Highlights from the LHC Physics Experiments – ‘Unravelling the secrets of the Universe’

Richard Hawkings (CERN)

OPAC Topical Workshop, 27/6/2013

- The LHC experiments and their workings
- Exploring the Standard Model
- The story of the Higgs
  - From the beginning to 4th July 2012
  - What we have done in the last year
- What next – supersymmetry (SUSY) and/or more?
- Conclusions

  - **Disclaimer**: Mainly concentrating on the physics program of ATLAS and CMS, and using more ATLAS results for illustration …
  - http://atlas.ch/ , http://cms.web.cern.ch/org/cms-public

Experiments at the LHC

- 4 large detectors in caverns ~ 100m underground

ATLAS and CMS

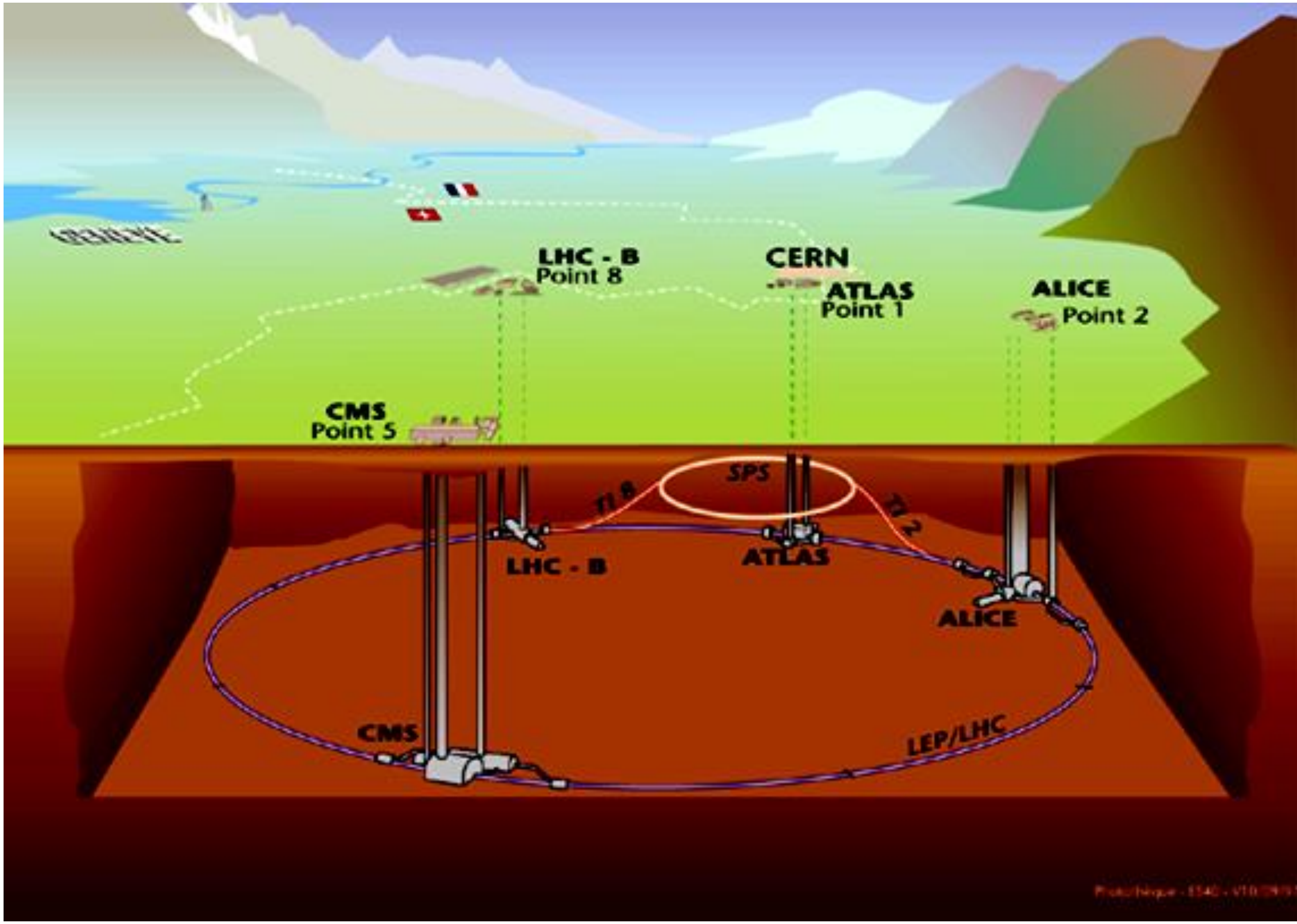
- General purpose detectors for discovery and precision SM measurements
- Similar physics goals, complementary designs

LHCb

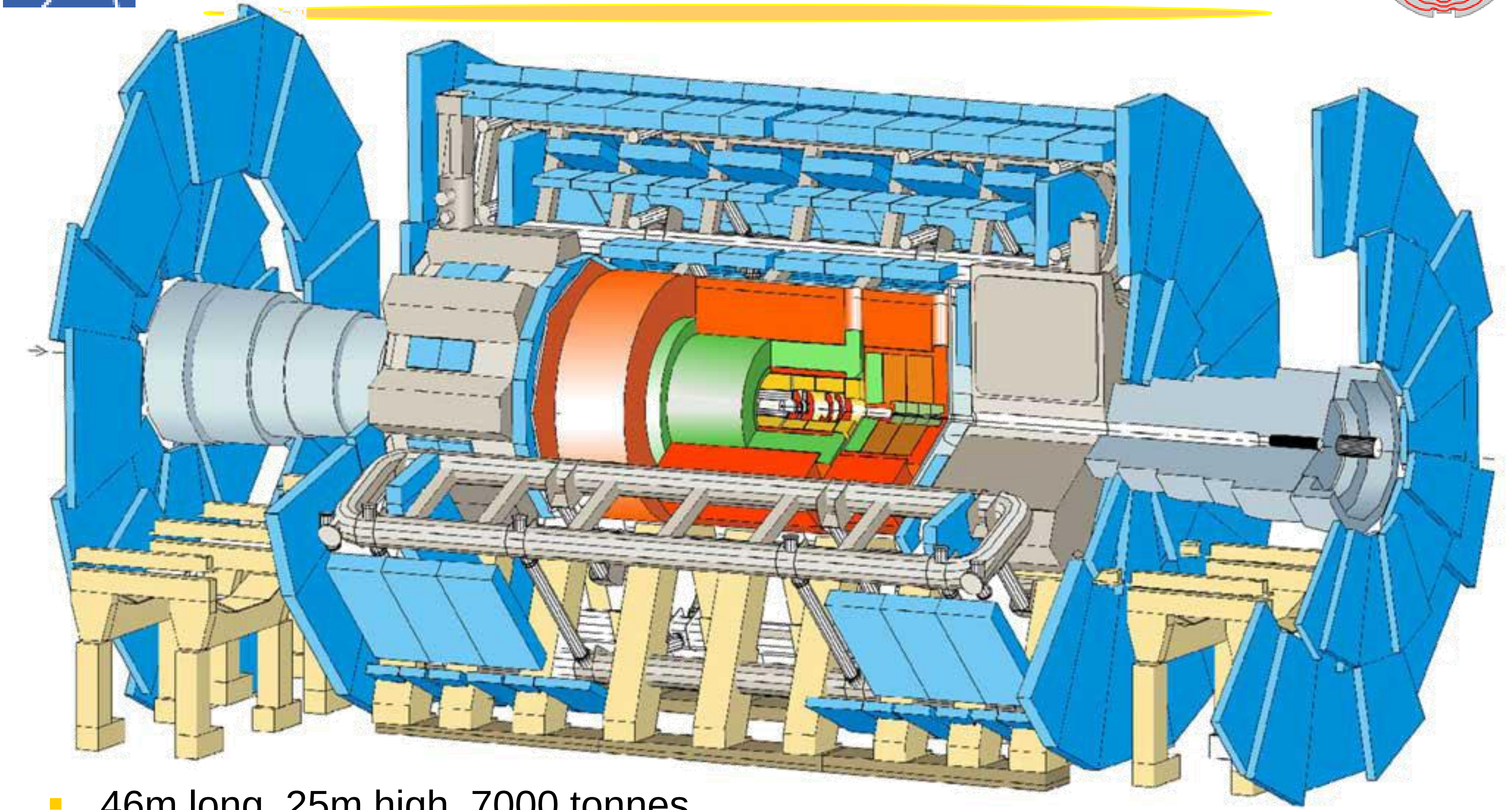
- Specialist detector for flavour physics (e.g. CP violation)

ALICE

- Specialist experiment for heavy-ion physics
- Pb+Pb in 2010,11
- Pb+p in early 2013

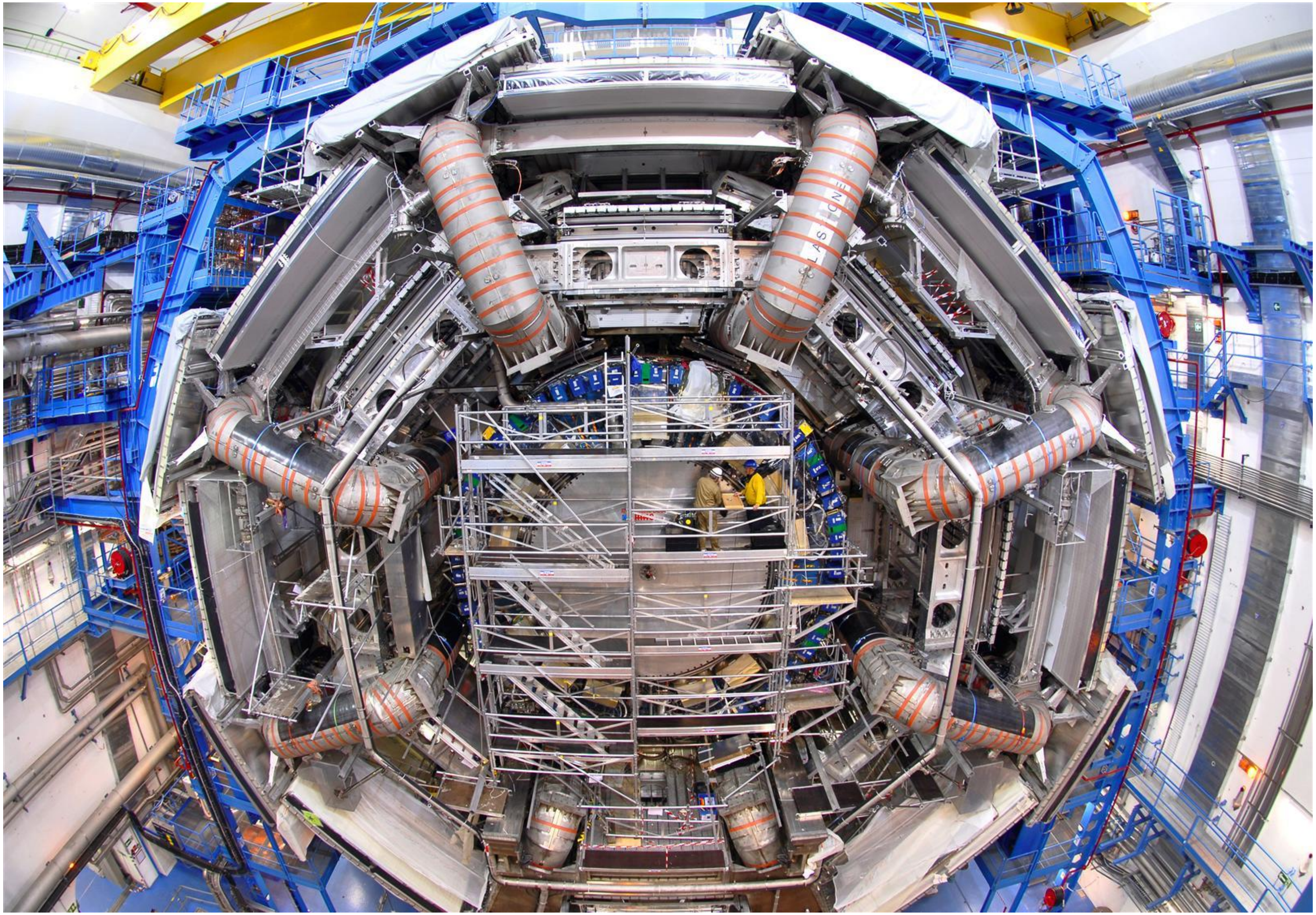


The ATLAS detector

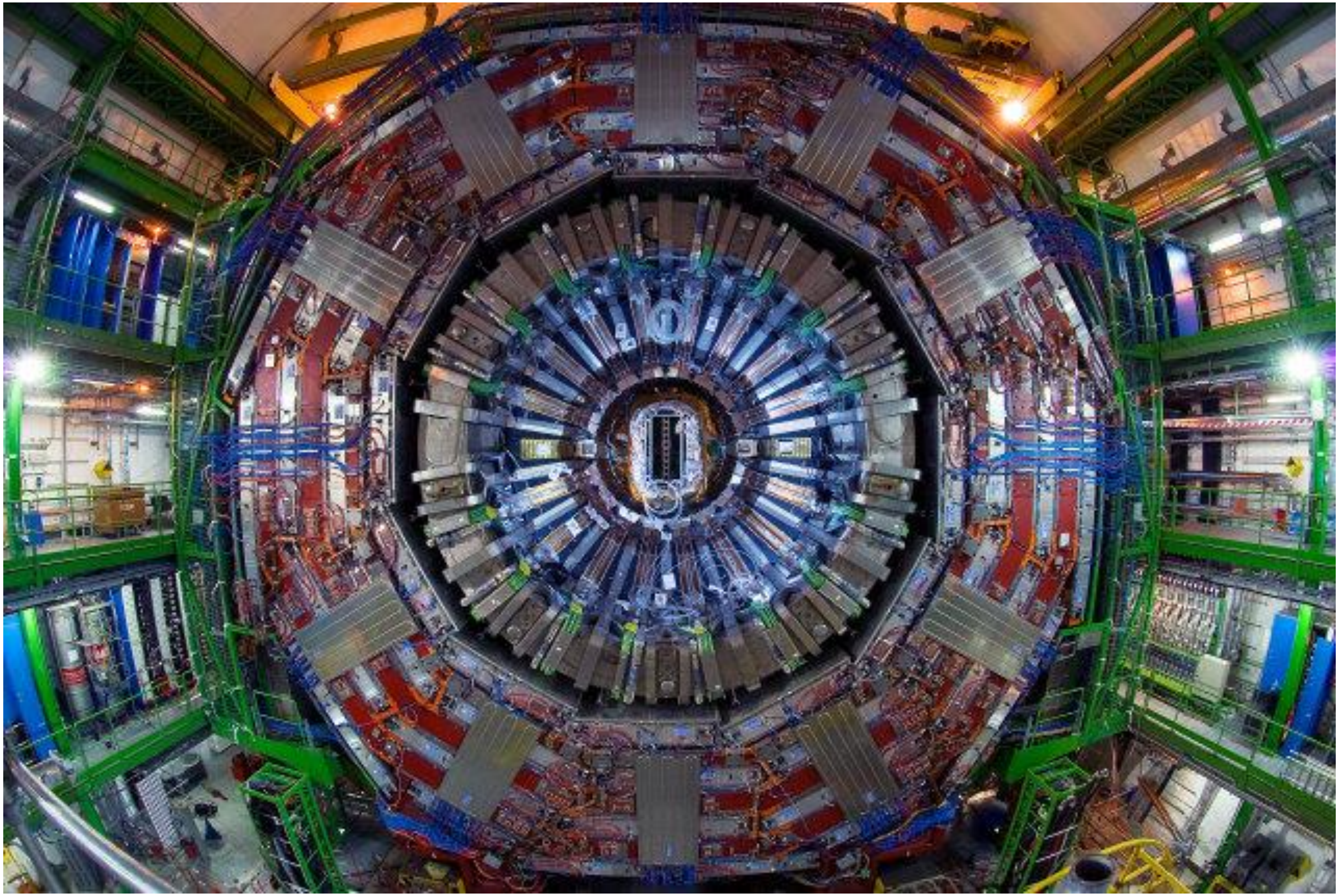


- 46m long, 25m high, 7000 tonnes
  - Surrounding the collision point as far as possible …

The ATLAS cavern is crowded…

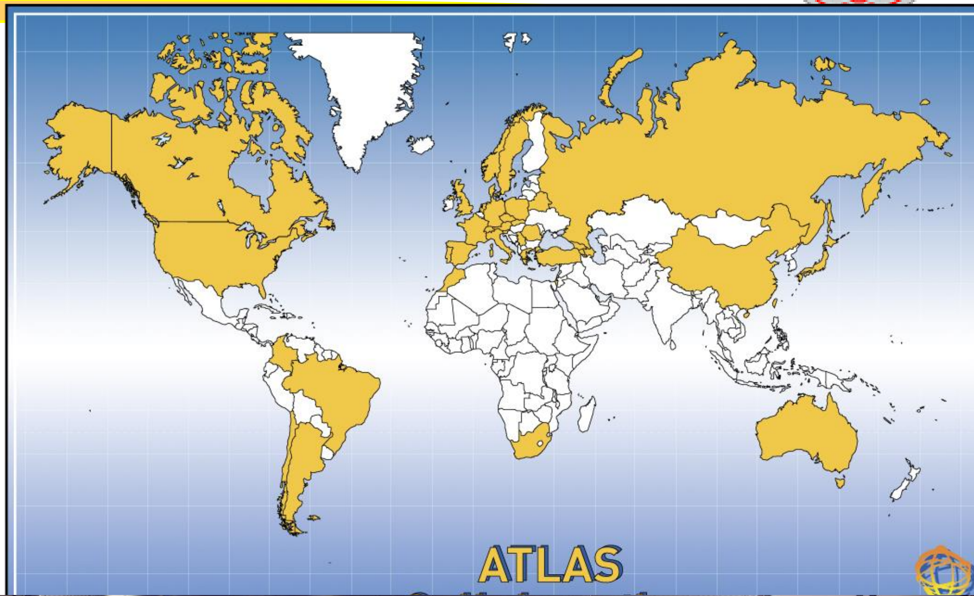


So is the CMS cavern



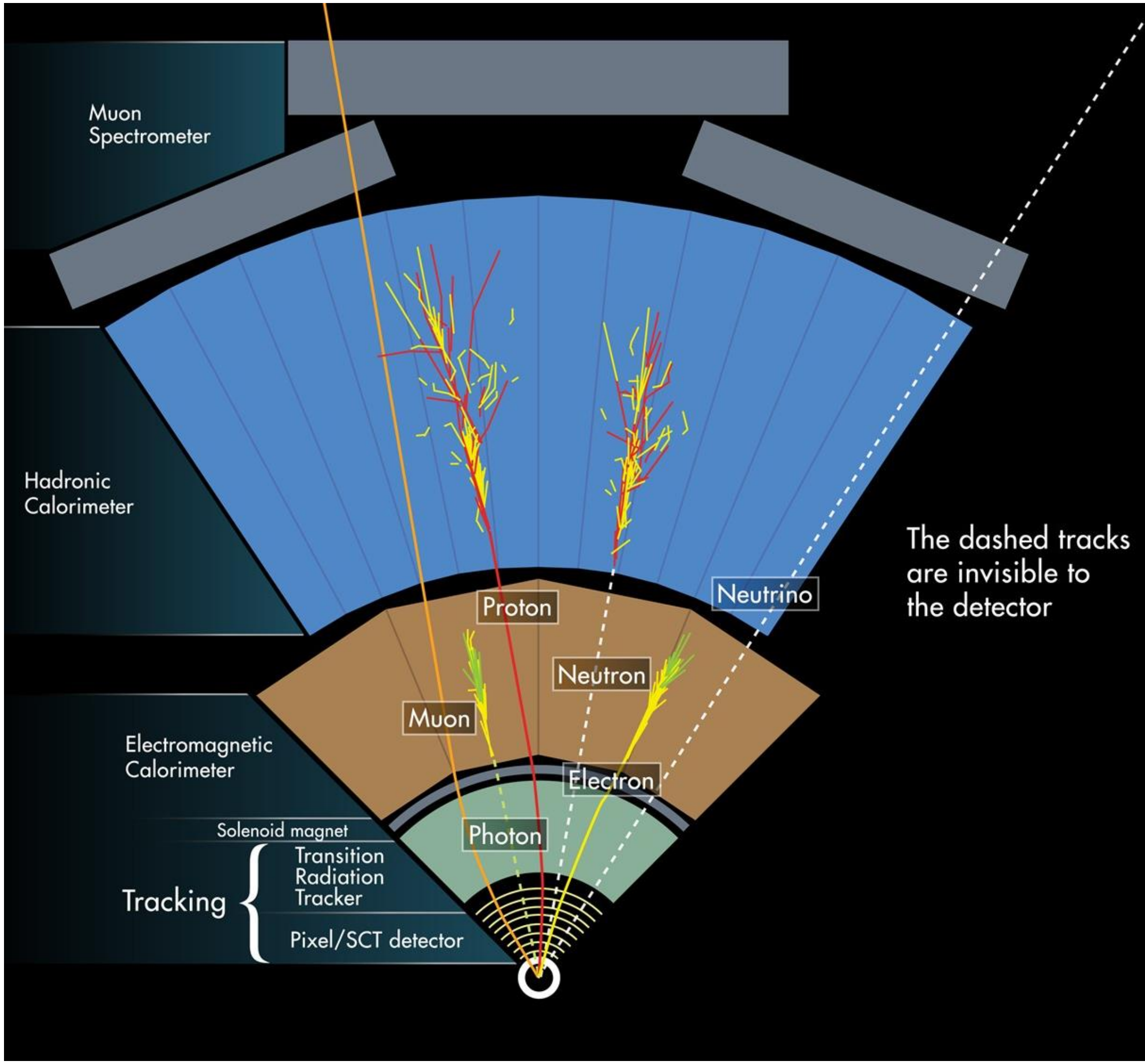
Experiments are worldwide collaborations

- ATLAS and CMS each have ~3000 people, ~200 institutes
  - Physicists, engineers, technicians, computer scientists, support staff



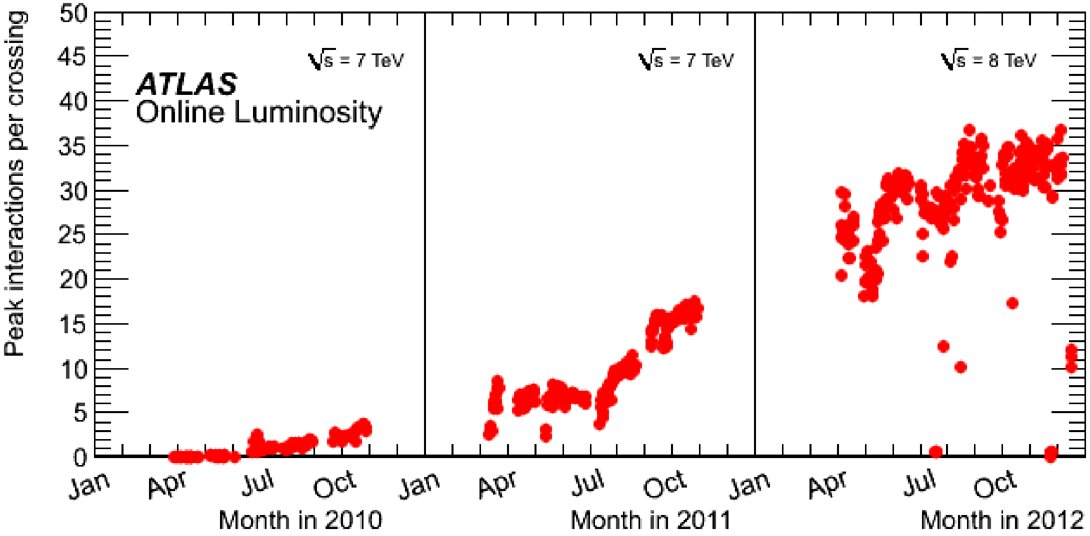
An LHC detector (ATLAS)

- Detector built in layers:
  - Measure as much as possible about particles in each collision
    - Type, energy and direction
  - Tracking, EM/hadronic calorimeters and muon detectors
- Different particles' interactions:
  - **Electron**: track and EM shower
  - **Photon**: no track, EM shower
  - **Proton, pion**: track, small EM shower, large hadronic shower
  - **Muon**: track, little in EM/hadronic calorimeter, external track
  - **Neutrino**: nothing!
    - Infer from the 'balance' of everything else

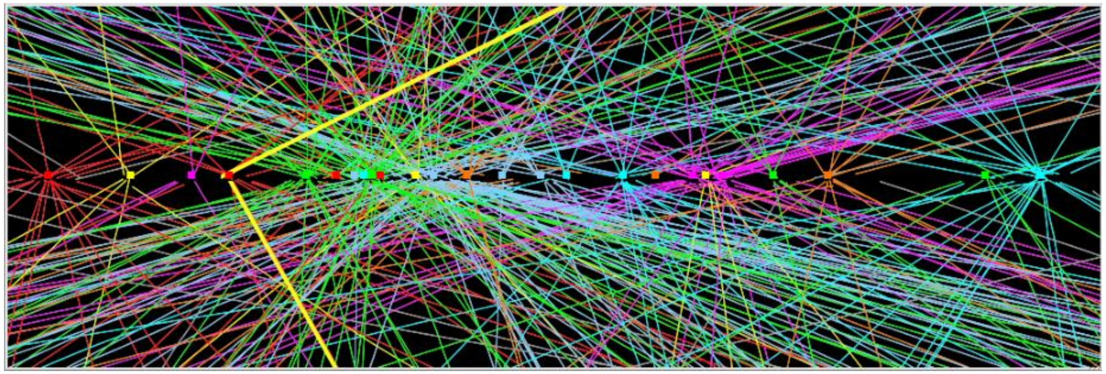


The challenge to the detectors

- LHC luminosity up to 7 10^{33} $cm^{-2}s^{-1}$
  - Bunches of up to ~1.6 10^{11} protons, spaced by 50ns
  - Up to ~35 pp interactions per bunch crossing at start of fill in 2012
    - Like looking for a needle in a haystack … new haystacks every 50ns
- Most of these interactions are ‘soft’ and uninteresting
  - But produce a background of 1000s of tracks and soft energy deposits overlaid on the interesting collision
  - Degrades measurement resolution
- Harsh radiation environment
  - Type inversion in silicon sensors
  - Eventual activation of detectors
  - Neutron background and SEU



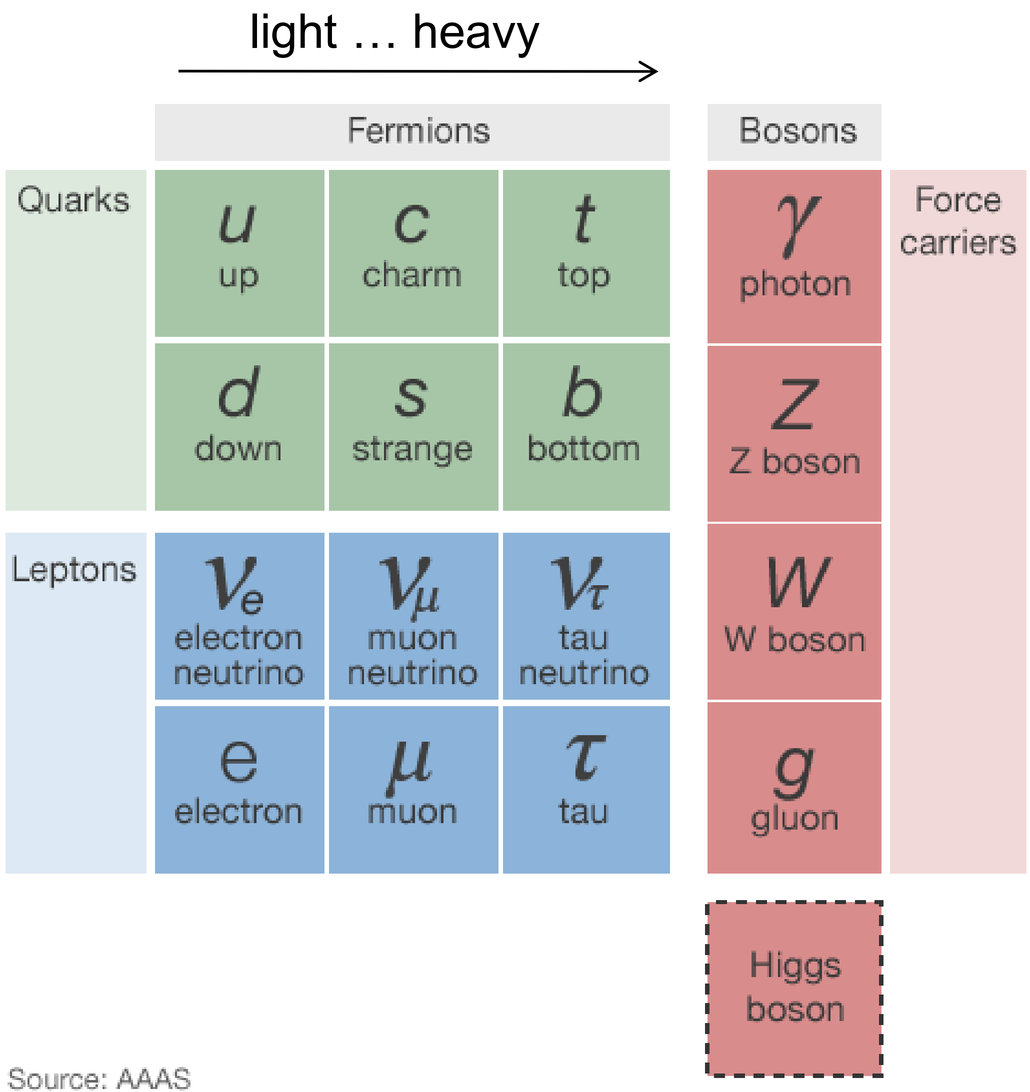
Z→μμ event with ~25 reconstructed vertices



20 cm

The particle zoo

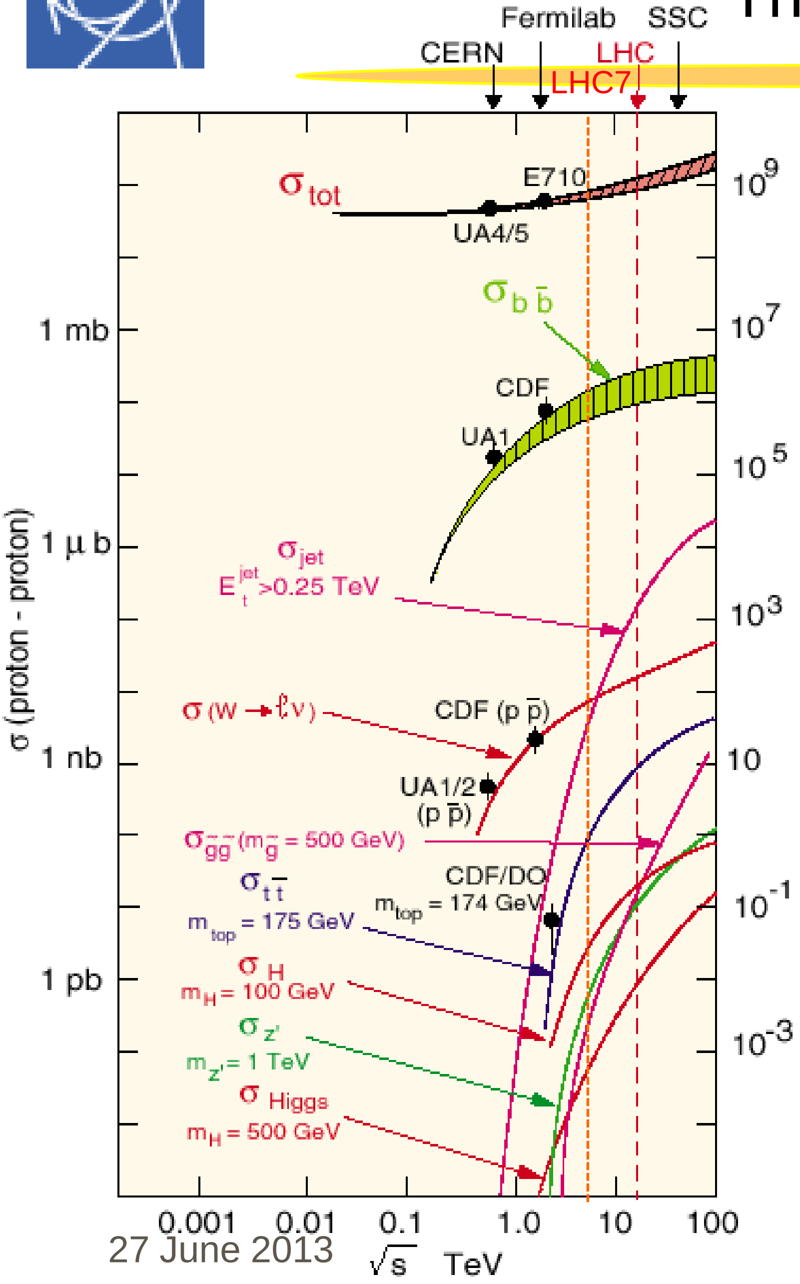
- State of the nation (Standard Model):
  - Quarks: spin ½, charge 1/3e, 2/3e
    - Bound by QCD (strong force) in 2s and 3s into hadrons, cannot be ‘free’
    - Up/down make up proton and neutron
    - 100s of exotic hadrons
    - Top quark anomalous – heavy as Au
  - Leptons: spin ½, charge 0 or 1
    - Only feel EW interactions
    - Electron and neutrino, heavier cousins muon (cosmic rays), tau
  - 3 families/generations of each
  - Force carriers – spin 1 bosons
    - Photon (electromagnetism), W/Z (weak force), gluon (strong force)
  - Higgs boson (?) – connected with mass
- LHC – Higgs, top, bottom, W, Z, γ, …
  - And the unknown …



	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
				Higgs boson	

Source: AAAS

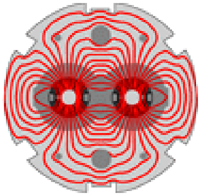
The LHC physics landscape



- More interesting processes hiding in an overwhelming background
  - Rates for nominal LHC, 14 TeV, L=10^{34}cm^{-2}s^{-1}

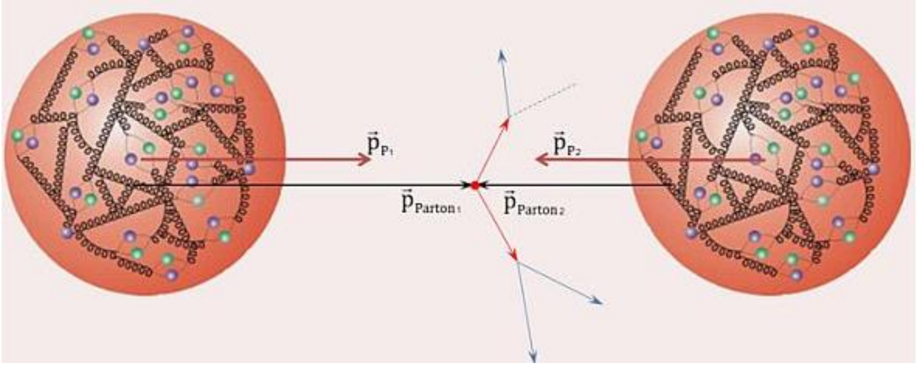
Process	Rate @14TeV
Inelsatic pp collision	10^9 Hz
B-quark pair production	10^6 Hz
Jet production, E_T>250 GeV	10^3 Hz
$W \to l\nu$	10^2 Hz
Top-quark pair production	10 Hz
Higgs (m_H=100 GeV)	0.2 Hz

- Not all these events can be recorded
  - Multi-level online trigger system to reduce rate to ~400 Hz for offline storage
  - Based on detecting energetic leptons (e,μ,τ), photons, jets or overall energy imbalance
  - Trigger strategy defines physics we can study

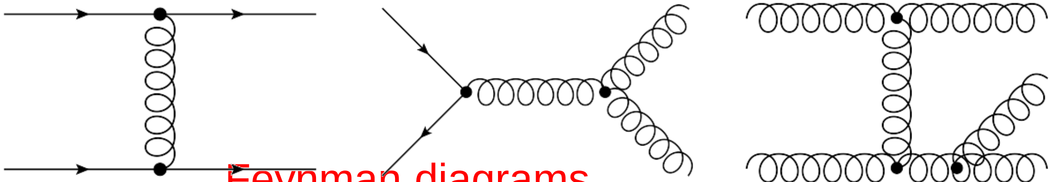


Production of jets

- Protons are composite objects
  - 3 ‘valence’ quarks carrying most momentum
  - A ‘sea’ of quarks/antiquarks and gluons
- Collision ‘picks out’ quark/gluon from each
  - To make the ‘hard scattering’ collision

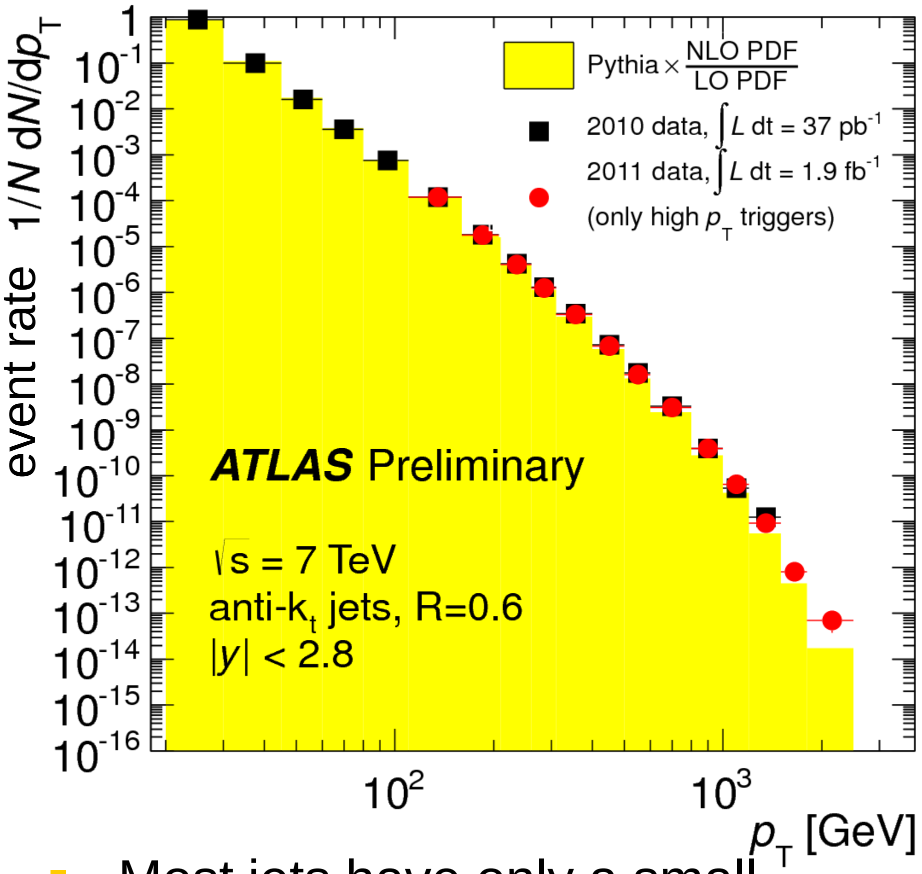


- Hard collisions scatter quarks or gluons



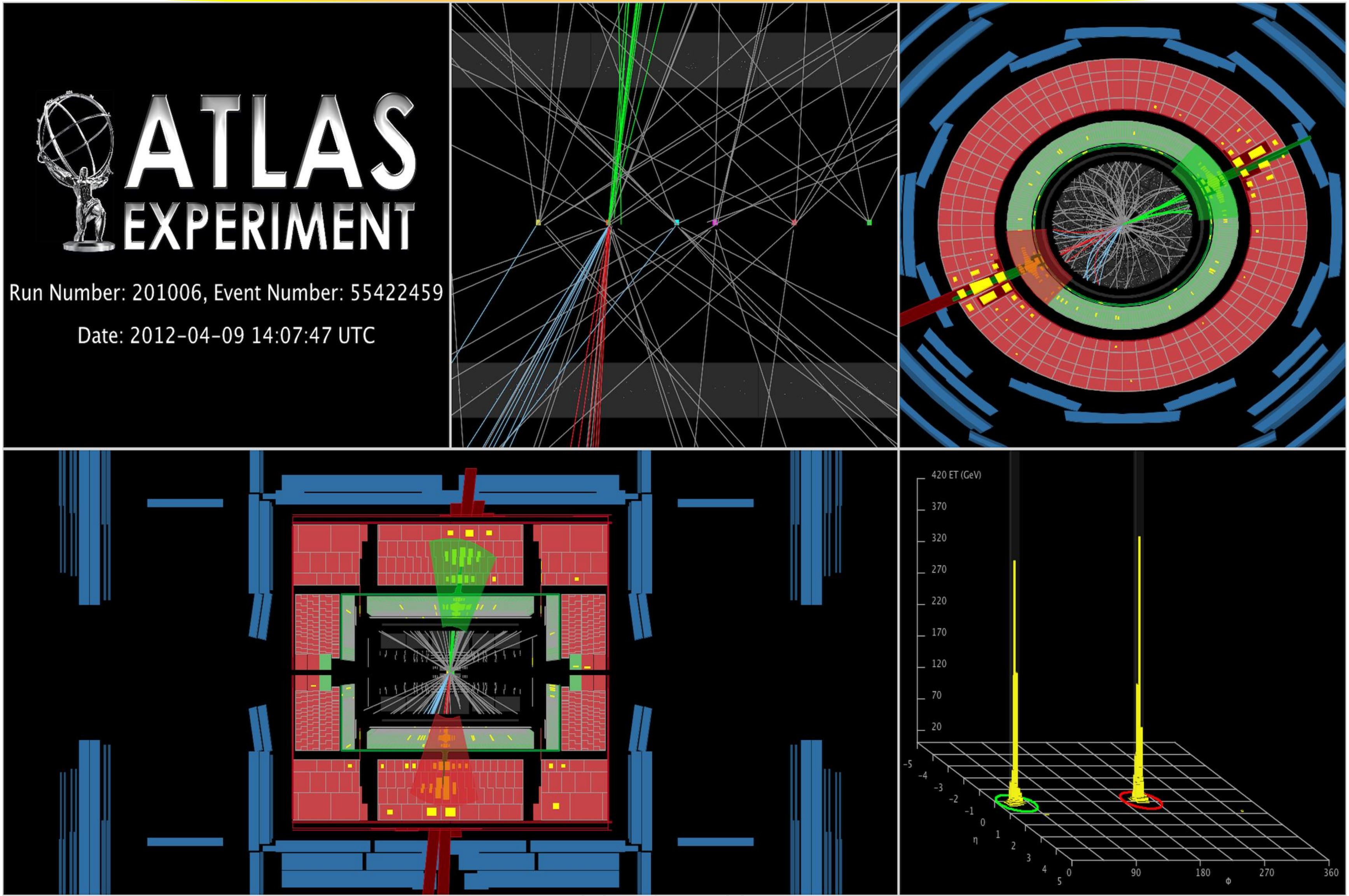
Feynman diagrams

  - Outgoing quarks/gluons produce ‘jets’ of particles we see in the detector



- Most jets have only a small fraction of the proton’s momentum
  - Compare to simulation models – a vital tool in understanding the data

A di-jet event from ATLAS

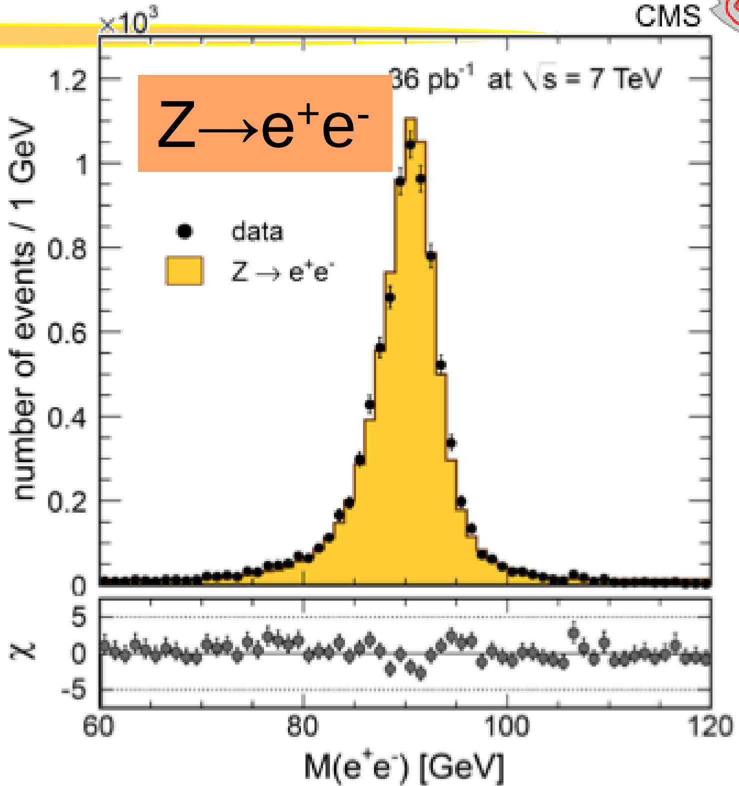


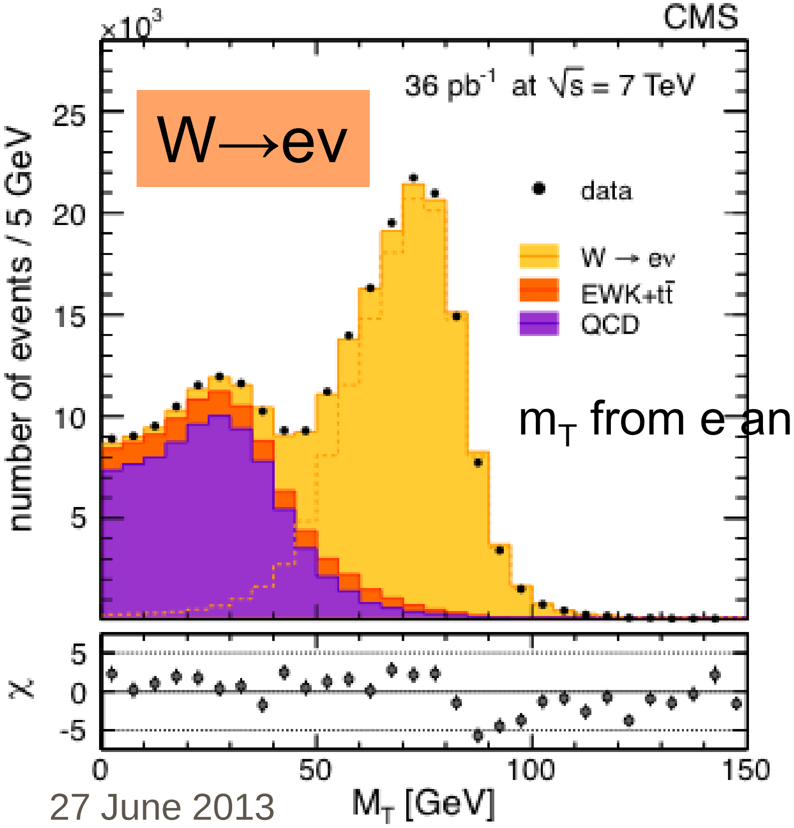
Run Number: 201006, Event Number: 55422459

Date: 2012-04-09 14:07:47 UTC

W and Z bosons

- W (80 GeV) and Z (91 GeV)
  - Force carriers of the weak force
  - Discovered at CERN in 1980s, now produced copiously in LHC collisions
  - Decay to leptons: W→e/μ ν, Z→ll

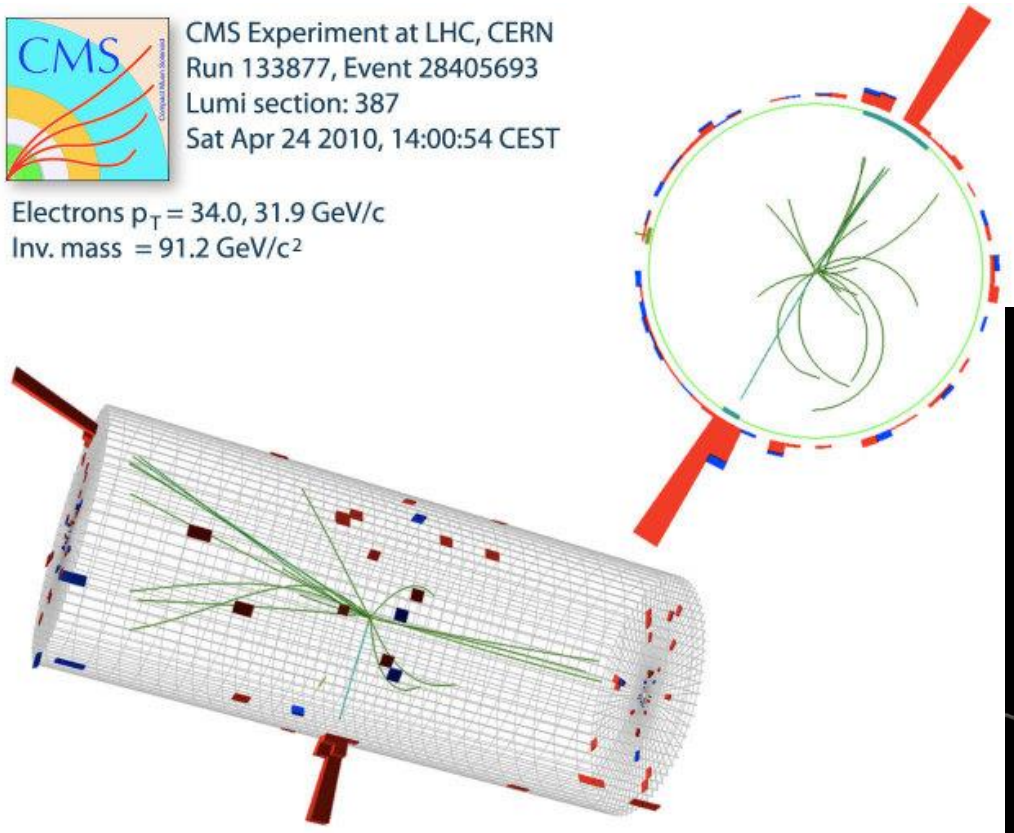




m_T from e and ν

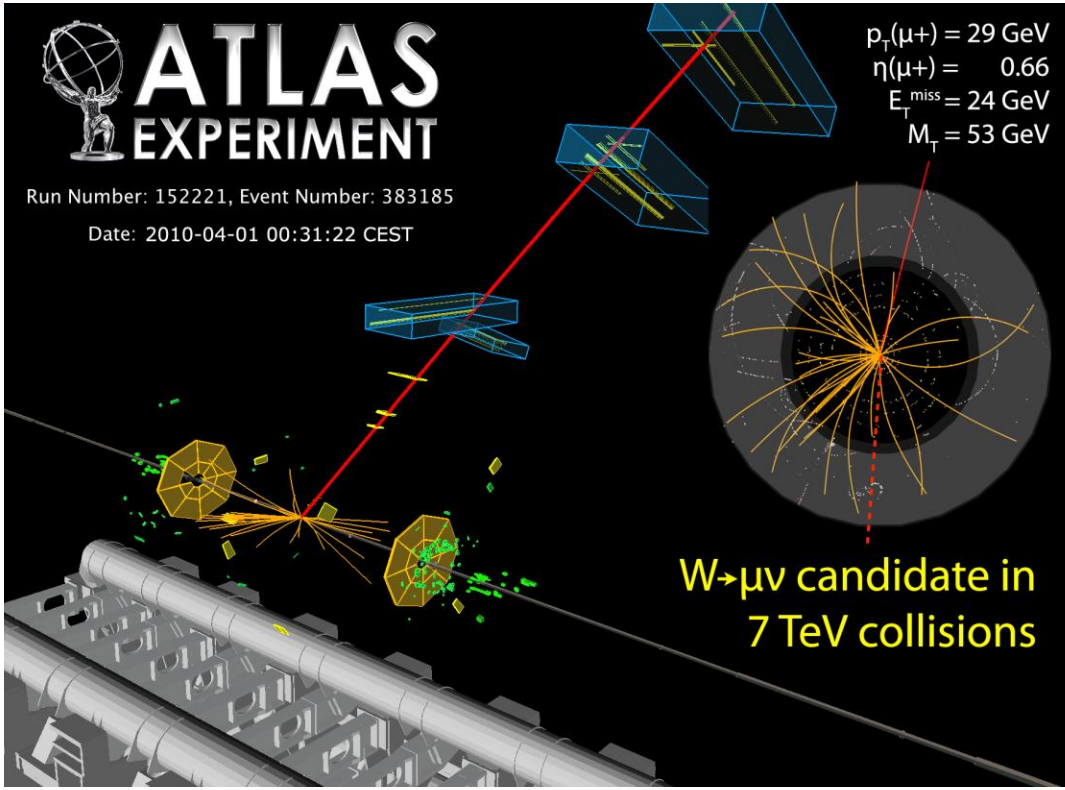
- Important tools for calibration of e and μ measurements, and missing energy (ν)
- Interesting physics measurements
  - Proton structure, W/Z+jets production
- Produced in decay of heavier objects
  - Top quarks, Higgs bosons, new particles?

W and Z events



CMS Z→e^+e^-

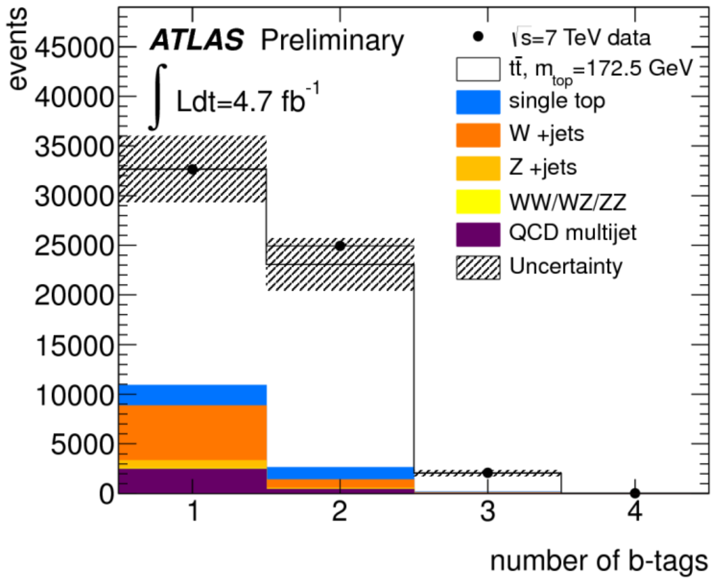
ATLAS W→μν

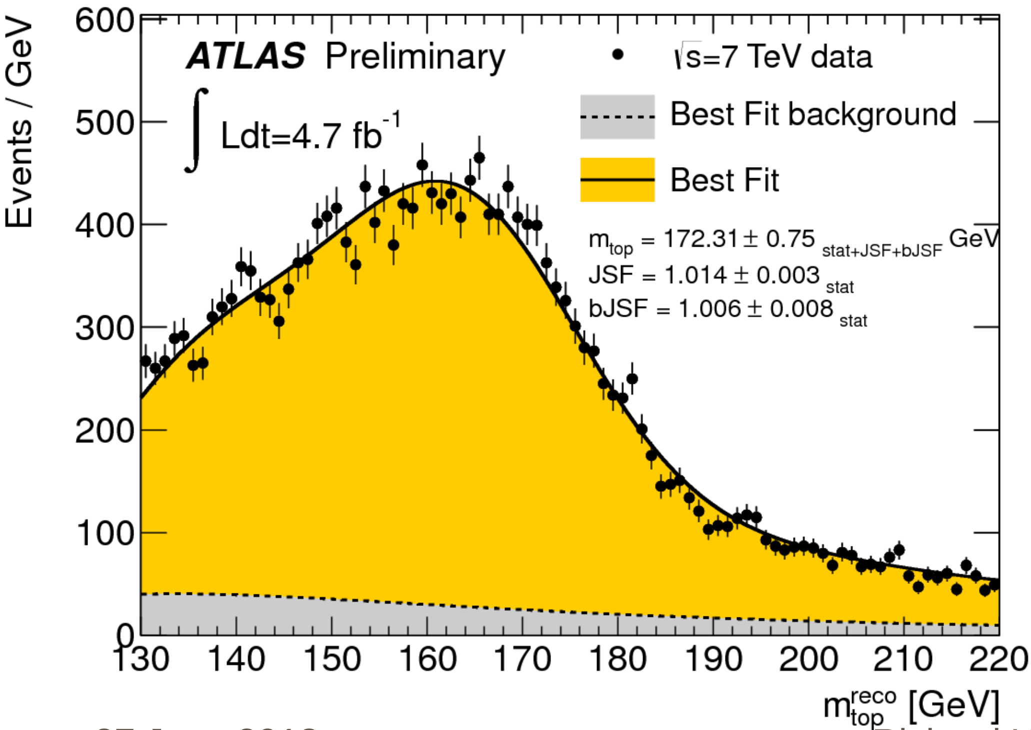


Top quark production

- Top quark as heavy as a gold nucleus (~173 GeV)
  - Mainly produced in pairs, decays as t→Wb
    - W can be detected in decays to leptons or quarks (jets)
  - b-quark produces a jet with a b-hadron, b-hadron decays a few mm from the interaction point
    - ‘b-tagged’ jets are a good signature of top production

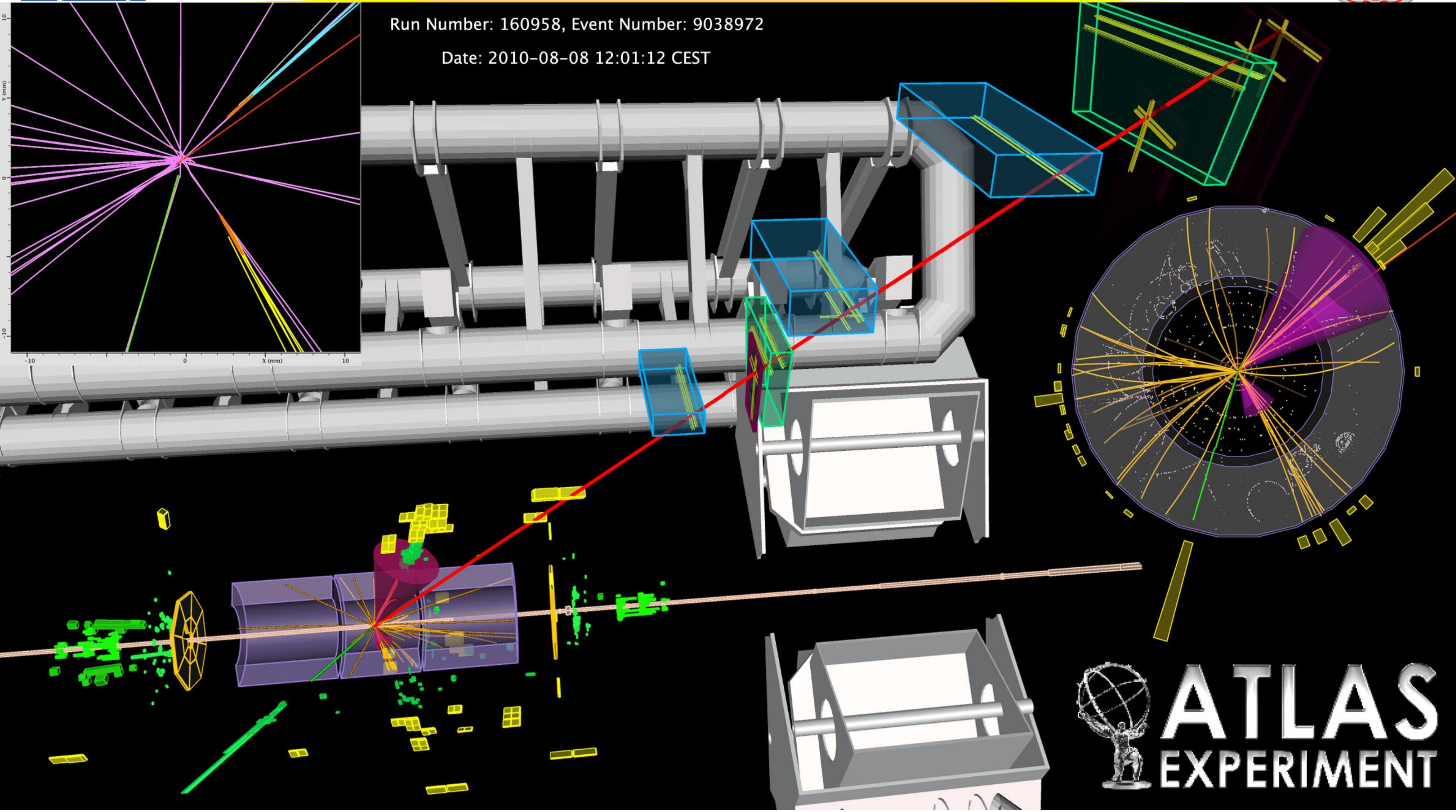
tt→WbWb→lvbqqb





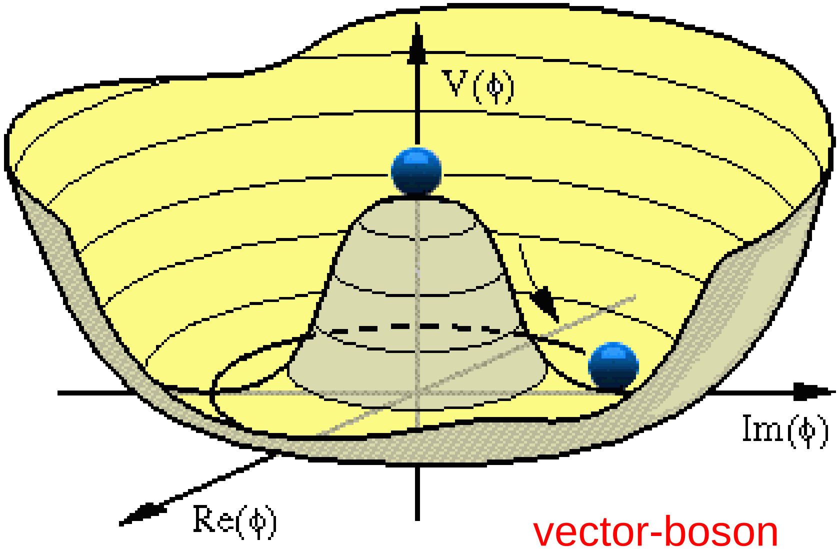
- Top decays before forming hadrons
  - Only ‘bare’ quark we can study
  - Mass measured from decay products
- Large mass of the top is a mystery
  - Is it connected to the Higgs?
  - LHC is the first top ‘factory’ where we can study it in detail

A tt→eμννbb top pair candidate

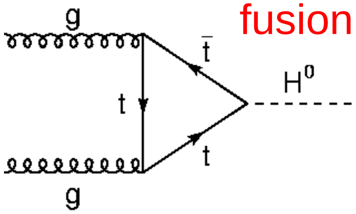


The Higgs boson

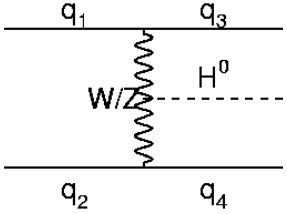
- Elegant unified theory for the W, Z and photon
  - But requires them to be massless
- Postulate an additional 'Higgs field' with 4 d.o.f. whose minimum potential is **not at zero**
  - Spontaneous symmetry breaking, idea also applicable in other areas of physics
- Once symmetry is broken, 3 d.o.f. go to make W^+, W^- and Z massive (longitudinal component)
  - One is left over – the scalar Higgs boson H
- Interactions of H with other bosons are completely specified – only mass m_H is free
  - Predictions for production and decay vs m_H
  - Extend to fermions – a 'Yukawa' coupling to H proportional to mass of each fermion
- A beautiful theory from the 1960s
  - Precision studies e.g. from LEP indirectly felt the influence of the Higgs, suggested m_H~100 GeV



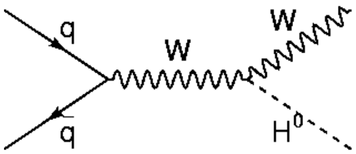
(a) gluon-gluon fusion



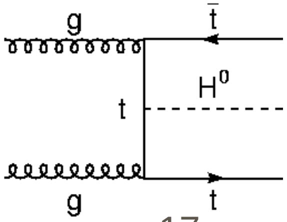
vector-boson fusion (b)



(c) associated production

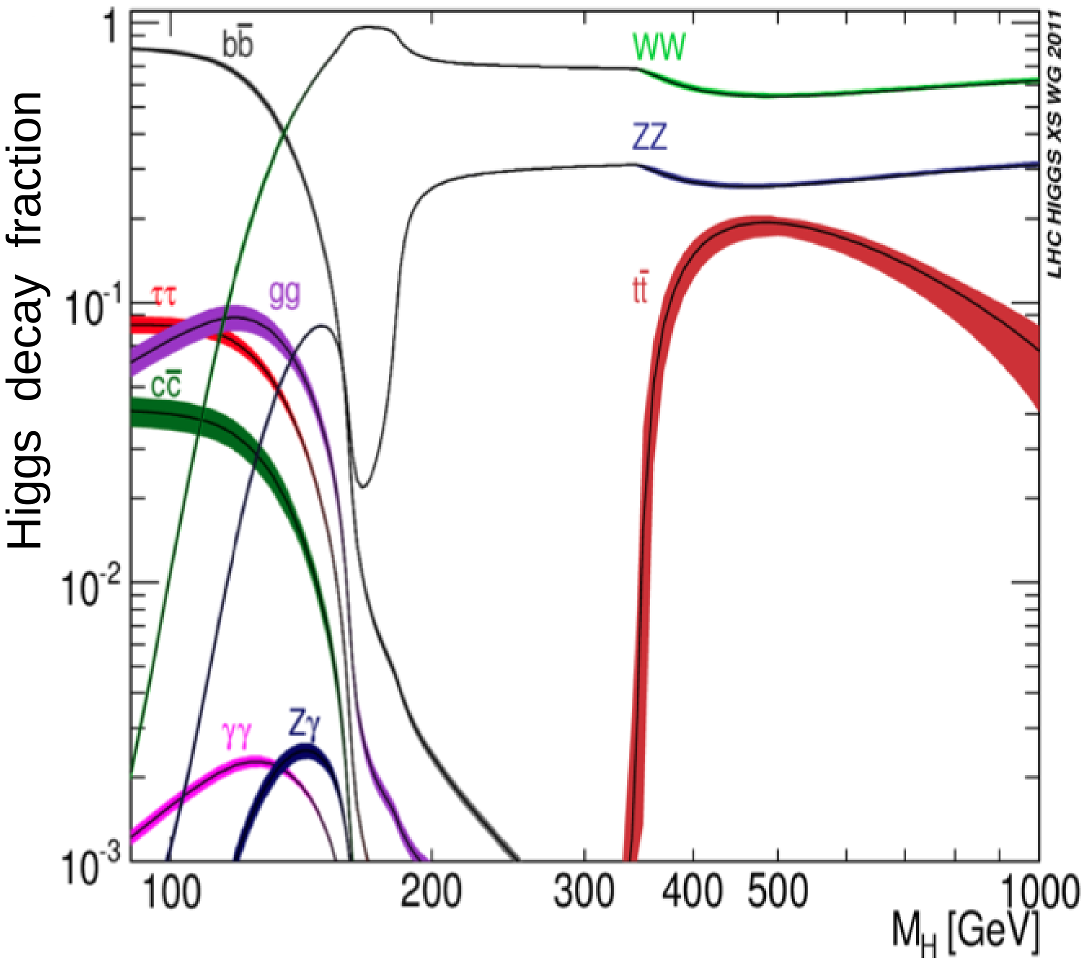


(d) ttH



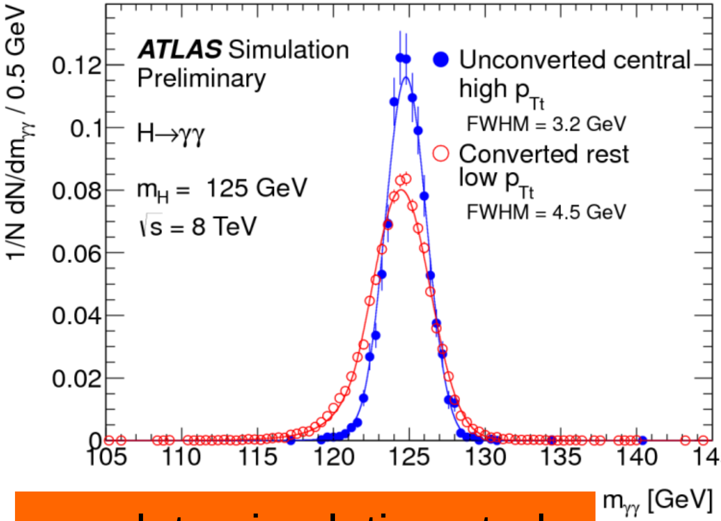
Searching for the Higgs

- What are we looking for?
  - Higgs boson has a very short lifetime – look for its decay products
  - Relation of Higgs to mass – likes to decay to the heaviest objects possible
  - bb quark/antiquark pair for low m_H, then WW, ZZ if heavy enough
  - H→γγ in ~0.2% of cases if light
- Where to look
  - In Standard Model, Higgs mass m_H is a free parameter
    - But must be <≈700 GeV for the theory to make sense
  - Searches at LEP and Tevatron
    - m_H>114 GeV, not around 160 GeV
  - Look everywhere: 114<m_H<700 GeV
    - In many different decay modes

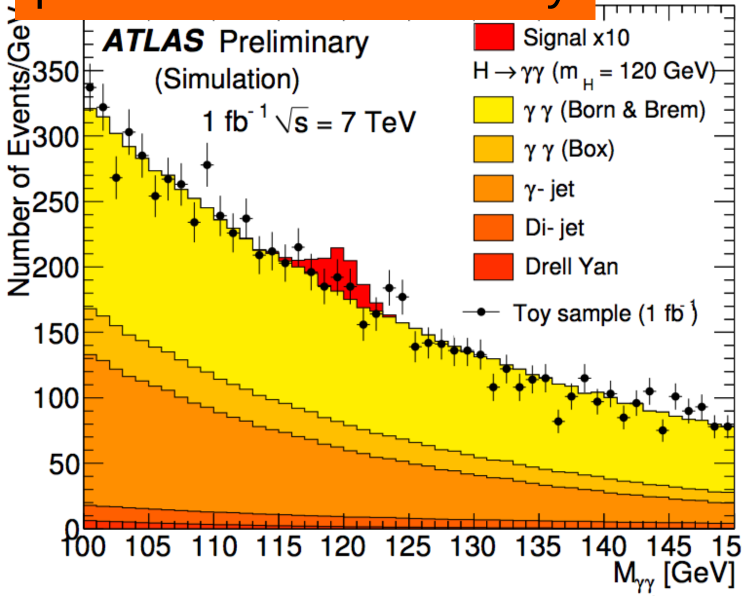


The H→γγ decay mode

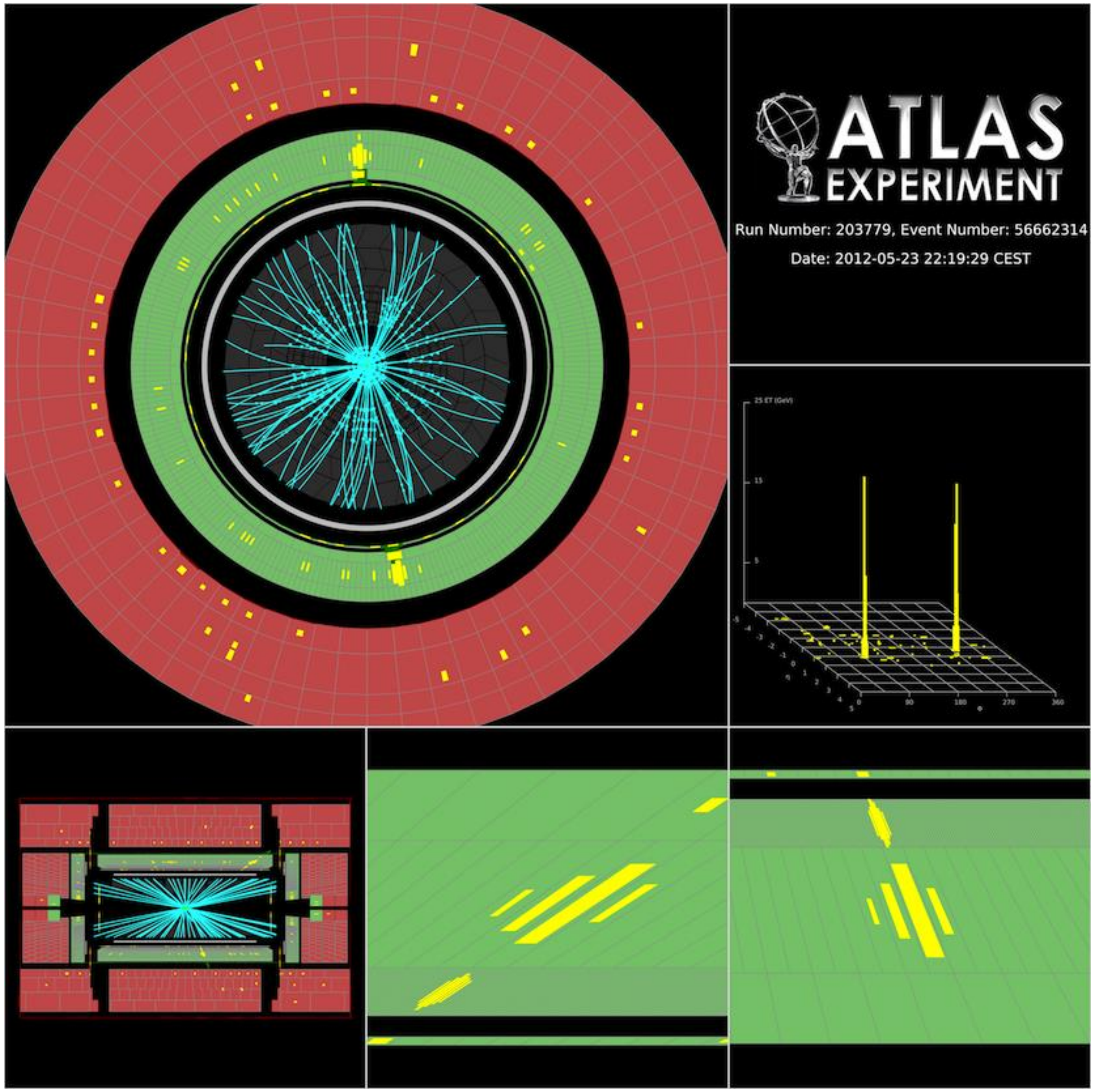
- Happens rarely, but γ (photons) can be identified with high efficiency and good precision
  - Isolated narrow shower in the calorimeter
  - No associated inner detector track
- Select events with pairs of photons
  - Calculate $m_{\gamma\gamma}=\sqrt{(E_1E_2(1-\cos\alpha))}$
    - Energies of two photons and their opening angle
  - Need precise energy and angular resolution
    - Well-measured events give narrower peak
- $m_{\gamma\gamma}$ for Higgs signal shows a peak at m_H
  - Unfortunately a lot of background from
    - 'Continuum' γγ production
    - γ+jet and jet+jet events with a jet misidentified as γ
  - Fortunately this background is smooth and can be fitted directly from the data
- Need a lot of events, see if a peak emerges …



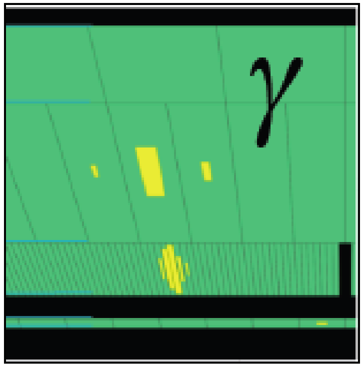
pre-data simulation study

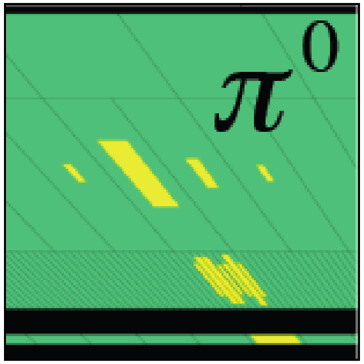


H→γγ candidate event in ATLAS



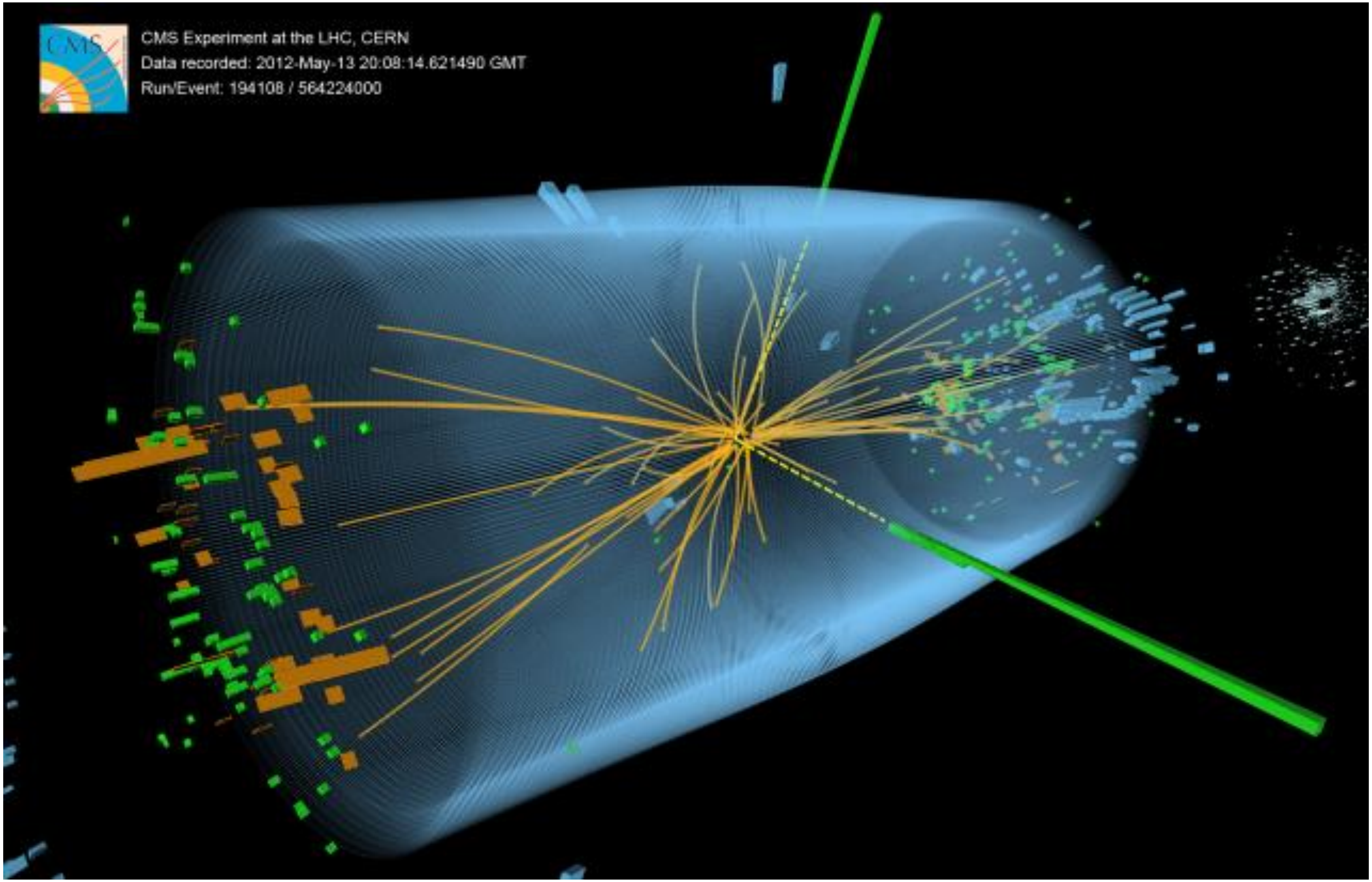
- Separation of γ and π^0
  - π^0 from jet decays to two closely separated γ
  - Can be resolved thanks to finely-segmented calorimeter



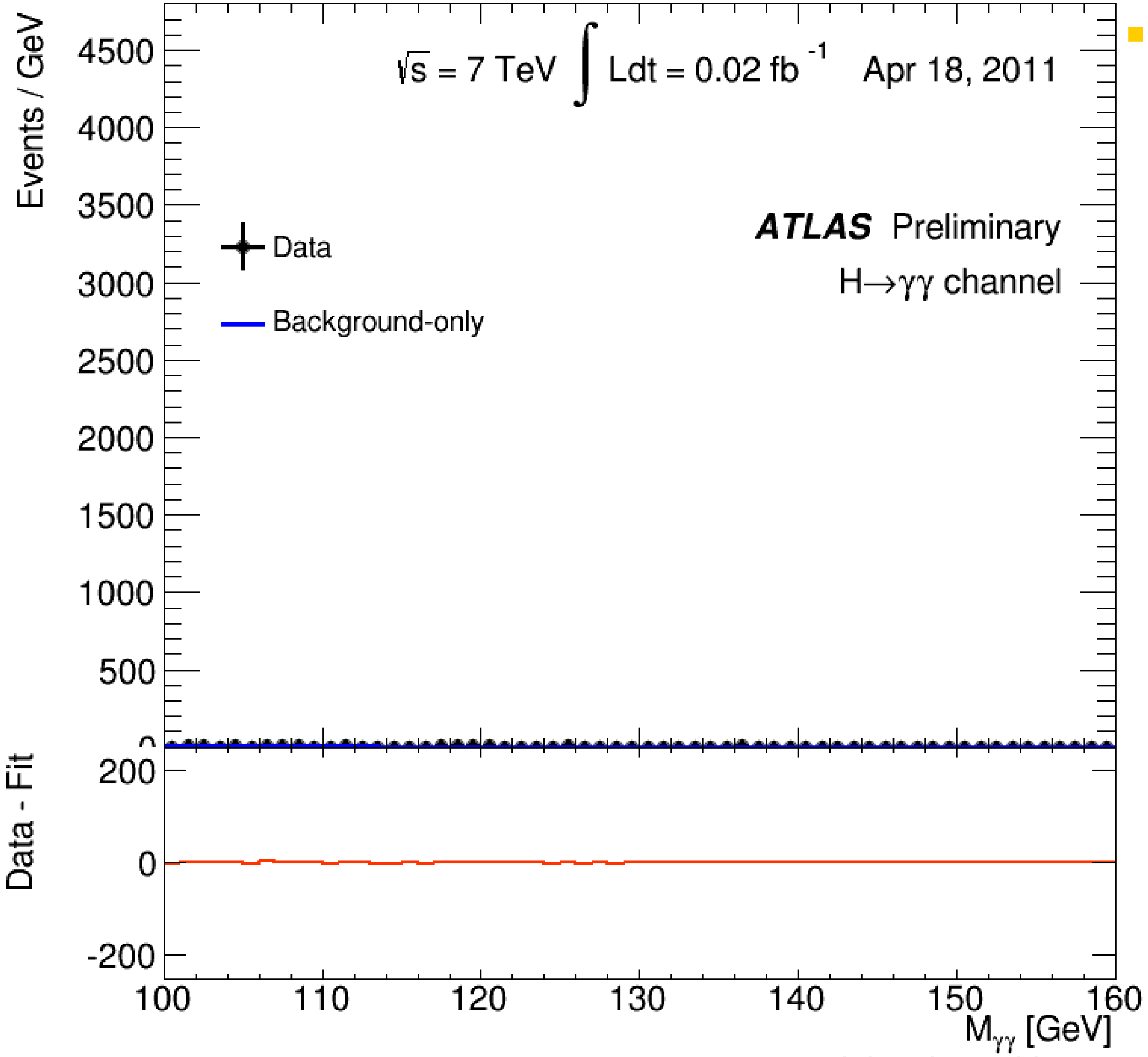


  - Also gives photon direction to locate primary vertex and measure opening angle

H→γγ candidate event in CMS



Just collect the data: H→γγ accumulation

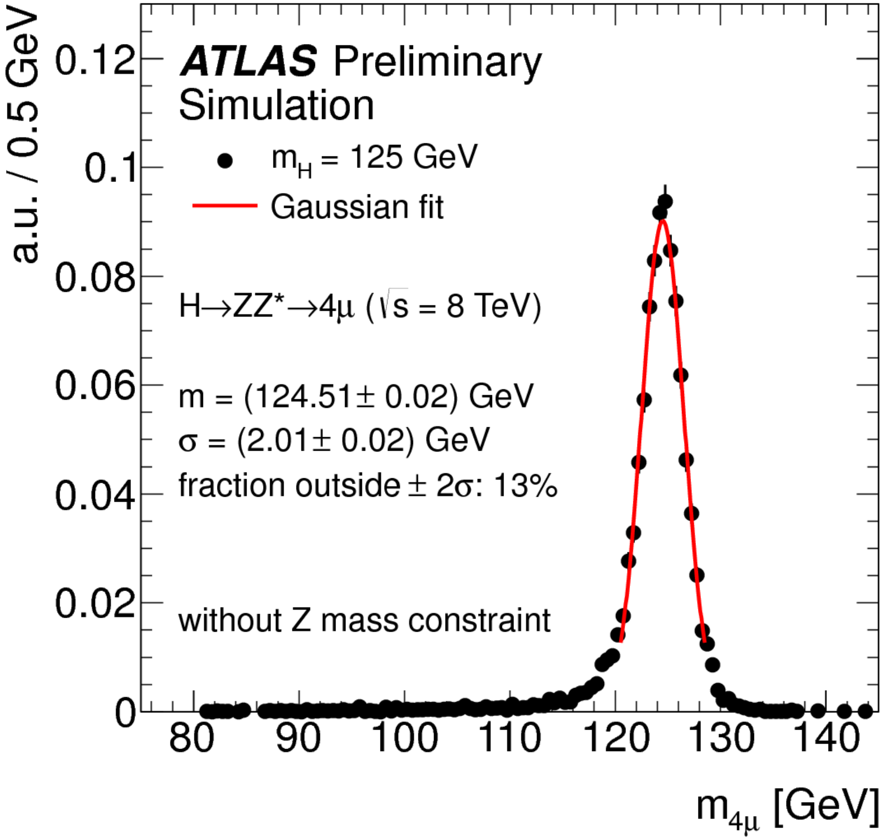


- Plot of evolving $m_{\gamma\gamma}$ in ATLAS
  - Upper plot - all events in 2011 and 2012 data, as they arrive..
  - Lower plot - difference between data and smooth fit function representing continuum background
  - Combined 2011+2012 data:
    - **7.4σ** significance peak
    - m_H=126.8±0.2±0.7 GeV
  - Similar H→γγ from CMS
    - **3.2σ** significance peak
    - m_H=125.4±0.5±0.6 GeV

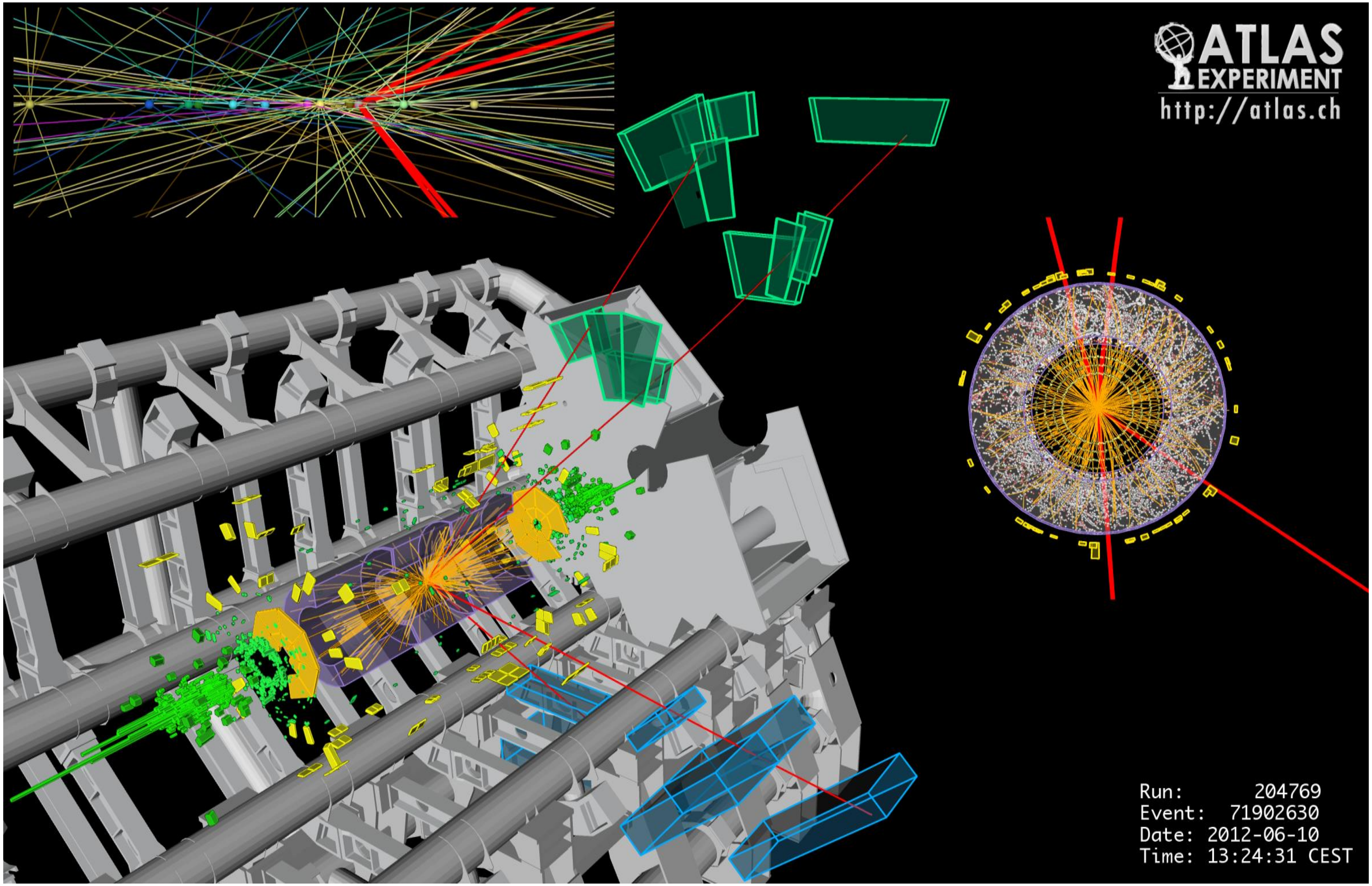
The H→ZZ(*)→4-leptons decay mode

- Decay of Z→ee or Z→μμ easy to see
  - Electrons and muons reconstructed with high efficiency, good mass resolution
  - Combine 2 Z in the same event, and look for H→ZZ→4e, 4μ, or 2e2μ
    - Hope to see a narrow peak …
  - For $m_H > 2m_Z$, most powerful channel
  - For lower m_H, one Z is 'off mass shell' (*), so decay is highly suppressed
  - Combined with fraction of Z→ee or →μμ of 7%, only 1 in 10^{-4} H gives a 4l final state
    - Only a handful of events expected
    - Emphasis on high reconstruction efficiency for e and μ down to low energies
    - Make every event count
- Expected backgrounds also low
  - Continuum ZZ(*) small below $2m_Z$
  - Some contribution from Z+'fake' leptons

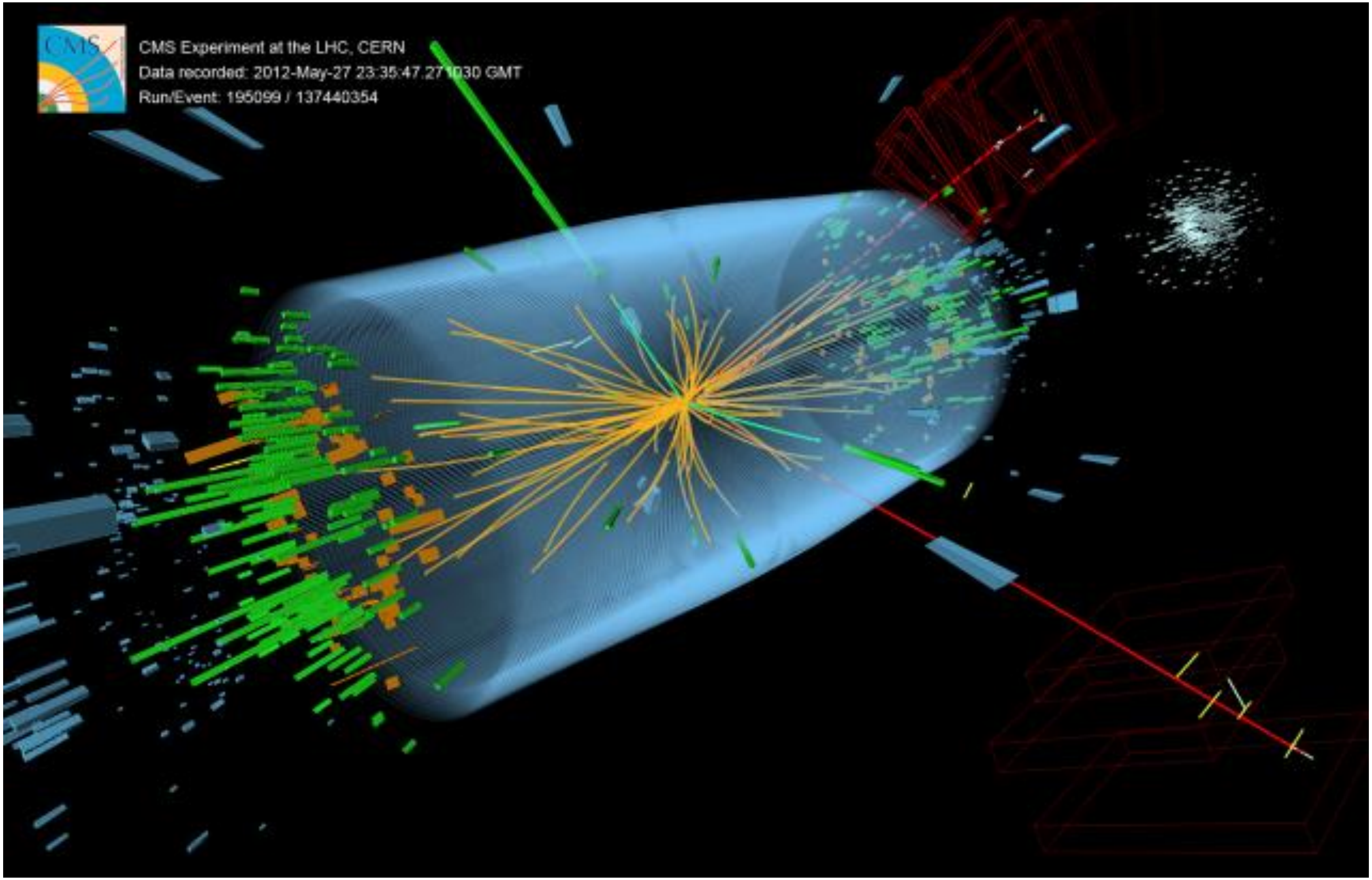
H→ZZ→4μ simulation



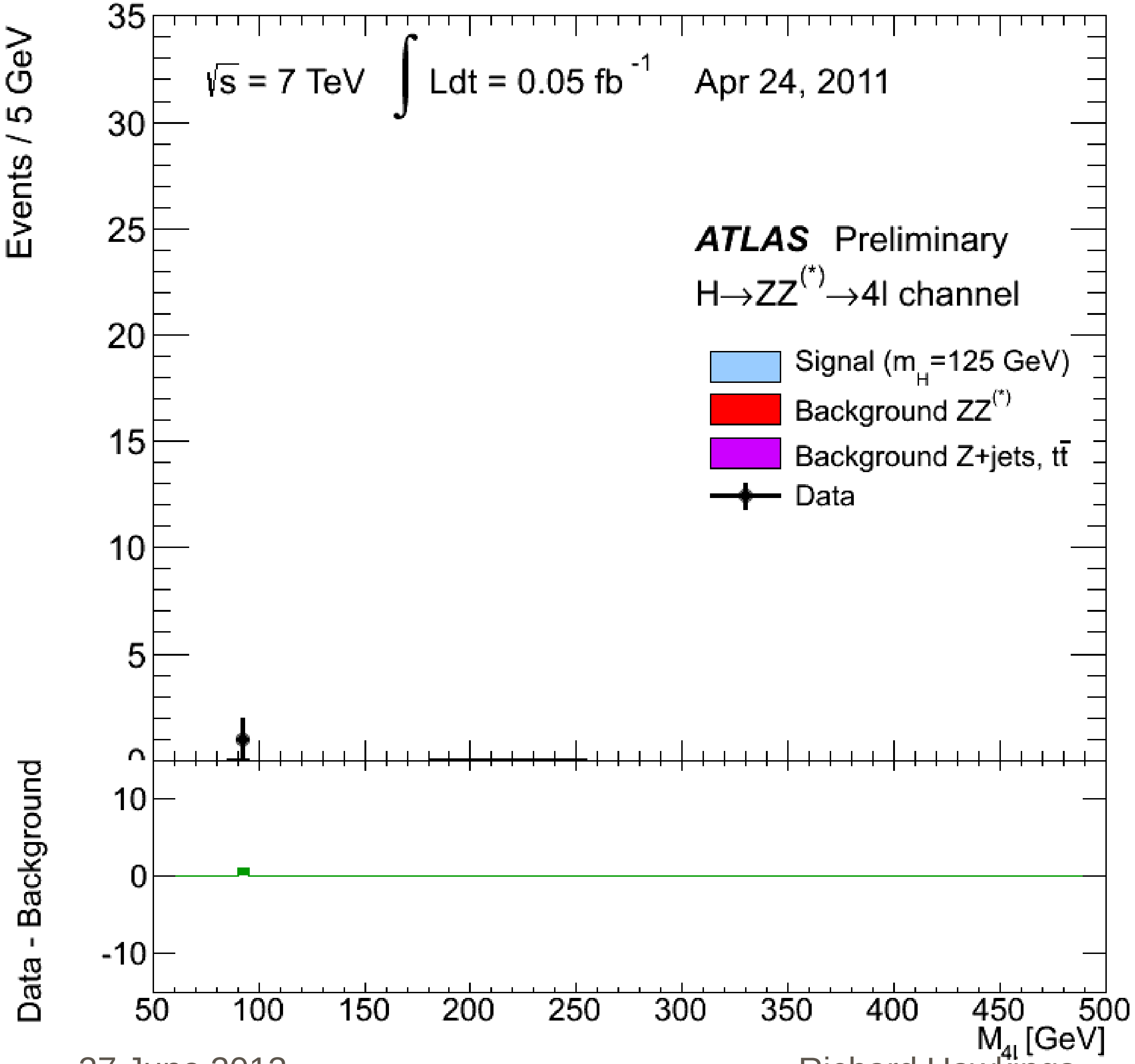
H→ZZ(*)→4μ candidate event in ATLAS



H→ZZ(*)→2e2μ candidate event in CMS

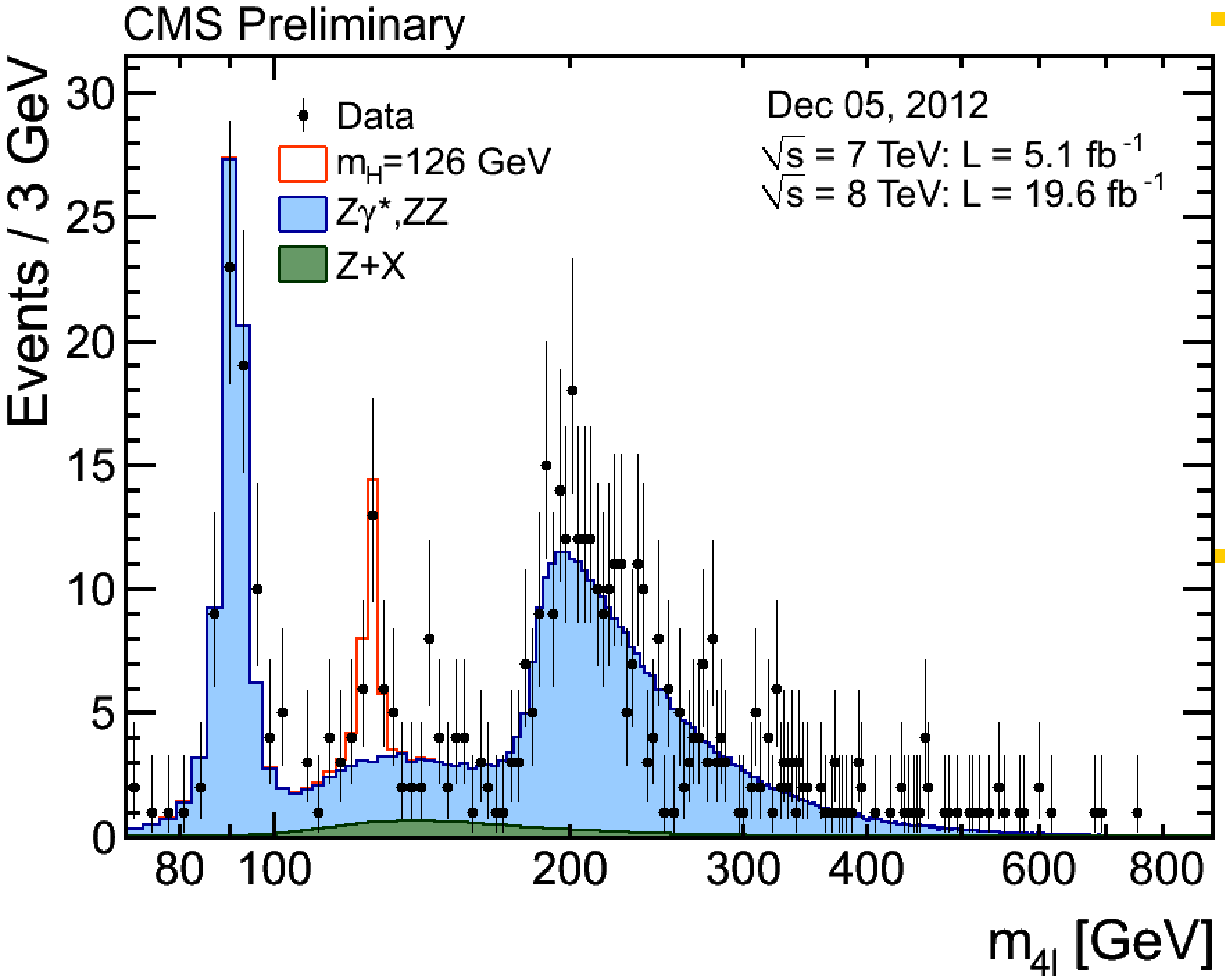


Just collect the data: H→ZZ(*)→4l in ATLAS



- Plot of evolving m_{4l} in ATLAS
  - Upper plot - all events in 2011 and 2012 data, as they arrive
    - Expectation from backgrounds superimposed, including single Z→4l
  - Lower plot – excess of data over background expectation
- With all 2011+2012 data
  - **6.6σ** significance peak
  - m_H=124.3±0.6±0.4 GeV

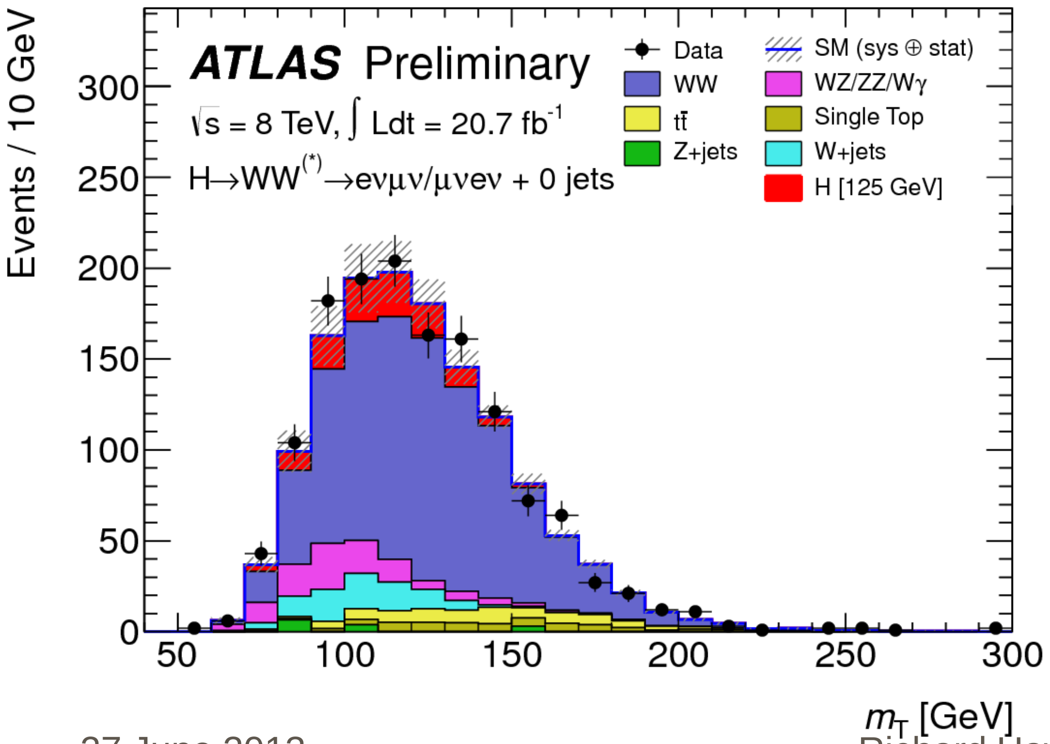
Just collect the data: H→ZZ(*)→4l in CMS

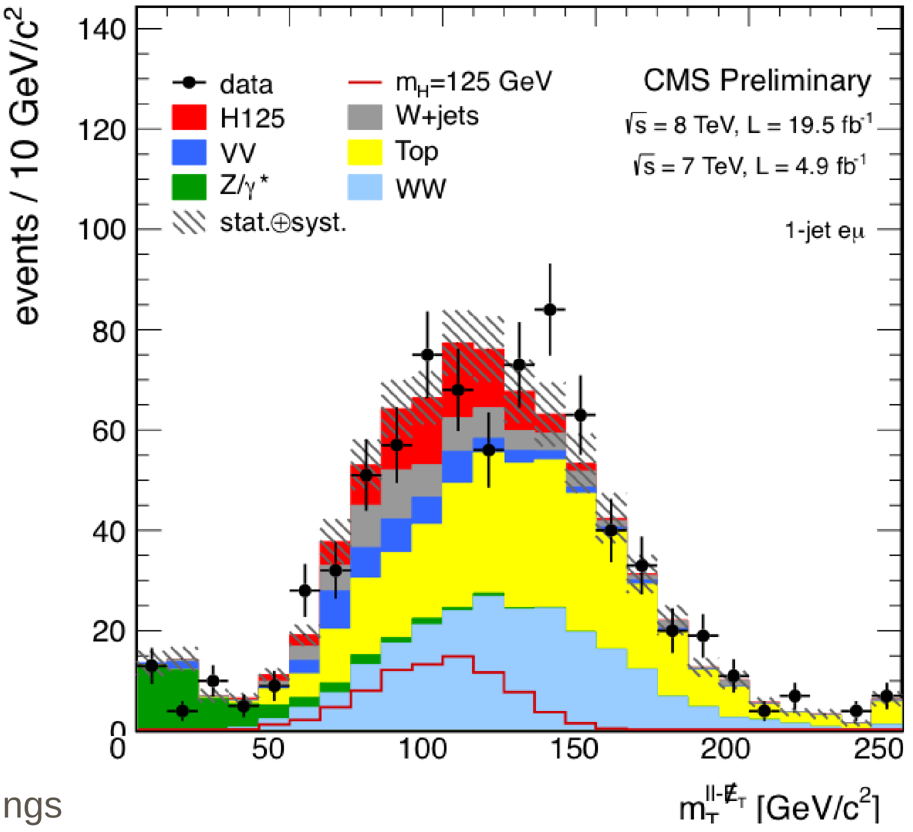


- Plot of evolving m_{4l} in CMS
  - All events from 2011 and 2012 as they arrive
  - Expectation from backgrounds superimposed, including single Z→4l
- With all 2011+2012 data
  - **6.7σ** significance peak
  - m_H=125.8±0.5±0.2 GeV

The H→WW(*)→2l2ν decay mode

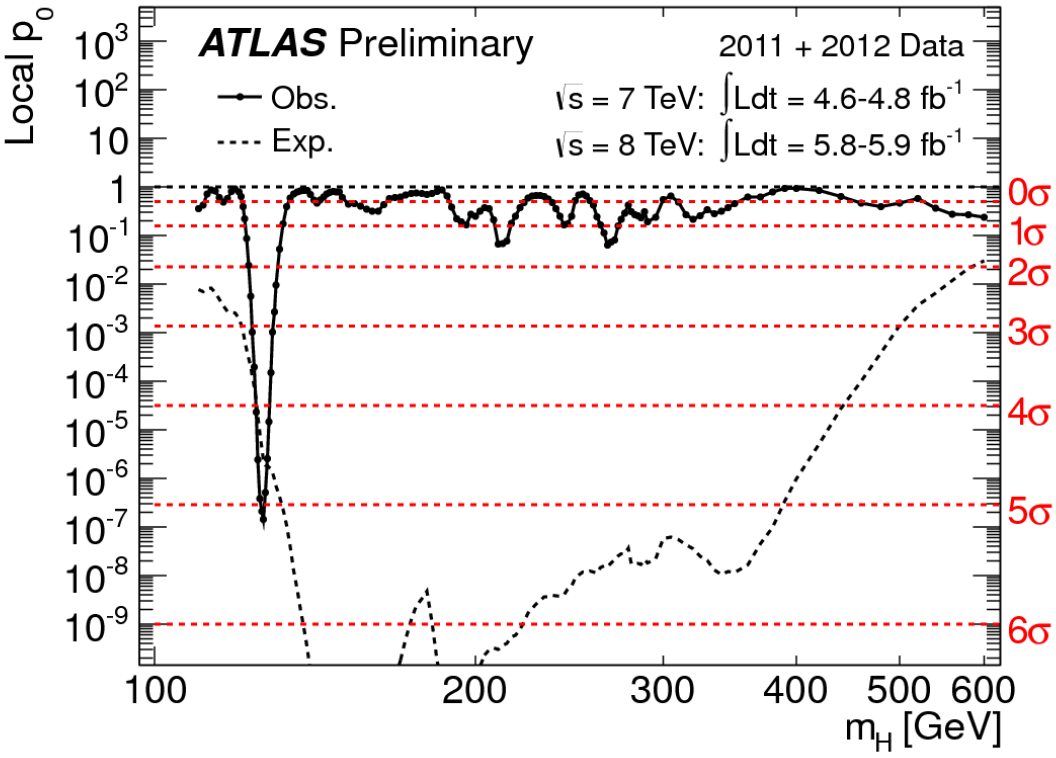
- H→WW(*) similar sensitivity to H→ZZ(*), but with lower threshold of 160 GeV
  - But W→eν or W→μν, one detectable lepton and one undetectable neutrino
  - Two neutrinos in Higgs decay – not enough information to determine the mass
    - Use a ‘transverse mass’ which has a lower, broad peak
  - Backgrounds (WW continuum, top-pair) peak in same region – need precise understanding from control measurements

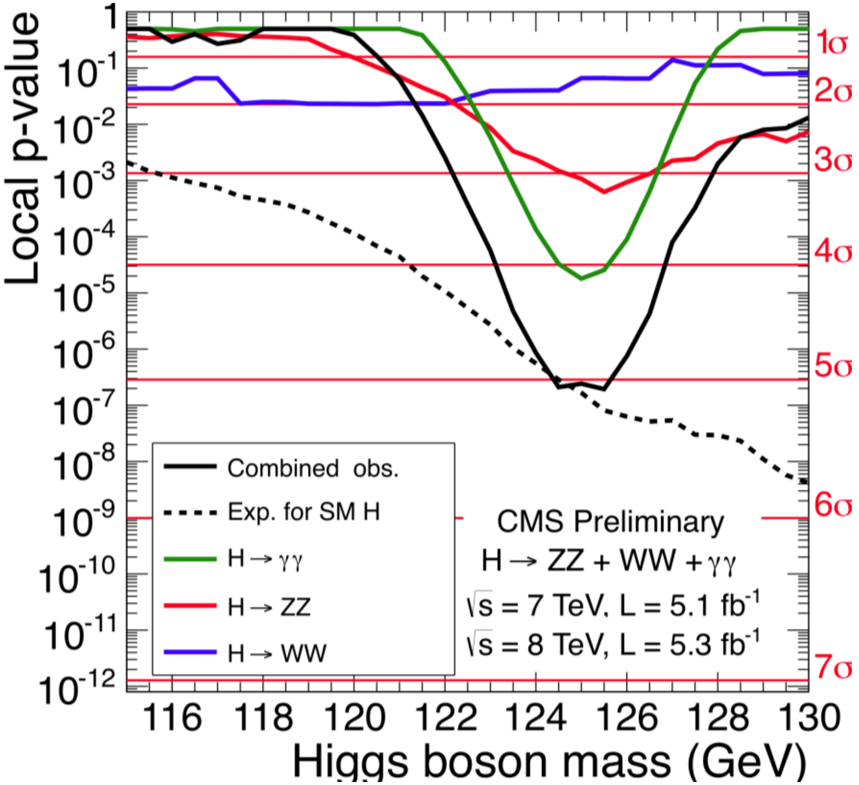




Results on 4th July 2012 – Higgs independence day

- By late June 2012, both experiments had accumulated enough evidence to announce the discovery of a new particle at ~125 GeV
  - Quantified by p_0 – probability that a ‘background-only’ experiment would look at least this signal-like (i.e. if you repeated the whole LHC program lots of times)
    - Evaluate as a function of hypothesised m_H, nothing except at ~125 GeV

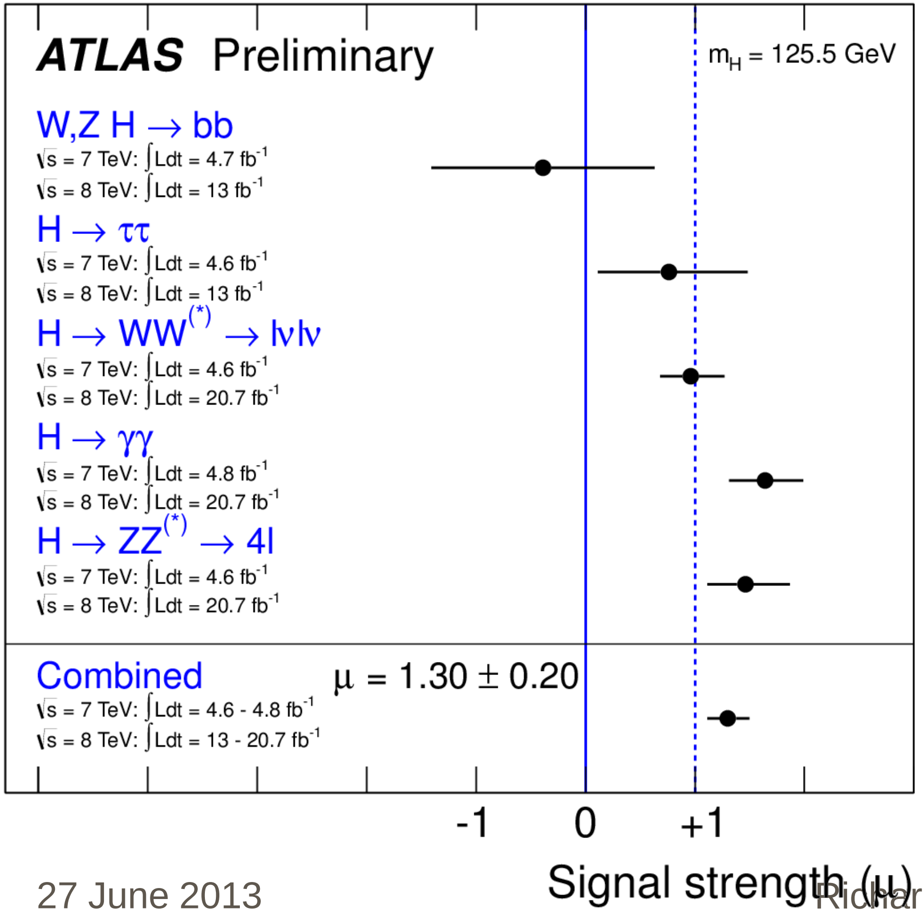


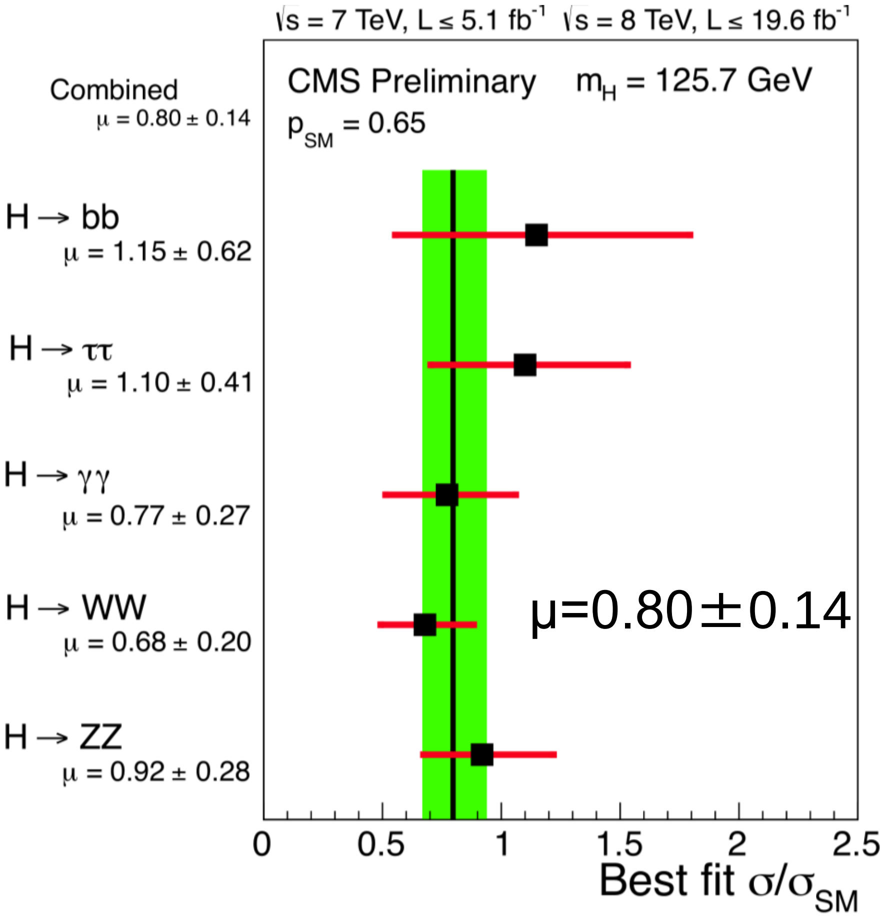


Higgs independence day

Results now - consolidation and consistency

- With full 2011-12 data, Higgs is established in γγ, ZZ and WW decay modes
  - Measure the signal strength μ, the ratio of signal rate to that expected in SM
  - Generally good agreement, though ATLAS a bit high in H→γγ

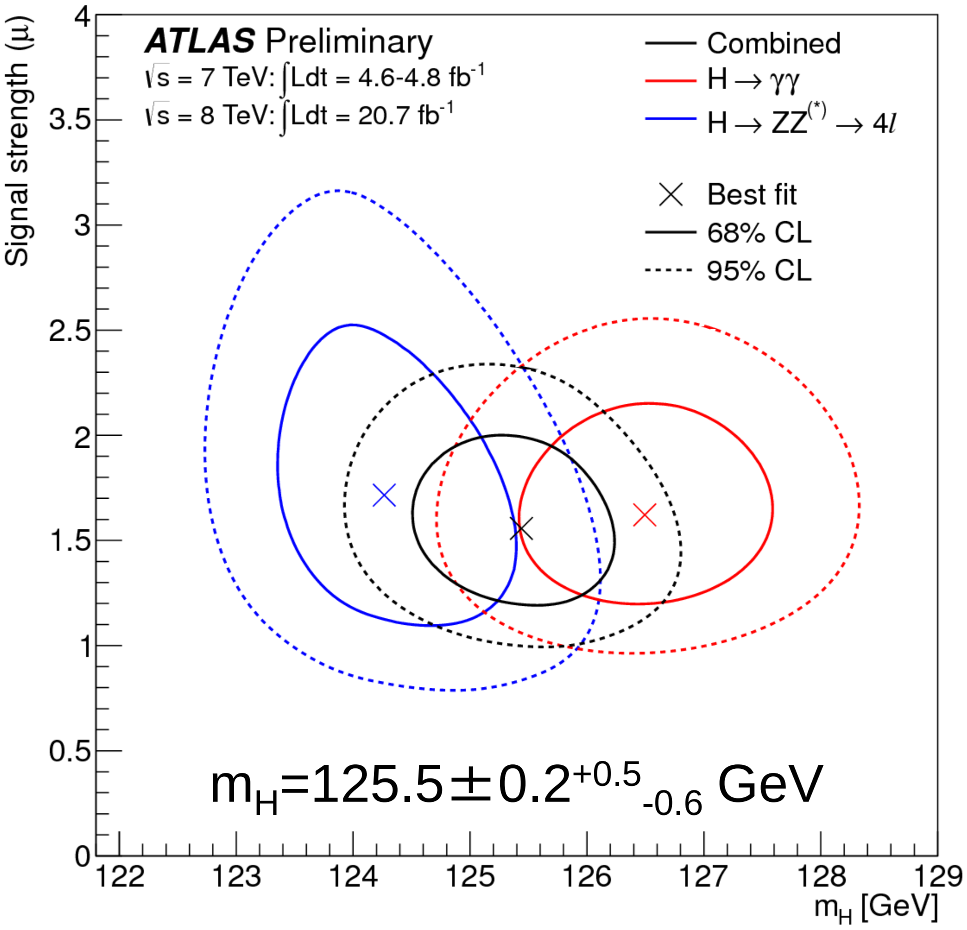




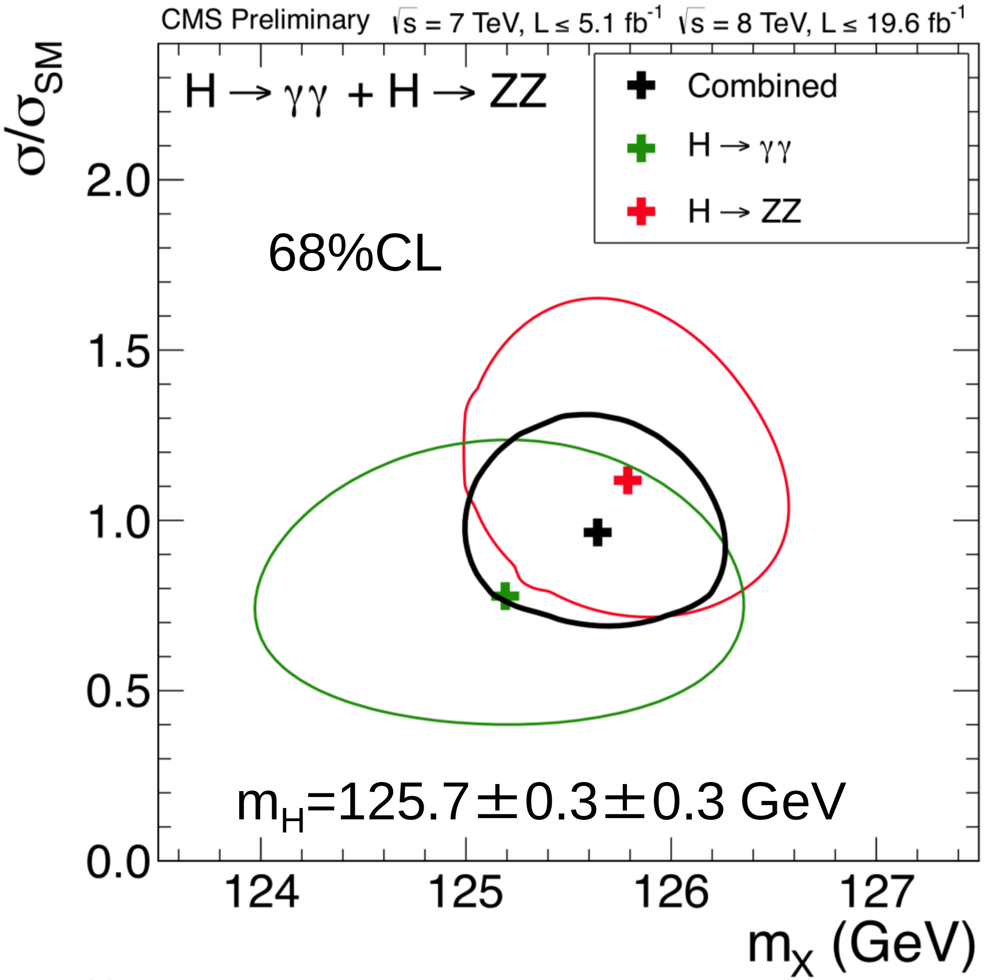
μ=0.80±0.14

The Higgs mass

- Mass is measured with high precision in H→γγ and H→ZZ(*)→4l channels
  - Results are consistent between channels and between experiments



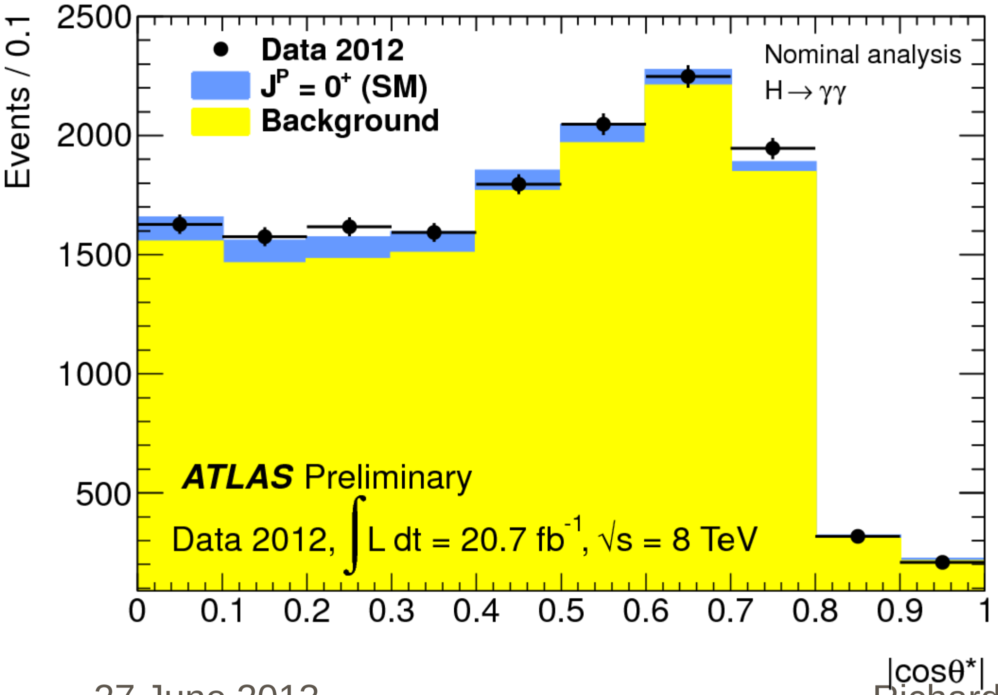
m_H=125.5±0.2$^{+0.5}_{-0.6}$ GeV

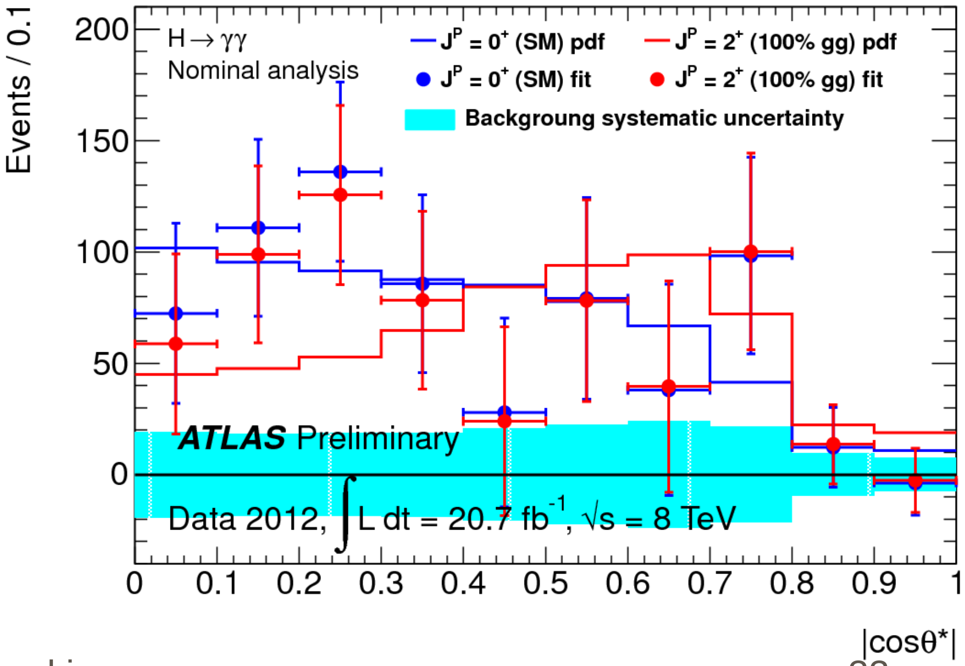


m_H=125.7±0.3±0.3 GeV

The Higgs spin in H→γγ

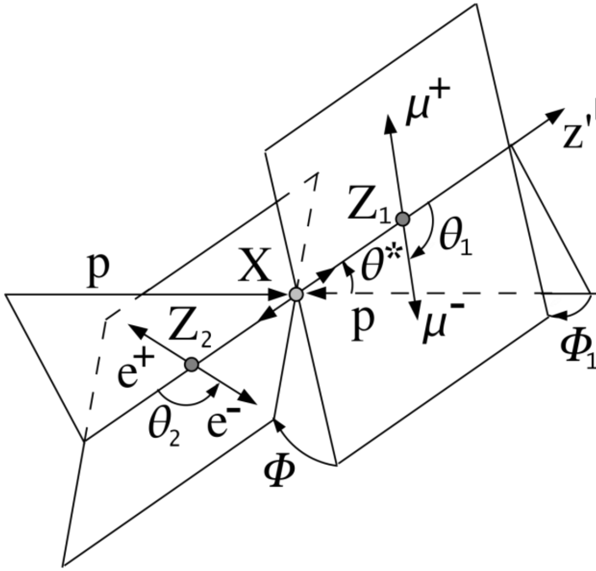
- Prediction: Higgs is a **scalar** particle – spin-0, no intrinsic angular momentum
  - All other fundamental particles are spin ½ (e, ν, q…) or spin-1 (γ, g, W,Z)
- Spin-0 particle decays isotropically in its rest frame – no spin axis
  - Spin-1 particle cannot decay to γγ, various possibilities for spin-2
- Large background and angular distribution distorted by acceptance effects
  - Nevertheless, spin 2+ produced by gluon-gluon fusion excluded at 99% CL

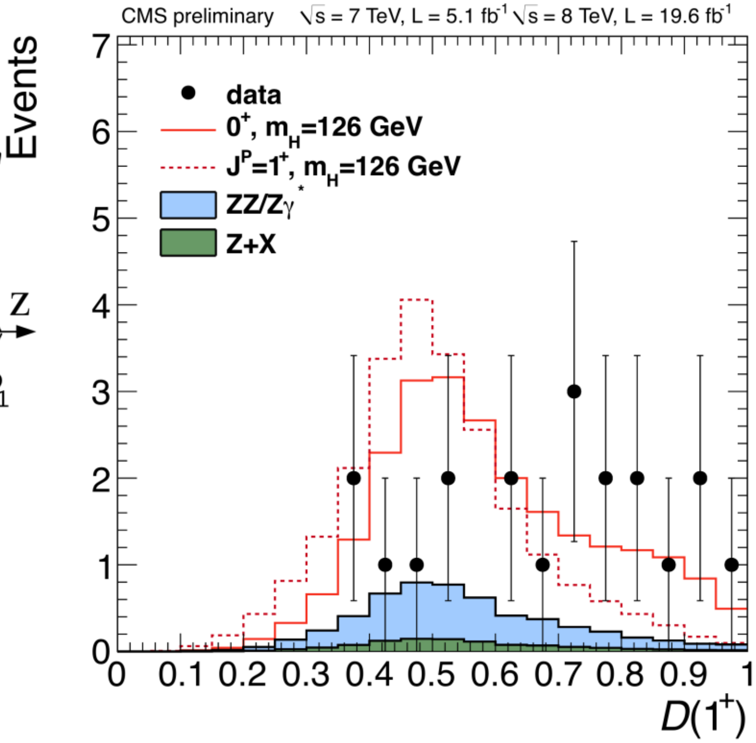


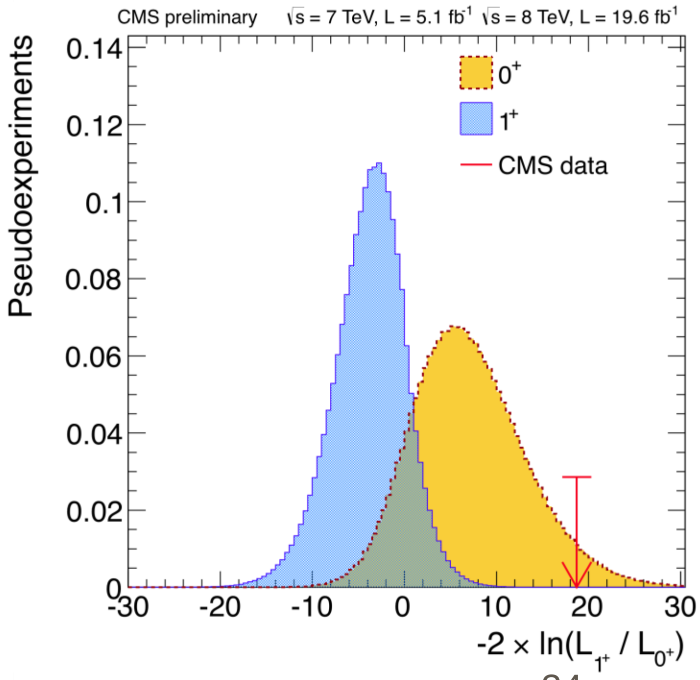


Higgs spin in H→ZZ(*)→4-leptons

- H→ZZ→4l decay also offers opportunity to test spin-1 hypotheses
  - Complex final state – 2 production and 3 decay angles
  - Combine all information into a discriminant D to test between hypotheses
    - Which origin is more likely, given the particle directions and energies in each event
  - Construct distributions of expected D for both hypotheses, compare to data
    - In this case, alternative spin /parity1+ hypothesis excluded at > 99% CL

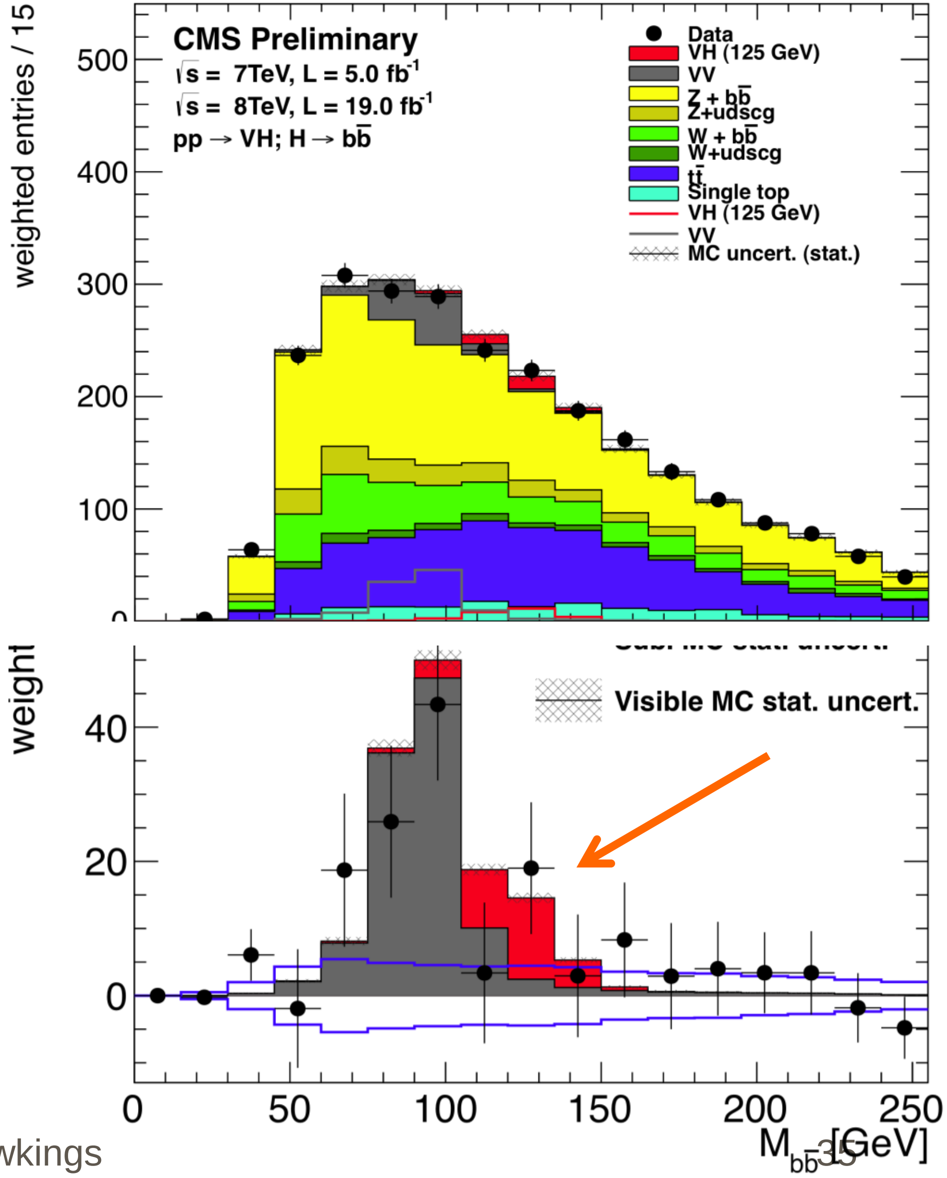






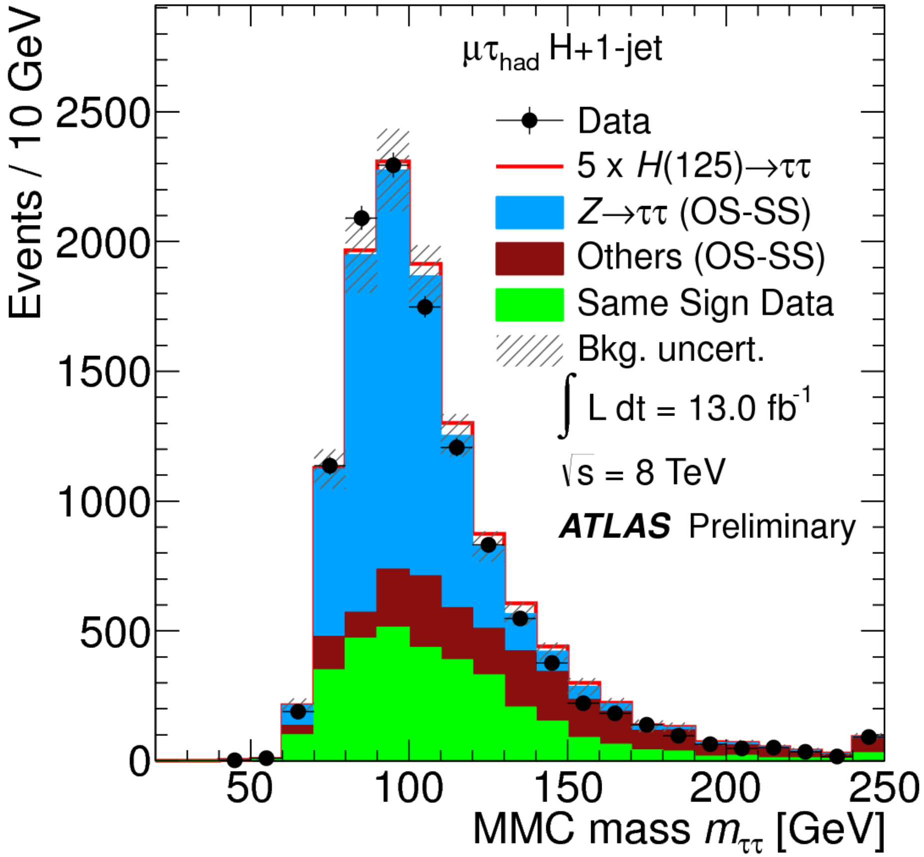
Higgs decay to b-quarks?

- Consistent picture emerged with rare Higgs decays to W, Z and γ
  - But ~60% of Higgs at LHC decay to b-quark/antiquark pairs (bb)
    - Cannot be isolated due to much larger rate of bb from QCD processes
- Look for **associated production** of H in conjunction with W or Z
  - WH→lνbb, ZH→llbb or ννbb
  - Background much reduced, but still Wbb / Zbb or WZ/ZZ with Z→bb
  - Z mass is 91 GeV, close to H at 125 GeV – a ‘shoulder’ on Z-peak
    - Limited mass resolution for bb states
  - Crucial to control backgrounds precisely
- CMS has 2.1σ with full 2011+2012 data
  - ATLAS still analysing the data…



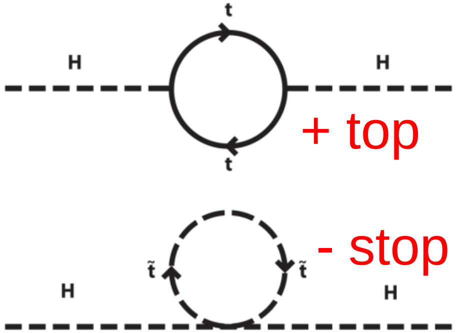
Higgs decays to tau-leptons and more

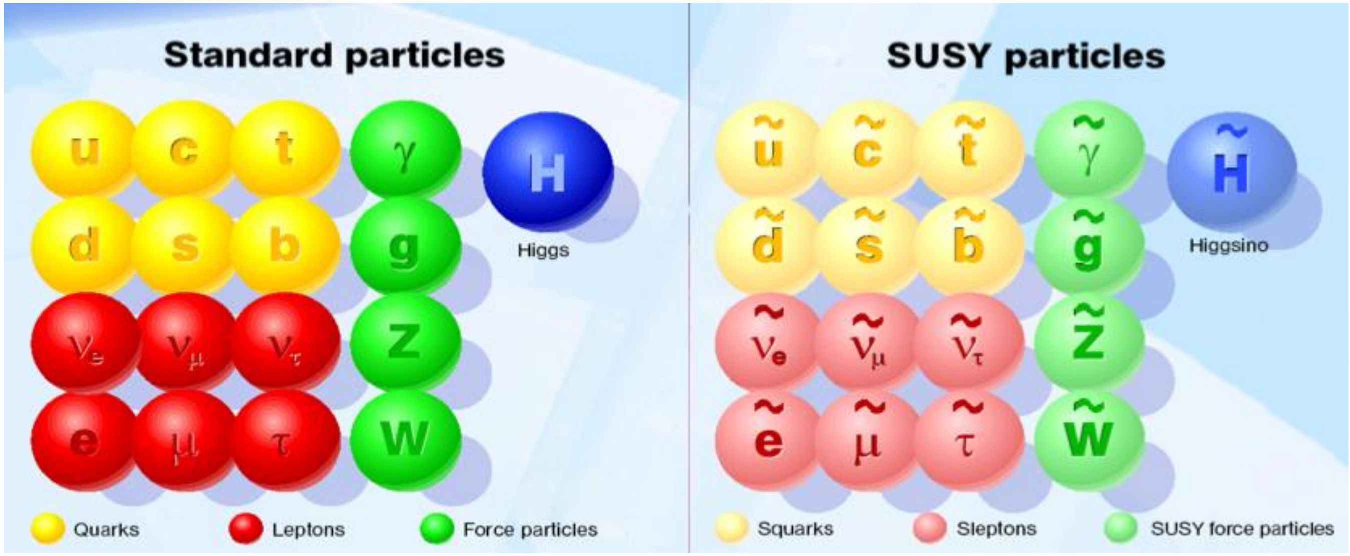
- Expect 6% Higgs decays to tau leptons (τ)
  - Taus decay to e/μ+2ν (missing energy) or a narrow jet of hadrons
  - Again, difficult to separate from background, especially Z→ττ
    - Need signatures with extra jets, improve S/B
  - Results nearing sensitivity to expected SM rate, but not yet conclusive
- Next steps for Higgs studies – what is the nature of this particle, are there more?
  - Try to confirm decays to bb or ττ
  - Measure properties of as many decays as possible, check ‘couplings’ vs. prediction
  - Rule out other spin hypotheses
  - Look for more Higgs bosons!
    - The SM is only the simplest Higgs theory
- Need more LHC data – wait for 2015



But we are not satisfied …

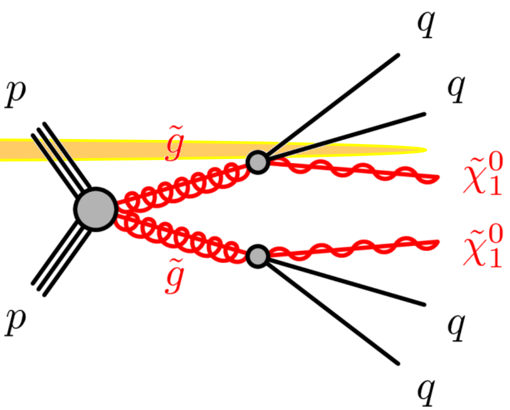
- Higgs mass is very sensitive to ‘loop corrections’ involving other particles
  - Should ‘naturally’ push its mass towards the Planck scale (10^{19} GeV) where all forces are expected to unify
  - But it is light – suggests huge cancellations in contributions from different particles
    - Many theorists find this unnatural and unsatisfactory – the ‘hierarchy problem’
- Supersymmetry
  - Partner for each particle
  - Spin differing by ½ unit



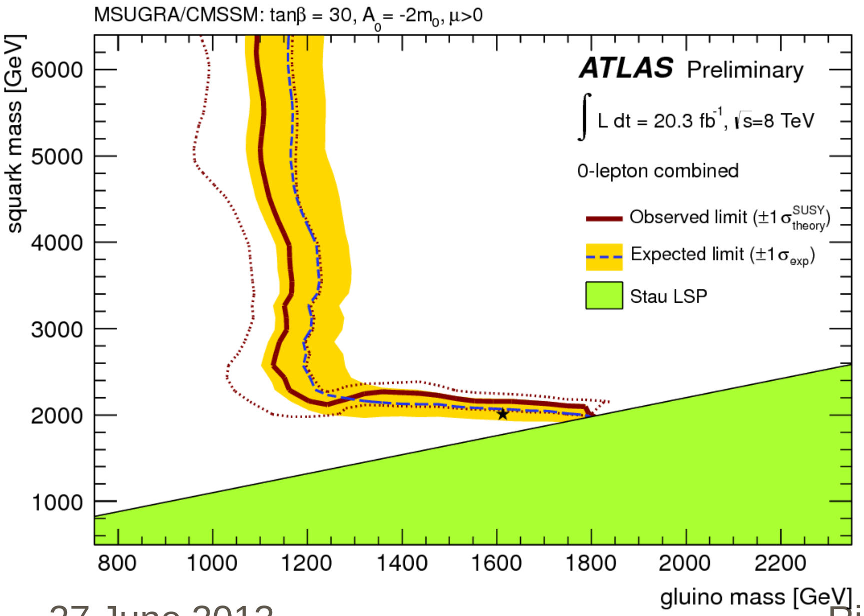


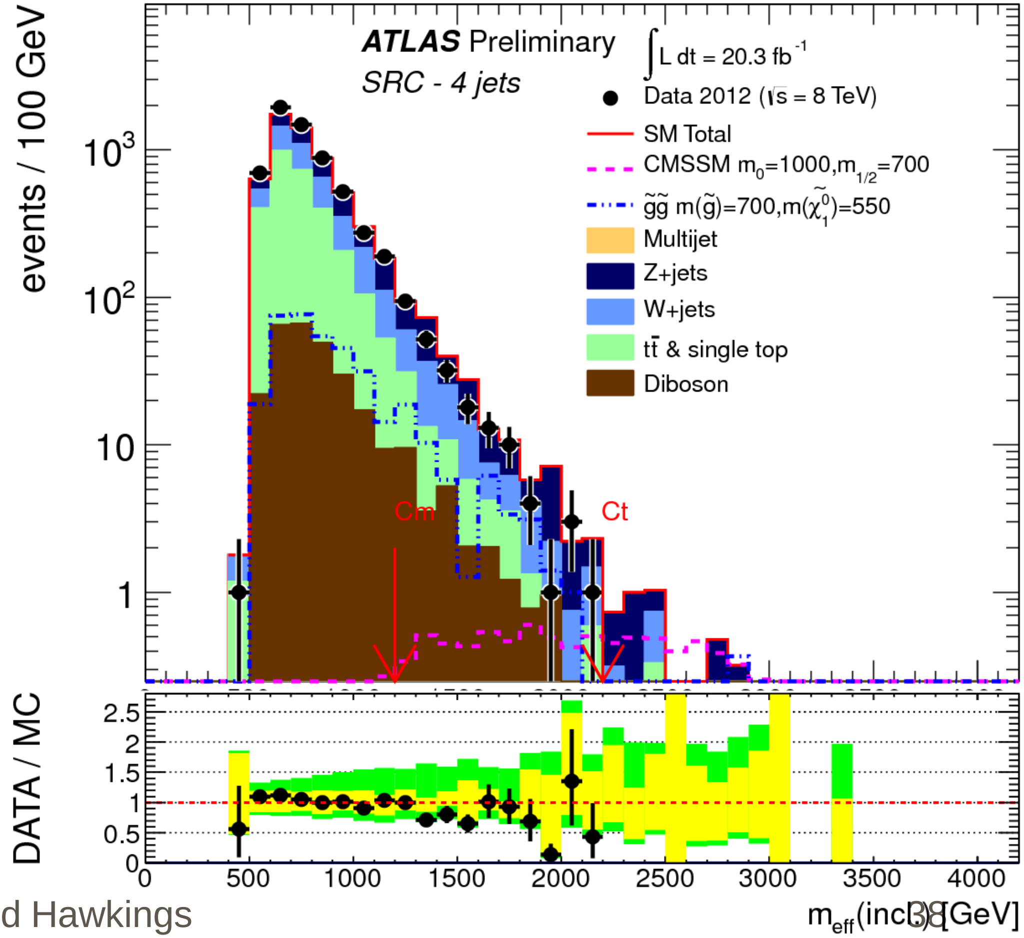
  - Opposite-sign contribution exactly cancels the contribution of each SM particle
    - Some versions also predicts a stable ‘lightest supersymmetric particle’ ⇒ dark matter
- But all these extra particles have not been found – heavier than SM partners?

SUSY searches I



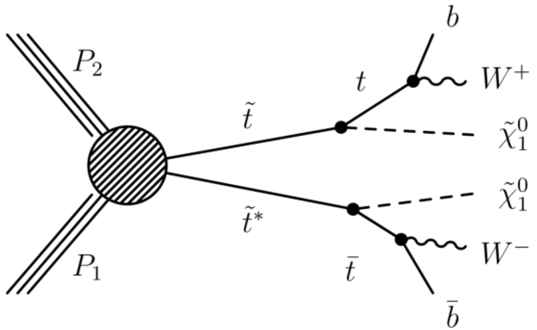
- Squarks/gluinos expected in pairs
  - Decay to jets (from quarks) + ‘missing’ energy from escaping LSP
  - Look for excess of events with large missing energy and m_{eff}
    - M_{eff}=Sum(jet pT)+missing E_T
  - So far, no ‘smoking guns’ – can only exclude regions in parameter space



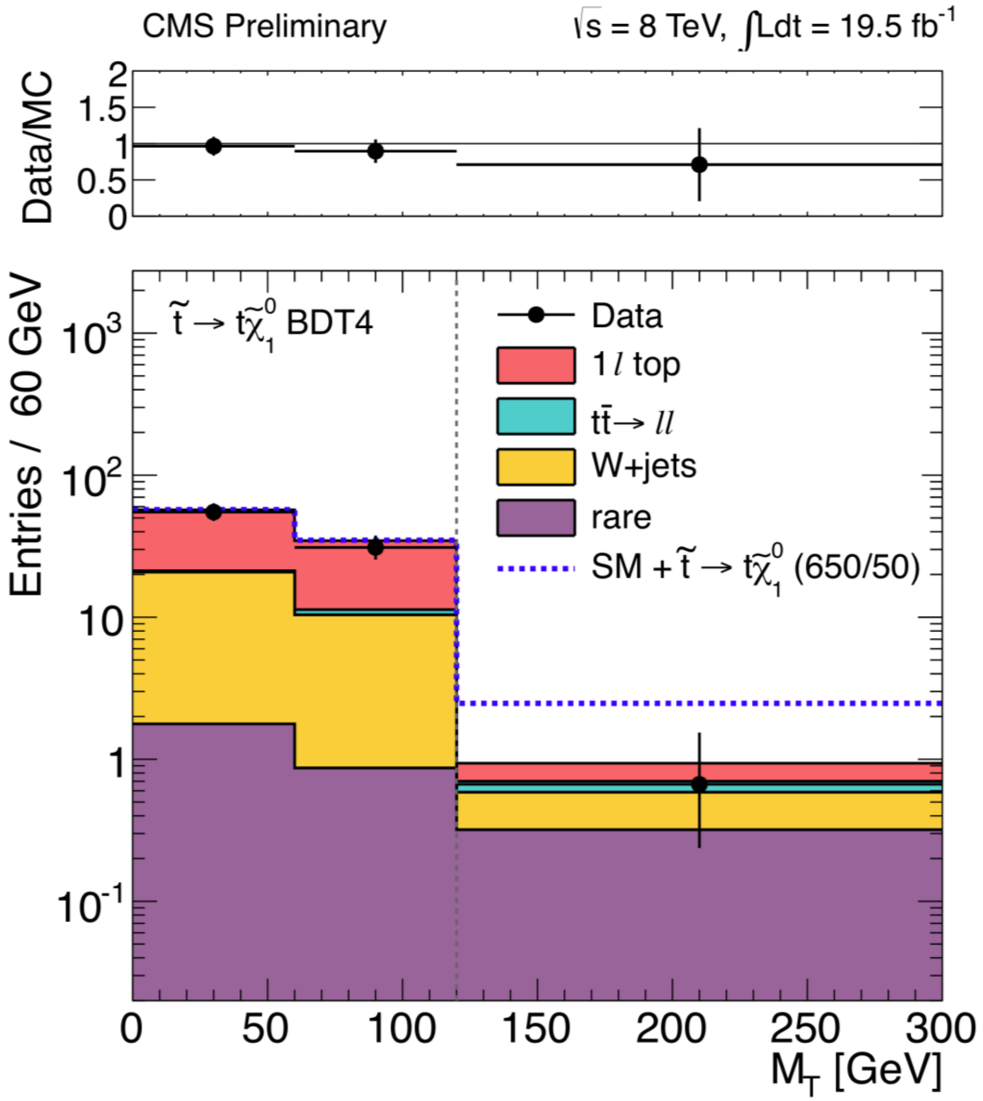


SUSY searches II

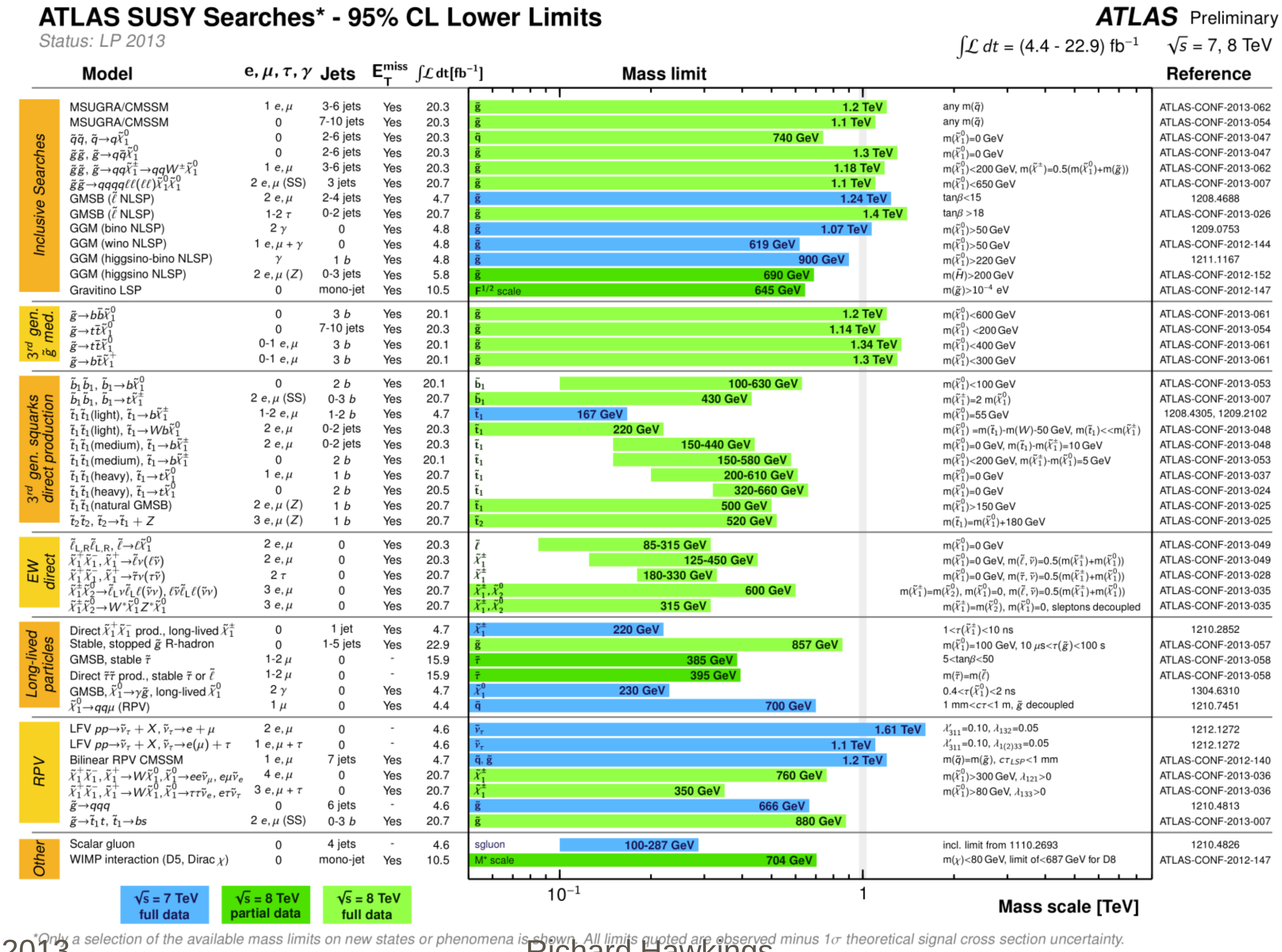
- SUSY particles expected below 1 TeV if relevant to hierarchy problem
  - Less ambitious – only 3rd generation (stop, stbottom) light, rest very heavy?
- Dedicated searches for stop, sbottom



  - Fight against top-pair background, e.g. requiring b-jets, large transverse mass M_T
  - No sign yet, but analysis ongoing …
- Other SUSY searches
  - Look for gauginos instead of squark/gluino
  - LSP may not be stable (R-parity violation)
    - Particles decaying far from collision point



Desperately seeking SUSY – in ATLAS



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: LP 2013

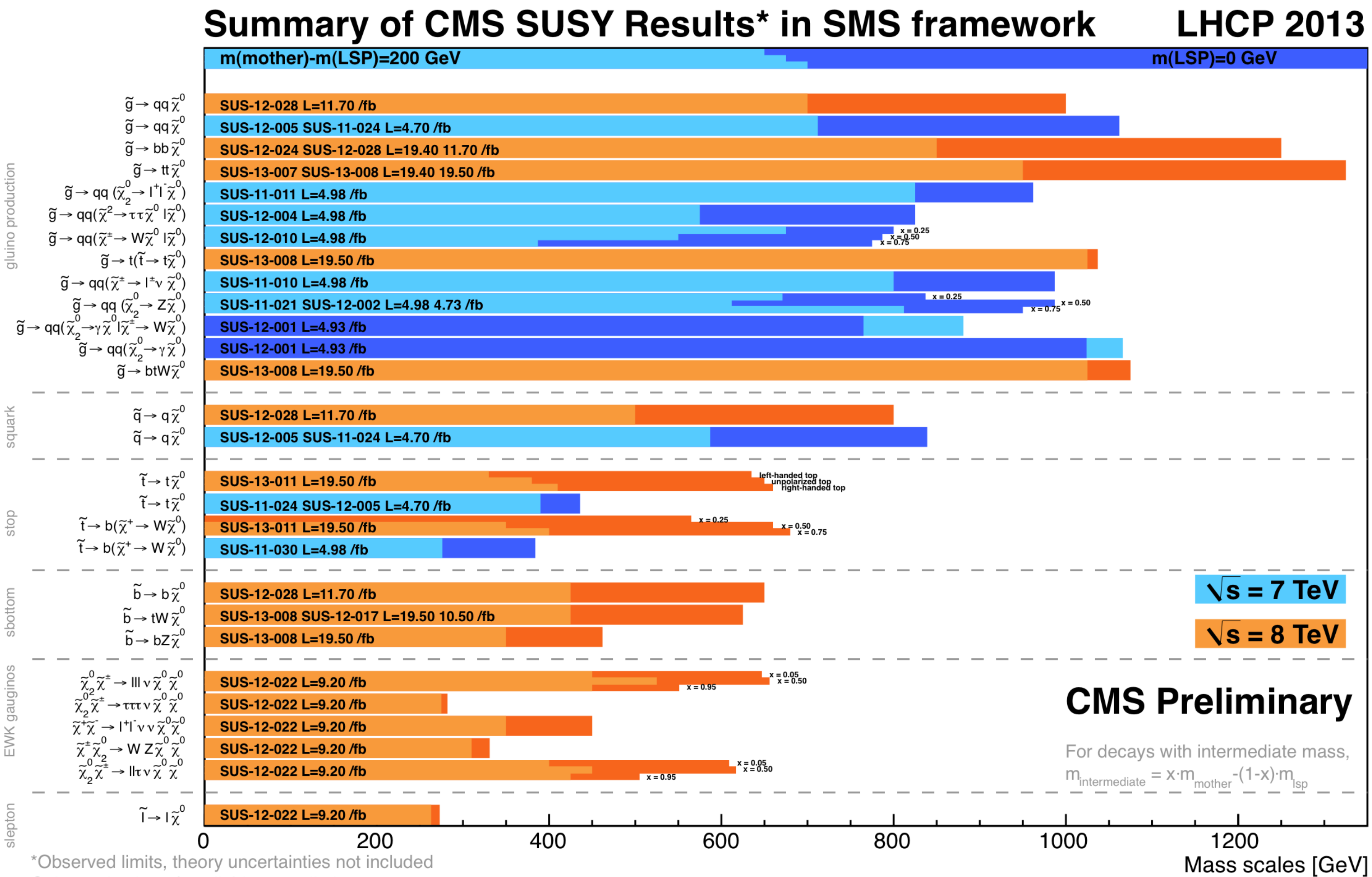
ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (4.4 - 22.9) fb^{-1} $\sqrt{s}$ = 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	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}^0_1\tilde{\chi}^0_1$	2 e,μ (SS)	3 jets	Yes	20.7	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}^0_1$)<650 GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$ 1.07 TeV	m($\tilde{\chi}^0_1$)>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e,\mu+\gamma$	0	Yes	4.8	$\tilde{g}$ 619 GeV	m($\tilde{\chi}^0_1$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	m($\tilde{\chi}^0_1$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m($\tilde{H}$)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	F$^{1/2}$ scale 645 GeV	m($\tilde{g}$)>10^{-4} eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	m($\tilde{\chi}^0_1$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.14 TeV	m($\tilde{\chi}^0_1$) <200 GeV	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}^0_1$)<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-630 GeV	m($\tilde{\chi}^0_1$)<100 GeV	ATLAS-CONF-2013-053
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 430 GeV	m($\tilde{\chi}^\pm_1$)=2 m($\tilde{\chi}^0_1$)	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 167 GeV	m($\tilde{\chi}^0_1$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 220 GeV	m($\tilde{\chi}^0_1$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}^\pm_1$)	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 150-440 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^\pm_1$)=10 GeV	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	m($\tilde{\chi}^0_1$)>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 520 GeV	m($\tilde{t}_1$)=m($\tilde{\chi}^0_1$)+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 85-315 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}^\pm_1$ 125-450 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2013-049
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	0	Yes	20.7	$\tilde{\chi}^\pm_1$ 180-330 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2013-028
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.7	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 600 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2013-035
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W^*\tilde{\chi}^0_1Z^*\tilde{\chi}^0_1$	3 e,μ	0	Yes	20.7	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 315 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, sleptons decoupled	ATLAS-CONF-2013-035
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	0	1 jet	Yes	4.7	$\tilde{\chi}^\pm_1$ 220 GeV	1<τ($\tilde{\chi}^\pm_1$)<10 ns	1210.2852
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 857 GeV	m($\tilde{\chi}^0_1$)=100 GeV, 10 μs<τ($\tilde{g}$)<100 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$	1-2 μ	0	-	15.9	$\tilde{\tau}$ 385 GeV	5<tanβ<50	ATLAS-CONF-2013-058
	Direct $\tilde{\tau}\tilde{\tau}$ prod., stable $\tilde{\tau}$ or $\tilde{\ell}$	1-2 μ	0	-	15.9	$\tilde{\tau}$ 395 GeV	m($\tilde{\tau}$)=m($\tilde{\ell}$)	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{g}$, long-lived $\tilde{\chi}^0_1$	2 γ	0	Yes	4.7	$\tilde{\chi}^0_1$ 230 GeV	0.4<τ($\tilde{\chi}^0_1$)<2 ns	1304.6310
	$\tilde{\chi}^0_1\to qq\mu$ (RPV)	1 μ	0	Yes	4.4	$\tilde{q}$ 700 GeV	1 mm<$c\tau$<1 m, $\tilde{g}$ decoupled	1210.7451
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e,μ	0	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	0	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q}$, $\tilde{g}$ 1.2 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e,μ	0	Yes	20.7	$\tilde{\chi}^\pm_1$ 760 GeV	m($\tilde{\chi}^0_1$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	0	Yes	20.7	$\tilde{\chi}^\pm_1$ 350 GeV	m($\tilde{\chi}^0_1$)>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6 jets	-	4.6	$\tilde{g}$ 666 GeV		1210.4813
	$\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

*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.

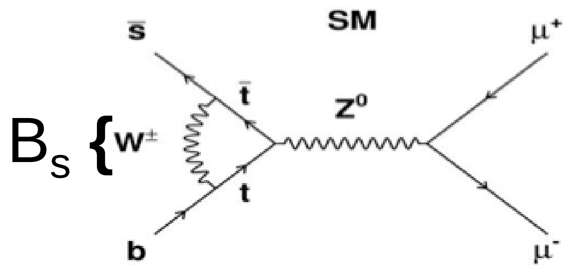
Desperately seeking SUSY – in CMS



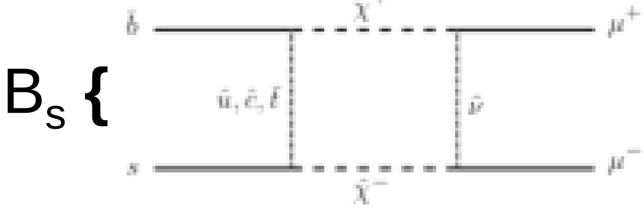
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

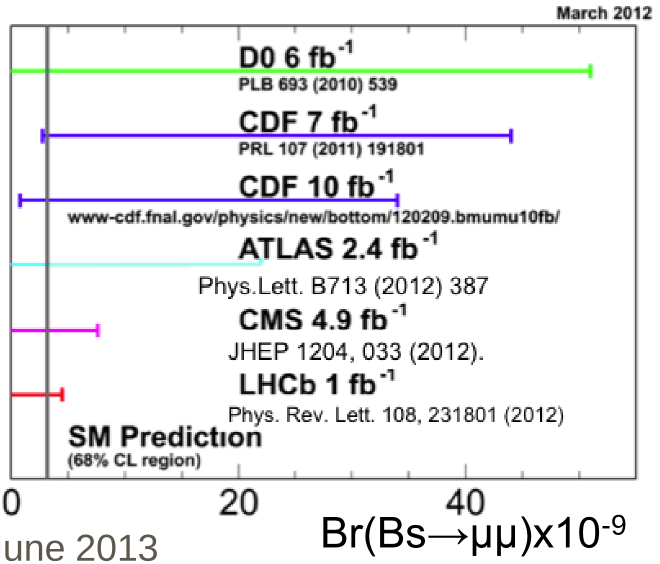
Rare b-decays, another window on SUSY

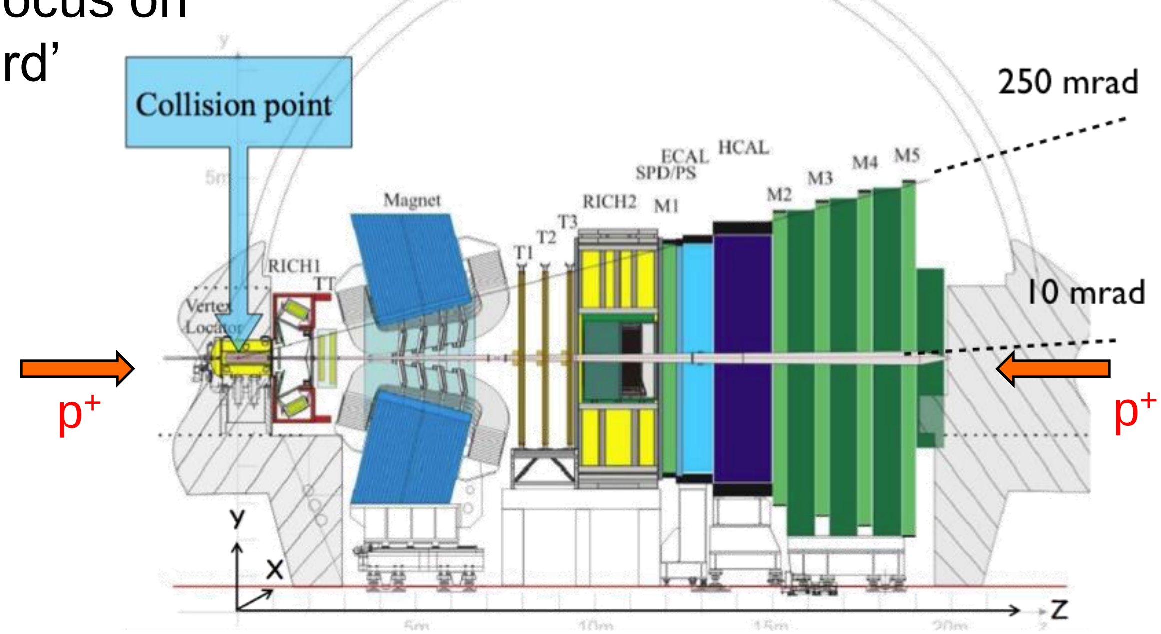
- Decays of B-mesons (bound state of a b and another quark) can 'feel' effect of SUSY
  - In SM, fraction of $B_s \rightarrow \mu\mu$ is 3.5 10^{-9} – **tiny!**
  - In SUSY or other theories, can be significantly enhanced due to extra diagrams
- Long experimental effort to probe this decay
  - Need to study tens of billions of B mesons
- LHCb detector specifically built to focus on b-decays, many of which go 'forward'



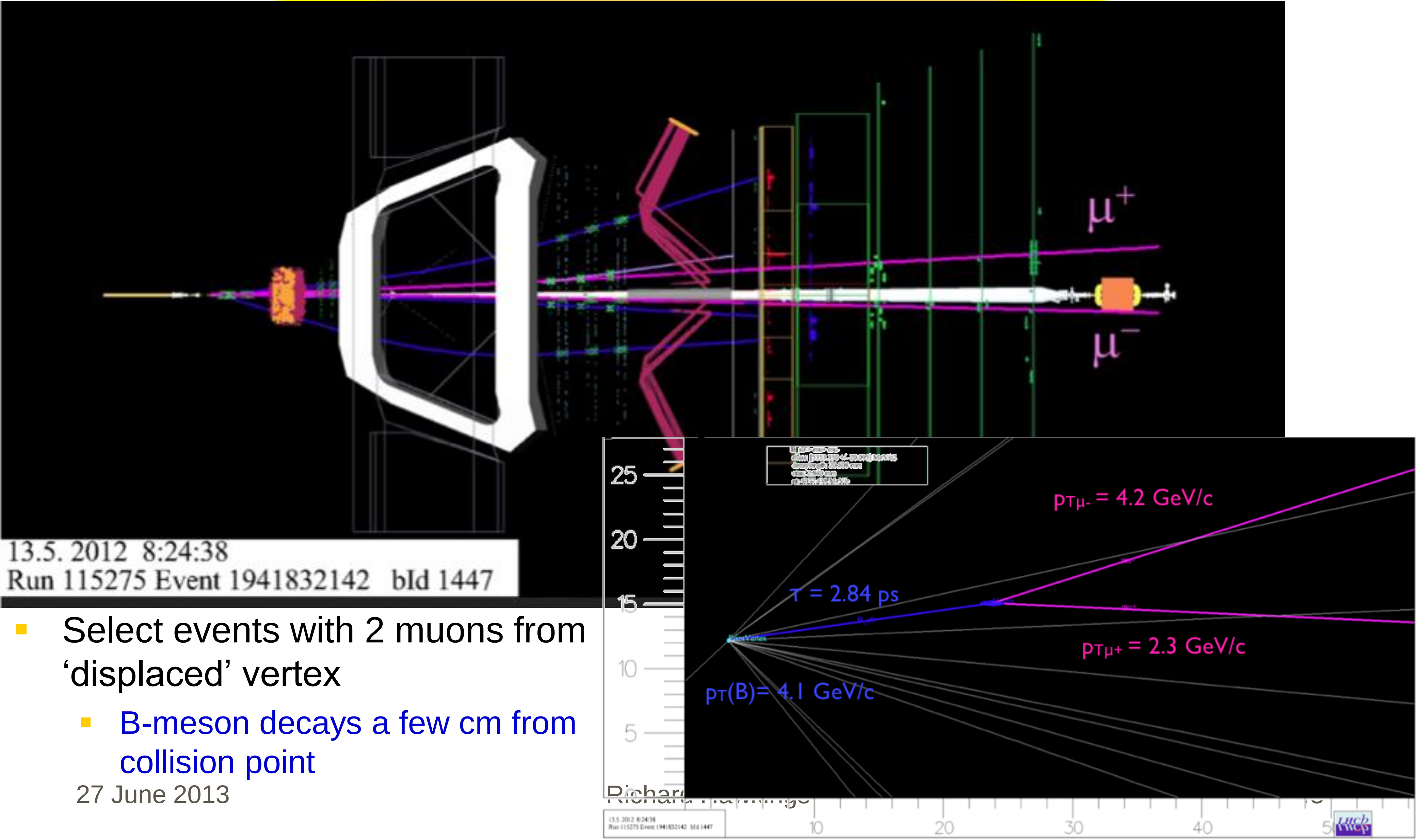
SUSY?







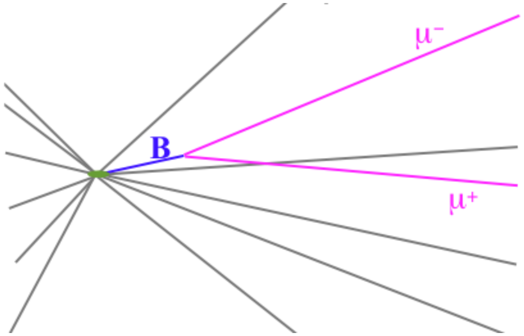
$B_s \rightarrow \mu^+\mu^-$ candidate in LHCb detector

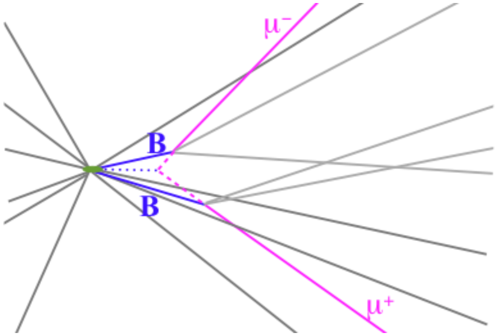


- Select events with 2 muons from 'displaced' vertex
  - B-meson decays a few cm from collision point

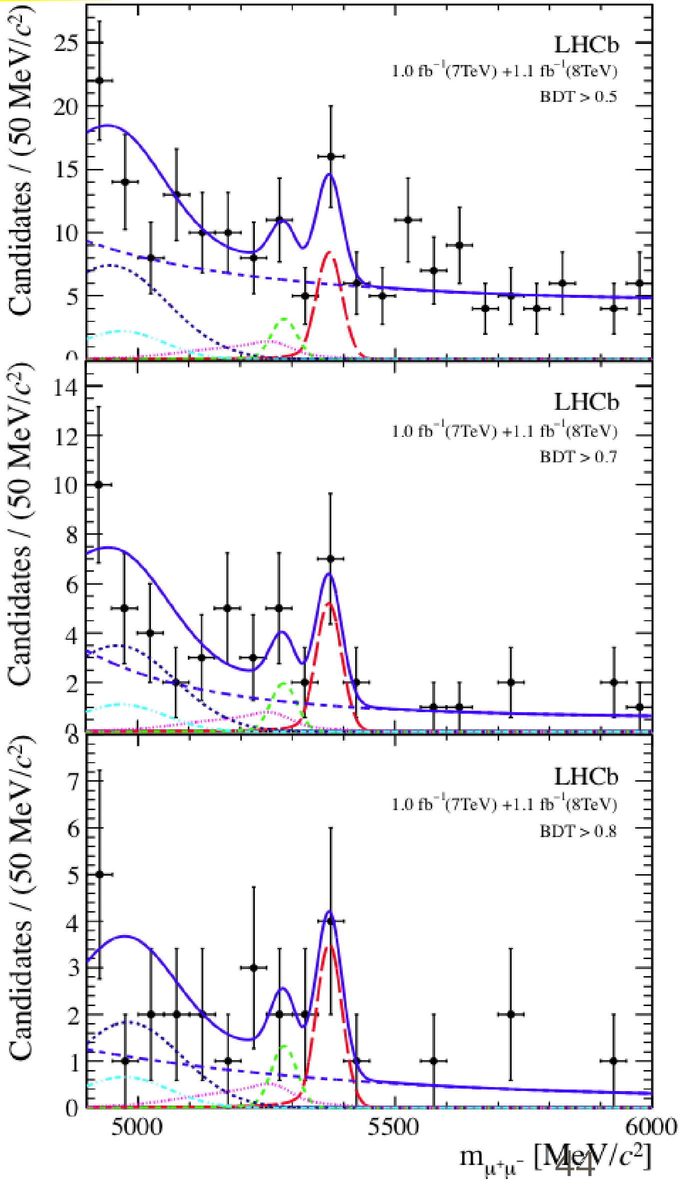
Measurement of $B_s \rightarrow \mu^+\mu^-$ decay

- Huge data reduction online and offline to select two-muon candidate events
  - Remaining background from muons from 2 different $B \rightarrow \mu + X$ decays in same event



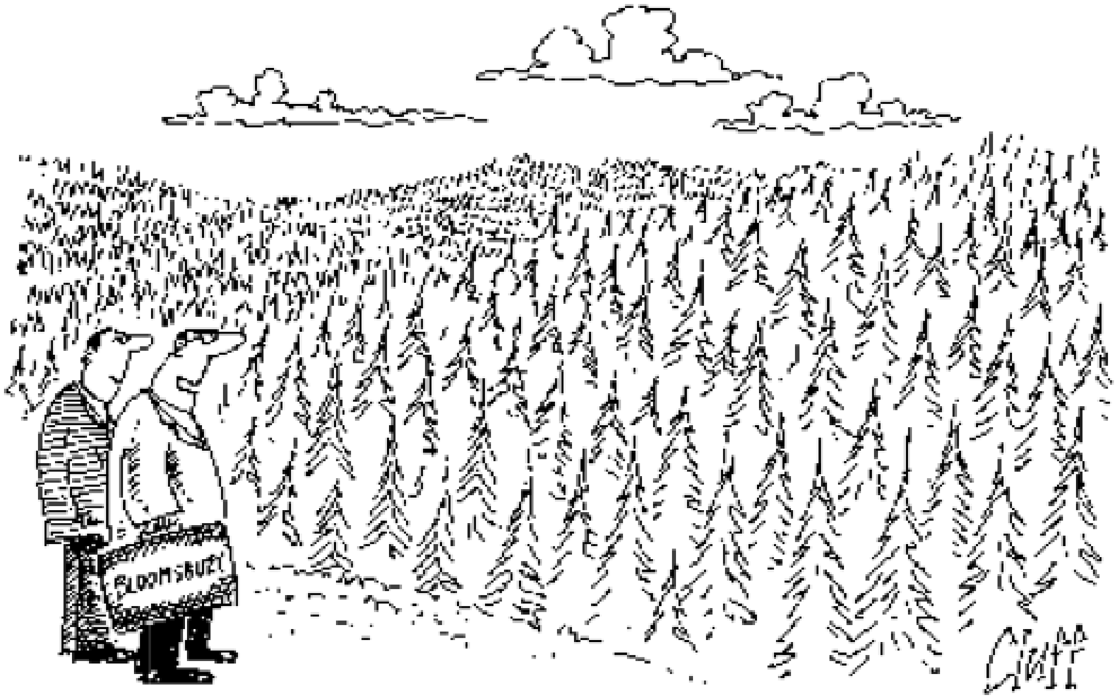


- Reconstruct invariant mass of μμ, look for peak
  - Cut on kinematic and particle ID quantities (BDT) to reduce background…
  - Significant peak (3.5σ), $Br(Bs \rightarrow \mu\mu) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$
- Triumph of experimental work, and SM prediction
  - Significant constraint on SUSY and other theories



Is SUSY dead?

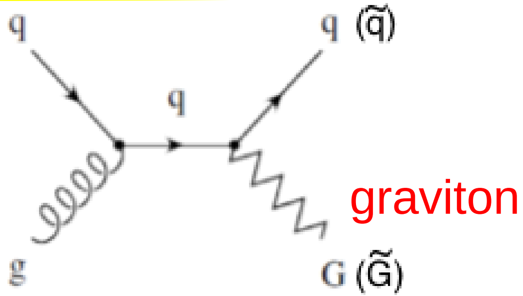
- SUSY remains ‘an attractive theory supported by a great mass of no evidence’
    - Unlikely evidence will be found in the 2011-2012 dataset now
- But unwilling to give it up …
    - Focus on 3rd generation (stop etc)
    - ‘Compressed’ or ’stealth’ scenarios where mass splittings are very small – hard to pick out from background
    - More unusual signatures
- SUSY is a general class of theories – moving away from ‘minimal’ models
    - Good ‘benchmark’ for other theories
- Hope for surprises in 2015
    - Mass reach will be almost doubled

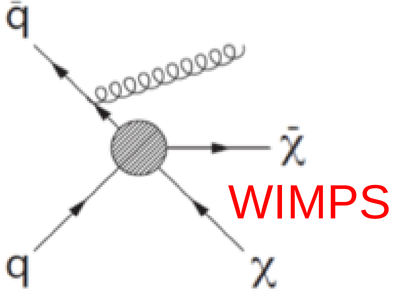


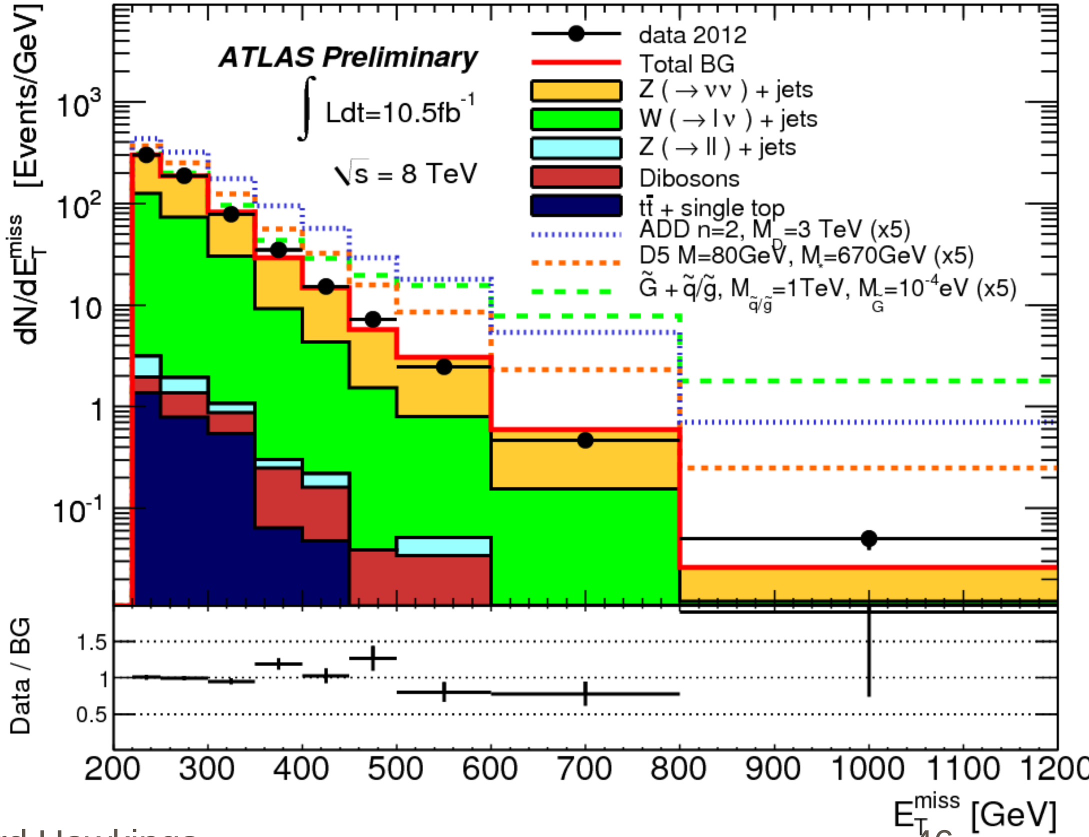
‘One day all these trees will be SUSY phenomenology papers’

Extra dimensions / dark matter

- Perhaps gravity appears weak because it acts in 4+n dimensions
    - The n extra dimensions (ED) are ‘rolled up’, and we only see gravity’s weaker ‘echo’ in our 4 dim world
    - Brings unification scale down to ~TeV
- ADD model – gravitons (G) could be produced and ‘disappear’ into ED …
    - Look for unbalanced events with one jet recoiling against nothing
- Also sensitive to pair production of ‘WIMPS’ (X) in the GeV-TeV range
    - Weakly interacting massive particle – candidate for dark matter
- Nothing found so far; LHC experiments can constrain these models

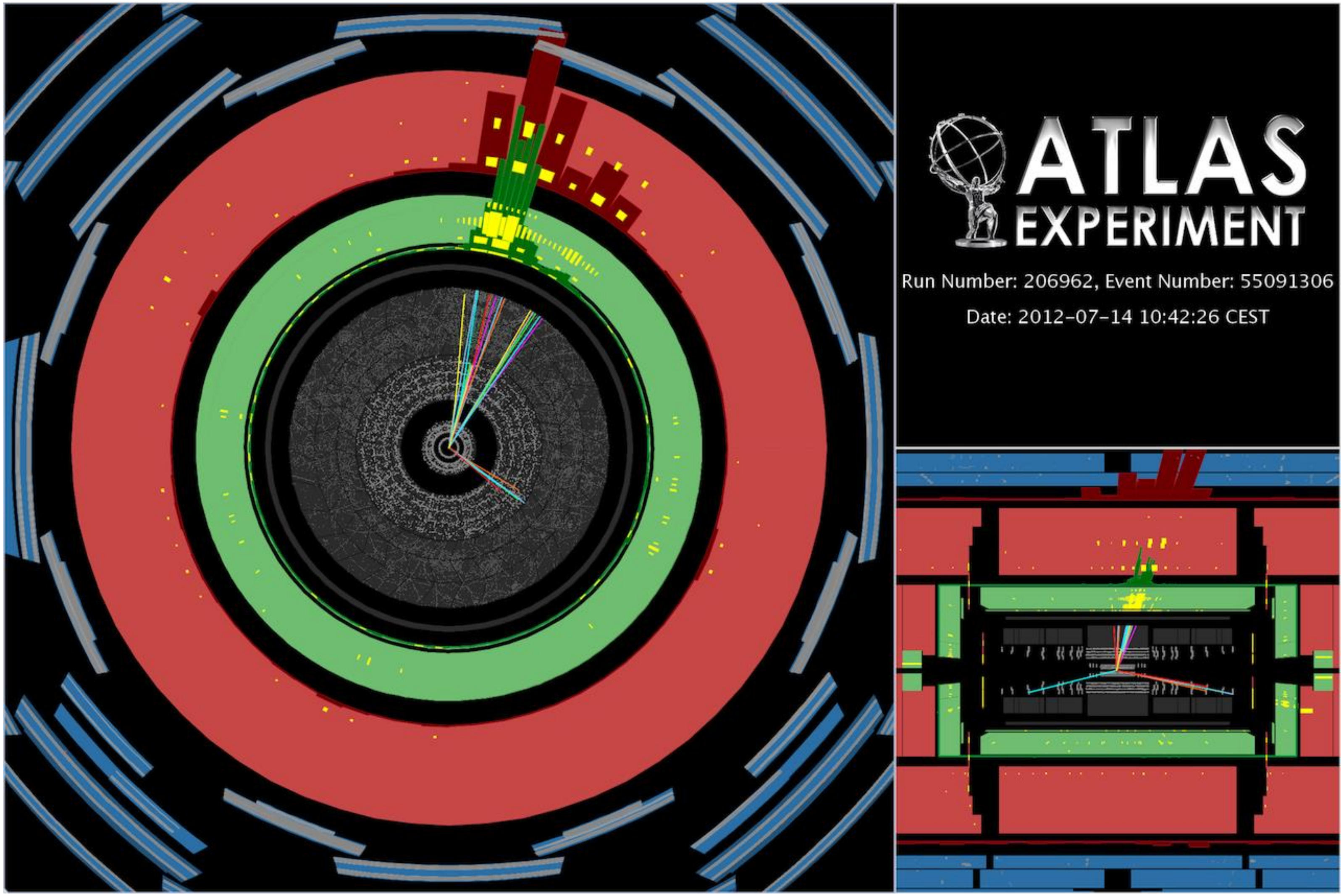






Monojet candidate event in ATLAS

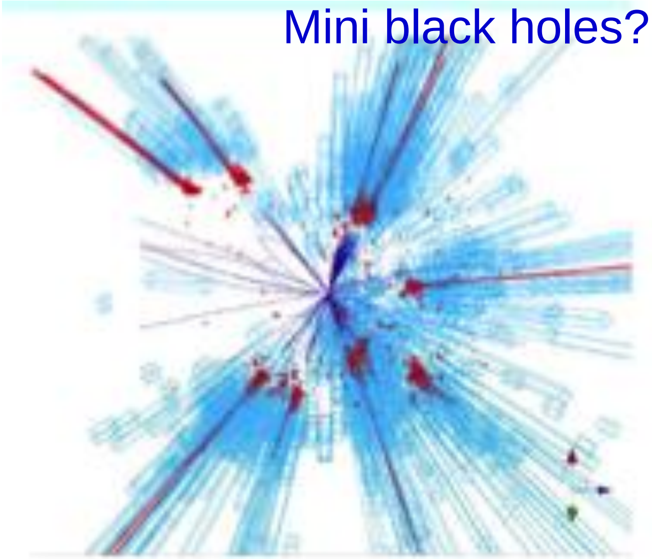
- Could also be from Z(→νν)+jets production …



Other possibilities …

- Many other exciting possibilities for things we might find
  - New quarks, leptons or heavy neutrinos, new heavy gauge bosons: W/Z-prime
  - Models where Higgs is a bound state, e.g. Technicolour
  - More Higgs bosons – Higgs doublet, triplet, Little Higgs models
  - Something in the top quark sector – production or decay?

Murayama LP03



Mini black holes?

- Unlikely now to see more at 8 TeV
- Need more energy, more luminosity
  - ⇒ LHC upgrades

Conclusions

- LHC has been a long time coming, but a fantastic machine for particle physics
  - Machine and detector performance have exceeded our expectations
  - We can do physics with 35 pileup events per collision
  - Standard Model works remarkably well at LHC energies
  - **We have found a Higgs boson**
    - Looks Standard Model-like so far, but it is early days
    - We are only at the start of Higgs boson physics studies
  - We haven’t found anything beyond the SM yet, but there is no shortage of ideas

- Looking forward to the 13-14 TeV run starting in 2015
  - We have a lot of new territory to explore
  - And a physics case and program of detector upgrades for the next 10-20 years

- LHC performance is the key to all this – please help us!