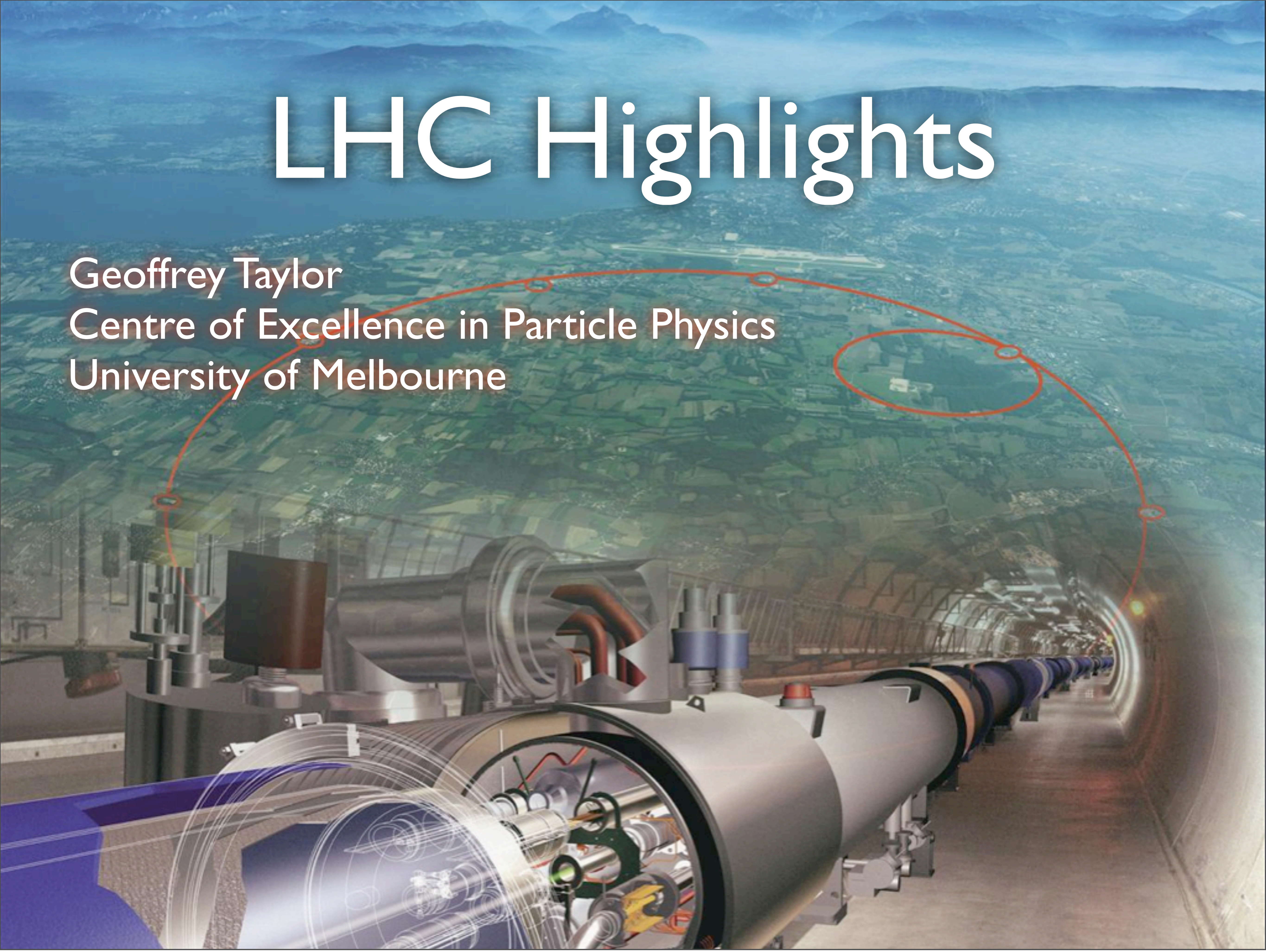


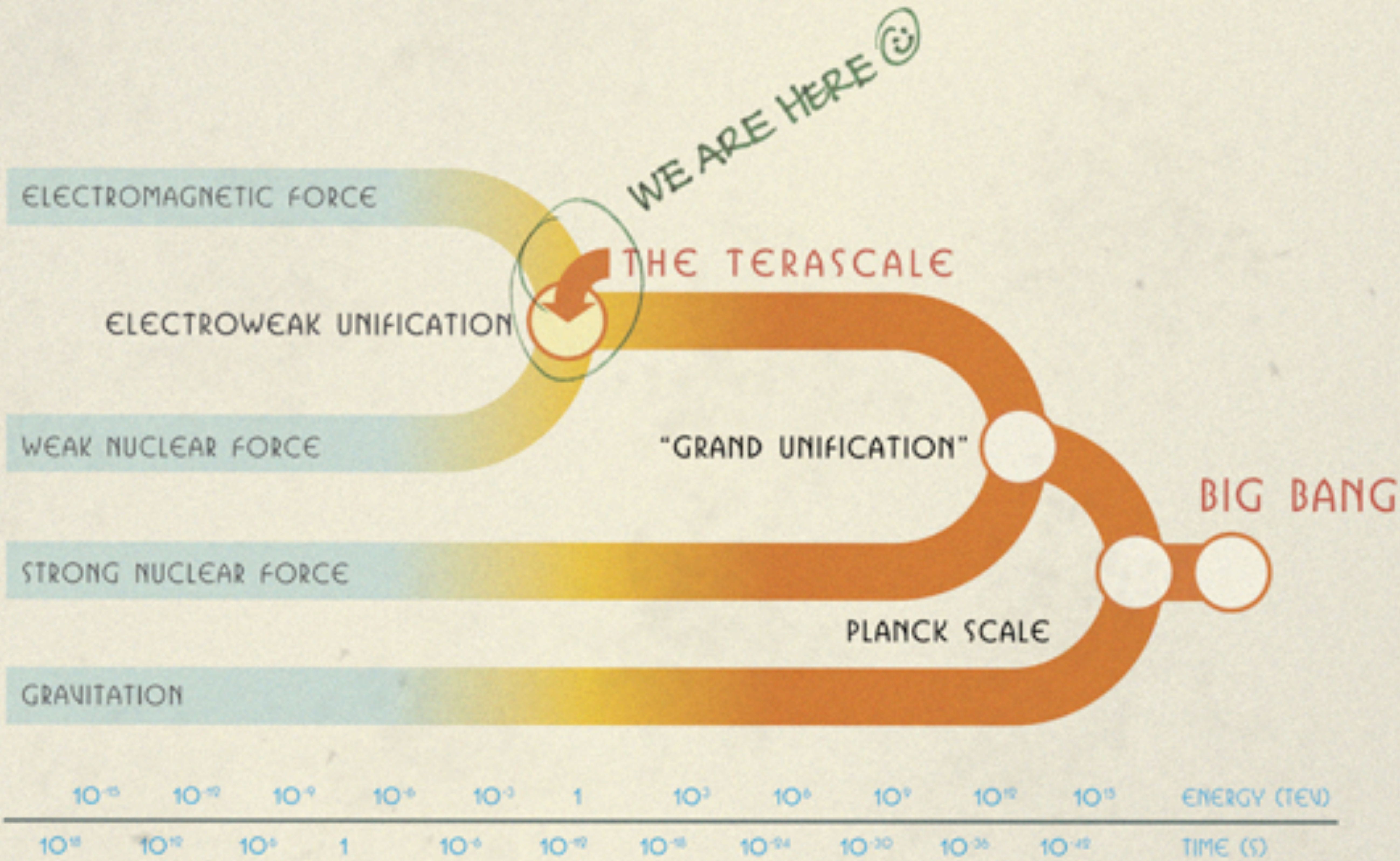
LHC Highlights

Geoffrey Taylor
Centre of Excellence in Particle Physics
University of Melbourne

Key Questions

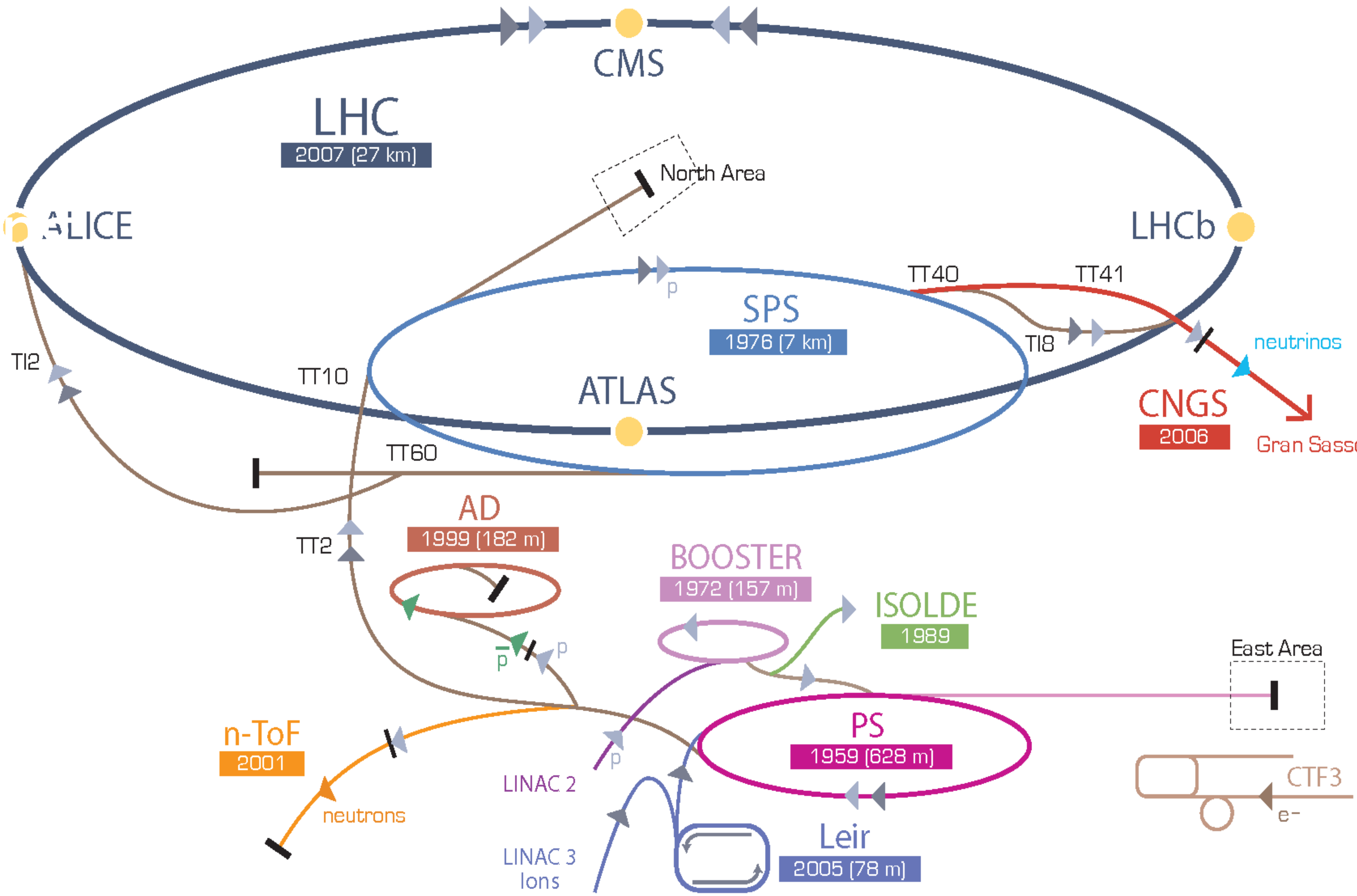
- What is the origin of Electroweak Symmetry Breaking? Origin of Mass?
- Where is all the Anti-Matter?
- Were the fundamental forces once unified?
- Are there extra dimensions? Dark Matter?

New particles should appear at the TeV scale,
in reach of the LHC



ELECTROMAGNETIC FORCE
WE ARE HERE ☺
THE TERASCALE
ELECTROWEAK UNIFICATION
WEAK NUCLEAR FORCE
"GRAND UNIFICATION"
BIG BANG
STRONG NUCLEAR FORCE
PLANCK SCALE
GRAVITATION
10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} ENERGY (TEV)
10^{18} 10^{12} 10^{6} 1 10^{-6} 10^{-12} 10^{-18} 10^{-24} 10^{-30} 10^{-36} 10^{-42} TIME (S)

CERN Accelerator Complex

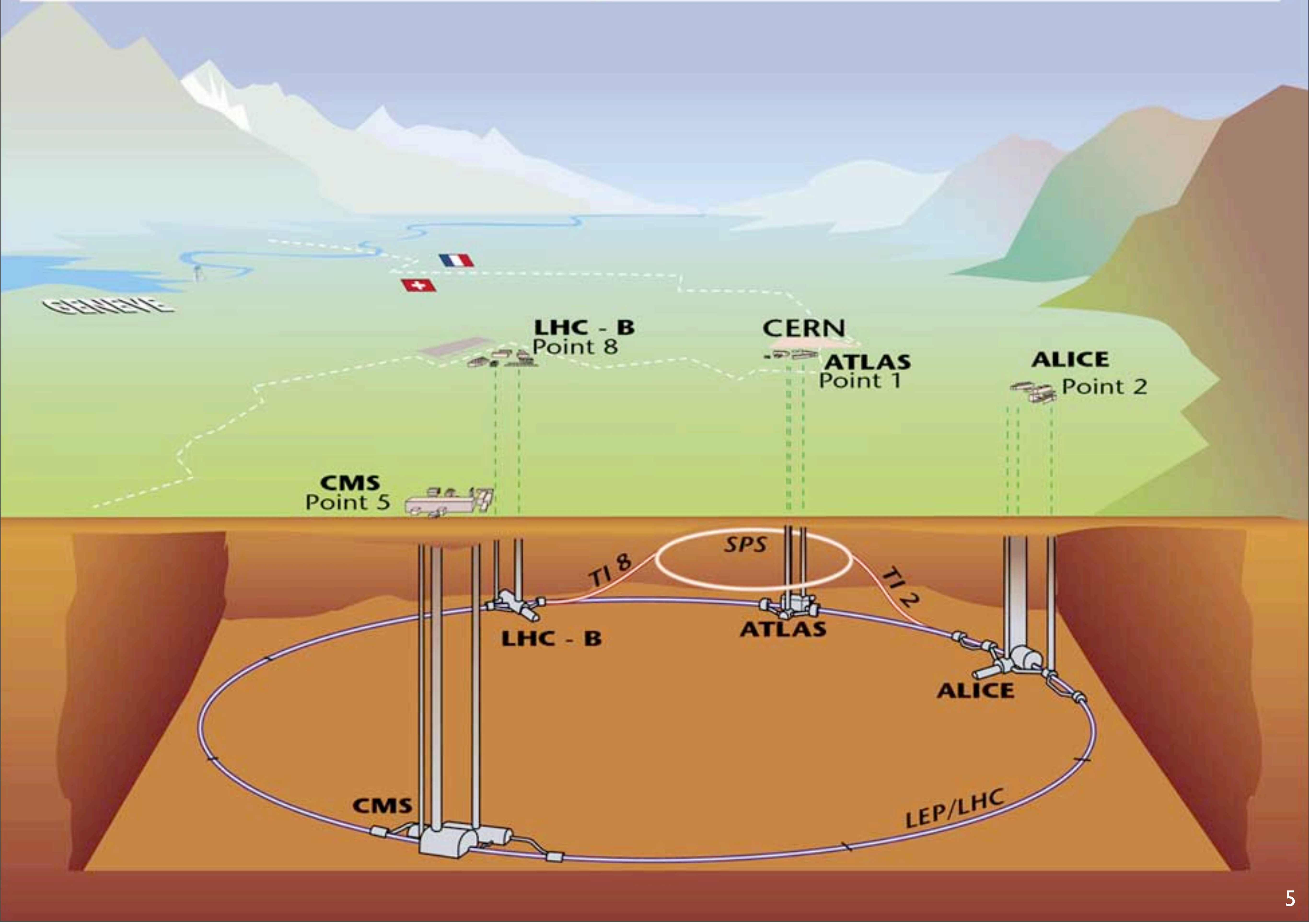


p (proton) ion neutrons p̄ (antiproton) proton/antiproton conversion neutrinos electron

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

Overall view of the LHC experiments.



LHC Experiments

- ATLAS/CMS :
  - Electroweak Symmetry Breaking
  - Supersymmetry
  - Extra Dimensions, Exotics
- LHCb :
  - CKM Measurements
    - (Matter/Anti-Matter Imbalance)
  - Precision tests of the standard model
- ALICE :
  - Properties of the Quark-Gluon Plasma

LHC Experiments

- ATLAS/CMS :
  - Electroweak Symmetry Breaking
  - Supersymmetry
  - Extra Dimensions, Exotics

Also smaller experiments: Totem, Alpha

  - CKM Measurements
    - (Matter/Anti-Matter Imbalance)
  - Precision tests of the standard model
- ALICE :
  - Properties of the Quark-Gluon Plasma

LHC Experiments

- ATLAS/CMS :
  - Electroweak Symmetry Breaking
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- LHCb :
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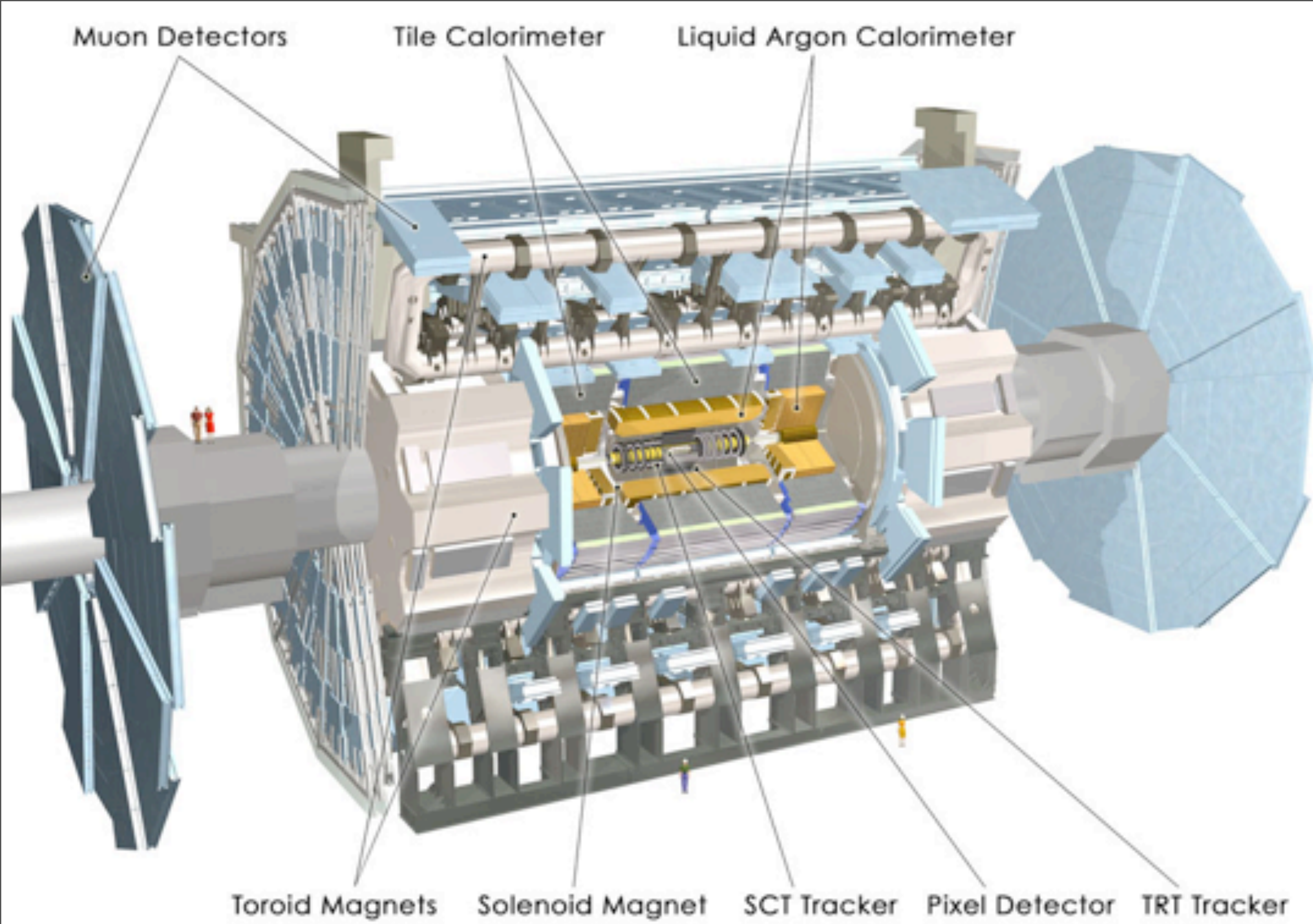
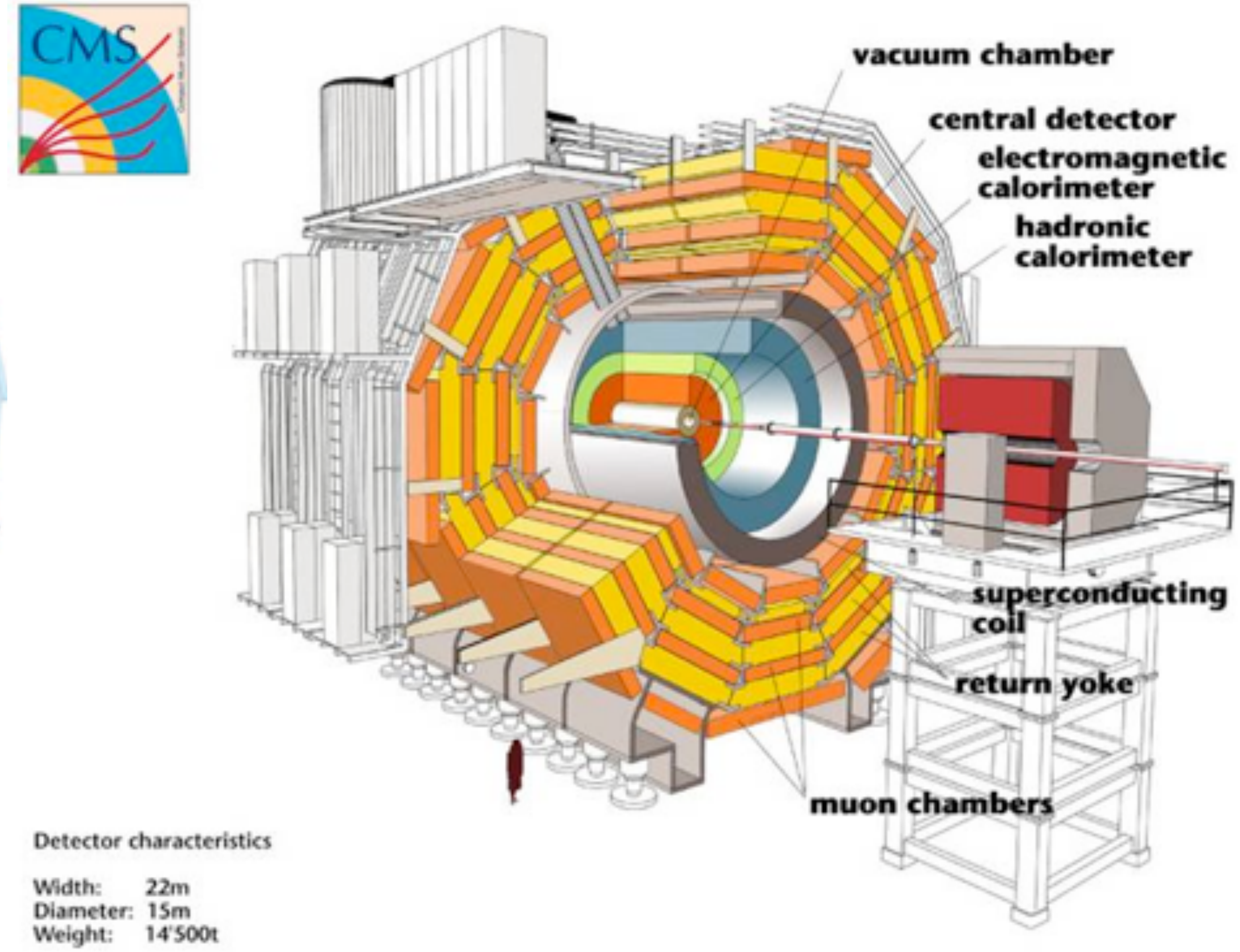
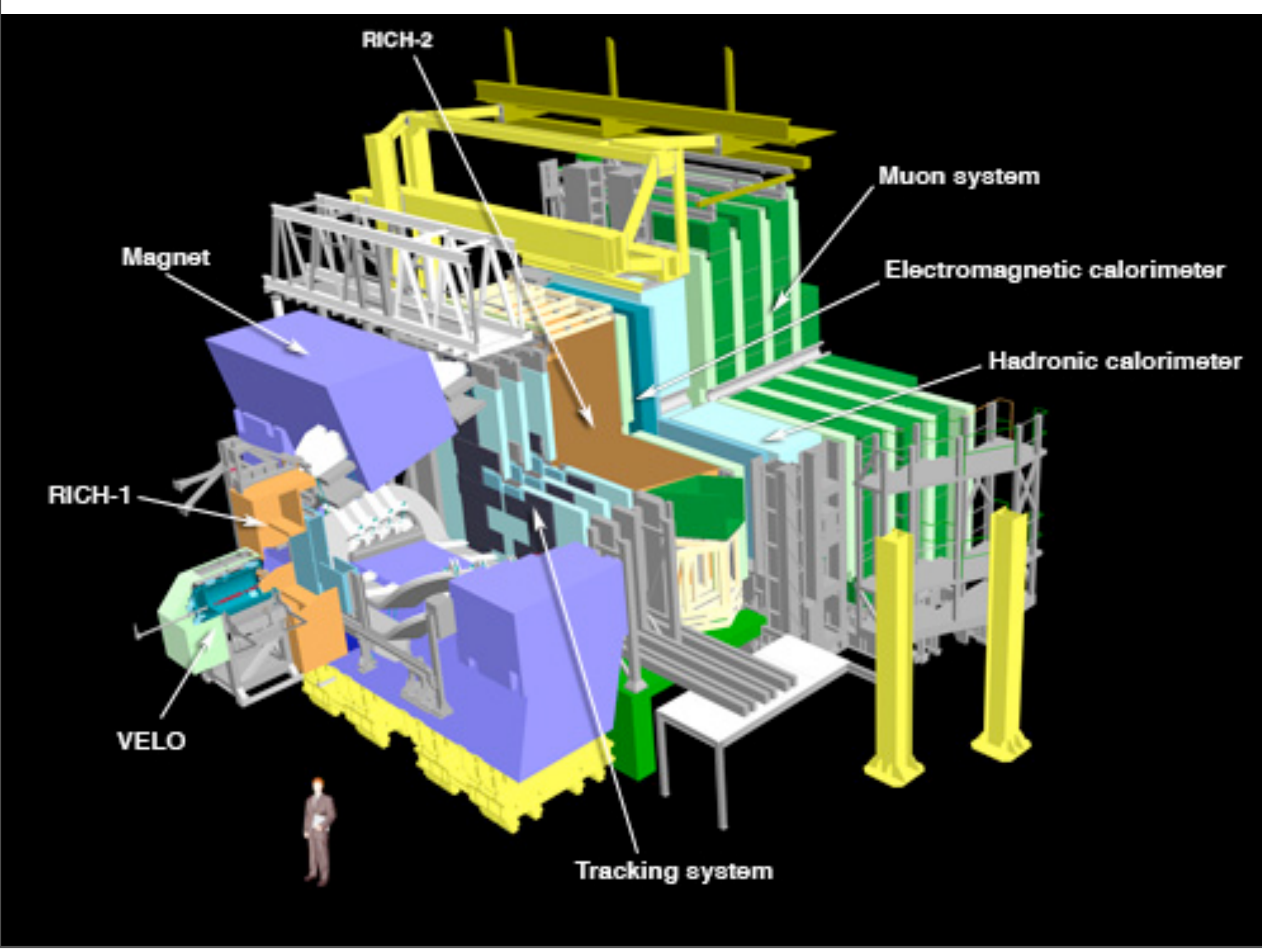
  - Properties of the Quark-Gluon Plasma


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker


CMS
vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers
Detector characteristics
Width: 22m
Diameter: 15m
Weight: 14'500t


RICH-2
Muon system
Magnet
Electromagnetic calorimeter
Hadronic calorimeter
RICH-1
VELO
Tracking system


Alice

LHC Beginning & Beyond

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

2009 — LHC start up, $\sqrt{s}$ = 900 GeV

2010
2011 — $\sqrt{s}$ = 7-8 TeV , L = 6 to 8•10^{33}cm^{-2}s^{-1}, bunch spacing **50 ns**
2012 — **~25 fb^{-1}**

2013 — **LS1** — Go to design energy, nominal luminosity
2014
2015 — $\sqrt{s}$ = 13-14 TeV, L = 1•10^{34}cm^{-2}s^{-1}, bunch spacing **25 ns**
(likely to be more)
2016
2017 — **~50 fb^{-1}**

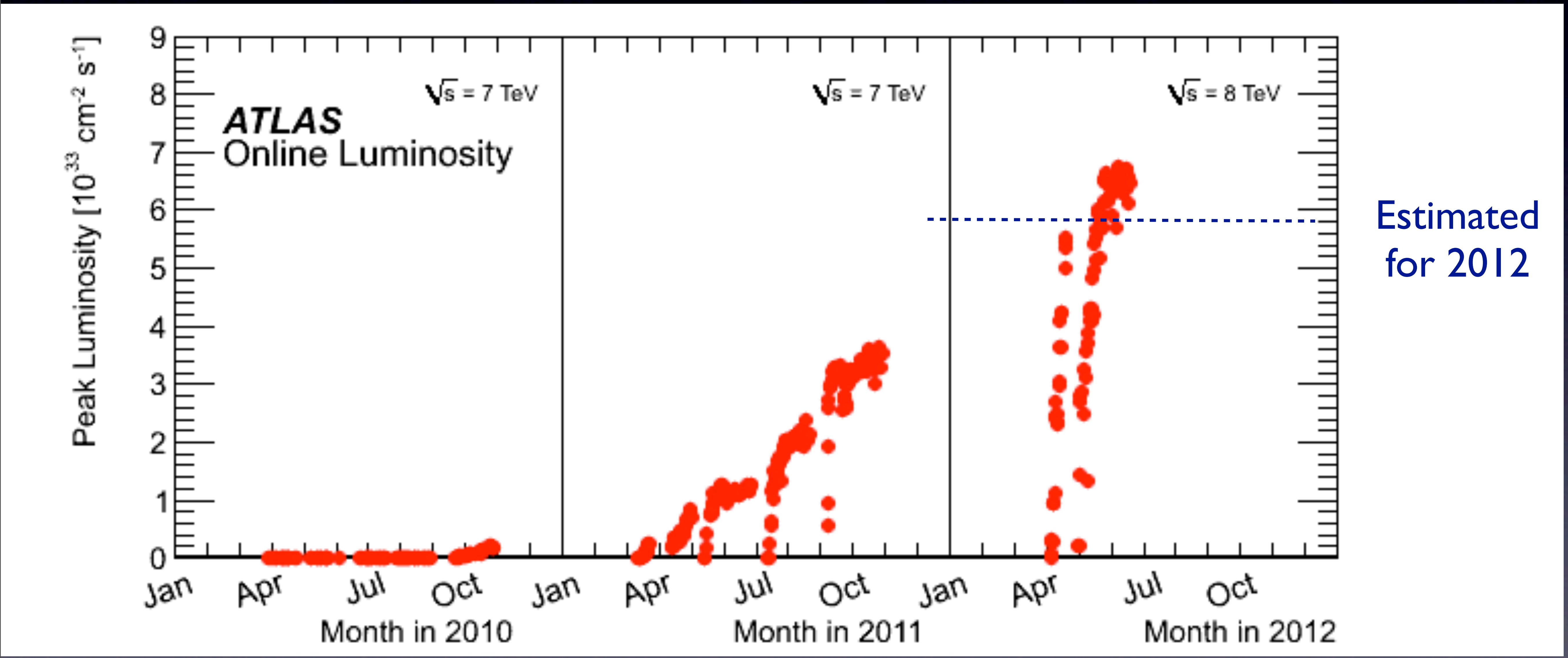
2018 — **LS2** — Injector & LHC Phase I upgrade to full design luminosity
2019
2020 — $\sqrt{s}$ = 14 TeV, L = 2•10^{34}cm^{-2}s^{-1}, bunch spacing **25 ns**
(likely to be more)
2021 — **~300 fb^{-1}**

2022 — **LS3** — HL-LHC Phase-2 upgrade, crab cavities?, IR
2023
$\sqrt{s}$ = 14 TeV, L = 5•10^{34}cm^{-2}s^{-1}, bunch spacing **25 ns**
Plan for 50% more
2030? — **~3000 fb^{-1}**

- 2009-today: Run 1 : 7-8 TeV centre of mass energy. Peak Luminosity 6.66 x 10^{33} $cm^{-2}s^{-1}$
- 2013-2014 : Shut down to prepare machine for design energy (14 TeV) and nominal luminosity ($10^{34}cm^{-2}s^{-1}$)
- 2015-2016 : Operation at design

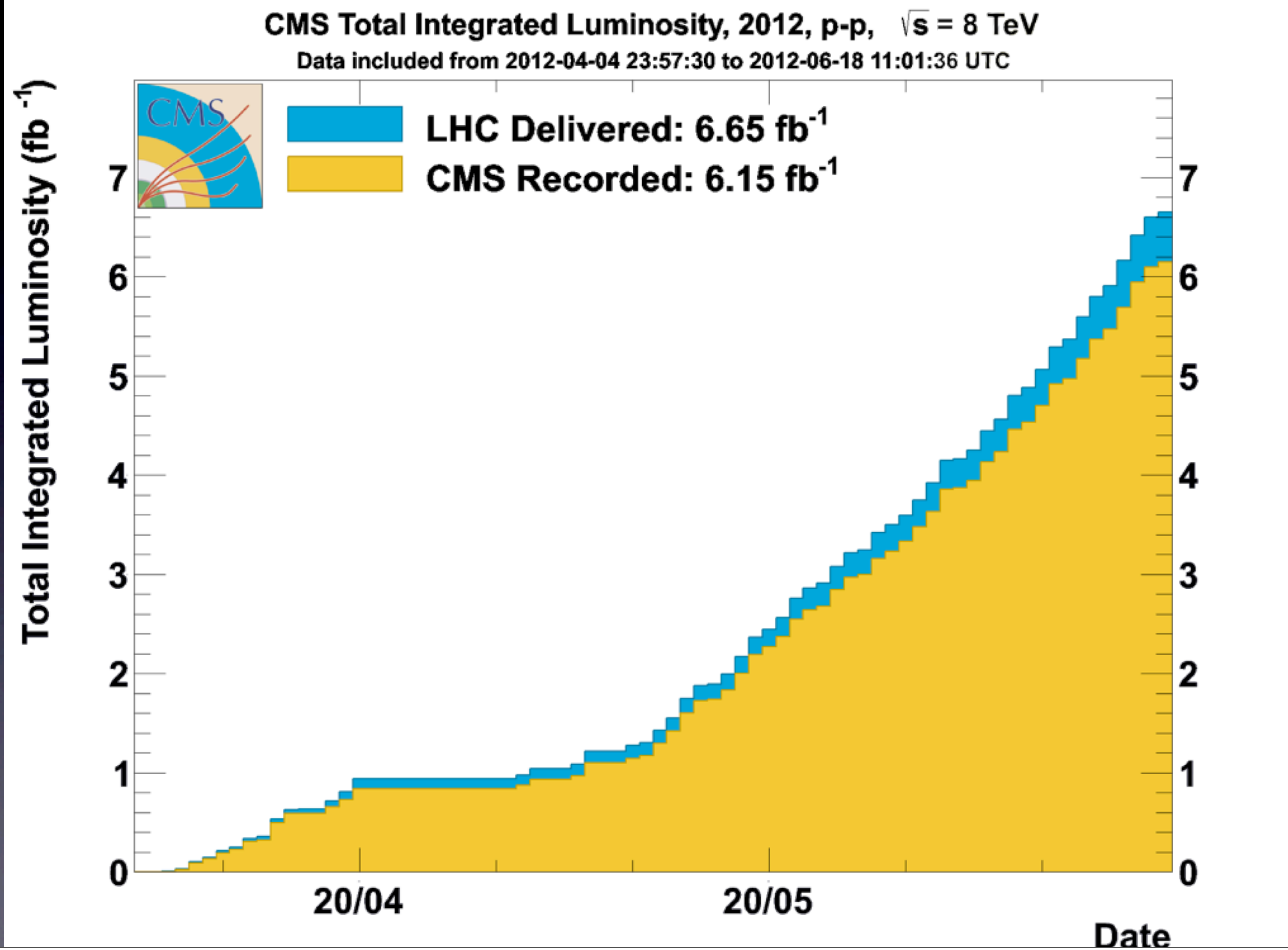
LHC Peak Luminosity

- http://lpc.web.cern.ch/lpc/lumiplots.htm

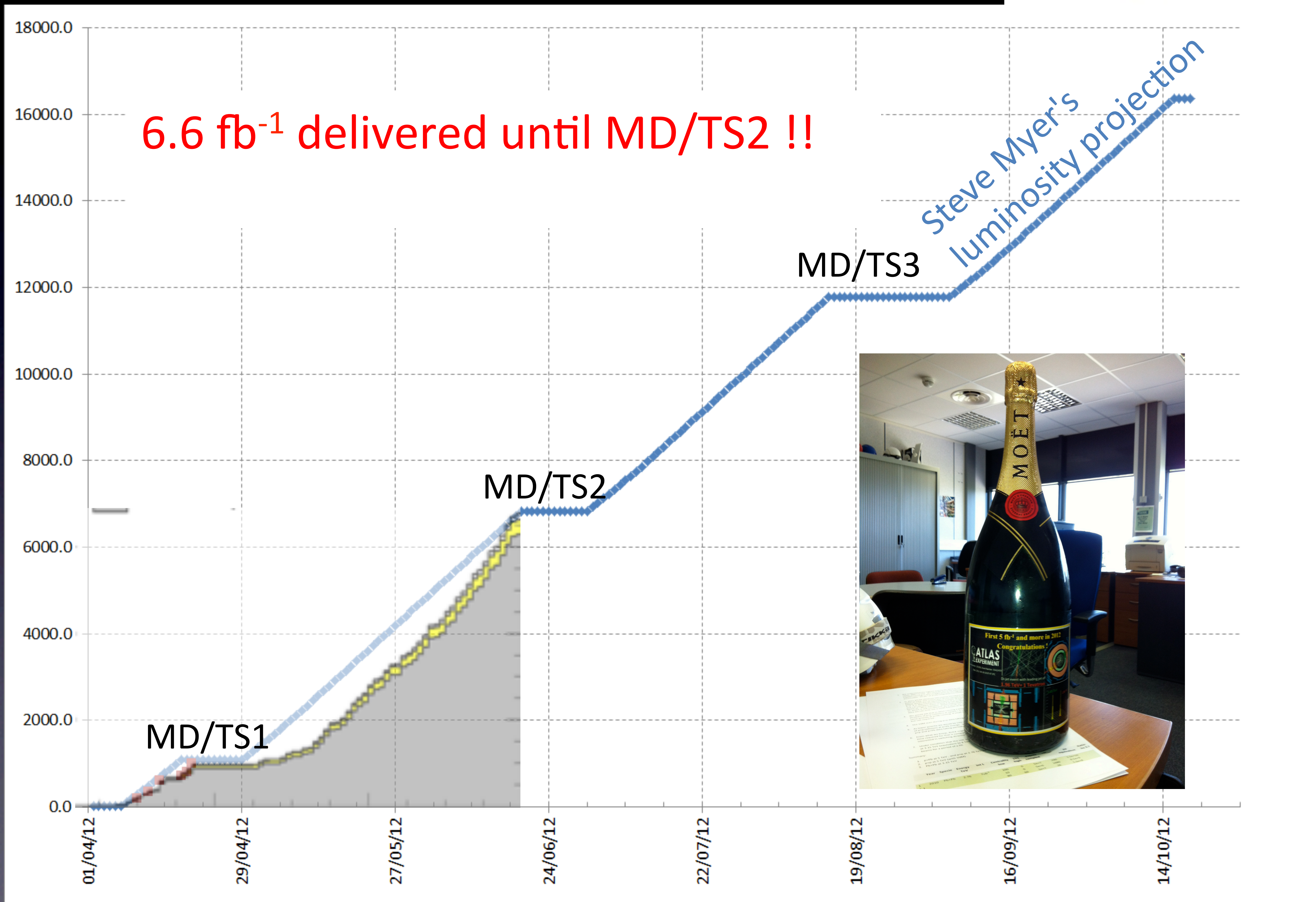


Estimated for 2012

Tuesday, 26 June 12

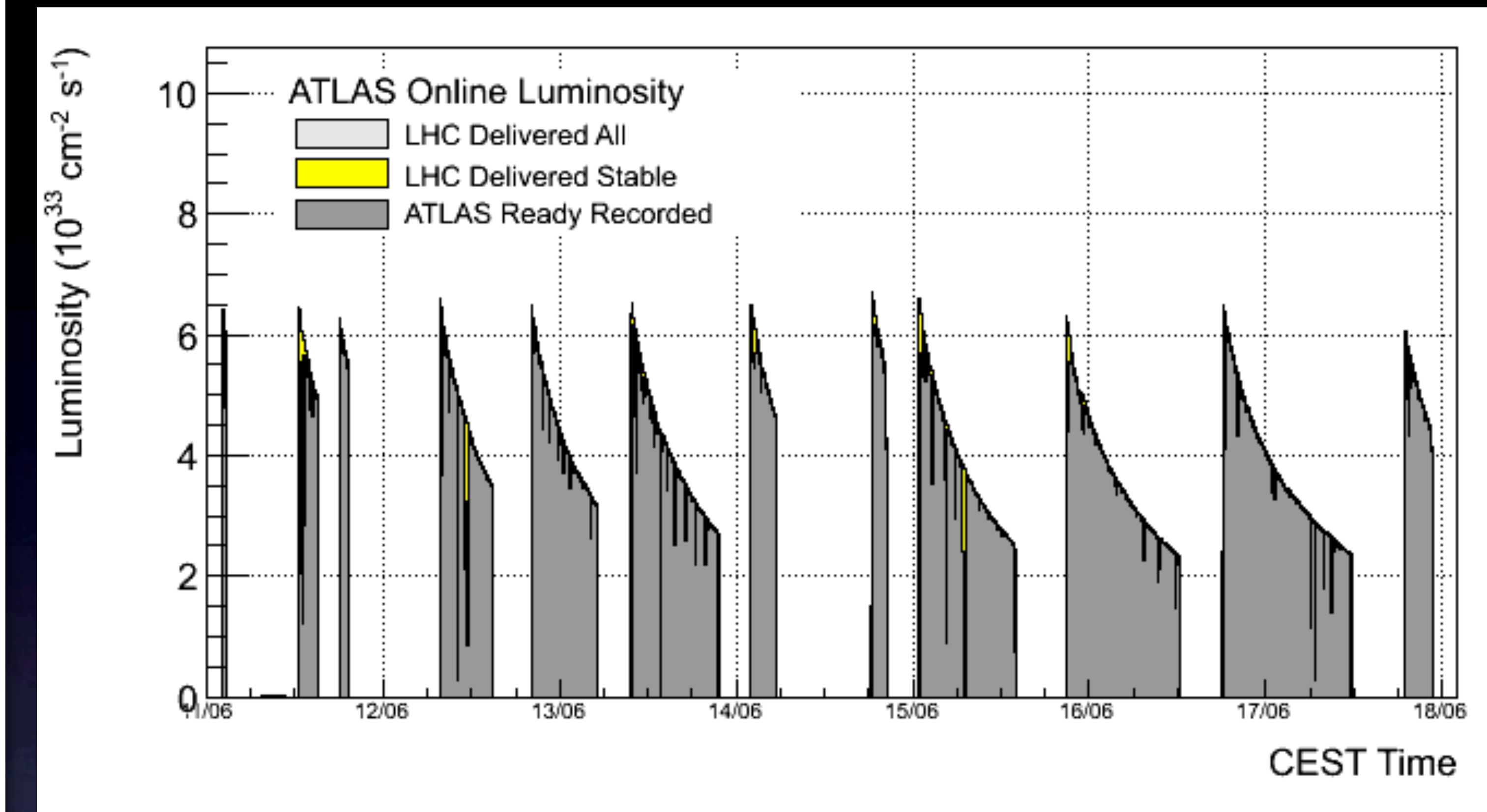

CMS Total Integrated Luminosity, 2012, p-p, √s = 8 TeV
Data included from 2012-04-04 23:57:30 to 2012-06-18 11:01:36 UTC
CMS
LHC Delivered: 6.65 fb-1
CMS Recorded: 6.15 fb-1
Total Integrated Luminosity (fb-1)
0
1
2
3
4
5
6
7
20/04
20/05
Date

Impressive Luminosity Race with an Amazing Finish!



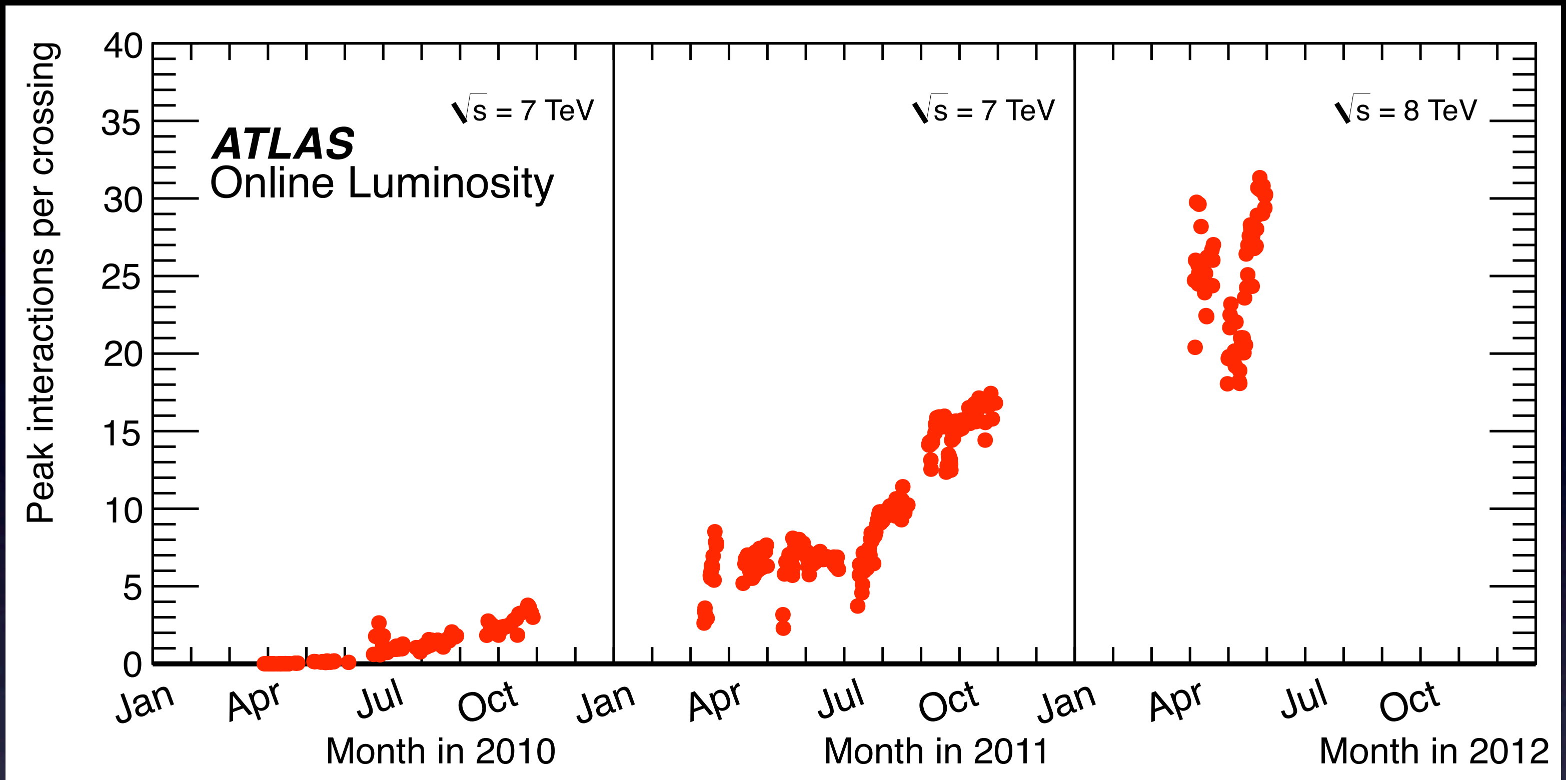
An extremely successful week 24

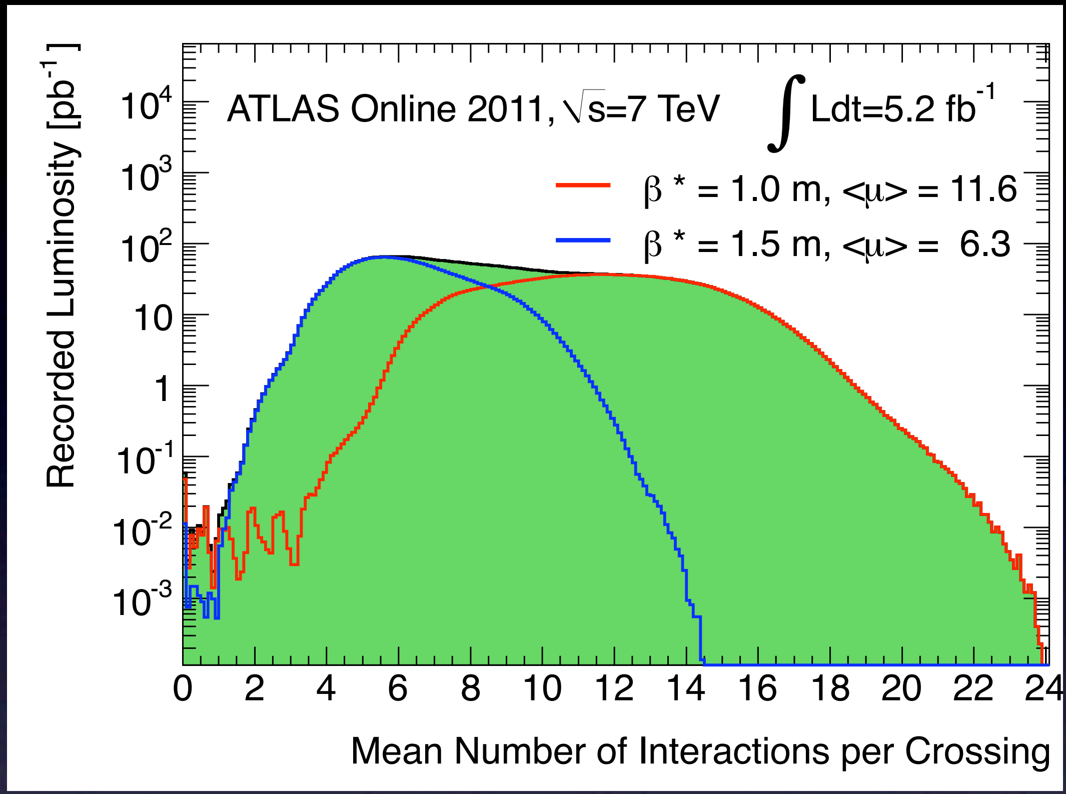
- Very stable operation with
  - ~6.5 e33
  - 1.5e11 ppb
- 1.33 fb-1 recorded in one week!!
- 51% of the time in stable beams
- Total 18.7% ‘down time’
  - MKI waiting for cool down: 13h40'
  - Injectors: 6h30'
  - Waiting for experiments: 3h28'

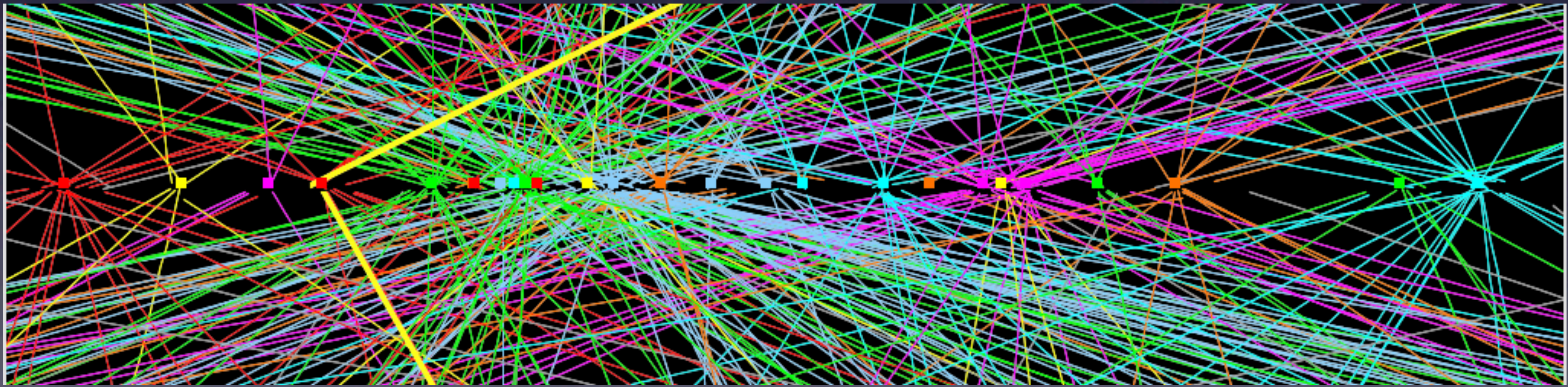


Peak Stable Luminosity Delivered	6.76×10^{33} cm^{-2}s^{-1}	Fill 2710	12/06/06, 15:52
Maximum Luminosity Delivered in one fill	237.32 pb^{-1}	Fill 2692	12/06/02, 01:55
Maximum Luminosity Delivered in one day	250.94 pb^{-1}	Saturday 16 June, 2012	
Maximum Luminosity Delivered in 7 days	1350.14 pb^{-1}	Sunday 10 June, 2012 - Saturday 16 June, 2012	
Maximum Colliding Bunches	1380	Fill 2660	12/05/24, 13:17
Maximum Peak Events per Bunch Crossing	43.81	Fill 2479	12/04/06, 10:22
Maximum Average Events per Bunch Crossing	31.87	Fill 2710	12/06/06, 15:52
Longest Time in Stable Beams for one fill	22.8 hours	Fill 2692	12/06/02, 05:10
Longest Time in Stable Beams for one day	20.5 hours (85.6%)	Saturday 02 June, 2012	
Longest Time in Stable Beams for 7 days	90.0 hours (53.6%)	Sunday 10 June, 2012 - Saturday 16 June, 2012	
Fastest Turnaround to Stable Beams	2.13 hours	Fill 2472	12/04/05, 15:46

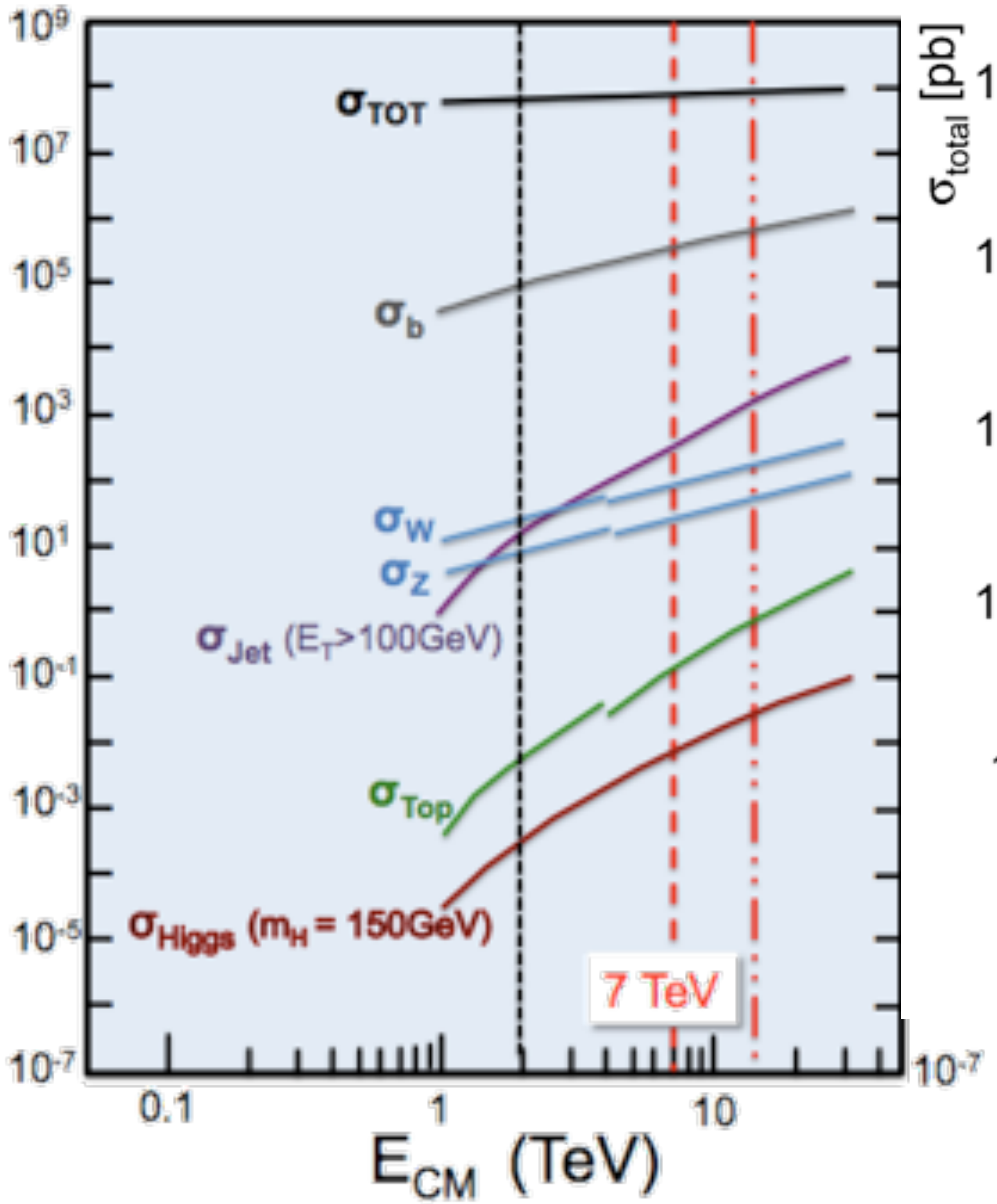
LHC Collision Conditions

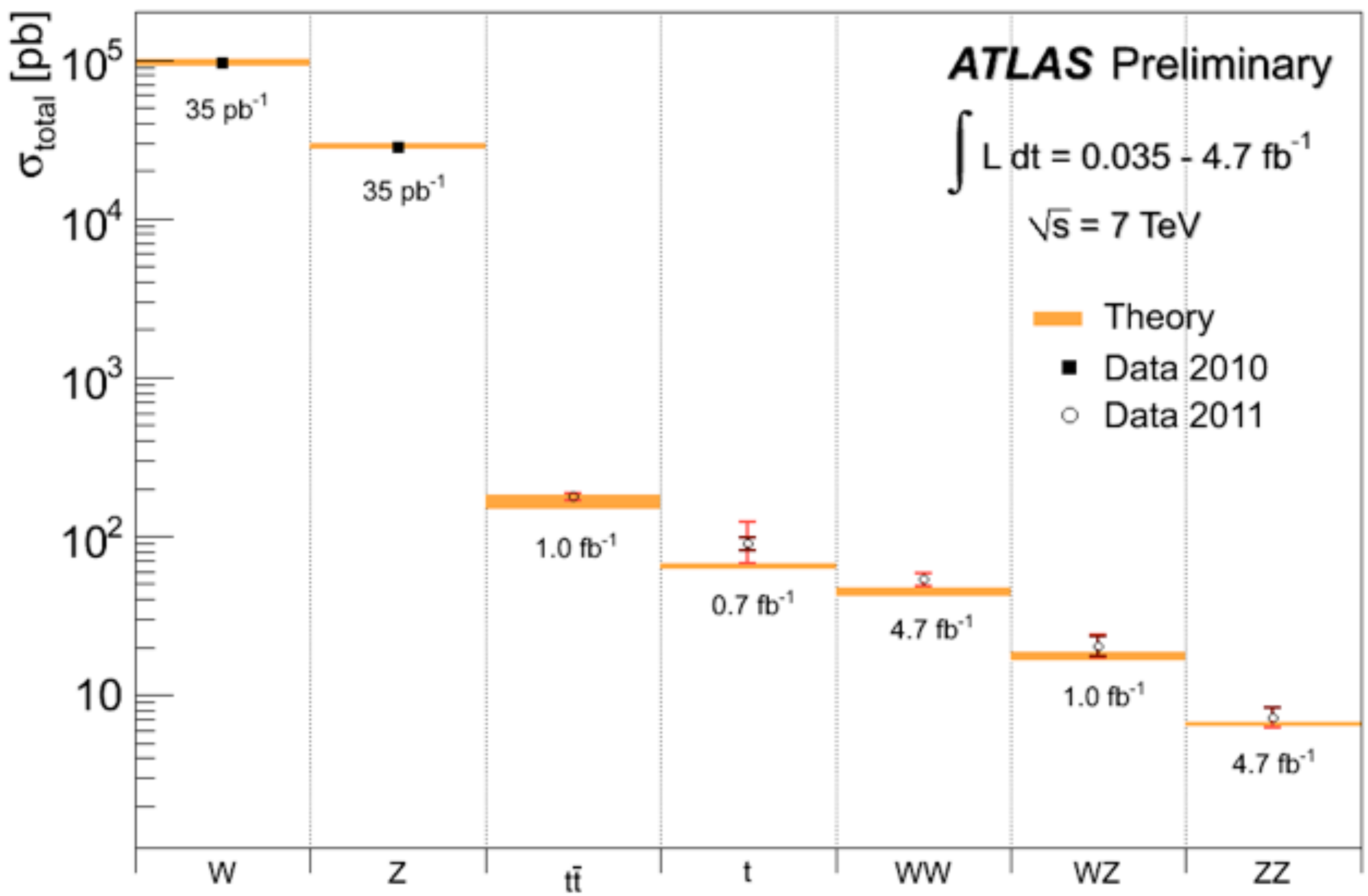




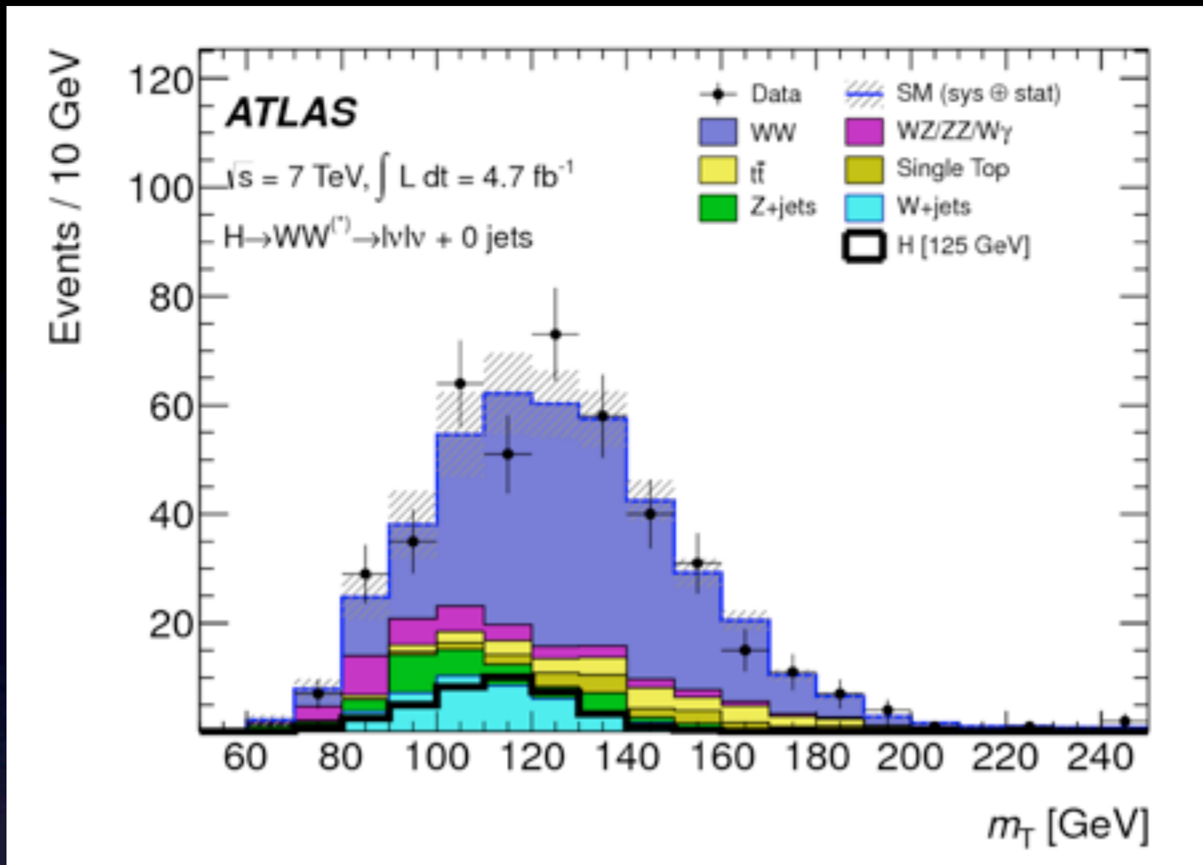


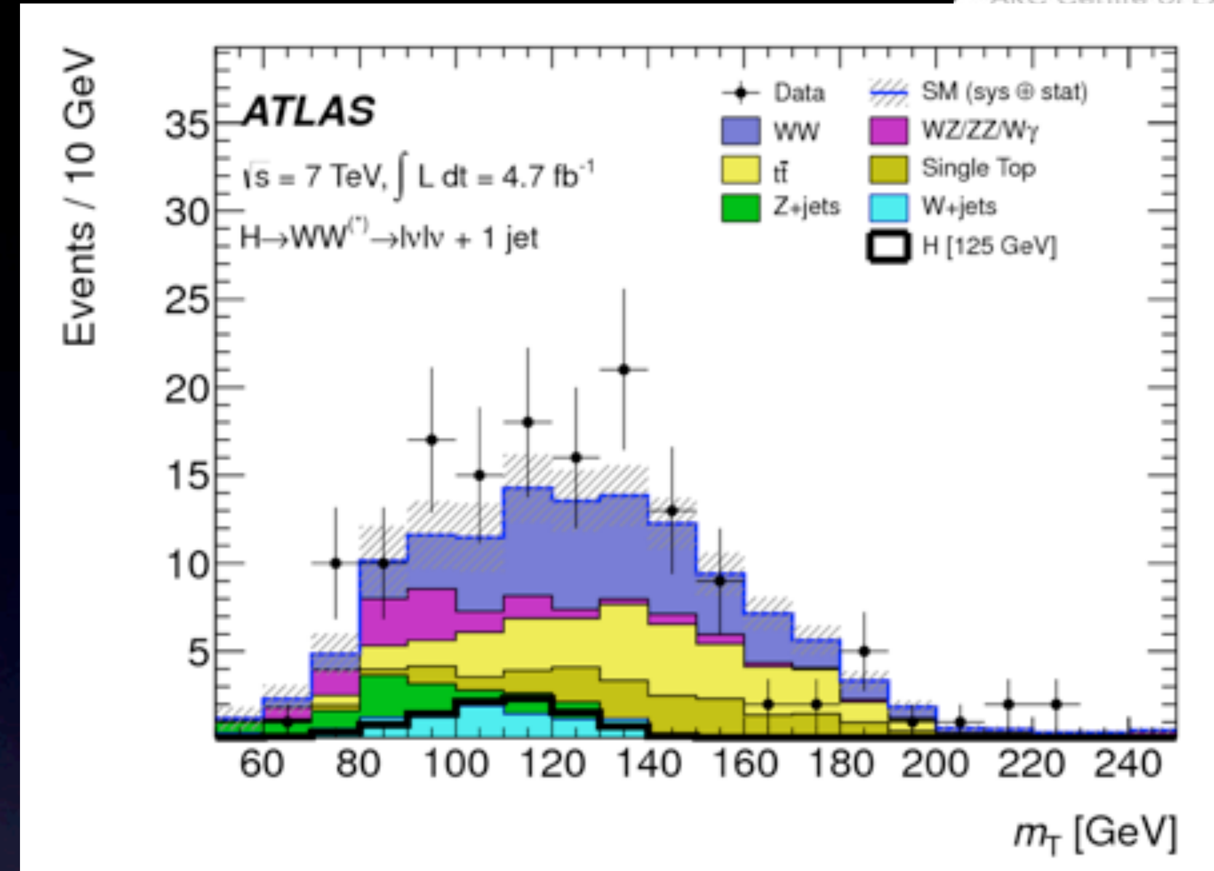
Re-discovery of the SM

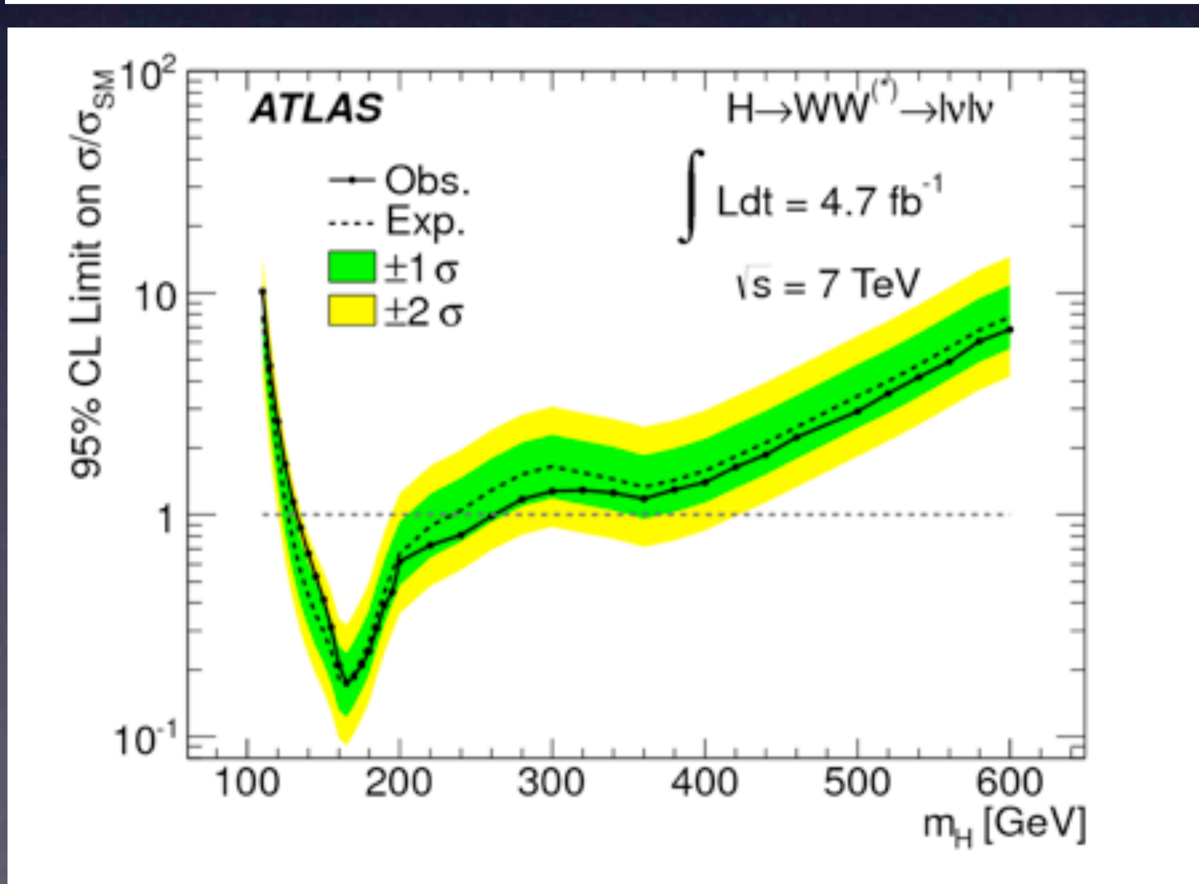


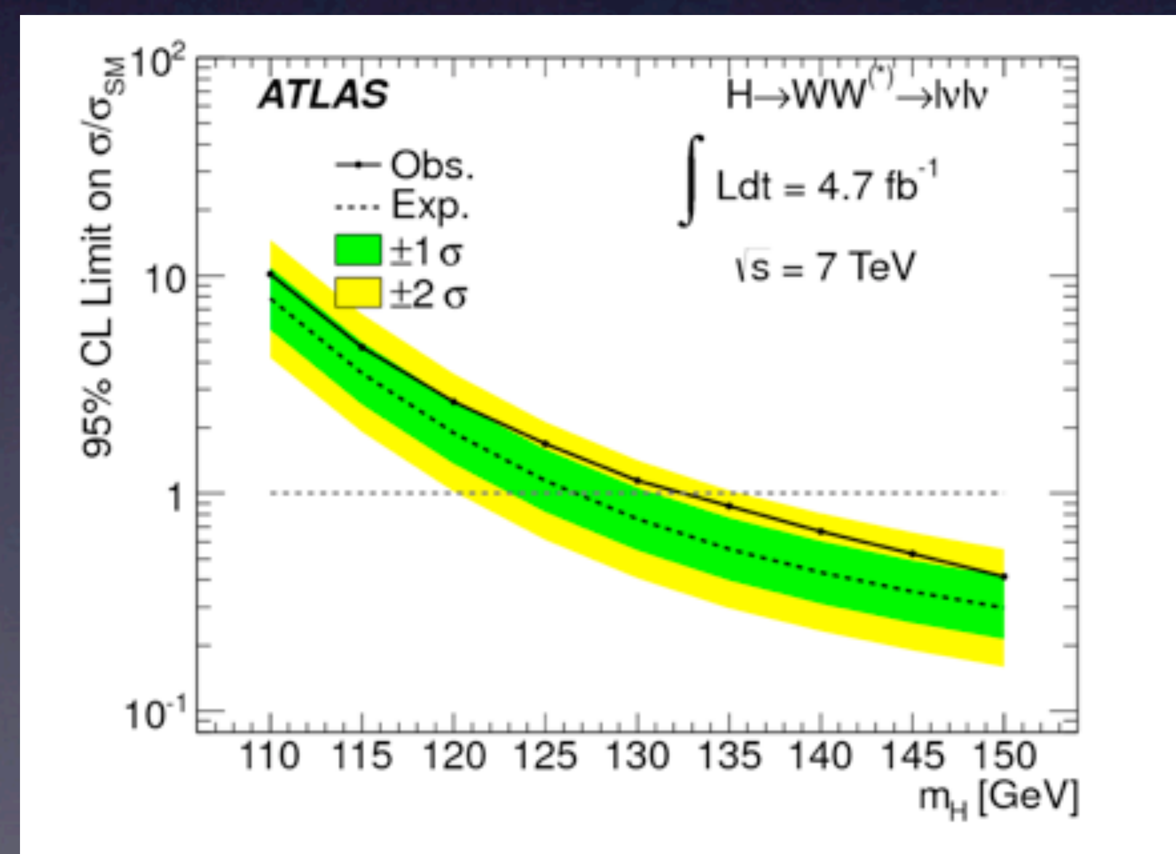


A Higgs Search (H->WW*) @ ATLAS





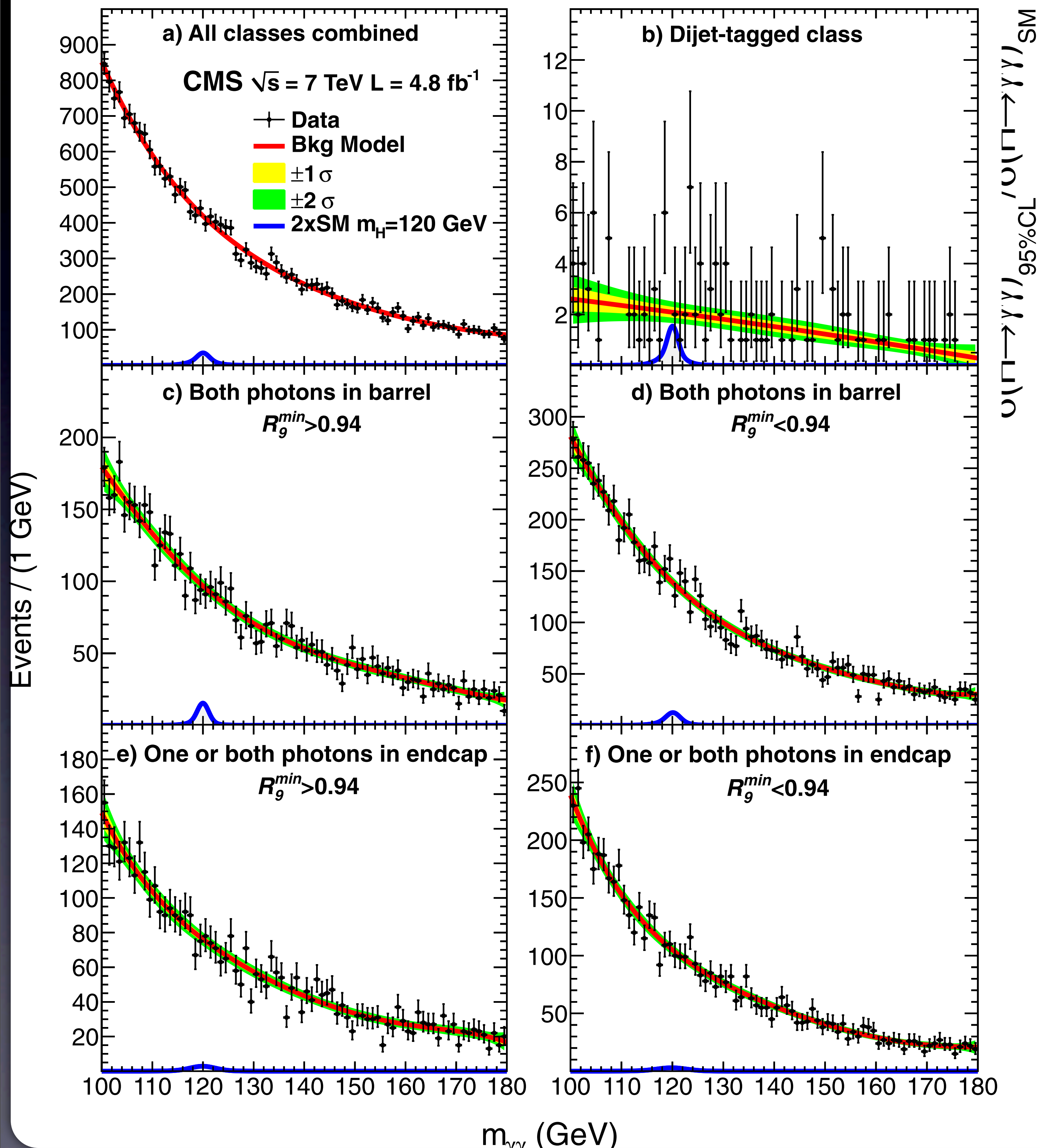


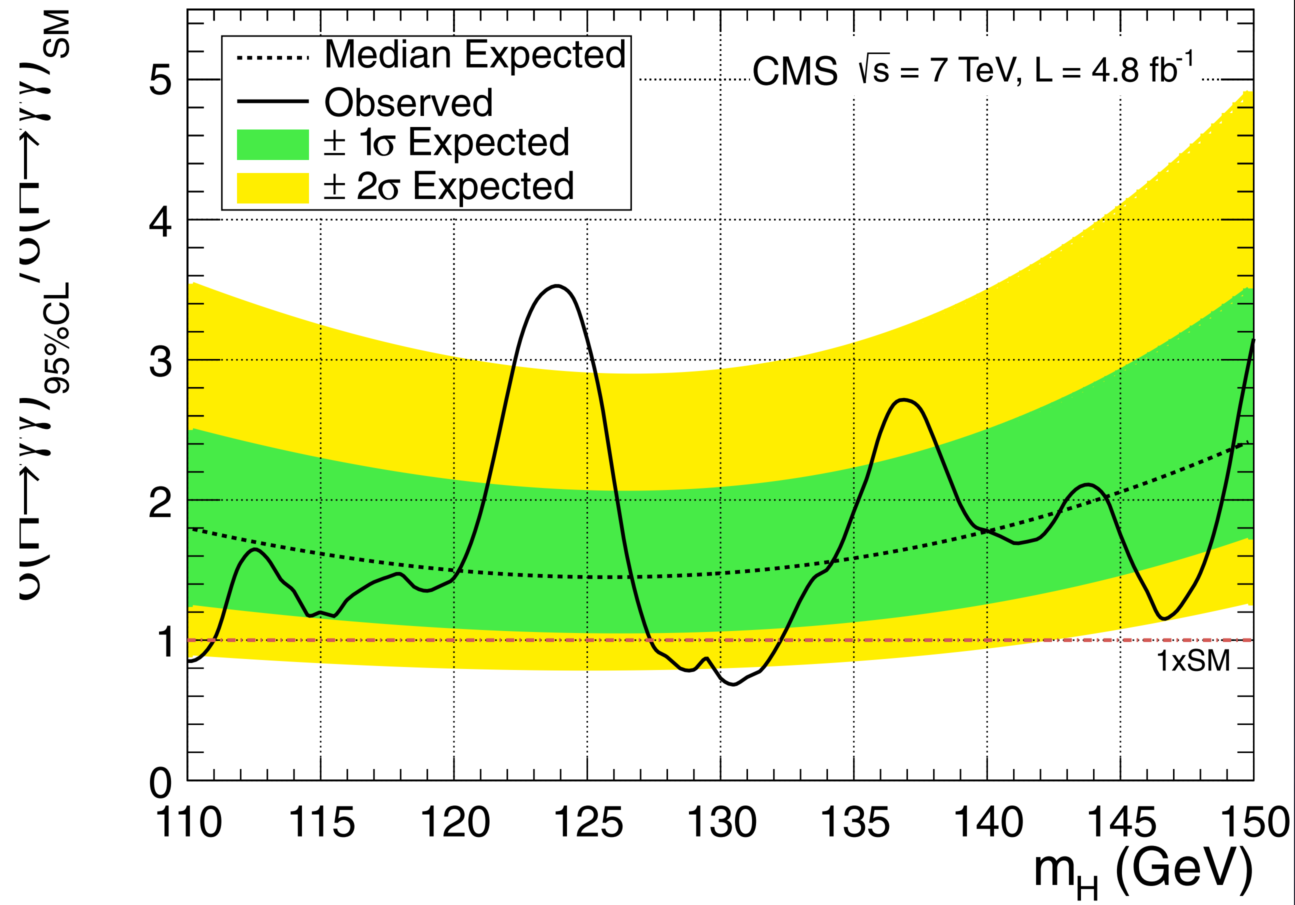


CERN-PH-EP-2012-126
e-Print: arXiv:1206.0756 [hep-ex]

A Higgs Search (H->γγ) @ CMS

ARC Centre of Excellence for Particle Physics at the Terascale





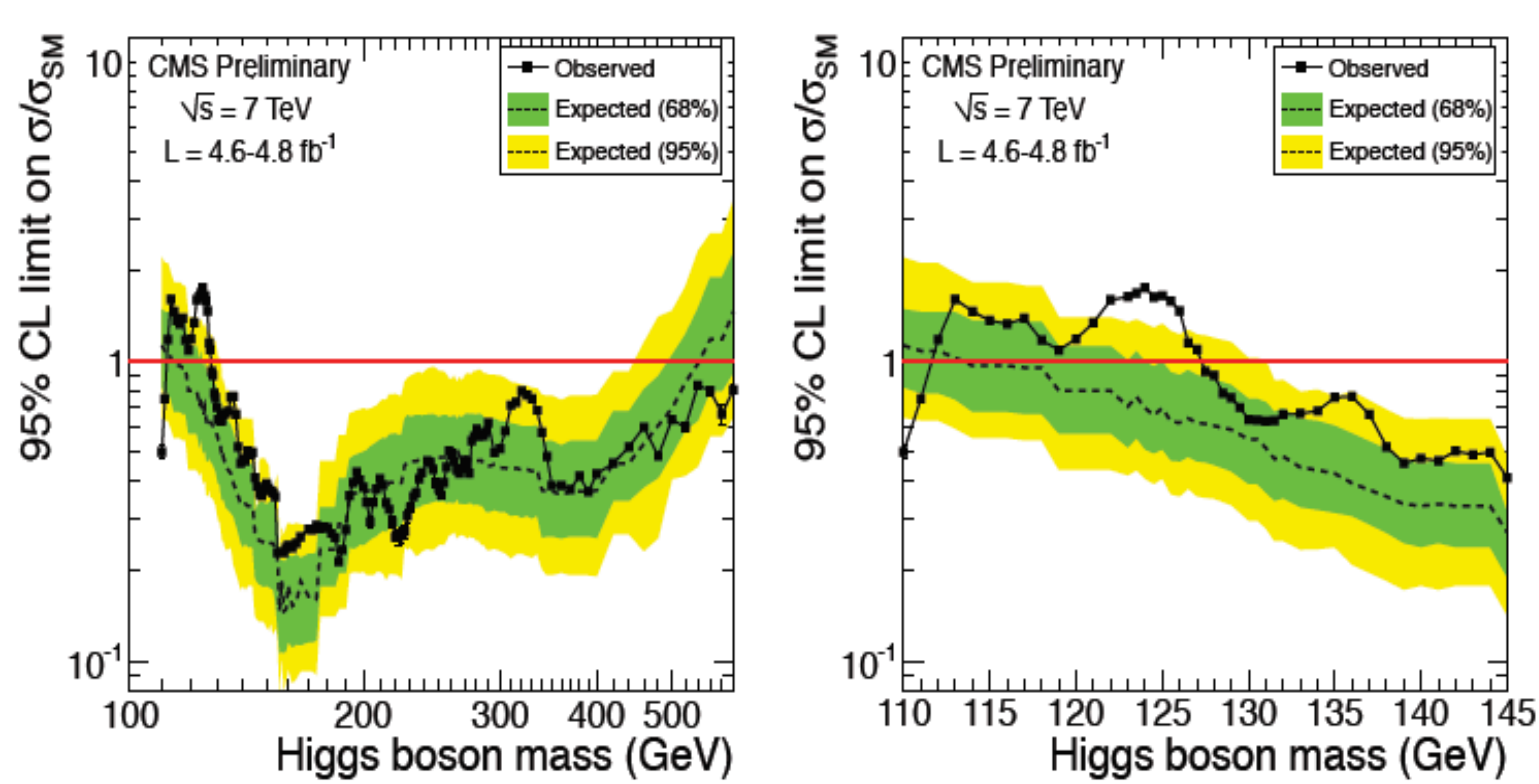
Phys. Lett. B 710 (2012) 403-425

Discovery?

- Finding the Higgs is a discovery!
- Not finding the SM Higgs is a discovery!

- LHC will elucidate spontaneous symmetry breaking. How do the W and Z get their mass? Let alone all other elementary particles?

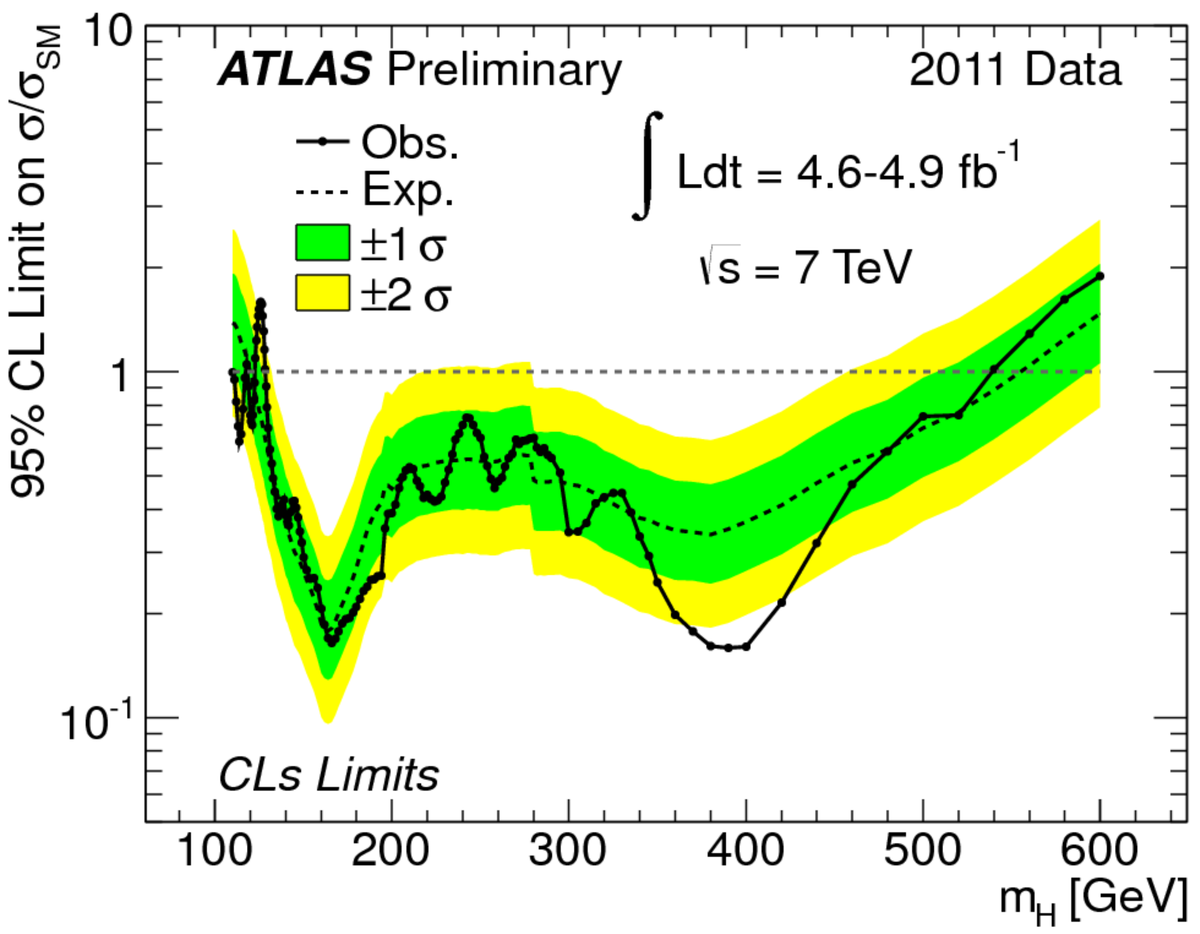
Higgs Search Limits

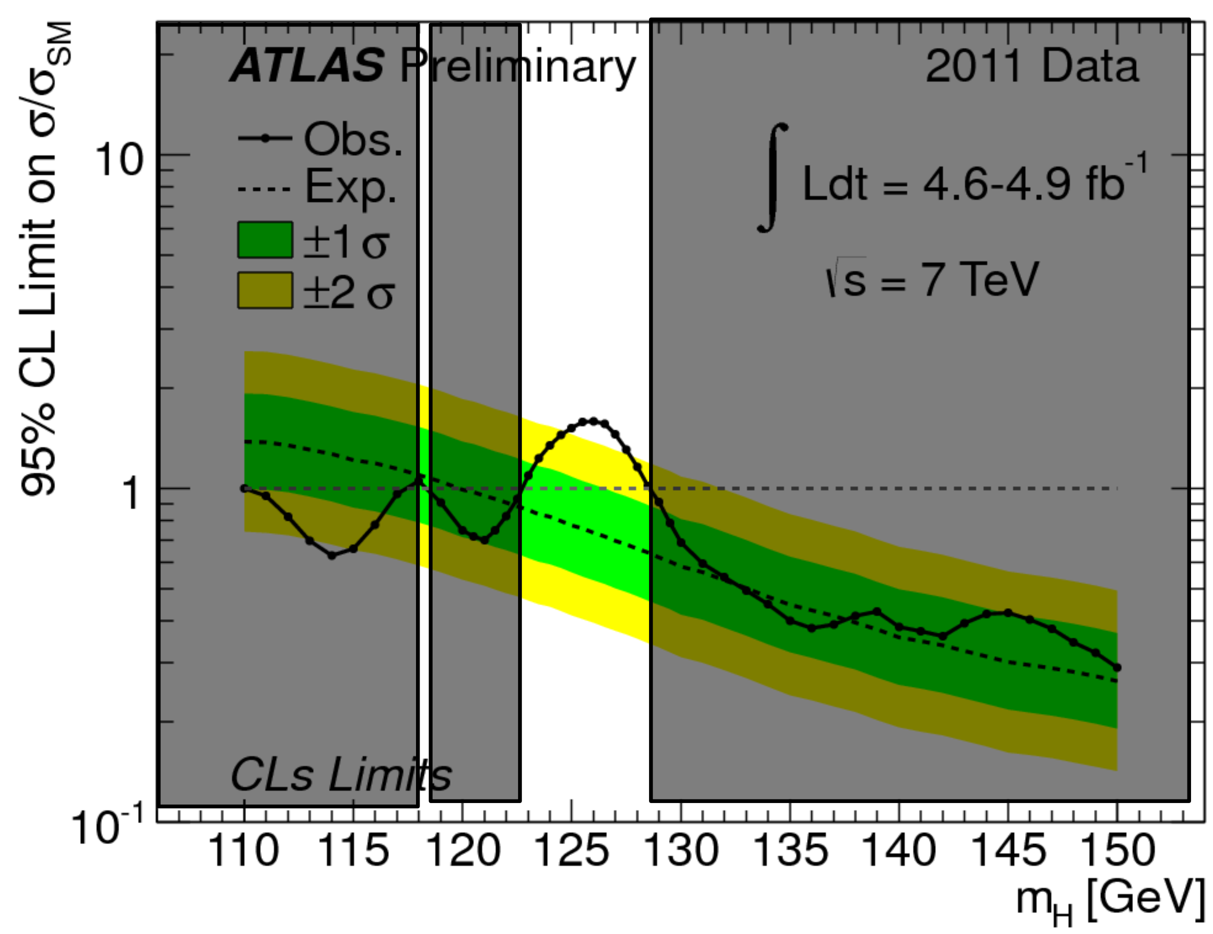


It took ~30 years to experimentally restrict the SM Higgs mass to be above 114 GeV
CMS and ATLAS independently eliminated another ~475 GeV of the range in 2011

"Expected" exclusion 114.5 - 543 GeV
Observed exclusion 127.5 - 600 GeV

Higgs Search Limits: ATLAS





Excluded at 95% CL

Expected if no signal
120-555 GeV

110 < mH < 122.5 GeV (except 117.5-118.5)
129 < mH < 539 GeV

One window left open?
Have a new peak at ICHEP 2012

A standard model Higgs?

- Is the particle we are calling a Higgs, a real Higgs? A real Higgs would decay to WW* much more often than it decays to γγ
- Decay to two photons proceeds via indirect decay. If it happens more often than expected
  - Higgs couplings to top and W don't match prediction OR
  - Unknown heavy particles are mediating the decay
- Must proceed to measure decays to fermions: leptons and quarks ($H \rightarrow \tau\tau$ & $H \rightarrow bb$)

Retrospective

- In 2008 ATLAS performed studies involving state of the art simulations in a rigorous effort to prepare for the start of data taking at the LHC
- Culminated in a ~1850 page document it reported what was expected to be searched for or measured and to what exclusion or precision at collision energy of 14 TeV
  - (arXiv:0901.0512 - citations > 700)
- In 2012 we can look back and measure our progress with respect to expectation
  - (Higgs is the best case study)

Higgs Expectations @ 14 TeV

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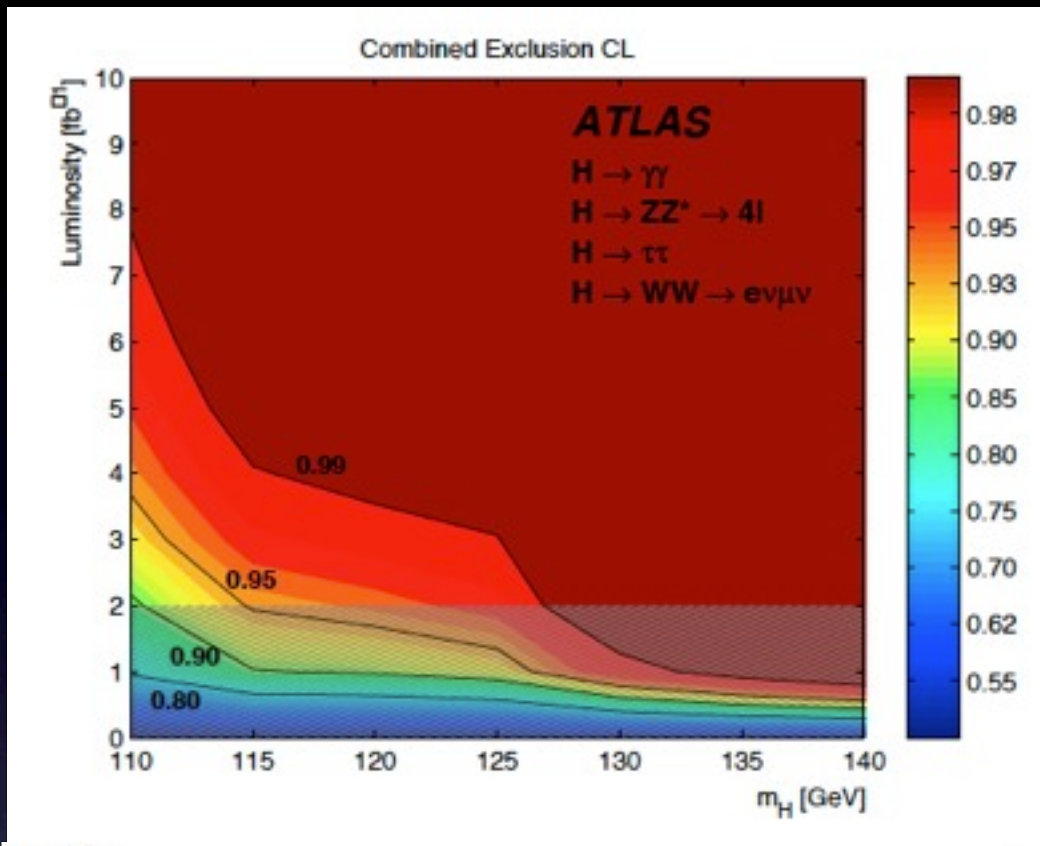
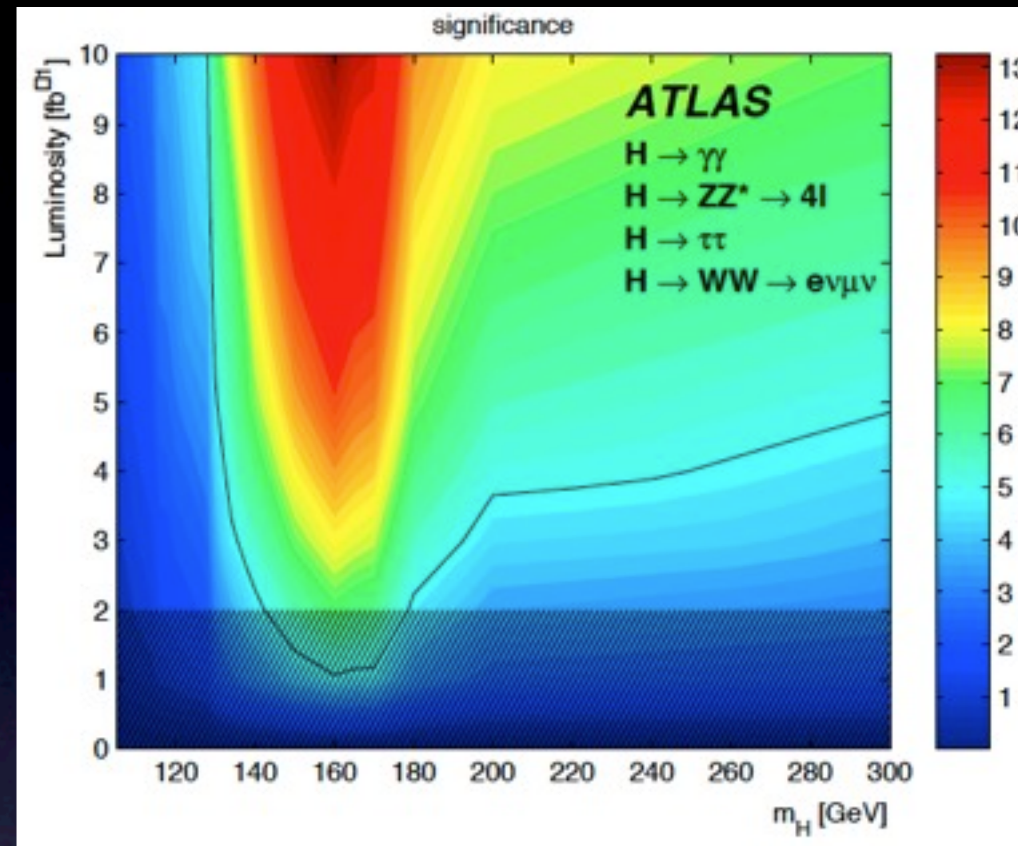
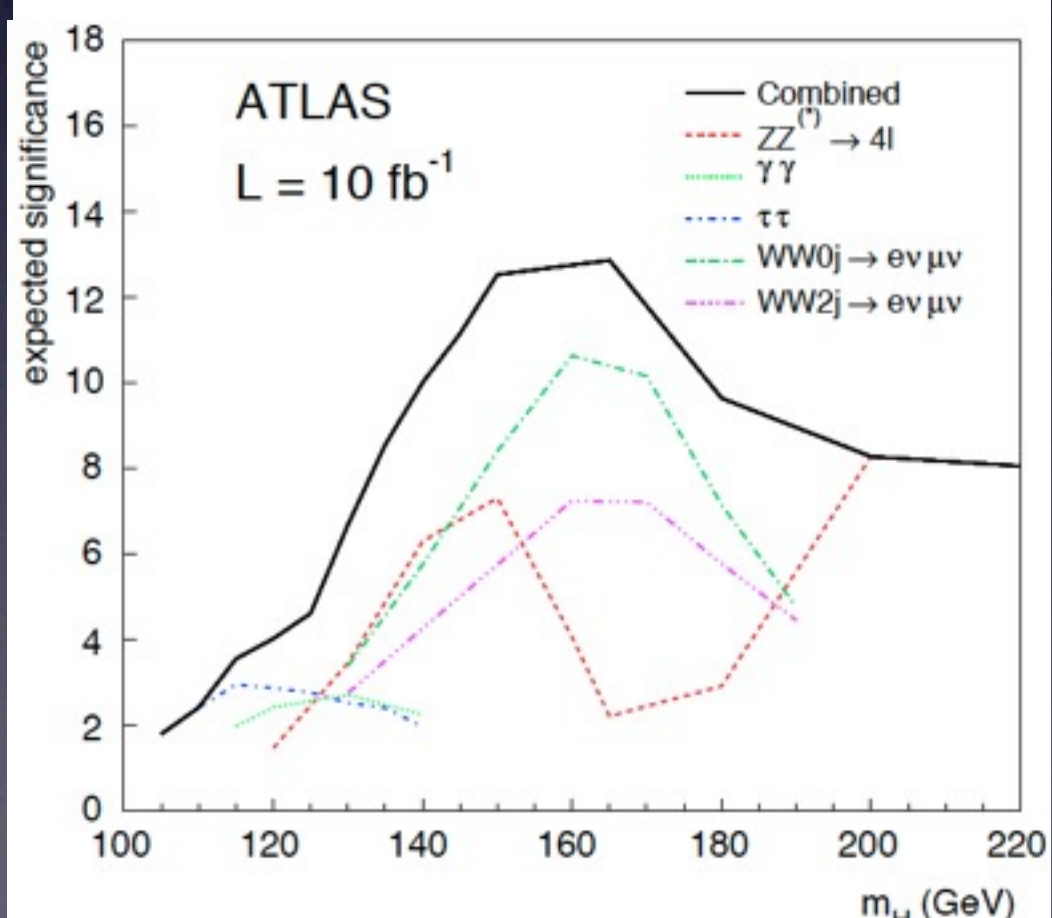


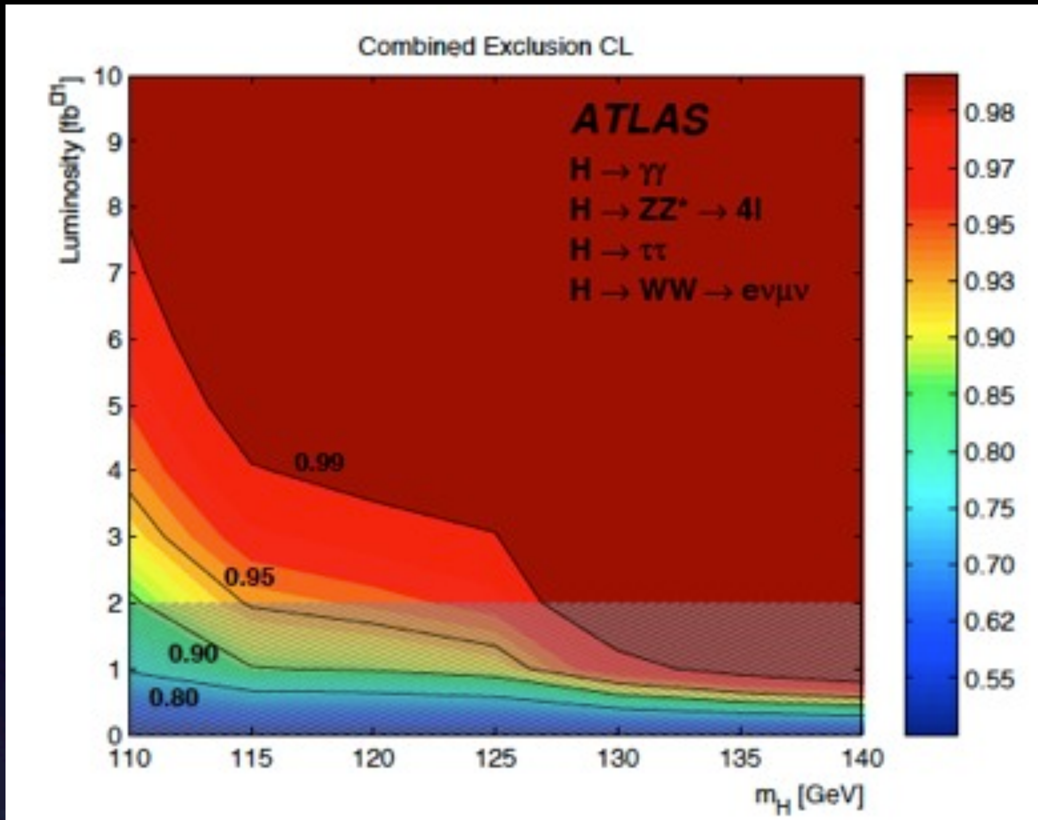


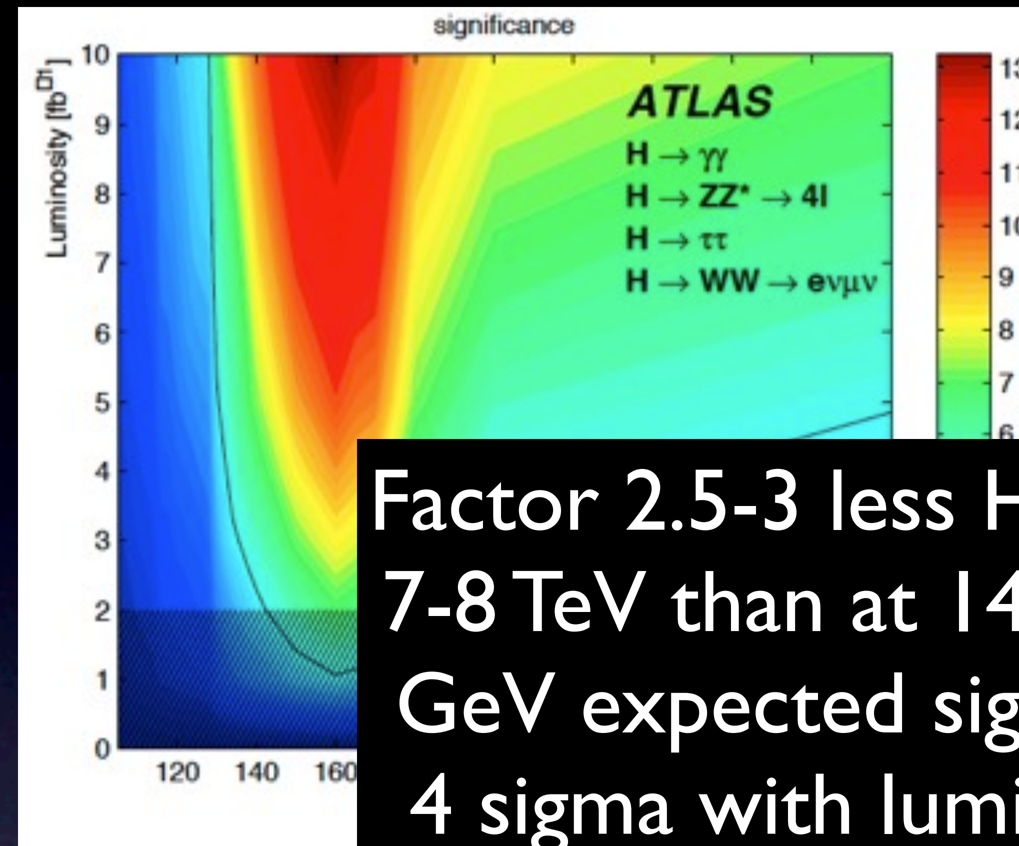


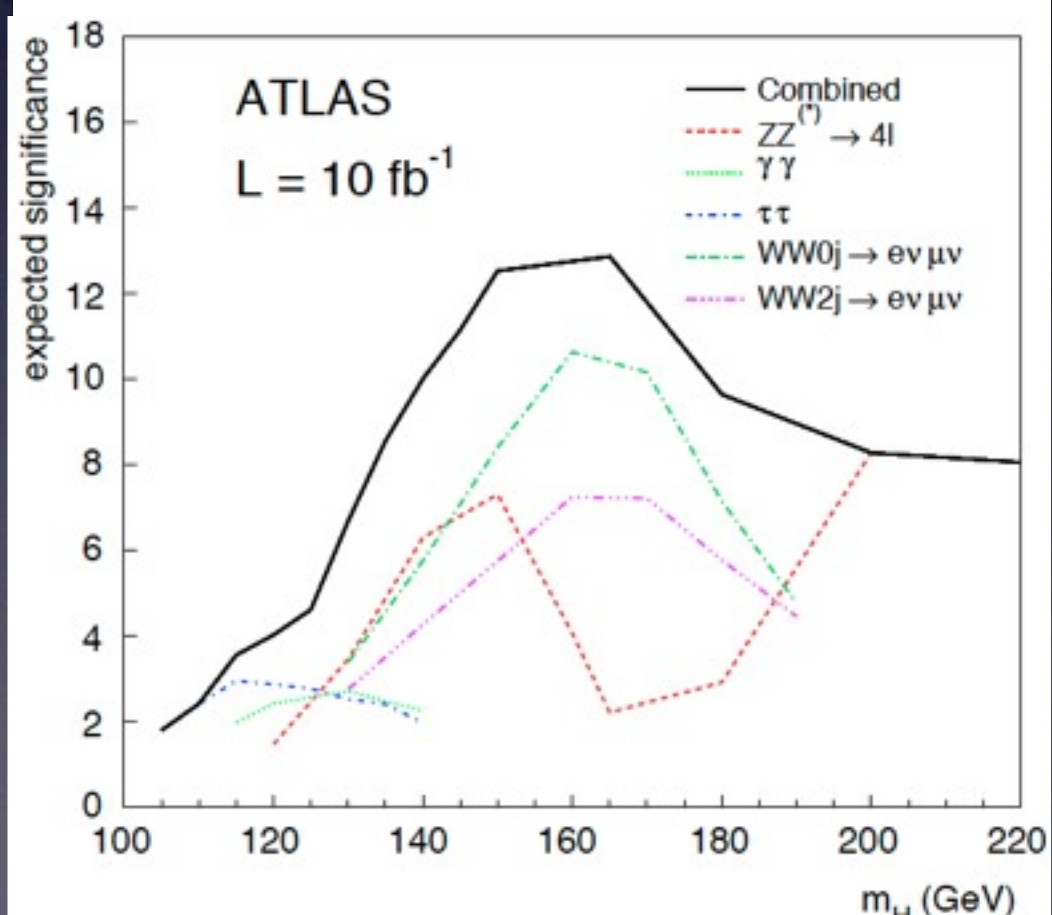
$\sqrt{s}$ (TeV)	σ(gg→H) (pb) m(H) = 125 GeV
7	15
8	20
14	50

Higgs Expectations @ 14 TeV

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale





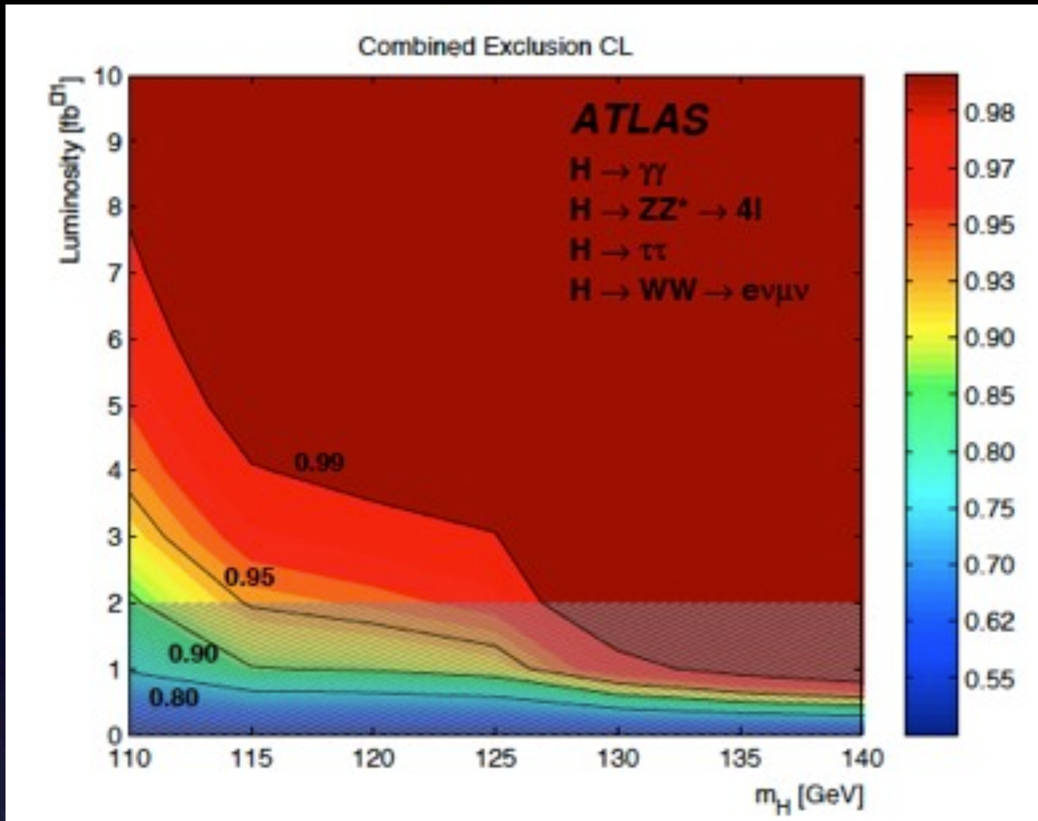


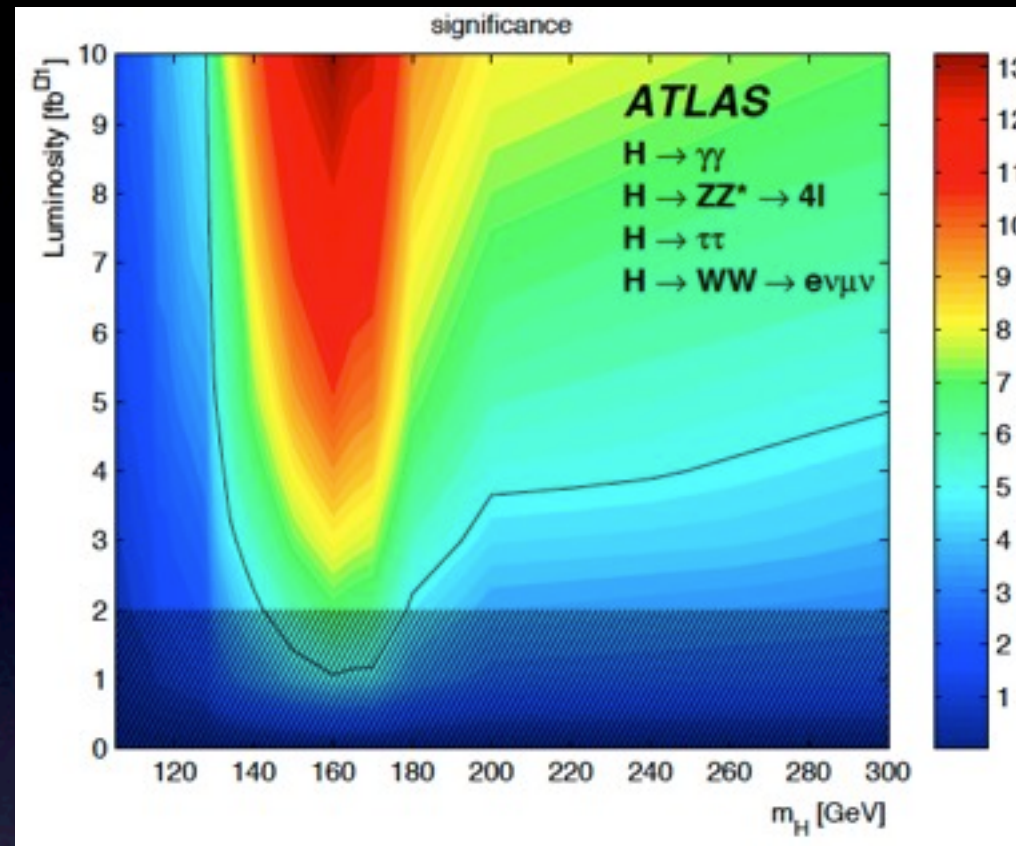
Factor 2.5-3 less Higgs events at 7-8 TeV than at 14 TeV - at 125 GeV expected significance was 4 sigma with luminosity of 10/fb.

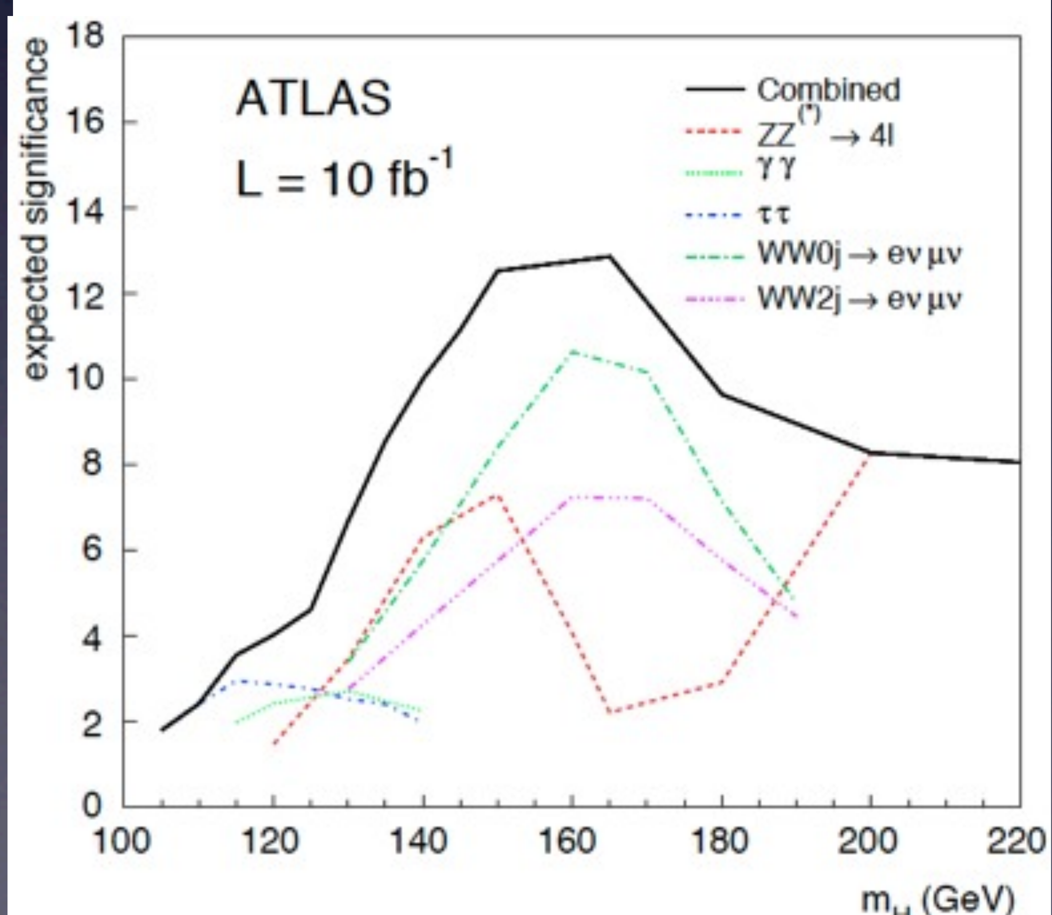
With ~15/fb at 7-8 TeV, the significance is greater than 5 sigma. Basically in three years of data-taking analyses have improved by a factor of 2. Remarkable achievement!

√s (TeV	
7	
8	
14	

Higgs Expectations @ 14 TeV







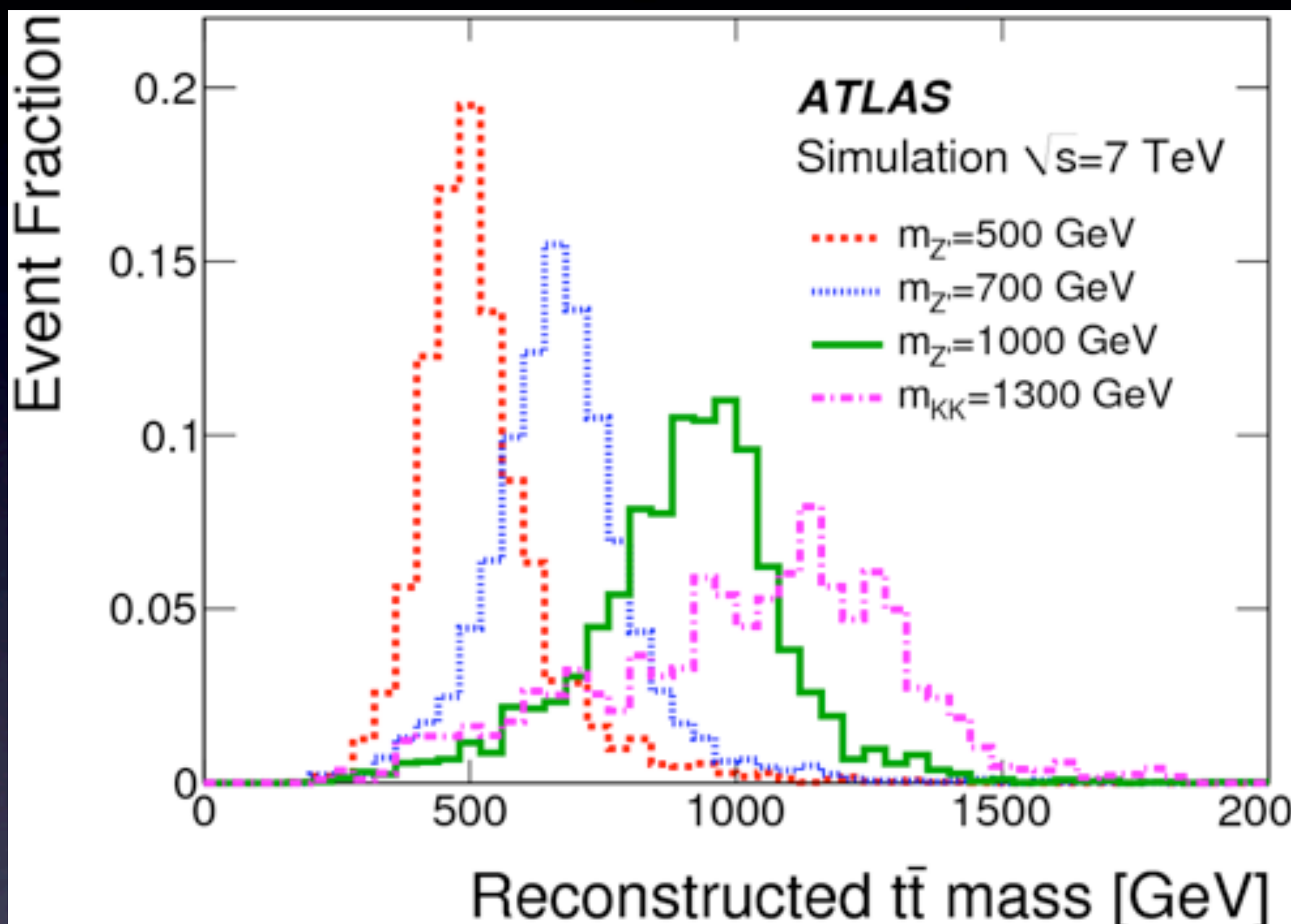
√s (TeV)	σ(gg→H) (pb) m(H) = 125 GeV
7	15
8	20
14	50

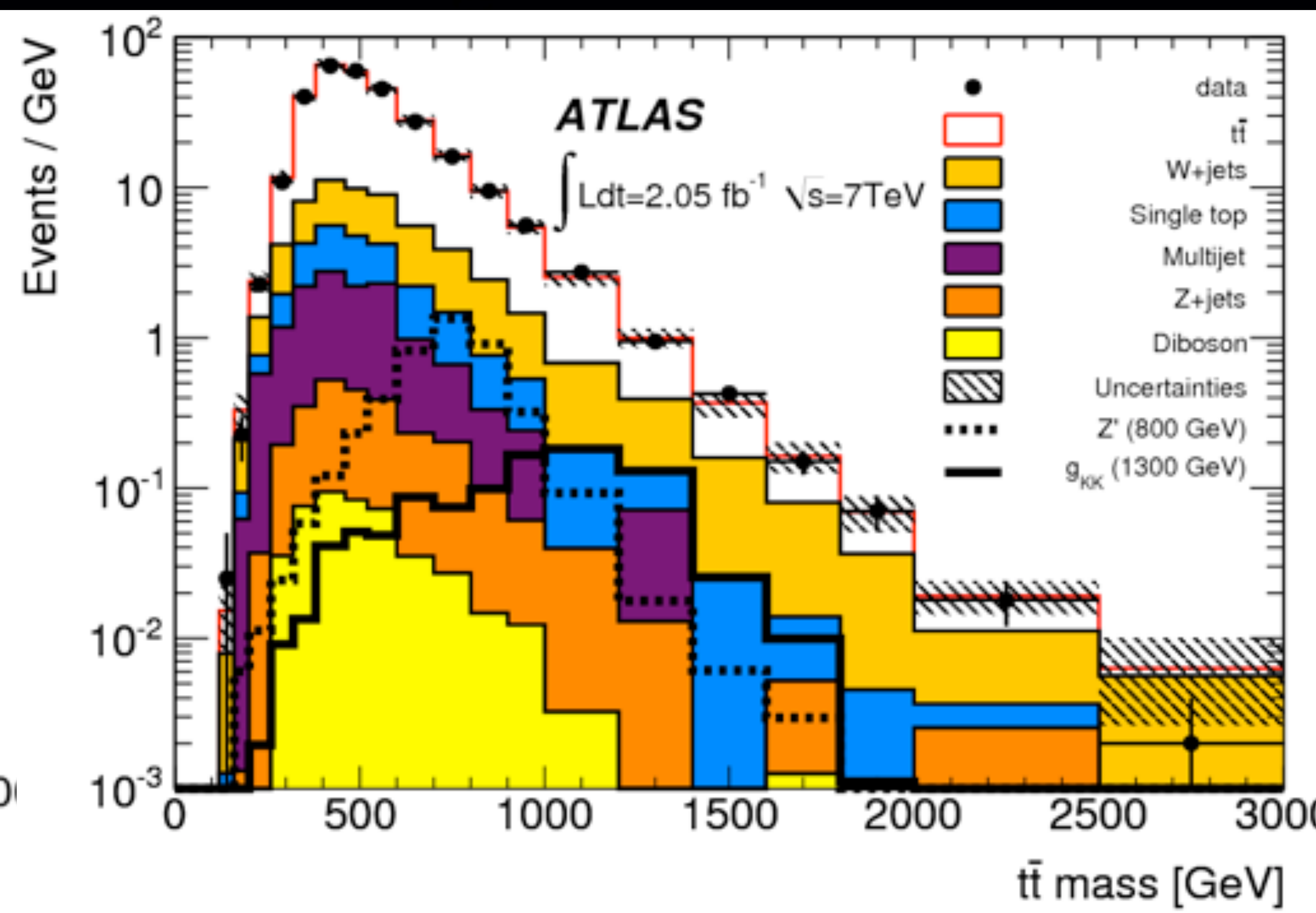
Physics Beyond the SM

- Has the LHC ...
  - made dark matter?
  - made weird heavy particles? Black holes?
  - found sources of CP asymmetry that help bridge the gap between the minuscule amount in the SM and that observed in the Universe
- No evidence for any of it yet, but as David Gross said at EPS2011 “we’re only at the beginning of a long journey”. We expect to accumulate 100 times more data, so let’s be optimistic.

Particles decaying to Top

Kaluza-Klein gluon excitation in the Randall-Sundrum model



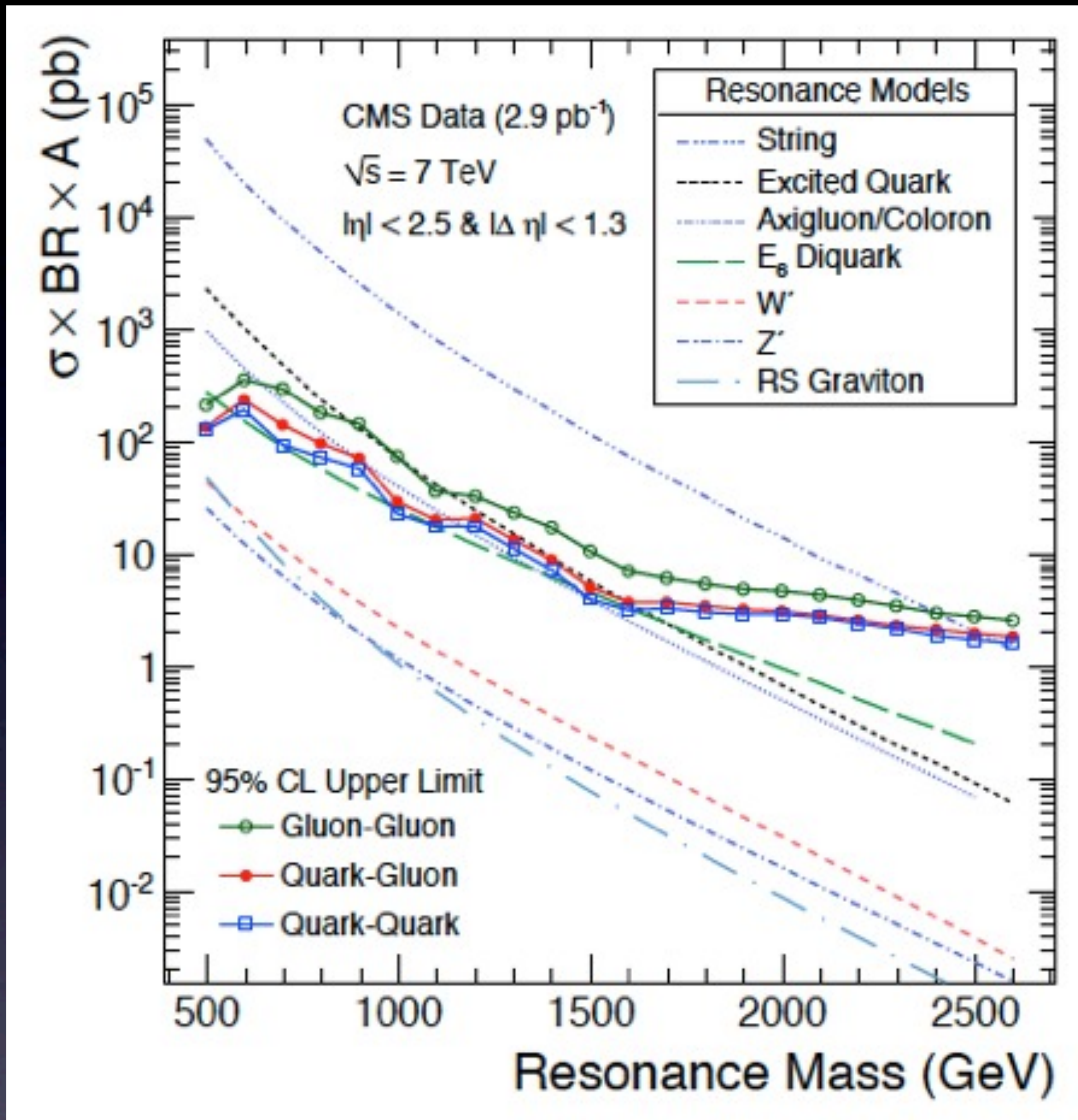


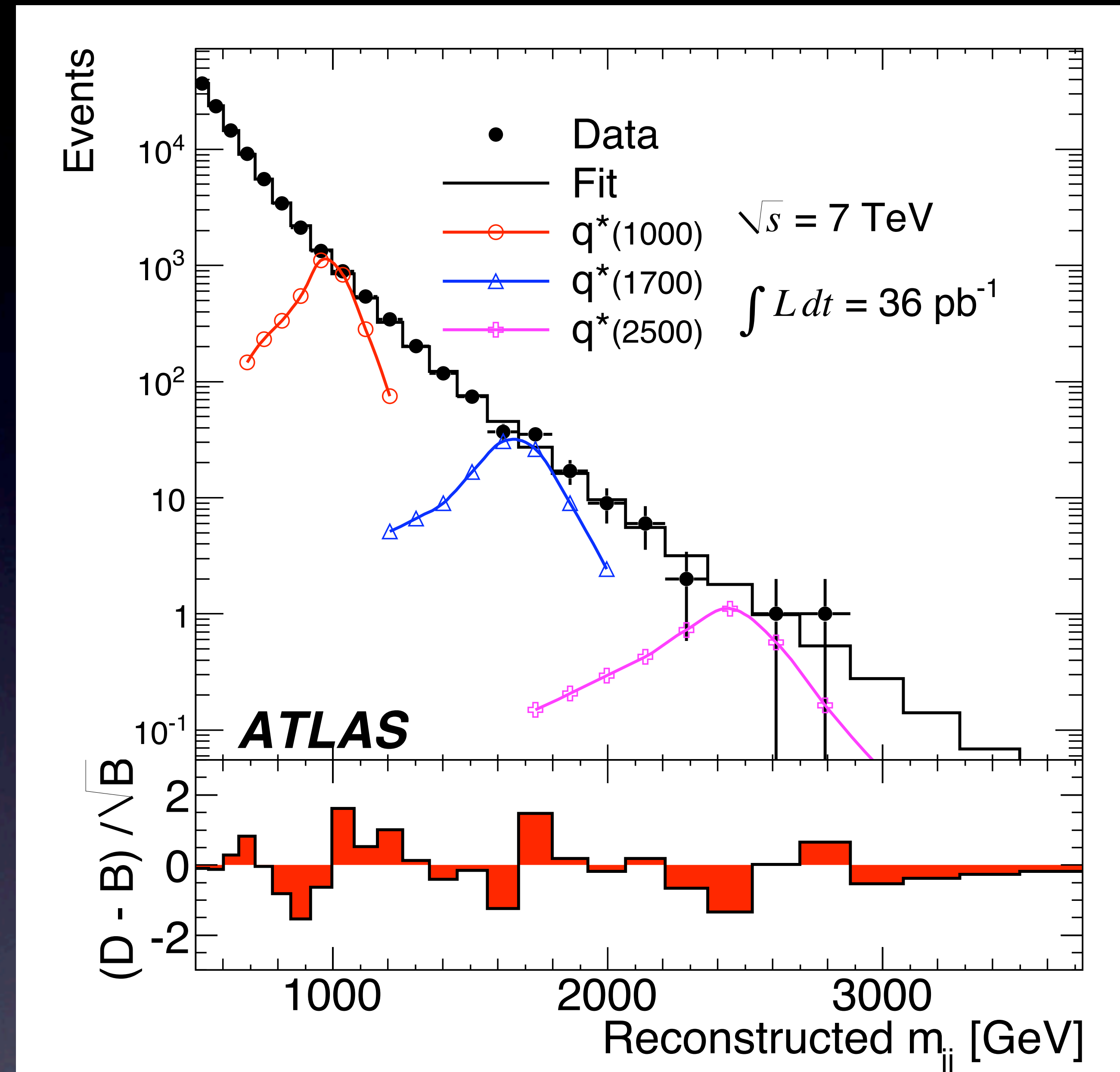
For narrow Z's, 95%CL limits range from 9.3-0.95 pb in the range m_Z' = 500 GeV -1300 GeV.

The excluded mass region for a leptophobic topcolour Z' boson (Kaluza-Klein gluon excitation in the Randall-Sundrum model): m_Z' < 880 GeV (m_{g_KK} < 1130 GeV).

CERN-PH-EP-2012-122
e-Print: arXiv:1205.5371 [hep-ex]

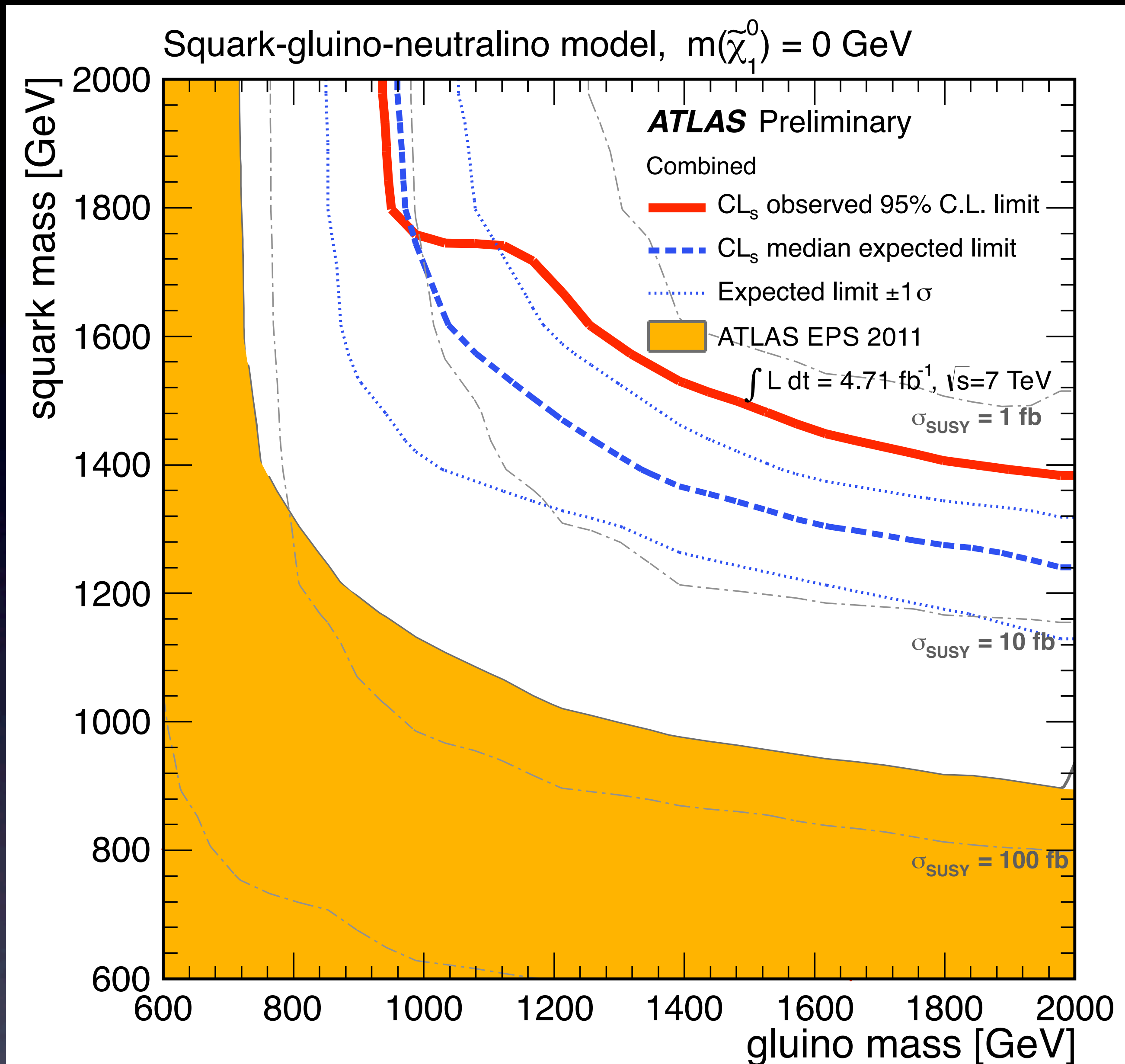
Di-jet Resonance Searches

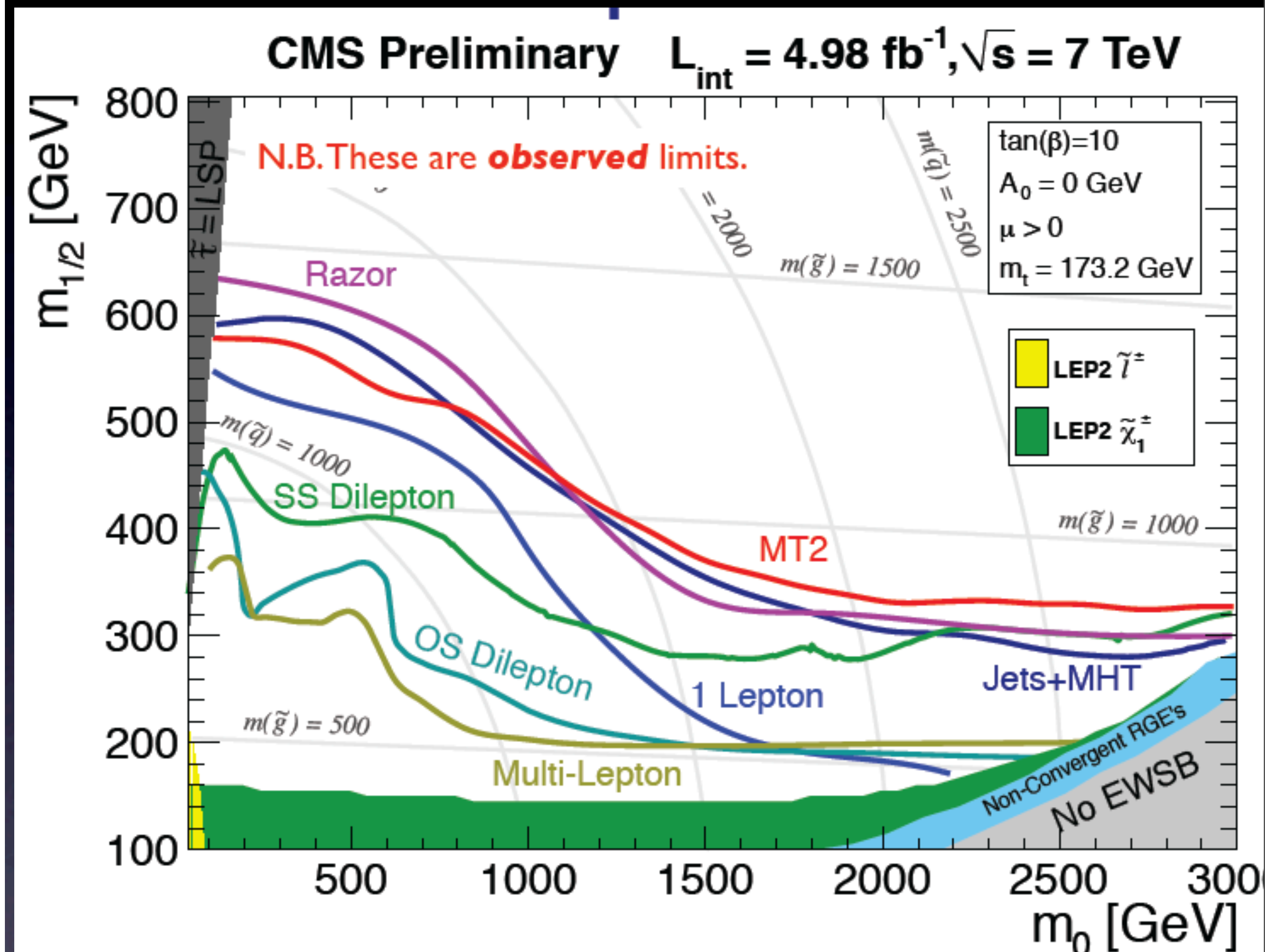




- Test of QCD & Large sensitivity to new physics
- Resonances decaying into two quarks or gluons, excited quarks
- ATLAS 36/pb. Exclude 95% C.L. 0.60 < m(q*) < 2.64 TeV. CMS similar analysis with 2.9/pb

SUSY constraints

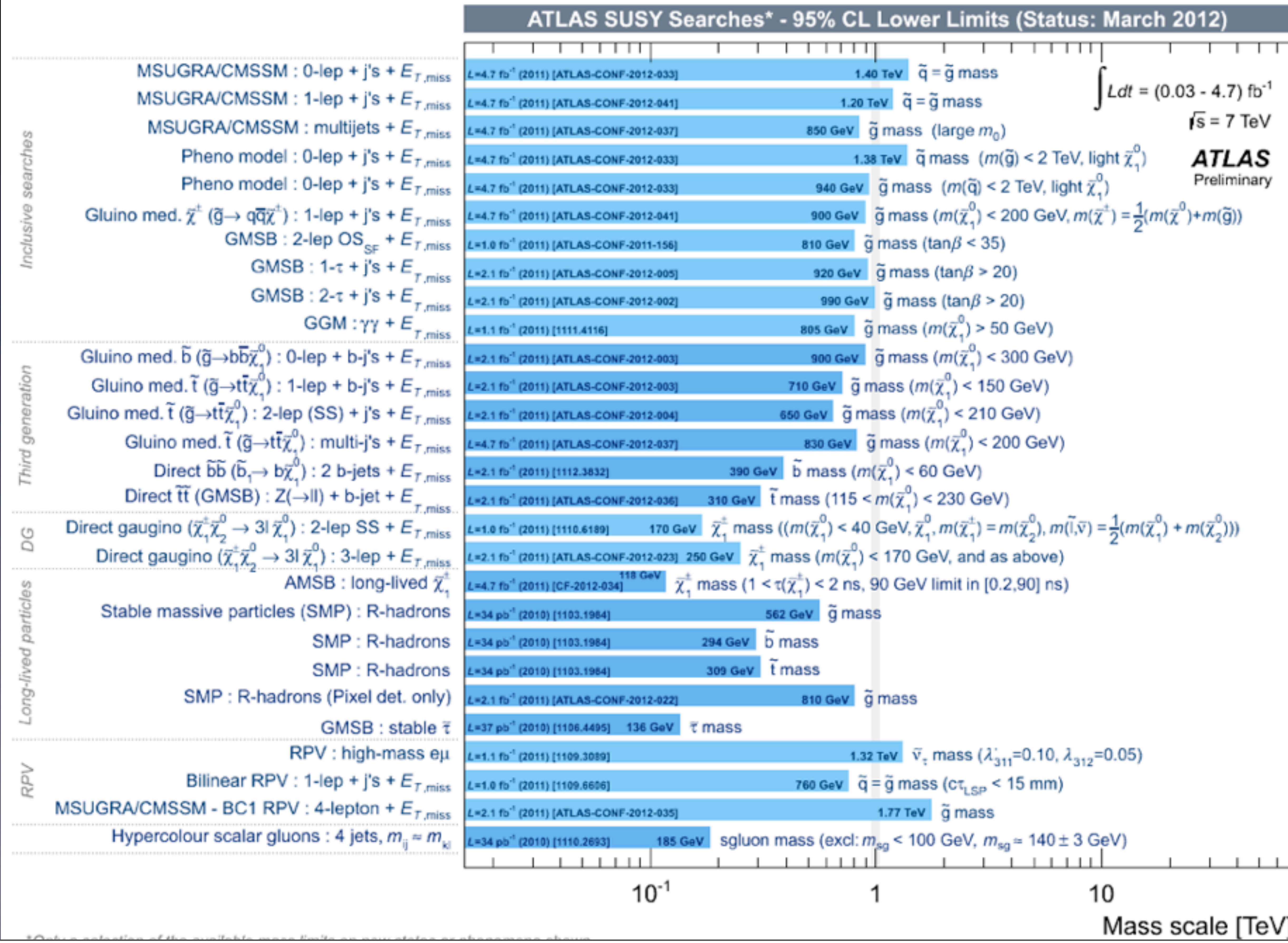




0-lepton jet+MET channels most sensitive to gluino and squark production (Simplified Model - assumes only squarks gluino & LSP)

Changing neutralino mass and allowing for richer SUSY particle content weakens constraints (more room to search)

ATLAS Mass Reach for SUSY



ATLAS Mass Reach for Exotics

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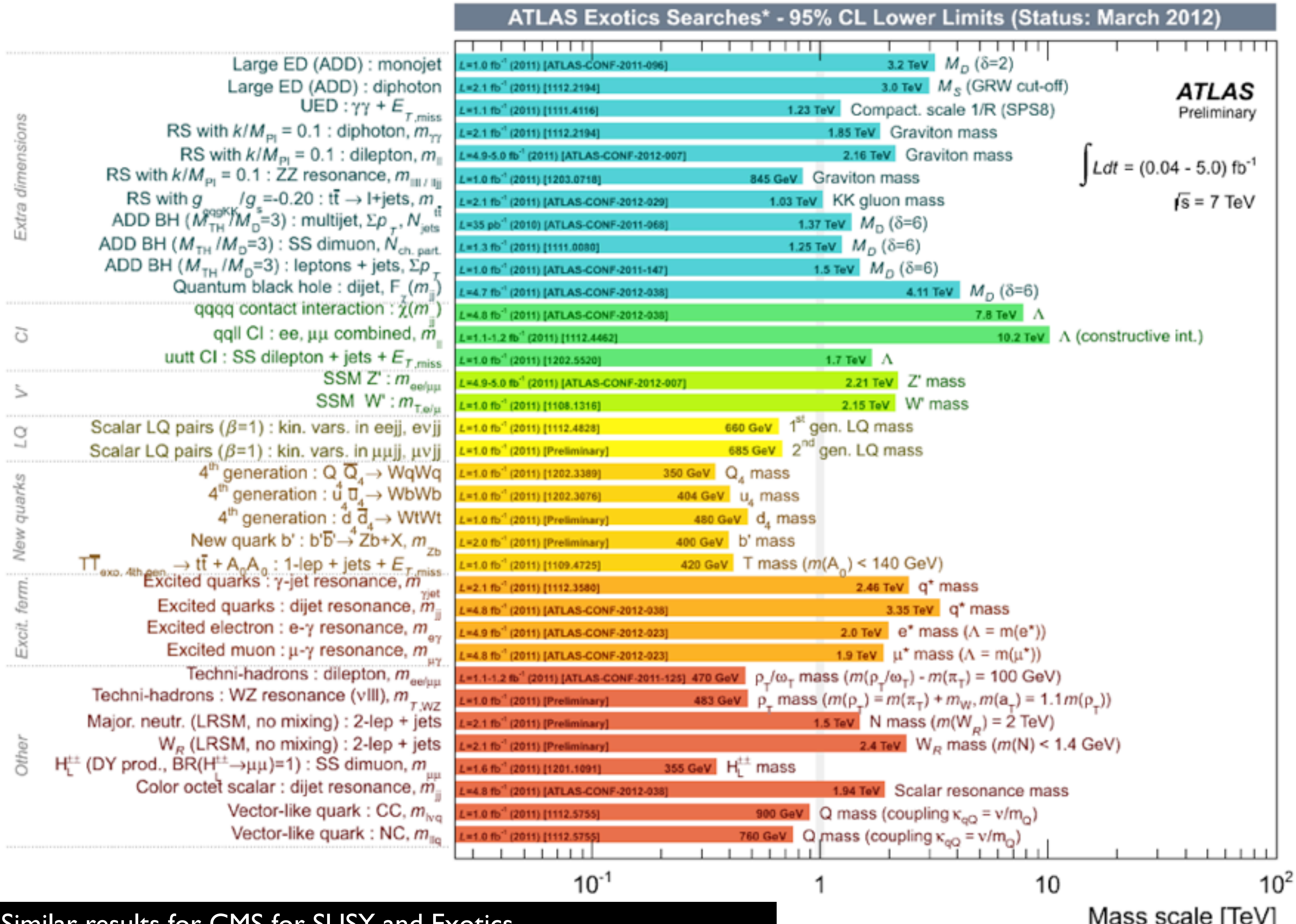


Similar results for CMS for SUSY and Exotics
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

Is SUSY beyond reach?

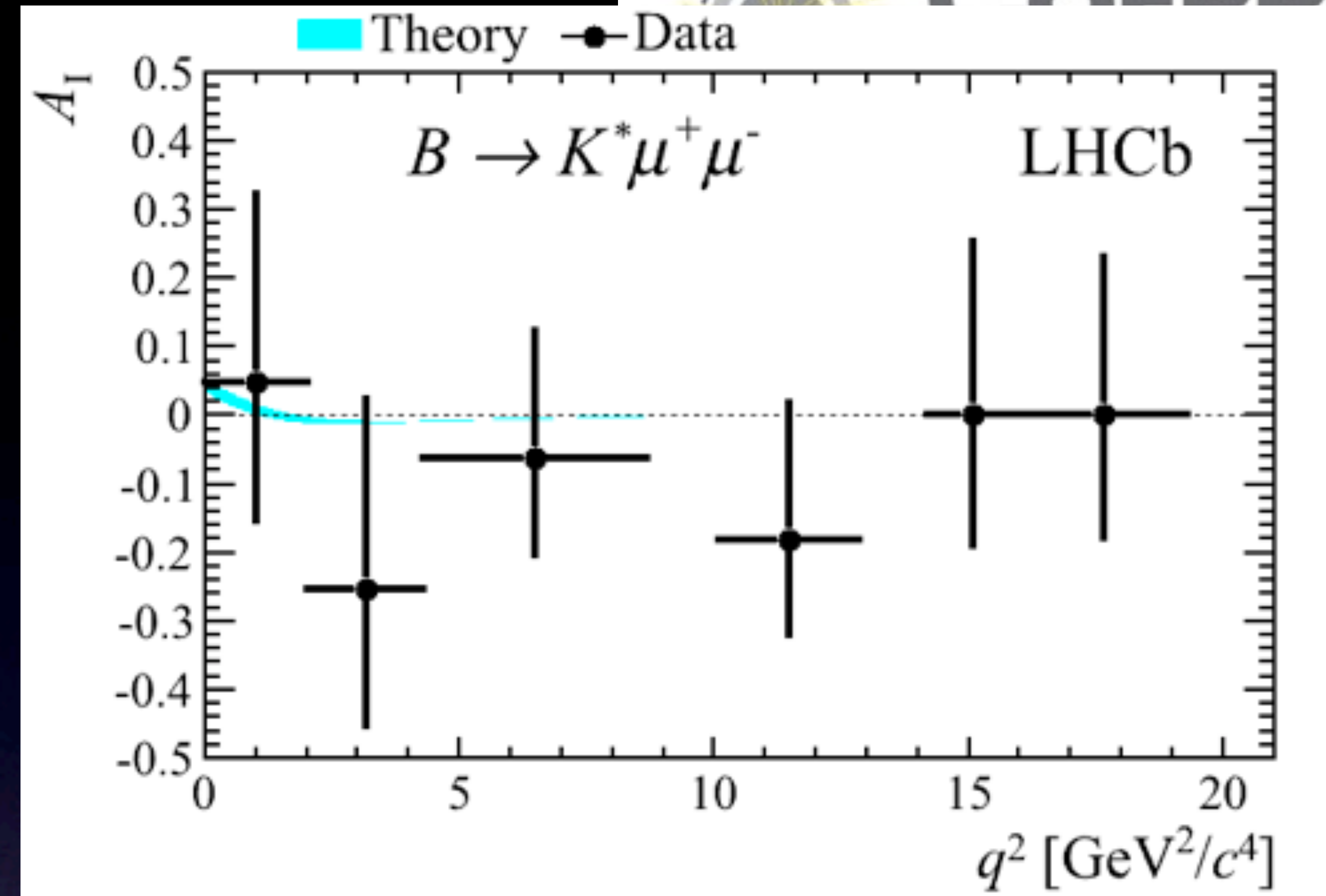
- Pre-LHC : SUSY predicted particles at the Terascale
- Today : SUSY is directly being pushed beyond the Terascale > 1 TeV
- Precision flavor physics e.g LHCb (Belle, Babar elsewhere) > 10 TeV
- Naturalness requires SUSY to have fairly light stops to cancel "un-naturally" large corrections to the Higgs mass

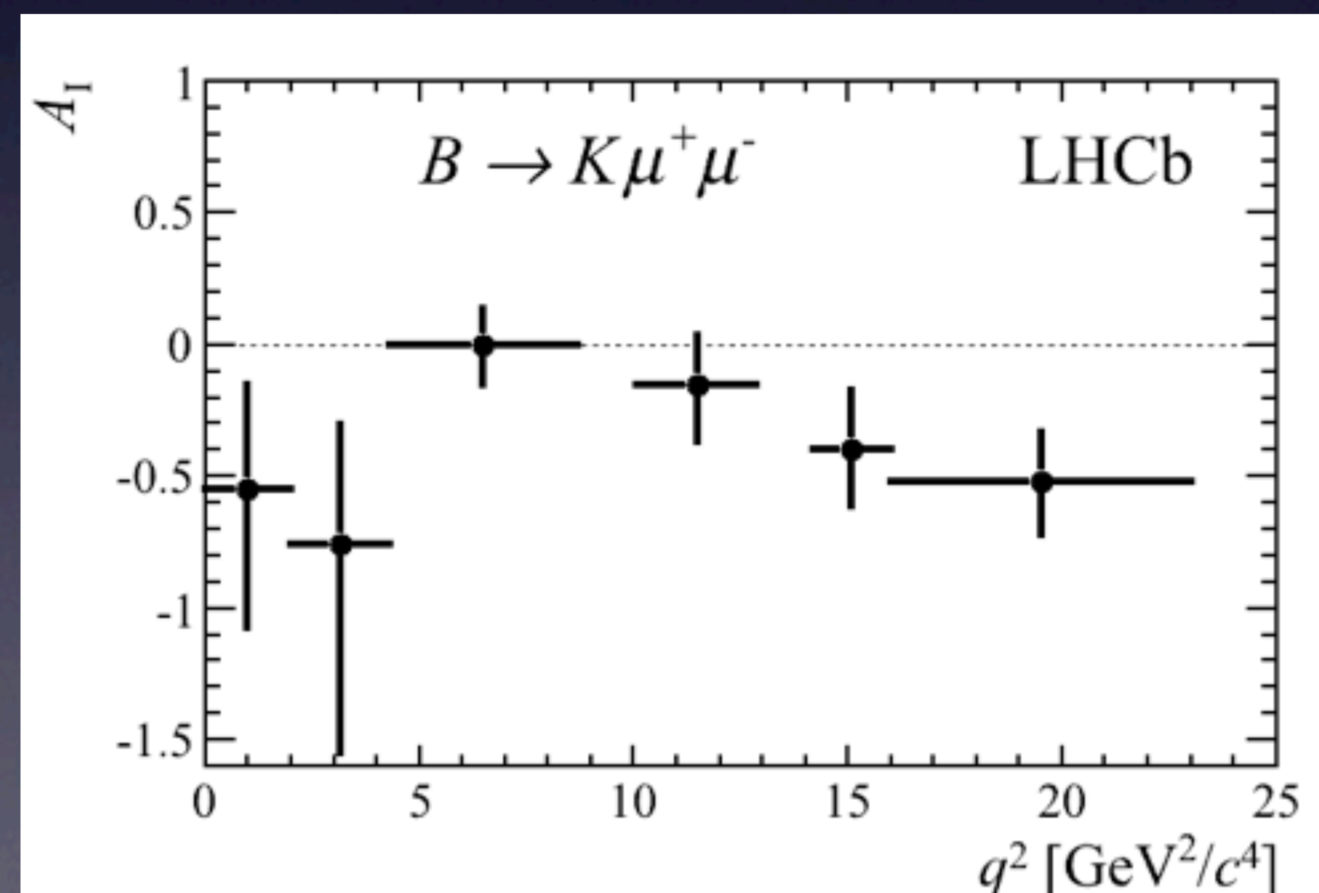
Precision Tests of the Standard Model

LHCb

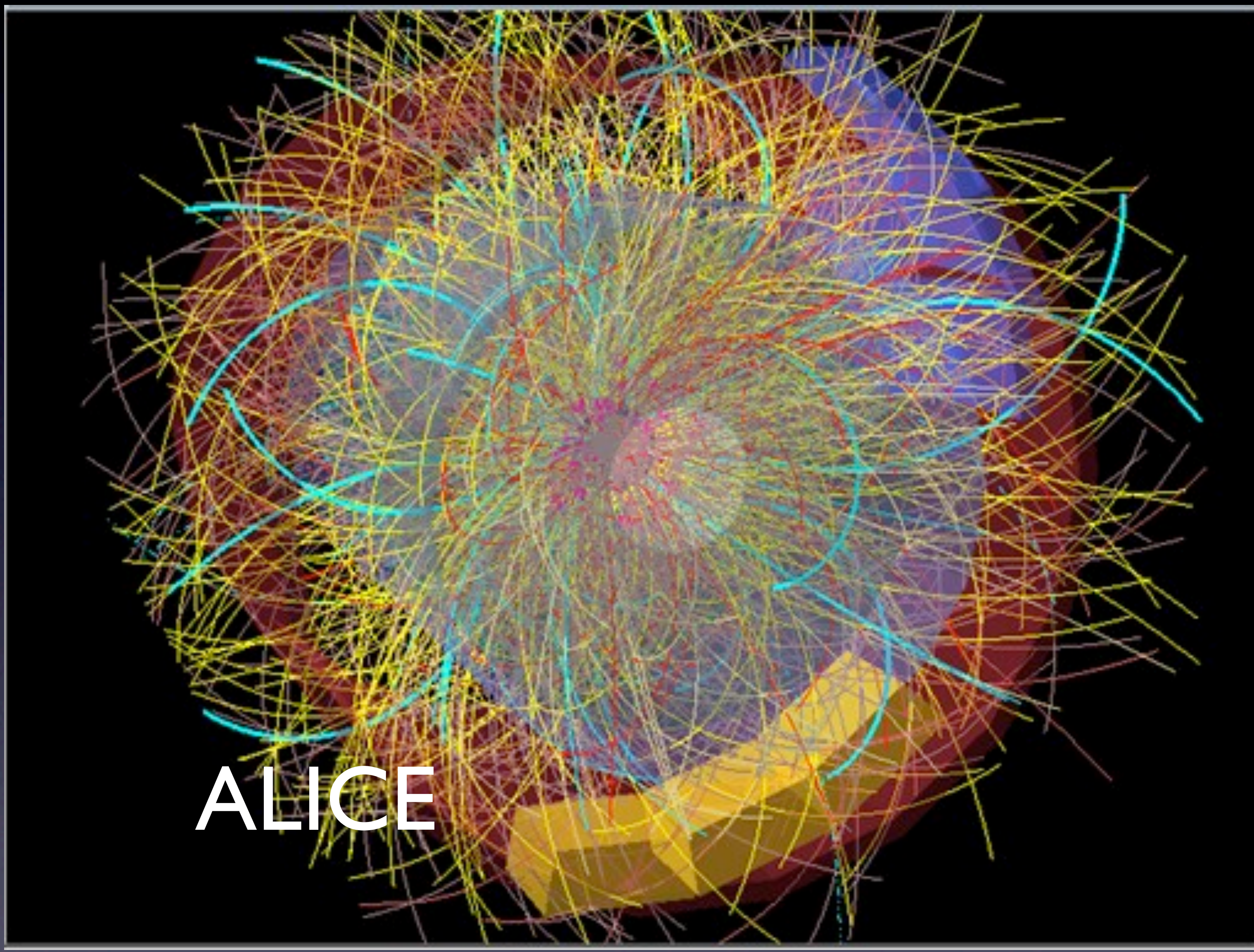
- Sensitive probe of new physics.
    - Virtual loops
- Measurement of the Isospin asymmetry in B->K μμ turned up an asymmetry which no one expected
- arXiv:1205.3422 [hep-ex]
- Awaiting SM prediction

More on LHCb results in upcoming talk





Heavy Ion Physics



Exact mechanism that causes confinement remains unknown

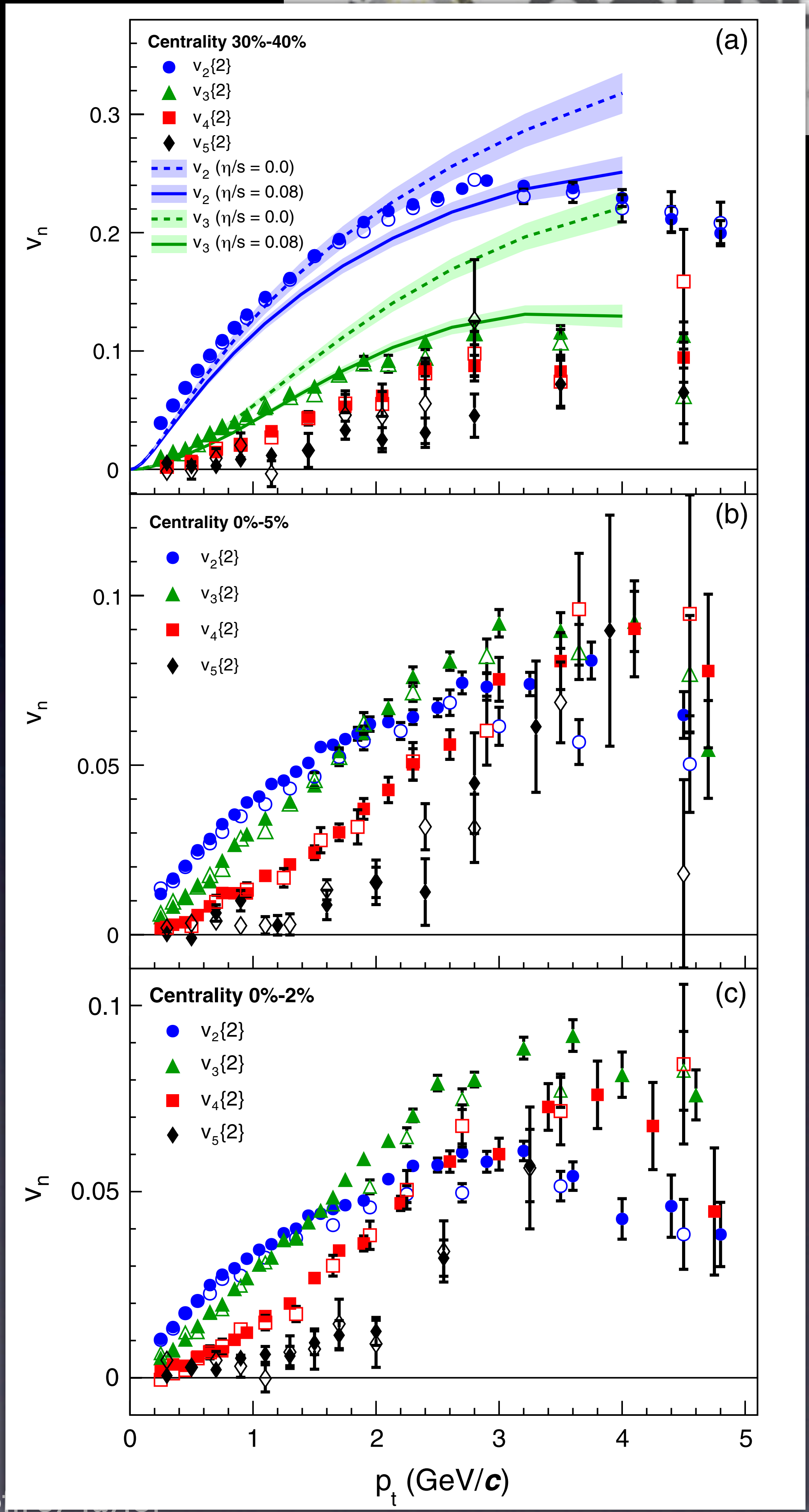
Is the mechanism that confines quarks inside protons responsible for most of the mass in matter?

Properties of qg-Plasma

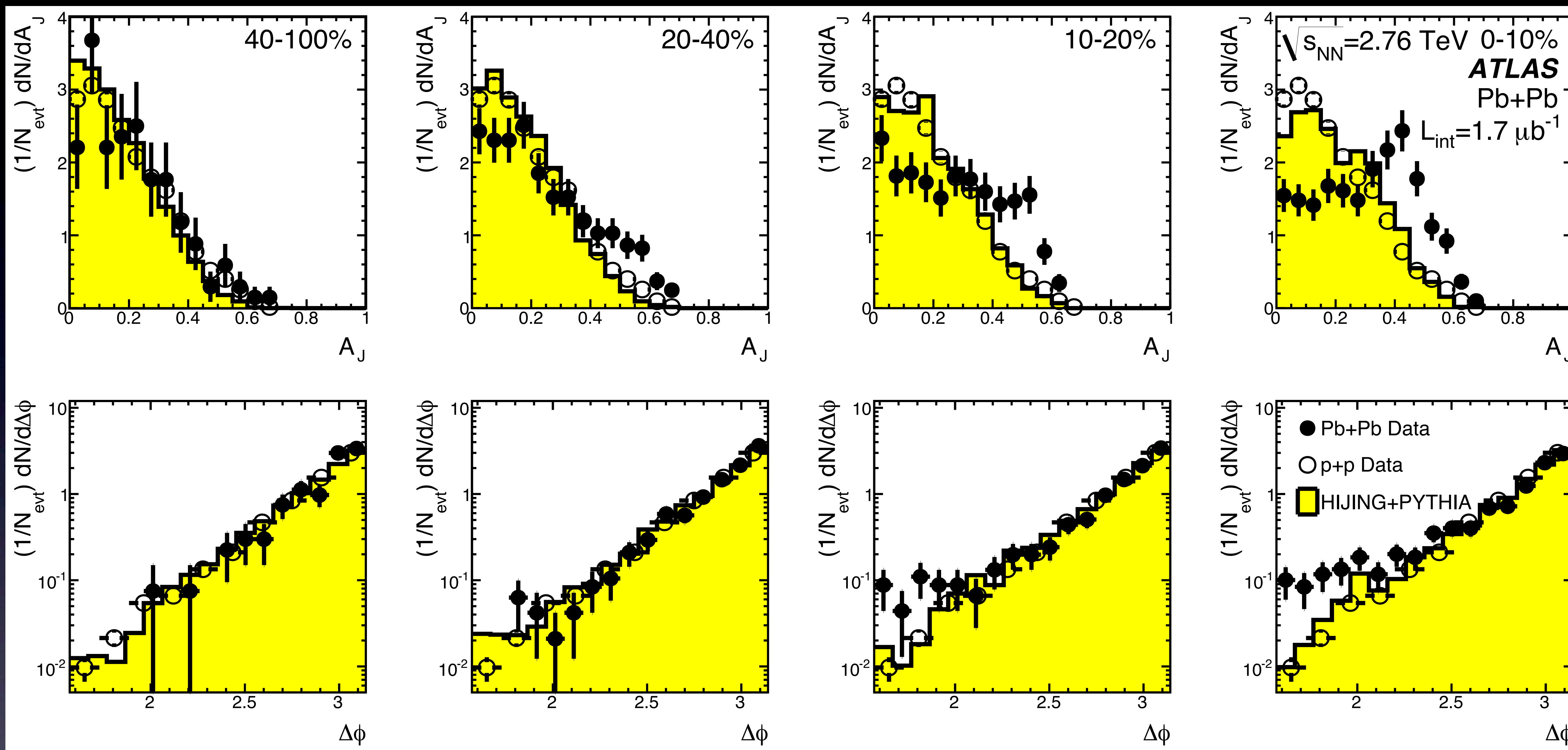
- QCD predicts the existence of quark-gluon plasma at high energy density
- Azimuthal distribution of particles in the plane perpendicular to the beam direction (azimuthal anisotropy)
- Higher Harmonic Anisotropic Flow Measurements of Charged Particles in Pb-Pb collitions at sqrt(s)= 2.76 TeV
- Fourier coefficients

$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$$

- First measurements of particle flow v3, v4 and v5!
- PRL 107, 032301 (2011)



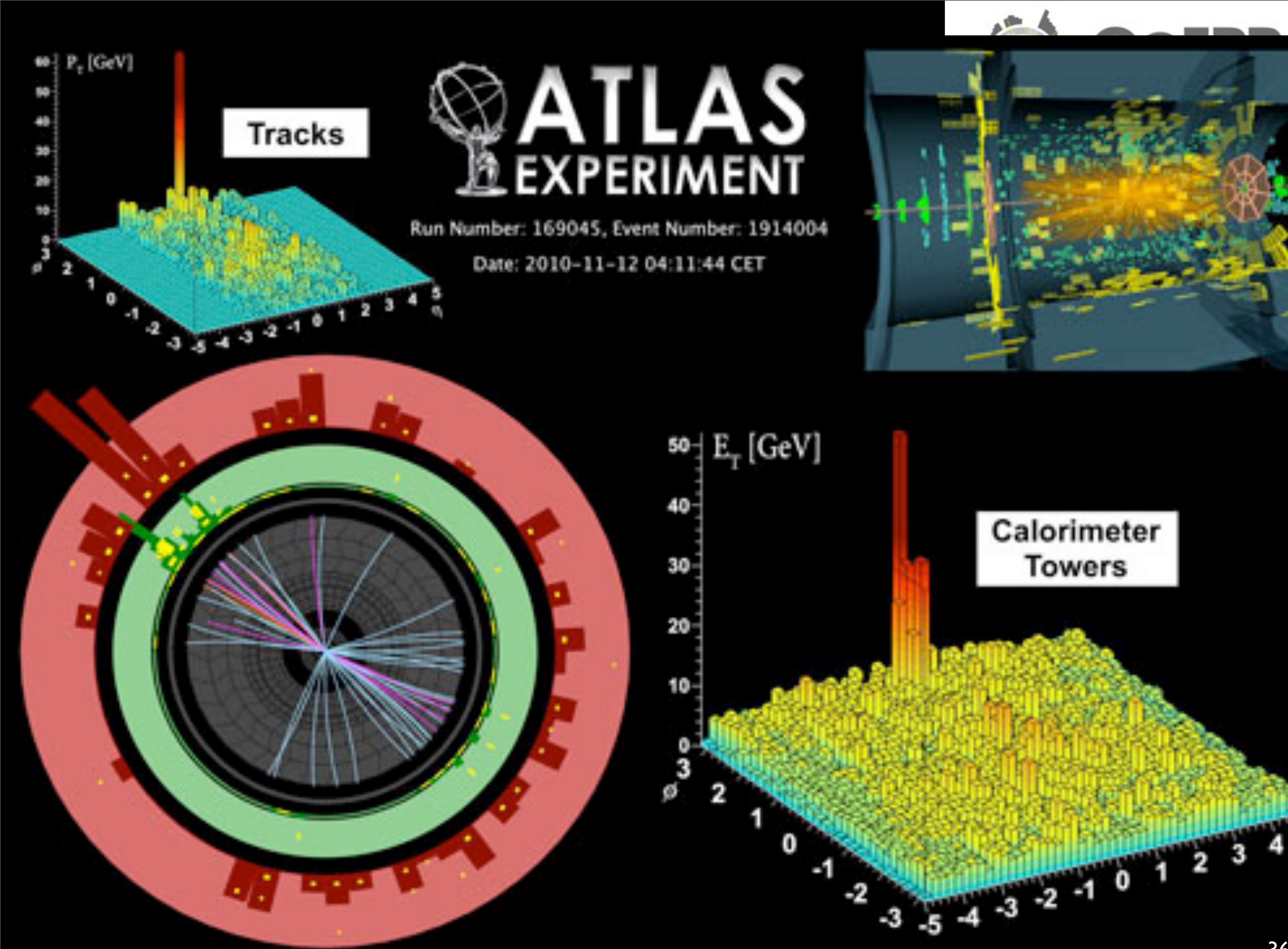
Jet Quenching @ ATLAS



Ultra-relativistic heavy ion collisions are expected to produce hot and dense QCD matter.

High pT quarks or gluons are expected lose energy or have their parton shower modified in the medium of high color-charge density.

May lead to modified jet yields or structure, phenomenon known as "jet quenching"



Tracks
ATLAS
EXPERIMENT
Run Number: 169045, Event Number: 1914004
Date: 2010-11-12 04:11:44 CET
P_T [GeV]
E_T [GeV]
Calorimeter
Towers

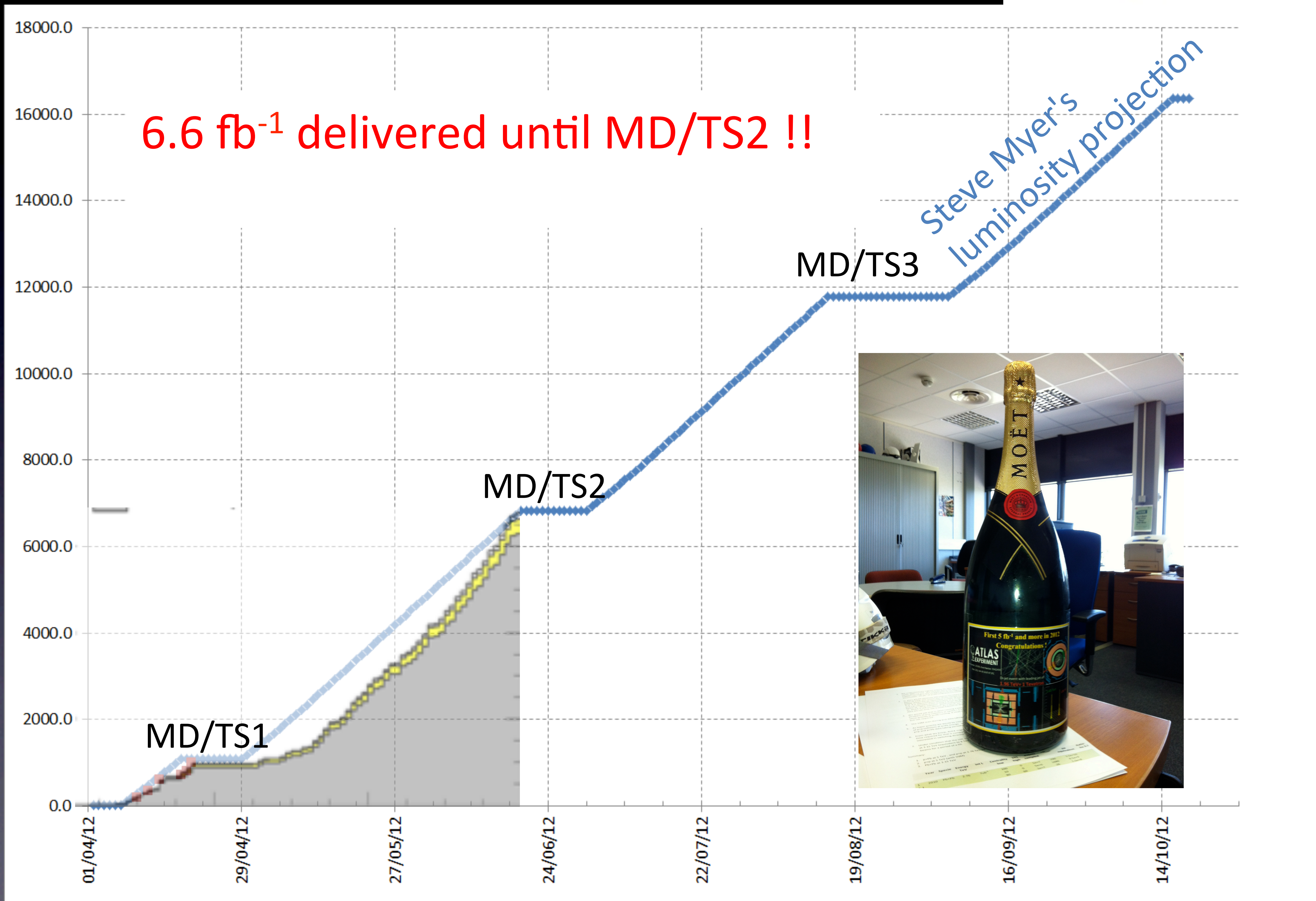
2012 LHC Goals

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

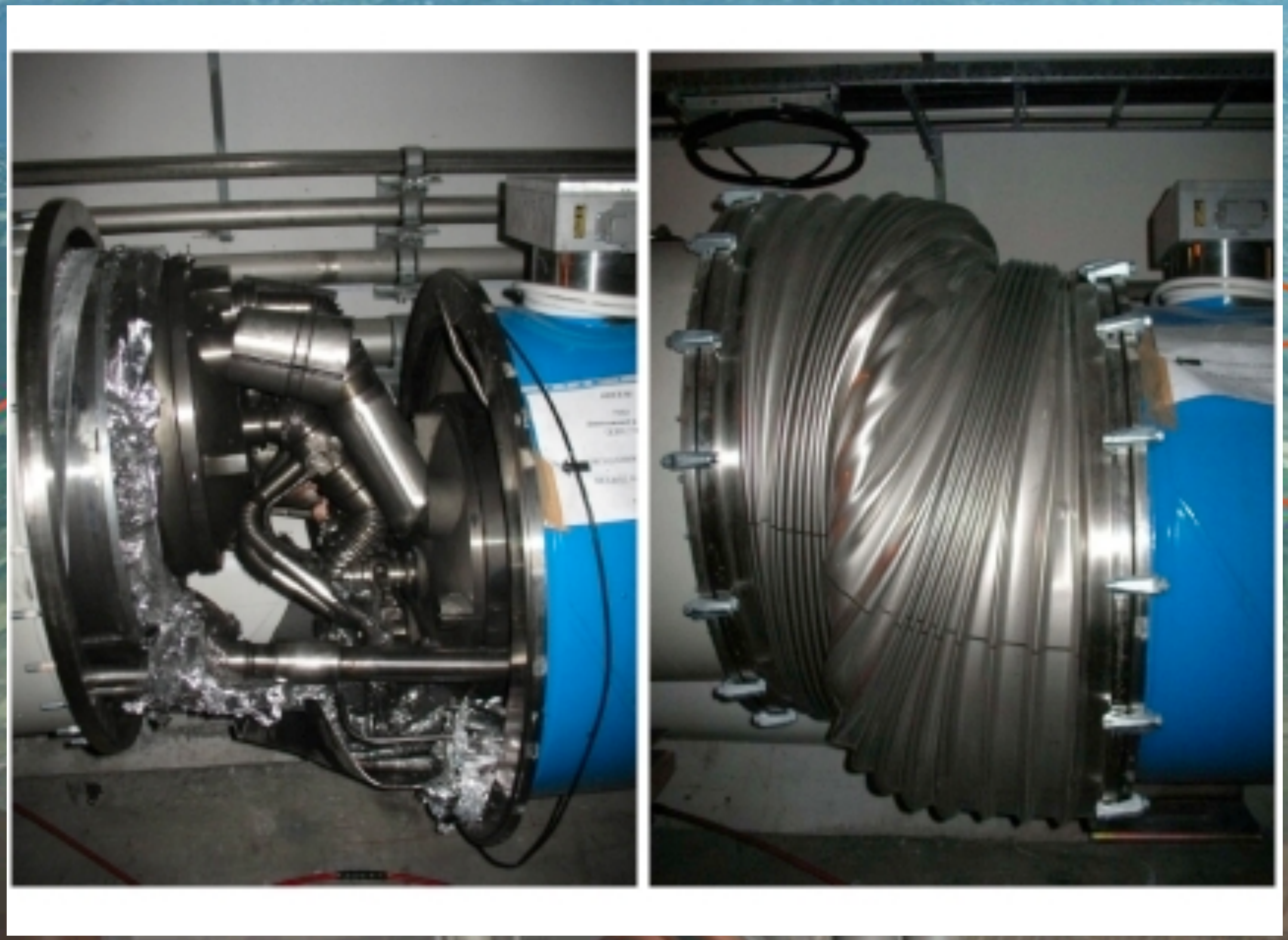
- Allow ATLAS and CMS to independently discover the Higgs before the shutdown (LS1)
- Run with Pb-p collisions at the end of 2012
- Machine studies with 25 ns bunch spacing and pileup to ensure smooth operation after LS1
- Data needed for Higgs discovery

Year	Data(/fb)/Beam E(TeV)	Significance (σ)
2011	5 / 3.5	2.5
2012	11.5 /4.0	5

Impressive Luminosity Race with an Amazing Finish!



LHC Lowlights



Summary

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

2009		LHC start up, $\sqrt{s}$ = 900 GeV
2010		
2011		$\sqrt{s}$ = 7-8 TeV , L = 6 to $8 \cdot 10^{33}$ $cm^{-2}s^{-1}$, bunch spacing **50 ns**
2012		~25 fb^{-1}
2013	LS1	Go to design energy, nominal luminosity
2014		
2015		$\sqrt{s}$ = 13-14 TeV, L = $1 \cdot 10^{34}$ $cm^{-2}s^{-1}$, bunch spacing **25 ns**
2016		**(likely to be more)**
2017		~50 fb^{-1}
2018	LS2	Injector & LHC Phase I upgrade to full design luminosity
2019		
2020		$\sqrt{s}$ = 14 TeV, L = $2 \cdot 10^{34}$ $cm^{-2}s^{-1}$, bunch spacing **25 ns**
2021		**(likely to be more)** ~300 fb^{-1}
2022	LS3	HL-LHC Phase-2 upgrade, crab cavities?, IR
2023		$\sqrt{s}$ = 14 TeV, L = $5 \cdot 10^{34}$ $cm^{-2}s^{-1}$, bunch spacing **25 ns**
2030?		**Plan for 50% more** ~3000 fb^{-1}

- Remarkable that with ~1/2 design energy (but with great progress on the luminosity front) the LHC has achieved so already.
- With plans for massive increases in data at higher energies in the future the LHC will without doubt be extremely productive

last word from CERN DG

Nevertheless, at less than two weeks from the start of the ICHEP conference, the news from the experiments is exciting. As I reported to Council, the hints that were reported in the 2011 data last December are still present in the 2012 data. Furthermore, refinements of the analysis of the 2011 data have confirmed the hints reported in December. It is too early for the experiments to say whether the significance is enough to claim a discovery, but whatever the news, it will be reported at CERN on Wednesday 4 July with a live two-way video link to the scientists gathering in Melbourne for ICHEP2012.