Search for the $Z\gamma$ Decay Mode of the Higgs Boson and for New High-Mass Resonances

at 13 TeV with the ATLAS Detector

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DESY

Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

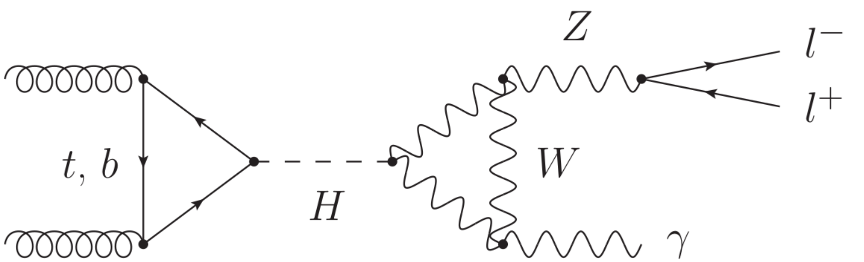
HELMHOLTZ ASSOCIATION

ATLAS EXPERIMENT

Motivation & Introduction

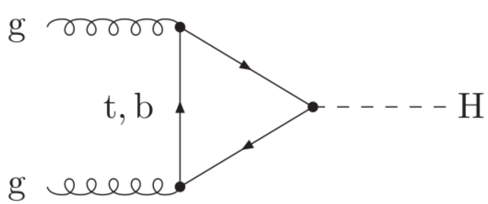
➔ $H \to Z(l^+l^-)\gamma$ not yet observed

- This is expected! Rare decay

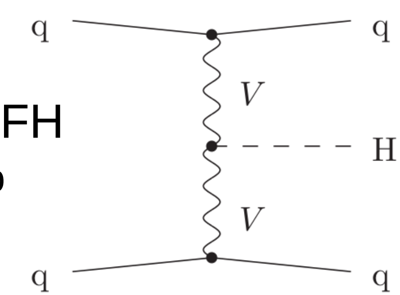


$$\mathcal{BR}(H \to Z\gamma) = 0.155\% \quad \text{and} \quad \mathcal{BR}(Z \to e^+e^-/\mu^+\mu^-) = 6.8\%$$

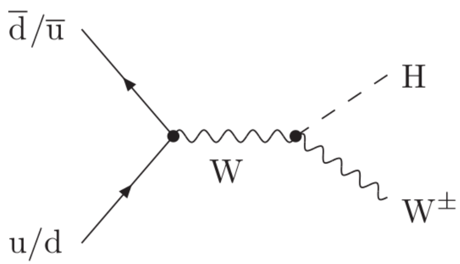
ggH
86%



VBFH
7%



WH
3%



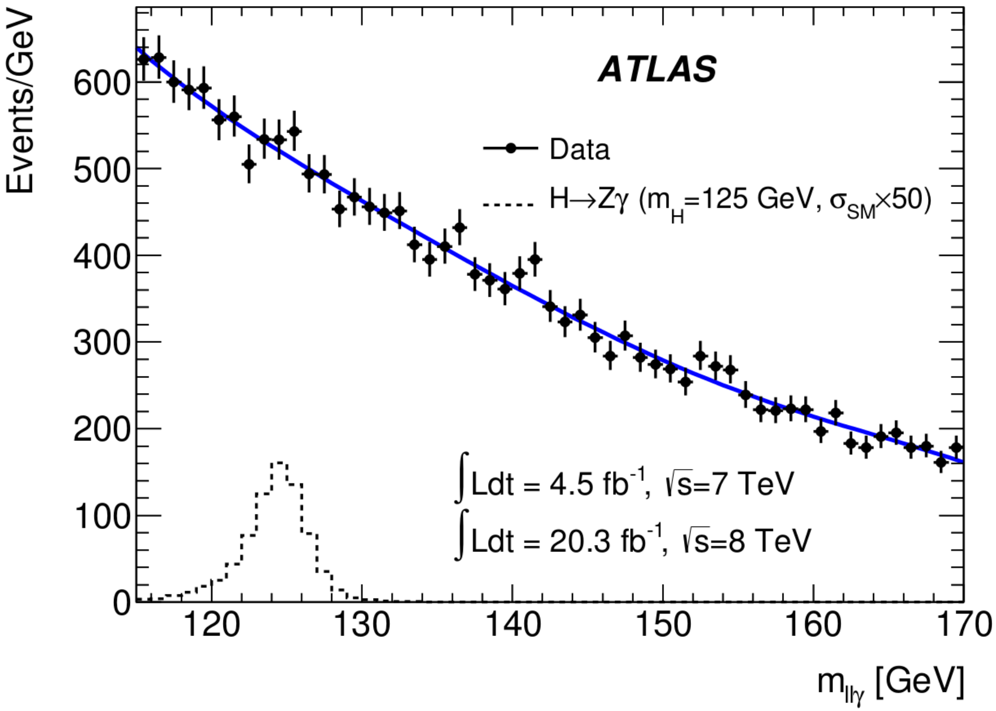
➔ Is still interesting

- Rate as expected in standard model?
- Higgs is a neutral scalar of a different nature? Composite? Additional uncoloured charged particles in the loop?
- Some models predict enhancement of $H \to Z\gamma$

➔ Narrow spin-0 and spin-2 high-mass resonance (X) search

Analysis Strategy

- Main observable: $m_{ll\gamma}$-distribution
- Event selection
  - 1 Photon and a pair of opposite-sign electrons / muons
- Event categorisation
  - 6 categories for $H \to Z\gamma$ and 2 categories for $X \to Z\gamma$
  - Separate, data-driven signal & background models in each category



- Unbinned likelihood fit
  - Simultaneously for all events and categories
  - Looking for excesses of data above fitted background
- Parameters of interest
  - Signal strength $\mu = \frac{(\sigma \cdot \mathcal{BR})_{\text{obs}}}{(\sigma \cdot \mathcal{BR})_{\text{SM}}}$ for $H \to Z\gamma$ (low-mass)
  - Cross section times branching ratio $\sigma \times \mathcal{BR}$ for $X \to Z\gamma$ (high-mass)

Event Selection

- Largely common event selection strategy for both mass regions with a few different final selection criteria
- Corrections to improve $m_{ll\gamma}$ mass resolution
  - Clustering of final state radiation off muons
  - Kinematic fit of lepton momenta to match Z boson lineshape
- Backgrounds
  - Non-resonant $Z+\gamma$ production
  - $Z+\mathrm{jet}$ with jets misidentified as photons

Common selection

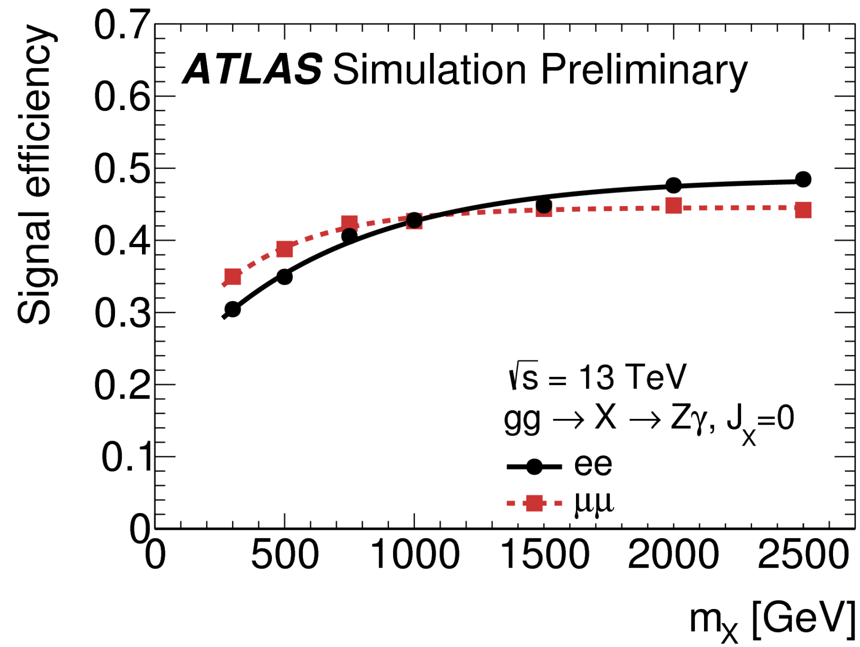
- Single/Di-lepton triggers
- At least 2 opposite-sign leptons
- At least 1 photon
- At least 1 H/X candidate
- Lepton pair in Z mass window
- Photon ID & isolation

Higgs Search

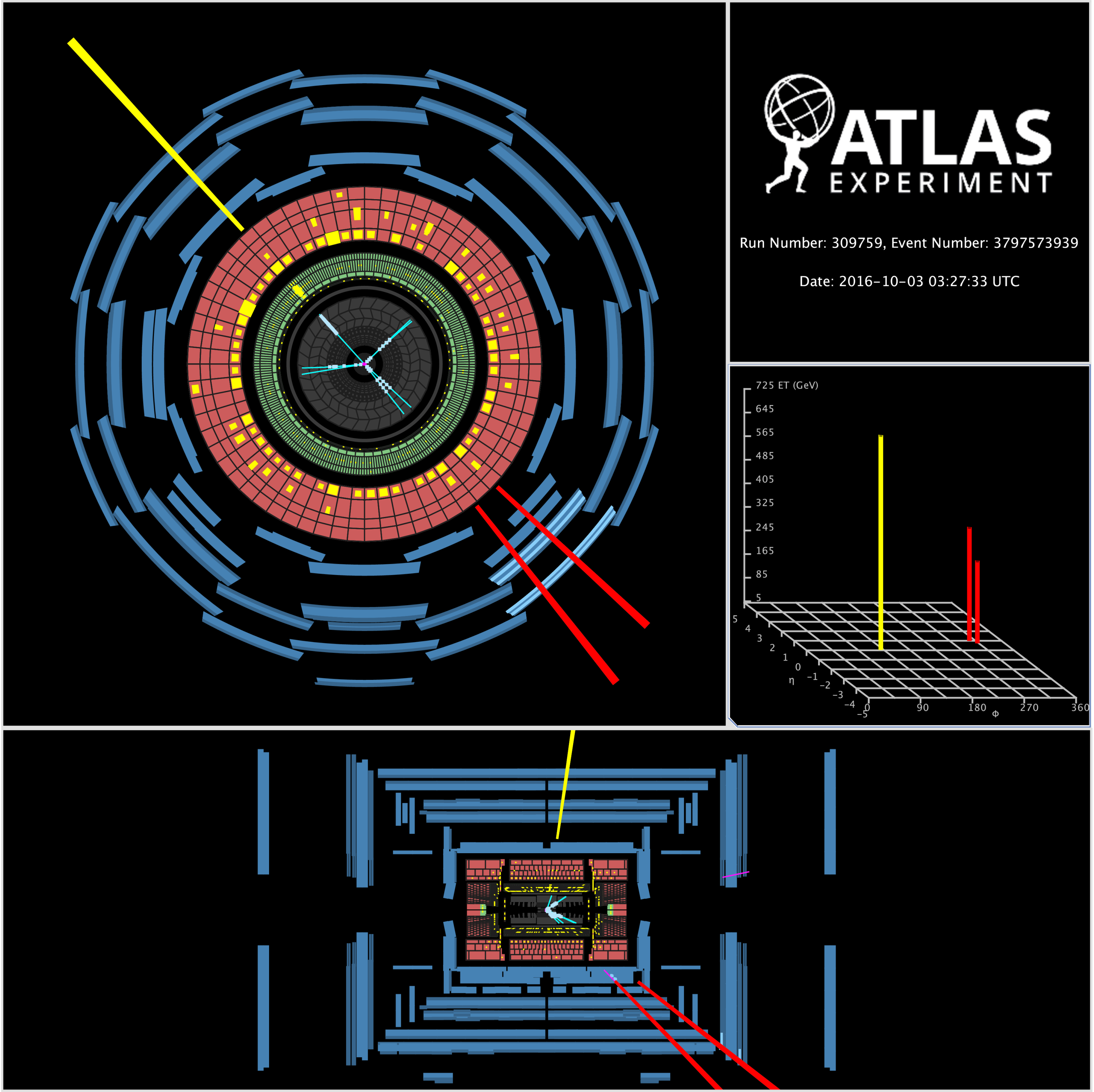
- $p_T^\gamma \geq 15$ GeV
- $m_{ll\gamma} \in [115, 170]$ GeV

High-Mass Search

- $p_T^\gamma \geq 50$ GeV
- $p_T^\gamma / m_{ll\gamma} \geq 0.3$
- $m_{ll\gamma} \geq 200$ GeV

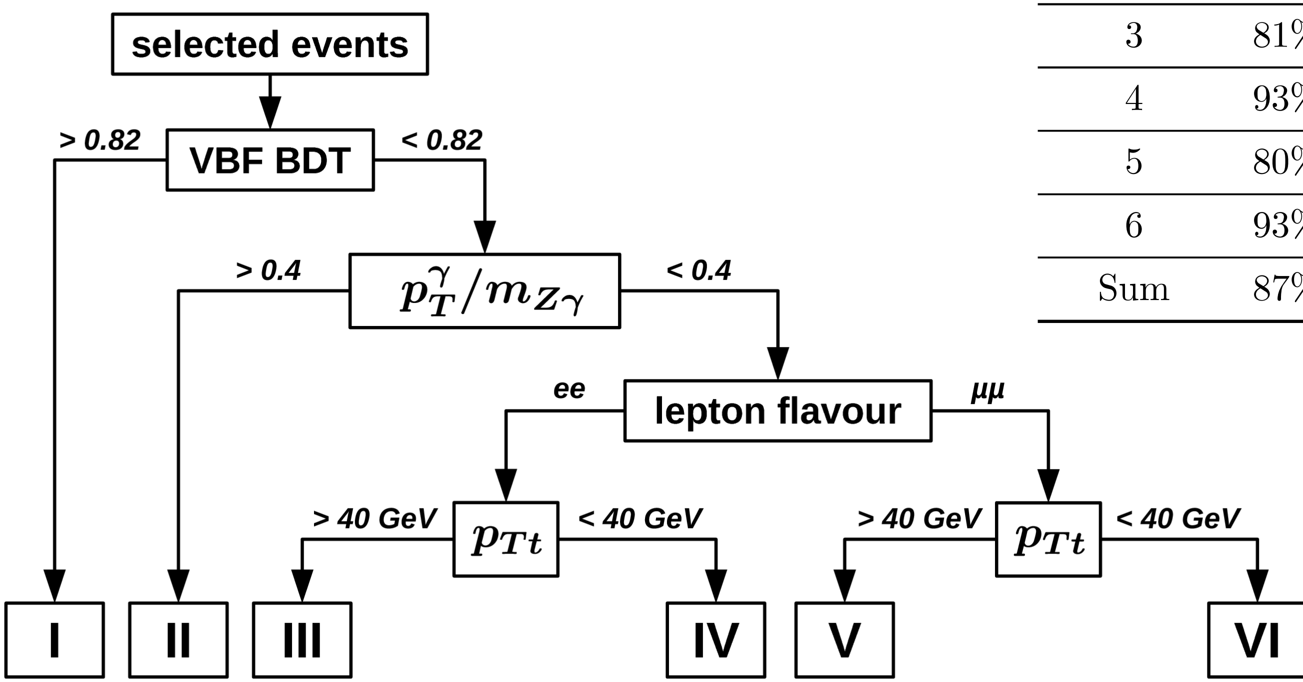


- High-mass selection
- $Z \to \mu\mu$ event with $m_{Z\gamma} = 1.57\ \text{TeV}$
- Event with the largest invariant mass



Event Categorisation

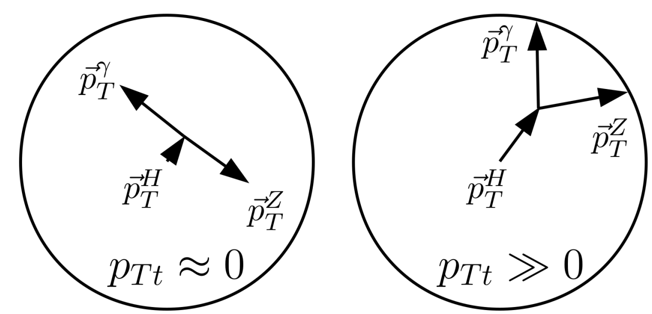
➔ Higgs Search: 6 categories



Expected signal event yields for 36.1/fb and category decomposition

Category	Production Mode ggH	VBFH	WH	ZH	Expected $H \to Z\gamma$ Events
1	31%	68%	1.3%	0.6%	1.3
2	72%	14%	8.3%	5.3%	2.5
3	81%	11%	4.7%	3.3%	3.6
4	93%	4.1%	1.5%	1.1%	12
5	80%	11%	4.8%	3.1%	4.4
6	93%	4.1%	1.5%	1.0%	16
Sum	87%	8.3%	2.6%	1.7%	40

$$p_{Tt} = (\vec{p}_T^Z + \vec{p}_T^\gamma) \times \frac{\vec{p}_T^Z - \vec{p}_T^\gamma}{|\vec{p}_T^Z - \vec{p}_T^\gamma|} = -2\frac{\vec{p}_T^Z \times \vec{p}_T^\gamma}{|\vec{p}_T^Z - \vec{p}_T^\gamma|}$$



transverse plane

➔ High-Mass Search: 2 categories

- $ee\gamma$ and $\mu\mu\gamma$

Likelihood Function

- Unbinned likelihood fit to the $m_{ll\gamma}$-distribution

$$L(\mu, \{\theta\}) = \frac{e^{-N} N^n}{n!} \times \left(\prod_{i=1}^{n} f_{\text{tot}}(m_{ll\gamma}^{(i)}, \mu, \{\theta\}) \right) \times G(\{\theta\})$$

normalisation | loop over data events | signal and background modelling | penalty terms

- Signal and background modelling

$$f_{\text{tot}} = \frac{1}{N} \sum_{c} \left\{ \left[N_{\text{sig}}^{(c)} + N_{\text{spur}}^{(c)} \right] \cdot f_{\text{sig}}^{(c)} + N_{\text{bkg}}^{(c)} \cdot f_{\text{bkg}}^{(c)} \right\}$$

with

$$N_{\text{sig}}^{(c)} = \left(\int \mathcal{L} dt \right) \cdot \sum_{p} \sigma_p \cdot \mathcal{BR} \cdot \mu \cdot \mathcal{A}_p \cdot \epsilon_p^{(c)}$$

- n observed events
- N expected events
- Signal strength μ
- Nuisance parameters $\{\theta\}$
- Category c
- Signal and background shapes $f_{\text{sig}}^{(c)}$ and $f_{\text{bkg}}^{(c)}$
- Integrated luminosity $\int \mathcal{L} dt$
- Production mode p
- Total production cross sections σ_p and branching ratio $\mathcal{BR}$
- Acceptance x selection efficiency $\mathcal{A}_p$
- Category population fractions $\epsilon_p^{(c)}$

Signal Parameterisation

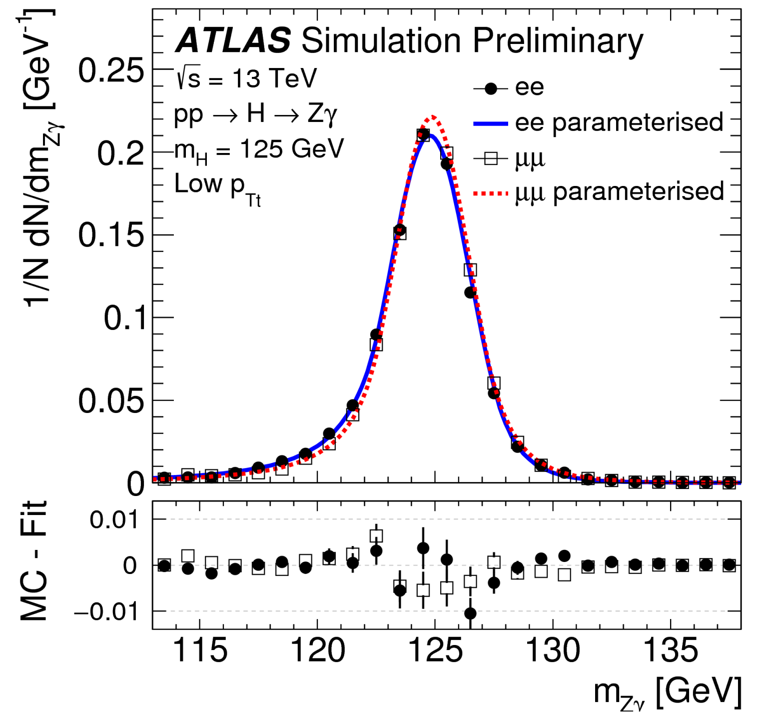
- Analytical model
  - Double-sided Crystal Ball function
  - Parameters from fit to Monte Carlo

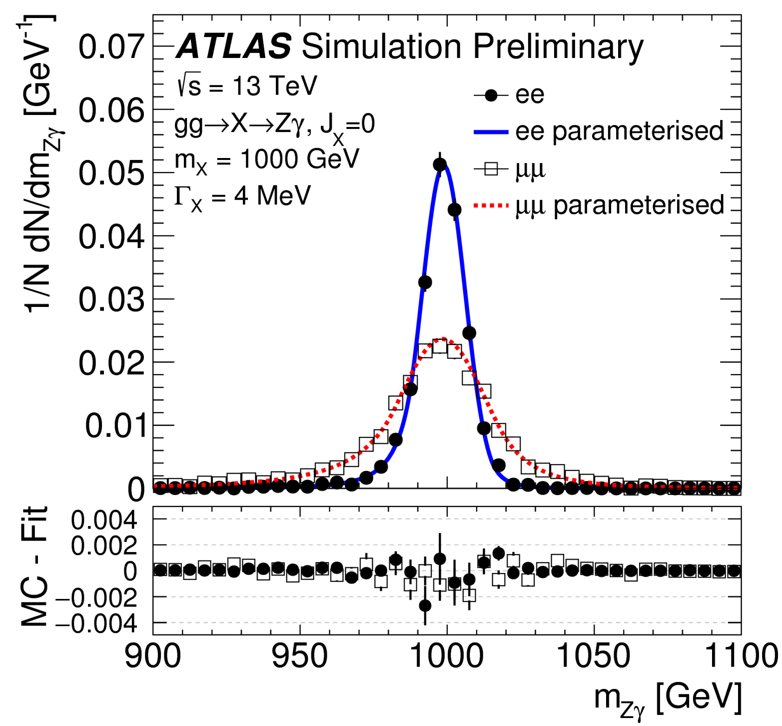
  for both mass regions
  - Written without normalisation:

$$\propto \begin{cases} (c_{\text{low}} - t)^{-n_{\text{low}}} & \text{for } t \leq -\alpha_{\text{low}} \\ e^{-t^2/2} & \text{for } t \in [-\alpha_{\text{low}}, \alpha_{\text{high}}] \\ (c_{\text{high}} + t)^{-n_{\text{high}}} & \text{for } t \geq \alpha_{\text{high}} \end{cases}$$

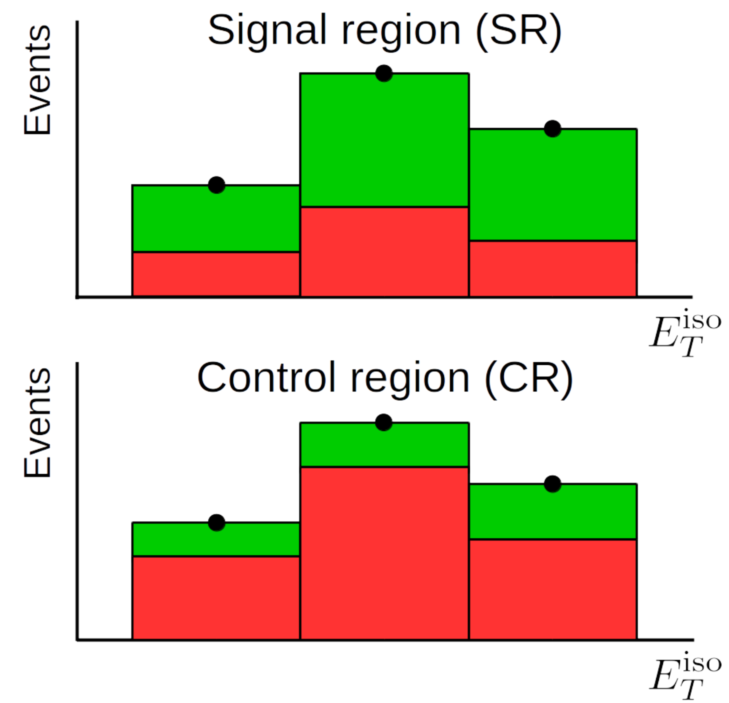
with $t = (m_{ll\gamma} - m_X - \mu_{\text{CB}})/\sigma_{\text{CB}}$

- High-mass search
  - Parameterisation of signal efficiency times acceptance as a function of mass





Background Decomposition



- Backgrounds
  - Non-resonant $Z + \gamma$ production
  - $Z + j$ with jets misidentified as photons
- Method: Isolation template fit
  - Binned fit to the calorimeter isolation distribution
  - Signal region: tight photon identification
  - Control region: require modified loose but veto tight photon identification

$$N_i^{\mathrm{SR}} = f_i N_{Z\gamma}^{\mathrm{SR}} + \frac{N_{Zj,i}}{\sum_k N_{Zj,k}} N_{Zj}^{\mathrm{SR}}$$

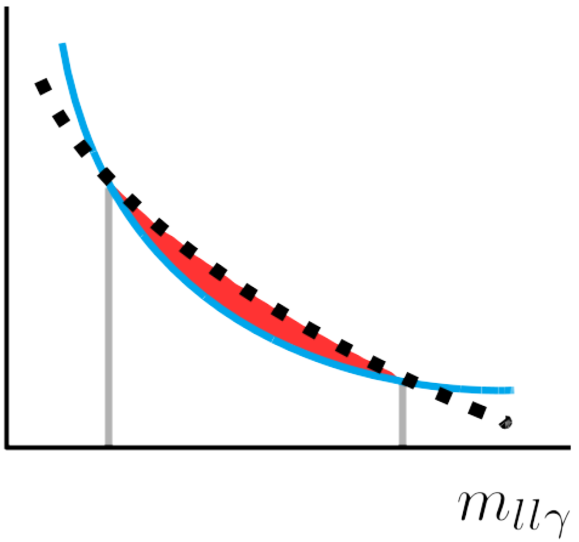
$$N_i^{\mathrm{CR}} = f_i l_i N_{Z\gamma}^{\mathrm{SR}} + N_{Zj,i}$$

- Signal shape f_i and leakage l_i from MC
- Total yields $N_{Z\gamma}^{\mathrm{SR}}$ and N_{Zj}^{SR} in SR from fit
- Zj shape from fit
- Assumption: Zj shape same in SR and CR

- Results
  - Higgs search: $N_{Z\gamma}^{\mathrm{SR}} / \left(N_{Z\gamma}^{\mathrm{SR}} + N_{Zj}^{\mathrm{SR}}\right) = 84\%$
  - High-mass search: $N_{Z\gamma}^{\mathrm{SR}} / \left(N_{Z\gamma}^{\mathrm{SR}} + N_{Zj}^{\mathrm{SR}}\right) = 92\%$
- Cross checked with 2D (photon identification & isolation) sideband-based method

Background Parameterisation

- Background Model
  - Functional form from Monte Carlo
  - Parameter values from fit to data
- Evaluation of bias / spurious signal
  - Choice of background functions may induce would-be signal $N_{\rm spur}$
  - Evaluated by performing S+B fit to B-only $m_{ll\gamma}$-distribution
  - Because of limited Zj MC statistics, use hybrid MC / data-driven technique to create B-only distribution



Background Parameterisation

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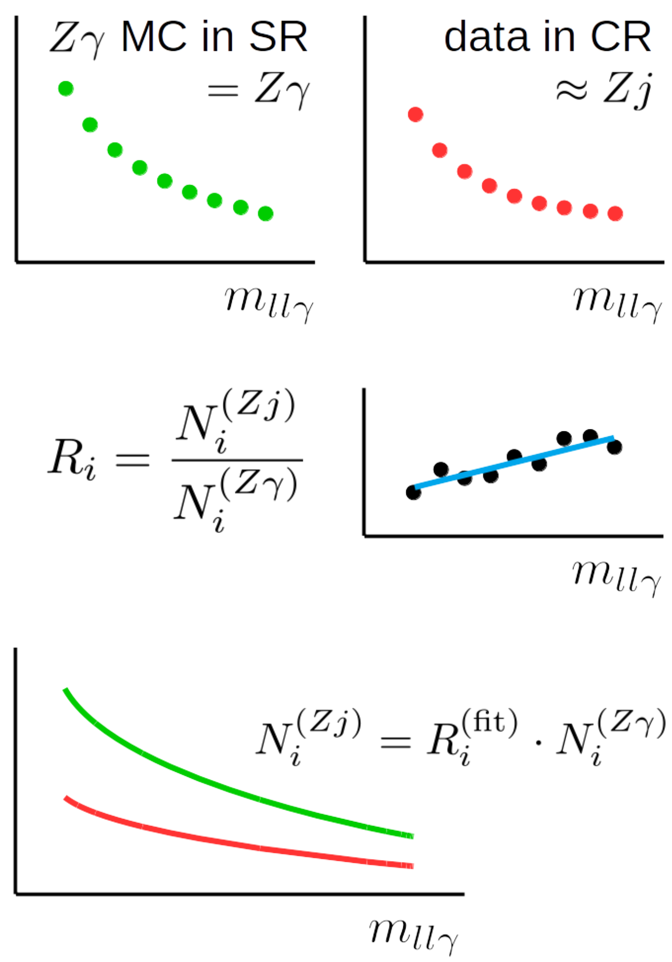
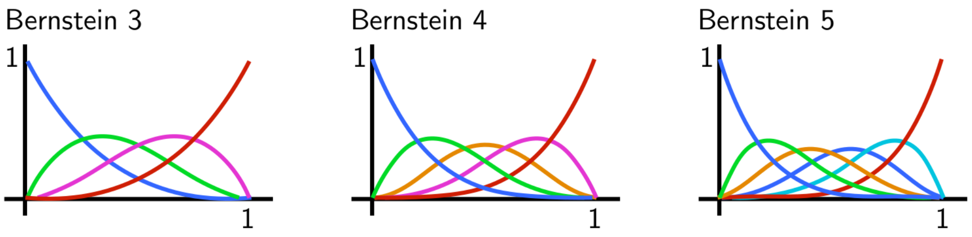


Background Parameterisation

- Results of background modelling
  - Low-mass search:
    2^{nd}- and 4^{th}-order
    Bernstein polynomials
  - High-mass search:
    $f_{\mathrm{bkg}} \propto (1 - x^{1/3})^b x^{a_0}$



The Bernstein Functions

- F-test: Check if higher-order parameterisation with more degrees of freedom would be beneficial
  - Better description of data vs. worse sensitivity
  - Test statistic

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

  - Confirms chosen functional forms / orders

Experimental Uncertainties

- Uncertainties on signal modelling
  - Lepton and photon energy and momentum scales and resolutions
- Uncertainties on background modelling
  - Spurious signal
- Uncertainties on signal yield
  - Luminosity
- Uncertainties on signal efficiency
  - Pile-up
  - Photon and lepton reconstruction, identification, isolation, trigger efficiency
  - Low-mass VBF category: jet energy scale and resolution

Overview of Theory Uncertainties

$H \to Z\gamma$ **Search**

➔ Uncertainties on cross sections and branching ratio

	ggH	VBF	WH	ZH
scale	3.9%	0.4%	0.6%	3.4%
PDF	3.2%	2.1%	1.9%	1.6%

	BR
total	5.8%

Additional 5% uncertainty on other interfering Higgs decays

From state-of-the-art calculations arXiv:1610.07922 [hep-ph]

➔ Uncertainties on category population fractions

- Missing higher-order QCD corrections in the ggH production mode
  - HRes ggH inclusive scale variations in the p_T^H spectrum
  - MCFM ggH H+2j at NLO scale variations for contamination of VBF category
- Modelling uncertainty of variables entering the VBF BDT
- PDF uncertainties
  - Evaluated with PDF4LHC15
- Underlying event uncertainty
  - Comparison of Pythia8 with MPI On vs Off

➔ Uncertainty on acceptance x selection efficiency

- Comparison of Pythia8 with MPI On vs Off

Fixed-Order Stewart-Tackmann Uncertainties

$H \to Z\gamma$ **Search**

➔ Parametrisation of covariance matrix for 2 categories

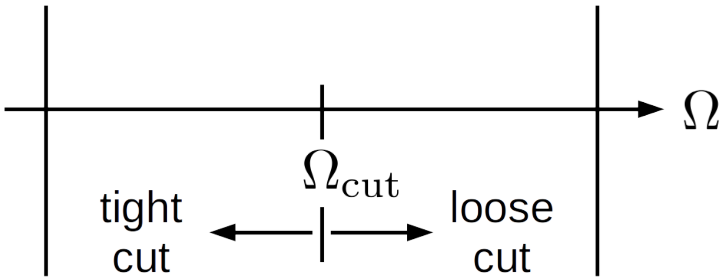
- e.g. in jet bins $\{\sigma_{=N}, \sigma_{\geq N+1}\}$

$$C = \Delta_y^2 \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + \Delta_m^2 \begin{pmatrix} +1 & -1 \\ -1 & +1 \end{pmatrix}$$

  - Δ_y Overall yield uncertainty
  - Δ_m Migration uncertainty

are calculated from perturbative scale variations

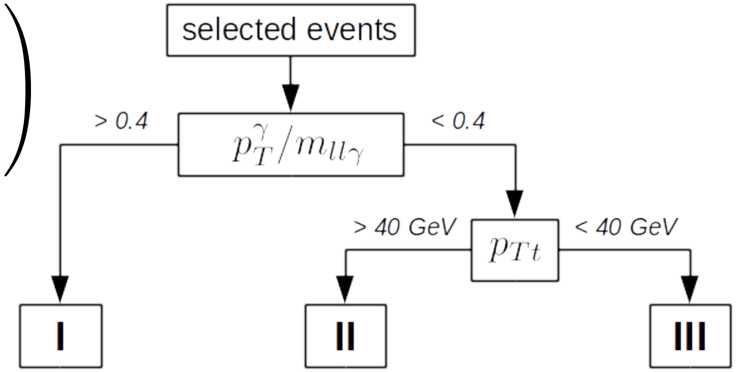
e.g. $= N$ vs. $\geq N+1$ jets



➔ Possible complications depending on the categorisation: Contributions may be distributed across multiple categories

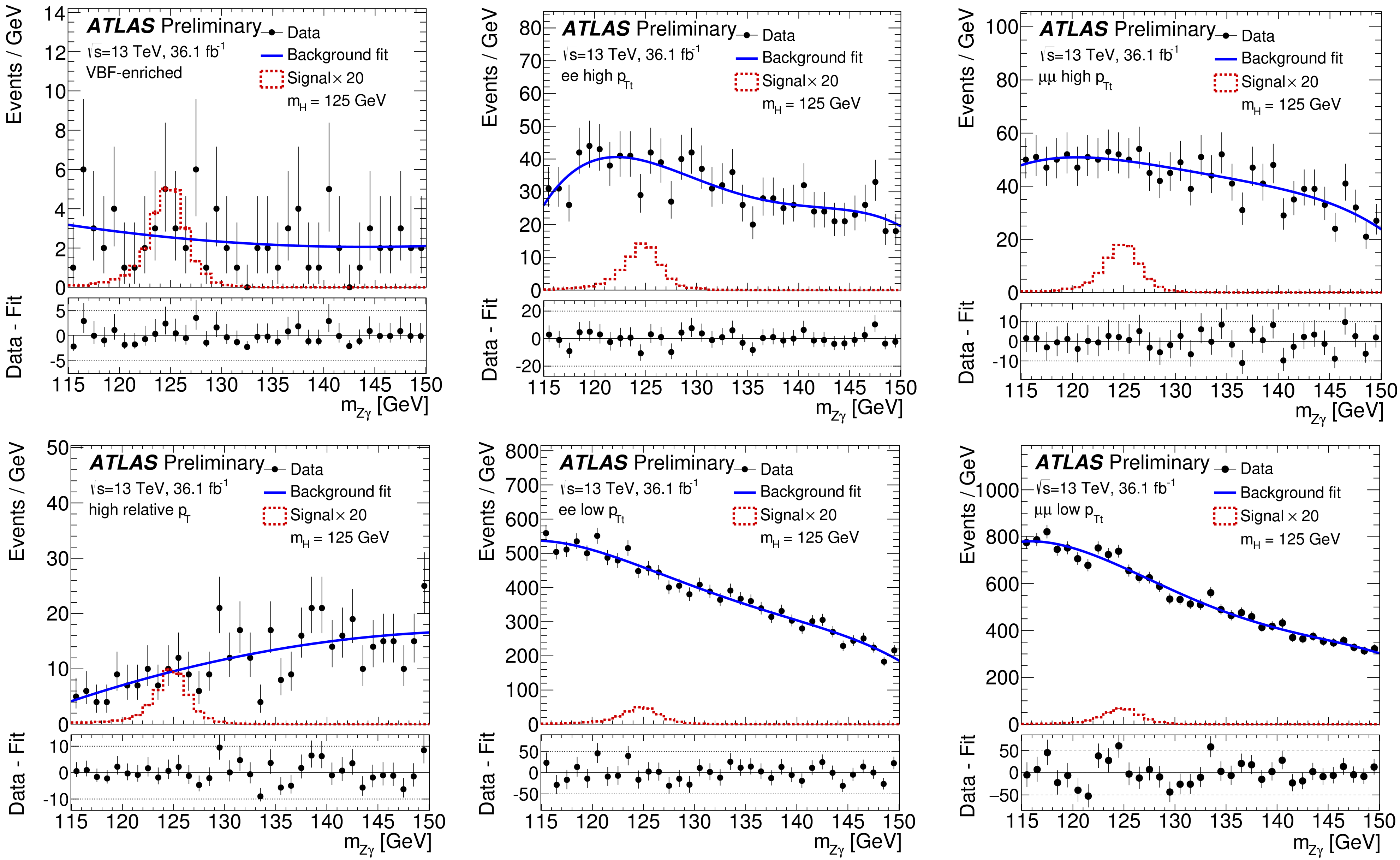
$$C = \Delta_y^2 \begin{pmatrix} 0 & 0 & 0 \\ 0 & \alpha_2^2 & \alpha_2\alpha_3 \\ 0 & \alpha_2\alpha_3 & \alpha_3^2 \end{pmatrix} + \Delta_m^2 \begin{pmatrix} 1 & -\beta_2 & -\beta_3 \\ -\beta_2 & \beta_2^2 & \beta_2\beta_3 \\ -\beta_3 & \beta_2\beta_3 & \beta_3^2 \end{pmatrix}$$

- $\{\alpha_i\}$: rescaled category population fractions
- $\{\beta_i\}$: category population fractions in absence of first category



Results: Invariant Mass Distributions

$H \to Z\gamma$ **Search**



➔ Data and fitted background in the different categories

Results: Limits

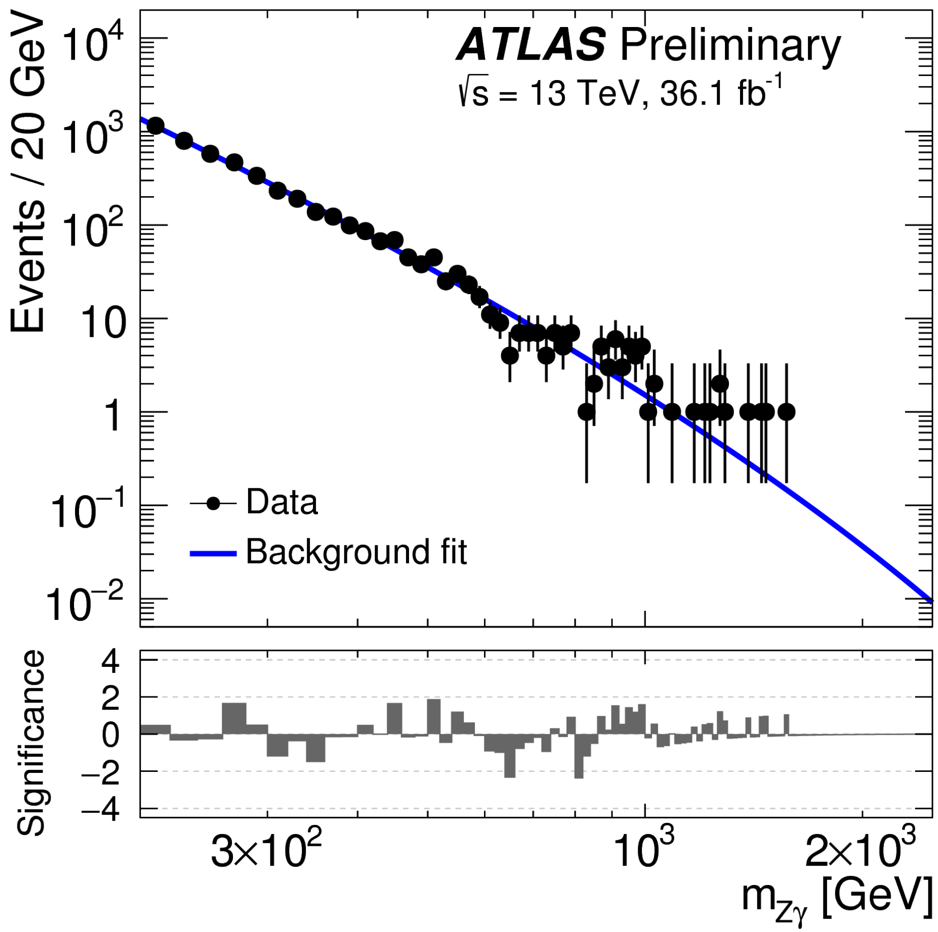
$H \to Z\gamma$ **Search**

- No significant localised excess above background-only hypothesis near Higgs mass
- p_0-value and significance at $m_H = 125.09$ GeV
  - Expected: $p_0 = 0.33$ → local significance 0.5σ
  - Observed: $p_0 = 0.16$ → local significance 1.0σ
- Limit on signal strength $\mu = (\sigma \cdot \mathcal{BR})_{\rm obs}/(\sigma \cdot \mathcal{BR})_{\rm SM}$
  - Expected (no Higgs boson): $\mu < 4.4$
  - Expected (SM Higgs boson): $\mu < 5.2$
  - Observed: $\mu < 6.6$
- Limit on $\sigma(pp \to H) \cdot \mathcal{BR}(H \to Z\gamma) < 547$ fb
- Limit on $\mathcal{BR}(H \to Z\gamma) < 0.01$

All limits at 95% CL

Results: Invariant Mass Distribution

$X \to Z\gamma$ **Search**

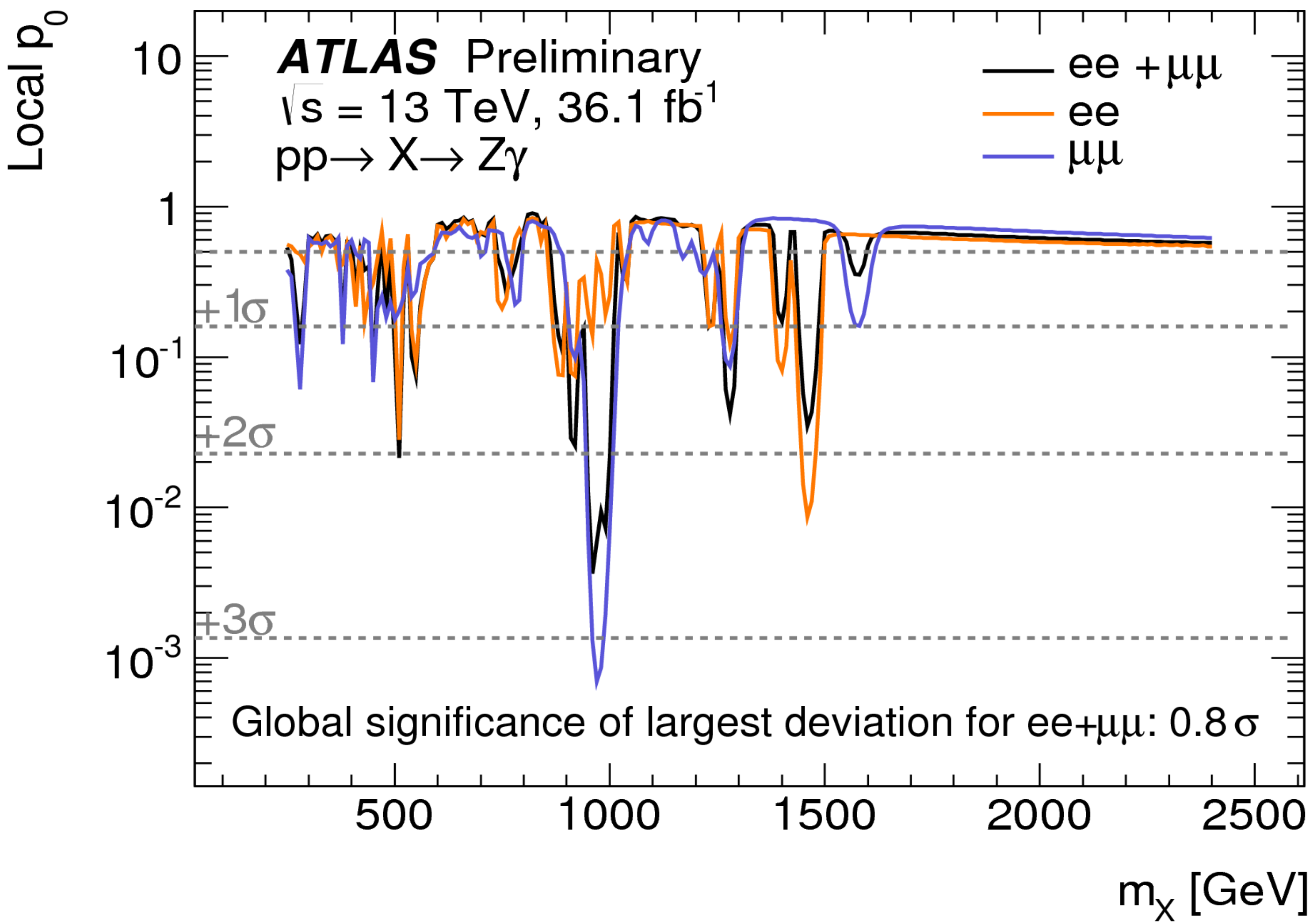


➔ Data and fitted background for inclusive high-mass selection

- Background-only fit performed in mass range [200, 2500] GeV

Results: Local p_0-Value

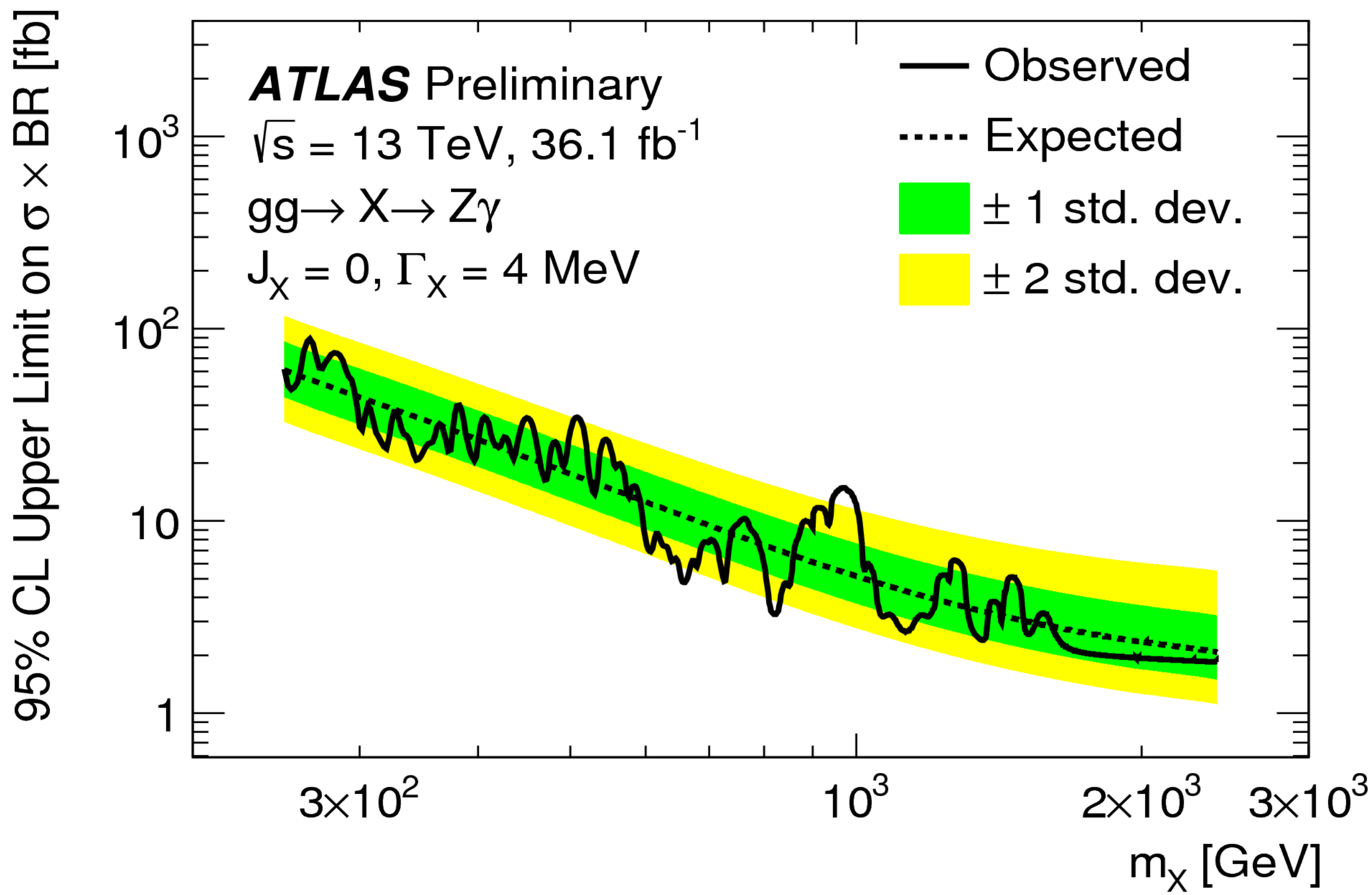
$X \to Z\gamma$
Search



- Largest significance: 2.7σ (local) $\to$ 0.8σ (global)
  - Mass range $m_X \in [250, 2400]$ GeV

Results: Limits on $\sigma \times \mathcal{BR}$

$X \rightarrow Z\gamma$ Search



➔ Observed limits on $\sigma(pp \rightarrow X) \cdot \mathcal{BR}(X \rightarrow Z\gamma)$ at 95% CL

- Spin-0 resonance: 88 fb - 1.8 fb
- Spin-2 resonance: 117 fb – 2.4 fb (gg) and 94 fb – 1.5 fb $(q\bar{q})$

Summary

- Brand-new search for the $Z(l^+l^-)\gamma$ decay mode of the Higgs boson and of narrow high-mass resonances with the ATLAS detector
  - Based on the full 13 TeV dataset from 2015 / 2016 with 36.1 / fb
- Low-mass search
  - No significant excess above background-only expectation
  - 95% CL limit on signal strength $\mu < 6.6$ corresponding to $\sigma(pp \to H) \cdot \mathcal{BR}(H \to Z\gamma) < 547 \text{ fb}$ and $\mathcal{BR}(H \to Z\gamma) < 0.01$
- High-mass search
  - Searching for narrow spin-0 and spin-2 resonances in the mass range $m_{ll\gamma} \in [250, 2400] \text{ GeV}$
  - No significant excess above background-only expectation
  - 95% CL limits on $\sigma(pp \to X) \cdot \mathcal{BR}(X \to Z\gamma)$ between 117 fb and 1.5 fb
- Paper is on its way...

Thanks for your attention!

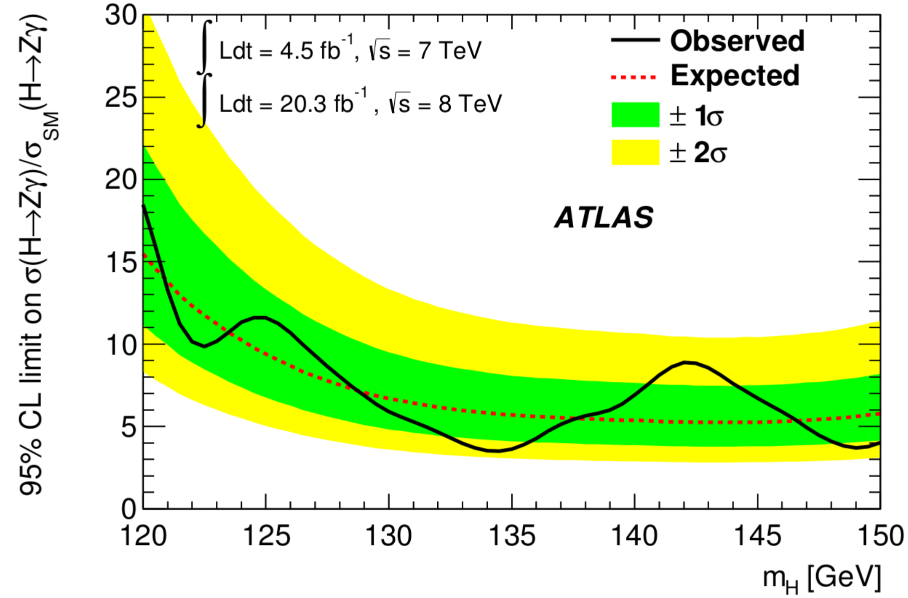
Backup

Previous Measurements

➔ Run 1 arXiv:1402.3051 [hep-ex]

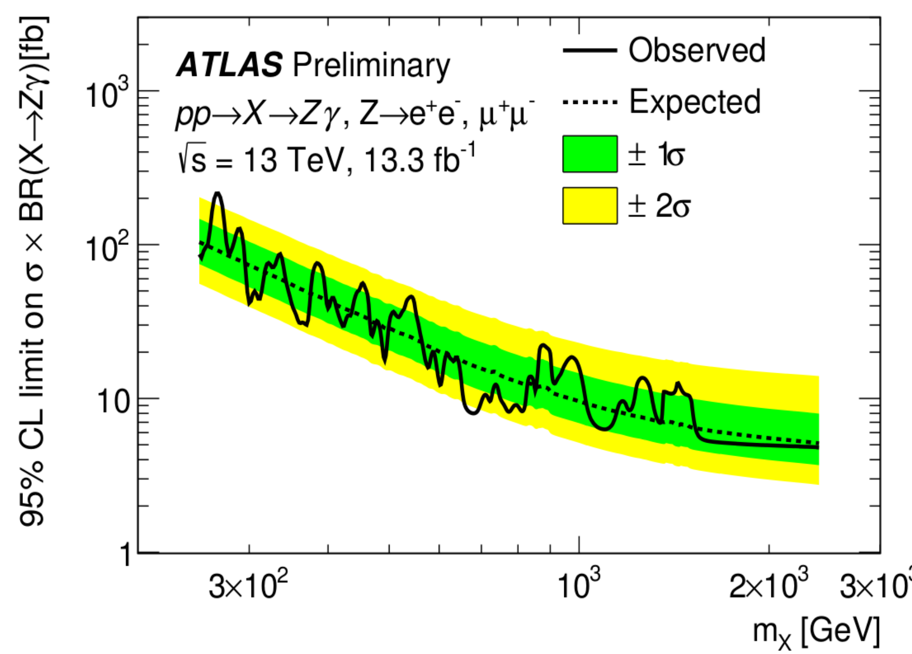
- Higgs search in leptonic Z channel using 2011 + 2012 datasets with 4.5/fb (7 TeV) + 20.3/fb (8 TeV)
- Expected limit: $\mu = \sigma/\sigma_{\rm SM} = 9$
- Observed limit: $\mu = \sigma/\sigma_{\rm SM} = 11$

(for $m_H = 125.5\ \text{GeV}$)



➔ Run 2 ATLAS-CONF-2016-044

- High-mass resonance search in leptonic Z channel using 2015 + 2016 dataset with 13.3/fb
- Limits on $\sigma(X) \times \mathcal{BR}(X \to Z\gamma)$



➔ **Now:** Both Higgs search and high-mass search in the leptonic Z channel using full 2015 + 2016 dataset with 36.1/fb (13 TeV)

Cowan, Cranmer, Gross, Vitells
arXiv:1007.1727 [physics.data-an]

Statistics Procedures

- Testing for a signal
  - Test statistic

$$t_0 = -2\ln\frac{L(0,\hat{\hat{\theta}}_0)}{L(\hat{\mu},\hat{\theta}_{\hat{\mu}})}$$

- Setting upper limits
  - Test statistic

$$q_\mu = \begin{cases} -2\ln\frac{L(\mu,\hat{\hat{\theta}}_\mu)}{L(\hat{\mu},\hat{\theta}_{\hat{\mu}})} & \text{if } \hat{\mu} \le \mu \\ 0 & \text{if } \hat{\mu} > \mu \end{cases}$$

  - Vary hypothesised μ until crossing pre-defined confidence level (CL) $1-\alpha$

- Accepting / rejecting the null hypothesis

$$p = \int_{q_{\rm obs}}^{\infty} f(q|\mu)dq \begin{cases} < \alpha & \rightarrow \text{reject} \\ > \alpha & \rightarrow \text{accept} \end{cases}$$