Hunting for the Higgs Boson and more at the LHC

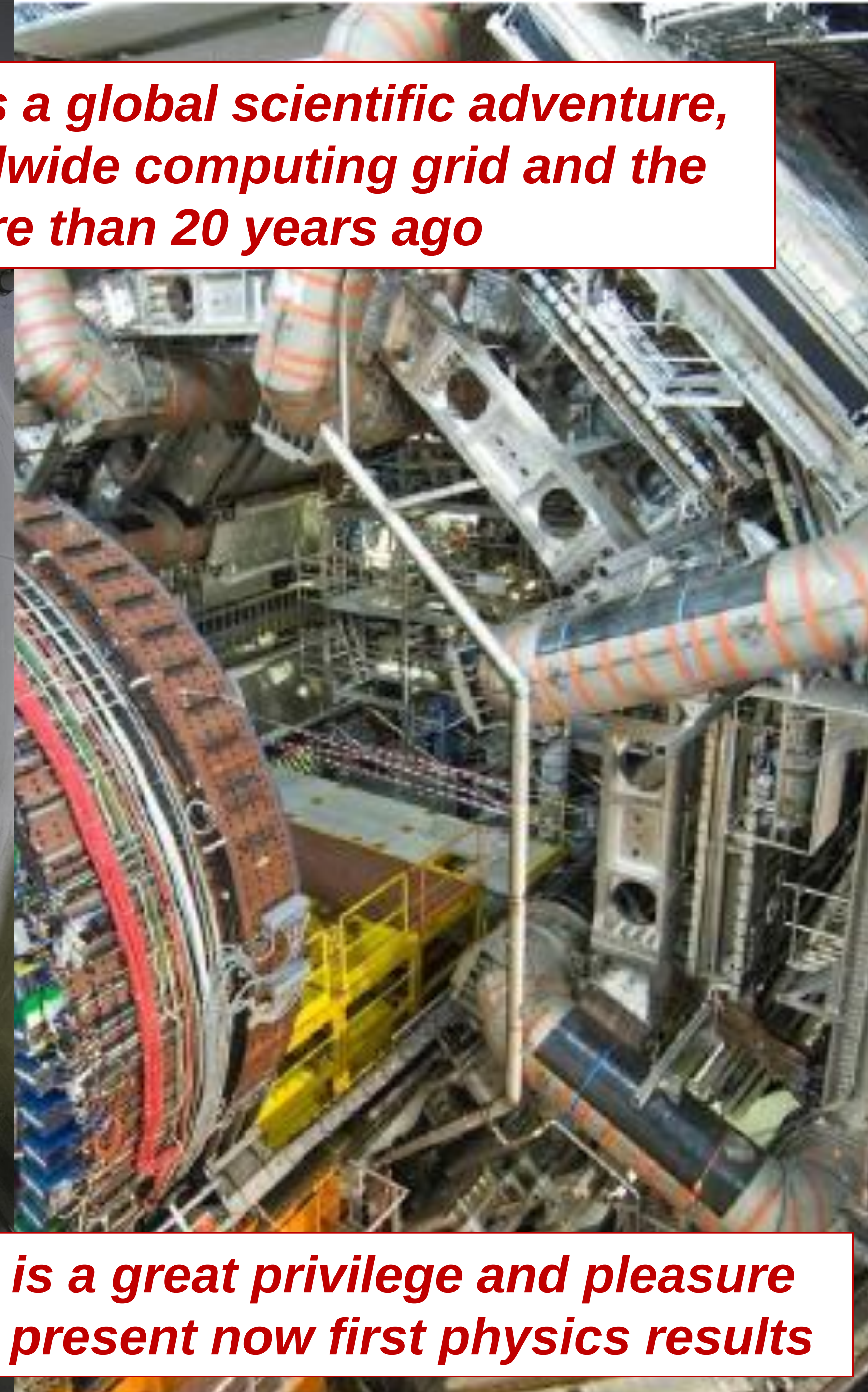
Drawing by
Sergio Cittolin

Committee for the Collaboration of the Czech Republic with CERN and the Czech Physical Society

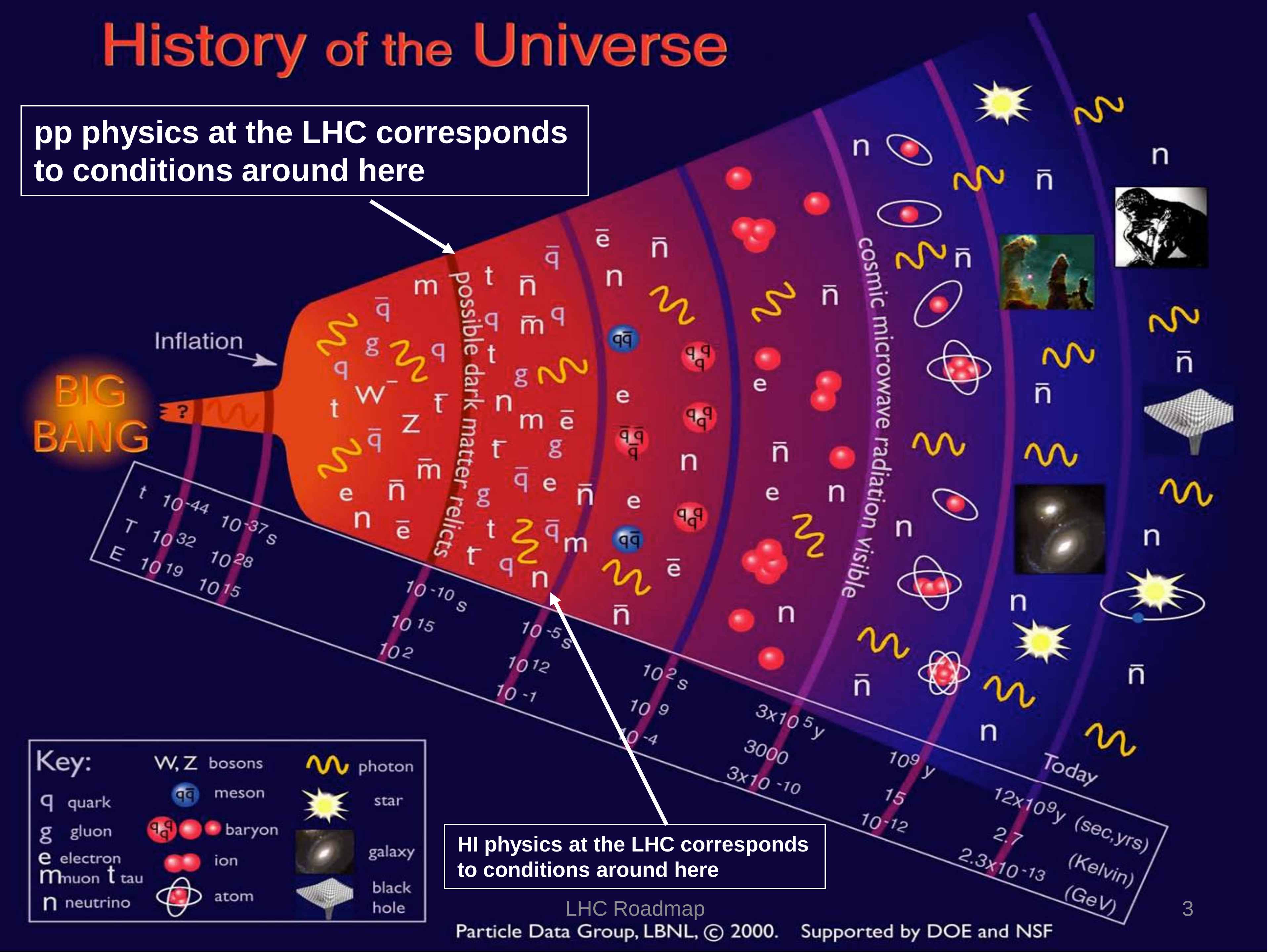
With recent results from ATLAS and CMS

Peter Jenni (CERN)
25th October 2012

The Large Hadron Collider project is a global scientific adventure, including the accelerator, the worldwide computing grid and the experiments, initiated more than 20 years ago

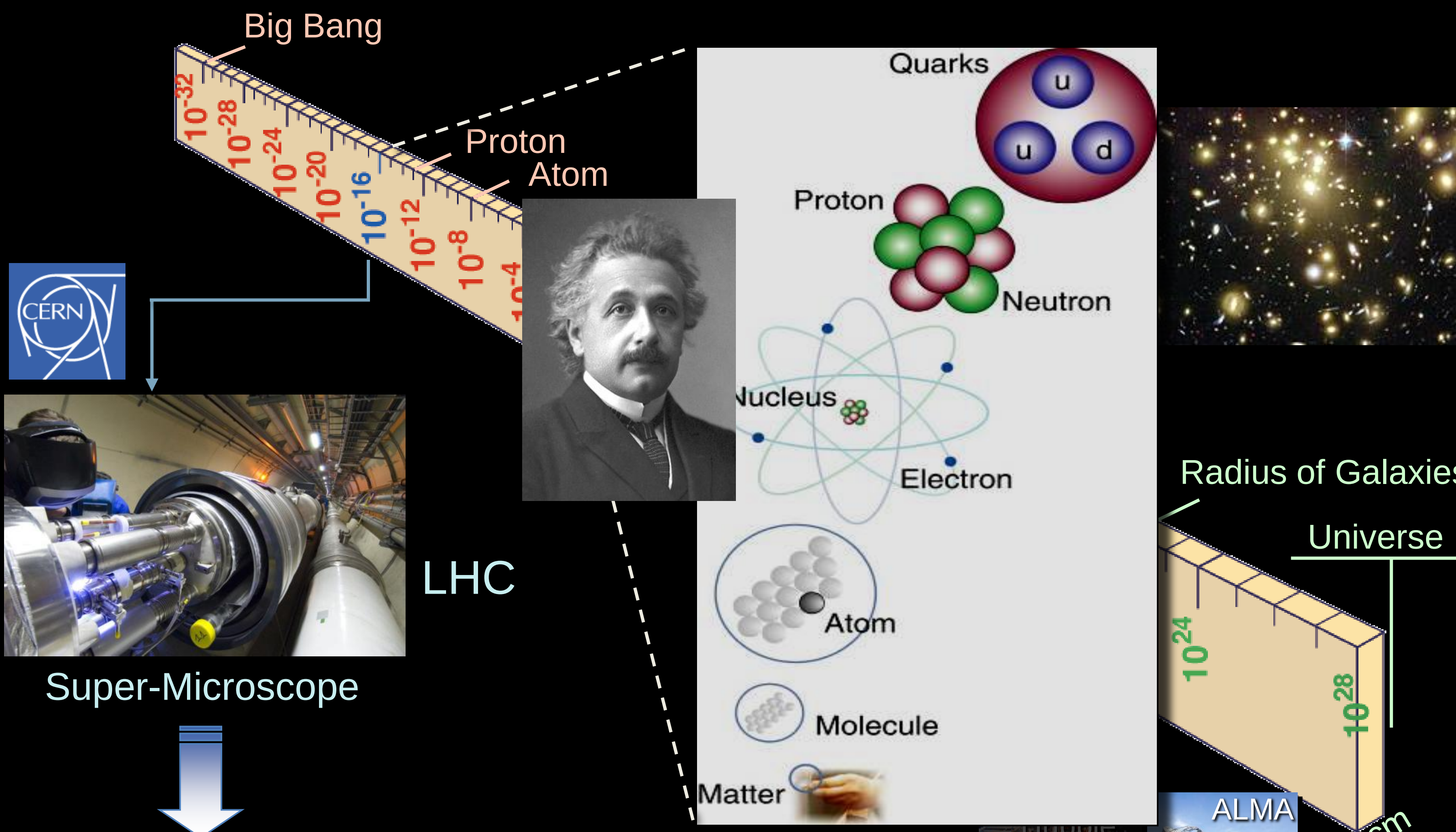


It is a great privilege and pleasure to present now first physics results



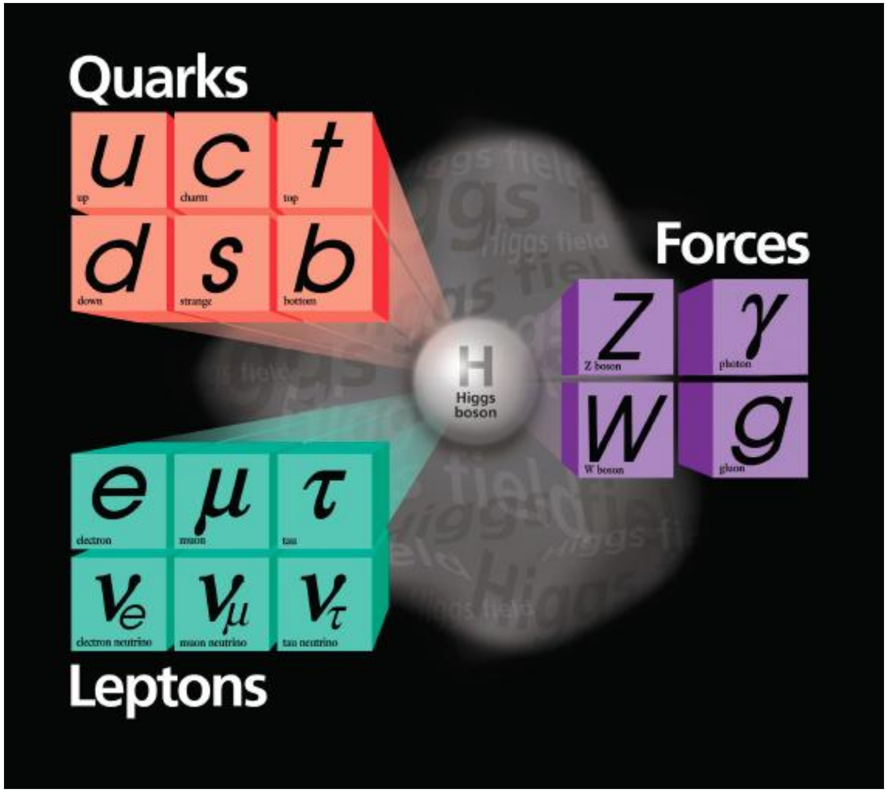
pp physics at the LHC corresponds to conditions around here

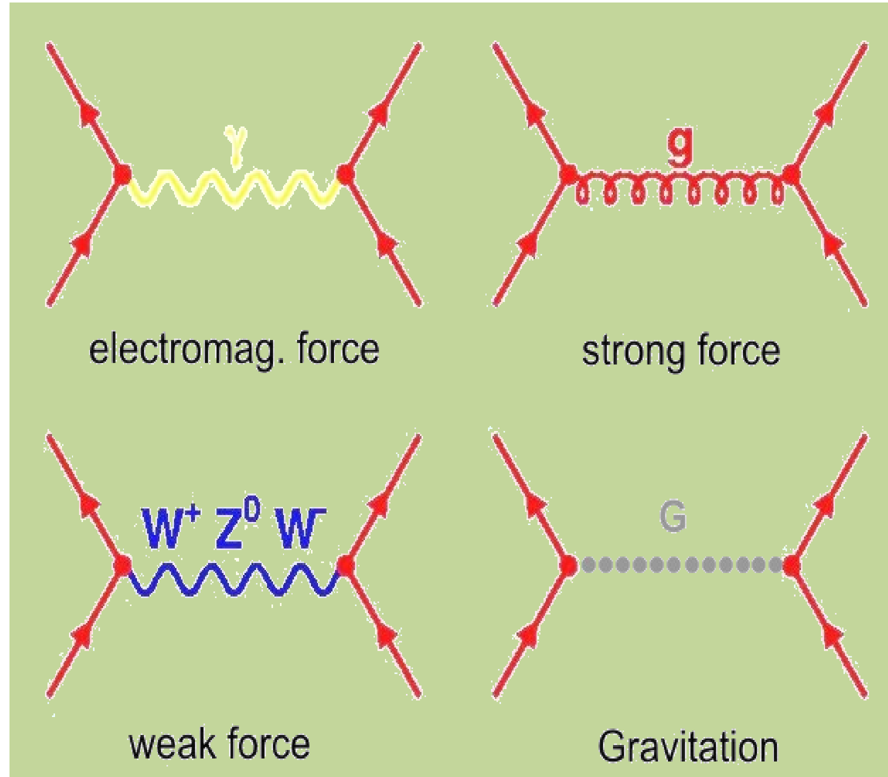
HI physics at the LHC corresponds to conditions around here



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

The Standard Model of Particle Physics



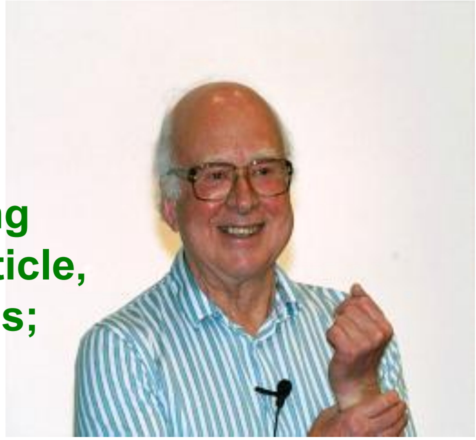


(i) Constituents of matter: quarks and leptons

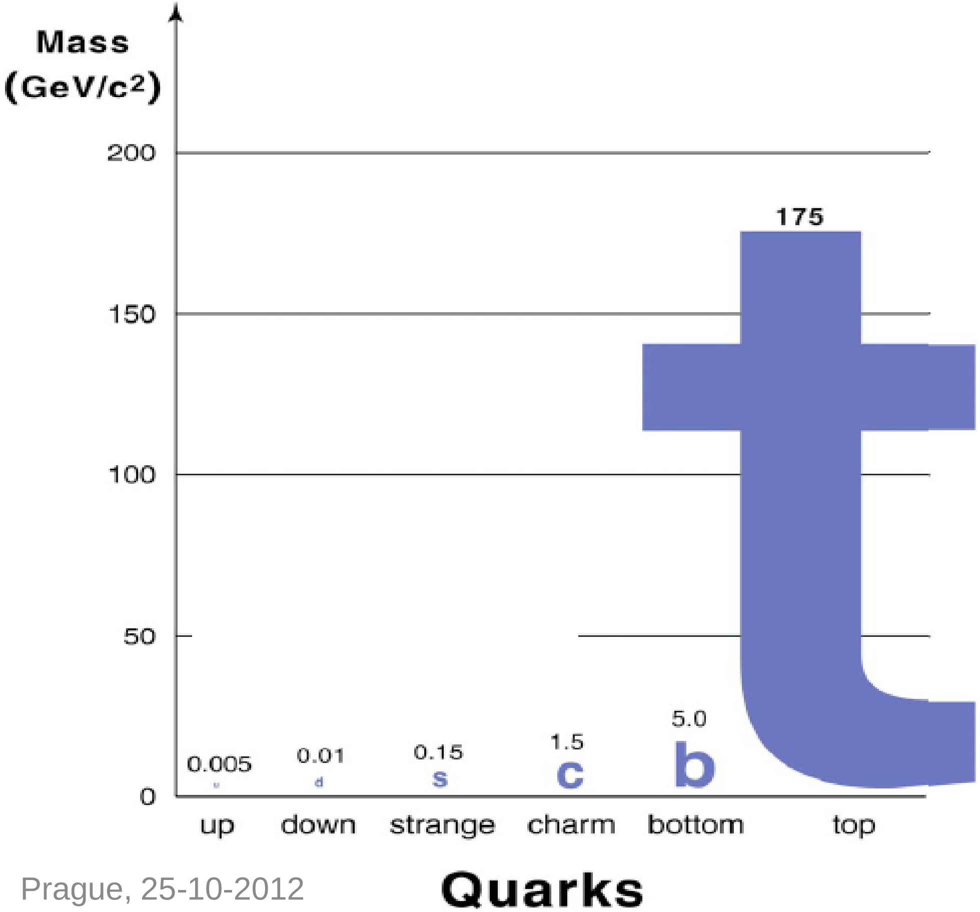
(ii) Four fundamental forces
(described by quantum field theories, except gravitation)

(iii) The Higgs field (problem of mass)

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



The mass mystery could be solved with the 'EW symmetry breaking mechanism' which predicts the existence of a new elementary particle, the 'Higgs' particle (theory 1964: R. Brout and F. Englert; P.W. Higgs; G.S. Guralnik, C.R. Hagen and T.W.B. Kibble)



Peter Higgs

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

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

Francois Englert

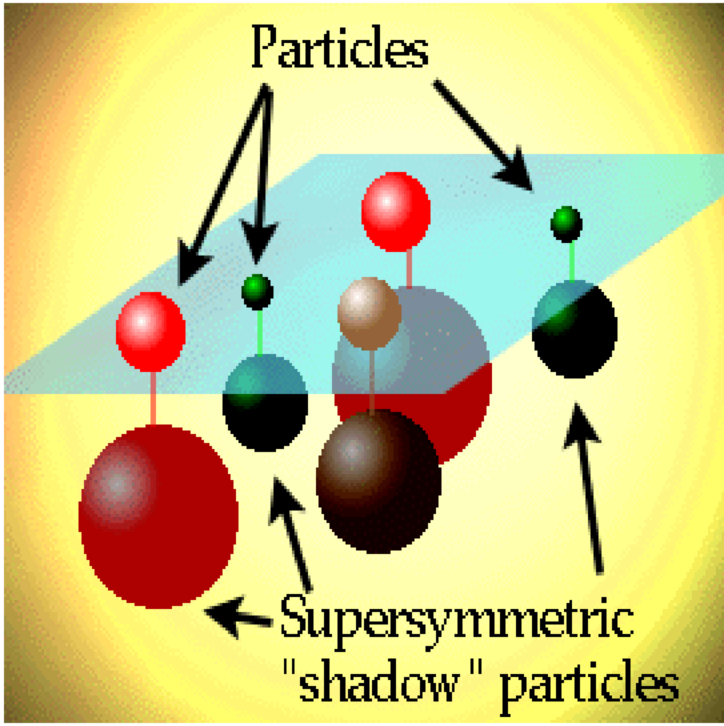
Supersymmetry (SUSY)

(Julius Wess and Bruno Zumino, 1974)

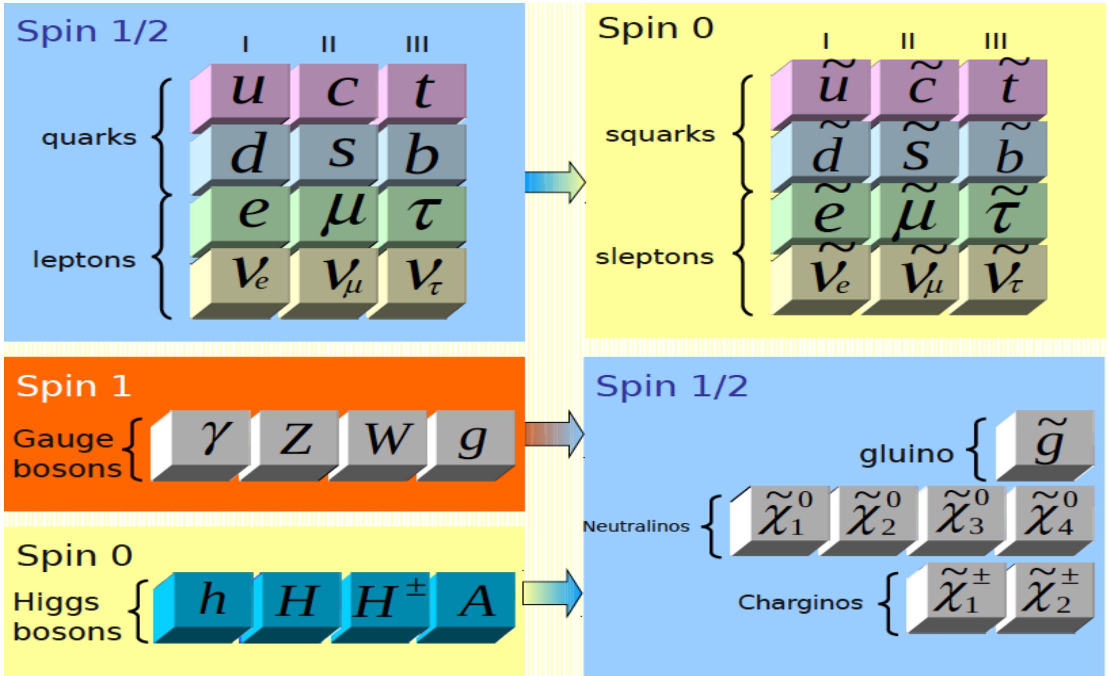
Establishes a symmetry between fermions (matter) and bosons (forces):

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

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



Our known world… Maybe a new world?



Motivation:

- Unification (fermions-bosons, matter-forces)

- Solves some deep problems of the Standard Model

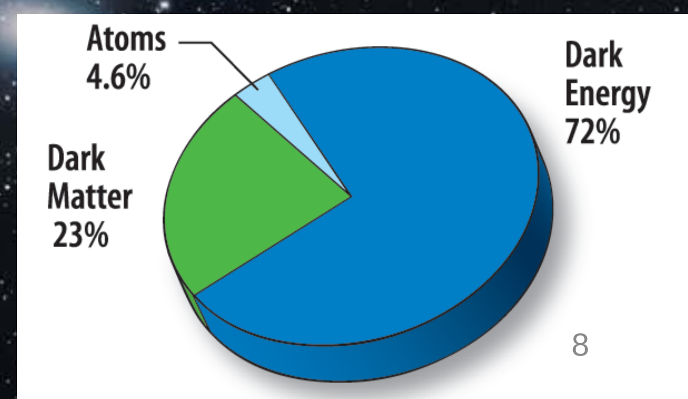
Dark Matter in the Universe

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

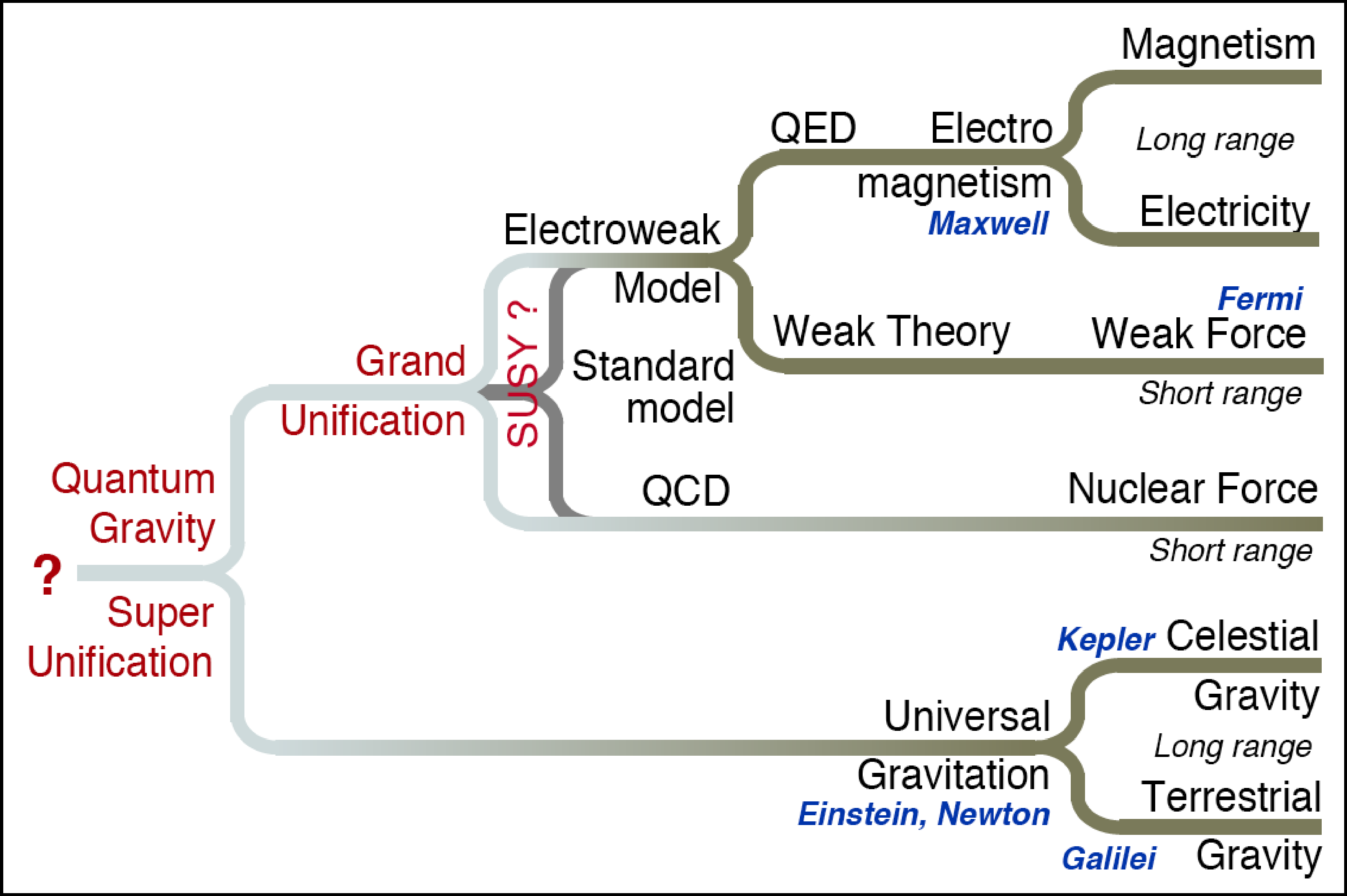
Vera Rubin ~ 1970

'Supersymmetric' particles ?

F. Zwicky 1898-1974



Unification of Forces



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**

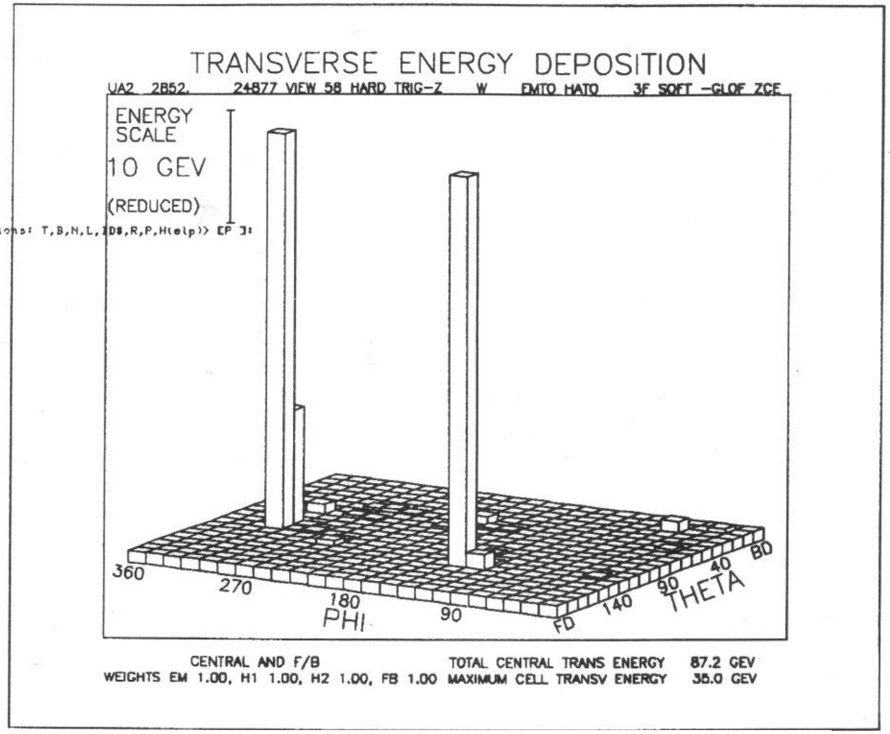
1981 **LEP was approved with a large and long (27 km) tunnel**

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

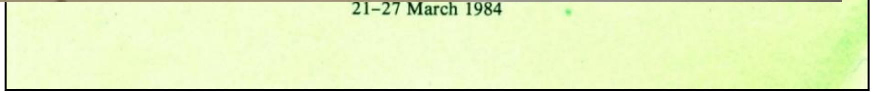
The real belief that a 'dirty' hadron collider can actually do great discovery physics came from UA1 and UA2 with their W and Z boson discoveries at CERN

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)



ATLAS was borne with the Letter of Intent (LoI), submitted on 1st October 1992, 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)

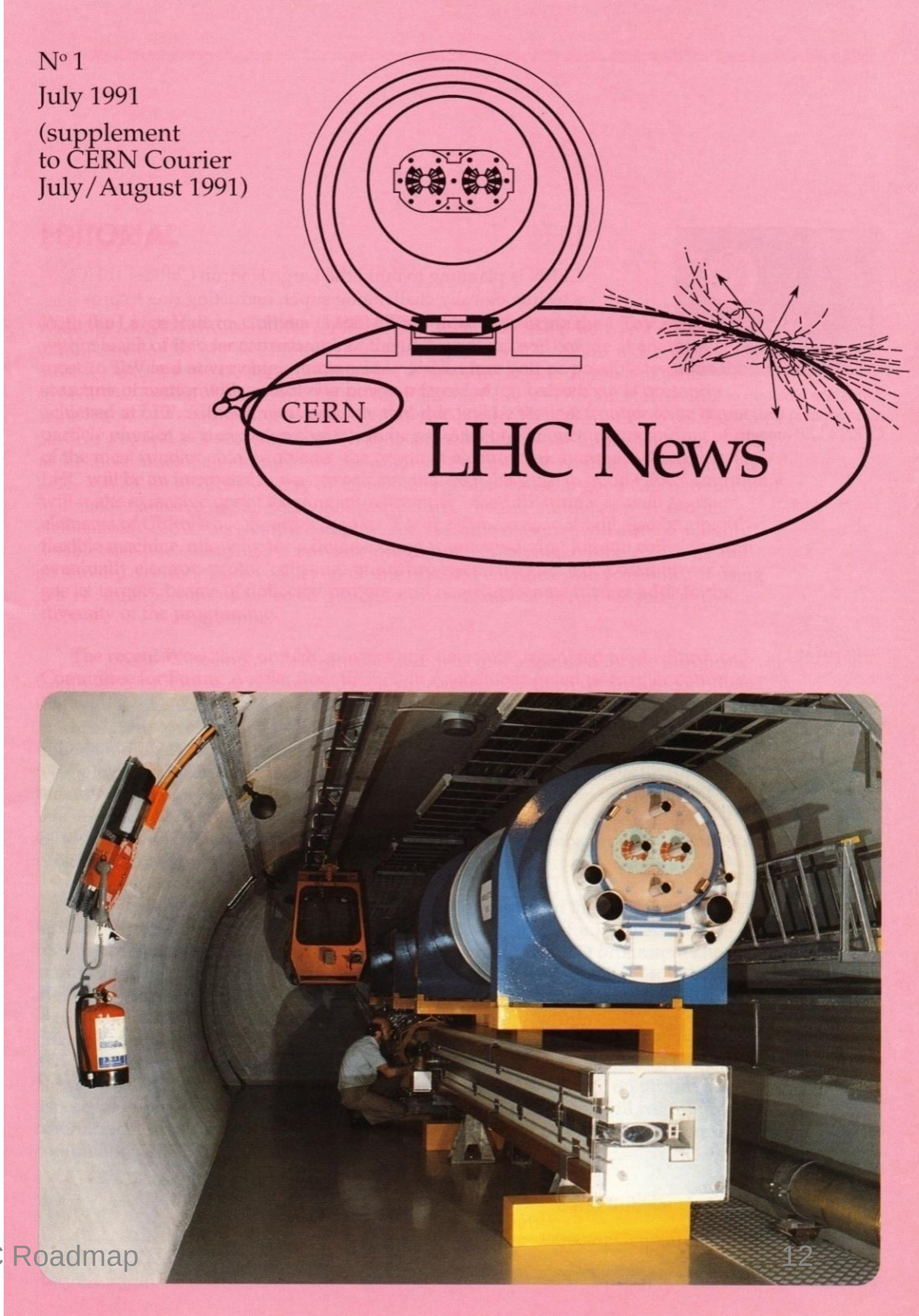
1993 December proposal of LHC with commissioning in 2002

1994 June Council:

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

16 December 1994 Council:

(Two-stage) construction of LHC was approved



The two-stage approval of LHC was understood to be modified in case sufficient CERN non-member state contributions would become available

A lot of LHC campaigns and negotiations took place in the years 1995 - 1997, including also the experiments

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

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

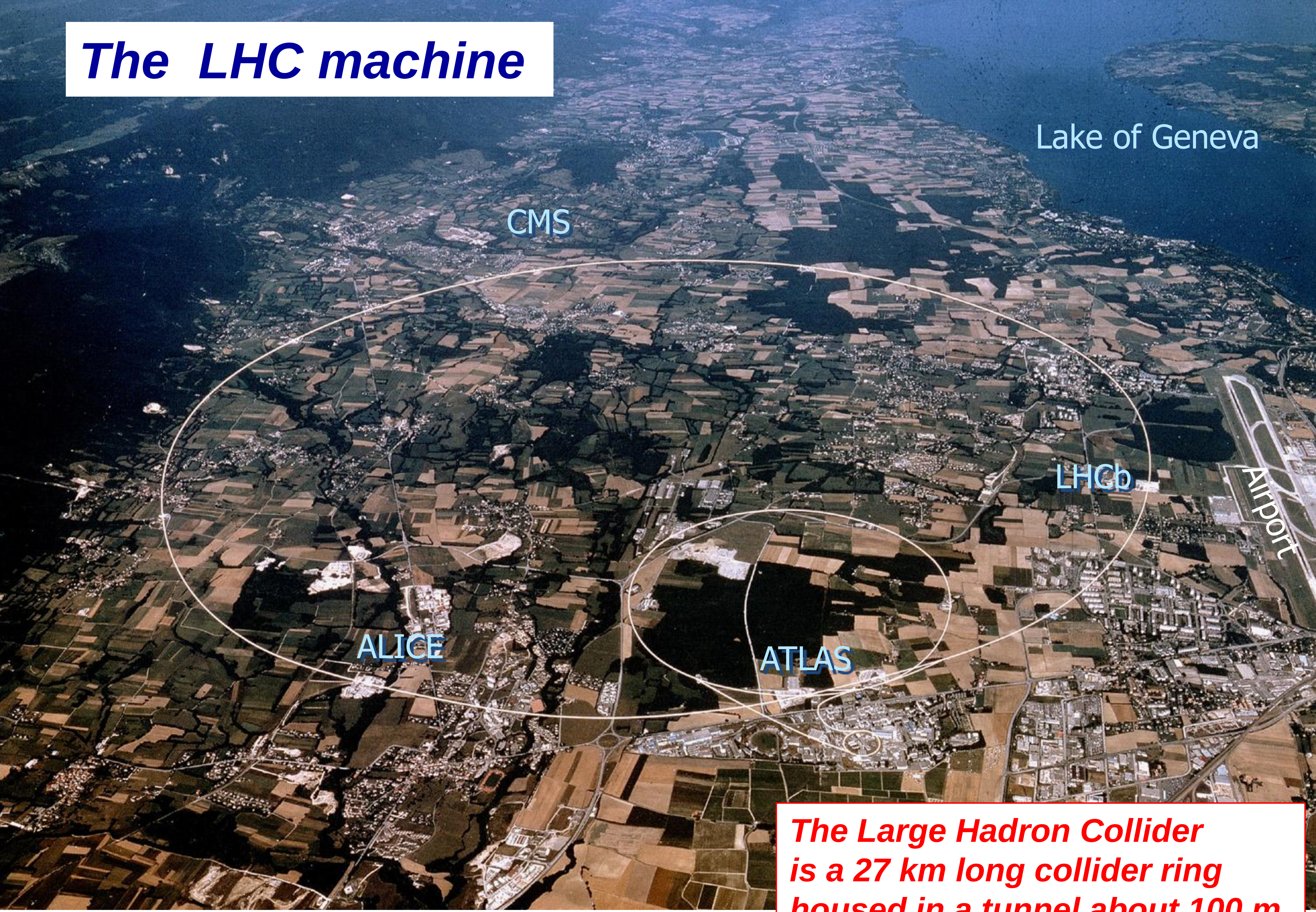
1997

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

Signature of the US-CERN agreement in December 1997:
R Eisenstein (NSF), C Llewellyn Smith (CERN DG), M Krebs (DOE)

The first picture on the Web in 1992 !

The LHC machine

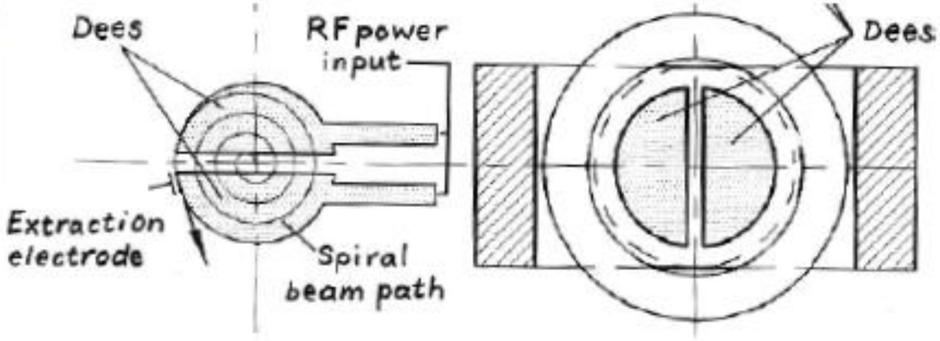


The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

The first cyclotron and the Berkeley one

Ernest Lawrence
(1901 - 1958)

The first circular accelerator (Berkeley 1930)

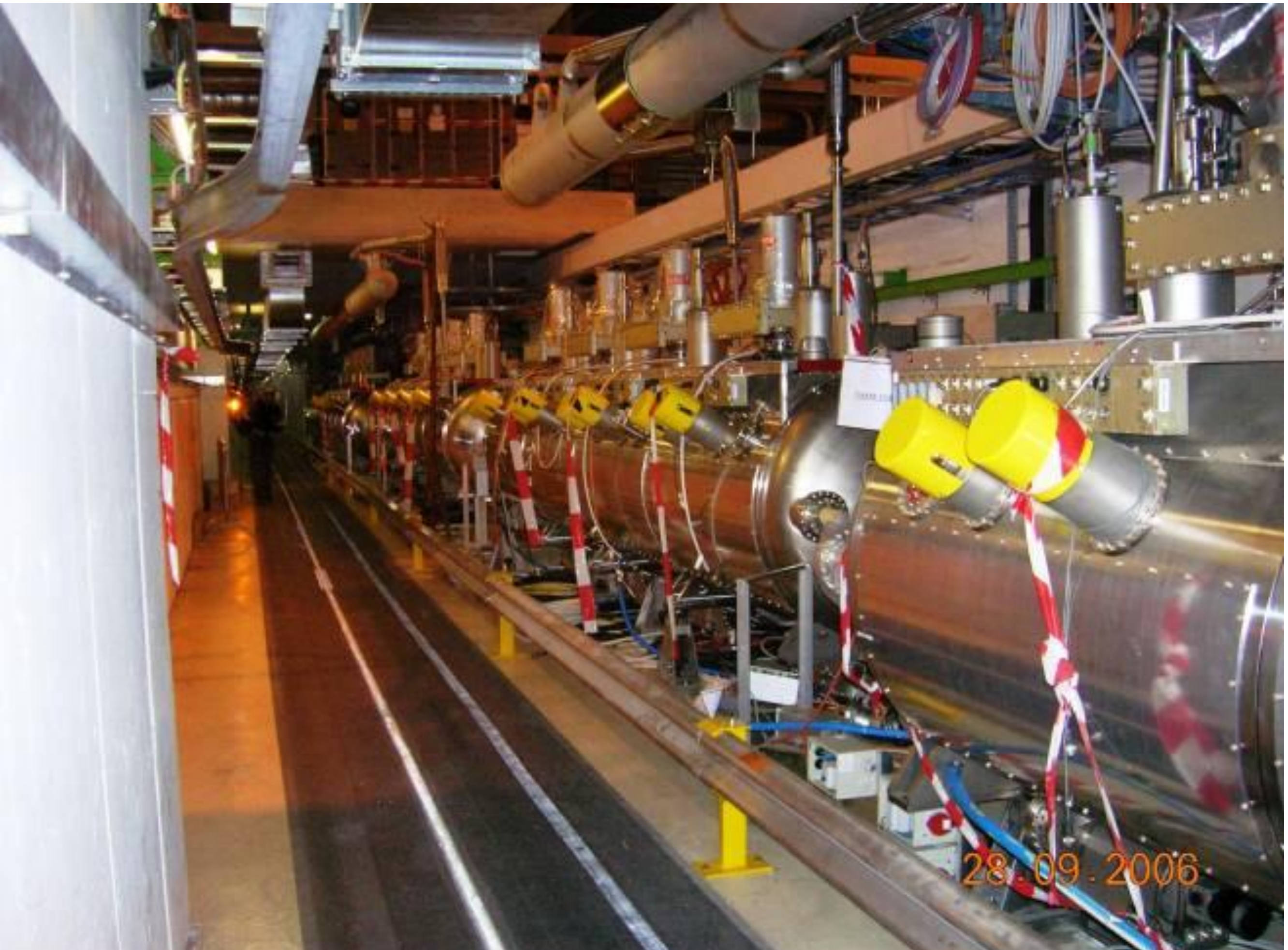


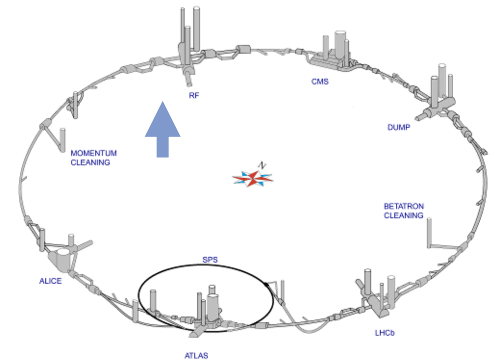
The most challenging components are the 1232 high-tech superconducting dipole magnets

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

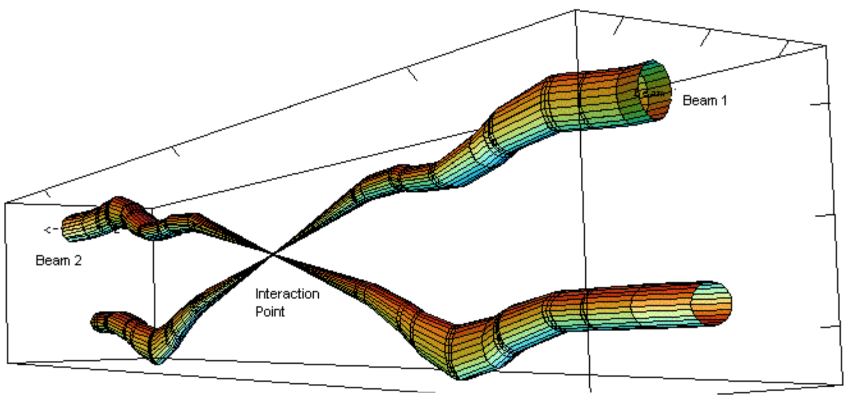




Note: The acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), because of the ~ $1/m^4$ behaviour of the synchrotron radiation energy losses [~ E^4_{beam}/Rm^4]

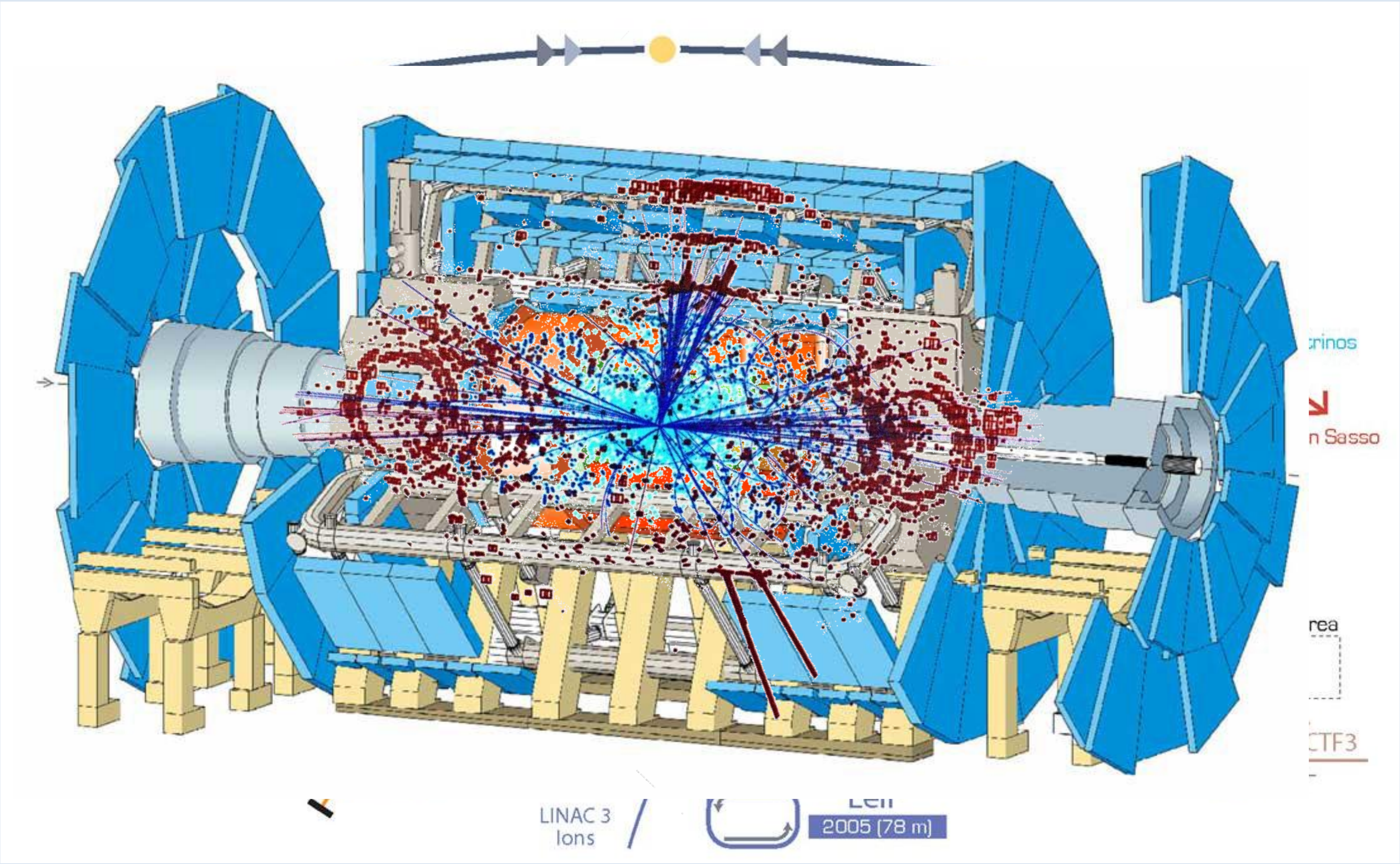
	LHC at 7 TeV	LEP at 100 GeV
Synchrotron radiation loss	6.7 keV/turn	3 GeV/turn
Peak accelerating voltage	16 MV/beam	3600 MV/beam

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

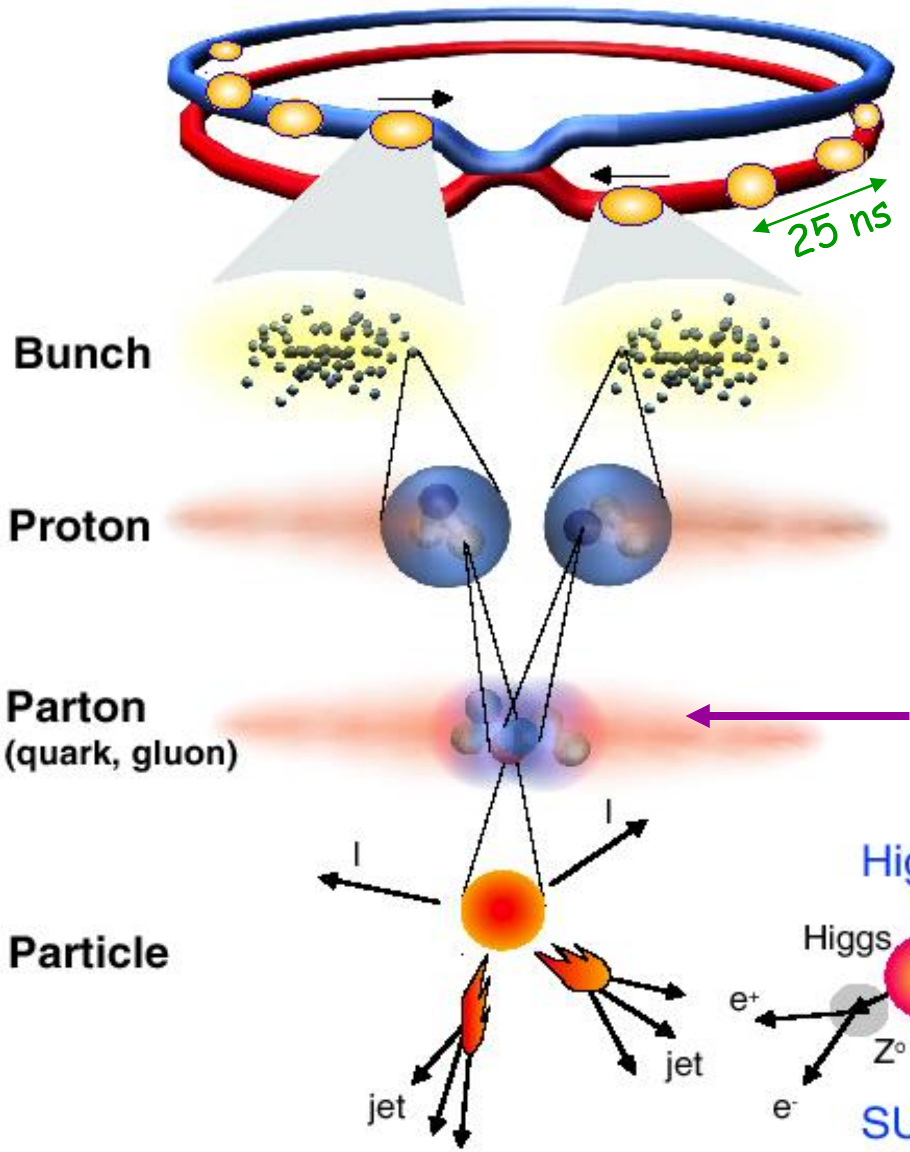


Relative beam sizes around the collision point

CERN’s particle accelerator chain



Collisions at LHC



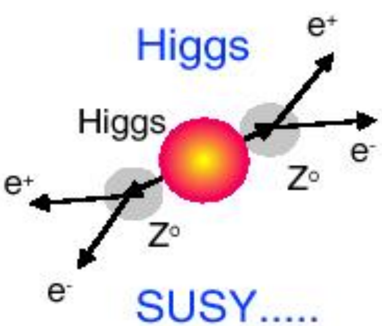
Proton-Proton	
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate:

N = L x σ (pp) ≈ 10^9 interactions/s

Mostly soft (low p_T) events

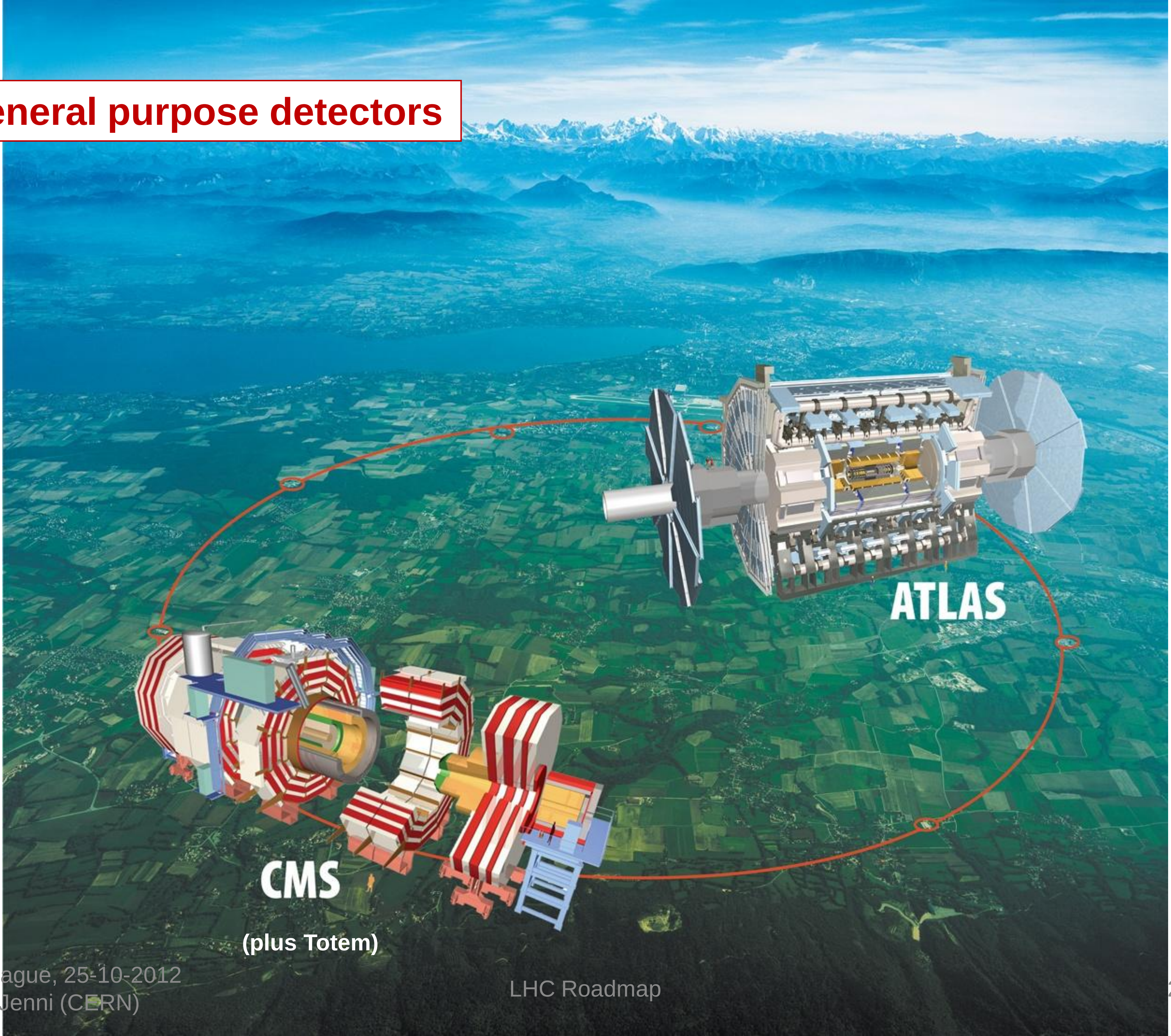
Interesting hard (high-p_T) events are rare



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

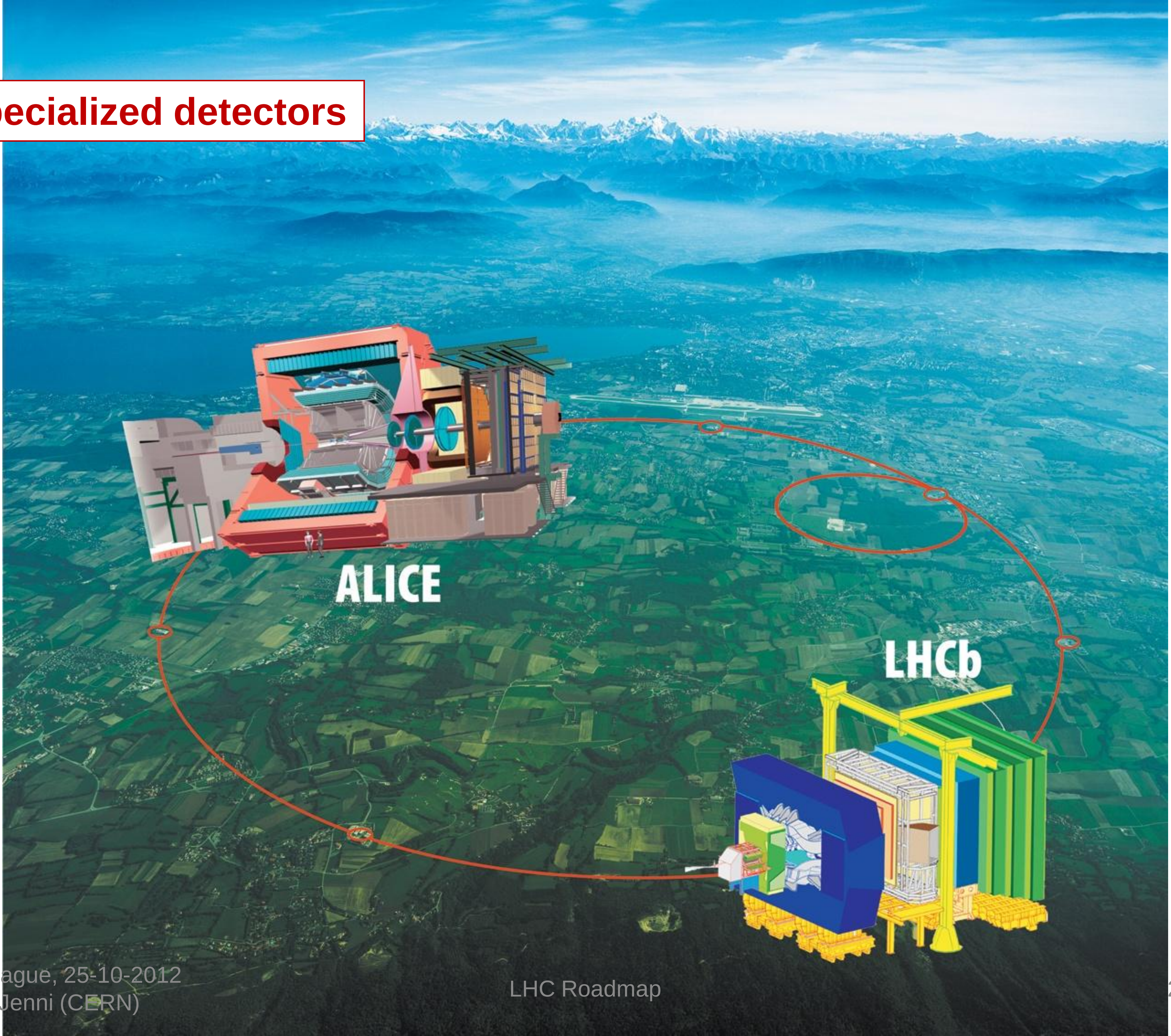
→ very powerful detectors needed

General purpose detectors



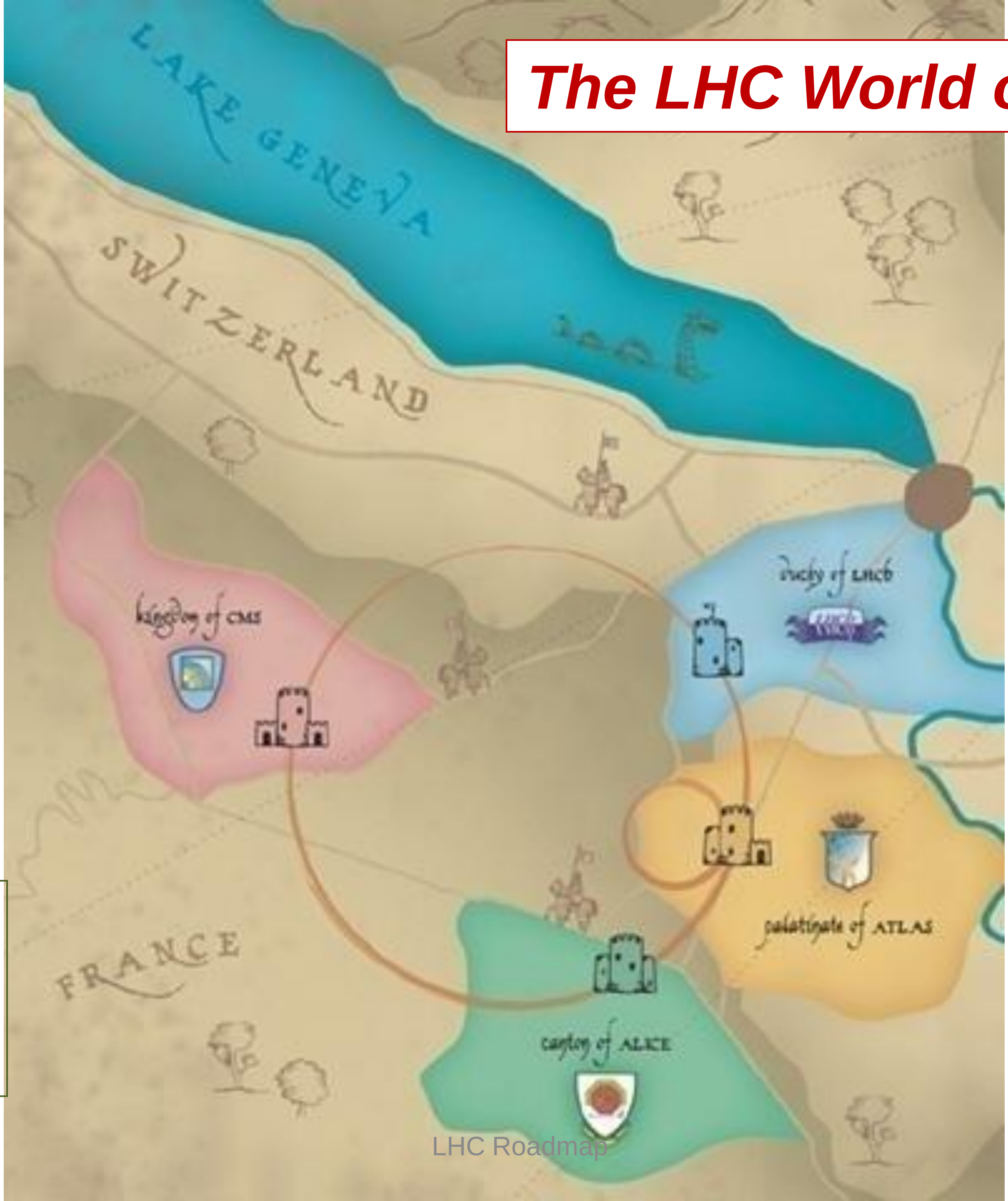
(plus Totem)

Specialized detectors



The LHC World of CERN

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

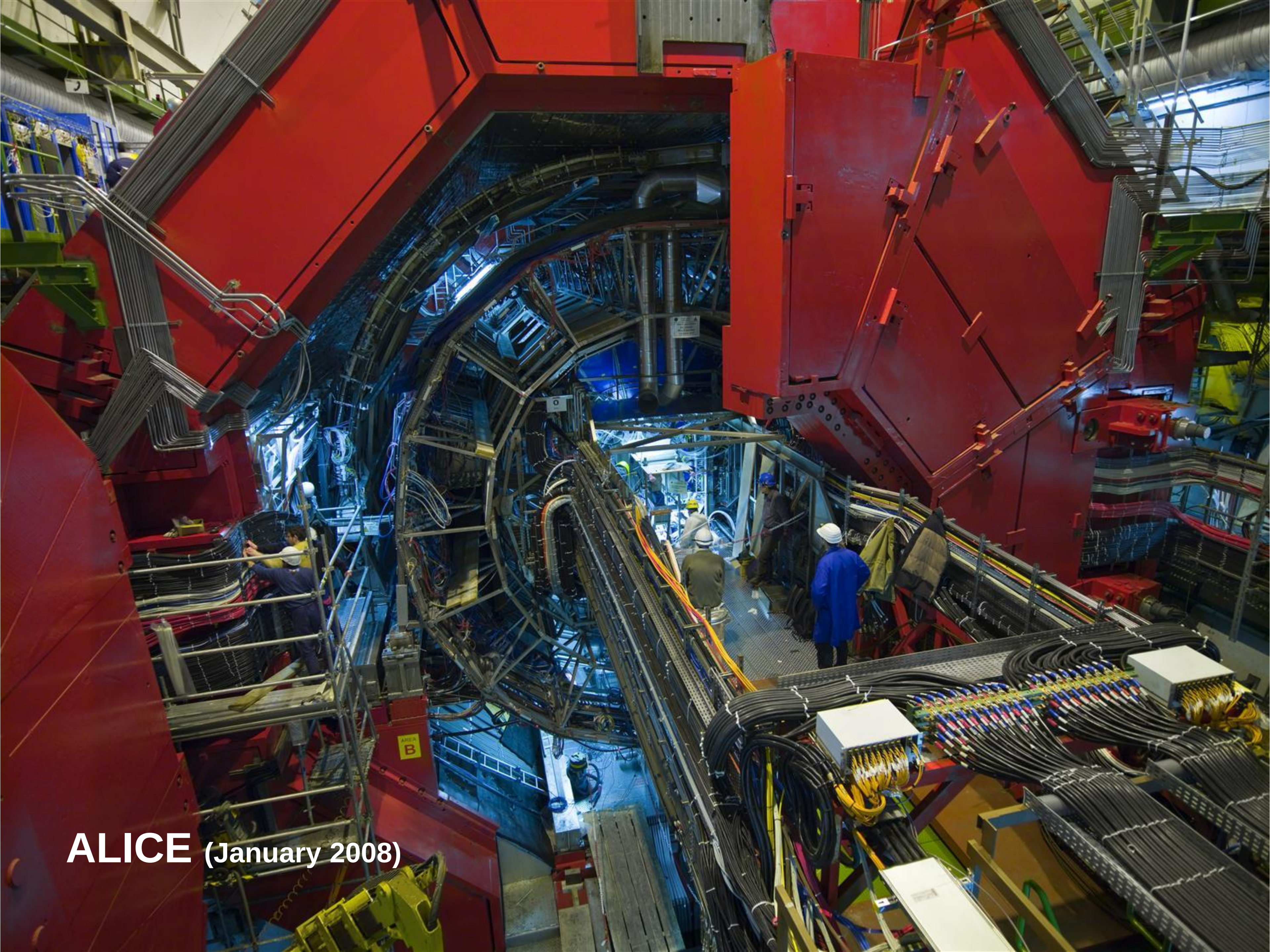


CMS
3000 Physicists
184 Institutions
38 countries
550 MCHF

LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

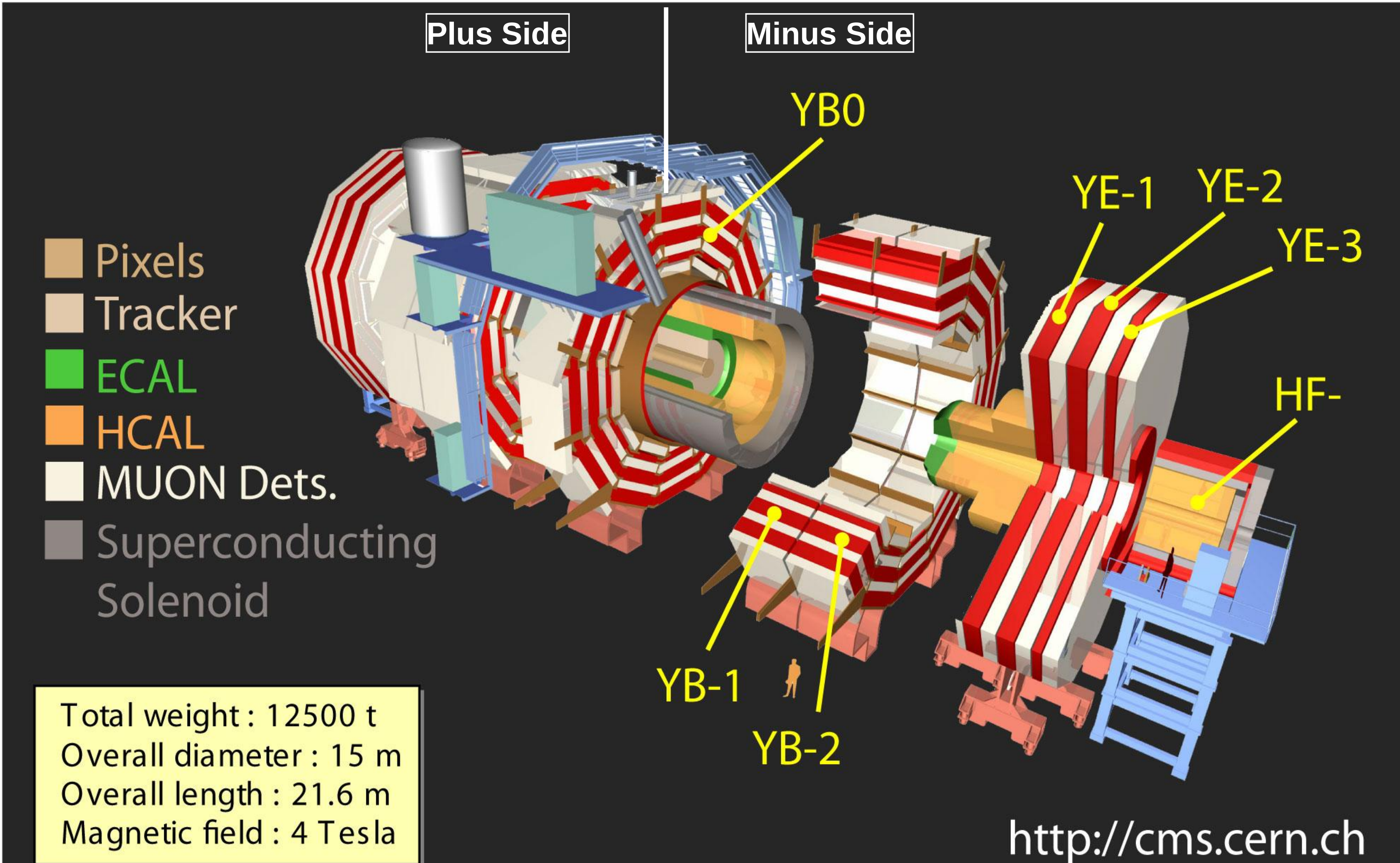
ATLAS
3000 Physicists
176 Institutions
38 countries
550 MCHF

ALICE
1000 Physicists
105 Institutions
30 countries
150 MCHF

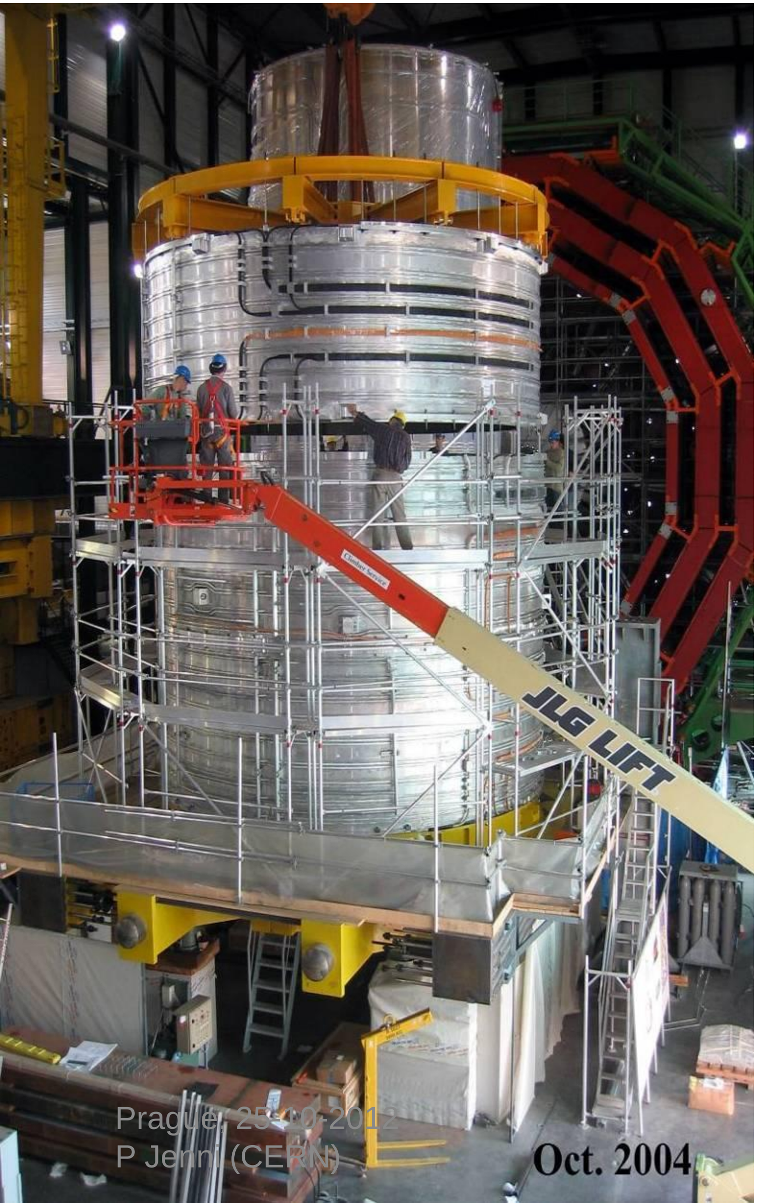


ALICE **(January 2008)**

Exploded View of CMS



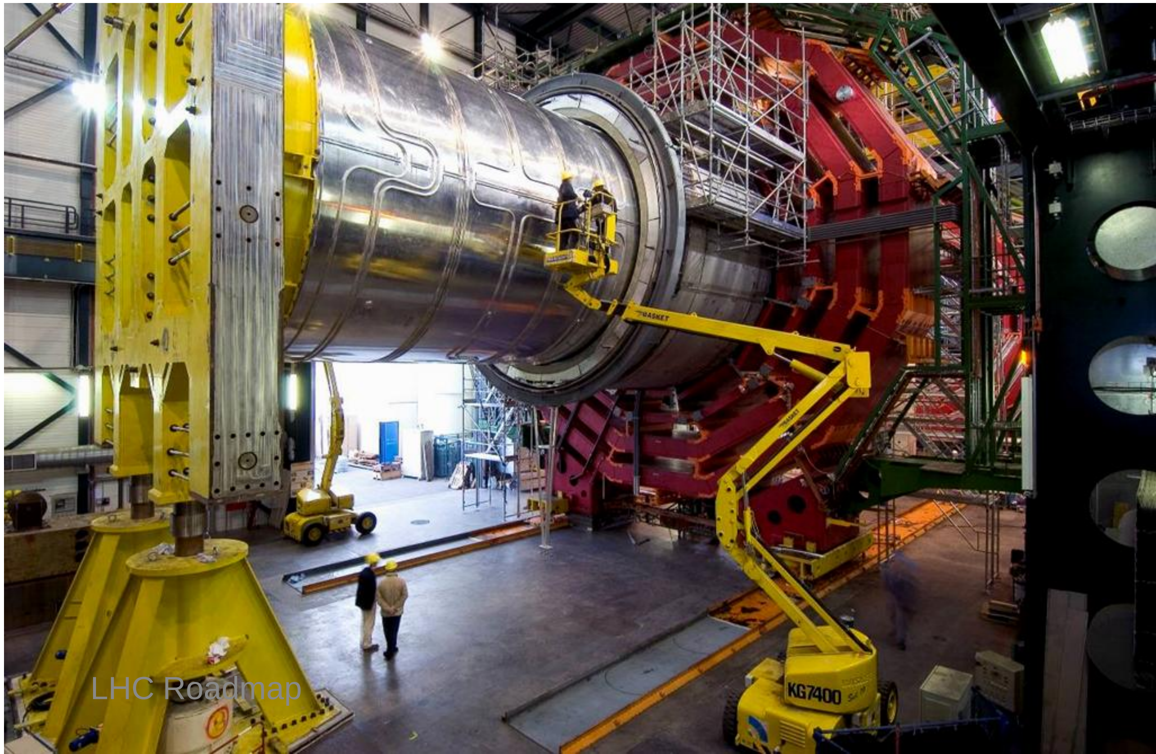
An Example of an Engineering Challenge: CMS Solenoid



CMS solenoid:

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

Tested at full current in Summer 2006



CMS before closure 2008

ATLAS Collaboration

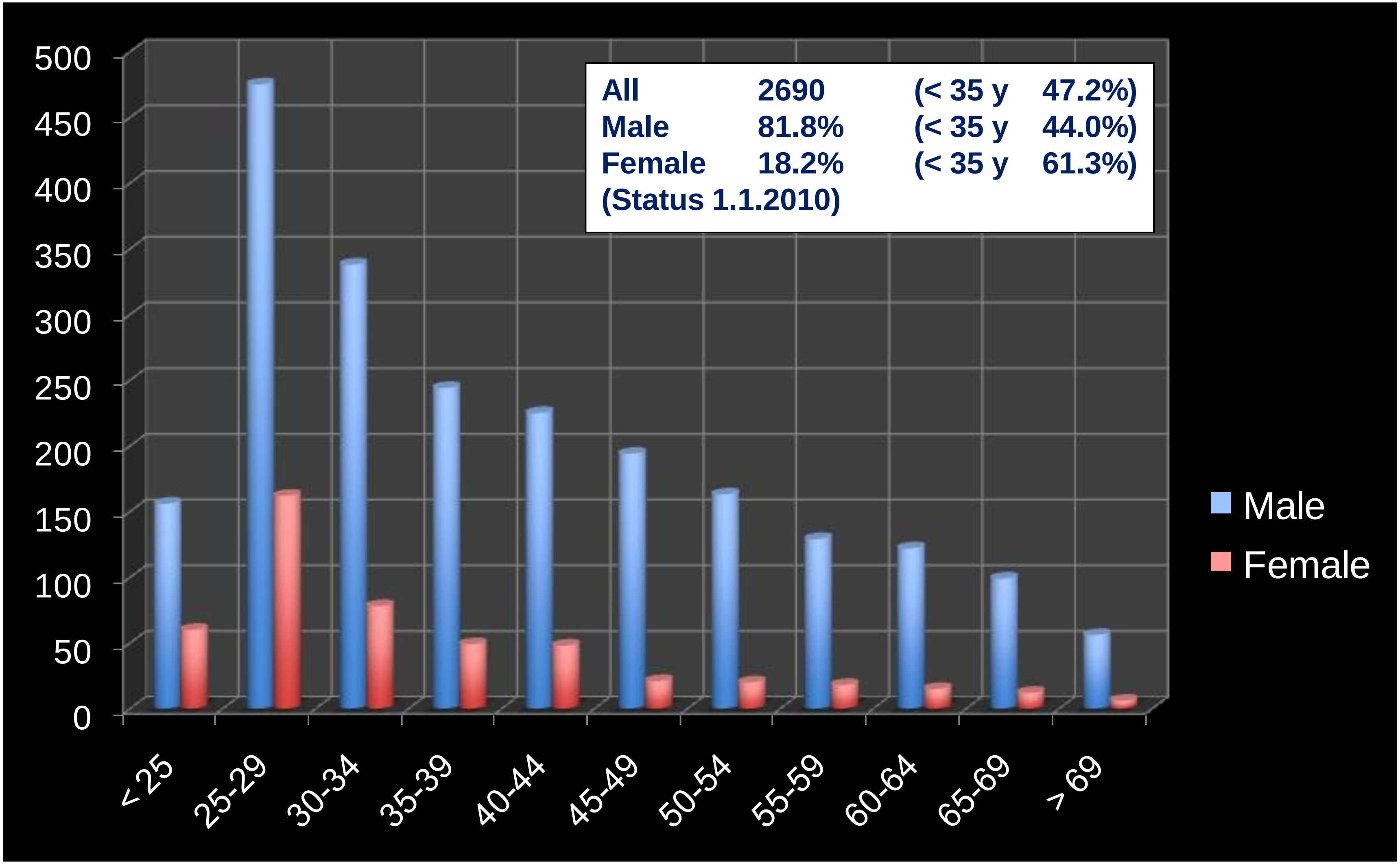
(Status June 2012)

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

ATLAS enjoys a longstanding and very fruitful partnership with the Czech groups 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, 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



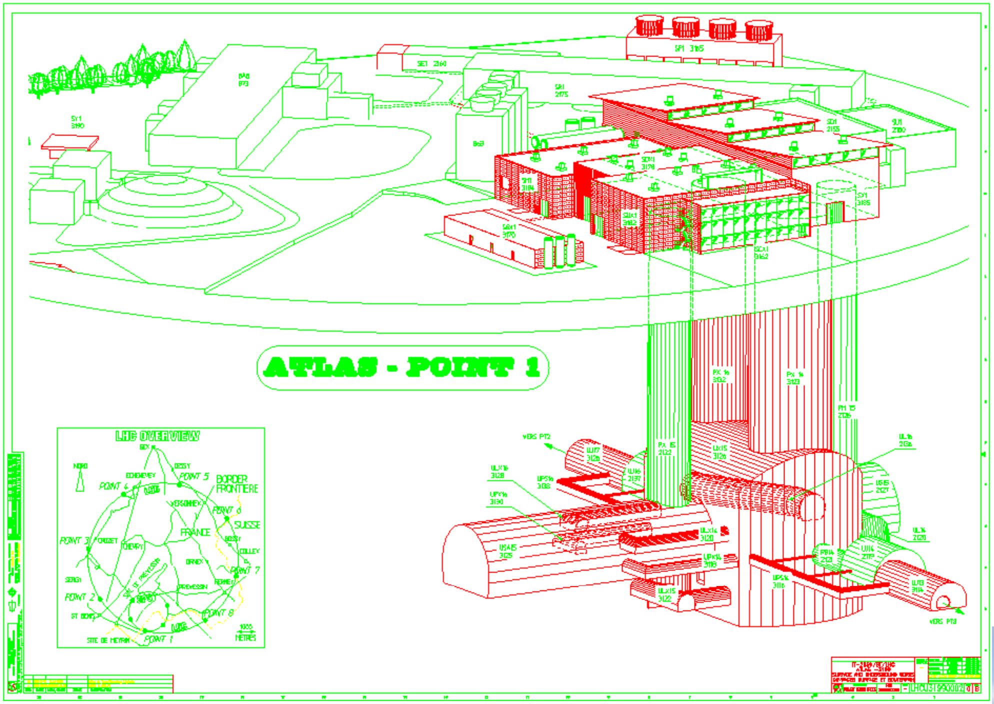
All	2690	(< 35 y	47.2%)
Male	81.8%	(< 35 y	44.0%)
Female	18.2%	(< 35 y	61.3%)
(Status 1.1.2010)			

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

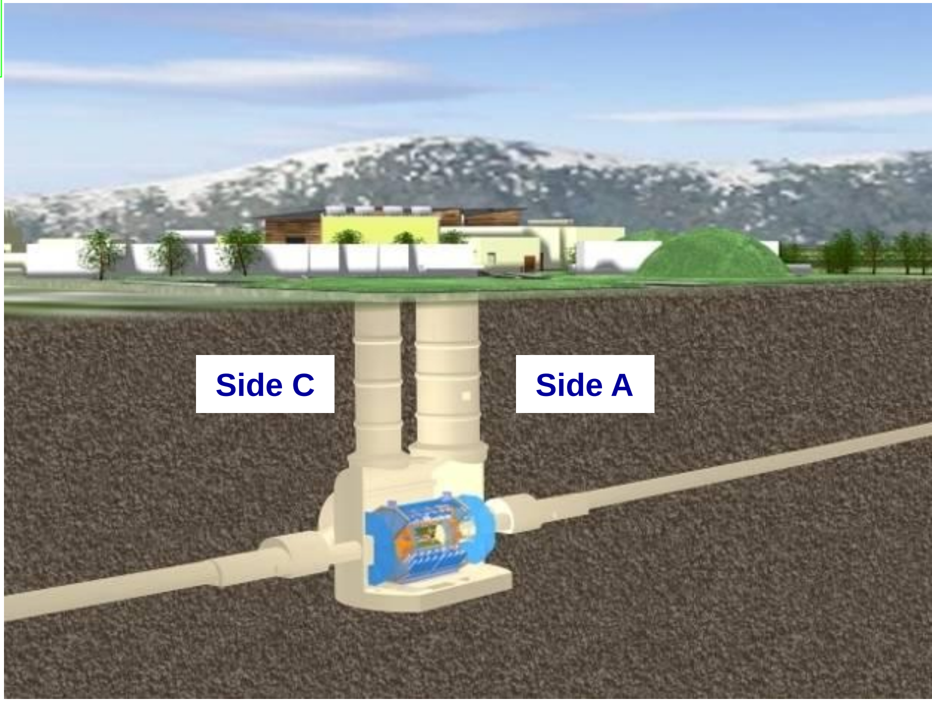
An important milestone was the ATLAS Collaboration meeting in Prague 2003, just before we started installing the detector

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

The Underground Cavern at Point-1 for the ATLAS Detector



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

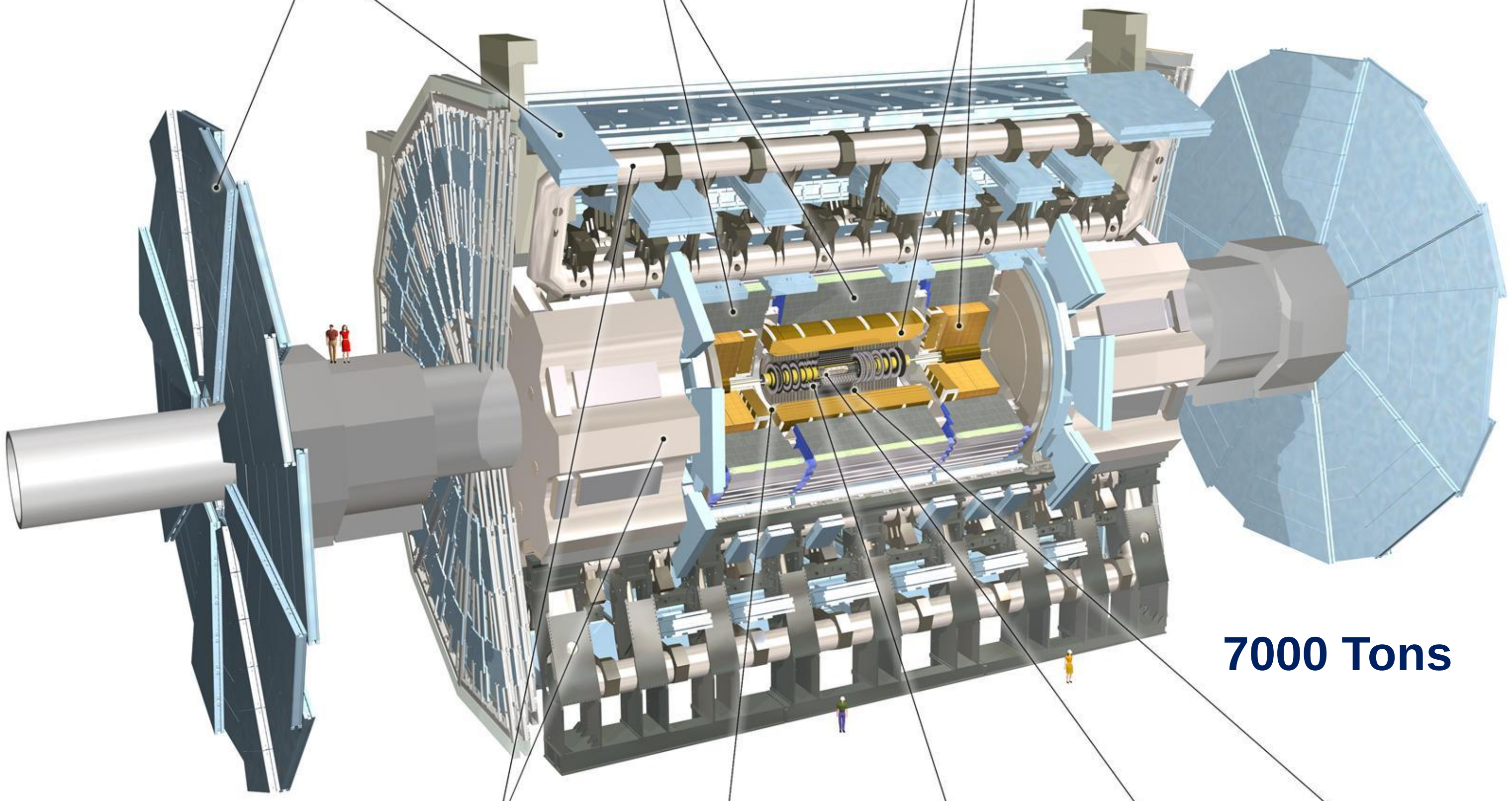


ATLAS Detector

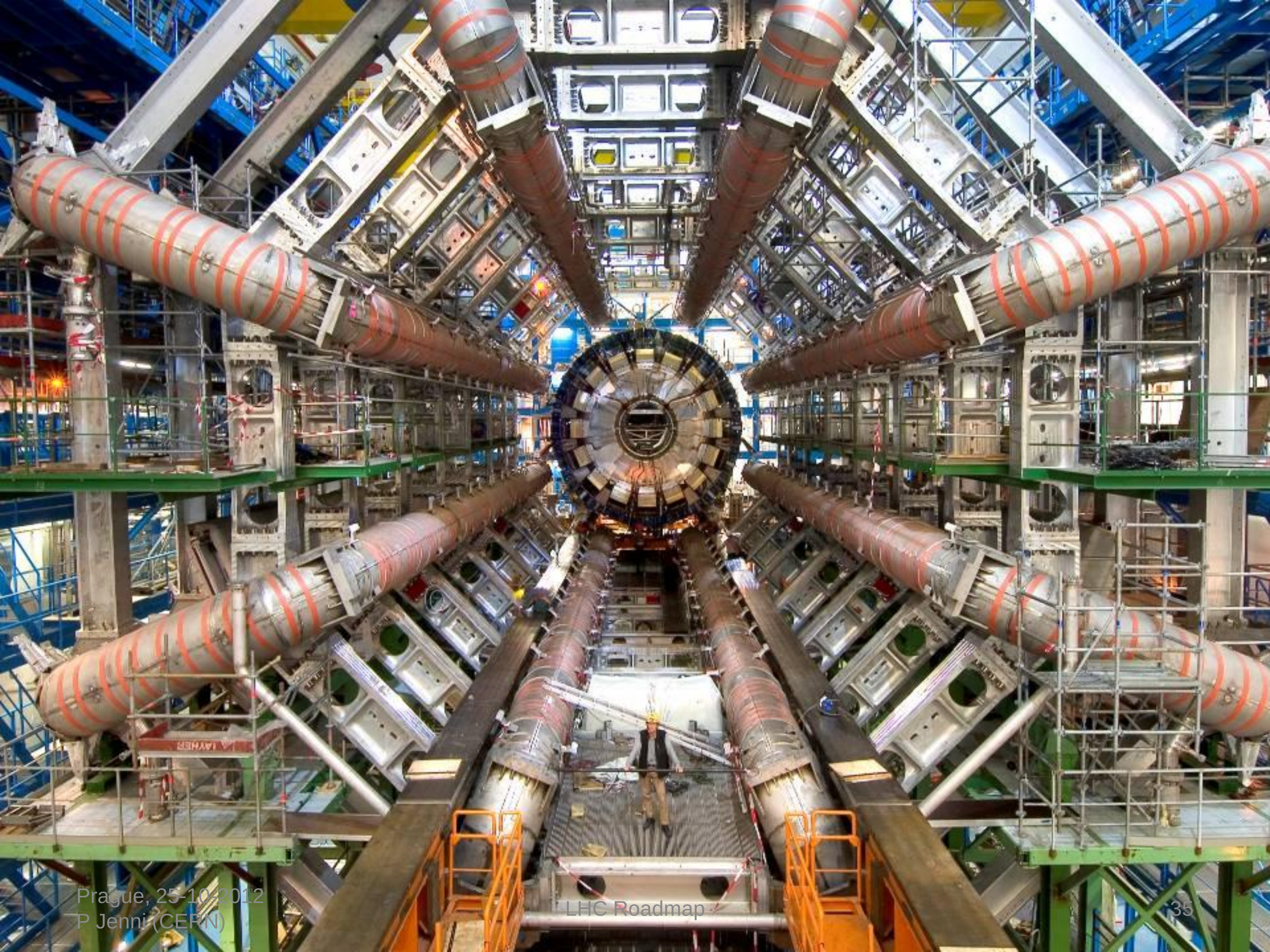
ATLAS superimposed to the 5 floors of building 40

45 m

24 m

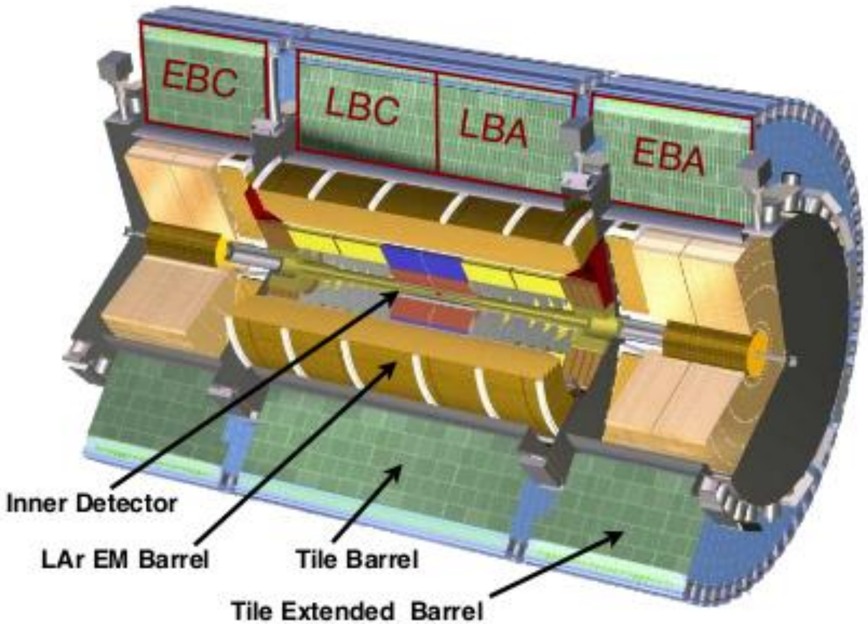


7000 Tons

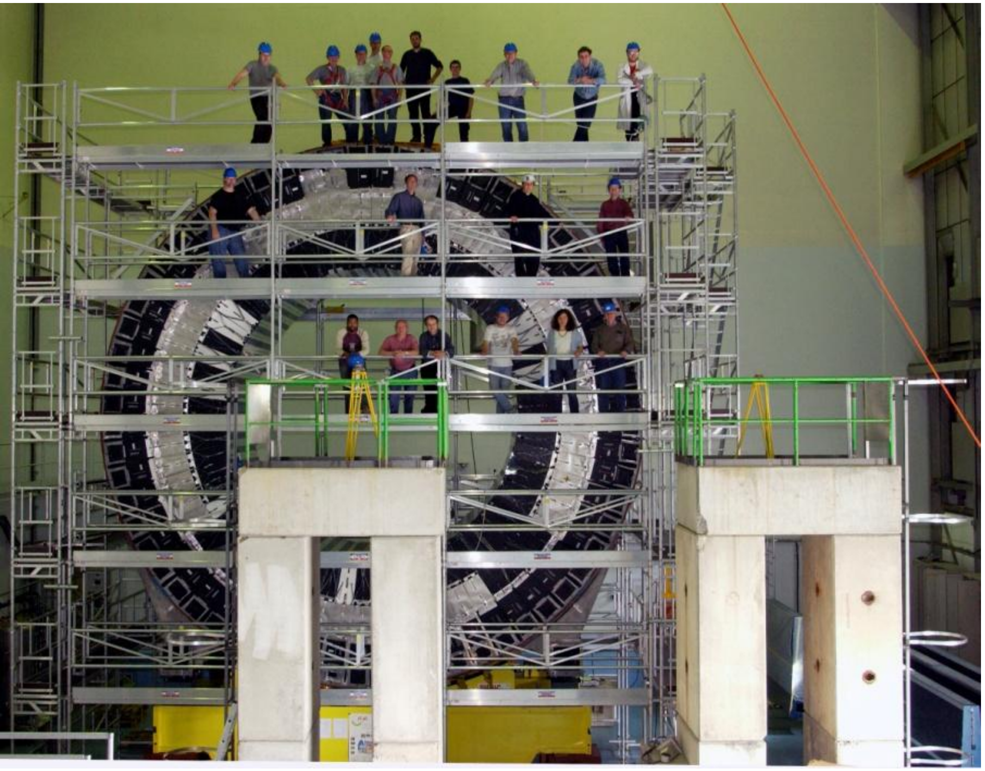


Hector Berlioz, “Les Troyens”, opera in five acts
Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009

Tile Calorimeter



EBC pre-assembly on the surface, April 2003



Rupert Leitner Project Leader 2001-2004

Tile Calorimeter sub-module construction in Prague 1999

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

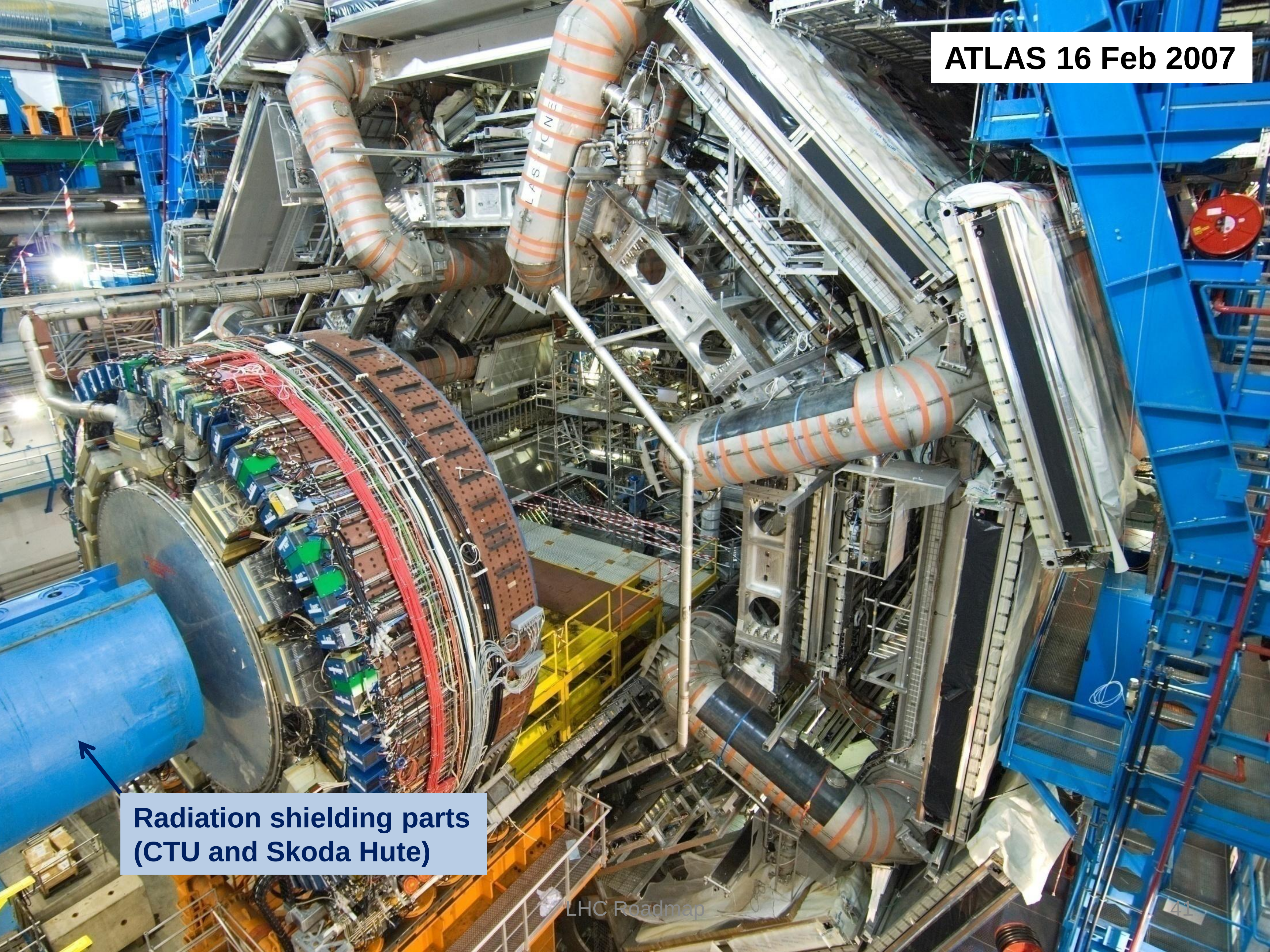
Transport of part of the Barrel Tile Calorimeter to the experimental area Point-1 (Sep 2004)

EBA assembly 24 May 2006

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

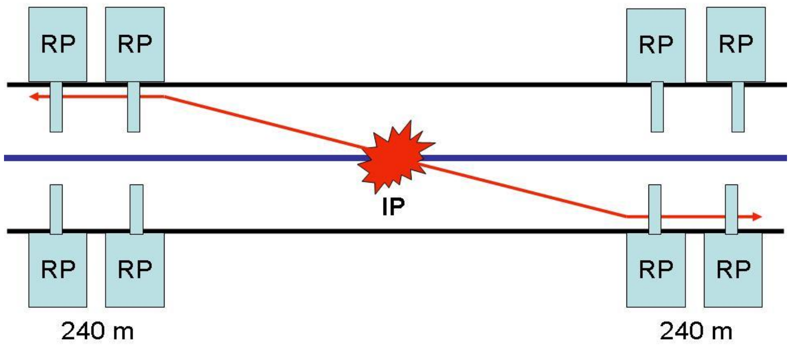
ATLAS Supplier Award ceremony for 'On Semiconductor' (ex 'Tesla') in 2007

(Also 'Skoda Hute' received the same award in 2004 for their shielding work)


ATLAS 16 Feb 2007
Radiation shielding parts
(CTU and Skoda Hute)

ATLAS Roman Pots (ALFA)

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

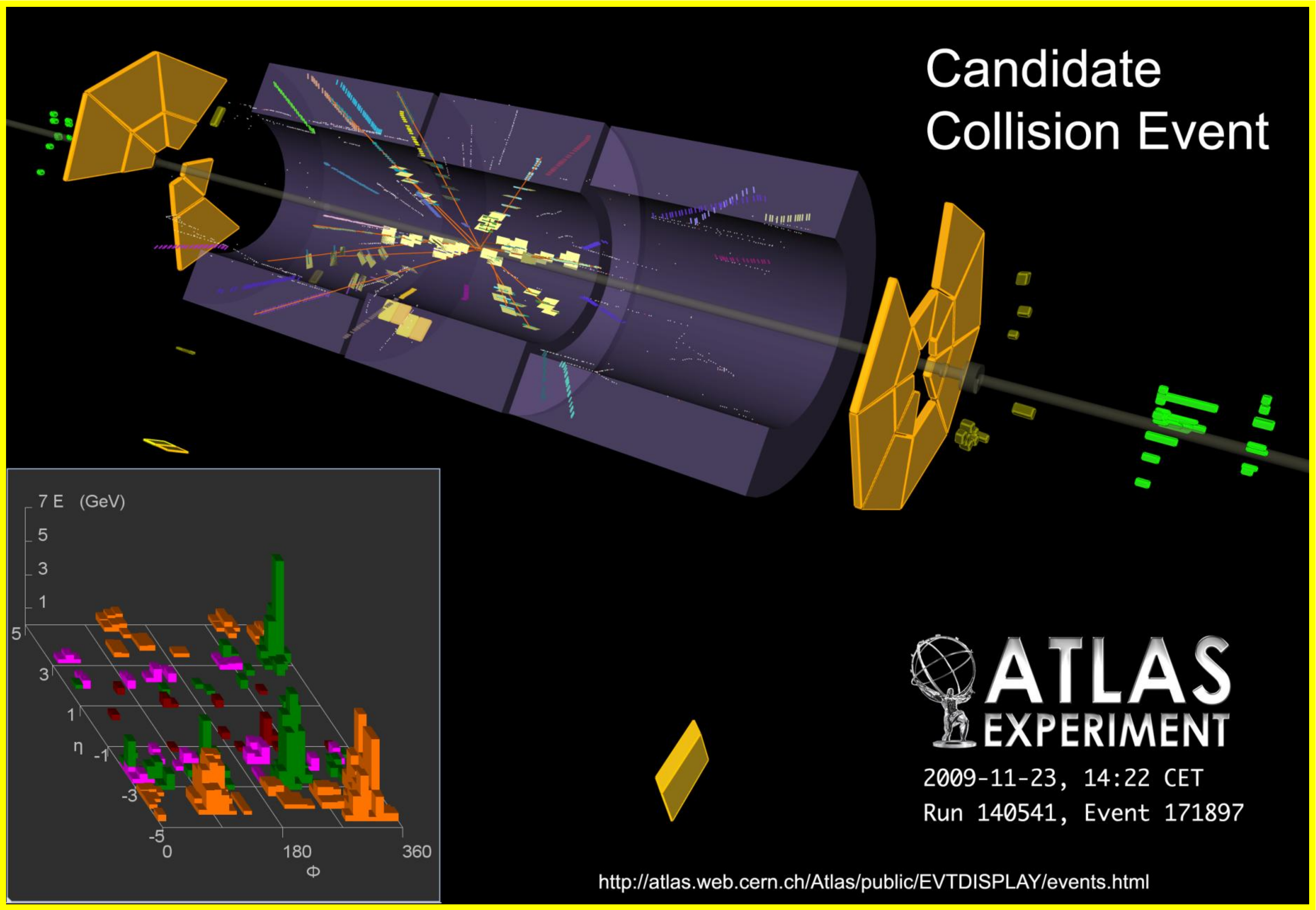


Absolute
Luminosity
For
ATLAS

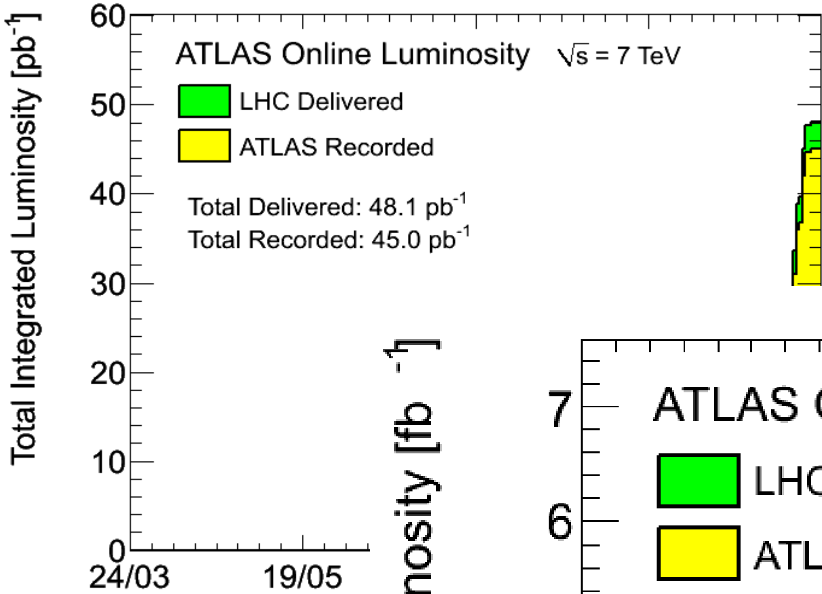
Roman Pots mechanics, based on Czech work in the Totem experiment

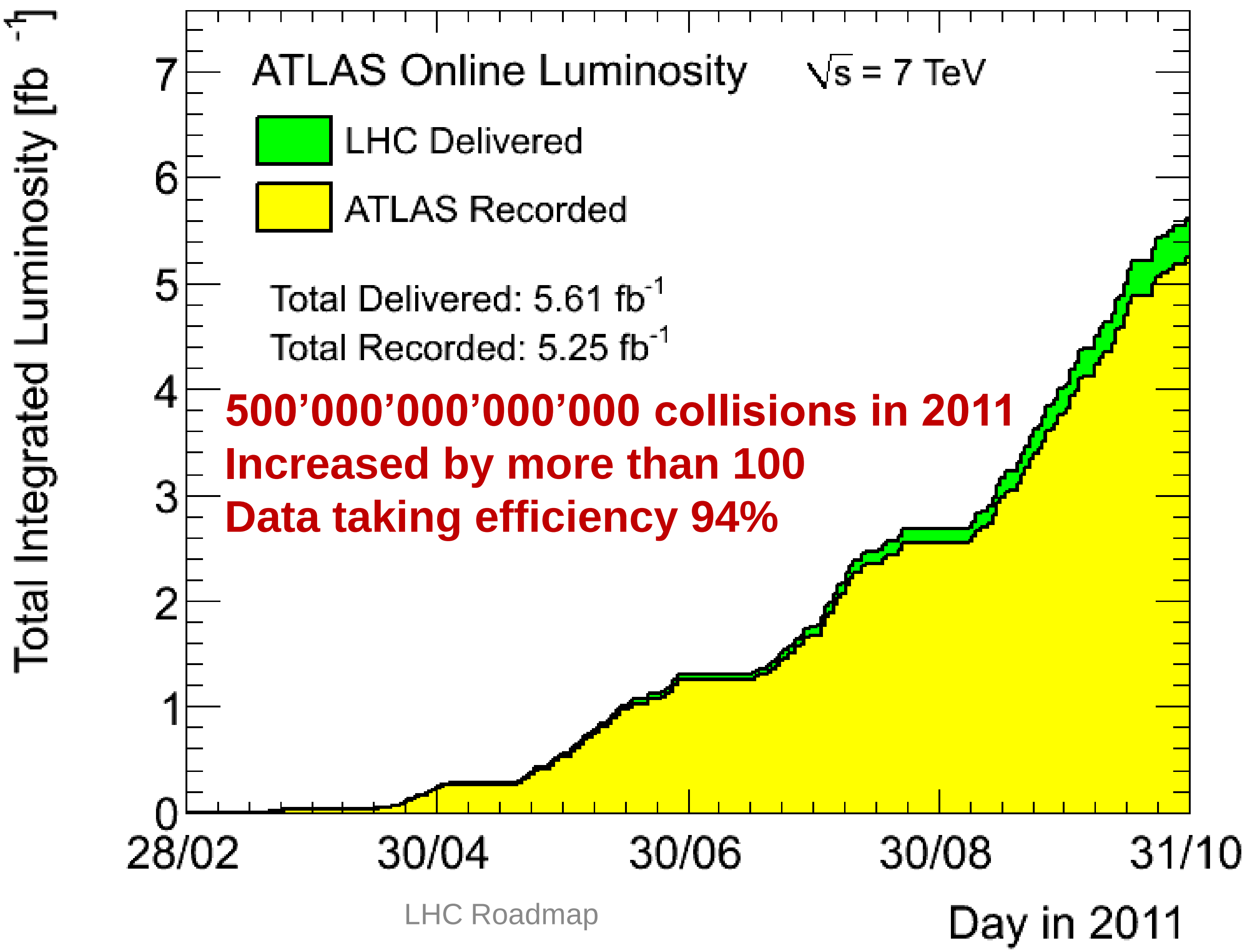
The joy in the ATLAS Control Room when the first LHC beam collided on November 23rd, 2009....

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



A lot of exciting physics results were already possible thanks to the superb LHC performance in 2011

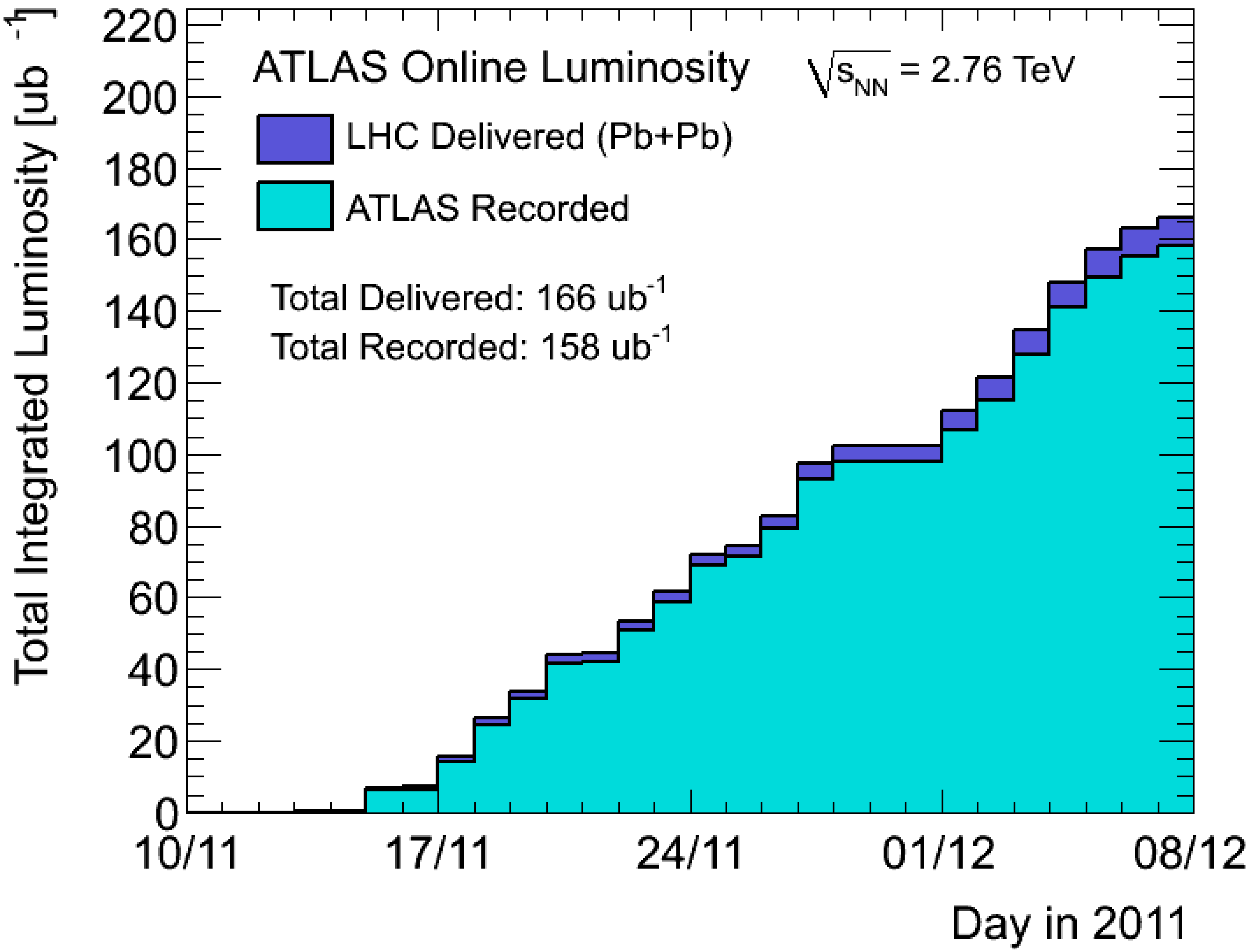




500’000’000’000’000 collisions in 2011
Increased by more than 100
Data taking efficiency 94%

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

Heavy Ion Running in 2011



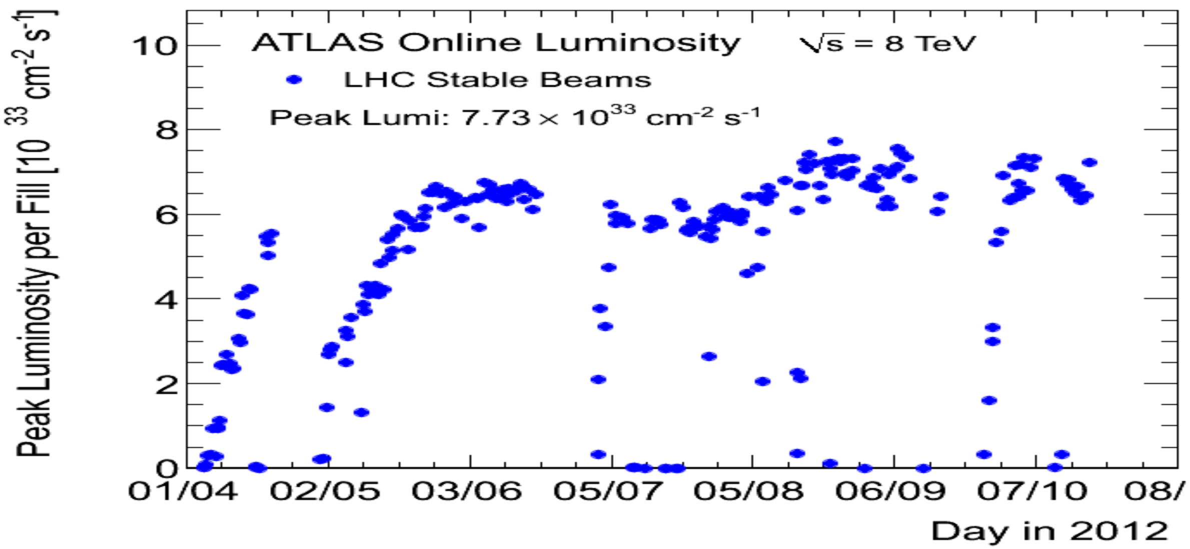
During the short Winter shut-down on 8 March 2012:
Visit of the Deputy Minister Ivan Wilhelm in ATLAS

Current LHC Operation:

1380 bunches per beam

50 ns bunch spacing

1.5 x 10^{11} protons / bunch

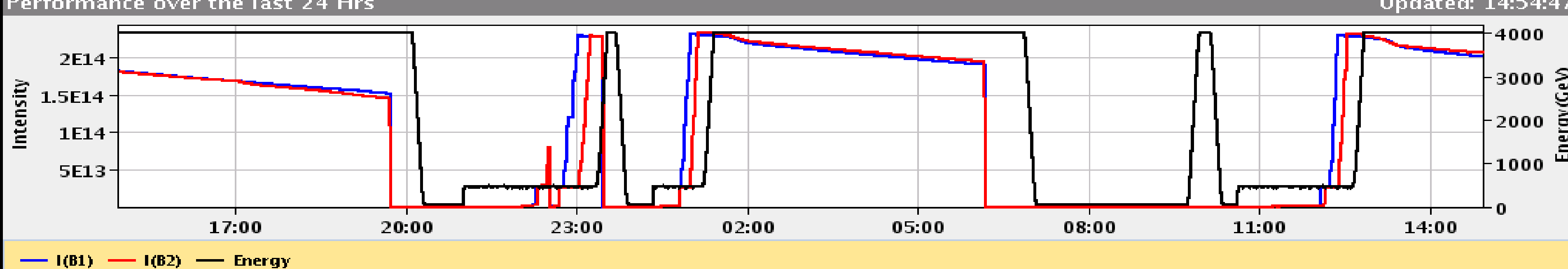


22–Oct–2012 14:54:48 Fill #: 3208 Energy: 4000 GeV I(B1): 2.02e+14 I(B2): 2.07e+14

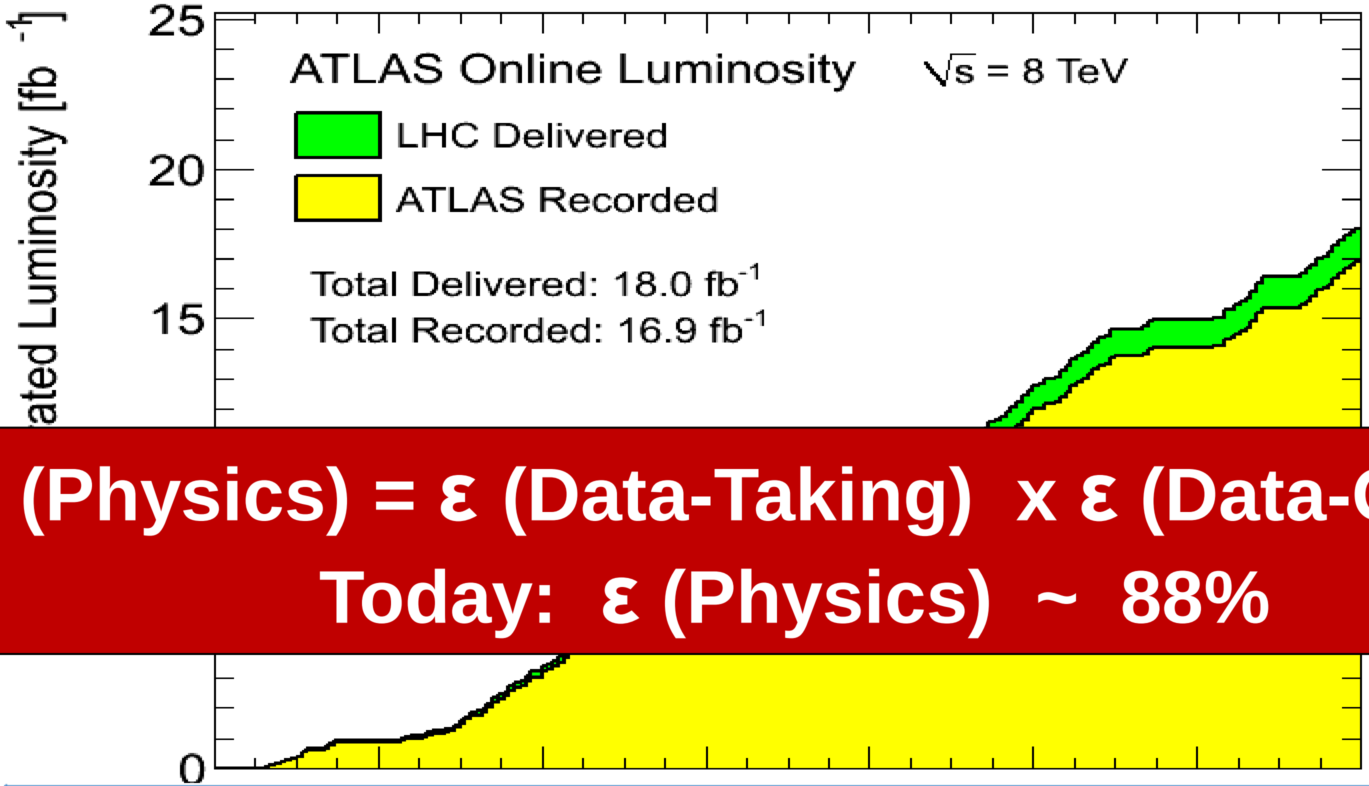
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi [(ub.s)^–1]	5394.2	5.976	5253.7	398.0
BRAN Luminosity [(ub.s)^–1]	5351.2	3.943	4618.0	240.2
Fill Luminosity (nb)^–1	28330.6	30.5	24854.2	1727.9
BKGD 1	0.724	0.834	2.375	0.911
BKGD 2	104.642	0.000	3.854	27.452
BKGD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



But the LHC (at 8 TeV) and ATLAS performances are even more fantastic this year



ε (Physics) = ε (Data-Taking) x ε (Data-Quality)

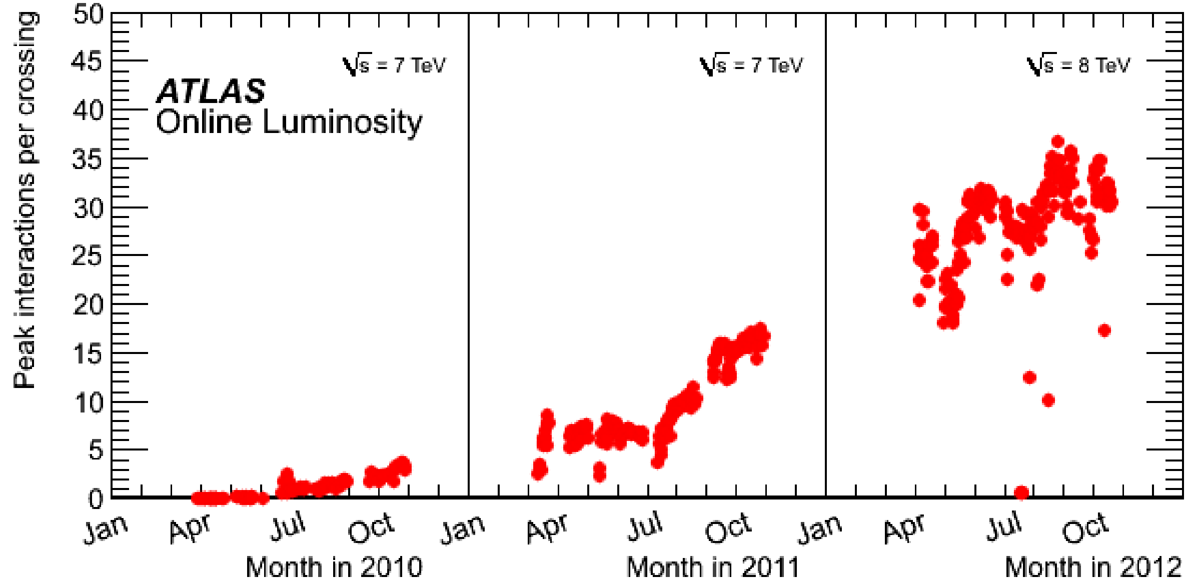
Today: ε (Physics) ~ 88%

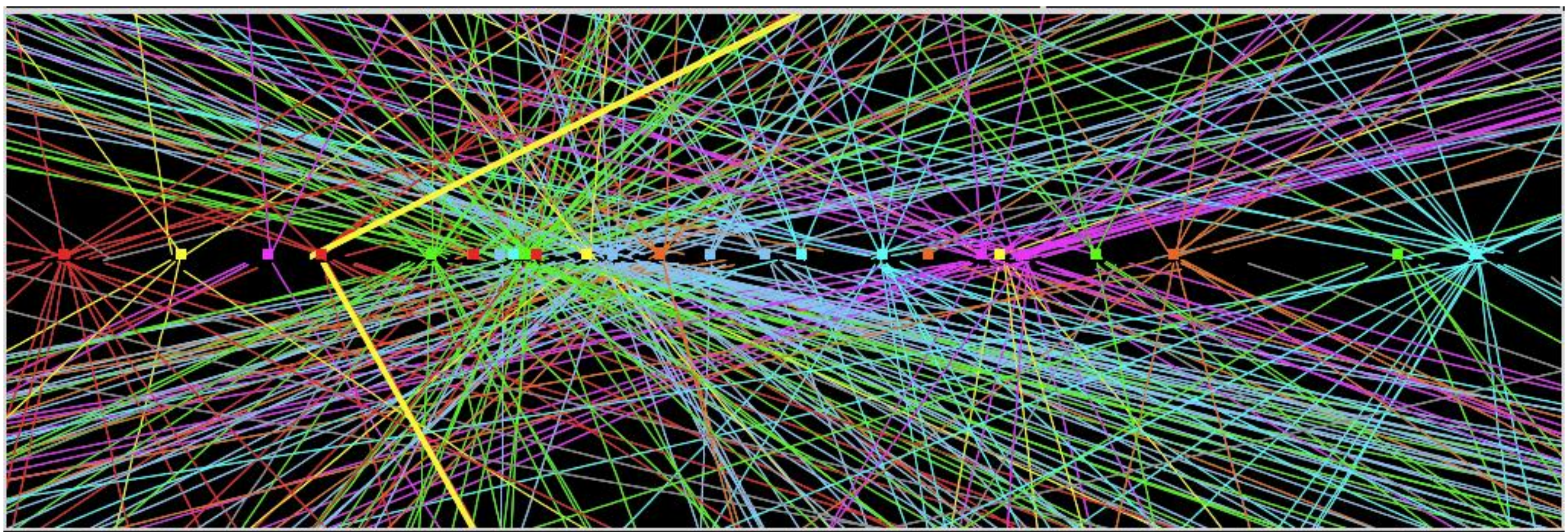
Data Quality	ATLAS p-p run: April-Sept. 2012									
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.3	99.5	97.0	99.6	99.9	99.8	99.9	99.9	99.7	99.2
All good for physics: 93.7%										

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and September 17th (in %) – corresponding to 14.0 fb^{-1} of recorded data. The inefficiencies in the LAr calorimeter will partially be recovered in the future.

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

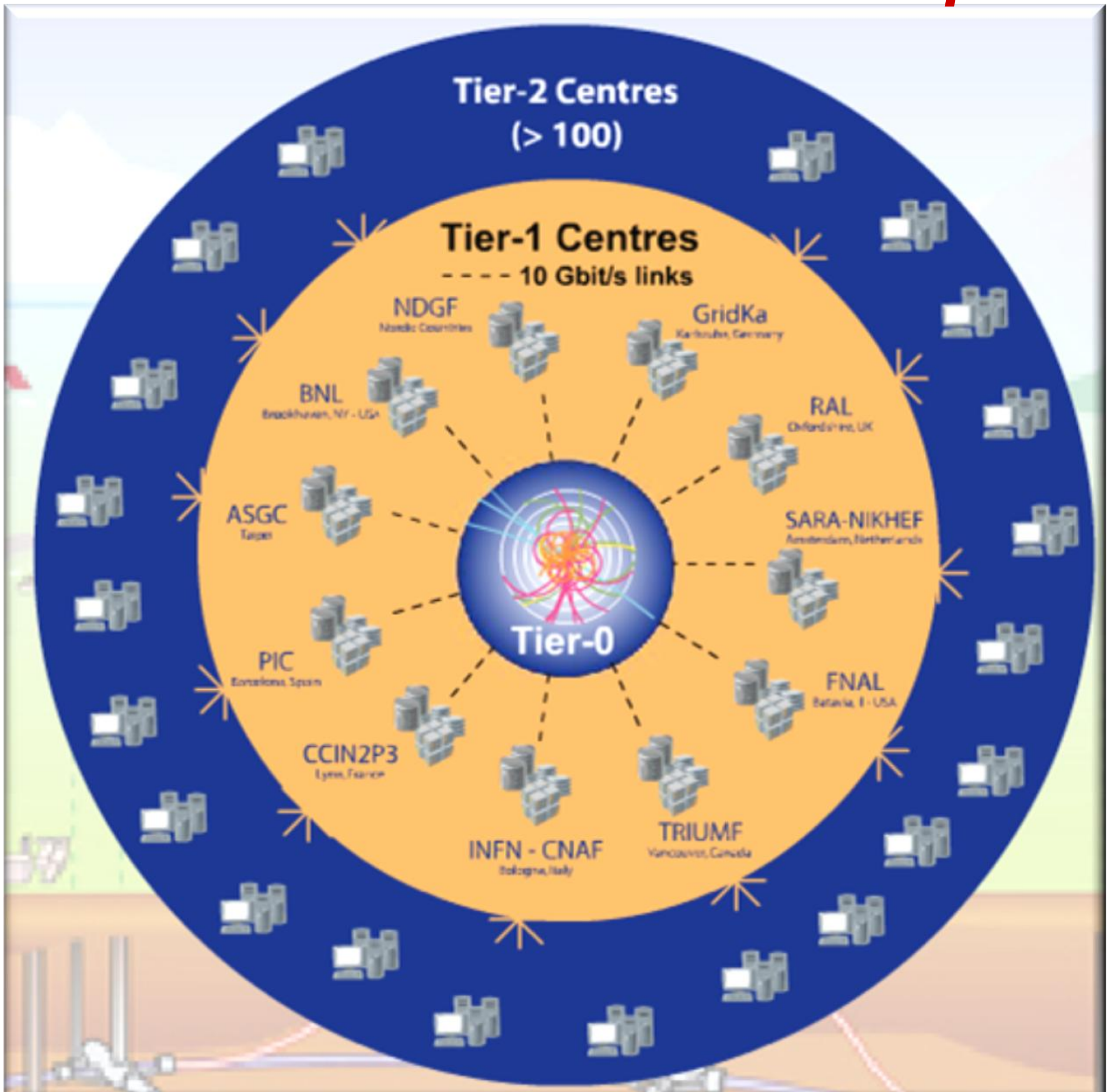
- **Trigger**
- **Pile-up**
- **Maintain accuracy of the the measurements in this environment**





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

The Worldwide LHC Computing Grid (wLCG)



WLCG
Worldwide LHC Computing Grid

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

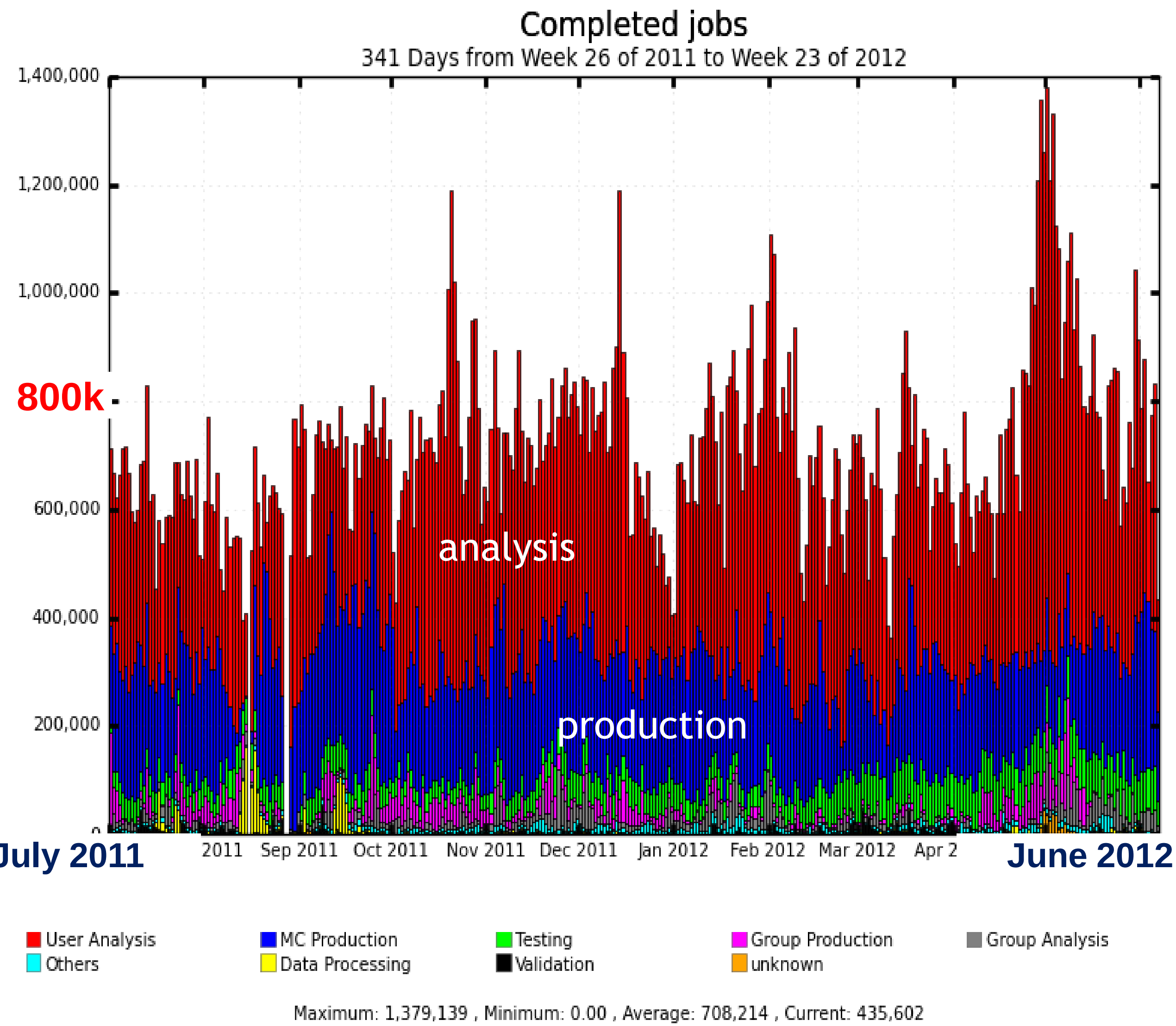
Tier-1 (11 centres):
- Permanent storage
- Re-processing
- Analysis
- Simulation

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

The large ATLAS Prague Tier-2 works very efficiently

Computing Grid Delivers Physics

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



Data preparation:

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

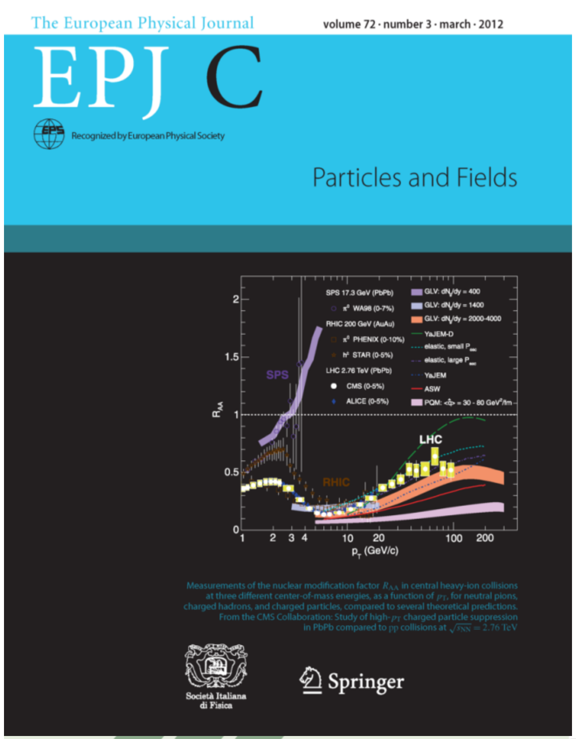
The high quality of the WLCG computing system allows LHC experiments to show results from data taken just few weeks before

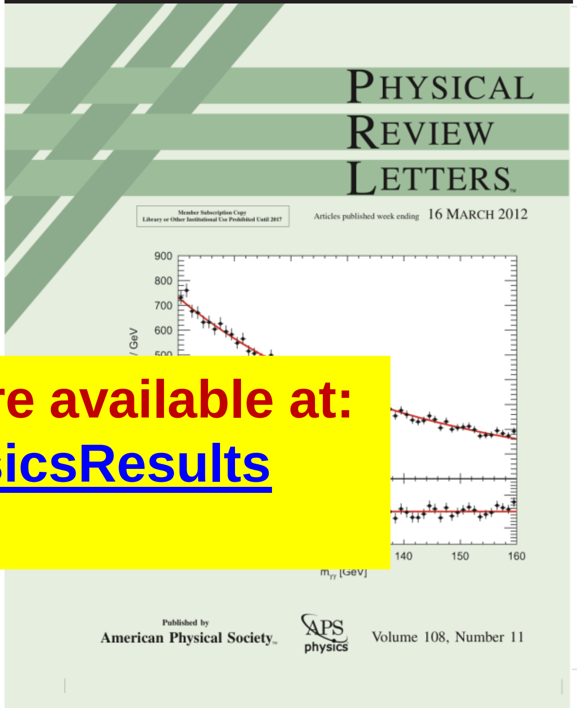
First Physics Highlights

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

It is obviously not possible to cover all these results…

No attempt is made to show in a democratic way always CMS and ATLAS results, but often ATLAS examples are given that represent typically results from both!





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

Physics Highlights:

General event properties

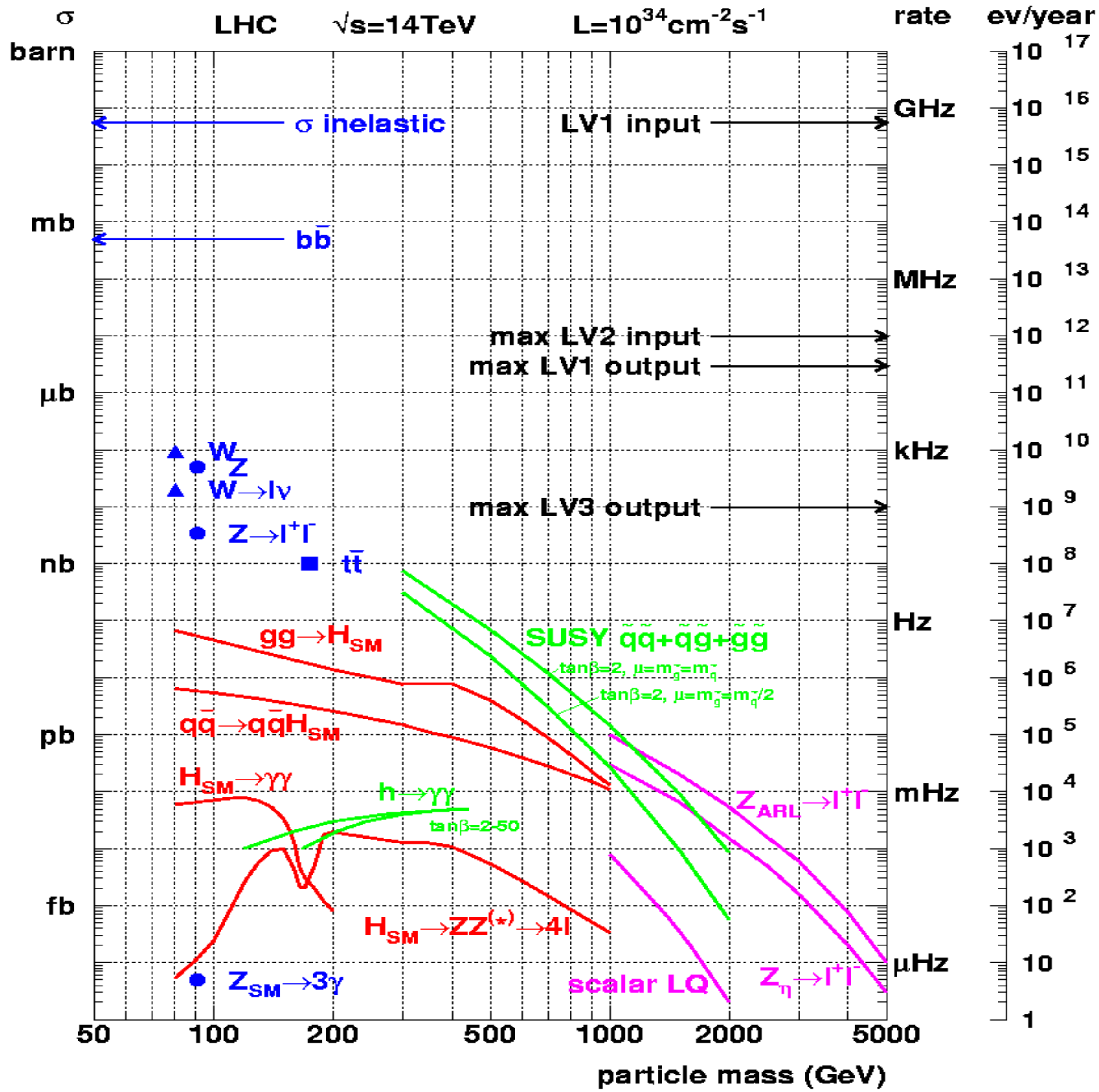
Heavy flavour physics

Standard Model physics including QCD jets

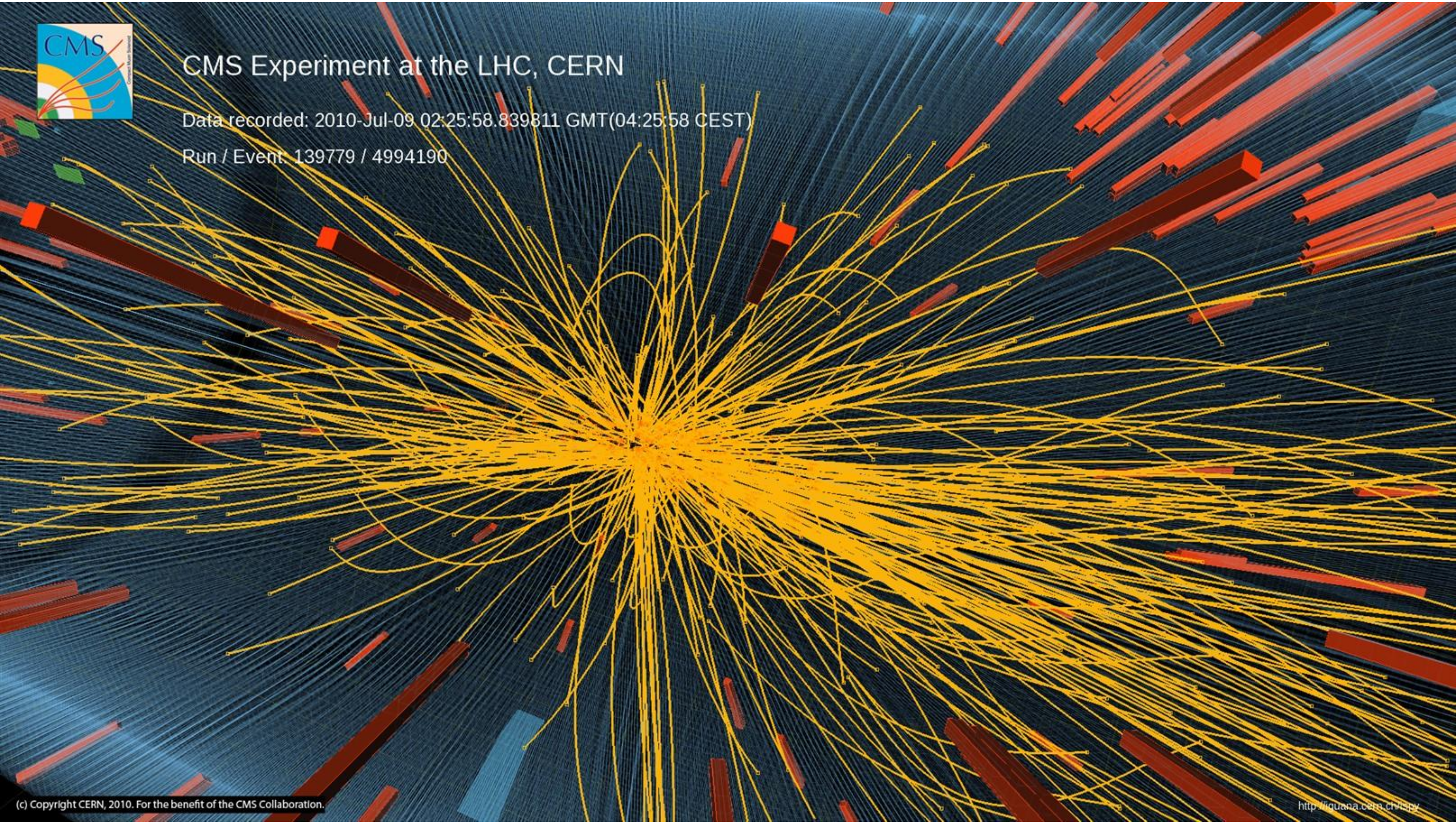
Higgs searches

Searches for SUSY

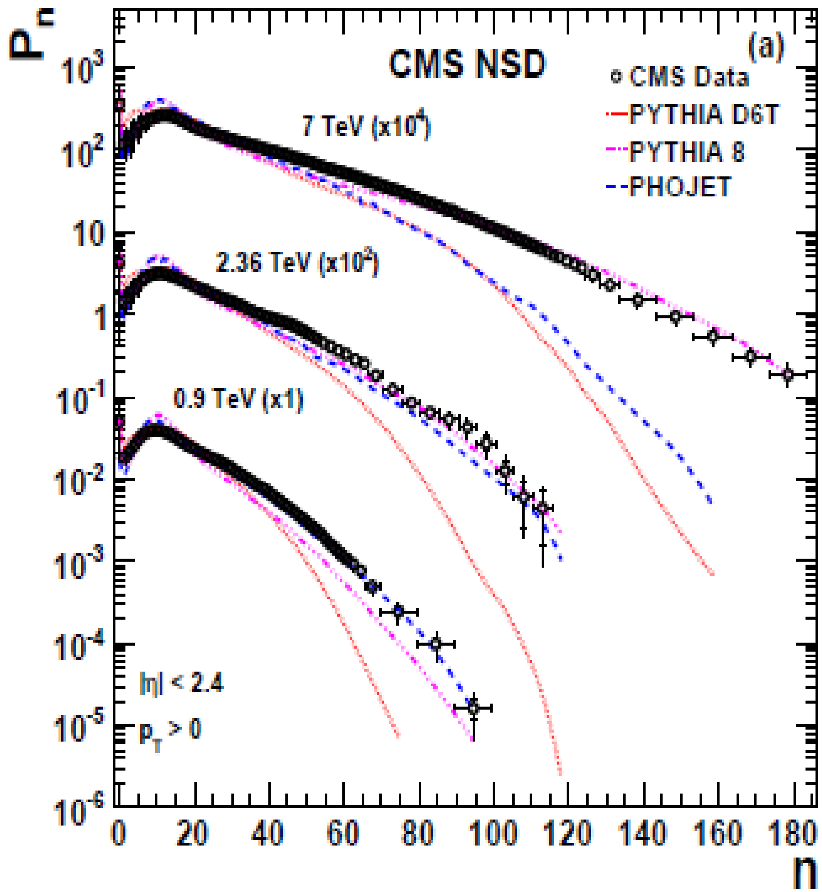
Examples of searches for ‘exotic’ new physics



General Event Properties and Resonances

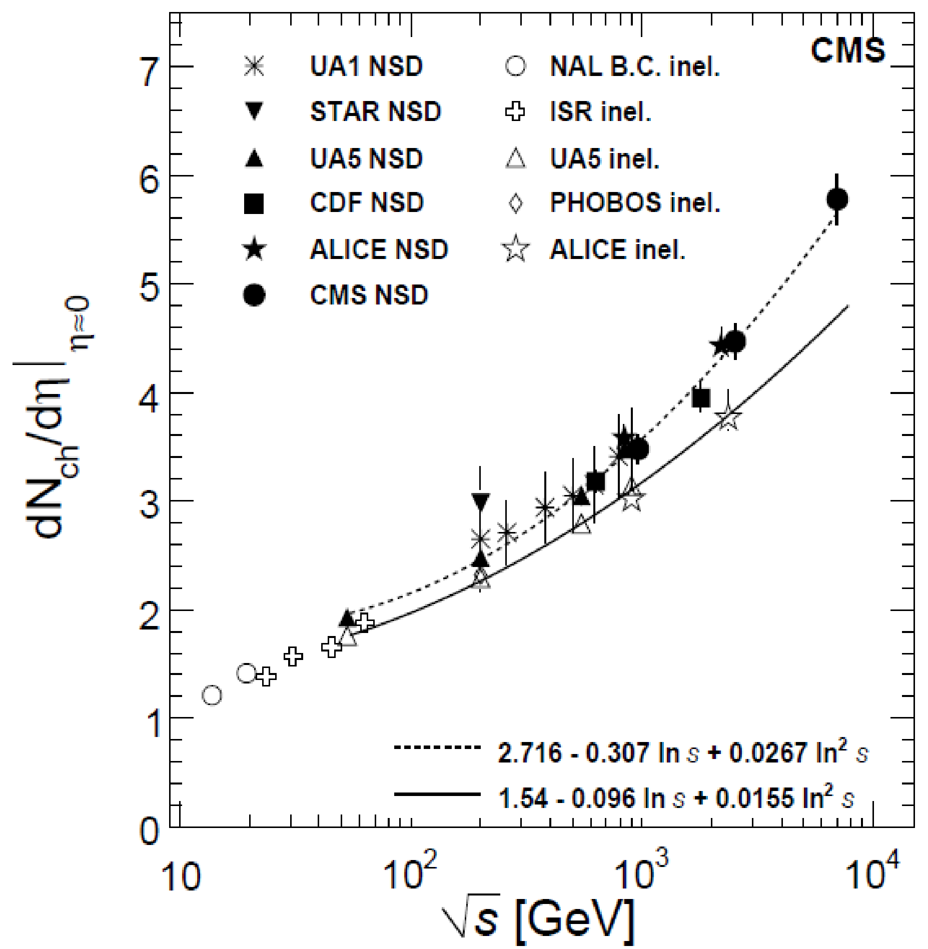


Charged hadron multiplicities at the three different √s



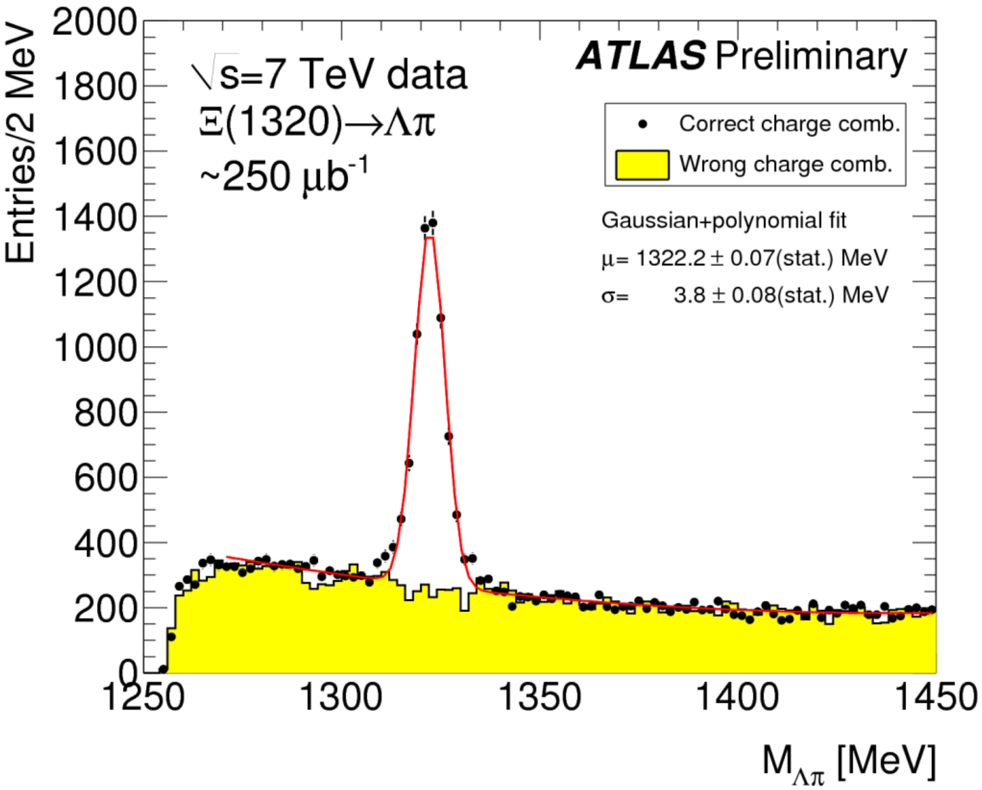
JHEP 01 (2011) 079

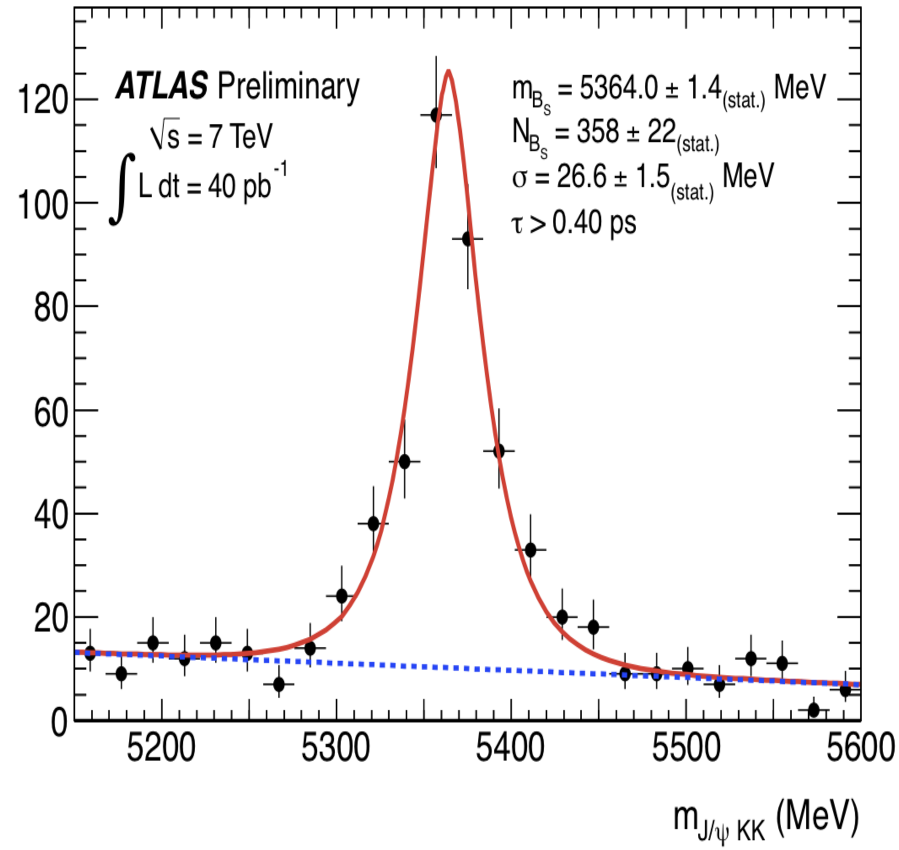
Average charged particle density for the central η region (pp and p̄p)



Phys. Rev. Lett. 105 (2010) 022002

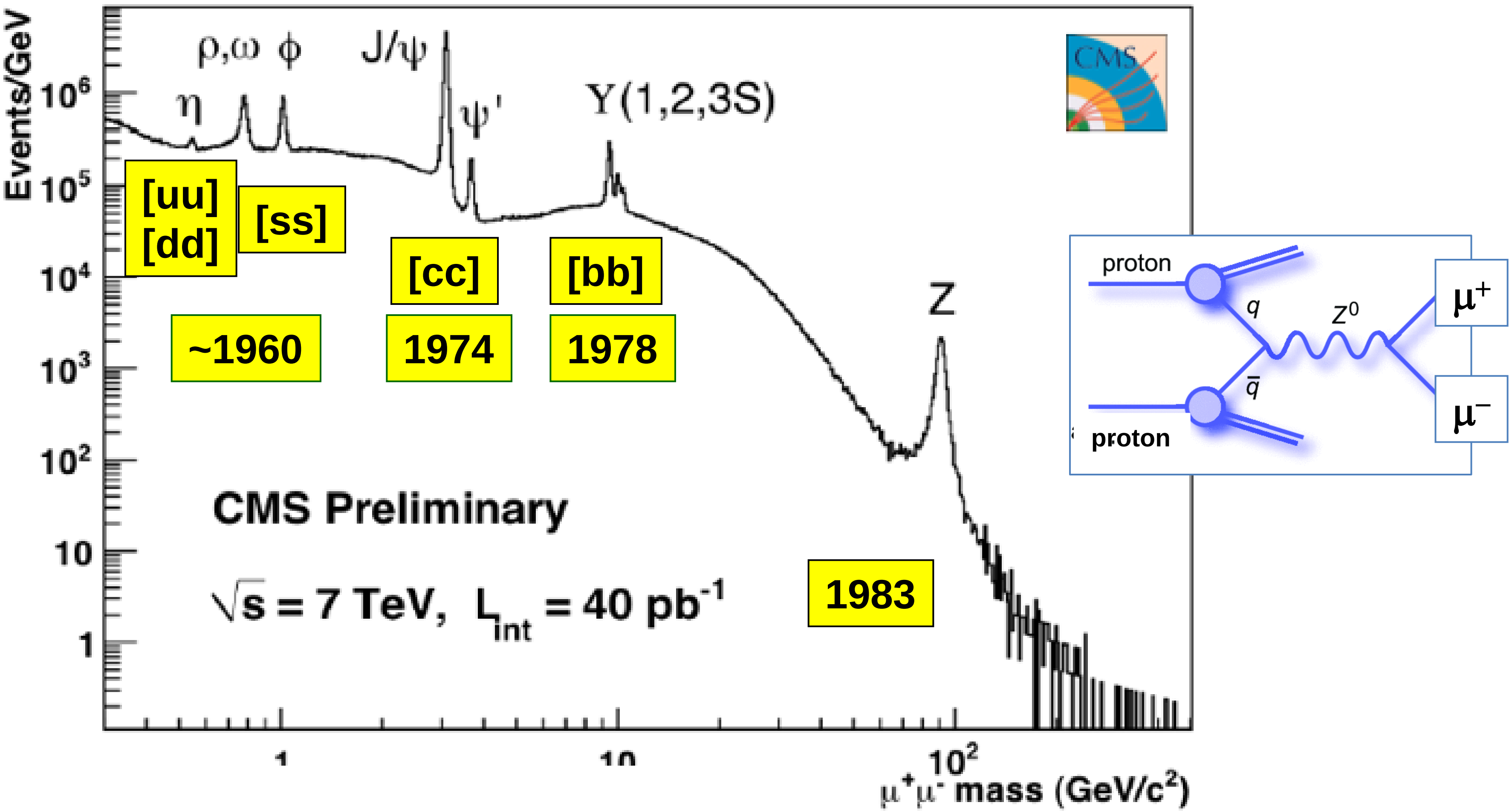
Examples of reconstructed final states





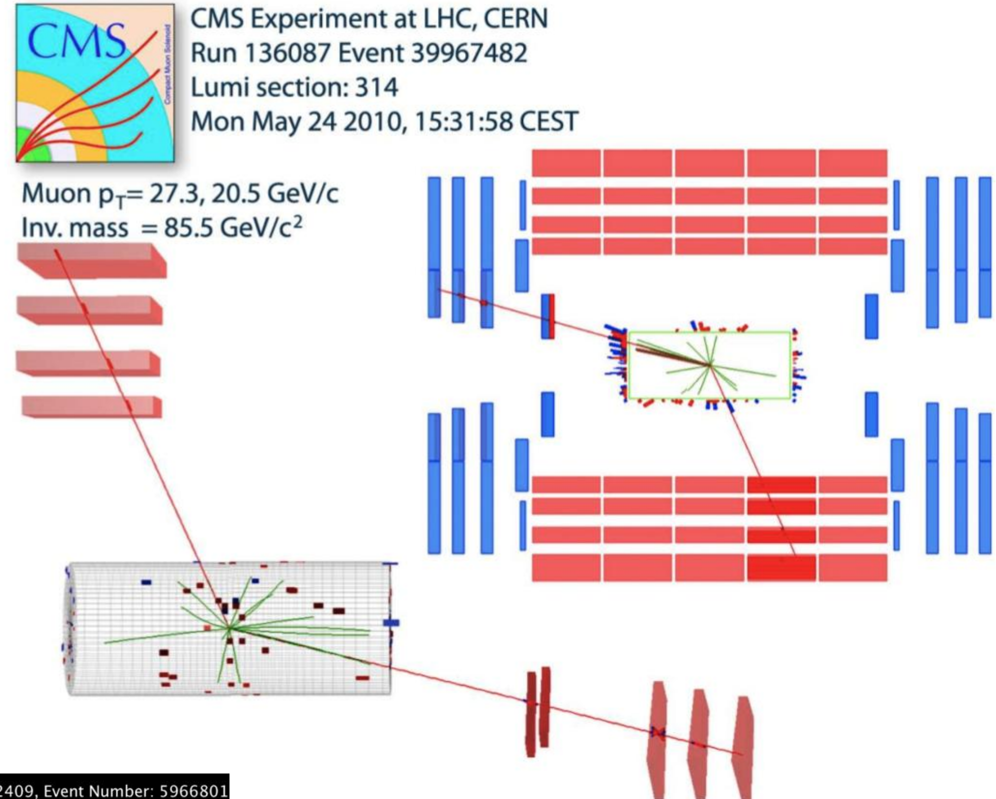
2010

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



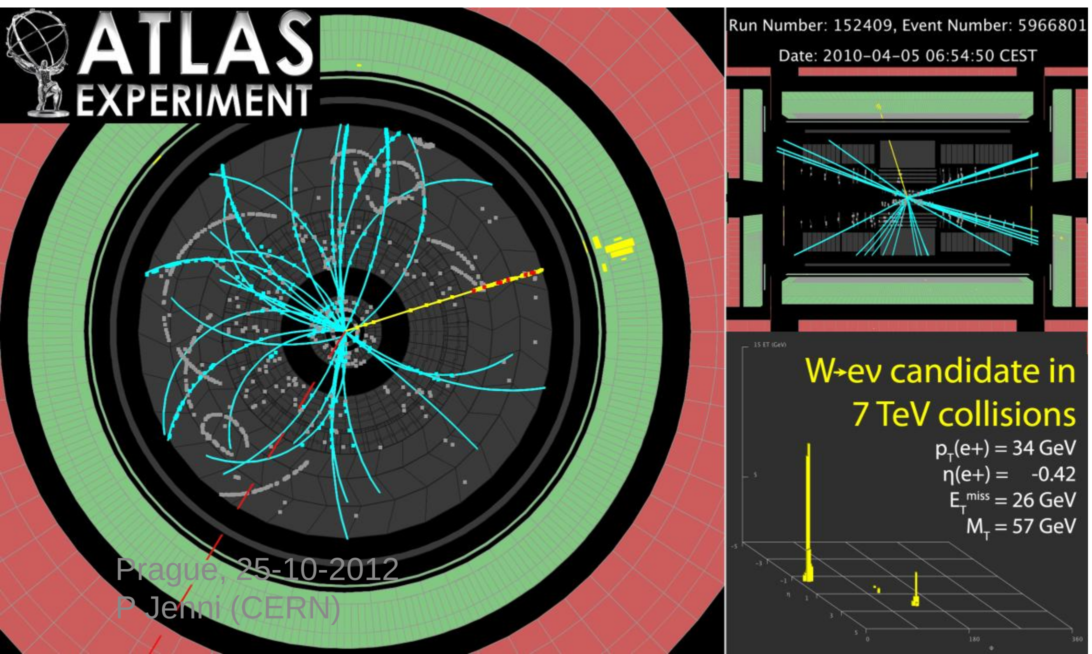
The di-muon spectrum recalls a long period of particle physics:
Well known quark-antiquark resonances (bound states) appear "online"

Standard Model Physics



Candidate Z → $\mu^+\mu^-$

W → eν candidate



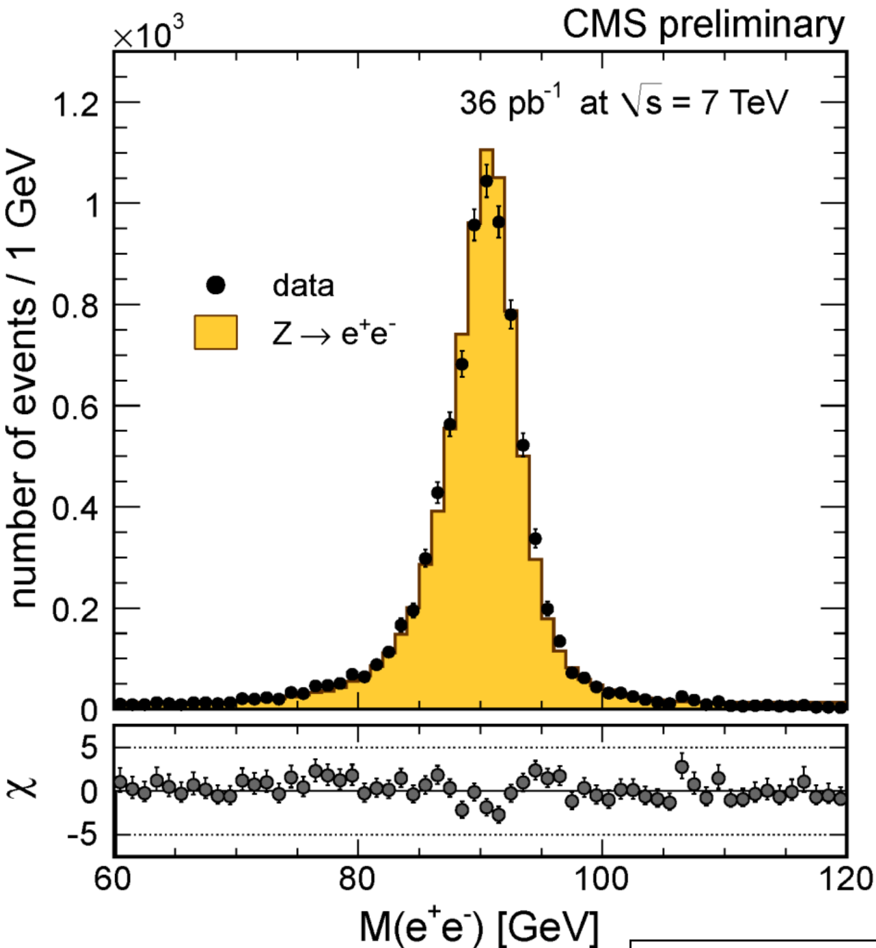
In its 2011 dataset (~ 5 fb^{-1}) ATLAS has:

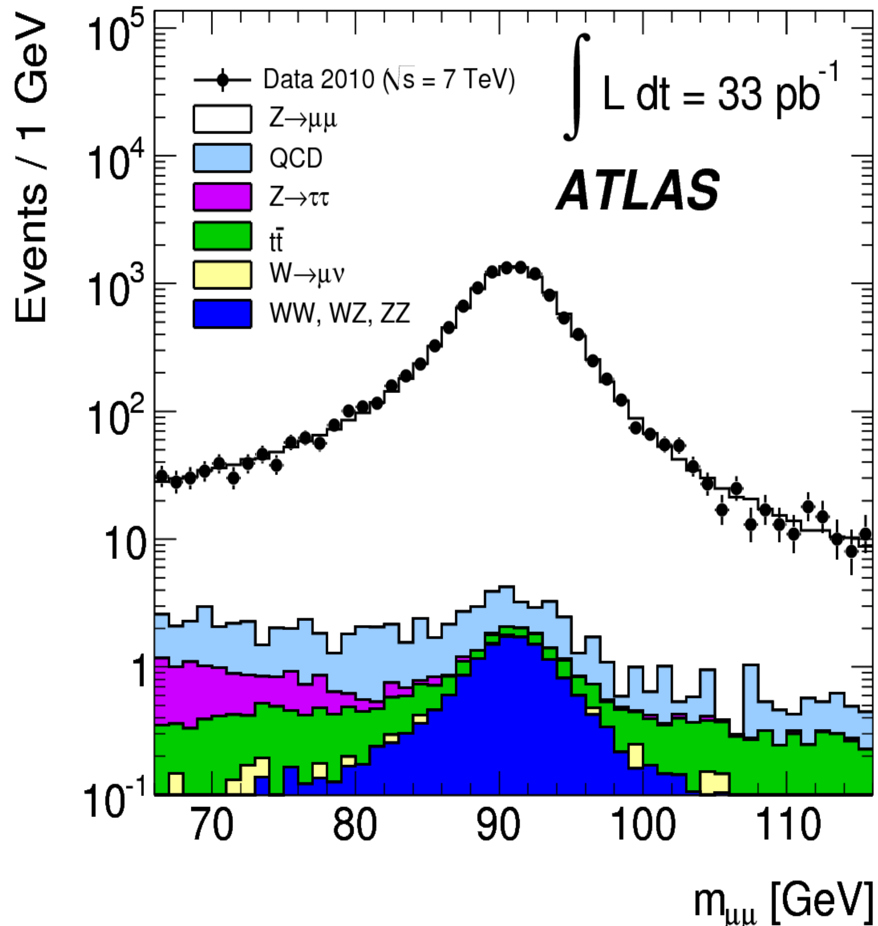
~ 30 M W→ μν, eν events
~ 3 M Z → μμ, ee events

after all selection cuts

Z and W production

Phys Rev D85 (2012) 072004



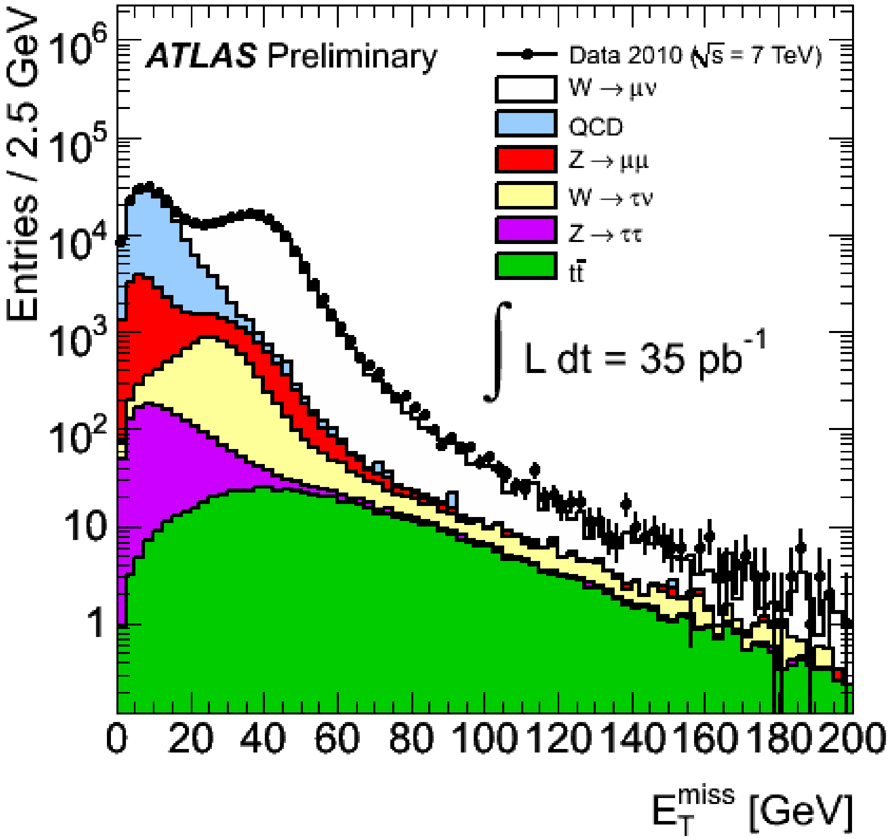


JHEP 10 (2011) 132

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

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

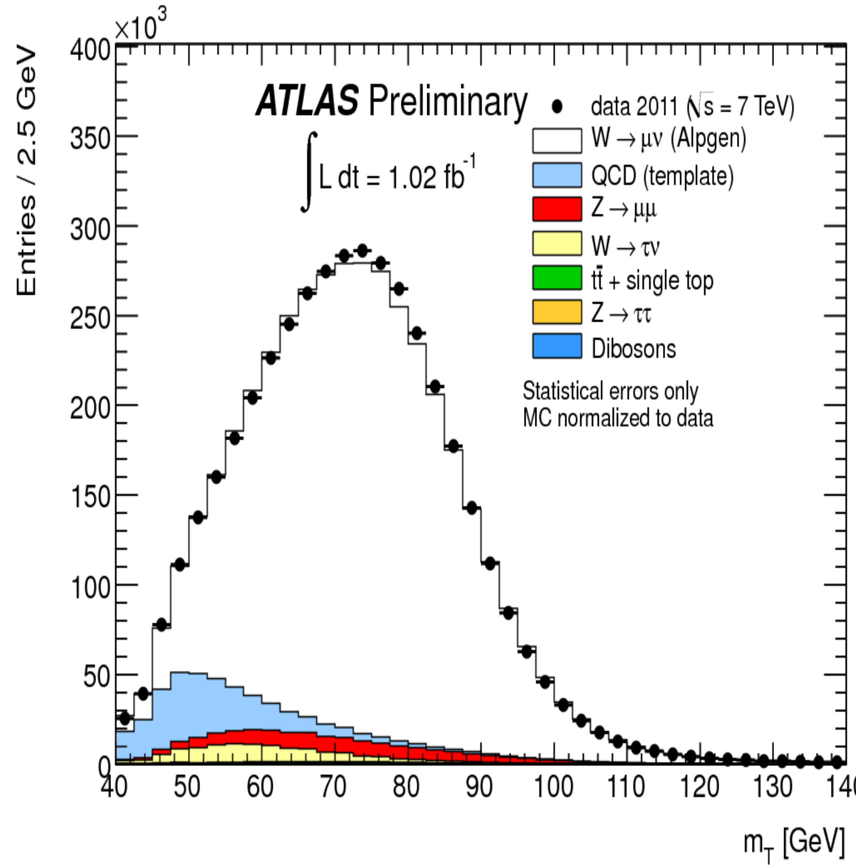
W transverse mass



Missing transverse energy from the W → μ + ν decays

ATLAS-CONF-2011-041

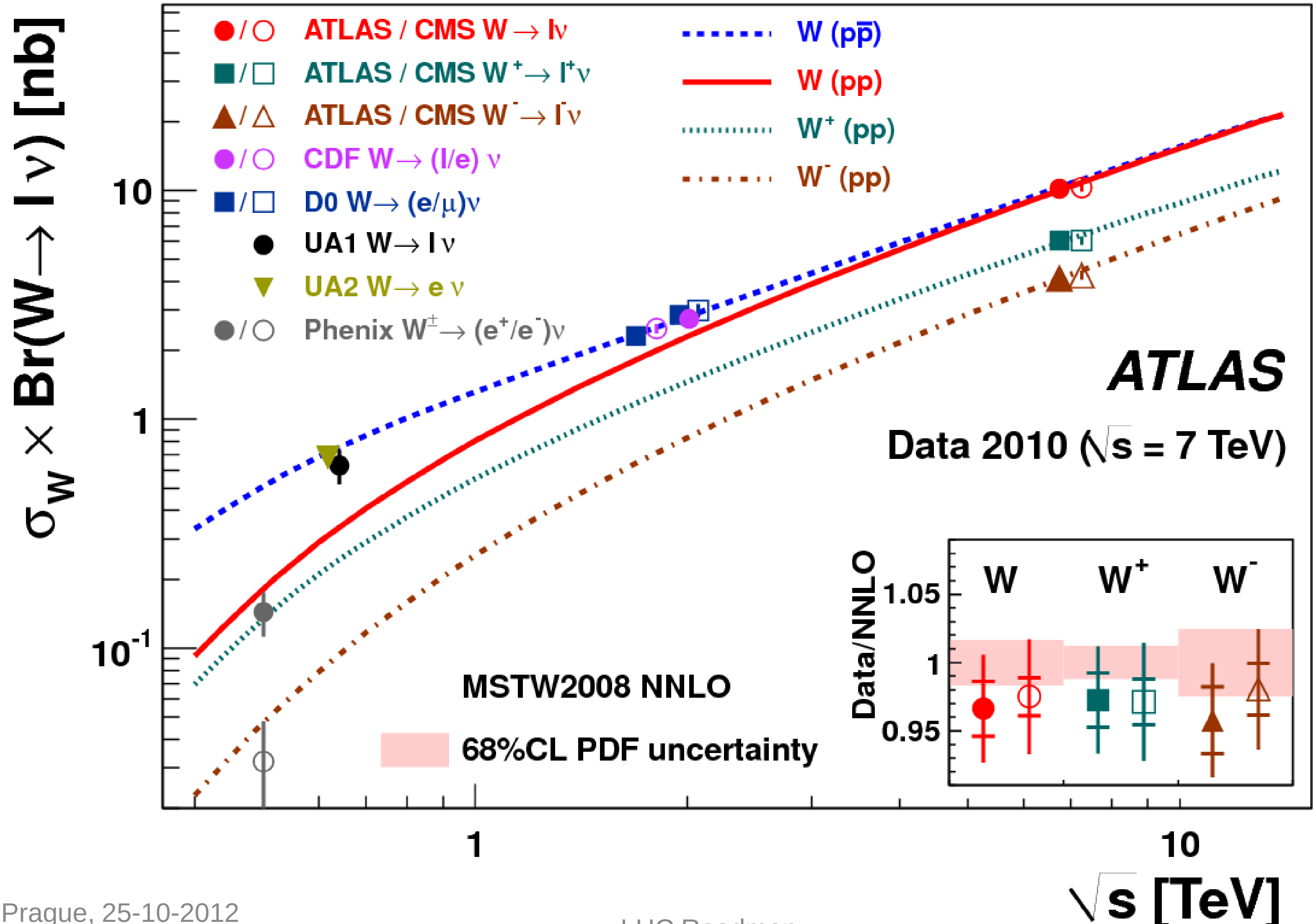
μ with p_T>20 GeV, E_T^{miss}>25 GeV



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

W cross section measurement with e and μ

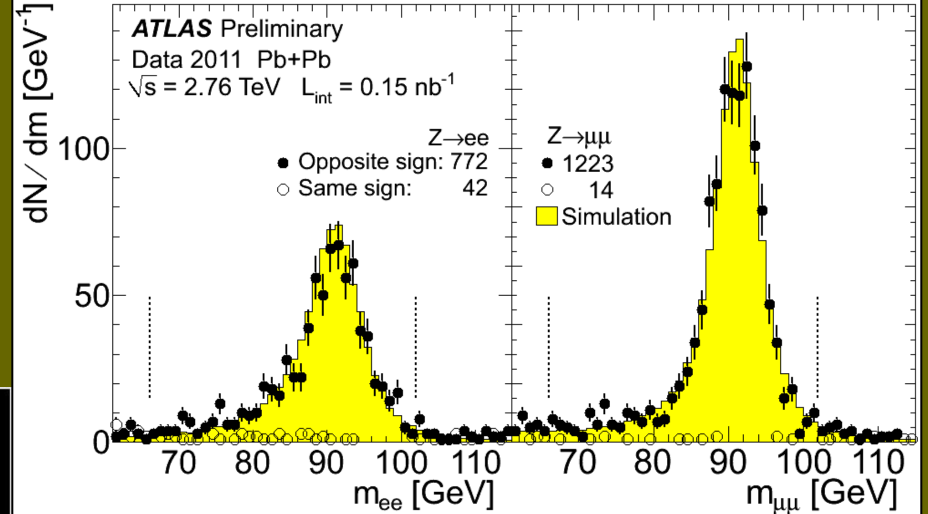
Phys Rev D85 (2012) 072004

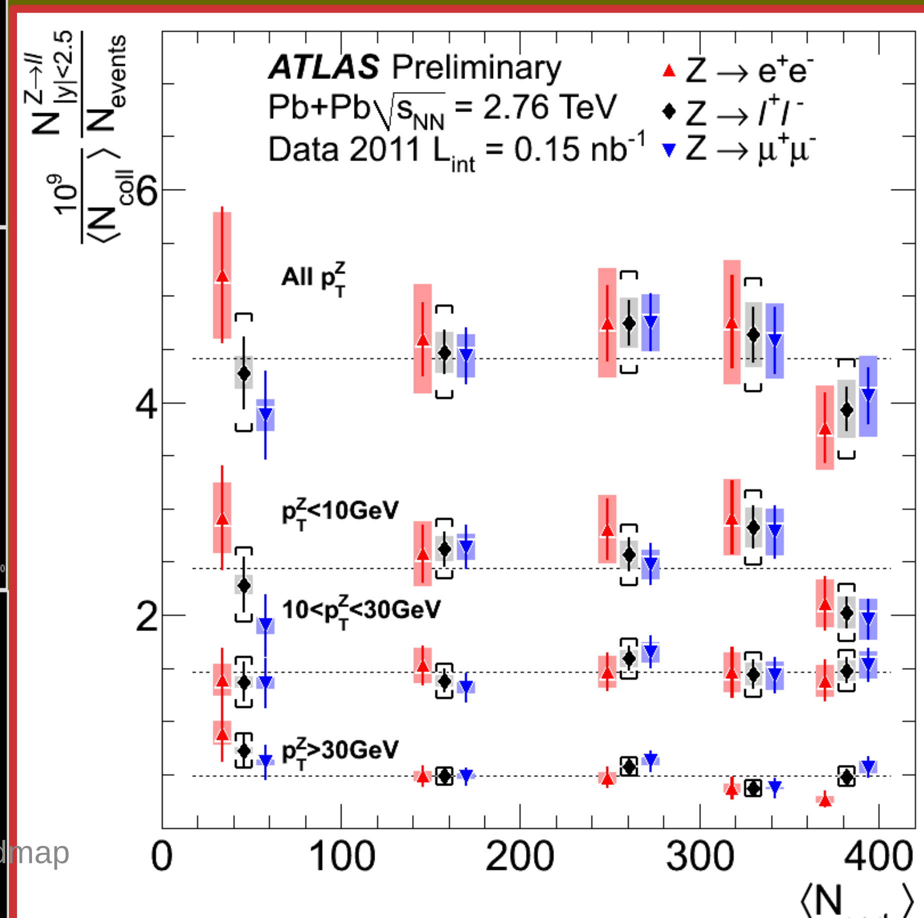


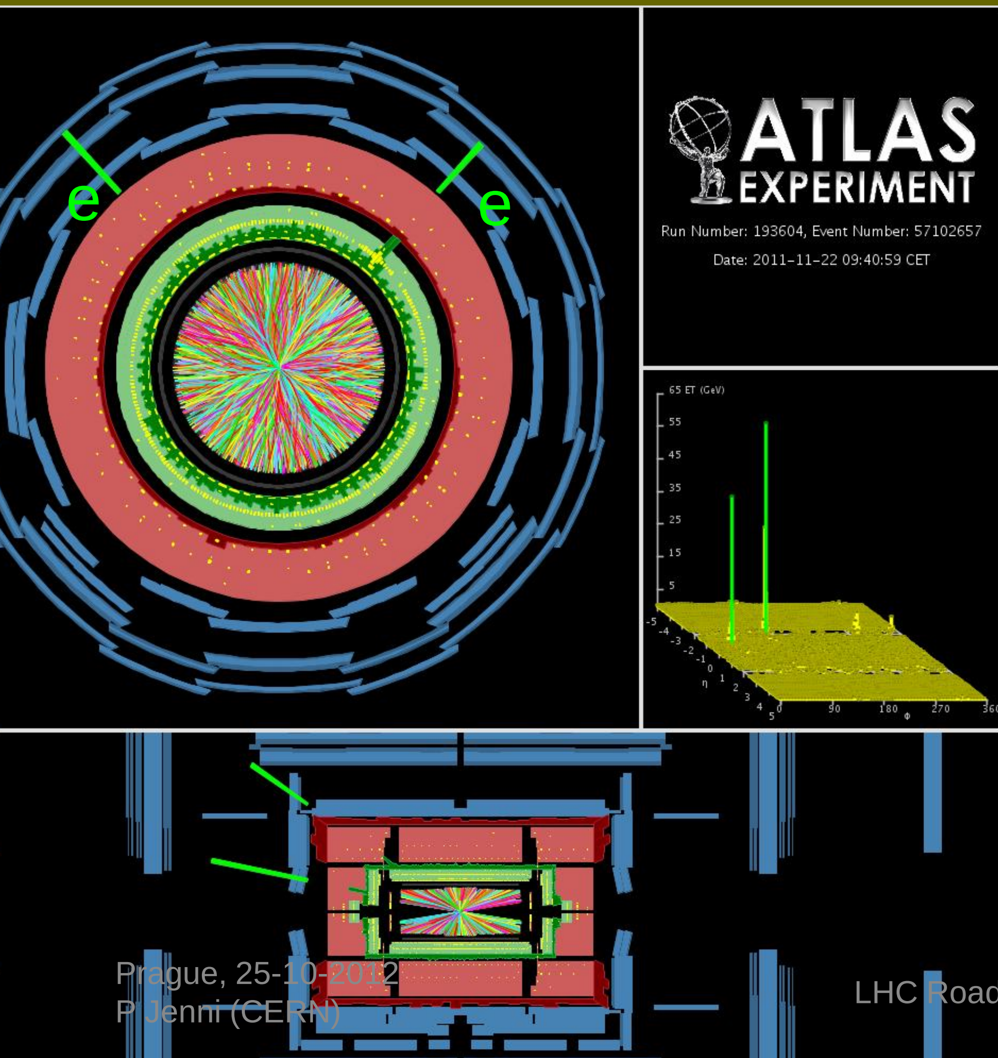
Z → ee, μμ in Heavy Ions

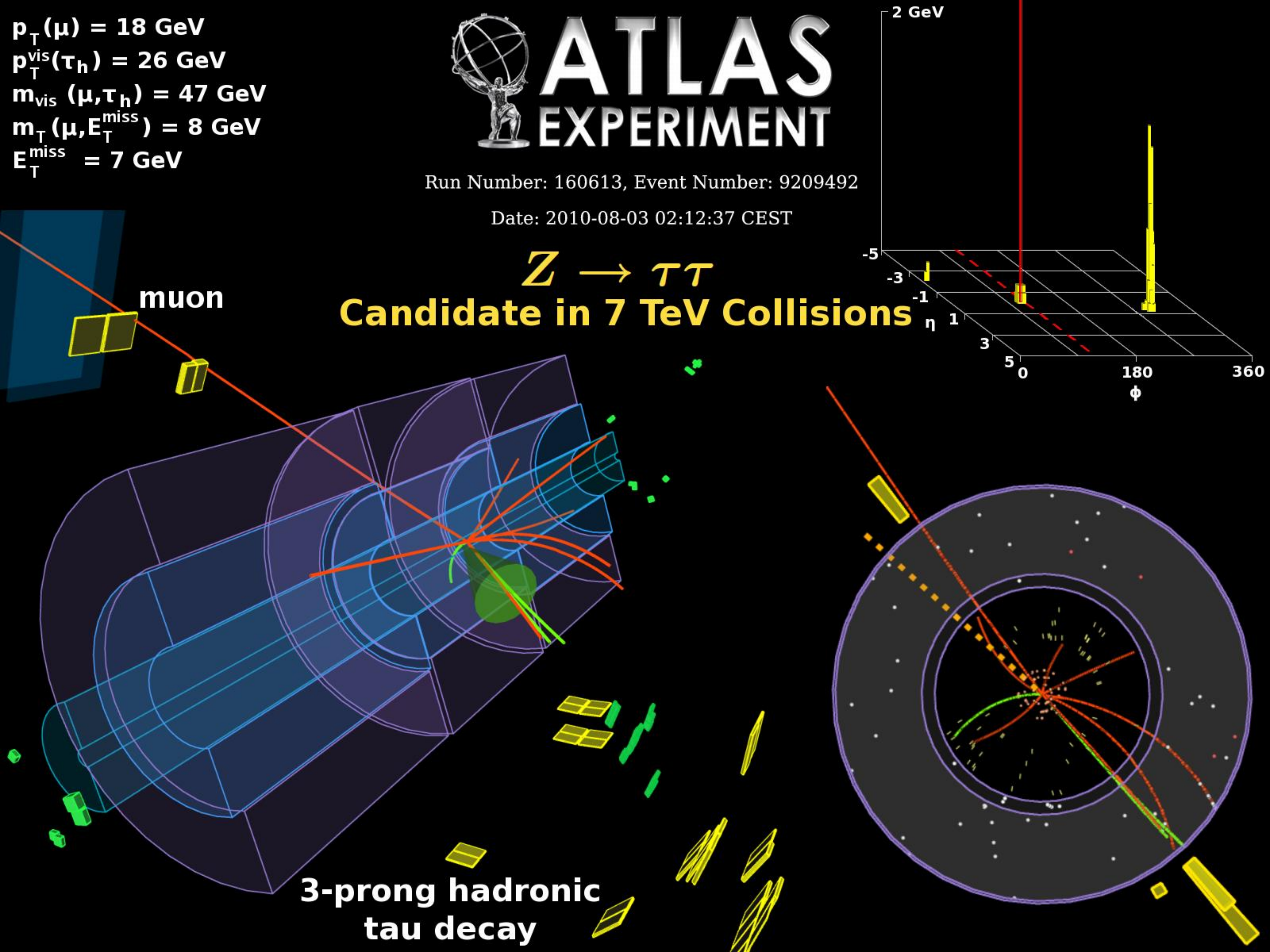
- Studied with full 2011 dataset (~ 150 μb^{-1})
- As expected: no suppression observed of the weakly interacting bosons

ATLAS-CONF-2012-119





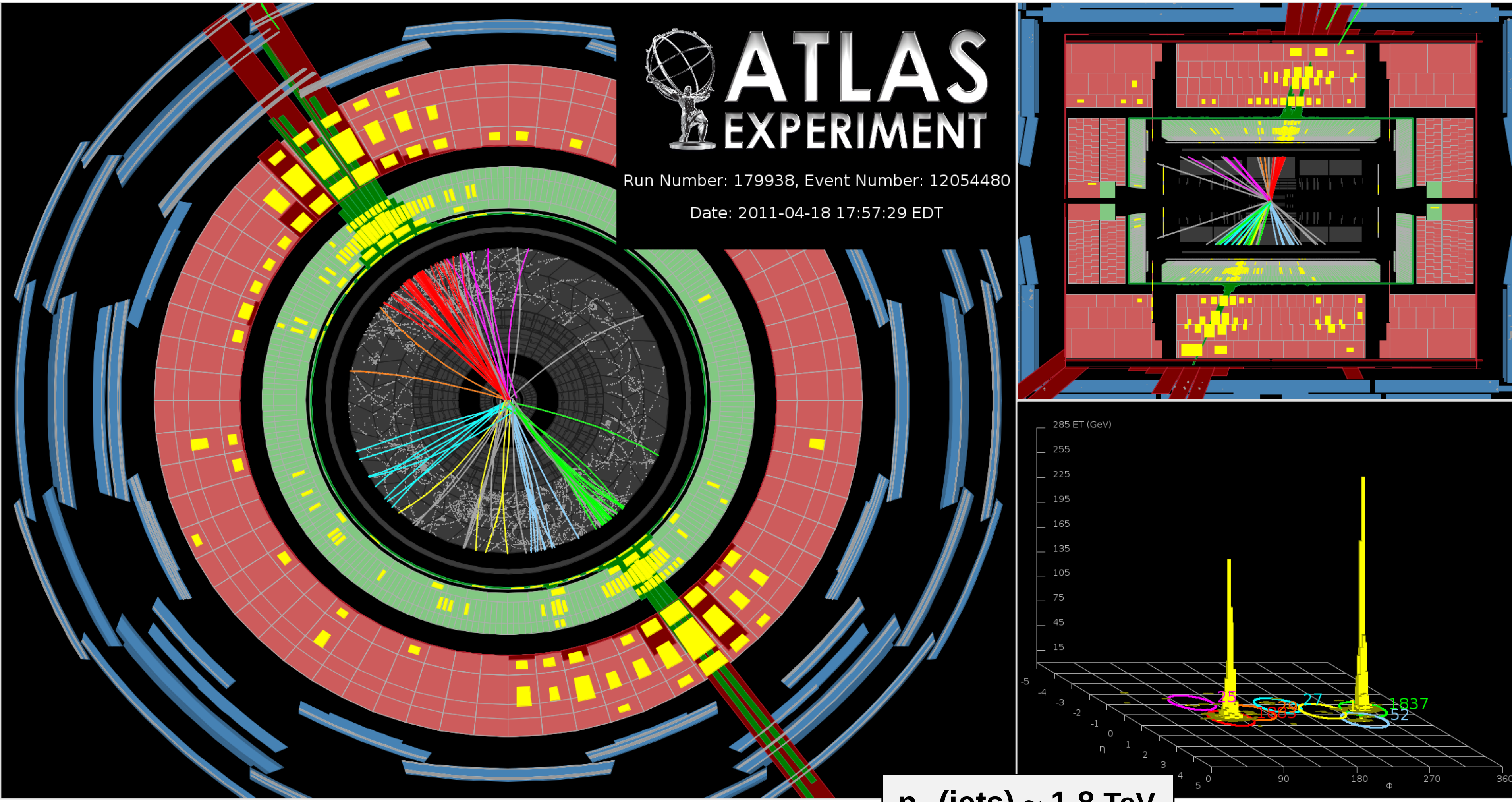




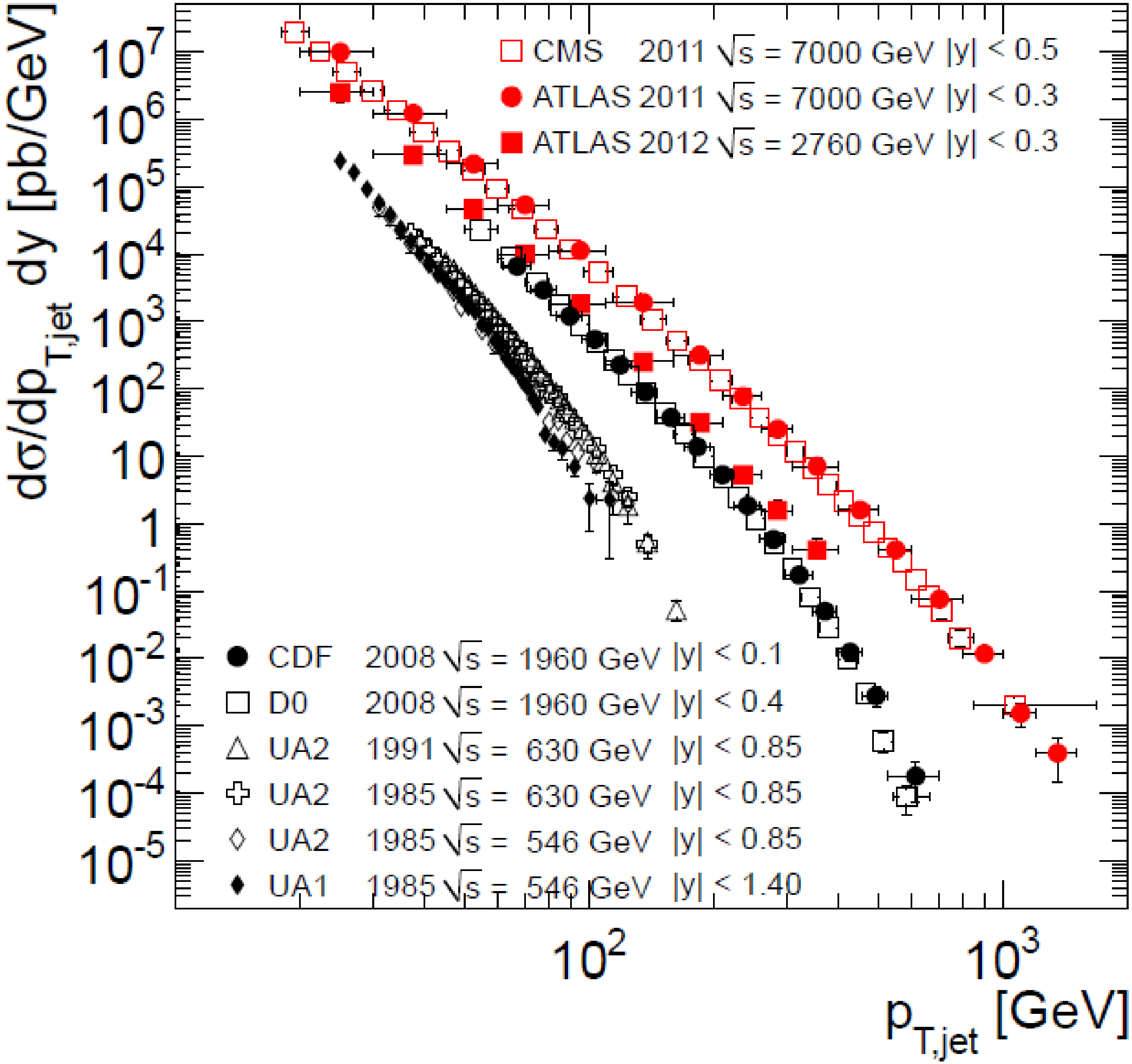
$p_T(\mu)$ = 18 GeV
$p_T^{vis}(\tau_h)$ = 26 GeV
$m_{vis}(\mu,\tau_h)$ = 47 GeV
$m_T(\mu,E_T^{miss})$ = 8 GeV
E_T^{miss} = 7 GeV
ATLAS EXPERIMENT
Run Number: 160613, Event Number: 9209492
Date: 2010-08-03 02:12:37 CEST
$Z \rightarrow \tau\tau$
Candidate in 7 TeV Collisions
muon
3-prong hadronic tau decay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

Jet physics

One of the most spectacular dijet events: M_{jj} ~ 4 TeV



p_T (jets) ~ 1.8 TeV



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
dσ/dp_T,jet dy [pb/GeV]
p_T,jet [GeV]

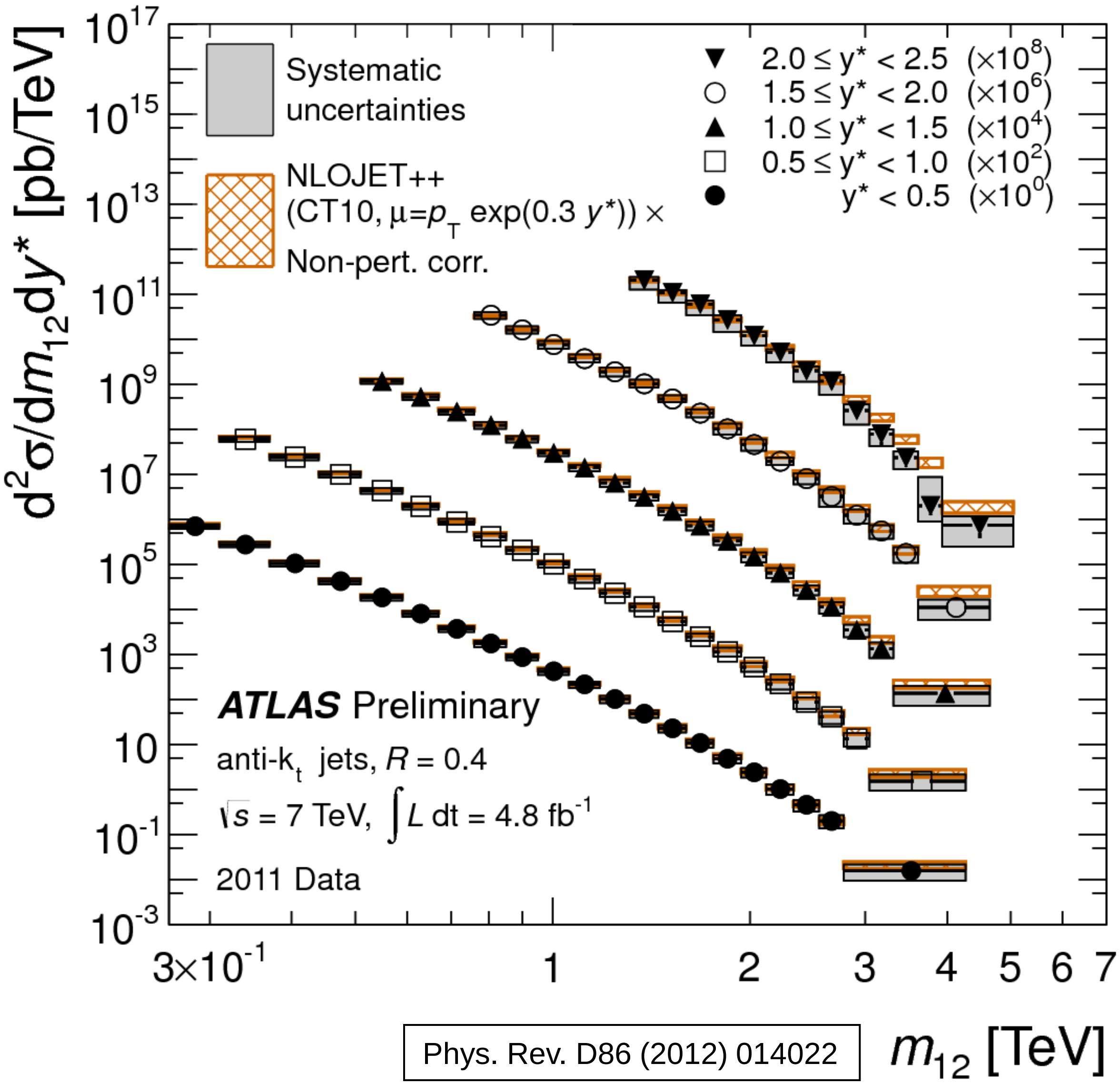
Very detailed jet measurements are now available from LHC that can be compared with QCD calculations …

Example:
The inclusive di-jet cross sections as a function of the di-jet mass for various rapidity separations

The data are spanning jets over a large phase space:

- **20 GeV < p_T < 2 TeV**
- **$|\eta|$ < 4.4**

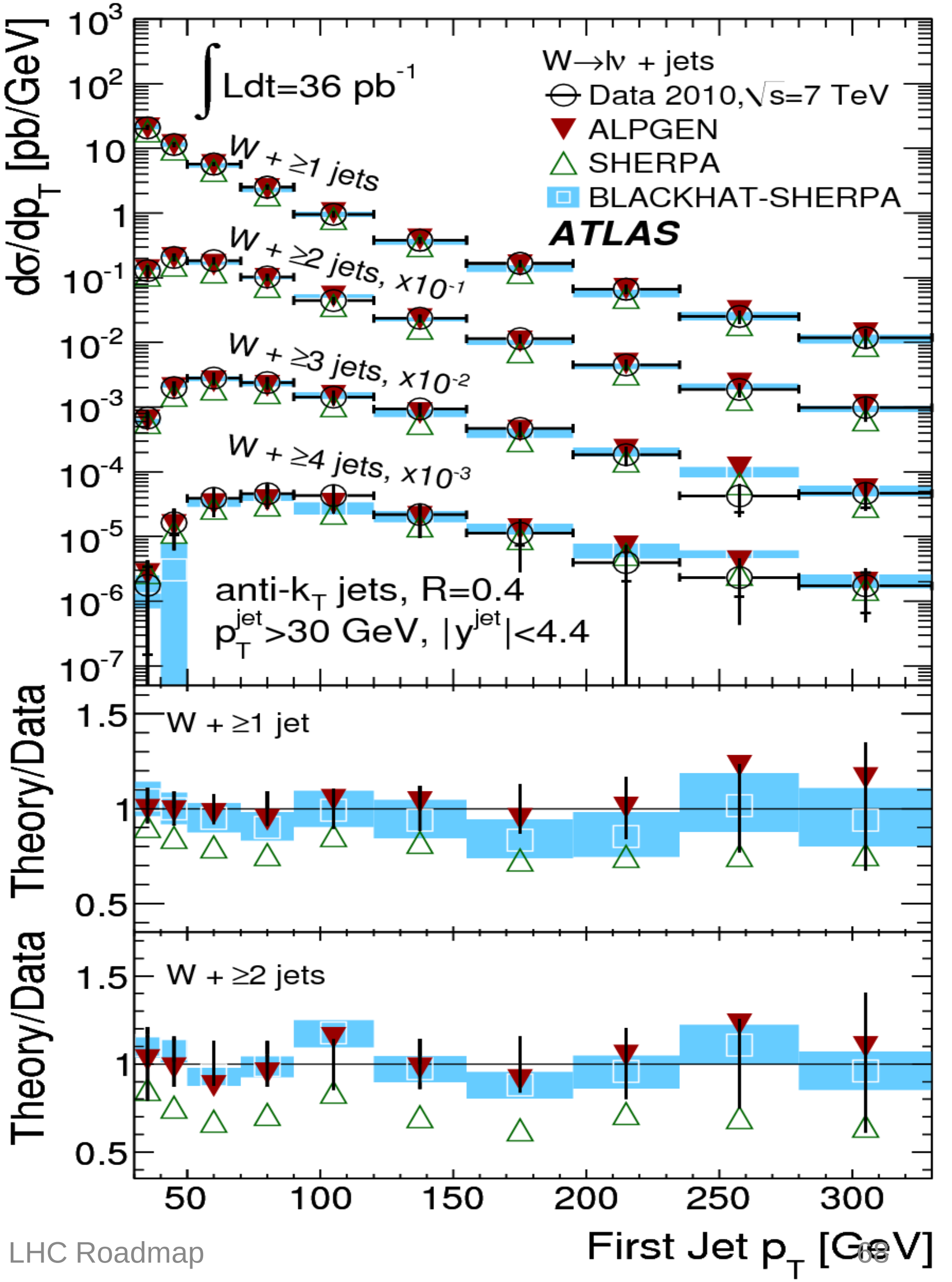
($y^* = 0.5\ |\eta_1 - \eta_2|$)



Phys. Rev. D86 (2012) 014022

W + jet(s) production

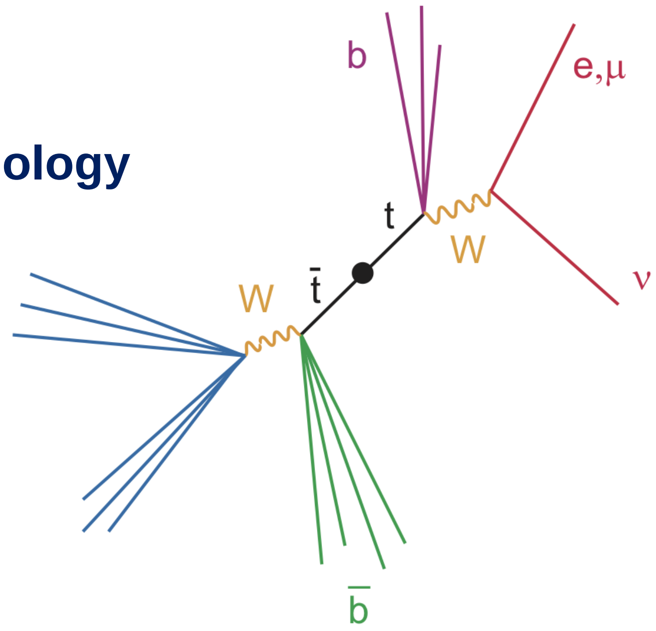
Both an interesting QCD measurement as well as a dominant background to many searches



Phys. Rev. D85 (2012) 092002

Top measurements

- **Complete set of ingredients to investigate production of ttbar, which is the next step in verifying the SM at the LHC:**
  - **e, μ, E_T^{miss}, jets, b-tag**

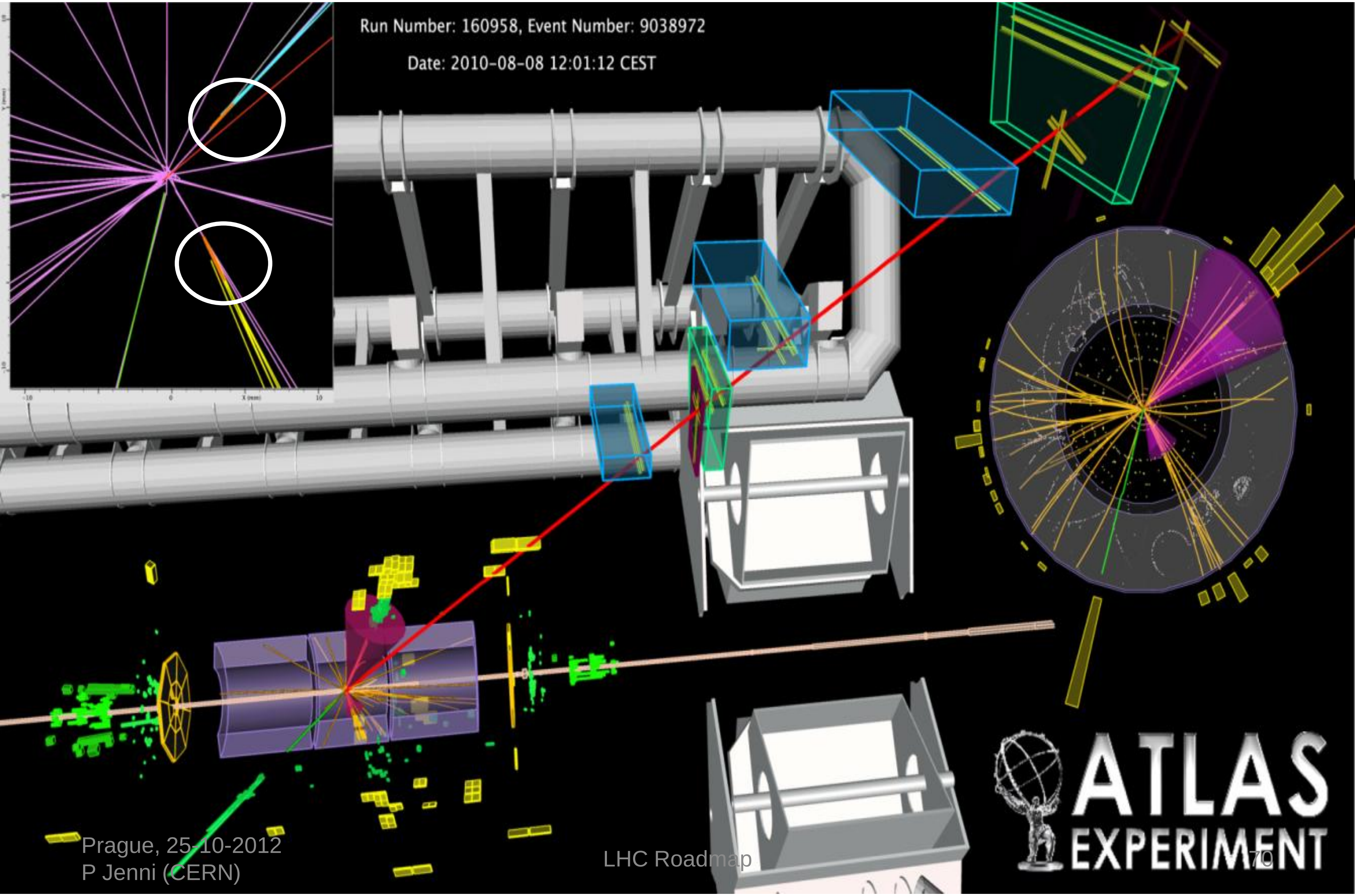


- **Assume all tops decay to Wb: event topology then depends on the W decays:**
  - **one lepton (e or μ), E_T^{miss}, jjbb (37.9%)**
  - **di-lepton (ee, $\mu\mu$ or eμ), E_T^{miss}, bb (6.46%)**

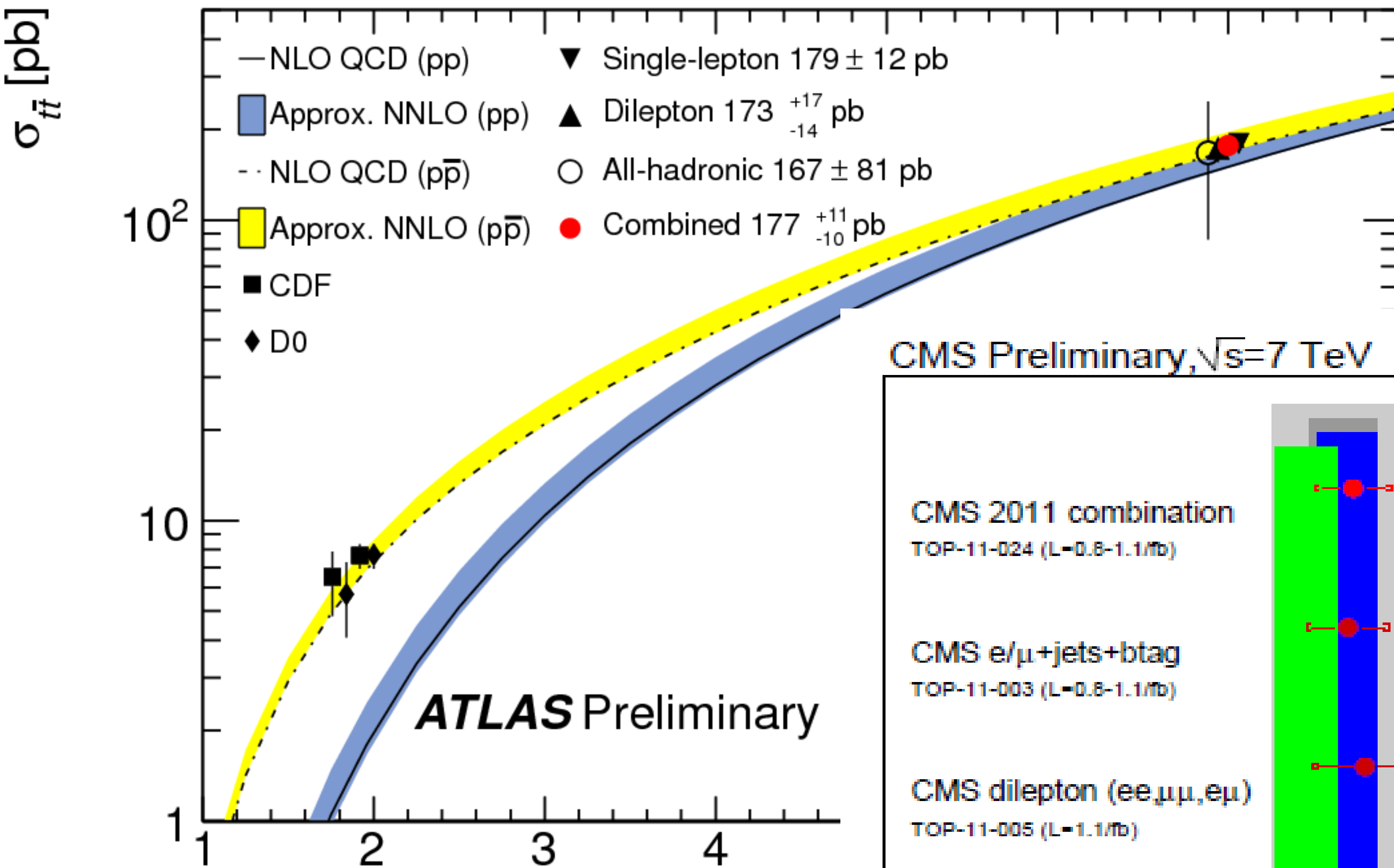
- **Data-driven methods to control QCD and W+jets backgrounds**

$t\bar{t}$ candidate event

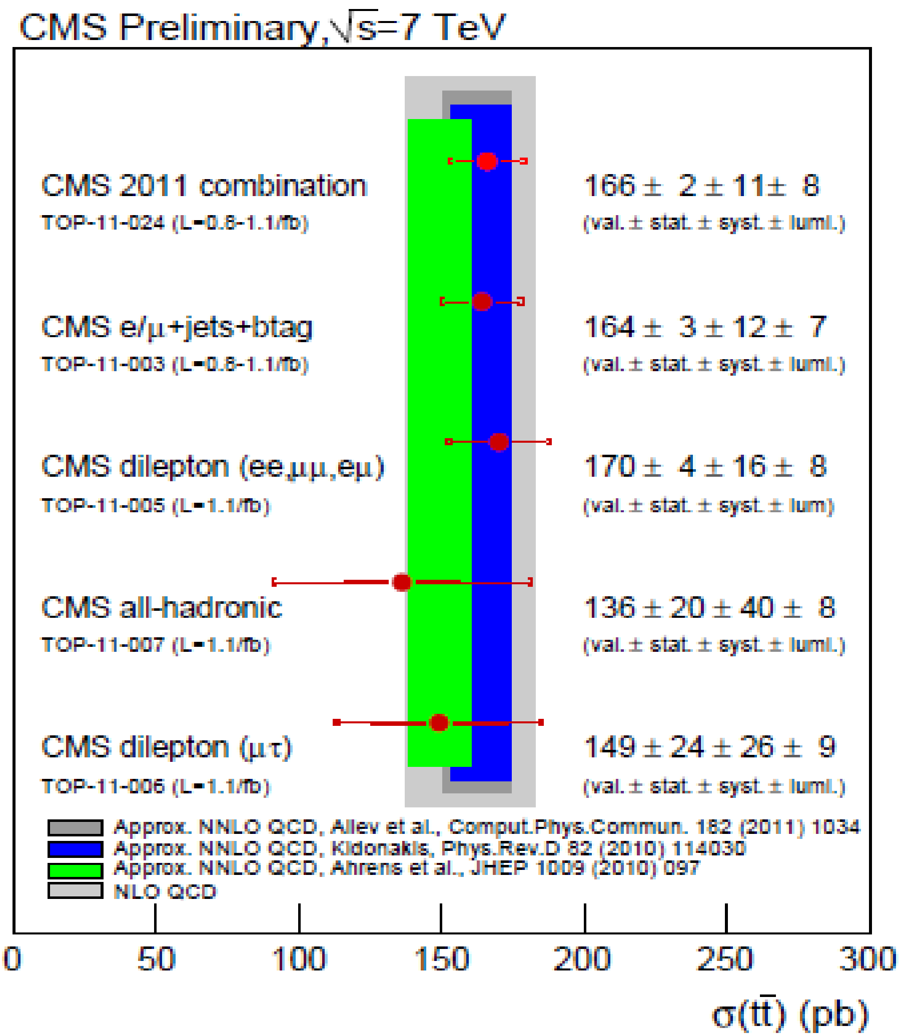
e + μ + 2 jets (b-tagged) +ETmiss



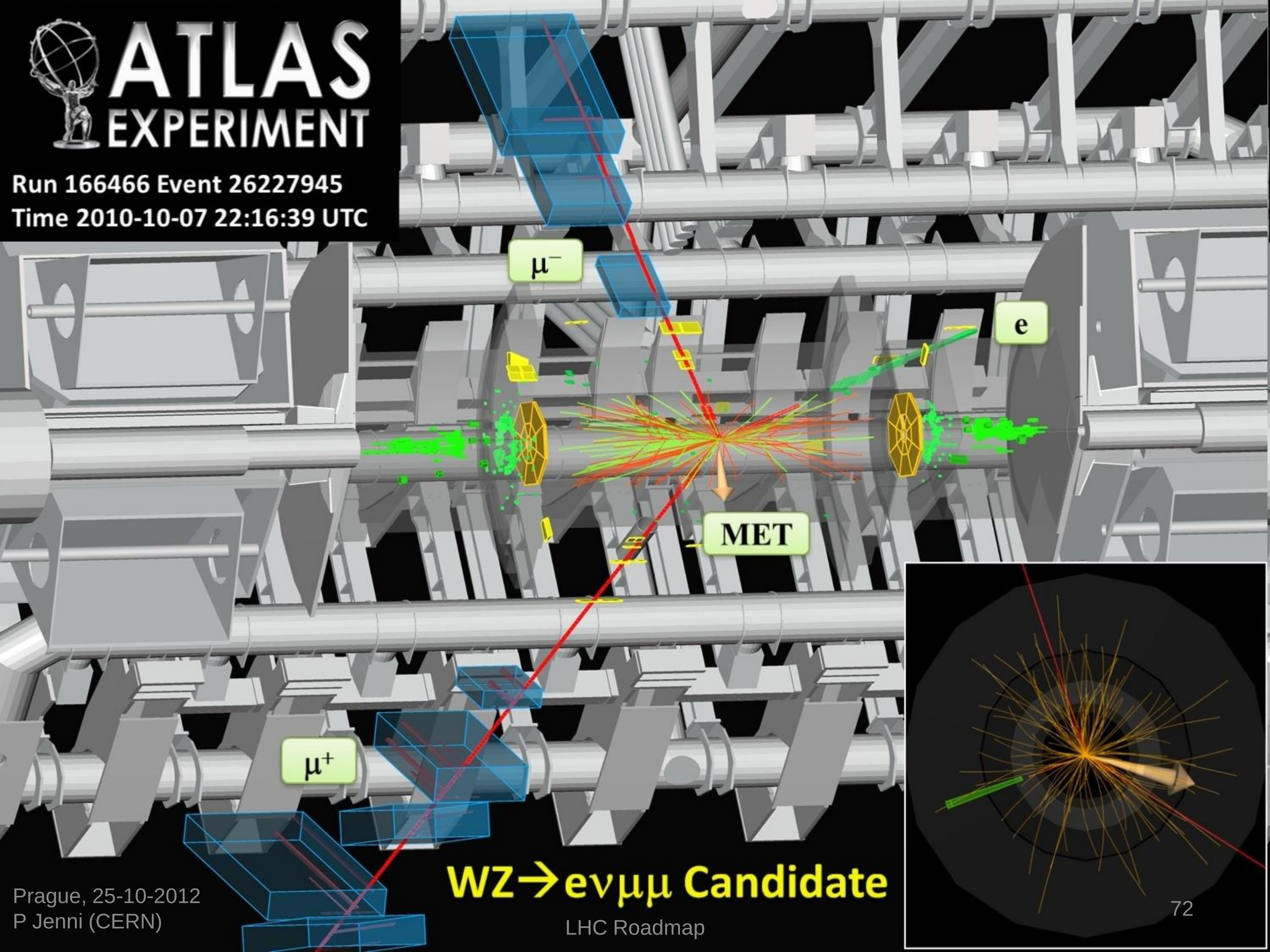
ATLAS-CONF-2012-024



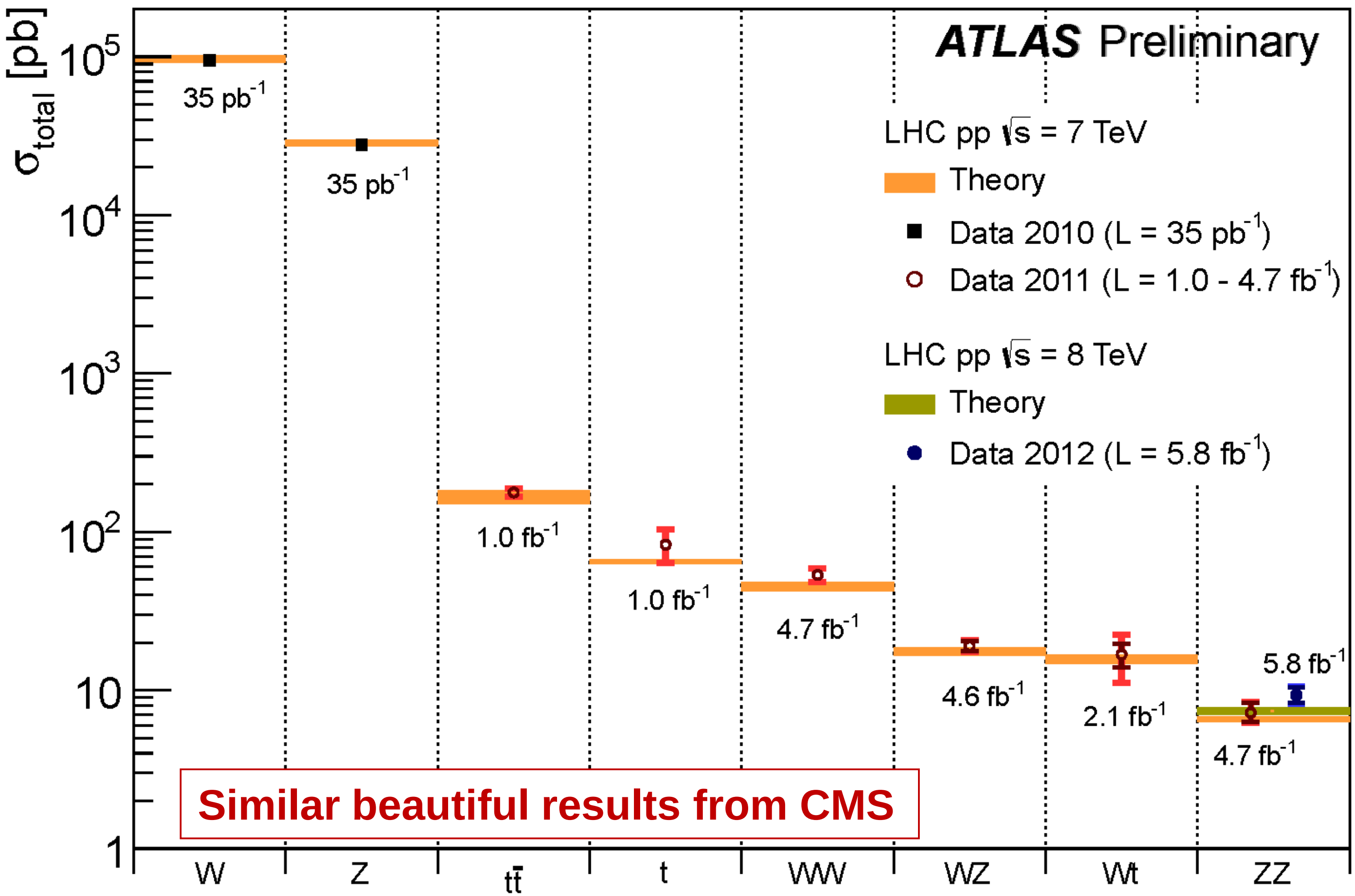
CMS-TOP-11-024



$t\bar{t}$ pair production cross-sections


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

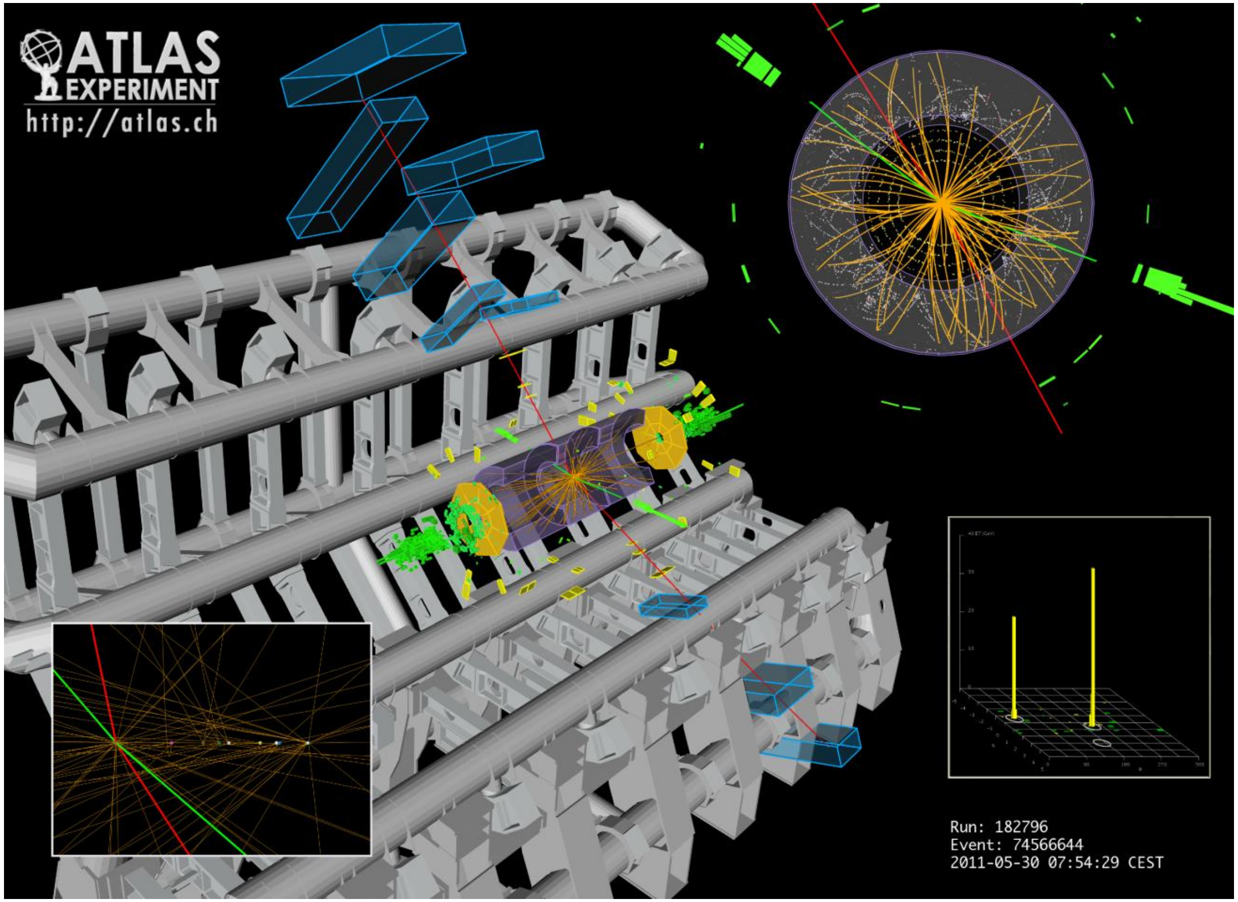
A summary of Standard Model measurements



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

We are in the year of the Dragon…

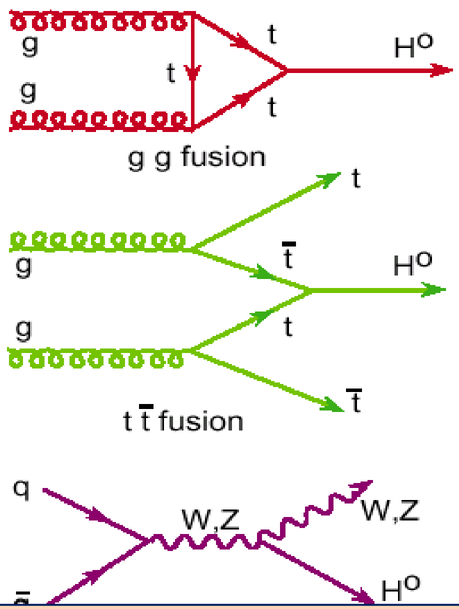
Candidate for a 124.5 GeV mass $H \rightarrow \mu\mu$ ee event in ATLAS

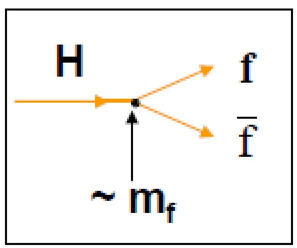


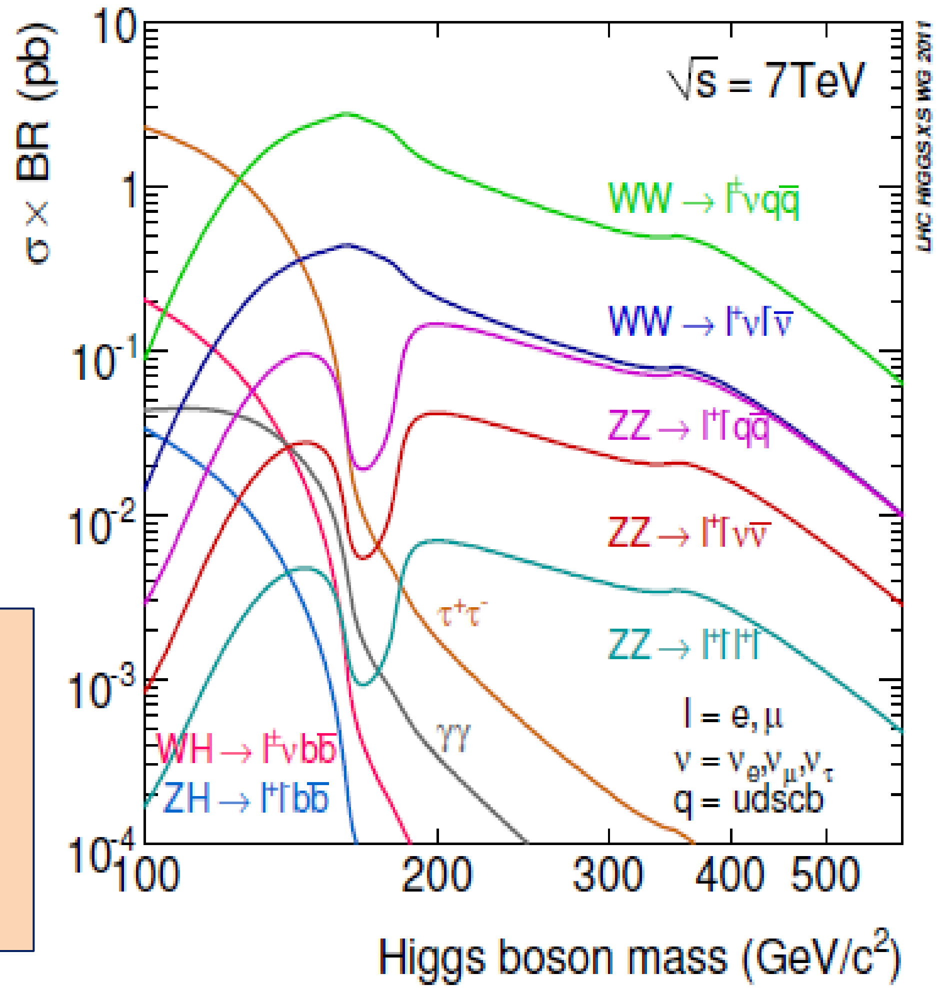
… but it will also be remembered as the one of the Higgs Boson !

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

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







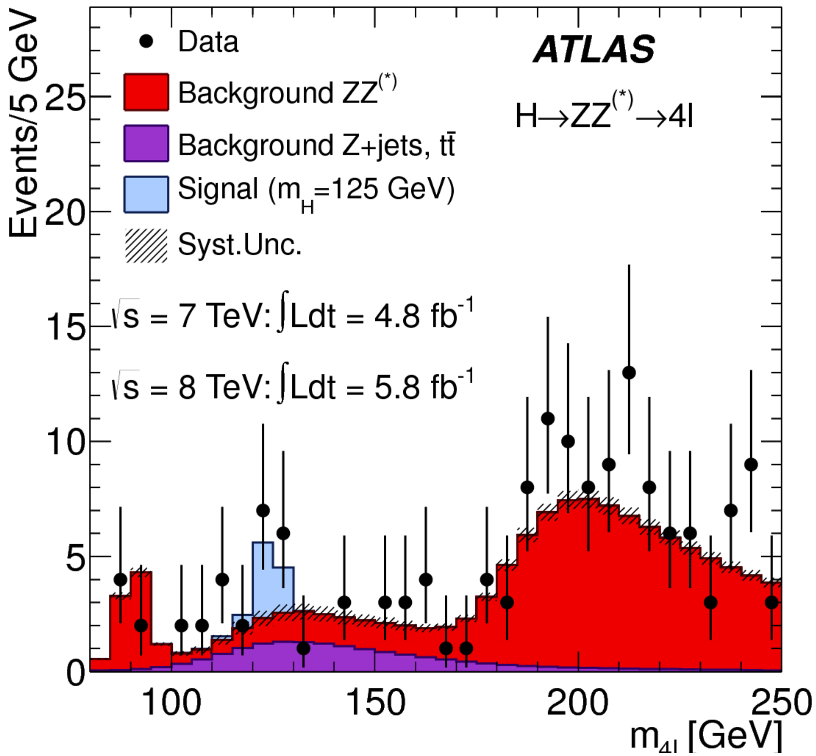
Best channels at the LHC:

< 130 GeV	**H→ γγ**
125-180 GeV	**H → WW$^{(*)}$→ lνlν**
125-300 GeV	**H→ ZZ$^{(*)}$→ llll**
300-600 GeV	**H→ ZZ→ llνν**

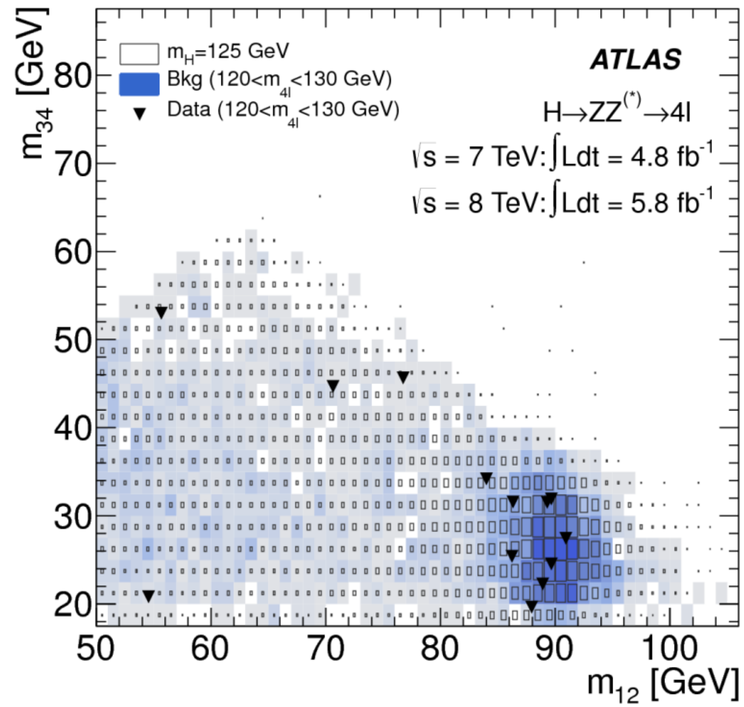
ATLAS H → ZZ(*) → 4l (4e, 4μ, 2e2μ)

- Rare process, small cross section: σ ~ 2-5 fb
- However: pure: S/B ~ 1
- 4 leptons: $p_T^{1,2,3,4}$ > 20, 20, 7, 7 GeV; $m_{12} = m_Z \pm 15$ GeV
- Main background: ZZ(*) (irreducible)

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

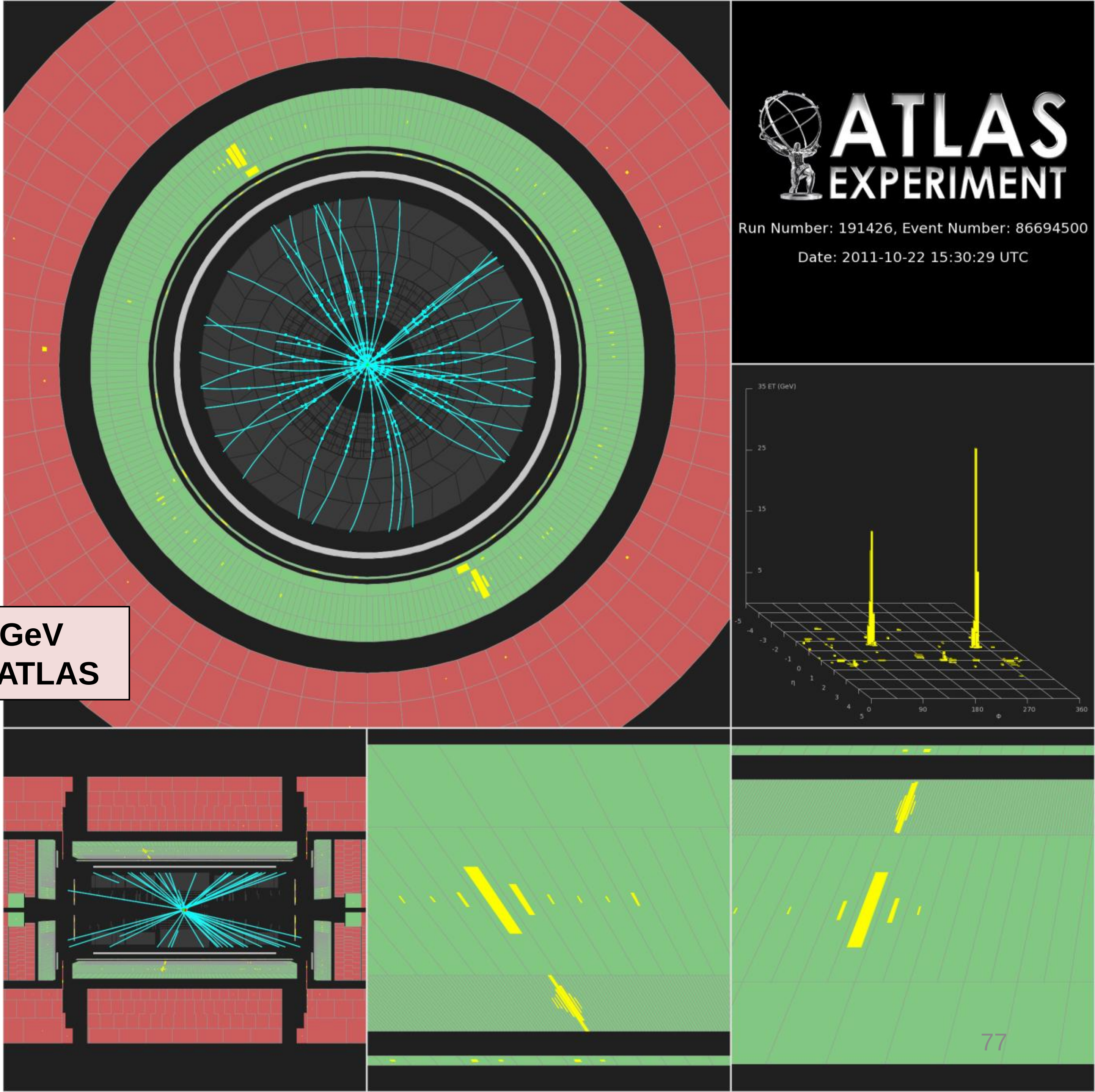


	Signal	$ZZ^{(*)}$	$Z+$jets, $t\bar{t}$	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
$2e2\mu/2\mu2e$	2.29± 0.33	0.80±0.05	1.27±0.19	5
$4e$	0.90±0.14	0.44±0.04	1.09±0.20	2



Phys. Lett. B 716 (2012) 1

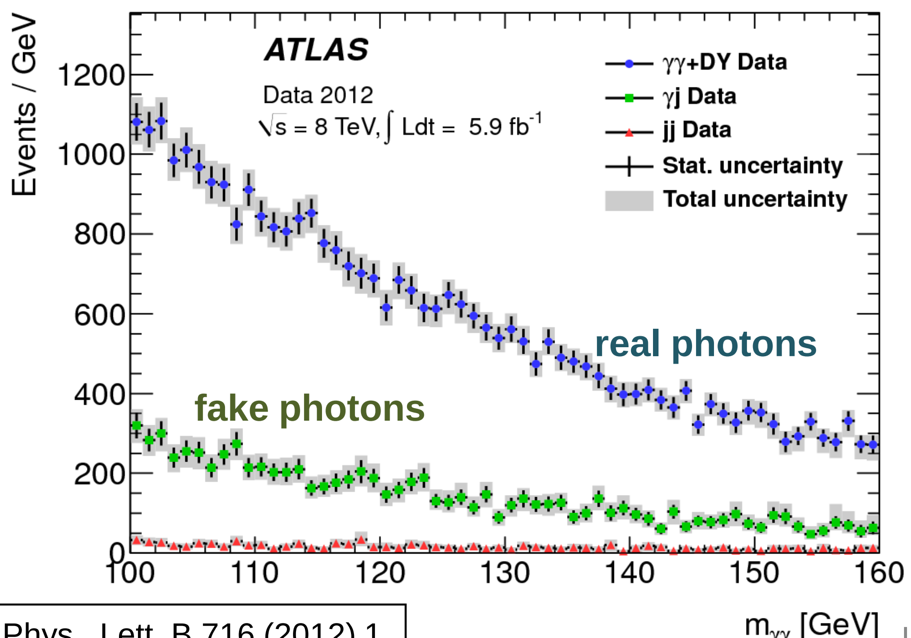
Candidate for a 126.6 GeV mass H $\rightarrow \gamma\gamma$ event in ATLAS

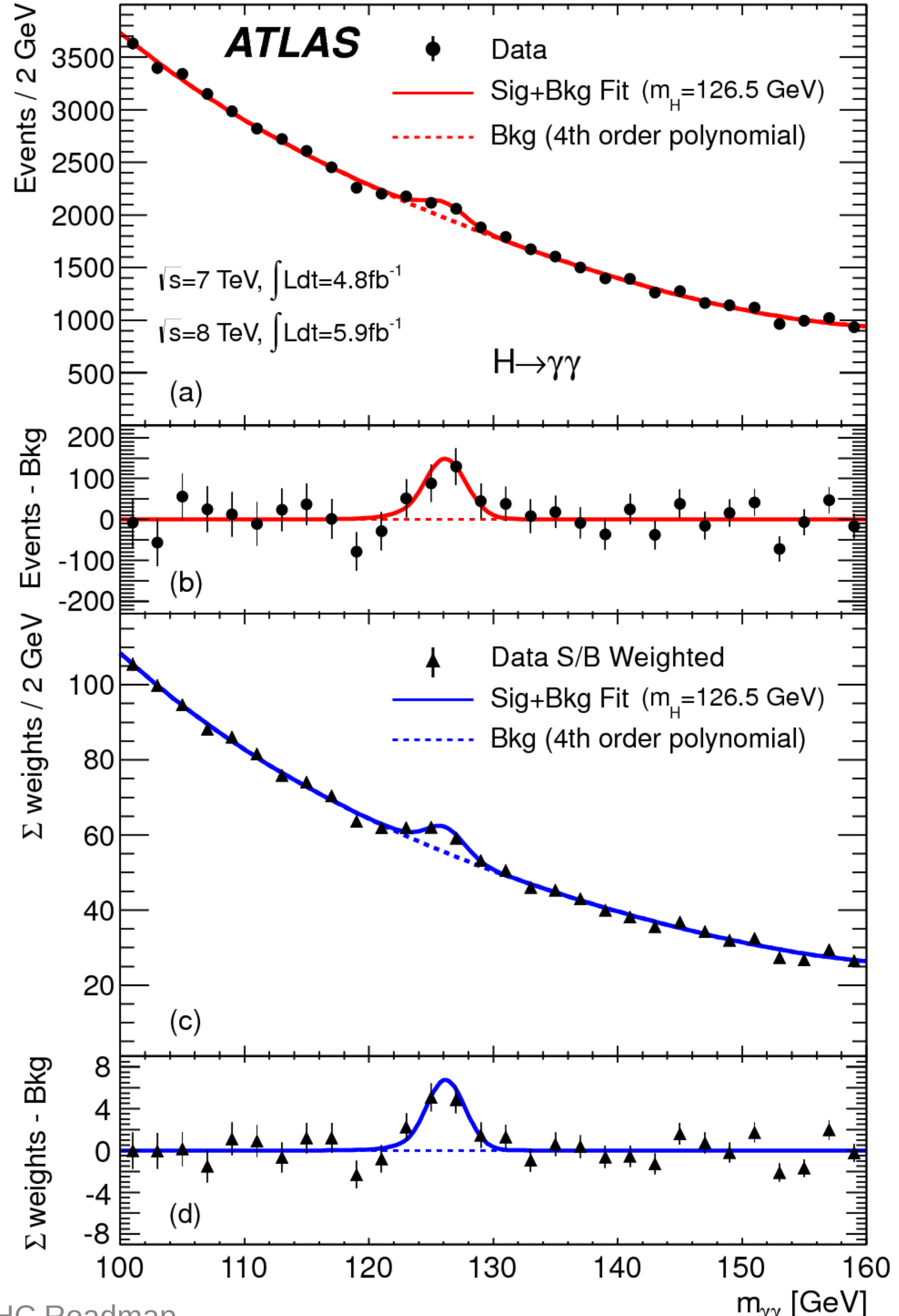


ATLAS H → γγ

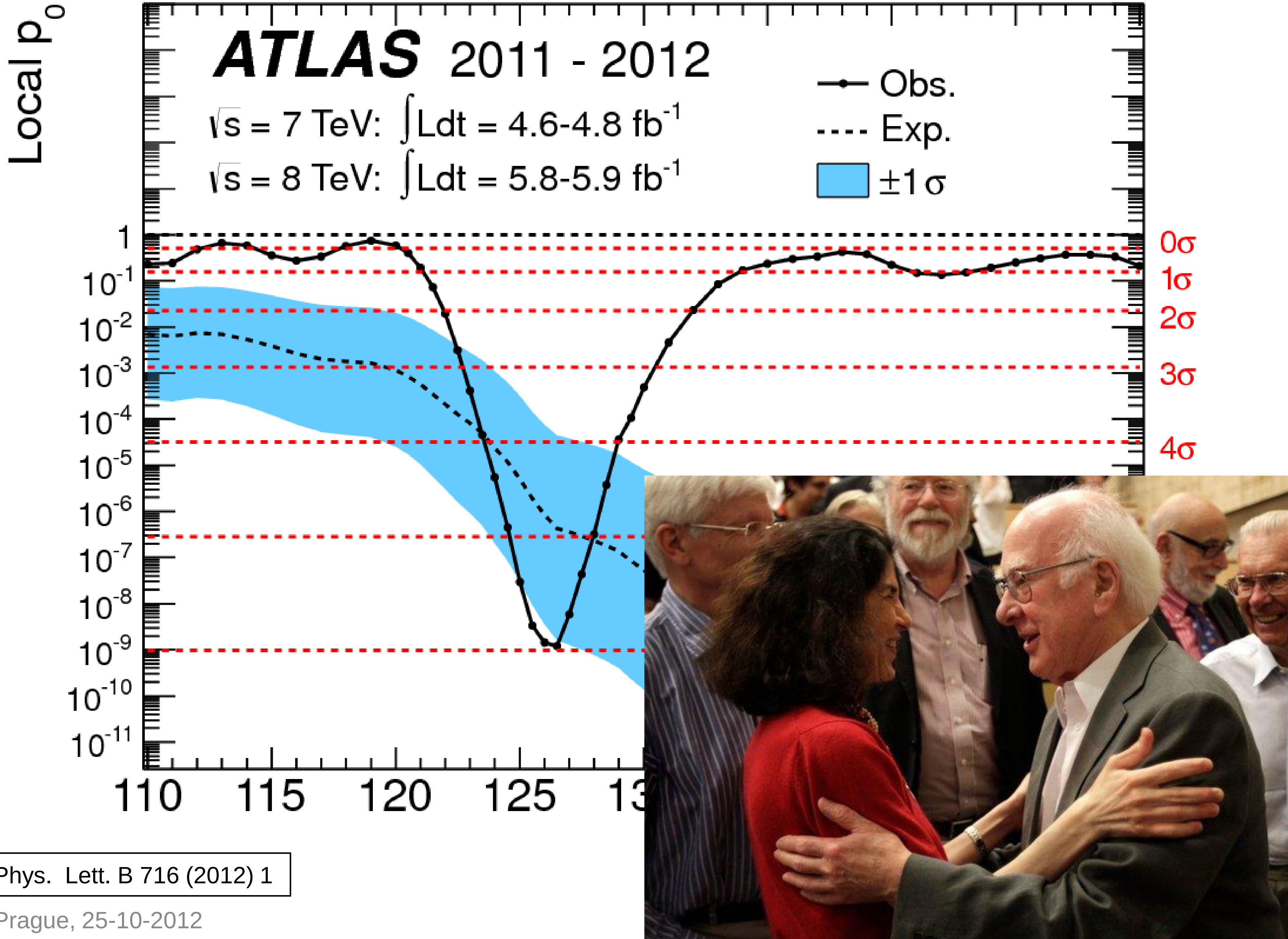
- Small cross-section: σ ~ 40 fb
- Expected S/B ~ 0.02
- Simple final state: two high-p_T isolated photons: E_T (γ_1, γ_2) > 40, 25 GeV
- Main background: γγ continuum (irreducible) and fake γ from γj and jj events (reducible)

Analysis is done separately in 10 subcategories with different resolutions and backgrounds, then statistically combined with a likelihood method



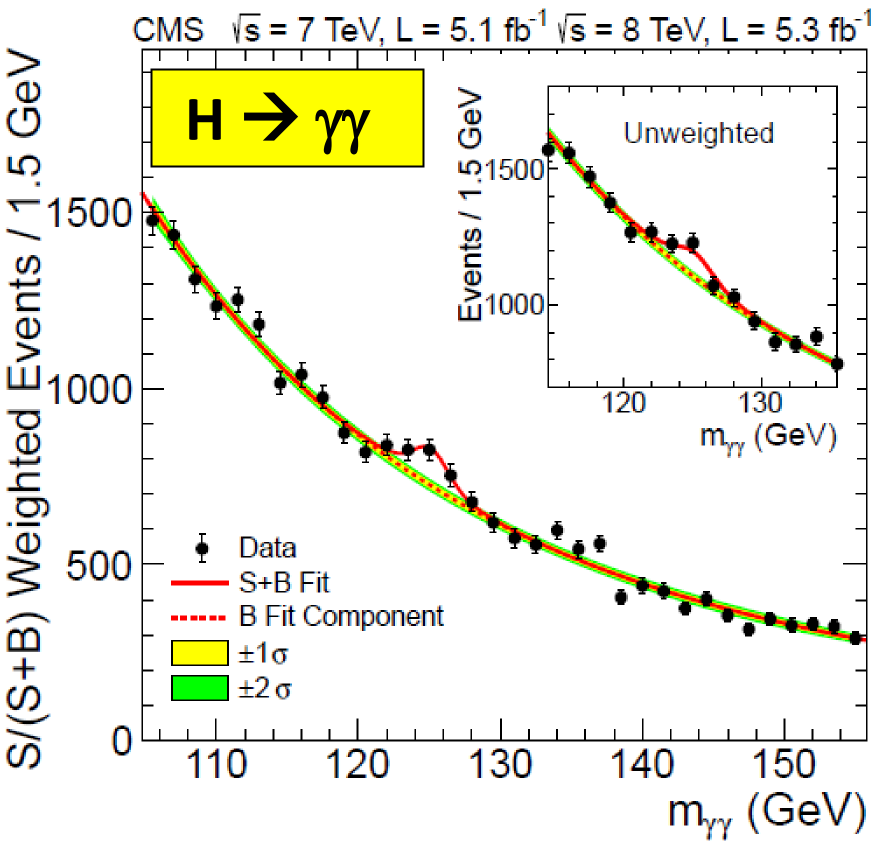


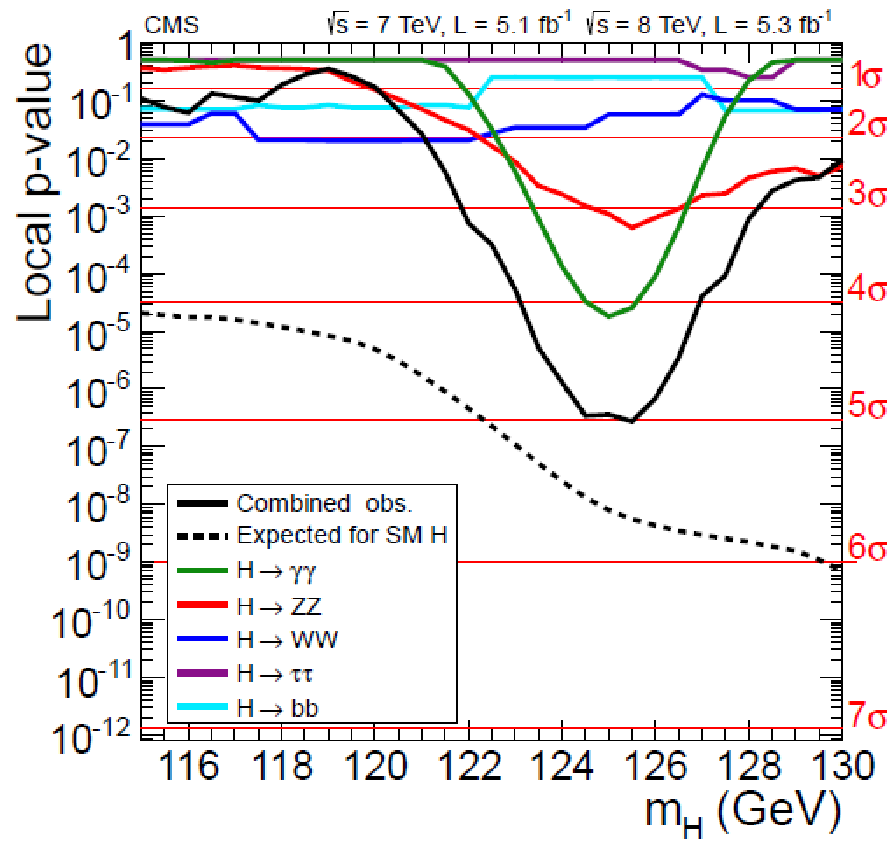
Phys. Lett. B 716 (2012) 1



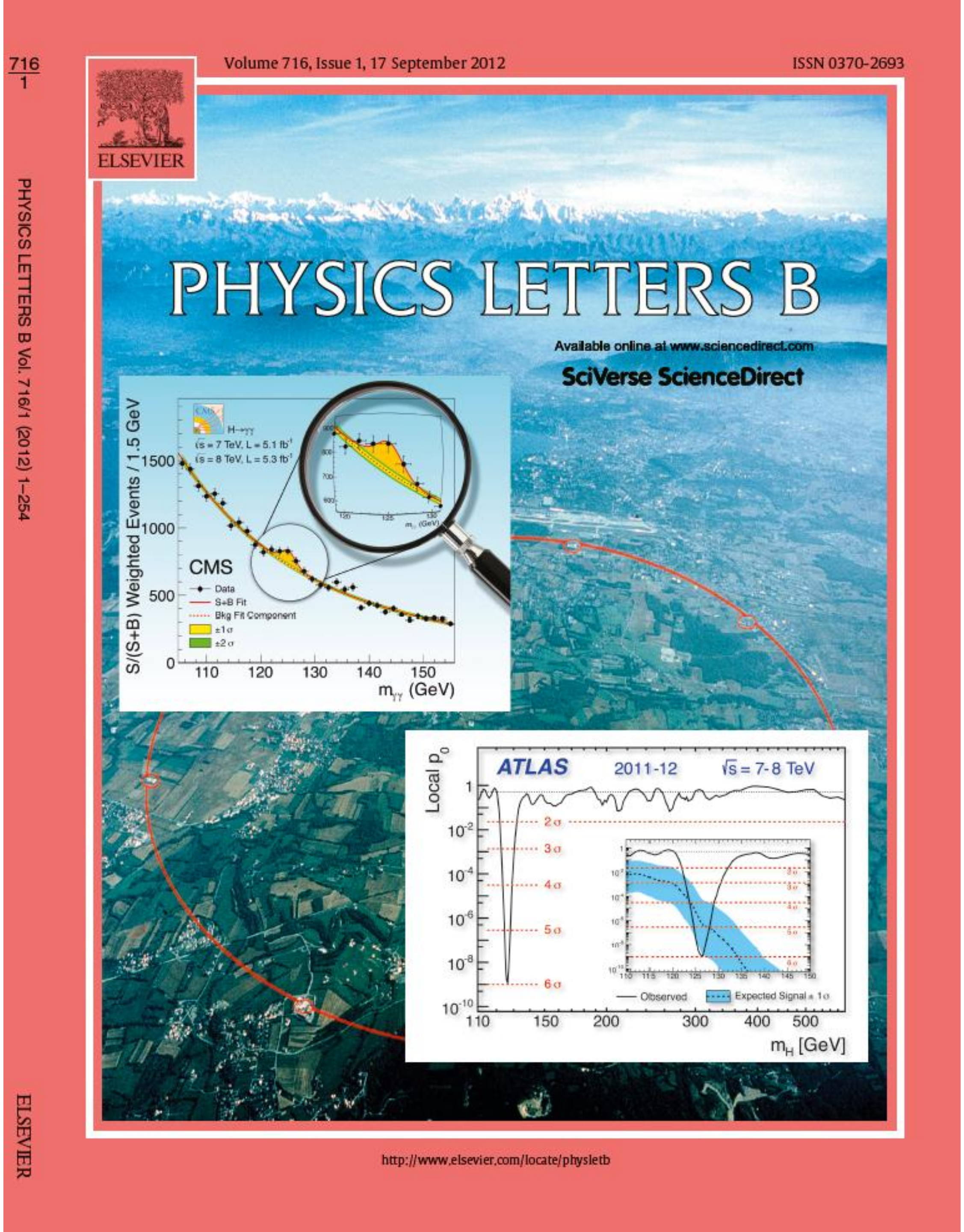
Phys. Lett. B 716 (2012) 1

CMS Higgs result example and summary





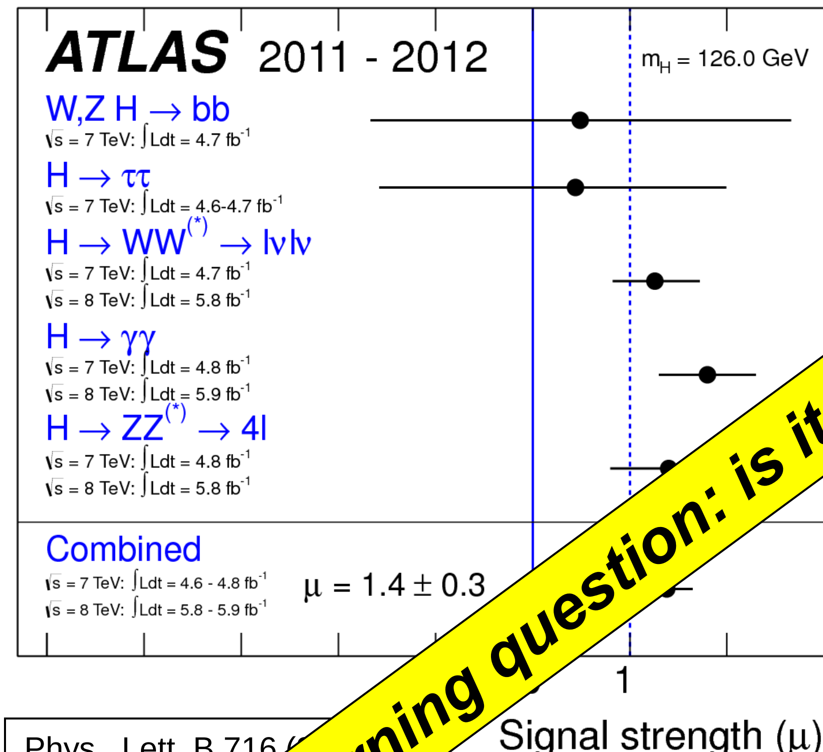
Phys. Lett. B 716 (2012) 30



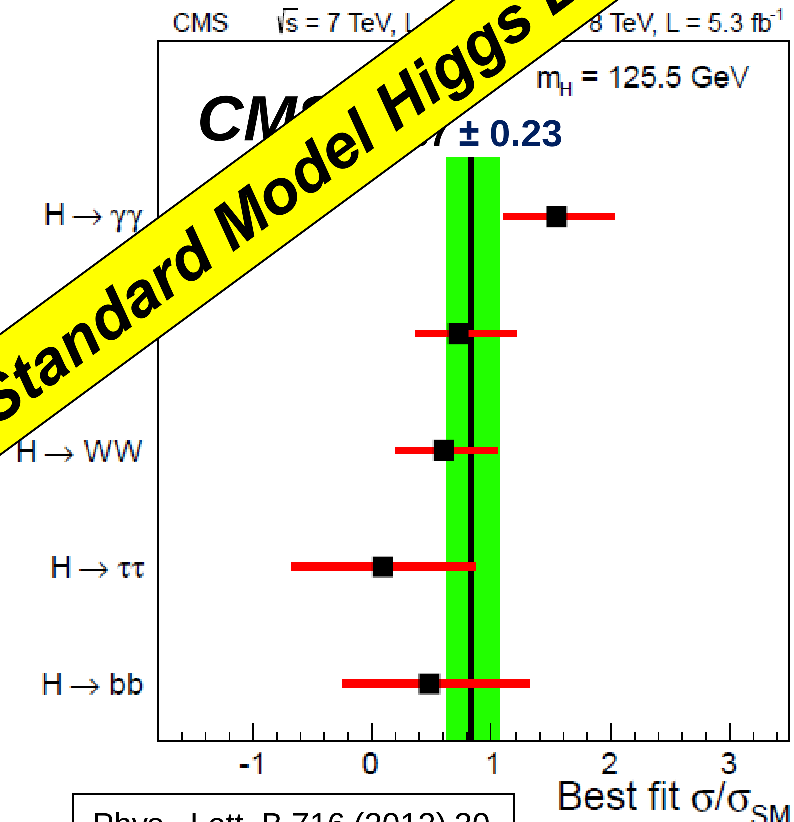
F Englert and P Higgs
CERN, 4th July 2012

Properties, as far as known with the limited statistics…

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



Phys. Lett. B 716 (



Phys. Lett. B 716 (2012) 30

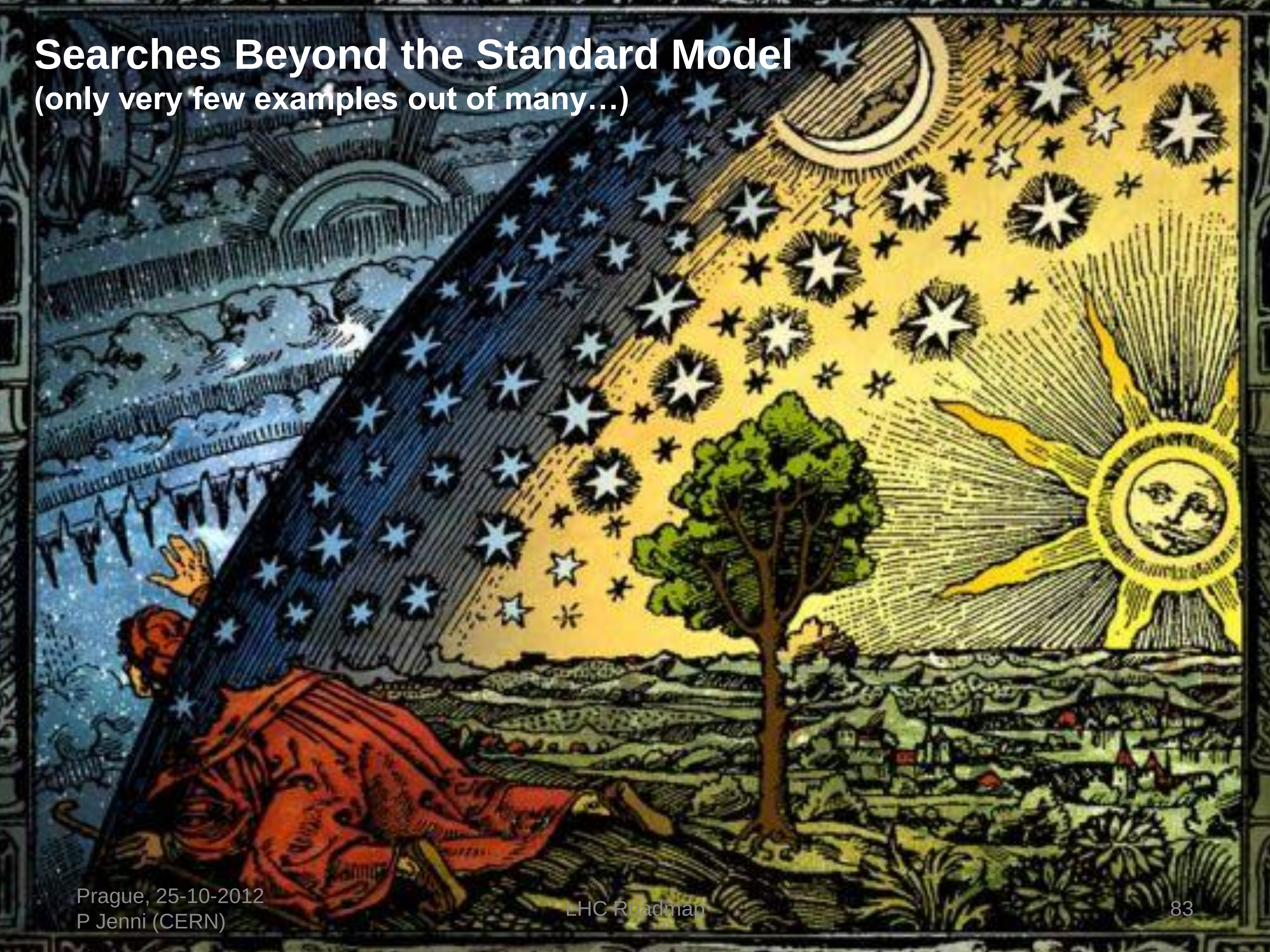
The burning question: is it the Standard Model Higgs Boson?

Mass = .0 ± 0.4 (stat) ± 0.4 (syst) GeV

Mass = 125.3 ± 0.4 (stat) ± 0.5 (syst) GeV

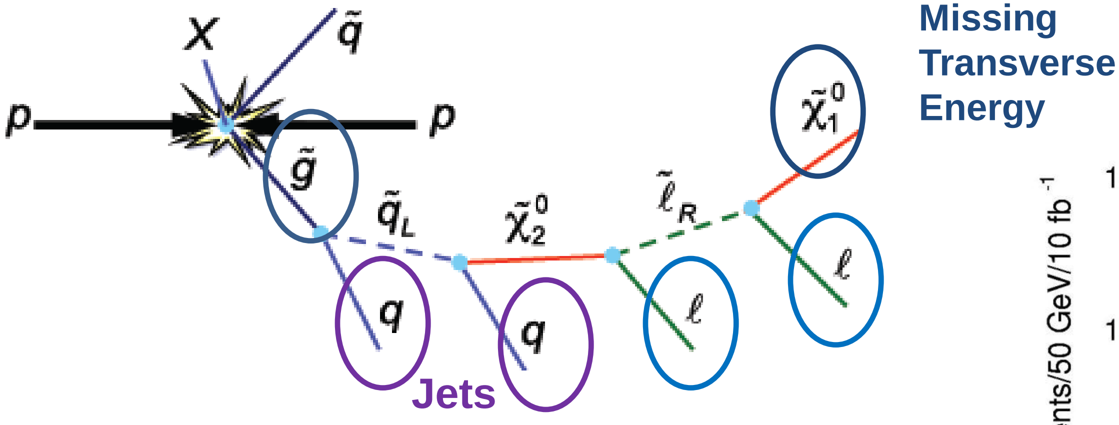
Searches Beyond the Standard Model

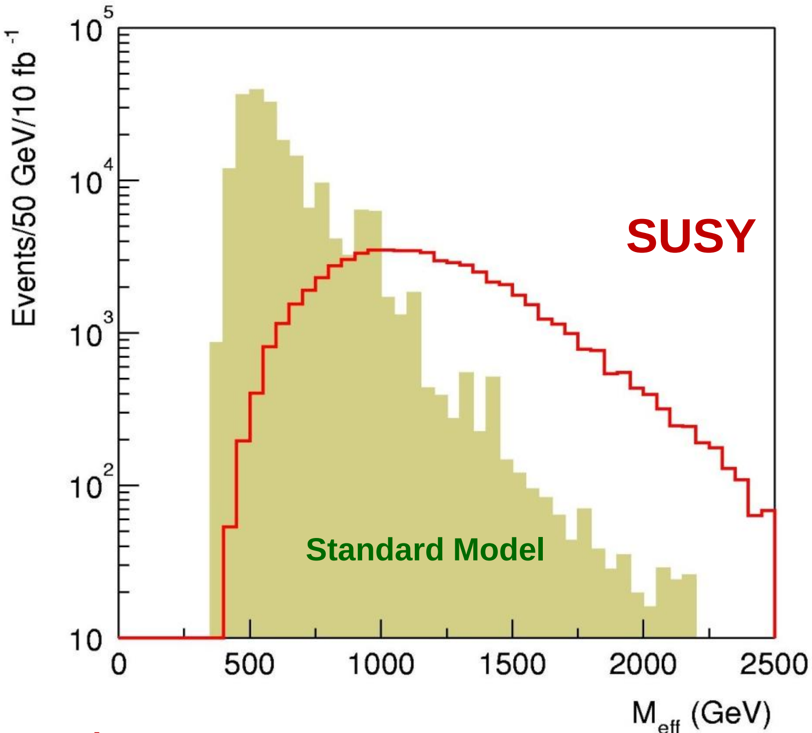
(only very few examples out of many…)



In practice SUSY searches at LHC are rather complicated

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





Meff = Etmiss + Σ pT(jets)

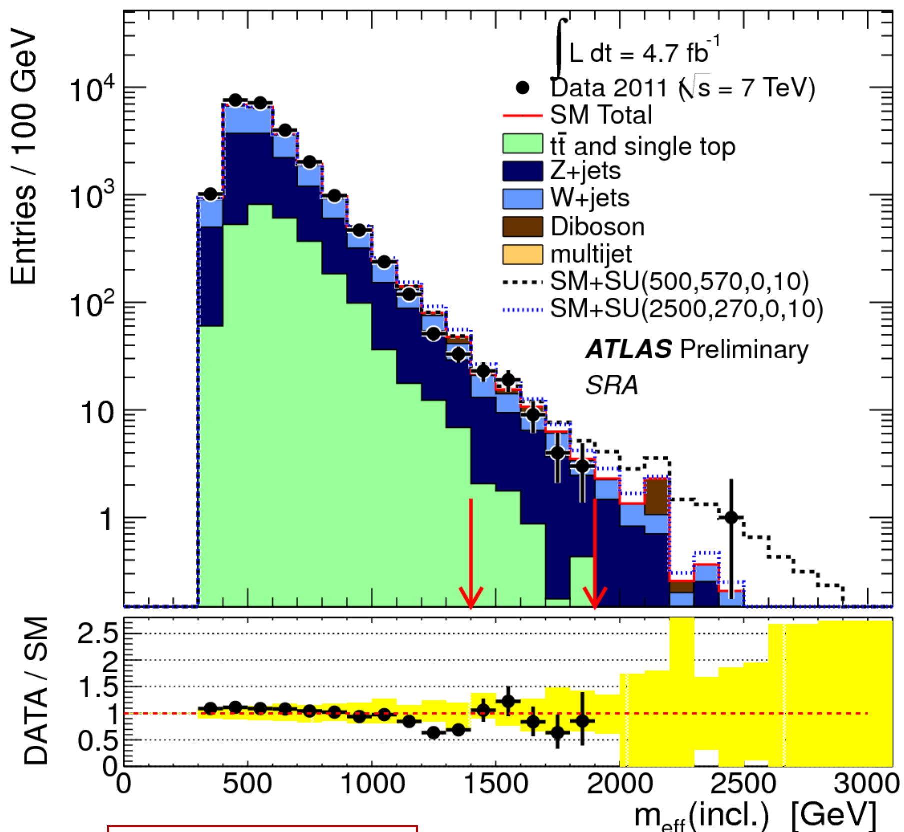
- **Focus on signatures covering large classes of models while strongly rejecting SM background**
  - **large missing E_T**
  - **High transverse momentum jets**
  - **Leptons**
    - **Perform separate analyses with and without lepton veto (0-lepton / 1-lepton / 2-leptons)**
  - **B-jets: to enhance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

Analyses re-optimized and updated with full 2011 Luminosity

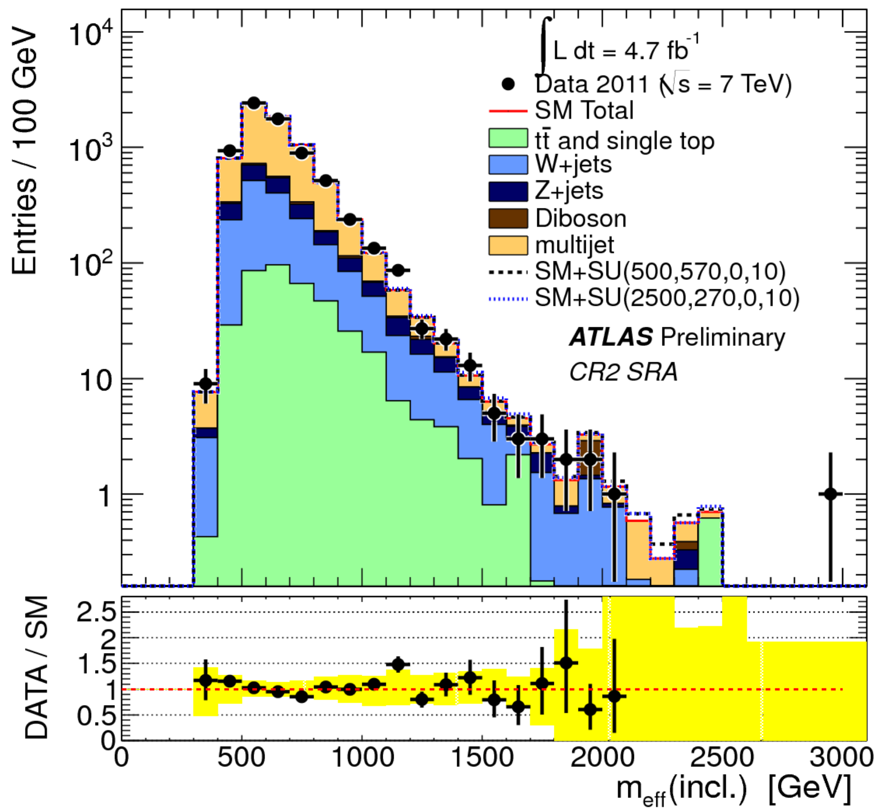
- **0-lepton + 2−6 jets + high MET (based on Et-miss+jet triggers)**
- **0-lepton + 6−9 (multi-)jets + MET (based on multi-jet triggers)**
- **1-lepton + 3,4 jets + high MET (based on lepton triggers)**

Example: O-leptons + 2-6 Jets analysis

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



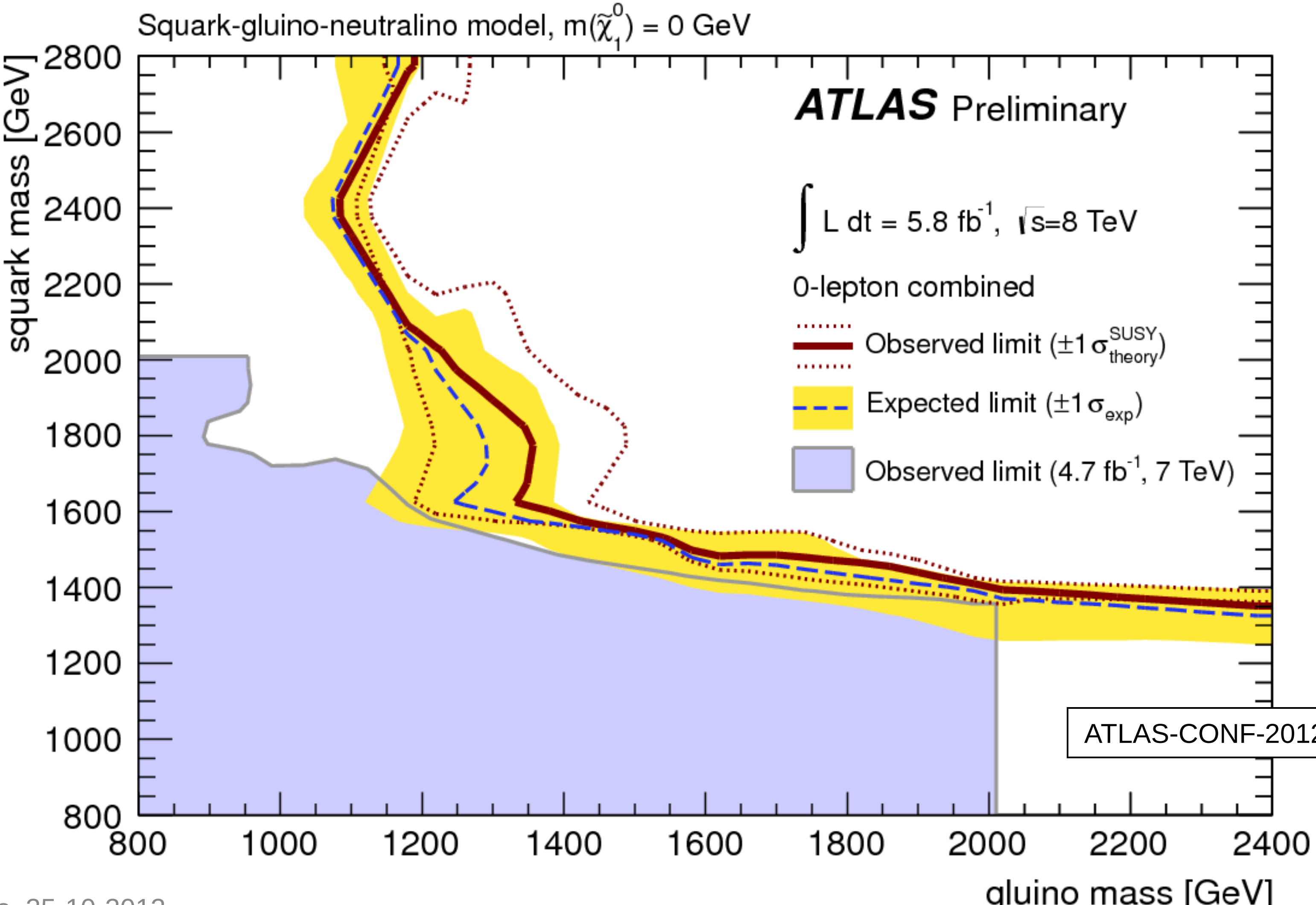
A signal region



A control region where no signal is expected

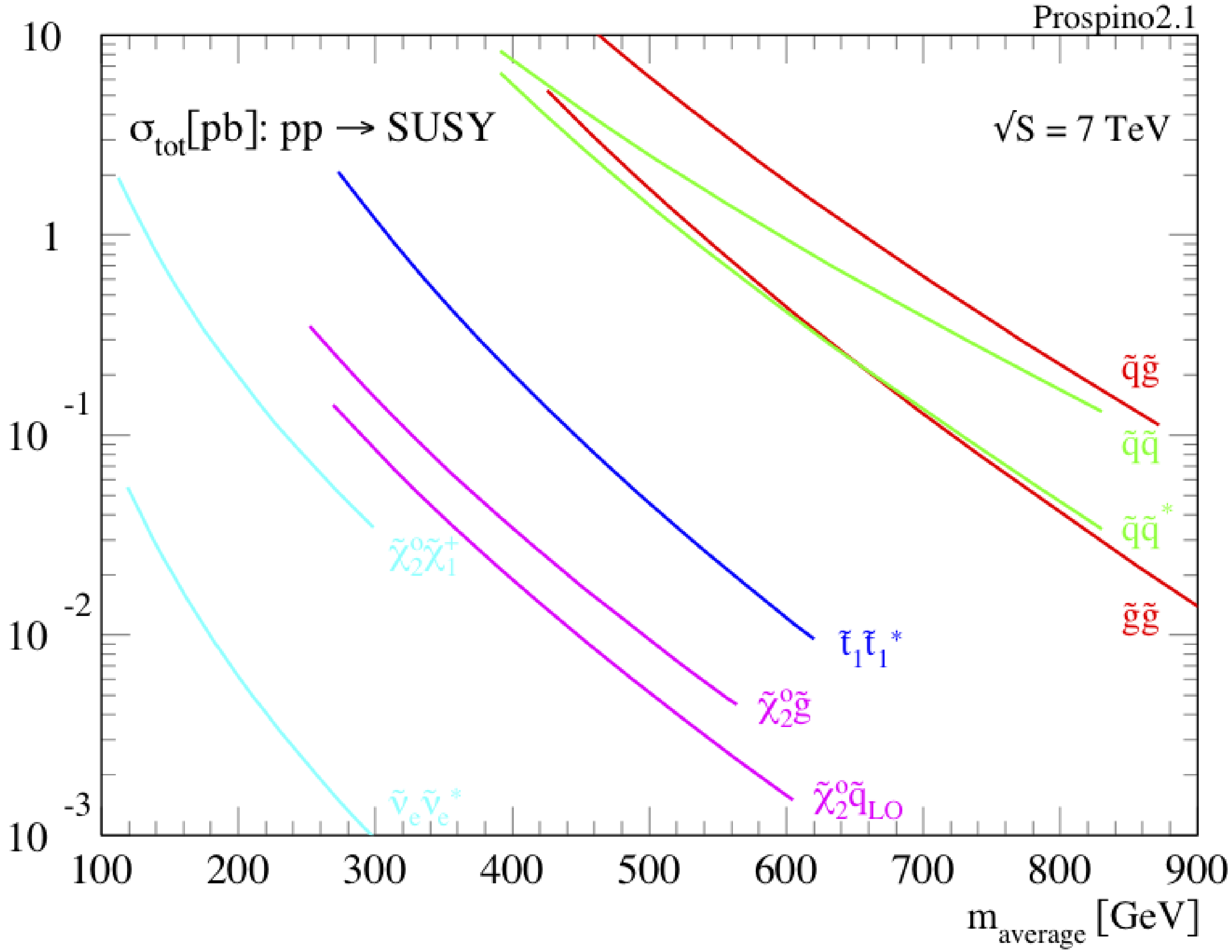
Interpretation of the results

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

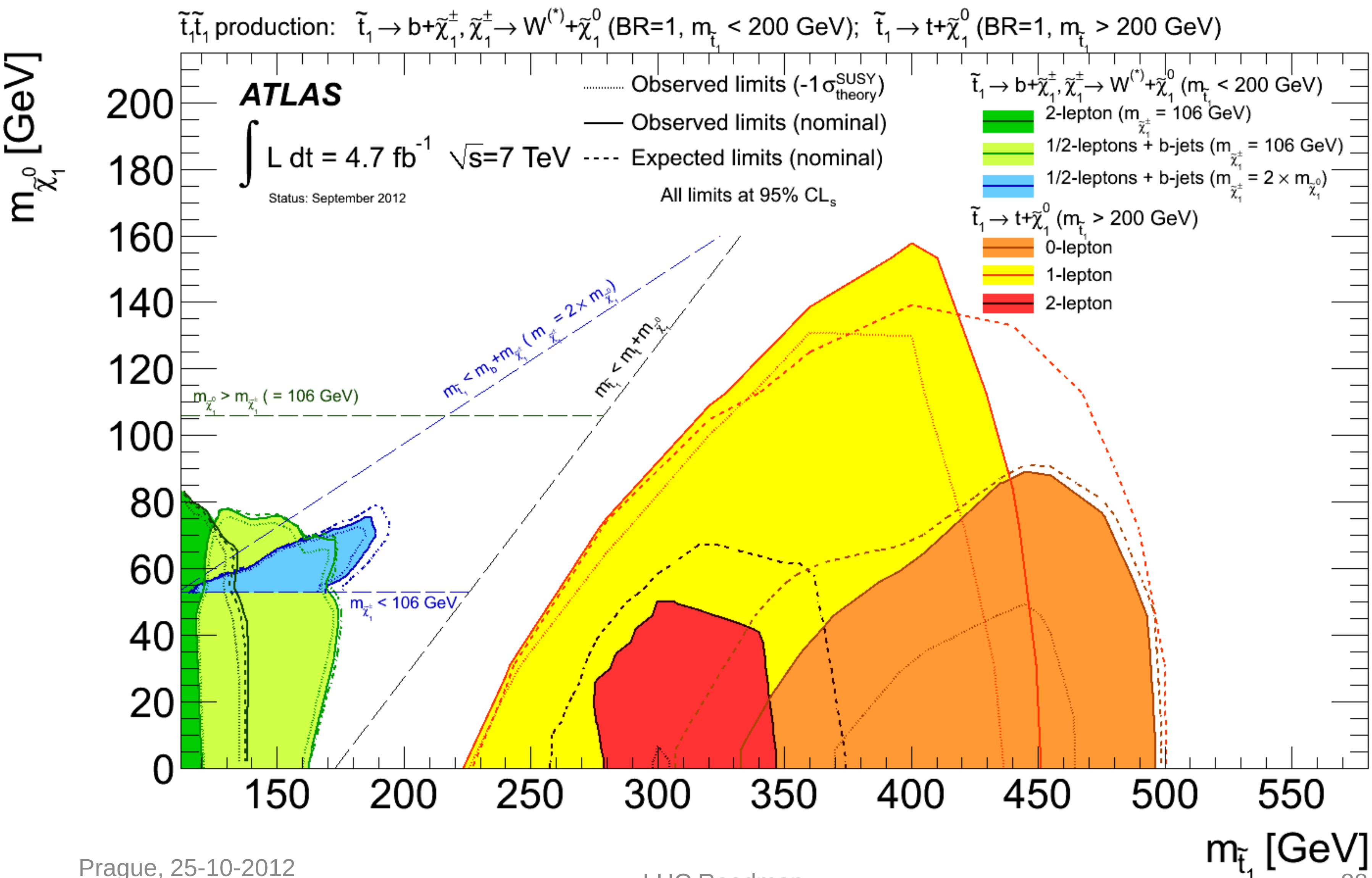


ATLAS-CONF-2012-0109

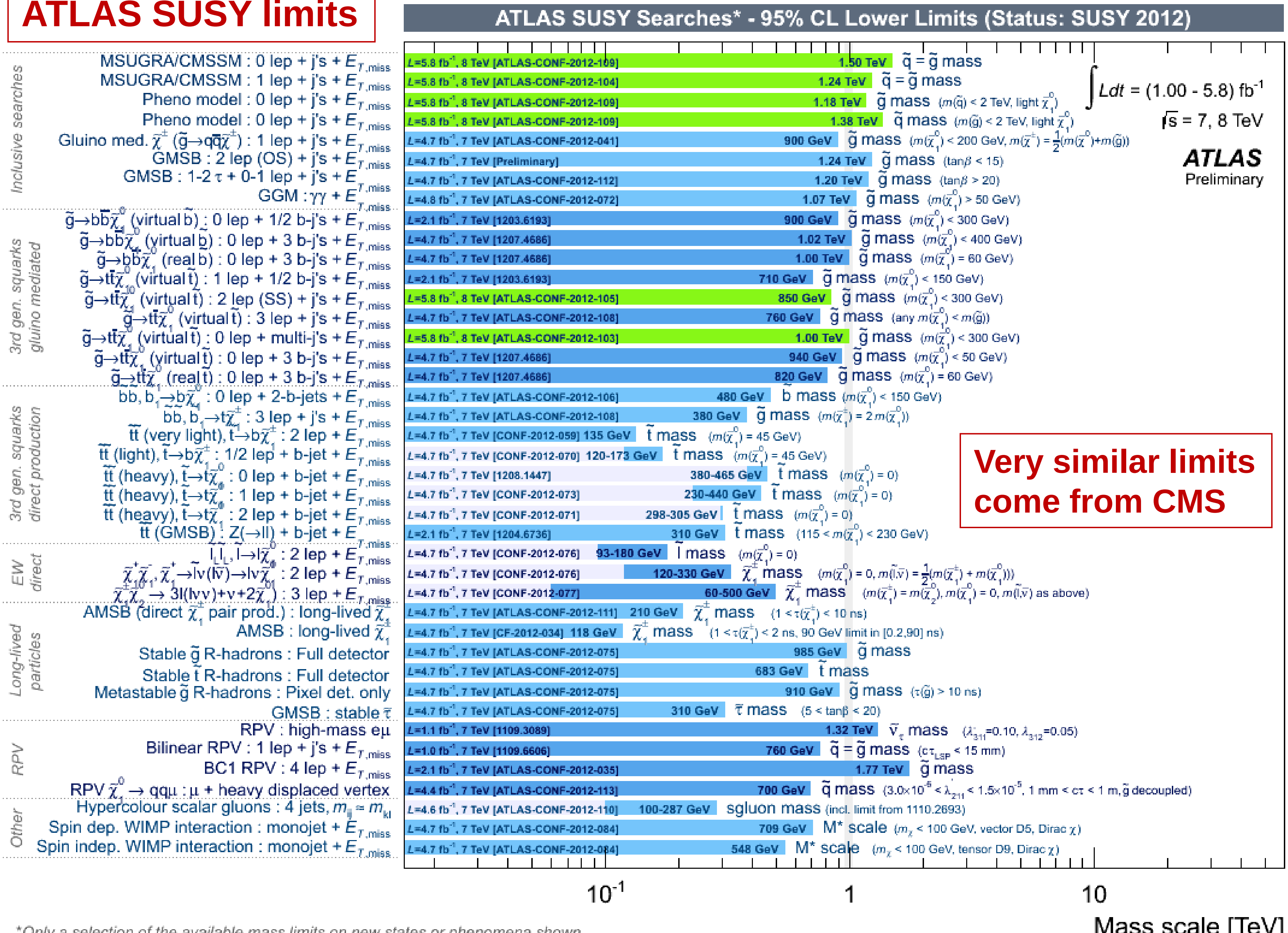
Expected production cross-sections at LHC



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



ATLAS SUSY limits



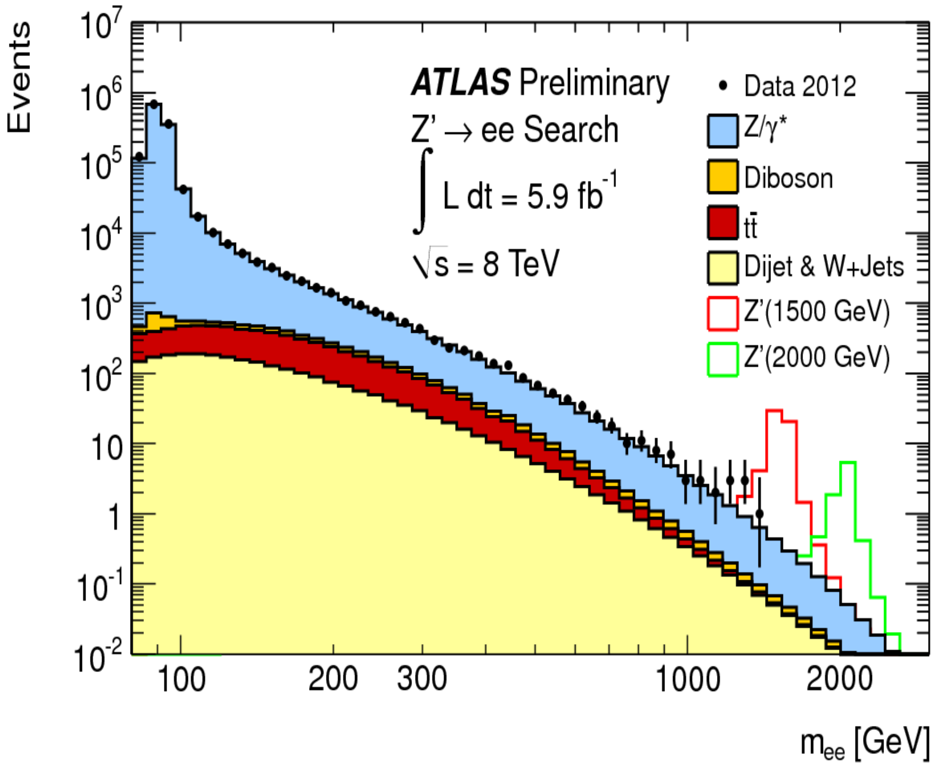
Very similar limits come from CMS

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

Searches for heavy W and Z like particles

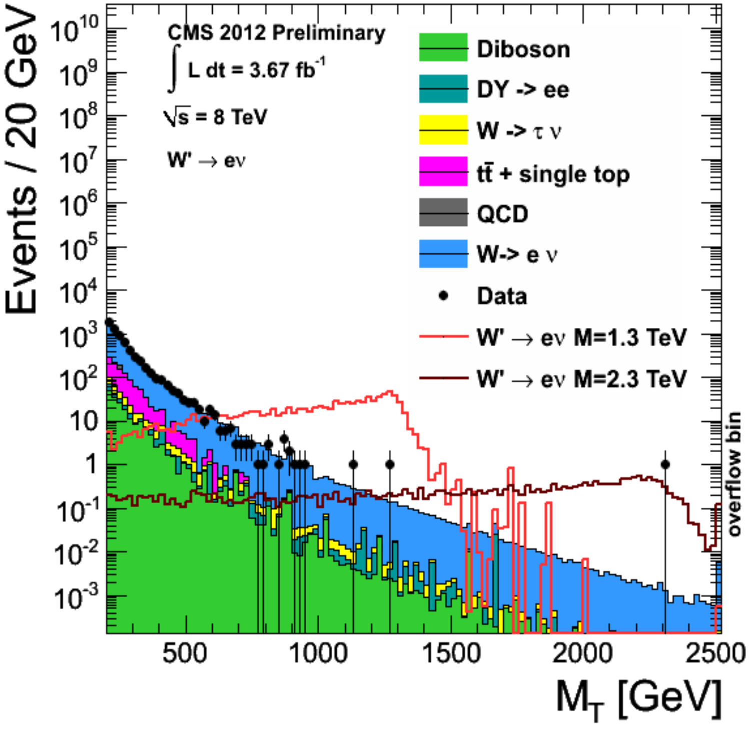
These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z': Di-lepton pairs

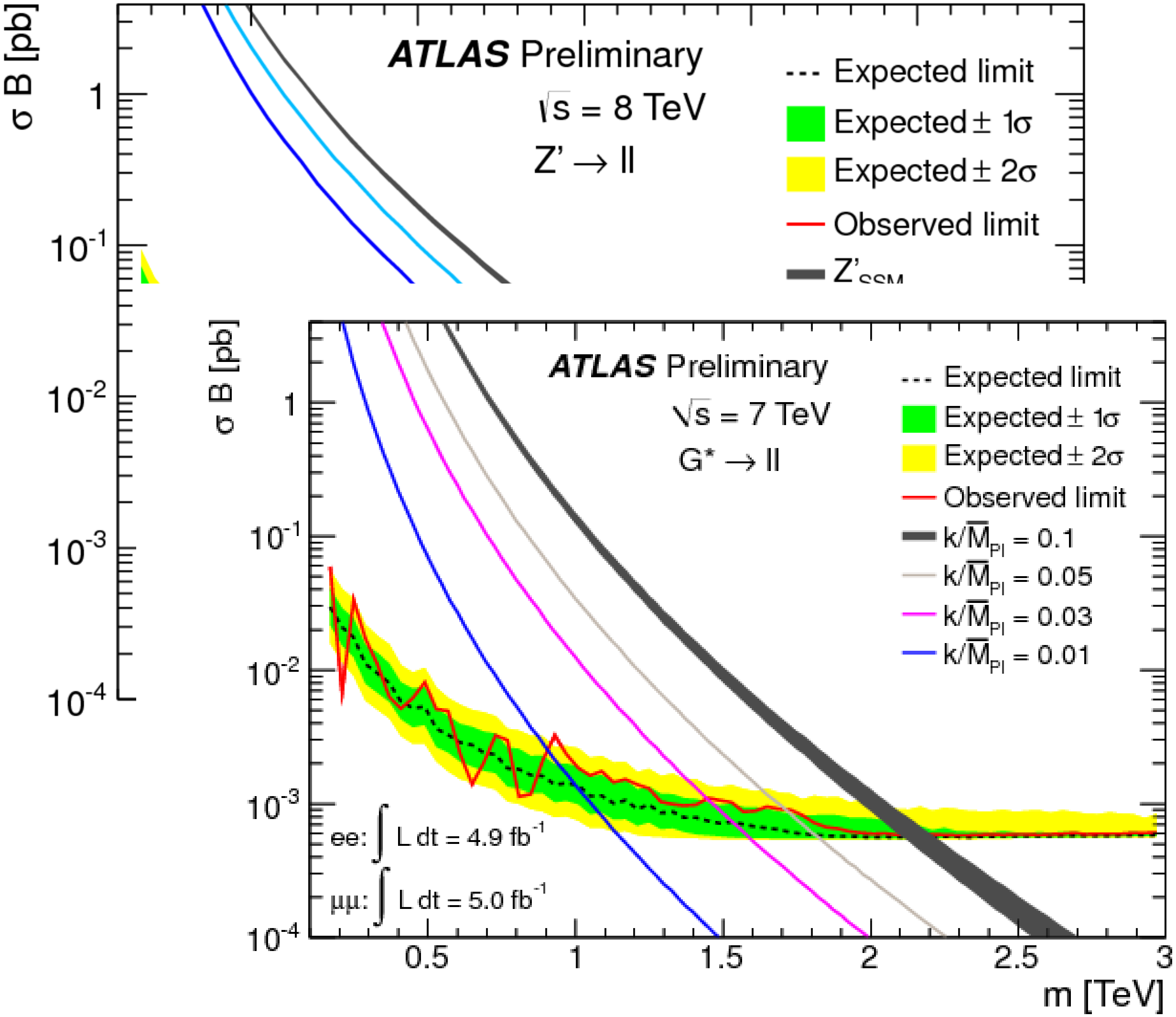


ATLAS-CONF-2012-129

W': Lepton + ETmiss



CMS-EXO-12-010



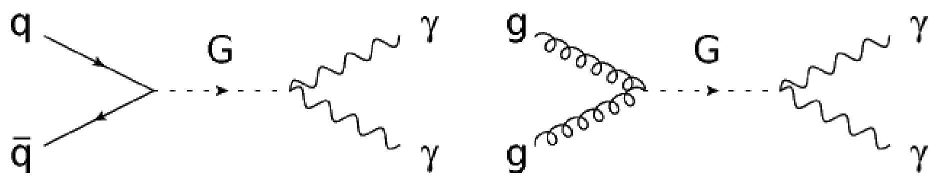
R Sundrum
L Randall
F Gianotti

ATLAS-CONF-2012-129

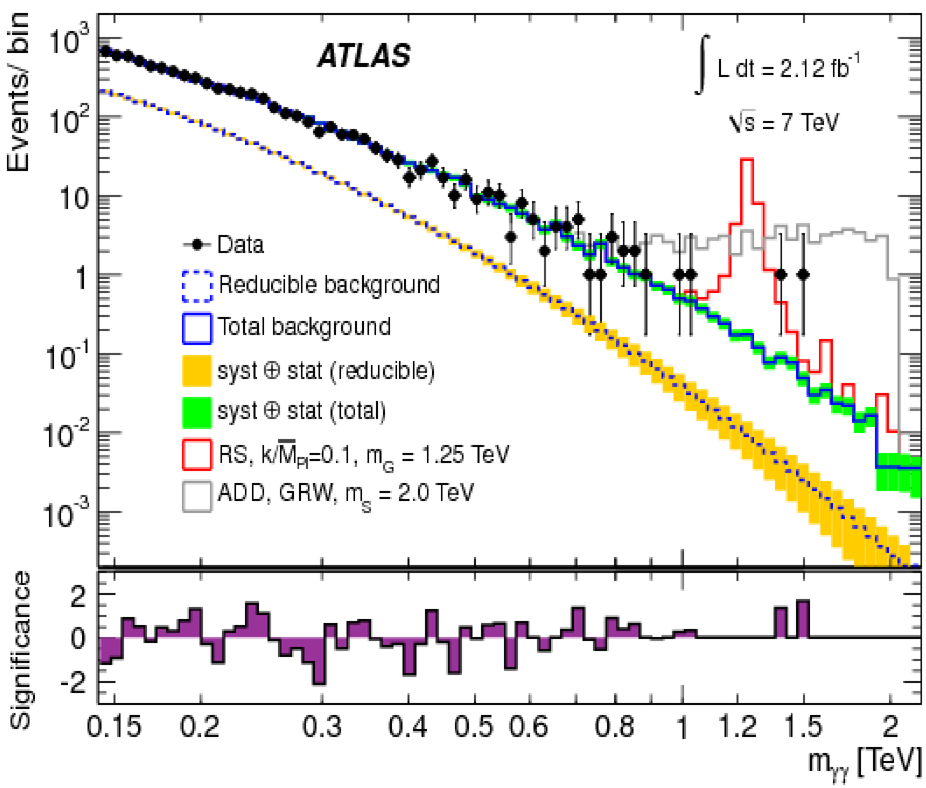
ATLAS-CONF-2012-007

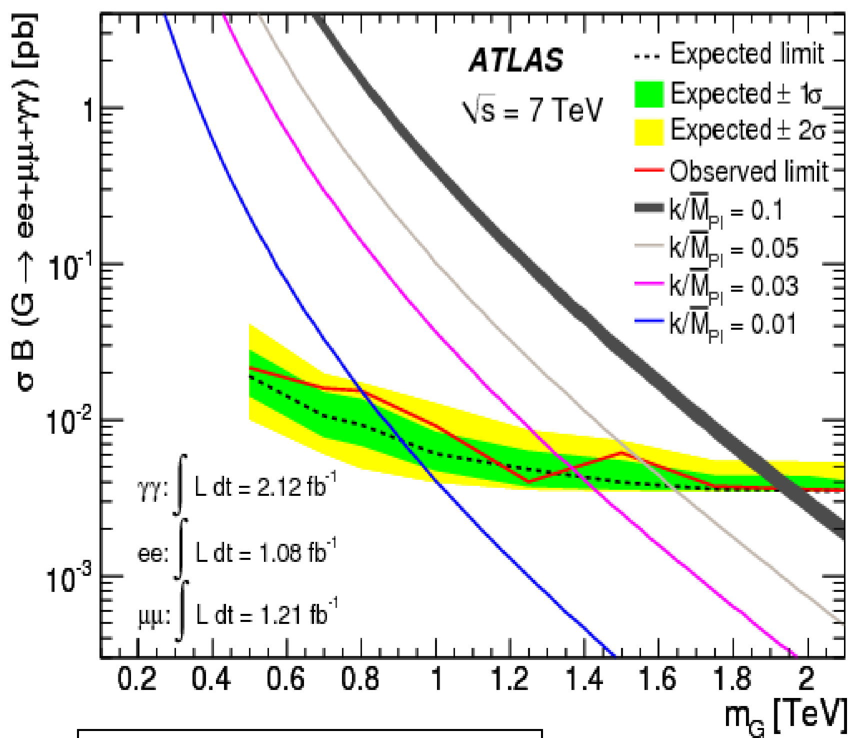
Randall-Sundrum Graviton

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)



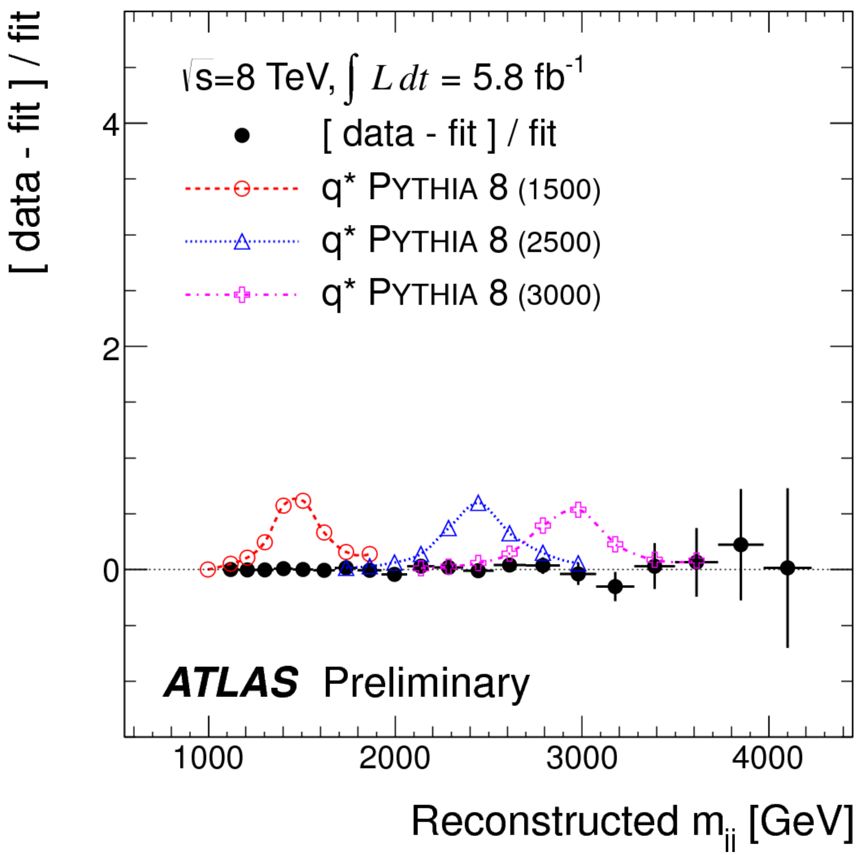


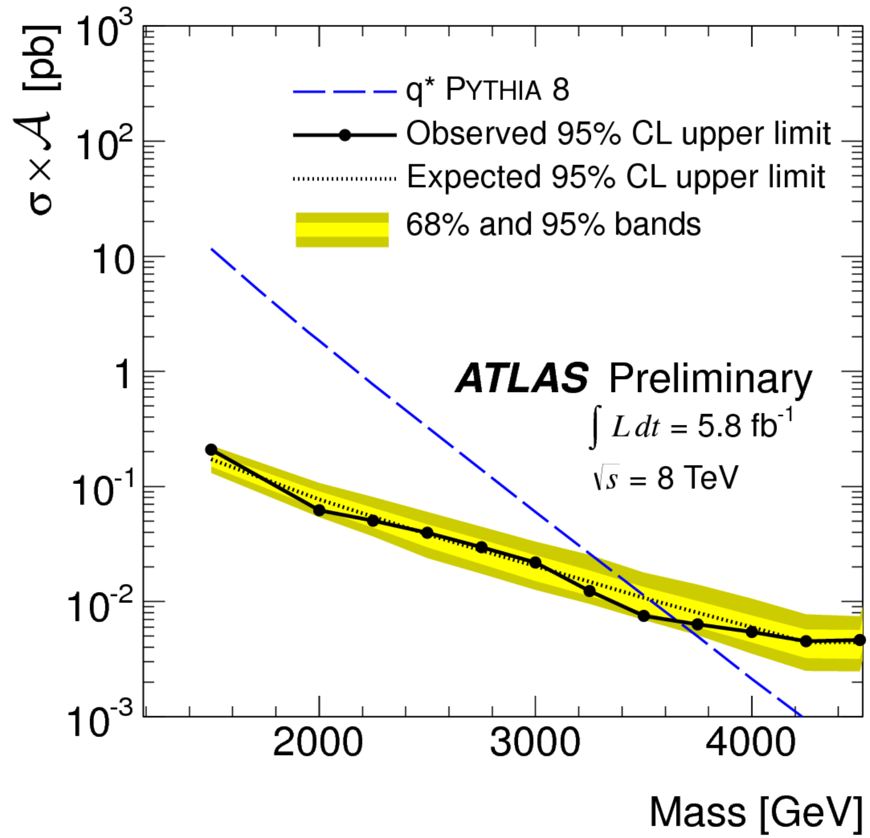
Phys. Lett. B710 (2012) 538

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

Search for resonances in the di-jet mass spectrum

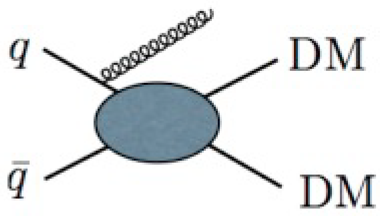
ATLAS-CONF-2012-088



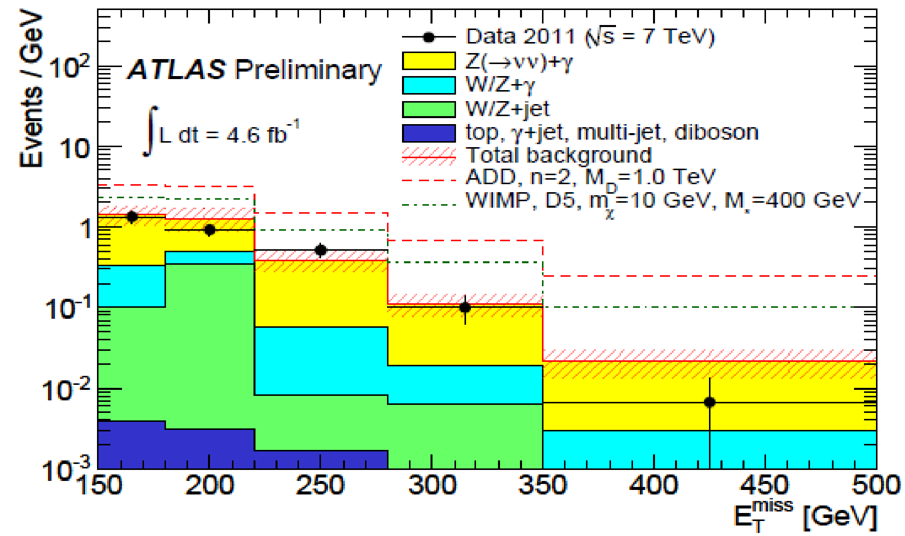


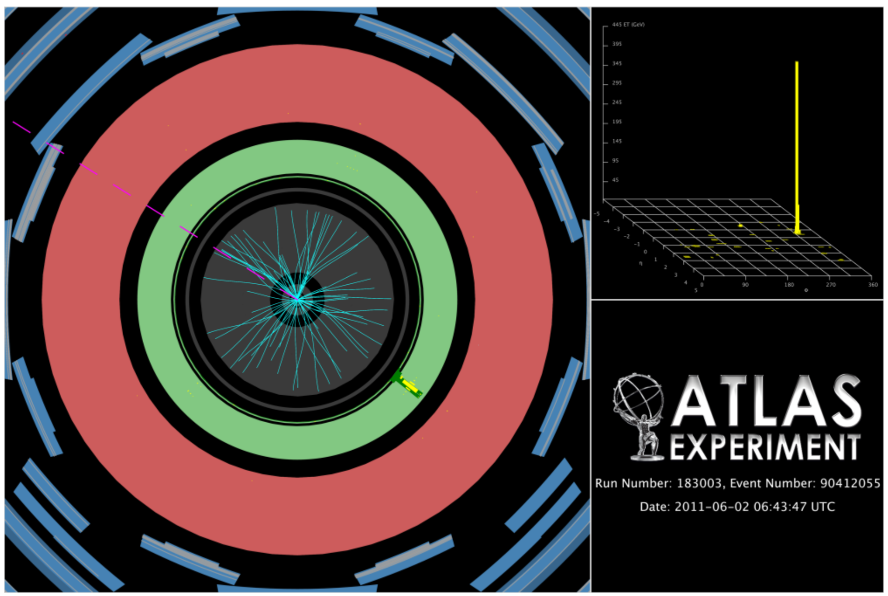
95% CL excluded mass: 3.66 TeV

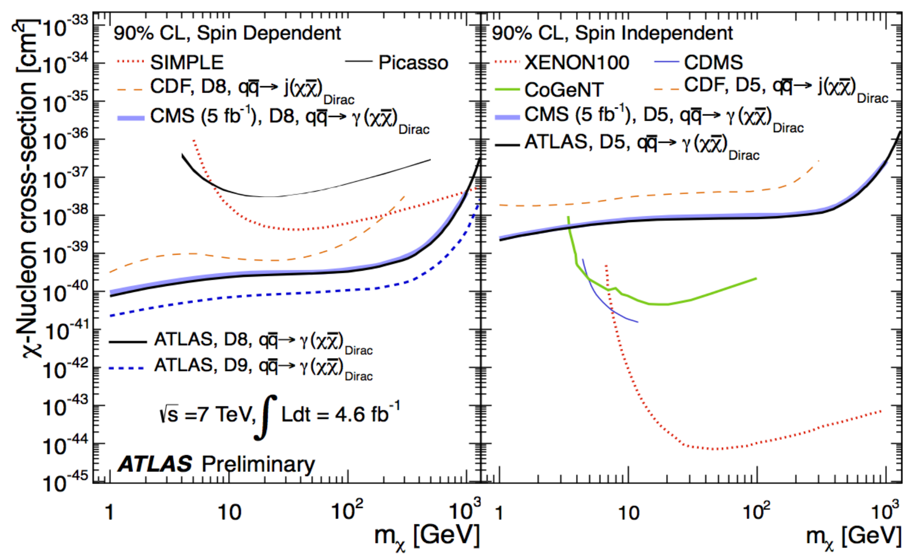
Search for direct Dark Matter (DM) particles in pair-production



A single photon (150 GeV) or jet plus ETmiss



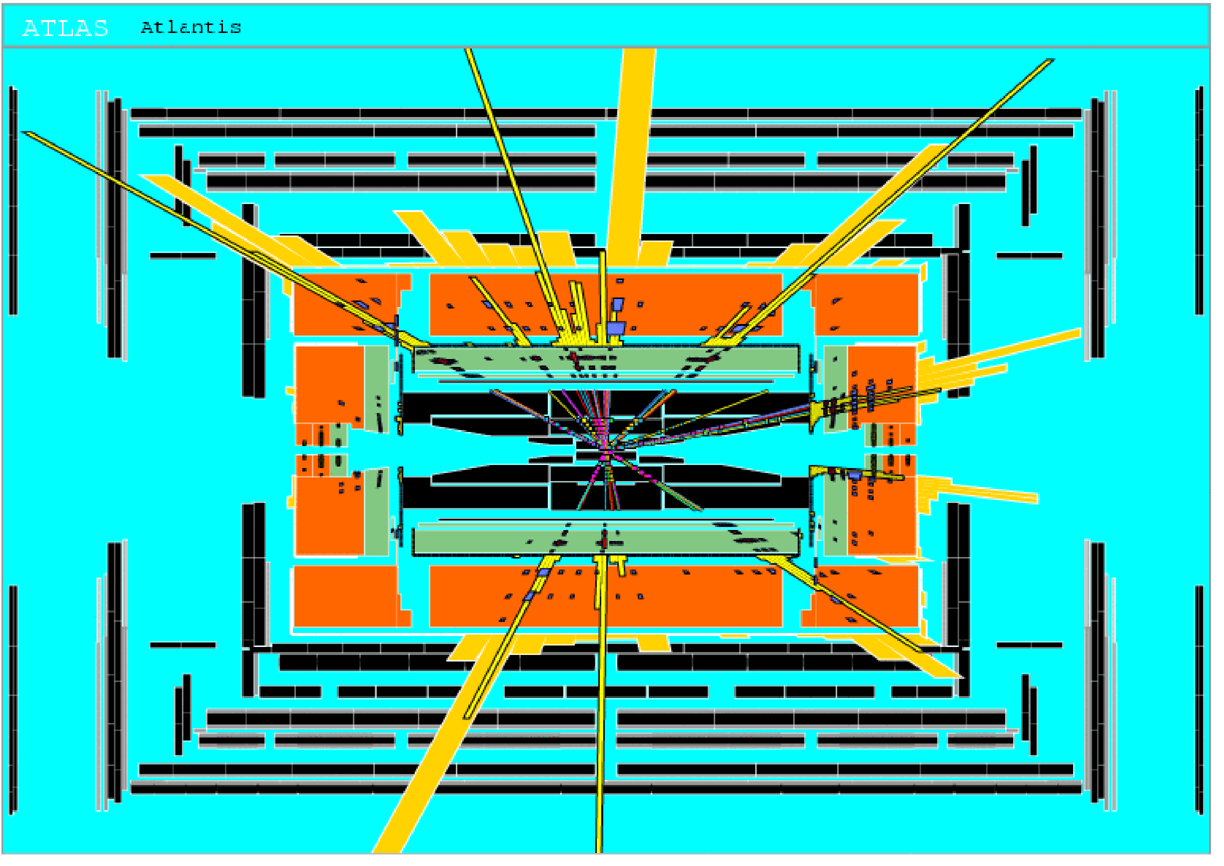




ATLAS-CONF-2012-085
arXiv:1210.4491v1[hep-ex]

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

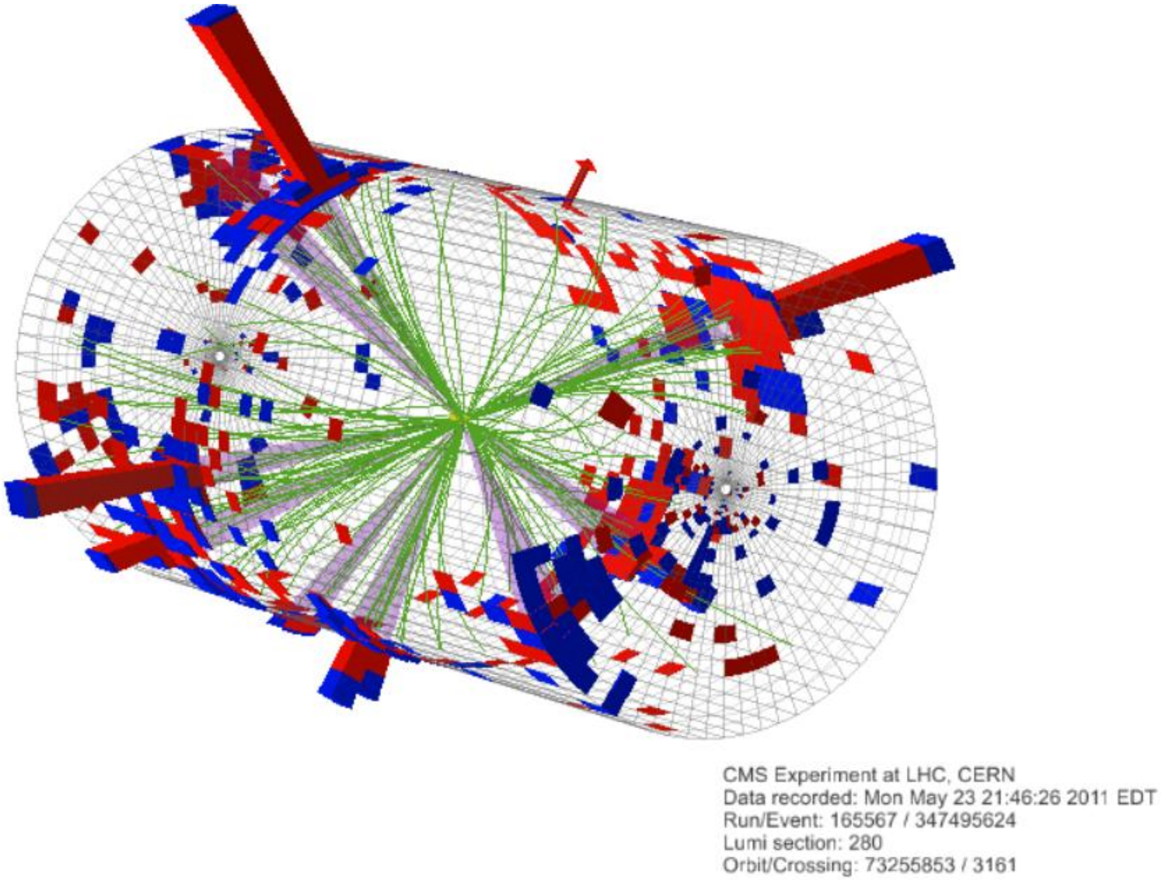
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



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

They decay immediately through Stephen Hawking radiation

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



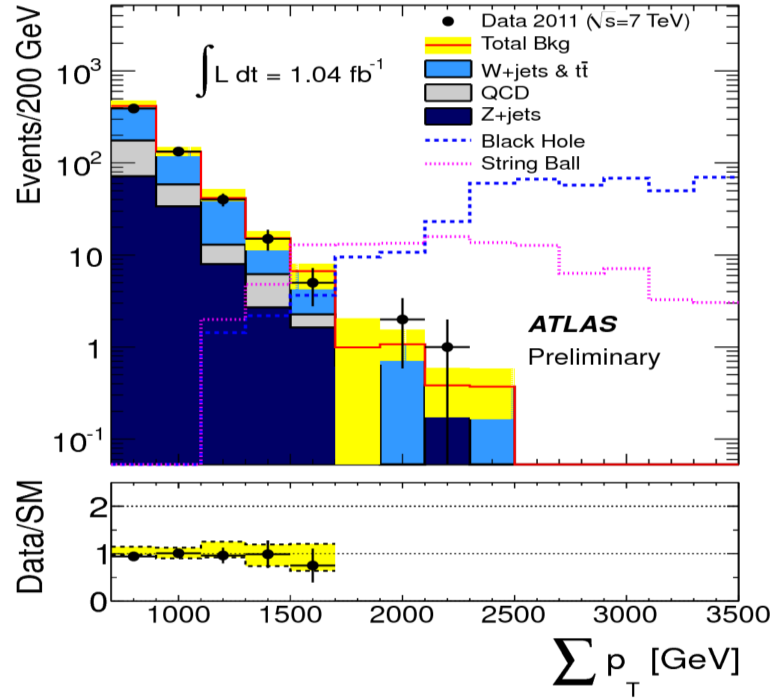
A real 'candidate' event of a 'black hole' in CMS with 9 jets and ST = 2.6 TeV

They decay immediately through Stephen Hawking radiation

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

Decay into many objects (jets, leptons, photons)

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

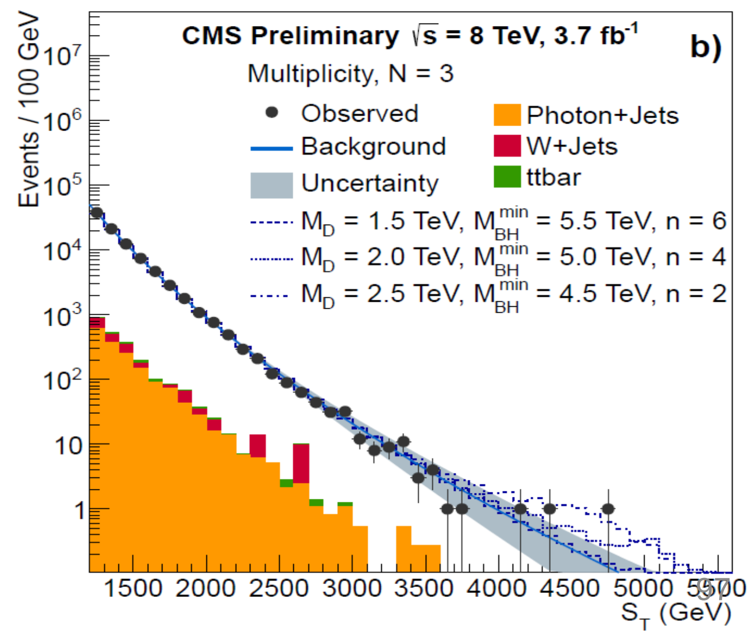


ΣP_T : scalar sum of the E_T of the N objects in the event

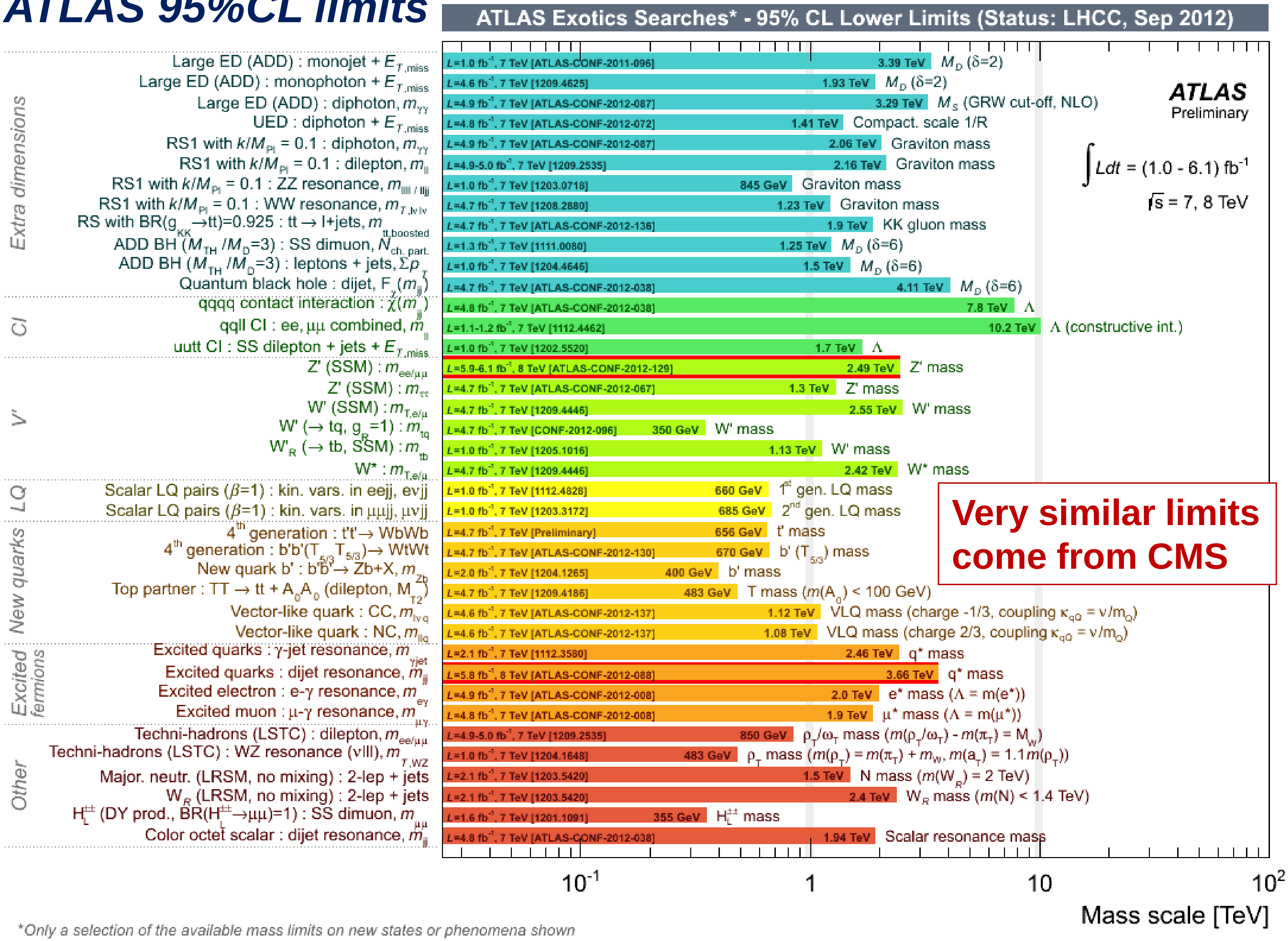
<u>Examples:</u> (ATLAS) at least one electron or muon and two or more jets, (CMS) any three objects

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

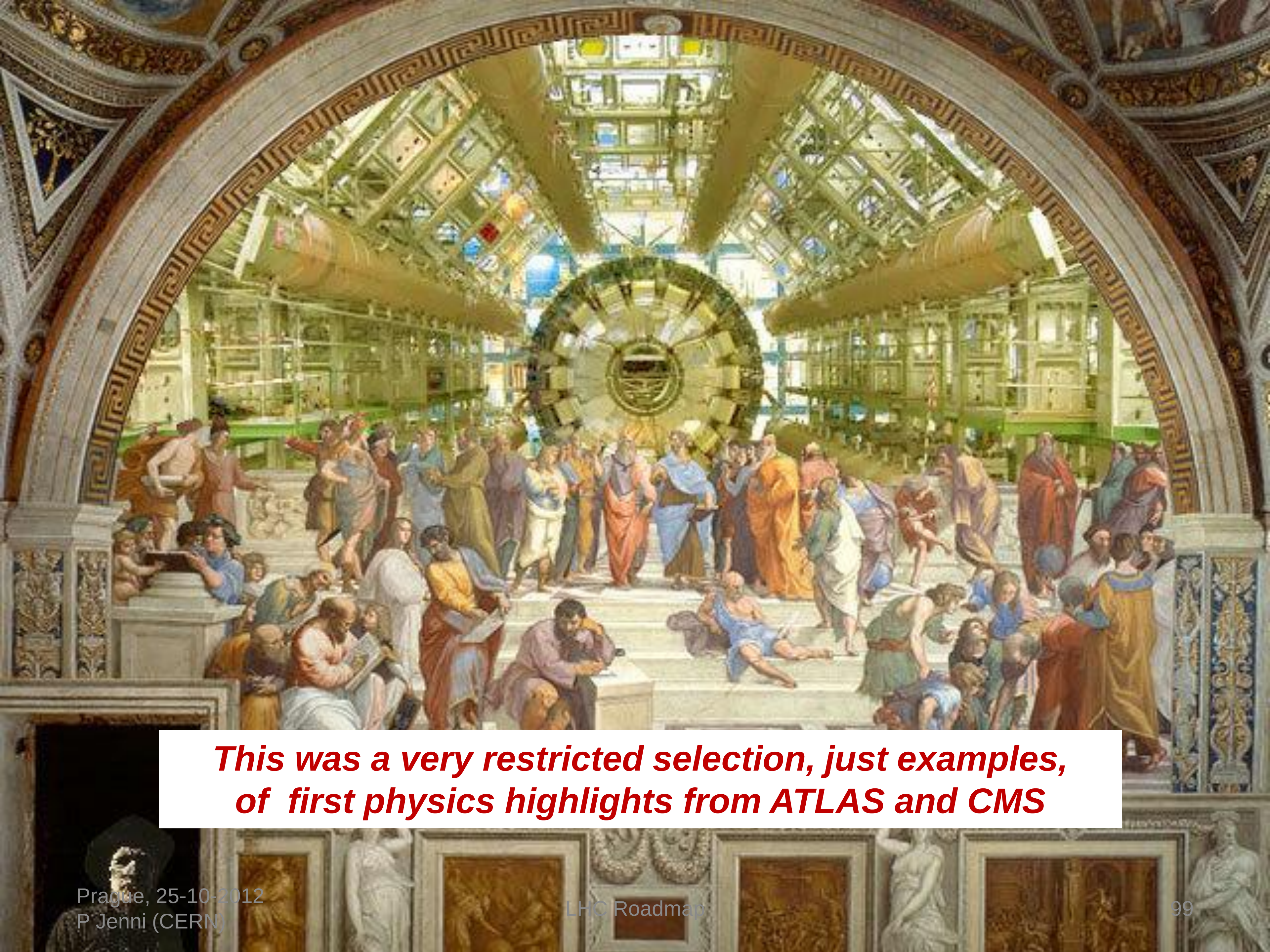
CMS-EXO-12-009



ATLAS 95%CL limits

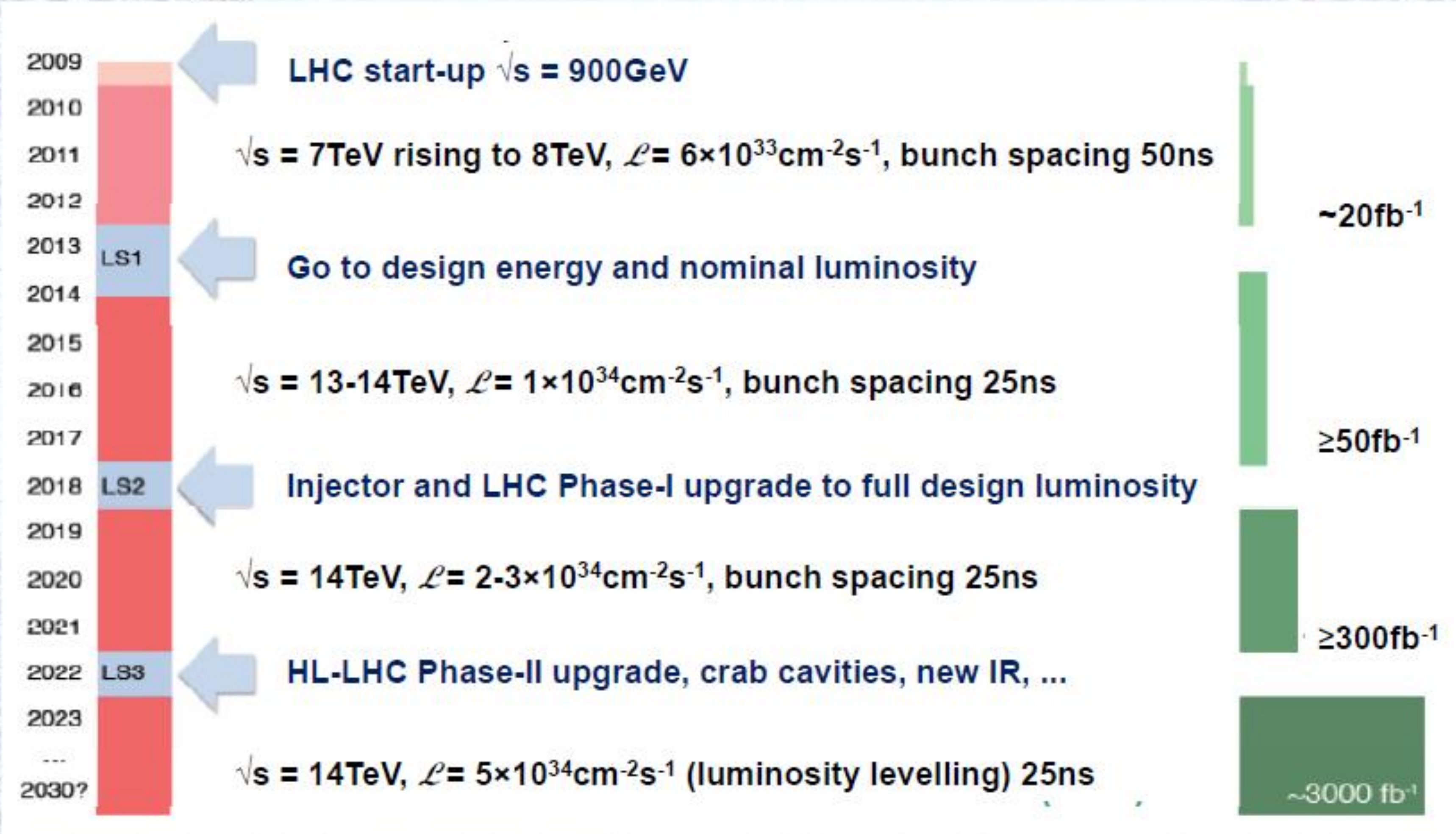


Very similar limits come from CMS



This was a very restricted selection, just examples, of first physics highlights from ATLAS and CMS

LHC Schedule Assumptions



20 years of working with the Czech colleagues and friends in ATLAS was a real pleasure, and we are looking forward to a bright common future with LHC and its upgrades of the machine and the experiment

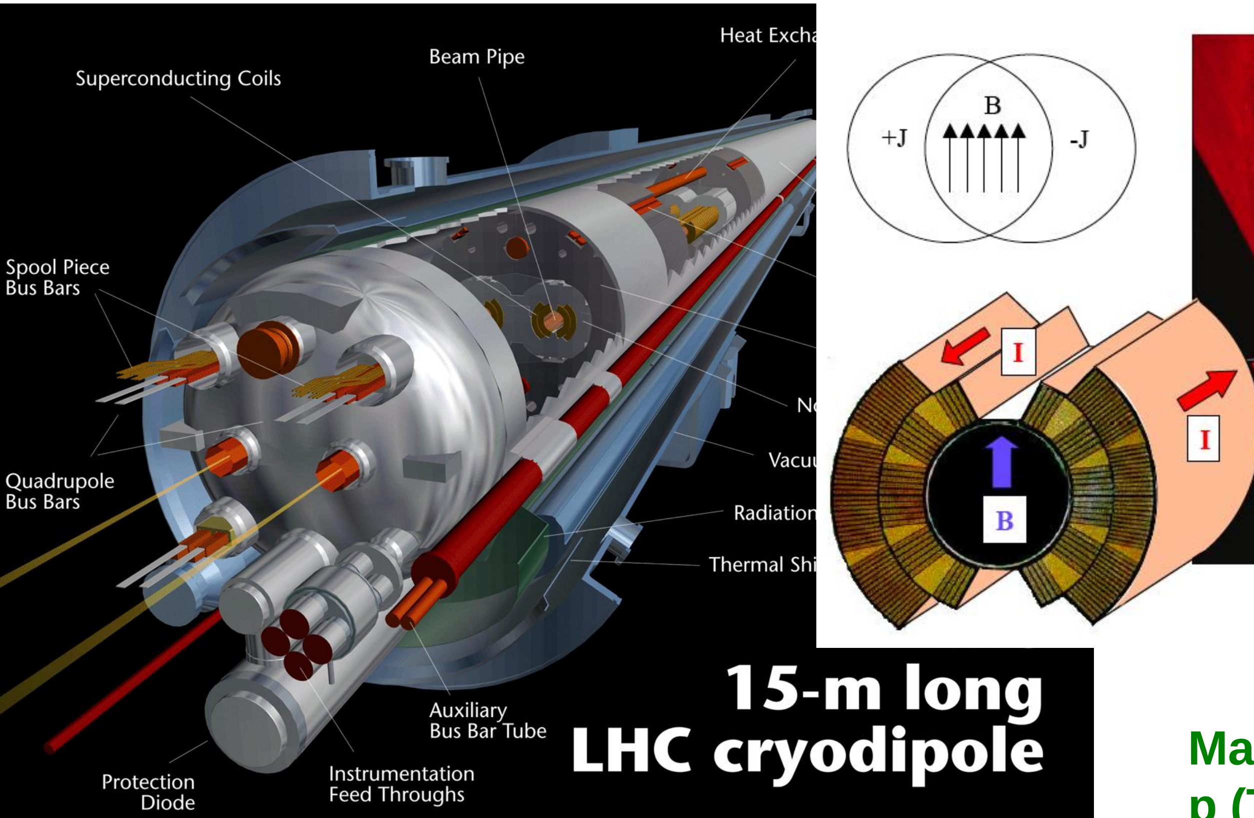
Exciting times for discoveries are ahead of us!

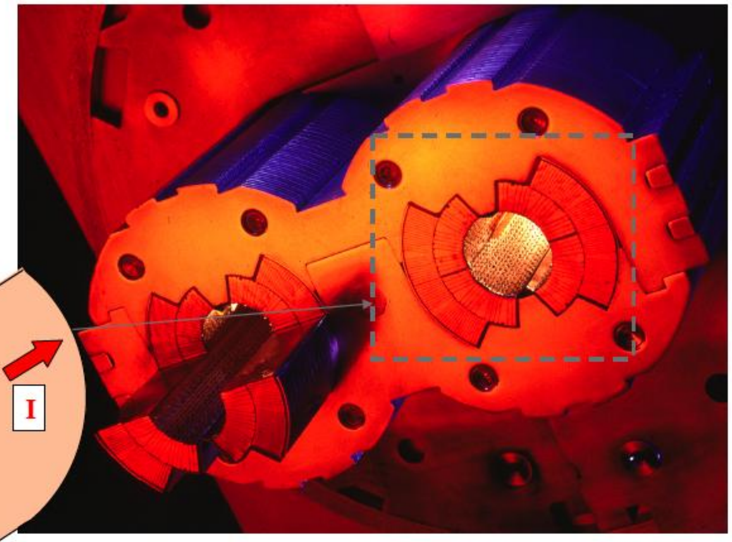
Thank You!

J Blaeu 1664

Spares

LHC Accelerator Challenge: Dipole Magnets





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

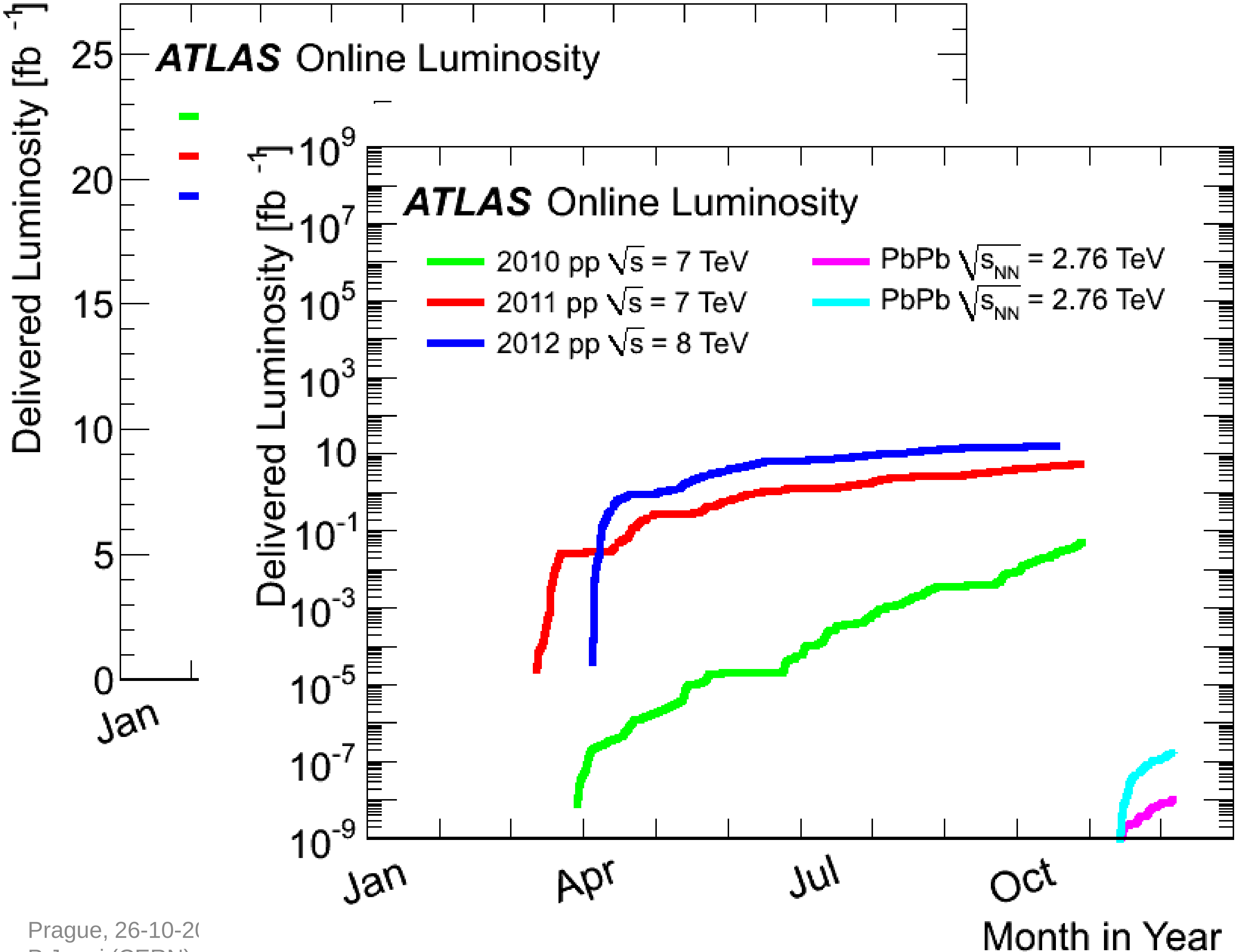
For p = 7 TeV and R = 4.3 km
⇨ B = 8.4 T
⇨ Current 12 kA

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

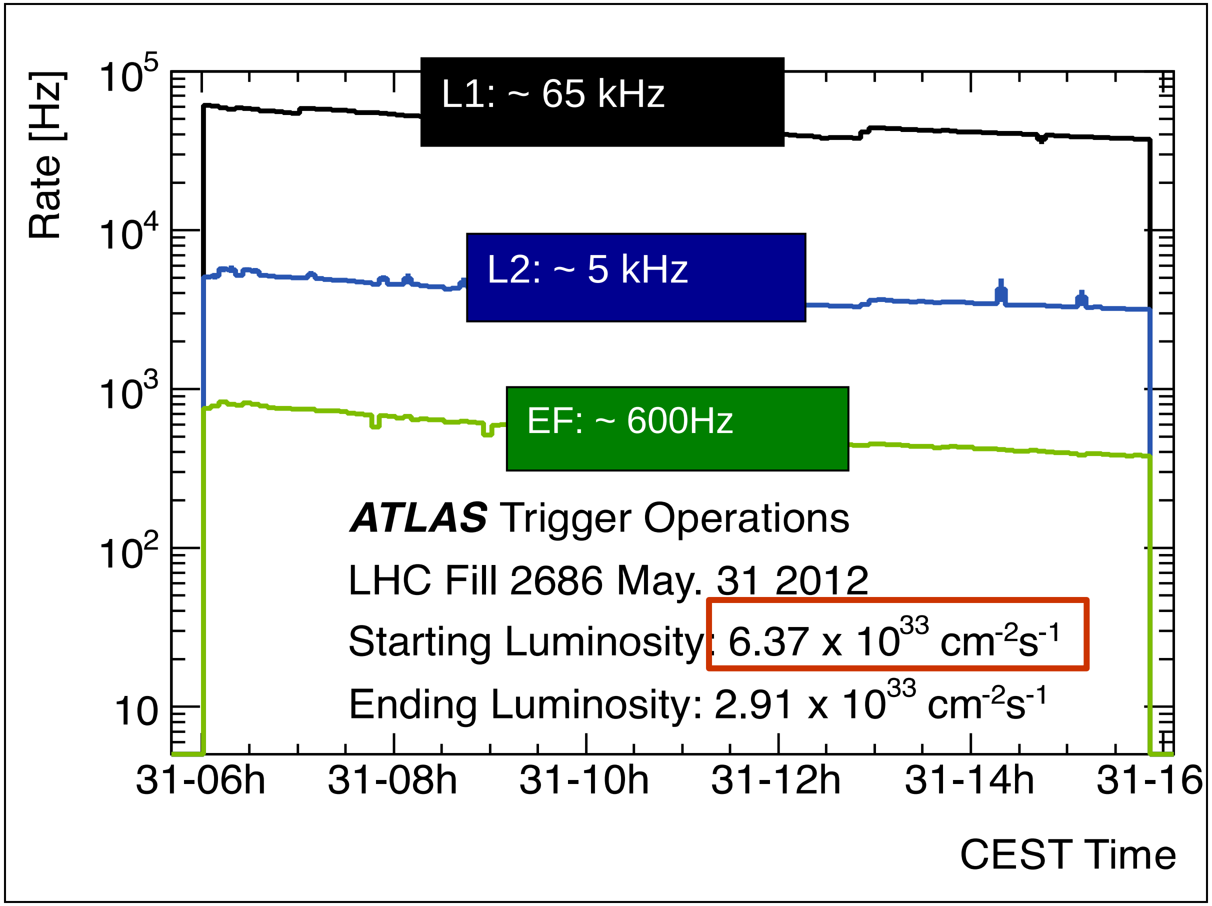
LHC magnets are cooled with pressurized superfluid helium

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


ATLAS Online Luminosity
Delivered Luminosity [fb^{-1}]
25
20
15
10
5
0
Jan
ATLAS Online Luminosity
Delivered Luminosity [fb^{-1}]
10^{9}
10^{7}
10^{5}
10^{3}
10
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
2010 pp $\sqrt{s}$ = 7 TeV
2011 pp $\sqrt{s}$ = 7 TeV
2012 pp $\sqrt{s}$ = 8 TeV
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Jan
Apr
Jul
Oct
Month in Year

Example for the typical trigger rates



Three levels of event selections:

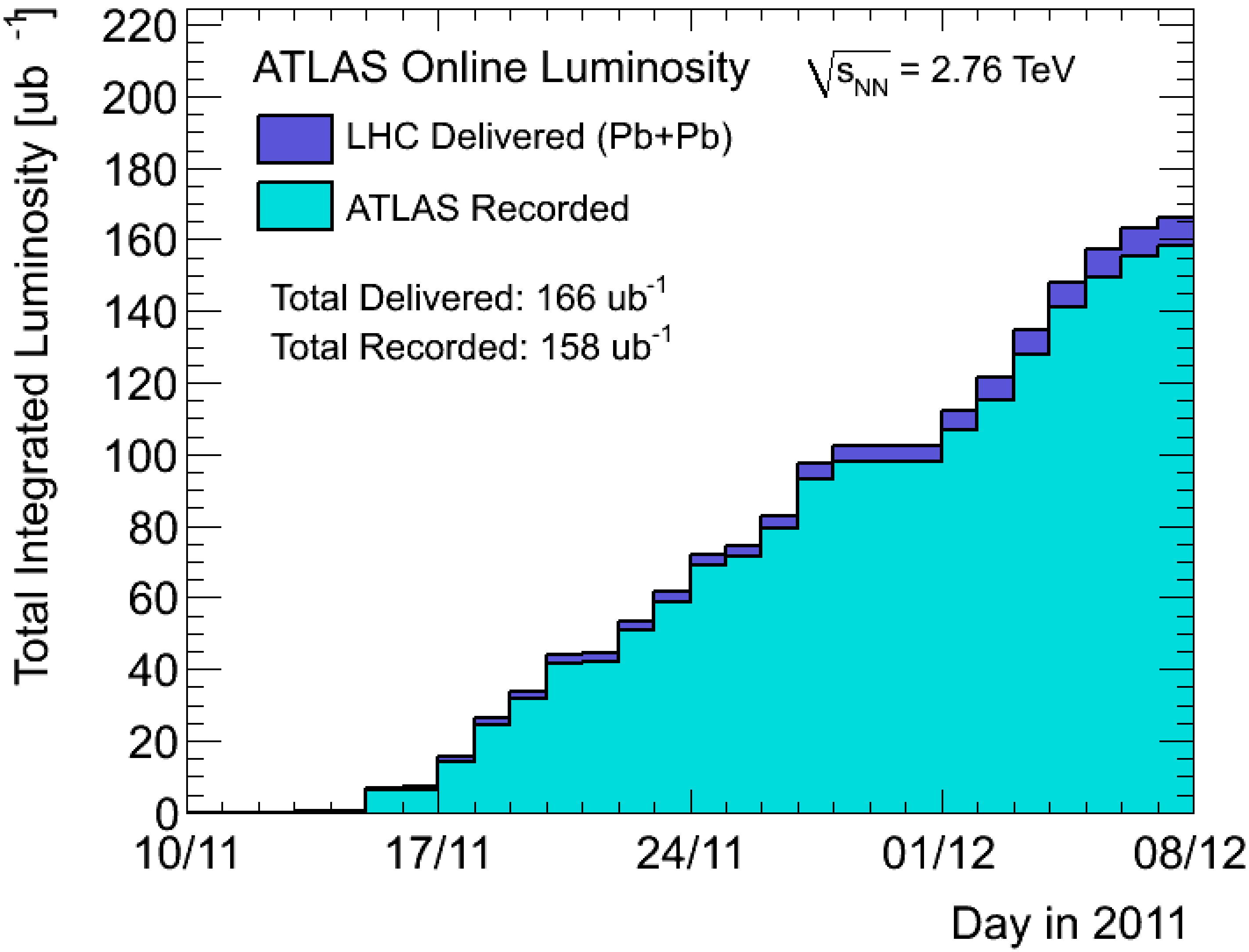
Level-1 underground with purpose-made electronics and processors

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)

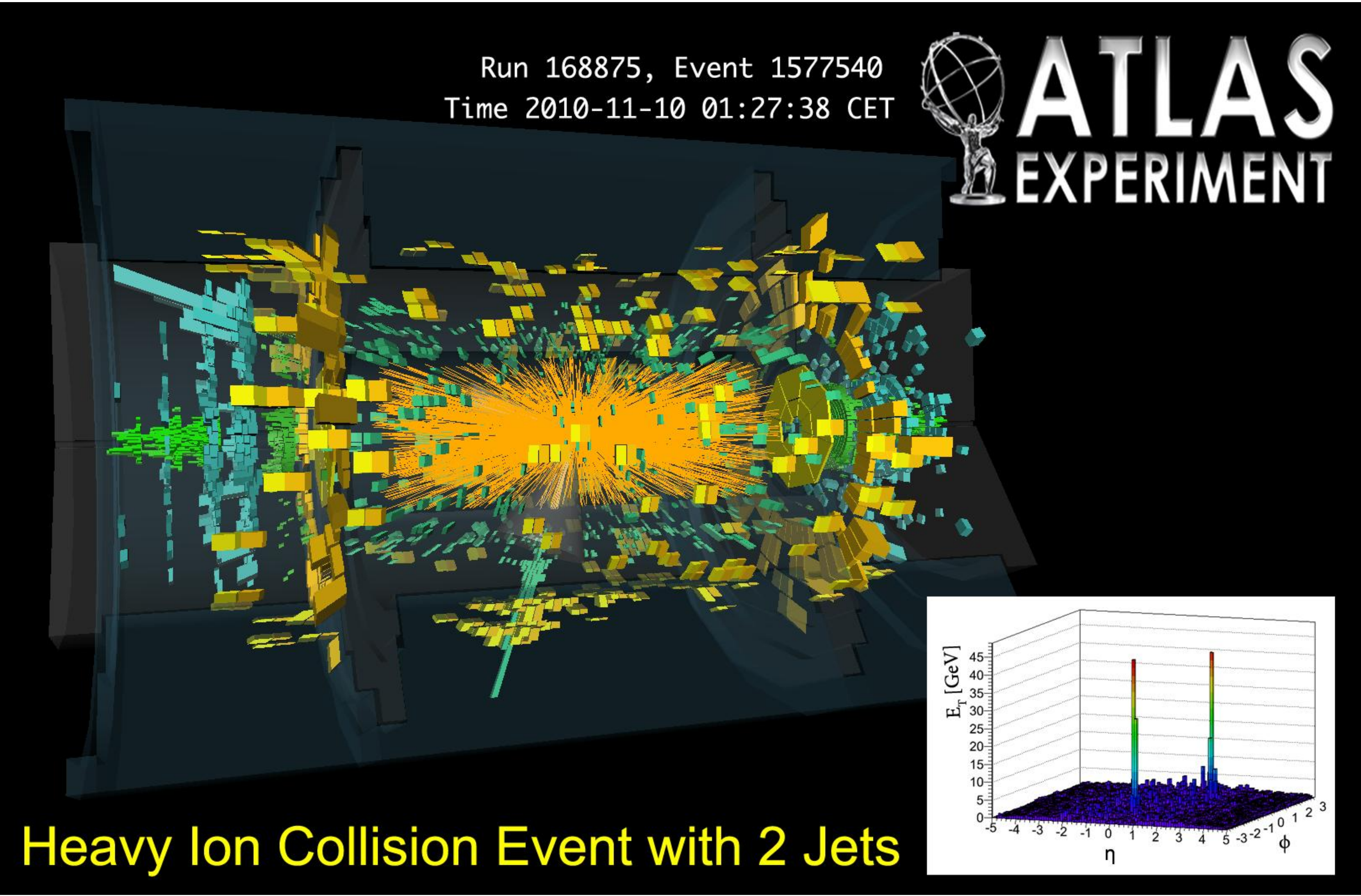
- ❑ **Typical recorded rates for main streams e/γ, Jets/τ/E_T^{miss} , Muons: ~ 100 Hz each**
- ❑ **Delayed stream (future Tier0 reconstruction): B-physics (~65 Hz) and Hadronic (~80 Hz)**
- ❑ **Note: currently 564 items in the trigger menu**

Heavy Ion Running in 2011



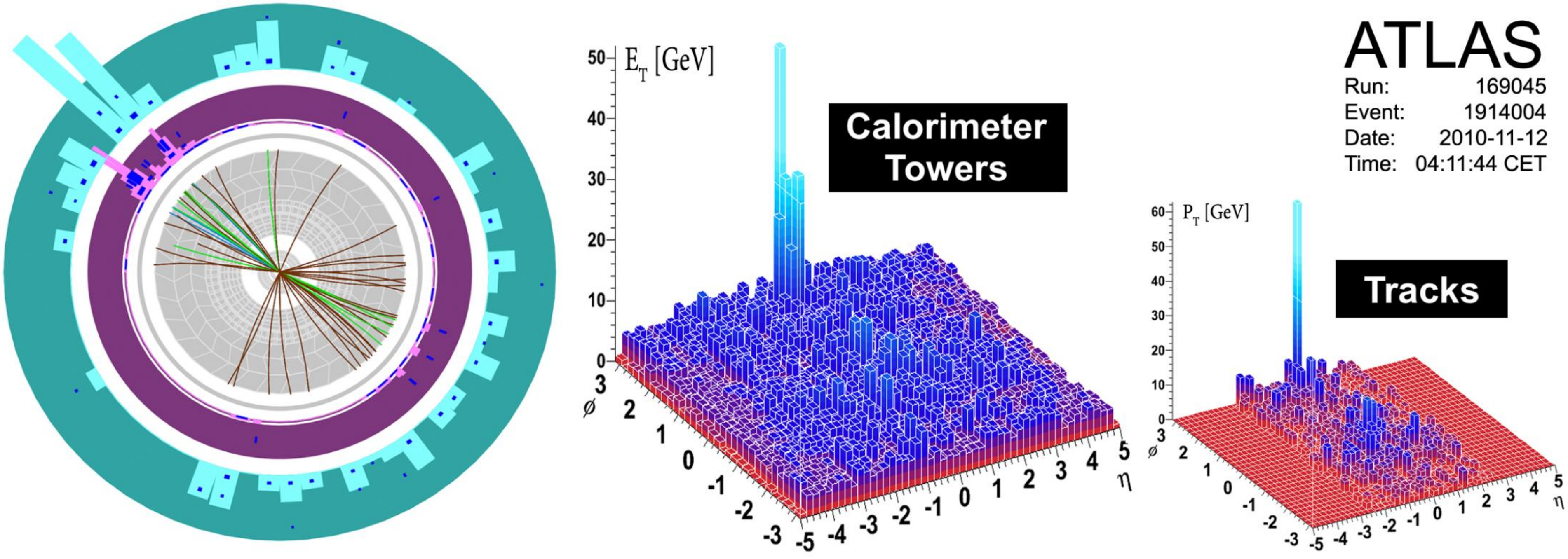
Pb-Pb event with jets

Uncorrected p_T of each jet ~160 GeV



Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector at the LHC

G. Aad *et al.* (The ATLAS Collaboration)*



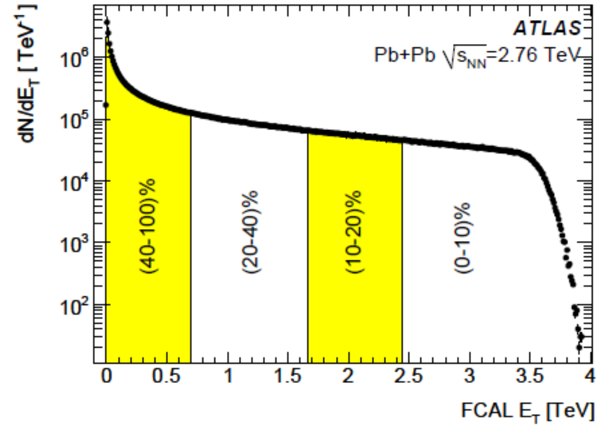
Phys. Rev. Lett. 105 (2010) 252303

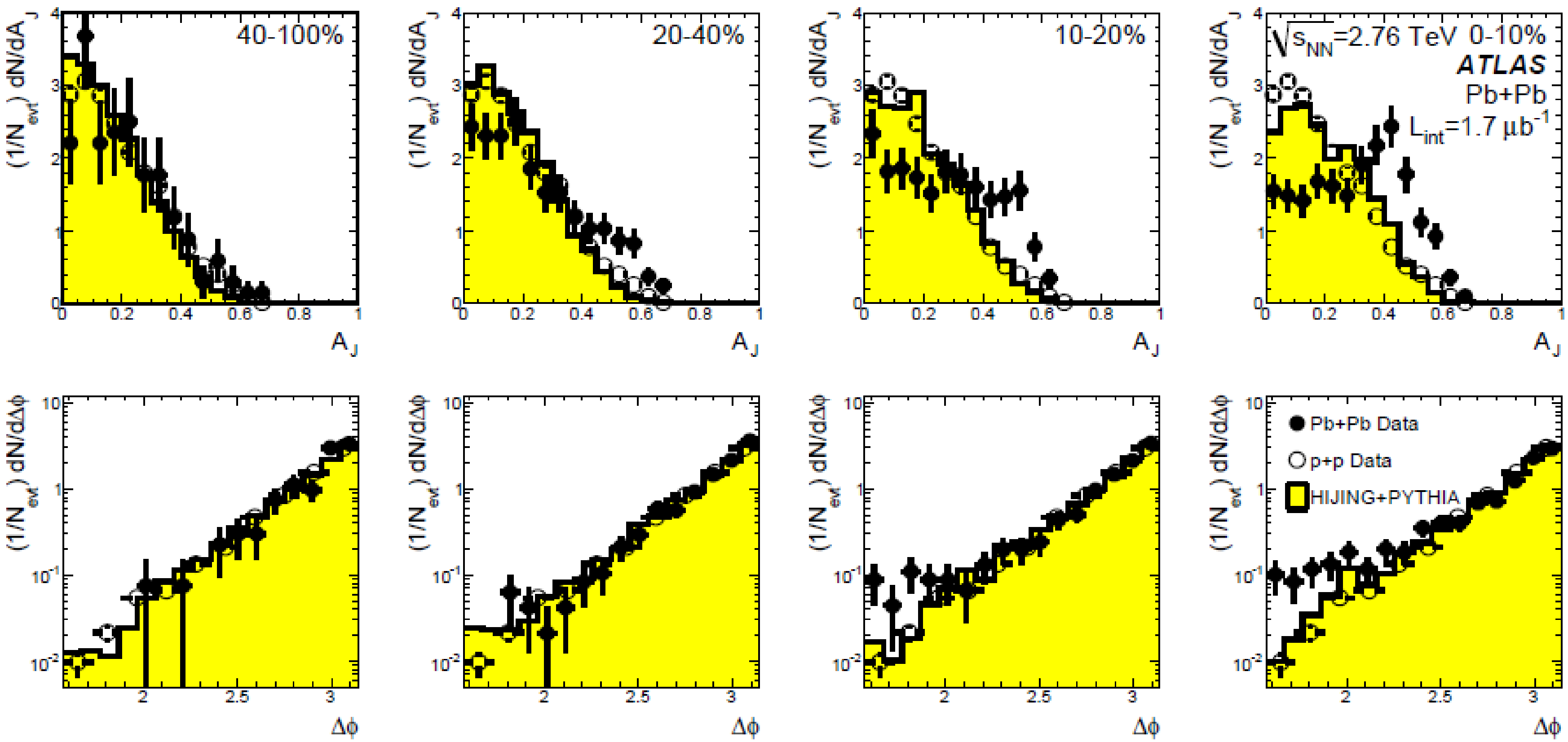
Measured di-jet asymmetry A_J as a function of the centrality

(1.7 μb^{-1})

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

Centrality bins defined with the ET in FCAL

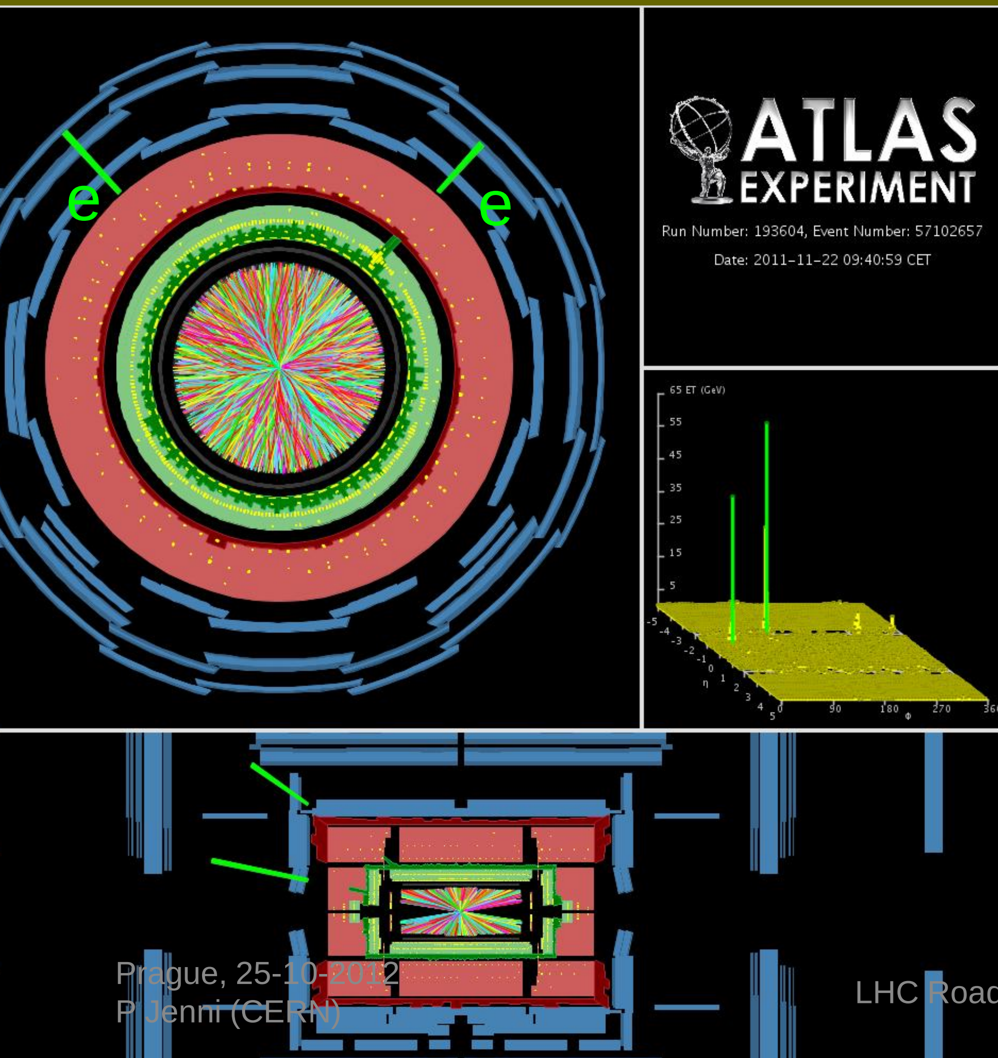


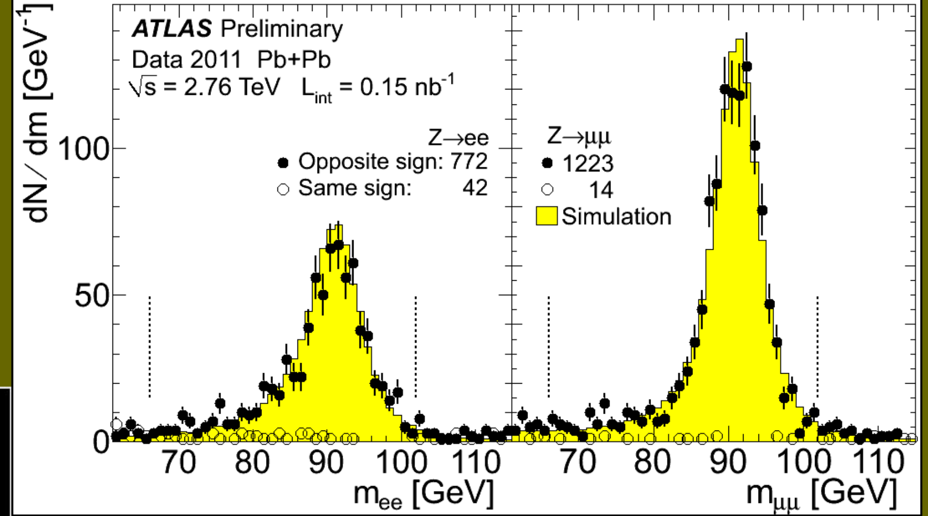


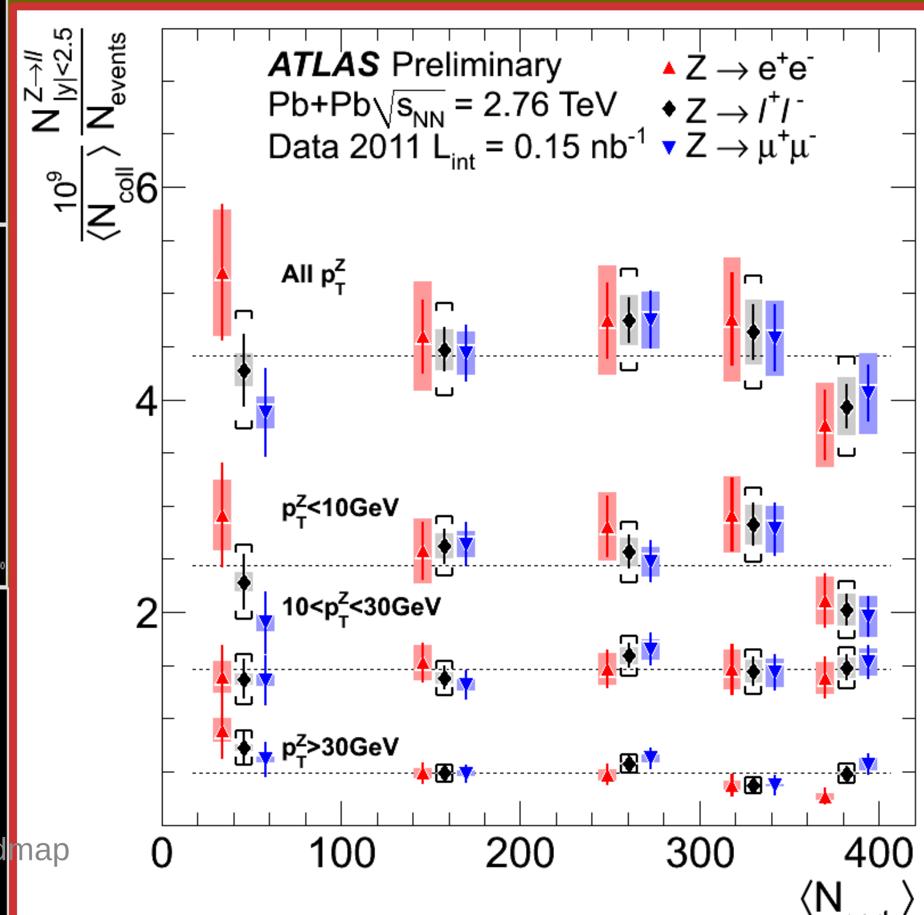
Such an effect could be the first direct indication of 'jet-quenching'

Z → ee, μμ in Heavy Ions

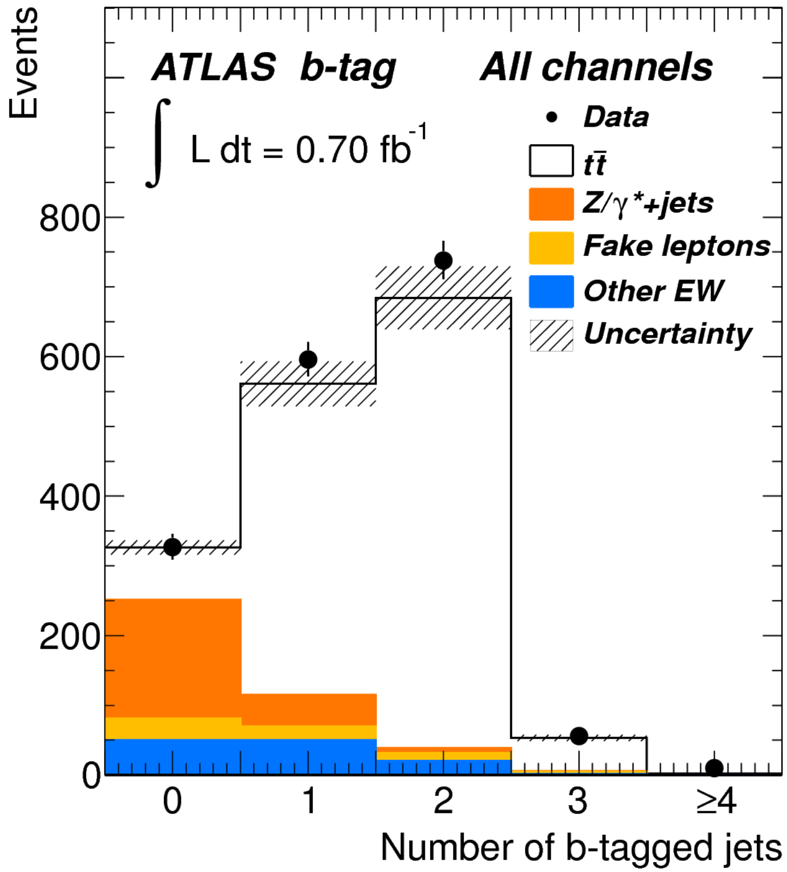
- Studied with full 2011 dataset (~ 150 μb^{-1})
- As expected: no suppression observed of the weakly interacting bosons

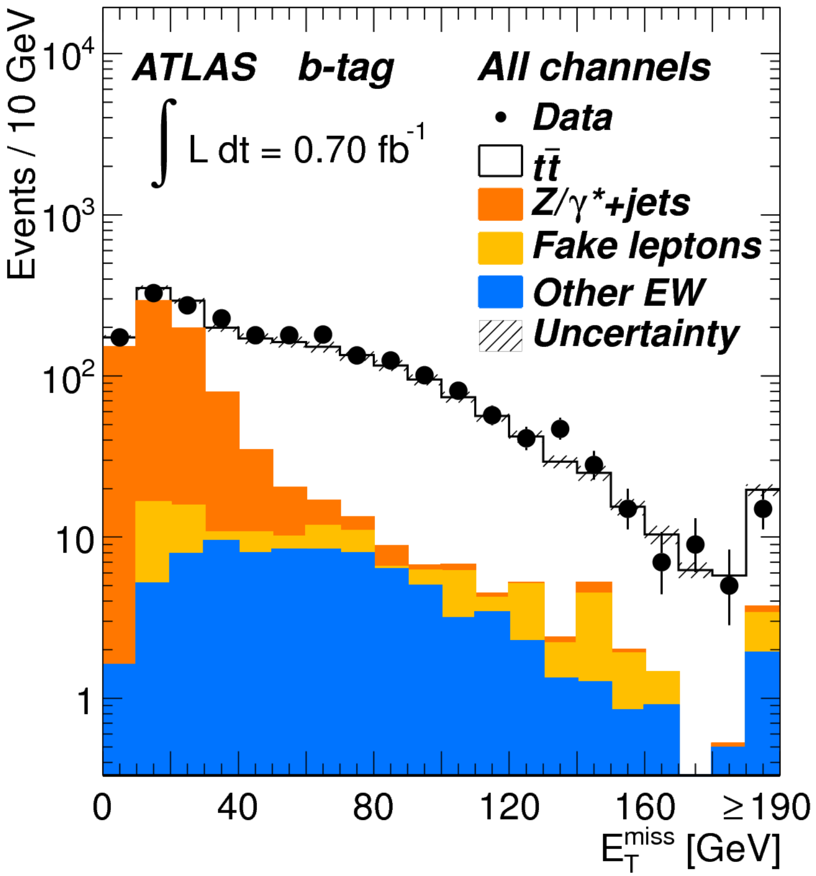






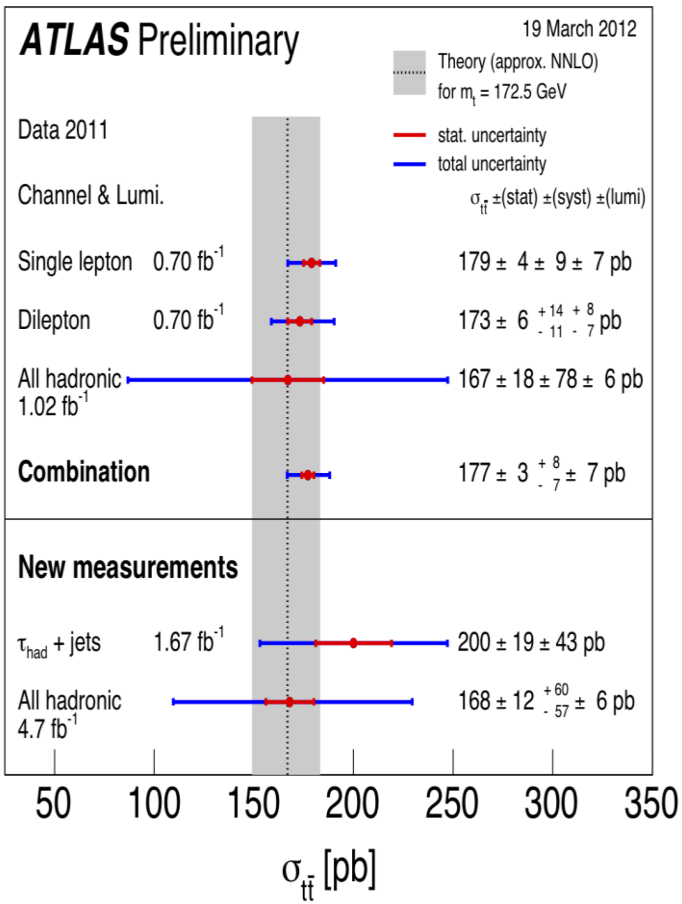
Example of top signals in the case of di-lepton channels

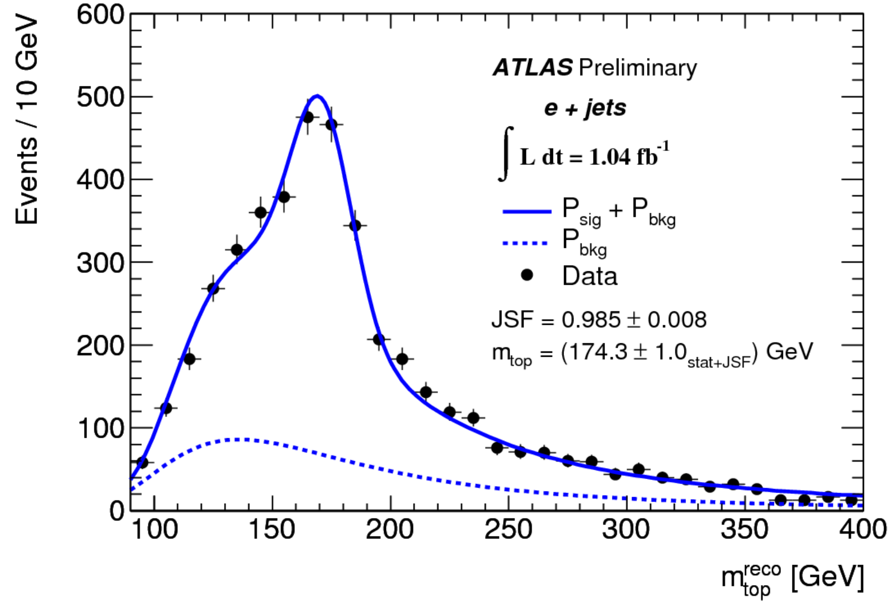


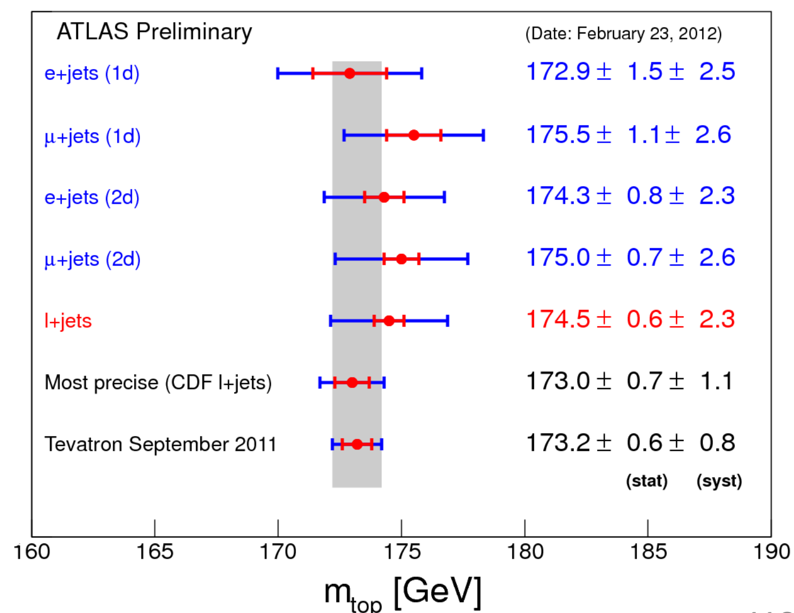


JHEP 1205 (2012) 059

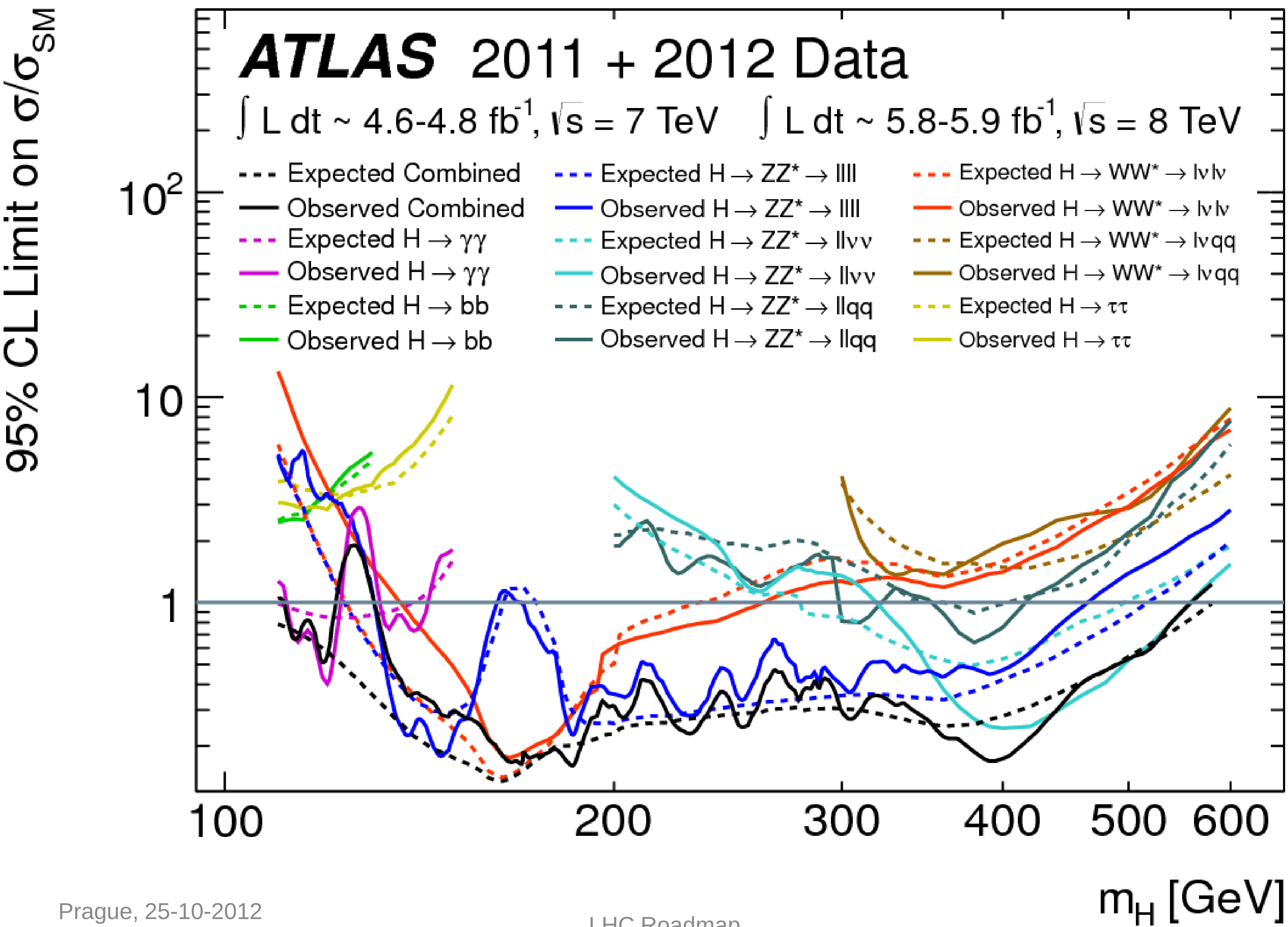
More details on top measurements...



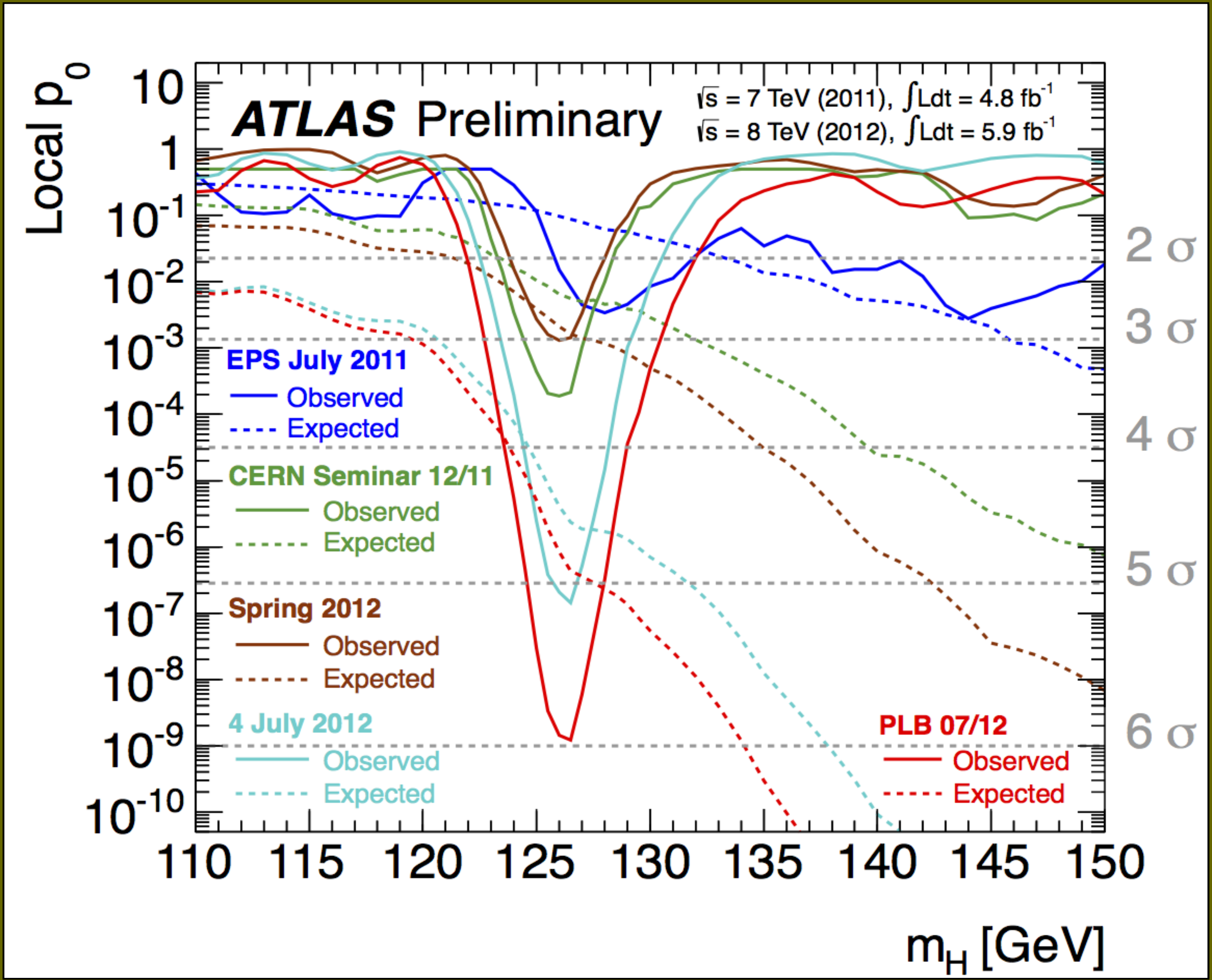




Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\, dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	4.8	[3]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet}\}$	4.8	[4]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu/\mu e, \mu\mu\} \otimes \{\text{0-jet, 1-jet, 2-jet}\} \otimes \{\text{low, high pile-up}\}$	4.7	[5]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{\text{0-jet}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jet}, VH\}$	4.7	[6]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{\text{0-jet}\} \otimes \{E_{\mathrm{T}}^{\mathrm{miss}} < 20\text{ GeV}, E_{\mathrm{T}}^{\mathrm{miss}} \geq 20\text{ GeV}\}$ $\oplus \{e, \mu\} \otimes \{\text{1-jet}\} \oplus \{\ell\} \otimes \{\text{2-jet}\}$	4.7	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{\text{1-jet}\}$	4.7	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\text{ GeV}\}$	4.6	[7]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-200, \geq 200\text{ GeV}\}$	4.7	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-200, \geq 200\text{ GeV}\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	5.8	[3]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet}\}$	5.9	[4]
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes \{\text{0-jet, 1-jet, 2-jet}\}$	5.8	[8]

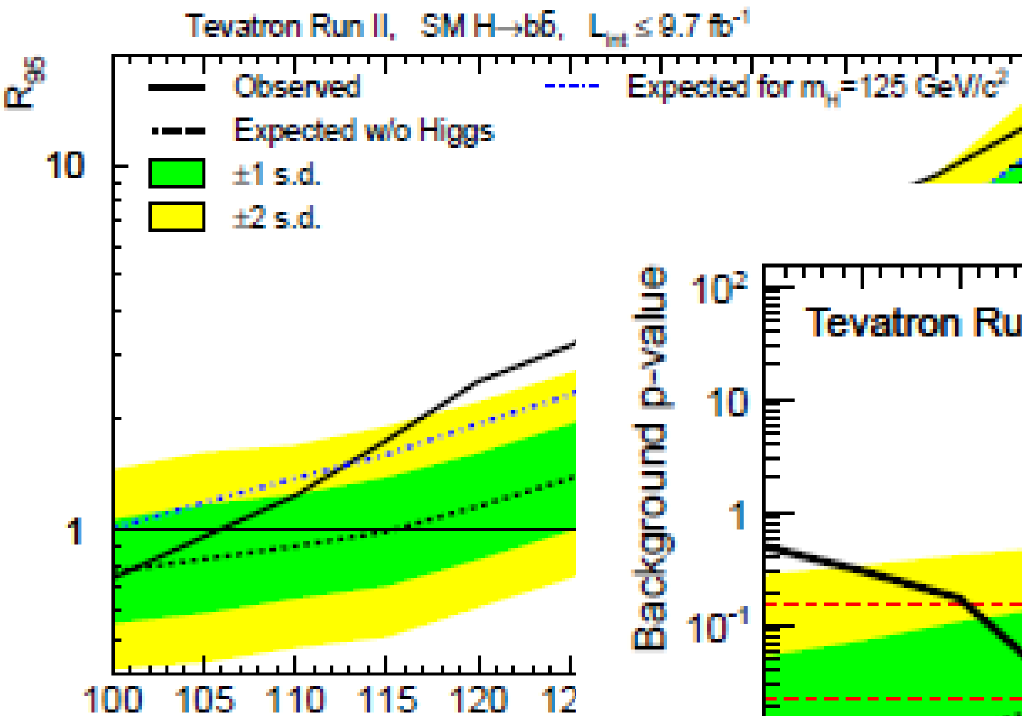

ATLAS 2011 + 2012 Data
∫ L dt ~ 4.6-4.8 fb-1, √s = 7 TeV ∫ L dt ~ 5.8-5.9 fb-1, √s = 8 TeV
Expected Combined
Observed Combined
Expected H → γγ
Observed H → γγ
Expected H → bb
Observed H → bb
Expected H → ZZ* → llll
Observed H → ZZ* → llll
Expected H → ZZ* → llνν
Observed H → ZZ* → llνν
Expected H → ZZ* → llqq
Observed H → ZZ* → llqq
Expected H → WW* → lνlν
Observed H → WW* → lνlν
Expected H → WW* → lνqq
Observed H → WW* → lνqq
Expected H → ττ
Observed H → ττ
95% CL Limit on σ/σSM
10²
10
1
100
200
300
400
500
600
mH [GeV]

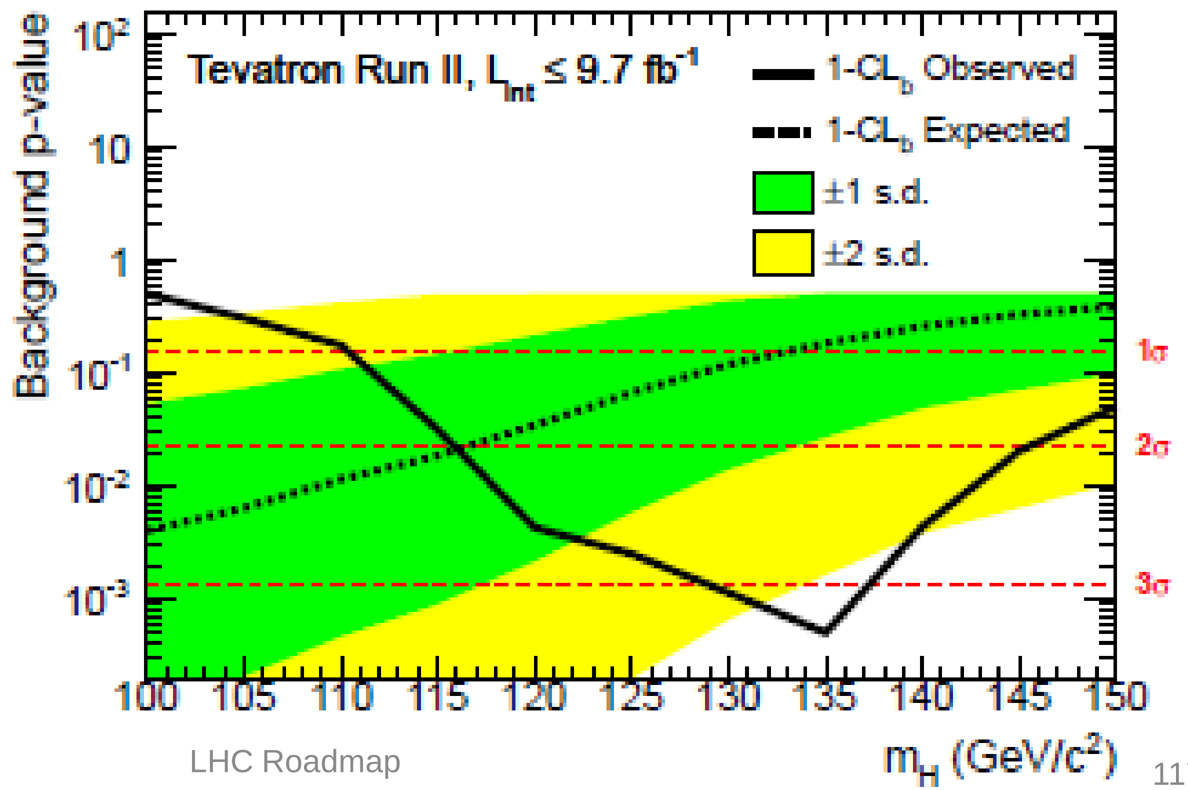
Evolution of the excess with time



CDF and D0 Collaborations

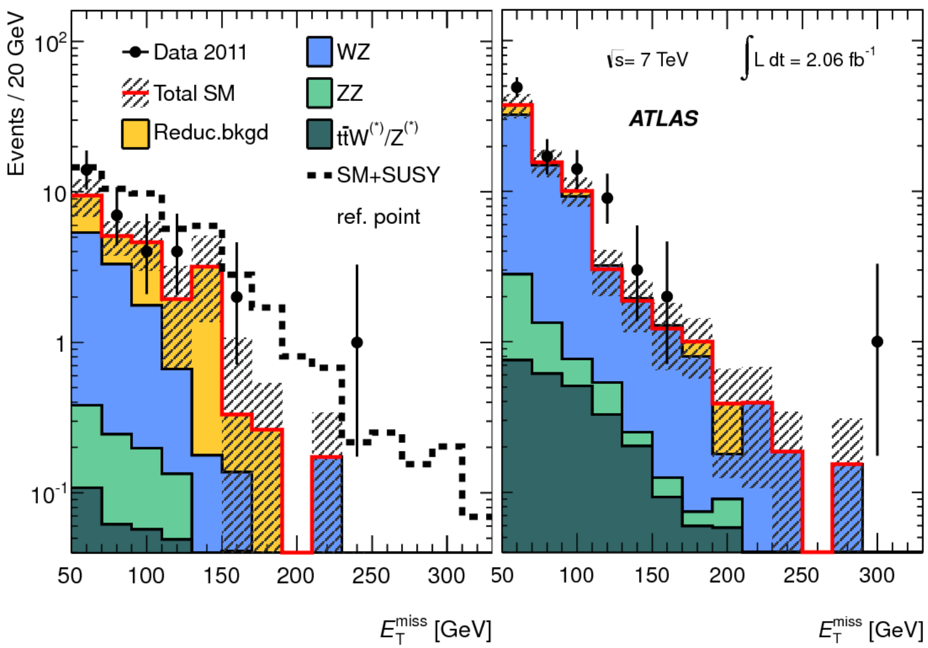
Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom quark pair in Higgs boson search at the Tevatron, submitted to Phys. Rev. Lett. (2012), arXiv:1207.6436.



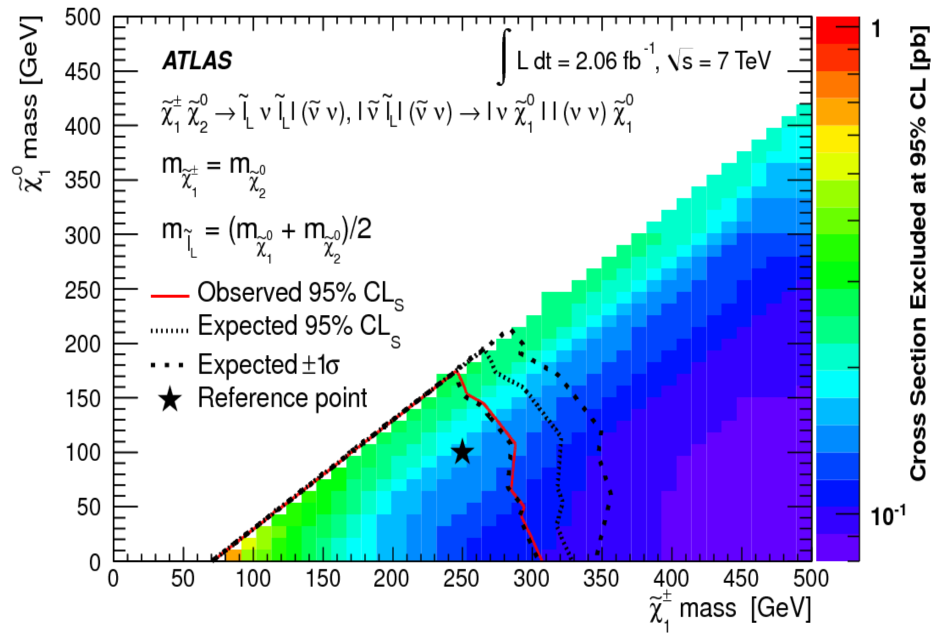


Searches for charginos/neutralinos

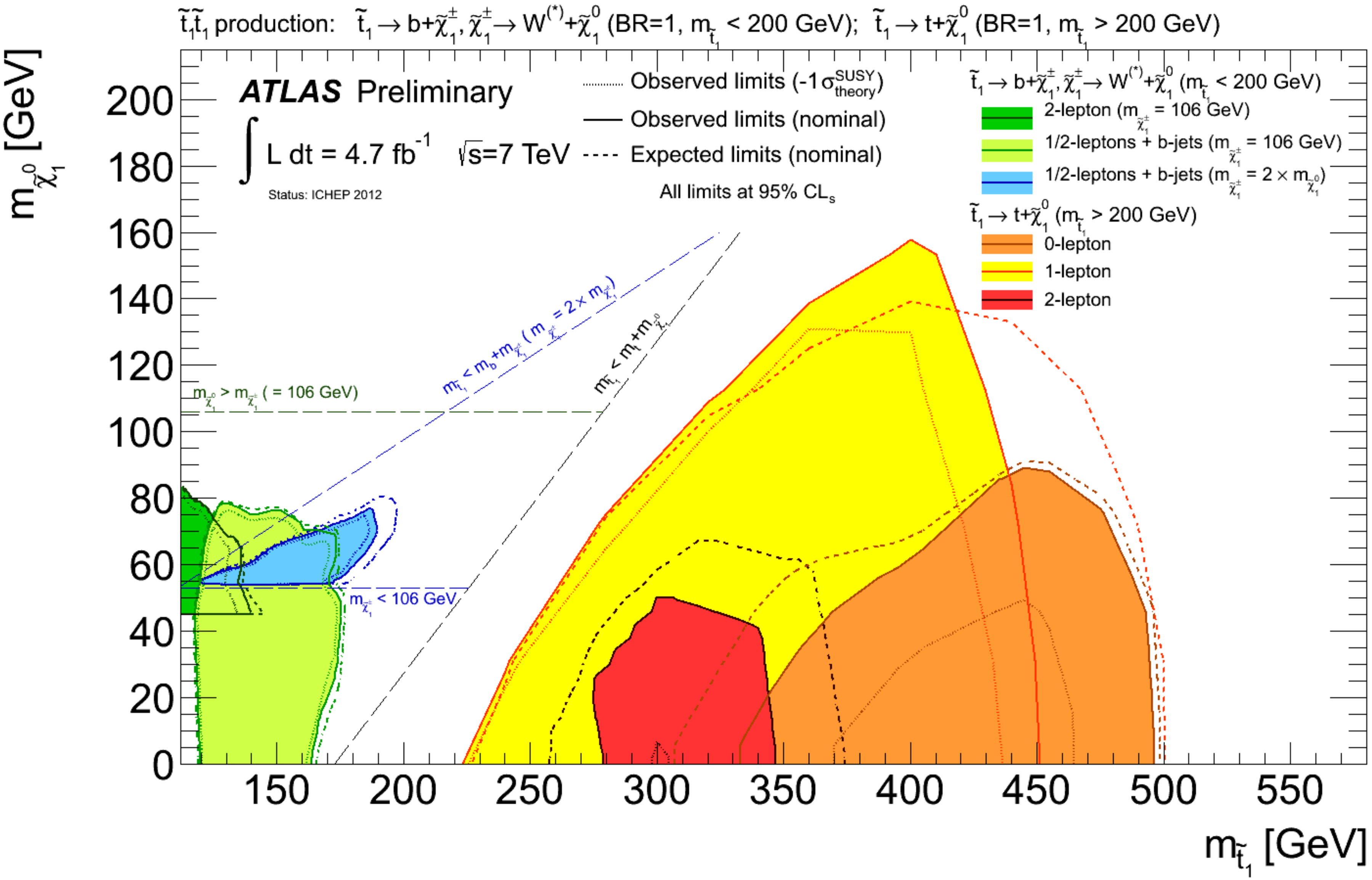
- Direct chargino/neutralino production cross section in the pb range
- ATLAS has searched for this in 3-lepton final state
- Limits in the $m(\chi^{\pm}_1/\chi^0_2) \sim 250$ GeV region have been set



(Z-depleted and Z-enriched signal regions)



Accepted in Phys. Rev. Lett.
arXiv:1204.5638v1[hep-ex]



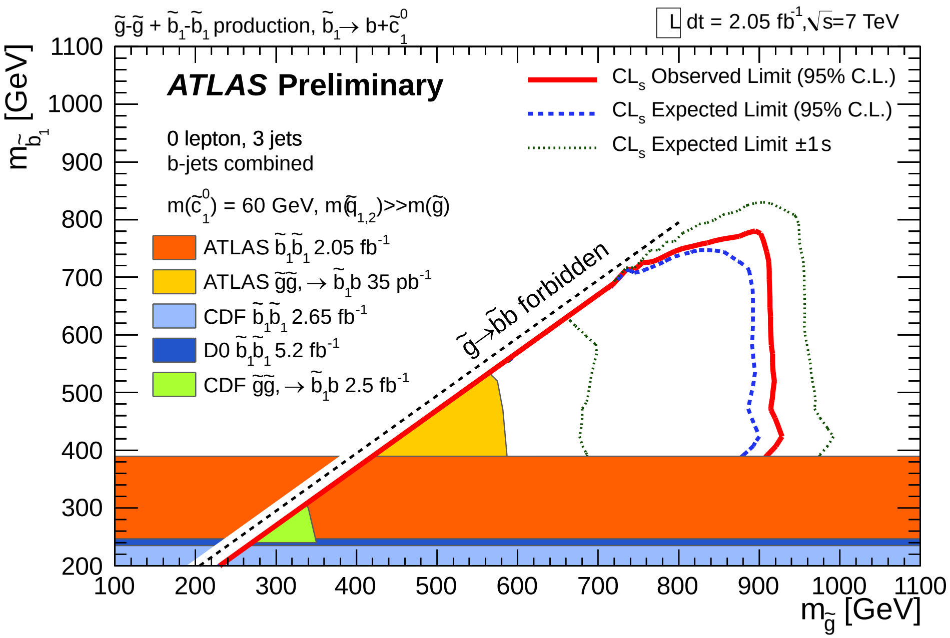
$\tilde{t}_1\tilde{t}_1$ production: $\tilde{t}_1 \to b+\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to W^{(*)}+\tilde{\chi}_1^0$ (BR=1, $m_{\tilde{t}_1}$ < 200 GeV); $\tilde{t}_1 \to t+\tilde{\chi}_1^0$ (BR=1, $m_{\tilde{t}_1}$ > 200 GeV)
ATLAS Preliminary
$\int L\,dt = 4.7\ fb^{-1}$ $\sqrt{s}$=7 TeV
Status: ICHEP 2012
Observed limits ($-1\sigma^{SUSY}_{theory}$)
Observed limits (nominal)
Expected limits (nominal)
All limits at 95% CL_s
$\tilde{t}_1 \to b+\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to W^{(*)}+\tilde{\chi}_1^0$ ($m_{\tilde{t}_1}$ < 200 GeV)
2-lepton ($m_{\tilde{\chi}_1^\pm}$ = 106 GeV)
1/2-leptons + b-jets ($m_{\tilde{\chi}_1^\pm}$ = 106 GeV)
1/2-leptons + b-jets ($m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$)
$\tilde{t}_1 \to t+\tilde{\chi}_1^0$ ($m_{\tilde{t}_1}$ > 200 GeV)
0-lepton
1-lepton
2-lepton
$m_{\tilde{\chi}_1^0} > m_{\tilde{\chi}_1^\pm}$ (= 106 GeV)
$m_{\tilde{t}_1} < m_b+m_{\tilde{\chi}_1^\pm}$ ($m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$)
$m_{\tilde{t}_1} < m_t+m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^\pm}$ < 106 GeV
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
20
40
60
80
100
120
140
160
180
200
150
200
250
300
350
400
450
500
550

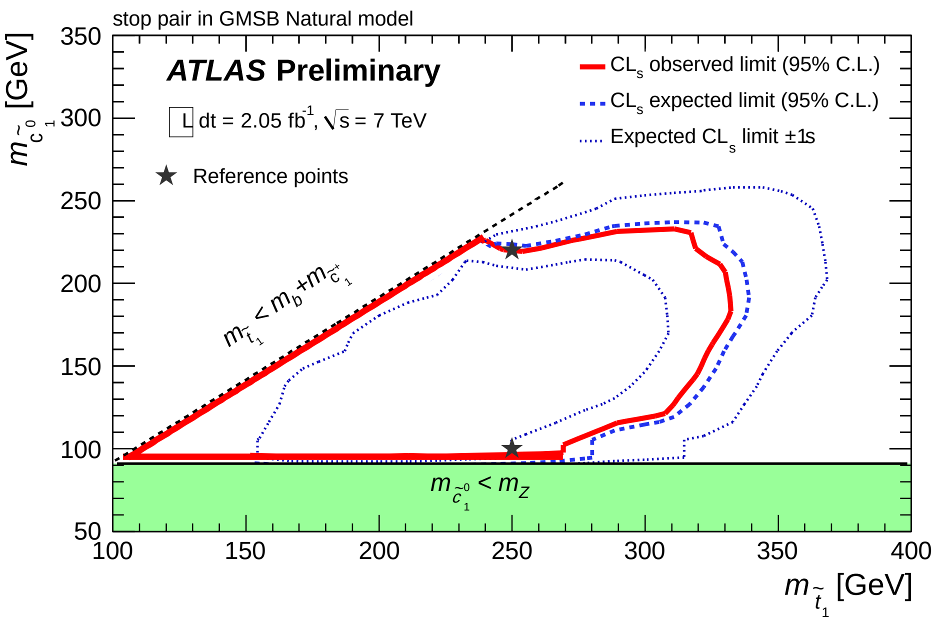
SUSY - 3rd generation squarks

- **Look for light stop and sbottom ("Naturalness"): from gluino decay + direct production**
  - **Gluino-mediated sbottom search in events w/ b-jets + 0,1-lepton + MET** [ATLAS-CONF 2012-003]
  - **Gluino-mediated stop search in events w/ SS dilepton + 4 jets + MET** [ATLAS-CONF 2012-004]
  - **Direct sbottom search in events w/ 2 b-jets + MET** [arXiv:1112.3832]
  - **Direct stop search in events w/ dilepton + b-jets (GMSB interpretation)** [ATLAS-CONF 2012-036]

Strong limits from search for gluino-mediated sbottom production in events with b-jets

First limits on direct stop pair production, assuming (a.o.) the decay chain: $t_1 \to t + \chi^0 \to t + Z(ll) + G$

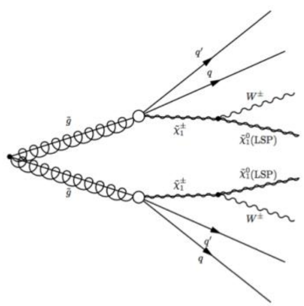




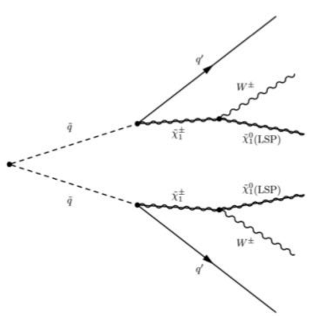
SUSY searches: "soft" leptons

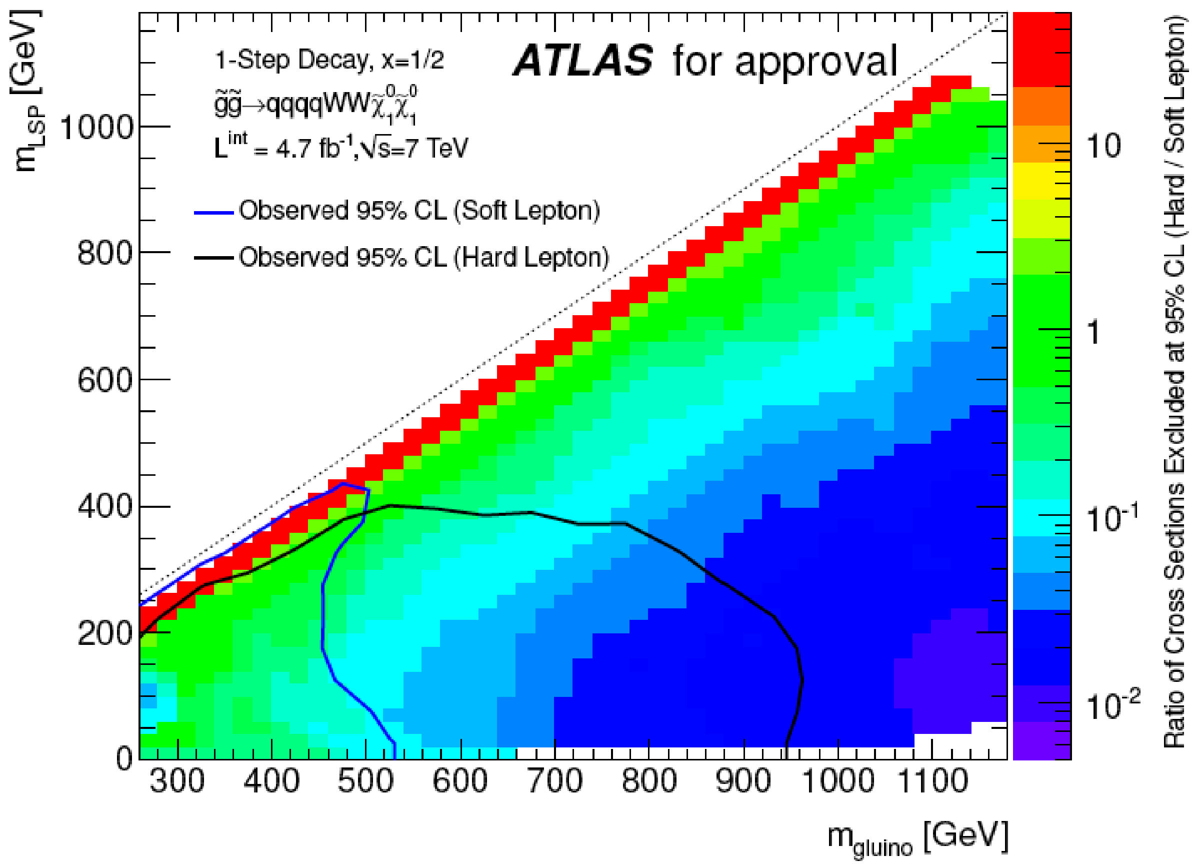
- **Dedicated search in "strong" production to deal with "compressed mass spectra (small DM)**

- **1-soft lepton + 2 jets + high MET**

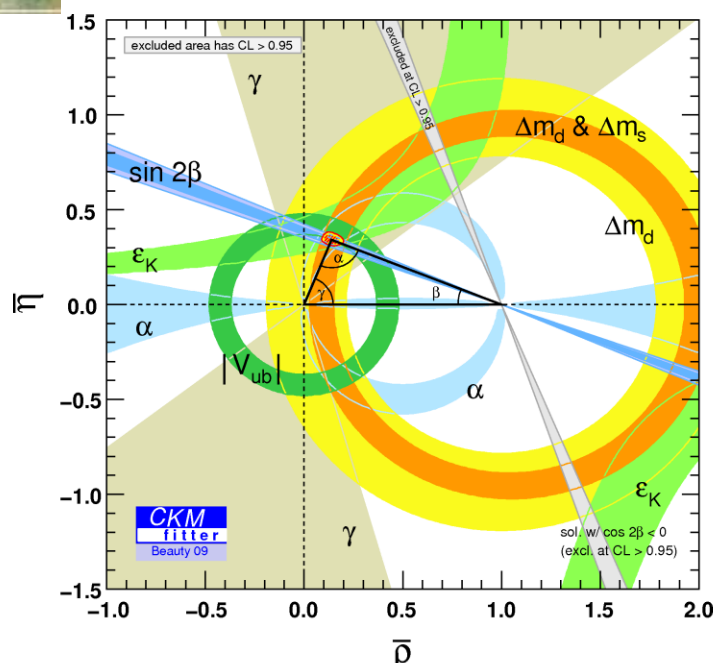


1-step simplified models leading to final states with leptons + jets + MET



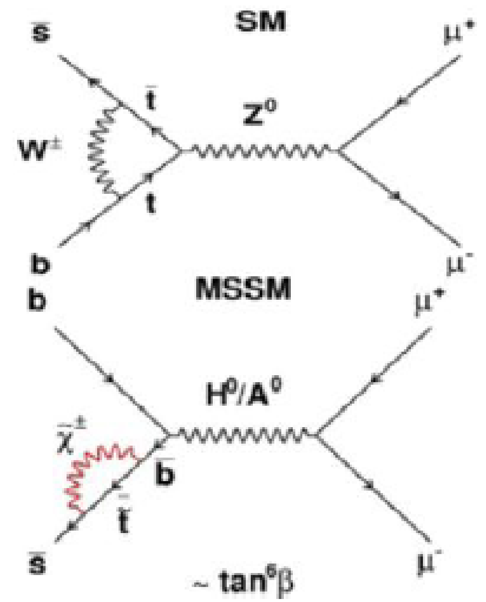


Early hints of news from 'Beyond the Standard Model' may come from 'beautiful' flavour physics...



Rare decays: $B_s \to \mu^+\mu^-$

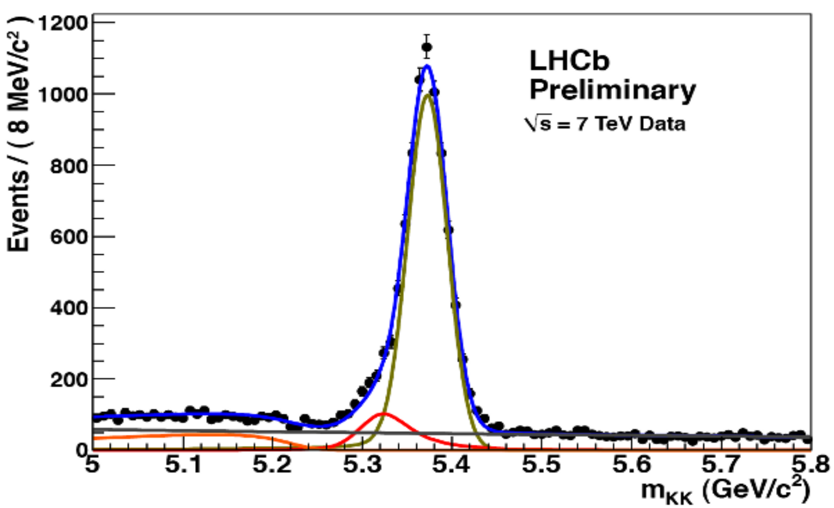
One of the most sensitive probes of New Physics



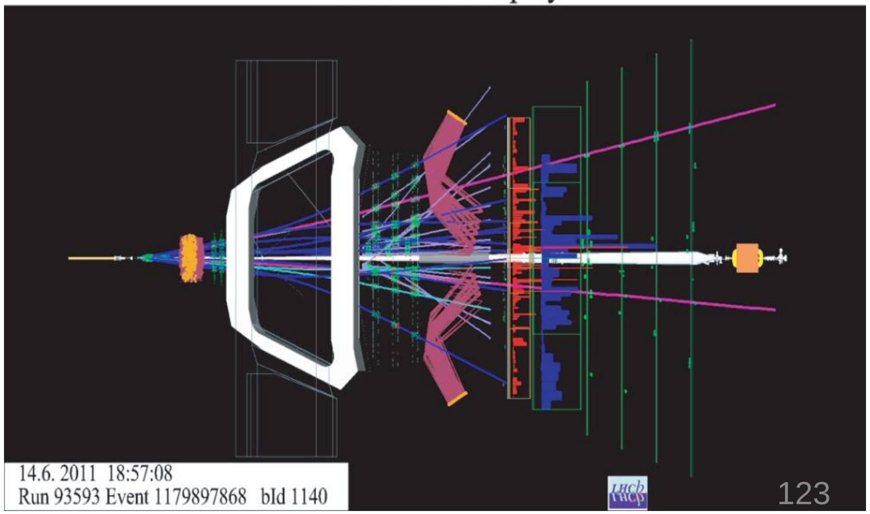
- Standard Model: FCNC, helicity suppressed:
  $Br(SM) = (3.2 \pm 0.2) \times 10^{-9}$

- Can be enhanced in NP models.

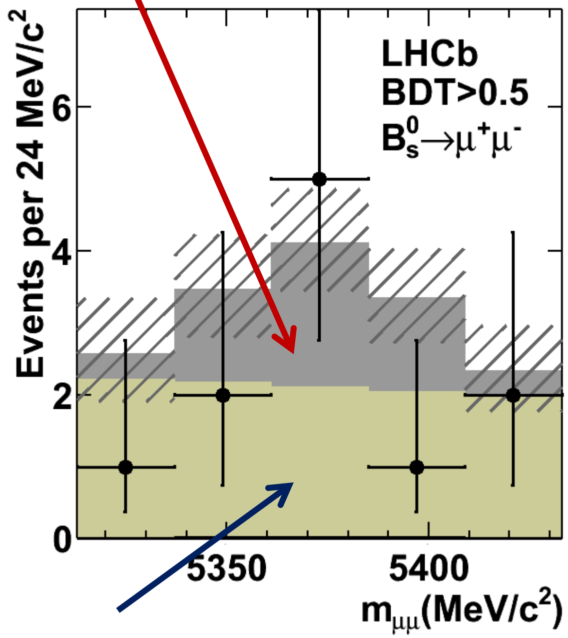
$$\text{MSSM:} \quad BR \propto \left(C_{S,P}^{MSSM}\right)^2 \propto \frac{\tan^6\beta}{M_A^4}$$



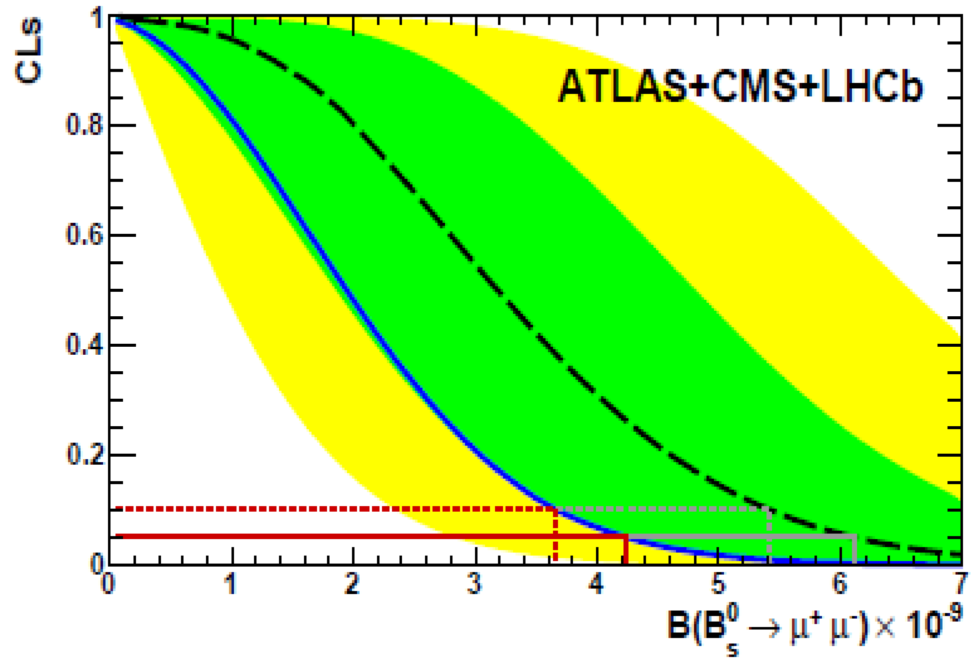
LHCb Event Display



Standard Model



Combinatorial Background



	CDF	CMS	Atlas	LHCb	SM
Luminosity (fb^{-1})	10	4.9	2.4	1.1	
$Br(B_d \to \mu^+\mu^-)$ 95% CL ($x10^{-9}$)	4.6	1.8		1.03	0.10 ± 0.01
$Br(B_s \to \mu^+\mu^-)$ 95% CL ($x10^{-9}$)	31	7.7	22	4.5	3.2 ± 0.2

→ No deviation (yet) observed from Standard Model (combined limit from all the 3 exp'ts is 4.2 x 10^{-9})

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