

SM $H \rightarrow \gamma\gamma$ discovery potential with ATLAS



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On Behalf of the ATLAS Collaboration

Physics at LHC 2008

Outline

- I. Introduction
- II. Experimental requirements
- III. Analysis strategies and results
- IV. Conclusions

Introduction

- Motivation for SM $H \rightarrow \gamma\gamma$
 - Sensitive at low Higgs mass region:
 $114 < M_H < 150 \text{ GeV}$.
 - Robust : side band.
- What is new ?
 - Simulation/reconstruction :
 - More realistic simulation.
 - Massive production of MC samples for the Computing System Commissioning (CSC) since 2006.
 - QCD higher order corrections in MC.
 - Signal and background processes' cross-sections known to NLO.
 - Contributions of reducible backgrounds' fragmentation from hard partons to photons are taken into account.
 - Updated analysis strategies:
 - Inclusive vs Combined analysis (H+0jet, 1jet and 2jets).
 - One variable ($M_{\gamma\gamma}$) vs additional variables ($P_{T\gamma\gamma}$ and $\cos \Theta_{\gamma}^*$).
 - Significance: Event counting vs maximum likelihood fit based.

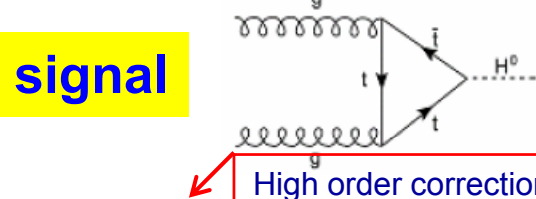
Main Experimental Issues

- **Need good energy and angular resolution** to achieve $\sim 1\%$ resolution in Higgs mass reconstruction
 - **Photon Calibration** energy scale and resolution
 - Separation of converted and unconverted photons
 - **Photon angle correction**
 - Photon angle from calorimeter pointing and tracking-based vertices
- **Need good photon identification** to reject the large QCD background
 - Rejection larger than 10^3 per single jet with photon efficiency larger than 80%.

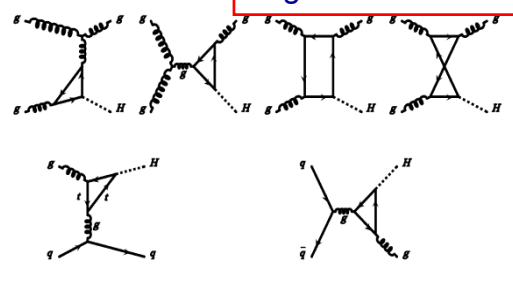
Signal and Backgrounds for $H \rightarrow \gamma\gamma$

gg Fusion: Dominant

signal



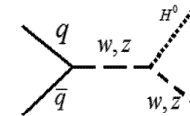
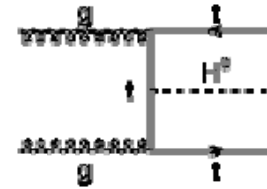
High order correction



Vector Boson Fusion (VBF):
Second largest



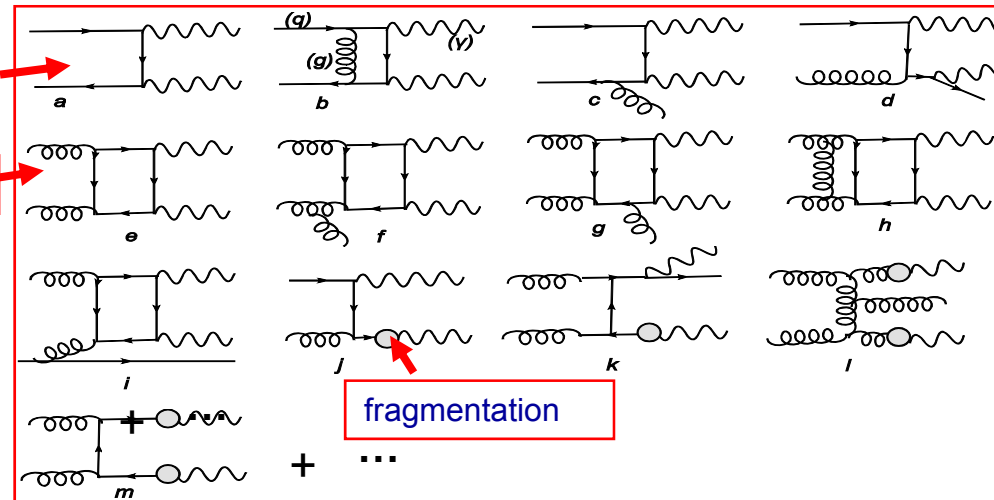
Associated: small cross-section



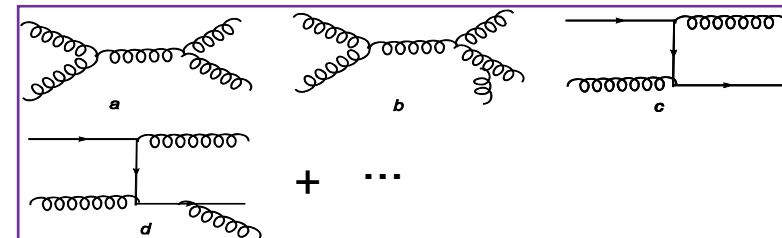
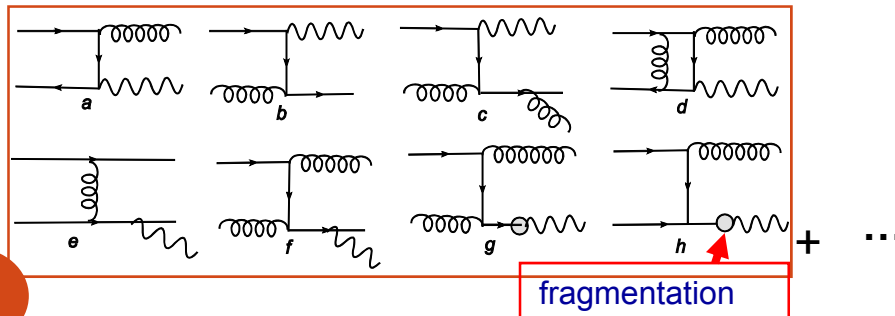
Irreducible:
(real) γ + (Jets)

Born

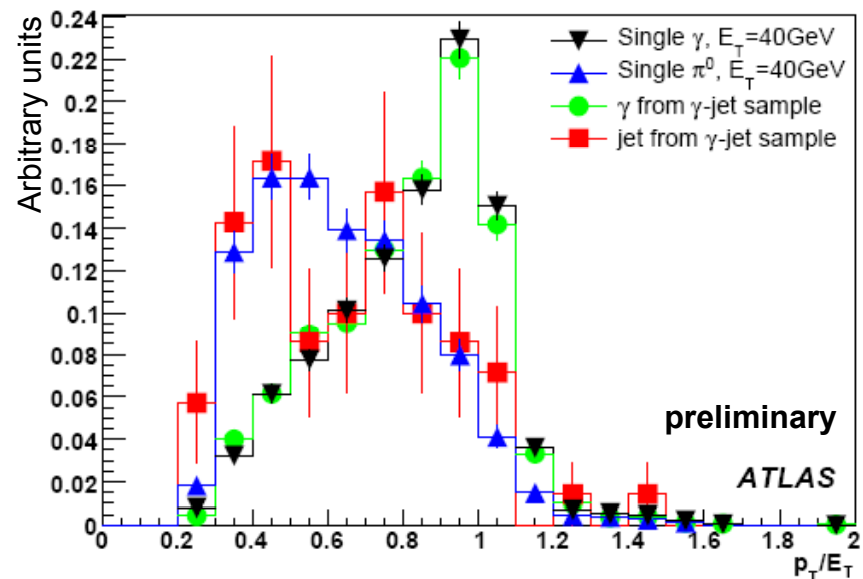
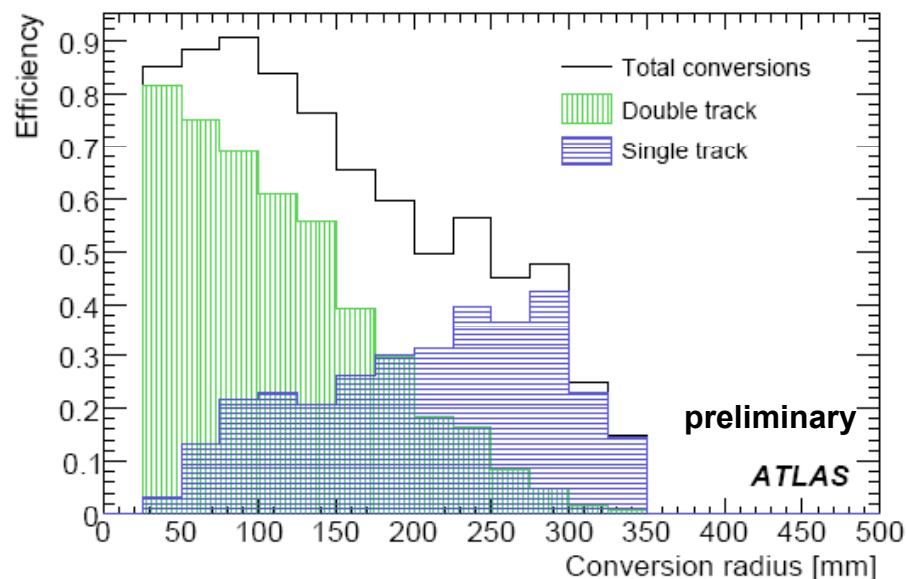
Box



Reducible (fake) γ : $\gamma j(\text{jets}) \rightarrow \gamma(\text{jets})$, $jj(\text{jets}) \rightarrow \gamma(\text{jets})$



Photon Conversion



- Around 50% selected $H \rightarrow \gamma\gamma$ events have at least one true conversion with a radius smaller than 80 cm.
- An algorithm tagging early converted photons based on reconstructed single/double tracks has a high tagging efficiency for those photons (left plot).
- P_T/E_T (right plot) provides additional discriminating power between selected converted photons and those from π^0 .

Calibration and vertex correction for Photons

- Calibration

- Longitudinal weights calibration:

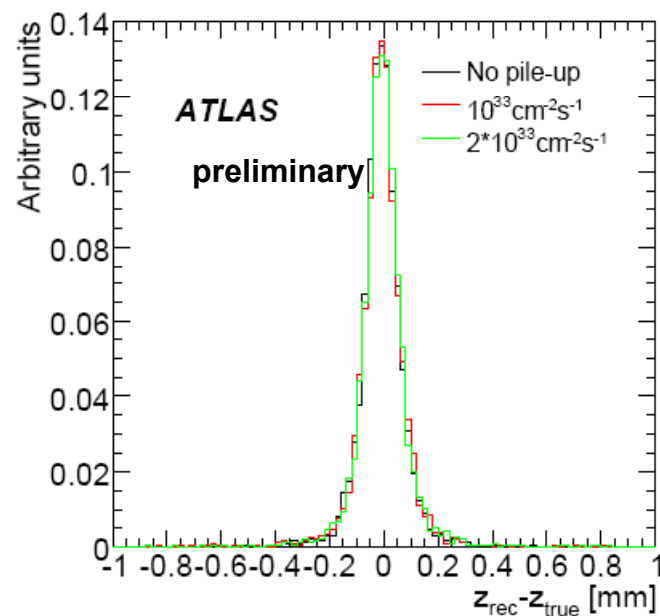
$$E_{rec} = s(b + W_0 E_{pres} + E_1 + E_2 + W_3 E_3)$$

- 3x5 cluster for unconverted photon
 - 3x7 cluster for converted photon
 - Refined energy correction
 - Lateral leakage and ϕ/η modulation
 - Refined position correction:
 - S-shape (η correction) and Phi-offset

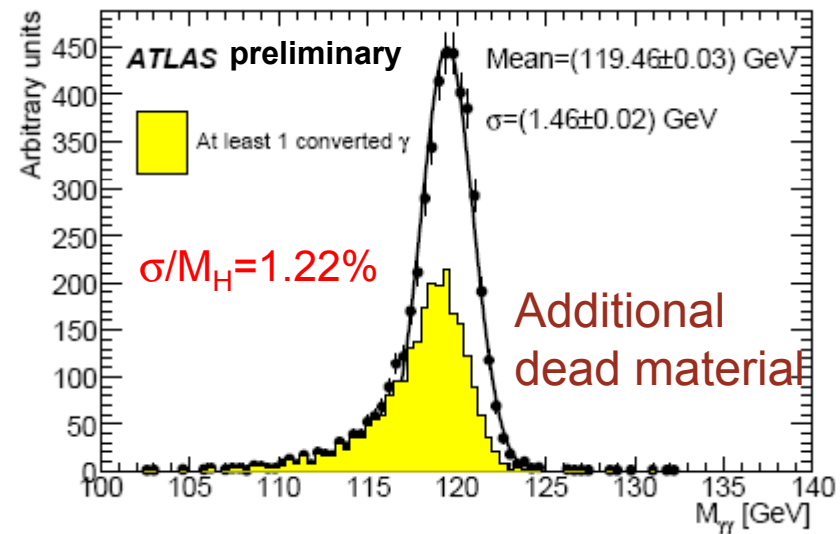
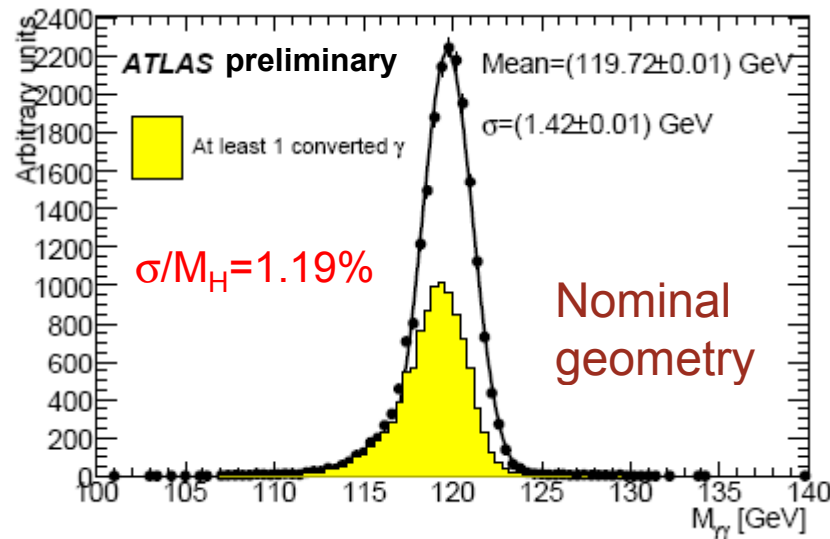
- Vertex correction

- Precise measurement of Z vertex is very important to improve the Higgs mass resolution.
 - Method : a linear fit of multi-layer centers of the EM shower + event vertex
 - The best Higgs boson position accuracy is achieved, with a Gaussian width 0.07 mm (see plot).
 - A likelihood method is used to distinguish the hard scattering vertices from pile-up vertices.

$$m_{\gamma\gamma} = \sqrt{2E_{\gamma 1} E_{\gamma 2} (1 - \cos(\theta_{\gamma 1} - \theta_{\gamma 2}))}$$



Results of calibration and vertex correction



ATLAS preliminary

m_H	120 GeV		130 GeV		140 GeV	
	No pileup	pileup	No pile up	pileup	No pileup	pileup
Mass fitted (GeV)	119.46	119.47	129.47	129.41	139.41	139.41
σ_m (GeV)	1.46	1.52	1.54	1.62	1.66	1.69

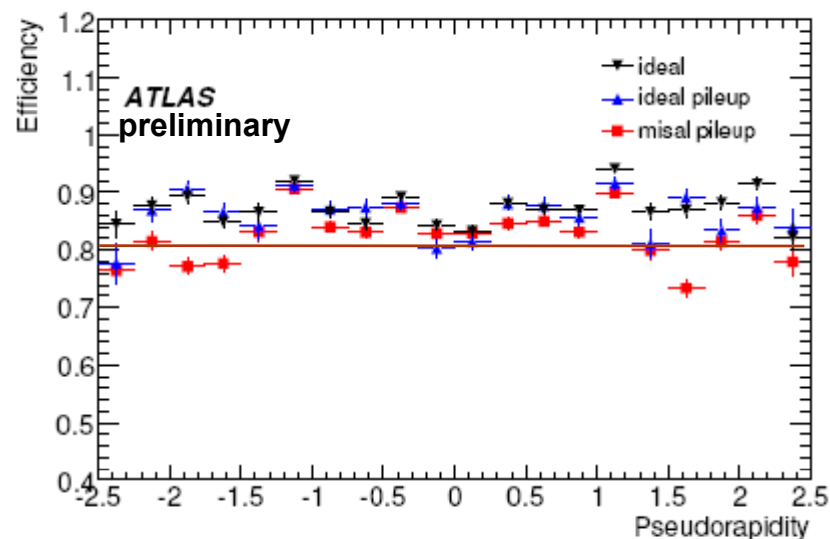
➤ The reconstructed mass peaks for geometries with nominal and additional dead material are shown.

➤ σ/M_H is close to 1.2%, degrading by a few percent with $10^{33}\text{s}^{-1}\text{cm}^{-2}$ pileup.

9/29/2008

Photon ID and jet rejection

- Three photon id methods:
 - Cut based (current analysis)
 - Likelihood ratio algorithm
 - H-Matrix method



ATLAS preliminary

	All	quark-jet	gluon-jet
Rejection (before isolation)	5070 ± 120	1770 ± 50	15000 ± 700
Rejection (after isolation)	8160 ± 250	2760 ± 100	27500 ± 2000

- Rejection of gluon-initiated jets is much higher than that of quark-initiated jets.
- After photon identification, the fake photons are dominated by π^0 .

Cuts for Analyses

Trigger and photon reconstruction identification, calibration (vertex correction) are applied beforehand

Inclusive/H+0jet

1	$P_{T\gamma 1} > 40 \text{ GeV}, P_{T\gamma 2} > 25 \text{ GeV}$
2	Mass Window ($\pm 1.4\sigma$)

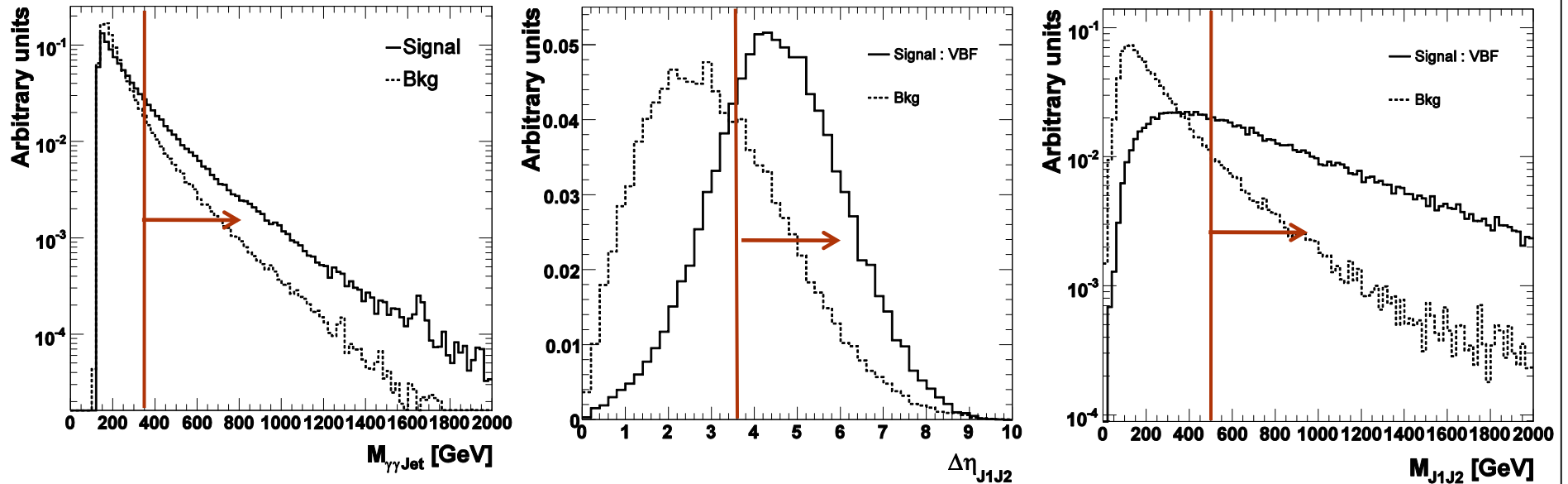
H+1jet

1	$P_{T\gamma 1} > 45 \text{ GeV}, P_{T\gamma 2} > 25 \text{ GeV}$
2	$P_{TJ1} > 20 \text{ GeV}, \eta_{j1} < 5.0$
3	$M_{\gamma j} > 350 \text{ GeV}$
4	Mass Window ($\pm 1.4\sigma$)

H+2jets (VBF)

1	$P_{T\gamma 1} > 50 \text{ GeV}, P_{T\gamma 2} > 25 \text{ GeV}$
2	$\eta_{J1} \bullet \eta_{J2} < 0, P_{TJ1} > 40 \text{ GeV}, P_{TJ2} > 20 \text{ GeV}, \Delta\eta_{j1j2} > 3.6$
3	Photons in between tagging jets
4	$M_{J1J2} > 500 \text{ GeV}$
5	Central jet veto ($P_{TJ} > 20 \text{ GeV} \mid \eta < 3.2$)
6	Mass window ($\pm 1.4\sigma$)

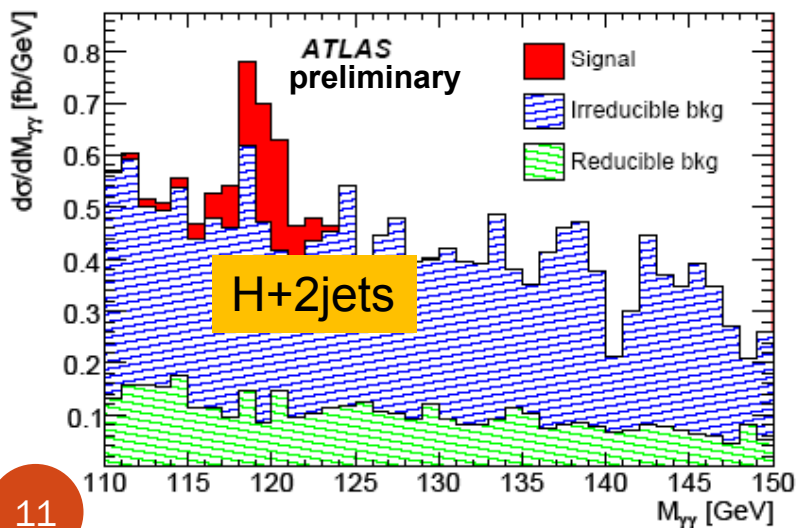
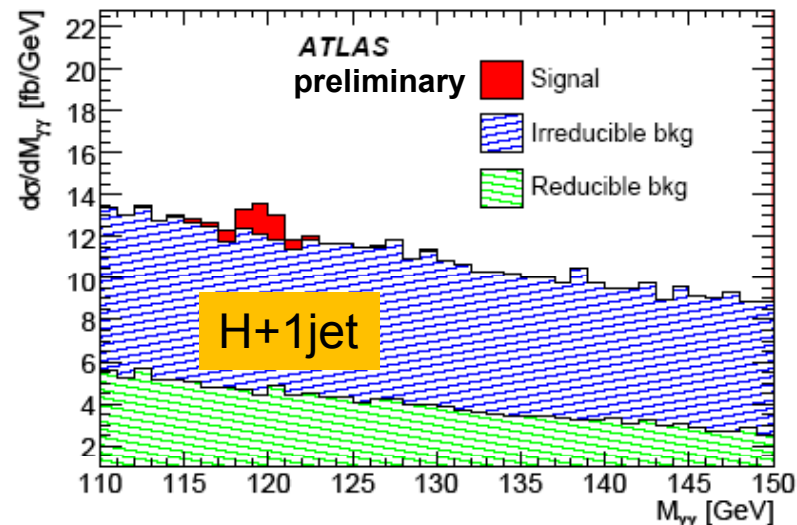
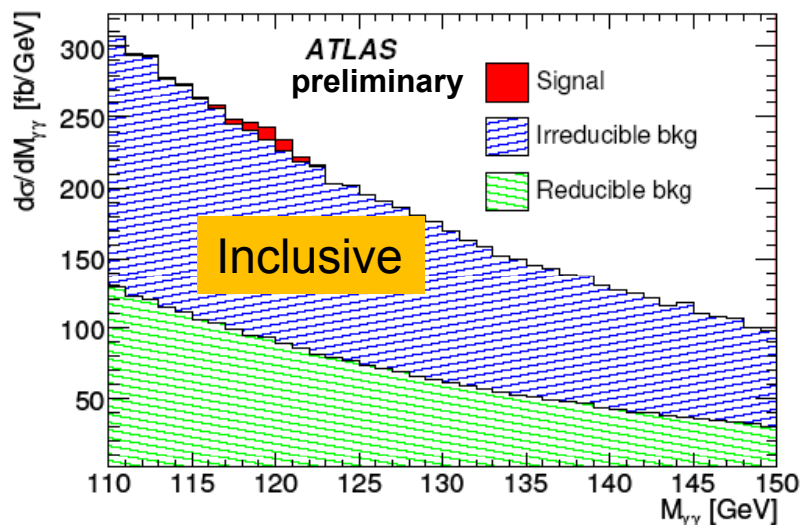
Discriminating variables



- $M_{\gamma\gamma\text{jet}}$ (left plot) is used in H+1jet analysis.
- $\Delta\eta_{J1J2}$ (middle plot) and M_{J1J2} (right plot) are for H+2jets analysis.
- The cuts of those variables can be optimized with data.

Results of Inclusive , H+1jet, H+2jet (VBF)

$M_H = 120 \text{ GeV}$



Cross-section (unit fb) with $\pm 1.4\sigma$ after analyses cuts

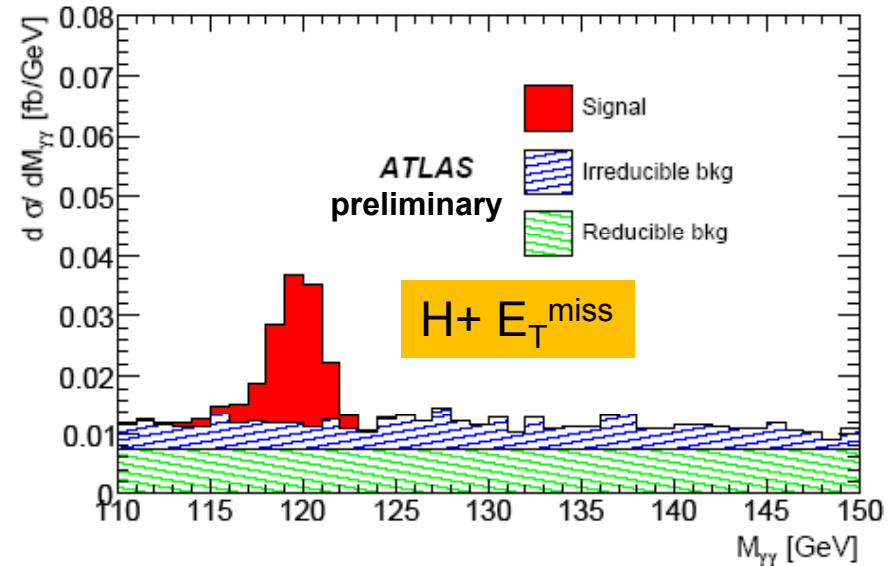
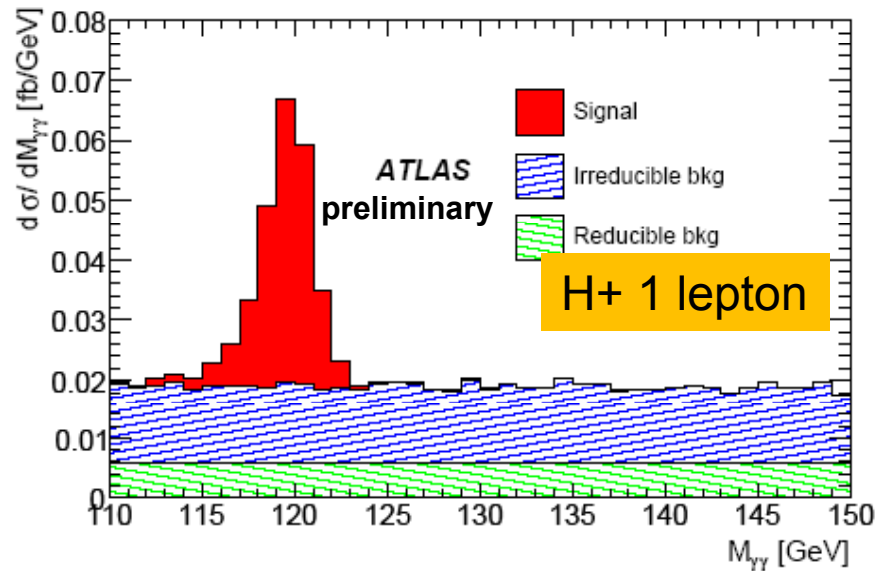
ATLAS preliminary

	Inclusive	H+1jet	H+2jet
Signal	25.4	4.0	0.97
Background	929	49	1.95

- The analyses have various sensitivities.
- Inclusive analysis has well defined side-band.
 - Robust in extrapolating background shapes.

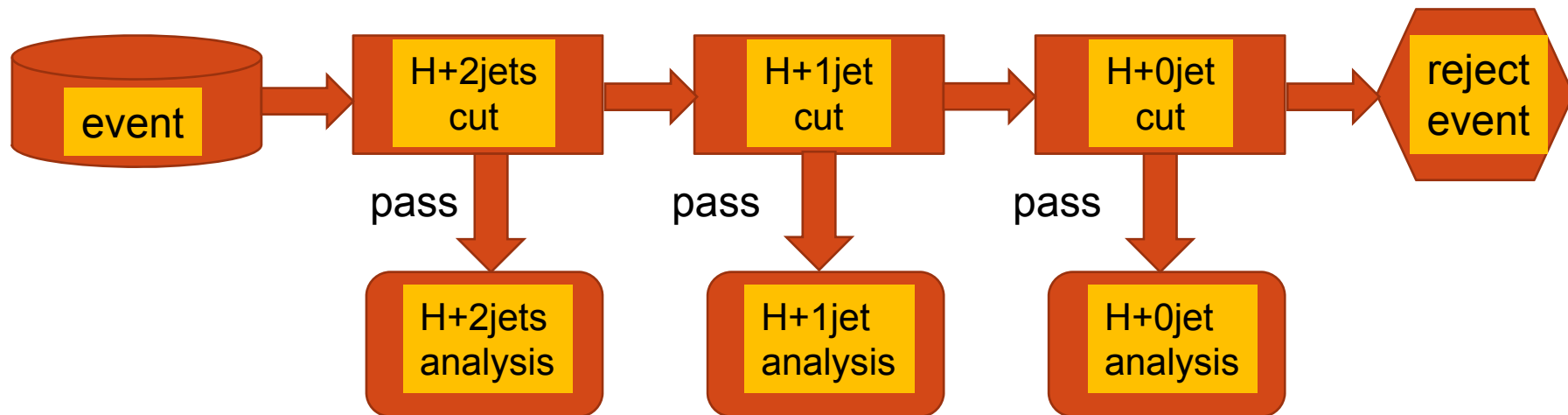
In addition: $H+E_T^{\text{miss}}$ and $H+1 \text{ lepton}$ from associated production

$M_H=120\text{GeV}$



- The signal for Higgs+missing E_T and Higgs+1 lepton is mostly from $ttH(\rightarrow\gamma\gamma)$ and W/ZH .
- Background mostly from $W+\gamma(\gamma)$, $tt(\text{bar})+\gamma(\gamma)$, $Z+\gamma\gamma$ and $\gamma\gamma$
- Reducible backgrounds (γ -jets, jets) are negligible.

Combined analysis for H+0jet, 1jet and 2jets



- Events passed inclusive cuts are divided into (H+0jet,1jet,2jets) sub-channels:
 - All events from the inclusive analysis are used, and each is used only once
- Take advantage of the different sensitivities from three individual sub-channels.

Signal significances (from event counting) for an
integrated luminosity of 10 fb^{-1}

ATLAS preliminary

m_H [GeV]	Analysis			
	Inclusive	$H + 1\text{jet}$	$H + 2\text{jet}$	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

- The mass window is $\pm 1.4\sigma_{\gamma\gamma}$.
- Combined significance obtained as the sum in quadrature of $H+0\text{jet}$ (not inclusive), $H+1\text{jet}$, $H+2\text{jets}$.
- The combined significance is $\sim 25\%$ higher than the significance of the inclusive analysis.

Signal significance computation with maximum likelihood fit

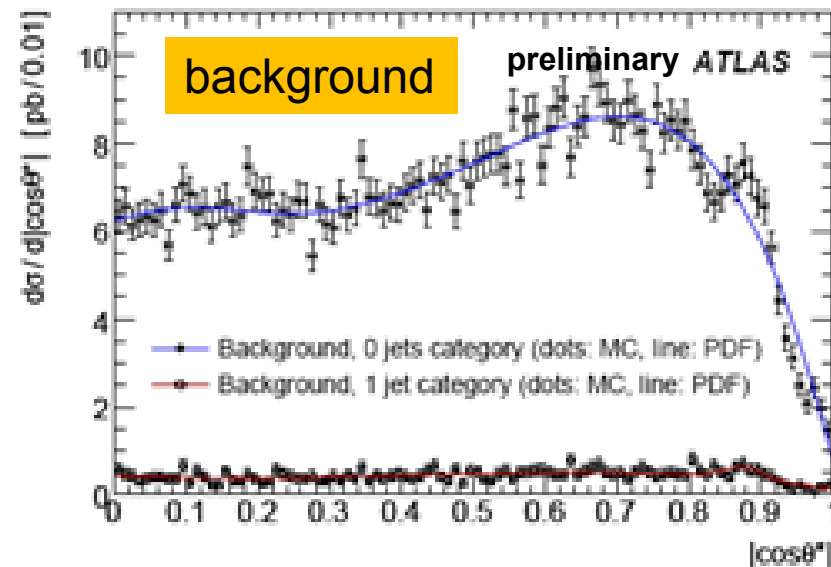
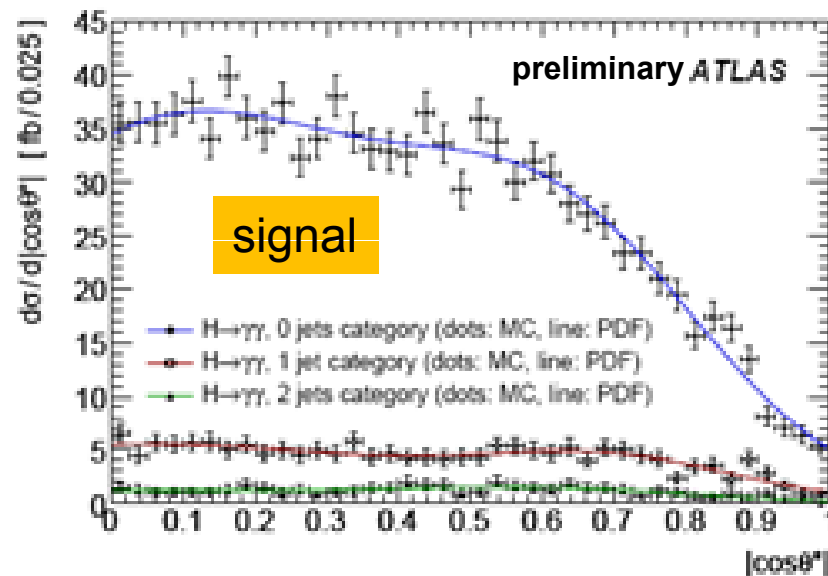
Fit variables: $M_{\gamma\gamma}$, $P_{T\gamma\gamma}$, $\cos(\Theta_\gamma^*)$ (relatively low correlations).

Based on RooFit

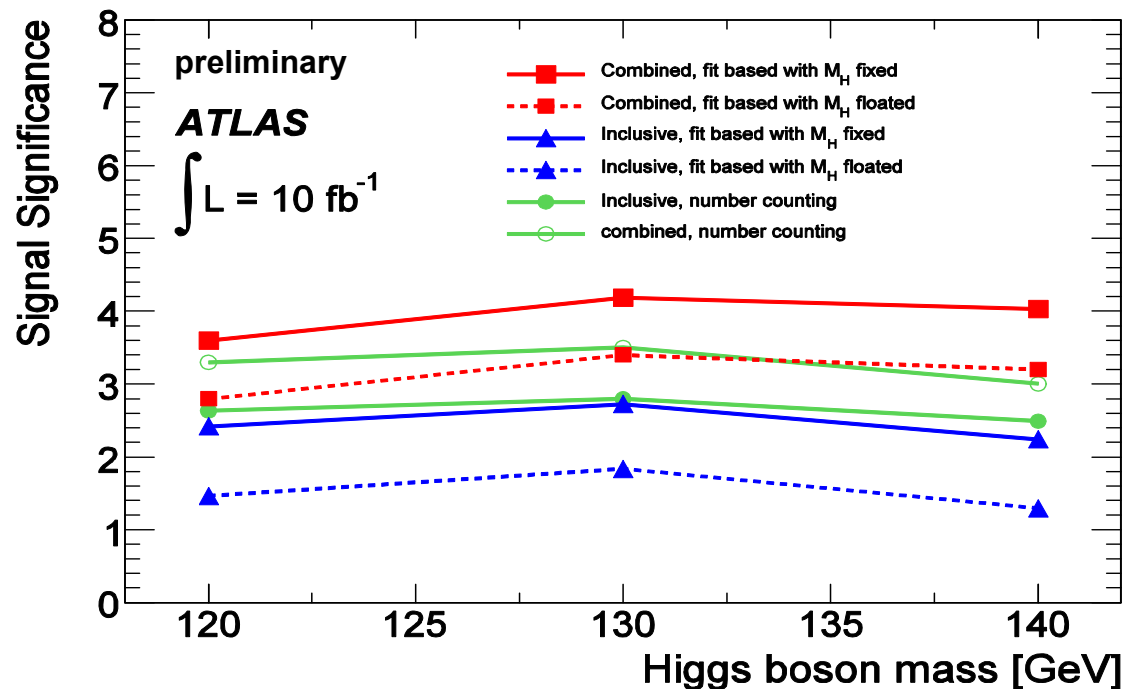
Classification 1: three η categories for photons in order to group photons with similar $M_{\gamma\gamma}$ resolutions together.

Classification 2: classify three jet categories (H+0jet, H+1jet, H+2jets).

Combination of different classifications and discriminating variables is obtained by doing a single simultaneous fit



Signal significances with mass scan



- The gain in significance obtained by doing a **combined fit** (including three fit variables and different classifications) is **~40%** with respect to the **inclusive analysis** (for 10 fb^{-1}).
- For a fixed Higgs mass fit, the 5σ discovery can be achieved with **~20 fb^{-1}** .
- For the fit with Higgs mass floating, the 5σ discovery can be expected with **~30 fb^{-1}** .
 - ❑ The unknown location of the resonance reduces the expected sensitivity.

Conclusions

- The impact of detector performance on $H \rightarrow \gamma\gamma$ channel has been studied:
 - Our current knowledge of the detector allows us to achieve the performance required for this analysis.
 - Extensive work is needed to understand the detector performance with early data.
- The inclusive study has been readdressed,
 - The $H+1\text{jet}$, $H+2\text{jets}$ have been studied,
 - $H+1\text{lepton}$ and $H+E_T^{\text{miss}}$ are investigated.
- The combined analysis for $H+0\text{jet}$, 1jet and 2jets has been proposed and the improvement of significance is about 25% wrt the inclusive one.
- Significance studies have been done using also maximum likelihood fit with various event classifications and discriminating variables.
 - Enhance the significance $\sim 40\%$ wrt the inclusive one.
 - It is possible to have 5σ discovery with integrated luminosity $20\text{-}30 \text{ fb}^{-1}$.

Backup Slides

Trigger for $H \rightarrow \gamma\gamma$

- Level 1: calorimeter which pass Region of Interest (ROI) data to Level 2.
- Level 2: refine the analysis of LVL1 across different detectors.
- Level 3: analysis data in the full detector and do more complicated physics analysis.

The efficiency on $H \rightarrow \gamma\gamma$ normalized wrt kinematic cuts.

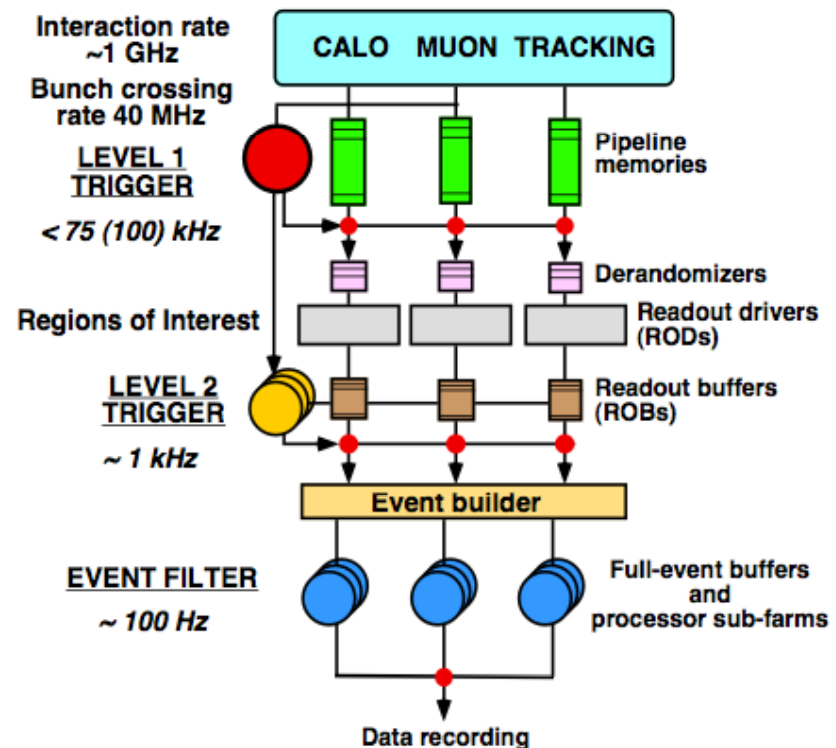


Table 7: Efficiency for the 2g17i menu item to trigger on $H \rightarrow \gamma\gamma$ events with $m_H = 120$ GeV, normalized with respect to the offline selections.

ATLAS preliminary

Trigger Level	2g17i Trigger efficiency
L1	96 ± 0.3
L2 Calo	95 ± 0.4
EF Calo	94 ± 0.4

Summary of MC's and initial cross-sections for different signals and backgrounds

signal

- Signal : the cross-section unit is pb.
- the branching ratio is corrected from HDecay (2×10^{-3} for $M_H = 120 \text{ GeV}$).
- All signal cross-sections are normalized to the NLO cross-sections taking into account only QCD corrections.

m_H	<i>gg Fusion</i>		<i>VBF</i>		<i>WH</i>		<i>ZH</i>		<i>ttH</i>	
σ calculator	<i>HIGLU</i>		<i>VV2H</i>		<i>V2HV</i>		<i>H2HV</i>		<i>HQQ</i>	
Generator (fullsim)	<i>MC@NLO</i>		<i>PYTHIA</i>		<i>PYTHIA</i>		<i>PYTHIA</i>		<i>PYTHIA</i>	
	LO	NLO	LO	NLO	LO	NLO	LO	NLO	LO	NLO
120	20.170	36.506	4.25	4.47	1.4140	1.7351	0.7517	0.9210	0.537	0.669
130	17.491	31.763	3.93	4.13	1.0949	1.3463	0.5852	0.7185	0.428	0.534
140	15.314	27.858	3.63	3.81	0.8600	1.0612	0.4617	0.5688	0.345	0.431

background

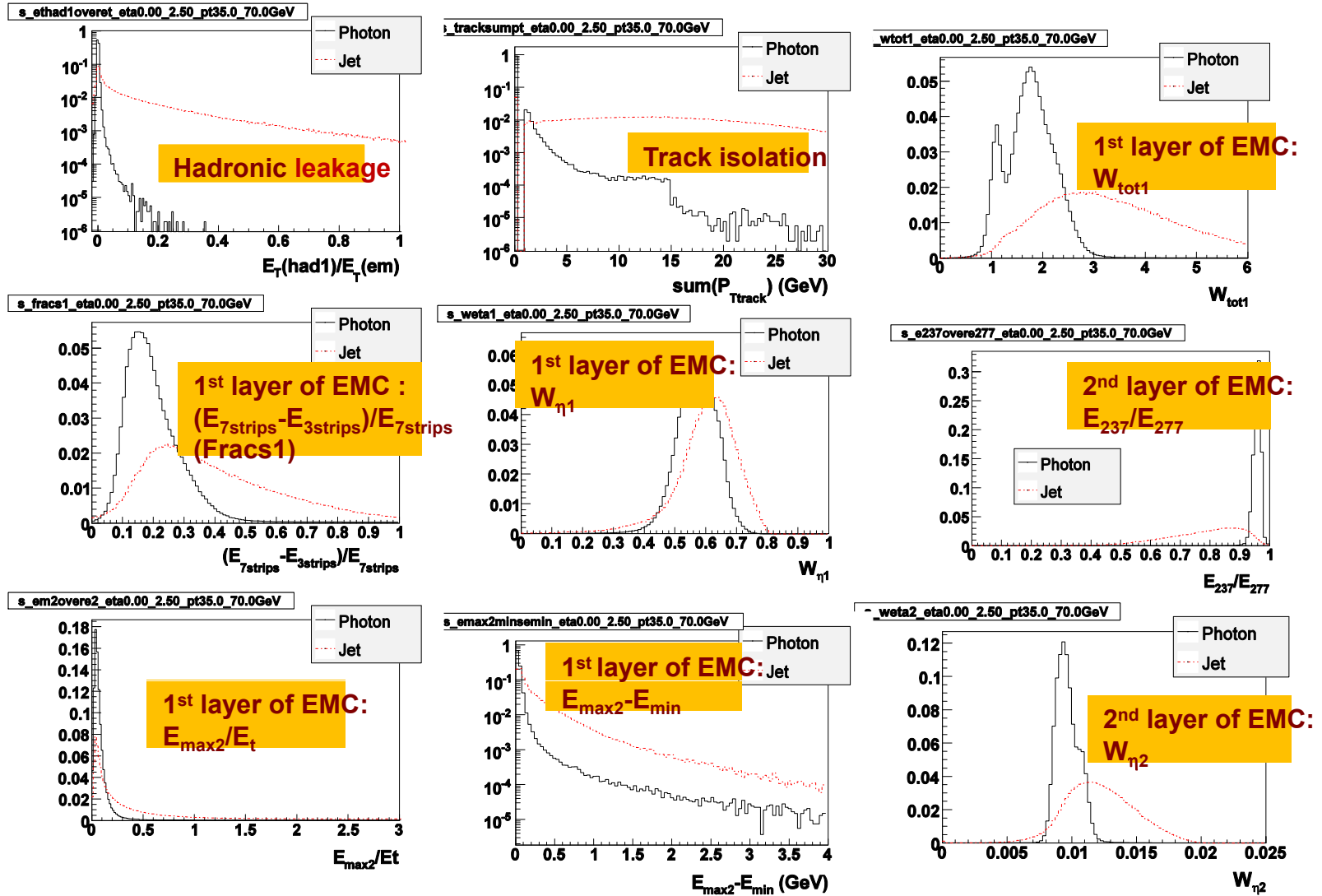
- ResBos and DIPHOX agreement better than 10%.
- For γj : $\sigma_{\text{JETPHOX}}/\sigma_{\text{PYTHIA}} \sim 2.1$
- For jj : $\sigma_{\text{NLOJET}}/\sigma_{\text{PYTHIA}} \sim 1.3$

ATLAS preliminary

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

Photon identification variables

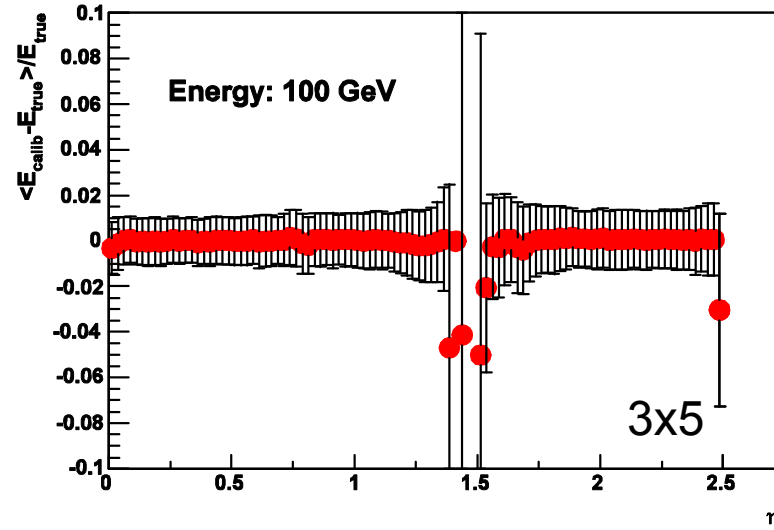
Shower shape variables and track isolations are used.



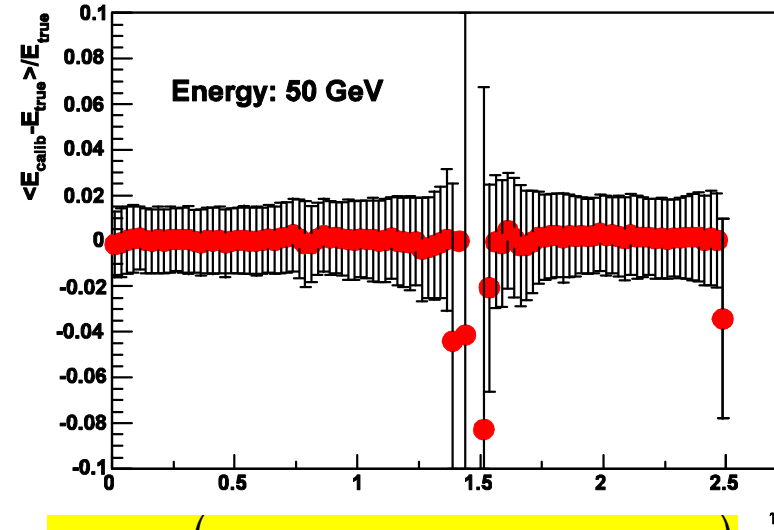
Calibration with longitudinal weights

Linearities and resolutions after applying the weights.

Graph

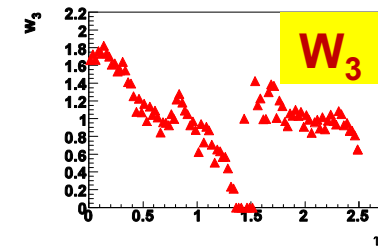
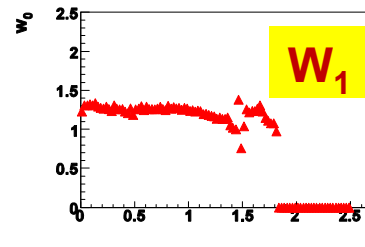
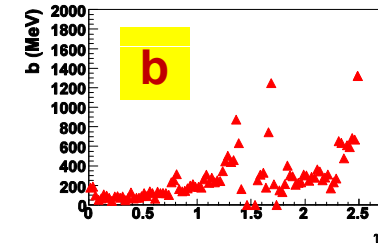
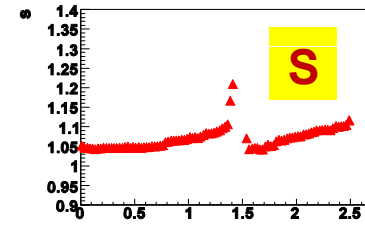
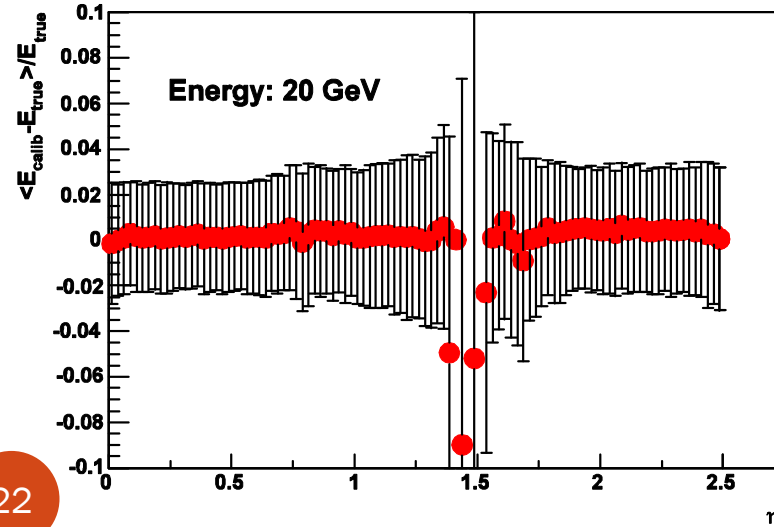


Graph

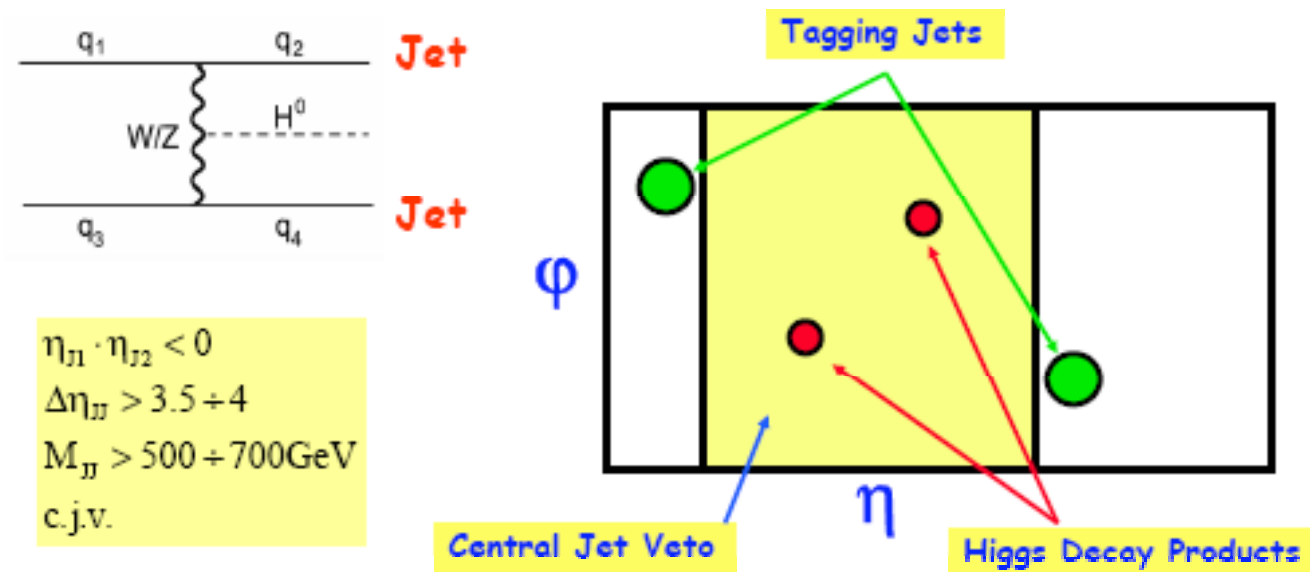


$$E_{\text{rec}} = s(b + W_0 E_{\text{pres}} + E_1 + E_2 + W_3 E_3)$$

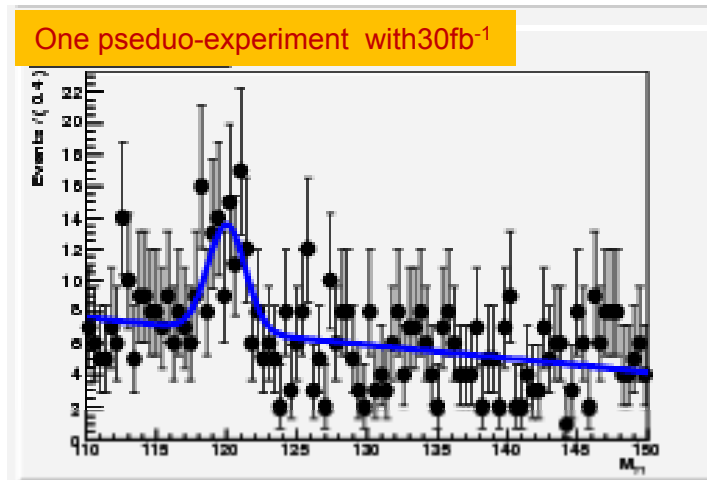
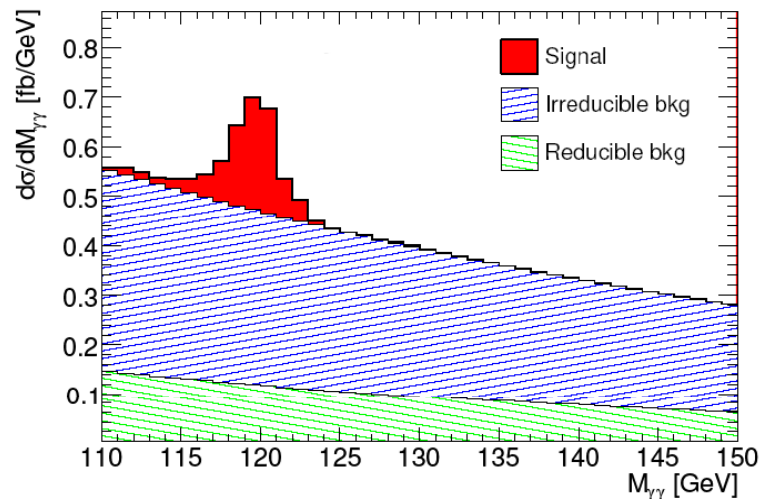
Graph



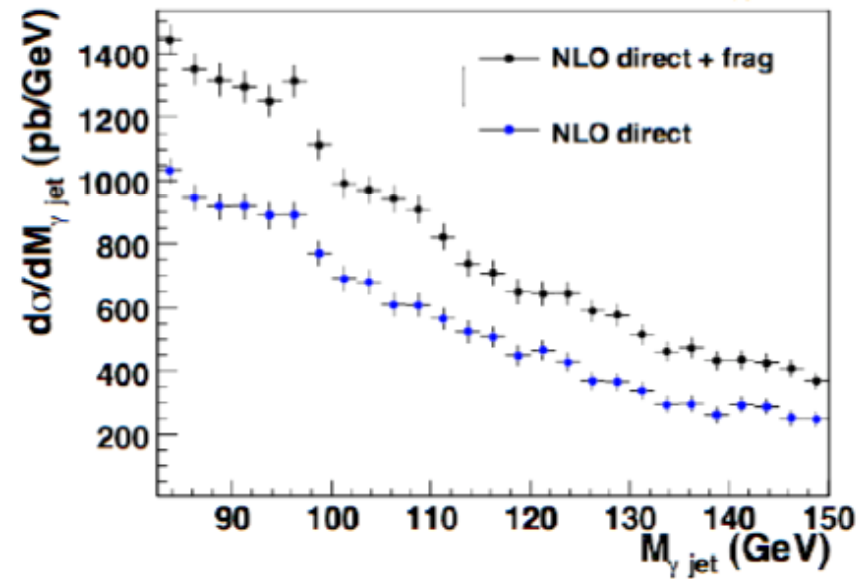
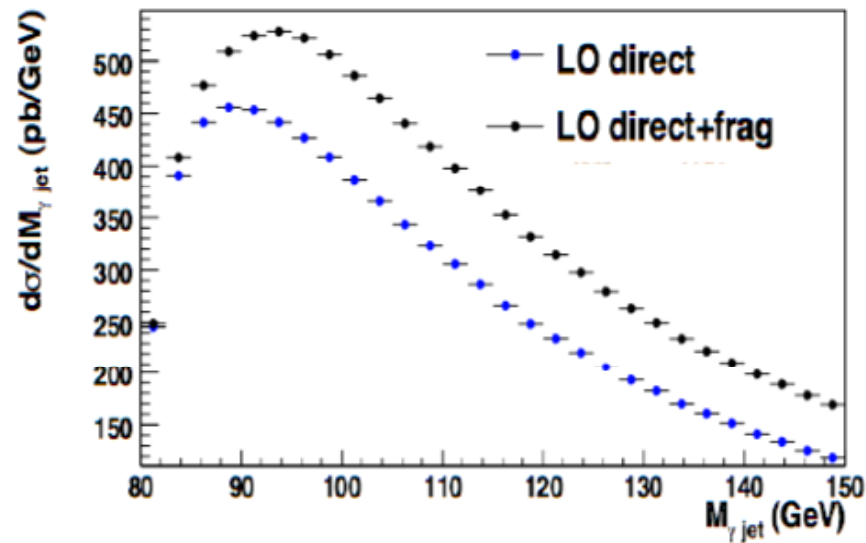
VBF $H \rightarrow \gamma\gamma$ sub-channel



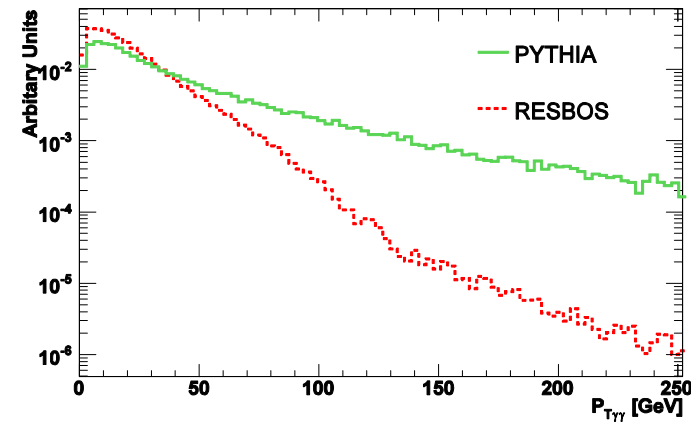
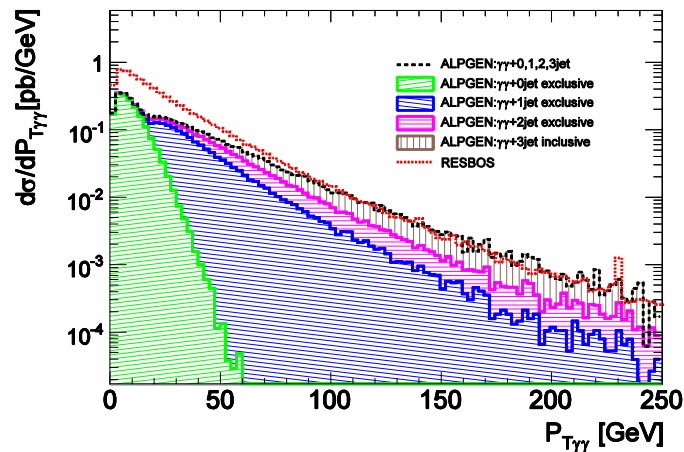
Good S/B. High statistical fluctuation expected at low luminosity



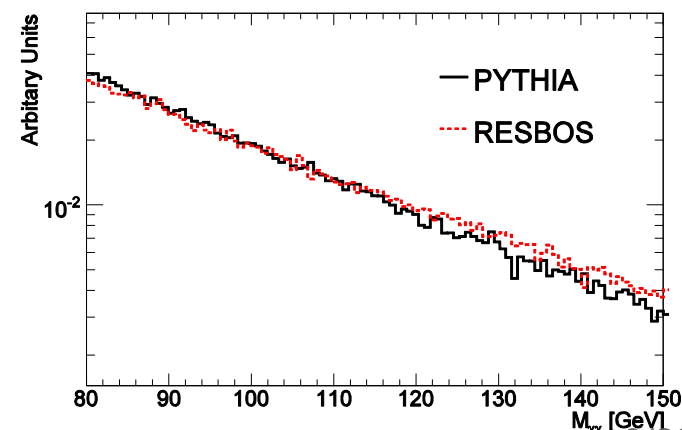
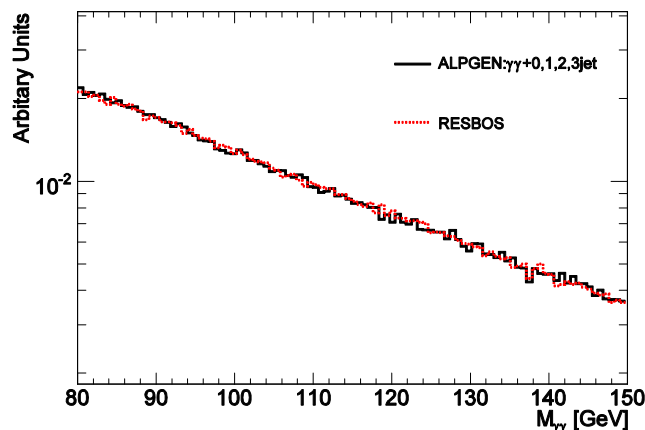
Jetphox results for high order and fragmentation



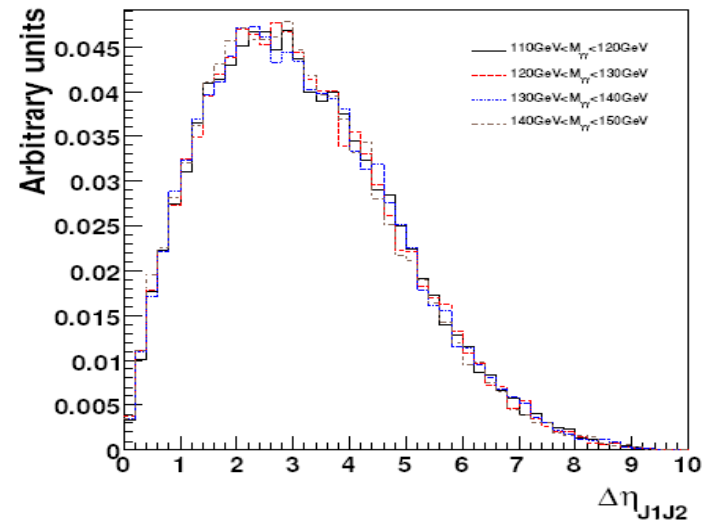
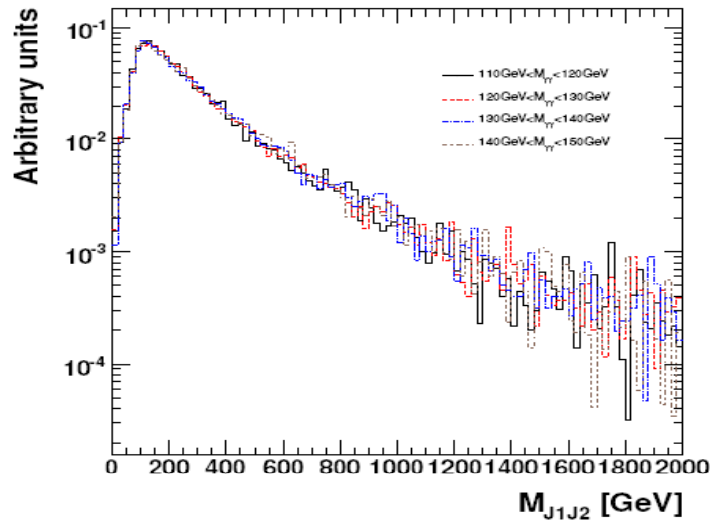
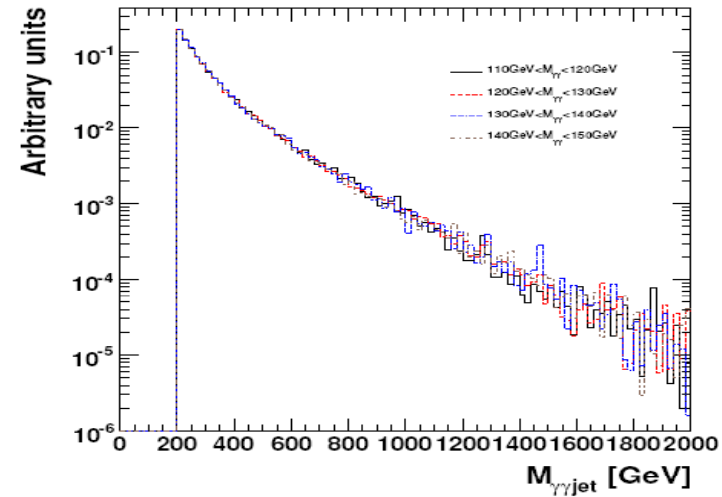
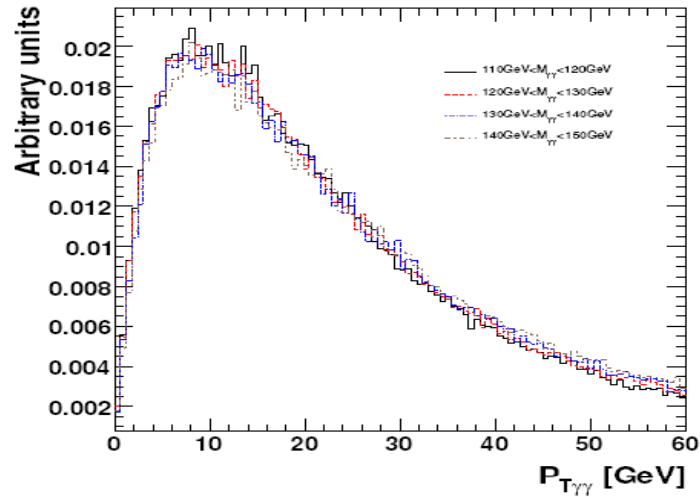
Reweighting ALPGEN/PYTHIA w.r.t RESBOS for Born/Box processes



- MC's ALPGEN (Born) (upper left plot) and PYTHIA (box) (upper right plot) has LO cross-section.
- RESBOS has NLO and re-summation calculation, however in parton level.
- Solution: Reweighting alpgen/pythia $P_{T\gamma\gamma}$ them w.r.t RESBOS .
- $M_{\gamma\gamma}$ distributions are reasonable consistent after reweighting (bottom plots).



Correlation study between kinematic variables and $M_{\gamma\gamma}$ for background



maximum likelihood fit for signal significance computation

Likelihood:
$$L = \prod_{c=1}^{n_{cas}} e^{-N^c} \prod_{i=1}^{N^c} f_i^c \text{ with: } f_i^c(\mu, p^c) = \mu N_s^c f_{si}^c(p^c) + N_b^c f_{bi}^c(p^c)$$

Where: μ corresponds to the hypothesis ($\mu=1$ standard model)

N_s^c presents the signal events in classification c .

$f_{si}^c(p^c)$ is the signal PDF in classification c .

$f_{bi}^c(p^c)$ is the background PDF in classification c .

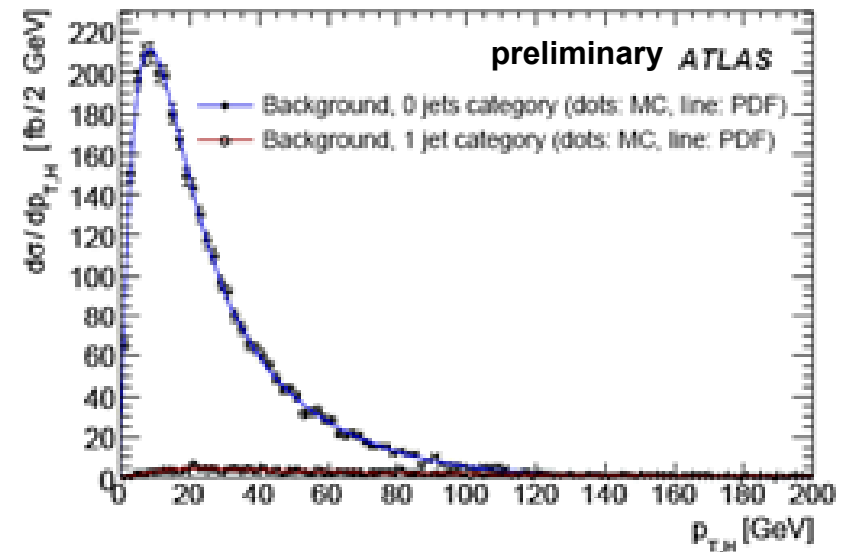
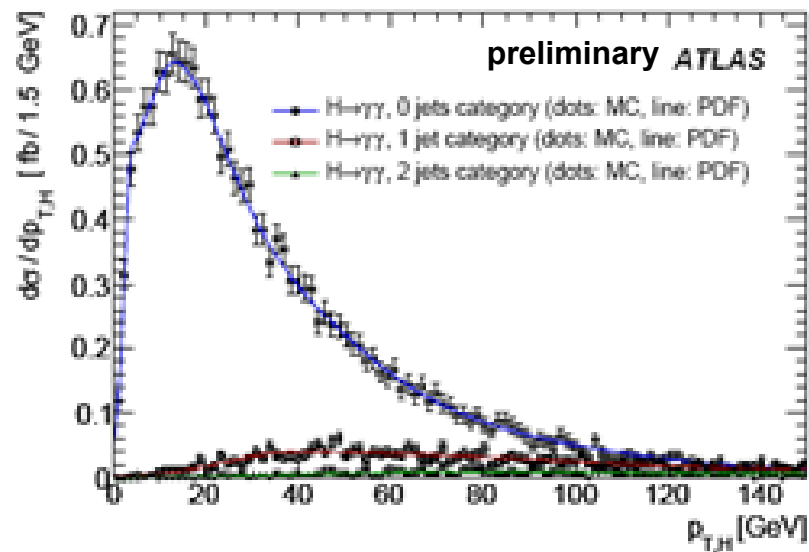
N_b^c presents the background events in classification c .

$$N^c = N_s^c + N_b^c$$

Technically, $NLL(\mu, p) = -\log(L(\mu, p))$ is used in the fit.

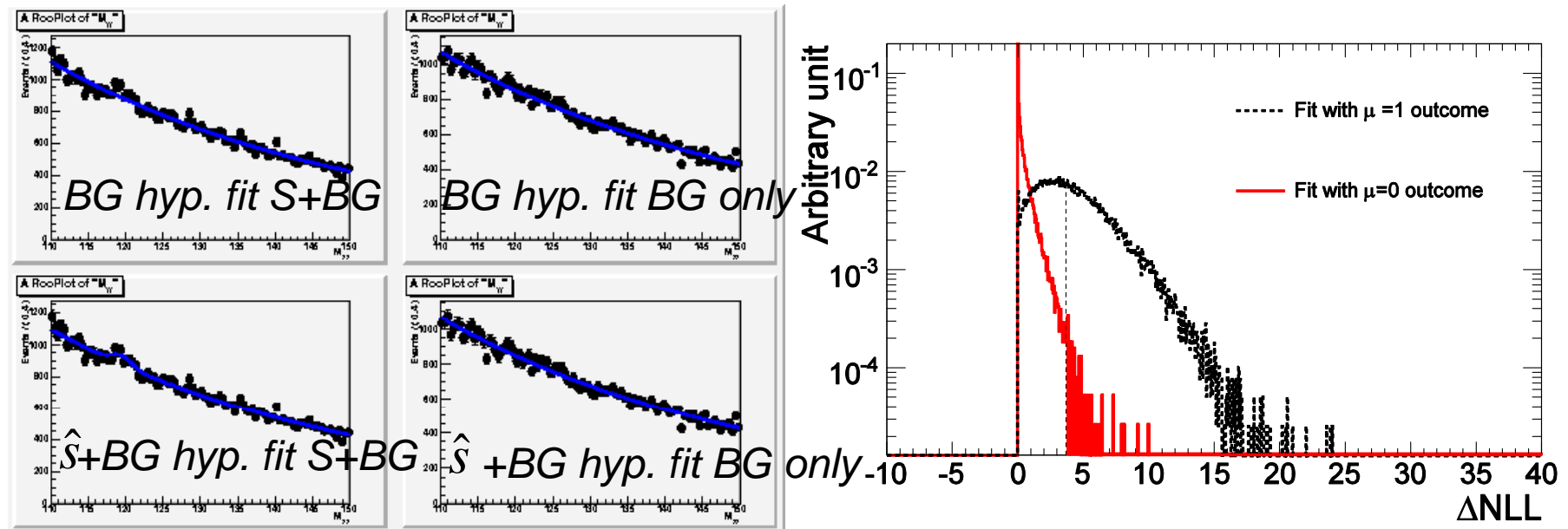
Test some hypothesis : $\Delta NLL(\mu) = NLL(\mu) - NLL(\hat{\mu})$
(e.g. hypothesis $\mu=0$ for discovery, $\mu=1$ for exclusion)

$P_{T\gamma\gamma}$ for signal and background



Procedure to compute the significance with maximum likelihood fit

- Compute NLL distributions from Toy Monte Carlo:
 1. Randomly generate a pseudo-experimental outcome.
 2. Perform fits (RooFit) with $S+B$ hypothesis with μ free NLL($\hat{\mu}$) and BG (Background-only) hypothesis, compute $\Delta\text{NLL}(\mu=0)$
 3. Repeat many times to get a probability distribution
- Compute two probability distributions:
 1. for outcomes with signal (“S+B toy MC”, $\mu=1$) and
 2. For outcomes without signal (“BG-only toy MC”)
 - Compute CL_B from plots $\Delta\text{NLL}(\text{BG-only toy MC})$ and $\Delta\text{NLL}(\text{S+B toy MC})$ and convert it into significance (integrating from the median of S+B toy MC while computing CL_B) as right plot shows.



Signal systematics

source	Relative effect(%)
luminosity	3
γ ID eff.	0.2
γ fake rate	20
γ energy scale	0.5
γ resolution	0.5
jet energy scale	7
jet resolution	75% $\sqrt{(E)}$ + 7% (when $ \eta < 3.2$) 110% $\sqrt{(E)}$ + 10% (when $ \eta > 3.2$)

Table 6.1: Estimated scale of signal systematics.

source	Inclusive		H+1jet		H+2jets	
	gg Fusion	VBF	gg Fusion	VBF	gg Fusion	VBF
luminosity	3	3	3	3	3	3
γ ID eff.	+/-0.3	+/-0.4	+/-0.3	+/-0.4	+/-2.3	+/-0.4
γ fake rate	+/-0.1	+/-0.0	+/-0.0	+/-0.0	+/-0.8	+/-0.1
γ energy scale	+/-0.2	+/-0.2	+0.6/-0.5	+0.5/-0.7	+/-0.0	+0.3/-0.2
γ resolution	+/-0.1	+/-0.0	+/-0.0	+/-0.0	+/-0.0	+/-0.1
jet energy scale	N/A	N/A	+9.9/-12.8	+5.5/-6.1	+18.5/-23.0	+4.9/-8.7
jet resolution	N/A	N/A	+/-0.2	+/-0.1	+/-2.3	+/-0.6
total	3.0	3.0	+10.3/-13.1	+6.3/-6.9	+19.0/-23.5	+5.8/-9.2

Table 6.2: The impact (%) of signal systematics on the signal efficiency.

$\gamma\gamma$ and γj systematic uncertainties

Table 9: Summary of the relative systematic uncertainties on the $\gamma\gamma$ and γj processes.

Potential sources	$\gamma\gamma$	γj
Scale dependence	5%	22%
Fragmentation	6%	2%
PDF	10%	7%
Total	18%	23%