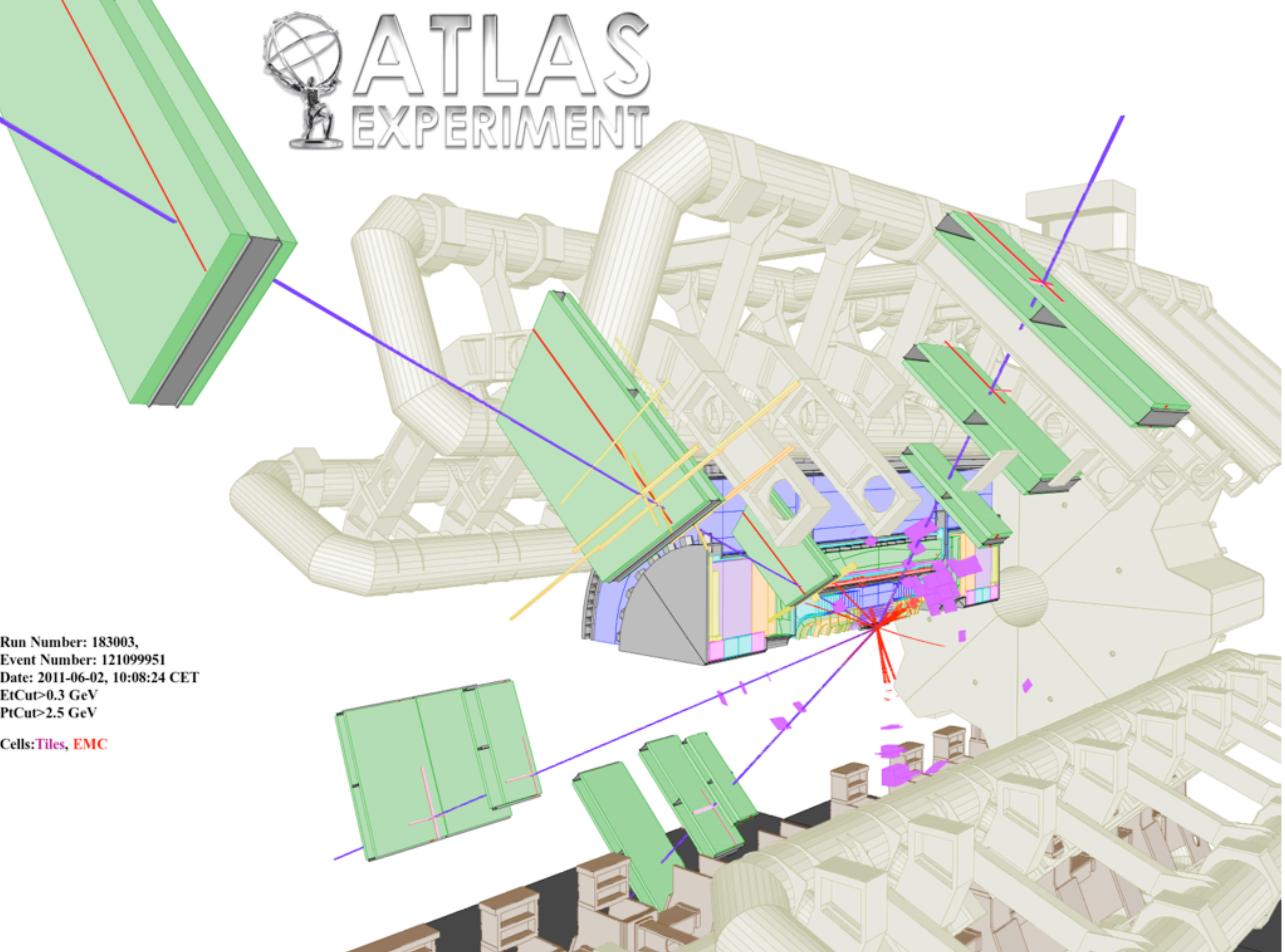


# Search for the SM Higgs boson in the $H \to ZZ^{(*)} \to 4l$ decay channel with ATLAS

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on behalf of the ATLAS collaboration

UNIVERSITY OF BIRMINGHAM

International Conference in High Energy Physics
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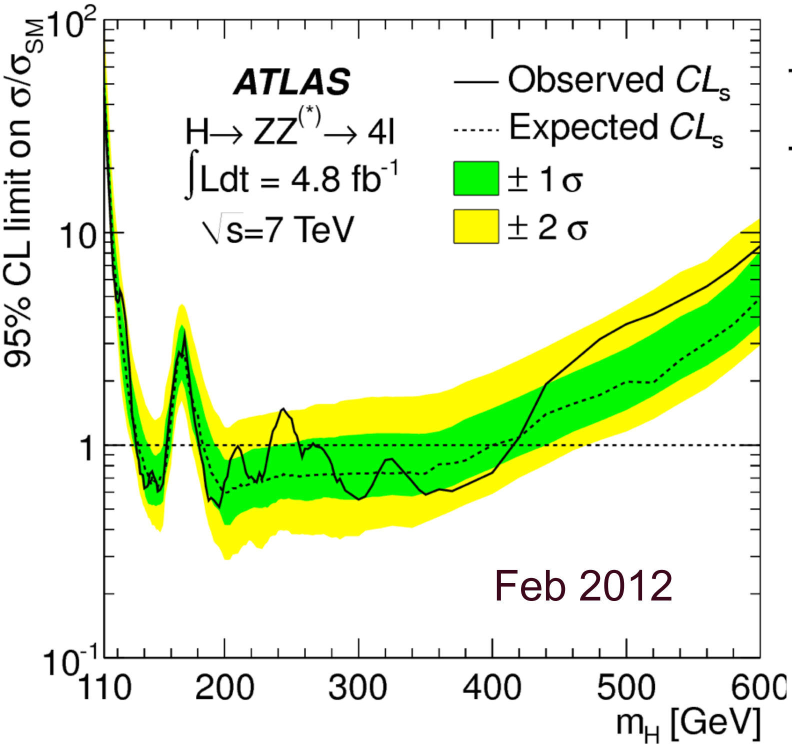
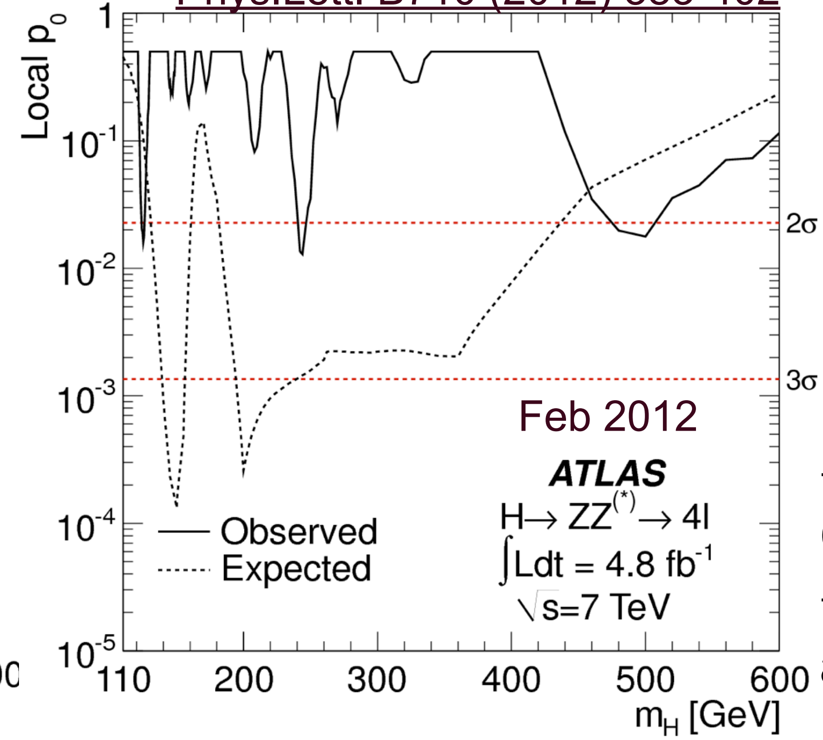
# Introduction




Phys.Lett. B710 (2012) 383-402




$H \to ZZ^{(*)} \to 4l$ (l=e,μ)

Backgrounds

$ZZ^{(*)} \to 4l$ and for $m_{4l} < 2m_Z$

Z+jets (Z+light jets/$Zb\bar{b}$) and $t\bar{t}$

Results in 2011

→ Exclude large $m_H$ range
(134-156, 182-233, 256-265, 268-415 GeV)
→ Observed excesses at ~2σ level (local)
at $m_H$ = 125, 244, 500 GeV

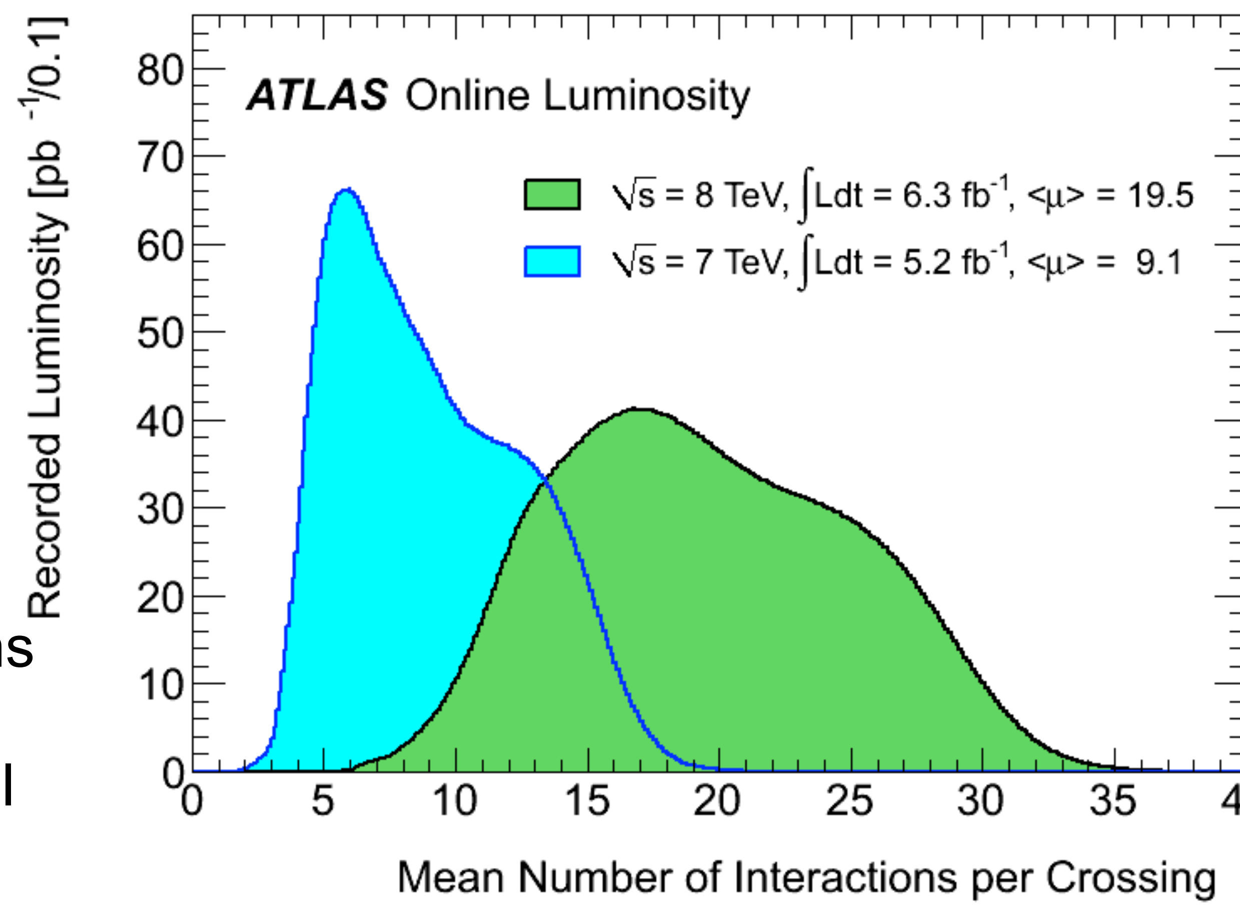
**7 TeV data sample (2011)**

- 5.3 $fb^{-1}$ recorded → 4.8 $fb^{-1}$ for physics (~90%)
- Peak stable luminosity $3.6 \times 10^{33} cm^{-2}s^{-1}$

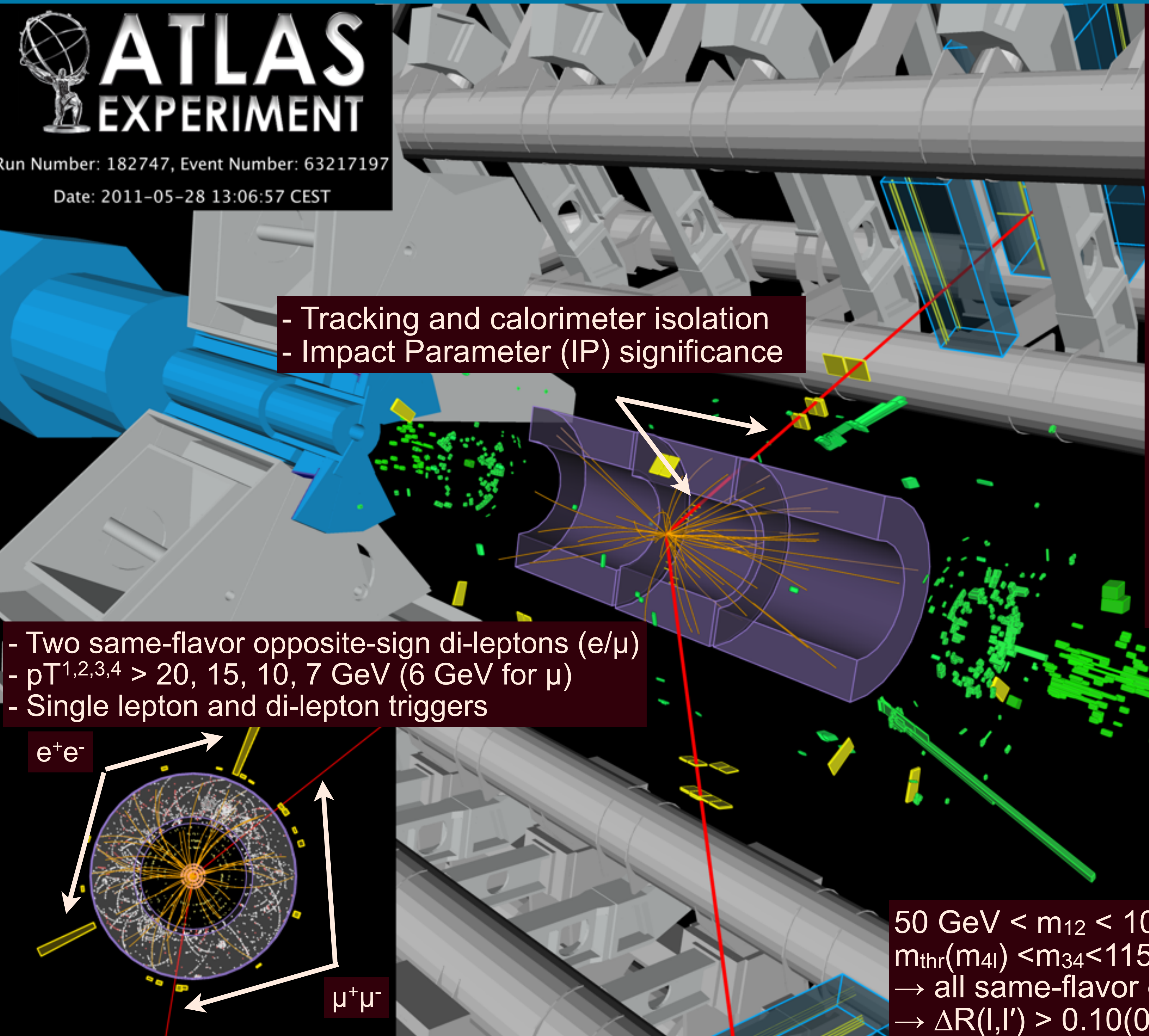
**8 TeV data sample (2012)**

- 6.3 $fb^{-1}$ recorded → 5.8 $fb^{-1}$ for physics (~92%)
- Peak stable luminosity $6.8 \times 10^{33} cm^{-2}s^{-1}$

Pile-up in 2012 exceeding detector design specifications
→ Maintain excellent detector performance
→ Proper modeling of conditions in simulation essential



# Event Selection




- Tracking and calorimeter isolation
- Impact Parameter (IP) significance

- Two same-flavor opposite-sign di-leptons (e/μ)
- $p_T^{1,2,3,4}$ > 20, 15, 10, 7 GeV (6 GeV for μ)
- Single lepton and di-lepton triggers

<u>Publication</u> opted for robustness

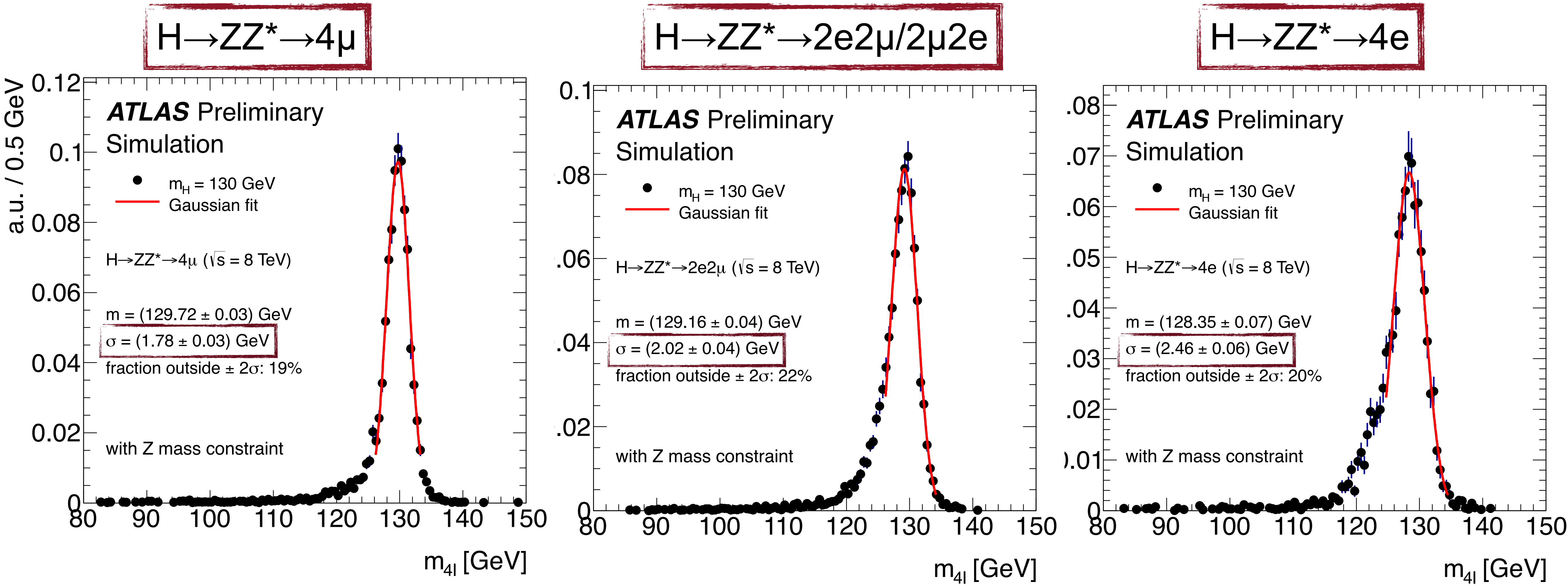
["on-shell" Z-boson ($m_Z$±15GeV)]

<u>Updated analysis</u>

- Optimized for low $m_H$
- Study backgrounds in data
  - side-bands/background dominated regions
  - mostly 2011 data
  - 2012 data once available
  - data-driven estimates
- Once above studies completed
  → signal region

50 GeV < $m_{12}$ < 106 GeV,
$m_{thr}(m_{4l})$ <$m_{34}$<115 GeV $m_{thr}$ =17.5 - 50 GeV
→ all same-flavor opposite-sign pairs $m_{ll}$>5 GeV
→ ΔR(l,l′) > 0.10(0.20) for all same(different)-flavor

# Mass resolution




Typical search for narrow peak on top of smooth background

→ Resolution crucial for sensitivity!

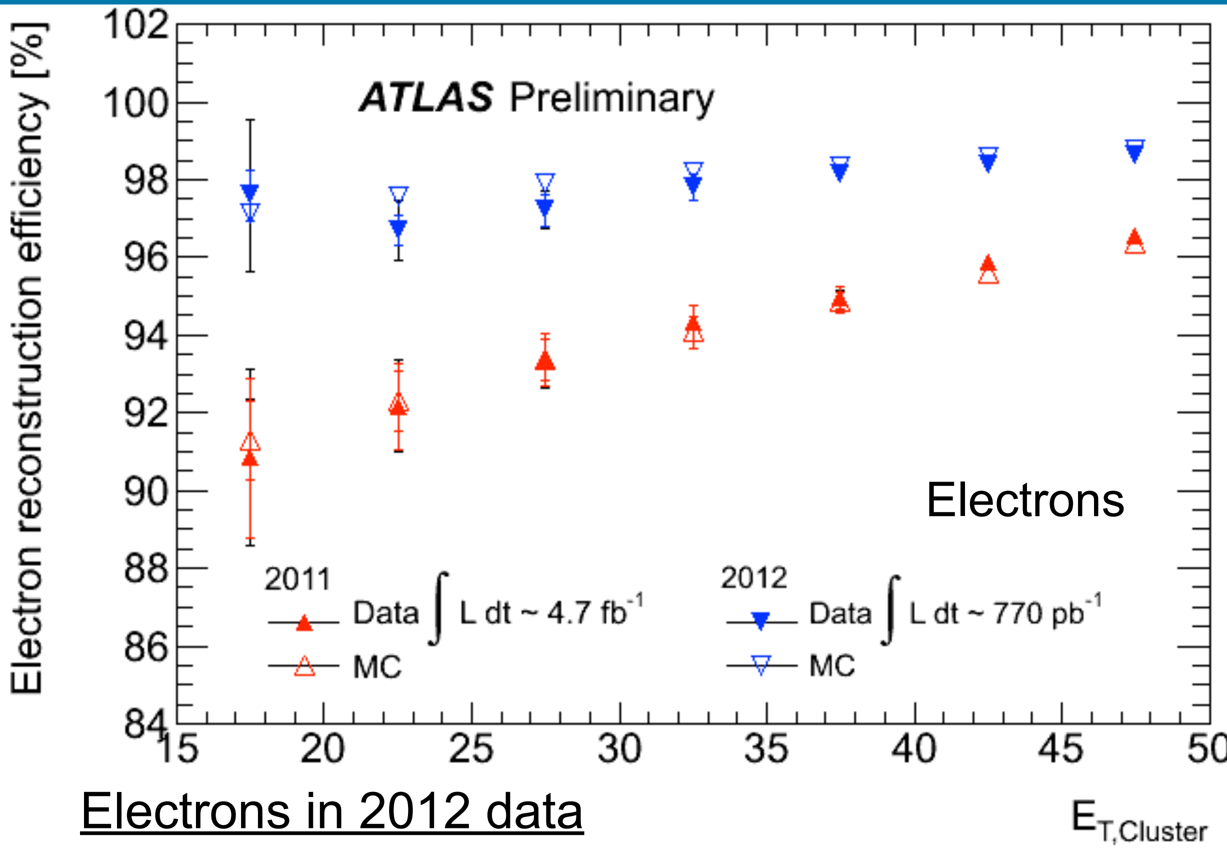
→ Final states separated in 4μ, 2μ2e, 2e2μ, 4e

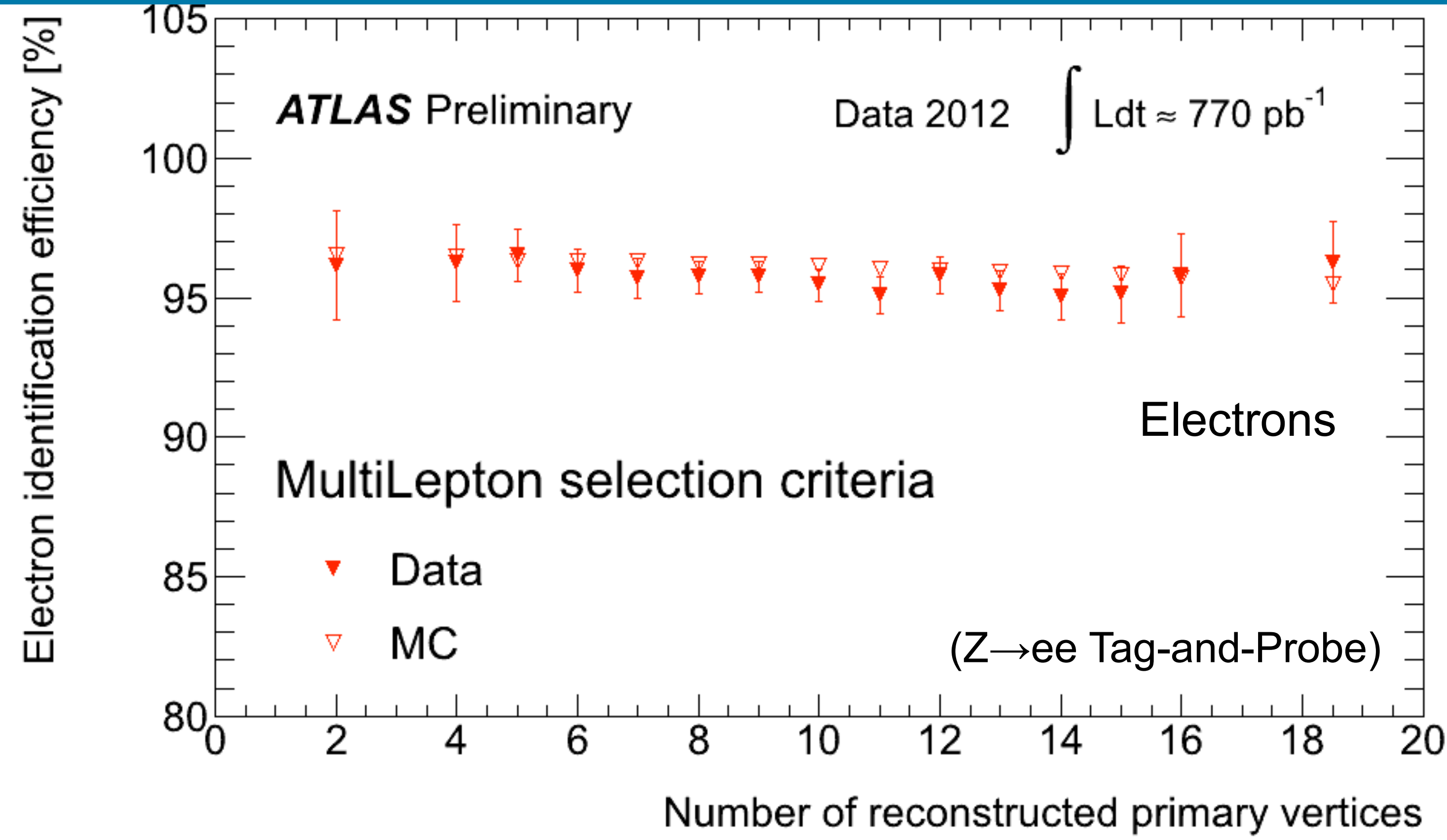
ATLAS detector provides excellent resolution!

→ Relative resolution of 1.6 - 2.1% for $m_H$=130 GeV

Further improved by using $m_Z$ constrained fit

→ Relative resolution of 1.3 - 1.9% for $m_H$=130 GeV



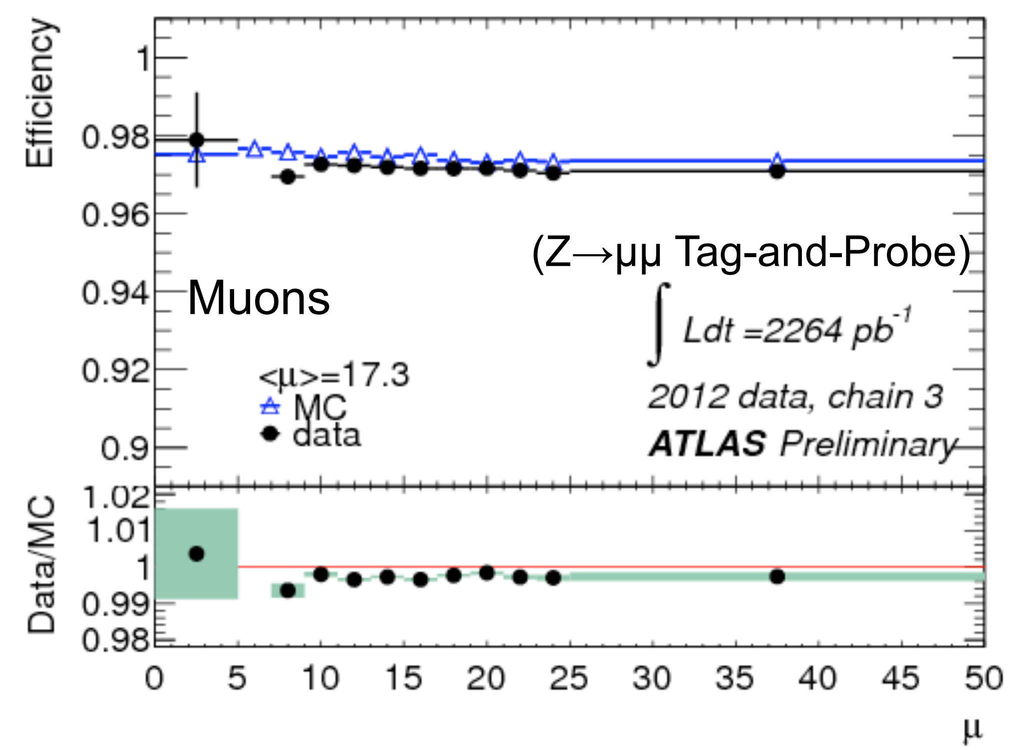




## Electrons in 2012 data

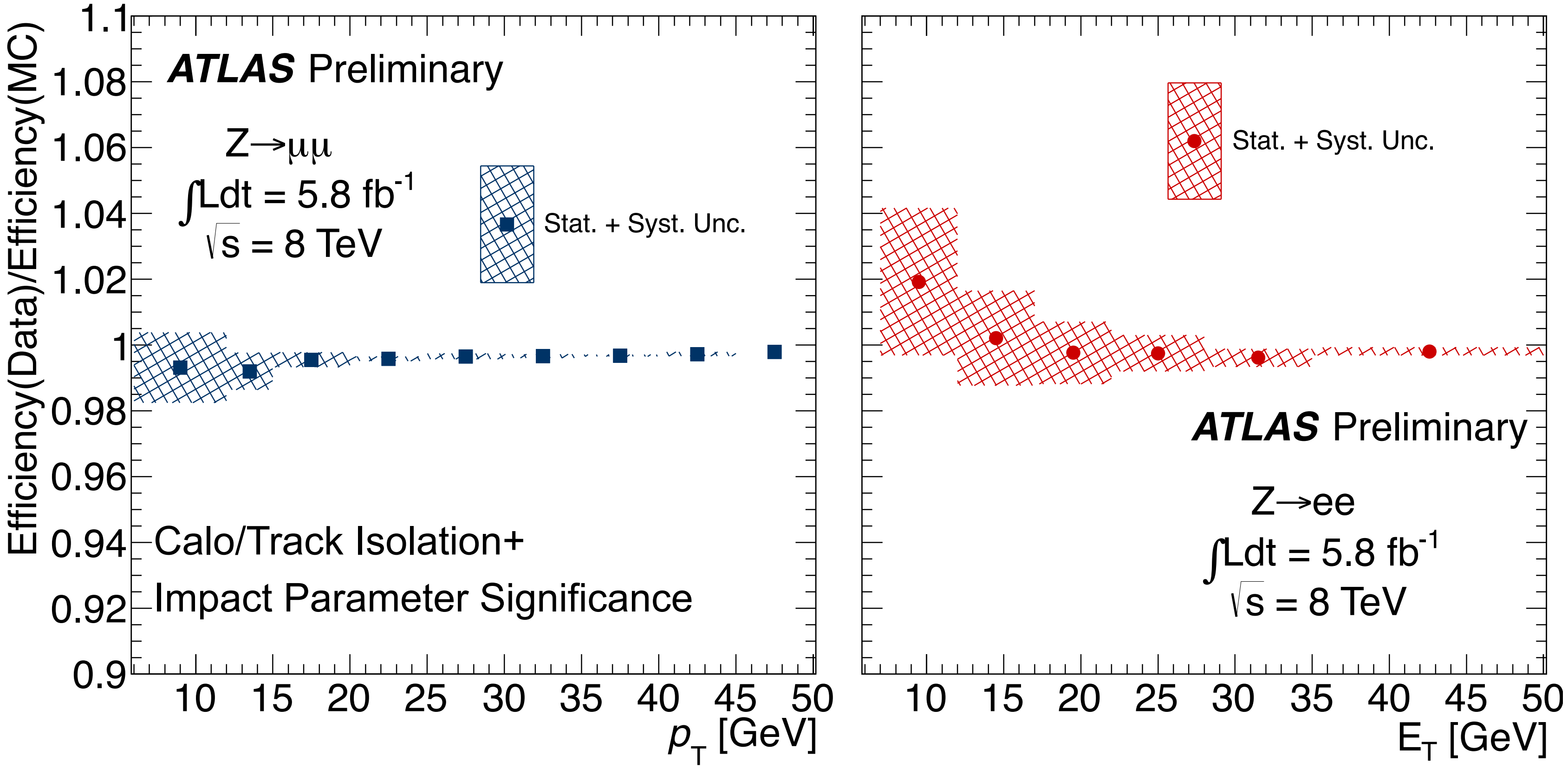
- Improved electron reconstruction!
  - New pattern finding/track-fit
- Improved electron identification!
  - Pile-up robust
  - Higher rejection and efficiency with respect to 2011 data
- Pile-up robust calorimeter-based isolation

## Muons

- Combining/Matching Inner Detector (ID) tracks with complete or partial tracks in Muon Spectrometer (MS)
- Extend muon coverage:
  - ID-track + energy deposit profile in calorimeter ($|\eta|<0.1$/$p_T>15$ GeV)
  - MS stand-alone ($2.5<|\eta|<2.7$)



# Event Selection Performance Checks



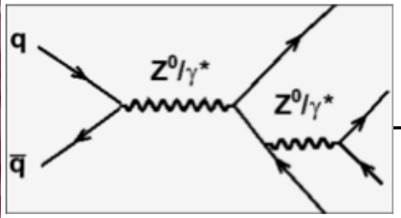

Isolation/IP requirement performance controlled from data

→ Signal-like leptons: Z→ll tag-and-probe

→ Background-like leptons: Z+'μ'and Z+'e'

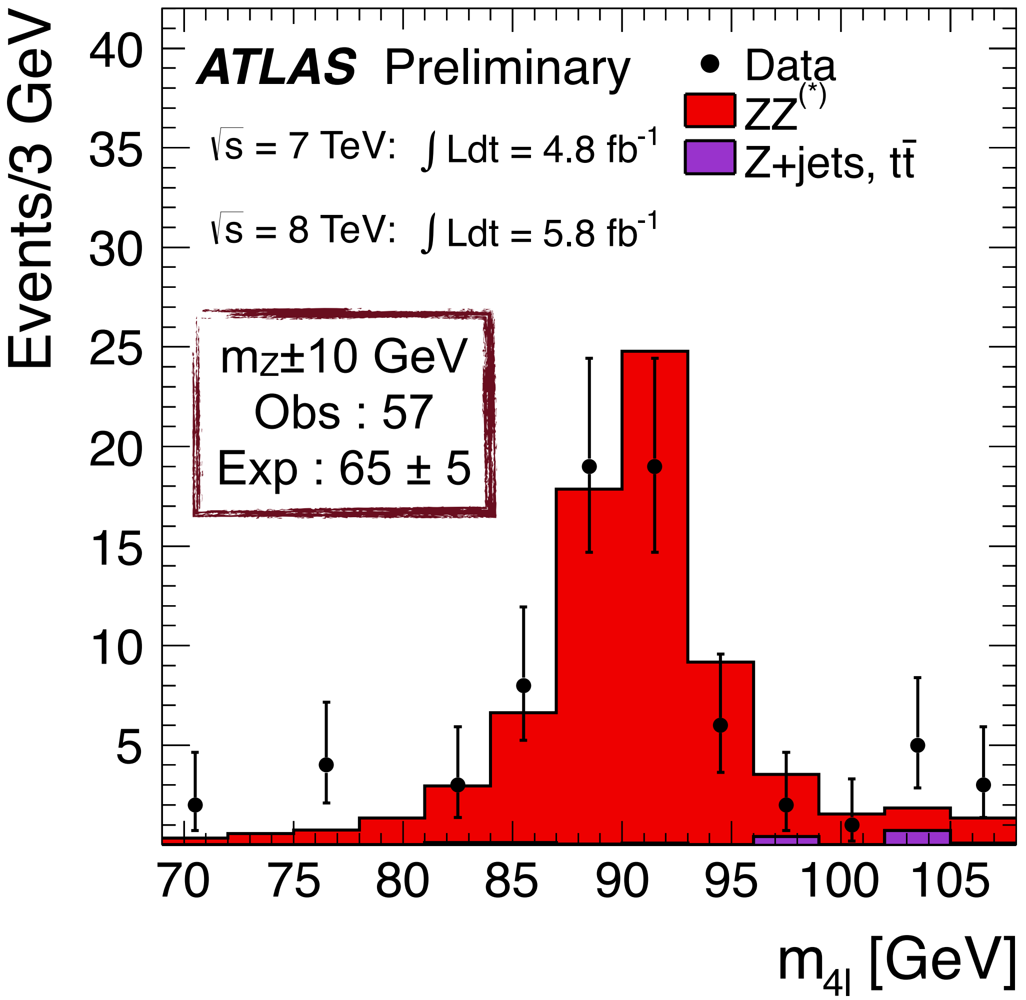
pp→Z→4l

Relax analysis requirements: $m_{12}$>30 GeV, $m_{34}$>5 GeV and lower $p_T$ for muons (>4 GeV)

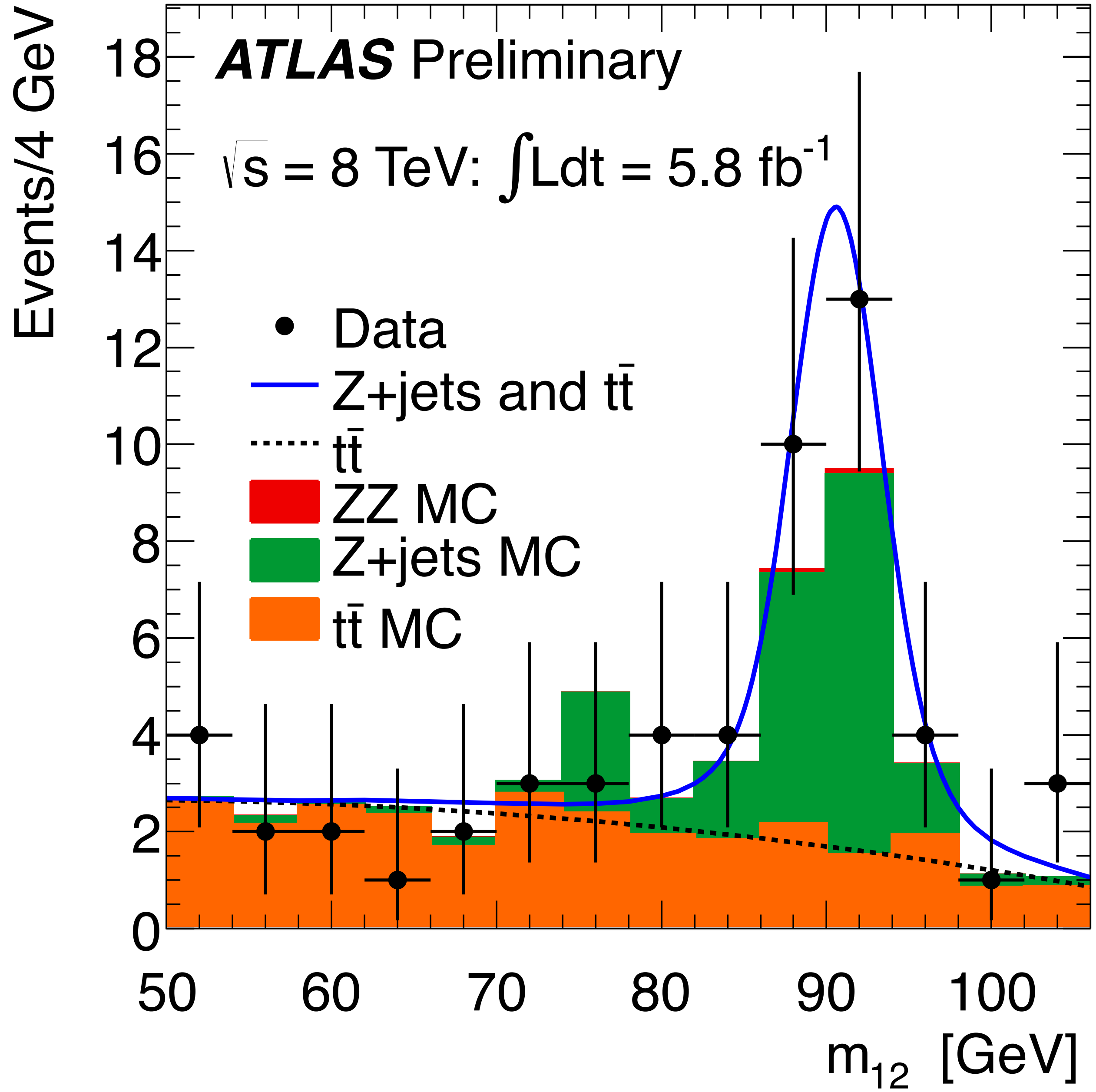



→ Cross-check of analysis configuration

→ Indicates (again) reasonable behavior of lepton reconstruction/identification



# Background Estimates: ll+μμ




Main contributions from Zbb̄ and tt̄

**$m_{12}$ fit**

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

**$e^{\pm}\mu^{\mp}+\mu^{\pm}\mu^{\mp}$**

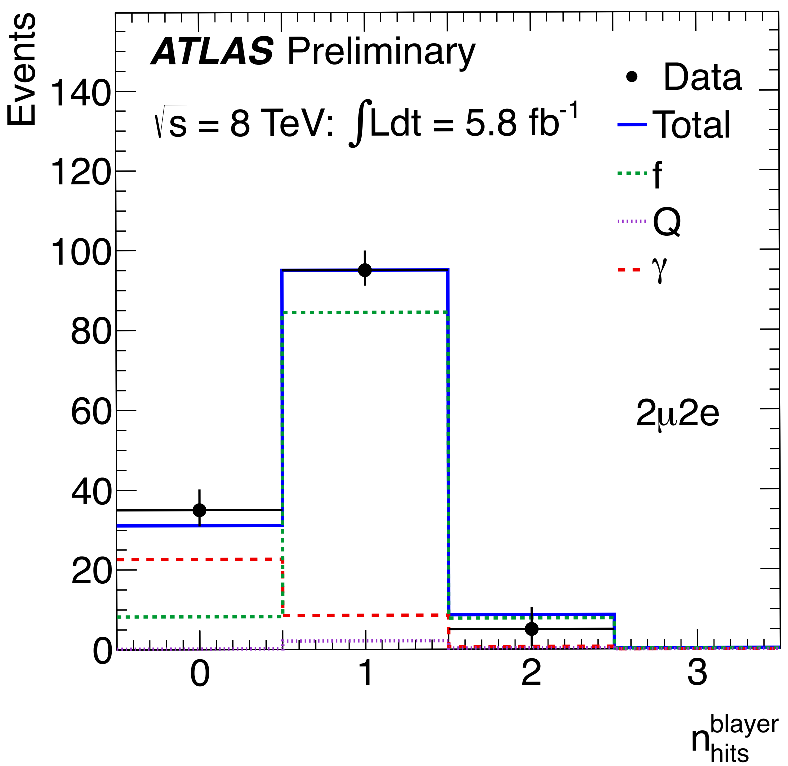
- $e^{\pm}\mu^{\mp}$ leading di-lepton with Z→ll veto → tt̄ dominated
- Observed 16 (8) events compared to 18.9±1.1 (11.0 ± 0.6) expected in 8 (7) TeV
- Extrapolation to signal region → compatible results with $m_{12}$ fit

# Background Estimates: ll+ee

- Main contribution: Z+jets
  - Hadrons mis-identified as electrons (f)
  - Electrons from photon conversions (c/γ)
  - Electrons from semi-leptonic decays of heavy flavour (Q)
- Background composition crucial to extrapolate to Signal Region
- Use the strengths of the detector to constrain the composition
  - Transition Radiation
  - Number of B-layer hits
  - Fraction of energy in first sampling of e/m calorimeter
  - Lateral containment of cluster along φ in 2nd e/m sampling

8 TeV — Analysis phase-space, but relaxing electron identification for sub-leading di-electron

| | 4e | | 2μ2e | |
|---|---|---|---|---|
| | 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 |



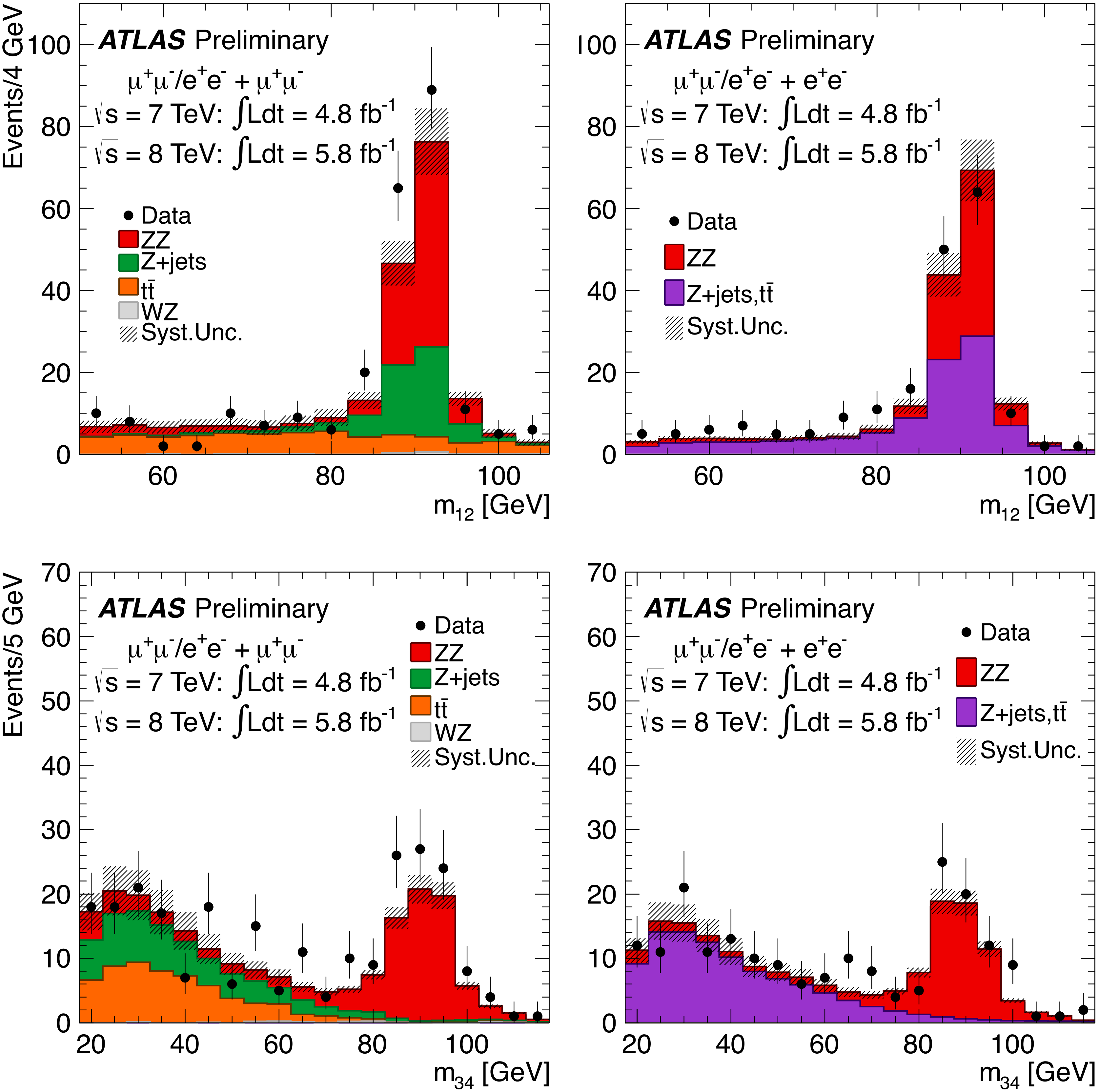

### Base-line method

- Relax identification in sub-leading di-electron
- Categorize events [also check MC description]
- Extrapolate yields in each category to the signal region using MC

### Alternative method in Same-Charge sub-leading di-electron

- Relax requirements on softest electron
- Composition from fit (separate Conversions/Hadrons)

# Background Estimates: Control Regions




Background-dominated Control Region
→ Remove isolation/impact parameter requirements on sub-leading di-lepton
→ Normalize to data-driven estimates
→ Normalization/shape of reducible backgrounds well described

# Background Estimates: Overview

8 TeV

| Method | Estimated nr. of events |
|---|---|
| $4\mu$ | |
| $m_{12}$ 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 nr. of events |
|---|---|
| $4\mu$ | |
| $m_{12}$ 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) | $2.2 \pm 0.5 \pm 0.3$ |

value ± stat ± syst

→ Multiple methods used, yielding compatible results

→ For each channel, the "†" symbol indicates the method used for the nominal normalization

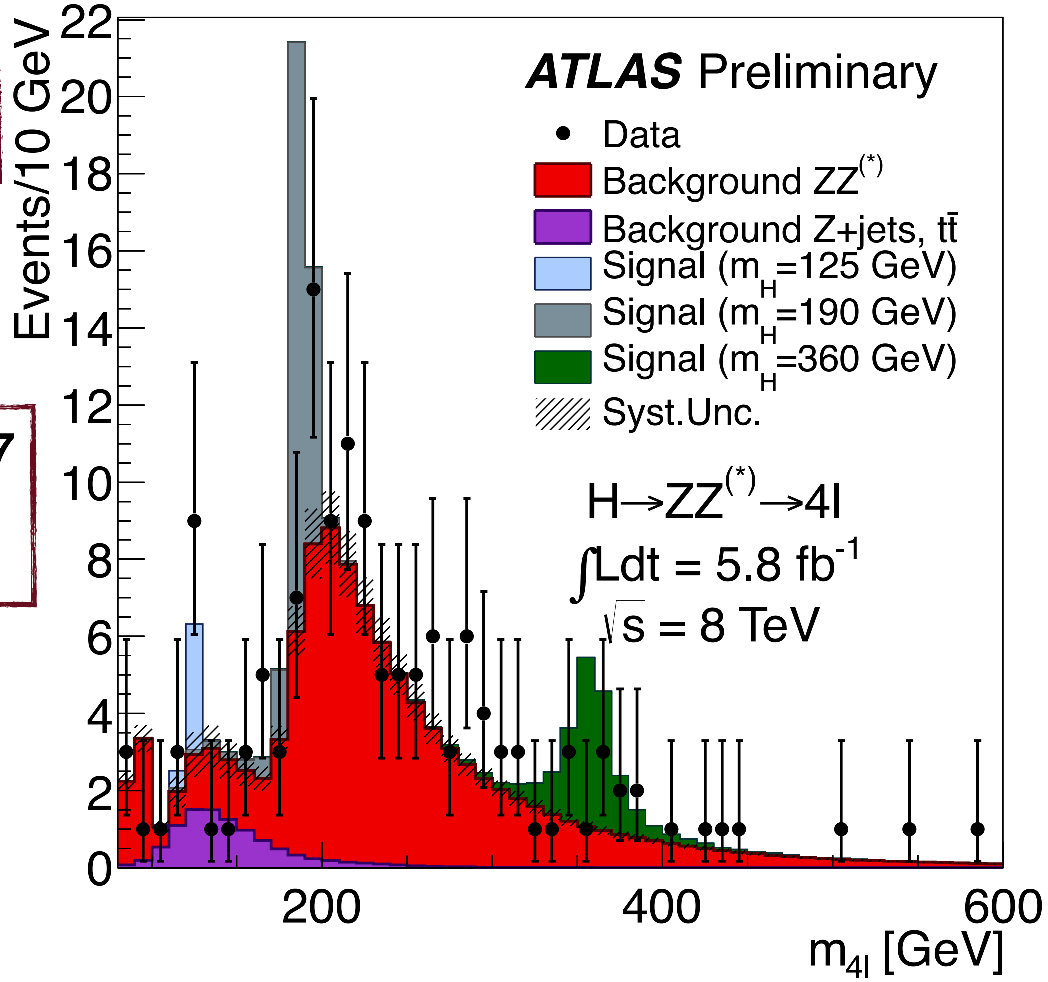
→ Uncertainties vary between 20% and 70% depending on background and data sample

# Results of Event Selection

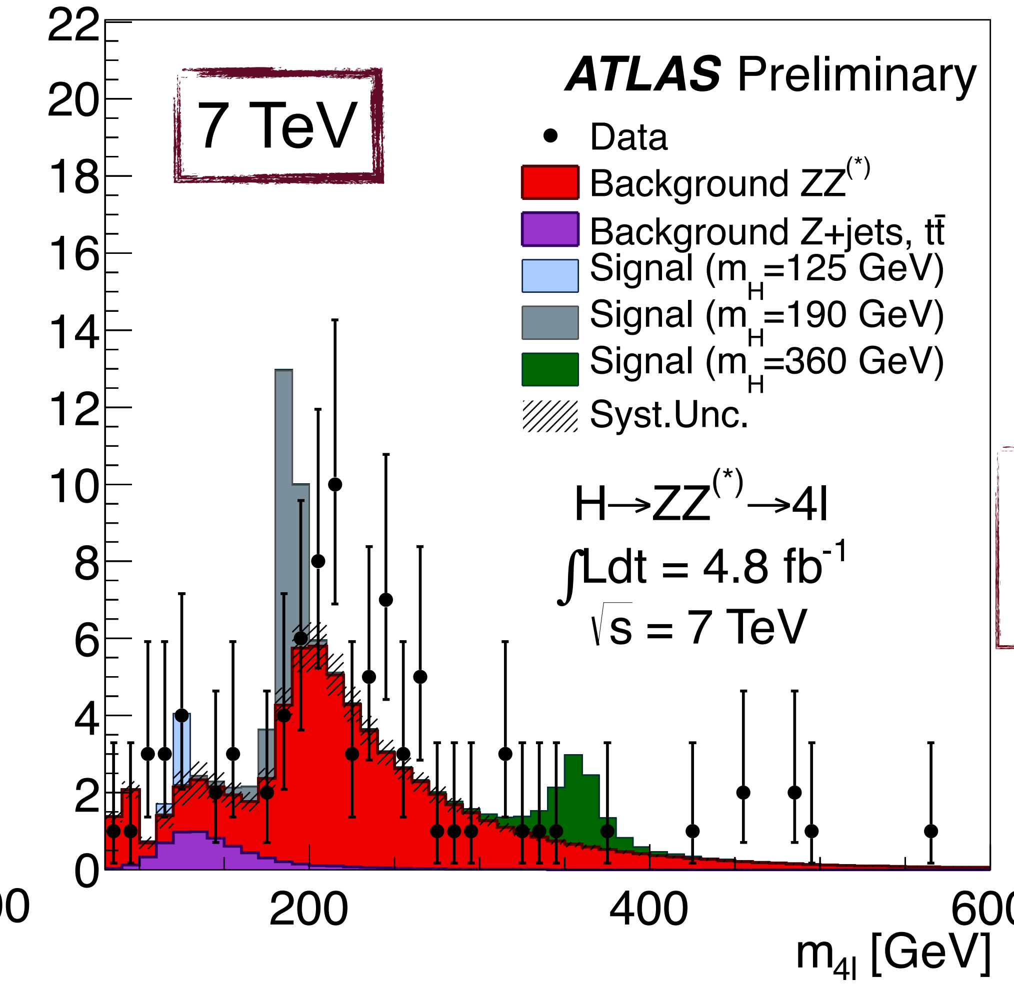
8 TeV

Exp. 109±7

Obs. 142




7 TeV




Exp. 71±5

Obs. 88

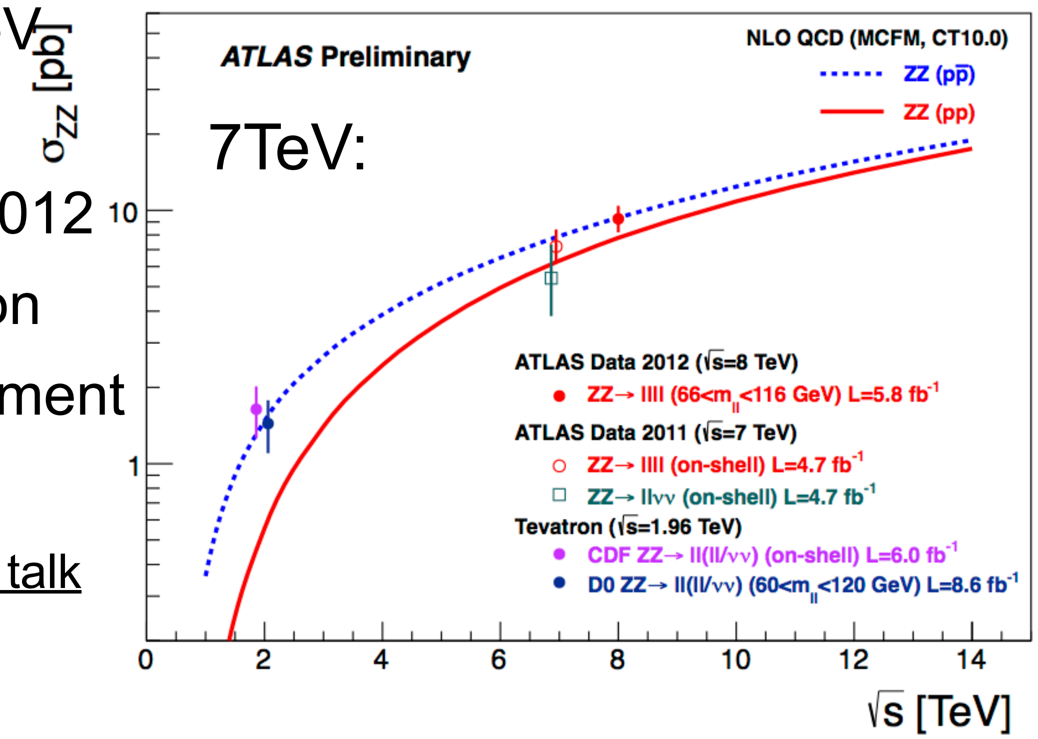
Observed events in the range $80 < m_{4l} < 600$ GeV for 7 and 8 TeV

For $m_{4l}>160$ GeV:

→ Observe ~20-30% more events than expected for 2011 and 2012

→ Events have the expected characteristics for ZZ→4l production

→ Reflected in the ATLAS ZZ production cross-section measurement




7 TeV Measurement: $(7.2^{+1.2}_{-1.0})$ pb

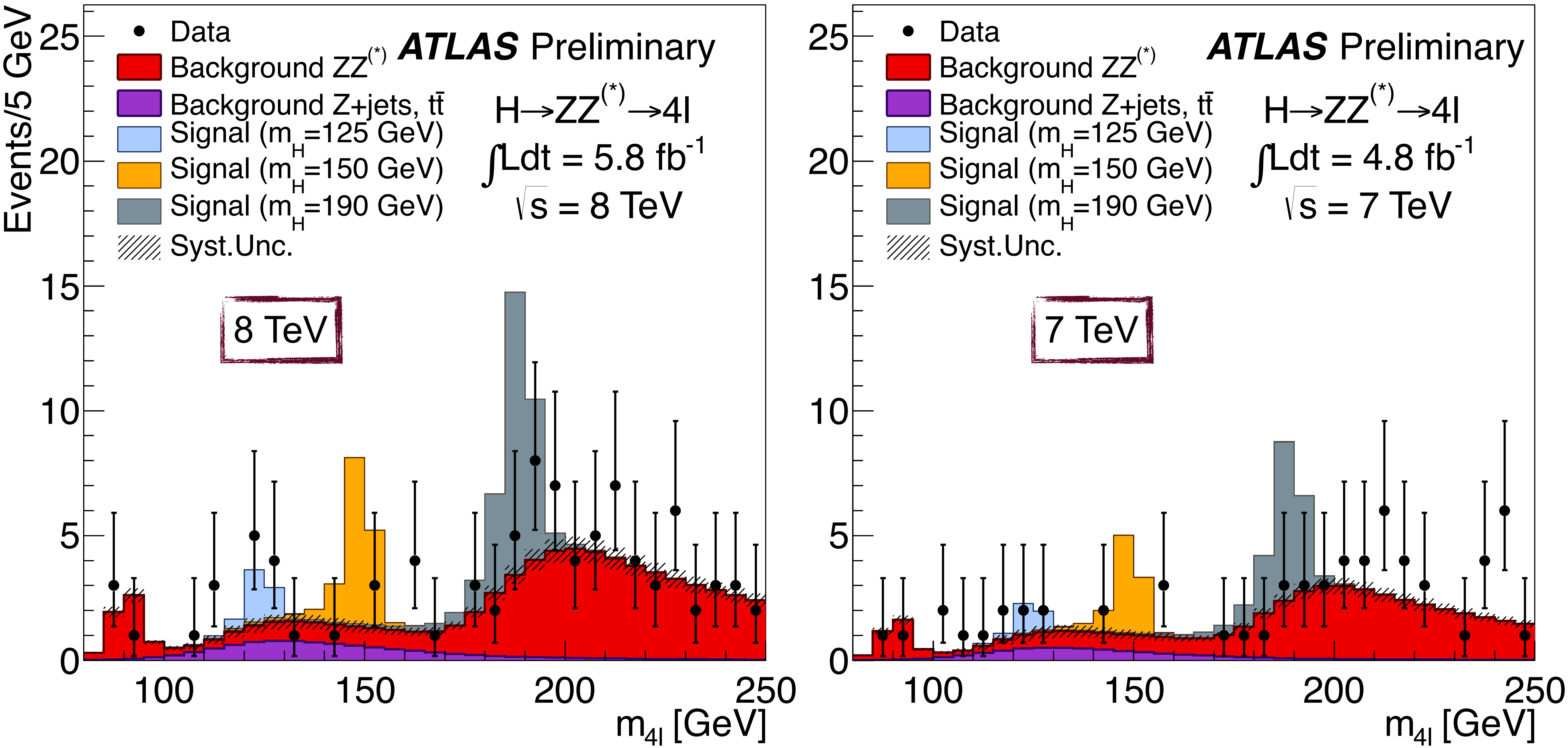
7 TeV NLO Prediction: $(6.5^{+0.3}_{-0.2})$ pb

8 TeV Measurement: $(9.3^{+1.2}_{-1.1})$ pb

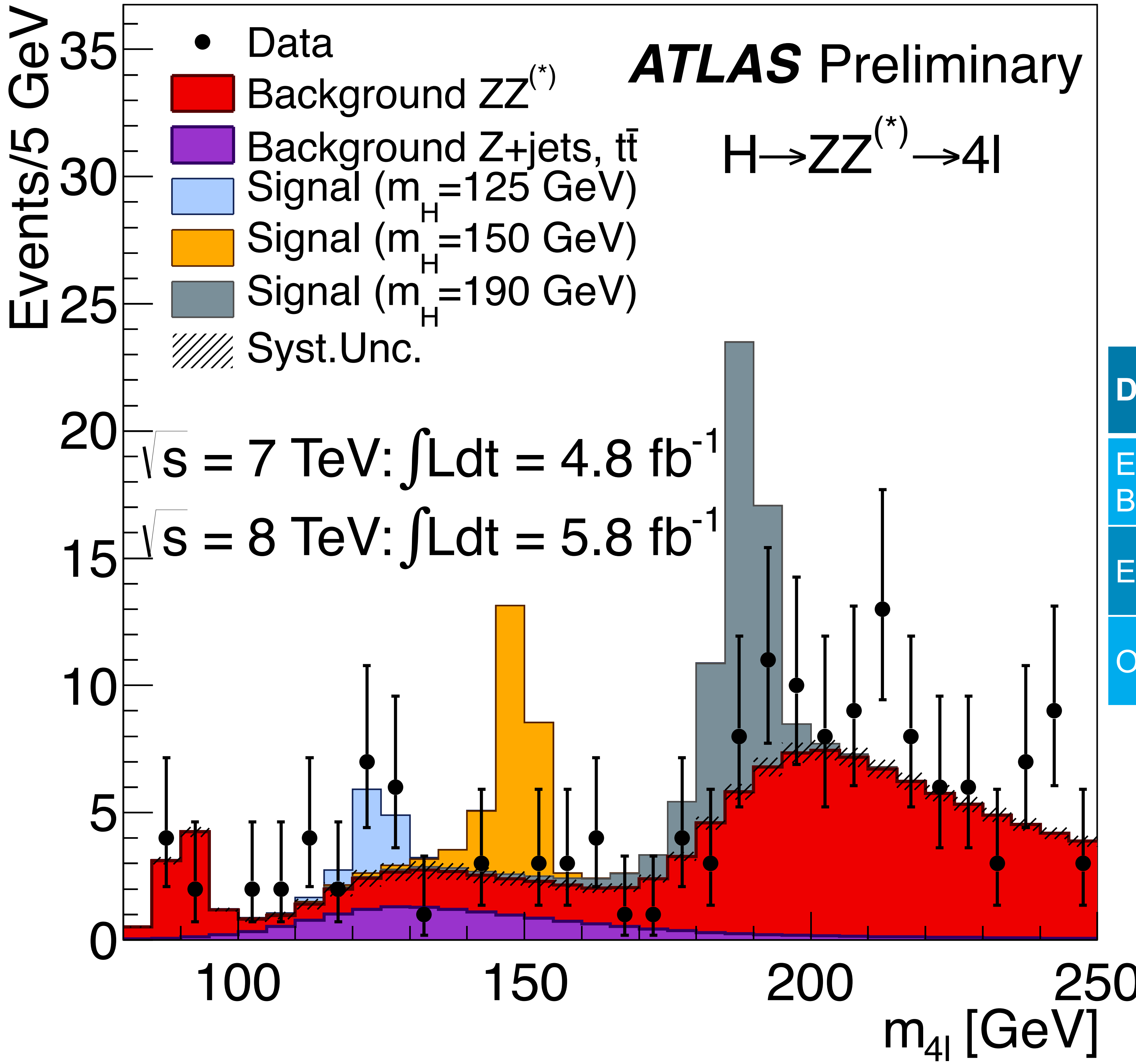
8 TeV NLO Prediction: $(7.4\pm0.4)$ pb

see ATLAS Diboson talk

# Results of Event Selection



# Results of Event Selection




for $m_{4l}$ region with 125±5GeV

| Dataset | 2011 | 2012 | Combined |
|---|---|---|---|
| Exp. Background | 2.1±0.3 | 2.9±0.4 | 5.1±0.8 |
| Exp. Signal | 2.0±0.3 | 3.3±0.5 | 5.3±0.8 |
| Observed | 4 | 9 | 13 |

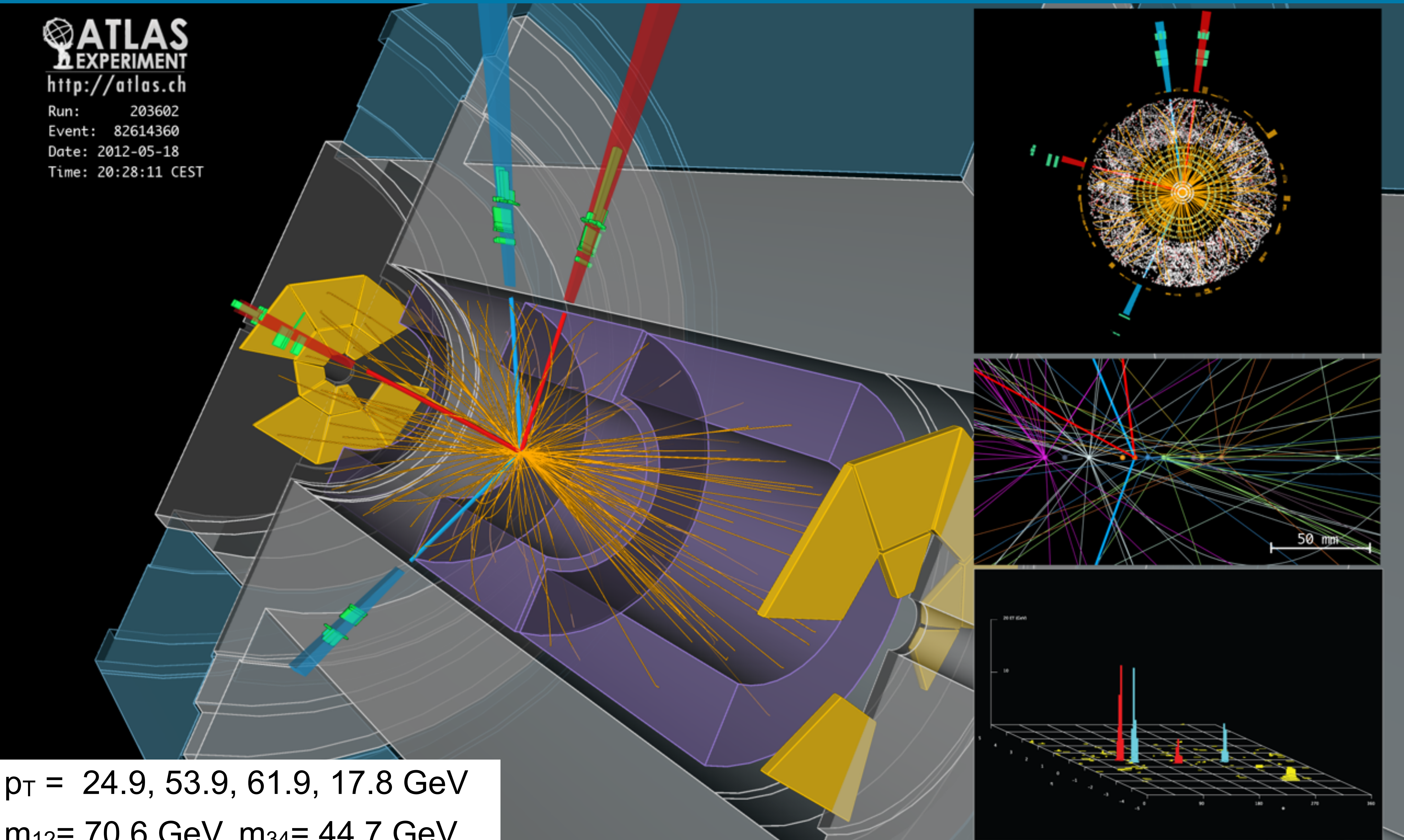
Expected S/B for $m_H$=125 GeV

4μ ~1.6

2e2μ/2μ2e ~1.0

4e ~0.6

# eeee candidate with $m_{4l}$ = 124.6 GeV

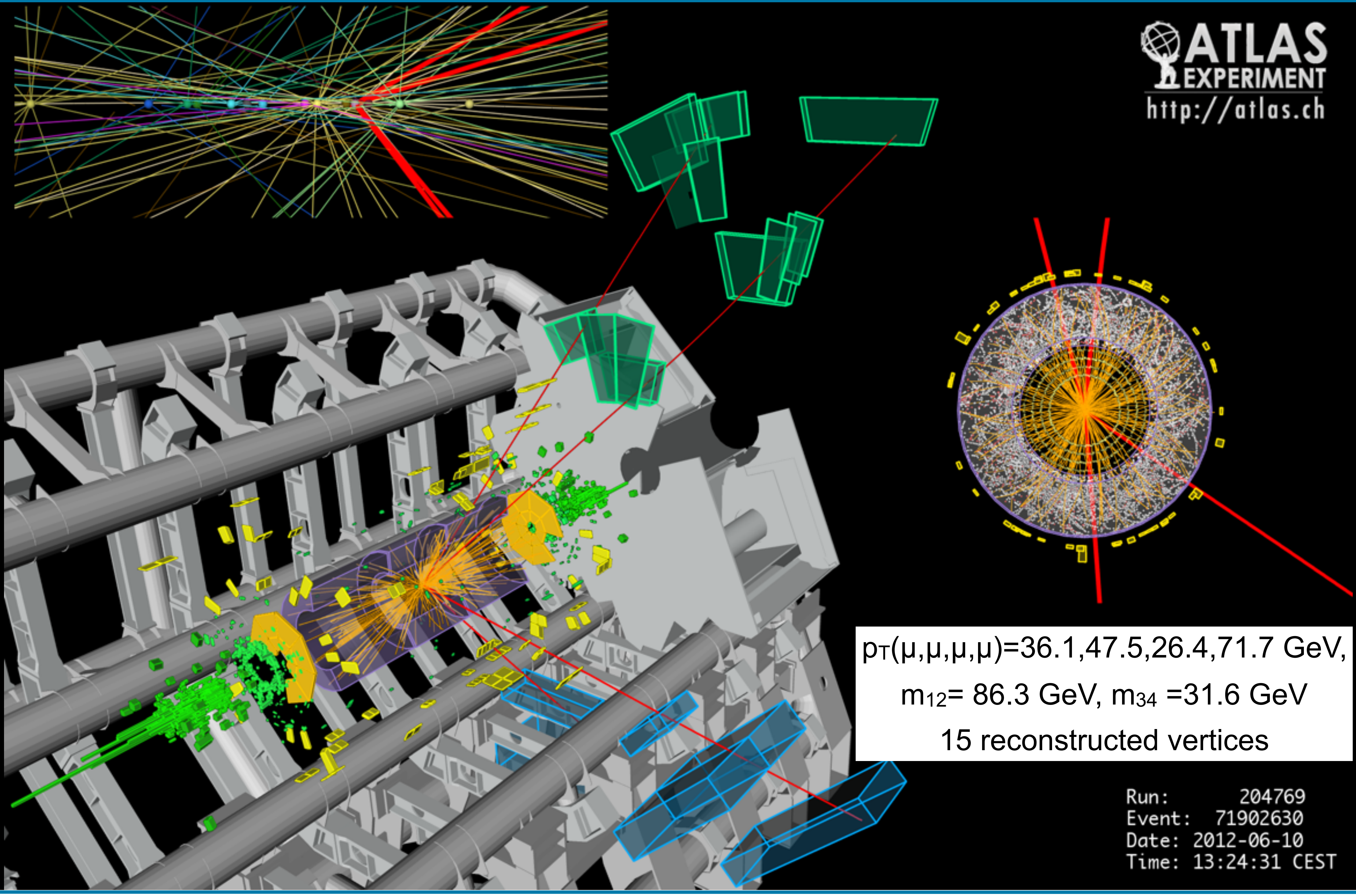



$p_T$ = 24.9, 53.9, 61.9, 17.8 GeV

$m_{12}$= 70.6 GeV, $m_{34}$= 44.7 GeV

12 reconstructed vertices

# μμμμ candidate with $m_{4l}$ = 125.1 GeV




$p_T(\mu,\mu,\mu,\mu)$=36.1,47.5,26.4,71.7 GeV,

$m_{12}$= 86.3 GeV, $m_{34}$ =31.6 GeV

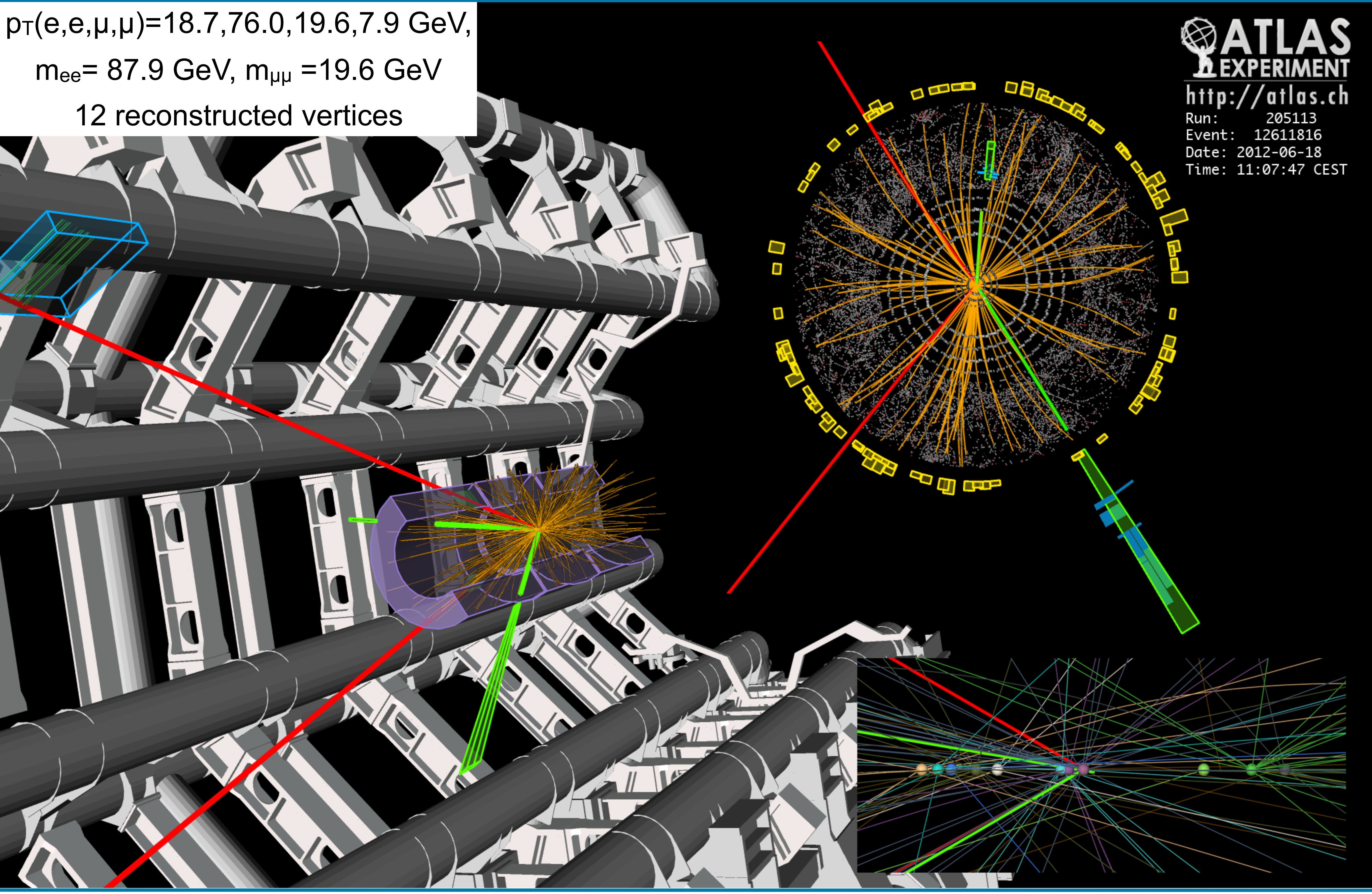
15 reconstructed vertices

# eeμμ candidate with $m_{4l}$ = 123.9 GeV

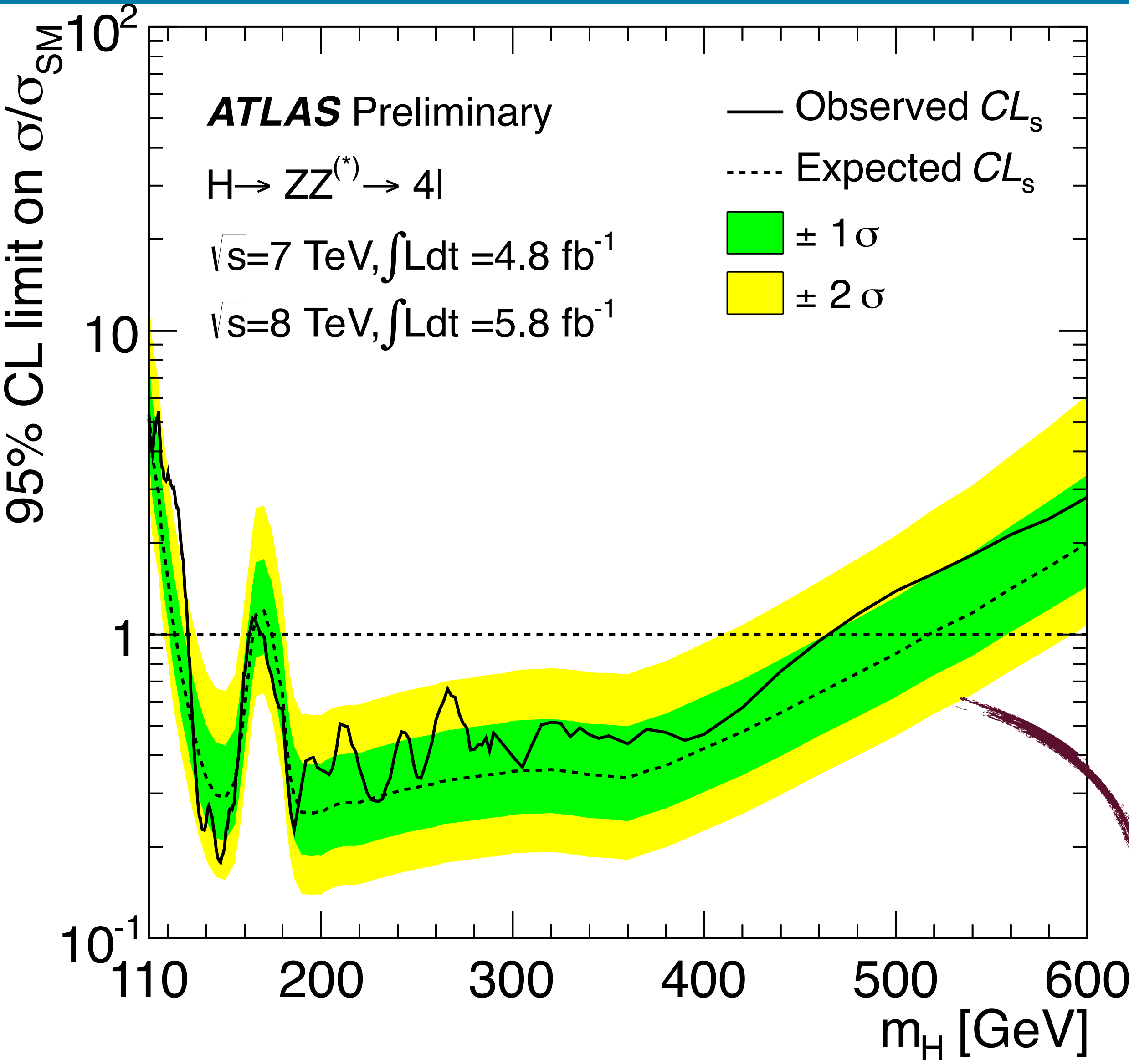
$p_T$(e,e,μ,μ)=18.7,76.0,19.6,7.9 GeV,

$m_{ee}$= 87.9 GeV, $m_{\mu\mu}$ =19.6 GeV

12 reconstructed vertices

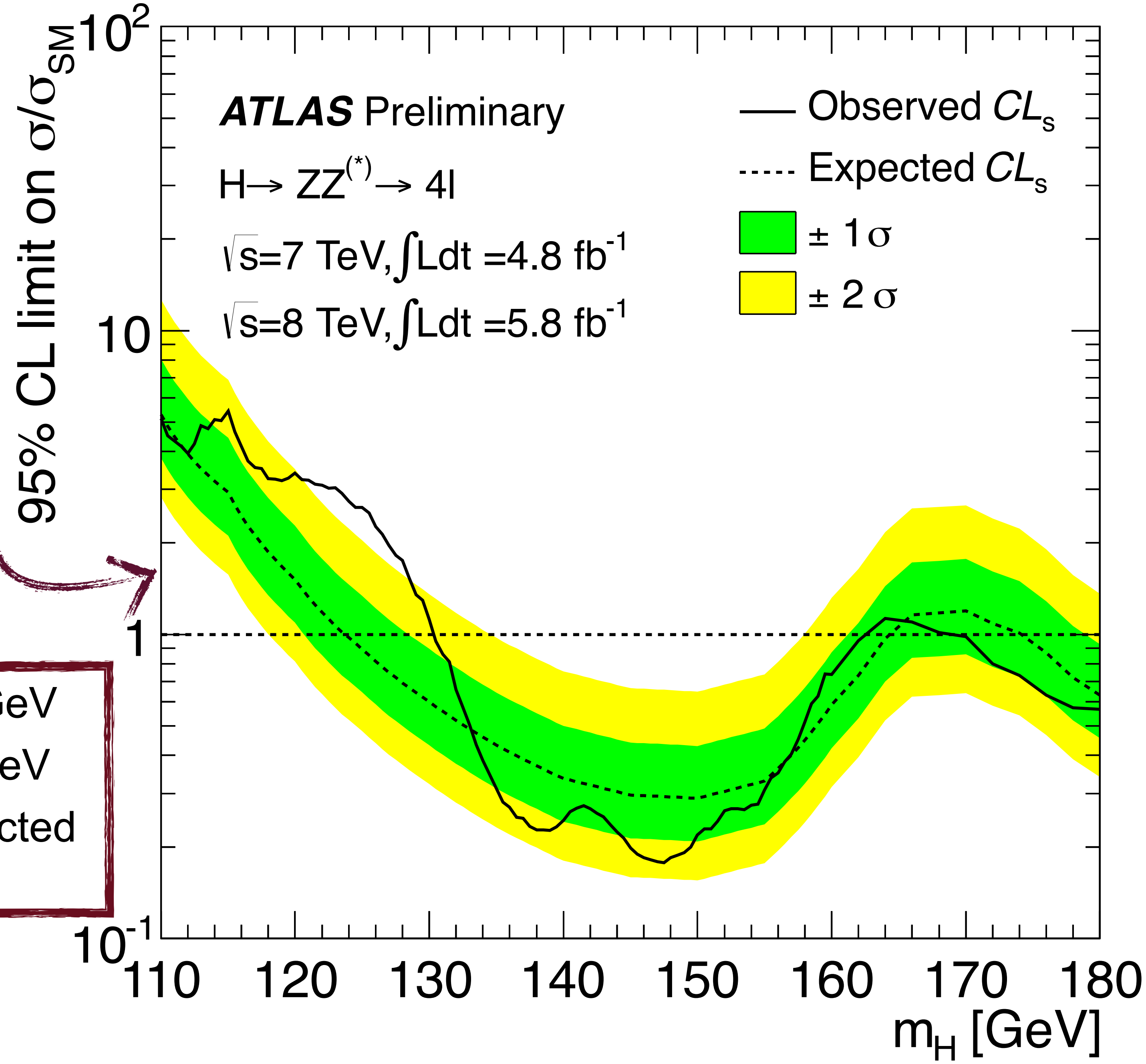


# Exclusions



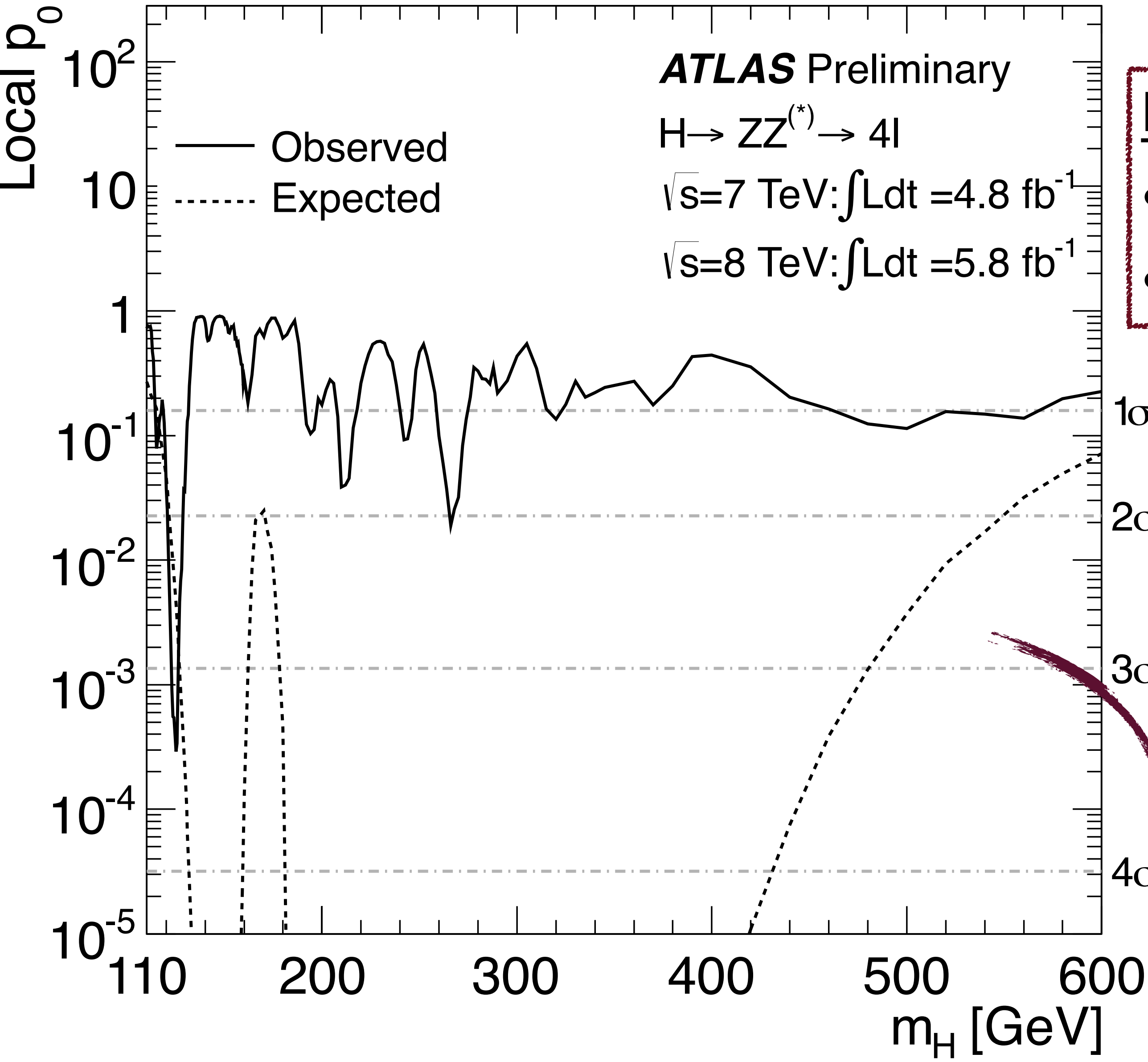

Statistics Treatment:

- profile likelihood ratio [Eur.Phys.J.C71:1554,2011]
  → nuisance parameters for systematic uncertainties
- exclusion limits using $CL_S$ [J. Phys. G 28 (2002) 2693-2704]



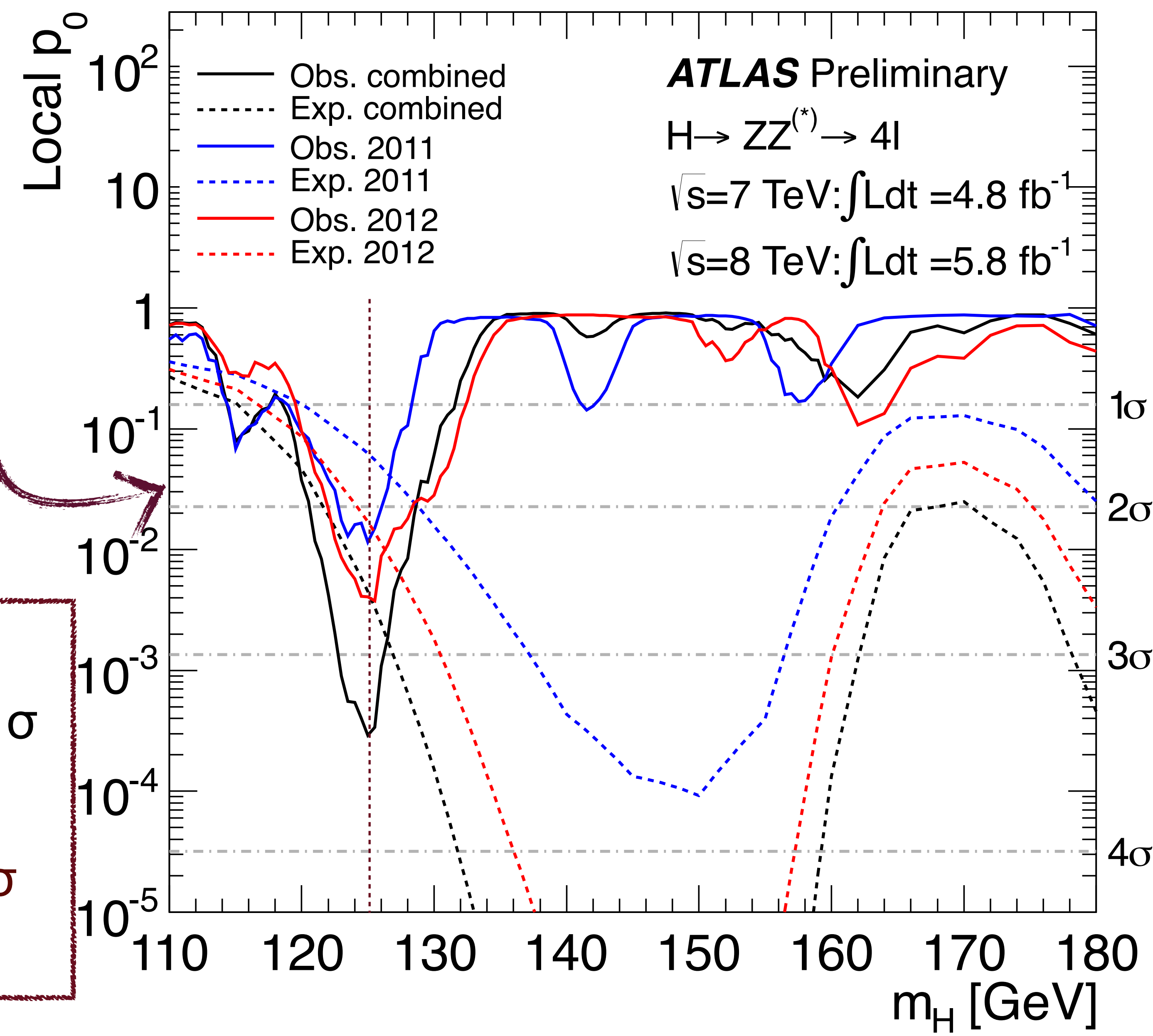

- Observed exclusion : 131-162 GeV and 170 - 460 GeV
- Expected exclusion : 124-164 GeV and 176 - 500 GeV
- For $m_H$ ~120-130 GeV much weaker limit than expected in the background-only hypothesis

# Significance of Excesses




For high $m_H$:

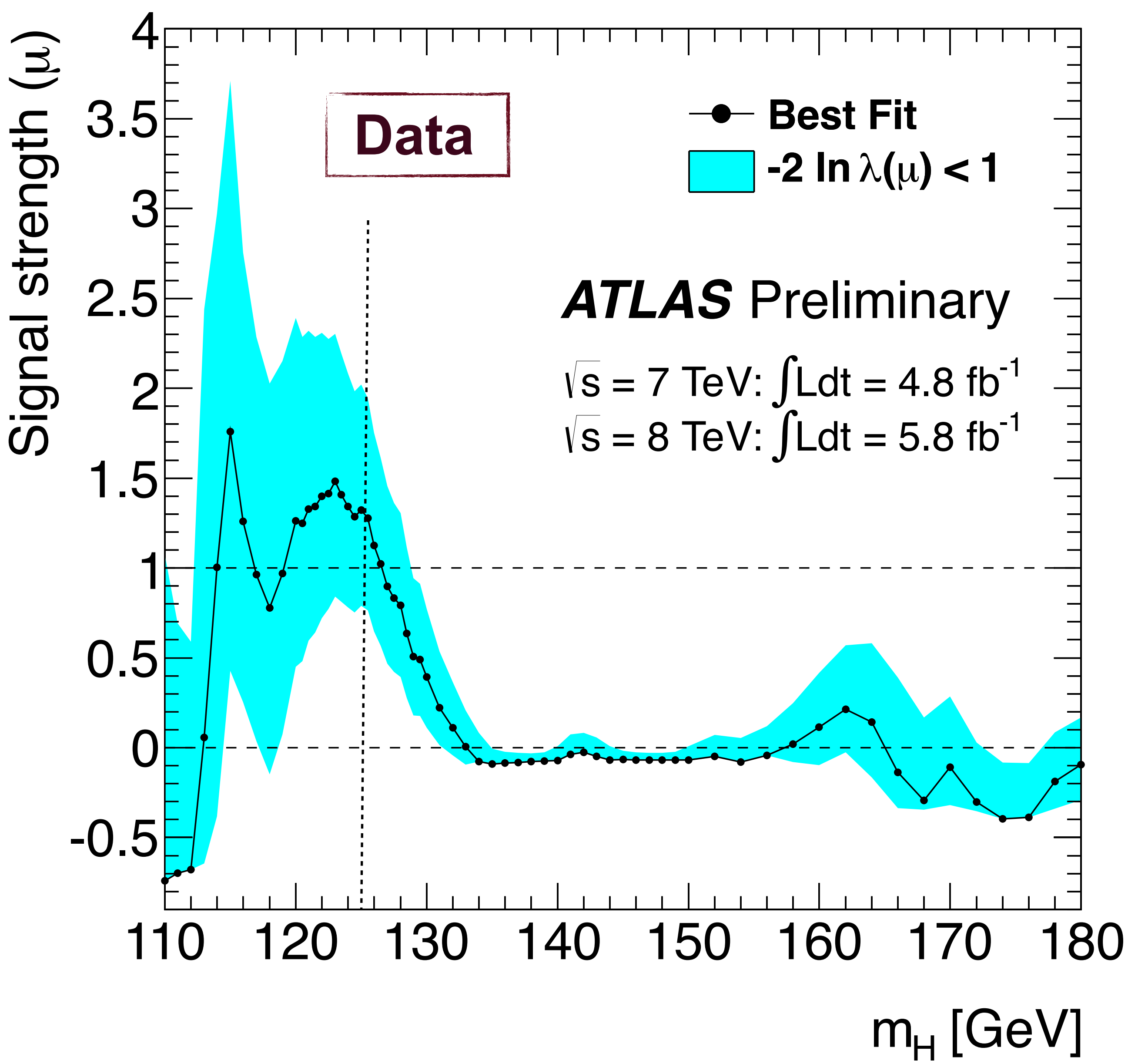
- small (<2σ) upward fluctuations are observed
- not "aligning" between 7 and 8 TeV data samples

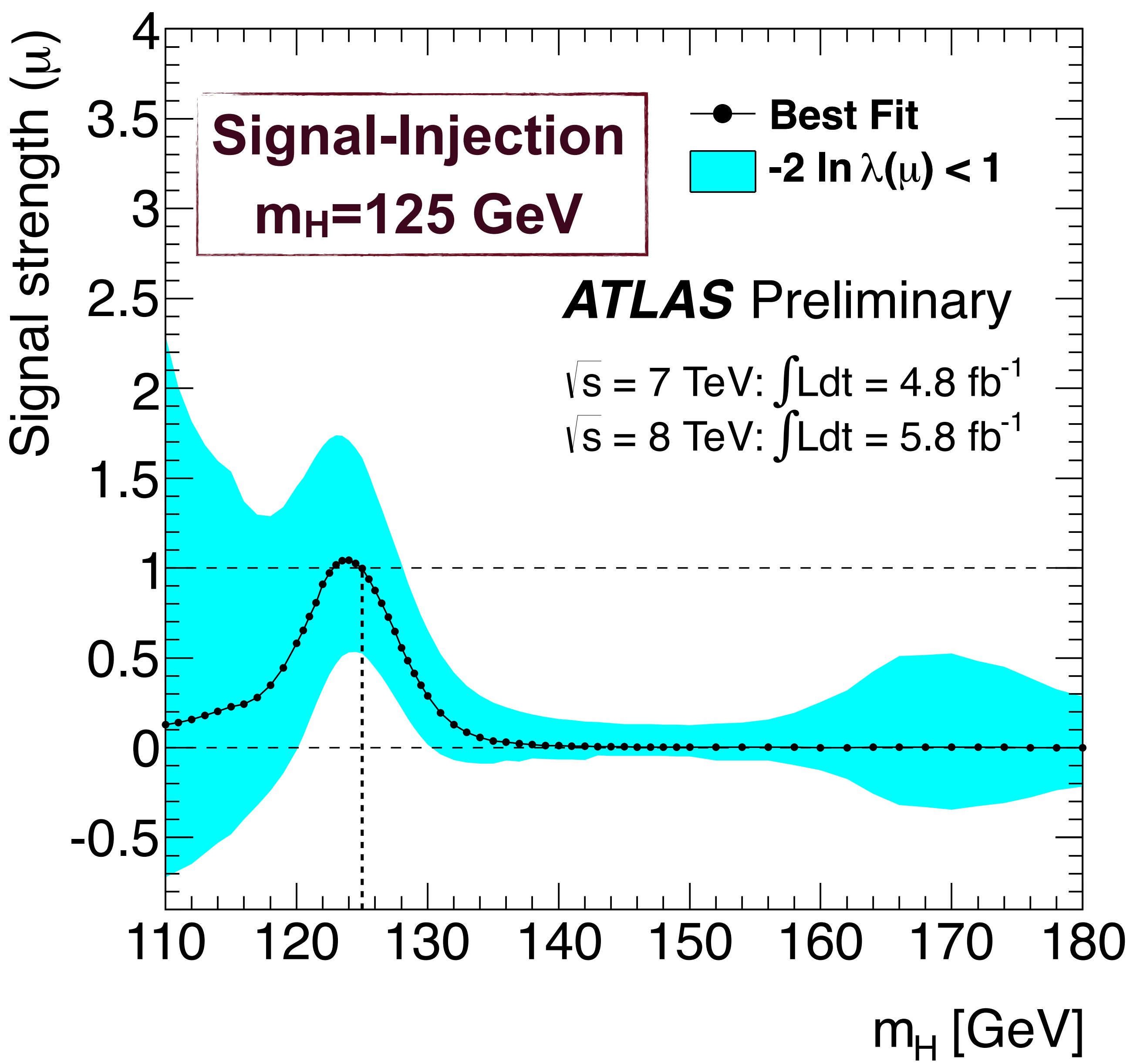



For low $m_H$:

- 8 TeV (2012): 2.7σ at 125.5 GeV, expected 2.1σ
- 7 TeV (2011): 2.3σ at 125 GeV, expected 1.5σ
- Combined: **3.4σ** at $m_H$=125 GeV, expected 2.6σ
- 2.5σ after look-elsewhere effect (110-141 GeV)

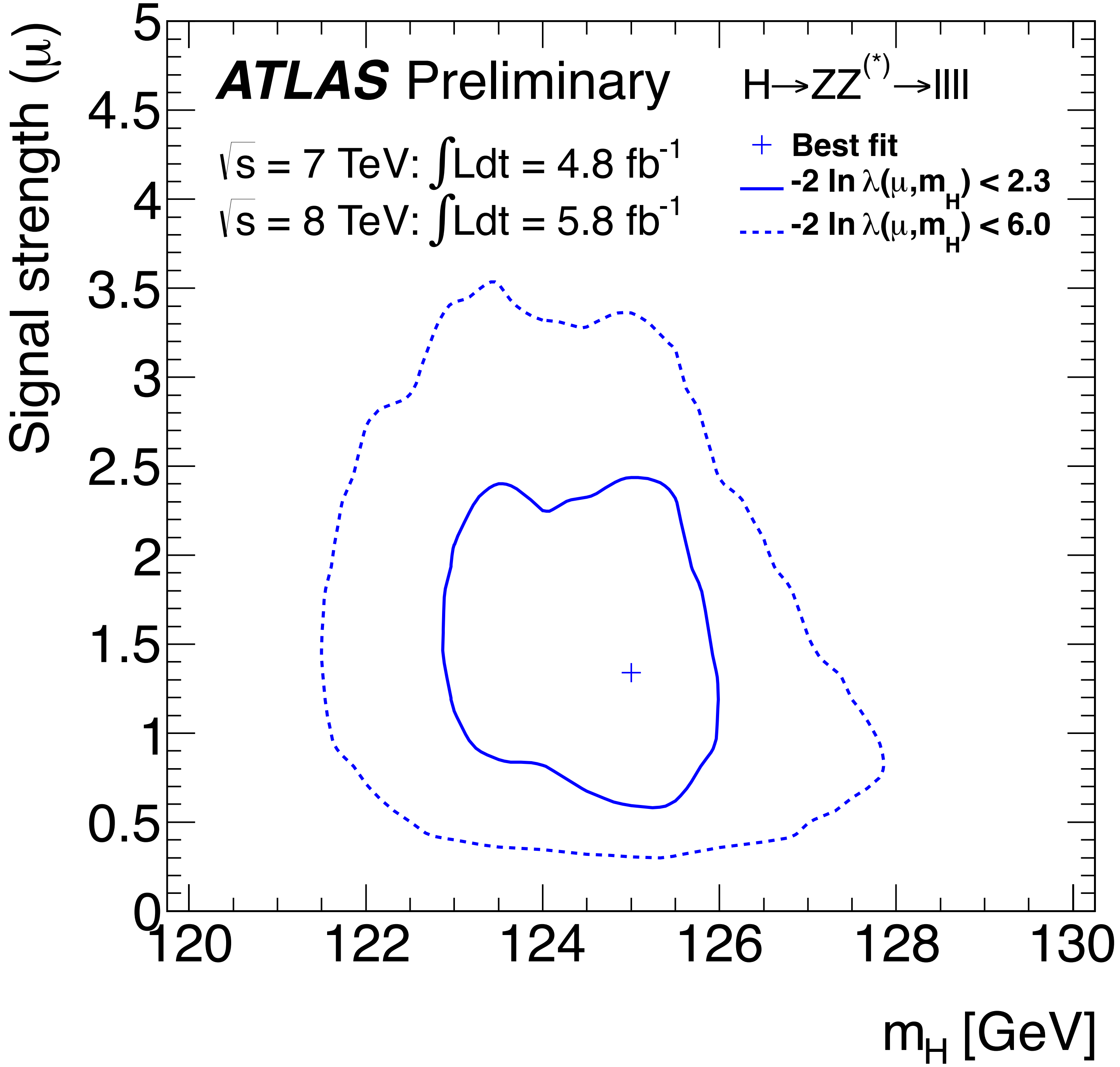
# Signal Strength




- Signal strength (μ) = (signal rate from fit to data)/(expected SM signal rate at given $m_H$)
- Best-fit value for $m_H$ =125 GeV: μ=1.3 ± 0.6

# Likelihood Contours: Signal Strength vs $m_H$



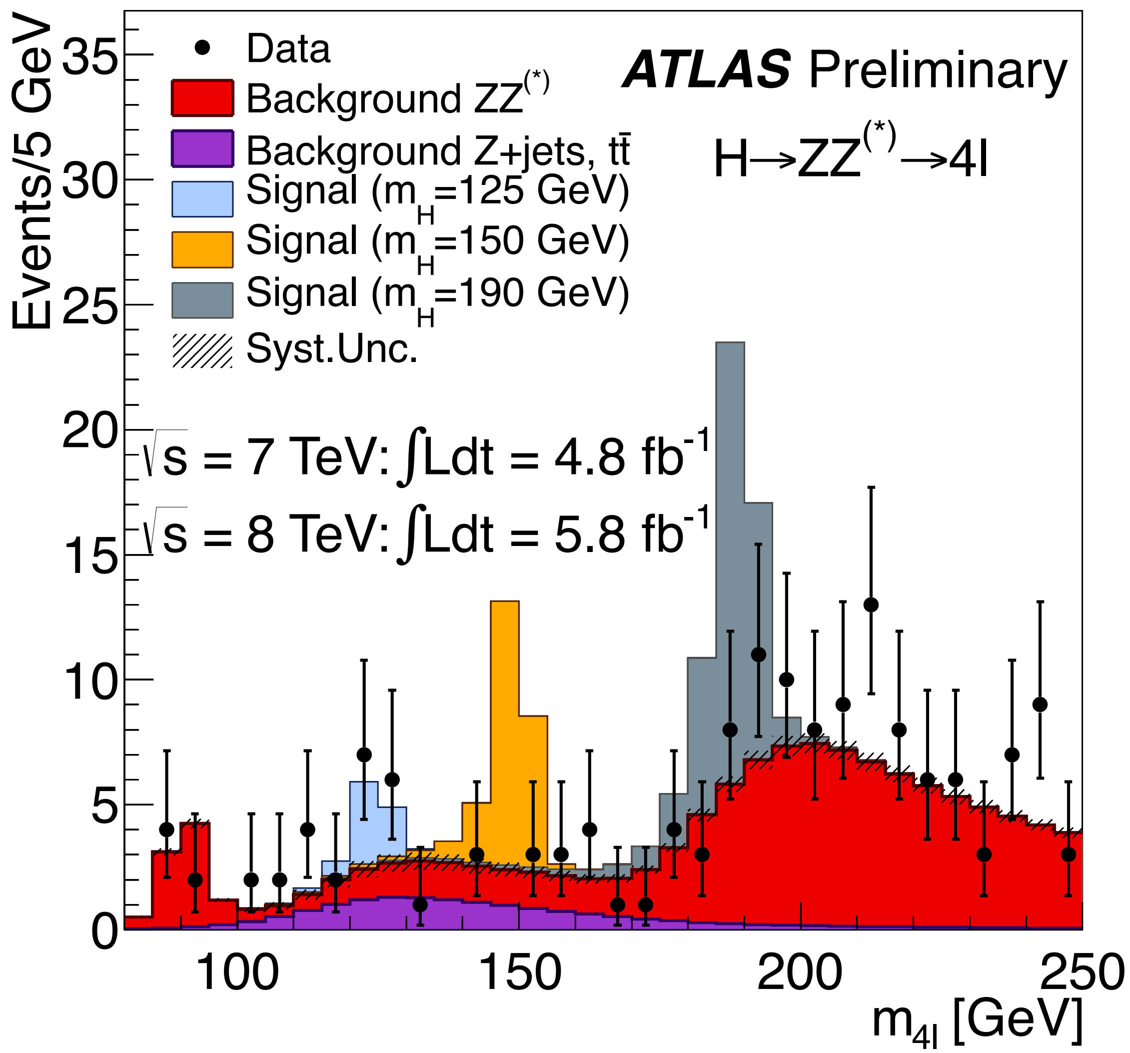

2D likelihood fit to signal mass and strength.

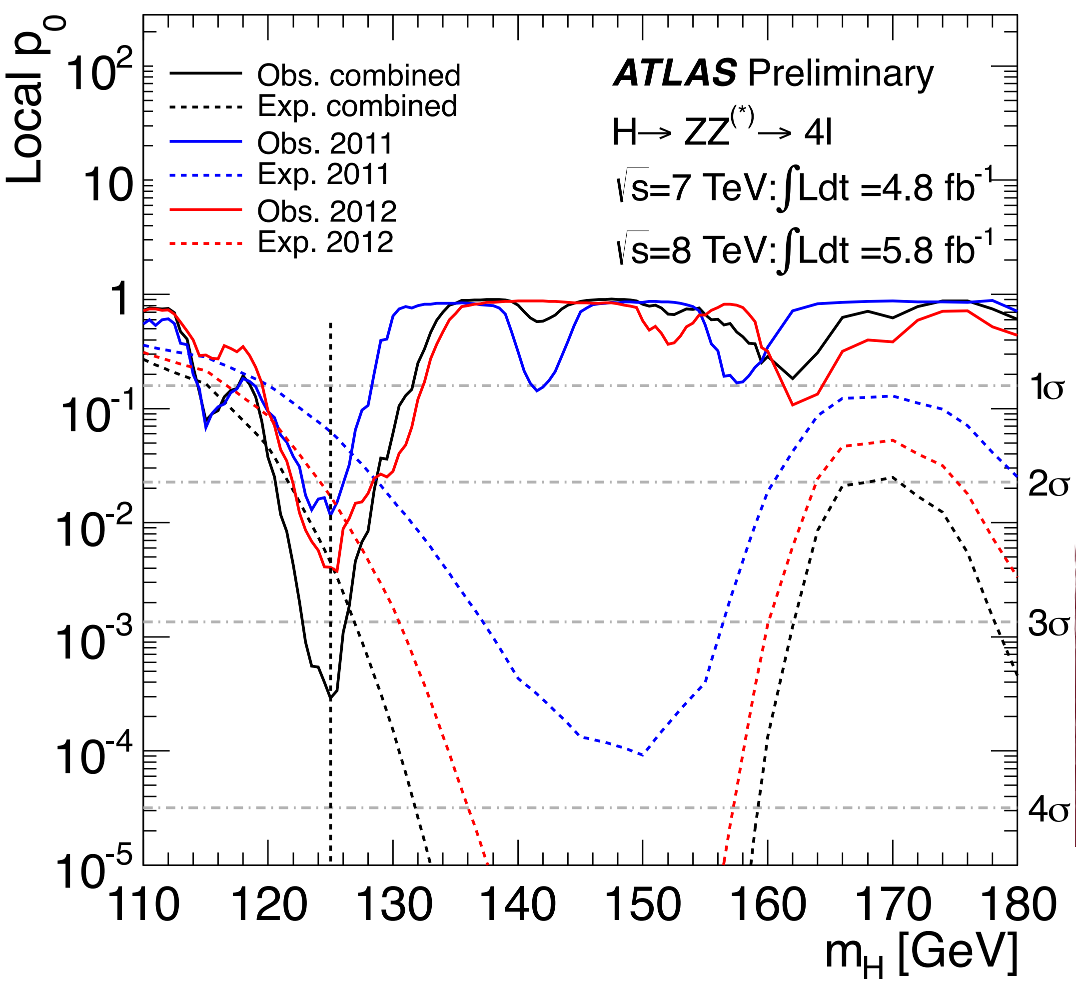
Curves show approximate 68% (full) and 95% (dashed) CL contours

# Summary

Great progress has been made to improve on:

- **Lepton performance and pile-up robustness**
  - in particular electron reconstruction and identification
- **Sensitivity for the low $m_H$ region**
- **Robust background estimation methods**
  - with multiple methods per background



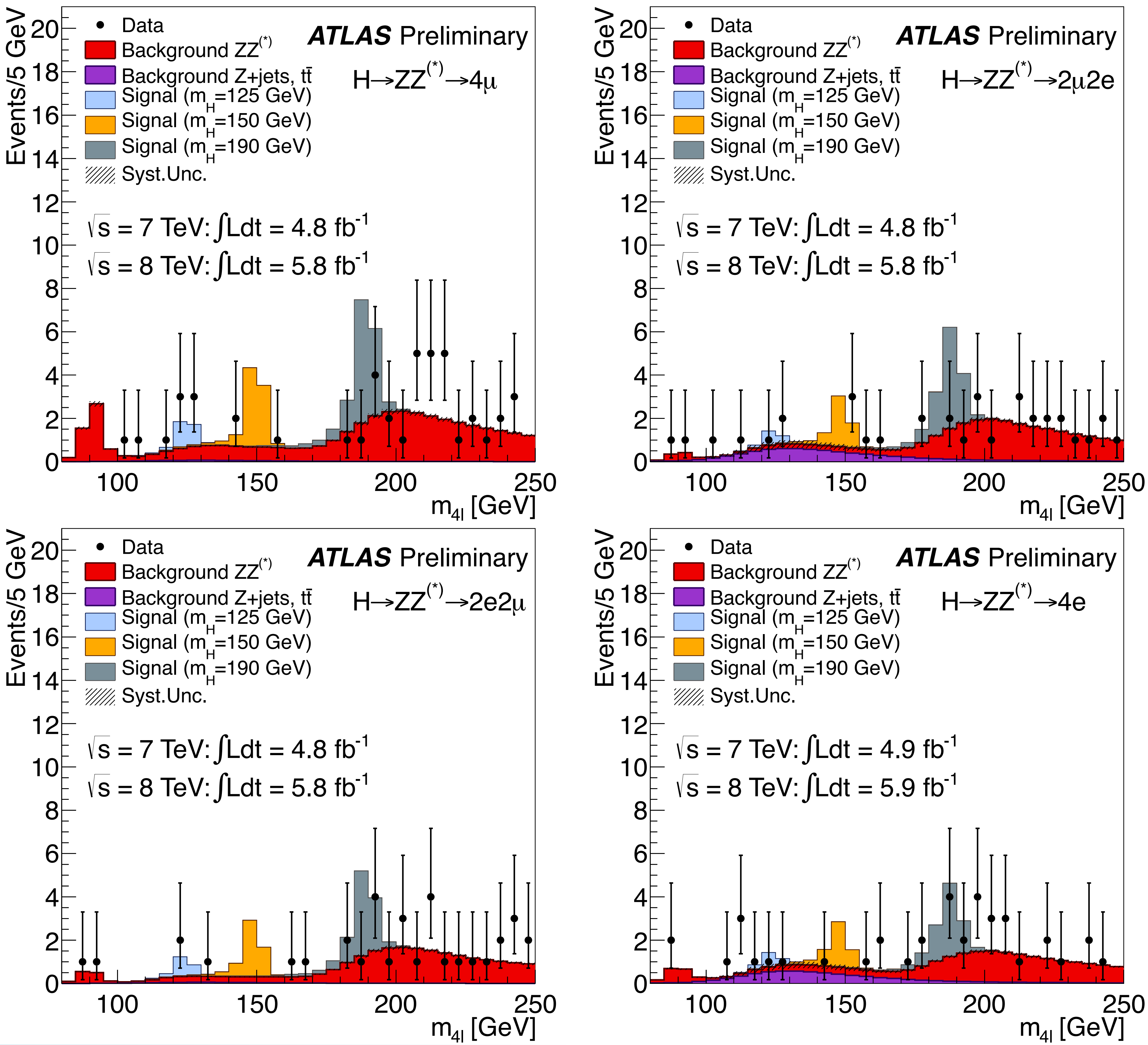

The ATLAS $H \to ZZ^{(*)} \to 4l$ search, observed an excess of events over the background only hypothesis at $m_H$~125 GeV

→ Consistent in both 2011 and 2012 datasets.

→ Combining datasets, **3.4σ** local significance [2.5σ global significance (110-141 GeV)]

# Additional Slides

# Results per final state




Signal Efficiency

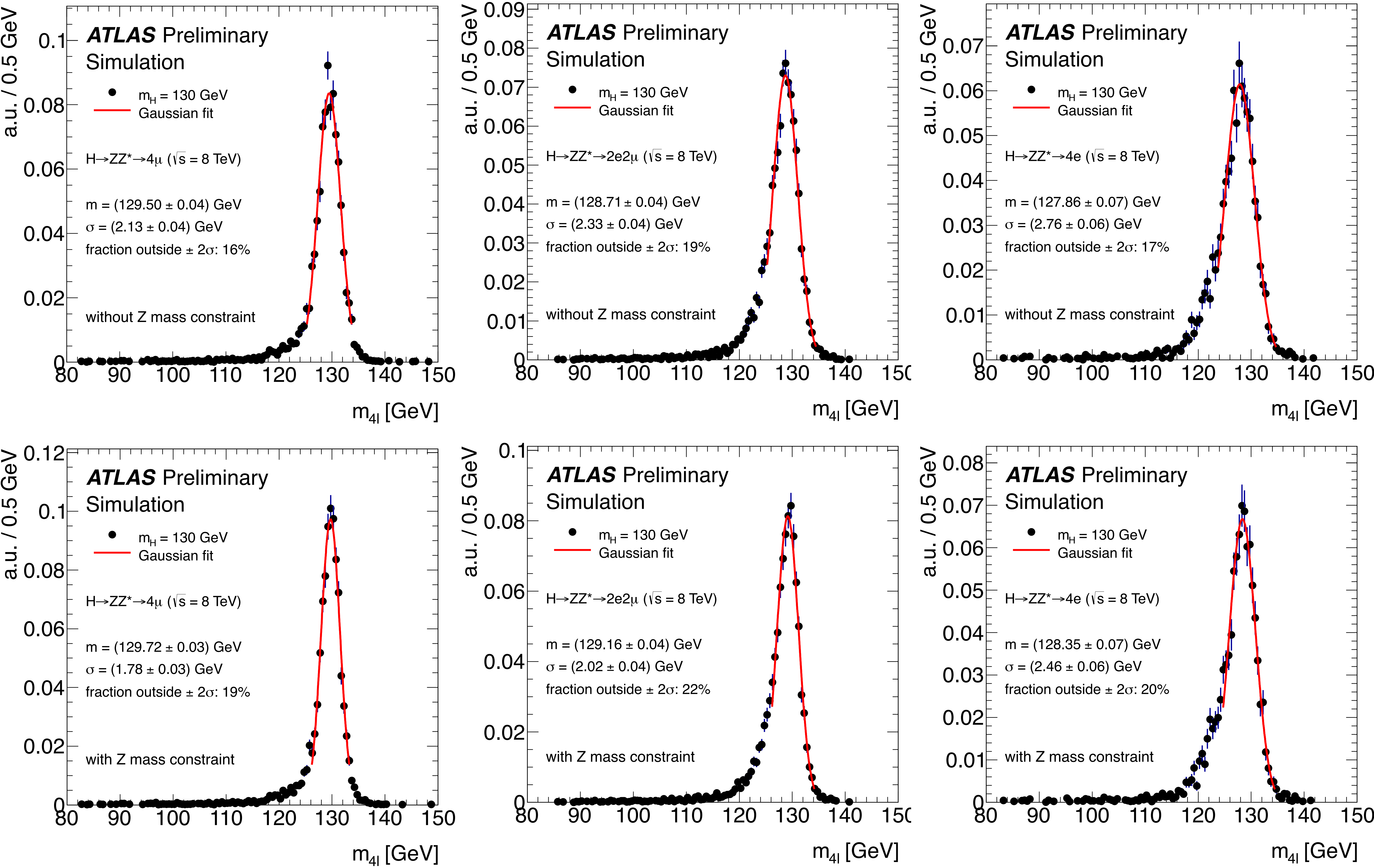
for $m_H$=130 GeV

4μ ~41%

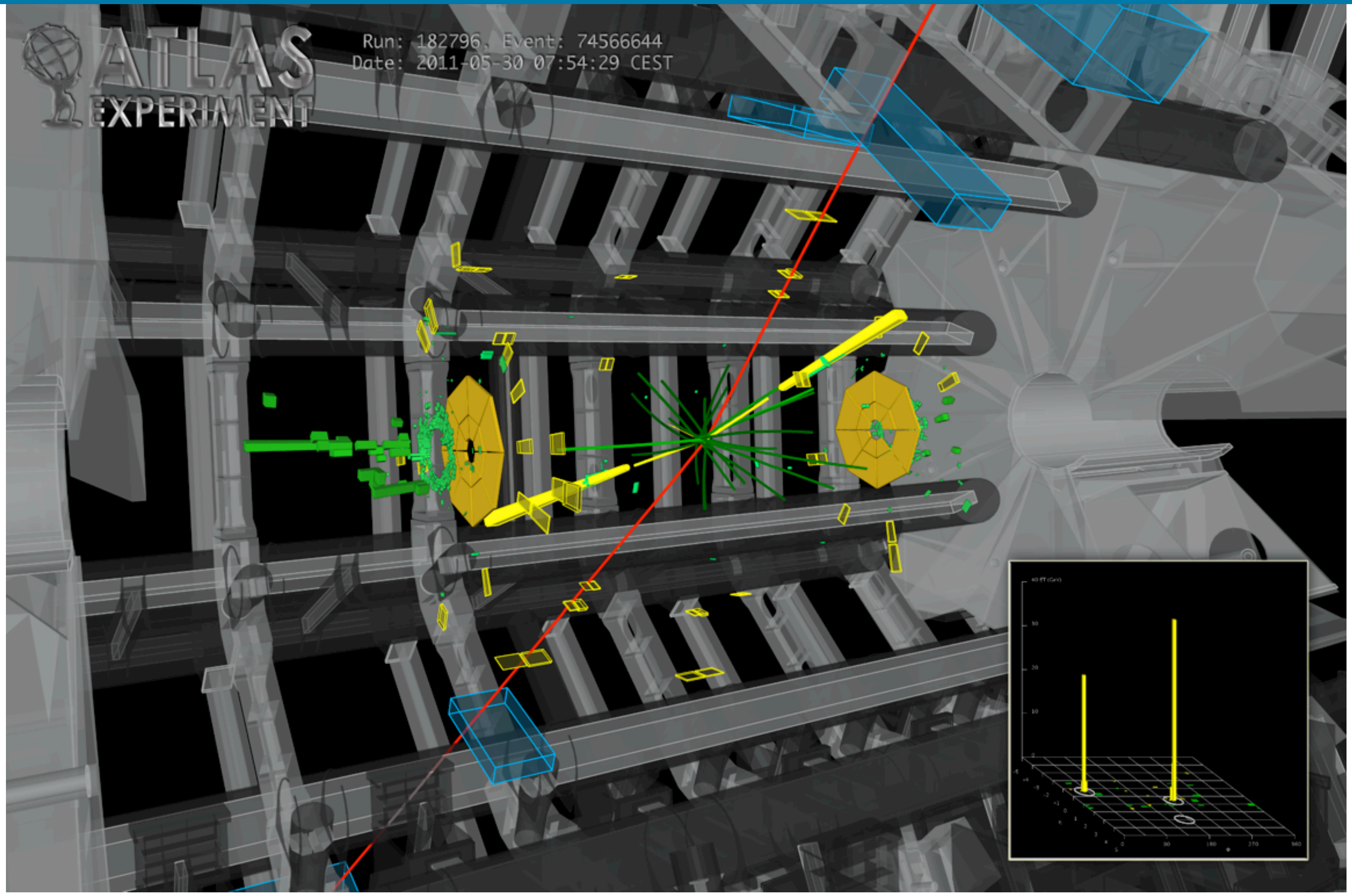
2e2μ/2μ2e ~27%

4e ~23%

# Mass resolution



# Event Selection




→ Require a pair of same-flavour opposite-charge di-leptons
→ $p_T^{1,2,3,4}$ > 20, 15, 10, 7 GeV (6 GeV for μ)
→ Leading di-lepton mass : $50 < m_{12} < 106$ GeV
→ Sub-leading di-lepton mass : $m_{thr}(m_{4l}) < m_{34} < 115$ GeV, $m_{thr}$= 17.5 - 50 GeV
→ Reject quadruplet if alternative same-flavour opposite-charge pair gives $m_{ll} < 5$ GeV
→ $\Delta R(l,l') > 0.10(0.20)$ for all same(different)-flavour leptons in the quadruplet
→ Track and calorimeter isolation/impact parameter significance

| $m_{4\ell}$ (GeV) | ≤120 | 130 | 150 | 160 | 165 | 180 | ≥190 |
|---|---|---|---|---|---|---|---|
| threshold (GeV) | 17.5 | 22.5 | 30 | 30 | 35 | 40 | 50 |

# ll+ee

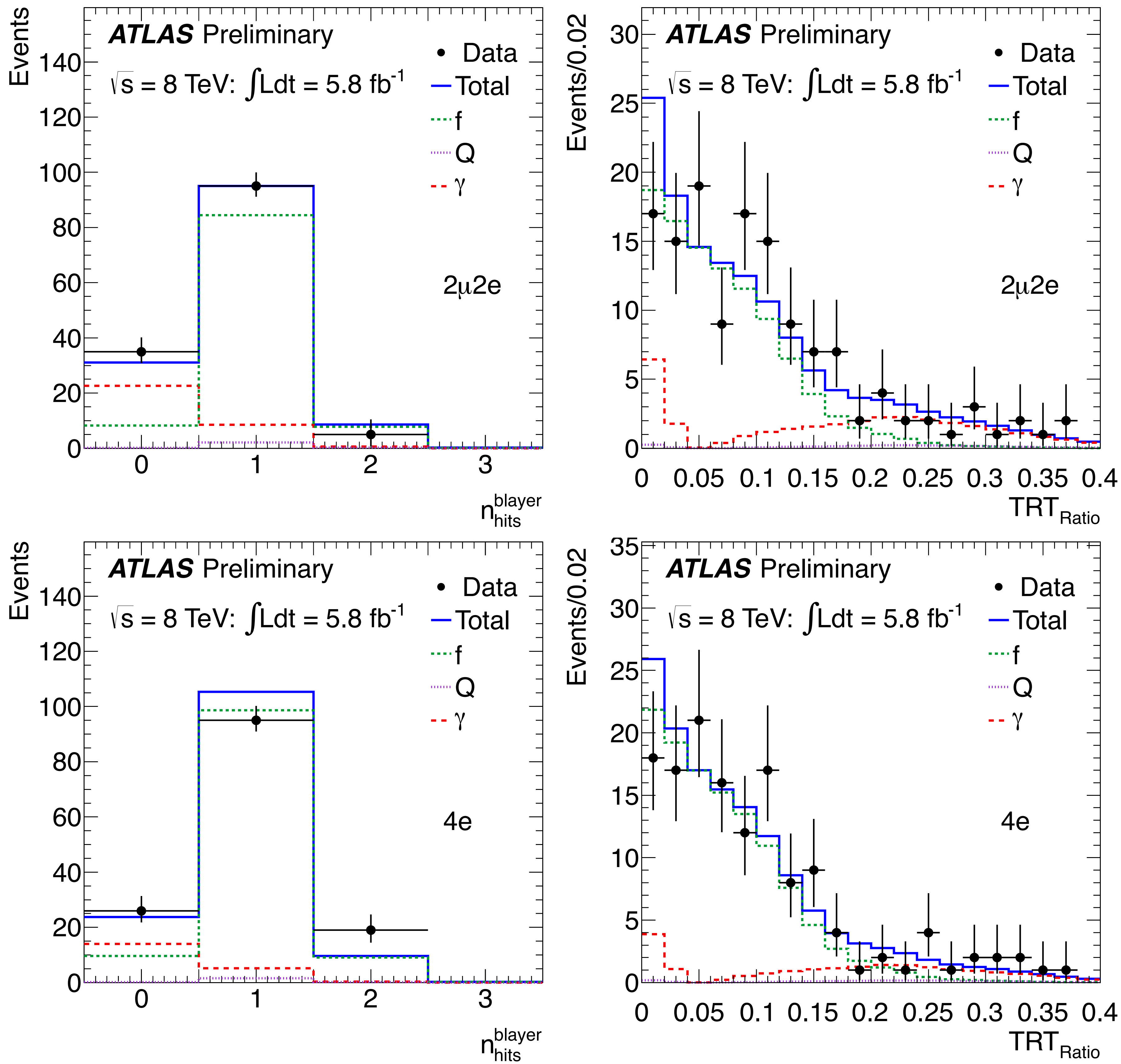
8 TeV

| | 4$e$ | | 2$\mu$2$e$ | |
|---|---|---|---|---|
| | 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 |

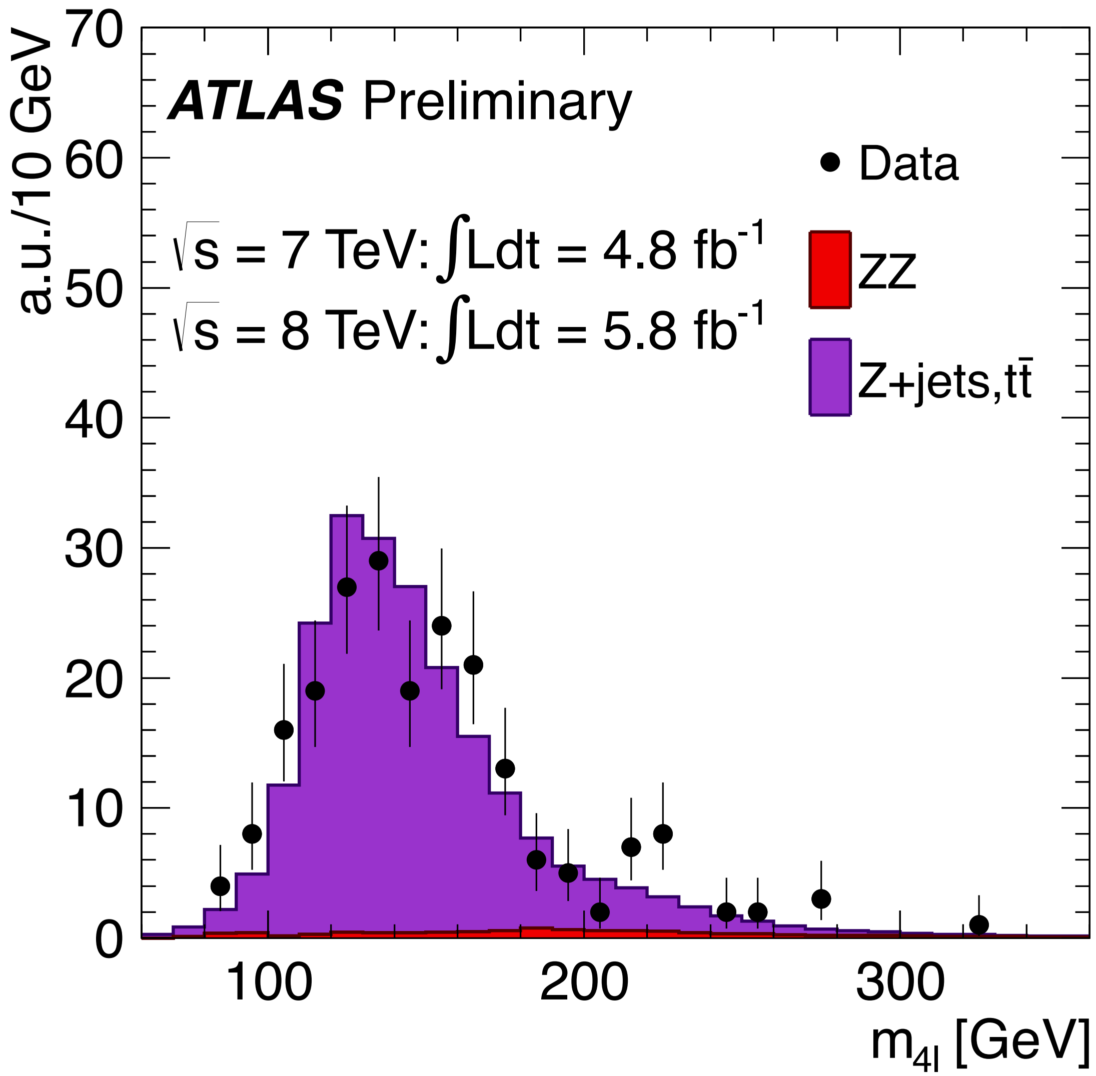
7 TeV

| | 4$e$ | | 2$\mu$2$e$ | |
|---|---|---|---|---|
| | Data | MC | Data | MC |
| EE | 11 | 11.2±0.6 | 8 | 15.0±0.9 |
| EC | 4 | 2.5±0.8 | 3 | 3.0±1.1 |
| EF | 6 | 9.7±1.4 | 5 | 6.6±1.1 |
| CE | 5 | 1.5±0.7 | 6 | 4.5±1.6 |
| CC | 2 | 1.4±0.7 | 2 | 1.5±1.0 |
| CF | 7 | 4.7±1.2 | 10 | 9.9±2.3 |
| FE | 5 | 3.1±0.6 | 4 | 4.5±1.0 |
| FC | 5 | 3.0±1.0 | 4 | 6.3±1.8 |
| FF | 12 | 11.0±1.9 | 17 | 13.4±2.6 |
| Total | 57 | 48±3 | 59 | 65±5 |

# 3l+1l

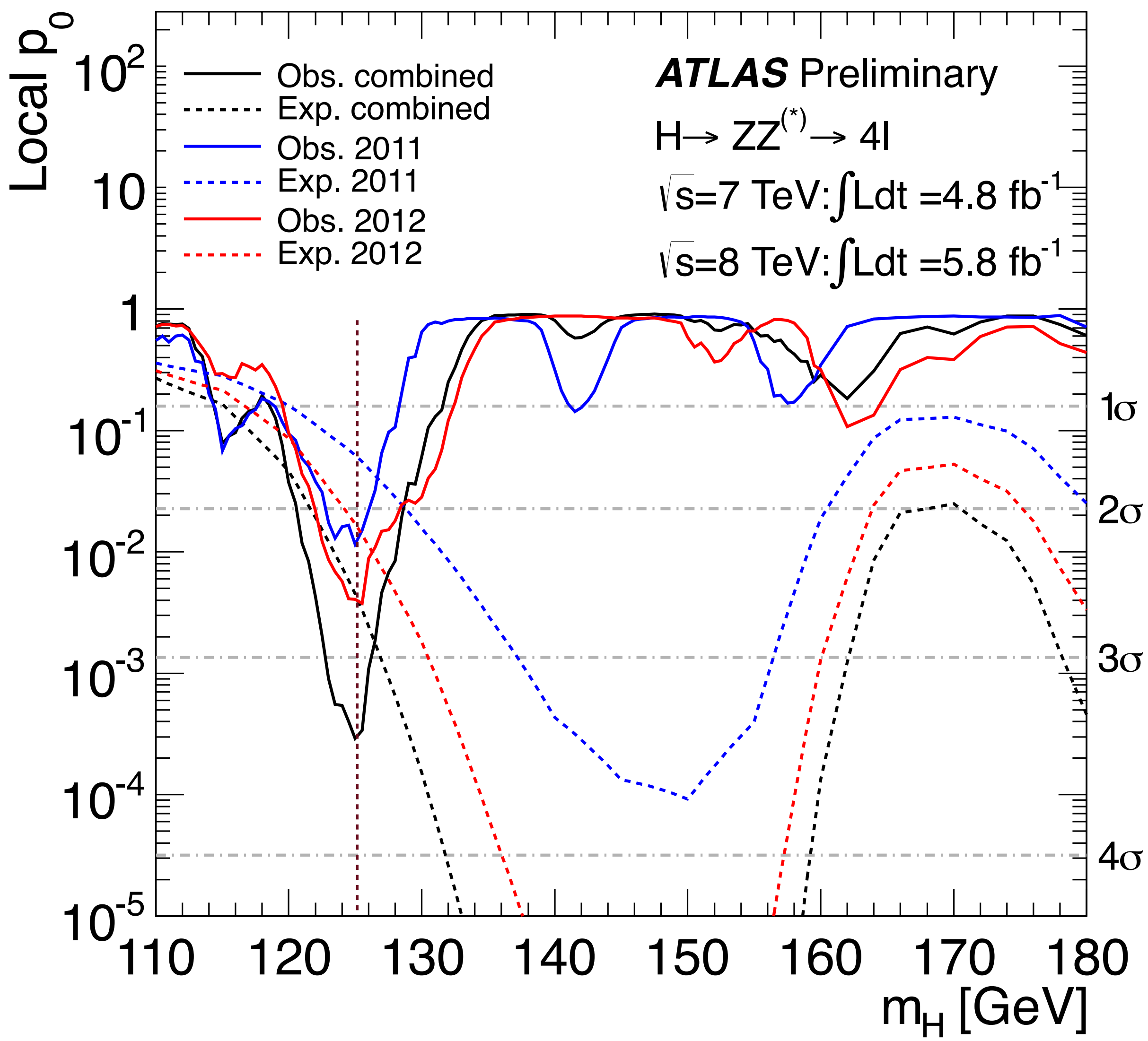

ATLAS Preliminary
$\sqrt{s}$ = 8 TeV: ∫Ldt = 5.8 fb$^{-1}$
Data
Total
f
Q
γ
2μ2e
Events
$n_{hits}^{blayer}$
ATLAS Preliminary
$\sqrt{s}$ = 8 TeV: ∫Ldt = 5.8 fb$^{-1}$
Data
Total
f
Q
γ
2μ2e
Events/0.02
$TRT_{Ratio}$
ATLAS Preliminary
$\sqrt{s}$ = 8 TeV: ∫Ldt = 5.8 fb$^{-1}$
Data
Total
f
Q
γ
4e
Events
$n_{hits}^{blayer}$
ATLAS Preliminary
$\sqrt{s}$ = 8 TeV: ∫Ldt = 5.8 fb$^{-1}$
Data
Total
f
Q
γ
4e
Events/0.02
$TRT_{Ratio}$

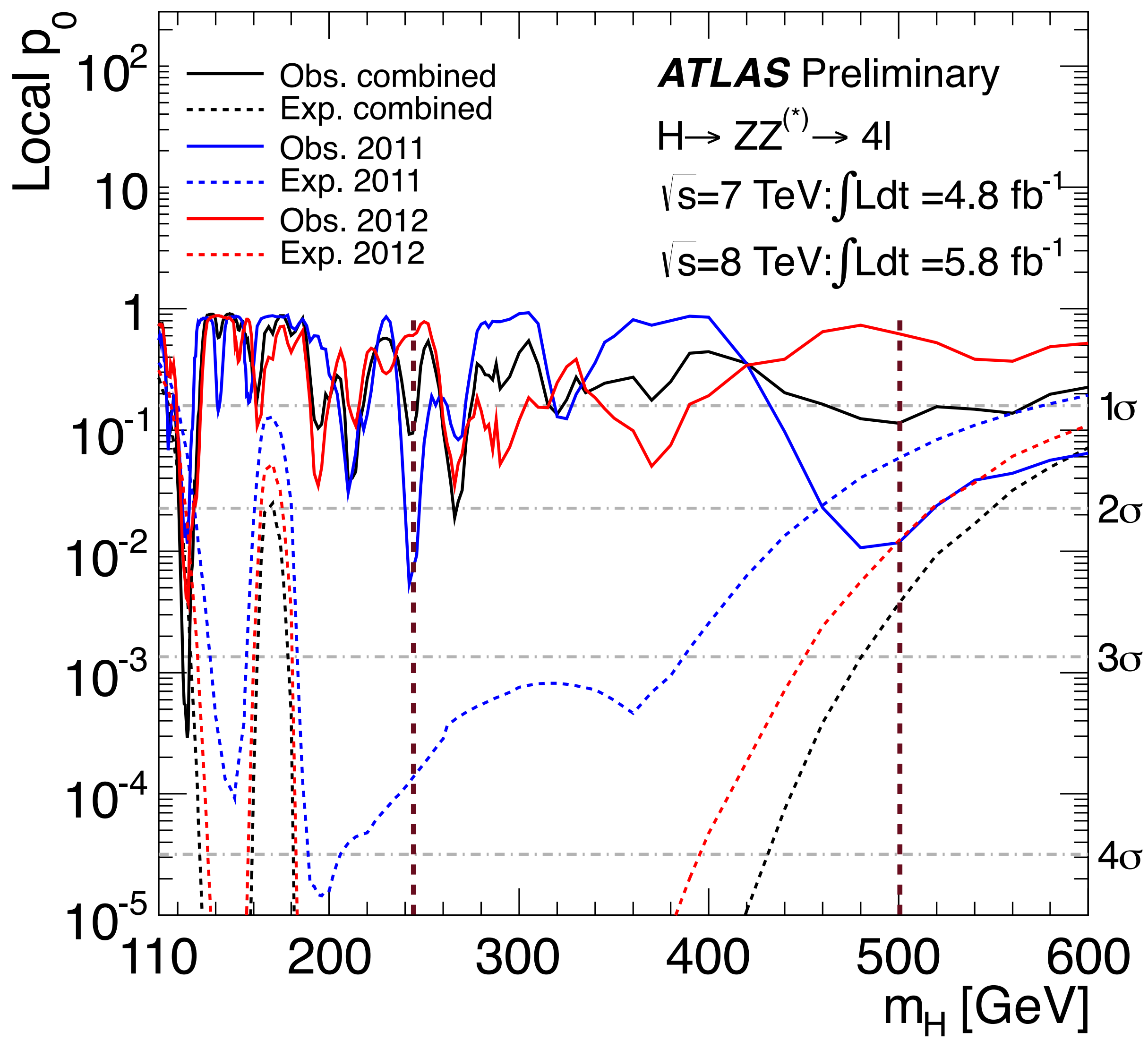
# Background Estimates: Shape



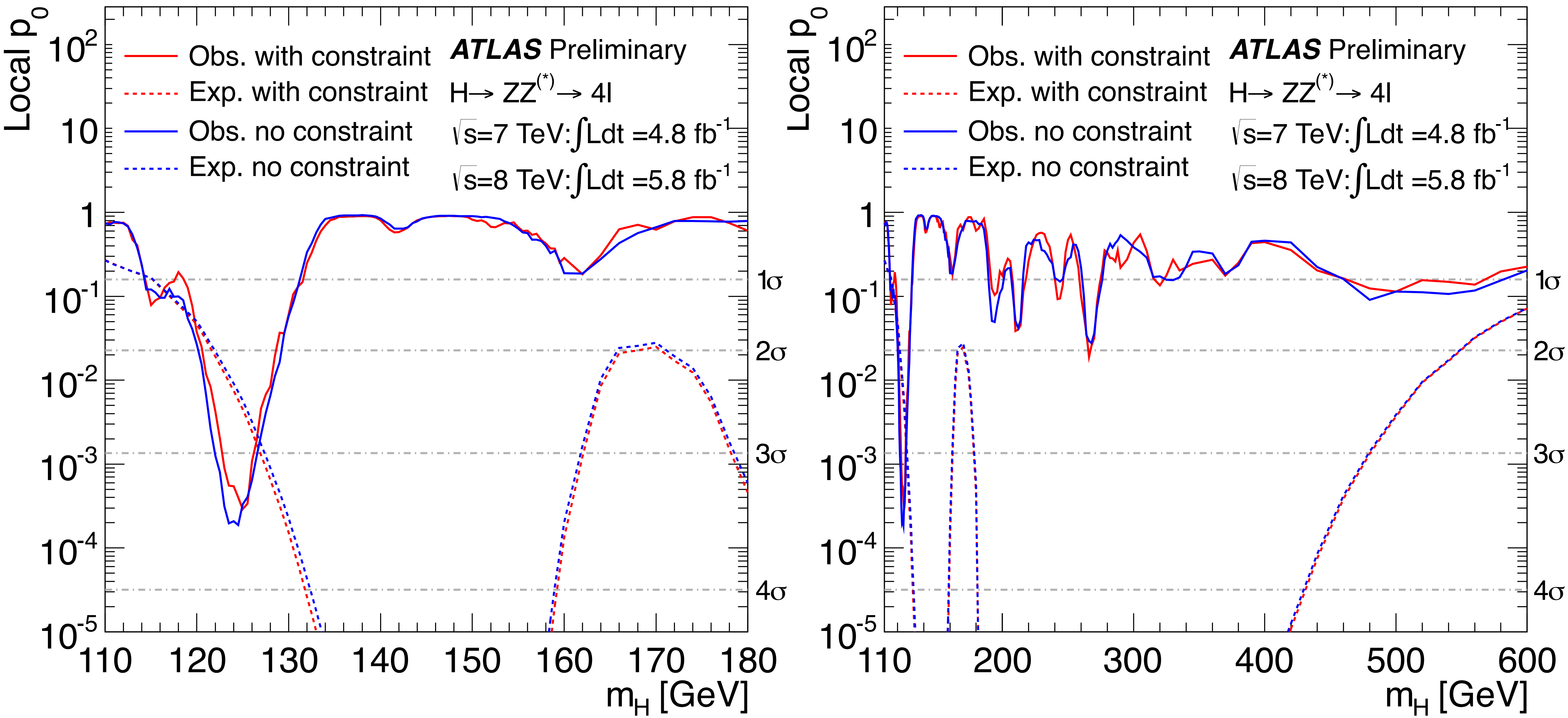

- Shape of reducible background is important
- Kinematic shape template prepared from simulation
- Verify with data:
  - Analysis phase-space, require that sub-leading di-lepton fails isolation or impact parameter requirements
  - Templated shape describes this $m_{4l}$ distribution
  - Additional templates (systematic uncertainty) based on variations of analysis requirements

# Significance of Excesses

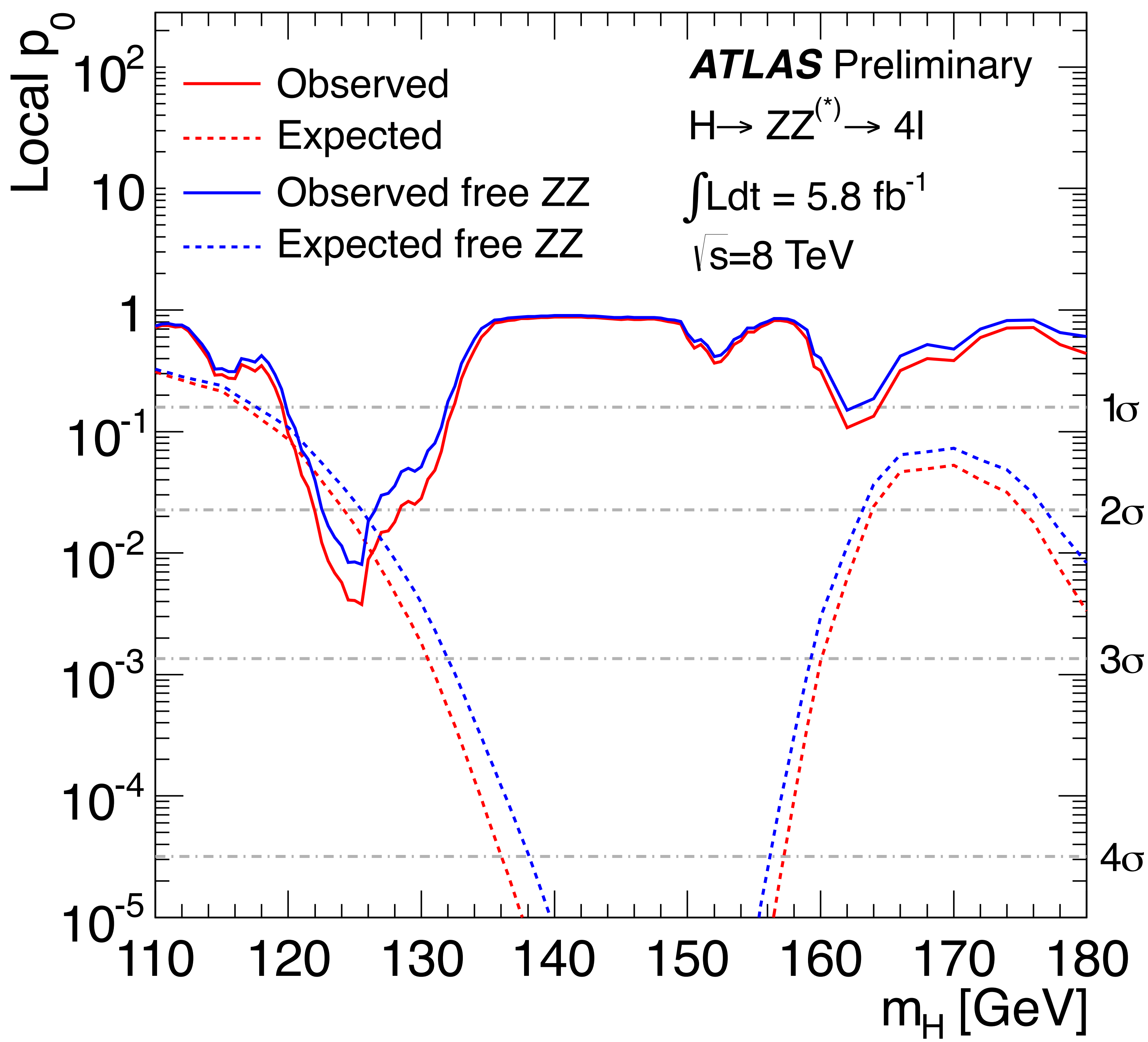


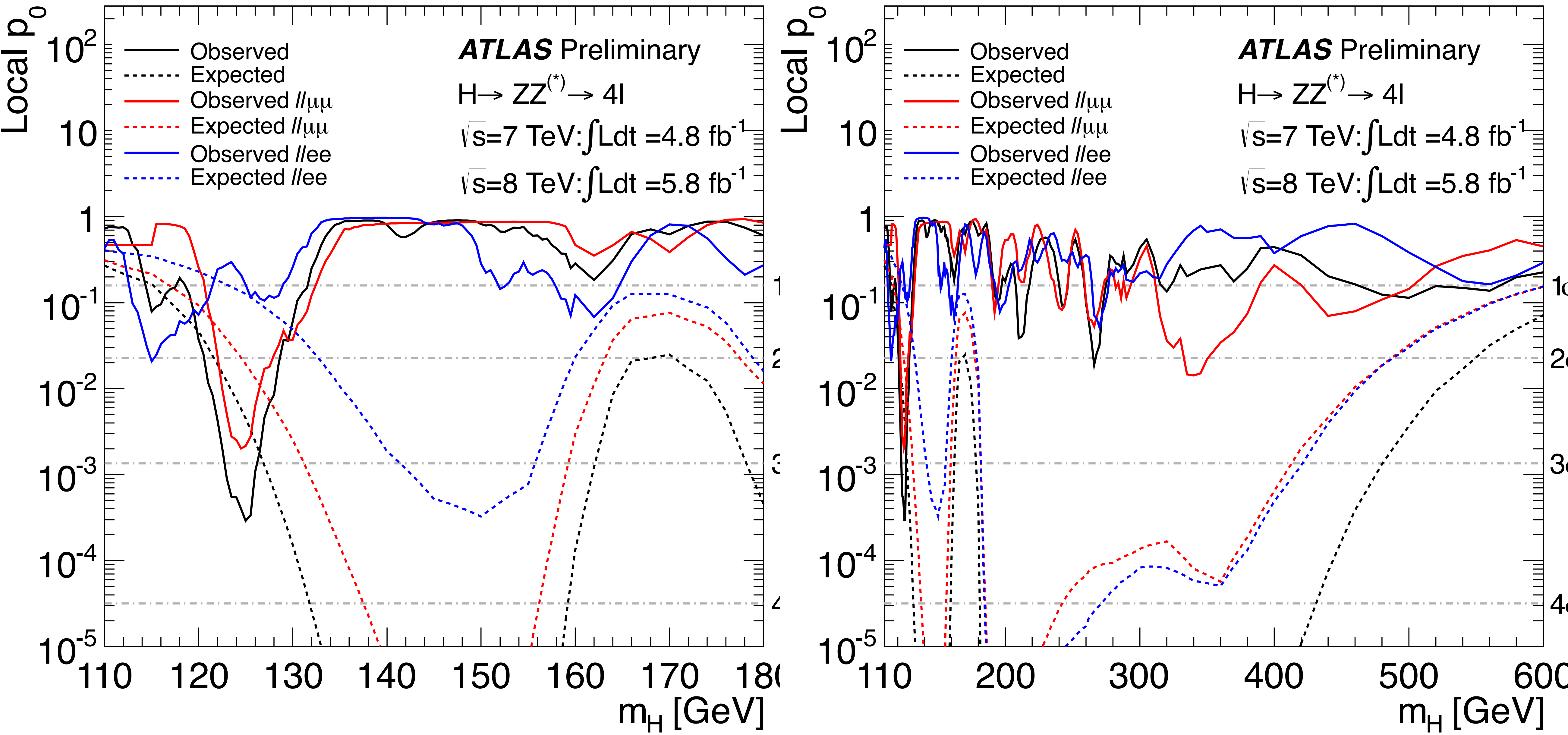
# Effect of Z mass constraint



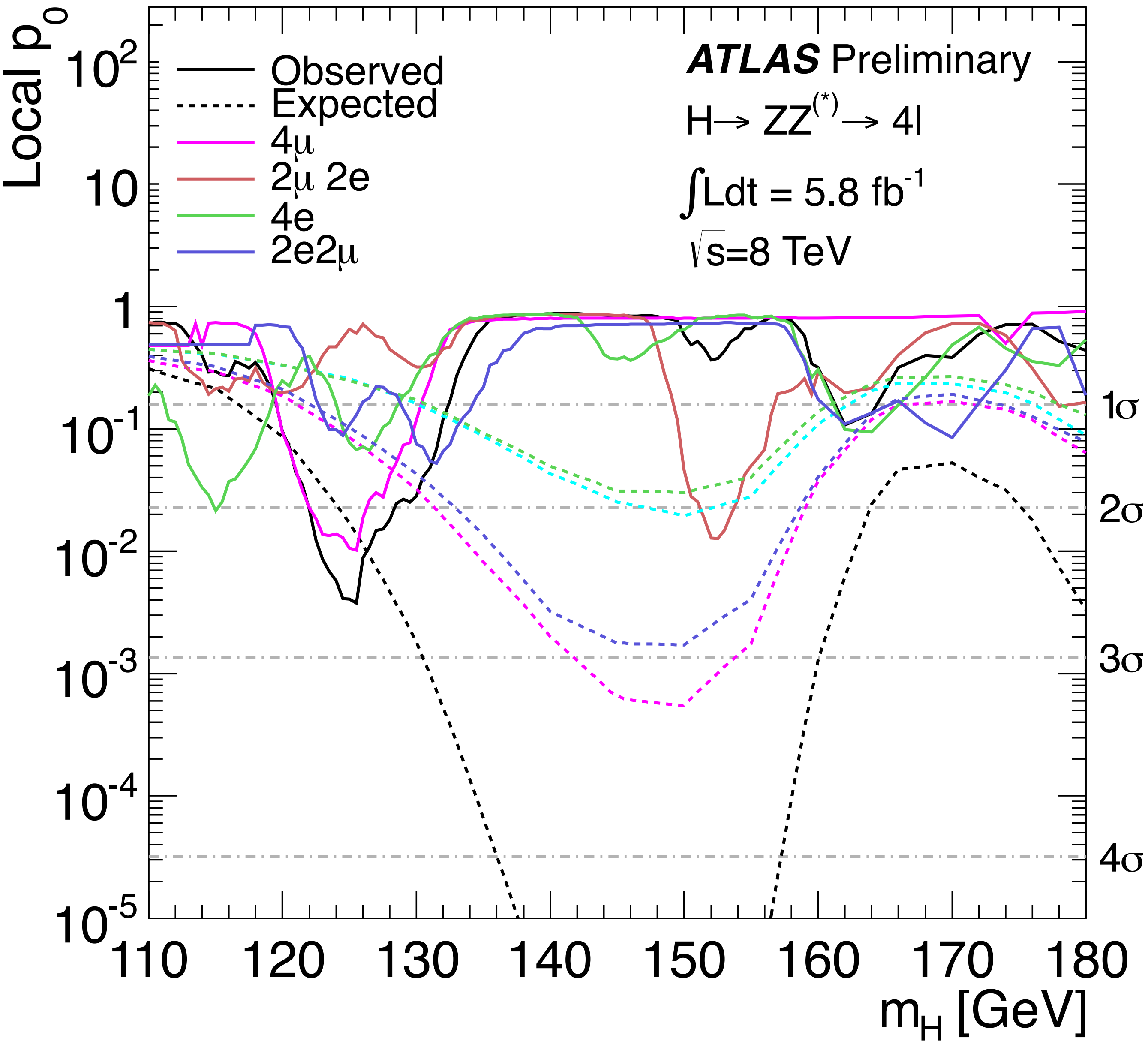
# ZZ normalization directly from the data

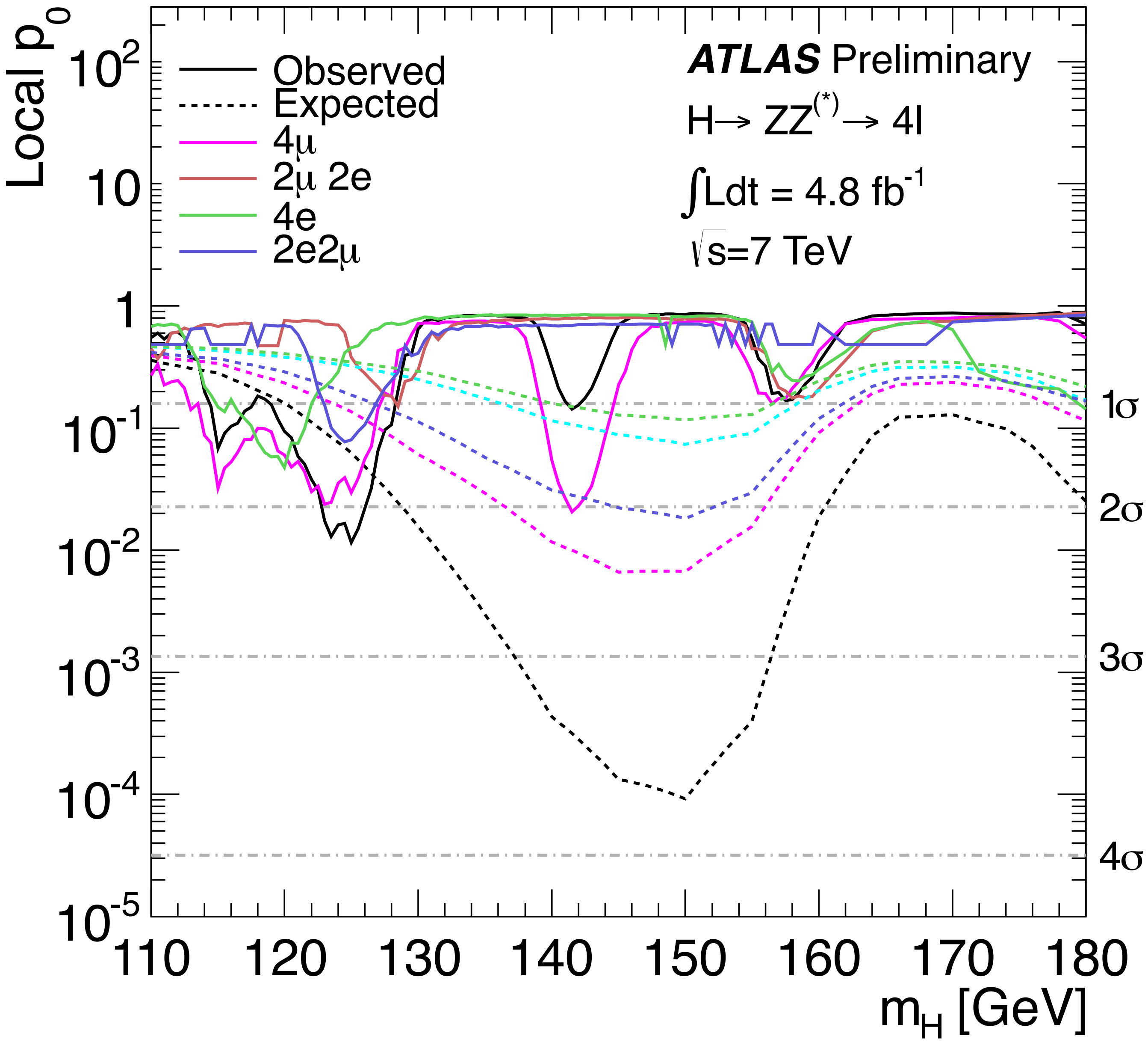


# Separating according to sub-leading di-lepton flavour

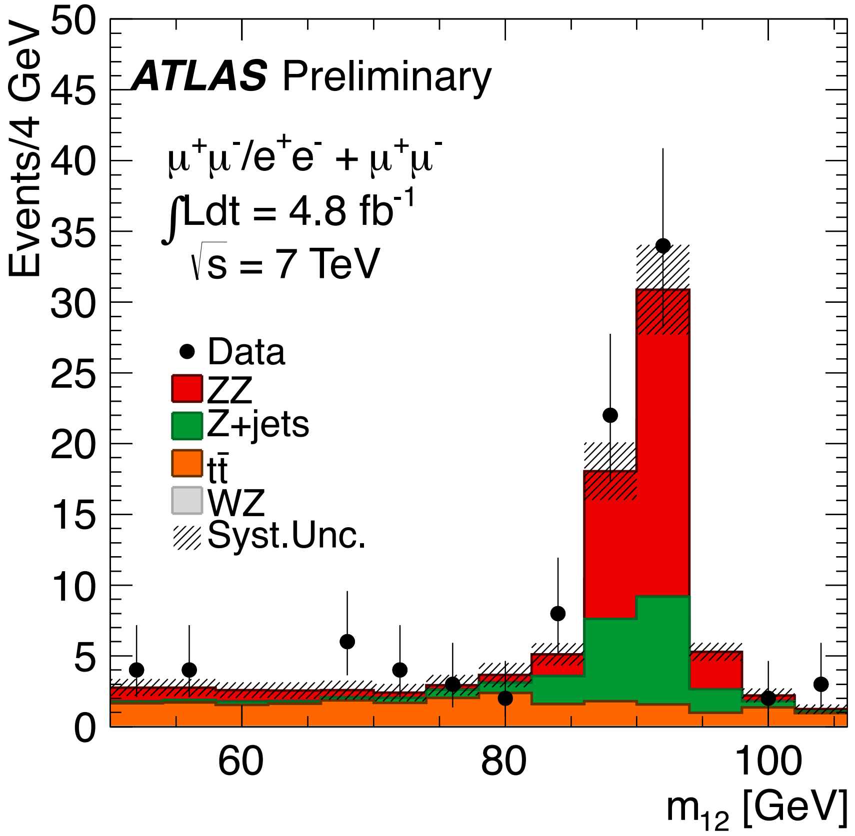


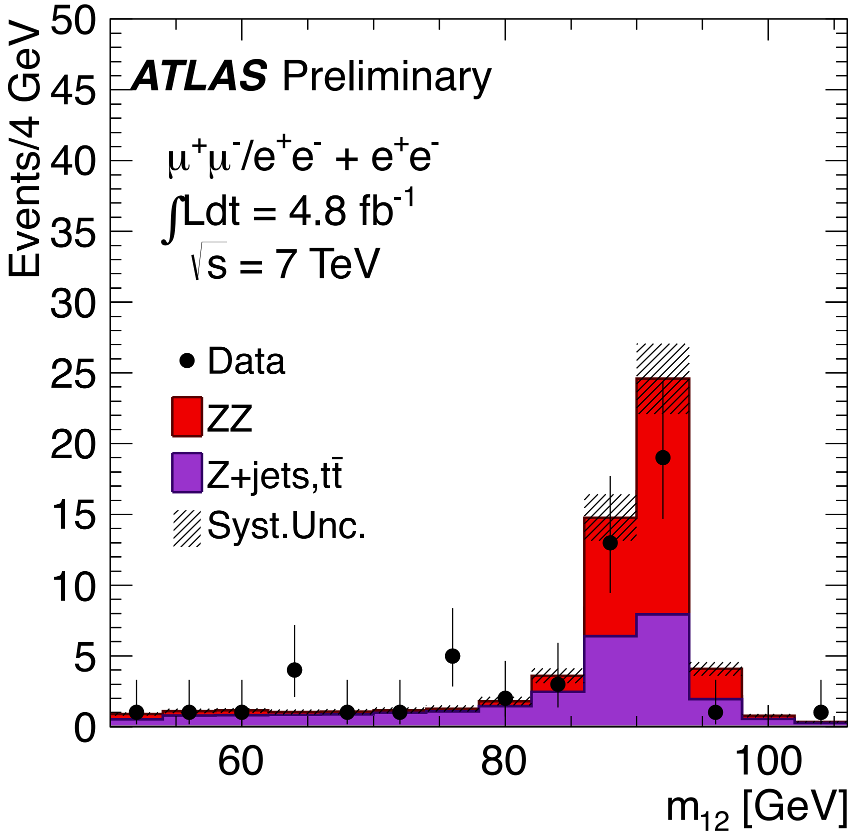
# Separating final states

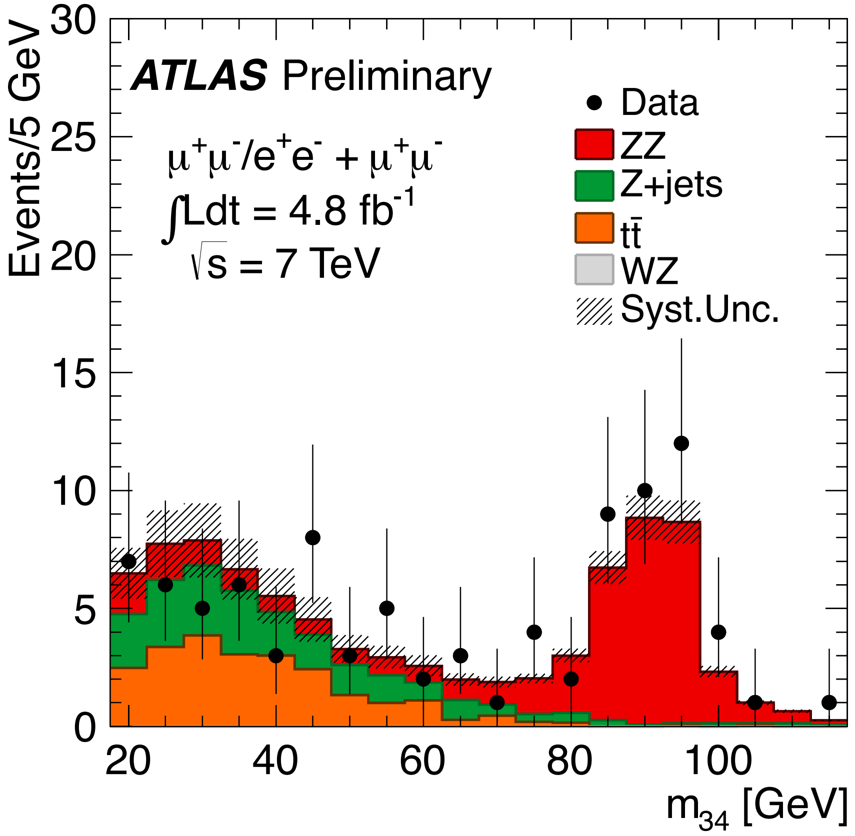


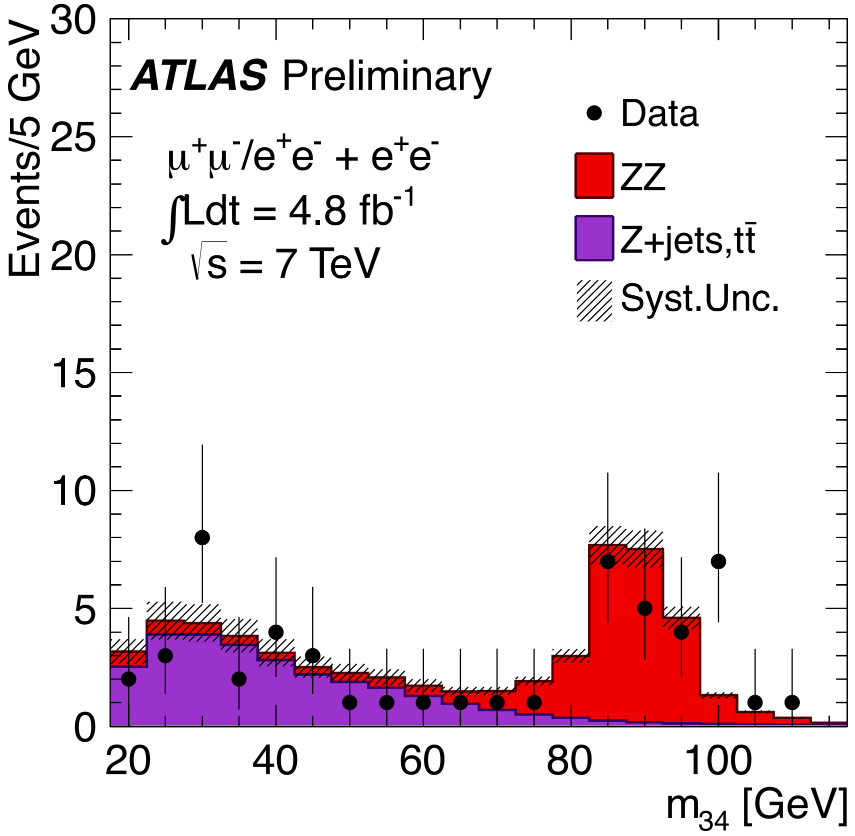



# Background Estimates: Control Regions 2011

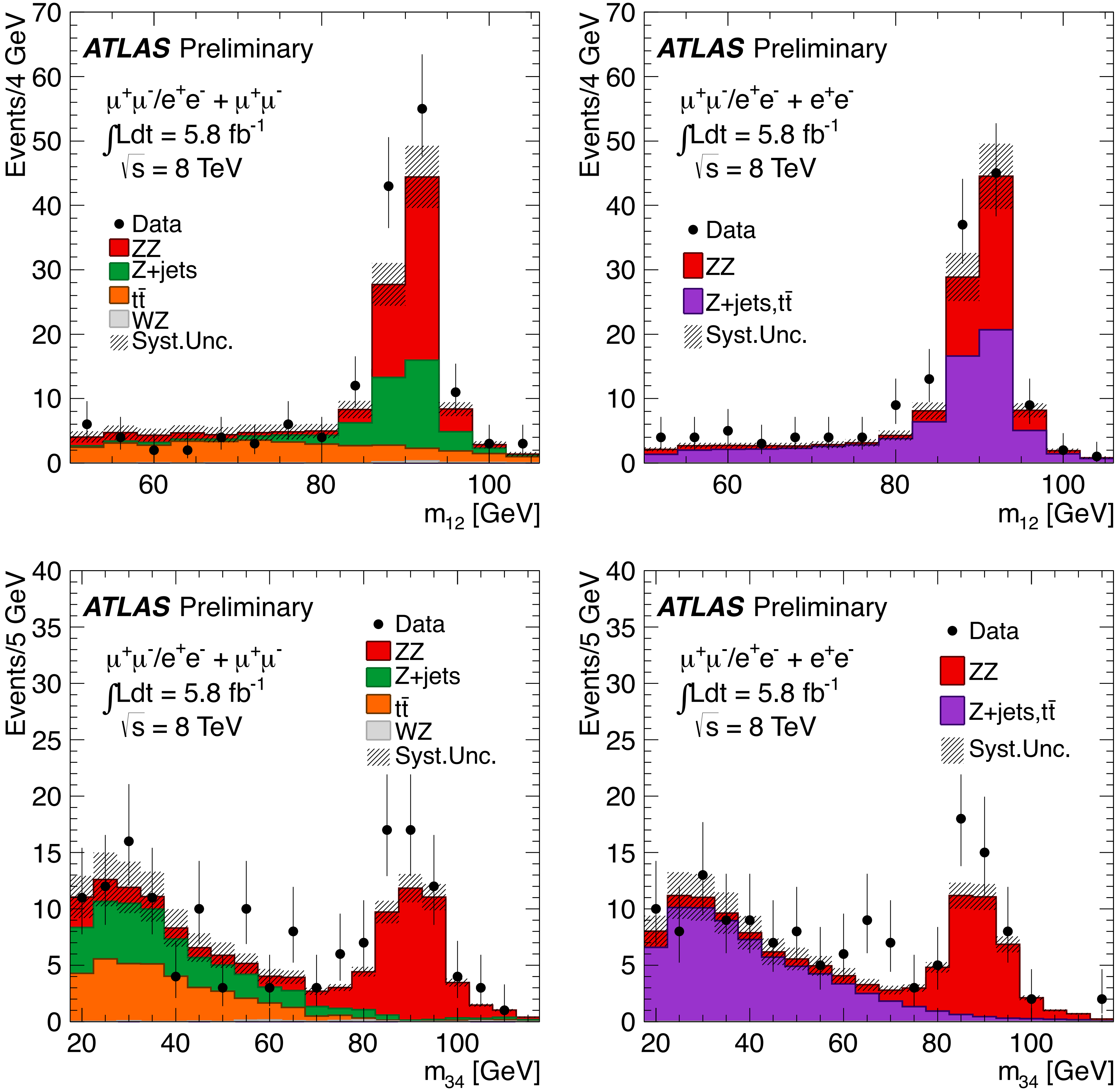


# Background Estimates: Control Regions 2012

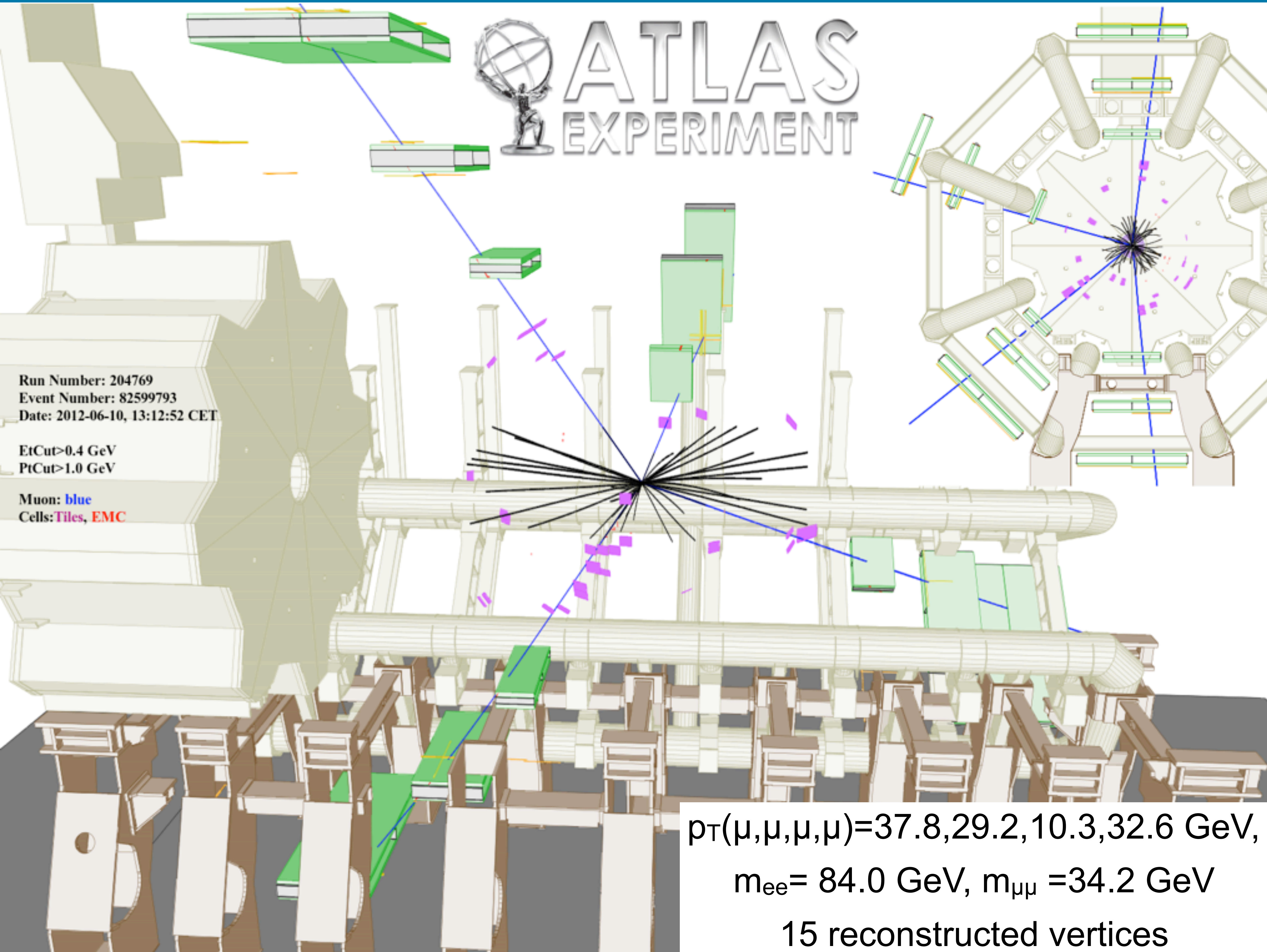


# Expected/Observed yields

| | $4\mu$ | | $2e2\mu/2\mu2e$ | | $4e$ | |
|---|---|---|---|---|---|---|
| | 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 | |

Low mass/ High mass separation at $m_{4l}$ of 160 GeV

# μμμμ candidate with $m_{4l}$ = 123.5 GeV




$p_T(\mu,\mu,\mu,\mu)$=37.8,29.2,10.3,32.6 GeV,

$m_{ee}$= 84.0 GeV, $m_{\mu\mu}$ =34.2 GeV

15 reconstructed vertices