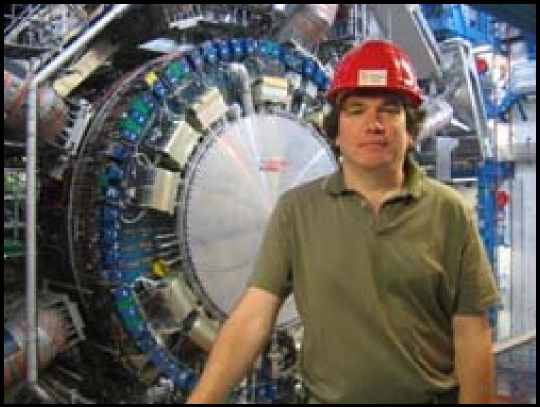
CU Physics Department Colloquium

Monday, September 26, 2011 4:10 PM 428 Pupin Hall

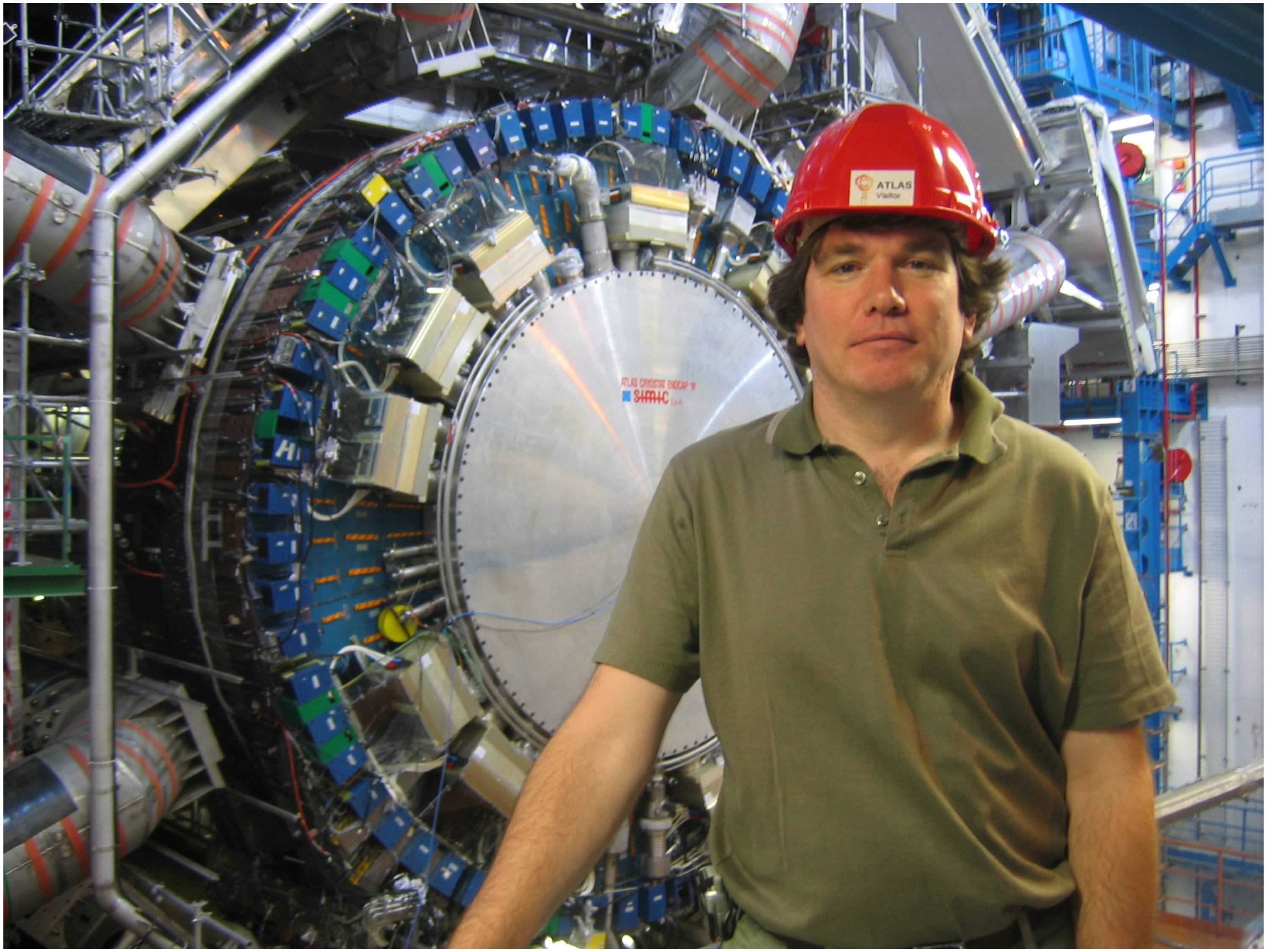
News from the LHC: Tightening the Noose on the Standard Model

With the recent turn-on of CERN's Large Hadron Collider (LHC), particle physics has entered a new era in the exploration of physics at the TeV scale. The LHC, the world's highest energy particle accelerator, has been performing extremely well.The large data sample already recorded by the ATLAS detector at the LHC allows probes of TeV scale physics with unprecedented sensitivity. Recent ATLAS results will be discussed, including the race to discover, or else rule out, the Standard Model Higgs bosonas the origin of mass, as well as searches for new physics beyond the Standard Model.



John Parsons, Columbia University

News from the Large Hadron Collider: Tightening the Noose on the Standard Model



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

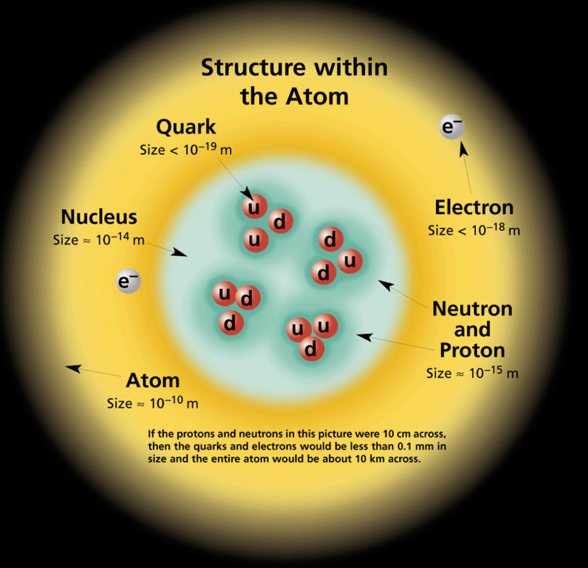
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = $1.05\text{x}10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for **two u quarks at:** 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for **two u quarks at:** 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for **two protons in nucleus**	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

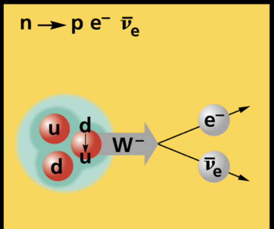
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

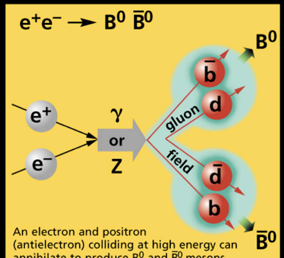
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



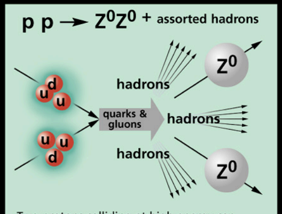
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
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CPEP is a non-profit organization of teachers, physicists, and educators. Send mail to: CPEP, MS 50-308, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720. For information on charts, text materials, hands-on classroom activities, and workshops, see:

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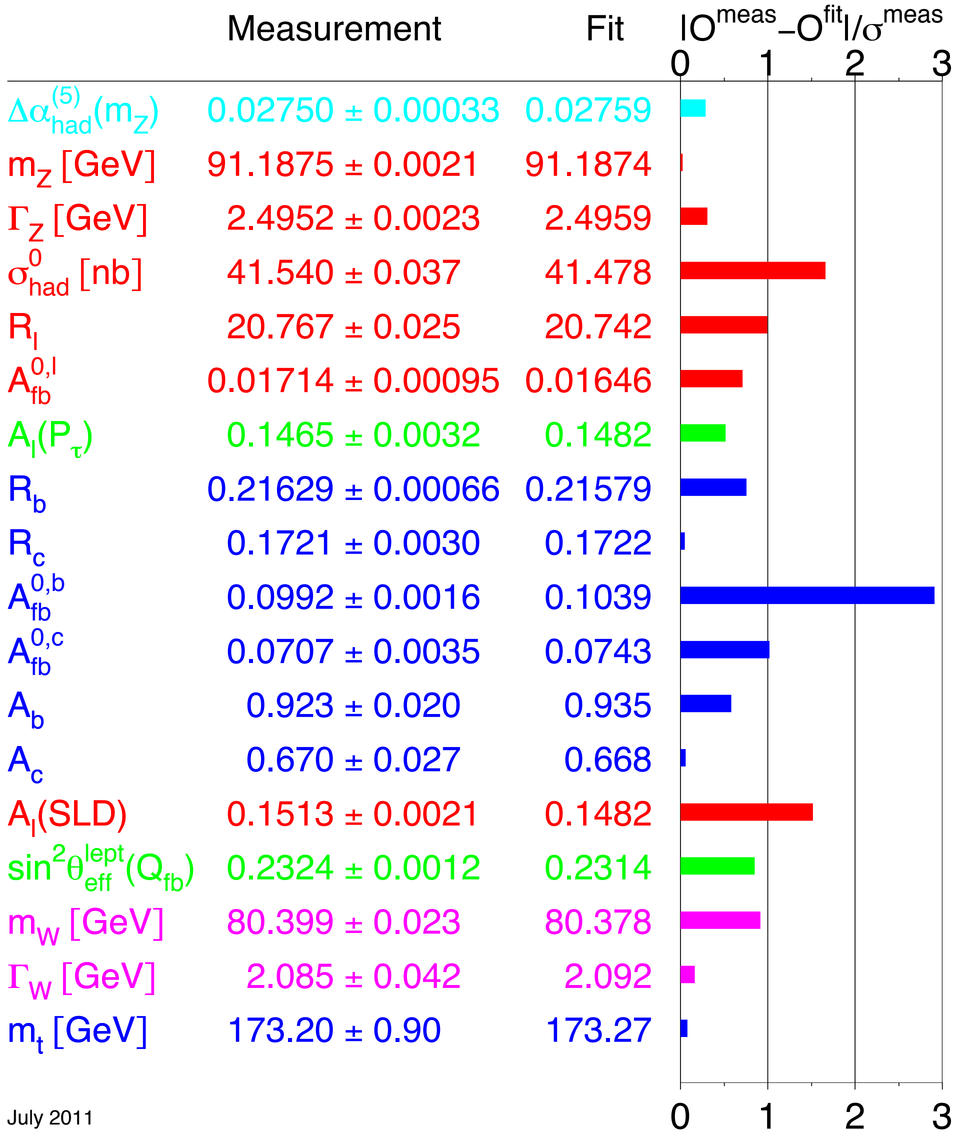
(Some of the) Experimental Tests of the SM

- **SM has been very extensively tested, and describes nature very well**



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
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	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1039
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27

July 2011

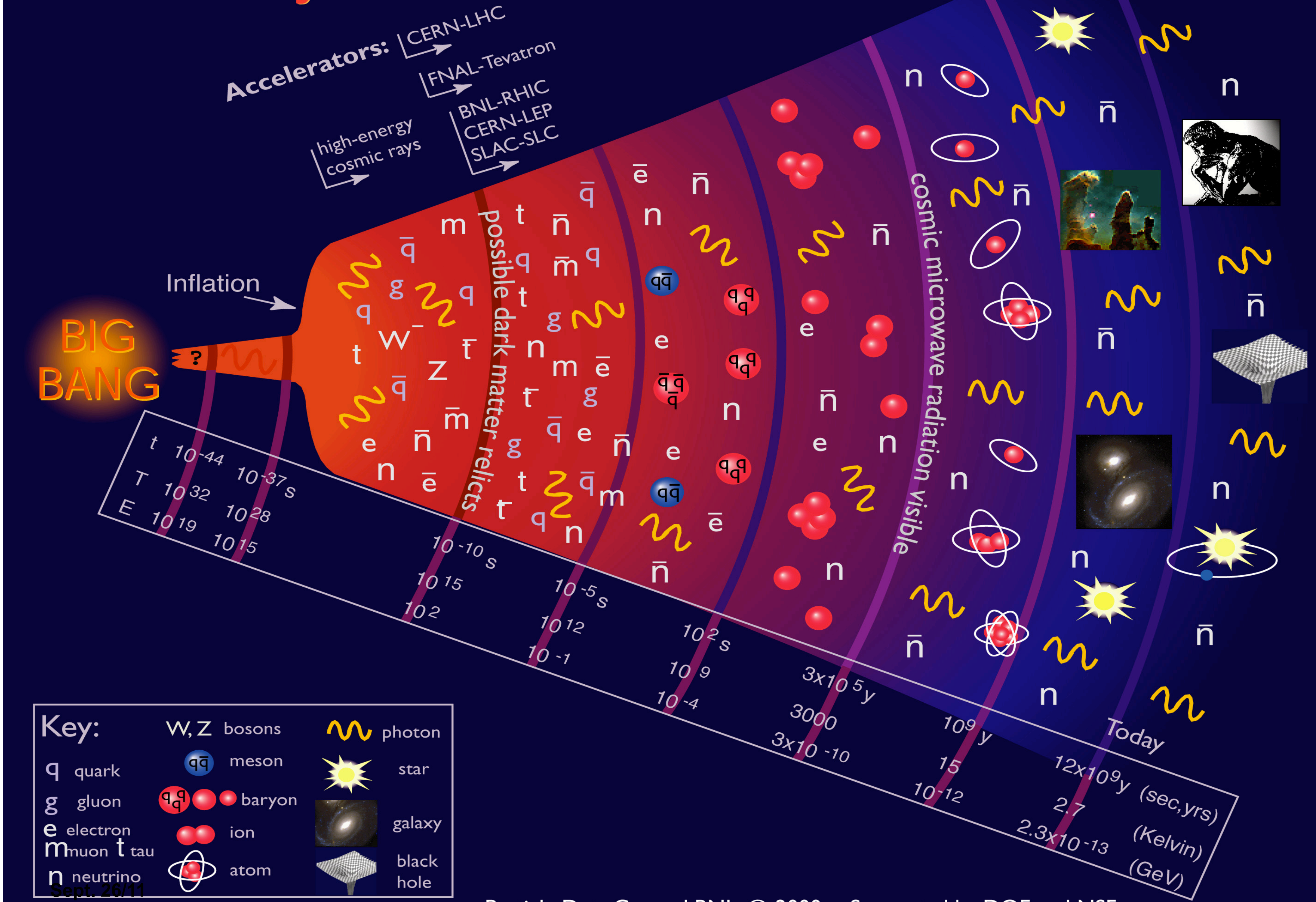
Problems with the SM

Successes of the SM

- SM describes our experimental data very well, at typically % level
  - So, why are most physicists convinced it is wrong??
- For one thing, the SM has 19 free parameters which cannot be calculated within the SM, the values of which must be provided by experiment
  - this "incompleteness" suggests the SM is not the final answer!
- We do not understand the matter-antimatter asymmetry in the universe
- Gravity is not included within the SM
- We have not verified the SM explanation of particle masses

  (ie. we have not [yet] found the Higgs boson required by the SM)
- We do not know what makes up the Dark Matter that contributes ~1/4 of the energy content of the universe
- We do not know the nature of the Dark Energy that dominates the energy content of the universe

History of the Universe



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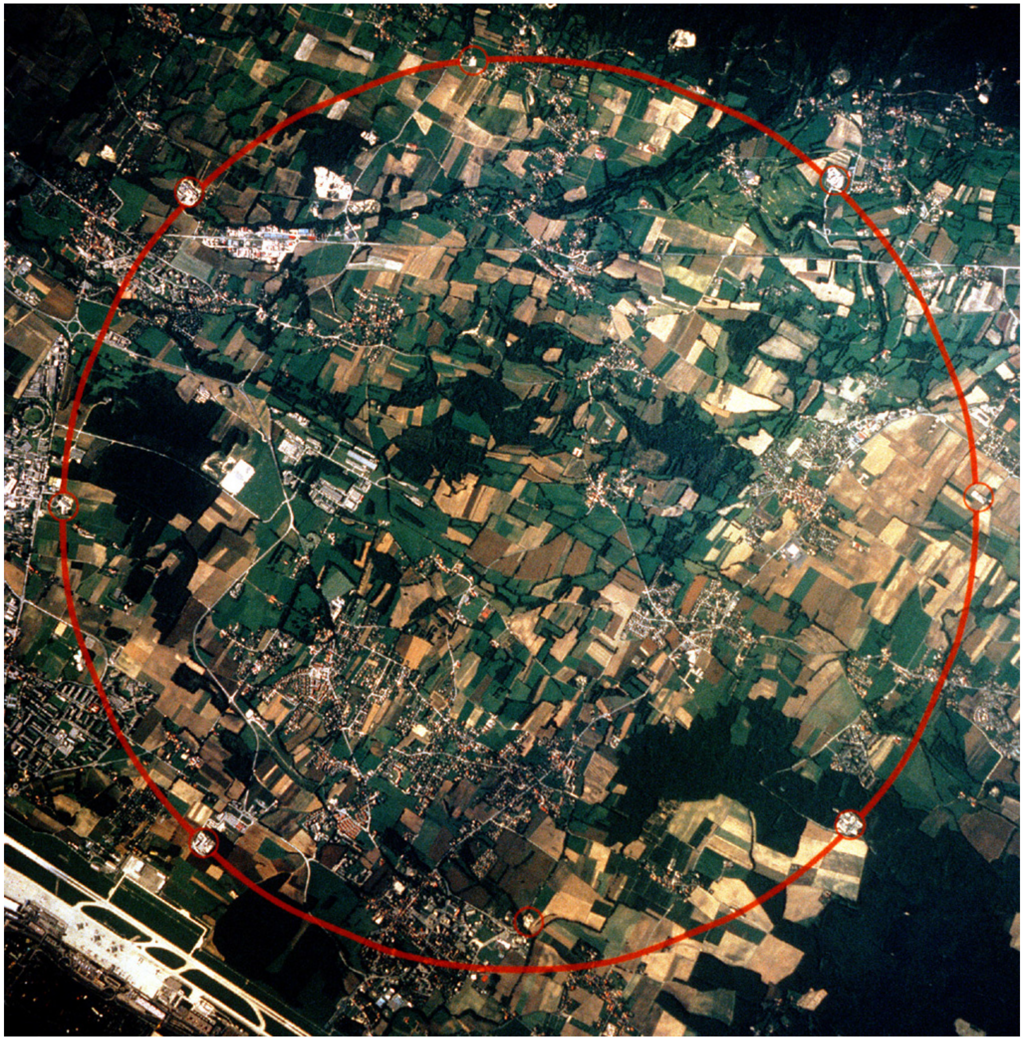
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

The Large Hadron Collider

- The LHC is the world’s most powerful particle accelerator
- Built in a tunnel 27 km around, 100 m underground, near Geneva
- Protons travel around ring 11,245 times per sec (speed = 0.99999999 c)
- The counter-circulating proton beams are so intense that they will produce ~900 million collisions per second!

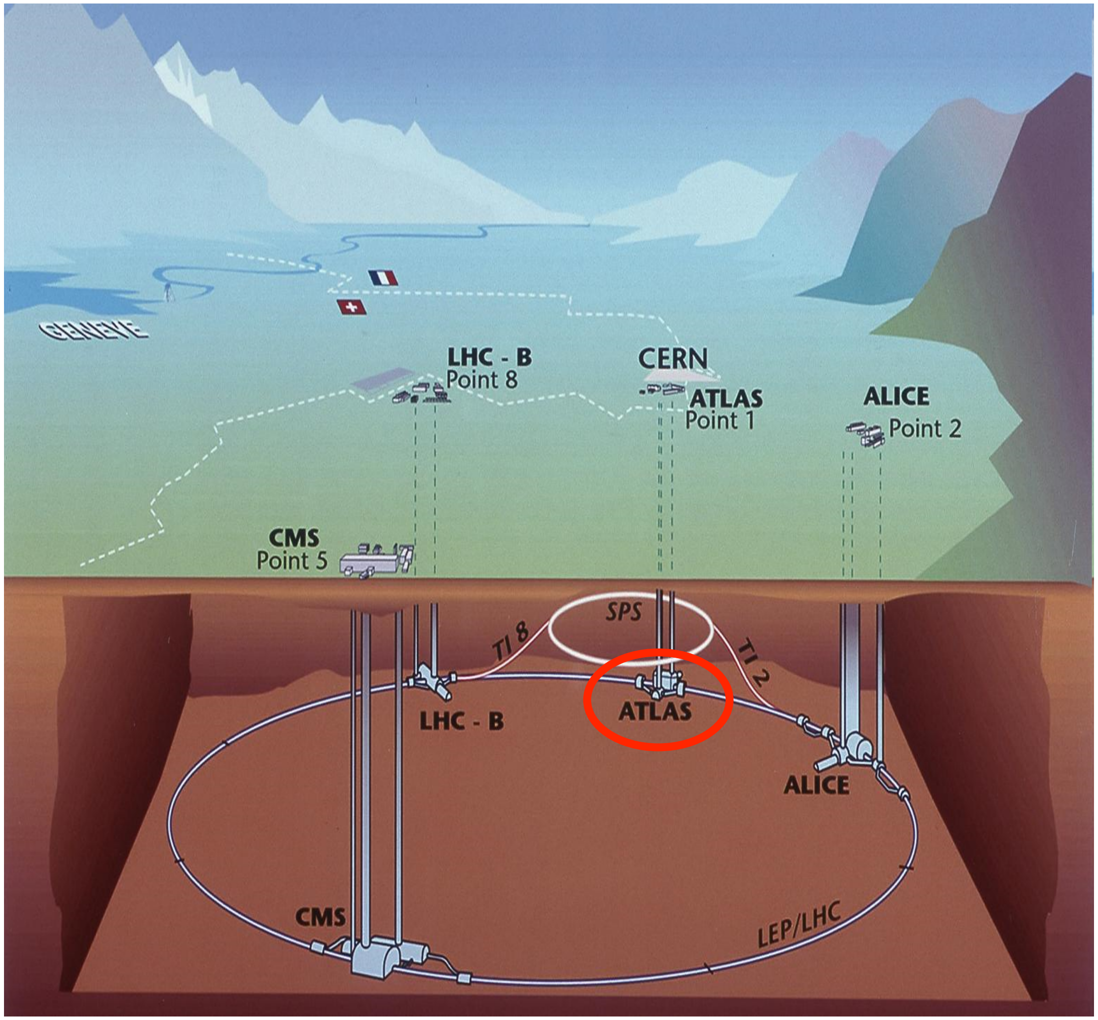


Experiments at the LHC

- There are 4 experiments at the LHC

- Two (ATLAS, CMS) are large, competing, general purpose experiments

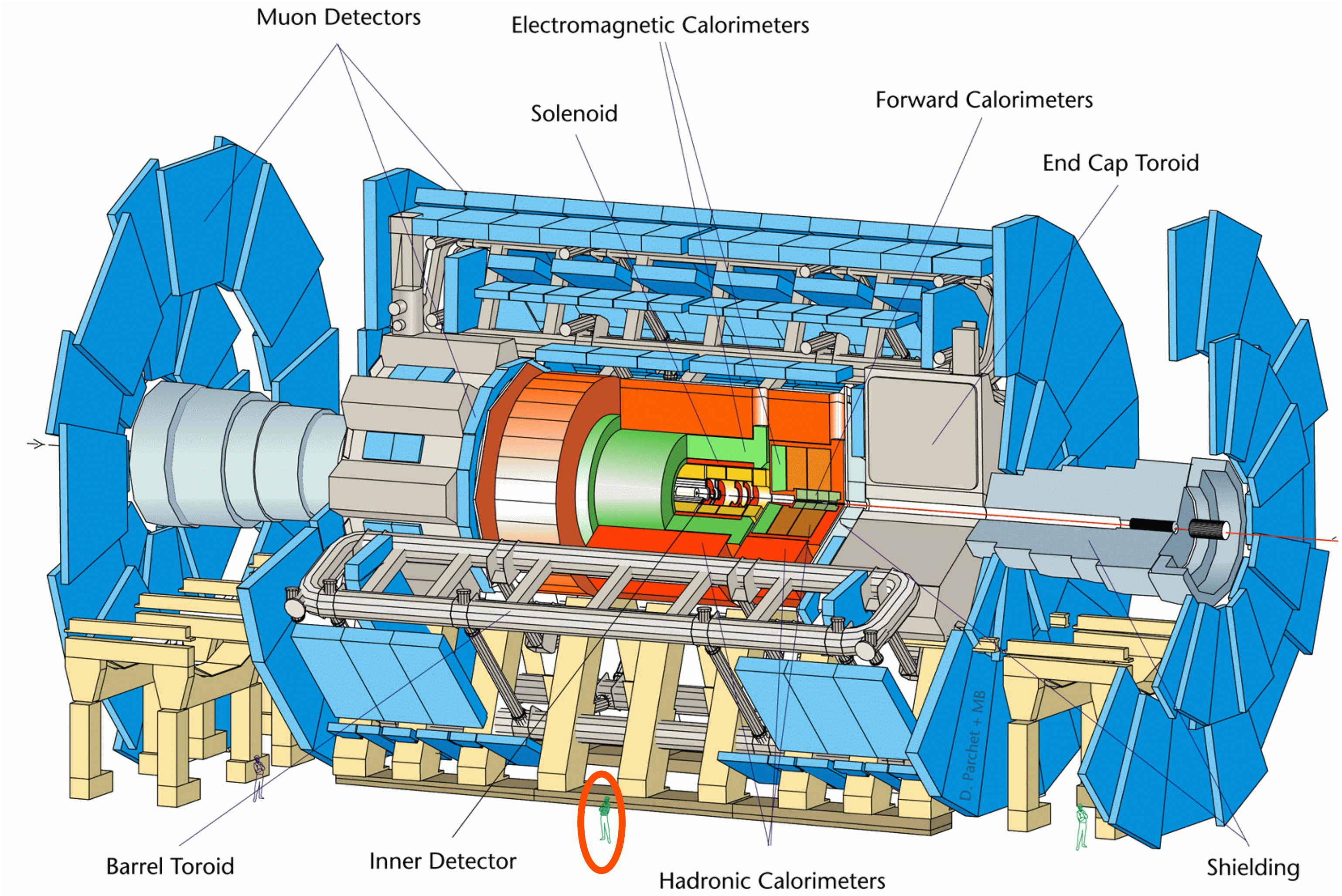
- The other two (LHC-B, ALICE) are smaller experiments which target particular aspects of the experimental program



38 Countries
174 Institutions
3000 Scientists
1000 Students

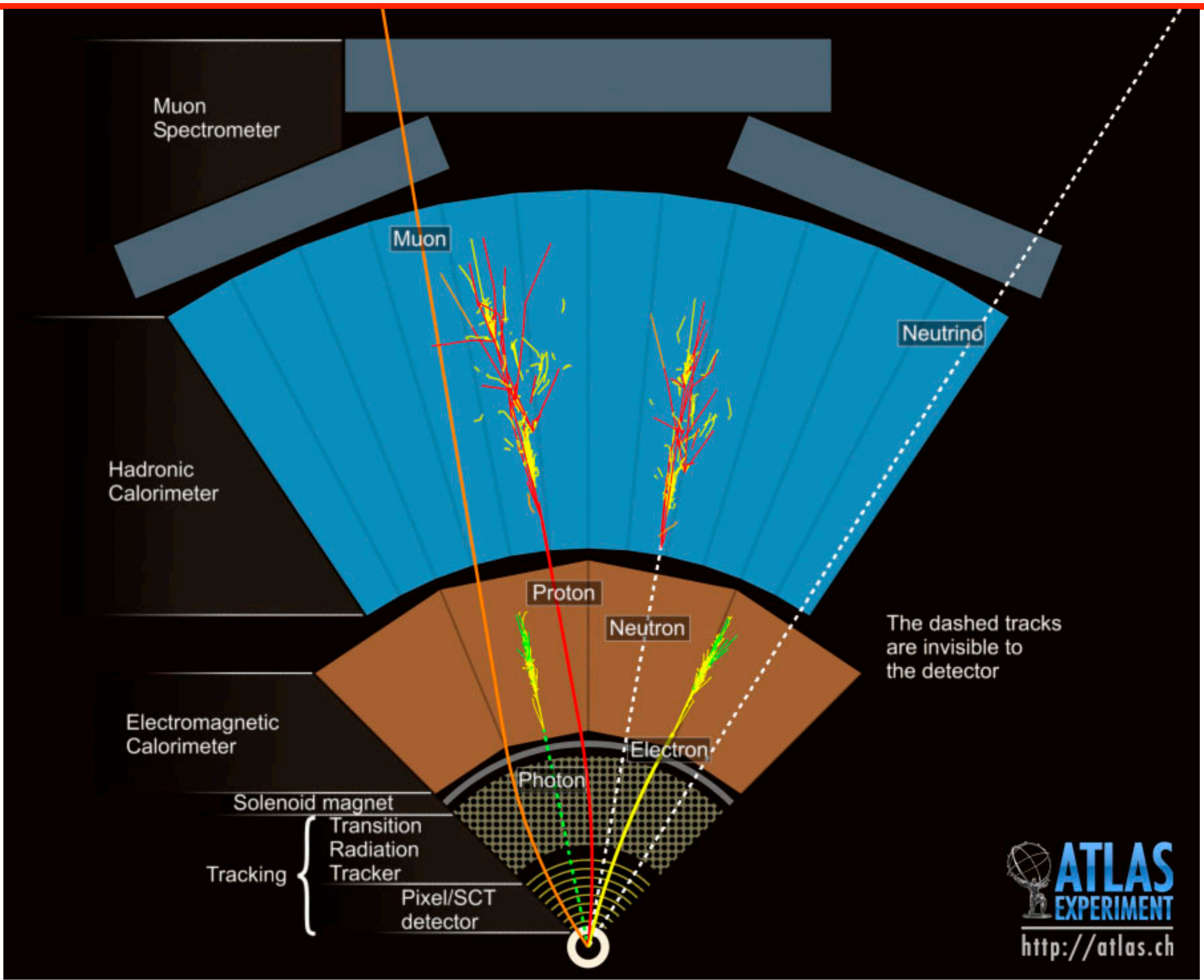
ATLAS Collaboration

The ATLAS Detector



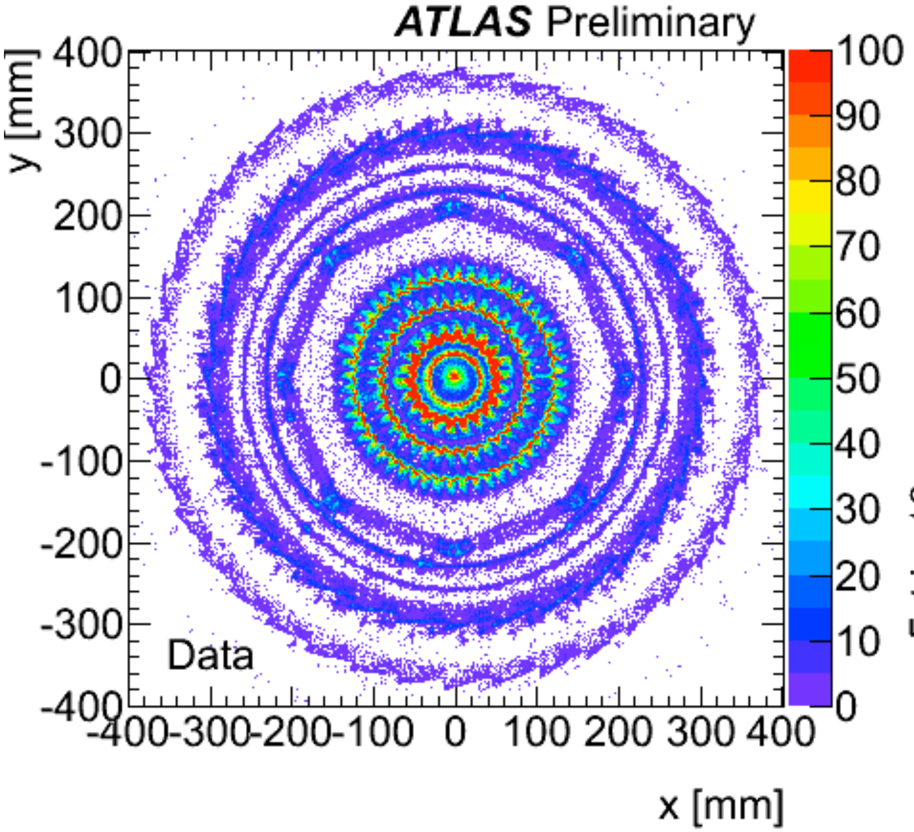
- **Overall length = 42 m, diameter = 22 m, weight = 7000 tons**

ATLAS Detector Principles

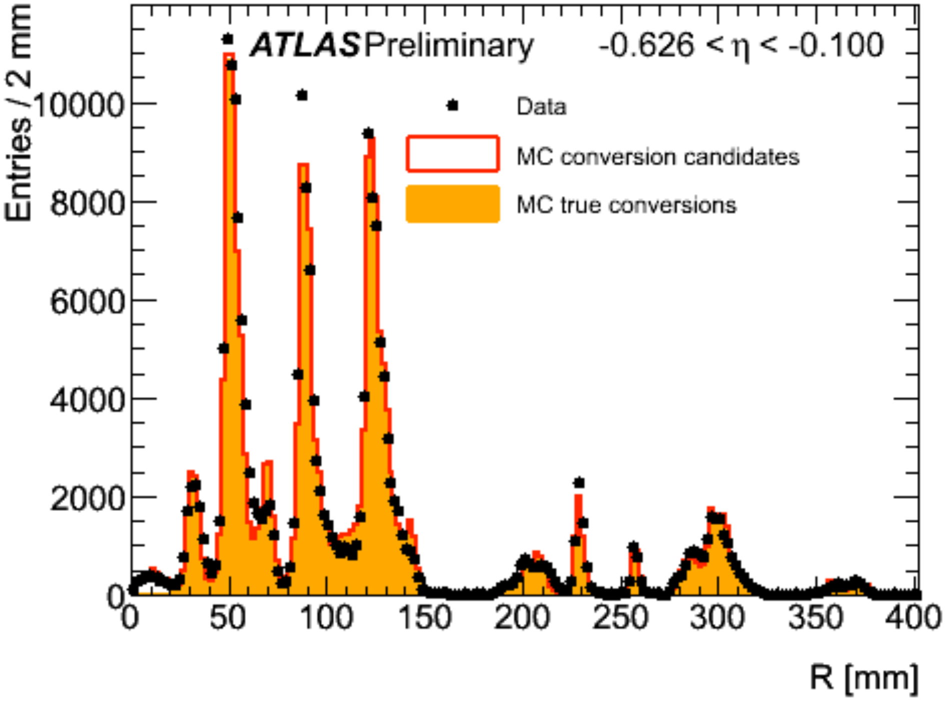


The dashed tracks are invisible to the detector

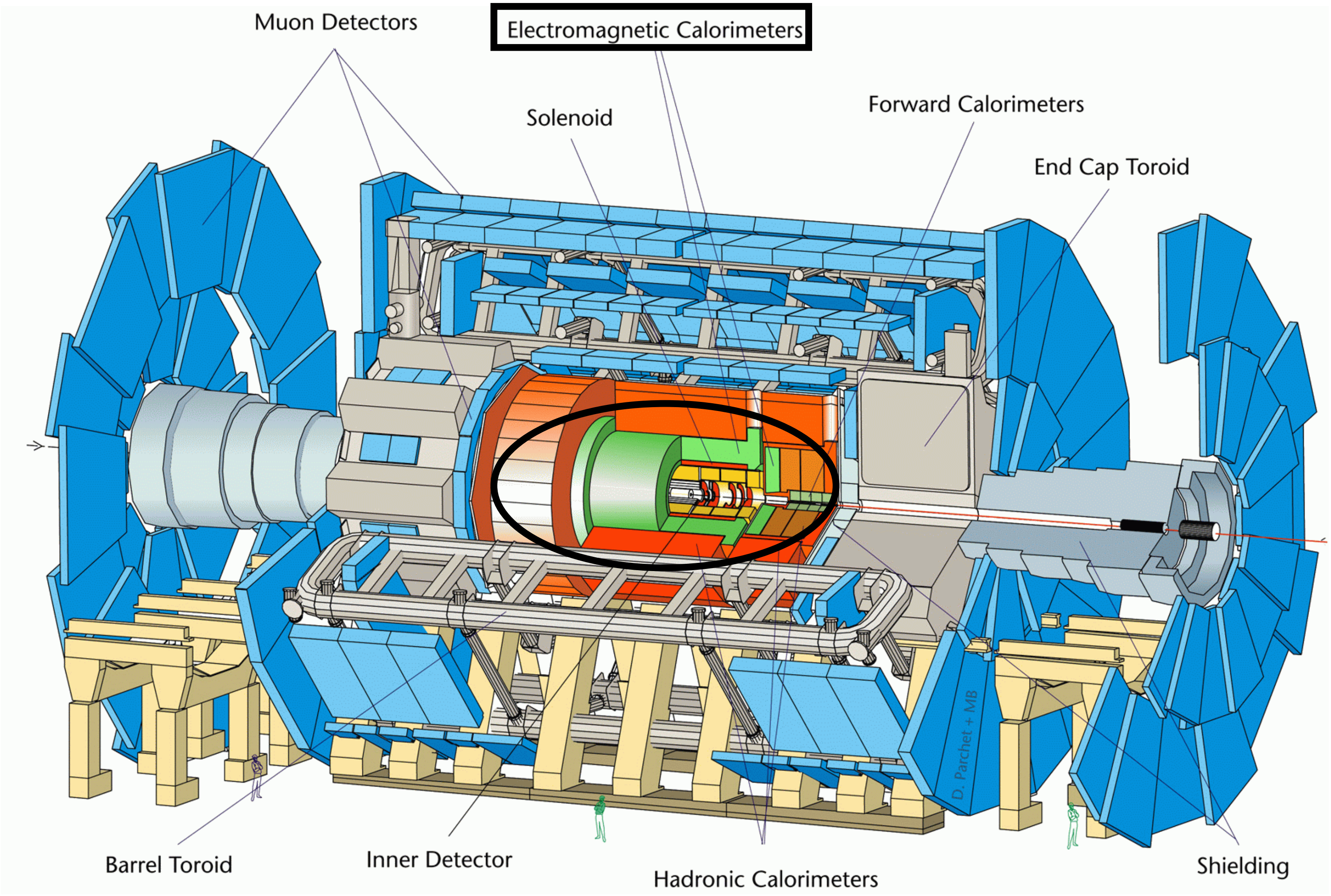
Si Tracker as Seen by Converted Photons



Good data/MC agreement

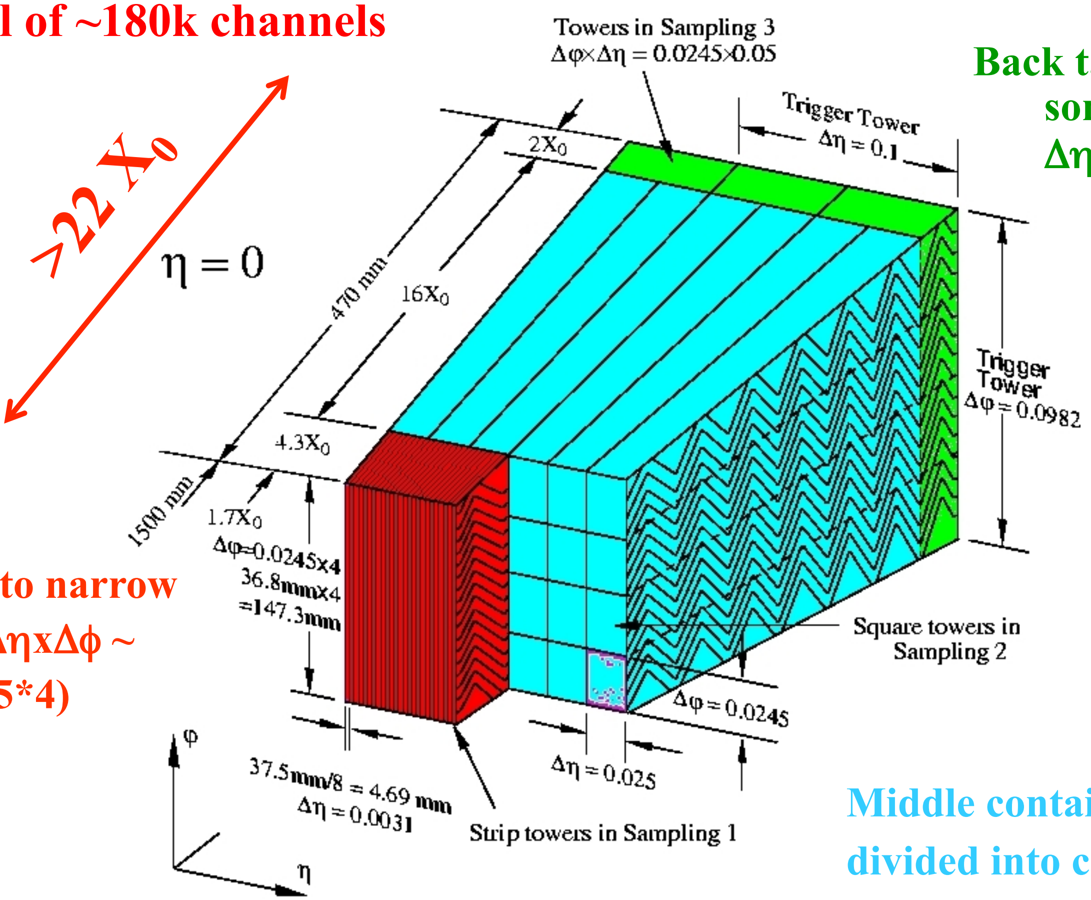


The ATLAS Detector



EM Calorimeter Segmentation

- Pb:LAr “accordion” sampling calorimeter, with 3 longitudinal (depth) segments of varying transverse segmentation
  - Total of ~180k channels

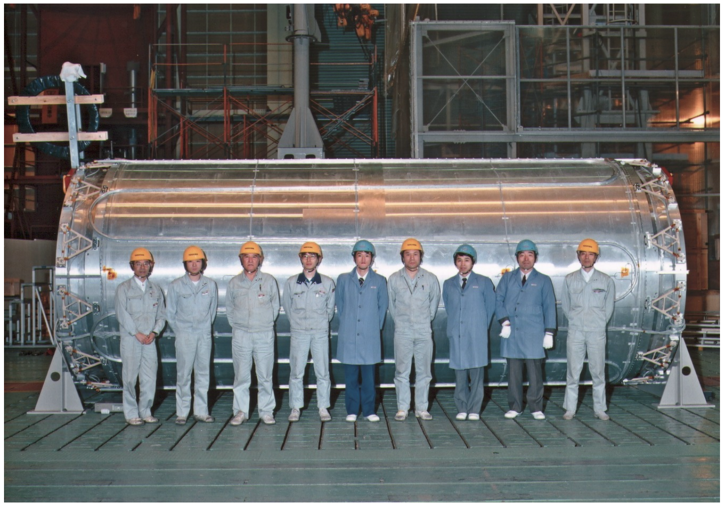


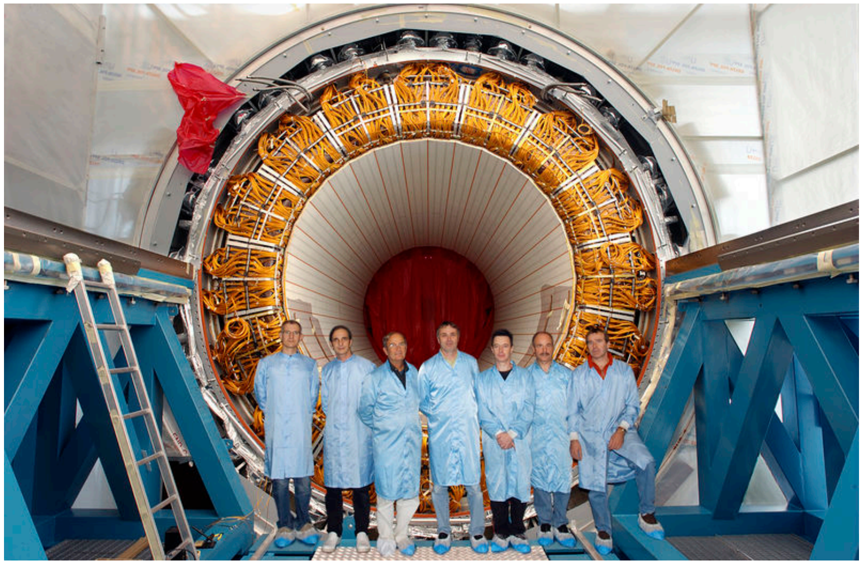
Back tail-catcher has somewhat coarser $\Delta\eta x\Delta\phi \sim 0.05 \times 0.025$

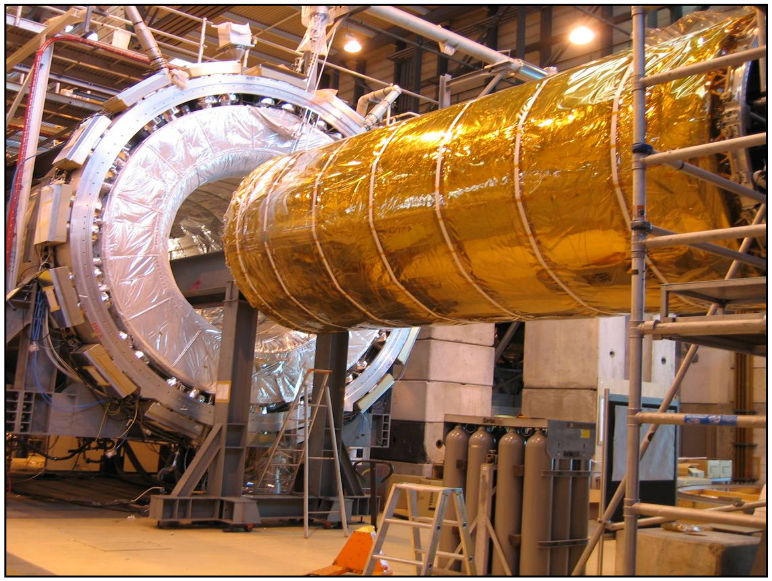
Front divided into narrow “eta strips” of $\Delta\eta x\Delta\phi \sim (0.025/8) \times (0.025*4)$

Middle contains most of energy; divided into cells of $\Delta\eta x\Delta\phi \sim 0.025 \times 0.025$

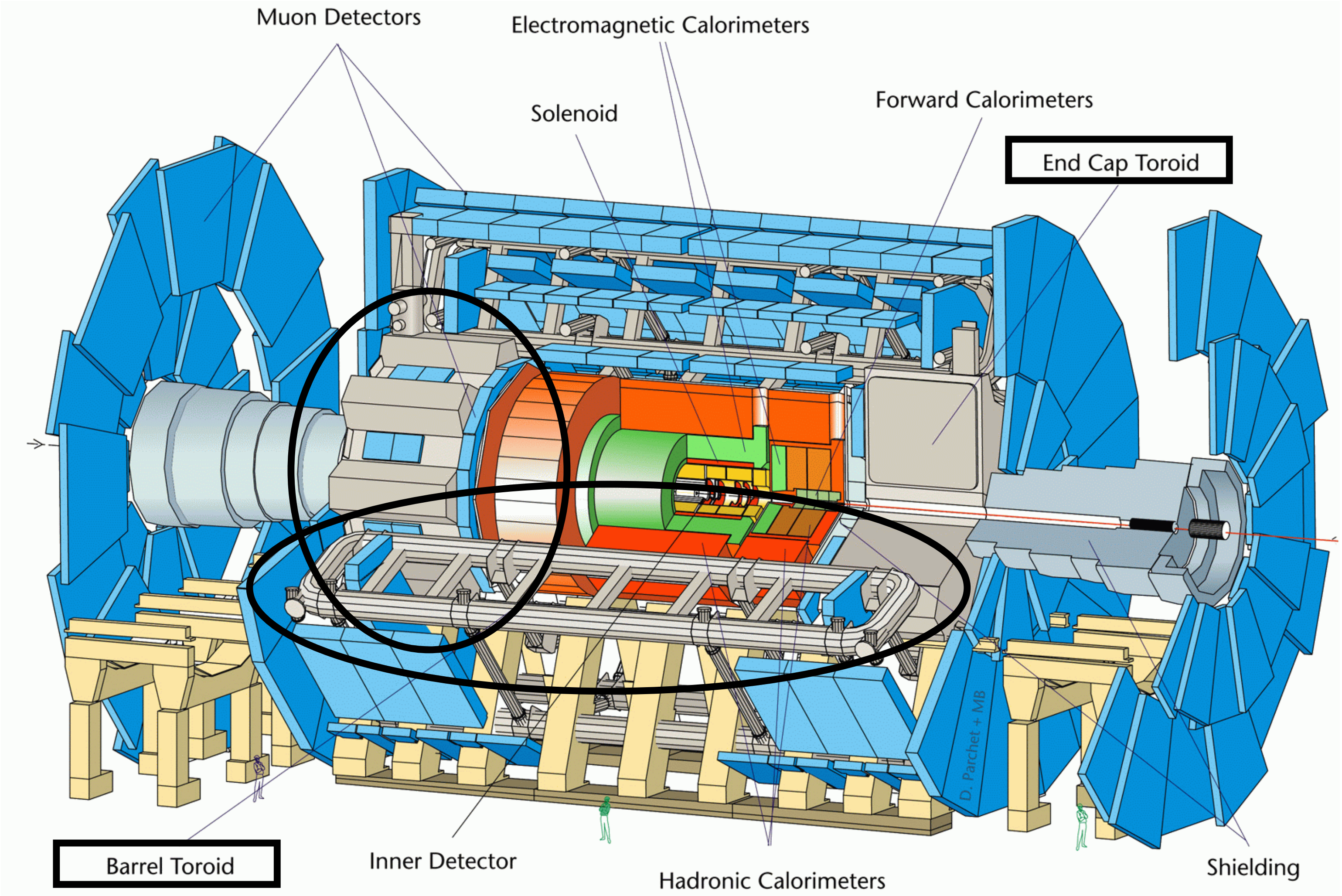
ATLAS Barrel Cryostat and Superconducting Solenoid



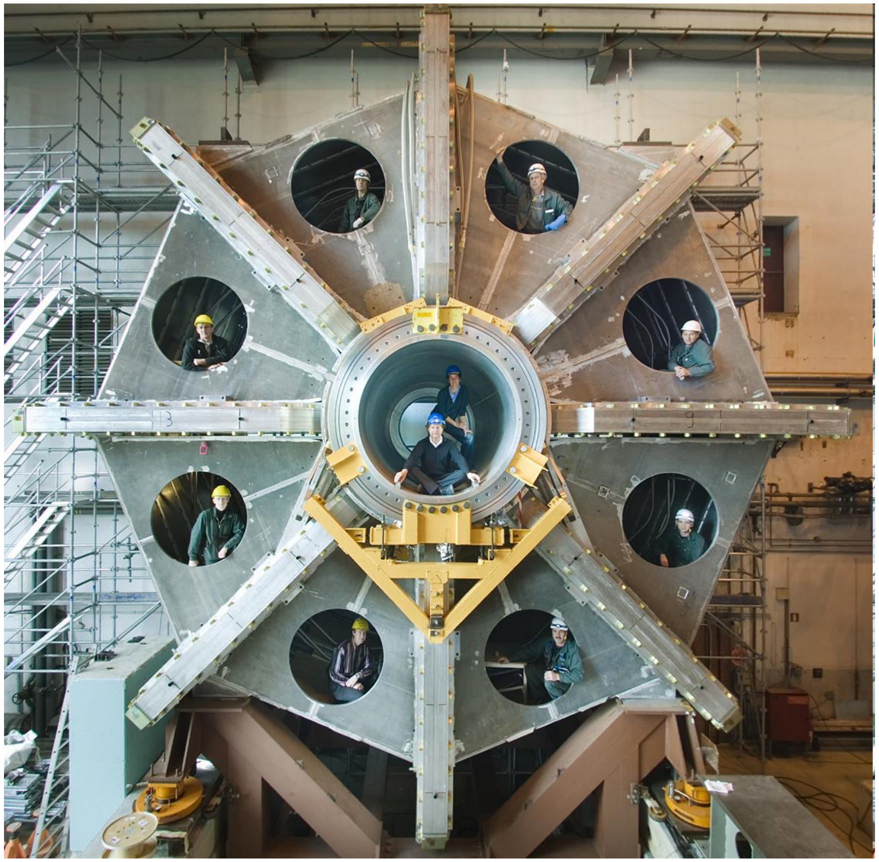




The ATLAS Detector



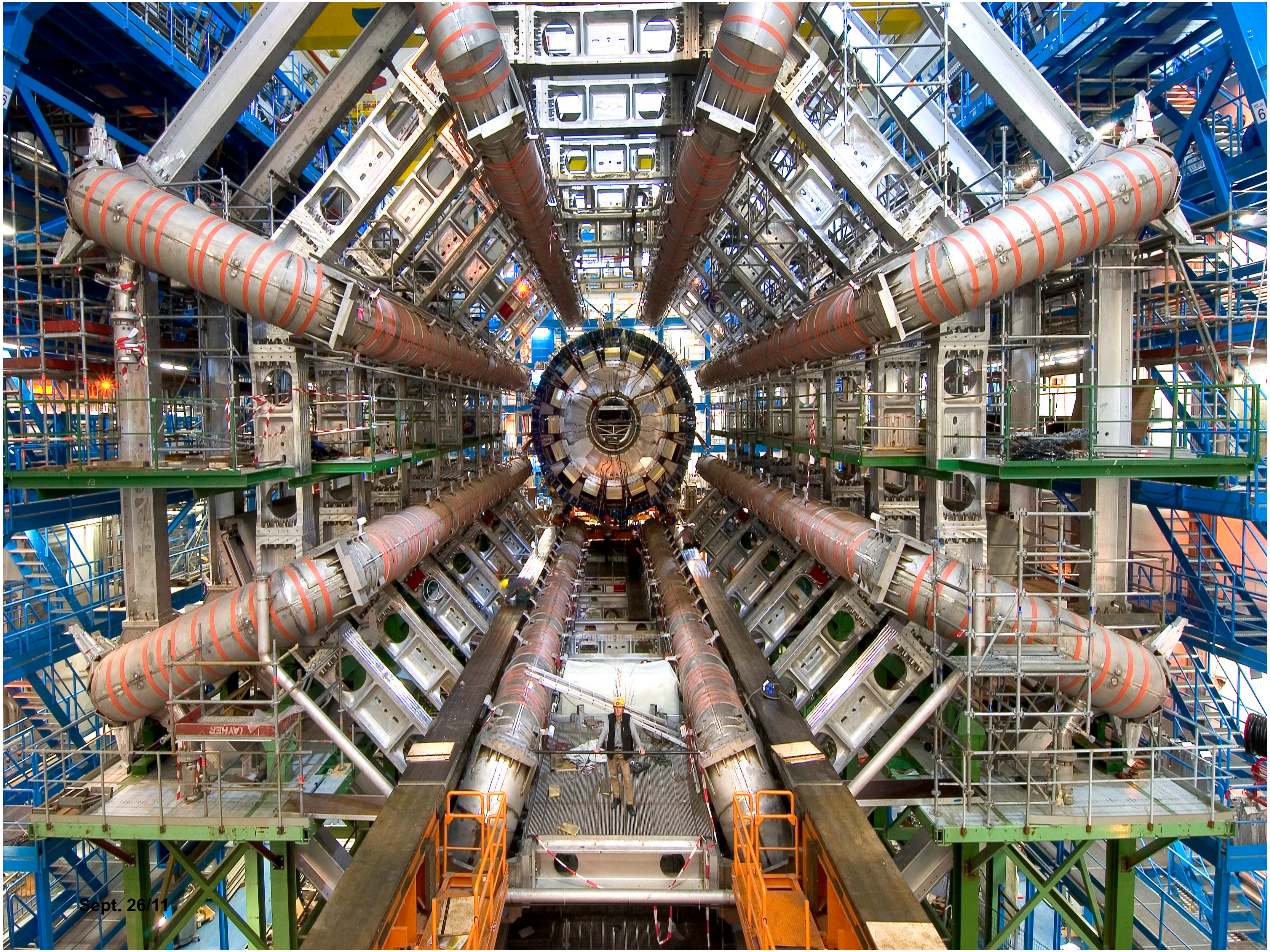
ATLAS Toroidal Magnet System



Endcap toroid

Barrel toroid

- 90 km of superconductor, 700 ton cold mass
- total energy stored in magnetic field: 1.55 GJ



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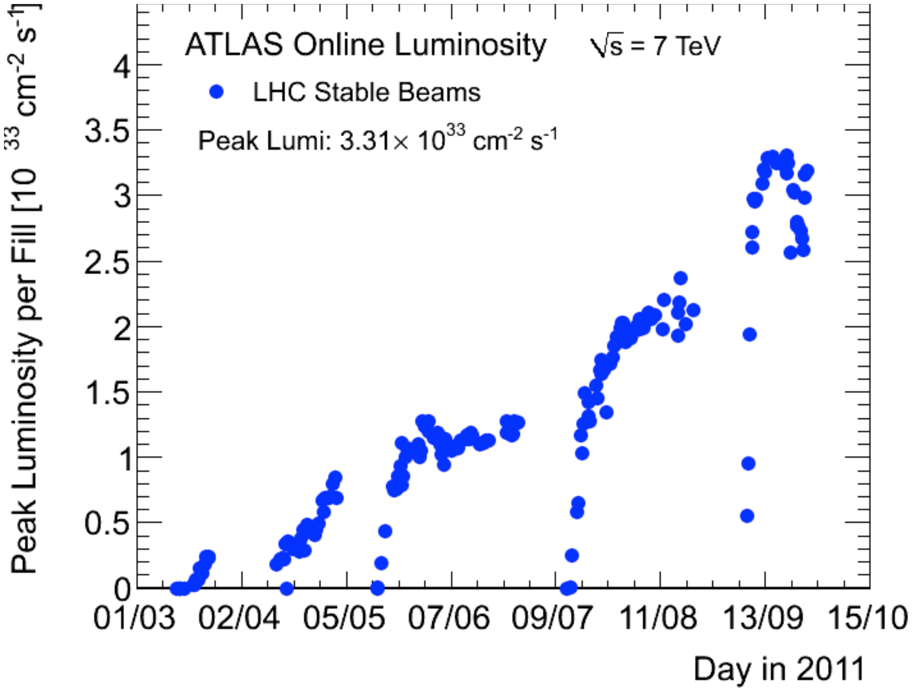
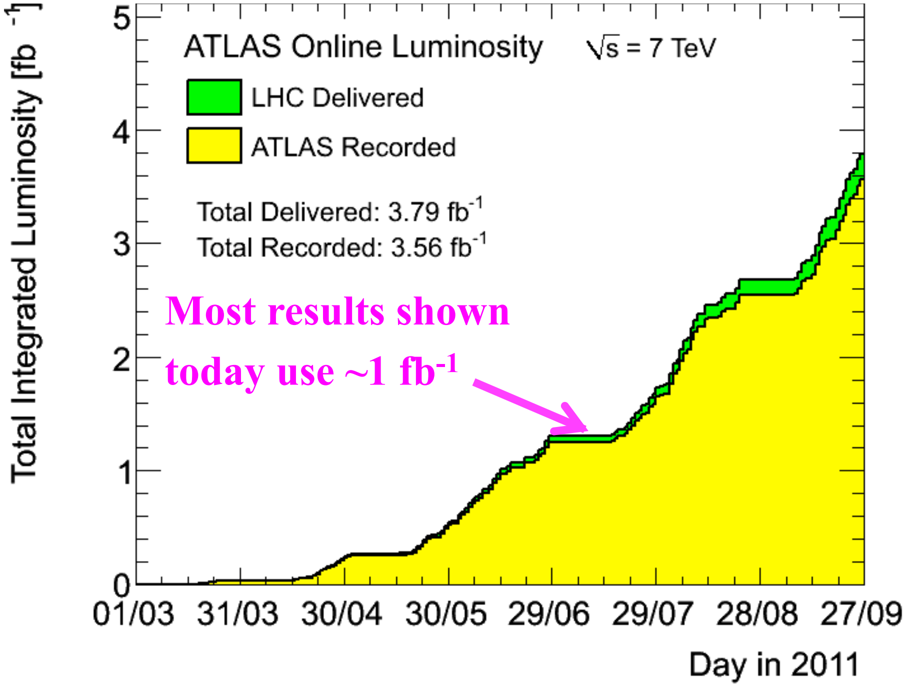
LHC Performance

- LHC operating with 1380 bunches (max. possible given current 50 ns separation)
- In April 2011, LHC exceeded Tevatron as highest luminosity hadron collider
- 2011 LHC goals: reach instantaneous lumi. of ~ 10^{33} cm^{-2} s^{-1} and deliver ~ 1 fb^{-1}
- LHC has recently reached instantaneous lumi. of ~ 3.3 x 10^{33} cm^{-2} s^{-1} (beam power ~ 107 MJ!) and has already delivered ~ 3.8 fb^{-1} !

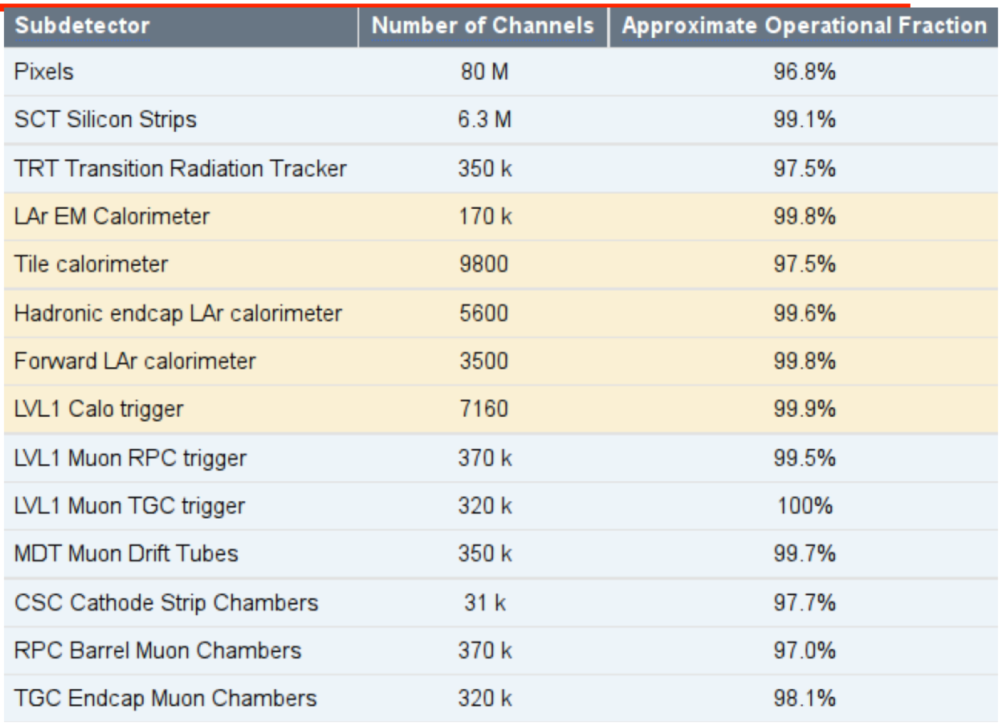




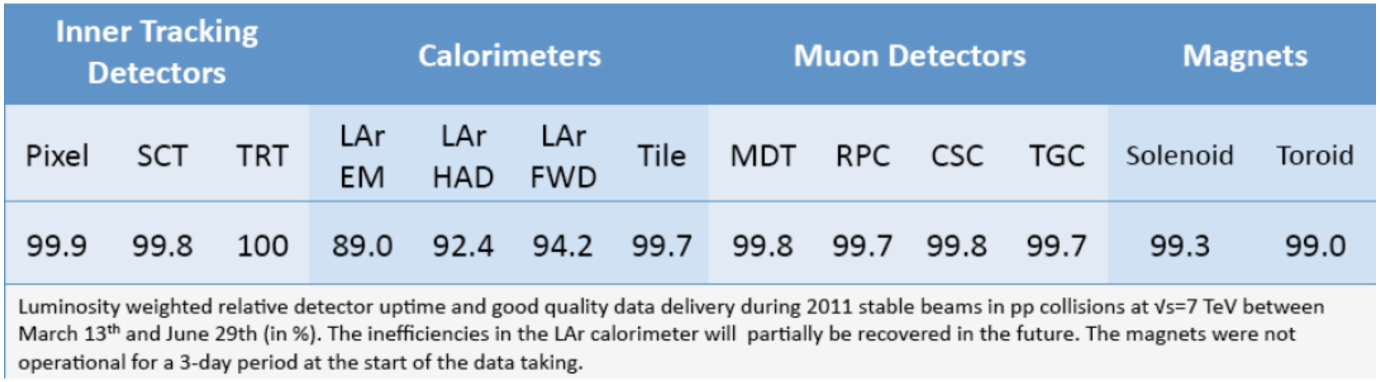
Most results shown today use ~1 fb^{-1}

ATLAS Data Taking Performance

- **Typ. ATLAS data taking efficiency is ~ 94%**
- **Detector subsystems have >~ 97% of their channels operational**



Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	96.8%
SCT Silicon Strips	6.3 M	99.1%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.8%
Tile calorimeter	9800	97.5%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	99.9%
LVL1 Muon RPC trigger	370 k	99.5%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	97.7%
RPC Barrel Muon Chambers	370 k	97.0%
TGC Endcap Muon Chambers	320 k	98.1%



Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.8	100	89.0	92.4	94.2	99.7	99.8	99.7	99.8	99.7	99.3	99.0

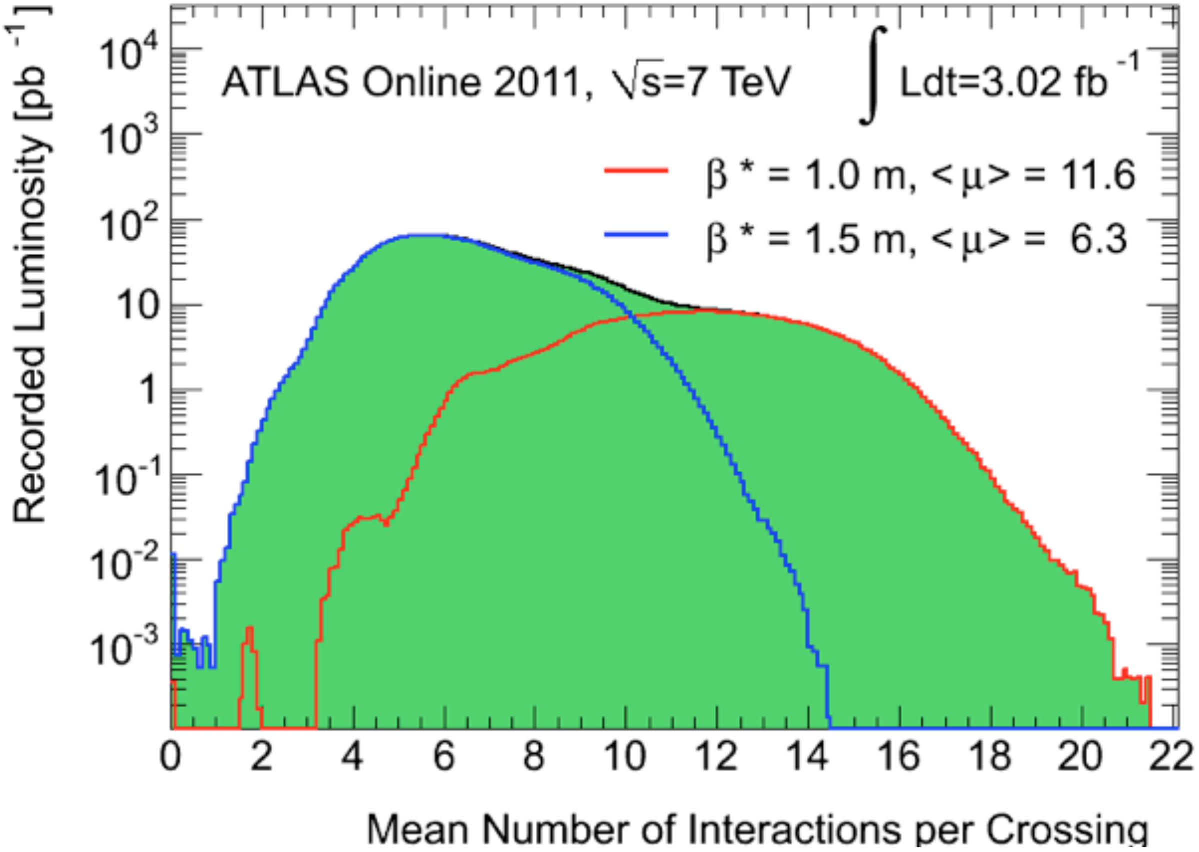
Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at $\sqrt{s}$=7 TeV between March 13th and June 29th (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future. The magnets were not operational for a 3-day period at the start of the data taking.

Fraction of data that is good for analysis

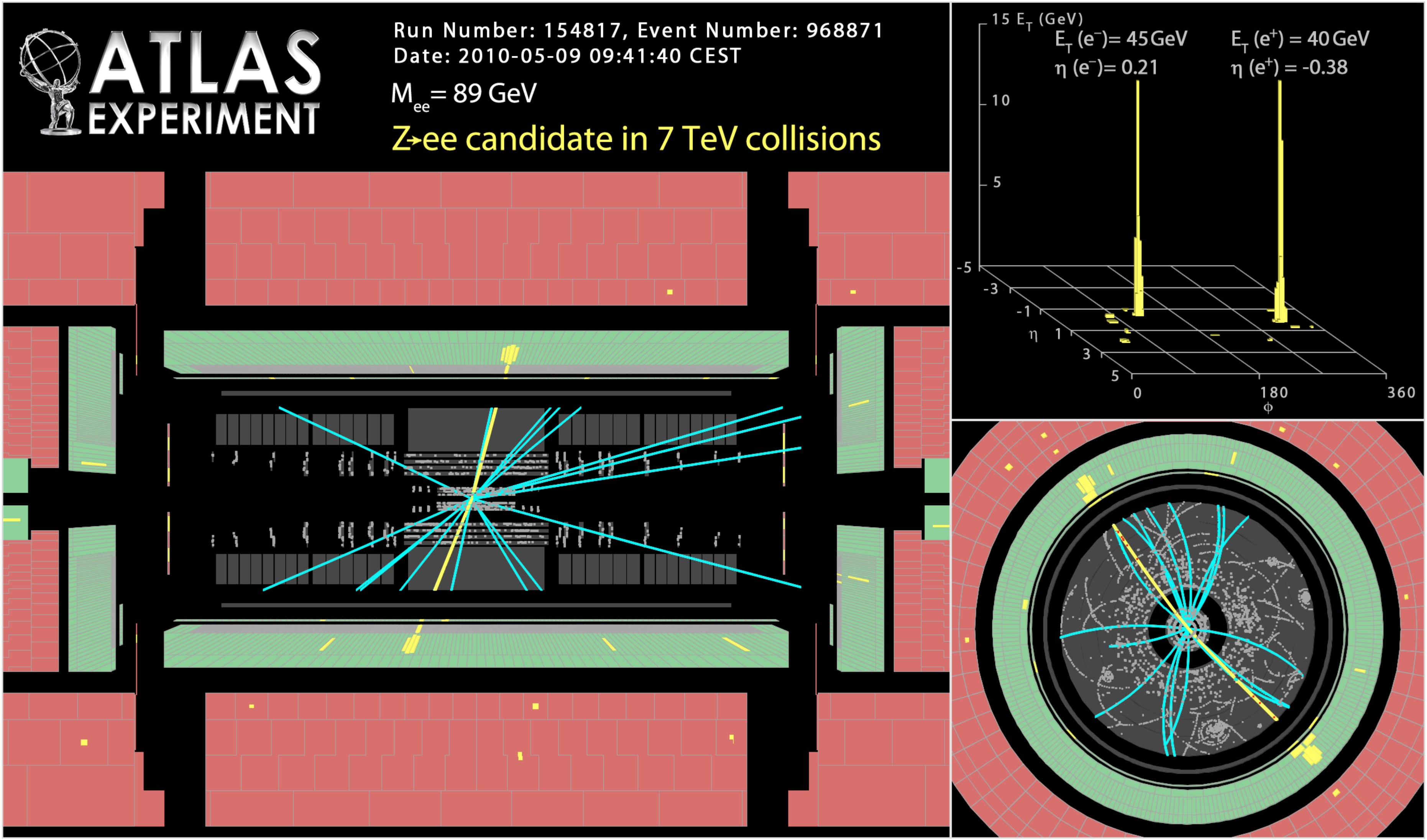
(LAr > 96% after recent reprocessing)

Pileup !

- During LHC planning phase, had assumed 2 phases of (25 ns) operation:
  - 3 yrs at 1E33 (30 fb^{-1}) ➔ essentially no pileup (~2 collisions/bunch crossing)
  - Then increase to 1E34 (design lumi) ➔ ~23 interactions/bunch crossing
- With recent LHC run conditions (L$_{inst.}$ ~ 3E33 at 50 ns), have already reached an avg of ~12 collisions/bunch crossing (and some evts with > 20 interactions/bc)



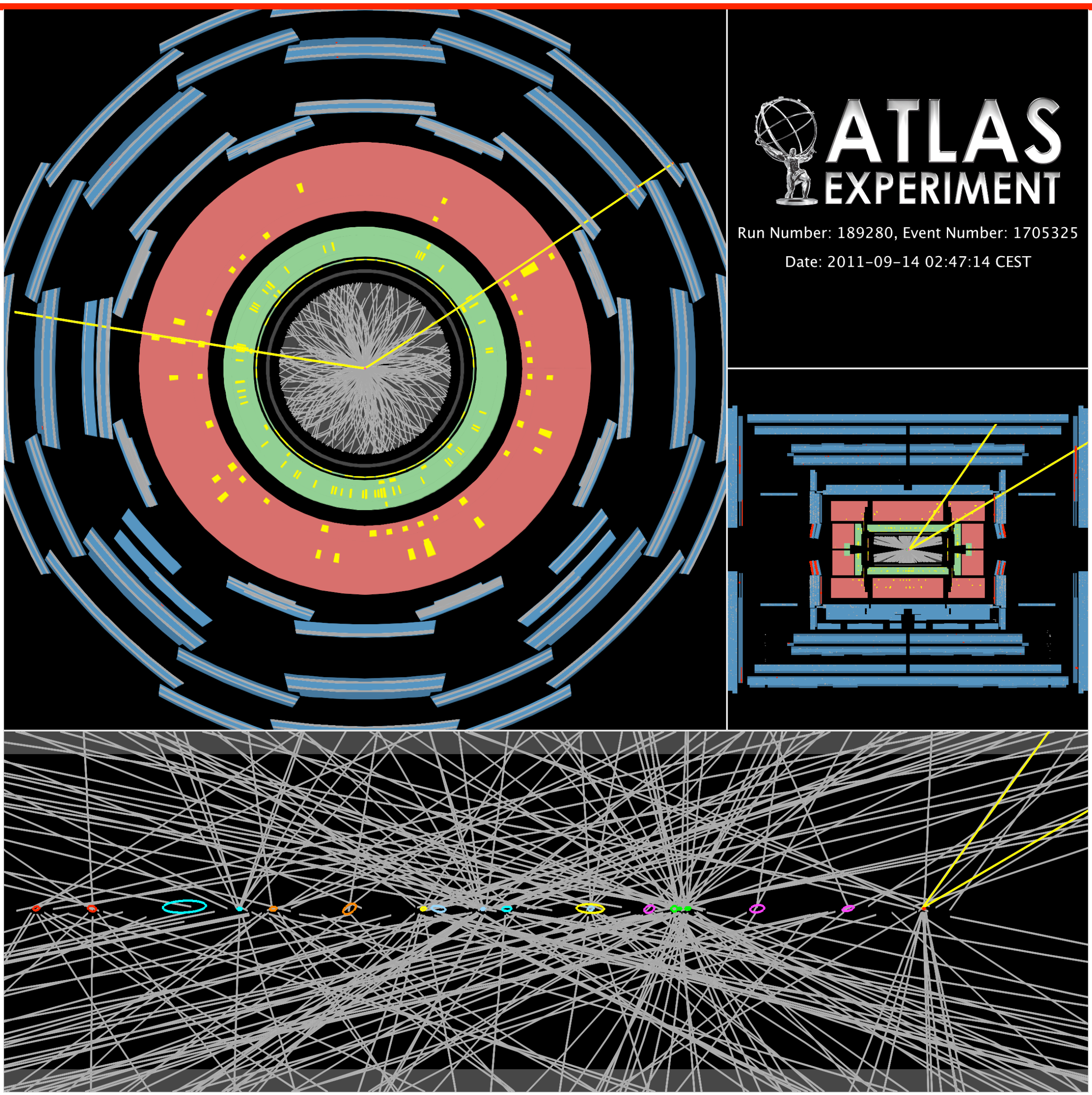
Z → ee Candidate in 2010 Data Taking



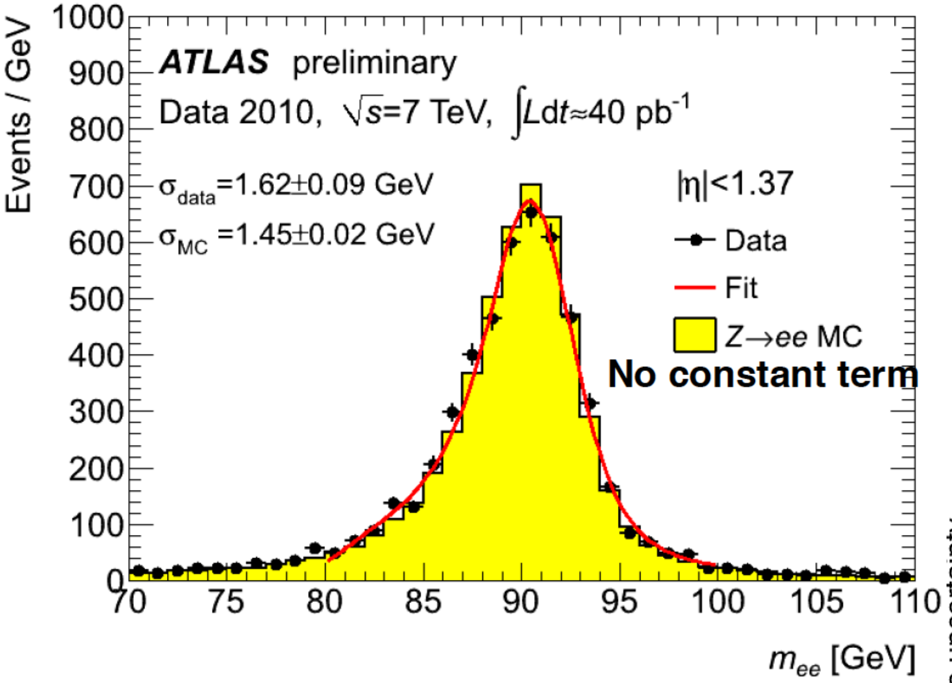
Pileup in 2011 Data!

Z → μμ event

with 20 vertices!



ATLAS Performance: Electrons (and Photons)



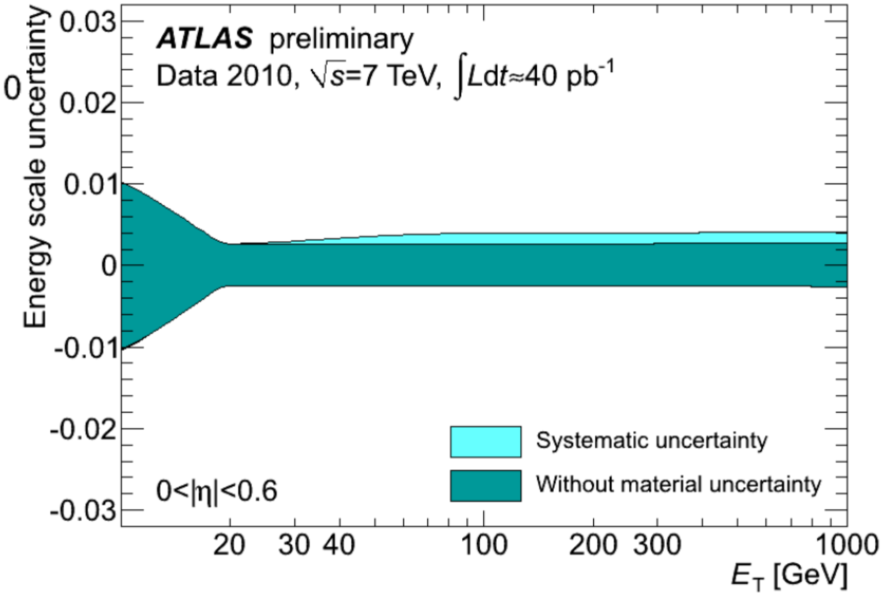
No constant term

Constant term in EM energy resolution (design goal = 0.7%)

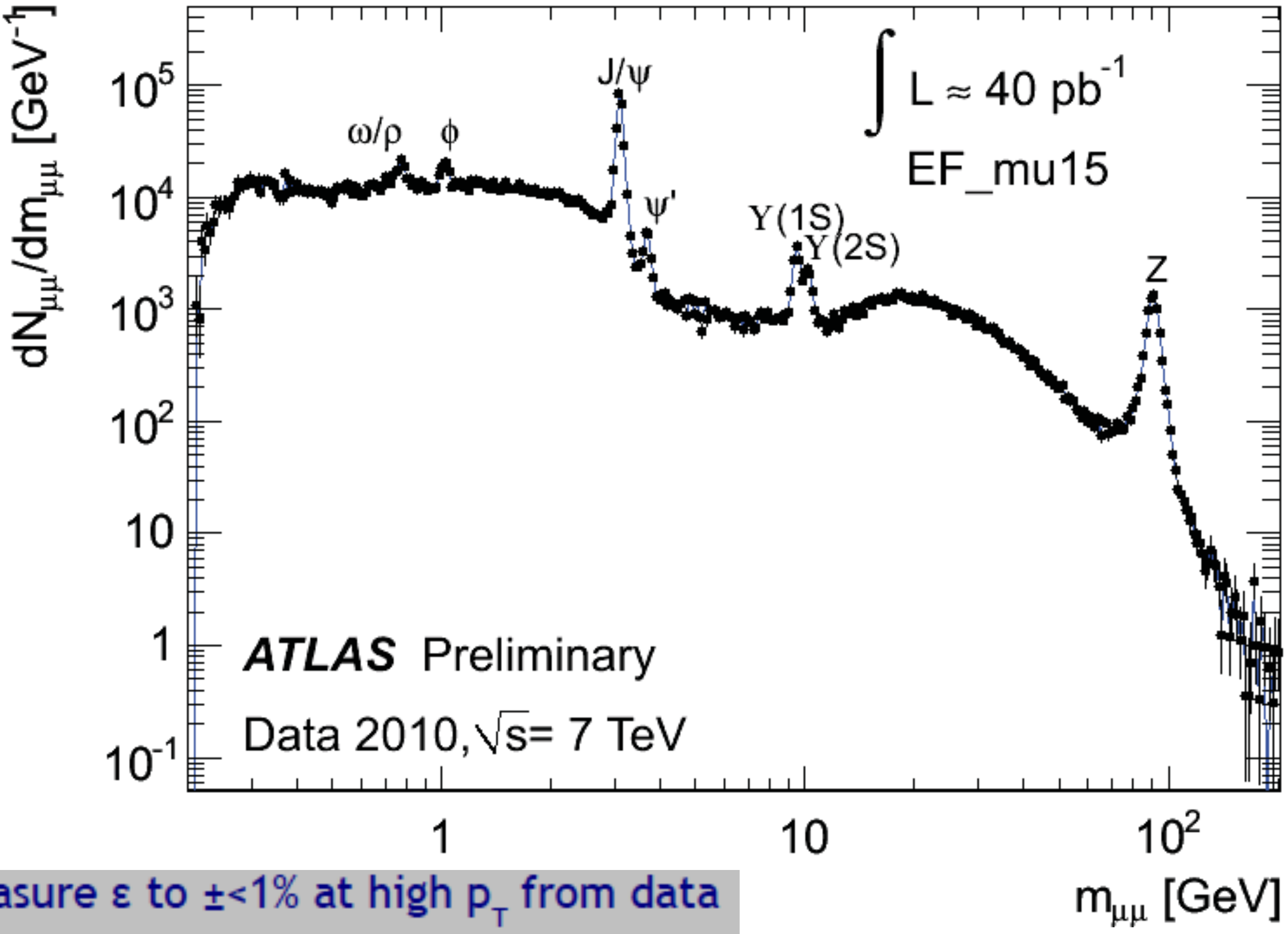
$1.1^{+0.5}_{-0.6}\%$ in the barrel

$1.8^{+0.5}_{-0.6}\%$ in the End-Cap

Uncertainty in EM energy scale ~ 0.3 – 0.6%



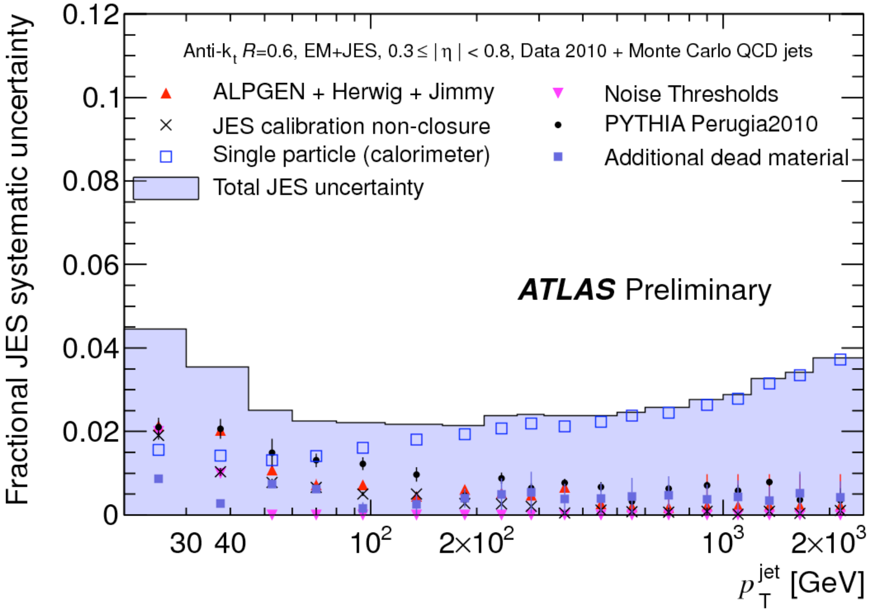
ATLAS Performance: Muons



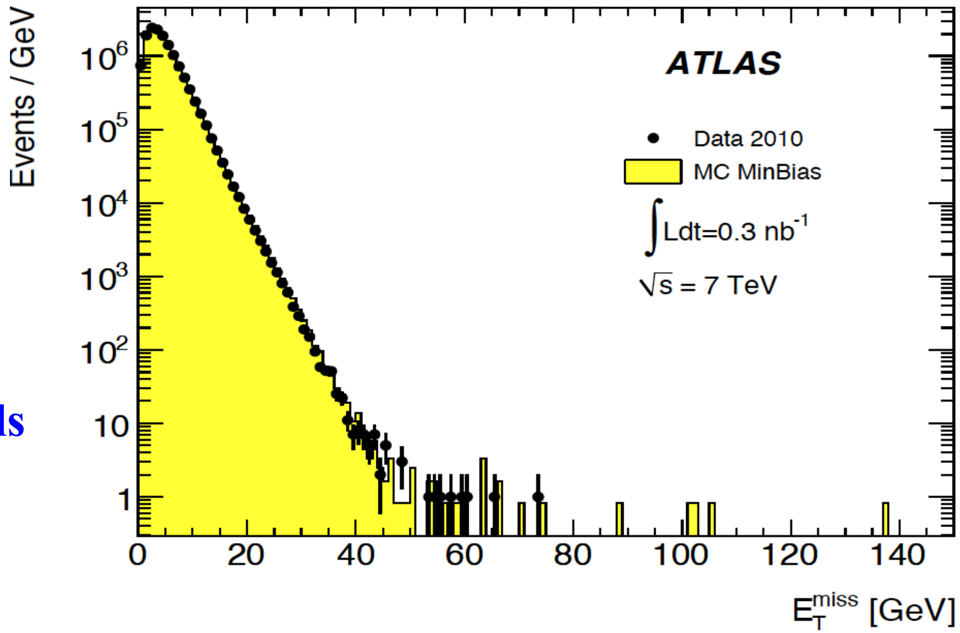
Measure ε to ±<1% at high p_T from data

$\Delta p_T/p_T$=13% at 1 TeV (barrel)

ATLAS Performance: Jets and $E_T$miss

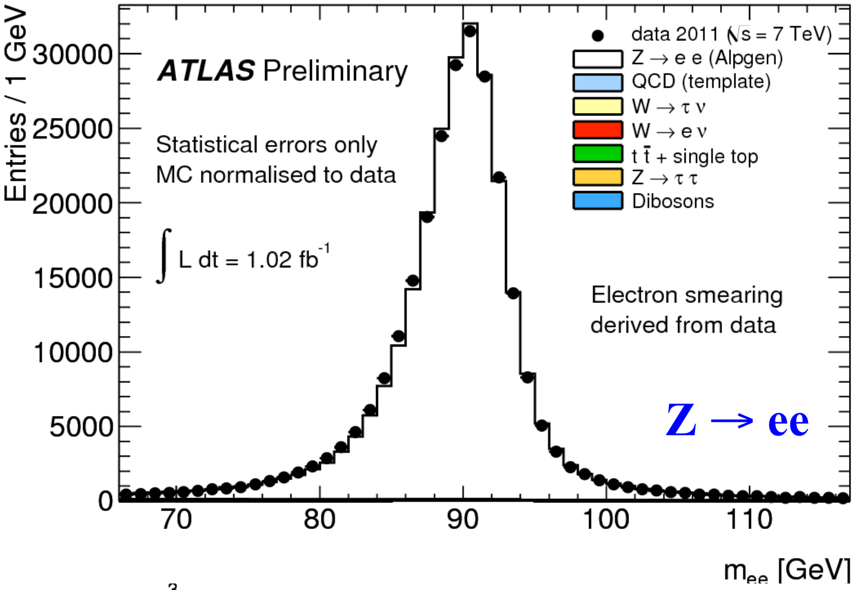


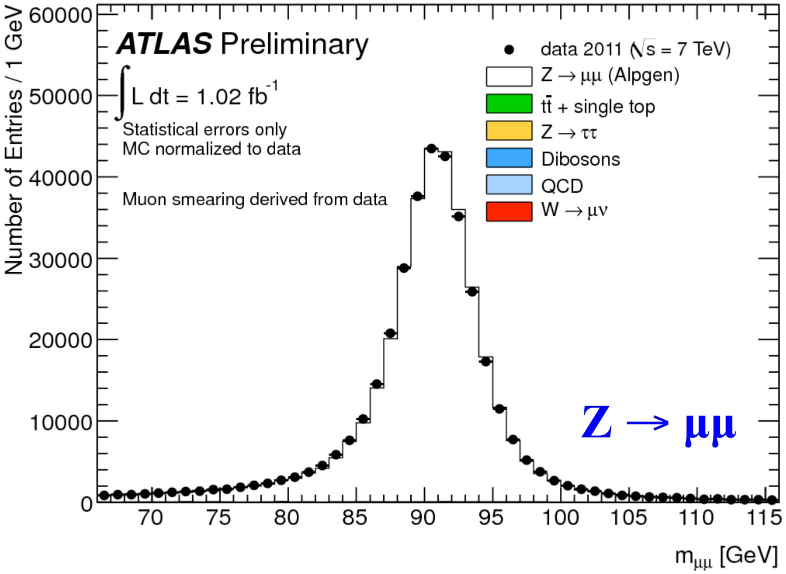
Uncertainty in jet energy scale
~ 3-4% in 2010 data
(slightly larger in 2011 so far, due to pileup)

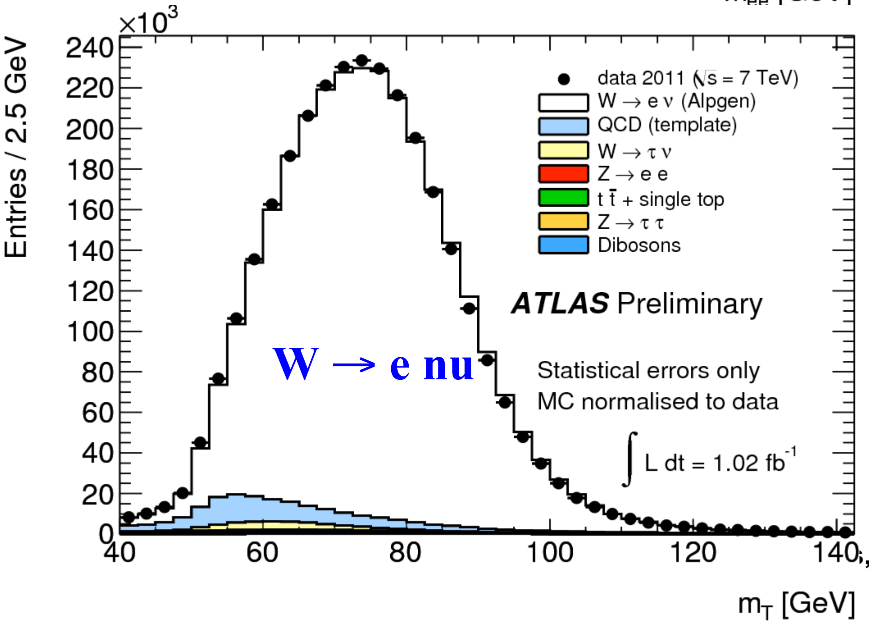


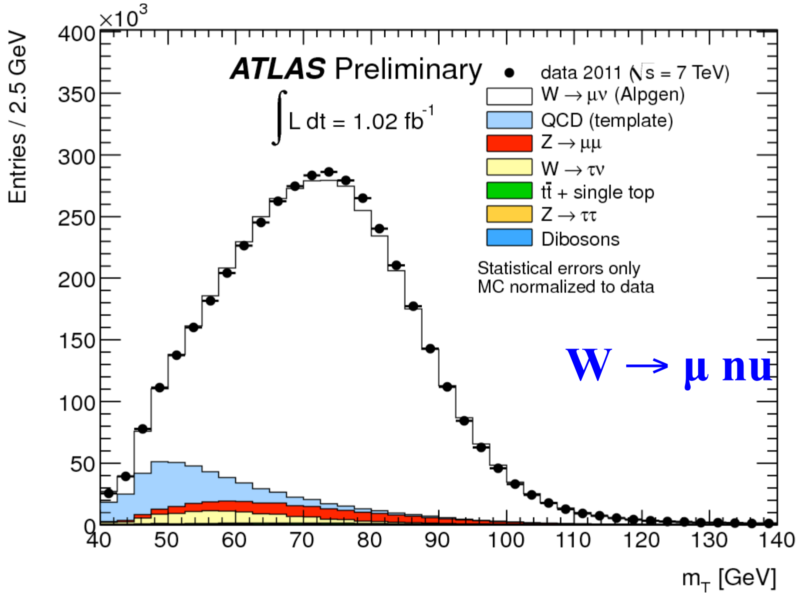
Good data/MC agreement in tails of $E_T$miss distribution

“Rediscovering” the Standard Model

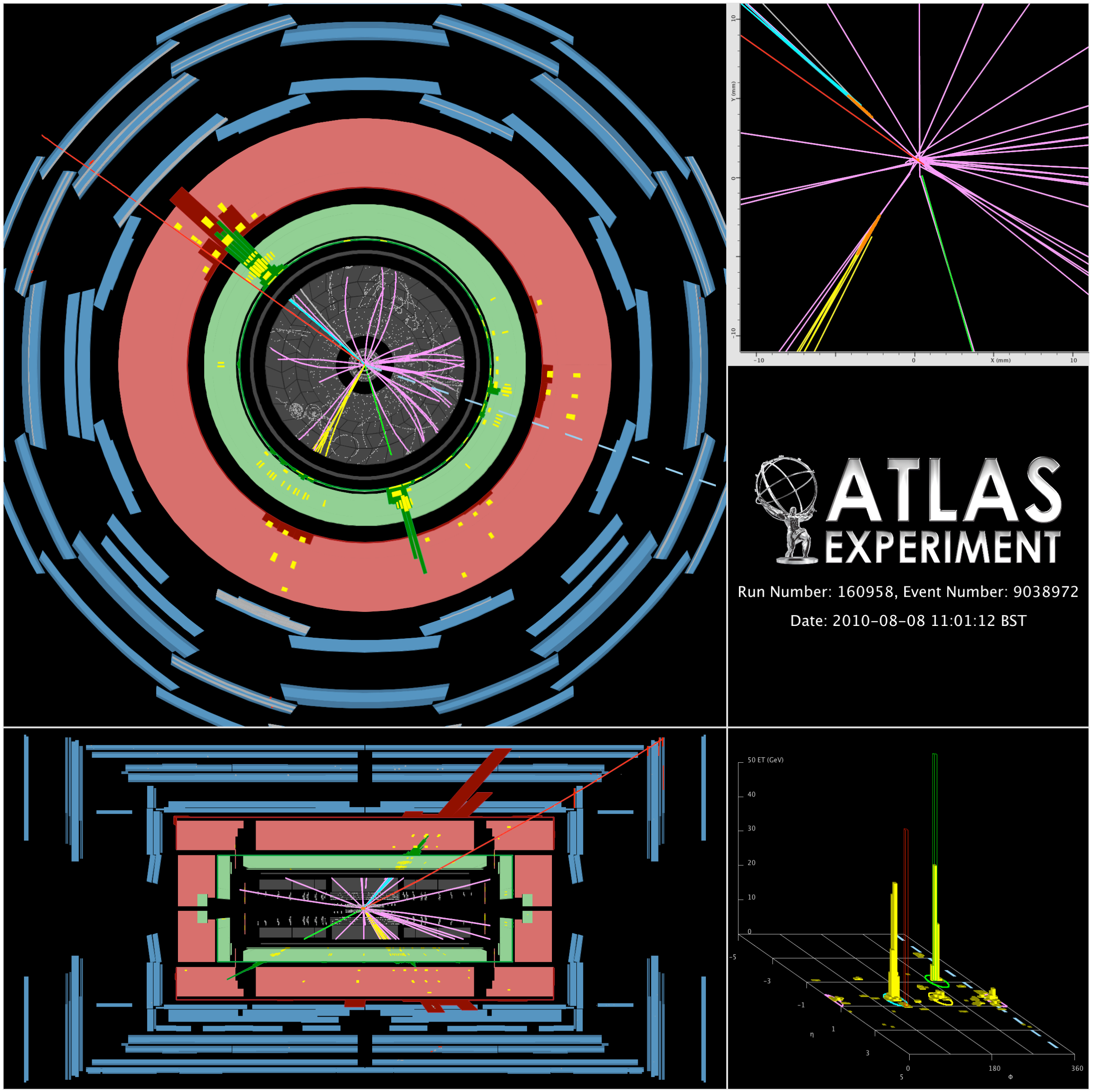






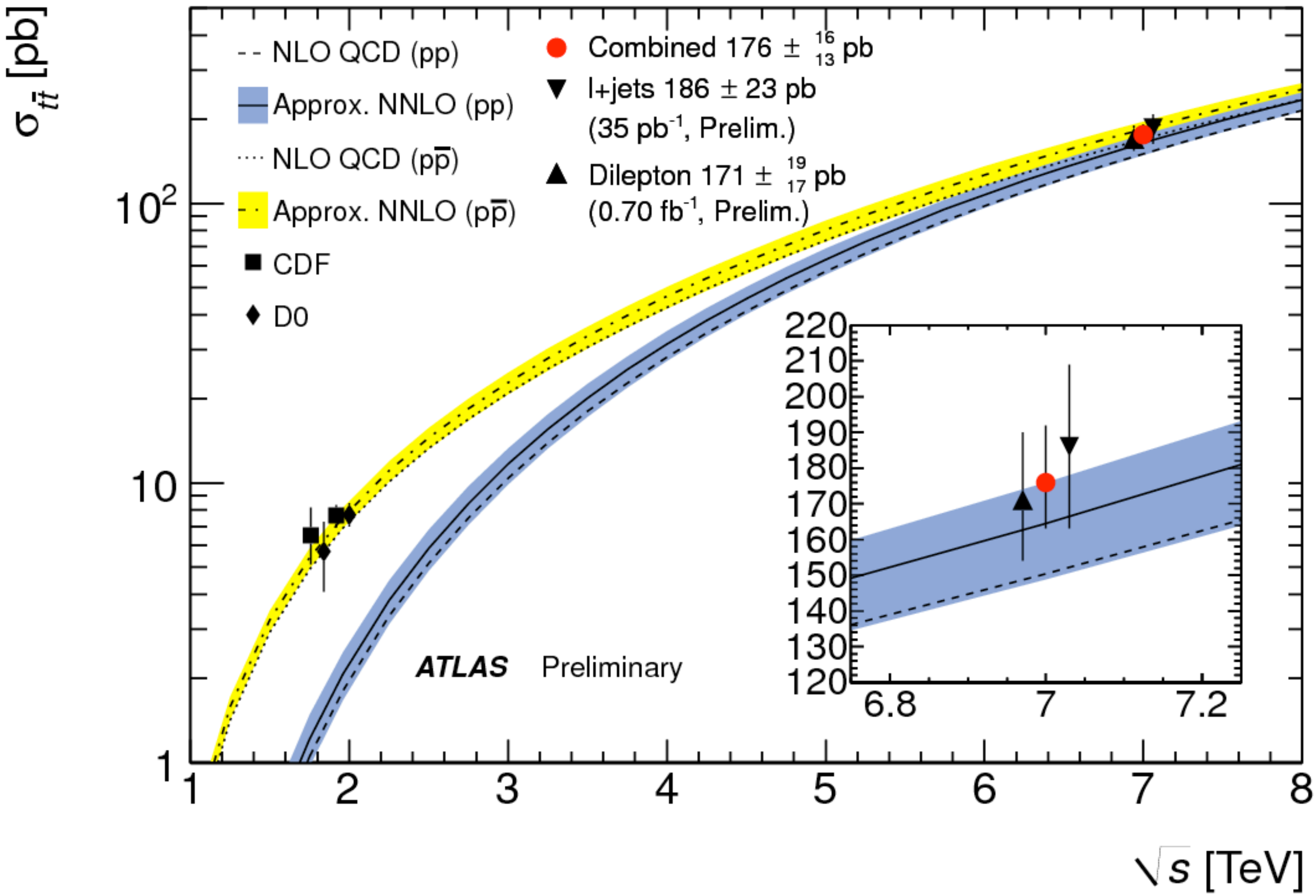


t tbar → eμ + X Candidate Event

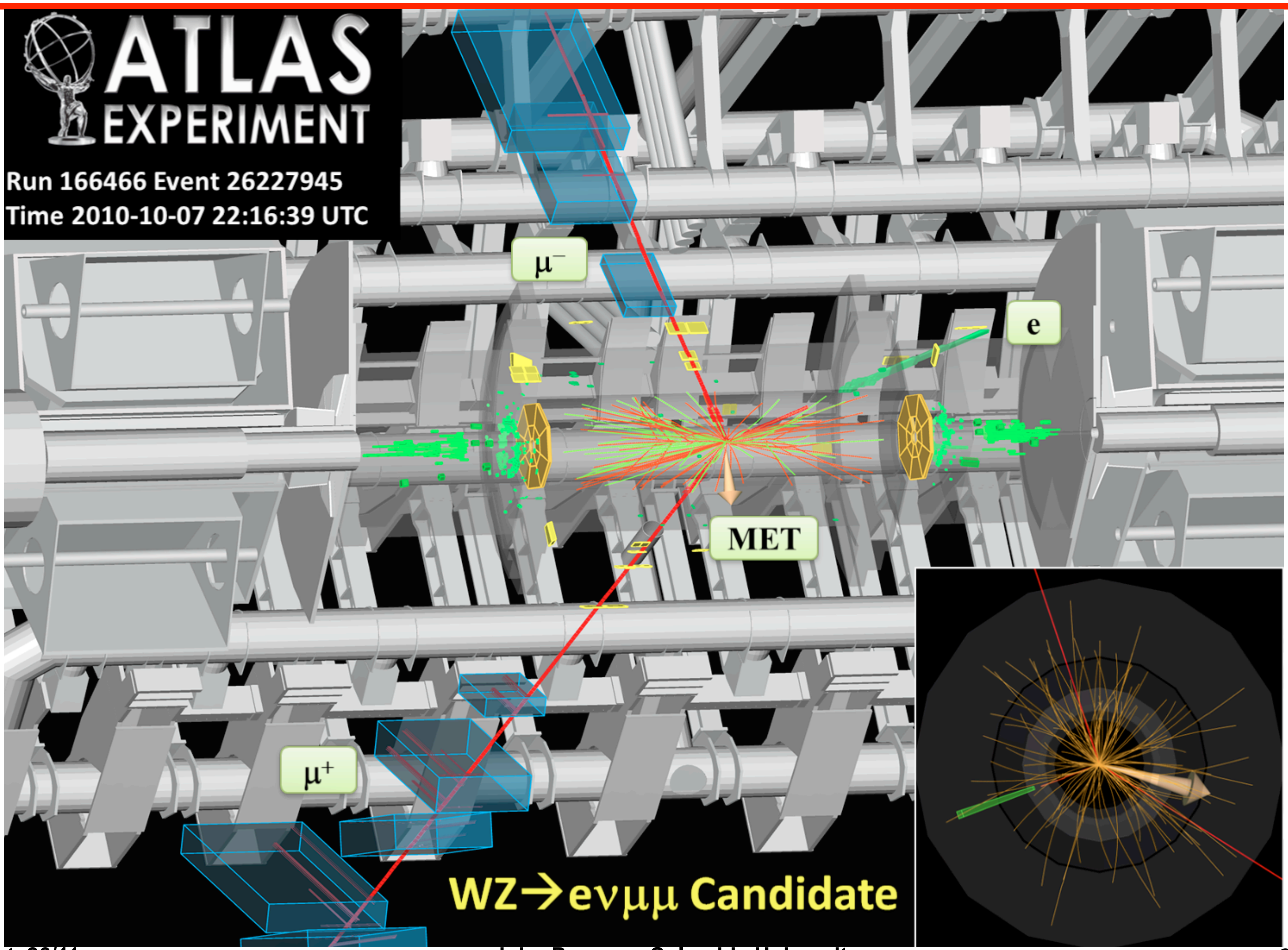


2 b-tagged jets

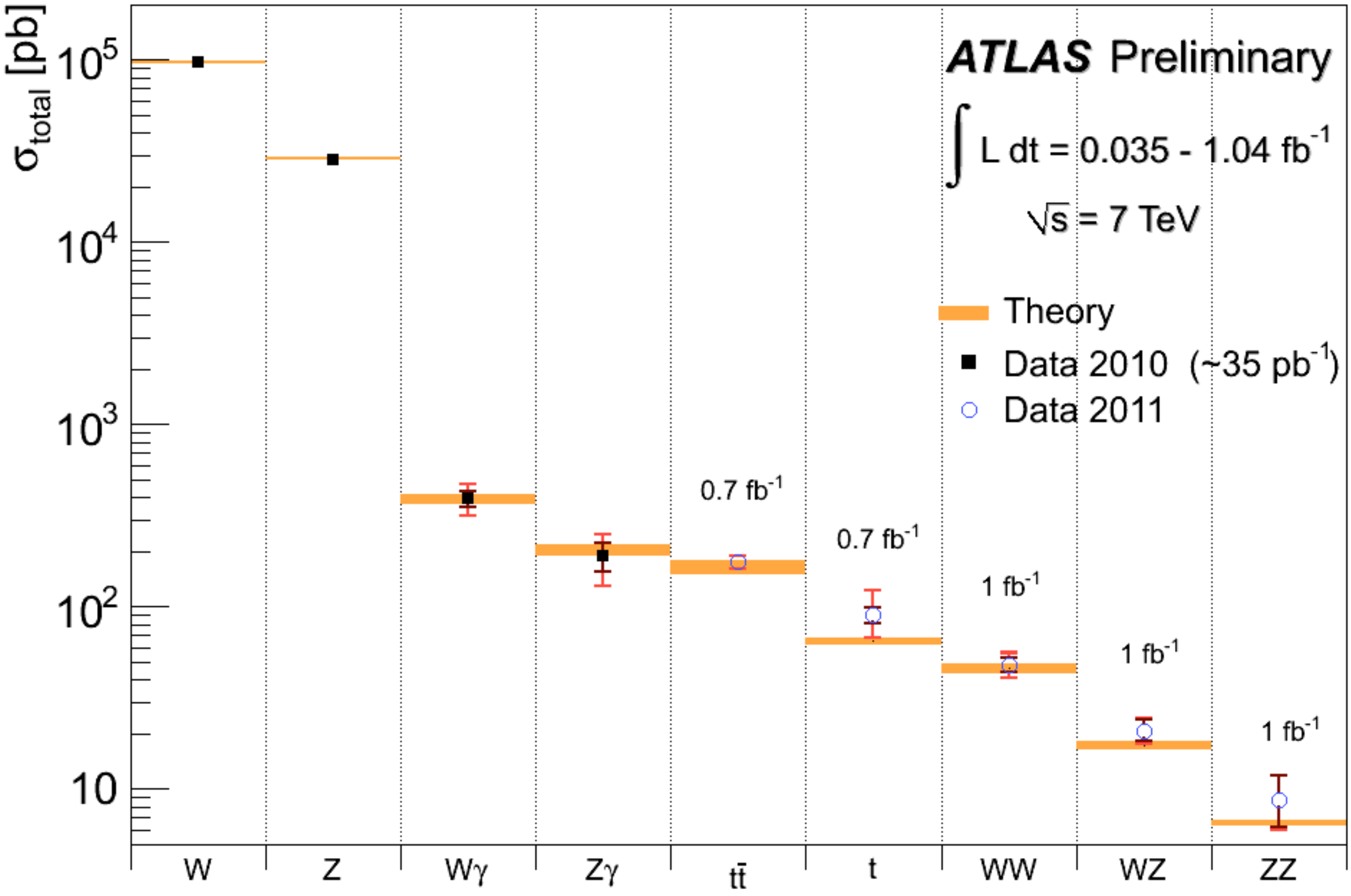
Measurement of t tbar Cross Section



Diboson Production

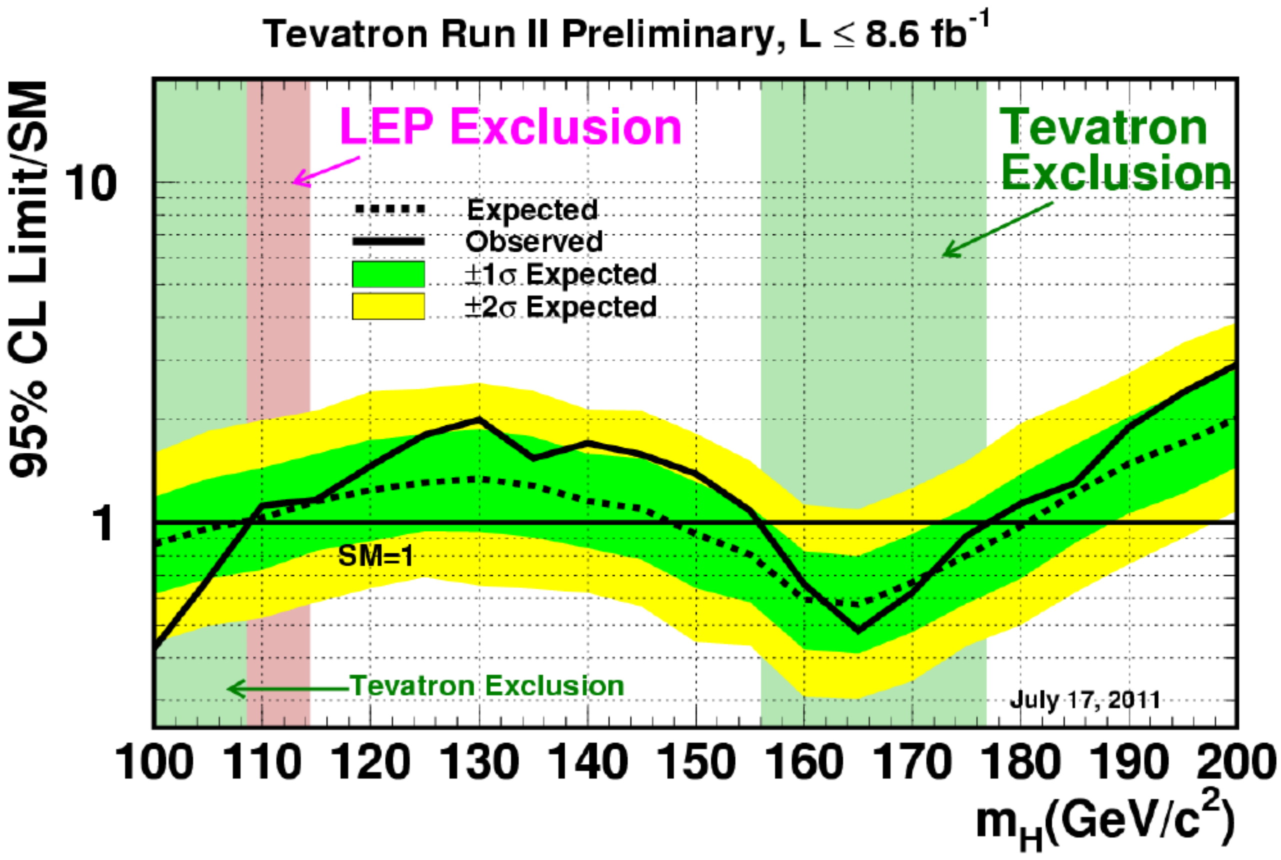


SM Cross Section Measurements



SM Higgs Situation Before LHC Results

LEP exclusion: m(H) < 114.4 GeV

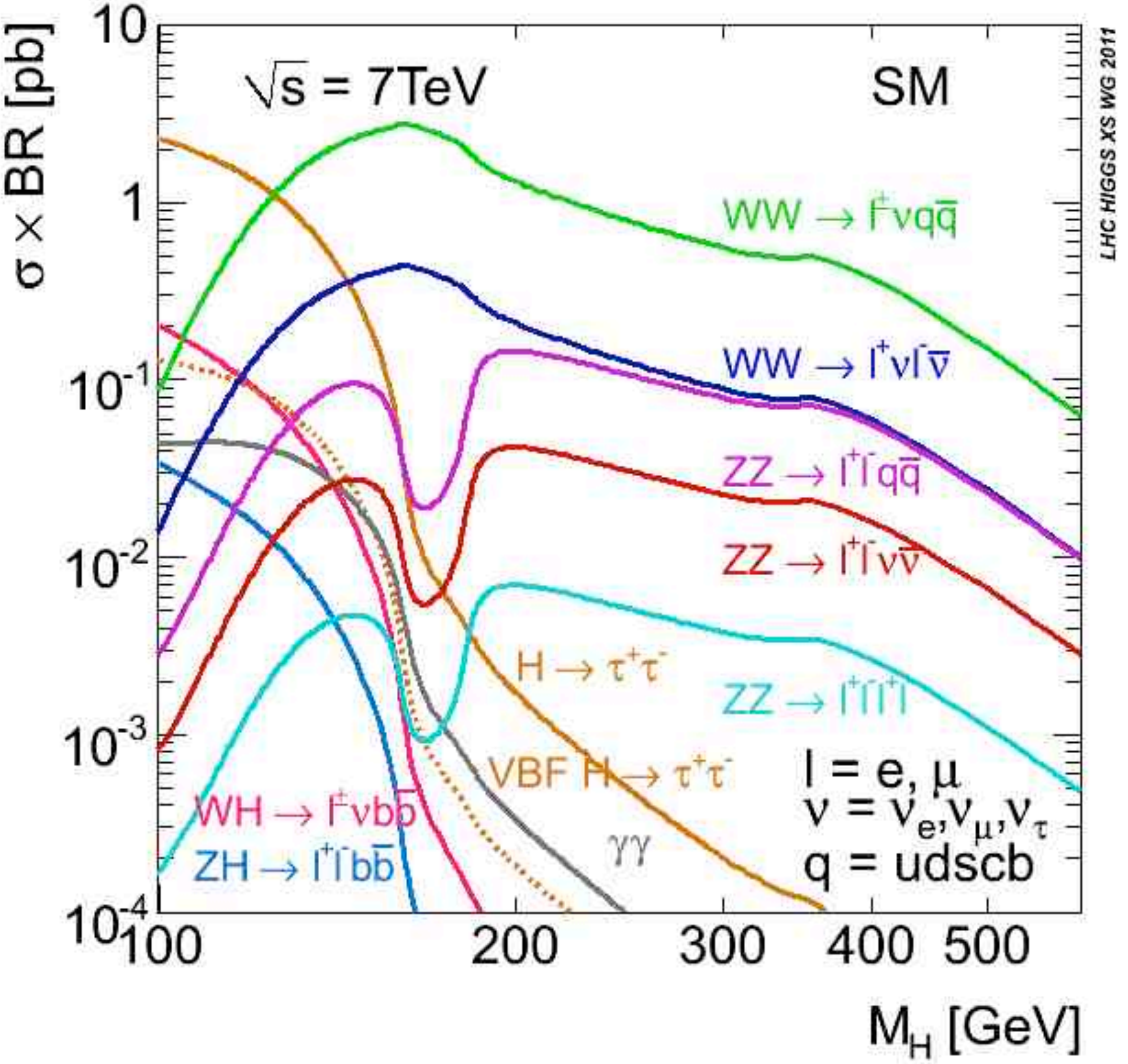


Latest Tevatron combination

Observed exclusion:
100-109 and 156-177 GeV

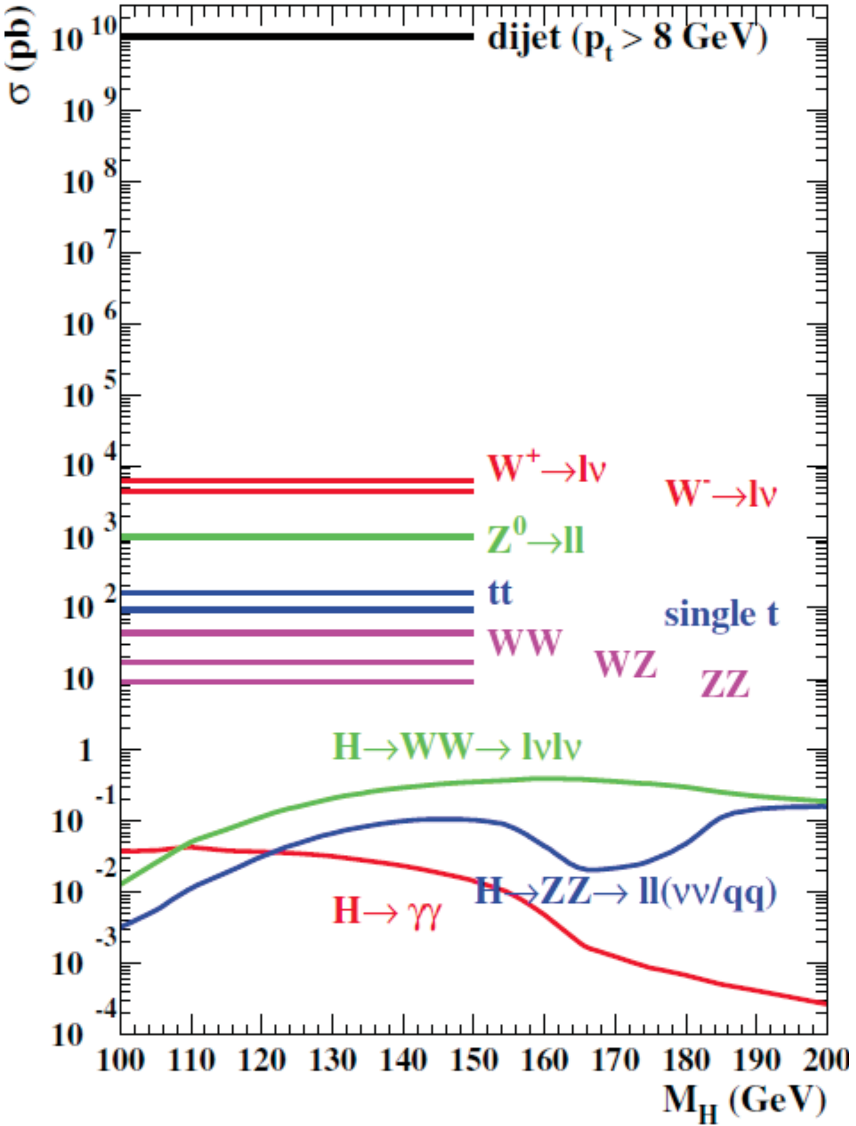
Expected exclusion:
100-108 and 148-181 GeV

SM Higgs Search Channels



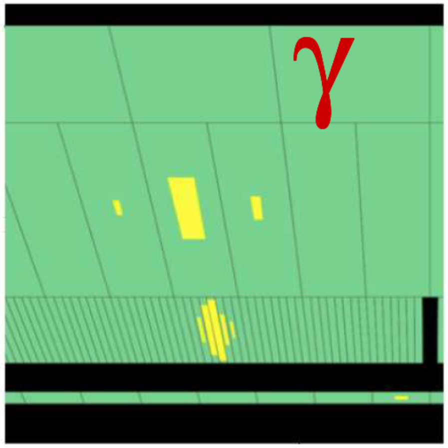
The SM Higgs Challenge !

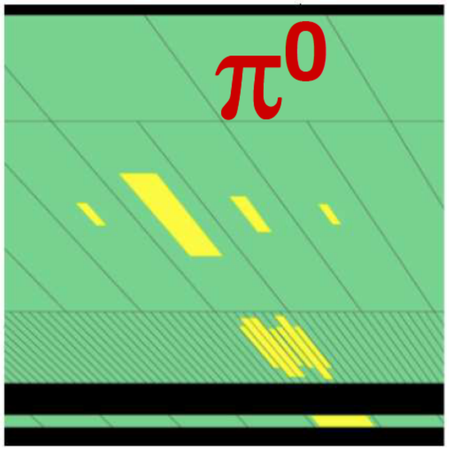
- **< 1 detectable Higgs boson per 10^{12} collisions !**



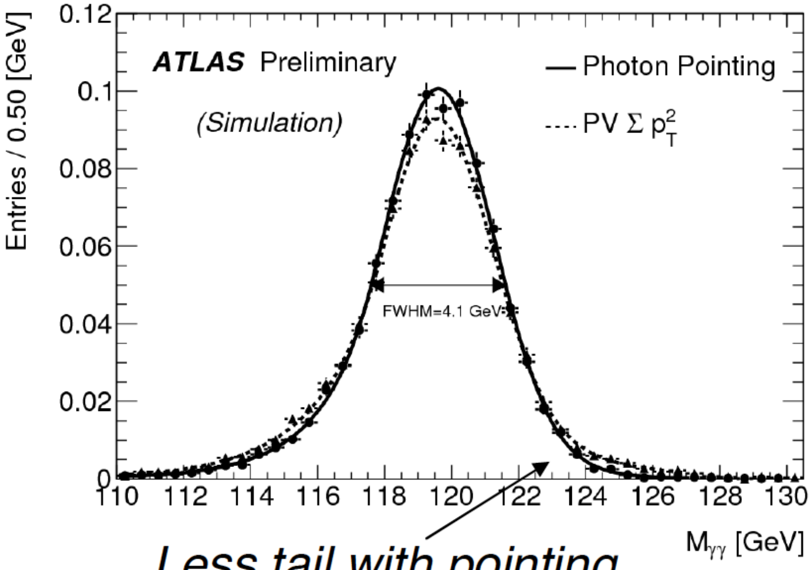
H → $\gamma\gamma$

- Need excellent γ-jet separation to control reducible jet-jet and γ-jet bkgnds, which have cross-sections ~ $2x10^6$ and 800 times larger than irreducible $\gamma\gamma$
  - An important ingredient is γ-π^0 separation, using fine granularity of EMcalorimeter





<μ>~5

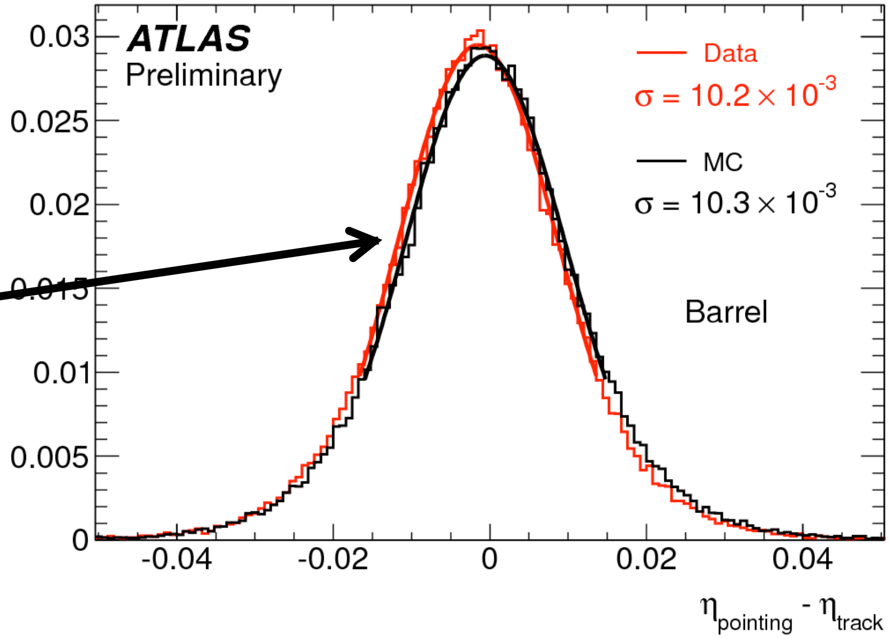


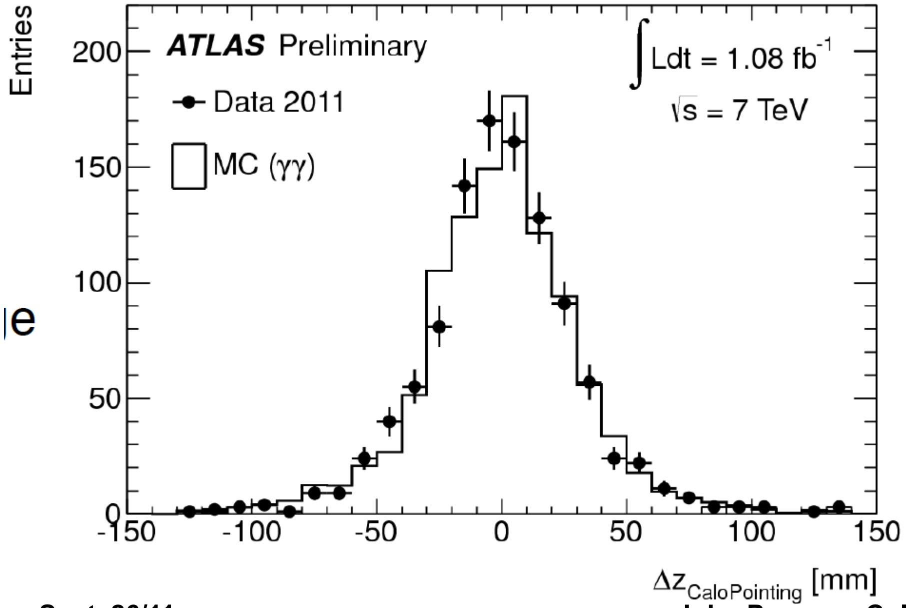
Less tail with pointing

- Need to reconstruct mass peak on top of large irreducible $\gamma\gamma$ bkgnd
  - Requires excellent EM energy res'n as well as ability to find vertex (either by association with tracks or by EMCAL "pointing")
  - As pileup increases, use of pointing will be even more valuable

EM Calorimeter Pointing

- **Can use fine granularity of EM calorimeter to measure trajectory of photons (and therefore point back to correct production vertex)**
- **Validate pointing performance with Z → ee events**



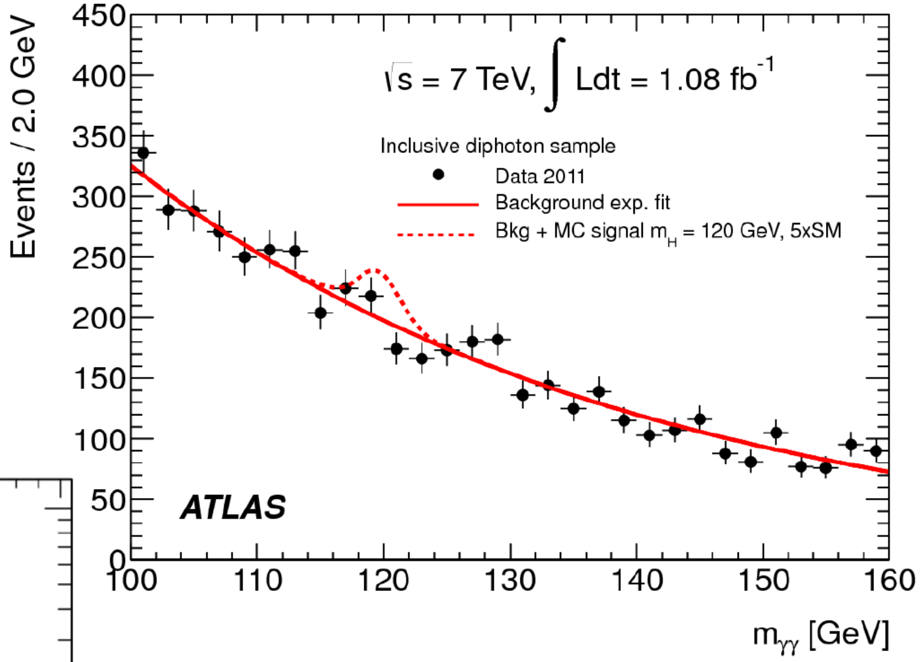


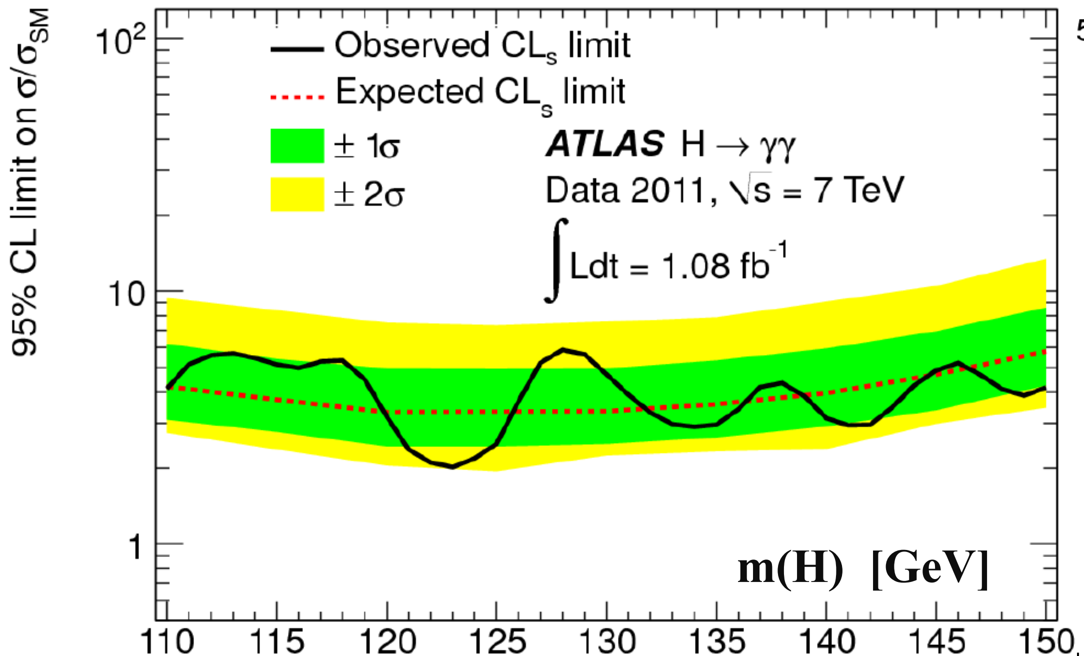
- **Angular resolution corresponds to resolution of the average z-position at the beamline of the 2 photons ~ 1.5 cm**

(cf. beam spread of σ ~ 5.6 cm)

$H \rightarrow \gamma\gamma$ Results

- After final selection, purity of sample (ie. % of true diphoton events) is ~ 72%
- No excess seen in diphoton invariant mass spectrum





- Set limit on SM Higgs :

  ~ (3-4)X SM cross section, using 1 fb^{-1}

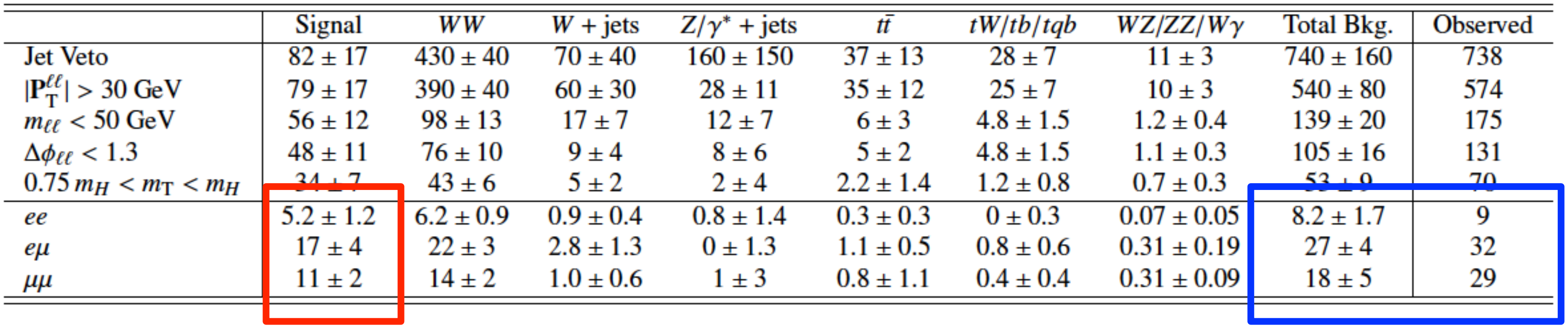
H → $WW^{(*)}$ → lnu lnu

- **Important channel for low/intermediate masses**
- **Main challenge arises from lack of mass peak due to neutrinos**

➔ is essentially a counting experiment

Table 4: The expected numbers of signal ($m_H = 150$ GeV) and background events for the H+0 jet analysis in 1.7 fb^{-1} of integrated luminosity, as well as the observed numbers of events in data. The yields for the ee, $e\mu$, and $\mu\mu$ channels are added together, the composition in each of the lepton flavor channels is shown only for the final stage of the selections. The W+jets background is entirely determined from data, whereas for the other processes the expectations are taken from simulation. The uncertainties shown are the combination of the statistical and all systematic uncertainties.

H + 0 jet channel results with 1.7 fb^{-1}



	Signal	WW	W + jets	Z/γ^* + jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
Jet Veto	82 ± 17	430 ± 40	70 ± 40	160 ± 150	37 ± 13	28 ± 7	11 ± 3	740 ± 160	738
$\lvert \mathbf{P}_T^{\ell\ell} \rvert > 30$ GeV	79 ± 17	390 ± 40	60 ± 30	28 ± 11	35 ± 12	25 ± 7	10 ± 3	540 ± 80	574
$m_{\ell\ell} < 50$ GeV	56 ± 12	98 ± 13	17 ± 7	12 ± 7	6 ± 3	4.8 ± 1.5	1.2 ± 0.4	139 ± 20	175
$\Delta\phi_{\ell\ell} < 1.3$	48 ± 11	76 ± 10	9 ± 4	8 ± 6	5 ± 2	4.8 ± 1.5	1.1 ± 0.3	105 ± 16	131
$0.75\, m_H < m_T < m_H$	34 ± 7	43 ± 6	5 ± 2	2 ± 4	2.2 ± 1.4	1.2 ± 0.8	0.7 ± 0.3	53 ± 9	70
ee	5.2 ± 1.2	6.2 ± 0.9	0.9 ± 0.4	0.8 ± 1.4	0.3 ± 0.3	0 ± 0.3	0.07 ± 0.05	8.2 ± 1.7	9
$e\mu$	17 ± 4	22 ± 3	2.8 ± 1.3	0 ± 1.3	1.1 ± 0.5	0.8 ± 0.6	0.31 ± 0.19	27 ± 4	32
$\mu\mu$	11 ± 2	14 ± 2	1.0 ± 0.6	1 ± 3	0.8 ± 1.1	0.4 ± 0.4	0.31 ± 0.09	18 ± 5	29

Expected signal for m(H) = 150 GeV

Expected bkgnd and observed Nevts

H → $WW^{(*)}$ → lnu lnu

- **H + 1 jet channel results with 1.7 fb^{-1}**

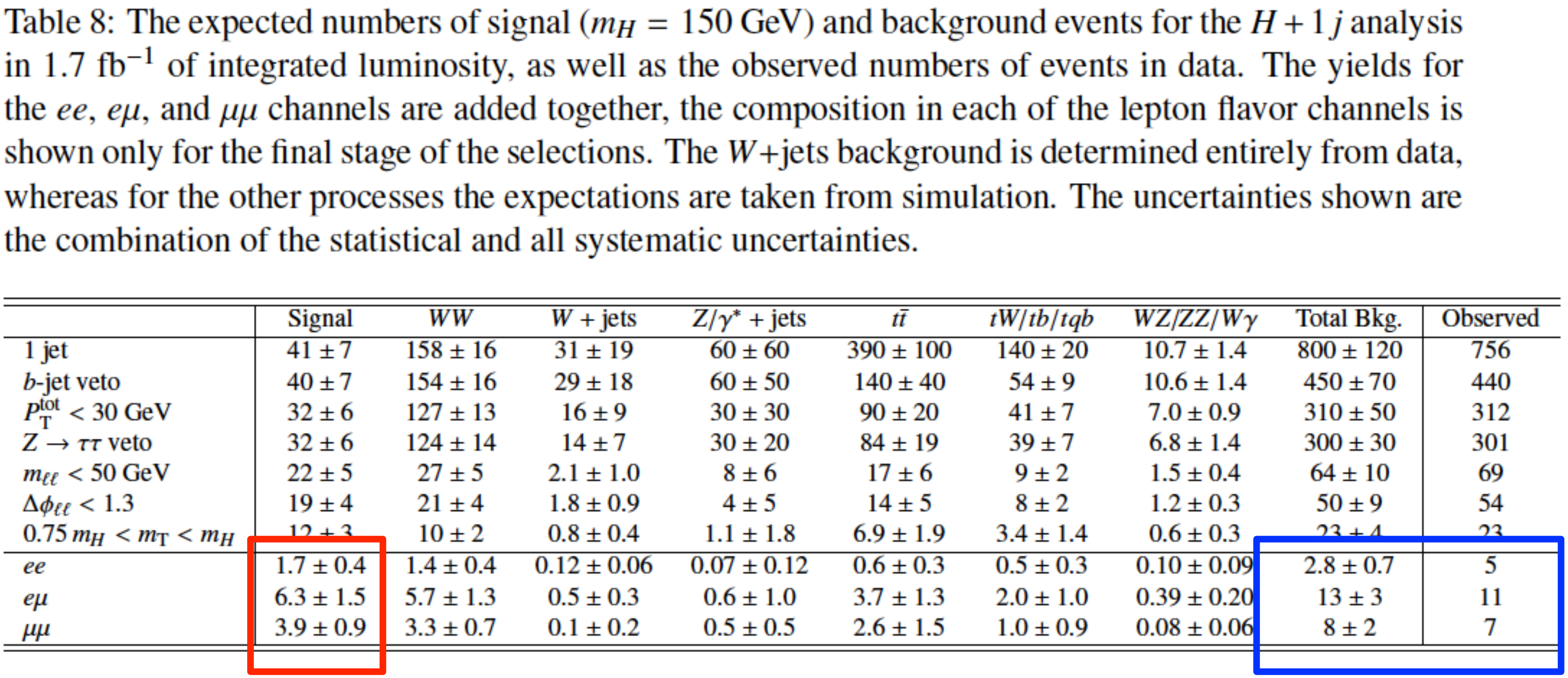


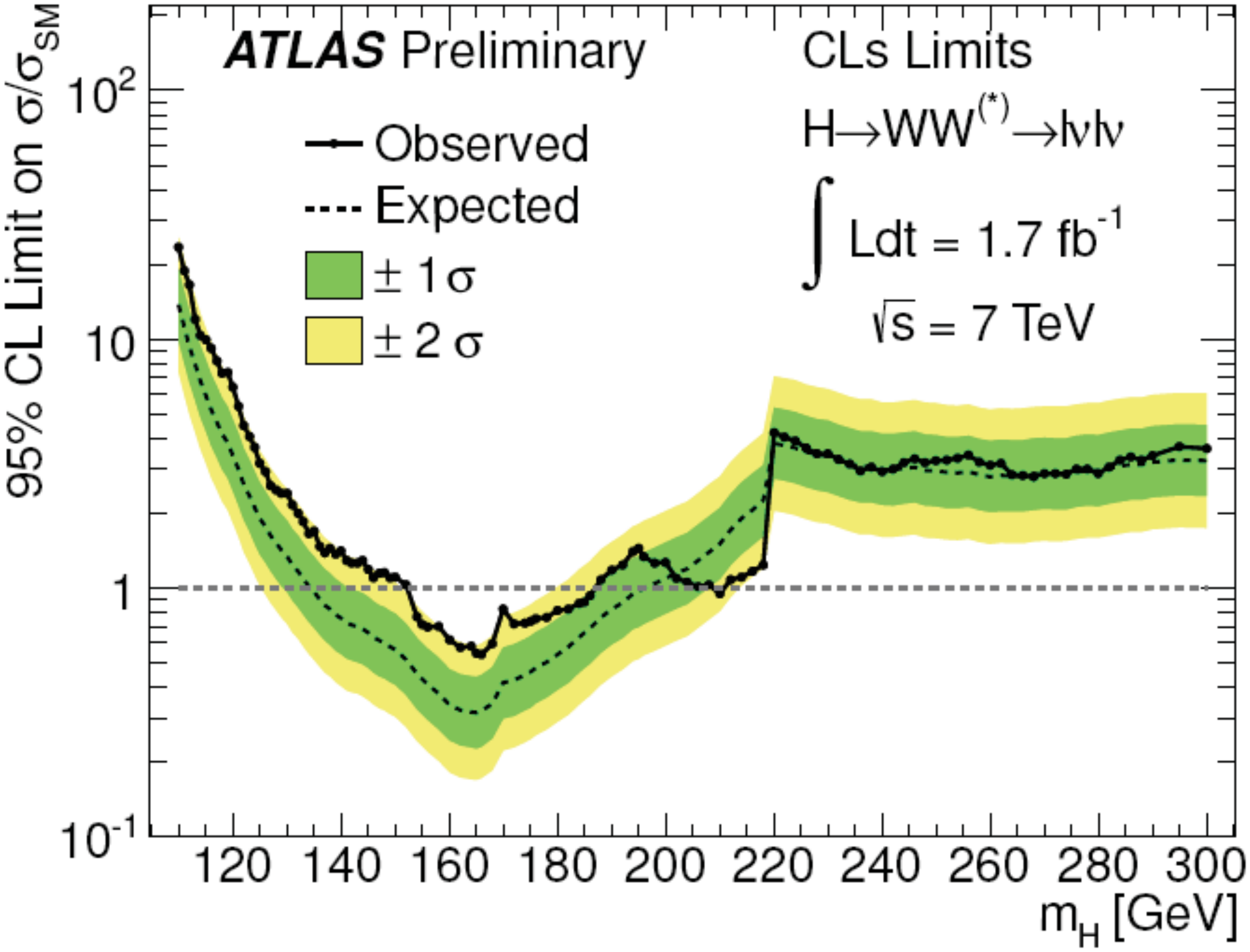
Table 8: The expected numbers of signal (m_H = 150 GeV) and background events for the $H + 1\,j$ analysis in 1.7 fb^{-1} of integrated luminosity, as well as the observed numbers of events in data. The yields for the ee, $e\mu$, and $\mu\mu$ channels are added together, the composition in each of the lepton flavor channels is shown only for the final stage of the selections. The W+jets background is determined entirely from data, whereas for the other processes the expectations are taken from simulation. The uncertainties shown are the combination of the statistical and all systematic uncertainties.

	Signal	WW	W + jets	Z/γ^* + jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
1 jet	41 ± 7	158 ± 16	31 ± 19	60 ± 60	390 ± 100	140 ± 20	10.7 ± 1.4	800 ± 120	756
b-jet veto	40 ± 7	154 ± 16	29 ± 18	60 ± 50	140 ± 40	54 ± 9	10.6 ± 1.4	450 ± 70	440
$P_T^{\text{tot}} < 30$ GeV	32 ± 6	127 ± 13	16 ± 9	30 ± 30	90 ± 20	41 ± 7	7.0 ± 0.9	310 ± 50	312
$Z \rightarrow \tau\tau$ veto	32 ± 6	124 ± 14	14 ± 7	30 ± 20	84 ± 19	39 ± 7	6.8 ± 1.4	300 ± 30	301
$m_{\ell\ell} < 50$ GeV	22 ± 5	27 ± 5	2.1 ± 1.0	8 ± 6	17 ± 6	9 ± 2	1.5 ± 0.4	64 ± 10	69
$\Delta\phi_{\ell\ell} < 1.3$	19 ± 4	21 ± 4	1.8 ± 0.9	4 ± 5	14 ± 5	8 ± 2	1.2 ± 0.3	50 ± 9	54
$0.75\, m_H < m_T < m_H$	12 ± 3	10 ± 2	0.8 ± 0.4	1.1 ± 1.8	6.9 ± 1.9	3.4 ± 1.4	0.6 ± 0.3	23 ± 4	23
ee	1.7 ± 0.4	1.4 ± 0.4	0.12 ± 0.06	0.07 ± 0.12	0.6 ± 0.3	0.5 ± 0.3	0.10 ± 0.09	2.8 ± 0.7	5
$e\mu$	6.3 ± 1.5	5.7 ± 1.3	0.5 ± 0.3	0.6 ± 1.0	3.7 ± 1.3	2.0 ± 1.0	0.39 ± 0.20	13 ± 3	11
$\mu\mu$	3.9 ± 0.9	3.3 ± 0.7	0.1 ± 0.2	0.5 ± 0.5	2.6 ± 1.5	1.0 ± 0.9	0.08 ± 0.06	8 ± 2	7

Expected signal for m(H) = 150 GeV

Expected bkgnd and observed Nevts

Results from H → $WW^{(*)}$ → lnu lnu

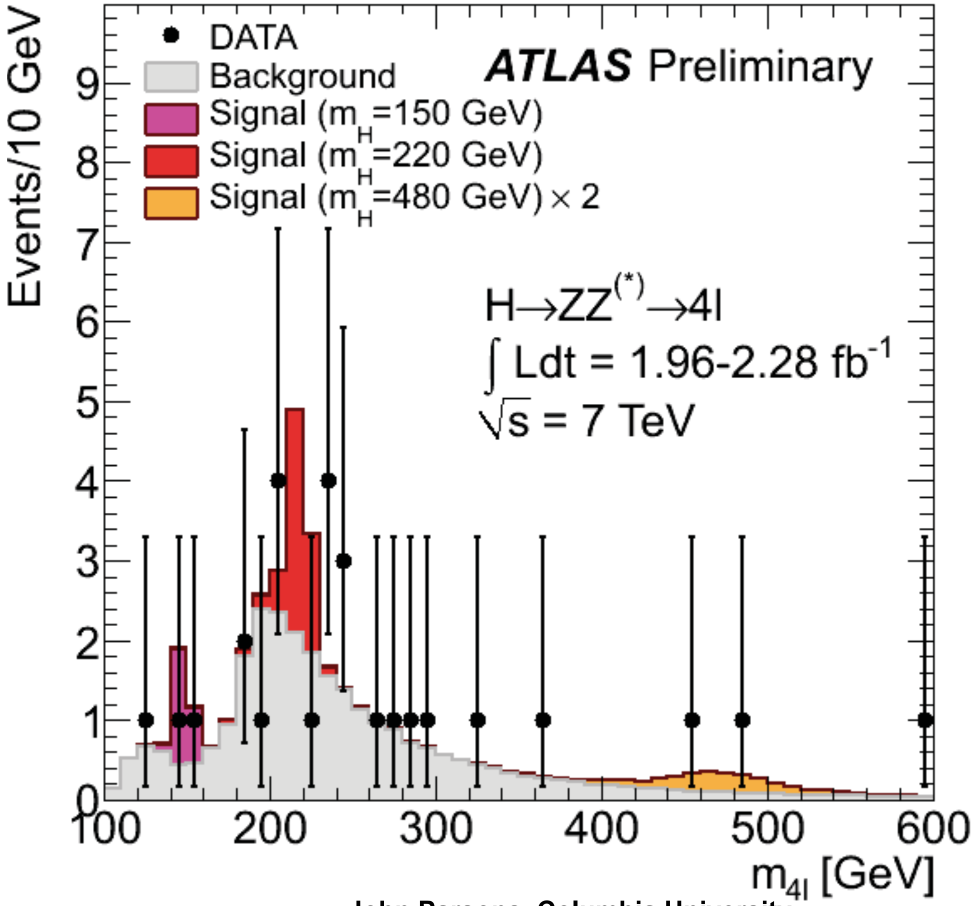


SM Higgs excluded @ 95% CL for m(H) in range 154-185 GeV

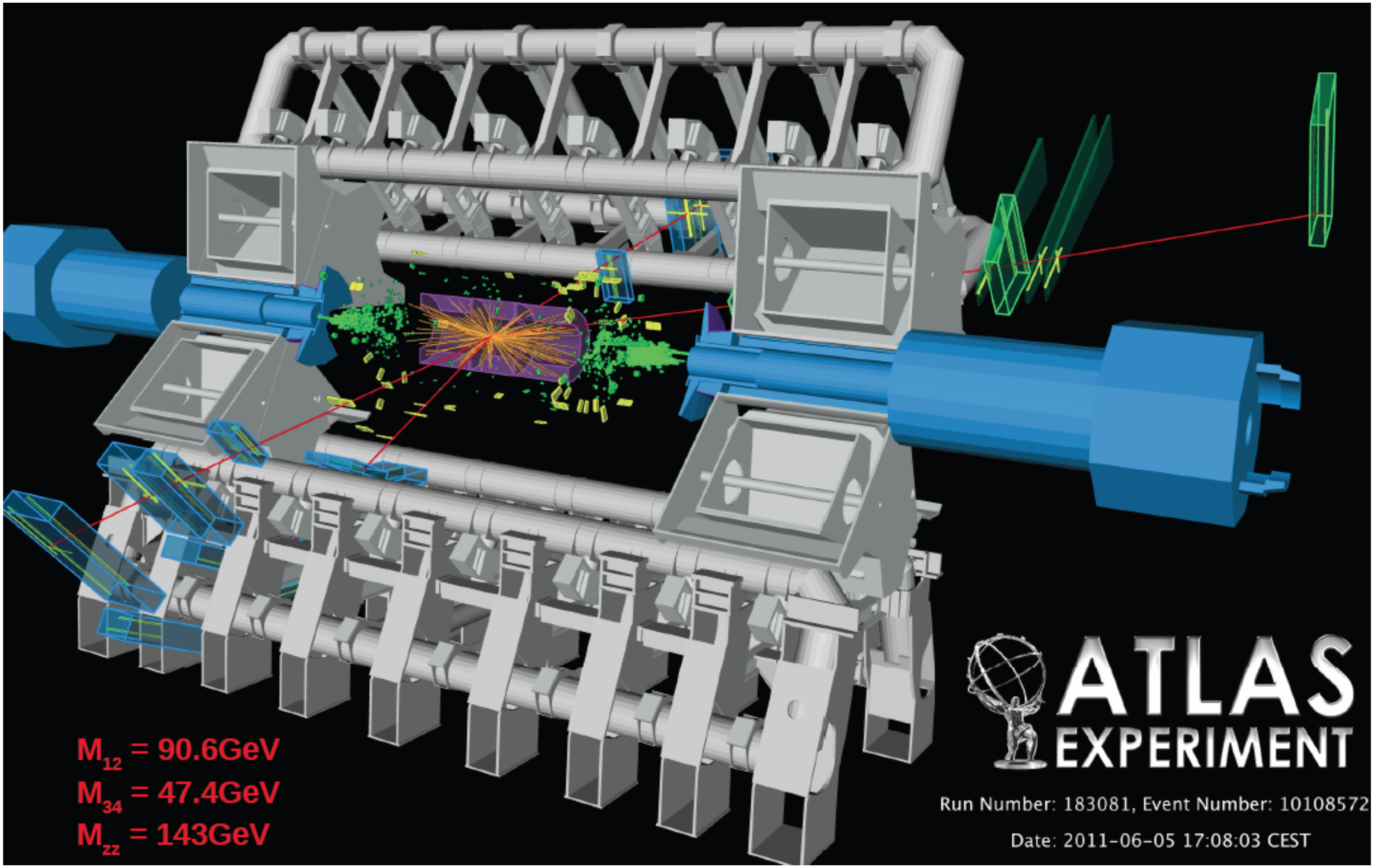
(expected exclusion is 135-196 GeV)

$H \rightarrow ZZ^{(*)} \rightarrow ll\ ll$

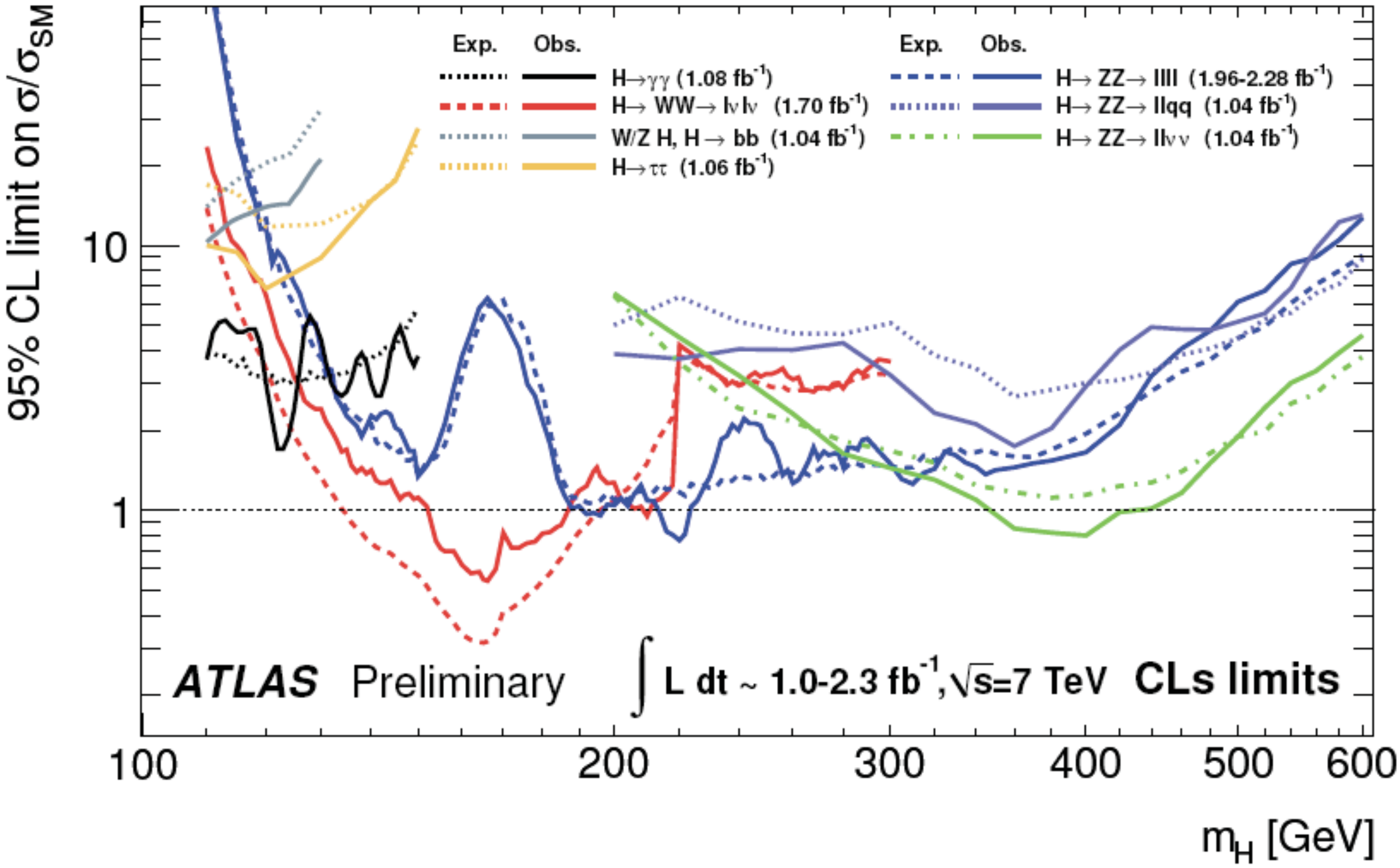
- Very clean, "golden channel"
    - Runs out of statistics at high mass, so there revert to decays with higher BR's, such as $H \rightarrow ZZ^{(*)} \rightarrow ll$ nunu and $H \rightarrow ZZ^{(*)} \rightarrow ll\ qq$



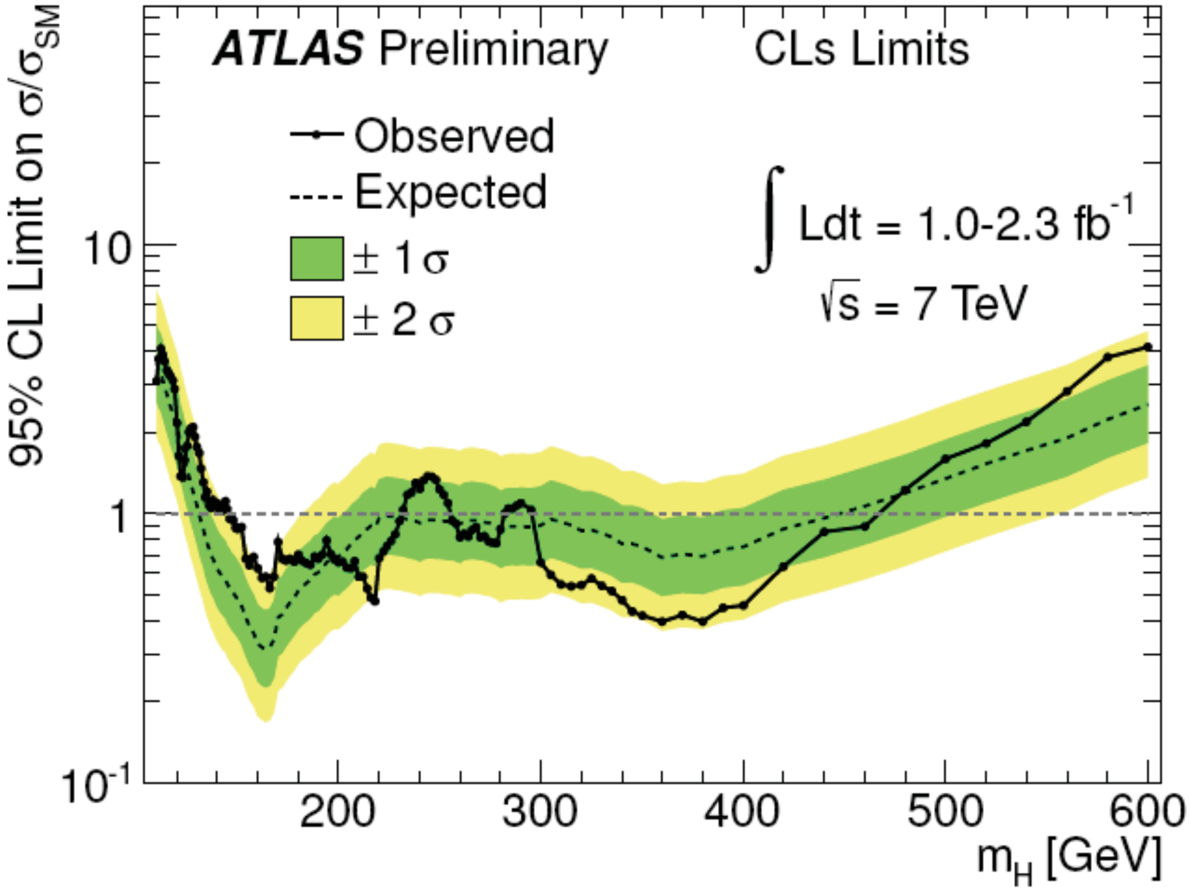
ZZ* → μμμμ Candidate



Overview of ATLAS SM Higgs Results



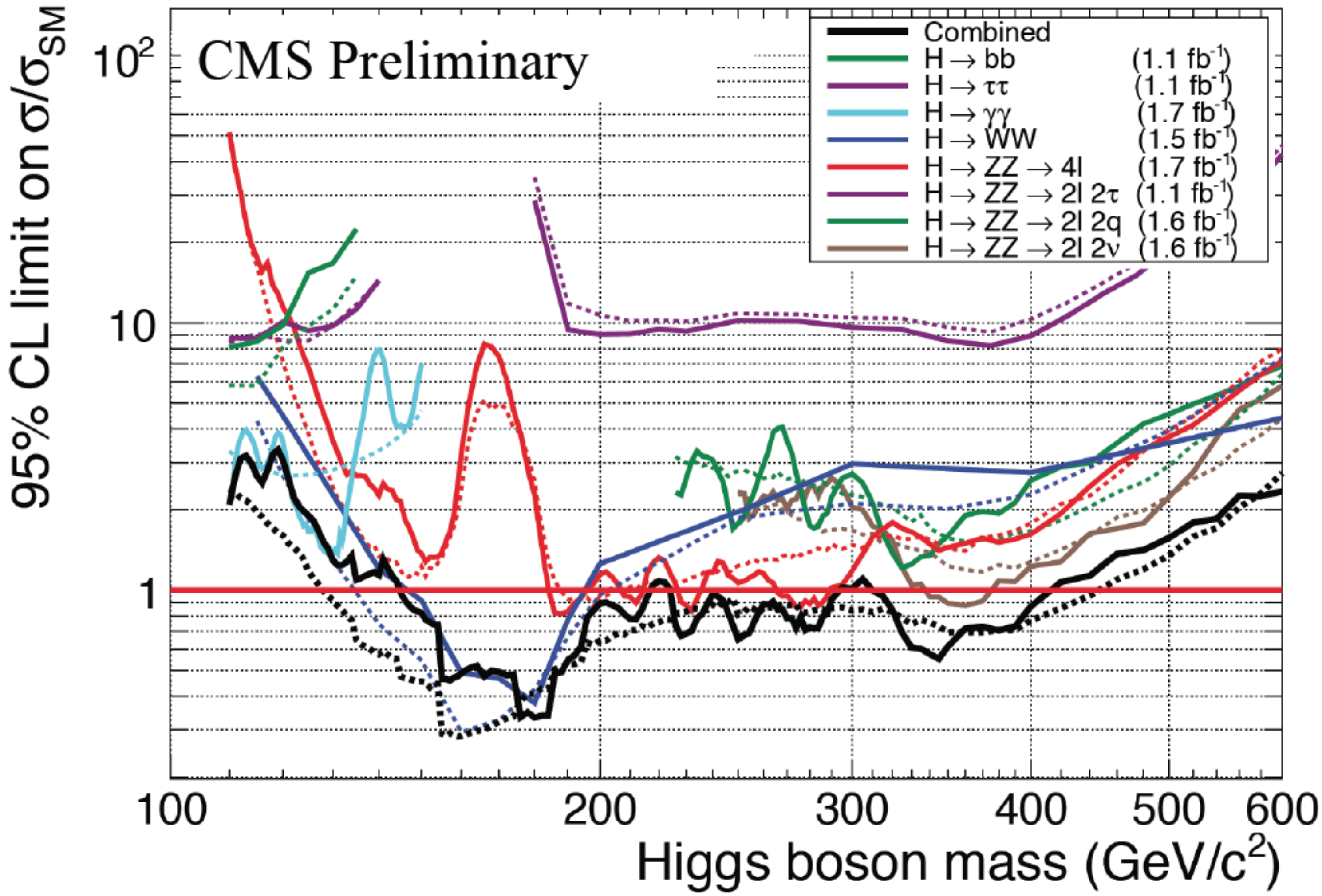
Combination of ATLAS SM Higgs Results



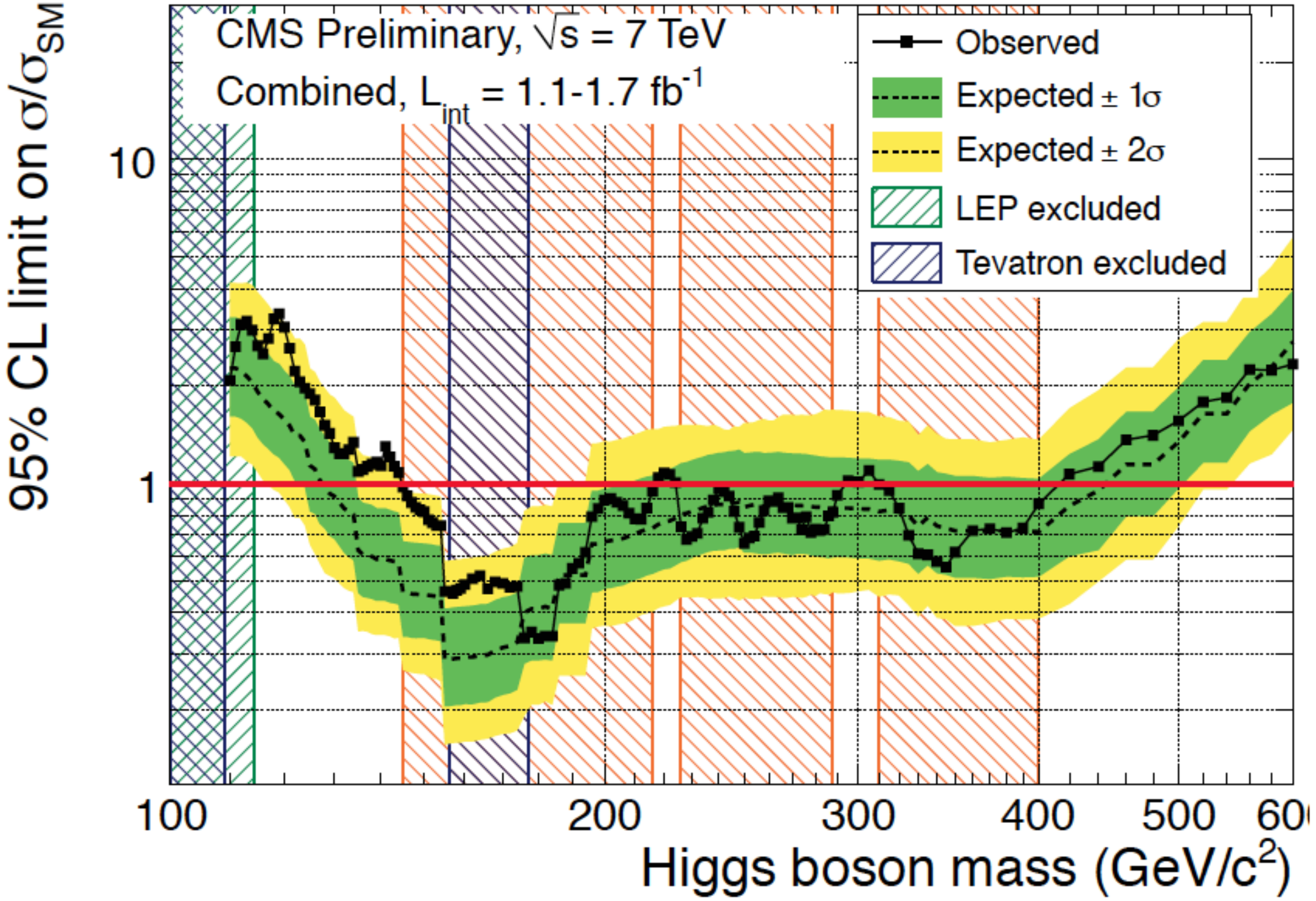
SM Higgs boson mass excluded at 95% CL :
146-232, 256-282, 296-466 GeV

Expected exclusion range: 131 – 447 GeV

What about CMS Higgs Results?



CMS SM Higgs Combination



Expected exclusion mass range: 130 – 440 GeV
Observed exclusion mass range: 145-216, 226-288, 310-400 GeV

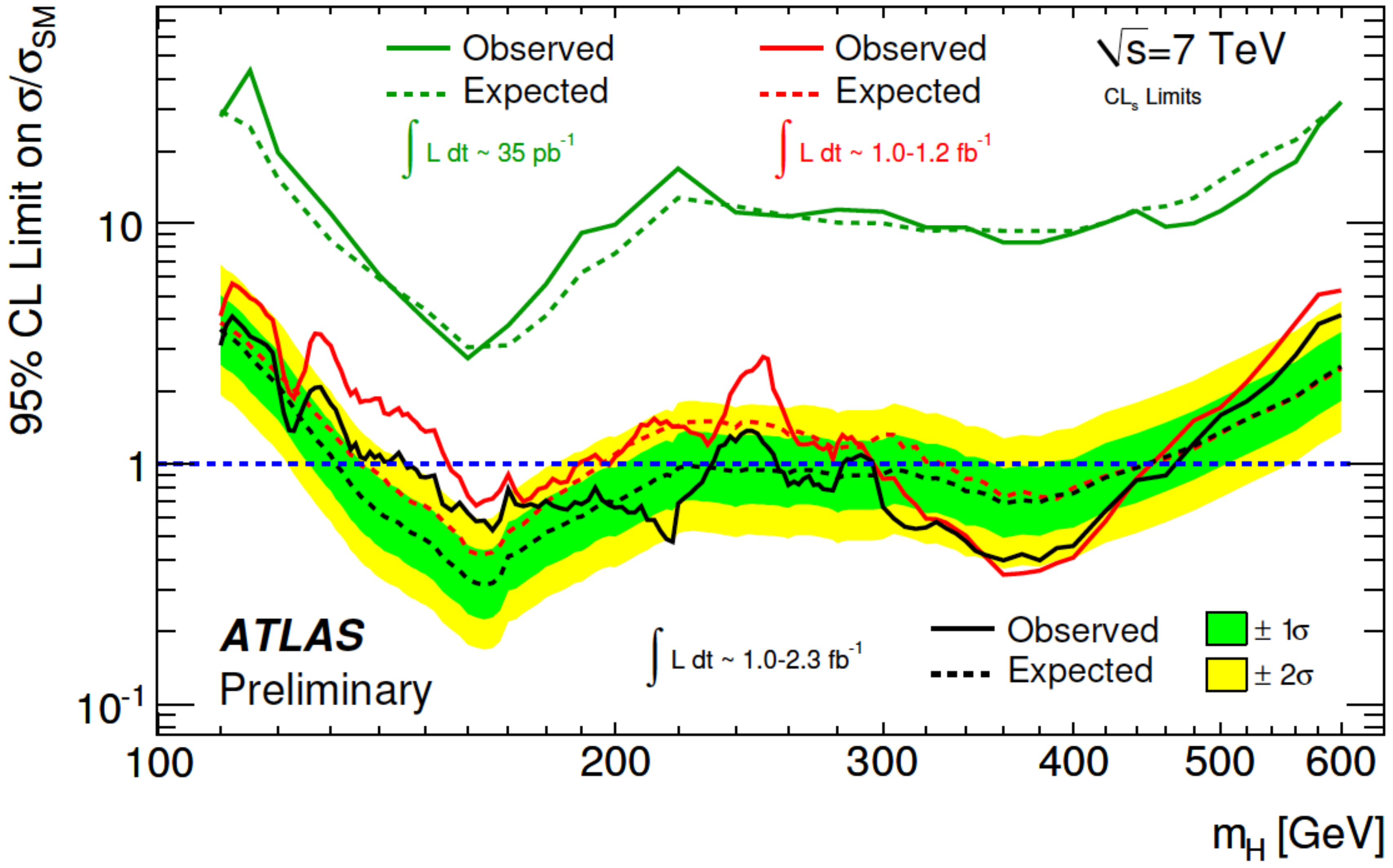
Comparison of Most Recent SM Higgs Limits

- Tevatron combination (CDF + DZero) – up to 8.6 fb^{-1}
  - Observed exclusion: 100-109 and 156-177 GeV
  - Expected exclusion: 100-108 and 148-181 GeV

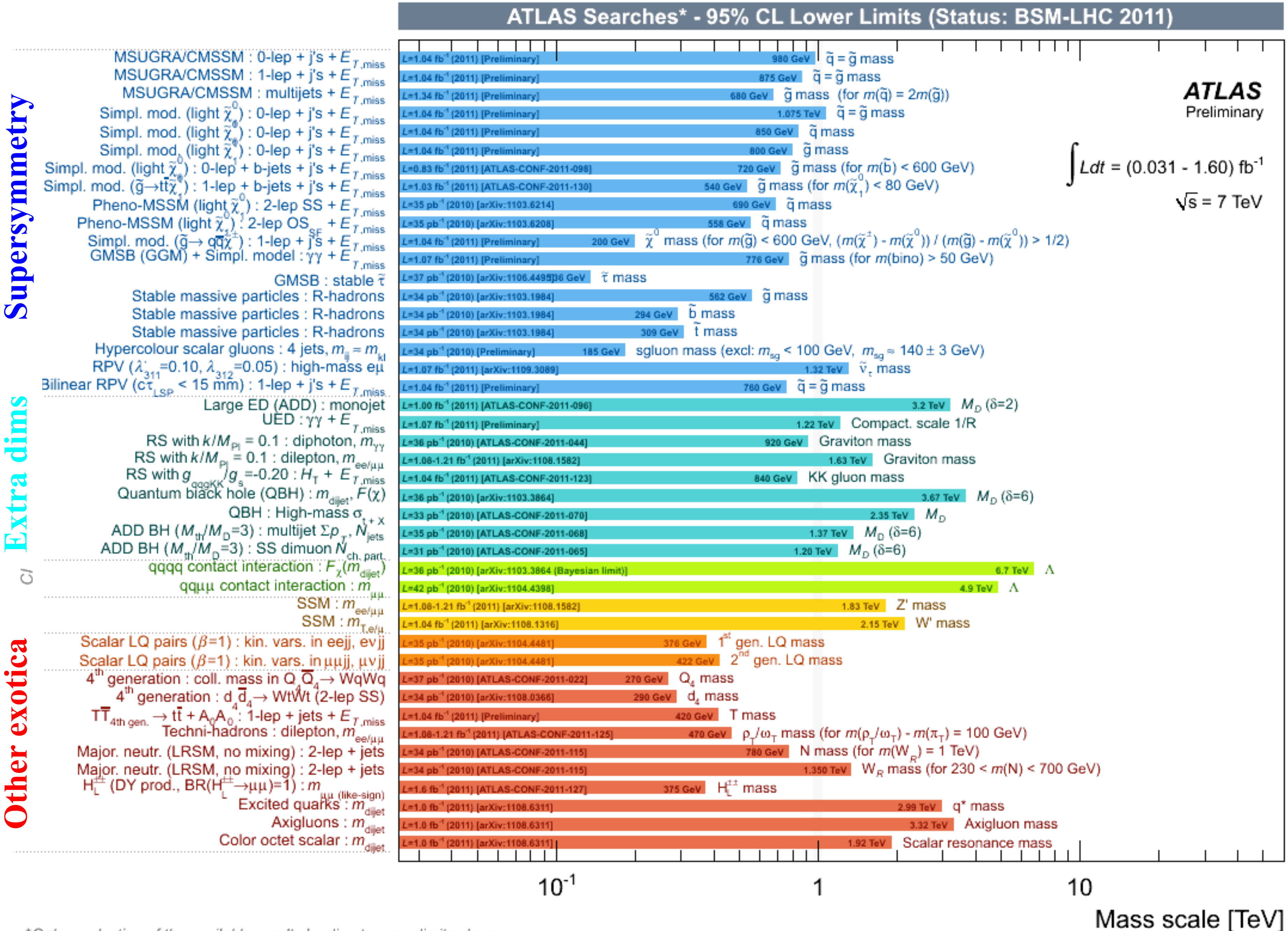
- ATLAS – up to 2.3 fb^{-1}
  - Observed exclusion: 146-232, 256-282, 296-466 GeV
  - Expected exclusion: 131-447 GeV

- CMS – up to 1.7 fb^{-1}
  - Observed exclusion: 145-216, 226-288, 310-400 GeV
  - Expected exclusion: 130-440 GeV

Rate of Progress in ATLAS Combined SM Higgs Result



Selected Examples of ATLAS Searches for BSM Physics



*Only a selection of the available results leading to mass limits shown

Models with Extra Dimensions

- Motivated by string theory, models arose in the late 1990s using extra dimensions to try explain the hierarchy problem of the SM

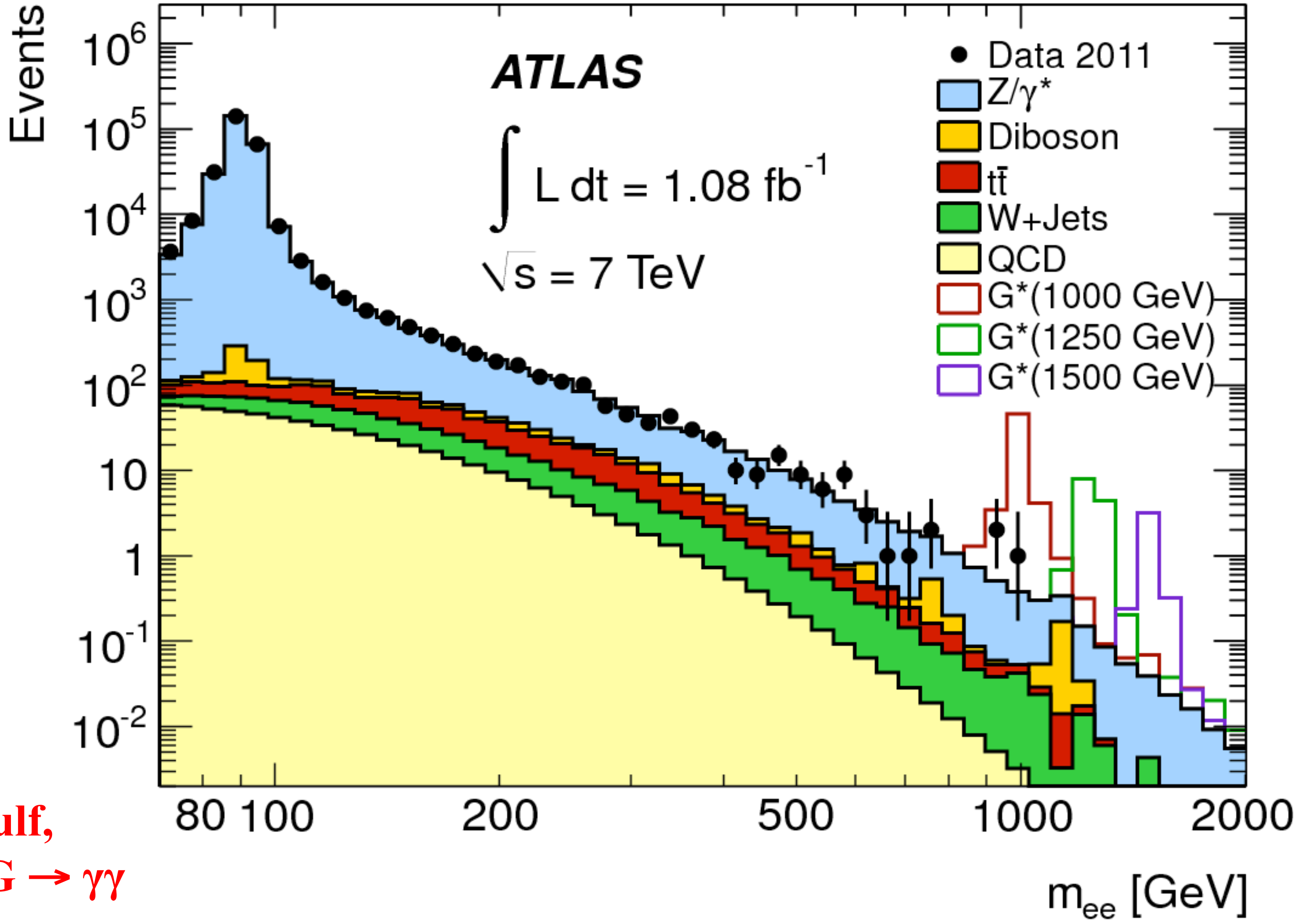
- The original proposal of Arkani-Hamed, Dimopoulos and Dvali (ADD) postulated the existence of a number n of large (~1 /eV) extra flat spatial dimensions, into which only gravity can propagate
  - Expect “Kaluza-Klein (KK) tower” of massive (eV-spaced, ie. almost continuous) graviton states which, if produced, would escape detection → $E_T$miss

- A year later, Randall and Sundrum (RS) proposed a model with an additional ~1/TeV-scale “warped” extra dimension
  - KK tower of TeV-spaced massive gravitons, which decay to SM particles

- While both models originally assumed only gravity could propagate in the bulk, it was soon realized that a subset, or even all, of the SM particles could also
  - In “Universal Extra Dimensions” case, expect KK towers for all SM particles

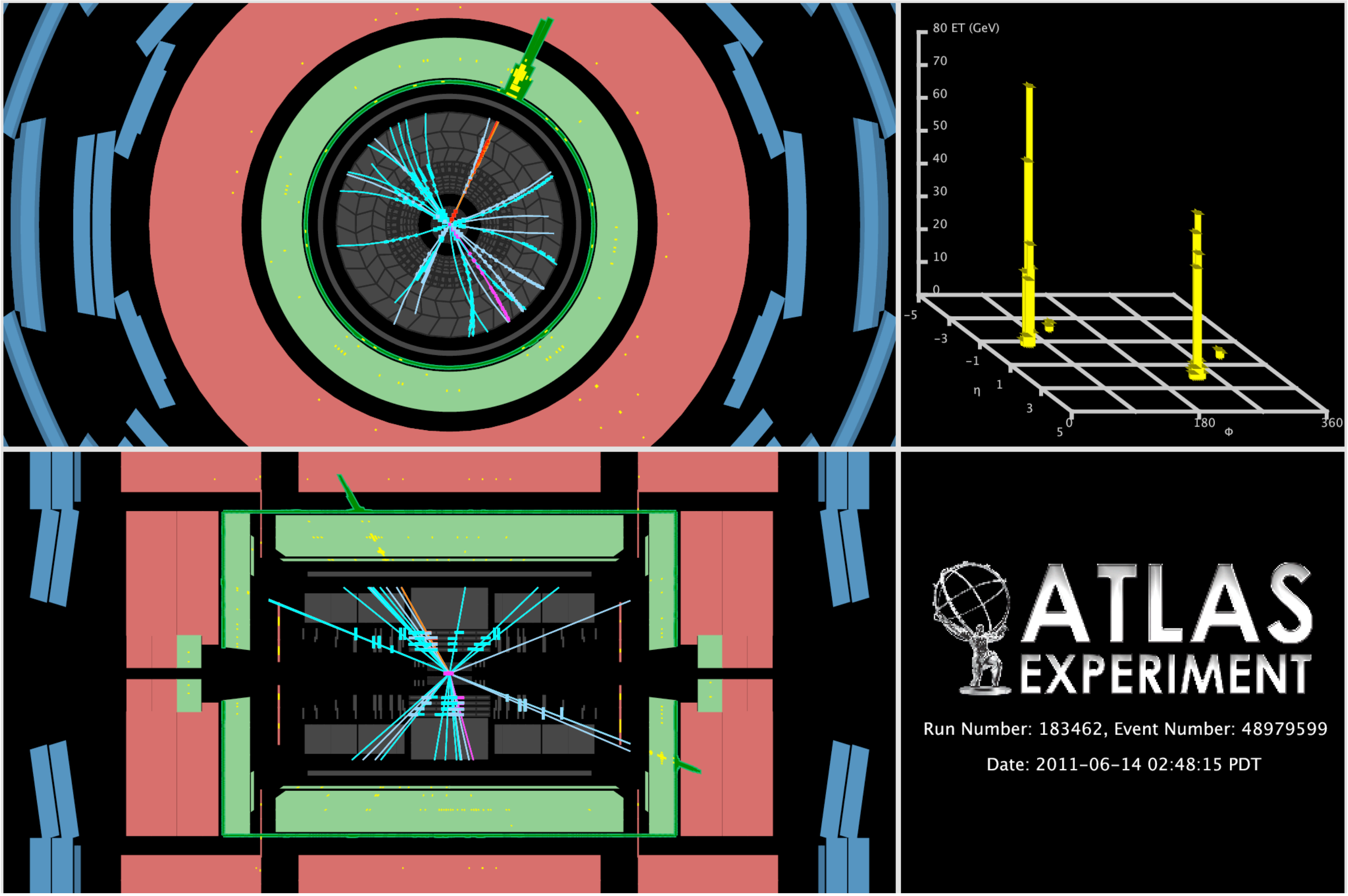
Search for RS Graviton

- **Can search for lightest RS KK graviton by looking for a resonance at high mass in the invariant mass distribution of SM particle-antiparticle pairs**



**Ph.D. thesis of E. Wulf,
RS G → ee and G → $\gamma\gamma$**

Dielectron Event with m(ee) = 959 GeV

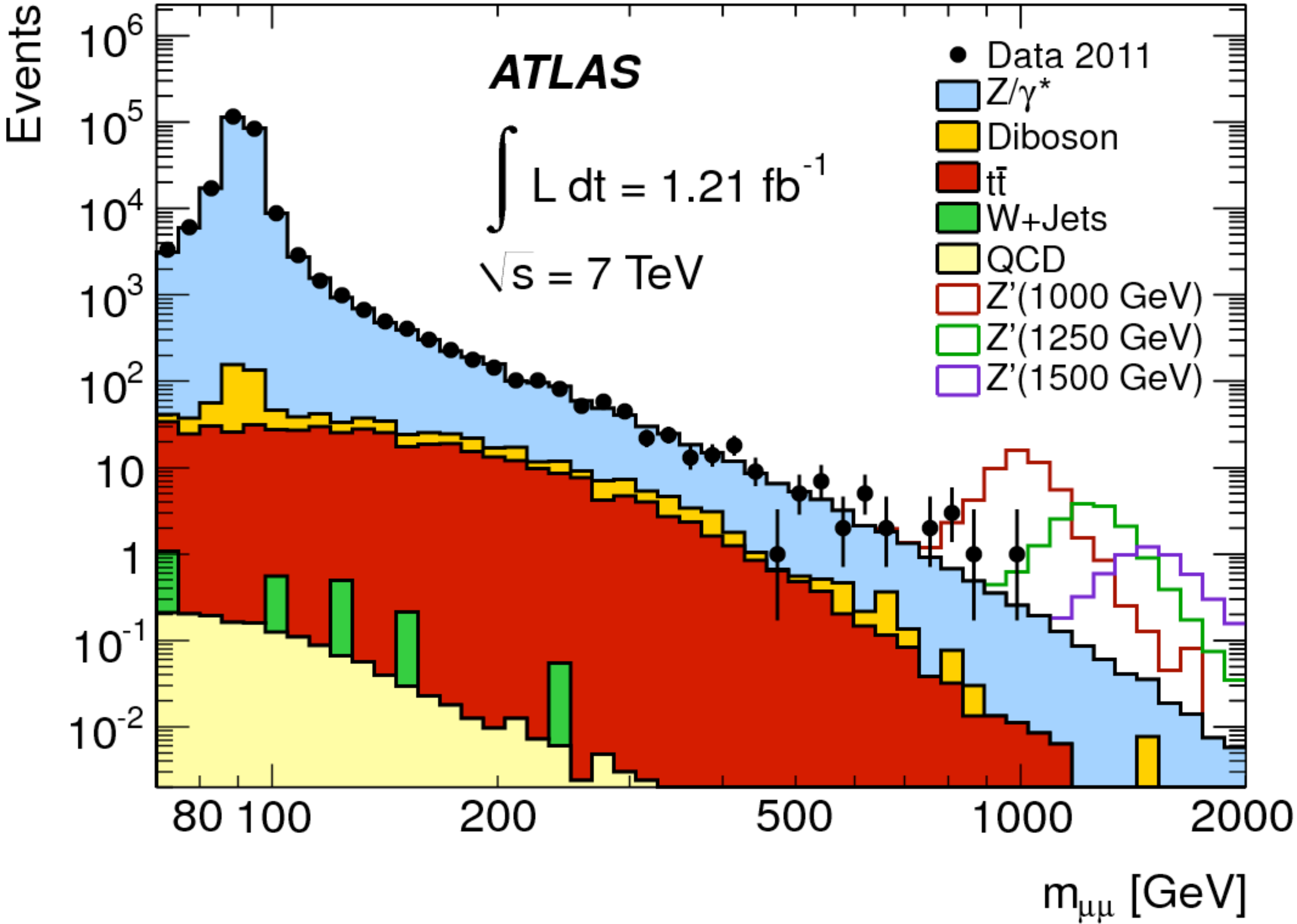


Run Number: 183462, Event Number: 48979599

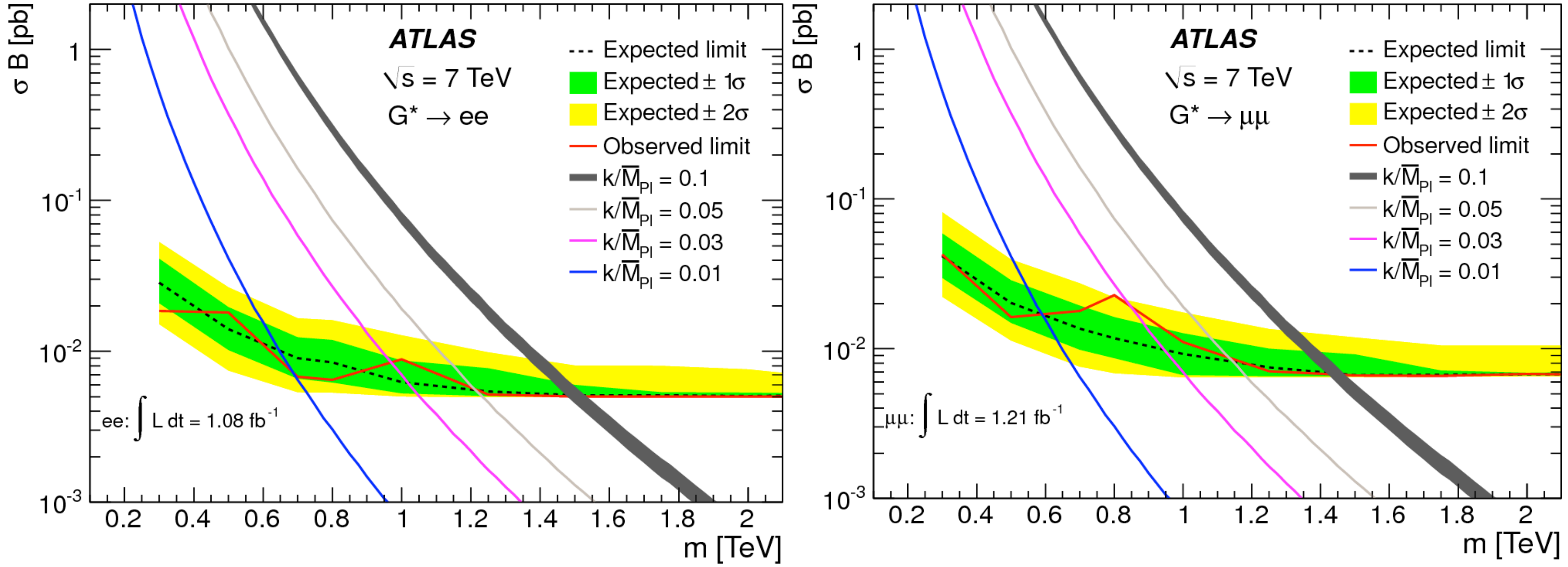
Date: 2011-06-14 02:48:15 PDT

Search for Z’ → μμ

- **In addition to RS Graviton, can use high mass dilepton spectrum to search for heavy Z’ bosons**



RS Graviton and Z' Search Results



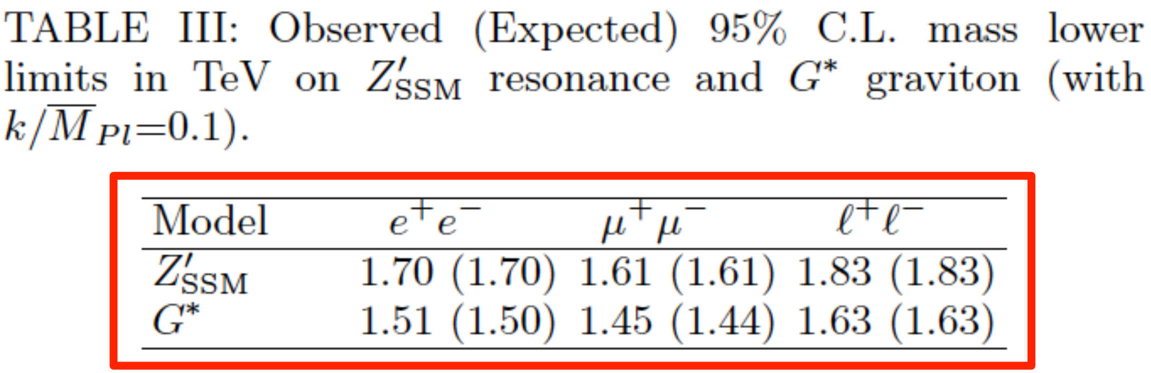
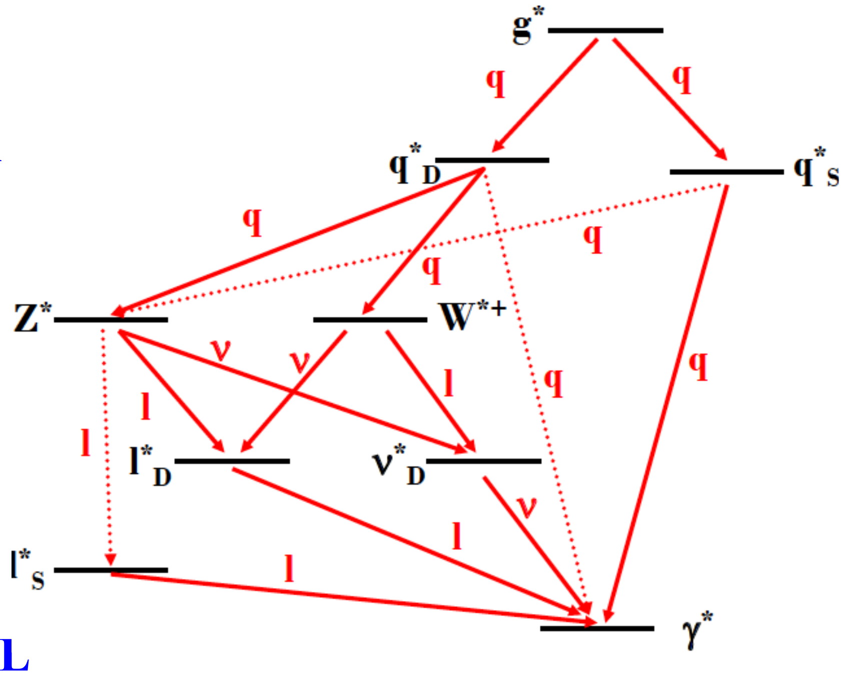


TABLE III: Observed (Expected) 95% C.L. mass lower limits in TeV on Z'_{SSM} resonance and G^* graviton (with $k/\overline{M}_{Pl}$=0.1).

Model	e^+e^-	$\mu^+\mu^-$	$\ell^+\ell^-$
Z'_{SSM}	1.70 (1.70)	1.61 (1.61)	1.83 (1.83)
G^*	1.51 (1.50)	1.45 (1.44)	1.63 (1.63)

UED Analysis in $\gamma\gamma + E_T$miss Final State

- Consider case of 1 UED with compactification radius R, embedded in larger space of N “ADD-type” extra dimensions
- Pair of KK quarks/gluons would cascade decay down to “LKP”, the lightest KK photon
- If “KK parity” broken by gravitational interactions, allows decay $\gamma^* \rightarrow \gamma + G$
- Final state would be $\gamma\gamma + E_T$miss
- Previous D0 limit (from former Columbia student’s thesis) was 1/R > 477 GeV @ 95% CL

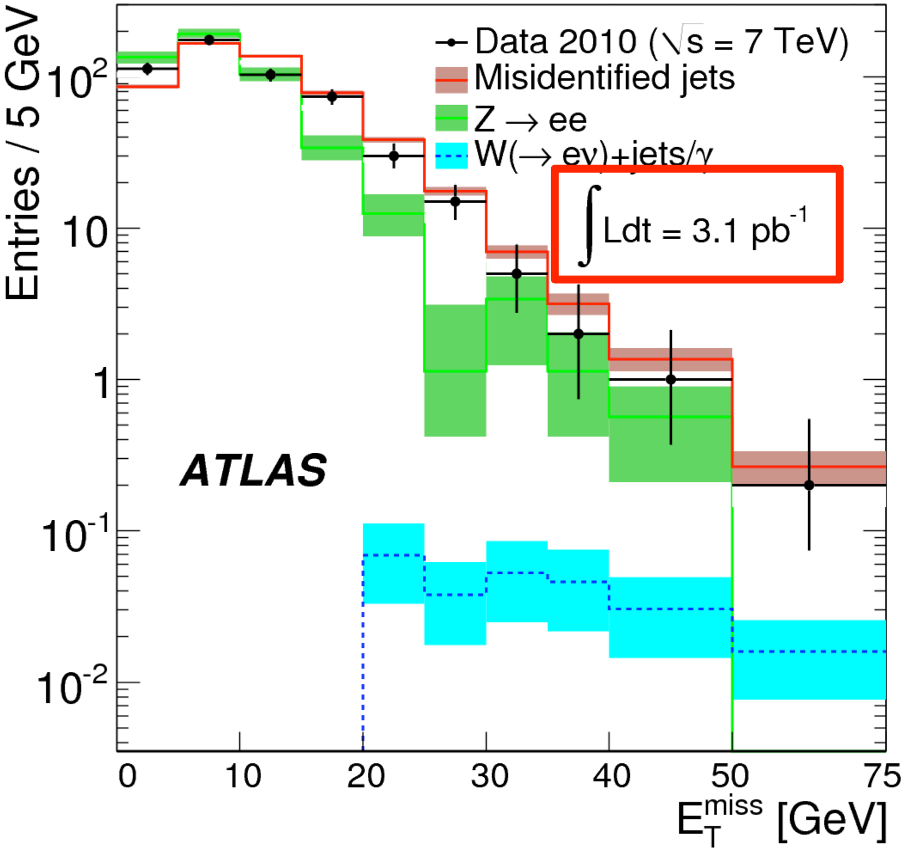


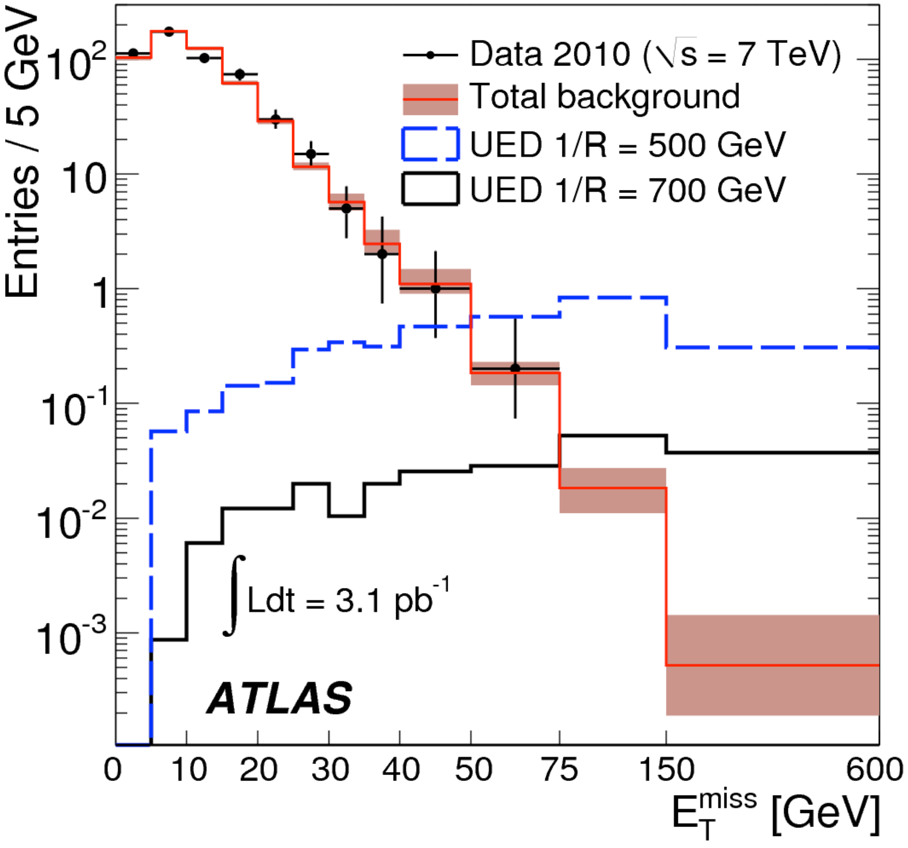
- First ATLAS result (one of first BSM results, using only 3 pb^{-1} !) increased this limit to 1/R > 728 GeV @ 95% CL

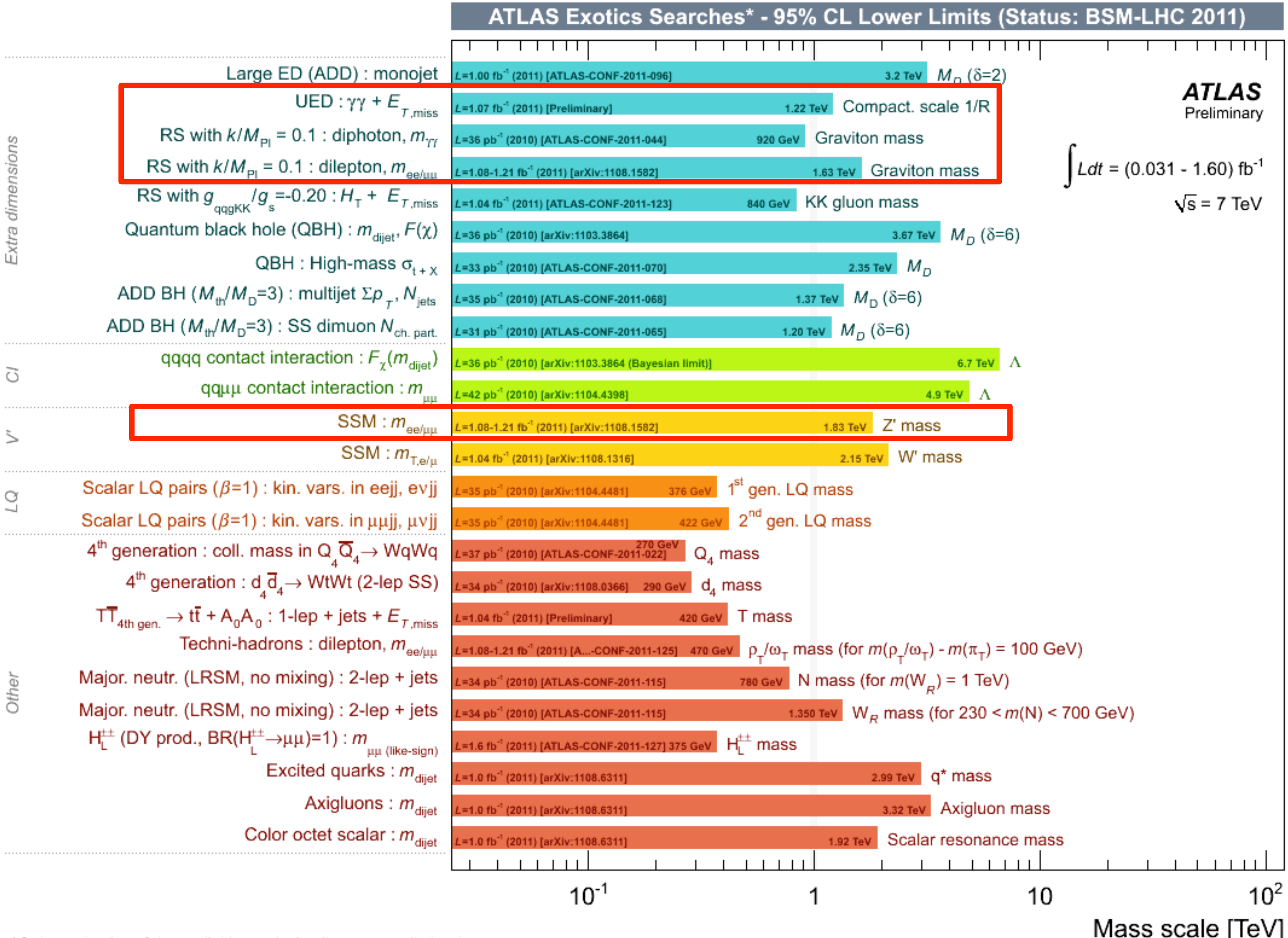
(recent update with 1 fb^{-1} increases further, to 1/R > 1226 GeV)

UED Analysis in γγ + $E_T$miss Final State

- **Given quality of understanding of detector from day one, we were able with VERY early data in 2010 to already demonstrate our control of the backgrounds, and in particular tails in $E_T$miss distribution**





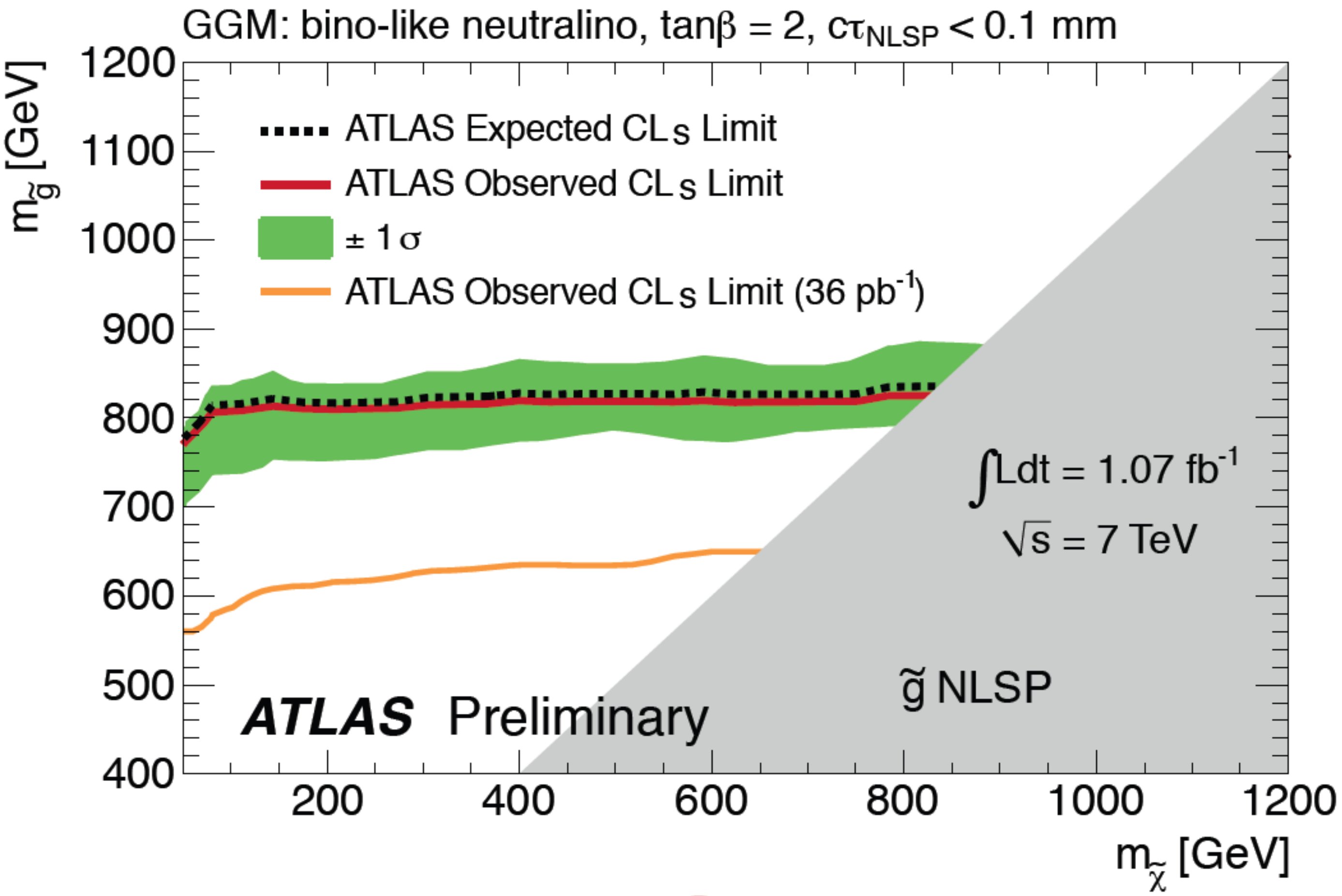


*Only a selection of the available results leading to mass limits shown

Gauge Mediated SUSY Breaking Models

- In GMSB models, SUSY breaking communicated by usual gauge interactions
  - An advantage is the “natural” absence of FCNC
- In GMSB models, a light (~keV) gravitino is the LSP
  - Phenomenology dominated by nature of “next-to-lightest” SUSY particle (NLSP)
- NLSP can be lighest neutralino, which then decays via $\chi_1^0 \rightarrow \gamma + G$
- Assuming R parity conversation, strong production of squark and/or gluino pairs leads to a final state of $\gamma\gamma + E_T$miss
  - Can reinterpret UED study of this final state in GMSB context

GMSB $\gamma\gamma + E_T$miss Result

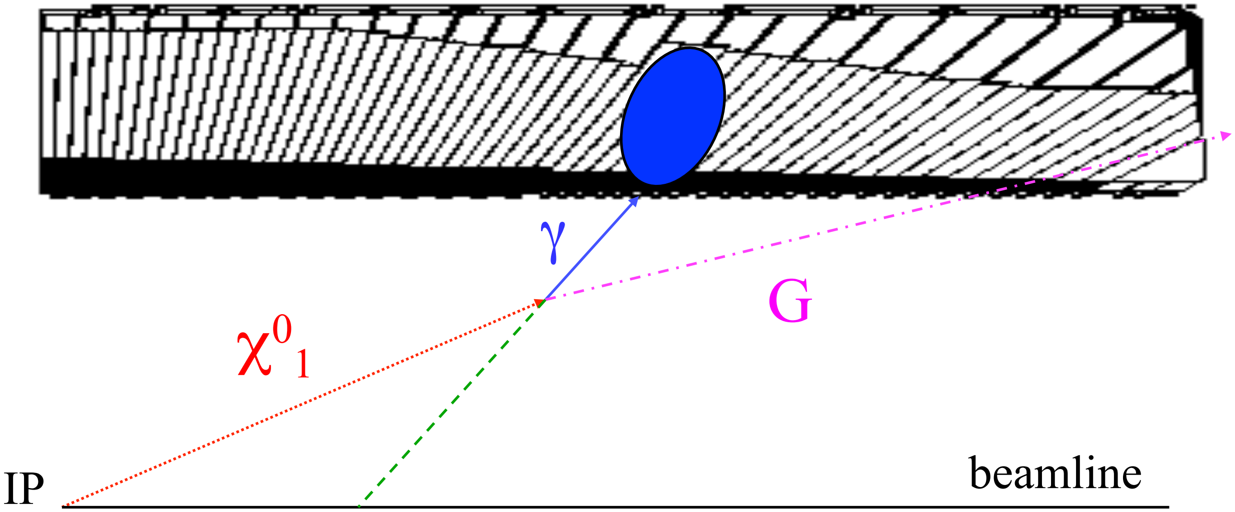


$M_{gluino} > 776$ GeV

for $M_{bino} > 50$ GeV

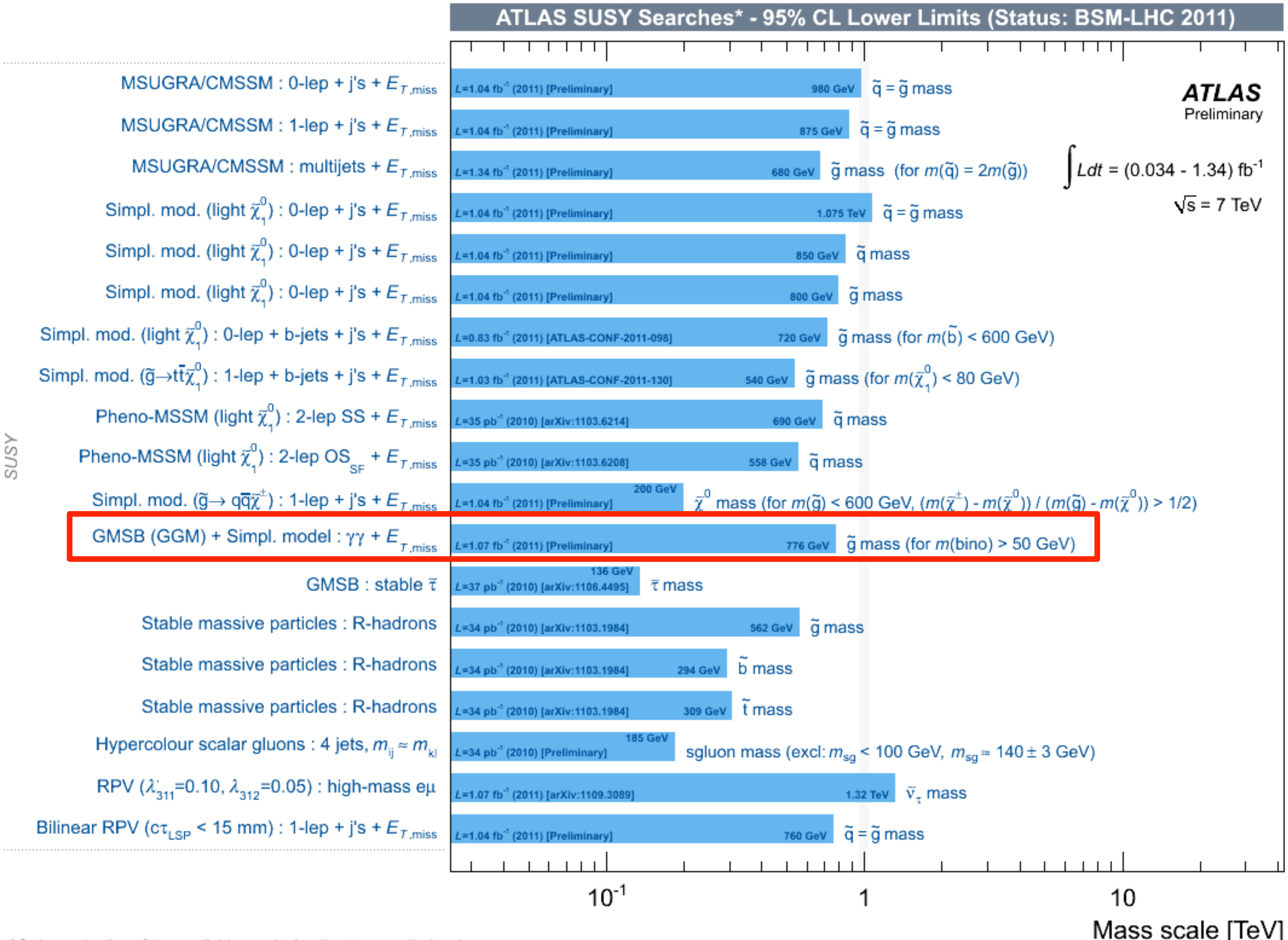
GMSB (cont'd)

- In GMSB, NLSP can have a finite lifetime, giving rise to the possibility of photons which are non-pointing and delayed, as compared to those coming from prompt production/decays (Ph.D. thesis of N. Nikiforou)



- Use ability of EM calorimeter, using its fine segmentation, to measure trajectory of photon (as shown before for $H \rightarrow \gamma\gamma$ analysis)

- Can also use excellent timing resolution of the EM calorimeter
  - Currently, we have calibrated the timing with a resolution of ~ 600 ps
  - Good first step, but there a lot of work to do to reach final expected value of ~ 100 ps (fortunately, we have a lot of data to work with!)



*Only a selection of the available results leading to mass limits shown

Summary and Outlook

- ATLAS has recorded > 3.5 fb^{-1} of 7 TeV pp collisions
- Physics analysis is in full swing
  - During 2010, collected ~ 40 pb^{-1} and submitted 16 papers
  - During 2011, submitted 54 papers so far (with 20 more undergoing internal review)
- So far, no sign of new physics (despite many searches probing scales > 1 TeV)
- SM Higgs boson running out of places to hide:
  - Excluded at 95% CL for m(H) in ranges 146-232, 256-282, 296-466 GeV
  - Data taken by end of 2011 run should be sufficient to cover mass range down to LEP limit
- These are exciting times, and the outlook is very bright!
  - Plan to run at 7 TeV (or perhaps slightly higher) thru end of 2012, before shutting down to prepare for operation at 14 TeV design energy
  - Longer term planning for lumi. upgrade (and even eventual energy upgrade) are already underway