The Large Hadron Collider -
status, highlight results and future prospects

- the structure of matter
- LHC, ATLAS and CMS: status and performance
- challenging the Standard Model
- search for physics BSM
- Higgs hunting
- future prospects

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The „Standard Model" of Particle Physics

... is rather simple (und „übersichtlich"):

Elementary Particles

	Generation 1	Generation 2	Generation 3
Quarks	**u** **d**	**c** **s**	**t** **b**
Leptons	ν_e **e**	ν_μ μ	ν_τ τ

... as well as anti-particles

Elementary Forces

	exchange boson	relative strength
Strong	g	1
el.-magn.	γ	1/137
Weak	$W^\pm, Z^0$	10^{-14}
Gravitation	*G*	10^{-40}

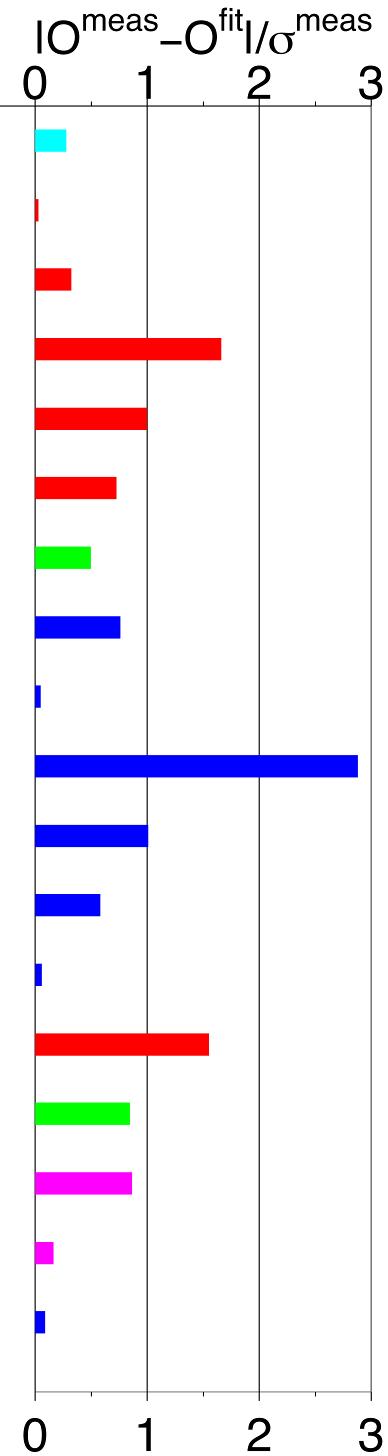
... describes the unified electro-weak interaction and the Strong force with gauge invariant quantum field theories;

... is extremely successful in consistently and precisely describing all particle reactions observed to date

... provides a consistent (yet incomplete) picture of the evolution of the very early universe -> particle cosmology

The „Standard Model“ of Particle Physics

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4



July 2010

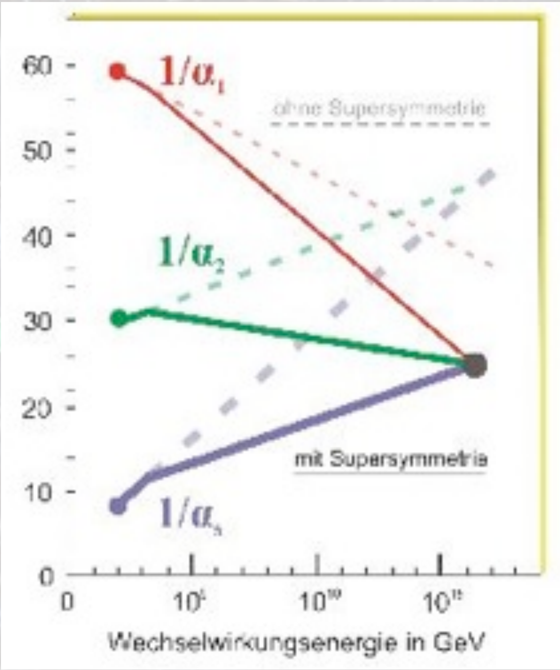
- shows no significant discrepancies between data and theorie -- however it leaves open fundamental questions

Limitations of the SM:

- it makes unphysical predictions at very high energies:
  - at E > 1 TeV, violates unitarity for some reactions

- it is incomplete :
  - too many free parameters (26 masses, couplings ... -> experiment)
  - symmetry breaking mechanism unclear (Higgs mechanism, masses)

- it leaves open many fundamental questions :
  - why are there 3 families of quarks and leptons ?
  - why is (electron charge) = -(proton charge) ?
  - what happened to the anti-matter in the universe ?
  - do forces unify at high energies (GUT) ?
  - ....

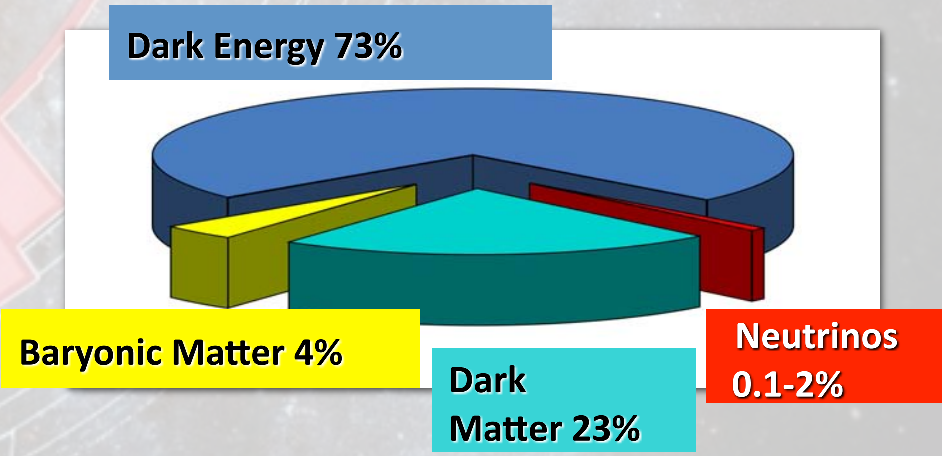


-> SM is only an effective theory

-> there must be physics beyond SM (BSM)

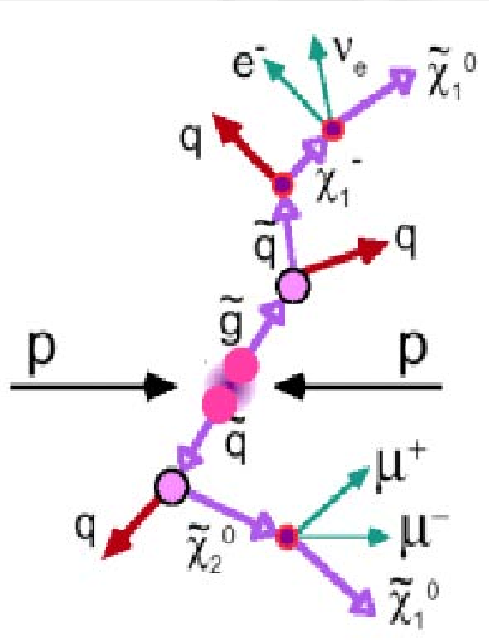
today, there are few but significant signals for BSM physics:

- neutrinos are not massless
- 95% of the mass/energy budget of the universe cannot be explained by SM particles and forces:
  - Dark Matter (23%)
  - Dark Energy (73%)

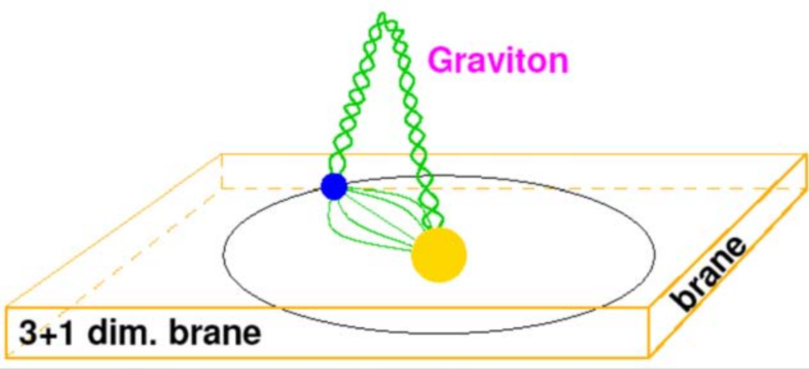


the most *en vogue* candidates to solve (some of) these problems:

- Supersymmetry (SUSY)
  - \+ fully compatible with and supported by GUT's
  - \+ offers excellent Dark Matter candidates
  - \+ theory finite and computable up to Planck Mass
  - \+ essential for realisation of string theory (including quantum gravity)
  - \- no SUSY signals seen yet (LEP, Tevatron)
  - \- (too) many free parameters, large parameter space



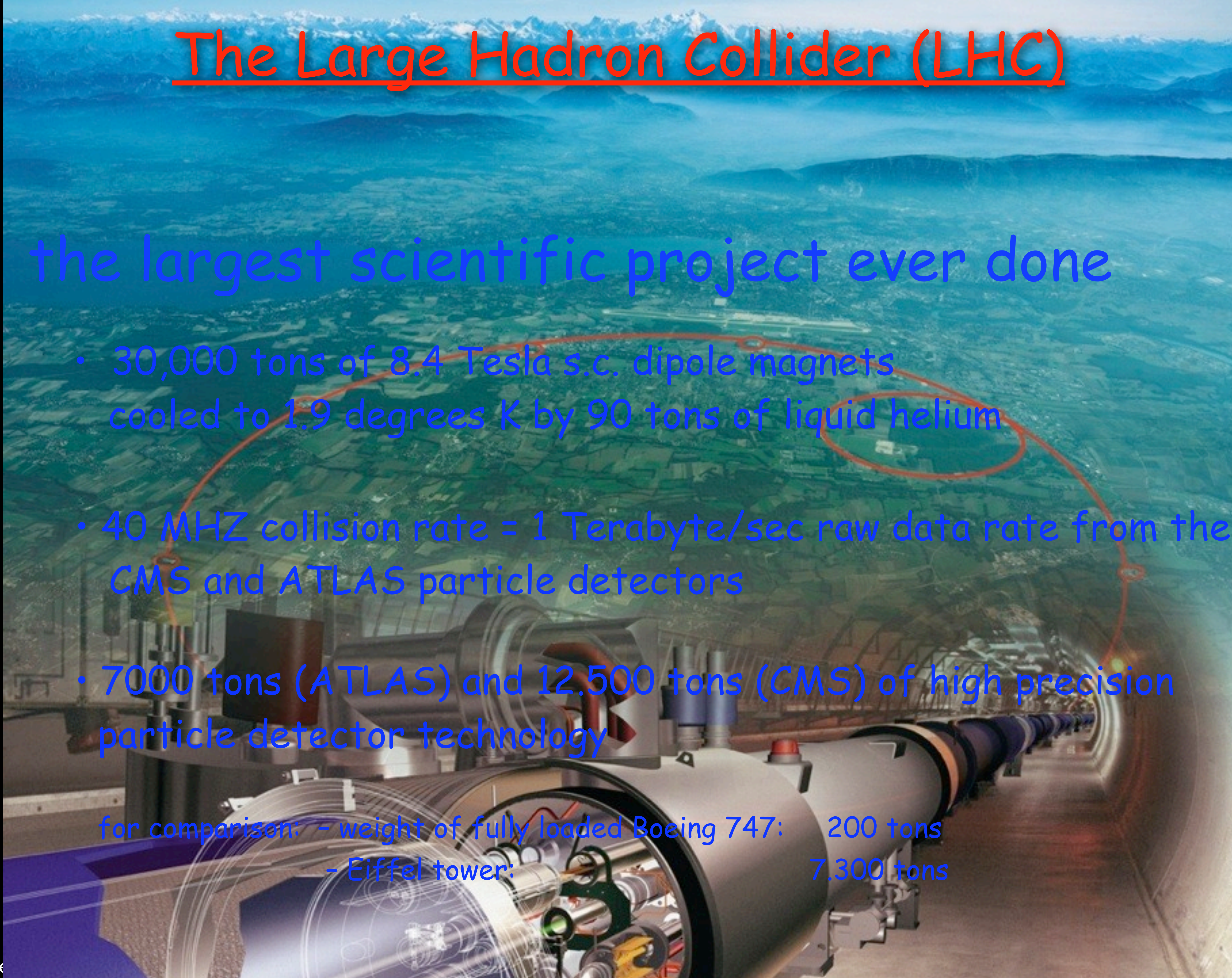
- Extra Space Dimensions
  - \+ would solve hierarchy problem (M_{Planck} -> O(1 TeV
  - \+ inspired by string theory: compactified extra dimensions
  - +- exciting scenarios, but cannot solve many of above problems?
  - \- large model dependences



since March 2010, the future has just begun: the LHC collides protons at 7 TeV c.m. !

ATLAS control room; 30.3.2010 13:01

The Large Hadron Collider (LHC)

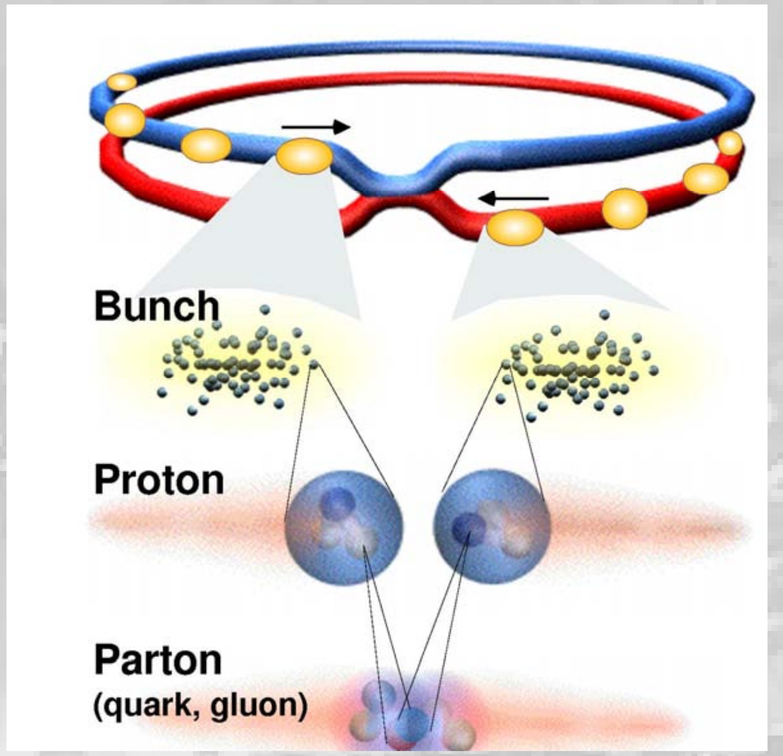


the largest scientific project ever done

- 30,000 tons of 8.4 Tesla s.c. dipole magnets
  cooled to 1.9 degrees K by 90 tons of liquid helium
- 40 MHZ collision rate = 1 Terabyte/sec raw data rate from the CMS and ATLAS particle detectors
- 7000 tons (ATLAS) and 12,500 tons (CMS) of high precision particle detector technology

for comparison: – weight of fully loaded Boeing 747: 200 tons
– Eiffel tower: 7,300 tons

The Large Hadron Collider (LHC)



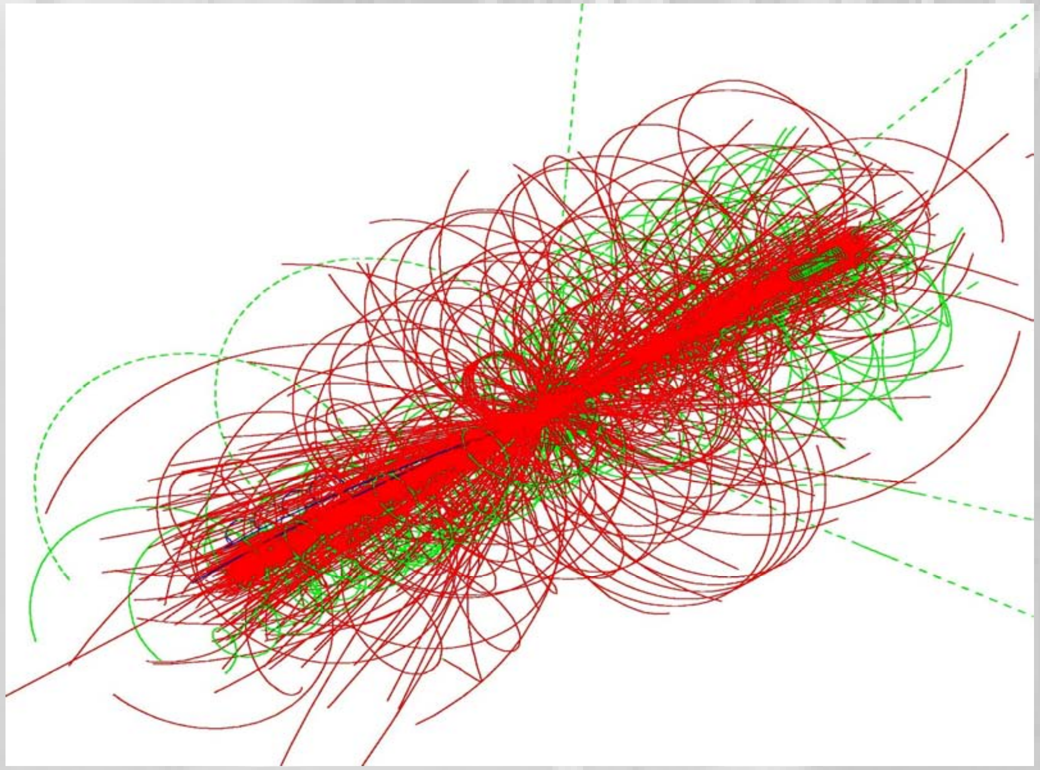
Proton – Proton collisions at 14 TeV c.m. energy

2835 x 2835 bunches
distance: 7.5 m (25 ns)

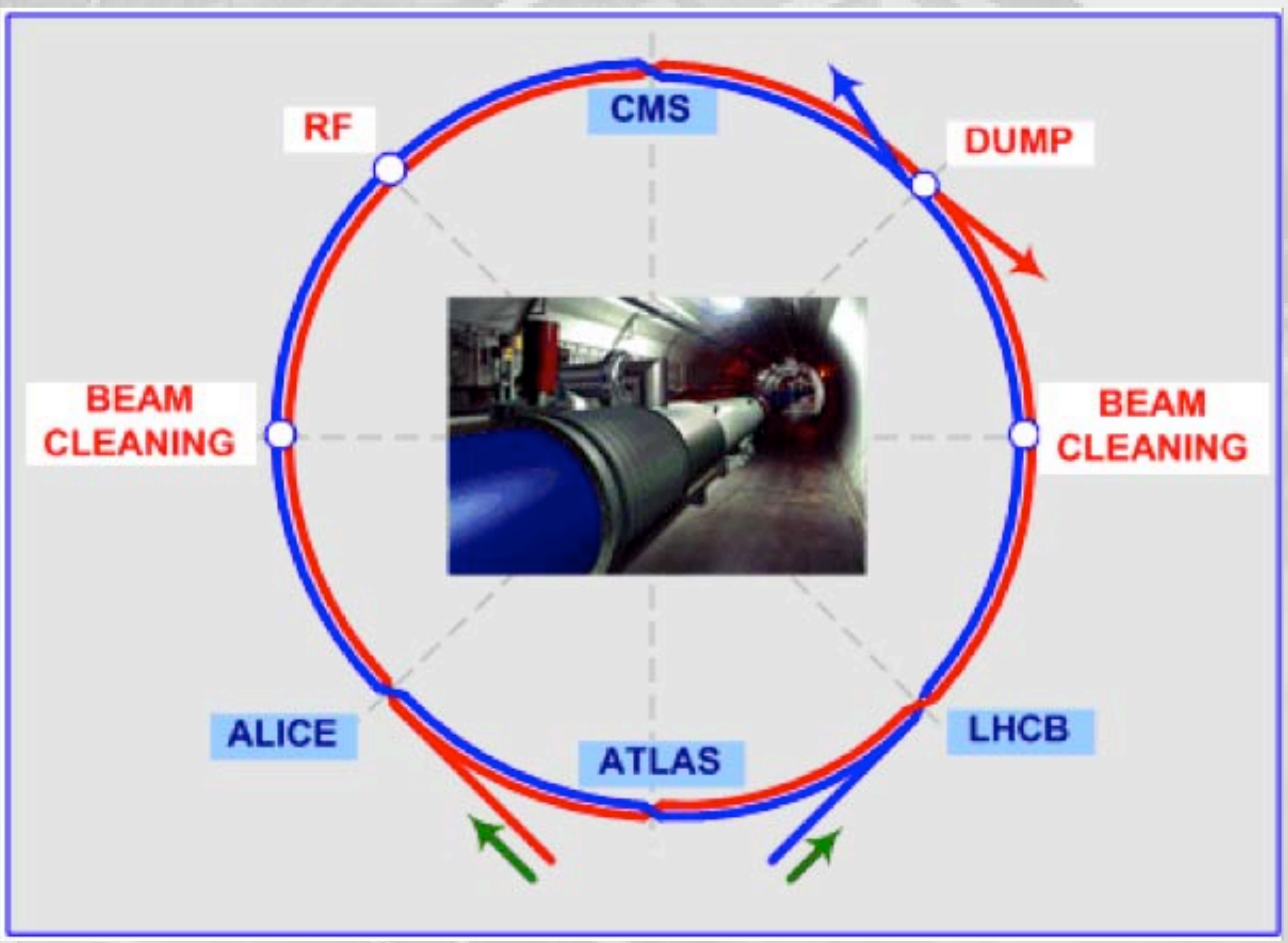
10^{11} Protons / bunch
Collision rate: 40 million / sec.
Luminosity: $L = 10^{34}$ cm^{-2} sec^{-1}

Proton-Proton collisions: ~10^9 / sec
(about 23 pp-interactions per bunch crossing)

~1600 charged particles in detector



high demands on detectors


CMS
RF
DUMP
BEAM
CLEANING
BEAM
CLEANING
ALICE
ATLAS
LHCB

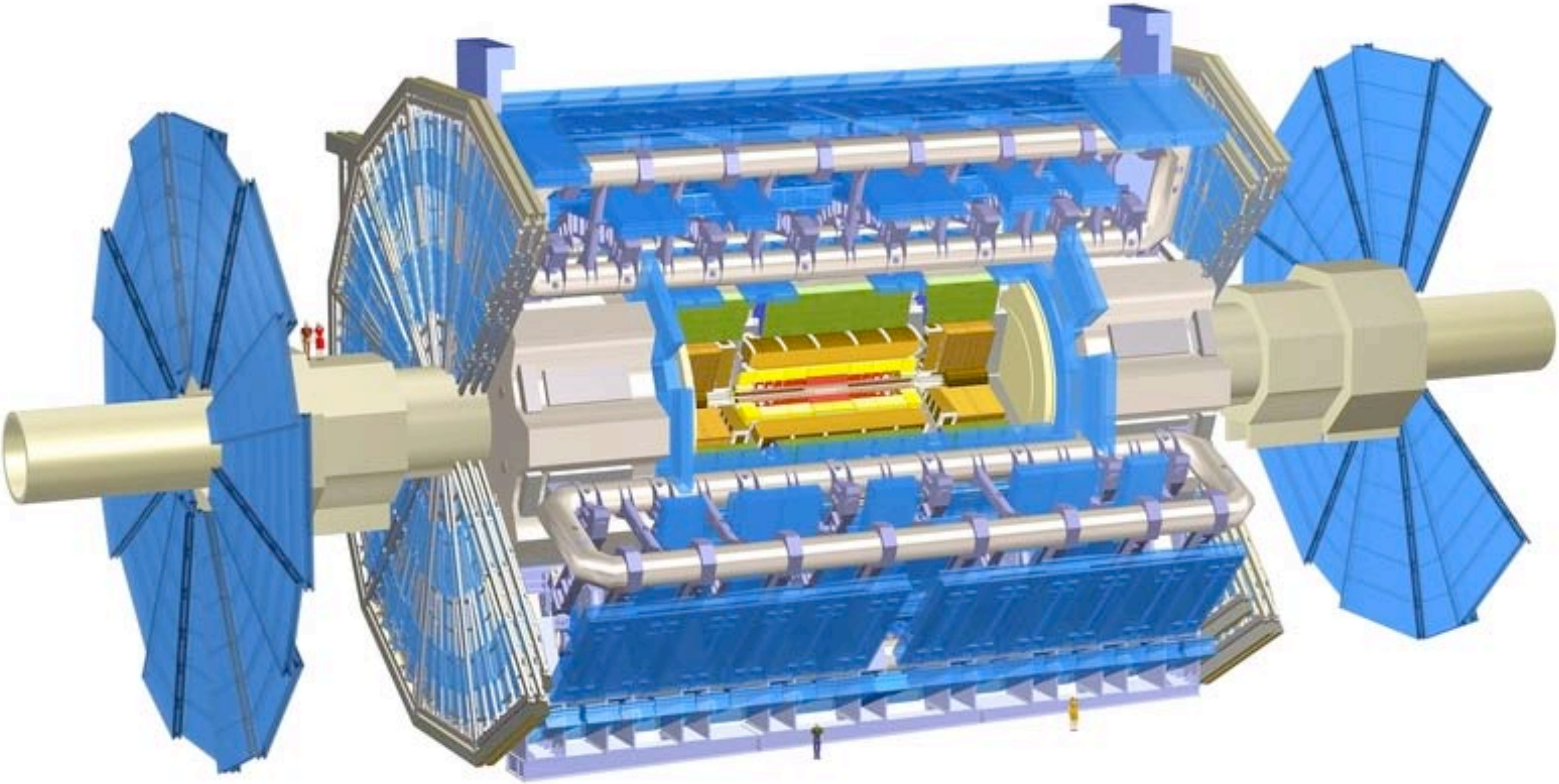
LHC Tunnel (12/2005)

The ATLAS Detector at the LHC

Length: 44 m
Height: 22 m
Weight: 7000 t

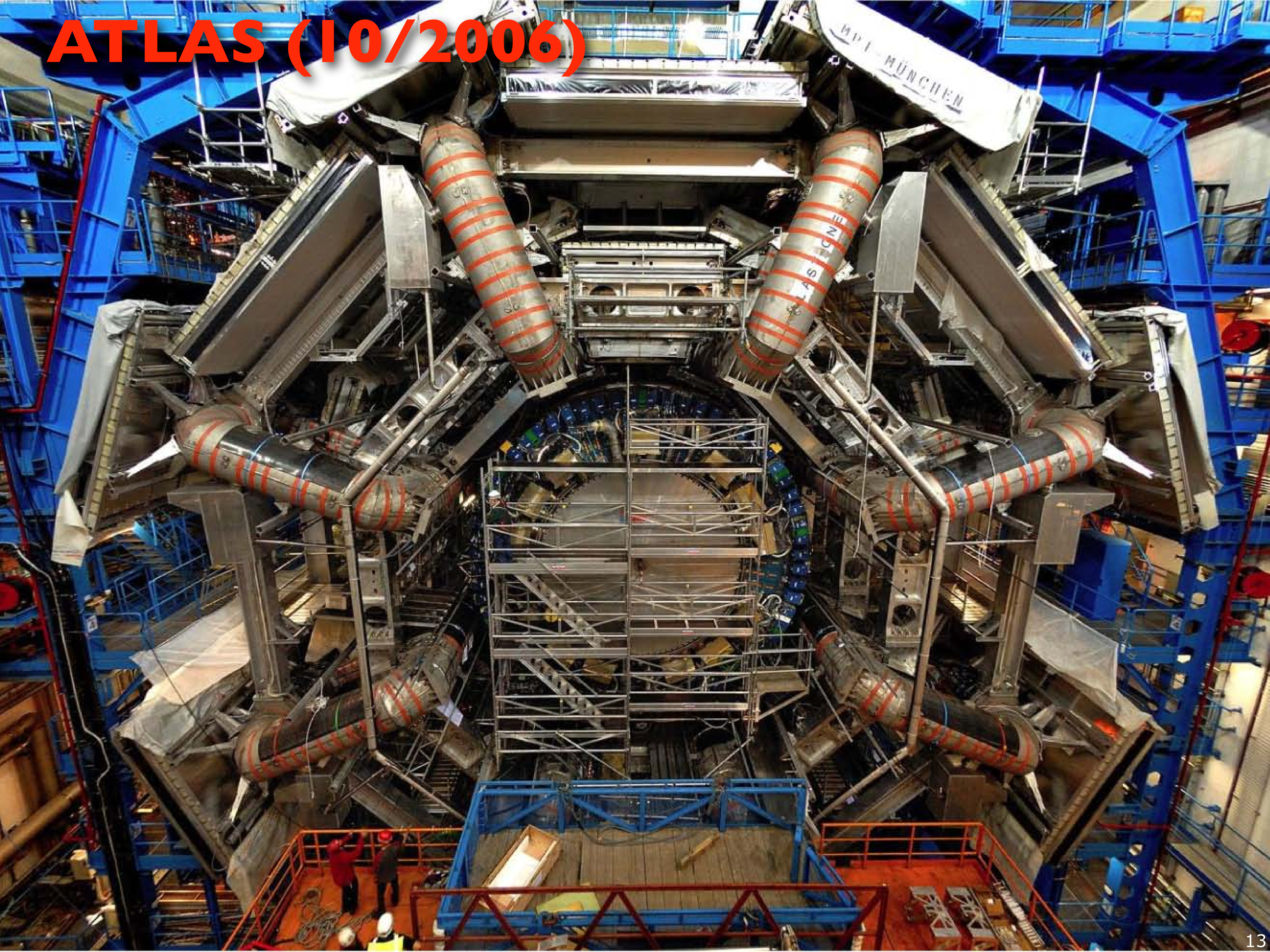
3000 Physicists & Engineers (incl. 1000 Students)
178 Institutes
38 Nations

$150 \cdot 10^{6}$ electronic readout channels
40 MHz collision rate
10^{14} B/s raw data flux

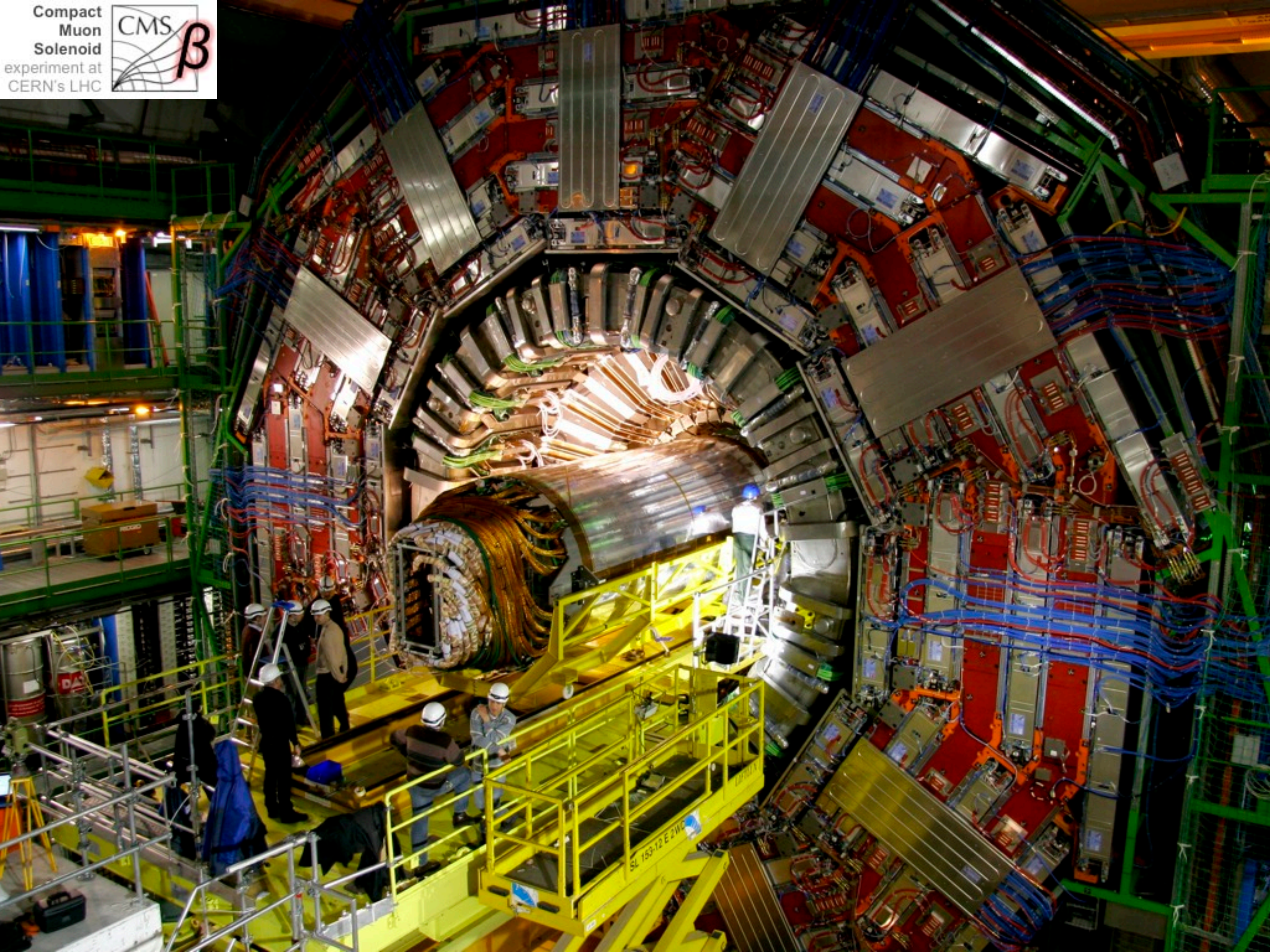


Planning & construction 1990 to 2007, operation from 2009, for ~ 15-20 years

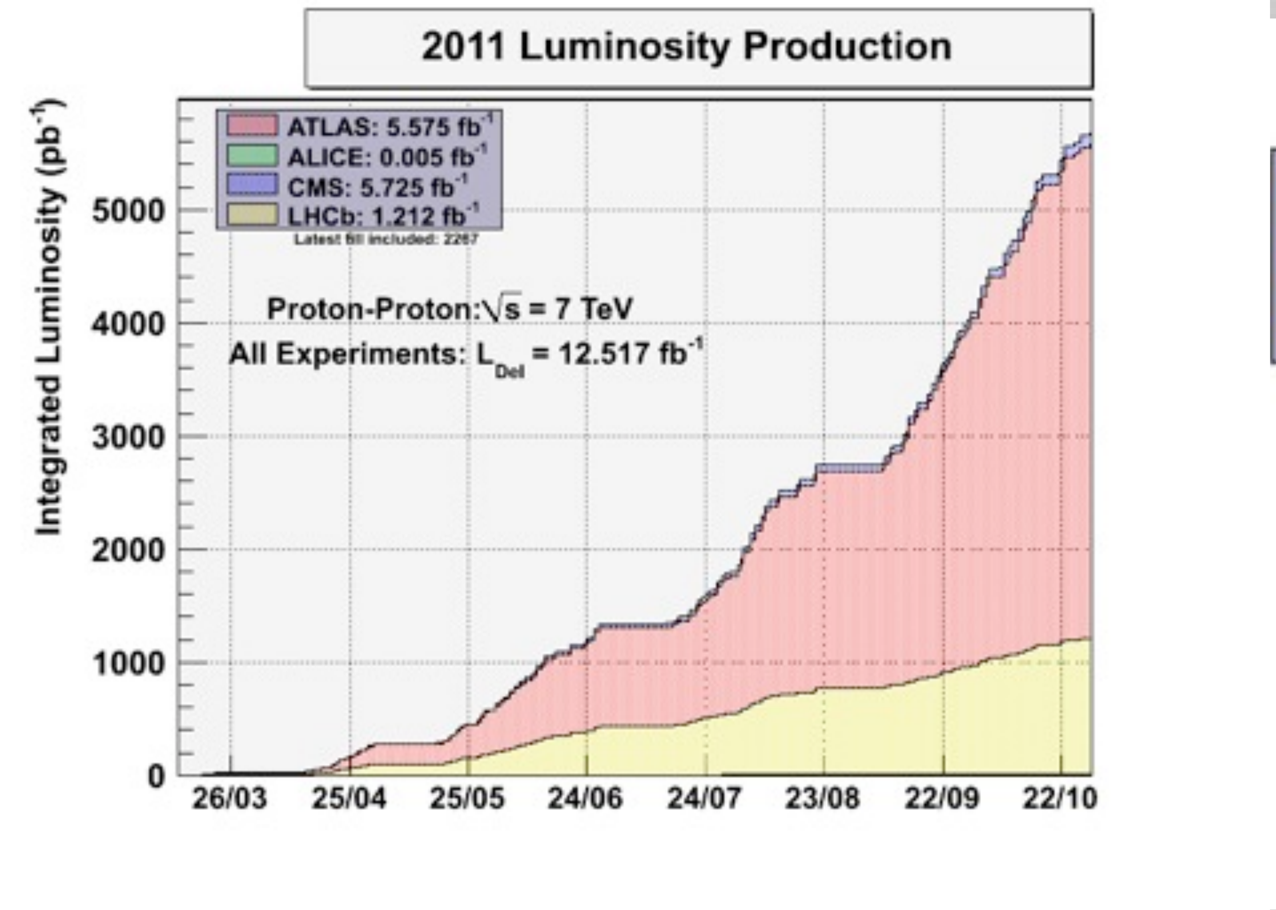
ATLAS (10/2006)

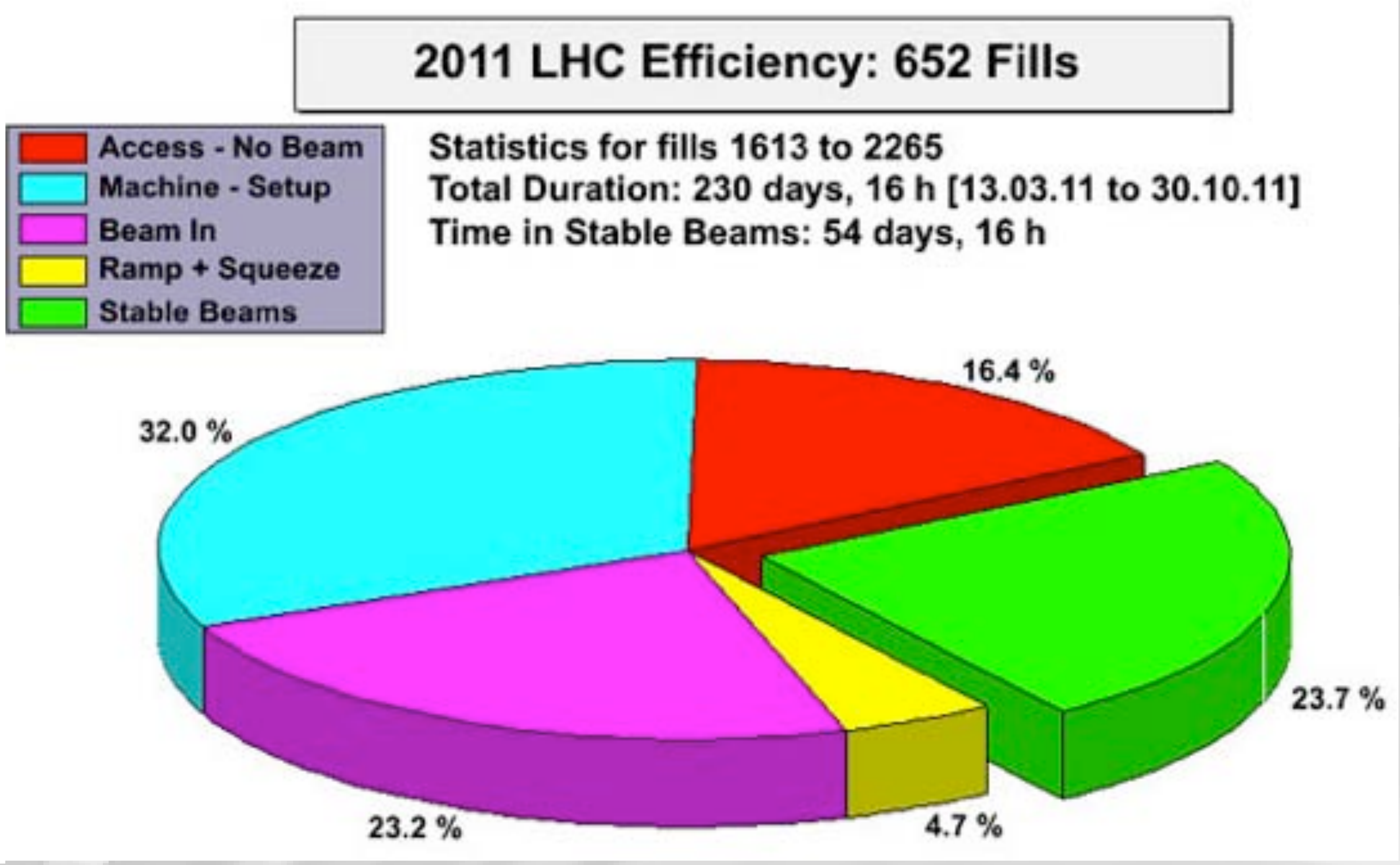


Compact
Muon
Solenoid
experiment at
CERN's LHC



LHC: Integrated luminosity until end-of-run 2011 (pp)





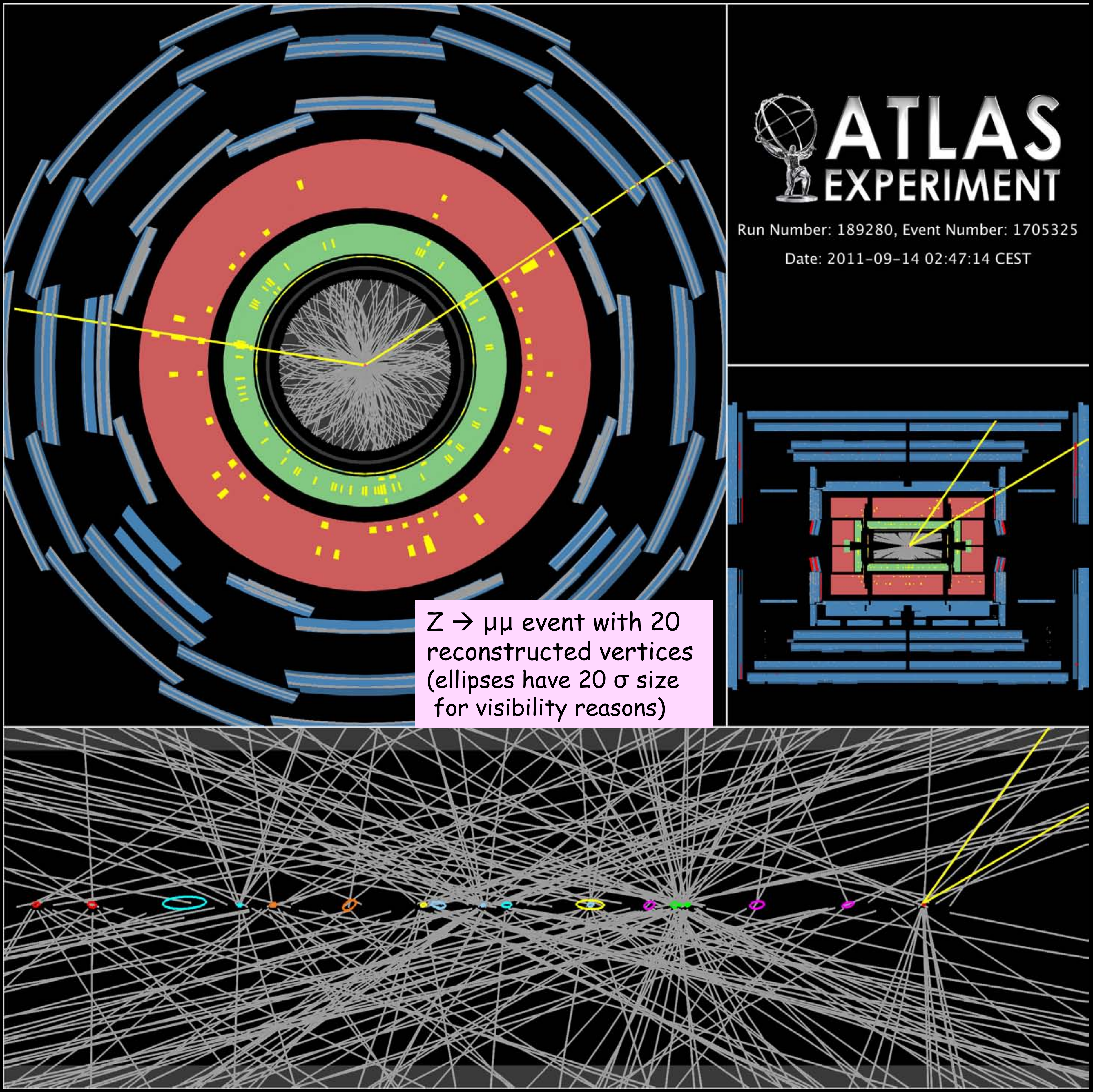
LHC Peak luminosity reached :
$L \sim 3.5 \times 10^{33}$ cm^{-2} s^{-1} (design: 10^{34})

(data statistics 2011: 100x 2010)

Overall ATLAS/CMS data taking efficiency (with full detector on): 95%

pile-up:

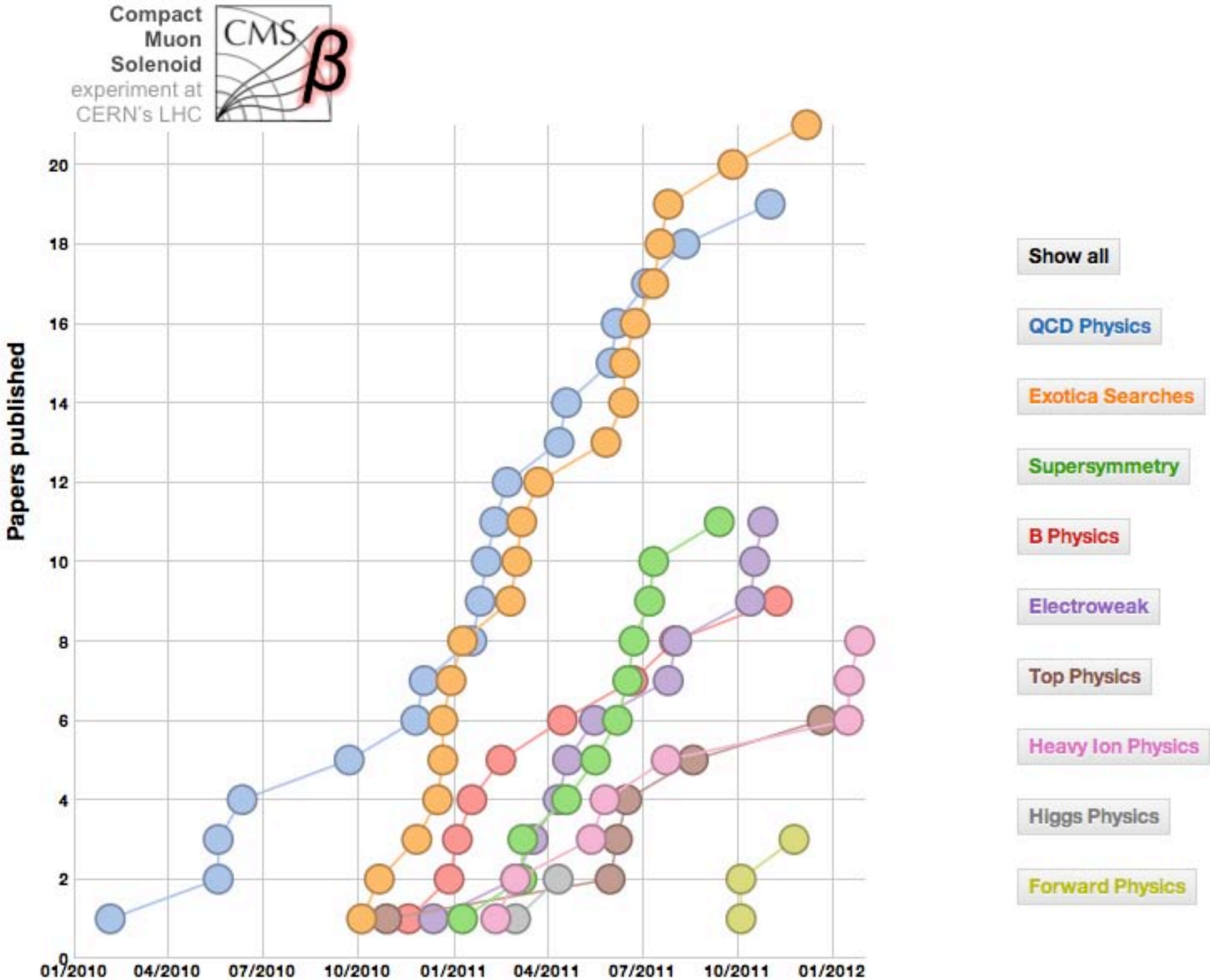
- 10-20 collisions per bunch crossing
- detector and electronics have to cope with large data rates
- physics analysis of data has to cope with large backgrounds



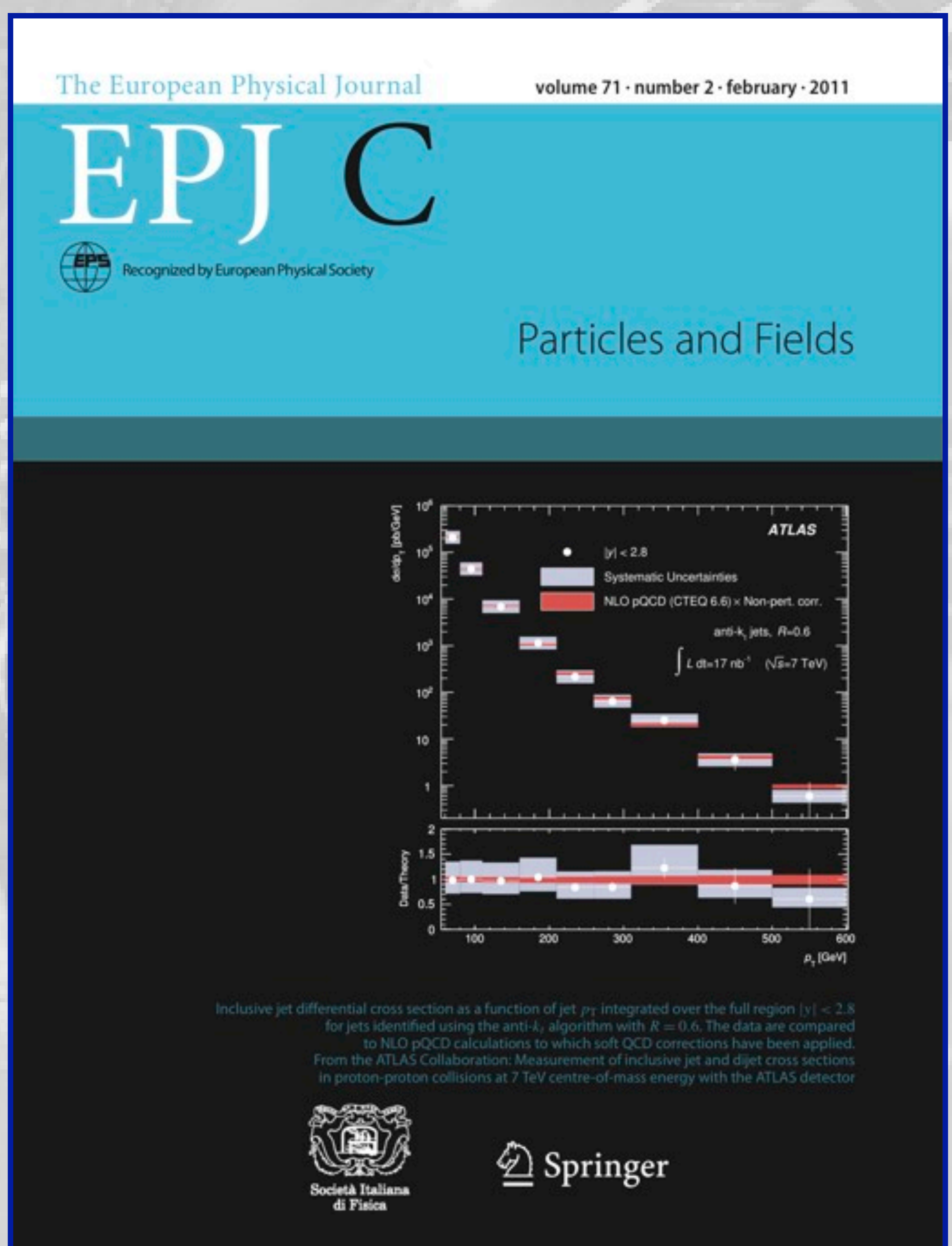
Summary of LHC / detector performance:

- LHC delivered an unexpected large amount of high quality data (>5.5. fb-1) in 2011
- LHC reached ~1/3 of the nominal luminosity (10^{34} cm^{-1} s^{-1})
- due to safe operation criteria, LHC can only run only at 50% of the anticipated maximum c.m. energy (14 TeV)
- all particle detectors performed excellently from day one of collision data
- large pile-up rates (15-20 collisions per crossing) and huge data rates challenge data taking and analyses

timeline of CMS physics publications



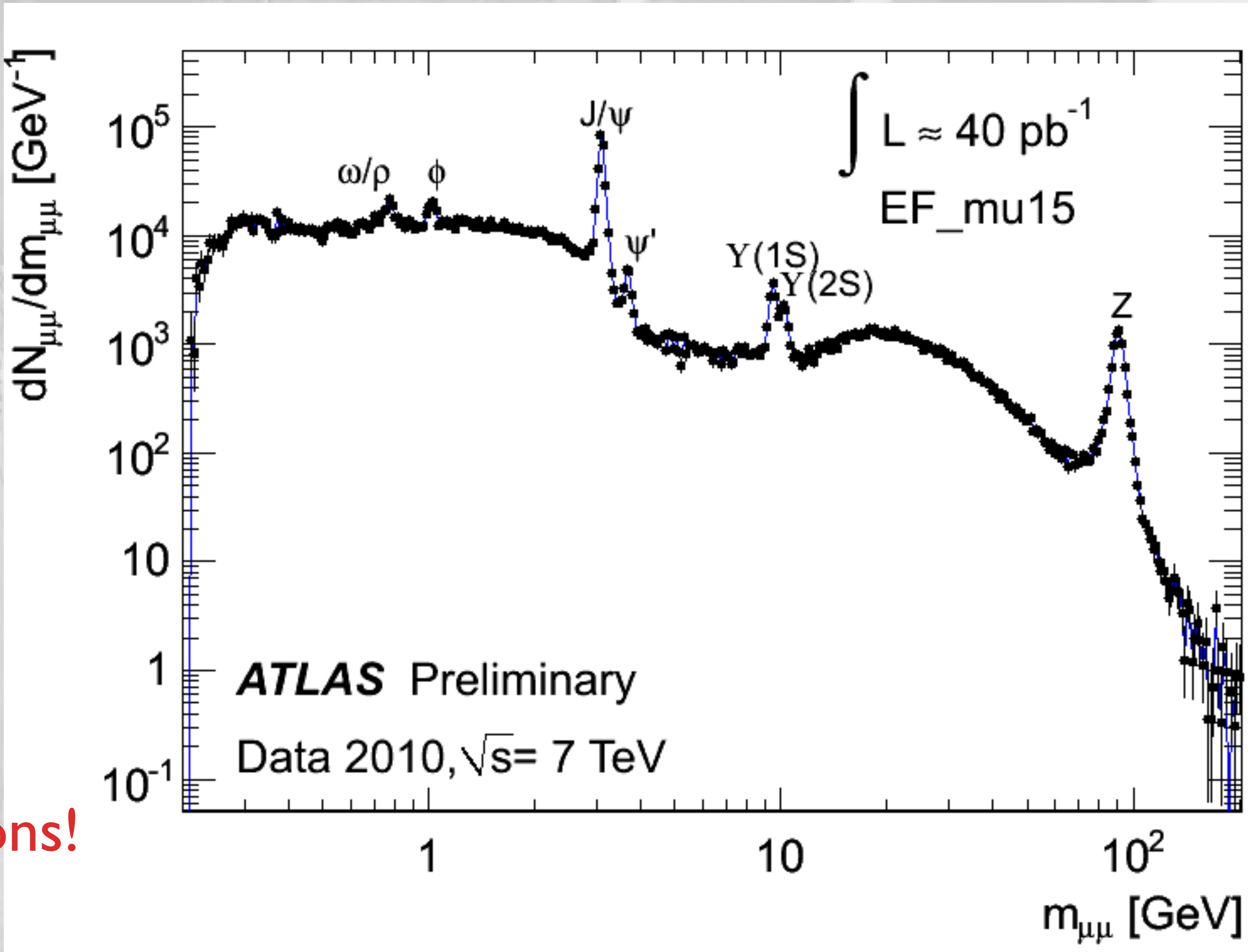
>100 publications of ATLAS on LHC data



hadron jets !

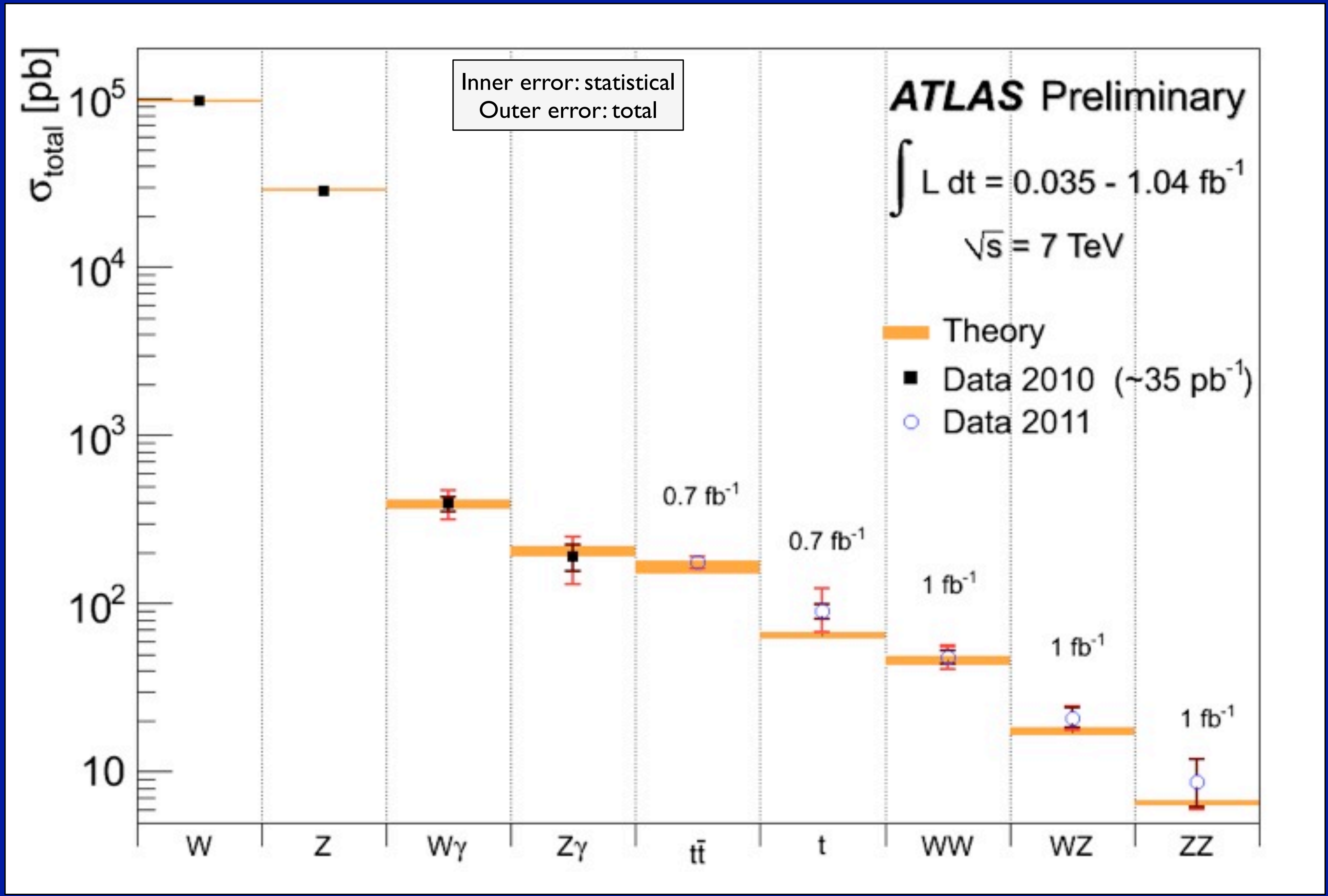
LHC results I: the „rediscovery" of the SM

di-muon invariant mass spectrum



leptons!

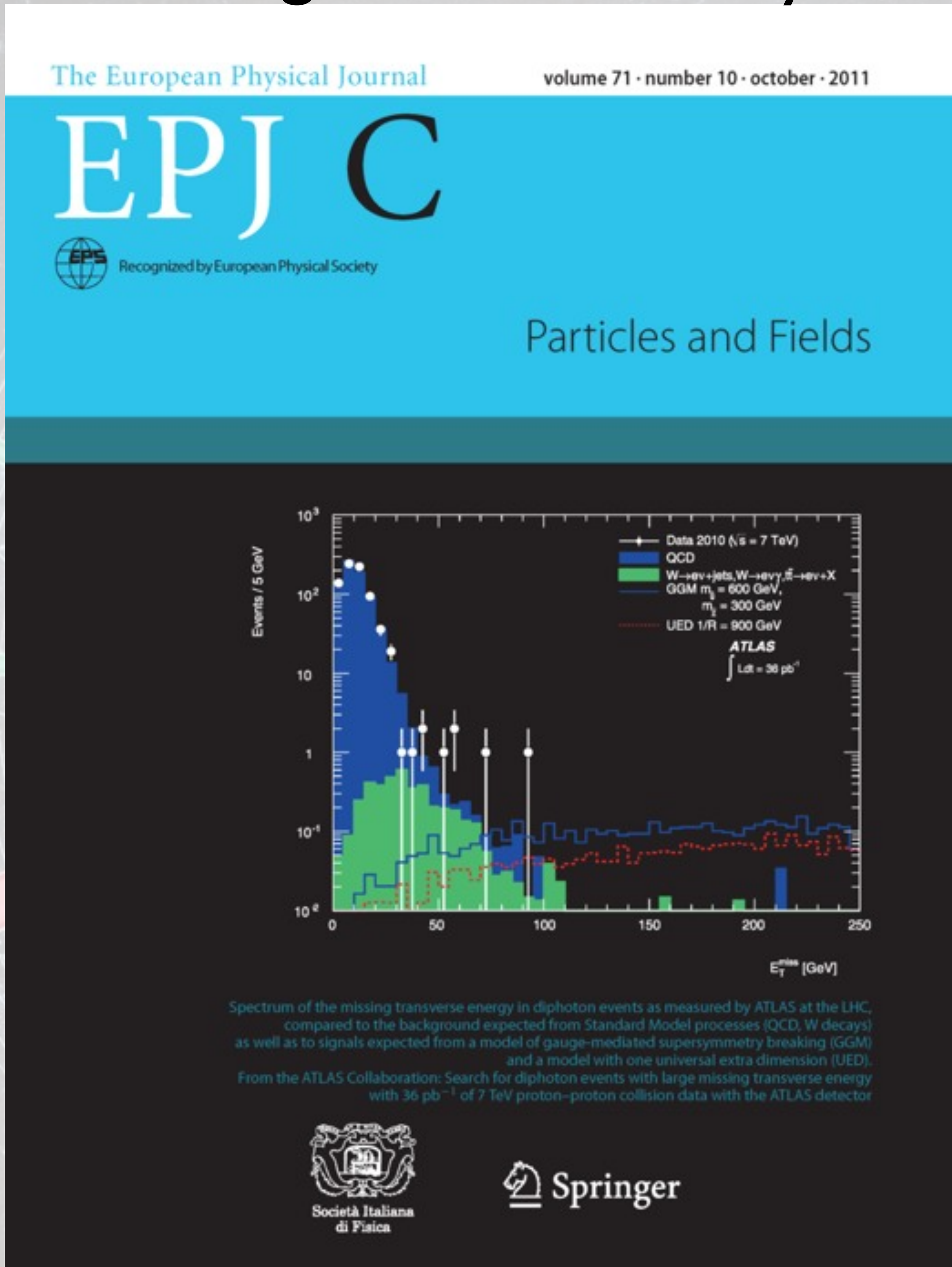
Summary of main electroweak and top quark cross-section measurements



Good agreement with SM expectations (within present uncertainties)

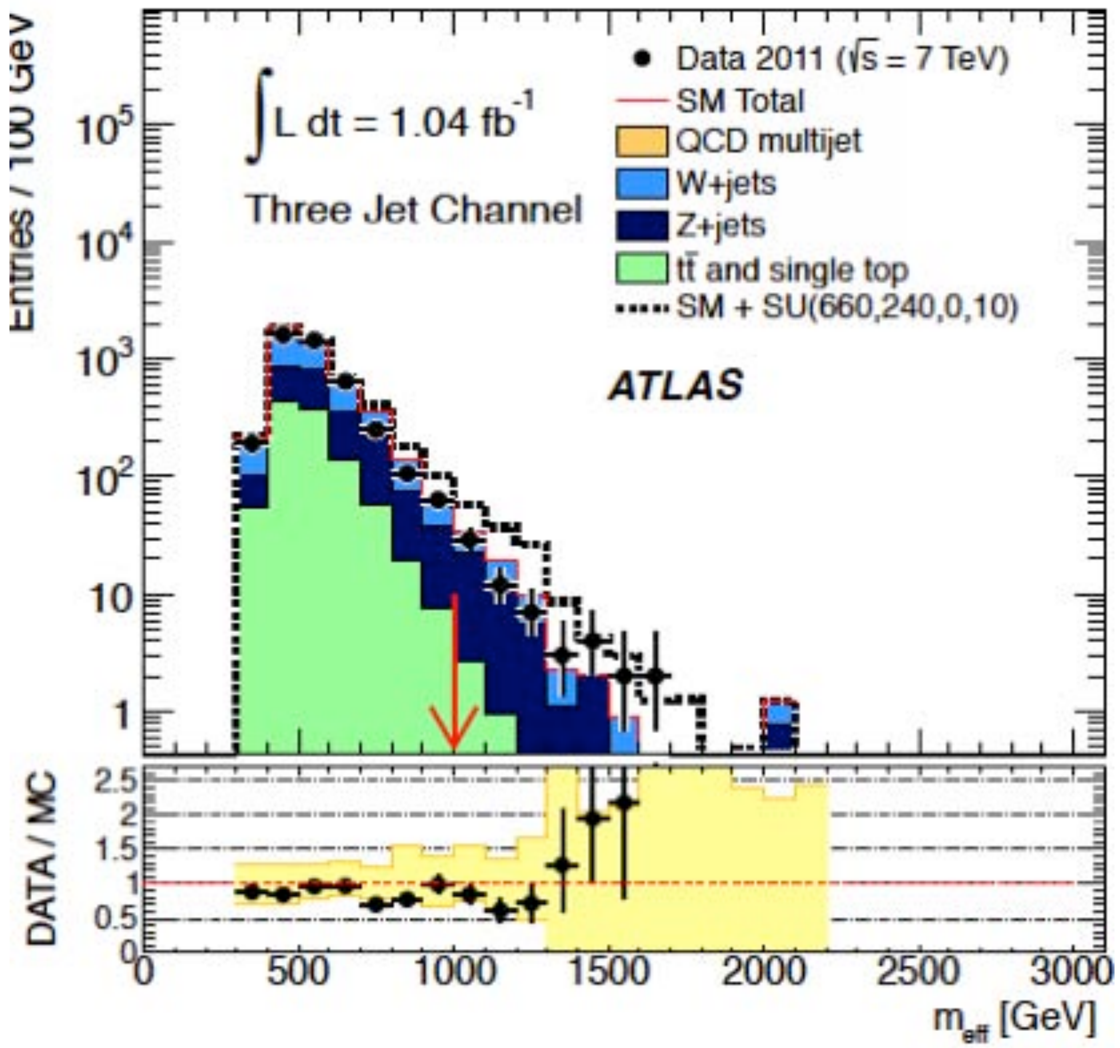
searches for signals of New Physics (BSM)

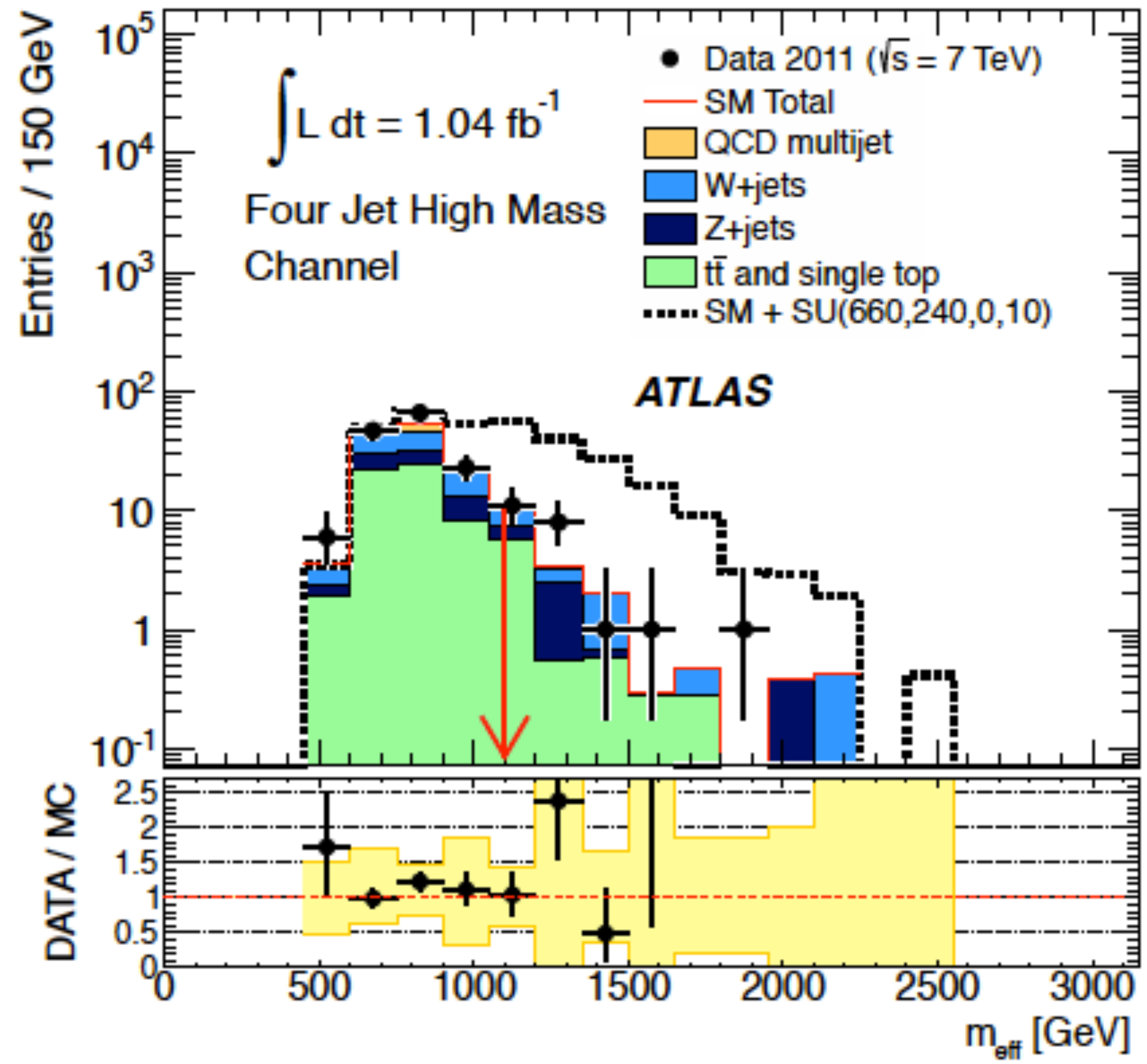
missing
E_t !



Example: search for squarks and gluinos

using final states with high p_T jets and large E_T (and NO leptons)



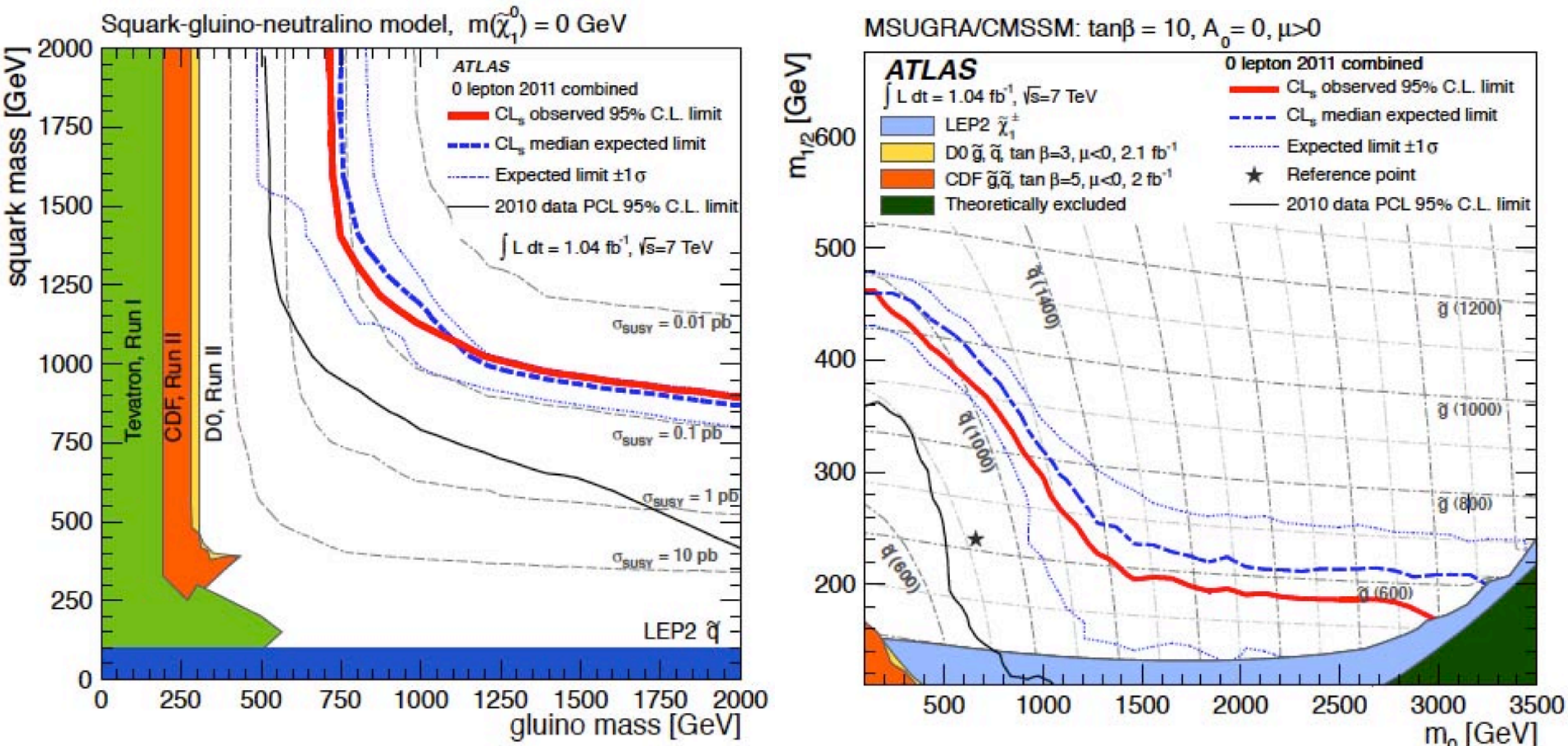


$$M_{eff} = E_T^{miss} + \Sigma \left|p_T^{jet}\right|$$

arXiv:1109.6572v1 [hep-ex]

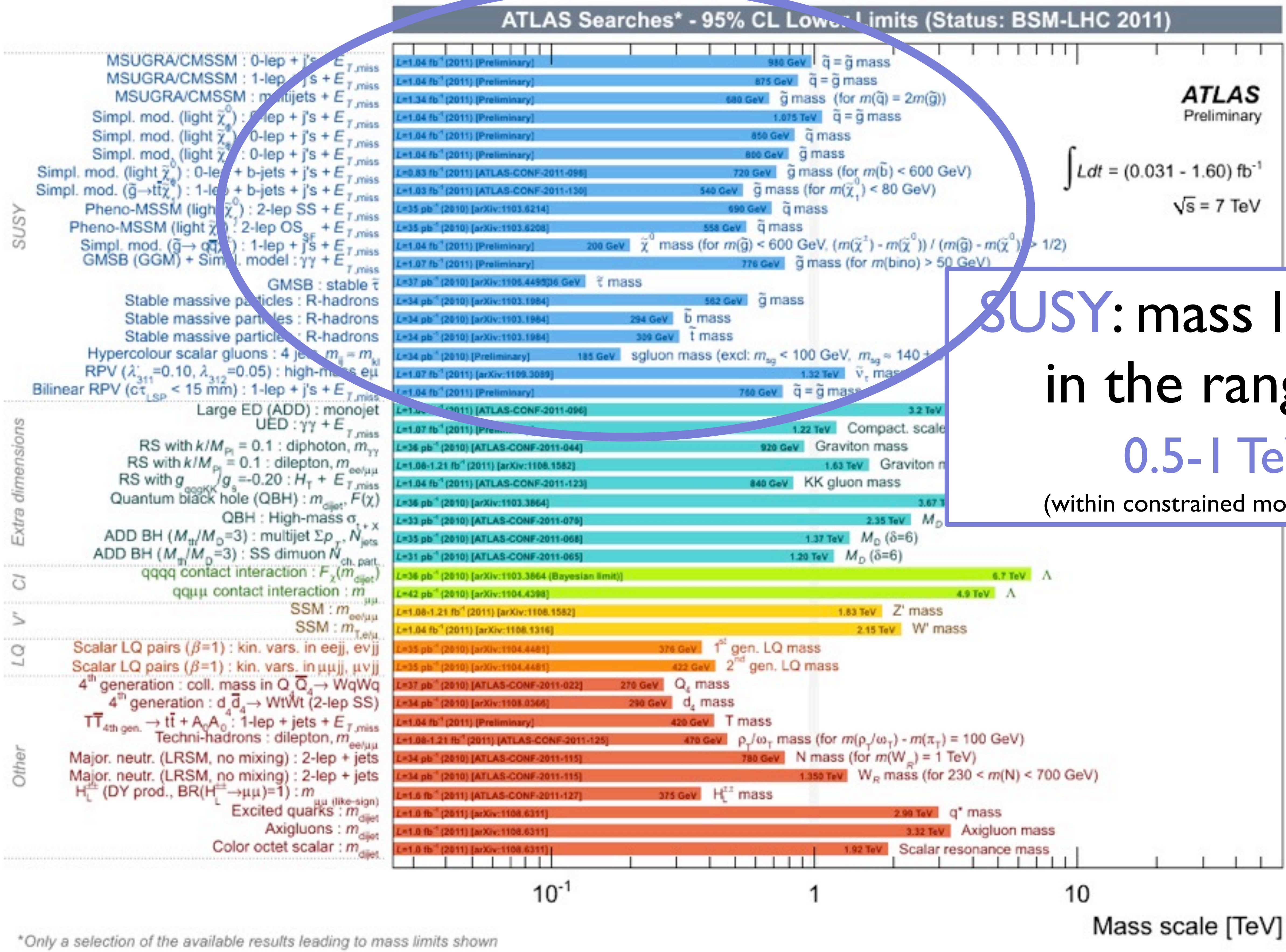
Example: search for squarks and gluinos

using final states with high p_T jets and large E_T (and NO leptons)



- for equal mass gluinos and squarks: exclusion for masses < O(1TeV)

Results of main searches for New Physics

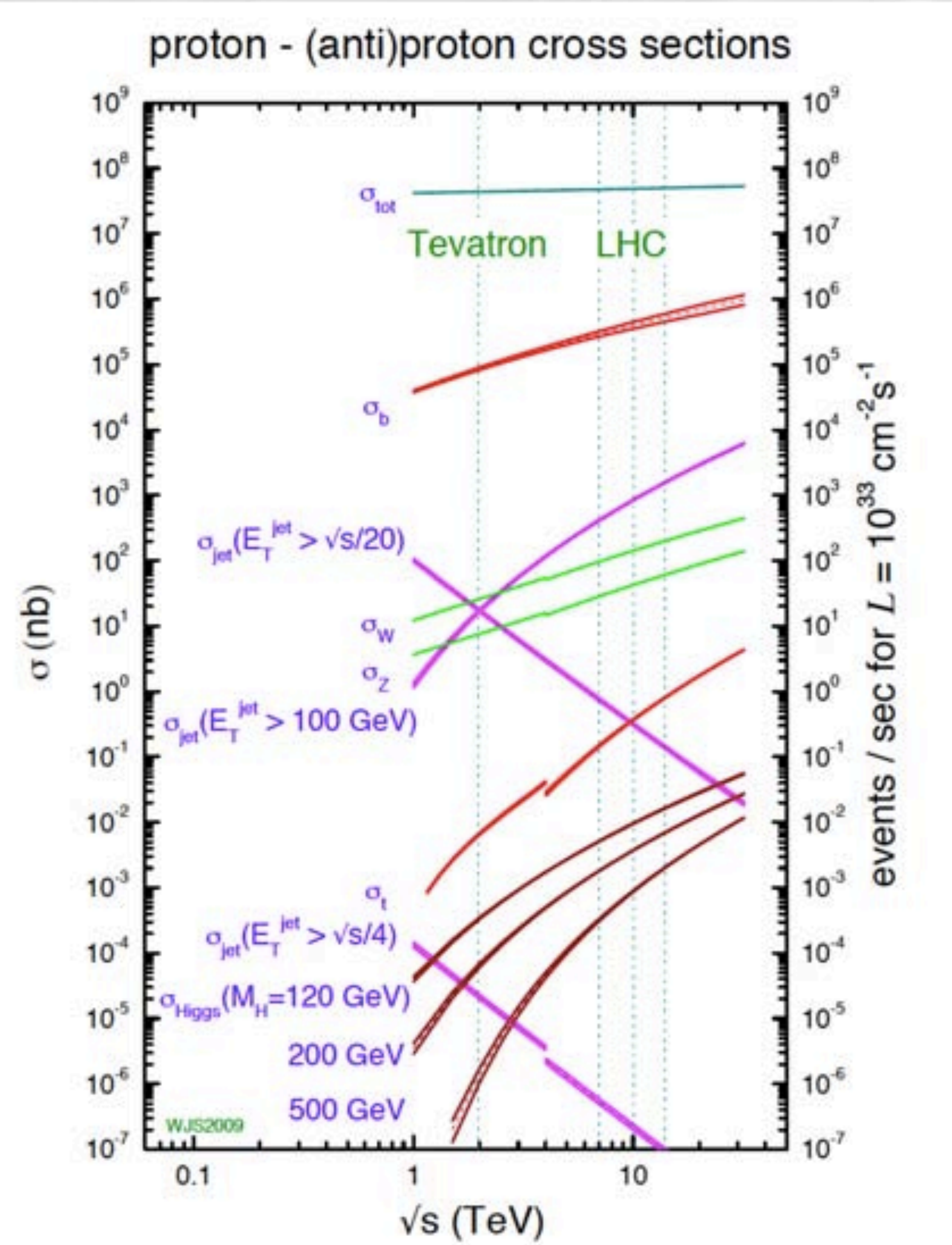


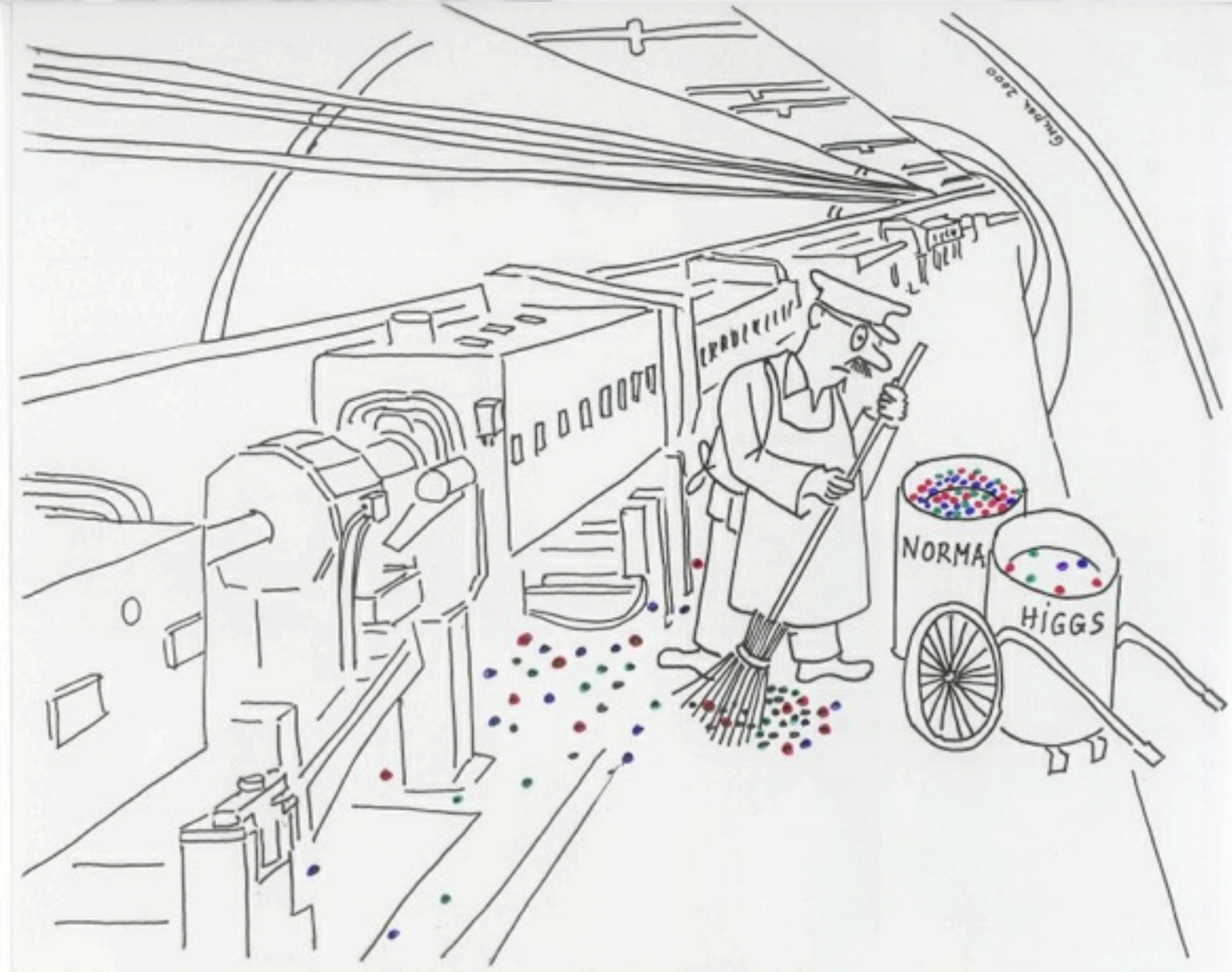
SUSY: mass limits in the range 0.5-1 TeV

(within constrained models)

Search for the (SM) Higgs boson

Higgs production:

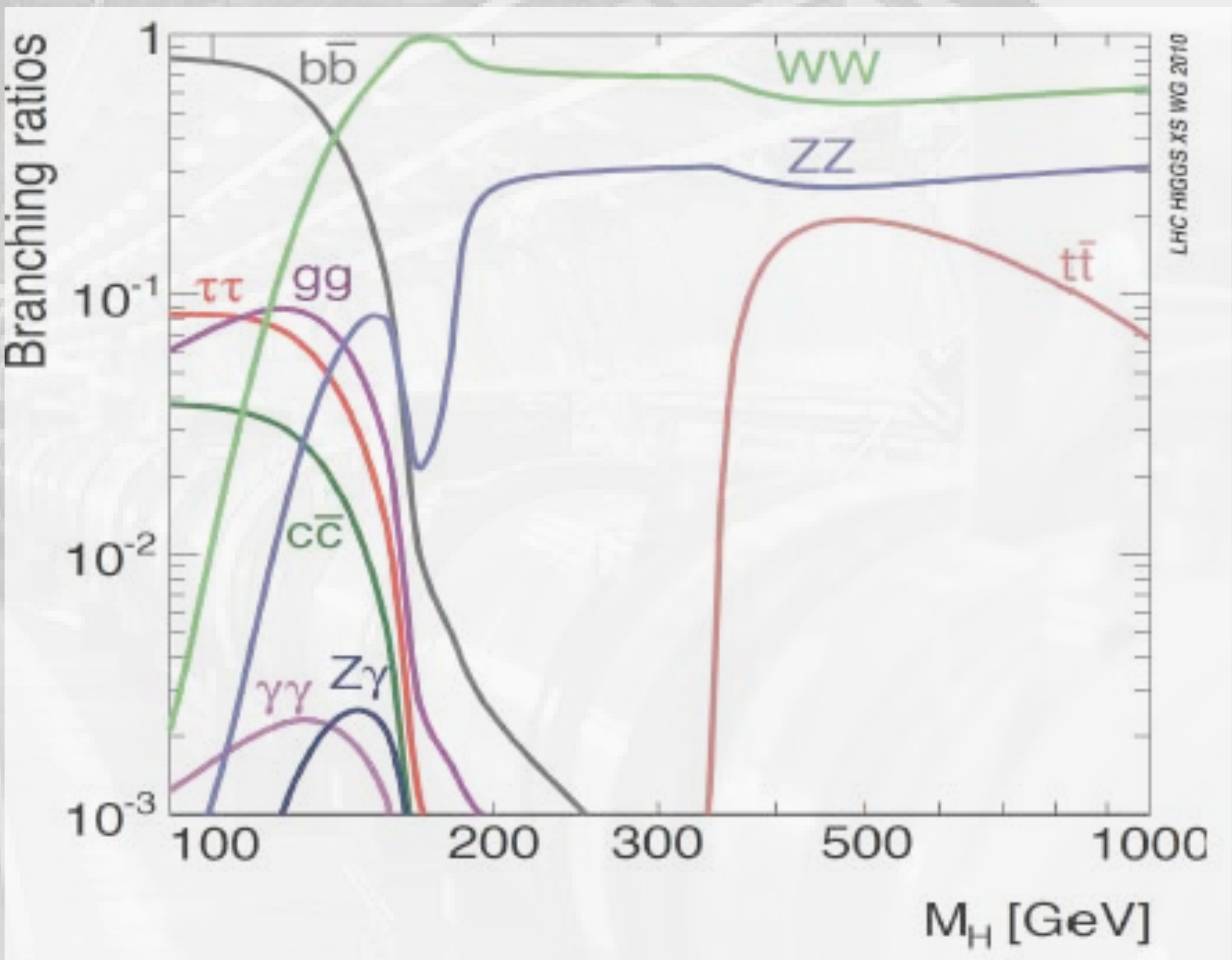




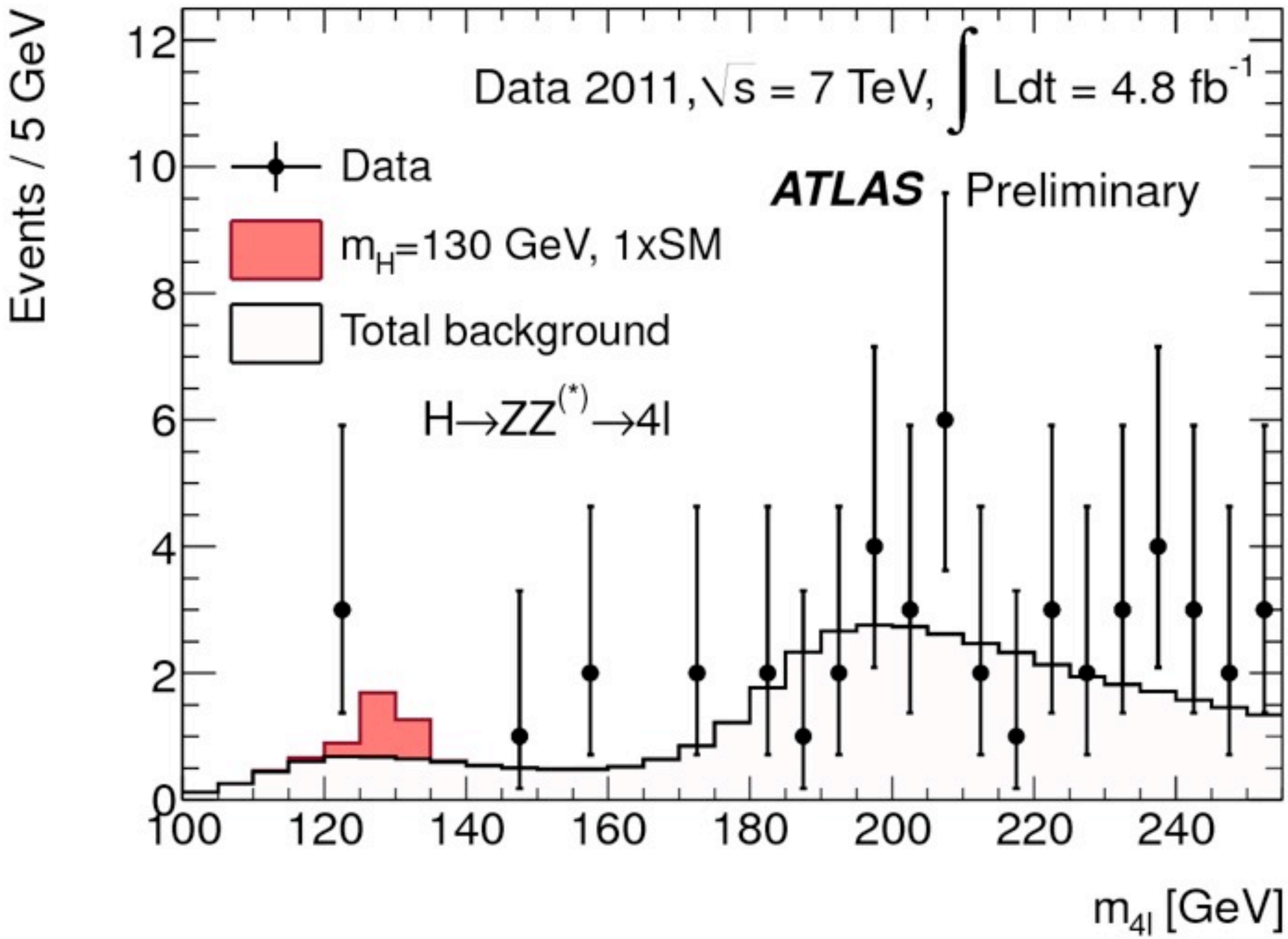
... a very rare process !

Search for the (SM) Higgs boson

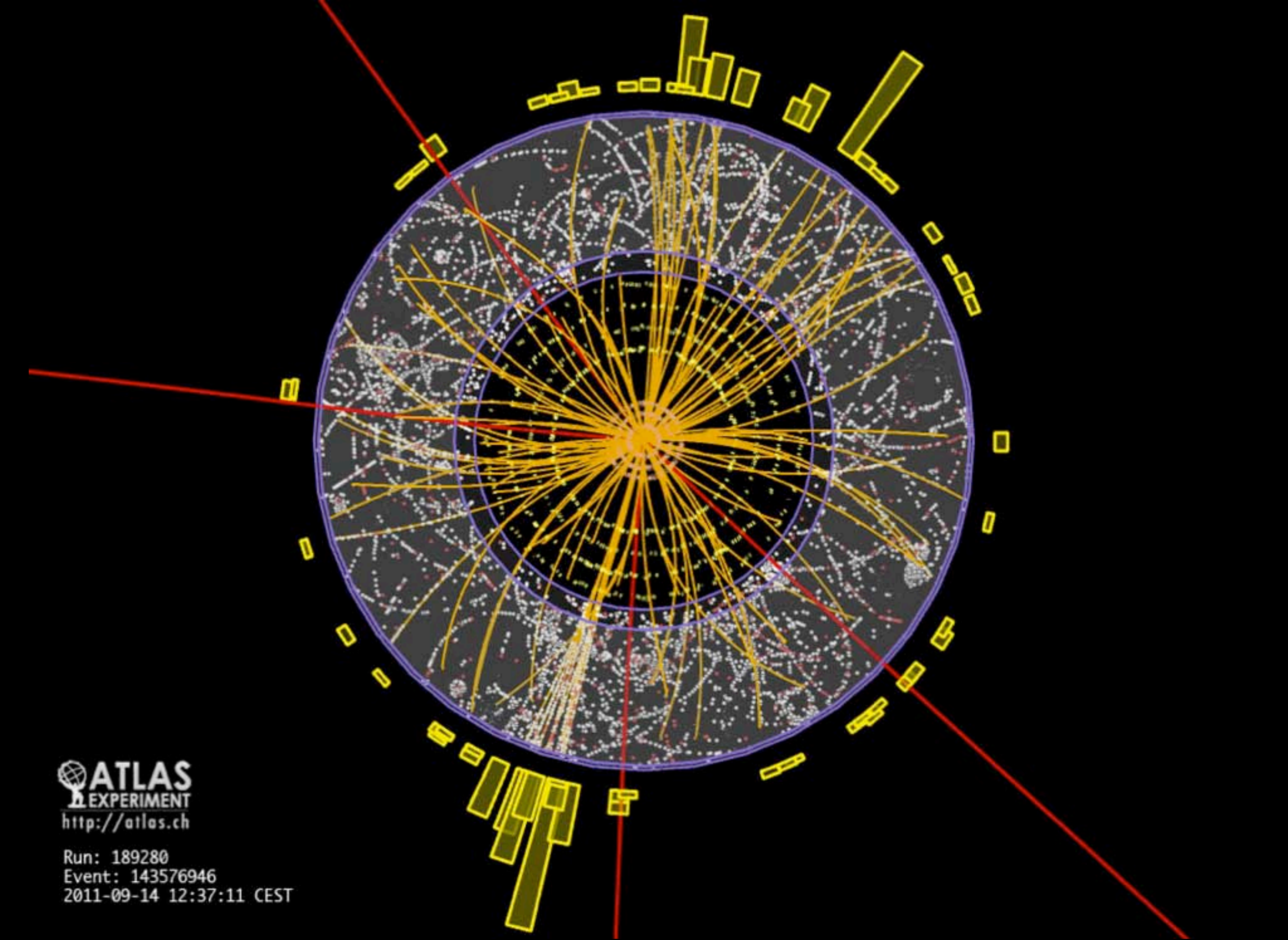
Higgs decays:



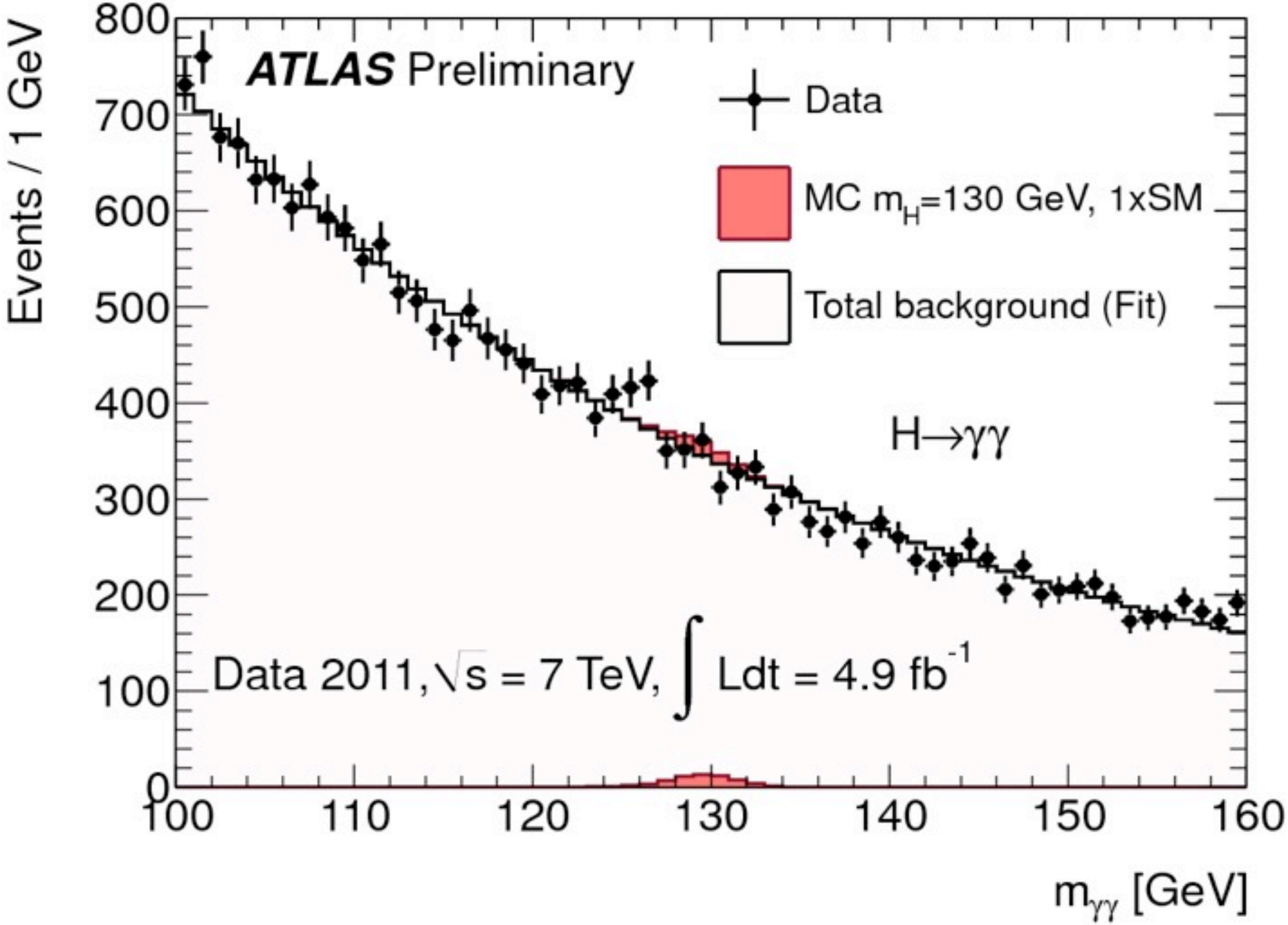
ATLAS: H –> ZZ –> ll ll



• n.b.: good mass resolution, small background, but low statistics at small masses (off-peak Z)!

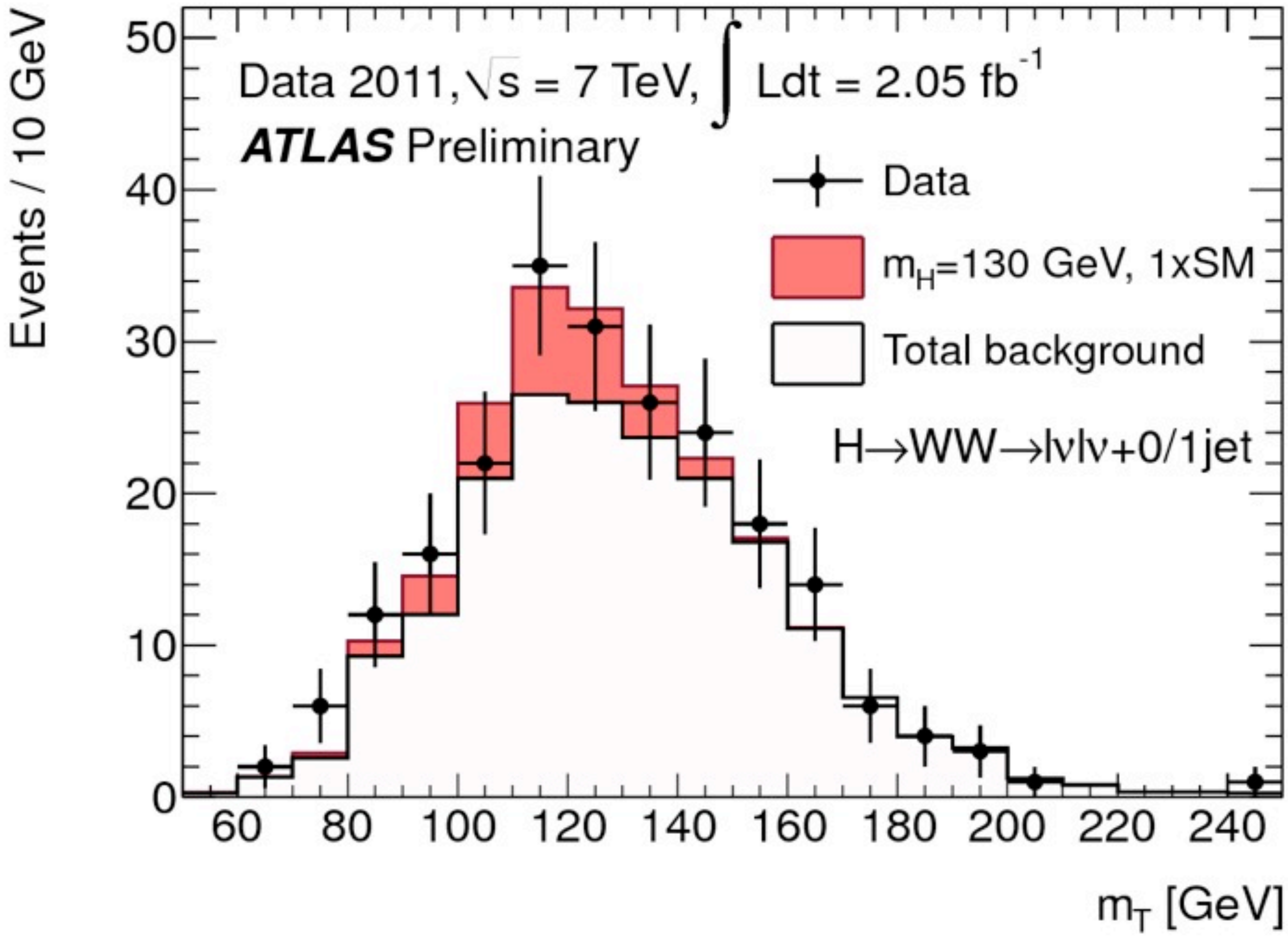

ATLAS
EXPERIMENT
http://atlas.ch
Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST

H –> γγ

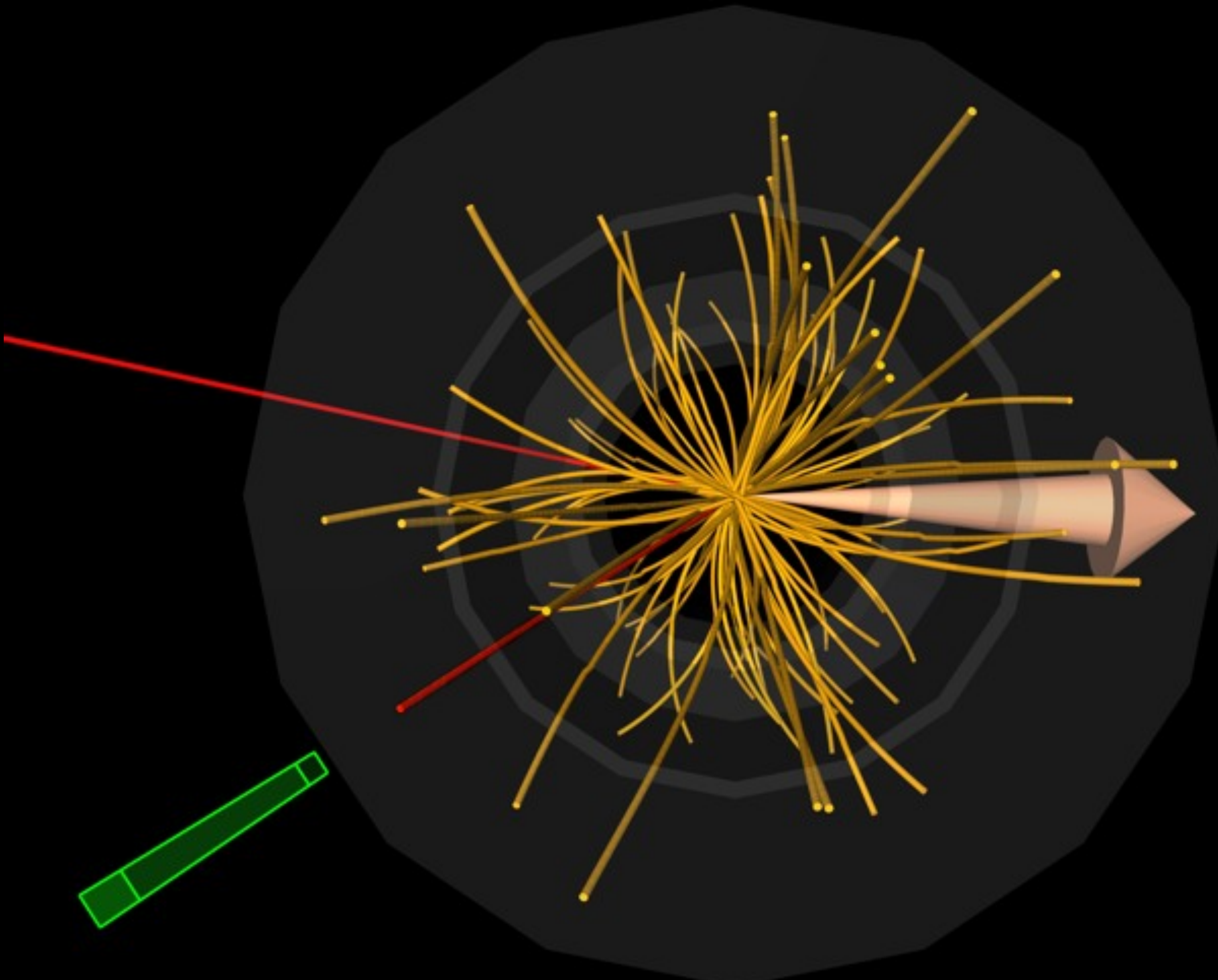


• n.b.: good mass resolution, but large background

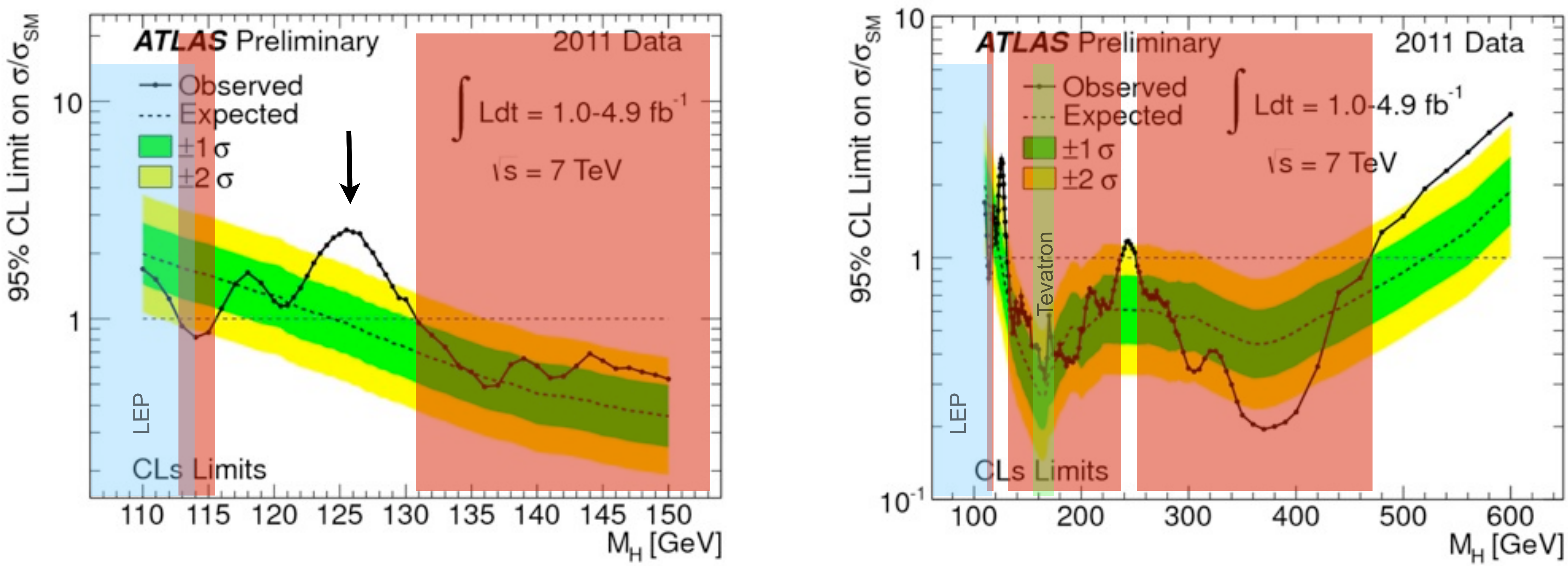
H –> WW –> $l\nu$ $l\nu$



- n.b.: limited mass resolution due to missing energy (2 ν's !!)



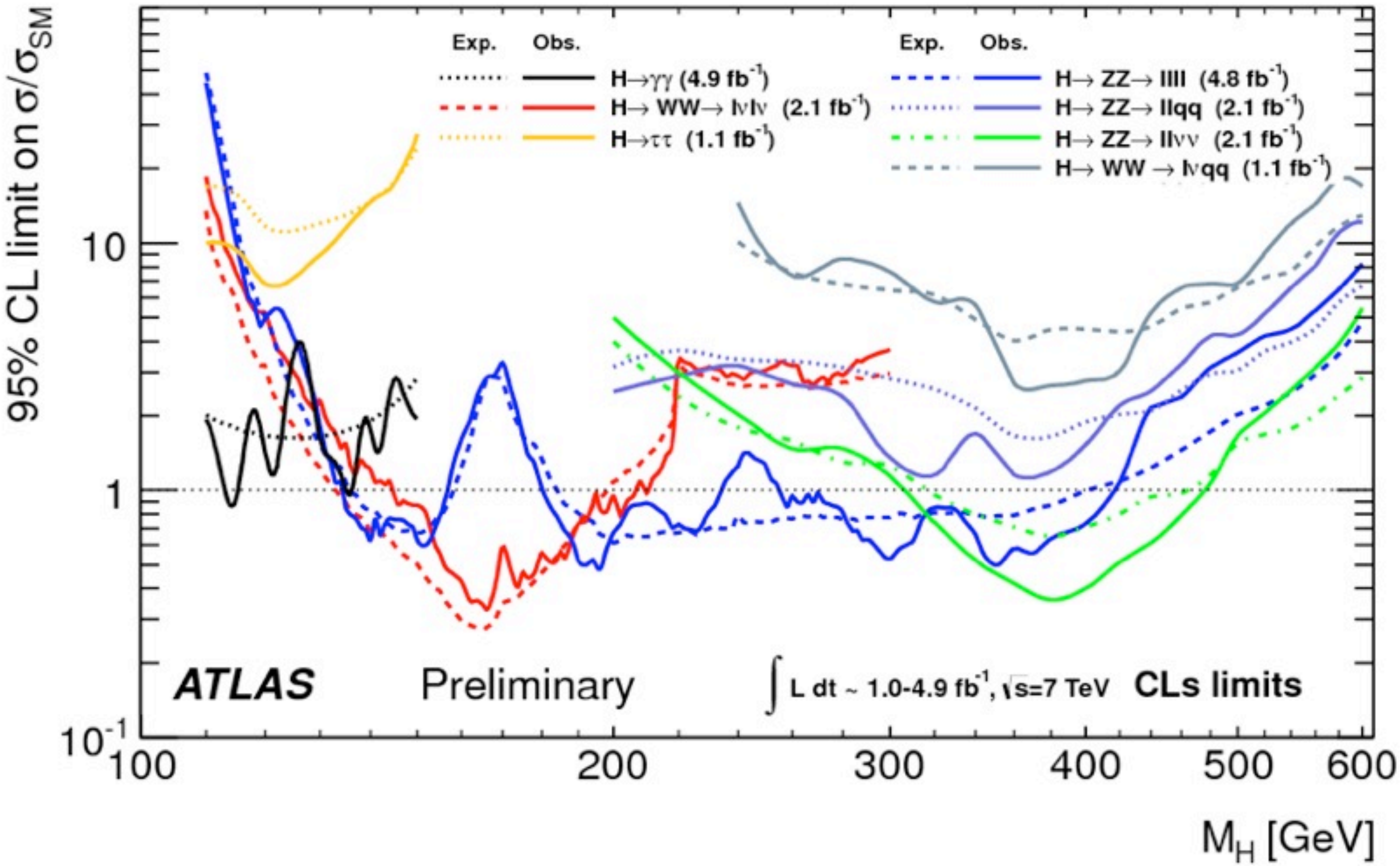
ATLAS combination of all channels (status: Dec. 2011):



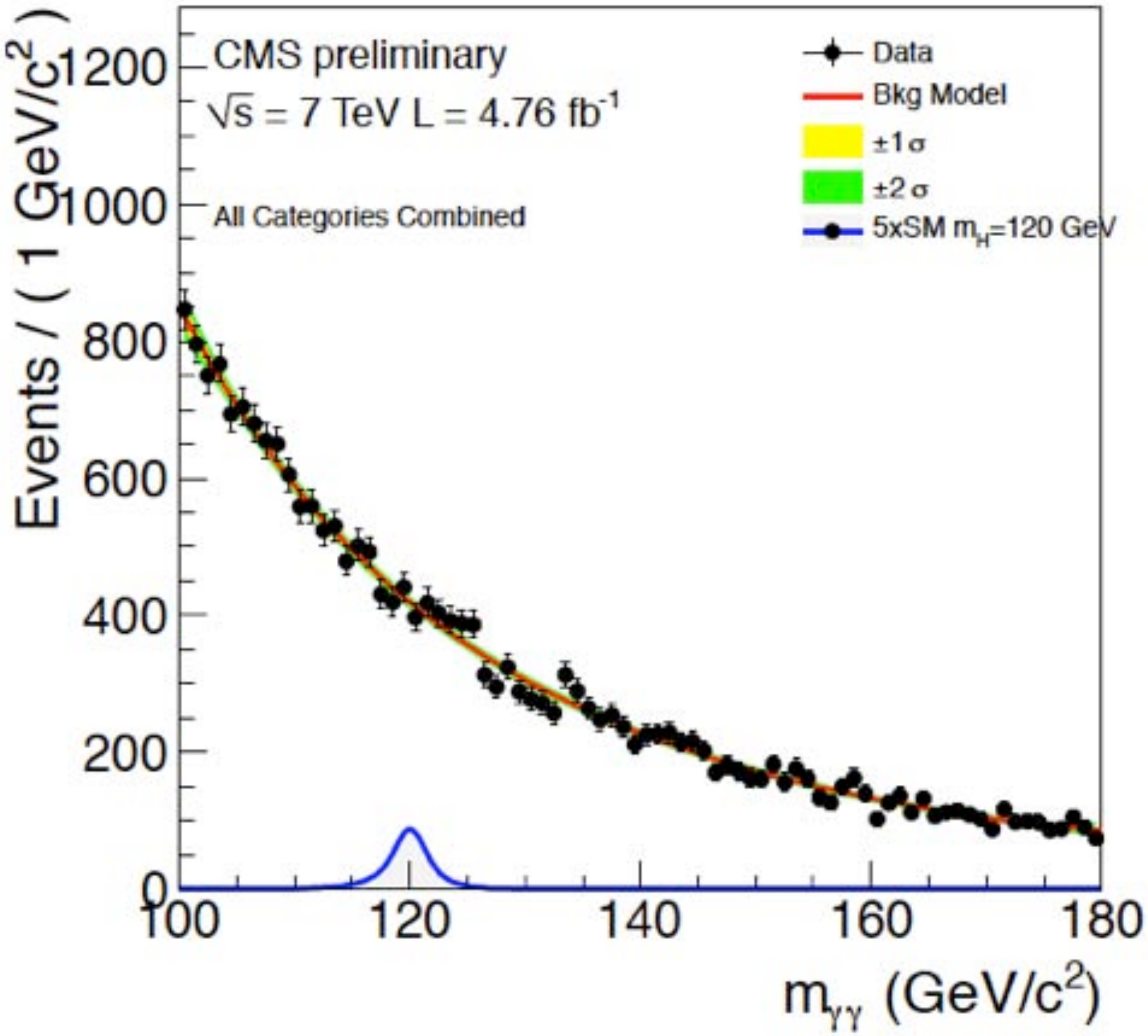
- exclusion of existence of SM Higgs (at least 95% c.l.):
  112,7 < M_H < 115.5 GeV; 131 < M_H < 237 GeV; 251 < M_H < 468 GeV

- local excess at M ~ 126 GeV (significance: 2.9 std. dev.)

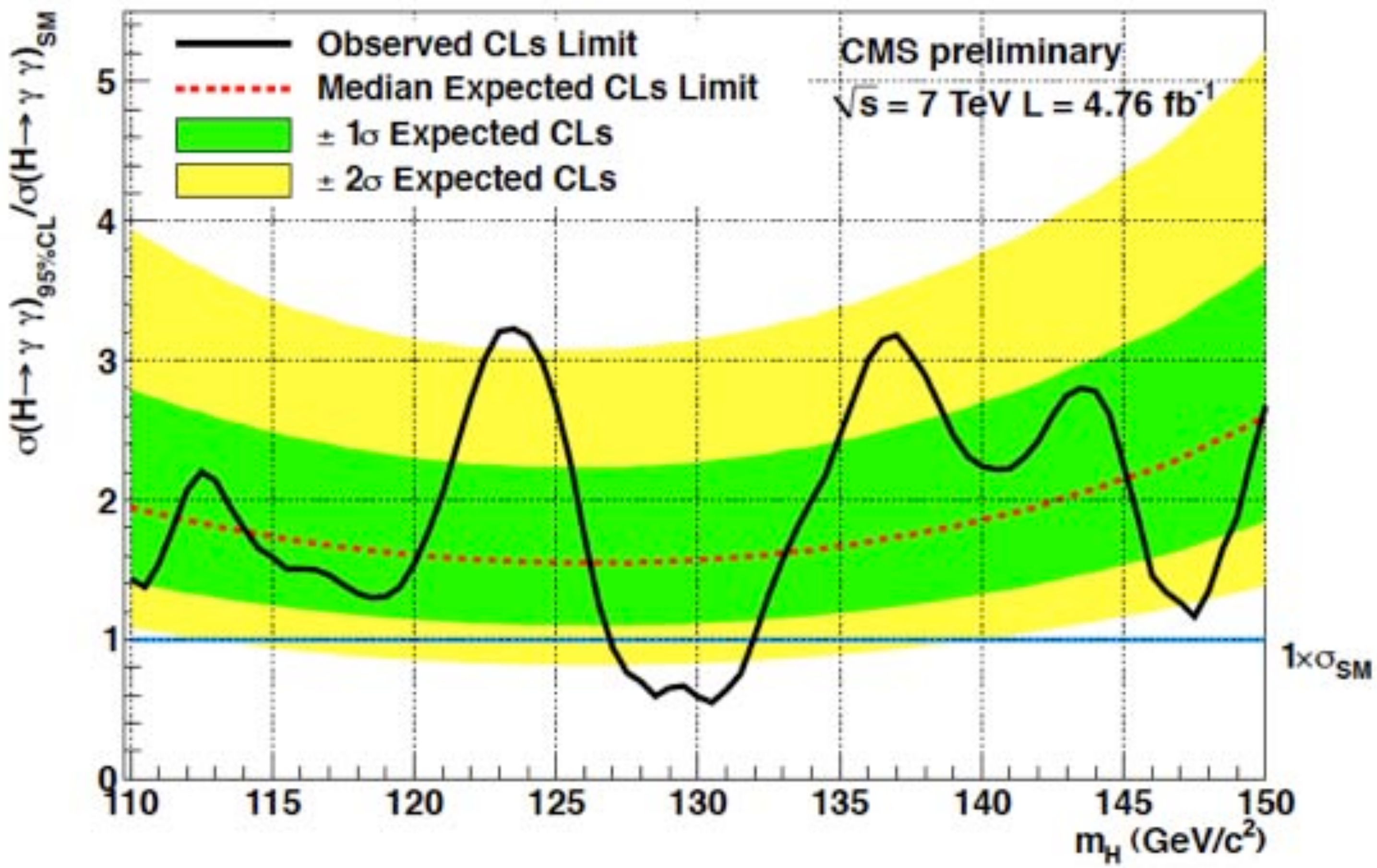
ATLAS single channel results



CMS: H –> γγ

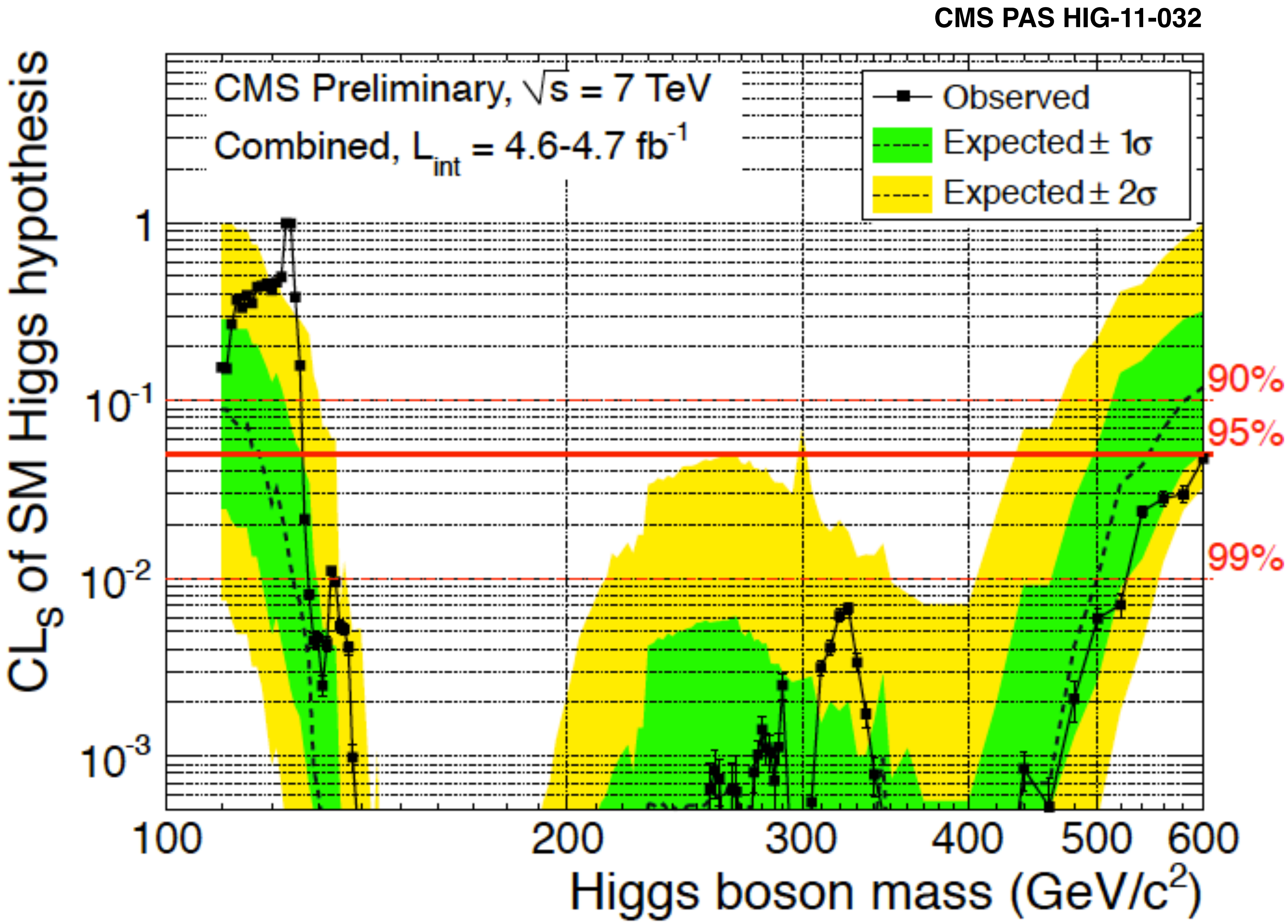


CMS preliminary
√s = 7 TeV L = 4.76 fb-1
All Categories Combined
Data
Bkg Model
±1 σ
±2 σ
5xSM mH=120 GeV
Events / (1 GeV/c2)
mγγ (GeV/c2)



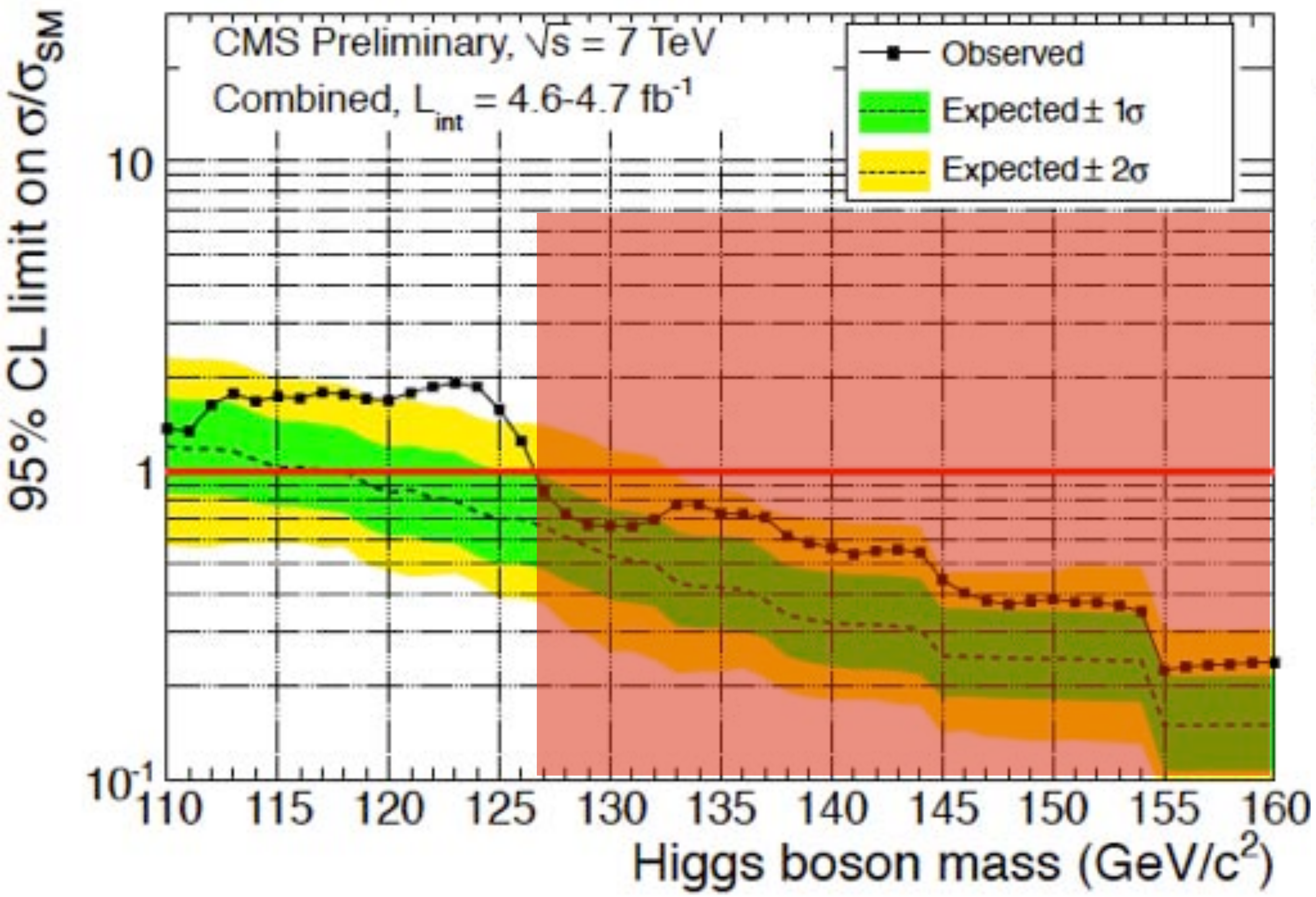
Observed CLs Limit
Median Expected CLs Limit
± 1σ Expected CLs
± 2σ Expected CLs
CMS preliminary
√s = 7 TeV L = 4.76 fb-1
1×σSM
σ(H→γγ)95%CL/σ(H→γγ)SM
mH (GeV/c2)

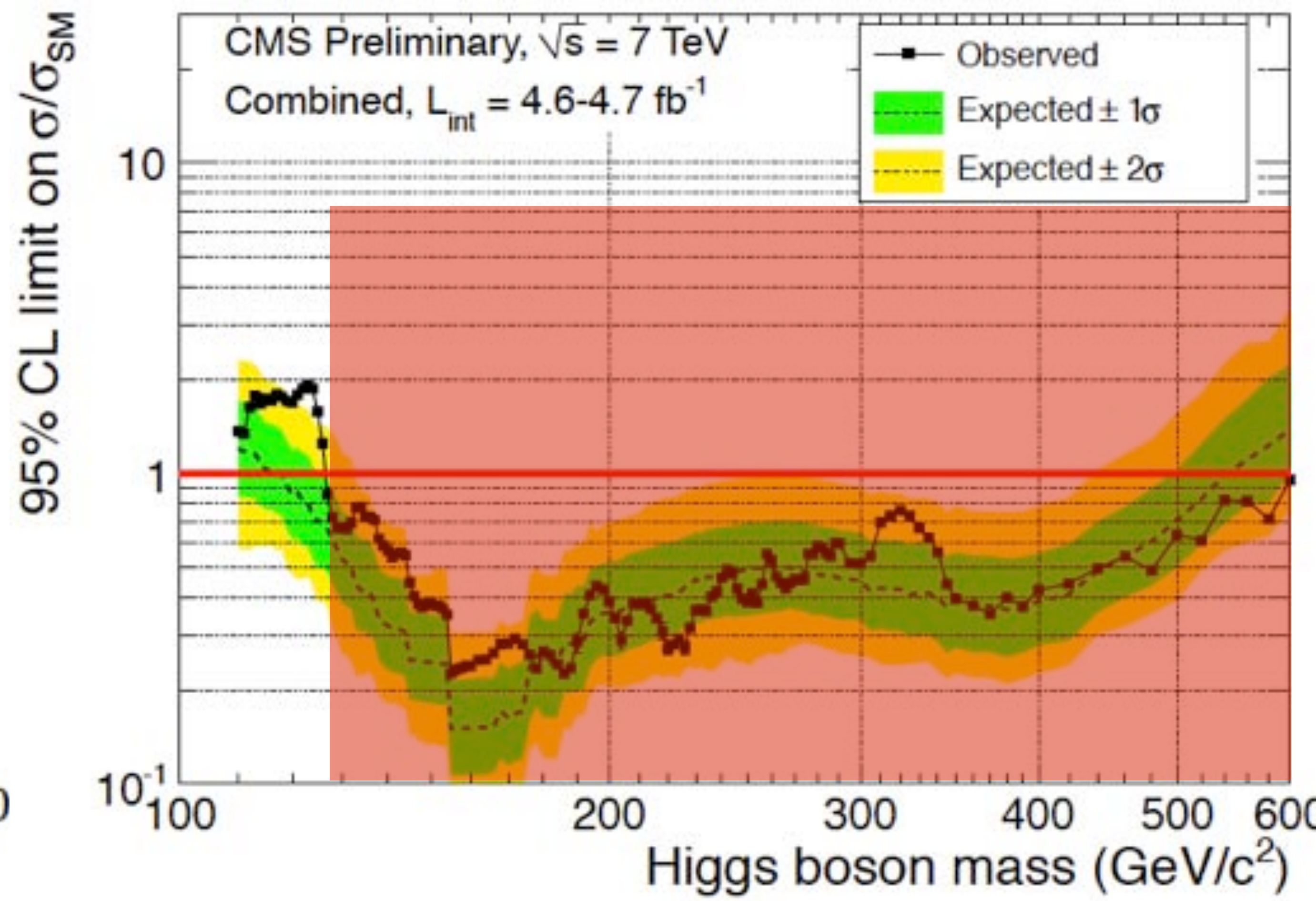
CMS: combined SM Higgs analysis



CMS: combined SM Higgs analysis

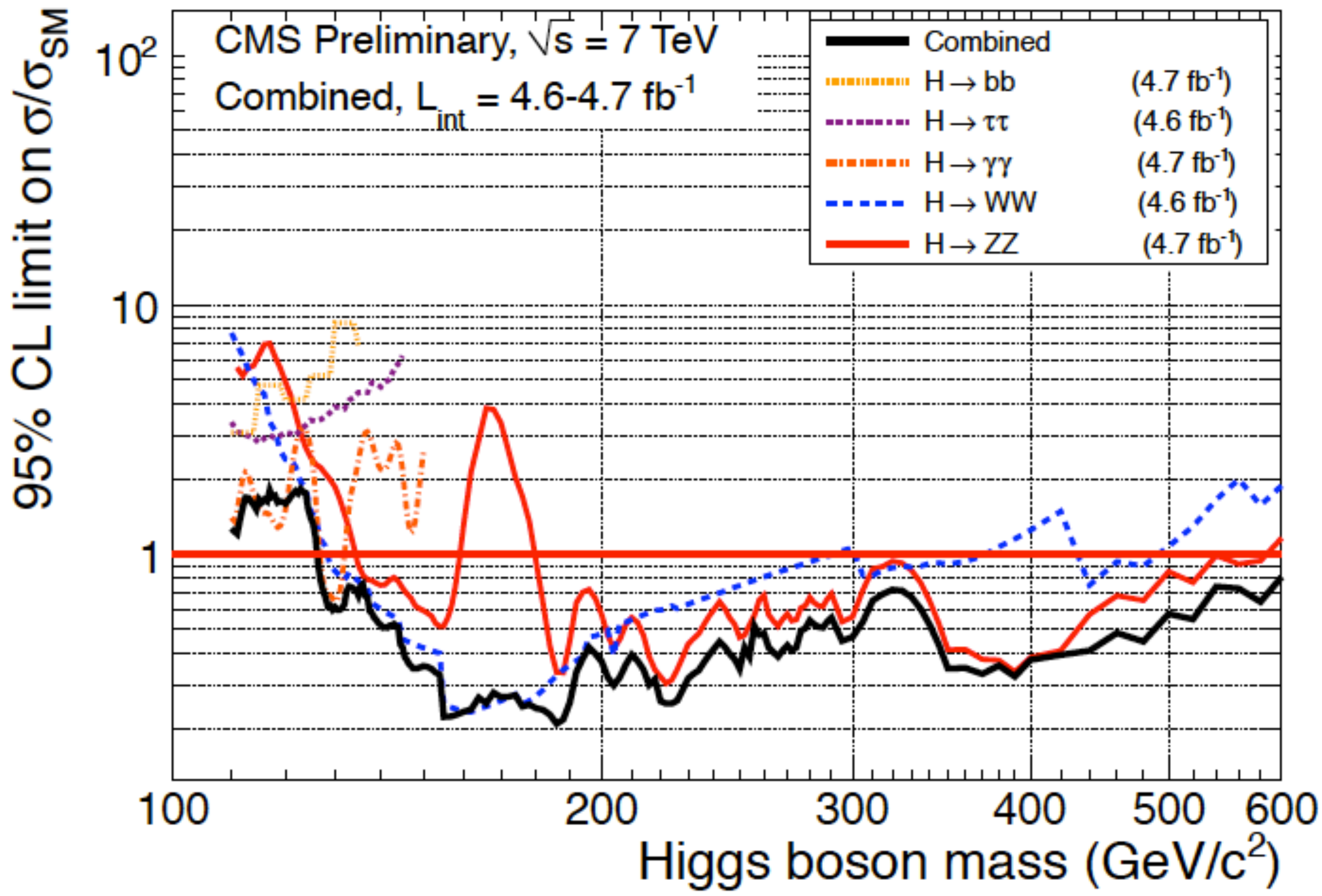
CMS PAS HIG-11-032





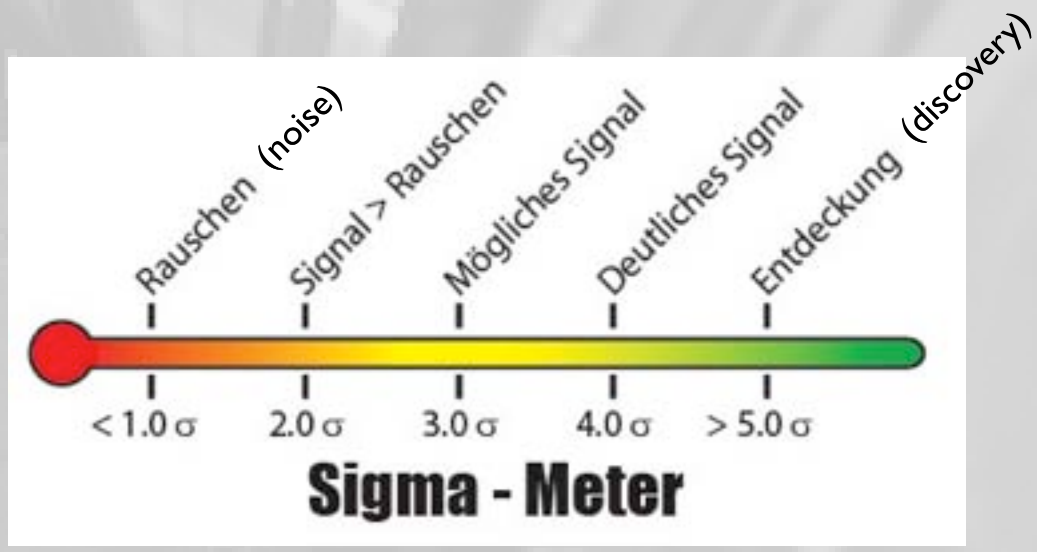
exclusion: 127 < Mh < 600 GeV (95% c.l.)
expected: 117 < Mh < 543 GeV (95% c.l.)

max. local significance: 2.6 σ
incl. look elsewhere (110-145 GeV): 1.9 σ


CMS Preliminary, √s = 7 TeV
Combined, L_int = 4.6-4.7 fb^-1
Combined
H → bb (4.7 fb^-1)
H → ττ (4.6 fb^-1)
H → γγ (4.7 fb^-1)
H → WW (4.6 fb^-1)
H → ZZ (4.7 fb^-1)
95% CL limit on σ/σ_SM
10^2
10
1
100
200
300
400
500
600
Higgs boson mass (GeV/c^2)

Summary of physics results:

- SM significantly challenged; still in very (*too?*) good shape!
- extensive searches for physics BSM without positive result; exclusion of many processes up to and beyond masses of O(1 TeV) –> still large phase space region to go ...
- possible signal of „light“ SM Higgs boson at ~125 GeV (in several decay channels, both by ATLAS and CMS); local significance $\sim 3\sigma$; incl. „look-elsewhere“: $\sim 2\sigma$



LHC - future planning:

2012:

- collisions at 7 (possibly 8!) TeV
- will reach (~half to total) Design-Luminosity
- expect ~3-times statistics of 2011(i.e.: ~12-15 fb^{-1})

-> establishment or exclusion of SM Higgs Boson (5 std.dev.)

2013 / 2014:

- 15-19 months shut-down (installation of final safety systems for highest magnet currents to reach design-energy of 14 TeV)

2014 - 2016:

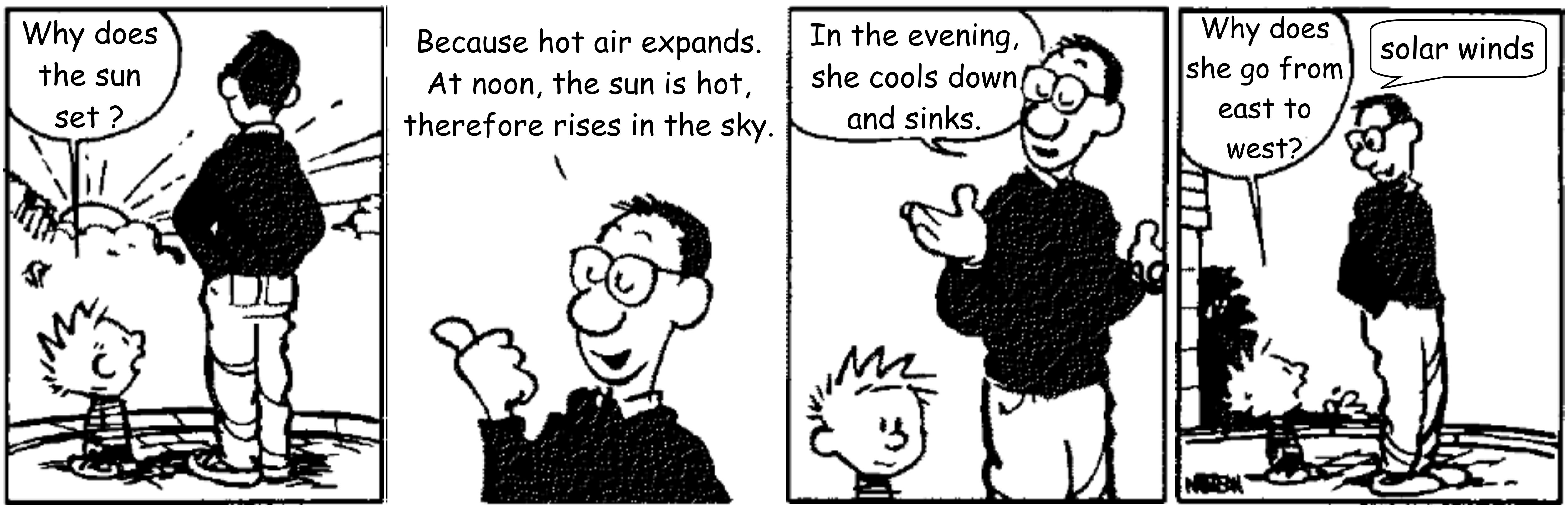
- full energy (14 TeV) and luminosity (10^{34} cm^{-2} s^{-1})

from ~ 2020:

- upgrade of LHC (and of detectors) to hl-LHC (luminosity x 5)

… and why do we do all this ?

why do we need (such complex and expensive) fundamental research?



in order to understand our World!

http://www.mpp.mpg.de