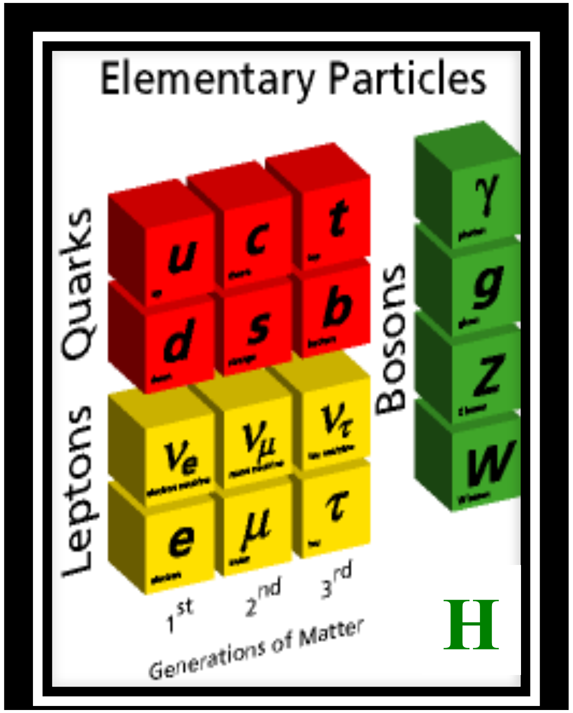
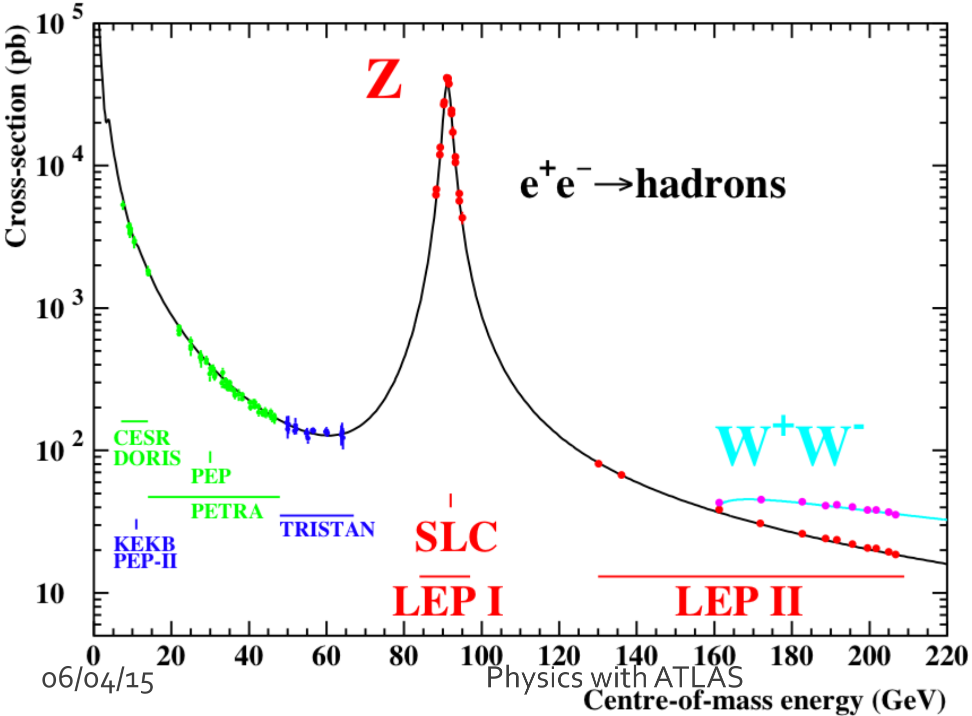
A trip through some ATLAS achievements

PHYSICS OF THE EARLY UNIVERSE

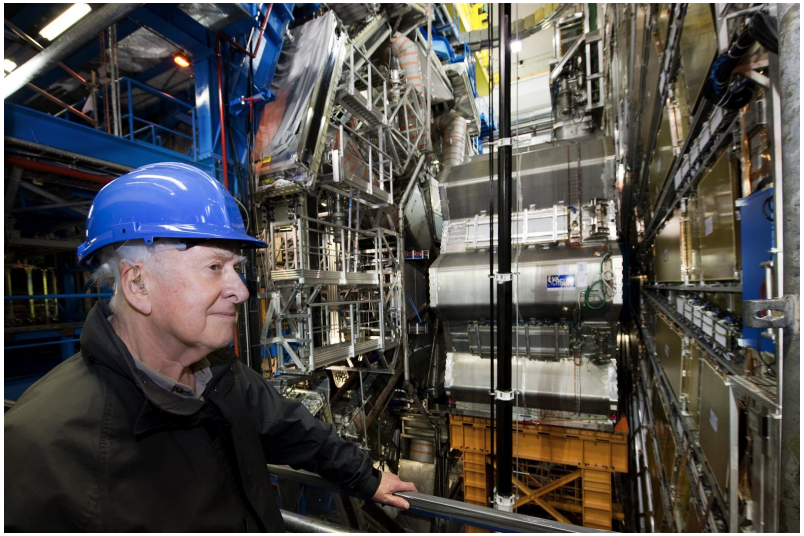


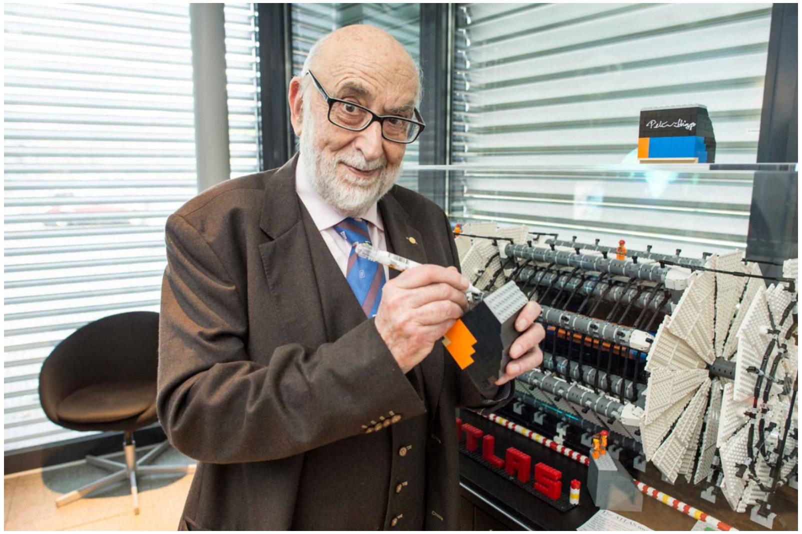
- All forces in nature obey a form of symmetry.
  - Gauge-symmetry
- The Standard Model (SM) describes interactions between elementary particles grouped in 3 families of quarks and leptons

- The Standard Model
  - unifies Electromagnetism (long range, macroscopic, photon has no mass) and Weak force (short range, microscopic, W and Z are heavy) …at high energies
  - describes (almost) all current particle physics data

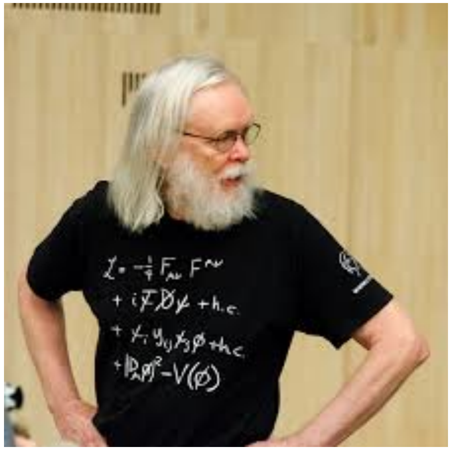


- The Electroweak symmetry must be broken at low energies in order to give the weak bosons (W,Z), as well as all matter particles, masses.
- A scalar field requiring a new particle, the Higgs Boson …





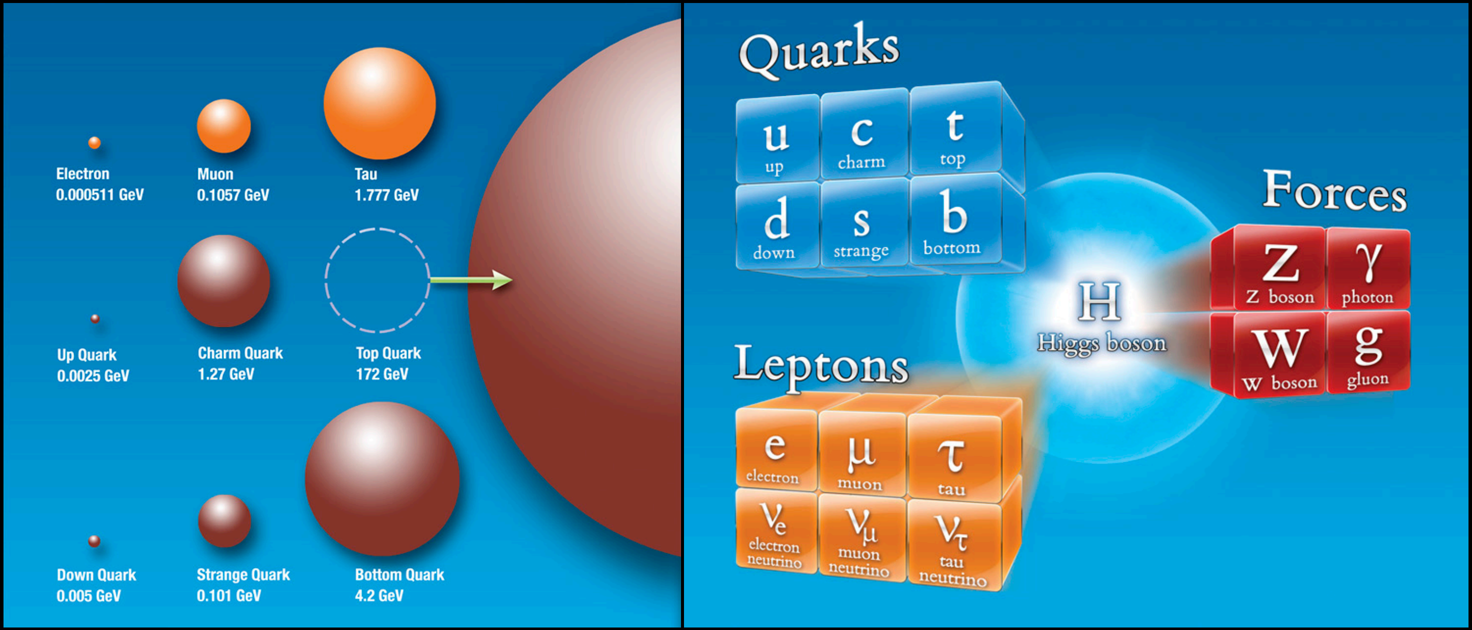
- Whole Universe swims in an invisible, cosmic field, Higgs-field, which acts on particles and provide them with what is called mass.
- All fields have associated boson. The Higgs-field has its Higgs-boson.



See Last year's lecture: **The Higgs boson and beyond**

The Standard Theory of Particles and Forces

- Forces are dictated by (gauge) symmetries
  - Fermions in 3! = $SU(3)_C*[SU(2)_L*U(1)_Y]$ → QCD + Electroweak ("=" QED + Weak)



- Symmetries of laws do not necessarily lead to symmetries of outcomes
  - Electroweak symmetry spontaneously broken – Brout Englert Higgs mechanism
  - BEH "hides" EW symmetry, gives masses to weak gauge bosons and "approves" fermion masses, predicts couplings of particles to Higgs, and more
- Higgs boson mass is not predicted by the SM
- → Must be measured!

Origin of mass

http://www.atlas.ch/multimedia/4-muon-event.html#origin-of-mass

LHC Physics

- Particle collisions at LHC
  - proton + proton
    - Study Standard Model, including Higgs, in new energy domain
    - Search for new physics capable of explaining various mysteries
    - Be ready for surprises
  - LHC collides also heavy ions: pb-pb and p-pb
    - High energies and high densities
    - New state of matter, quark-gluon plasma, …

$$N_{\text{Physics}} = \sigma_{\text{Physics}} \left(\int \mathcal{L} dt \right)_{\text{Beams}}$$

- Sensitivity to rare phenomena
  - with small cross sections
  - depends on the luminosity

Number of collisions
$N = L . \sigma\ (pp \rightarrow X)$

Luminosity L

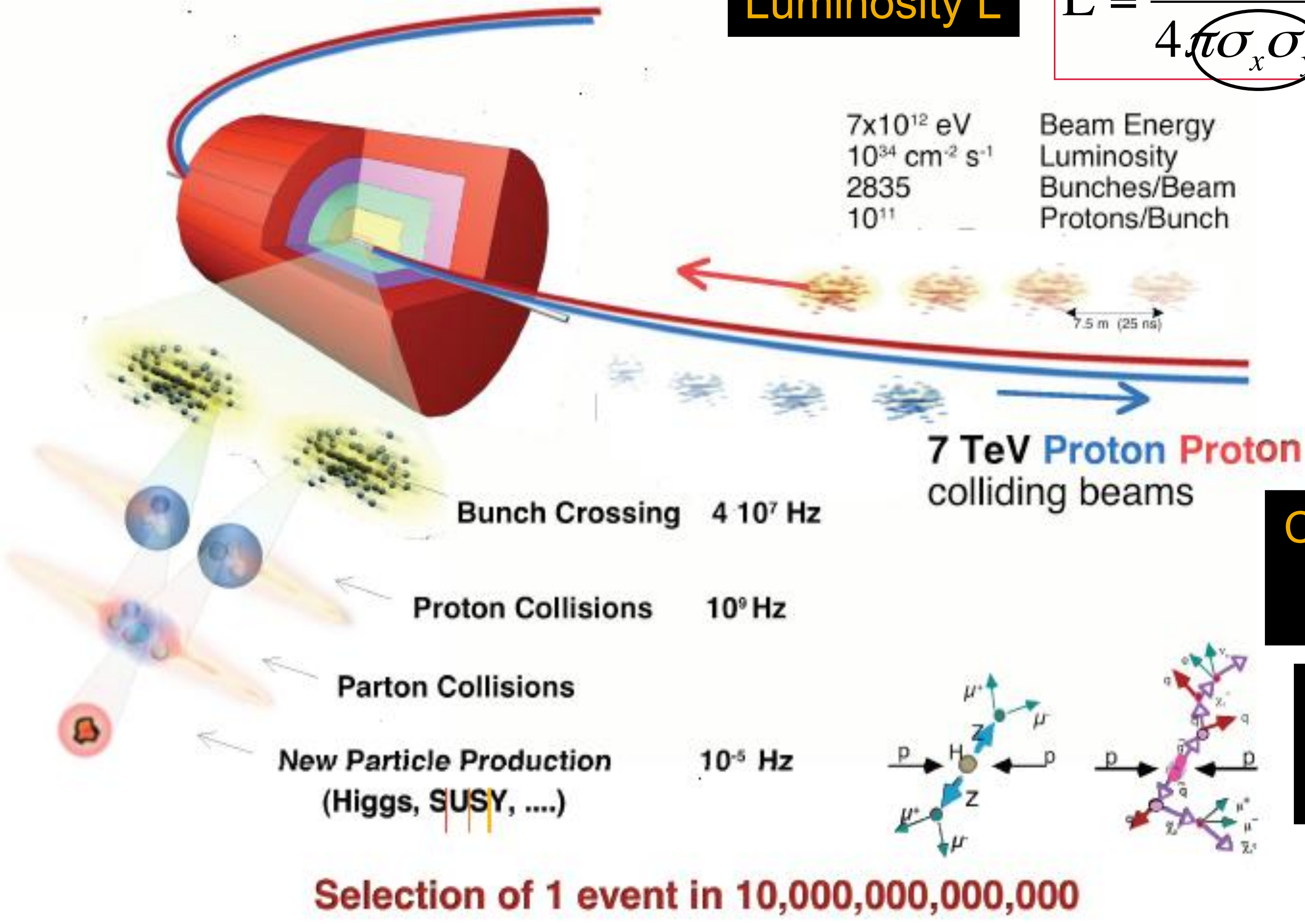
n. of protons per bunch

n. of bunches

$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y}$$

n. of turns per second

beam size at IP ($\sigma_{x,y}$ = 16 μm)



7×10^{12} eV	Beam Energy
10^{34} cm^{-2} s^{-1}	Luminosity
2835	Bunches/Beam
10^{11}	Protons/Bunch

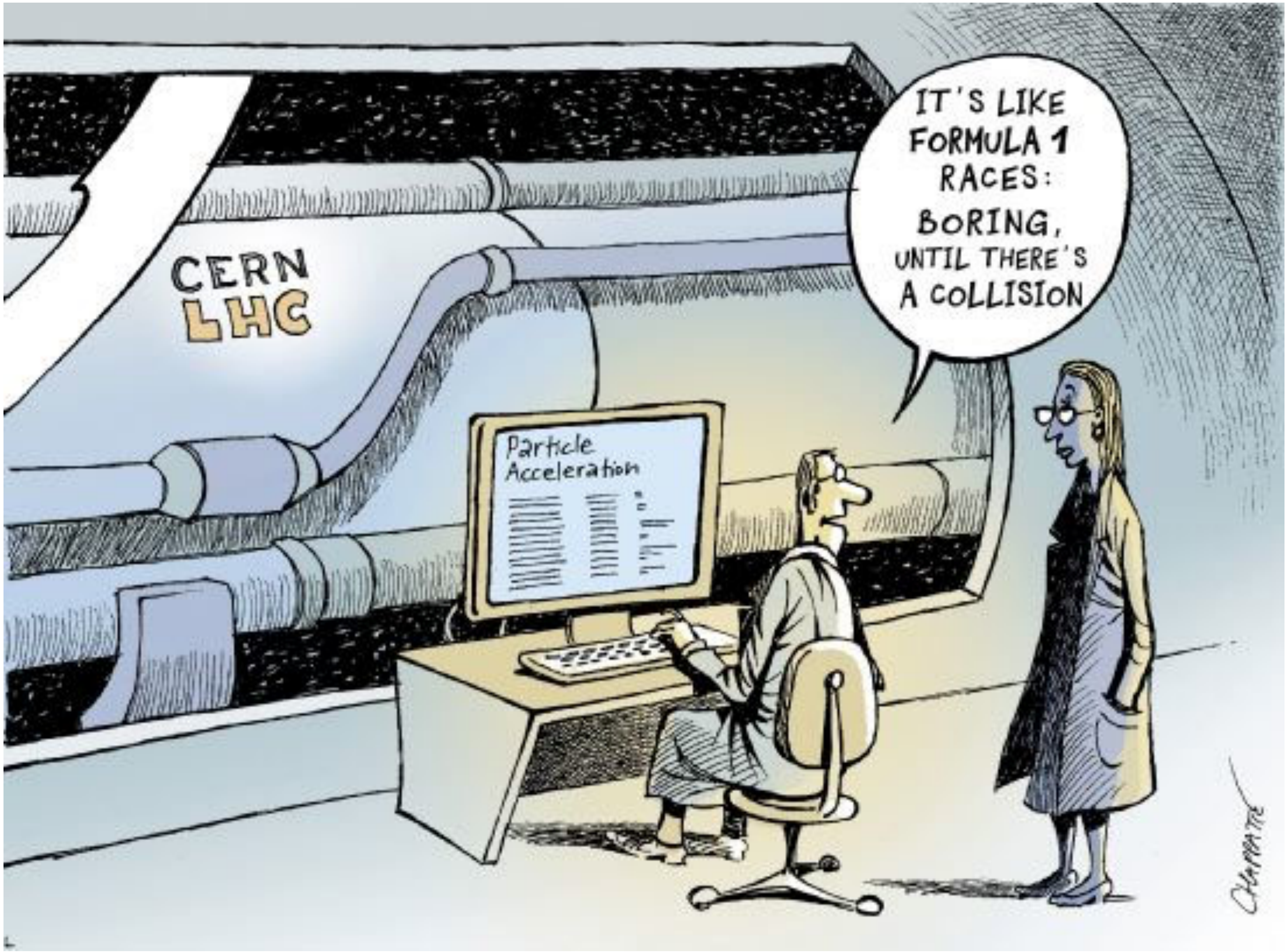
7 TeV Proton Proton
colliding beams

Bunch Crossing	**4 10^{7} Hz**
Proton Collisions	**10^{9} Hz**
Parton Collisions	
New Particle Production **(Higgs, SUSY, ...)**	**10^{-5} Hz**

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

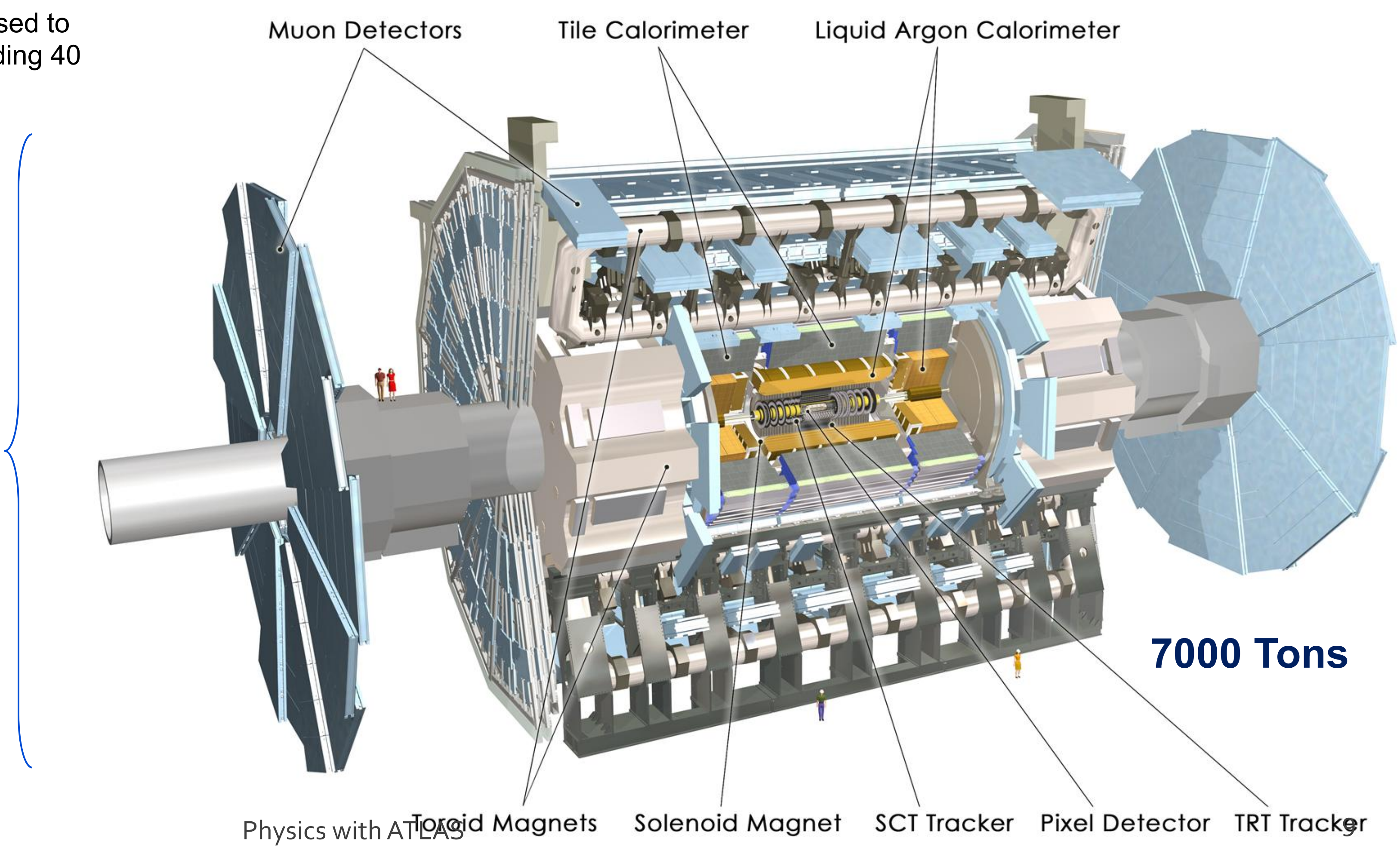
Cross-section
σ

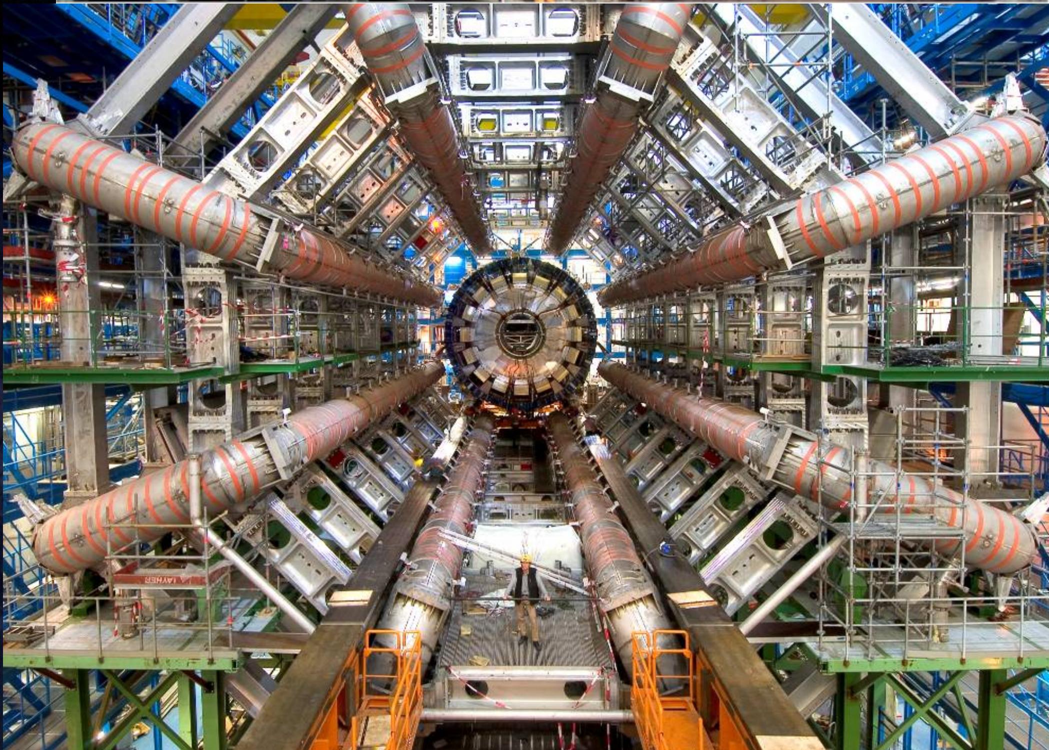
Very small for new processes


CERN
LHC
Particle Acceleration
IT'S LIKE FORMULA 1 RACES: BORING, UNTIL THERE'S A COLLISION
CHAPPATTE

ATLAS
Multipurpose Detector

ATLAS superimposed to
the 5 floors of building 40

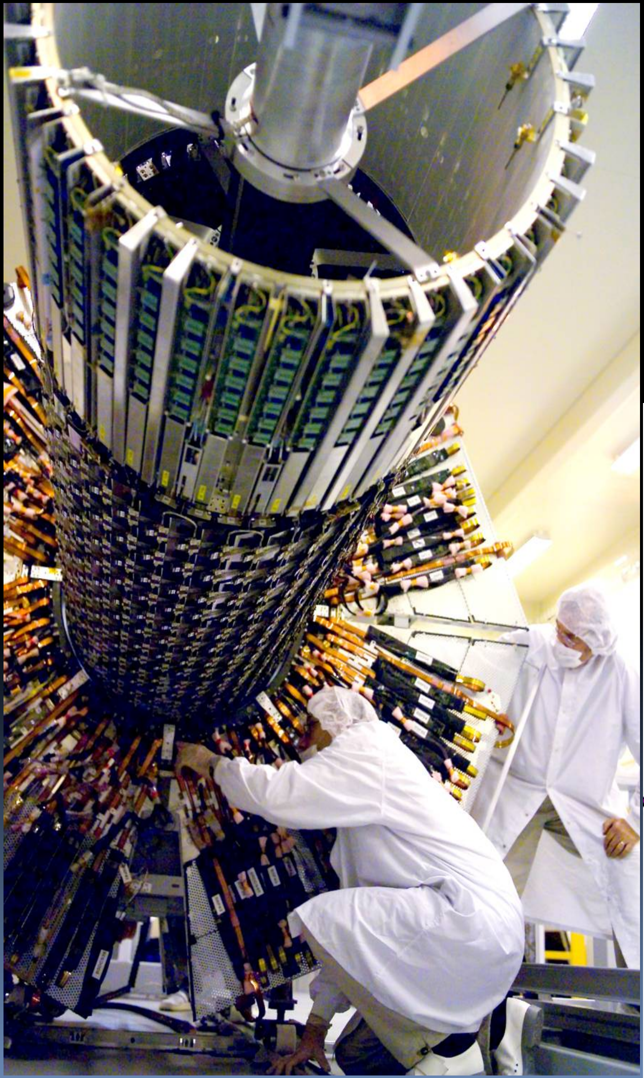


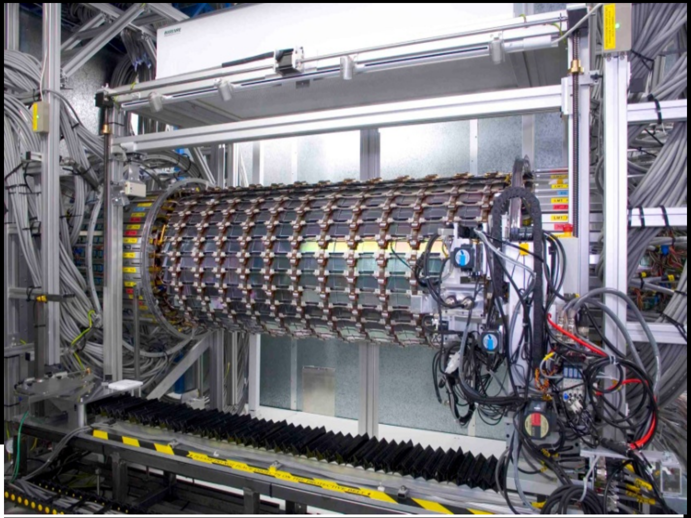


Let’s build ATLAS in ~ 1 minute … or 3 or 5

http://www.atlas.ch/multimedia/4-muon-event.html#atlas-built-1-minute

One of the Norwegian contributions to ATLAS: "Semi Conductor Tracker" (SCT) – Oslo, Bergen, Uppsala made 320 silicon-modules ~ 15% of ATLAS needs

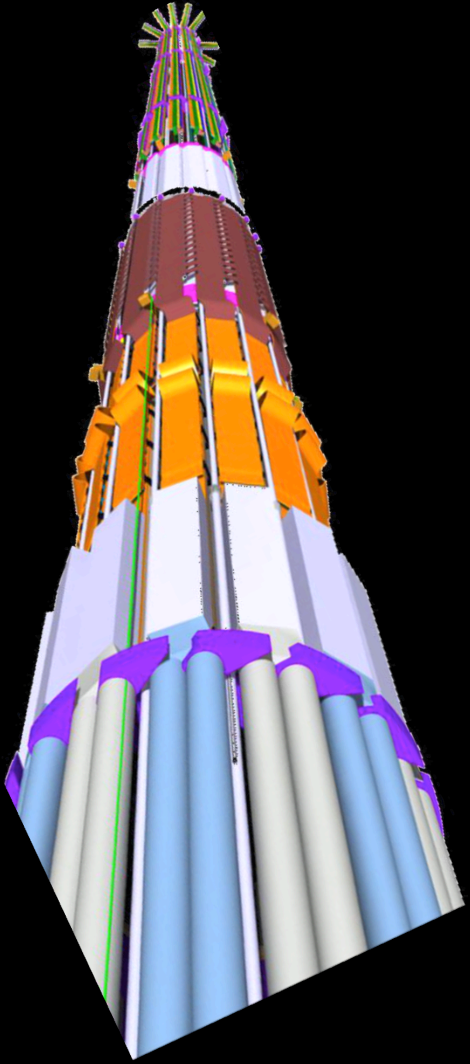




ATLAS upgrade

➔Insertable pixel B-Layer

➔ 3D-Pixel R&D



eeμμ event
in p-p collisions

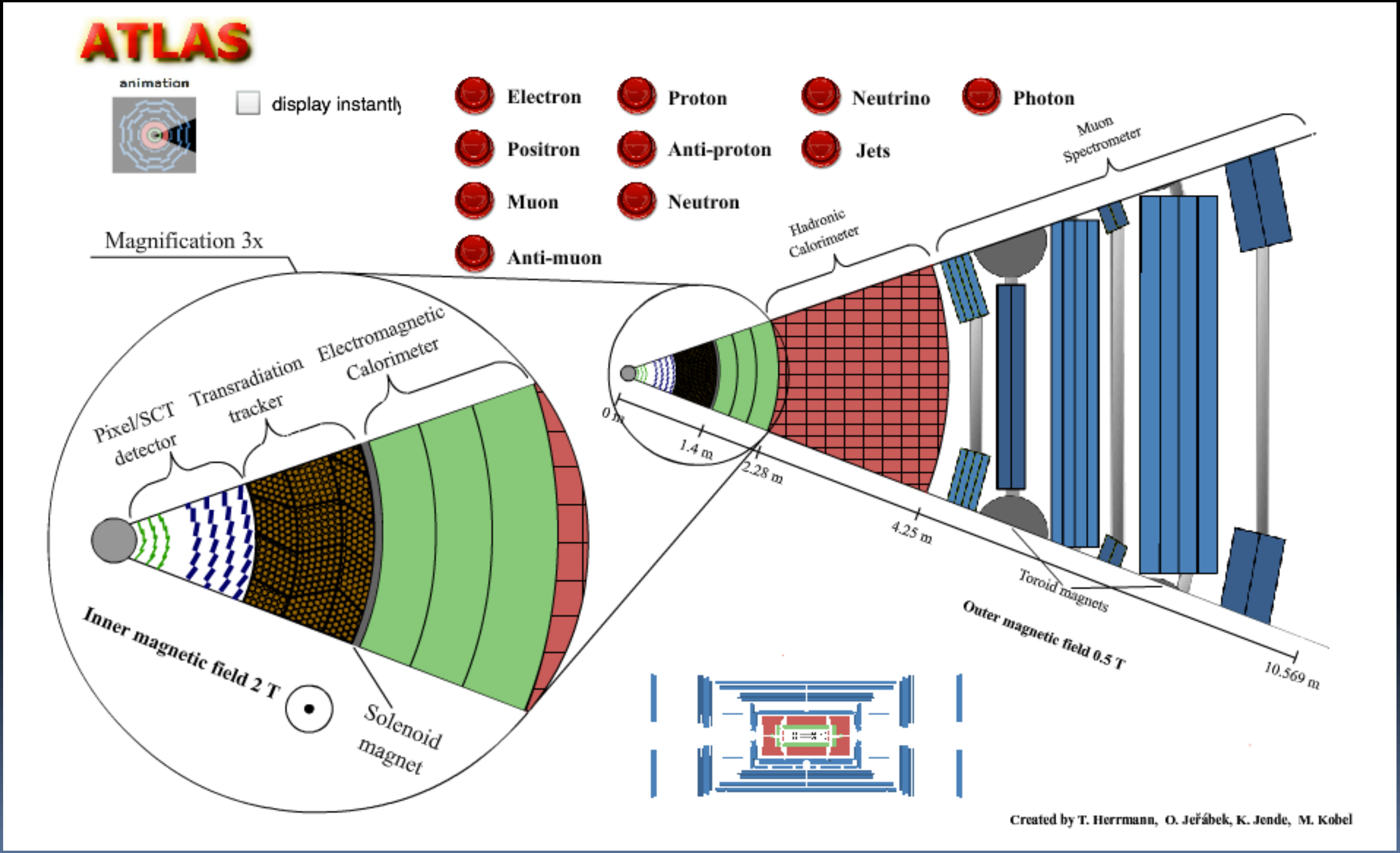
http://www.atlas.ch/multimedia/4-muon-event.html#2-electron-2-muon-event

Heavy Ion Collision

http://www.atlas.ch/multimedia/4-muon-event.html#heavy-ion-event

Particle identification

http://www.atlas.ch/multimedia/4-muon-event.html#episode-2
http://folk.uio.no/farido/teilchenidentifikation.pdf

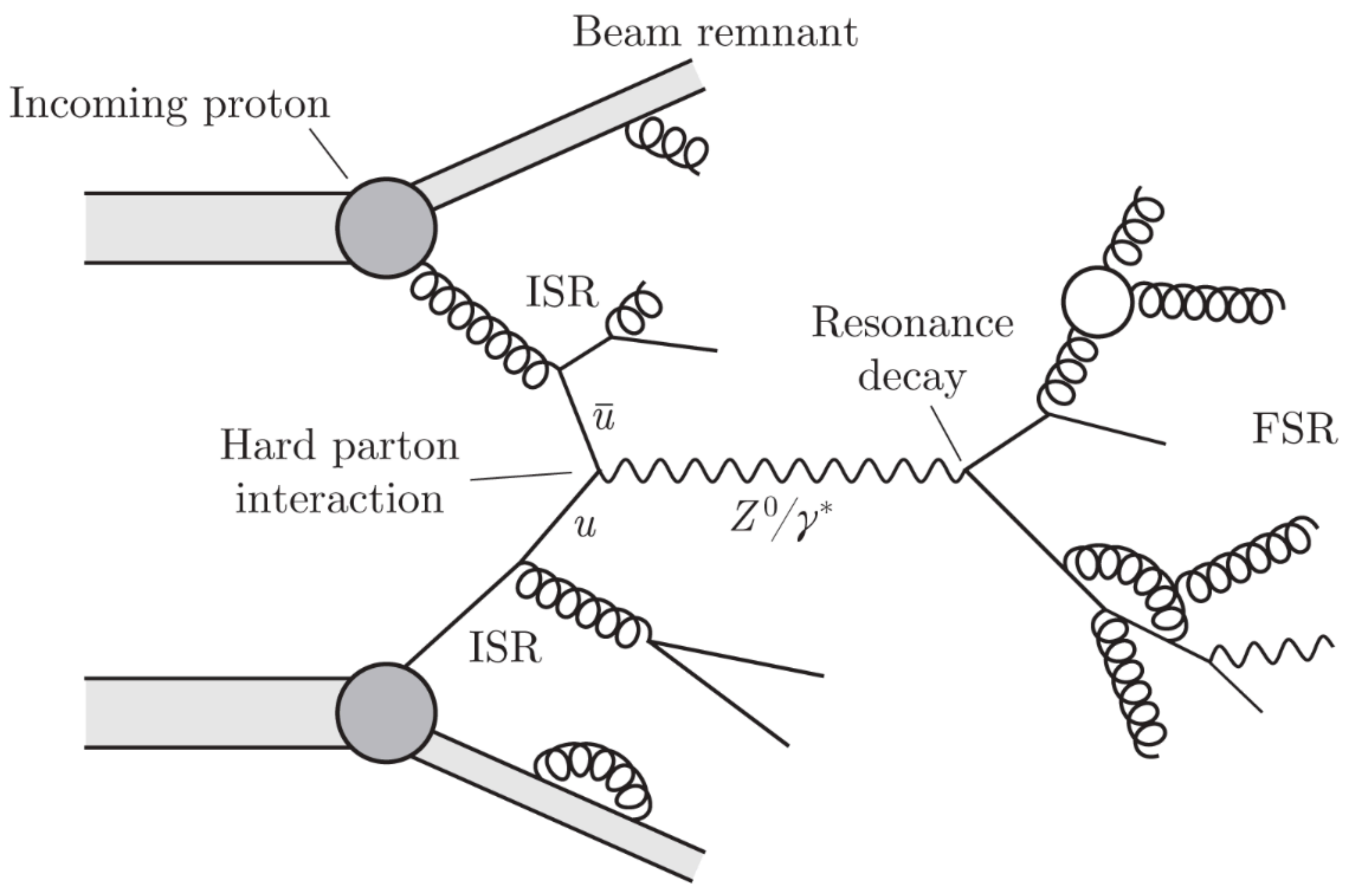


Why LHC

- Several accelerators / colliders built to discover (among others) the Higgs particle

- LHC was planned not to miss the Higgs
- LHC is a discovery machine

In reality only a fraction of the pp energy is available to produce "new" particles

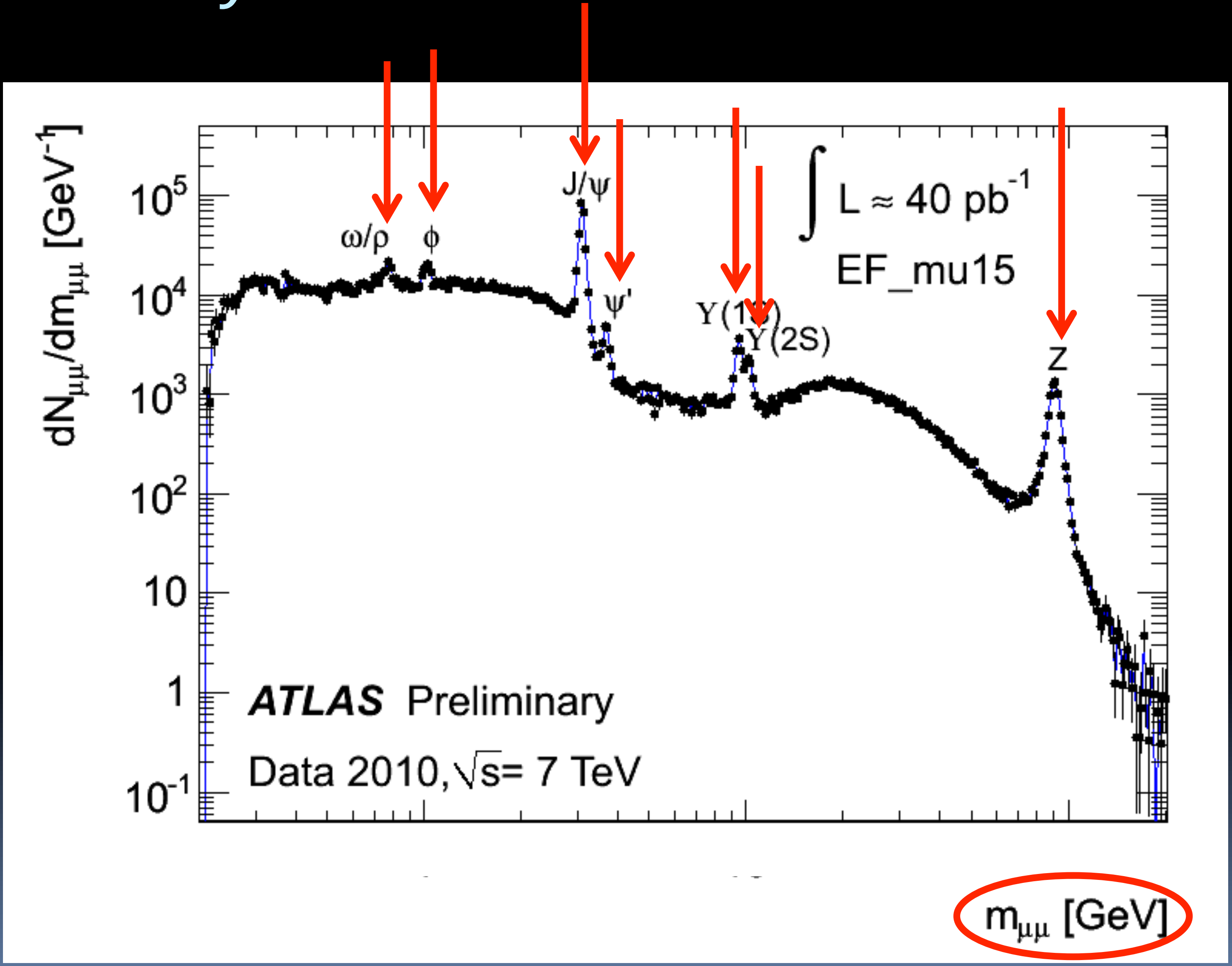


Complementary role of collisions with various beams:

- e+e-
- ep
- pp
- ppbar
- nuN
- nue
- heavy ion - HI
- p HI
-…

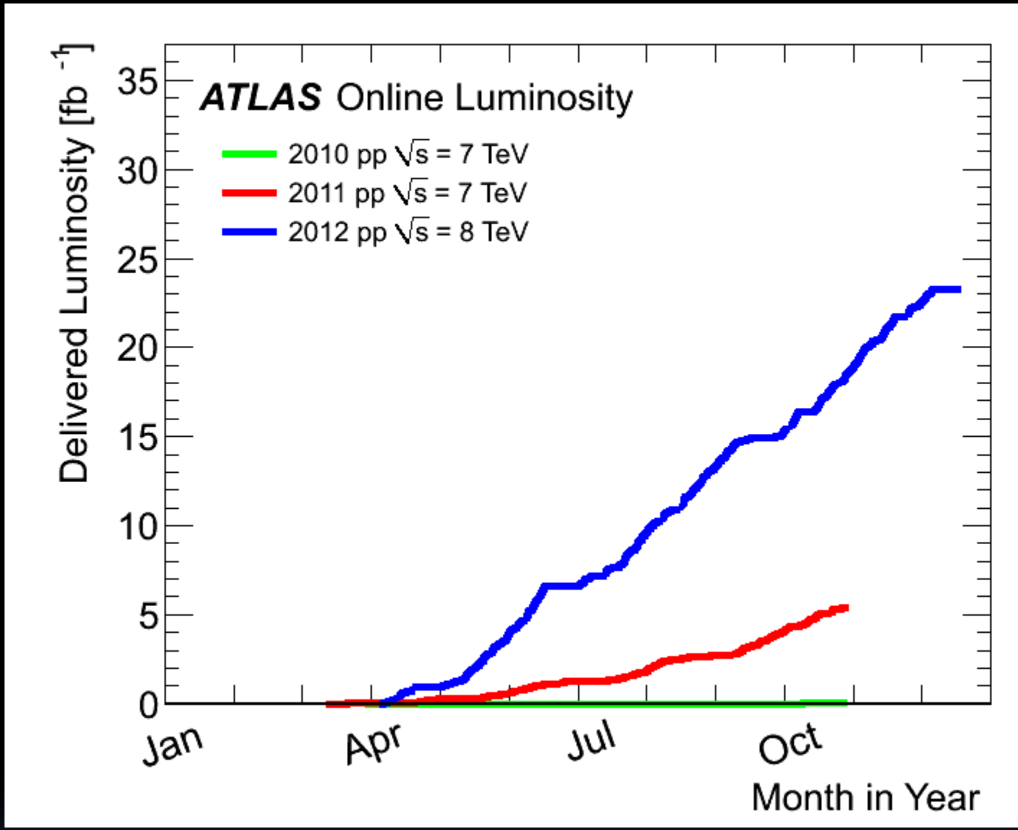
- pp at fixed energy equivalent to quark/gluon collisions at various energies

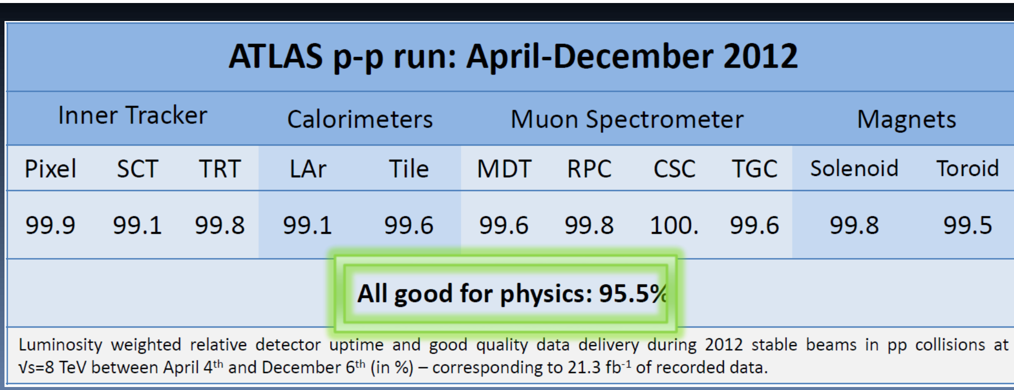
Everything in place? or Particle physics history in a short time



LHC and ATLAS performance

- Excellent LHC performance 12>11>10
  - Max luminosity already 80% of design value
  - 2010: 0.05 fb^{-1} at 7TeV
  - 2011: 5.6 fb^{-1} at 7TeV
  - 2012: 23 fb^{-1} at 8TeV
- ATLAS recorded 90% of luminosity delivered by LHC → ~25 fb^{-1}
- Excellent detector performance →





ATLAS p-p run: April-December 2012

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5

All good for physics: 95.5%

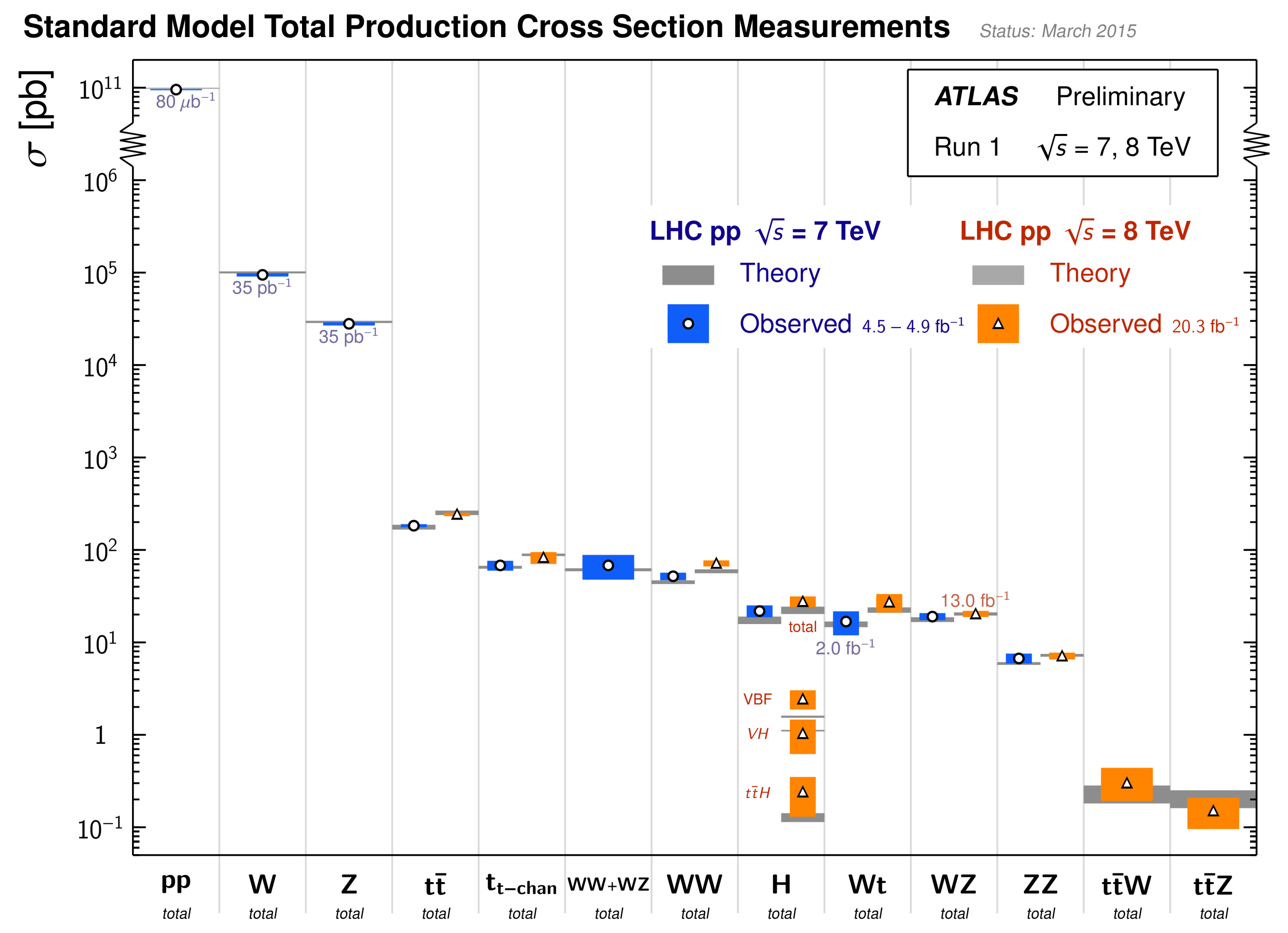
Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.3 fb^{-1} of recorded data.

Access to physics

- Full dataset 2010-2012 after typical selection cuts ~25 fb^{-1}
  - W→lν ~100 M
  - Z→ll ~10 M
  - tt→l+X ~0.4M
  - >400 Higgs

- LHC is W, Z, top factory …

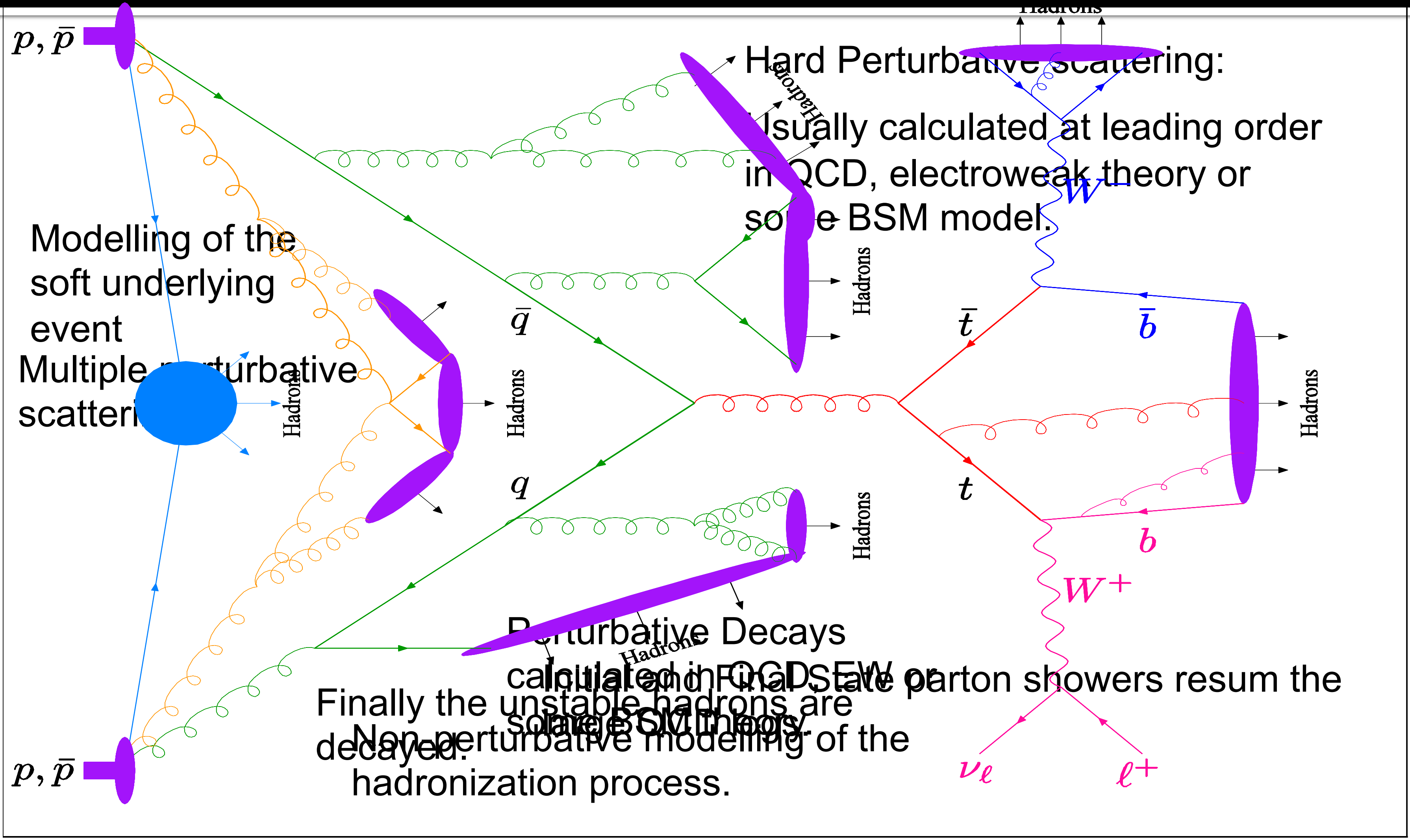
- ATLAS made 3 discoveries, one per year
  - 2010: Jet quenching
  - 2011: New B meson
  - 2012: Higgs



Standard Model: 3!=3*2*1

- SM very successful …
  - Higgs looks like Higgs and probably Standard & Minimal
    - (For good or for bad?)
  - LHC Top factory
  - $SU(2)_L$*U(1) gauge structure
  - QCD works well …

A Monte Carlo event



Hard Perturbative scattering:

Usually calculated at leading order in QCD, electroweak theory or some BSM model.

Modelling of the soft underlying event

Multiple perturbative scattering.

Perturbative Decays calculated in QCD, EW or some BSM theory.

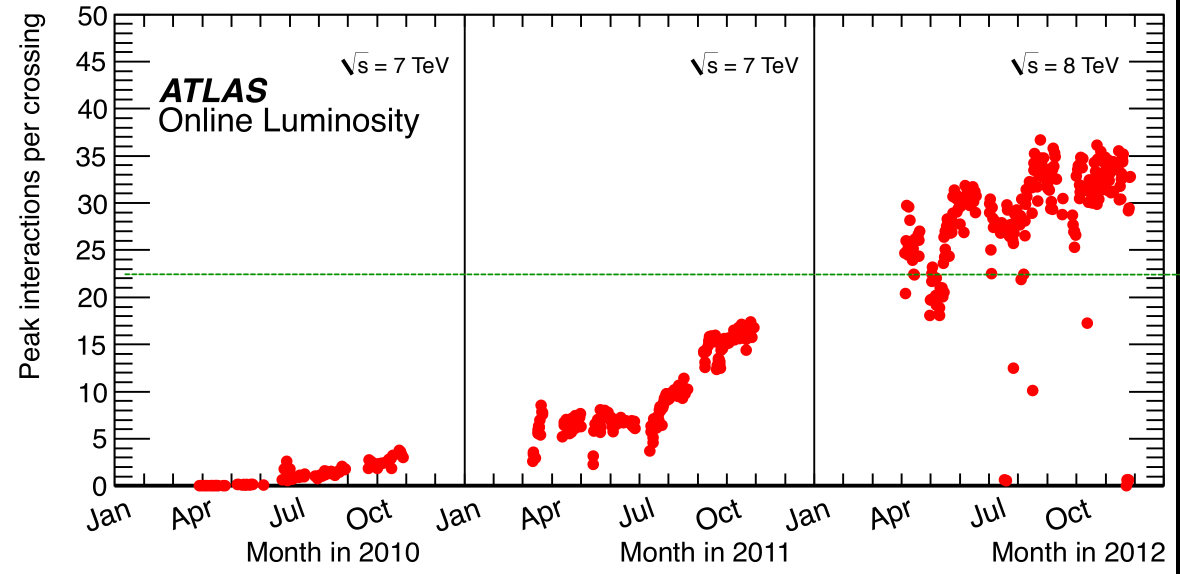
Initial and Final State parton showers resum the large QCD logs.

Finally the unstable hadrons are decayed.

Non-perturbative modelling of the hadronization process.

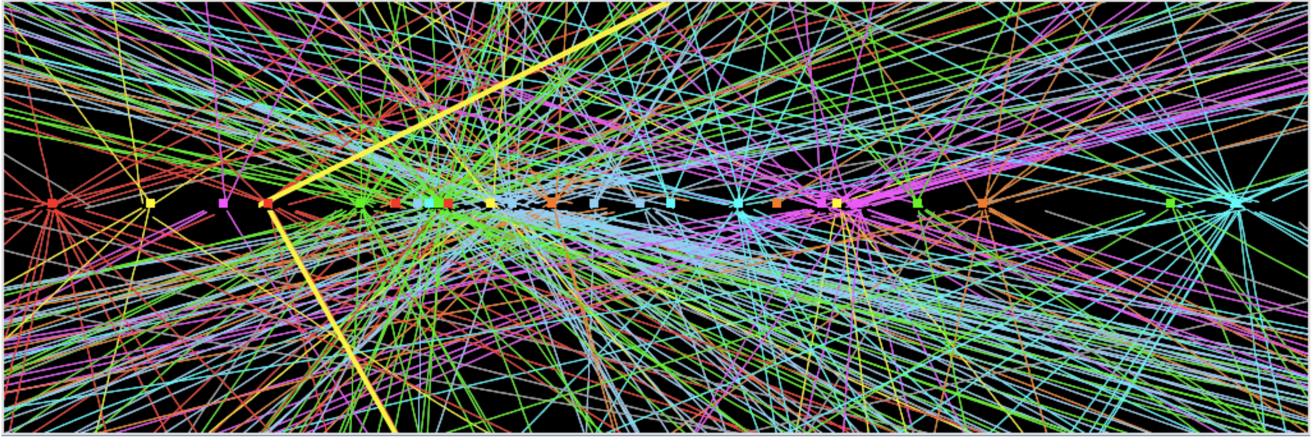
Tough conditions with many interactions per beam crossing

- ATLAS detector functioned well despite recording many interactions per collision
  - Due to increase in luminosity



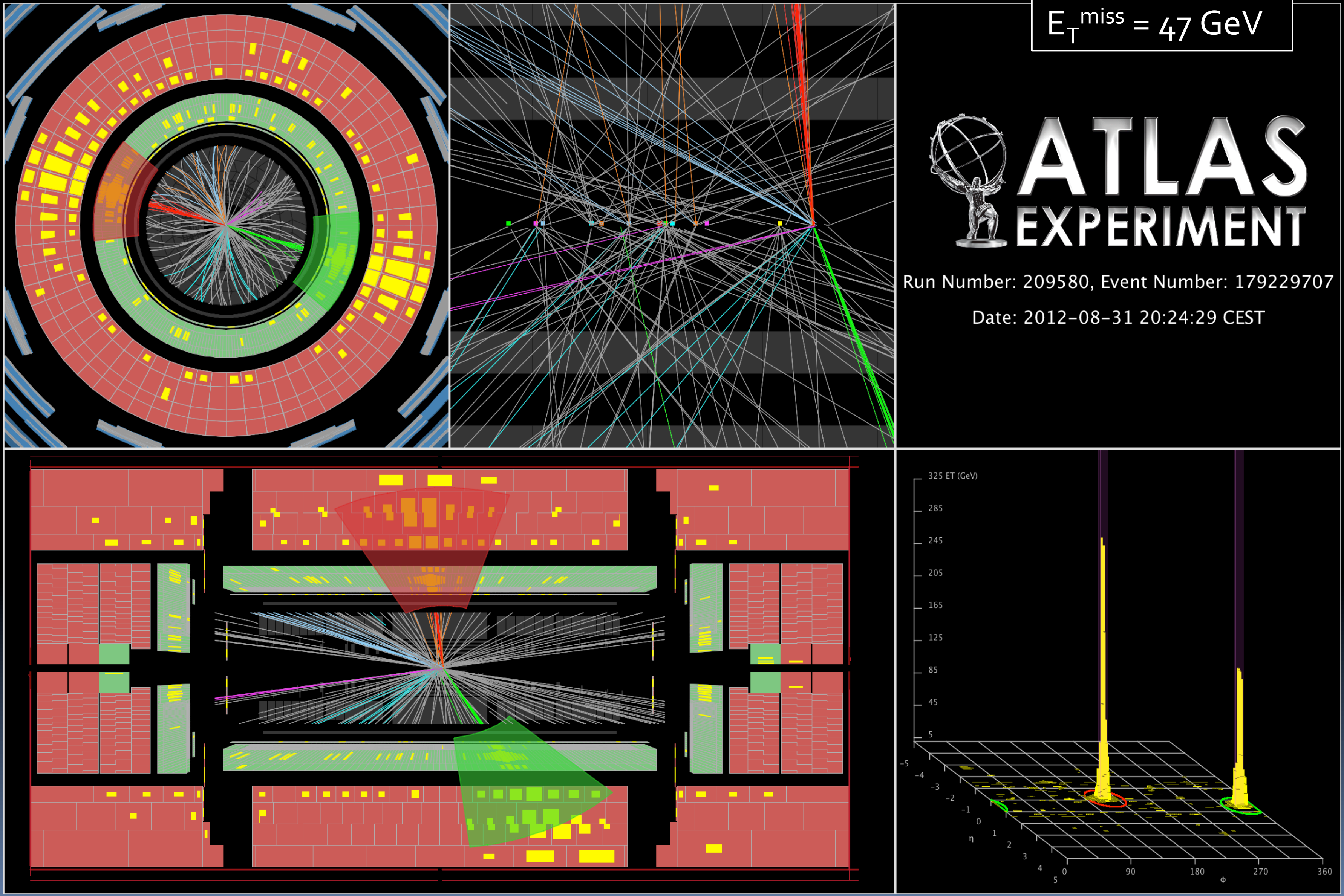
Design value (expected to be reached at L=10^{34} !)

- *Z* boson decay to μμ with many reconstructed vertices



High-pT di-jet: M_{jj} = 4.7 TeV!

m_{jj} = 4.7 TeV
p_T^j = 2.3 TeV
E_T^{miss} = 47 GeV

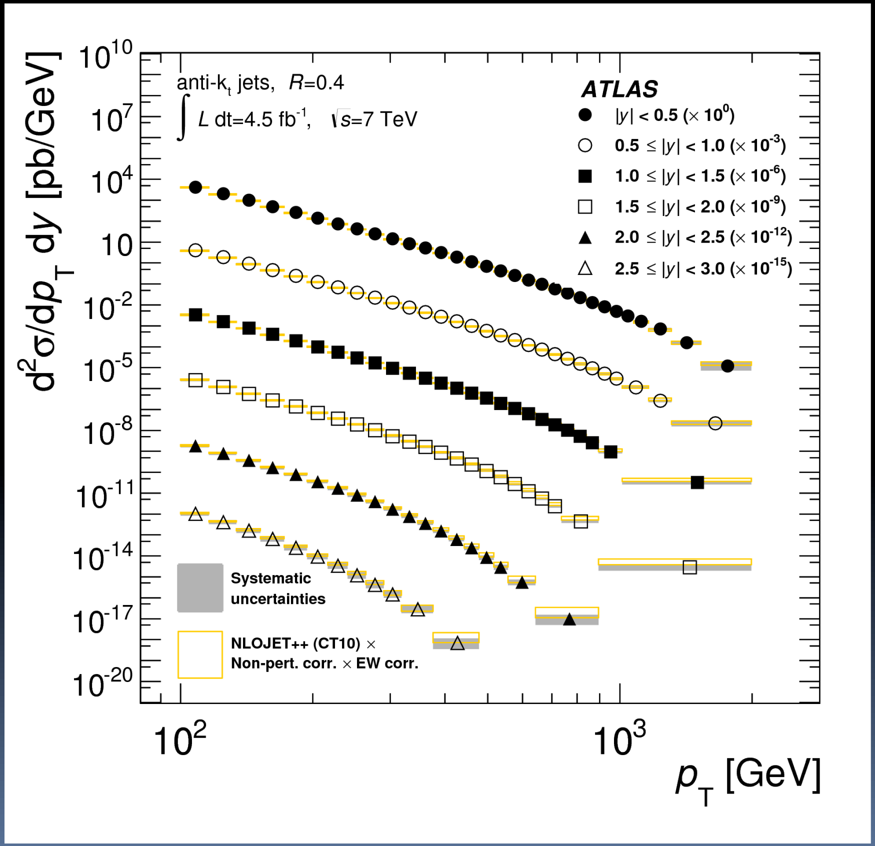


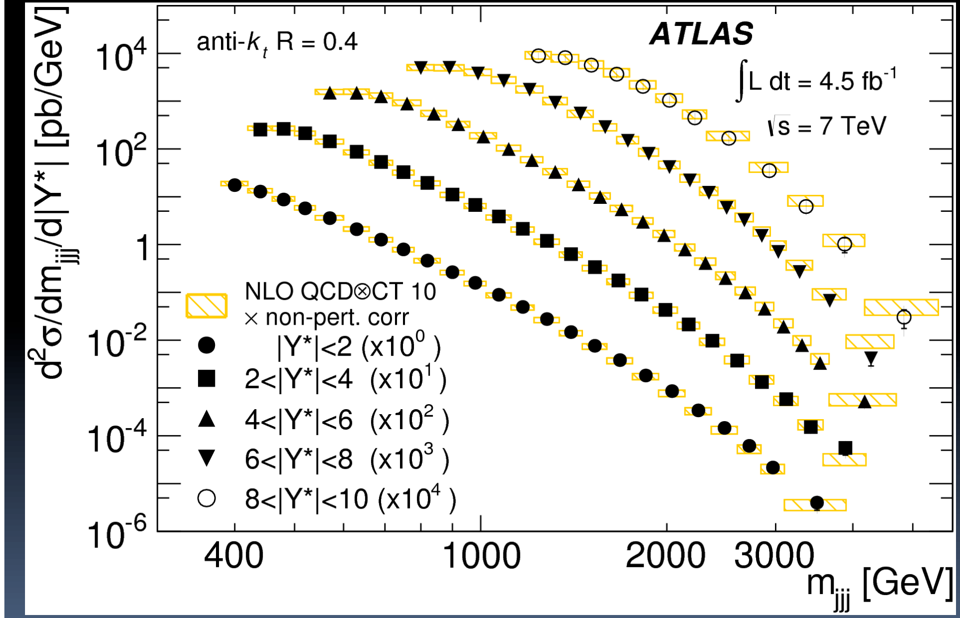
Run Number: 209580, Event Number: 179229707

Date: 2012-08-31 20:24:29 CEST

QCD Jets

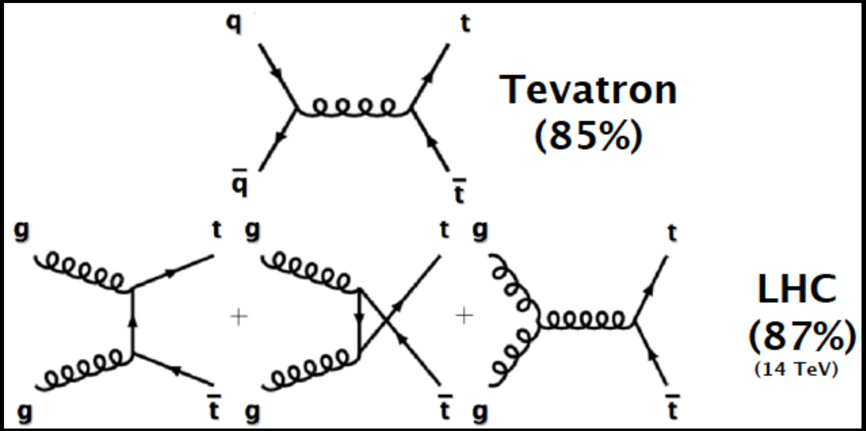
- Inclusive Jet cross sections
  - QCD works well and fits data over 10 orders of magnitude!

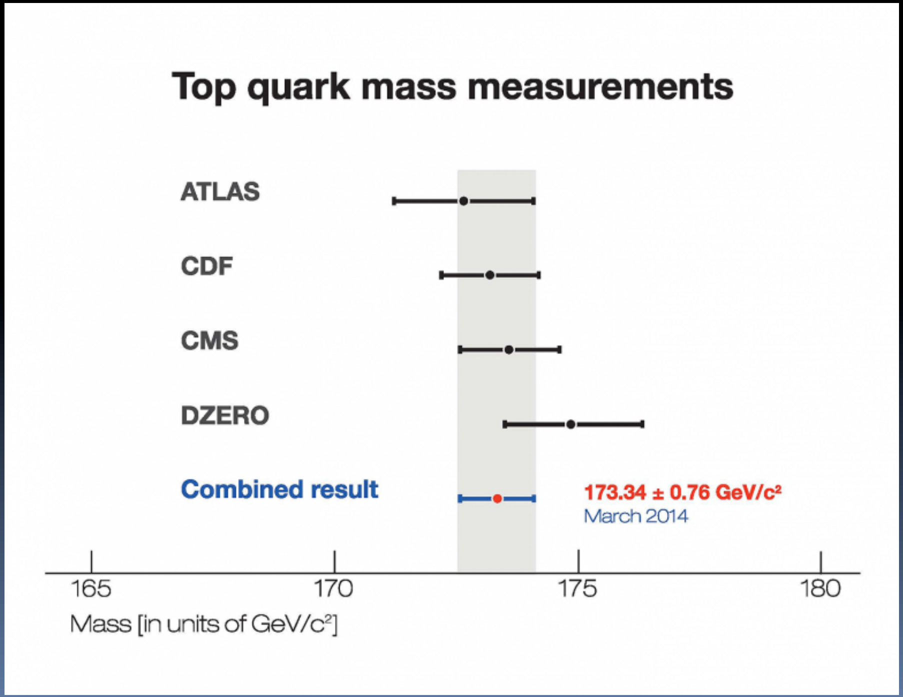


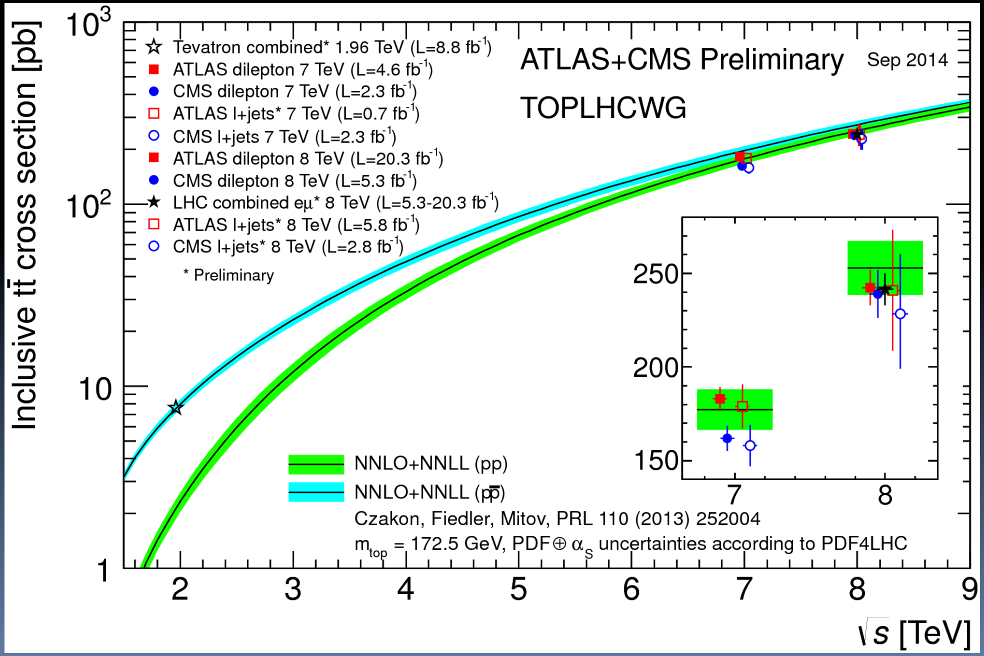


Top quark @ ATLAS ++

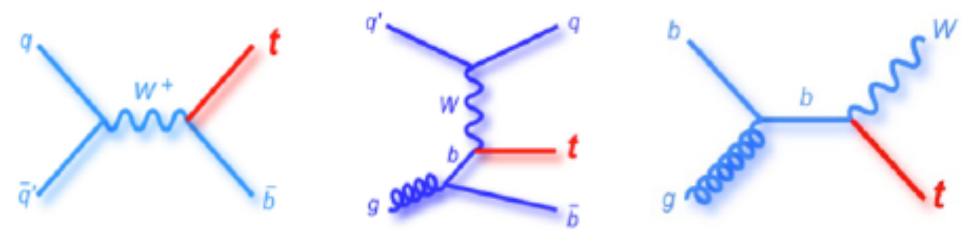
- Ttbar, single top cross sections
- Top mass, …

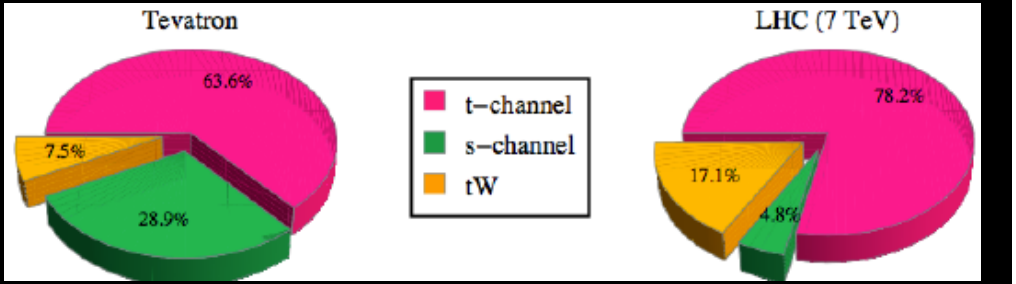


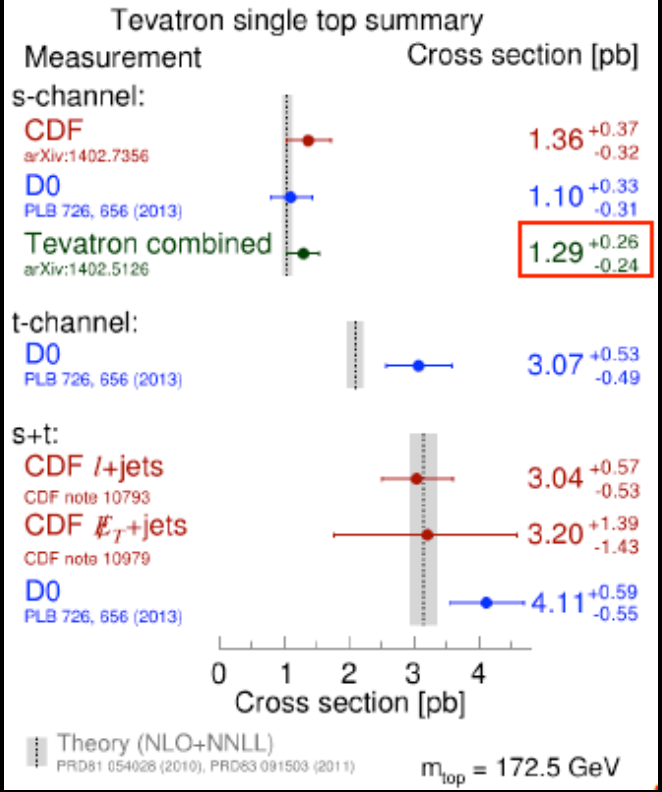


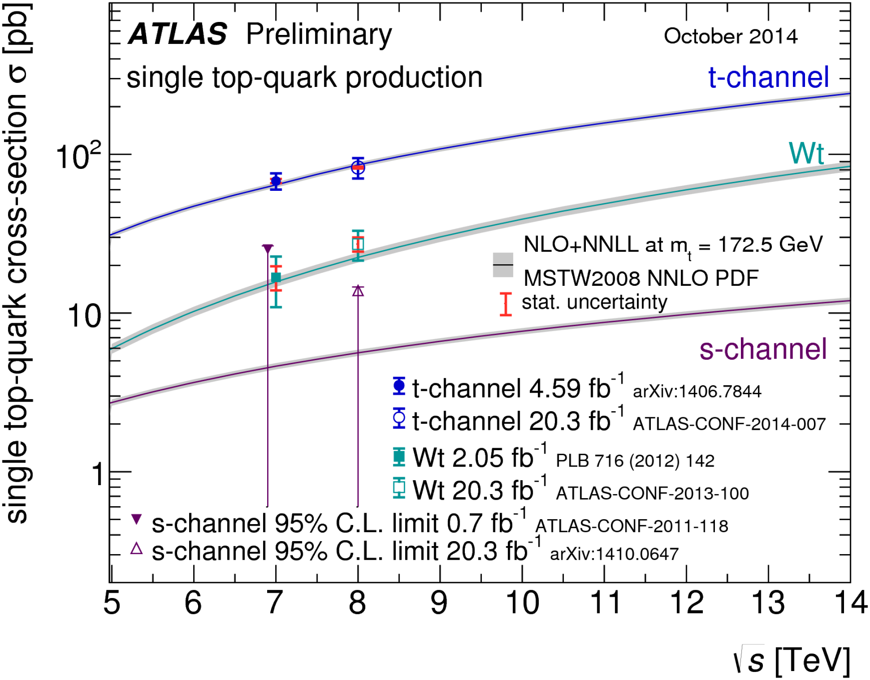


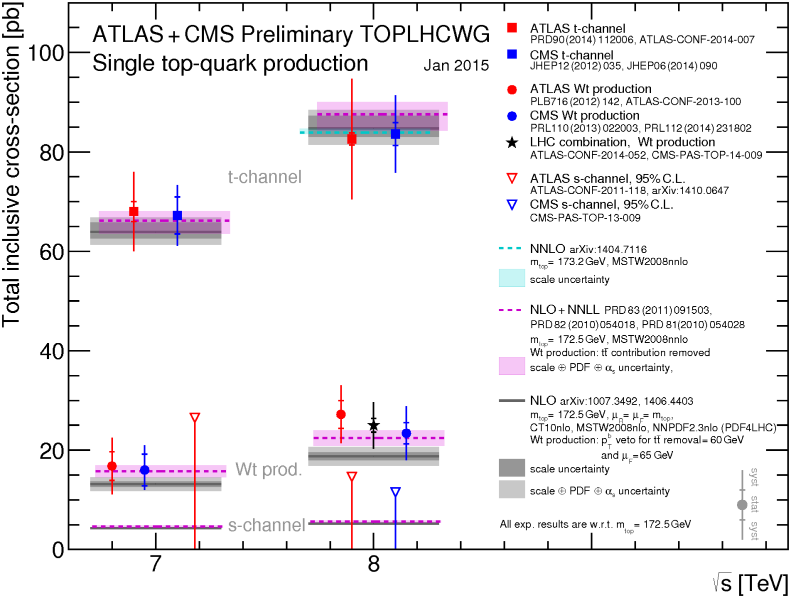
Single top @ ATLAS ++





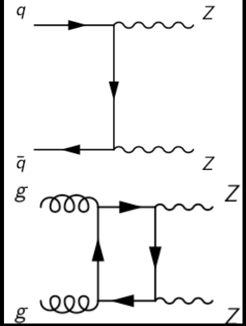






Electroweak symmetry validated at LHC

- ATLAS results
  - Triple Gauge Couplings investigated
  - Quartic couplings – next step
- Gauge boson self-coupling as predicted by SM
  - γWW, ZWW , Yes - No evidence of γZZ, ZZZ



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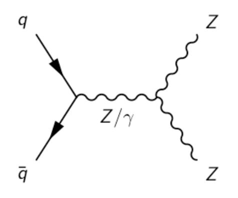

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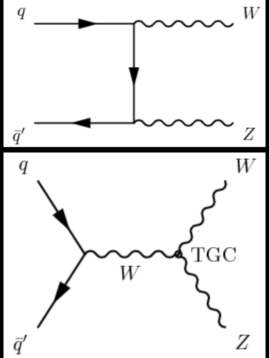

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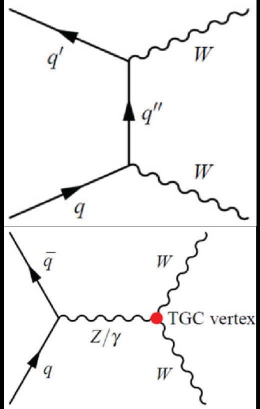

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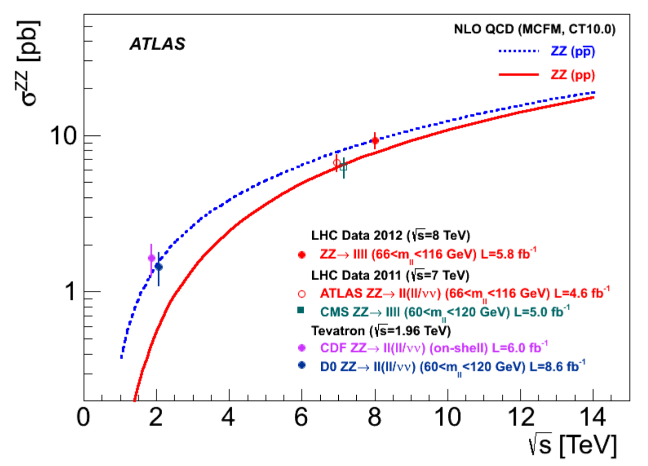
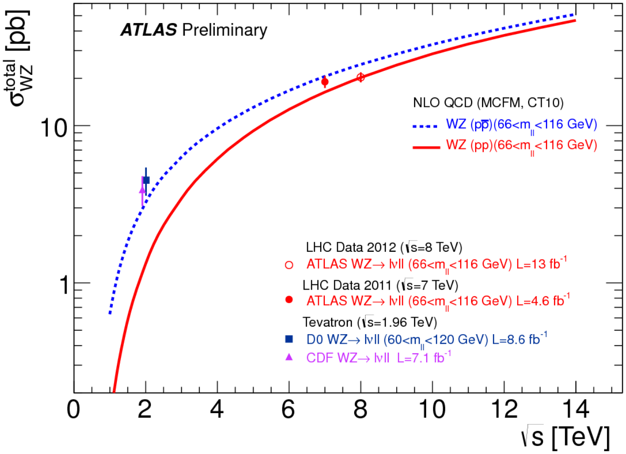
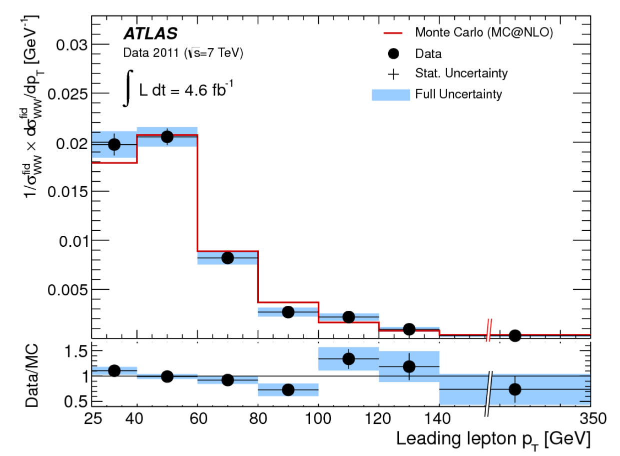
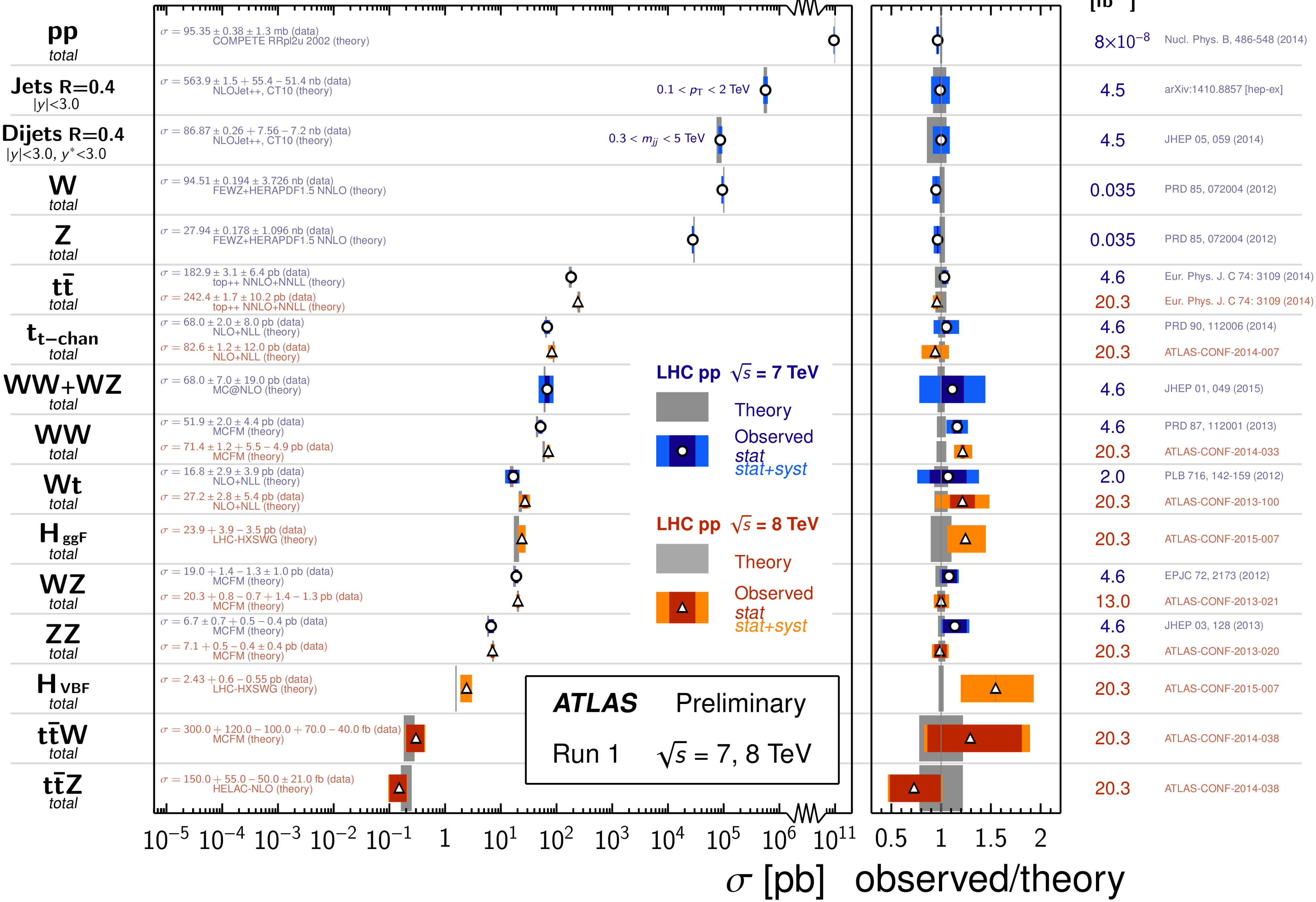






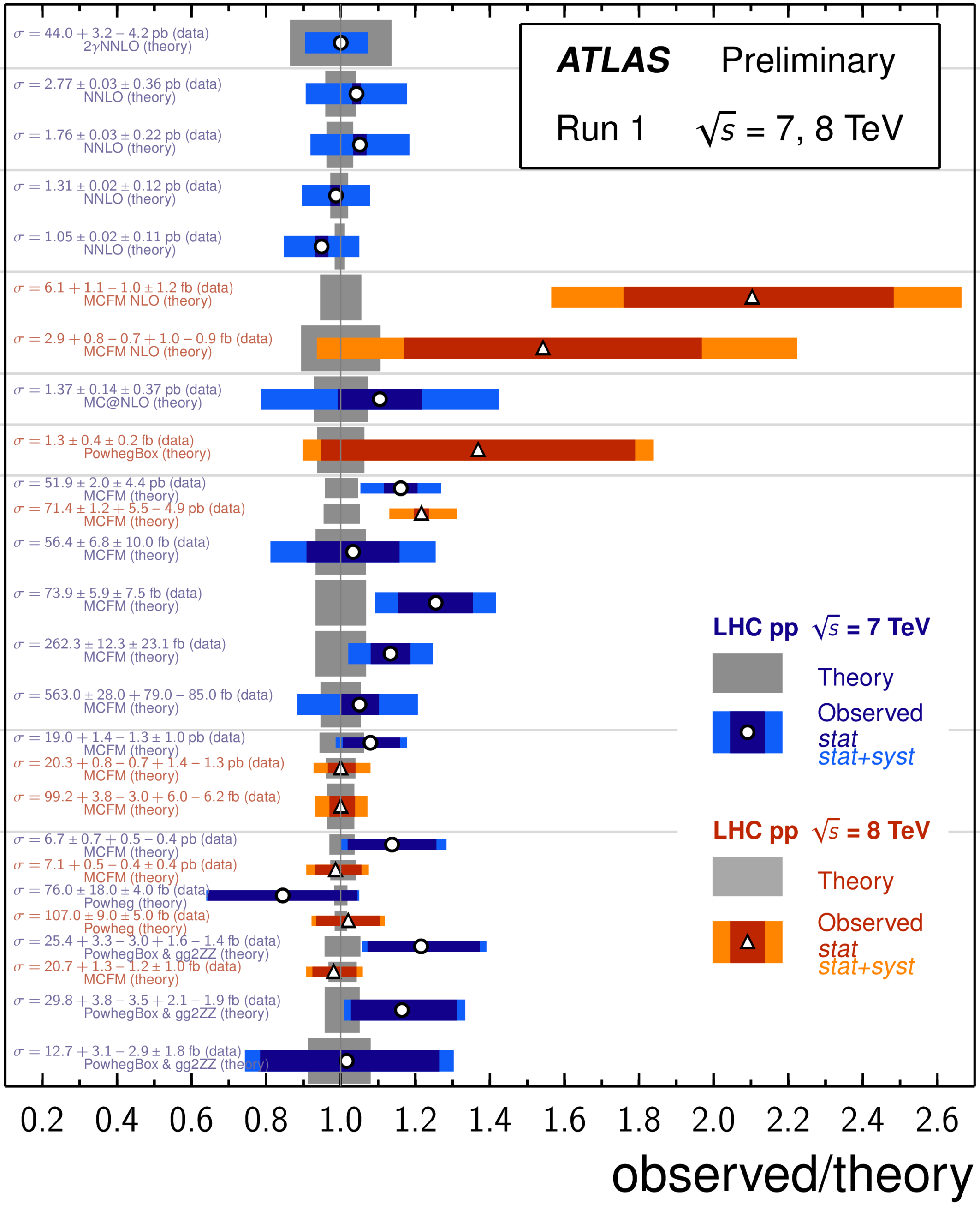
Standard Model Total Production Cross Section Measurements

Status: March 2015



Multiboson Cross Section Measurements

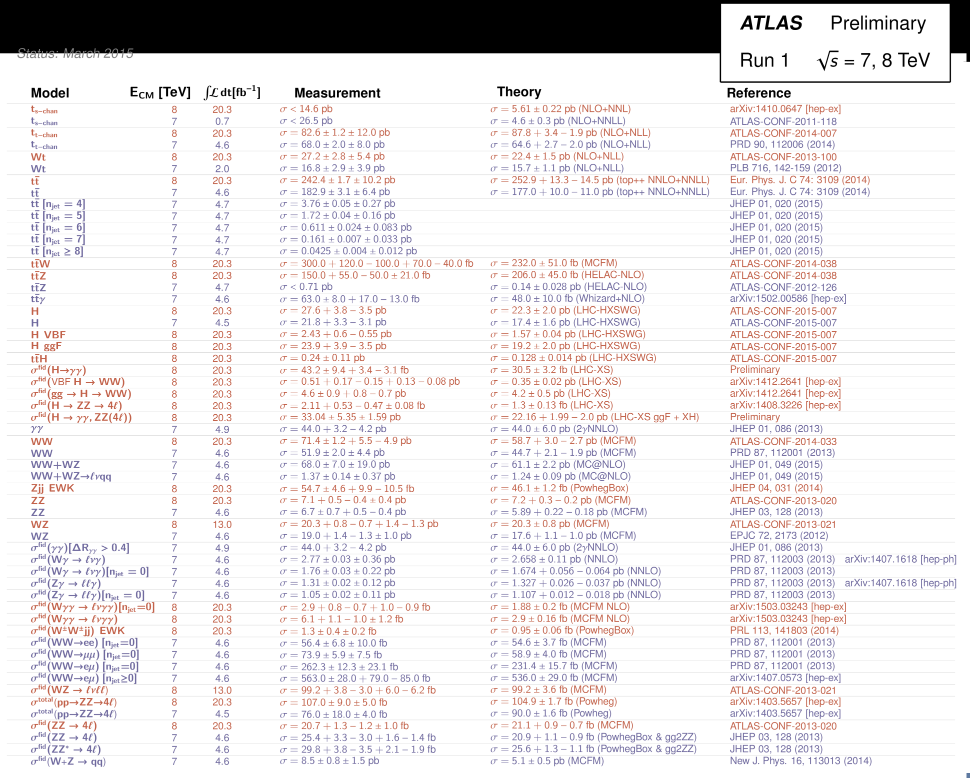
Status: March 2015



		$\int\mathcal{L}\,dt$ [fb^{-1}]	Reference
$\sigma^{fid}(\gamma\gamma)[\Delta R_{\gamma\gamma} > 0.4]$	$\sigma = 44.0 + 3.2 - 4.2$ pb (data) 2γNNLO (theory)	4.9	JHEP 01, 086 (2013)
$\sigma^{fid}(W\gamma \rightarrow \ell\nu\gamma)$	$\sigma = 2.77 \pm 0.03 \pm 0.36$ pb (data) NNLO (theory)	4.6	PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
$-[n_{jet} = 0]$	$\sigma = 1.76 \pm 0.03 \pm 0.22$ pb (data) NNLO (theory)	4.6	PRD 87, 112003 (2013)
$\sigma^{fid}(Z\gamma \rightarrow \ell\ell\gamma)$	$\sigma = 1.31 \pm 0.02 \pm 0.12$ pb (data) NNLO (theory)	4.6	PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
$-[n_{jet} = 0]$	$\sigma = 1.05 \pm 0.02 \pm 0.11$ pb (data) NNLO (theory)	4.6	PRD 87, 112003 (2013)
$\sigma^{fid}(W\gamma\gamma \rightarrow \ell\nu\gamma\gamma)$	$\sigma = 6.1 + 1.1 - 1.0 \pm 1.2$ fb (data) MCFM NLO (theory)	20.3	arXiv:1503.03243 [hep-ex]
$-[n_{jet} = 0]$	$\sigma = 2.9 + 0.8 - 0.7 + 1.0 - 0.9$ fb (data) MCFM NLO (theory)	20.3	arXiv:1503.03243 [hep-ex]
$\sigma^{fid}(pp \rightarrow WV \rightarrow \ell\nu qq)$	$\sigma = 1.37 \pm 0.14 \pm 0.37$ pb (data) MC@NLO (theory)	4.6	JHEP 01, 049 (2015)
$\sigma^{fid}(W^{\pm}W^{\pm}jj)$ EWK	$\sigma = 1.3 \pm 0.4 \pm 0.2$ fb (data) PowhegBox (theory)	20.3	PRL 113, 141803 (2014)
$\sigma^{total}(pp \rightarrow WW)$	$\sigma = 51.9 \pm 2.0 \pm 4.4$ pb (data) MCFM (theory)	4.6	PRD 87, 112001 (2013)
	$\sigma = 71.4 \pm 1.2 + 5.5 - 4.9$ pb (data) MCFM (theory)	20.3	ATLAS-CONF-2014-033
$-\sigma^{fid}(WW \rightarrow ee)\ [n_{jet}=0]$	$\sigma = 56.4 \pm 6.8 \pm 10.0$ fb (data) MCFM (theory)	4.6	PRD 87, 112001 (2013)
$-\sigma^{fid}(WW \rightarrow \mu\mu)\ [n_{jet}=0]$	$\sigma = 73.9 \pm 5.9 \pm 7.5$ fb (data) MCFM (theory)	4.6	PRD 87, 112001 (2013)
$-\sigma^{fid}(WW \rightarrow e\mu)\ [n_{jet}=0]$	$\sigma = 262.3 \pm 12.3 \pm 23.1$ fb (data) MCFM (theory)	4.6	PRD 87, 112001 (2013)
$-\sigma^{fid}(WW \rightarrow e\mu)\ [n_{jet}\geq 0]$	$\sigma = 563.0 \pm 28.0 + 79.0 - 85.0$ fb (data) MCFM (theory)	4.6	arXiv:1407.0573 [hep-ex]
$\sigma^{total}(pp \rightarrow WZ)$	$\sigma = 19.0 + 1.4 - 1.3 \pm 1.0$ pb (data) MCFM (theory)	4.6	EPJC 72, 2173 (2012)
	$\sigma = 20.3 + 0.8 - 0.7 + 1.4 - 1.3$ pb (data) MCFM (theory)	13.0	ATLAS-CONF-2013-021
$-\sigma^{fid}(WZ \rightarrow \ell\nu\ell\ell)$	$\sigma = 99.2 + 3.8 - 3.0 + 6.0 - 6.2$ fb (data) MCFM (theory)	13.0	ATLAS-CONF-2013-021
$\sigma^{total}(pp \rightarrow ZZ)$	$\sigma = 6.7 \pm 0.7 + 0.5 - 0.4$ pb (data) MCFM (theory)	4.6	JHEP 03, 128 (2013)
	$\sigma = 7.1 + 0.5 - 0.4 \pm 0.4$ pb (data) MCFM (theory)	20.3	ATLAS-CONF-2013-020
$-\sigma^{total}(pp \rightarrow ZZ \rightarrow 4\ell)$	$\sigma = 76.0 \pm 18.0 \pm 4.0$ fb (data) Powheg (theory)	4.5	arXiv:1403.5657 [hep-ex]
	$\sigma = 107.0 \pm 9.0 \pm 5.0$ fb (data) Powheg (theory)	20.3	arXiv:1403.5657 [hep-ex]
$-\sigma^{fid}(ZZ \rightarrow 4\ell)$	$\sigma = 25.4 + 3.3 - 3.0 + 1.6 - 1.4$ fb (data) PowhegBox & gg2ZZ (theory)	4.6	JHEP 03, 128 (2013)
	$\sigma = 20.7 + 1.3 - 1.2 \pm 1.0$ fb (data) MCFM (theory)	20.3	ATLAS-CONF-2013-020
$-\sigma^{fid}(ZZ^{*} \rightarrow 4\ell)$	$\sigma = 29.8 + 3.8 - 3.5 + 2.1 - 1.9$ fb (data) PowhegBox & gg2ZZ (theory)	4.6	JHEP 03, 128 (2013)
$-\sigma^{fid}(ZZ^{*} \rightarrow \ell\ell\nu\nu)$	$\sigma = 12.7 + 3.1 - 2.9 \pm 1.8$ fb (data) PowhegBox & gg2ZZ (theory)	4.6	JHEP 03, 128 (2013)

Importance of measurements

- … especially at new energy scales

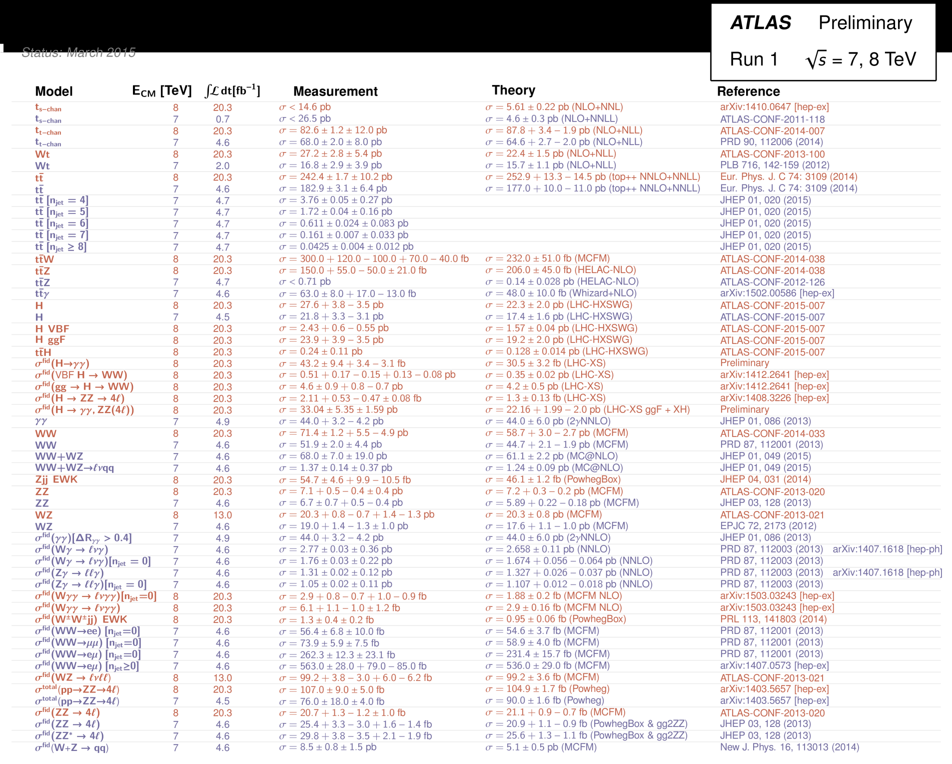


ATLAS Preliminary

Run 1 $\sqrt{s}$ = 7, 8 TeV

Status: March 2015

Model	E_{CM} [TeV]	$\int\mathcal{L}\,dt[fb^{-1}]$	Measurement	Theory	Reference
t_{s-chan}	8	20.3	$\sigma < 14.6$ pb	$\sigma = 5.61 \pm 0.22$ pb (NLO+NNL)	arXiv:1410.0647 [hep-ex]
t_{s-chan}	7	0.7	$\sigma < 26.5$ pb	$\sigma = 4.6 \pm 0.3$ pb (NLO+NNLL)	ATLAS-CONF-2011-118
t_{t-chan}	8	20.3	$\sigma = 82.6 \pm 1.2 \pm 12.0$ pb	$\sigma = 87.8 + 3.4 - 1.9$ pb (NLO+NLL)	ATLAS-CONF-2014-007
t_{t-chan}	7	4.6	$\sigma = 68.0 \pm 2.0 \pm 8.0$ pb	$\sigma = 64.6 + 2.7 - 2.0$ pb (NLO+NLL)	PRD 90, 112006 (2014)
Wt	8	20.3	$\sigma = 27.2 \pm 2.8 \pm 5.4$ pb	$\sigma = 22.4 \pm 1.5$ pb (NLO+NLL)	ATLAS-CONF-2013-100
Wt	7	2.0	$\sigma = 16.8 \pm 2.9 \pm 3.9$ pb	$\sigma = 15.7 \pm 1.1$ pb (NLO+NLL)	PLB 716, 142-159 (2012)
$t\bar{t}$	8	20.3	$\sigma = 242.4 \pm 1.7 \pm 10.2$ pb	$\sigma = 252.9 + 13.3 - 14.5$ pb (top++ NNLO+NNLL)	Eur. Phys. J. C 74: 3109 (2014)
$t\bar{t}$	7	4.6	$\sigma = 182.9 \pm 3.1 \pm 6.4$ pb	$\sigma = 177.0 + 10.0 - 11.0$ pb (top++ NNLO+NNLL)	Eur. Phys. J. C 74: 3109 (2014)
$t\bar{t}$ [$n_{jet} = 4$]	7	4.7	$\sigma = 3.76 \pm 0.05 \pm 0.27$ pb		JHEP 01, 020 (2015)
$t\bar{t}$ [$n_{jet} = 5$]	7	4.7	$\sigma = 1.72 \pm 0.04 \pm 0.16$ pb		JHEP 01, 020 (2015)
$t\bar{t}$ [$n_{jet} = 6$]	7	4.7	$\sigma = 0.611 \pm 0.024 \pm 0.083$ pb		JHEP 01, 020 (2015)
$t\bar{t}$ [$n_{jet} = 7$]	7	4.7	$\sigma = 0.161 \pm 0.007 \pm 0.033$ pb		JHEP 01, 020 (2015)
$t\bar{t}$ [$n_{jet} \geq 8$]	7	4.7	$\sigma = 0.0425 \pm 0.004 \pm 0.012$ pb		JHEP 01, 020 (2015)
$t\bar{t}W$	8	20.3	$\sigma = 300.0 + 120.0 - 100.0 + 70.0 - 40.0$ fb	$\sigma = 232.0 \pm 51.0$ fb (MCFM)	ATLAS-CONF-2014-038
$t\bar{t}Z$	8	20.3	$\sigma = 150.0 + 55.0 - 50.0 \pm 21.0$ fb	$\sigma = 206.0 \pm 45.0$ fb (HELAC-NLO)	ATLAS-CONF-2014-038
$t\bar{t}Z$	7	4.7	$\sigma < 0.71$ pb	$\sigma = 0.14 \pm 0.028$ pb (HELAC-NLO)	ATLAS-CONF-2012-126
$t\bar{t}\gamma$	7	4.6	$\sigma = 63.0 \pm 8.0 + 17.0 - 13.0$ fb	$\sigma = 48.0 \pm 10.0$ fb (Whizard+NLO)	arXiv:1502.00586 [hep-ex]
H	8	20.3	$\sigma = 27.6 + 3.8 - 3.5$ pb	$\sigma = 22.3 \pm 2.0$ pb (LHC-HXSWG)	ATLAS-CONF-2015-007
H	7	4.5	$\sigma = 21.8 + 3.3 - 3.1$ pb	$\sigma = 17.4 \pm 1.6$ pb (LHC-HXSWG)	ATLAS-CONF-2015-007
H VBF	8	20.3	$\sigma = 2.43 + 0.6 - 0.55$ pb	$\sigma = 1.57 \pm 0.04$ pb (LHC-HXSWG)	ATLAS-CONF-2015-007
H ggF	8	20.3	$\sigma = 23.9 + 3.9 - 3.5$ pb	$\sigma = 19.2 \pm 2.0$ pb (LHC-HXSWG)	ATLAS-CONF-2015-007
$t\bar{t}H$	8	20.3	$\sigma = 0.24 \pm 0.11$ pb	$\sigma = 0.128 \pm 0.014$ pb (LHC-HXSWG)	ATLAS-CONF-2015-007
$\sigma^{fid}(H \rightarrow \gamma\gamma)$	8	20.3	$\sigma = 43.2 \pm 9.4 + 3.4 - 3.1$ fb	$\sigma = 30.5 \pm 3.2$ fb (LHC-XS)	Preliminary
σ^{fid}(VBF $H \rightarrow WW$)	8	20.3	$\sigma = 0.51 + 0.17 - 0.15 + 0.13 - 0.08$ pb	$\sigma = 0.35 \pm 0.02$ pb (LHC-XS)	arXiv:1412.2641 [hep-ex]
$\sigma^{fid}(gg \rightarrow H \rightarrow WW)$	8	20.3	$\sigma = 4.6 \pm 0.9 + 0.8 - 0.7$ pb	$\sigma = 4.2 \pm 0.5$ pb (LHC-XS)	arXiv:1412.2641 [hep-ex]
$\sigma^{fid}(H \rightarrow ZZ \rightarrow 4\ell)$	8	20.3	$\sigma = 2.11 + 0.53 - 0.47 \pm 0.08$ fb	$\sigma = 1.3 \pm 0.13$ fb (LHC-XS)	arXiv:1408.3226 [hep-ex]
$\sigma^{fid}(H \rightarrow \gamma\gamma, ZZ(4\ell))$	8	20.3	$\sigma = 33.04 \pm 5.35 \pm 1.59$ pb	$\sigma = 22.16 + 1.99 - 2.0$ pb (LHC-XS ggF + XH)	Preliminary
$\gamma\gamma$	7	4.9	$\sigma = 44.0 + 3.2 - 4.2$ pb	$\sigma = 44.0 \pm 6.0$ pb (2γNNLO)	JHEP 01, 086 (2013)
WW	8	20.3	$\sigma = 71.4 \pm 1.2 + 5.5 - 4.9$ pb	$\sigma = 58.7 + 3.0 - 2.7$ pb (MCFM)	ATLAS-CONF-2014-033
WW	7	4.6	$\sigma = 51.9 \pm 2.0 \pm 4.4$ pb	$\sigma = 44.7 + 2.1 - 1.9$ pb (MCFM)	PRD 87, 112001 (2013)
WW+WZ	7	4.6	$\sigma = 68.0 \pm 7.0 \pm 19.0$ pb	$\sigma = 61.1 \pm 2.2$ pb (MC@NLO)	JHEP 01, 049 (2015)
$WW+WZ \rightarrow \ell\nu qq$	7	4.6	$\sigma = 1.37 \pm 0.14 \pm 0.37$ pb	$\sigma = 1.24 \pm 0.09$ pb (MC@NLO)	JHEP 01, 049 (2015)
Zjj EWK	8	20.3	$\sigma = 54.7 \pm 4.6 + 9.9 - 10.5$ fb	$\sigma = 46.1 \pm 1.2$ fb (PowhegBox)	JHEP 04, 031 (2014)
ZZ	8	20.3	$\sigma = 7.1 + 0.5 - 0.4 \pm 0.4$ pb	$\sigma = 7.2 + 0.3 - 0.2$ pb (MCFM)	ATLAS-CONF-2013-020
ZZ	7	4.6	$\sigma = 6.7 \pm 0.7 + 0.5 - 0.4$ pb	$\sigma = 5.89 + 0.22 - 0.18$ pb (MCFM)	JHEP 03, 128 (2013)
WZ	8	13.0	$\sigma = 20.3 + 0.8 - 0.7 + 1.4 - 1.3$ pb	$\sigma = 20.3 \pm 0.8$ pb (MCFM)	ATLAS-CONF-2013-021
WZ	7	4.6	$\sigma = 19.0 + 1.4 - 1.3 \pm 1.0$ pb	$\sigma = 17.6 + 1.1 - 1.0$ pb (MCFM)	EPJC 72, 2173 (2012)
$\sigma^{fid}(\gamma\gamma)[\Delta R_{\gamma\gamma} > 0.4]$	7	4.9	$\sigma = 44.0 + 3.2 - 4.2$ pb	$\sigma = 44.0 \pm 6.0$ pb (2γNNLO)	JHEP 01, 086 (2013)
$\sigma^{fid}(W\gamma \rightarrow \ell\nu\gamma)$	7	4.6	$\sigma = 2.77 \pm 0.03 \pm 0.36$ pb	$\sigma = 2.658 \pm 0.11$ pb (NNLO)	PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
$\sigma^{fid}(W\gamma \rightarrow \ell\nu\gamma)[n_{jet} = 0]$	7	4.6	$\sigma = 1.76 \pm 0.03 \pm 0.22$ pb	$\sigma = 1.674 + 0.056 - 0.064$ pb (NNLO)	PRD 87, 112003 (2013)
$\sigma^{fid}(Z\gamma \rightarrow \ell\ell\gamma)$	7	4.6	$\sigma = 1.31 \pm 0.02 \pm 0.12$ pb	$\sigma = 1.327 + 0.026 - 0.037$ pb (NNLO)	PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
$\sigma^{fid}(Z\gamma \rightarrow \ell\ell\gamma)[n_{jet} = 0]$	7	4.6	$\sigma = 1.05 \pm 0.02 \pm 0.11$ pb	$\sigma = 1.107 + 0.012 - 0.018$ pb (NNLO)	PRD 87, 112003 (2013)
$\sigma^{fid}(W\gamma\gamma \rightarrow \ell\nu\gamma\gamma)[n_{jet}=0]$	8	20.3	$\sigma = 2.9 + 0.8 - 0.7 + 1.0 - 0.9$ fb	$\sigma = 1.88 \pm 0.2$ fb (MCFM NLO)	arXiv:1503.03243 [hep-ex]
$\sigma^{fid}(W\gamma\gamma \rightarrow \ell\nu\gamma\gamma)$	8	20.3	$\sigma = 6.1 + 1.1 - 1.0 \pm 1.2$ fb	$\sigma = 2.9 \pm 0.16$ fb (MCFM NLO)	arXiv:1503.03243 [hep-ex]
$\sigma^{fid}(W^{\pm}W^{\pm}jj)$ EWK	8	20.3	$\sigma = 1.3 \pm 0.4 \pm 0.2$ fb	$\sigma = 0.95 \pm 0.06$ fb (PowhegBox)	PRL 113, 141803 (2014)
$\sigma^{fid}(WW \rightarrow ee)$ [$n_{jet}=0$]	7	4.6	$\sigma = 56.4 \pm 6.8 \pm 10.0$ fb	$\sigma = 54.6 \pm 3.7$ fb (MCFM)	PRD 87, 112001 (2013)
$\sigma^{fid}(WW \rightarrow \mu\mu)$ [$n_{jet}=0$]	7	4.6	$\sigma = 73.9 \pm 5.9 \pm 7.5$ fb	$\sigma = 58.9 \pm 4.0$ fb (MCFM)	PRD 87, 112001 (2013)
$\sigma^{fid}(WW \rightarrow e\mu)$ [$n_{jet}=0$]	7	4.6	$\sigma = 262.3 \pm 12.3 \pm 23.1$ fb	$\sigma = 231.4 \pm 15.7$ fb (MCFM)	PRD 87, 112001 (2013)
$\sigma^{fid}(WW \rightarrow e\mu)$ [$n_{jet} \geq 0$]	7	4.6	$\sigma = 563.0 \pm 28.0 + 79.0 - 85.0$ fb	$\sigma = 536.0 \pm 29.0$ fb (MCFM)	arXiv:1407.0573 [hep-ex]
$\sigma^{fid}(WZ \rightarrow \ell\nu\ell\ell)$	8	13.0	$\sigma = 99.2 + 3.8 - 3.0 + 6.0 - 6.2$ fb	$\sigma = 99.2 \pm 3.6$ fb (MCFM)	ATLAS-CONF-2013-021
$\sigma^{total}(pp \rightarrow ZZ \rightarrow 4\ell)$	8	20.3	$\sigma = 107.0 \pm 9.0 \pm 5.0$ fb	$\sigma = 104.9 \pm 1.7$ fb (Powheg)	arXiv:1403.5657 [hep-ex]
$\sigma^{total}(pp \rightarrow ZZ \rightarrow 4\ell)$	7	4.5	$\sigma = 76.0 \pm 18.0 \pm 4.0$ fb	$\sigma = 90.0 \pm 1.6$ fb (Powheg)	arXiv:1403.5657 [hep-ex]
$\sigma^{fid}(ZZ \rightarrow 4\ell)$	8	20.3	$\sigma = 20.7 + 1.3 - 1.2 \pm 1.0$ fb	$\sigma = 21.1 + 0.9 - 0.7$ fb (MCFM)	ATLAS-CONF-2013-020
$\sigma^{fid}(ZZ \rightarrow 4\ell)$	7	4.6	$\sigma = 25.4 + 3.3 - 3.0 + 1.6 - 1.4$ fb	$\sigma = 20.9 + 1.1 - 0.9$ fb (PowhegBox & gg2ZZ)	JHEP 03, 128 (2013)
$\sigma^{fid}(ZZ^{*} \rightarrow 4\ell)$	7	4.6	$\sigma = 29.8 + 3.8 - 3.5 + 2.1 - 1.9$ fb	$\sigma = 25.6 + 1.3 - 1.1$ fb (PowhegBox & gg2ZZ)	JHEP 03, 128 (2013)
$\sigma^{fid}(W+Z \rightarrow qq)$	7	4.6	$\sigma = 8.5 \pm 0.8 \pm 1.5$ pb	$\sigma = 5.1 \pm 0.5$ pb (MCFM)	New J. Phys. 16, 113013 (2014)



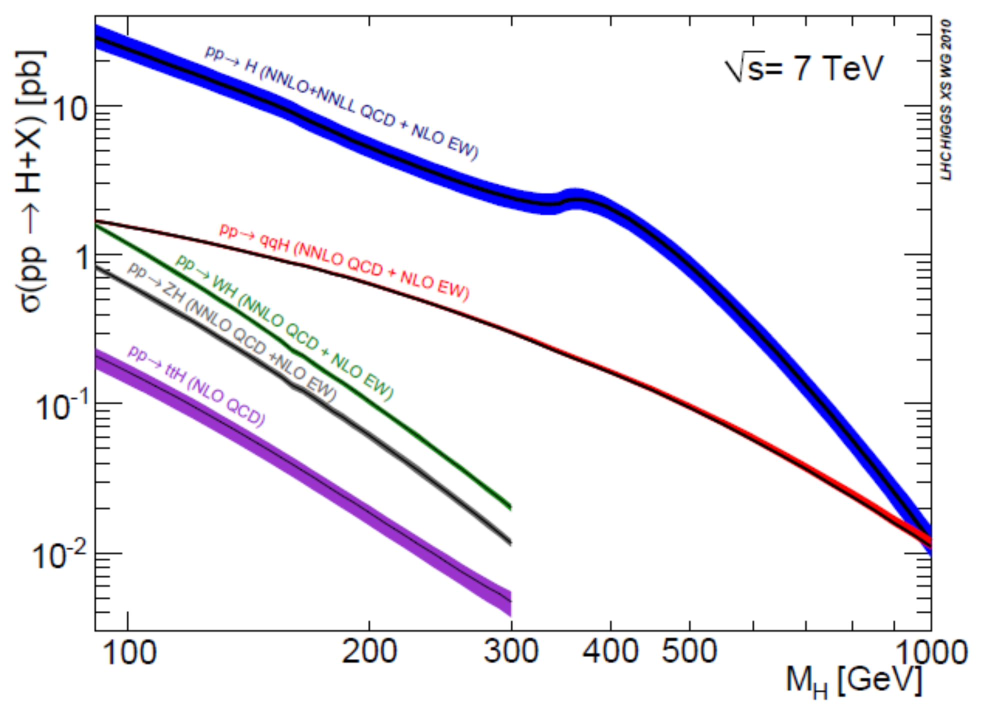
ATLAS Preliminary

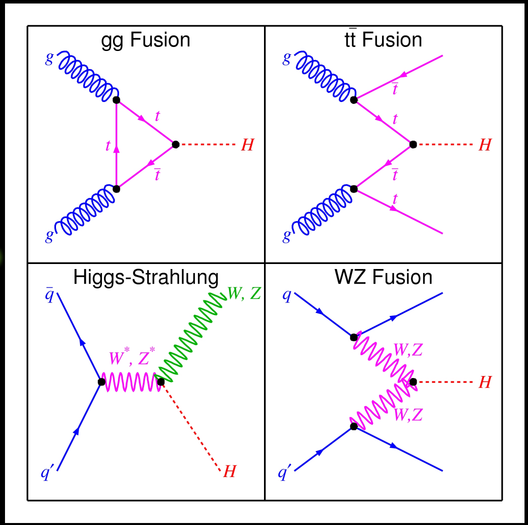
Run 1 $\sqrt{s}$ = 7, 8 TeV

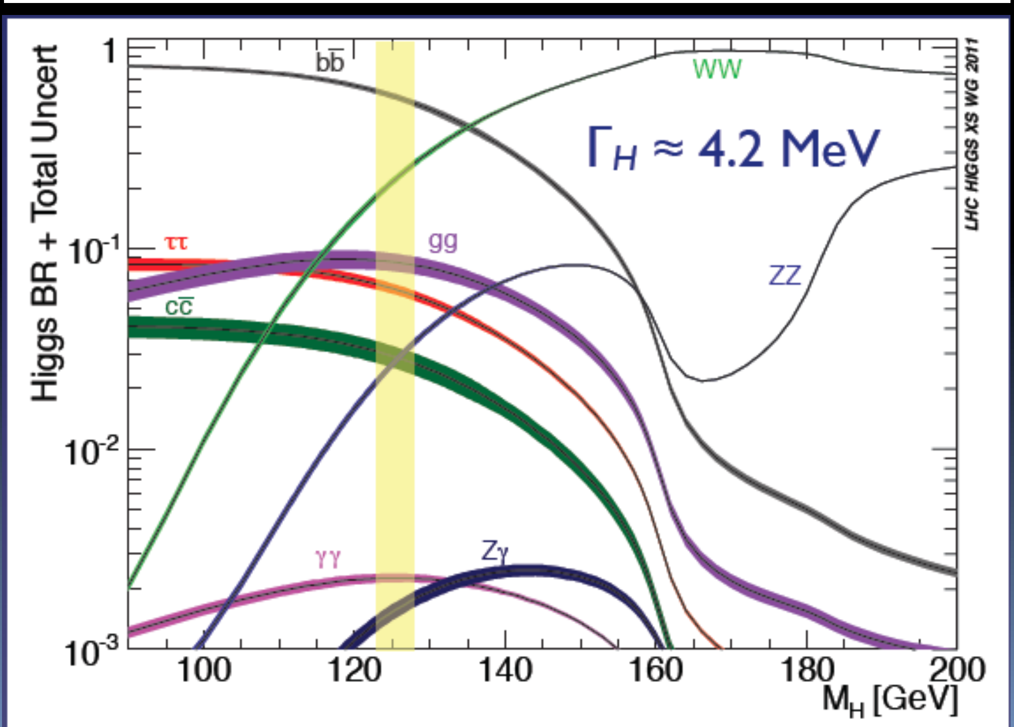
Status: March 2015

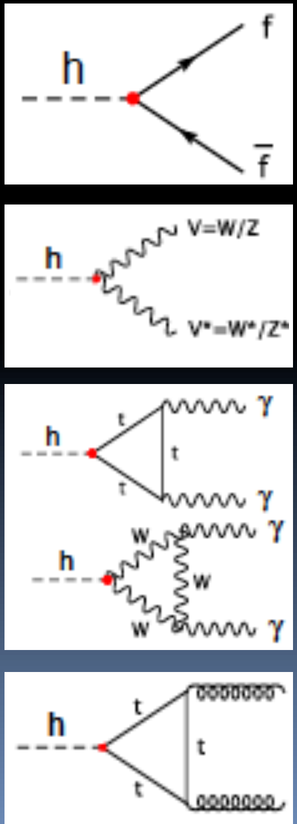
Model	E_{CM} [TeV]	$\int\mathcal{L}\,dt[fb^{-1}]$	Measurement	Theory	Reference
t_{s-chan}	8	20.3	$\sigma < 14.6$ pb	$\sigma = 5.61 \pm 0.22$ pb (NLO+NNL)	arXiv:1410.0647 [hep-ex]
t_{s-chan}	7	0.7	$\sigma < 26.5$ pb	$\sigma = 4.6 \pm 0.3$ pb (NLO+NNLL)	ATLAS-CONF-2011-118
t_{t-chan}	8	20.3	$\sigma = 82.6 \pm 1.2 \pm 12.0$ pb	$\sigma = 87.8 + 3.4 - 1.9$ pb (NLO+NLL)	ATLAS-CONF-2014-007
t_{t-chan}	7	4.6	$\sigma = 68.0 \pm 2.0 \pm 8.0$ pb	$\sigma = 64.6 + 2.7 - 2.0$ pb (NLO+NLL)	PRD 90, 112006 (2014)
Wt	8	20.3	$\sigma = 27.2 \pm 2.8 \pm 5.4$ pb	$\sigma = 22.4 \pm 1.5$ pb (NLO+NLL)	ATLAS-CONF-2013-100
Wt	7	2.0	$\sigma = 16.8 \pm 2.9 \pm 3.9$ pb	$\sigma = 15.7 \pm 1.1$ pb (NLO+NLL)	PLB 716, 142-159 (2012)
$t\bar{t}$	8	20.3	$\sigma = 242.4 \pm 1.7 \pm 10.2$ pb	$\sigma = 252.9 + 13.3 - 14.5$ pb (top++ NNLO+NNLL)	Eur. Phys. J. C 74: 3109 (2014)
$t\bar{t}$	7	4.6	$\sigma = 182.9 \pm 3.1 \pm 6.4$ pb	$\sigma = 177.0 + 10.0 - 11.0$ pb (top++ NNLO+NNLL)	Eur. Phys. J. C 74: 3109 (2014)
$t\bar{t}$ [$n_{jet} = 4$]	7	4.7	$\sigma = 3.76 \pm 0.05 \pm 0.27$ pb		JHEP 01, 020 (2015)
$t\bar{t}$ [$n_{jet} = 5$]	7	4.7	$\sigma = 1.72 \pm 0.04 \pm 0.16$ pb		JHEP 01, 020 (2015)
$t\bar{t}$ [$n_{jet} = 6$]	7	4.7	$\sigma = 0.611 \pm 0.024 \pm 0.083$ pb		JHEP 01, 020 (2015)
$t\bar{t}$ [$n_{jet} = 7$]	7	4.7	$\sigma = 0.161 \pm 0.007 \pm 0.033$ pb		JHEP 01, 020 (2015)
$t\bar{t}$ [$n_{jet} \geq 8$]	7	4.7	$\sigma = 0.0425 \pm 0.004 \pm 0.012$ pb		JHEP 01, 020 (2015)
$t\bar{t}W$	8	20.3	$\sigma = 300.0 + 120.0 - 100.0 + 70.0 - 40.0$ fb	$\sigma = 232.0 \pm 51.0$ fb (MCFM)	ATLAS-CONF-2014-038
$t\bar{t}Z$	8	20.3	$\sigma = 150.0 + 55.0 - 50.0 \pm 21.0$ fb	$\sigma = 206.0 \pm 45.0$ fb (HELAC-NLO)	ATLAS-CONF-2014-038
$t\bar{t}Z$	7	4.7	$\sigma < 0.71$ pb	$\sigma = 0.14 \pm 0.028$ pb (HELAC-NLO)	ATLAS-CONF-2012-126
$t\bar{t}\gamma$	7	4.6	$\sigma = 63.0 \pm 8.0 + 17.0 - 13.0$ fb	$\sigma = 48.0 \pm 10.0$ fb (Whizard+NLO)	arXiv:1502.00586 [hep-ex]
H	8	20.3	$\sigma = 27.6 + 3.8 - 3.5$ pb	$\sigma = 22.3 \pm 2.0$ pb (LHC-HXSWG)	ATLAS-CONF-2015-007
H	7	4.5	$\sigma = 21.8 + 3.3 - 3.1$ pb	$\sigma = 17.4 \pm 1.6$ pb (LHC-HXSWG)	ATLAS-CONF-2015-007
H VBF	8	20.3	$\sigma = 2.43 + 0.6 - 0.55$ pb	$\sigma = 1.57 \pm 0.04$ pb (LHC-HXSWG)	ATLAS-CONF-2015-007
H ggF	8	20.3	$\sigma = 23.9 + 3.9 - 3.5$ pb	$\sigma = 19.2 \pm 2.0$ pb (LHC-HXSWG)	ATLAS-CONF-2015-007
$t\bar{t}H$	8	20.3	$\sigma = 0.24 \pm 0.11$ pb	$\sigma = 0.128 \pm 0.014$ pb (LHC-HXSWG)	ATLAS-CONF-2015-007
$\sigma^{fid}(H \rightarrow \gamma\gamma)$	8	20.3	$\sigma = 43.2 \pm 9.4 + 3.4 - 3.1$ fb	$\sigma = 30.5 \pm 3.2$ fb (LHC-XS)	Preliminary
σ^{fid}(VBF $H \rightarrow WW$)	8	20.3	$\sigma = 0.51 + 0.17 - 0.15 + 0.13 - 0.08$ pb	$\sigma = 0.35 \pm 0.02$ pb (LHC-XS)	arXiv:1412.2641 [hep-ex]
$\sigma^{fid}(gg \rightarrow H \rightarrow WW)$	8	20.3	$\sigma = 4.6 \pm 0.9 + 0.8 - 0.7$ pb	$\sigma = 4.2 \pm 0.5$ pb (LHC-XS)	arXiv:1412.2641 [hep-ex]
$\sigma^{fid}(H \rightarrow ZZ \rightarrow 4\ell)$	8	20.3	$\sigma = 2.11 + 0.53 - 0.47 \pm 0.08$ fb	$\sigma = 1.3 \pm 0.13$ fb (LHC-XS)	arXiv:1408.3226 [hep-ex]
$\sigma^{fid}(H \rightarrow \gamma\gamma, ZZ(4\ell))$	8	20.3	$\sigma = 33.04 \pm 5.35 \pm 1.59$ pb	$\sigma = 22.16 + 1.99 - 2.0$ pb (LHC-XS ggF + XH)	Preliminary
$\gamma\gamma$	7	4.9	$\sigma = 44.0 + 3.2 - 4.2$ pb	$\sigma = 44.0 \pm 6.0$ pb (2γNNLO)	JHEP 01, 086 (2013)
WW	8	20.3	$\sigma = 71.4 \pm 1.2 + 5.5 - 4.9$ pb	$\sigma = 58.7 + 3.0 - 2.7$ pb (MCFM)	ATLAS-CONF-2014-033
WW	7	4.6	$\sigma = 51.9 \pm 2.0 \pm 4.4$ pb	$\sigma = 44.7 + 2.1 - 1.9$ pb (MCFM)	PRD 87, 112001 (2013)
WW+WZ	7	4.6	$\sigma = 68.0 \pm 7.0 \pm 19.0$ pb	$\sigma = 61.1 \pm 2.2$ pb (MC@NLO)	JHEP 01, 049 (2015)
$WW+WZ \rightarrow \ell\nu qq$	7	4.6	$\sigma = 1.37 \pm 0.14 \pm 0.37$ pb	$\sigma = 1.24 \pm 0.09$ pb (MC@NLO)	JHEP 01, 049 (2015)
Zjj EWK	8	20.3	$\sigma = 54.7 \pm 4.6 + 9.9 - 10.5$ fb	$\sigma = 46.1 \pm 1.2$ fb (PowhegBox)	JHEP 04, 031 (2014)
ZZ	8	20.3	$\sigma = 7.1 + 0.5 - 0.4 \pm 0.4$ pb	$\sigma = 7.2 + 0.3 - 0.2$ pb (MCFM)	ATLAS-CONF-2013-020
ZZ	7	4.6	$\sigma = 6.7 \pm 0.7 + 0.5 - 0.4$ pb	$\sigma = 5.89 + 0.22 - 0.18$ pb (MCFM)	JHEP 03, 128 (2013)
WZ	8	13.0	$\sigma = 20.3 + 0.8 - 0.7 + 1.4 - 1.3$ pb	$\sigma = 20.3 \pm 0.8$ pb (MCFM)	ATLAS-CONF-2013-021
WZ	7	4.6	$\sigma = 19.0 + 1.4 - 1.3 \pm 1.0$ pb	$\sigma = 17.6 + 1.1 - 1.0$ pb (MCFM)	EPJC 72, 2173 (2012)
$\sigma^{fid}(\gamma\gamma)[\Delta R_{\gamma\gamma} > 0.4]$	7	4.9	$\sigma = 44.0 + 3.2 - 4.2$ pb	$\sigma = 44.0 \pm 6.0$ pb (2γNNLO)	JHEP 01, 086 (2013)
$\sigma^{fid}(W\gamma \rightarrow \ell\nu\gamma)$	7	4.6	$\sigma = 2.77 \pm 0.03 \pm 0.36$ pb	$\sigma = 2.658 \pm 0.11$ pb (NNLO)	PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
$\sigma^{fid}(W\gamma \rightarrow \ell\nu\gamma)[n_{jet} = 0]$	7	4.6	$\sigma = 1.76 \pm 0.03 \pm 0.22$ pb	$\sigma = 1.674 + 0.056 - 0.064$ pb (NNLO)	PRD 87, 112003 (2013)
$\sigma^{fid}(Z\gamma \rightarrow \ell\ell\gamma)$	7	4.6	$\sigma = 1.31 \pm 0.02 \pm 0.12$ pb	$\sigma = 1.327 + 0.026 - 0.037$ pb (NNLO)	PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
$\sigma^{fid}(Z\gamma \rightarrow \ell\ell\gamma)[n_{jet} = 0]$	7	4.6	$\sigma = 1.05 \pm 0.02 \pm 0.11$ pb	$\sigma = 1.107 + 0.012 - 0.018$ pb (NNLO)	PRD 87, 112003 (2013)
$\sigma^{fid}(W\gamma\gamma \rightarrow \ell\nu\gamma\gamma)[n_{jet}=0]$	8	20.3	$\sigma = 2.9 + 0.8 - 0.7 + 1.0 - 0.9$ fb	$\sigma = 1.88 \pm 0.2$ fb (MCFM NLO)	arXiv:1503.03243 [hep-ex]
$\sigma^{fid}(W\gamma\gamma \rightarrow \ell\nu\gamma\gamma)$	8	20.3	$\sigma = 6.1 + 1.1 - 1.0 \pm 1.2$ fb	$\sigma = 2.9 \pm 0.16$ fb (MCFM NLO)	arXiv:1503.03243 [hep-ex]
$\sigma^{fid}(W^{\pm}W^{\pm}jj)$ EWK	8	20.3	$\sigma = 1.3 \pm 0.4 \pm 0.2$ fb	$\sigma = 0.95 \pm 0.06$ fb (PowhegBox)	PRL 113, 141803 (2014)
$\sigma^{fid}(WW \rightarrow ee)$ [$n_{jet}=0$]	7	4.6	$\sigma = 56.4 \pm 6.8 \pm 10.0$ fb	$\sigma = 54.6 \pm 3.7$ fb (MCFM)	PRD 87, 112001 (2013)
$\sigma^{fid}(WW \rightarrow \mu\mu)$ [$n_{jet}=0$]	7	4.6	$\sigma = 73.9 \pm 5.9 \pm 7.5$ fb	$\sigma = 58.9 \pm 4.0$ fb (MCFM)	PRD 87, 112001 (2013)
$\sigma^{fid}(WW \rightarrow e\mu)$ [$n_{jet}=0$]	7	4.6	$\sigma = 262.3 \pm 12.3 \pm 23.1$ fb	$\sigma = 231.4 \pm 15.7$ fb (MCFM)	PRD 87, 112001 (2013)
$\sigma^{fid}(WW \rightarrow e\mu)$ [$n_{jet} \geq 0$]	7	4.6	$\sigma = 563.0 \pm 28.0 + 79.0 - 85.0$ fb	$\sigma = 536.0 \pm 29.0$ fb (MCFM)	arXiv:1407.0573 [hep-ex]
$\sigma^{fid}(WZ \rightarrow \ell\nu\ell\ell)$	8	13.0	$\sigma = 99.2 + 3.8 - 3.0 + 6.0 - 6.2$ fb	$\sigma = 99.2 \pm 3.6$ fb (MCFM)	ATLAS-CONF-2013-021
$\sigma^{total}(pp \rightarrow ZZ \rightarrow 4\ell)$	8	20.3	$\sigma = 107.0 \pm 9.0 \pm 5.0$ fb	$\sigma = 104.9 \pm 1.7$ fb (Powheg)	arXiv:1403.5657 [hep-ex]
$\sigma^{total}(pp \rightarrow ZZ \rightarrow 4\ell)$	7	4.5	$\sigma = 76.0 \pm 18.0 \pm 4.0$ fb	$\sigma = 90.0 \pm 1.6$ fb (Powheg)	arXiv:1403.5657 [hep-ex]
$\sigma^{fid}(ZZ \rightarrow 4\ell)$	8	20.3	$\sigma = 20.7 + 1.3 - 1.2 \pm 1.0$ fb	$\sigma = 21.1 + 0.9 - 0.7$ fb (MCFM)	ATLAS-CONF-2013-020
$\sigma^{fid}(ZZ \rightarrow 4\ell)$	7	4.6	$\sigma = 25.4 + 3.3 - 3.0 + 1.6 - 1.4$ fb	$\sigma = 20.9 + 1.1 - 0.9$ fb (PowhegBox & gg2ZZ)	JHEP 03, 128 (2013)
$\sigma^{fid}(ZZ^{*} \rightarrow 4\ell)$	7	4.6	$\sigma = 29.8 + 3.8 - 3.5 + 2.1 - 1.9$ fb	$\sigma = 25.6 + 1.3 - 1.1$ fb (PowhegBox & gg2ZZ)	JHEP 03, 128 (2013)
$\sigma^{fid}(W+Z \rightarrow qq)$	7	4.6	$\sigma = 8.5 \pm 0.8 \pm 1.5$ pb	$\sigma = 5.1 \pm 0.5$ pb (MCFM)	New J. Phys. 16, 113013 (2014)

Higgs production and decay at LHC



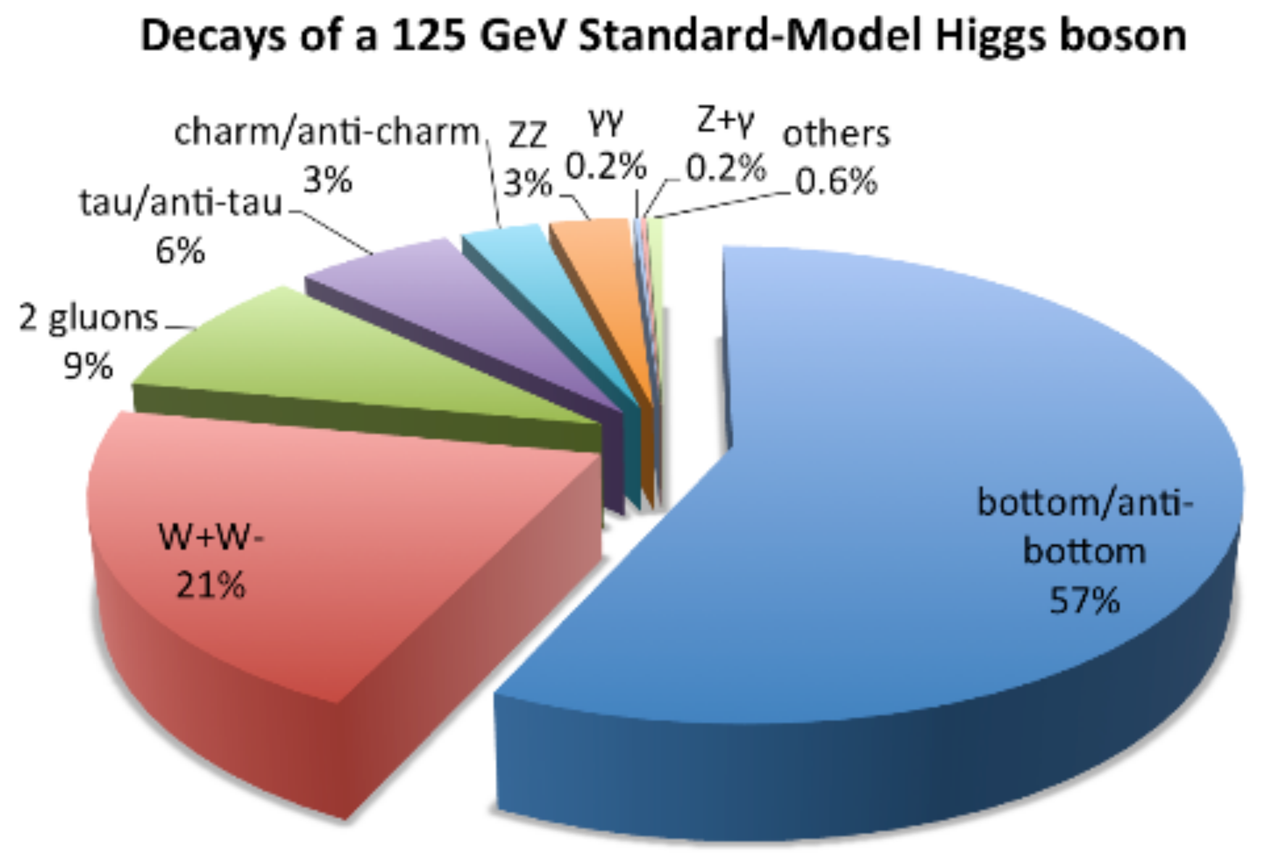




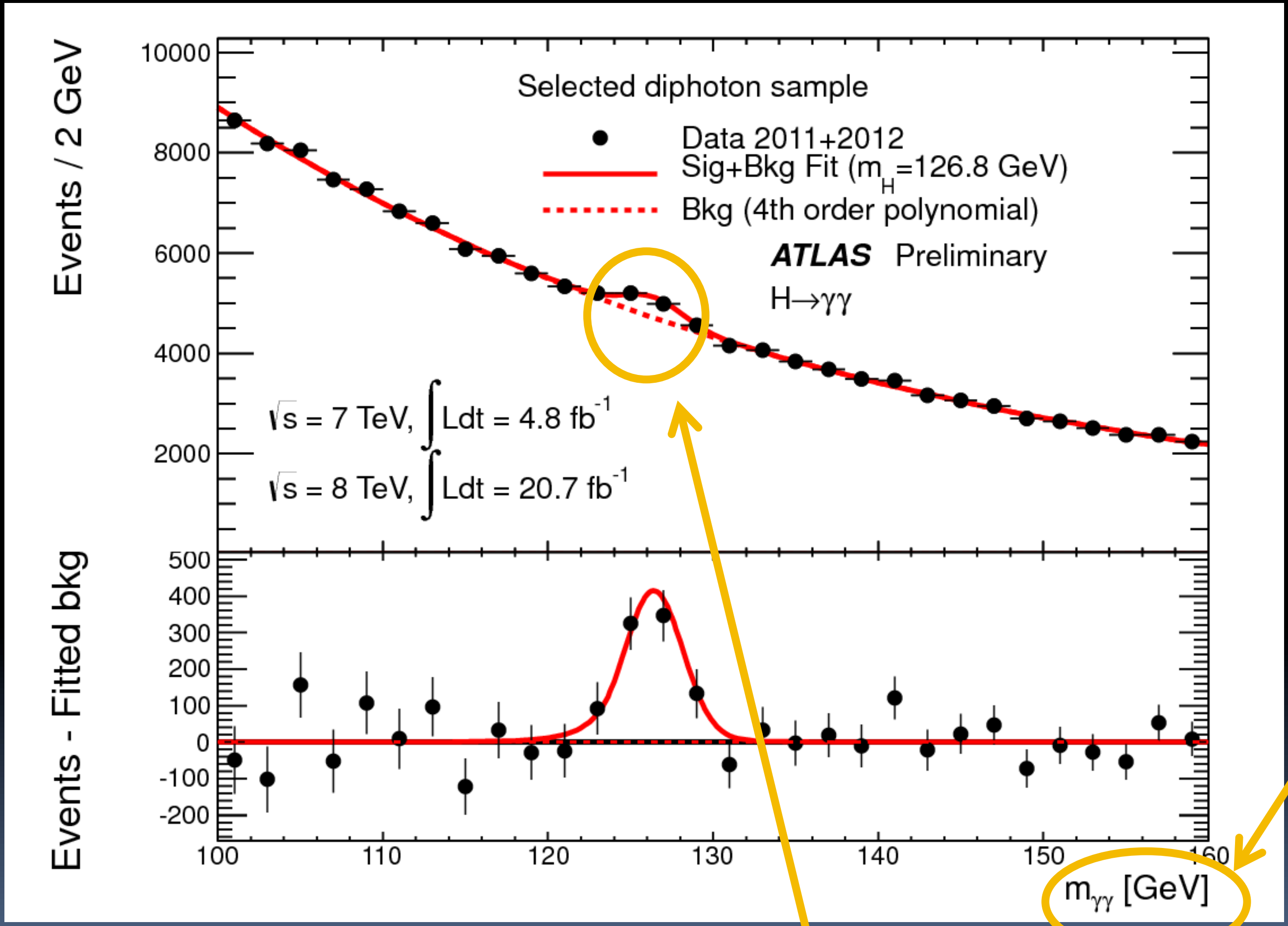


- 125 GeV … a rather good compromise
- 4/5 production processes
- ≥5 decay channels

The 125 GeV Higgs cake …



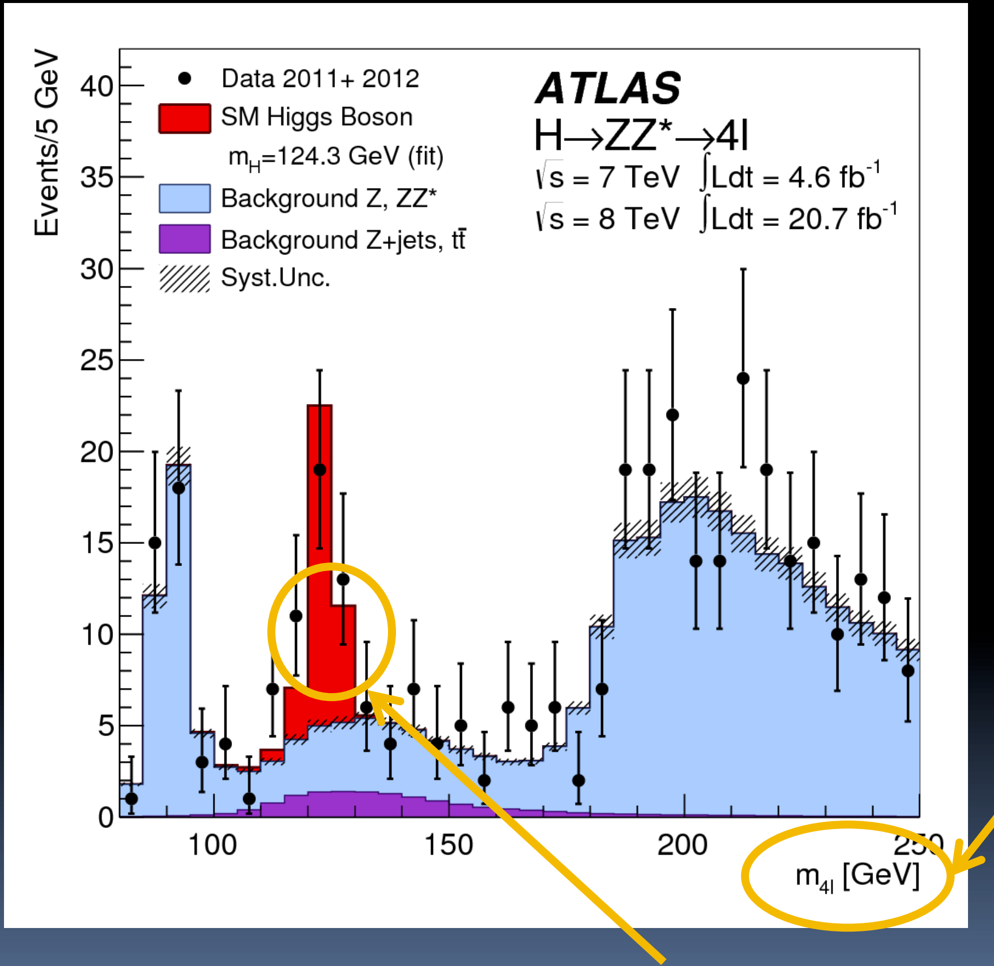
Anything new?



Invariant mass of photons

Higgs particle at 126 GeV!

Anything new?

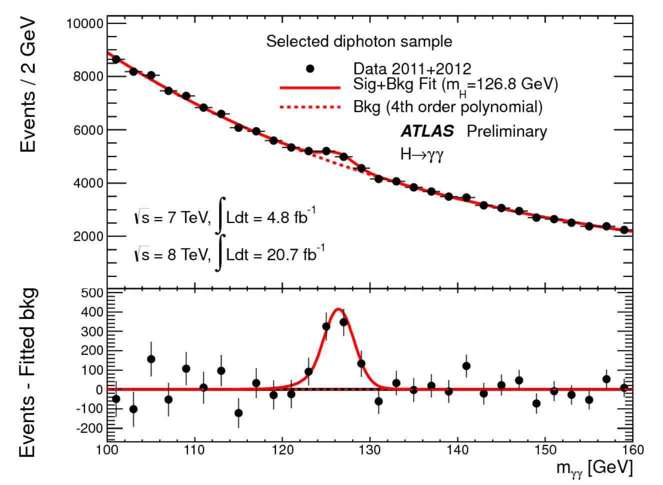


Invariant mass of 4 leptons

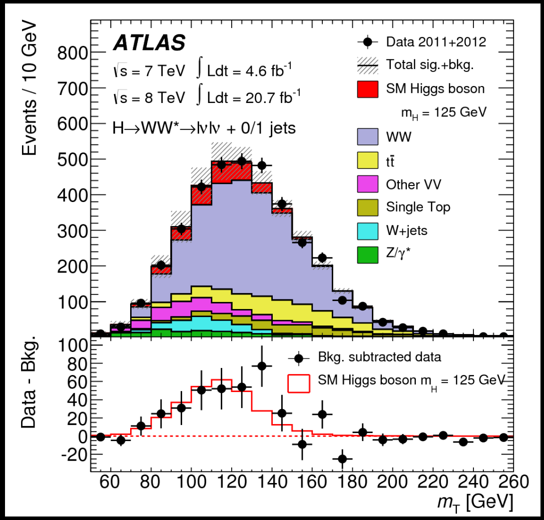
Higgs particle at 125 GeV

Higgs discovery?

H→γγ

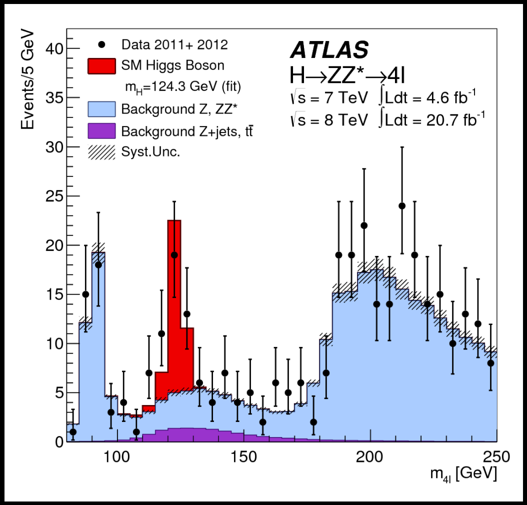


H→WW*→lνlν

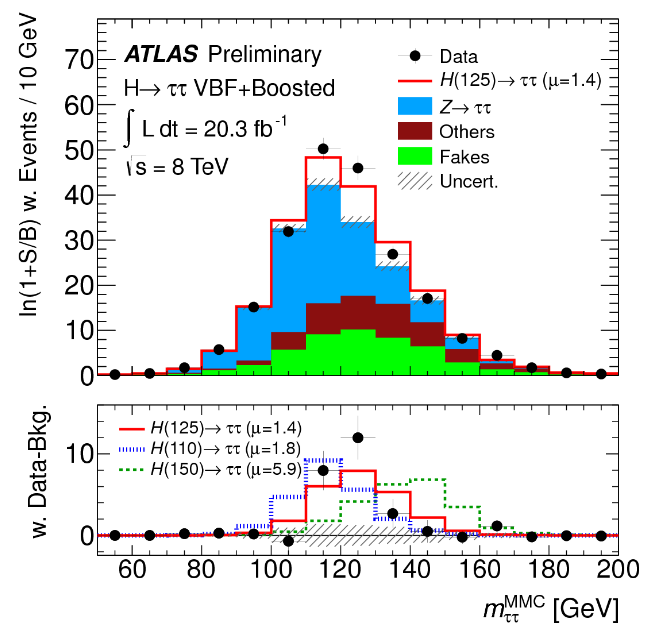


$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{\text{miss}})^2}$$

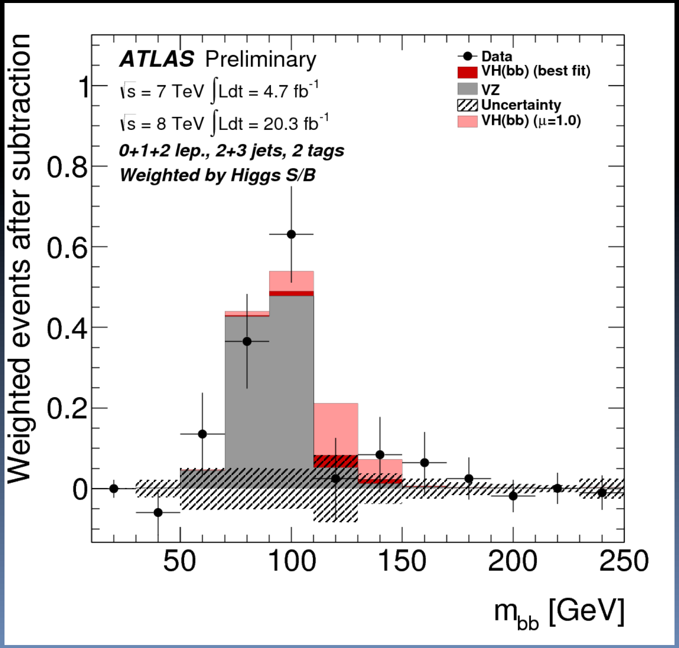
H→ZZ*→llll



H→ττ



H→bb

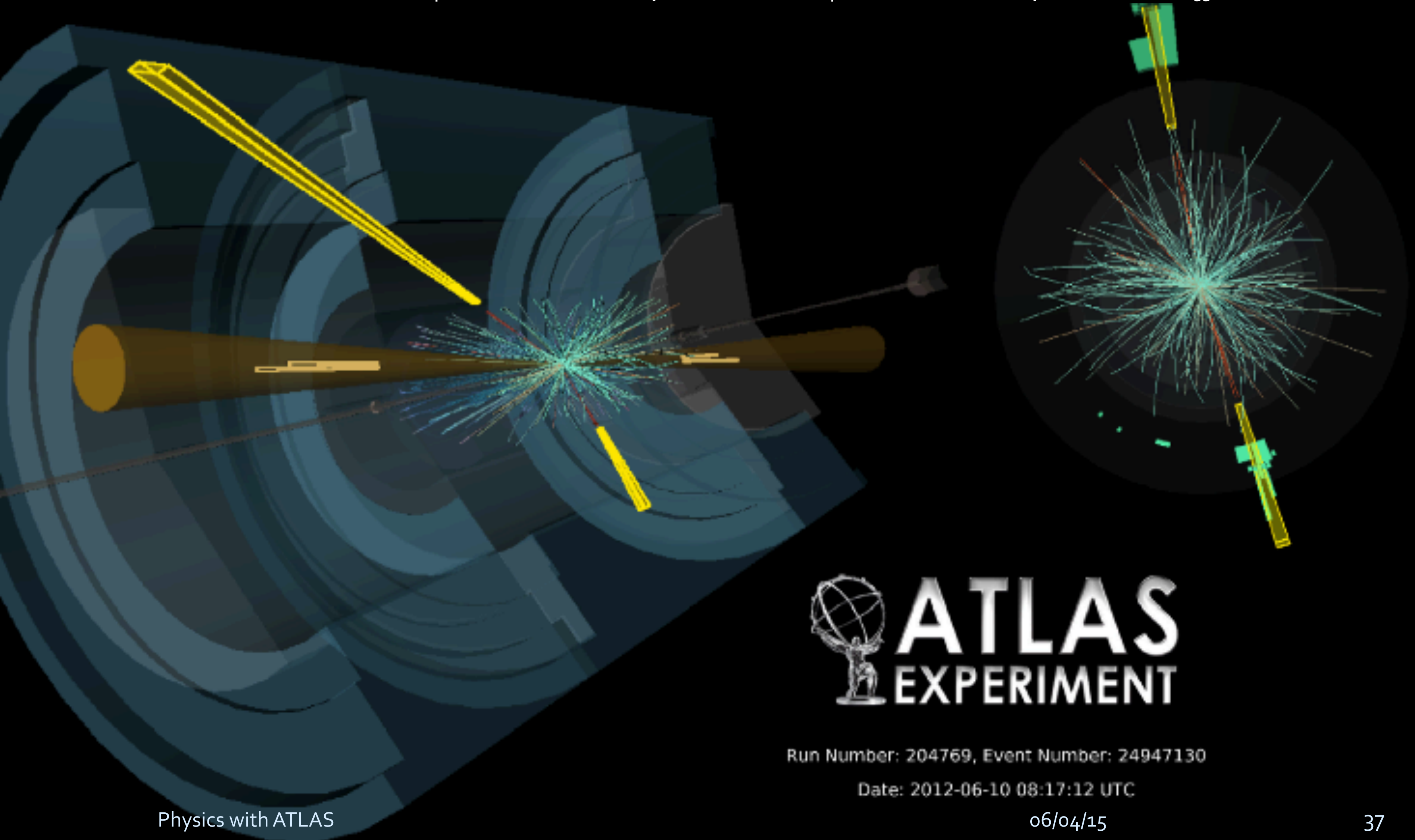


- Fermions
- Tau evidence 4σ
- Bottom decays still need be confirmed

H→γγ

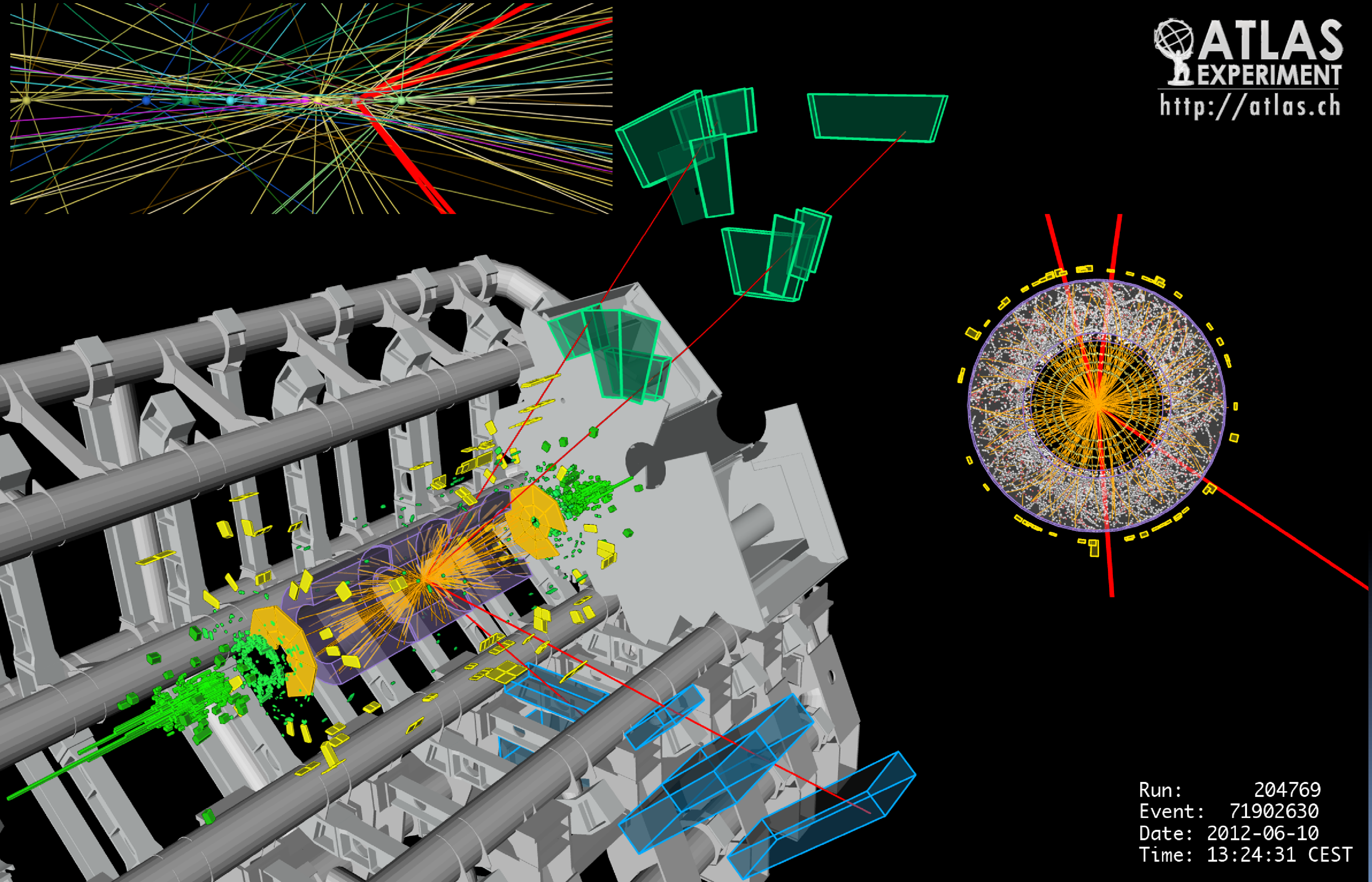
Vector Boson Fusion candidate at √s=8TeV
2 converted photons and two high-mass jets

- Photons: (E_T = 80.1 GeV, η = 1.01); (E_T = 36.2 GeV and η = −0.17)
- Measured di-photon mass = 126.9 GeV
- Jets: (E_T = 121.6 GeV, η = -2.90); (E_T = 82.8 GeV, η = 2.72) ; Mjj=1.67 TeV



$H \rightarrow ZZ^* \rightarrow \mu^+\mu^-\mu^+\mu^-$

$m_4=127.4$ GeV. $m_{12}=86.6$ GeV, $m_{34}=31.6$ GeV

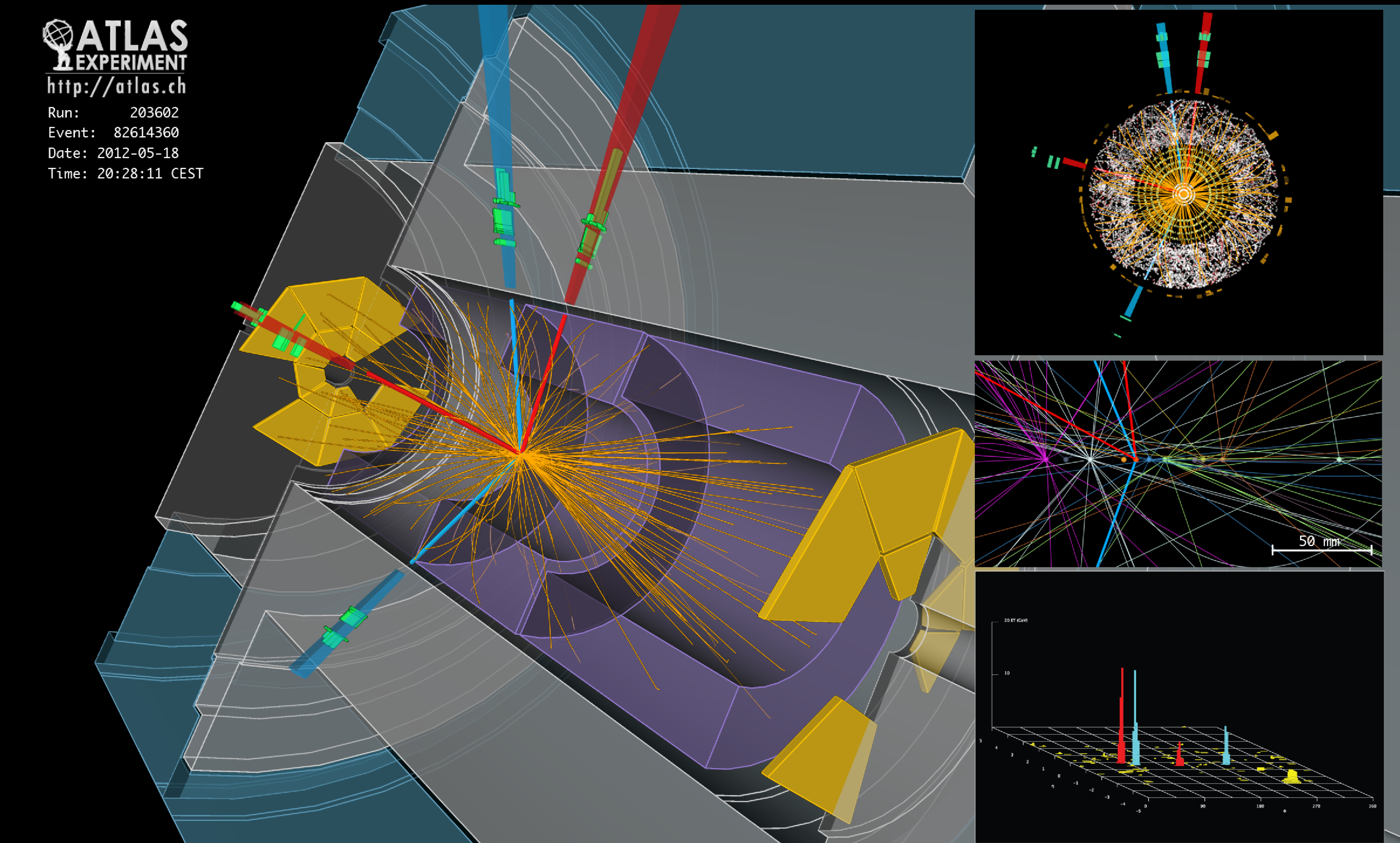


ATLAS EXPERIMENT
http://atlas.ch

```
Run:       204769
Event:   71902630
Date:  2012-06-10
Time:  13:24:31 CEST
```

$H \rightarrow ZZ^* \rightarrow e^+e^-e^+e^-$

m_4=124.6 GeV. m_{12}=70.6 GeV, m_{34}=44.7 GeV

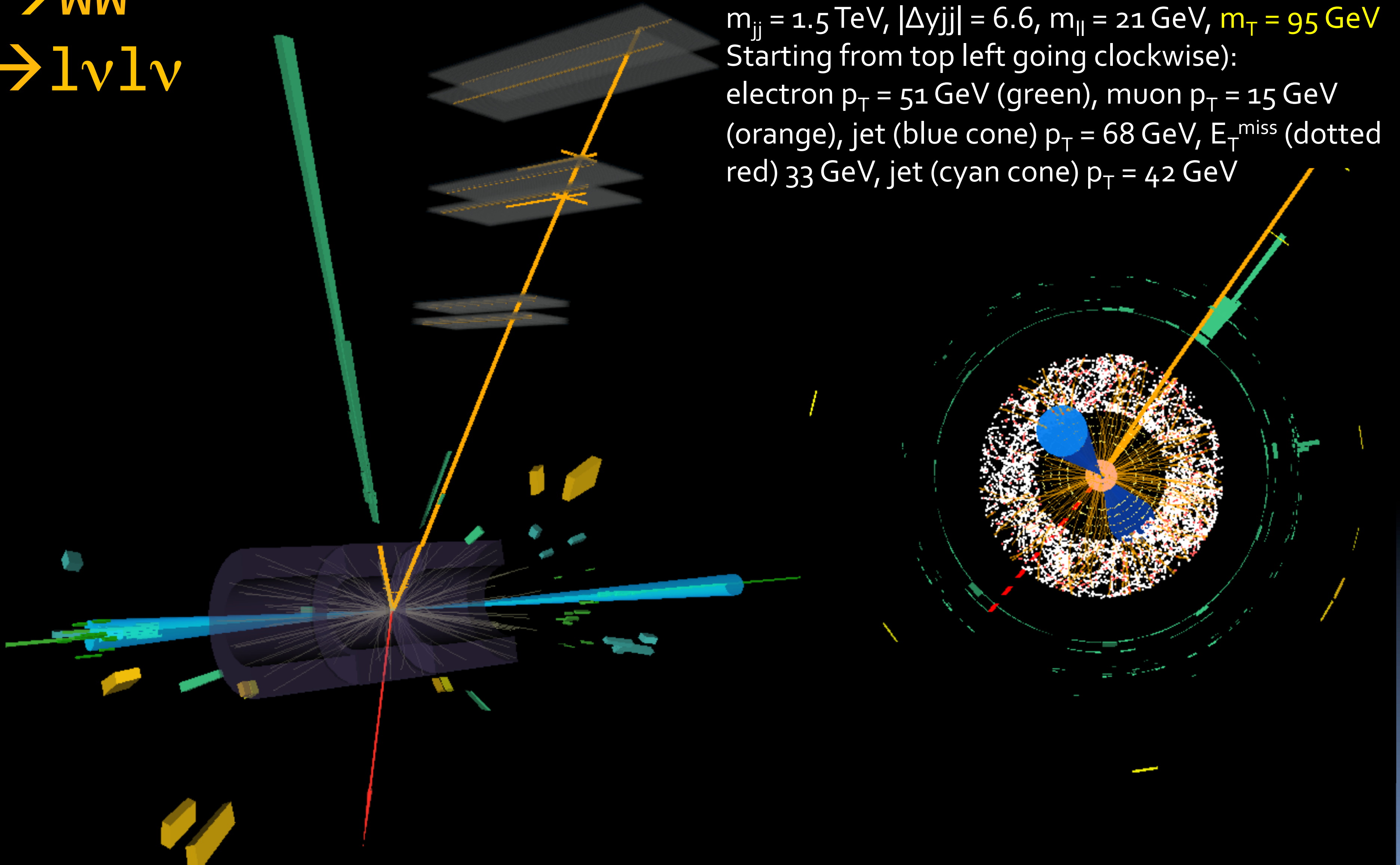


ATLAS EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST

Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET

$H \rightarrow WW^{(*)} \rightarrow e\nu\, \mu\, \nu$ + 2 jets produced via VBF, $qq \rightarrow Hqq$.
m_{jj} = 1.5 TeV, $|\Delta yjj|$ = 6.6, m_{ll} = 21 GeV, m_T = 95 GeV
Starting from top left going clockwise):
electron p_T = 51 GeV (green), muon p_T = 15 GeV (orange), jet (blue cone) p_T = 68 GeV, E_T^{miss} (dotted red) 33 GeV, jet (cyan cone) p_T = 42 GeV

$H \rightarrow WW^*$
$\rightarrow l\nu l\nu$

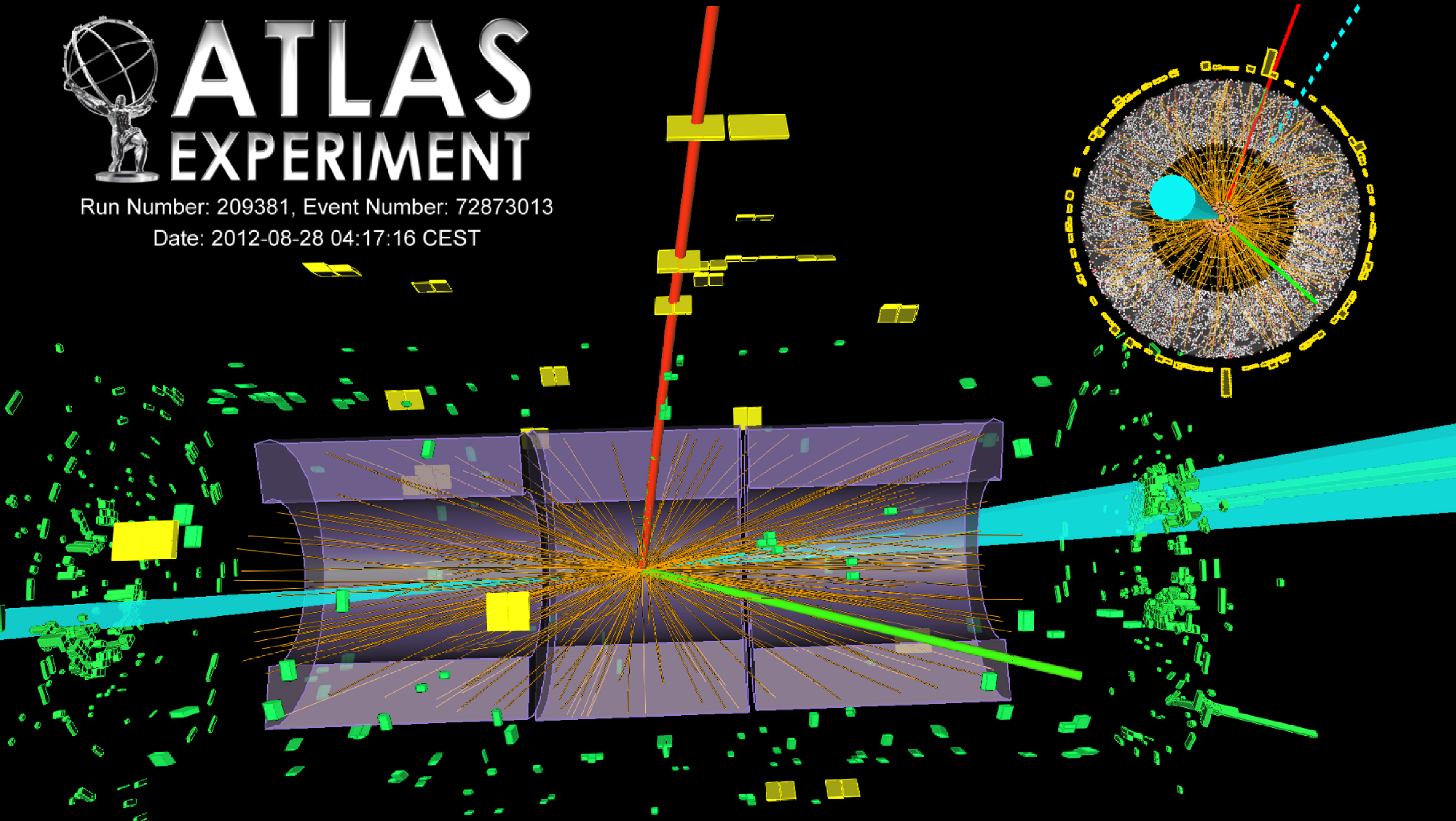


H→ττ candidate

$H \rightarrow \tau_{\{lep\}}\tau_{\{lep\}}$ analysis (VBF category), one τ decays to an electron and the other to a muon

- Electron (green) p_T = 17 GeV; - Muon (red) p_T = 20 GeV
- E_T^{miss} =43 GeV (dashed line); - 2 VBF jets (cones) m_{jj}=1610 GeV
- $m_{\tau\tau}$=126 GeV

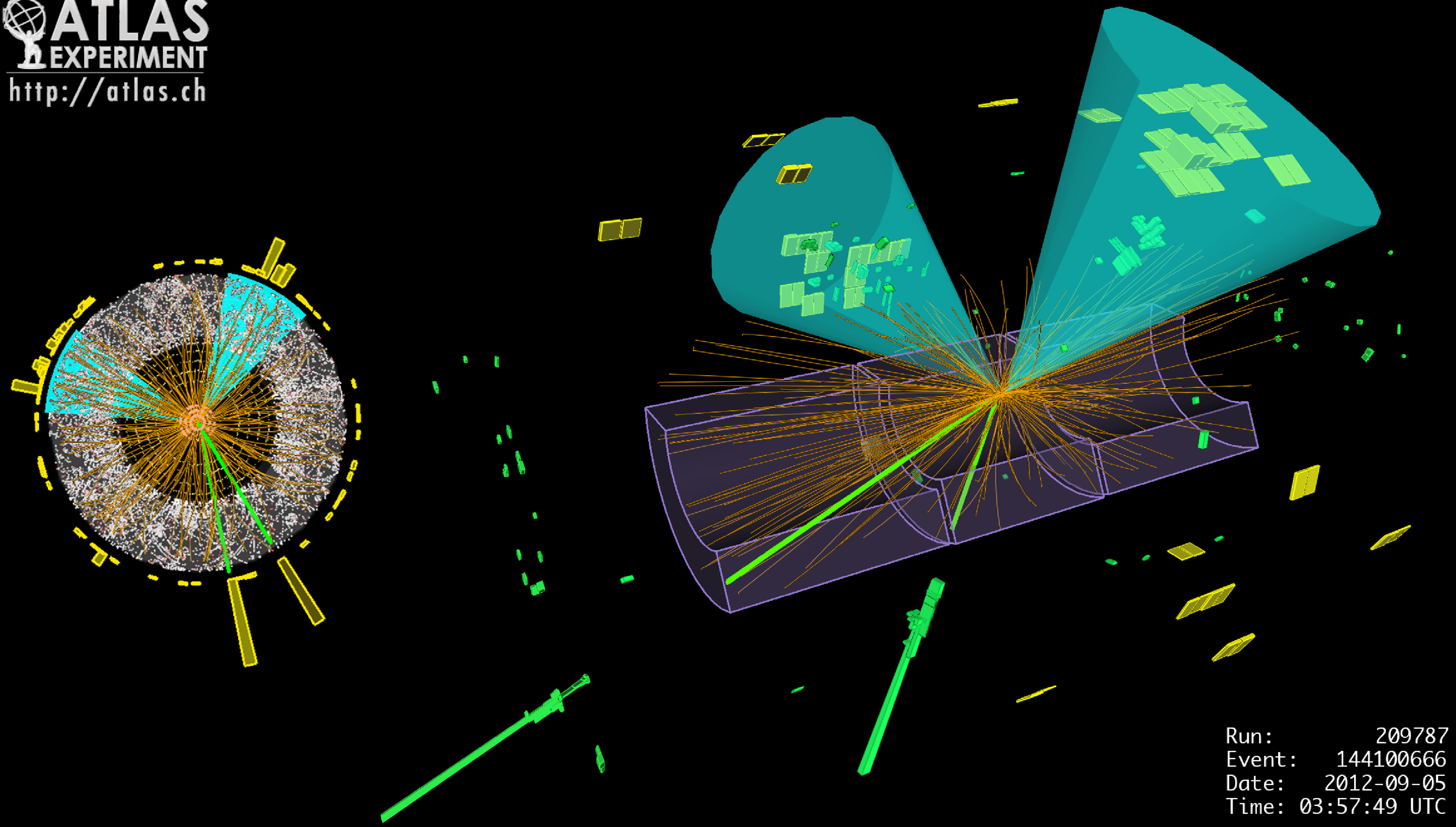
ATLAS EXPERIMENT



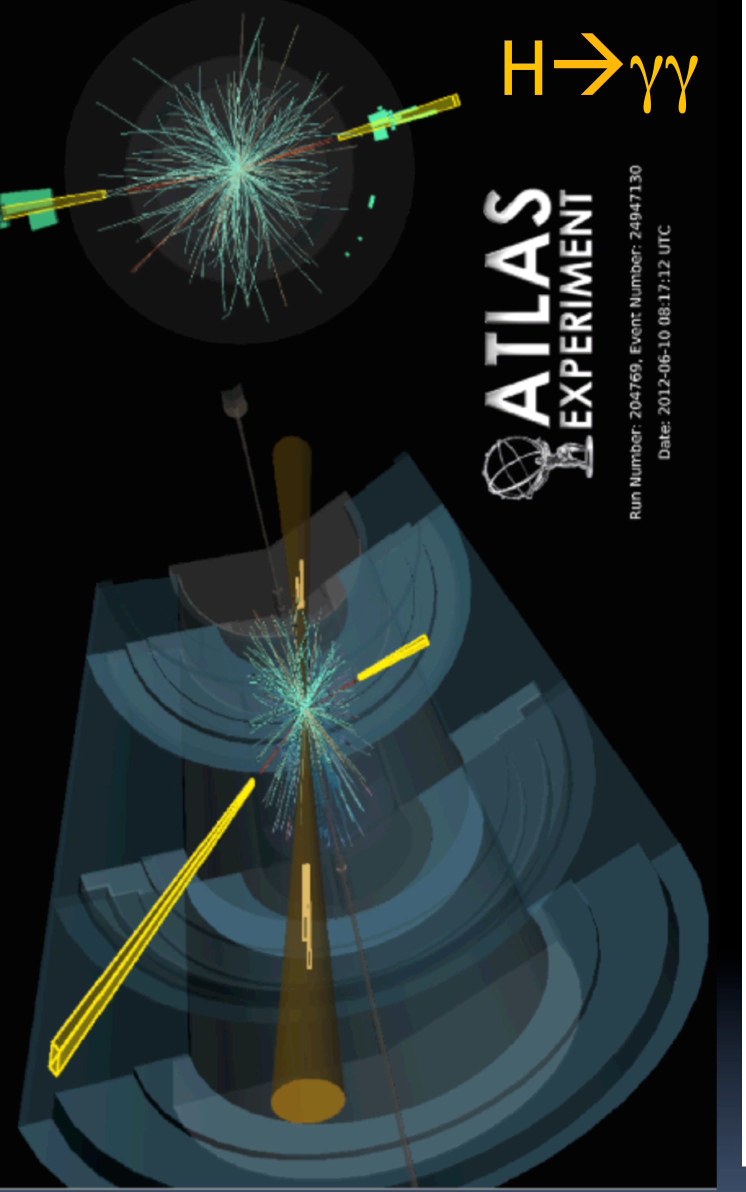
H→b-bbar candidate

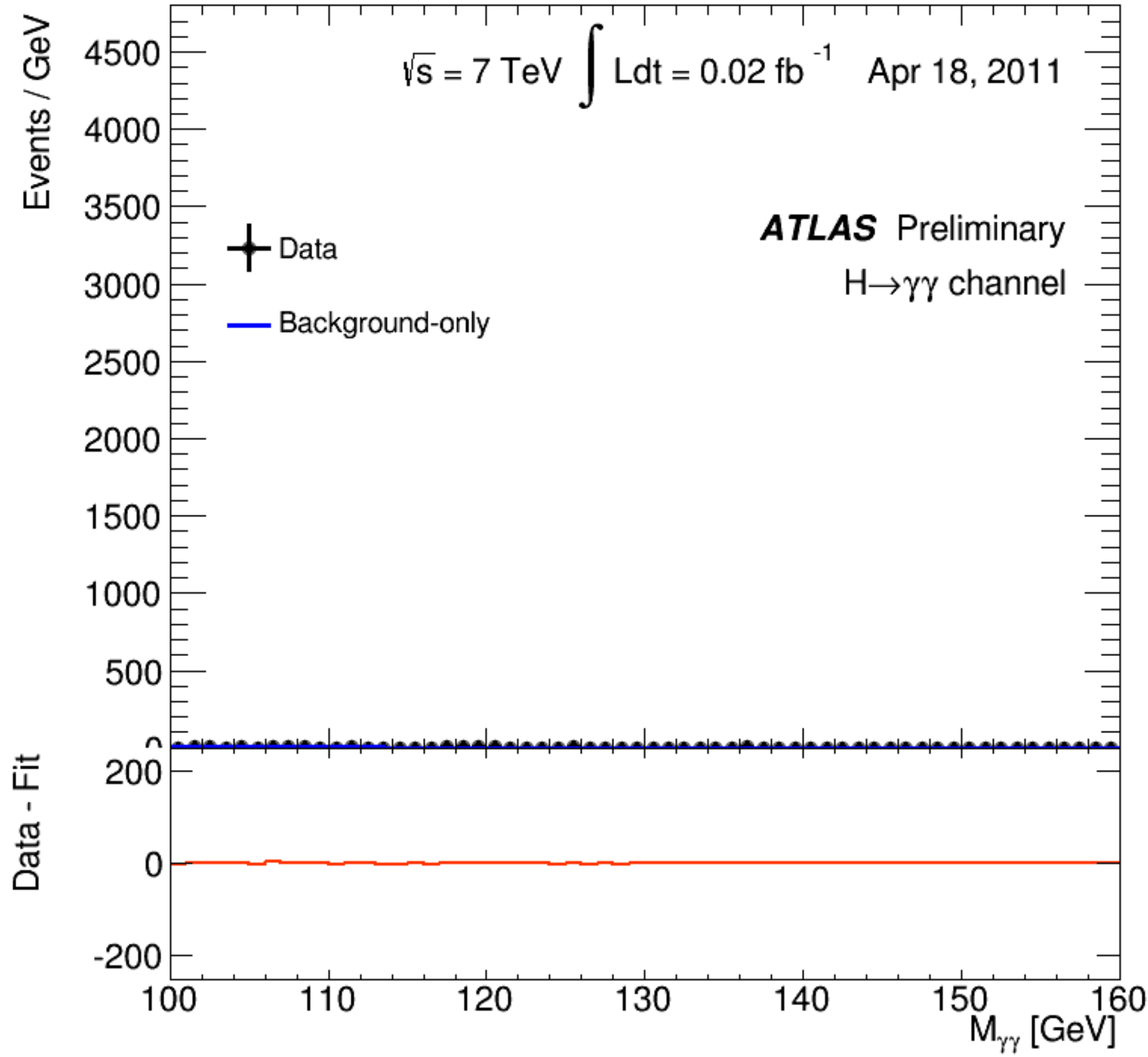
- 2 identified b-jets (p_T=70 GeV, p_T=65 GeV, m_{bb}=122 GeV)
- 2 electrons (p_T=63 GeV, p_T=54 GeV).

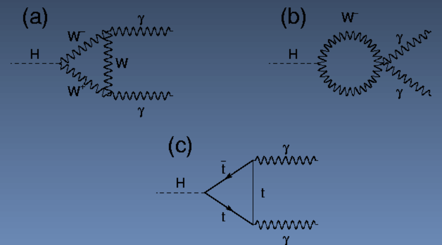
ATLAS EXPERIMENT
http://atlas.ch

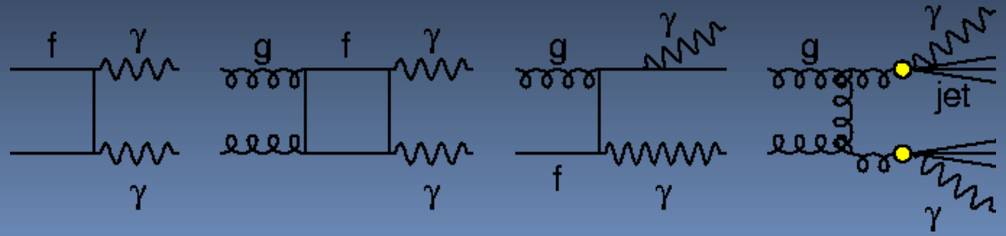


H→γγ

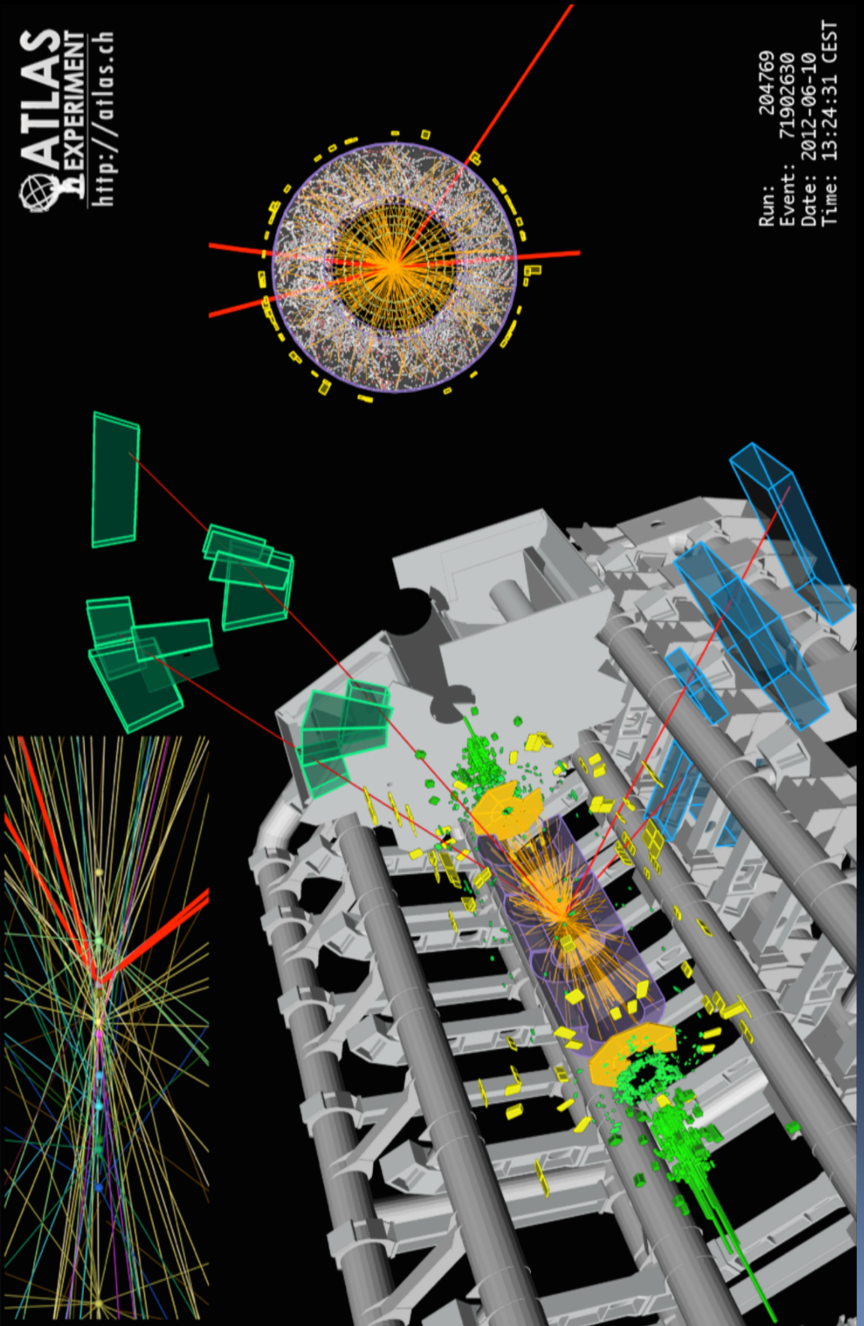

ATLAS EXPERIMENT
Run Number: 204769, Event Number: 24947130
Date: 2012-06-10 08:17:12 UTC

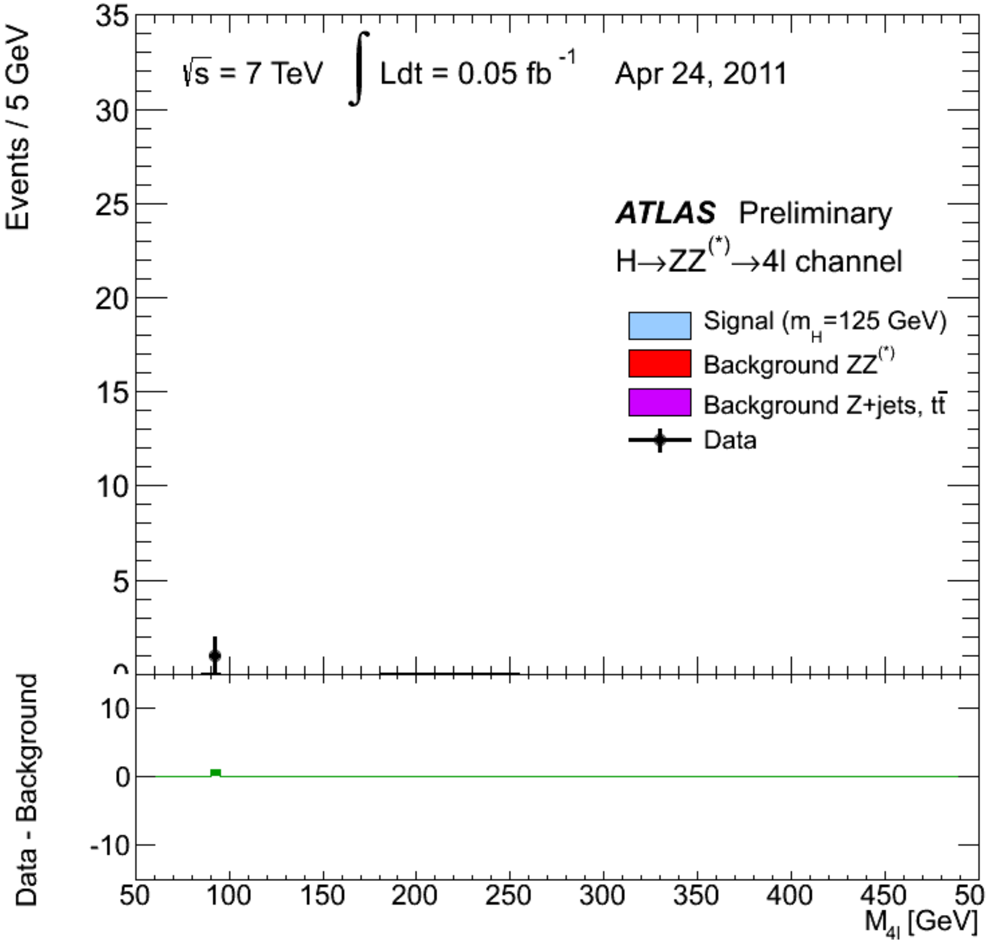

√s = 7 TeV ∫Ldt = 0.02 fb^-1 Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Data - Fit
200
0
-200
100
110
120
130
140
150
160
M_γγ [GeV]


(a)
H
W
W
W
γ
γ
(b)
W
H
γ
γ
(c)
H
t
t
t
γ
γ


f
γ
γ
g
f
γ
γ
g
γ
f
γ
g
γ
jet
γ

$H \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$

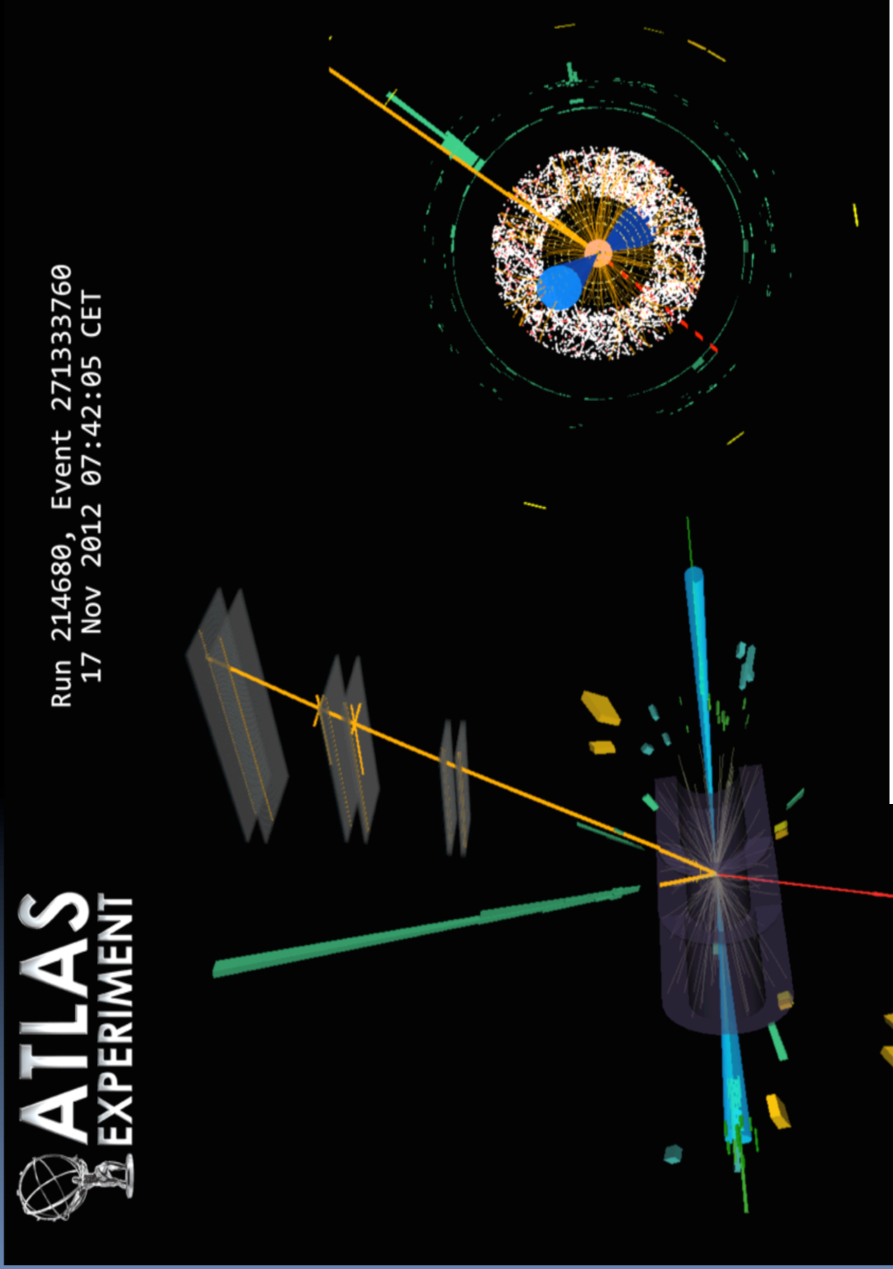


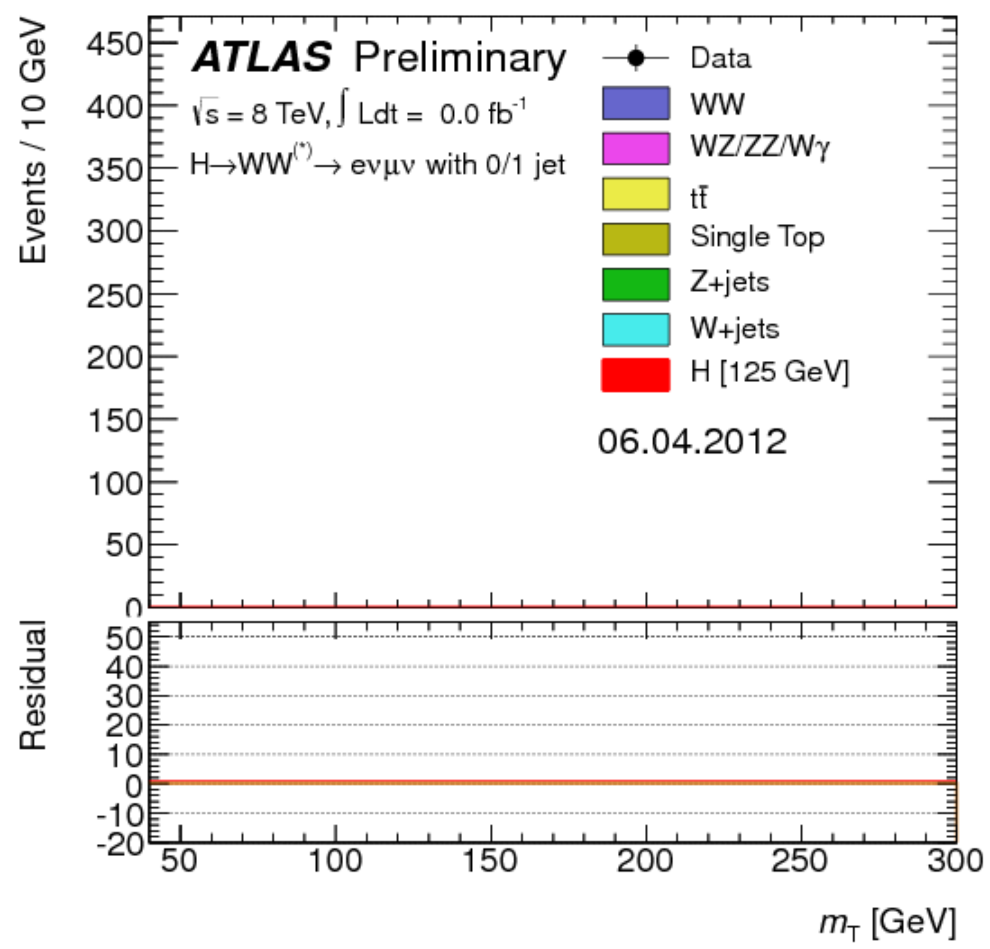


Understanding of "background" is important

- Most of which is due to important physics at the heart of the gauge structure / symmetry of electroweak interaction
- Higgs showed up between 2 relatively busy regions!

$H \rightarrow WW^* \rightarrow l\nu l\nu$



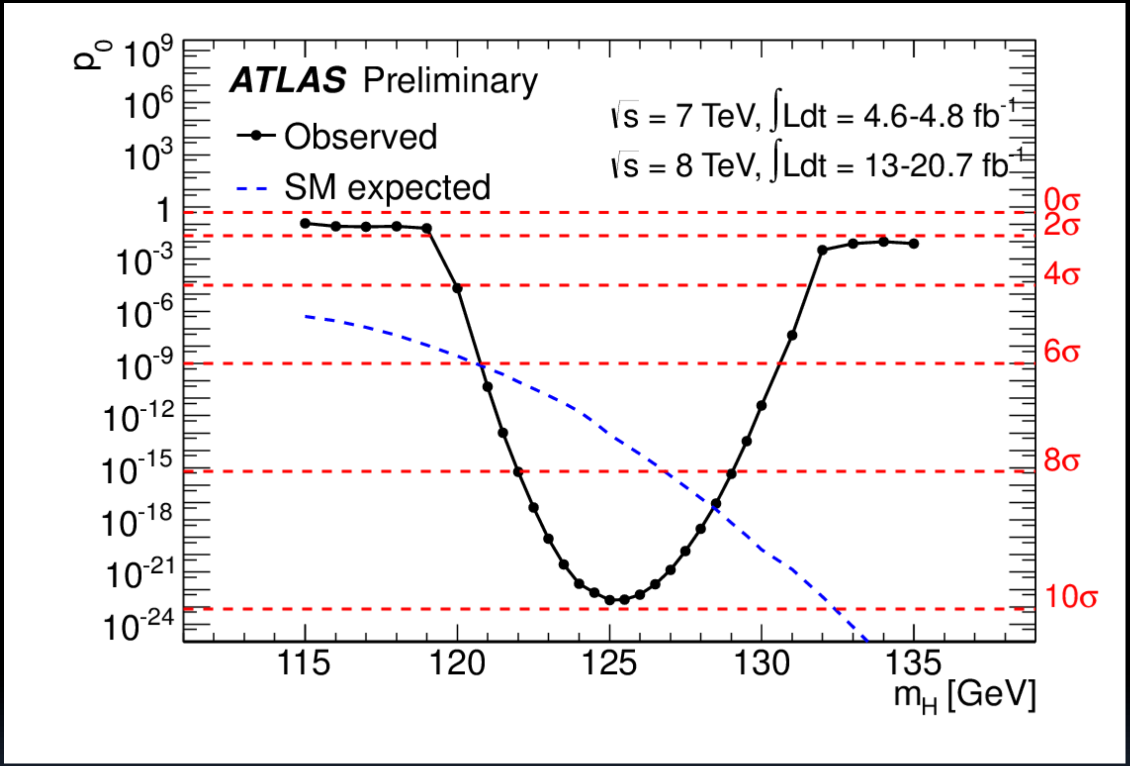


$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

- Understanding of background is crucial
  - Most of which is due to important physics
  - at the heart of the gauge structure / symmetry of electroweak interaction

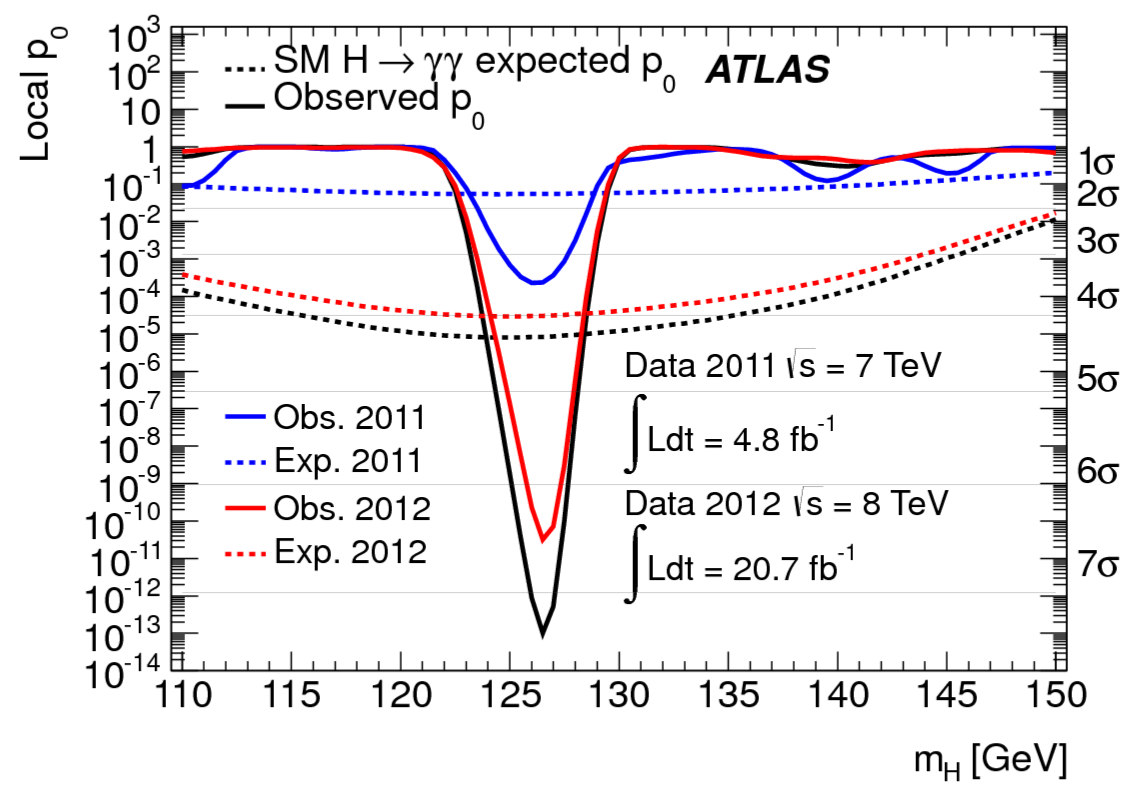
A new particle discovered

- Local probability p_o for a background-only experiment to be more signal-like than the observation as a function of m_H
- Combination of all channels
  - $\tau\tau$ and bb not all included yet



- 10σ signal @ M~125.5 GeV
- Probability of background fluctuation: ~10^{-23}

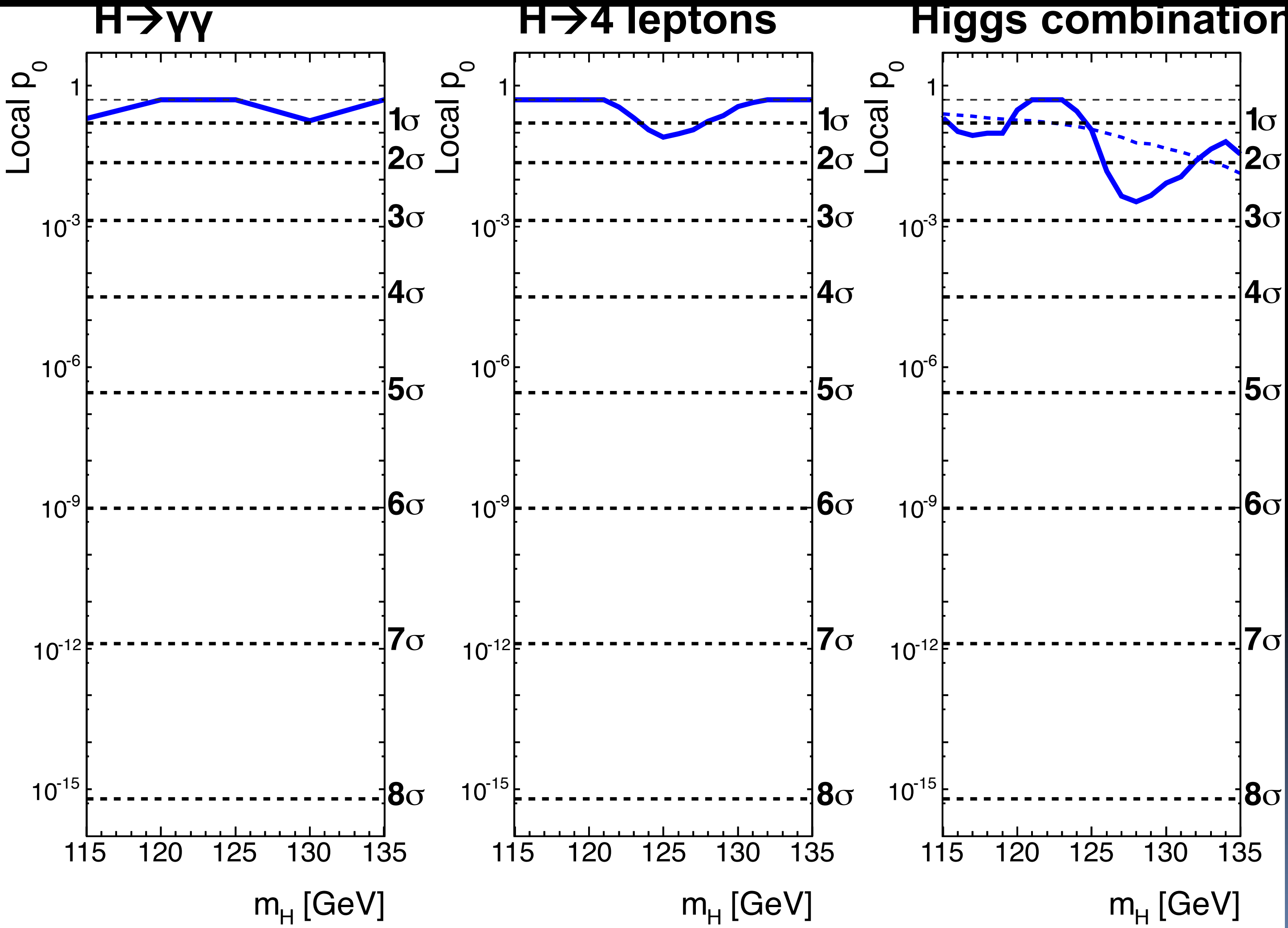
- Observed local p_o as a function of the Higgs boson mass m_H for the $\sqrt{s}$ = 7TeV data(blue), the $\sqrt{s}$ = 8TeV data (red) and their combination (black)



From excess to discovery (ATLAS)

progressive significance(p0) plots

Local p_0: probability that the background fluctuates to the observed data (or higher)

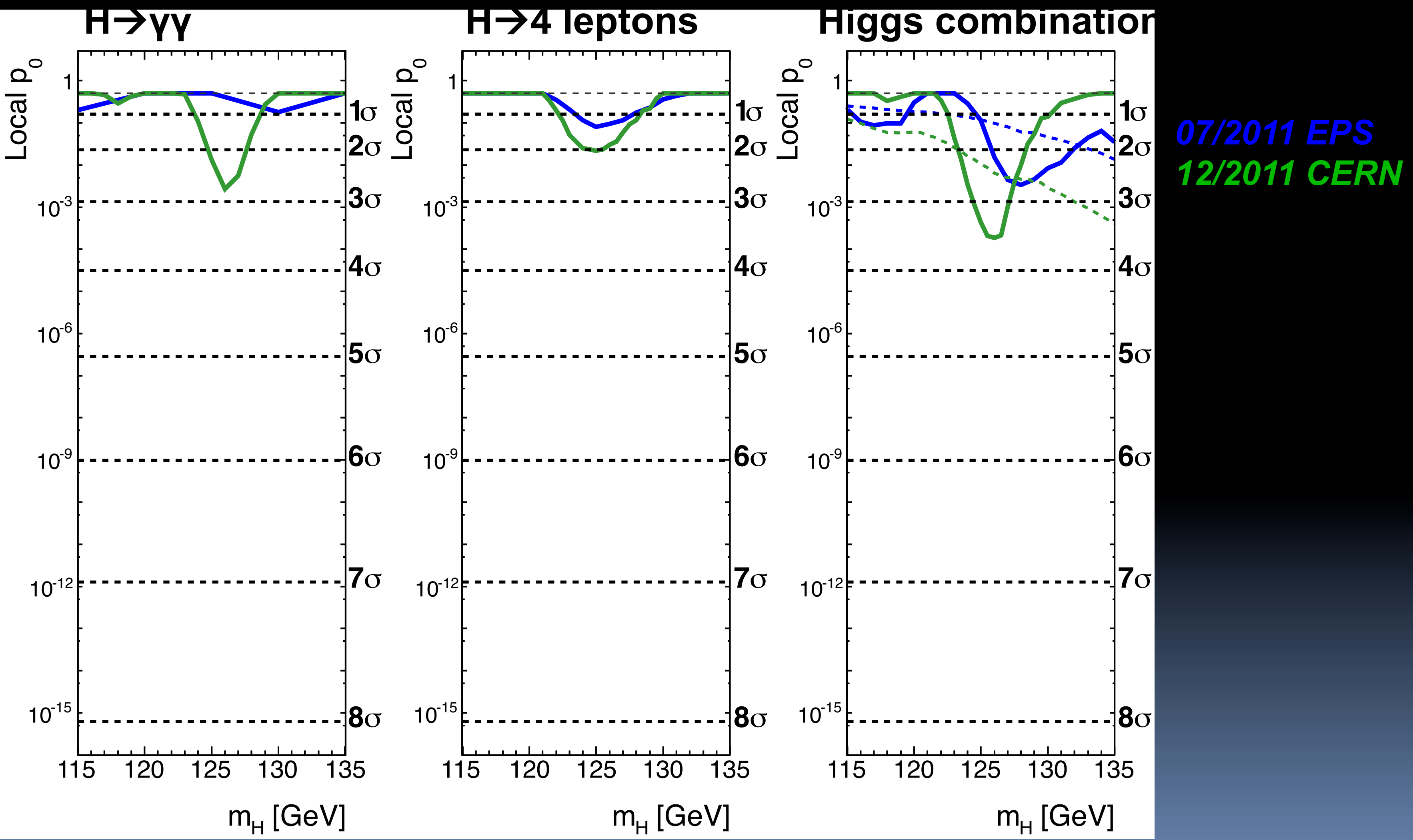


07/2011 EPS

From excess to discovery (ATLAS)

progressive significance(p0) plots

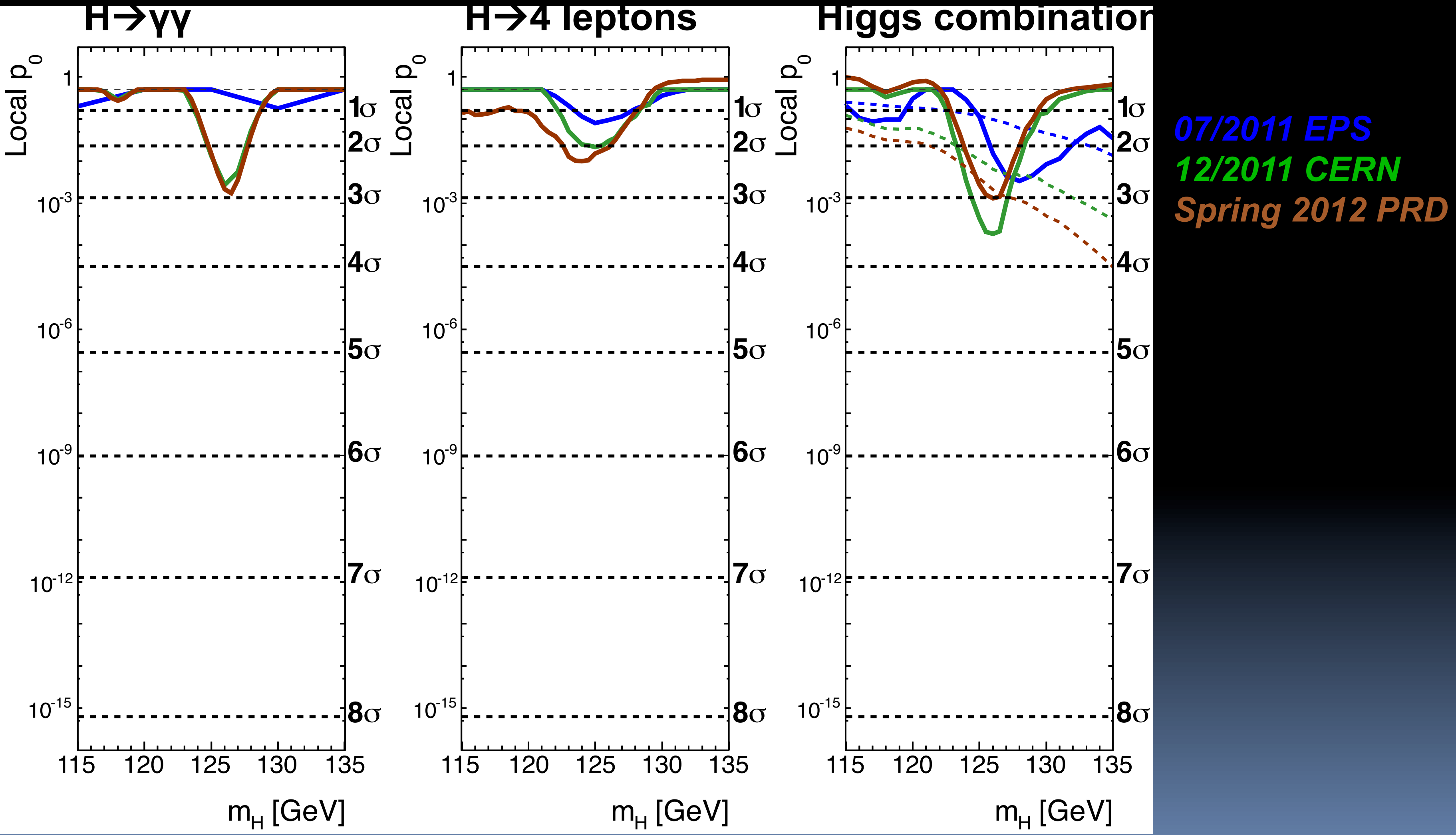
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

progressive significance(p0) plots

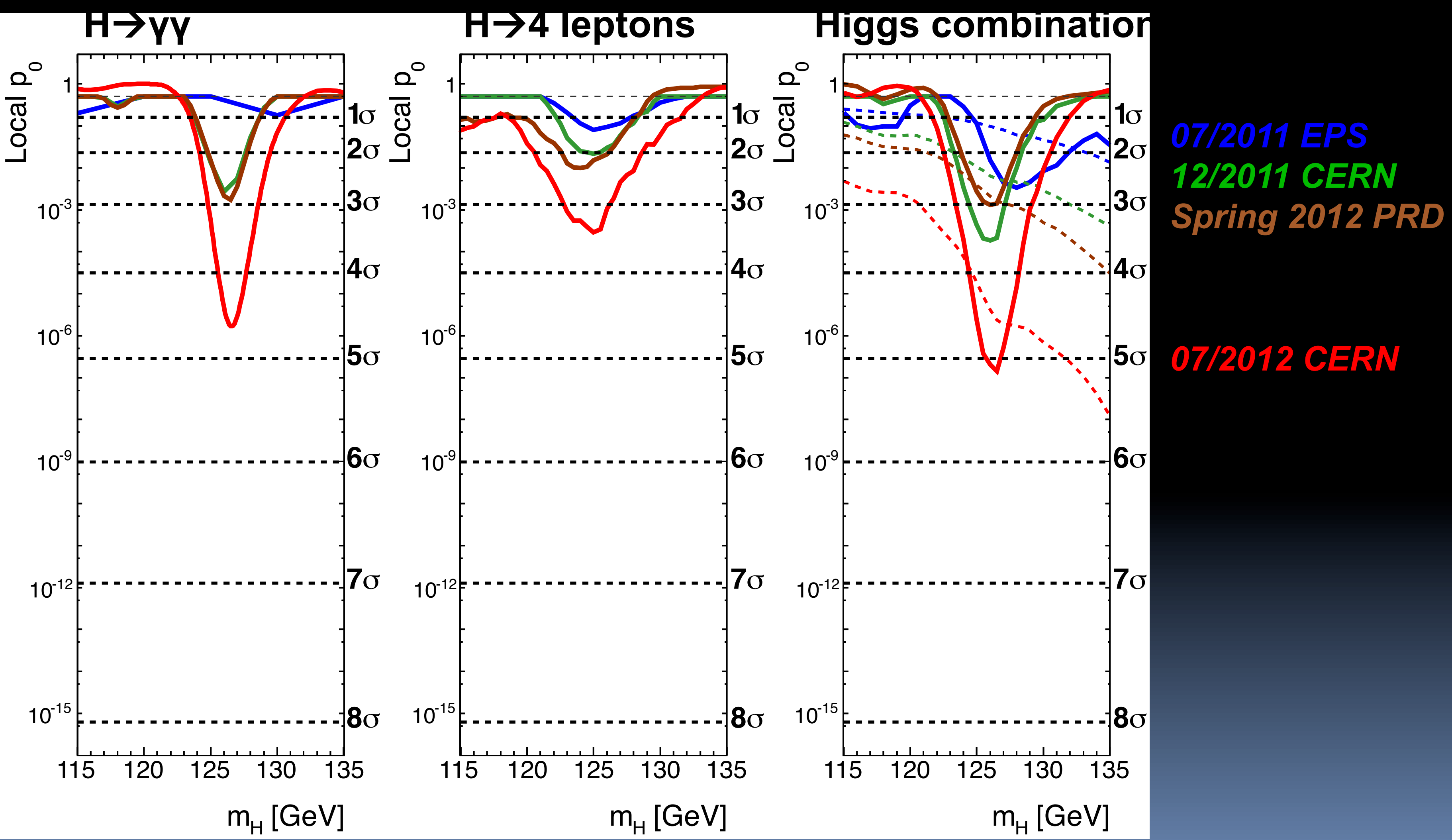
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

progressive significance(p0) plots

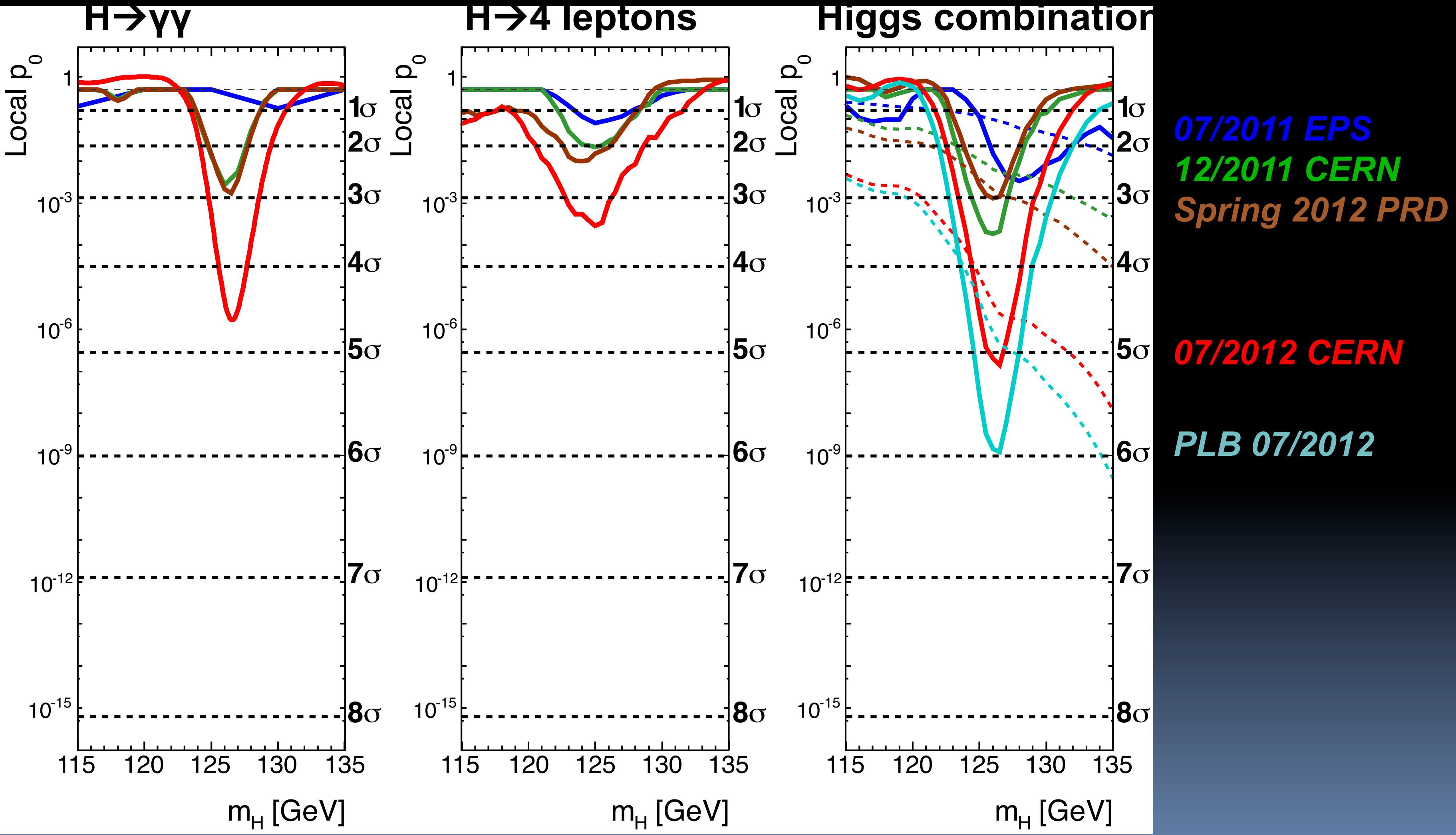
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

progressive significance(p0) plots

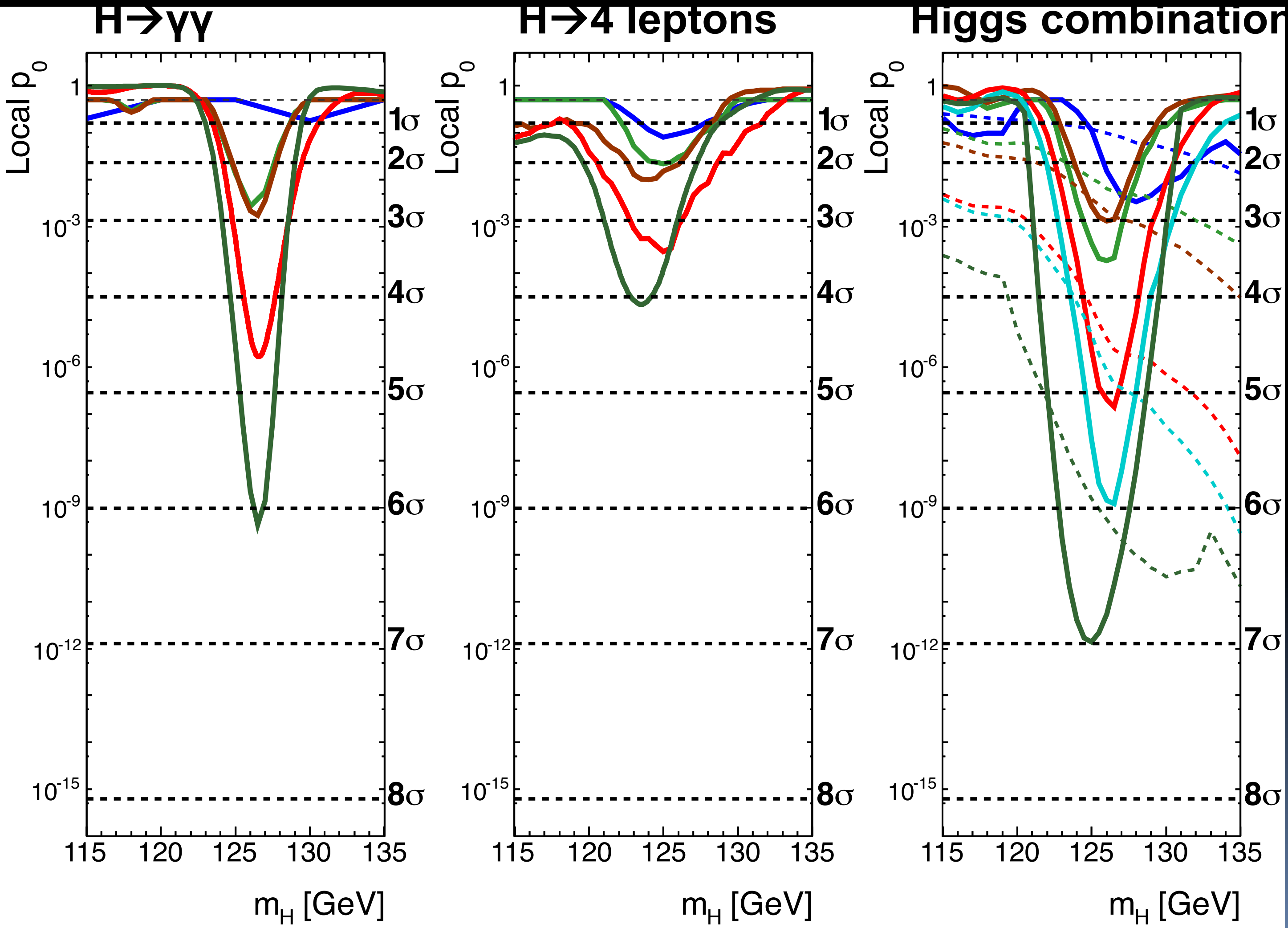
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

progressive significance(p0) plots

Local p_0: probability that the background fluctuates to the observed data (or higher)



07/2011 EPS

12/2011 CERN

Spring 2012 PRD

07/2012 CERN

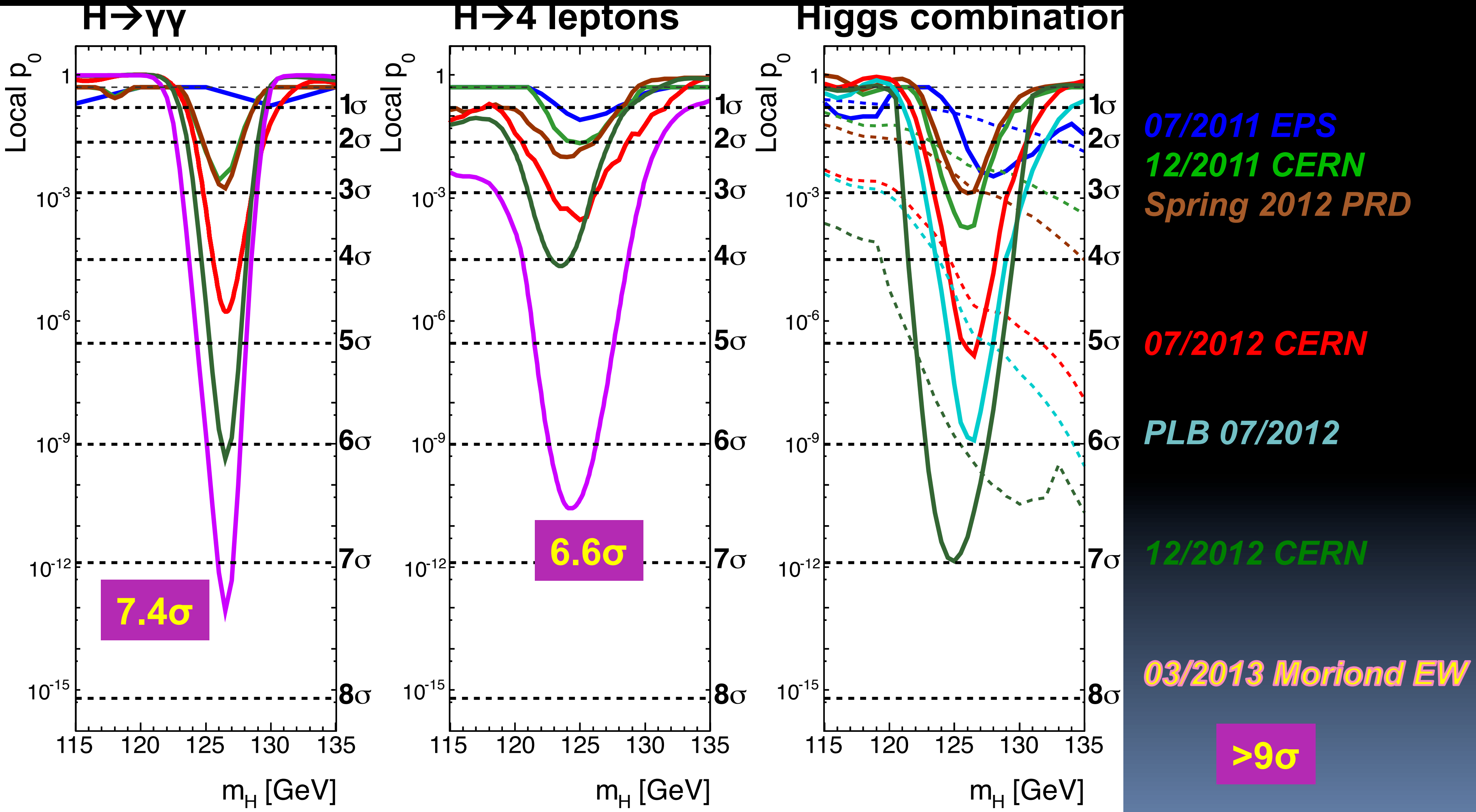
PLB 07/2012

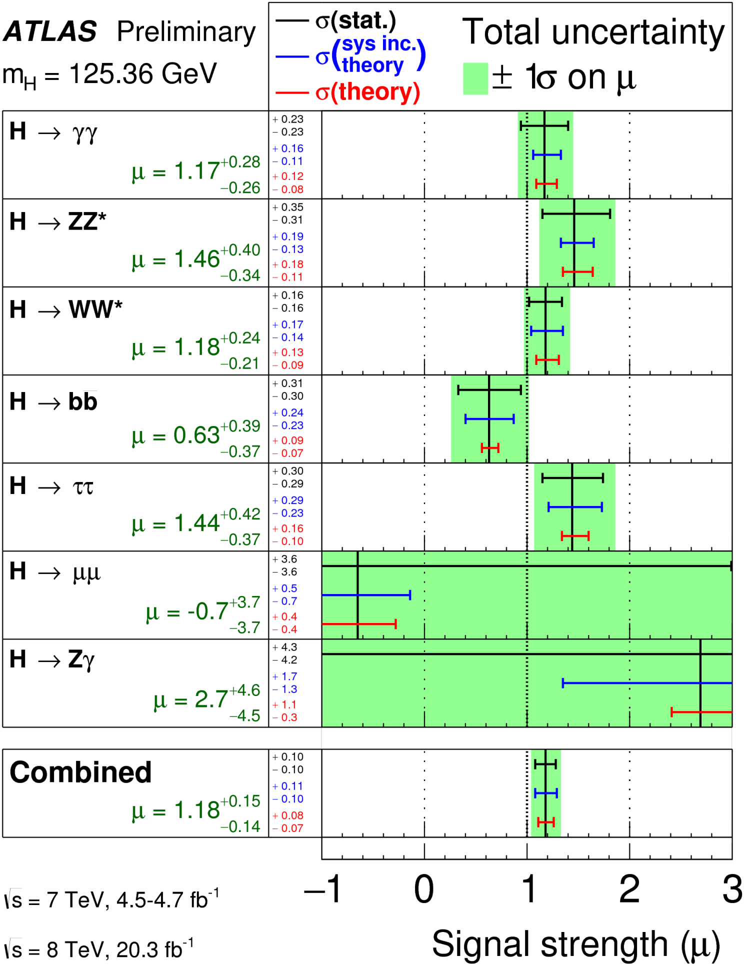
12/2012 CERN

From excess to discovery (ATLAS)

progressive significance(p0) plots

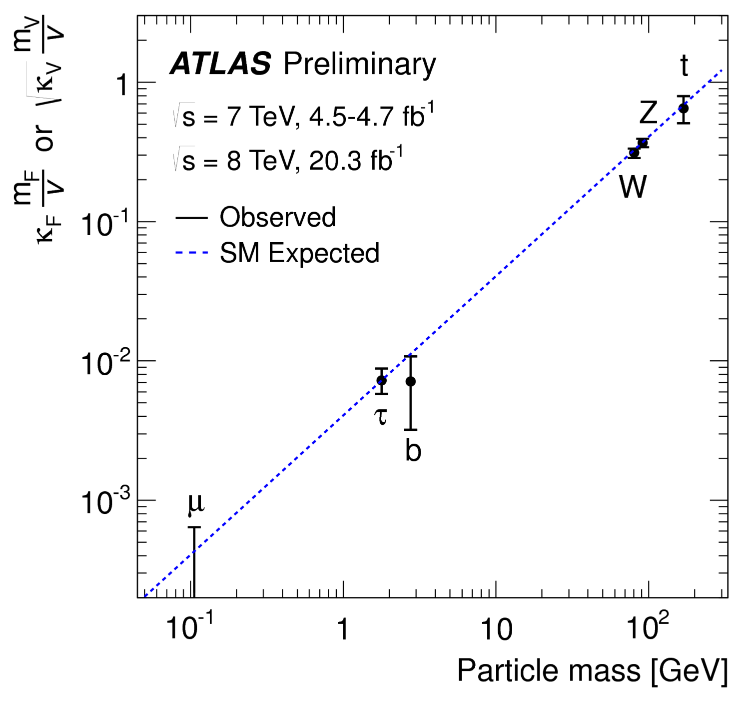
Local p_0: probability that the background fluctuates to the observed data (or higher)





Decays to bosons established, evidence for ττ, …

- Measurements of the signal strength parameter μ for m_H =125.36 GeV for the individual channels and their combination
- Combination of all channels
- Consistency with SM: $1.18^{+0.15}_{-0.14}$
- Quantum numbers consistant with Scalar: $J^{PC}=0^{++}$



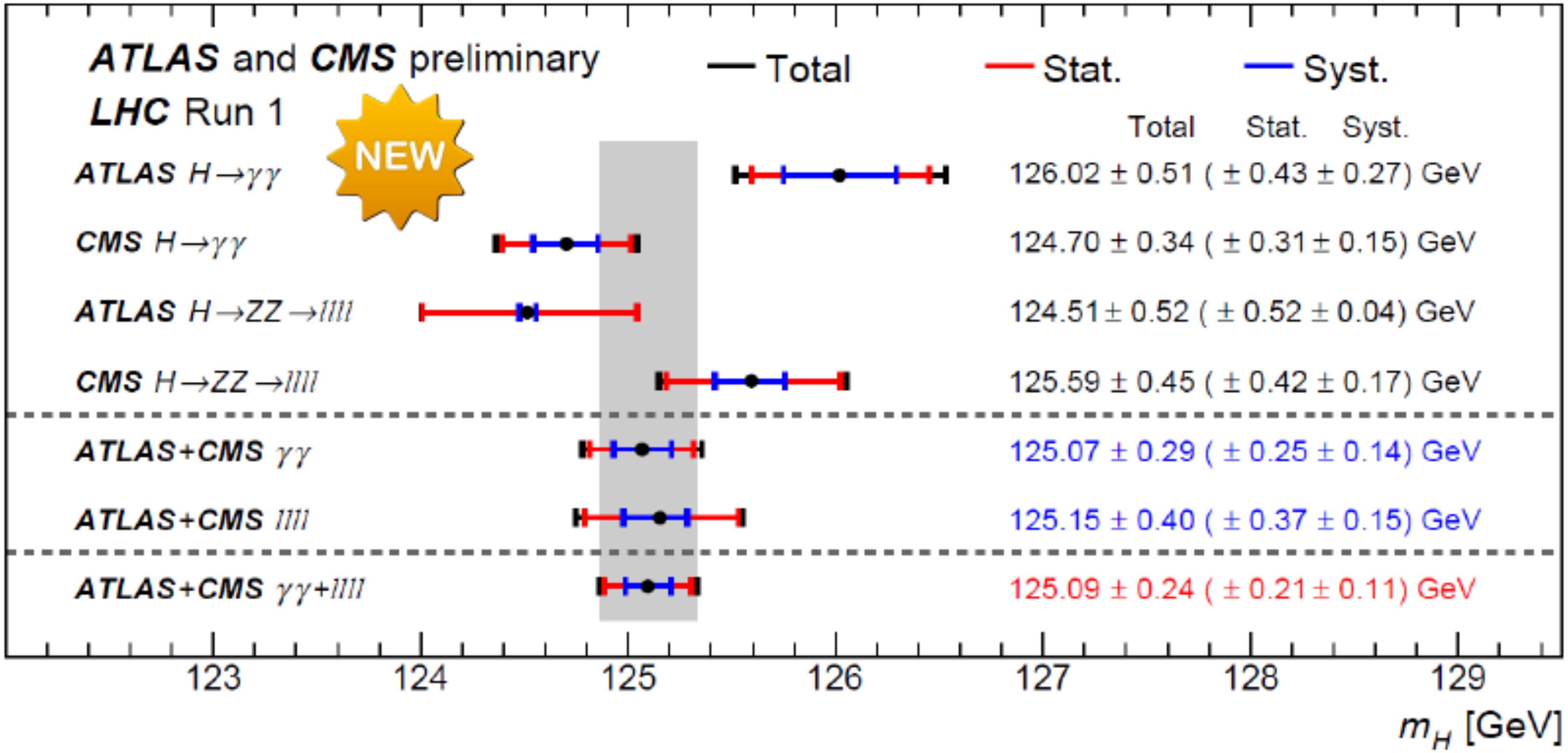
- Decays to fermions – difficult channels with high background – are a priority, especially bb (B~57%!)
- Searches for rare decays started: Zγ, μμ, …. Hidden decays, …
- Reduced coupling consistent with SM

ATLAS+CMS Higgs mass combination

… and the ATLAS+CMS combined Higgs boson mass is:

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$ **(0.19% precision!)**

$$= 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \text{ GeV}$$

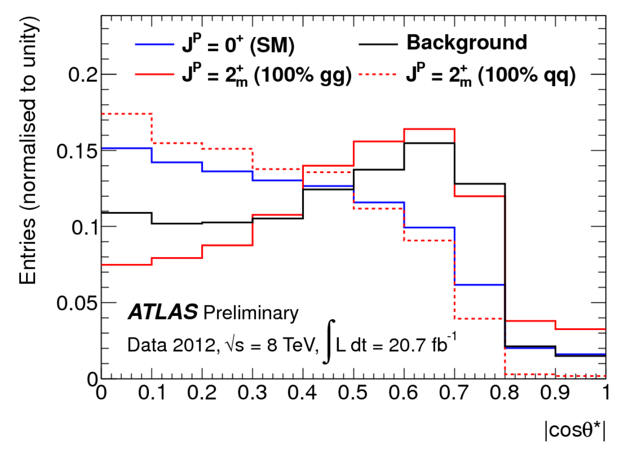


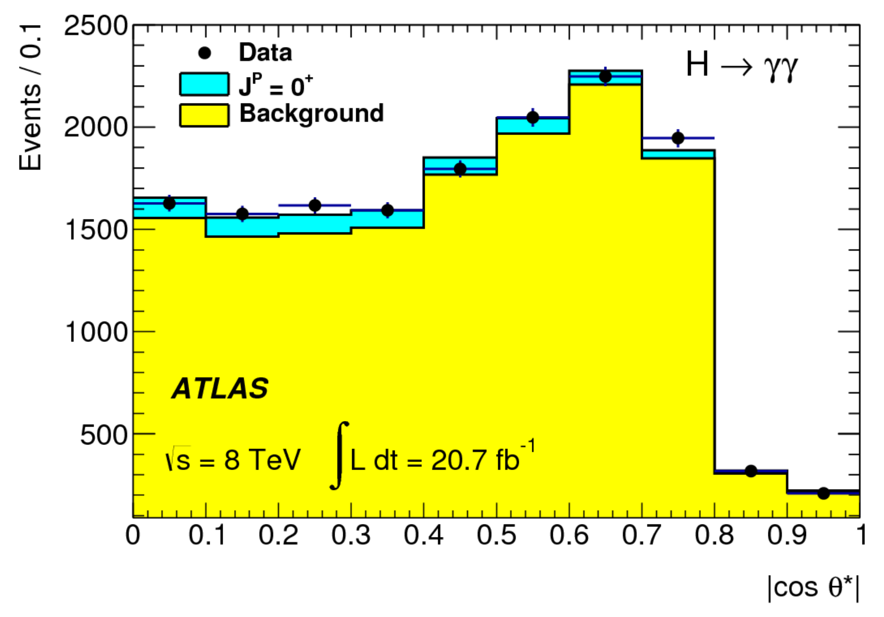
Compatibility of the 4 m_H measurements with the combined mass: 7-10%

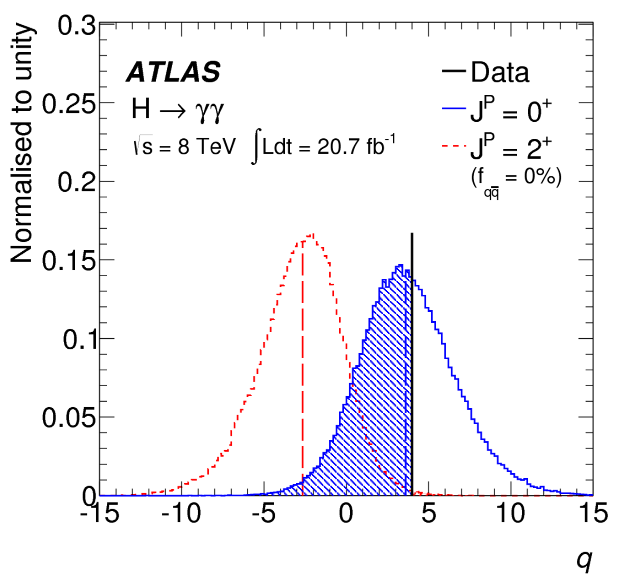
Is the new boson a Higgs?

- Measure its quantum numbers! Spin, parity, c-parity: J^{PC}=? If Higgs: 0^{++}
- Decay angle of H→γγ
  - Expected

data (background not subtracted)





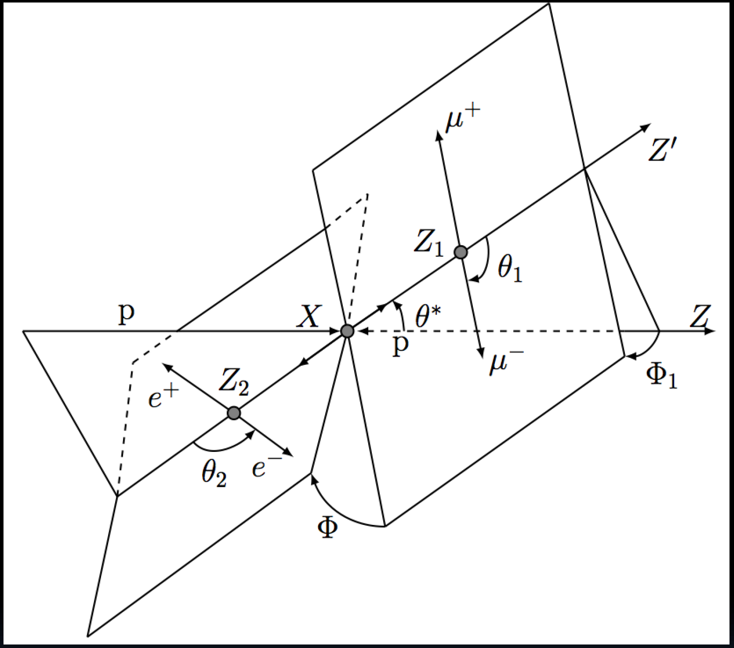


- "The hypothesis of a spin-2 particle (Graviton-like) produced by gluon fusion is excluded at 99% CL"

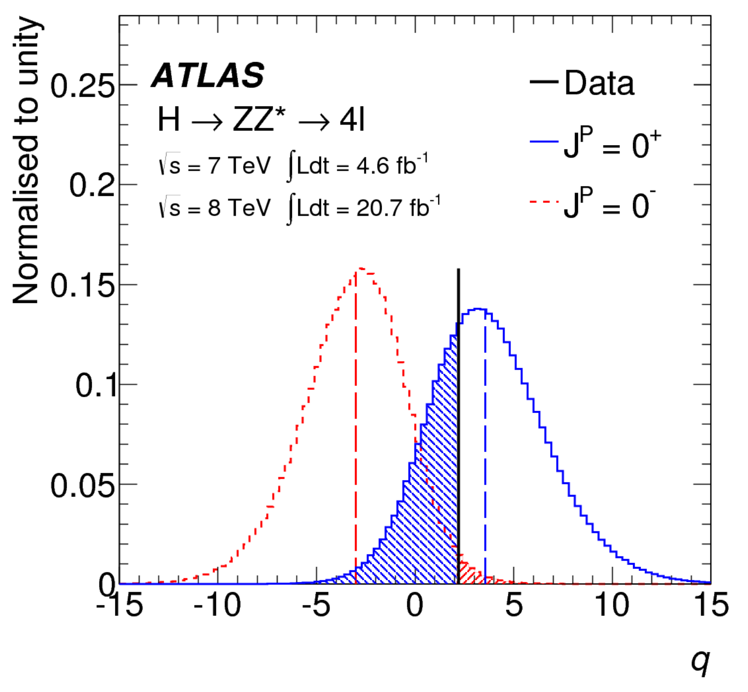
- Spin 1 cannot decay to γγ …

Is the new boson a Higgs?

- Define production & decay angle for H→ZZ→4l
  - Beam axis in the lab frame, the Z_1 and Z_2 in X rest frame and leptons in their corresponding parent rest frames



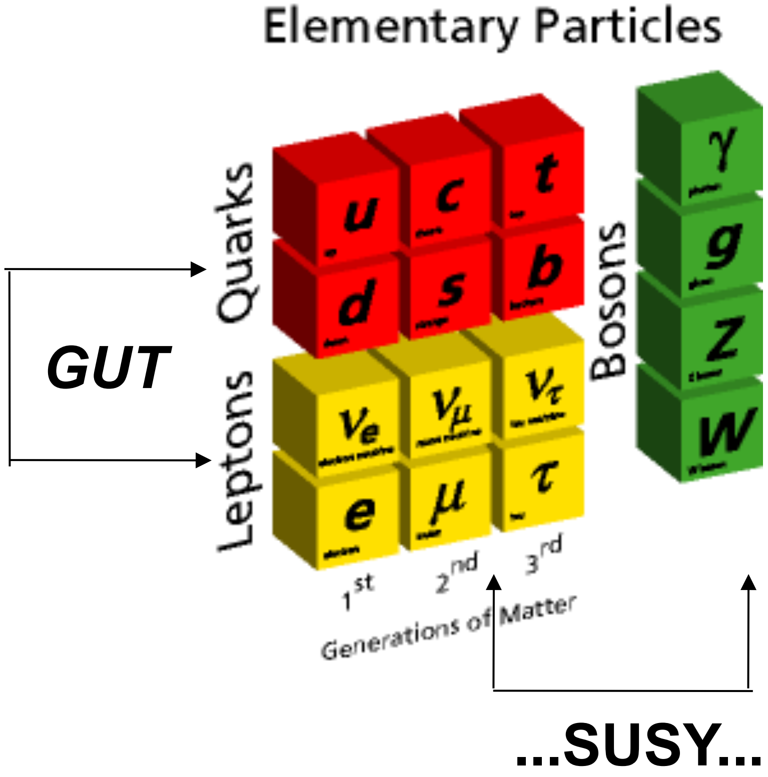
- Likelihood ratio for various hypotheses



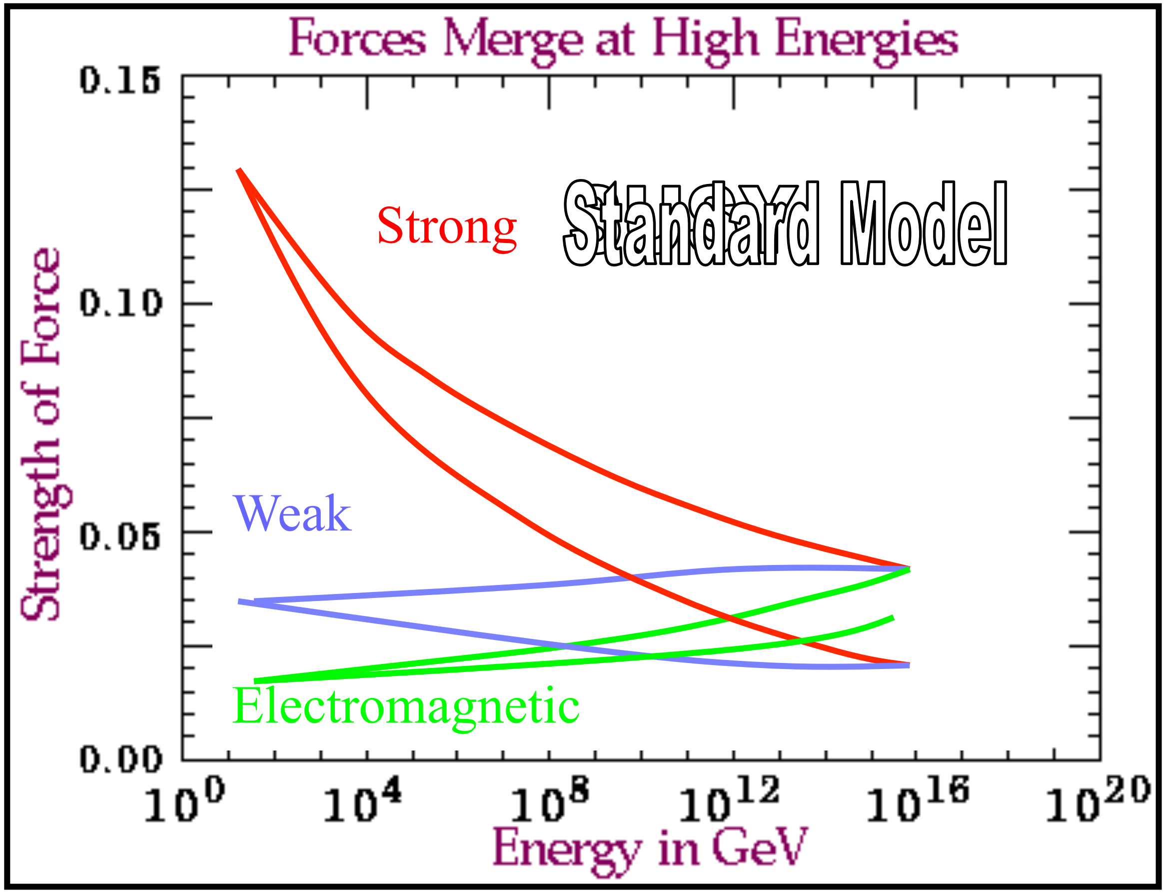
- Higgs-like boson found to be compatible with SM expectation of 0^+ when compared pair-wise with 0− , 1+ , 1− , 2+ , and 2−
- 0^- and 1^+ states are excluded at the 97.8% C.L.
- WW analysis leads to similar conclusions

Grand Unification Theories (GUT) and SuperSymmetry (SUSY)

- Current data also hint at a unification between Strong and Electroweak forces … at much larger energies, GUT scale.
- GUT is a symmetry between Leptons and Quarks
  - unifies strong and electroweak forces
- SUSY unifies "matter and force particles": "matter-force duality"
  - relates particles of different spins: Fermions-Bosons
  - introduces super-partners to each SM particle
  - requires 5 Higgs particles
  - provides DM candidate

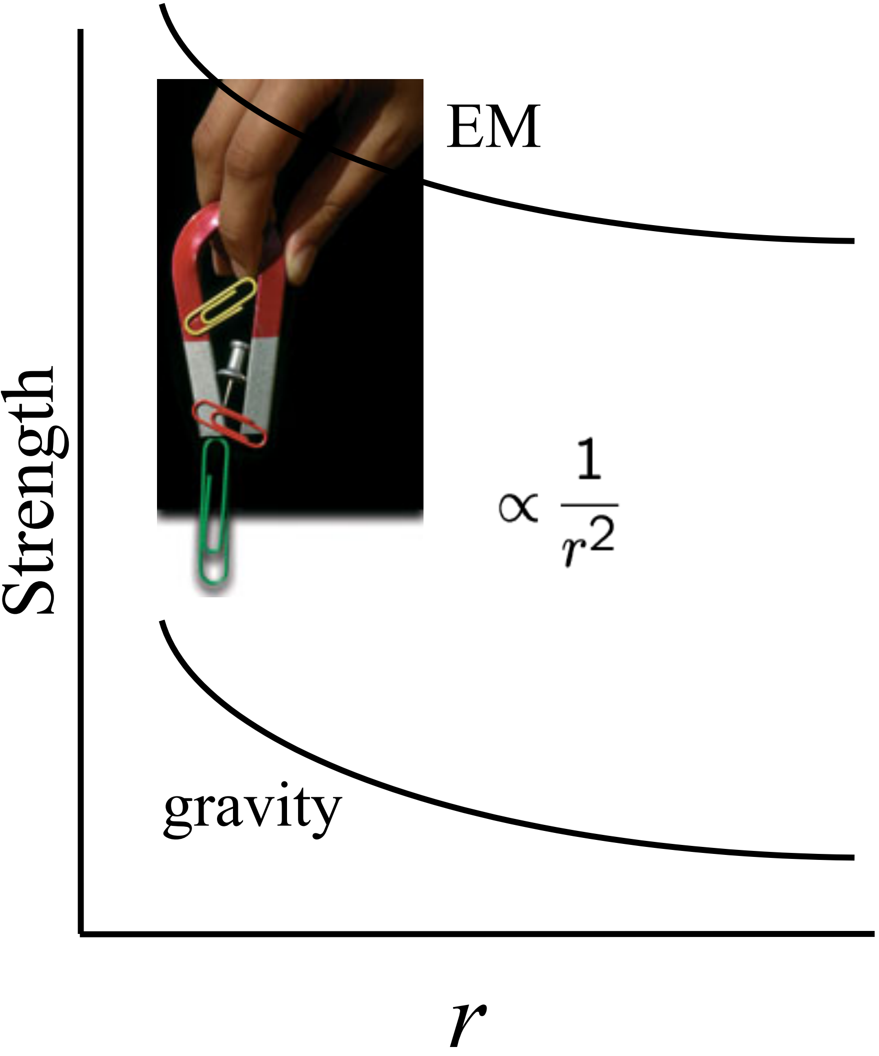


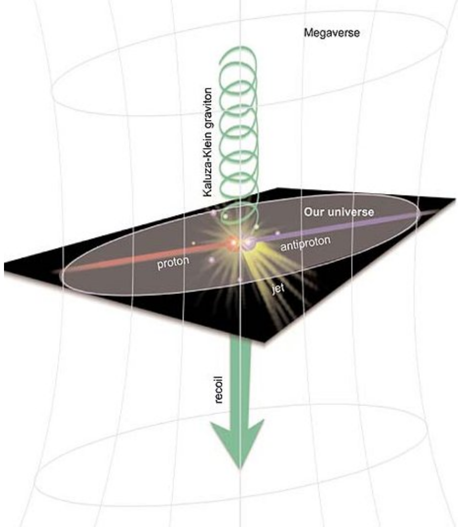
SUSY helps Grand Unification

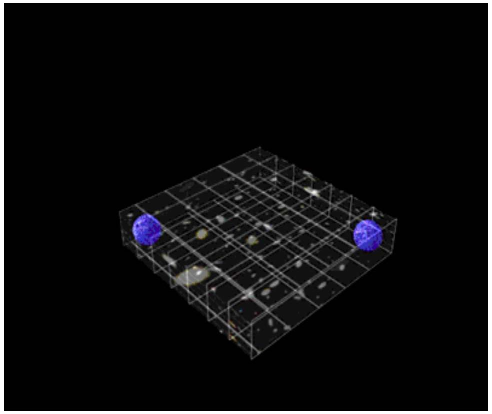


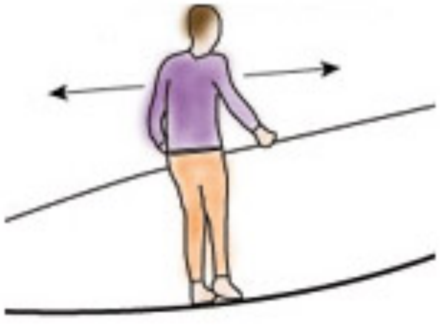
Why is gravity much weaker than EM?

Imagine extra space dimensions only "seen" by gravity …

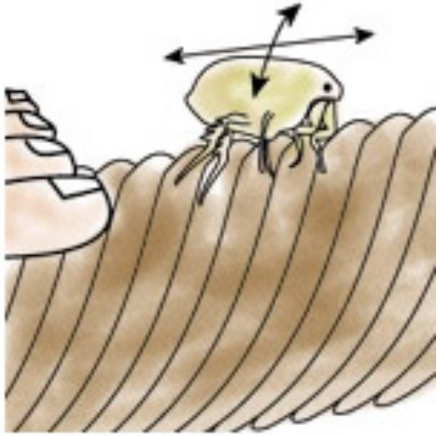








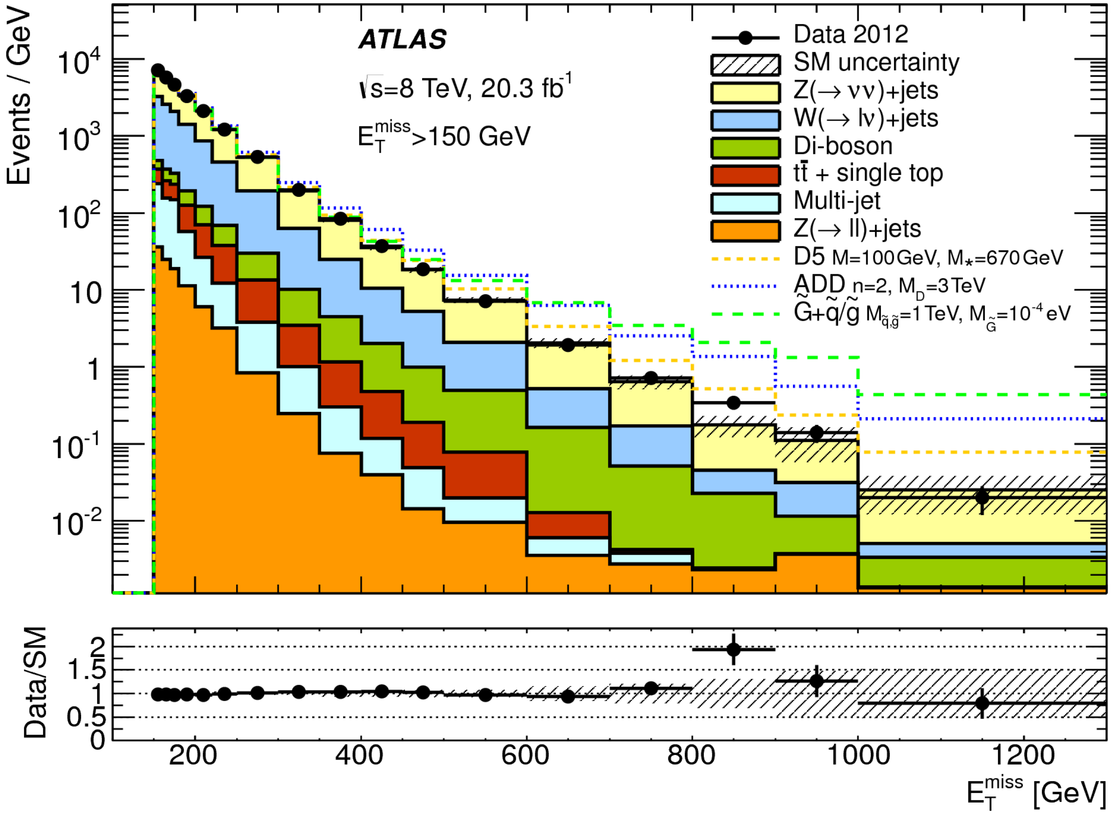
An acrobat can only move in one dimension along a rope..



...but a flea can move in two dimensions.

Looking at the dark side of matter

- Measured distribution of the missing transverse momentum for monojet events.
- Data in agreement with SM prediction (histogram).
- For illustration, shown
  - distributions of signals from WIMPs production, large extra spatial dimensions, and light gravitino production

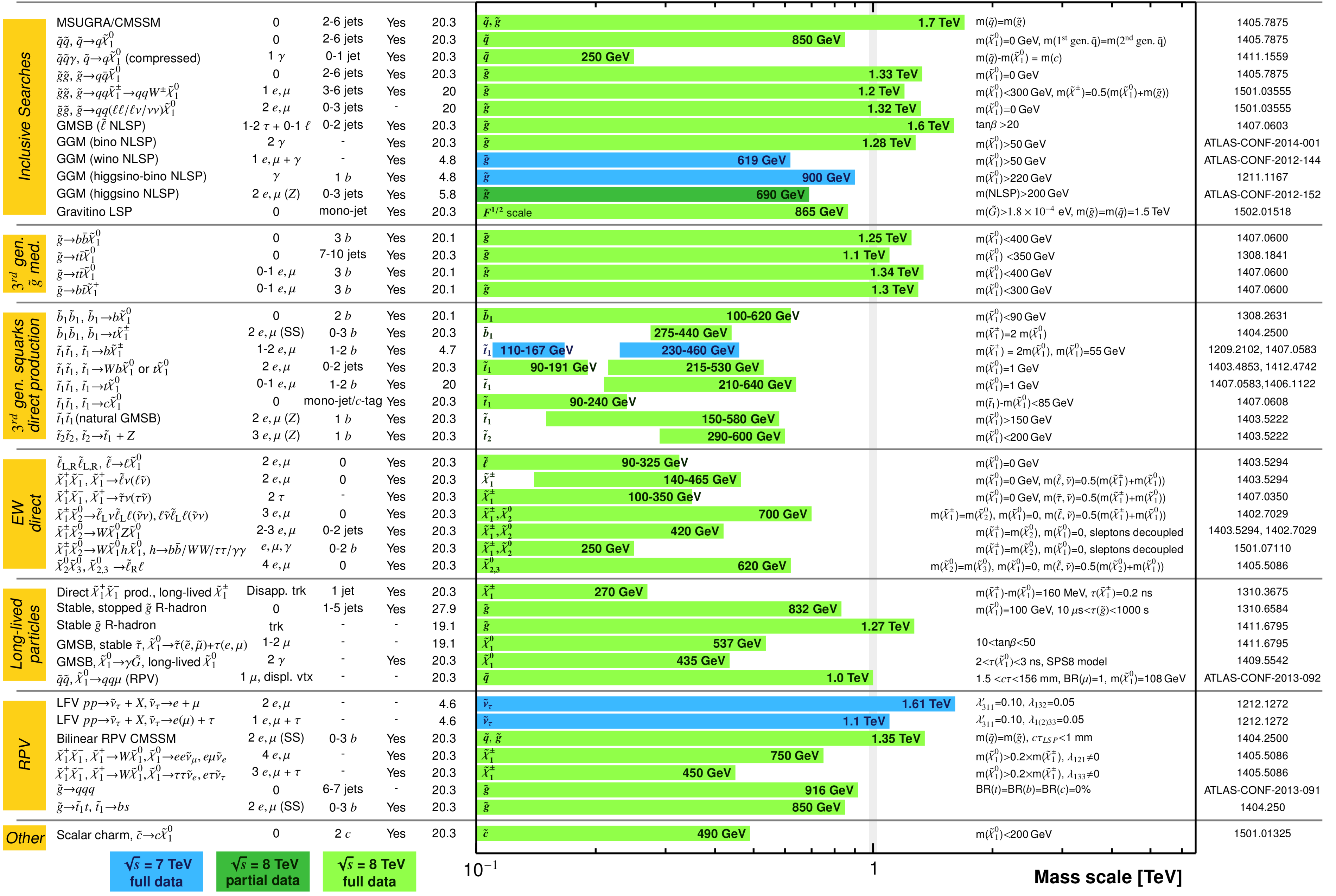


ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV



	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1405.7875
	$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1^{st} gen. $\tilde{q}$)=m(2^{nd} gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}\gamma, \tilde{q}\rightarrow q\tilde{\chi}_1^0$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$) = m(c)	1411.1559
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qq\tilde{\chi}_1^{\pm}\rightarrow qqW^{\pm}\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	m($\tilde{\chi}_1^0$)<300 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	1501.03555
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\rightarrow b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV, 230-460 GeV	m($\tilde{\chi}_1^{\pm}$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 90-191 GeV, 215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	0-1 e, μ	1-2 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1407.0583,1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\rightarrow\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 700 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 420 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 250 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\rightarrow\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	1310.3675
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\rightarrow\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	2<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\rightarrow qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\rightarrow e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\rightarrow\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\rightarrow qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\rightarrow\tilde{t}_1 t, \tilde{t}_1\rightarrow bs$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar charm, $\tilde{c}\rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

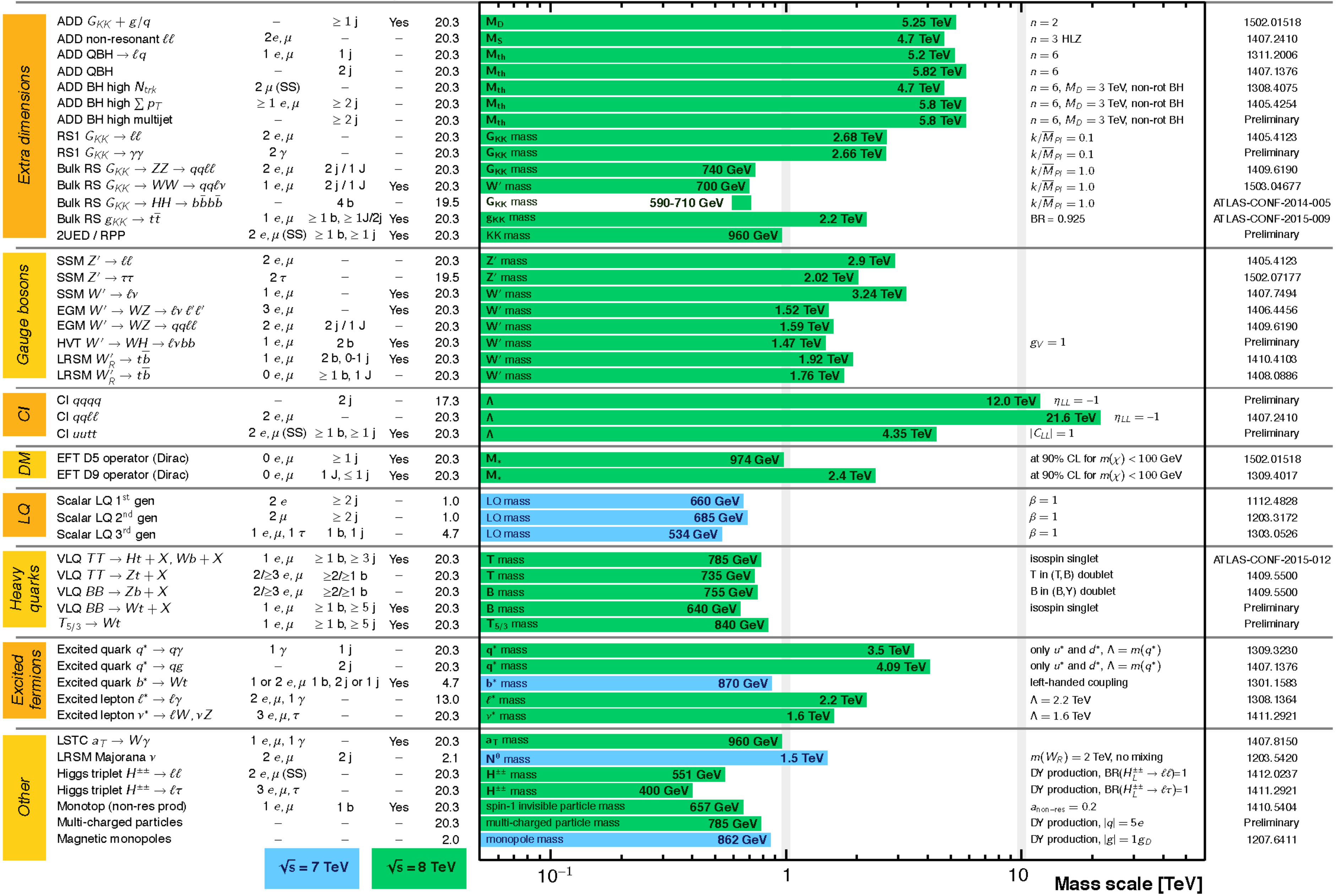
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2015

ATLAS Preliminary

$\int\mathcal{L}\,dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7,\ 8$ TeV



	Model	ℓ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	20.3	🟩 M_D 5.25 TeV	$n = 2$	1502.01518
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	🟩 M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\rightarrow \ell q$	1 e, μ	1 j	–	20.3	🟩 M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	🟩 M_{th} 5.82 TeV	$n = 6$	1407.1376
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	🟩 M_{th} 4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	🟩 M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1405.4254
	ADD BH high multijet	–	≥ 2 j	–	20.3	🟩 M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	Preliminary
	RS1 $G_{KK} \rightarrow \ell\ell$	2 e, μ	–	–	20.3	🟩 G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	20.3	🟩 G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	Preliminary
	Bulk RS $G_{KK} \rightarrow ZZ \rightarrow qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	🟩 G_{KK} mass 740 GeV	$k/\overline{M}_{Pl} = 1.0$	1409.6190
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	1 e, μ	2 j / 1 J	Yes	20.3	🟩 W' mass 700 GeV	$k/\overline{M}_{Pl} = 1.0$	1503.04677
	Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	–	4 b	–	19.5	🟩 G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \rightarrow t\bar{t}$	1 e, μ	≥ 1 b, $\geq$ 1J/2j	Yes	20.3	🟩 g_{KK} mass 2.2 TeV	BR = 0.925	ATLAS-CONF-2015-009
	2UED / RPP	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	🟩 KK mass 960 GeV		Preliminary
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	20.3	🟩 Z' mass 2.9 TeV		1405.4123
	SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	19.5	🟩 Z' mass 2.02 TeV		1502.07177
	SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	20.3	🟩 W' mass 3.24 TeV		1407.7494
	EGM $W' \rightarrow WZ \rightarrow \ell\nu\,\ell'\ell'$	3 e, μ	–	Yes	20.3	🟩 W' mass 1.52 TeV		1406.4456
	EGM $W' \rightarrow WZ \rightarrow qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	🟩 W' mass 1.59 TeV		1409.6190
	HVT $W' \rightarrow WH \rightarrow \ell\nu bb$	1 e, μ	2 b	Yes	20.3	🟩 W' mass 1.47 TeV	$g_V = 1$	Preliminary
	LRSM $W'_R \rightarrow t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	20.3	🟩 W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \rightarrow t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	17.3	🟩 Λ 12.0 TeV	$\eta_{LL} = -1$	Preliminary
	CI $qq\ell\ell$	2 e, μ	–	–	20.3	🟩 Λ 21.6 TeV	$\eta_{LL} = -1$	1407.2410
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	🟩 Λ 4.35 TeV	$\lvert C_{LL}\rvert = 1$	Preliminary
DM	EFT D5 operator (Dirac)	0 e, μ	≥ 1 j	Yes	20.3	🟩 M_* 974 GeV	at 90% CL for $m(\chi) < 100$ GeV	1502.01518
	EFT D9 operator (Dirac)	0 e, μ	1 J, ≤ 1 j	Yes	20.3	🟩 M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1^{st} gen	2 e	≥ 2 j	–	1.0	🟦 LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2^{nd} gen	2 μ	≥ 2 j	–	1.0	🟦 LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3^{rd} gen	1 e, μ, 1 τ	1 b, 1 j	–	4.7	🟦 LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	VLQ $TT \rightarrow Ht + X, Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	🟩 T mass 785 GeV	isospin singlet	ATLAS-CONF-2015-012
	VLQ $TT \rightarrow Zt + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	🟩 T mass 735 GeV	T in (T,B) doublet	1409.5500
	VLQ $BB \rightarrow Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	🟩 B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $BB \rightarrow Wt + X$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	🟩 B mass 640 GeV	isospin singlet	Preliminary
	$T_{5/3} \rightarrow Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	🟩 $T_{5/3}$ mass 840 GeV		Preliminary
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	–	20.3	🟩 q* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \rightarrow qg$	–	2 j	–	20.3	🟩 q* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1407.1376
	Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	🟦 b* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \rightarrow \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	🟩 ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
	Excited lepton $\nu^* \rightarrow \ell W, \nu Z$	3 e, μ, τ	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \rightarrow W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	🟩 a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	2.1	🟦 N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2 e, μ (SS)	–	–	20.3	🟩 $H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	Preliminary
	Magnetic monopoles	–	–	–	2.0	🟦 monopole mass 862 GeV	DY production, $\lvert g\rvert = 1g_D$	1207.6411

🟦 $\sqrt{s}$ = 7 TeV 🟩 $\sqrt{s}$ = 8 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

Introduction

Excited Fermions

Compositeness

Leptoquarks

Vector-like Quarks

Heavy Gauge Bosons

Monopoles

Gravitons

Extra Dimensions

Dark Matter

Technicolour

What & How?

- Heavy gauge bosons, Z′ and W′,
  - From higher symmetry (e.g. E6) breaking, and more
- Composite models for quarks, q*, and leptons, l*
  - with substructure scale Λ
- Randal-Sundrum gravitons, G* and
- G*$_{bulk}$, from warped extra dimensions
- Low-scale strings with large EDs,
  - and TeV^{-1} Kaluza-Klein excitations of γ/Z
- Technicolor, Chiral bosons (W*/Z*)
- Quantum black holes, ADD, CI (non res′) …

- "Simple"
  - ll
  - $\gamma\gamma$
  - ZZ, WW, …
  - …
- Traditional
  - Jets or Rutherford – Hammer method
  - Missing
- Mix
  - "Leptons-quarks-gauge bosons-missing"
- Innovate
  - "Lepton-jets"

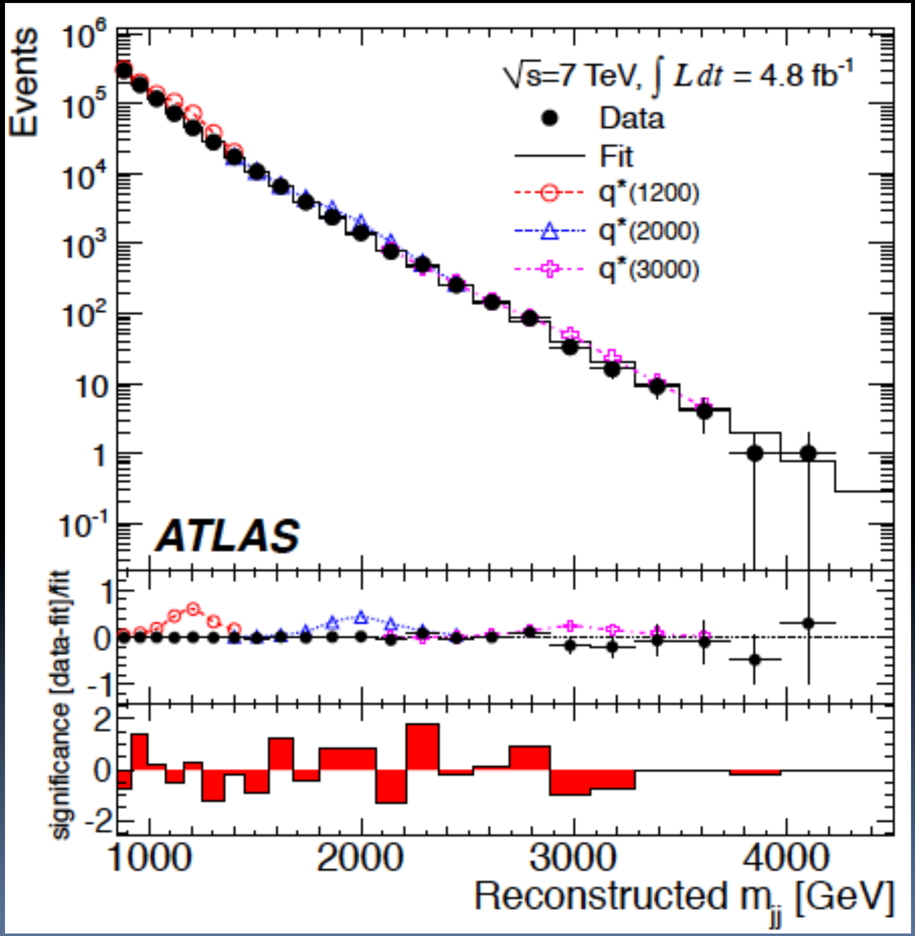
New phenomena in di-jets

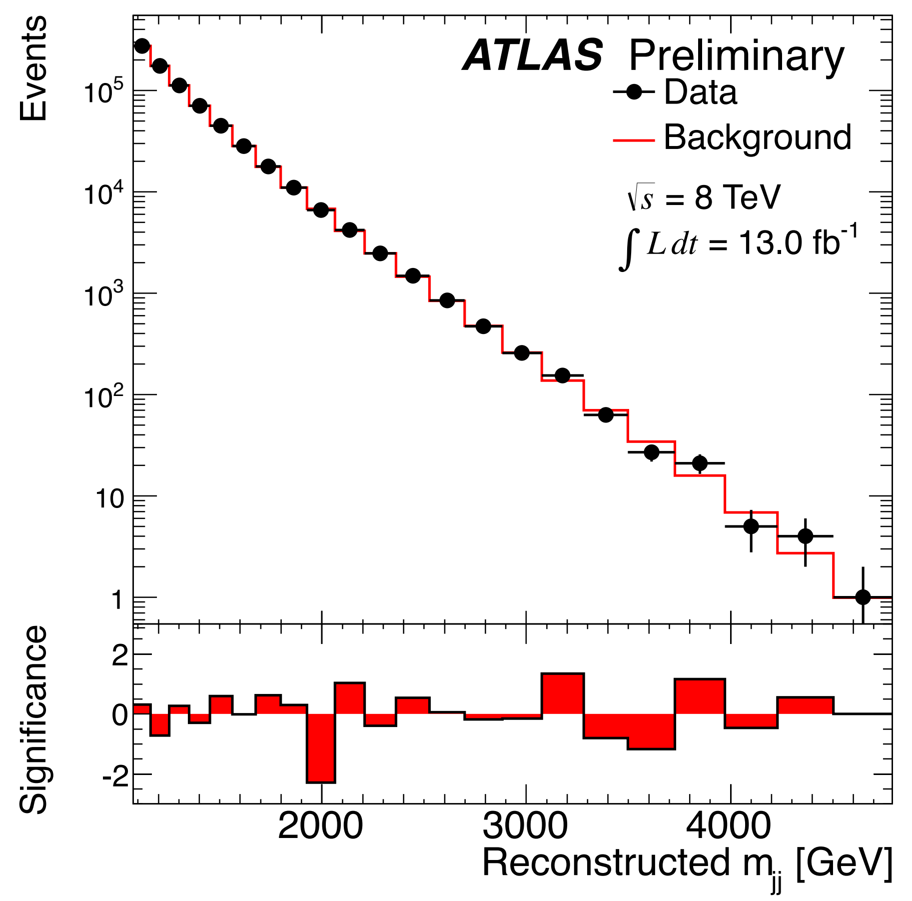
- New physics
  - new particles could be produced,
  - new interactions between particles could manifest themselves,
  - interactions resulting from the unification of SM with gravity could appear in the TeV range
  - probe the structure of the fundamental constituents of matter at the smallest distance scales
    - experimental test of the size of quarks.

Di-jet invariant mass

- Background fit

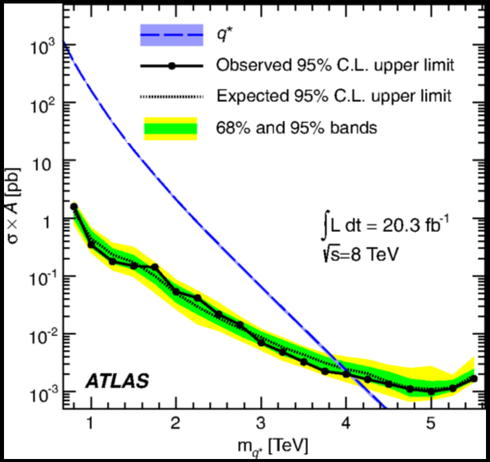
$$f(x) = p_1(1-x)^{p_2} x^{p_3+p_4 \ln x}$$





Search for new phenomena in the dijet mass distribution using *pp* collision data at √s=8 TeV with the ATLAS detector

Phys. Rev. D 91, 052007 http://dx.doi.org/10.1103/PhysRevD.91.052007



- Modification of di-jet mass and angular distributions
- Excited quarks
- M(q*)>4.06 TeV

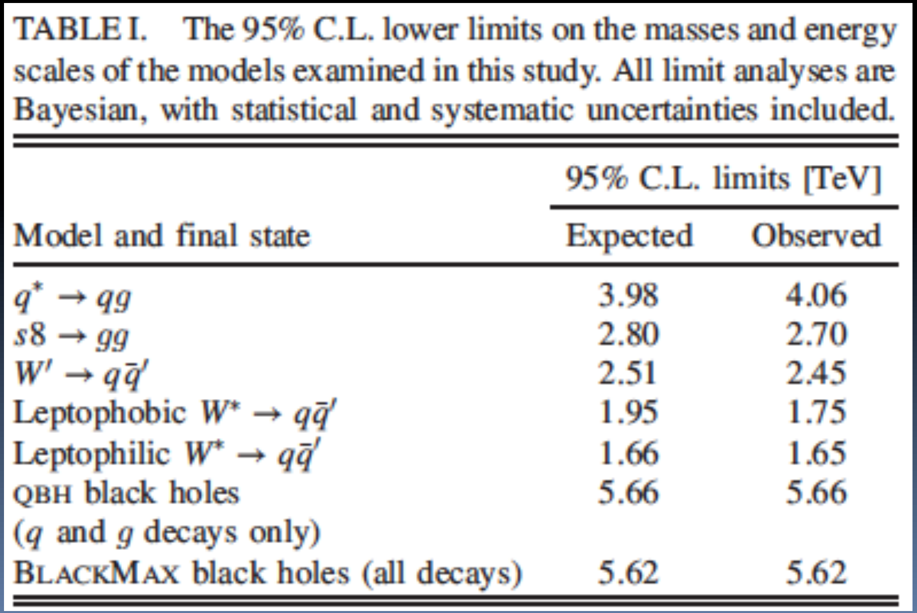
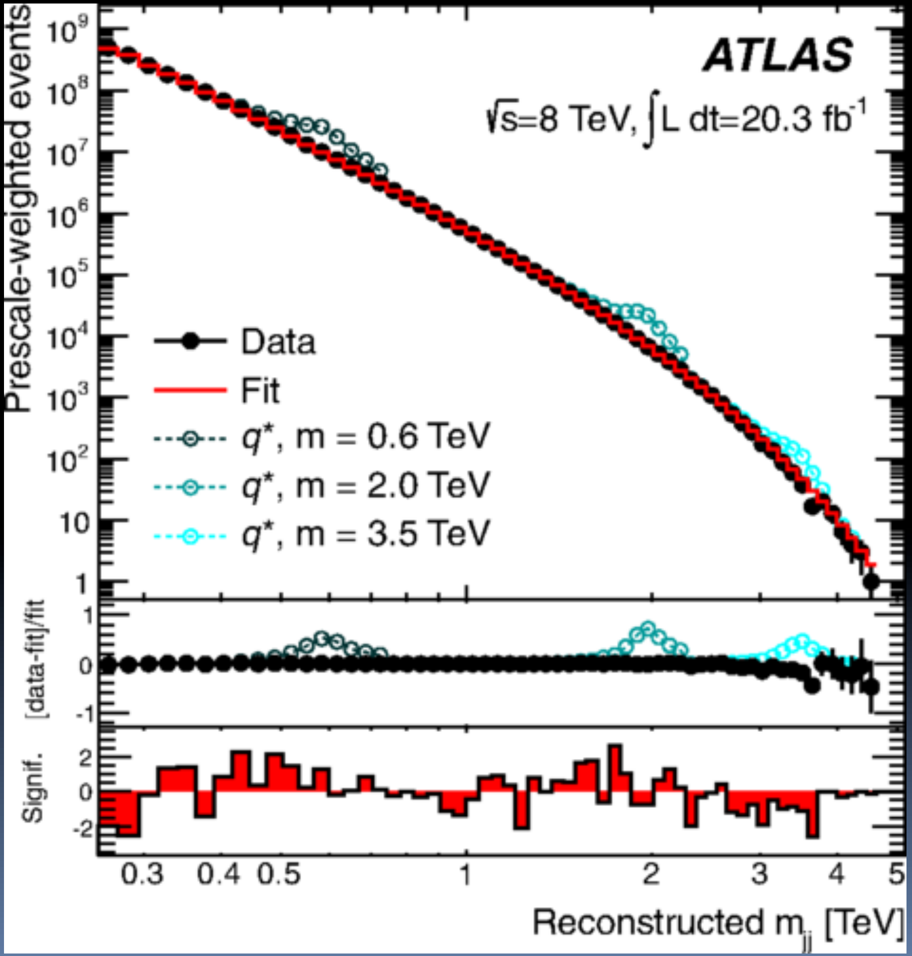


TABLE I. The 95% C.L. lower limits on the masses and energy scales of the models examined in this study. All limit analyses are Bayesian, with statistical and systematic uncertainties included.

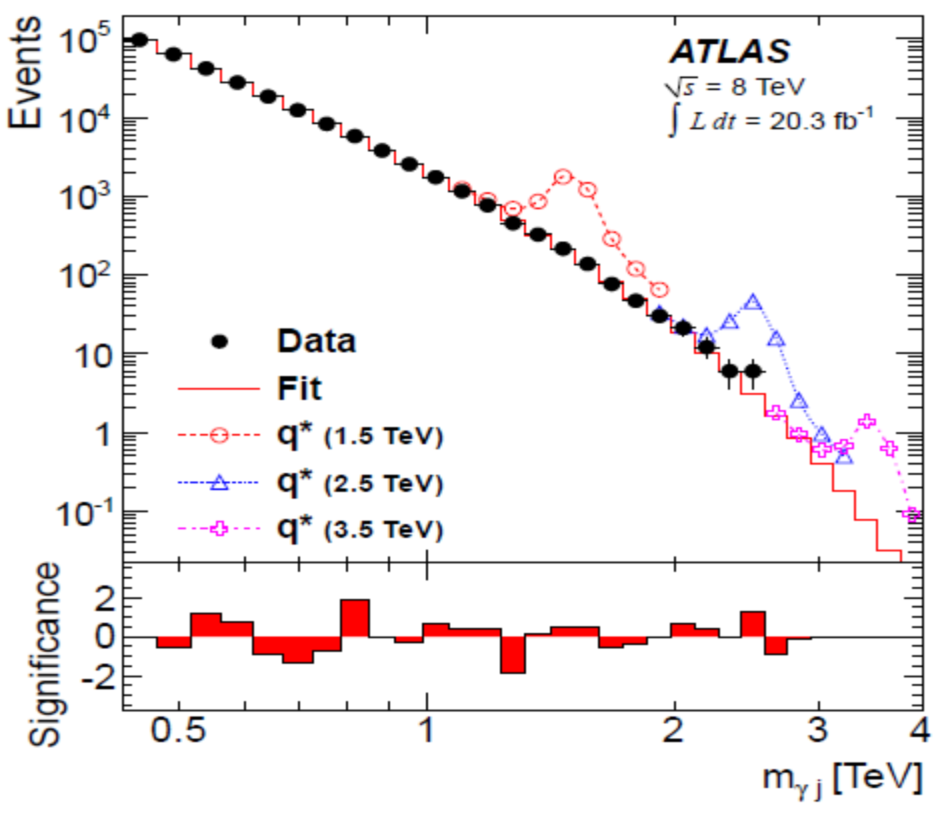
	95% C.L. limits [TeV]	
Model and final state	Expected	Observed
$q^* \rightarrow qg$	3.98	4.06
$s8 \rightarrow gg$	2.80	2.70
$W' \rightarrow q\bar{q}'$	2.51	2.45
Leptophobic $W^* \rightarrow q\bar{q}'$	1.95	1.75
Leptophilic $W^* \rightarrow q\bar{q}'$	1.66	1.65
QBH black holes (q and g decays only)	5.66	5.66
BLACKMAX black holes (all decays)	5.62	5.62

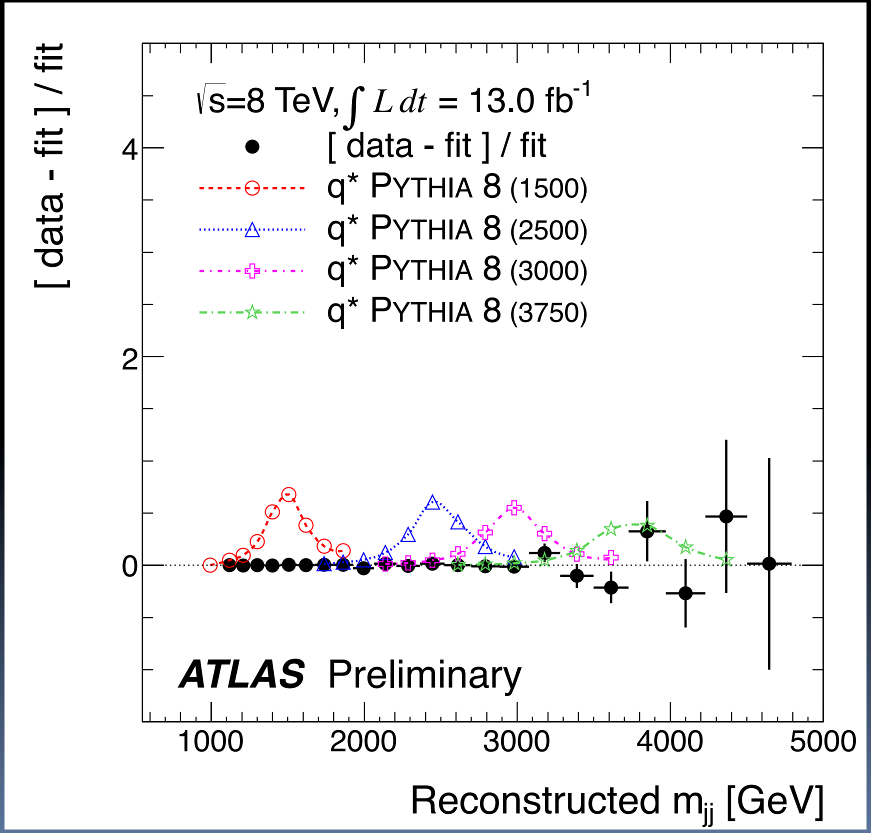


Excited quarks

- q*→qγ
  - Exclude m(q*)<3.5 TeV @ 95% CL

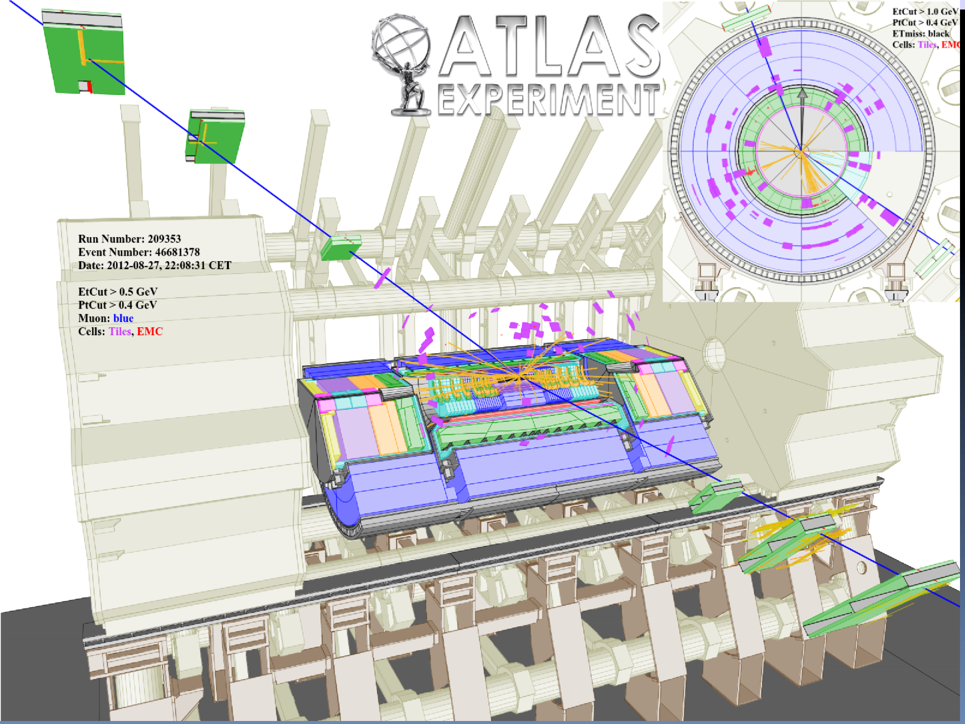
- Modification of di-jet mass and angular distributions
- Observed & fitted di-jet mass: 8TeV data
  - Comparison to 4 q^* models
  - $M_{q*} > 3.84$ TeV (95% CL)

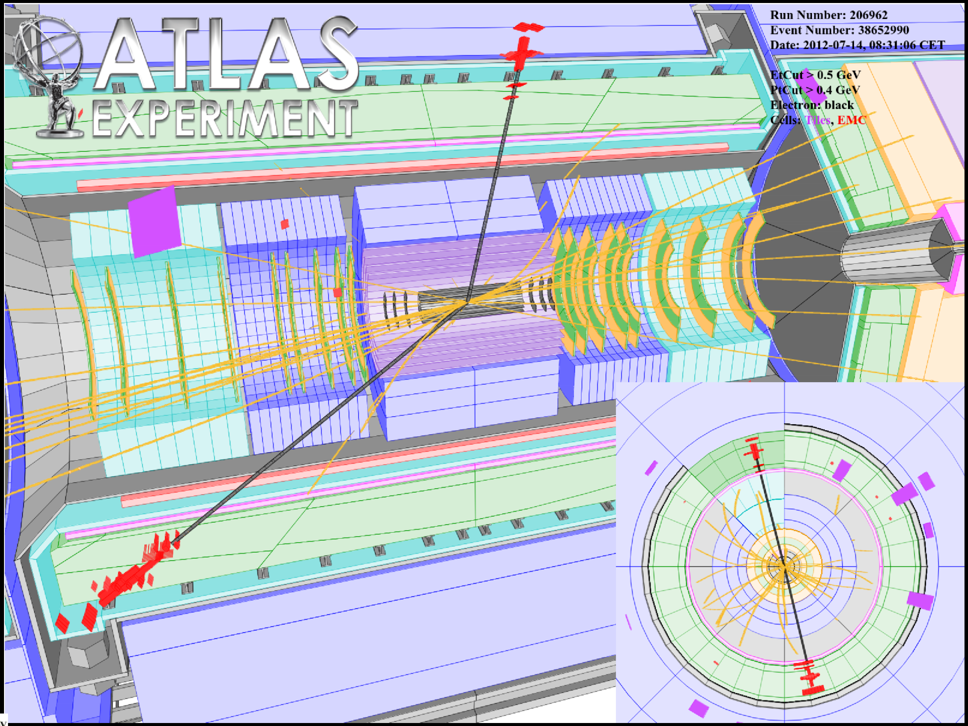




High p_T leptons

- Transverse momentum & rapidity:
  - Muon1: $p_T = 653$ GeV ; $\eta = 0.99$
  - Muon2: $p_T = 646$ GeV ; $\eta = 0.85$
- Invariant mass: $M_{\mu\mu}$=1844 GeV.





- Transverse momentum & rapidity:
  - Electron 1: $p_T = 588$ GeV ; $\eta = 1.25$
  - Electron 2: $p_T = 584$ GeV ; $\eta = -0.29$
- Invariant mass: M_{ee}=1541 GeV.

Search for Di-lepton resonances: Z’, Z*, G*, QBH,…

http://journals.aps.org/prd/pdf/10.1103/PhysRevD.90.052005

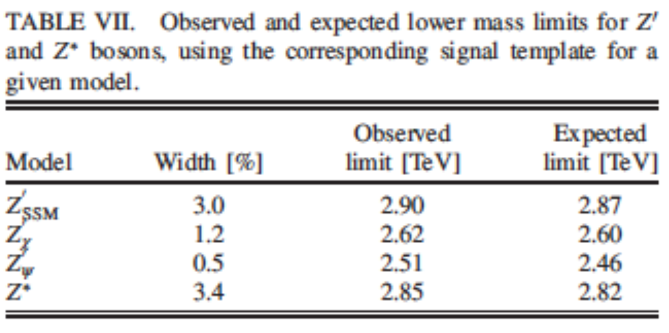


TABLE VII. Observed and expected lower mass limits for Z' and Z^* bosons, using the corresponding signal template for a given model.

Model	Width [%]	Observed limit [TeV]	Expected limit [TeV]
Z'_{SSM}	3.0	2.90	2.87
Z'_{χ}	1.2	2.62	2.60
Z'_{ψ}	0.5	2.51	2.46
Z^*	3.4	2.85	2.82

- Sequential SM
  - $M_{Z'} > 2.90$ TeV
- E_6-inspired models
  - $M_{Z'} > 2.51 – 2.62$ TeV
- $M_{Z*} > 2.85$ TeV

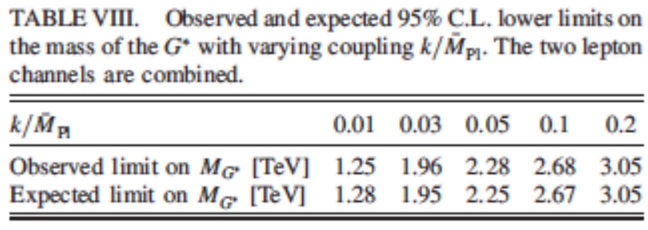
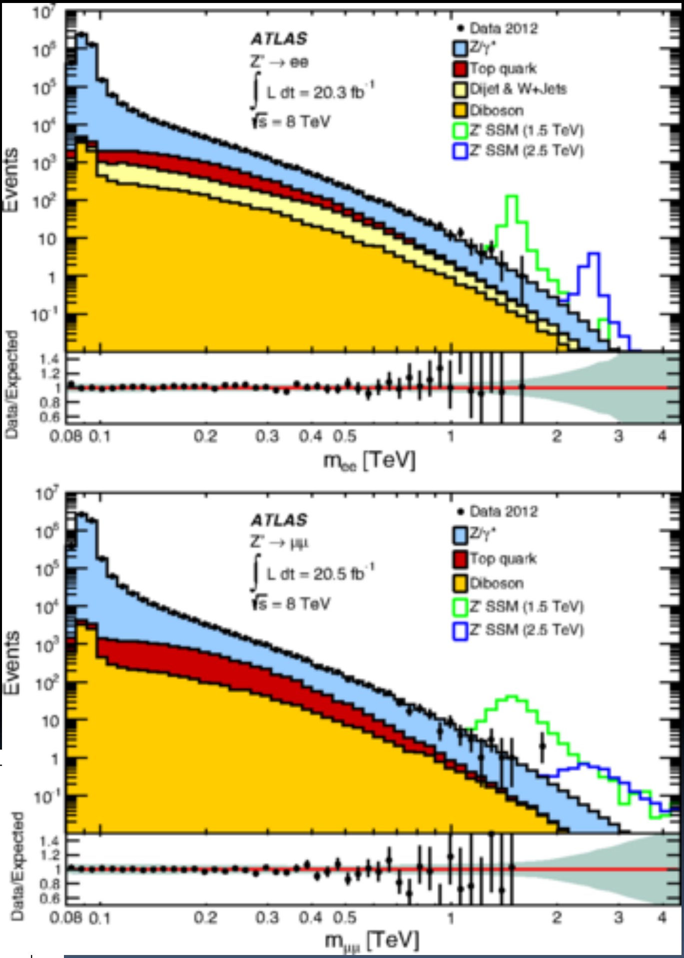
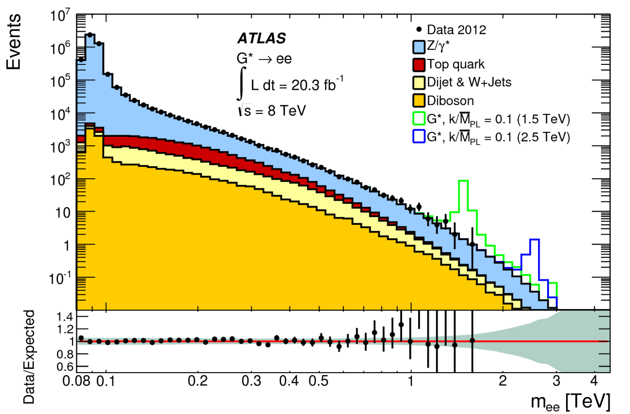


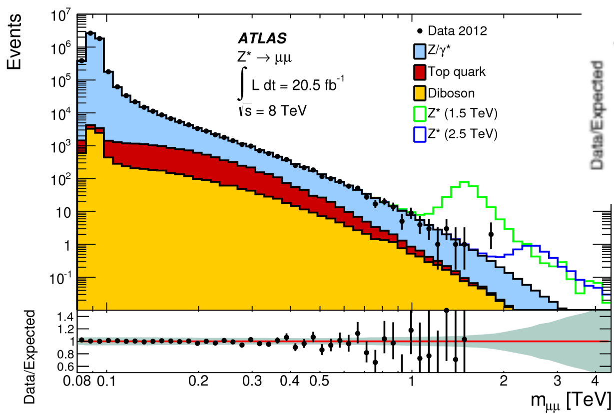
TABLE VIII. Observed and expected 95% C.L. lower limits on the mass of the G^* with varying coupling $k/\bar{M}_{Pl}$. The two lepton channels are combined.

$k/\bar{M}_{Pl}$	0.01	0.03	0.05	0.1	0.2
Observed limit on M_{G^*} [TeV]	1.25	1.96	2.28	2.68	3.05
Expected limit on M_{G^*} [TeV]	1.28	1.95	2.25	2.67	3.05

- Randall-Sundrum Graviton (extra space dimensions)
  - $M_{G*} > 2.61$ TeV (0.1)

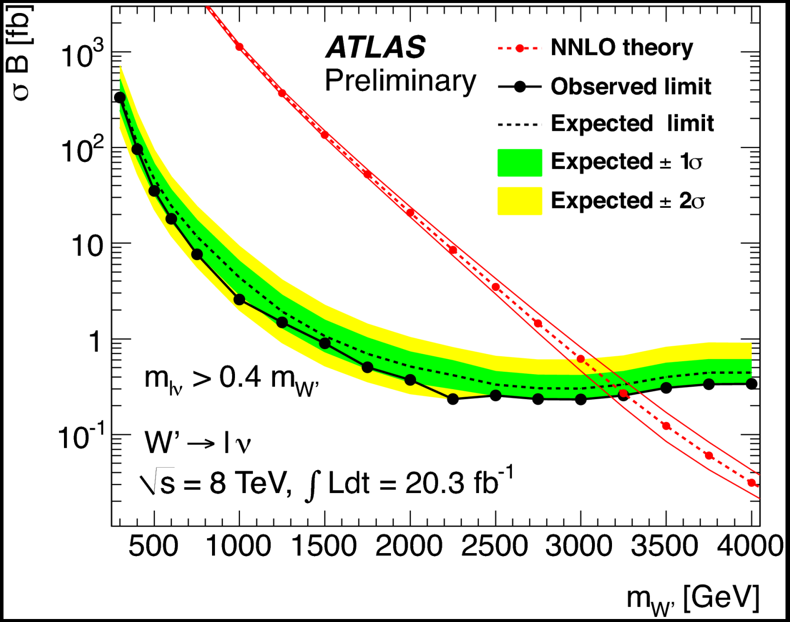






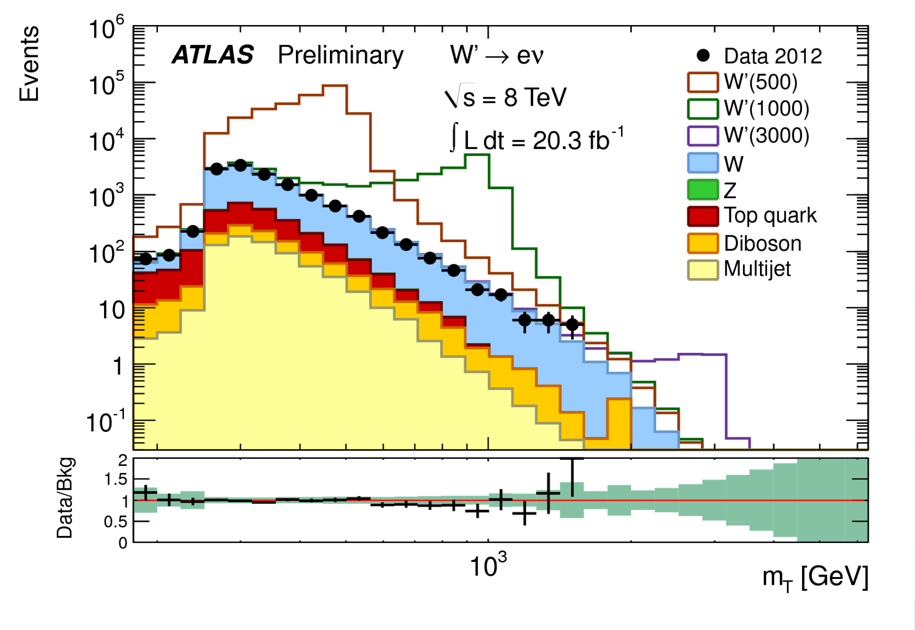
New gauge boson W'→lν

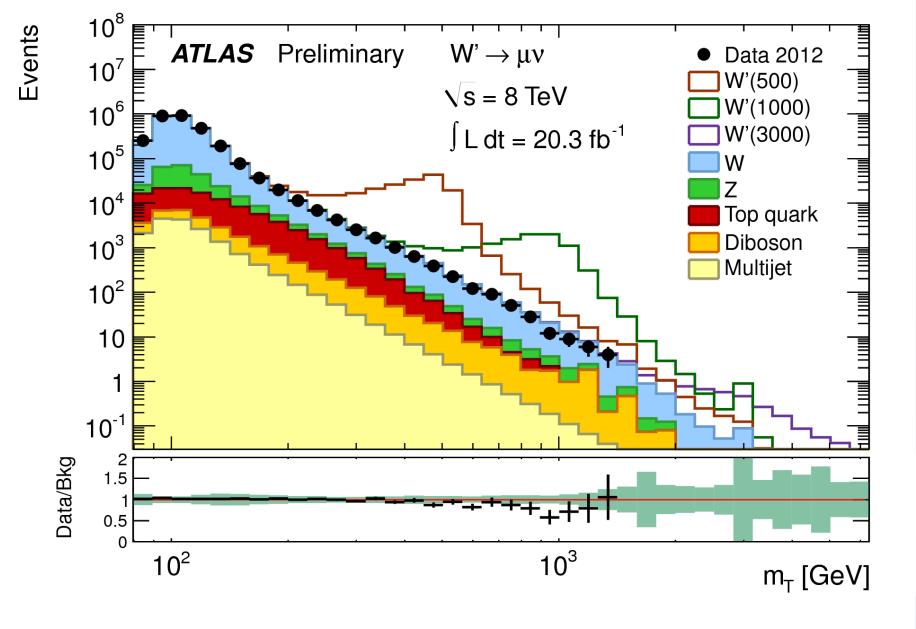
http://cds.cern.ch/record/1692660



- Limits on σB for W′ in the combination e,μ channels
- Transverse mass $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \varphi_{\ell\nu})}$

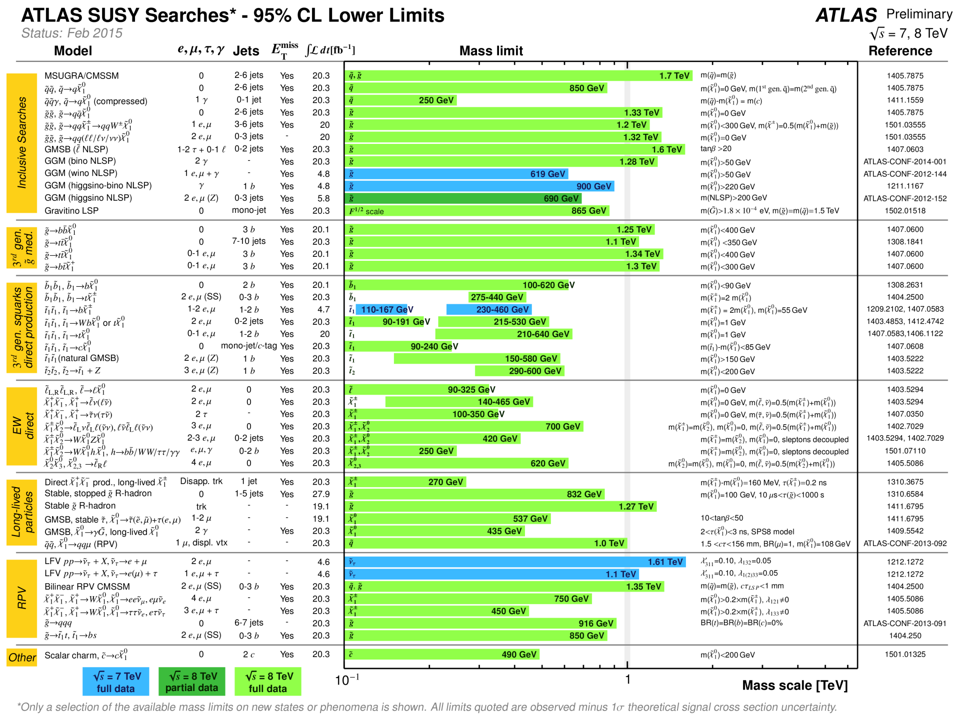
$M_{W'}$>3.27TeV M_{W*}>3.17TeV



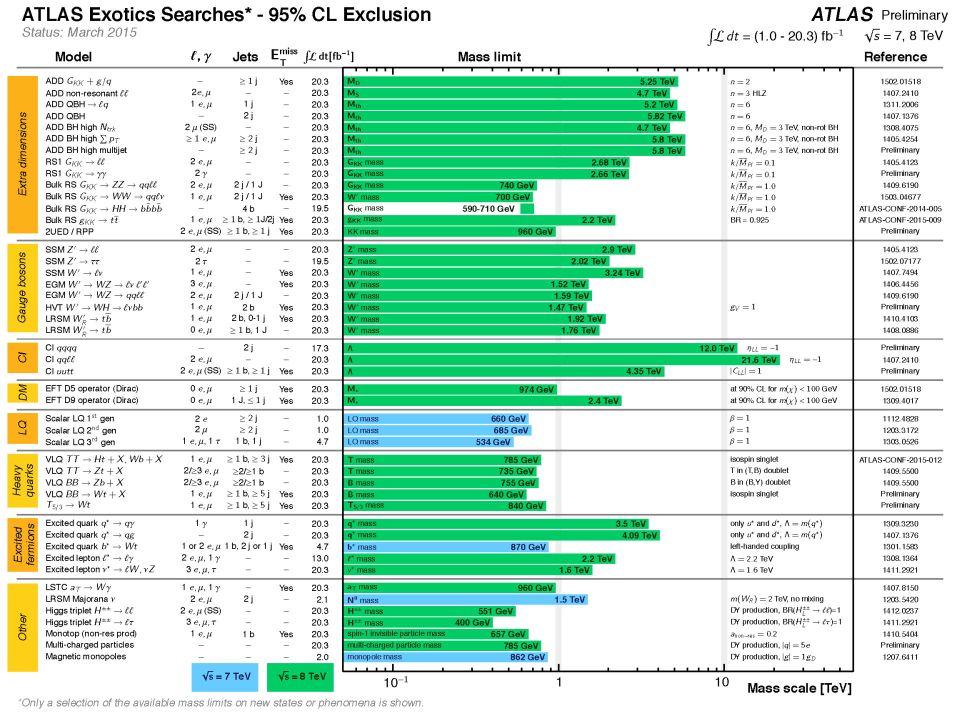


Physics of/beyond the Standard Model of EW+QCD

- Despite enormous gains in mass reach since the previous experiments, there is as yet no direct evidence for Supersymmetry or more exotic physics beyond the SM.



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



*Only a selection of the available mass limits on new states or phenomena is shown.

- However, we have collected only a few % of the data planned for the full LHC program and already in 2015 the doubling of the collision energy could yield some surprises … stay tuned

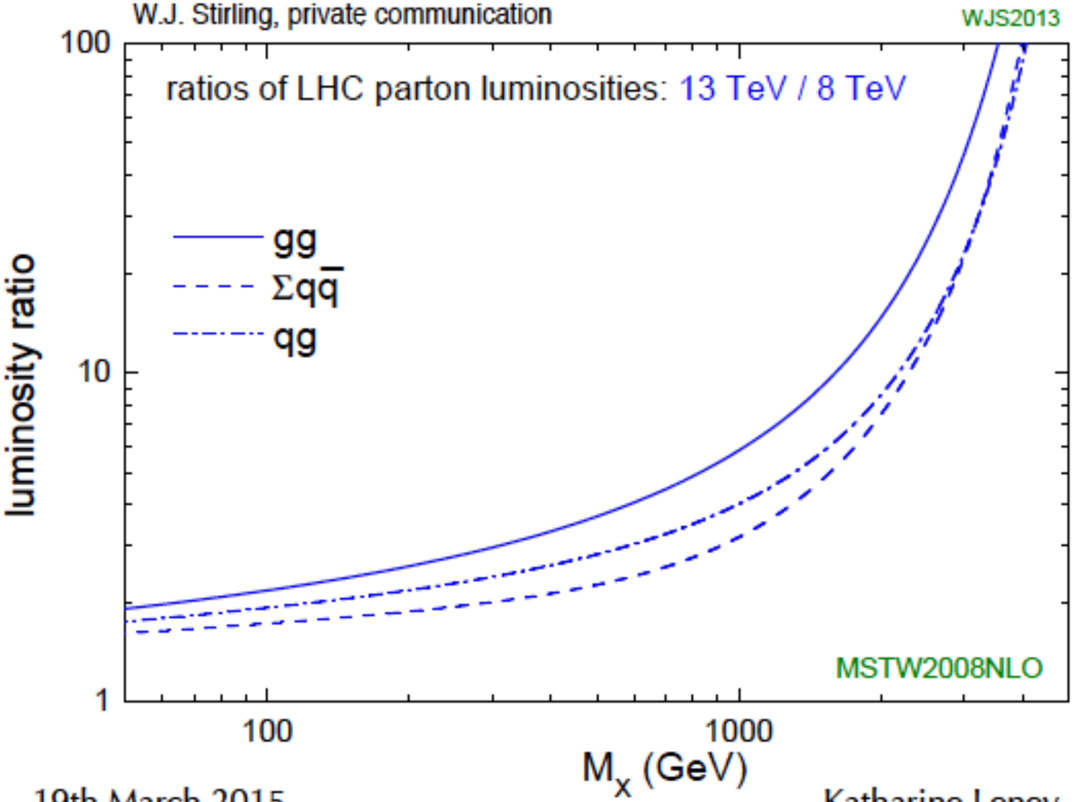
Prospects for Exotics Searches in Run 2

LHC Run 2:

2015-2018
√s = 13 TeV
100 fb^{-1}
μ = 50

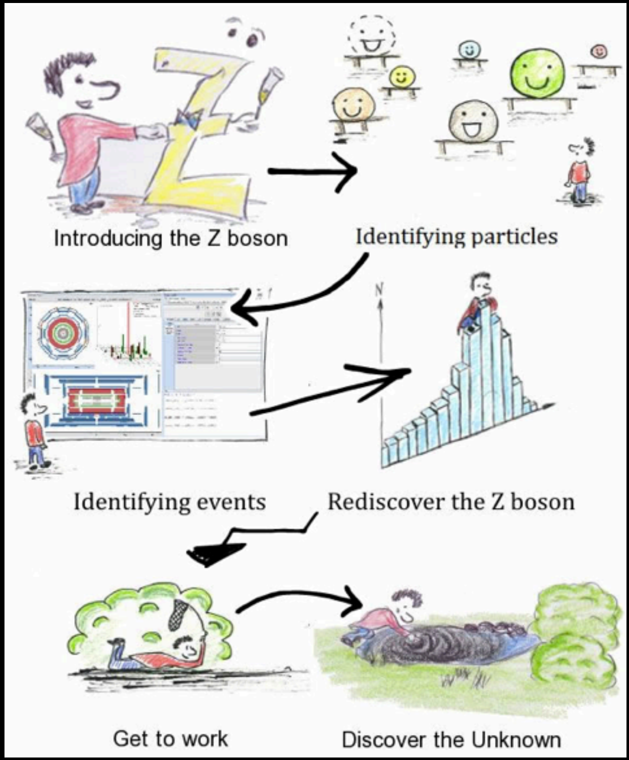
Access processes with smaller cross-sections and/or higher mass

$\frac{\sigma(\sqrt{s}=13\ \text{TeV})}{\sigma(\sqrt{s}=8\ \text{TeV})}$	gg	Σqq
M_X = 1 TeV	~6	~3.5
M_X = 2 TeV	~15	~7
M_X = 3 TeV	~50	~25
M_X = 4 TeV	~400	~100



W.J. Stirling, private communication

Is there anything beyond the Standard Model?

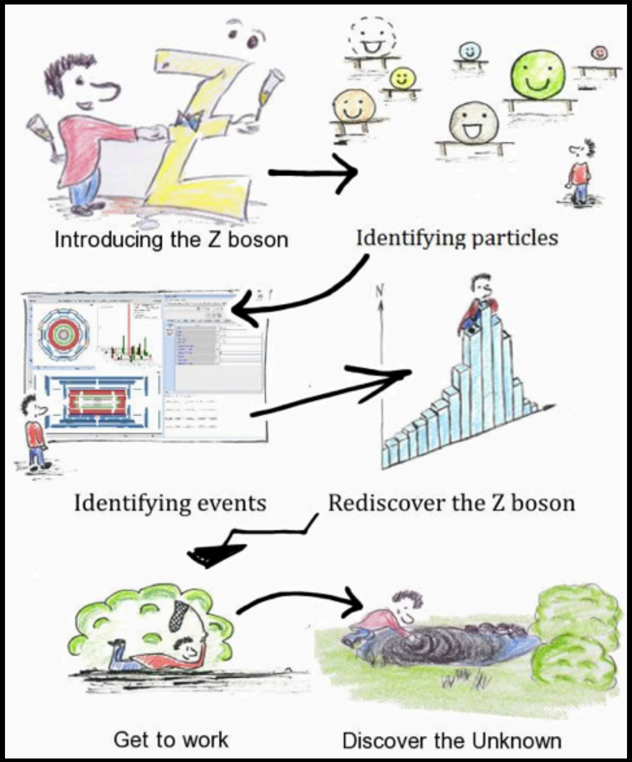


- You want to learn more?

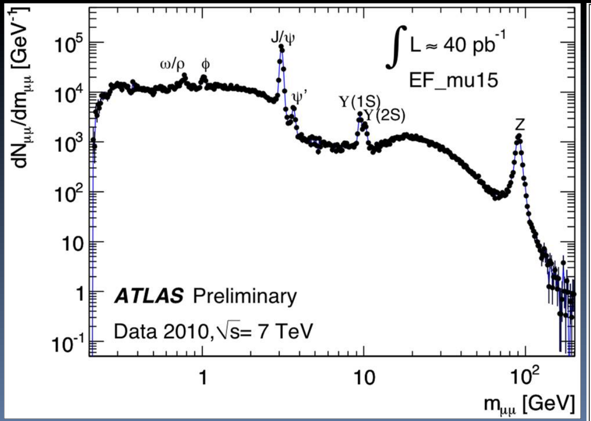
- join LHC Masterclasses
  - 2011-12: J/ψ, Υ, Z,Z′
  - 2013: +Higgs-like
  - > 2014: + Whatever-like we will discover

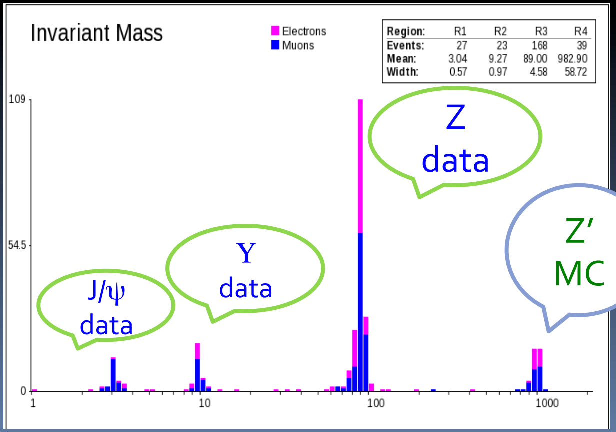
Outreach & Education

Link to Z-Path

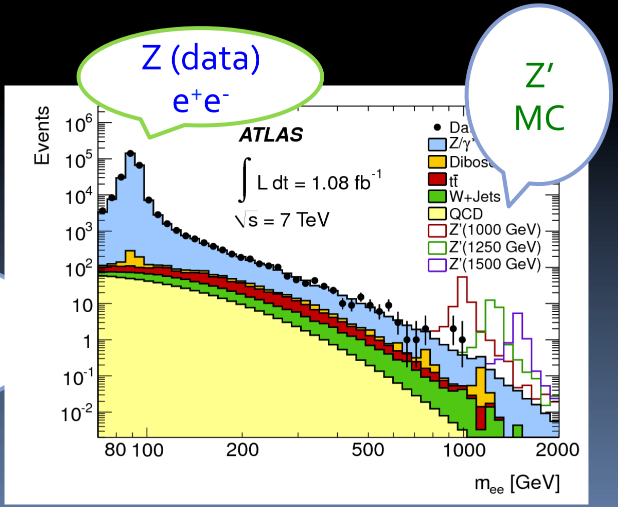


- UiO has been leading the development of educational material and methods based on fresh LHC data through the International Particle Physics Outreach Group (IPPOG).
- ATLAS Z^0 package, Invariant mass as a tool to identify known short-lived particles and discover new ones
  - allows high school students to work with real LHC data, is the most popular among all packages from LHC experiments.
  - Master classes 2012-2015: most institutes all over the world conducted the Z-path – a great success.
- Compare students results to ATLAS measurement

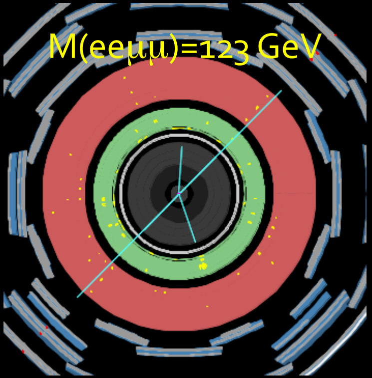




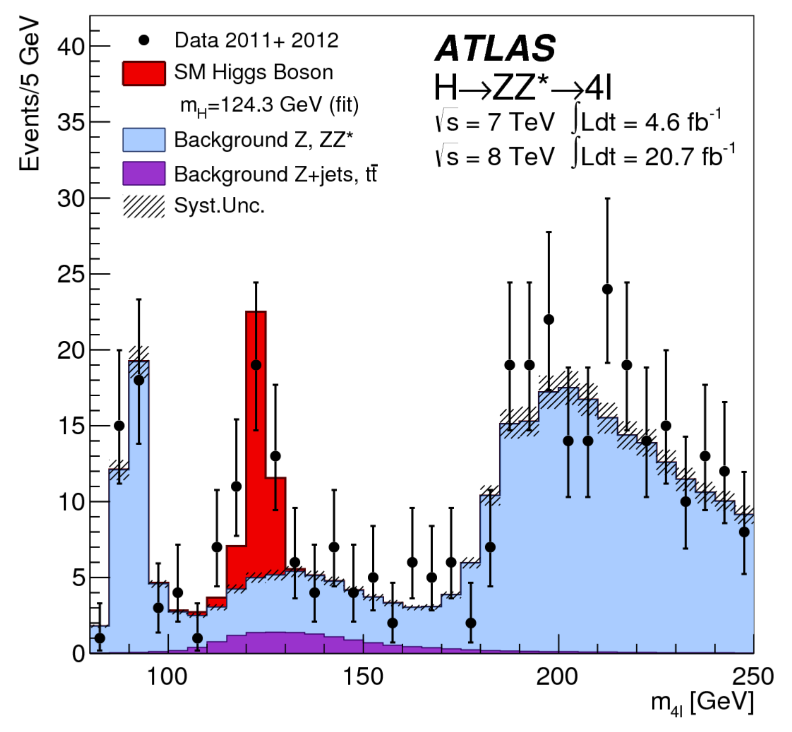
Region:	R1	R2	R3	R4
Events:	27	23	168	39
Mean:	3.04	9.27	89.00	982.90
Width:	0.57	0.97	4.58	58.72

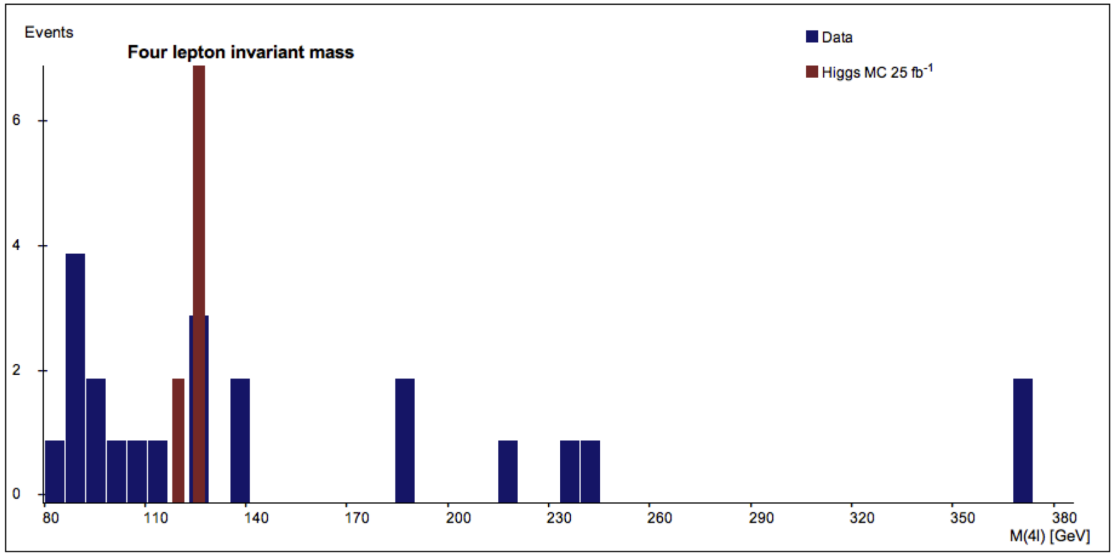


Higgs search H→4l
ATLAS vs IMC Students



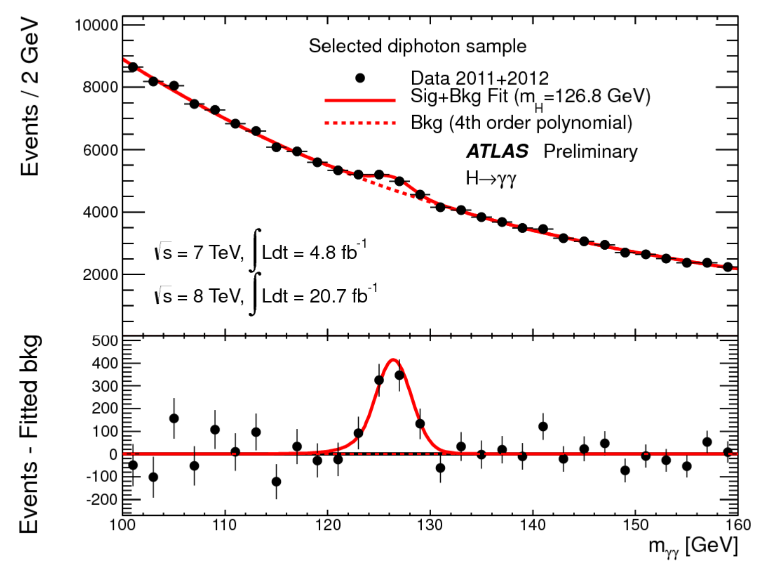
- ATLAS results
  - H→ZZ*→llll
  - 25.3 fb-1
- You have searched for Higgs
  - H→llll with 1 fb-1
- You have 2 candidates at ~125 GeV
  - 1 compatible with what ATLAS has observed
  - The other event corresponds to ZJ/ψ→4l
  - With 25 fb-1, you would see ~10 events on top of very small background

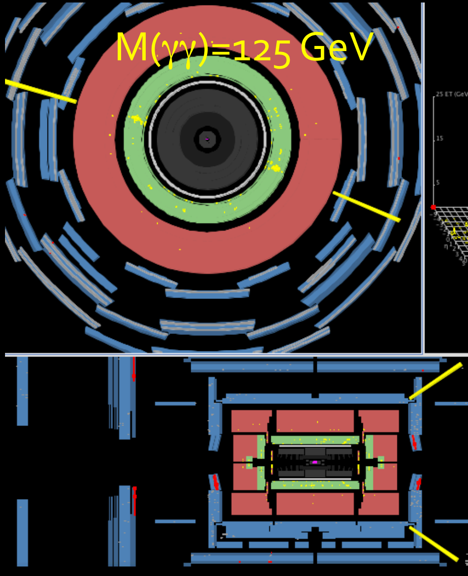




Higgs search H→γγ ATLAS vs Students

- ATLAS results: H→γγ
  - 25.5 fb-1 → clear signal

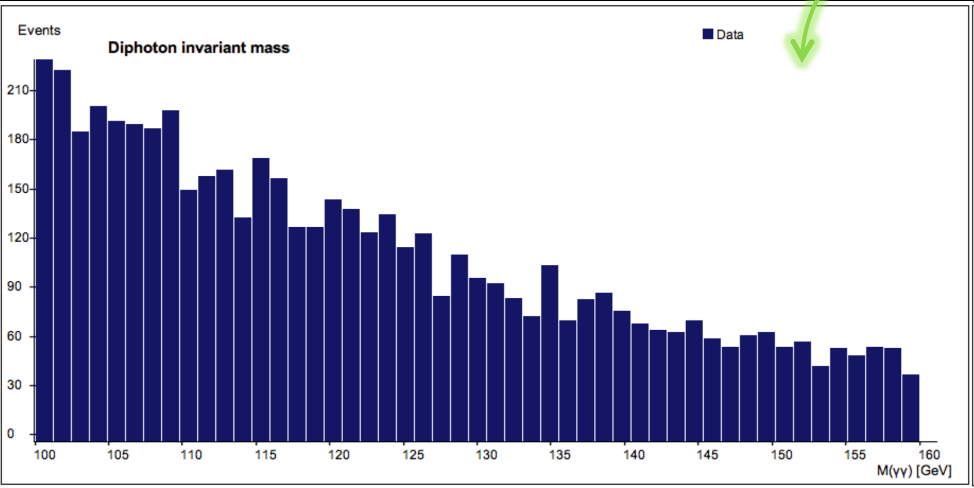


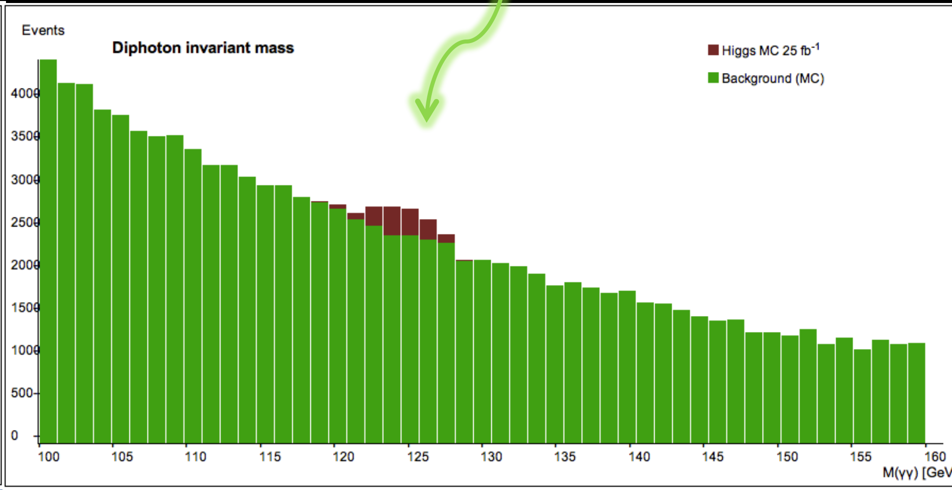


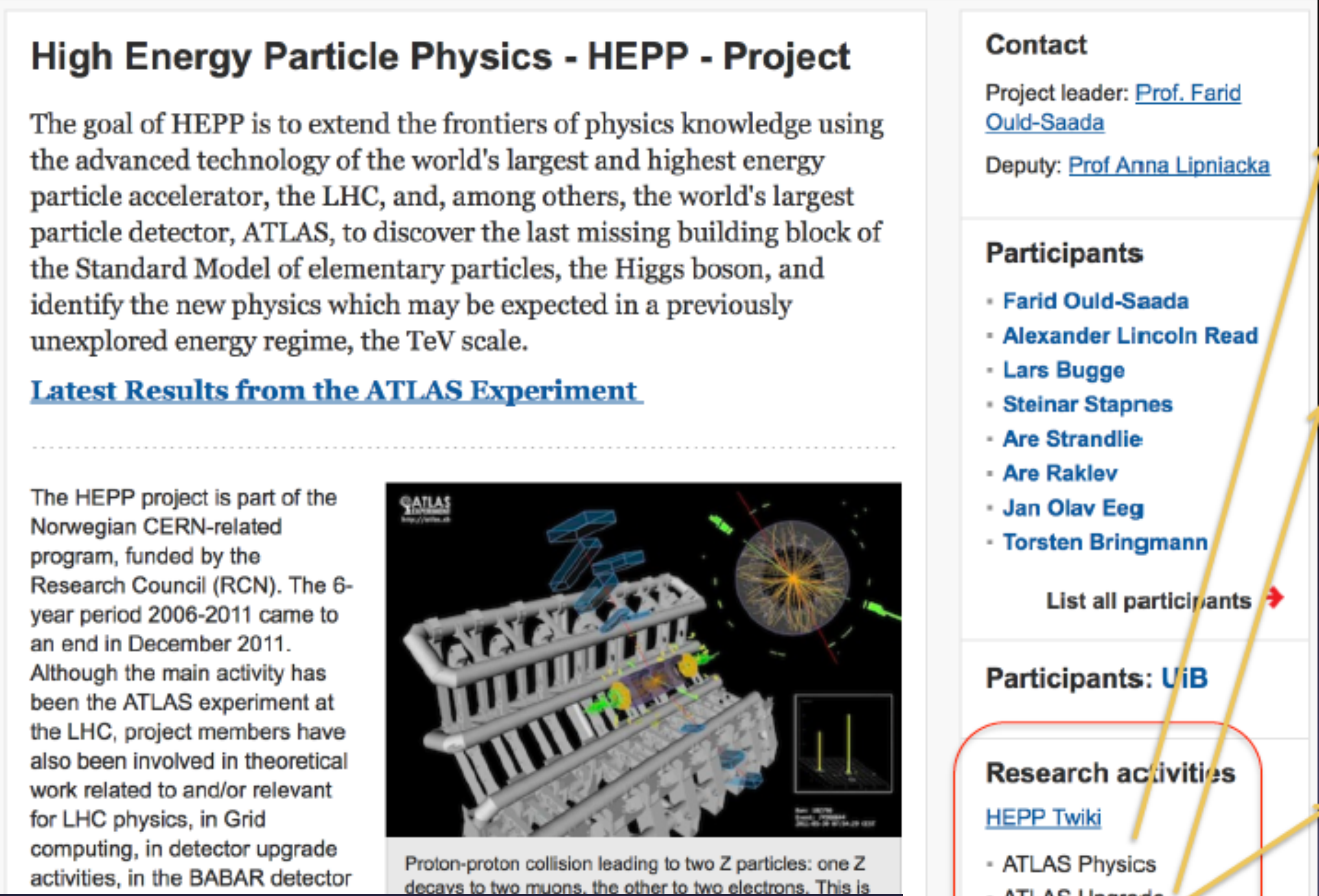
- You have searched for Higgs
  - H→γγ with 1 fb-1

You have several candidates at ~125 GeV

- You don't have enough statistics to reproduce the ATLAS result
- With 25 fb-1, you would clearly observe a signal on top of a large background.







High Energy Particle Physics - HEPP - Project

The goal of HEPP is to extend the frontiers of physics knowledge using the advanced technology of the world's largest and highest energy particle accelerator, the LHC, and, among others, the world's largest particle detector, ATLAS, to discover the last missing building block of the Standard Model of elementary particles, the Higgs boson, and identify the new physics which may be expected in a previously unexplored energy regime, the TeV scale.

Latest Results from the ATLAS Experiment

The HEPP project is part of the Norwegian CERN-related program, funded by the Research Council (RCN). The 6-year period 2006-2011 came to an end in December 2011. Although the main activity has been the ATLAS experiment at the LHC, project members have also been involved in theoretical work related to and/or relevant for LHC physics, in Grid computing, in detector upgrade activities, in the BABAR detector

Proton-proton collision leading to two Z particles: one Z decays to two muons, the other to two electrons. This is

Contact

Project leader: Prof. Farid Ould-Saada

Deputy: Prof Anna Lipniacka

Participants

- **Farid Ould-Saada**
- **Alexander Lincoln Read**
- **Lars Bugge**
- **Steinar Stapnes**
- **Are Strandlie**
- **Are Raklev**
- **Jan Olav Eeg**
- **Torsten Bringmann**

List all participants ➔

Participants: UiB

Research activities

HEPP Twiki

- ATLAS Physics
- ATLAS Upgrade
- Computing
- Theory
- Outreach

ATLAS physics
- SUSY & DM
- New forces
- New dimensions,
- Higgs

ATLAS detector R&D: Si Pixels
- Insertable B-layer
- New Inner Tracker

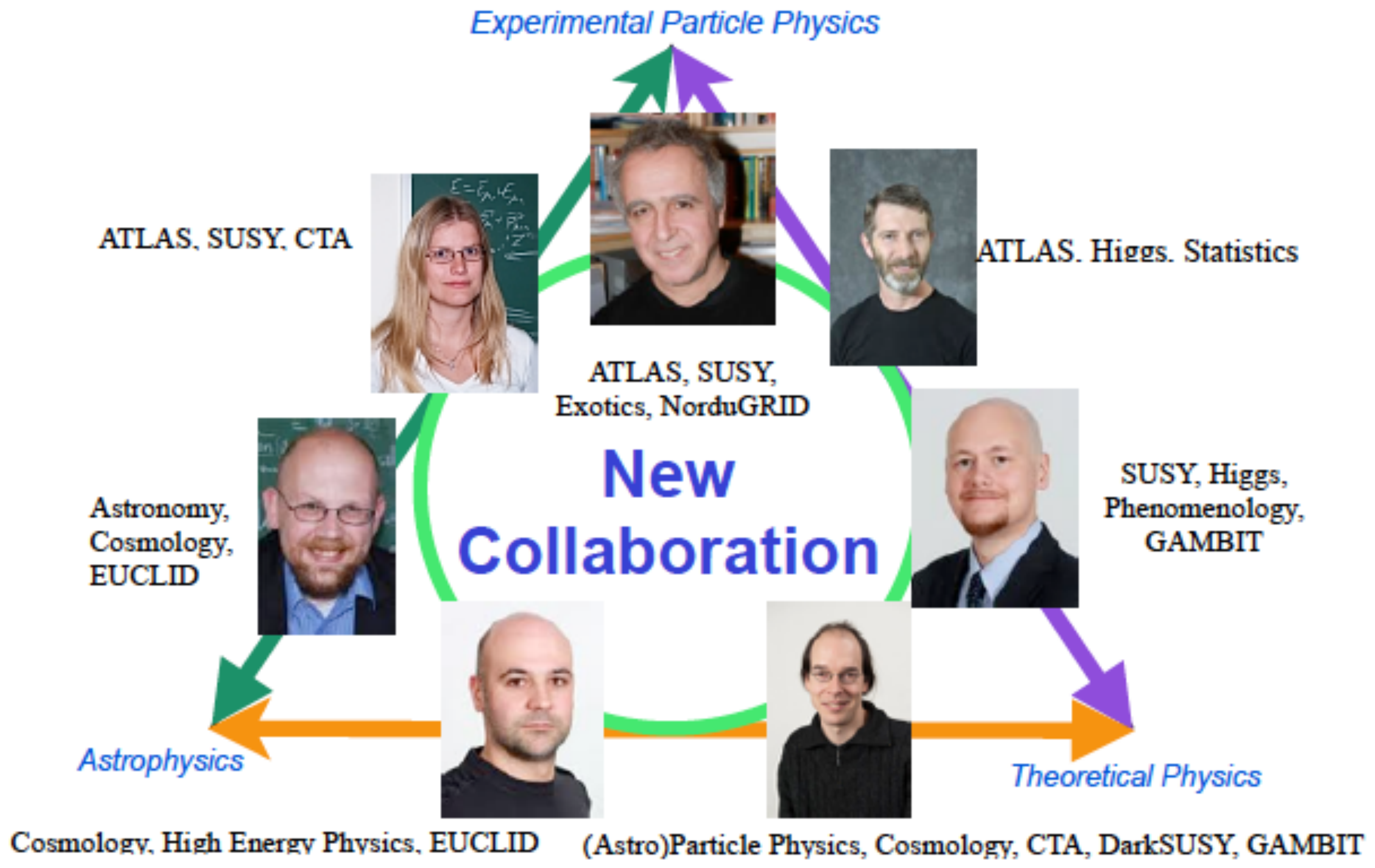
- NorduGrid ARC middleware R&D
- AtlasTier-1
- Atlas computing, software, data management, new data/analysis models, operations
- HPCs,
- Atlas@home

- IPPOG, IMC
- Education material
- Data access, preservation

Particle physics theory

Strategic Dark Matter Initiative – SDI

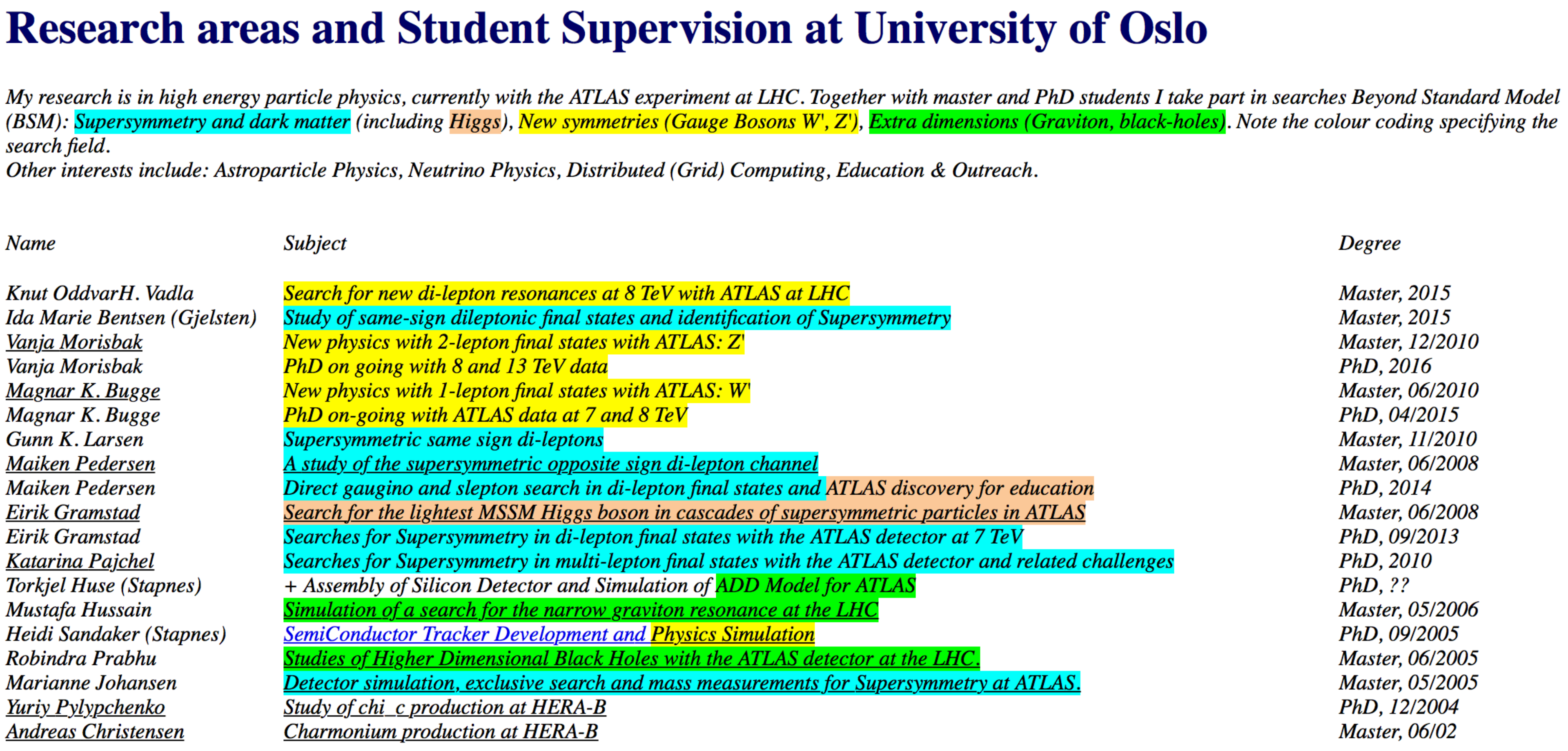
- 1 post-doc, 1 PhD (2015), 4 PhDs (2016), …
- Cross disciplinary



Recent UiO PhDs with ATLAS data

- Katarina Pajchel, "*Searches for Supersymmetry in multi-lepton final states with the ATLAS detector and related challenges*", supervisors F. Ould-Saada, L. Bugge, 2011
- Lillian Smestad, "*The Search for the Standard Model Higgs Boson in $H \to \gamma\gamma$ Decays with the ATLAS Detector in 4.9 fb^{-1} of 2011 Data at $\sqrt{s} = 7$ TeV*", supervisor A. Read, 2013
- Eirik Gramstad, "*Searches for Supersymmetry in di-lepton final states with the ATLAS detector at 7 TeV*", *supervisor F. Ould-Saada, 2013*
- Maiken Pedersen, "*Direct gaugino and slepton search in di-lepton final states and ATLAS discovery for education*", *supervisor F. Ould-Saada, 2014*
- Magnar Bugge, "*Search for new charged bosons and dark matter in final states with one lepton and missing transverse energy with the ATLAS detector at the LHC*", supervisor F. Ould-Saada, 30.4.2015

My research field –
examples of master and phd subjets



Research areas and Student Supervision at University of Oslo

My research is in high energy particle physics, currently with the ATLAS experiment at LHC. Together with master and PhD students I take part in searches Beyond Standard Model (BSM): Supersymmetry and dark matter (including Higgs), New symmetries (Gauge Bosons W', Z'), Extra dimensions (Graviton, black-holes). Note the colour coding specifying the search field.
Other interests include: Astroparticle Physics, Neutrino Physics, Distributed (Grid) Computing, Education & Outreach.

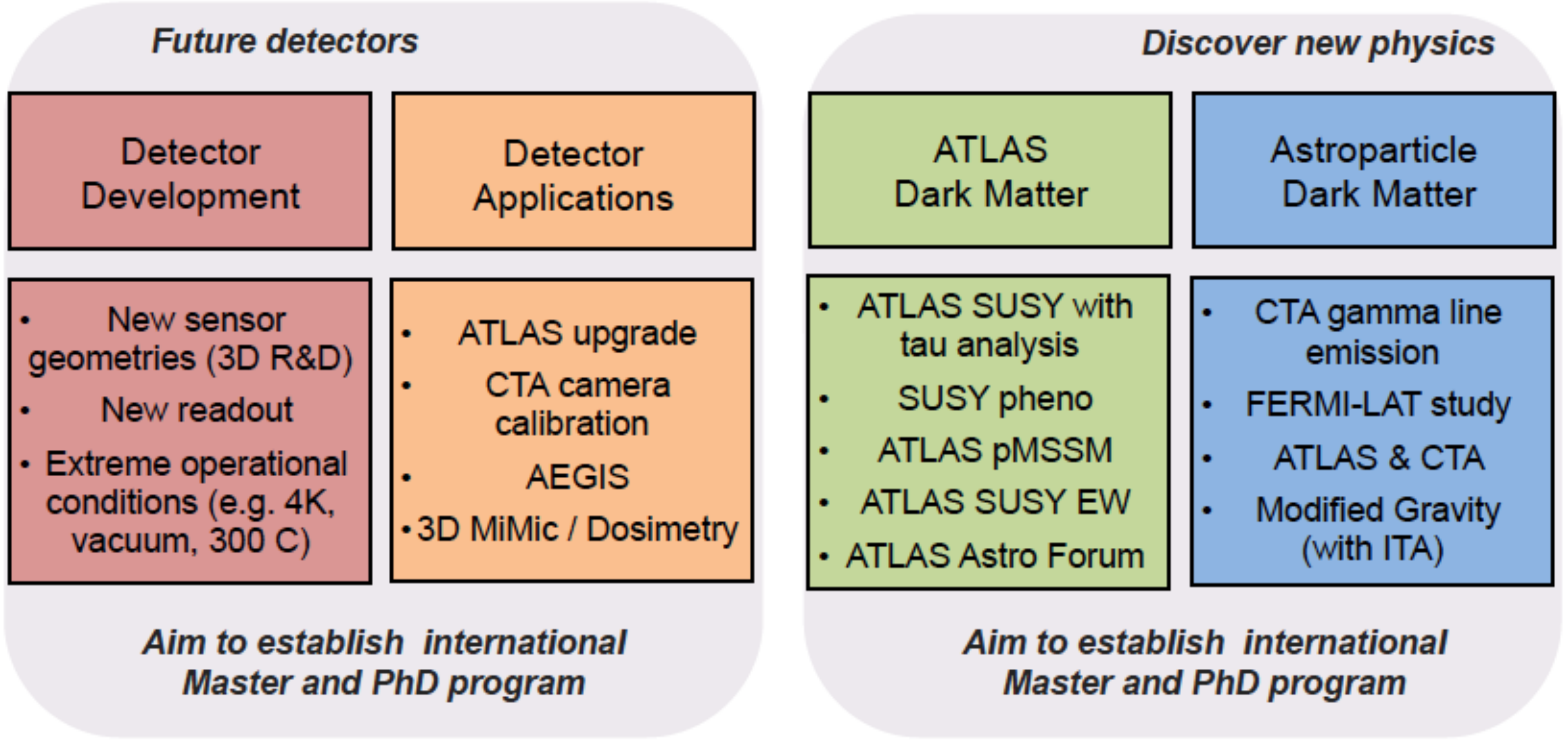
Name	*Subject*	*Degree*
Knut OddvarH. Vadla	*Search for new di-lepton resonances at 8 TeV with ATLAS at LHC*	*Master, 2015*
Ida Marie Bentsen (Gjelsten)	*Study of same-sign dileptonic final states and identification of Supersymmetry*	*Master, 2015*
Vanja Morisbak	*New physics with 2-lepton final states with ATLAS: Z'*	*Master, 12/2010*
Vanja Morisbak	*PhD on going with 8 and 13 TeV data*	*PhD, 2016*
Magnar K. Bugge	*New physics with 1-lepton final states with ATLAS: W'*	*Master, 06/2010*
Magnar K. Bugge	*PhD on-going with ATLAS data at 7 and 8 TeV*	*PhD, 04/2015*
Gunn K. Larsen	*Supersymmetric same sign di-leptons*	*Master, 11/2010*
Maiken Pedersen	*A study of the supersymmetric opposite sign di-lepton channel*	*Master, 06/2008*
Maiken Pedersen	*Direct gaugino and slepton search in di-lepton final states and ATLAS discovery for education*	*PhD, 2014*
Eirik Gramstad	*Search for the lightest MSSM Higgs boson in cascades of supersymmetric particles in ATLAS*	*Master, 06/2008*
Eirik Gramstad	*Searches for Supersymmetry in di-lepton final states with the ATLAS detector at 7 TeV*	*PhD, 09/2013*
Katarina Pajchel	*Searches for Supersymmetry in multi-lepton final states with the ATLAS detector and related challenges*	*PhD, 2010*
Torkjel Huse (Stapnes)	*+ Assembly of Silicon Detector and Simulation of ADD Model for ATLAS*	*PhD, ??*
Mustafa Hussain	*Simulation of a search for the narrow graviton resonance at the LHC*	*Master, 05/2006*
Heidi Sandaker (Stapnes)	*SemiConductor Tracker Development and Physics Simulation*	*PhD, 09/2005*
Robindra Prabhu	*Studies of Higher Dimensional Black Holes with the ATLAS detector at the LHC.*	*Master, 06/2005*
Marianne Johansen	*Detector simulation, exclusive search and mass measurements for Supersymmetry at ATLAS.*	*Master, 05/2005*
Yuriy Pylypchenko	*Study of chi_c production at HERA-B*	*PhD, 12/2004*
Andreas Christensen	*Charmonium production at HERA-B*	*Master, 06/02*

Possible Master subjects within ATLAS

Contact: Prof. Farid Ould-Saada, FØ377, Farid.Ould-Saada@fys.uio.no

- *Searches for Supersymmetry, Dark matter and beyond Standard Model Higgs. The studies include a search optimization, analysis of ATLAS data at 13 & 14 TeV and interpretation of results, also in the context of astro-particle physics.*
- *Search for new fundamental forces mediated by new gauge bosons: Study and implementation of various theories beyond the Standard Model and analysis of ATLAS data at 13 & 14TeV.*
- *Search for signatures of gravity at the LHC with ATLAS: new space dimensions, gravitons and Black Holes. Study and implementation of various theories beyond the Standard Model and analysis of ATLAS data at 13 & 14TeV.*
- *Model independent searches for new physics in final states with leptons with the ATLAS detector at the LHC. The work consists at looking for and quantifying deviations to Standard Model predictions and at measuring the properties of any new observed particle: measure mass and width, infer spin and possibly parity and charge conjugation quantum numbers from the measured angular distributions in the center of mass of the resonance.*
- *Higgs boson studies and measurement of its properties.*
- *Distributed computing for data intensive science at the exascale, distributed data management and Middleware development; development of new computing software tools and data models.*
- *Development of educational material based on ATLAS data and discoveries. The target consists of high-school as well as university students.*
- *Development, test and commissioning of silicon pixel detectors for the ATLAS detector upgrade*

More CERN-related particle/astro-particle physics theses



Future detectors

Detector Development

- New sensor geometries (3D R&D)
- New readout
- Extreme operational conditions (e.g. 4K, vacuum, 300 C)

Detector Applications

- ATLAS upgrade
- CTA camera calibration
- AEGIS
- 3D MiMic / Dosimetry

Aim to establish international Master and PhD program

Discover new physics

ATLAS Dark Matter

- ATLAS SUSY with tau analysis
- SUSY pheno
- ATLAS pMSSM
- ATLAS SUSY EW
- ATLAS Astro Forum

Astroparticle Dark Matter

- CTA gamma line emission
- FERMI-LAT study
- ATLAS & CTA
- Modified Gravity (with ITA)

Aim to establish international Master and PhD program

UiO/HEPP @ ATLAS

- SCT, 3D-pixels, silison sensors
  - New pixel layer, 3D-pixel R&D in prep of New tracker
- Computing, Grid, New software developments
- Super-symmetry
  - Sleptons: super partners of leptons
  - Gauginos: super partners of gauge bosons & Higgs
  - SUSY phenomenology
  - Supersymmetric Higgs
- Exotic particles
  - New gauge bosons, including superstring-inspired
  - : $Z' \rightarrow ll$, $W' \rightarrow l\nu$, Z^*, W^*
  - New space dimensions: Graviton: $G^* \rightarrow ll$, Blackholes
  - Independent search for new phenomena
  - SM and New physics for education
  - …
- Higgs
  - $H \rightarrow \gamma\gamma$ channel
  - Charged Higgs search
  - Higgs for education
- Outreach & Education

Just in case you might be interested ☺