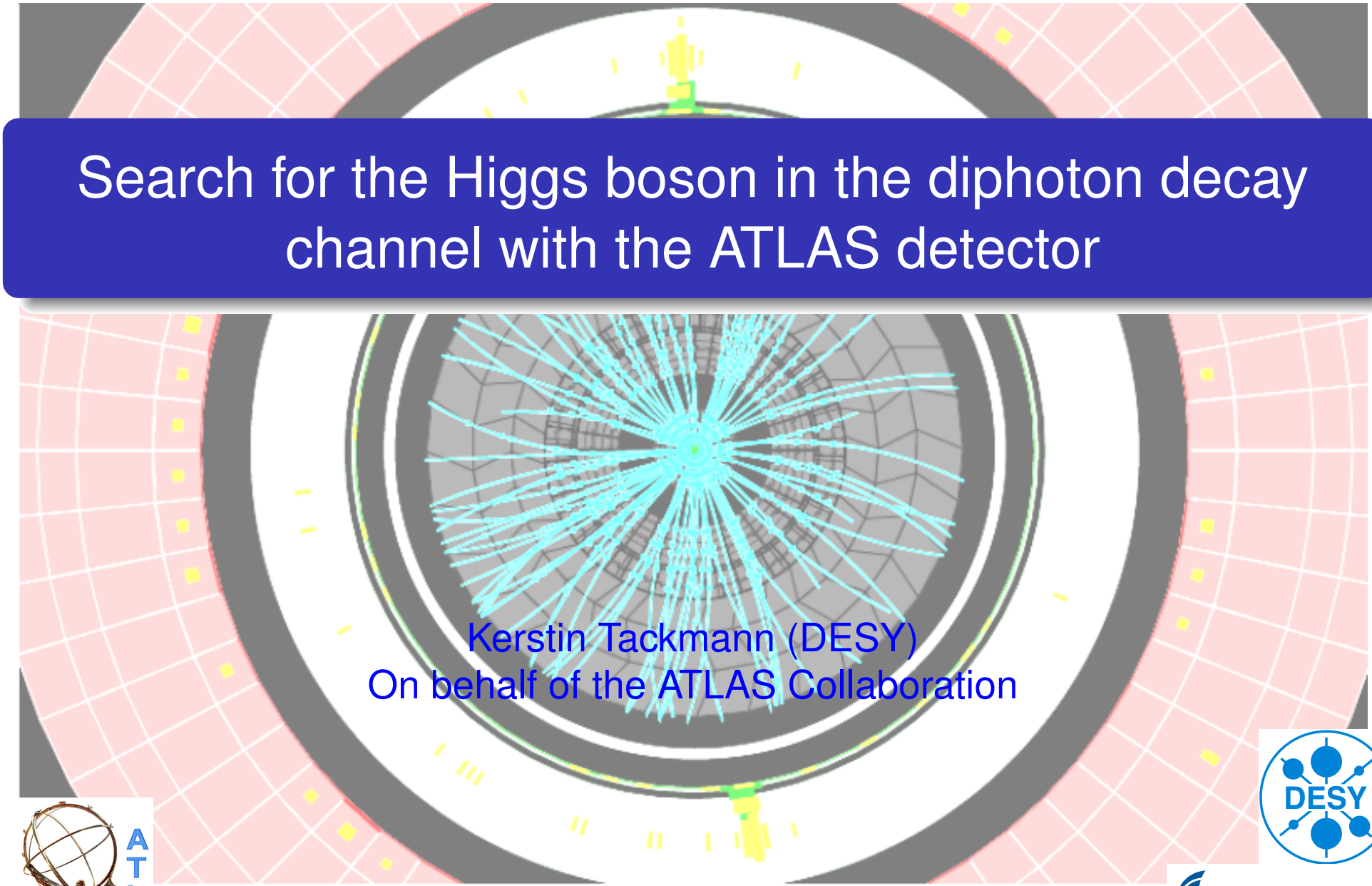
Search for the Higgs boson in the diphoton decay channel with the ATLAS detector

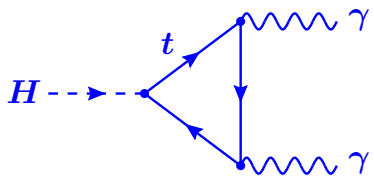


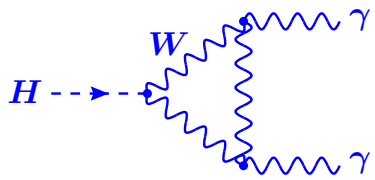
Kerstin Tackmann (DESY)
On behalf of the ATLAS Collaboration

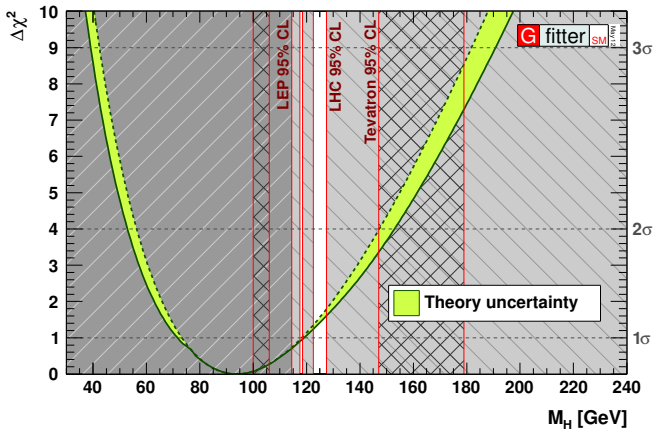
ICHEP 2012 – July 7, 2012 – Melbourne, Australia

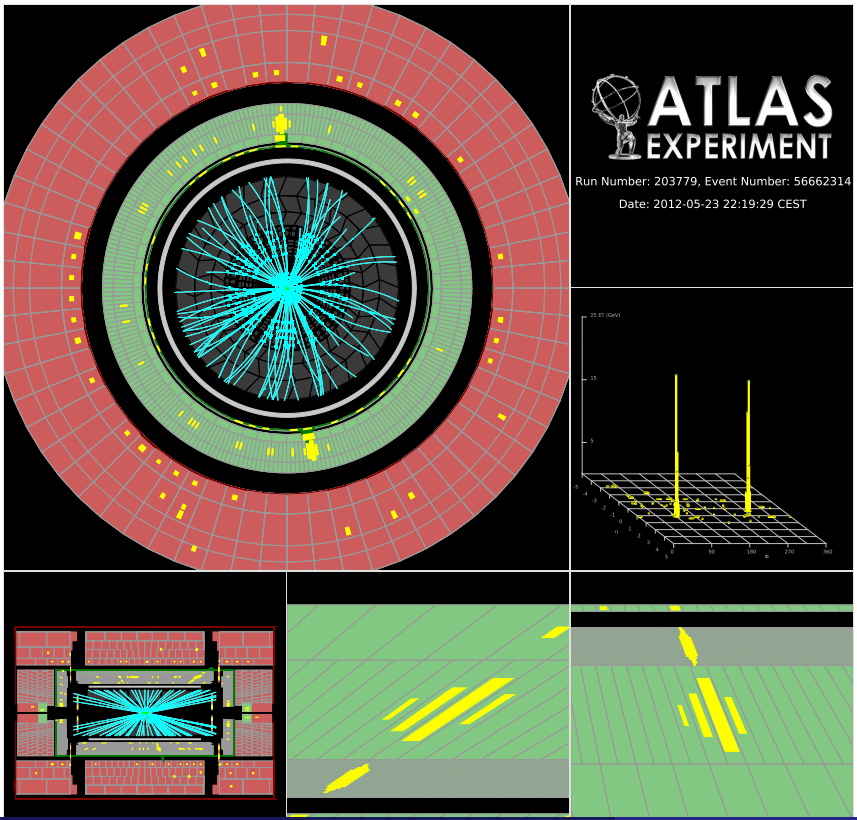
$H \to \gamma\gamma$ and the Low-Mass Higgs

- Large event yield despite low branching fraction ($\sim 0.2\%$) expect ~185 signal events







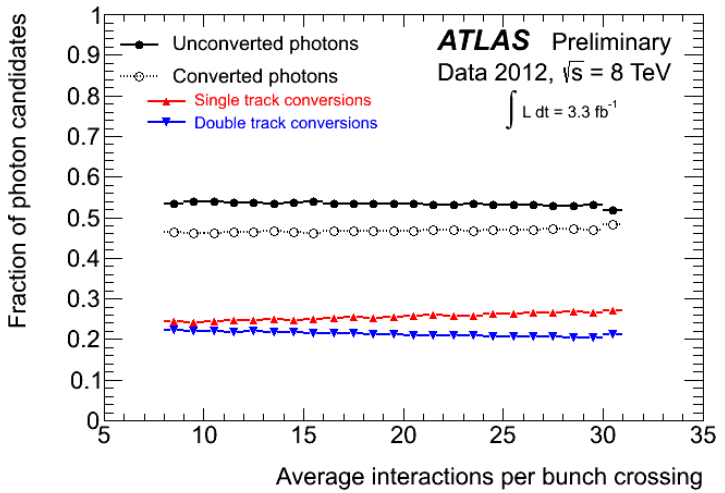


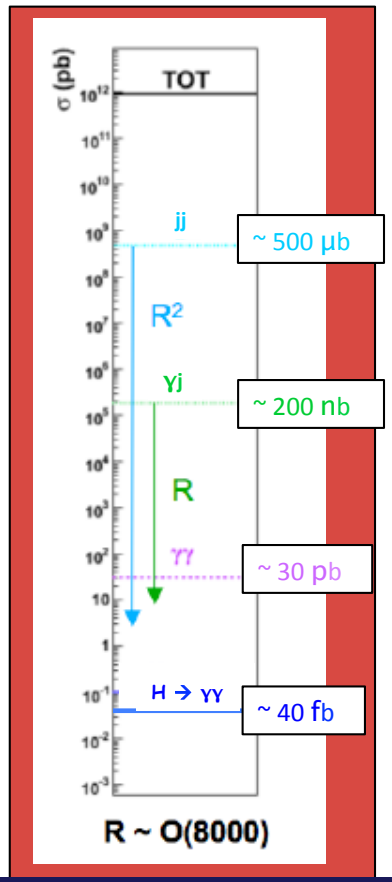
- Comparably simple final state: 2 high-p_T isolated photons
  - ⋆ $p_T^1 > 40\,\mathrm{GeV}$, $p_T^2 > 30\,\mathrm{GeV}$
- Excellent mass resolution ($\sim 1.6\,\mathrm{GeV}$, $\sim 90\%$ in $\pm 2\sigma$)

$7\,\mathrm{TeV}$ data ($4.8\,\mathrm{fb}^{-1}$): Improved analysis
$8\,\mathrm{TeV}$ data ($5.9\,\mathrm{fb}^{-1}$): New!

Photon Reconstruction and Identification

- Photon reconstruction from clusters in LAr calorimeter and conversion vertices in Inner Detector
- Need powerful jet-rejection to suppress dominant background ($\mathcal{O}(10^4)$)



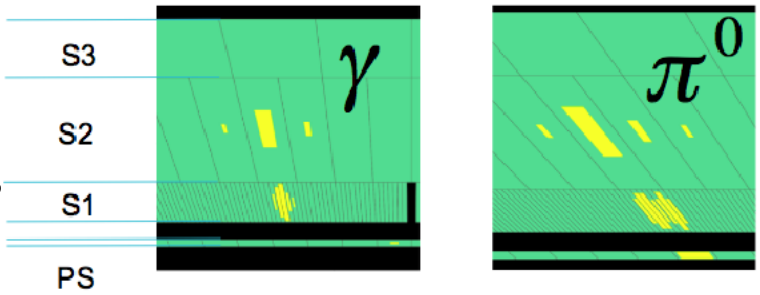


Shower-shaped based photon identification

- $7\,\mathrm{TeV}$: Neural network
- $8\,\mathrm{TeV}$: Rectangular cuts

85% to $> 95\%$ efficient (for isolated photons)

Checked on data with $Z \to \ell^+\ell^-\gamma$, $Z \to e^+e^-$, sideband method



Shower shapes in finely segmented (first layer) of calorimeter

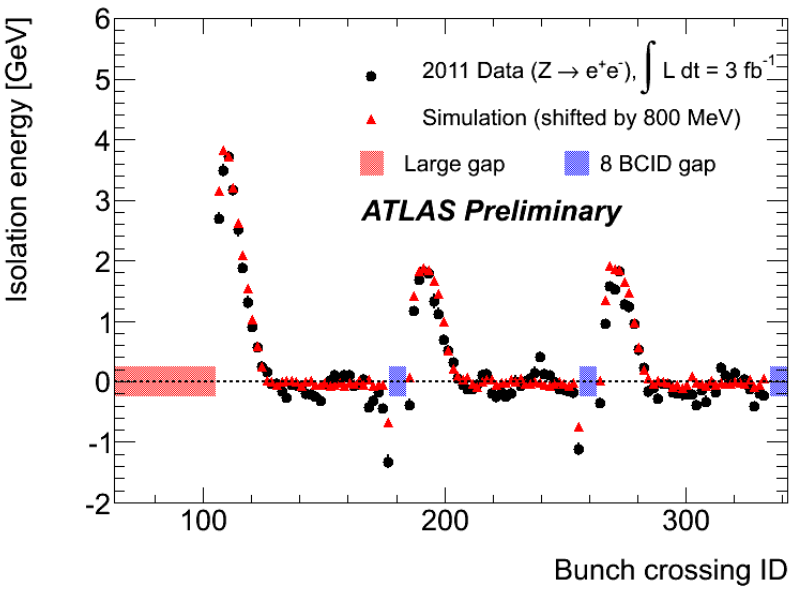
Photon Isolation

Photon isolation computed from positive-energy topological clusters in calorimeter with $\Delta R < 0.4$

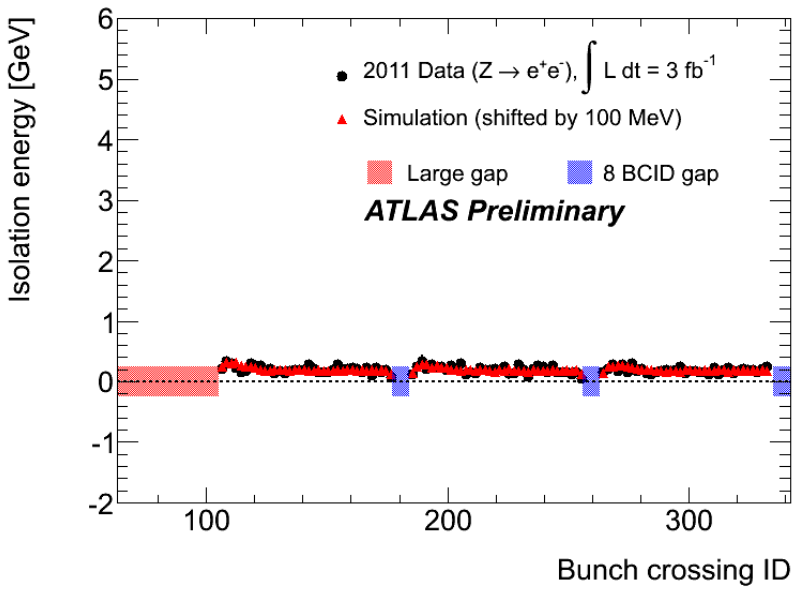
- Corrected for pileup and underlying event contributions by subtracting ambient energy density event-by-event

Good stability with position of colliding bunches in train $\longrightarrow$ robust with pileup

Cell-based isolation (old)



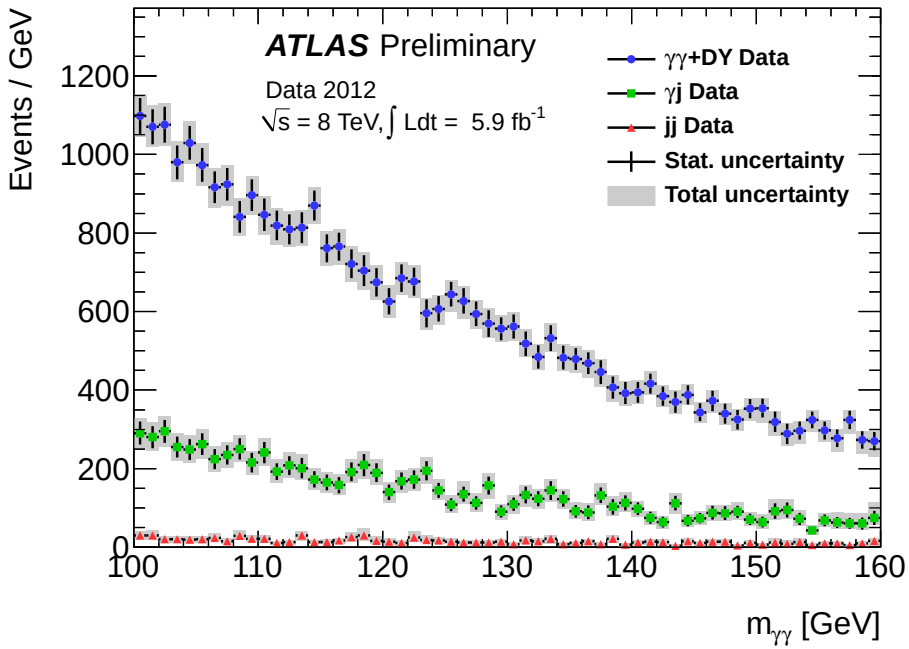
Cluster-based isolation (new)



Imperfect cancellation of in-time and out-of-time pileup

Sample Composition

- Sample composition after photon identification and isolation based on sidebands (in shower shapes and isolation)
- Background composition used for
  - ⋆ Monitoring performance of photon identification
  - ⋆ Background parametrization studies



	$\gamma\gamma$+DY	γ-jet	jet-jet
$\mathbf{7\,TeV}$ (NN ID)	$\mathbf{(80 \pm 4)\%}$	$\mathbf{(19 \pm 3)\%}$	$\mathbf{(1.8 \pm 0.5)\%}$
$\mathbf{8\,TeV}$ (Cut ID)	$\mathbf{(75 \pm 3)\%}$	$\mathbf{(22 \pm 2)\%}$	$\mathbf{(2.6 \pm 0.5)\%}$

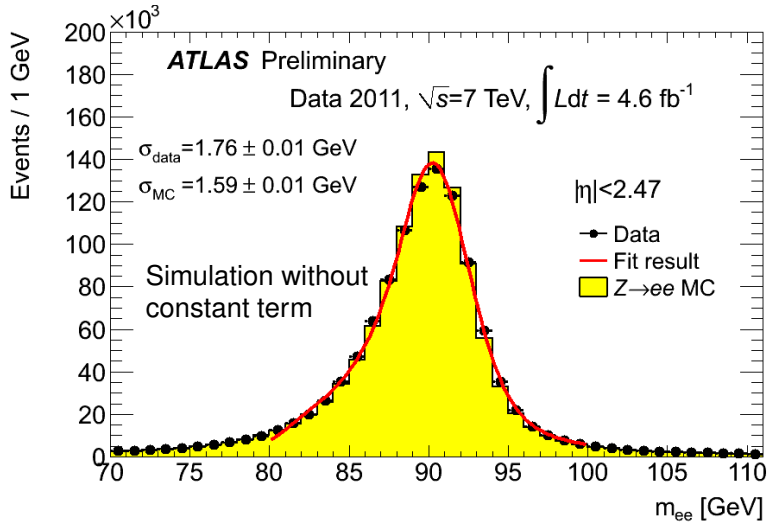
Drell-Yan (DY) background from $e^{\pm}$ misreconstructed as photon, studied with $e^{\pm}\gamma$ candidates ($\sim$ 325 (270) events out of 24k (35k) events)

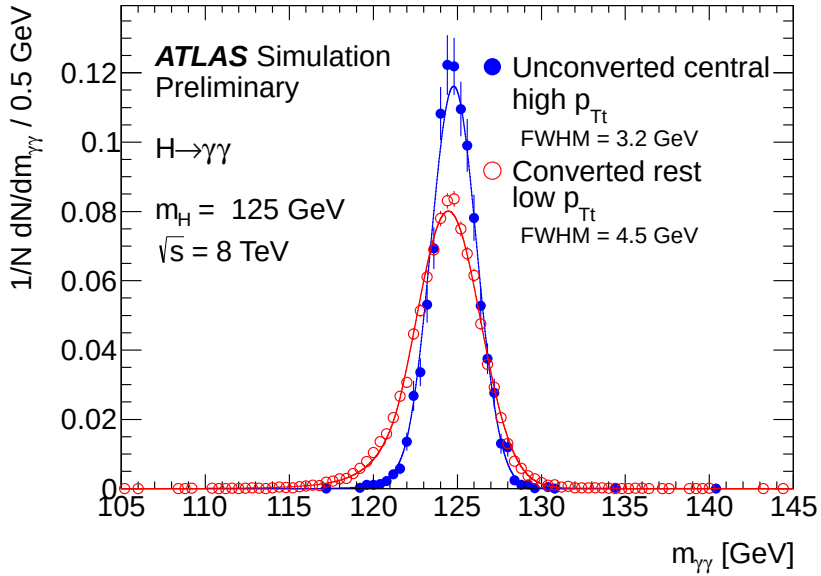
Energy Calibration and Invariant Mass Resolution

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

- MC-based calibration improved with energy scale and resolution corrections based on $Z \to e^+e^-$, $W \to e\nu$, $J/\Psi \to e^+e^-$
- Energy scale at m_Z known to 0.3%, uniformity (constant term) 1% in barrel, $1.2 - 2.1\%$ in endcap
- "Transport" of corrections from $e^\pm$ to photons based on simulation

  Systematic uncertainties dominated by description of material effects, cross checked with photon conversions, hadronic interactions, $e^\pm$ shower shapes and E/p, ...





Photon Pointing and Primary Vertex Selection

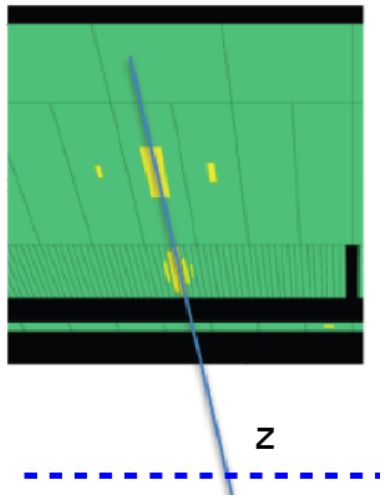
$$m_{\gamma\gamma}^2 = E_1 E_2 (1 - \cos\alpha)$$

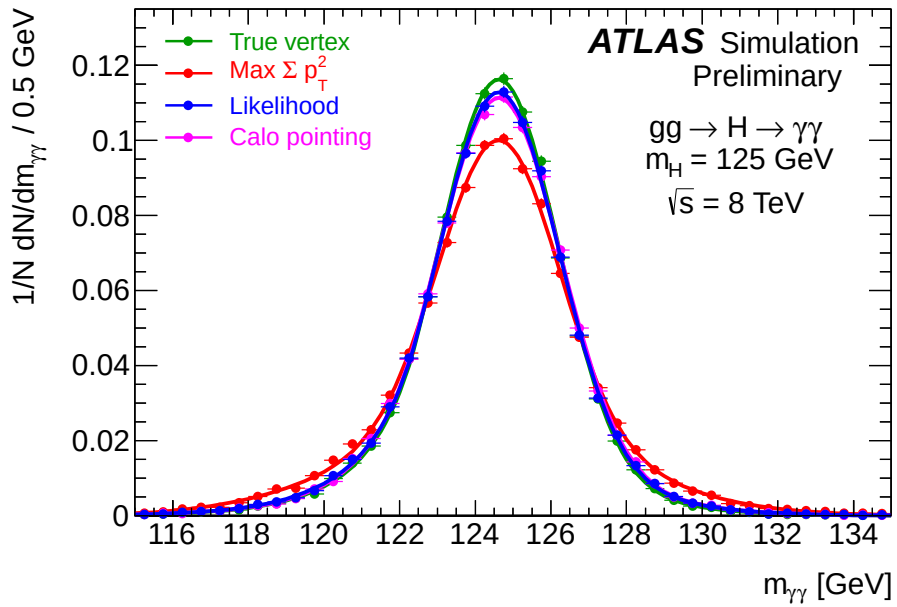
Improve photon angle measurement using likelihood based on

- Photon pointing
  - ⋆ Photon direction measured from calorimeter using longitudinal segmentation
  - ⋆ Position of conversion vertex for converted photons (with Si hits) — $7\ \mathrm{TeV}$ only
  - ⋆ Constraint to LHC beam spot
  - $\longrightarrow$ Measure primary vertex position to $\sim 1.5\,\mathrm{cm}$
- Highest $\Sigma_{\mathrm{tracks}} p_T^2$ primary vertex from tracking

$\longrightarrow$ Contribution of angle measurement to mass resolution negligible already without primary vertex information

- ⋆ Robust with respect to pileup





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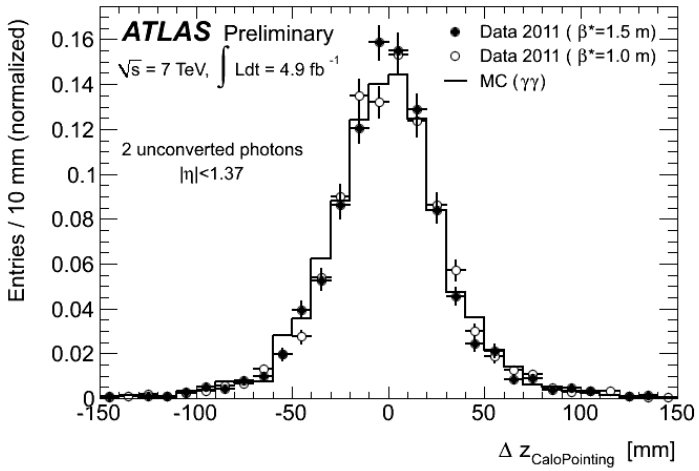

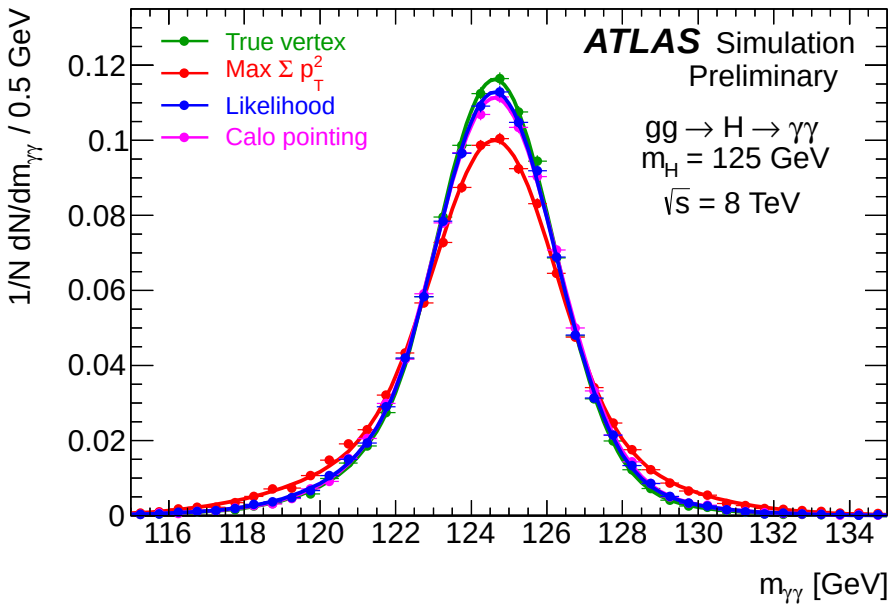

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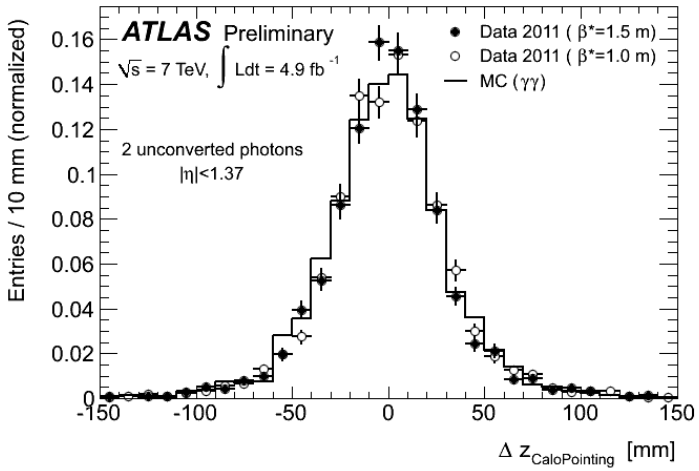
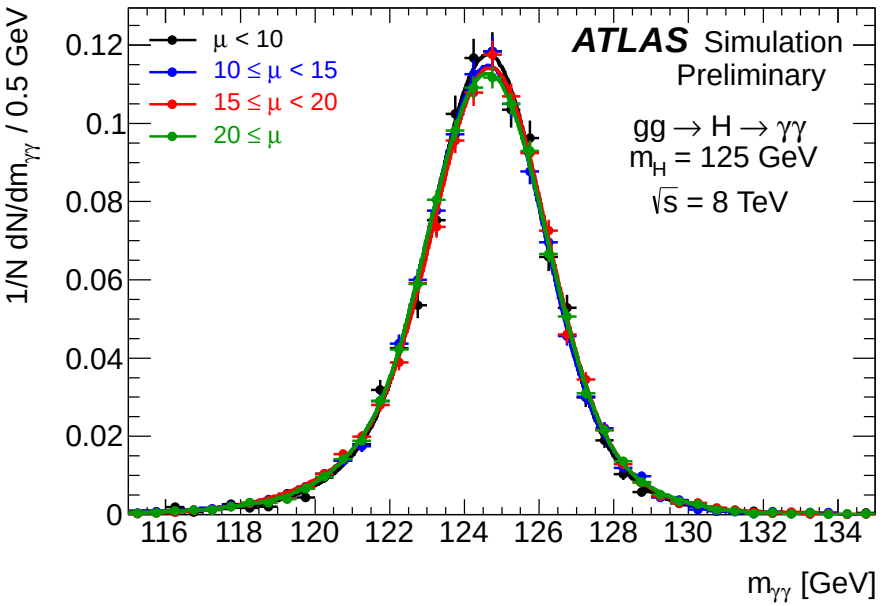




Event Categorization

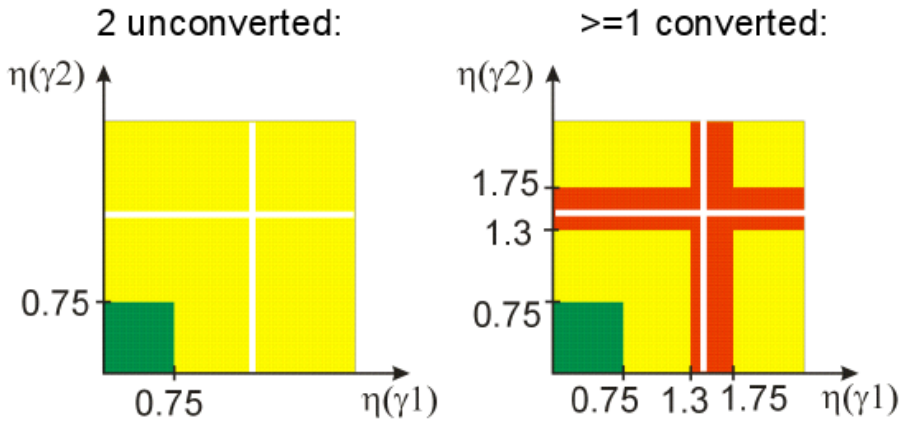
- Events passing 2-jets selection form the new 2-jets category Next slide!
- Remaining events are categorized based on conversion properties and photon direction:

Both unconverted:

- Central
- Rest

At least one converted:

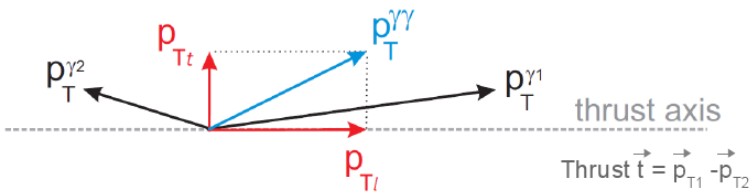
- Central
- Transition
- Rest

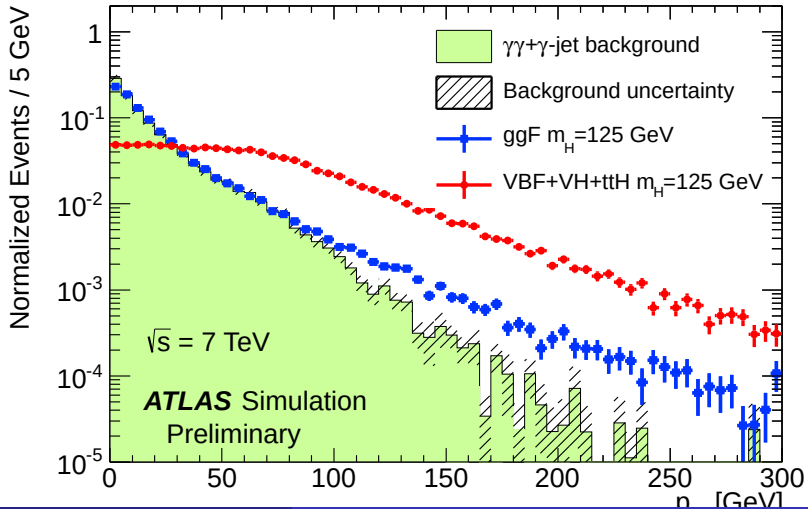


Resolution:

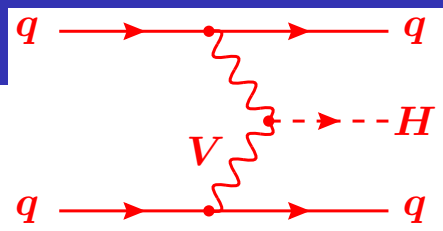
Good
Medium
Poor

Central and Rest divided into $p_{Tt} < 60\,\mathrm{GeV}$ and $p_{Tt} > 60\,\mathrm{GeV}$





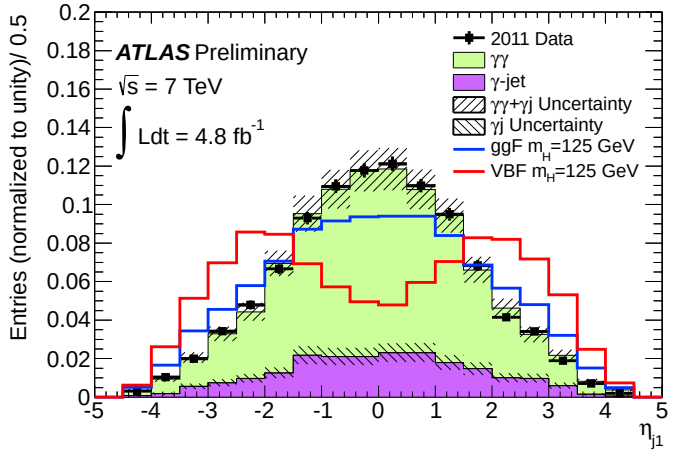
2-Jets Selection

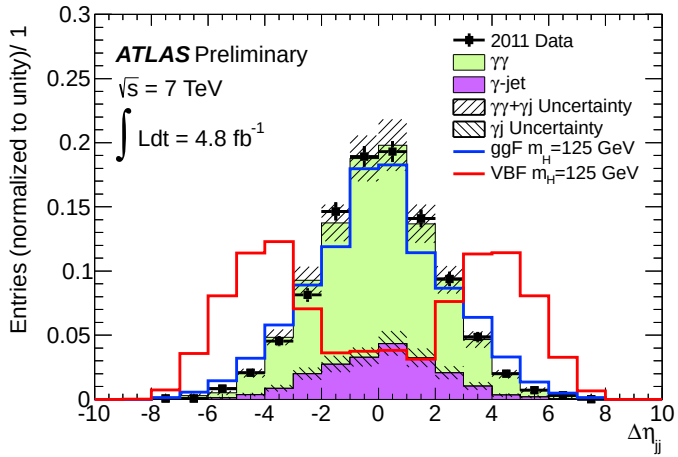


Select VBF-like signature

- ⋆ High signal-to-noise category ($\sim 20\%$)
- ⋆ Separate different Higgs production channels

- 2 jets with $|\eta| < 4.5$, with |JVF|*> 0.75 and $p_T > 25\,\mathrm{GeV}$
  - ⋆ Tightened to $p_T > 30\,\mathrm{GeV}$ for $|\eta| > 2.5$ for $\sqrt{s} = 8\,\mathrm{TeV}$
- Jet separation $\Delta\eta_{jj} > 2.8$
- Invariant mass $M_{jj} > 400\,\mathrm{GeV}$
- $|\Delta\phi_{jj-\gamma\gamma}| > 2.6$





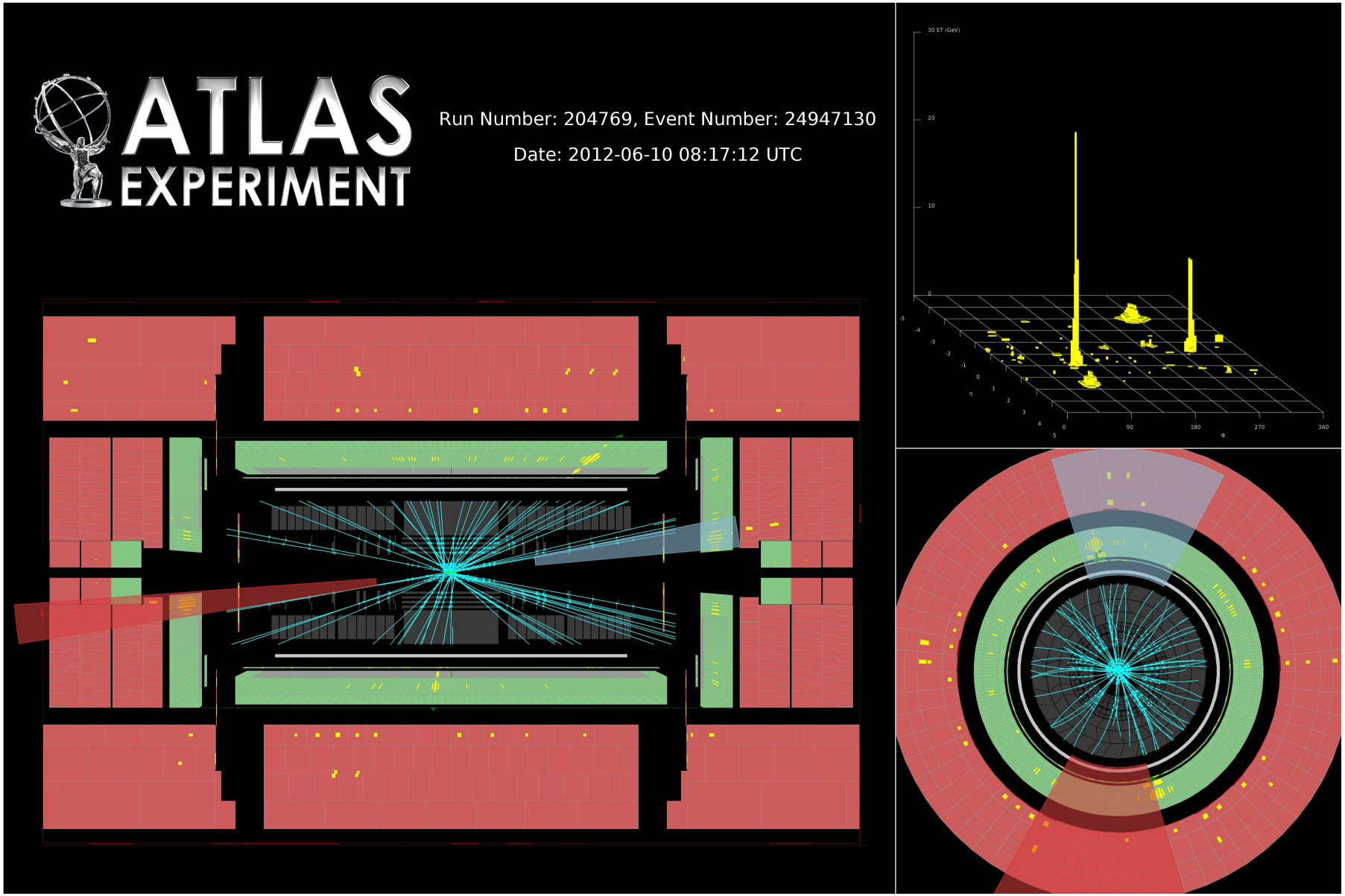
*Jet-Vertex-Fraction: sum of the p_T carried by tracks in the jet and associated to vertex divided by the total p_T carried by all the tracks associated to the jet

⋆ Needs good selection of hard-interaction primary vertex

2-jets category contains about

	7 TeV	8 TeV
VBF	77%	68%
$gg \to H$	23%	30%

2-Jets Candidate



Categories @ 8 TeV

Strength of categorization: different resolution, different S/B ($1\% - 20\%$)

Category	σ_{CB} [GeV]	FWHM [GeV]	Observed [N_{evt}]	S [N_{evt}]	B [N_{evt}]
Inclusive	1.63	3.87	3693	100.4	3635
Unconverted central, low p_{Tt}	1.45	3.42	235	13.0	215
Unconverted central, high p_{Tt}	1.37	3.23	15	2.3	14
Unconverted rest, low p_{Tt}	1.57	3.72	1131	28.3	1133
Unconverted rest, high p_{Tt}	1.51	3.55	75	4.8	68
Converted central, low p_{Tt}	1.67	3.94	208	8.2	193
Converted central, high p_{Tt}	1.50	3.54	13	1.5	10
Converted rest, low p_{Tt}	1.93	4.54	1350	24.6	1346
Converted rest, high p_{Tt}	1.68	3.96	69	4.1	72
Converted transition	2.65	6.24	880	11.7	845
2-jets	1.57	3.70	18	2.6	12

in a window that would contain 90% of signal events

"High"-statistics categories and 2-jets expected to dominate result

Background Parametrization (I)

Choice of background parametrization has to take into account different aspects

- Parametrizations needs to be flexible enough to describe shape well (in different categories)
- Limited number of parameters to not loose statistical power

Systematic uncertainty from choice of background parametrization: estimated from fit results (S+B) with a given parametrization to high statistics background samples ($\longrightarrow$ "spurious signal")

Various background parametrizations have been considered

- Simple and double exponentials
- Exponential with modified turn-on
- Exponentials of polynomials of second and third order
- Various orders of Bernstein polynomials

Background Parametrization (II)

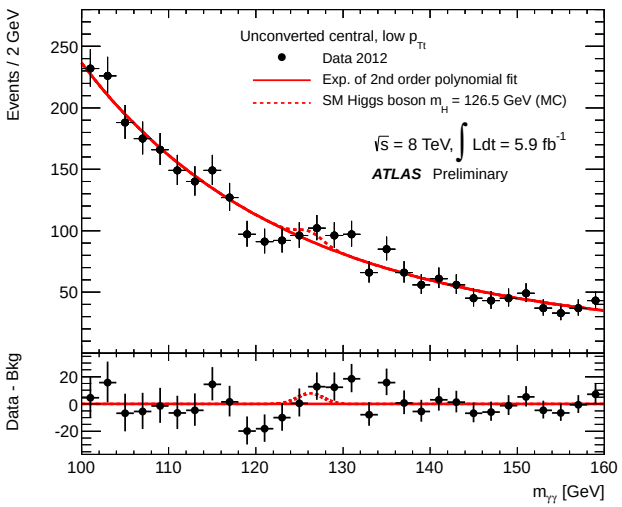
- Different parametrizations for different categories
- Choose the most performant parametrization that has small enough systematics:
  1. Accept model if the spurious signal is $< \mathbf{10\%}$ of expected signal or $< \mathbf{20\%}$ of fitted signal uncertainty
  2. Among the models left, choose the one with the best expected $\boldsymbol{p_0}$ at $\mathbf{125\ GeV}$

Category	Parametrization	Uncertainty $[N_{evt}]$	
		$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
Inclusive	4th order pol.	7.3	10.6
Unconverted central, low p_{Tt}	Exp. of 2nd order pol.	2.1	3.0
Unconverted central, high p_{Tt}	Exponential	0.2	0.3
Unconverted rest, low p_{Tt}	4th order pol.	2.2	3.3
Unconverted rest, high p_{Tt}	Exponential	0.5	0.8
Converted central, low p_{Tt}	Exp. of 2nd order pol.	1.6	2.3
Converted central, high p_{Tt}	Exponential	0.3	0.4
Converted rest, low p_{Tt}	4th order pol.	4.6	6.8
Converted rest, high p_{Tt}	Exponential	0.5	0.7
Converted transition	Exp. of 2nd order pol.	3.2	4.6
2-jets	Exponential	0.4	0.6

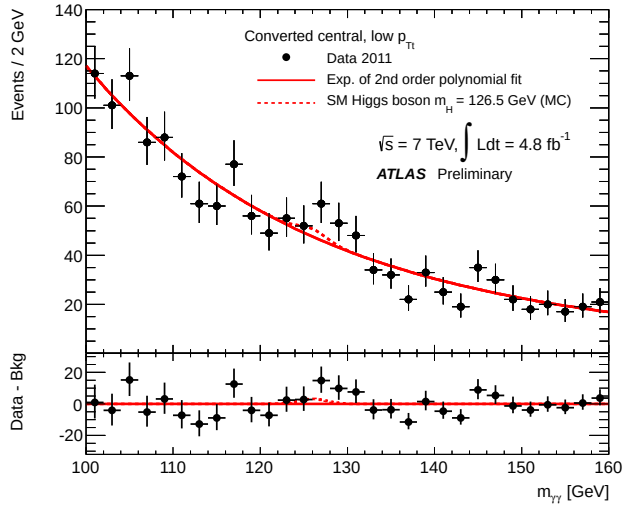
- Background models:
  - ⋆ $\gamma\gamma$ Sherpa, Diphox and Resbos
  - ⋆ γjet Sherpa
  - ⋆ jetjet Pythia
- Detector effects included through weighting and smearing
- Cross checks performed with data-driven background samples

Invariant Mass Spectra (Background-Only Fits)

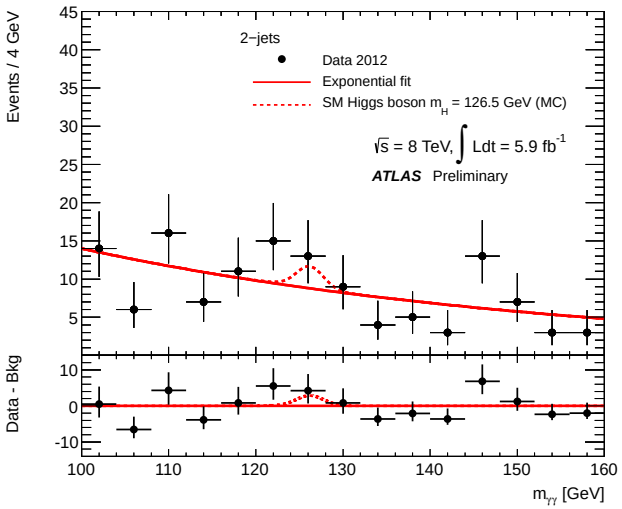
Unconverted central, low p_{Tt} (8 TeV)



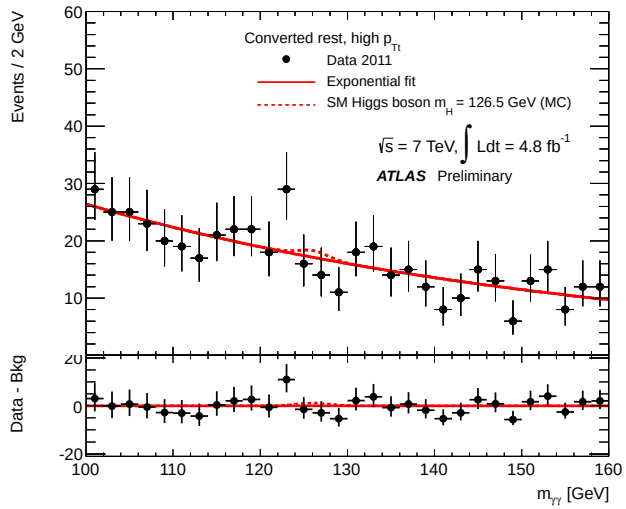
Converted central, low p_{Tt} (7 TeV)



2jet (8 TeV)

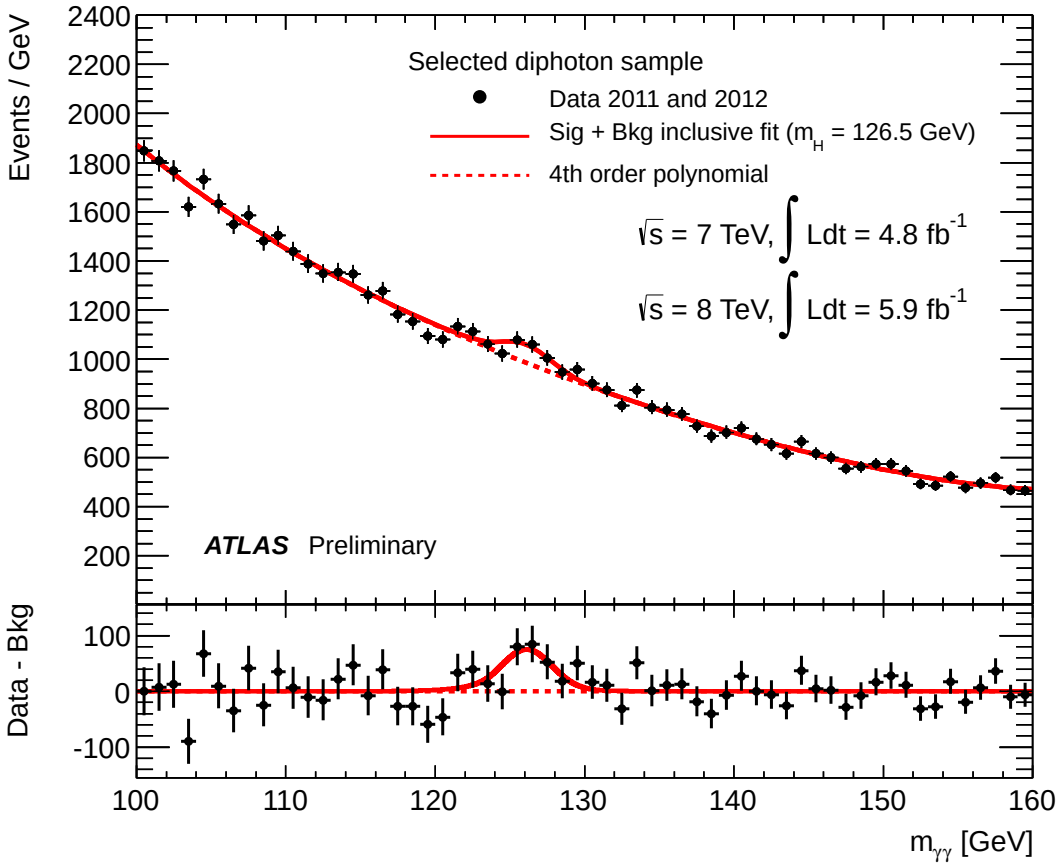


Converted rest, high p_{Tt} (7 TeV)



Mass Spectrum and Systematic Uncertainties

7 TeV + 8 TeV data



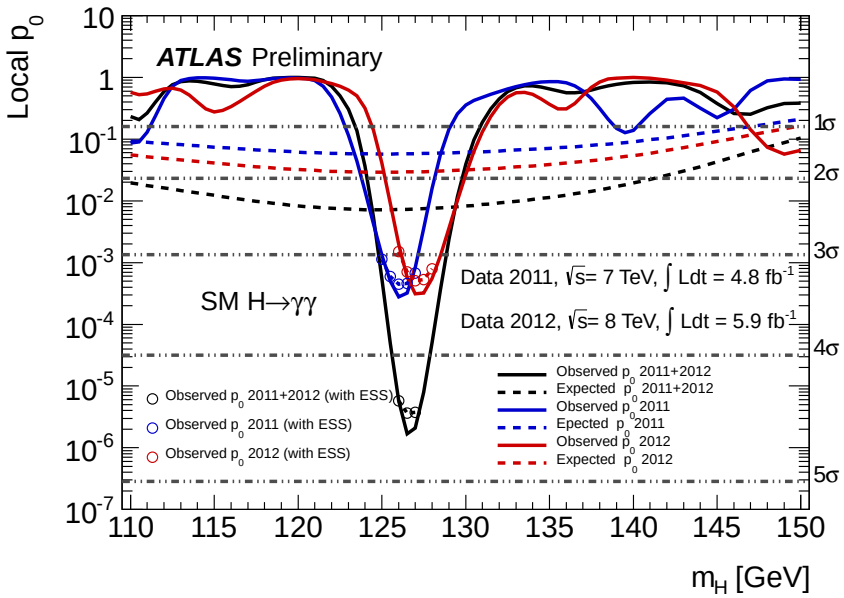
Background+signal fit, signal fixed at **126.5 GeV**

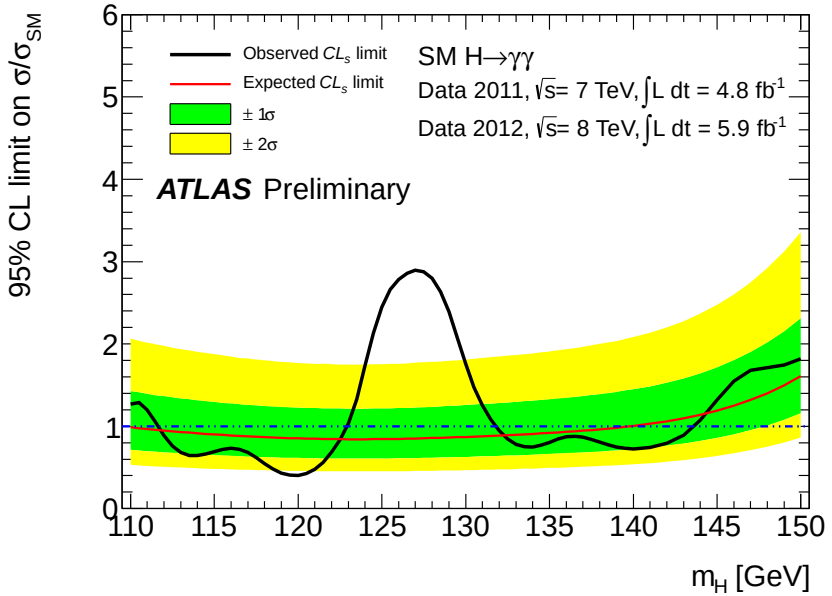
23788 events (**7 TeV**)
35271 events (**8 TeV**)

Largest uncertainties

	7 TeV	**8 TeV**
Photon id efficiency	8.4%	10.8%
Theory	up to **25%** ($gg \to H + 2$ jets)	
Jet E-scale (2-jets)	9-18%	
Underl. evt. (2-jets)	6-30%	
Higgs p_T	up to 12.5%	
Bkgd Param (evts)	0.2-4.6	0.3-6.8
$m_{\gamma\gamma}$ resolution	**14%**	
γ energy scale	**0.6%**	

Consistency with Background-only and Limits





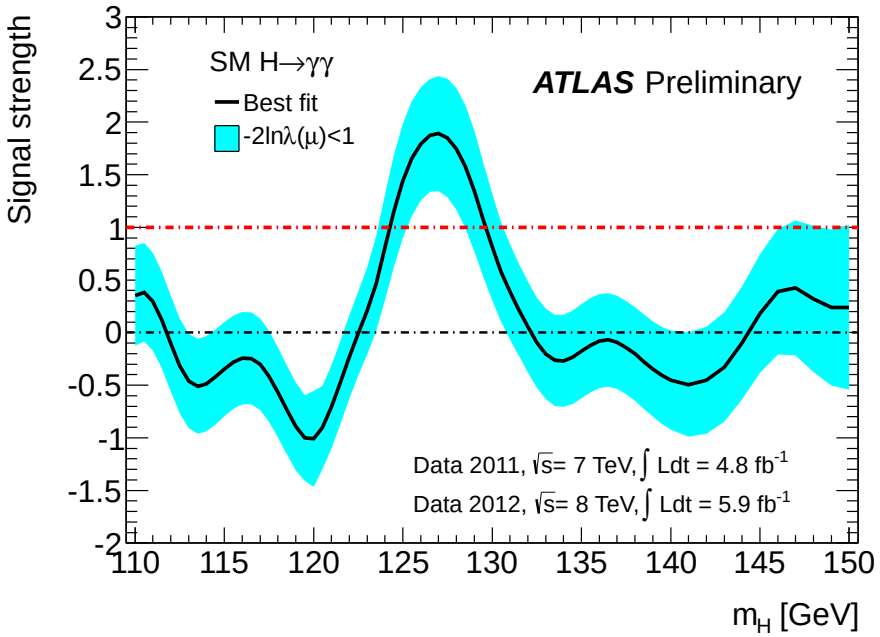
Maximum deviation from background-only expectation at $m_H = 126.5\,\mathrm{GeV}$

- Local significance 4.5σ (exp 2.4σ)
  - ⋆ **7 TeV** 3.3σ (exp 1.6σ) $126\,\mathrm{GeV}$
  - ⋆ **8 TeV** 3.3σ (exp 1.9σ) $127\,\mathrm{GeV}$
- Global significance (fluctuation anywhere in $110\,\mathrm{GeV}$ -$150\,\mathrm{GeV}$) 3.6σ
- Analysis without categories 3.5σ (local, no photon energy scale systematics (⟶ decrease by $0.1 - 0.2\sigma$))

SM Higgs boson excluded for m_H $(112-122.5)\,\mathrm{GeV}$, $(132-143)\,\mathrm{GeV}$ (Expected $(110 - 139.5)\,\mathrm{GeV}$)

Fitted Signal Strength

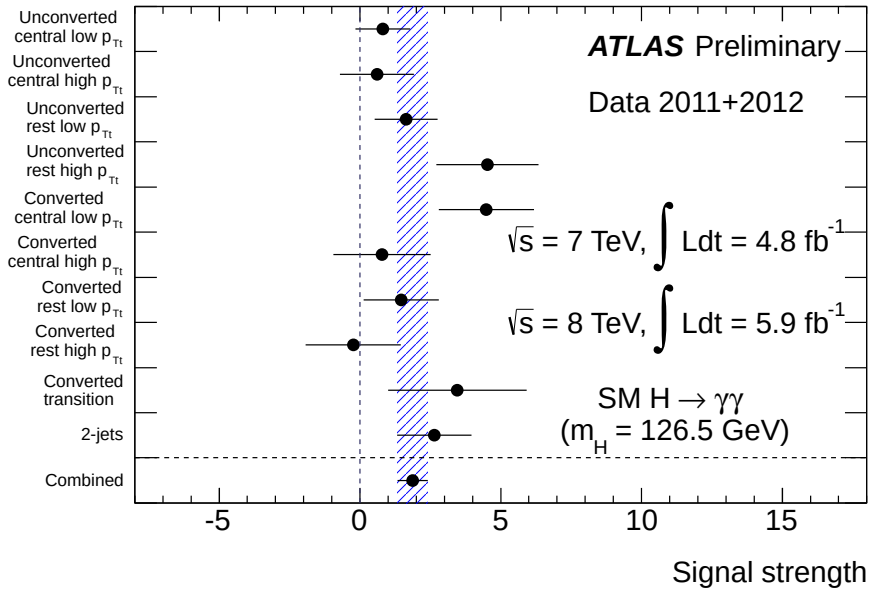
Fitted signal strength



Best fit for $m_H = 126.5\,\mathrm{GeV}$

$\mu = 1.9 \pm 0.5$

Per Category



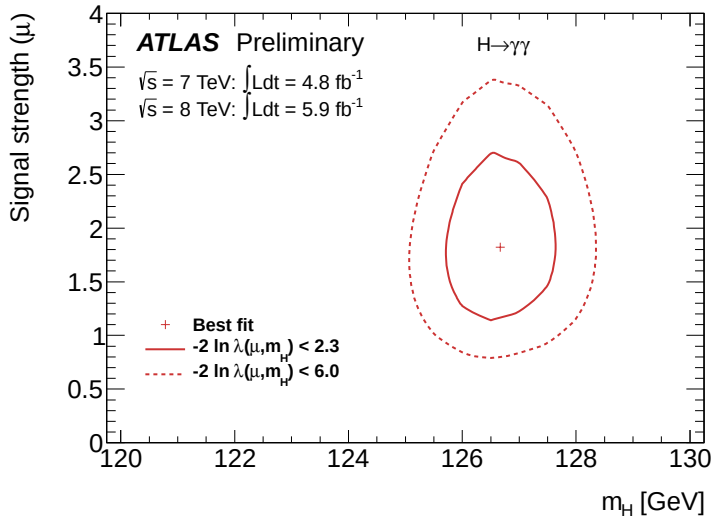
Consistent results from different categories

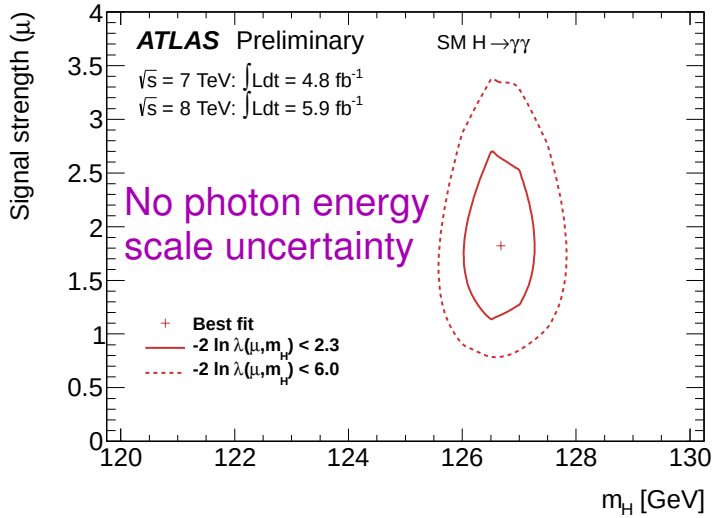
Summary

- Evidence for narrow resonance in diphoton invariant mass spectrum around $126.5\,\mathrm{GeV}$
- 4.5σ local significance (3.6σ global significance)
- Excess compatible between $\sqrt{s} = 7\,\mathrm{TeV}$ and $8\,\mathrm{TeV}$ data
- If we interpret this as a SM Higgs, $\mu = 1.9 \pm 0.5$

More details: ATLAS-CONF-2012-091
and in the backup

Likelihood contours (68% and 95% CL)





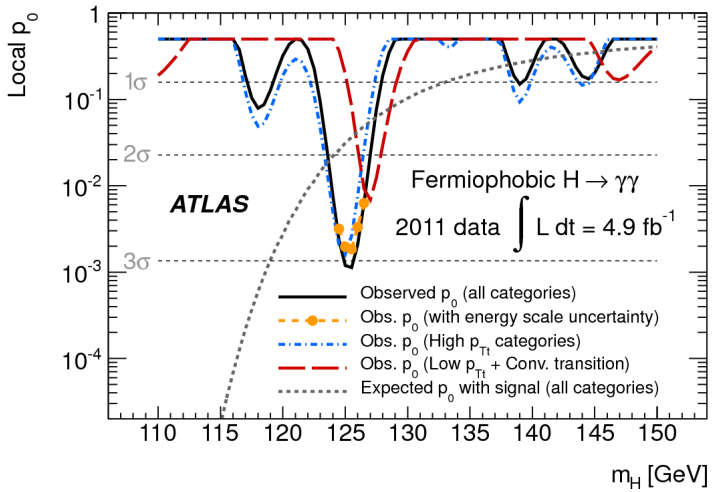
- Related signatures have been studied
  - ★ Fermiophobic Higgs model
  - ★ $H \longrightarrow aa \longrightarrow 4\gamma$ with light CP-odd pseudoscalar a

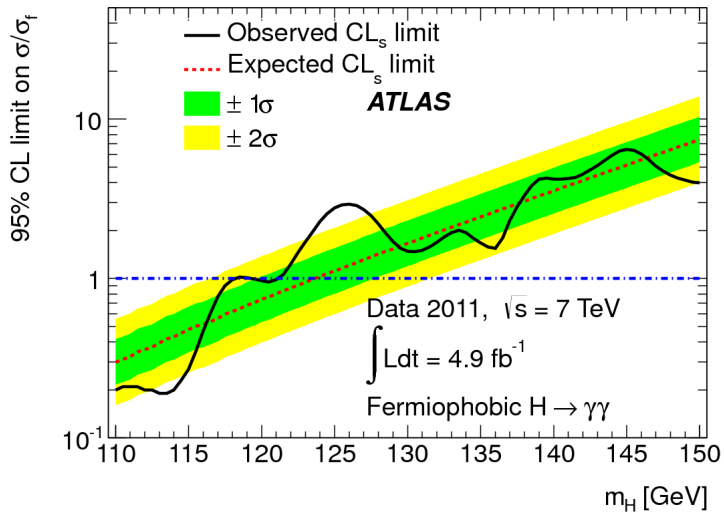
$\longrightarrow$ Backup slides

Backup

Fermiophobic Interpretation ($4.9\,\mathrm{fb}^{-1}$ @ $7\,\mathrm{TeV}$)

- Benchmark model with no Higgs couplings to fermions, bosonic couplings at SM values
  - ⋆ Higgs production through VBF, WH, ZH
  - ⋆ $H \to \gamma\gamma$ enhanced compared to SM for $m_H < 125\,\mathrm{GeV}$
- Similar event selection and categorization as SM analysis
  - ⋆ $p_T^2 > 25\,\mathrm{GeV}$, cell-based isolation
  - ⋆ Cut-based photon identification
  - ⋆ No 2-jets category
- Largest deviation from bkgd-only at $m_H = 125.5\,\mathrm{GeV}$
  - ⋆ Local significance 2.9σ
  - ⋆ Global significance 1.6σ

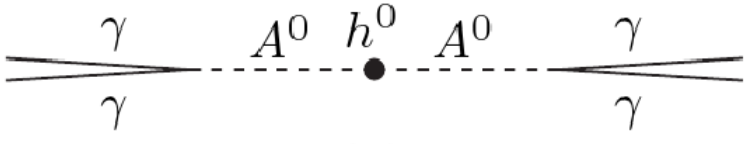




Fermiophobic Higgs model excluded for $m_H = (110.0 - 118.0)\,\mathrm{GeV}$ and $m_H = (119.5 - 121.0)\,\mathrm{GeV}$ @ 95% CL

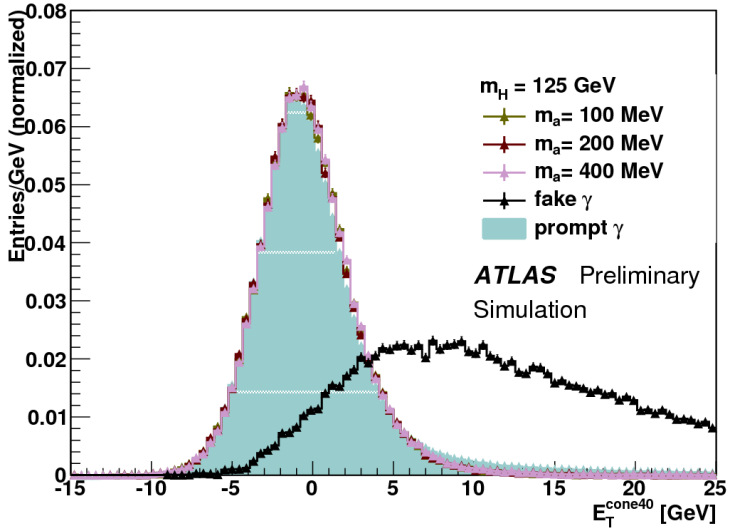
Search for $H \to aa \to 4\gamma$ ($4.9\,\mathrm{fb}^{-1}$ @ $7\,\mathrm{TeV}$)

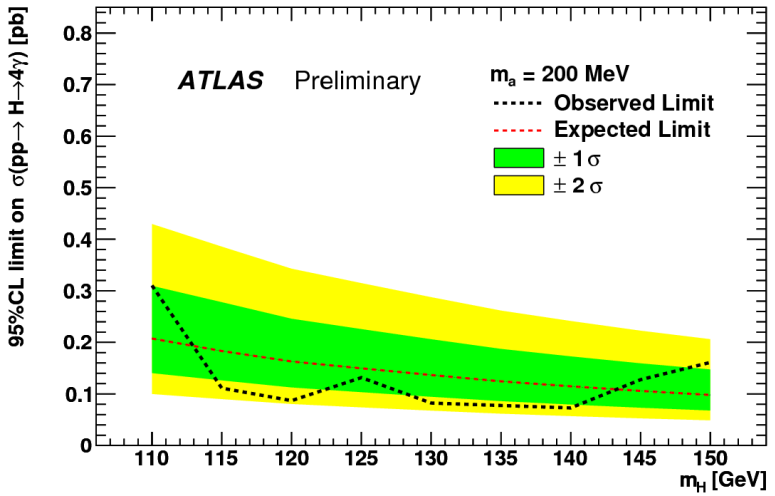
- Various models with extended Higgs sector (MCHM, NMSSM) predict light CP-odd scalar a with $H \to aa$
- If $m_a < 3m_{\pi^0}$: $a \to \gamma\gamma$ with large BF



Assume decay length $< 0.5\,\mathrm{m}$

- Reconstructed as events with two photon candidates since photons from a decay overlap in calorimeter
- Dedicated $a \to \gamma\gamma$ "photon" selection to account for wider shower shapes with substructure ($\sim$ "isolated (heavy) π^0")





(Model-independent) Limits on $\sigma(pp \to H) \times \mathcal{B}(H \to aa \to 4\gamma)$ set below $0.2\,\mathrm{pb}$ for most of the studied Higgs and a masses

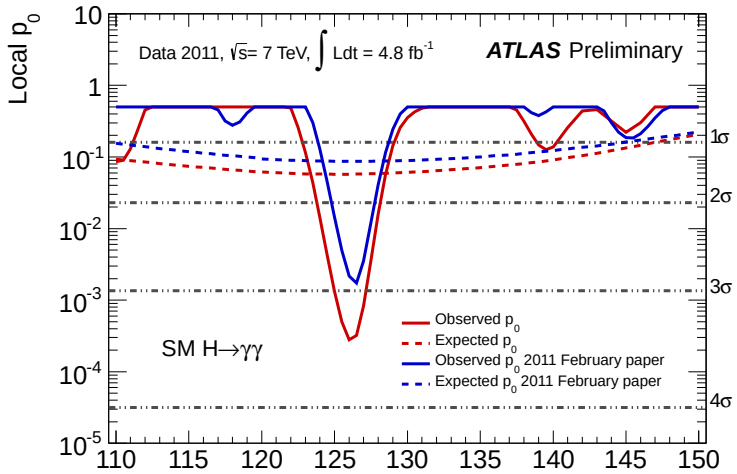
Comparison of Old and New $7\,\mathrm{TeV}$ Analysis

15% expected improvement

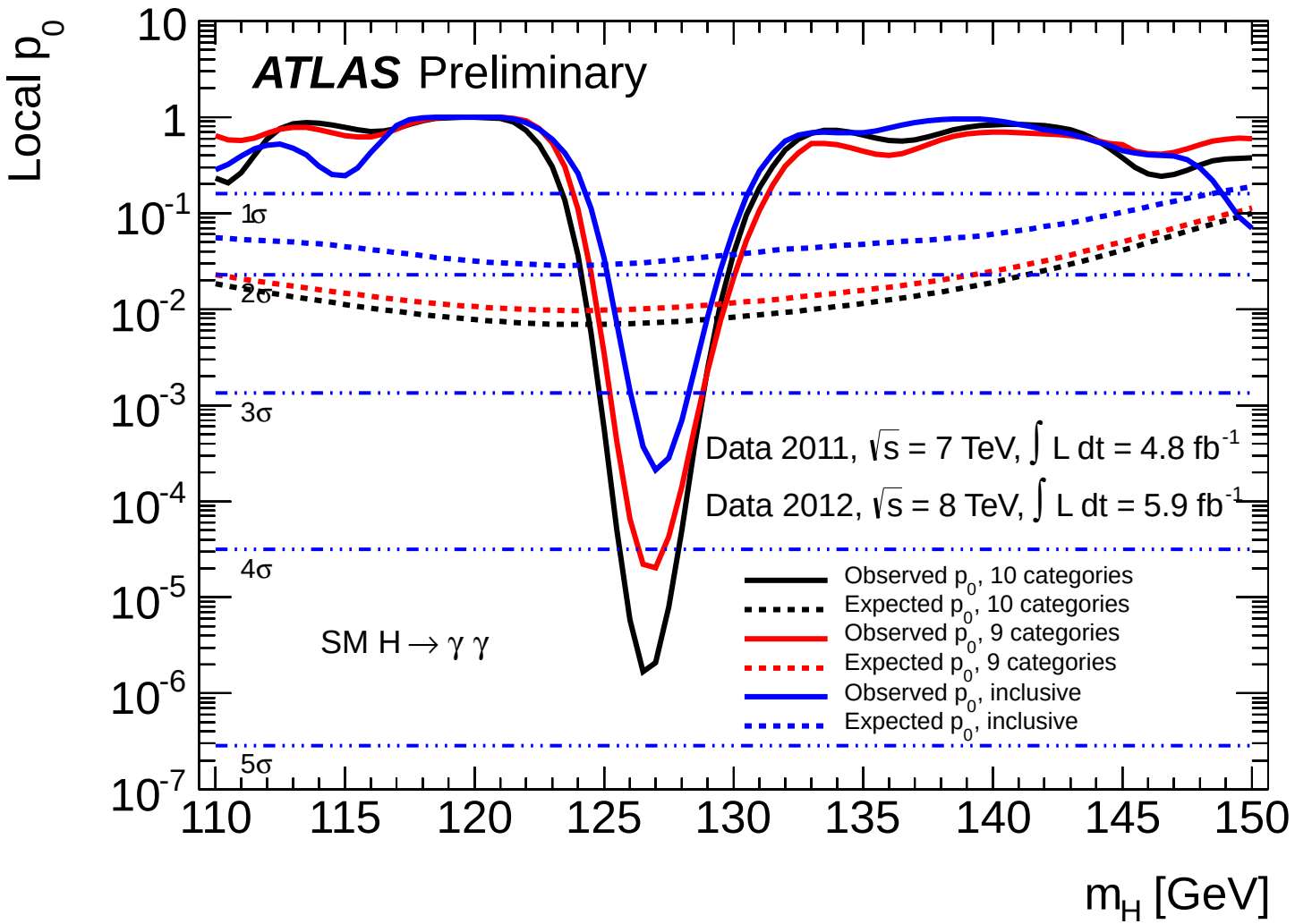
Published analysis	Present $7\,\mathrm{TeV}$ analysis
$p_T^2 > 25\,\mathrm{GeV}$	$p_T^2 > 30\,\mathrm{GeV}$
Cut-based photon id	Neural neutwork photon id
Cell-based isolation	Cluster-based isolation
p_{Tt} categories: $40\,\mathrm{GeV}$	p_{Tt} categories: $60\,\mathrm{GeV}$
9 categories	10 categories (2-jets)
Pointing primary vertex	Likelihood primary vertex
Exponential background shape	New background parametrization

Differences in $8\,\mathrm{TeV}$ analysis

- Pileup-robust cut-based photon id
- Pileup-robust conversion reconstruction



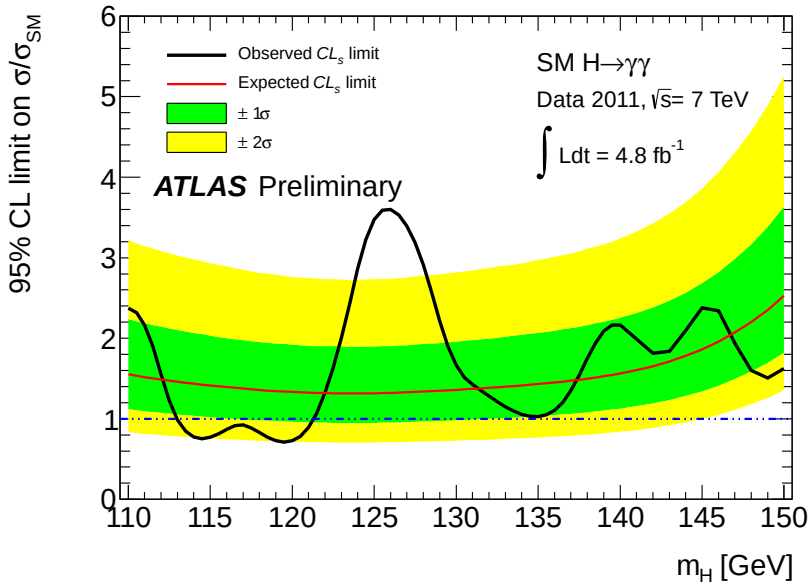
Comparison to Inclusive Analysis



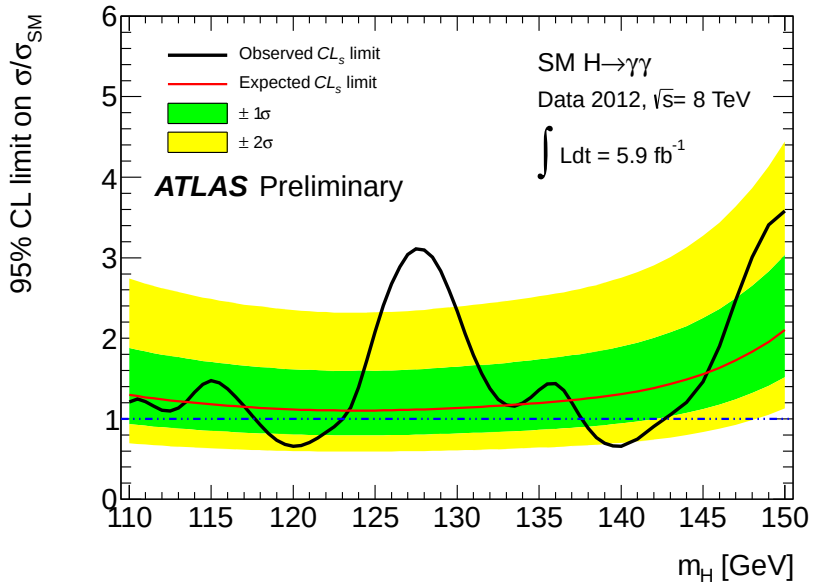
and with 9 categories (no 2-jets category)

Exclusion Limits at 7 TeV and 8 TeV

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



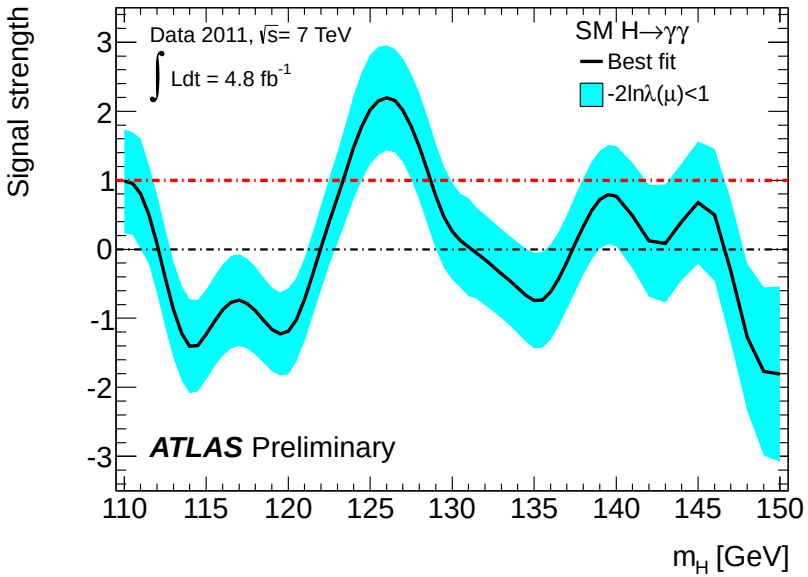
$\sqrt{s} = 8\,\mathrm{TeV}$



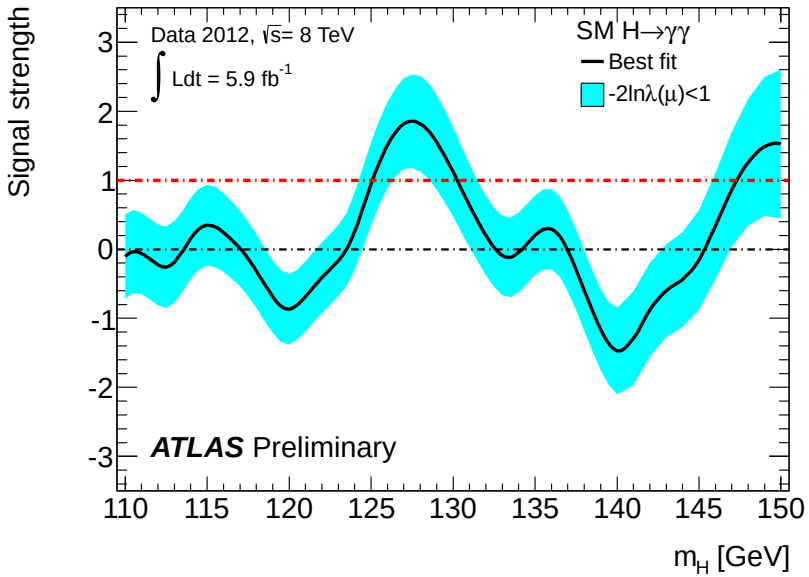
- Behavior away from excess mostly different between the two data samples

Fitted Signal Strength at 7 TeV and 8 TeV

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

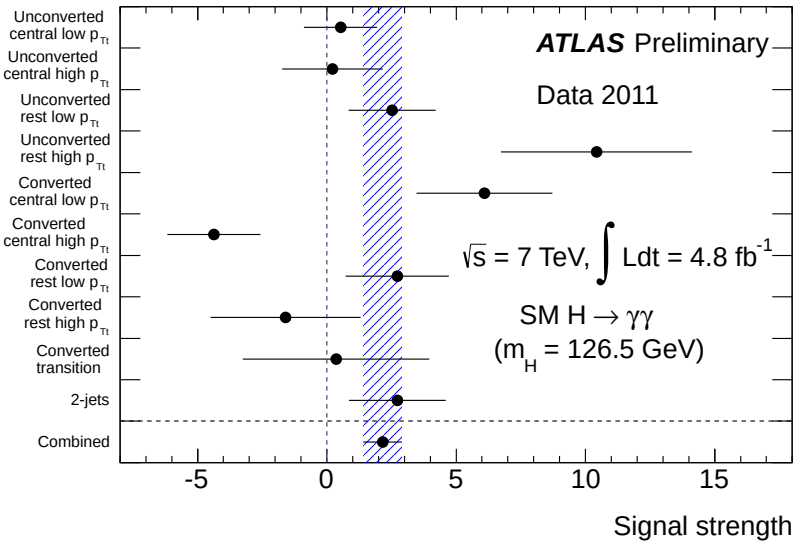


$\sqrt{s} = 8\,\mathrm{TeV}$

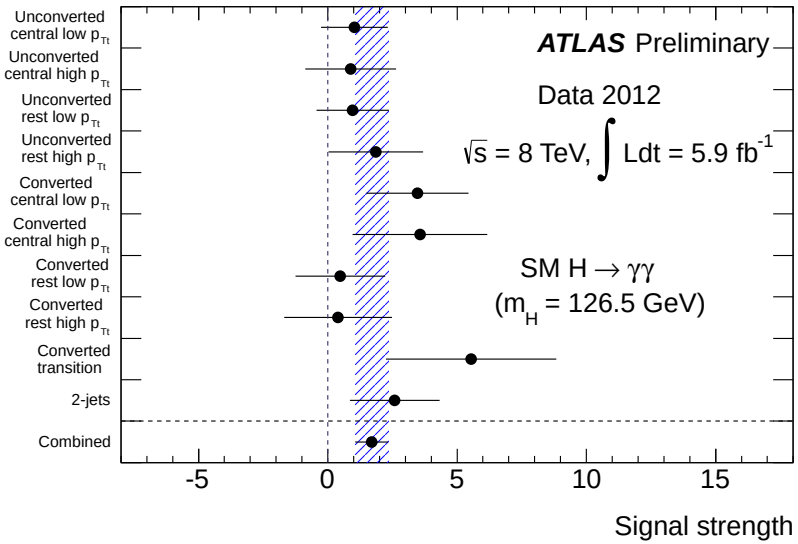


Signal Strength per Category at 7 TeV and 8 TeV

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

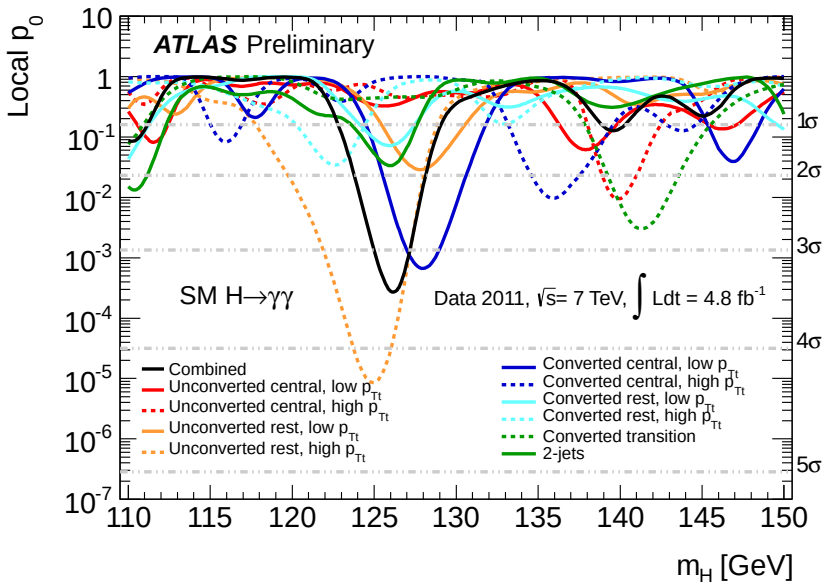


$\sqrt{s} = 8\,\mathrm{TeV}$

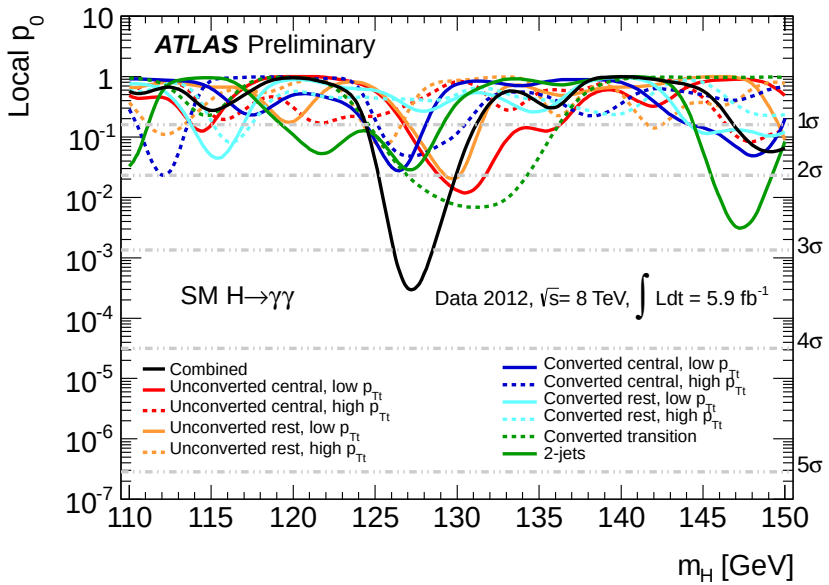


p_0 per Category at $7\,\mathrm{TeV}$ and $8\,\mathrm{TeV}$

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

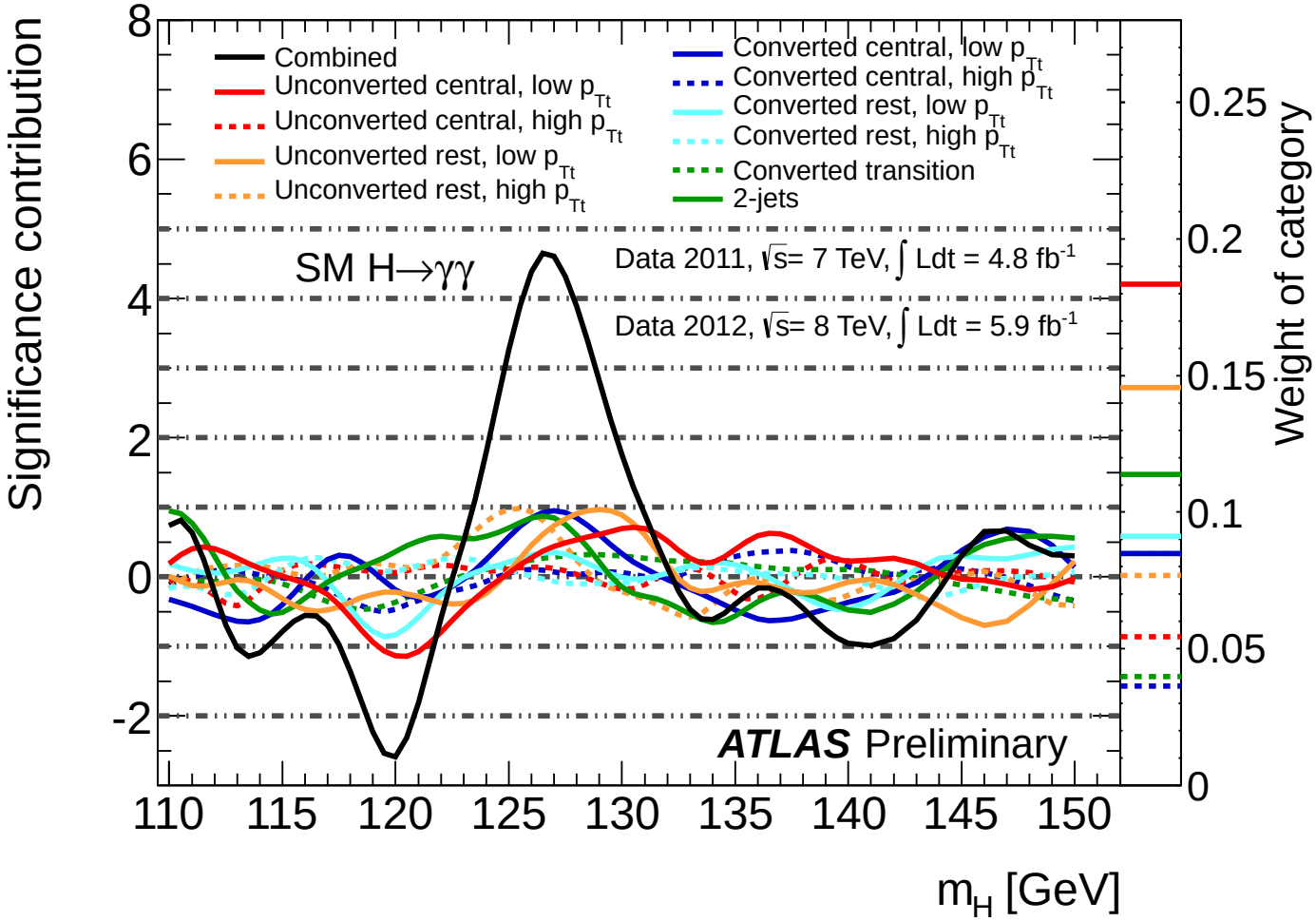


$\sqrt{s} = 8\,\mathrm{TeV}$



- Categories contribute differently between the $7\,\mathrm{TeV}$ and $8\,\mathrm{TeV}$ data samples

Contribution of Each Category



Contribution of each category to observed significance (each category weighted according to its observed importance, right: expected weights)