Laboratoire Leprince-Ringuet

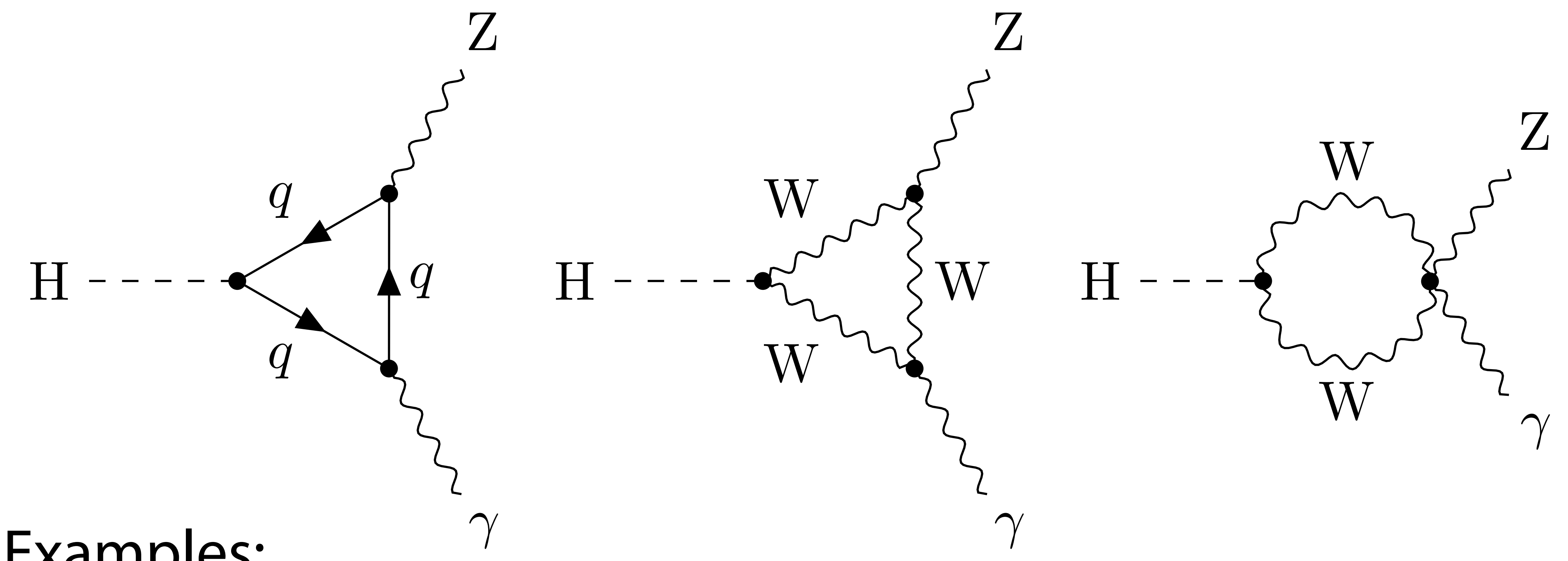
Evidence for H → Zγ in the combination of ATLAS and CMS results

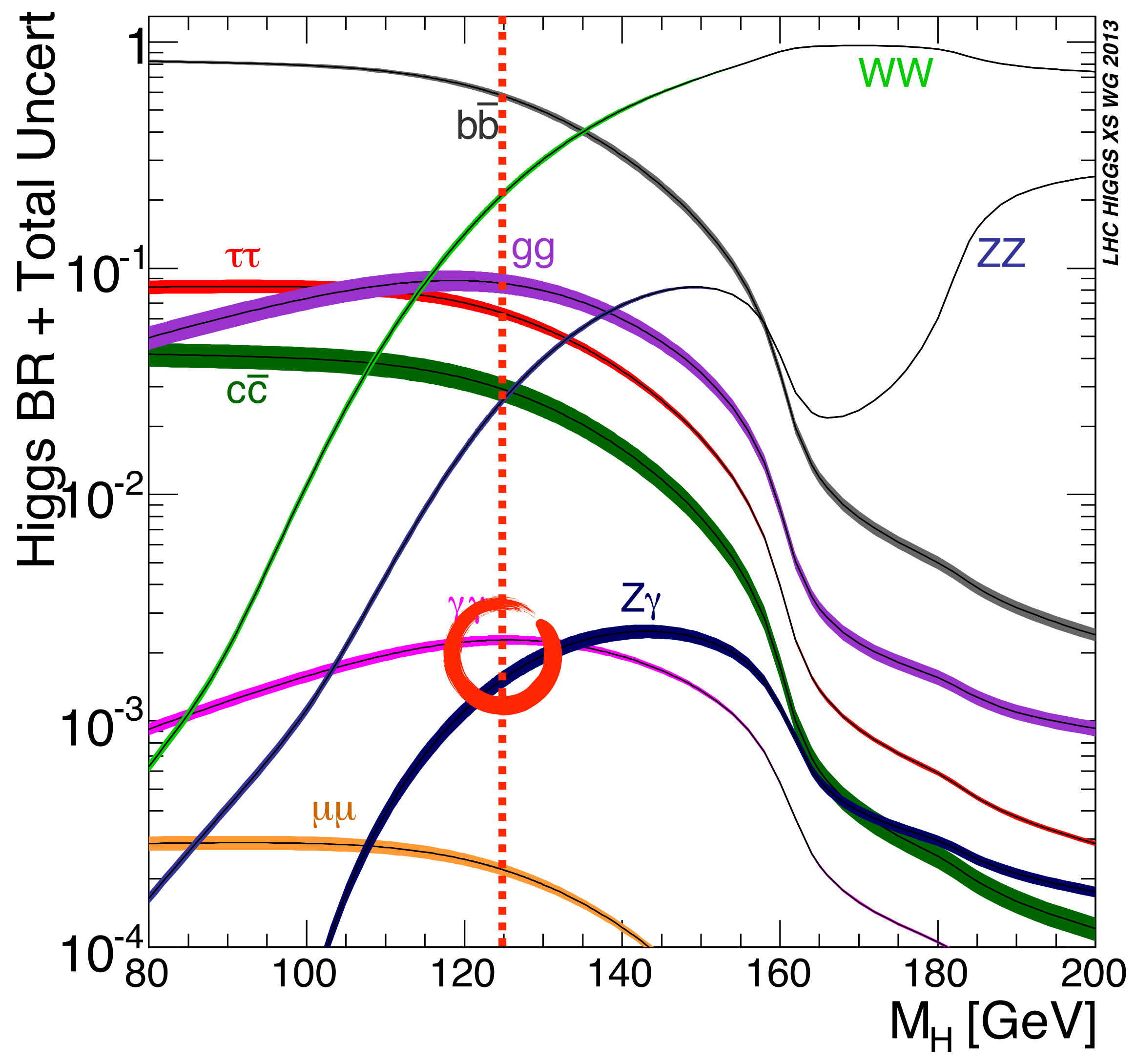
IRN Terascale | 26 October 2023

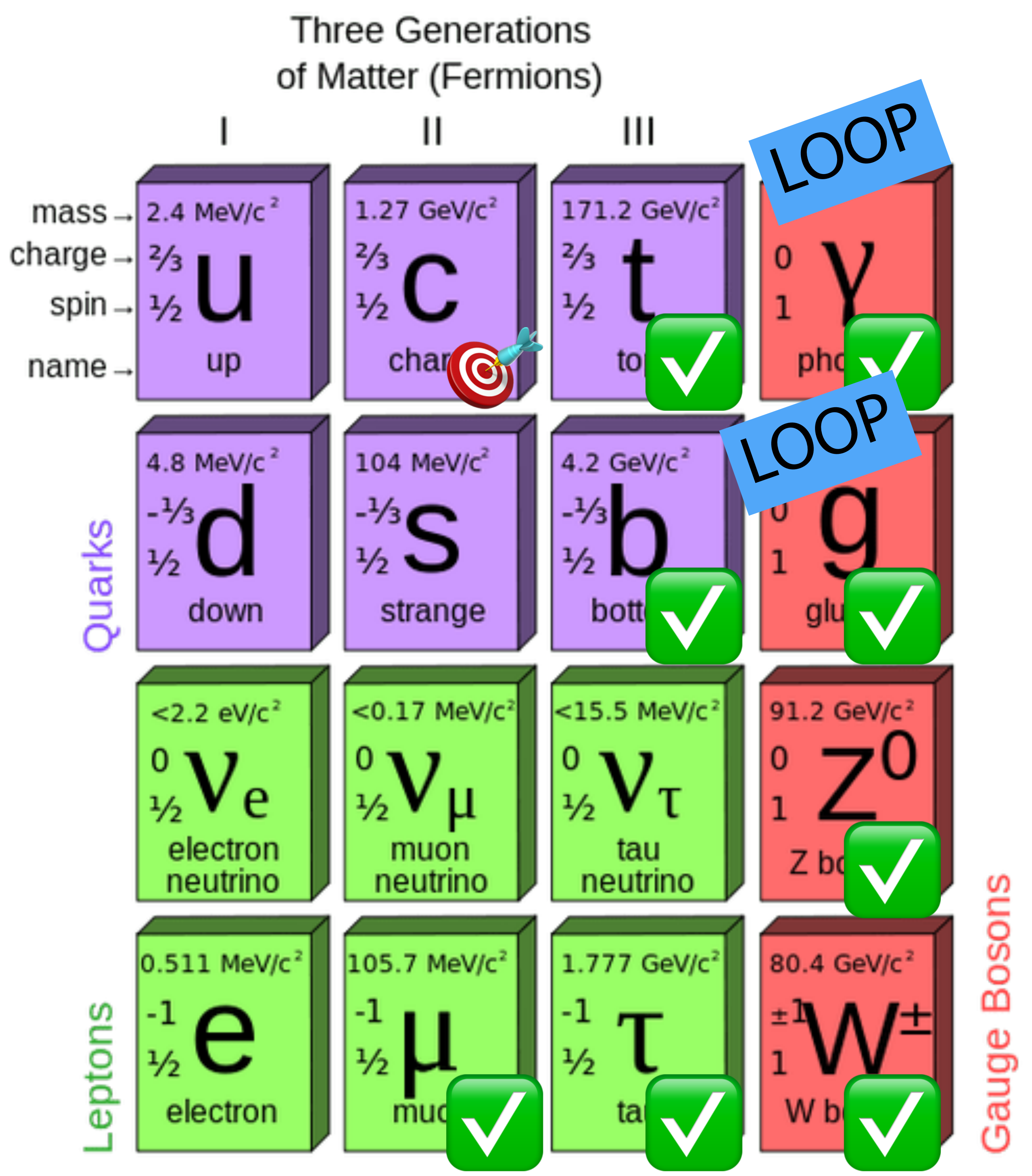
Andrew Gilbert

Introduction

- CMS and ATLAS have extensive programmes to characterise the properties of the Higgs boson
  - Wide range of production and decay processes probed ⇒ established couplings to fermions and vector bosons
- Target more rare and challenging signatures, e.g. H→Zγ
  - Small branching fraction, 1.5 x10^{-3}. Similar to H→γγ but require Z→ee/μμ on top
  - Loop decay ⇒ sensitive to new physics that could modify BF
  - In particular, models can modify B(H→Zγ) / B(H→γγ)





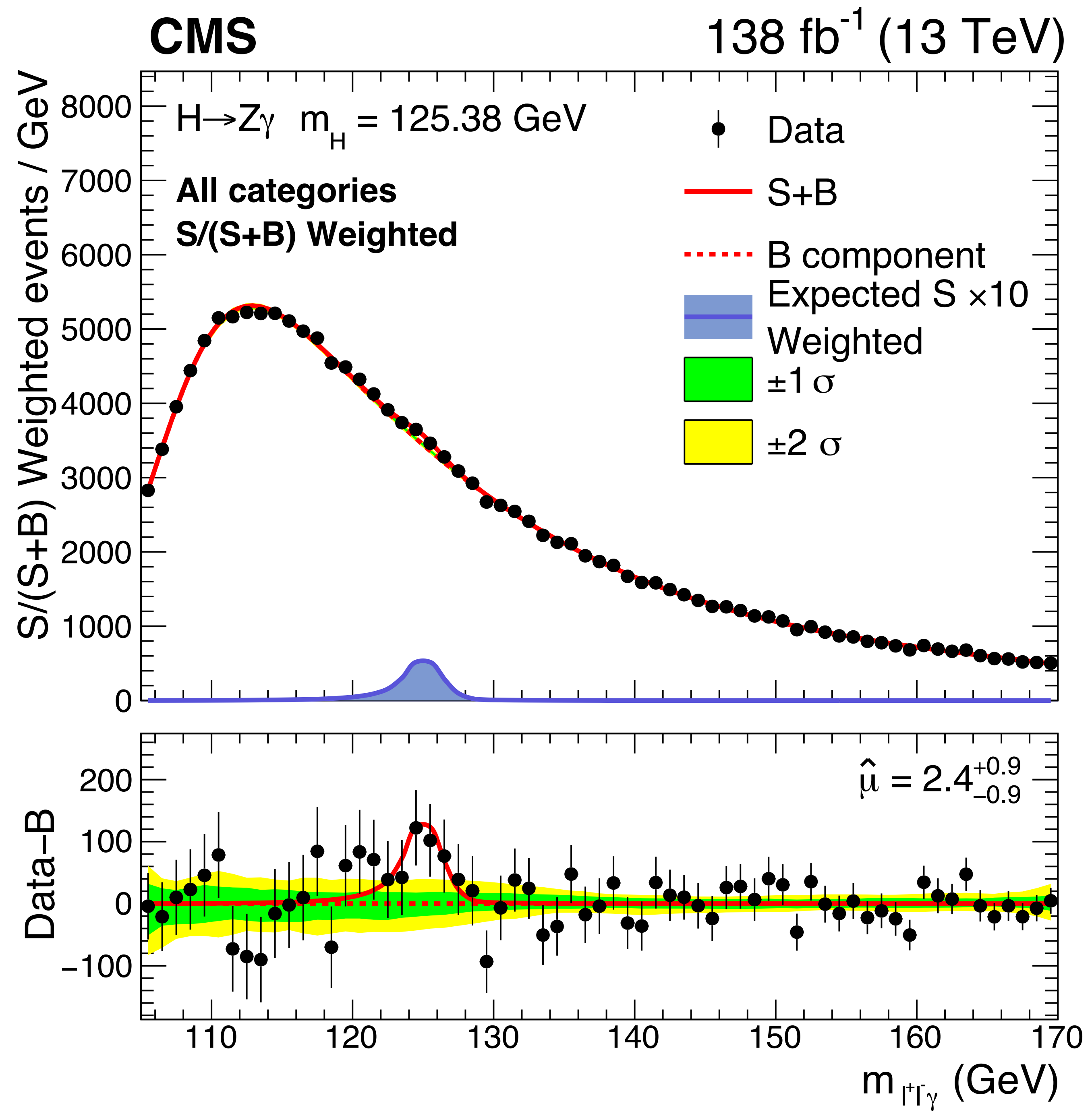


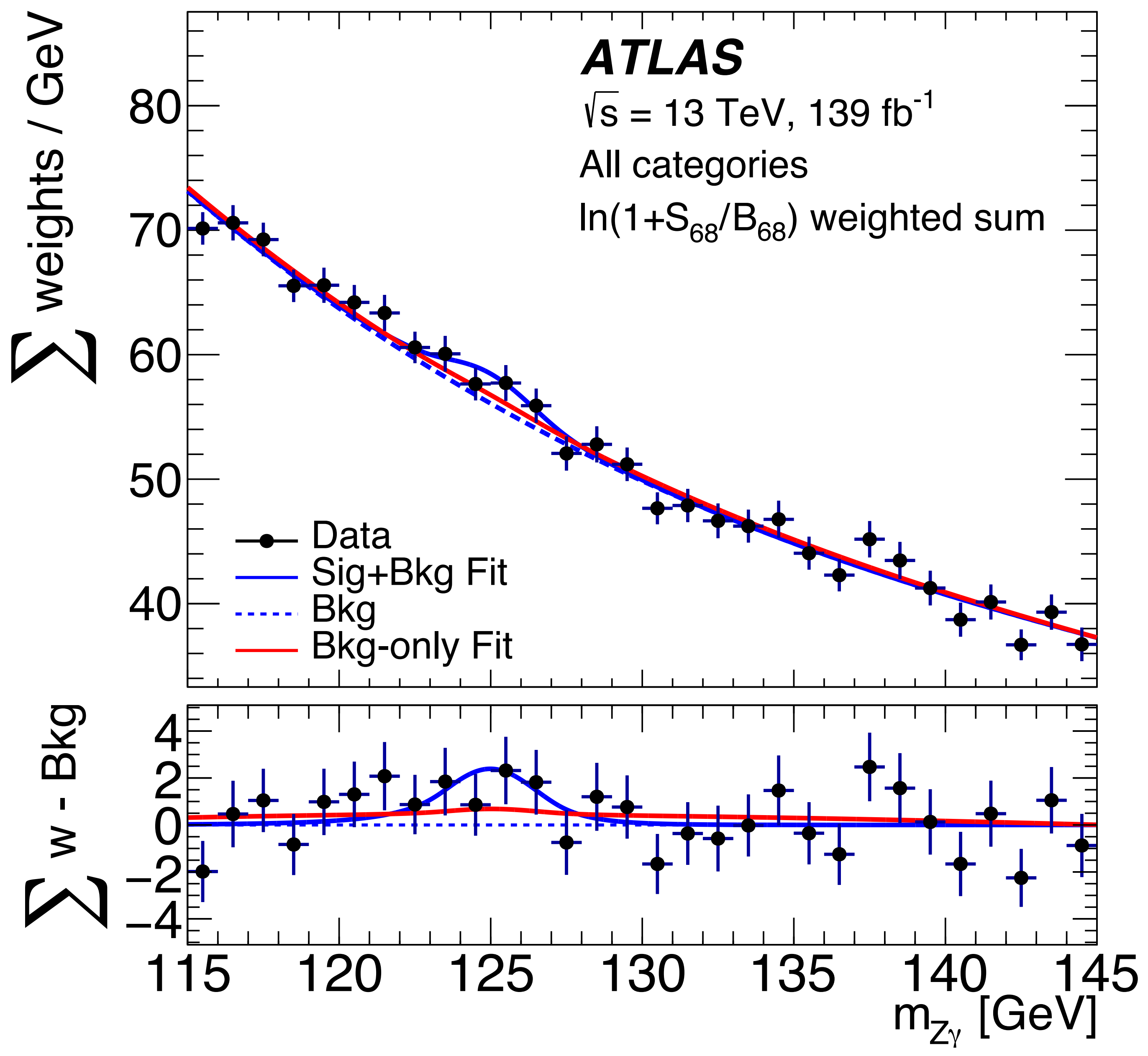
- Examples:
  - Models where Higgs boson is a **composite state**, a **pseudo Nambu–Goldstone boson**, or a neutral scalar originating from a different source
  - Models with **additional** colourless charged **scalars**, **leptons** or **vector bosons** that couple to the Higgs boson
-

Introduction

- CMS and ATLAS have searched for the H→Zγ decay using Run 2 data
  - Using the llγ final state, with $m_{ll} > 50$ GeV
- Similar strategies: categorise events to exploit production mode kinematics and fit $m_{ll\gamma}$ distribution in each category, with analytic functions for background

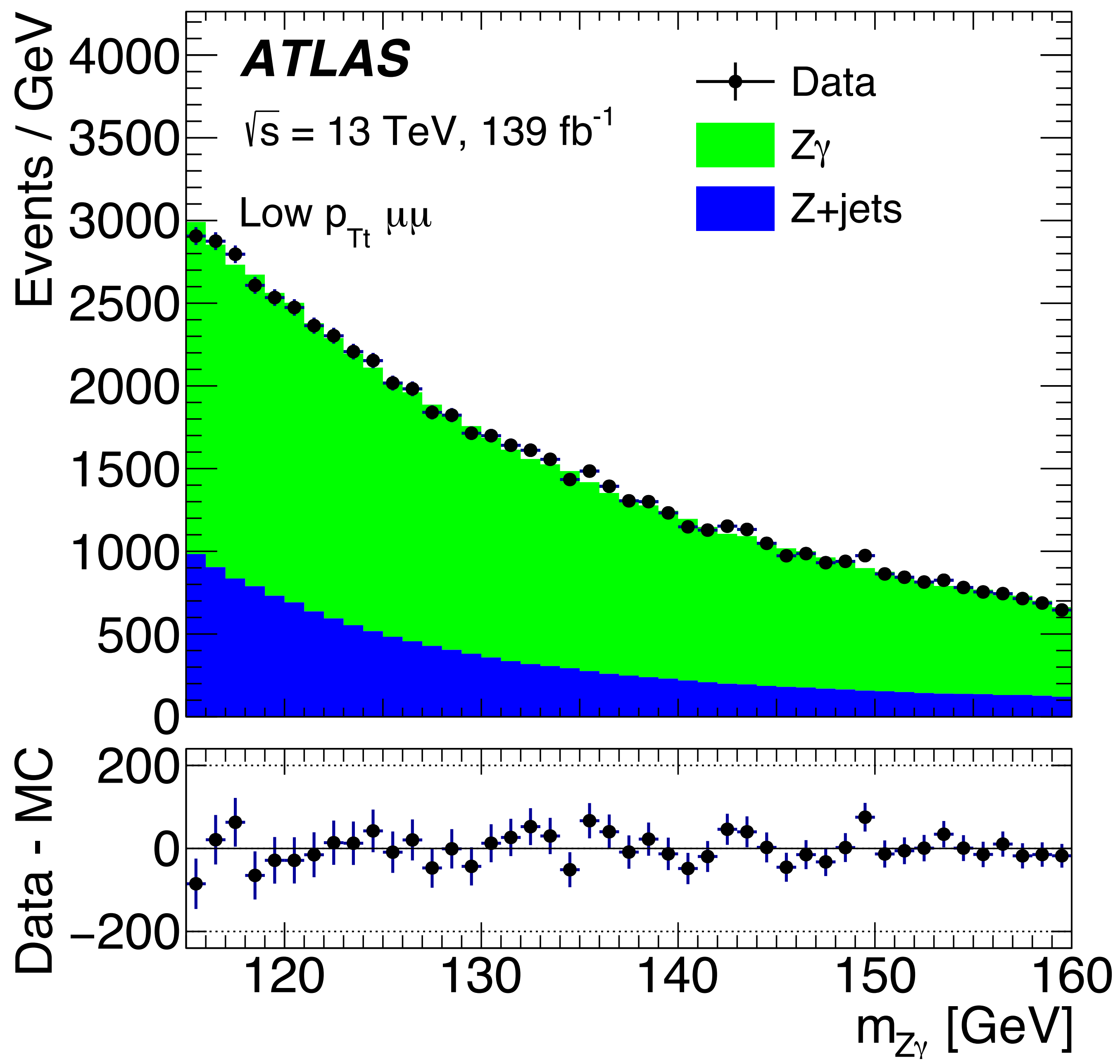
	JHEP 05 (2023) 233 **CMS**	*PLB 809 (2020) 135754* **ATLAS**
No. categories	8	6
Prod modes	ggF, VBF, VH+ttH (lep)	ggF, VBF
Background uncertainty	Discrete profiling	Spurious signal
m_H	125.38 GeV	125.09 GeV
Signal strength	2.4 ± 0.9 (stat) ± 0.3 (syst)	2.0 ± 0.9 (stat) ± 0.4 (syst)
Significance Obs (Exp)	2.7 (1.2)	2.2 (1.2)

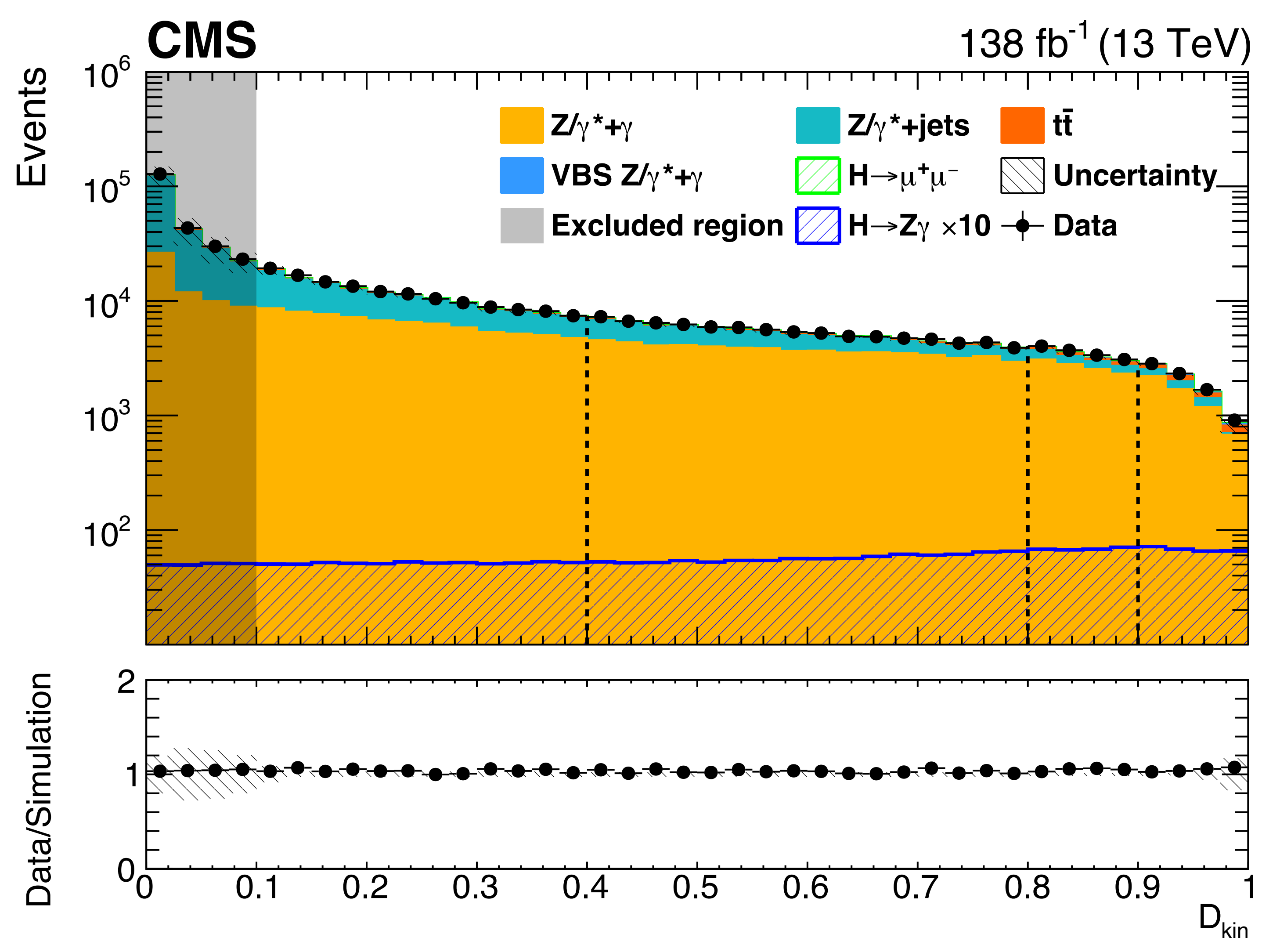


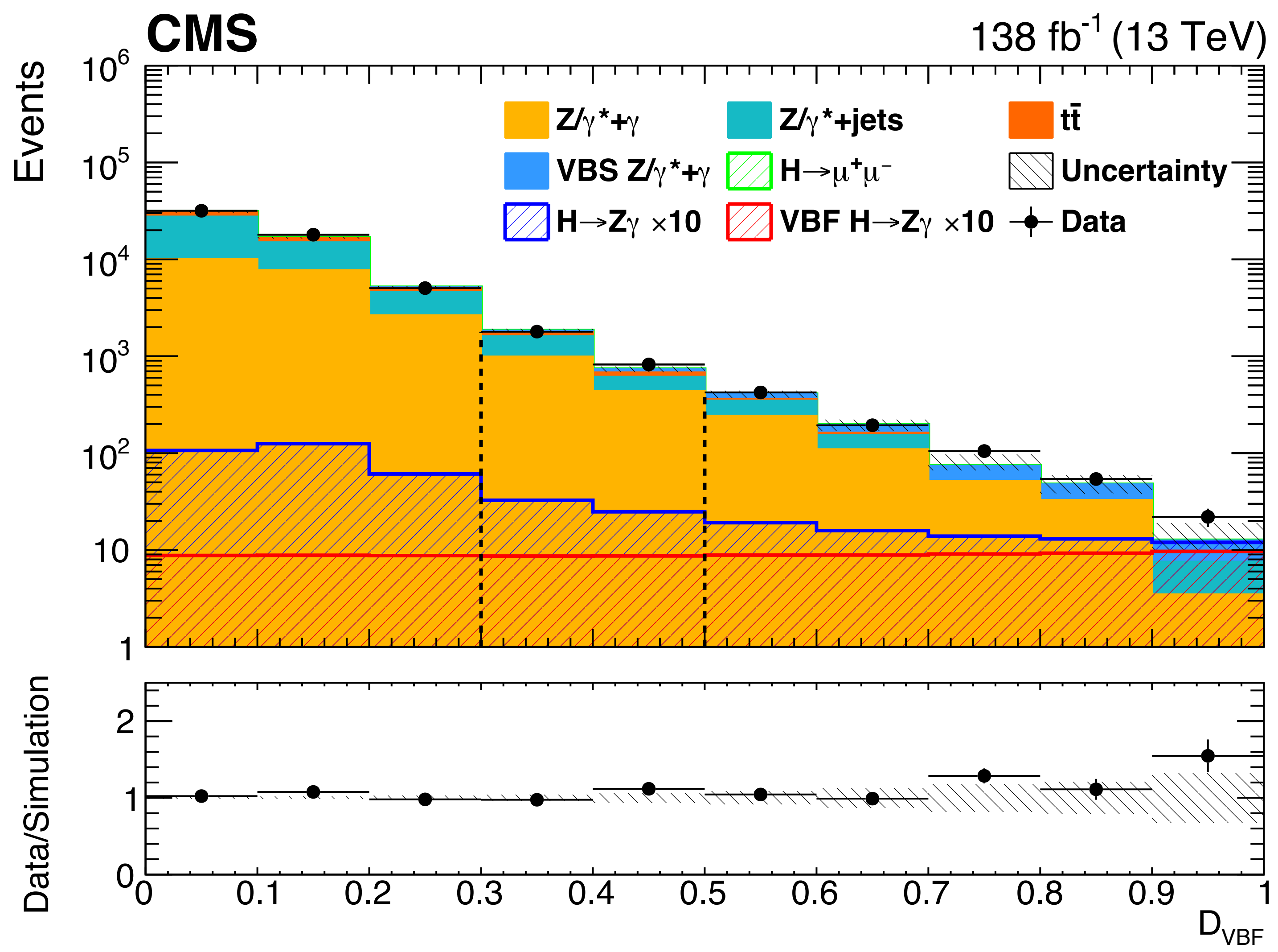


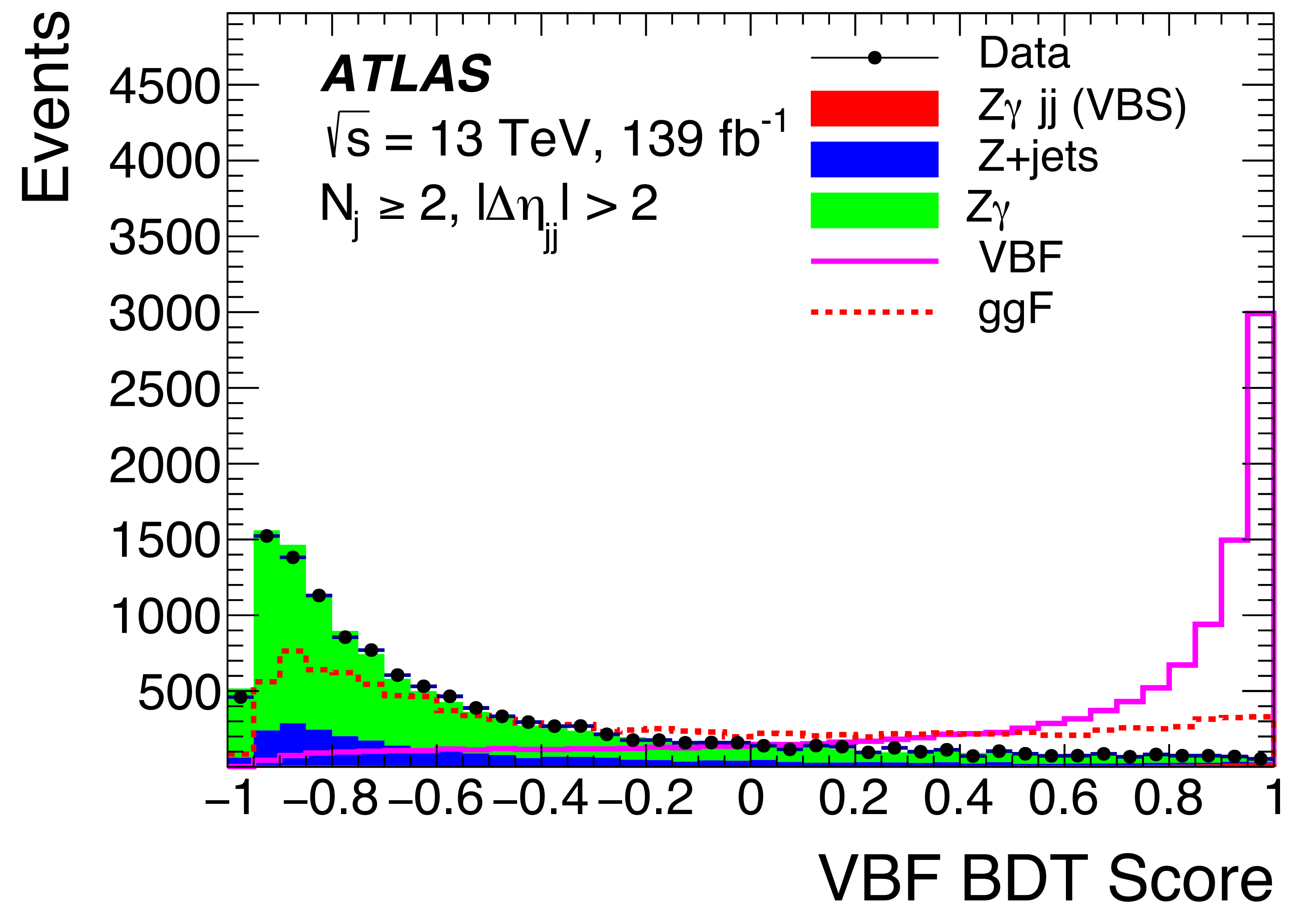
Analysis strategies

- Main backgrounds: standard model **Zγ production**, **Z+jets** with **jet faking photon**
- Target specific Higgs boson production modes and exploit topological & kinematic differences
- Dedicated selections for vector-boson fusion production
  - Use of multivariate discriminators to define optimal event categories
  - **ATLAS**: 1 VBF enriched category, **CMS**: 3 di-jet categories (with varying VBF purity)
- CMS: lepton-tag category for VH and ttH associated production
- Remaining events split into: **ATLAS** 5 categories using kinematic cuts; **CMS** 4 categories in slices of kinematic BDT



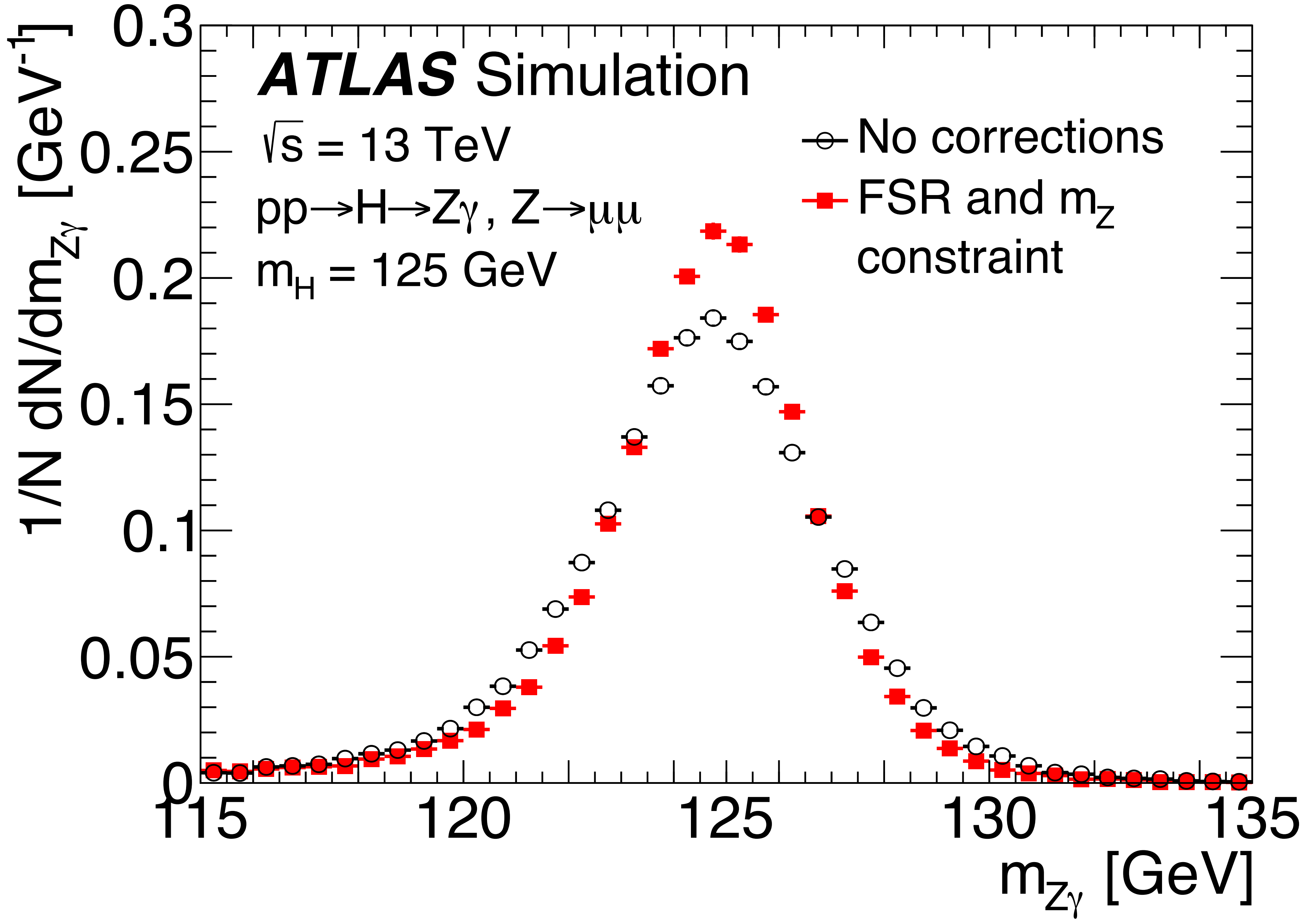






$m_{ll\gamma}$ reconstruction

- Signal from narrow peak in the invariant mass of the $l^+l^-\gamma$ system
- Apply dedicated final-state radiation corrections to the momenta of muons with nearby photons
- Kinematic fits for the dilepton mass using Breit–Wigner to model the *Z* boson resonance
  - Improves resolution by 10-30%
  - Resulting $m_{ll\gamma}$ resolution is 1.4–2 GeV, depending on the final state and event topology



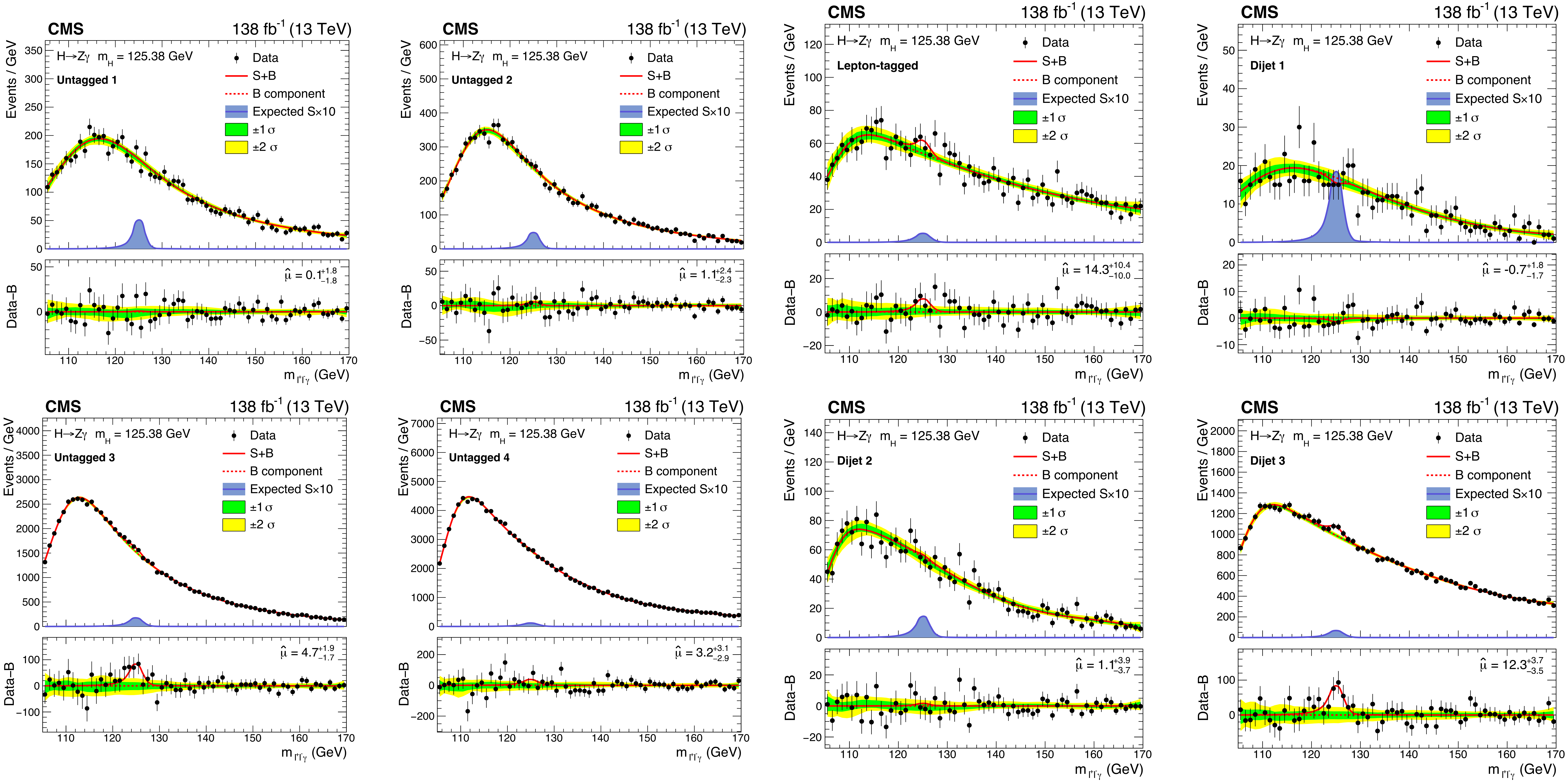
ATLAS

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

CMS

138 fb^{-1}	Lepton		Dijet 1	Dijet 2	Dijet 3	Untagged 1	Untagged 2	Untagged 3	Untagged 4
SM signal yield									
ggH	0.51	e^+e^-	1.10	1.62	9.44	6.89	7.35	29.8	22.5
		$\mu^+\mu^-$	1.41	2.05	12.1	8.52	9.17	38.0	29.0
VBF	0.09	e^+e^-	1.94	0.76	1.13	0.71	0.35	0.92	0.51
		$\mu^+\mu^-$	2.40	0.97	1.43	0.89	0.43	1.18	0.65
VH + $t\bar{t}$H	1.84	e^+e^-	0.04	0.13	1.89	0.31	0.17	0.45	0.27
		$\mu^+\mu^-$	0.05	0.16	2.36	0.39	0.21	0.57	0.33
SM resonant background									
$H \to \mu^+\mu^-$	0.14	$\mu^+\mu^-$	0.27	0.27	0.43	0.62	0.49	2.02	1.78
Mass resolution (GeV)	2.12	e^+e^-	1.91	2.06	2.15	1.80	1.97	2.12	2.33
		$\mu^+\mu^-$	1.52	1.61	1.72	1.37	1.42	1.62	1.83
Data yield	1485		168	589	11596	1485	1541	2559	17608
$S/\sqrt{B}$	0.06		0.54	0.24	0.26	0.45	0.35	0.53	0.30

Event Categorisation - CMS

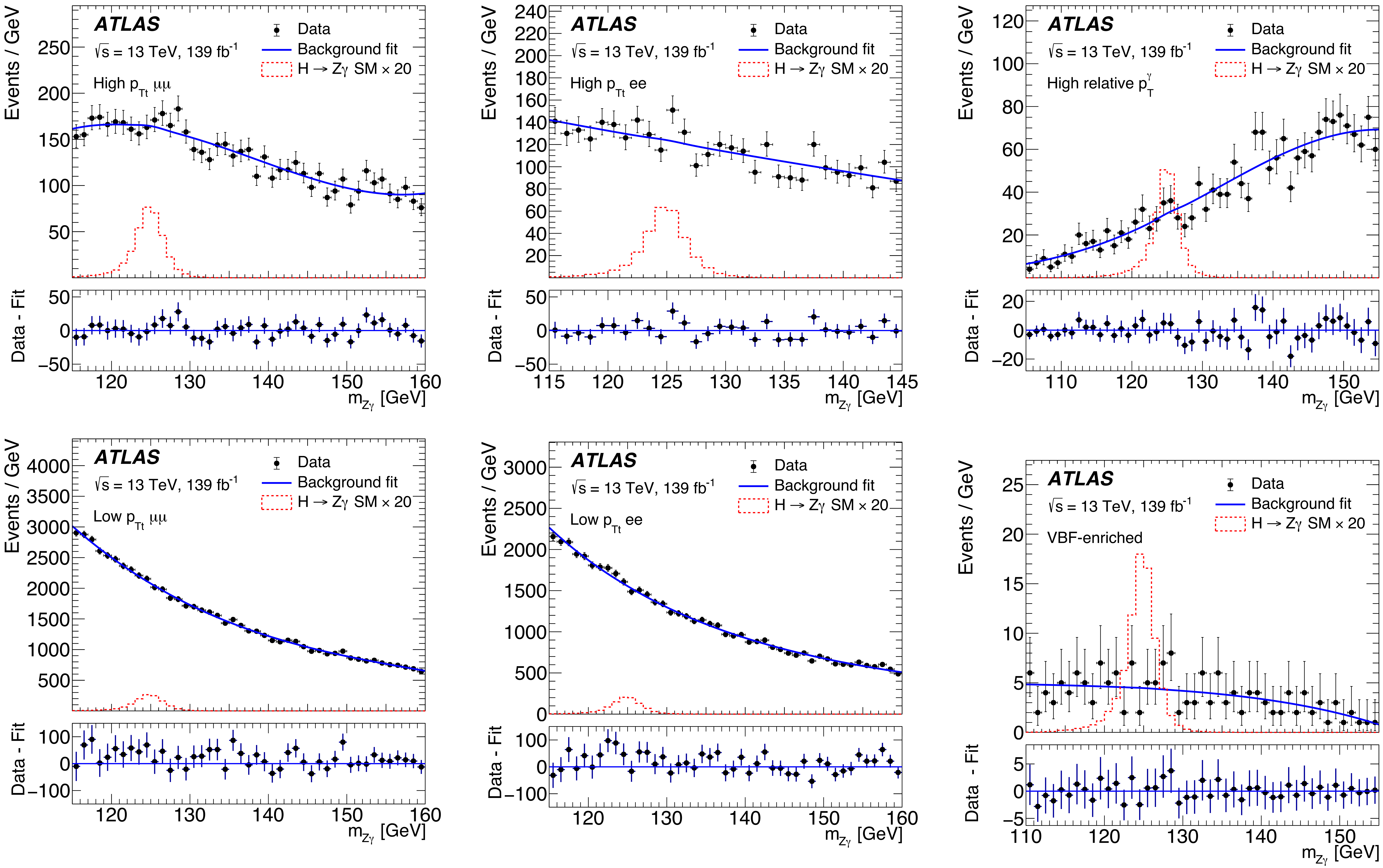


Event Categorisation - ATLAS

p_{Tt} : component of Zγ p_T perp. to difference of Z and γ 3-momenta

⇒

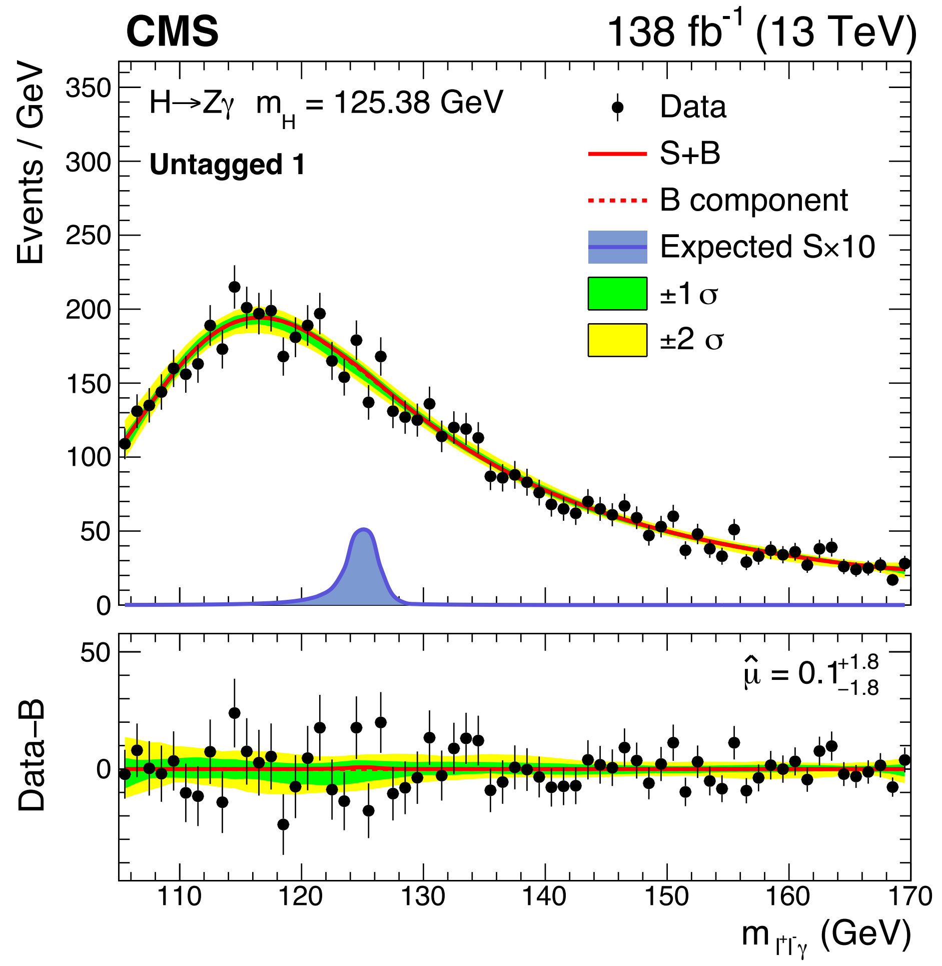
Similar to p_T, but better resolution



$p_T^{\gamma}/m_{Z\gamma} > 0.4$

Background modelling

$$\mathcal{F}(m_{\ell^+\ell^-\gamma}; \mu, \sigma, s, \vec{\alpha}) = \int_{105}^{170} \mathcal{N}(m_{\ell^+\ell^-\gamma} - t; \mu, \sigma) f(t; \vec{\alpha}) \Theta(t; s) dt$$



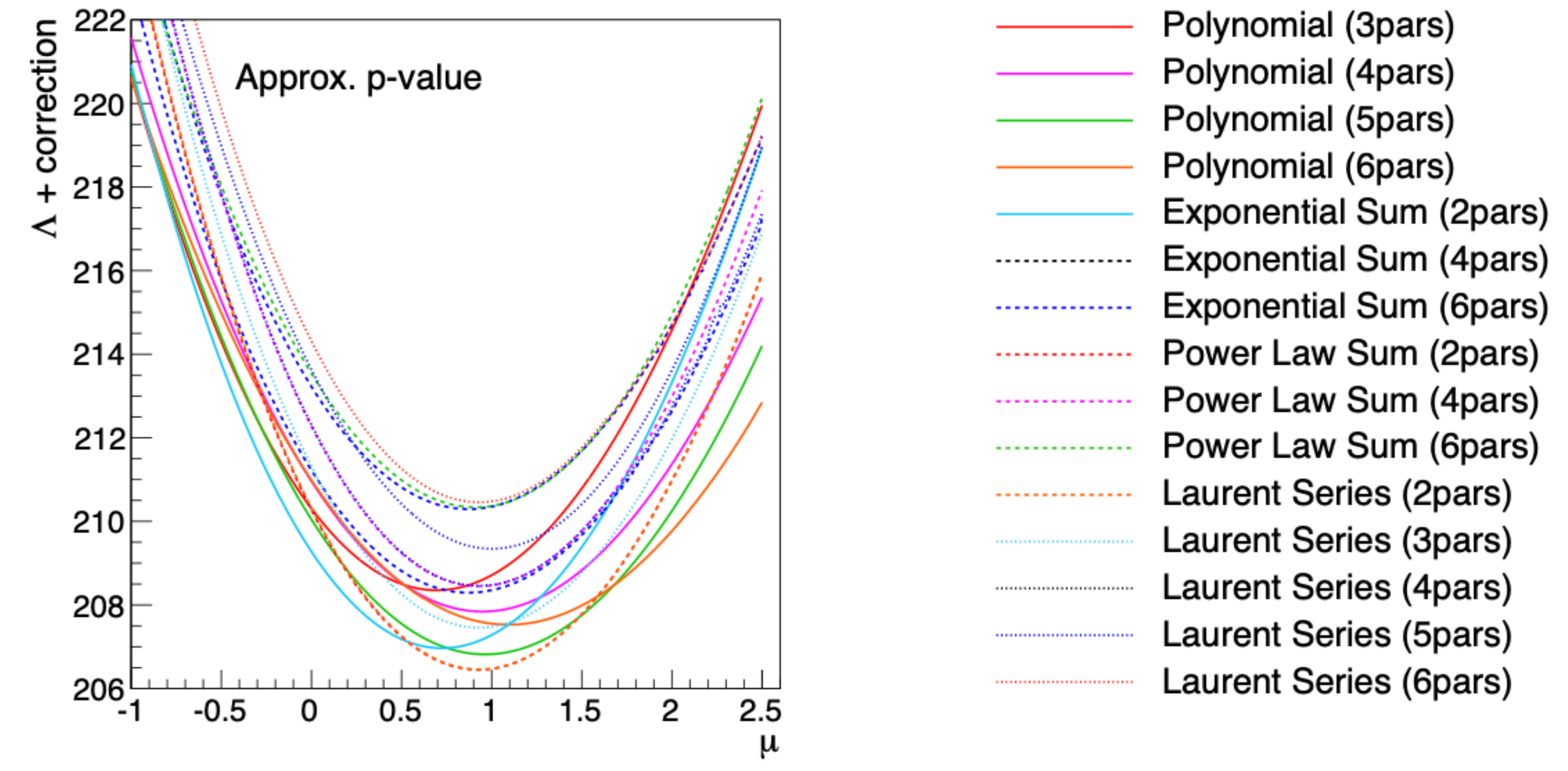
- Parametric function chosen from several families:
  - Exponential, power law, Laurent, Bernstein polynomial
  - **CMS:** multiplied by step-function and convoluted with Gaussian for low mass turn-on

- Selection procedure:
  - **ATLAS:** simultaneous optimisation of fit range and function
    ⇒ aims to reduce bias on extracted signal yield
    - Find function with good χ2, prefer fewer parameters, minimise bias from "spurious signal" in fits to background templates
  - **CMS:** discrete profiling method
    - Treat choice of functional form as a discrete nuisance parameter in the fit, and profile in likelihood scan
    - Demonstrated to minimize bias and has good coverage properties
    - Penalty term applied for functions with higher numbers of free parameters

ATLAS functions

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

Example from: 1408.6865



Systematic uncertainties

- Overall, analyses are statistically limited, and systematics do not play a large role
- Most impacting uncertainties:
  - **Theoretical uncertainties** on SM Higgs cross section and B(H→Zγ)
  - **Underlying event / parton shower**
  - **Efficiency uncertainties** for leptons and photons
  - Background modelling:
    - Absorbed into statistical uncertainty for CMS
    - Spurious signal uncertainty 1.5-39% for ATLAS

CMS uncertainties

Sources	Uncertainty (%)	Year-to-year correlation
Normalization		
Theoretical		
– $\mathcal{B}(H \to Z\gamma)$	5.7	Yes
– ggH cross section (μ_F, μ_R)	3.9	Yes
– ggH cross section (α_S)	2.6	Yes
– ggH cross section (PDF)	1.9	Yes
– VBF cross section (μ_F, μ_R)	0.4	Yes
– VBF cross section (α_S)	0.5	Yes
– VBF cross section (PDF)	2.1	Yes
– WH cross section (μ_F, μ_R)	$^{+0.6}_{-0.7}$	Yes
– WH cross section (PDF)	1.7	Yes
– ZH cross section (μ_F, μ_R)	$^{+3.8}_{-3.1}$	Yes
– ZH cross section (PDF)	1.3	Yes
– WH/ZH cross section (α_S)	0.9	Yes
– $t\bar{t}H$ cross section (μ_F, μ_R)	$^{+5.8}_{-9.2}$	Yes
– $t\bar{t}H$ cross section (α_S)	2.0	Yes
– $t\bar{t}H$ cross section (PDF)	3.0	Yes
Underlying event and parton shower	3.7–4.4	Partial
Integrated luminosity	1.2–2.5	Partial
L1 trigger	0.1–0.4	No
Trigger		
– Electron channel	0.9–1.9	No
– Muon channel	0.1–0.4	No
Photon identification and isolation	0.2–5.0	Yes
Lepton identification and isolation		
– Electron channel	0.5–0.7	Yes
– Muon channel	0.3–0.4	Yes
Pileup	0.4–1.0	Yes
Kinematic BDT	2.5–3.7	Yes
VBF BDT	5.9–14.0	Yes
Shape parameters		
Photon energy and momentum		
– Signal mean	0.1–0.4	Yes
– Signal resolution	3.1–5.9	Yes
Lepton energy and momentum		
– Signal mean	0.007	Yes
– Signal resolution	0.007–0.010	Yes

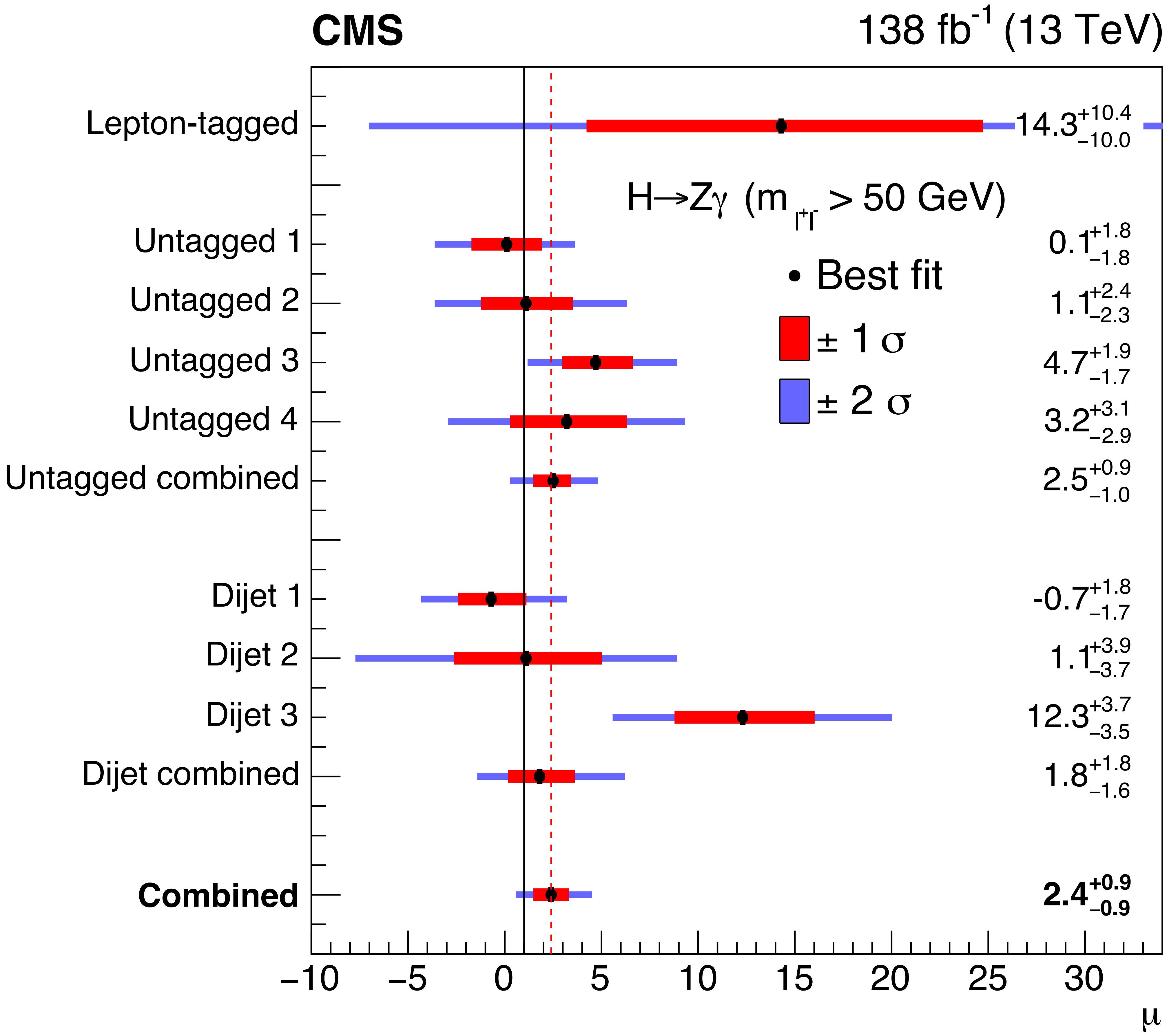
ATLAS uncertainties

Sources	
Total cross-section and efficiency [%]	
ggF Underlying event	1.3
perturbative order	4.7–9.6
PDF and α_s	1.8–2.8
$B(H \to Z\gamma)$	5.7
Total (total cross-section and efficiency)	7.5–11
Category acceptance [%]	
ggF Underlying event	0.1–11
ggF H p_T perturbative order	0.3–0.4
ggF in VBF-enriched category	37
ggF in high relative p_T category	21
ggF in other categories	10–15
Other production modes	1.0–15
PDF and α_s	0.4–3.5
Total (category acceptance)	11–37

Sources	$H \to Z\gamma$
Luminosity [%]	
Luminosity	1.7
Signal efficiency [%]	
Modelling of pile-up interactions	0.0–0.2
Photon identification efficiency	0.8–1.8
Photon isolation efficiency	0.7–1.9
Electron identification efficiency	0.0–2.3
Electron isolation efficiency	0.0–0.1
Electron reconstruction efficiency	0.0–0.5
Electron trigger efficiency	0.0–0.1
Muon selection efficiency	0.0–0.6
Muon trigger efficiency	0.0–1.6
Jet energy scale	0.0–3.5
Jet resolution	0.0–15
Jet pile-up	0.0–7.5
Jet flavor	0.0–11
Signal modelling on σ_{CB} [%]	
Electron and photon energy resolution	0.5–3.4
Muon – Inner detector resolution	0.0–1.2
Muon – Muon spectrometer resolution	0.0–3.4
Signal modelling on μ_{CB} [%]	
Electron and photon energy scale	0.09–0.15
Muon momentum scale	0.0–0.03
Higgs boson mass measurement	0.19
Background modelling [number of spurious signal events]	
Spurious signal	1.5–39

Results per category

- Results from respective CMS and ATLAS publications:



ATLAS results

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)

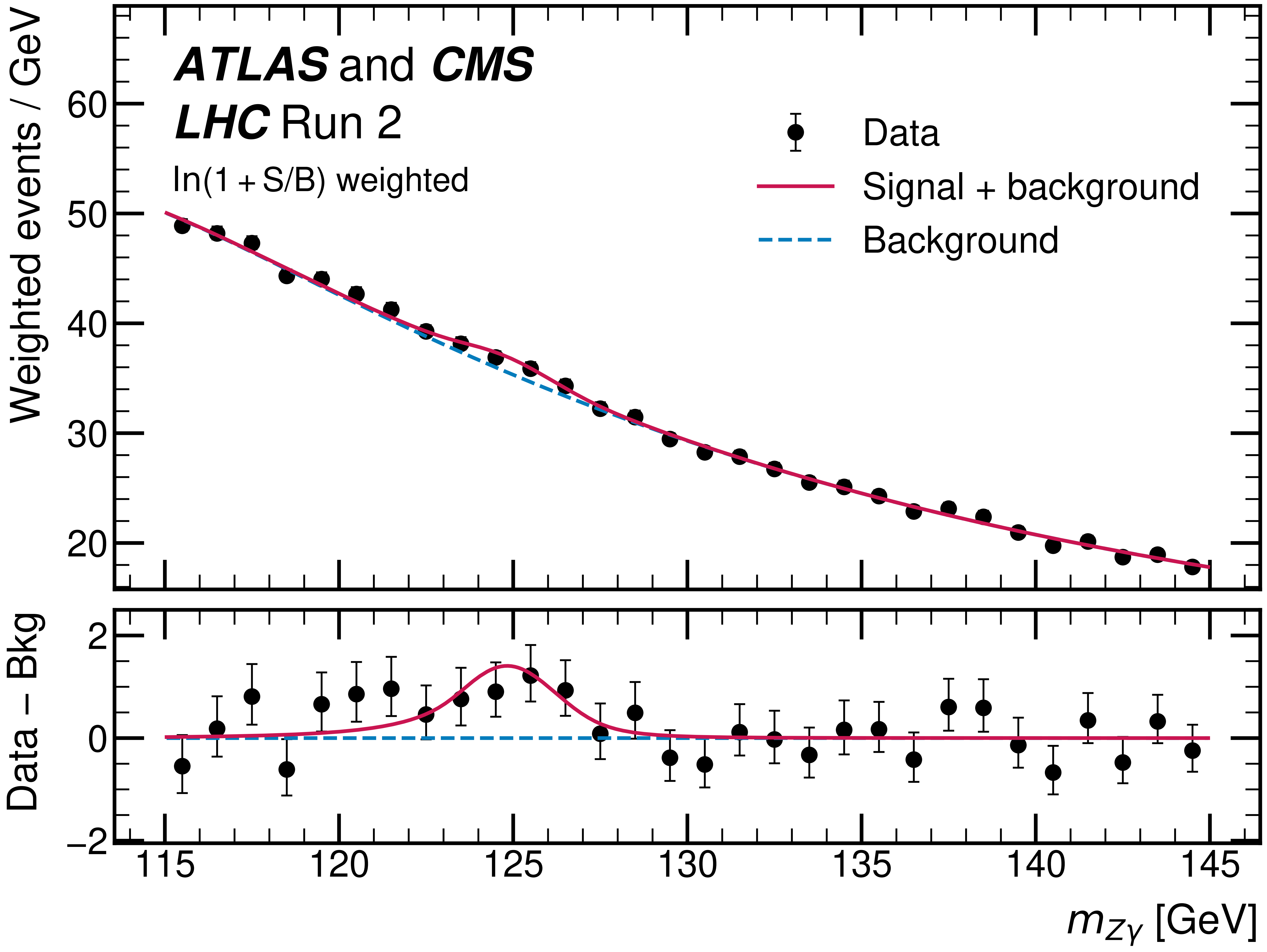
- CMS dijet 3 category has more significant excess. Mutual channel compatibility p-value 0.2% (2.3 s.d)

Combination procedure

- Combination performed at the level of the likelihood function ⇒ fit to combined ATLAS+CMS data set
  - First CMS+ATLAS Higgs combination using Run 2 data
- Correlation of systematic uncertainties
  - Experimental uncertainties treated as uncorrelated between experiments
  - Theory uncertainties: main ggH cross section and $H \to Z\gamma$ branching fraction uncertainties (highest impact)
- Other production mode uncertainties (scale/PDF) implemented differently ⇒ not correlated
  - Approximate attempts to correlate PDF and other scale uncertainties give negligible difference to the results
  - Luminosity correlation for Run 2 not yet known. Tests with toys assuming fully correlated or uncorrelated show negligible bias
- Treatment of m_H:
  - CMS result reported only for m_H = 125.38 GeV, ATLAS for only 125.09 GeV
  - Combined results evaluated for both mass values, no difference within the quoted precision

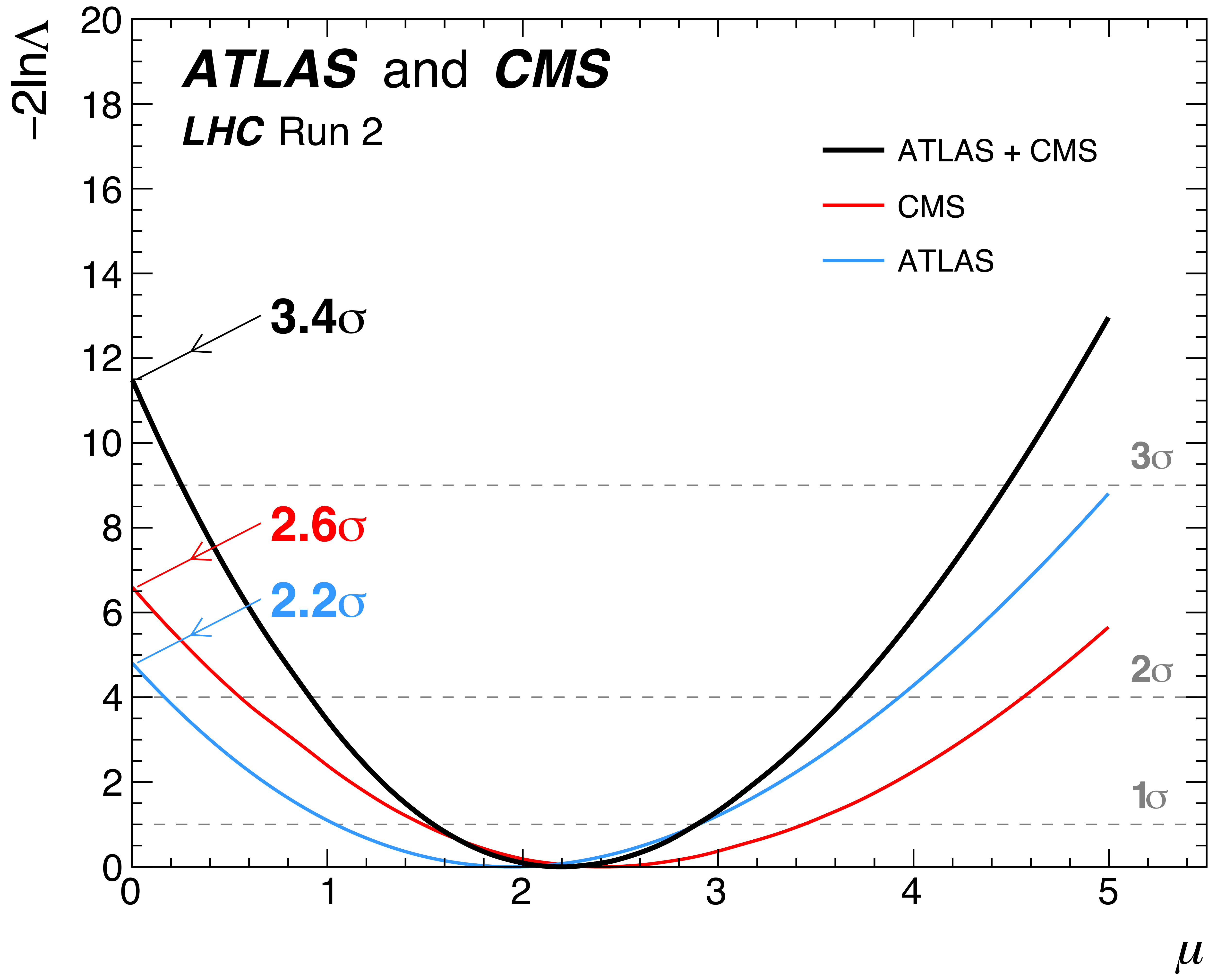
Results

- Summary showing events summed from all ATLAS and CMS categories
- Only the common subrange in $m_{Z\gamma}$ is visualized
  - Full ranges used in the signal extraction fit
- Each category are weighted by ln(1+S/B)
  - Proxy for category sensitivity
  - S and B are the observed signal and background yields in that category, in the 120–130 GeV interval
- Visible excess between 123-127 GeV, consistent with shape expected for signal



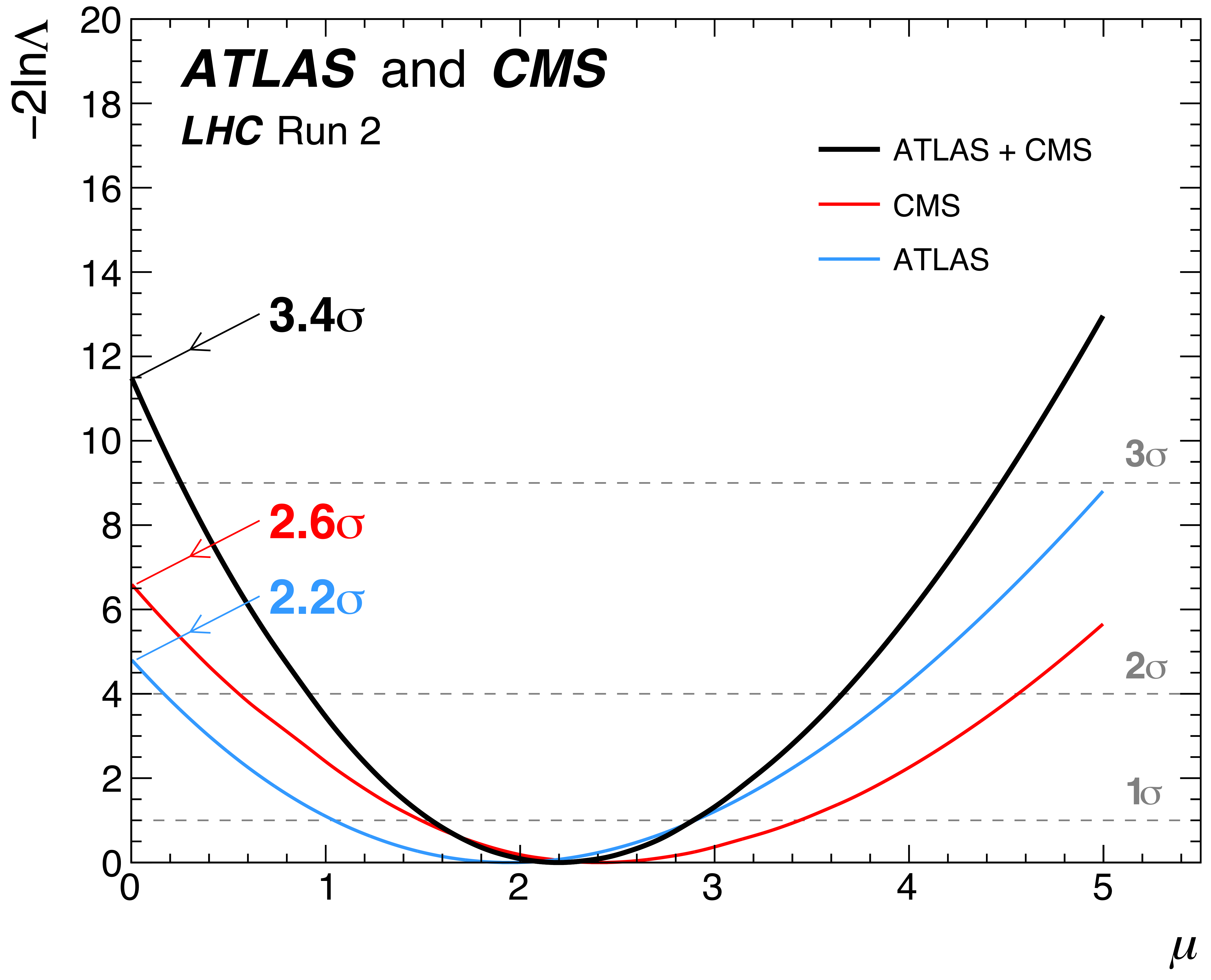
Results

- Signal strength: 2.2 ± 0.6(stat) ± 0.3 (syst)
  = **2.2 ± 0.7** (1.0 ± 0.6 expected)
- Significance of **3.4 standard deviations**
- Assuming SM production cross sections:
  - **B(H→Zγ) = (3.4 ± 1.1) x 10^{-3}**
- Mutual compatibility between all 14 categories:
  - p-value > 0.12
- Compatibility with SM hypothesis: **1.9 s.d.**
- Goodness-of-fit of the model to the data:
  - p-value > 0.90



Summary

- **First evidence of the H→Zγ decay**
  - Some tension with SM prediction, not yet significant
- Paper has been submitted for publication in PRL
- First CMS-ATLAS Higgs combination in Run 2
- Excellent preparation for full CMS+ATLAS Run 2 combination
  - Allow to perform more detailed tests, including measurement of Zγ/γγ ratio
  - Interpretations in the effective field theory framework



Backup