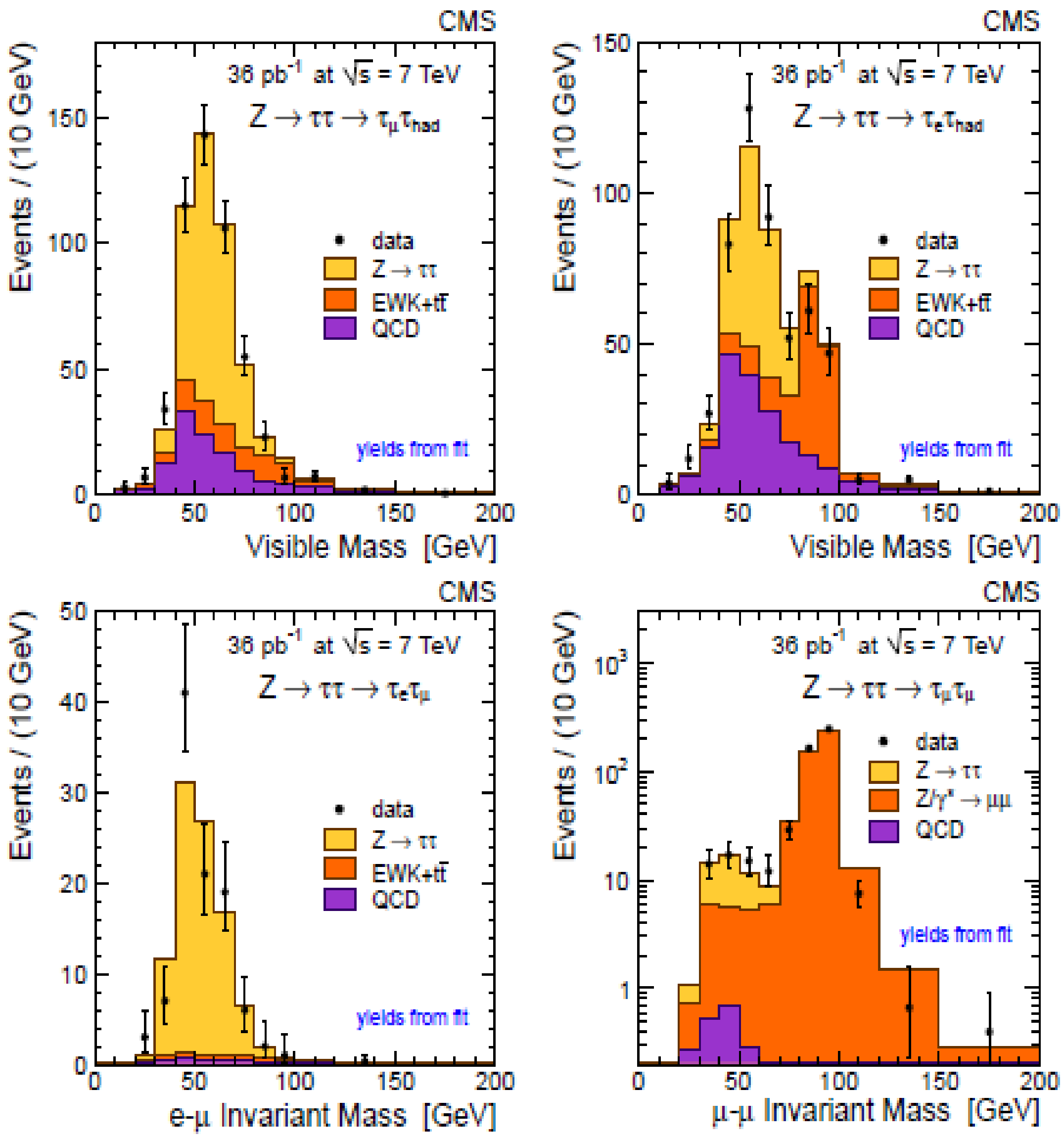
Lepton charge asymmetry from W decays in pp collisions at 7 TeV

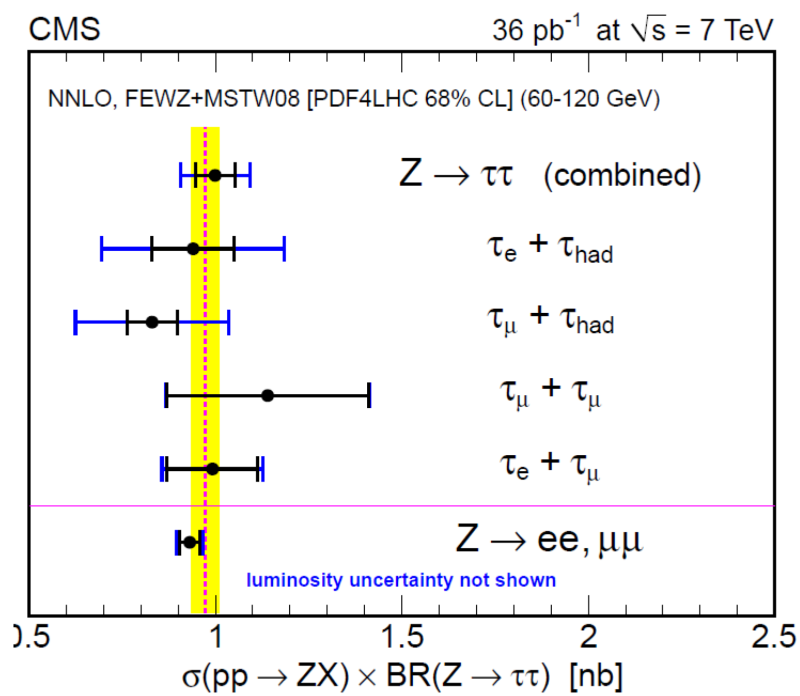
$$A(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})},$$



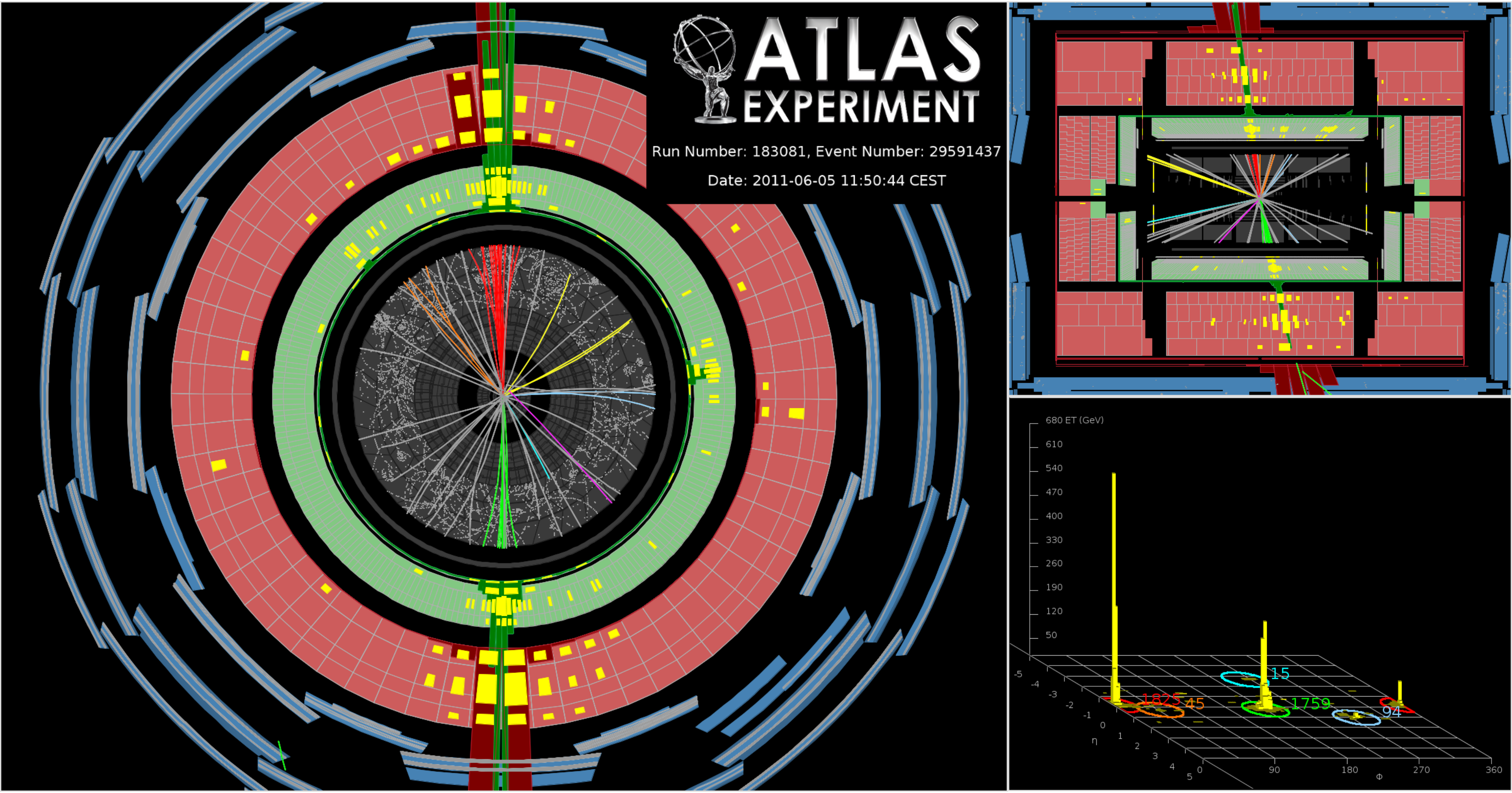
ATLAS-CONF-2011-129
LHCb-CONF-2011-039
CMS-EWK-10-006 (aXiv:1103.3407)

Example of using τ's





Sub. to JHEP
arXiv:1104.1617[hep-ex]

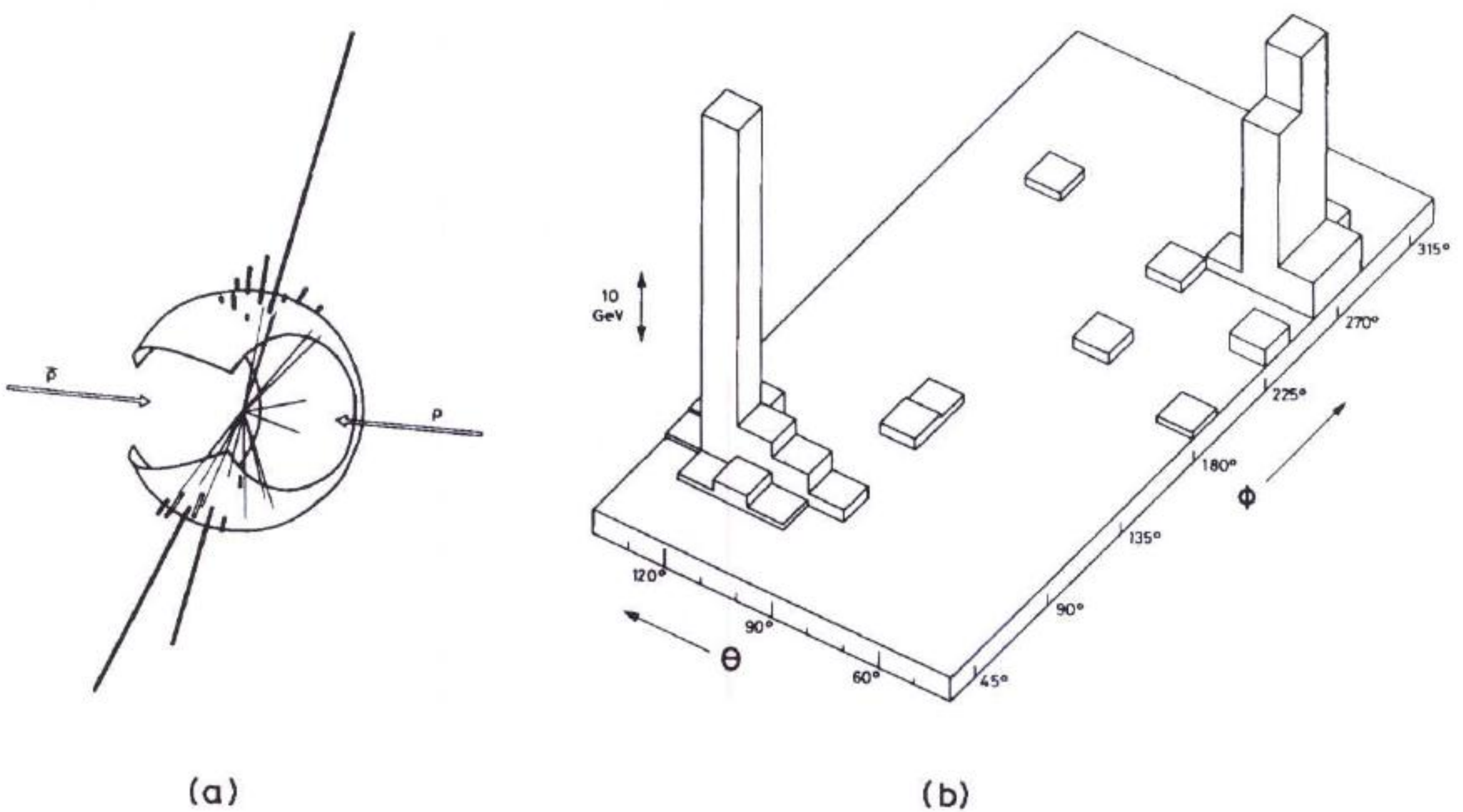


Jets

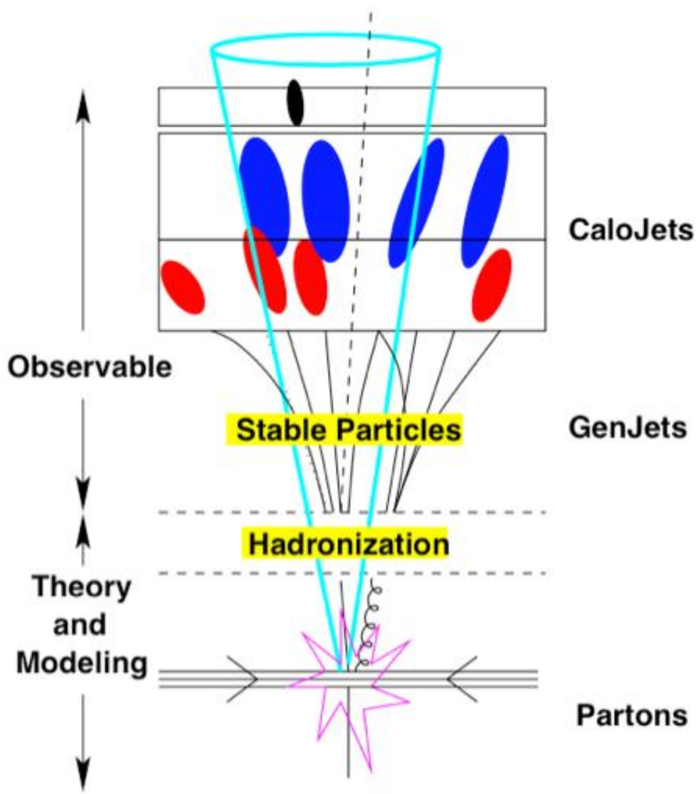
Jets with 1.9 and 1.7 TeV transverse momenta (p_T)

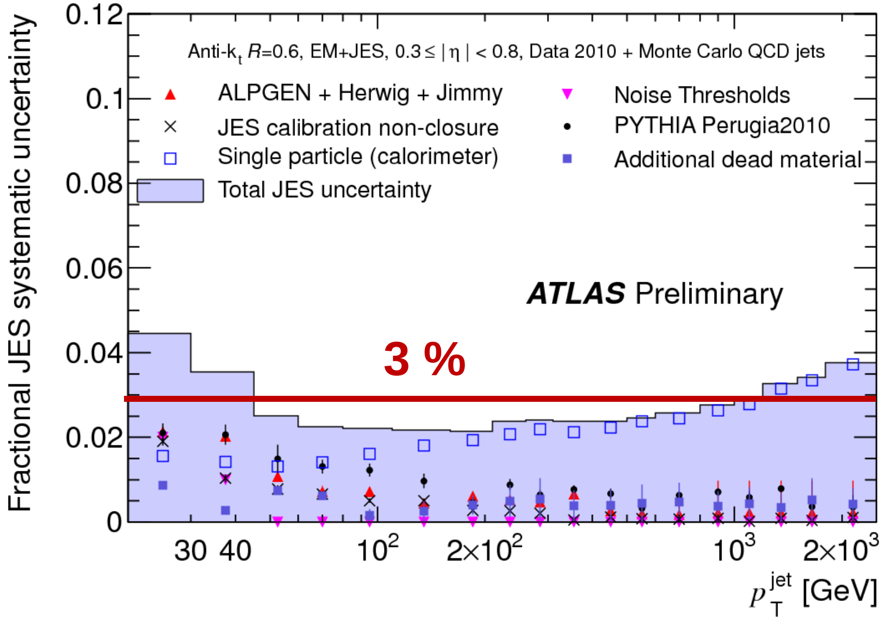
Note also that the event displays have become more sophisticated since the first spectacular events, hand-drawn, at a hadron collider …

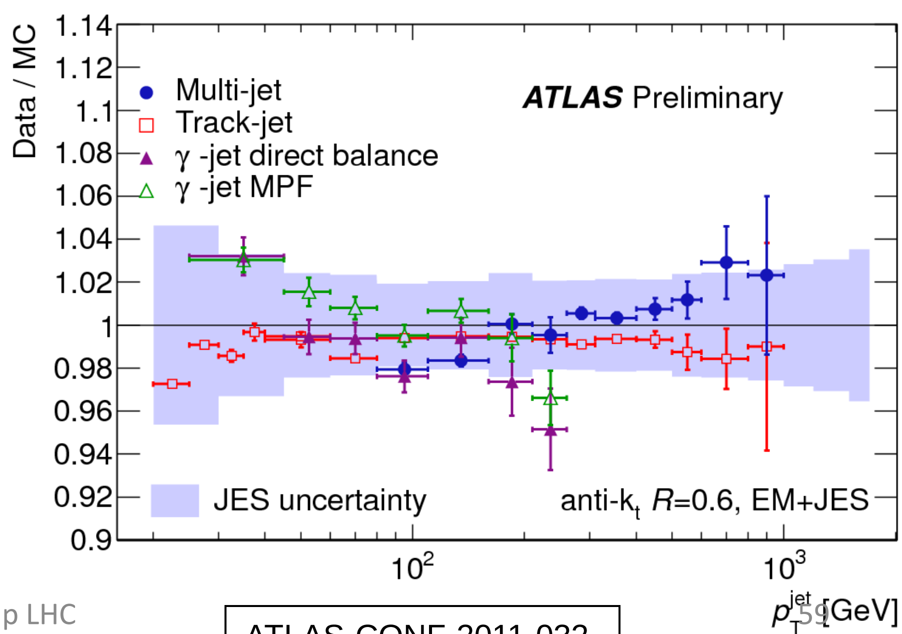
Volume 118B, number 1, 2, 3 PHYSICS LETTERS 2 December 1982



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



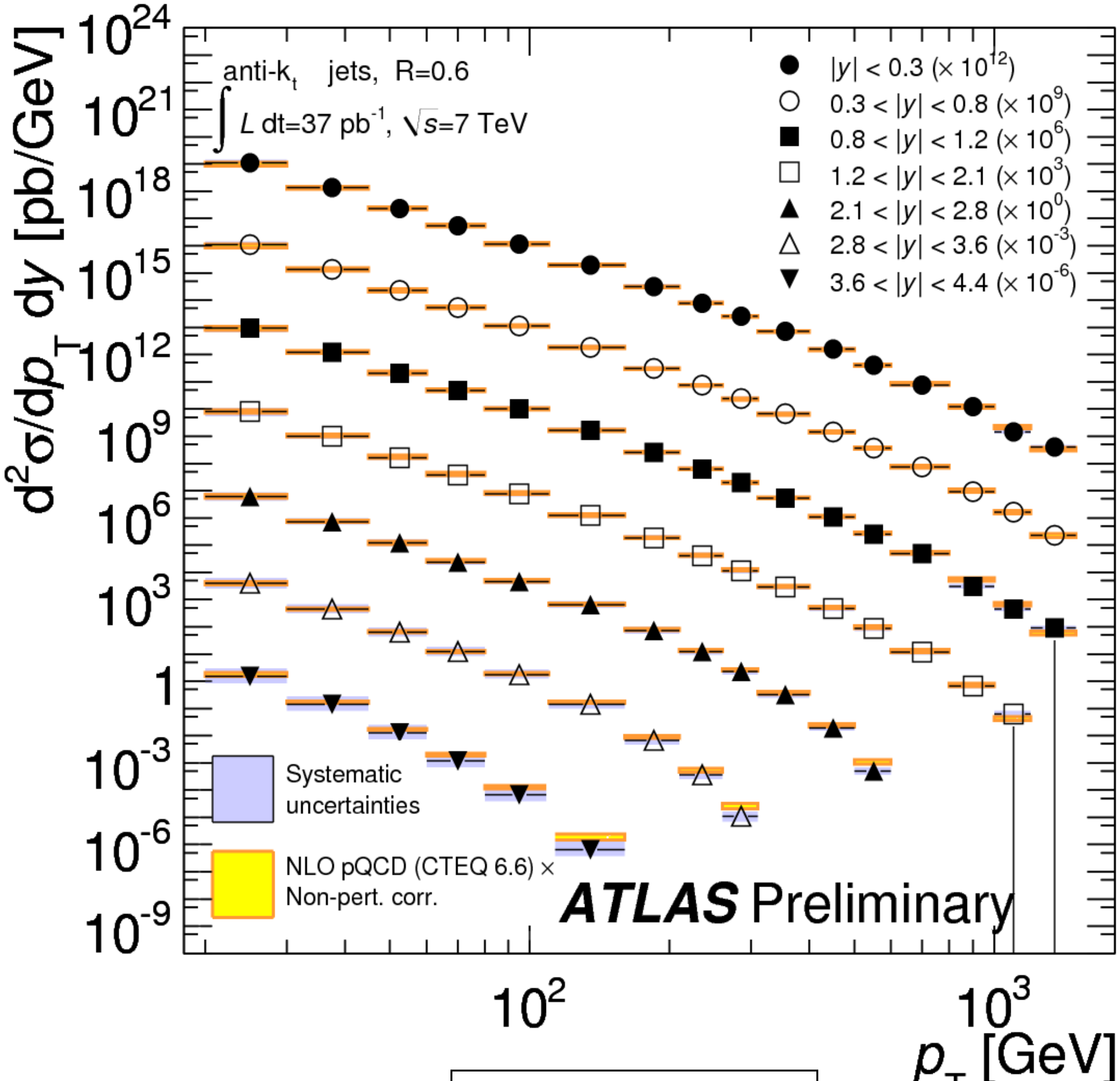




ATLAS-CONF-2011-032

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

Inclusive jet cross sections in various rapidity intervals



The data are spanning:

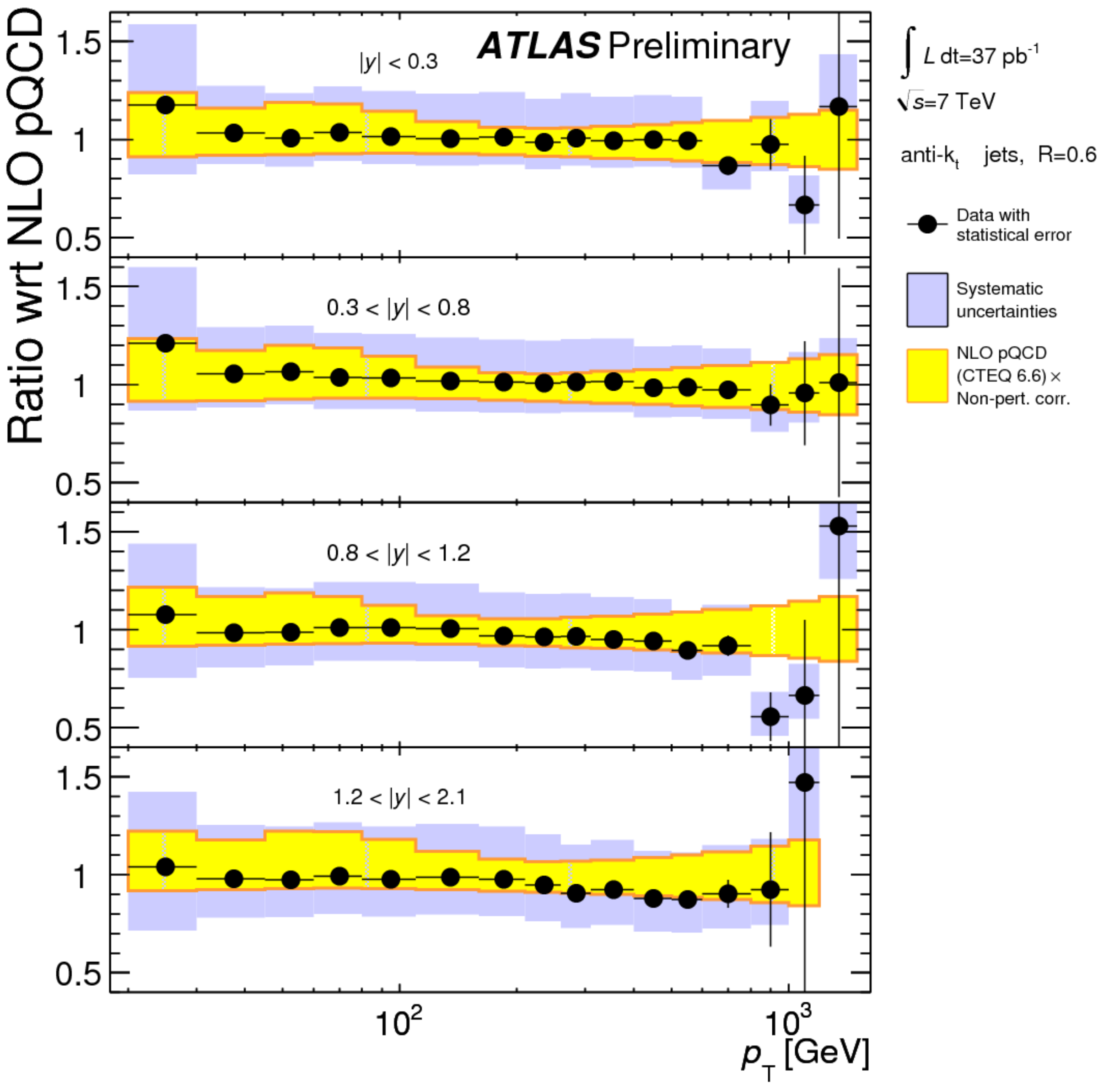
- **20 GeV < p_T < 1500 GeV**
- **$|\eta|$ < 4.4**
- **Up to 12 orders of magnitudes in cross-sections**

ATLAS-CONF-2011-047

Systematic uncertainty dominated by JES

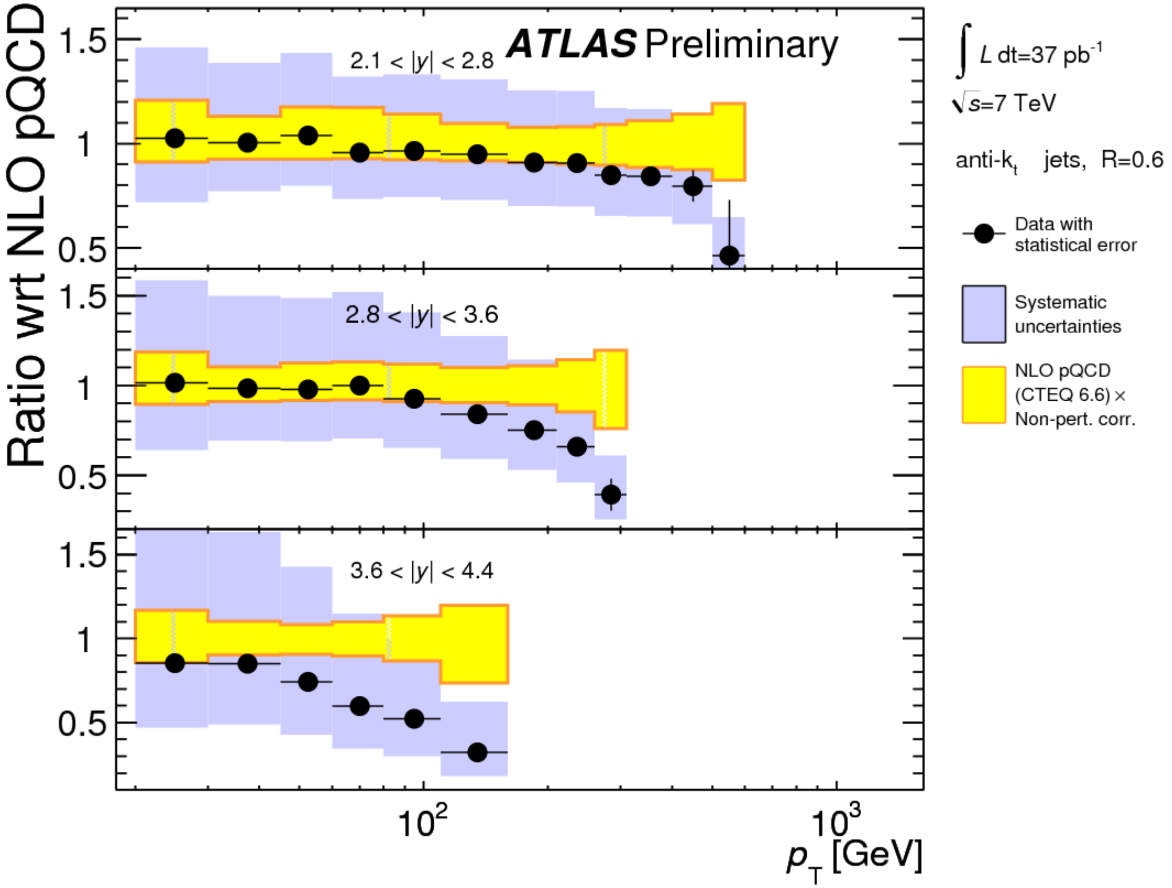
Good agreement between data and NLO pQCD with various PDFs globally…

Many detailed multi-jet measurements as well as studies of jet properties have been published



ATLAS-CONF-2011-047

Systematic uncertainty dominated by JES

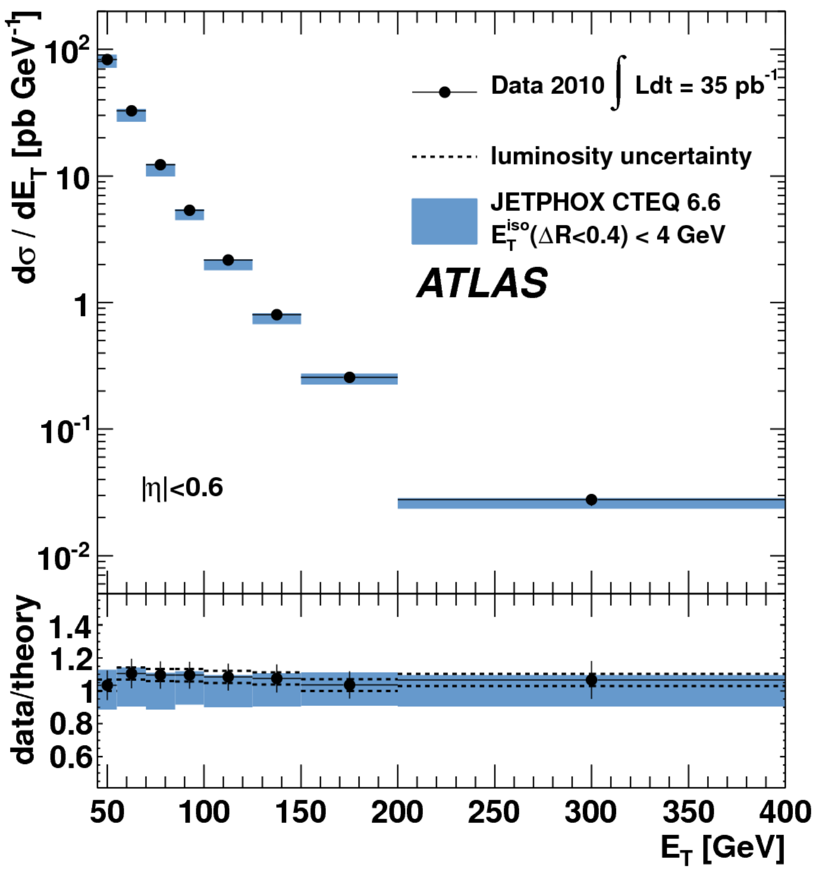


… except in some specific regions, for example in the forward directions

→Should be able soon to constrain PDFs

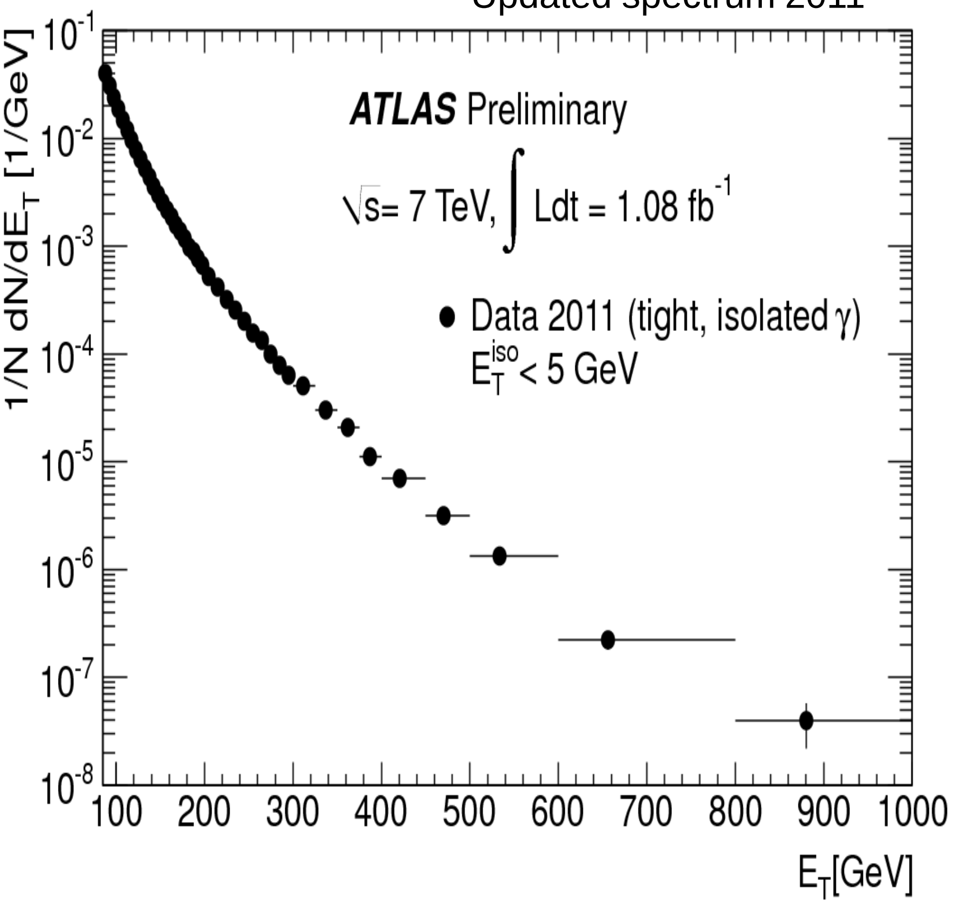
ATLAS-CONF-2011-047

Example of inclusive isolated prompt photon cross-sections

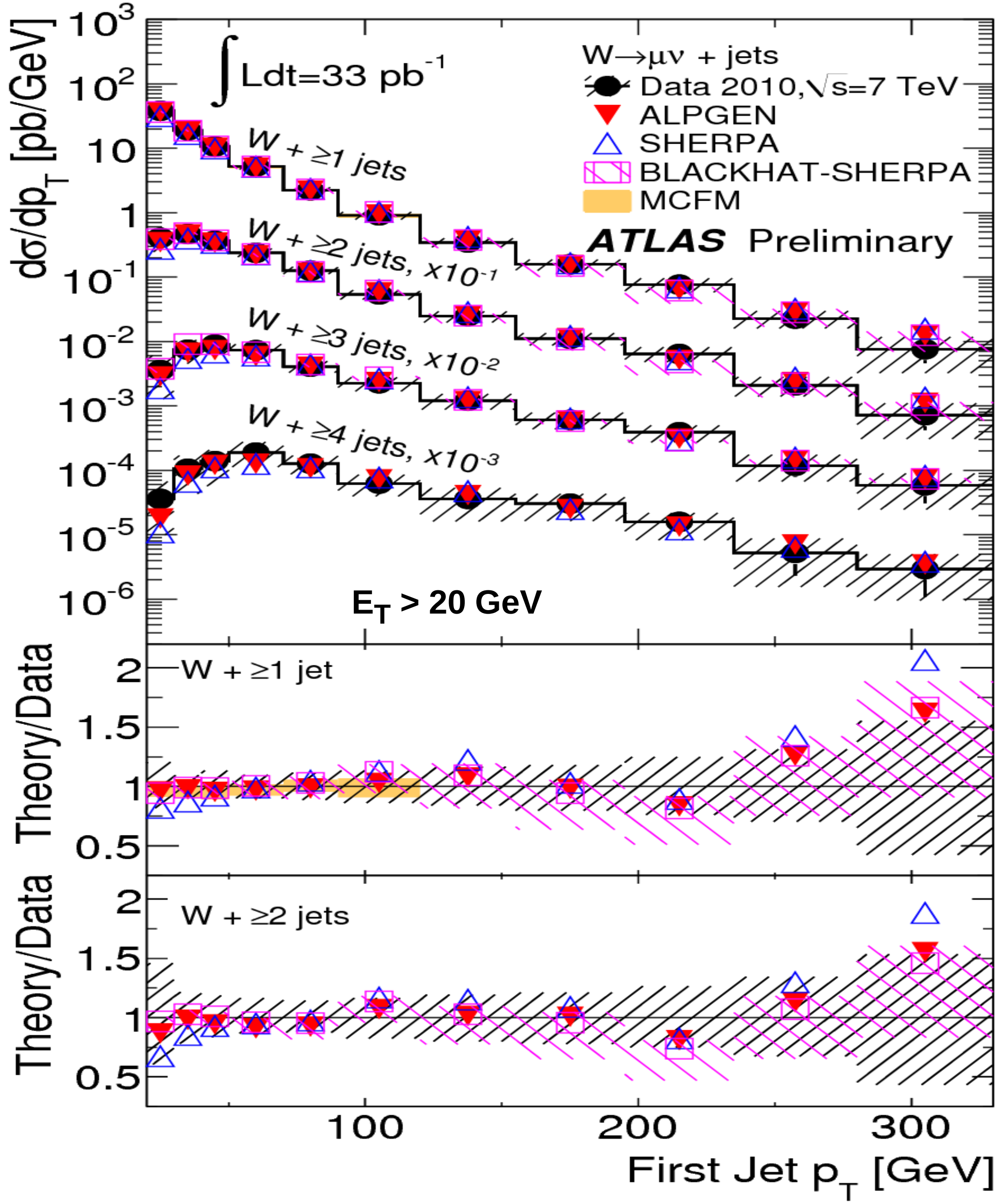


Sub. To Phys. Lett. B
arXiv:1108.0251v1[hep-ex]

Updated spectrum 2011



W + jet(s) production



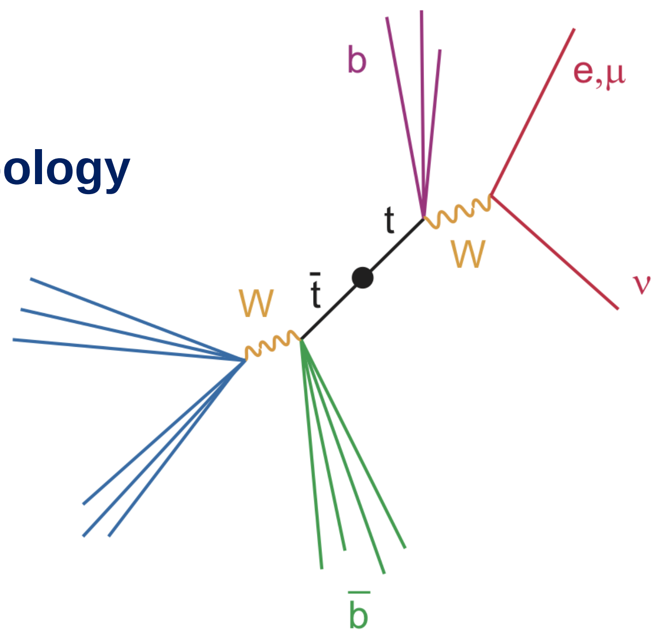
Both an interesting QCD measurement as well as a dominant background to searches

ATLAS-CONF-2011-060

LHC measurements of the top cross section

- **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**

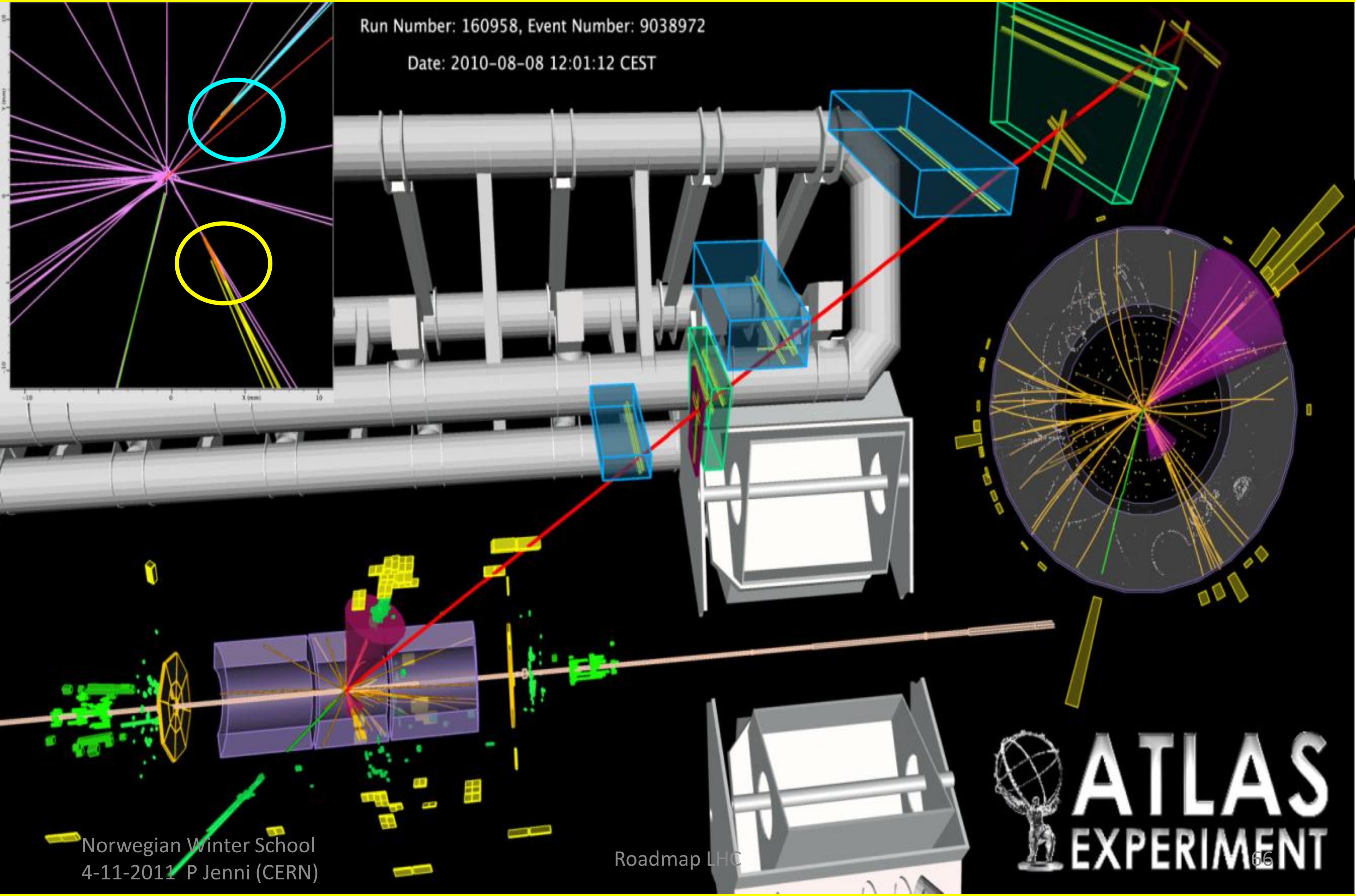
- **Assume all tops decay to Wb: event topology then depends on the W decays:**
  - **one lepton (e or μ), E_T^{miss}, jjbb (37.9%)**
  - **di-lepton (ee, μμ or eμ), E_T^{miss}, bb (6.46%)**



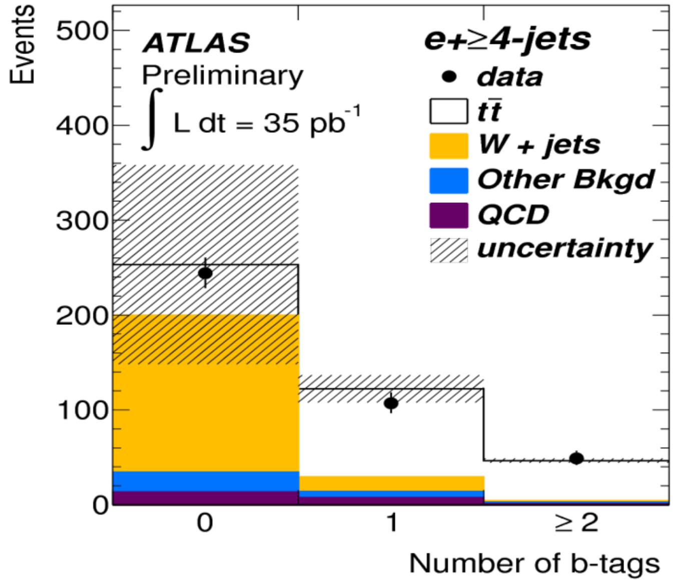
- **Data-driven methods to control QCD and W+jets backgrounds**

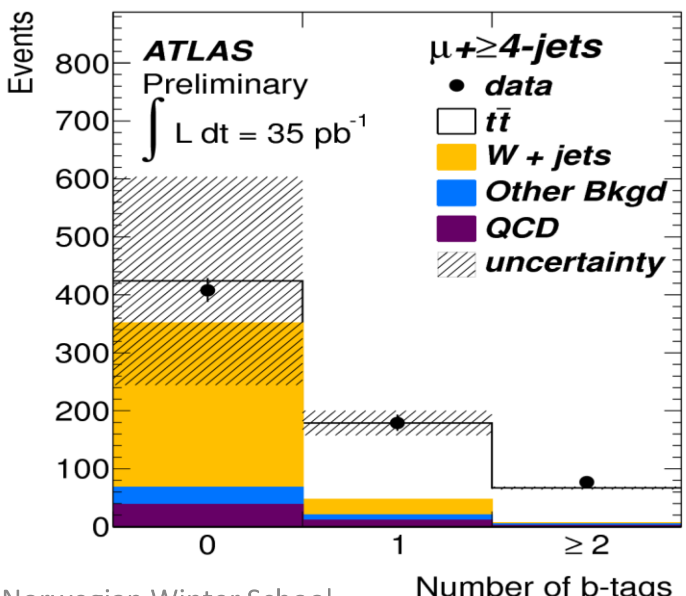
$t\bar{t}$ candidate event

e + μ + 2 jets (b-tagged) +ETmiss

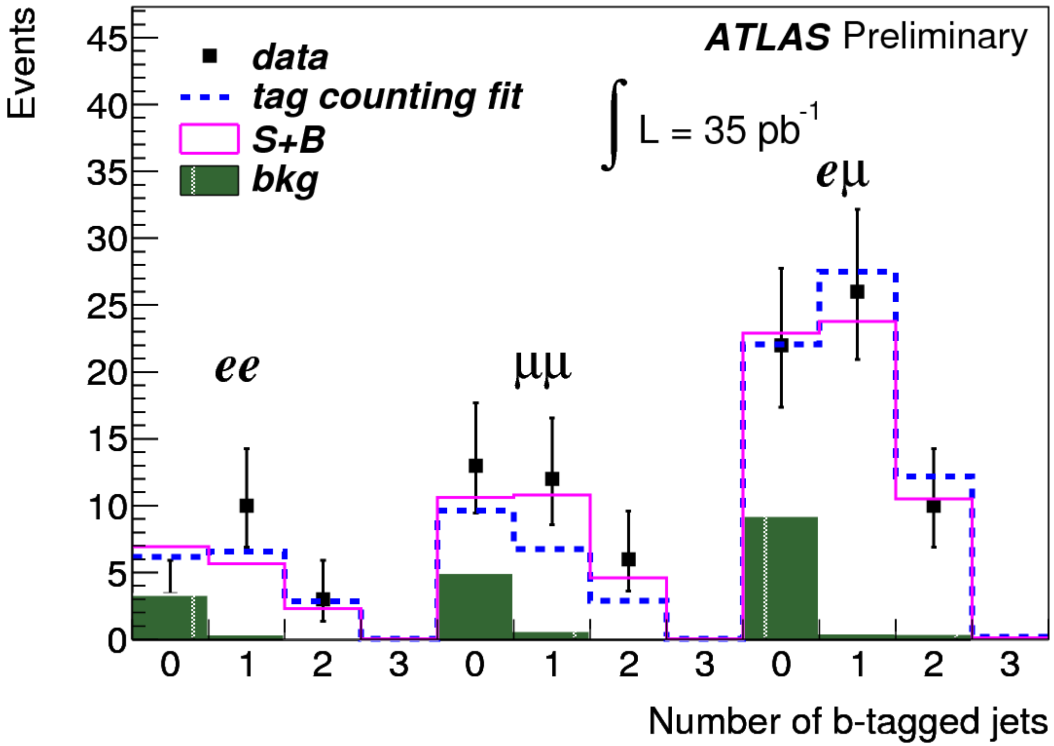


1 lepton + 4 jets + ETmiss





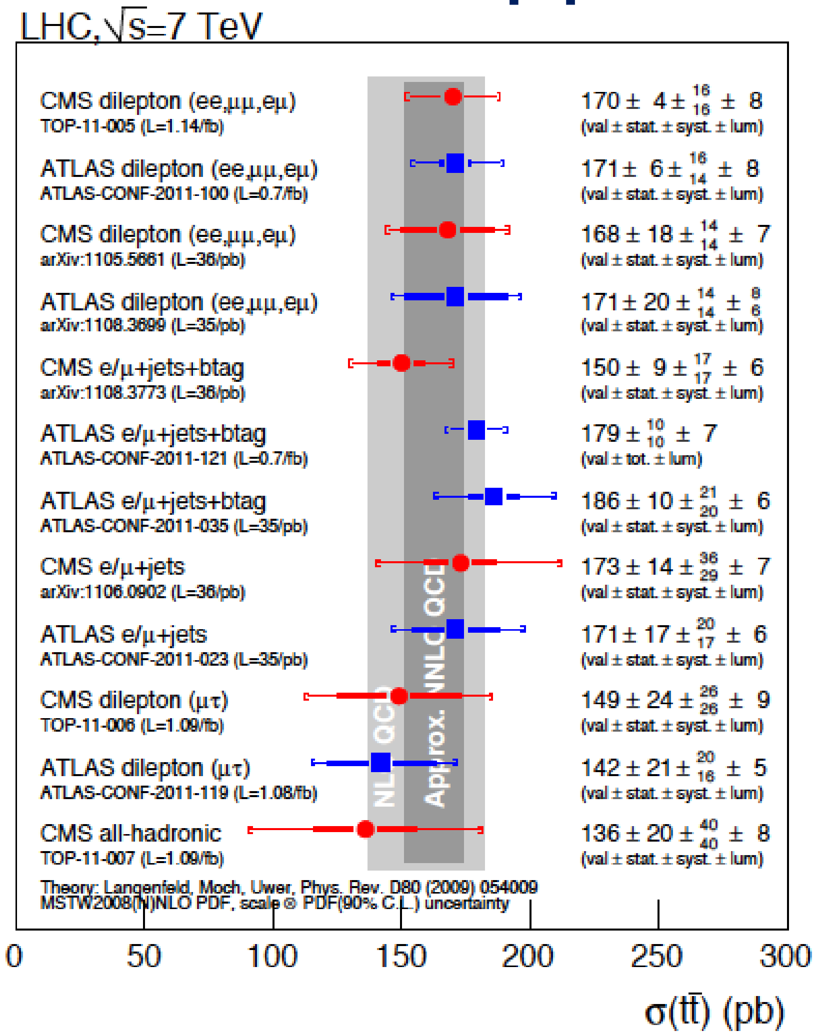
2 leptons + jets + ETmiss

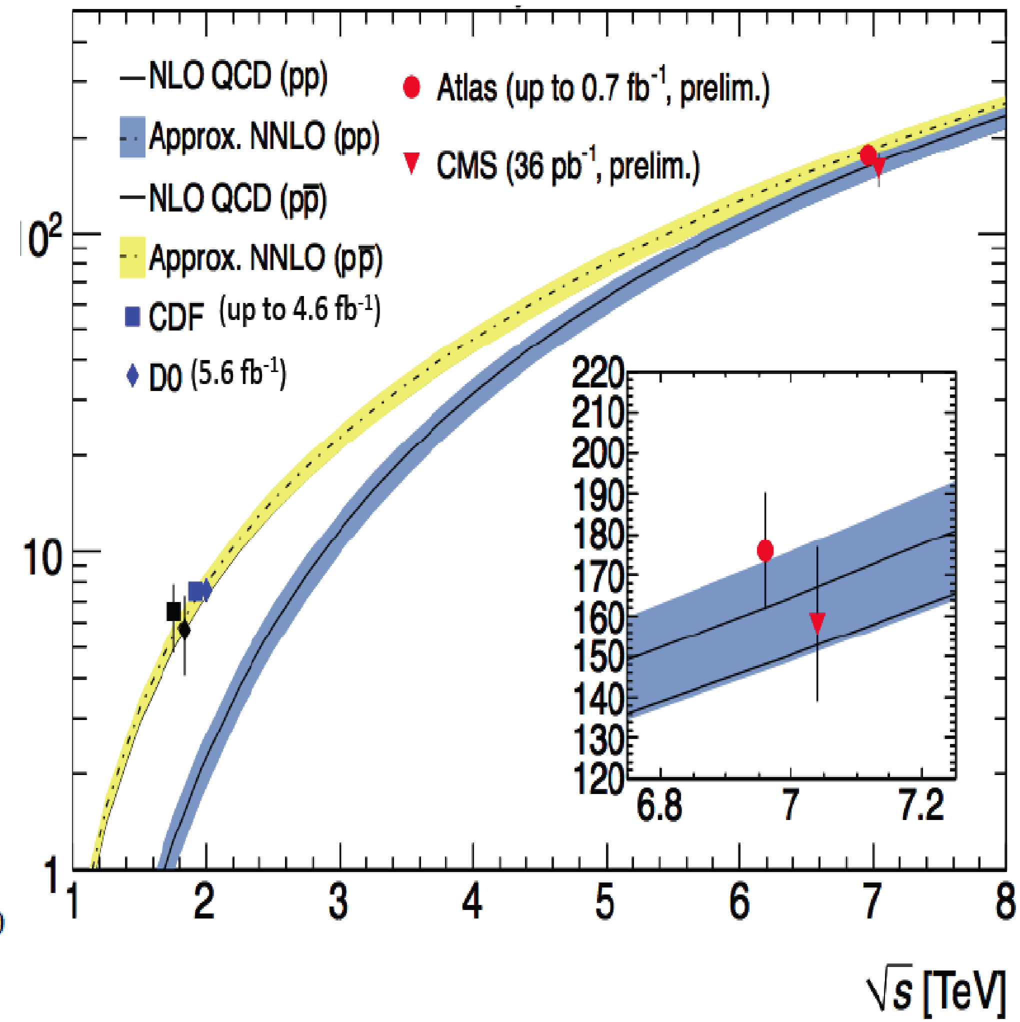


ATLAS-CONF-2011-035

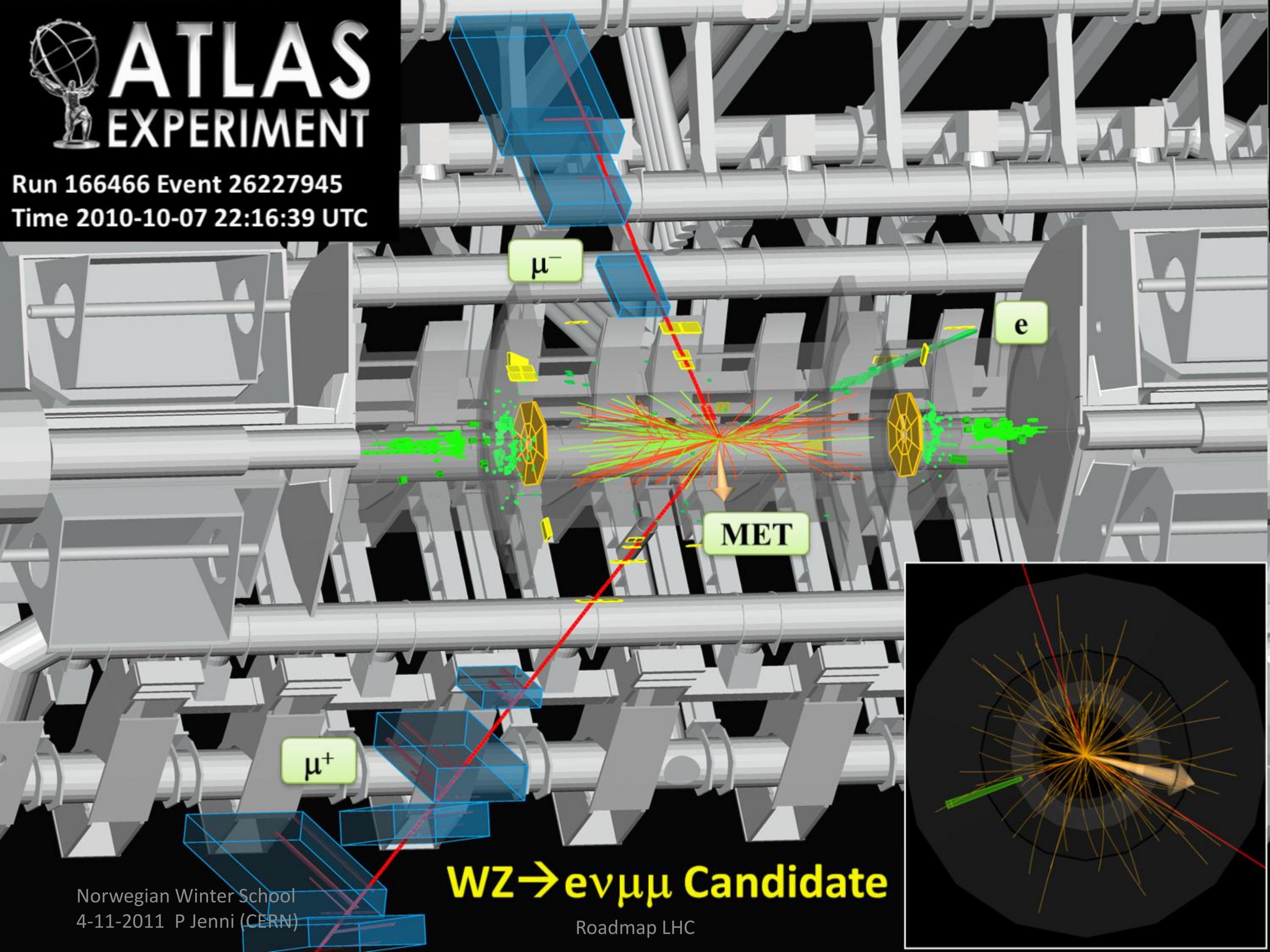
Sub. to Phys Lett B
arXiv:1108.3699[hep-ex]

Top pair cross section measurements at LHC

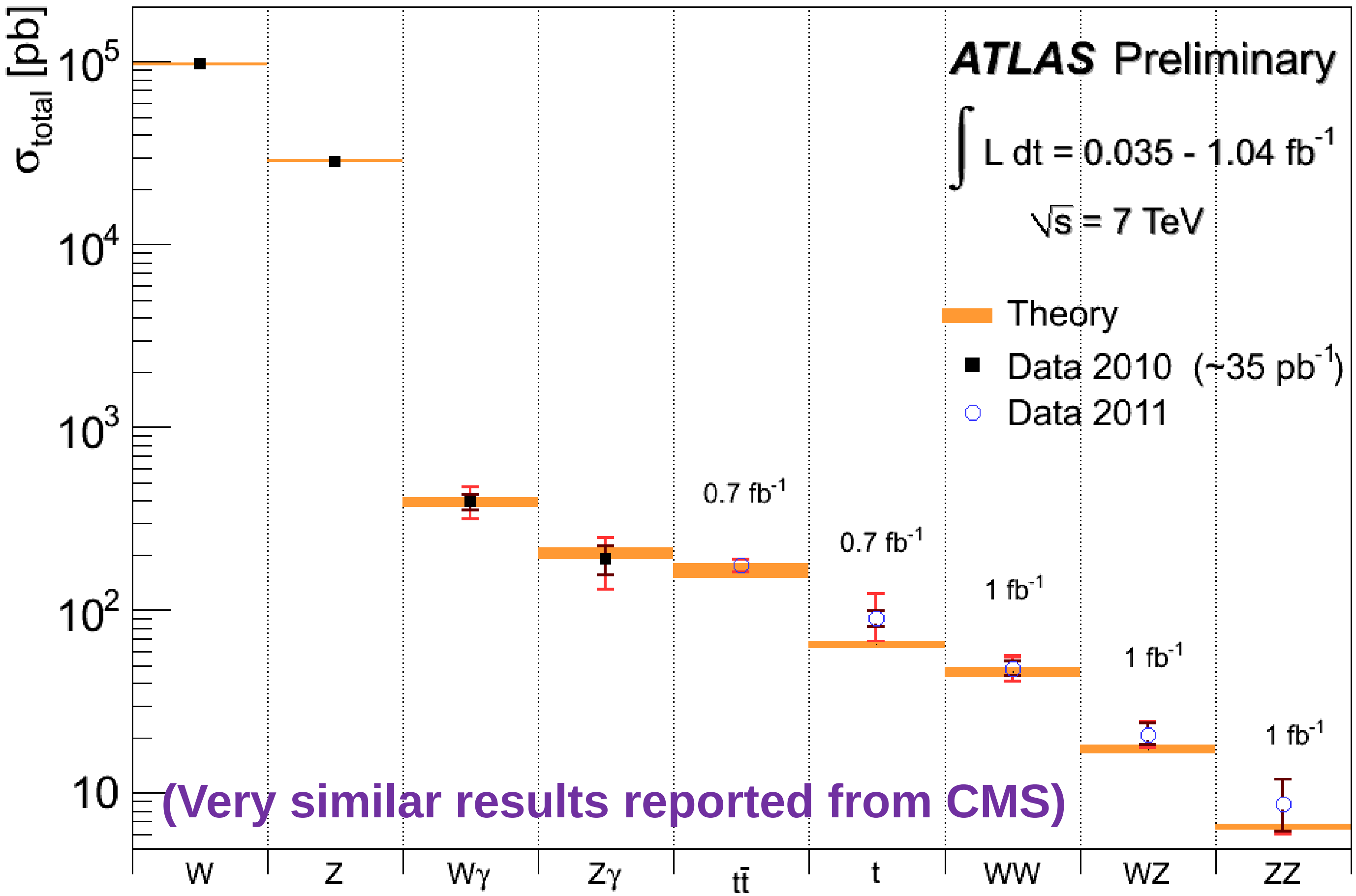




(ATLAS and CMS have also made first single top cross-section measurements in agreement with NLO QCD expectations)


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

A summary of ATLAS Standard Model measurements at 7 TeV



The excellent performance in measuring Standard Model physics gives confidence for the readiness of the 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.) $\rightarrow$ 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, $Z \rightarrow ll$, …) ✓
- "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,…) ✓

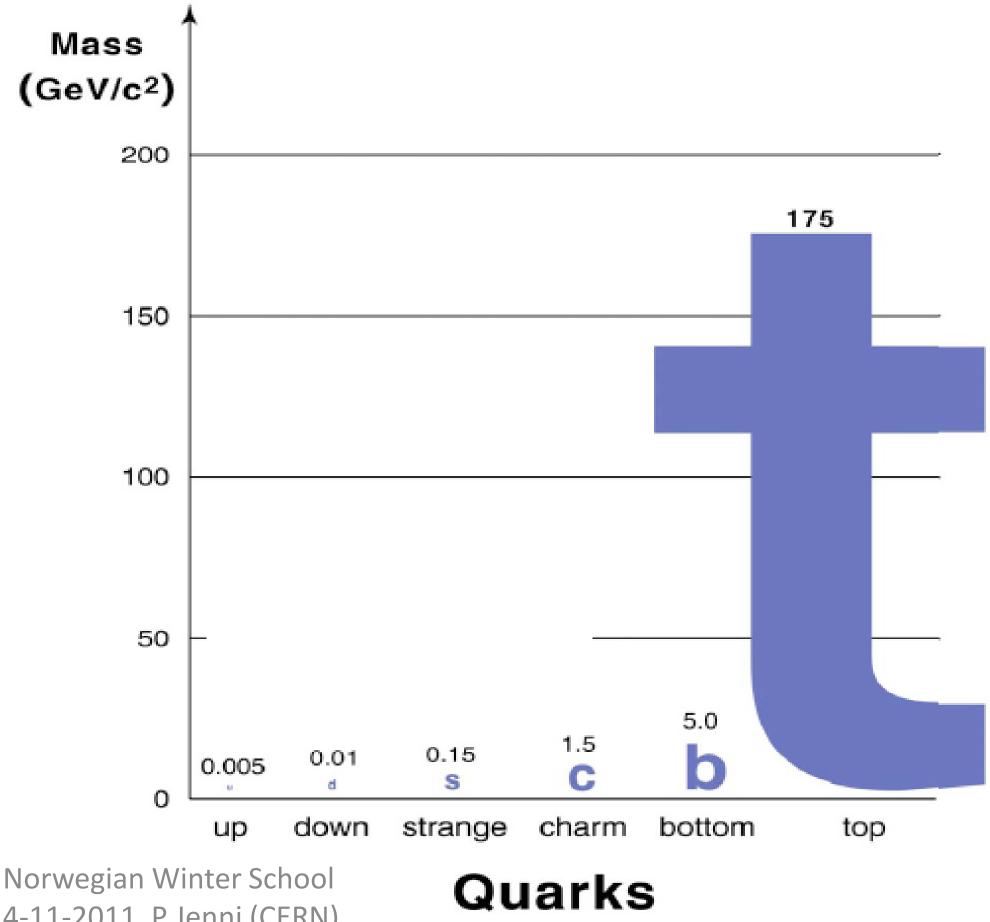
↓

Prepare the road to discoveries …

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

The mass mystery could be solved with the 'Higgs mechanism' which predicts the existence of a new elementary particle, the 'Higgs' particle (theory 1964, P. Higgs, R. Brout and F. Englert)

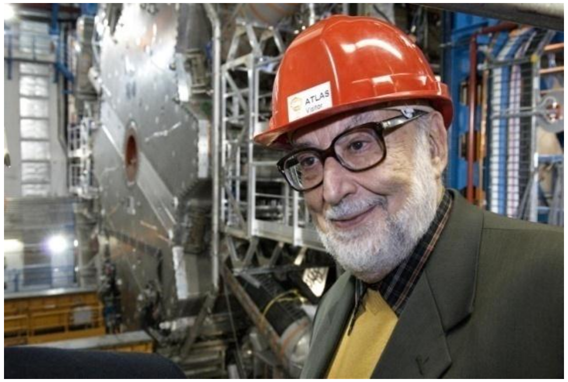
Peter Higgs



The Higgs (H) particle has been searched for since decades at accelerators, but not yet found…

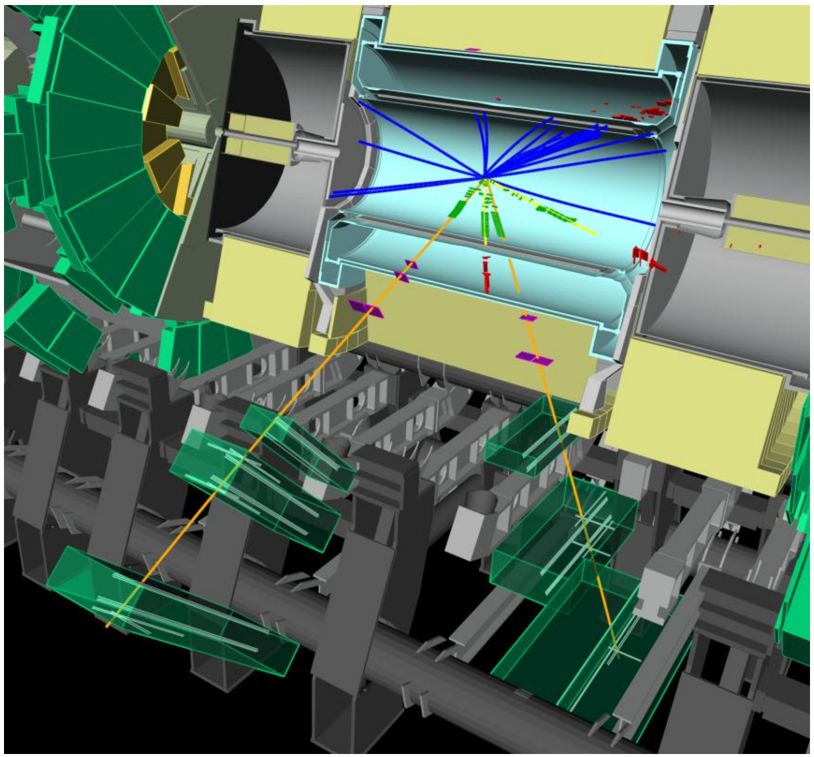
The LHC has sufficient energy to produce it for sure, if it exists

Francois Englert

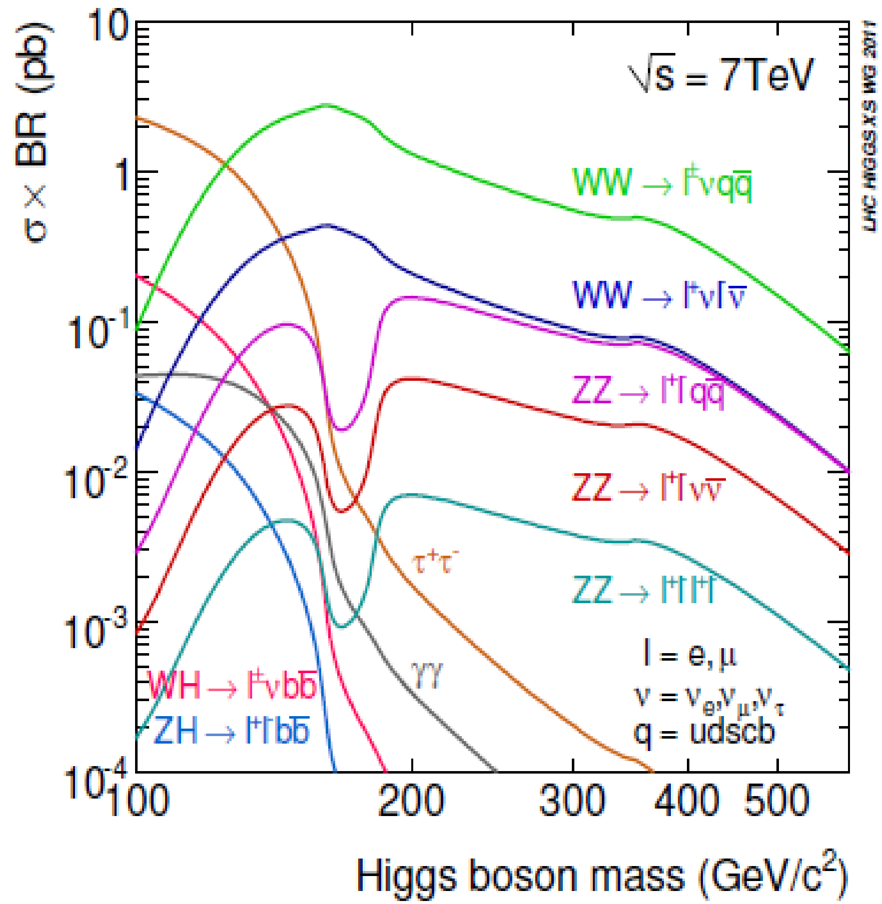


Search for the boson (H) of the EW symmetry breaking (Brout, Englert, and Higgs)

SM H boson production cross sections times observable decay branching ratios at 7 TeV

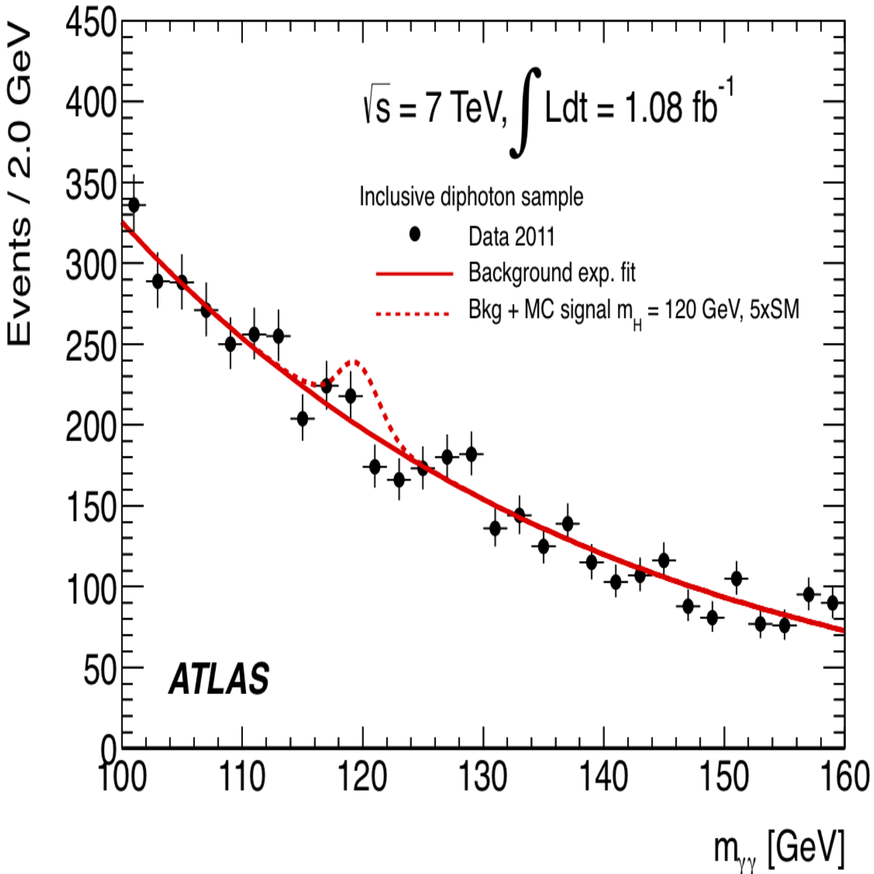


Simulation of a 130 GeV mass $H \rightarrow \mu\mu$ ee event in ATLAS

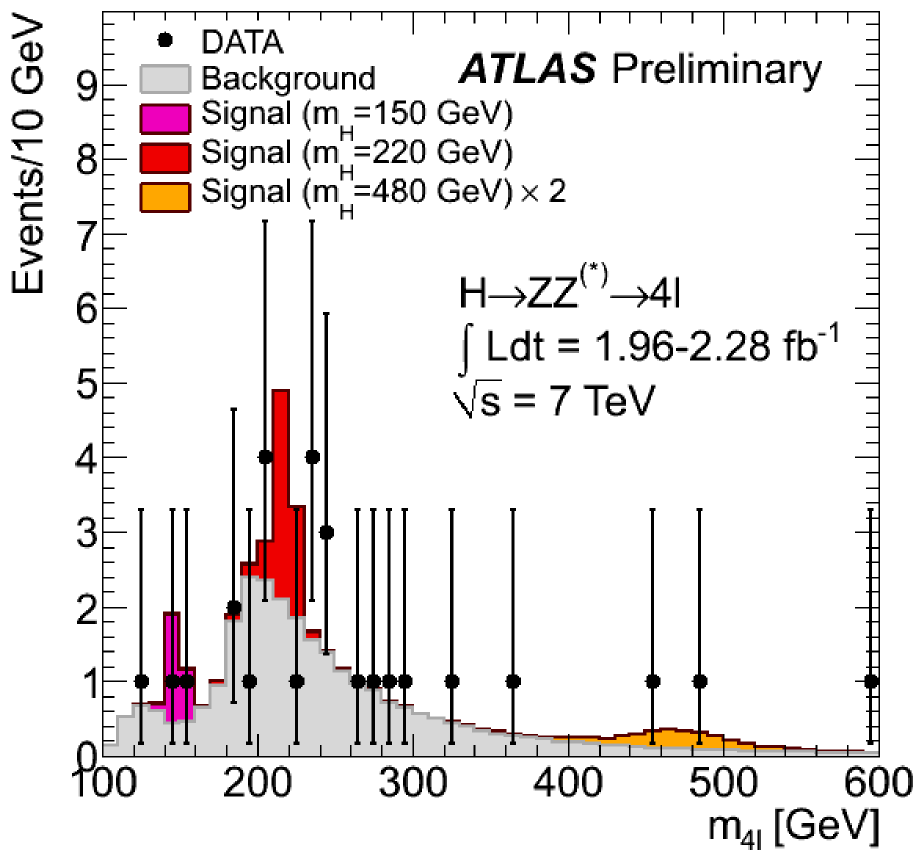


Two examples of ‘easy’ searches (where one would expect a mass peak)

ATLAS-CONF-2011-135

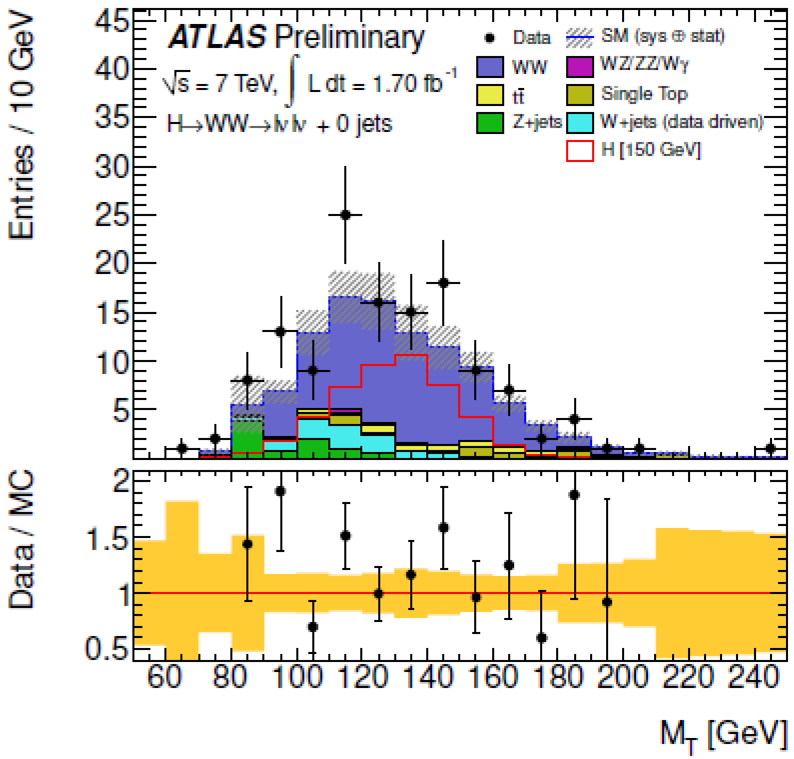


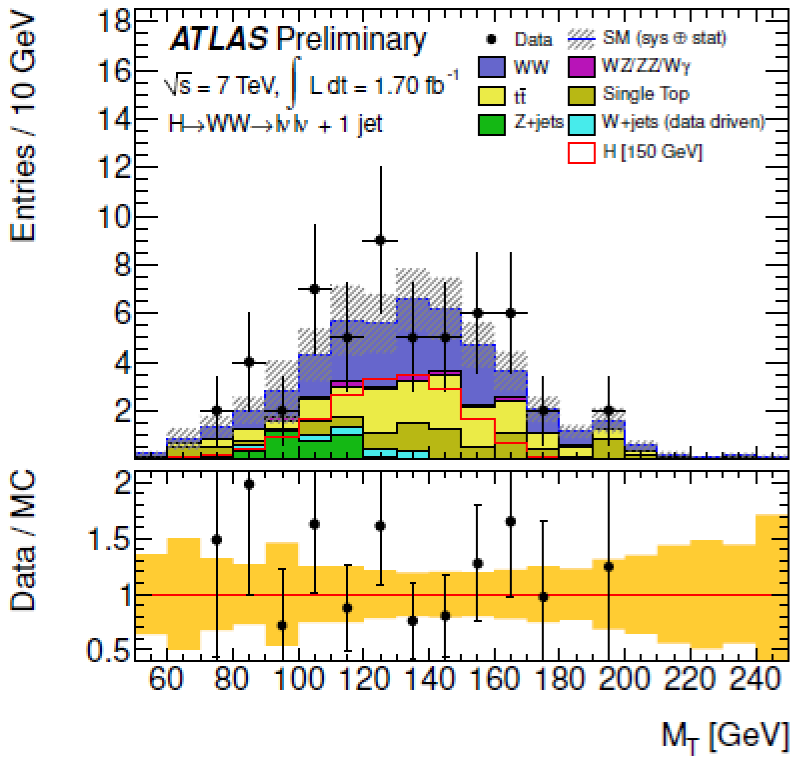
H → γγ



H → ZZ$^{(*)}$ → 4 leptons

An example of 'difficult' search channel (no peak, counting experiment)



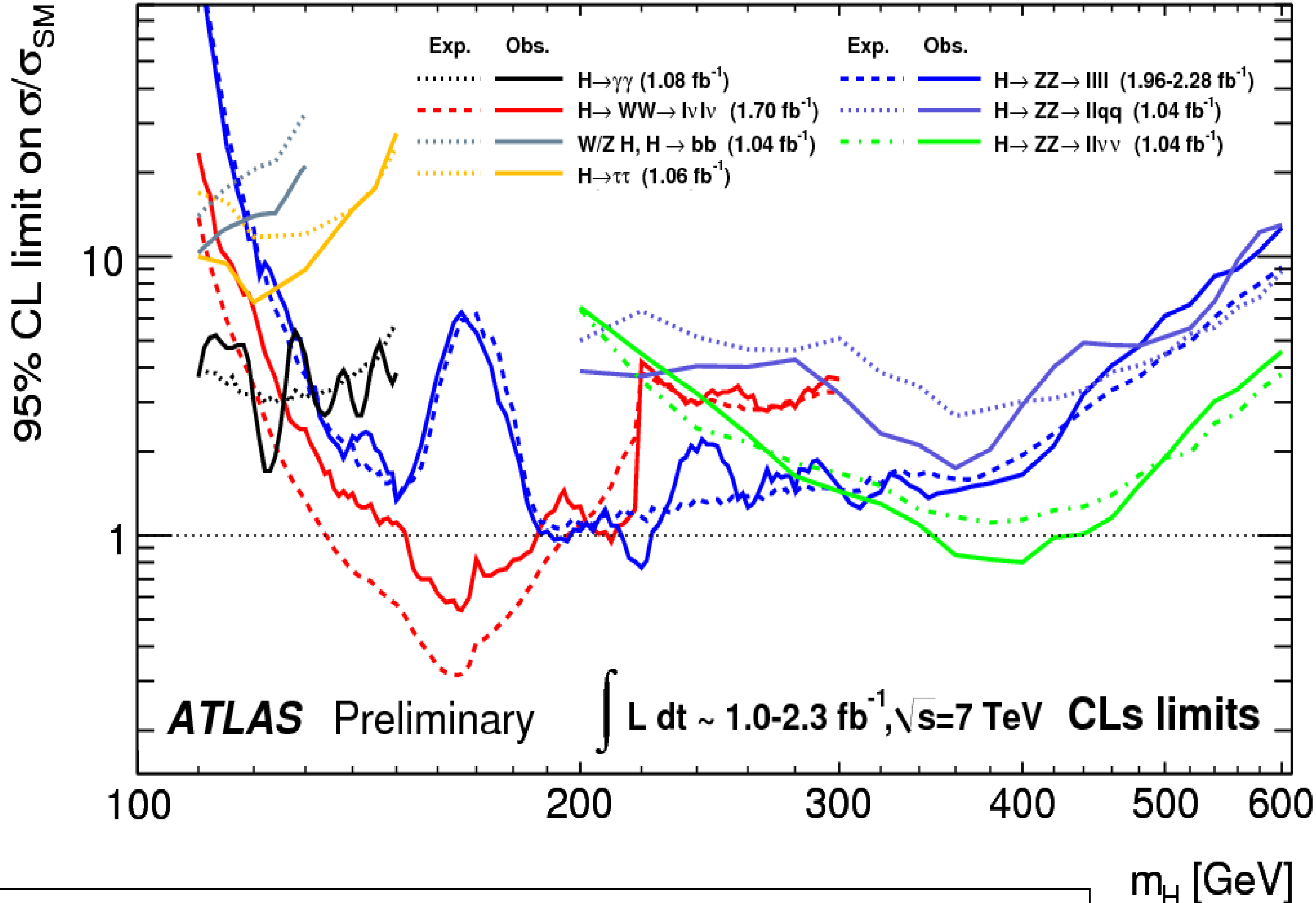


	WW	ttbar	Total SM back.	Data	Higgs m_H=150
0-jet	43±6	2.2±1.4	53±9	70	34±7
1-jet	10±2	6.9±1.9	23±4	23	12±3

H → WW(*) → lν lν

(l = e or μ)

ATLAS-CONF-2011-135

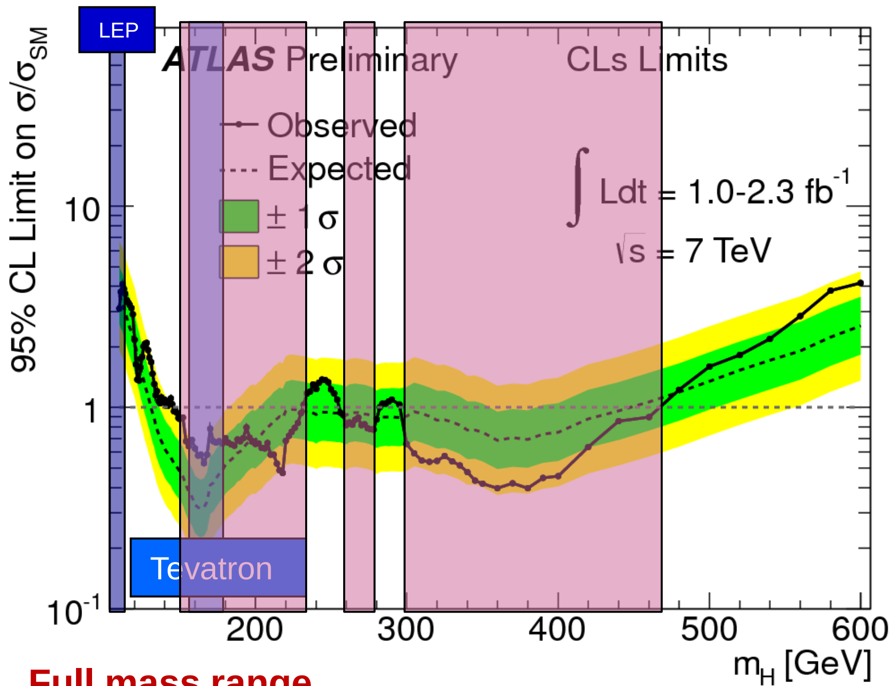


H→ γγ	: most sensitive channel $m_H \leq 120$ GeV
H→ $WW^{(*)}$→ lvlv	: most sensitive channel $130 \leq m_H < 180$ GeV
H→ $ZZ^{(*)}$ → 4l	: most sensitive channel $180 \leq m_H \leq 300$ GeV and most convincing channel down to ~ 130 GeV
H→ ZZ→ llvv	: most sensitive channel $300 < m_H \leq 600$ GeV

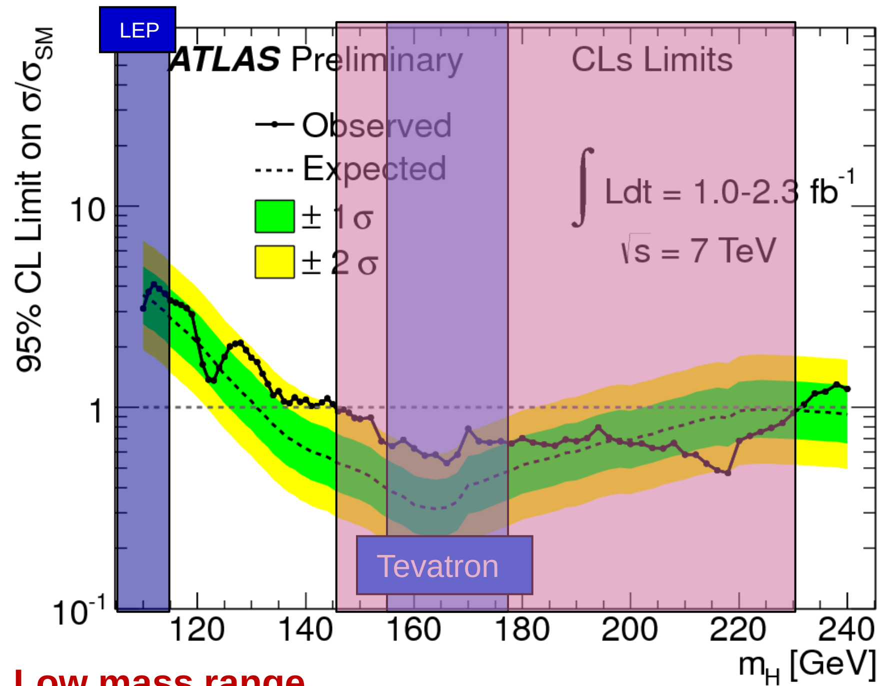
ATLAS-CONF-2011-135

Combination of all channels in ATLAS

ATLAS-CONF-2011-135



Full mass range

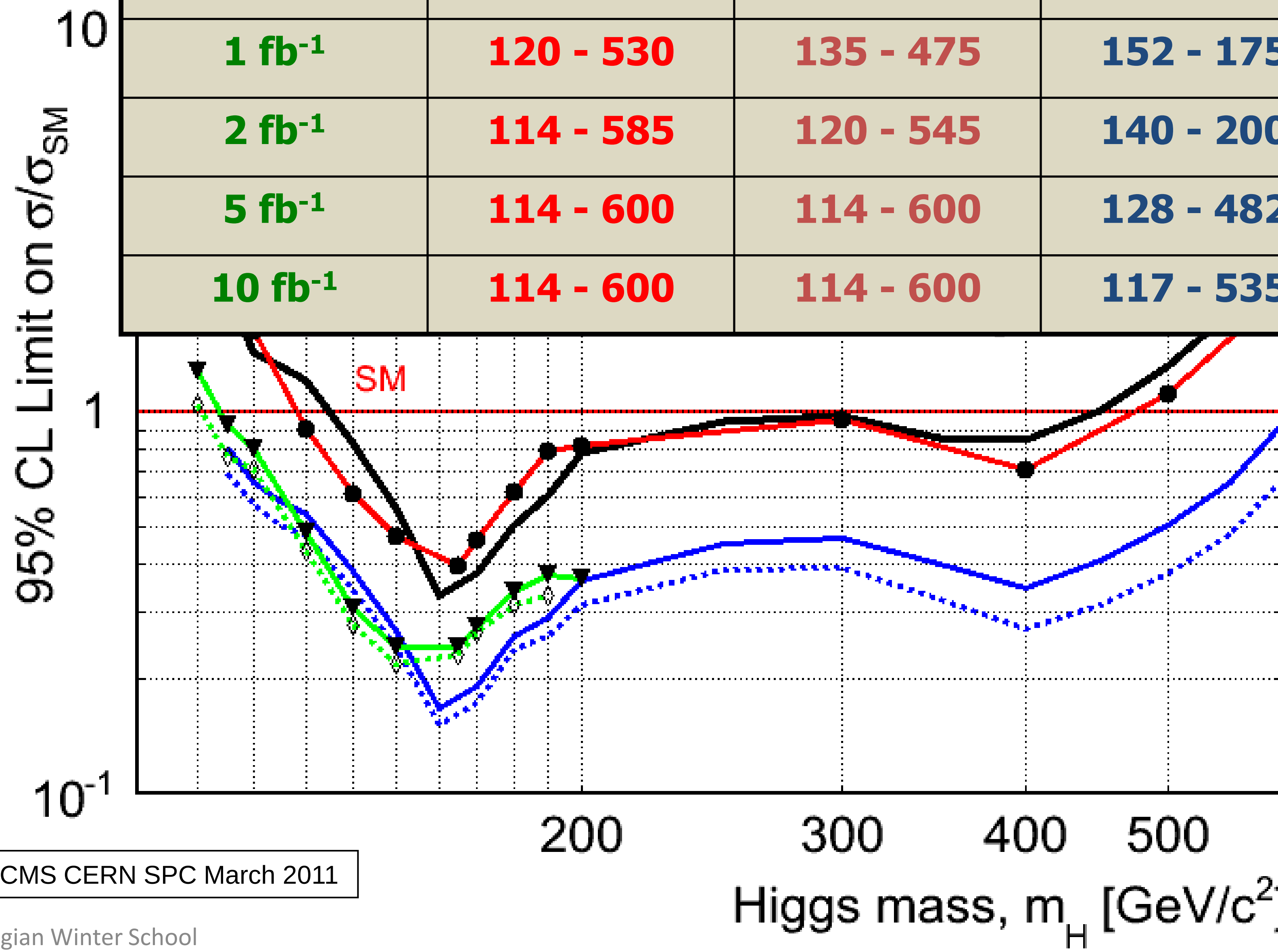


Low mass range

Excluded by ATLAS at 95% CL : 146-466 GeV, except 232-256, 282-296 GeV
Expected if no signal at 95% CL : 131-447 GeV

- ❑ **The best-motivated low-mass region (EW fit: m_H < 161 GeV 95% CL) still open to exploration**
- ❑ **Data are today within ±2σ of expectation for no signal → no significant excess**

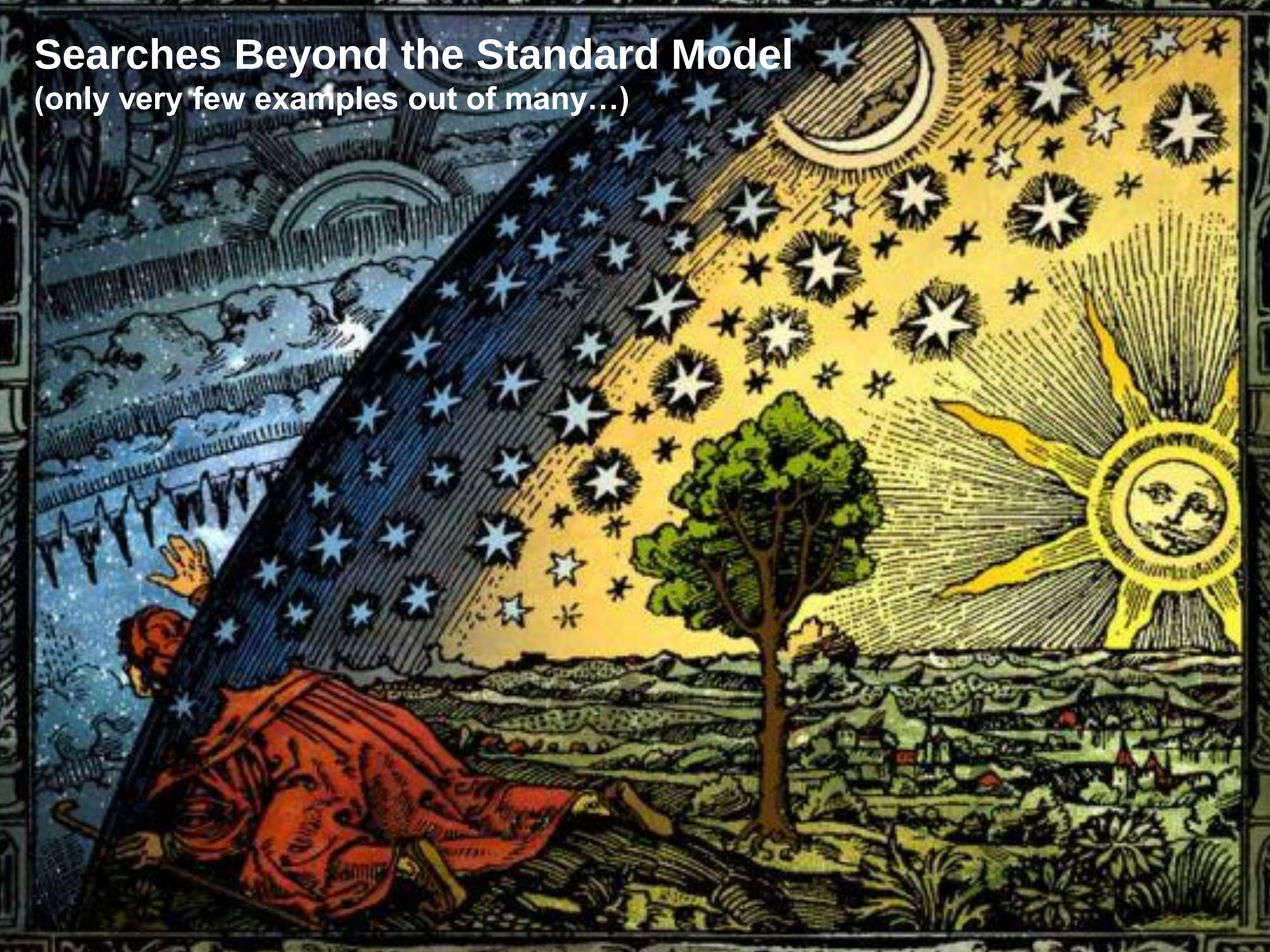
ATLAS+CMS 7 TeV	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535

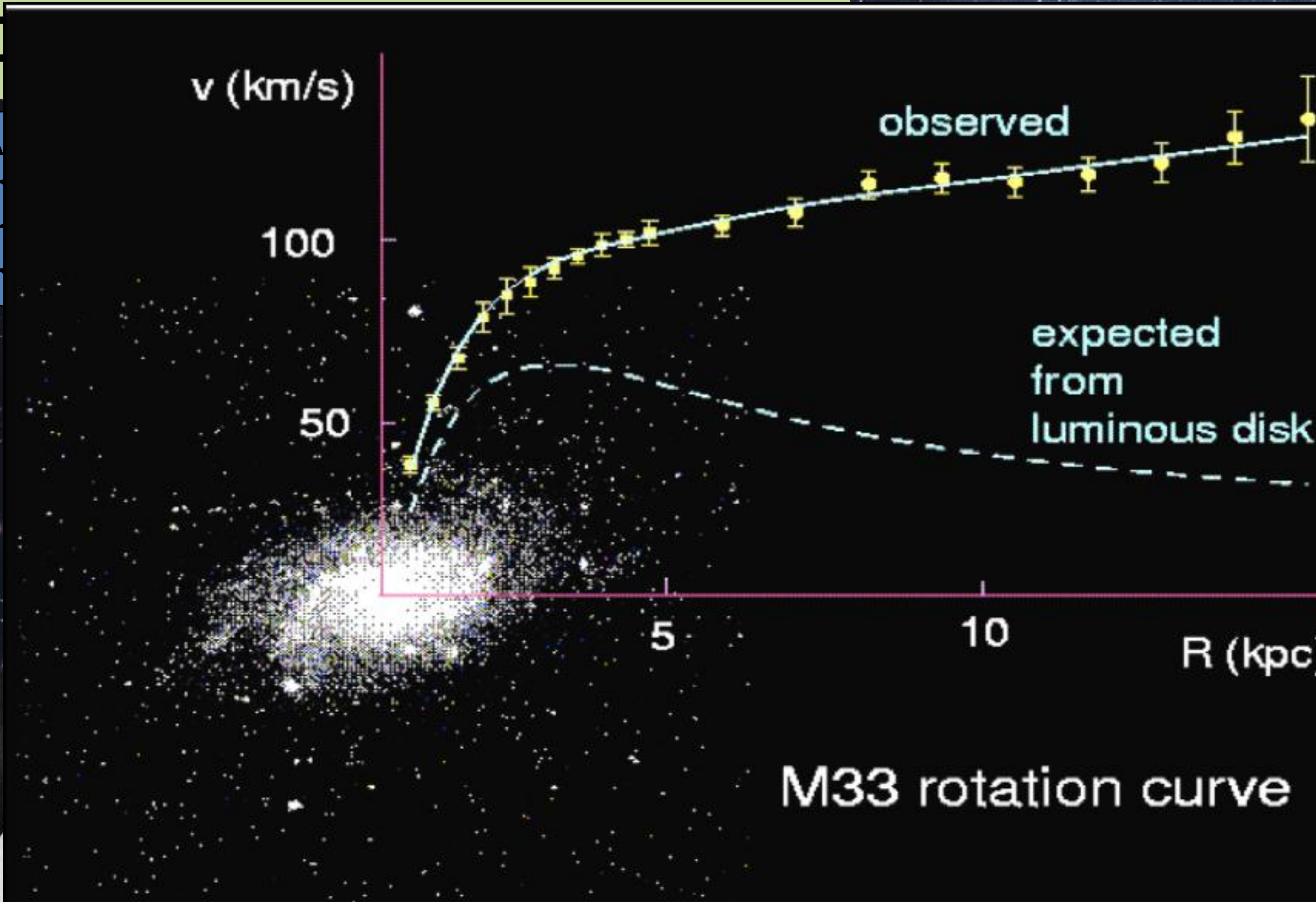


ATLAS+CMS CERN SPC March 2011

Searches Beyond the Standard Model

(only very few examples out of many…)

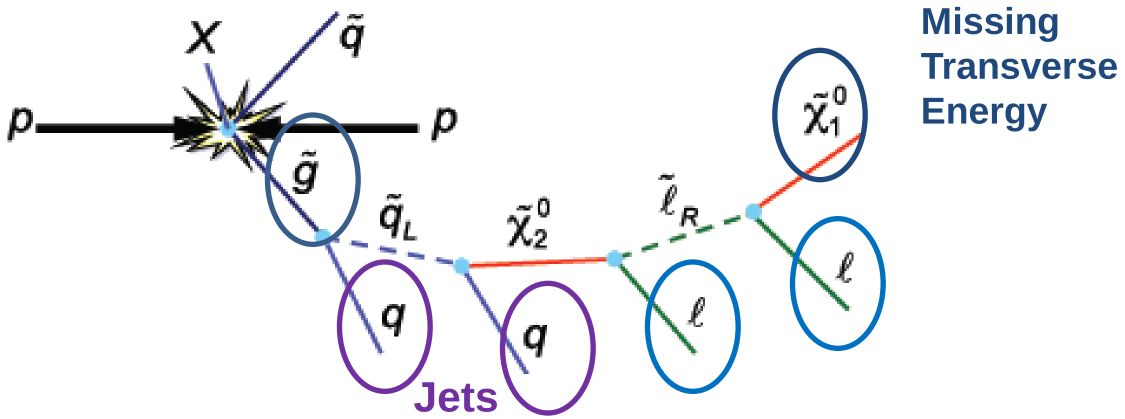




F. Zwicky 1898-1974

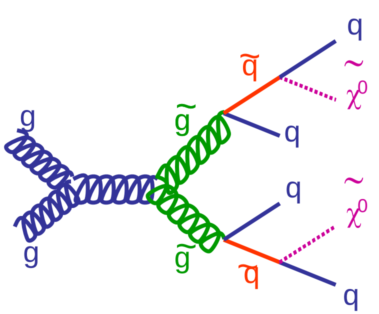
In practice the SUSY searches at LHC are rather complicated

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



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

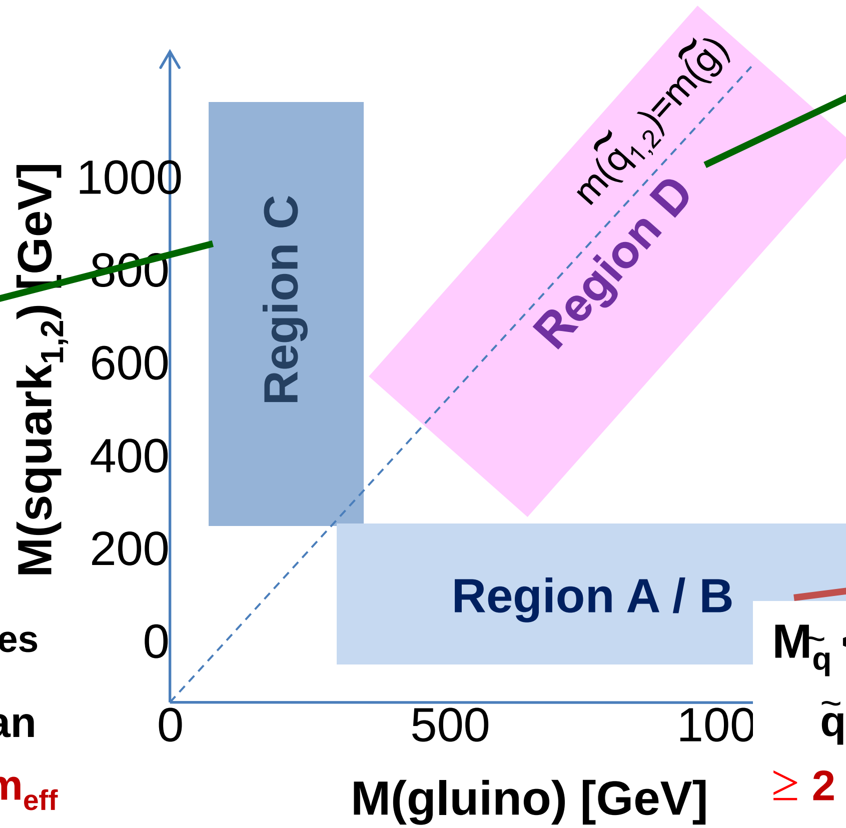
Signal regions sensitivity

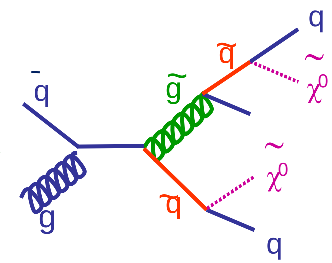


$M_{\tilde{q}} > M_{\tilde{g}}$

$\tilde{g}\tilde{g}$ production dominates

≥4 jets expected, 1 can be soft, selection in m_{eff}

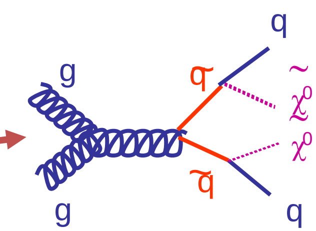




$M_{\tilde{q}} \sim M_{\tilde{g}}$

$\tilde{q}\tilde{g}$ production dominates

≥ 3 jets expected, high m_{eff}



$M_{\tilde{q}} < M_{\tilde{g}}$

$\tilde{q}\tilde{q}$ production dominates

≥ 2 jets expected

m_{eff} or m_{T2} selection

→ for high(B) / low(A) masses

→ exploit dependence in $\Delta M(\tilde{q}_{1,2}-\tilde{\chi}_0^1)$

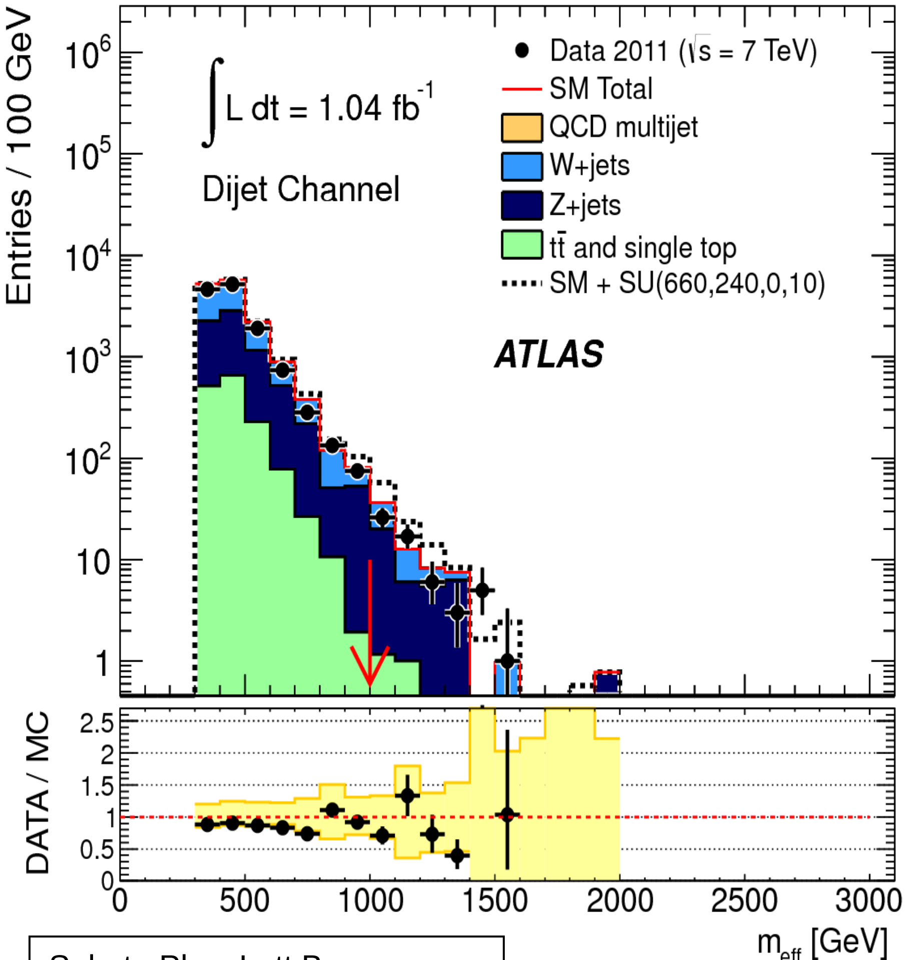
m_{eff} scalar sum pT
m_{T2} transverse mass variable

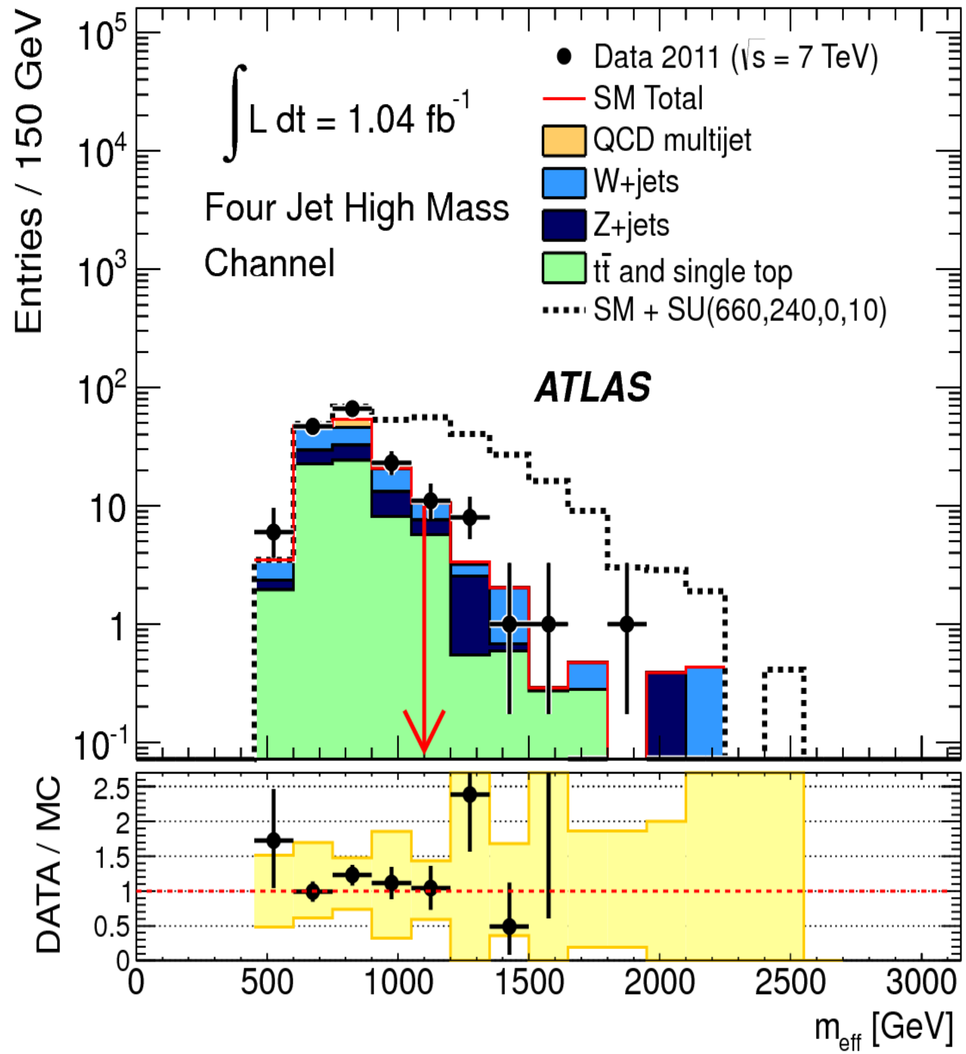
Just as an example:

SUSY in 0-lepton channel

Multi-jet plus E_T^{miss}, e/μ veto

(no SUSY signal excess over backgrounds in low and high jet multiplicity events)

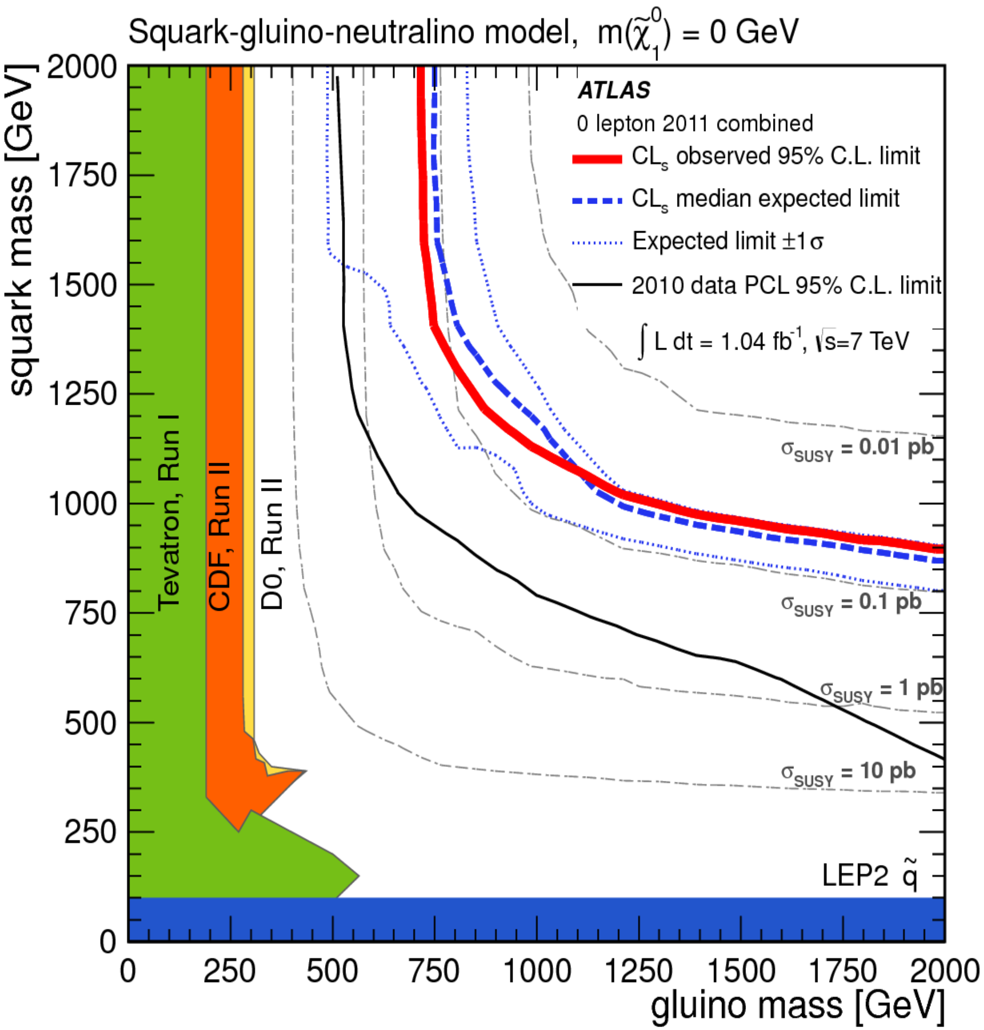


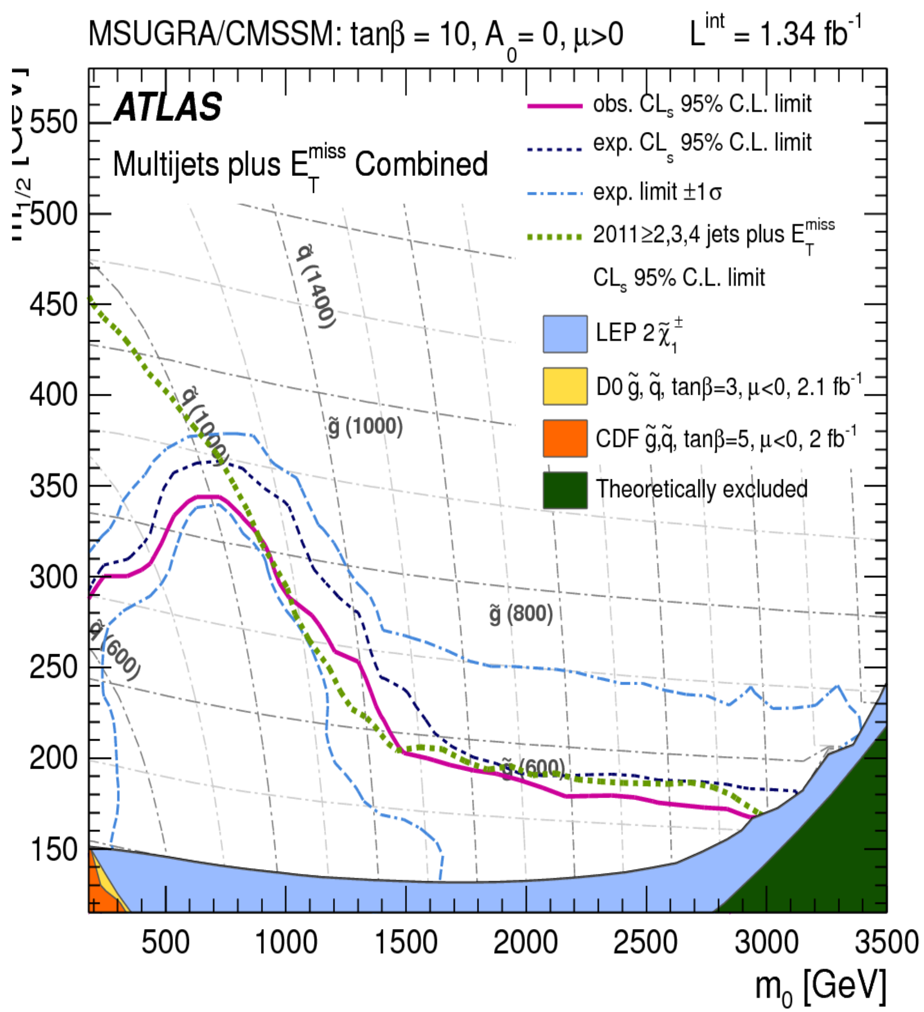


Sub. to Phys Lett B
arXiv:1109.6572v1[hep-ex]

m_{eff} = scalar sum (E_T miss + all jet E_T)

Sample ATLAS SUSY exclusion limits

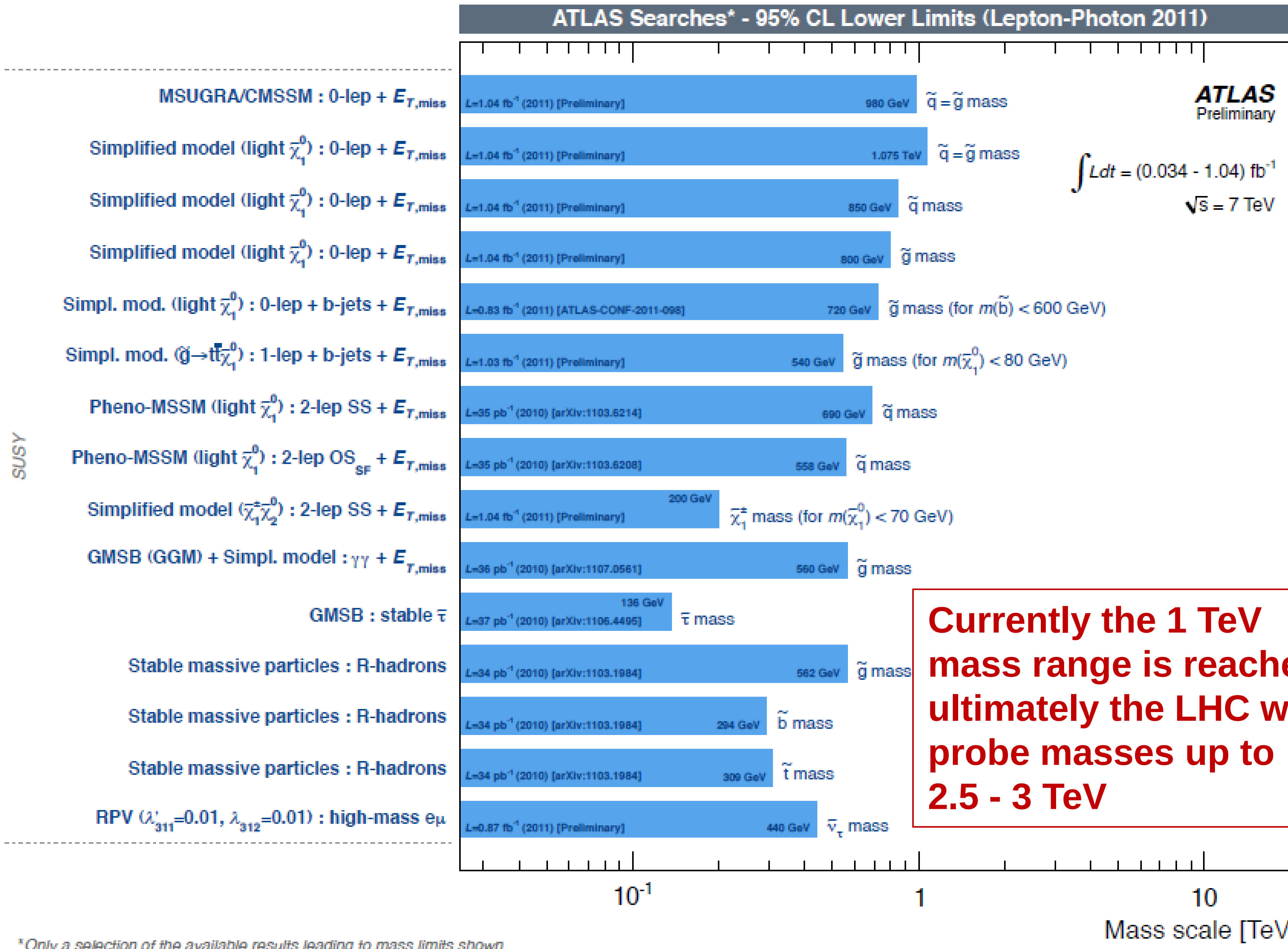




Simplified model with two q generations, $m(\chi_1^0)$~0
m_g>800 GeV, m_q>850 GeV (valid for m_{LSP} < 200 GeV)
Equal mass case: $m_g=m_q$>1.075 TeV

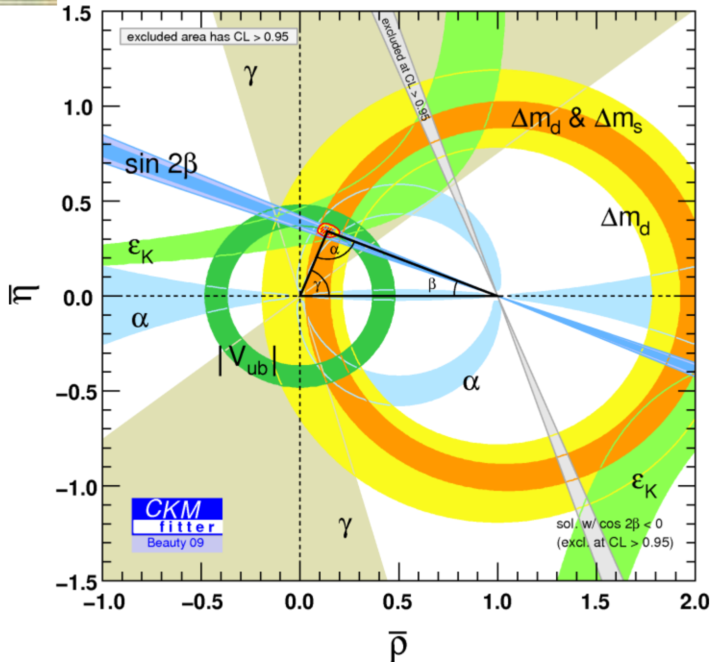
Sub. to Phys Lett B
arXiv:1109.6572v1[hep-ex]

A non-exhaustive summary of current SUSY limits (CMS has similar limits)



Currently the 1 TeV mass range is reached, ultimately the LHC will probe masses up to 2.5 - 3 TeV

Early hints of news from 'Beyond the Standard Model' may come from 'beautiful' flavour physics...

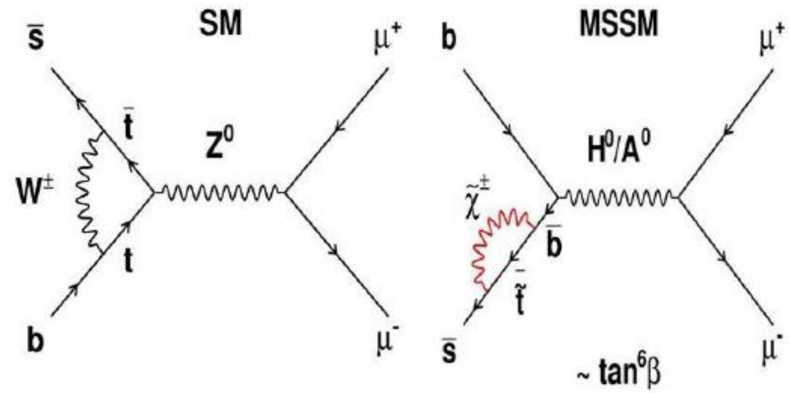


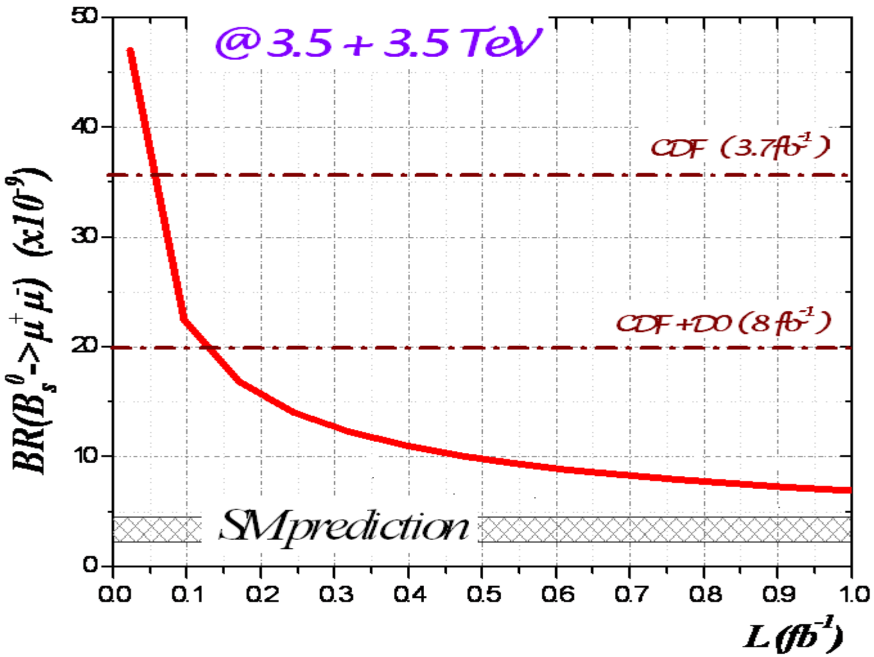
Search for $B \rightarrow \mu^+\mu^-$

Very rare and golden FCNC b→d,s transition

Mode	SM
$B_s \rightarrow \mu^+\mu^-$	$3.2 \pm 0.2\ 10^{-9}$
$B^0 \rightarrow \mu^+\mu^-$	$0.10 \pm 0.01\ 10^{-9}$

A.J.Buras: arXiv:1012.1447
E. Gamiz et al: Phys.Rev.D 80 (2009) 014503





Strongly enhanced in MSSM

$$B\left(B_s \rightarrow \mu^+\mu^-\right) \propto \frac{\tan^6 \beta}{M_A^4}$$

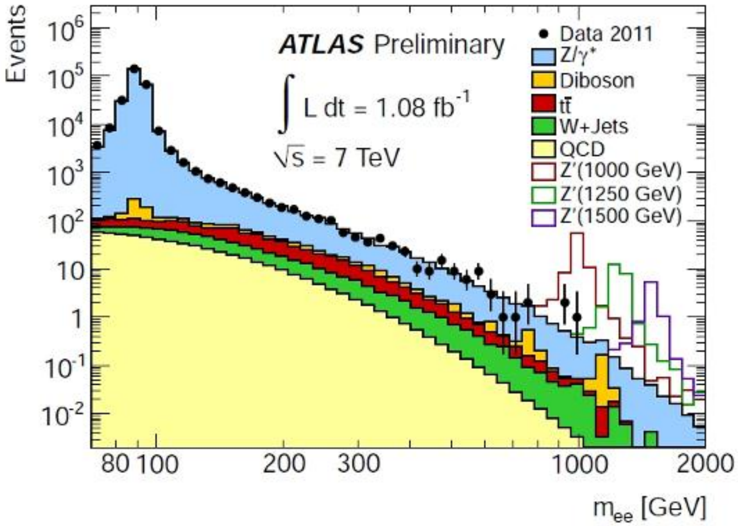
Best 9% CL B_s limits reported at EPS-2011

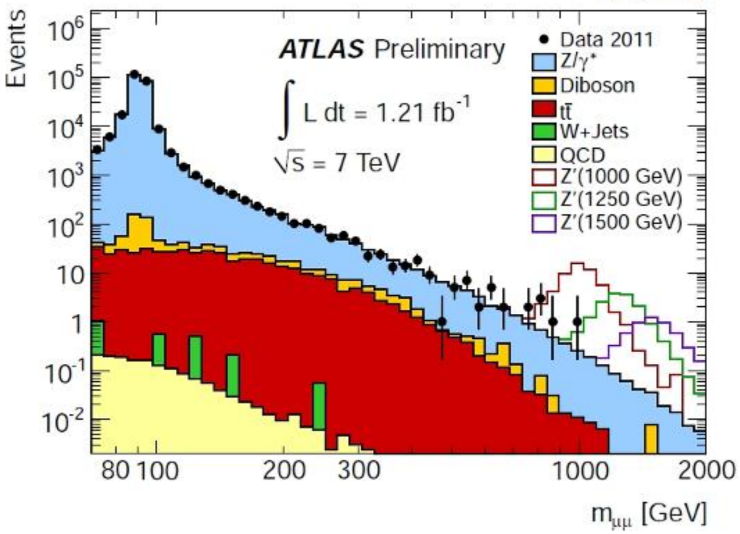
LHCb	BR < 1.5 10^{-8} (300 pb^{-1})
CMS	BR < 1.9 10^{-8} (1.14 fb^{-1})
Combined	BR < 1.08 10^{-8}

LHCb-CONF-2011-047
CMS-PAS-BPH-11-019

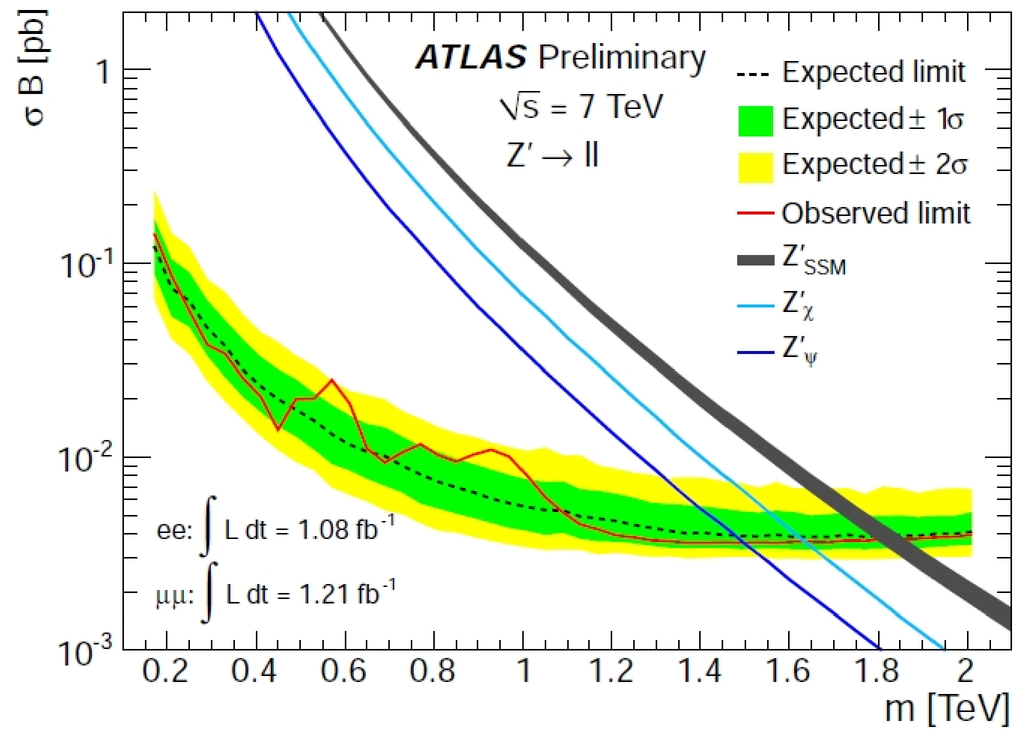
Searches for heavy W and Z like particles

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





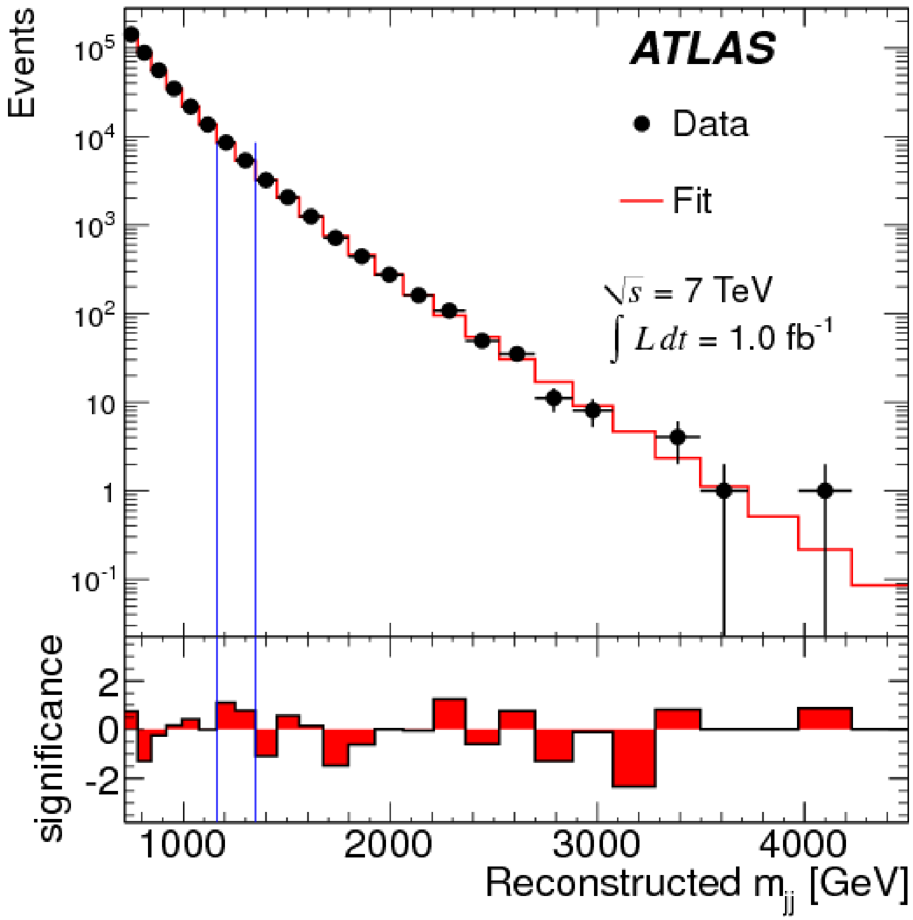
Sub. to Phys Rev Lett
arXiv:1108.1582v1[hep-ex]

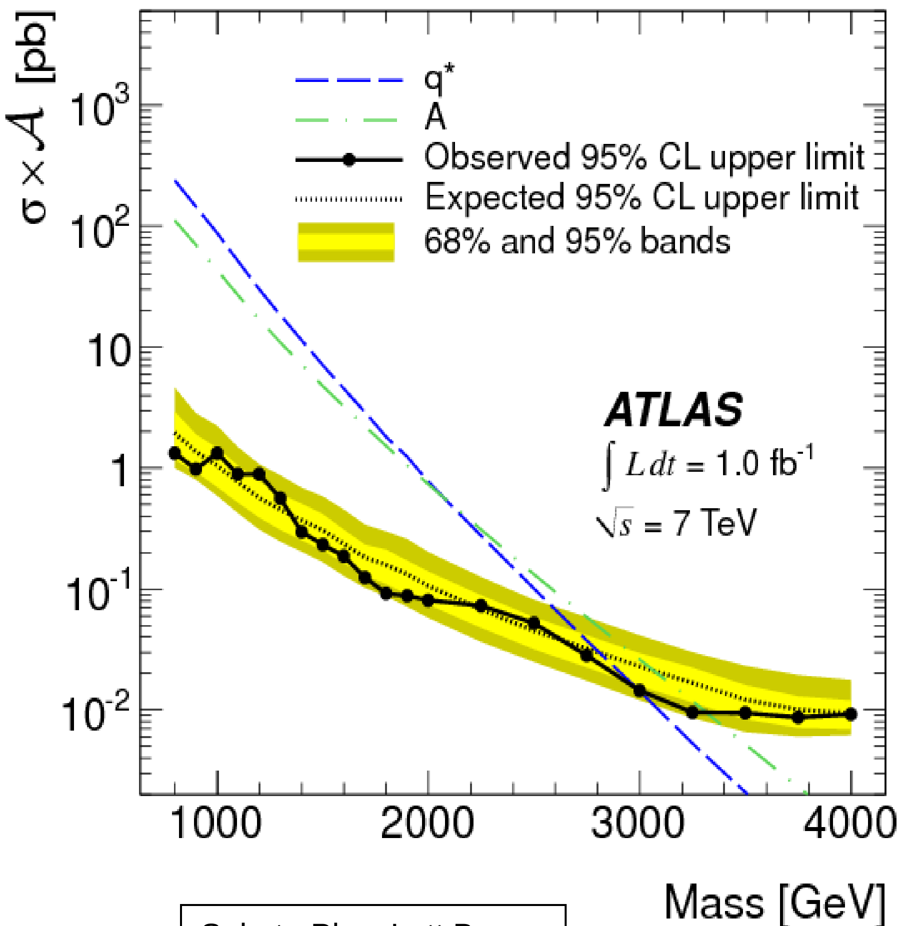


Ultimately the reach of such searches will probe masses beyond 5 TeV

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

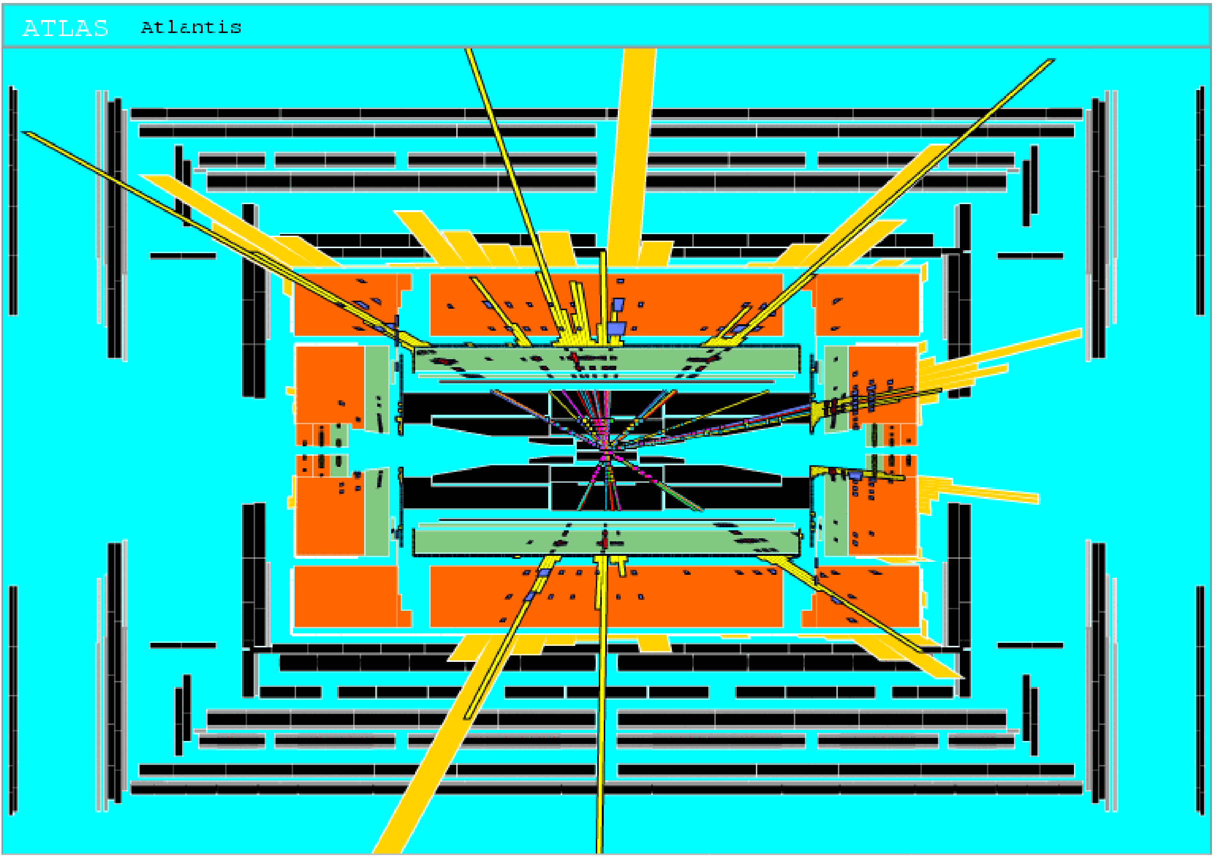
Search for resonances in the di-jet mass spectrum





Sub. to Phys Lett B
arXiv:1108.6311[hep-ex]

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

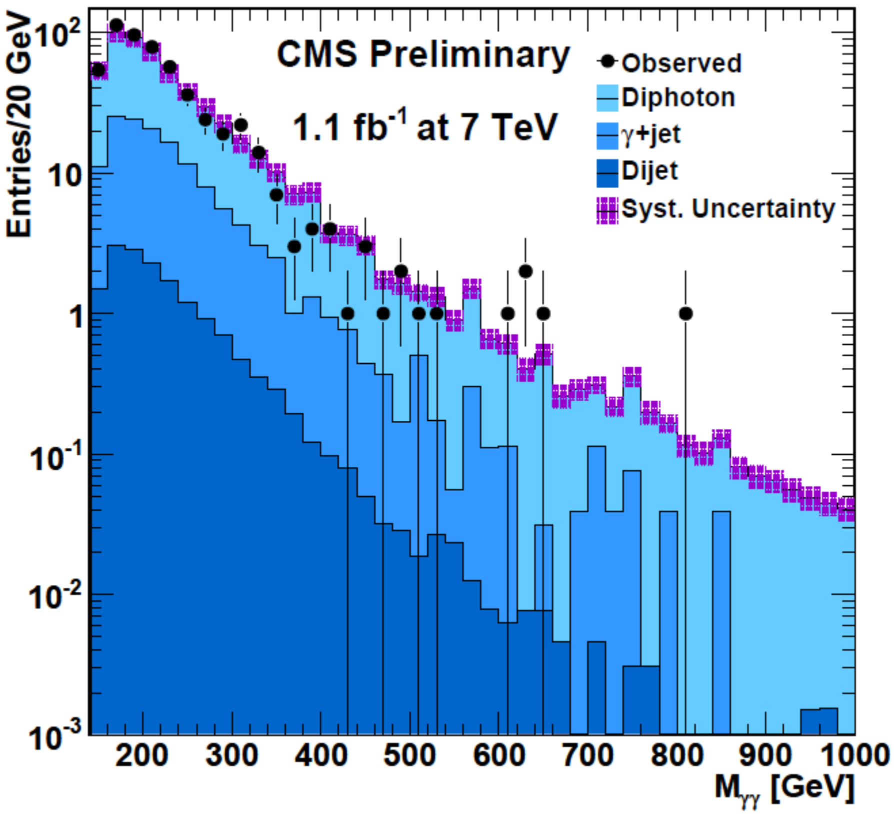


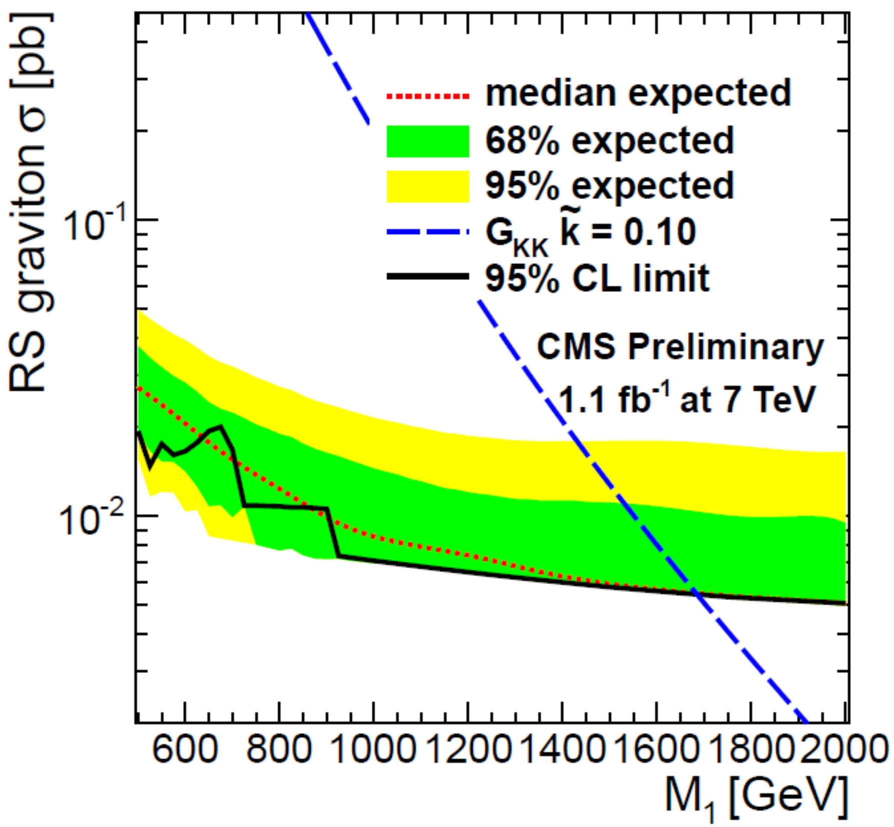
Simulation of a black hole event with M_{BH} ~ 8 TeV in ATLAS

They decay immediately through Stephen Hawking radiation

A CMS example of searches for New Physics as deviations from QCD behaviour in the di-photon distribution

Randall-Sundrum KK graviton excitation

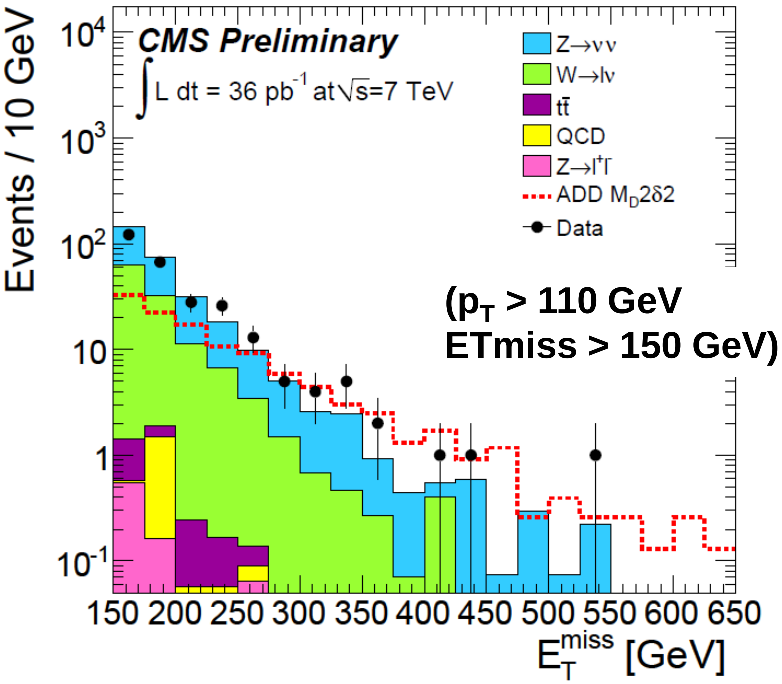




CMS-PAS-EXO-11-038

Two more examples of exotic signatures

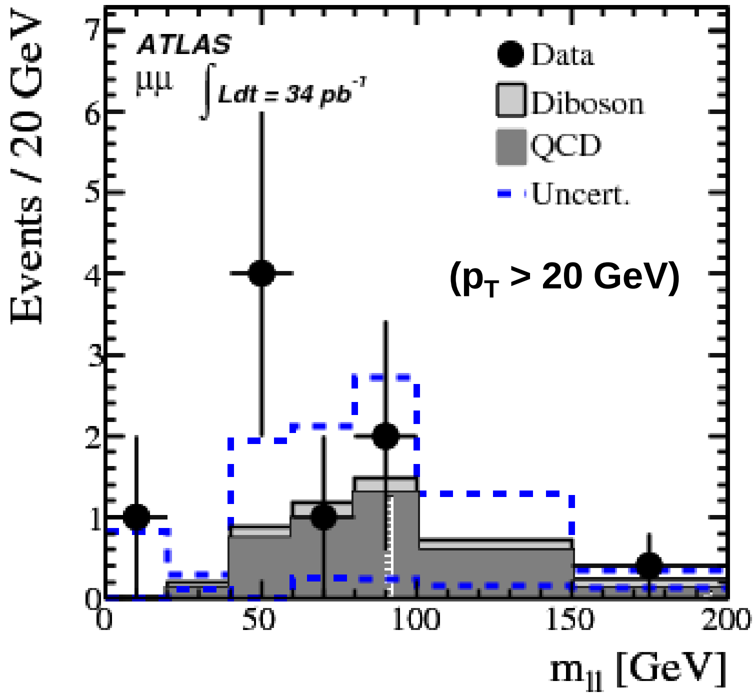
Mono-jet plus missing E_T



Such signature could occur in models:
- -Large Extra Dimensions (ADD)
- -Unparticle
- -Split SUSY
- -Dark Matter
- -…

Sub. to Phys Rev Lett
arXiv:1106.4775[hep-ex]

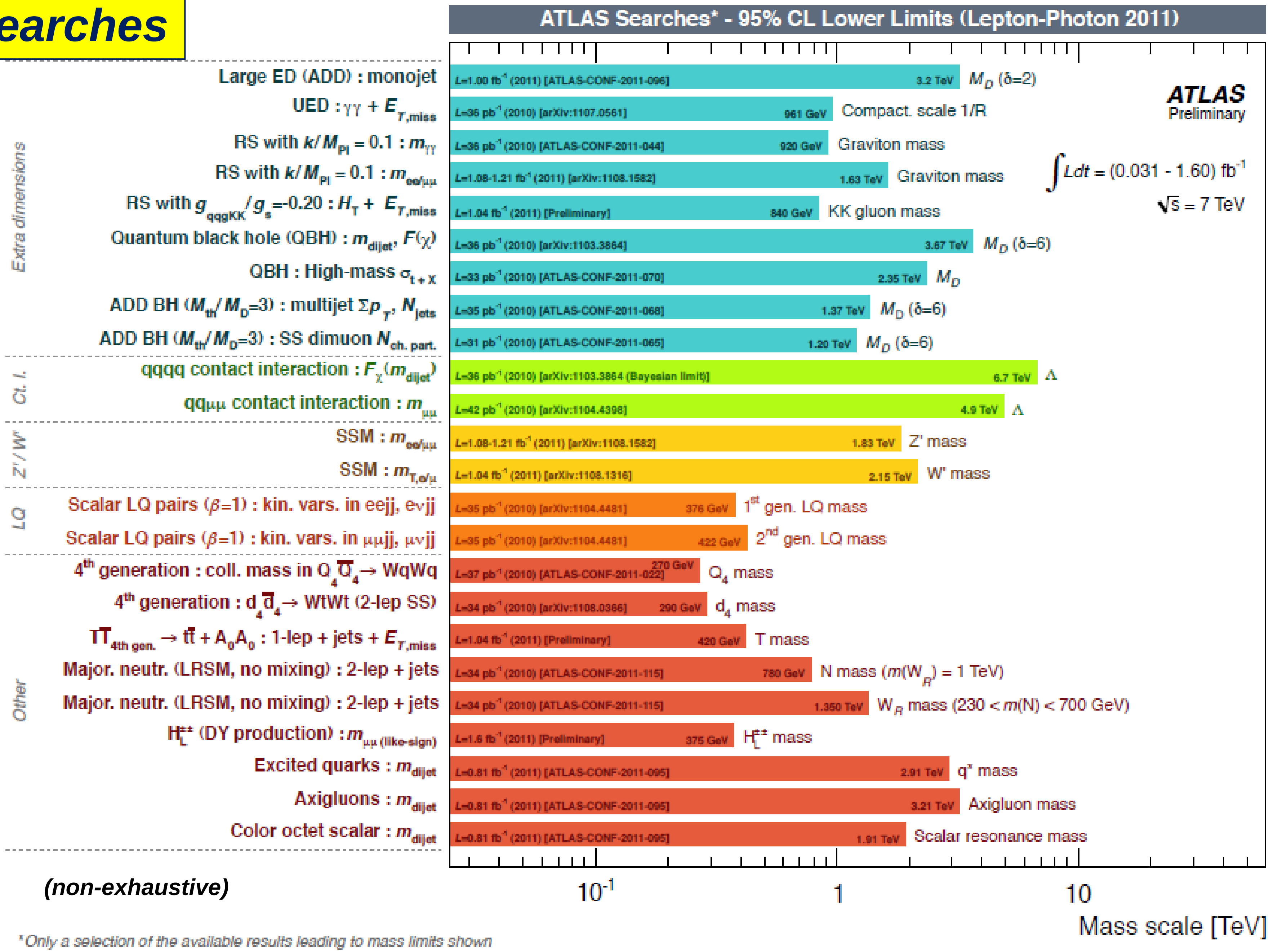
Same-sign di-leptons



Such signature could occur in models:
- -Majorana neutrinos
- -Universal Extra Dimensions
- -4^{th} generation quarks
- -…

Sub. to JHEP
arXiv:1108.0366v1[hep-ex]

Searches



(non-exhaustive)

Note that all public results from CMS and ATLAS are available at:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Exciting times are ahead of us!

Thank You!

Spares

CERN was founded 1954: 12 European States

"Science for Peace"

Today: 20 Member States

~ 2300 staff
~ 930 other paid personnel
> 10500 users
Budget (2011) ~1000 MCHF

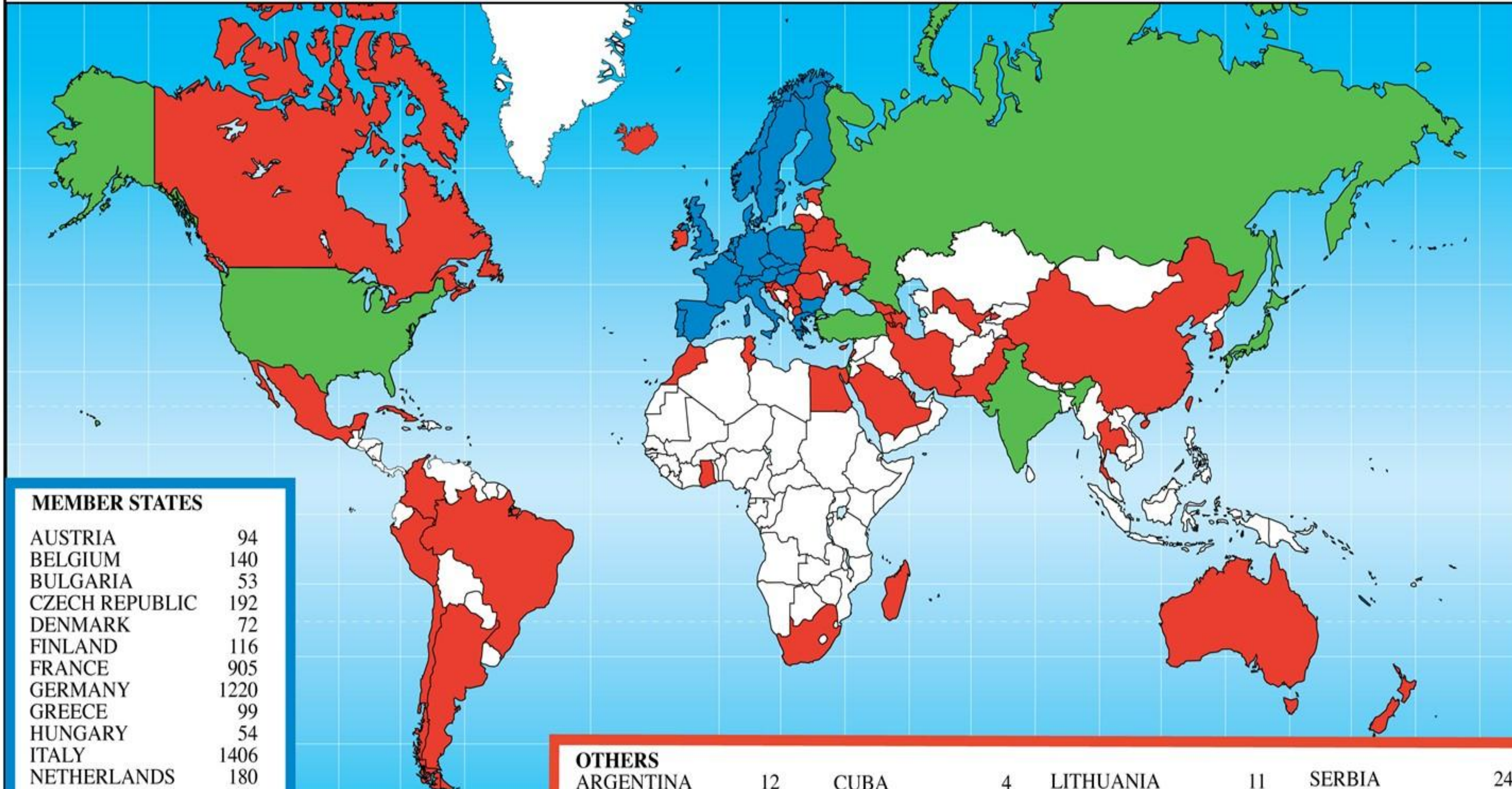
5 applicants for MS:
Cyprus, Israel, Serbia, Slovenia, Turkey
and **Associate Membership** discussions: Brazil, Ukraine, India, ...

20 Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

1 Candidate for Accession: Romania

8 Observers to Council: India, Israel, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and UNESCO

Distribution of All CERN Users by Nation of Institute on 27 June 2011



MEMBER STATES

AUSTRIA	94
BELGIUM	140
BULGARIA	53
CZECH REPUBLIC	192
DENMARK	72
FINLAND	116
FRANCE	905
GERMANY	1220
GREECE	99
HUNGARY	54
ITALY	1406
NETHERLANDS	180
NORWAY	93
POLAND	205
PORTUGAL	141
SLOVAKIA	63
SPAIN	339
SWEDEN	79
SWITZERLAND	359
UNITED KINGDOM	732

6542

OBSERVER STATES

INDIA	109
ISRAEL	60
JAPAN	190
RUSSIA	822
TURKEY	79
USA	1786

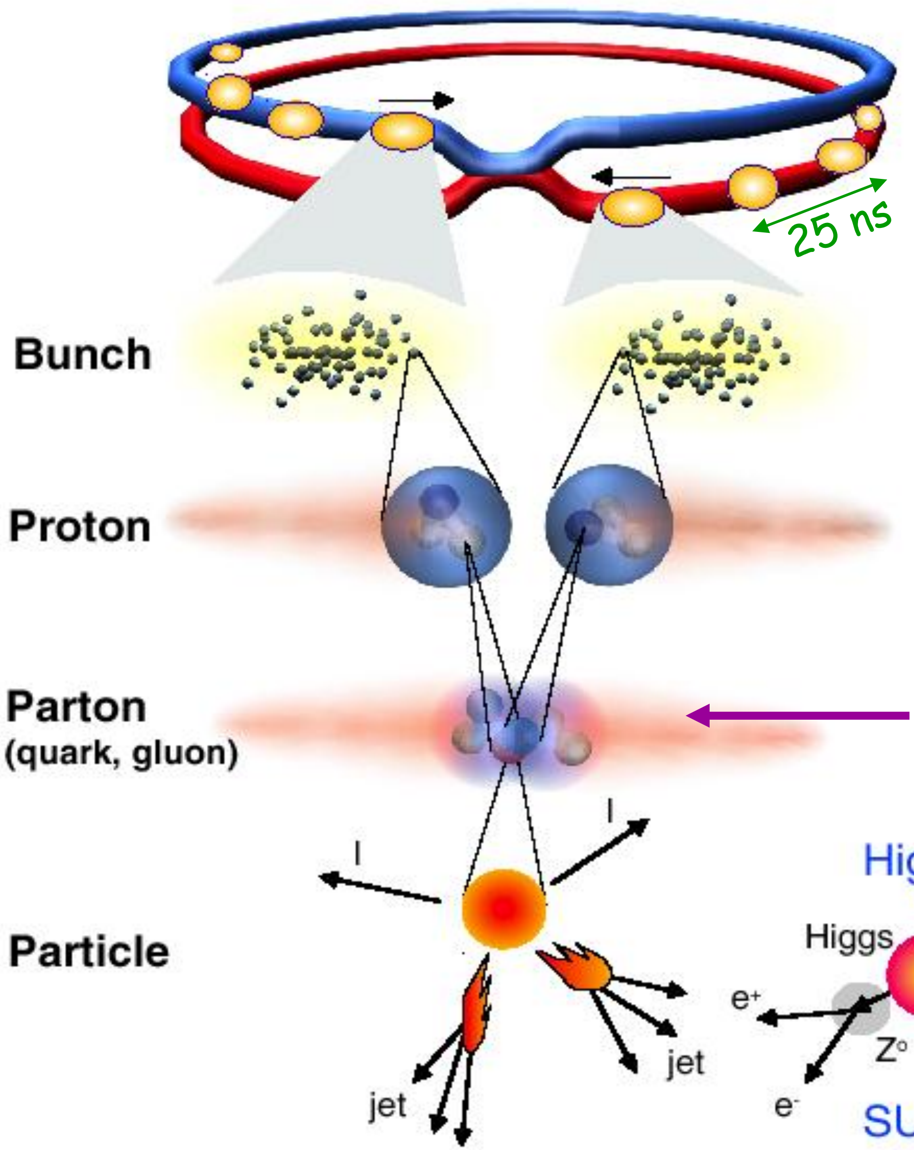
3046

OTHERS

ARGENTINA	12
ARMENIA	12
AUSTRALIA	22
AZERBAIJAN	1
BELARUS	19
BRAZIL	79
CANADA	160
CHILE	3
CHINA	87
CHINA (TAIPEI)	53
COLOMBIA	13
CROATIA	15
CUBA	4
CYPRUS	6
EGYPT	6
ESTONIA	18
GEORGIA	10
GHANA	1
HONG KONG	1
ICELAND	3
IRAN	15
IRELAND	13
KOREA	85
LEBANON	1
LITHUANIA	11
MADAGASCAR	1
MALTA	1
MEXICO	39
MONTENEGRO	1
MOROCCO	7
NEW ZEALAND	9
PAKISTAN	19
PERU	2
QATAR	1
ROMANIA	66
SAUDI ARABIA	2
SERBIA	24
SINGAPORE	1
SLOVENIA	31
SOUTH AFRICA	15
THAILAND	1
F.Y.R.O.M.	3
TUNISIA	1
UKRAINE	19
UZBEKISTAN	1

894

Collisions at LHC



Proton-Proton

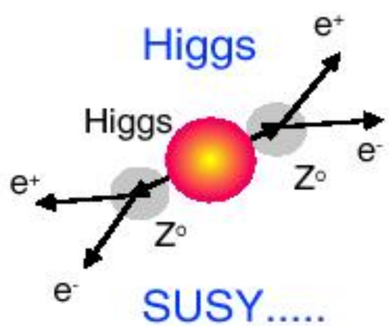
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate:

N = L x σ (pp) ≈ 10^9 interactions/s

Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare

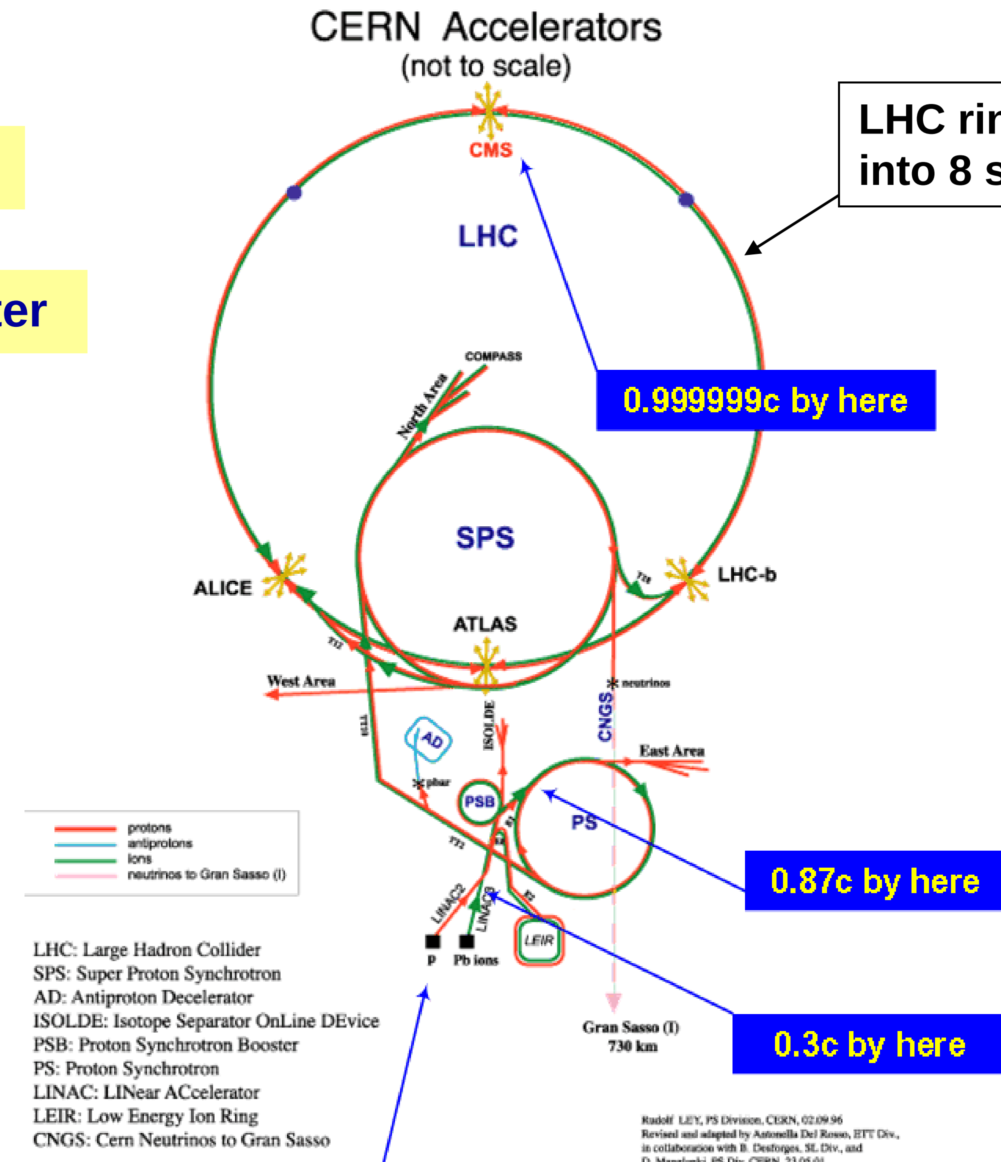


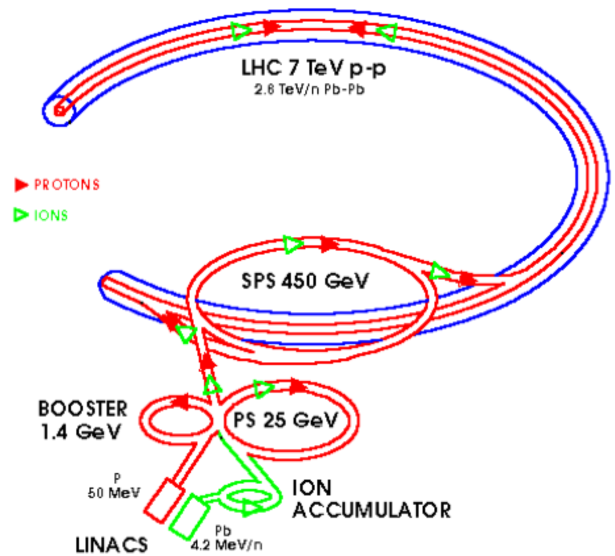
Selection of 1 in 10,000,000,000,000

→ very powerful detectors needed

The full LHC accelerator complex

Linac → Booster → PS → SPS → LHC

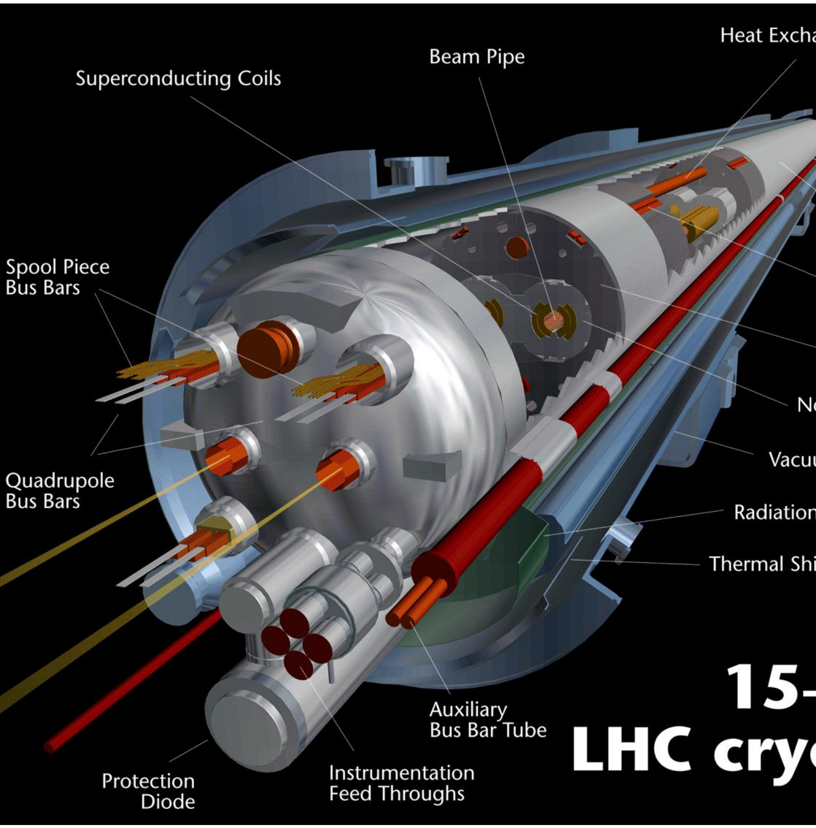


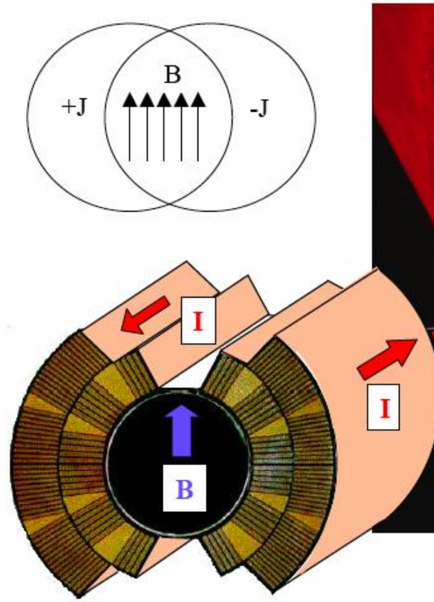


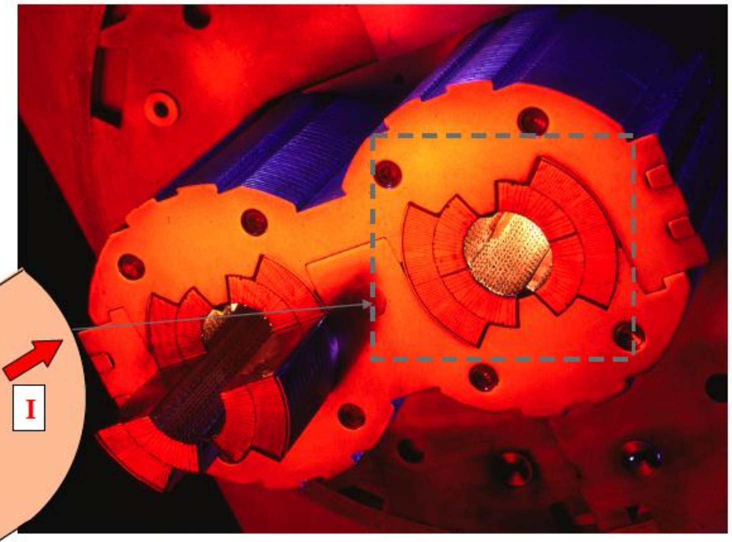
Start the protons out here

> 50 years of CERN history still alive and operational

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)

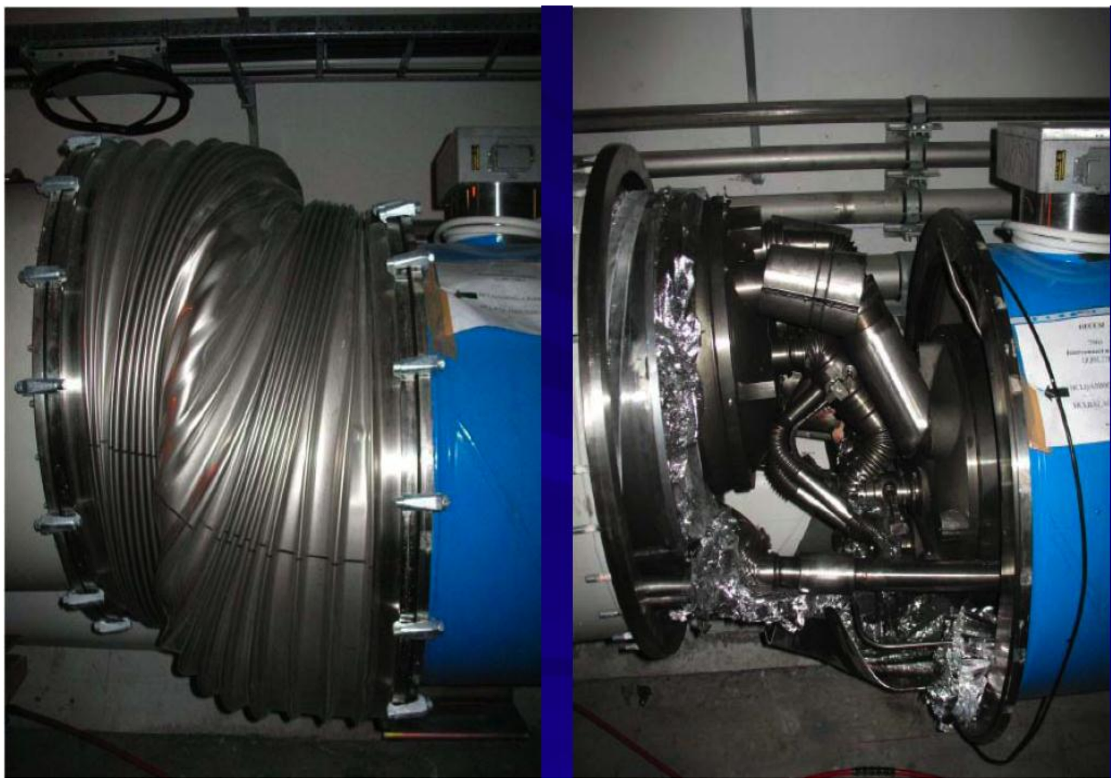
LHC magnets are cooled with pressurized superfluid helium

Examples of collateral damage after the 19th September 2008 incident

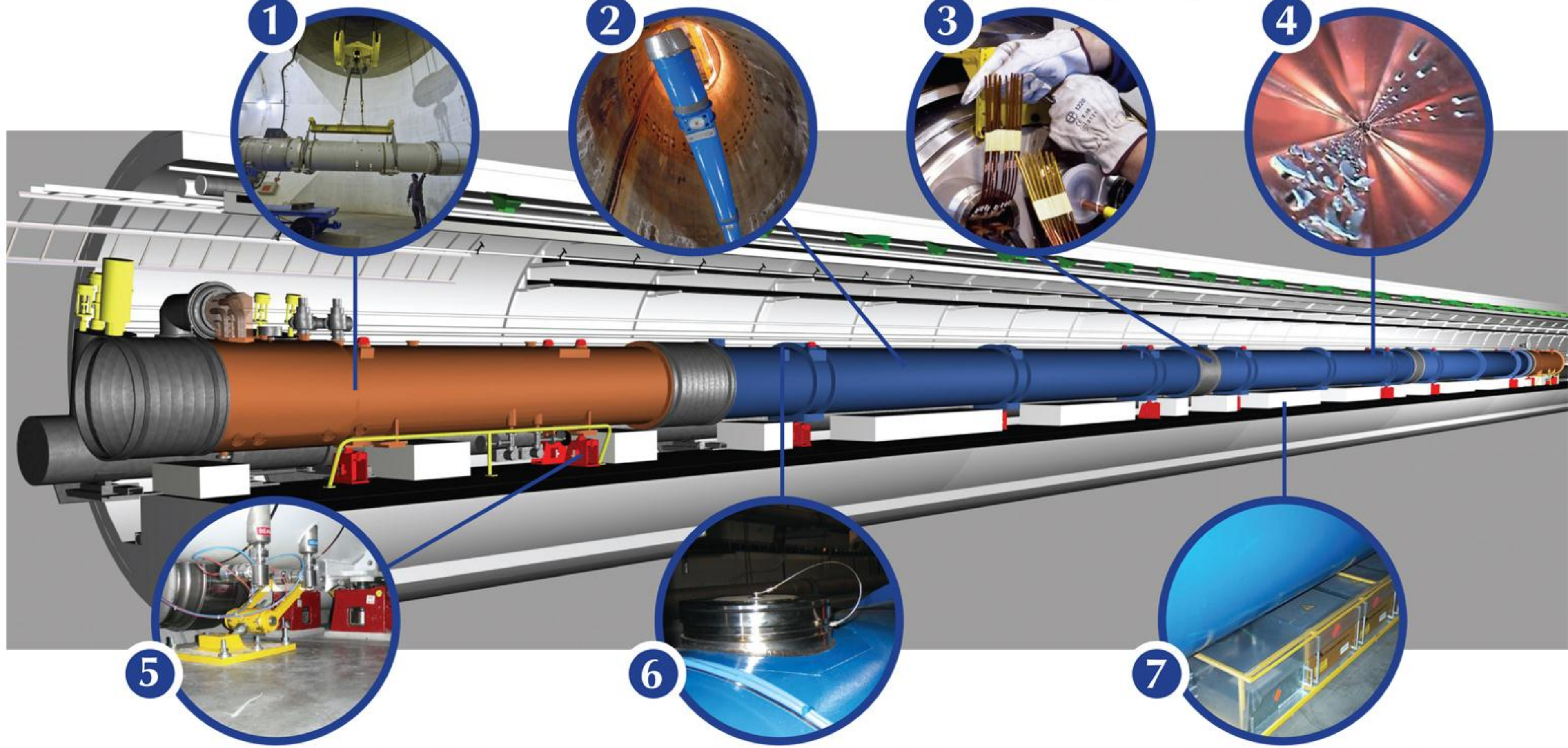
Most likely, an electrical arc developed, which punctured the Helium enclosure

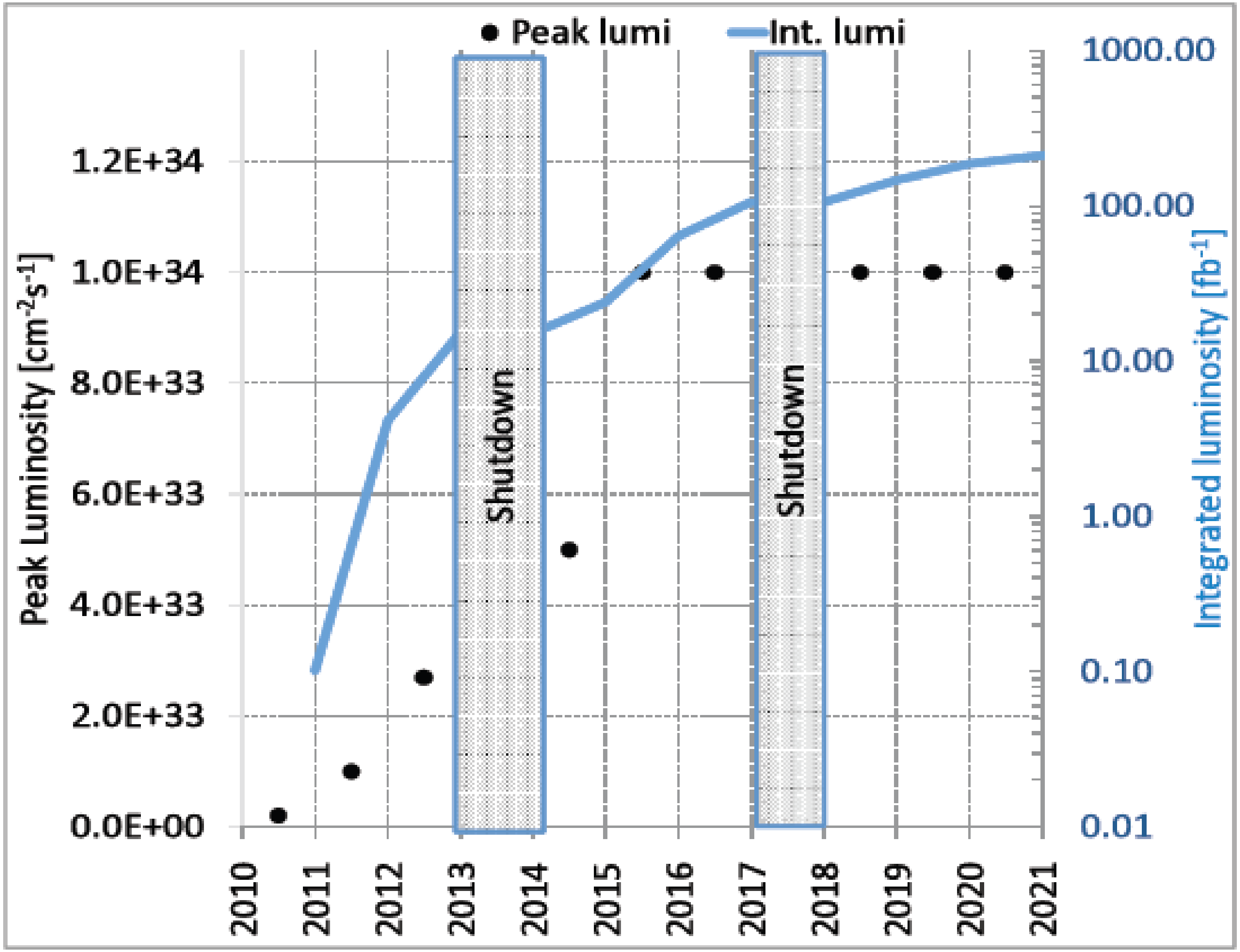
High pressure build-up damaged the magnet interconnects and the super-insulation

Perforation of the beam tubes resulted in pollution of the vacuum system with soot from the vaporization and with debris from the super insulation.



The LHC repairs in detail





Peak lumi
Int. lumi
Peak Luminosity [cm-2s-1]
Integrated luminosity [fb-1]
1.2E+34
1.0E+34
8.0E+33
6.0E+33
4.0E+33
2.0E+33
0.0E+00
1000.00
100.00
10.00
1.00
0.10
0.01
Shutdown
Shutdown
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021