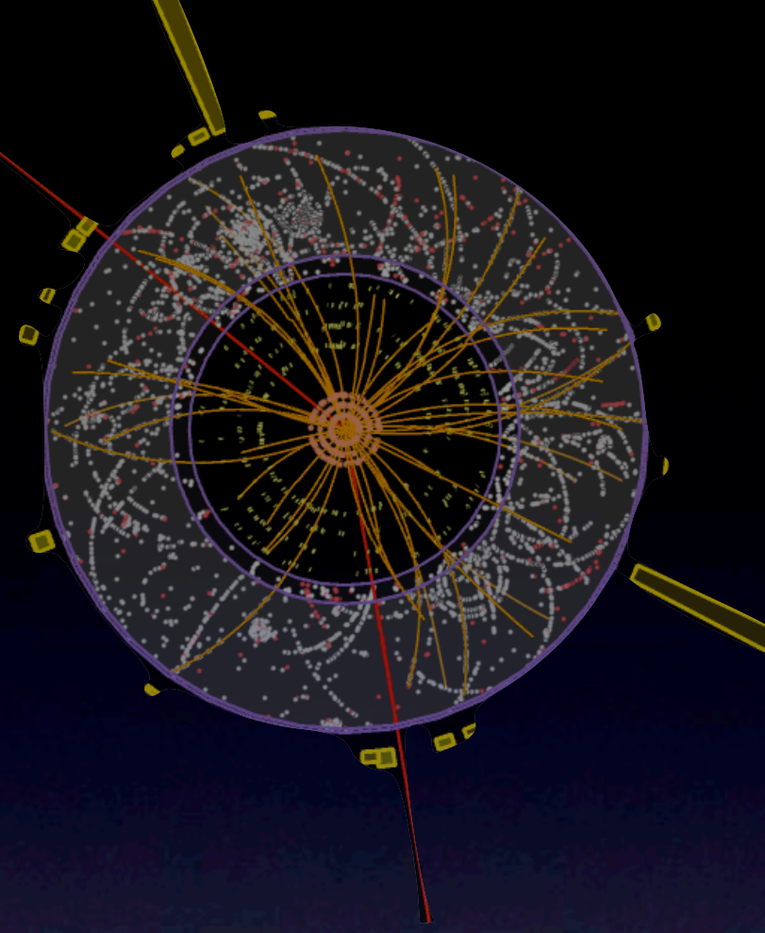
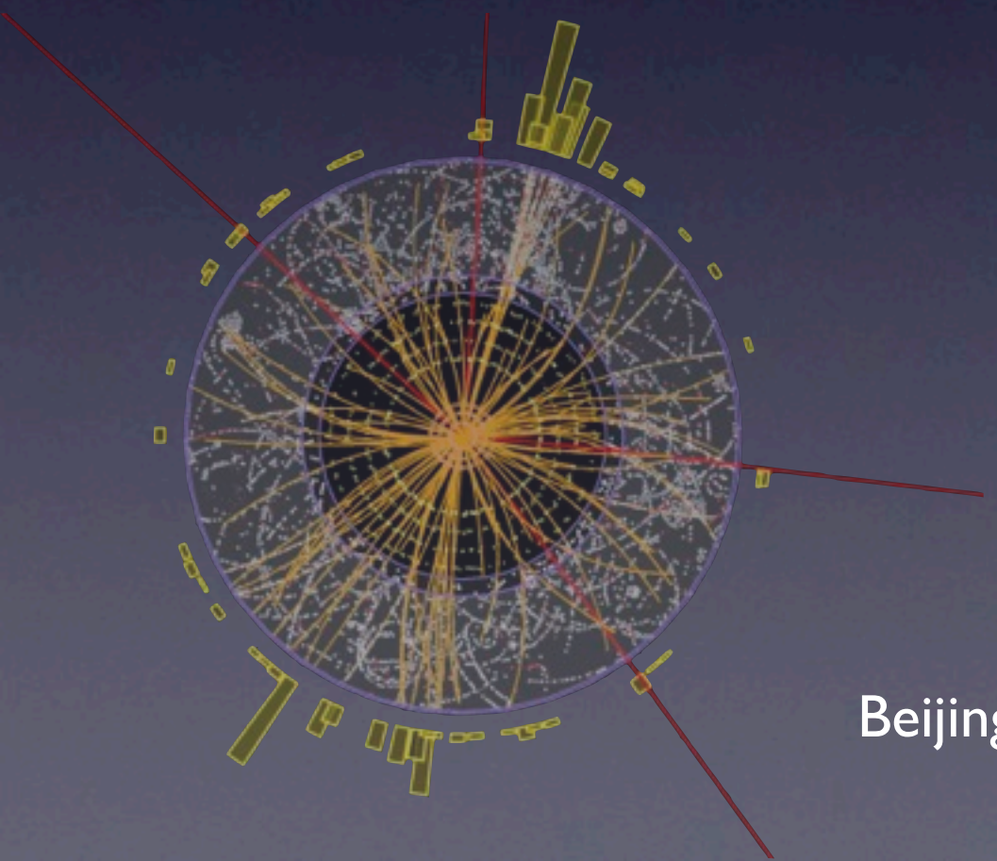


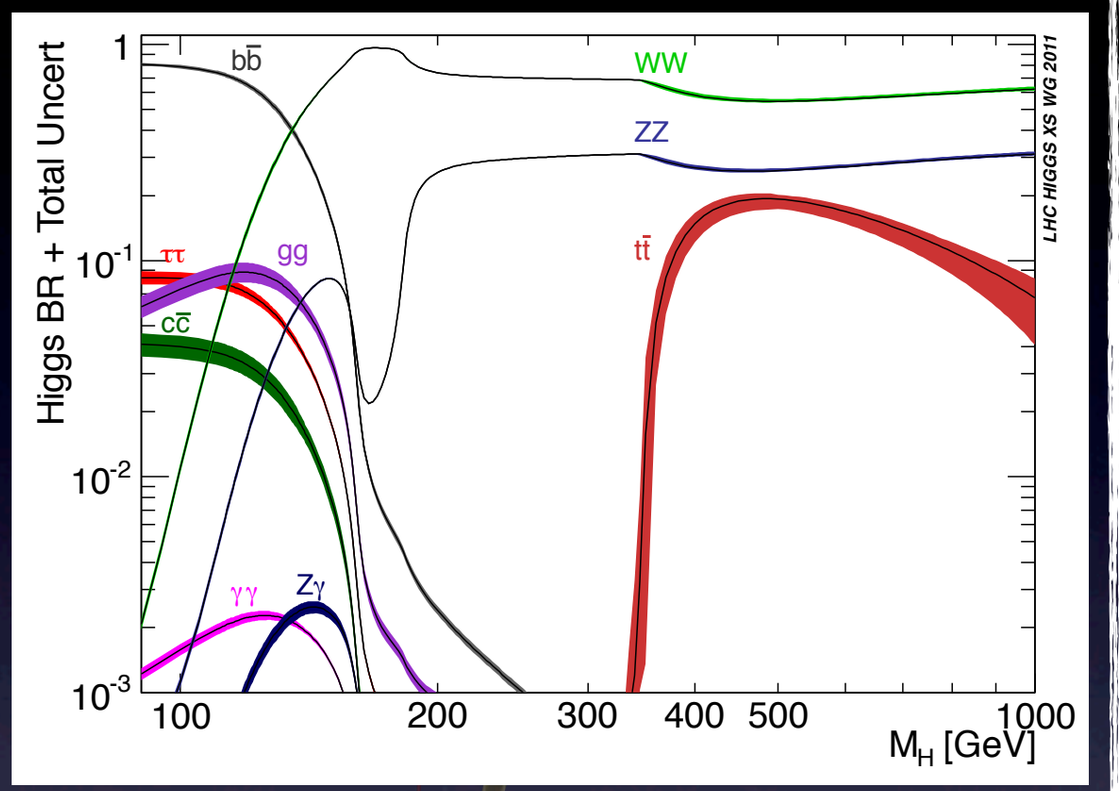
Search for the Standard Model Higgs boson in the $H \to ZZ^{(*)} \to 4l$ decay channel with the ATLAS detector



Julia Hoffman
Southern Methodist University
on behalf of the ATLAS Collaboration

SUSY 2012
Beijing, August 13 - August 18 2012

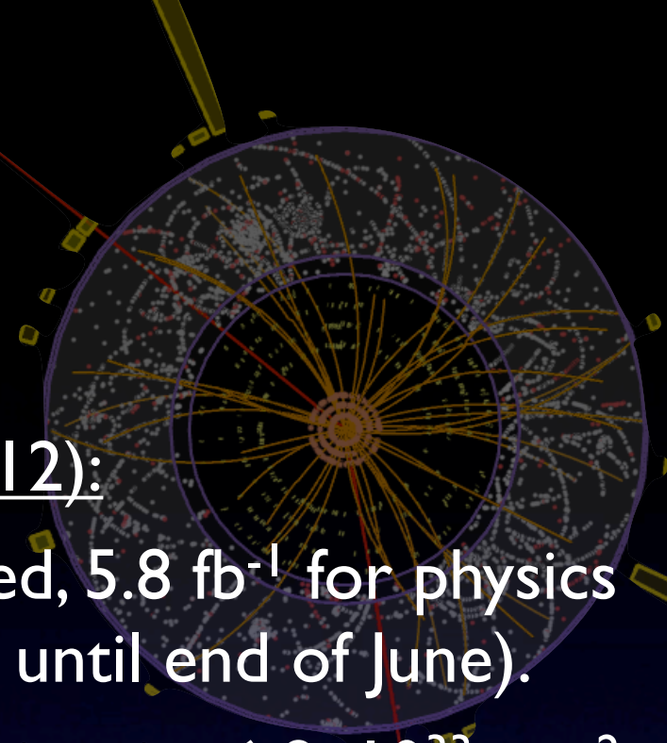
Introduction



- Signature: $H \rightarrow ZZ^{(*)} \rightarrow 4l$ ($l = e, \mu$)
- Four final states: 4e, 4μ, 2e2μ, 2μ2e.
- The "golden channel":
  - Small rates, but high S/B
  - Can be fully reconstructed: mass resolution ~2% at m_H=130 GeV.
- Cross section × BR (at m_H=125 GeV):
  - ~4 fb at $\sqrt{s}$=7 TeV
  - ~5 fb at $\sqrt{s}$=8 TeV
- Mass range under consideration: 110 GeV to 600 GeV.

- Backgrounds:
  - Irreducible (dominant for $m_H > 2m_Z$): $pp \rightarrow ZZ^{(*)} \rightarrow 4l$.
  - Reducible ($m_H < 2m_Z$): Z+jets, $Zb\bar{b}$, $t\bar{t}$.

Dataset

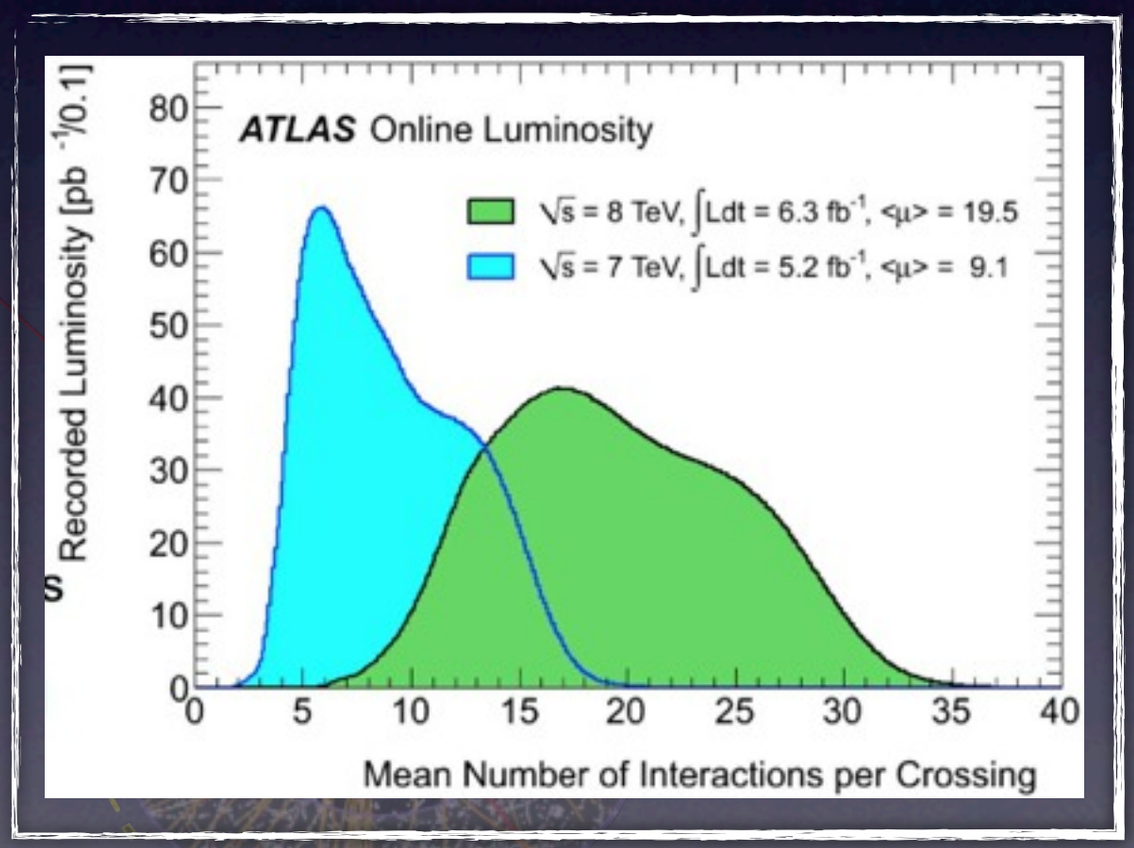


<u>7 TeV dataset (2011):</u>

- 5.3 fb^{-1} recorded, 4.8 fb^{-1} for physics.
- Peak stable luminosity 3.6×10^{33} $cm^{-2}s^{-1}$.

<u>8 TeV dataset (2012):</u>

- 6.3 fb^{-1} recorded, 5.8 fb^{-1} for physics (data collected until end of June).
- Peak stable luminosity 6.8×10^{33} $cm^{-2}s^{-1}$.

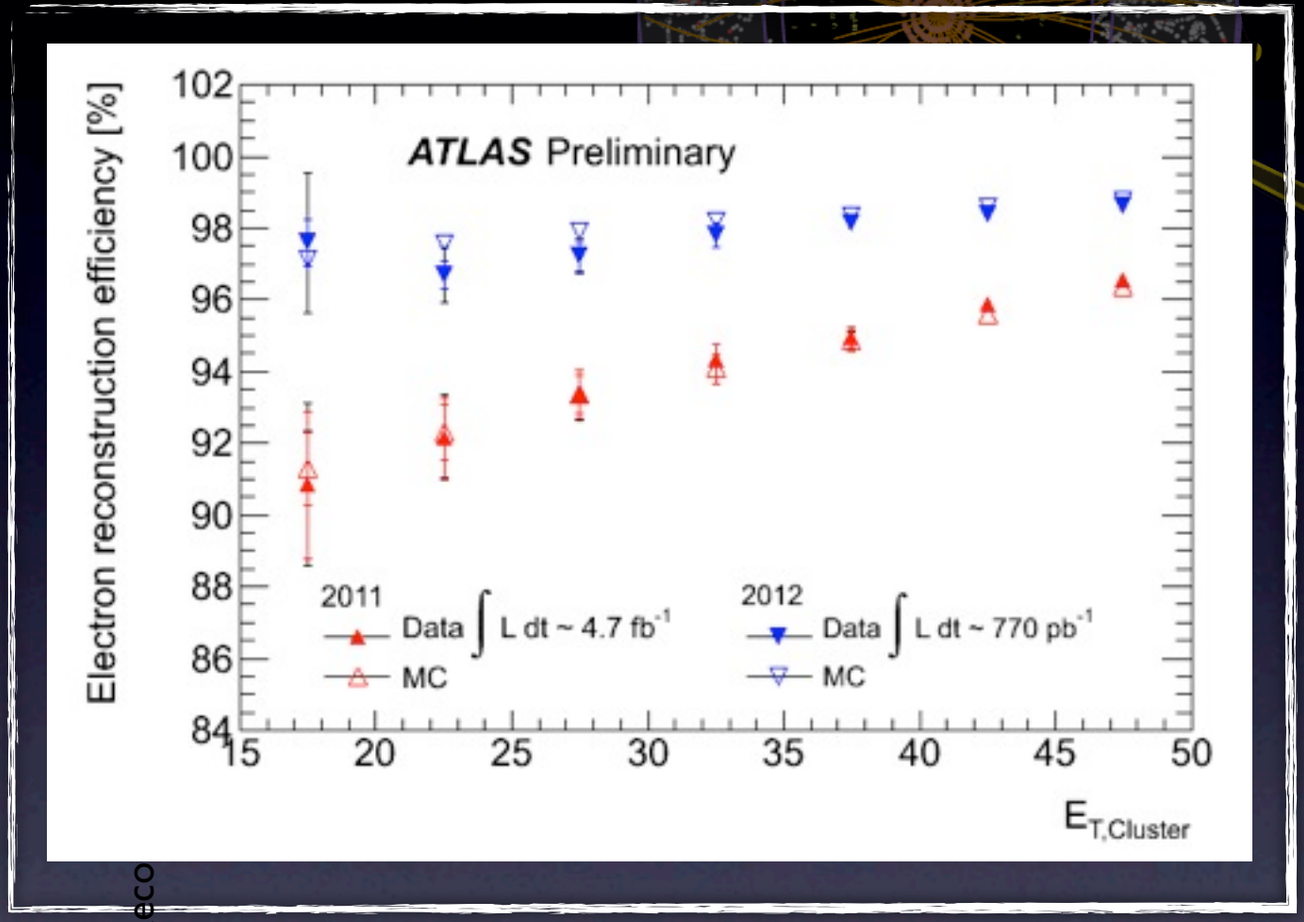


- Substantially more pileup in 2012
  - Detector performance and simulation are directly affected!
- Need to:
  - maintain level of detector performance
  - ensure proper modeling in simulation

Lepton Reconstruction and Identification

Electrons in 2012 data (8TeV)

- Improved reconstruction
  - New pattern finding/track fit
- Improved identification
  - Pile-up robust
  - Higher rejection and efficiency than in 2011
  - Improved track-cluster matching, to recover electrons undergoing hard bremmstrahlung



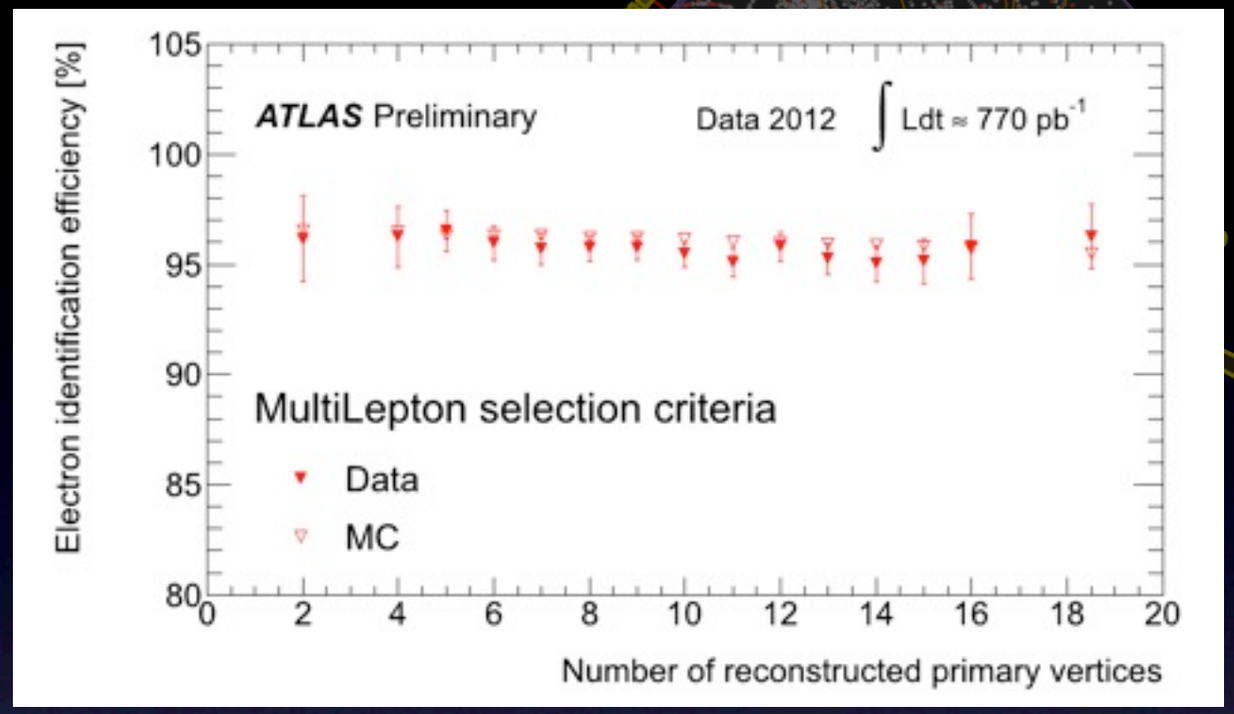
Muons

- Use ID tracks matched with partial or complete track segments in the muon spectrometer
- Extended coverage:
  - ID tracks + energy deposits in calorimeter ($|\eta|<0.1$, $p_T>15$GeV)
  - Muon Spectrometer stand-alone ($2.5<|\eta|<2.7$)

Lepton Reconstruction and Identification

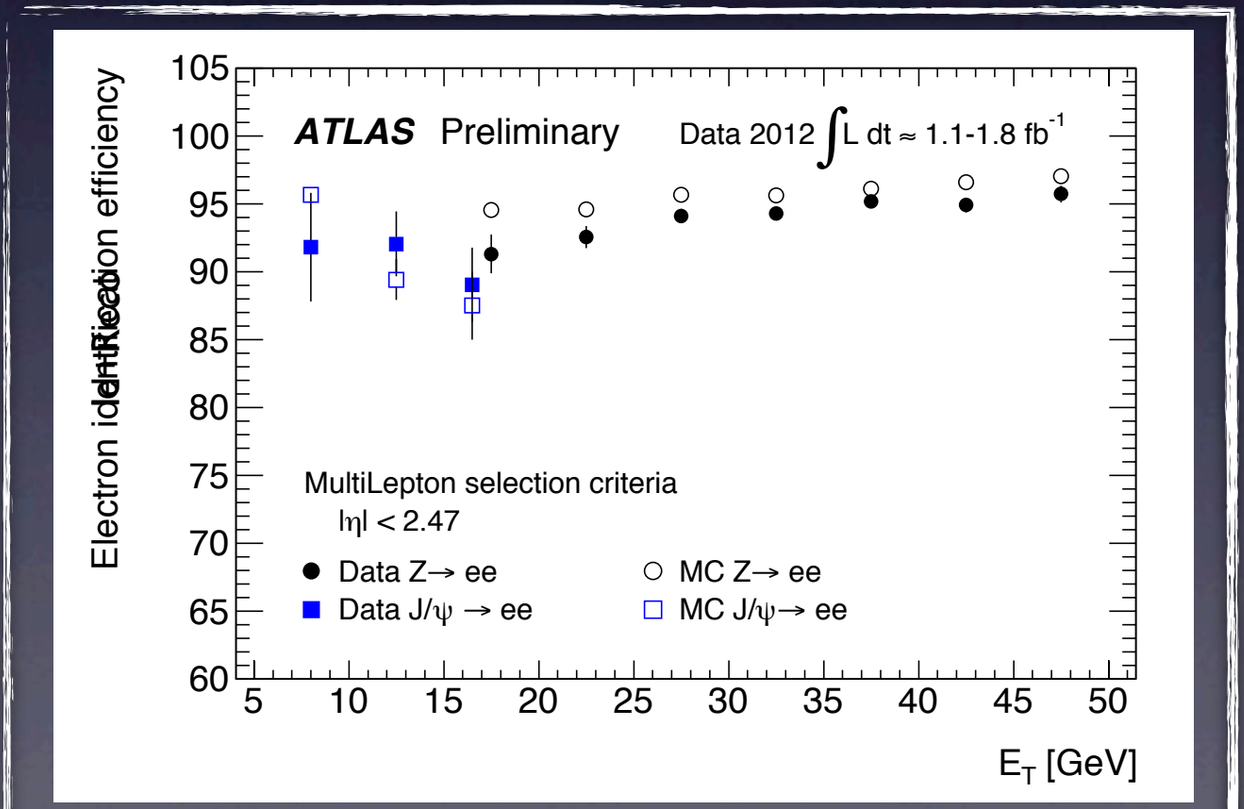
Electrons in 2012 data (8TeV)

- Improved reconstruction
  - New pattern finding/track fit
- Improved identification
  - Pile-up robust
  - Higher rejection and efficiency than in 2011
  - Improved track-cluster matching, to recover electrons undergoing hard bremmstrahlung



Muons

- Use ID tracks matched with partial or complete track segments in the muon spectrometer
- Extended coverage:
  - ID tracks + energy deposits in calorimeter ($|\eta|<0.1$, $p_T>15$GeV)
  - Muon Spectrometer stand-alone ($2.5<|\eta|<2.7$)



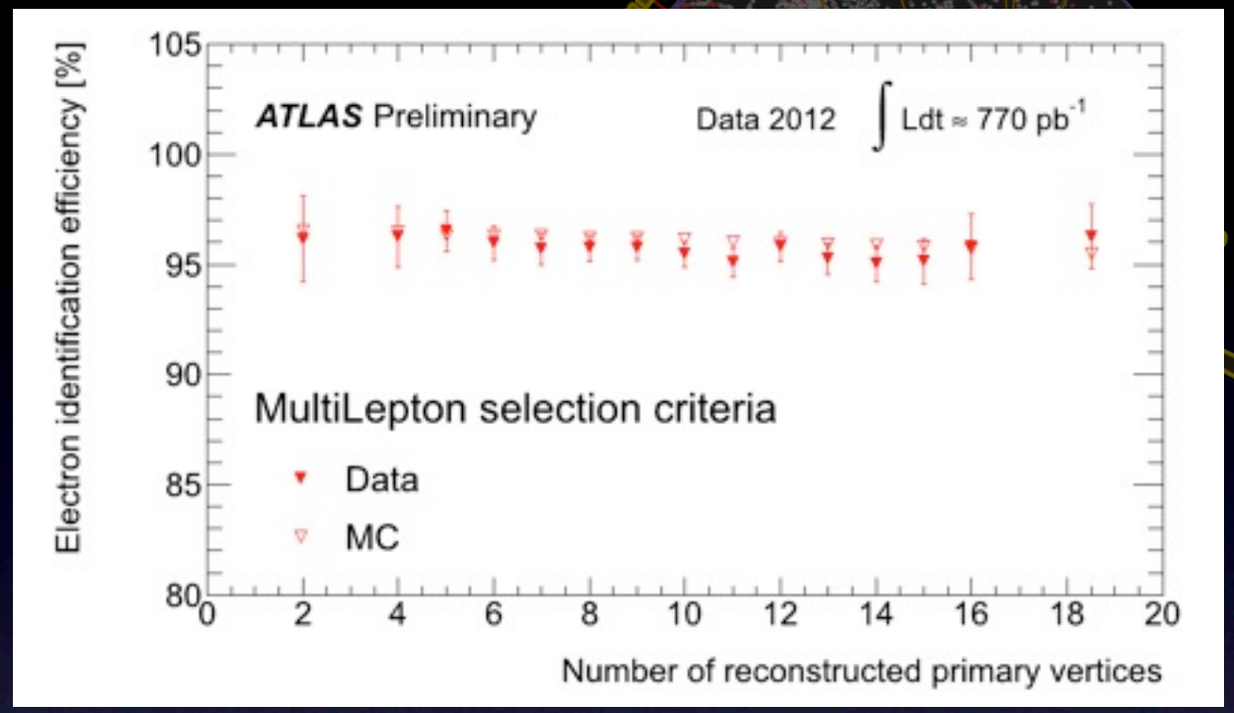
Lepton Reconstruction and Identification

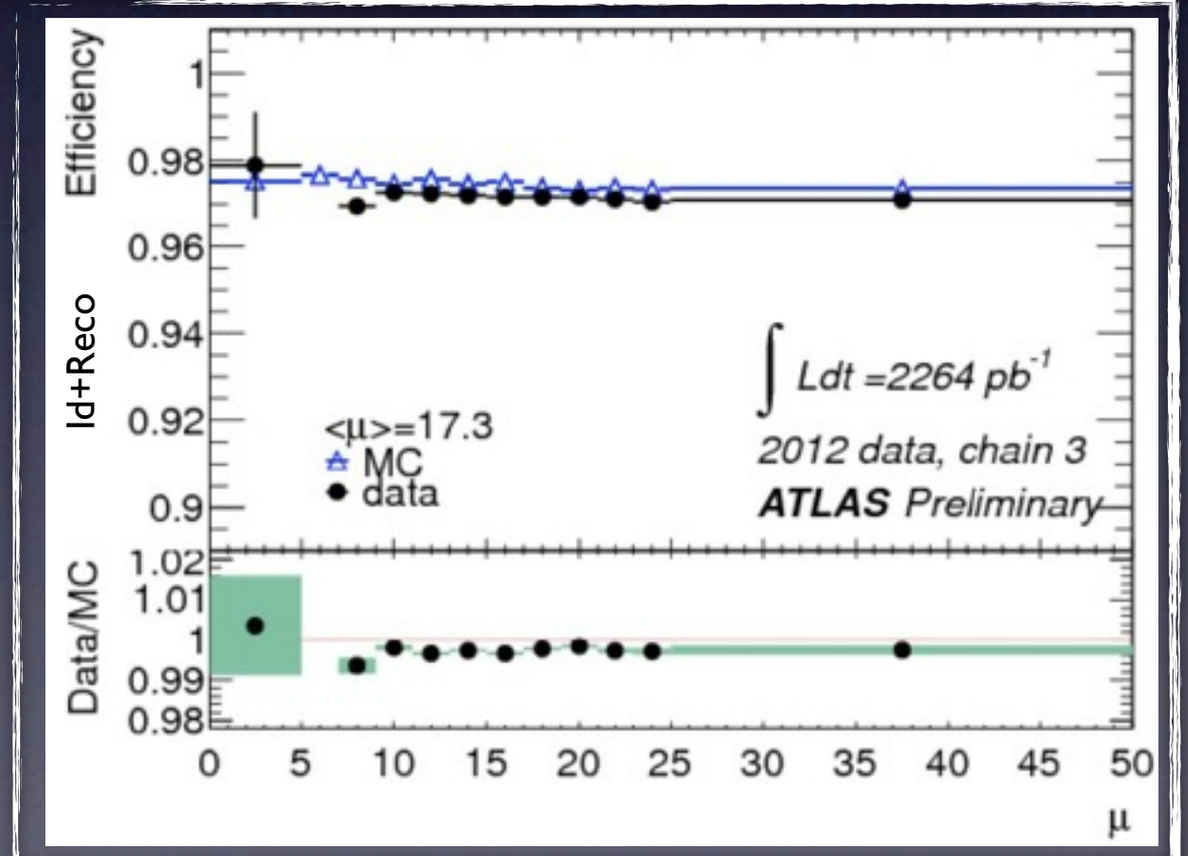
Electrons in 2012 data (8TeV)

- Improved reconstruction
  - New pattern finding/track fit
- Improved identification
  - Pile-up robust
  - Higher rejection and efficiency than in 2011
  - Improved track-cluster matching, to recover electrons undergoing hard bremmstrahlung

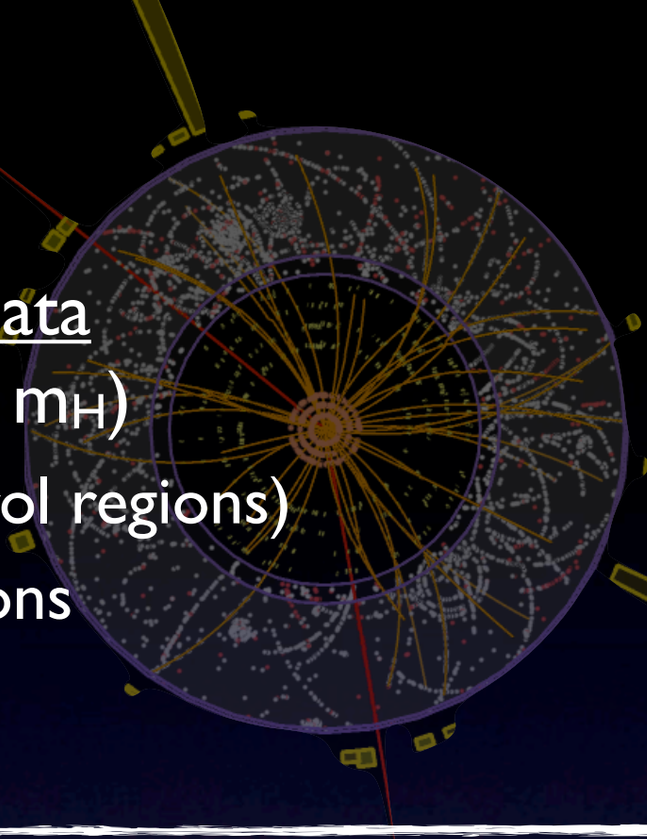
Muons

- Use ID tracks matched with partial or complete track segments in the muon spectrometer
- Extended coverage:
  - ID tracks + energy deposits in calorimeter ($|\eta|<0.1$, $p_T>15$GeV)
  - Muon Spectrometer stand-alone ($2.5<|\eta|<2.7$)





Analysis Selection



Updated analysis for 2011 and 2012 data
(improved expected sensitivity for low m_H)

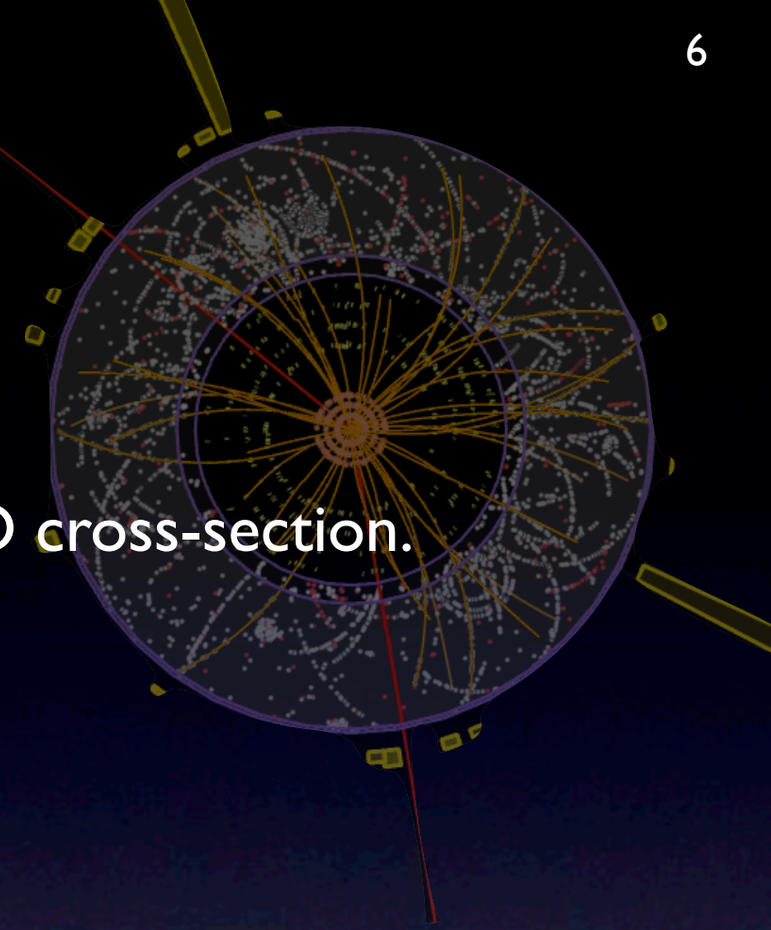
- Estimate backgrounds using data (sidebands, control regions)
- Development based only on MC and control regions

$\Delta R=\sqrt{\Delta\eta^2+\Delta\varphi^2}$

Selection

- Single lepton and di-lepton triggers
- At least two pairs of opposite-charge, same-flavor leptons (e,μ)
- p_T thresholds: 20, 15, 10, 7 GeV (6 GeV for muons)
- Leading pair: $50 < m_{12} < 106$ GeV
- Sub-leading pair: $m_{thr} < m_{34} < 115$ GeV,
  m_{thr}= 17.5 - 50 GeV (m_{4l} dependent)
- $\Delta R(l,l') > 0.1$ (0.2) for all same (different)-flavor
- J/Ψ veto: same-flavor, opposite-charge pair with $m_{ll}<5$ GeV
- Tracking and calorimeter isolation:
  - $P_{T\ \Delta R=0.2}/p_T<0.15$, $E_{T\ \Delta R=0.2}/E_T<0.3$ (0.15 for muons outside the acceptance of the tracker)
- Impact parameter significance (IP): $|d_0/\sigma(d_0)|< 3.5$ (6.5 for electrons)

Background Estimation



Irreducible (Standard Model $ZZ^{(*)}$):

- MC simulation normalized to theory cross-section
  both gg and qq production (PowHeg, qq2ZZ), MCFM NLO cross-section.

Reducible (ll+jets and $t\bar{t}$):

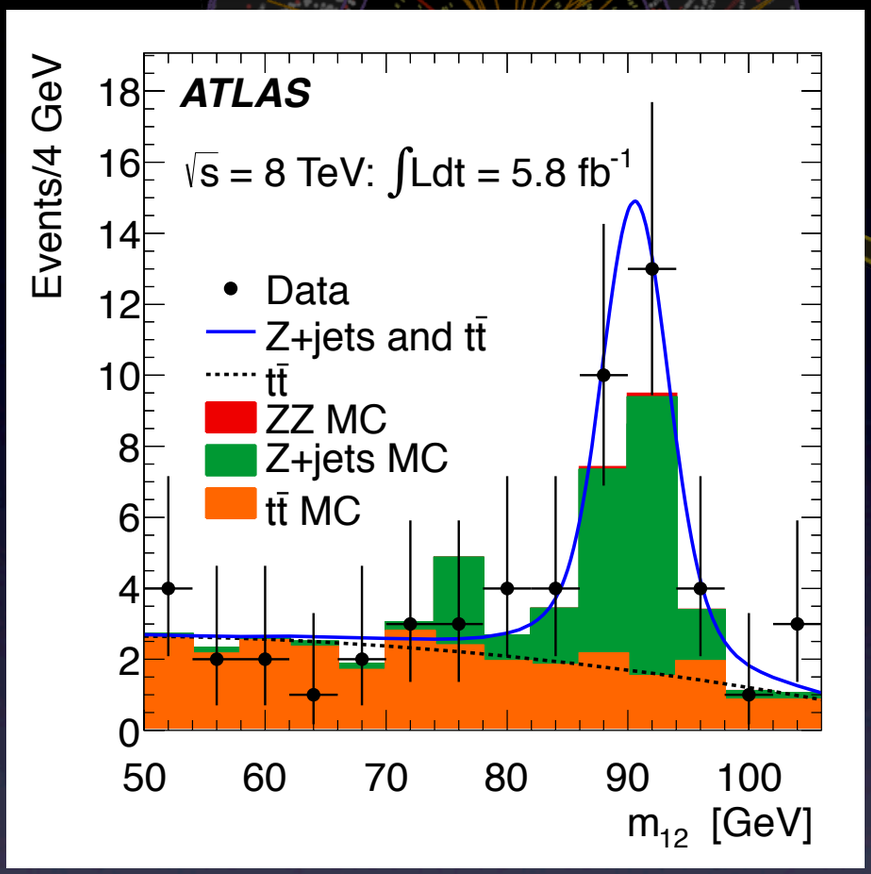
- Comparable to $ZZ^{(*)}$ in the low mass region.
- Estimated using data-driven methods.
- Background composition depends on flavor of sub-leading lepton pair → different approaches for ll+μμ and ll+ee:
  - ll+μμ (4μ, 2e2μ):
    - $t\bar{t}$ and $Zb\bar{b}$ from a fit to m_{12} (primary)
    - $t\bar{t}$ from eμ+μμ (cross check)
  - ll+ee (2μ2e, 4e):
    - Z+XX control samples (primary)
    - 3l + l (same-sign) (cross check)
- General strategy: loosen or revert selection, obtain composition, extrapolate to signal region

Background Estimation: ll+μμ

Main contributions from $Z\bar{b}\bar{b}$ and $\bar{t}\bar{t}$

m_{12} fit - primary method

- Control region:
- Sub-leading di-muon
  - Remove isolation requirement
  - Fail IP significance requirement (removes ZZ(*))
- m_{12} spectrum: $Z\bar{b}\bar{b}/\bar{t}\bar{t}$ contributions clearly separated
- Obtain yields by fit of the two components
- Extrapolate to Signal Region
  - Transfer factors from MC
  - Cross-checked with data



$e^{\pm}\mu^{\mp}+\mu^{\pm}\mu^{\mp}$- cross check

- $e^{\pm}\mu^{\mp}$ leading di-lepton with Z→ll veto ($\bar{t}\bar{t}$ dominated)
- Extrapolation to signal region → compatible results with m_{12} fit

Background Contribution: ll+ee

Main contributions from Z+jets

Primary method

- Analysis phase-space
- Relax identification in sub-leading di-electron
- Classify electron pairs (p_T-ordered) in types: EE, EC, EF, CE, CC, CF, FE, FC, FF
- Extrapolate yields in each category to the signal region using MC

8 TeV	$4e$		$2\mu 2e$	
	Data	MC	Data	MC
EE	32	22.7±4.8	31	24.9±5.0
EC	6	6.0±2.5	2	1.9±1.4
EF	18	19.0±4.4	26	15.3±3.9
CE	4	8.8±3.0	6	5.1±2.3
CC	1	5.3±2.3	6	4.2±2.0
CF	12	8.8±3.0	15	15.3±3.9
FE	16	5.7±2.4	12	8.4±2.9
FC	6	6.5±2.6	7	4.3±2.1
FF	12	17.4±4.2	16	33.6±5.8
Total	107	100±10	121	113±11

Categories from MC

- Jets mis-identified as electrons (F)
- Electrons from photon conversions (C)
- Electrons from semi-leptonic decays of heavy flavor (E)

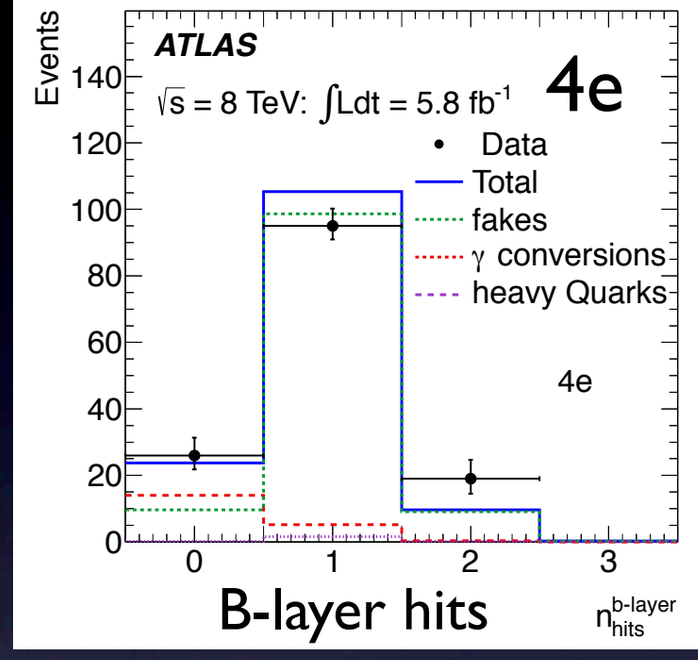
Background Contribution: ll+ee

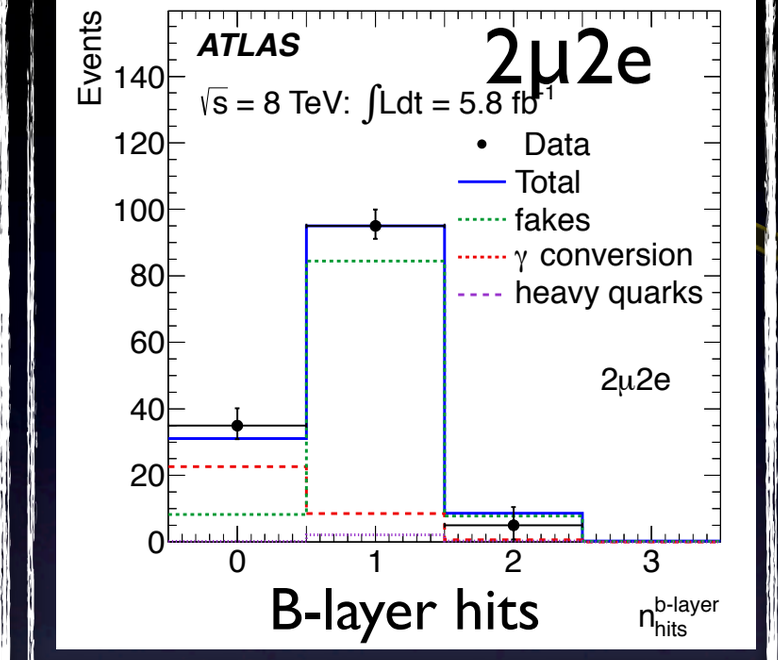
Main contributions from Z+jets

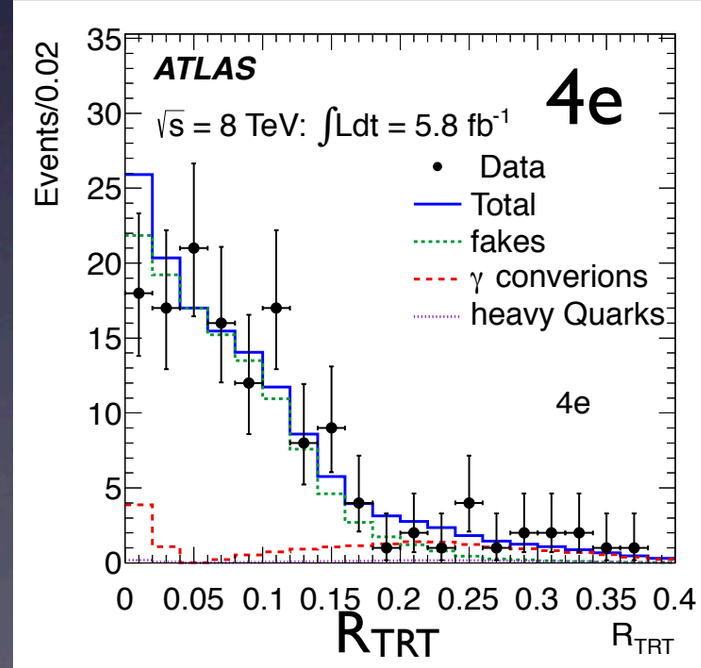
3l+1 cross-check method

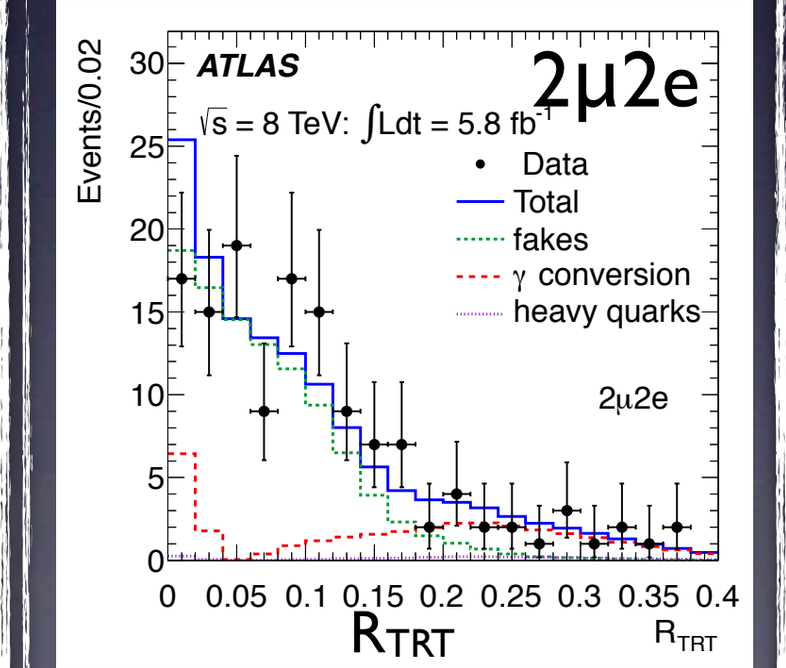
Three highest-p_T leptons pass analysis cuts

- Relax requirements on softest electron
- Composition from 2D fit for
  - Number of b-layer hits (Inner Detector)
  - Transition-radiation hits (Transition Radiation Tracker)



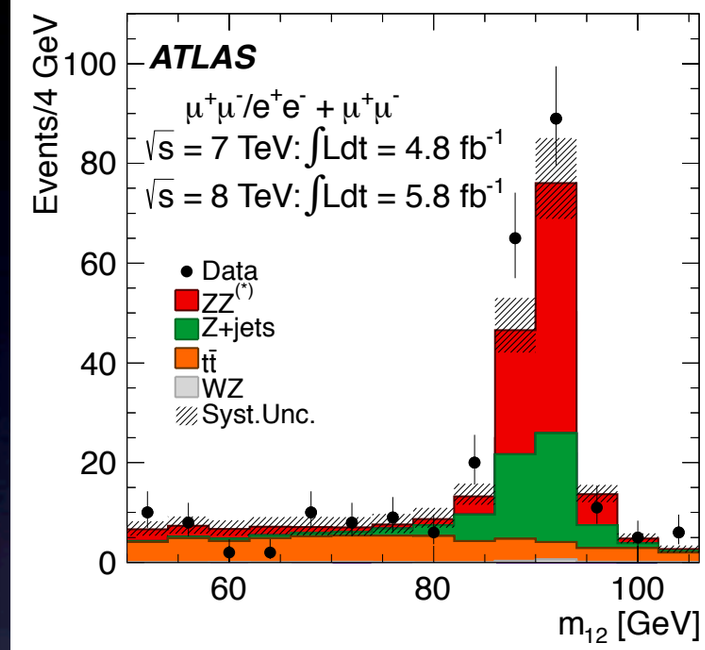


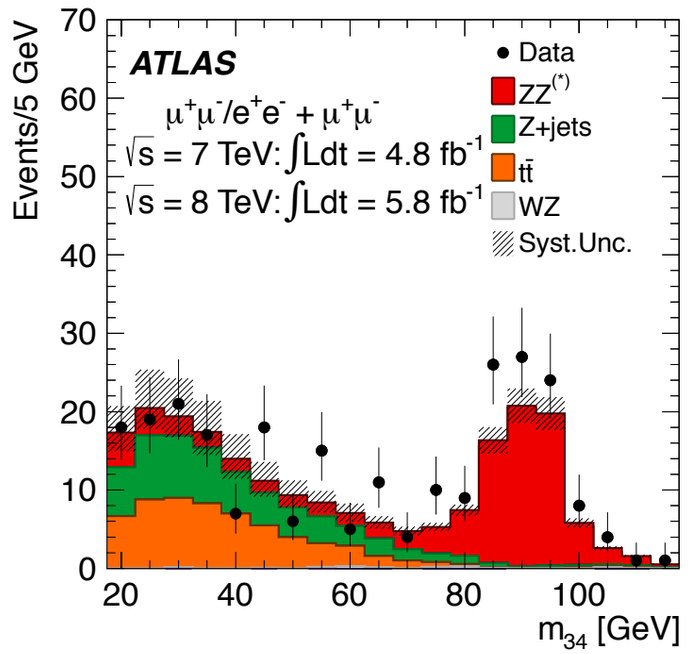




Background Estimation: Control Plots

Z+μμ

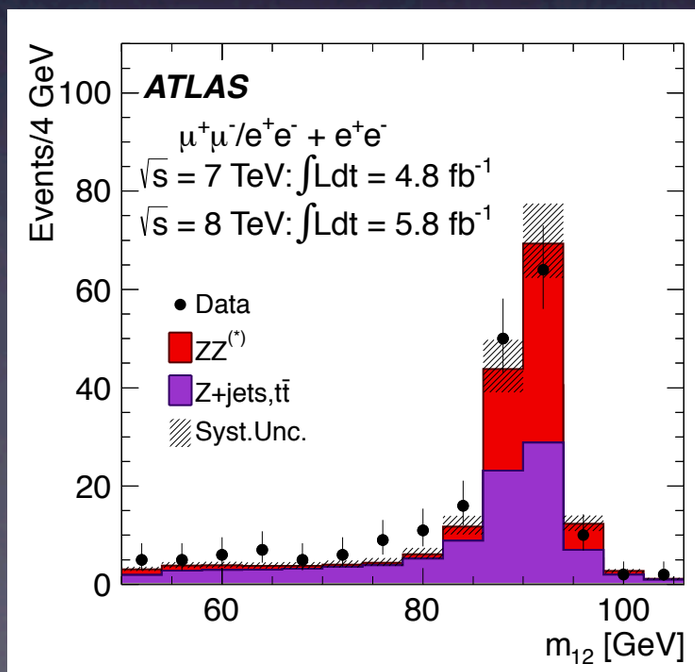


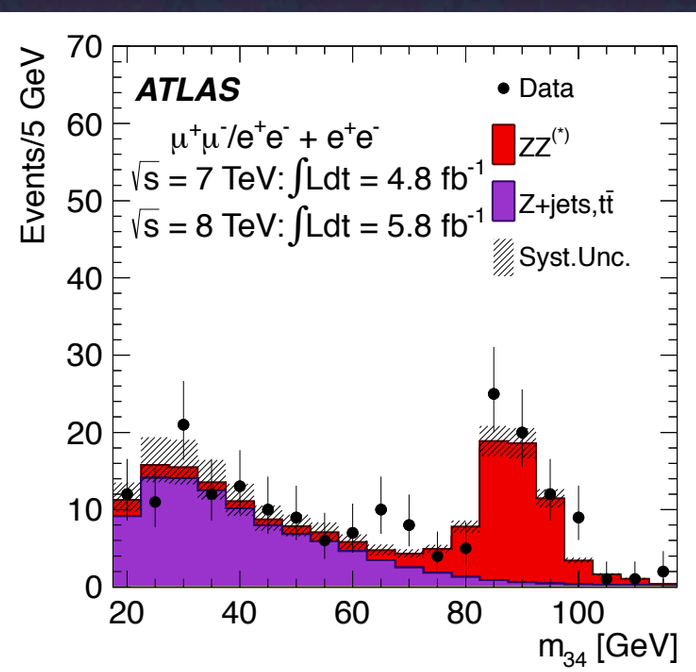


Background normalization is also checked on leading di-lepton mass (m_{12}) and sub-leading di-lepton mass (m_{34})

Z+ee

- Remove isolation/impact parameter requirements on sub-leading di-lepton
- Normalize to data-driven estimates
- Normalization and shape are in good agreement between data and MC





Background Estimation: Summary

8 TeV

Method	Estimated number of events
4μ	
m_{12} fit: Z + jets contribution	$0.51\pm 0.13 \pm 0.16^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.044\pm 0.015\pm 0.015^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.058\pm 0.015\pm 0.019$
$2e2\mu$	
m_{12} fit: Z + jets contribution	$0.41\pm 0.10 \pm 0.13^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.040\pm 0.013\pm 0.013^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.051\pm 0.013\pm 0.017$
$2\mu 2e$	
$\ell\ell + e^{\pm}e^{\mp}$	$4.9\pm 0.8 \pm 0.7^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$4.1\pm 0.6 \pm 0.8$
$3\ell + \ell$ (same-sign)	$3.5\pm 0.5 \pm 0.5$
$4e$	
$\ell\ell + e^{\pm}e^{\mp}$	$3.9\pm 0.7 \pm 0.8^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.1\pm 0.5 \pm 0.6$
$3\ell + \ell$ (same-sign)	$3.0\pm 0.4 \pm 0.4$

7 TeV

Method	Estimated number of events
4μ	
m_{12} fit: Z + jets contribution	$0.25\pm 0.10 \pm 0.08^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.022\pm 0.010\pm 0.011^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.025\pm 0.009\pm 0.014$
$2e2\mu$	
m_{12} fit: Z + jets contribution	$0.20\pm 0.08 \pm 0.06^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.020\pm 0.009\pm 0.011^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.024\pm 0.009\pm 0.014$
$2\mu 2e$	
$\ell\ell + e^{\pm}e^{\mp}$	$2.6\pm 0.4 \pm 0.4^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.7\pm 0.9 \pm 0.6$
$3\ell + \ell$ (same-sign)	$2.0\pm 0.5 \pm 0.3$
$4e$	
$\ell\ell + e^{\pm}e^{\mp}$	$3.1\pm 0.6 \pm 0.5^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.2\pm 0.6 \pm 0.5$
$3\ell + \ell$ (same-sign)	$2.2\pm 0.5 \pm 0.3$

- More than one method per channel, yielding compatible results
- Uncertainties 20%-70% depending on background and data sample

Background Estimation: Summary

8 TeV

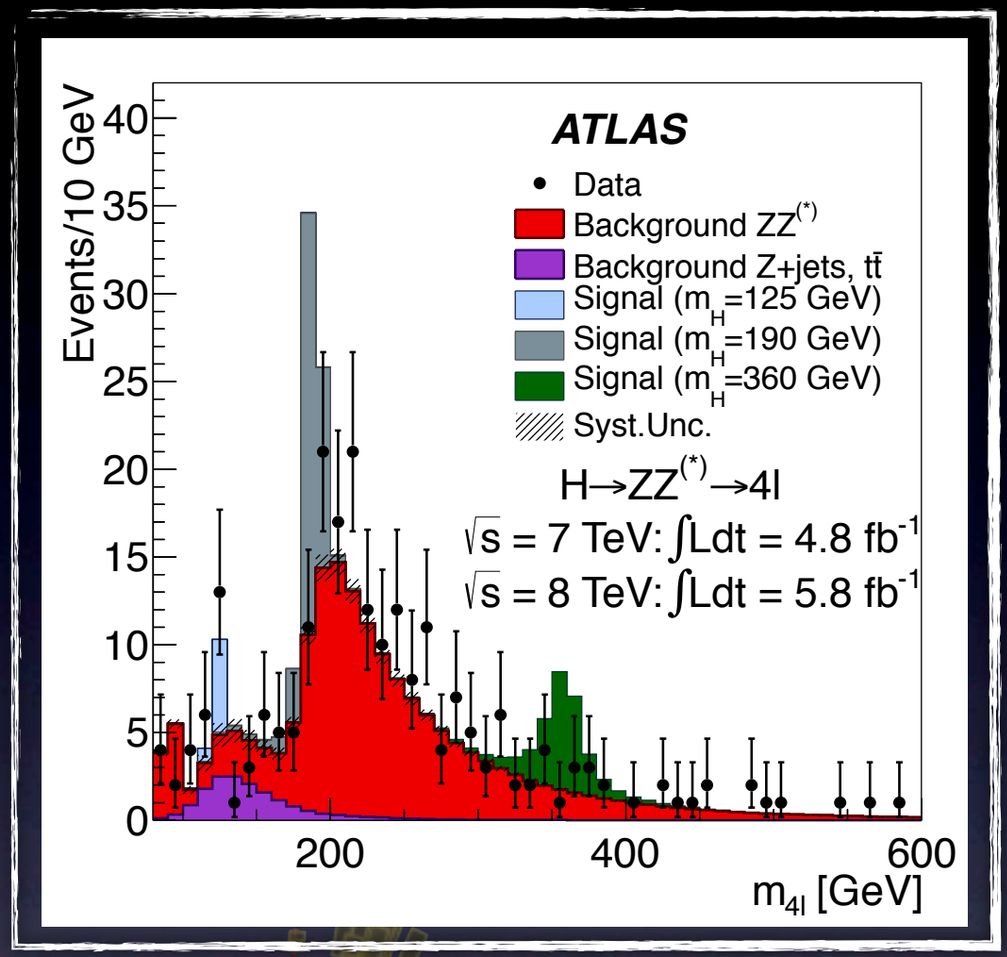
Method	Estimated number of events
4μ	
m_{12} fit: Z + jets contribution	$0.51\pm 0.13 \pm 0.16^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.044\pm 0.015\pm 0.015^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.058\pm 0.015\pm 0.019$
$2e2\mu$	
m_{12} fit: Z + jets contribution	$0.41\pm 0.10 \pm 0.13^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.040\pm 0.013\pm 0.013^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.051\pm 0.013\pm 0.017$
$2\mu 2e$	
$\ell\ell + e^{\pm}e^{\mp}$	$4.9\pm 0.8 \pm 0.7^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$4.1\pm 0.6 \pm 0.8$
$3\ell + \ell$ (same-sign)	$3.5\pm 0.5 \pm 0.5$
$4e$	
$\ell\ell + e^{\pm}e^{+}$	$3.9\pm 0.7 \pm 0.8^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.1\pm 0.5 \pm 0.6$
$3\ell + \ell$ (same-sign)	$3.0\pm 0.4 \pm 0.4$

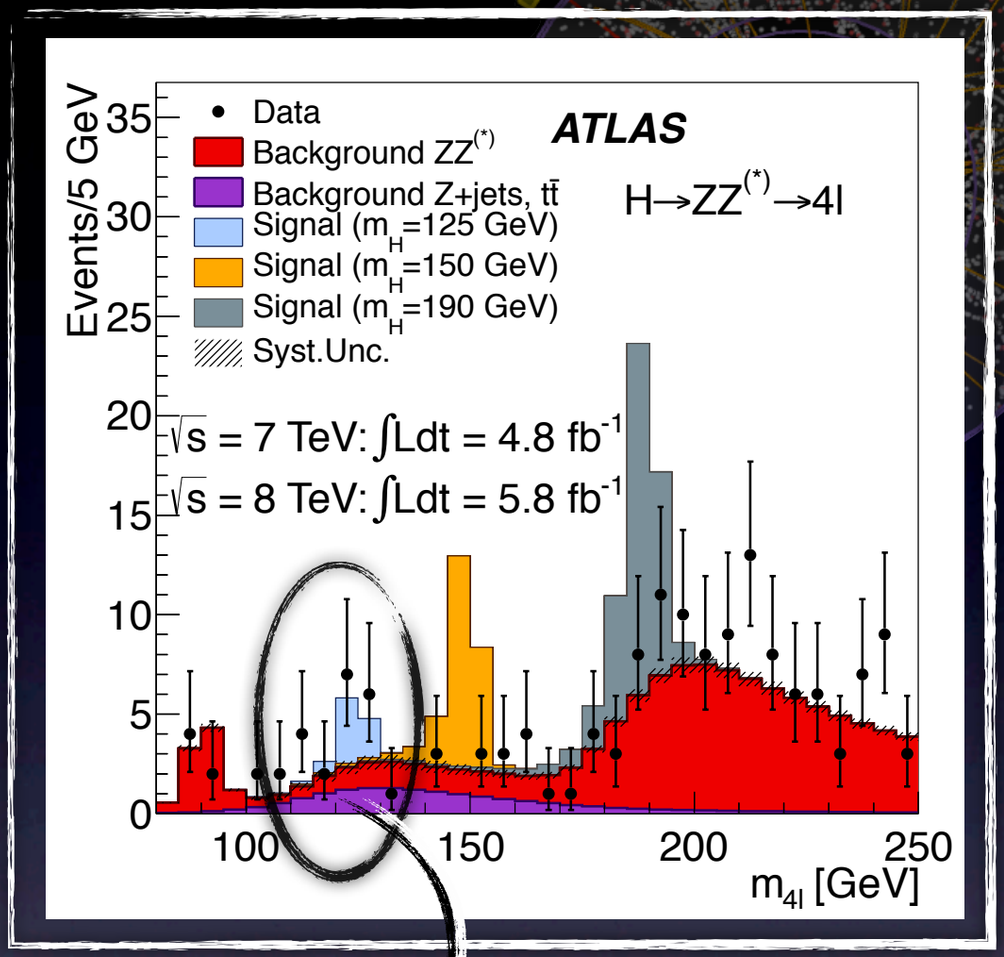
7 TeV

Method	Estimated number of events
4μ	
m_{12} fit: Z + jets contribution	$0.25\pm 0.10 \pm 0.08^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.022\pm 0.010\pm 0.011^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.025\pm 0.009\pm 0.014$
$2e2\mu$	
m_{12} fit: Z + jets contribution	$0.20\pm 0.08 \pm 0.06^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.020\pm 0.009\pm 0.011^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.024\pm 0.009\pm 0.014$
$2\mu 2e$	
$\ell\ell + e^{\pm}e^{\mp}$	$2.6\pm 0.4 \pm 0.4^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.7\pm 0.9 \pm 0.6$
$3\ell + \ell$ (same-sign)	$2.0\pm 0.5 \pm 0.3$
$4e$	
$\ell\ell + e^{\pm}e^{\mp}$	$3.1\pm 0.6 \pm 0.5^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.2\pm 0.6 \pm 0.5$
$3\ell + \ell$ (same-sign)	$2.2\pm 0.5 \pm 0.3$

- More than one method per channel, yielding compatible results
- Uncertainties 20%-70% depending on background and data sample

Event Selection: Results



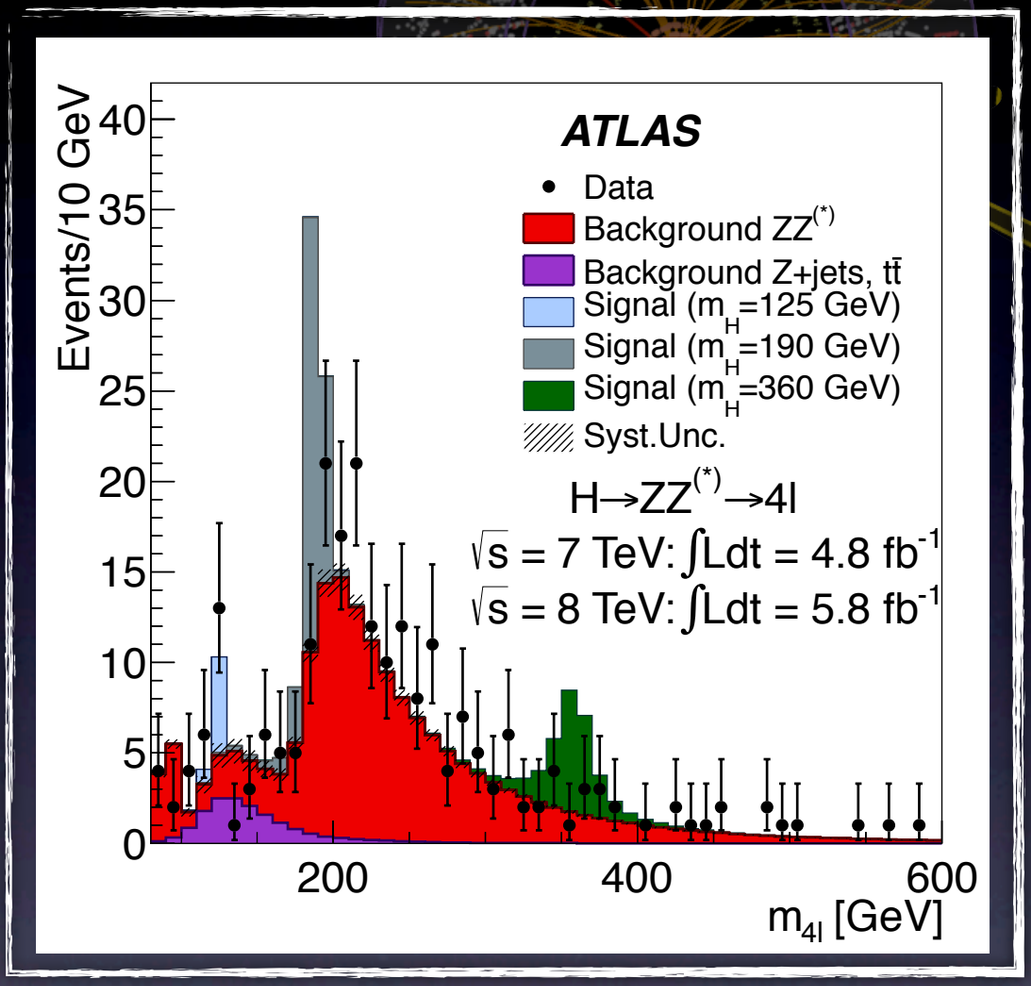


m_{4l}: 125 ± 5 GeV	2011	2012	2011+2012
Data	4	9	13
Expected Signal	2.0±0.3	3.3±0.5	5.3±0.8
Expected Background	2.1±0.3	2.9±0.4	5.1±0.8

Event Selection: Results

- For m_{4l} > 160GeV, data is 20-30% above MC expectation for 2011 and 2012.
- Events are consistent with ZZ production.
- Reflected in ATLAS ZZ production cross-section measurement.

7 TeV Measurement: $(7.2^{+1.2}_{-1.0})$ pb
7 TeV NLO Prediction: $(6.5^{+0.3}_{-0.2})$ pb
8 TeV Measurement: $(9.3^{+1.2}_{-1.1})$ pb
8 TeV NLO Prediction: (7.4±0.4) pb

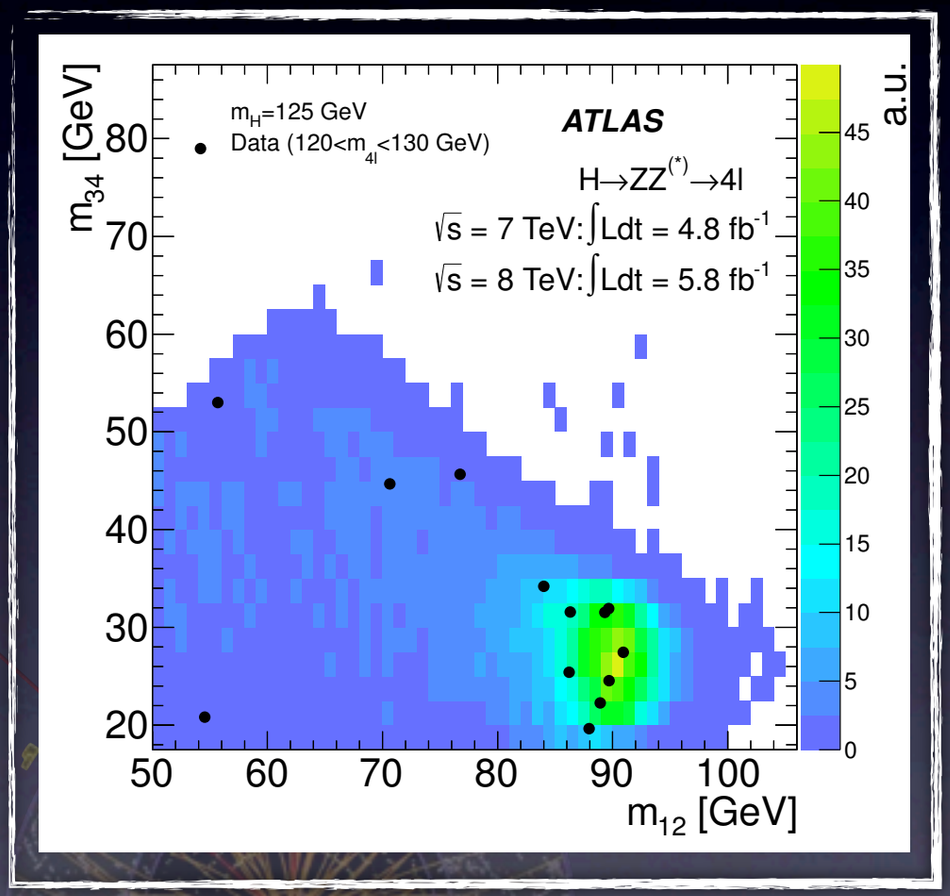


- Normalization is done with data and not constrained from theory.
- No significant modification of the observed and expected p0 in the low m_H region was observed.

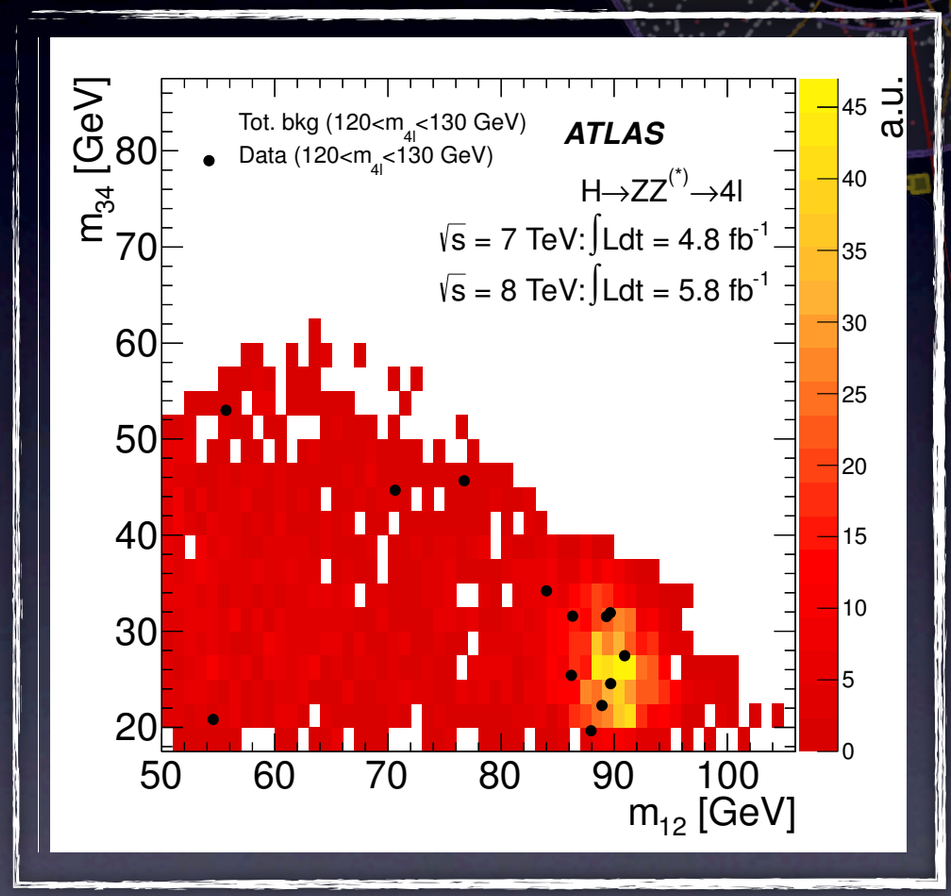
ATLAS-CONF-2012-092,
arXiv:1207.7214v1

Event Selection: Results

Signal m_H=125GeV



Total background $120 < m_{4l} < 130$ GeV
$ZZ^{(*)}$, Z+jets, $t\bar{t}$



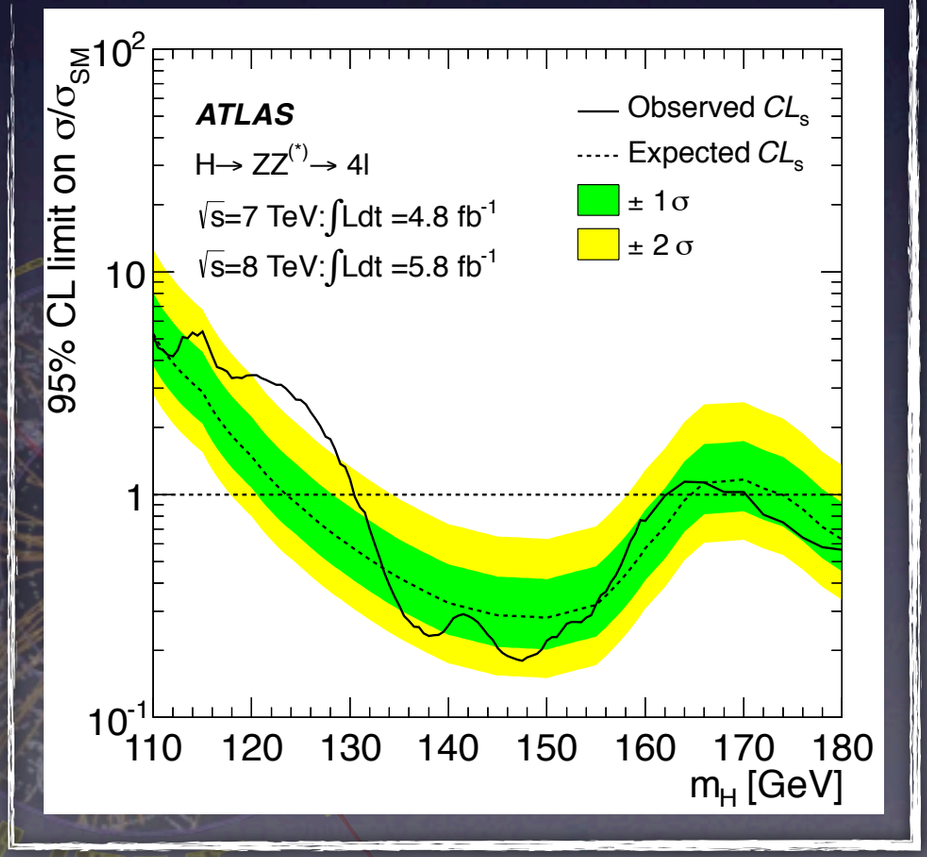
m_{34} vs m_{12} invariant mass, before the application of Z-mass constrained kinematic fit.

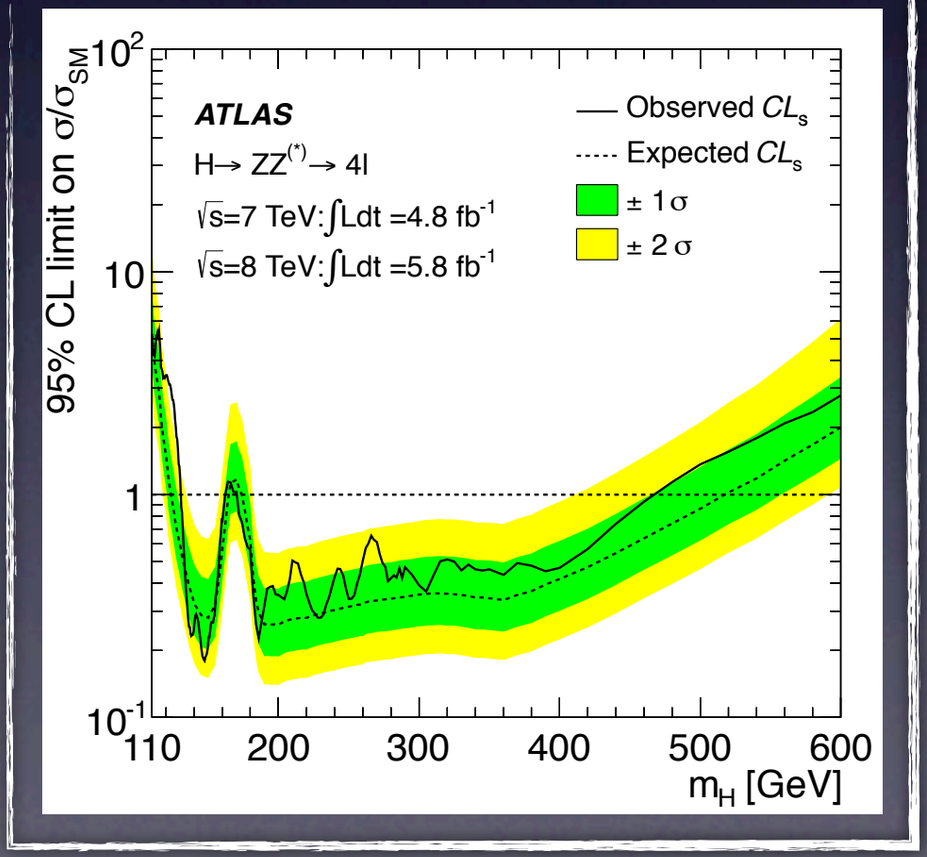
arXiv:1207.7214v1
(CERN-PH-EP-2012-218)

Exclusion Limits

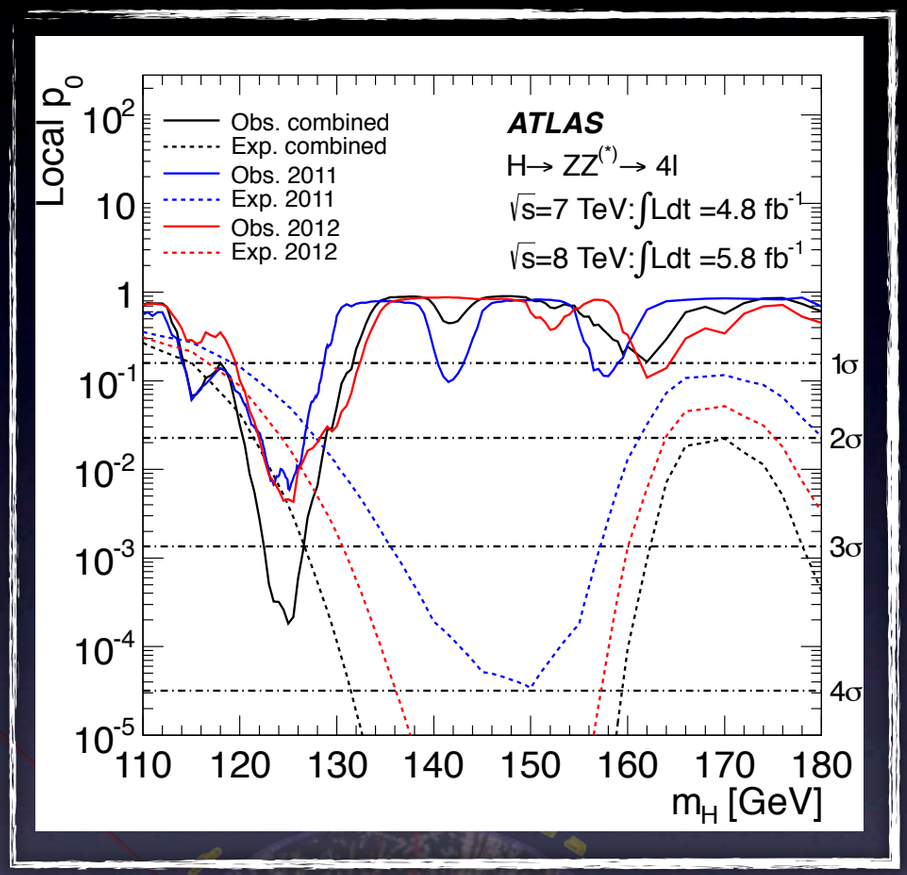
95% CL upper limits on the Standard Model Higgs boson production (divided by the expected SM Higgs boson cross section) as a function of m_H

- Exclusion:
  - Expected: 124-164 and 176-500 GeV
  - Observed: 131-162 and 170-460 GeV
- Limit weaker than expected at 120-130 GeV





Significance of Excess (testing background-only hypothesis)

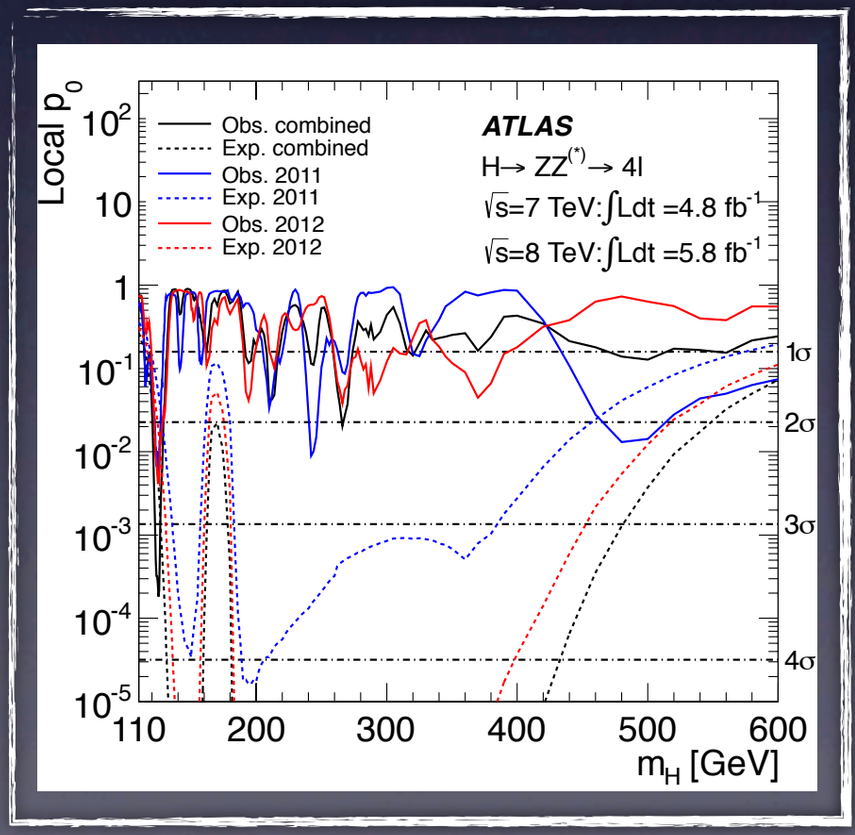


Low m_H:

- Consistent excesses in 2011 and 2012
- Combined: 3.4σ @ 125 GeV (expected: 2.6)
  - with Look Elsewhere Effect for the range 110-141 GeV: 2.5σ

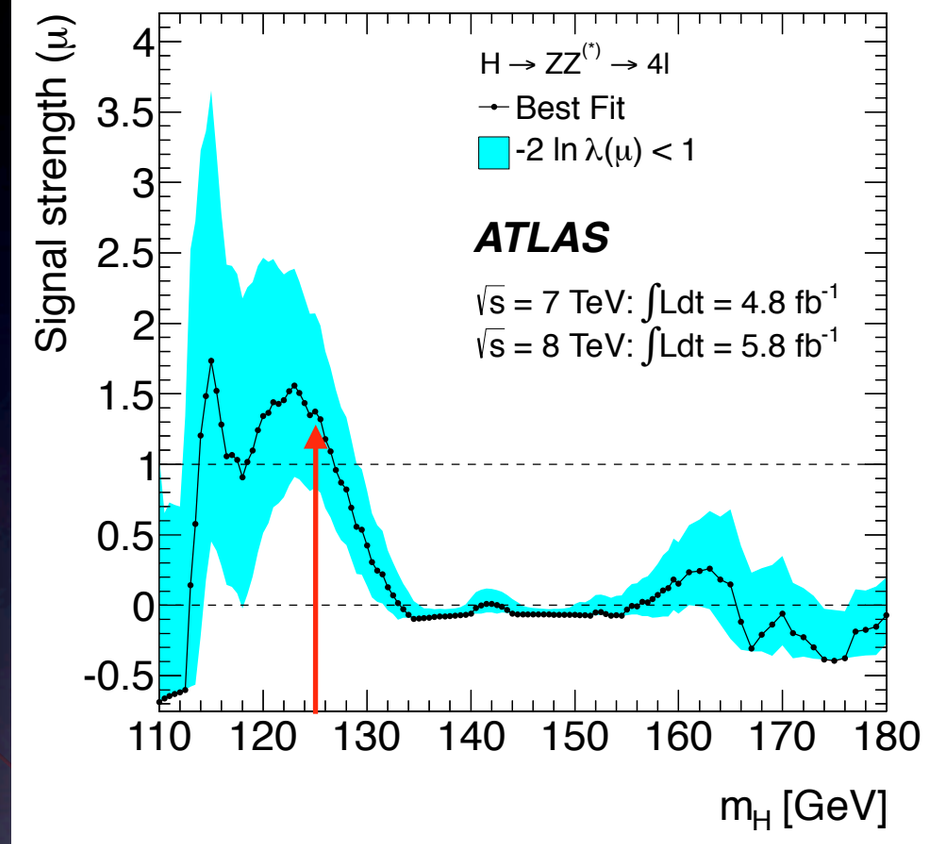
High m_H:

- Small fluctuations from background, not consistent between 7 and 8 TeV data

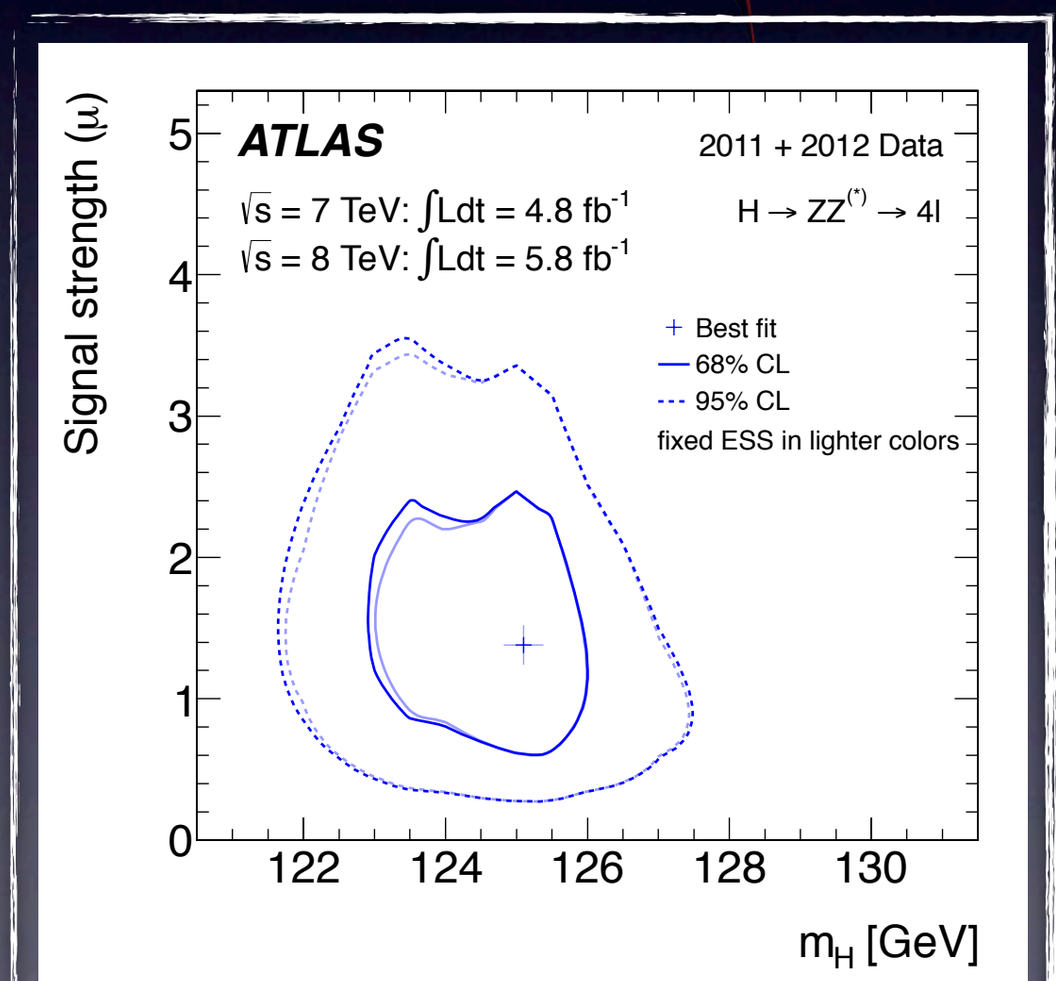


	mH [GeV]	Exp	Obs
2011	125	1.6σ	2.3σ
2012	125.5	2.1σ	2.7σ

Signal Strength



μ → Ratio between the observed signal rate fitting data and the rate expected from the Standard Model at a given m_H



In the 2D profile likelihood fit to signal strength and m_H the best fit is at m_H=125 GeV (lowest p0):

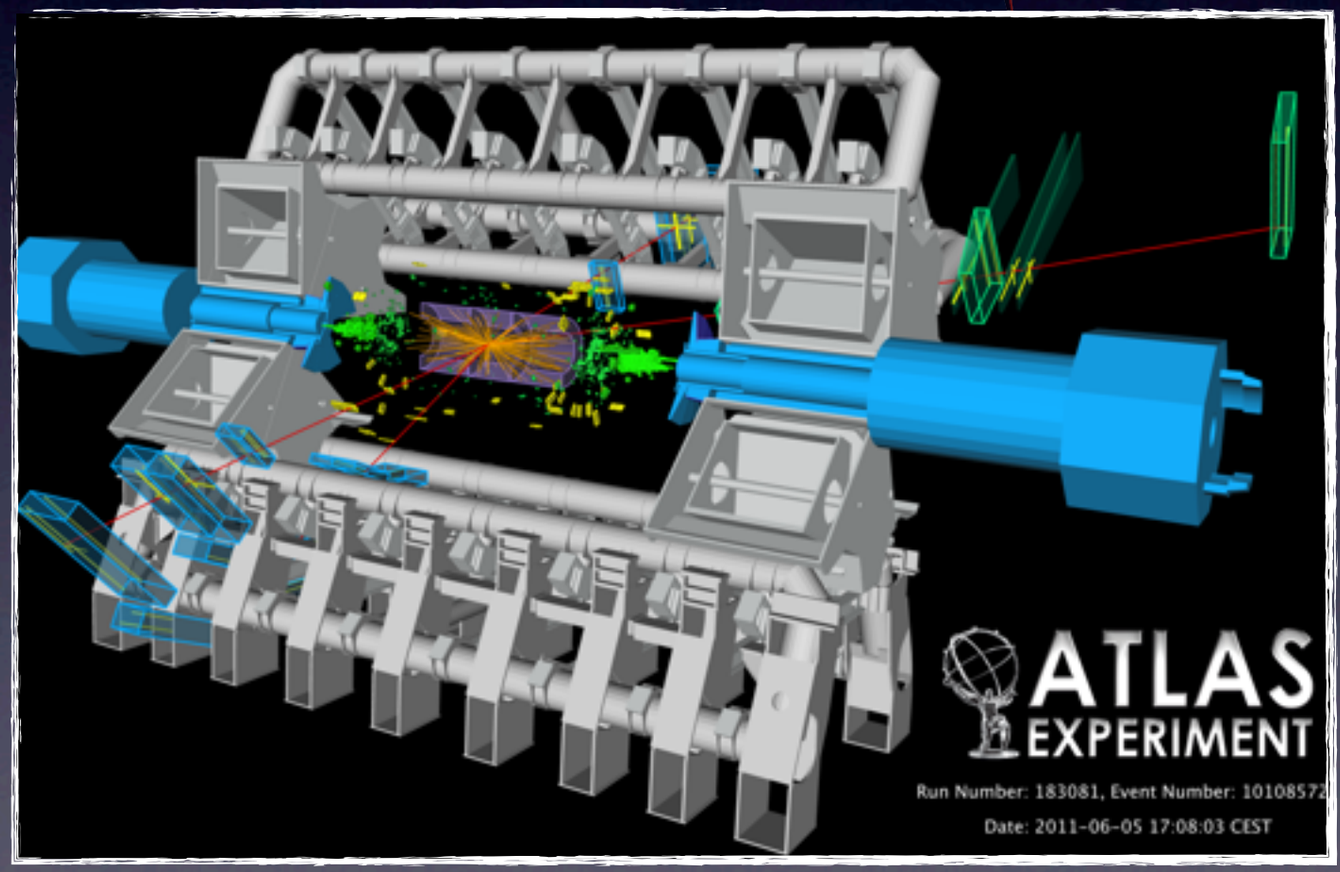
$\mu = 1.3 \pm 0.6$

Summary

- Great progress has been made on lepton performance and pile-up robustness (especially for electrons).
- Improved analysis with more sensitivity in the low mass region.

An excess of events is observed at m_H ~125 GeV.

- Consistent in 2011 and 2012 data.
- Combining the two datasets gives local significance of 3.4σ (global 2.5σ in the range 110-141 GeV).

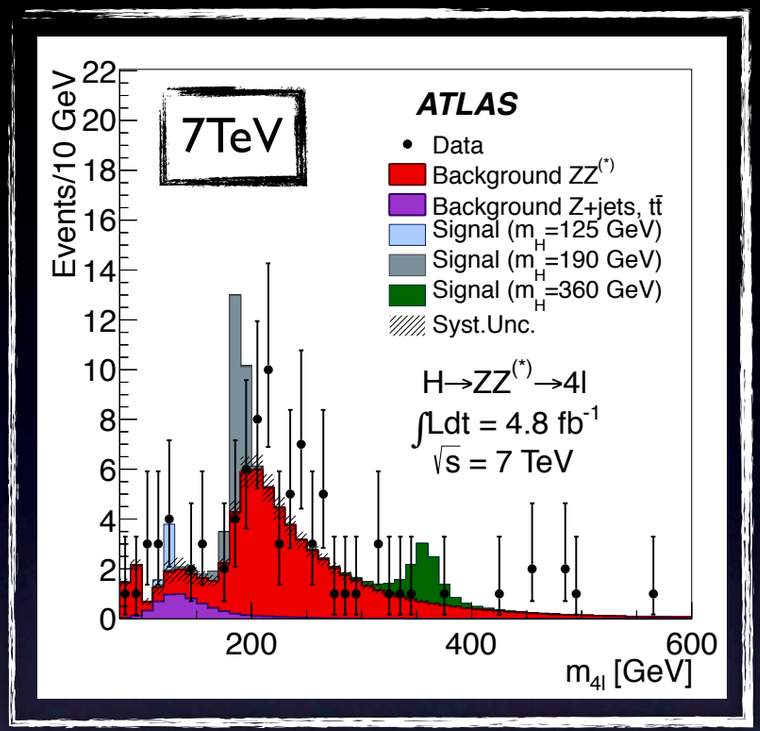


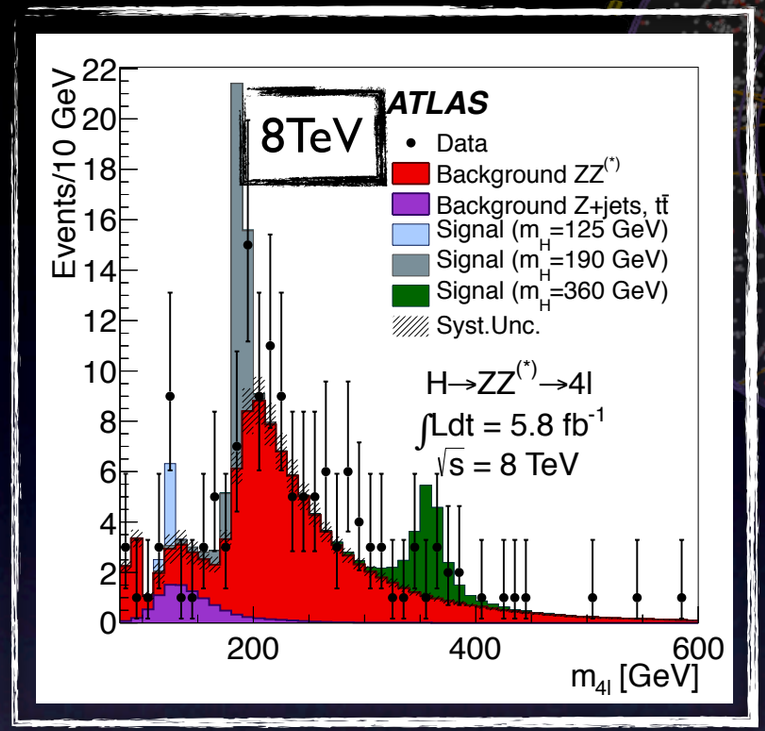
With data pouring in every day the task now is to pin down the mass, determine spin, parity, decays...

Backup Slides

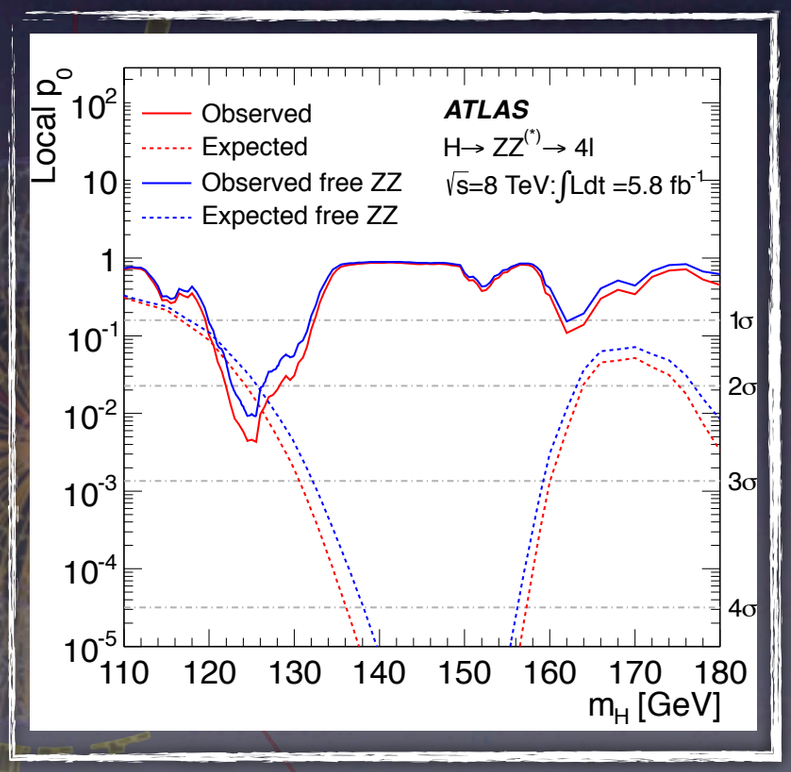
Event Selection: Results

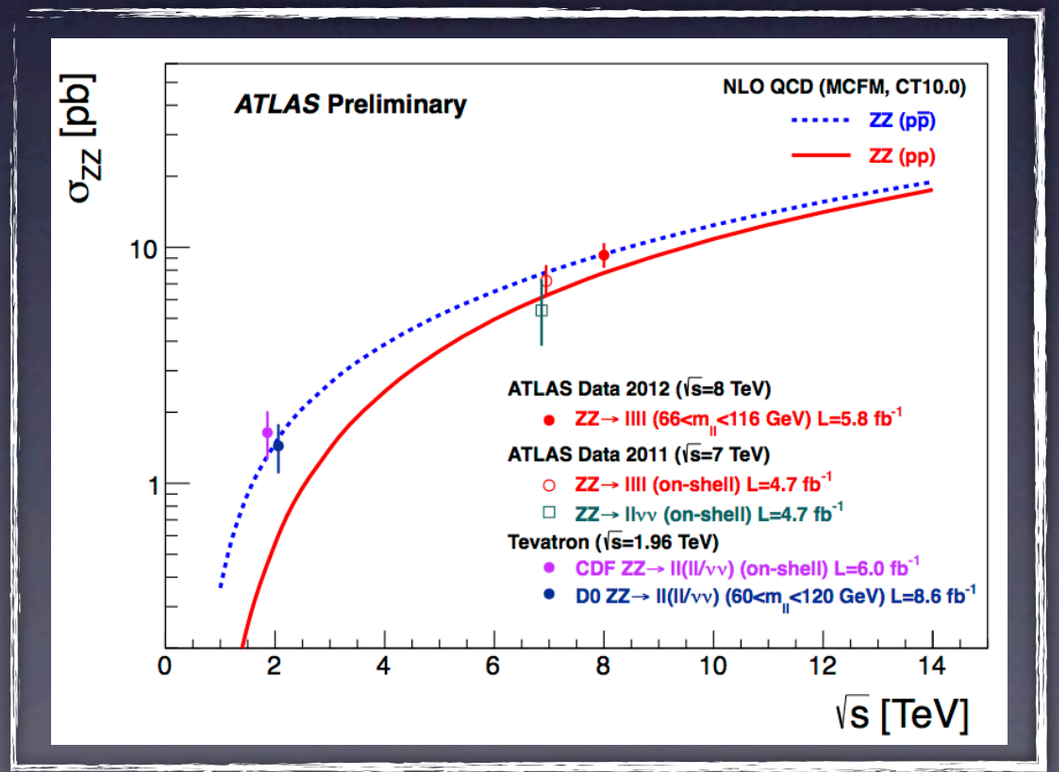
Exp. 71±5
Obs. 88



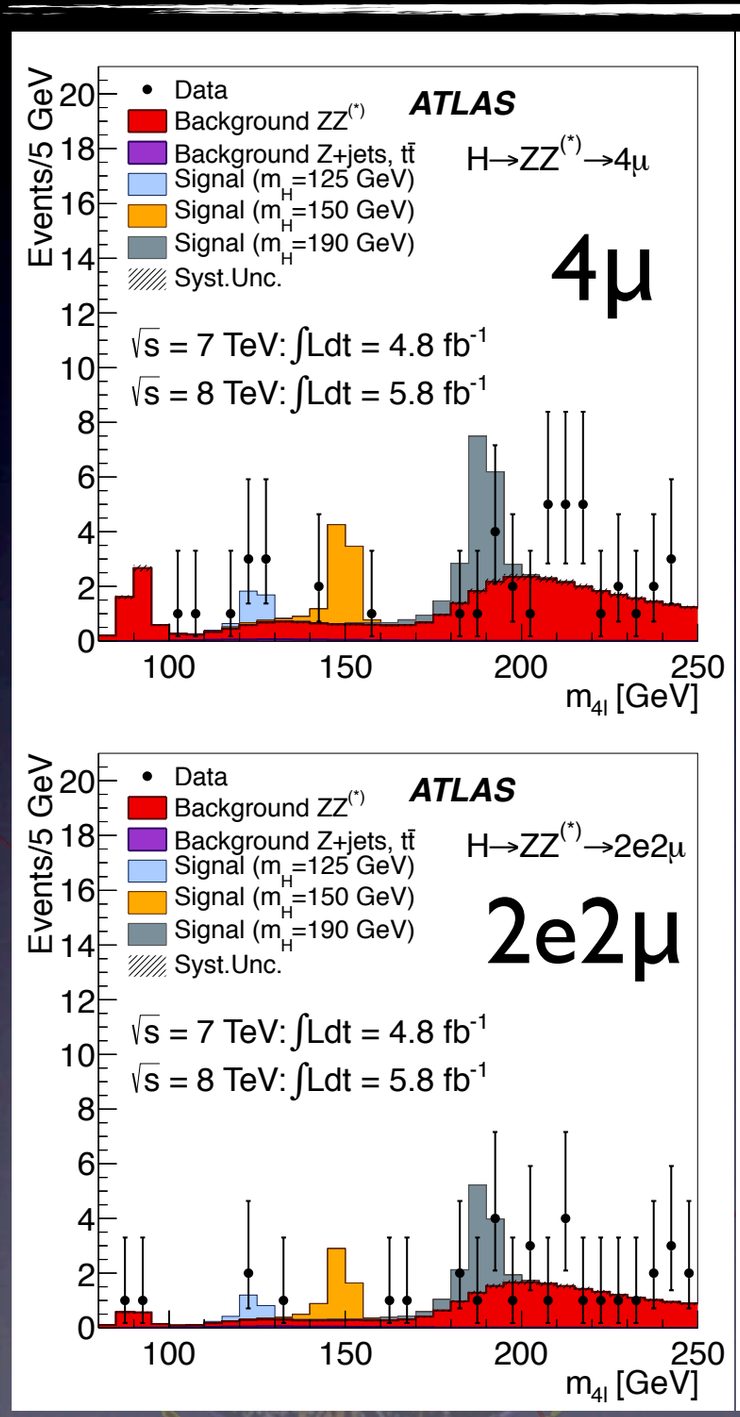


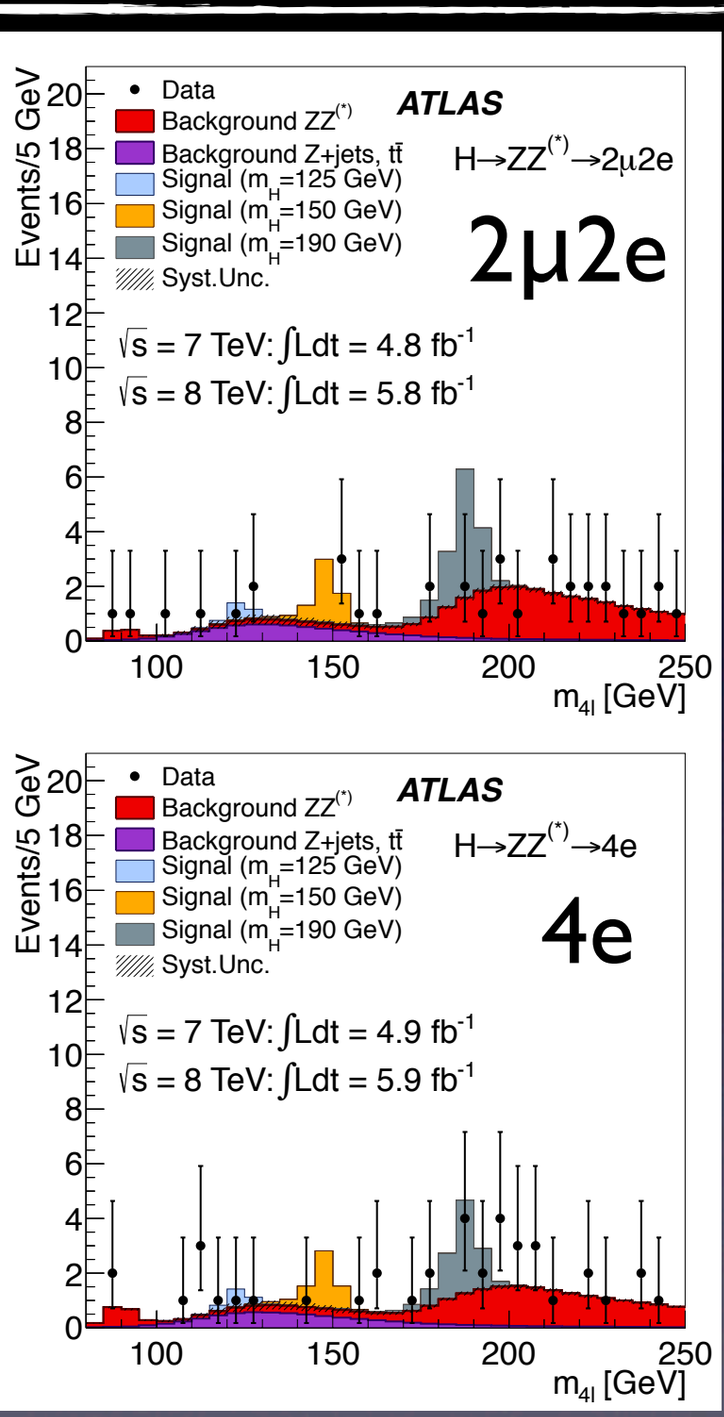
Exp. 109±7
Obs. 142





Selection Results per Final State

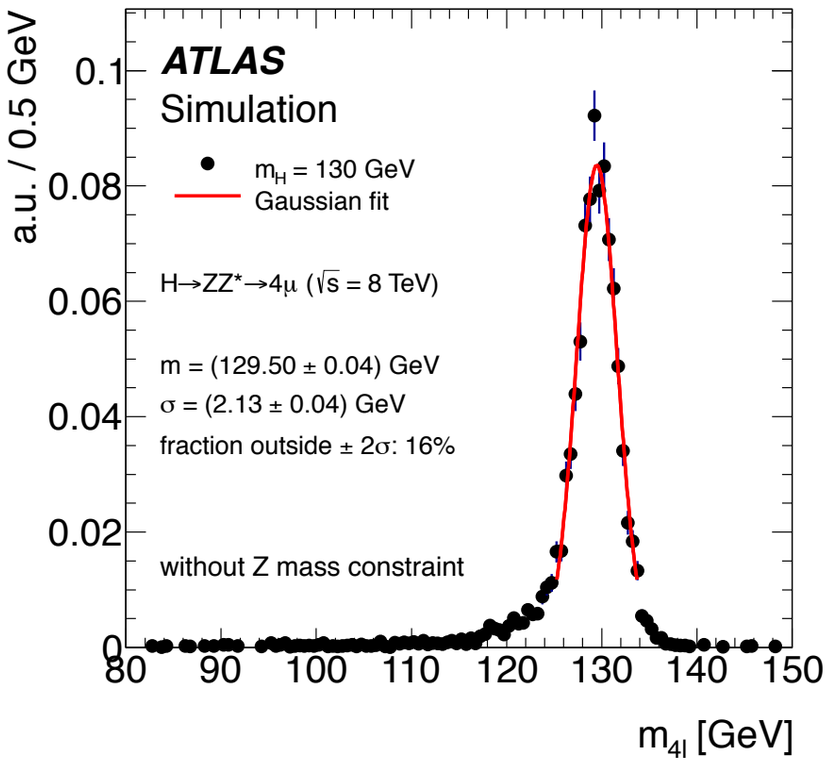


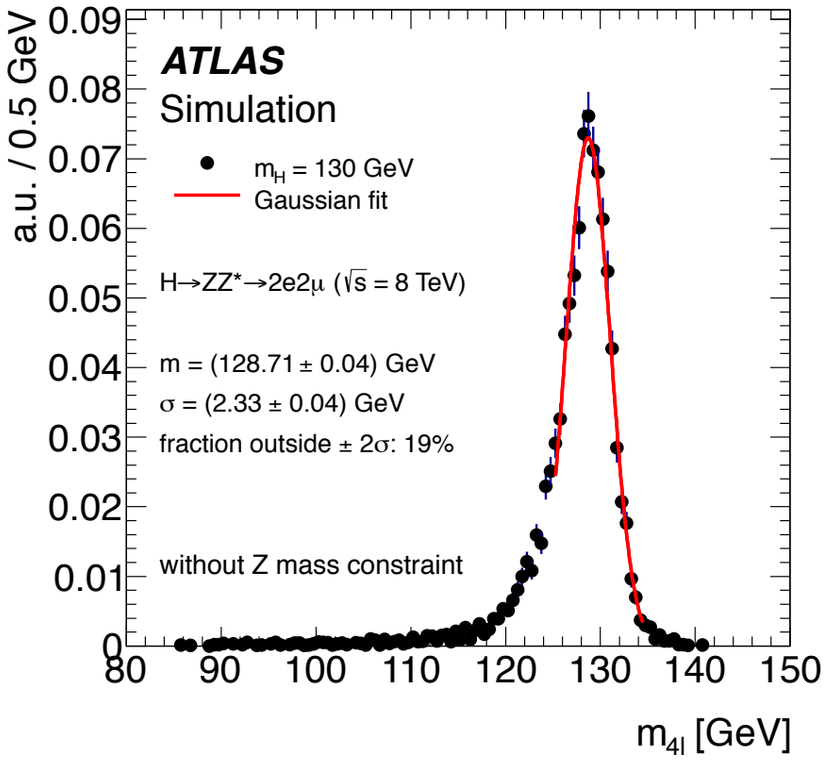


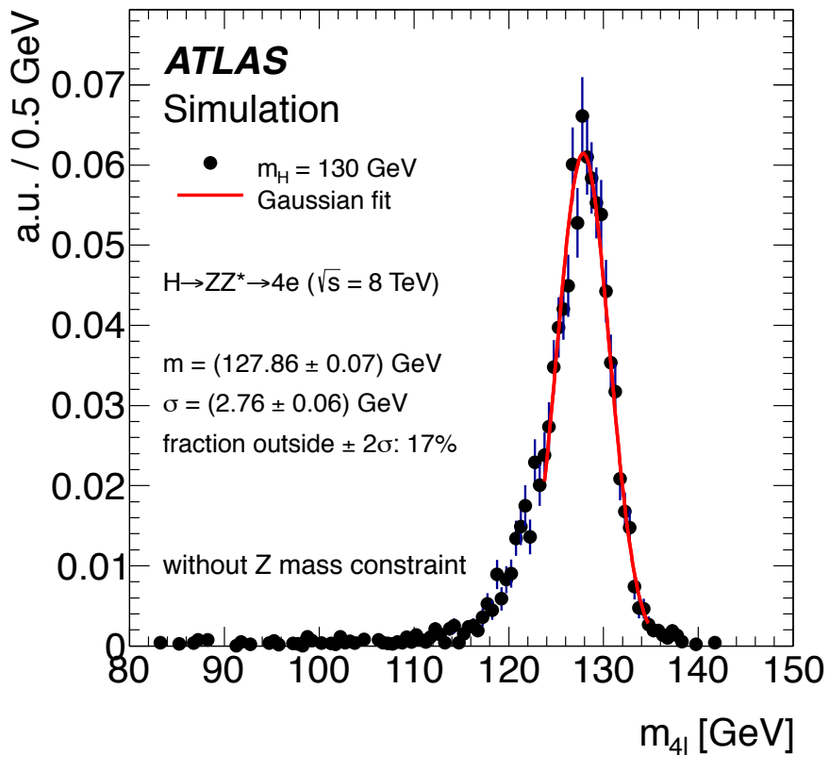
Signal efficiency for m_H=130 GeV

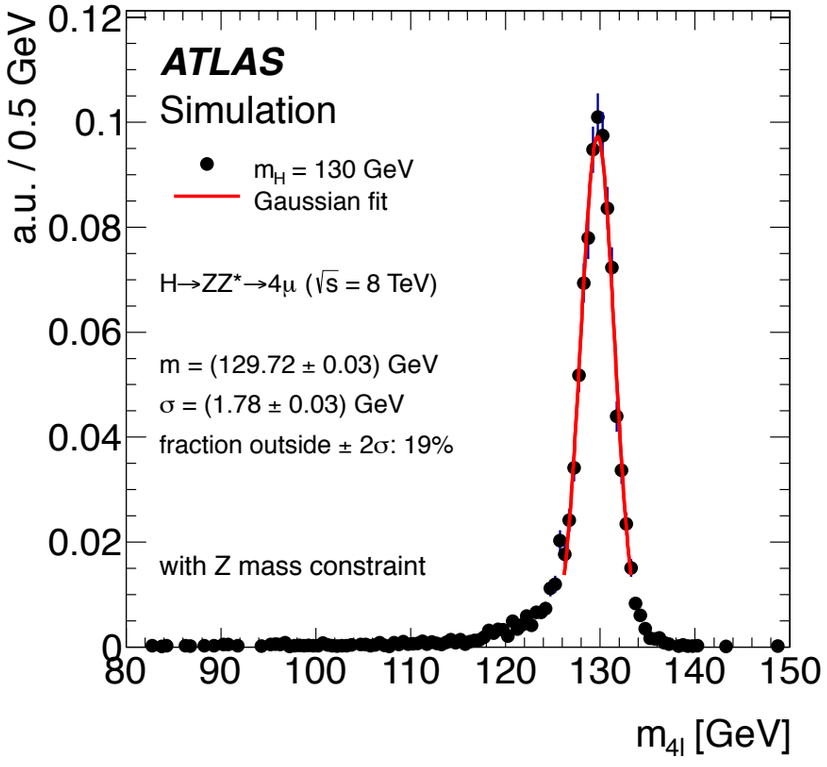
- 4μ ~41%
- 2e2μ/2μ2e ~27%
- 4e ~23%

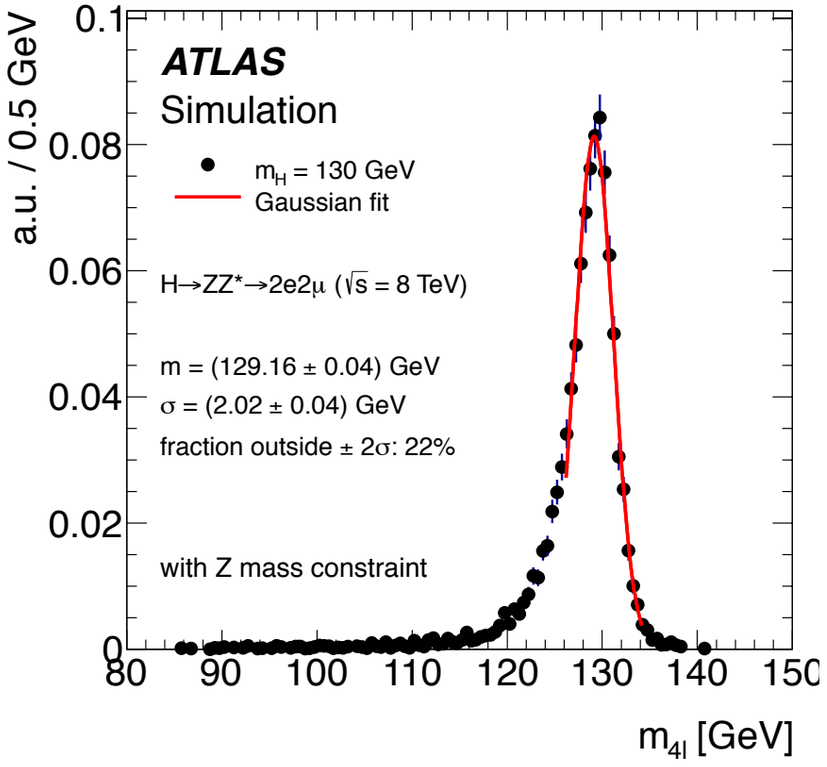
Mass Resolution

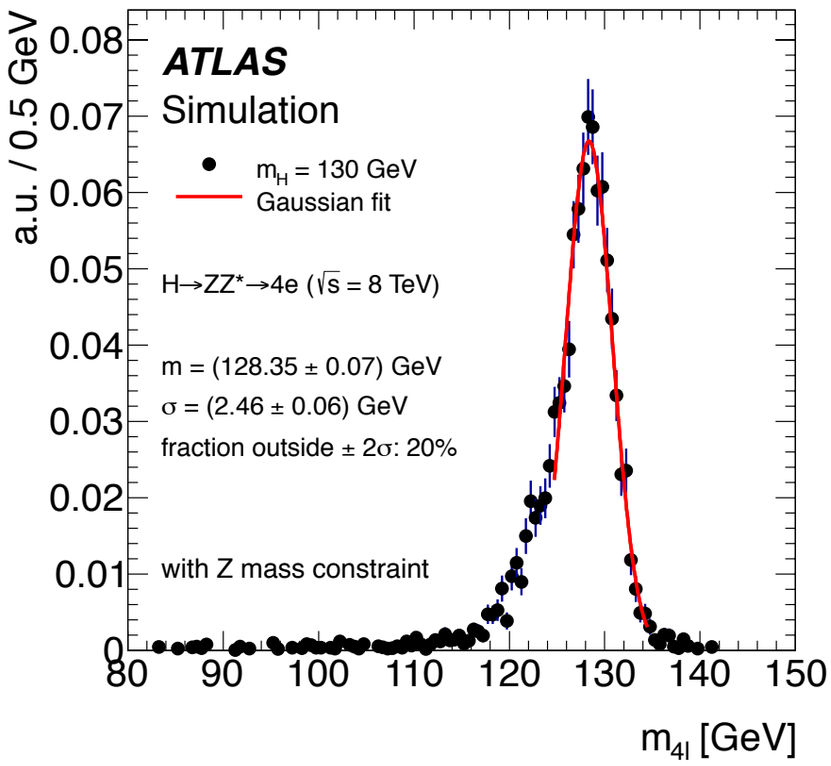








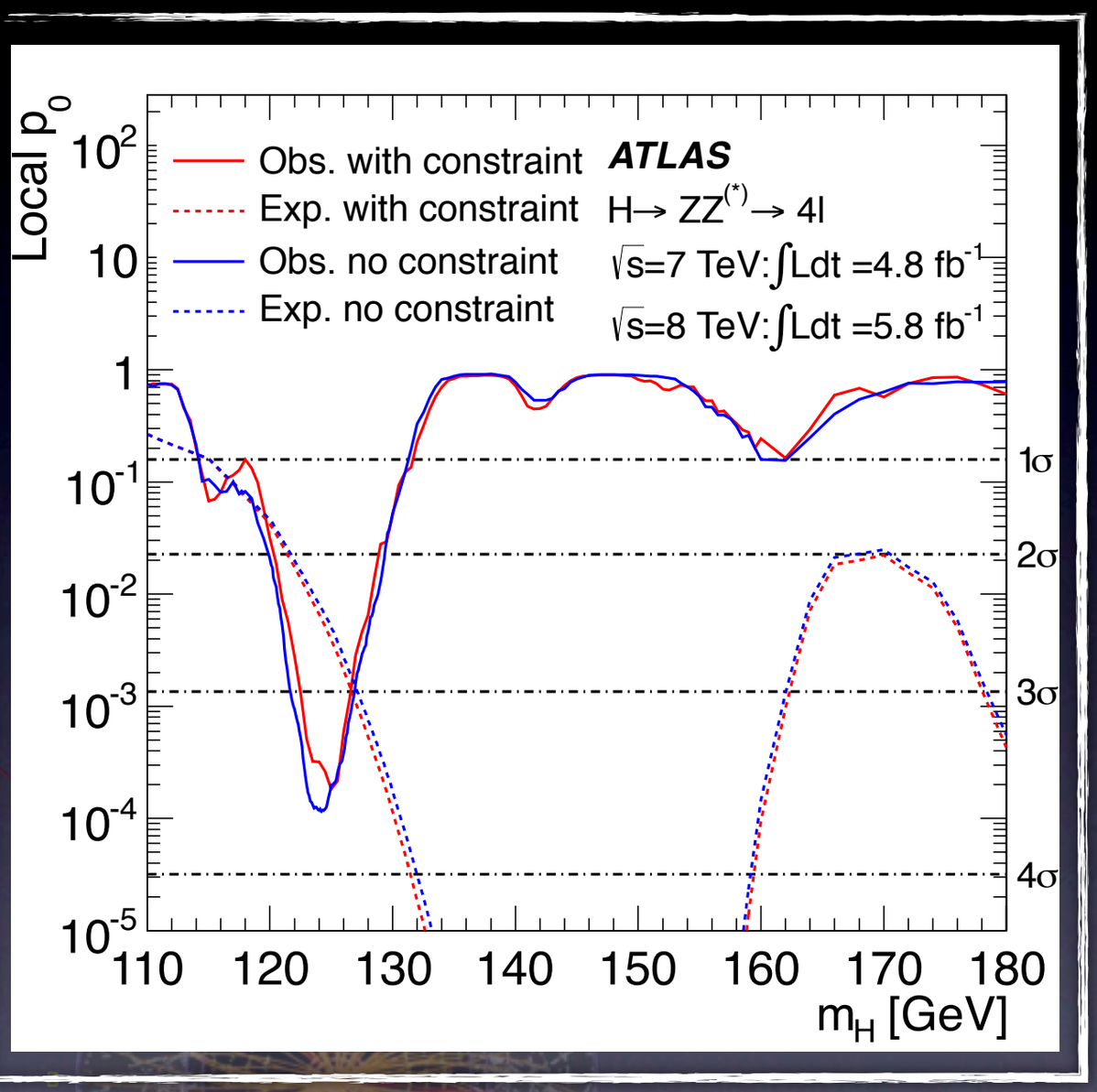


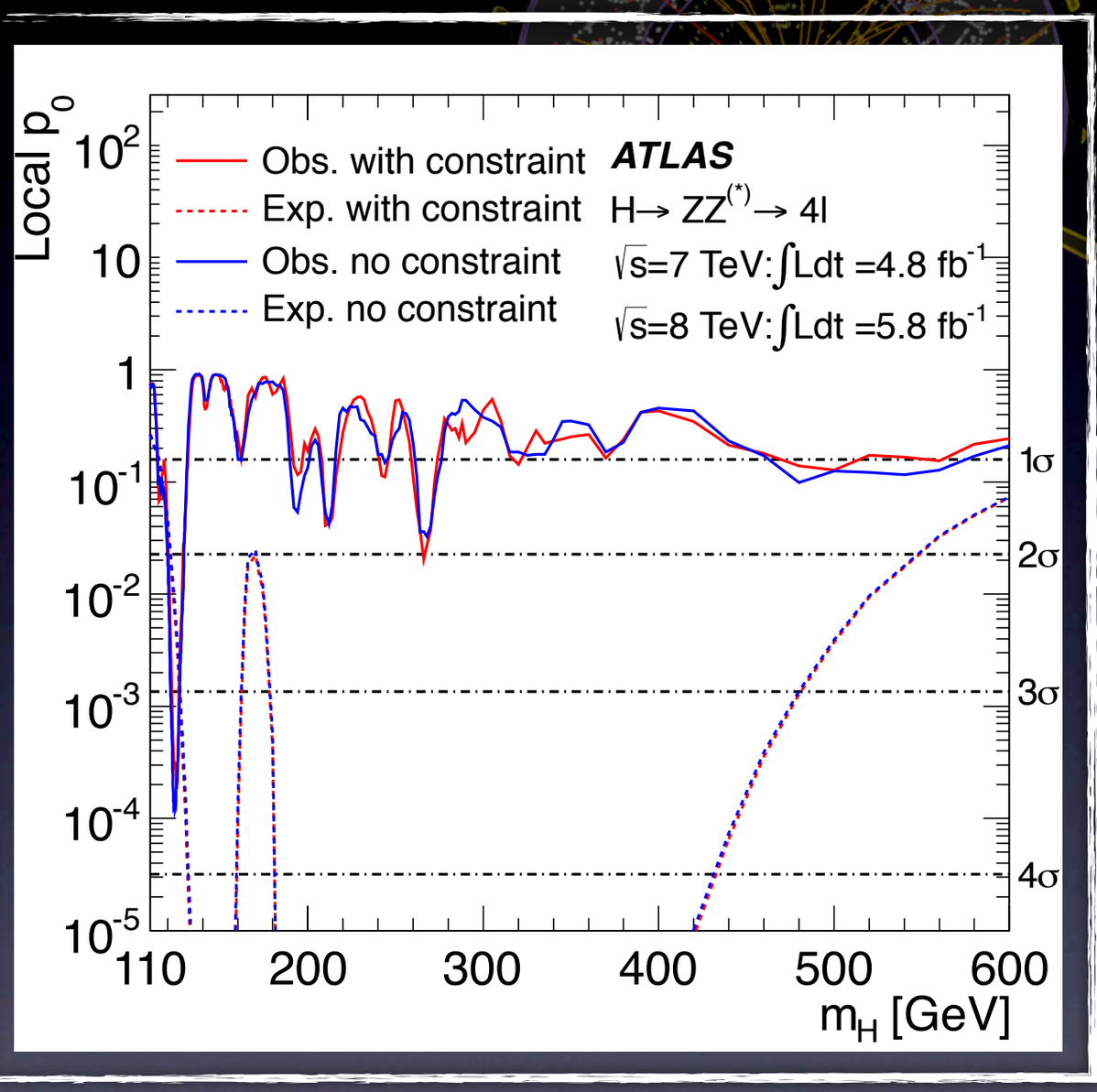


Expected/Observed Yields

	4μ		$2e2\mu/2\mu2e$		$4e$	
	Low mass	High mass	Low mass	High mass	Low mass	High mass
$\sqrt{s} = 8$ TeV						
Int. Luminosity	5.8 fb^{-1}		5.8 fb^{-1}		5.9 fb^{-1}	
$ZZ^{(*)}$	6.3±0.3	27.5±1.9	3.7±0.2	41.7±3.0	2.9±0.3	17.7±1.4
Z + jets, and $t\bar{t}$	0.4±0.2	0.15±0.07	3.9±0.9	1.4±0.3	2.9±0.8	1.0±0.3
Total Background	6.7±0.3	27.6±1.9	7.6±1.0	43.1±3.0	5.7±0.8	18.8±1.4
Data	4	34	11	61	7	25
$m_H = 125$ GeV	1.4±0.2		1.7±0.2		0.8±0.1	
$m_H = 150$ GeV	4.5±0.6		5.9±0.8		2.7±0.4	
$m_H = 190$ GeV	8.2±1.0		12.5±1.7		5.3±0.8	
$m_H = 400$ GeV	3.9±0.5		6.6±0.9		2.9±0.4	
$\sqrt{s} = 7$ TeV						
Int. Luminosity	4.8 fb^{-1}		4.8 fb^{-1}		4.9 fb^{-1}	
$ZZ^{(*)}$	4.9±0.2	18.1±1.3	3.1±0.2	27.3±2.0	1.6±0.2	10.2±0.8
Z + jets, and $t\bar{t}$	0.2±0.1	0.07±0.03	2.1±0.5	0.7±0.2	2.3±0.6	0.8±0.2
Total Background	5.1±0.2	18.2±1.3	5.1±0.5	28.0±2.0	3.9±0.6	11.0±0.8
Data	8	25	5	28	4	18
$m_H = 125$ GeV	1.0±0.1		1.0±0.1		0.37±0.05	
$m_H = 150$ GeV	3.0±0.4		3.4±0.5		1.4±0.2	
$m_H = 190$ GeV	5.1±0.6		7.4±1.0		2.8±0.4	
$m_H = 400$ GeV	2.3±0.3		3.8±0.5		1.6±0.2	

Significance of Excess

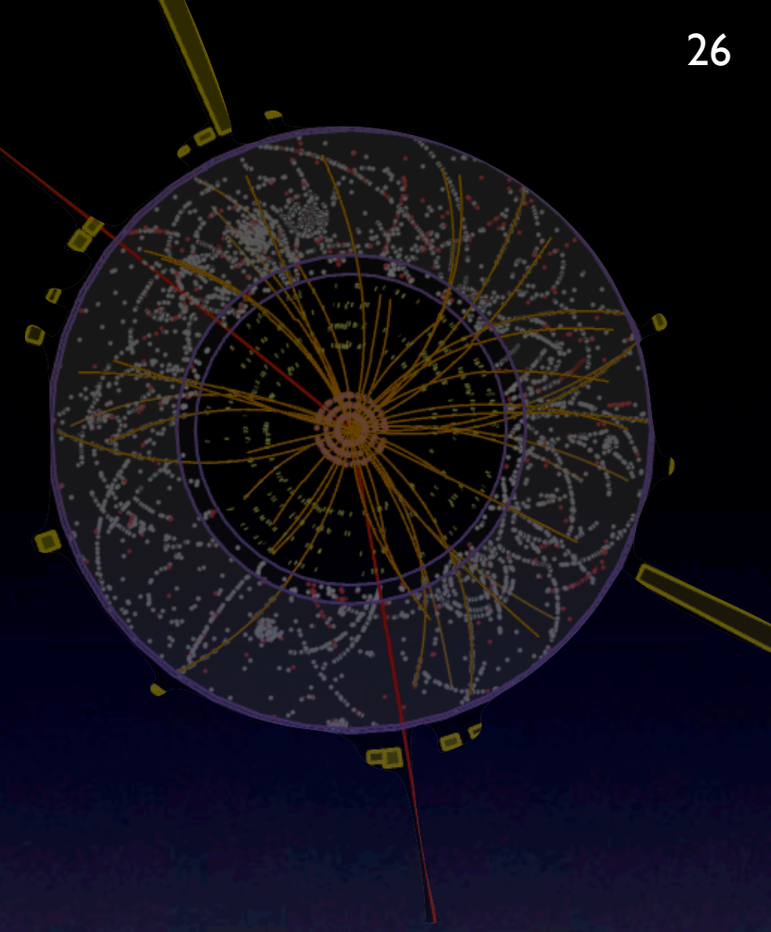


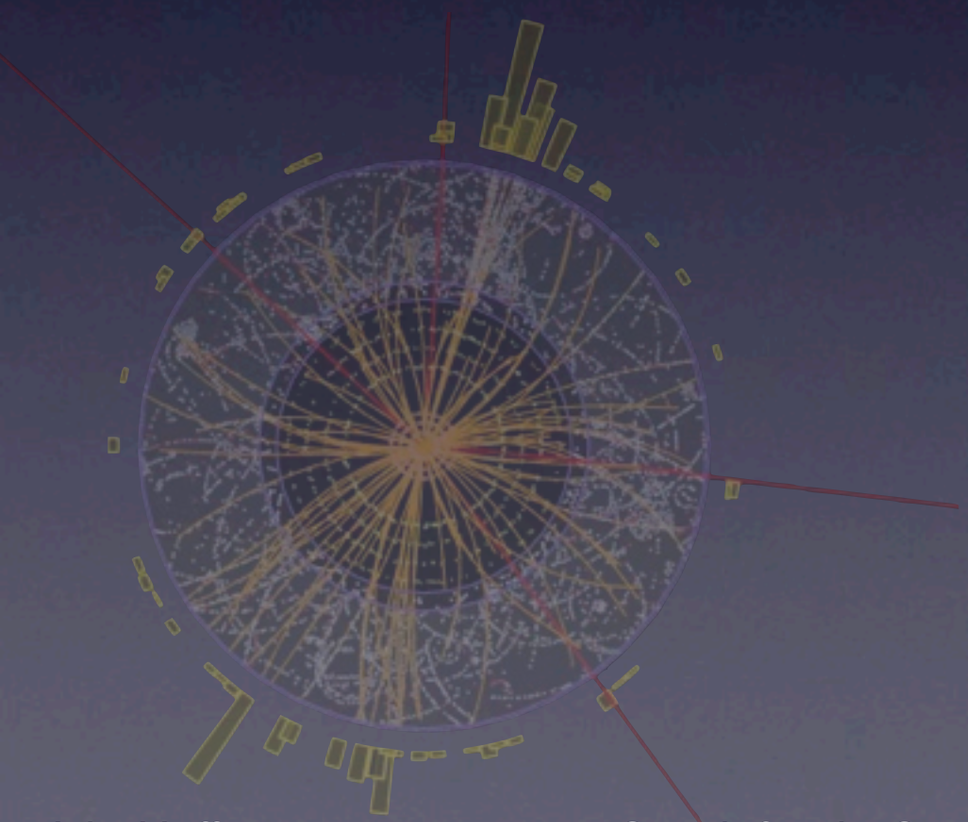


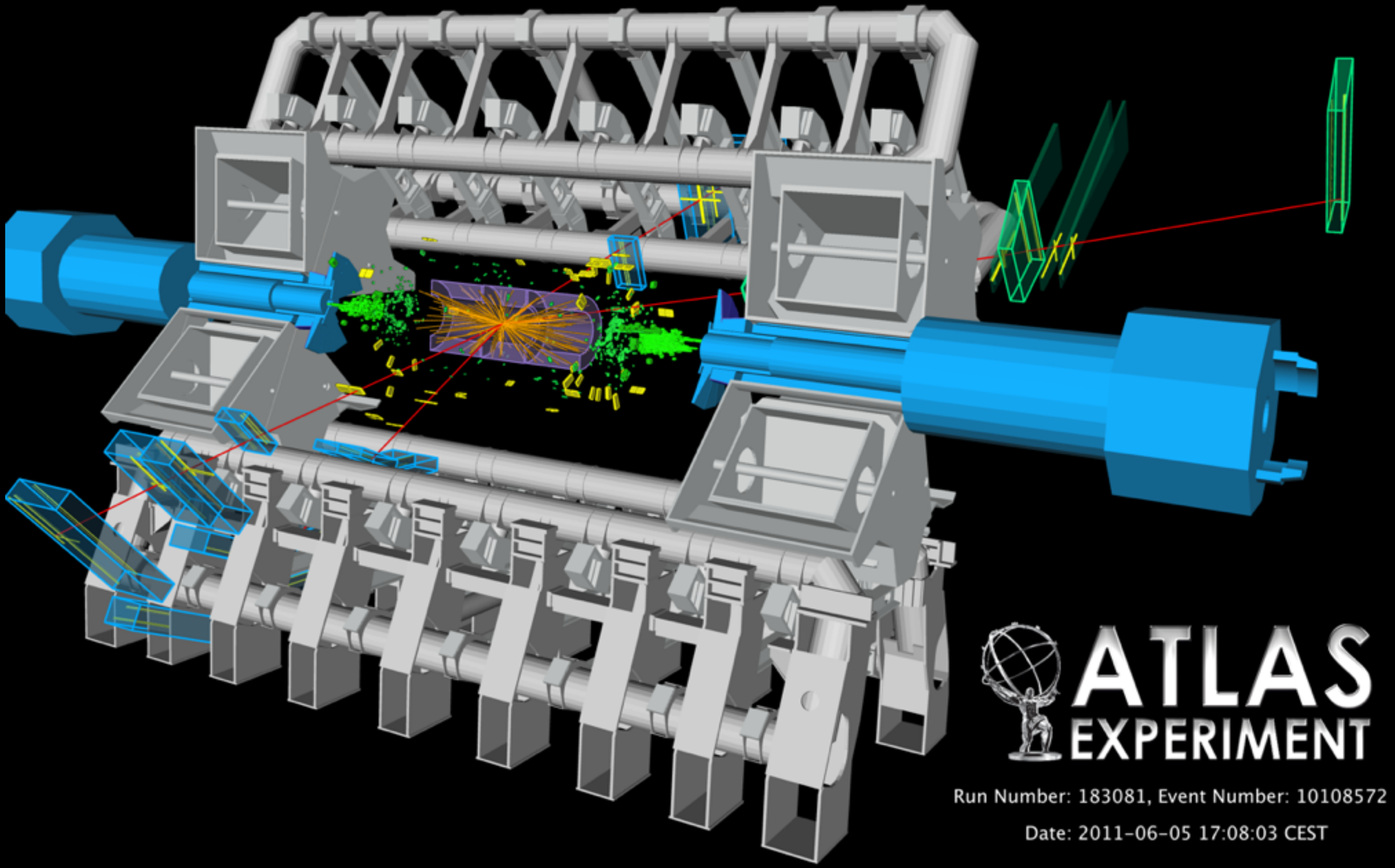
Event Selection in More Detail

Event Selection							
Kinematic Selection	At least one quadruplet of leptons consisting of two pairs of same flavor opposite charge leptons fulfilling the following requirements: $p_T^{1,2,3,4}$ > 20, 15, 10, 7 GeV (6 GeV for μ) Leading di-lepton pair mass requirement 50 < m_{12} <105 GeV Sub-leading di-lepton pair mass requirement $m_{threshold}$<m_{34}<115 GeV $\Delta R_{(l,l')}$> 0.1 for all leptons in the quadruplet.						
Isolation	$\Delta R(l,l') > 0.10$ (0.20) for all same (different) -flavor leptons in the quadruplet						
Impact parameter significance, J/Ψ veto	Reject quadruplet if alternative same-flavor opposite-charge pair gives m_{ll} < 5 GeV Track and calorimeter isolation/impact parameter significance						
Sub-leading di-lepton pair mass requirements							
m_{4l} (GeV)	≤120	130	150	160	165	180	≥190
threshold (GeV)	17.5	22.5	30	30	35	40	50

Event Displays



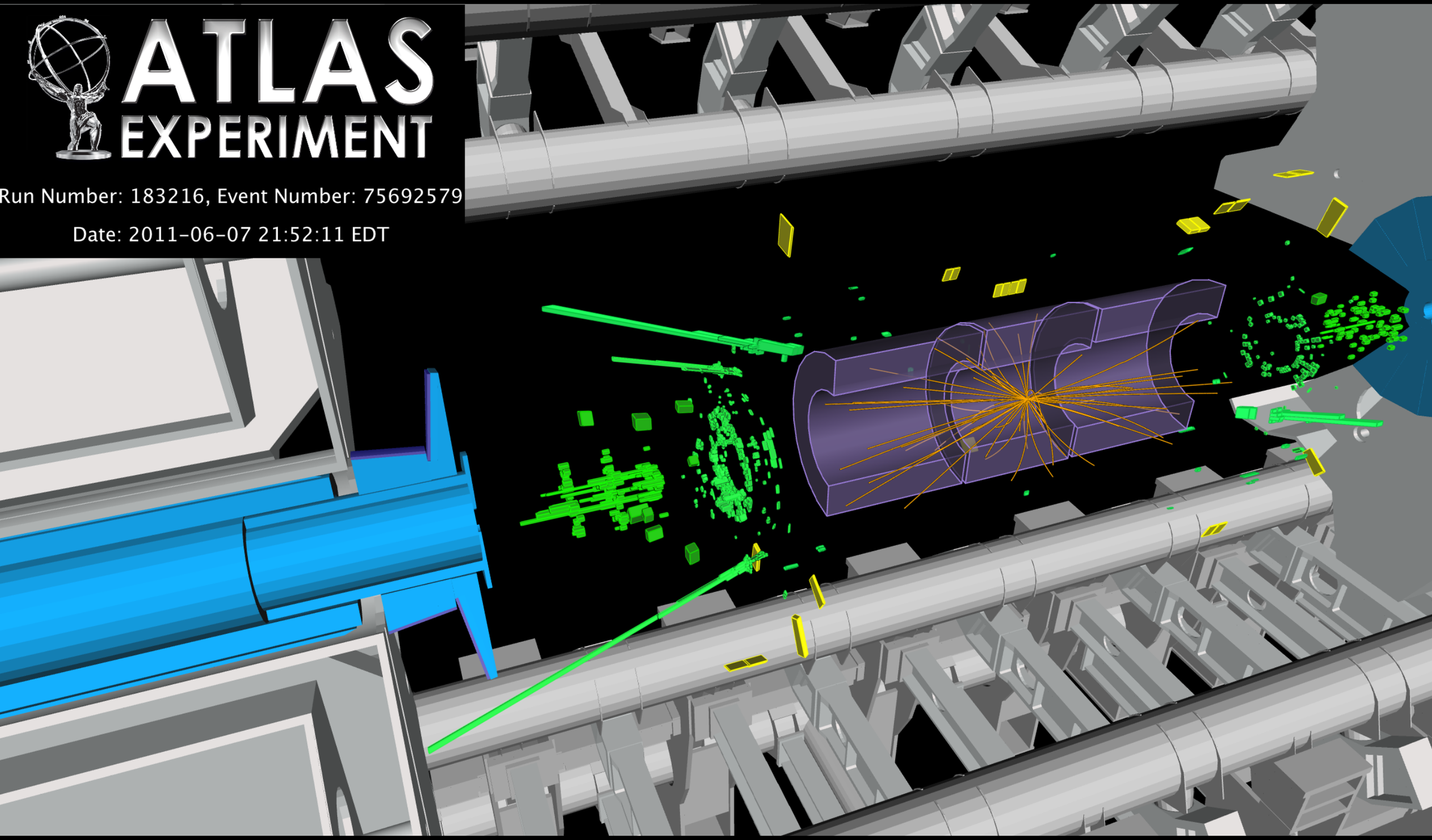



ATLAS
EXPERIMENT
Run Number: 183081, Event Number: 10108572
Date: 2011-06-05 17:08:03 CEST

ATLAS EXPERIMENT

Run Number: 183216, Event Number: 75692579

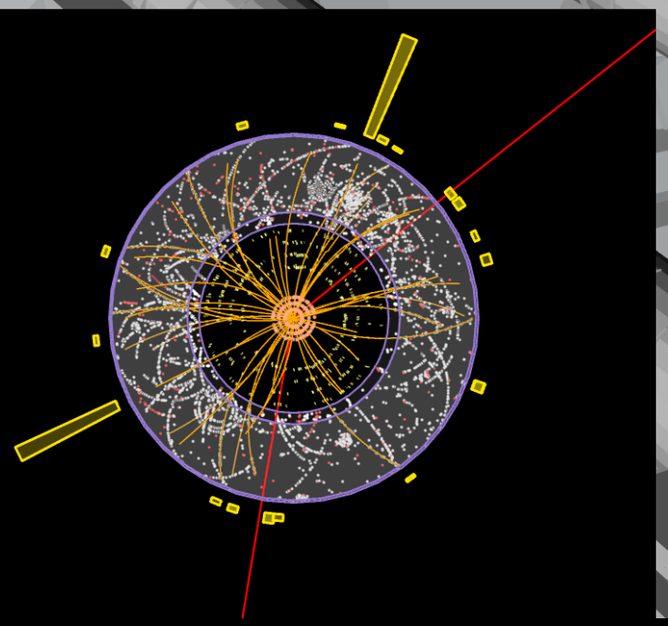
Date: 2011-06-07 21:52:11 EDT



ATLAS EXPERIMENT

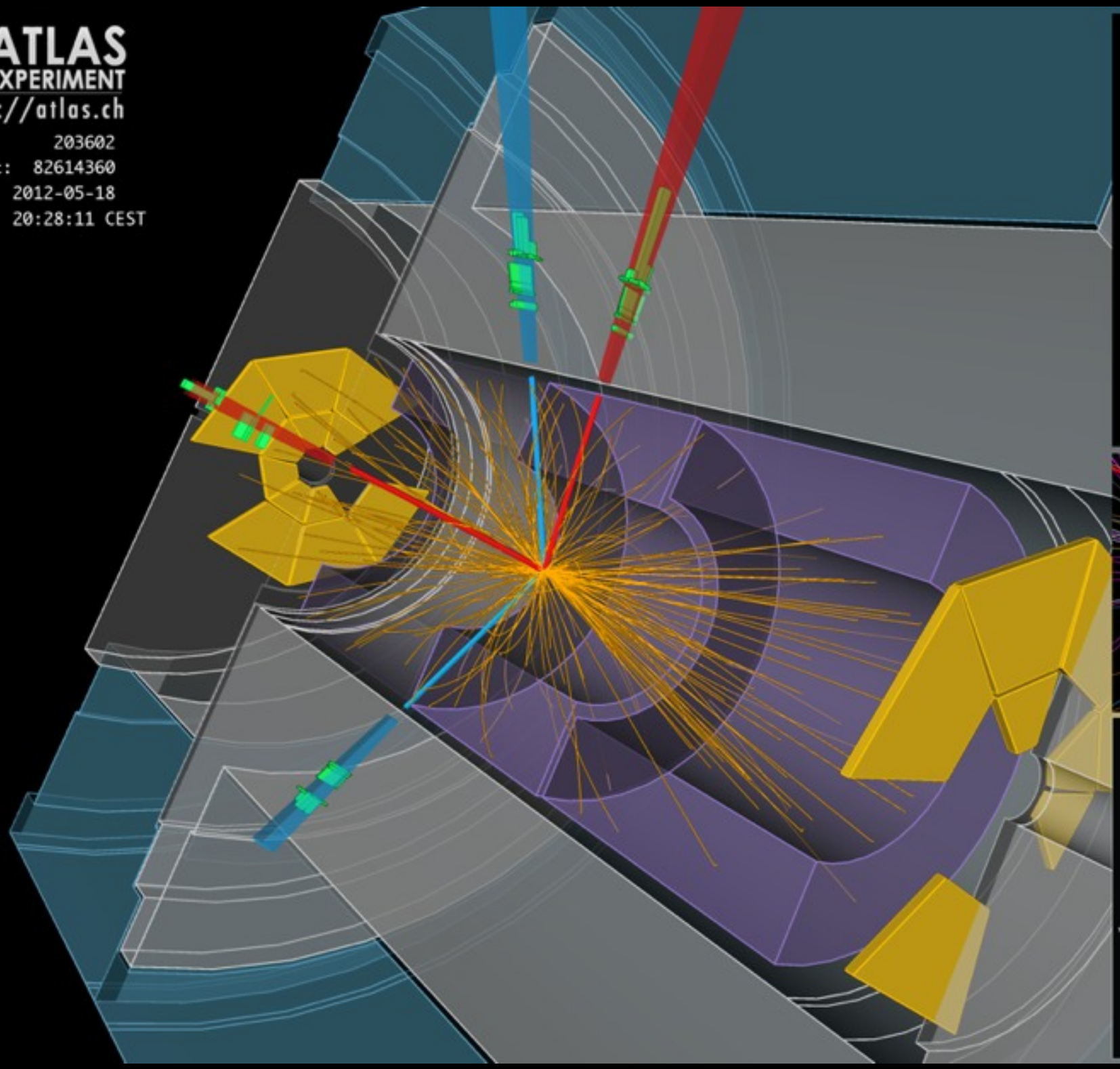
Run Number: 182747, Event Number: 63217197

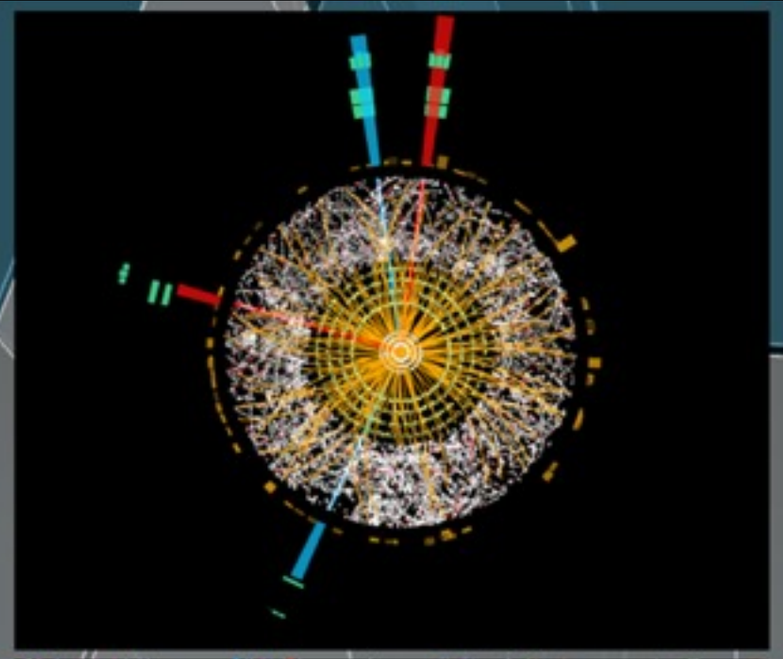
Date: 2011-05-28 13:06:57 CEST

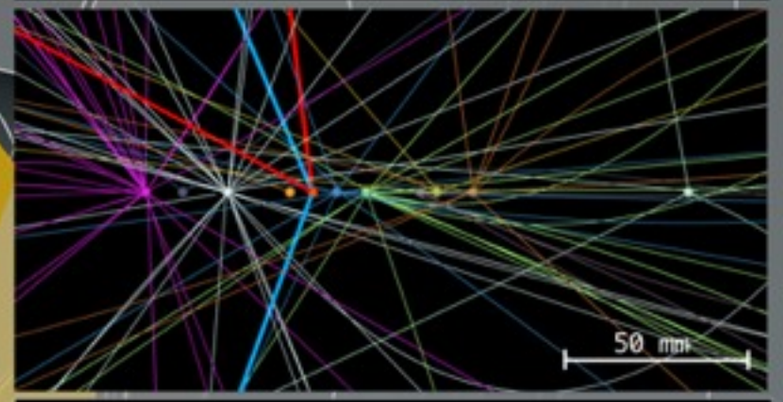


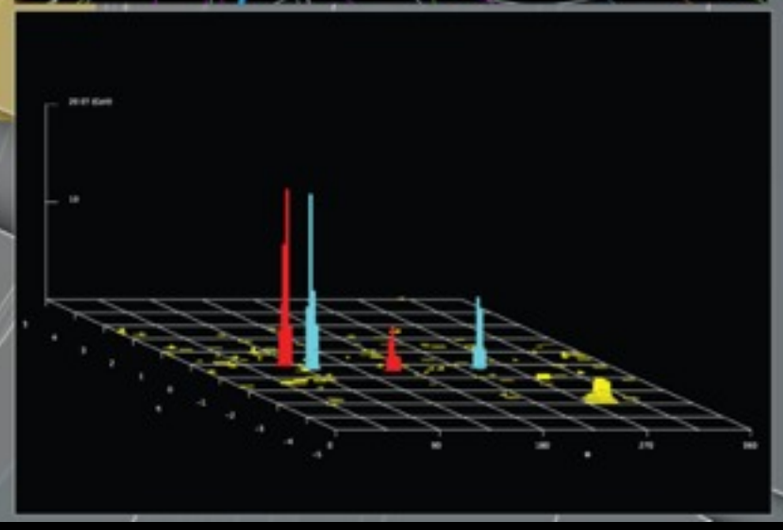
ATLAS EXPERIMENT
http://atlas.ch

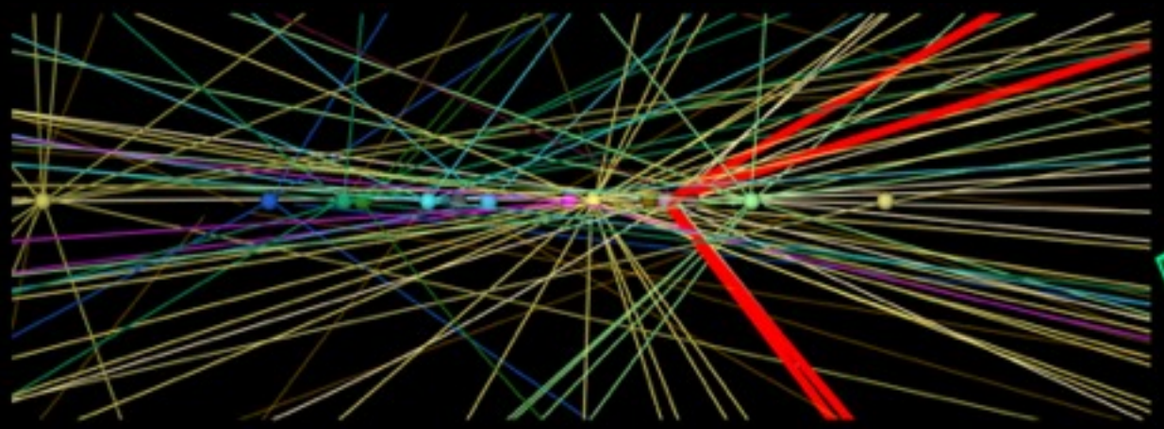
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST

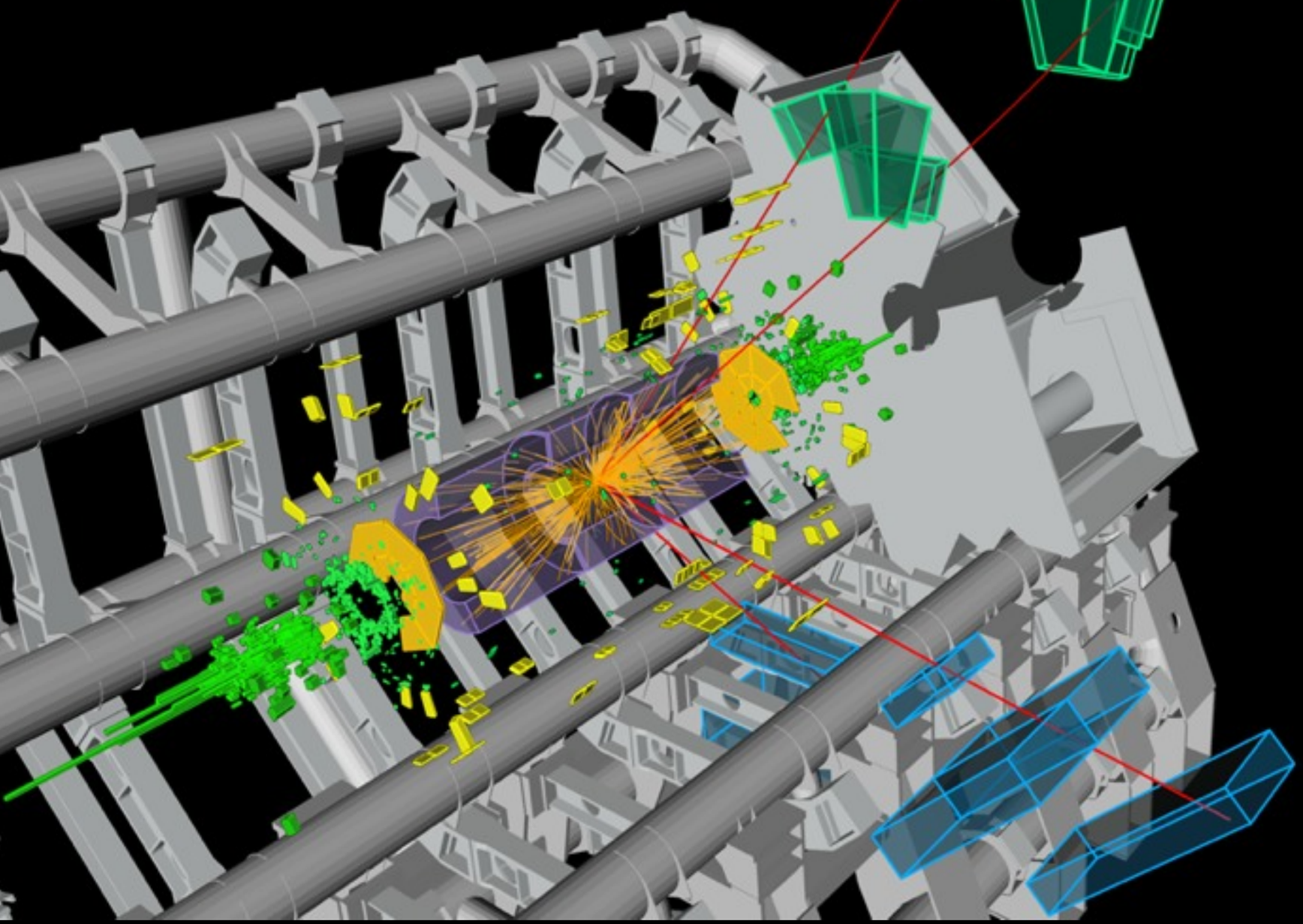


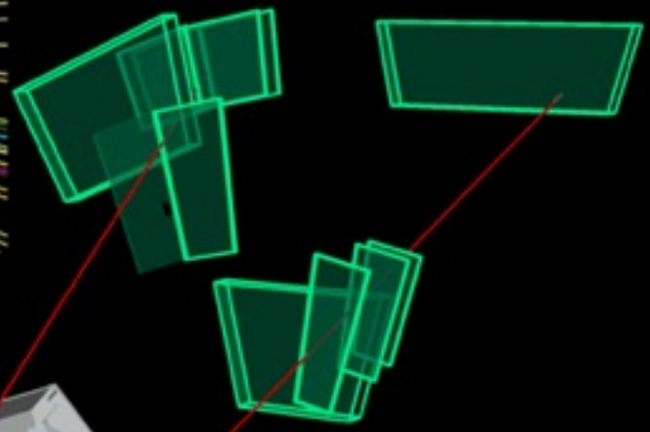


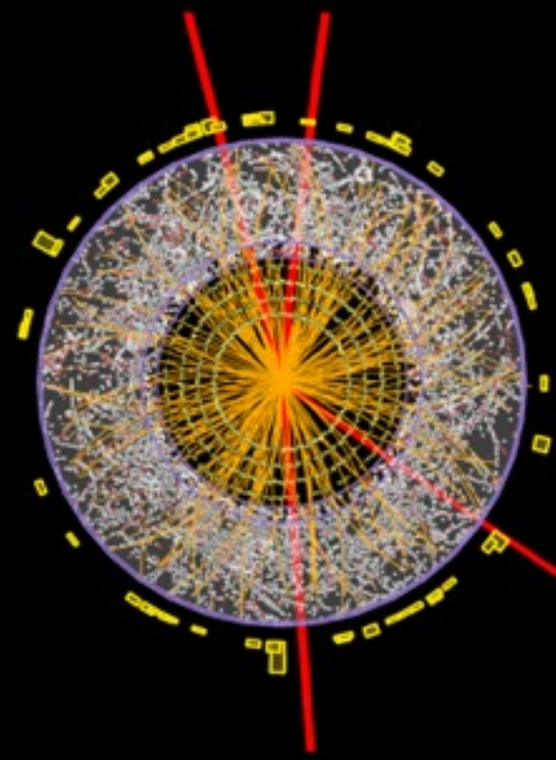












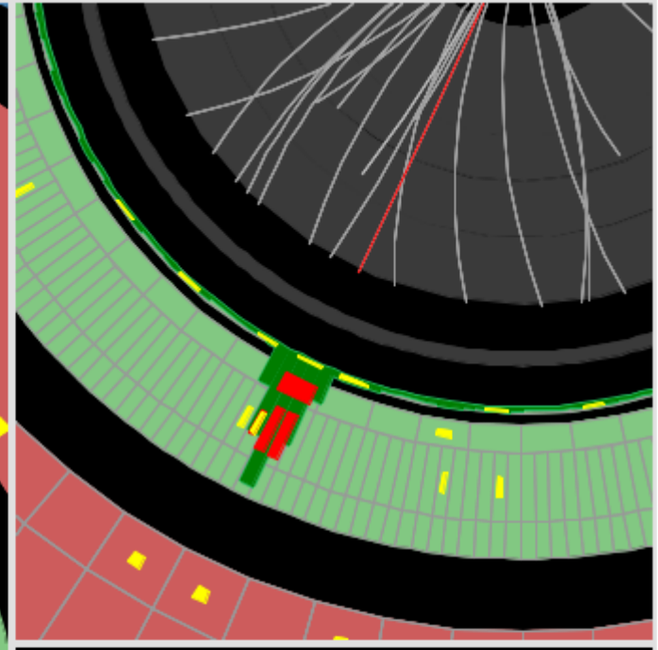
ATLAS EXPERIMENT
http://atlas.ch

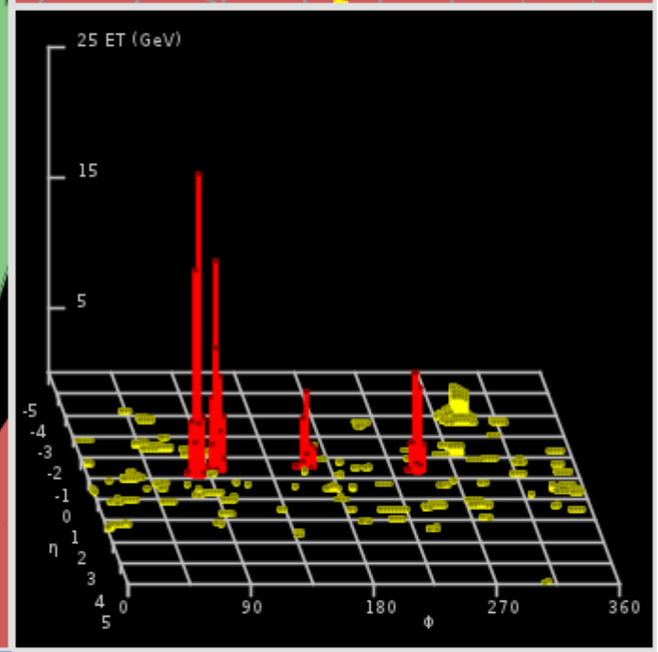
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

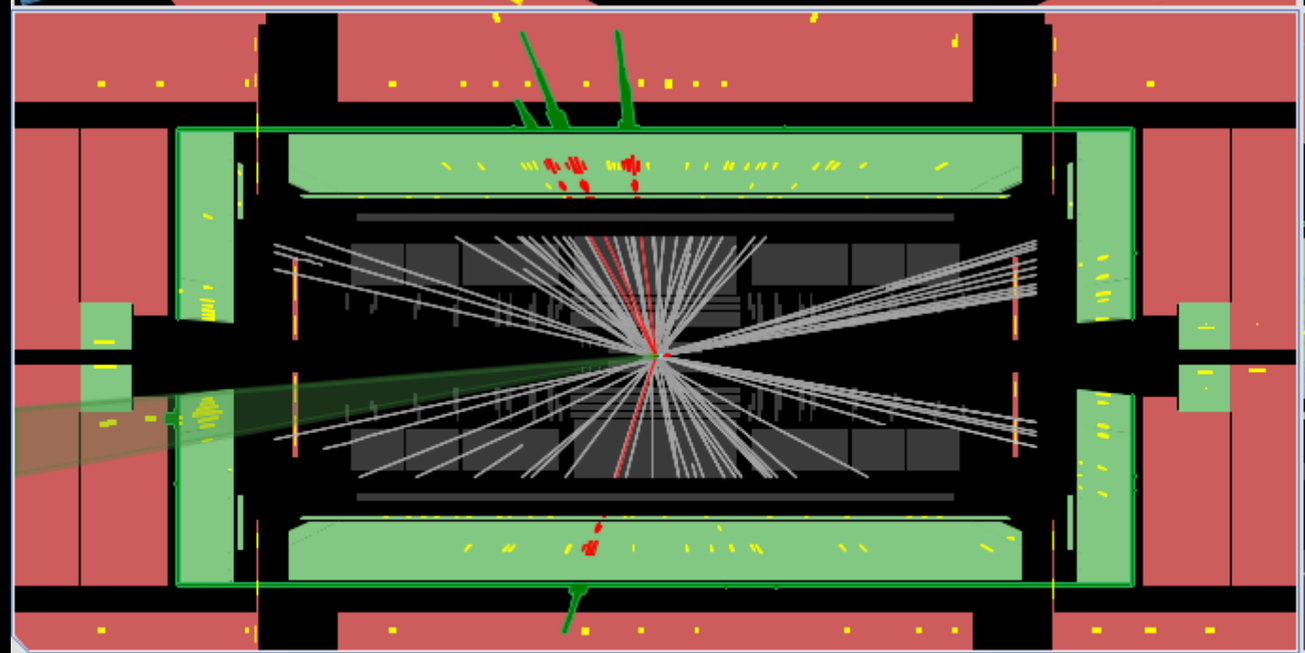
ATLAS EXPERIMENT

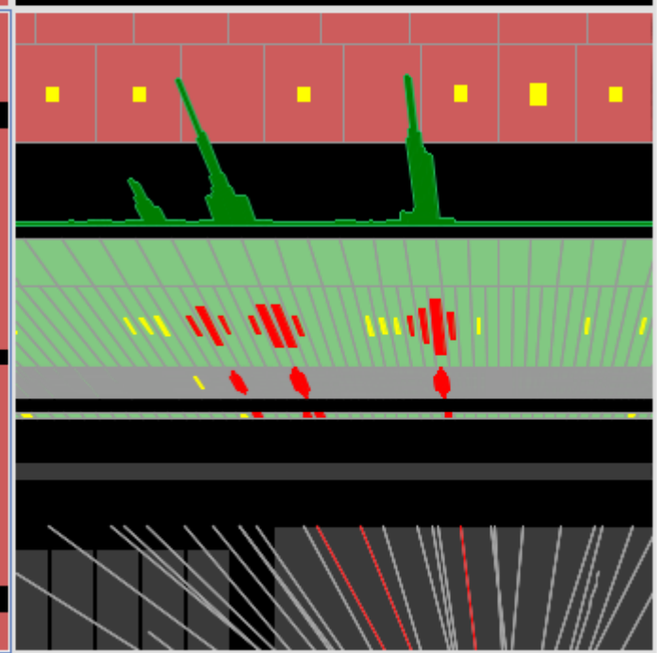
Run Number: 203602, Event Number: 82614360

Date: 2012-05-18 20:28:11 CEST







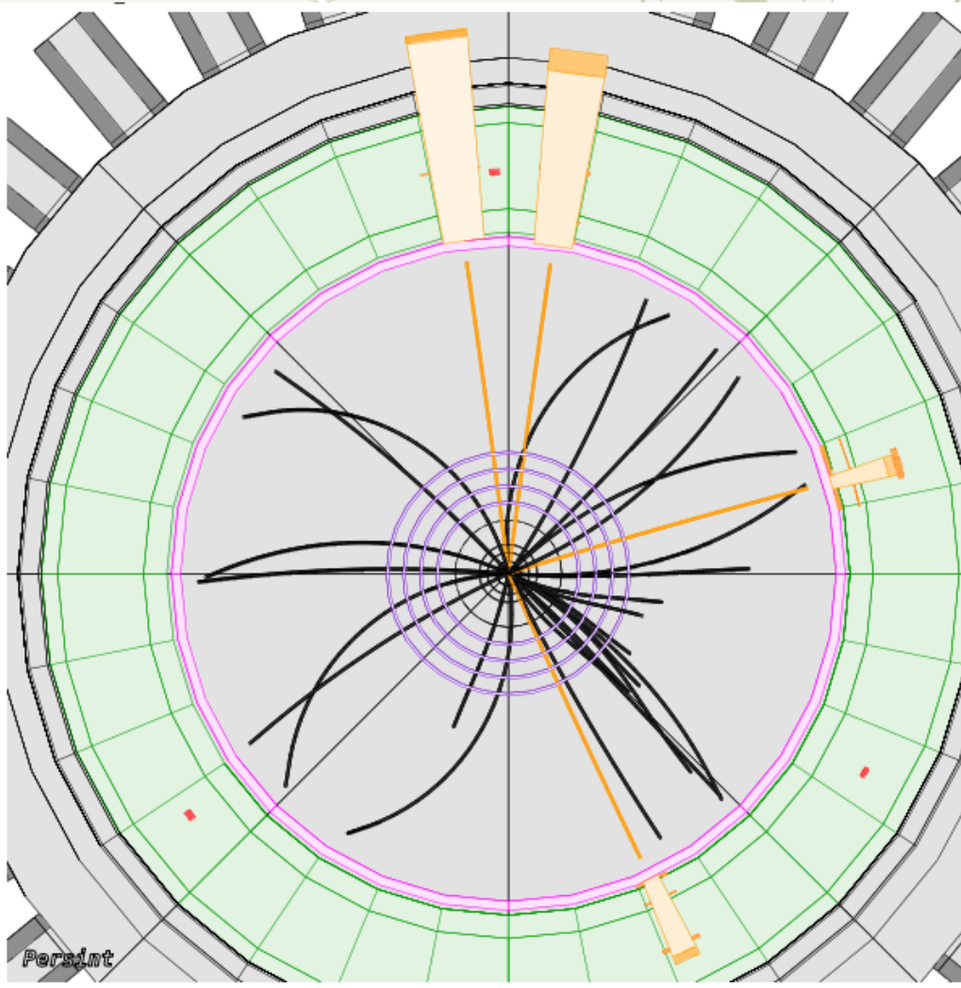


ATLAS EXPERIMENT

Run Number: 203602,
Event Number: 82614360
Date: 2012-05-18, 19:28:11 CET

EtCut>0.40 GeV
PtCut>0.55 GeV
Vertex Cuts:
Z direction <1cm,
Rphi <1cm

Electron:orange
Cells:Tiles, EMC
Collection:e/g



Persint