Higgs Searches in ATLAS

A. Schaffer
LAL, Univ Paris-Sud, IN2P3/CNRS, Orsay, France
On behalf of the ATLAS Collaboration

PHYSICS IN COLLISIONS 2012

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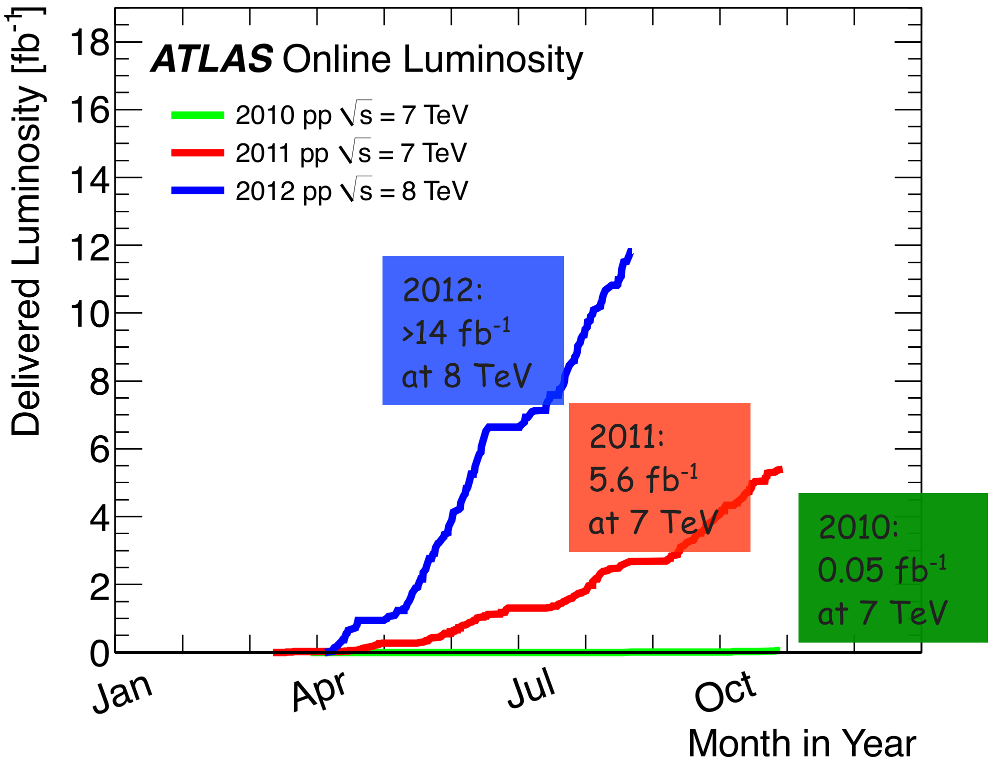
Higgs searches in ATLAS

- We present results for data taken in 2011 at $\sqrt{s} = 7$ TeV (~4.9 fb^{-1}) and 2012 at $\sqrt{s} = 8$ TeV (~5.8 fb^{-1})
- Outline
  - The new particle discovery (Phys Lett B 716 (2012), pp. 1-29)
    - Overview of the SM search channels
    - Results for high-mass Higgs, H->bb, H->$\tau\tau$
    - Details of the main discovery channels:
      - H->$ZZ^{(*)}$->4l, H->$\gamma\gamma$, H->$WW^{(*)}$->lνlν
    - Combined results and properties
  - Beyond the SM Higgs Searches

Delivered luminosity since the beginning



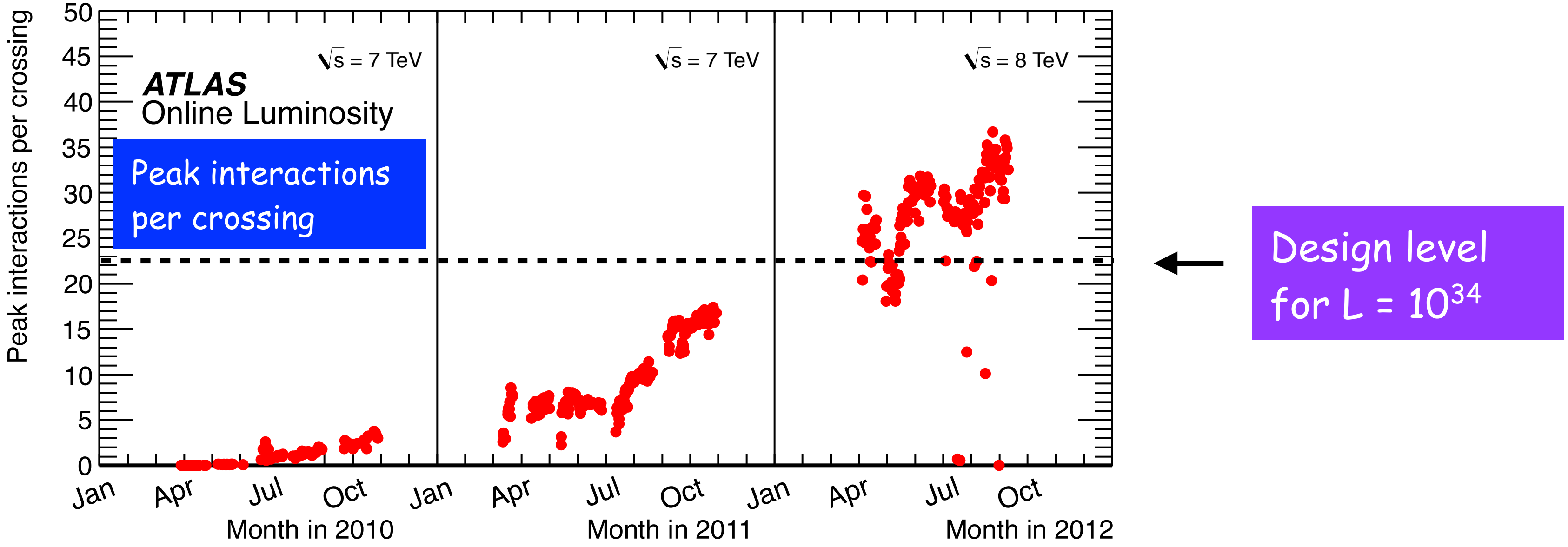
~90% (~85%) of delivered data is available for analysis in 2012 (2011)

2011 / 2012

Fraction of non-operational channels: (depends upon detector)	Few permil to 4%
Data-taking efficiency = (recorded lumi)/(delivered lumi)	93.5% / 94.5%
Good quality data fraction, used for analysis	90% / 94%

Big challenge with increasing lumi: pileup

Peak luminosity now ~7 10^{33}



Huge effort to mitigate the effect of pileup for the 2012 data-taking

- Developed pile-up robust fast trigger and offline algorithms
- Optimized reconstruction and identification of physics objects (e,γ,μ,τ,jet,E_T^{miss})

=> independent of pileup, similar or better performance as for 2011 data

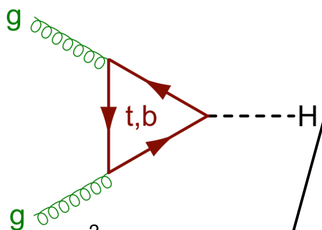
- Precise modeling of in-time and out-of-time pile-up simulation
- Flexible computing model to handle x2 trigger rate and x2 event size

Higgs analysis approach

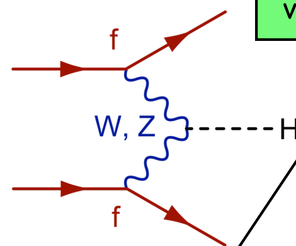
- All analysis signal regions are blinded until backgrounds are understood and agree with MC
- Optimizations are performed before signal unblinding
- Most analyses have re-optimized using 2011 data, then apply to both the 2011 and 2012 data

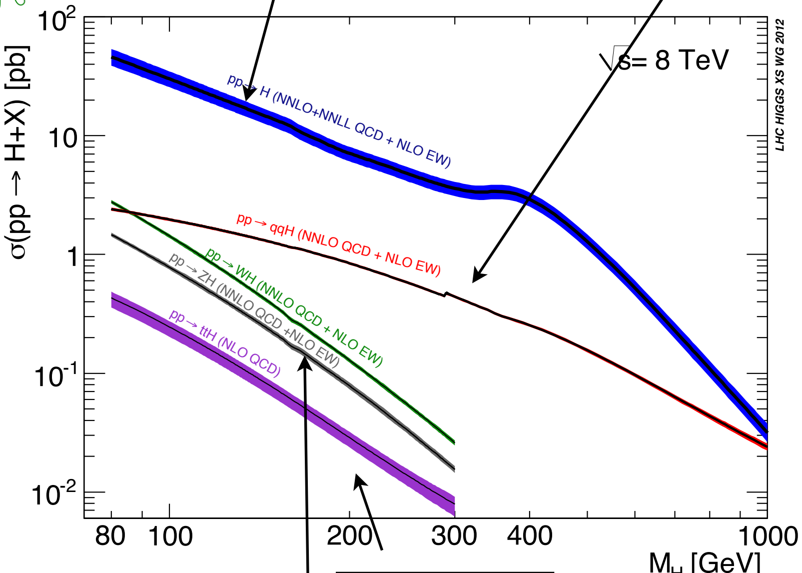
SM Higgs production and decay modes

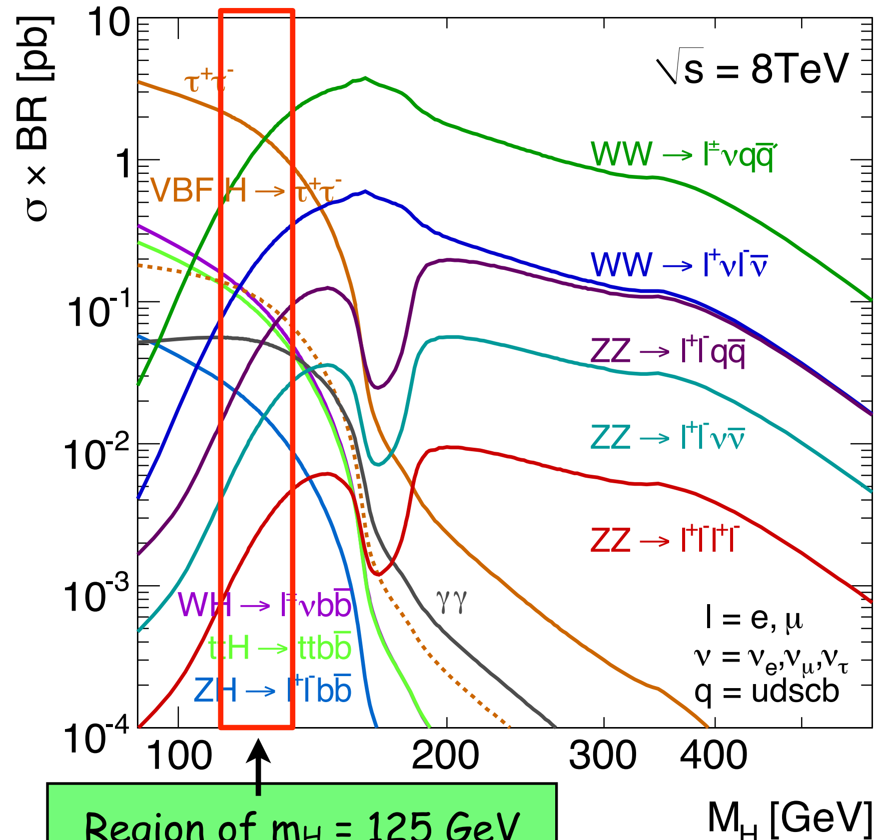
gluon-gluon fusion



vector boson fusion

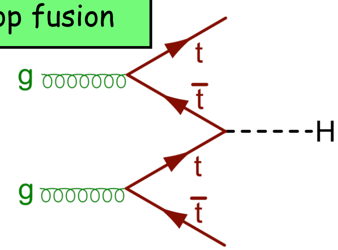


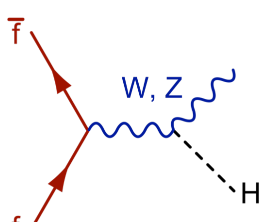




Region of m_H = 125 GeV
"thank you nature"

Top fusion





Higgs Strahlung

Total width: 4 MeV for m_H = 125 GeV
30 GeV for m_H = 400 GeV
120 GeV for m_H = 600 GeV

Vector boson fusion (VBF):

- Importance:
  - Vector coupling as opposed to the fermion coupling for ggF
  - Provides clean signature with forward jets => improved S/B

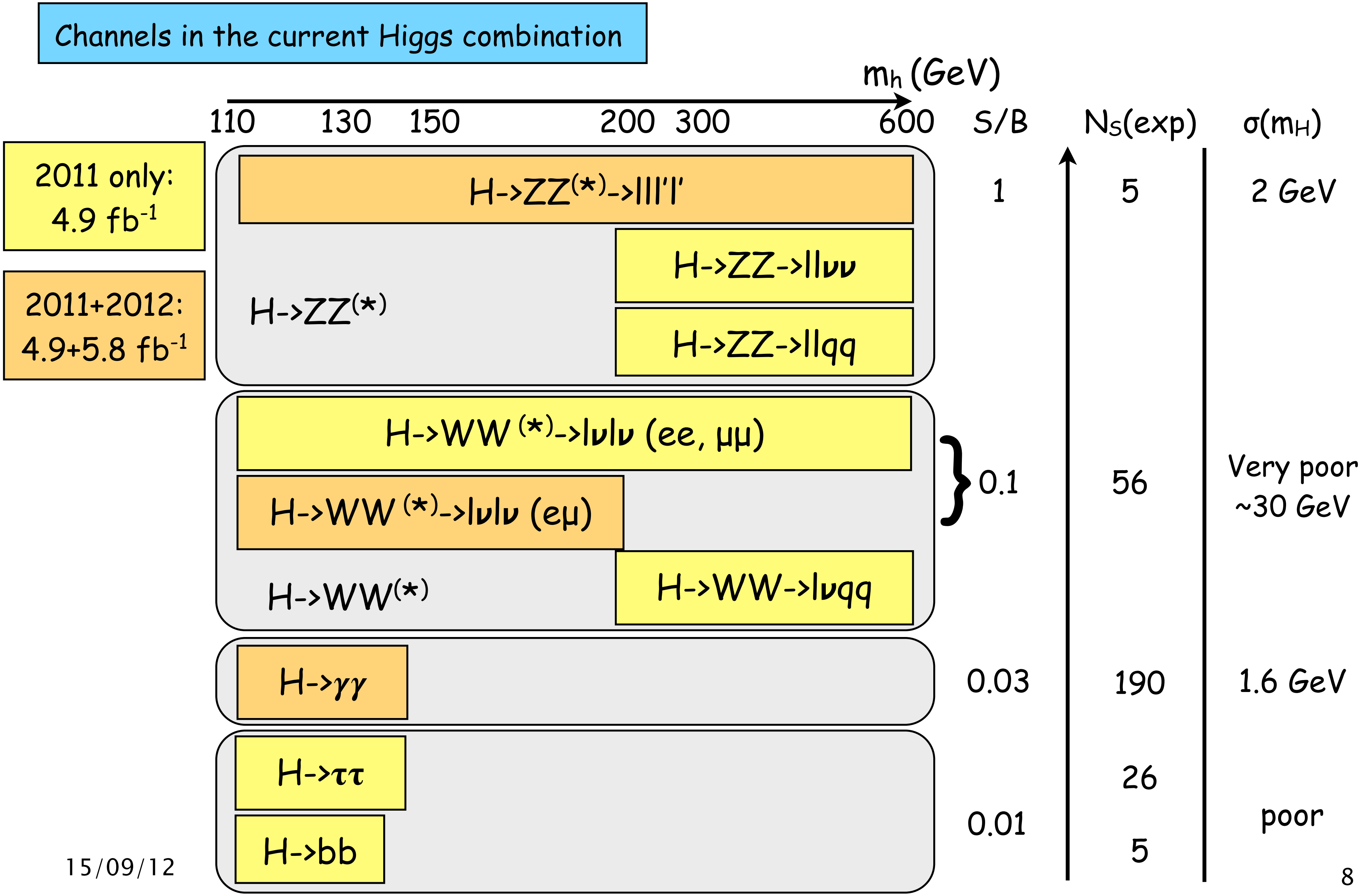
- Drawback: ~8% of ggF cross section

➡Impact today is somewhat limited, but will be of increasing importance in the near future

- Signature:
  - Well separated jets: $\Delta|\eta| \sim 3 - 4$
  - Large invariant: $m_{jj} \sim 500 - 700$ GeV
  - Back-to-back in φ
  - Little central jet activity (no color exchange via W):
    - can apply a central jet veto

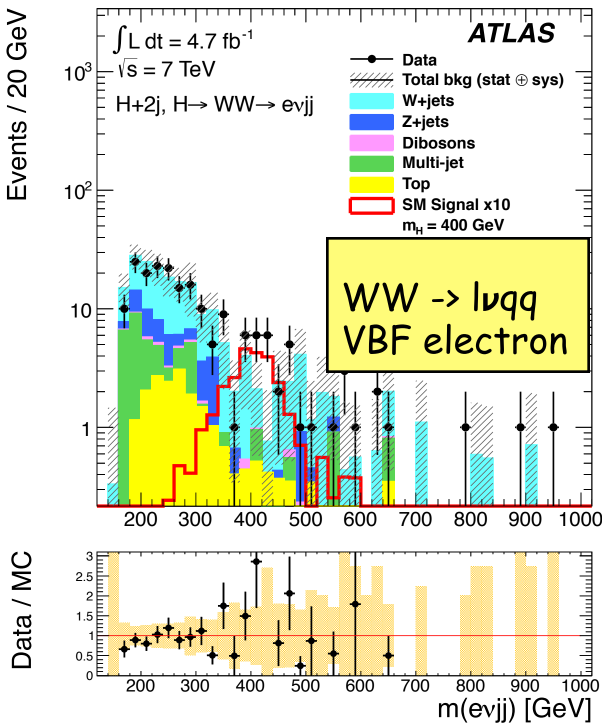
- Typical contamination from ggF + 2 jets ~25-30%

Overview of SM Higgs search channels



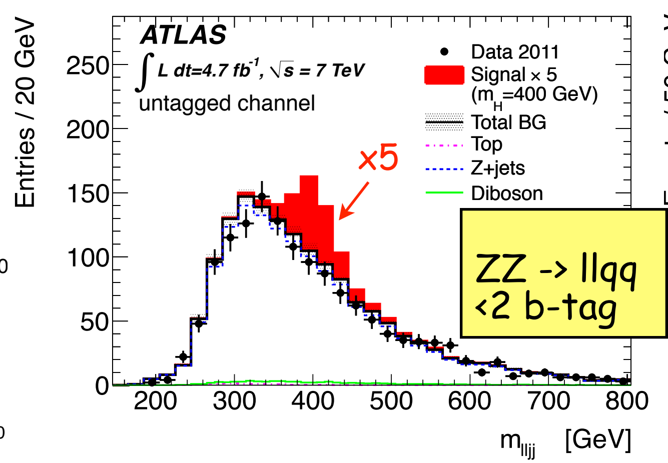
High mass searches

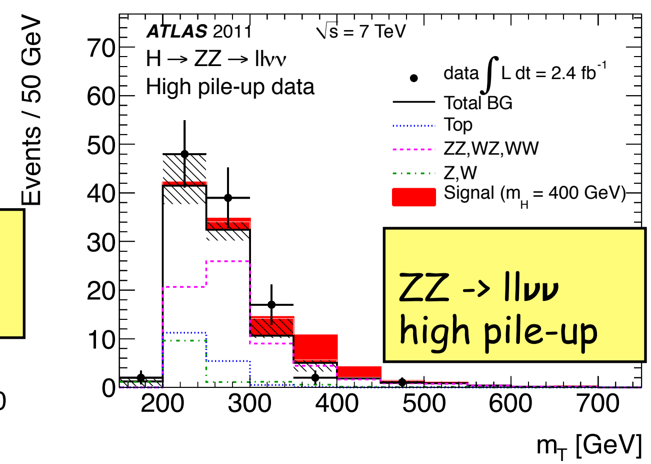
Channel	Analysis categories	Discriminate variable
H -> WW -> lνqq	0, 1 jet (gg), 2 jet (VBF)	$m_{l\nu qq}$ with $m_{l\nu} = m_W$
H -> ZZ -> llqq	2 b-tag jets and <2 b-tagged jets	m_{llqq} with $m_{ll} = m_Z$
H -> ZZ -> llνν	Low and high pileup	Transverse mass (2ν)



Main backgrounds:

W+jets, Z+jets, top, di-bosons, multi-jets

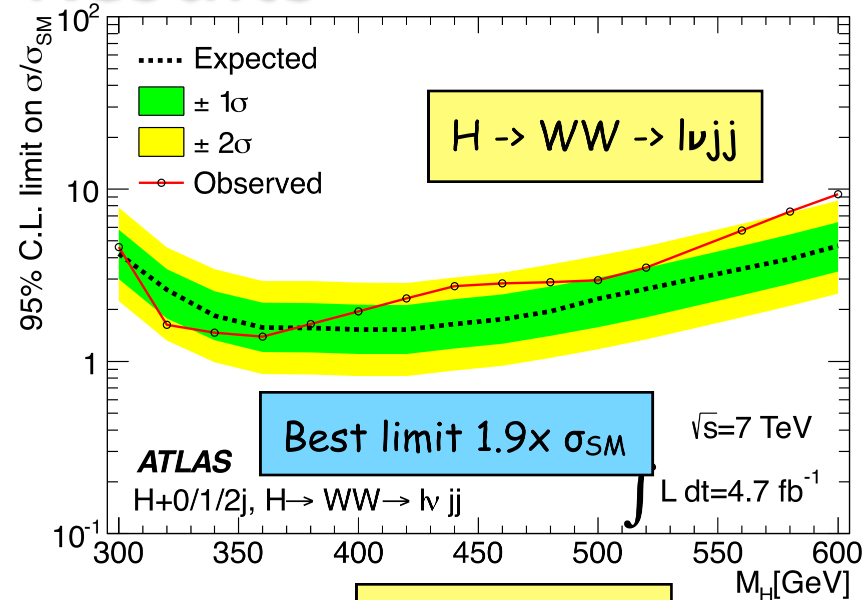




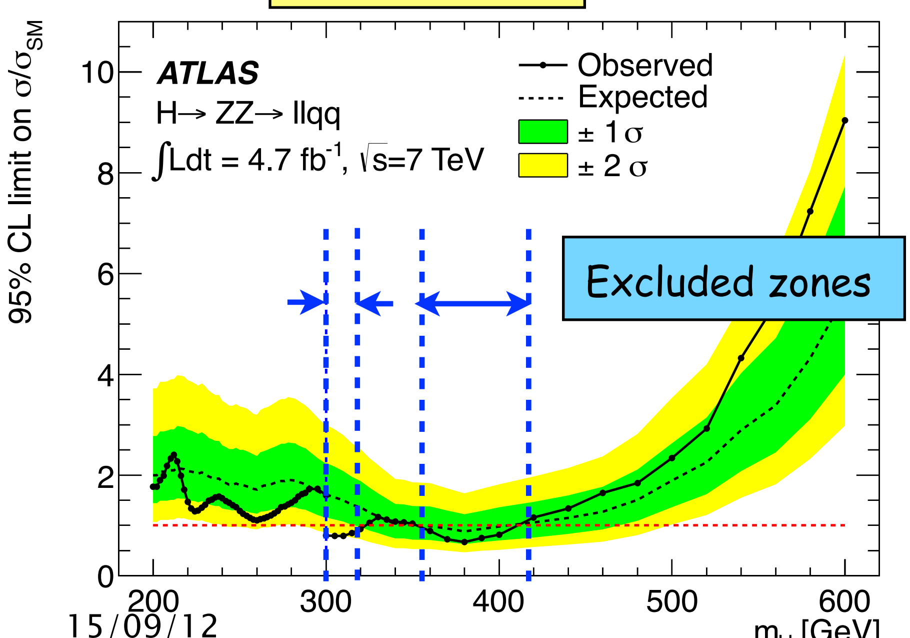
High mass searches: Results

- **No excess in m_H 200-560 GeV**

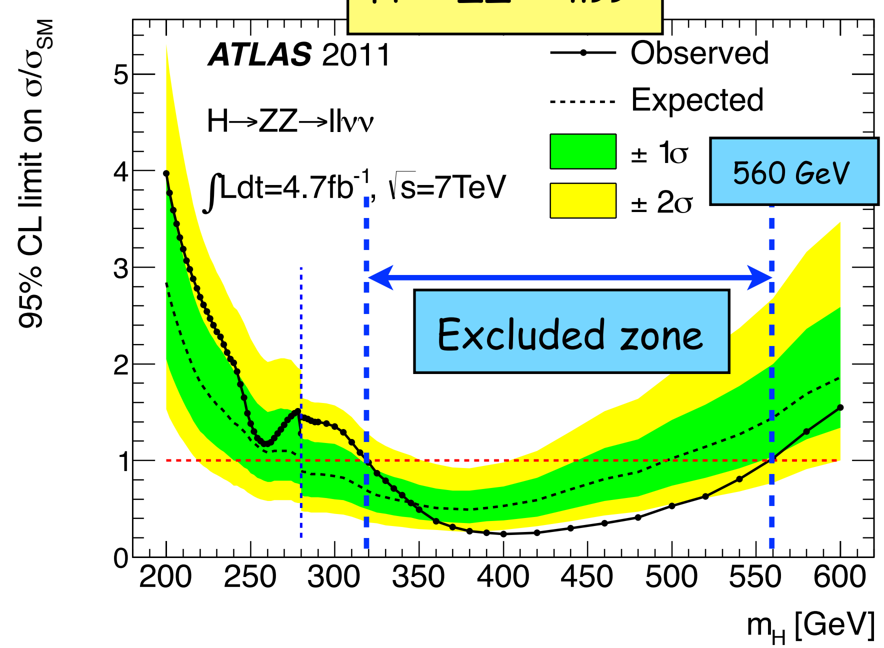
H -> WW -> lνlν and H -> ZZ -> 4l also important to fully exclude above 200 GeV



H -> ZZ -> llqq



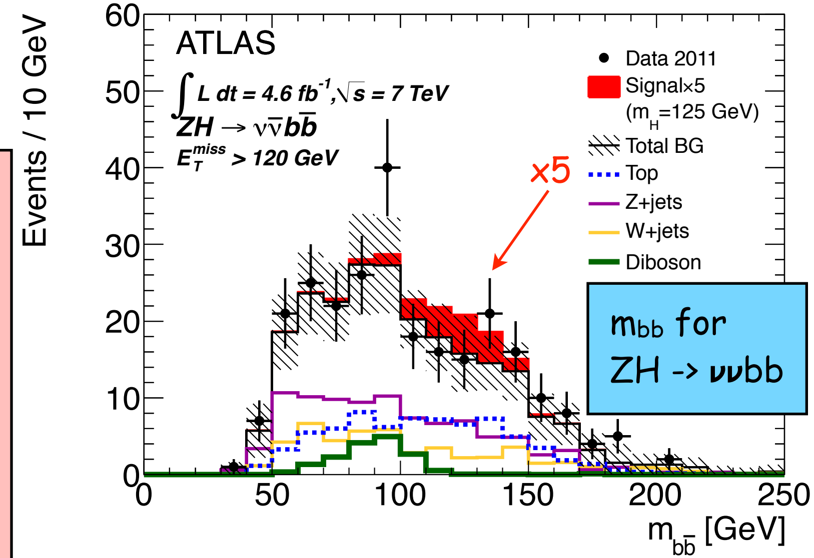
H -> ZZ -> llνν

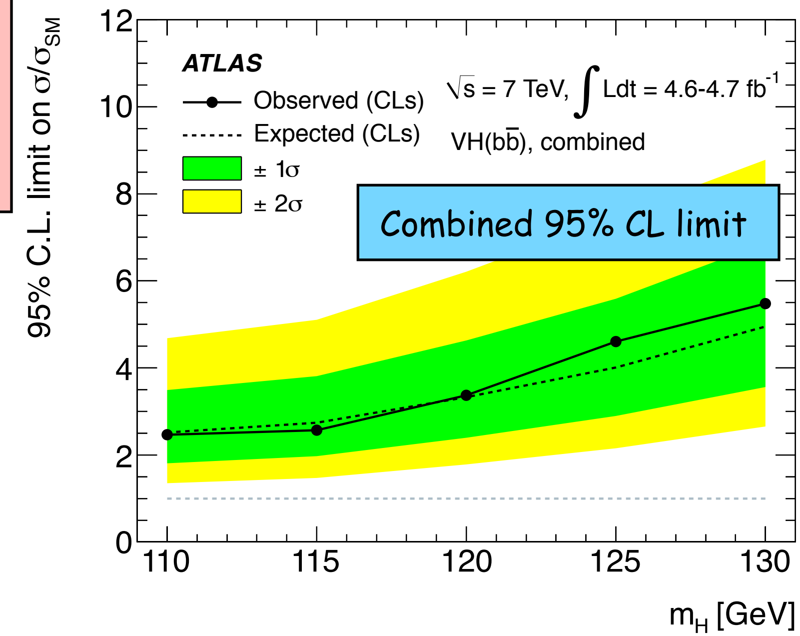


Low mass Fermion channels: H->bb

2011 data: 4.7 fb^{-1}

- **Characteristics:**
  - Three decay channels studied:
    - ZH -> llbb
    - ZH -> **νν**bb
    - WH -> lbb
  - Require exactly 2 b-jets
  - Analysis categories: different $p_T^{W/Z}$, E_T^{miss} bins
  - Backgrounds: W+jets, Z+jets, top, dibosons, multijets



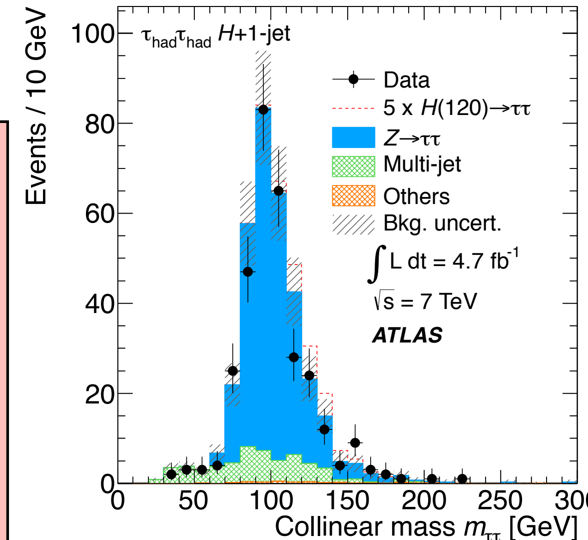


Sensitivity reaches 3.5 x σ_{SM} at m_H = 125 GeV

Low mass Fermion channels: H->ττ

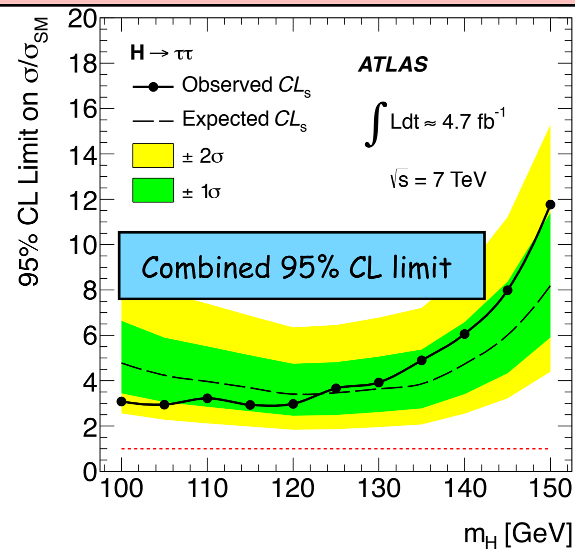
2011 data: 4.7 fb^{-1}

- **Characteristics:**
  - Three decay channels studied:
    - H -> ττ -> $\tau_{lep}\tau_{lep}$ (τ_{lep} == $e\nu_\tau\nu_e$ or $\mu\nu_\tau\nu_\mu$)
    - H -> ττ -> $\tau_{lep}\tau_{had}$
    - H -> ττ -> $\tau_{had}\tau_{had}$
  - Analysis categories: 0,1 jet (gg), 2-jet - VBF and VH
  - Backgrounds:
    - Z->ττ (irreducible), estimated from 'embedding' Z-> μμ events with simulated τ's
    - τ/leptons fakes - estimated with control regions

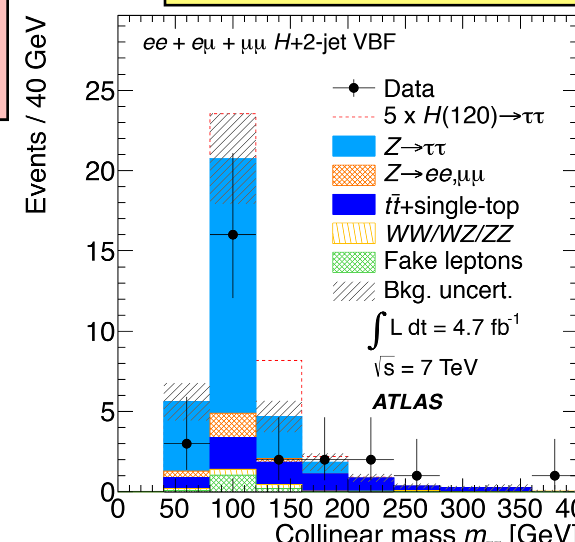


$m_{\tau\tau}$ for $\tau_{had}\tau_{had}$ 1-jet

Sensitivity reaches ~3.2 x σ_{SM} at m_H = 125 GeV



Combined 95% CL limit



$m_{\tau\tau}$ for lνν lνν VBF

$H\to ZZ^*\to 4l$ (4e, 2e2μ, 4μ2e, 4μ)

$\sigma \times BR \sim 2.5$ fb at $m_H \sim 125$ GeV (8 TeV)

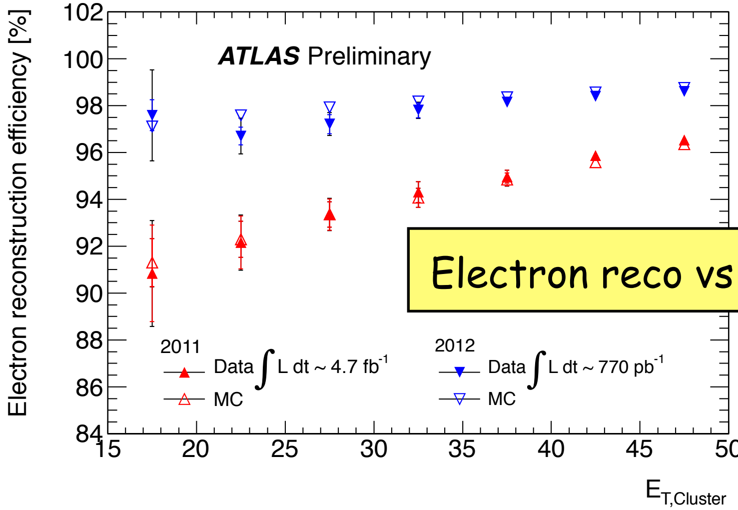
- **Tiny rate, but**:
  - S/B ~1
  - Fully reconstructed final state => clear peak above background!
- **Backgrounds**:
  - Irreducible: pp -> ZZ* -> 4l
  - Reducible (at low mass < $2m_Z$): Z+jets, Zbb, tt
    - Suppress with isolation and impact parameter cuts on softest leptons

- **Crucial experimental aspects**:
  - High lepton acceptance, reconstruction and identification down to low p_T
  - Good lepton energy/momentum resolution
  - Good control of reducible backgrounds (Z+jets, Zbb, tt) in low mass region
    - ➡Cannot rely on MC alone (theoretical uncertainties, b/j->l modeling)
    - ➡Must validate MC with data enriched control samples

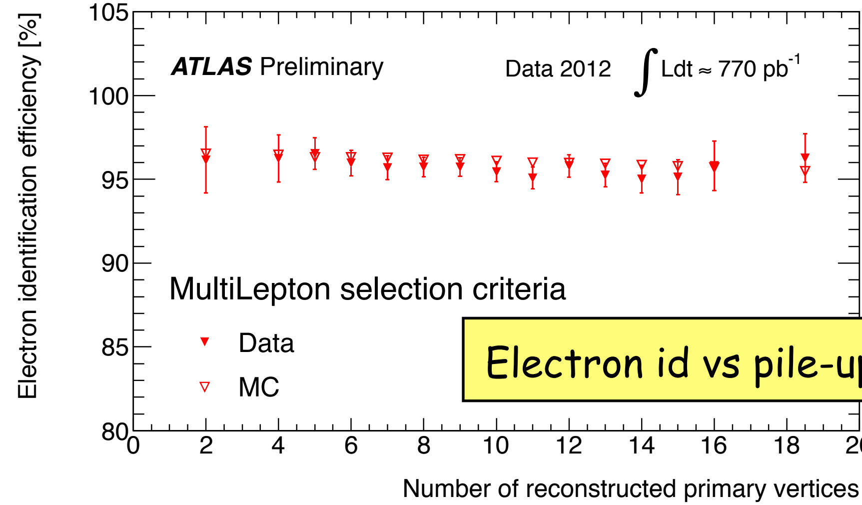
- **Improvements in the analysis for both 2011 and 2012 data**
  - Optimized/relaxed kinematic cuts (e.g. m_{12}) to increase sensitivity at low mass
  - Increased electron reconstruction and identification efficiency at low p_T, increased pileup robustness with negligible increase in reducible backgrounds

➡Gains: 20% (4μ) to 30% (4e) in sensitivity compared to previous analysis

H->4l lepton reconstruction and identification



Electron reco vs Et

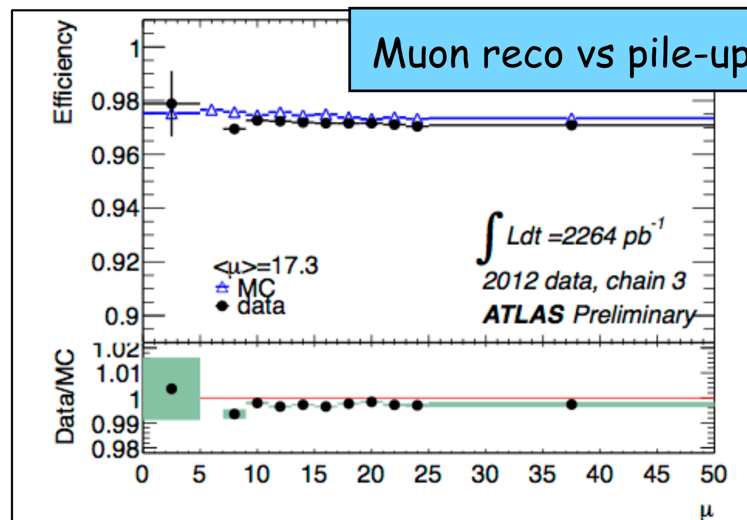


Electron id vs pile-up

Improved electron reconstruction =>
98% efficiency flat in Et

Improved electron identification =>
>95% efficiency flat in pile-up

Muon reconstruction efficiency ~98%
=> flat in pile-up



Muon reco vs pile-up

- Combined reco/selection efficiency:
  - ~37% - 4μ
  - ~21% - 2e2μ 7 & 8 TeV data
  - ~18% - 4e

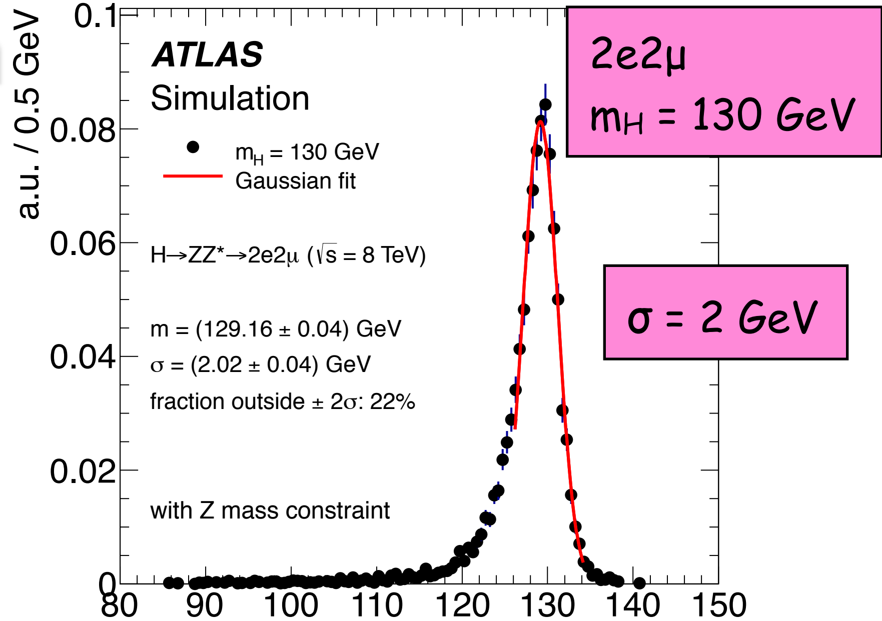
H->4l mass resolution

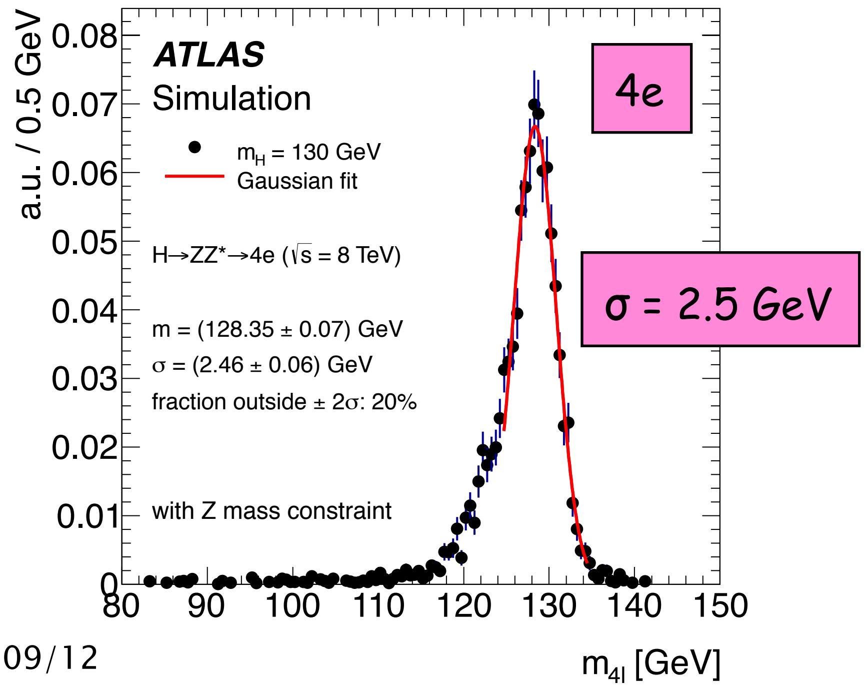
Main discriminant variable:

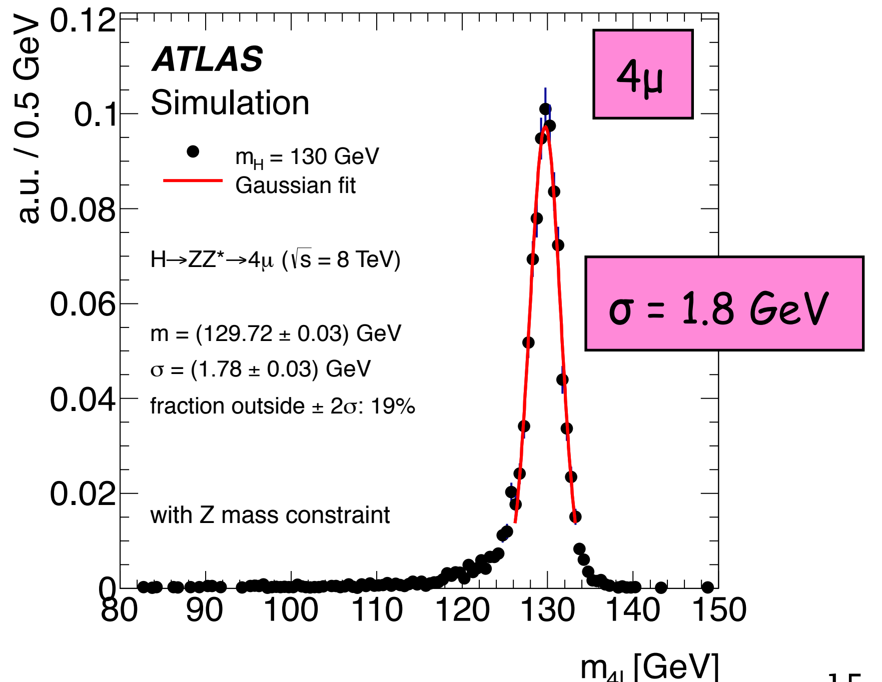
- Four lepton invariant mass

Resolution:

- 1.3% to 1.9% for m_H = 130 GeV with mass constraint
- Mass constraint improvement ~15%





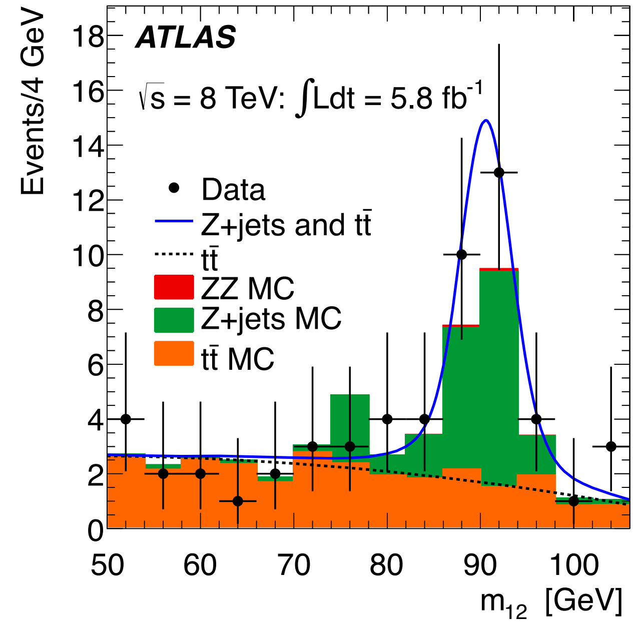


H->4l backgrounds

Background	Origin	Estimate
4l-irreducible	pp -> ZZ(*)	MC
ll + μμ	tt and Z+jets (bb)	Control region + MC extrapolation
ll + ee	Z + jets: hadrons, conversions and b-decays	Control region + MC extrapolation

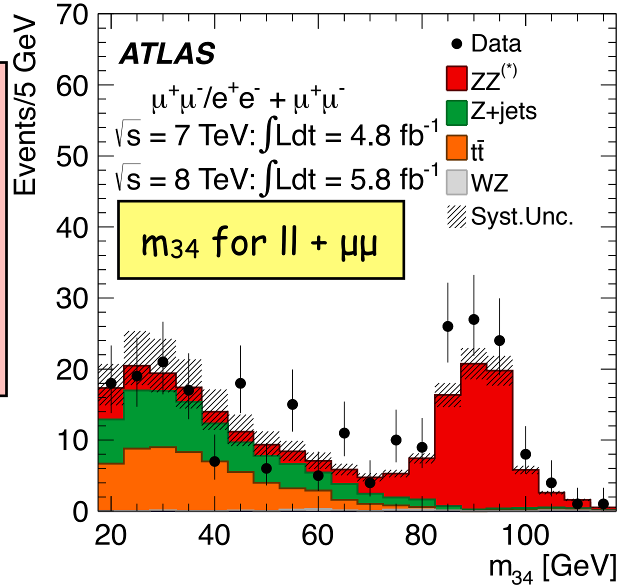
ll + μμ: m_{12} control region

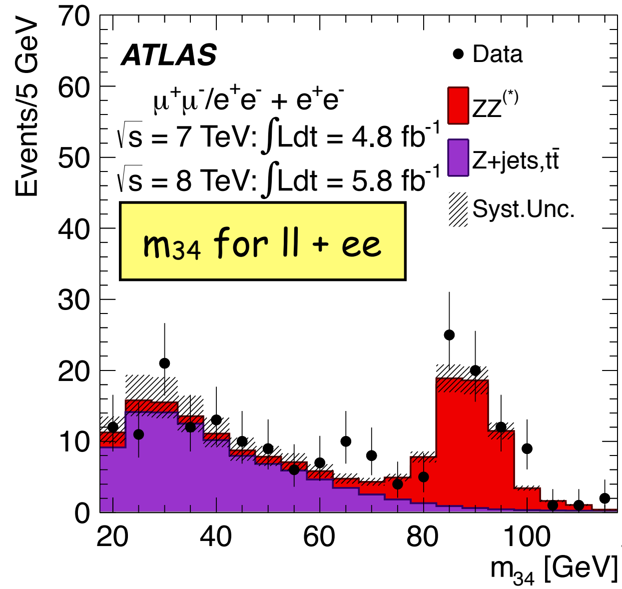
- Remove isolation and invert impact parameter cuts



m_{34} control regions

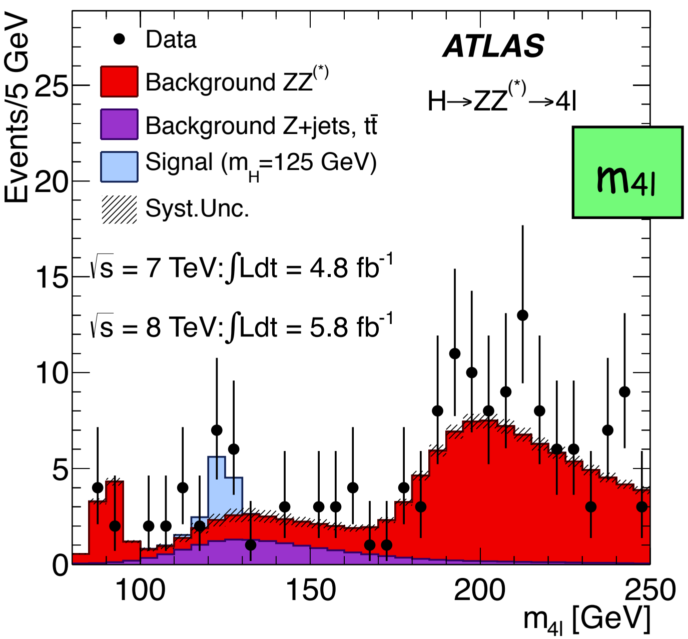
- Remove isolation and impact parameter cuts
- Normalize MC to data-driven estimate



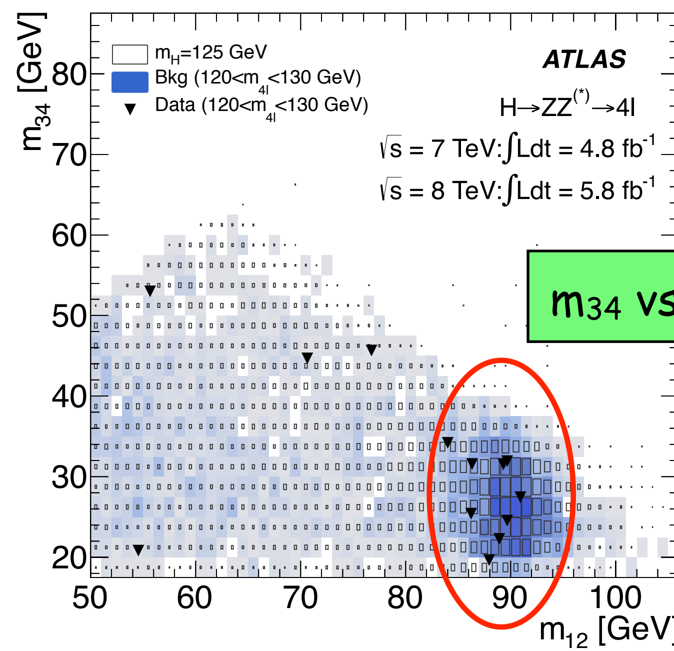


H->4l Results

Expected signal/background and observed events in m_H = 125 ± 5 GeV				
	Signal	$ZZ^{(*)}$	Z+jets	Observed
4μ	2.1 ± 0.3	1.12 ± 0.05	0.13 ± 0.04	6
2e2μ/2μ2e	2.3 ± 0.3	0.80 ± 0.05	1.3 ± 0.2	5
4e	0.9 ± 0.1	0.44 ± 0.04	1.1 ± 0.2	2
Total	5.3 ± 0.8	2.4 ± 0.1	2.5 ± 0.4	13



m_{4l}



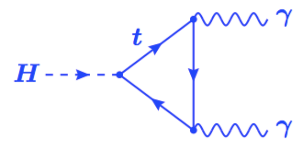
m_{34} vs m_{12}

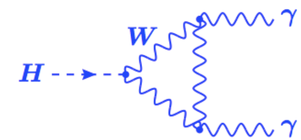
H->$\gamma\gamma$

110 GeV < m_H < 150 GeV

σ x BR ~50 fb at m_H~126 GeV (8 TeV)

- **Simple topology:** Two high p_T isolated photons
  - E_T ($\gamma_1\gamma_2$) > 40, 30 GeV
- Main **background**: $\gamma\gamma$ continuum (irreducible, smooth)





To increase sensitivity, events divided into 10 categories based on γ rapidity, converted/ unconverted γ, p_{Tt} ($p_T^{\gamma\gamma}$ perpendicular to $\gamma\gamma$ thrust axis), and 2 jets

- **Main improvements in the new analysis**:
  - 2 jet category introduced => selection targeting VBF process
  - γ identification (NN used for 2011 data) and isolation (improved pile-up treatment)
    - ➡Expected gain in sensitivity: +15%

After all selections, expect (10.7 fb^{-1}, m_H ~ 126 GeV, 90% signal in mass window):
- ~170 signal events (total signal efficiency ~40%)
- ~6340 background events

➡S/B: ~3% inclusive (~20% in 2 jet category)

- **Crucial experimental aspects:**
  - Excellent $\gamma\gamma$ mass resolution to see peak above irreducible background
  - Powerful γ identification to suppress γj and jj backgrounds with jet -> π^0 -> fake γ
    - (cross sections are 10^4-10^7 larger that the $\gamma\gamma$ background)

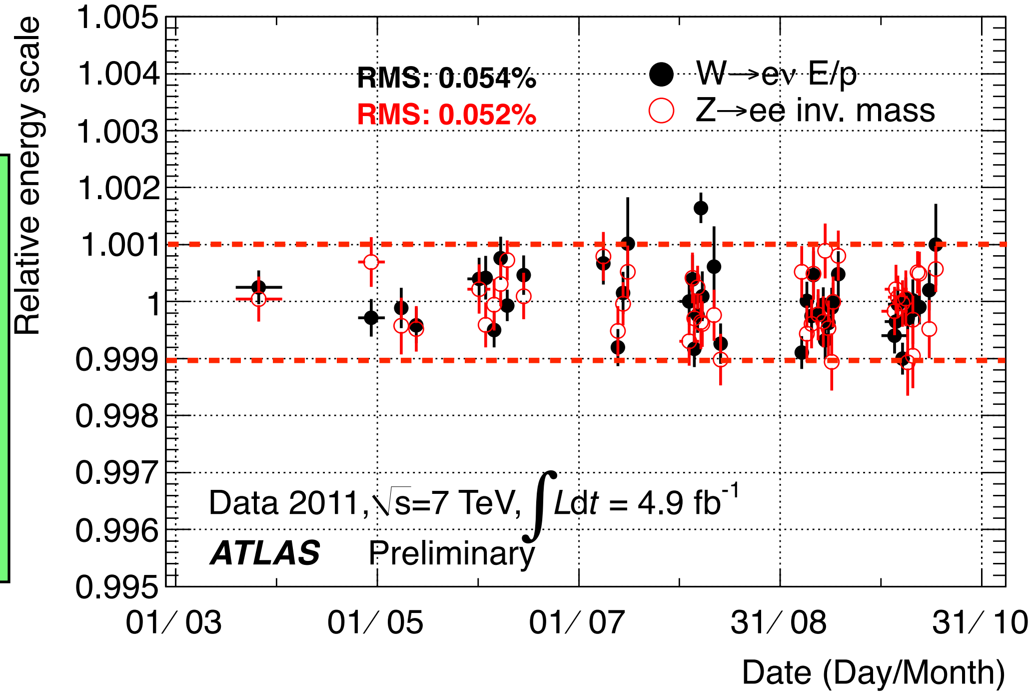
H->γγ mass resolution

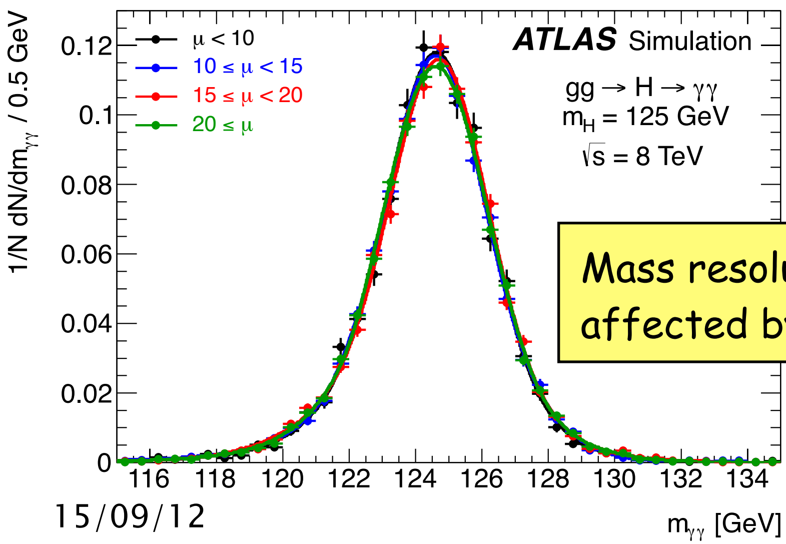
Stability of EM calorimeter response vs time (and pile-up) for full 2011 run is < 0.1%

$$m^2_{\gamma\gamma} = E_1 E_2 (1 - \cos\alpha)$$

Present understanding for the calorimeter EM response (from Z,J/ψ -> ee, W->eν and MC):

- E-scale at m_Z known to ~0.3%
- Linearity known better than 1%
- "Uniformity" (constant term for resolution): 1% (2.5%) in barrel (endcap)





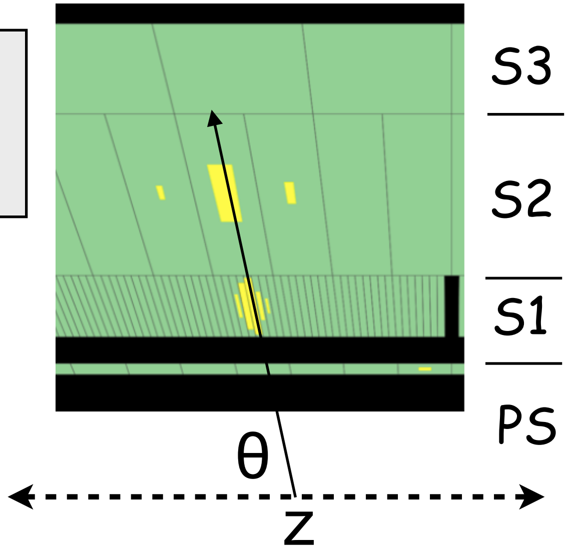
Electron scale is transported to photons using MC (small systematics from material effects)

Mass resolution not affected by pile-up

Mass resolution of inclusive sample: 1.6 GeV
Fraction of events in 2σ is 90%

$m^2_{\gamma\gamma} = E_1 E_2 (1 - \cos\alpha)$

α is the opening angle of the two photons

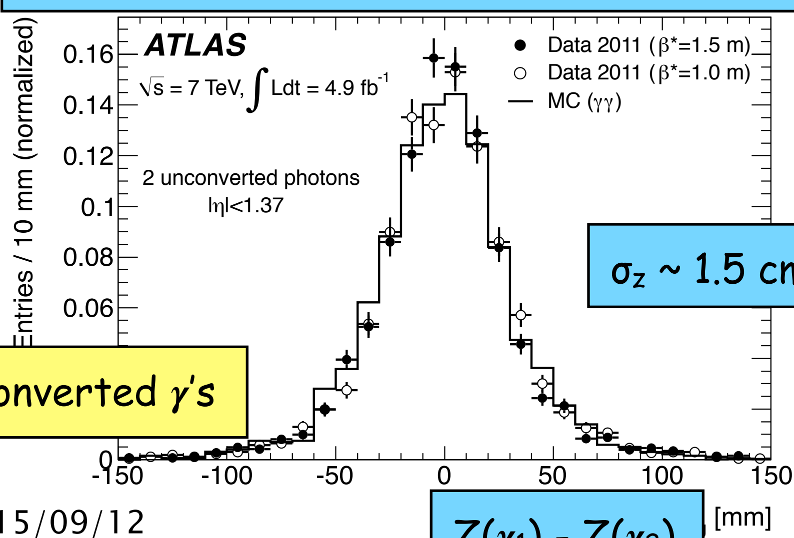


High pile-up: many vertices distributed over LHC beam spot: σ_z ~5-6 cm
➡difficult to know which one has produced the $\gamma\gamma$ pair

Determine primary vertex from:
- EM calorimeter longitudinal (and lateral) segmentation
- Tracks from the photon conversion

Measured γ direction with calo
=> get Z of primary vertex

Z-vertex measured in $\gamma\gamma$ events from "calo-pointing"



σ_z ~ 1.5 cm

Unconverted γ's

$Z(\gamma_1) - Z(\gamma_2)$

- Calo-pointing alone reduces the beam-spot spread from 5-6 cm to 1.5 cm
➡Enough to make the angular term contribution to the mass resolution negligible

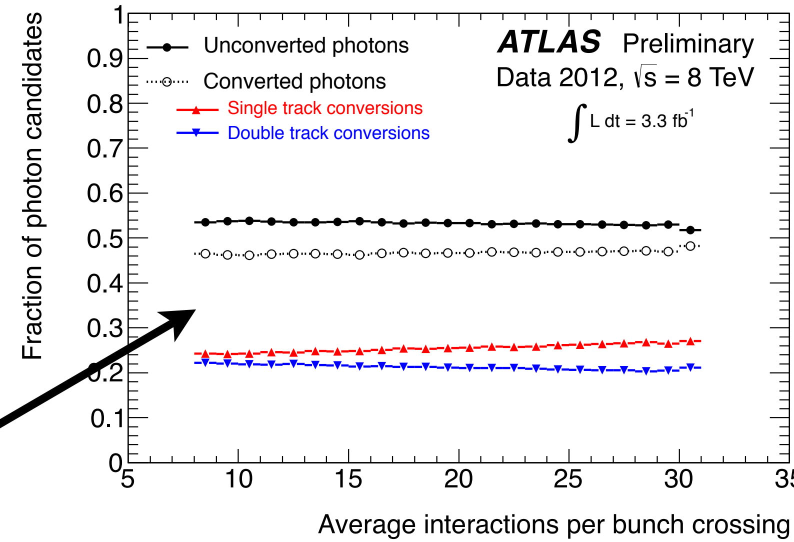
- Addition of the track information is needed to reject fake jets for 2j/VBF

Photon reconstruction and γ/jet separation

- Photons reconstructed from clusters in calorimeter and conversion vertices in InnerDetector
- Jet background reduced via shower shape and isolation cuts

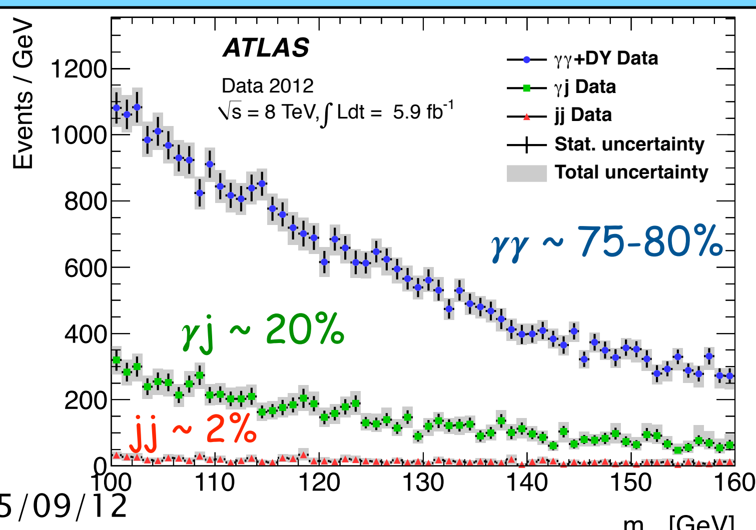
Fraction of converted/unconverted γ vs pile-up stable (<1%)

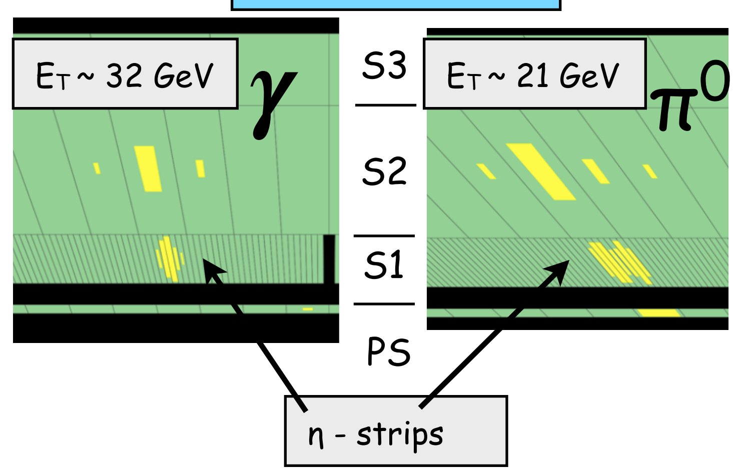
- Little migration between categories => accurate specific calibration



High $\gamma\gamma$ purity:
$R_j \sim 10^4$
$\varepsilon(\gamma) \sim 90\%$

Data-driven decomposition of selected $\gamma\gamma$ sample





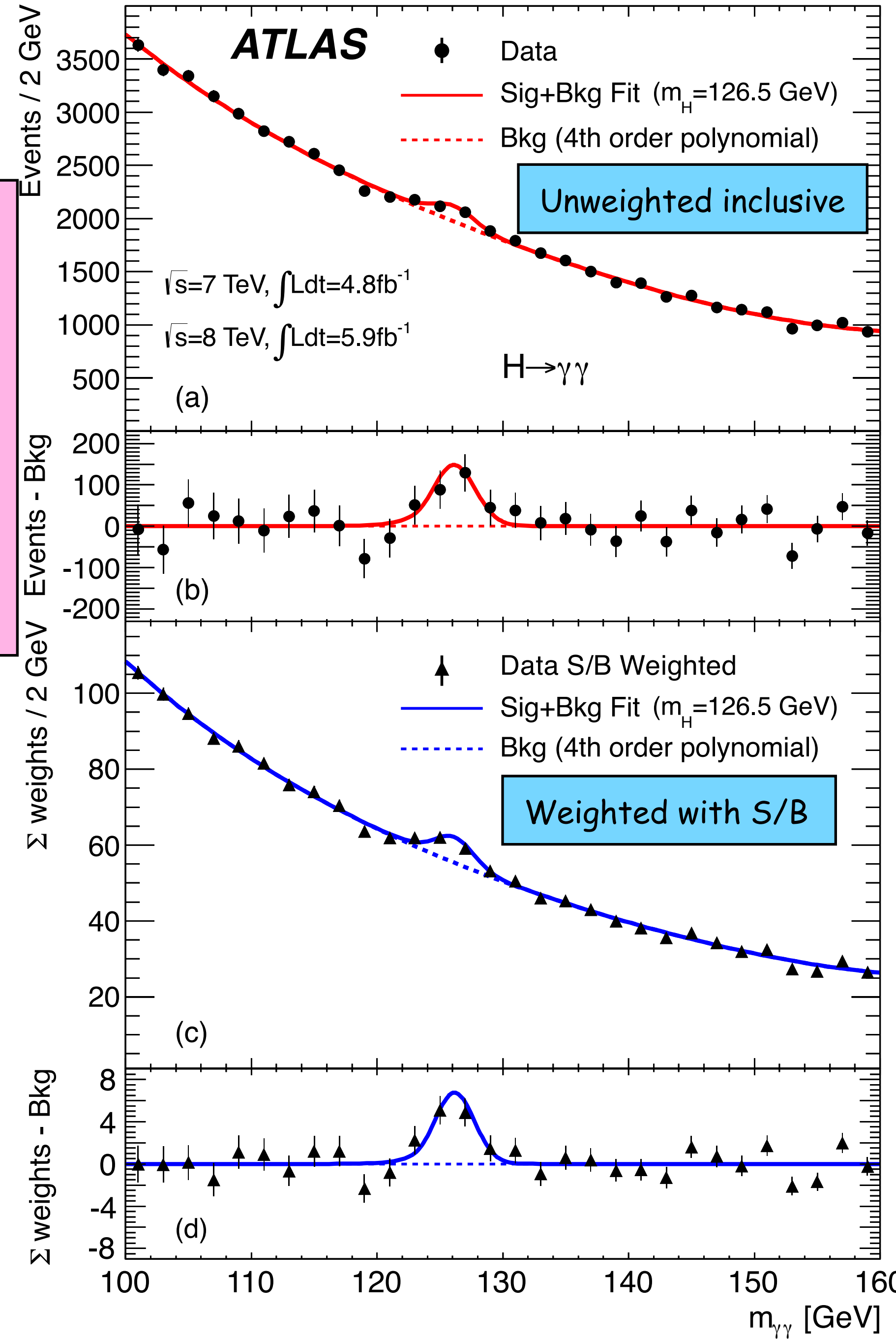
H->γγ results

Total after selection: 590059 events

- ✳$m_{\gamma\gamma}$ spectrum fit, **for each category**, with Crystal Ball + Gaussian for signal plus background parameterization (e.g. exp, Bernstein polynomials, …)
- ✳Bkg param chosen from fit to MC model requiring:
  - ✳err < 10% x S or <20% x √B
- ✳Bkg syst uncertainty is max deviation of the parameterization from the modeled background over the full mass range (Sherpa, Resbos, Diphox)

Main systematic uncertainties

Signal yield	
Theory	~20%
Photon efficiency	~10%
Background model	10-25%
Category migration	
Higgs p_T modeling	up to ~10%
Conv/unconv γ	up to ~6%
Jet E-scale	up to 20% (2j/VBF)
Underlying event	up to 30% (2j/VBF)
H->γγ mass resolution	~14%
Photon E-scale	~0.6%



$H \to WW^{(*)} \to l\nu l\nu$

$\sigma \times BR$ ~110 fb for eμ at m_H~125 GeV (8 TeV)

Simple topology: Two opposite charge, high p_T isolated leptons with large E_T^{miss}

High rate, but limited mass resolution

Backgrounds categorized according to number of jets:

- H + 0j : WW, Z/W + jets
- H + 1j : WW, top
- H ≥ 2j : top

Preselection:

'tight' leptons p_T > 15, 25 GeV

$E_{T,rel}^{miss}$ > 25 GeV

p_T^{jet} > 25 (30) GeV in $|\eta|$<2.5 (2.5-4.5)

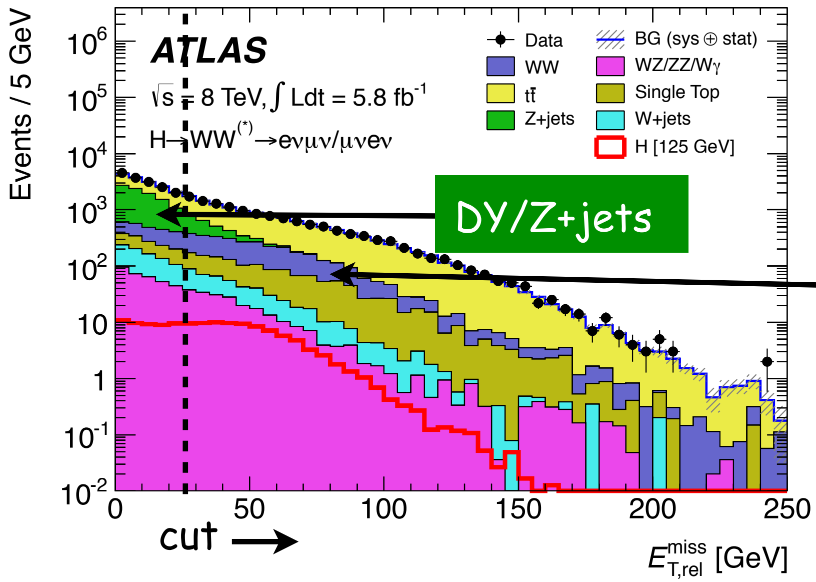
Main handles to fight backgrounds:

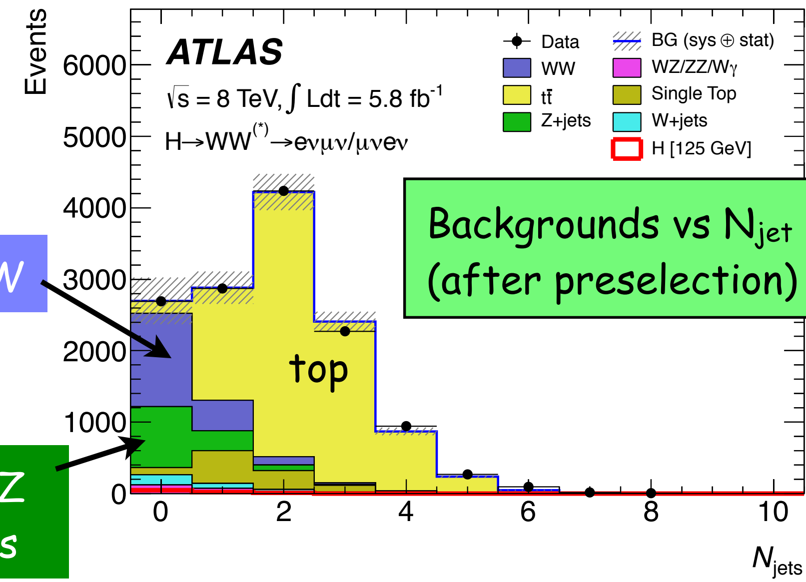
- WW:
  - SM Higgs spin 0 => small di-lepton opening angle and mass
- Top: b-tag

The 2012 data analysis:

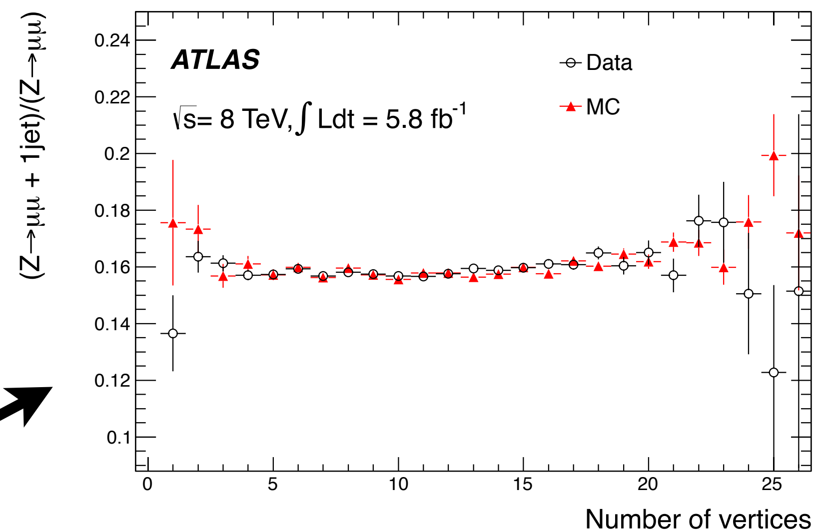
- Due to higher pileup, E_T^{miss} resolution is worse and Drell/Yan (Z+jets) increases
  - ➡**Only the eμ channel is evaluated** - most sensitive channel
    (residual Drell/Yan background is from $Z \to \tau\tau \to e\nu\nu\ \mu\nu\nu$)
- To minimize the impact of mis-measured leptons and jets, E_T^{miss} is projected transverse to the nearest lepton/jet if closer than π/2
  - ➡ $E_{T,rel}^{miss}$ is used for selection

WW(*)->lνlν: Data/MC for $E_{T,rel}^{miss}$ and N_{jet}





$E_{T,rel}^{miss}$ and N_{jets} distributions for data and MC
- MC is normalized by WW and top data control regions



Jets are reconstructed with anti-Kt algorithm with >50% of tracks coming from the same vertex (JVF)
Good reco stability vs pileup as seen in Z-> μμ + 1jet / Z-> μμ ratio

$WW^{(*)}$->$l\nu l\nu$: further selection per N_{jet} category

0-jet:

- Dilepton p_T^{ll} > 30 GeV for Drell/Yan

1-jet:

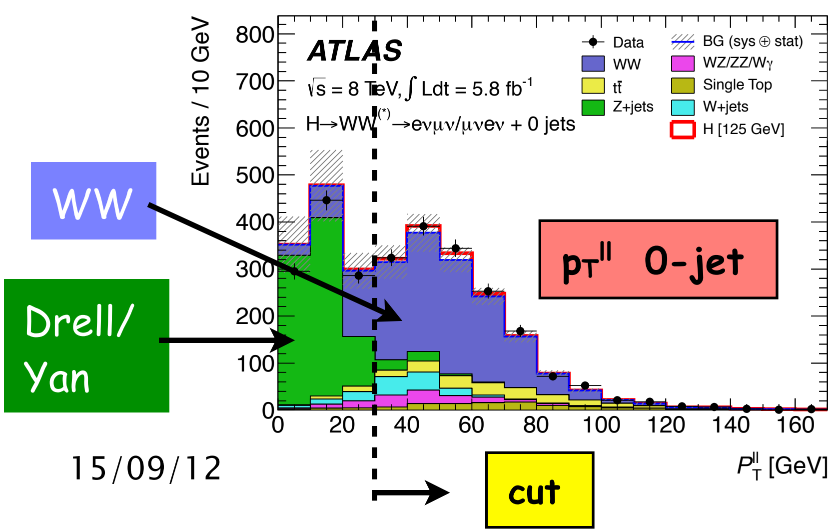
- B-tag veto for top
- Total transverse momentum < 30 GeV to remove top with extra jets below threshold
- $|m_{\tau\tau} - m_Z|$ > 25 GeV for Drell/Yan

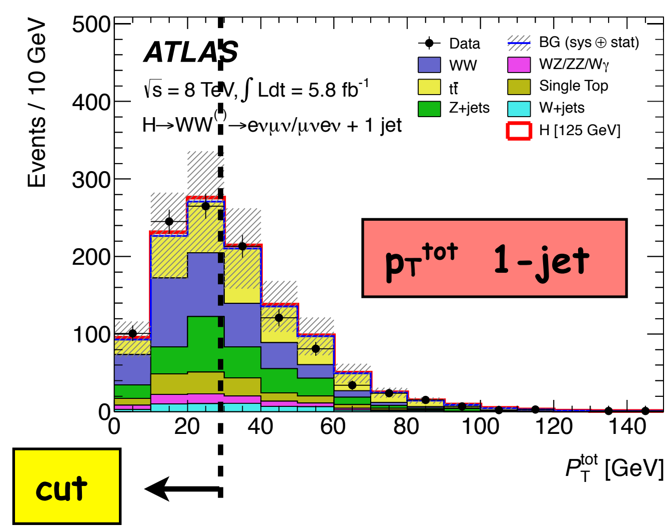
2-jet: (in addition to 1-jet selection)

- **VBF selection**:
  - $|\Delta y_{jj}|$ > 3.8 - rapidity gap
  - Veto central jet with p_T > 25 GeV
  - M_{jj} > 500 GeV

All categories: spin 0 correlation for di-leptons

- $\Delta\varphi_{ll}$ < 1.8
- m_{ll} < 50 (80) GeV for the 0, 1 (2) jets case

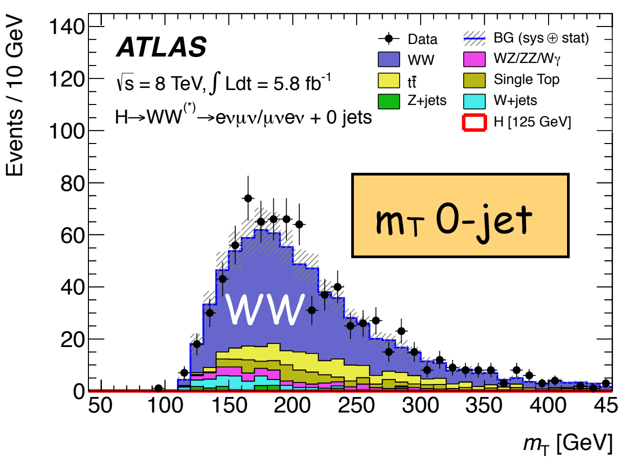


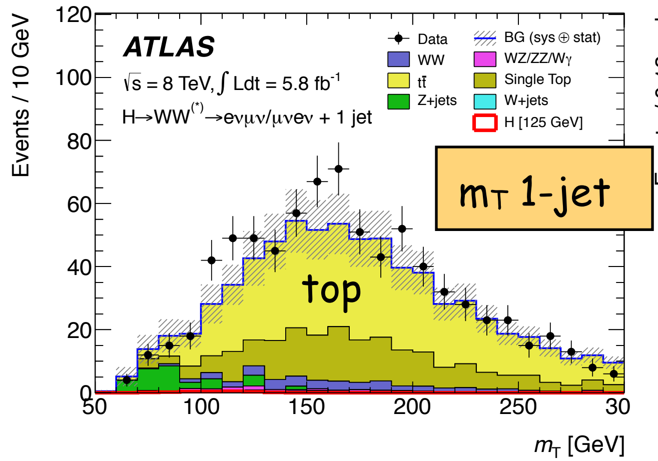


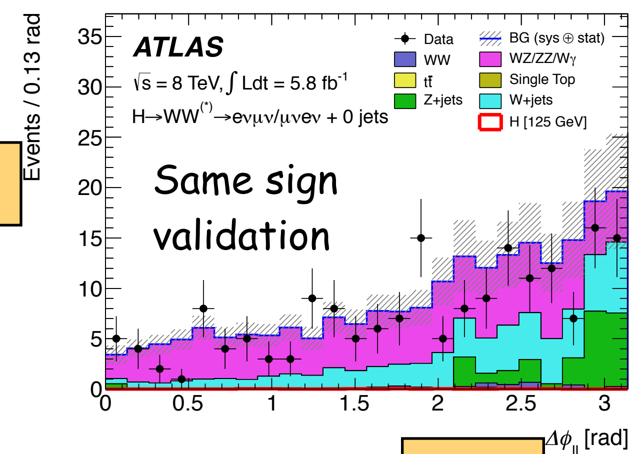
$WW^{(*)}$->lνlν: backgrounds

- **Background estimation:**
  - WW, top: normalize MC to data in bkg-enriched control regions
  - W+jets fully evaluated from data
  - Small bkg from Drell-Yan and di-boson other than WW is estimated from MC

Several control regions to evaluate the backgrounds, and validation regions to check the estimations







Δφll

Transverse mass: $m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - |p_T^{ll} + E_T^{miss}|^2}$

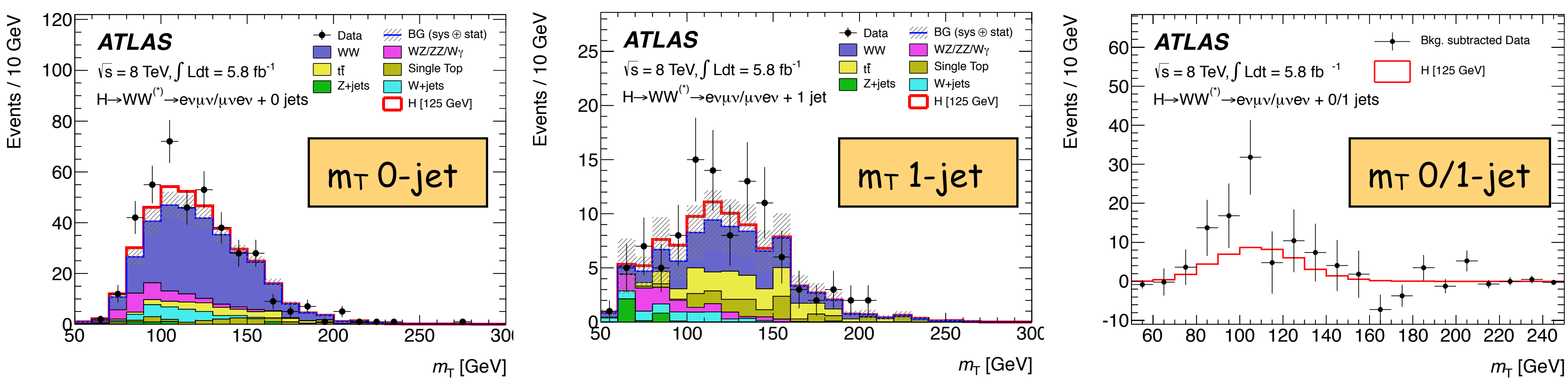
$WW^{(*)}$->lνlν: Results 2012 data

Expected signal and background, and observed events for m_H = 125 GeV

(with additional cut: 0.75 * m_H < m_T < m_H - not used in final result)

	0-jet	1-jet	2-jet
Signal	20 ± 4	5 ± 2	0.34 ± 0.07
WW	101 ± 13	12 ± 5	0.10 ± 0.14
$WZ^{(*)}/ZZ/W\gamma^{(*)}$	12 ± 3	1.9 ± 1.1	0.10 ± 0.10
$t\bar{t}$	8 ± 2	6 ± 2	0.15 ± 0.10
$tW/tb/tqb$	3.4 ± 1.5	3.7 ± 1.6	–
$Z/\gamma^* +$ jets	1.9 ± 1.3	0.10 ± 0.10	–
$W +$ jets	15 ± 7	2 ± 1	–
Total background	142 ± 16	26 ± 6	0.35 ± 0.18
Observed	185	38	0

Transverse mass distributions for 0-jet, 1-jet and with background subtracted



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Combined results: statistical procedure

- **Statistical procedure:**
  - **Global signal strength factor μ:** scale factor for number of predicted SM events
    - $\mu = 0$ is background only
    - $\mu = 1$ is SM Higgs boson + background
  - **Test statistic**: $\lambda(\mu)$ - profile likelihood ratio
    - Likelihood includes systematic uncertainties and correlations
  - **Exclusion limits based on CL_S prescription**
    - SM Higgs at m_H is excluded when $CL_S < 5\%$ for $\mu = 1$
  - **Significance of an excess is quantified by the p_0:**
    - Probability of background fluctuating to ≥ excess number of events seen
    - Can also be given in number of standard deviations
    - Provides a "local significance"
    - For a "global significance" one includes a "look-elsewhere" effect which depends on the mass window

Combined results: channels used

For both 2011 data at 7 TeV (4.7-4.8 fb^{-1}) and 2012 "ICHEP" data at 8 TeV (5.8-5.9 fb^{-1})

Higgs Boson Decay	Subsequent Decay	Sub-Channels	m_H Range [GeV]	$\int L\,dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV			
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	110–600	4.8	[87]
	$\ell\ell\nu\bar{\nu}$	$\{ee, \mu\mu\} \otimes$ {low, high pile-up}	200–280–600	4.7	[125]
	$\ell\ell q\bar{q}$	{b-tagged, untagged}	200–300–600	4.7	[126]
$H \to \gamma\gamma$	–	10 categories $\{p_{Tt} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus$ {2-jet}	110–150	4.8	[127]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu/\mu e, \mu\mu\} \otimes$ {0-jet, 1-jet, 2-jet} $\otimes$ {low, high pile-up}	110–200–300–600	4.7	[106]
	$\ell\nu qq'$	$\{e, \mu\} \otimes$ {0-jet, 1-jet, 2-jet}	300–600	4.7	[128]
$H \to \tau\tau$	$\tau_{lep}\tau_{lep}$	$\{e\mu\} \otimes$ {0-jet} $\oplus \{\ell\ell\} \otimes$ {1-jet, 2-jet, VH}	110–150	4.7	[129]
	$\tau_{lep}\tau_{had}$	$\{e, \mu\} \otimes$ {0-jet} $\otimes \{E_T^{miss} < 20$ GeV, $E_T^{miss} \geq 20$ GeV$\}$ $\oplus \{e, \mu\} \otimes$ {1-jet} $\oplus \{\ell\} \otimes$ {2-jet}	110–150	4.7	
	$\tau_{had}\tau_{had}$	{1-jet}	110–150	4.7	
$VH \to Vbb$	$Z \to \nu\nu$	$E_T^{miss} \in \{120-160, 160-200, \geq 200$ GeV$\}$	110–130	4.6	[130]
	$W \to \ell\nu$	$p_T^W \in \{< 50, 50-100, 100-200, \geq 200$ GeV$\}$	110–130	4.7	
	$Z \to \ell\ell$	$p_T^Z \in \{< 50, 50-100, 100-200, \geq 200$ GeV$\}$	110–130	4.7	
		2012 $\sqrt{s}$ =8 TeV			
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	110–600	5.8	[87]
$H \to \gamma\gamma$	–	10 categories $\{p_{Tt} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus$ {2-jet}	110–150	5.9	[127]
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes$ {0-jet, 1-jet, 2-jet}	110–200	5.8	[131]

Note that the analyses have been improved for the 7 TeV data for H -> ZZ $^{(*)}$ -> 4l and H->$\gamma\gamma$

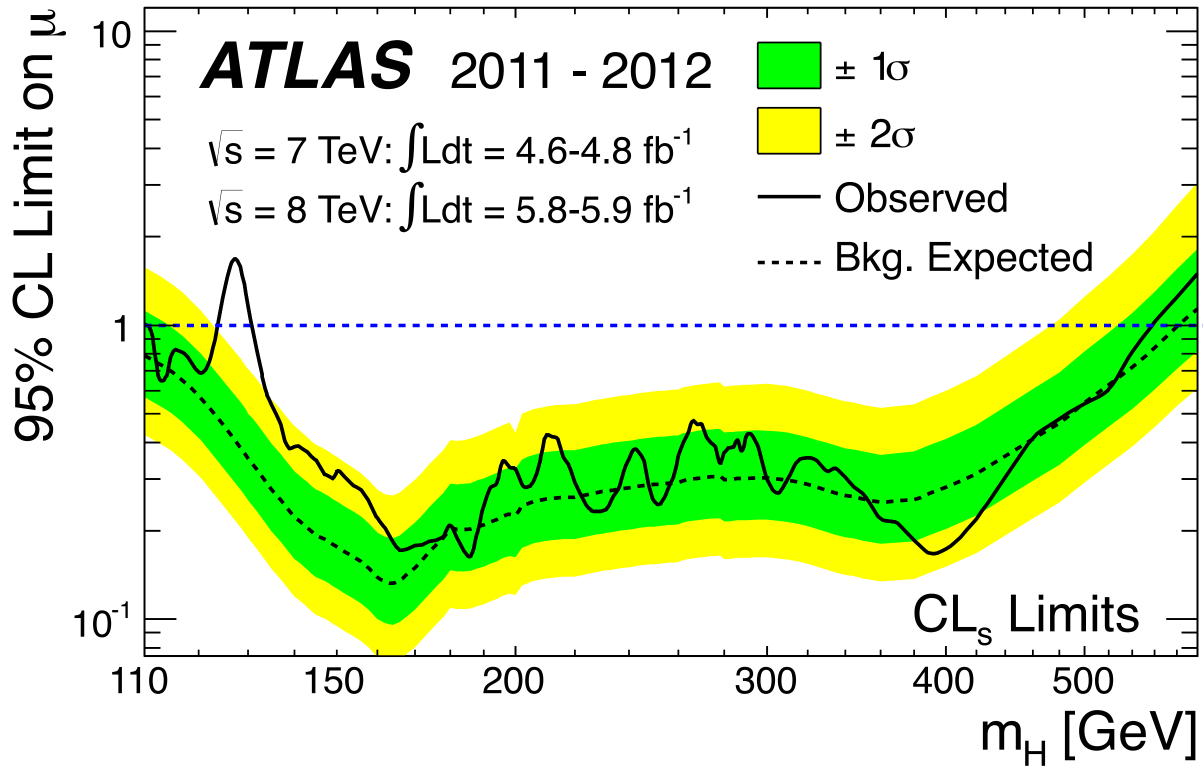
Combined search results: excluded mass

95% CL exclusion:

- Expected - 110 GeV to 582 GeV
- Observed - 111-122 GeV and 131-559 GeV

99% CL exclusion:

- Expected - 113 GeV to 532 GeV
- Observed - 113-114, 117-121, and 132-527 GeV



Combined search results: observed excess

Excess of events see near 126 GeV in the $H \to ZZ^{(*)} \to 4l$ and $H \to \gamma\gamma$ for both the 2011 and 2012 data

High mass resolution channels

Local p_0

3.6σ obs/2.7σ exp at m_H = 125 GeV

$H \to ZZ^{(*)} \to 4l$

4.5σ obs/2.5σ exp at m_H = 125 GeV

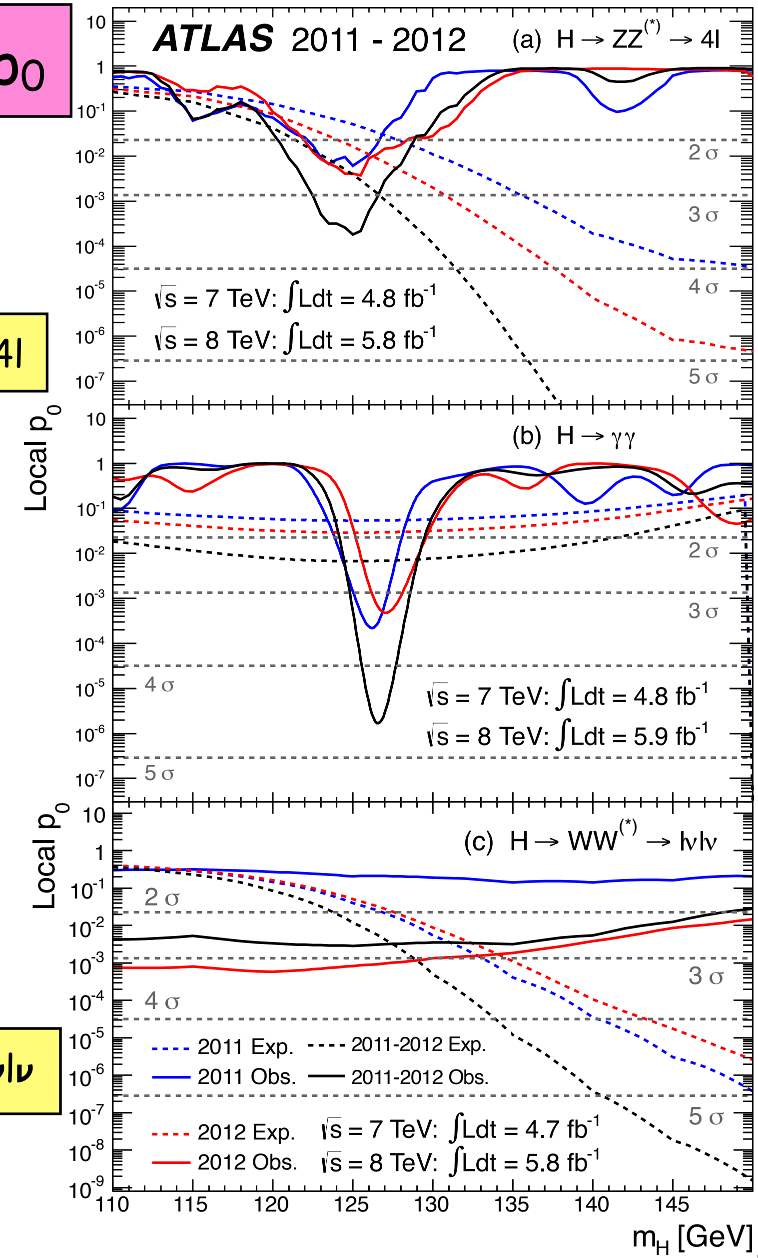
$H \to \gamma\gamma$

Excess is confirmed by $H \to WW^{(*)} \to l\nu l\nu$

Highly sensitive, but poor resolution

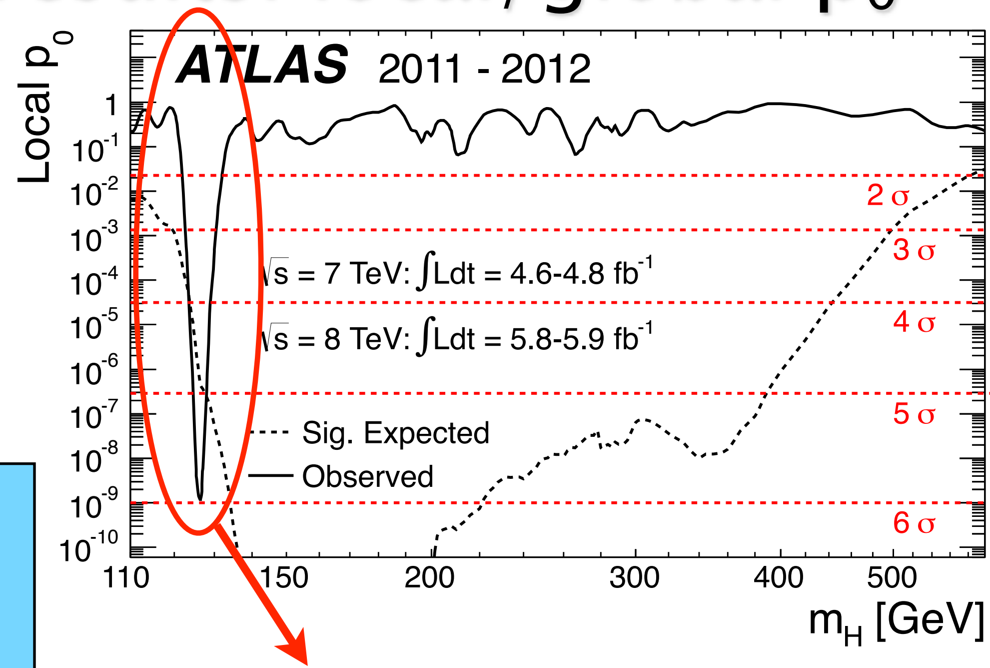
2.8σ obs/2.3σ exp at m_H = 125 GeV

$H \to WW^{(*)} \to l\nu l\nu$

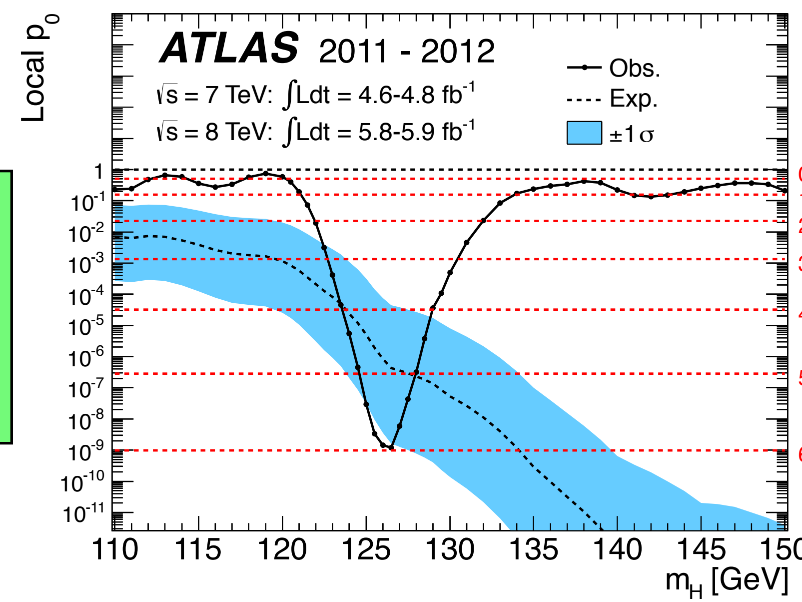


Combined search results: local/global p_0

Largest significance is 5.9σ at 126.5 GeV (4.9σ expected)



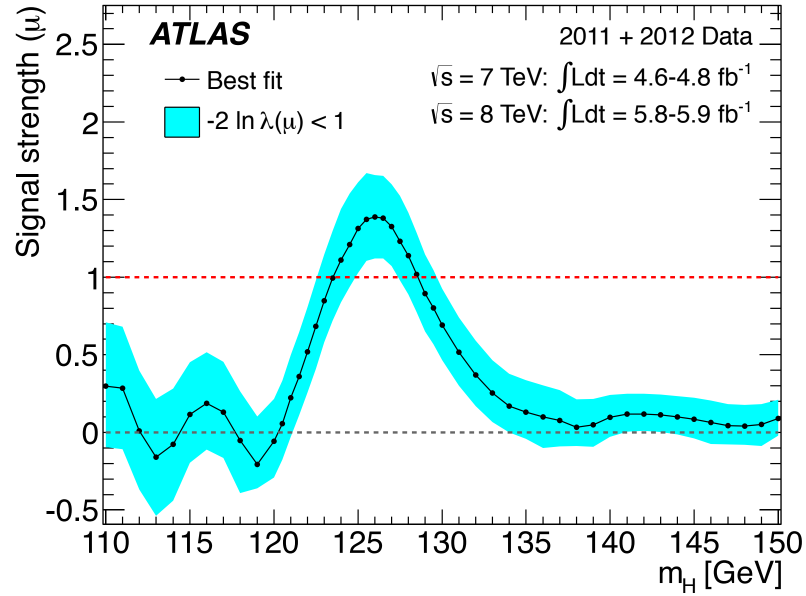
For 2012 data alone significance is 4.9σ (3.8σ expected)
$H \to ZZ^{(*)} \to 4l$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to l\nu l\nu$



Global significance ('look-elsewhere' effect) is 5.1σ in mass range 110-600 GeV
Increases to 5.3σ in the mass range 110-150 GeV
(~mass not excluded at 99% CL)

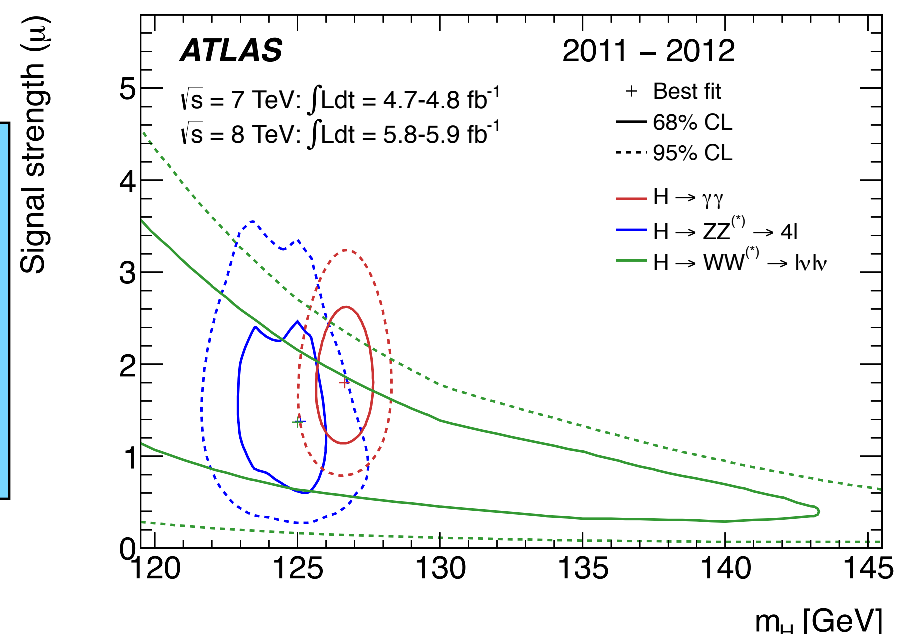
Signal strength and mass estimate

The best fit signal strength $\hat{\mu}$ is 1.4 ± 0.3, consistent with a SM Higgs boson hypothesis μ = 1



Mass compatibility:

- The mass is estimated in each channel with a 2-d likelihood fit to μ and m_H
- Probability of a separation greater than seen with H->4l and H->$\gamma\gamma$ is 8%



Mass measurement:

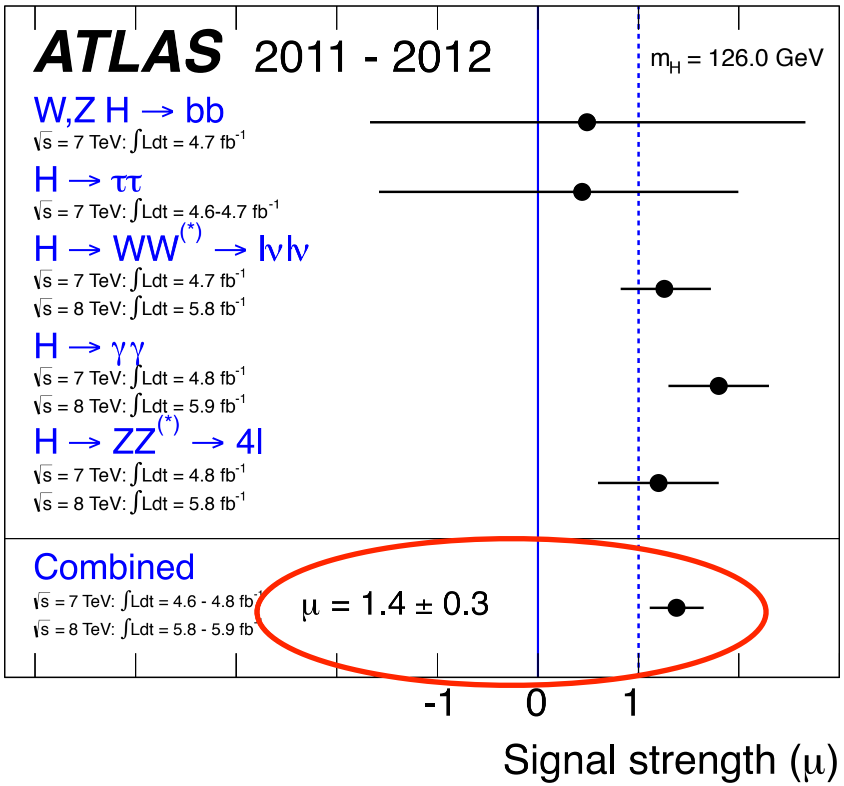
- Estimated m_H with a profile likelihood ratio for H->ZZ(*)->4l and H->$\gamma\gamma$ allowing μ to vary
- Main systematic from energy scale

m_H = 126.0 ± 0.4 (stat) ± 0.4 (syst) GeV

Consistency with SM Higgs

Signal strengths of individual channels (SM: $\mu = 1$)

Combined signal strength compatible with 1



H -> ZZ(*) -> 4l	1.2 ± 0.6
H -> $\gamma\gamma$	1.8 ± 0.5
H->WW(*)->lνlν	1.3 ± 0.5

Coupling property measurement scale factors

Can further explore the couplings of the Higgs sector with following assumptions:

- One single resonance
- SM spin/CP (0^{++})
- Negligible width: i.e. $\sigma \times BR\ (ii \to H \to ff) = \sigma_{ii} * \Gamma_{ff} / \Gamma_H$

Introduce coupling scale factors κ_i for SM deviations:

e.g. for $gg \to H \to \gamma\gamma$:

$$(\sigma \times BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \times BR_{SM}(H \to \gamma\gamma) \times \kappa_g^2\, \kappa_\gamma^2 / \kappa_H^2$$

I.e. $\sigma_{ii} / \sigma_{SM} = \Gamma_{ii} / \Gamma_{SM} = \kappa_i^2$

So we have scale factors: κ_W, κ_Z, κ_t, κ_b, κ_τ, $\kappa_g(\kappa_t, \kappa_b, m_H)$, $\kappa_\gamma(\kappa_W, \kappa_t, \kappa_b, \kappa_\tau, m_H)$

➡Due to loops κ_g and κ_γ are "effective" scale factors

Use 1-d and 2-d profile likelihoods for scale factor estimates

Coupling property measurements

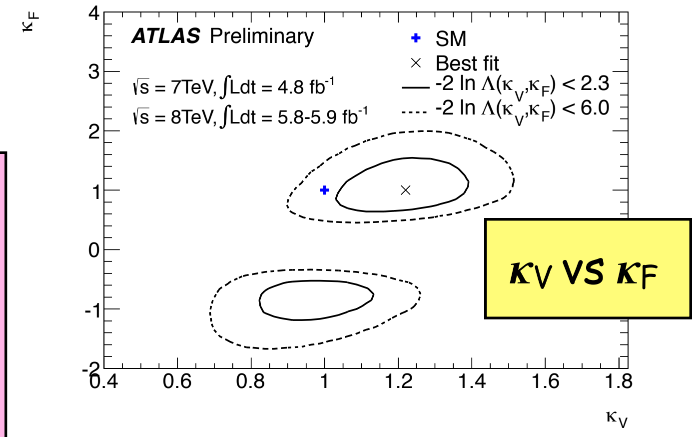
m_H is set to 126 GeV

Couplings to Fermions and Vector Gauge Bosons:

assume: $\kappa_V = \kappa_W = \kappa_Z$, and $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$

κ_F = [-1.0, -0.7] or [0.7, 1.3] 68% CL

κ_V = [0.9, 1.0] or [1.1, 1.3] 68% CL

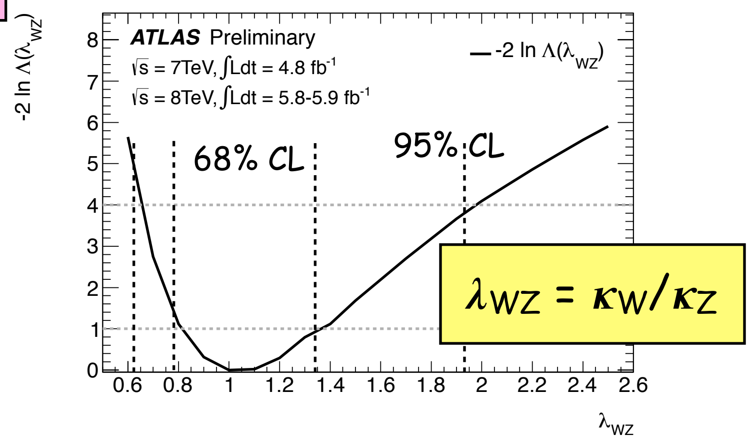


W and Z coupling:

W and Z scale factors are required to be ~same by $SU(2)_V$ and the LEP ρ parameter

$\lambda_{WZ} = \kappa_W/\kappa_Z = 1.07^{+0.35}_{-0.27}$

Theory and expt uncertainties have small effect in ratio



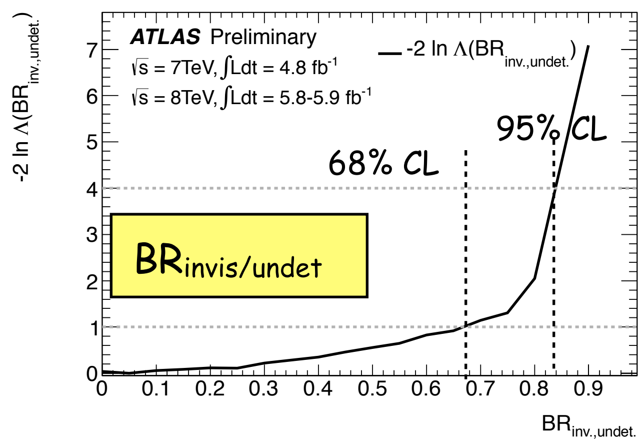
Probing non-SM contributions:

New particles can enter into loops for gg -> H and H -> γγ

All scale factors of known particles are set to 1

Allow invisible or undetected decays to enter into the BR:

$BR_{invis/undet}$ < 0.68 for 68% CL (0.84 for 95% CL)



Coupling property measurements

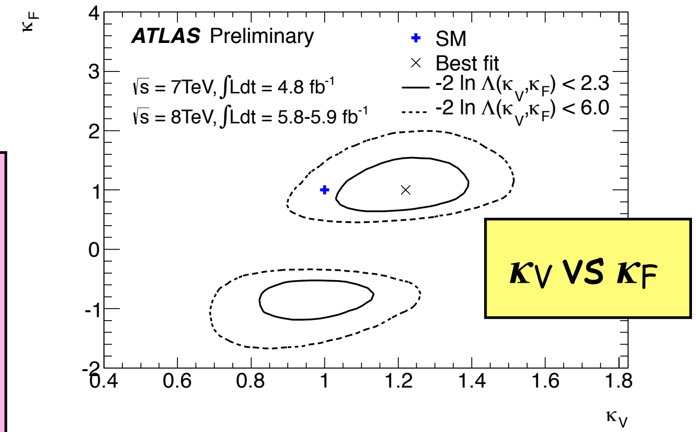
m_H is set to 126 GeV

Couplings to Fermions and Vector Gauge Bosons:

assume: $\kappa_V = \kappa_W = \kappa_Z$, and $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$

κ_F = [-1.0, -0.7] or [0.7, 1.3] 68% CL

κ_V = [0.9, 1.0] or [1.1, 1.3] 68% CL



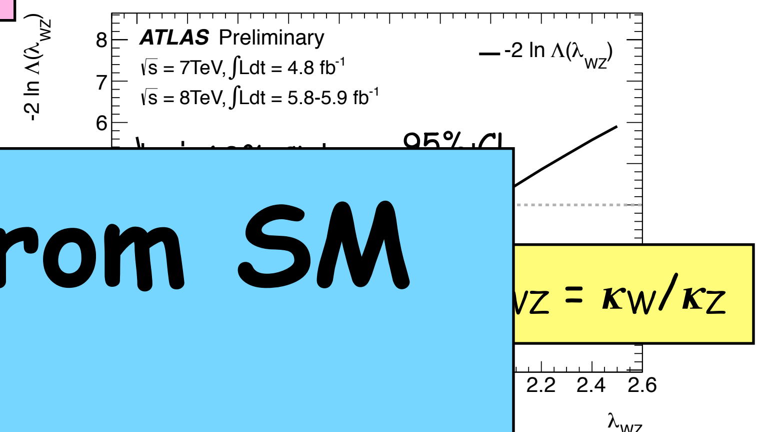
W and Z coupling:

W and Z scale factors are required to be

~same by SU

$\lambda_{WZ} = \kappa_W/\kappa_Z$

Theory and exp



No deviation from SM has been seen!

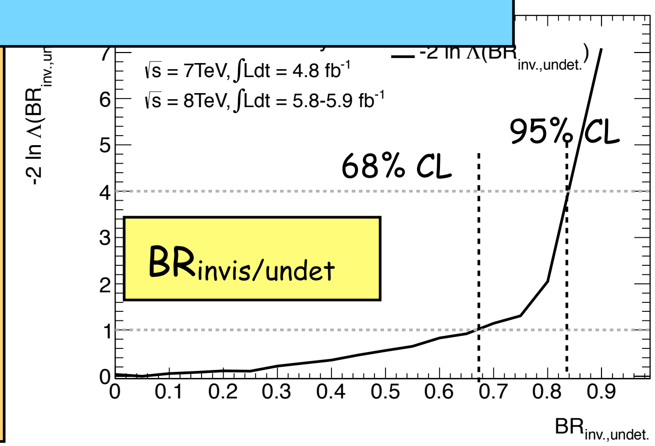
Probing non-SM contributions:

New particles can enter into loops for gg -> H and H -> $\gamma\gamma$

All scale factors of known particles are set to 1

Allow invisible or undetected decays to enter into the BR:

$BR_{invis/undet}$ < 0.68 for 68% CL (0.84 for 95% CL)



Coupling property measurements

Understanding the couplings to Fermions and Vector Gauge Bosons:
assume: $\kappa_V = \kappa_W = \kappa_Z$, and $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$

The relation of κ_V and κ_F to the overall signal strengths can be seen via the two equations:

gg->top loop-> H

H ->top loop-> $\gamma\gamma$

H ->W loop-> $\gamma\gamma$

interference

$$(gg \to H \to \gamma\gamma) = \kappa_F^2 \times (0.1\kappa_F^2 + 1.6\kappa_V^2 - 0.7\kappa_V\kappa_F) / (0.7\kappa_F^2 + 0.3\kappa_V^2)$$

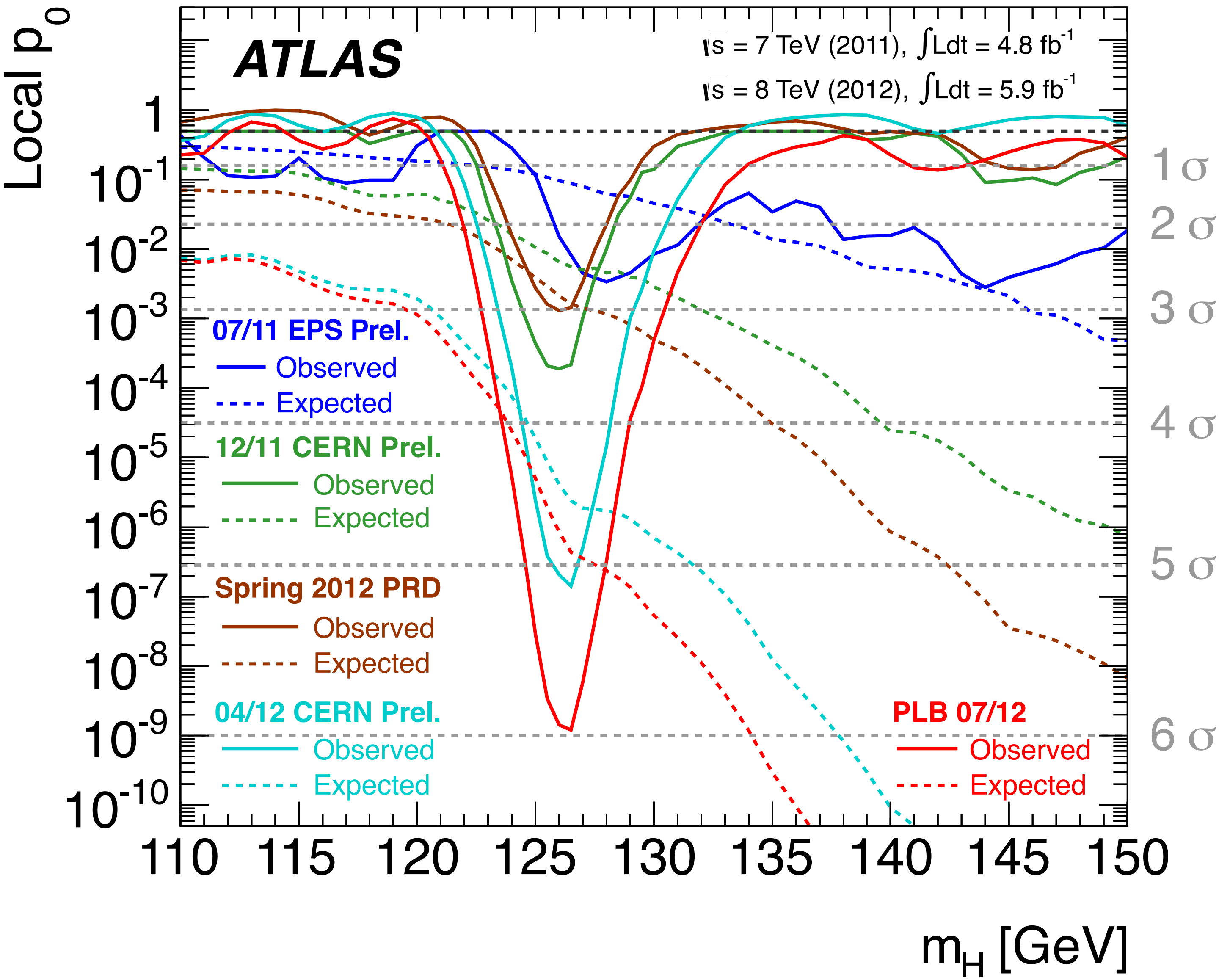
=> A $\gamma\gamma$ signal strength > 1 translates into κ_V greater than 1

$$(gg \to H \to WW) = \kappa_F^2 \times \kappa_V^2/(0.7\kappa_F^2 + 0.3\kappa_V^2)$$

gg->top loop-> H

H ->WW

Evolution of the signal significance with time



Beyond Standard Model Higgs

Non-minimal Higgs sectors have additional Higgs doublets/singlets:

- MSSM is a 2HDM and has 2 CP-even neutral Higgs bosons (h, H), charged Higgs bosons, and CP-odd neutral Higgs boson A
- MSSM is parameterized by $\tan\beta = v_u/v_d$ and m_A at tree level
  - In general, coupling to vector bosons suppressed, and
  - b, τ (down-type fermion) coupling is enhanced for large $\tan\beta$

Is what we see "just" the SM Higgs, or one of several BSM Higgses?

➡Can be seen by deviations in the production or decay of the particle we have found, or by the observation of additional Higgs particles.

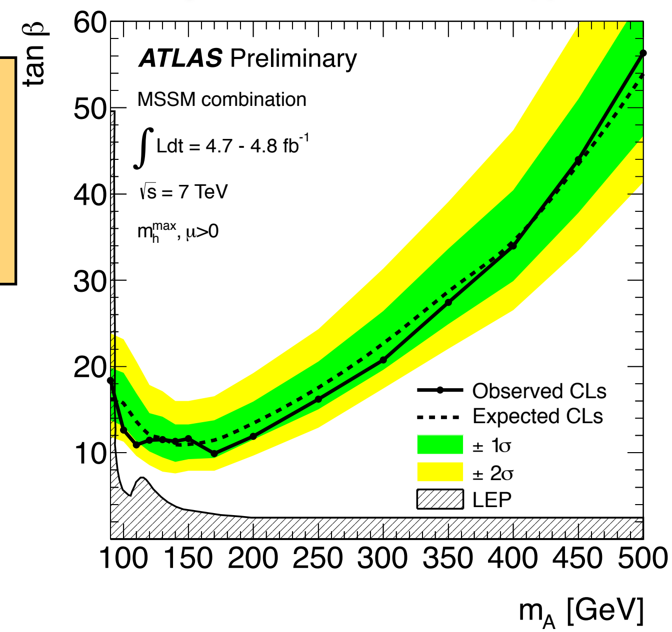
Note that in the "decoupling limit" ($m_A \geq 2m_Z$), m_h couplings becomes SM-like

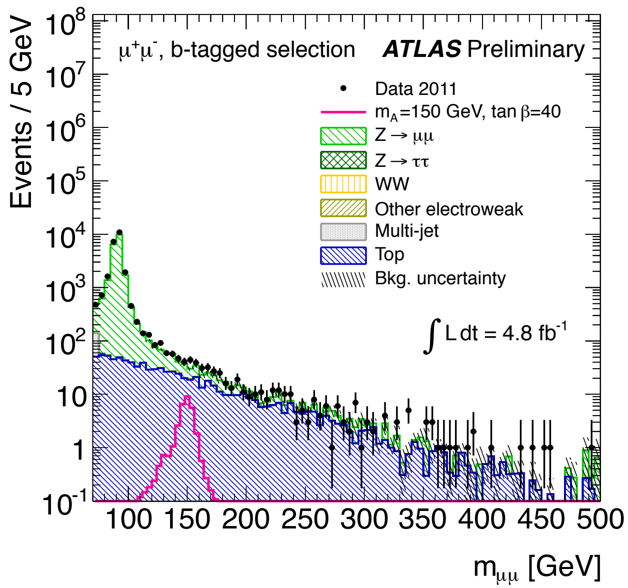
- Other scalers may be too heavy to see
- m_H = 125 GeV also implies heavy squarks and/or large stop mixing

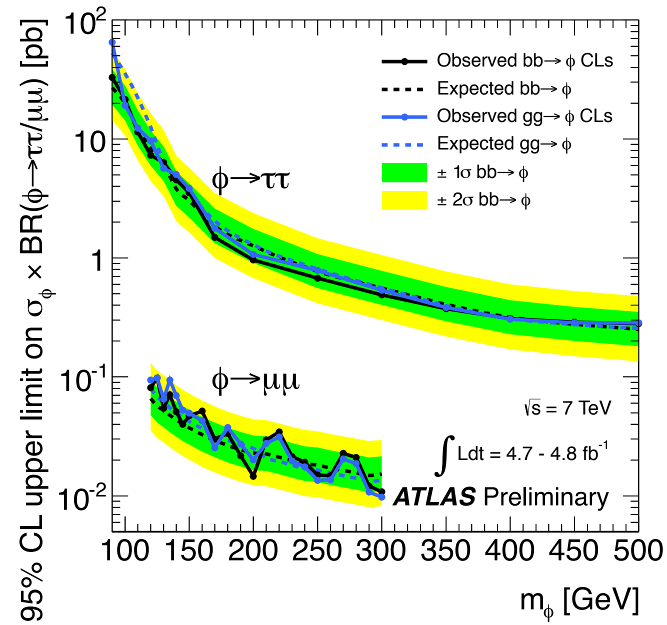
We present the most recent neutral and charged Higgs search results with 2011 data which provide constraints in the $\tan\beta$ vs m_A plane

MSSM neutral Higgs search – 2011 4.7 fb^{-1}

Search for h,H,A->ττ (BR~10%), μμ (BR~0.04%) with (bb associated prod) or without (gg fusion) b-tag jets







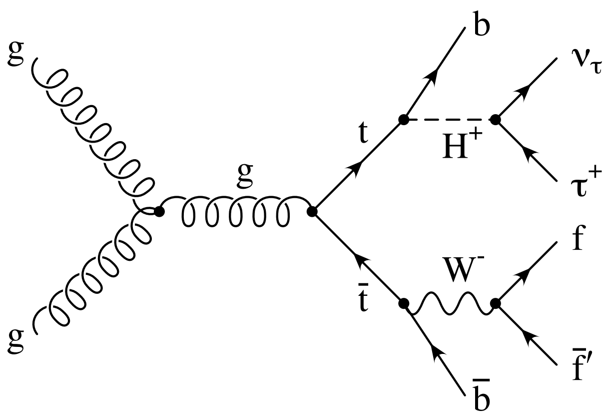
Results interpreted using the m_h^{max} scenario:

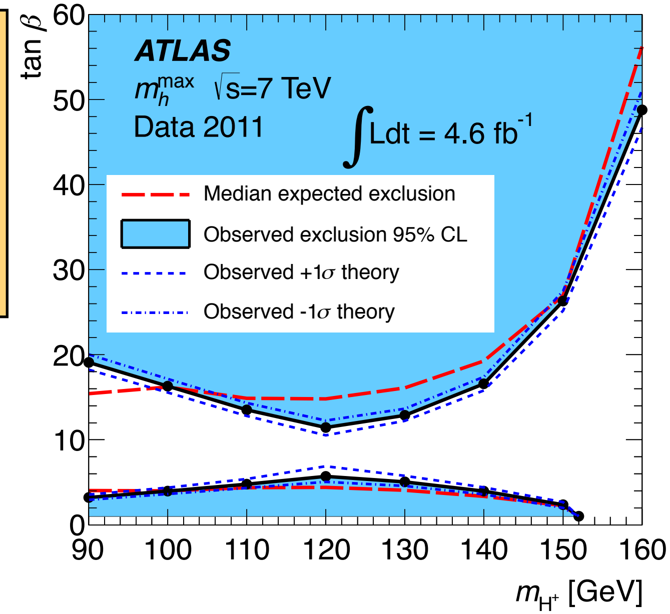
- Stringent tanβ bounds in the non-decoupling region (m_A < 150 GeV)

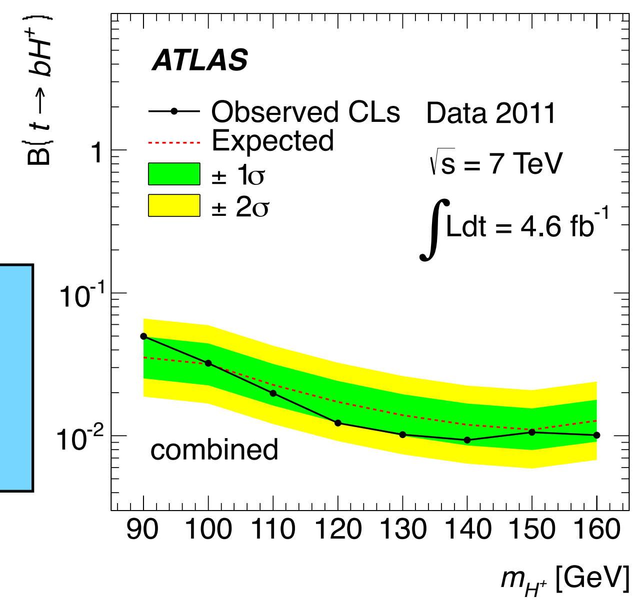
MSSM charged Higgs search – 2011 4.6 fb^{-1}

Search for $H^{\pm} \to \tau^{\pm}\nu$ produced in tt events:

- 3 final states are considered:
  - bb(qq)($\tau_{lep}\nu$)
  - bb(qq)($\tau_{lep}\nu$)







Results interpreted using the m_h^{max} scenario:

- Stringent tanβ bounds in the non-decoupling region (mA < 150 GeV)

Conclusions

- **Discovery of new boson consistent with the SM Higgs**
  - ~6σ significance coming from the three most sensitive channels:
    - 3.6σ H->ZZ (*)->4l, 4.5σ H->$\gamma\gamma$, 2.8σ H->WW(*)->lνlν

- **Awaiting updates with 2012 data for measurements with direct coupling to fermions: H->bb and H->$\tau\tau$**

- **An important next step is to measure its spin/parity**

- **An exciting new period is opening up to measure in detail the properties of this new boson to first determine whether it is the SM Higgs and test for physics Beyond the Standard Model**

Backup

Bibliography – publications

•Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1-29

•Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to a b-quark pair with the ATLAS detector, PLB, arXiv:1207.0210

•Search for the Standard Model Higgs boson in the H -> tau tau decay mode in sqrt(s) = 7 TeV pp collisions with ATLAS, JHEP, arXiv:1206.5971

•Search for the Higgs boson in the H->WW->lvjj decay channel at sqrt{s}=7 TeV with the ATLAS detector, PLB, arXiv:1206.6074

•Search for a Standard Model Higgs boson in the mass range 200-600 GeV in the H->ZZ->llqq decay channel with the ATLAS Detector, PLB, arXiv:1206.2443

•Search for the Standard Model Higgs boson in the H -> WW -> lnulnu decay mode with 4.7 fb-1 of ATLAS data at sqrt(s) = 7 TeV, Phys.Lett.B 716 (2012) 62-81, arXiv:1206.0756

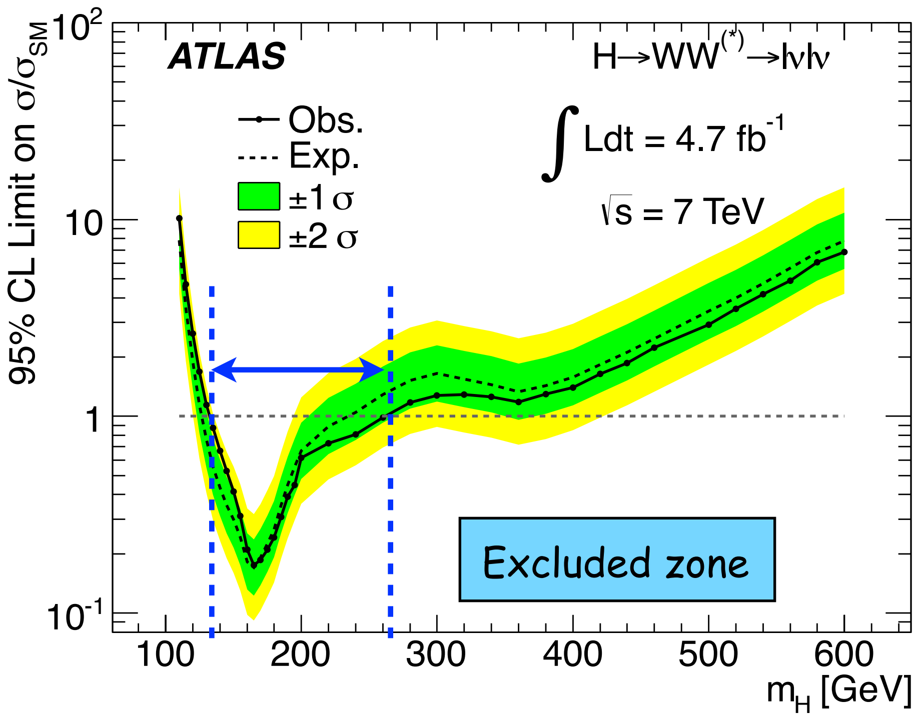
•Search for a Standard Model Higgs boson in the H -> ZZ -> llnunu decay channel using 4.7 fb-1 of sqrt(s) = 7 TeV data with the ATLAS Detector, PLB, arXiv:1205.6744

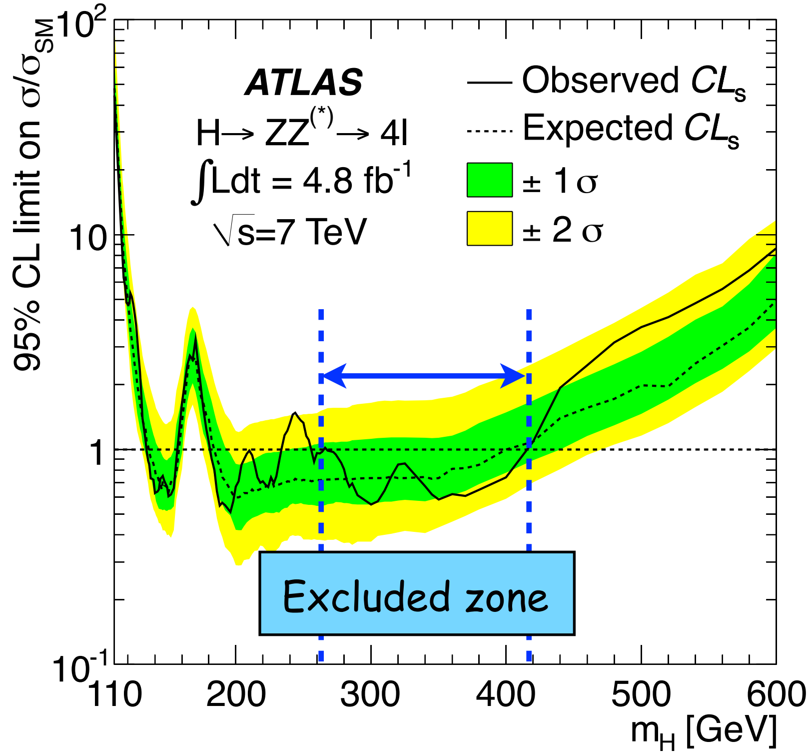
Bibliography - publications (2)

•Search for a Standard Model Higgs boson in the mass range 200-600 GeV in the H->ZZ->llqq decay channel with the ATLAS Detector, PLB, arXiv:1206.2443

•Search for charged Higgs bosons decaying via H+ -> tau nu in top quark pair events using pp collision data at sqrt(s) = 7 TeV with the ATLAS detector, Eur.Phys.J c72 (2012) 2062, arXiv:1204.2760

High mass exclusion: WW->lνlν and H4l





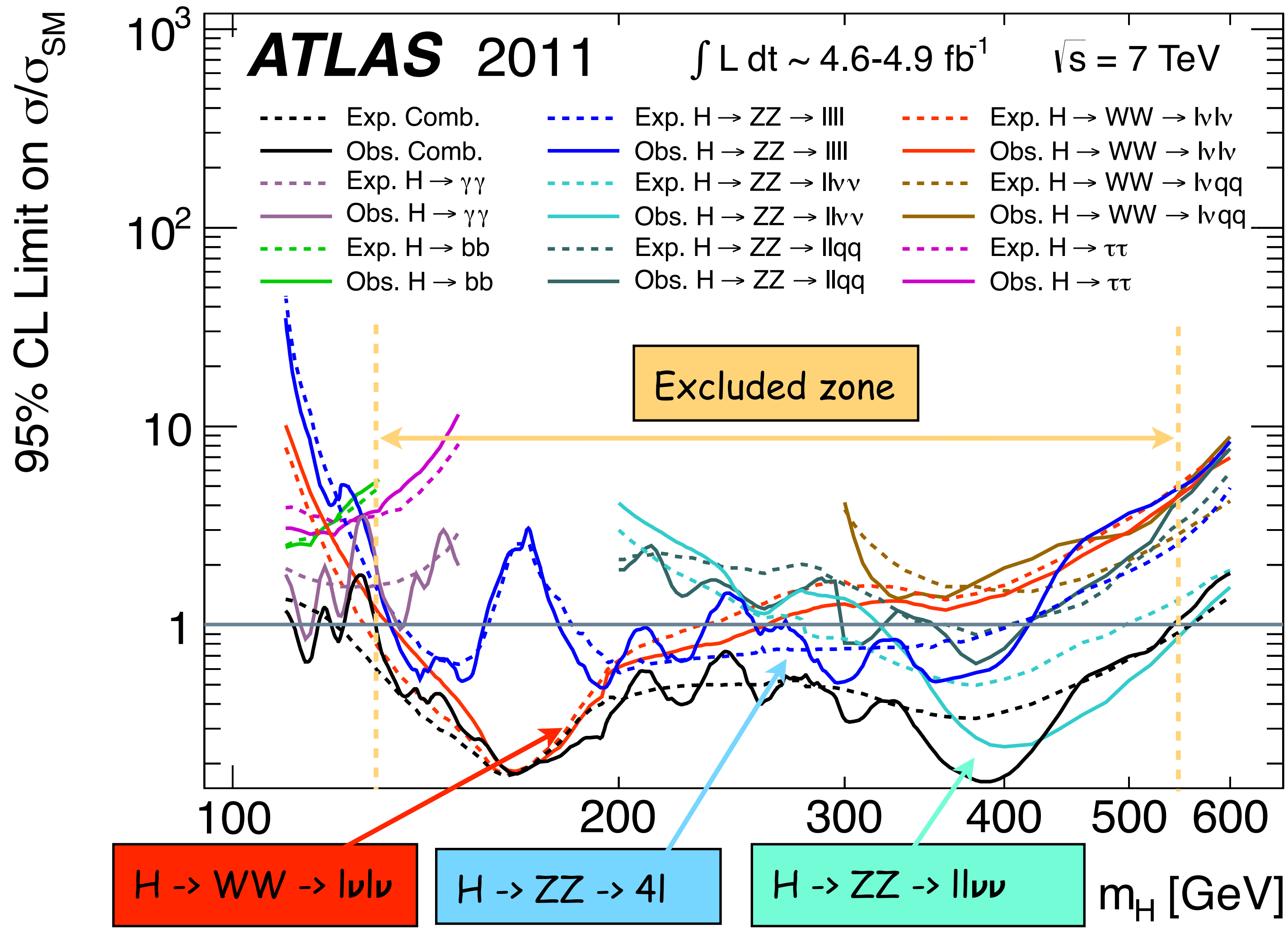
H -> WW -> lνlν

H -> ZZ -> 4l

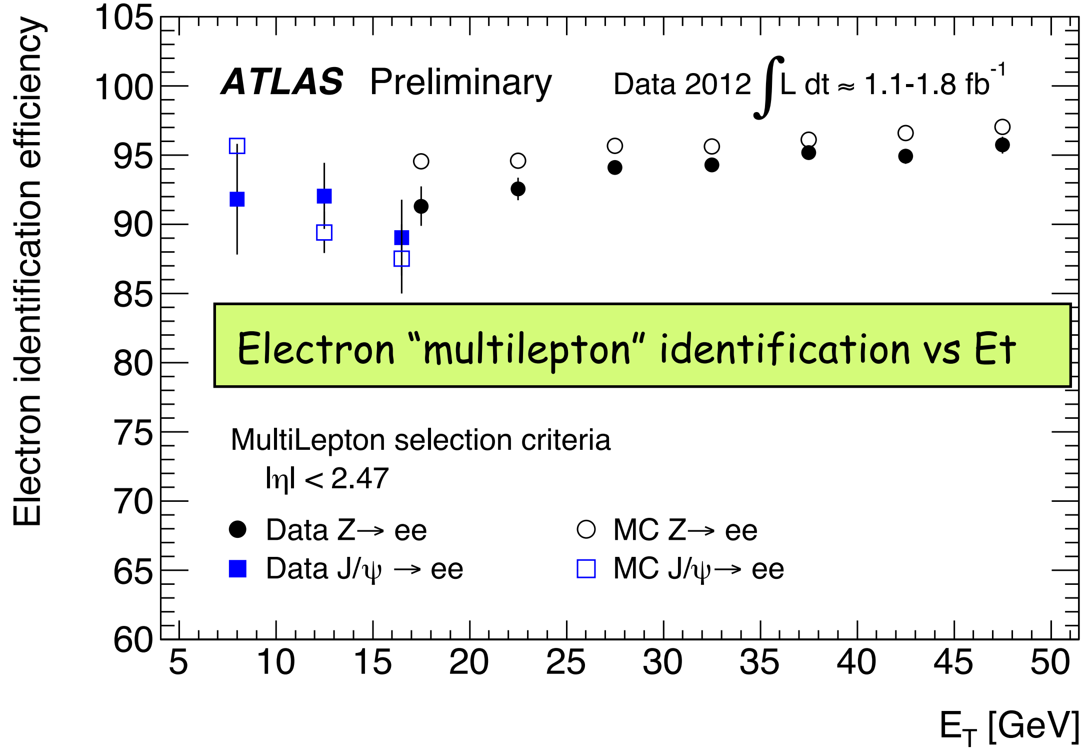
High mass exclusion: individual channels

High mass exclusion comes primarily from:

- WW->lνlν (<270 GeV) ZZ->4l (180-400 Gev) and ZZ->llνν (325-560 GeV)



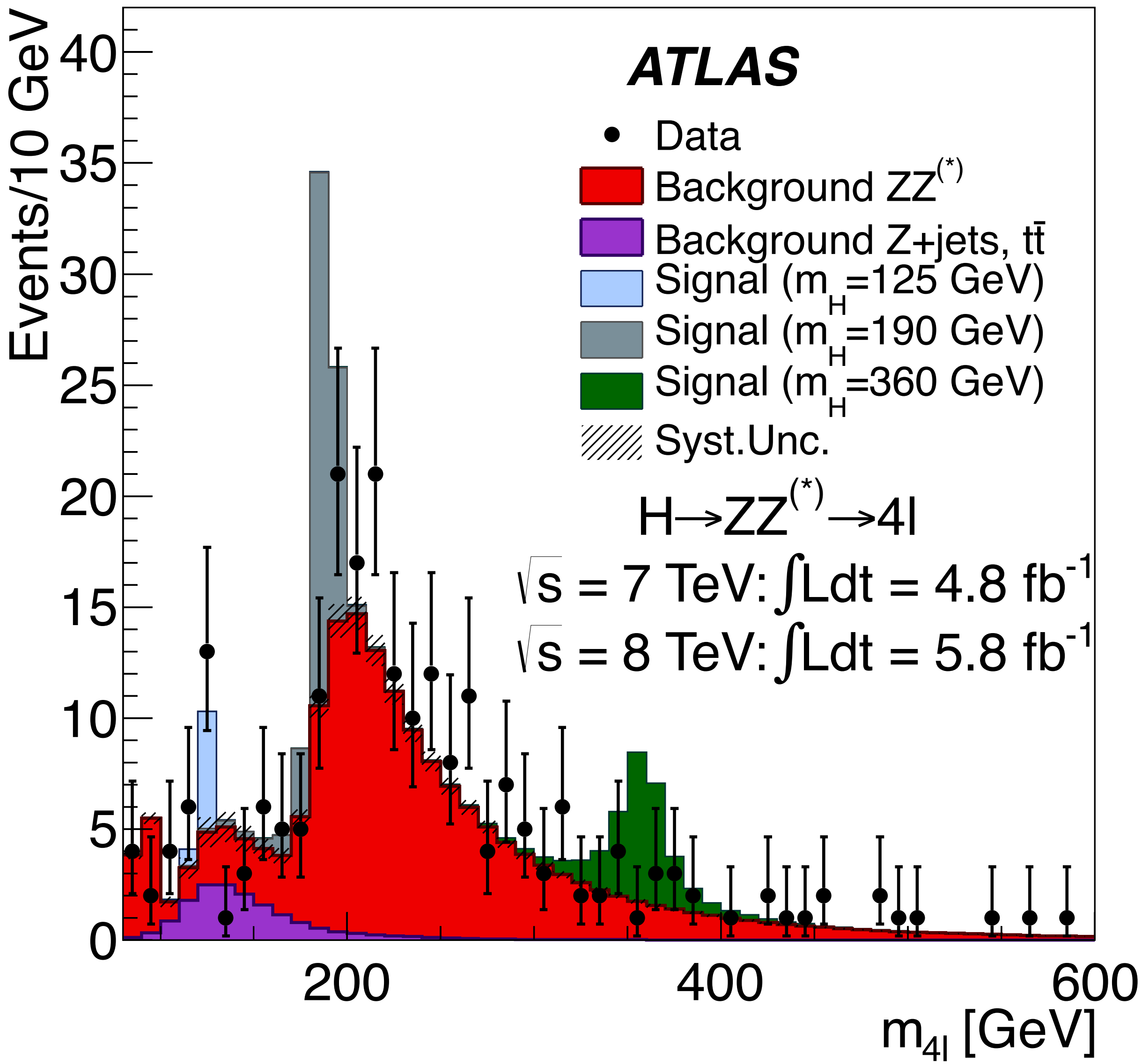
H->ZZ*->4 l : Multilepton identification



H->ZZ$^{(*)}$->4 l : Selection

- Single and di-lepton triggers
- At least two pairs of opposite-charge same-flavor leptons (e/μ)
- Pt thresholds: 7/6, 10, 15, 20 GeV (e/μ)
- $50 < m_{12} < 106$ GeV, m_{4l}-dependent cut on m_{34}: $17.5 < m_{34} < 115$ GeV
- All same-flavor, opposite-sign pairs $m_{ll} > 5$ GeV (J/Psi veto)
- $\Delta R_{ll} < 0.1$ (0.2) for all same (different)-flavor
- Tracking and calorimeter isolation:
  - Ptcone20/$p_T < 0.15$, Etcone20/$E_T < 0.3$ (0.15 for muons outside the acceptance of the tracker)
- $|d_0/\sigma(d_0)| < 3.5$ (6.5) for μ(e)

H->ZZ$^{(*)}$->4 l: full mass range



H->ZZ*->4l: Signal & background estimates vs data for full mass range (7 & 8 TeV data)

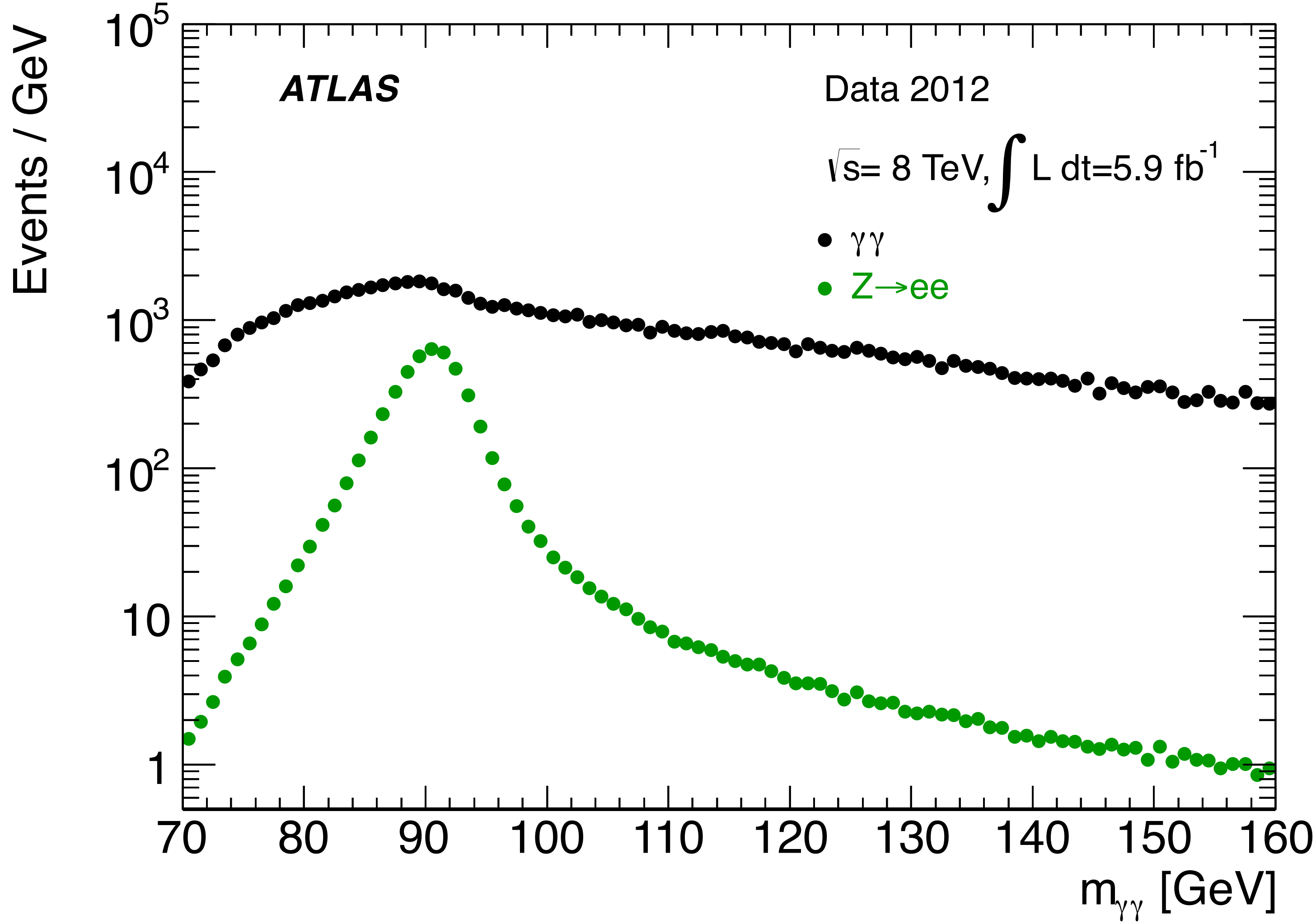
	4μ		$2e2\mu/2\mu2e$		$4e$	
	Low mass	High mass	Low mass	High mass	Low mass	High mass
	$\sqrt{s}$ = 8 TeV					
Int. Luminosity	5.8 fb^{-1}		5.8 fb^{-1}		5.9 fb^{-1}	
$ZZ^{(*)}$	6.3±0.3	27.5±1.9	3.7±0.2	41.7±3.0	2.9±0.3	17.7±1.4
Z + jets, and $t\bar{t}$	0.4±0.2	0.15±0.07	3.9±0.9	1.4±0.3	2.9±0.8	1.0±0.3
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	

H->ZZ*->4l:

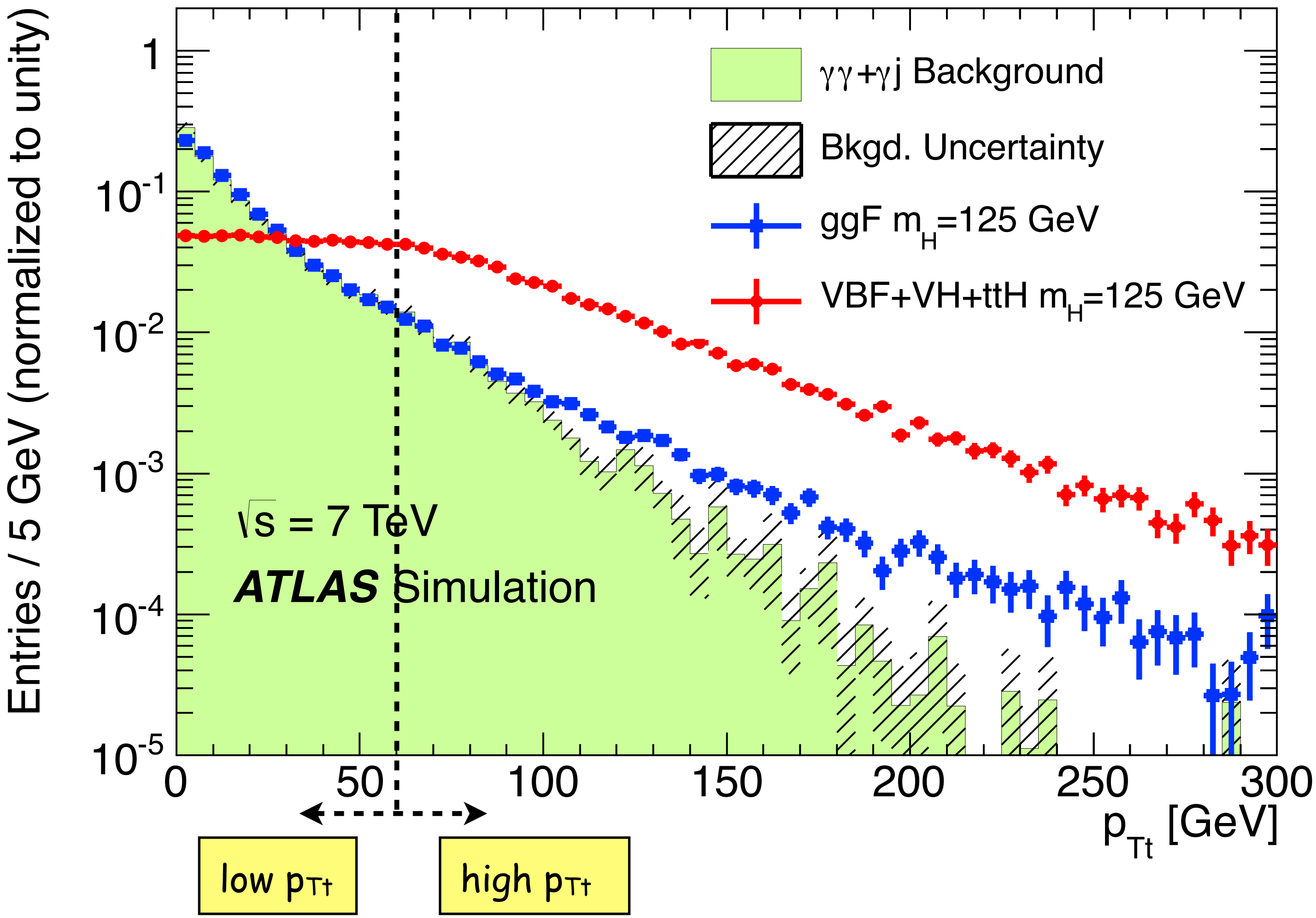
Signal & background estimates vs observed events for m_H = 125 GeV

	$\sqrt{s}$ = 8 TeV			$\sqrt{s}$ = 7 TeV			$\sqrt{s}$ = 8 TeV and $\sqrt{s}$ = 7 TeV		
				4μ					
m_H	exp. signal	exp. bkg	obs	exp. signal	exp. bkg	obs	exp. signal	exp. bkg	obs
120	0.68±0.09	0.61± 0.04	2	0.48±0.06	0.46± 0.03	2	1.16± 0.15	1.07± 0.07	4
125	1.25±0.17	0.74± 0.05	4	0.84±0.11	0.56± 0.03	2	2.09± 0.28	1.30± 0.08	6
130	1.88±0.25	0.81± 0.05	2	1.38±0.18	0.63± 0.03	1	3.26± 0.43	1.44± 0.08	3
				$2e2\mu/2\mu2e$					
m_H	exp. signal	exp. bkg	obs	exp. signal	exp. bkg	obs	exp. signal	exp. bkg	obs
120	0.81±0.12	1.15± 0.17	2	0.48±0.07	0.78± 0.10	1	1.29± 0.19	1.93± 0.18	3
125	1.45±0.20	1.30± 0.19	3	0.83±0.11	0.89± 0.11	2	2.28± 0.31	2.19± 0.21	5
130	2.24±0.32	1.34± 0.20	2	1.27±0.17	0.94± 0.11	1	3.51± 0.49	2.28± 0.21	3
				$4e$					
m_H	exp. signal	exp. bkg	obs	exp. signal	exp. bkg	obs	exp. signal	exp. bkg	obs
120	0.35±0.05	0.79±0.15	1	0.15±0.02	0.60±0.12	1	0.50±0.07	1.39±0.19	2
125	0.61±0.09	0.90±0.17	2	0.28±0.04	0.69±0.13	0	0.89±0.13	1.59±0.22	2
130	0.91±0.15	0.96±0.17	1	0.42±0.06	0.74±0.14	0	1.33±0.21	1.70±0.22	1

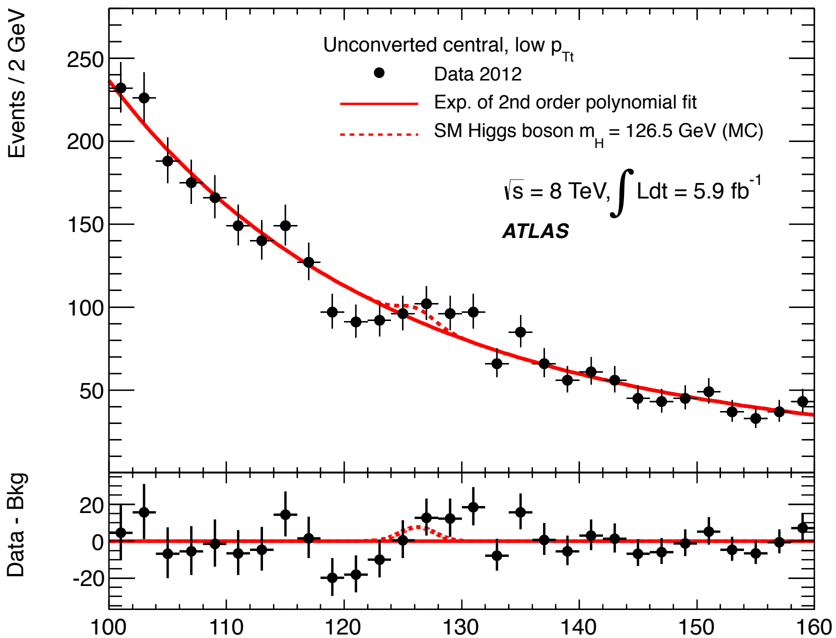
H->$\gamma\gamma$: background from Z->ee estimate



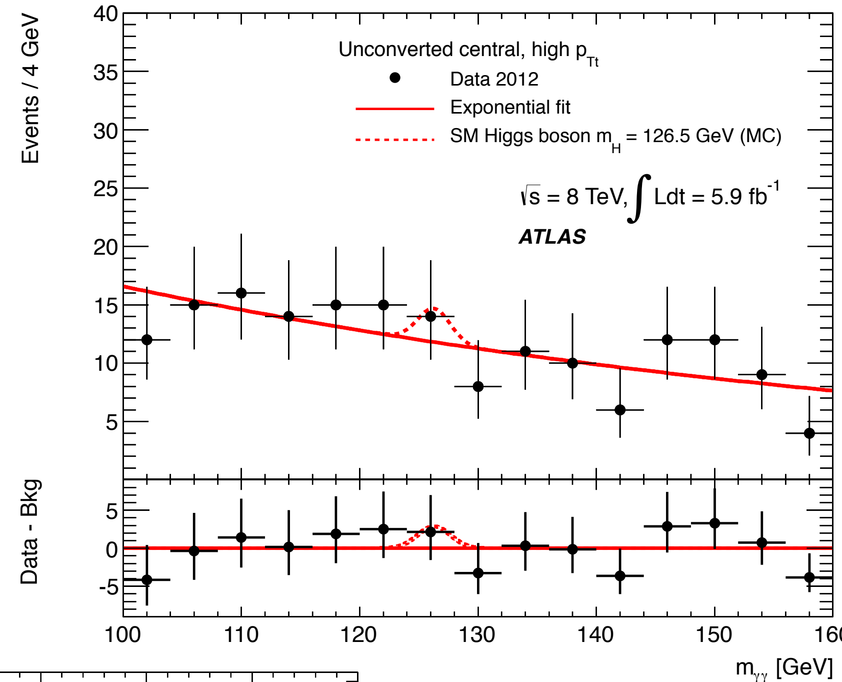
H->$\gamma\gamma$: P_T^t separation of ggF and VBF



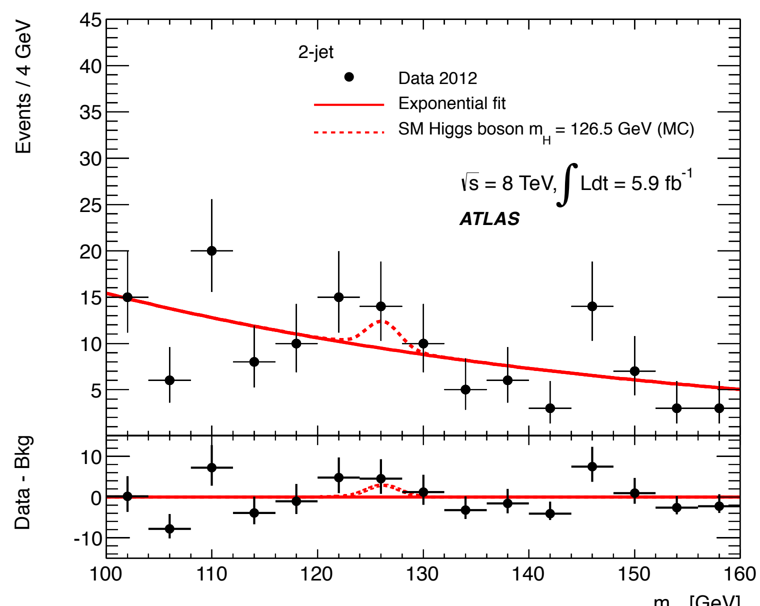
H->$\gamma\gamma$: background-only fits



Unconverted central, low p_{Tt}

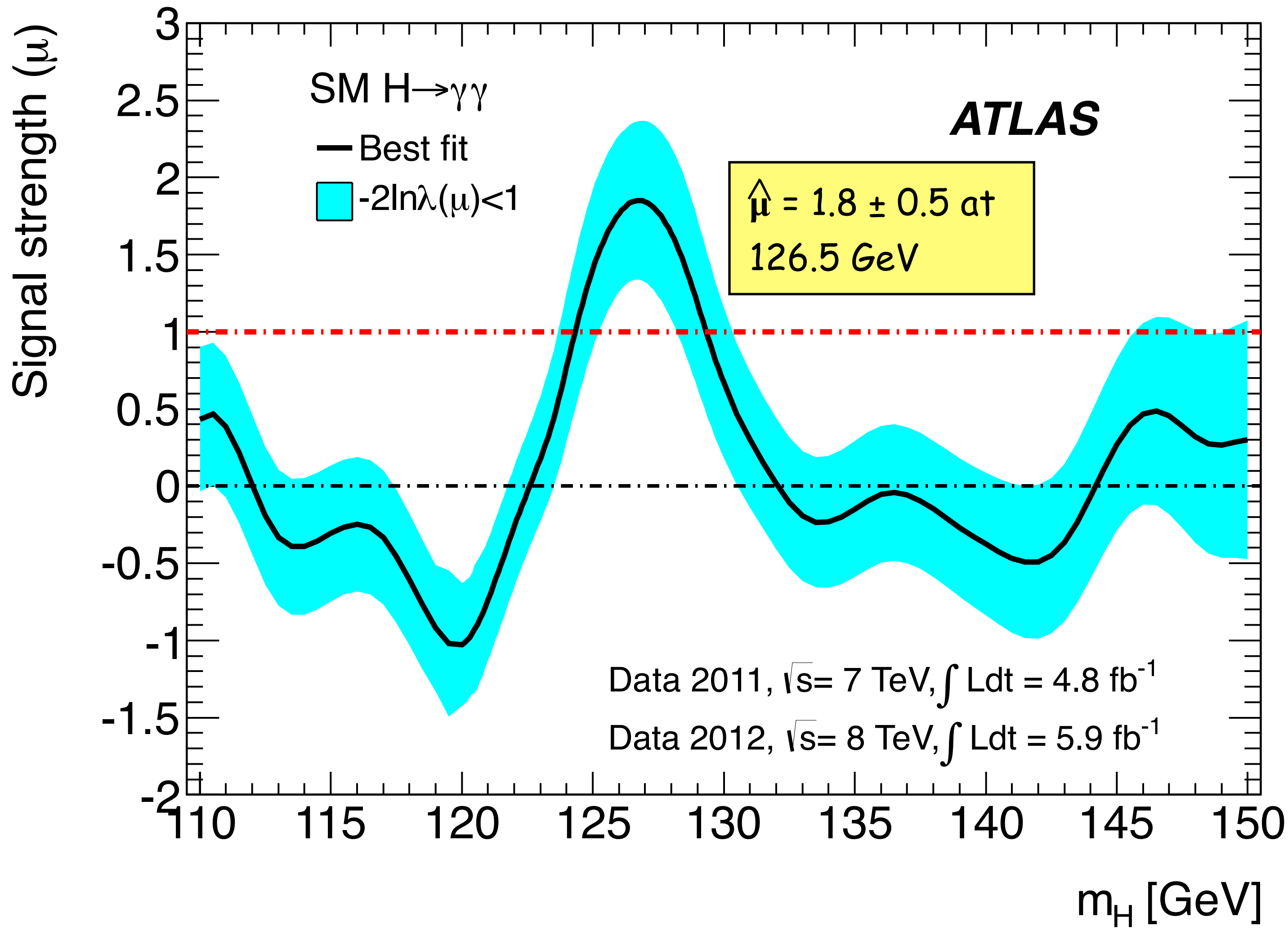


Unconverted central, high p_{Tt}

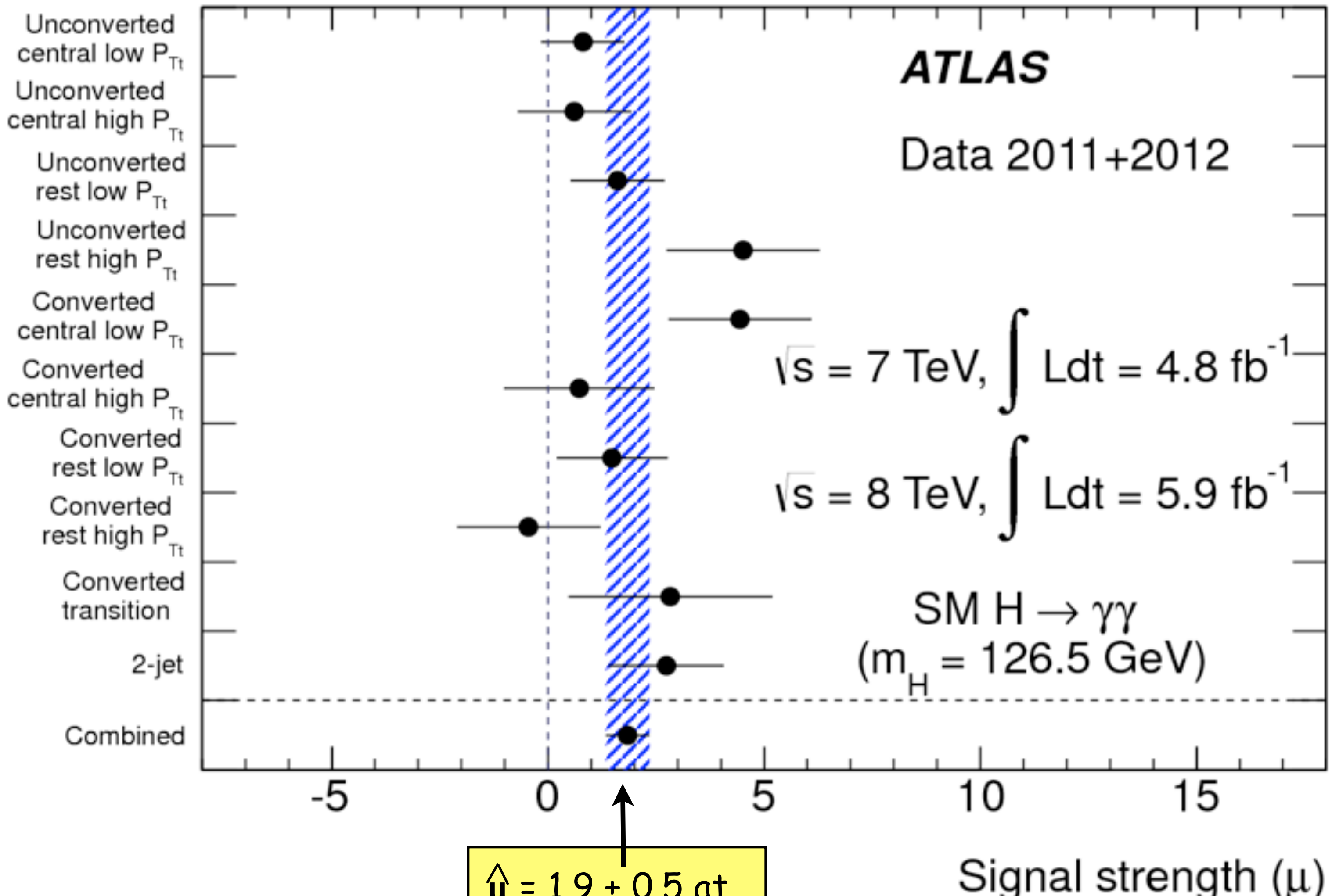


2-jet

H->$\gamma\gamma$: signal strength $\hat{\mu}$

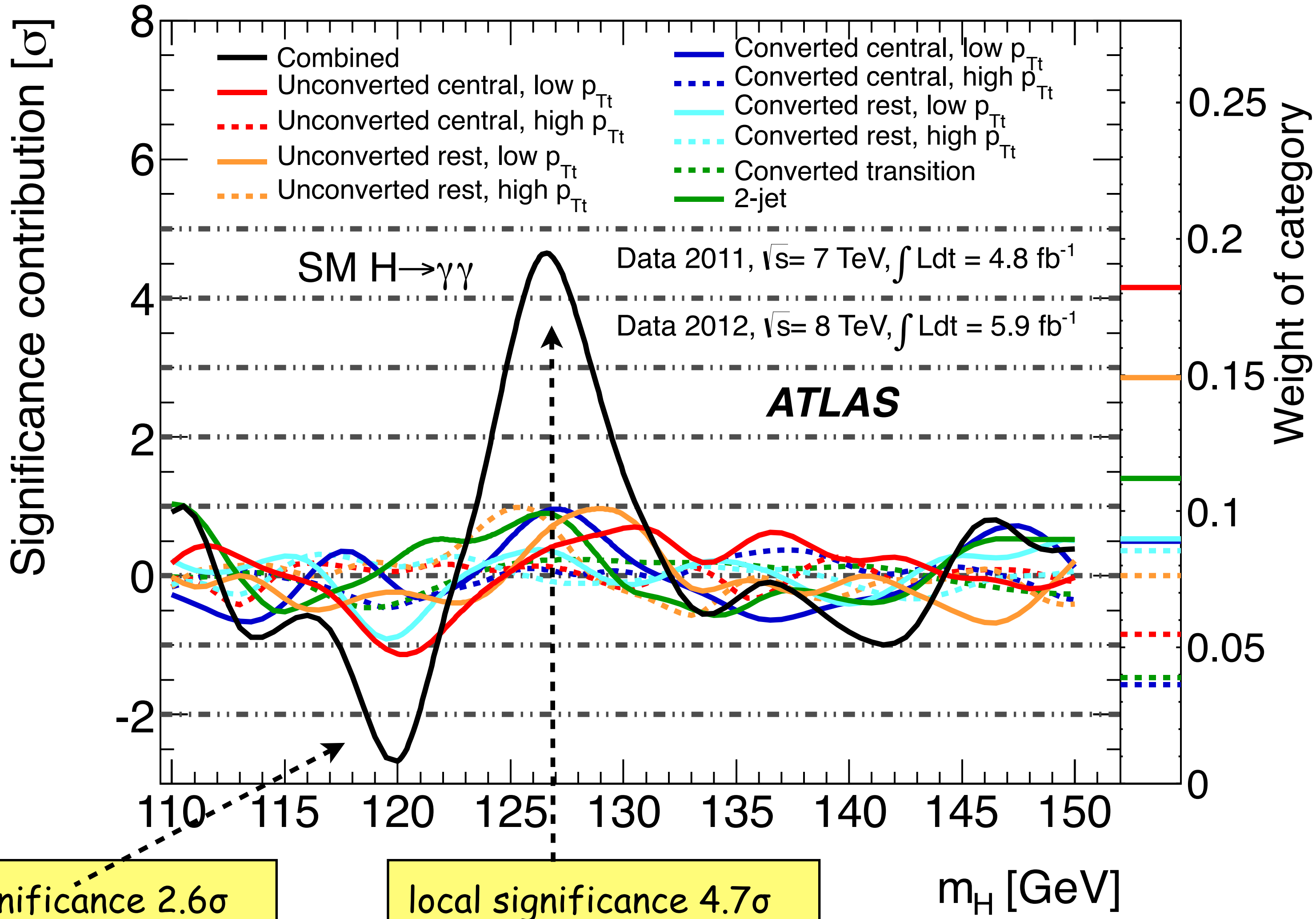


H->$\gamma\gamma$: signal strength for individual categories



$\hat{\mu}$ = 1.9 ± 0.5 at 126.5 GeV

H->$\gamma\gamma$: weighted significance per category



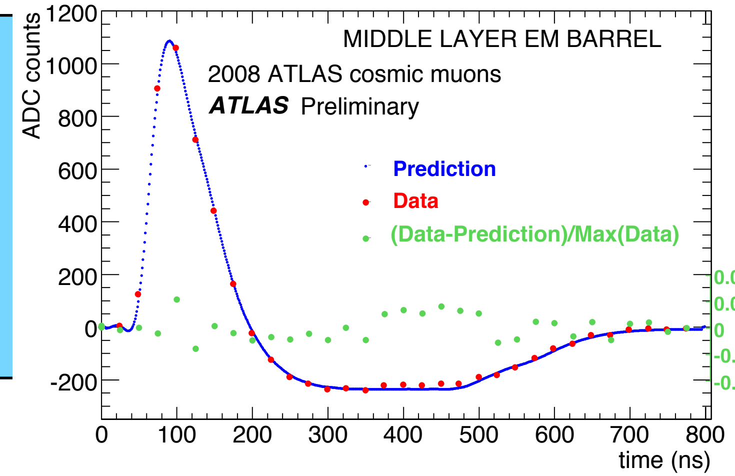
local significance 2.6σ
global significance 1.2σ

local significance 4.7σ
global significance 3.6σ

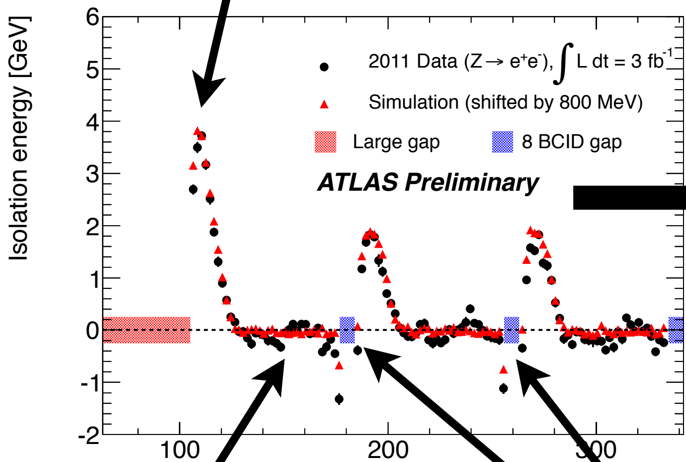
Photon isolation requirement is ET < 4 GeV inside a cone $\Delta R < 0.4$ around the γ direction
Pile-up contribution is subtracted using an "ambient energy density" event-by-event

If subtraction is not perfect, residual dependence of the isolation energy on the bunch position in the train is observed, due to the impact of the out-of-time pile-up from neighboring bunches convolved with the EM calorimeter pulse shape

Calorimeter bipolar pulse shape: average pile-up is zero over ~600 ns (~12 bunches)

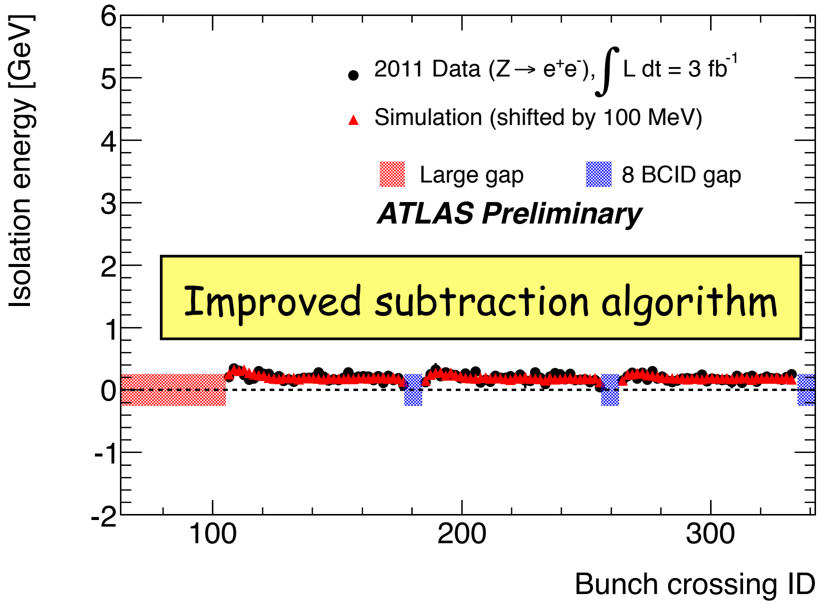


Beginning of the train: no cancellation from previous bunches



12 bunches in train: full cancellation

Empty bunches



Improved subtraction algorithm

Characterization of excess for H->ZZ (*)->4l, H->$\gamma\gamma$ and H->WW(*) -> lνlν

Search channel	Dataset	m_{max} [GeV]	Z_l [σ]	$E(Z_l)$ [σ]	$\hat{\mu}(m_H = 126$ GeV)	Expected exclusion [GeV]	Observed exclusion [GeV]
$H \to ZZ^{(*)} \to 4\ell$	7 TeV	125.0	2.5	1.6	1.7 ± 1.1		
	8 TeV	125.5	2.6	2.1	1.3 ± 0.8		
	7 & 8 TeV	125.0	3.6	2.7	1.4 ± 0.6	124–164, 176–500	131–162, 170–460
$H \to \gamma\gamma$	7 TeV	126.0	3.4	1.6	2.2 ± 0.7		
	8 TeV	127.0	3.2	1.9	1.5 ± 0.6		
	7 & 8 TeV	126.5	4.5	2.5	1.8 ± 0.5	110–140	112–123, 132–143
$H \to WW^{(*)} \to \ell\nu\ell\nu$	7 TeV	135.0	1.1	3.4	0.5 ± 0.6		
	8 TeV	120.0	3.3	1.0	1.9 ± 0.7		
	7 & 8 TeV	125.0	2.8	2.3	1.3 ± 0.5	124–233	137–261
Combined	7 TeV	126.5	3.6	3.2	1.2 ± 0.4		
	8 TeV	126.5	4.9	3.8	1.5 ± 0.4		
	7 & 8 TeV	126.5	6.0	4.9	1.4 ± 0.3	110–582 113–532 (*)	111–122, 131–559 113–114, 117–121, 132–527 (*)