Search for the Standard Model $H \rightarrow \gamma\gamma$ decays with the ATLAS detector at the LHC

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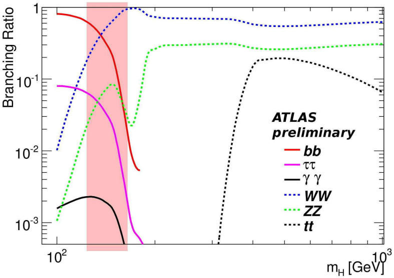
Introduction

- $H \to \gamma\gamma$ is one of the most promising discovery channels for a SM Higgs boson in low mass region ($114 < m_{\mathrm{H}} < 150\mathrm{GeV}$)



- Small branching ratio ($2.23 \cdot 10^{-2}$ for $m_H = 120\mathrm{GeV}$)

BUT

- Simple signature
- Very good mass resolution ($\approx$1.5GeV)

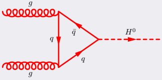
→ Need good photon reconstruction/identification
→ Need proper conversion handling
→ Need good photons direction measurement

- QCD higher order corrections are considered for both signal and background
- Contribution of fragmentation from hard partons to photons taken into account
- Inclusive analysis and diphoton production in association with jets considered
- Significance computed with max. likelihood fit compared to event counting
- Studies based on a realistic detector simulation of MC signal and background

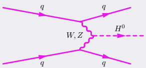
Signal and background

Higgs boson production

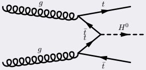
- gg fusion



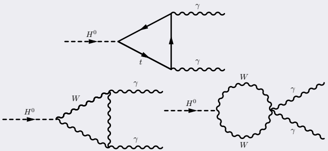
- Vector Boson Fusion (VBF)

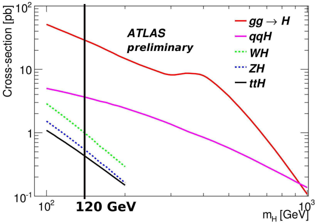


- Associated production with W, Z or $t\bar{t}$



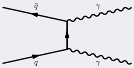
Signal

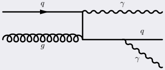


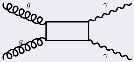


Background

- Irreducible : $\gamma\gamma$(+jets) (Born, fragmentation processes, box)





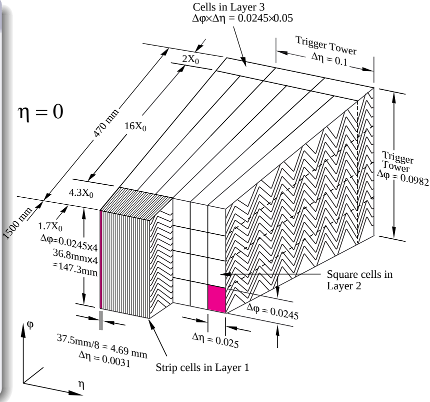


- Reducible : γ/jet(s), jet(s)/jet(s)

Photon reconstruction and identification

Reconstruction and calibration

- Photon reconstructed from EM clusters
  (Barrel : 3×7 in $\eta \times \phi$ for converted photons, 3×5 for unconverted photons, EndCap : 5×5)
- Cluster position corrected for known systematic biases
- Energy reconstructed using longitudinal weights to correct :
  → Energy loss in front of the calorimeter
  → Longitudinal leakage
  → Energy loss outside the cluster
- Different weights for unconverted photons and converted photons

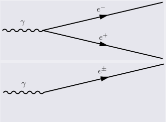


Identification and isolation

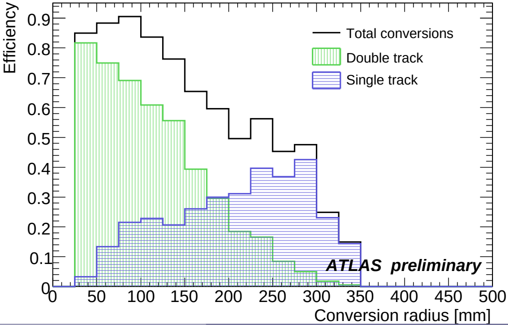
- To reduce background from jets faking photons below irreducible background
- Identification with cut based method (on shower shape parameters)
  → Middle layer and hadronic calorimeter : Jet rejection with wide showers
  → Strips Fine segmentation : γ/π^0 separation
- Isolation (using tracks)

Conversion reconstruction

- MC studies : 57% of $H \rightarrow \gamma\gamma$ events have ≥ 1 conversion ($R_{conv} < 800mm$)
- 2 types of converted photons are used :



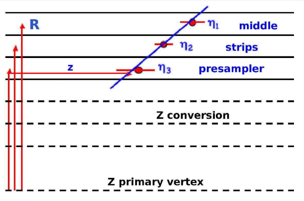
  - Double track conversions → Reconstructed by a vertexing algorithm using 2 tracks with opposite charges as input
  - Single track conversions → Separation of primary electron from conversion electron with the signal in the first pixel layer
- Reconstruction efficiency $\approx$ 66.4% for conversions with $R_{conv} < 400mm$
  (with the reconstruction software version used for this analysis)



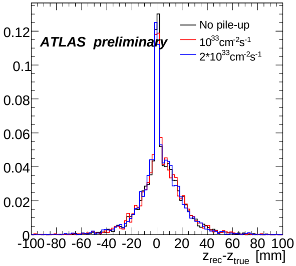
Pointing - Primary Vertex

- Precise measurement of the primary vertex position is very important to improve the Higgs mass resolution
- Iterative method to measure photons directions - Linear fit using :

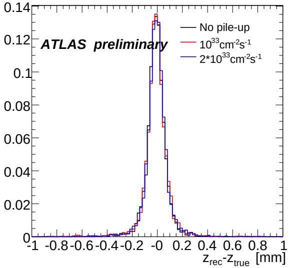
→ Multi-layer structure of the EM calorimeter
→ Position of the conversion vertex used when possible
→ And reconstructed primary vertex position computed by the tracker and selected among high luminosity vertices



$Z_{\text{rec}} - Z_{\text{true}}$
WITHOUT reconstructed primary vertex
$\sigma_{\text{tails}} = 8\text{mm}$

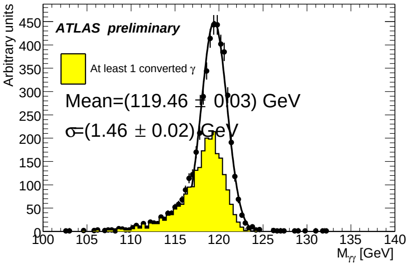


$Z_{\text{rec}} - Z_{\text{true}}$
WITH reconstructed primary vertex
$\sigma_{\text{peak}} = 0.07\text{mm}$



Invariant mass and resolution

- Mass resolution is determined from an asymetric Gaussian fit ($[-2\sigma, +3\sigma]$) on the invariant di-photon mass peak

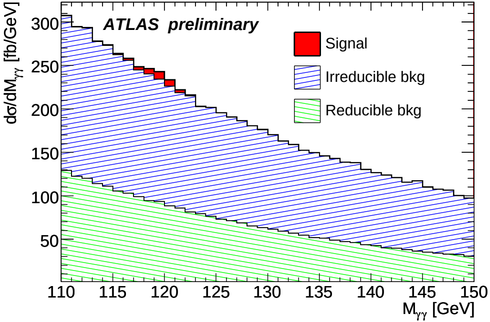


m_H	120GeV		130GeV	
	No pileup	Pileup	No pileup	Pileup
Mass fitted (GeV)	119.46	119.47	129.47	129.41
σ_m (GeV)	1.46	1.52	1.54	1.62

- The relative mass resolution σ_m/m is close to 1.2% degrading by a few percent when $10^{33}\text{cm}^{-2}\text{s}^{-1}$ pileup is added

Inclusive analysis

- $0 < |\eta| < 1.37$, $1.52 < |\eta| < 2.37$ (motivated by offline photon identification and fake rate)
  $\Rightarrow$ Also applied in H+1jet and H+2jets analysis
- $p_T^{\gamma_1} > 40$GeV, $p_T^{\gamma_2} > 25$GeV (obtained from optimization studies)



Expected cross sections :

σ_{signal}	25.4 fb
$\sigma_{\text{background}}$	947 fb

in a mass window of $m_{\gamma\gamma} \pm 1.4\sigma$

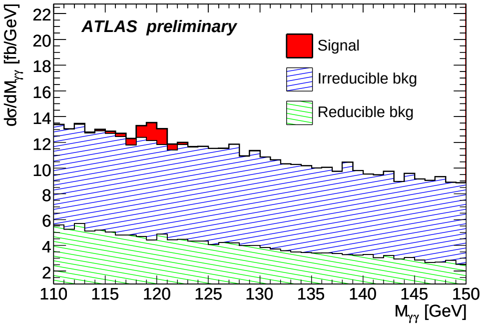
$S/B = 0.02$

K-factor applied : $K_{\gamma j} = 2.1$ and $K_{jj} = 1.3$

H+1jet analysis

Leading jet in $gg \to Hj$ and VBF tends to be harder and more separated from $\gamma\gamma$ than from background events

- ${p_T}^{\gamma_1} > 45\text{GeV}$, ${p_T}^{\gamma_2} > 25\text{GeV}$
- ≥ 1 hadronic jet with ${p_T}^{\text{jet}} > 20\text{GeV}$ in $|\eta| < 5$ (motivated by the ability to calibrate hadronic jets in ATLAS)
- $m_{\gamma\gamma\text{jet}} > 350\text{GeV}$



VBF + more jets with $gg \to H$

Expected cross sections :

	Inclusive	H+1jet
σ_{signal}	25.4 fb	4.0 fb
$\sigma_{\text{background}}$	947 fb	49 fb

in a mass window of $m_{\gamma\gamma} = 120 \pm 2\text{GeV}$

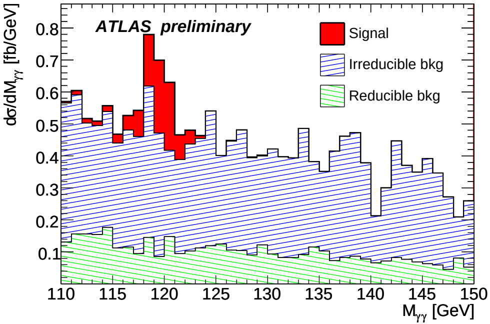
$S/B = 0.08$

H+2jets analysis

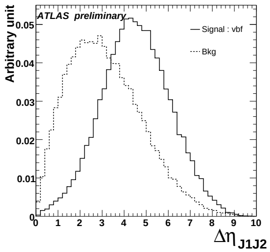
- $p_T^{\gamma_1} > 50\text{GeV}$, $p_T^{\gamma_2} > 25\text{GeV}$
- ≥ 2 hadronic jets with $p_T^{\text{jet}_1} > 40\text{GeV}$, $p_T^{\text{jet}_2} > 20\text{GeV}$ in $|\eta| < 5$
- Jets in opposite direction : $\eta_1\eta_2 < 0$ (VBF process at LO produces 2 high p_T and relatively forward jets in opposite hemisphere)
- $\Delta\eta_{jj} > 3.6$
- $m_{jj} > 500\text{GeV}$

} Pseudorapidity gap and invariant mass of signal jets tend to be significantly larger than those expected for background processes

- Photons in between tagging jets
- Central jet veto : $p_T > 20\text{GeV}$, $|\eta| < 3.2$



Mainly VBF



H+2jets analysis

- $p_T^{\gamma_1} > 50\text{GeV}$, $p_T^{\gamma_2} > 25\text{GeV}$
- ≥ 2 hadronic jets with $p_T^{\text{jet}_1} > 40\text{GeV}$, $p_T^{\text{jet}_2} > 20\text{GeV}$ in $|\eta| < 5$
- Jets in opposite direction : $\eta_1\eta_2 < 0$ (VBF process at LO produces 2 high p_T and relatively forward jets in opposite hemisphere)
- $\Delta\eta_{jj} > 3.6$
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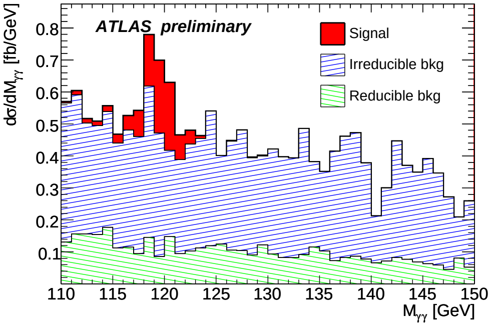


Mainly VBF

Expected cross sections :

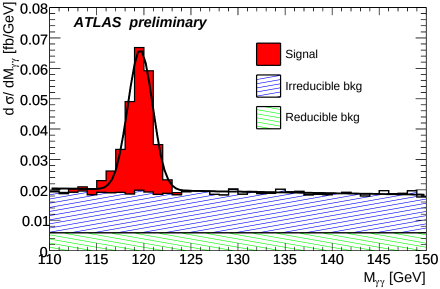
	Inclusive	H+1jet	H+2jets
σ_{sig}	25.4 fb	4.0 fb	0.97 fb
σ_{bkg}	947 fb	49 fb	1.95 fb

in a mass window of $m_{\gamma\gamma} = 120 \pm 2\text{GeV}$

$S/B = 0.5$

H+E_T^{miss} and H+1 lepton from associated production

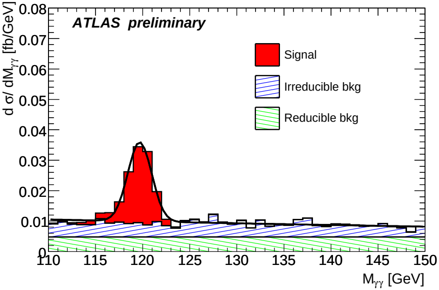
H+E_T^{miss}+1 lepton



Signal : Mainly from $WH \to \ell\nu\gamma\gamma$ and $t\bar{t}H$

$S/B \approx 1.7$

H+E_T^{miss}



Signal : Mainly from $ZH \to \nu\nu\gamma\gamma$

$S/B \approx 2$

Expected cross sections :

	Inclusive	H+1jet	H+2jets	H+E_T^{miss}+1 lepton	H+E_T^{miss}
σ_{sig}	25.4 fb	4.0 fb	0.97 fb	0.126 fb	0.072 fb
σ_{bkg}	947 fb	49 fb	1.95 fb	0.075 fb	0.036 fb

in a mass window of $m_{\gamma\gamma} = 120 \pm 2(1.8)$GeV for H+$E_T^{miss}$+1 lepton (for H+$E_T^{miss}$)

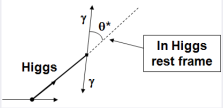
Maximum-likelihood fit

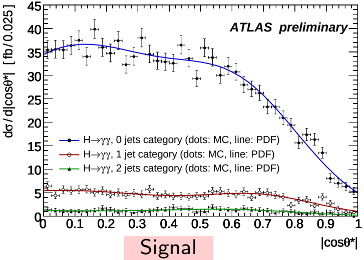
- Unbinned extended multivariate maximum likelihood fit

→ Takes the advantage of discrimination information from the kinematics and topological properties of $H \to \gamma\gamma$ decays

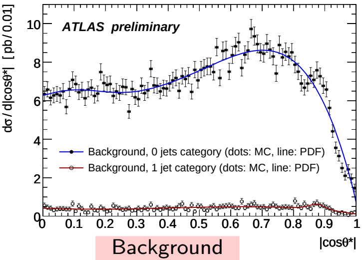
Fit variables

- $m_{\gamma\gamma}$
- $p_{T\,\mathrm{Higgs}}$
- $|cos\theta^*|$ where θ^* is the photon decay angle in the Higgs rest frame wrt Higgs lab flight direction





Signal



Background

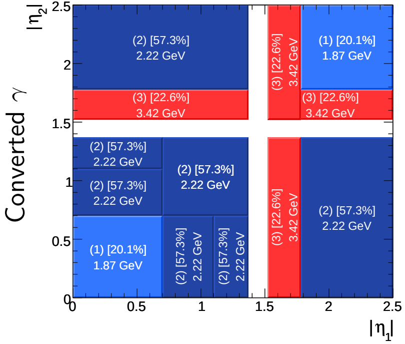
Maximum-likelihood fit

Categories used to split data into subsets

- Separate sub-population of events with different properties
- Different categories can have different values of PDF parameters or different PDFs altogether
- Gives finer-grained description of data / Increase significance / Reduces biases from correlations ⇒ Improves the accuracy of the likelihood model

Fit categories

- 3 η categories
- converted/unconverted photons categories
- 3 Higgs production categories : H + 0, 1, 2 jets



Discovery potential

- Expected signal significance for 10 fb^{-1} of integrated luminosity (in a mass window of $\pm 1.4\sigma$ around m_H)

Based on event counting

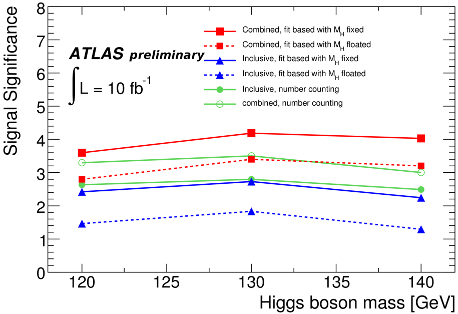
m_H (GeV)	Inclusive	H + 1 jet	H + 2 jets	Combined
120	2.6	1.8	1.9	3.3
130	2.8	2.0	2.1	3.5
140	2.5	1.8	1.7	3.0

$\Rightarrow$ Combined significance is $\approx$25% higher than significance of inclusive analysis

Using combined fit

m_H (GeV)	Floating mass	Fixed mass
120	2.8	3.6
130	3.4	4.2
140	3.2	4.0

$\Rightarrow$ Combined fit with fixed Higgs mass increases the significance by $\approx$40% with respect to inclusive analysis



Conclusion

- Combined analysis for H+0jet, H+1jet and H+2jets improves the significance by ≈25% with respect to inclusive analysis
- Use of an unbinned maximum-likelihood fit has been studied to enhance the expected sensitivity
  ⇒ Enhances the significance by ≈ 40% with respect to inclusive analysis
- 5σ discovery should be possible with integrated luminosity of 20-30fb^{-1}
- Many improvements since previous studies... and many areas are still going to be improved (conversions...)

⇒ *And of course : work will be needed to understand the detector performance with first data...*

BACKUP

Trigger

- L1 menu : 2EM13I $\rightarrow \geq 2$ isolated electron or photon candidates with $E_T = 13$GeV
- L2 and EF : 2g17i - Refine the analysis of L1

Efficiency for the 2g17i menu item to trigger on $H \rightarrow \gamma\gamma$ events with $m_H = 120$GeV - Normalized with respect to the offline selection

Trigger Level	2g17i Trigger efficiency
L1	96$\pm$0.3
L2 Calo	95$\pm$0.4
EF Calo	94$\pm$0.4

- Efficiency loss mainly due to the calorimeter isolation at L1 which is not applied in the offline photon selection
- 2g17i should be usable upt to luminosities of 10^{33}cm^{-2}s^{-1}

MC event generation

Signal

- Events generated using PYTHIA : LO matrix element calculation for all processes
- MC@NLO also used to simulate gluon fusion process
- HERWIG also used to model VBF process

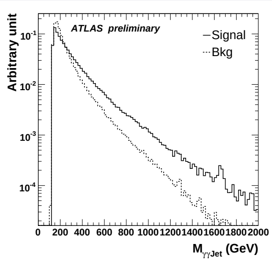
$\Rightarrow$ Full detector simulation used
All generated samples used for signal are normalized to the NLO cross-sections taking into account only QCD corrections

Background

Process	σ calculator	Cuts	σ (pb)	Full simulation # of events	Fast simulation # of events
$q\bar{q}, qg \rightarrow \gamma\gamma x$	ReBos/ DIPHOX	$80 < m_{\gamma\gamma} < 150$GeV $p_{T\gamma} > 25$GeV, $\lvert\eta\rvert < 2.5$	20.9	PYTHIA/ALPGEN 200000/1300000	ALPGEN 1670000
$gg \rightarrow \gamma\gamma$	ReBos	$80 < m_{\gamma\gamma} < 150$GeV $p_{T\gamma} > 25$GeV, $\lvert\eta\rvert < 2.5$	8.0	PYTHIA 200000	PYTHIA 850000
γj	JETPHOX	$p_{T\gamma} > 25$GeV	$180 \cdot 10^3$	PYTHIA 3000000	ALPGEN 36700000
jj	NLOJET++	$p_{T\gamma} > 25$GeV	$477 \cdot 10^6$	PYTHIA 10000000	ALPGEN 37000000

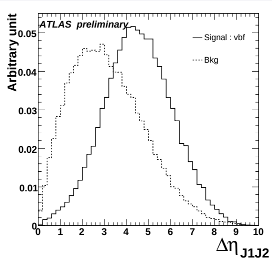
Discriminating variables for H+1, 2 jets analysis

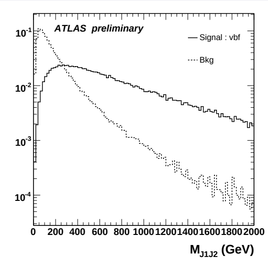
H+1 jet



- $m_{\gamma\gamma j} > 350\text{GeV}$

H+2 jets





- $\Delta\eta_{jj} > 3.6$
- $m_{jj} > 500\text{GeV}$

Fit – Fitter used

Hfitter Performs unbinned extended maximum likelihood fits, arbitrary number of samples, categories and fit variables (based on RooFit)

$$\text{Likelihood}: \boxed{L = \prod_{c=1}^{n_{\rm cat}} e^{-\overline{N}^c} \prod_{i=1}^{N^c} P_i^c}$$

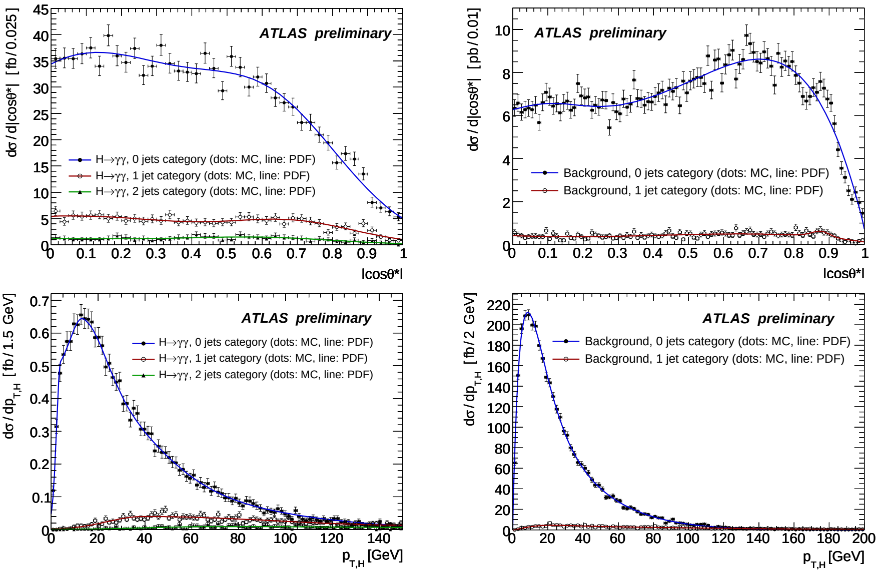
$$\text{with } P_i^c = N_H f_H^c P_{H,i}^c + \sum_{j=1}^{n_{\rm bkg}} N_{B_j}^c P_{B_j,i}^c \quad \text{and} \quad P_{U_j,i}^c = \prod_{k=1}^{n_{\rm var}} p_U^c(x_{k,i}) \quad \text{where} \quad U = H, B_j$$

and with

- N_H : total number of $H \longrightarrow \gamma\gamma$ events in sample sample
- c : category with distinct properties (η, p_T region, production mechanism...)
- f_H^c : fraction of signal events in category c
- $N_{B_j}^c$: number of background event of type j in category c
- $\overline{N}^c$: number of events expected in category c
- $n_{\rm bkg}$: number of background types γ/jet, 2γ+jet, di-jet, ...
- $p_U^c(x_{k,i})$: probability density for event i in category c of type U for dscriminant variable x_k

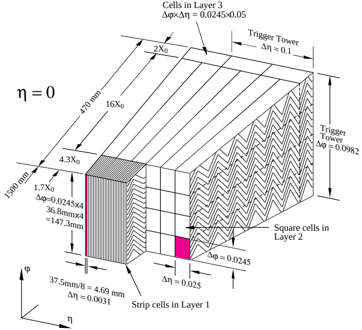
Fit

Signal | Background



(VBF topology not shown for background because of a too low relative cross-section)

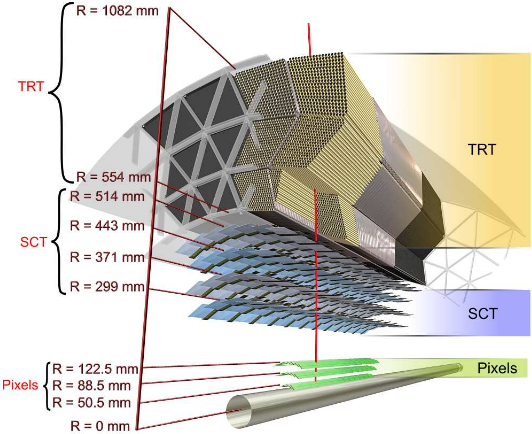
Calorimeter granularity



	$\lvert\eta\rvert$ *range*	Cell η size		Cell ϕ size	
		Layer 1	Layer 2	Layer 1	Layer 2
Barrel	0-1.4	0.025/8	0.025	0.1	0.025
	1.4-1.475	0.025	0.075	0.1	0.025
EndCap	1.375-1.425	0.05	0.05	0.1	0.025
	1.425-1.5	0.025	0.025	0.1	0.025
	1.5-1.8	0.025/8	0.025	0.1	0.025
	1.8-2.0	0.025/6	0.025	0.1	0.025
	2.0-2.4	0.025/4	0.025	0.1	0.025
	2.4-2.5	0.025	0.025	0.1	0.025

Granularity of layer 3 : $\Delta\eta \times \Delta\phi = 0.050 \times 0.025$

Inner detector



H+E_T^{miss} and H+1 lepton from associated production

H+E_T^{miss}+1 lepton

- Signal : Mainly from $WH \to \ell\nu\gamma\gamma$ and $t\bar{t}H$
- Background : Mainly from $t\bar{t}\gamma\gamma$, $W\gamma\gamma$ where W decays to $\ell\nu$ and $W\gamma \to e\nu\gamma$ where the other photon is radiated by the electron or is a jet faking photon

H+E_T^{miss}

- Signal : Mainly from $ZH \to \nu\nu\gamma\gamma$
- Background : Mainly from $t\bar{t}\gamma\gamma$, $Z\gamma\gamma$ and $W\gamma \to e\nu\gamma$ where the other photon is radiated by the electron or is a jet faking photon