Search for Rare and Lepton Flavor Violating Decays of the Higgs Boson With the ATLAS Detector

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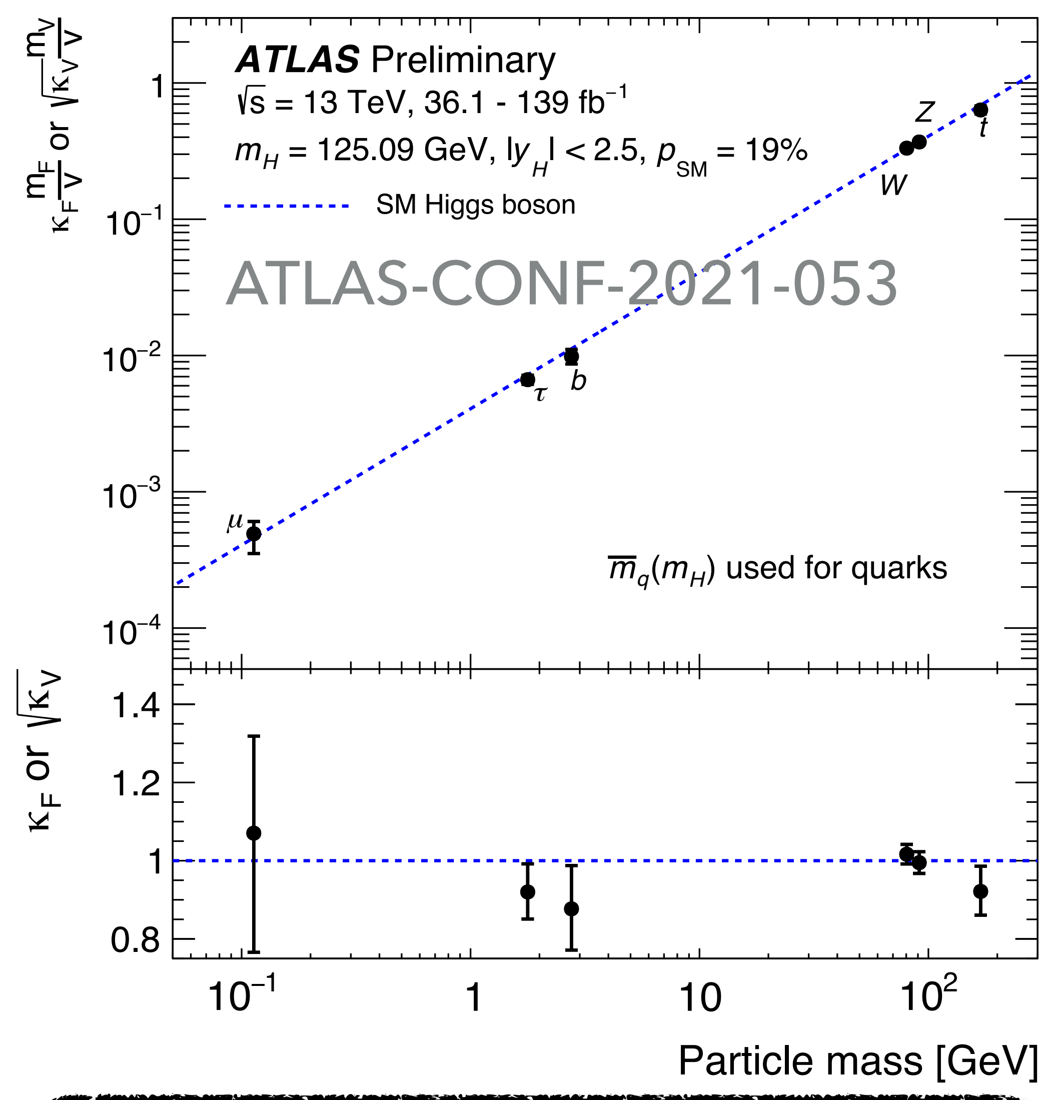
[1]IHEP

TeV Particle Astrophysics 2021

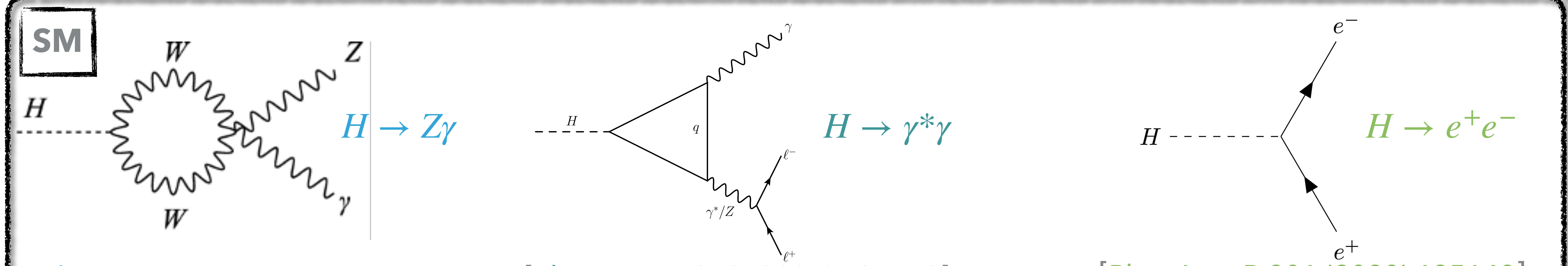
Oct. 27th, 2021

Introduction

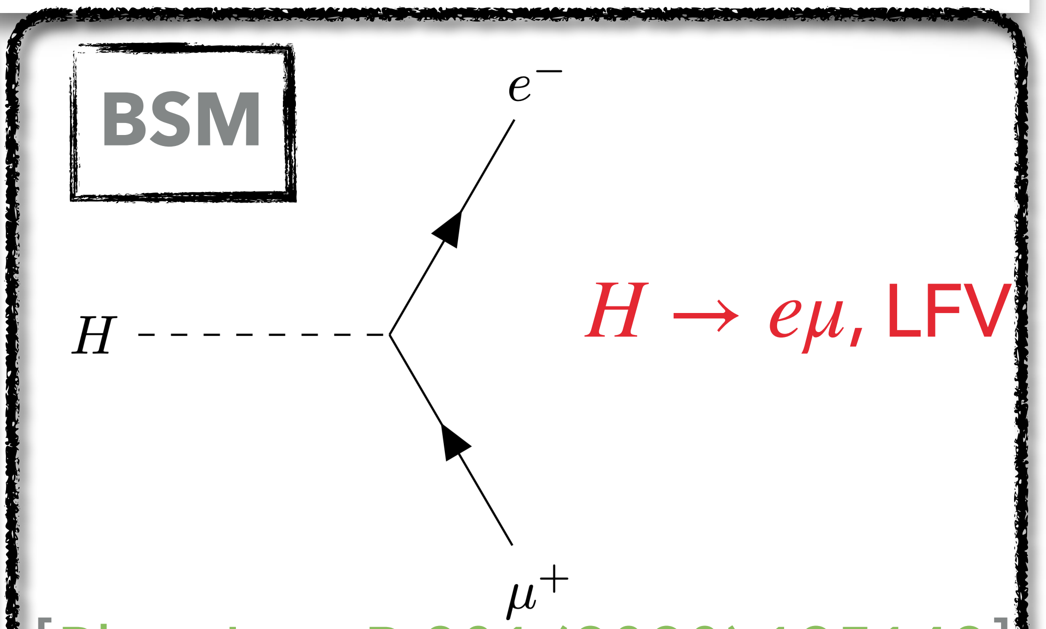
- Since the Higgs was discovered, its coupling properties to SM particles are precisely probed $\Longrightarrow$ providing stringent tests of the SM validity



- The SM predicts rare Higgs boson decay channels



[Phys. Lett. B 809 (2020) 135754] [Phys. Lett. B 819 (2021) 136412] [Phys. Lett. B 801 (2020) 135148]



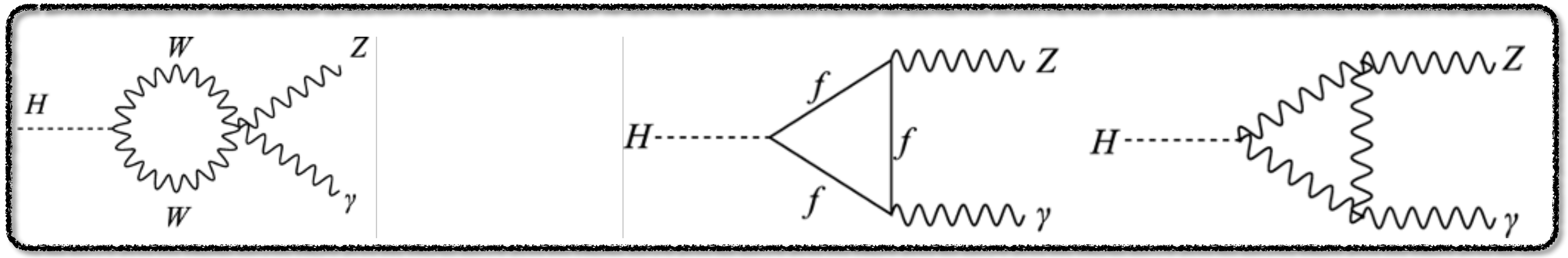
[Phys. Lett. B 801 (2020) 135148]

- Rare decay analyses are helpful for studying the CP and coupling properties of the Higgs boson in a complementary way to other analyses

- Lepton-flavor-violating (LFV) decays would be a clear physics sign BSM

$H \to Z\gamma$ search

- SM Higgs can decay into $Z\gamma$ through loop diagrams; The BR measurements are important for probing the Higgs properties, and for validating SM/BSM theories
  - $B(H \to Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$ at $m_H = 125.09$ GeV;

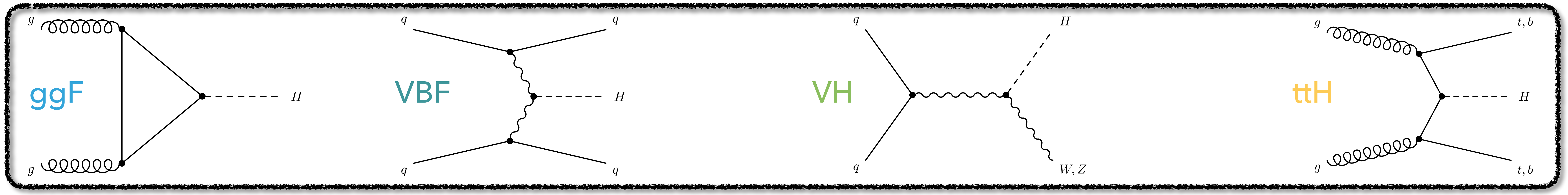


- Z to leptonic decays (e, μ) can be efficiently triggered and clearly distinguished from background
- $H \to Z(\to ll)\gamma$ can be reconstructed with good invariant mass resolution and relatively small backgrounds
- In the previous publications (36 fb^{-1}), no significant excess above the expected background is observed
-

Limit of XS x BR at 95% CL	
ATLAS [JHEP 10 (2017) 112]	6.6 (5.2) x SM
CMS [JHEP 11 (2018) 152]	7.4 (6.0) x SM

Analysis updates

- An updated search is presented (Phys. Lett. B 809 (2020) 135754) with full Run2 data (139 fb-1), with important updates
  - Increase in the size of dataset
  - More comprehensive Higgs production modes



  - Improved event categorization
  - Optimized lepton and photon ID criteria
  - $H \to \mu\mu$ (QED FSR) contamination is estimated to be ~2%
  - EWK $Z\gamma jj$ background is considered first time in the VBF category

Object/Event selection

Single lepton, di-lepton triggers

Electron
$p_T > 10$ GeV
$|\eta| < 2.47$
$|d_0|/\sigma_{d0} < 5$
$z_0 \sin\theta < 0.5$ mm
Loose ID

Muon
$p_T > 10$ GeV
$|\eta| < 2.7$
$|d_0|/\sigma_{d0} < 3$
$z_0 \sin\theta < 0.5$ mm
Medium ID

Photon
$p_T > 10$ GeV
$|\eta| < 2.37$
Tight ID

Jet
$p_T > 25$ GeV
$|\eta| < 4.4$

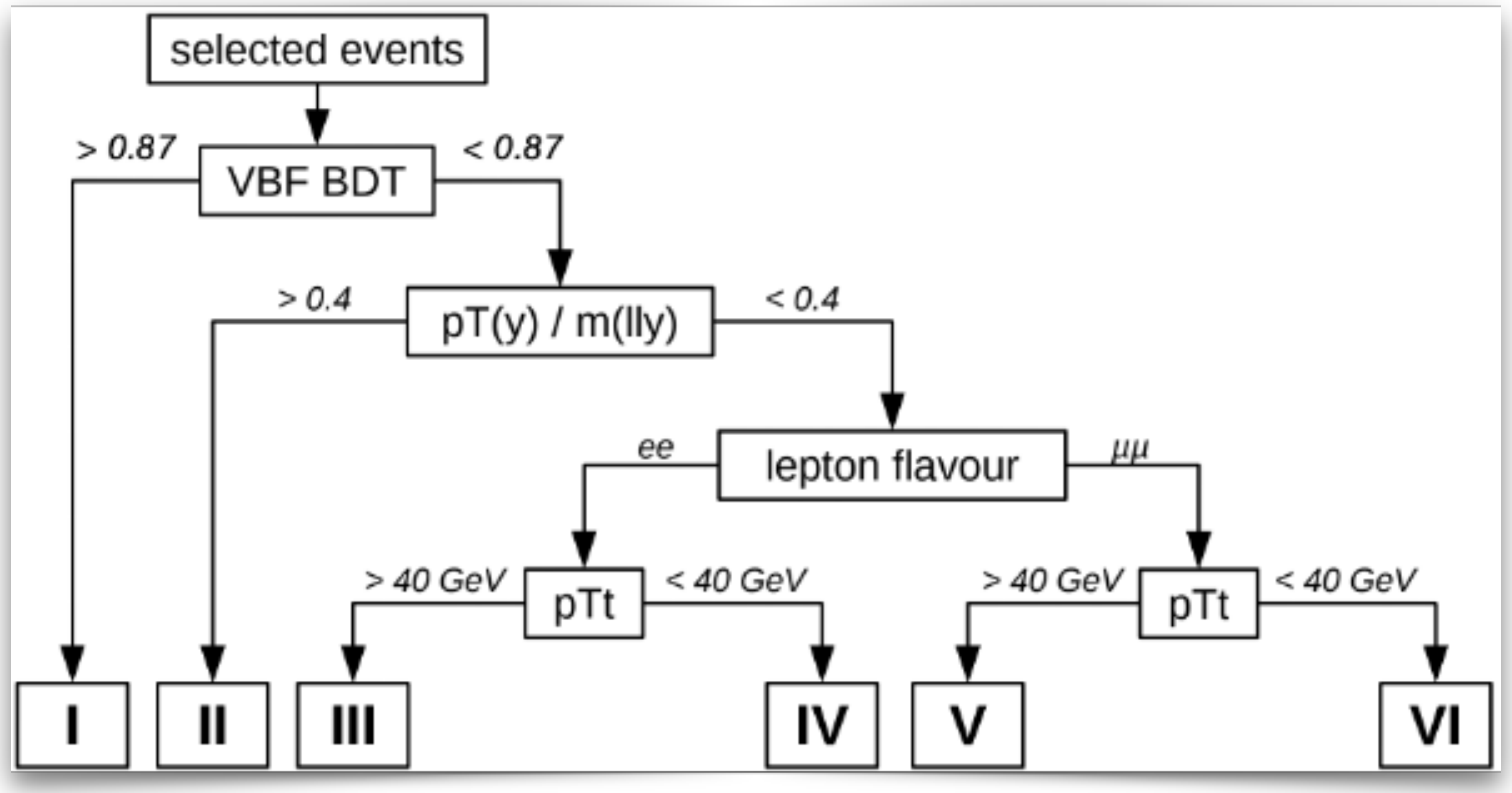
Z (ee or $\mu\mu$)
m_{ll} resolution correction (10 ~ 14%)
Kinematic fit
FSR correction
$50 < m_{ll} < 101$ GeV before correction
$|m_{ll} - m_Z| < 10$ GeV after

Leading γ

Higgs: $Z + \gamma$
$p_T^{\gamma}/m_{Z\gamma} > 0.12$
SR: $105 < m_{Z\gamma} < 160$ GeV
Sig efficiency: 20%

Categorization

- Events are classified into 6 categories to improve the sensitivity of the signal

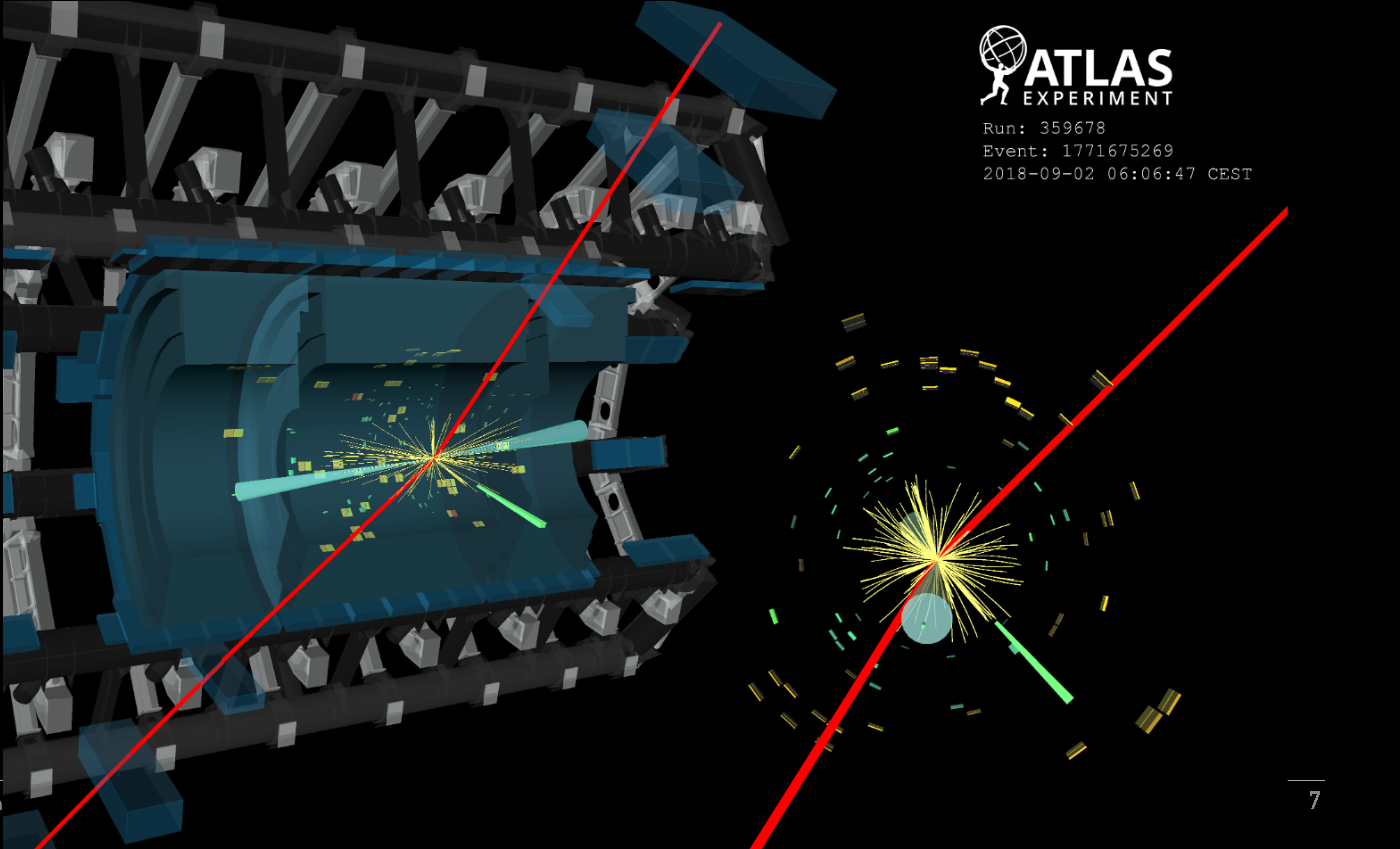


- The boundaries of the categories are determined to maximize the signal significance

Category	Events	S_{68}	B_{68}	w_{68} [GeV]	S_{68}/B_{68} [10^{-2}]	$S_{68}/\sqrt{S_{68}+B_{68}}$
VBF-enriched	194	2.7	18.7	3.7	14.3	0.58
High relative p_T	2276	7.6	112.8	3.7	6.7	0.69
High p_{Tt} ee	5567	9.9	444.0	3.8	2.2	0.46
Low p_{Tt} ee	76 679	34.5	6654.1	4.1	0.5	0.42
High p_{Tt} $\mu\mu$	6979	12.0	610.8	3.9	2.0	0.48
Low p_{Tt} $\mu\mu$	100 876	43.5	8861.5	4.0	0.5	0.46
Inclusive	192 571	110.2	16 701.9	4.0	0.7	0.85

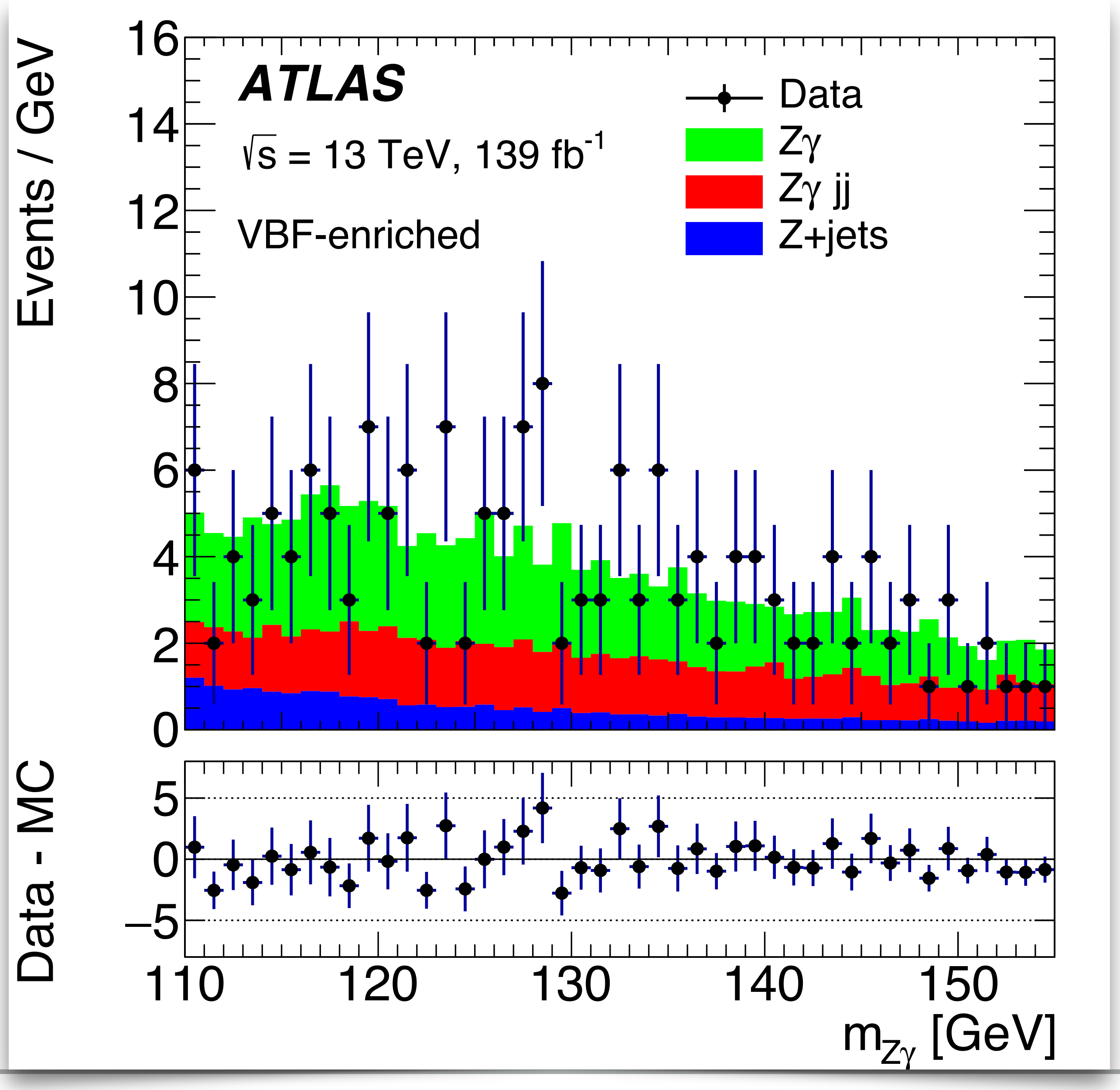
$$\sqrt{\sum Z_i^2} = 1.3$$

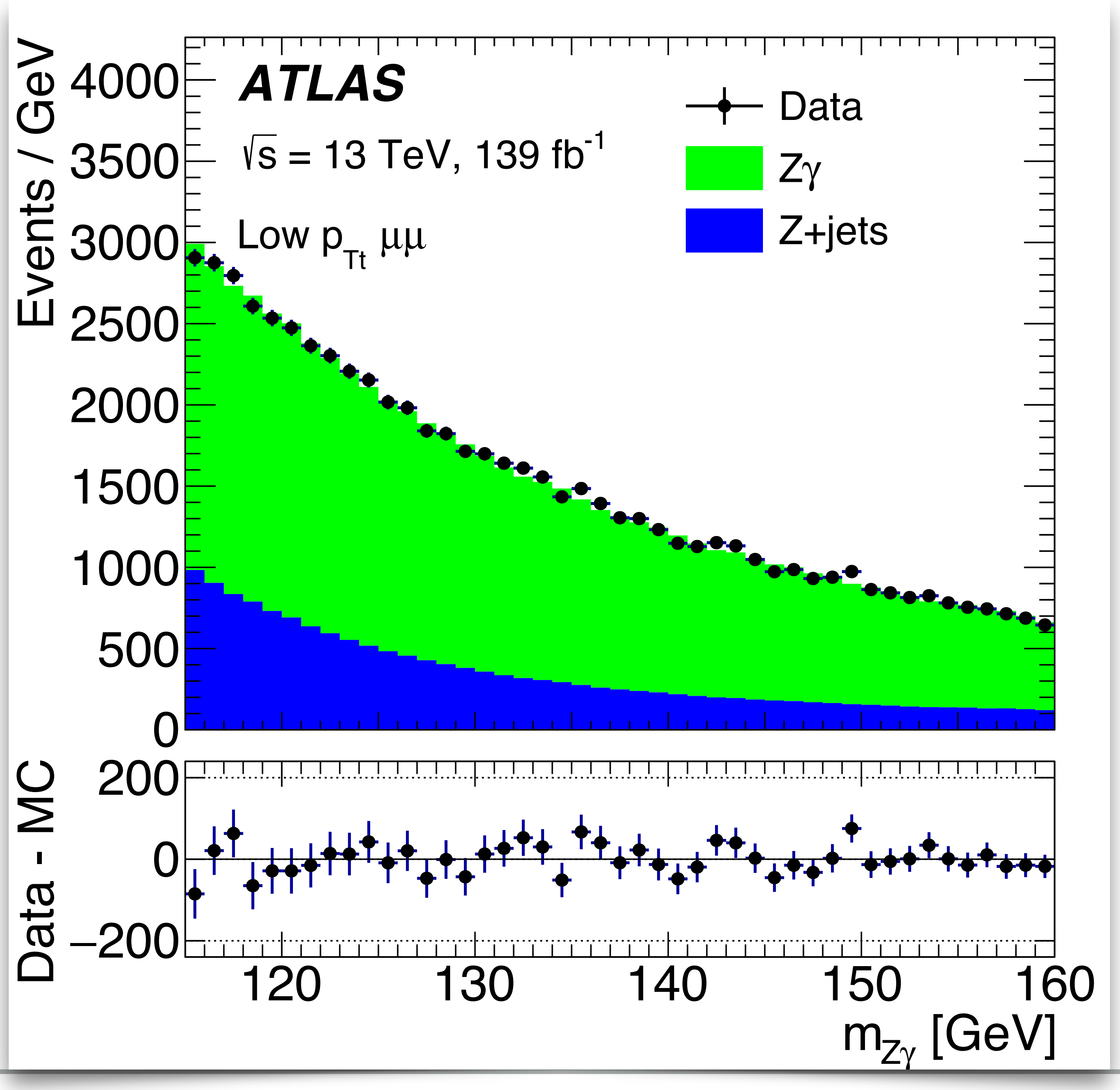
- The categorization improves the sensitivity by ~50% than the inclusive case


ATLAS
EXPERIMENT
Run: 359678
Event: 1771675269
2018-09-02 06:06:47 CEST

Background composition

- Background components: dominant $Z\gamma$, secondary $Z+j$ where jet is misidentified as photon
- 2D sideband method is applied to estimate fractions of background components
- The fraction of $Z\gamma$ background in inclusive case is $0.78^{+0.04}_{-0.09}$
- Data VS background template

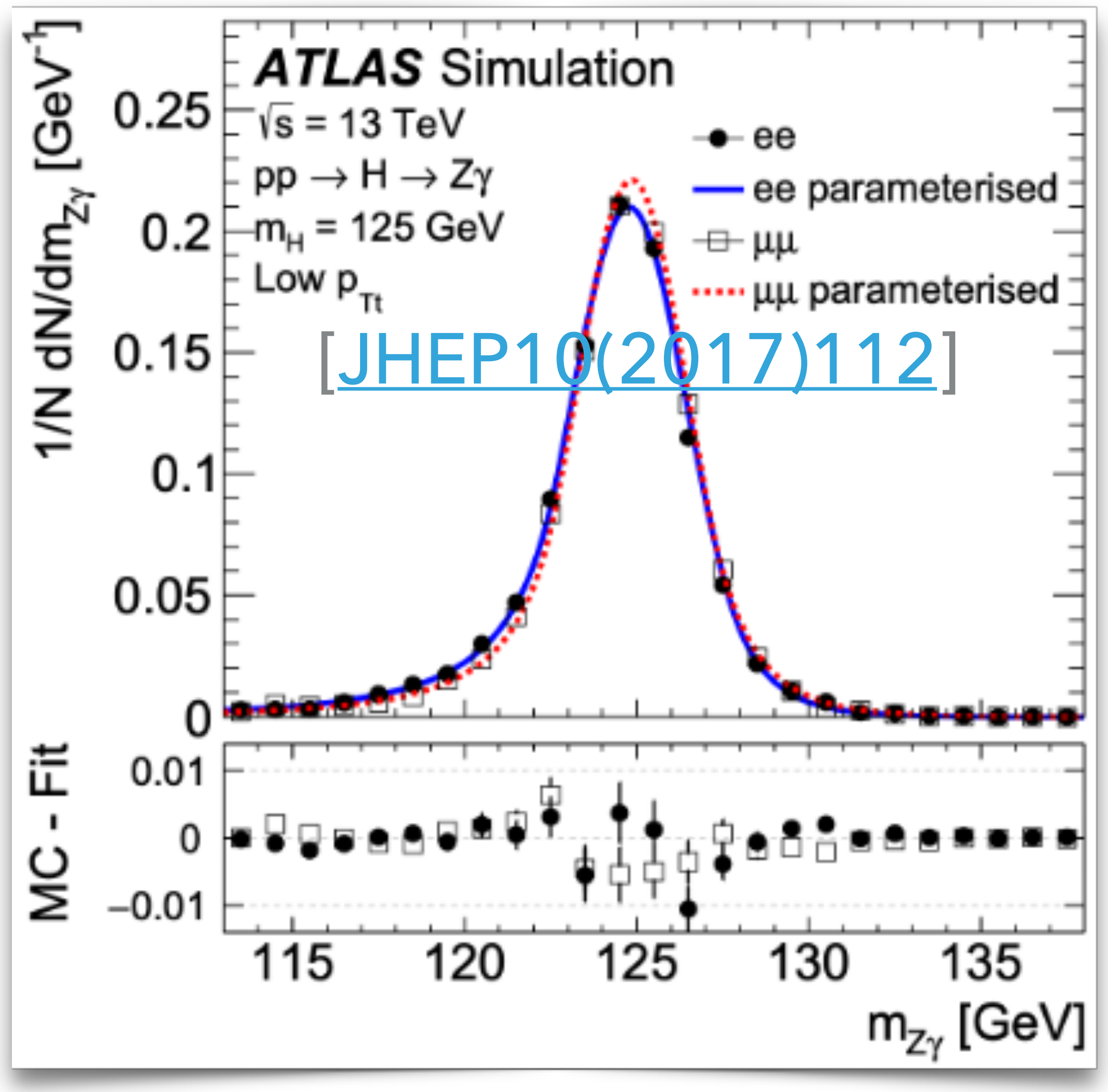




Signal/Background modeling

- The signal and background is extracted from $m_{Z\gamma}$ fit in data, assuming parametric models for signal and background
- Signal
  - Acceptance and parameters of the shape are obtained from MC
  - Well modeled by Double Sided Crystal Ball (DSCB) function

$$f(t) = N \times \begin{cases} e^{-\frac{1}{2}t^2} & \text{if } -\alpha_L \le t \le \alpha_H \\ e^{-\frac{1}{2}\alpha_L^2}[\frac{\alpha_L}{n_L}(\frac{n_L}{\alpha_L} - \alpha_L - t)]^{-n_L} & \text{if } t < -\alpha_L \\ e^{-\frac{1}{2}\alpha_H^2}[\frac{\alpha_H}{n_H}(\frac{n_H}{\alpha_H} - \alpha_H + t)]^{-n_H} & \text{if } t > \alpha_H \end{cases} \quad , t = (m_{Z\gamma} - \mu_{CB})/\sigma_{CB}$$



[JHEP10(2017)112]

- Background
  - Models are chosen using bkg template, value of parameters are determined by fitting $m_{Z\gamma}$ in data
  - The choice of analytical model and $m_{Z\gamma}$ fit range are optimized with spurious signal (details in backup) method
  - The optimal fit range and function are selected to achieve the highest expected signal significance, including the SS uncertainty

Category	Function Type	Fit range [GeV]
VBF-enriched	Second-order power function	110–155
High relative p_T	Second-order exponential polynomial	105–155
ee high p_{Tt}	Second-order Bernstein polynomial	115–145
ee low p_{Tt}	Second-order exponential polynomial	115–160
$\mu\mu$ high p_{Tt}	Third-order Bernstein polynomial	115–160
$\mu\mu$ low p_{Tt}	Third-order Bernstein polynomial	115–160

Systematic uncertainties

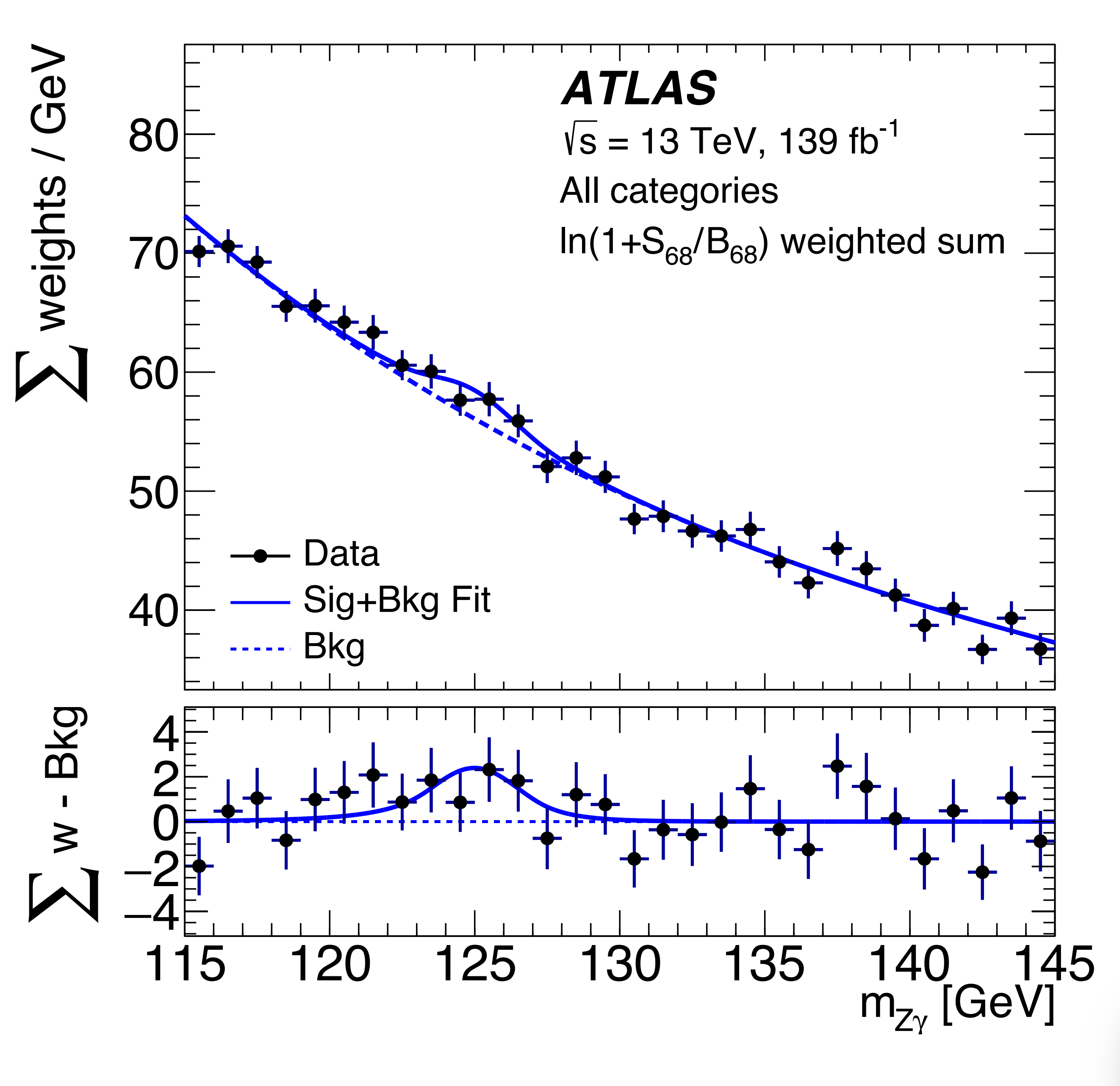
Uncertainty	$\Delta\mu/\mu$ (exp.)
Statistical uncertainty	82.8%
Spurious signal	28.4%
e/γ scale, resolution	2.4%
Luminosity	1.6%
Photon efficiency	1.8%
Jet	1.1%
Electron, Higgs mass, Muon, $H \to \mu\mu$ normalization, PRW	2.1%
QCD scale	6.1%
BR($H \to Z\gamma$) uncertainty	5.9%
UEPS	2.1%
PDF, α_s	2.8%
Total	88.1%

Dominant

Leading systematics

- All systematics have secondary contributions to the total uncertainty due to large statistical error

Result



Category	μ	Significance
VBF-enriched	$0.5^{+1.9}_{-1.7}$ $(1.0^{+2.0}_{-1.6})$	0.3 (0.6)
High relative p_T	$1.6^{+1.7}_{-1.6}$ $(1.0^{+1.7}_{-1.6})$	1.0 (0.6)
High p_{Tt} ee	$4.7^{+3.0}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low p_{Tt} ee	$3.9^{+2.8}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High p_{Tt} $\mu\mu$	$2.9^{+3.0}_{-2.8}$ $(1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low p_{Tt} $\mu\mu$	$0.8^{+2.6}_{-2.6}$ $(1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

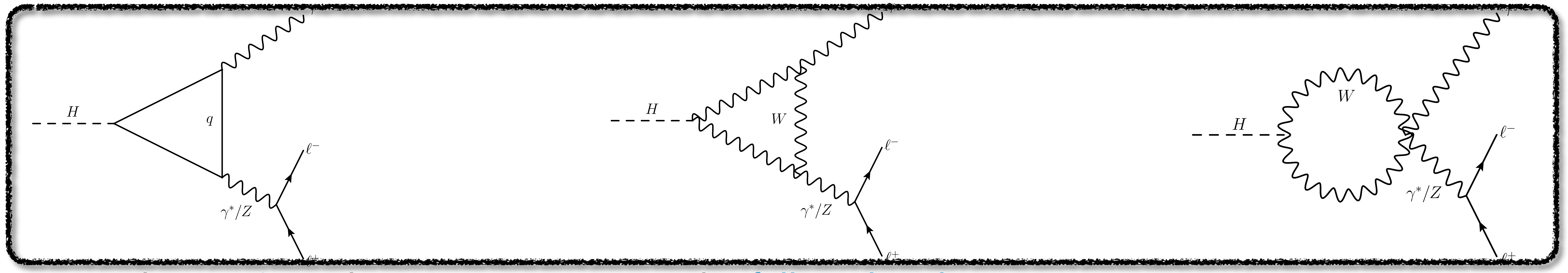
- $\mu = \frac{\sigma \times B}{(\sigma \times B)^{SM}} = 2.0 \pm 0.9(stat.)^{+0.4}_{-0.3}(syst.)$
- Exp $\mu = 1.0 \pm 0.8(stat.) \pm 0.3(syst.)$
- Total uncertainty is mainly contributed from statistical error
- Dominant systematics: SS uncertainty

Most stringent!	μ	$B(H \to Z\gamma)$	$\sigma(pp \to H) \times B(H \to Z\gamma)$
95% CL upper limit	3.6 (2.6) x SM	0.55%	305 fb

- Besides the increase the dataset, extra 20% improvement in expected sensitivity compared with the 36 fb^{-1} publication is from the improved analysis strategy (optimal object recommendation, improved categorization, …)

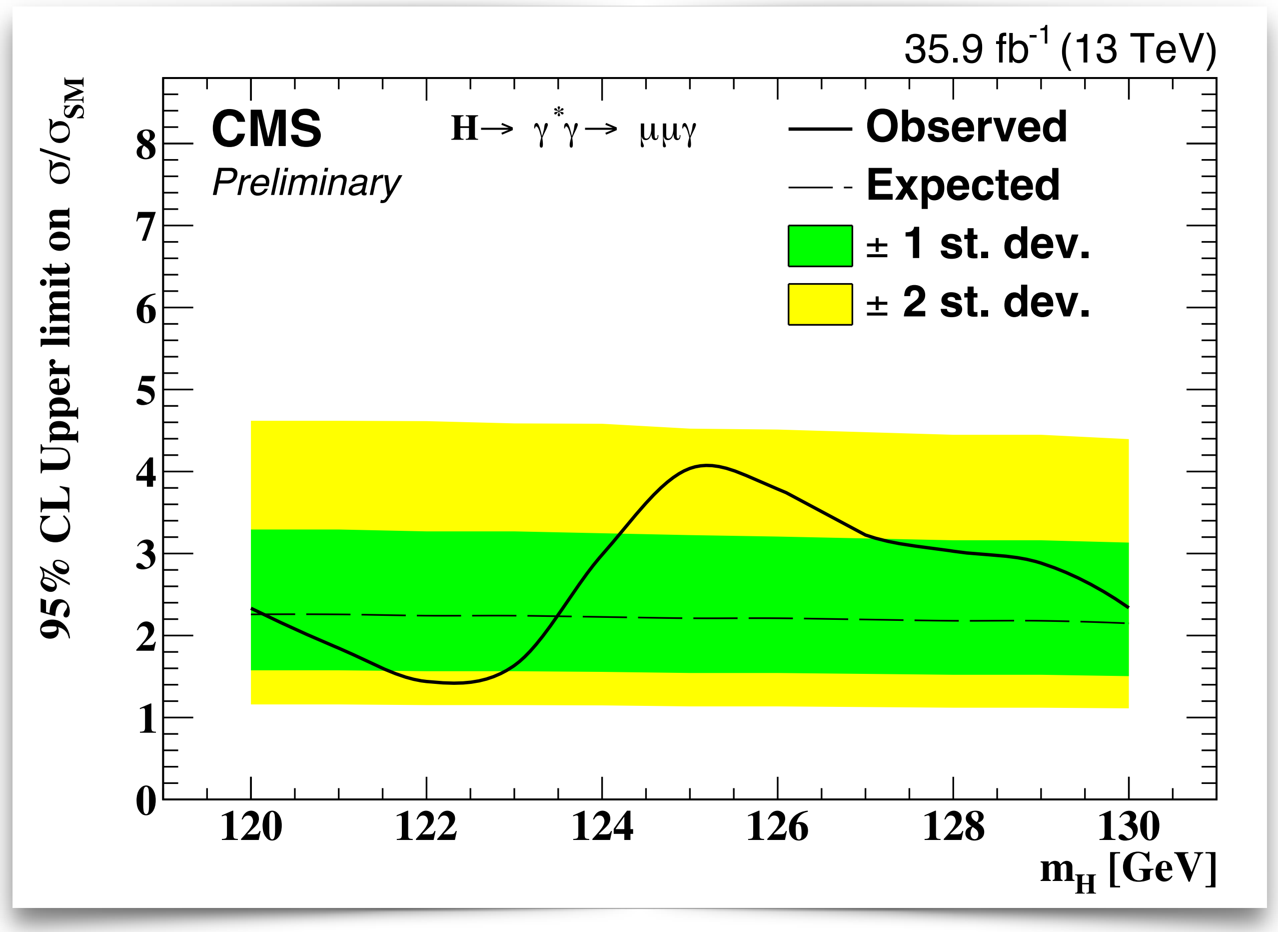
$H \to \gamma^*\gamma$ search

- $H \to \gamma^*\gamma \to ll\gamma$ ($m_{ll} < 30$ GeV) [Phys. Lett. B 819 (2021) 136412]
  - Complementary to the $Z\gamma$ search (lower m_{ll})
  - Paving the way for future analyses
    - CP properties of $ll\gamma$ final states [Eur. Phys. J. C 74 (2014) 3141], BSM couplings



- In the $H \to ll\gamma$ decay mode, $Z\gamma$, $\gamma^*\gamma$ and $\mu\mu(\gamma)$ processes can't be fully isolated
  - Fiducial cut: $m_{ll} < 30$ GeV, with dominant $H \to \gamma^*\gamma$
  - $B(H \to ee\gamma) = 7.20 \times 10^{-5}$, $B(H \to \mu\mu\gamma) = 3.42 \times 10^{-5}$

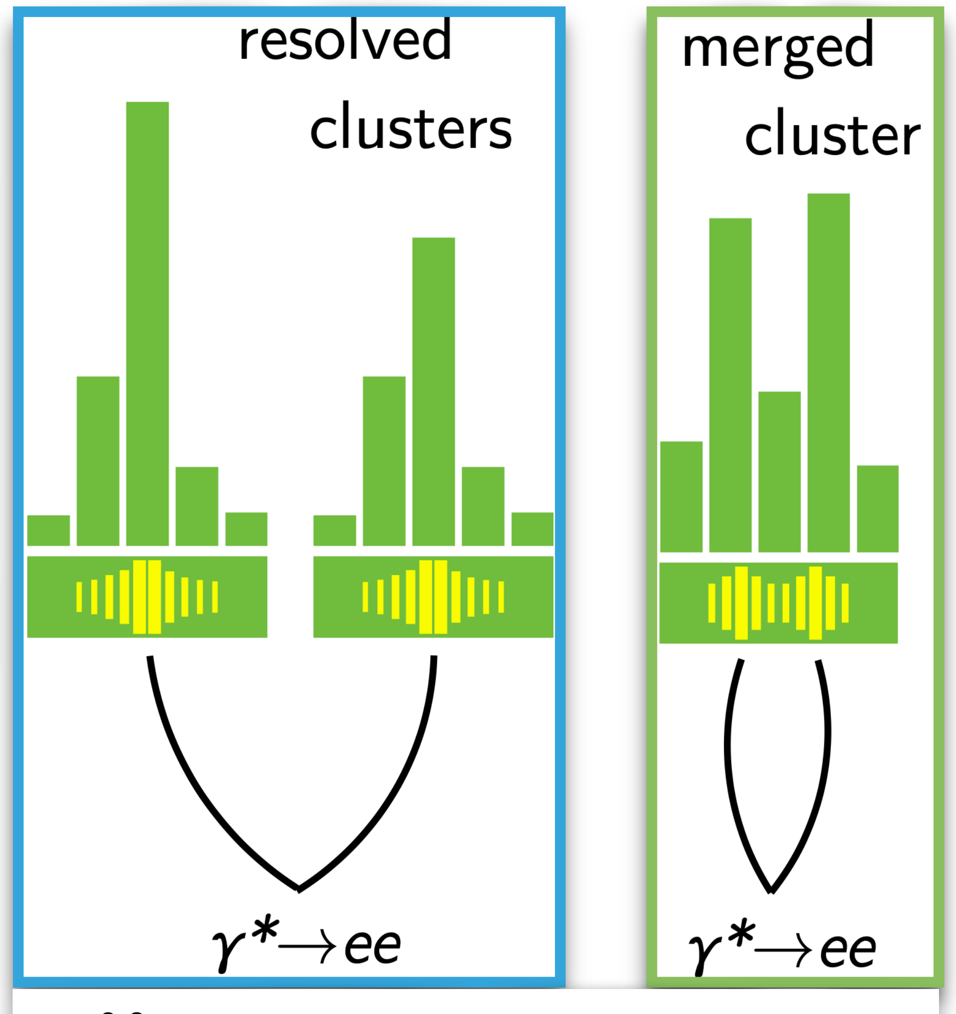
- Previous CMS result with 35.9 fb^{-1} data ($\mu\mu\gamma$) [CMS-PAS-HIG-17-007]
  - 95% CL exp. upper limit: 2.21 x SM



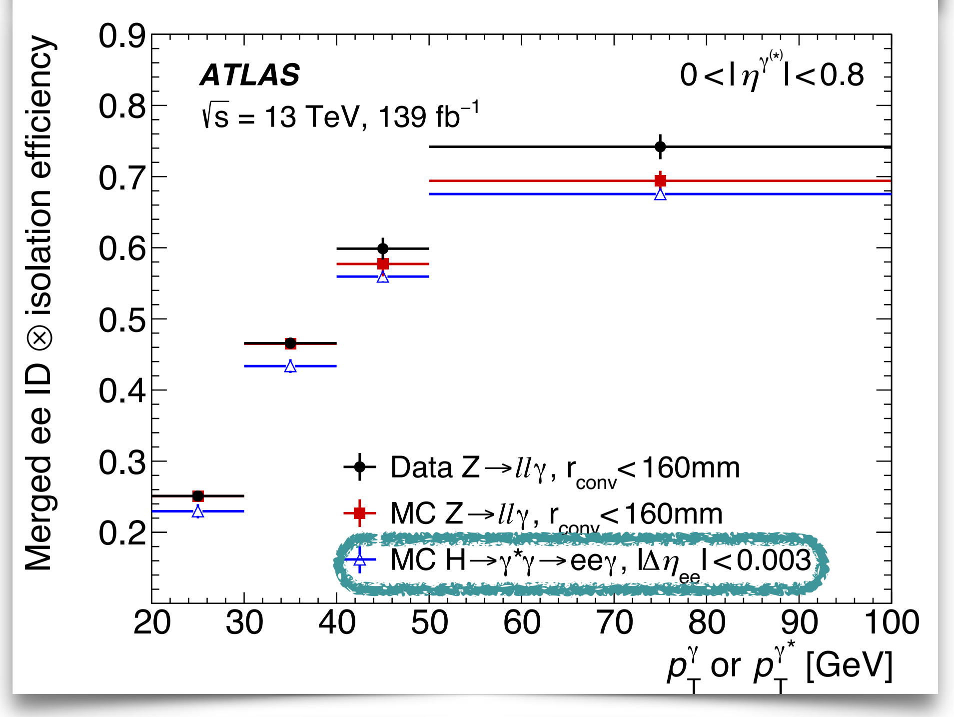
Objects/merged electron ID

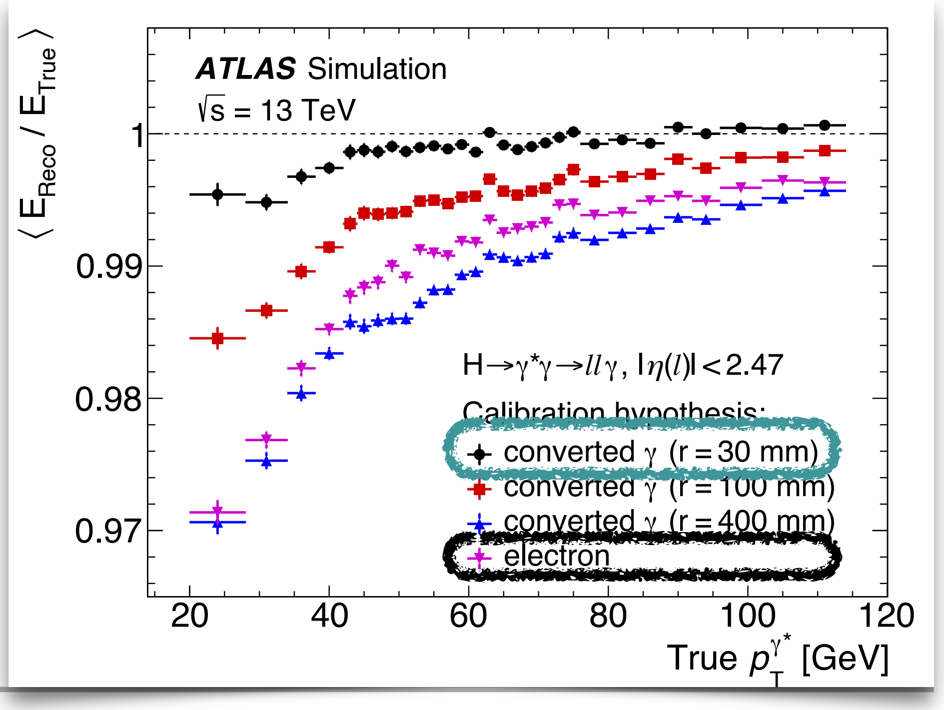
Cut	Photon	Resolved electron	Merged electron	Muon
p_T	>20 GeV	>4.5 GeV	>20 GeV	>3 GeV
Track		Innermost pixel hit		
		$d_0/\sigma_{d0} < 3$, $\lvert Z_0 \sin\theta \rvert < 0.5$ mm		
ID	Tight	Medium	Custom (TMVA)	Medium

- Single-l, $2l$, $\gamma - l$, $\gamma\gamma$, $\gamma - 2l$ triggers
  - e: dedicated $e - \gamma$ trigger with relaxed ID to allow merged electrons



- Merged electron ID
  - Due to spoiled shower shape variables, merged electrons perform badly with standard electron IDs
  - Derive dedicated ID using TMVA, efficiency: ~50%
  - Extract efficiency SF with early converted γ from $Z \to ll\gamma$ events
- Merged electron calibration
  - Due to small ΔR, merged electrons show bias using standard electron calibrations
  - Calibrate γ^* as an early converted photon ($r = 30$ mm), generally good performances





Event selection/categorization

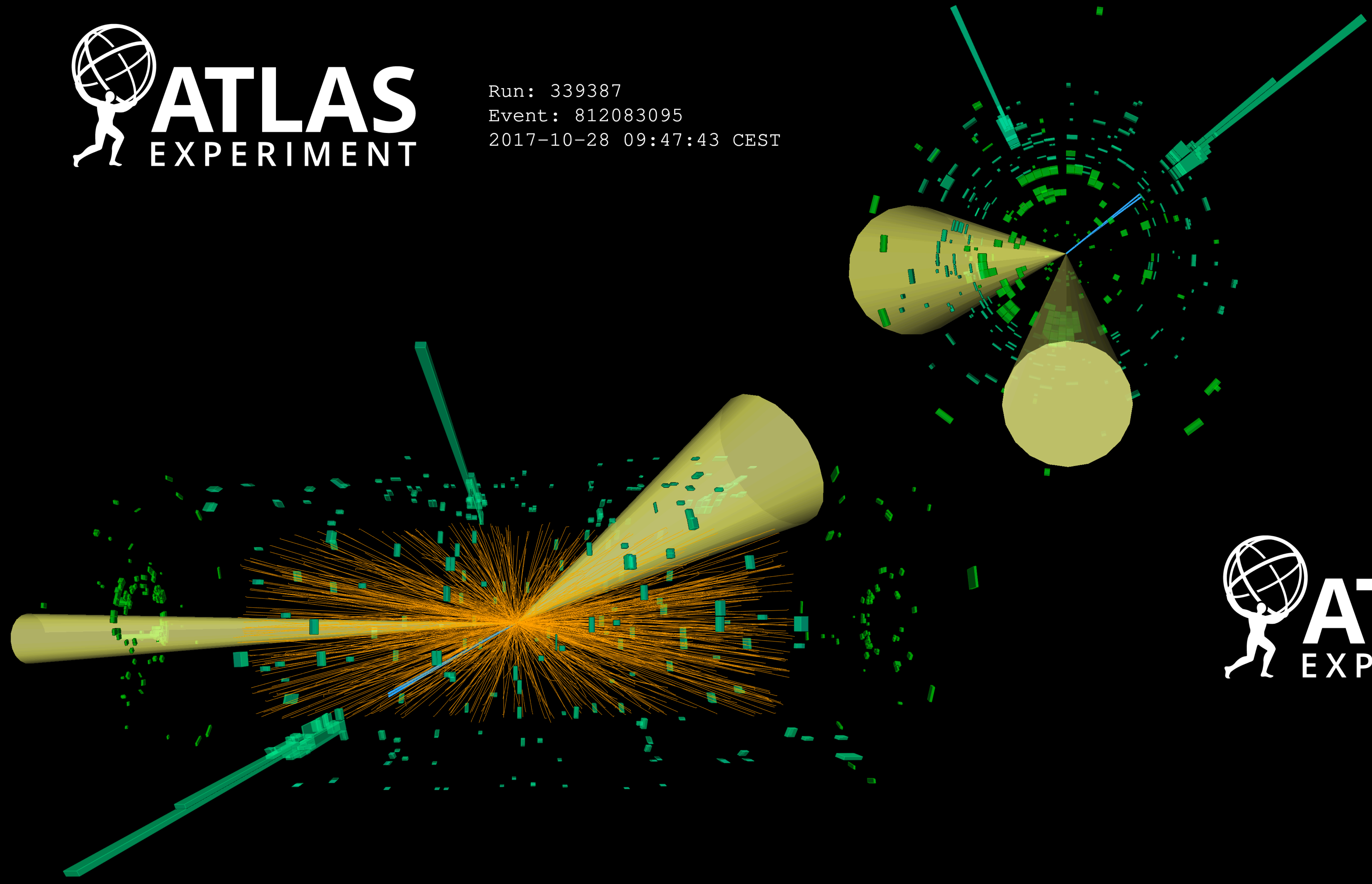
Event selection	
$m_{ll} < 30$ GeV	Suppress $Z \to ll$
$110 < m_{ll\gamma} < 160$ GeV	SR
$ee\gamma$: veto $2.5 < m_{ll} < 3.5$ GeV	Remove $J/\psi \to ll$
veto $8.0 < m_{ll} < 11.0$ GeV	
$\mu\mu\gamma$: veto $2.9 < m_{ll} < 3.3$ GeV	
veto $9.1 < m_{ll} < 10.6$ GeV	Remove $\Upsilon(nS) \to ll$
$p_T^{ll}/m_{ll\gamma} > 0.3$	
$p_T^{\gamma}/m_{ll\gamma} > 0.3$	

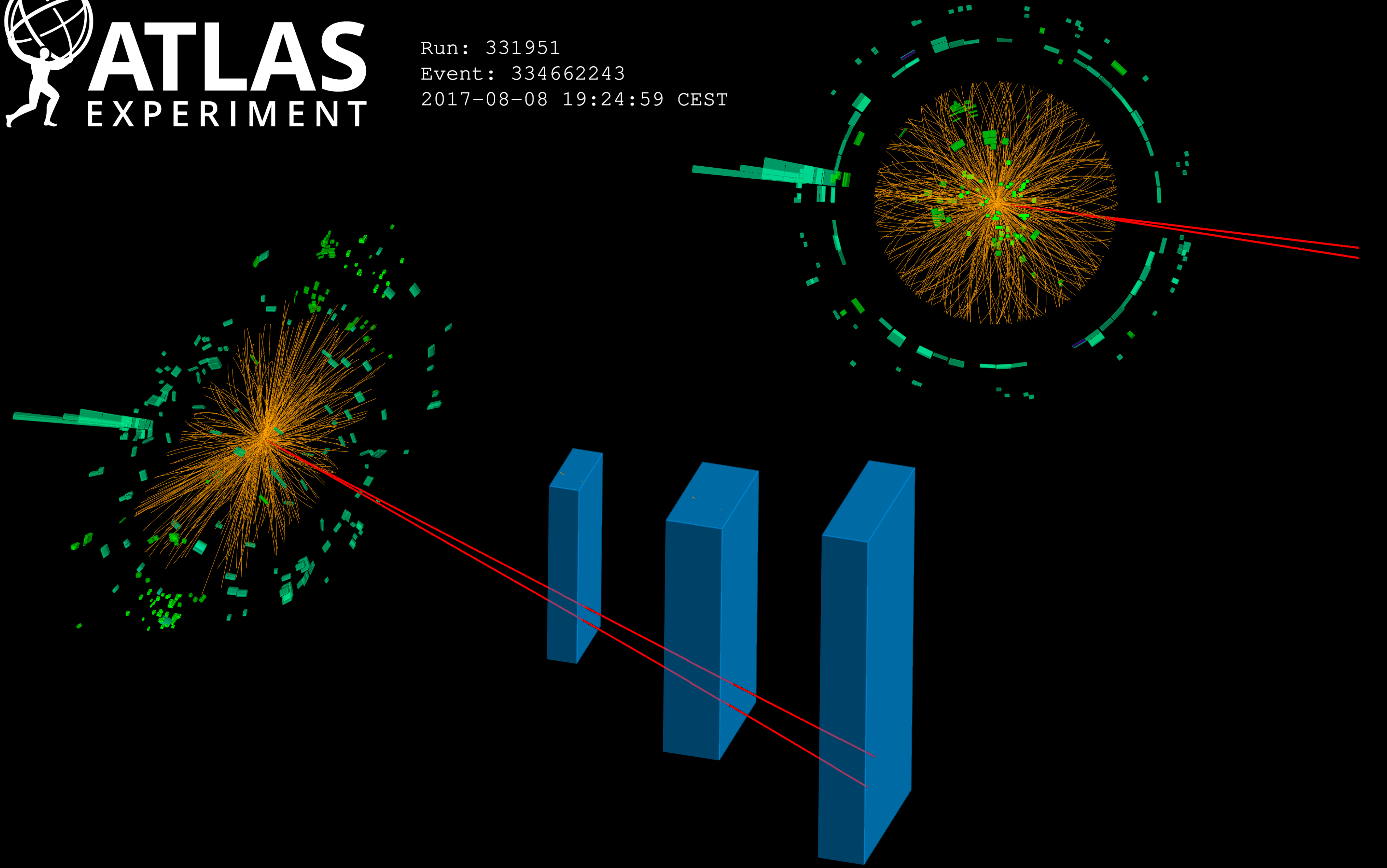
Category	Definition
VBF	$N_j \geq 2$, $p_T^j > 25$ GeV, $p_T^j > 30$ GeV ($\lvert\eta\rvert > 2.5$) $m_{jj} > 500$ GeV, $\lvert\eta_{Zepp}\rvert < 2$, $\Delta\eta_{jj} > 2.7$ $\Delta\phi(ll\gamma, jj) > 2.8$ $\min(\Delta R(\gamma/l, j)) > 1.5$
High p_{Tt}	Fails VBF category, $p_{Tt} > 100$ GeV
Low p_{Tt}	Remaining events

X 3 channels (9): resolved electron, merged electron, muon

- Event selections/categorization are determined with best expected significances

Category	Events	S_{90}	B_{90}^{N}	$B_{H\to\gamma\gamma}$	f_{90} [%]	Z_{90}
ee resolved VBF-enriched	10	0.4	1.6	0.009	20	0.3
ee merged VBF-enriched	15	0.8	2.0	0.07	27	0.5
$\mu\mu$ VBF-enriched	33	1.3	5.9	-	18	0.5
ee resolved high-p_{Tt}	86	1.1	12	0.02	9	0.3
ee merged high-p_{Tt}	162	2.5	18	0.2	12	0.6
$\mu\mu$ high-p_{Tt}	210	4.0	34	-	11	0.7
ee resolved low-p_{Tt}	3713	22	729	0.5	2.9	0.8
ee merged low-p_{Tt}	5103	29	942	2	3.0	1.0
$\mu\mu$ low-p_{Tt}	9813	61	1750	-	3.4	1.4

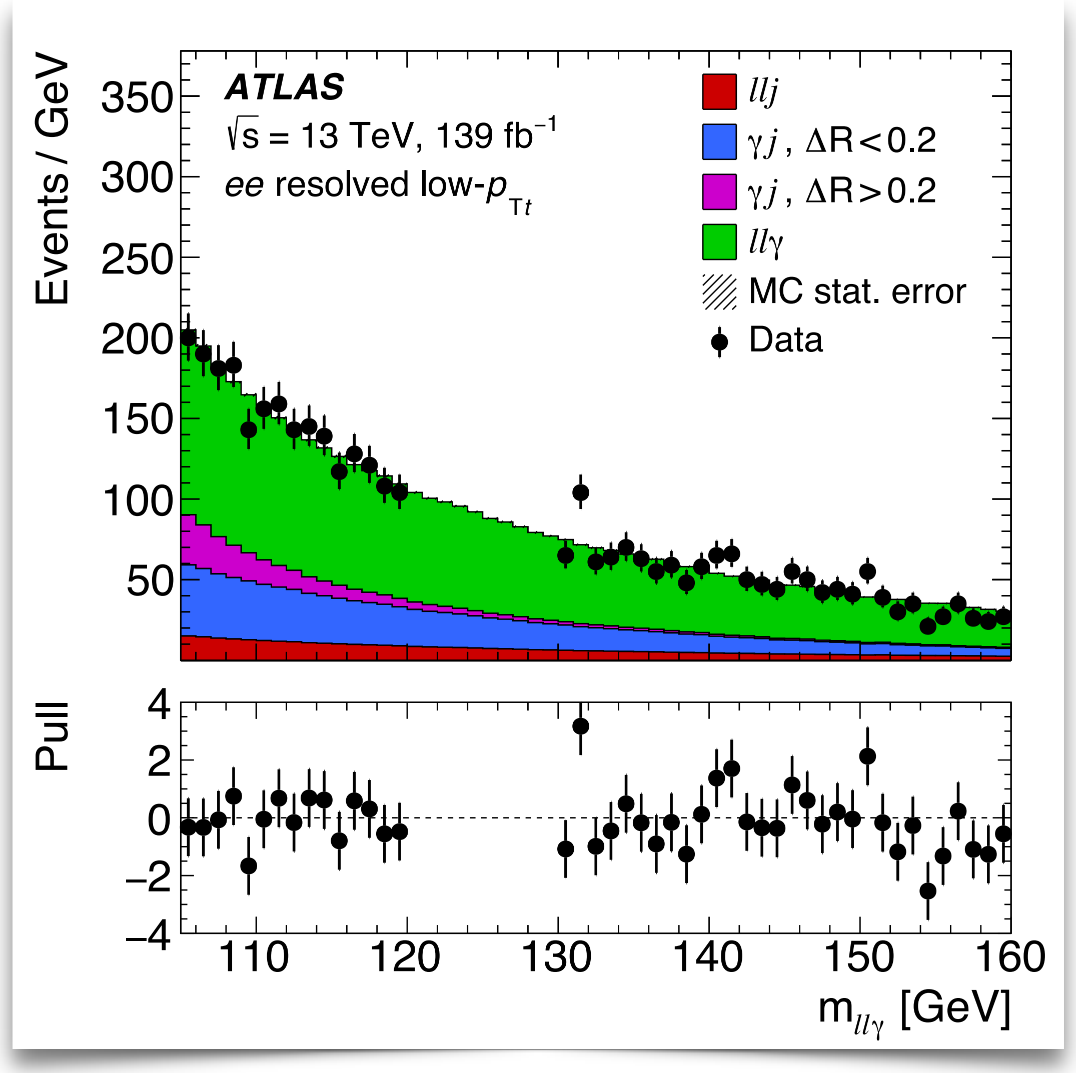


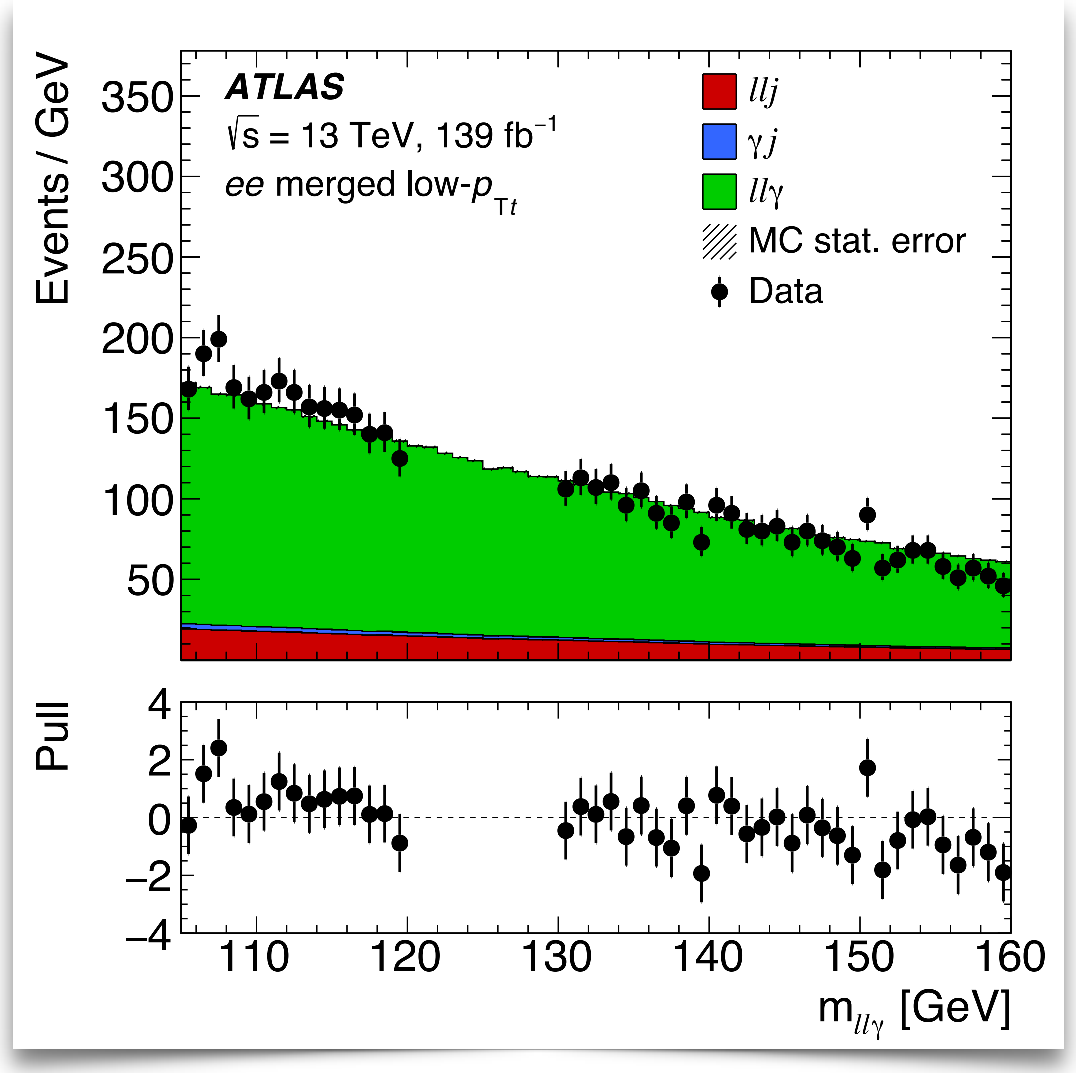


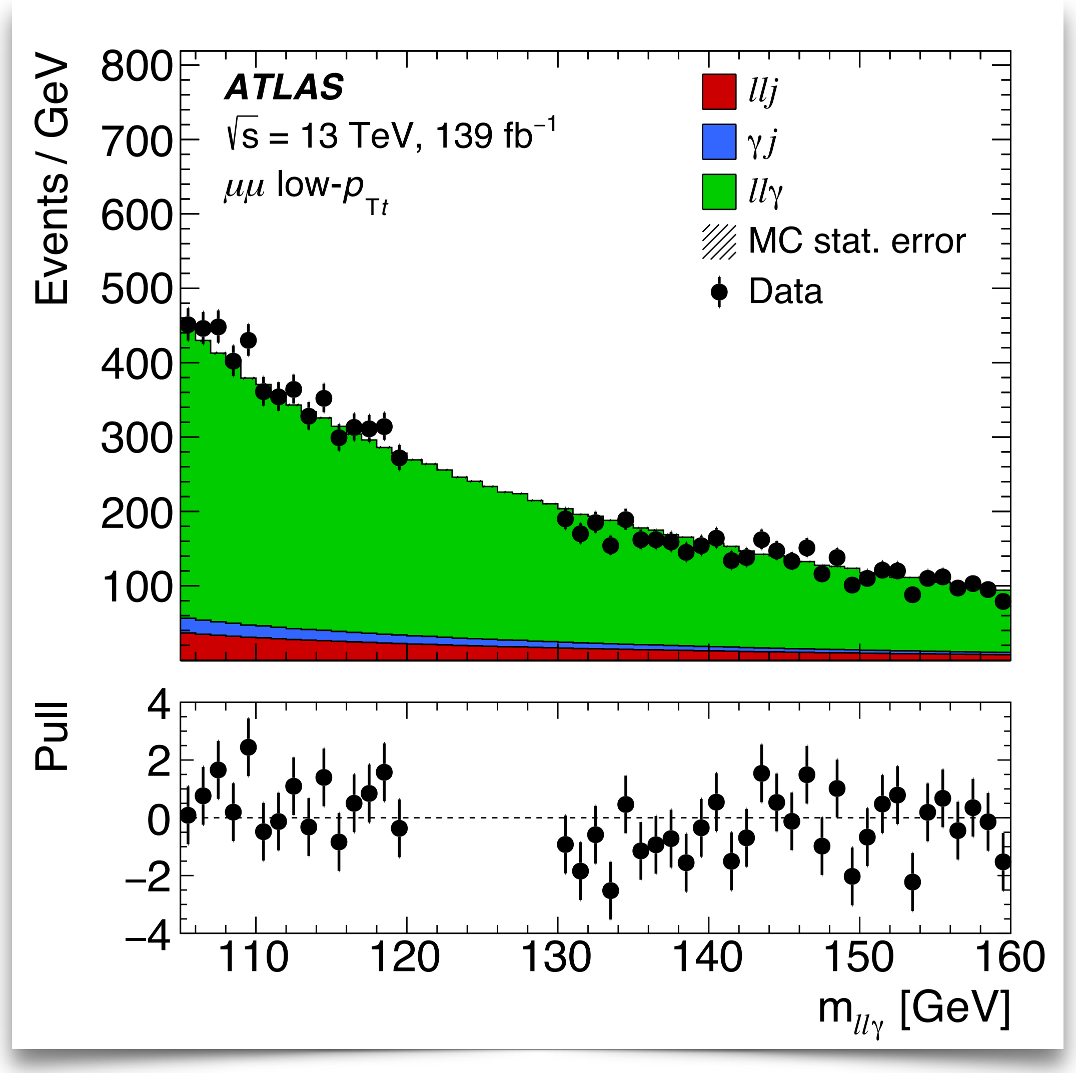
Search for rare and lepton flavor violating decays of the Higgs boso

Continuous bkg estimation

- Dominant $ll\gamma$, secondary jet events, where jets are mis-identified as γ, l
- Template/ABCD method is used to estimate fractions of background components
  - Jet fake rate $j \to \gamma$: 6-11%; $j \to \mu$: 4-15% ; $j \to e$: 2-27%





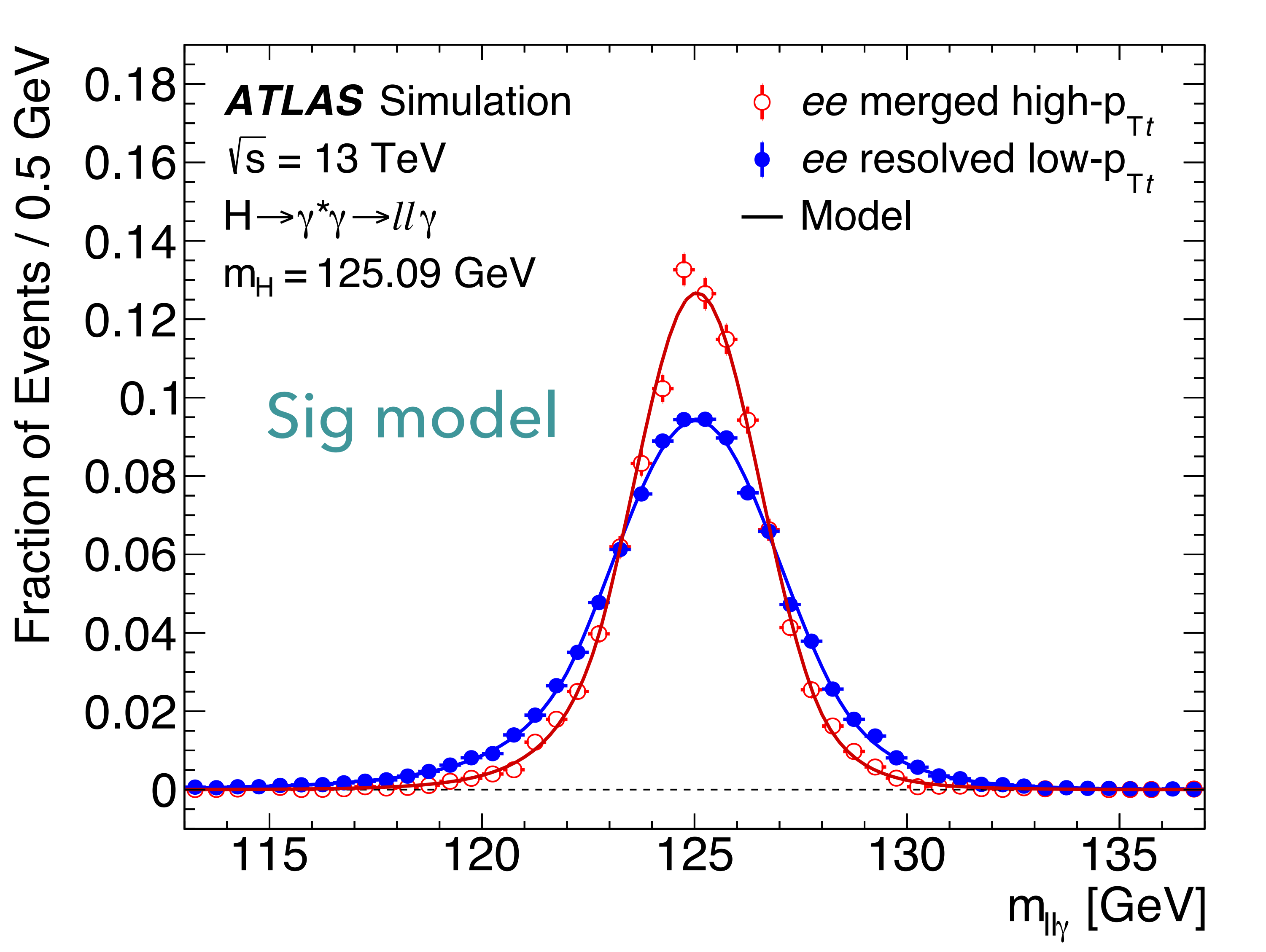


- Good agreement with data sidebands
  - The templates are used for function selection

Signal/Background parameterization

- Analysis strategy: simultaneous fit on $m_{ll\gamma}$ distribution with S+B models in the SR: [110,160] GeV
  - Sig model (DSCB)
    - Inc. $H \rightarrow \gamma\gamma$ bkg, where one of the photons converts to di-electrons
  - Bkg model
    - Spurious signal method is used to select background functions with low bias (SS) and low DOF

Sig model



Bkg model

Category	Model
Inclusive Dimuon	ExpPoly2
Inclusive Resolved-e	Pow
Inclusive Merged-e	ExpPoly2
VBF Dimuon	Pow
VBF Resolved-e	Exponential
VBF Merged-e	Pow
High-$p_{\mathrm{TThrust}}^{\ell\ell\gamma}$ Dimuon	Pow
High-$p_{\mathrm{TThrust}}^{\ell\ell\gamma}$ Resolved-e	Pow
High-$p_{\mathrm{TThrust}}^{\ell\ell\gamma}$ Merged-e	Pow

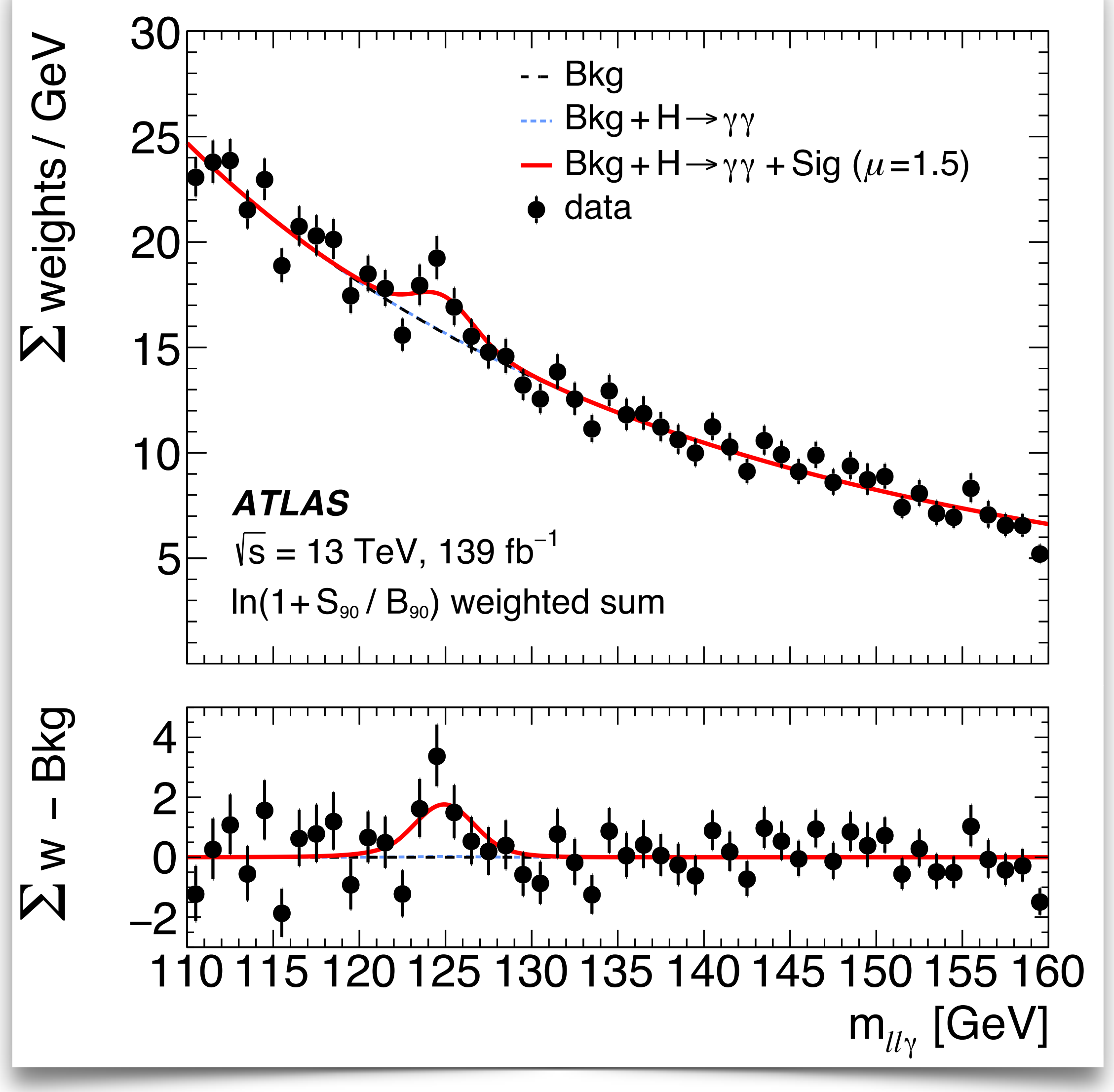
Systematic uncertainties

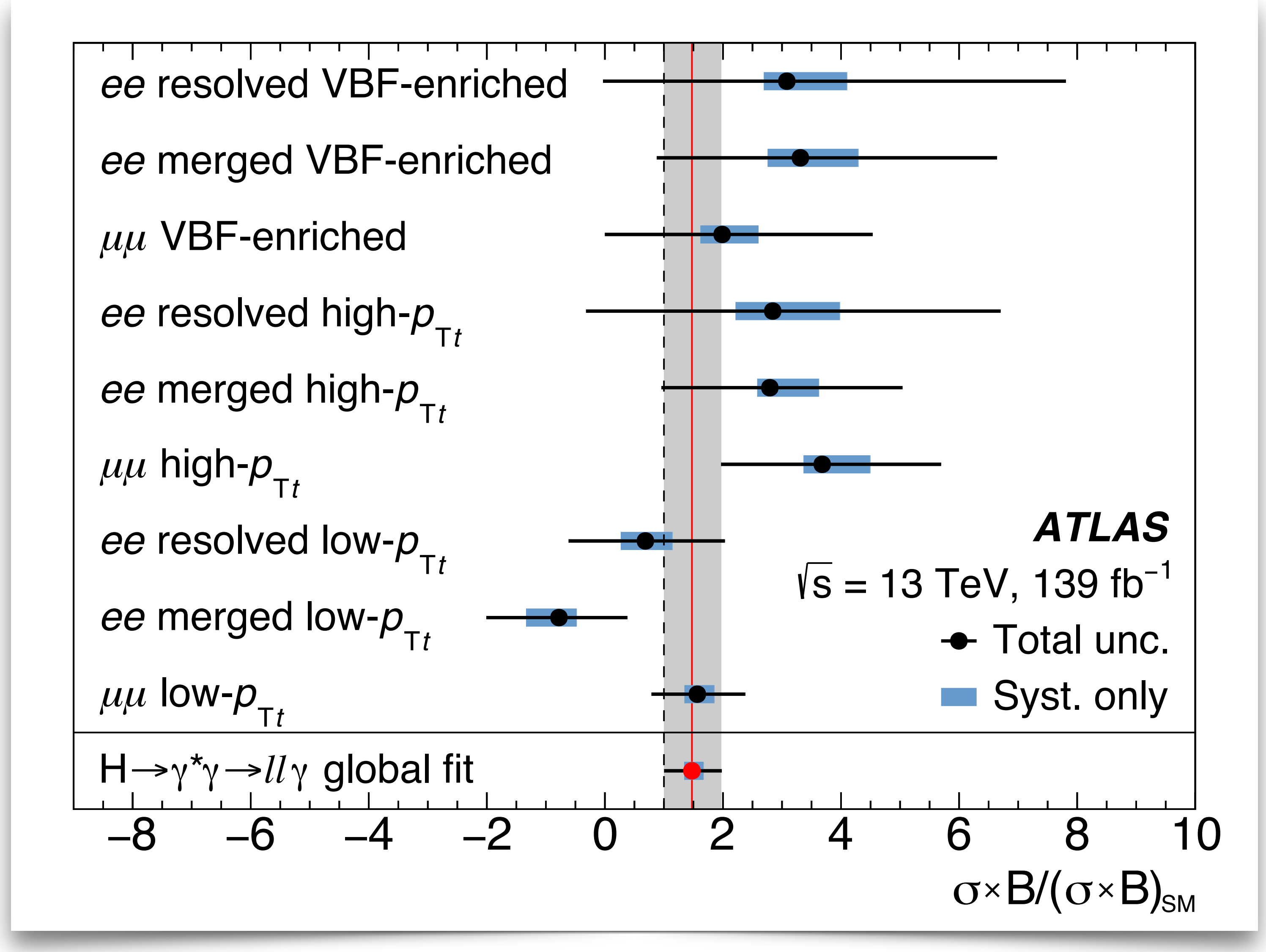
Uncertainty source [%]	μ	$\sigma \times \mathcal{B}$
Spurious Signal	6.1	
$\mathcal{B}(H \to \ell\ell\gamma)$	5.8	–
QCD scale	4.7	1.1
ℓ, γ, jets	4.0	
PDF	2.3	0.9
Luminosity	1.7	
Pile-up	1.7	
Minor prod. modes	0.8	
$H \to \gamma\gamma$ background	0.7	
Parton Shower	0.3	
Total systematic	11	7.9
Statistical	31	
Total	33	32

- Dominant systematics
  - Spurious Signal and lepton ID/calibration
- Theory uncertainties are reduced when performing the cross section measurement ($m_{ll} < 30$ GeV) as only acceptance effects are taken into account

Results

- First ATLAS $H \to ll\gamma$ result in $m_{ll} < 30$ GeV [Phys. Lett. B 819 (2021) 136412]





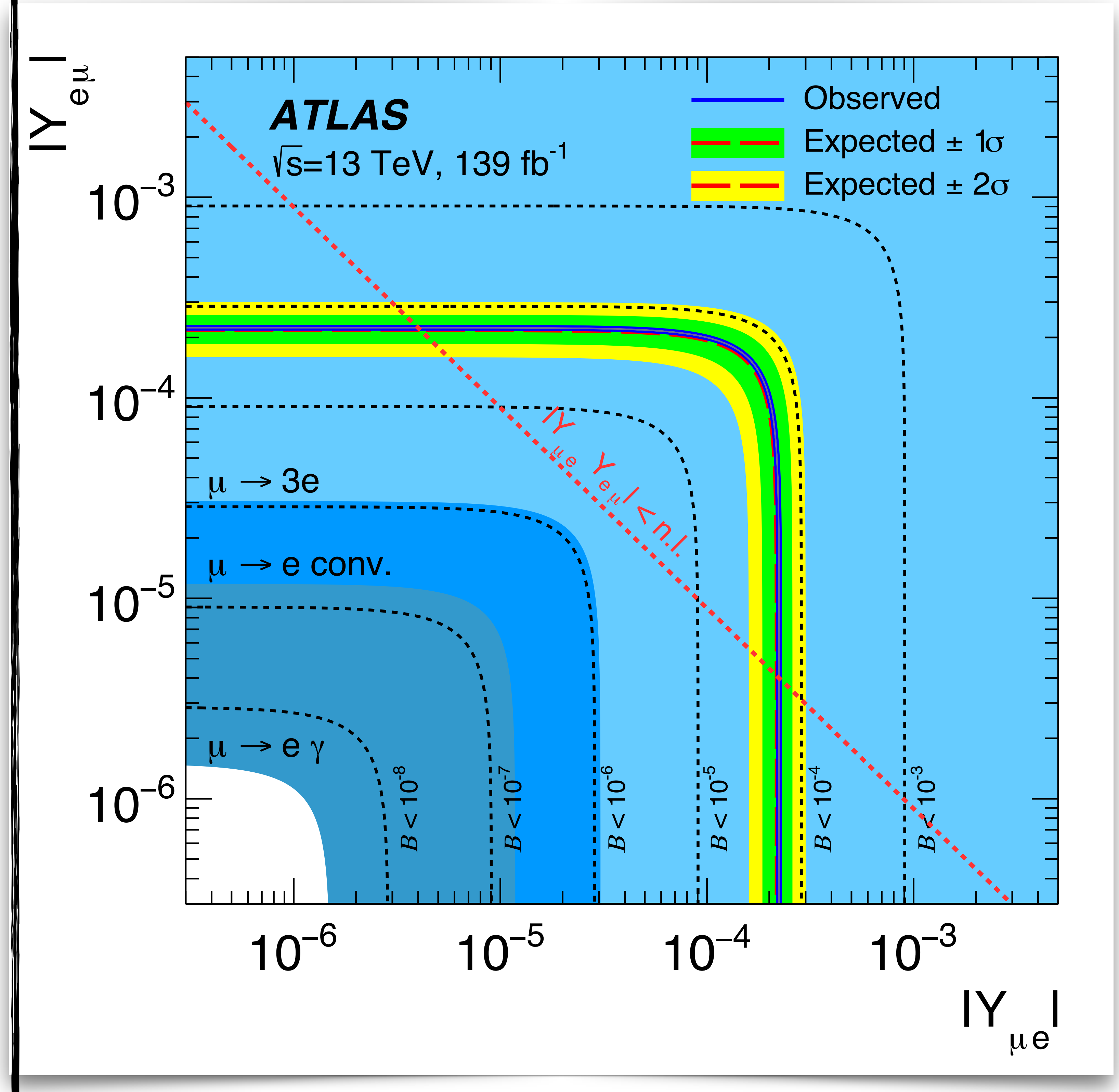
- Obs: $\mu = 1.5 \pm 0.5 = 1.5 \pm 0.5(stat.)^{+0.2}_{-0.1}(syst.)$
- Exp: $\mu = 1.0 \pm 0.5 = 1.0 \pm 0.5(stat.)^{+0.2}_{-0.1}(syst.)$
- $\sigma \times BR = 8.7^{+2.8}_{-2.7}$ fb $= 8.7 \pm 2.7(stat.)^{+0.7}_{-0.6}(syst.)$ fb
- Significance: 3.2σ (expected 2.1σ), first evidence!

- Signal strengths in categories are consistent with the global μ
- $\mu_{\mu\mu} = 2.0 \pm 0.7, \mu_{ee} = 1.0 \pm 0.7$

$H \to ee$ and $H \to e\mu$ LFV

- First searches [Phys. Lett. B 801 (2020) 135148] in ATLAS
- The searches complete the ATLAS measurements for Higgs boson to charged lepton decays

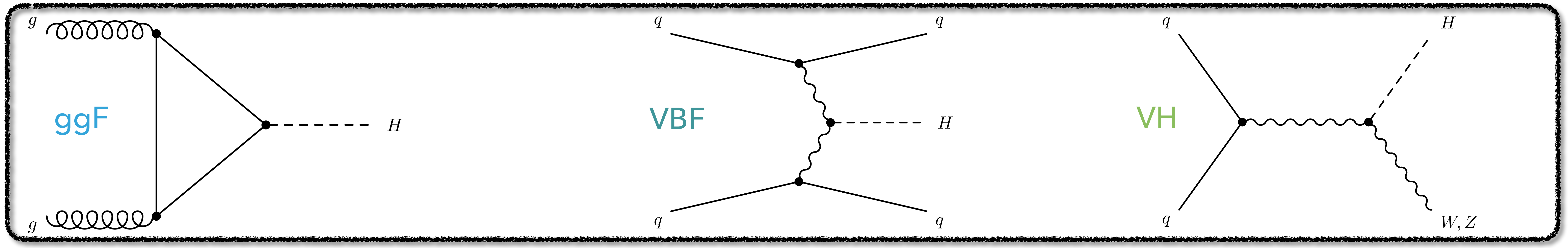
- $H \to ee$
  - $B(H \to ee) = 5 \times 10^{-9} \to$ far below sensitivity of the LHC
  - Bkg: dominating $Z/\gamma^* \to ee, t\bar{t}$
  - Interesting to check for BSM contributions
- $H \to e\mu$
  - BSM lepton-flavour-violating (LFV) decay
  - Strong indirect constraints on the off-diagonal Yukawa coupling $Y_{e\mu}$
  - Smaller backgrounds wrt $H \to ee$: $Z \to \tau\tau, WW, t\bar{t}$



MC/Data

- Full Run2 dataset, 139 fb^{-1}

- Signal



- Backgrounds $H \to ee$
  - $Z \to ee$ and VV, $t\bar{t}$
- Backgrounds $H \to e\mu$
  - Same MCs with $H \to ee$, + $Z \to \tau\tau \to l\nu\nu l\nu\nu$

Selection/Categorization

Object

	Electron	Muon	Jet
ID/Type	Loose LH	Loose	AntiKt4EMTopo
p_T [GeV]	>15		>25 ($\|\eta\| < 2.4$) >30 ($2.4 < \|\eta\| < 2.5$)
$\|\eta\|$	<2.47 (excl. crack)	<2.47 (derivation)	<4.5

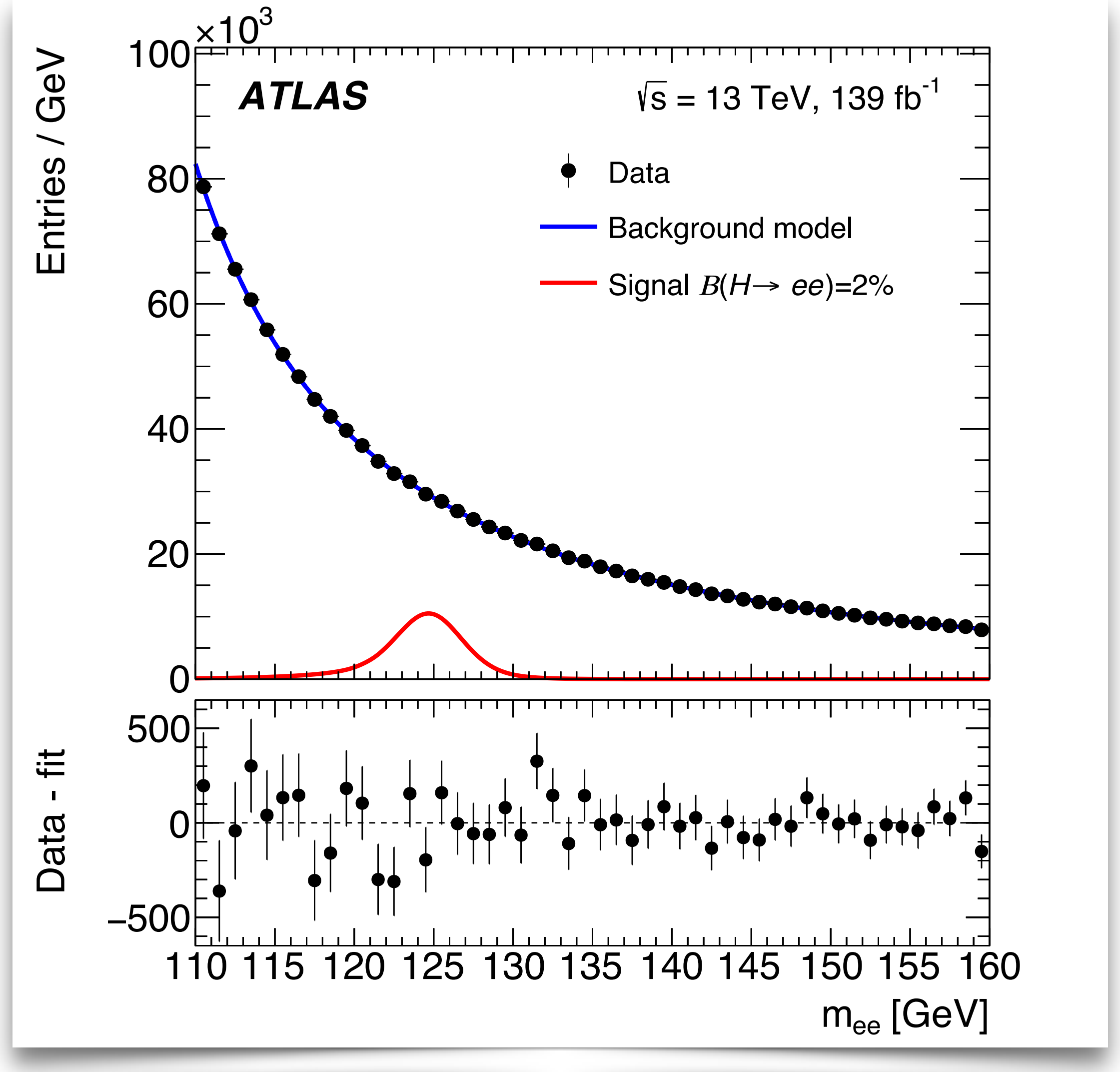
- $N_l \geq 2$, $p_T^{l1} > 27$ GeV, $p_T^{l2} > 15$ GeV
- $E_T^{miss}/\sqrt{H_T} < 3.5(1.75)$ GeV$^{1/2}$ in $ee(e\mu)$
- Remove events with at least one b-tagged jet

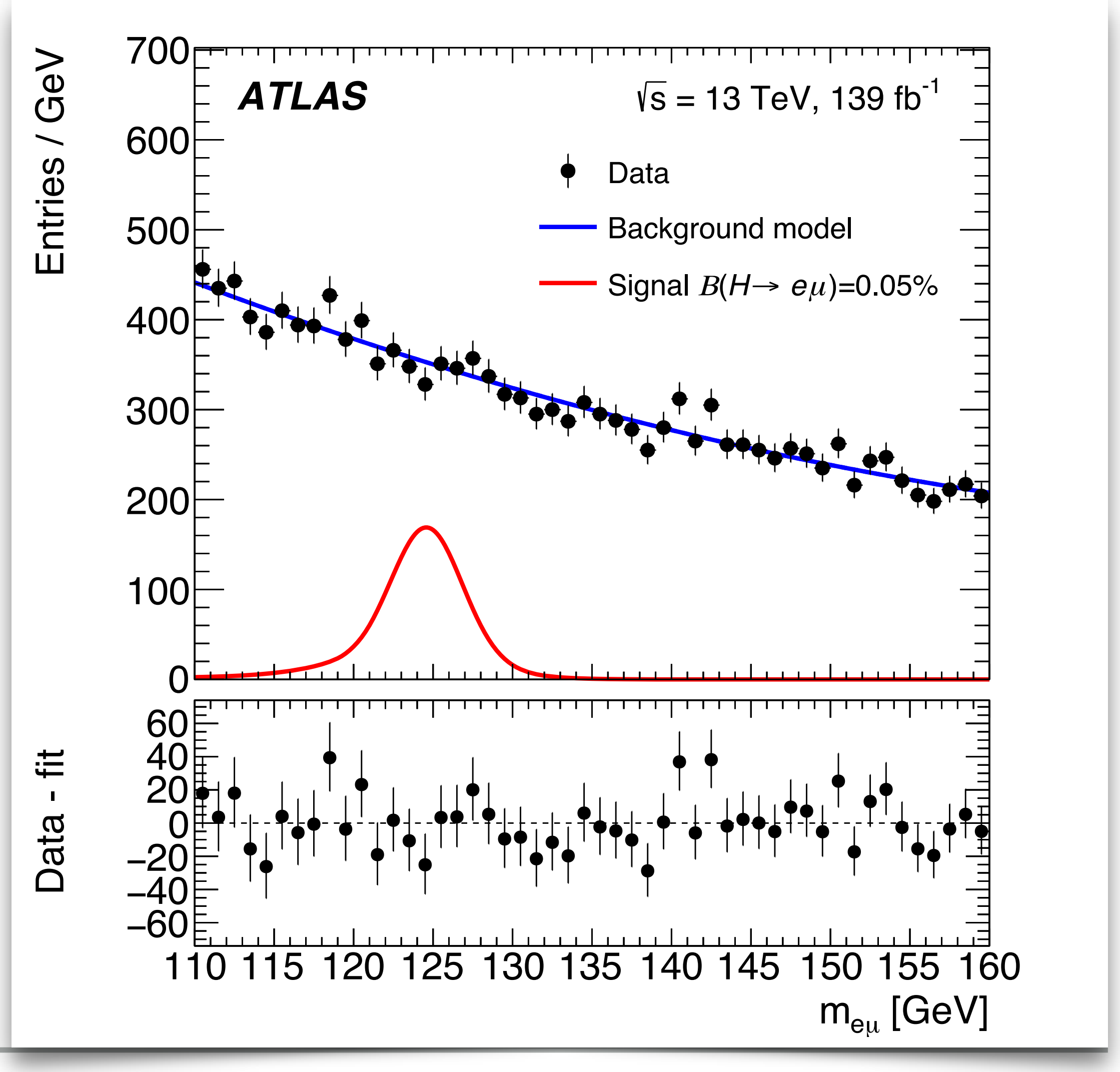
Suppress $t\bar{t}$ background

- SR: $110 < m_{ll} < 160$ GeV
- Categorization (7 for $H \to ee$, 8 for $H \to e\mu$)
  - Cut-based VBF category (with kinematic cuts on jets)
  - + whether both leptons are central ($|\eta| < 1.0$) and the p_T^{ll}: <15, 15-50, >50 GeV (low, mid and high) → 2 x 3 = 6
  - $H \to e\mu$: additional low p_T^l category: $p_T^{l2} < 27$ GeV

Signal/Background modeling

- Sig: Fit MC m_{ll} with Crystal Ball plus Gaussian
- Bkg
  - $H \to ee$: sum of Breit-Wigner (BW) convolved with a Gaussian (G), and an expo divided by a cubic function
    - $f_{bkg}(m_{ee}; M_Z, \Gamma_Z, \sigma_G, f, B) = f \cdot (BW(M_Z, \Gamma_Z) \otimes G(\sigma_G))(m_{ee}) + (1-f) \cdot (e^{Bm_{ee}})/m_{ee}^3$
    - Tested with DY MC with SS method (bias uncertainty)
  - $H \to e\mu$: 2nd order Bernstein polynomial (validated by F-test)
    - Additional test: fit the background MCs + fakes with the nominal fit model and a standard 2nd order polynomial
      - Difference in central values of exp. limits as uncertainty

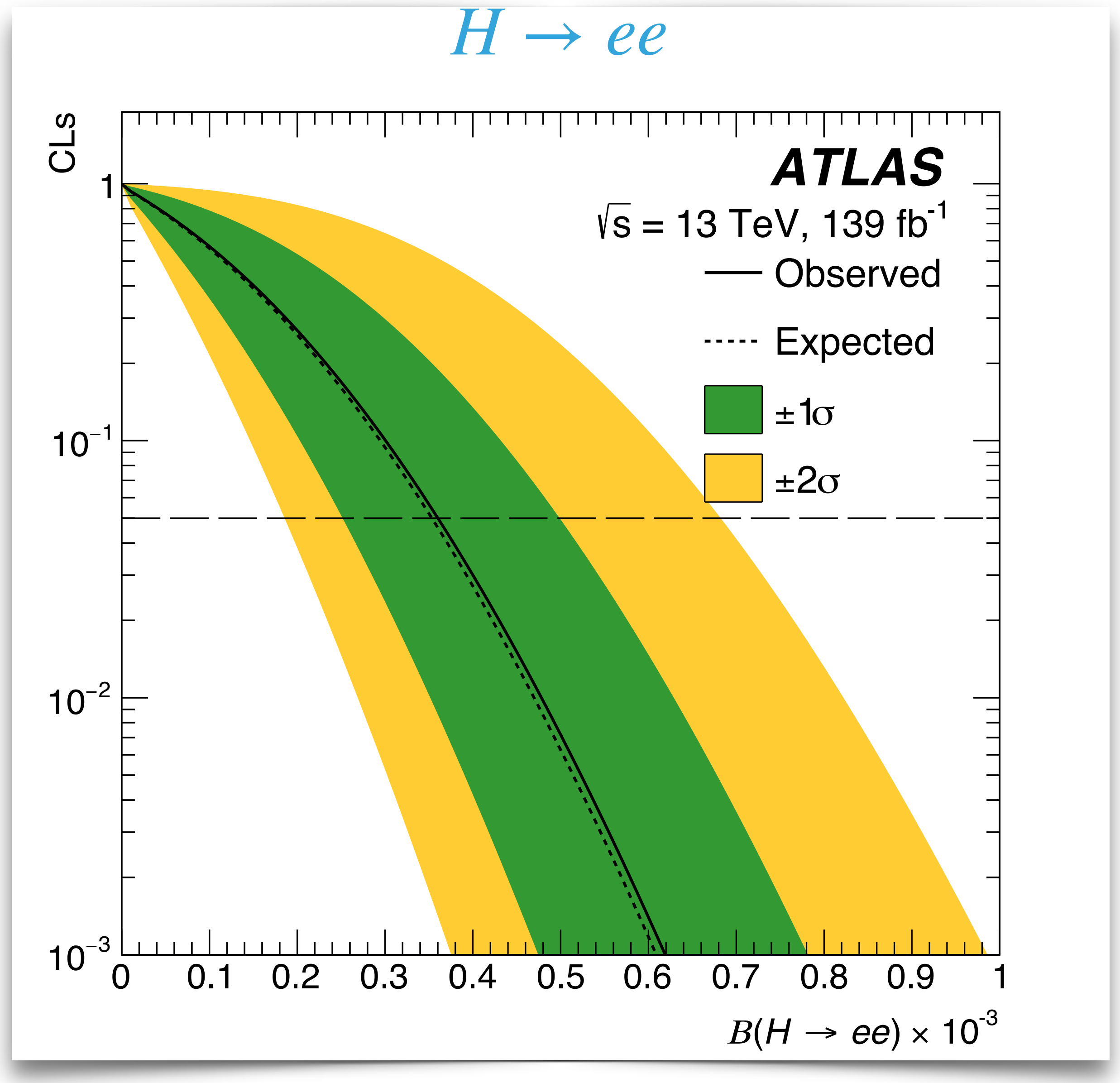


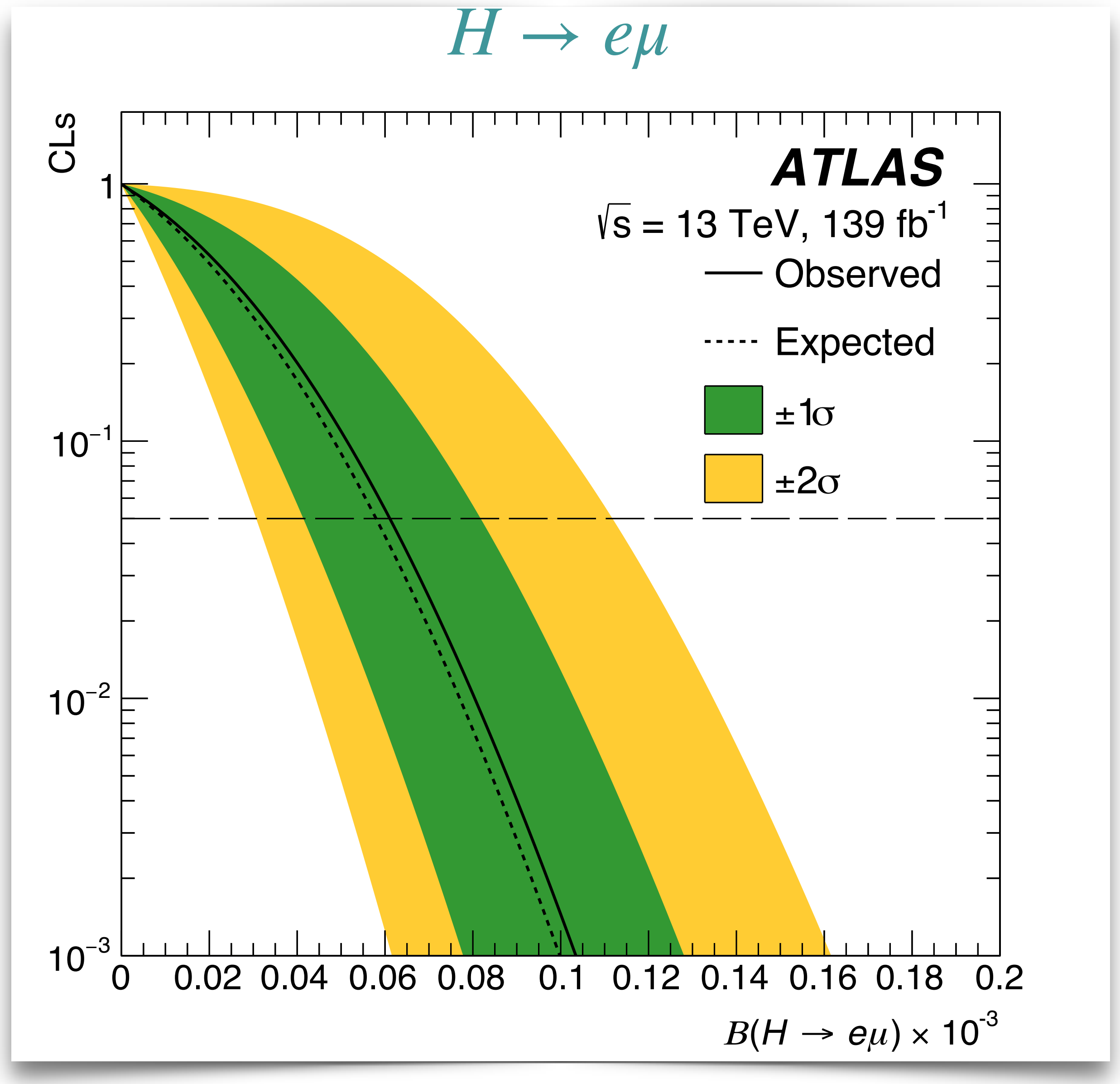


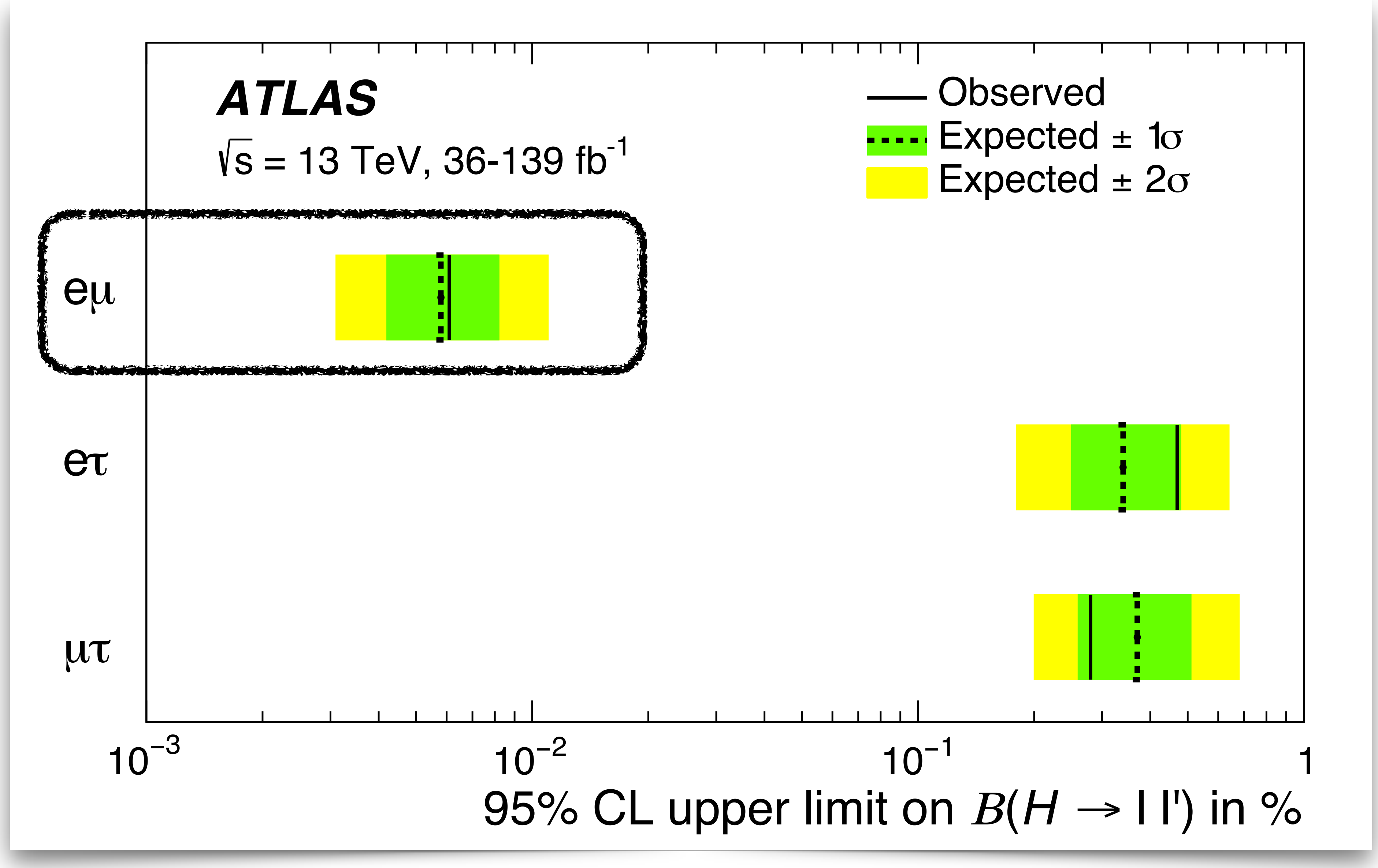
Systematics

- $H \to ee$
  - Leading systematics: SS
  - Sub-leading: electron RES
  - Smaller contributions: theory errors
- $H \to e\mu$
  - Leading: MET modeling as tighter cut on MET significance compared to $H \to ee$

Results and limits







- $Br(H \to ee) = (0.0 \pm 1.8) \times 10^{-4}$

	Obs	Exp	$+2\sigma$	$+2\sigma$	-1σ	-2σ
Upper limit	3.6×10^{-4}	3.5×10^{-4}	6.7×10^{-4}	4.9×10^{-4}	2.6×10^{-4}	1.9×10^{-4}

- $Br(H \to e\mu) = (0.4 \pm 2.9) \times 10^{-5}$

	Obs	Exp	$+2\sigma$	$+2\sigma$	-1σ	-2σ
Upper limit	6.1×10^{-5}	5.8×10^{-5}	1.1×10^{-4}	8.2×10^{-5}	4.2×10^{-5}	3.1×10^{-5}

Summary

- $H \to Z\gamma$ [Phys. Lett. B 809 (2020) 135754]
  - $\mu = 2.0^{+1.0}_{-0.9}(tot.)$, where the statistical uncertainty is dominant
  - The observed data are consistent with the expected background (significance: 2.2σ)
  - The 95% CL upper limit on the $\sigma \times B$ is 3.6 × SM (most stringent)
  - Extra 20% improvement in exp. sensitivity compared with the 36 fb^{-1} publication is from the optimized analysis strategy

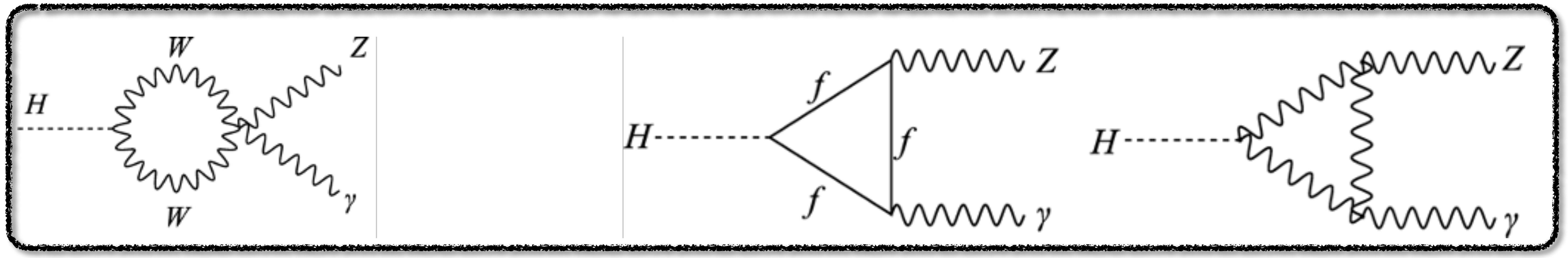
- $H \to ll\gamma$ ($m_{ll} < 30$ GeV) [Phys. Lett. B 819 (2021) 136412]
  - $\mu = 1.5 \pm 0.5$, $\sigma \times BR = 8.7^{+2.8}_{-2.7}$ fb
  - Significance: 3.2σ, first evidence!
  - First ATLAS $H \to ll\gamma$ result in $m_{ll} < 30$ GeV, Complementary to the $Z\gamma$ search

- $H \to ee$ and $H \to e\mu$ LFV [Phys. Lett. B 801 (2020) 135148]
  - Complete Higgs to charged lepton decay measurements in ATLAS, No excess for either channel
  - $Br(H \to ee) = (0.0 \pm 1.7(stat.) \pm 0.6(syst.)) \times 10^{-4}$, 95% CL: 3.6×10^{-4}
  - $Br(H \to e\mu) = (0.4 \pm 2.9(stat.) \pm 0.3(syst.)) \times 10^{-5}$, 95% CL: 6.1×10^{-5}

Backup

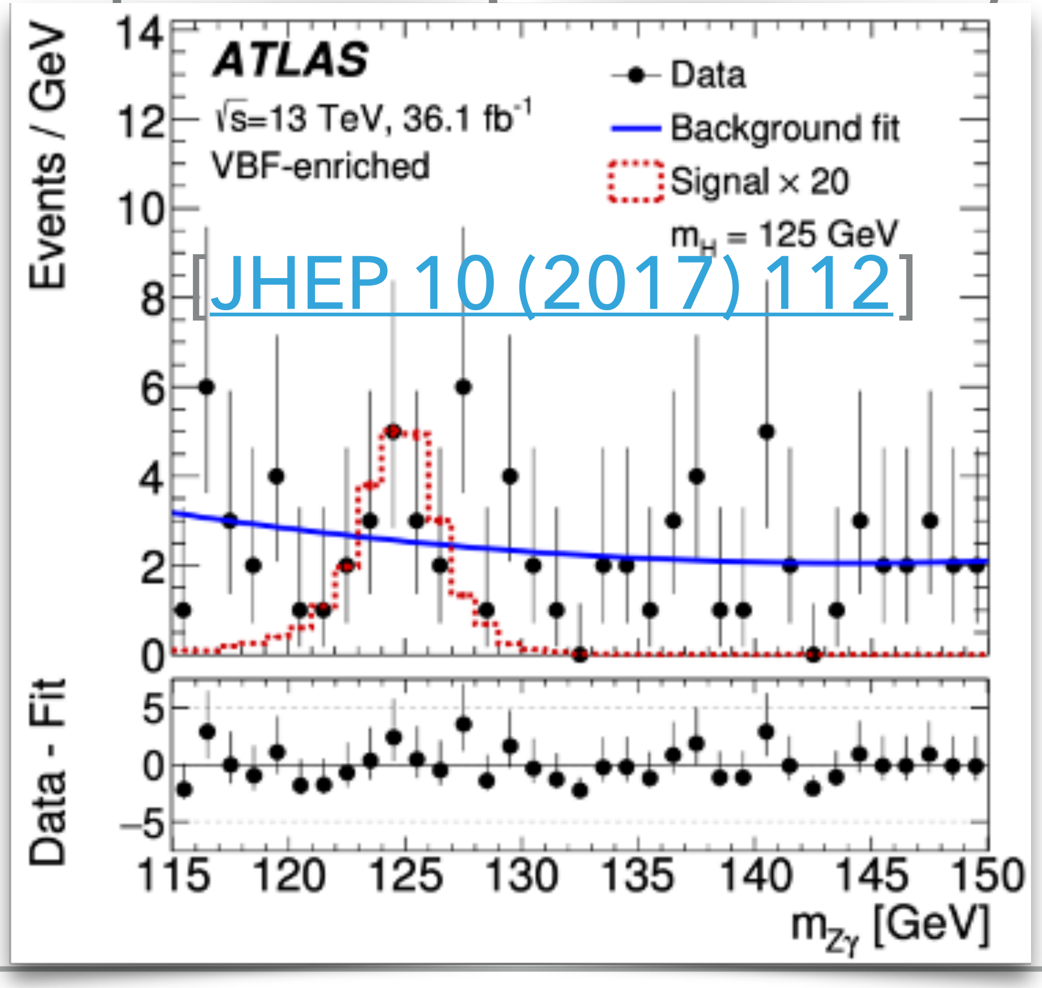
$H \to Z\gamma$ search

- SM Higgs can decay into $Z\gamma$ through loop diagrams, with predicted $B(H \to Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$ at $m_H = 125.09$ GeV; The BR measurements are important for probing the Higgs properties, and for validating SM/BSM theories

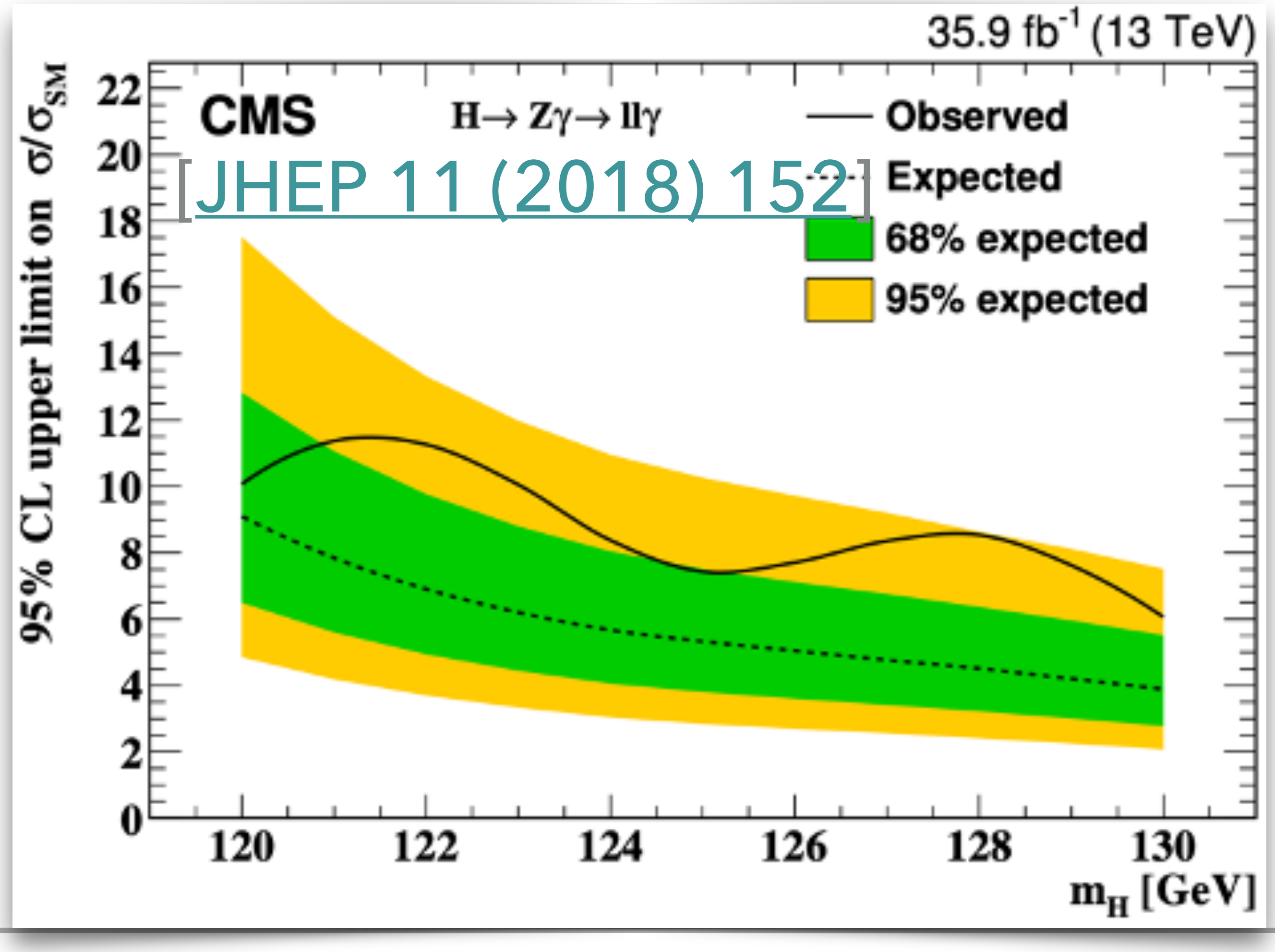


- Z to leptonic decays (e, μ) can be efficiently triggered and clearly distinguished from background; In addition, $H \to Z(\to ll)\gamma$ can be reconstructed with good invariant mass resolution and relatively small backgrounds

- In the previous publications, no significant excess of events above the expected background is observed



[JHEP 10 (2017) 112]



[JHEP 11 (2018) 152]

Limit of XS x BR at 95% CL	
ATLAS	6.6 (5.2) x SM
CMS	7.4 (6.0) x SM

-

Object/Event selection

- Single lepton, di-lepton triggers (efficiency: 95.6% for $ee\gamma$; 92.2% for $\mu\mu\gamma$)
- Object selection ($\gamma \geq 1$, e or $\mu \geq 2$, OS)

Looser ID cut comparing to the previous publication, which was Medium $\Longrightarrow$ higher signal acceptance

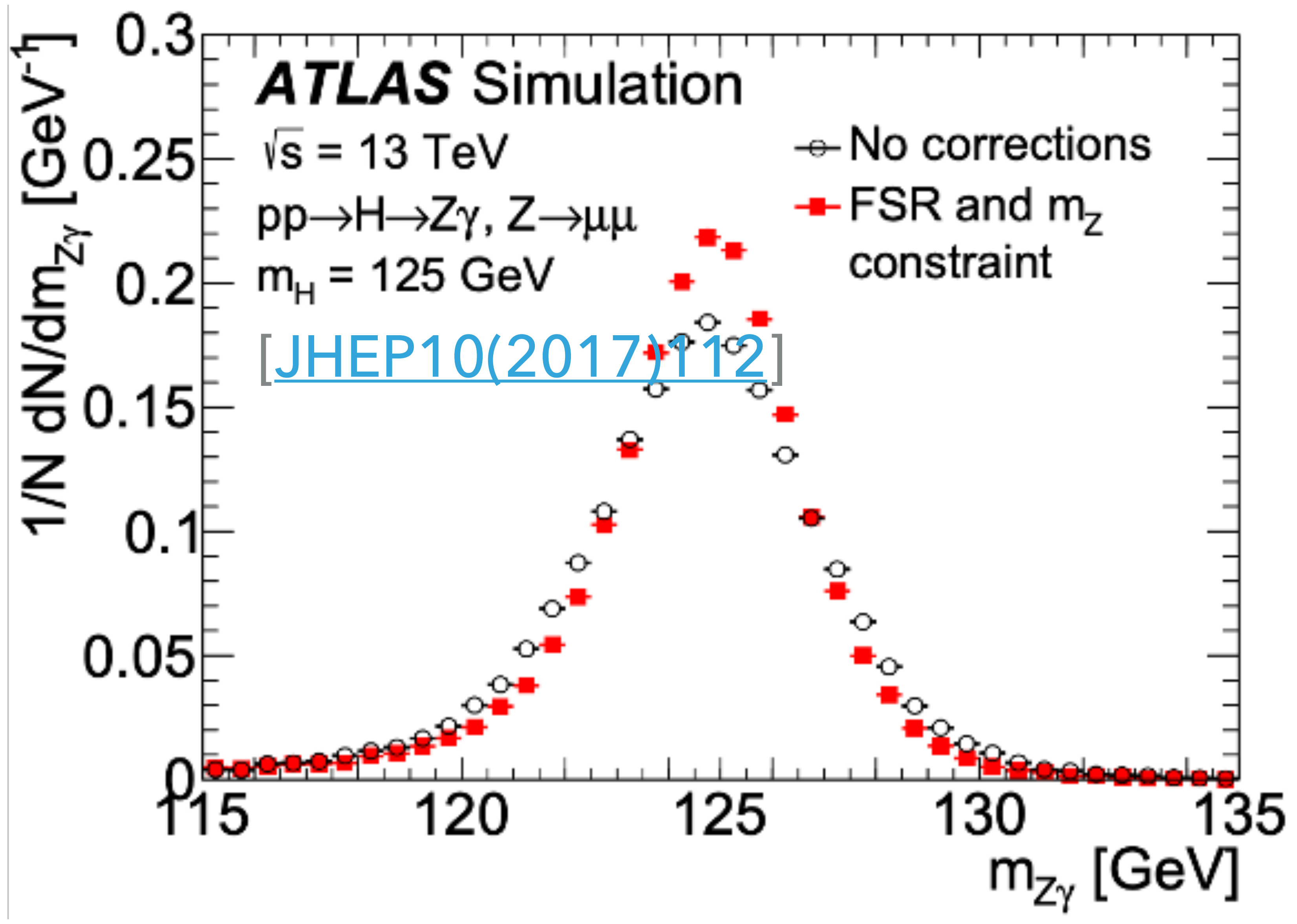
Cut	Electrons	Muons	Photons
p_T	> 10 GeV	> 10 GeV	> 10 GeV
$\|\eta\|$	$\|\eta\| < 2.47$	$\|\eta\| < 2.7$	$\|\eta\| < 2.37$
	exclude $1.37 < \|\eta\| < 1.52$	-	exclude $1.37 < \|\eta\| < 1.52$
$\|d_0\|/\sigma_{d_0}$	< 5	< 3	-
$z_0 \sin\theta$	< 0.5 mm	< 0.5 mm	-
Identification	Loose	Medium	Loose

- Z candidate: OS ee or $\mu\mu$
  - Mass resolution correction (10 ~ 14%)
    - Kinematic fit correction on m_{ll}
    - μ only: FSR correction
  - $50 < m_{ll} < 101$ GeV before mass resolution correction, 20 GeV mass window cut after

- Higgs candidate: Z candidate + leading γ
  - $p_T^\gamma / m_{Z\gamma} > 0.12$ to suppress background
  - SR: $105 < m_{Z\gamma} < 160$ GeV
- Total reconstruction/selection efficiency on signal: $20.4\% \pm 0.2\,\%$

Event selection

- Z candidate: OS ee or $\mu\mu$
  - $50 < m_{ll} < 101$ GeV before mass resolution correction
  - Mass resolution correction (10 ~ 14%)
    - μ only: FSR correction
    - Kinematic fit correction on m_{ll}
  - $|m_{ll} - m_Z(91.2 \text{ GeV})| < 10$ GeV after mass resolution correction; The closest di-lepton pair will be selected

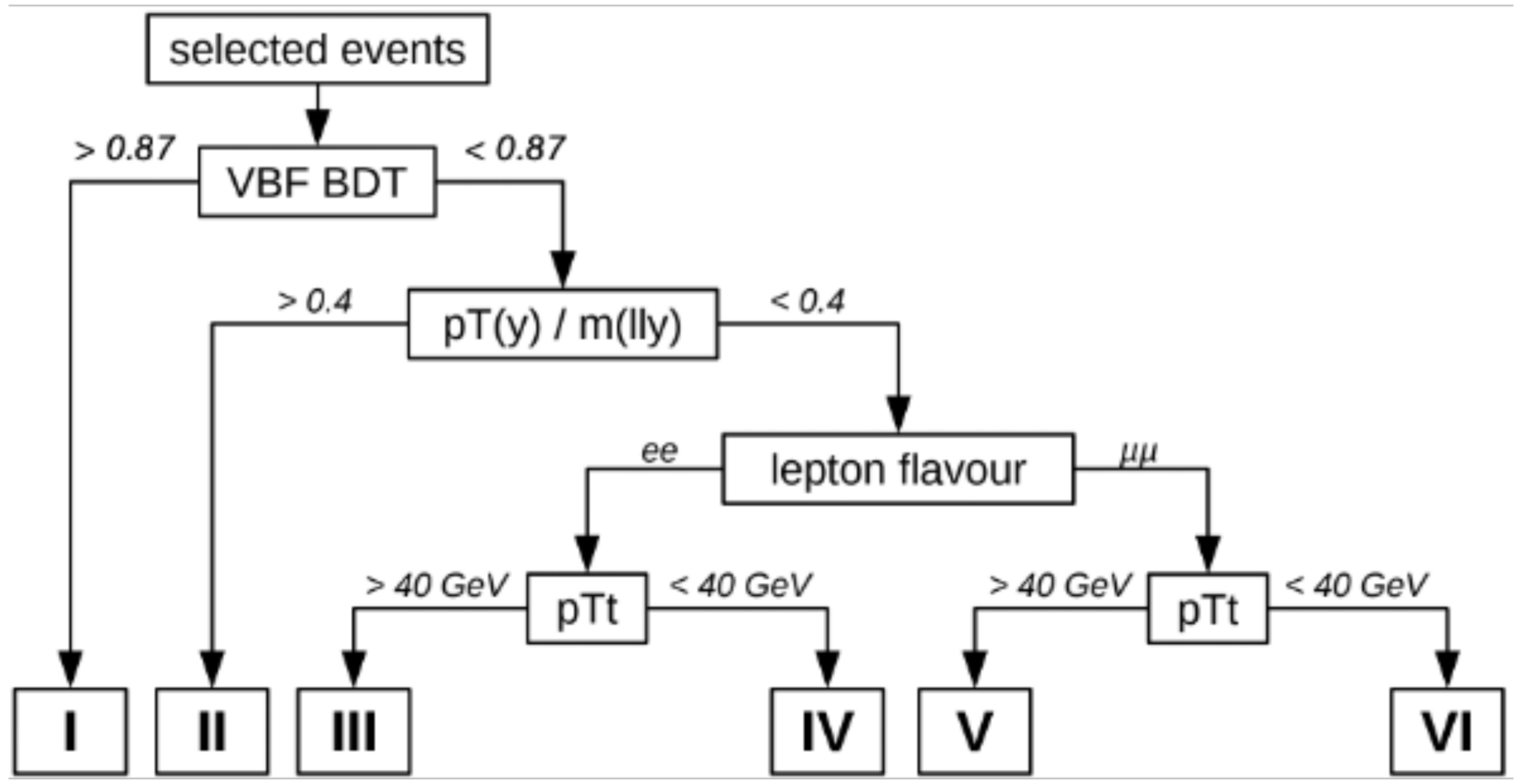


- Trigger match on the selected objects
- Higgs candidate
  - Z candidate + γ with leading p_T
  - $105 < m_{Z\gamma} < 160$ GeV
  - $p_T^{\gamma}/m_{Z\gamma} > 0.12$ to suppress background
- SR: Tight photon ID, FixedCutLoose isolation

- Total reconstruction/selection efficiency on signal: $20.4\% \pm 0.2\,\%$

Categorization

- Events are classified into 6 categories to improve the sensitivity of the signal

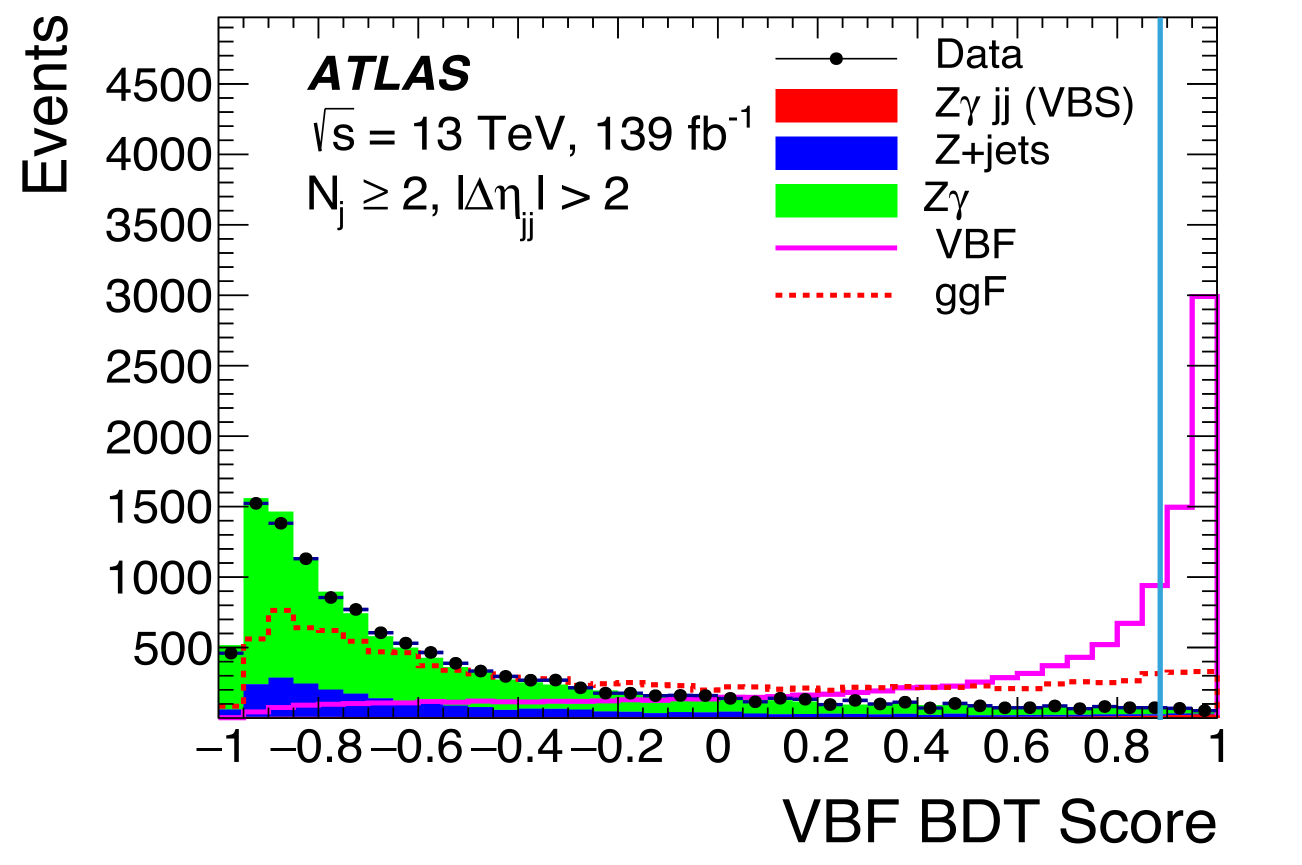


- The boundaries of the categories are determined to maximize the signal significance

I. VBF-enriched category, trained with BDT

- Precut: $N_j \geq 2$ (2 highest p_T jets are selected), $|\Delta\eta_{jj}| > 2$

Variables	Definition
$\Delta\Phi_{Z,\gamma}$	Azimuthal angle between di-lepton system and photon
$\Delta\eta_{jj}$	Pseudo-rapidity separation of dijet
$\Delta R^{min}_{\gamma or Z,j}$	Minimum ΔR between one object of the Zgamma and jets
m_{jj}	Invariant mass of dijet
p_{Tt}	Zgamma p_T projected perpendicular to the Zgamma thrust axis
$\eta^{Zeppenfeld}$	$\lvert\eta_{Z\gamma} - 0.5 * (\eta_{j1} + \eta_{j2})\rvert$
$\Delta\Phi_{Z\gamma,jj}$	Azimuthal angle between Zgamma and dijet system



Categorization

- Signal efficiency ϵ, fraction f of each production mode per category

Category	ggF ϵ[%]	ggF f[%]	VBF ϵ[%]	VBF f[%]	WH ϵ[%]	WH f[%]	ZH ϵ[%]	ZH f[%]	$t\bar{t}H$ ϵ[%]	$t\bar{t}H$ f[%]
VBF-enriched	0.15	27.5	5.1	71.6	0.11	0.5	0.08	0.2	0.07	0.1
High relative p_T	1.1	70.6	2.6	12.9	4.1	7.2	4.1	4.7	7.0	4.6
High p_{Tt} ee	1.7	79.9	2.9	10.8	3.3	4.4	3.4	2.9	3.8	1.9
Low p_{Tt} ee	6.8	93.6	3.5	3.8	3.5	1.3	3.7	0.9	3.1	0.4
High p_{Tt} $\mu\mu$	2.0	79.7	3.6	11.1	4.0	4.4	4.1	2.9	4.3	1.7
Low p_{Tt} $\mu\mu$	8.6	93.6	4.4	3.7	4.5	1.4	4.6	0.9	3.5	0.4
Total efficiency (%)	20.3		22.2		19.5		19.9		21.9	
Expected events	142		12.1		3.8		2.2		1.6	

- Expected signal significance

Category	Events	S_{68}	B_{68}	w_{68} [GeV]	S_{68}/B_{68} [10^{-2}]	$S_{68}/\sqrt{S_{68}+B_{68}}$
VBF-enriched	194	2.7	18.7	3.7	14.3	0.58
High relative p_T	2276	7.6	112.8	3.7	6.7	0.69
High p_{Tt} ee	5567	9.9	444.0	3.8	2.2	0.46
Low p_{Tt} ee	76 679	34.5	6654.1	4.1	0.5	0.42
High p_{Tt} $\mu\mu$	6979	12.0	610.8	3.9	2.0	0.48
Low p_{Tt} $\mu\mu$	100 876	43.5	8861.5	4.0	0.5	0.46
Inclusive	192 571	110.2	16 701.9	4.0	0.7	0.85

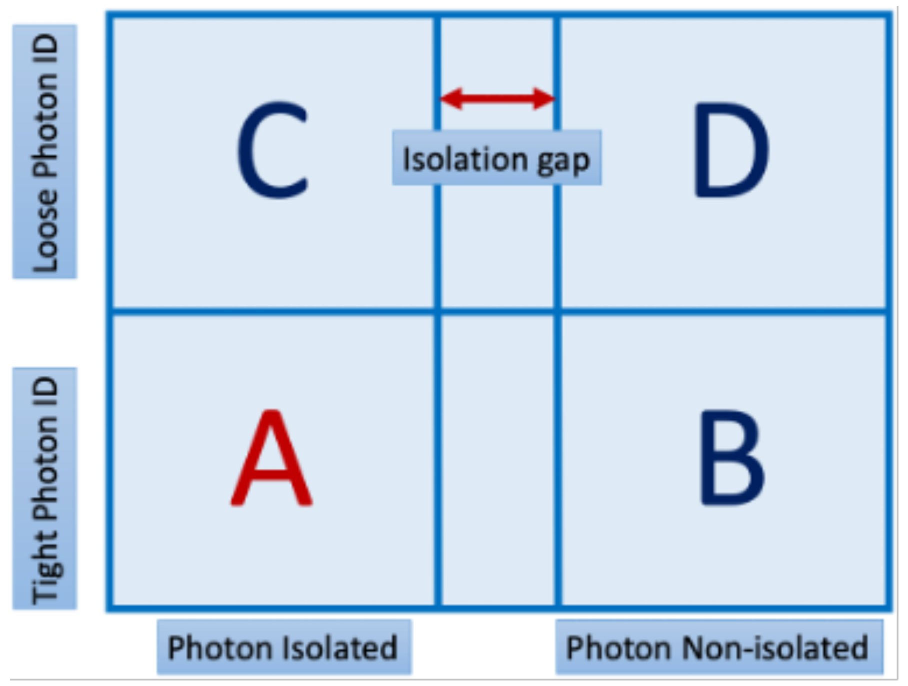
$$\sqrt{\sum Z_i^2} = 1.3$$

- Continuum $Z\gamma$ background has on average lower p_T of candidate than the signal $\Longrightarrow$ higher signal significance in the VBF-enriched, high relative p_T, high p_{Tt} categories

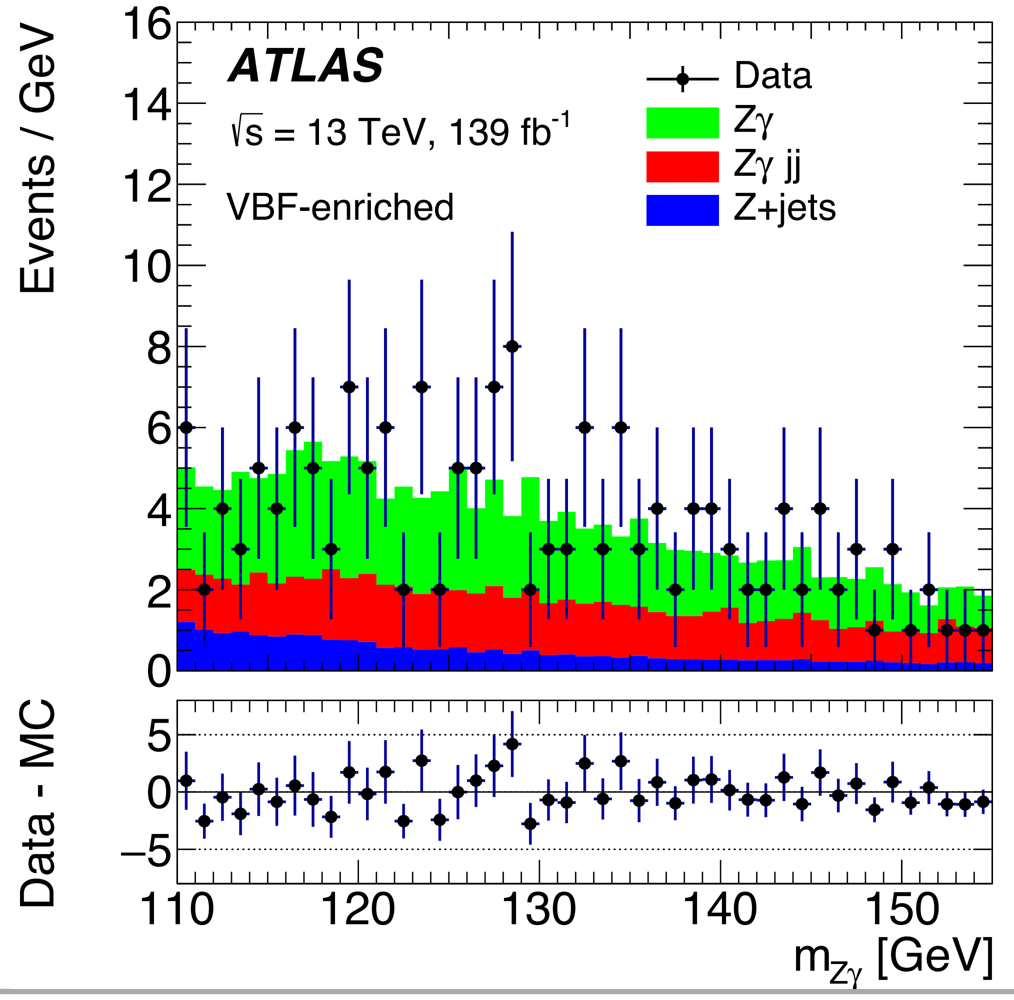
- The categorization improves the sensitivity by ~50% than the inclusive case

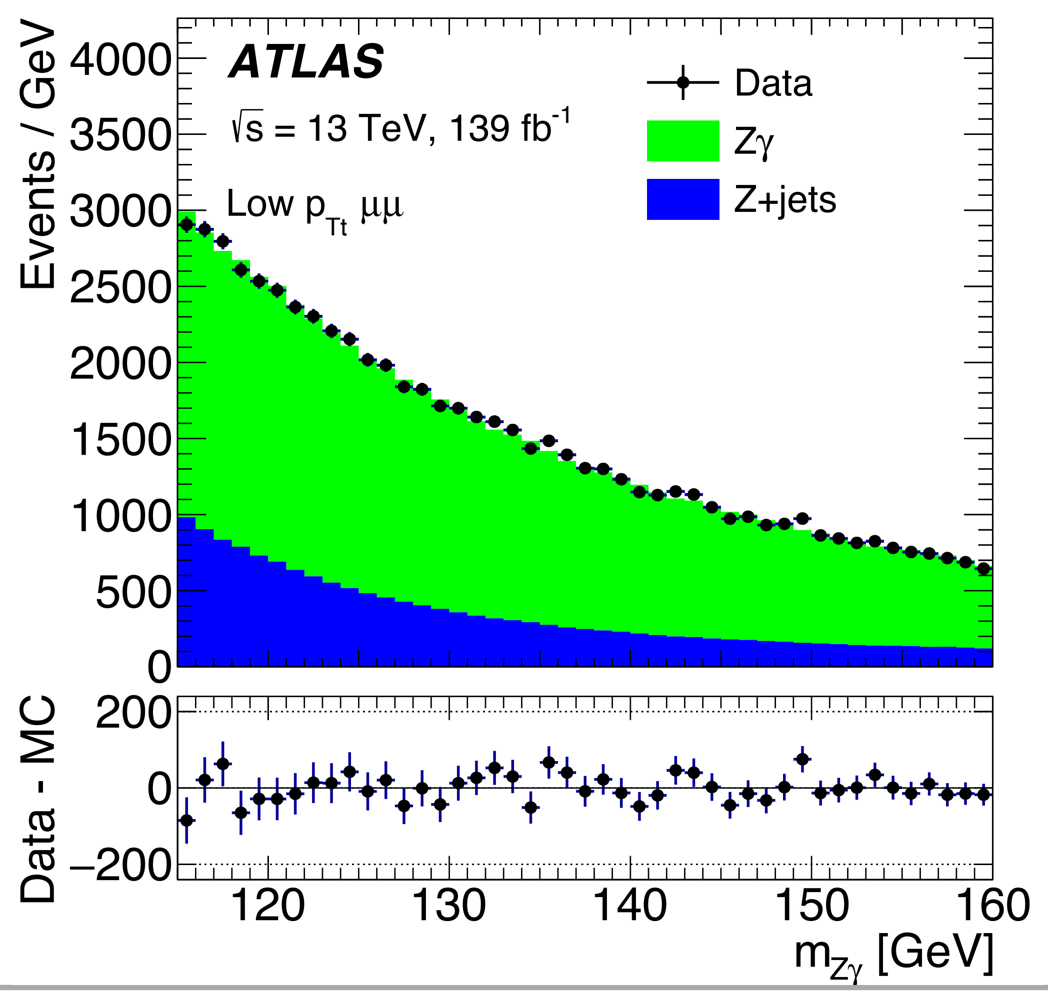
Background composition

- Background components: dominant $Z\gamma$, secondary $Z+j$ where jet is misidentified at photon
- 2D sideband method is applied to estimate fractions of background components based on photon ID/ISO performances



- $N_A^{Z\gamma} = N_A^{data} - (N_B^{data} - c_B N_A^{Z\gamma})\frac{N_C^{data} - c_C N_A^{Z\gamma}}{N_D^{data} - c_D N_A^{Z\gamma}} R^{Zj}$
  - $c_K \equiv N_K^{Z\gamma}/N_A^{Z\gamma}$, $Z\gamma$ leakage fractions extracted from $Z\gamma$ MC
  - $R^{Zj} \equiv \frac{N_A^{Zj} N_D^{Zj}}{N_B^{Zj} N_C^{Zj}}$, jet correlation factor between photon ID/ISO regions; Obtained from "prime" region data (fail photon ISO)
- The fraction of $Z\gamma$ background in inclusive case is $0.78^{+0.04}_{-0.09}$
- Data VS background template with background fraction applied



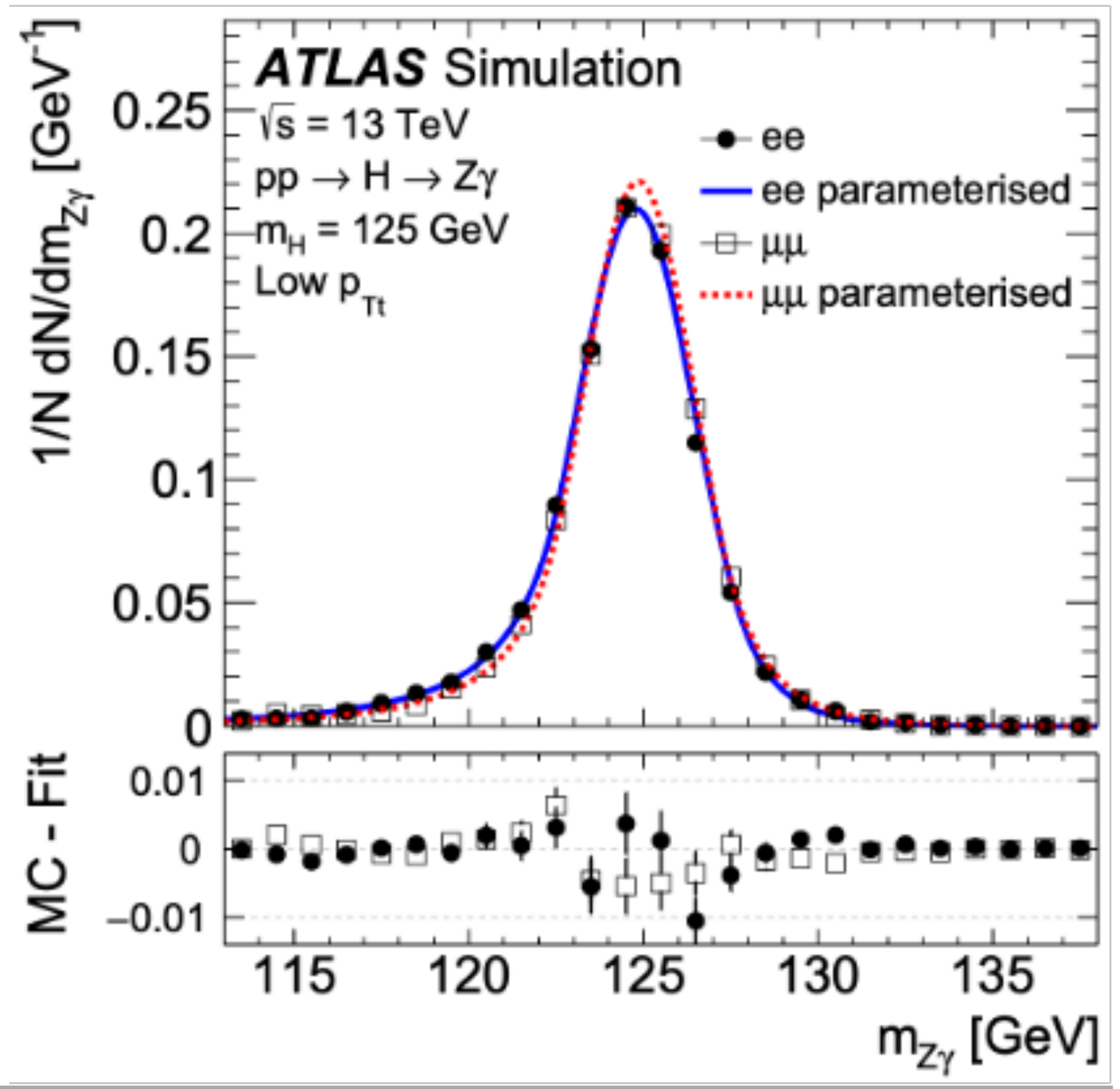


Signal modeling

- The signal and background will be extracted from $m_{Z\gamma}$ fit in data, assuming parametric models for signal and background
- Signal
  - Acceptance and parameters of the shape are obtained from MC
  - Well modeled by DSCB function

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

[JHEP10(2017)112]



Statistical procedures

- A profile-likelihood-ratio test statistic is used to search for a signal excess above the background by fitting on $m_{Z\gamma}$

$$\mathcal{L}\left((\mu,\boldsymbol{\theta})\middle|\{m^i_{Z\gamma}\}_{i=1..n}\right) = \frac{e^{-N(\mu,\boldsymbol{\theta})}N^n(\mu,\boldsymbol{\theta})}{n!}\left(\prod_{i=1}^{n} f_{\text{tot}}(m^i_{Z\gamma},\mu,\boldsymbol{\theta})\right) \times G(\boldsymbol{\theta})$$

Constraint term of NP

Poisson term

PDF for $m_{Z\gamma}$ distribution

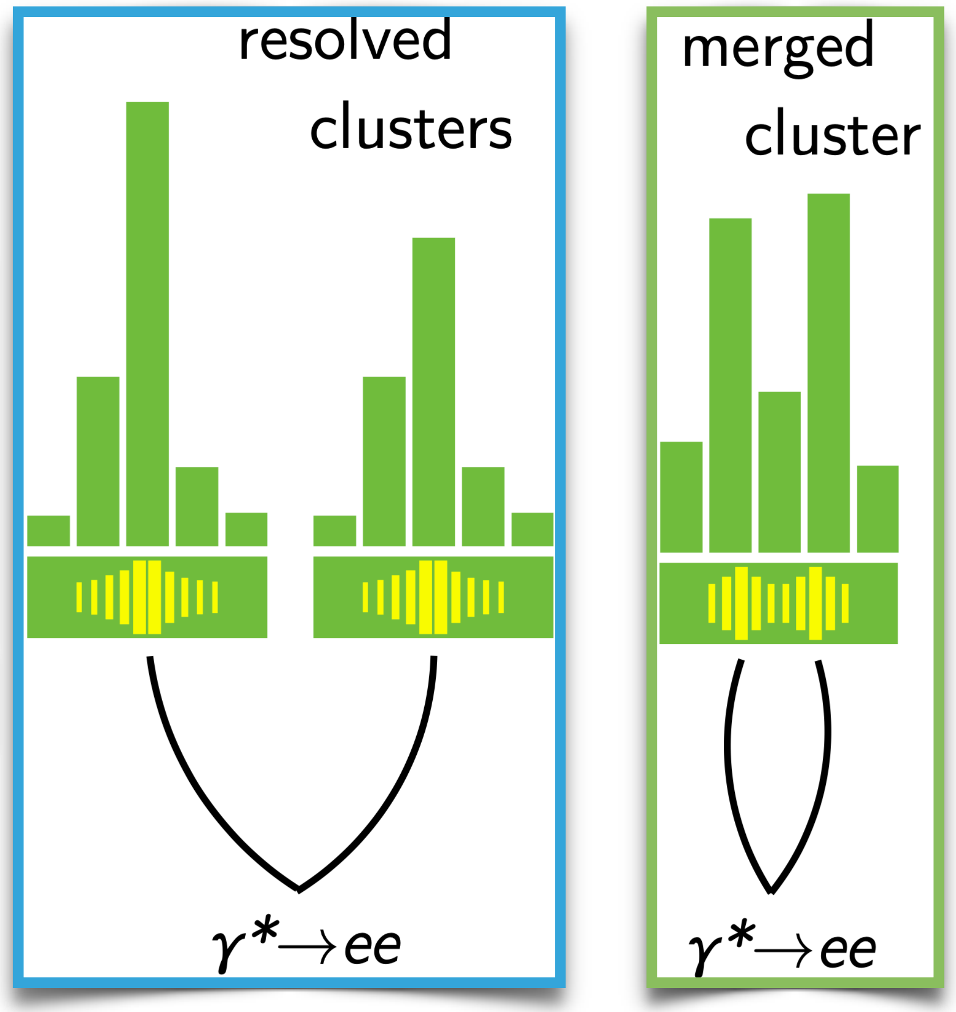
$$f_{\text{tot}}(m^i_{Z\gamma},\mu,\boldsymbol{\theta}) = \frac{1}{N}\sum_{c}\Big\{\Big[N^{(c)}_{\text{sig}}(m_X,\mu,\boldsymbol{\theta}_{\text{sig}}) + N^{(c)}_{\text{spur}}(m_X,\theta_{\text{spur}})\Big] \times f^{(c)}_{\text{sig}}(m^i_{Z\gamma},\boldsymbol{\theta}_{\text{sig}}) + N^{(c)}_{H\mu\mu}(m_X,\theta_{H\mu\mu}) \times f^{(c)}_{H\mu\mu}(m^i_{ll\gamma}) + N^{(c)}_{\text{bkg}} \times f^{(c)}_{\text{bkg}}(m^i_{Z\gamma},\boldsymbol{\theta}_{\text{bkg}})\Big\}$$

- Upper limits are set on $\sigma(pp \to H) \times B(H \to Z\gamma)$ at 95% CL using asymptotic approximation

$$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu) & \text{for } \mu \geq \hat{\mu} \\ 0 & \text{for } \mu < \hat{\mu} \end{cases} \quad \text{with} \quad \tilde{\lambda}(\mu) = \begin{cases} \ln\frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} & \text{for } \hat{\mu} \geq 0 \\ \ln\frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(0,\hat{\theta}(0))} & \text{for } \hat{\mu} < 0 \end{cases}$$

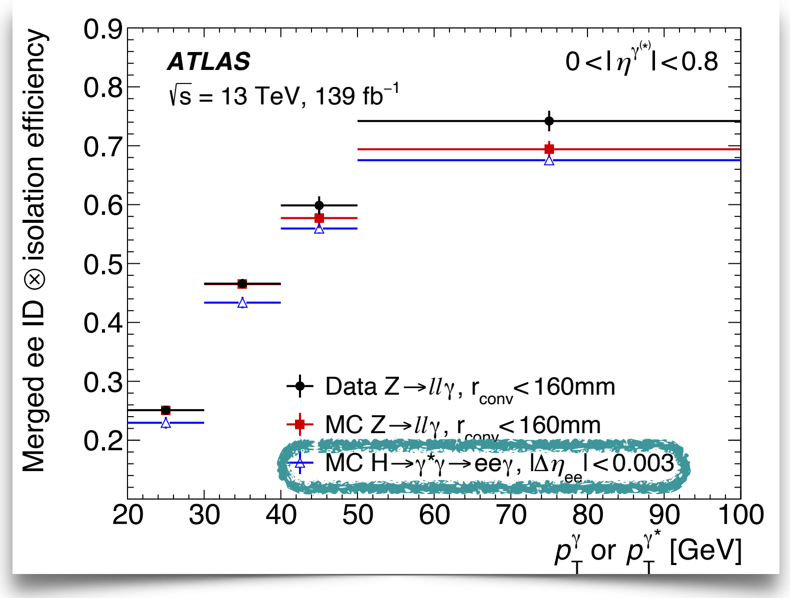
Objects/merged electron ID

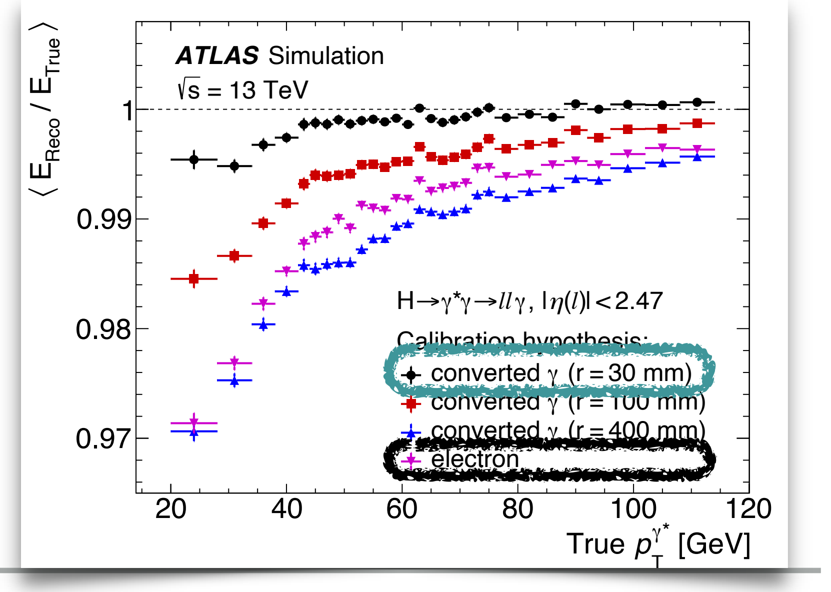
Cut	Photon	Resolved electron	Merged electron	Muon
p_T	>20 GeV	>4.5 GeV	>20 GeV	>3 GeV
Track		Innermost pixel hit	Innermost pixel hit	
		$d_0/\sigma_{d0} < 3$, $\lvert Z_0 \sin\theta \rvert < 0.5$ mm	$d_0/\sigma_{d0} < 3$, $\lvert Z_0 \sin\theta \rvert < 0.5$ mm	$d_0/\sigma_{d0} < 3$, $\lvert Z_0 \sin\theta \rvert < 0.5$ mm
ID	Tight	Medium	Custom (TMVA)	Medium



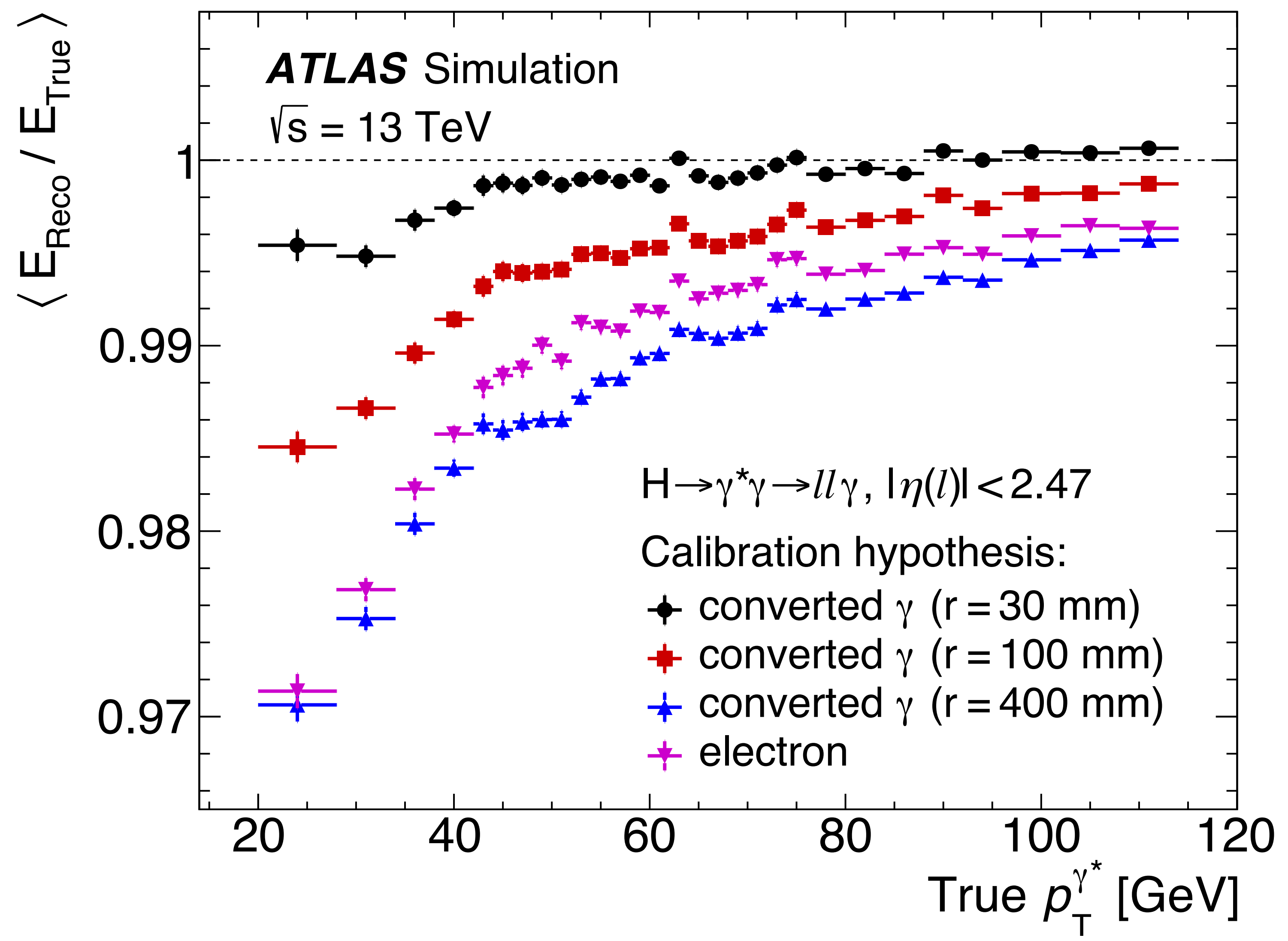
- Single-l, $2l$, $\gamma - l$, $\gamma\gamma$, $\gamma - 2l$ triggers
  - μ: 96.2% efficiency; e: dedicated $e - \gamma$ trigger with relaxed ID to allow merged electrons (resolved: 96.5%; merged: 99.8%)

- Merged electron ID
  - Due to spoiled shower shape variables, merged electrons perform badly with standard electron IDs
  - Derive dedicated ID using TMVA, efficiency: ~50%
  - Extract efficiency SF with early converted γ from $Z \to ll\gamma$ events
- Merged electron calibration
  - Due to small ΔR, merged electrons show bias using standard electron calibrations
  - Calibrate γ^* as an early converted photon ($r = 30$ mm), generally good performances



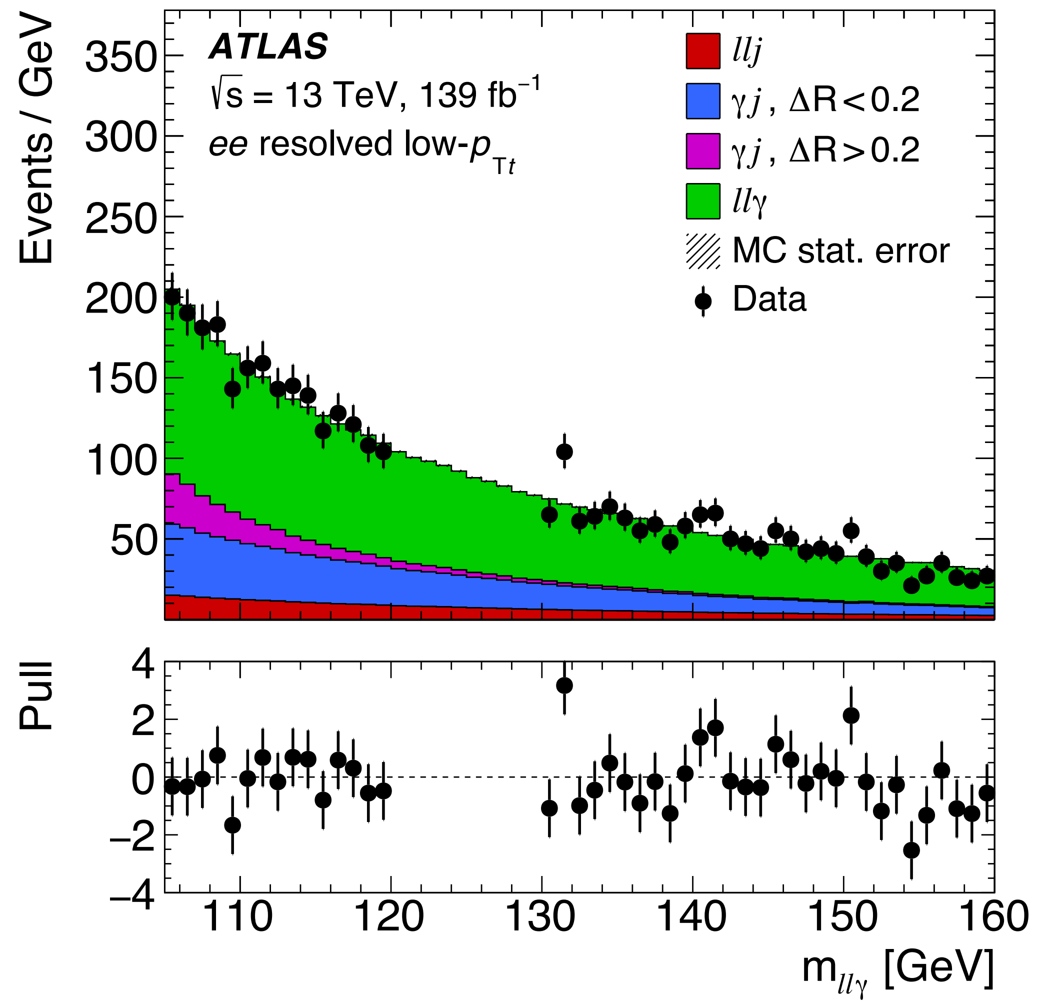


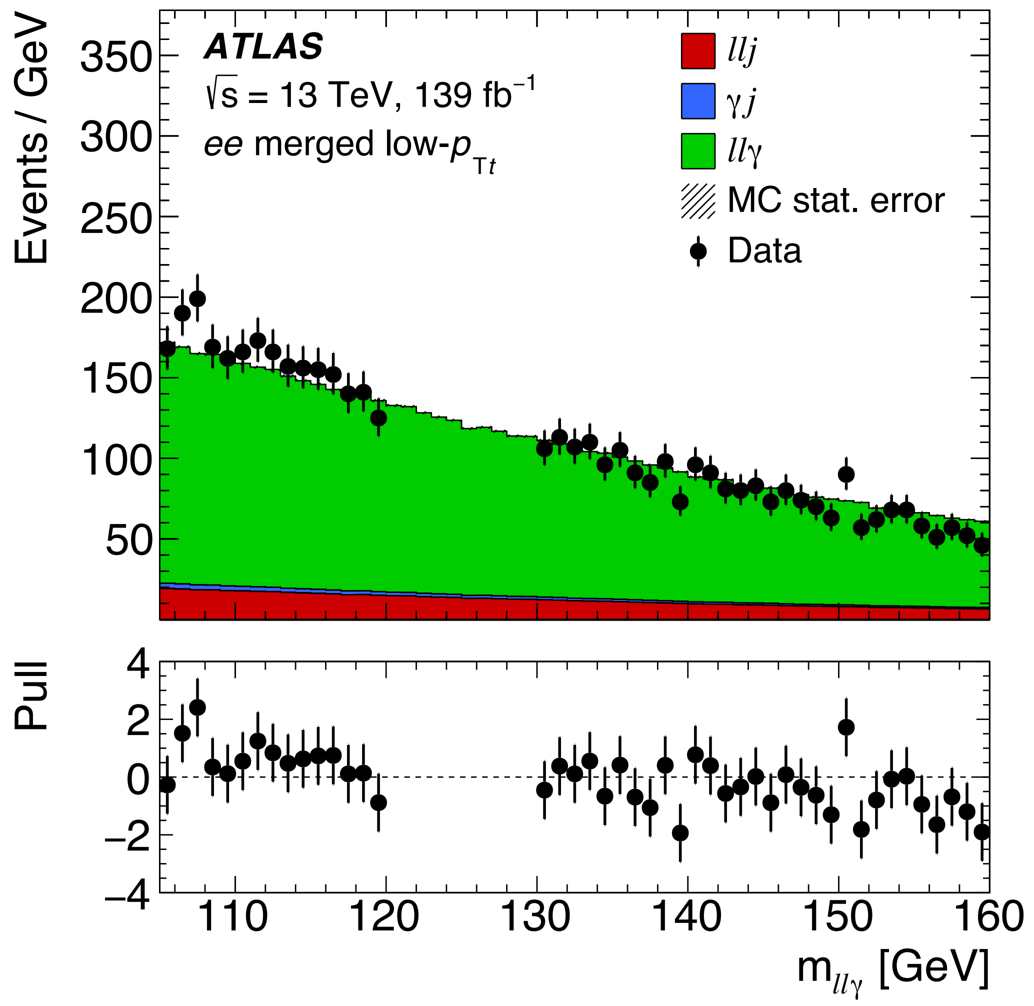
Merged electron calibration

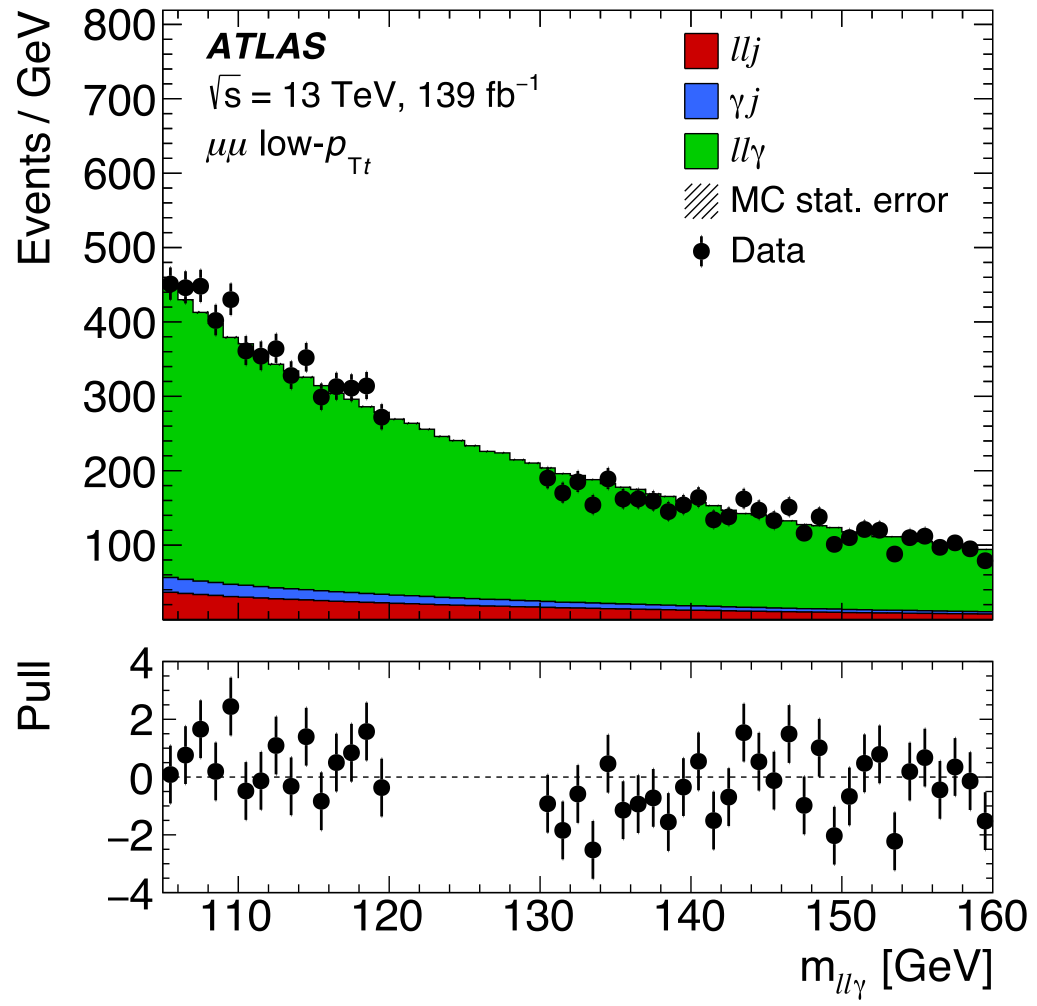


- Due to small ΔR, merged electrons (γ^*) show bias when calibrated using the standard electron calibration
- $\Longrightarrow$ Calibrate γ^* as an early converted photon ($r = 30$ mm), overall good performances
  - Beam pipe/innermost pixel layer location
- Inflate the resolution systematic uncertainty to be conservative

Deriving templates for modeling full background







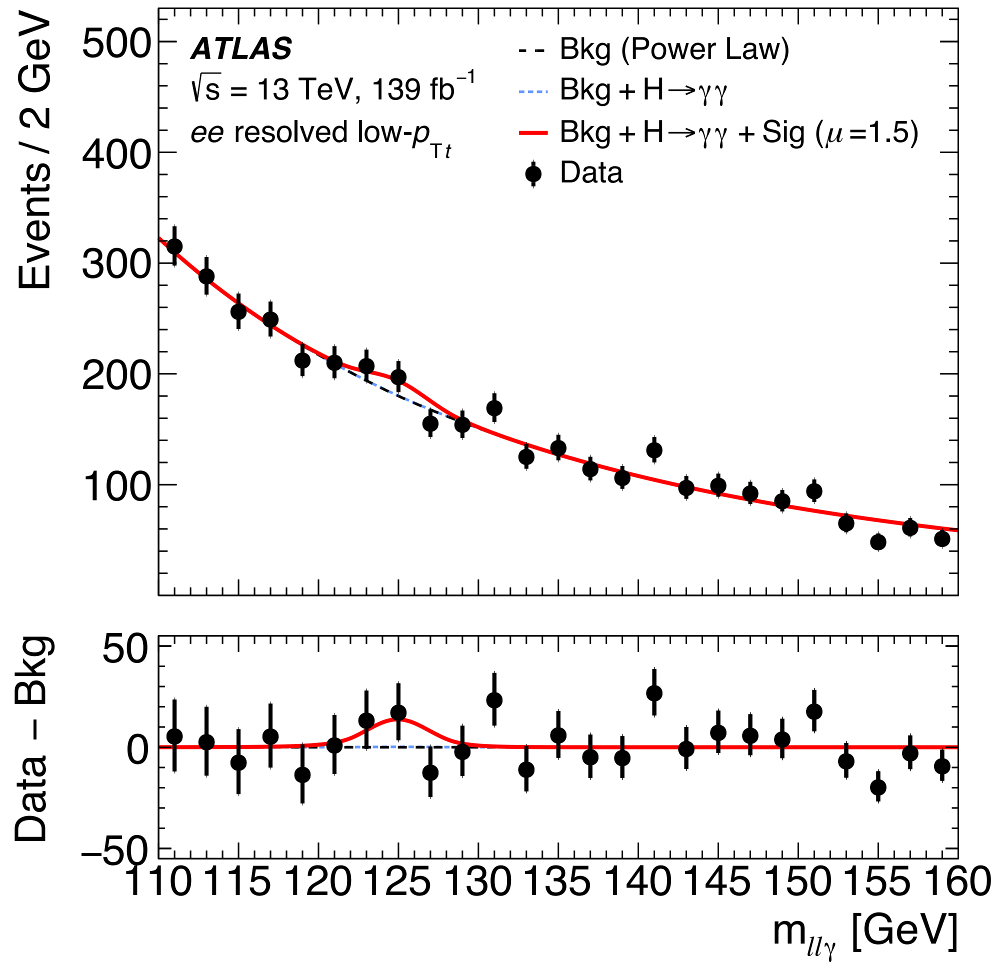
- Use LO Sherpa $ll\gamma$ to model the irreducible $ll\gamma$ background
  - Use a high-statistics (30M events) generator-level sample to avoid issues with template statistical fluctuations
  - Reweight this generator-level sample to account for reconstruction-level effects, validate with smaller FullSim sample
- Obtain shapes for fake backgrounds in data control regions (folded into $ll\gamma$ shape)
- Reasonable agreement with data sidebands
  - These templates are not directly used in the analysis fit, but instead used for bias studies and function selection
  - F-tests are performed on the final function choice to ensure that a higher-d-o-f function is not preferred

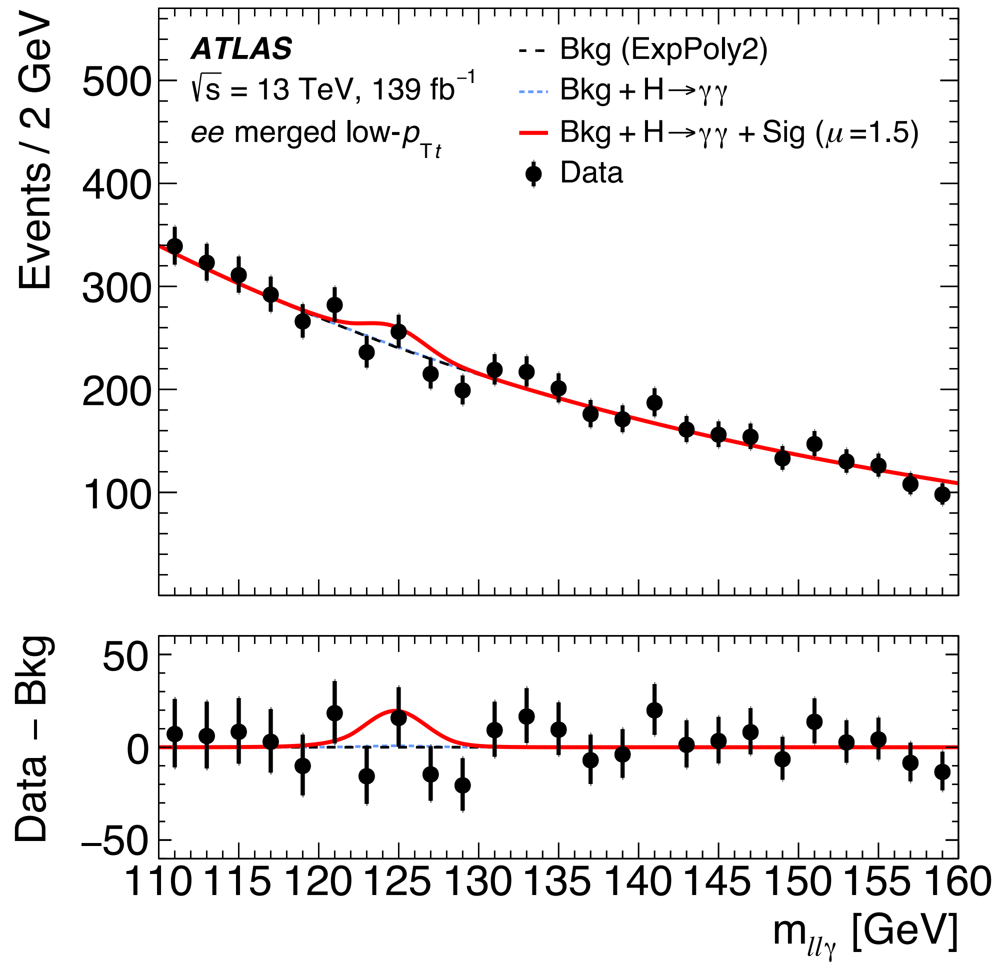
Selecting Background Functions

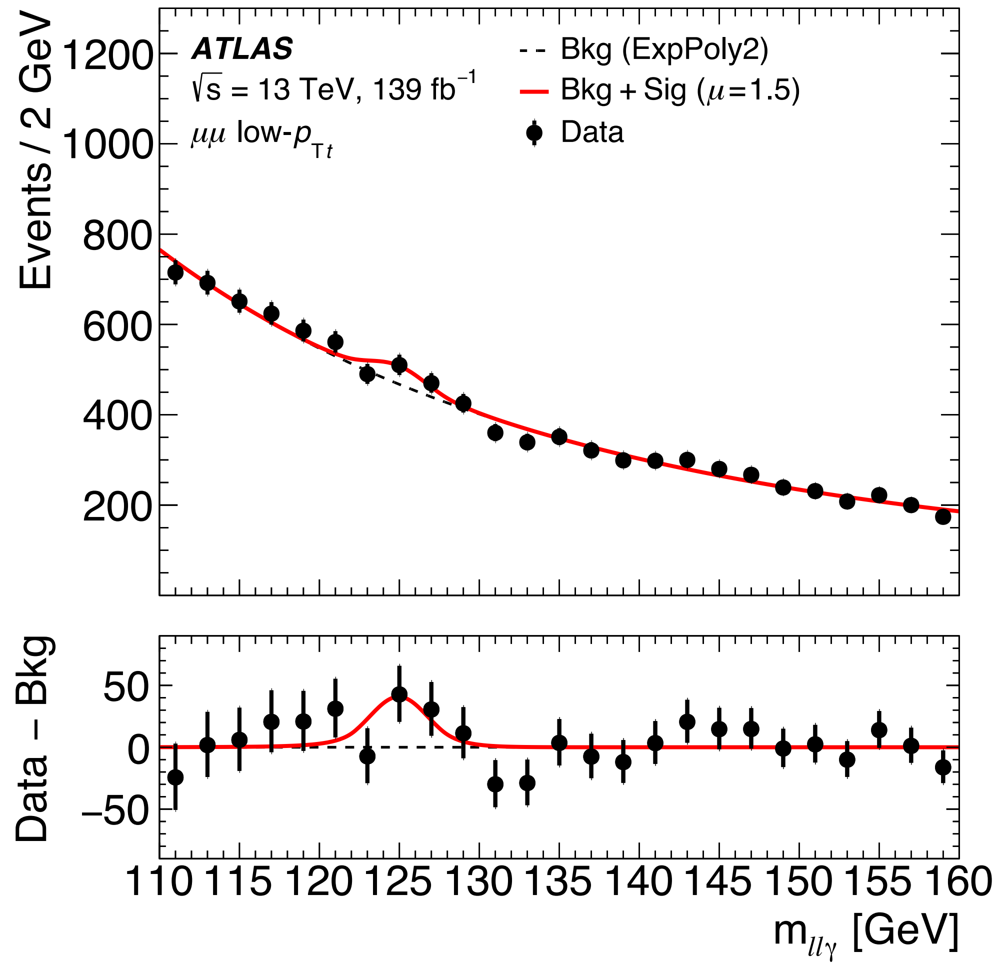
Category	Model
Inclusive Dimuon	ExpPoly2
Inclusive Resolved-e	Pow
Inclusive Merged-e	ExpPoly2
VBF Dimuon	Pow
VBF Resolved-e	Exponential
VBF Merged-e	Pow
High-$p_{\mathrm{TThrust}}^{\ell\ell\gamma}$ Dimuon	Pow
High-$p_{\mathrm{TThrust}}^{\ell\ell\gamma}$ Resolved-e	Pow
High-$p_{\mathrm{TThrust}}^{\ell\ell\gamma}$ Merged-e	Pow

- Use the Spurious signal method to select background functions in each category with low bias
  - Signal + Background fit to the background-only templates described earlier
  - Functions with low bias and with low degrees of freedom are preferred
  - Functions must additionally model the full range with a reasonable χ^2
- Spurious signal varies from 8–90% depending on the category
  - Categories with high spurious signal bias will have a $\gg$ stat. uncertainty

Results



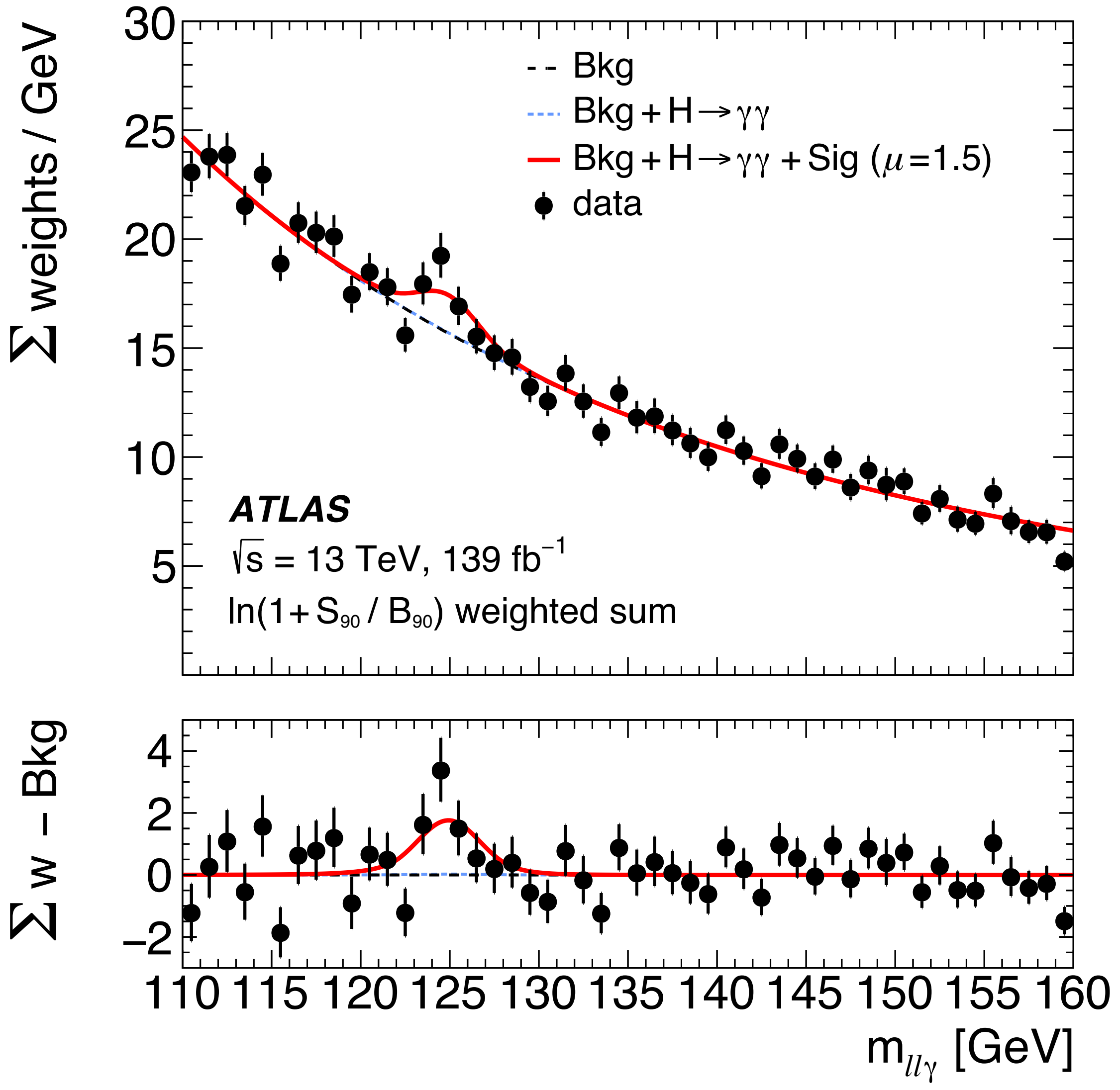


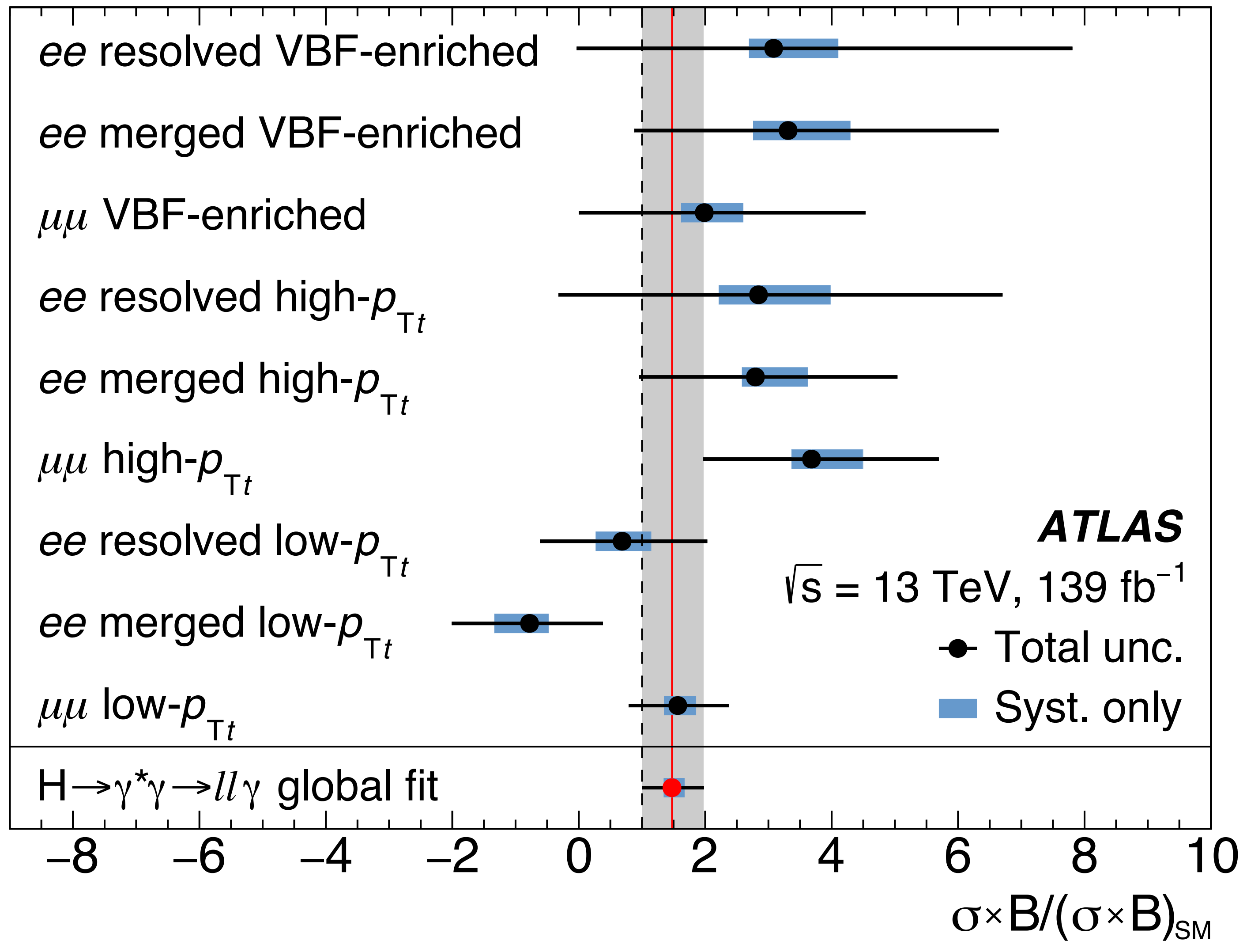


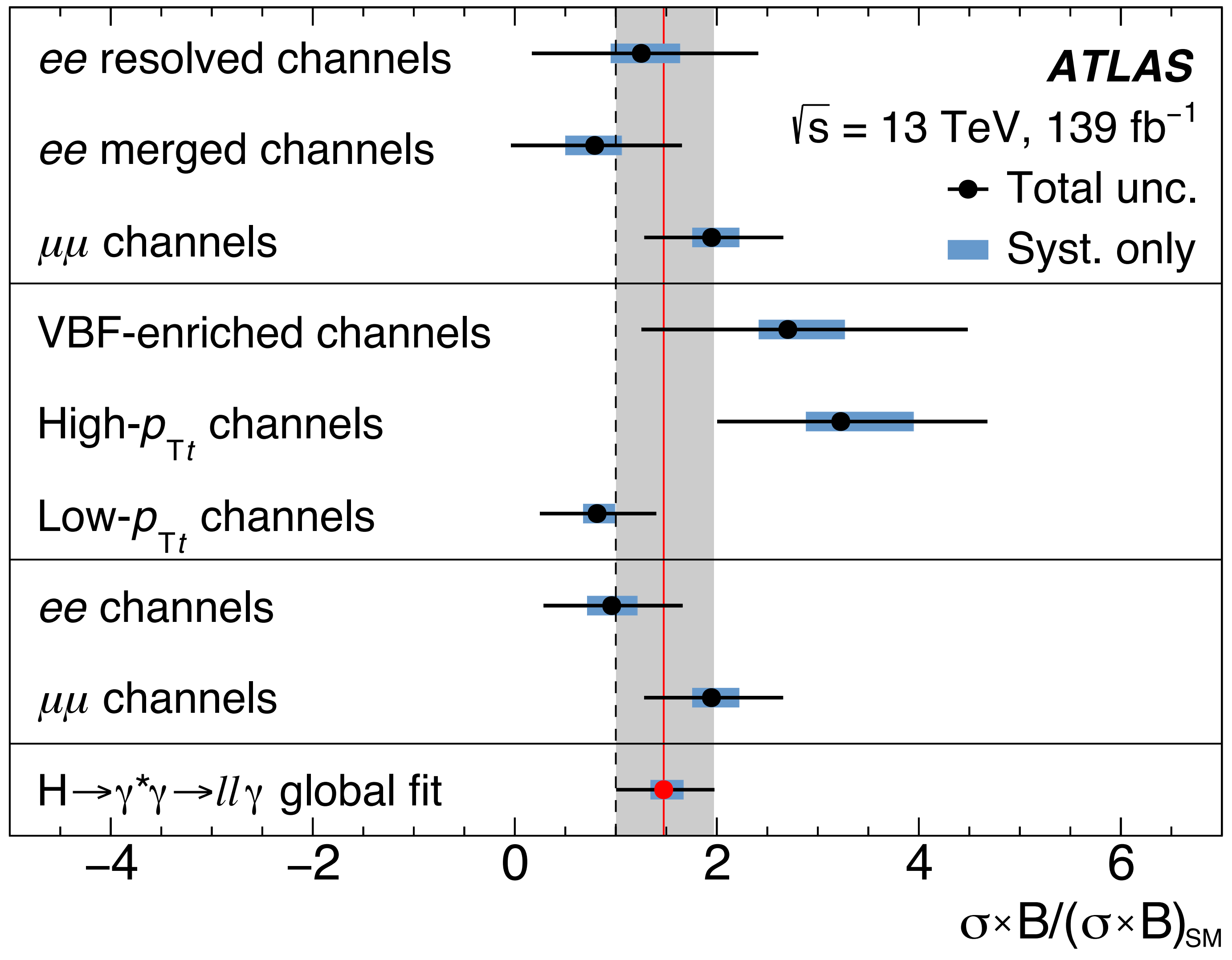
- Simultaneous fit in all categories

- Exp: $\mu = 1.0 \pm 0.5 = 1.0 \pm 0.5(stat.)^{+0.2}_{-0.1}(syst.)$
- Obs: $\mu = 1.5 \pm 0.5 = 1.5 \pm 0.5(stat.)^{+0.2}_{-0.1}(syst.)$
- $\sigma \times BR = 8.7^{+2.8}_{-2.7}$ fb $= 8.7 \pm 2.7(stat.)^{+0.7}_{-0.6}(syst.)$ fb
- Significance: 3.2σ (expected 2.1σ)

Results







- In order to test the consistency of measured signal in each category, run additional fits with μ in sub categories, channels
- In all cases, results are consistent with a healthy statistical variation
- Splitting into a muon and an electron result:
  - $\mu_{\mu\mu} = 2.0 \pm 0.7, \mu_{ee} = 1.0 \pm 0.7$

Signal modelling

- The signal MC m_{ll} distribution is fitted in each region with a Crystal Ball plus Gaussian function

  - $$\begin{aligned} & f_{sig}(m_{ll}; f, \alpha, n, \mu_{cb}, \sigma_{cb}, \mu_G, \sigma_G) \\ = & (1-f) \cdot CB(m_{ll}; \alpha, n, \mu_{cb}, \sigma_{cb}) \\ & +f \cdot G(m_{ll}; \mu_G, \sigma_G) \end{aligned}$$

  - n is fixed to1

  - Shape systematics can affect each parameter, such that each free parameter is approximately

    - $$x(\overrightarrow{\alpha}) = x_{nom}(1 + \sum_i \alpha_i \cdot \delta x_i)$$

Signal and background yields

$H \to ee$

Category	S	B	S/B	Data
Central Low $p_T^{\ell\ell}$	230	39200	0.0057	39872
Forward Low $p_T^{\ell\ell}$	390	98500	0.0039	100844
Central Medium $p_T^{\ell\ell}$	420	30700	0.014	31182
Forward Medium $p_T^{\ell\ell}$	710	74900	0.0095	76477
Central High $p_T^{\ell\ell}$	380	13400	0.028	13625
Forward High $p_T^{\ell\ell}$	590	29900	0.020	30164
VBF	120	2530	0.049	2561

$H \to e\mu$

Category	S	B	S/B	Data
Central Low $p_T^{\ell\ell}$	210	150	1.35	171
Forward Low $p_T^{\ell\ell}$	400	560	0.72	532
Central Medium $p_T^{\ell\ell}$	250	290	0.86	277
Forward Medium $p_T^{\ell\ell}$	450	830	0.54	854
Central High $p_T^{\ell\ell}$	180	280	0.65	299
Forward High $p_T^{\ell\ell}$	300	700	0.43	707
VBF	83	100	0.82	102
Low p_T^{ℓ}	89	600	0.15	558

- Expected sig/bkg yields, their ratio and obs. data events in each category for $120 < m_{ll} < 130$ GeV. The number of bkg events is obtained from bkg-only fit to the data. The signal is shown for a branching fraction of $B = 0.1\,\%$ for both channels

Systematics

Experimental
Electron
Muon
Jet
b-tagging
MET
Luminosity
Theoretical
QCD scale
PDF
PS
Spurious signal

- $H \to ee$
  - Leading systematics: SS
  - Sub-leading: electron RES
  - Smaller contributions: theory errors
- $H \to e\mu$
  - Leading: MET modelling as tighter cut on MET significance compared to $H \to ee$

$H \rightarrow e\mu$ background modeling uncertainty

- Background shape very simple and modeling uncertainty should be contained in statistical error

- As additional test, we fit the background MCs + fakes (SS data) with the nominal fit model and a standard second-order polynomial

  - Nominal: $\mu = -0.032 \pm 0.027$

  - Alternative fit: $\mu = -0.031 \pm 0.027$

- Difference in central values as uncertainty:1.7% of error at exp. limit $\mu = 0.059$