Analysis Necessities & Steps …

Photon reconstruction

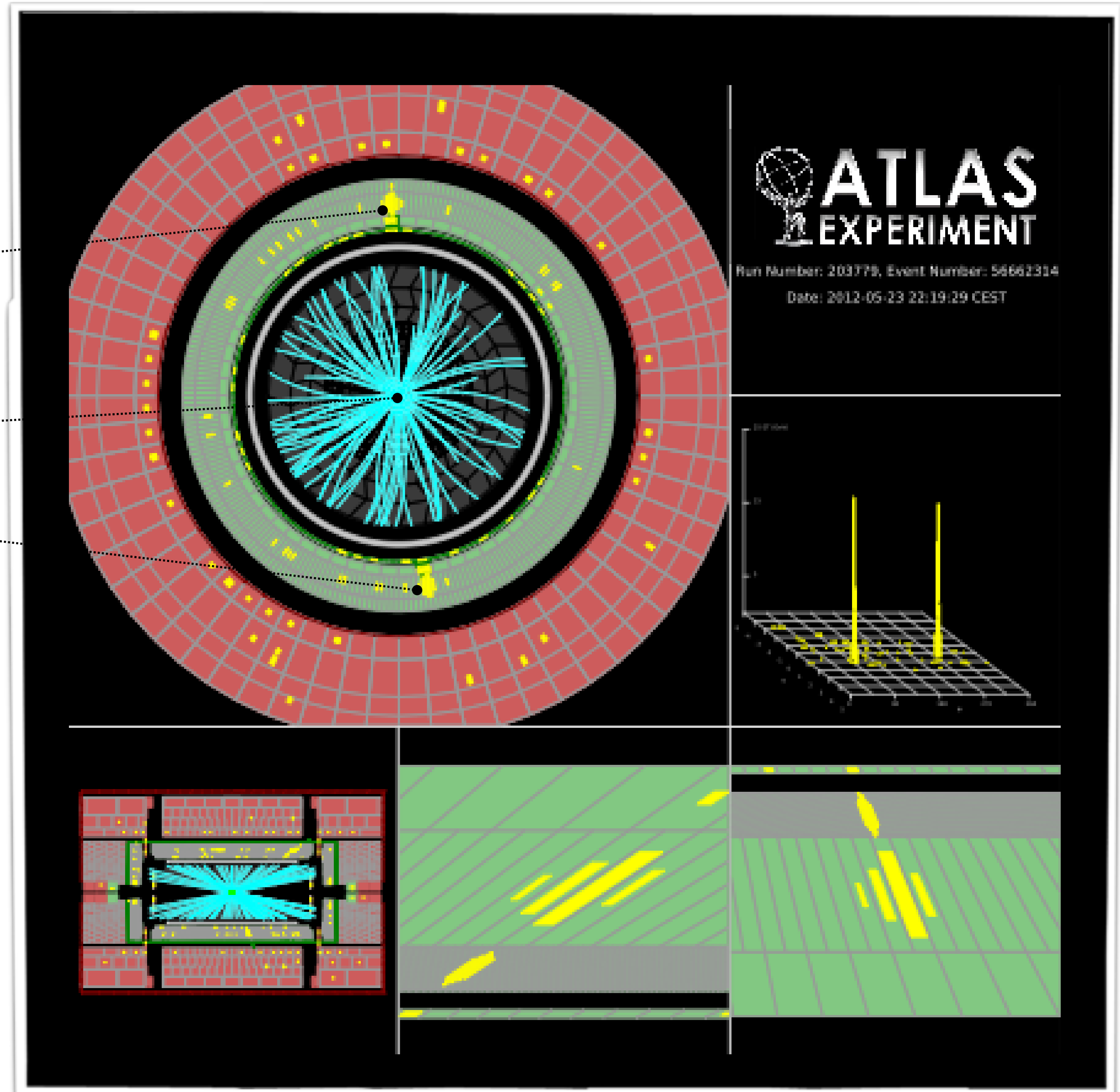
Photon identification

Photon isolation

Primary vertex

Energy calibration

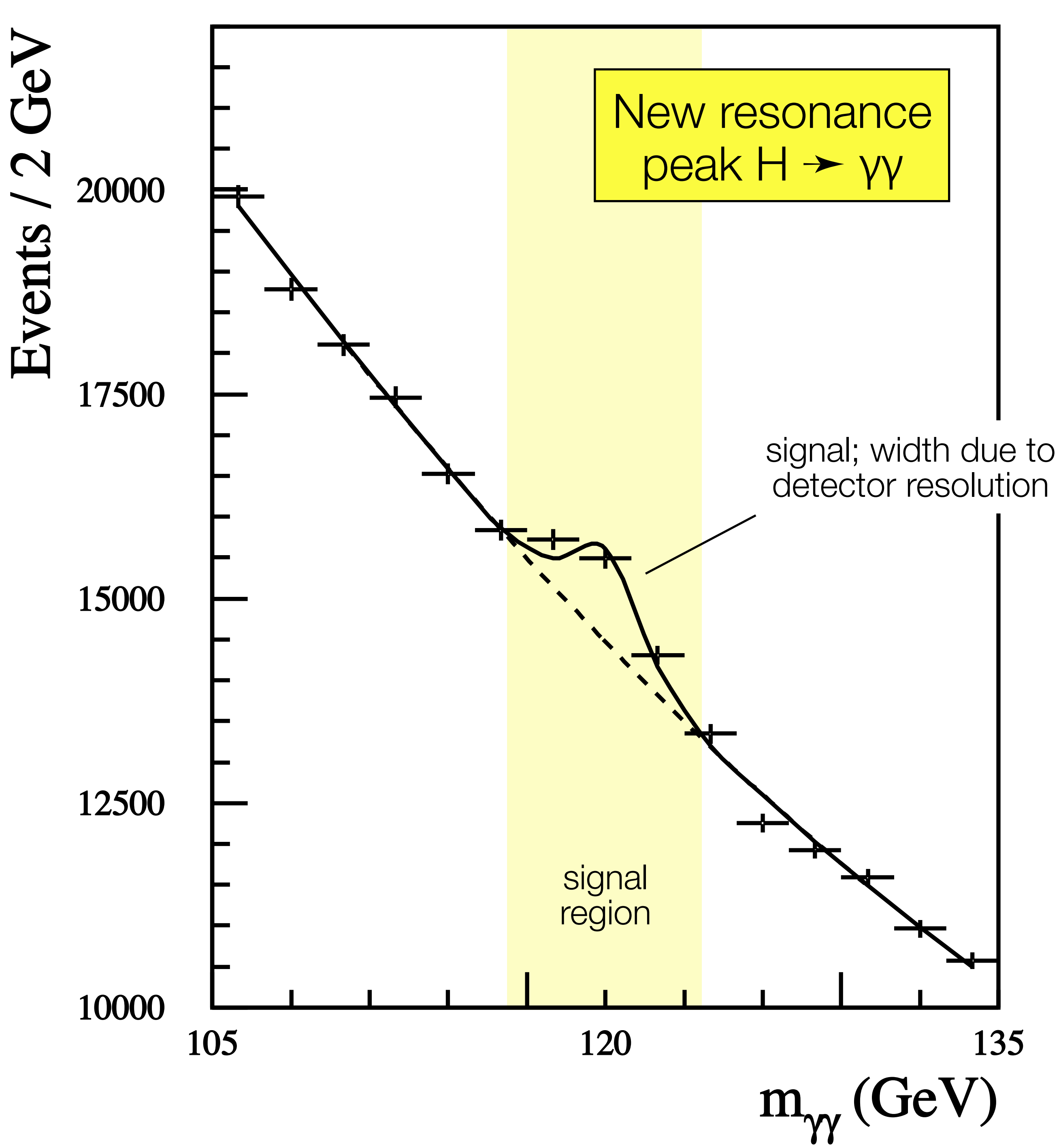
Background modeling



Event categories

Limits & signal strength

Energy Resolution



Signal significance:

$$S = \frac{N_S}{\sqrt{N_B + N_S}}$$

N_S: # signal events
N_B: # background events

... in peak region

Estimate

[assuming 1% resolution; $M_H \approx 120$ GeV]

$\sigma_{H\gamma\gamma}$ ~ 50 fb
$\sigma_{\gamma\gamma}$ ~ 2 pb/GeV [Γ_H ~ negligible …]

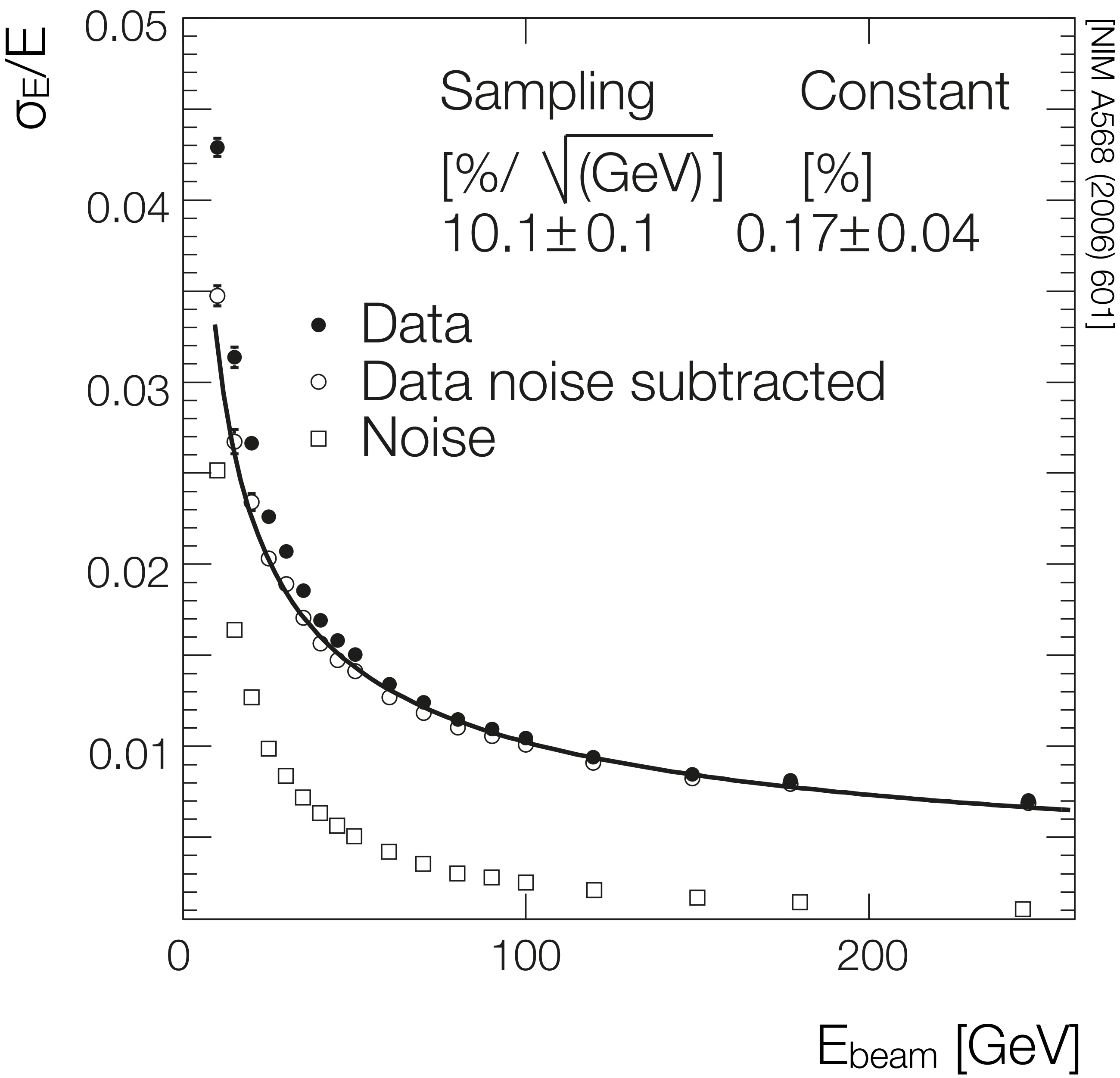
L = 20 fb^{-1}
N_s = 50 fb × 20 fb^{-1} = 1000
N_b = 4 pb × 20 fb^{-1} = 80.000

S = 3.5

[assuming: $\sigma(m_{\gamma\gamma})/m_{\gamma\gamma}$ ~ 1%]

Energy Resolution

Test Beam Result
Fractional Energy Resolution



Resolution @ 60 GeV:

$\sigma_E \approx 0.014$ [FWHM = 3.3 %]

Event numbers and mass resolution for the H ➛ γγ ATLAS analysis …

[Mass range: 100 - 160]

$\sqrt{s}$	7 TeV		8 TeV		
$\sigma \times B(H \to \gamma\gamma)$ [fb]		39		50	FWHM
Category	N_D	N_S	N_D	N_S	[GeV]
Unconv. central, low p_{Tt}	2054	10.5	2945	14.2	3.4
Unconv. central, high p_{Tt}	97	1.5	173	2.5	3.2
Unconv. rest, low p_{Tt}	7129	21.6	12136	30.9	3.7
Unconv. rest, high p_{Tt}	444	2.8	785	5.2	3.6
Conv. central, low p_{Tt}	1493	6.7	2015	8.9	3.9
Conv. central, high p_{Tt}	77	1.0	113	1.6	3.5
Conv. rest, low p_{Tt}	8313	21.1	11099	26.9	4.5
Conv. rest, high p_{Tt}	501	2.7	706	4.5	3.9
Conv. transition	3591	9.5	5140	12.8	6.1
2-jet	89	2.2	139	3.0	3.7
All categories (inclusive)	23788	79.6	35251	110.5	3.9

[ATLAS, Phys. Lett. B 716 (21012) 1]

Energy Calibration

Monte Carlo based calibration

Monte Carlo simulation tuned with Test Beam data.

Accurate description of materials is confirmed by measurements in data.

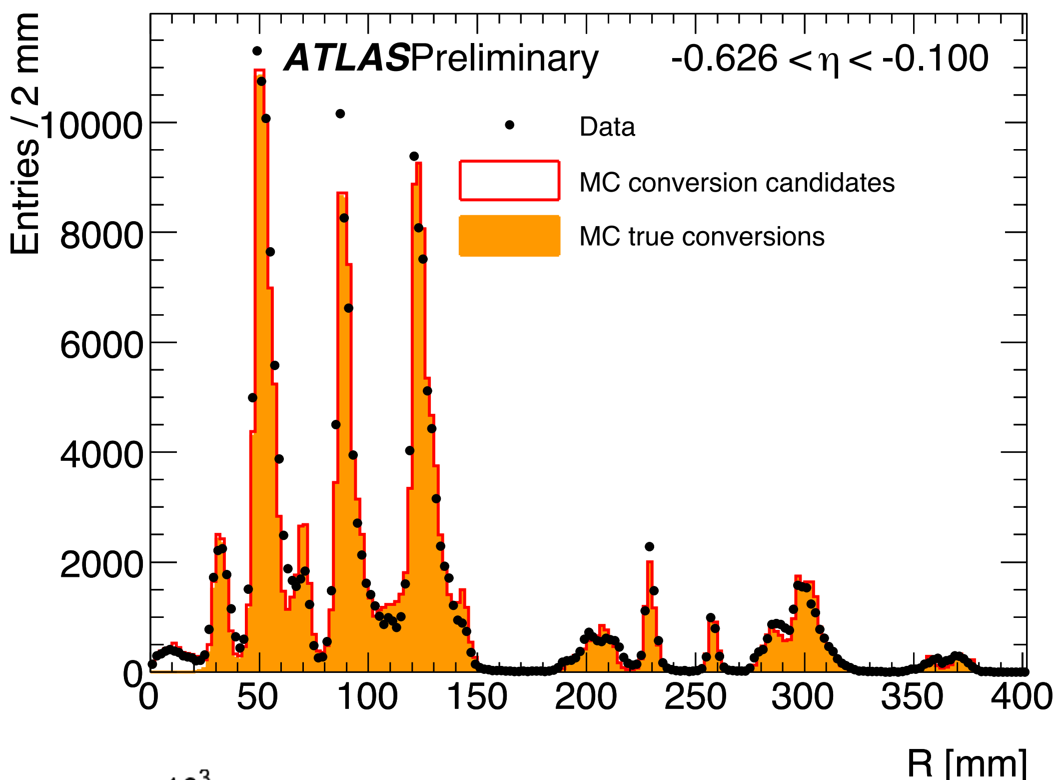
Energy scale corrections using Z ➛ ee decay data …

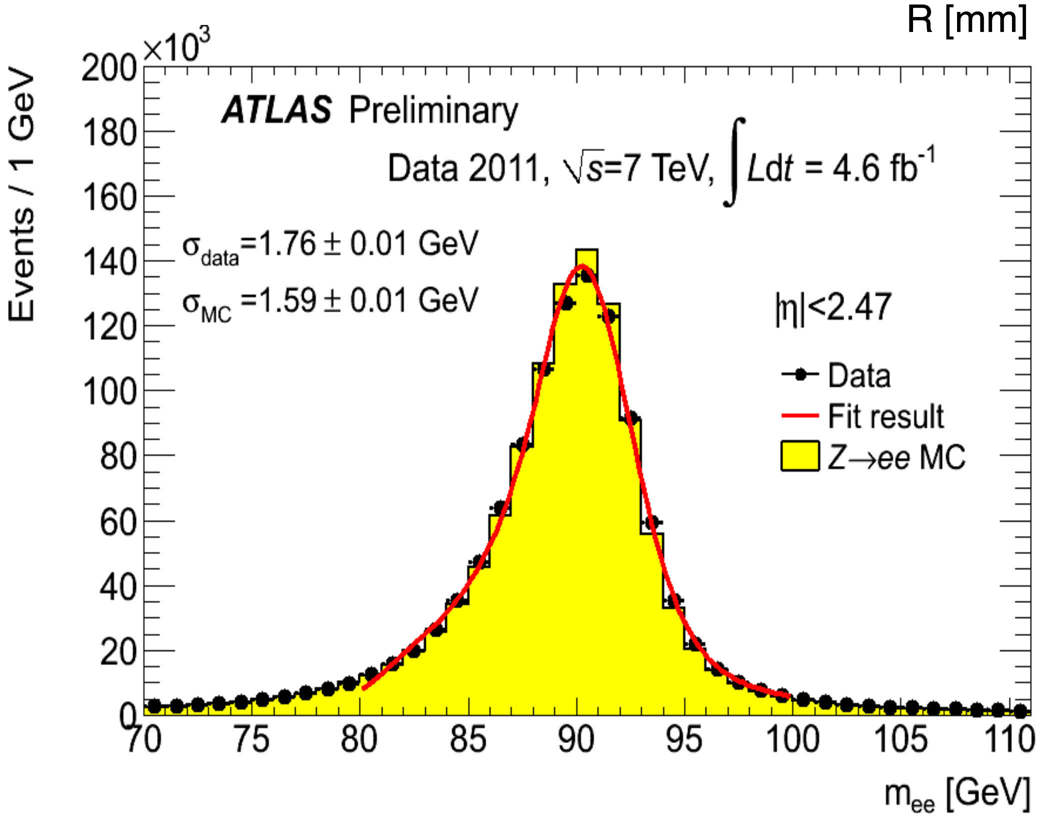
Energy scale correction applied to data …

Correction from a fit to the 2010 Z ➛ ee data …

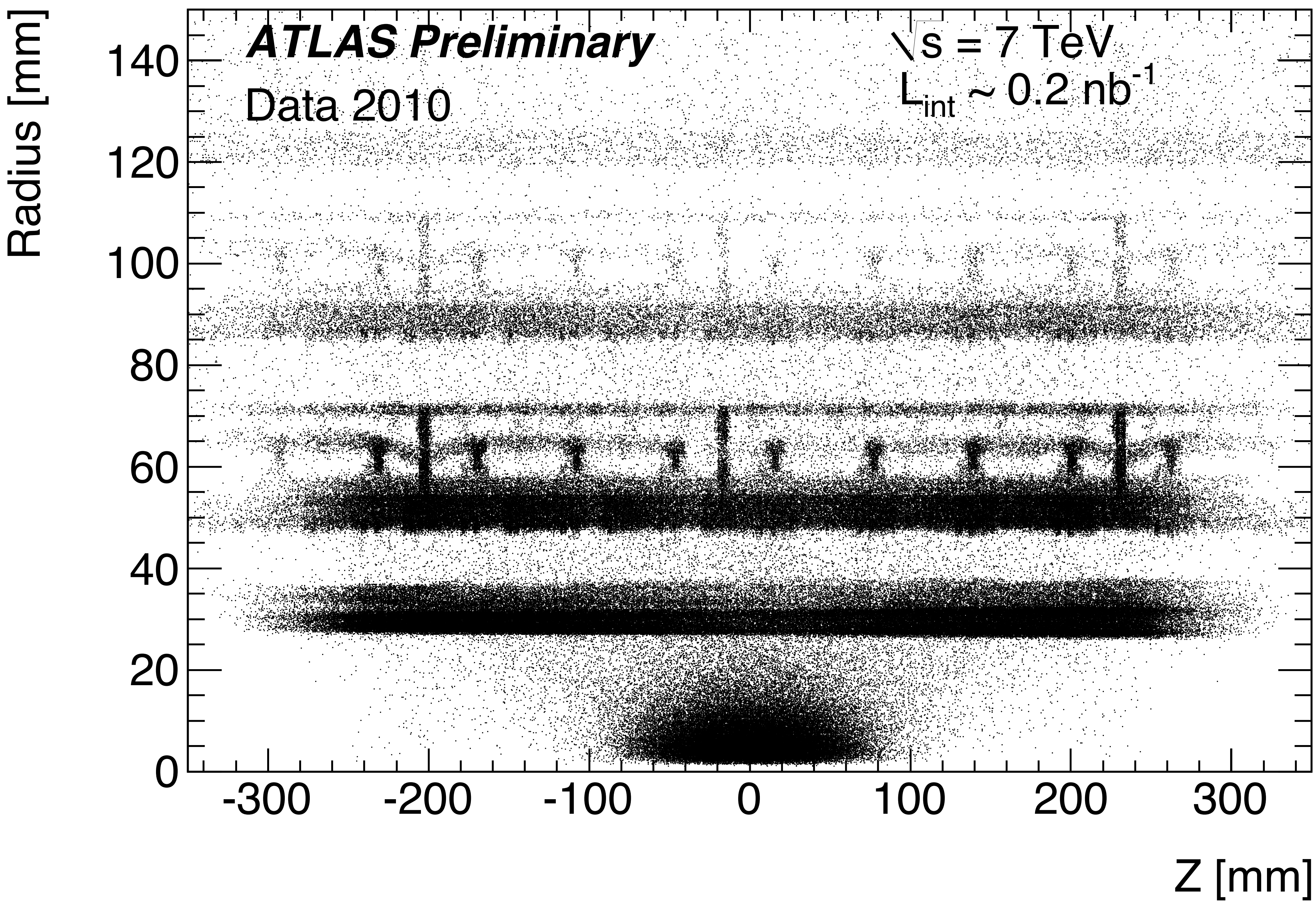
Extrapolation of energy scale correction from electron to photon is treated as uncertainty …

MC energy is smeared to match the energy resolution determined from data …



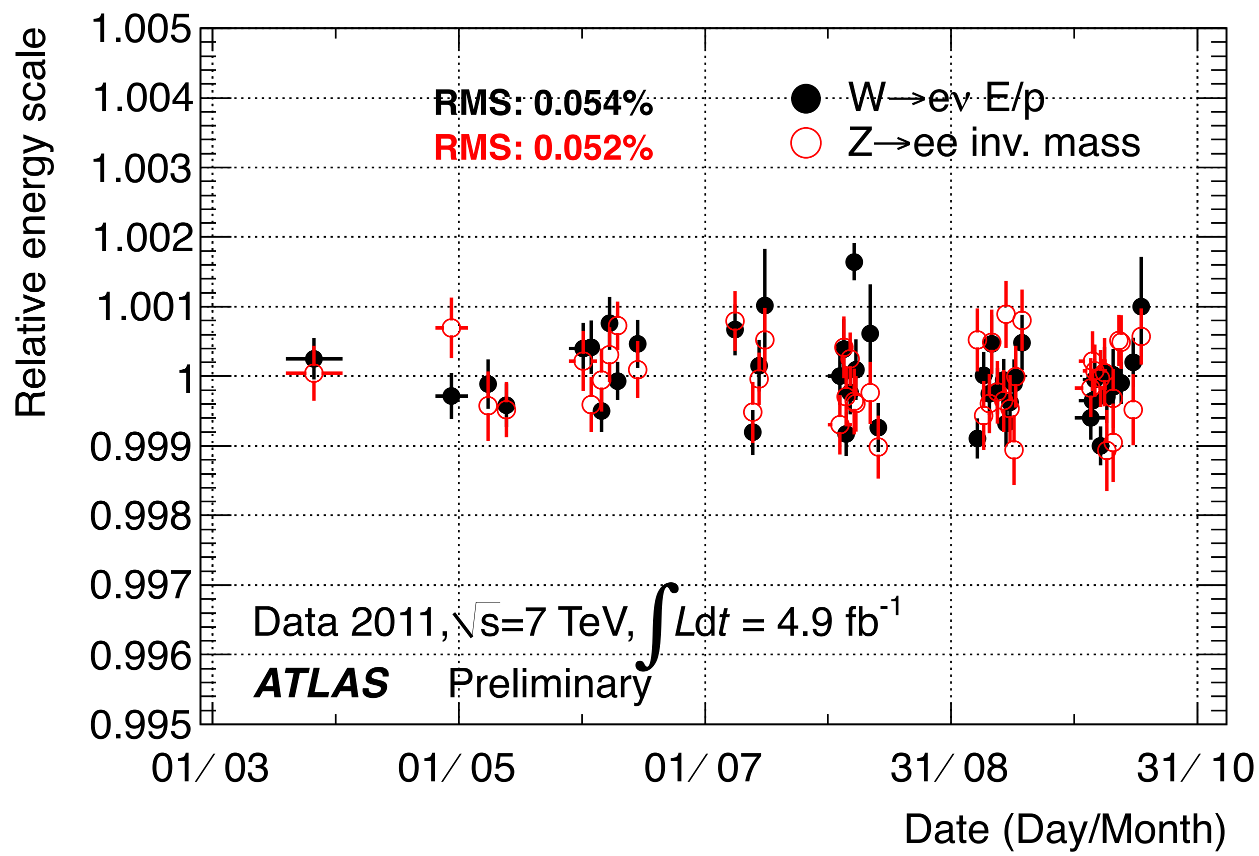


Reconstructed Vertex Distribution

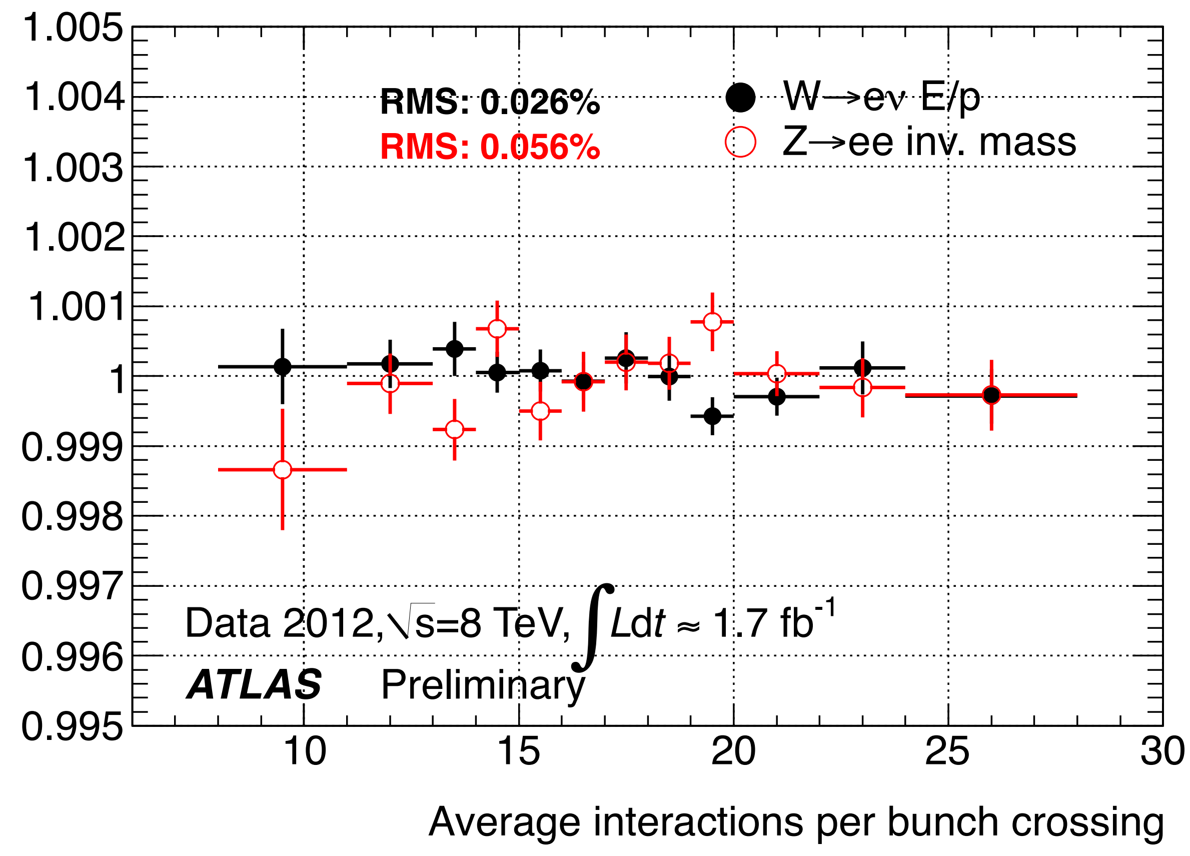


Energy Calibration

Relative Energy Scale
as function of time



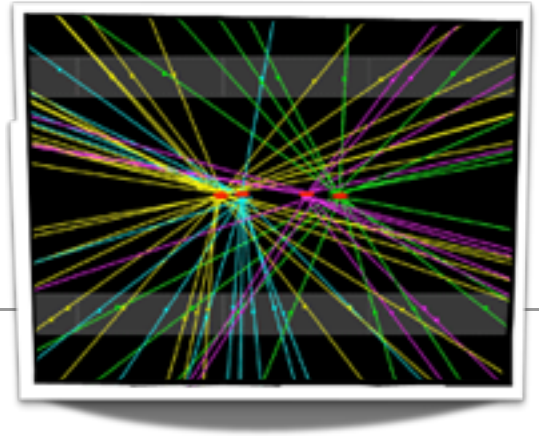
Relative Energy Scale
as function of interactions



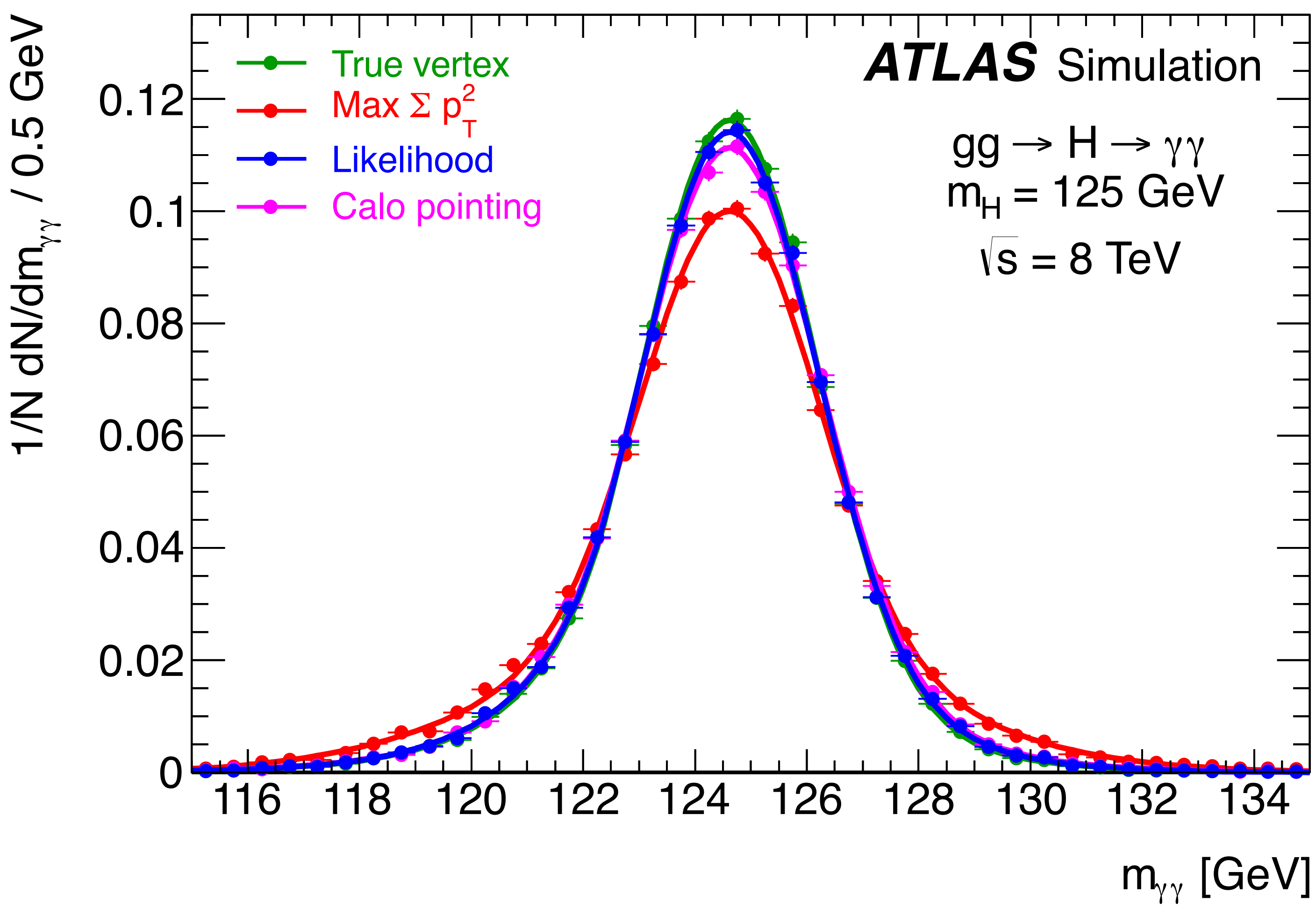
Excellent stability with time and pileup !

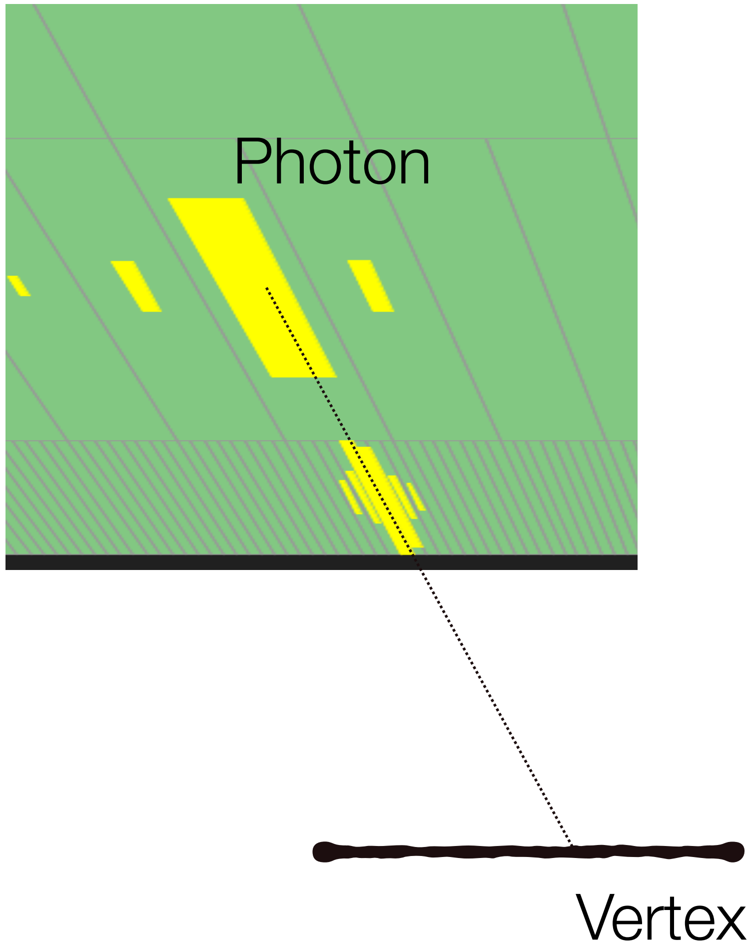
Di-photon mass resolution around 1 %

Di-Photon Vertex Selection



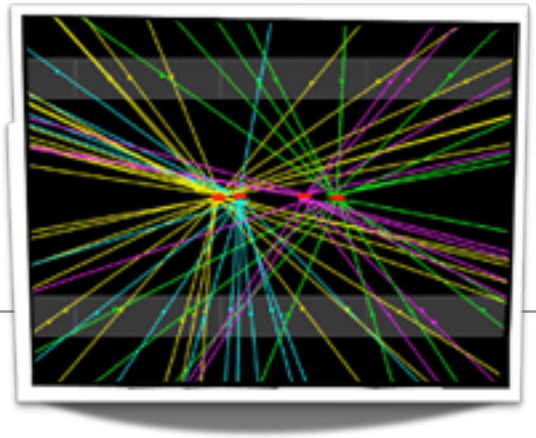
Likelihood combining calorimeter pointing, conversion vertex and track-based vertex selection used …



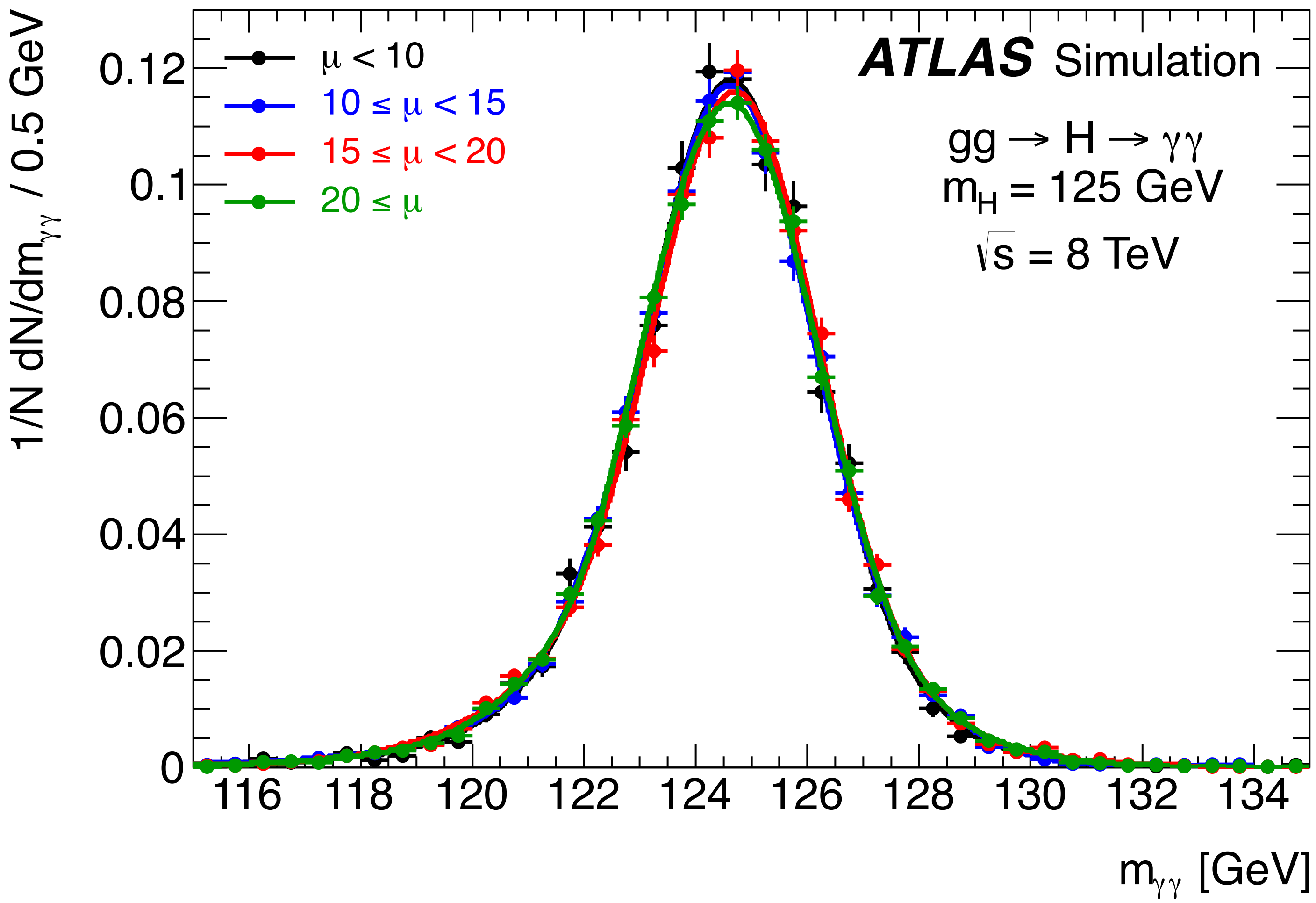


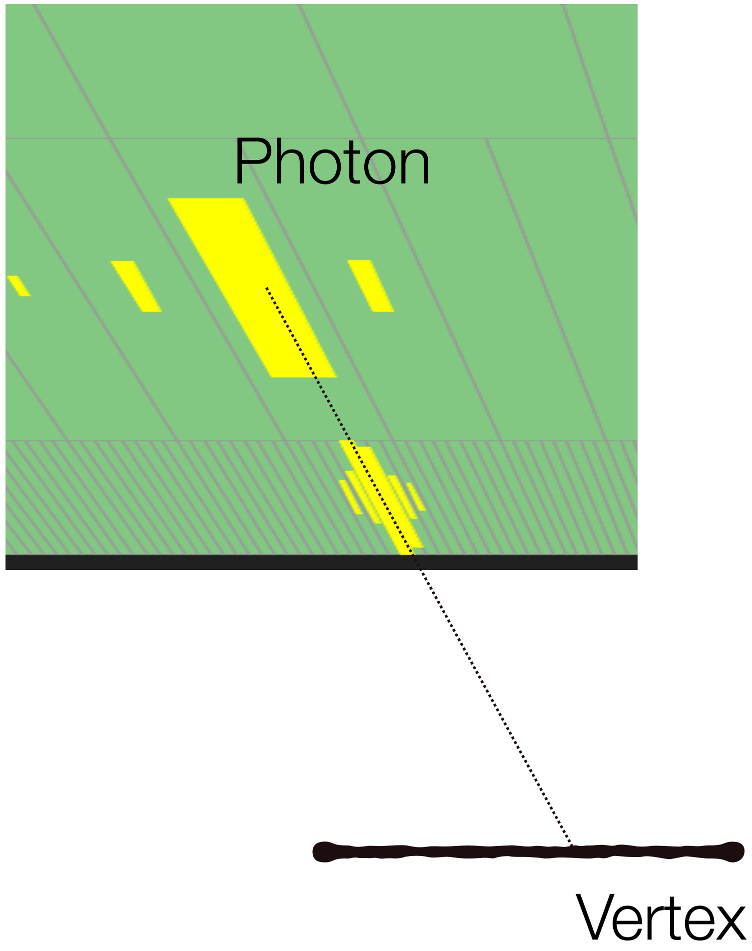
Improved resolution …

Di-Photon Vertex Selection



Likelihood combining calorimeter pointing, conversion vertex and track-based vertex selection used …



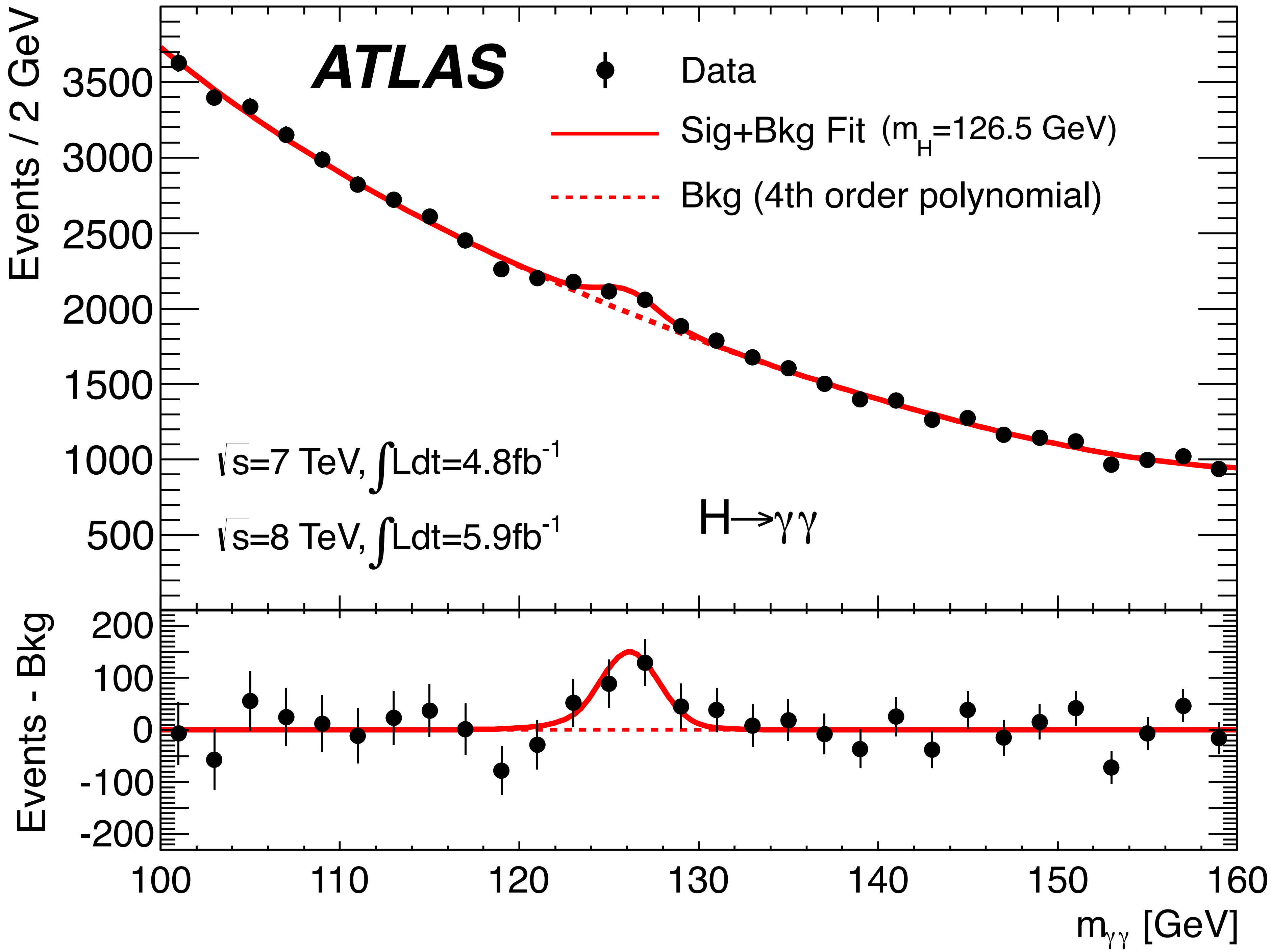


Robustness against pile-up …

ATLAS Result

Observation of a New Particle [H ➤ γγ]

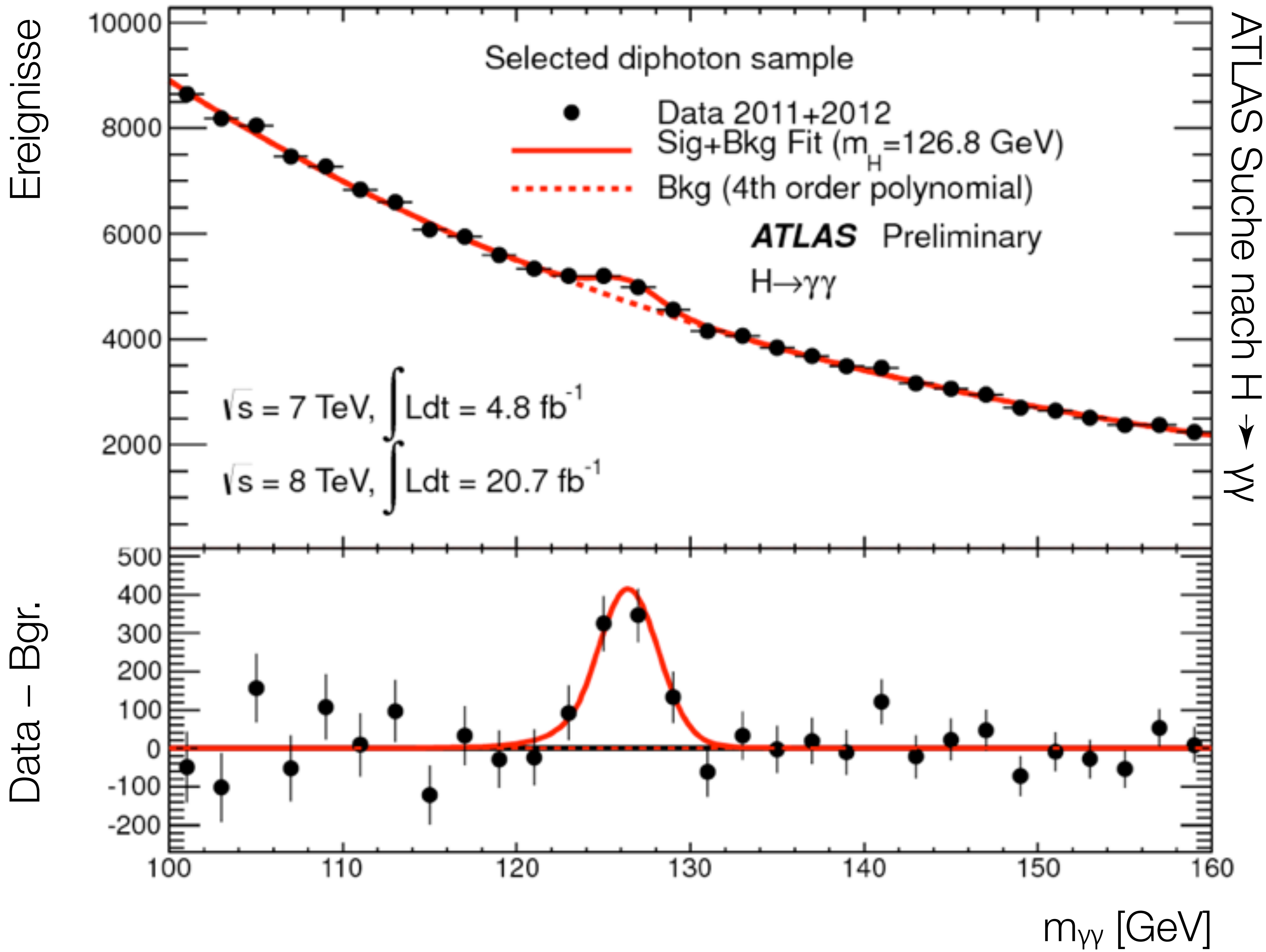
[Summer 2012]



ATLAS Result

Observation of a New Particle [H ➛ γγ]

[Spring 2013]



ATLAS-CONF-2013-012

Signal Model

Signal modeled using Crystal Ball function plus a broad Gaussian …
[Width dominated by detector resolution; Gaussian account for poorly measured energy]

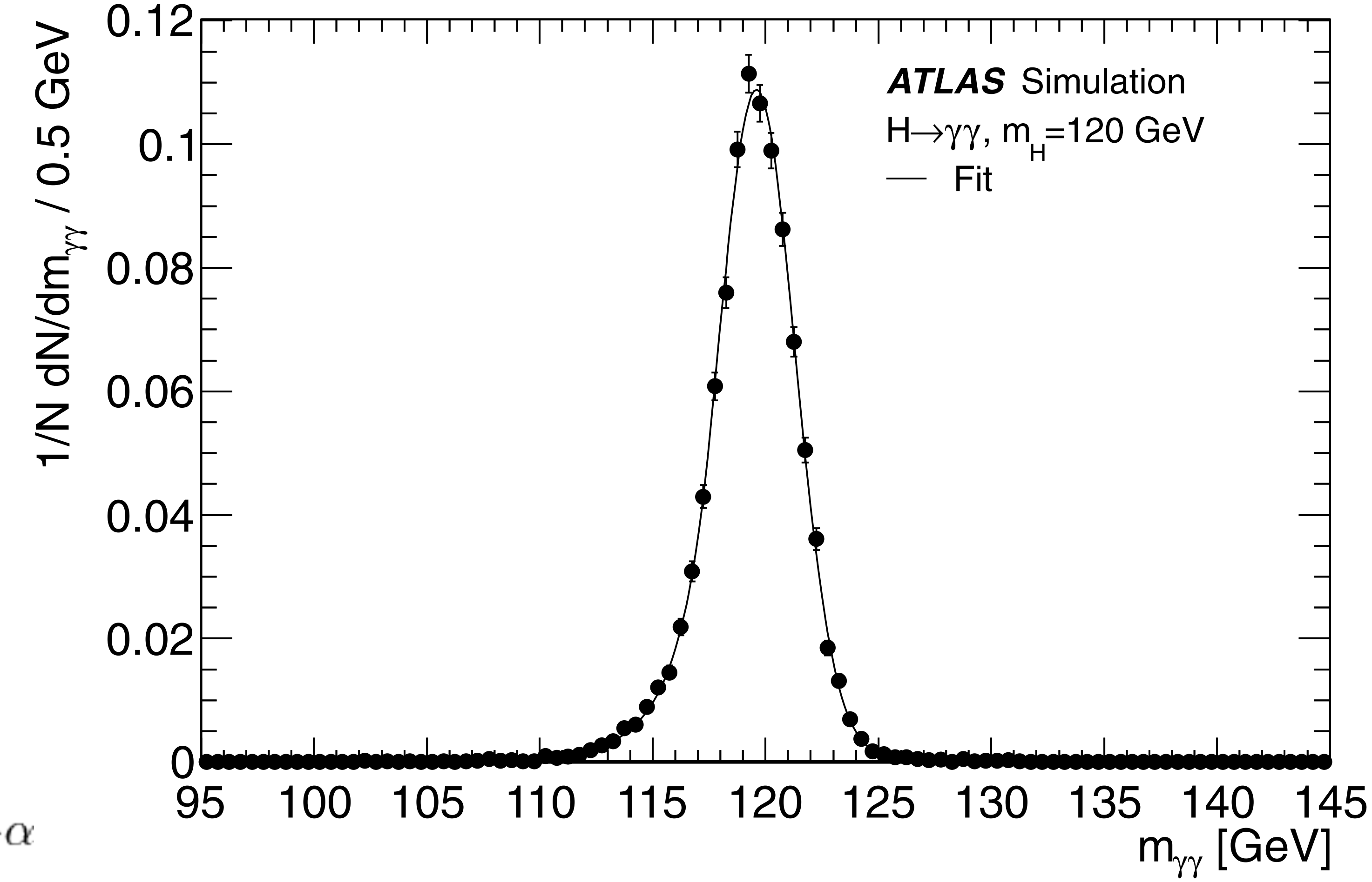
Taken from Monte Carlo …
[POWHEG and PYTHIA]

Crystal Ball function:
used to model various lossy processes
in high-energy physics

Asymmetric PDF
Central part: Gaussian
Low-end tail: power law
[below threshold -α]

$$f(x;\alpha,n,\bar{x},\sigma) =$$

$$= N \cdot \begin{cases} \exp\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right), & \text{falls } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot \left(B - \frac{x-\bar{x}}{\sigma}\right)^{-n}, & \text{falls } \frac{x-\bar{x}}{\sigma} \leqslant -\alpha \end{cases}$$



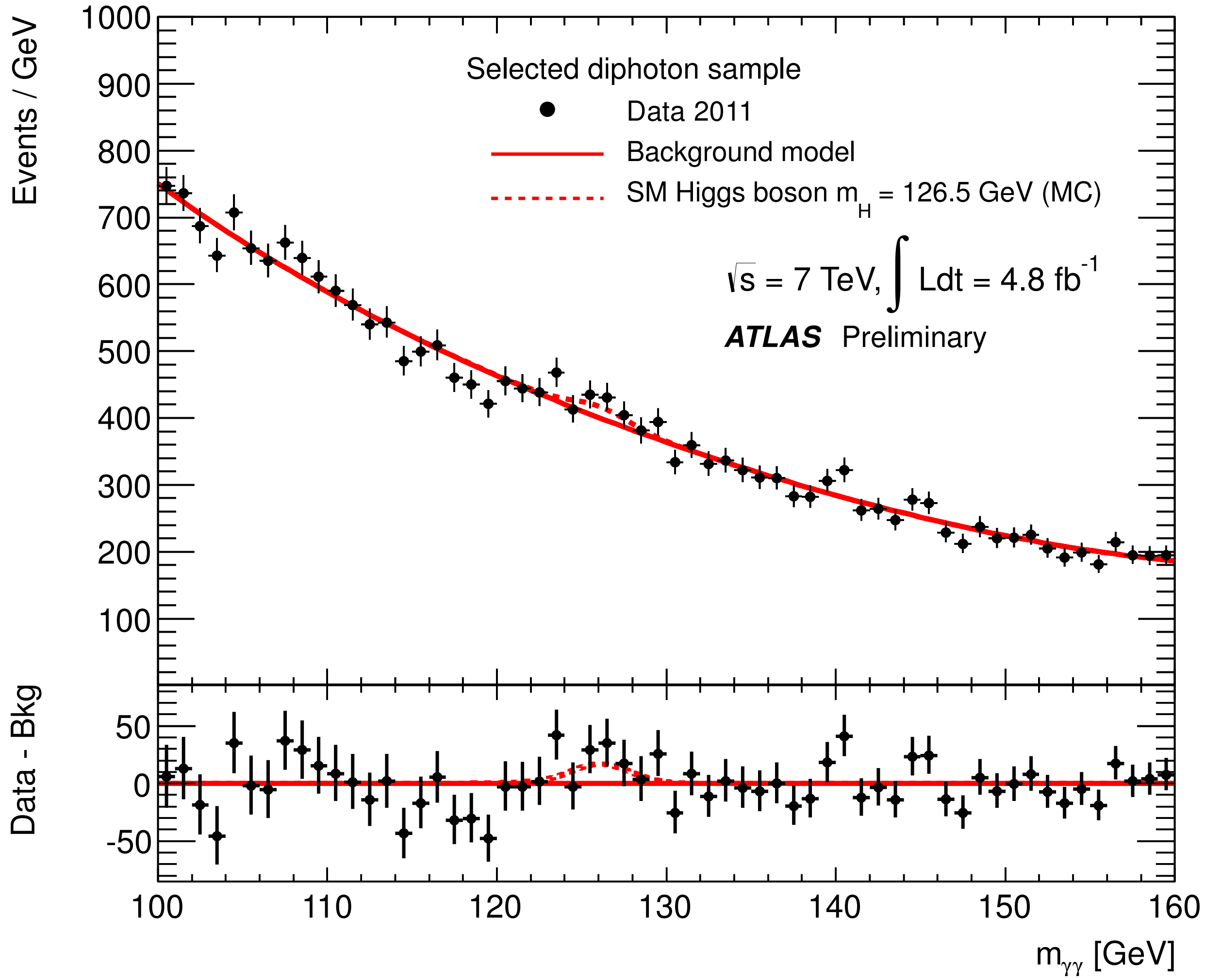
Distribution of the reconstructed di-photon
invariant mass of a simulated 120 GeV mass Higgs signal

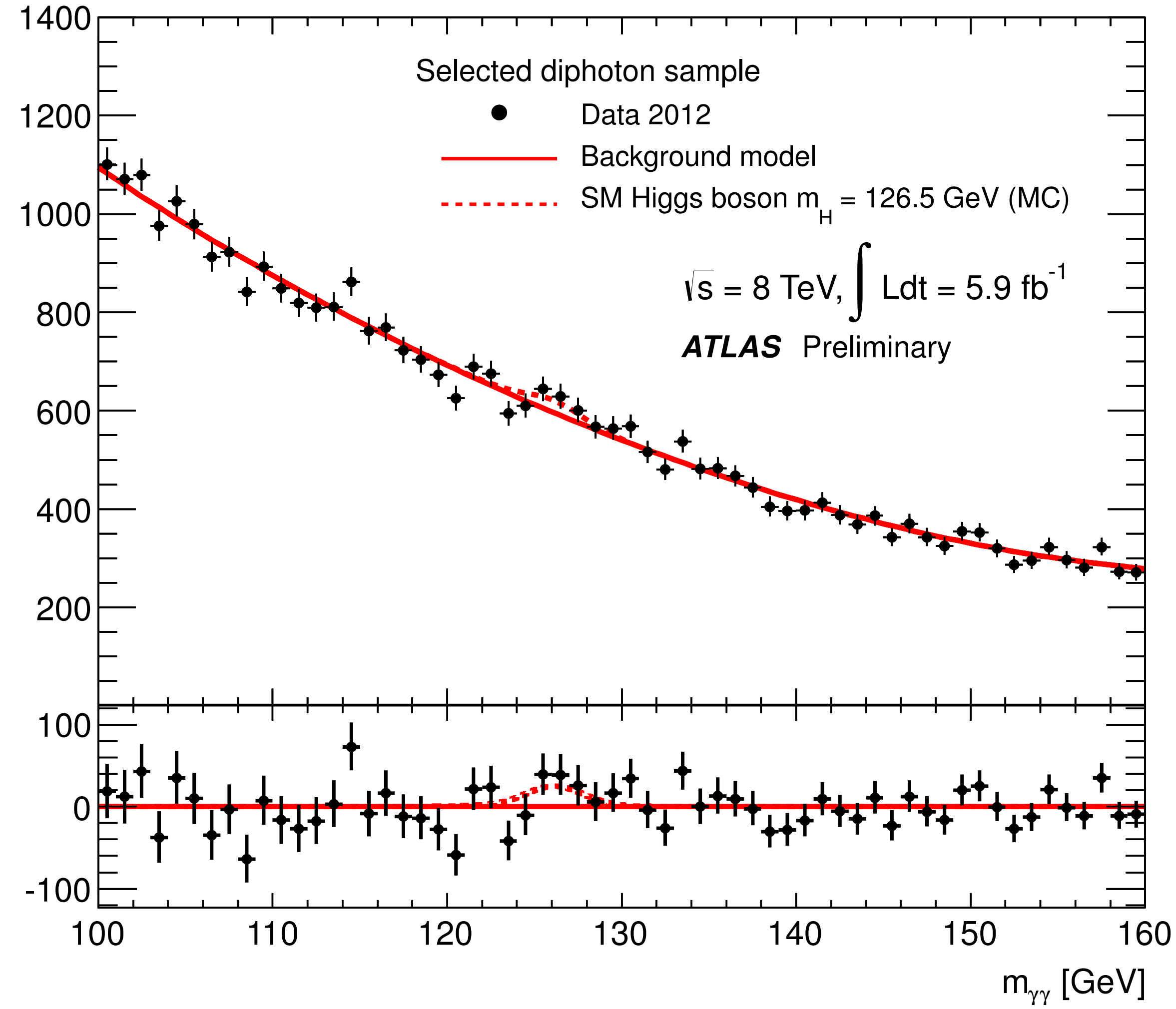
Background Model

Background obtained from fit to observed di-photon invariant mass distribution …
[Exponential, 4^{th}-order Bernstein polynomial, 4^{th} order polynomial, exponential function of a 2^{nd}-order polynomial]

Different parametrization chosen for different event categories …
[Limit potential bias while keeping good statistical power]

Uncertainty estimated using Monte Carlo …





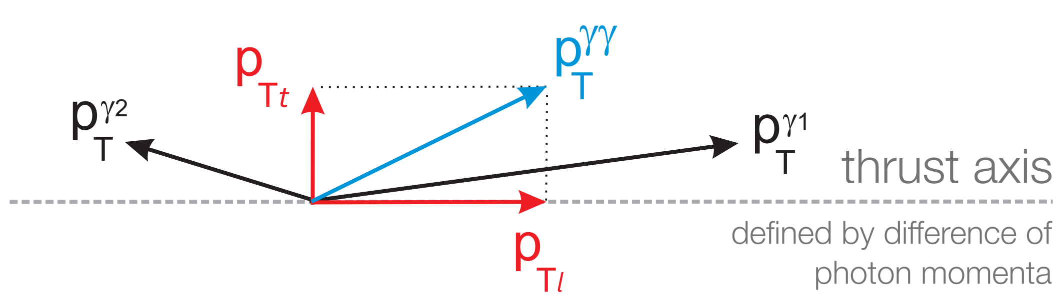
Event Categorization

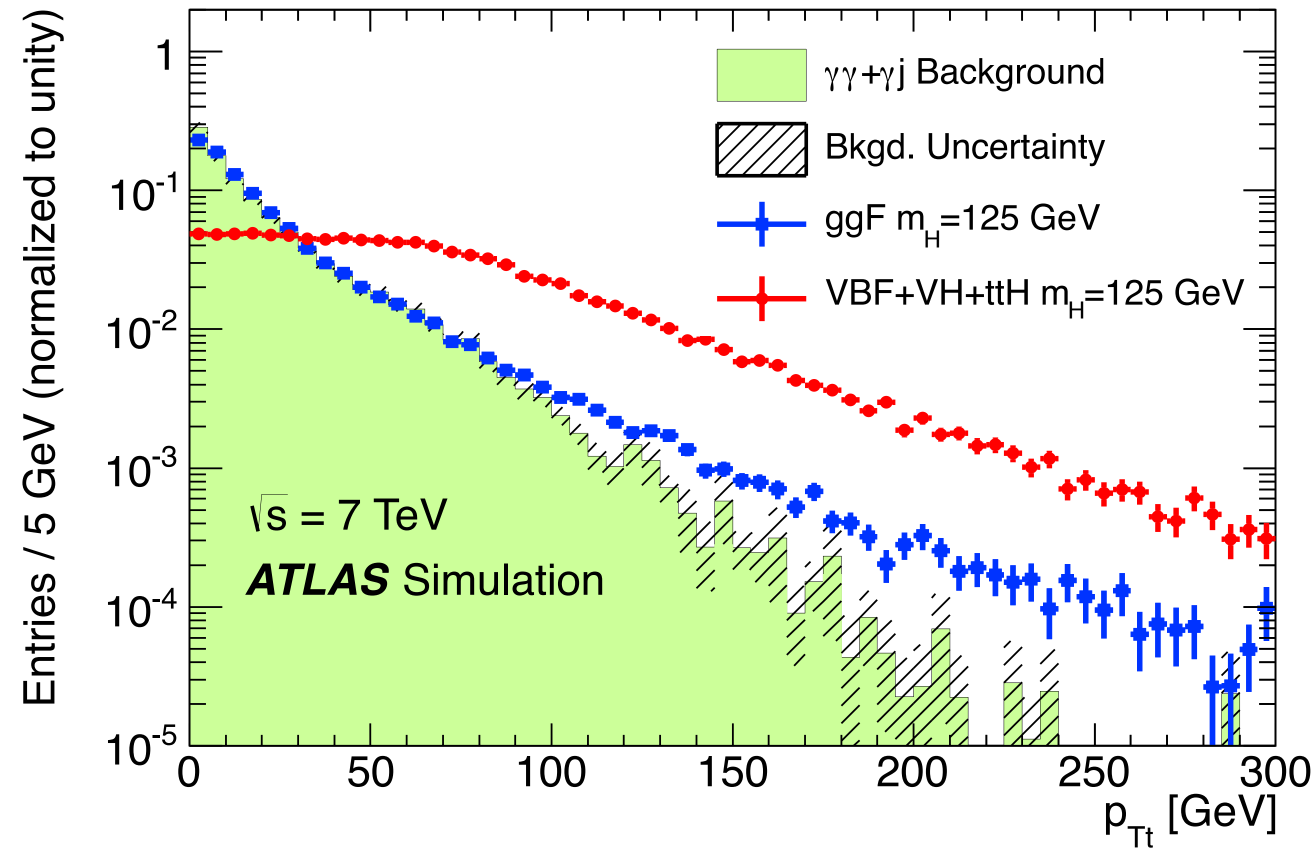
10 Categories

with different S/B and resolution
increases expected signal sensitivity by 25% …

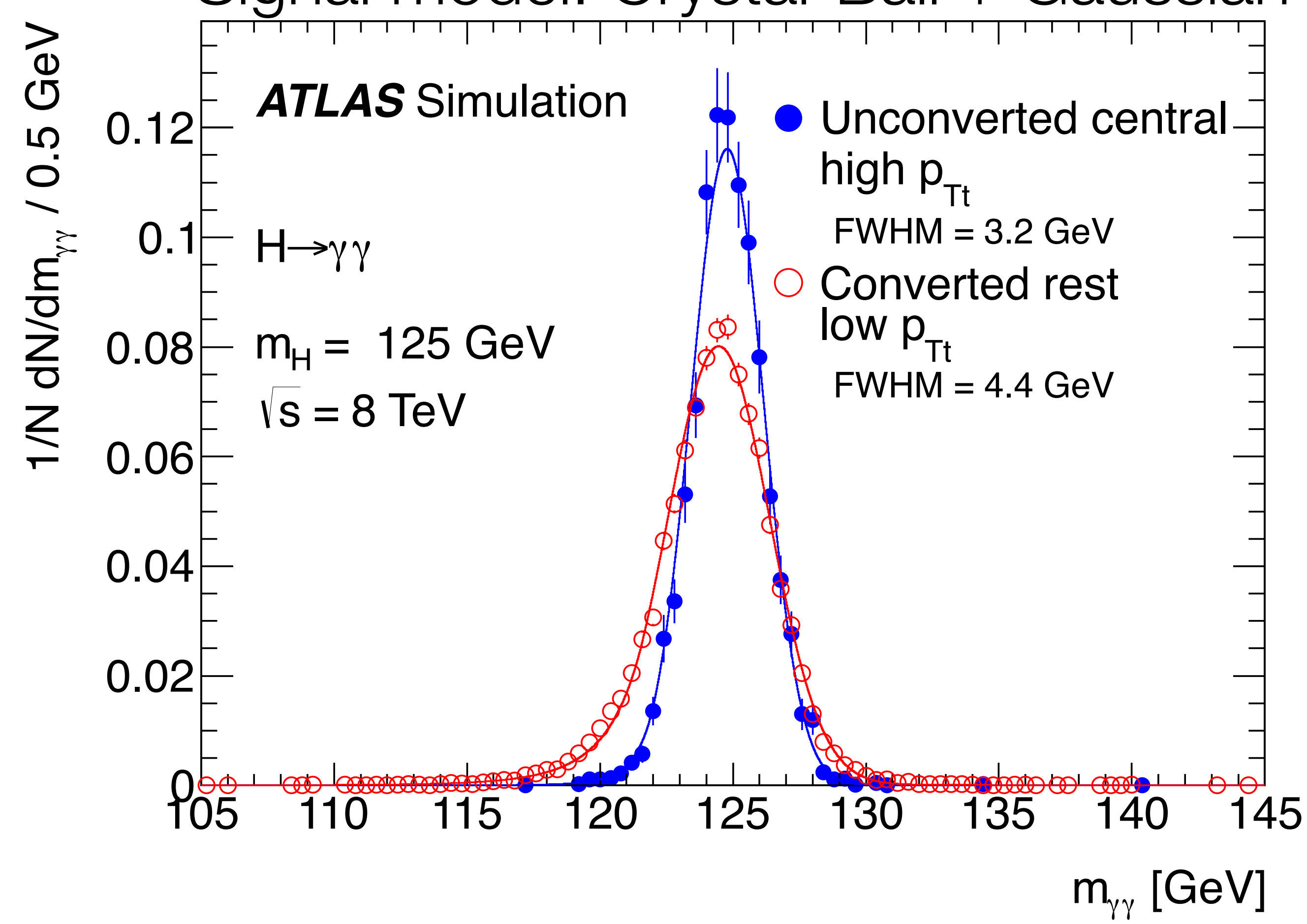
make use of conversion status, $|\eta|$, p_{Tt} [≳ 60 GeV], 2 jets category

Unconverted central, low p_{Tt}
Unconverted central, high p_{Tt}
Unconverted rest, low p_{Tt}
Unconverted rest, high p_{Tt}
Converted central, low p_{Tt}
Converted central, high p_{Tt}
Converted rest, low p_{Tt}
Converted rest, high p_{Tt}
Converted transition region
2-jet category

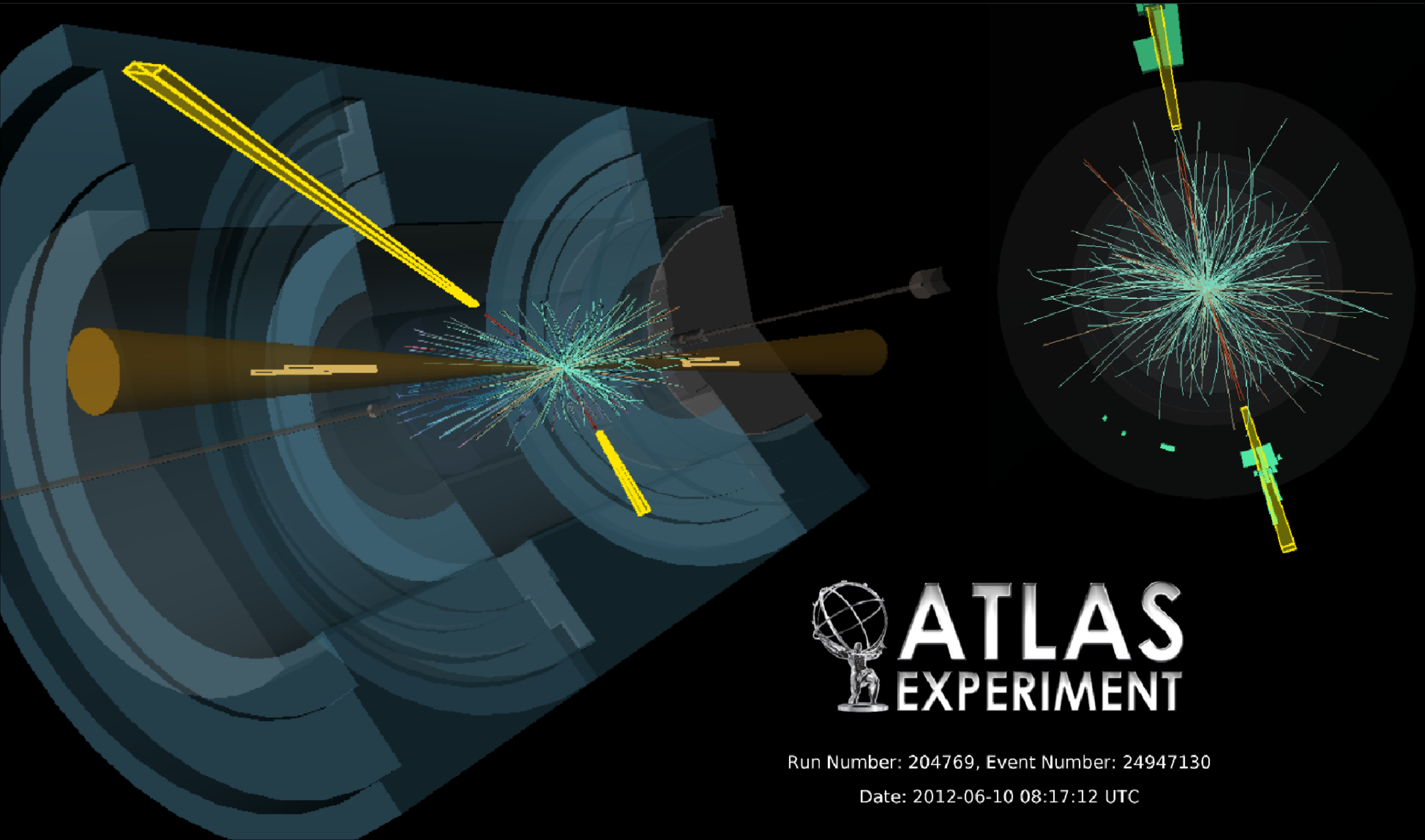




Signal model: Crystal-Ball + Gaussian

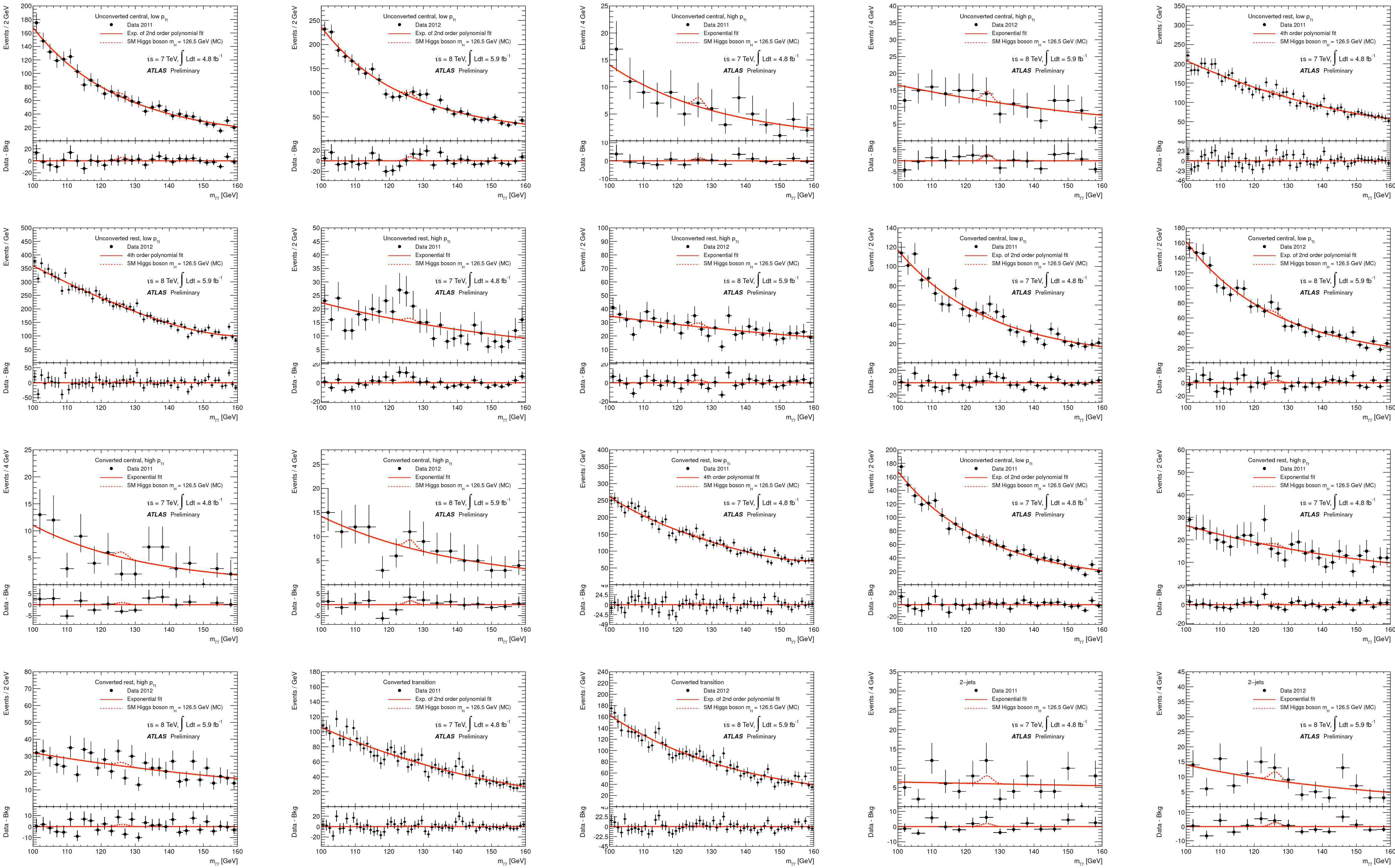


Higgs ➛ γγ + 2 jets



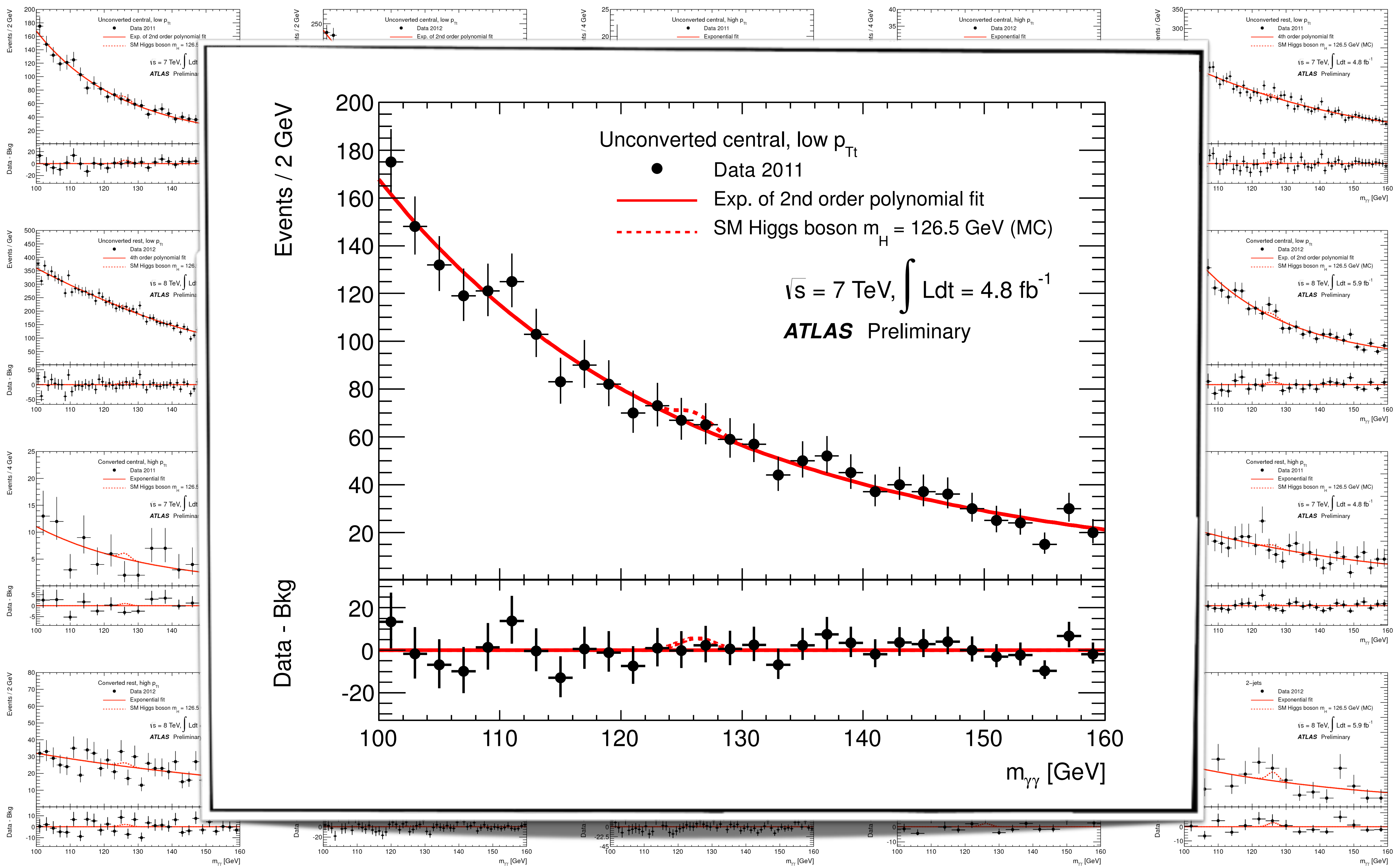
Mass Spectra for Different Categories

[2011 & 2012]

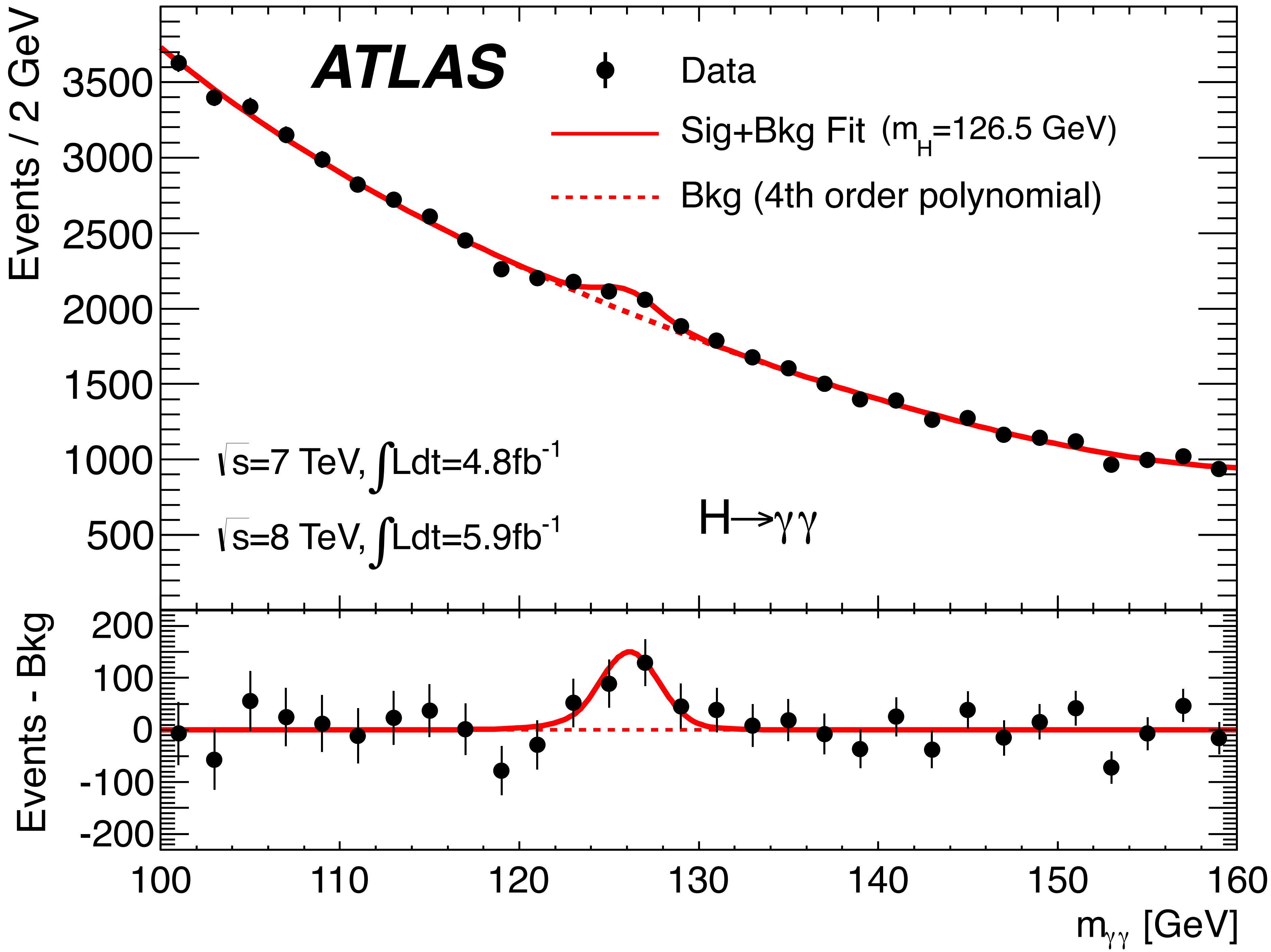


Mass Spectra for Different Categories

[2011 & 2012]



Observation or Fluctuation?



Signal Model Parameters

$$N \cdot \begin{cases} e^{-t^2/2} & \text{if } t > -\alpha \\ (\frac{n}{|\alpha|})^n \cdot e^{-|\alpha|^2/2} \cdot (\frac{n}{|\alpha|} - |\alpha| - t)^{-n} & \text{otherwise} \end{cases}$$

with

$$t = (m_{\gamma\gamma} - m_H - \delta_{m_H})/\sigma_{CB}$$

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

Estimating the Significance …

Naive approach:

$N_S \approx 200$ [120 - 130 GeV]
$N_B \approx 60000$ [100 - 160 GeV]

$S = 2$ [= 200/√10000]

as N_B needs to be
corrected to 10 GeV range

$\sqrt{s}$	7 TeV		8 TeV		
$\sigma \times B(H \to \gamma\gamma)$ [fb]		39		50	FWHM
Category	N_D	N_S	N_D	N_S	[GeV]
Unconv. central, low p_{Tt}	2054	10.5	2945	14.2	3.4
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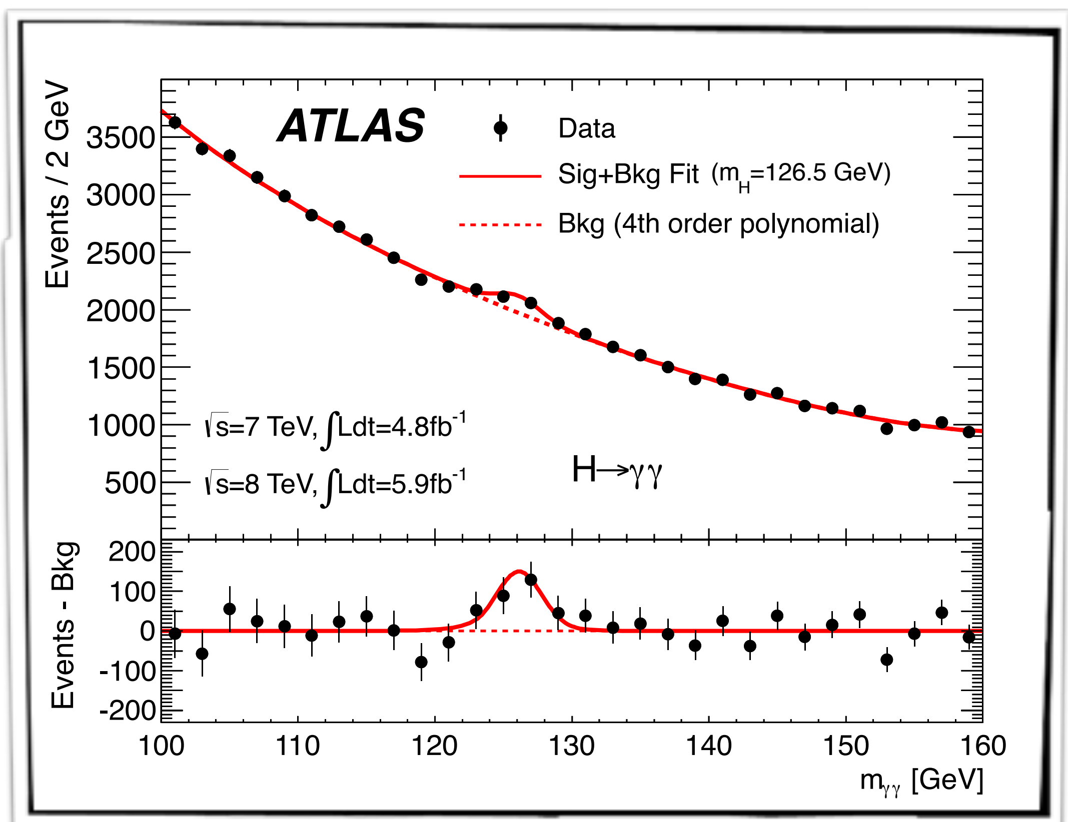
All categories (inclusive)	23788	79.6	35251	110.5	3.9



Use of extra information by
performing a fit to the background …

and optimizing by channel categorization …

Needs procedure to combine …

Background Model Systematics

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

Limit Setting Procedure

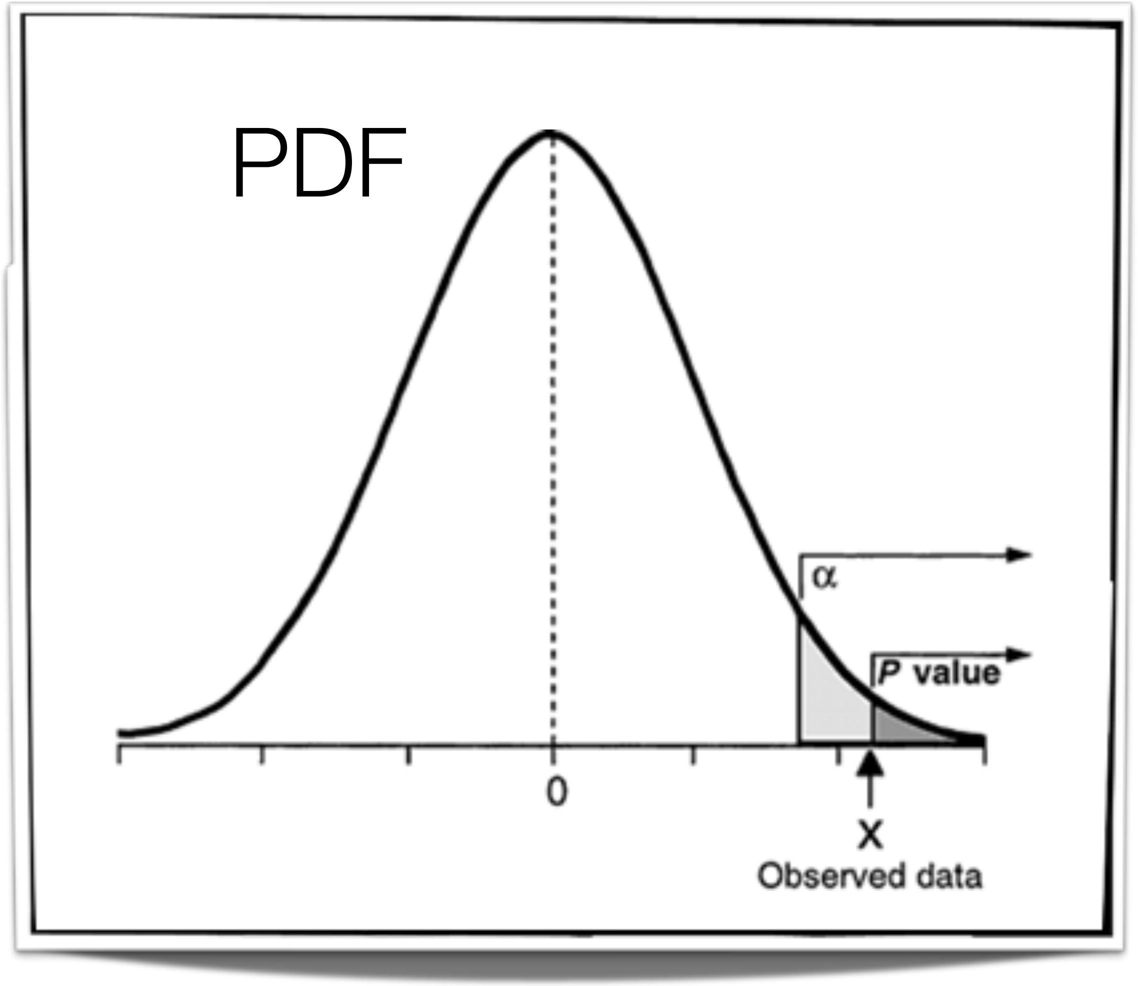
Discovery ...

A deviation from the expectation,
i.e. the background only hypothesis ...

p-value: probability that a result is
as or less compatible with expectation …

Control region α (or size α)
defines the significance level …

If $p < \alpha$ hypothesis is rejected …



Test statistics Q
for e.g. background only hypothesis

Exclusion: $\alpha = 5\%$ [typical]
i.e. exclusion with 95% CL …

Discovery: $\alpha = 2.87 \times 10^{-7}$ [corresponds to 5σ]

Limit Setting Procedure

[e.g. Dulat et al., arXiv:1204.3851v2]

$X = \{X_i\}$ Set of measurements, e.g. number of observed event in specific phase space region

$g(X_i|\mu, \nu)$ Probability density of X_i
with model parameters μ
with nuisance parameters ν = $\{\nu_j\}$

independent input, e.g. lumi

Probability to measure the values X in an single experiment:

$$P = \prod_{i=1}^{N} P(X_i) = \prod_{i=1}^{N} g(X_i|\mu,\nu) dX_i = L(X|\mu,\nu) \prod_{i=1}^{N} dX_i,$$

with

$P(X_i)$: probability to find the measurement within $X_i \pm dX_i$

$L(X|\mu,\nu) = \prod_{i=1}^{N} g(X_i|\mu,\nu)$: likelihood, or joint probability density

Limit Setting Procedure

[e.g. Dulat et al., arXiv:1204.3851v2]

Furthermore:

$$g(X_i \mid \mu, \nu) = e^{-\lambda_i} \lambda_i^{X_i} / X_i!$$

Poisson distribution
[as X_i very low compared to total event number]

$$\lambda_i = \lambda_i(\mu, \nu)$$
$$\lambda(\mu, \nu) = \{\lambda_i(\mu, \nu)\}$$

Expectation value
Depends on parameters μ and ν …

$$\pi(\tilde{\nu} | \nu)$$

Likelihood for nuisance parameters
[includes uncertainties on values of $\nu = \{\nu_j\}$]

Thus:

$$\mathcal{L}(X|\mu, \nu) = \prod_i \frac{e^{-\lambda_i(\mu,\nu)} \lambda_i^{X_i}(\mu, \nu)}{X_i!} \times \prod_j \pi_j(\tilde{\nu}_j | \nu_j).$$

Limit Setting Procedure

[e.g. Dulat et al., arXiv:1204.3851v2]

Likelihood ratio:

$$LR = \frac{\mathcal{L}(X|\mu,\nu)}{\mathcal{L}(X|\mu',\nu')}$$

Quantifies agreement of X with prediction λ(μ,ν) relativ to λ(μ′,ν′)

Profiled log-likelihood ratio:

Get's large if X disagrees with prediction …

$$q_\mu(X) = \begin{cases} -2\log\frac{\mathcal{L}(X|\mu,\hat{\nu}_\mu)}{\mathcal{L}(X|\mu',\hat{\nu}_{\mu'})} & ,\ \mu \geq \mu' \geq 0 \\ 0 & ,\ \text{else} \end{cases}$$

with

$$\mathcal{L}(X|\mu,\hat{\nu}_\mu) \geq \mathcal{L}(X|\mu,\nu) \quad \forall \quad \nu.$$

Maximized $\mathcal{L}$ for a fixed μ …

$$\mathcal{L}(X|\mu',\hat{\nu}_{\mu'}) \geq \mathcal{L}(X|\mu,\nu) \quad \forall \quad \mu,\nu.$$

Globally maximized $\mathcal{L}$ …

Limit Setting Procedure

[e.g. Dulat et al., arXiv:1204.3851v2]

Profiled
Log-likelihood ratio $q_\mu(X)$
depends on X and μ …

The distribution of $q_\mu(X)$ is
referred to as:

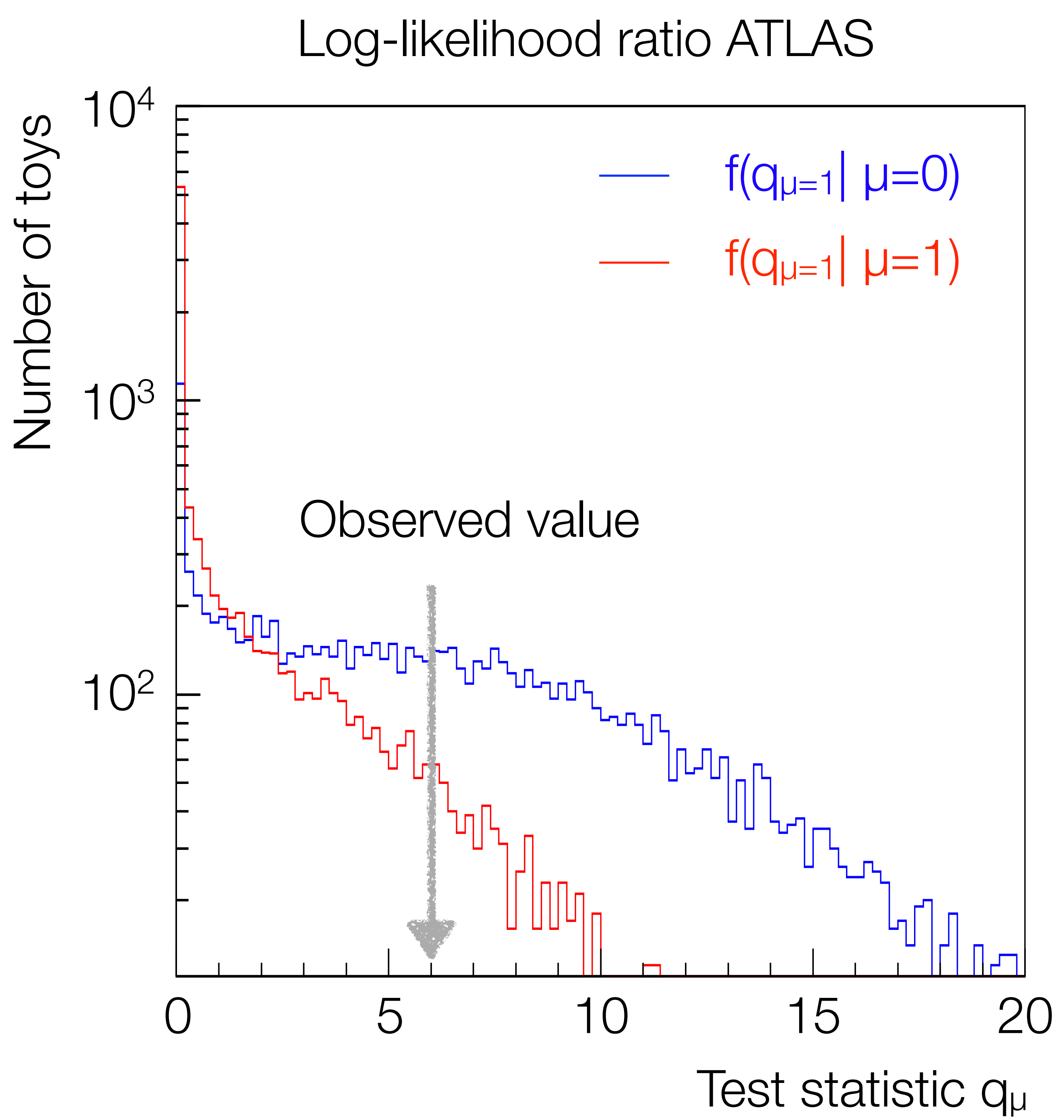
$$f(q_\mu|\mu, \hat{\nu}_\mu)$$

This distribution function
cannot be evaluated analytically …

Determination using MC …

P-value:

Probability, of q_μ with equal or lesser compatibility with the hypothesis relative to what is found with q_{obs}.



Limit Setting Procedure

[e.g. Dulat et al., arXiv:1204.3851v2]

Log-likelihood ratio $q_\mu(X)$ depends on X and μ …

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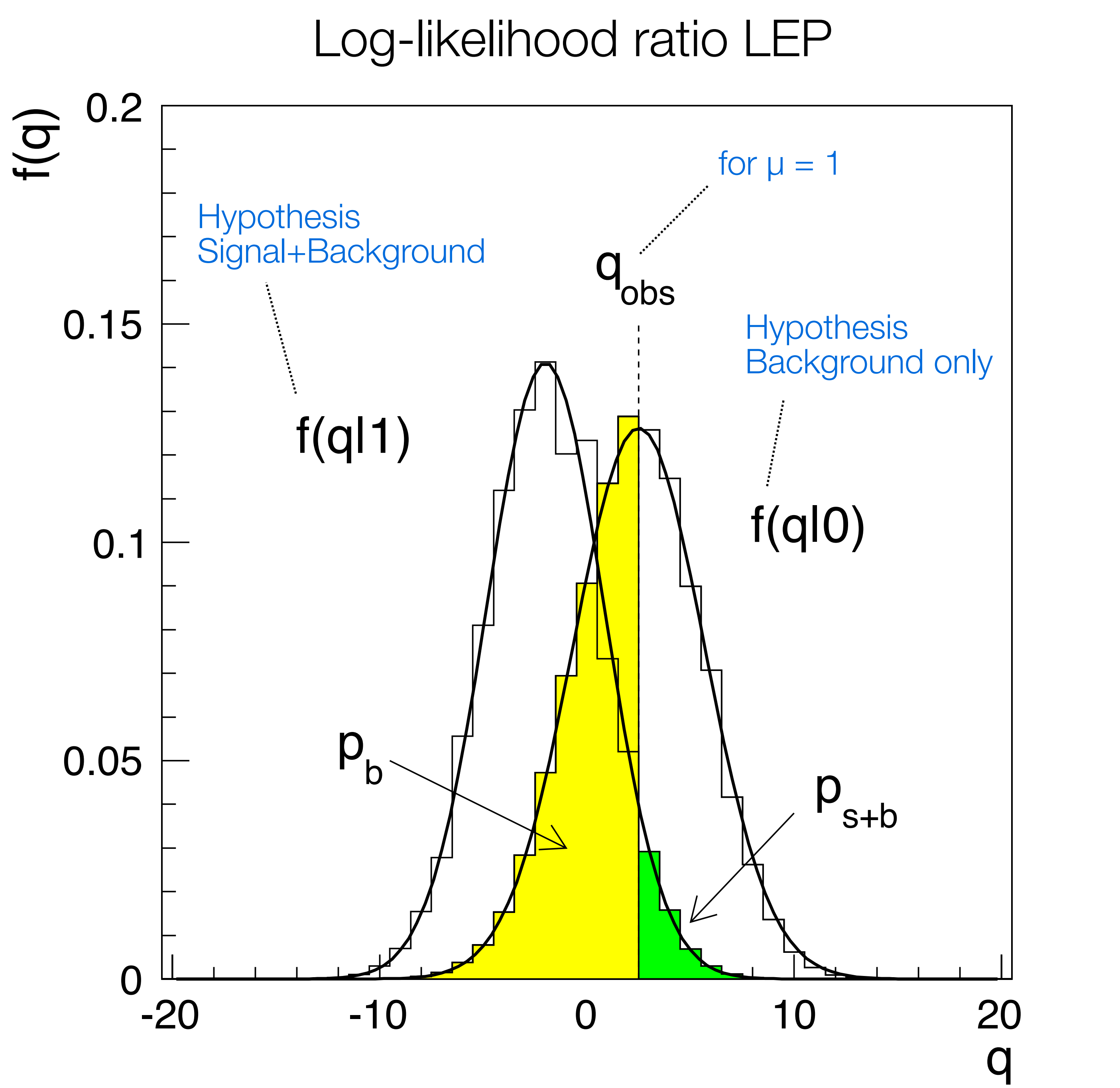


Limit Setting Procedure

[e.g. Dulat et al., arXiv:1204.3851v2]

Log-likelihood ratio …

$$p_{s+b} = P(q \geq q_{\rm obs}|s+b) =$$

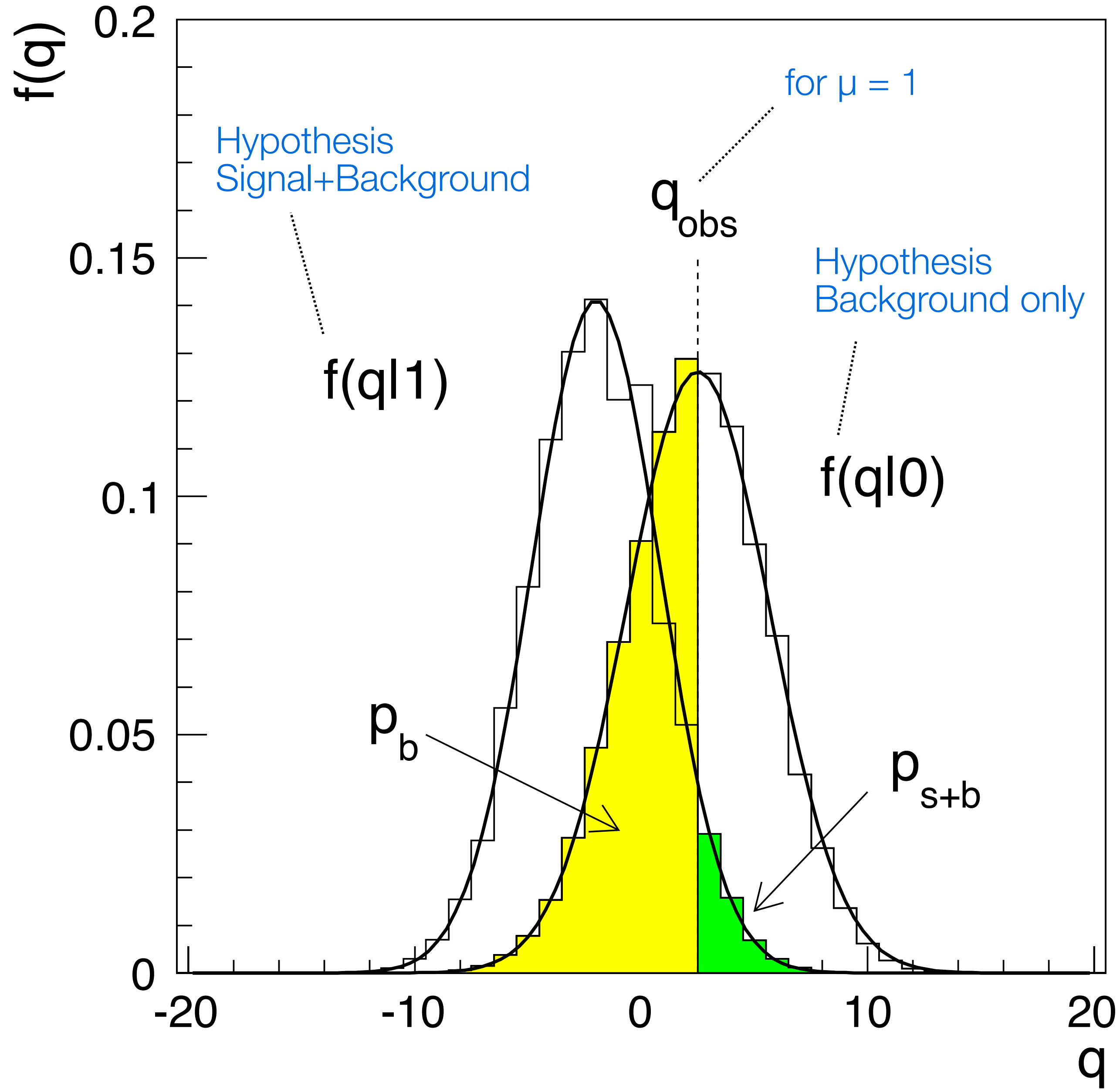
$$= \int_{q_{\rm obs}}^{\infty} f(q|s+b)\, dq$$

$$p_b = P(q \leq q_{\rm obs}|b) = \int_{-\infty}^{q_{\rm obs}} f(q|b)\, dq$$

P-value:

Probability, of q_μ with equal or lesser compatibility with the hypothesis relative to what is found with q_{obs}.

Log-likelihood ratio LEP



Limit Setting Procedure

[e.g. Dulat et al., arXiv:1204.3851v2]

Profiled
Log-likelihood ratio …

$$p_{s+b} = CL_{S+B}(\mu) = \int_{q_\mu(X)}^{\infty} dq_\mu f(q_\mu|\mu, \hat{\nu}_\mu)$$

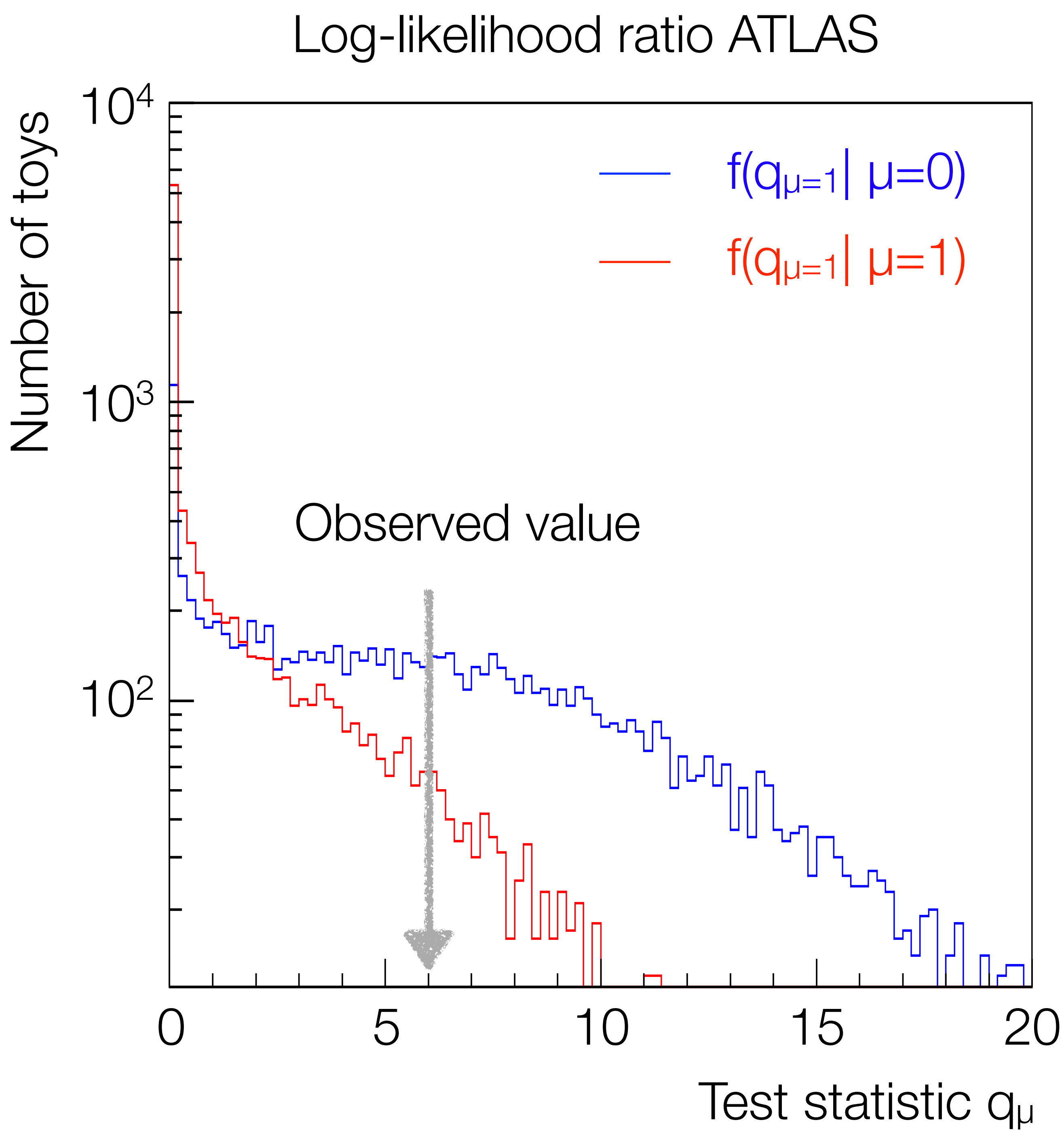
Probability of observing X′ with $q_\mu(X') \geq q_\mu(X)$
Large: observation compatible with λ(μ, …)

$$1 - p_b = 1 - CL_B(\mu) = \int_{q_\mu(X)}^{\infty} dq_\mu f(q_\mu|0, \hat{\nu}_0)$$

Probability of observing X′ with $q_\mu(X') \geq q_\mu(X)$
Large: observation disagrees with λ(0, …)

P-value:

Probability, of q_μ with equal or lesser compatibility with the hypothesis relative to what is found with q_{obs}.



Limit Setting Procedure

[e.g. Dulat et al., arXiv:1204.3851v2]

CL_S Method …

Penalization in case of small sensitivity …

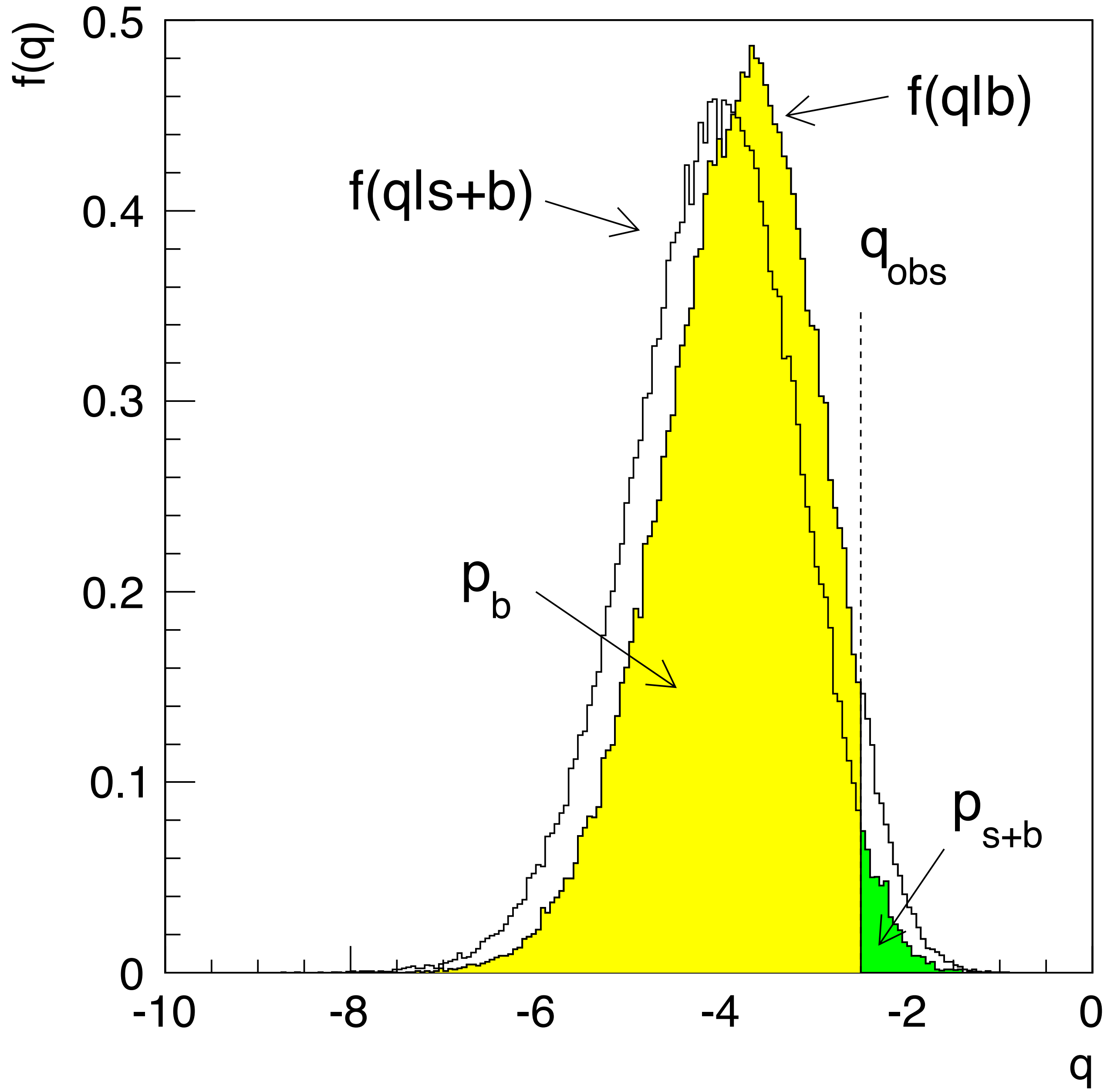
$$CL_S(\mu) \equiv \frac{CL_{S+B}(\mu)}{1 - CL_B(\mu)}$$

i.e.:

Penalization by dividing by $1-CL_B$
Wide separation: $1-CL_B \approx 1$ no penalty
Overlap: strong penalty.

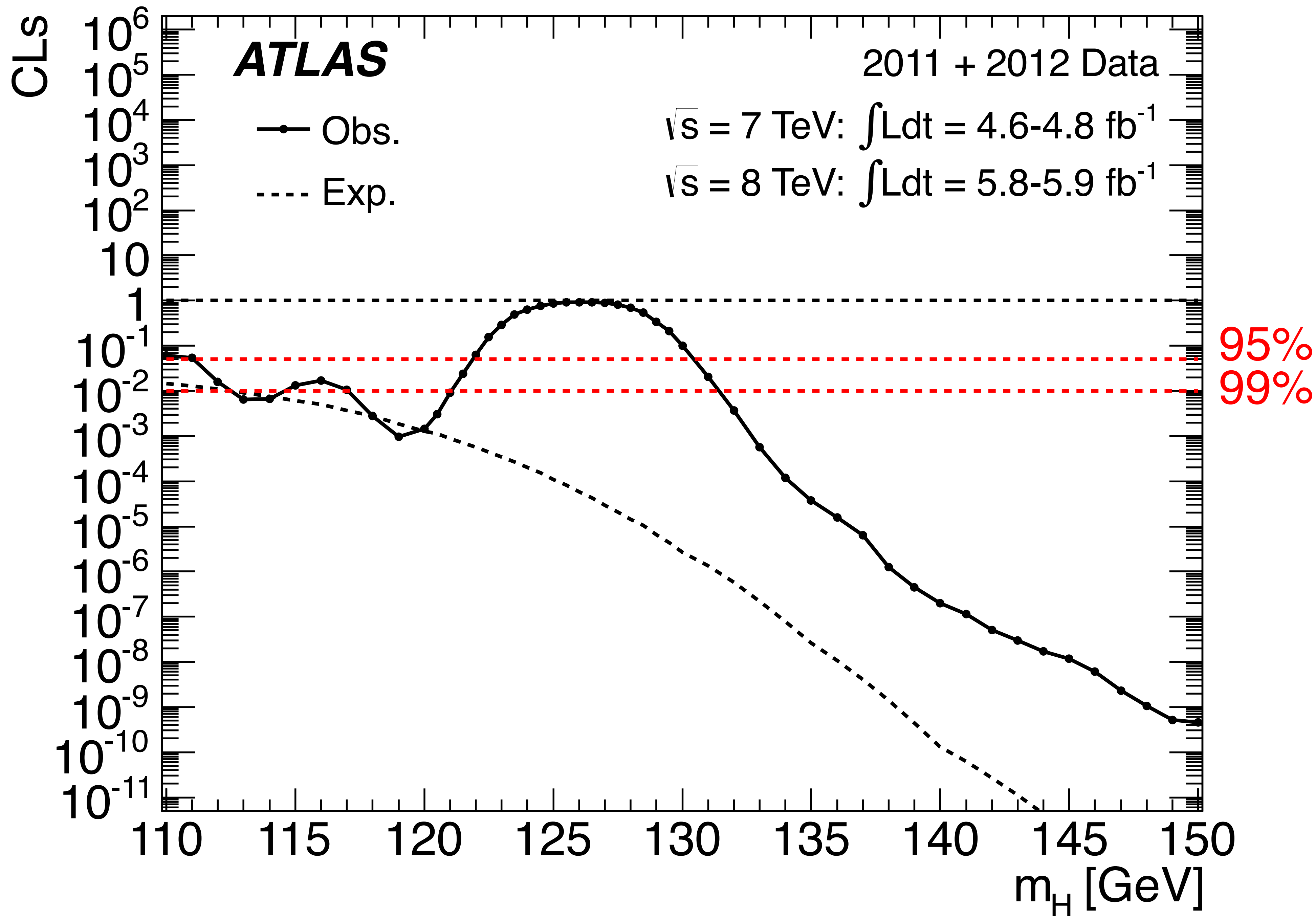
By this one prevents exclusion of models for which there is low sensitivity …

Log-likelihood ratio LEP



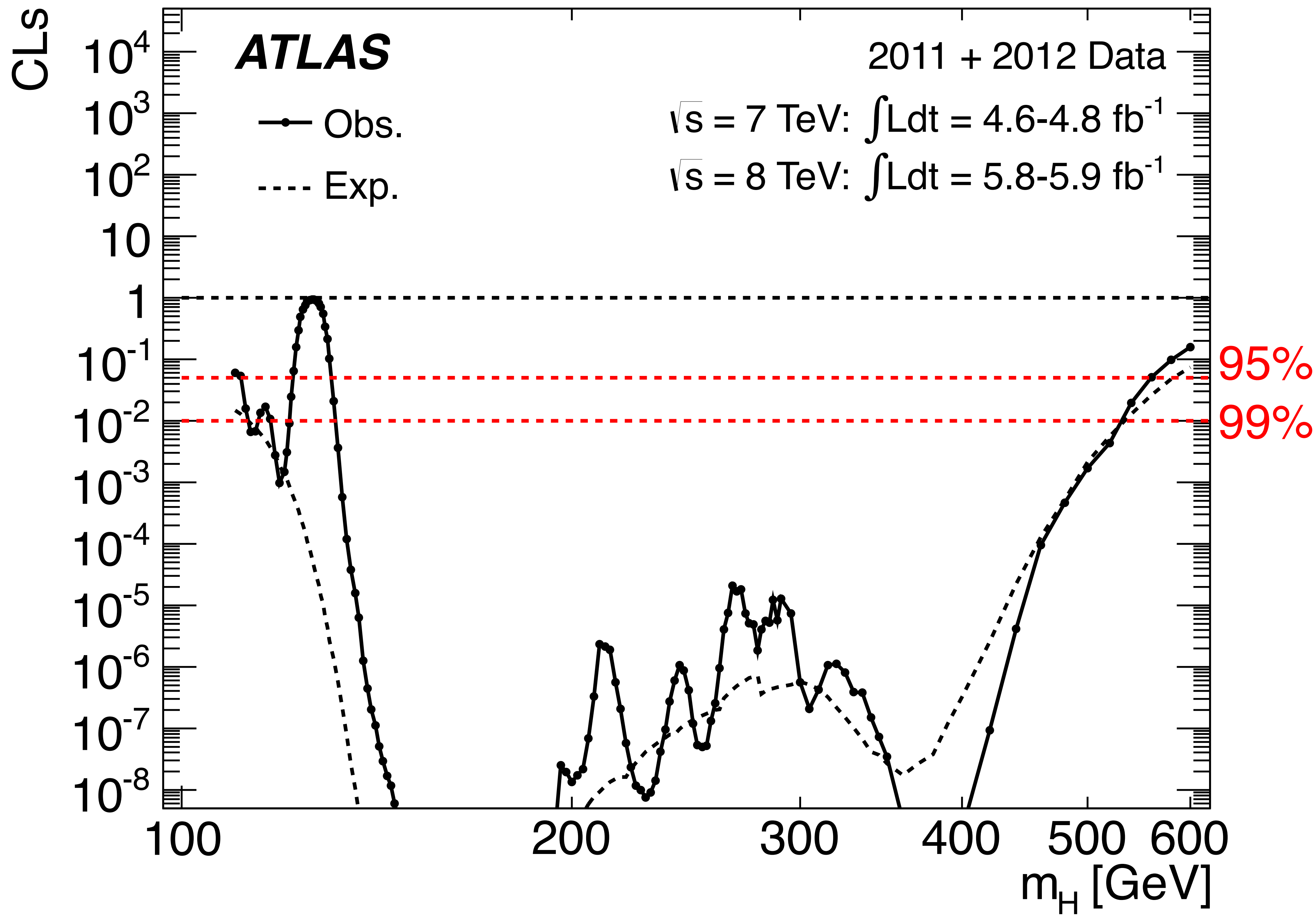
Testing the SM Higgs …

[CLs for mu=1]



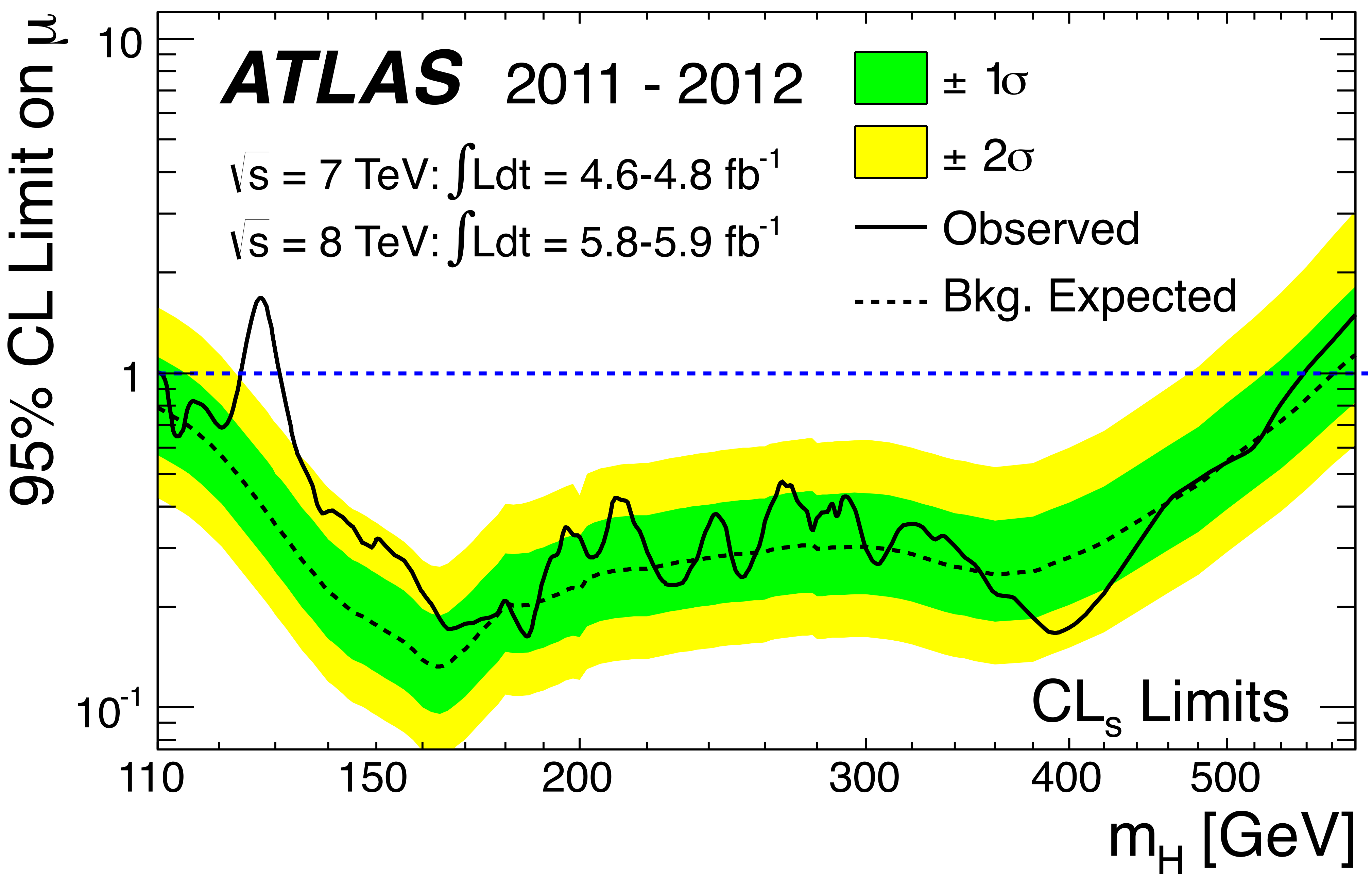
Testing the SM Higgs ...

[CL_s for mu=1]



Testing the SM Higgs …

$$\mu^{\alpha\%} = CL_S^{-1}(1-\alpha\%)$$



Testing the SM Higgs …

$$\mu^{\alpha\%} = CL_S^{-1}(1-\alpha\%)$$