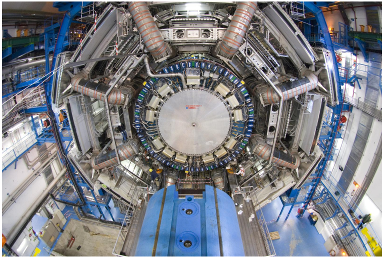
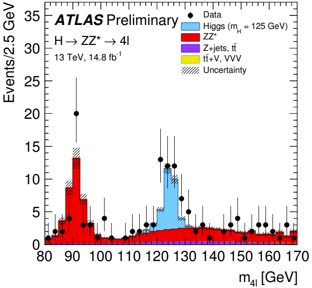
Searches for Rare Exclusive Higgs Boson Decays with ATLAS

Rhys Owen[1,2]
University of Birmingham[1], Rutherford Appleton Laboratory[2]
11th January 2017

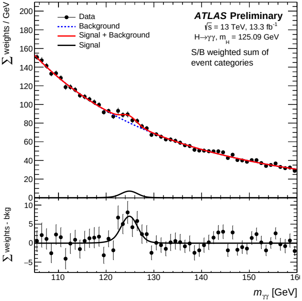


Introduction

- Higgs Boson discovered at LHC
- Leading discovery channels all involve bosons



ATLAS-CONF-2016-079



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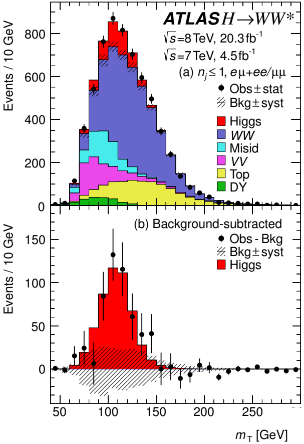
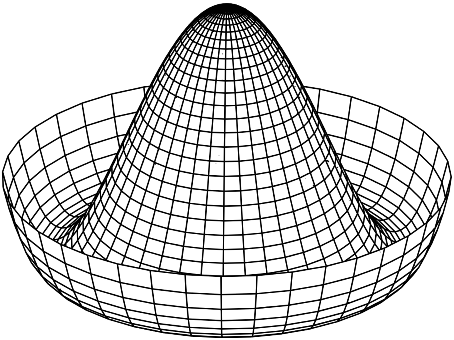


Phys.Rev. D92 (2015) no.1, 012006

BEH Mechanism

This mechanism underpins all of the Higgs Physics

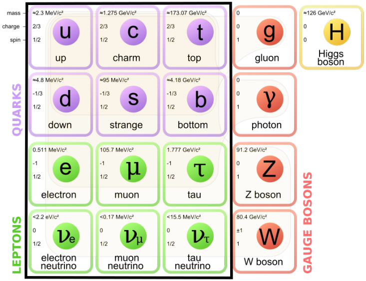
- Introduces a new field into the standard model
- $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$
- Four new degrees of freedom
  - 3 mix with the $W^{\pm}, Z^0$ giving them mass
  - The fourth gives rise to the standard model Higgs boson
- This explains the link between the Higgs boson, the electroweak bosons and their masses but says nothing about fermions



Fermion Masses

$$\mathcal{L}_{fermion} = -y_f \cdot [\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \bar{\phi} \psi_L]$$

$$\mathcal{L}_{fermion} = -\underbrace{\frac{y_f v}{\sqrt{2}} \cdot \bar{\psi}\psi}_{\text{mass term}} - \underbrace{\frac{y_f}{\sqrt{2}} \cdot h\bar{\psi}\psi}_{\text{Yukawa coupling term}}$$

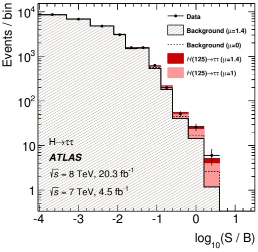


This combination of the Higgs field and fermions gives:

- gauge invariant mass terms for the fermions
- Introduces a Yukawa coupling directly between the fermions and the Higgs boson
- But masses are not generated directly by the spontaneous symmetry breaking as for the bosons

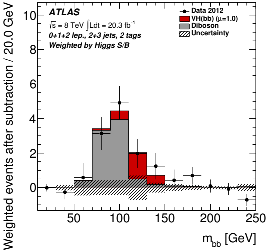
Existing Results

$H \to \tau\tau$



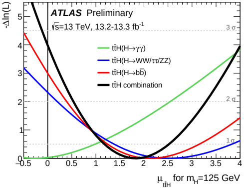
JHEP 04 (2015) 117

$H \to b\bar{b}$



JHEP 01 (2015) 069

top associated production

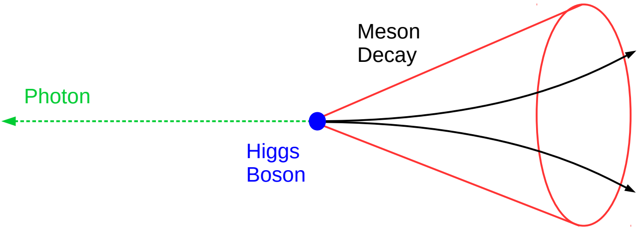


ATLAS-CONF-2016-068

There are several searches on-going with sensitivity to the Yukawa couplings

- The first direct evidence came from the observation of $H \to \tau\tau$ ($4.5(3.2)\sigma$)
- Most "Obvious" channels suffer from large backgrounds and other experimental challenges

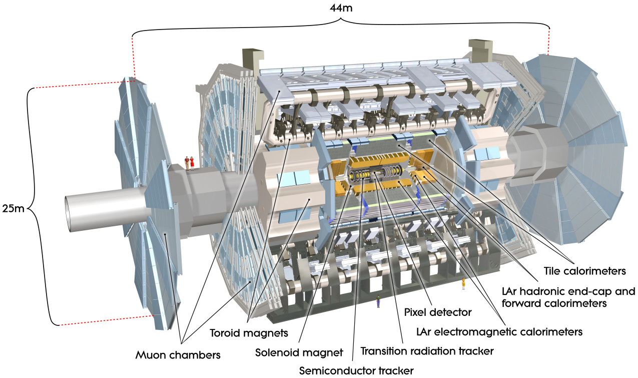
Higgs Boson $\rightarrow Q\gamma$



- One promising channel is Higgs boson decays to a photon and a meson
- Gives direct access the Yukawa couplings
- A distinctive topology to trigger and select the events
- At the cost of a small SM branching ratio

Channel	SM Branching Ratio
$BR(H \rightarrow c\bar{c})$	3×10^{-2}
$BR(H \rightarrow J/\psi\gamma)$	3×10^{-6}

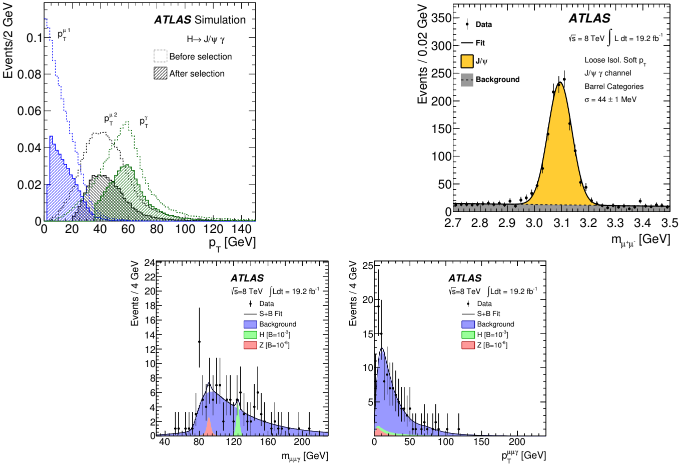
The ATLAS Experiment



The ATLAS experiment is a general purpose detector based at the Large Hadron Collider.

ATLAS Searches for Higgs Boson $\to J/\psi\gamma$ I

Phys. Rev. Lett. 114 (2015) 121801

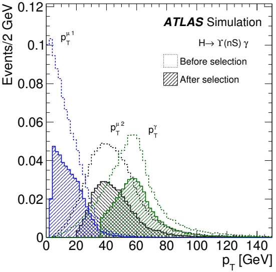


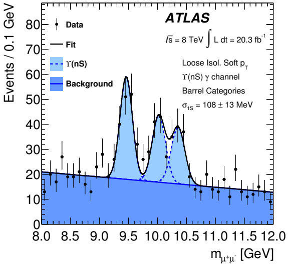
$$\boldsymbol{h \to J/\psi\gamma}$$

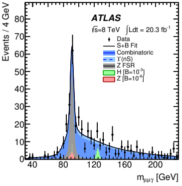
- First search for a decay of this type using $\sqrt{s} = 8\ \mathrm{TeV}$
- Previously presented in this forum by Andrew Chisholm

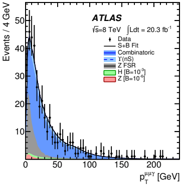
ATLAS Searches for Higgs Boson $\to \Upsilon(nS)\gamma$

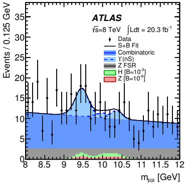
Phys. Rev. Lett. 114 (2015) 121801







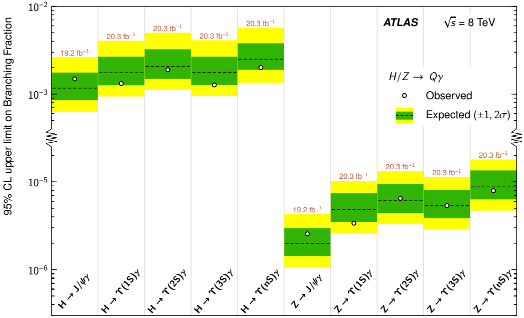




$$h \to \Upsilon(nS)\gamma$$

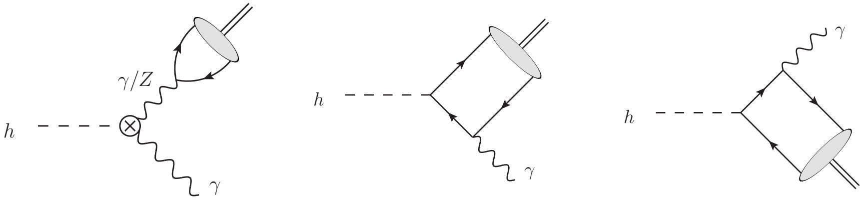
ATLAS Searches for Higgs Boson $\rightarrow J/\psi\gamma$ II

- Set limits on the Branching ratio of the order 1×10^{-3}
- Compared with a predicted SM branching ratio of 3×10^{-6} (JHEP 1508 (2015) 012)
- Any large deviation could be a sign of physics from beyond the standard model.



Phys. Rev. Lett. 114 (2015) 121801

ATLAS Searches for Higgs Boson $\rightarrow \phi\gamma$

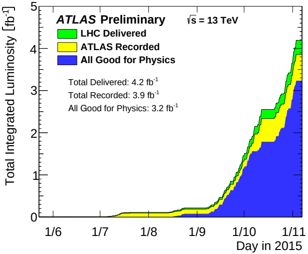


The Latest $Q\gamma$ search from ATLAS is for $H \rightarrow \phi\gamma$
Phys. Rev. Lett. 117, 111802

- This is an analogous decay to the $J/\psi\gamma$ decay mode
- SM prediction $\mathcal{B}(H \rightarrow \phi\gamma) = (2.3 \pm 0.1) \times 10^{-6}$(JHEP 1508 (2015) 012)
- The direct diagrams give access to the strange Yukawa coupling.

Analysis Strategy

- Analysis performed using 2015 pp dataset
- Data is selected with a dedicated trigger
- Backgrounds are modelled with a data driven model
- SM signals are generated using the ATLAS simulation infrastructure.
- These are combined in a Maximum Likelihood fit to obtain CL_s limits on the Branching Ratio



ATLAS pp 25ns run: August-November 2015										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
93.5	99.4	98.3	99.4	100	100	100	100	100	100	97.8
All Good for physics: 87.1% (3.2 fb^{-1})										

Luminosity weighted relative detector uptime and good data quality (DQ) efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at $\sqrt{s}$=13 TeV between August-November 2015, corresponding to an integrated luminosity of 3.7 fb^{-1}. The lower DQ efficiency in the Pixel detector is due to the IBL being turned off for two runs, corresponding to 0.2 fb^{-1}. Analyses that don't rely on the IBL can use those runs and thus use 3.4 fb^{-1} with a corresponding DQ efficiency of 93.1%.

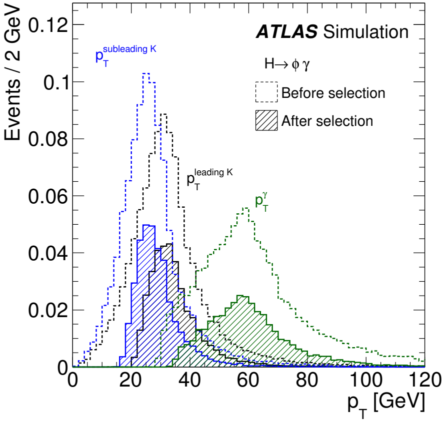
Event Selection

- Events from LHC stable beams with all ATLAS sub-detectors operating normally

Dedicated trigger

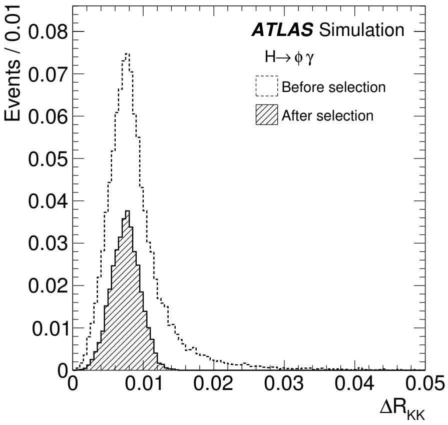
- Specificaly developed for this analysis
- photon of p_T greater than 35 GeV
- Two tracks consistent with the ϕ meson mass
- Leading track $p_T > 15$ GeV

Trigger efficiency is (w.r.t. offline selection) ≈ 80%



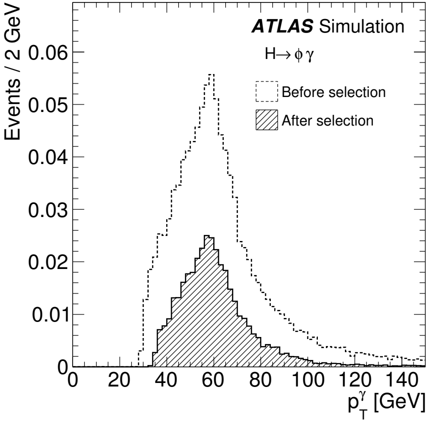
Track Selection

- ATLAS has no PID in the relevant p_T range
- All tracks assumed to to be $K^{\pm}$
- The $K^{\pm}$ with the highest p_T has the requirement $p_T > 20$ GeV
- $p_T > 15$ GeV is required for the second track
- di-track invariant mass is required to be within ± 20 MeV of the ϕ meson mass
- The sum of p_T of the tracks within $\Delta R = 0.2$ of the ϕ meson is required to be less than 10% of the di-track p_T (excluding the selected tracks)
- The tracks are expected to be very collimated.



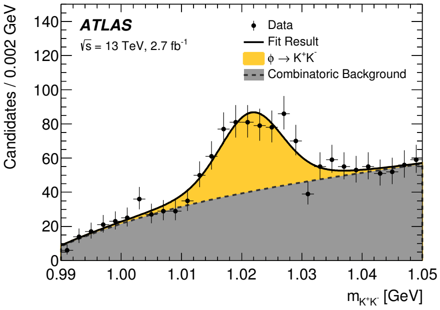
Photon Selection

- Photons reconstructed from clusters in the electromagnetic calorimeter
- Photon $p_T > 35$ GeV
- Within η acceptance $|\eta| < 2.37$ avoiding the transition region between calorimeter barrel and end-caps $1.37 < |\eta| < 1.52$
- Passing "Tight" photon identification requirements
- Both track and calorimeter isolation



Final $\phi\gamma$ Selection

- A further requirement is placed on the candidates that the azimuthal angle between the meson and the photon must be $\Delta\phi(K^+K^-, \gamma) > 0.5$
- in the case of multiple candidates in event a single $\phi\gamma$ pair is selected based on:
  - Highest photon p_T
  - Di-track pair closest to the ϕ mass
- A final p_T requirement is placed on the ϕ candidate dependant on the three body mass. 40 GeV at the Zmass rising linearly to 45 GeV at the Higgs boson mass



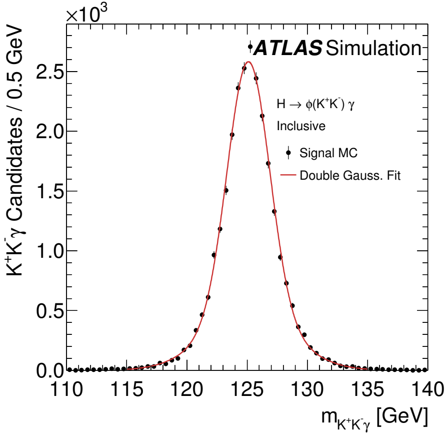
Signal Modelling

Several Higgs boson production modes considered

- Gluon fusion
- Vector Boson Fusion
- WH, ZH associated production
- Gluon fusion cross section scaled to include other processes

Higgs boson decay simulation

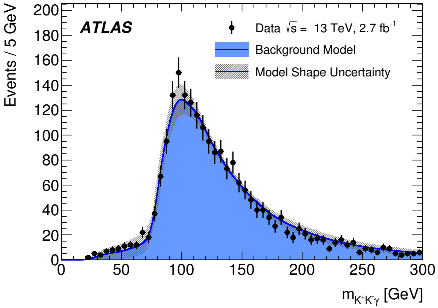
- Modelled in Pythia 8.1.86
- ϕ helicity not simulated but corrected for ($\approx 1\%$ effect)



Background Modelling

Background dominated by multijet and γ-jet events

- Data here from a loosened selection
- Background shows a kinematic peak at ≈ 100 GeV.
- Difficult to generate a Monte Carlo sample with a large acceptance to the signal region
- Also difficult to model with a reasonable polynomial
- Instead a nonparametric data driven method is used to model this shape



Background Procedure

Use loose selection of events

- The isolation cuts are removed
- The di-track $p_T$cut is loosened
- Selecting $\approx$ 4000 events

Produce Kinematic and Isolation PDF's

- The p_T,η,ϕ values for the candidate tracks and photons are transformed to PDFs
- PDFs are also generated for the associated isolation values
- Multidimensional PDFs are used to retain the correlations

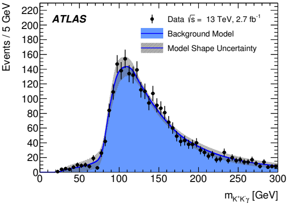
Create pseudo-candidates

- Kinematic variables are sampled from the PDFs (retaining their correlations)
- This enables the generation of a large ensemble of pseudo-candidates

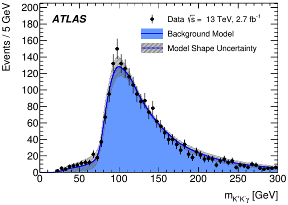
Background Validation

Generated pseudo-candidates then exbibit the same kinematic and isolation properties that they were modelled from

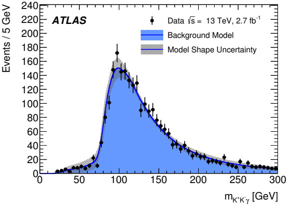
- Independently applying the loosened selection criteria shifts both the shape and normalisation of the data
- This is matched accurately with the behaviour of the pseudo-candidates



p_T CR



Photon Isolation CR

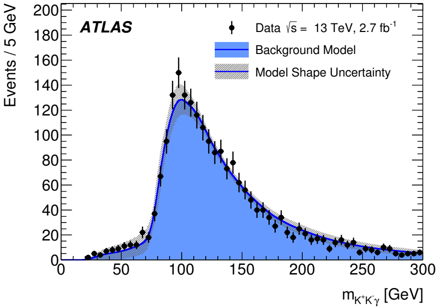


Meson Isolation

Background Systematics

The normalisation of the background is unconstrained in the final fit so the largest systematic effect would be from deviation in the shape

- These variations are introduced by altering the PDFs describing the di-track p_T and $\Delta\phi(K^+K^-, \gamma)$
- A further global shift of the three body mass shape is included motivated by the changes seen when removing the smallest correlation.
- These three shape variations describe the uncertainty shown in the plot.



Signal Systematics

The following systematics are calculated for the signal yield with the help of the ATLAS combined performance groups

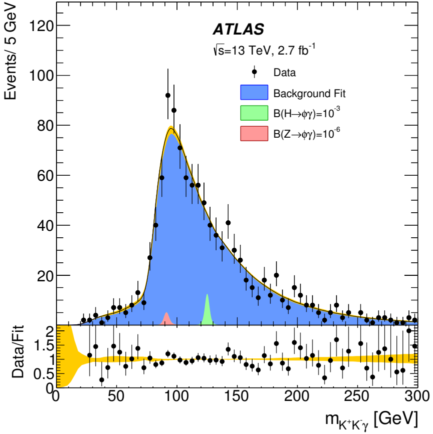
Systematic	Signal Uncertainty
Total H Cross section	12%
Trigger Efficiency	2%
Photon Identification and Reconstruction	2.6%
Track Reconstruction	6%
Luminosity	5%

- The track uncertainty covers material effects and the behaviour of the tracking algorithms with two close by tracks

Final $m_{K^+K^-\gamma}$ Fit

The final limits are determined using an unbinned maximum likelihood fit

- Signal modelled with a Gaussian with parameters from Monte Carlo
- The background shape is allowed to vary between the nominal and systematic templates.



Results

No significant excess was observed so limits are set on the branching ratio

Observed (Expected) Background					Expected Signal	
Mass Range [GeV]					Z	H
All	81–101		120–130		$\mathcal{B}[10^{-6}]$	$\mathcal{B}[10^{-3}]$
1065	288	(266 ± 9)	89	(87 ± 3)	6.7 ± 0.7	13.5 ± 1.5

- The small excess around 100 GeV is estimated to be $\approx 2\sigma$
- This leads to a slight degradation of the limits with respect to the expectation

Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}\,(H \to \phi\,\gamma)\,[\,10^{-3}\,]$	$1.5^{+0.7}_{-0.4}$	1.4
$\mathcal{B}\,(Z \to \phi\,\gamma)\,[\,10^{-6}\,]$	$4.4^{+2.0}_{-1.2}$	8.3

Future Prospects

Some preliminary studies of $H \to J/\psi\gamma$ at HL-LHC

- HL-LHC is targeting 3000fb^{-1}
- Meaning $\mathcal{O}(200M)$ Higgs bosons
- Interestingly as SM sensitivity for this channel is approached the channel $H \to \mu\mu$ where one of the muons emits a final state photon becomes a significant background

	Expected branching ratio limit at 95% CL		
	$\mathcal{B}(H \to J/\psi\gamma)$ [10^{-6}]		$\mathcal{B}(Z \to J/\psi\gamma)$ [10^{-7}]
	Cut Based	Multivariate Analysis	Cut Based
$300\,\text{fb}^{-1}$	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
$3000\,\text{fb}^{-1}$	55^{+24}_{-15}	44^{+19}_{-12}	$4.4^{+1.9}_{-1.1}$

	Standard Model expectation	
	$\mathcal{B}(H \to J/\psi\gamma)$ [10^{-6}]	$\mathcal{B}(Z \to J/\psi\gamma)$ [10^{-7}]
	2.9 ± 0.2	0.80 ± 0.05

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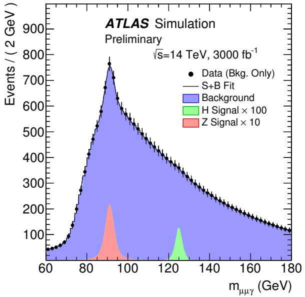

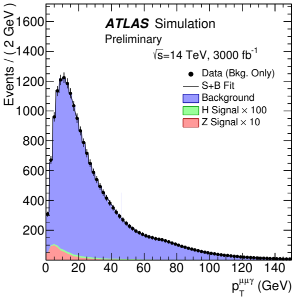

Conclusions

Discovering the Higgs boson was just the beginning

- Probing it's couplings especially to fermions can provide a telling window to the standard model
- Exclusive decays to mesons and photons can provide an opertunity to directly observe these couplings
- Work is on-going to explore these channels at the LHC with ATLAS