Search for Z-photon resonances with the ATLAS detector

Nathan Readioff

ATLAS EXPERIMENT

Enigmass
The enigma of mass

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Laboratoire de Physique Subatomique et de Cosmologie

Who I am…

- I'm from Wallasey, England
- Undergraduate degree taken at the University of Liverpool
  - Special four year course combining BSc and Masters
  - Masters project titled:
    - Search for evidence of gauge-mediated supersymmetry breaking in the scenario where the neutrino is long-lived
- Followed by PhD at the University of Liverpool
  - Search for resonances decaying to a Z boson and a photon in the ATLAS Detector using data from the Large Hadron Collider
  - Additional work on the ATLAS ITK upgrade project

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Introduction

- Introduction to the Higgs boson

- Search for H→Zγ decay
  - First studies using 7 and 8 TeV data (2011+2012)
  - Analysis refinements - Z mass slices technique
  - Latest results using 13 TeV data (2015+2016)

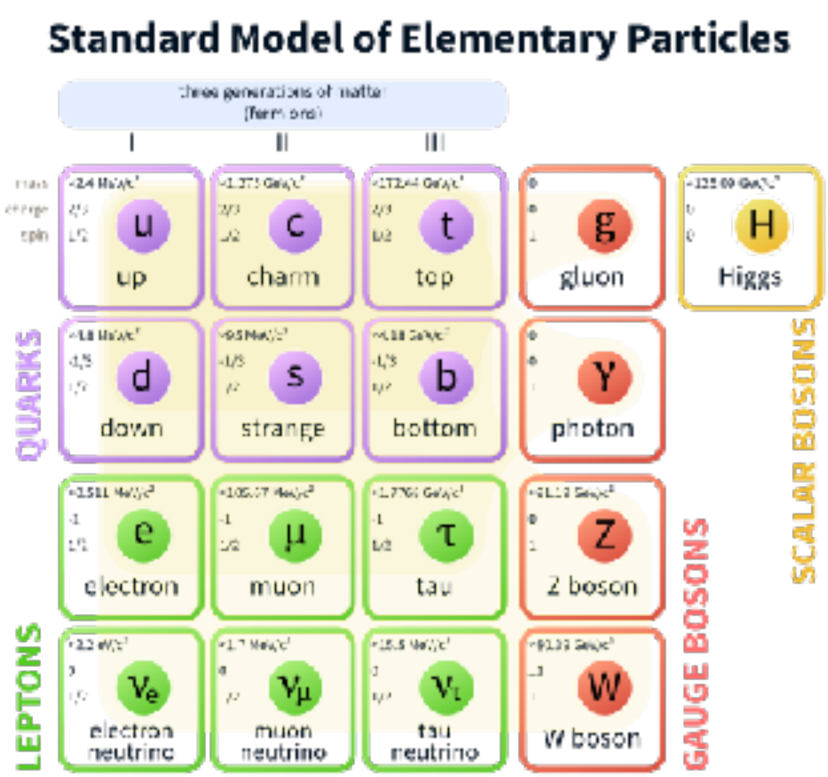
- Search for new exotic resonances, X, decaying via X→Zγ
  - Initial search using 8 TeV data (2012)
  - First search with early 13 TeV data set (2015)
  - Latest results with full 13 TeV data set (2015+2016)

The Electroweak Force

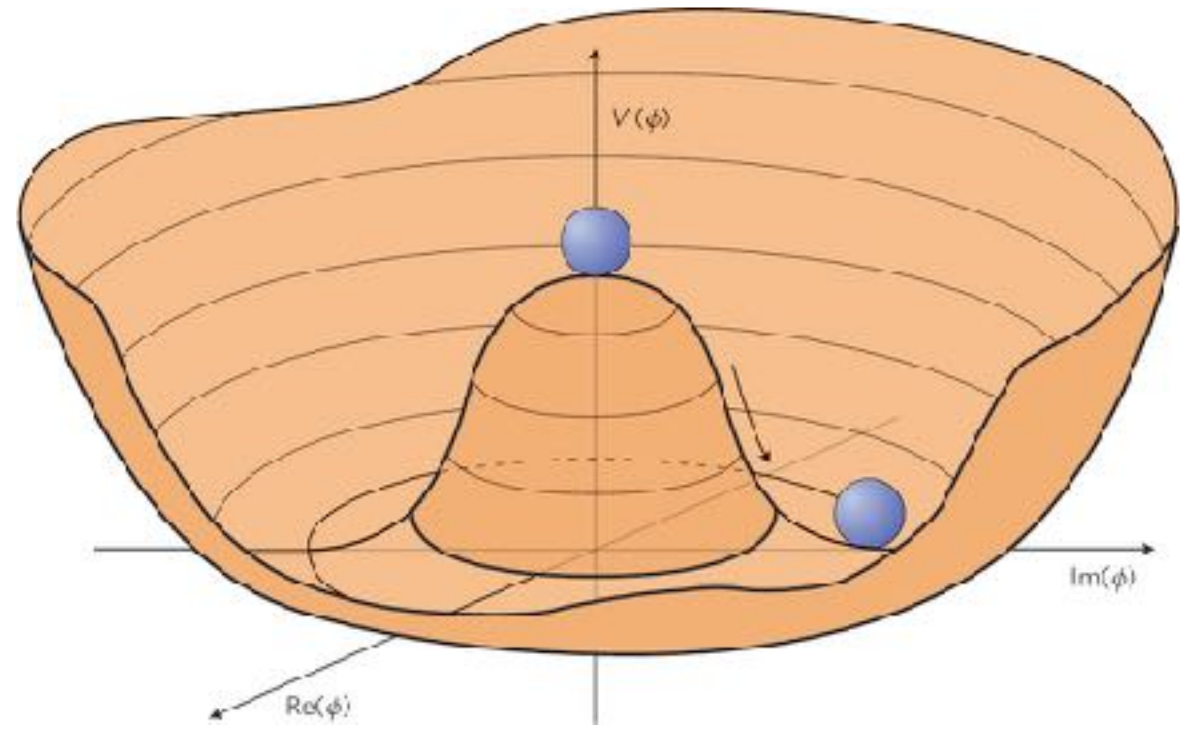
- The Standard Model describes three out of four interactions in Nature
  - Electromagnetism
  - Strong Nuclear Force
  - Weak Nuclear Force

- Electromagnetic and weak forces are two facets of a single force
  - Above a unification energy, forces merge into single "electroweak" force
  - Sheldon Glashow, Abdus Salam and Steven Weinberg shared 1979 Nobel Prize

- The resultant Lagrangian has just one problem: no mass terms
  - The photon, W and Z vector bosons should all therefore be massless
  - Photon is massless,
  - W boson has mass 80.4 GeV
  - Z has mass 91.2 GeV



The Brout-Englert-Higgs Mechanism



- Introduce a doublet of complex scalar fields

$$\Phi(x) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

- Choose a wine-bottle potential

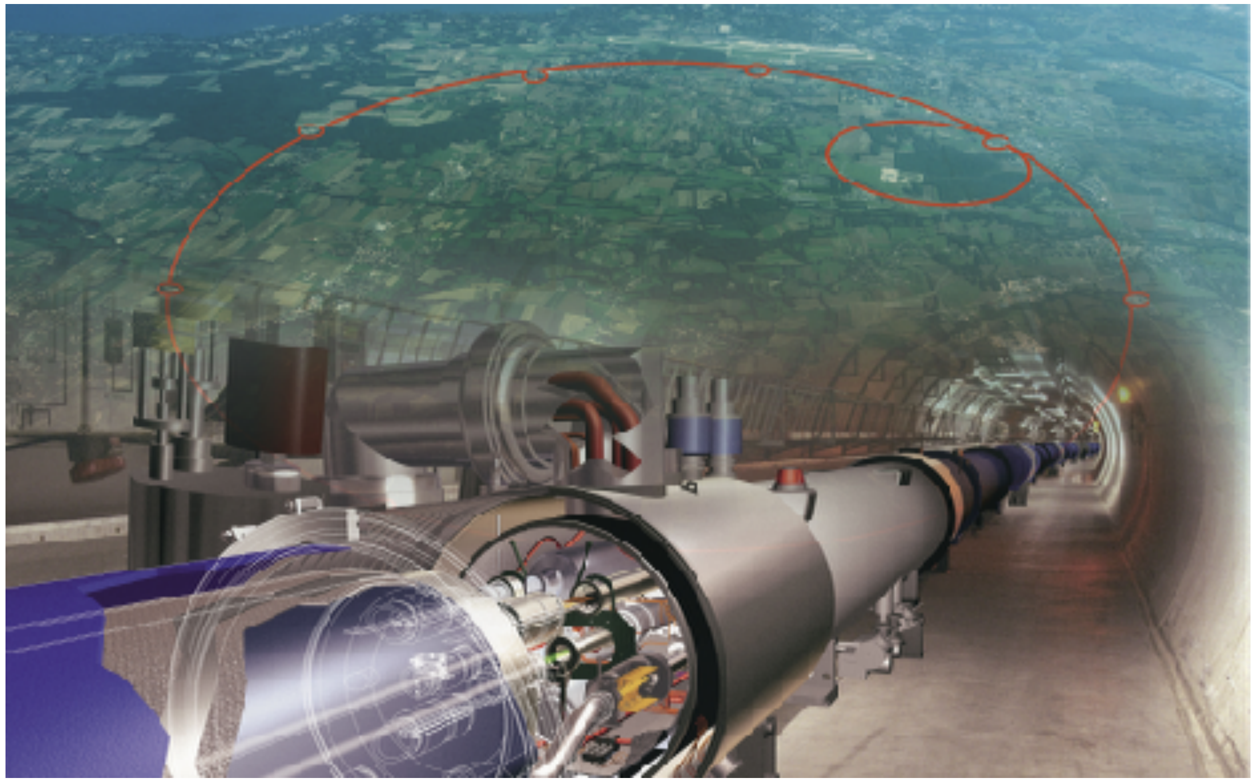
$$V(\Phi) = \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2$$

- The Lagrangian acquires the following terms:

$$\begin{aligned} \mathcal{L} &= (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) \\ &= \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{1}{4} g^2 \left(H^2 + 2vH + v^2\right) W_\mu^+ W^{-\mu} \\ &+ \frac{1}{8}\left(g^2 + g'^2\right)\left(H^2 + 2vH + v^2\right) Z_\mu Z^\mu \\ &+ \mu^2 H^2 + \frac{\lambda}{4}\left(H^4 + 4vH^3\right) \end{aligned}$$

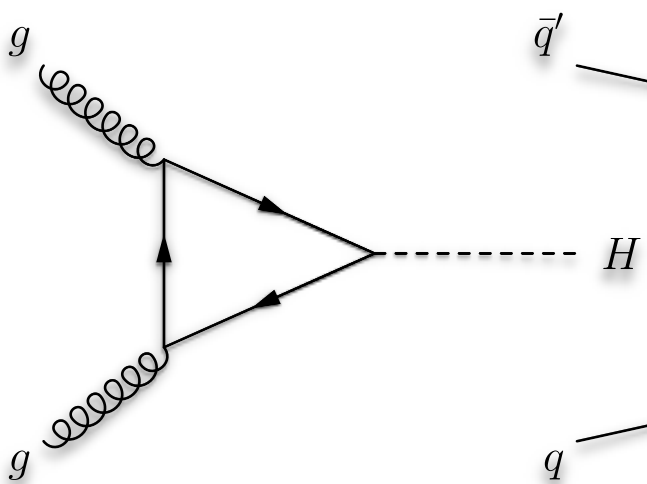
- No terms relating to the photon field - massless photon!
- Terms in W and Z: $M_W^2 W_\mu^+ W^{-\mu} = \frac{1}{4} g^2 v^2 W_\mu^+ W^{-\mu}, \quad \frac{1}{2} M_Z^2 Z_\mu Z^\mu = \frac{1}{8}\left(g^2 + g'^2\right) v^2 Z_\mu Z^\mu$
- Massive W and Z bosons!
- Residual term: $\frac{1}{2} M_H^2 H^2 = \left(\frac{1}{2}\mu^2 - \frac{3}{2}\lambda v^2\right) H^2 = \left(\frac{1}{2}\mu^2 - \frac{3}{2}\mu^2\right) H^2 = -\mu^2 H^2$
- Scalar field has an associated massive boson!

Production of the Higgs at the LHC

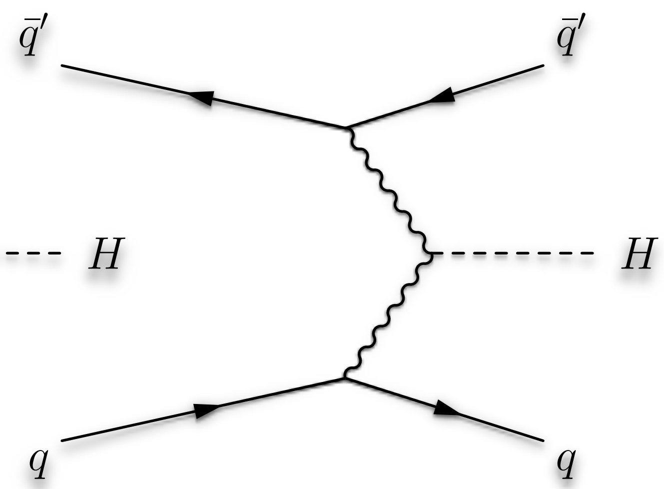


- LHC produces the Higgs through several mechanisms
  - Gluon-gluon fusion (ggF)
  - Vector boson fusion (VBF)
  - Production with associated vector boson (WH/ZH)
  - Production with associated $t\bar{t}$ pair ($t\bar{t}H$)

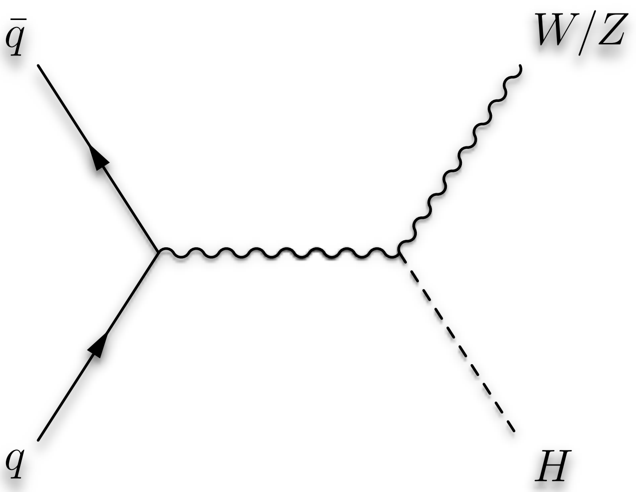
- Percentage mixture varies with $\sqrt{s}$ and m_H
- For $\sqrt{s}$ = 8 TeV, m_H = 125 GeV:
  - ggF dominates, with ~87% of the total
  - VBF is next, with ~7% of the total



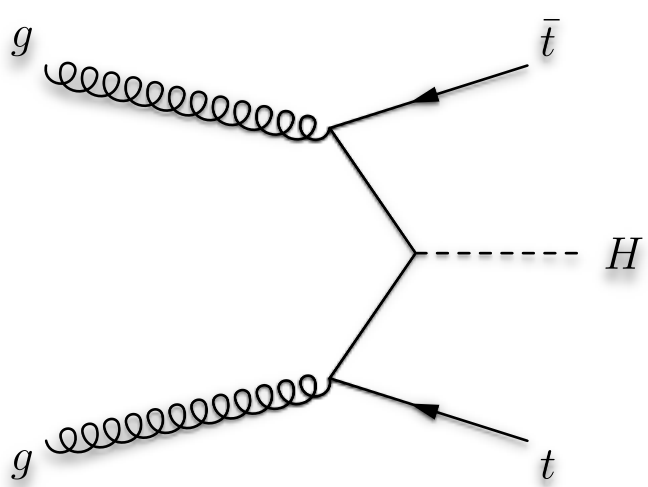
ggF



VBF



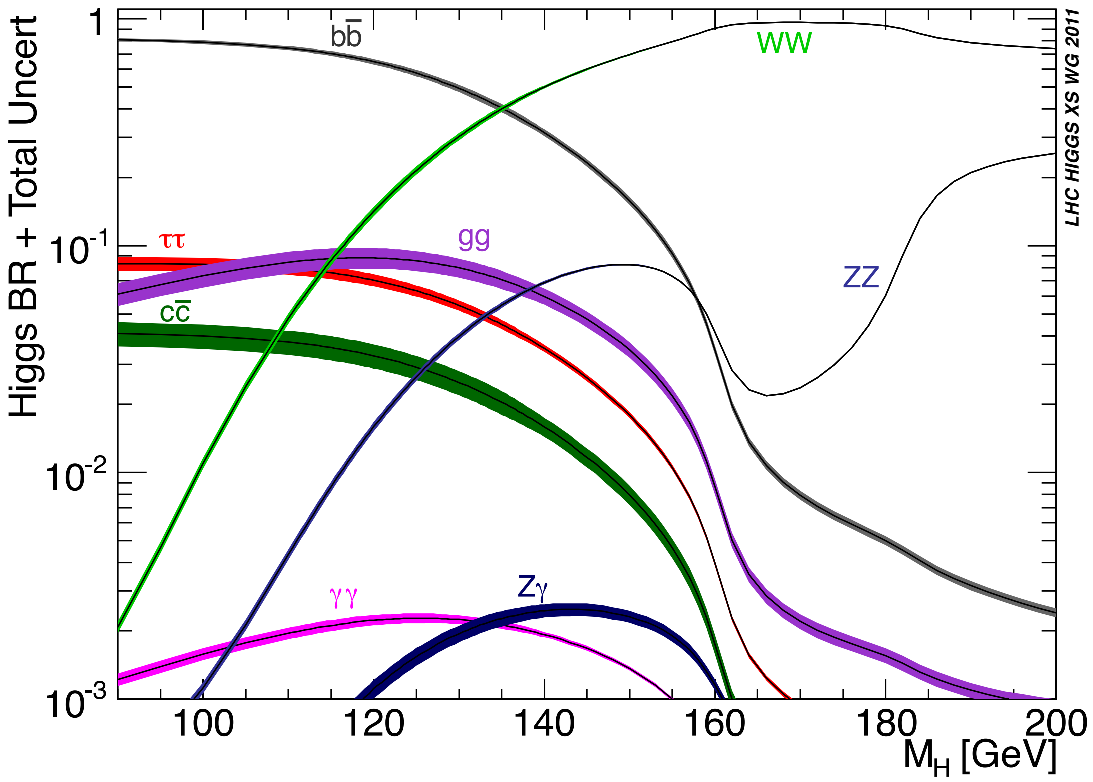
WH/ZH



$t\bar{t}H$

Discovery of the Higgs Boson

- Higgs boson discovery announced in July 2012



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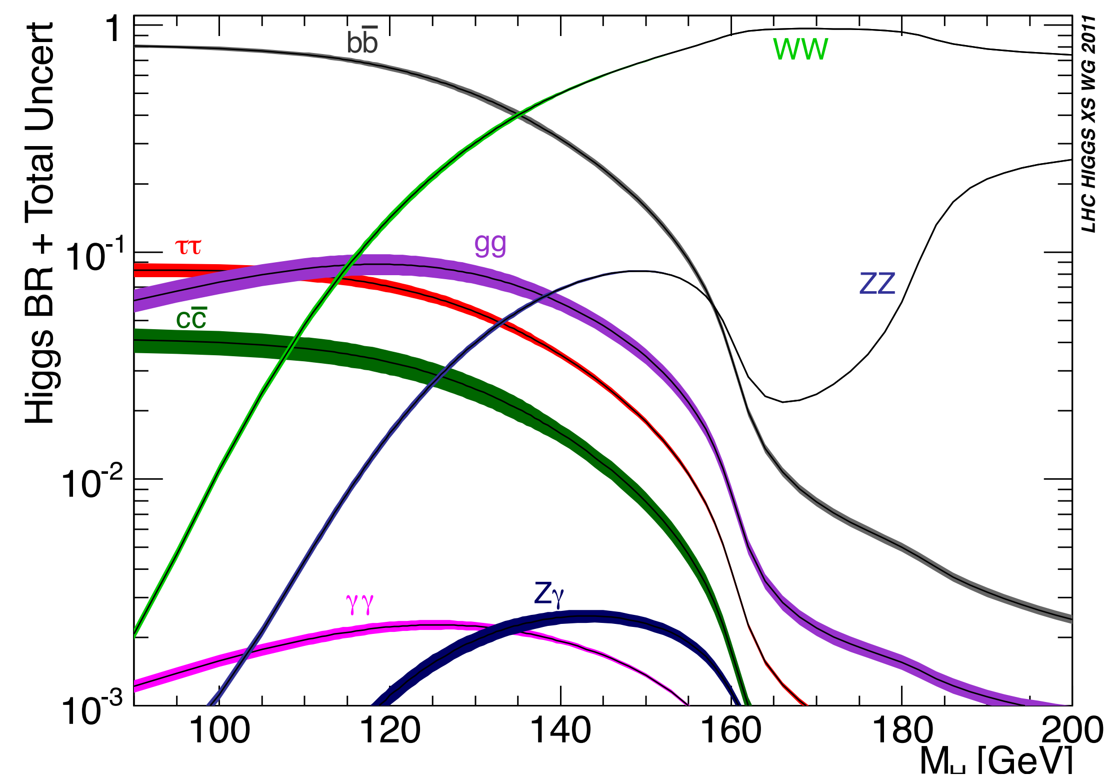
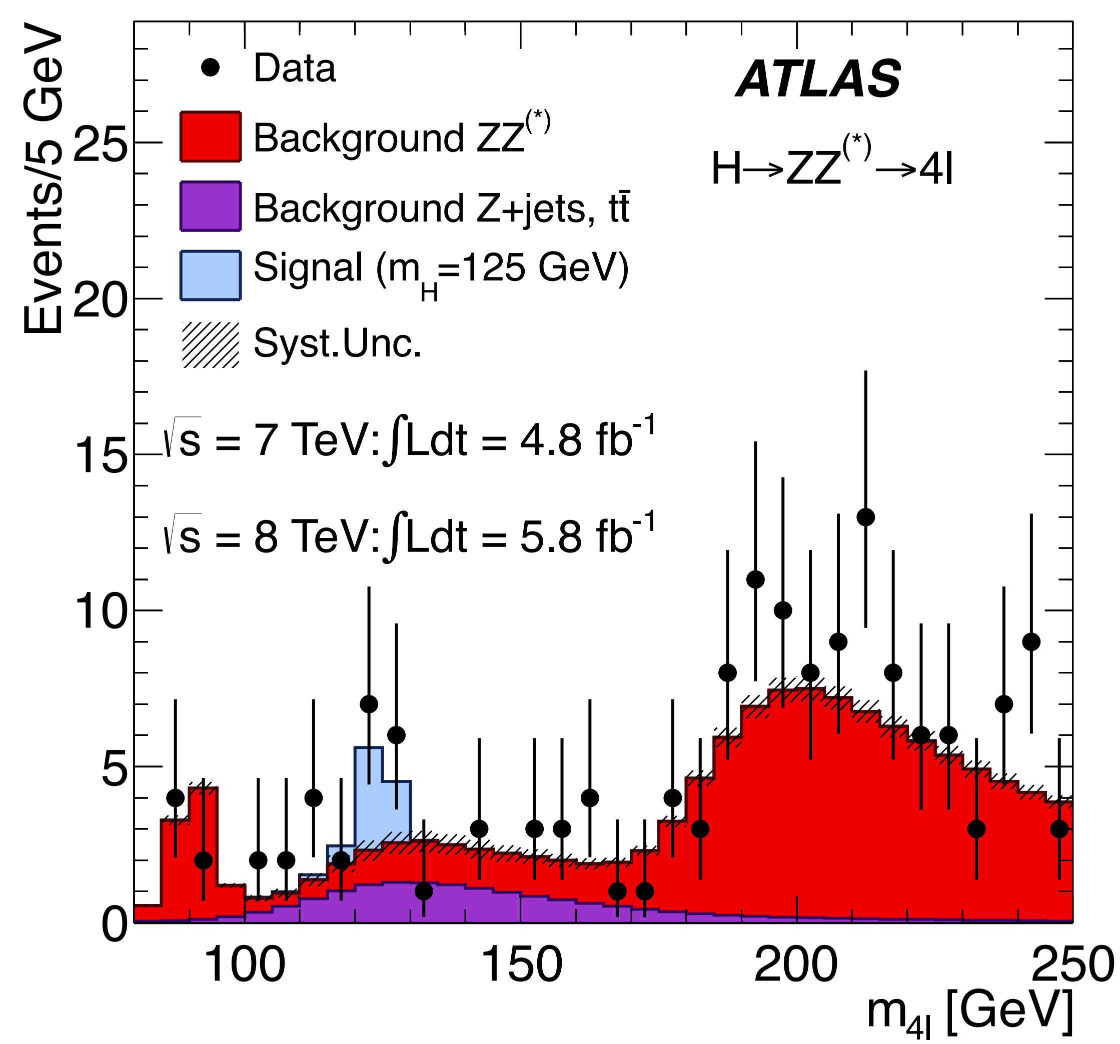
- Discovery made through study of the "golden channels"
  - $H \rightarrow ZZ$
  - $H \rightarrow \gamma\gamma$





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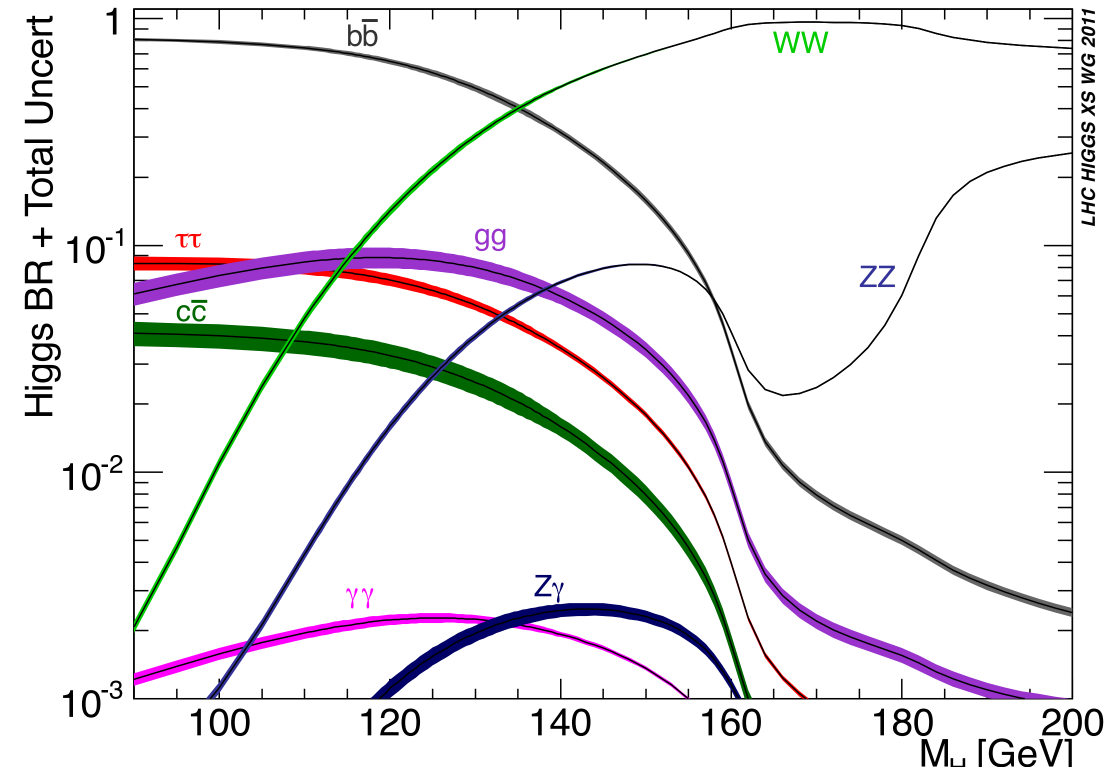
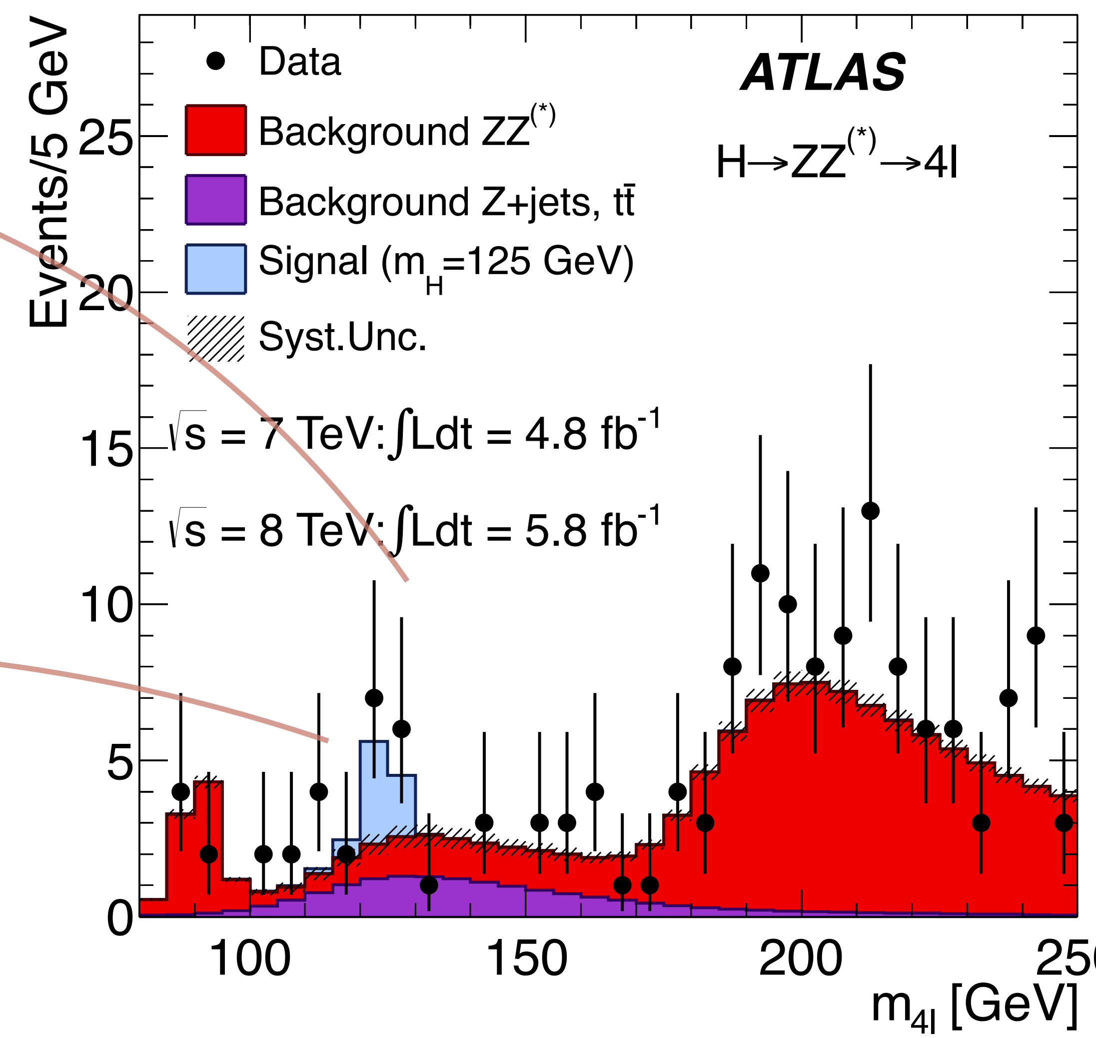
  - H→γγ





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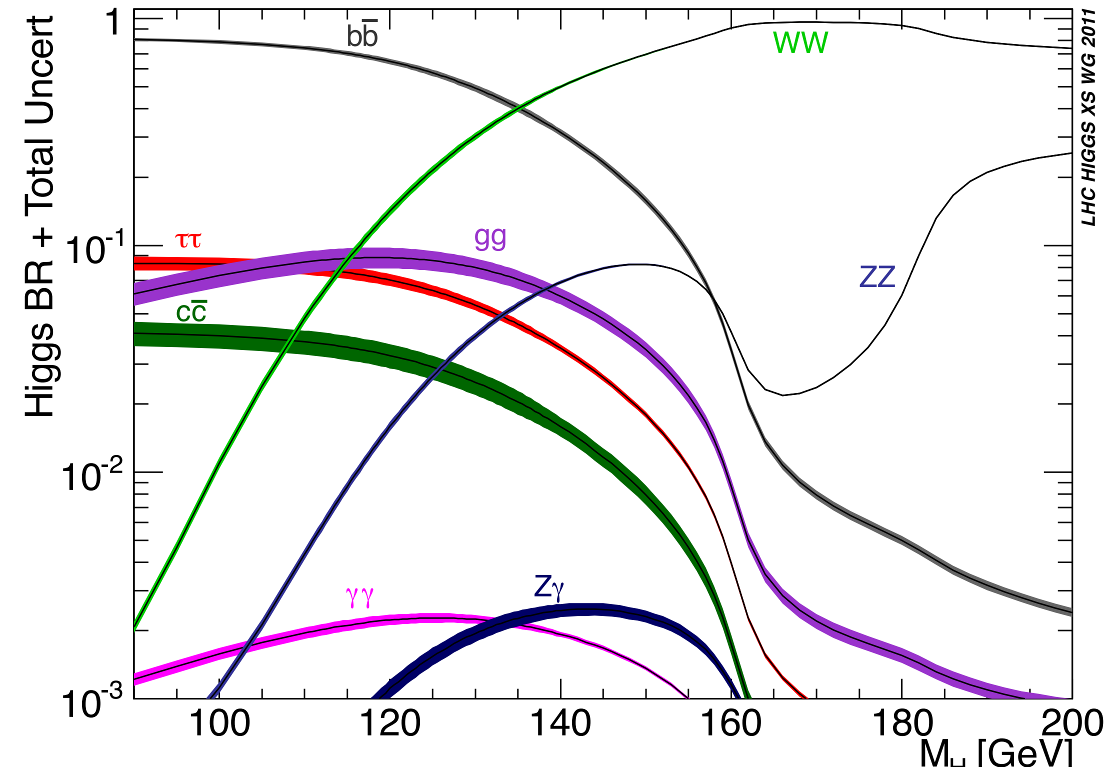
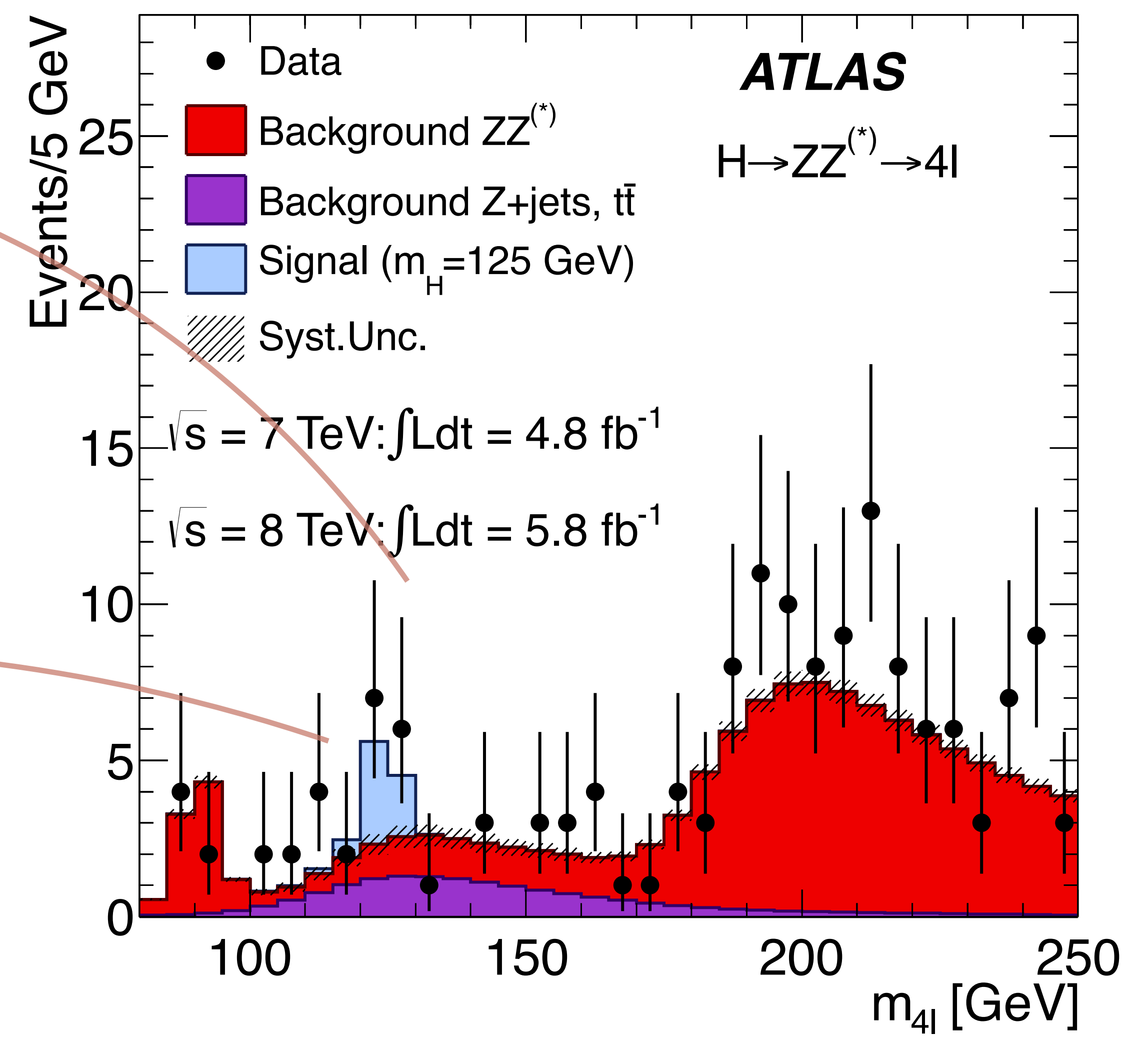
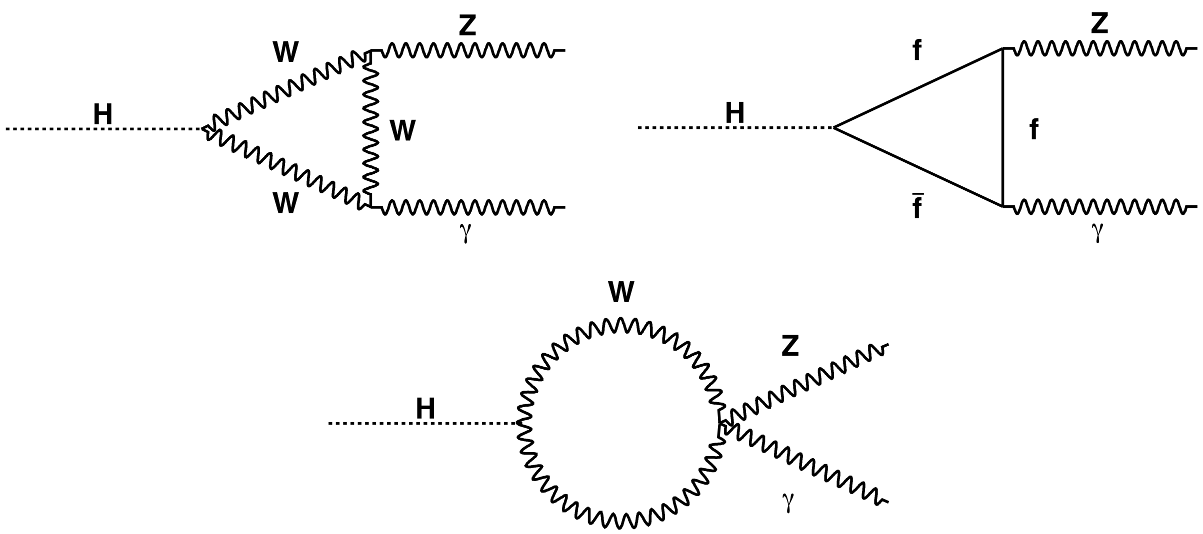
- Discovery made through study of the "golden channels"
  - $H \to ZZ$
  - $H \to \gamma\gamma$
- Channels significant because:
  - They have relatively low background
  - All final state particles can be fully reconstructed

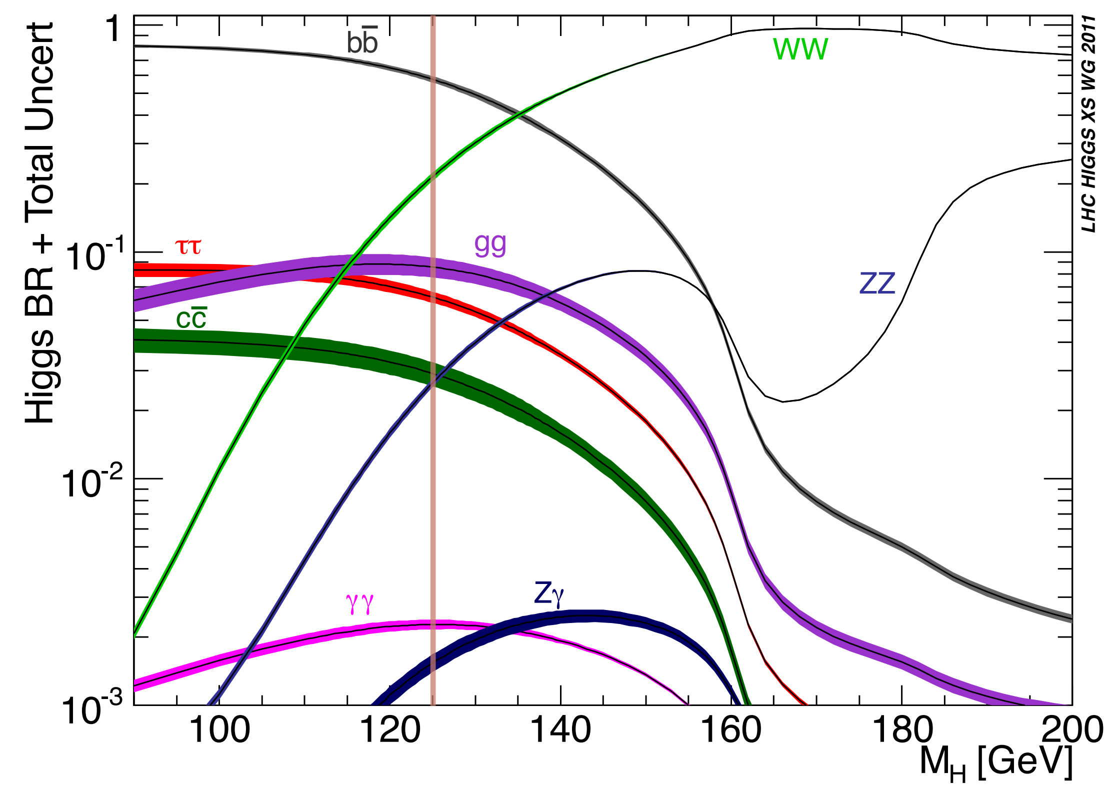




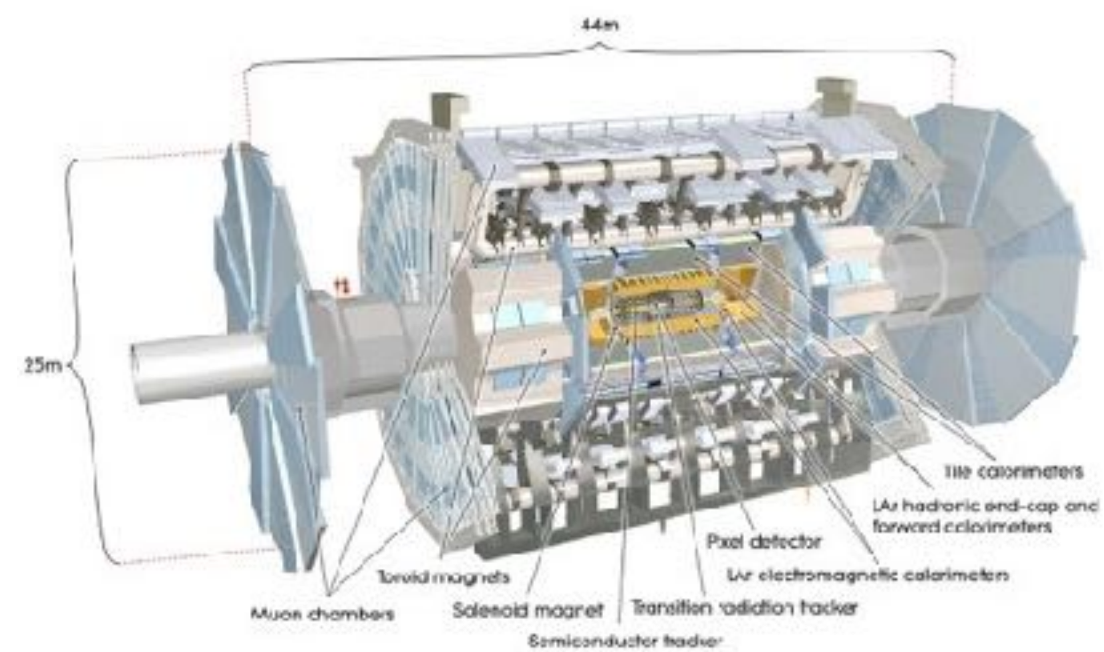
The H→Zγ Decay

- H→Zγ decay process is similar to H→γγ
  - Similar branching fraction (Zγ: 1.54×10^{-3}, γγ: 2.3×10^{-3})
  - Shared set of leading order-Feynman diagrams
- Decay proceeds through loops:





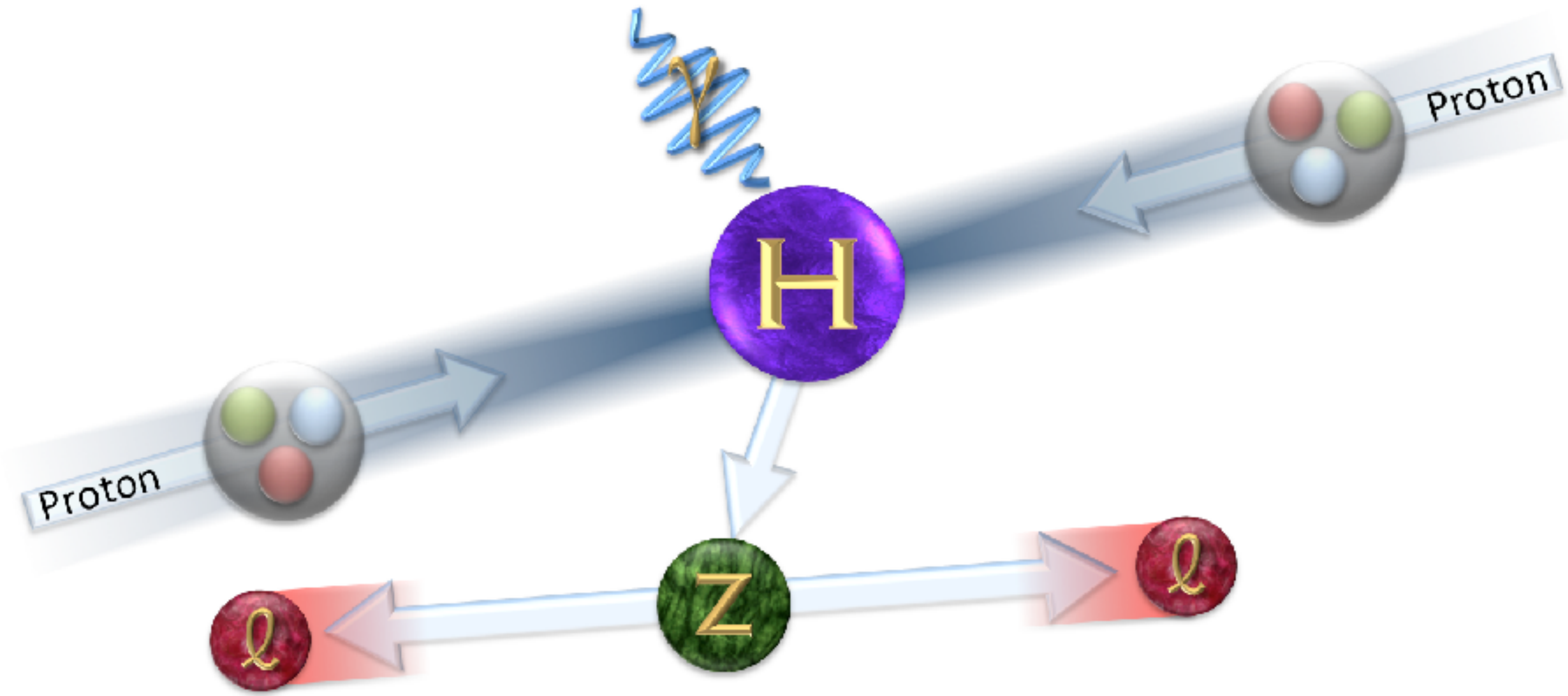
- W loops, and top-quark dominated fermion loops
- Modifications to BR(H→Zγ) expected if:
  - H is a non-Higgs neutral scalar
  - H is a composite state
  - H couples to new particles exchanged in loops:
    - colourless charged scalars, leptons, vector bosons



- BR(H→Zγ) and BR(H→γγ) could be affected differently
- Measurement of BR(H→Zγ)/BR(H→γγ) could provide valuable insights into BSM models

The H→Zγ Decay

- Z boson is unstable and immediately decays in various ways
  - Hadronic decays lack sensitivity at low mass
  - Invisible decays are beyond the scope of these studies
  - Focus given to leptonic decays
- Only Z→ee or Z→μμ decays are studied
  - Z→ττ is also possible, but τ leptons principally decay hadronically



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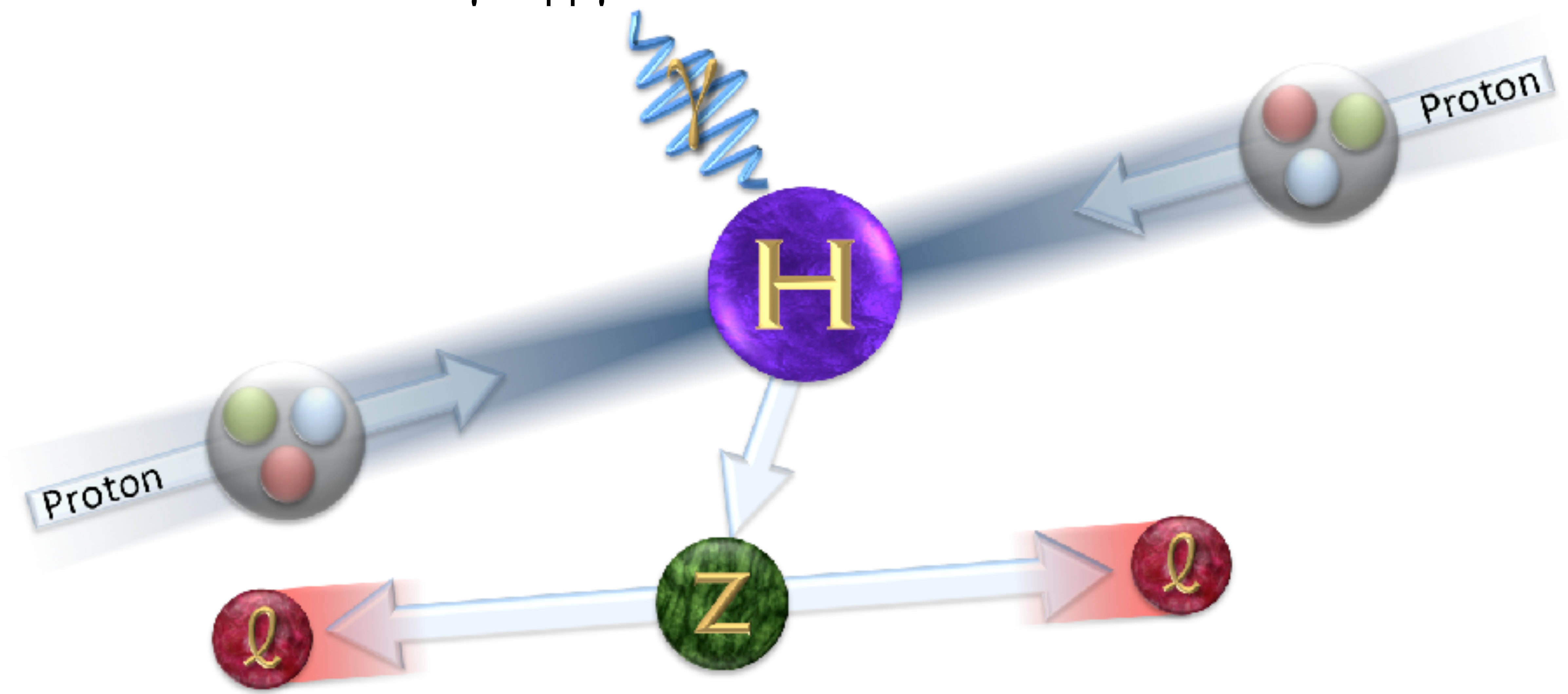
- Choose events with final state of $ee\gamma$ or $\mu\mu\gamma$



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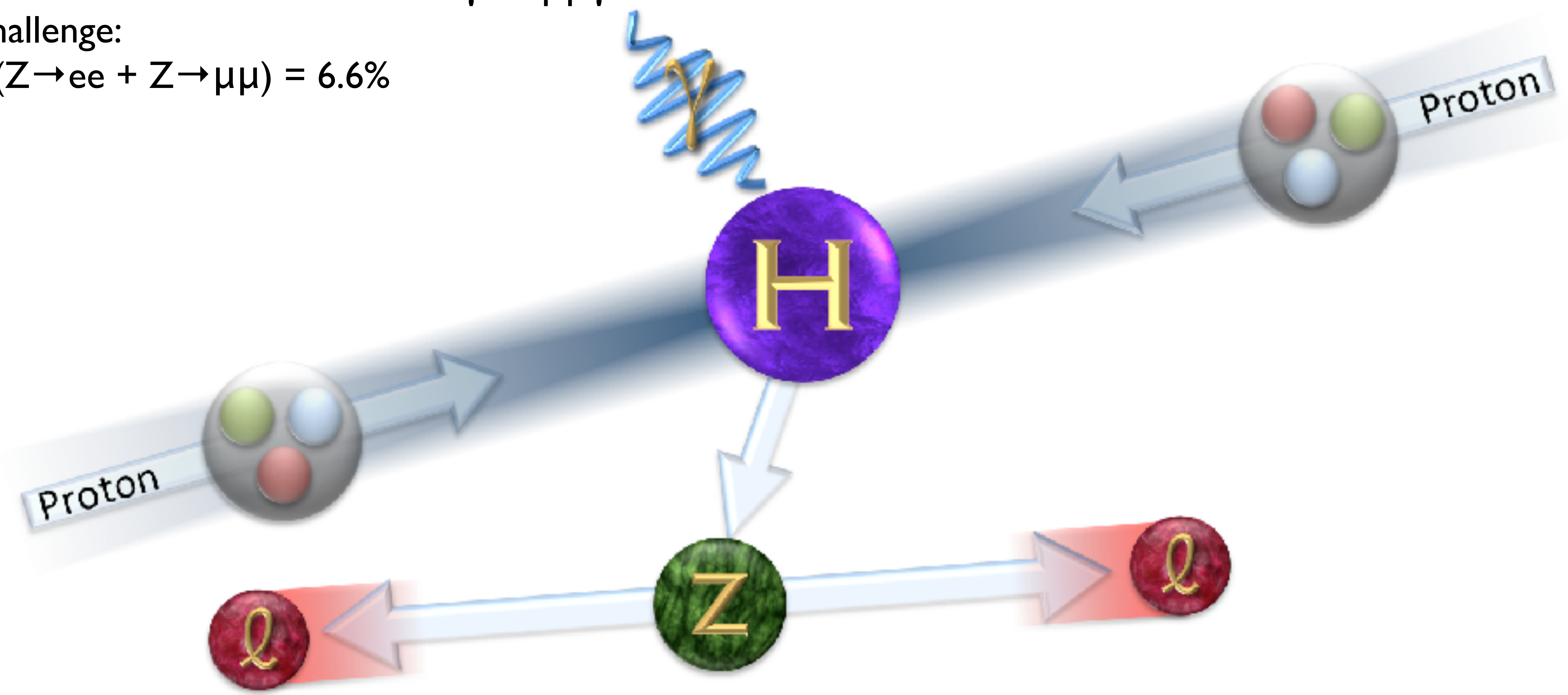
- The challenge:
  - $BR(Z \rightarrow ee + Z \rightarrow \mu\mu) = 6.6\%$



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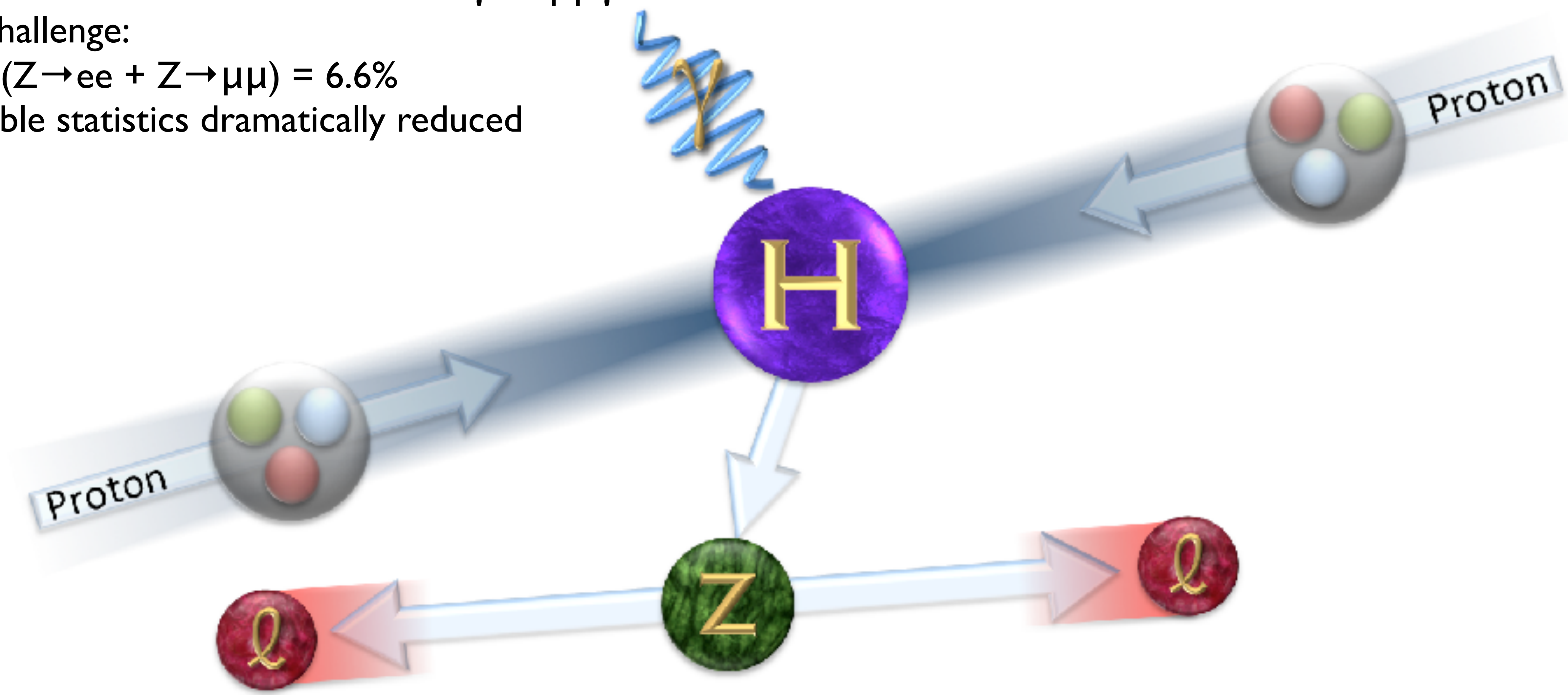
- Choose events with final state of eeγ or μμγ
- The challenge:
  - BR(Z→ee + Z→μμ) = 6.6%
- Available statistics dramatically reduced



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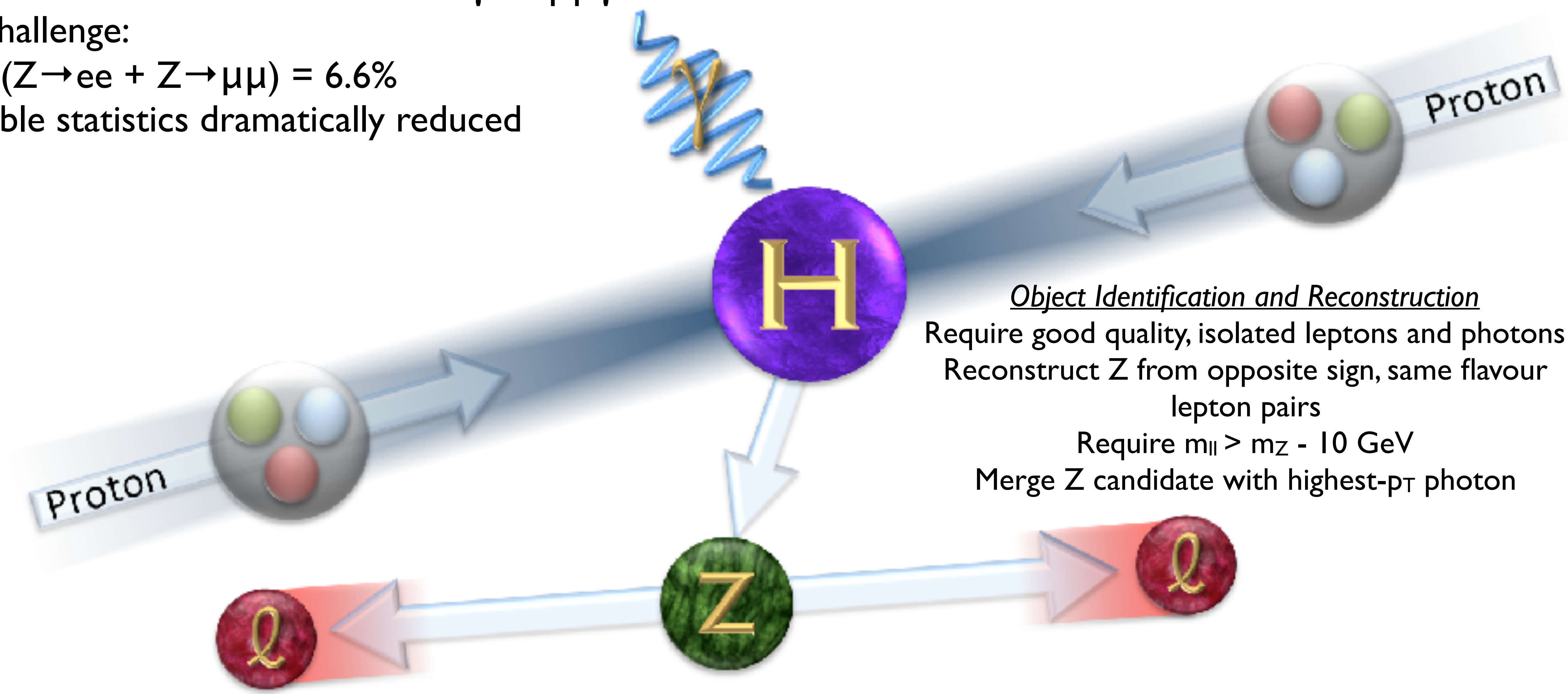


Object Identification and Reconstruction

Require good quality, isolated leptons and photons

Reconstruct Z from opposite sign, same flavour lepton pairs

Require $m_{ll} > m_Z$ - 10 GeV

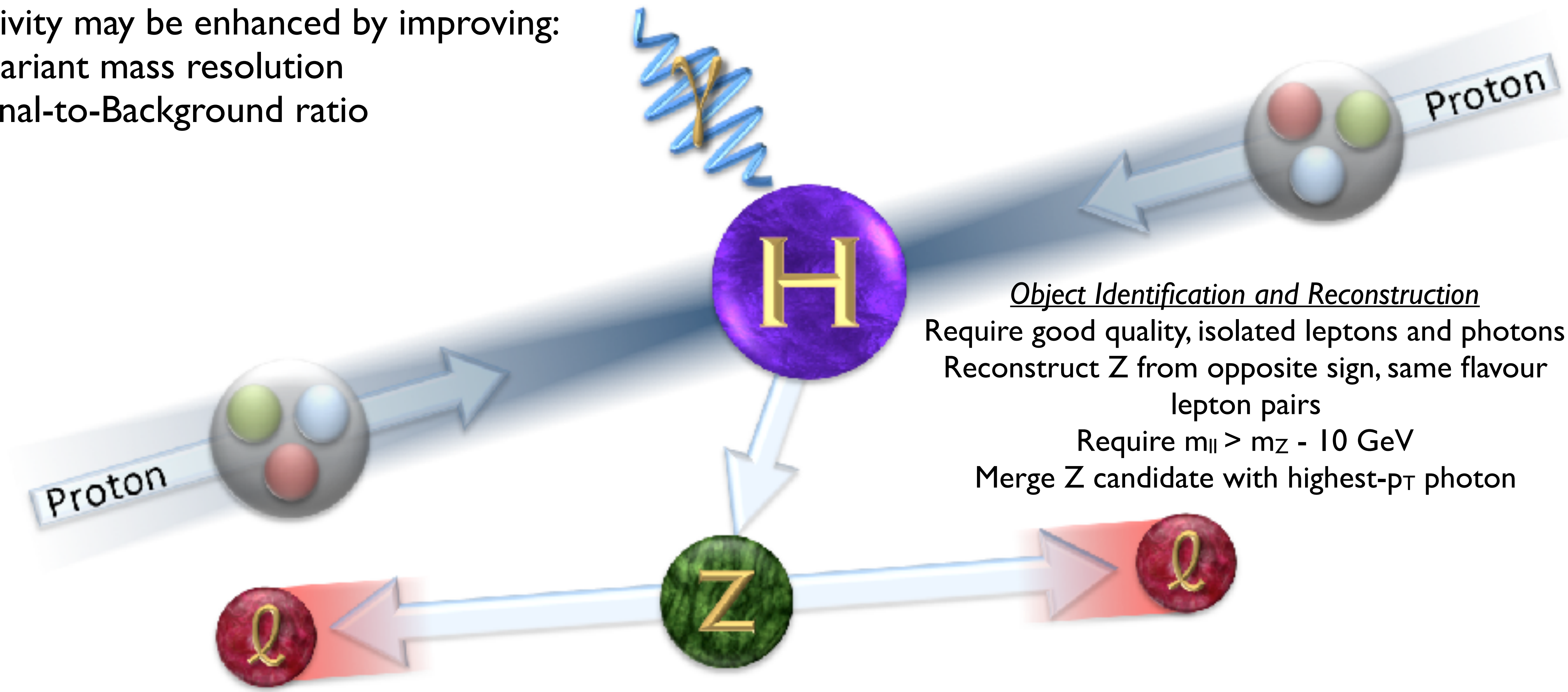
Merge Z candidate with highest-p_T photon

The Analysis

- Search is performed for excess events in the invariant mass spectrum, $m_{ll\gamma}$

- Mass spectrum fitted with a combined Signal+Background model
- Signal shape obtained from simulated Monte-Carlo samples
- Background shape obtained by fitting a function directly to data
  - Choice of function from studies with simulated Monte-Carlo background samples
  - Normalisation from data

- Signal-to-Background ratio is very small (<few %)
- Sensitivity may be enhanced by improving:
  - Invariant mass resolution
  - Signal-to-Background ratio



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- Photon origin set to the Primary Vertex
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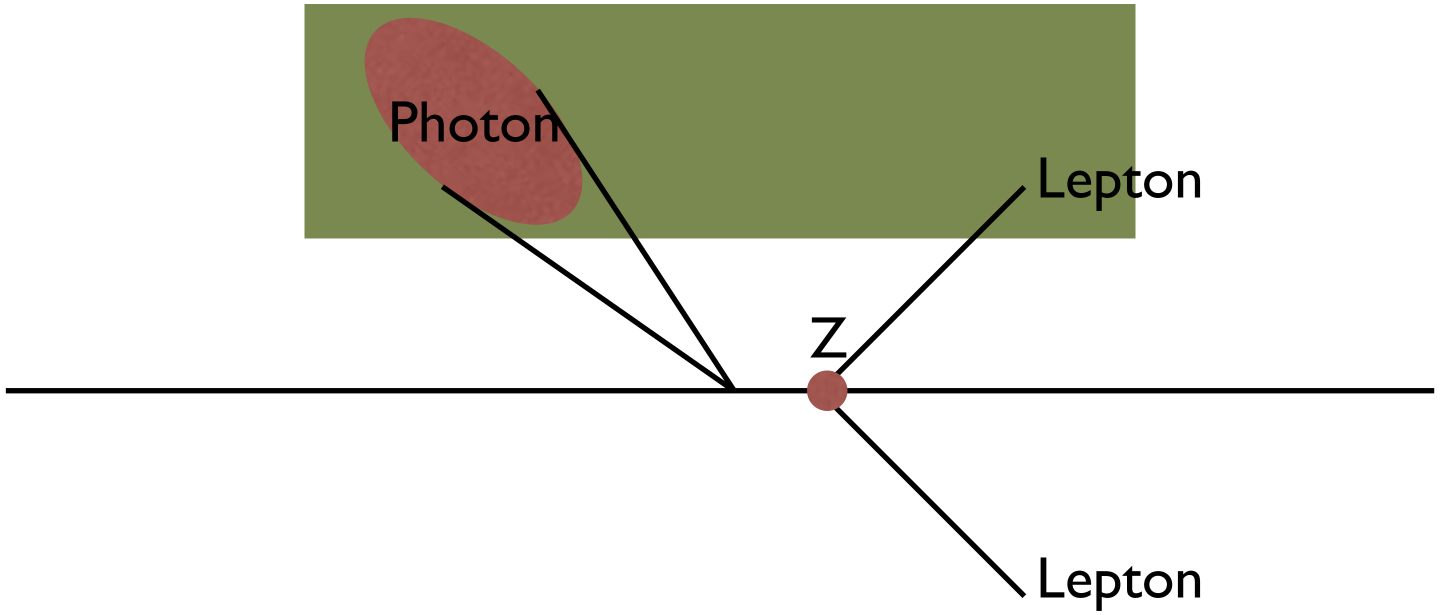

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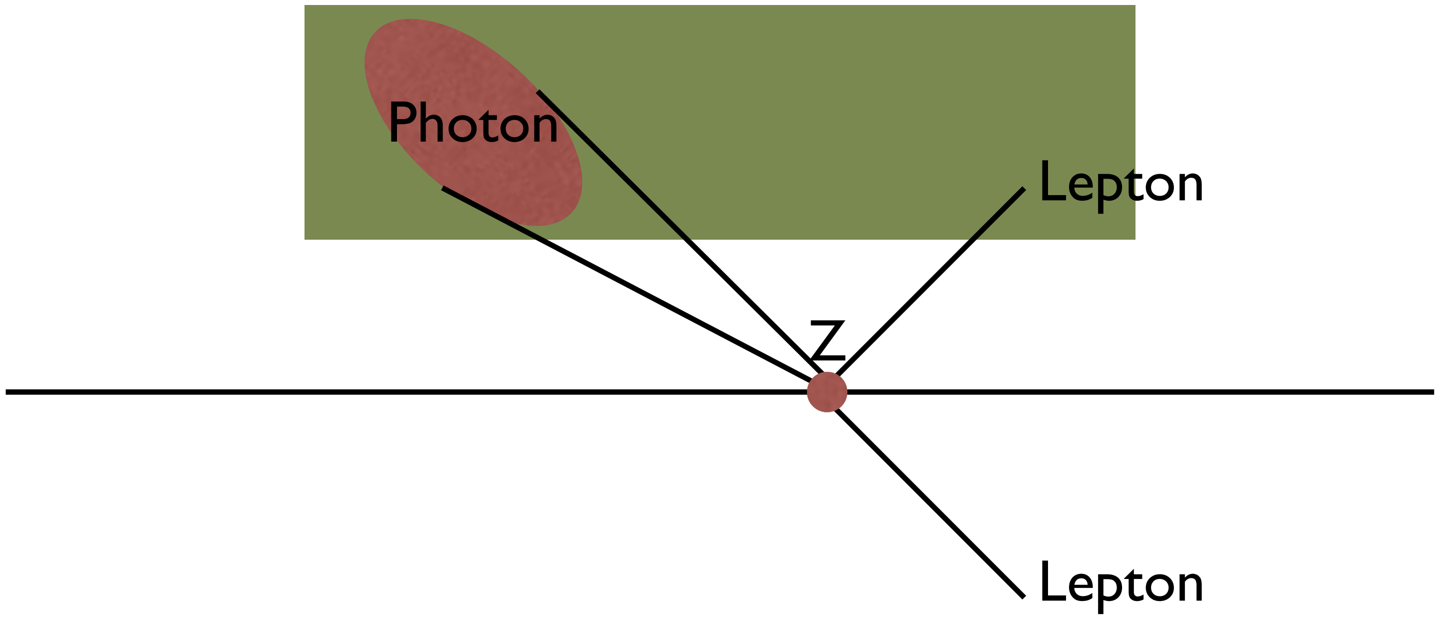

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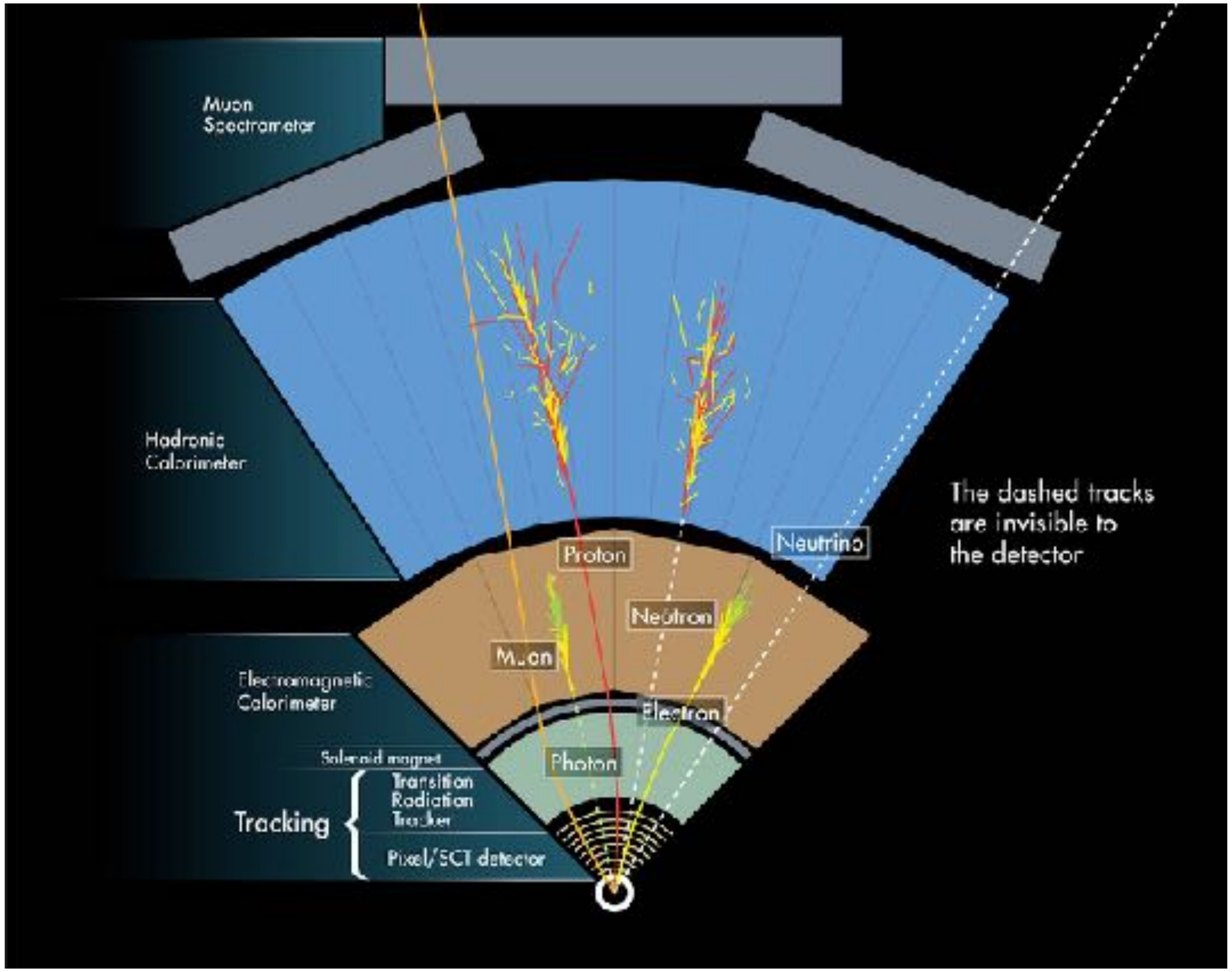
  - Negligible for electrons, where photon and electron electromagnetic showers overlap
  - Represents loss of energy in muons, and shifts m_{ll} distribution to lower energies
  - Photons identified within $\Delta R < 0.08$ or $\Delta R < 0.15$ (based on E_T) included in m_{ll}



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  - Process recovers momentum lost due to bremsstrahlung
  - Brings signal peak closer to true Higgs generated mass

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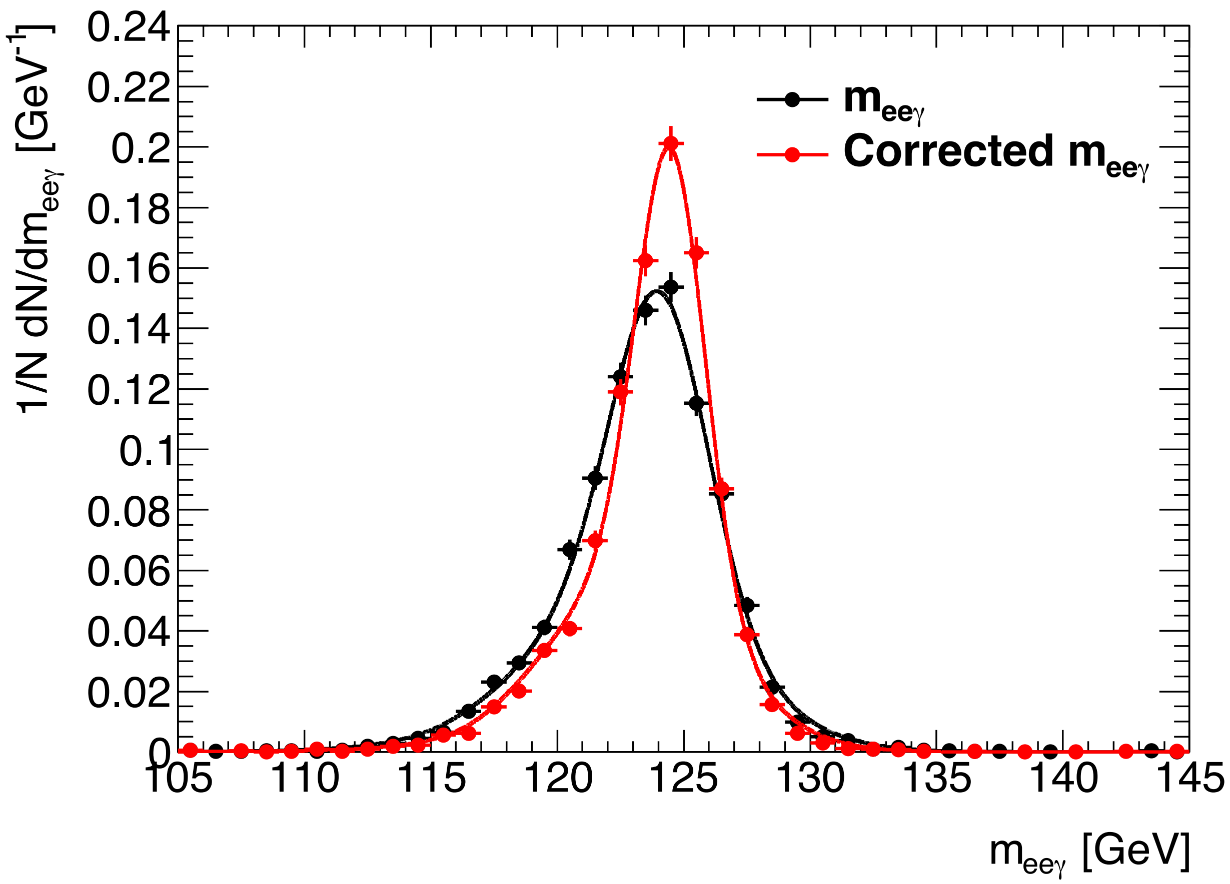
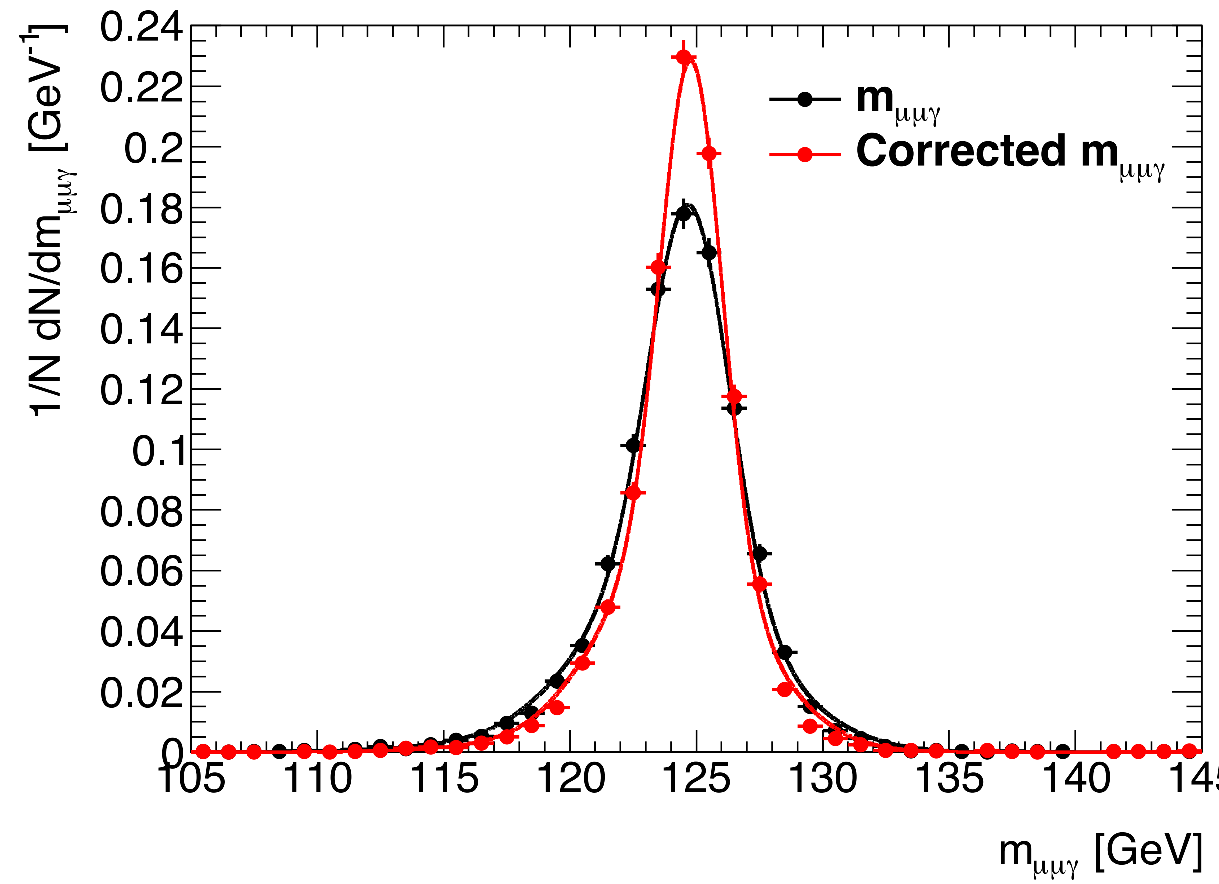
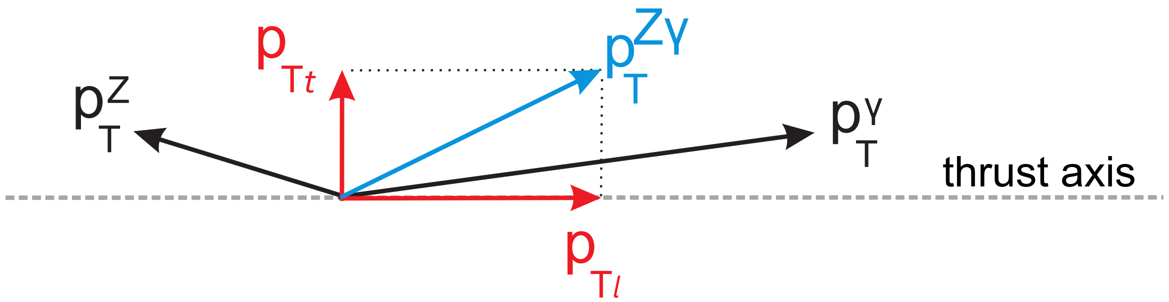




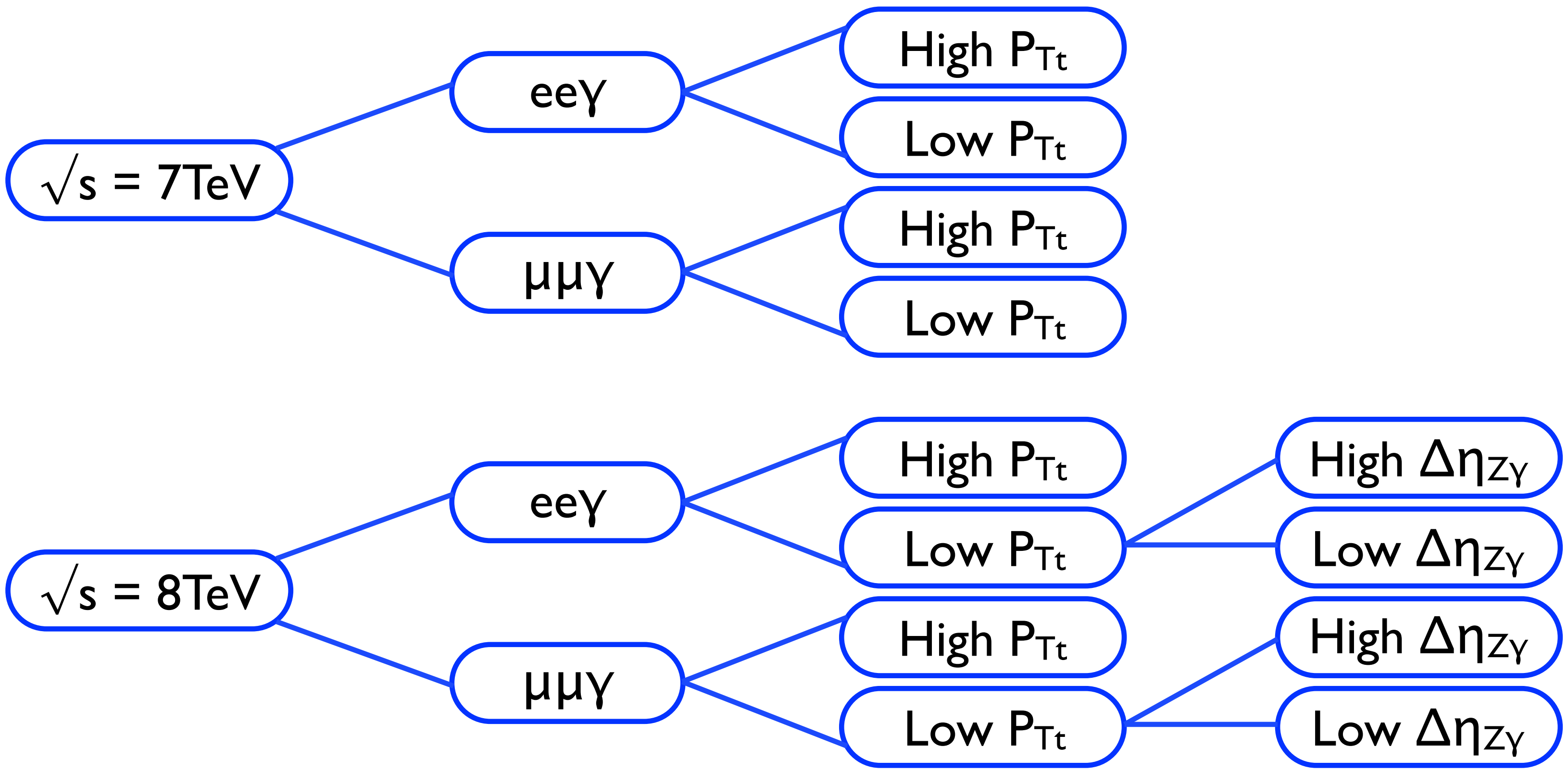
Improving Signal-to-Background Ratio: Event Categorisation

- Events are separated into orthogonal categories
- Each category will have its own:
  - signal resolution
  - signal-to-background ratio

- Events are filtered into ten categories according to:
  - Centre-of-mass collision energy
  - Final state
  - Higgs p_{Tt} (> or < 30GeV)
  - $\Delta\eta_{Z\gamma}$ (> or < 2.0)



Higgs p_{Tt} is component of Higgs momentum orthogonal to difference between Z and γ momenta



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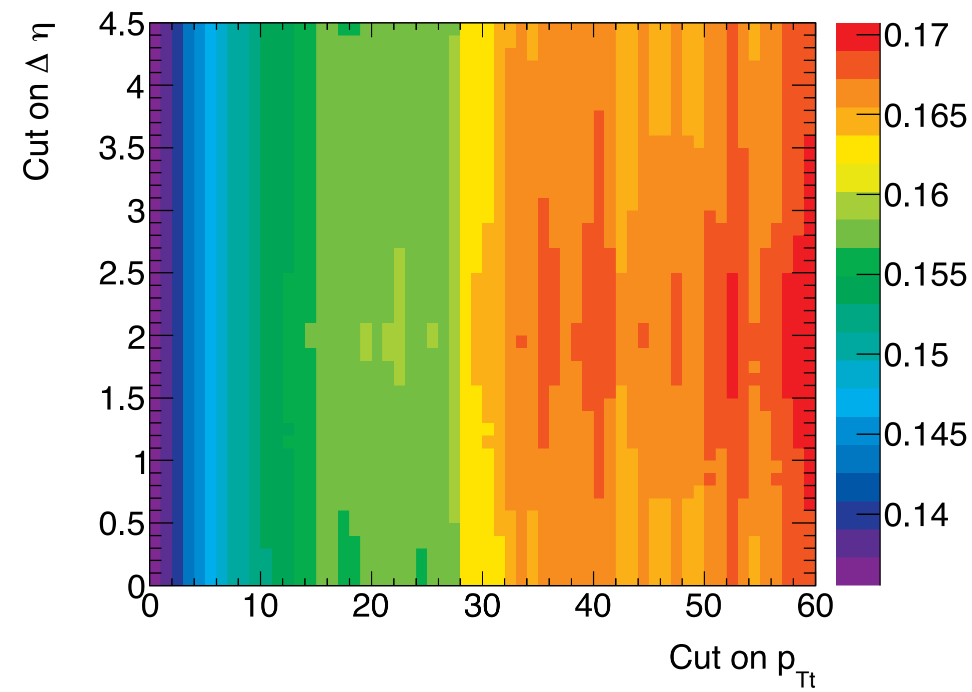
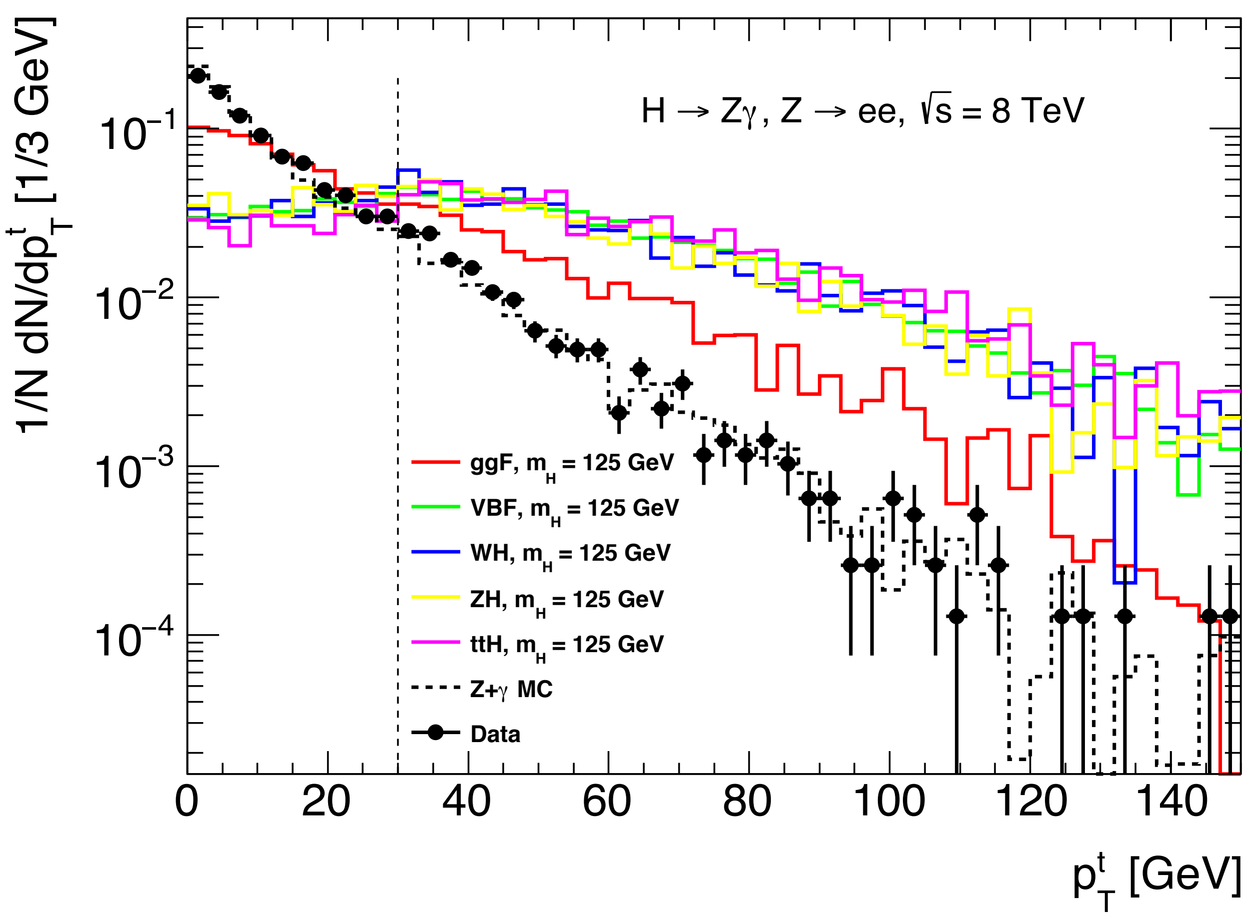
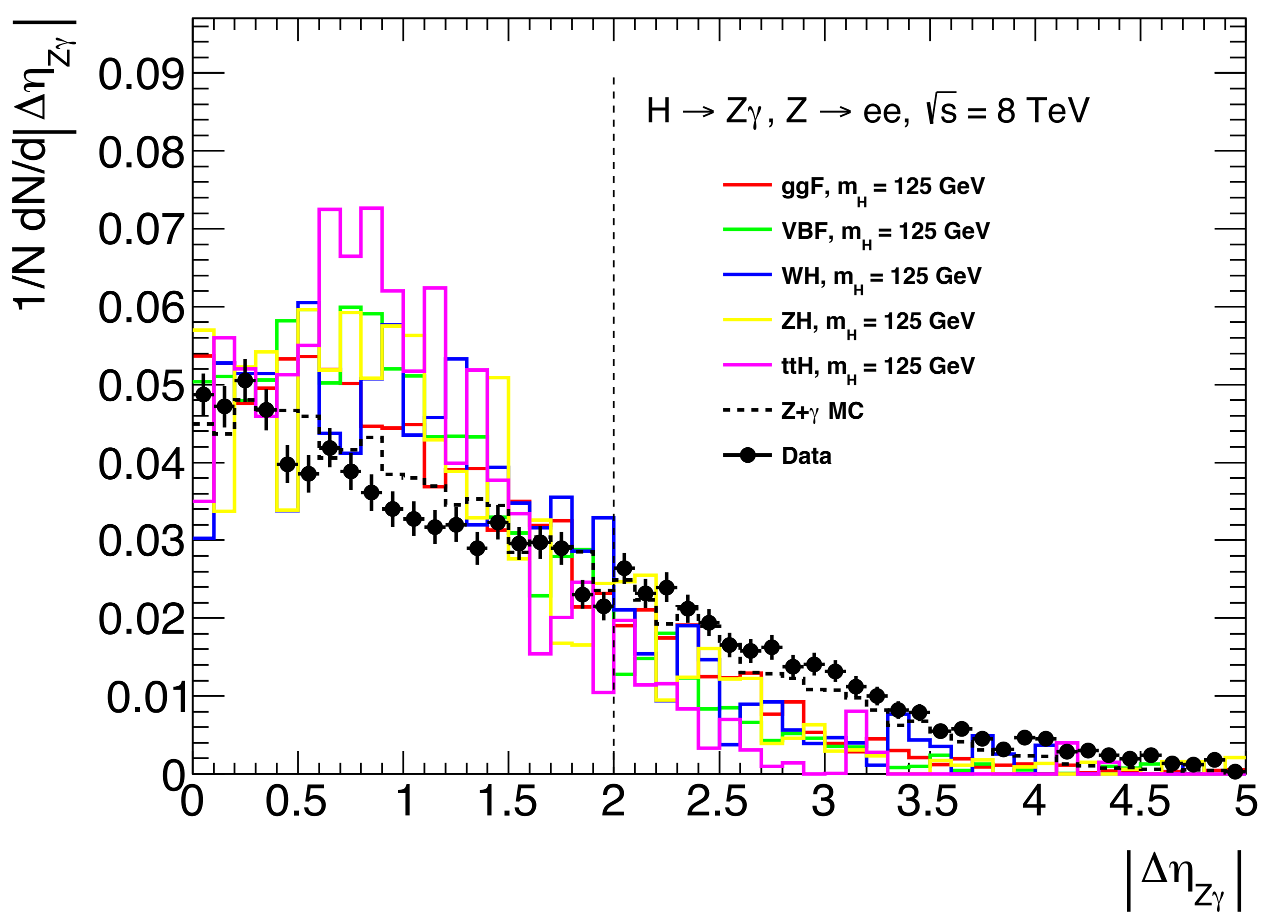
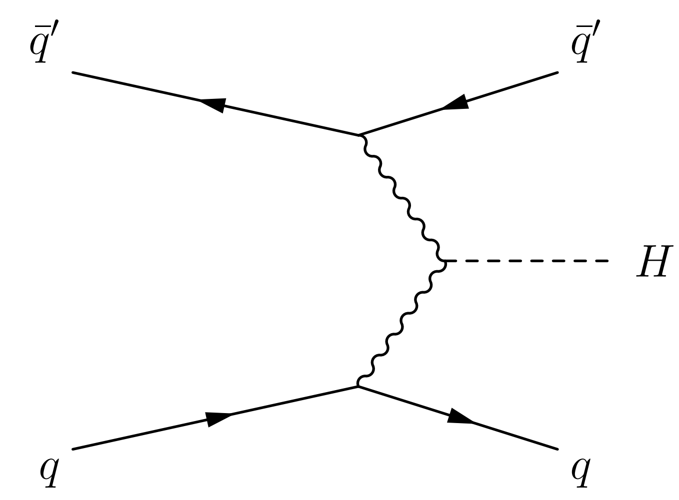






VBF Categorisation

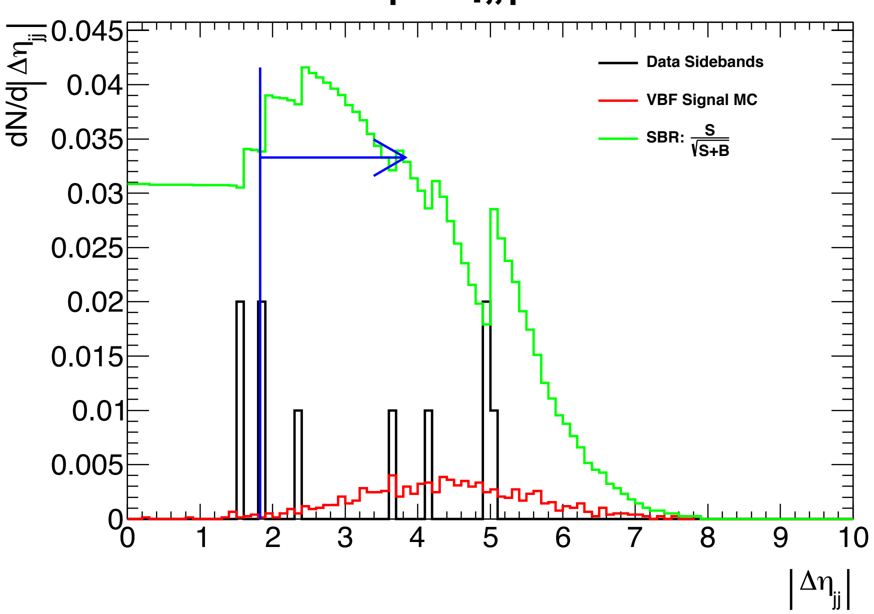
- Potential category for VBF events
- Events characterised by two forward jets
- Multiple jet and dijet variables considered
- Final variables:
  - $|\Delta\eta_{jj}|$
  - $|\Delta\varphi_{jj,H}|$
  - m_{jj}



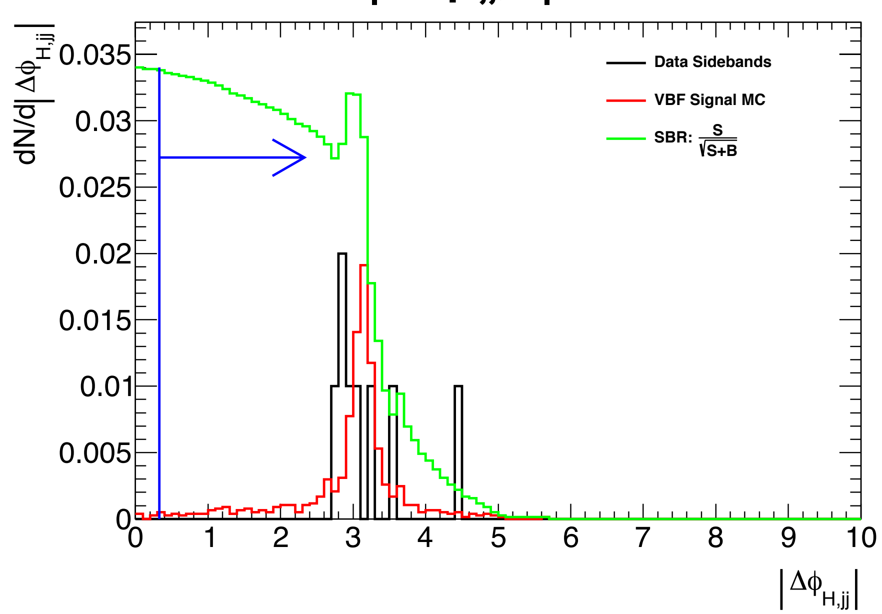
- Background taken from 5GeV data sidebands
- Signal from VBF MC
- Multivariate analysis performed to determine optimal cuts

- Ultimately too few events for selection to be practical

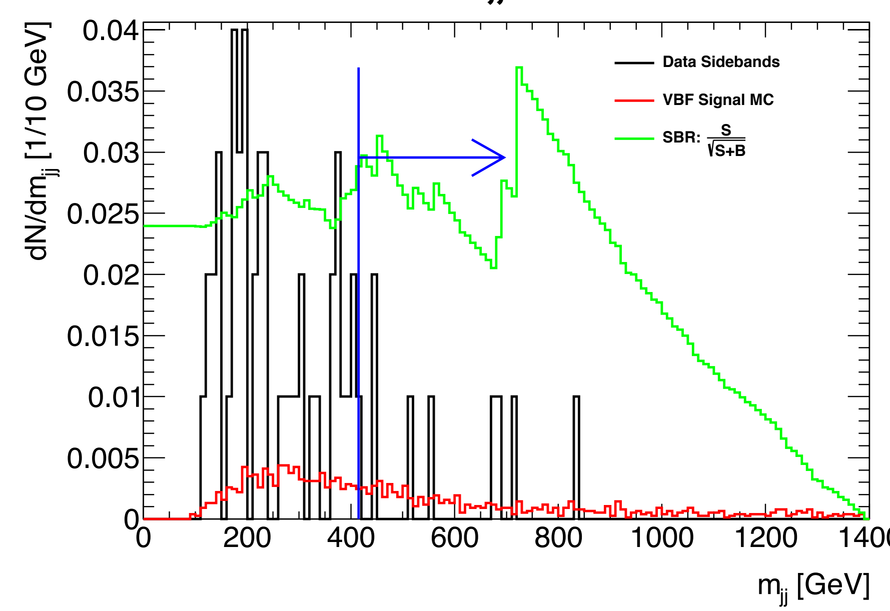
$|\Delta\eta_{jj}|$



$|\Delta\varphi_{jj,H}|$



m_{jj}



Background reduced by factor 100 for visibility

Signal Modelling

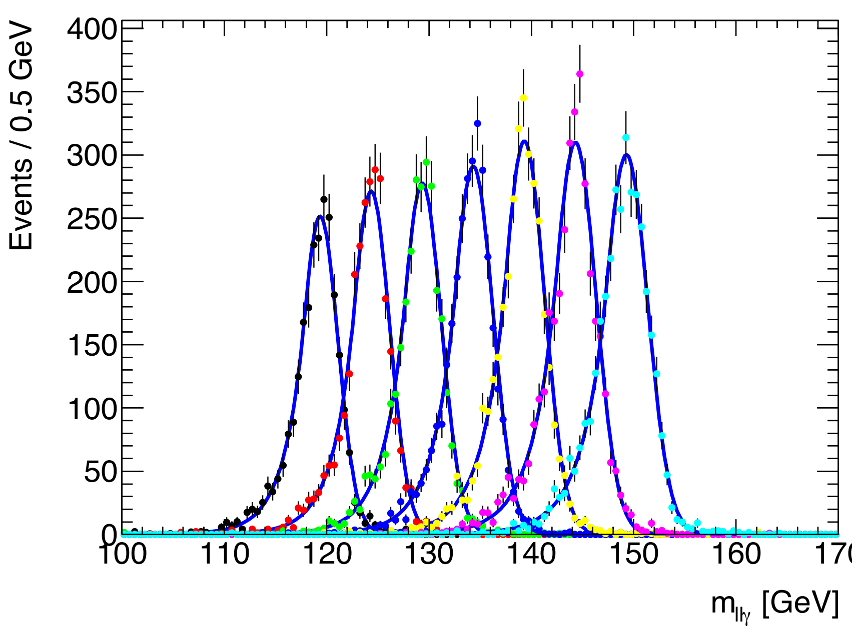
- MC signal samples generated for 7 mass points
  - m_H = 120, 125, 130, 135, 140, 145, 150 GeV
- Signal in each category modelled by summing Crystal Ball and Gauss functions

$$GA(x,\mu,\sigma) = N\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

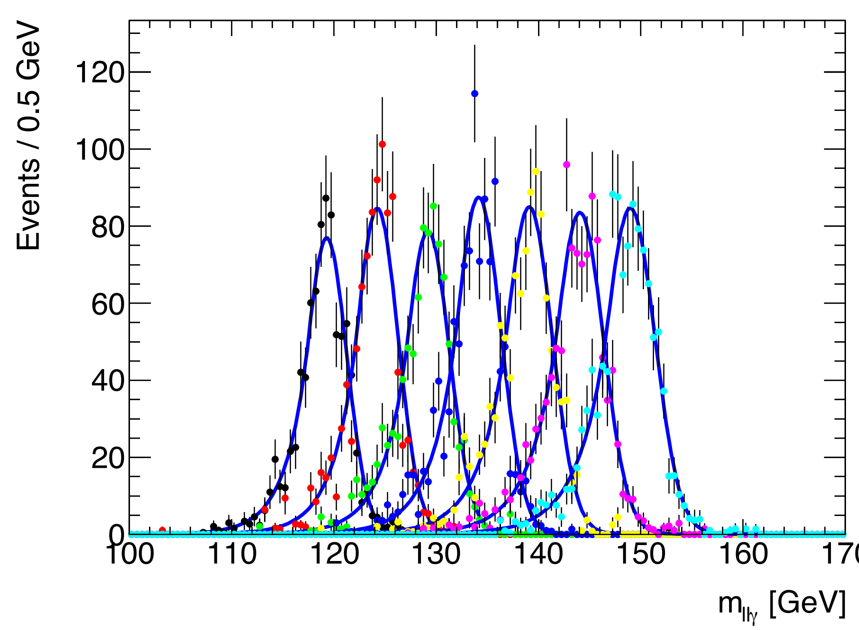
$$CB(x,\mu,\sigma,\alpha,n) = N\cdot\begin{cases} e^{-t^2/2} & \text{if } t > -\alpha \\ \left(\frac{n}{|\alpha|}\right)^n \cdot e^{-|\alpha|^2/2}\cdot\left(\frac{n}{|\alpha|}-|\alpha|-t\right)^{-n} & \text{if } t \le -\alpha \end{cases}$$

- Crystal Ball function is a Gaussian distribution with a power law tail
  - Used to capture the core of the distribution
- Gaussian function used to capture the tail of the distribution

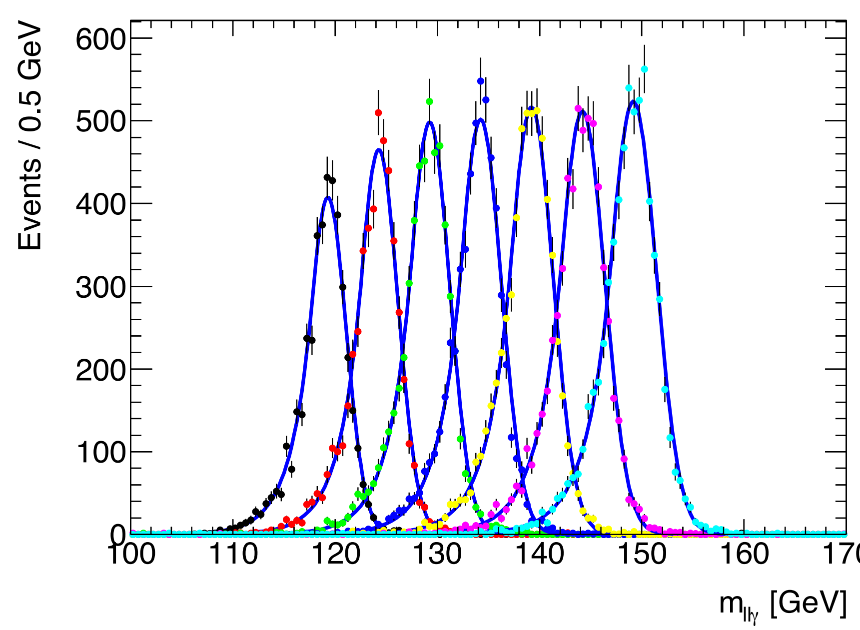
- Model parameters vary linearly with mass point, all mass points fitted simultaneously
- Model can then be generated for any arbitrary mass point



8 TeV, ggF, eeγ High p_{Tt}



8 TeV, ggF, eeγ Low p_{Tt}, High $\Delta\eta_{Z\gamma}$



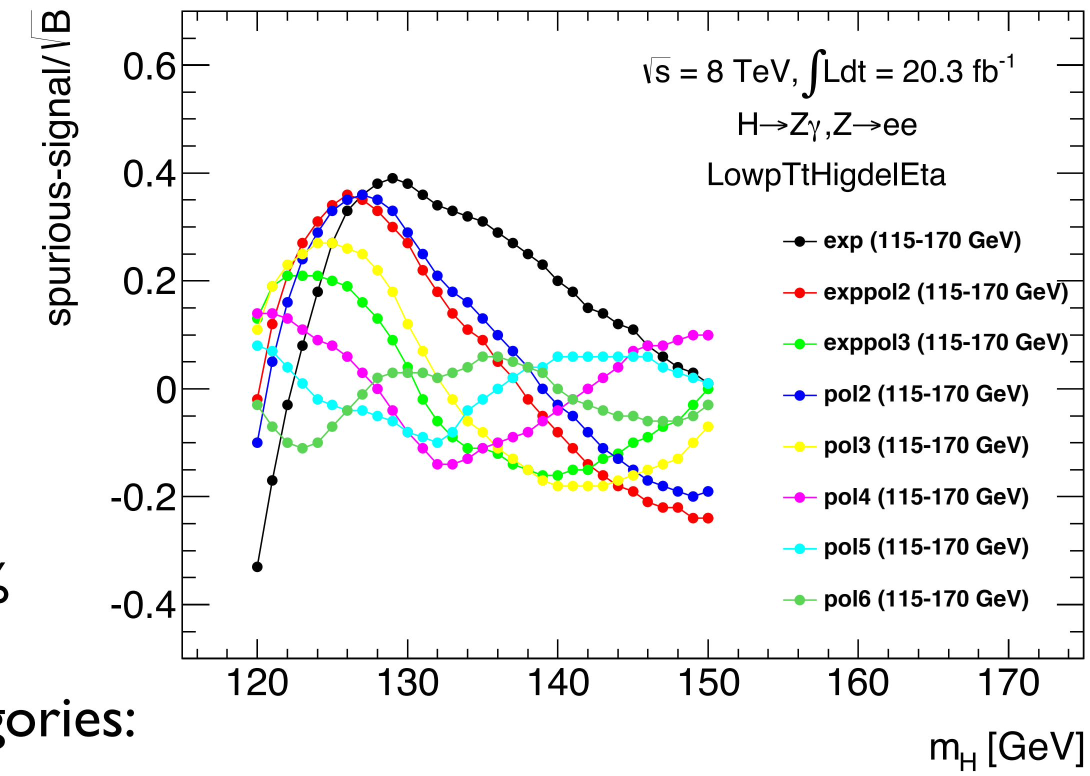
8 TeV, ggF, eeγ Low p_{Tt}, Low $\Delta\eta_{Z\gamma}$

Background Modelling

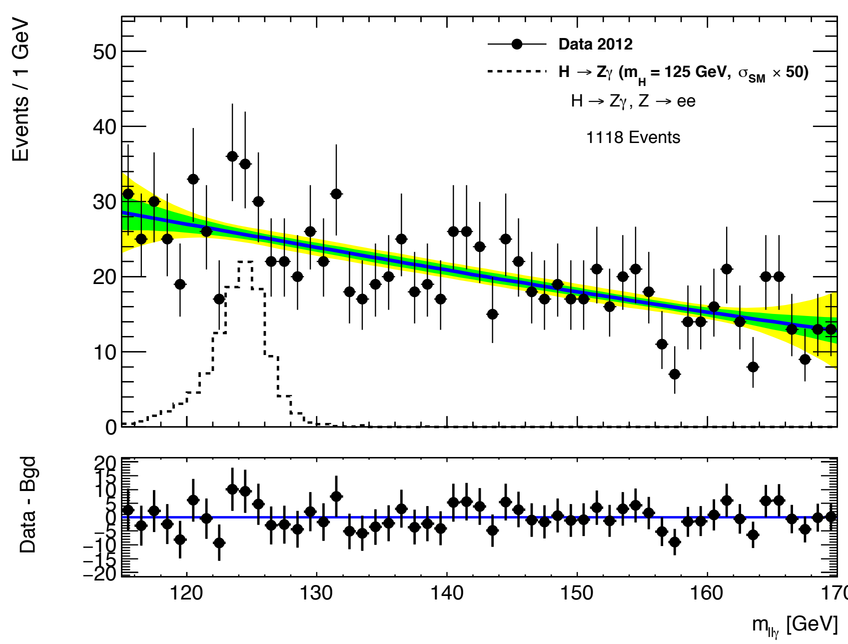
- Background is dominated by non-resonant Z+γ events
- Small contribution from Z+Jet events
  - Events where jet is misreconstructed as a photon

- Background modelled by fitting analytical function to data

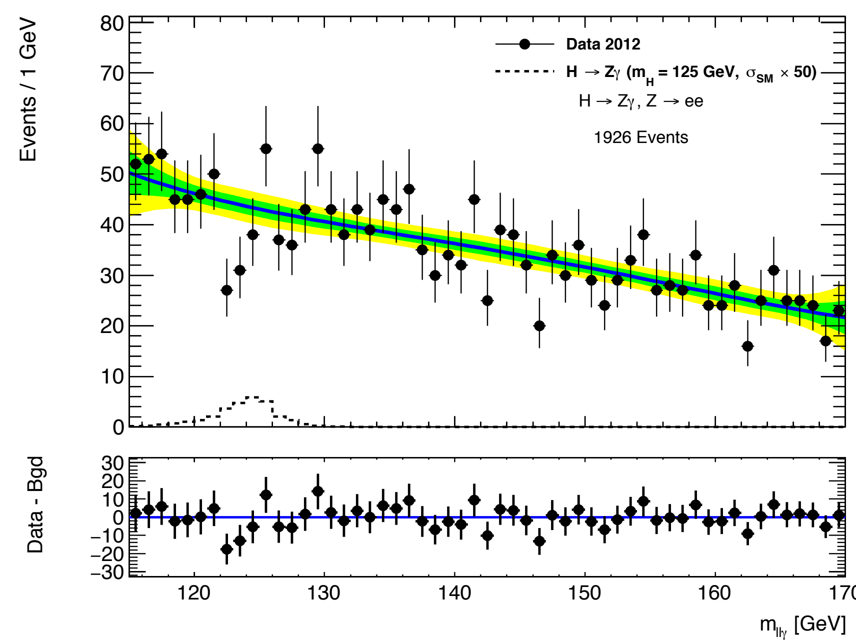
- Choice of model influenced by level of spurious signal:
  - Bias on signal yield from background model choice
  - Ratio of fitted signal yield to its uncertainty must be < 20%



- Several functions used to model background in different categories:
  - 4th- or 5th-order Chebychev polynomials,
  - Simple exponentials,
  - Exponentials of polynomials



8 TeV, ggF, eeγ High p_{Tt}



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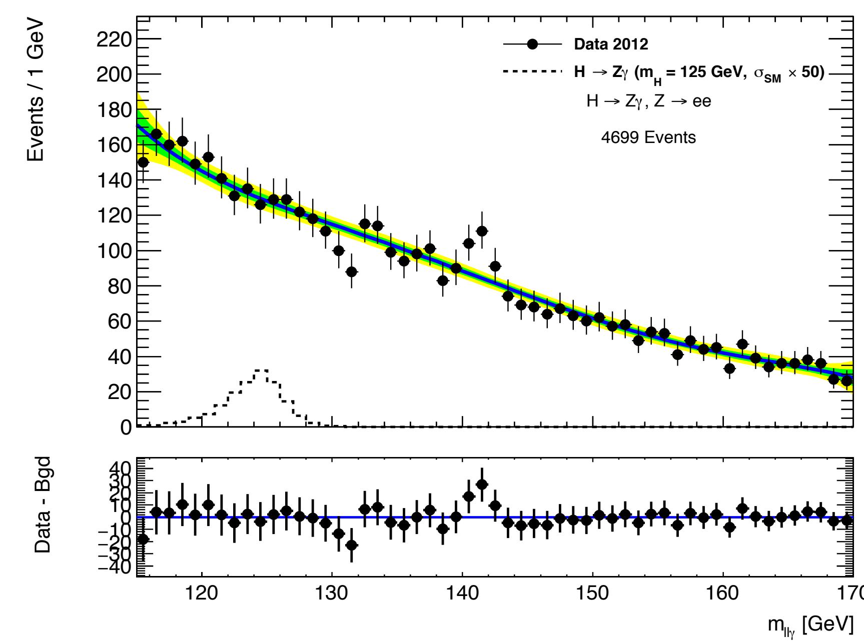


8 TeV, ggF, eeγ Low p_{Tt}, Low $\Delta\eta_{Z\gamma}$

Expected Limits

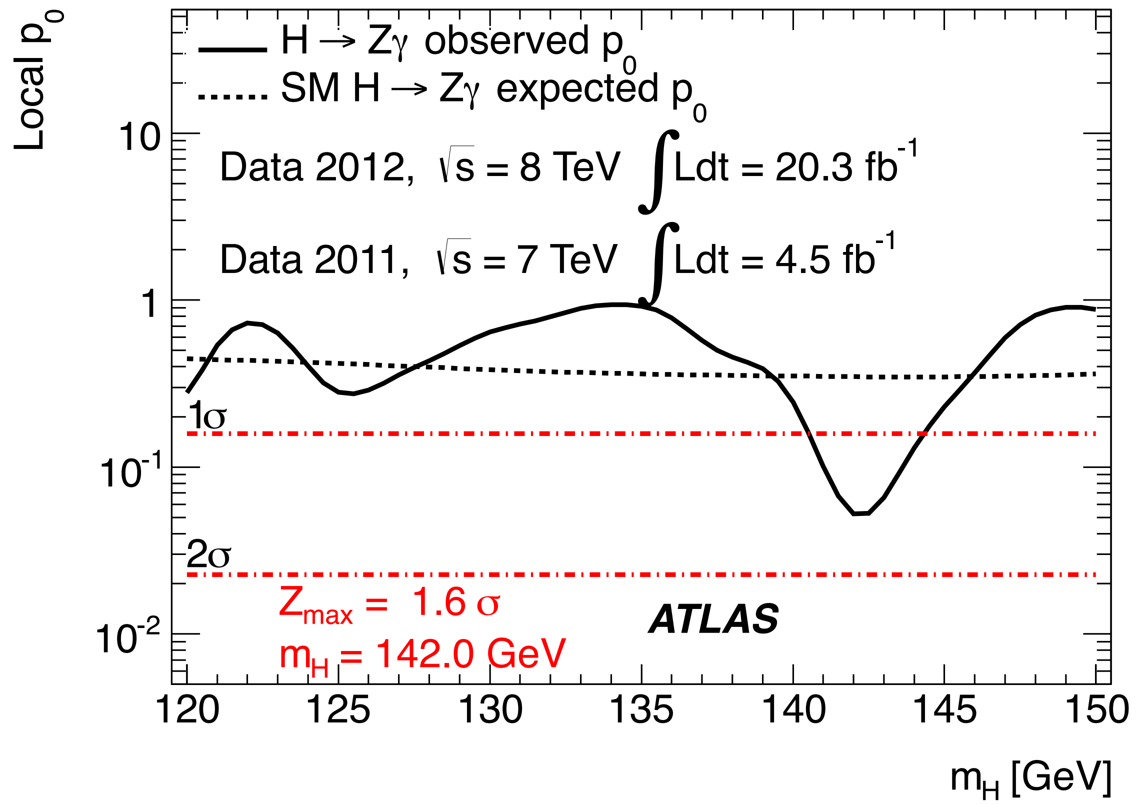
- Paper was published in March 2014
  - Phys. Lett. B 732C (2014), pp. 8-27

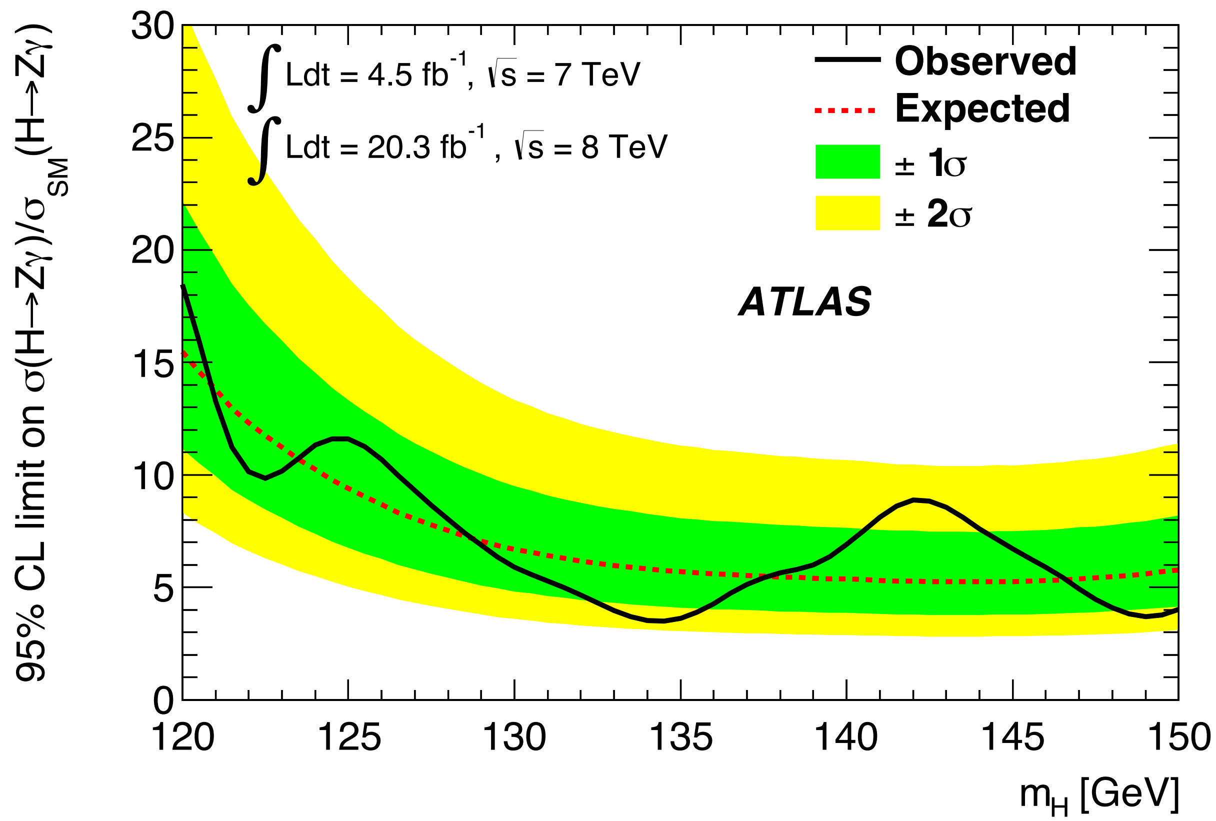
- No significant excesses identified
- Largest excess was 1.6σ at m_H = 141 GeV

- Limits on cross-section times branching ratio at 95% CL
  - $\sqrt{s}$ = 8 TeV : 0.13 to 0.5 pb

- Limits set on the relative signal strength
  - Divide cross-section by SM expectation
  - Expected limits vary from 5.1 to 15.8 x SM
  - Observed limits vary from 3.1 to 17.6 x SM

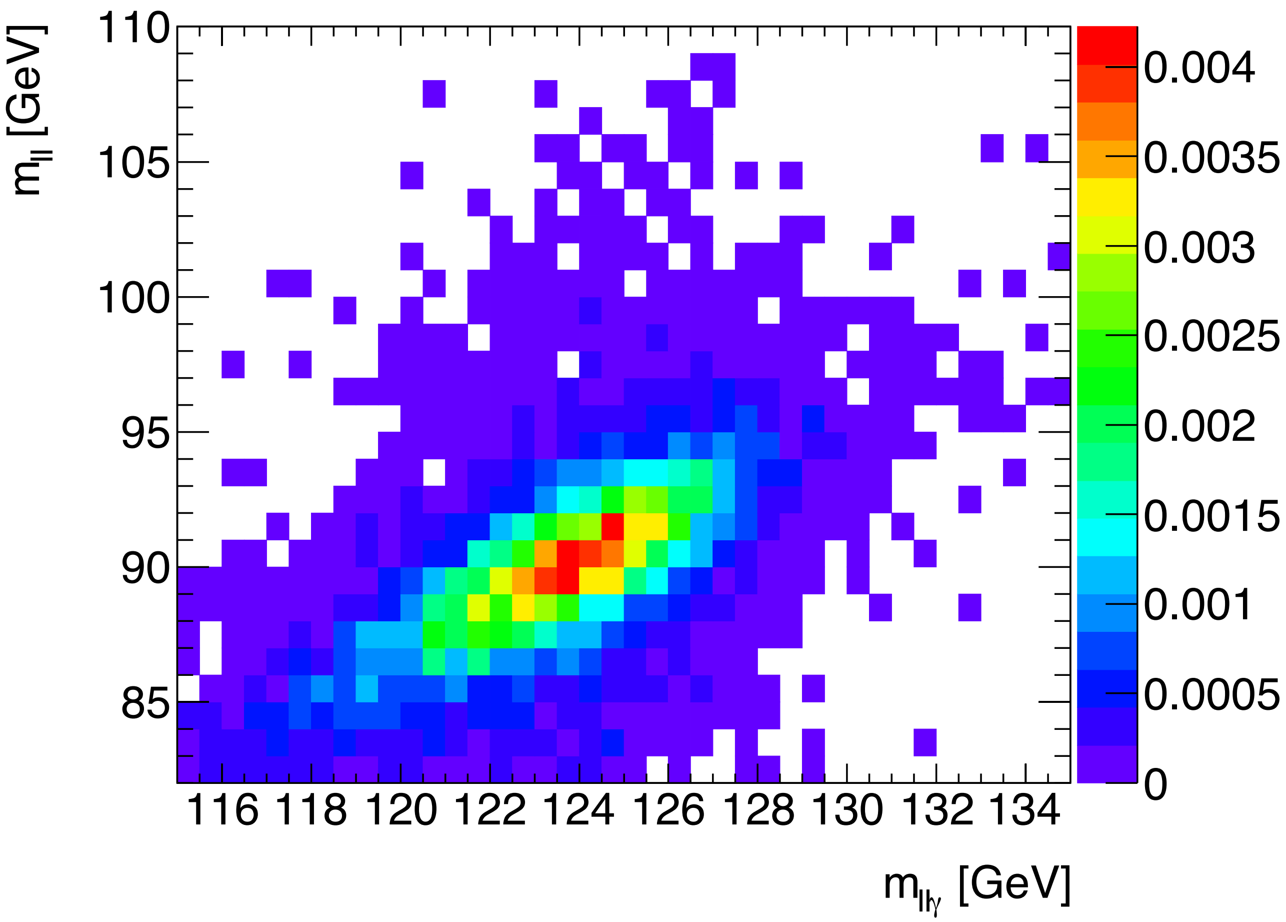
  - At 125.5 GeV:
    - Expected limit = 9.0 x SM
    - Observed Limit = 11.0 x SM



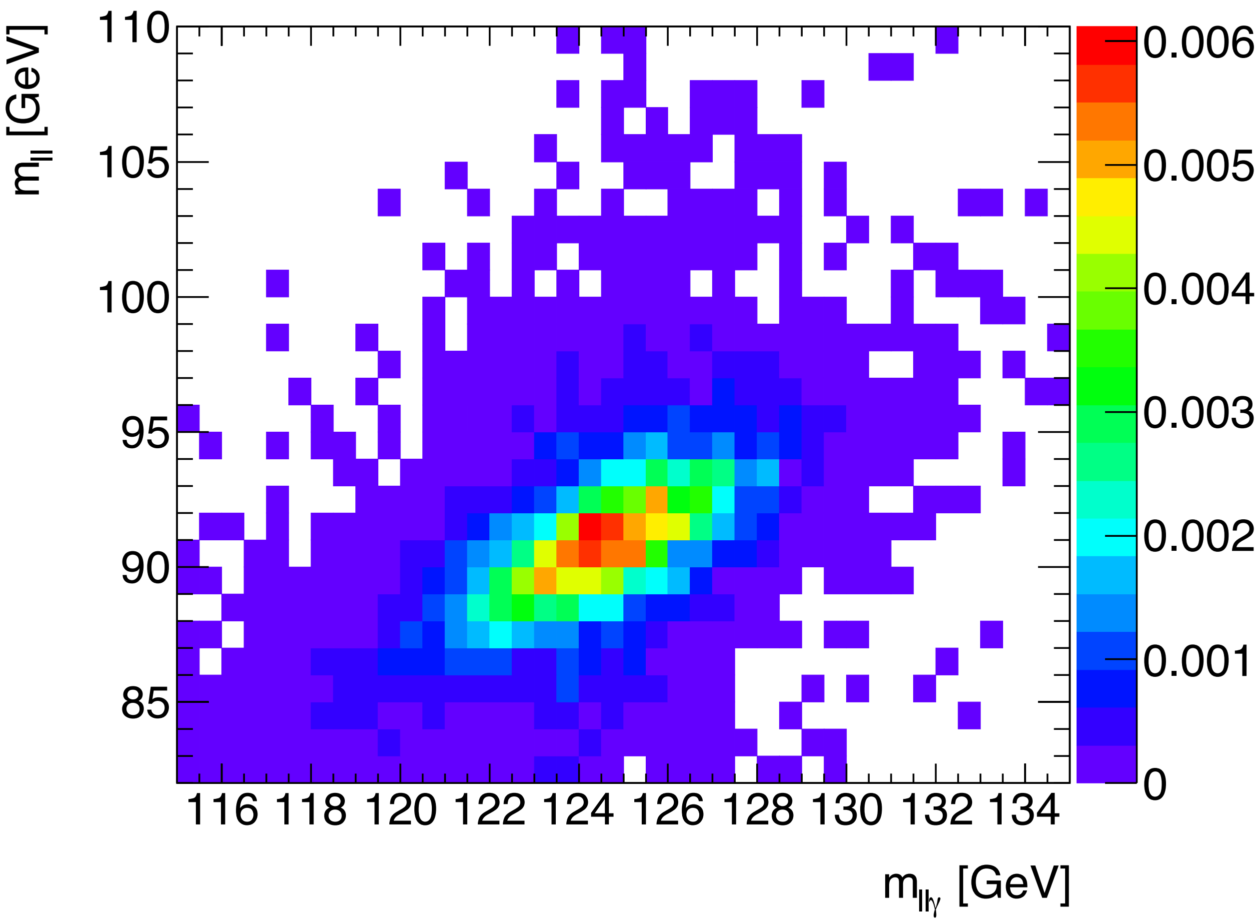


Improving The Limits: New Event Categorisation

- LHC shut down during 2013-2015
- Opportunity to further investigate Run 1 data



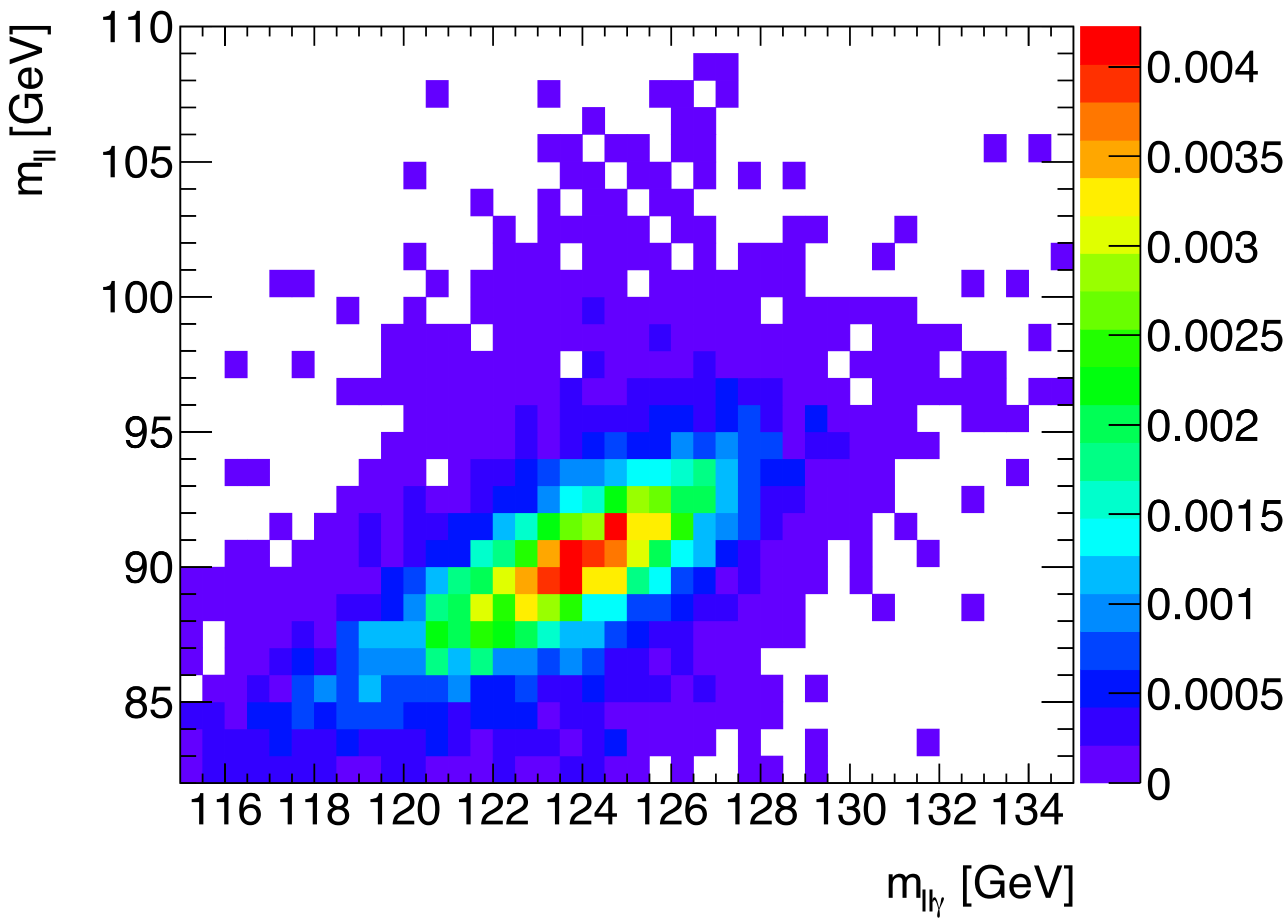
8TeV, ggF, m_H = 125 GeV, eeγ



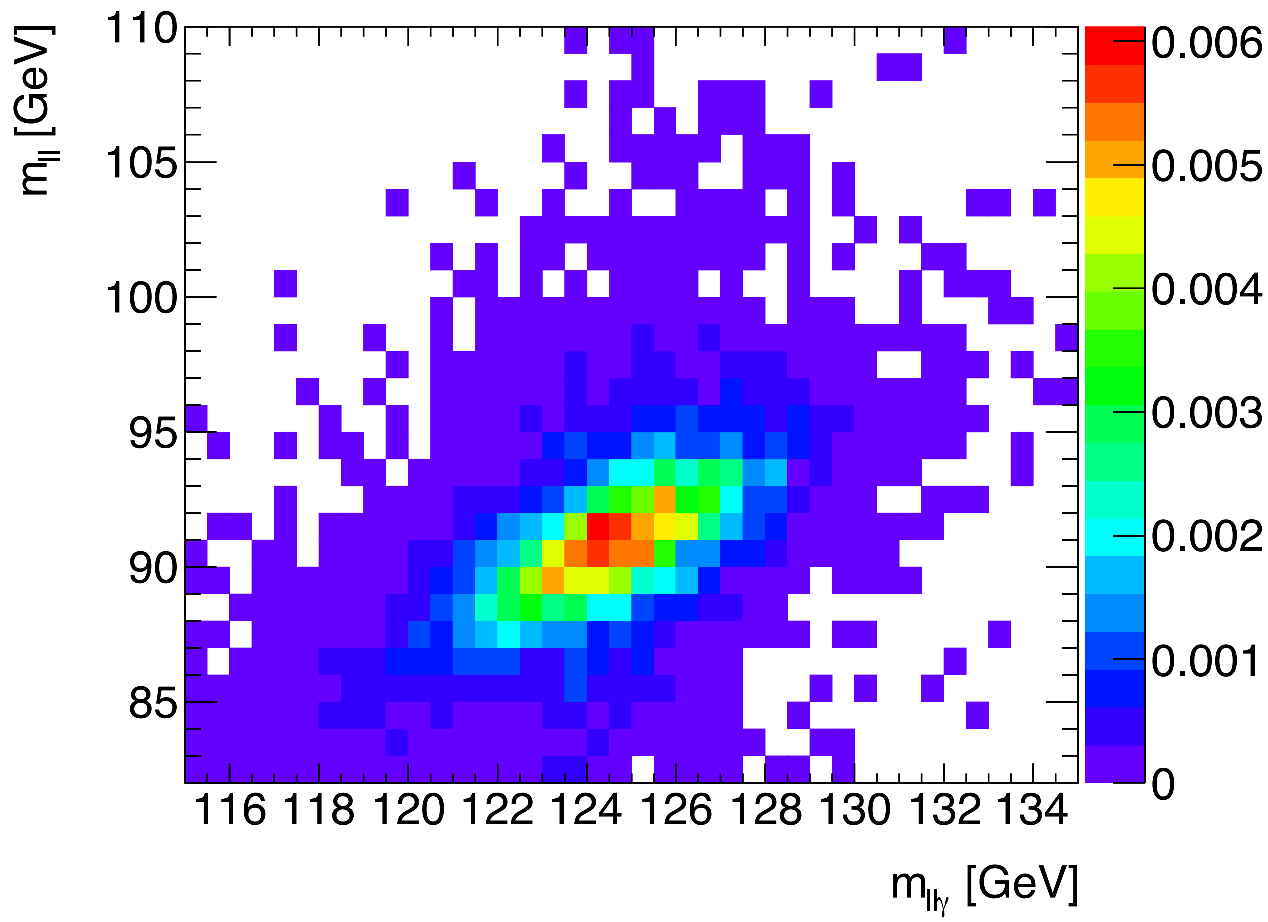
8TeV, ggF, m_H = 125 GeV, μμγ

Improving The Limits: New Event Categorisation

- LHC shut down during 2013-2015
- Opportunity to further investigate Run 1 data
- Strong correlation observed between reconstructed Z and Higgs boson masses
- Events concentrated at Z and Higgs mass poles



8TeV, ggF, m_H = 125 GeV, $ee\gamma$



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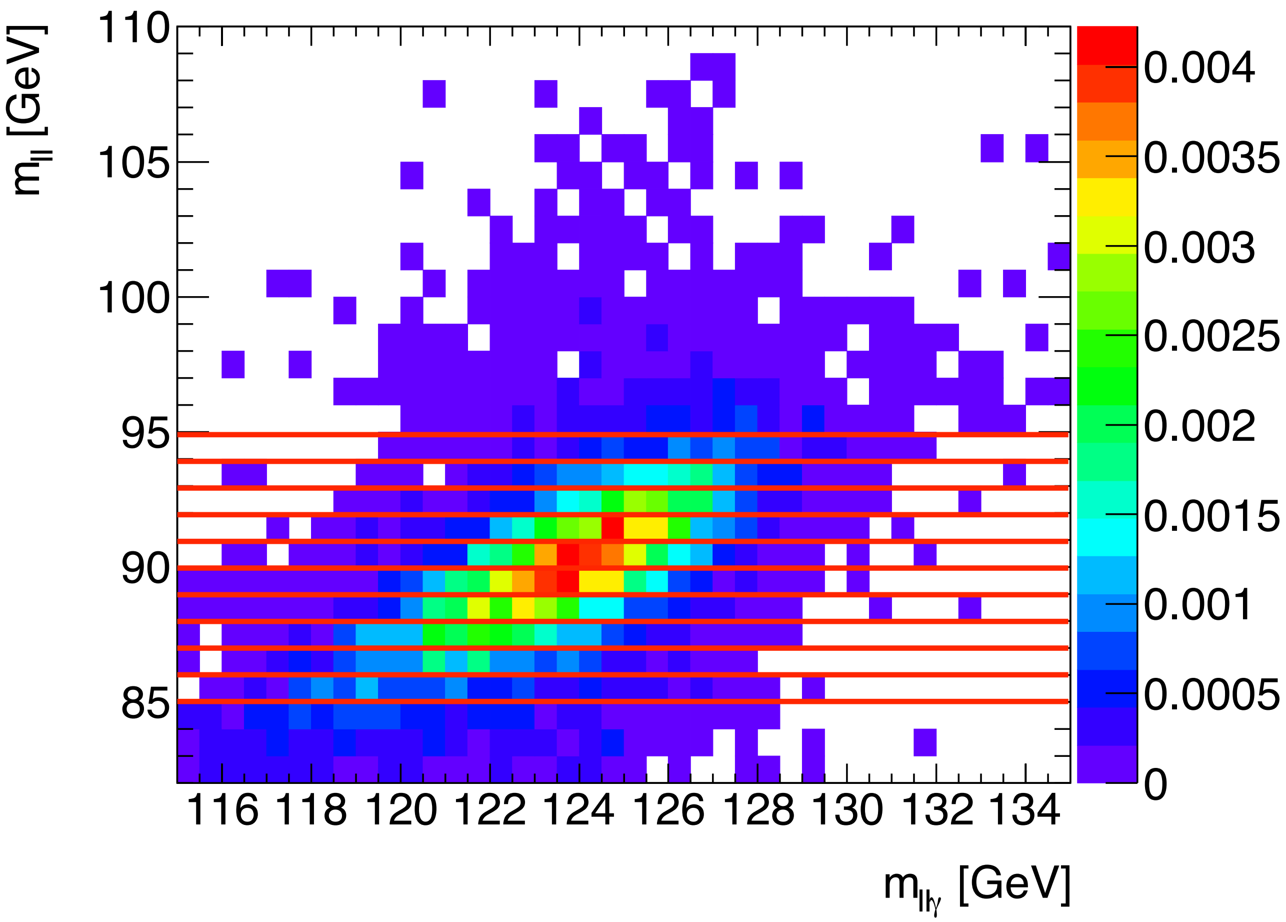
Improving The Limits: New Event Categorisation

- LHC shut down during 2013-2015
- Opportunity to further investigate Run 1 data
- Strong correlation observed between reconstructed Z and Higgs boson masses
- Events concentrated at Z and Higgs mass poles
- Exploit this by adding categories for given Z mass bins



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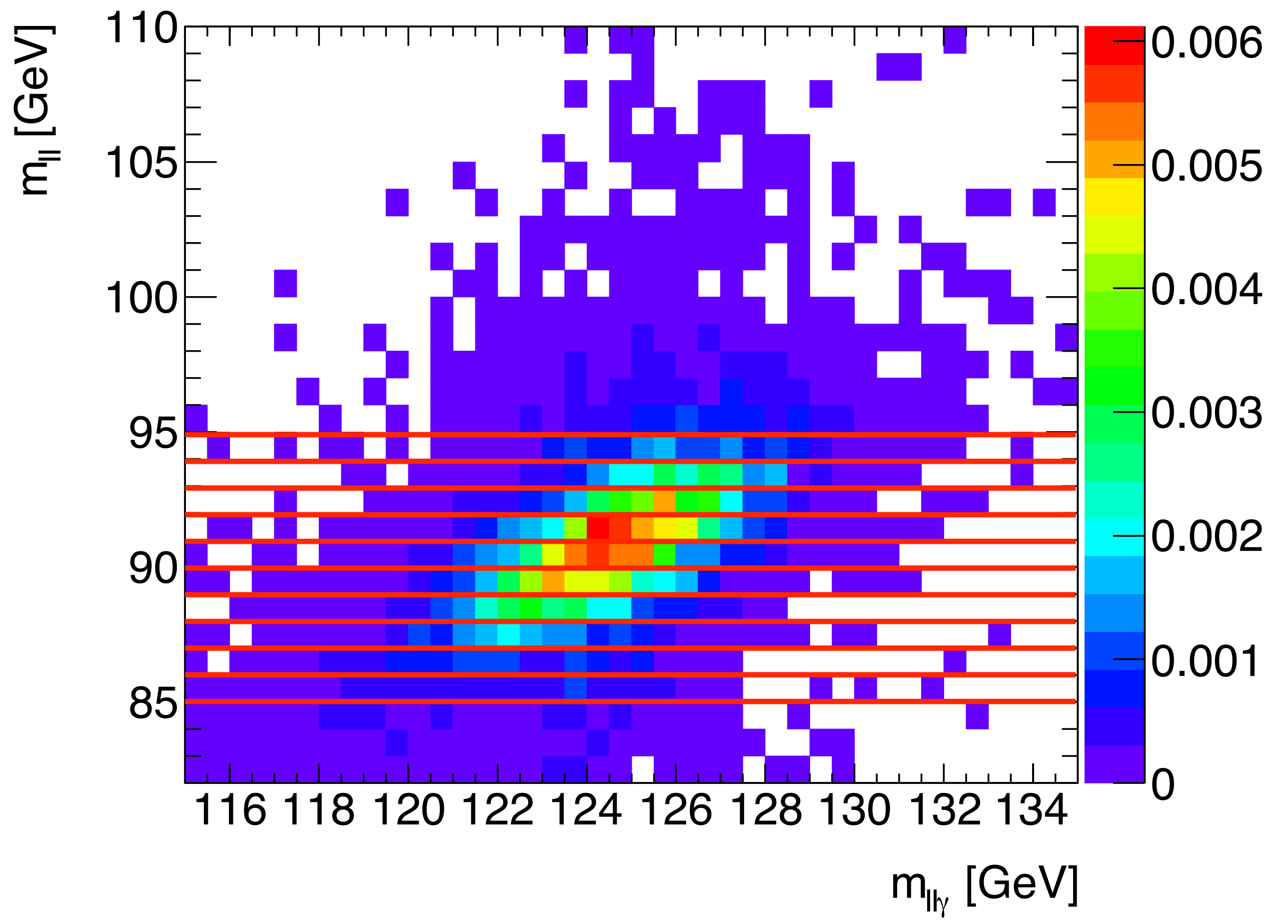
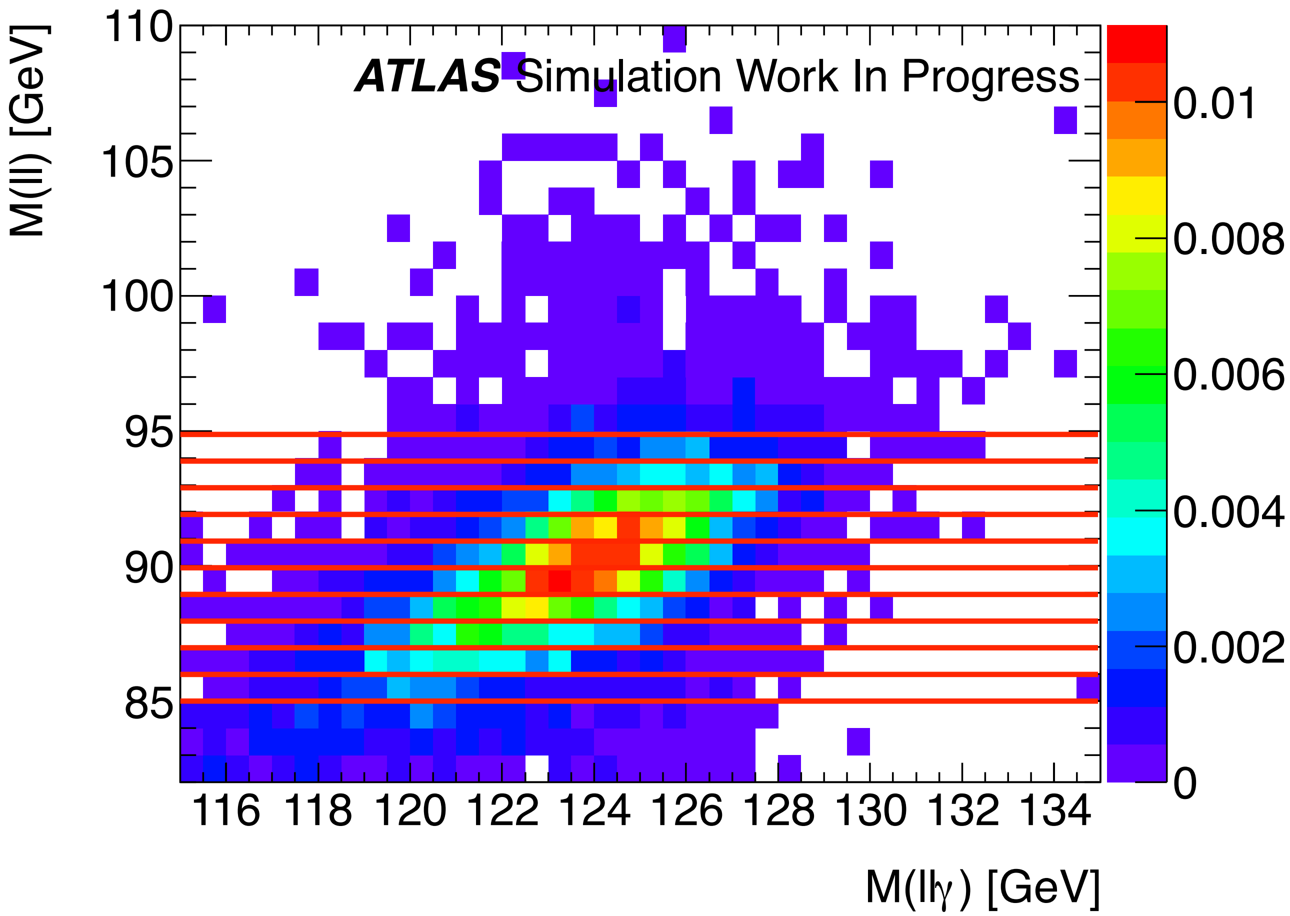


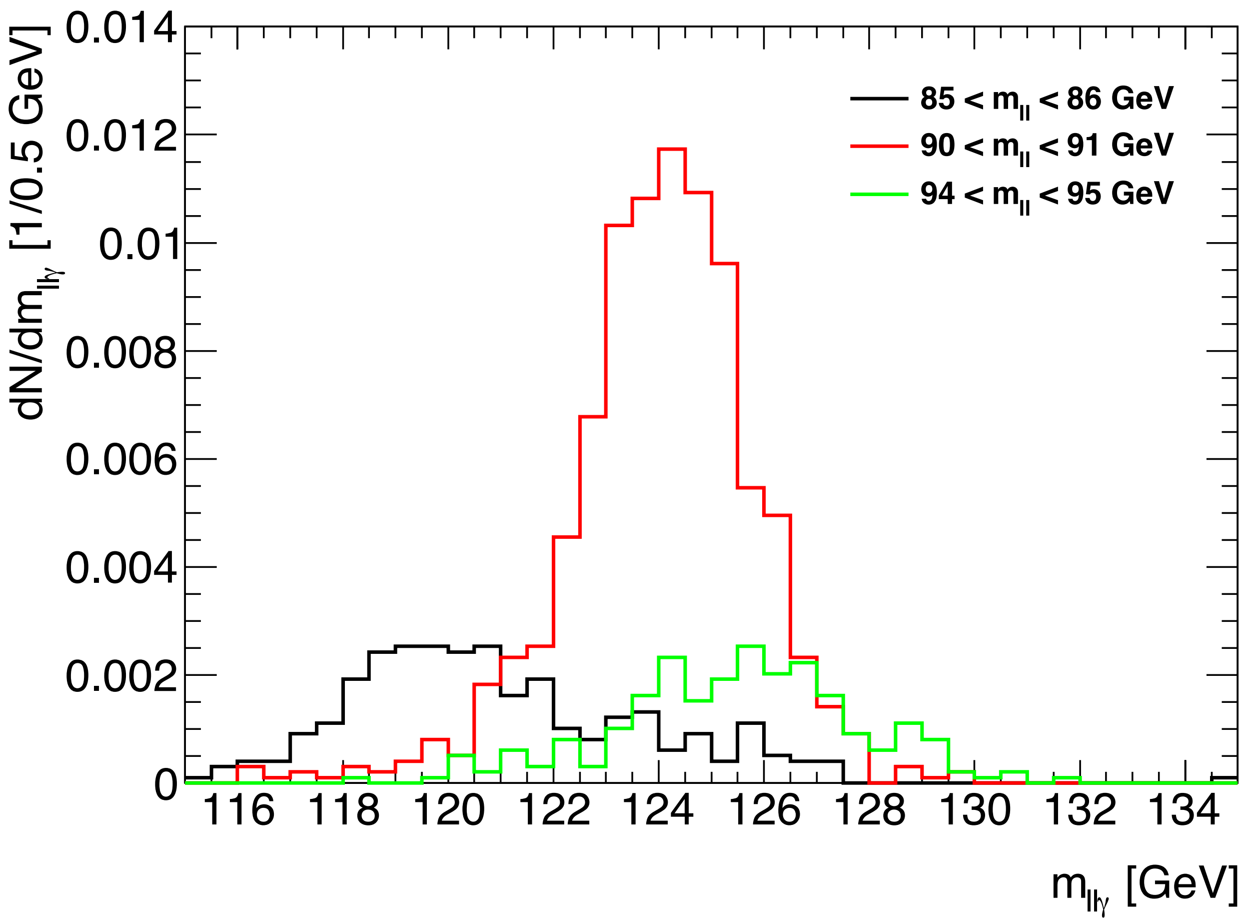
8TeV, ggF, m_H = 125 GeV, $\mu\mu\gamma$

Z Mass Slices

- Each Z slice has a different mass resolution
- Slices nearer the true Z Mass have better resolution, better signal-to-background ratio
  - Such slices contribute more to the expected limit
  - Z slices offer a way of improving sensitivity
- Standard analysis sees all slices merged together
  - Higgs peak smeared out, poorer resolution



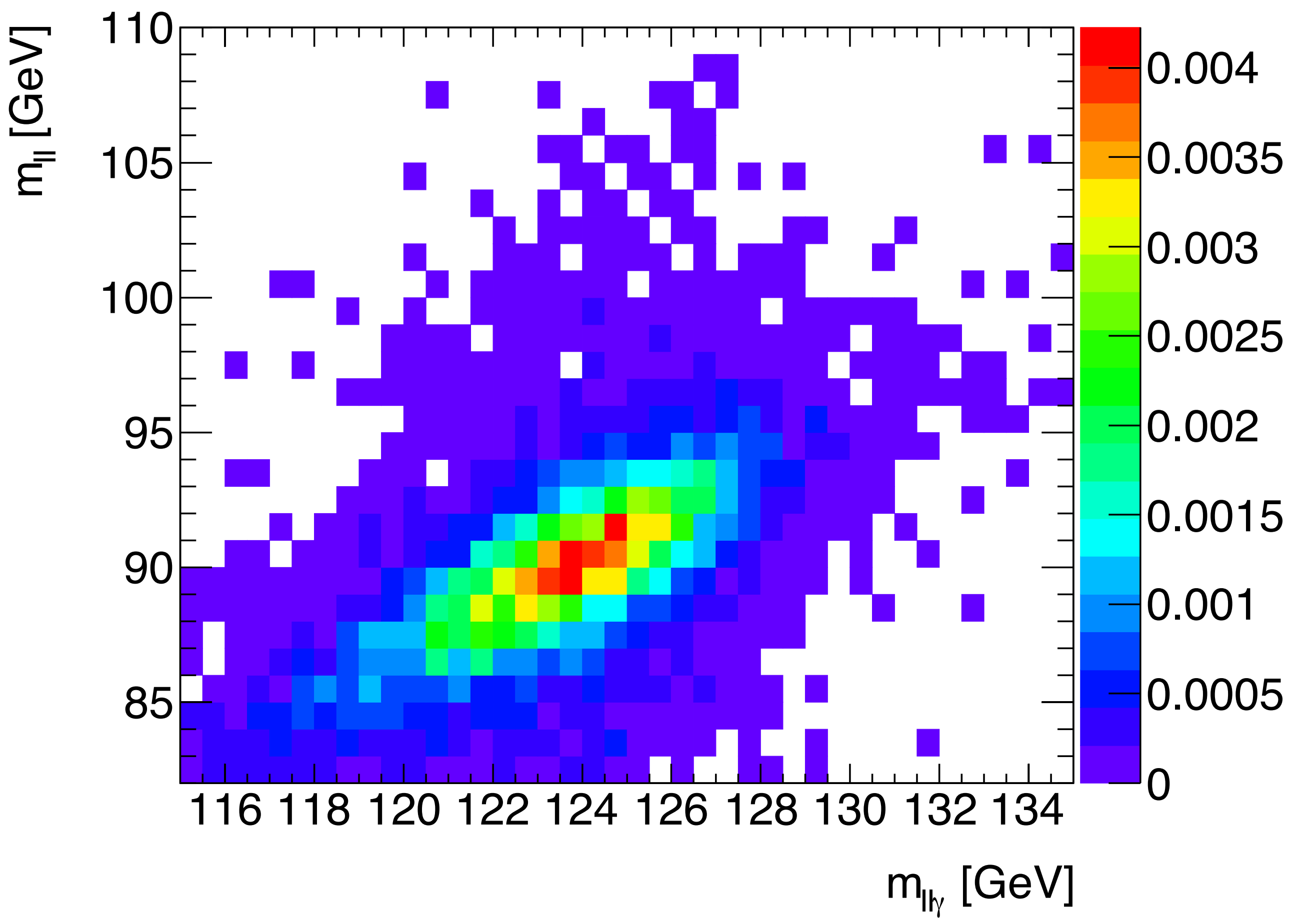
7TeV, ggF, m_H = 125 GeV, eeγ



7TeV, m_H = 125 GeV, eeγ

Z Mass Slices: Analysis overview

- Analysis follows the same procedure as before
- Several corrections not applied:
  - Impact of FSR was considered negligible for the purposes of this study
  - Z Mass constraint removed
    - Z-slices should perform the same job
    - Constraint moves event to peak region, loss of statistics in tail slices
    - Constraint makes correlations between m_{ll} and $m_{ll\gamma}$ more complicated



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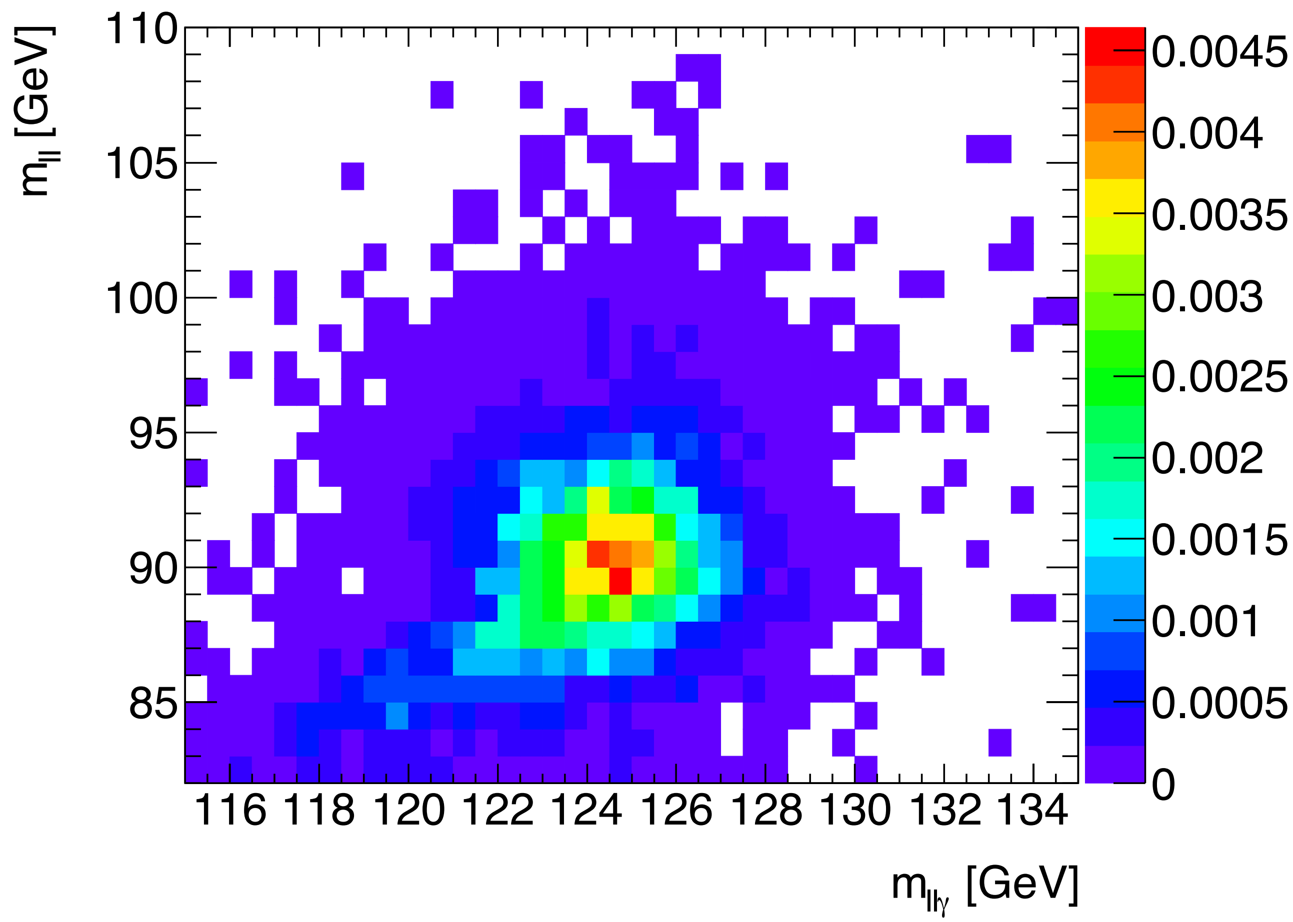
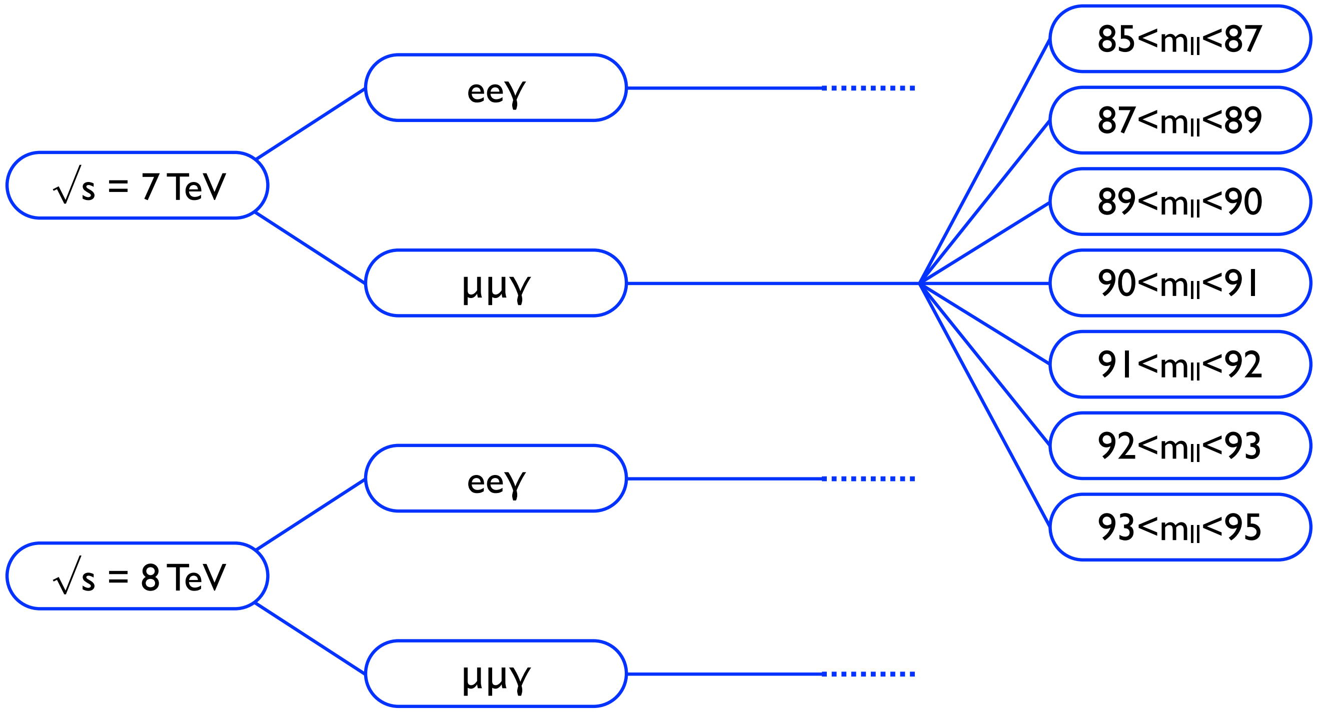


8TeV, mH = 125 GeV, eeγ,
Z Mass Constraint

Z Mass Slices: First Test

- Events categorised based on:
  - Centre-of-mass collision energy
  - Final state
  - Z Mass
- Note tails widen to 2GeV
  - Boost statistics in tails of m_{ll} distribution



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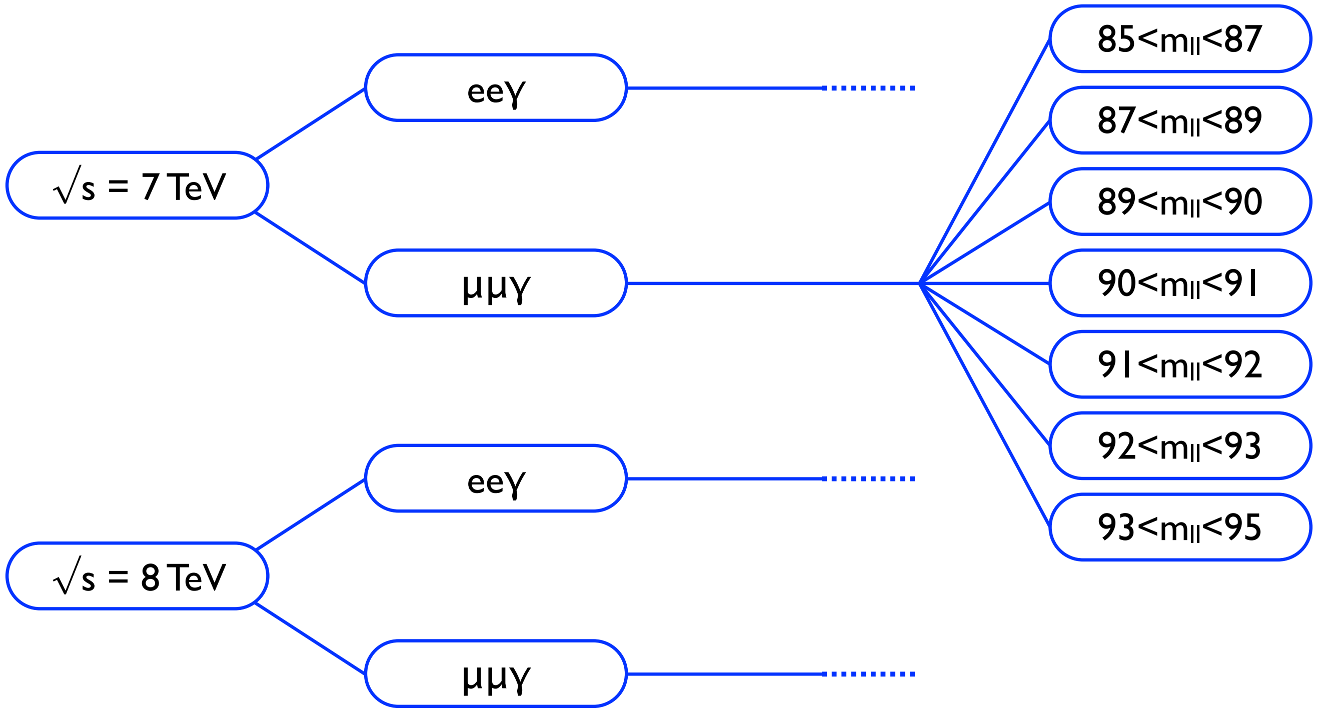
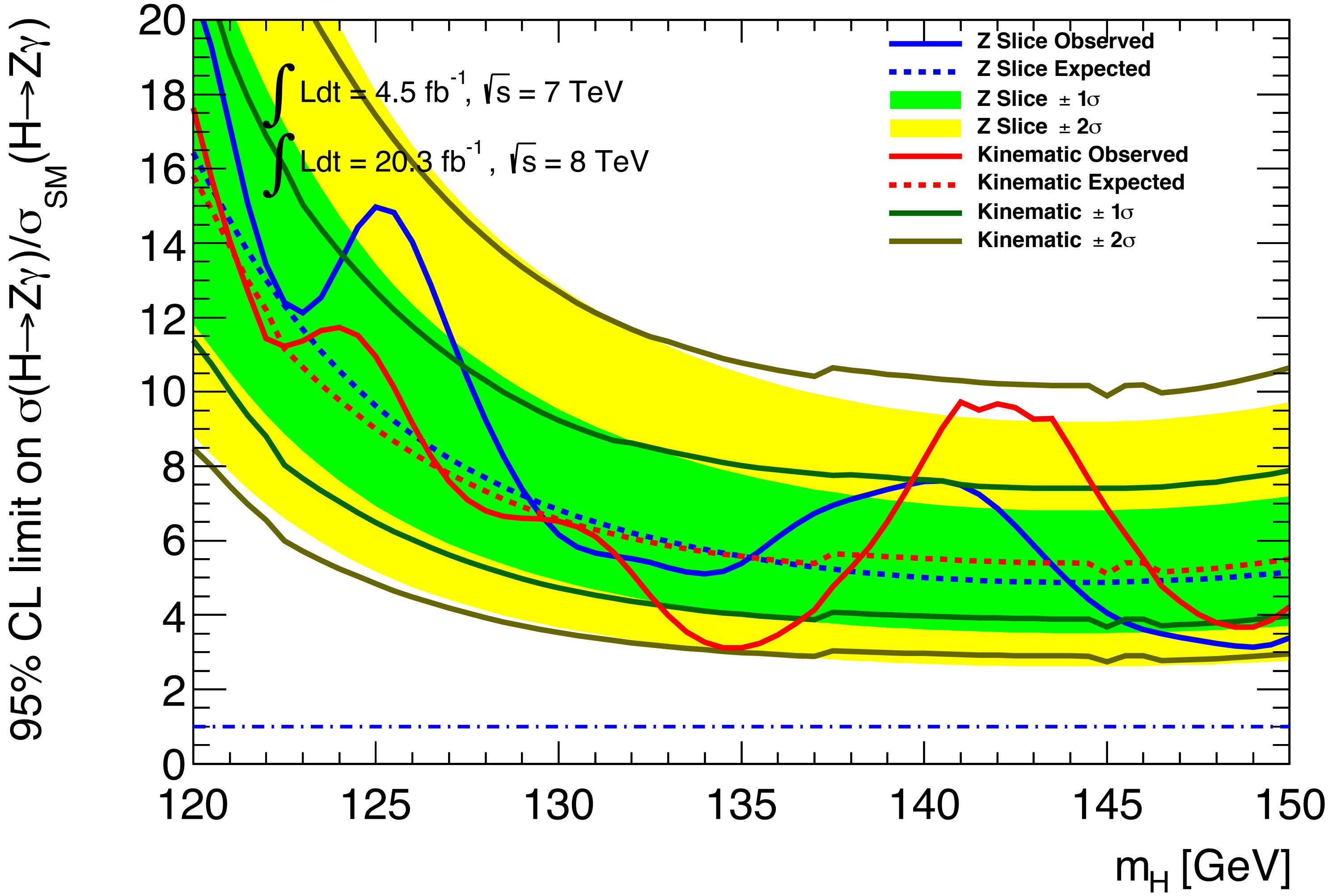
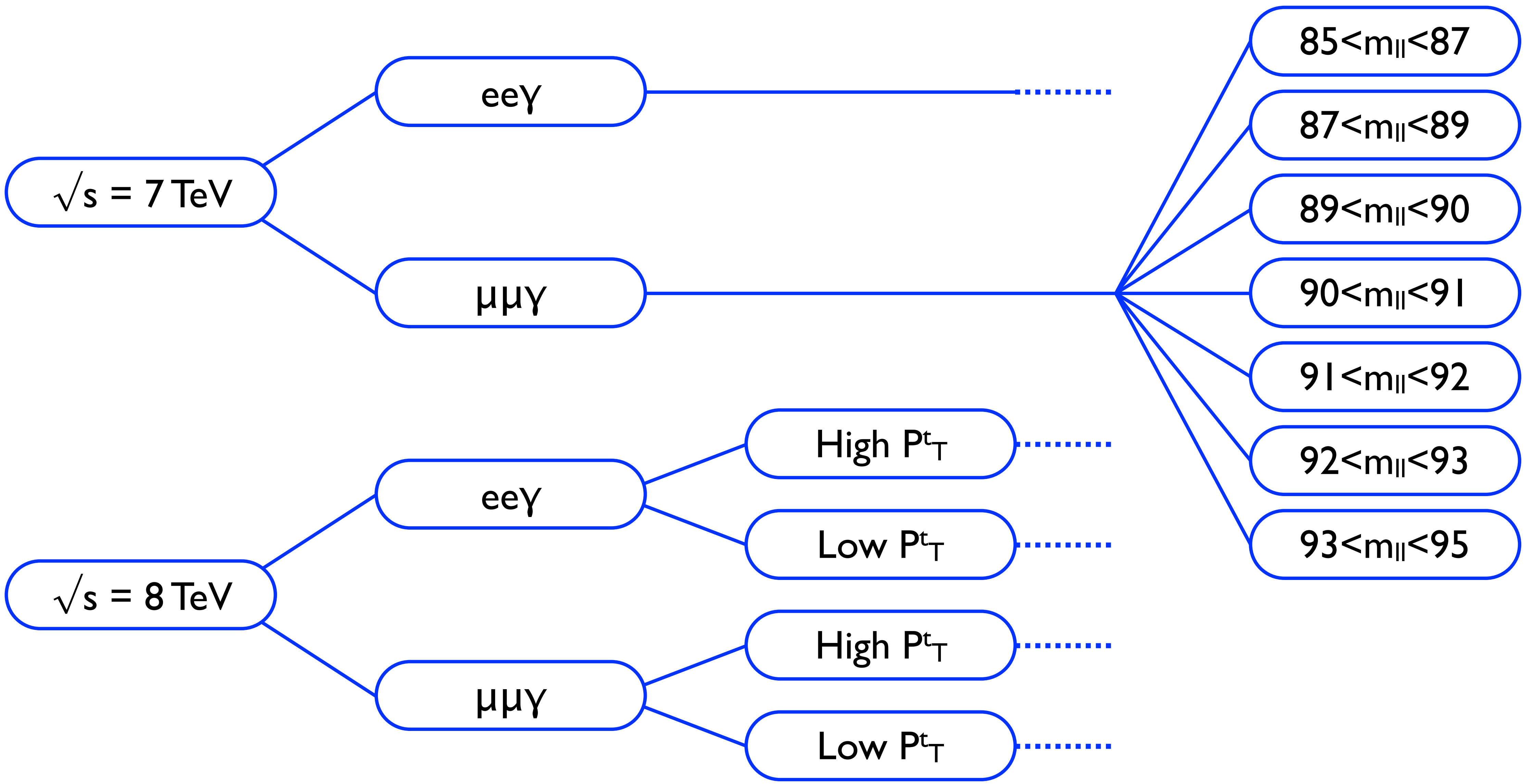


- Expected/Observed limits evaluated
- Expected limits comparable to kinematic analysis
- Observed limit enhanced at m_H = 125 GeV
- No real improvement though



Z Mass Slices: Final Event Categorisation

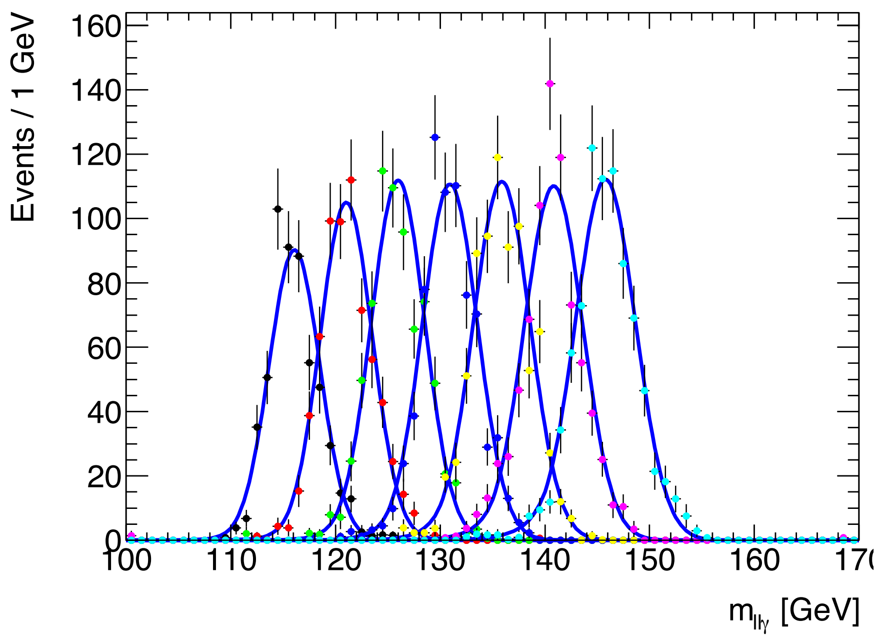
- Events categorised based on:
  - Centre-of-mass collision energy
  - Final state
  - Higgs p_{Tt} (> or < 30 GeV)
  - Z Mass
- 7 TeV has too few statistics to be split further
- 8 TeV cannot be further split by $\Delta\eta_{Z\gamma}$



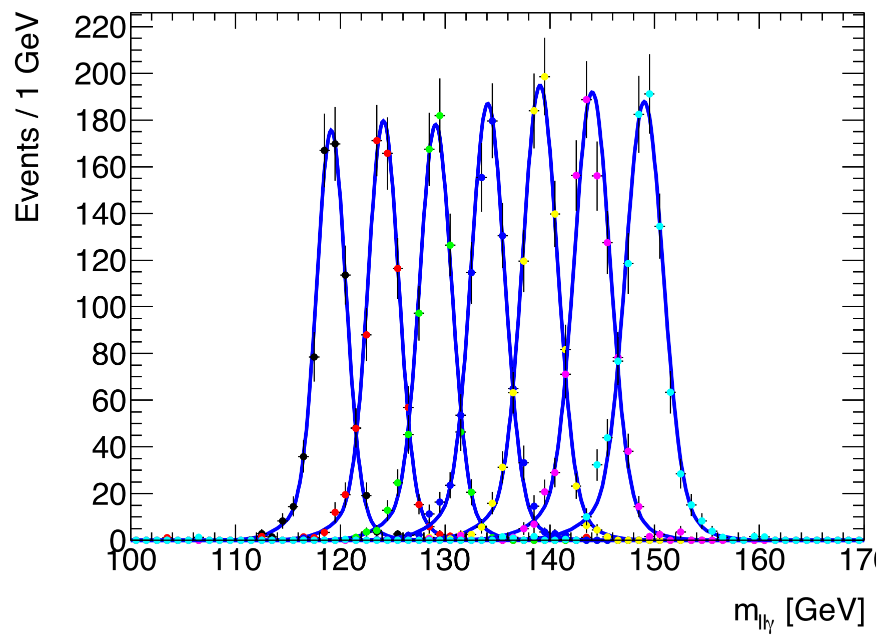
Z Mass Slices: Signal & Background Models

- Signal model remains a Crystal Ball (Core) + Gauss (tails)
  - Parameters vary linearly with nominal mass
  - All mass points fitted simultaneously
- Due to low statistics, background modelled as single exponential
  - More complex functions would be too distorted by local fluctuations

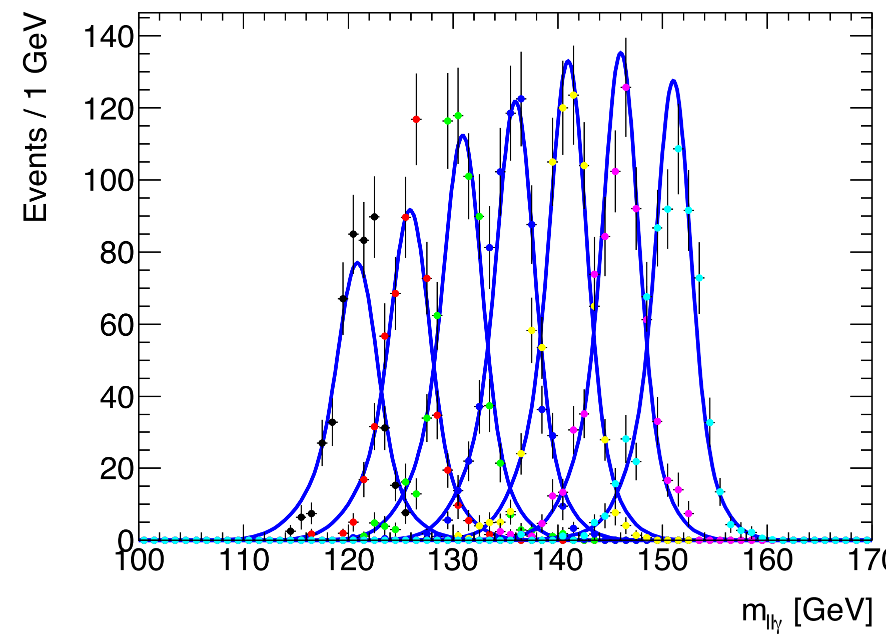
8TeV eeγ 85<Z<87 Low Ptt

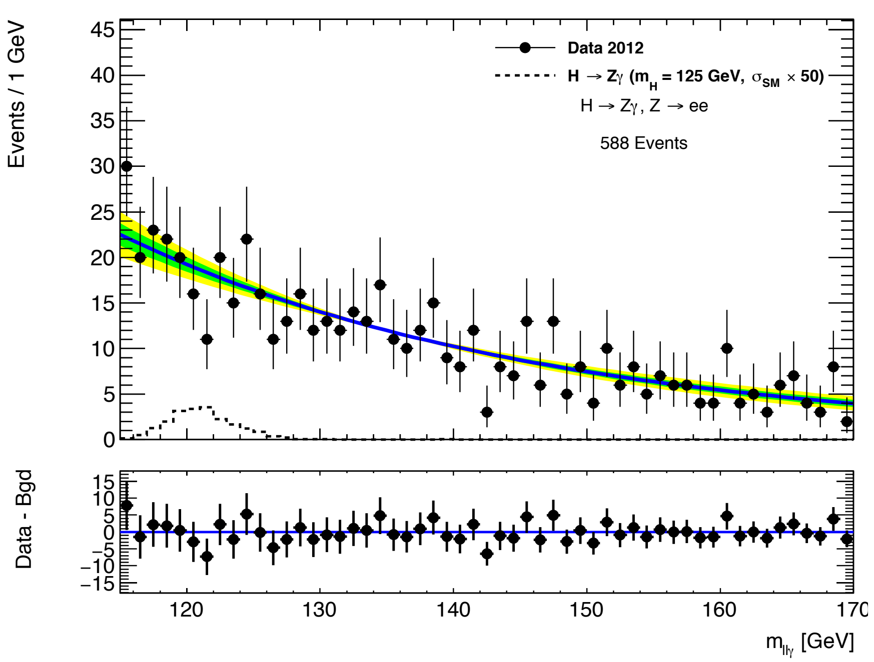


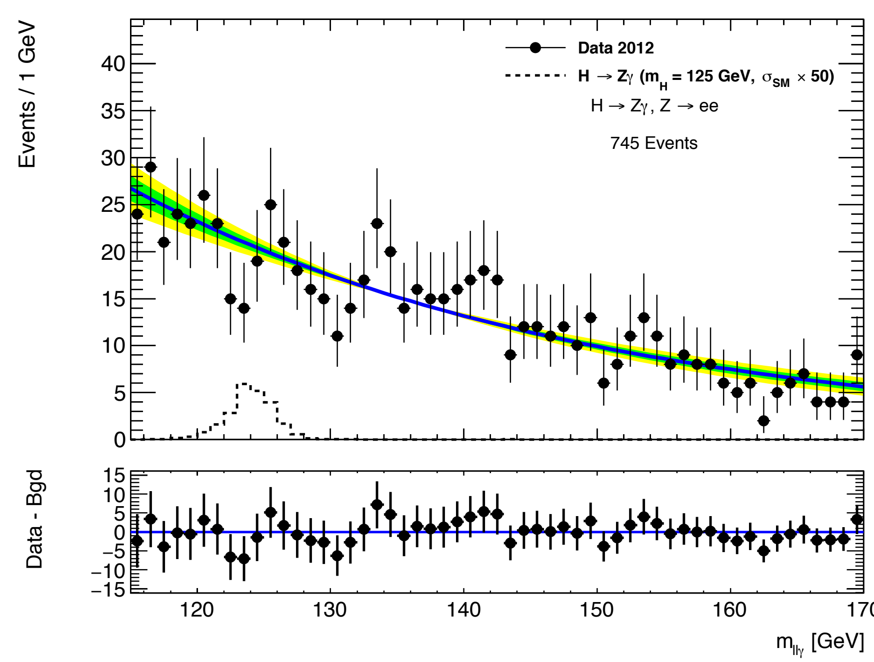
8TeV eeγ 90<Z<91 Low Ptt

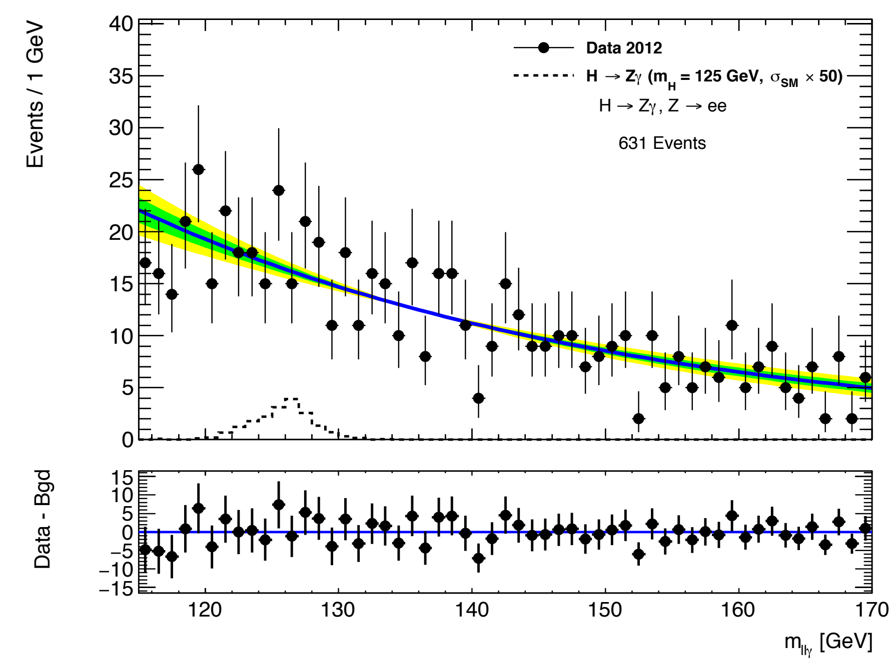


8TeV eeγ 93<Z<95 Low Ptt





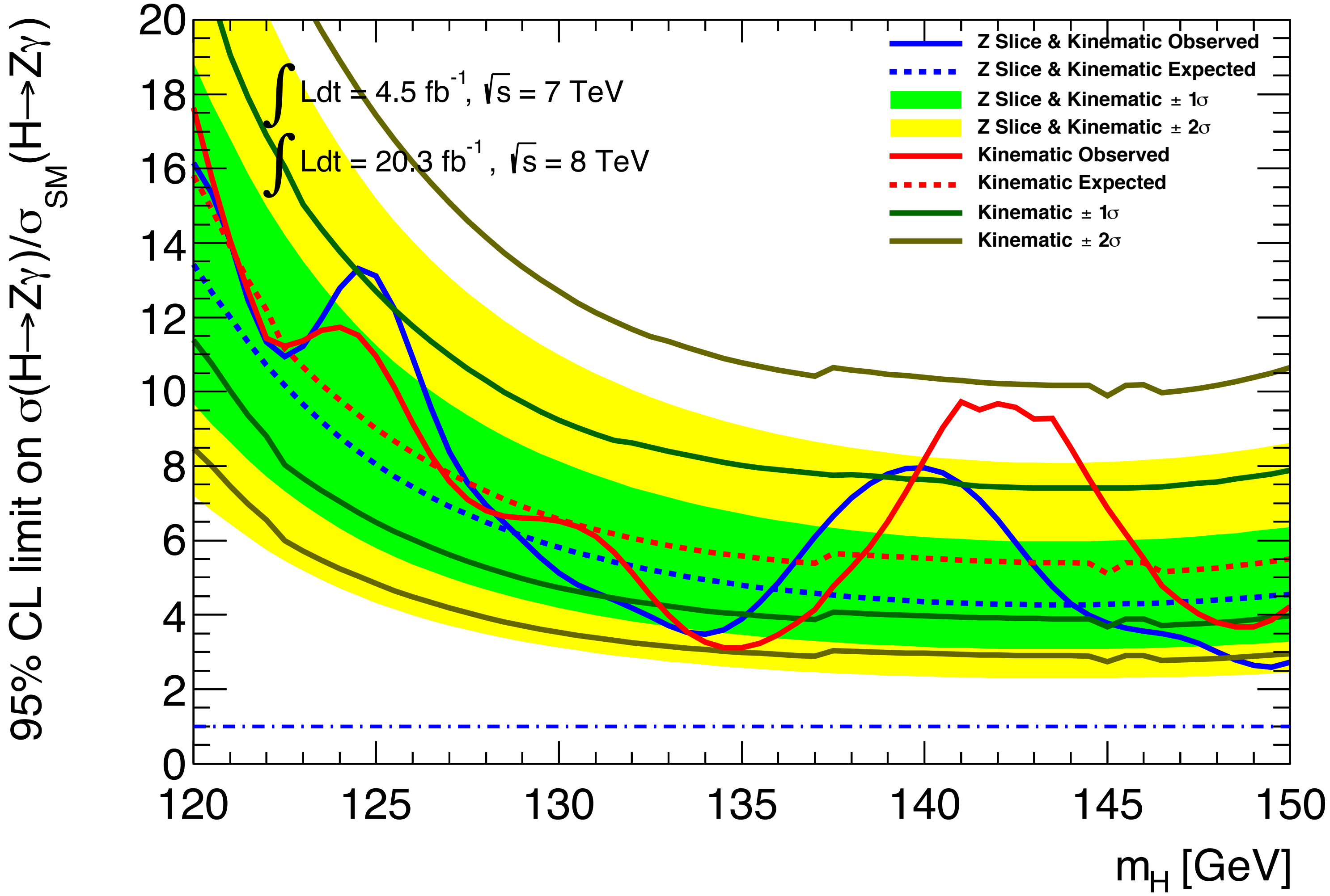




Z Mass Slices: Expected & Observed Limits

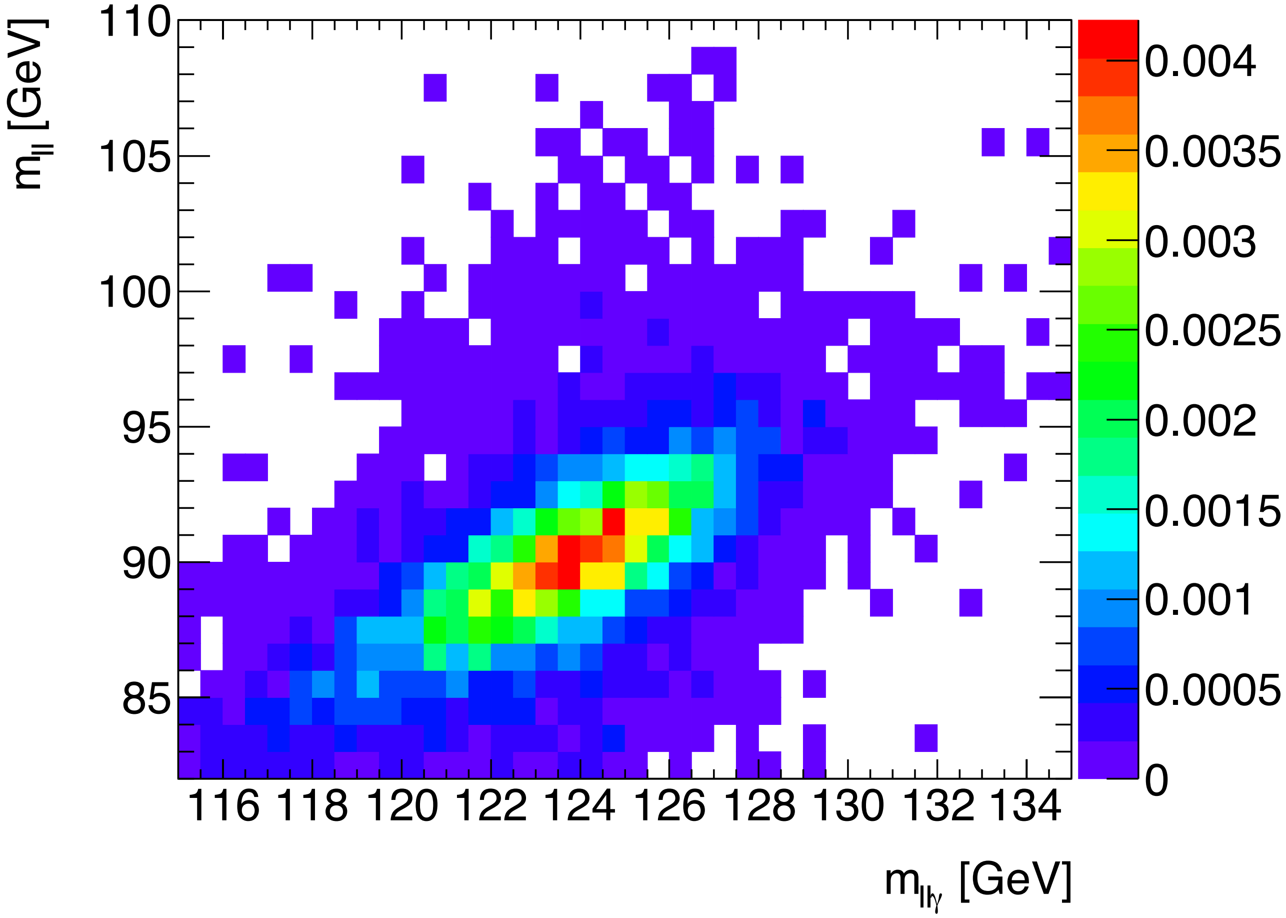
- Expected/Observed limits evaluated
- No systematic uncertainties re-evaluated

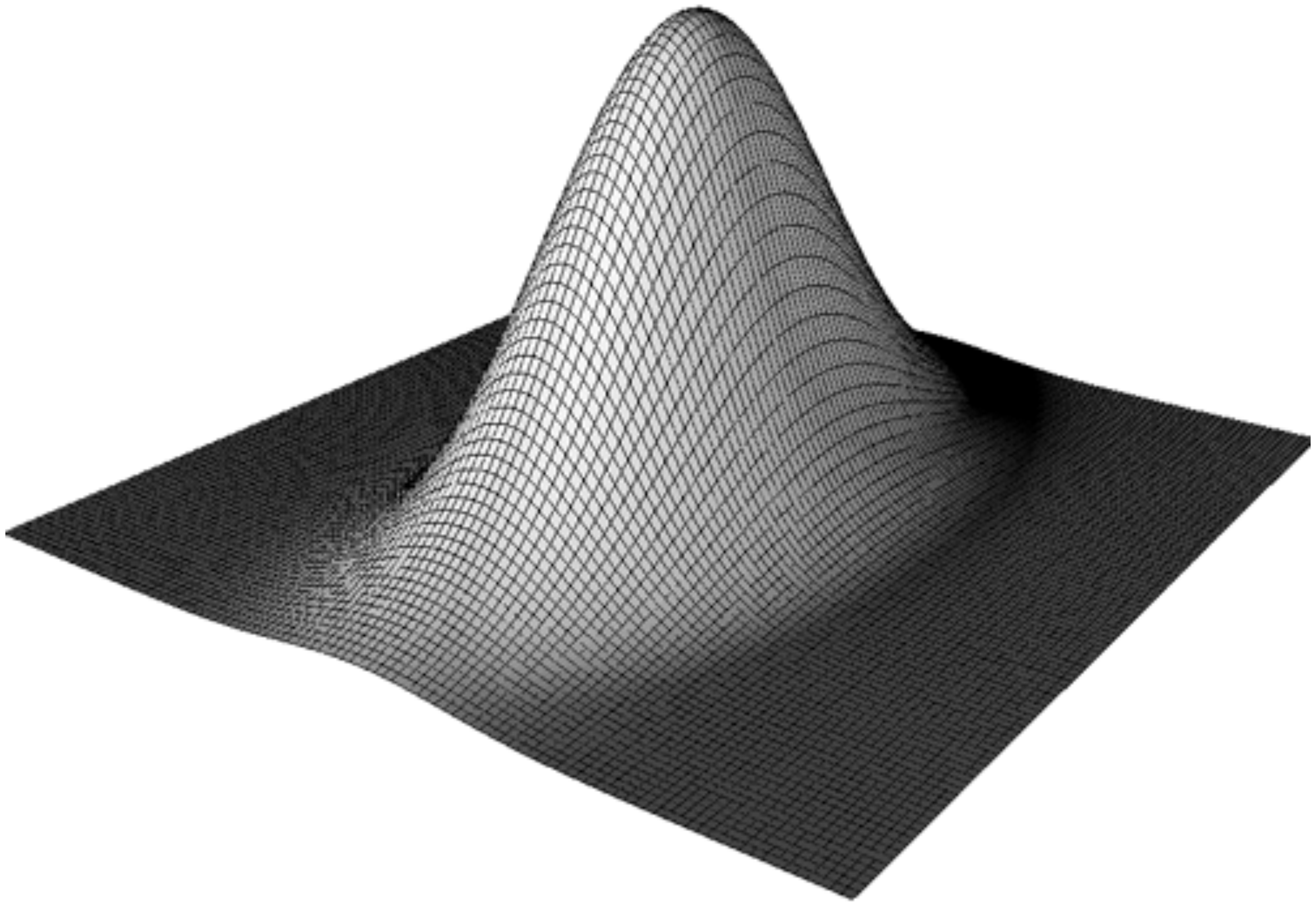
- At m_H = 125 GeV:
  - Expected (Kinematic) = 9.01*SM
  - Expected (Z Slices) = 8.05*SM
- Z slices reduce limits by ~10%



Z Mass Slices: Possible refinements

- The technique introduces multiple categories and associated systematic uncertainties
- Final model contains many parameters
- Signal and background could possibly be modelled using 2D functions…





Search for X→Zγ Decays

- LHC restarted June 2015
- First studies using 3.2 fb^{-1} of 13 TeV data completed by December 2015

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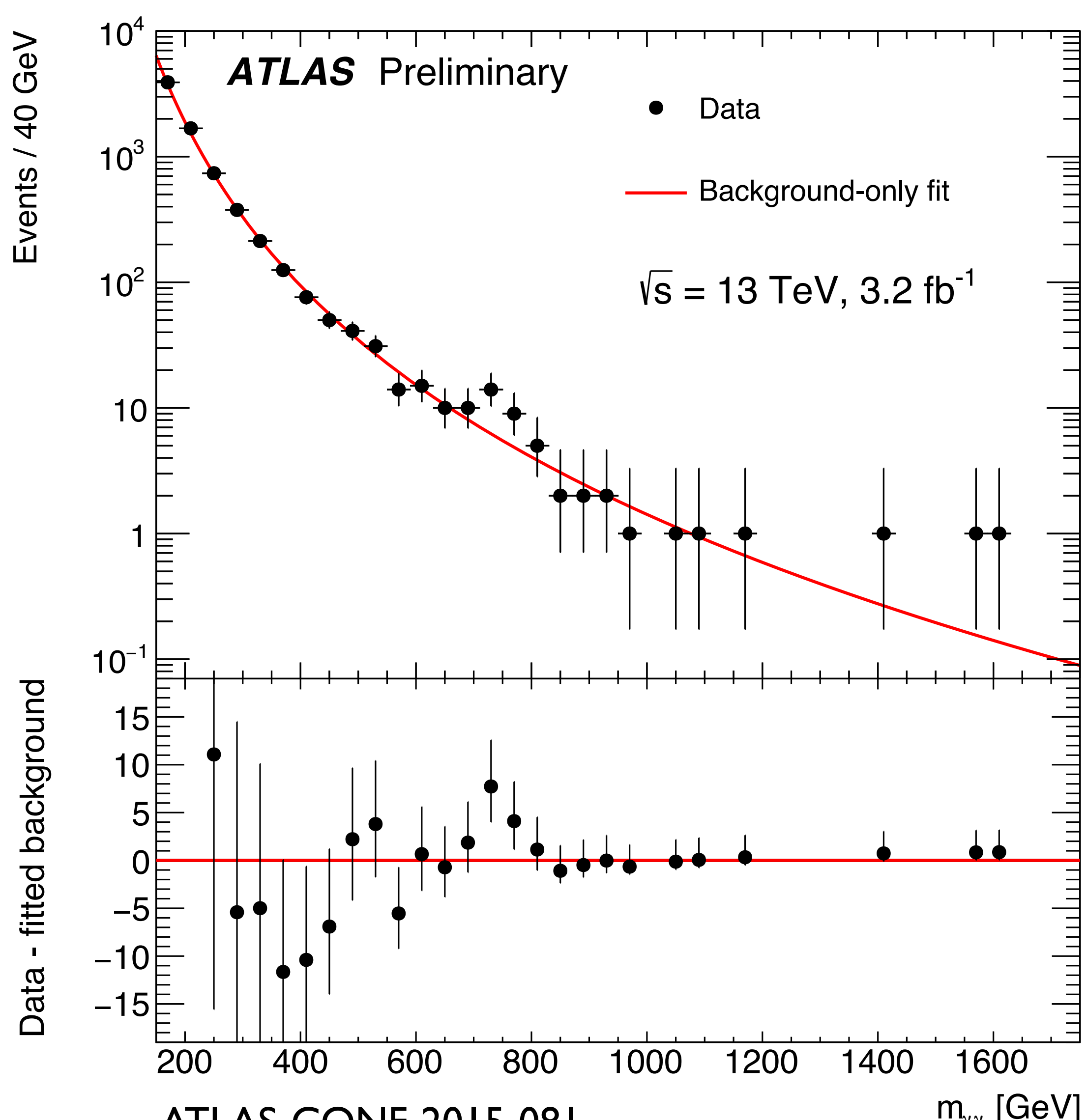
  - Could have been a statistical fluctuation
  - Could have been a new particle
- Similar excess reported by CMS



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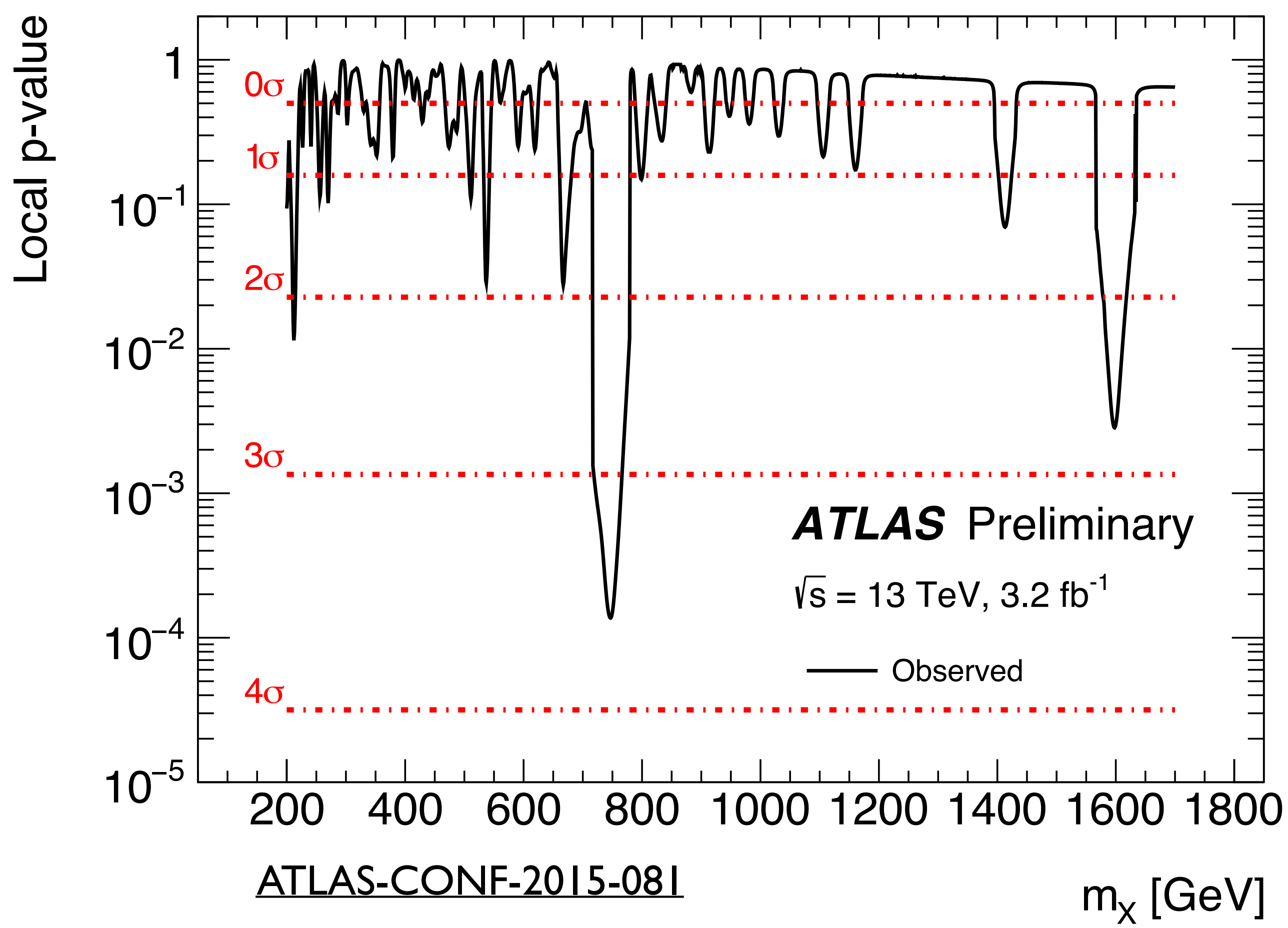

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Search for X→Zγ Decays

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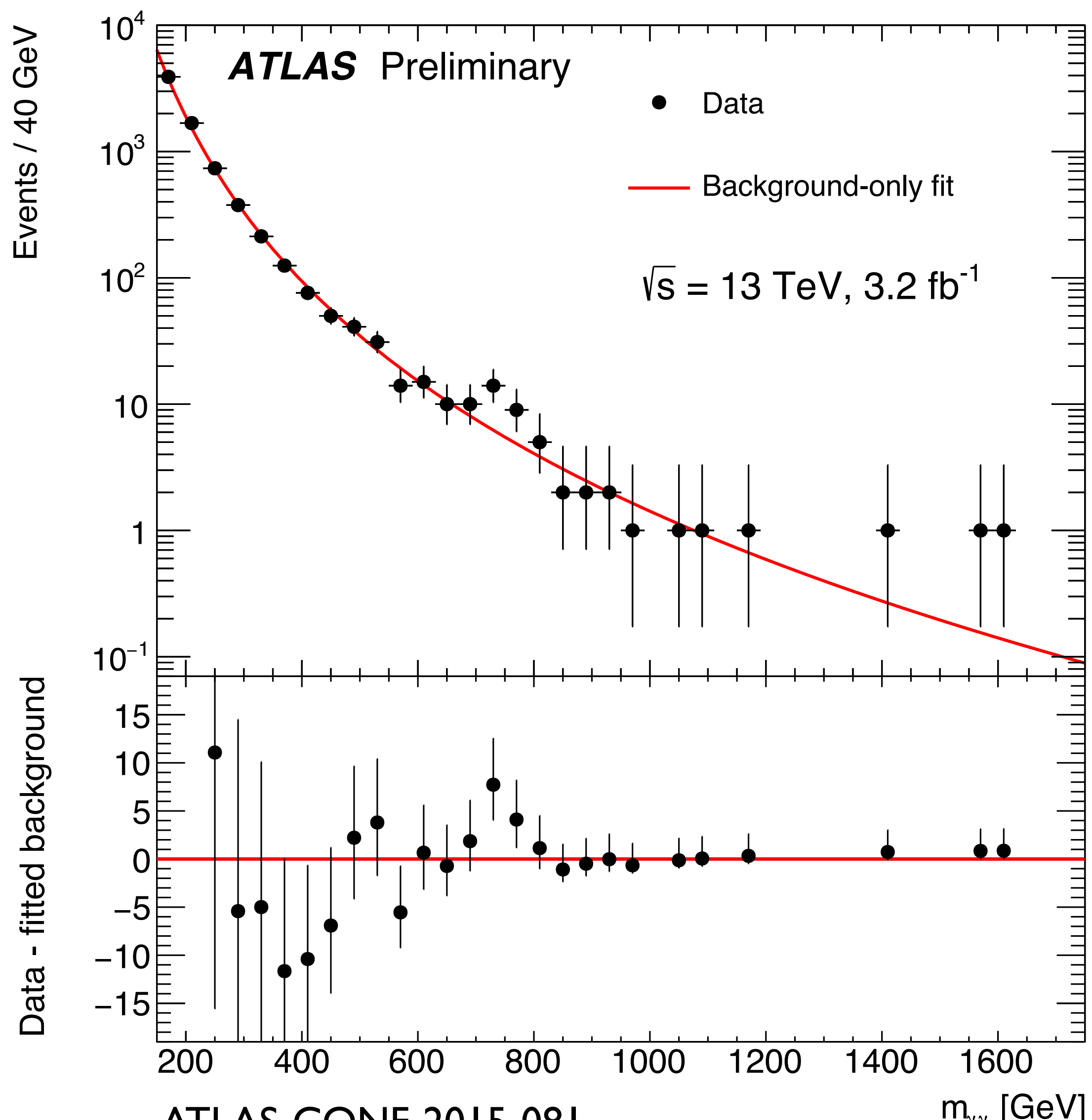
- First studies using 3.2 fb^{-1} of 13 TeV data completed by December 2015
- Diphoton channel reported a slight excess at 750 GeV
  - Could have been a statistical fluctuation
  - Could have been a new particle
- Similar excess reported by CMS
- Particles coupling to the photon expected to couple to the Z boson
  - A boson X undergoing X→γγ should also decay via X→Zγ



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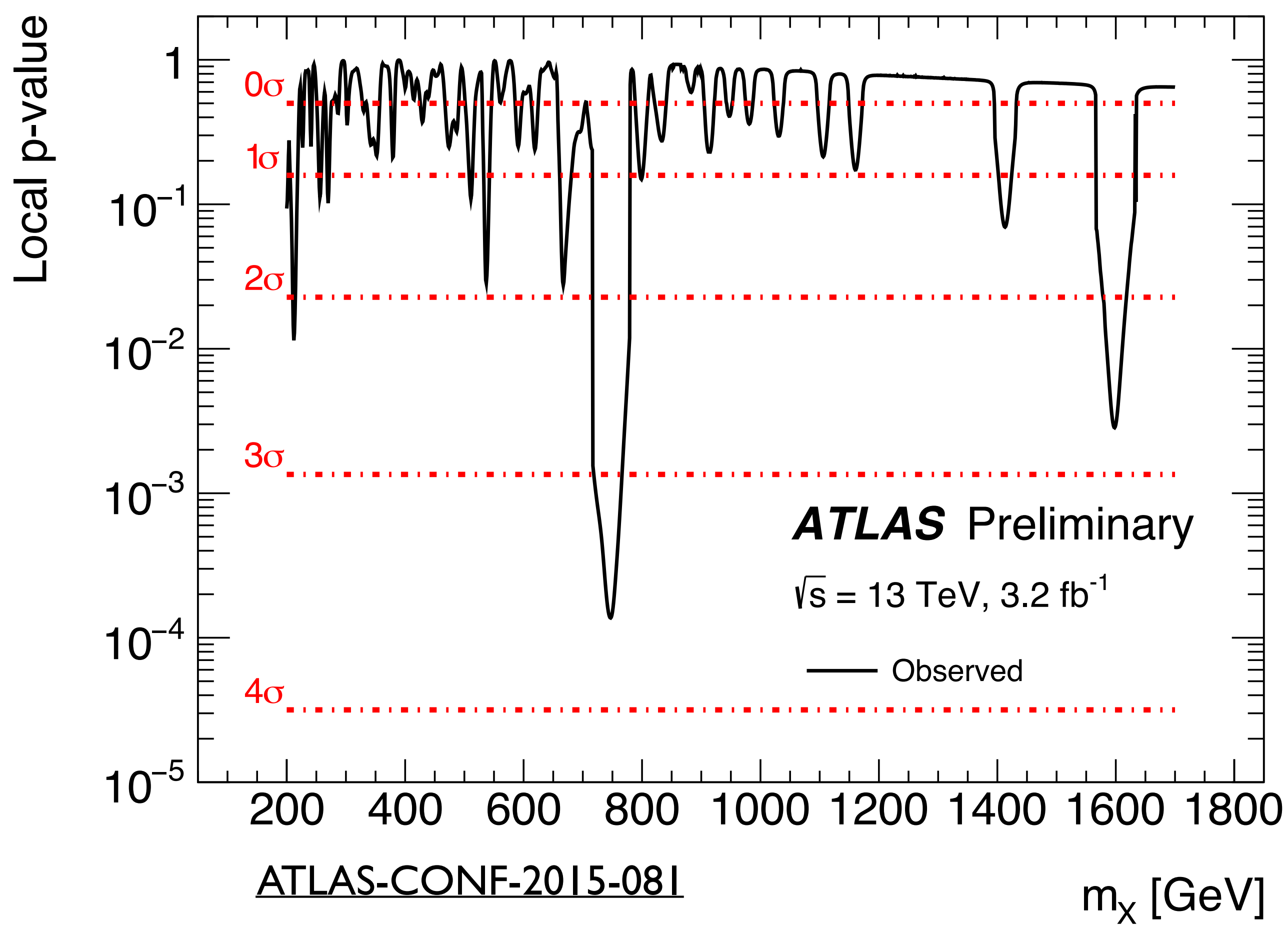

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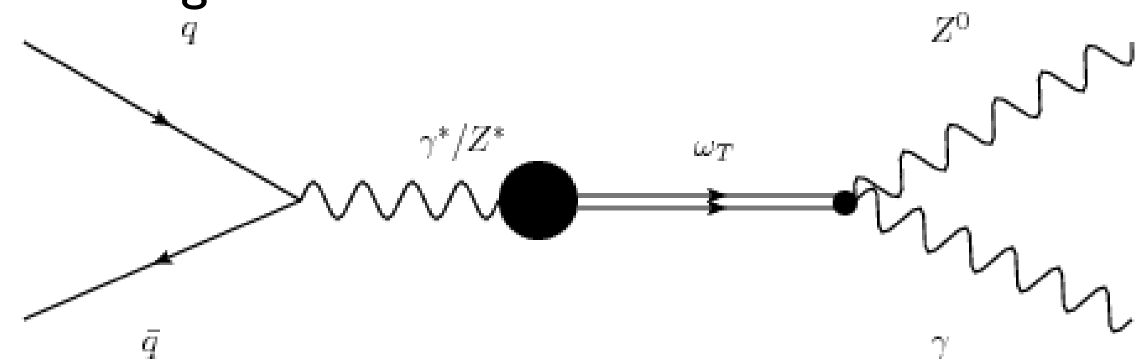
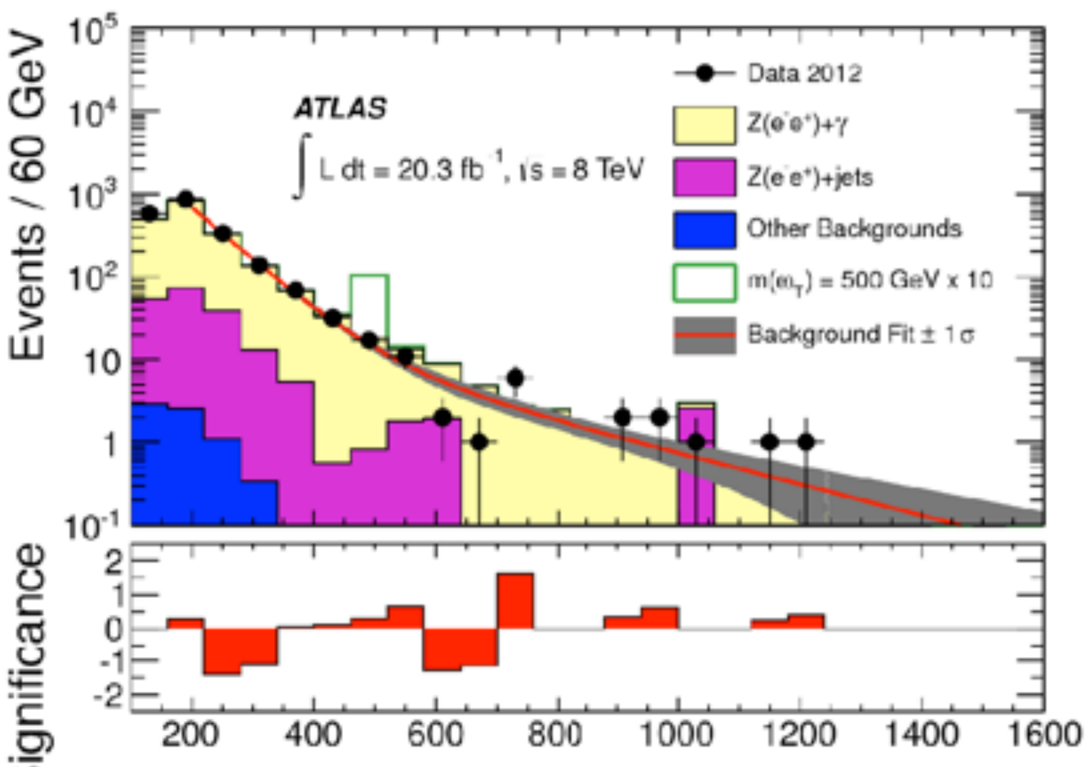
Run I results

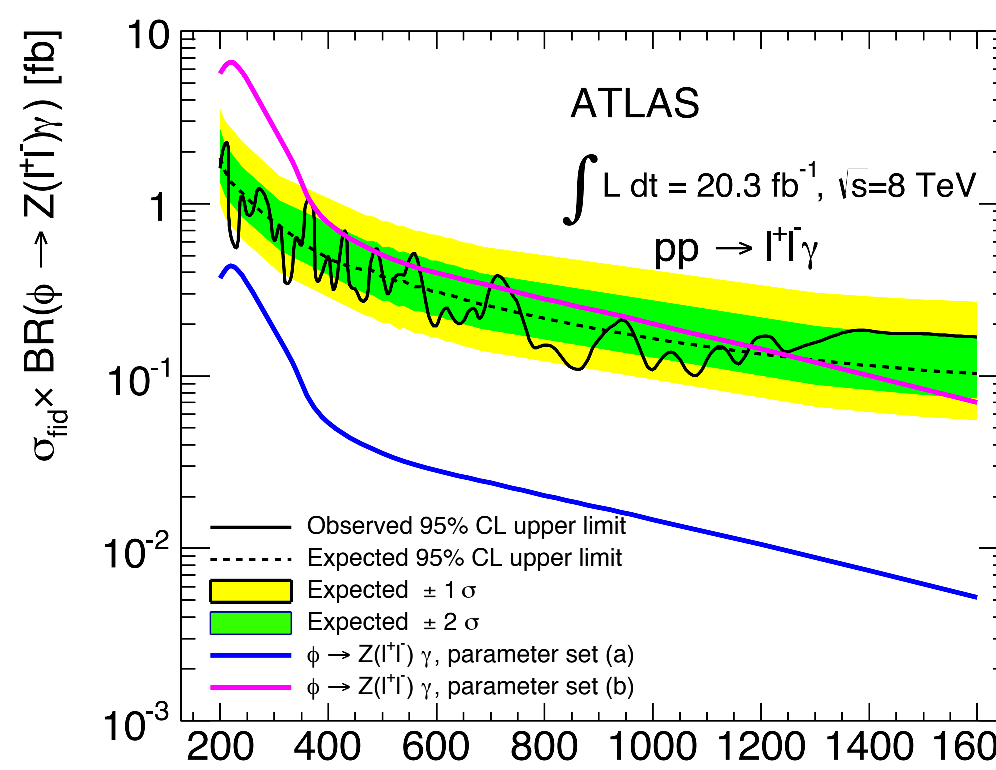
- An exotics search for high mass resonances decaying to Zγ was performed
- Run I analysis published in PLB 738 (2014) 428-447
- Search for singlet scalar resonance decaying to Zγ, Z→ll (where l = e or μ)
  - Used 20.3 fb^{-1} of 8 TeV data
  - 1σ excess at 700 GeV down to 0σ at 750 GeV
- Trivial matter to extend Run 2 SM H→Zγ software to search for high mass resonances



Three-body invariant mass distribution for the $e^+e^-\gamma$ final state.
The expected signal for a resonance mass of 500 GeV is superimposed.



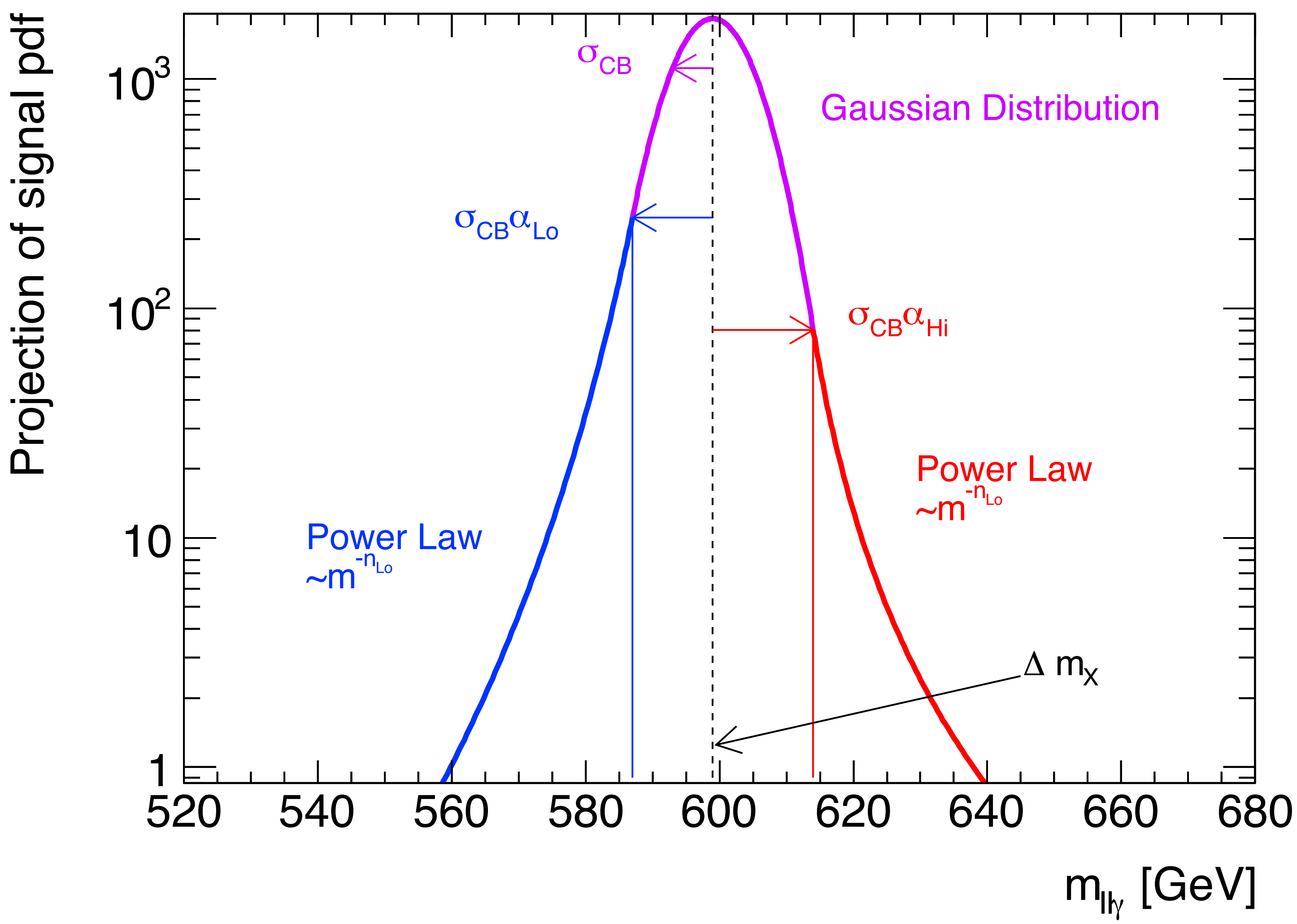
PLB 738 (2014) 428-447



PLB 738 (2014) 428-447

X→Zγ: Signal Modelling

- Signal MC samples generated using narrow width approximation
  - Higgs signal peak has width ~4.0MeV
- Mass points at: 200, 300, 500, 700, 750, 800, 1000, 1500 GeV
- Signal modelled with a double-sided Crystal Ball function



$$
N \cdot \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{\mathrm{Lo}} \leq t \leq \alpha_{\mathrm{Hi}} \\ \dfrac{e^{-0.5\alpha_{\mathrm{Lo}}^2}}{\left[\frac{\alpha_{\mathrm{Lo}}}{n_{\mathrm{Lo}}}\left(\frac{n_{\mathrm{Lo}}}{\alpha_{\mathrm{Lo}}} - \alpha_{\mathrm{Lo}} - t\right)\right]^{n_{\mathrm{Lo}}}} & \text{if } t < -\alpha_{\mathrm{Lo}} \\ \dfrac{e^{-0.5\alpha_{\mathrm{Hi}}^2}}{\left[\frac{\alpha_{\mathrm{Hi}}}{n_{\mathrm{Hi}}}\left(\frac{n_{\mathrm{Hi}}}{\alpha_{\mathrm{Hi}}} - \alpha_{\mathrm{Hi}} + t\right)\right]^{n_{\mathrm{Hi}}}} & \text{if } t > \alpha_{\mathrm{Hi}}, \end{cases}
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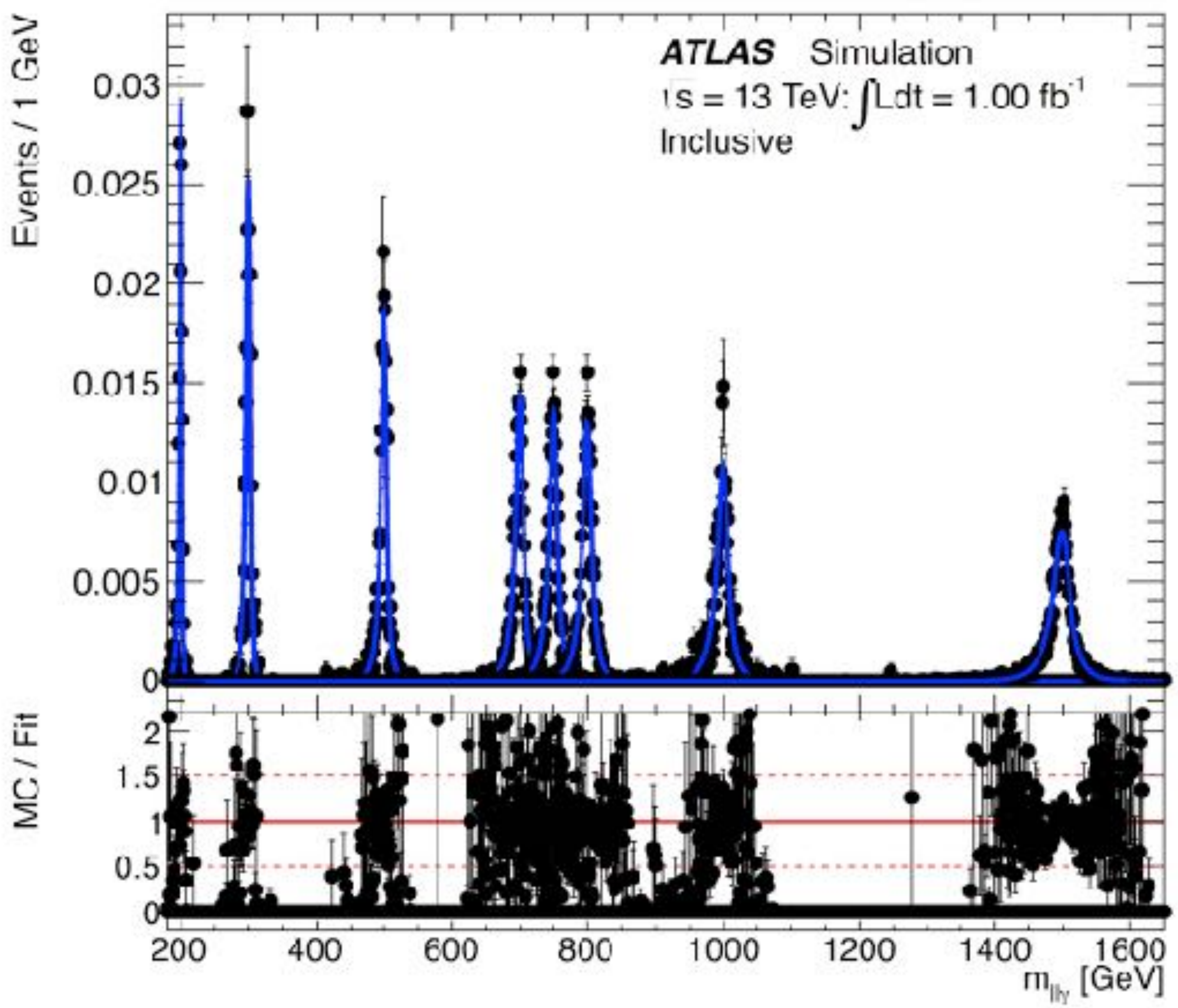

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Parameter dependence

Par	Mass Dependence
μ_{CB}	$a_\mu + b_\mu*x + c_\mu*x*x+m_X$
σ_{CB}	$a_\sigma + b_\sigma * x$
α_{lo}	$a_{\alpha lo} + b_{\alpha lo} /(x+c_{\alpha lo})$
α_{hi}	$a_{\alpha hi} + b_{\alpha hi} /(x+c_{\alpha hi})$
X	$(m_X-100)/100$

X→Zγ: Signal Modelling

- Signal MC samples generated using narrow width approximation
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- Mass points at: 200, 300, 500, 700, 750, 800, 1000, 1500 GeV
- Signal modelled with a double-sided Crystal Ball function
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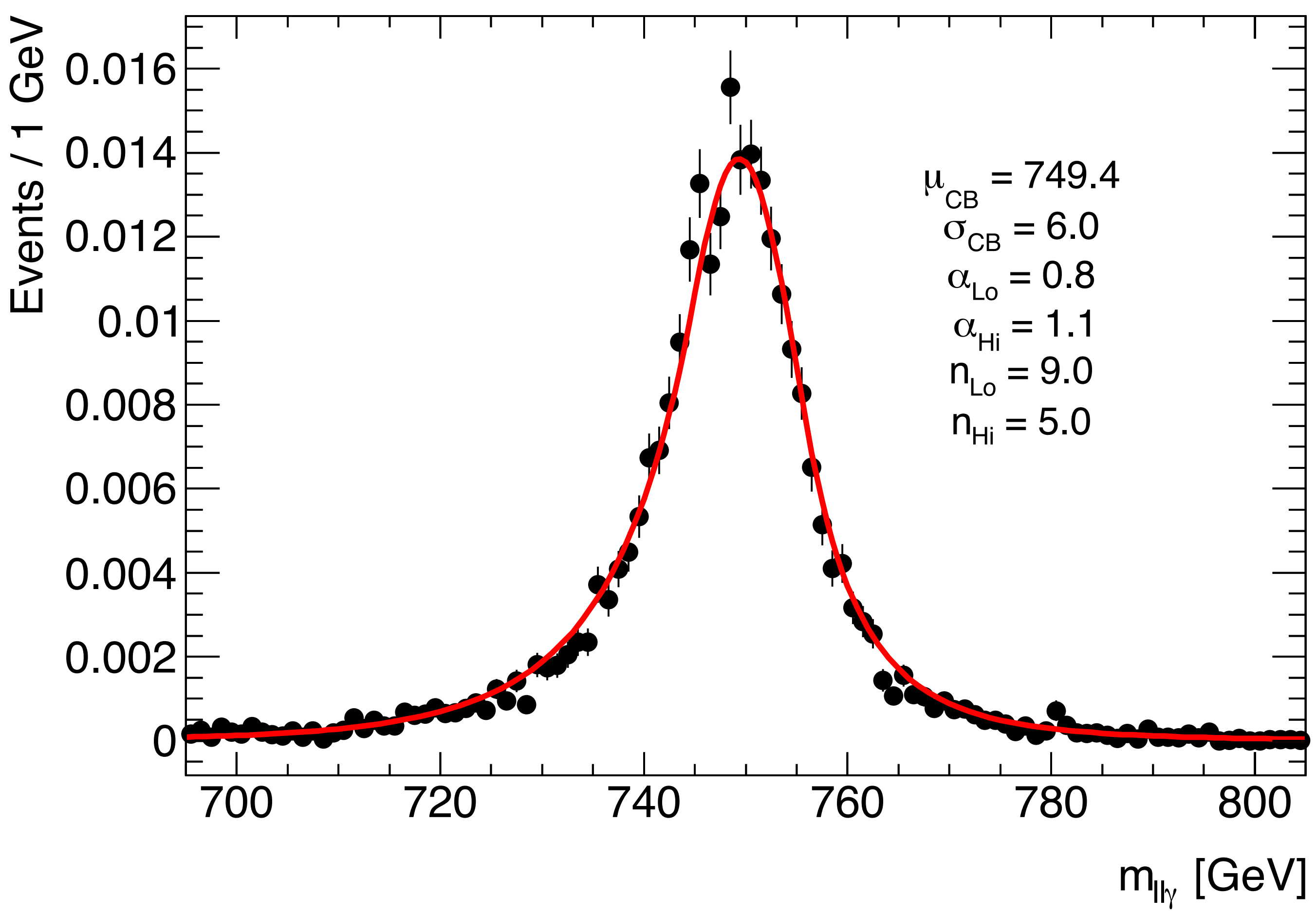

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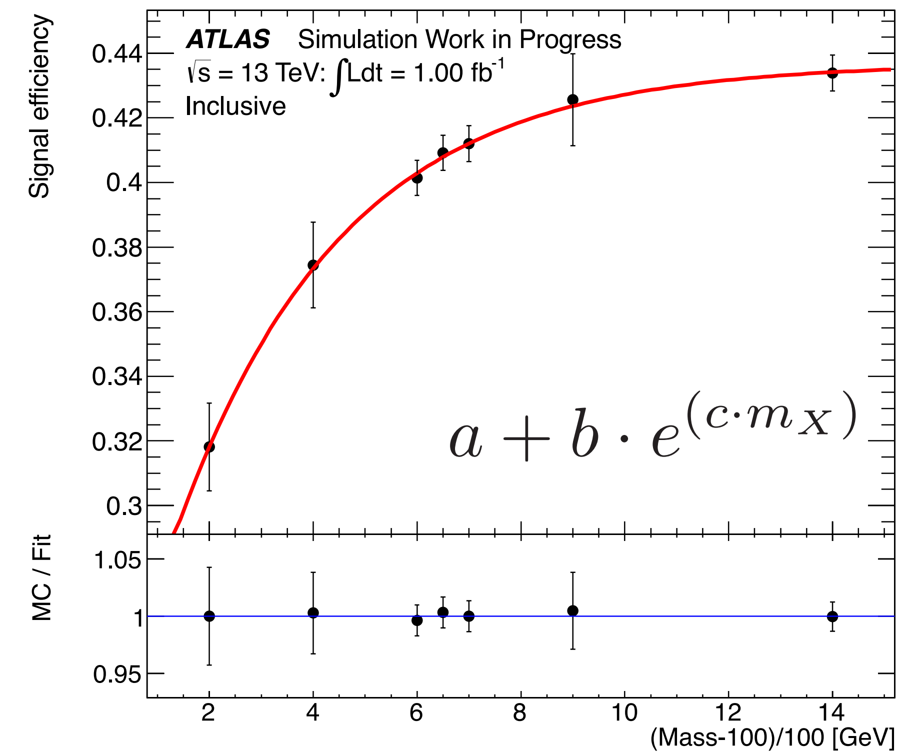
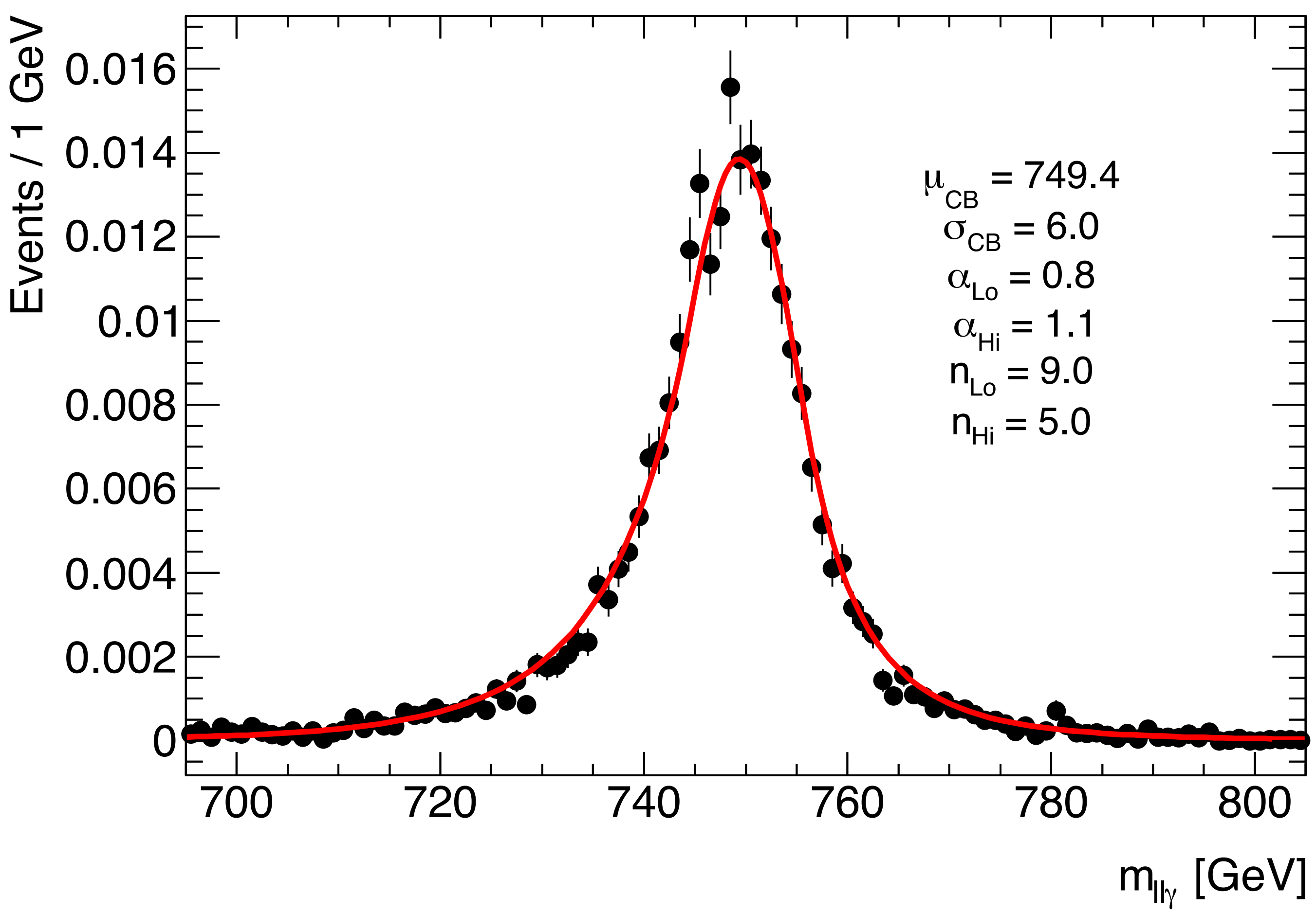
  - All parameters vary as a function of mass points
- Signal efficiency described by an exponential function





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X	$(m_X - 100)/100$

X→Zγ: Background Modelling

- Background determined by fitting function directly to data
- Selected background model used in other searches:
  - multi-jet, photon+jet and diphoton
- Class of functions have form:

$$f_{k;d}(x;b,\{a_k\}) = (1-x^d)^b x^{\sum_{j=0}^{k} a_j \log(x)^j},$$

- where:

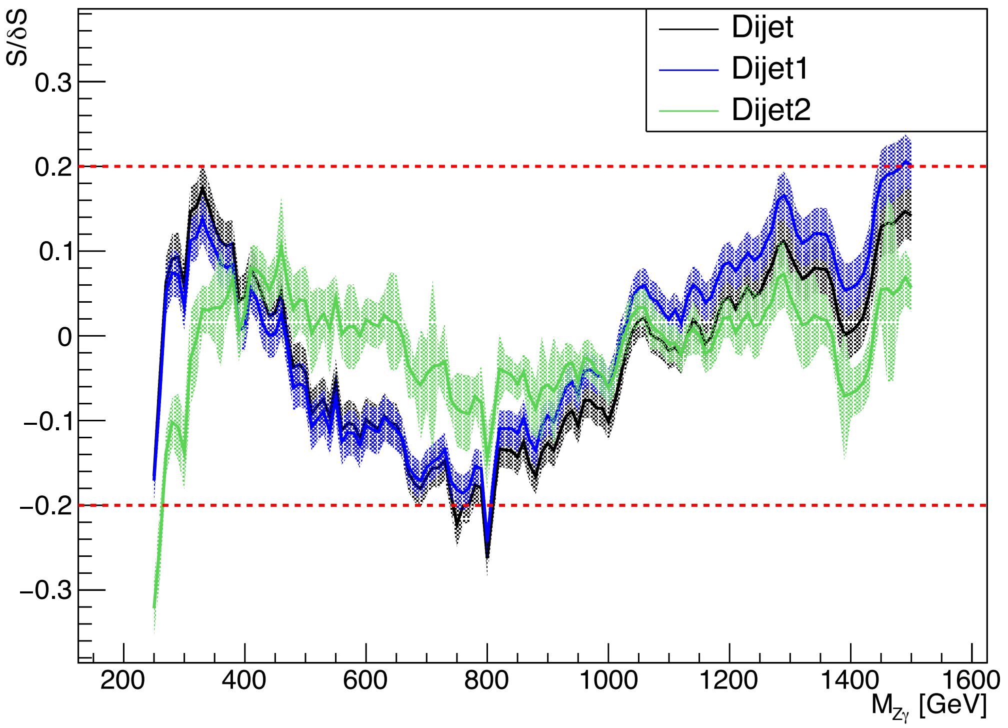
$$x = \frac{m_{\ell\ell\gamma}}{\sqrt{s}}$$

- F-Test:
  - Identify simplest model for which extra parameters do not significantly improve fit quality
- Spurious signal
  - Bias on signal yield from background model choice
  - Ratio of fitted signal yield to its uncertainty must be < 20%

- The simplest function is:

$$f_{k=0;d=1/3}(x;b,d,\{a_k\}) = (1-x^{1/3})^b x^{a_0}$$

- Spurious signal treated as systematic uncertainty
- Parameterised by the envelope of spurious signal at each mass point



X→Zγ: Background Modelling

- Background determined by fitting function directly to data
- Selected background model used in other searches:
  - multi-jet, photon+jet and diphoton
- Class of functions have form:

$$f_{k;d}(x;b,\{a_k\}) = (1-x^d)^b x^{\sum_{j=0}^{k} a_j \log(x)^j},$$

- where:

$$x = \frac{m_{\ell\ell\gamma}}{\sqrt{s}}$$

- F-Test:
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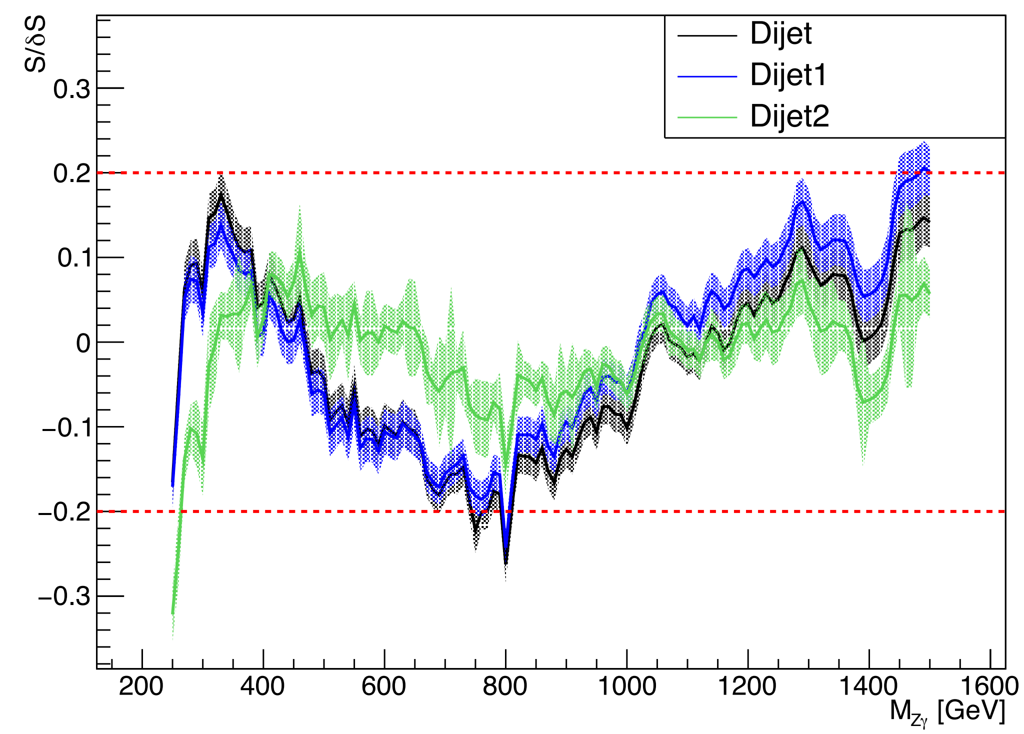
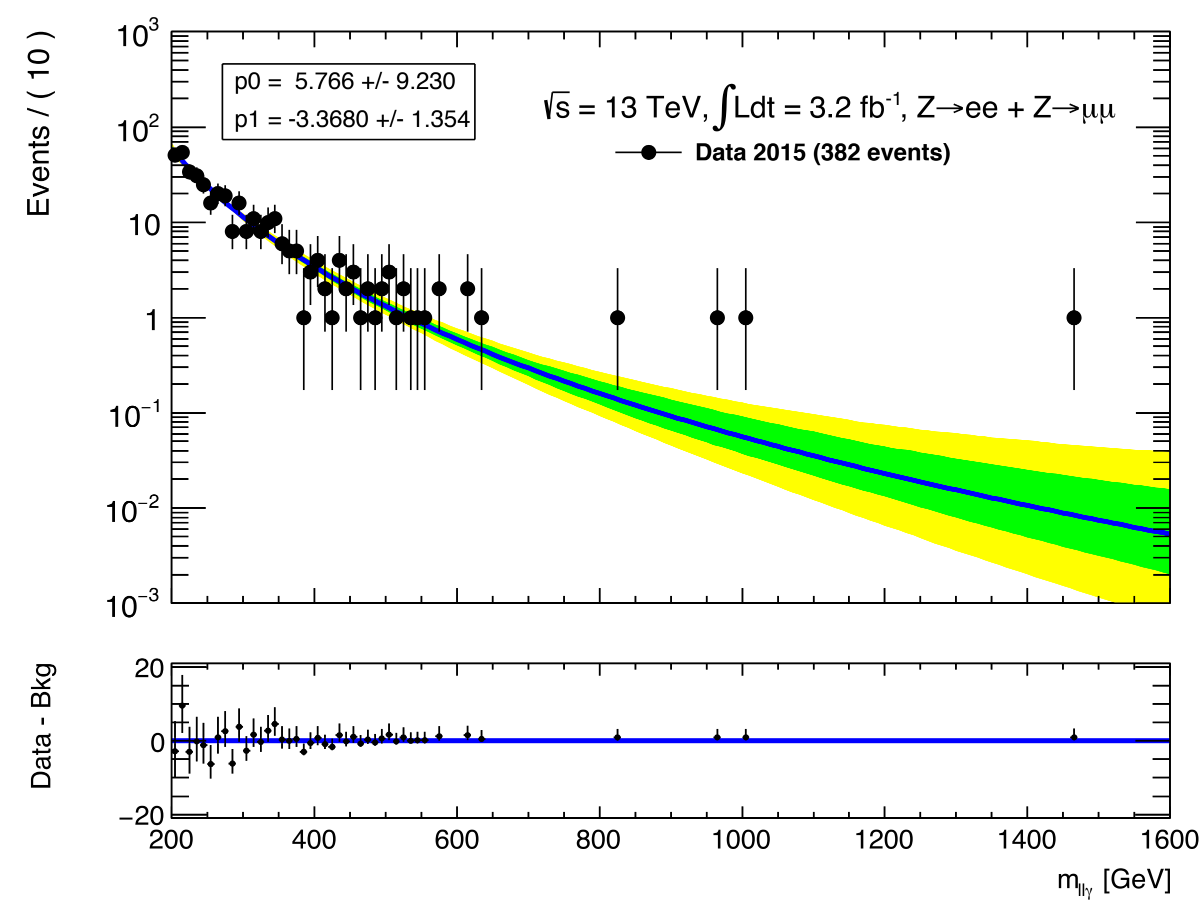
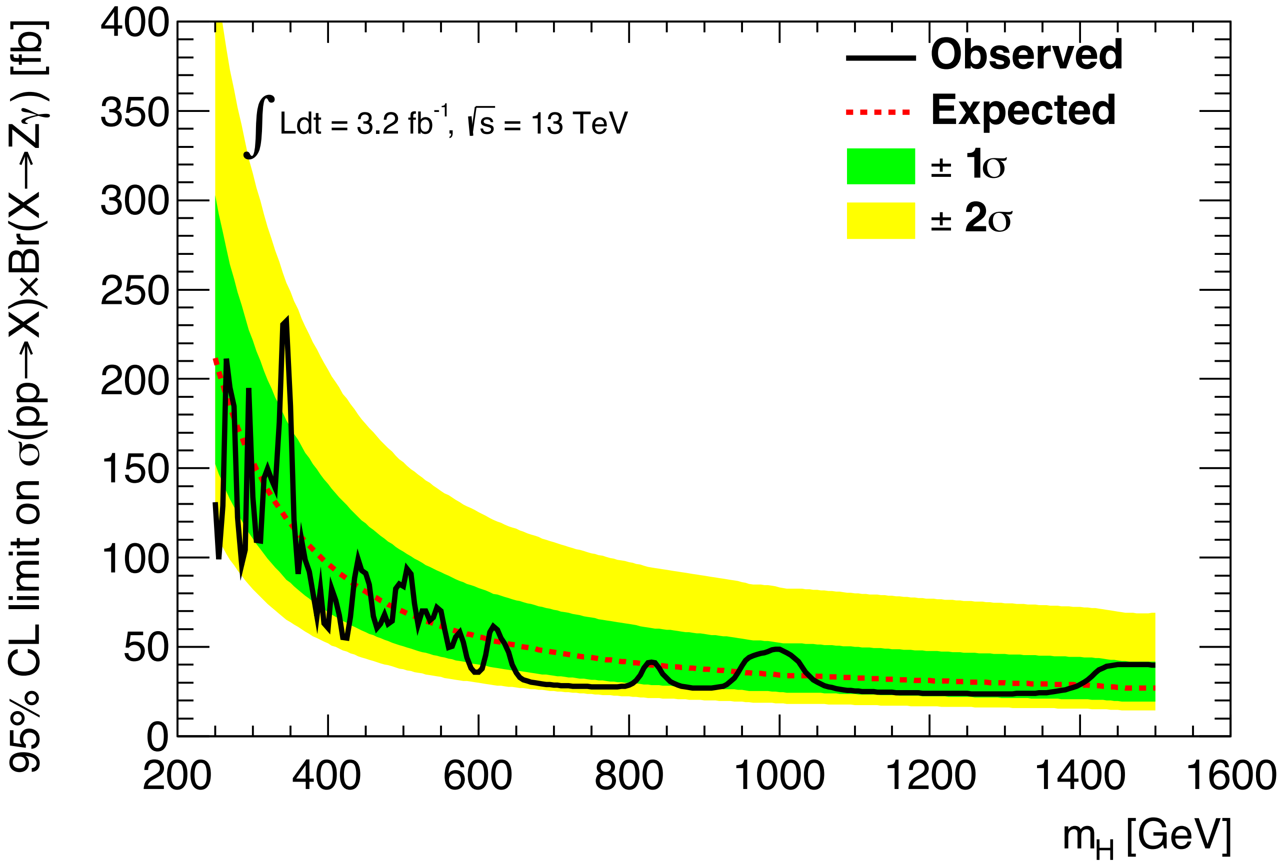
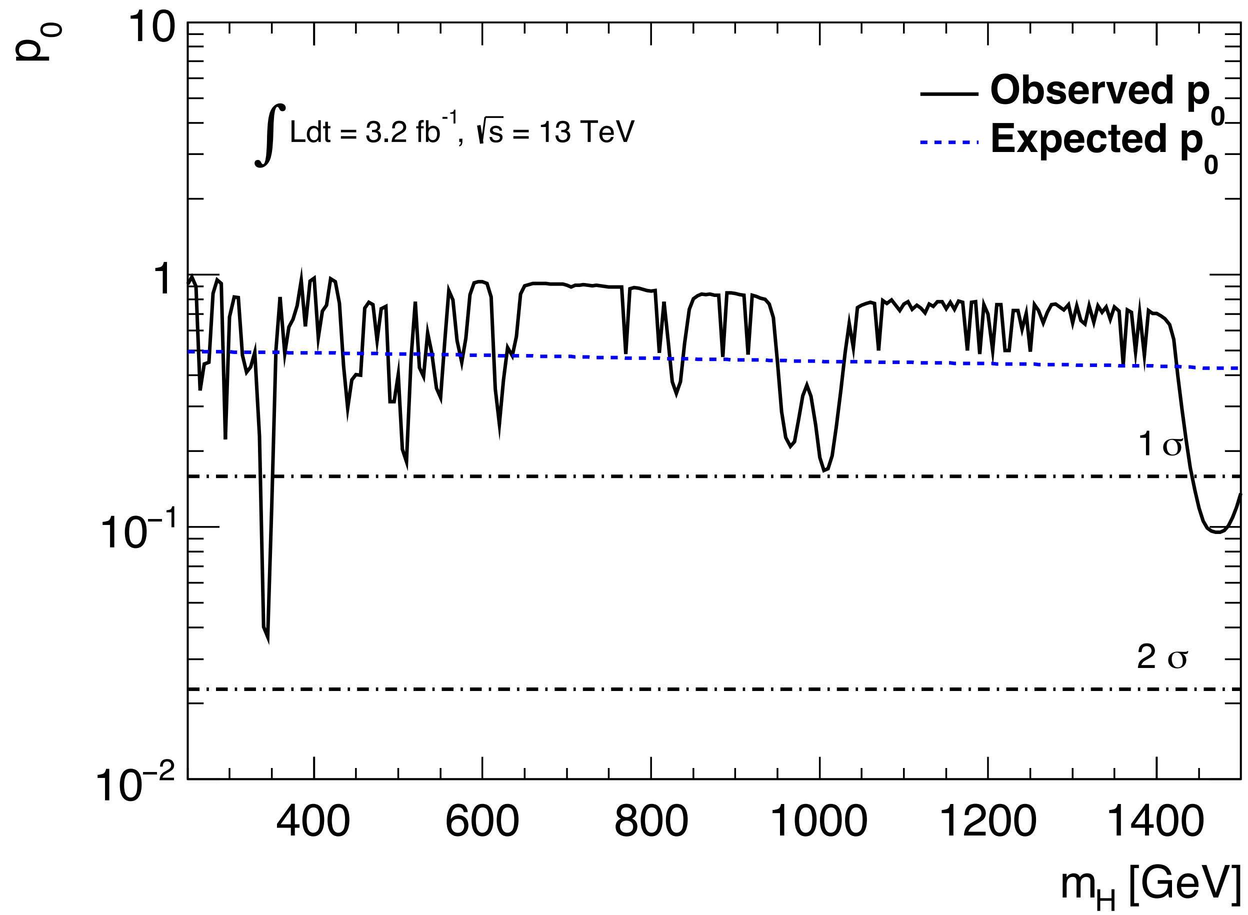




X→Zγ: Results

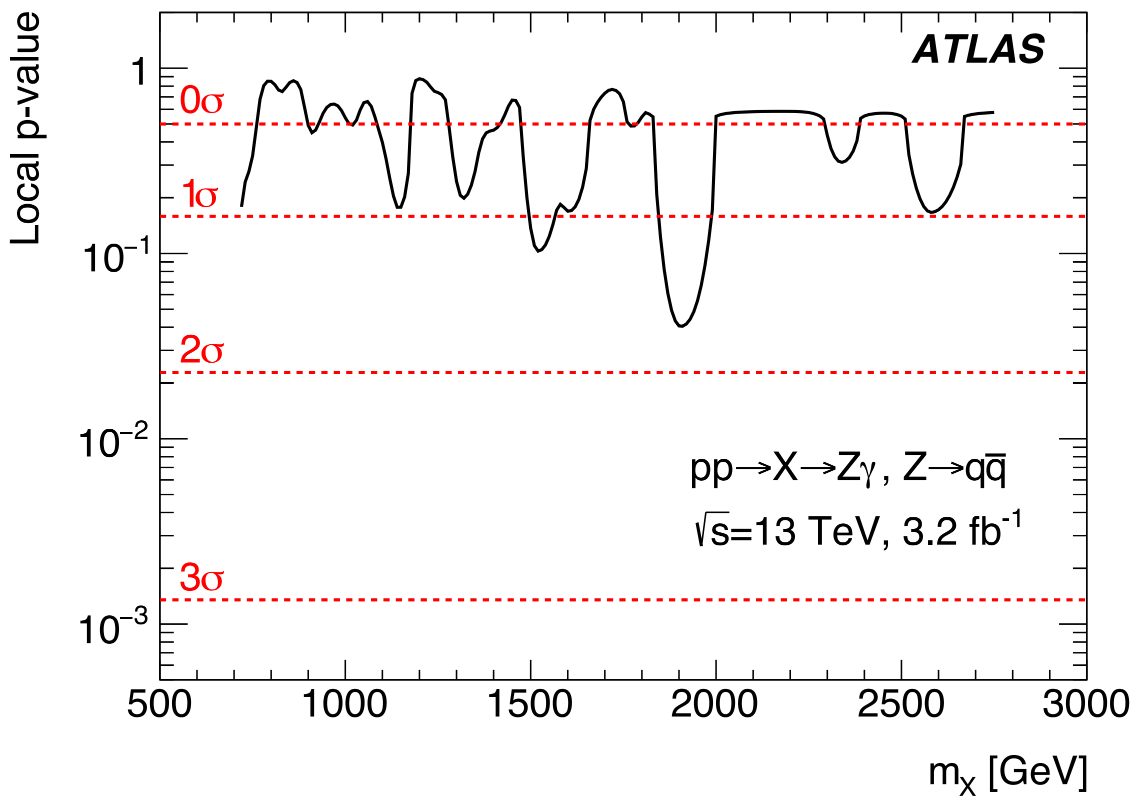
- Four candidate M(llγ) events with mass > 700 GeV
- Limits set on production cross-section (pp→X) x branching ratio (X→Zγ)
  - Expected limits range from 24.3 fb to 230 fb
  - Observed Limits range from 22.9 fb to 296 fb
  - Largest deviation from background-only hypothesis is ~2σ at ~350 GeV
- Analysis is dominated by statistical uncertainties
- Largest systematic uncertainty is on luminosity (±5%)

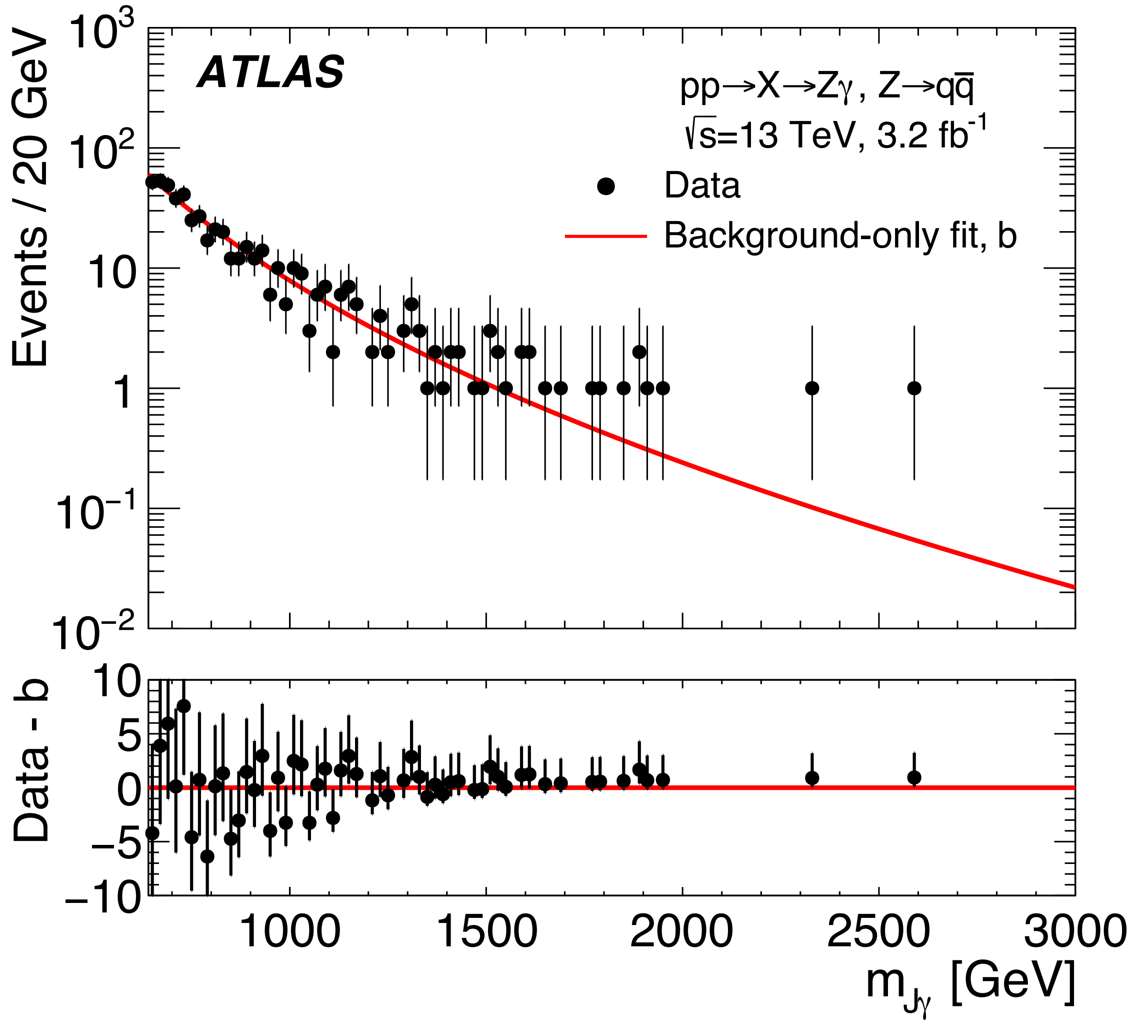


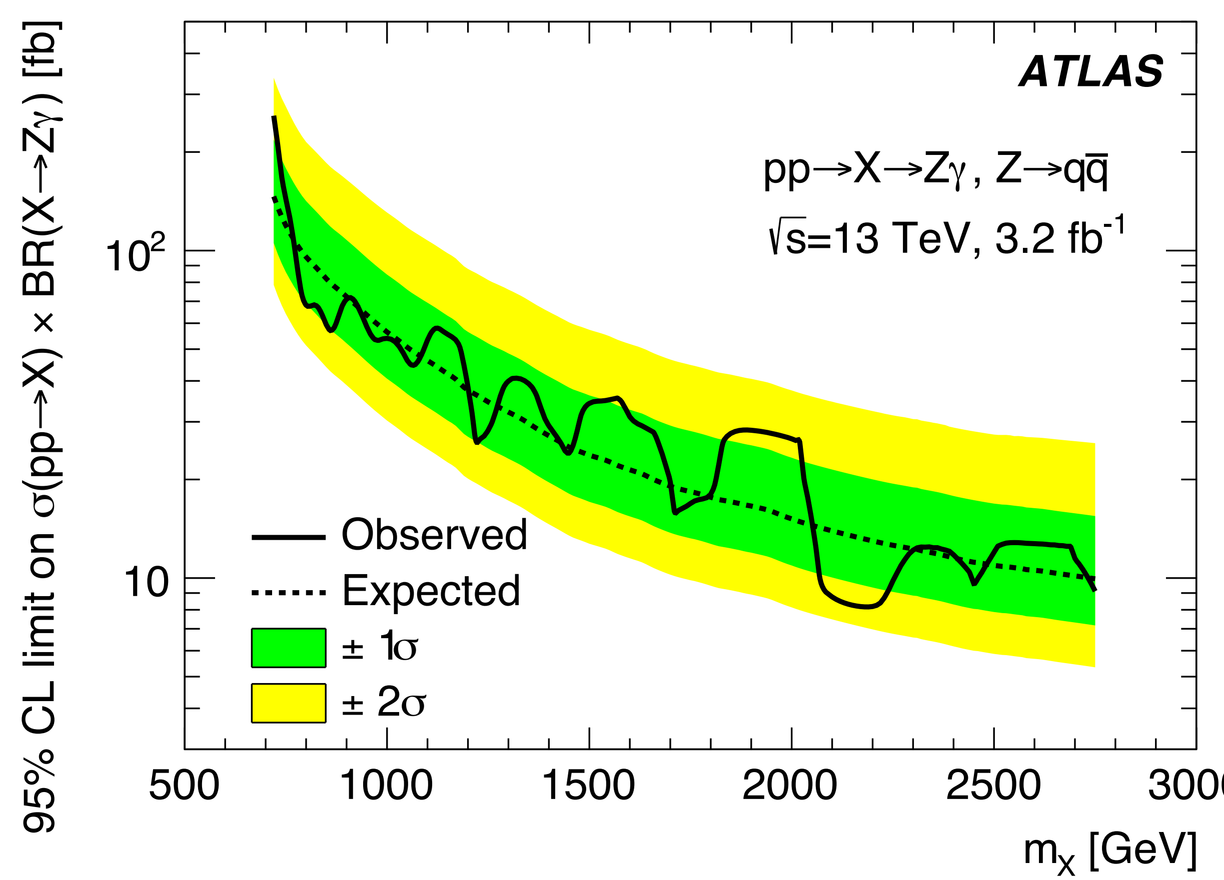


X→Zγ: Hadronic Z Decays

- Search looks for X→Zγ, Z→$q\bar{q}$
- Search performed using 3.2fb^{-1} of 13 TeV data
  - Published in PLB
- Boosted quark pair merge into single large radius jet
- Largest excess is 1.8σ for m_X = 1.9 TeV

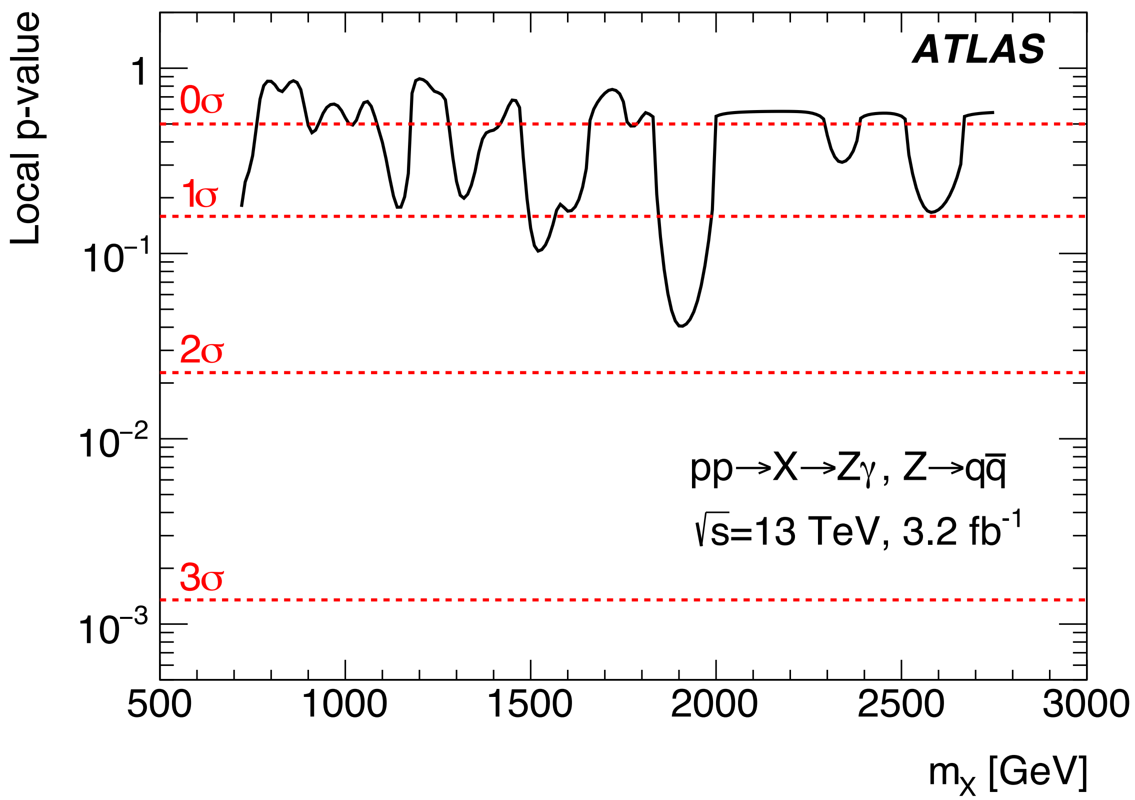


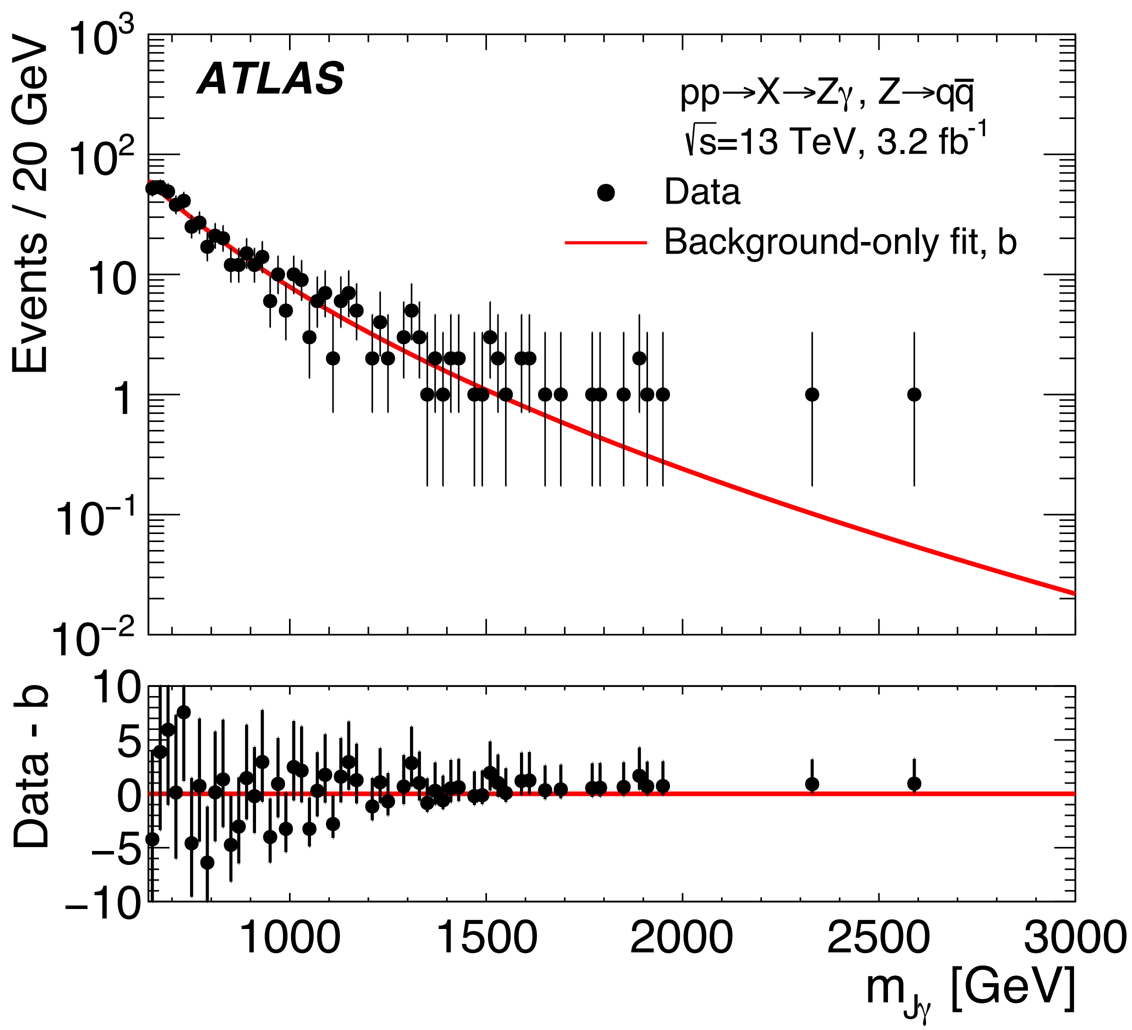


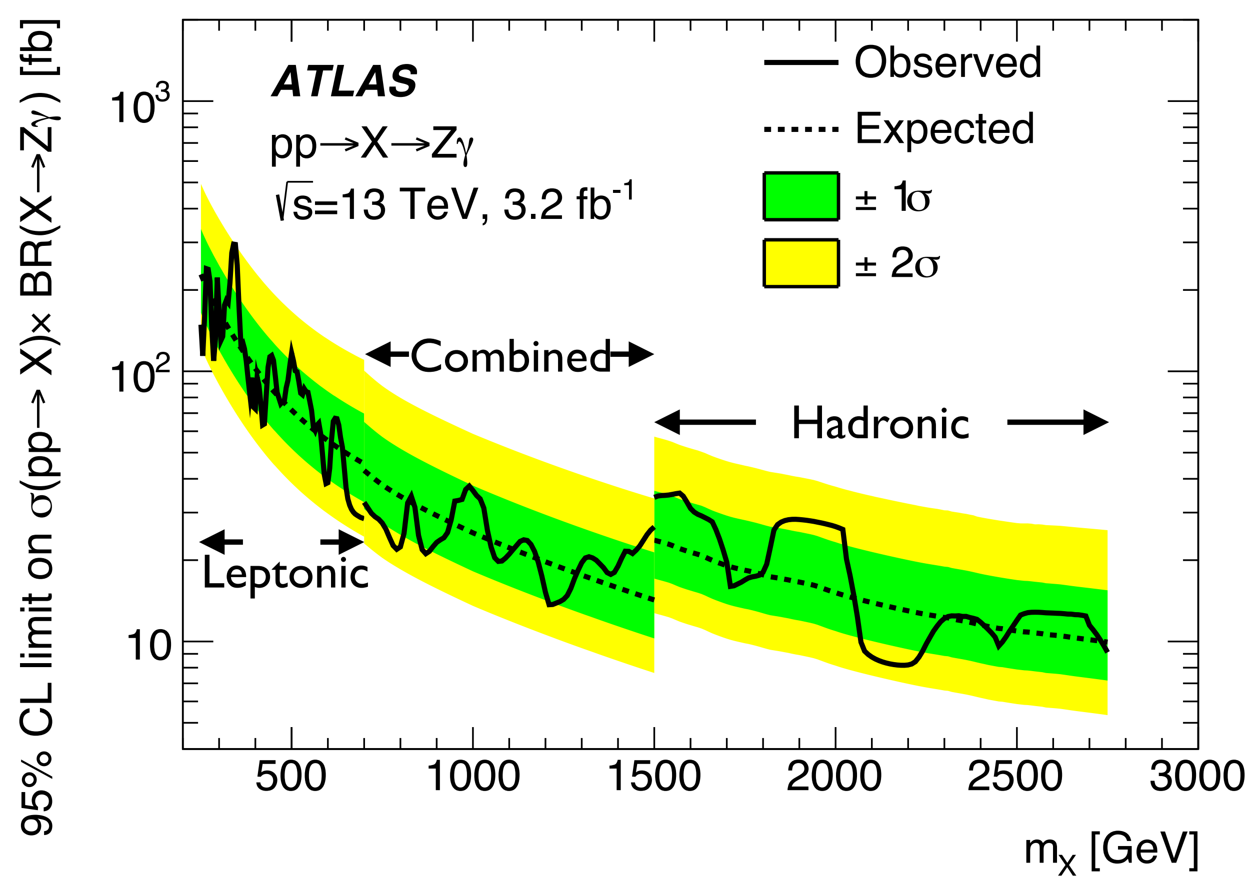


$X \rightarrow Z\gamma$: Hadronic Z Decays

- Search looks for $X \rightarrow Z\gamma$, $Z \rightarrow q\bar{q}$
- Search performed using 3.2fb^{-1} of 13 TeV data
  - Published in PLB
- Boosted quark pair merge into single large radius jet
- Largest excess is 1.8σ for m_X = 1.9 TeV
- Hadronic analysis better than leptonic for m_X>1.5TeV
  - Boosted jets merge into single large radius jet
  - More statistics in this region







After the PhD…

- Search for $X \rightarrow Z\gamma$ was refined using additional 13 TeV data recorded in 2016
  - Search using 13.3 fb^{-1} of 13 TeV data presented at ICHEP 2016
  - Diphoton excess at 750 GeV had disappeared
  - $X \rightarrow Z\gamma$ found no significant excesses

- Results supplanted by a new paper (currently being submitted to JHEP)
- Analysis utilises 33.1 fb^{-1} of 13 TeV data
- Paper features:
  - Updated search for $X \rightarrow Z\gamma$, $Z \rightarrow ll$ decays
  - First look at $H \rightarrow Z\gamma$, $Z \rightarrow ll$ in 13 TeV data

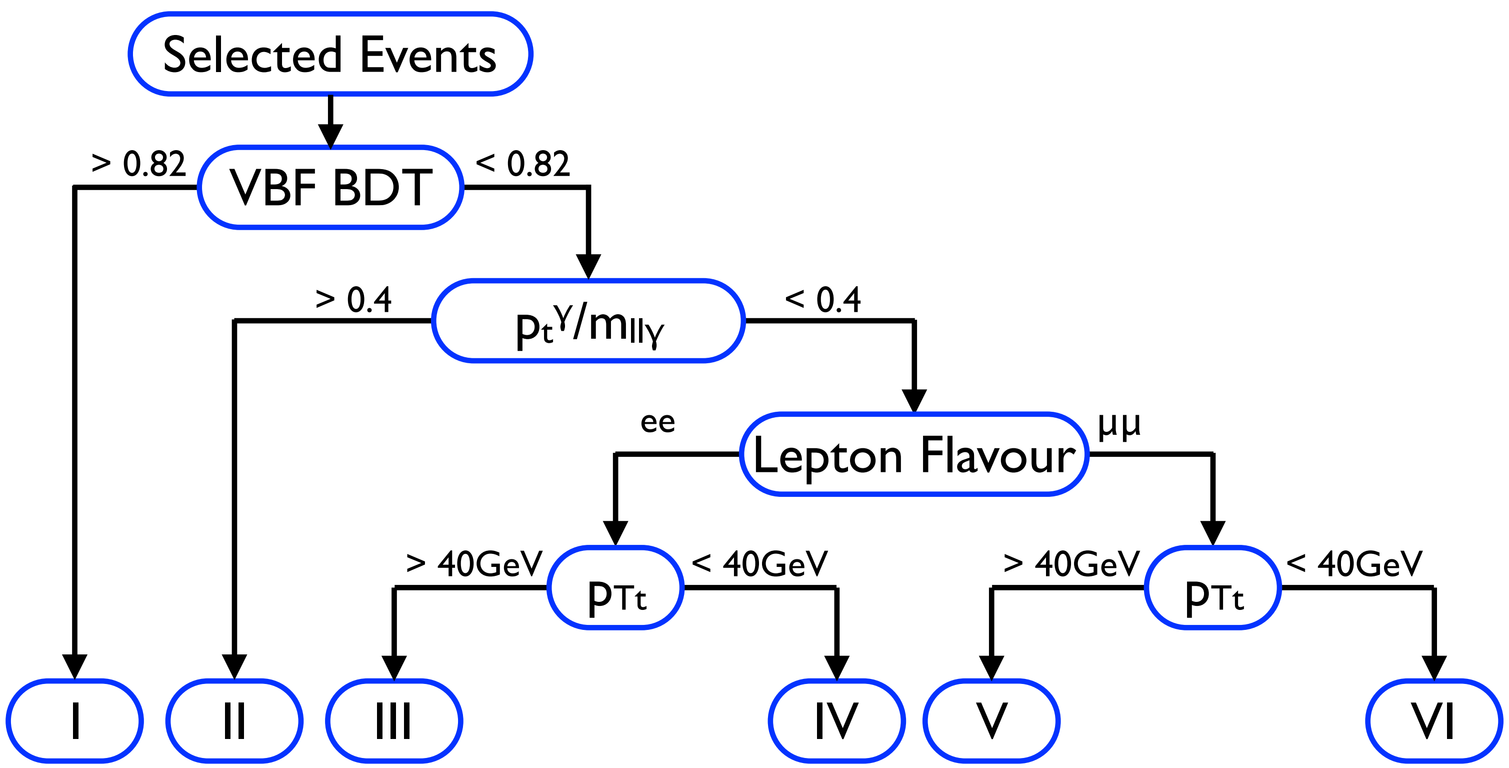
Low Mass Search: Improvements on Run I

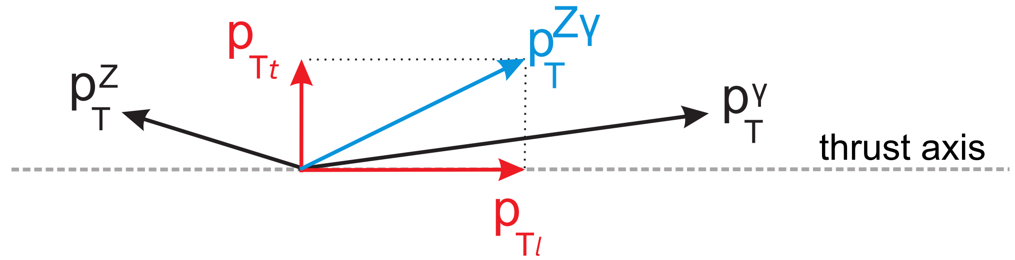
- Search for Standard Model Higgs boson
- Event categorisation re-optimised for higher statistics
- Categories based on p_{Tt} were used in Run I
  - Cuts reoptimised for new data set

- New category for $p_t^{\gamma}/m_{ll\gamma}$
  - Introduced for high mass search
  - Variable stable over wide range of $m_{ll\gamma}$ values

- Optimal cuts identified from 2D scan of variables
  - $p_t^{\gamma}/m_{ll\gamma} = 0.4$, $p_{Tt} = 40$ GeV

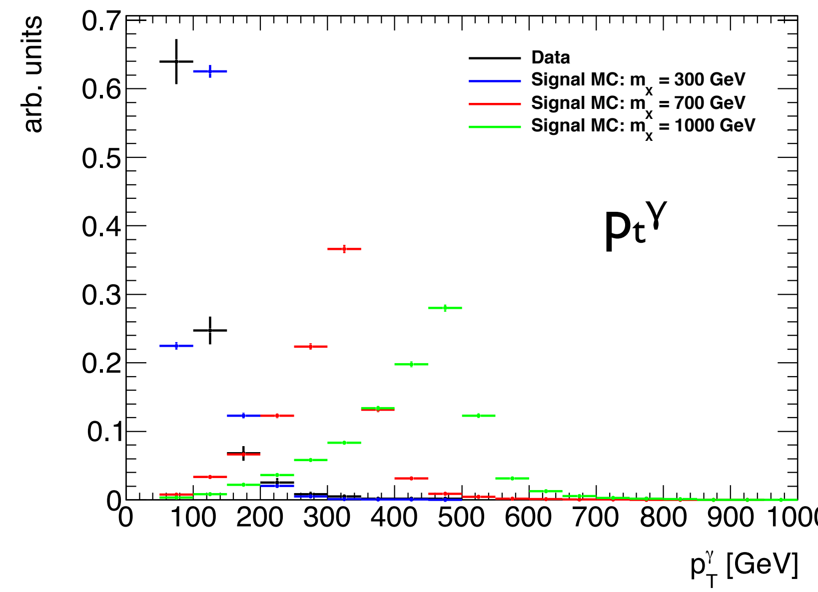
- New category gives 14% boost in sensitivity

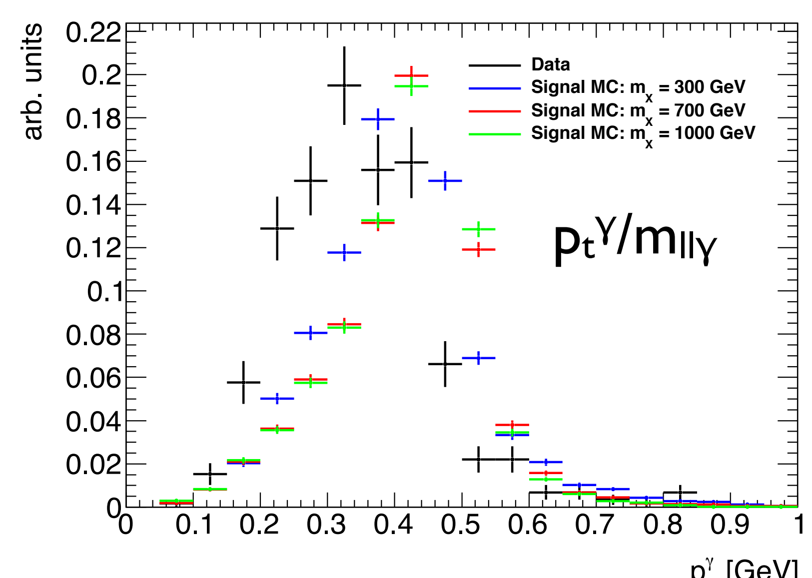




Higgs p_{Tt} is component of $m_{Z\gamma}$ momentum orthogonal to difference between Z and γ momenta

$$p_{\mathrm{Tt}} = 2\frac{|p_x^Z p_y^{\gamma} - p_x^{\gamma} p_y^Z|}{p_{\mathrm{t}}^{Z-\gamma}}$$

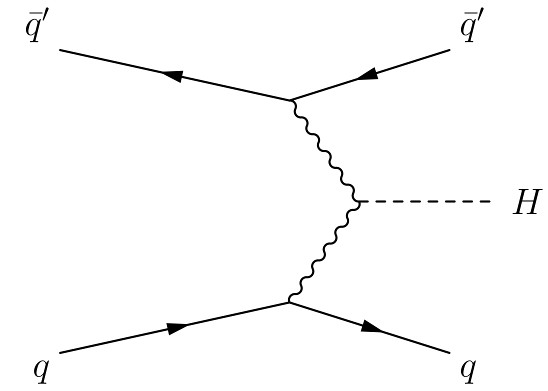




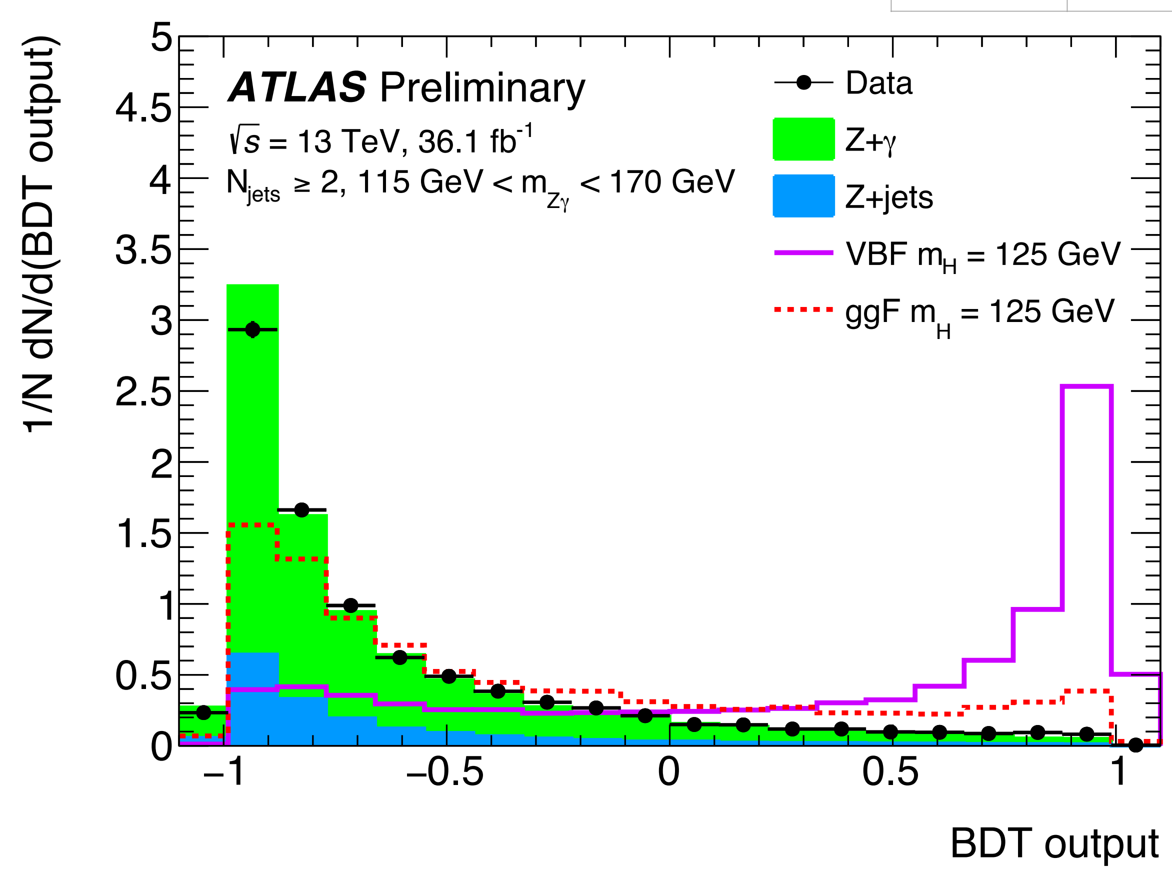
Low Mass Search: New VBF Category

- VBF category not possible using Run I data
- VBF production characterised by two forward jets
  - Large di-jet invariant mass,
  - High η separation of jets
- Main background
  - Zγ pair production with at least two jets
  - Single Z events with at least three jets and one fake photon

- Boosted decision tree combines six correlated variables
- Significance maximum for BDT response > 0.82
- Category increases sensitivity by 7.7%

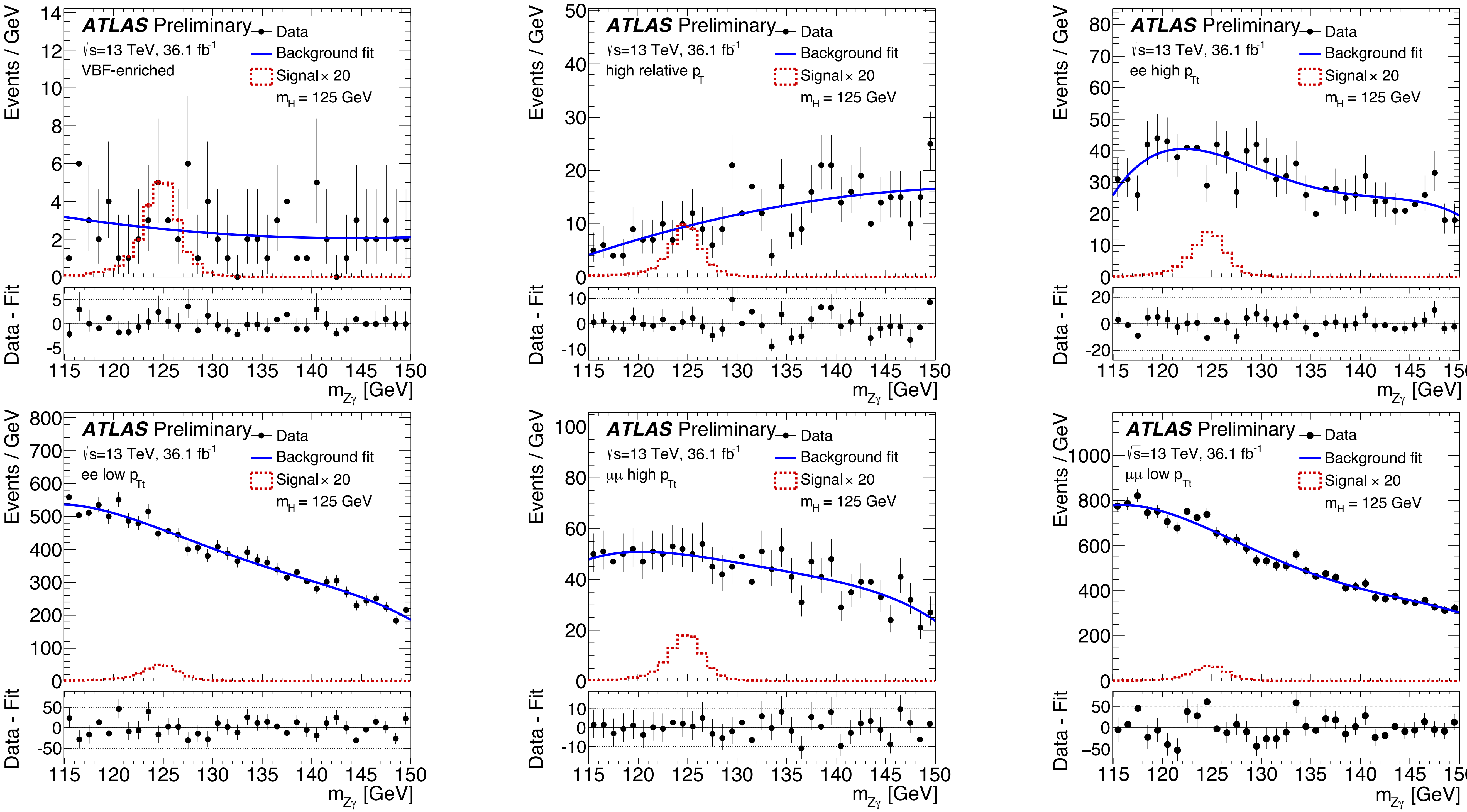


Variables	Mass Dependence
m_{jj}	Invariant mass of diet
$\Delta\eta_{jj}$	Pseudo-rapidty separation of diet
$\Delta\phi_{Z\gamma,jj}$	Azimuthal angle between Zγ and diet system
P_{Tt}	Zγ P_t projected perpendicular to Zγ thrust axis
$\Delta R_{\gamma \text{ or } Z,\, j}$	Minimum ΔR between one object of the Zγ and the corresponding leading jets
$\eta^{Zeppenfield}$	$\lvert\eta_{Z\gamma} - 0.5(\eta_{j1} + \eta_{j2})\rvert$



Low Mass Search: Signal and Background Modelling

- All signal samples modelled using a double-sided Crystal Ball function
- Test performed to identify background model with minimum “spurious signal”
  - Ratio of fitted signal yield to its uncertainty must be < 45%
- Background in each category modelled as Bernstein 2nd- or 4th- order polynomial

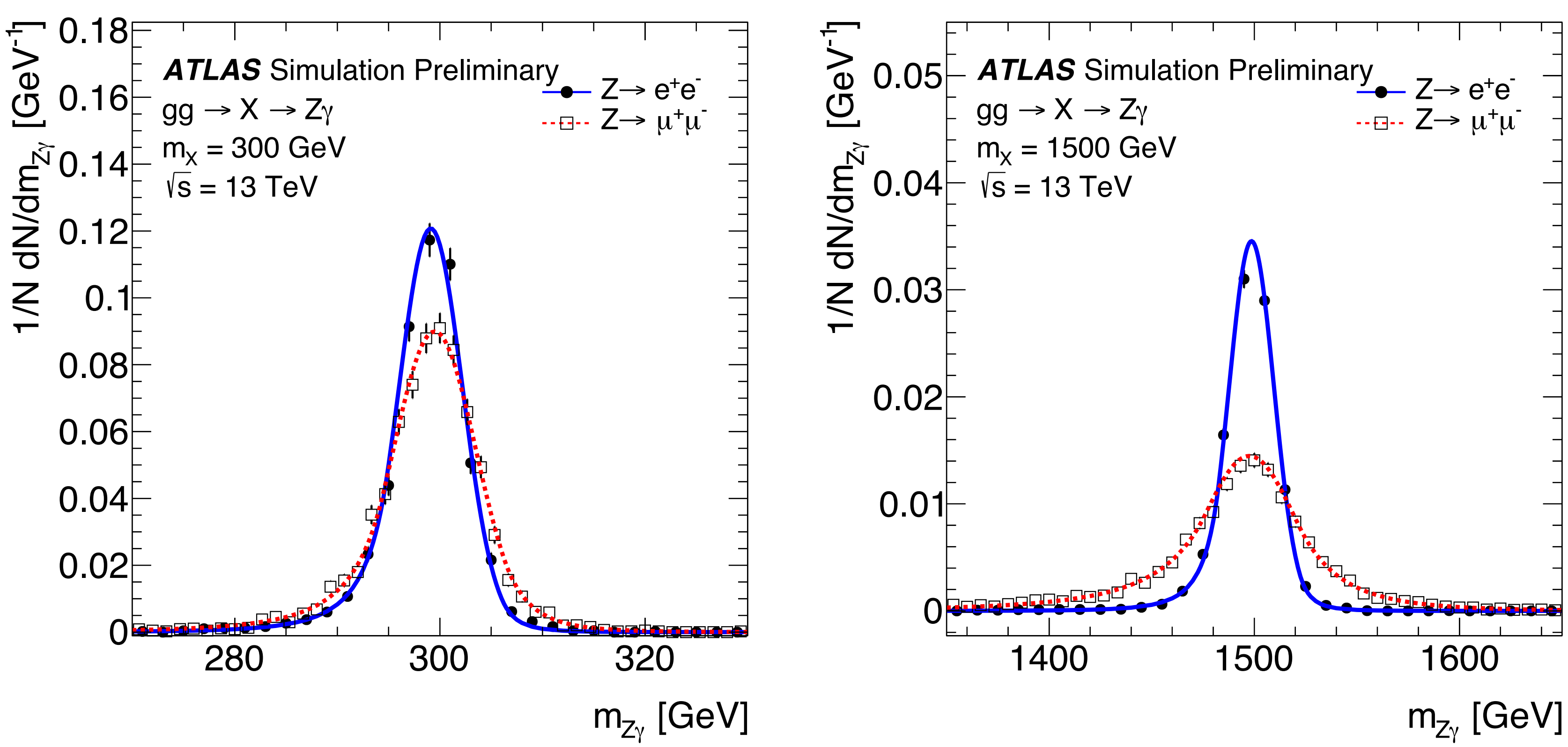


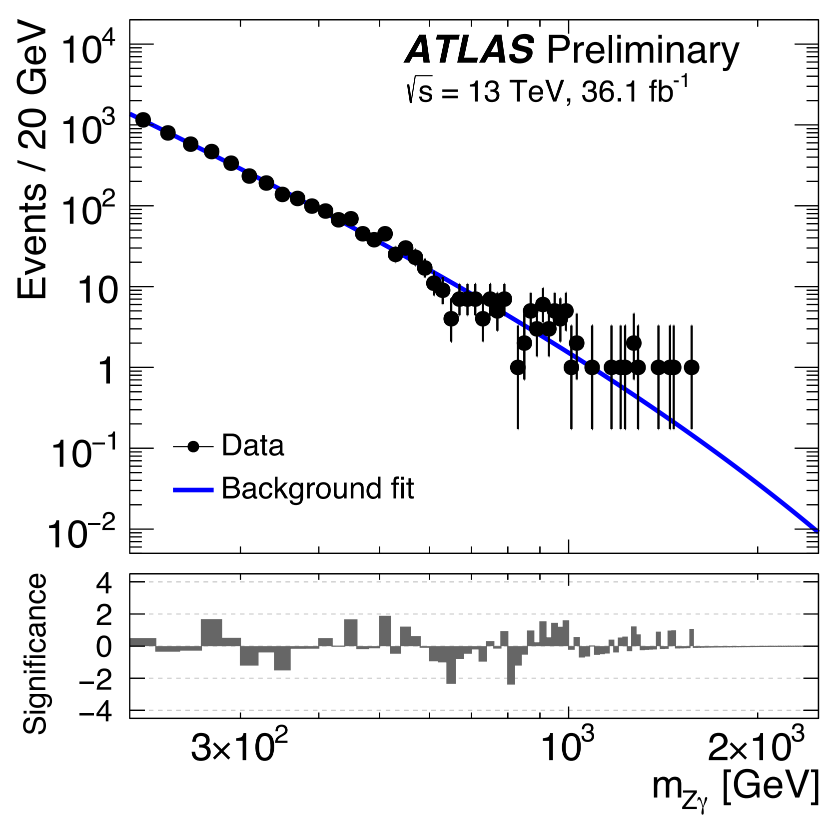
High Mass Search: Signal and Background Modelling

- All signal samples modelled using a double-sided Crystal Ball function
  - Samples generated for CP-even Spin-0 and Spin-2 resonances produced via ggF and VBF
- Background model unchanged from previous analysis
- One event category per final state
  - Exploits difference between eeγ and μμγ invariant mass resolutions

- Signal resolution varies from:
  - eeγ : 2.8 GeV (m_X = 200 GeV) to 16 GeV (m_X = 2.5 TeV)
  - μμγ : 3.1 GeV (m_X = 200 GeV) to 36 GeV (m_X = 2.5 TeV)
- Loss of precision in high-pT muon reconstruction

ICHEP 2016 analysis





Latest Results

- No significant excess at low mass
  - At mH = 125.09 GeV:
    - Expected limit at 95% CL = 5.2 x SM
    - Observed limit at 95% CL = 6.6 x SM
  - 55% gain in exclusion sensitivity over Run 1 result
  - 20% gain through analysis optimisations

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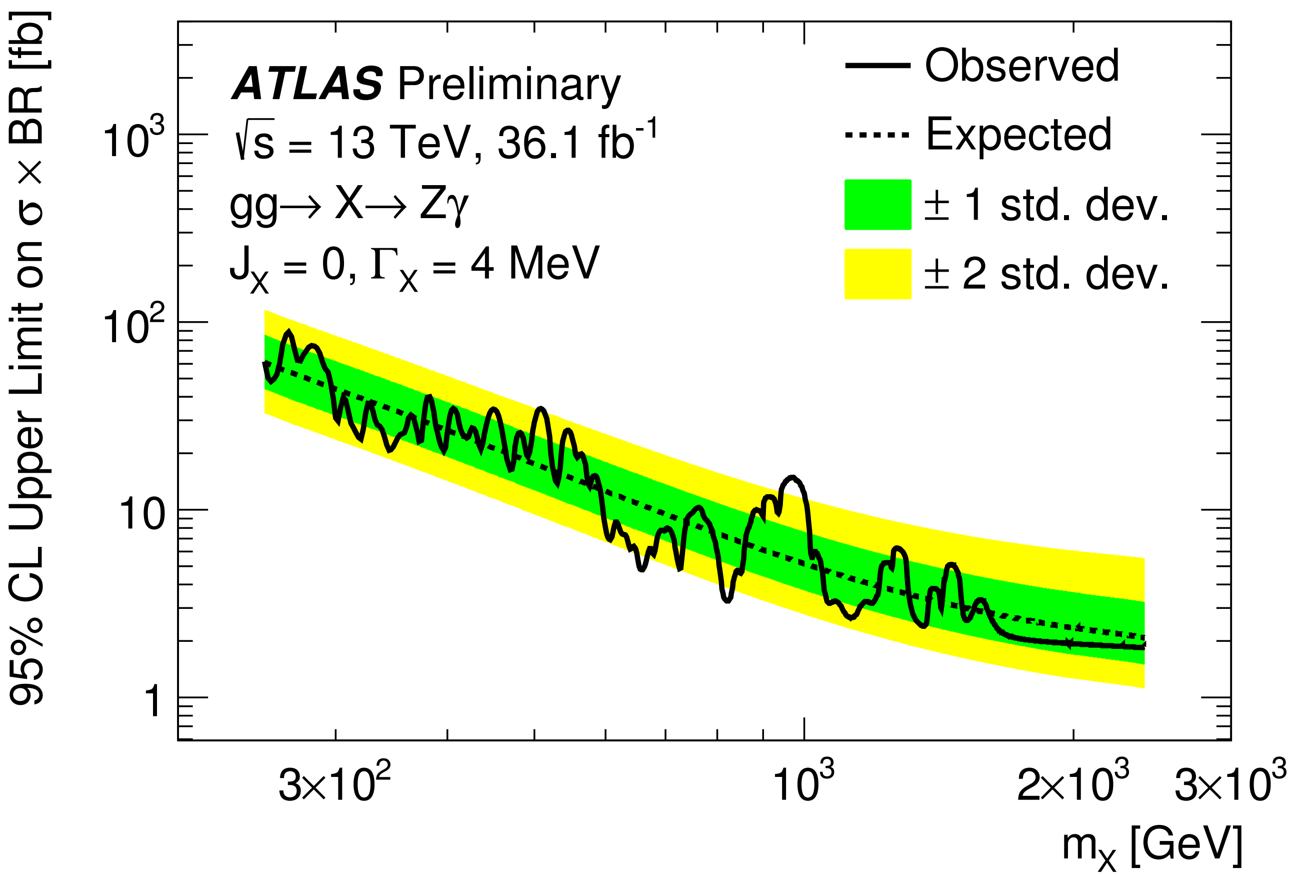
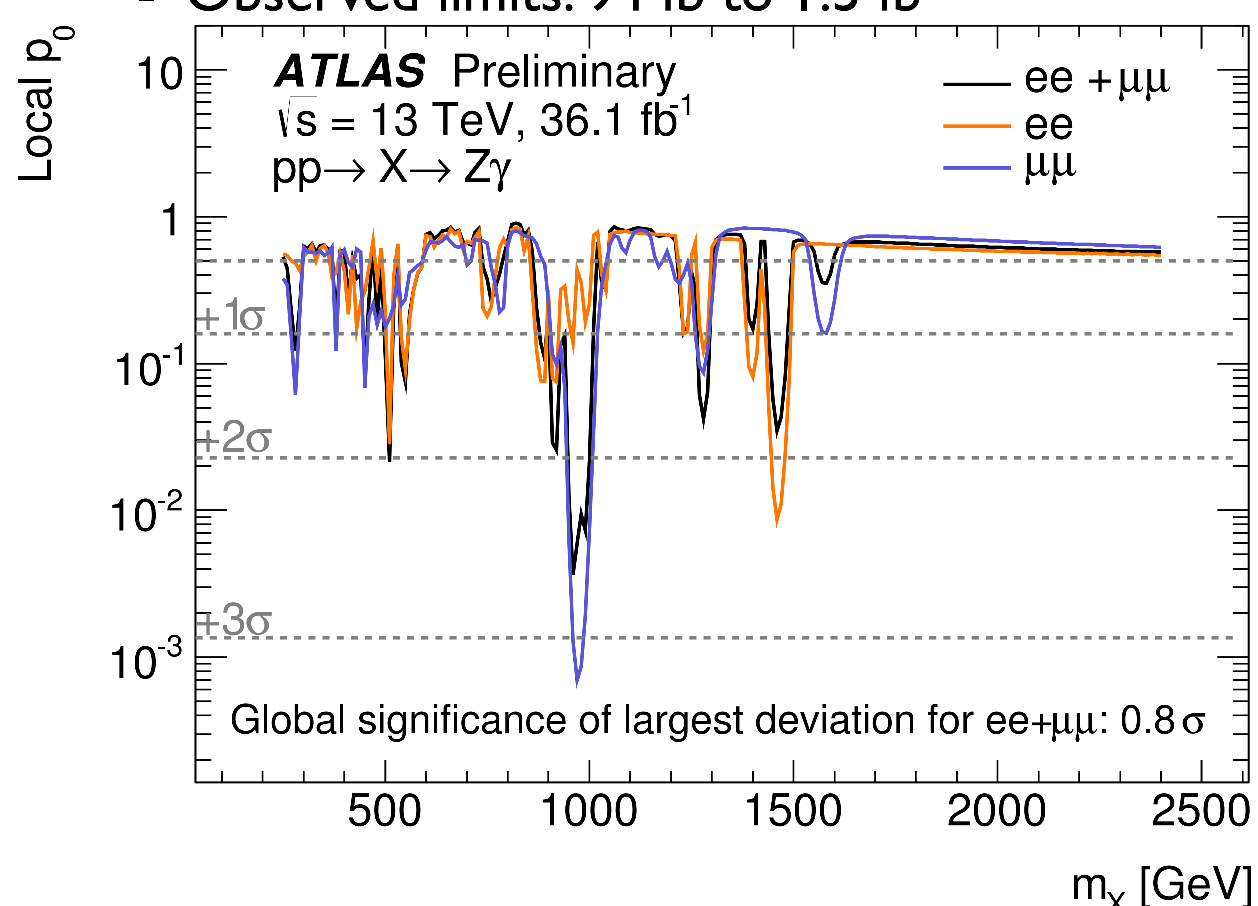
  - 55% gain in exclusion sensitivity over Run 1 result
  - 20% gain through analysis optimisations

- Largest $m_{ll\gamma}$ candidates found:
  - 1.47 TeV (eeγ)
  - 1.57 TeV ($\mu\mu\gamma$)
- No significant excess observed
- Limits set on $\sigma(pp\rightarrow X) \times BR(X\rightarrow Z\gamma)$ at 95% CL



Limits for Spin-0 hypothesis

- For Spin-0 resonance produced via ggF:
  - Over range m_X = 250 GeV to 2.4 TeV:
    - Expected limits: 61 fb to 2.1 fb
    - Observed limits: 88 fb to 1.8 fb
- For Spin-0 resonance produced via VBF:
  - Limits up to 4% lower
- Results also interpreted for Spin-2 resonance
  - For ggF, over range m_X = 250 GeV to 2.4 TeV:
    - Expected limits: 82 fb to 2.7 fb
    - Observed limits: 117 fb to 2.4 fb
  - For VBF, over range m_X = 250 GeV to 2.4 TeV:
    - Expected limits: 66 fb to 1.7 fb
    - Observed limits: 94 fb to 1.5 fb



Local p_0 for background-only hypothesis

The Future…

- ATLAS is getting closer to observing the Standard Model Higgs boson decaying to $Z\gamma$
- Old study on Run 2 prospects suggested that:
  - 300 fb^{-1} of 14 TeV data for expected limit of 2.53 x SM at 0.67σ
  - 3000 fb^{-1} of 14 TeV data for expected limit of 0.74 x SM at 2.12σ
  - Values are pessimistic!

- New analysis techniques can enhance the sensitivity, reducing the amount of data required
  - Z mass slices
  - Dedicated VBF category
  - $p_t^{\gamma}/m_{ll\gamma}$

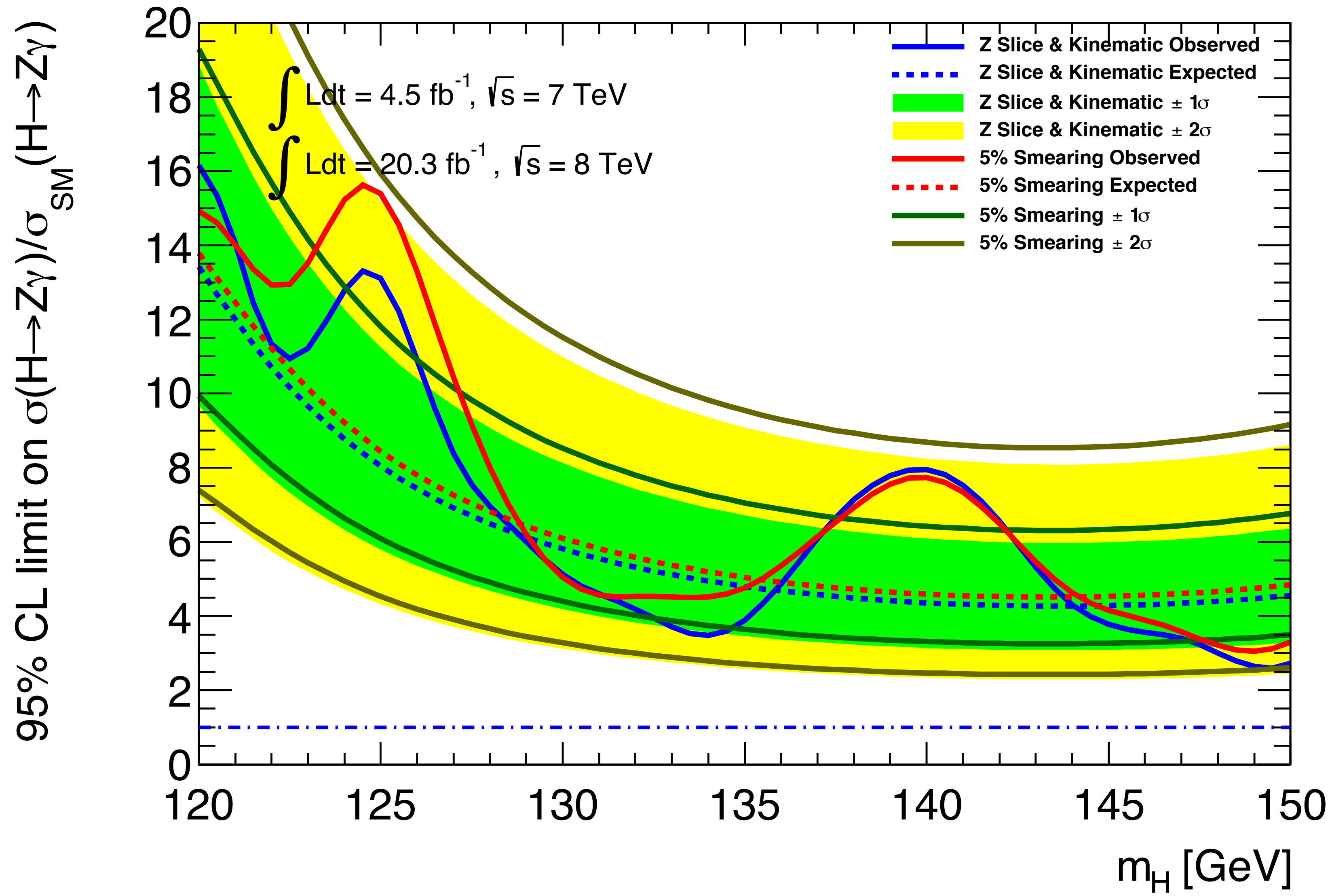
- The diphoton excess at 750 GeV disappeared with 2016 data
  - It remains important to search for new high mass particles
  - Discovery of any new resonance would be incredibly exciting!

Thank you for your attention

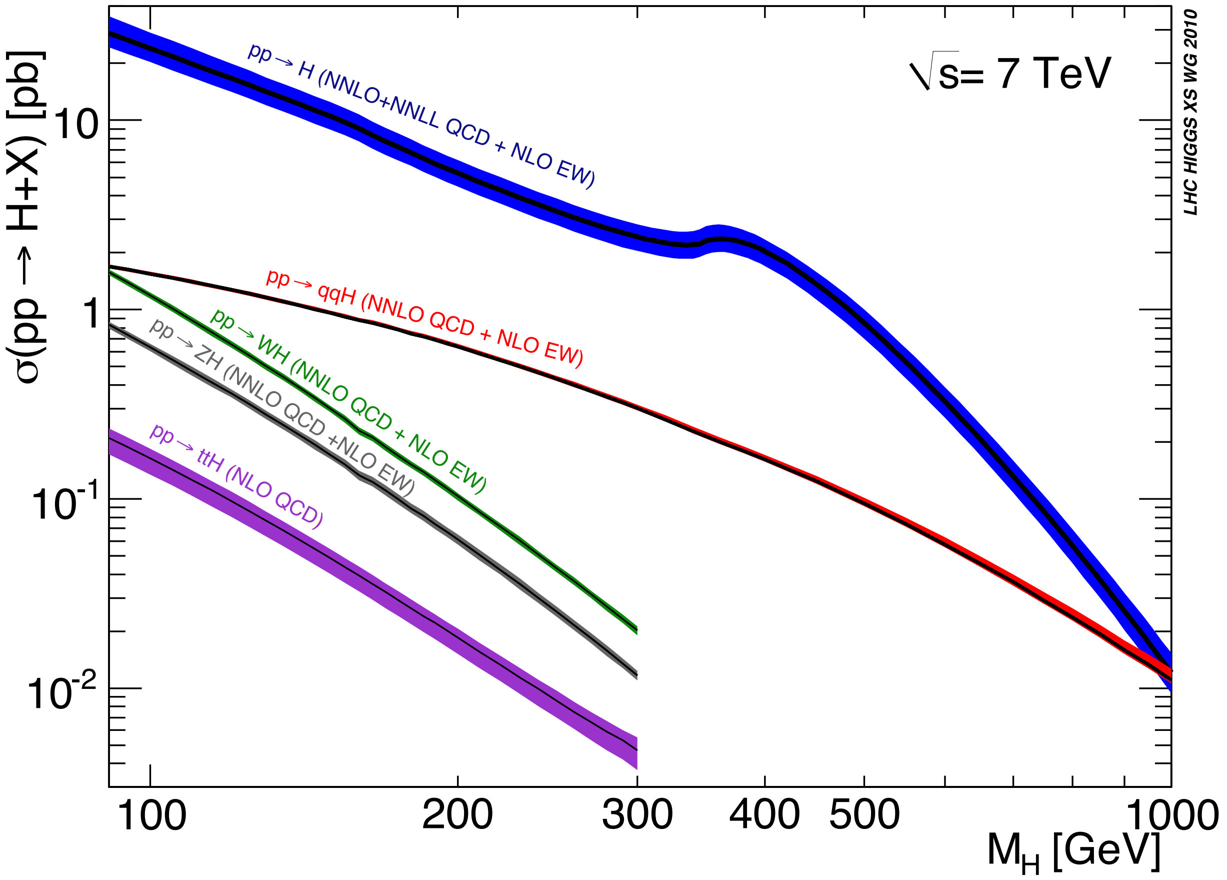
Backup

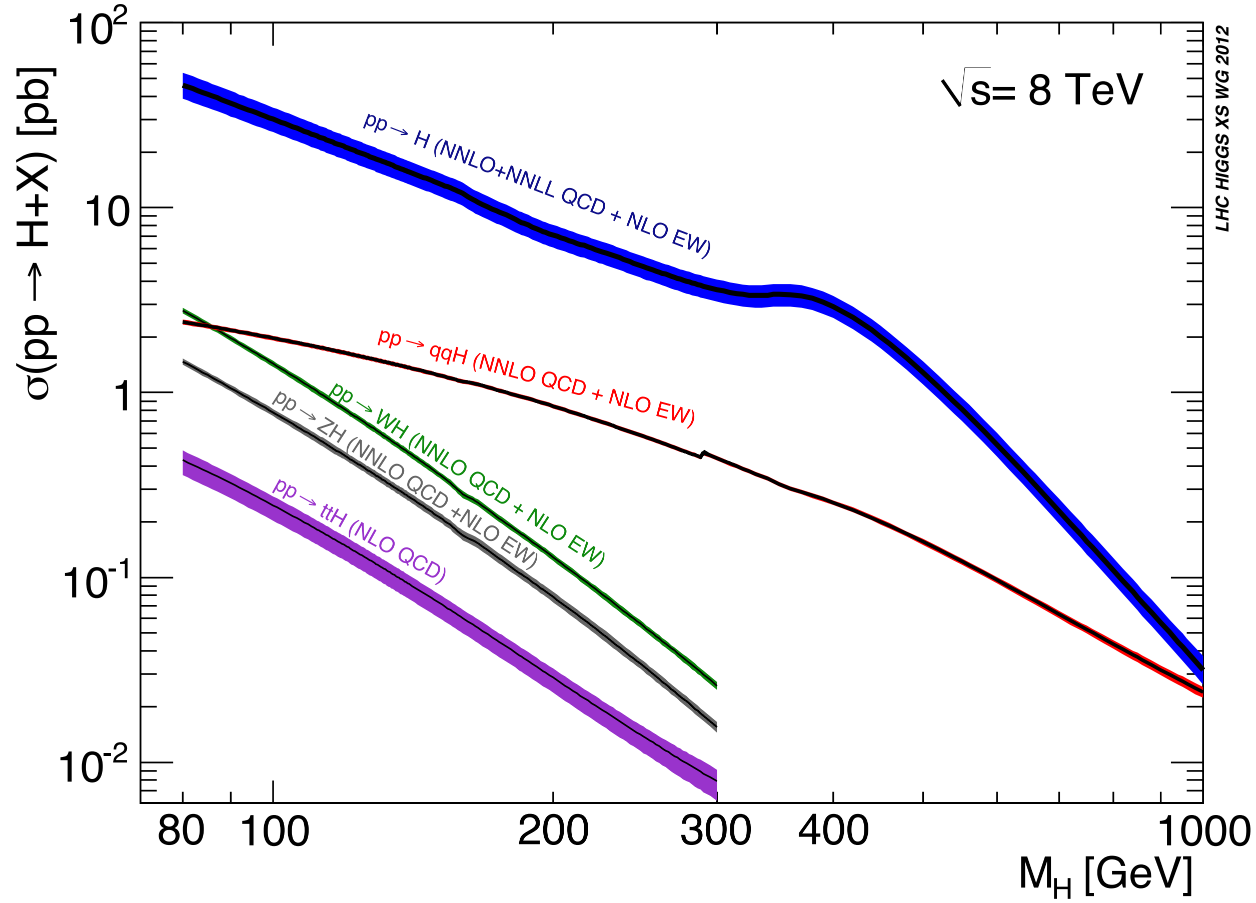
Z Mass Slices: Event Migration

- Events could be incorrectly assigned to a Z slice based on narrow width
- Kinematic analysis uses 5% systematic uncertainty on Mllg resolution.
- Reconstructed Z mass smeared by 5%
  - Z boson 4-vector reevaluated
  - Higgs boson recreated by combining Z candidate with original, unchanged photon
- Expected limit evaluated, shifts by 5%
  - Not a systematic uncertainty, but figure of merit for worst-case-scenario

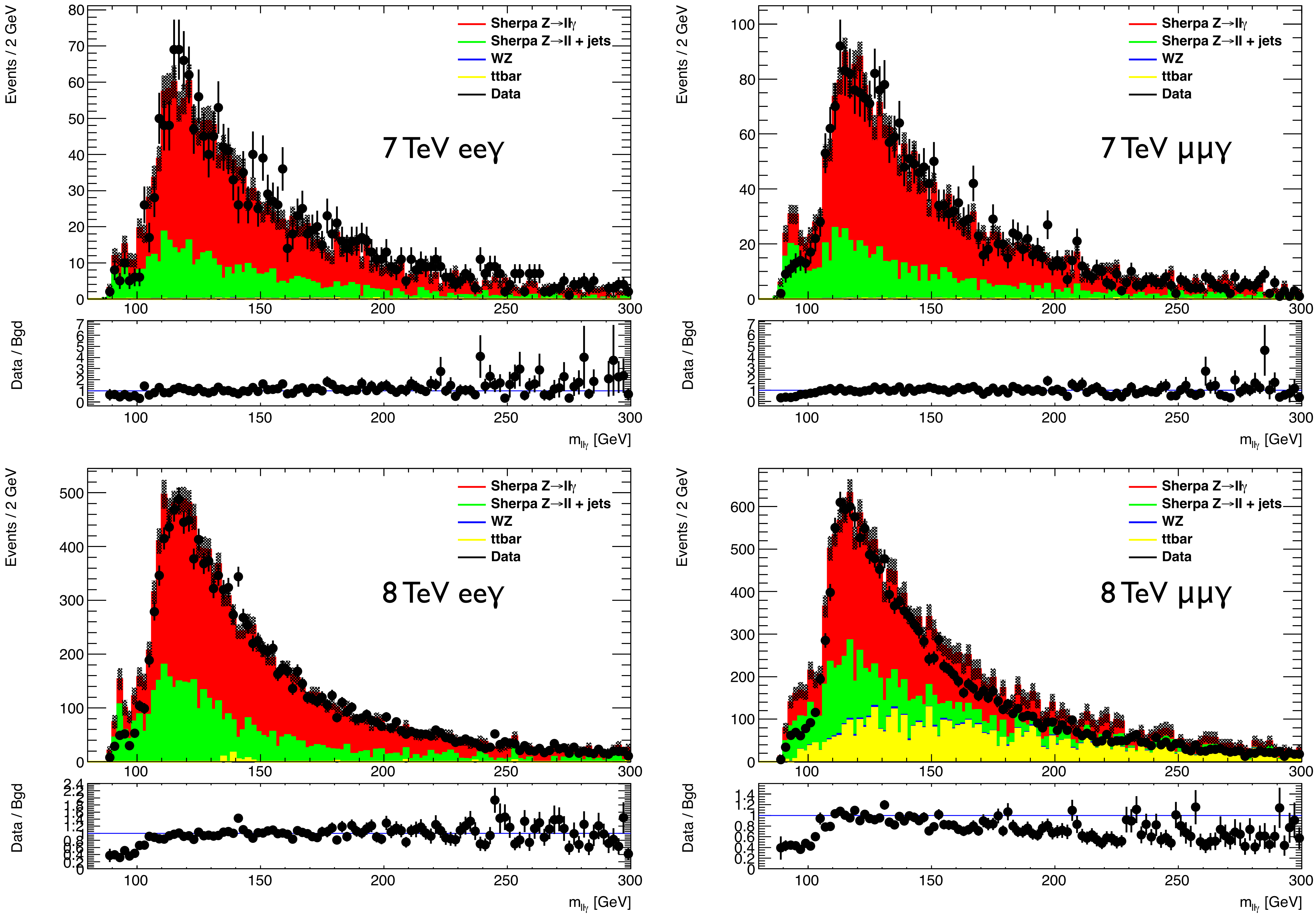


Higgs production cross-section vs mass

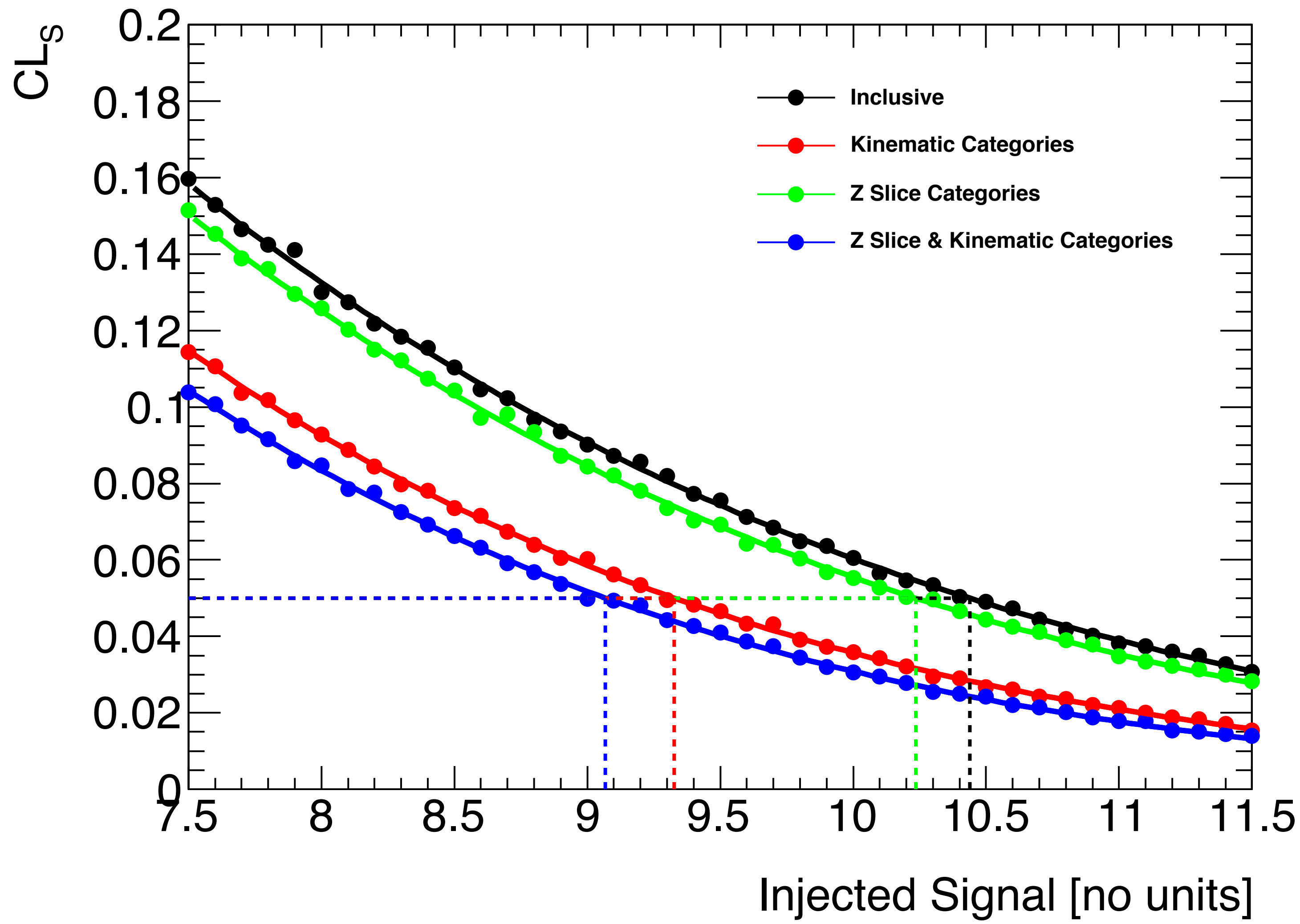




SM Higgs: Run 1 Background Composition

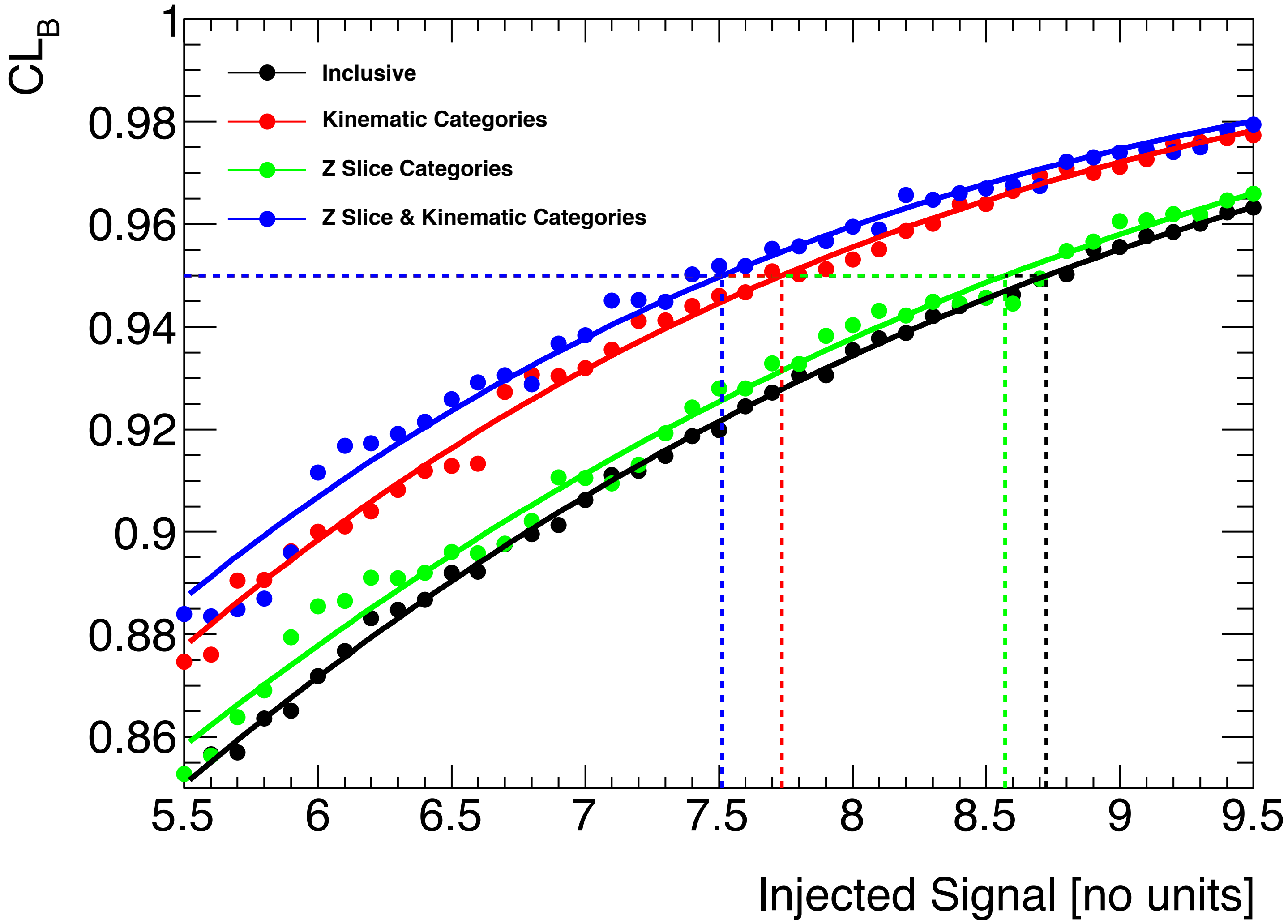


Z Slices: Proof of Concept 1



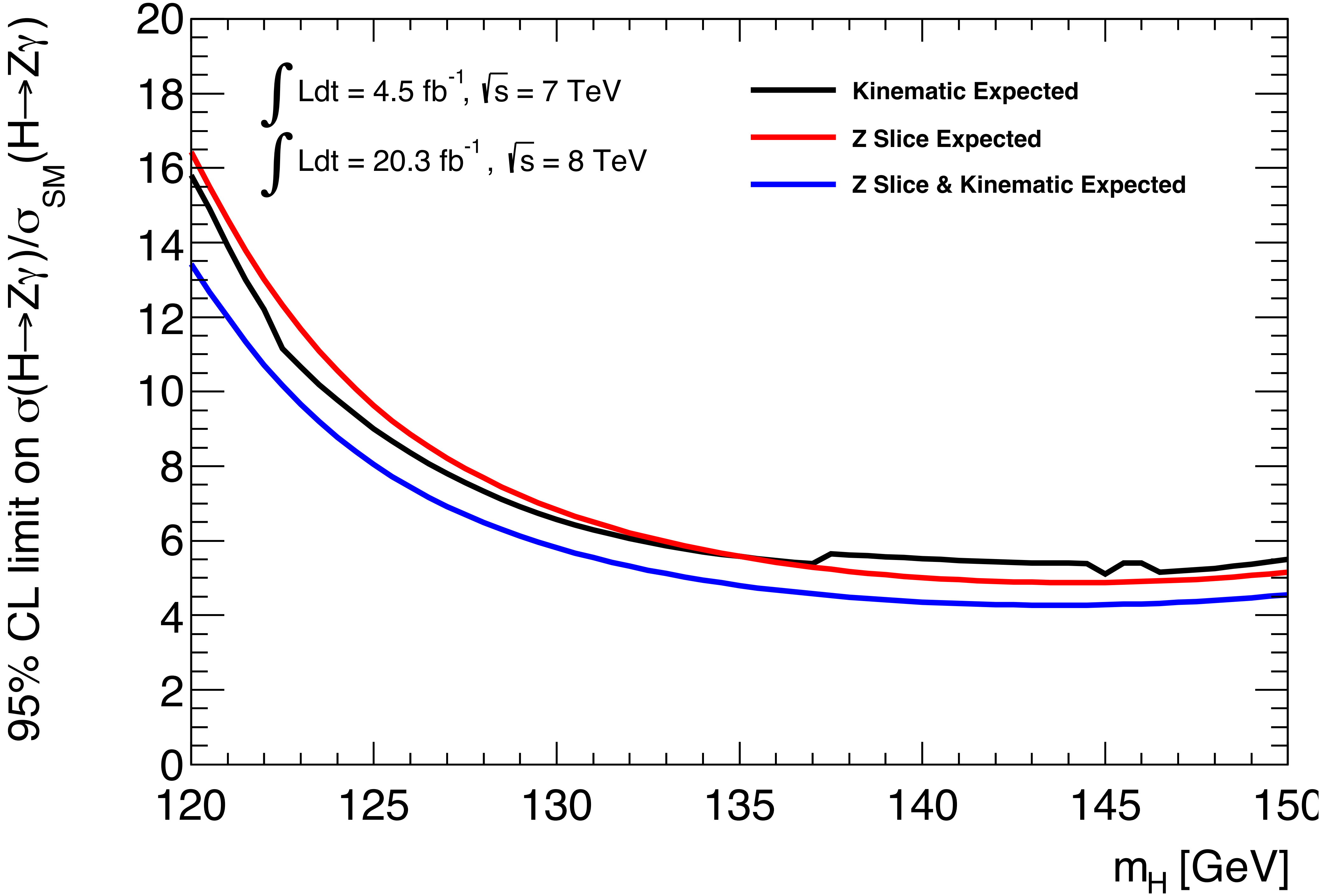
- Evaluate compatibility of the background-only case with a signal plus background hypothesis
- Level of signal in hypothesis increased in steps of 0.1 times the SM expectation
- Corresponding CLs value at each step evaluated
- Identify point where CLs falls below 5%

Z Slices: Proof of Concept 2



- Evaluate compatibility of the signal plus background case with a background-only hypothesis
- Level of signal in hypothesis increased in steps of 0.1 times the SM expectation
- Corresponding CLb value at each step evaluated
- Identify point where CLb rises above 95%

Z Slices: Impact on expected limits



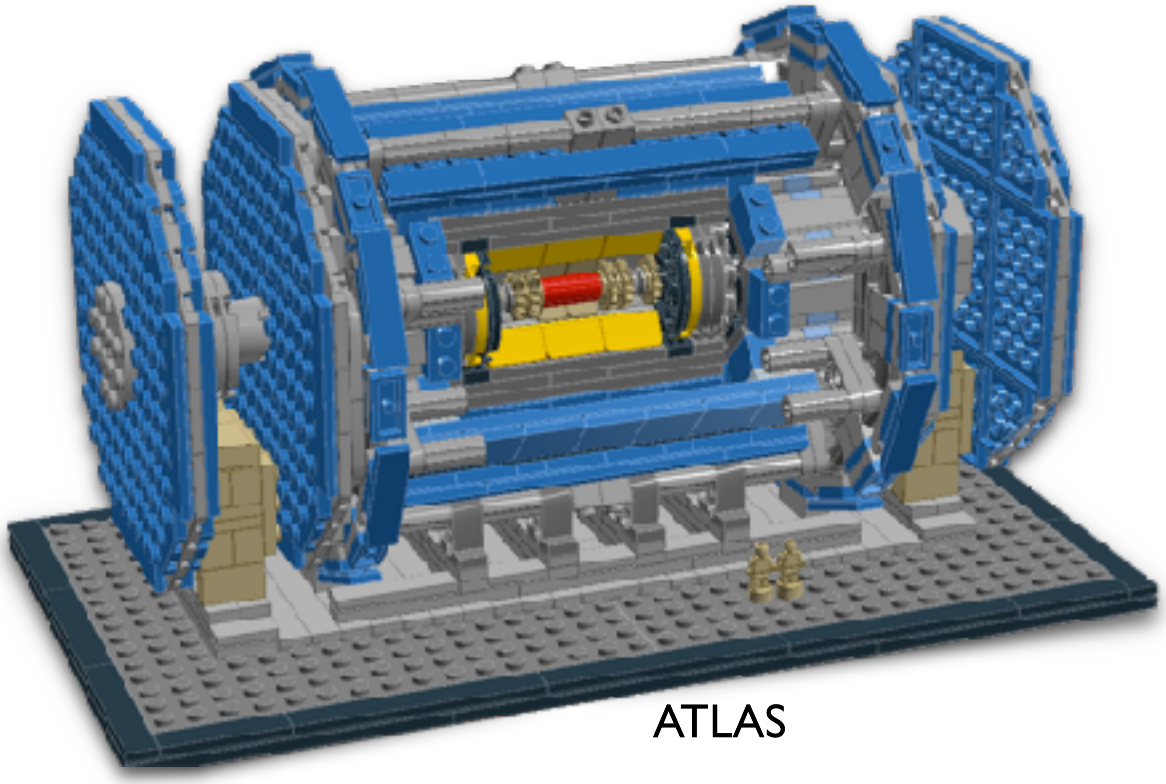
F-Test

- F-test used to identify if a more complex parameterisation will significantly improve the quality of the fit

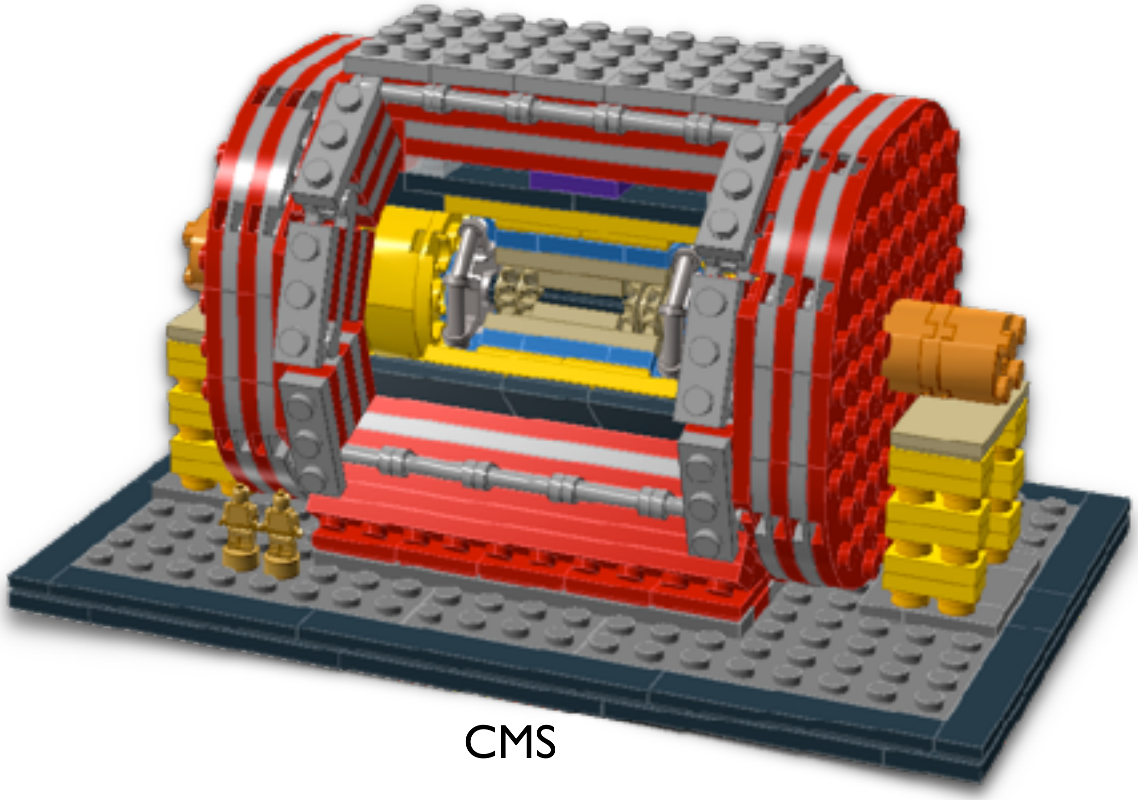
$$F = \frac{\frac{\chi_0^2 - \chi_1^2}{p_1 - p_0}}{\frac{\chi_1^2}{n - p_1}},$$

- X_0^2 (X_1^2) is the X^2 value of a binned fit with (less) more complex parameterisation
- p_k is the number of degrees of freedom of each fit
- n is the number of bins in the fitted distribution
- If probability of finding values of F more extreme than the value measured on data < 5%
  - Reject less complex parametrisation, use moire complex parametrisation
- Binning for F-test guarantees sufficient number of events in each bin

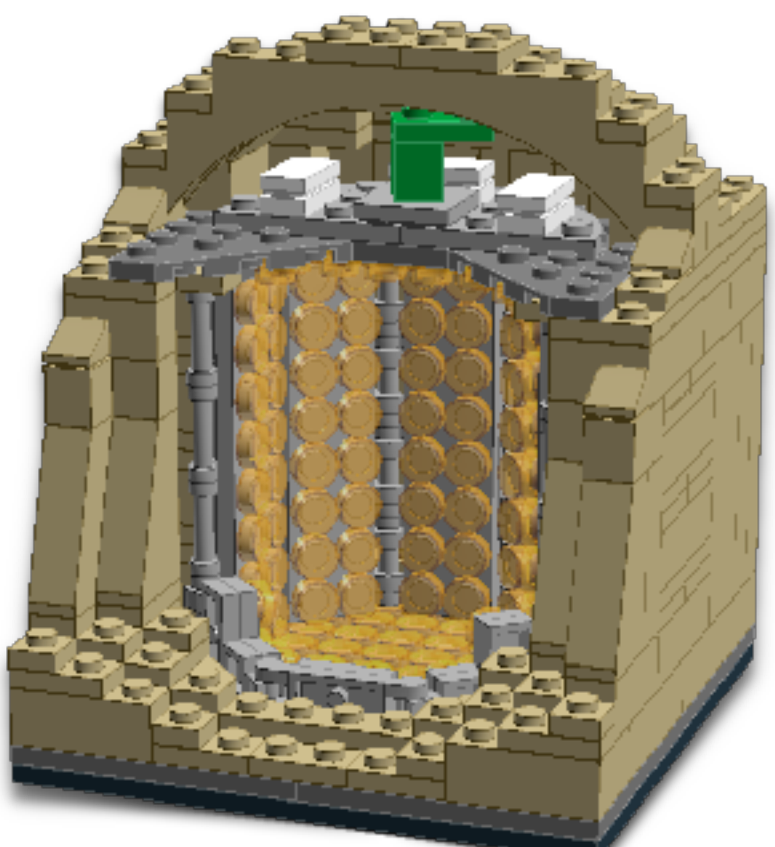
Who I am…



ATLAS

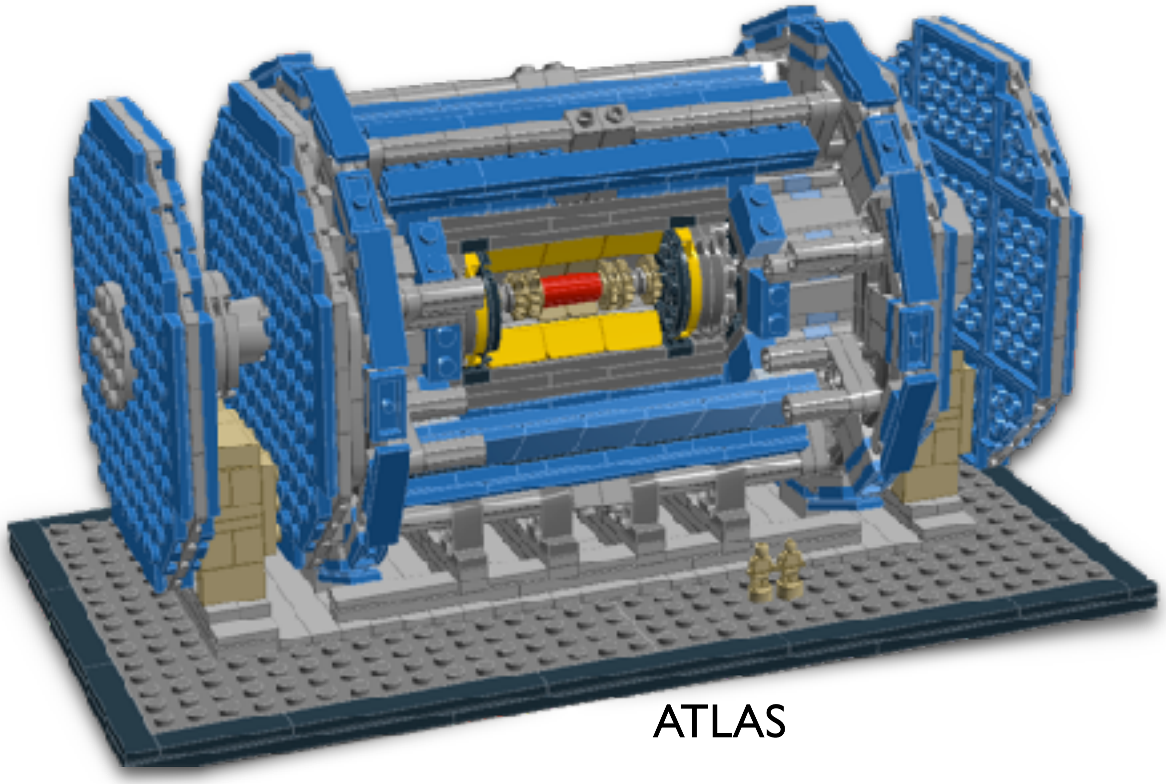


CMS

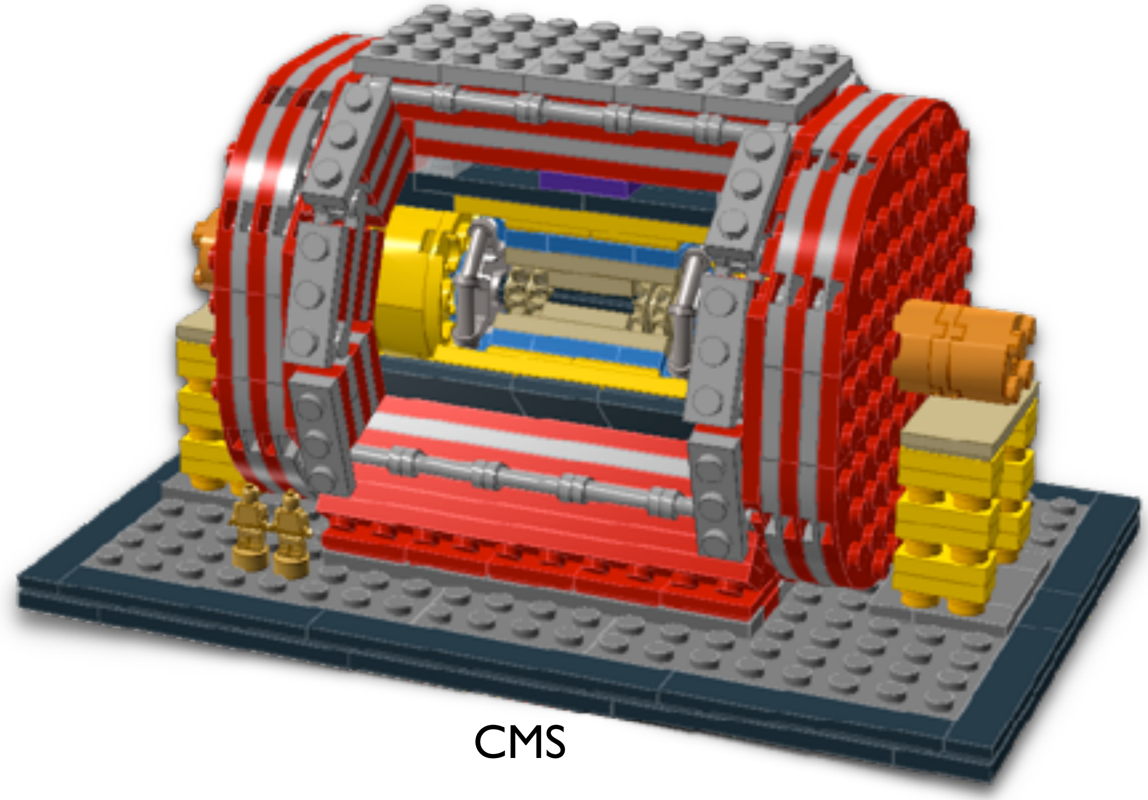


Super-Kamiokande

Who I am…



ATLAS



CMS

The Baby LHC

Super-Kamiokande