Rare Higgs and Z Boson Decays to a Meson and a Photon at the ATLAS experiment

R. Ward

University of Birmingham

Particle Physics Seminar

19th April 2023

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement no 714893 (ExclusiveHiggs)

Exclusive Higgs

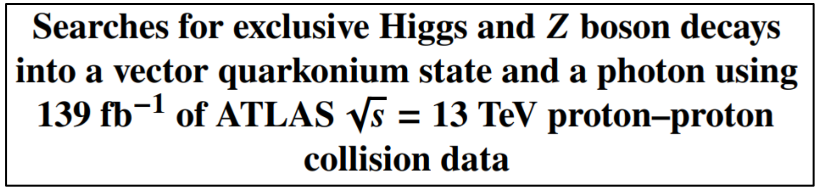
Decays of the Higgs and Z Bosons to a Meson and a Photon

- **ATLAS has set limits on 17 $H(Z) \to \mathcal{M}\gamma$ decay channels**
  - Distinct signatures, dedicated triggers, and novel background model methods

Time

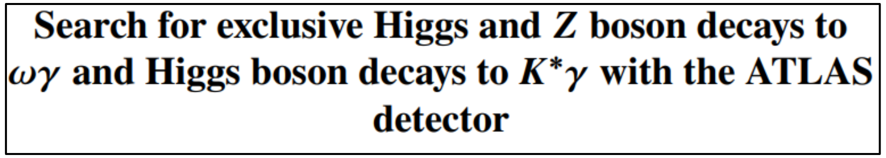
Decay Channels	$\sqrt{s}$ (TeV)	Luminosity (fb^{-1})	Publication
$H(Z) \to (J/\psi, \Upsilon(nS, n = 1,2,3)\gamma)$	8	20	*Phys.Rev.Lett.* 114 (2015) 12, 121801
$H(Z) \to \phi\gamma$	13	2.7	*Phys.Rev.Lett.* 117 (2016) 11, 111802
$\boldsymbol{H(Z) \to (\phi, \rho)\gamma}$	**13**	**36**	***JHEP* 07 (2018) 127**
$H(Z) \to (J/\psi, \psi(2S), \Upsilon(nS)\gamma)$	13	36	*Phys.Lett.B* 786 (2018) 134-155
$\boldsymbol{H(Z) \to (J/\psi, \psi(2S), \Upsilon(nS)\gamma)}$	**13**	**139**	**arXiv:2208.03122**
$\boldsymbol{H \to K^*\gamma + H(Z) \to \omega\gamma}$	**13**	**134 (90)**	**arXiv:2301.09938**

Bold = Latest Results



Searches for exclusive Higgs and Z boson decays into a vector quarkonium state and a photon using 139 fb^{-1} of ATLAS $\sqrt{s} = 13$ TeV proton–proton collision data

Accepted by EPJ C



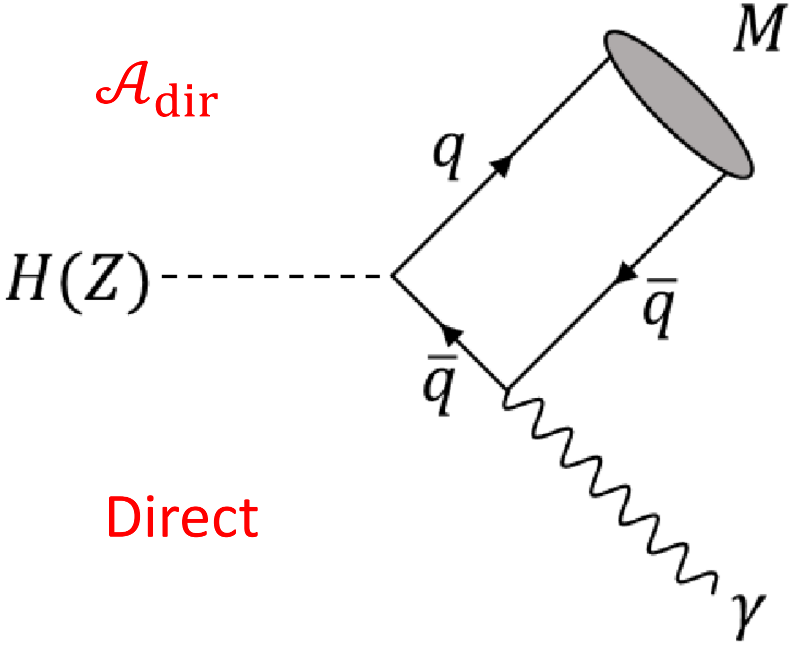
Search for exclusive Higgs and Z boson decays to $\omega\gamma$ and Higgs boson decays to $K^*\gamma$ with the ATLAS detector

Submitted to PLB

$H(Z) \rightarrow \mathcal{M}\gamma$: Motivation

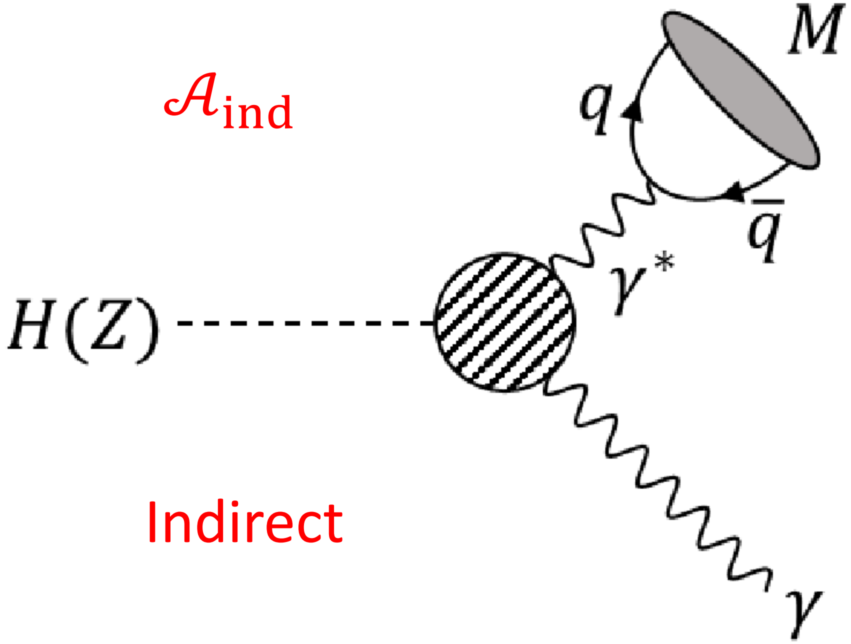
- Search for exclusive $H(Z) \rightarrow \mathcal{M}\gamma$ decays: $\mathcal{M}$ = vector mesons ($q\bar{q}$)
  - Two destructively interfering contributions to decay amplitude
  - Distinct signatures avoid large QCD backgrounds

$\mathcal{A}_{\text{dir}}$

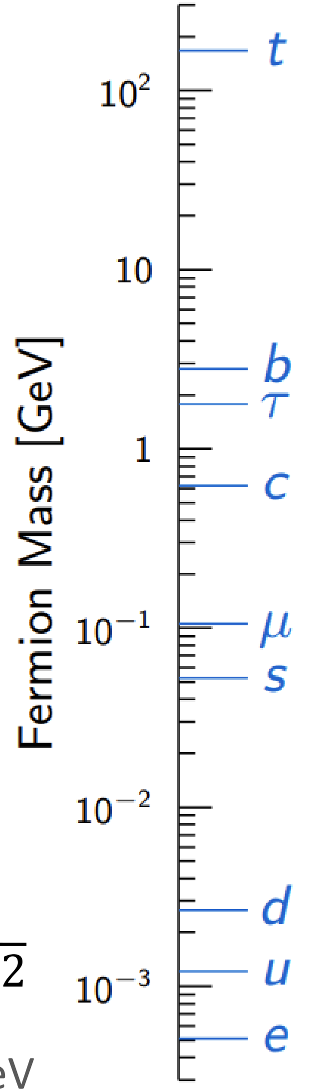


Direct

$\mathcal{A}_{\text{ind}}$



Indirect



- ***H* decays:** probe magnitude and sign of quark Yukawa couplings
  - Only evidence for Higgs-quark couplings to-date is for the t- and b-quarks
- ***Z* decays:** provide reference channels and tests of QCD factorisation

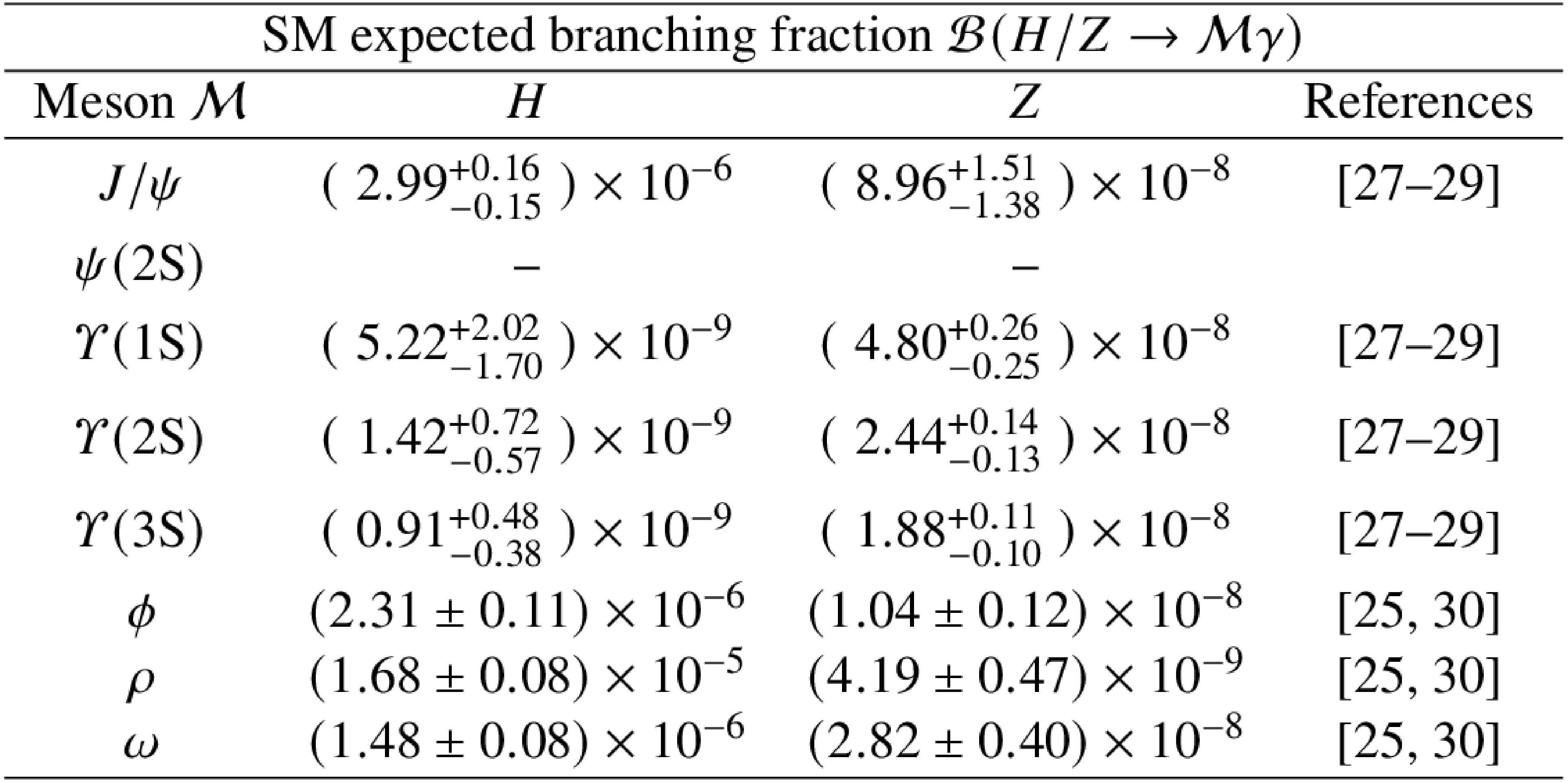
$$y_f^{SM} = \frac{m_f}{v}\sqrt{2}$$

$v \approx 246$ GeV

$H(Z) \rightarrow \mathcal{M}\gamma$: SM Branching Fractions

Heavy mesons (quarkonia) $q = b, c$

Light mesons $q = s, d, u$



SM expected branching fraction $\mathcal{B}(H/Z \rightarrow \mathcal{M}\gamma)$			
Meson $\mathcal{M}$	H	Z	References
J/ψ	$(2.99^{+0.16}_{-0.15}) \times 10^{-6}$	$(8.96^{+1.51}_{-1.38}) \times 10^{-8}$	[27–29]
$\psi(2S)$	–	–	
$\Upsilon(1S)$	$(5.22^{+2.02}_{-1.70}) \times 10^{-9}$	$(4.80^{+0.26}_{-0.25}) \times 10^{-8}$	[27–29]
$\Upsilon(2S)$	$(1.42^{+0.72}_{-0.57}) \times 10^{-9}$	$(2.44^{+0.14}_{-0.13}) \times 10^{-8}$	[27–29]
$\Upsilon(3S)$	$(0.91^{+0.48}_{-0.38}) \times 10^{-9}$	$(1.88^{+0.11}_{-0.10}) \times 10^{-8}$	[27–29]
ϕ	$(2.31 \pm 0.11) \times 10^{-6}$	$(1.04 \pm 0.12) \times 10^{-8}$	[25, 30]
ρ	$(1.68 \pm 0.08) \times 10^{-5}$	$(4.19 \pm 0.47) \times 10^{-9}$	[25, 30]
ω	$(1.48 \pm 0.08) \times 10^{-6}$	$(2.82 \pm 0.40) \times 10^{-8}$	[25, 30]

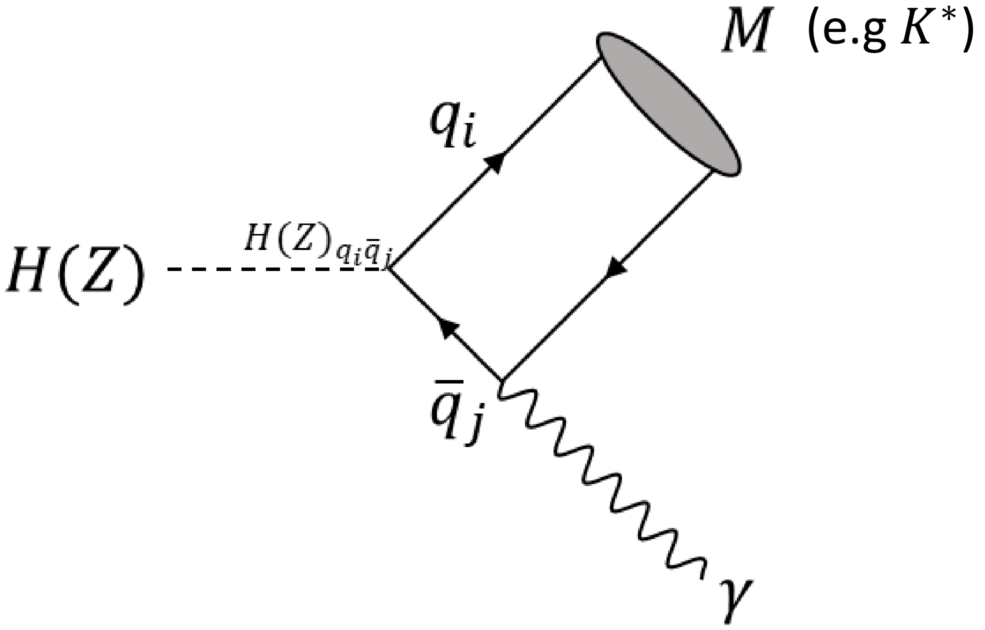
Theory Refs: 25: JHEP 08 (2015) 012, 27: Phys. Rev. D 95 (2017) 054018, 28: Phys. Rev. D 96 (2017) 116014, 29: Phys. Rev. D 97 (2018) 016009, 30: JHEP 04 (2015) 101

- $H \rightarrow \Upsilon(nS)\gamma$ particularly sensitive to BSM physics (e.g arXiv:2209.01200)

ATL-PHYS-PUB-2023-004

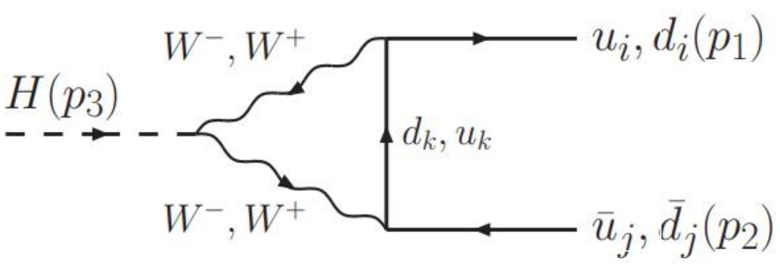
Flavour-Violating Radiative Decays of the Higgs and Z Bosons

- Choosing “flavoured” $\mathcal{M}$ $(q\bar{q}')$ probes flavour-violating couplings
  - Forbidden at tree-level within the SM
- Any observation at the LHC would imply new physics



$H(Z) \to \mathcal{M}\gamma$ via flavour-violating $H(Z) \to q_i\bar{q}_j$

J. Phys. G 47 (2020) 12, 125001



(Example Diagram)

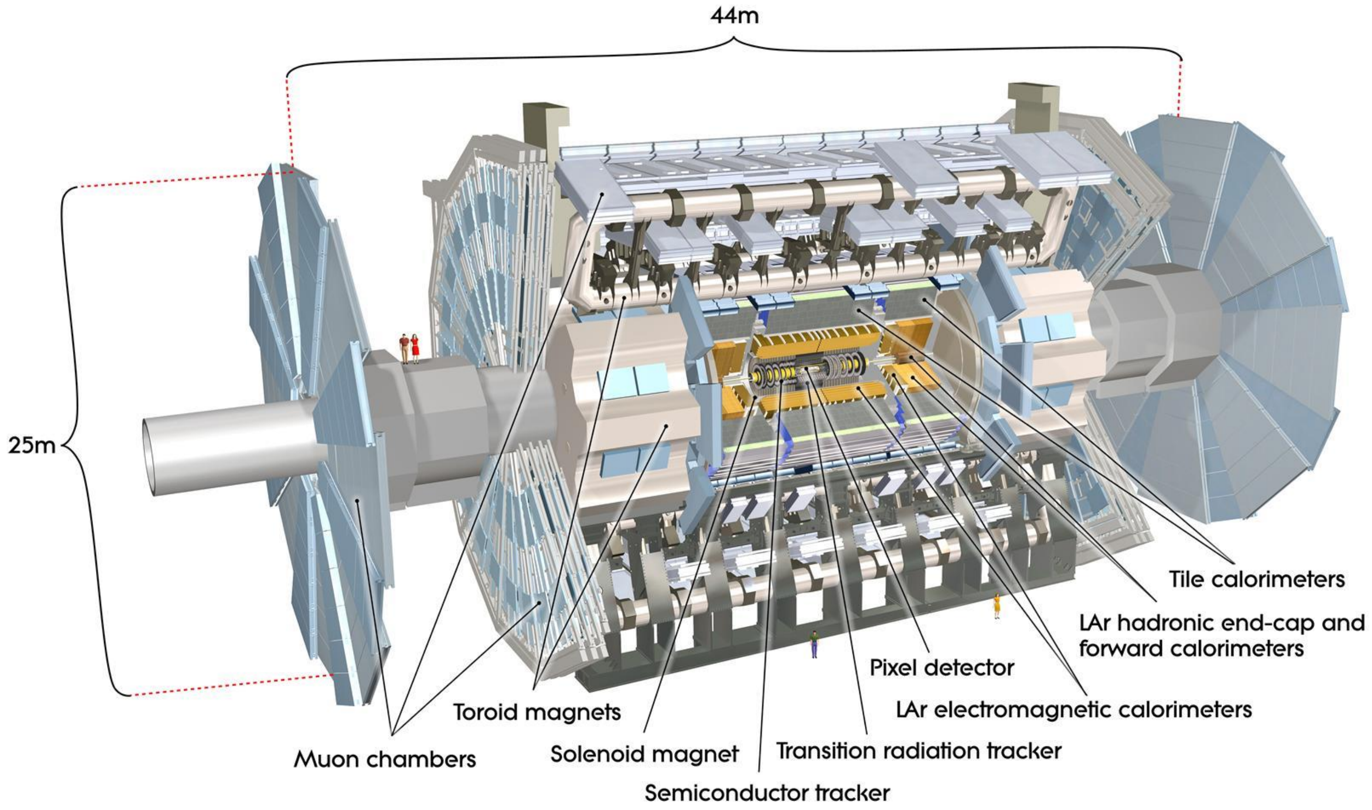
$H \to q_i q_j$	Br
$H \to uc$	5.00×10^{-20}
$H \to ds$	1.19×10^{-11}
$H \to db$	5.16×10^{-9}
$H \to sb$	1.15×10^{-7}

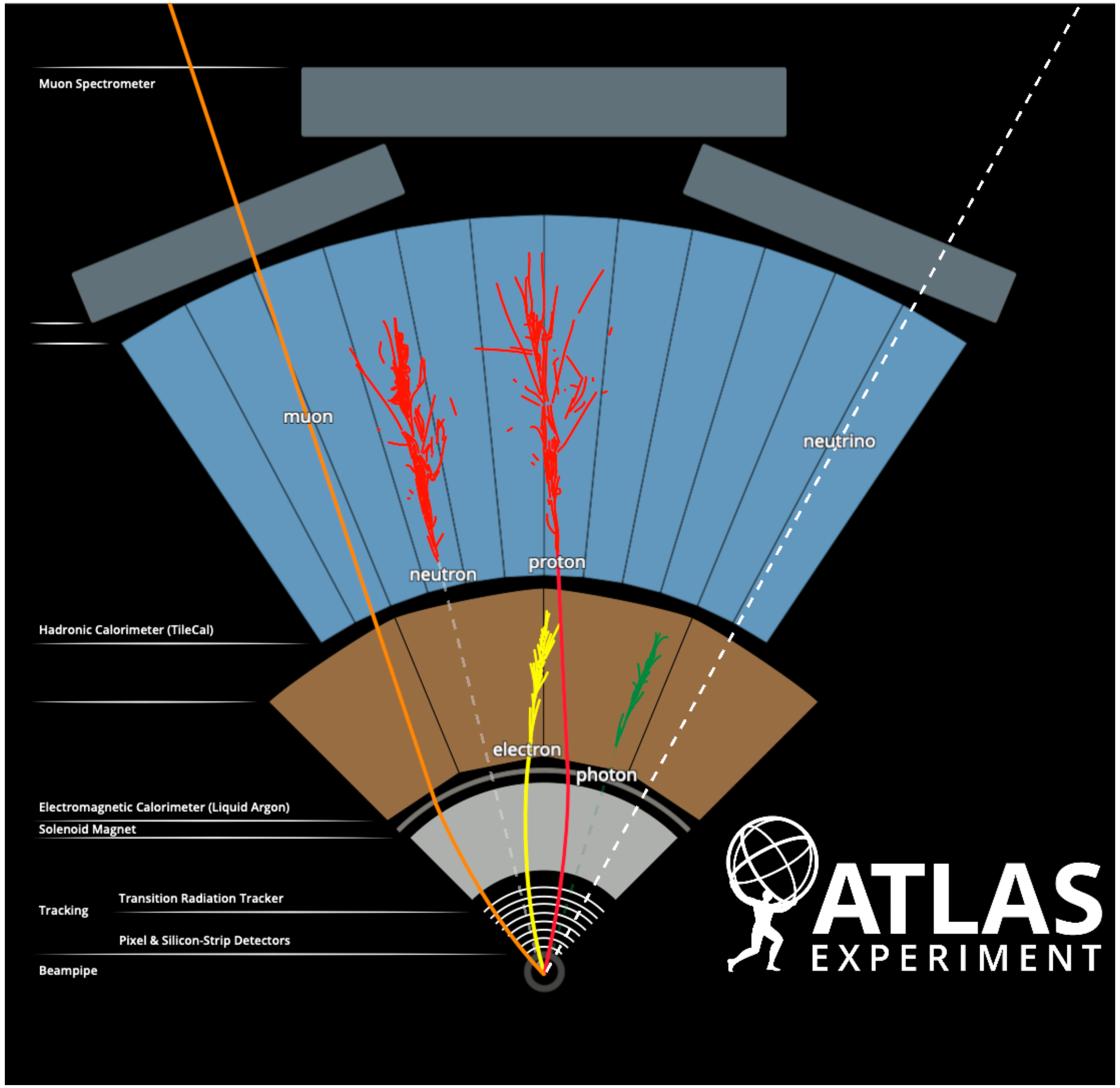
One-loop SM contributions to $H \to q_i\bar{q}_j$
($H \to \mathcal{M}\gamma$ needs additional γ radiation + hadronisation)

- Similar signatures to the rare SM decays

The ATLAS Experiment

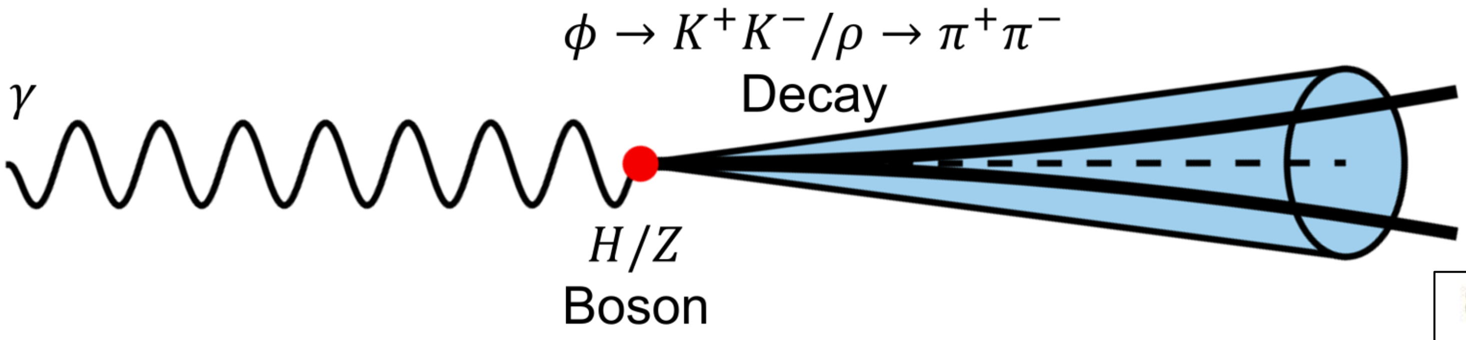
- General-purpose particle physics experiment at the LHC
  - 3k authors across 182 institutions in 42 countries





$H(Z) \rightarrow (\phi, \rho)\gamma$: Overview

- $H \rightarrow \phi(K^+K^-)\gamma$: s-quark coupling; $H \rightarrow \rho(\pi^+\pi^-)\gamma$: u/d-quark couplings
  - Two tracks and a photon in final state



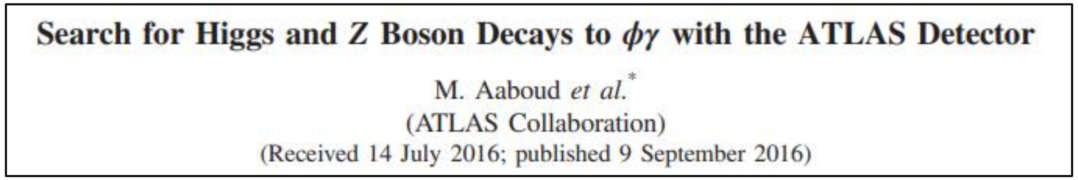
H decays

- $BR^{\text{SM}}_{H\rightarrow\phi\gamma} \approx 10^{-6}$
- $BR^{\text{SM}}_{H\rightarrow\rho\gamma} \approx 10^{-5}$

Z decays

- $BR^{\text{SM}}_{Z\rightarrow\phi\gamma} \approx 10^{-8}$
- $BR^{\text{SM}}_{Z\rightarrow\rho\gamma} \approx 10^{-9}$

SM Predictions

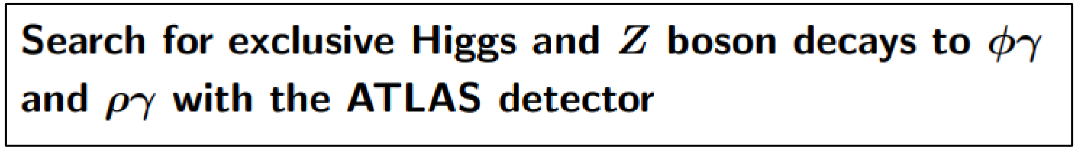


Search for Higgs and Z Boson Decays to $\phi\gamma$ with the ATLAS Detector

M. Aaboud *et al.**
(ATLAS Collaboration)
(Received 14 July 2016; published 9 September 2016)

Phys.Rev.Lett. 117 (2016) 11, 111802 – 1st iteration

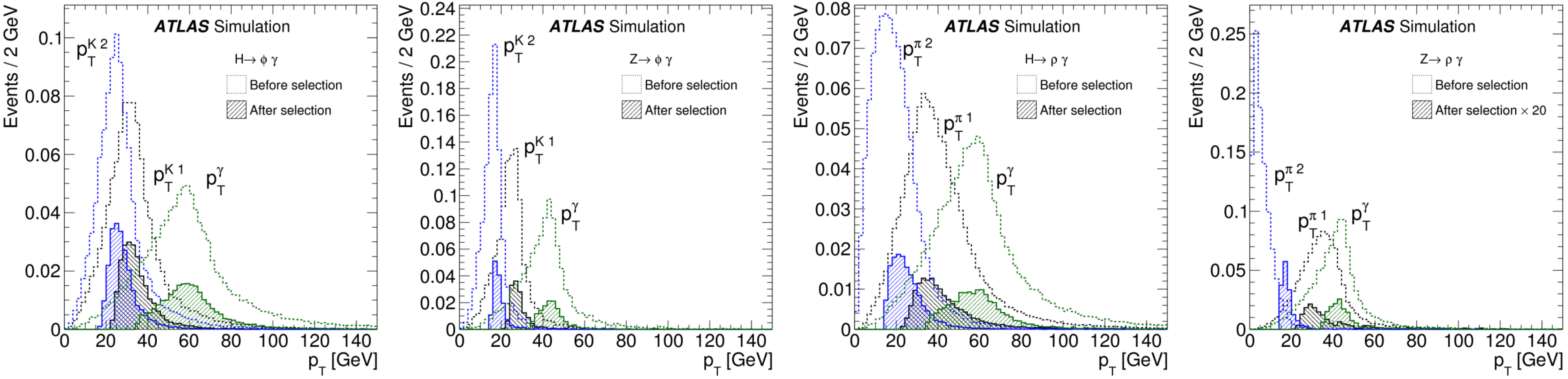
- **Dedicated** triggers based on single photon + modified τ-lepton algorithms to capture meson decay
- Non-parametric data-driven background model



Search for exclusive Higgs and Z boson decays to $\phi\gamma$ and $\rho\gamma$ with the ATLAS detector

JHEP 07 (2018) 127 – 2nd iteration (latest)

$H(Z) \rightarrow (\phi, \rho)\gamma$: Signal Efficiency



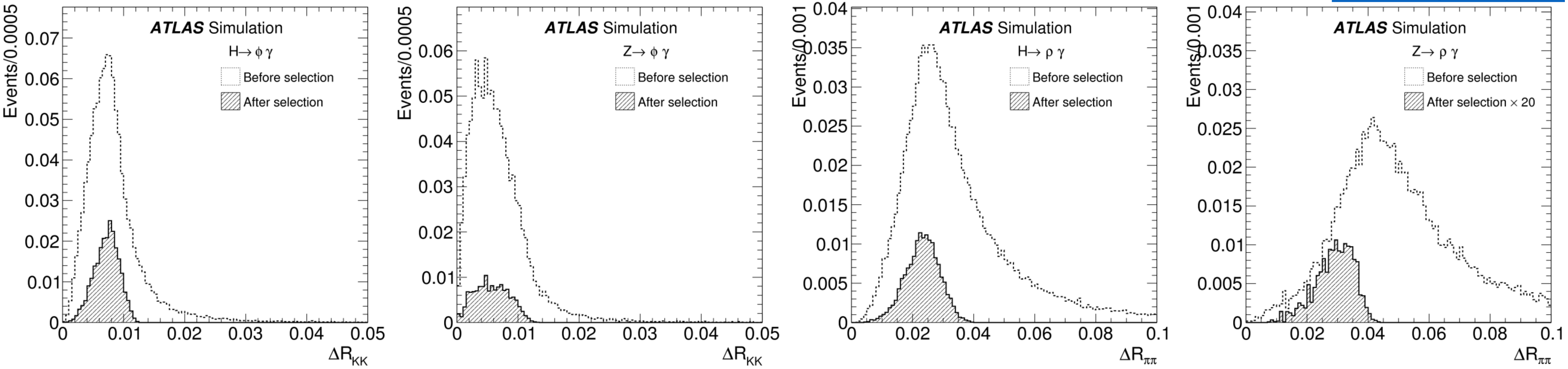
- Softer photon and track p_{T} in Z decays leads to smaller signal efficiencies than for H decays
- Decay products in $\phi\gamma$ higher than for $\rho\gamma$, leading to higher efficiencies

Total Signal Efficiency		
Decay Channel	Z Signal	H Signal
$\phi\gamma$	8%	17%
$\rho\gamma$	0.4%	10%

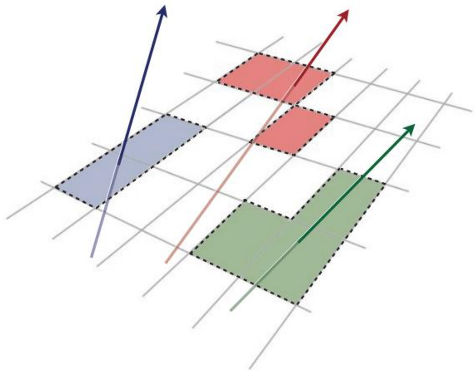
JHEP 07 (2018) 127

$H(Z) \to (\phi, \rho)\gamma$: Opening Angles

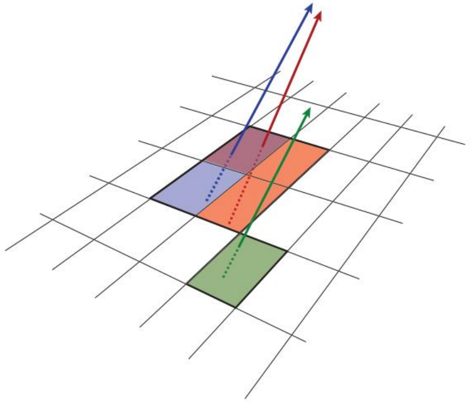
JHEP 07 (2018) 127



- Small opening angles between decay products
  - Particularly for $\phi \to K^+K^-$: tracking in dense environments



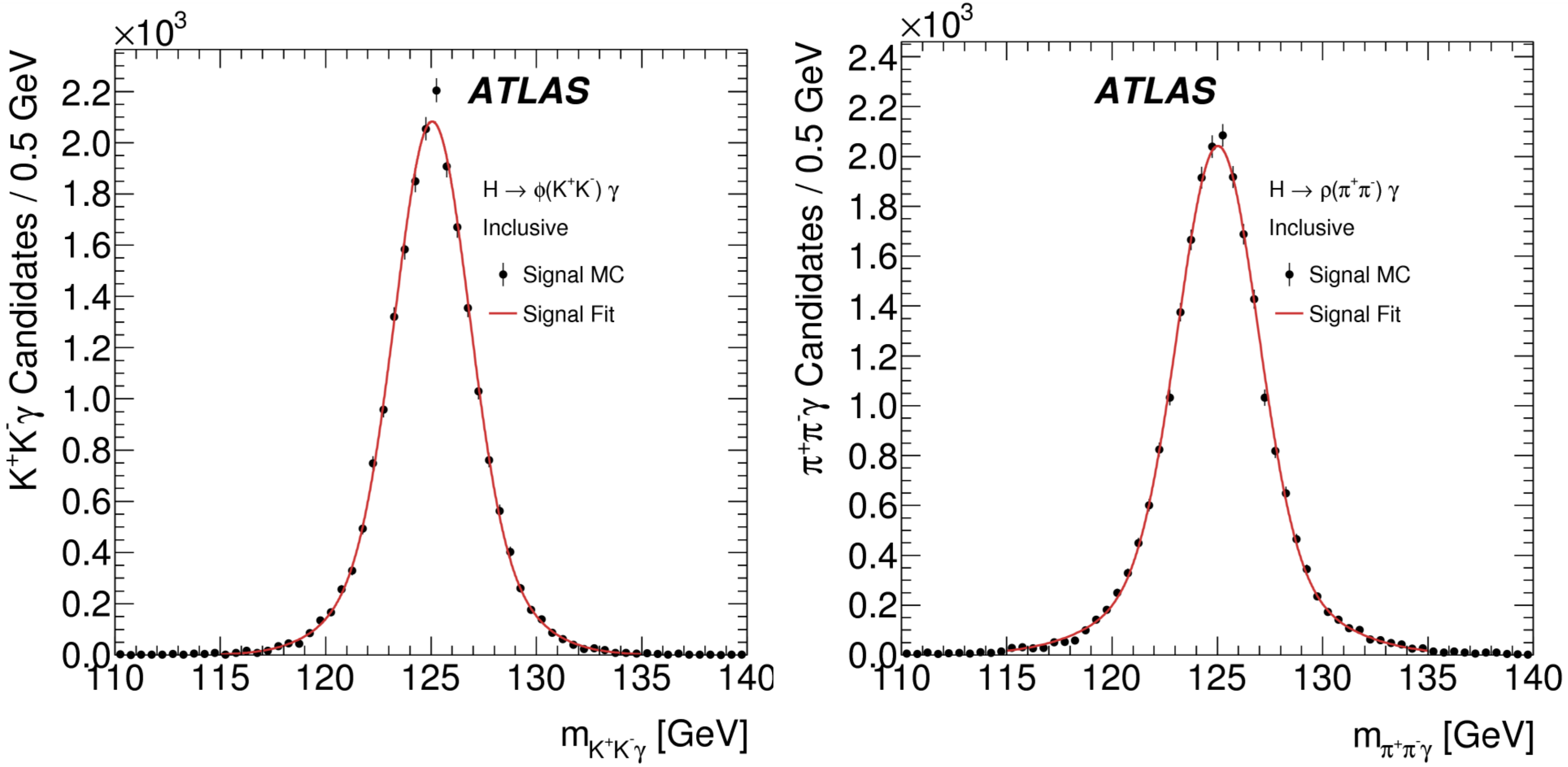
Single-Particle Clusters



Merged Clusters

Eur. Phys. J. C 77 (2017)

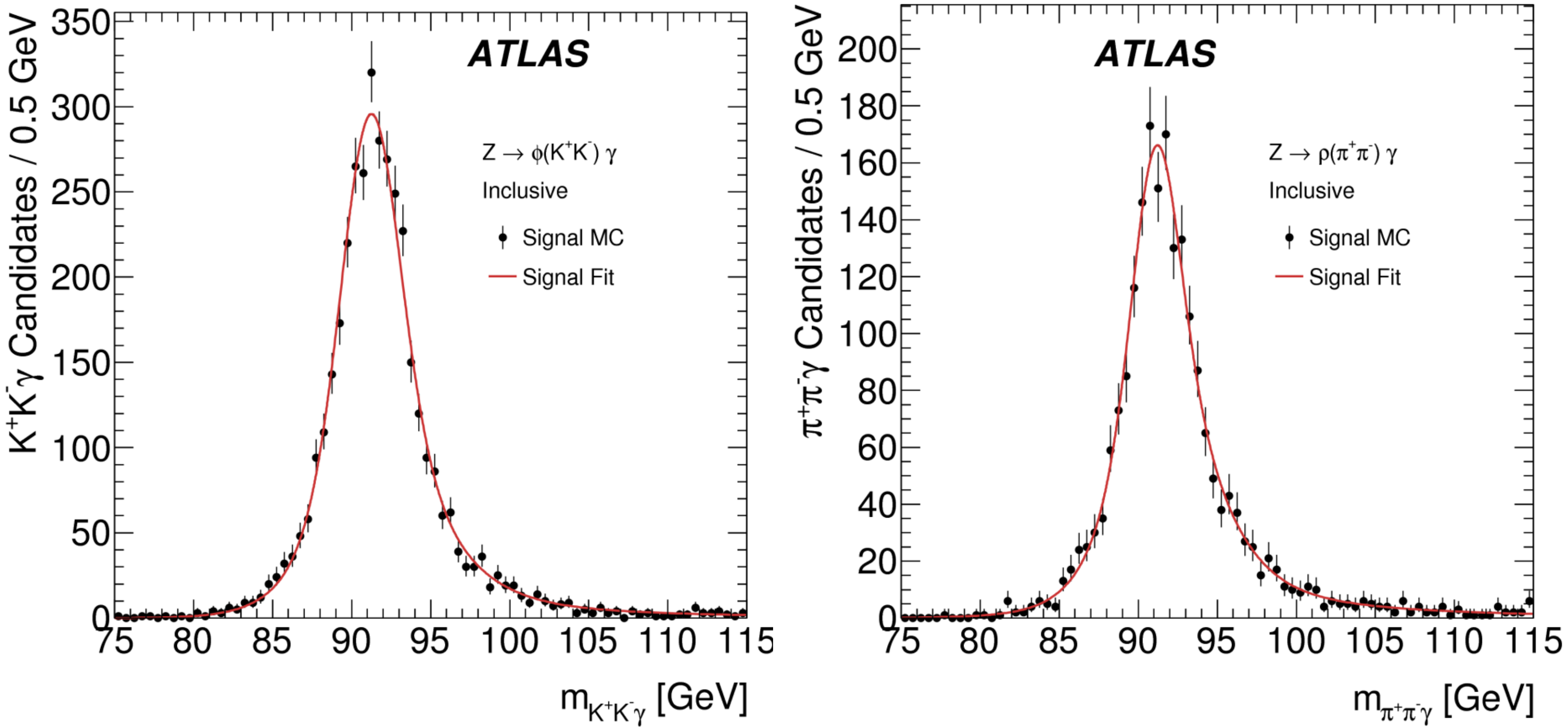
$H(Z) \rightarrow (\phi, \rho)\gamma$: Signal Modelling



- Higgs boson samples produced in separate decay modes (e.g ggH, VBF)
  - Shape: sum of two Gaussian distributions with common mean
  - Resolution: 1.8%

JHEP 07 (2018) 127

$H(Z) \rightarrow (\phi, \rho)\gamma$: Signal Modelling

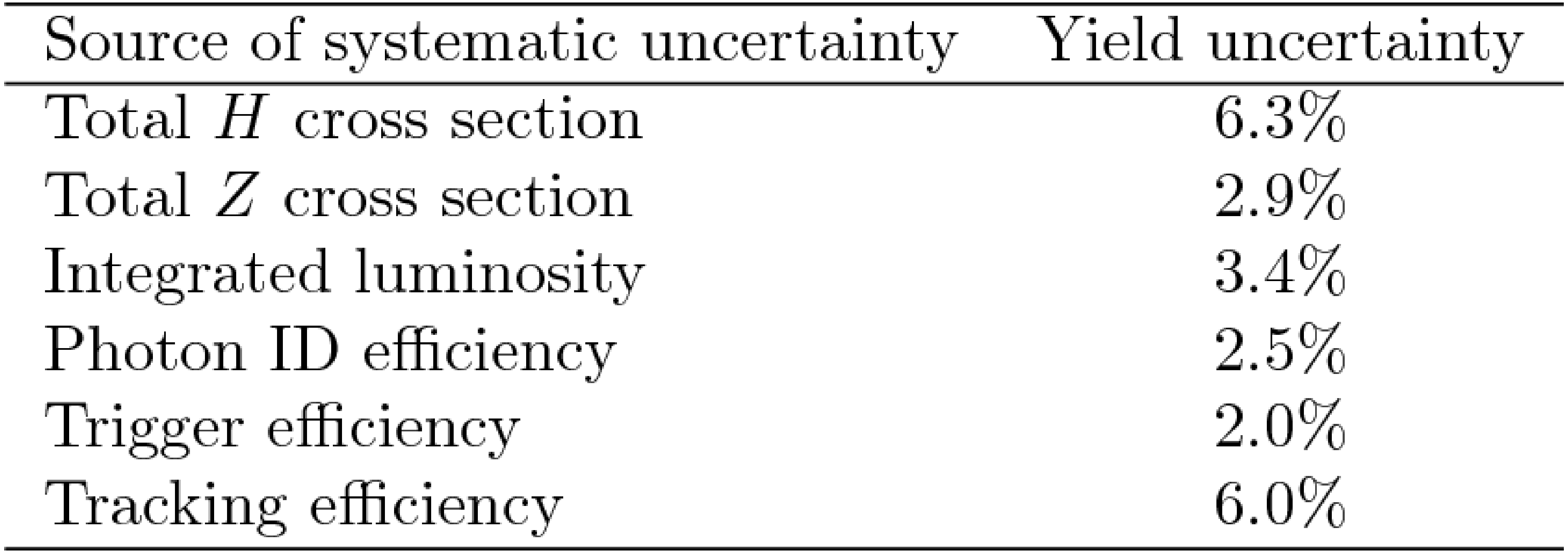


- Z boson samples produced inclusively
  - Shape: (sum of two Voigtian distributions) × efficiency factor
    - Voigtian: convolution of Gaussian (detector resolution) and Lorentz (Z width) distributions
    - Efficiency factor: accounts for turn-on in signal efficiency with Z mass
  - Resolution: 1.8%

JHEP 07 (2018) 127

$H(Z) \to (\phi, \rho)\gamma$: Signal Systematic Uncertainties

- Take into account relevant uncertainties on the total signal yield
  - Nuisance parameters with standard Gaussian constraints in maximum likelihood fit
  - Shape uncertainties found to be negligible



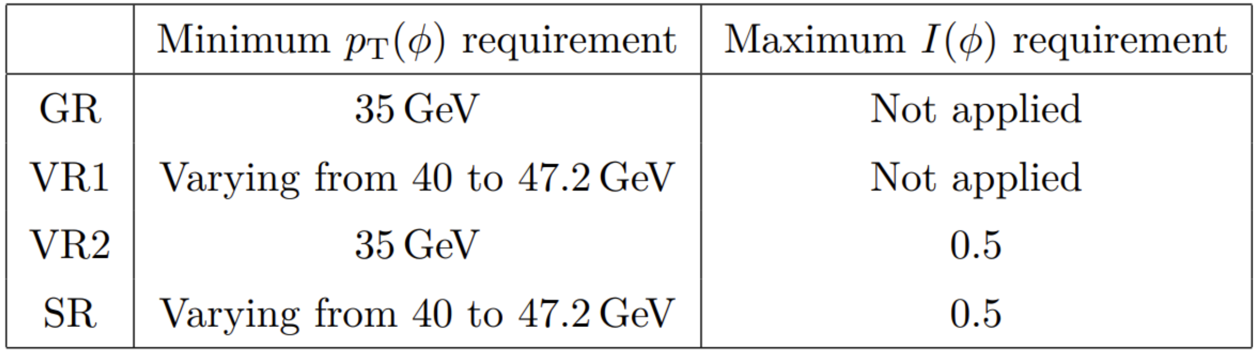
Source of systematic uncertainty	Yield uncertainty
Total H cross section	6.3%
Total Z cross section	2.9%
Integrated luminosity	3.4%
Photon ID efficiency	2.5%
Trigger efficiency	2.0%
Tracking efficiency	6.0%

JHEP 07 (2018) 127

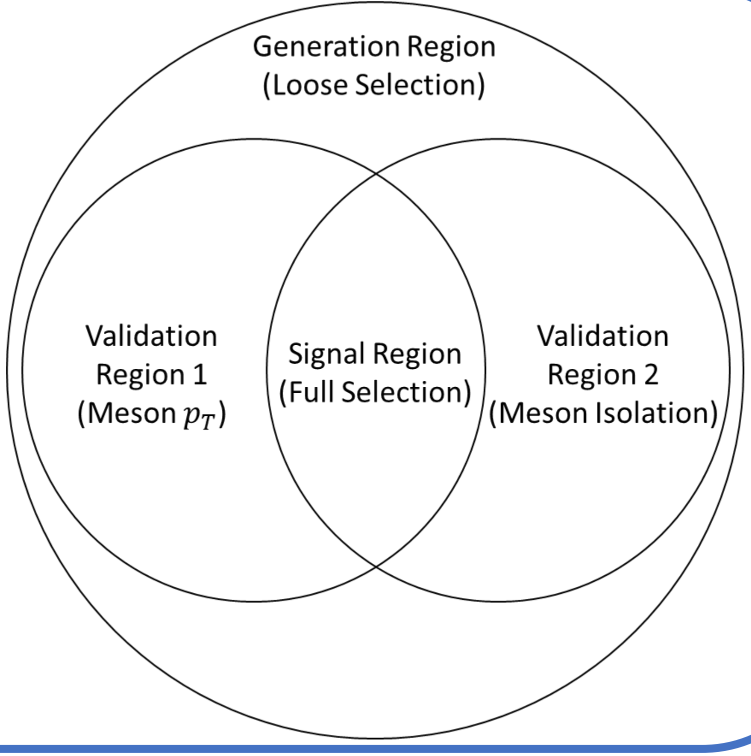
Aside: Non-Parametric Data Driven Background Modelling

- Non-parametric data-driven background model: JHEP 10 (2022) 001
  - Useful for non-resonant backgrounds consisting of a mix of processes
    - Complex shape: difficult to model analytically/parametrically
    - Complex processes: difficult to model with MC
  - $H \rightarrow \phi\gamma$ used as a case study with $m_{\phi\gamma}$ as the discriminant variable
    - Use γ+jet MC in model demonstration

1. Model correlations in data in loose Generation Region
2. Sample pseudo-events (e.g 4-momenta) using model
3. Apply Validation Region selection to evaluate performance
4. Apply Signal Region selection and smooth for final model



	Minimum $p_{\mathrm{T}}(\phi)$ requirement	Maximum $I(\phi)$ requirement
GR	35 GeV	Not applied
VR1	Varying from 40 to 47.2 GeV	Not applied
VR2	35 GeV	0.5
SR	Varying from 40 to 47.2 GeV	0.5



Generation Region
(Loose Selection)

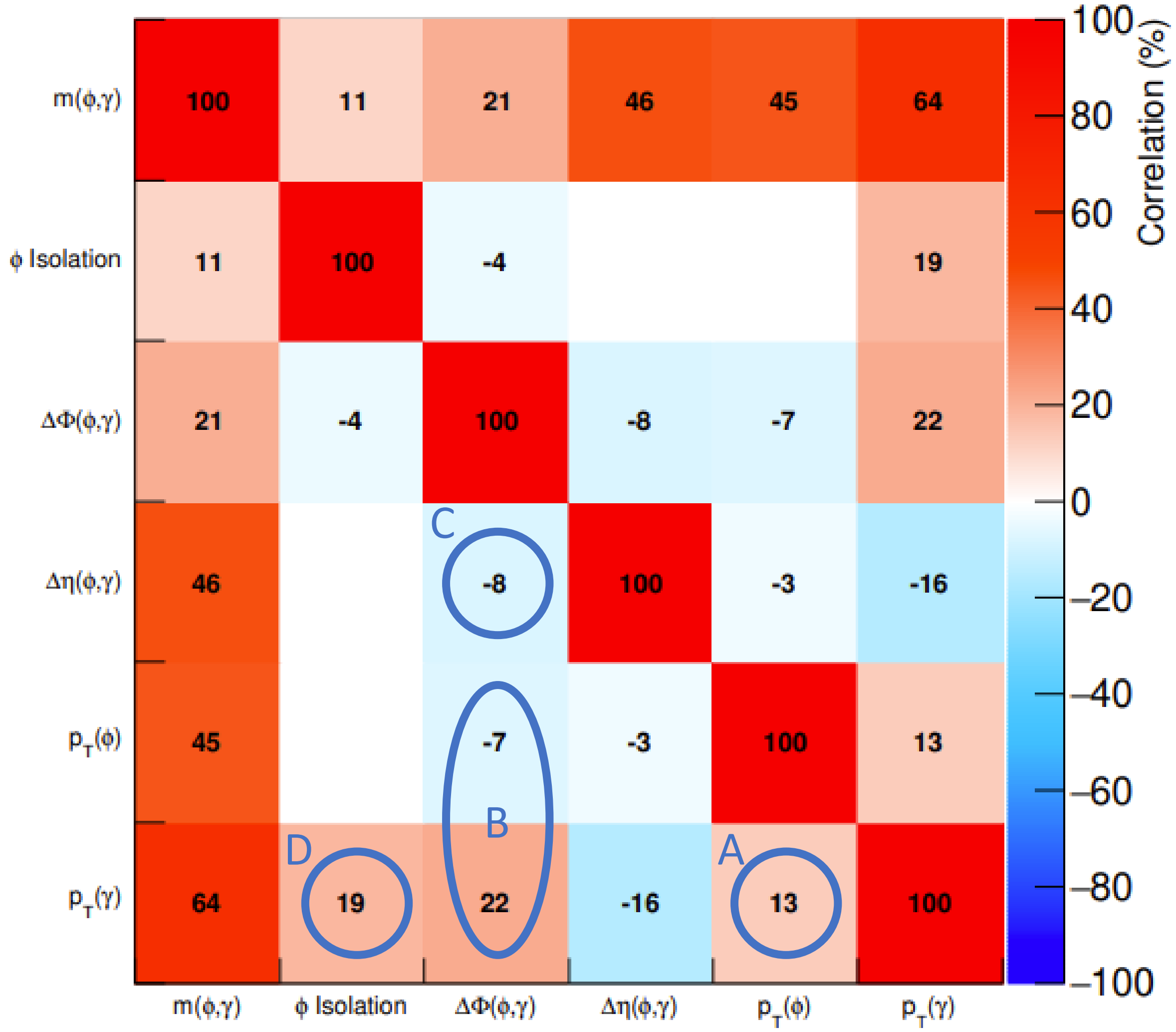
Validation
Region 1
(Meson p_T)

Signal Region
(Full Selection)

Validation
Region 2
(Meson Isolation)

Non-Parametric Data Driven Model: Sampling Scheme 1

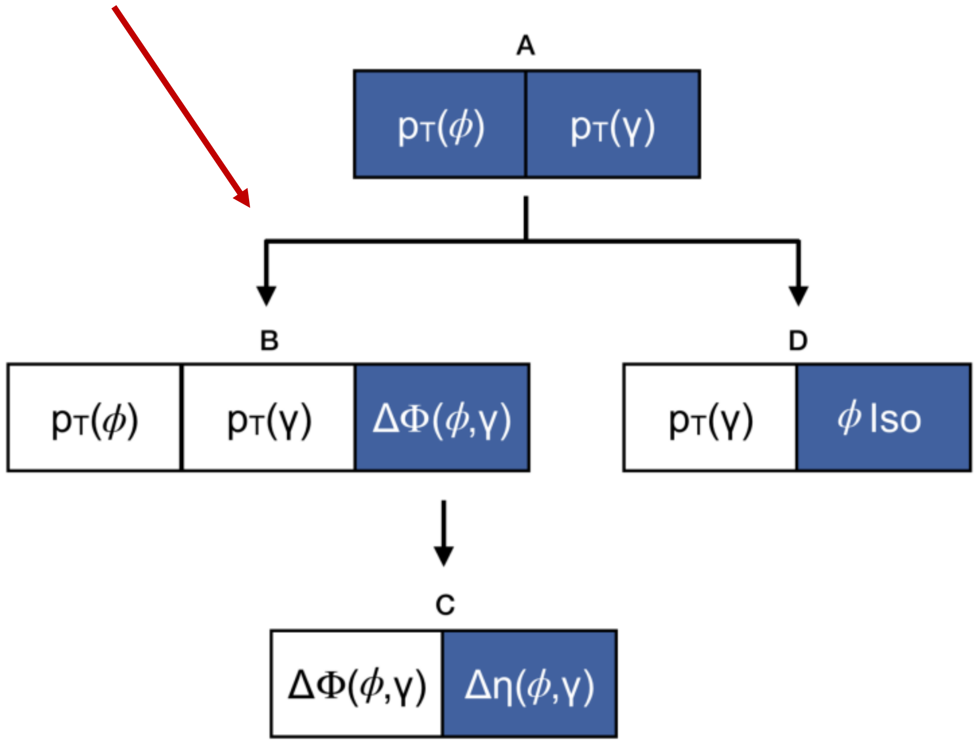
- Specific sampling scheme is based on studies of correlations between variables



	m(φ,γ)	φ Isolation	ΔΦ(φ,γ)	Δη(φ,γ)	p_T(φ)	p_T(γ)
m(φ,γ)	100	11	21	46	45	64
φ Isolation	11	100	-4			19
ΔΦ(φ,γ)	21	-4	100	-8	-7	22
Δη(φ,γ)	46		-8	100	-3	-16
p_T(φ)	45		-7	-3	100	13
p_T(γ)	64	19	22	-16	13	100

Correlations in “Data”

- Populate series of PDFs (histograms) using data in GR
  - Use these to sample pseudo-events



A
$p_T(\phi)$ | $p_T(\gamma)$

B
$p_T(\phi)$ | $p_T(\gamma)$ | $\Delta\Phi(\phi,\gamma)$

D
$p_T(\gamma)$ | ϕ Iso

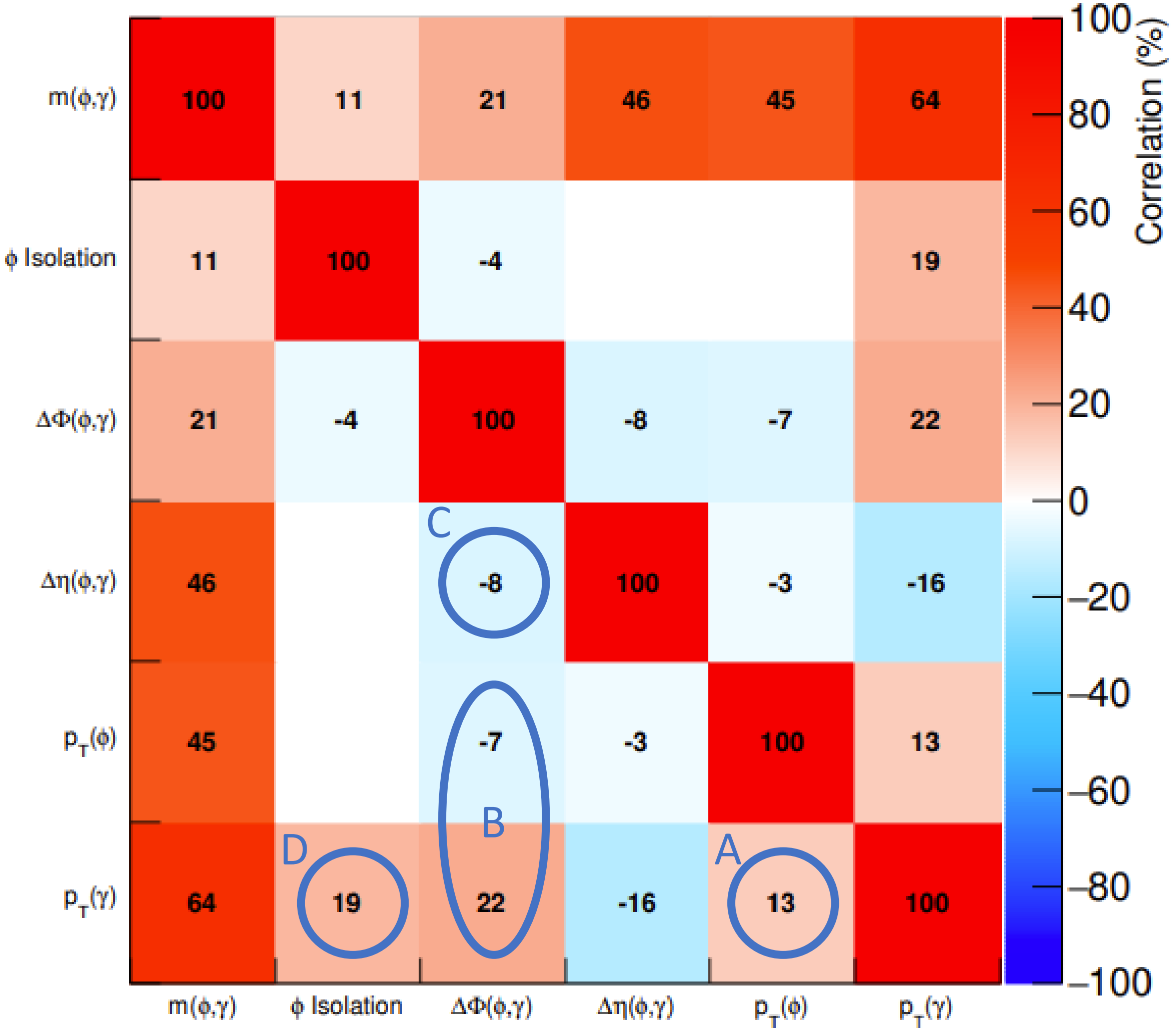
C
$\Delta\Phi(\phi,\gamma)$ | $\Delta\eta(\phi,\gamma)$

Sampling Scheme

JHEP 10 (2022) 001

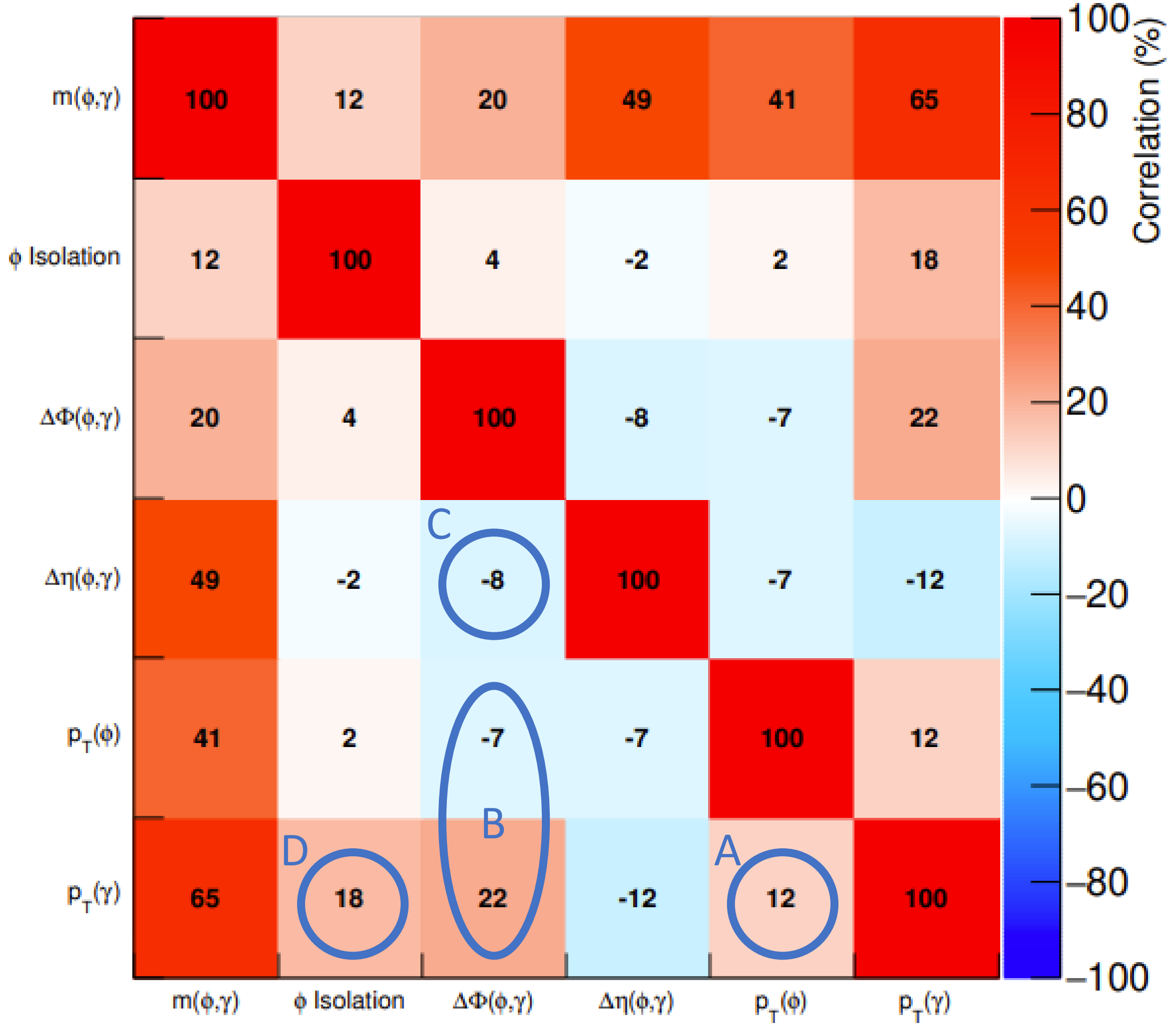
Non-Parametric Data Driven Model: Sampling Scheme 2

- Important correlations are reproduced in pseudo-events generated with model



	$m(\phi,\gamma)$	ϕ Isolation	$\Delta\Phi(\phi,\gamma)$	$\Delta\eta(\phi,\gamma)$	$p_T(\phi)$	$p_T(\gamma)$
$m(\phi,\gamma)$	100	11	21	46	45	64
ϕ Isolation	11	100	-4			19
$\Delta\Phi(\phi,\gamma)$	21	-4	100	-8	-7	22
$\Delta\eta(\phi,\gamma)$	46		-8	100	-3	-16
$p_T(\phi)$	45		-7	-3	100	13
$p_T(\gamma)$	64	19	22	-16	13	100

Correlations in “Data”



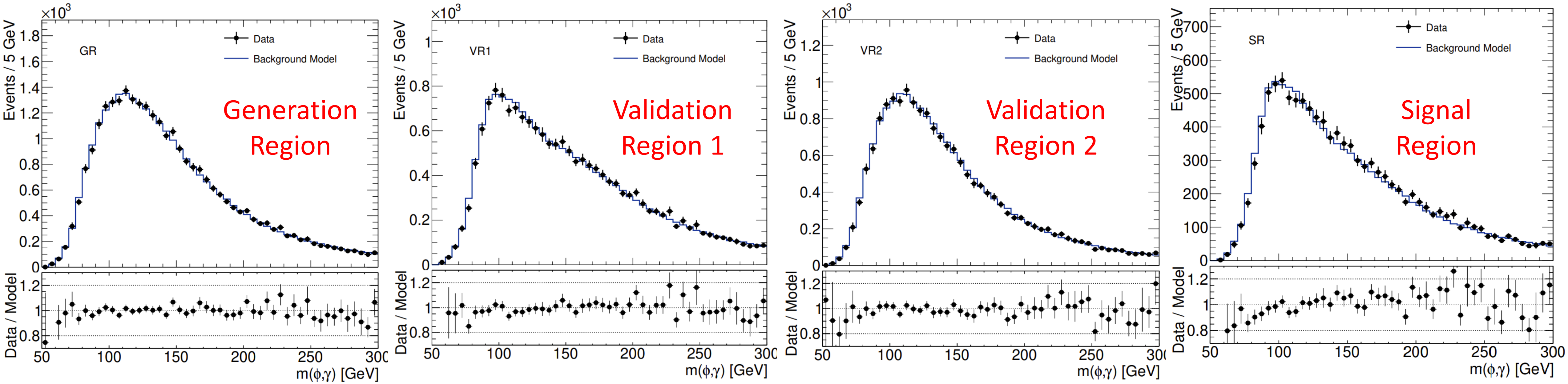
	$m(\phi,\gamma)$	ϕ Isolation	$\Delta\Phi(\phi,\gamma)$	$\Delta\eta(\phi,\gamma)$	$p_T(\phi)$	$p_T(\gamma)$
$m(\phi,\gamma)$	100	12	20	49	41	65
ϕ Isolation	12	100	4	-2	2	18
$\Delta\Phi(\phi,\gamma)$	20	4	100	-8	-7	22
$\Delta\eta(\phi,\gamma)$	49	-2	-8	100	-7	-12
$p_T(\phi)$	41	2	-7	-7	100	12
$p_T(\gamma)$	65	18	22	-12	12	100

Correlations in Model

JHEP 10 (2022) 001

Non-Parametric Data Driven Model: Demonstration

- Ultimately, only the modelling of the discriminant variable in the SR is important
  - Validation regions help troubleshoot where issues in model arise



Background model in each region (Pre-Fit)

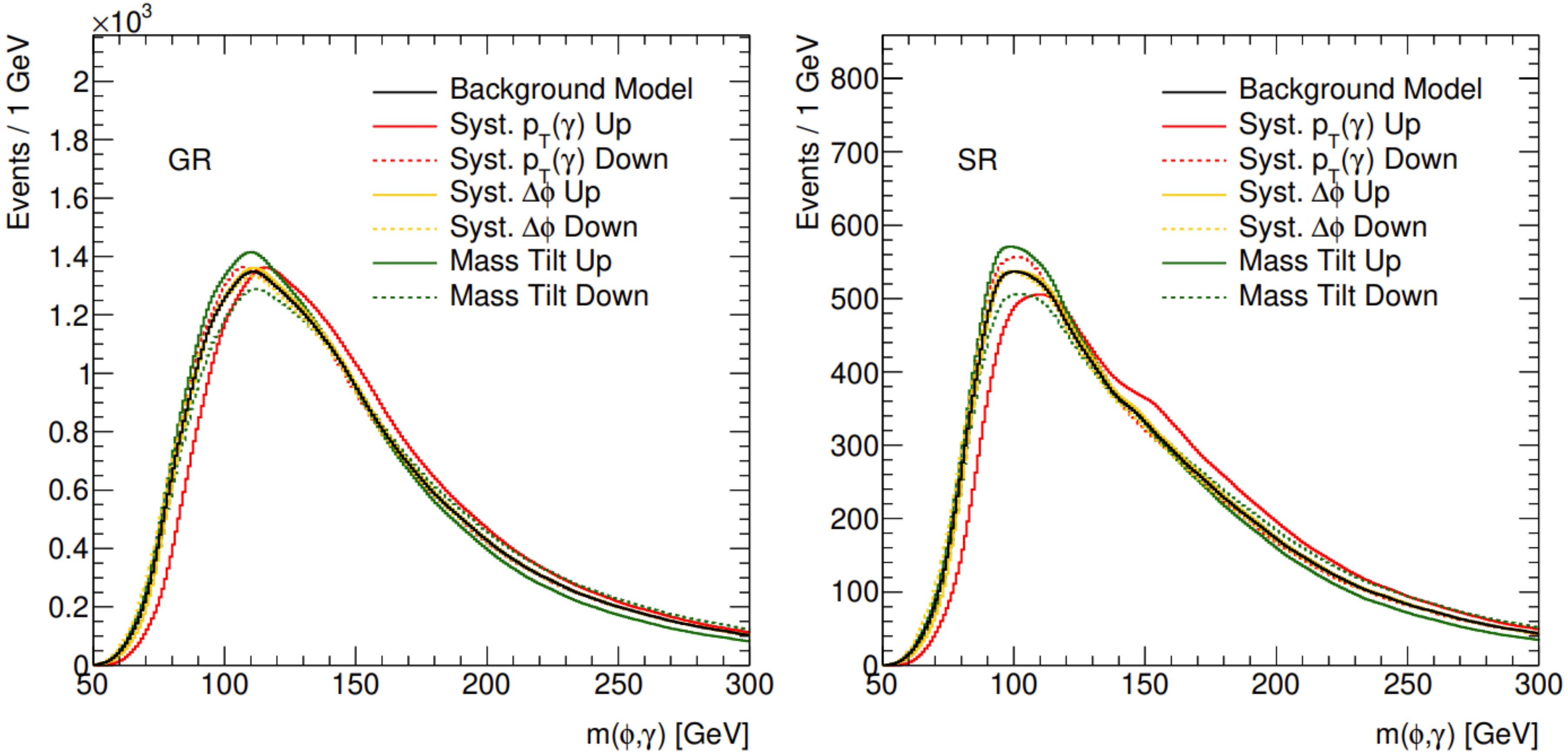
	Minimum $p_{\mathrm{T}}(\phi)$ requirement	Maximum $I(\phi)$ requirement
GR	35 GeV	Not applied
VR1	Varying from 40 to 47.2 GeV	Not applied
VR2	35 GeV	0.5
SR	Varying from 40 to 47.2 GeV	0.5

JHEP 10 (2022) 001

Non-Parametric Data Driven Model: Shape Systematics

- Typically define several shape uncertainties to allow model shape to adapt to SR
  - Generate alternate shapes by modifying generation procedure

- Mass tilt: reweight mass distribution with a linear function
  - Distribution can adapt to tilts in ratio
- p_{T} shift: shift generated photon p_{T} in GR
  - Distribution can shift higher/lower
- $\Delta\phi$ distortion: reweight generated $\Delta\phi$ in GR
  - Width of distribution can increase/decrease

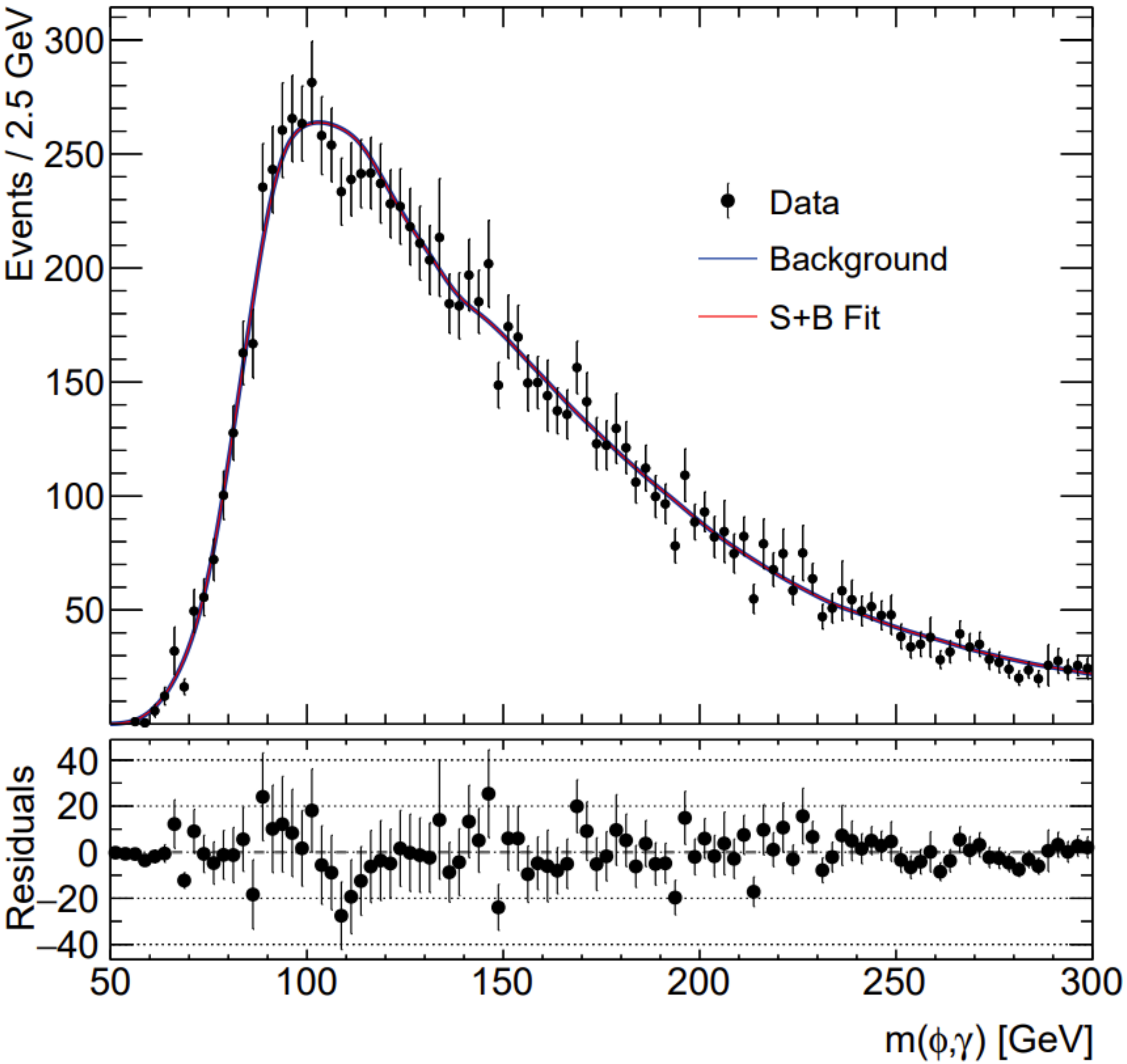


Systematic Shape Variations

JHEP 10 (2022) 001

Non-Parametric Data Driven Model: Post Fit

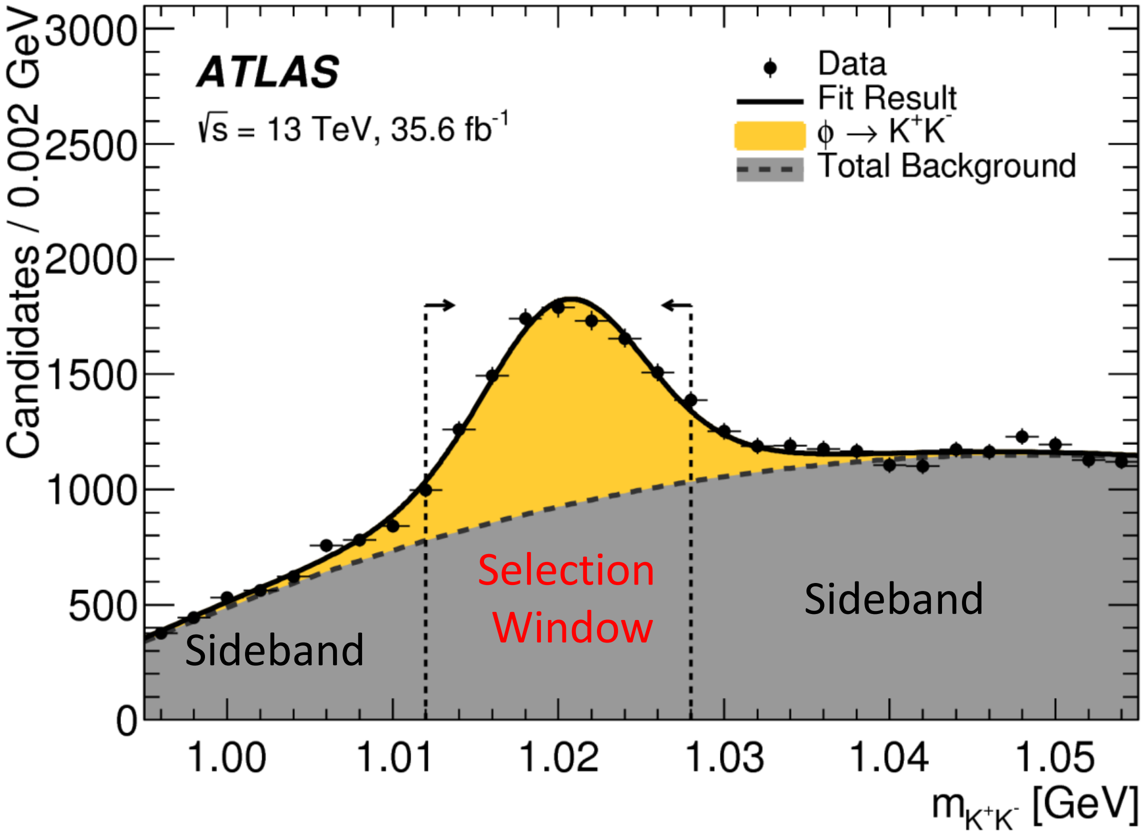
- Signal region background model post fit (including shape systematics)

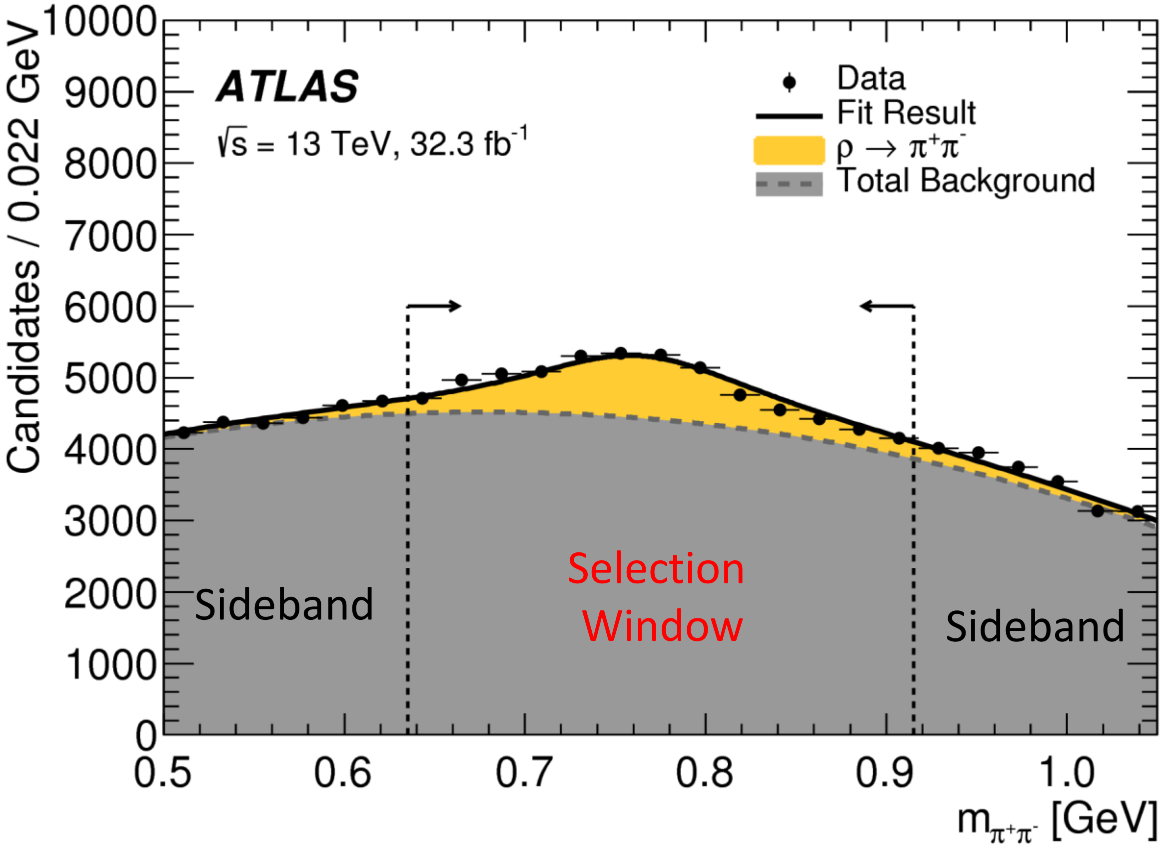


JHEP 10 (2022) 001

$H(Z) \rightarrow (\phi, \rho)\gamma$: Meson Reconstruction

- Define ϕ and ρ mass-sideband regions for further background validation

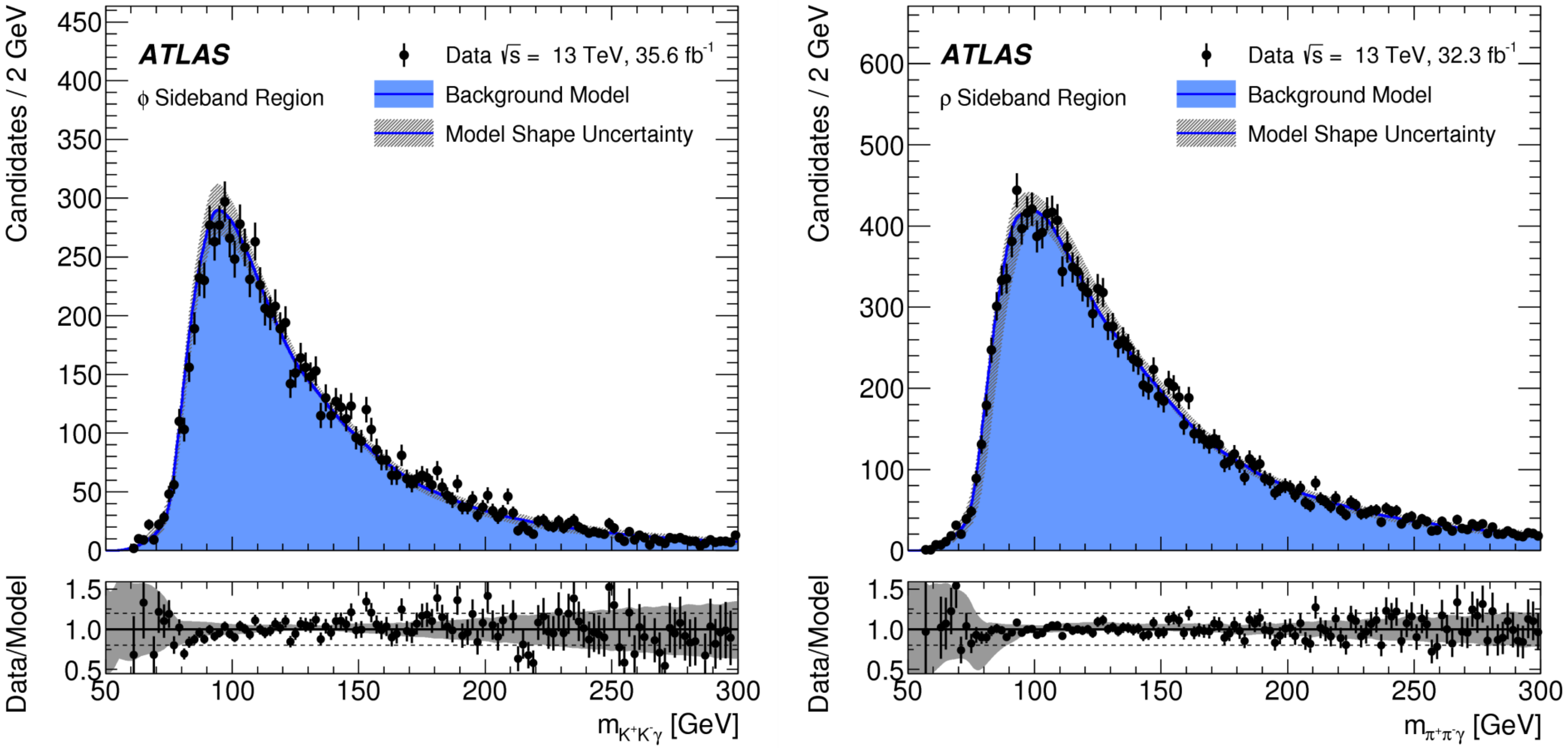




JHEP 07 (2018) 127

$H(Z) \rightarrow (\phi, \rho)\gamma$: Background Modelling

- Background is multi-jet and γ+jet sources – treat inclusively
  - Use non-parametric data-driven background model

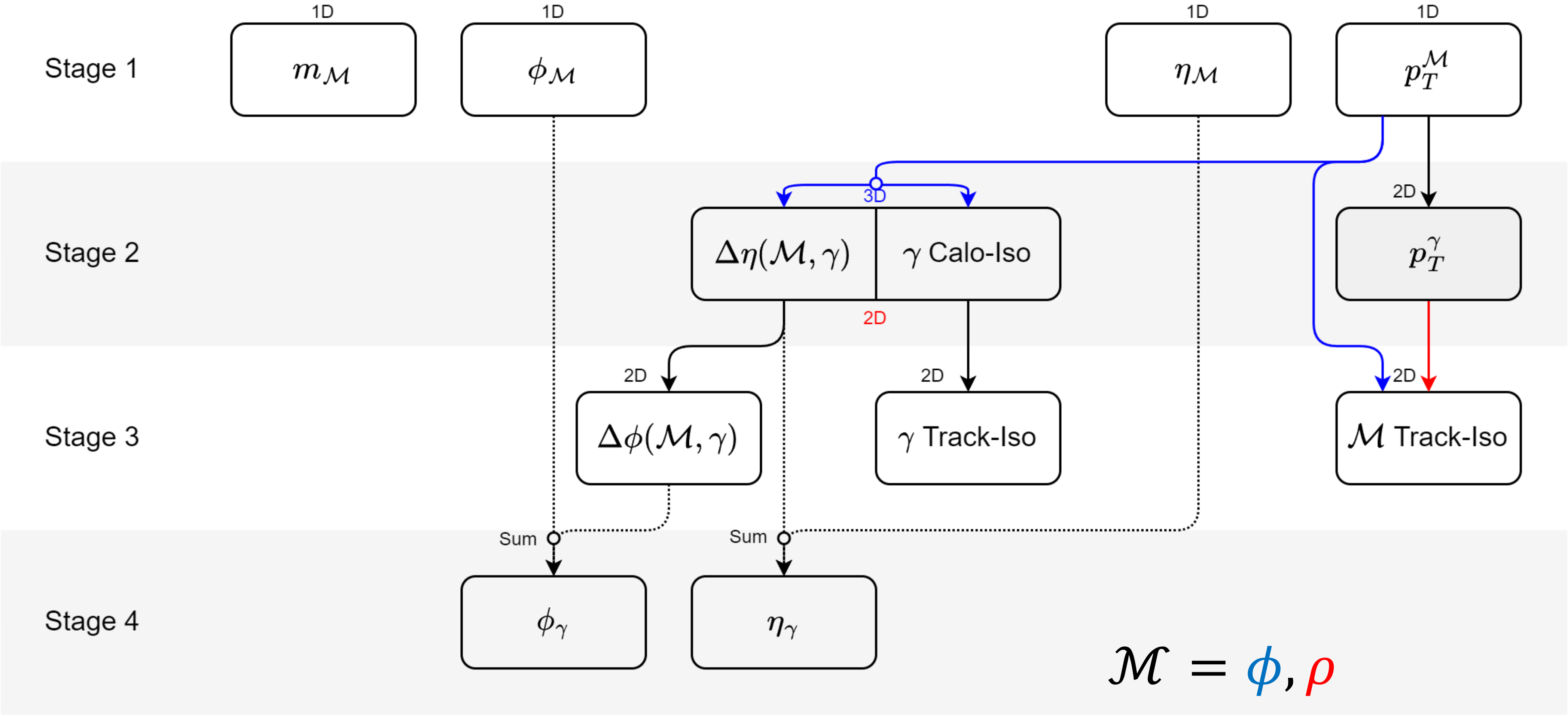


Background in ϕ/ρ-mass Sidebands (Pre-Fit)

JHEP 07 (2018) 127

$H(Z) \rightarrow (\phi, \rho)\gamma$: Background Sampling Sequence

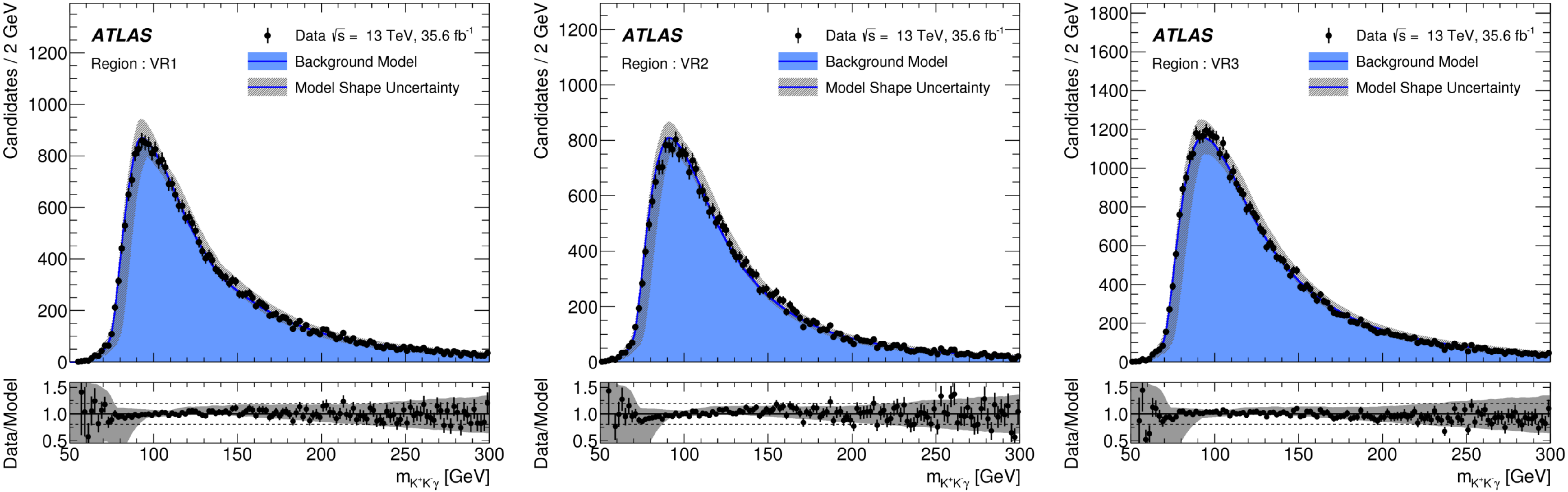
- Specific sampling scheme is flexible – can optimise based on correlations in each search
  - Blue = modelled in $\phi\gamma$; red = modelled in $\rho\gamma$



JHEP 07 (2018) 127

$H(Z) \rightarrow (\phi, \rho)\gamma$: Background Validation

- Validation plots are pre-fit
  - Uncertainty from three shape systematics: mass-tilt, $\Delta\phi$-distortion, p_{T}-shift

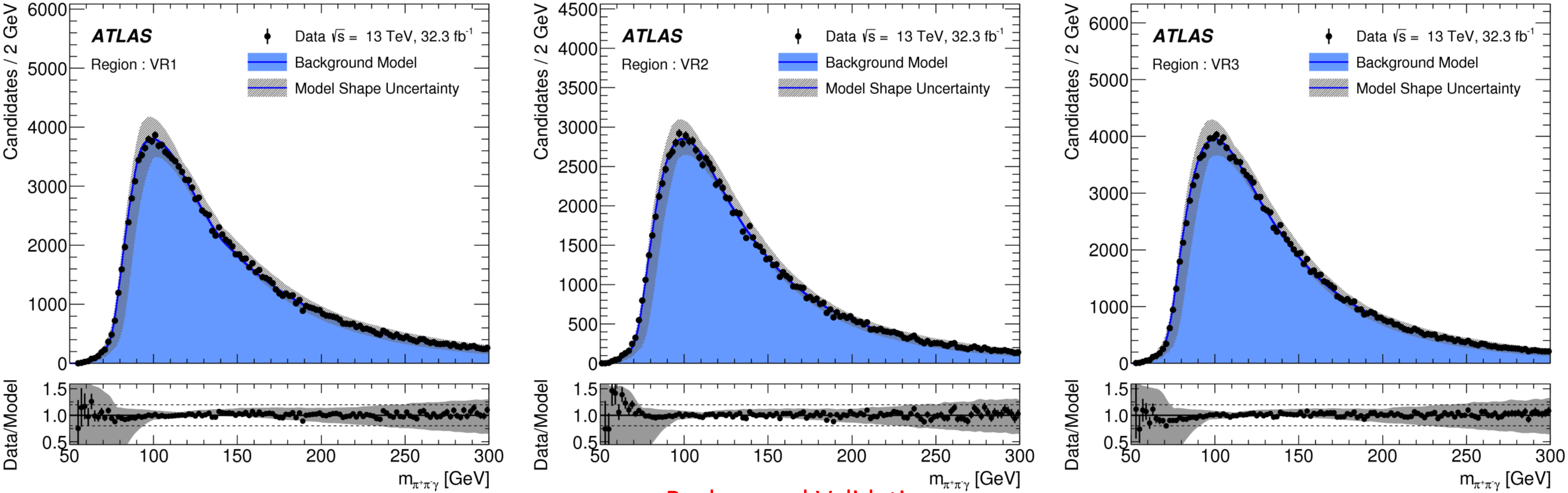


$\phi\gamma$ Background Validation

JHEP 07 (2018) 127

$H(Z) \rightarrow (\phi, \rho)\gamma$: Background Validation

- Validation plots are pre-fit
  - Uncertainty from three shape systematics: mass-tilt, $\Delta\phi$-distortion, p_{T}-shift

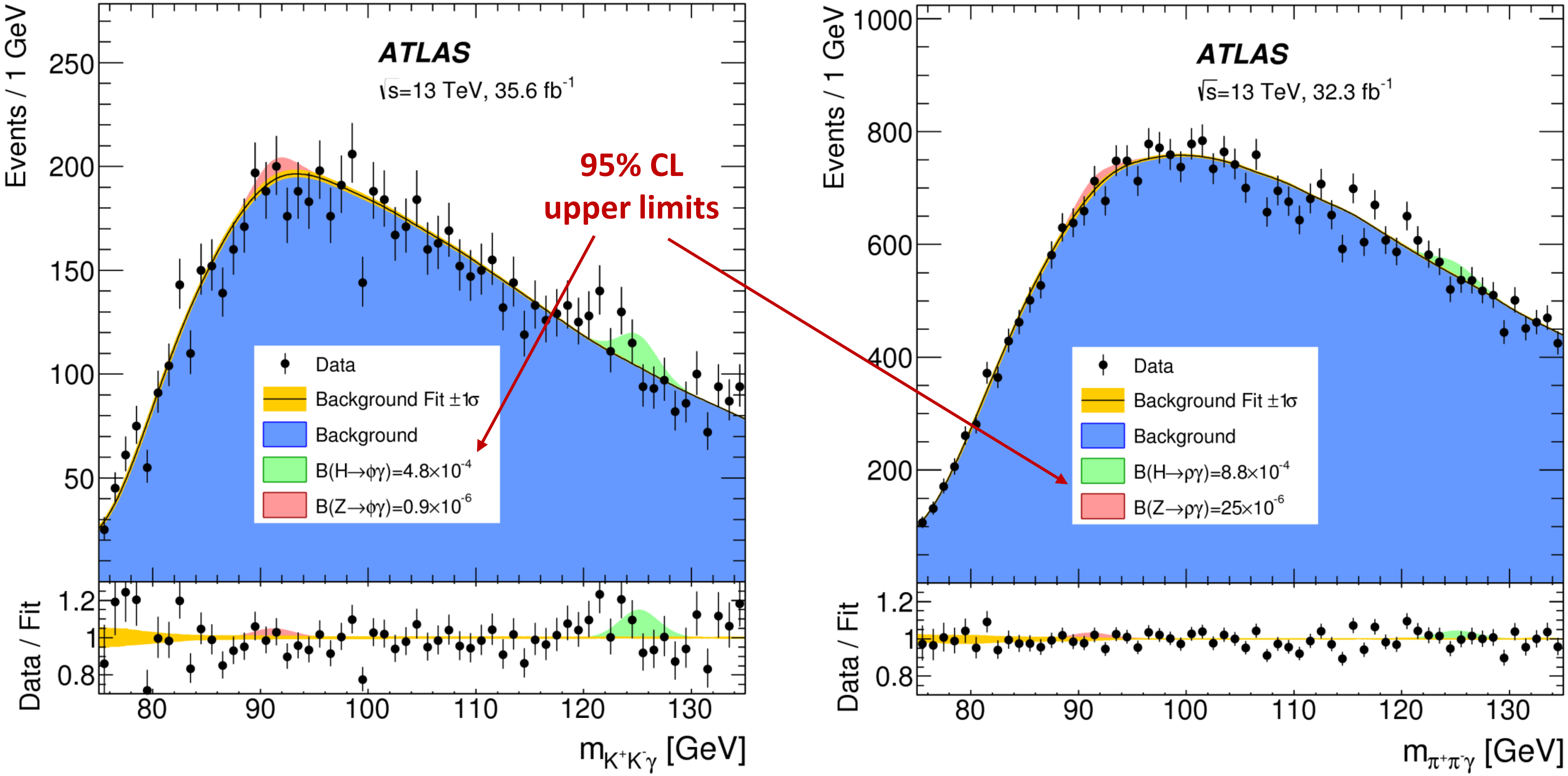


$\rho\gamma$ Background Validation

JHEP 07 (2018) 127

$H(Z) \rightarrow (\phi, \rho)\gamma$: Results

- Unbinned likelihood fit in $m(K^+K^-\gamma)$ and $m(\pi^+\pi^-\gamma)$

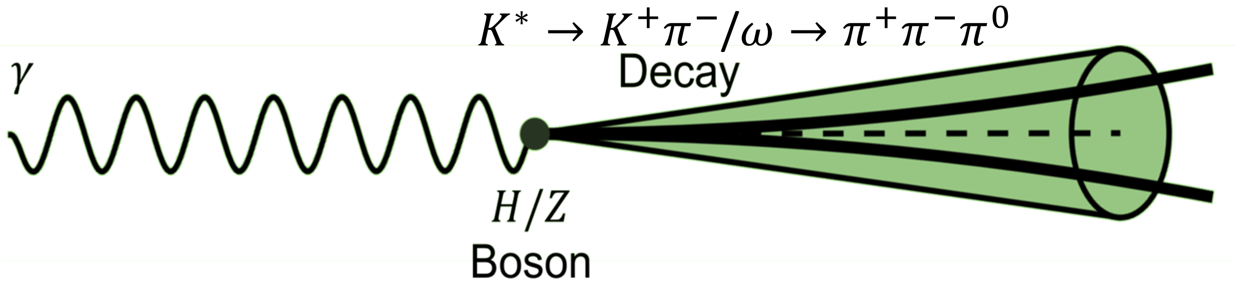


95% CL upper limits

JHEP 07 (2018) 127

$H \to K^*\gamma$ and $H(Z) \to \omega\gamma$: Overview

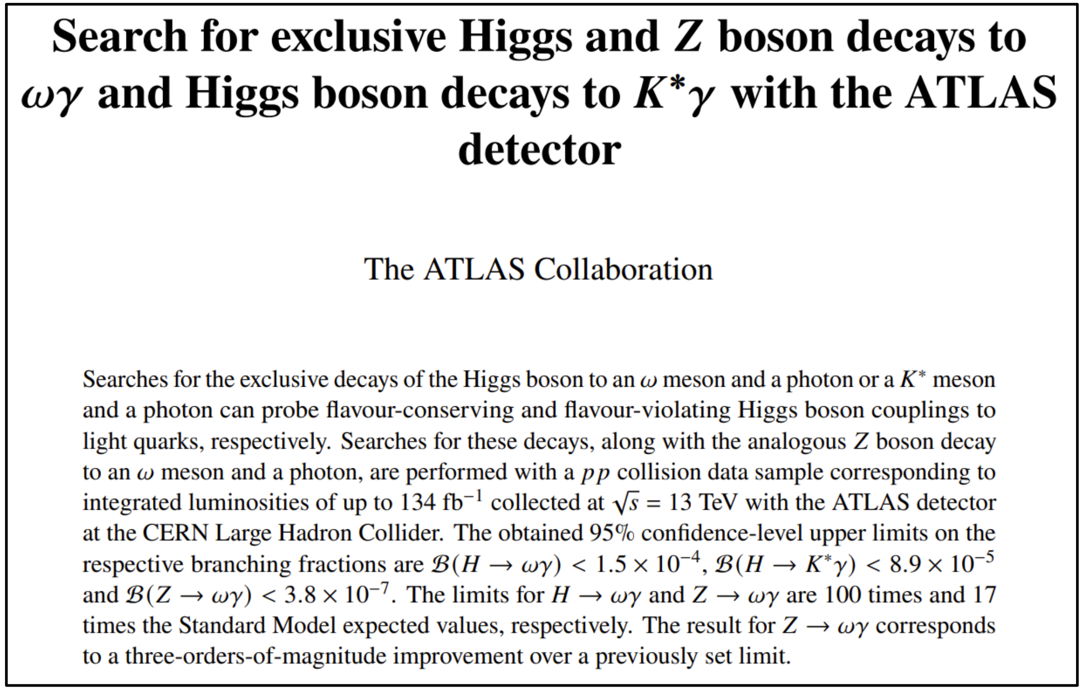
- $H \to K^*(K^-\pi^+)\gamma$: d/s-quark flavour-changing coupling
  - Two tracks and a photon in final state
    - Two possible mass hypotheses to assign K/π
- $H \to \omega(\pi^+\pi^-\pi^0)\gamma$: u/d-quark couplings
  - Two tracks, a photon **and a neutral pion** in final state



- **Dedicated** triggers based on single photon + modified τ-lepton algorithms
- First iteration of analysis
  - Similar strategy to $(\phi, \rho)\gamma$ decays

- $BR^{\mathrm{SM}}_{H\to\omega\gamma} \approx 10^{-6}$
- $BR^{\mathrm{SM}}_{Z\to\omega\gamma} \approx 10^{-8}$
- $BR^{\mathrm{SM}}_{H\to K^*\gamma} \ll 10^{-11}$

SM Predictions



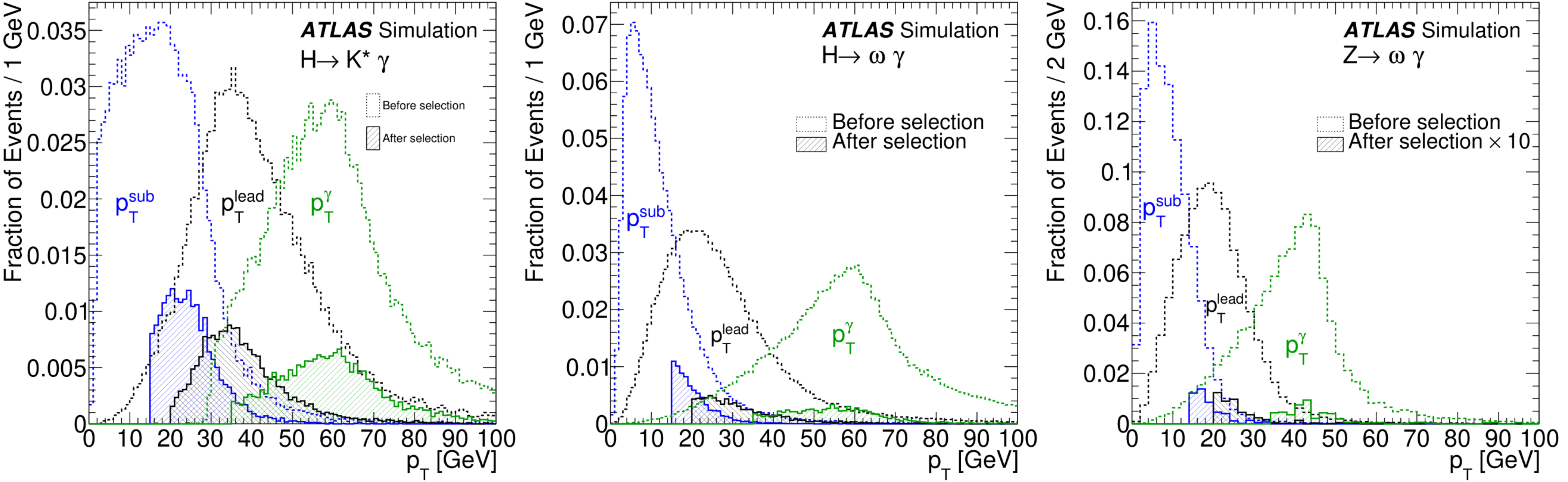
Search for exclusive Higgs and Z boson decays to $\omega\gamma$ and Higgs boson decays to $K^*\gamma$ with the ATLAS detector

The ATLAS Collaboration

Searches for the exclusive decays of the Higgs boson to an ω meson and a photon or a K^* meson and a photon can probe flavour-conserving and flavour-violating Higgs boson couplings to light quarks, respectively. Searches for these decays, along with the analogous Z boson decay to an ω meson and a photon, are performed with a pp collision data sample corresponding to integrated luminosities of up to 134 fb^{-1} collected at $\sqrt{s} = 13$ TeV with the ATLAS detector at the CERN Large Hadron Collider. The obtained 95% confidence-level upper limits on the respective branching fractions are $\mathcal{B}(H \to \omega\gamma) < 1.5 \times 10^{-4}$, $\mathcal{B}(H \to K^*\gamma) < 8.9 \times 10^{-5}$ and $\mathcal{B}(Z \to \omega\gamma) < 3.8 \times 10^{-7}$. The limits for $H \to \omega\gamma$ and $Z \to \omega\gamma$ are 100 times and 17 times the Standard Model expected values, respectively. The result for $Z \to \omega\gamma$ corresponds to a three-orders-of-magnitude improvement over a previously set limit.

arXiv:2301.09938 - Submitted to PLB

$H \to K^*\gamma$ and $H(Z) \to \omega\gamma$: Signal Efficiency and Shape



- Presence of π^0 in $H(Z) \to \omega\gamma$ reduces signal efficiency
- Shapes for $H \to K^*\gamma$ and $Z \to \omega\gamma$ same form as in $(\phi, \rho)\gamma$
  - $H \to \omega\gamma$ modelled with Gaussian + crystal-ball distribution

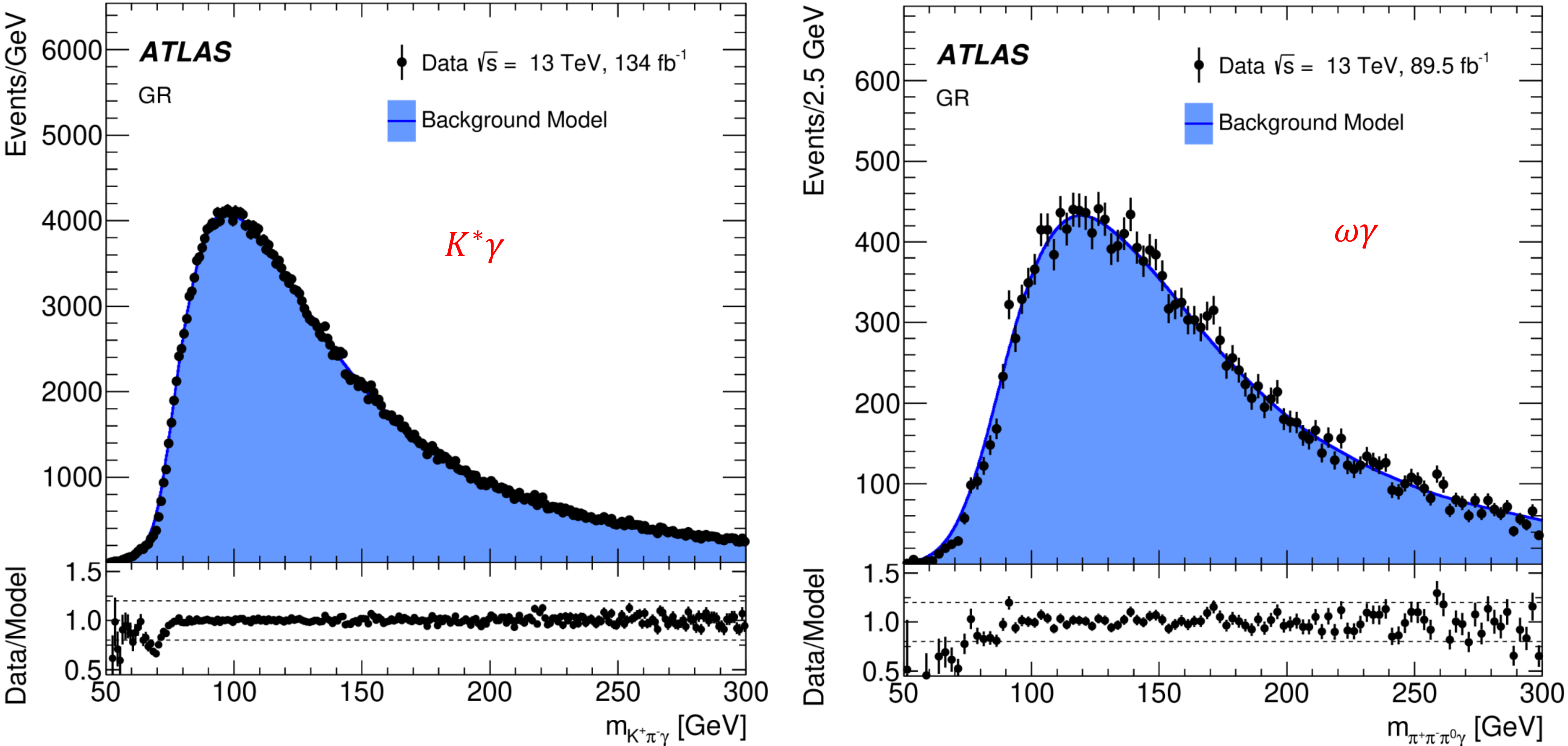
Total Signal Efficiency

$H \to K^*\gamma$	$H \to \omega\gamma$	$Z \to \omega\gamma$
28%	4.6%	1.4%

arXiv:2301.09938

$H \rightarrow K^{*}\gamma$ and $H(Z) \rightarrow \omega\gamma$: Background Model

- Background is multi-jet and γ+jet sources – treat inclusively
  - Use non-parametric data-driven background model

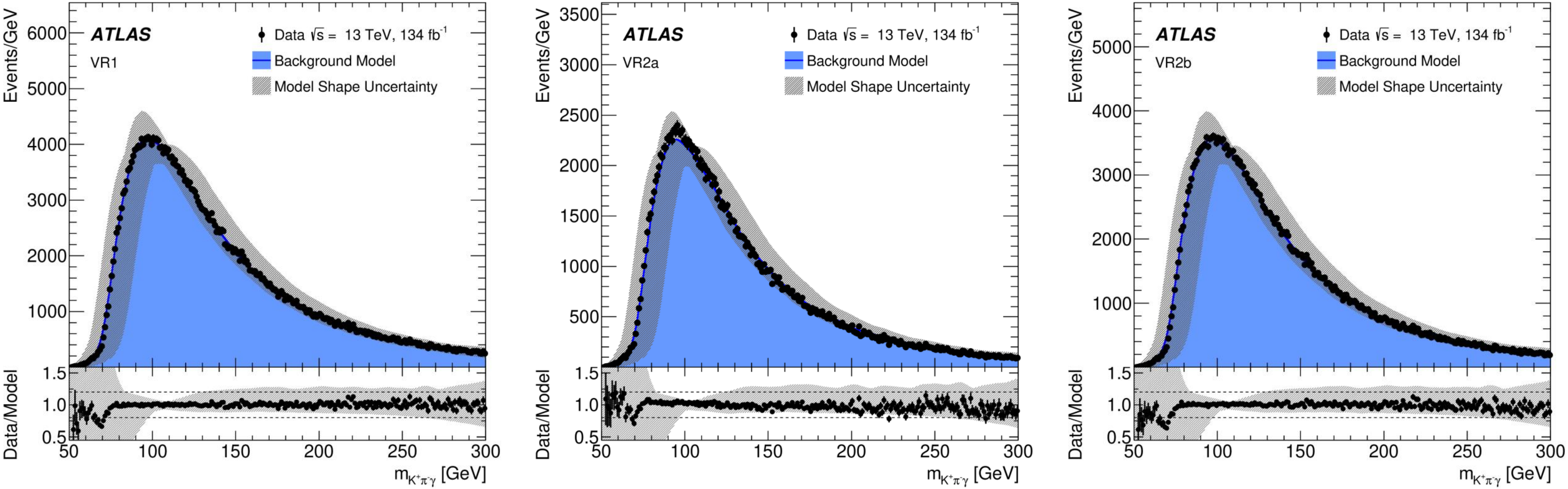


Background in Generation Region

arXiv:2301.09938

$H \to K^{*}\gamma$ and $H(Z) \to \omega\gamma$: Background Validation

- Validation plots are pre-fit
  - Uncertainty from three shape systematics: mass-tilt, $\Delta\phi$-distortion, p_{T}-shift

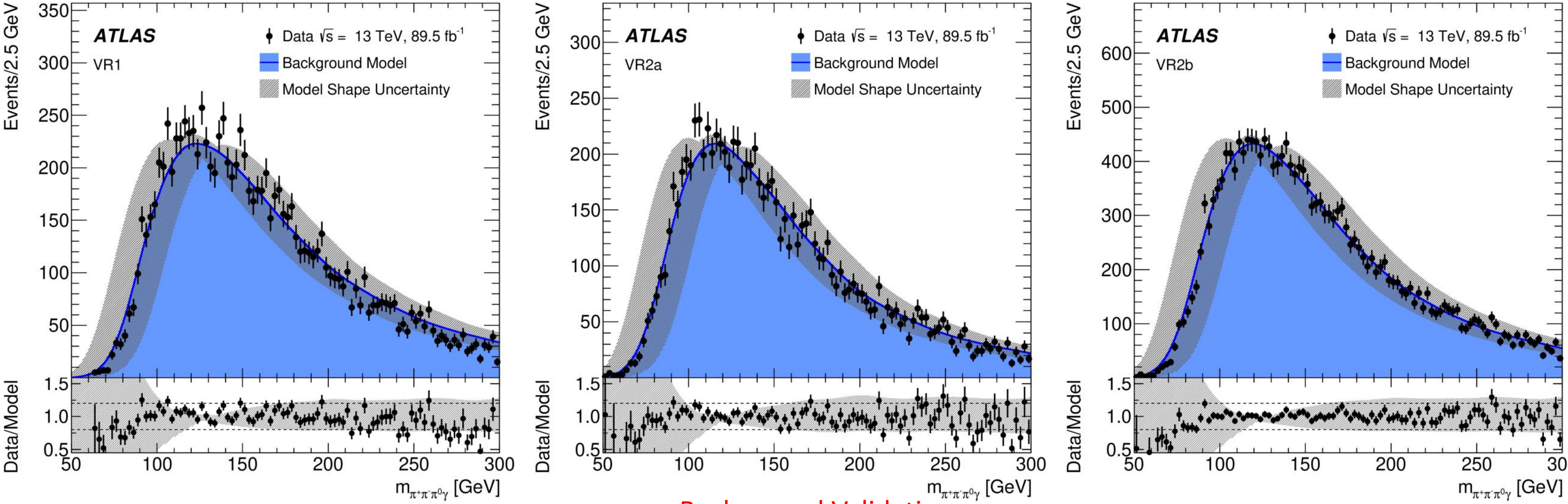


$K^{*}\gamma$ Background Validation

arXiv:2301.09938

$H \rightarrow K^{*}\gamma$ and $H(Z) \rightarrow \omega\gamma$: Background Validation

- Validation plots are pre-fit
  - Uncertainty from three shape systematics: mass-tilt, $\Delta\phi$-distortion, p_{T}-shift

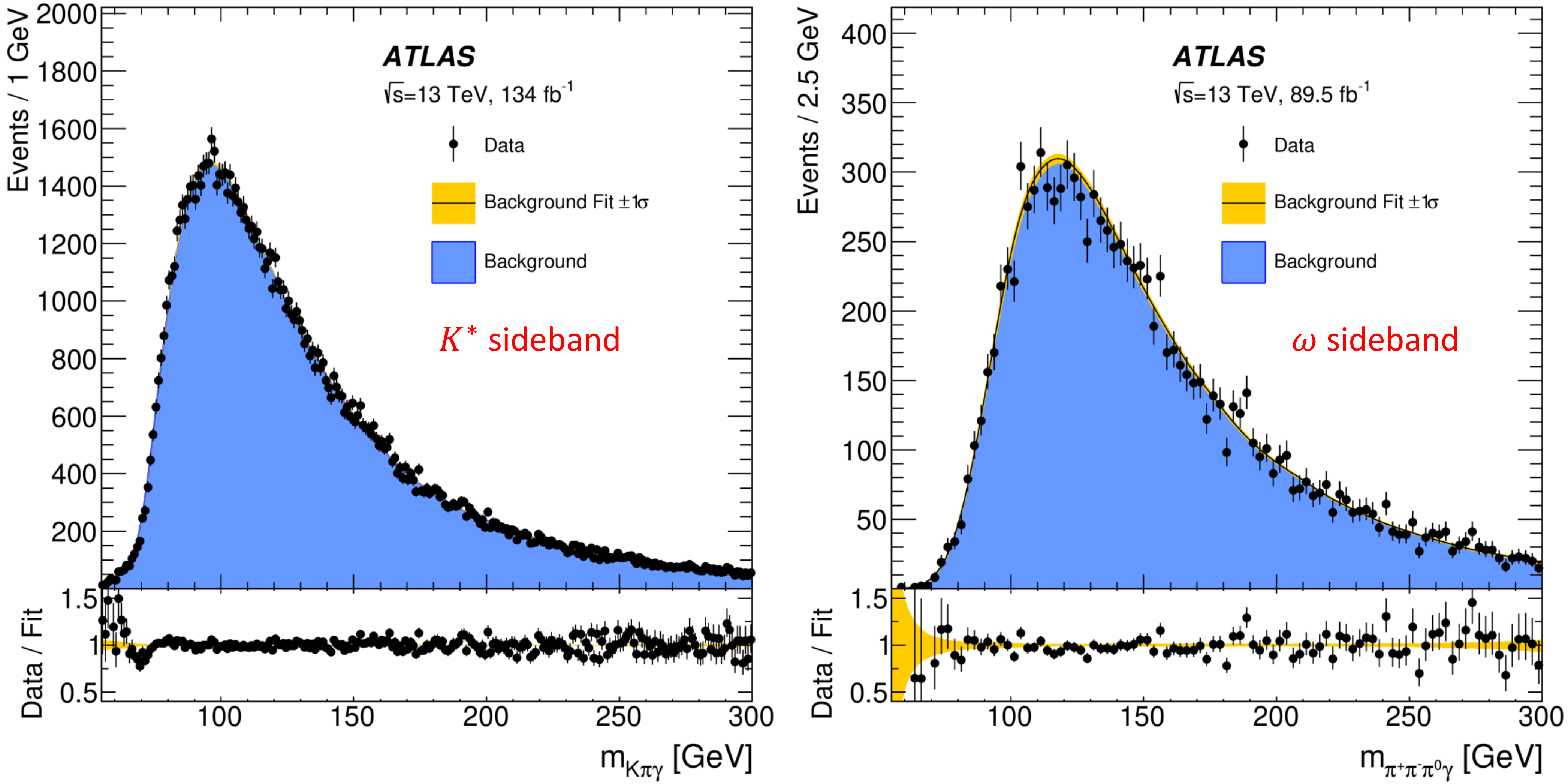


$\omega\gamma$ Background Validation

arXiv:2301.09938

$H \rightarrow K^{*}\gamma$ and $H(Z) \rightarrow \omega\gamma$: Sideband Validation

- Unbinned likelihood fit in $m(K^{\pm}\pi^{\mp}\gamma)$ and $m(\pi^{+}\pi^{-}\pi^{0}\gamma)$

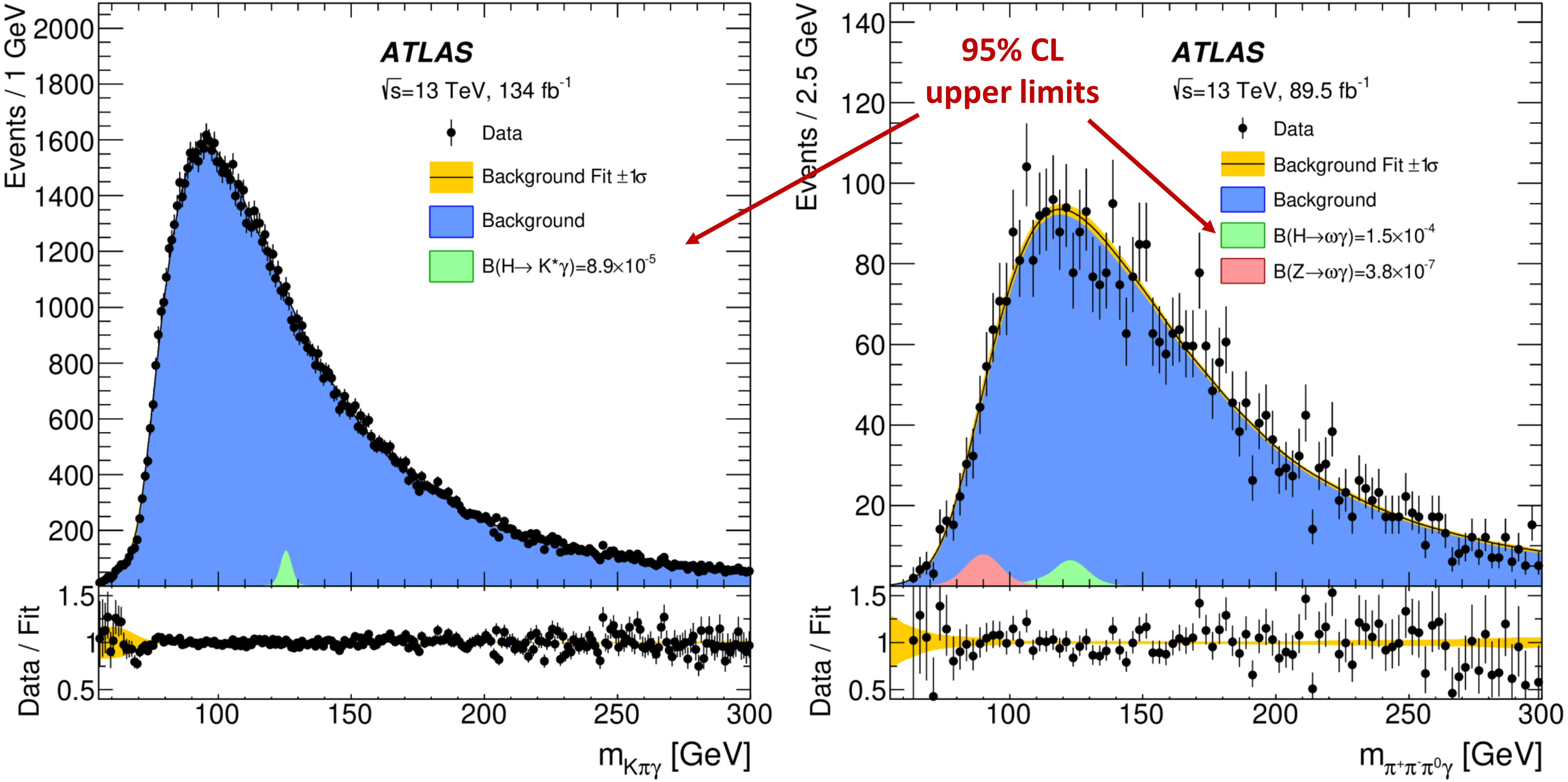


Background in Sidebands (Post-Fit)

arXiv:2301.09938

$H \to K^*\gamma$ and $H(Z) \to \omega\gamma$: Results

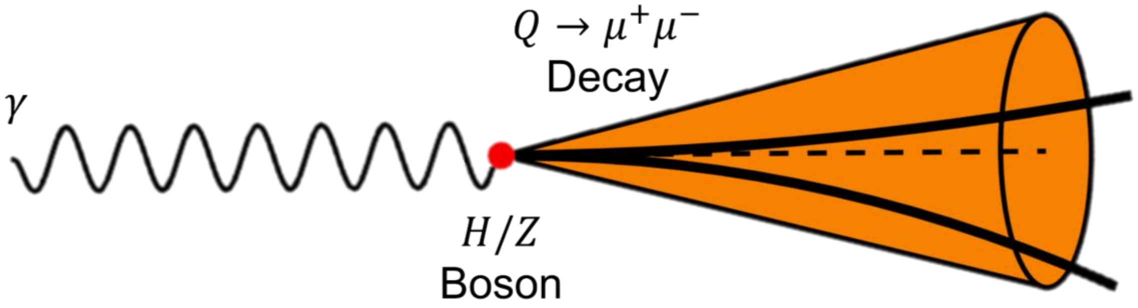
- Unbinned likelihood fit in $m(K^\pm\pi^\mp\gamma)$ and $m(\pi^+\pi^-\pi^0\gamma)$



arXiv:2301.09938

$H(Z) \to Q\gamma$: Overview

- $H \to Q(\mu^+\mu^-)\gamma$: b- and c-quark Yukawa couplings
  - Two muons and a photon in final state



- **Dedicated** single photon + muon triggers
- Use a **2D** fit in $m_{\mu^+\mu^-\gamma}$ vs $m_{\mu^+\mu^-}$

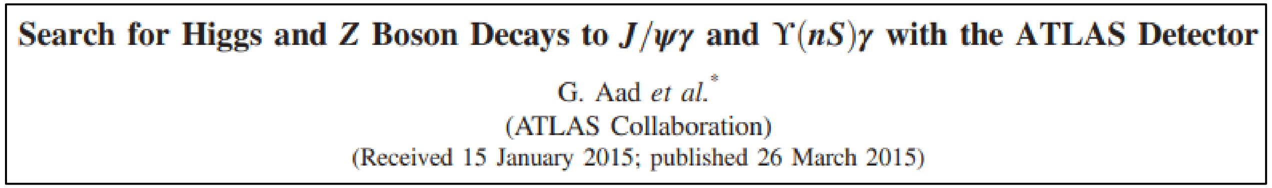
Charmonium: $Q = J/\psi, \psi(2S)$

- $BR^{SM}_{H\to\psi(nS)\gamma} \approx 10^{-6}$
- $|\mathcal{A}_{ind}| \approx 20 \times |\mathcal{A}_{dir}|$

Bottomonium: $Q = \Upsilon(1S, 2S, 3S)$

- $BR^{SM}_{H\to\Upsilon(nS)\gamma} \approx 10^{-9} - 10^{-8}$
- $\mathcal{A}_{ind}, \mathcal{A}_{dir}$ almost cancel in SM

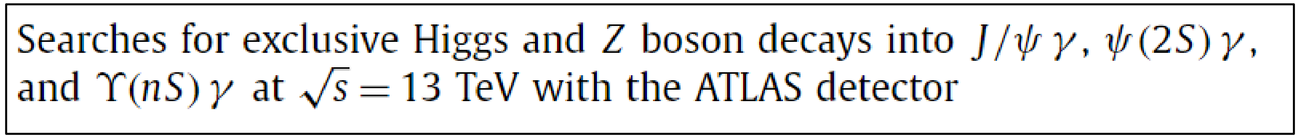
$BR^{SM}_{Z\to Q\gamma} \approx 10^{-8} - 10^{-7}$ SM Predictions



Search for Higgs and Z Boson Decays to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ with the ATLAS Detector

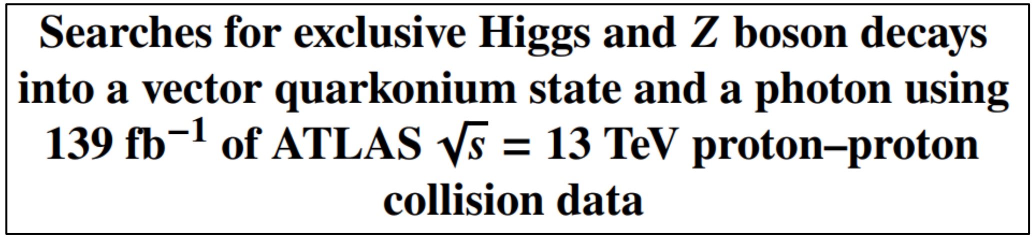
G. Aad *et al.**
(ATLAS Collaboration)
(Received 15 January 2015; published 26 March 2015)

Phys.Rev.Lett. 114 (2015) 12, 121801 – 1st iteration



Searches for exclusive Higgs and Z boson decays into $J/\psi\,\gamma$, $\psi(2S)\,\gamma$, and $\Upsilon(nS)\,\gamma$ at $\sqrt{s} = 13$ TeV with the ATLAS detector

Phys.Lett.B 786 (2018) 134-155 – 2nd iteration

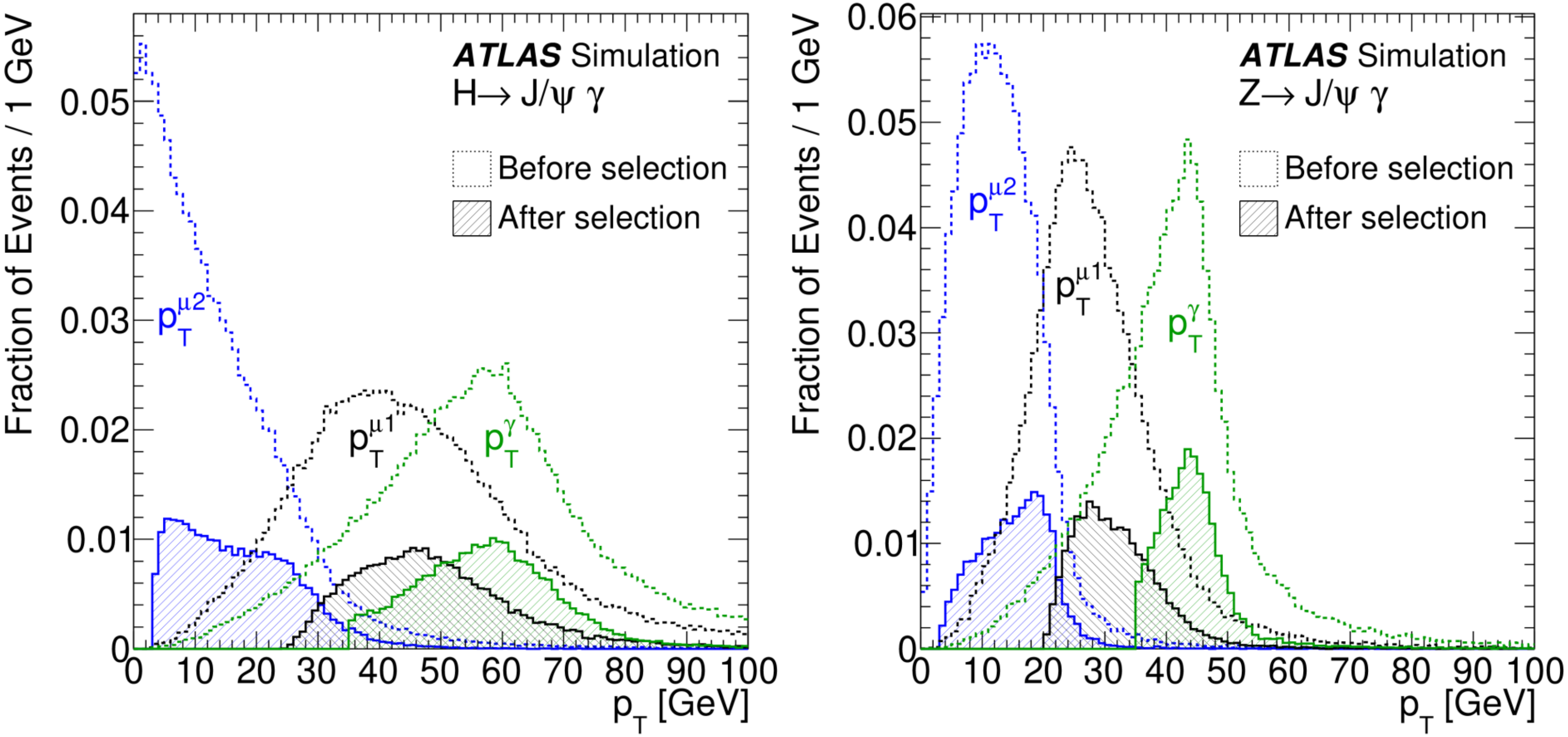


Searches for exclusive Higgs and Z boson decays into a vector quarkonium state and a photon using 139 fb^{-1} of ATLAS $\sqrt{s}$ = 13 TeV proton–proton collision data

arXiv:2208.03122 – 3rd iteration (Accepted by EPJ C)

$H(Z) \rightarrow Q\gamma$: Signal Efficiency

arXiv:2208.03122



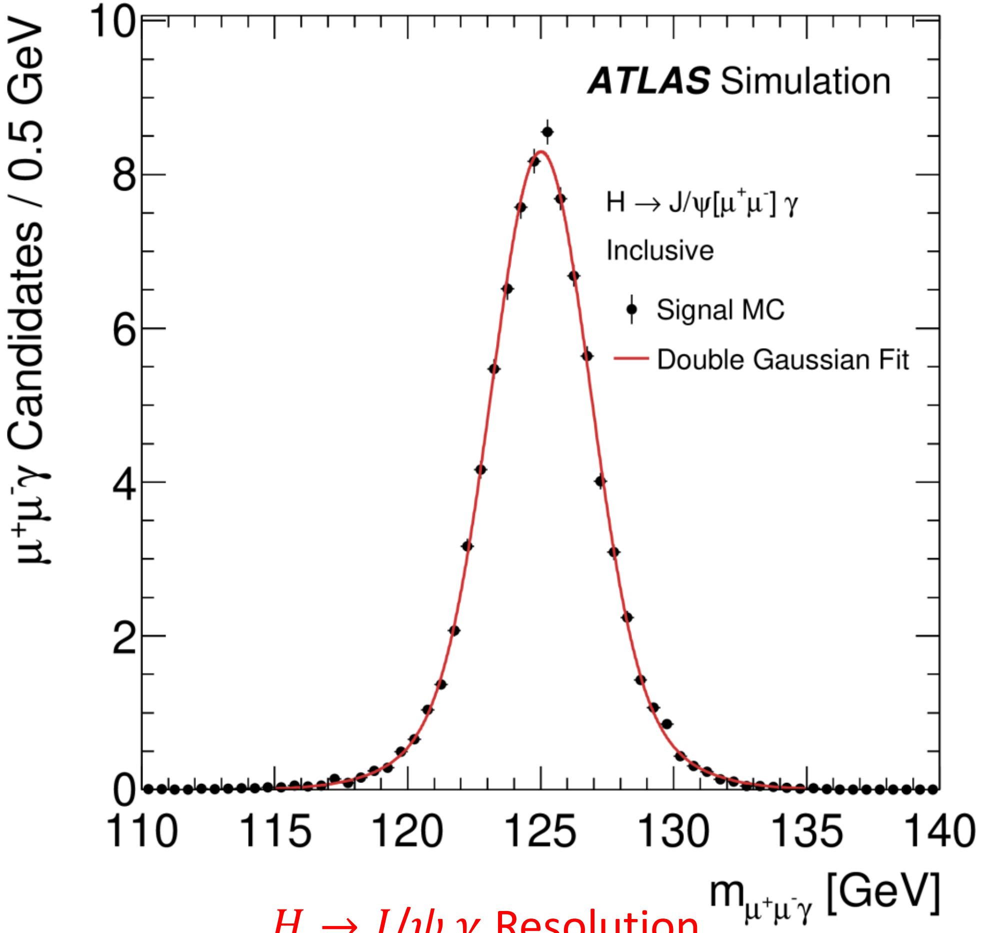
Generator-level p_T (J/ψ channels)

- Softer photon and muon p_T in Z decays leads to smaller signal efficiencies than for H decays
- Reject displaced vertices to avoid $b \rightarrow \psi(nS)$

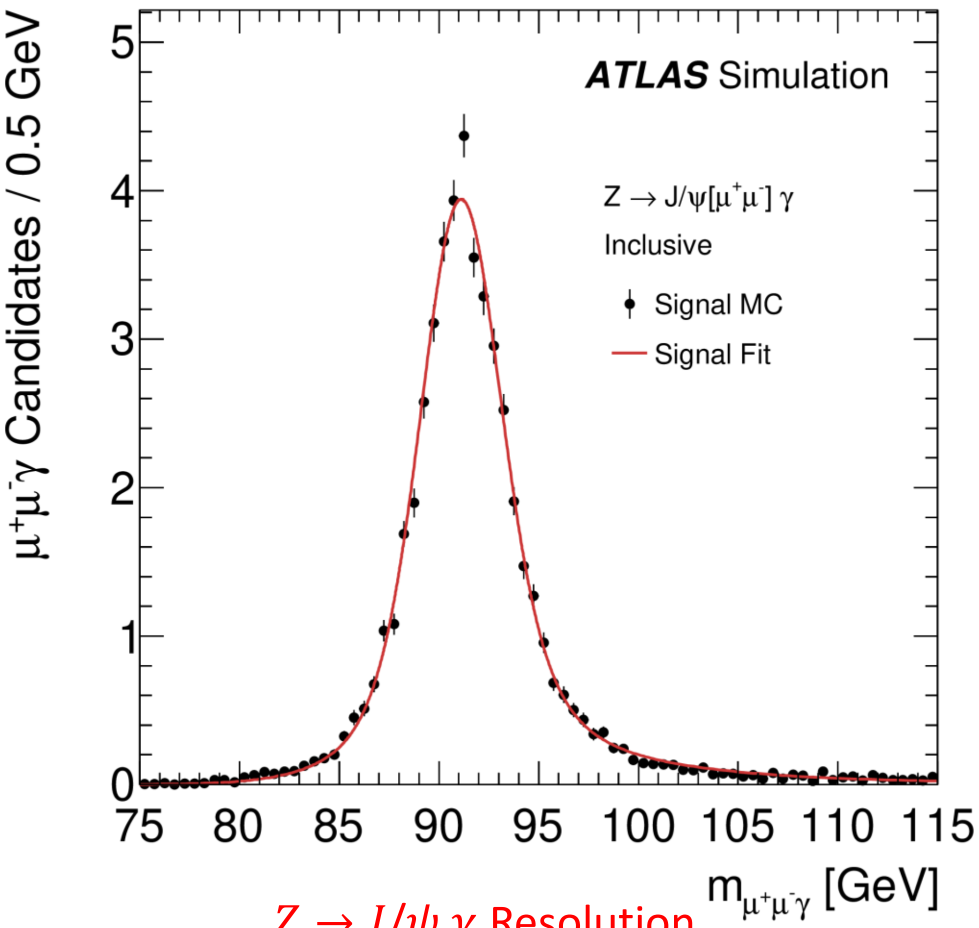
Total Signal Efficiency

Decay Channel	Z Signal	H Signal
$\psi(nS)\gamma$	11%	19%
$\Upsilon(nS)\gamma$	14%	21%

$H(Z) \rightarrow Q\gamma$: Signal Resolution



$H \rightarrow J/\psi\, \gamma$ Resolution



$Z \rightarrow J/\psi\, \gamma$ Resolution

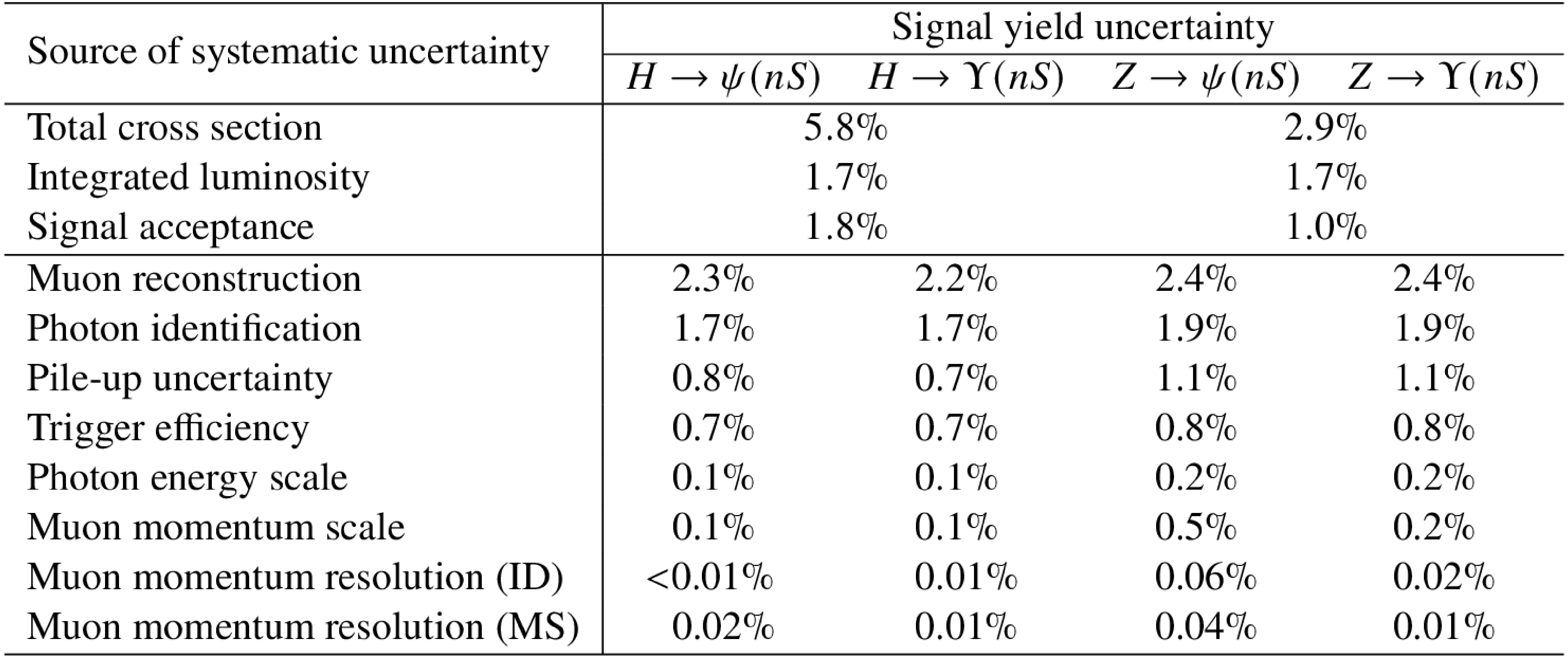
- Produce H samples by production mode
  - 2D Shape: Sum of two bivariate Gaussians
  - Resolution: $1.6 - 1.8\%$

arXiv:2208.03122

- Produce Z samples inclusively
  - 2D Shape: (double Voigtian × mass-dependent efficiency) × double Gaussian
  - Resolution: $1.6 - 1.8\%$

$H(Z) \rightarrow Q\gamma$: Signal Systematic Uncertainties

- Take into account relevant uncertainties on the total signal yield
  - Nuisance parameters with standard Gaussian constraints in maximum likelihood fit
  - Shape uncertainties found to be negligible

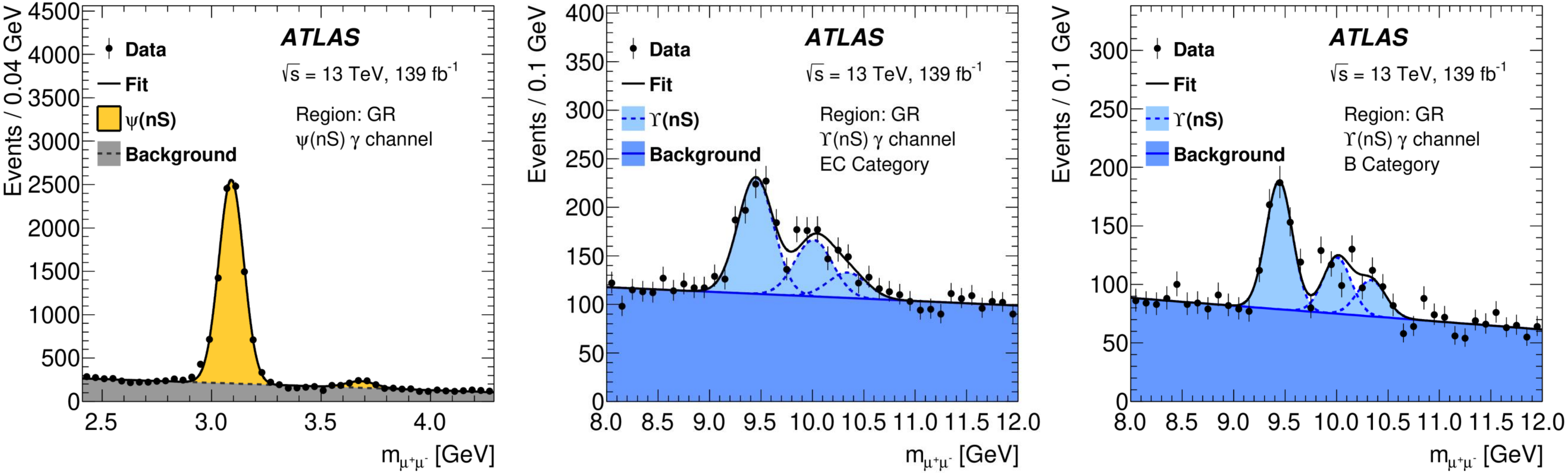


Source of systematic uncertainty	Signal yield uncertainty			
	$H \rightarrow \psi(nS)$	$H \rightarrow \Upsilon(nS)$	$Z \rightarrow \psi(nS)$	$Z \rightarrow \Upsilon(nS)$
Total cross section	5.8%		2.9%	
Integrated luminosity	1.7%		1.7%	
Signal acceptance	1.8%		1.0%	
Muon reconstruction	2.3%	2.2%	2.4%	2.4%
Photon identification	1.7%	1.7%	1.9%	1.9%
Pile-up uncertainty	0.8%	0.7%	1.1%	1.1%
Trigger efficiency	0.7%	0.7%	0.8%	0.8%
Photon energy scale	0.1%	0.1%	0.2%	0.2%
Muon momentum scale	0.1%	0.1%	0.5%	0.2%
Muon momentum resolution (ID)	<0.01%	0.01%	0.06%	0.02%
Muon momentum resolution (MS)	0.02%	0.01%	0.04%	0.01%

arXiv:2208.03122

$H(Z) \rightarrow \mathcal{Q}\gamma$: Quarkonium Reconstruction

- Split $\Upsilon(nS)$ into Barrel (B) and Endcap (EC) categories
  - Improved resolution in barrel helps resolve each state



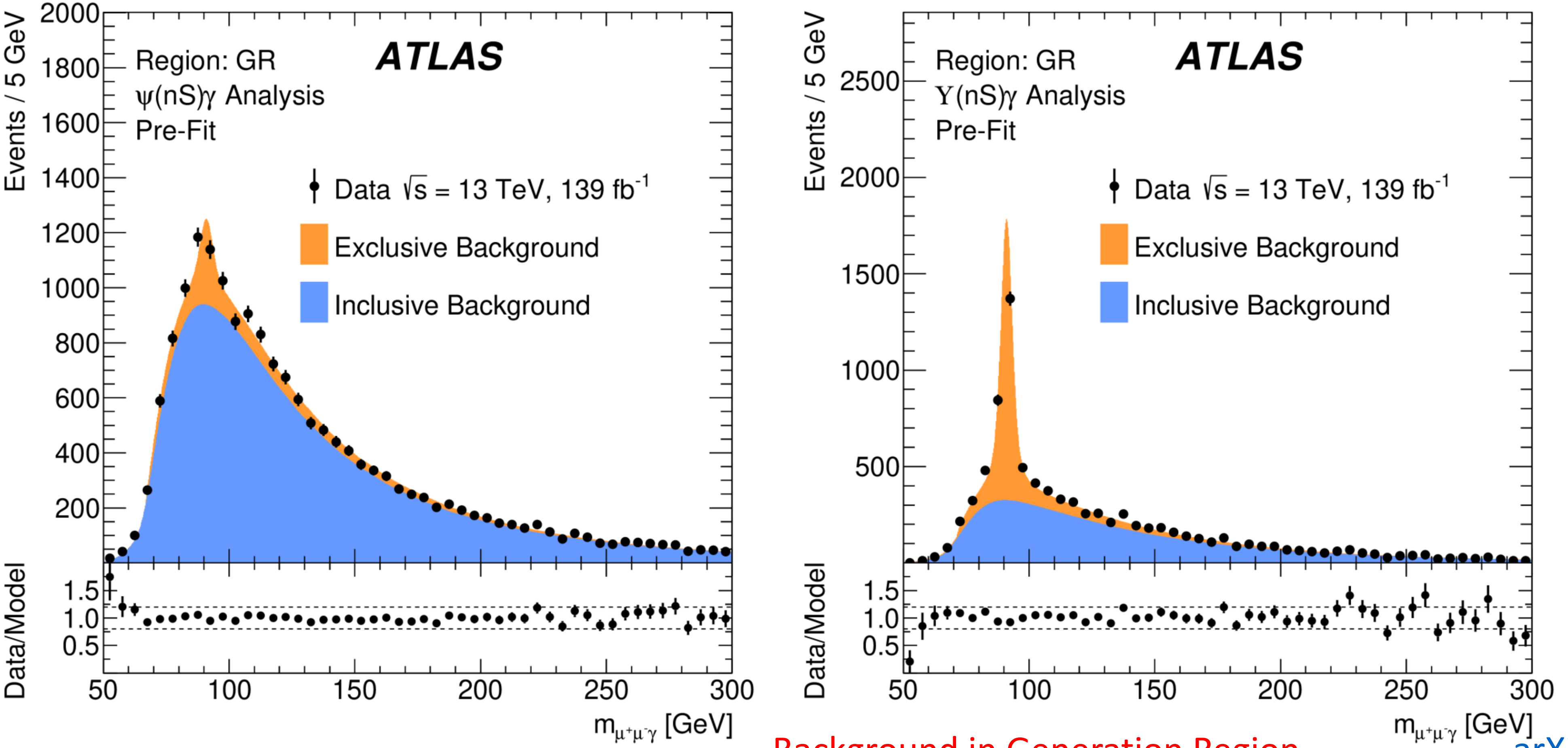
Meson Reconstruction in GR

arXiv:2208.03122

$H(Z) \to Q\gamma$: Background Modelling

- Exclusive background
  - $q\bar{q} \to \mu^+\mu^-\gamma$ production (Drell-Yan)
  - Analytical fit to simulated events

- Inclusive background
  - Multi-jet and γ+jet sources with $Q/\mu^+\mu^-$ production
  - Non-parametric data-driven background model

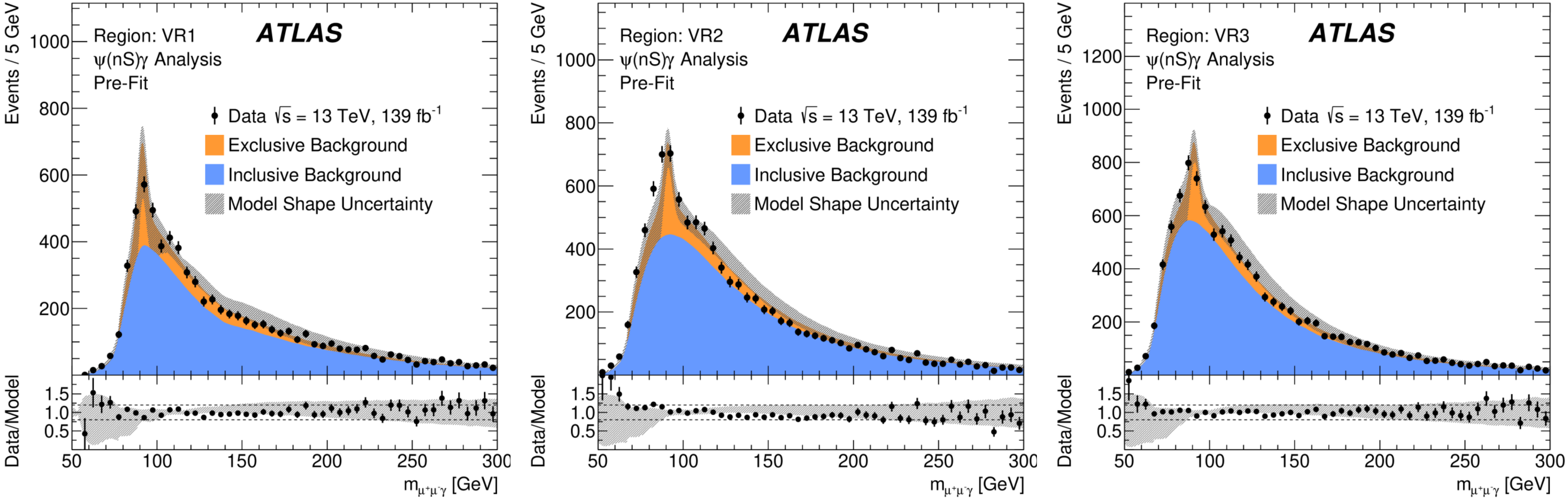


Background in Generation Region

arXiv:2208.03122

$H(Z) \rightarrow Q\gamma$: Background Validation and Systematic Uncertainties

- Validation plots are pre-fit
  - Uncertainty from three shape systematics: mass-tilt, $\Delta\phi$-distortion, p_{T}-shift



Region		$p_{\mathrm{T}}^{\mu\mu}$	Photon Isolation	Q Isolation
Generation Region	(GR)	> 30 GeV	Relaxed	Relaxed
Validation Region 1	(VR1)	Full	Relaxed	Relaxed
Validation Region 2	(VR2)	> 30 GeV	Relaxed	Full
Validation Region 3	(VR3)	> 30 GeV	Full	Relaxed
Signal Region	(SR)	Full	Full	Full

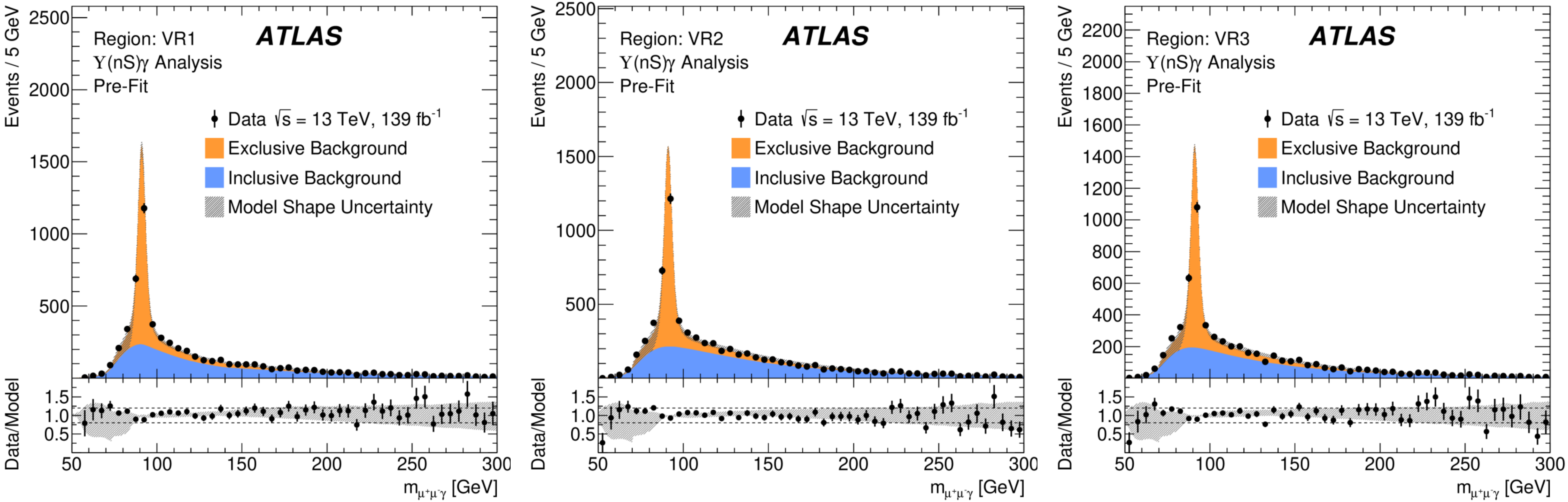
$\psi(nS)\gamma$ Background Validation

Region Definitions

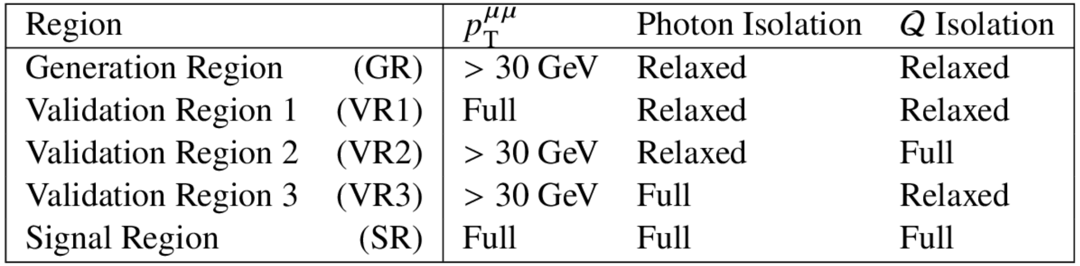
arXiv:2208.03122

$H(Z) \rightarrow Q\gamma$: Background Validation and Systematic Uncertainties

- Validation plots are pre-fit
  - Uncertainty from three shape systematics: mass-tilt, $\Delta\phi$-distortion, p_{T}-shift



$\Upsilon(nS)\gamma$ Background Validation

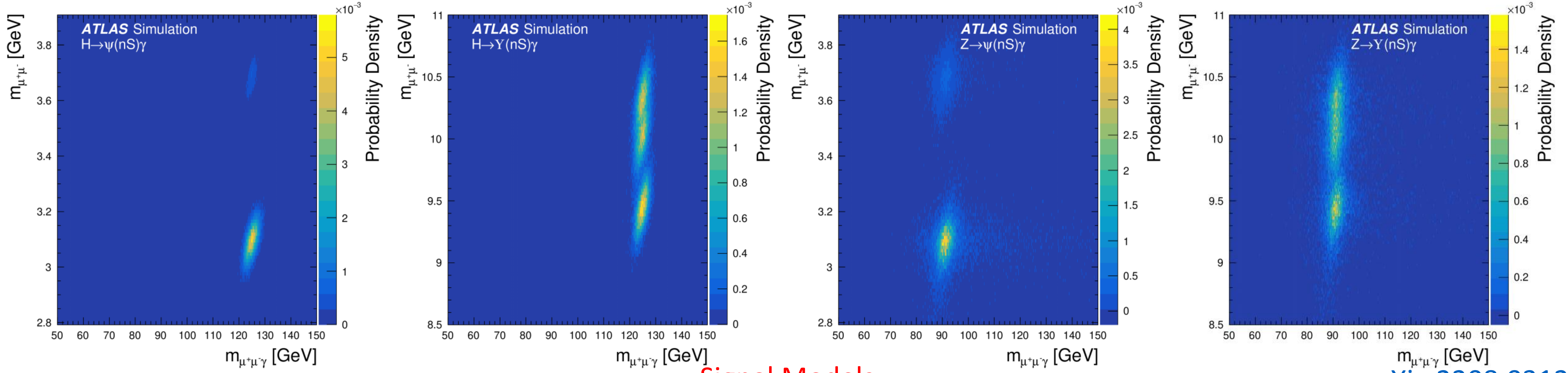


Region		$p_{\mathrm{T}}^{\mu\mu}$	Photon Isolation	Q Isolation
Generation Region	(GR)	> 30 GeV	Relaxed	Relaxed
Validation Region 1	(VR1)	Full	Relaxed	Relaxed
Validation Region 2	(VR2)	> 30 GeV	Relaxed	Full
Validation Region 3	(VR3)	> 30 GeV	Full	Relaxed
Signal Region	(SR)	Full	Full	Full

Region Definitions

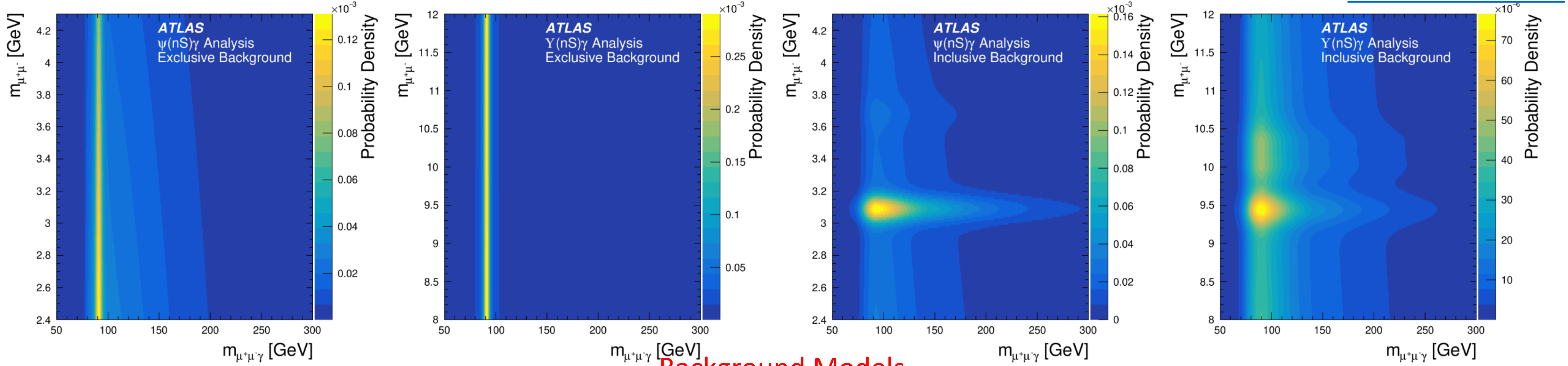
arXiv:2208.03122

$H(Z) \rightarrow Q\gamma$: Three-body Mass Versus Dimuon Mass



arXiv:2208.03122

Signal Models

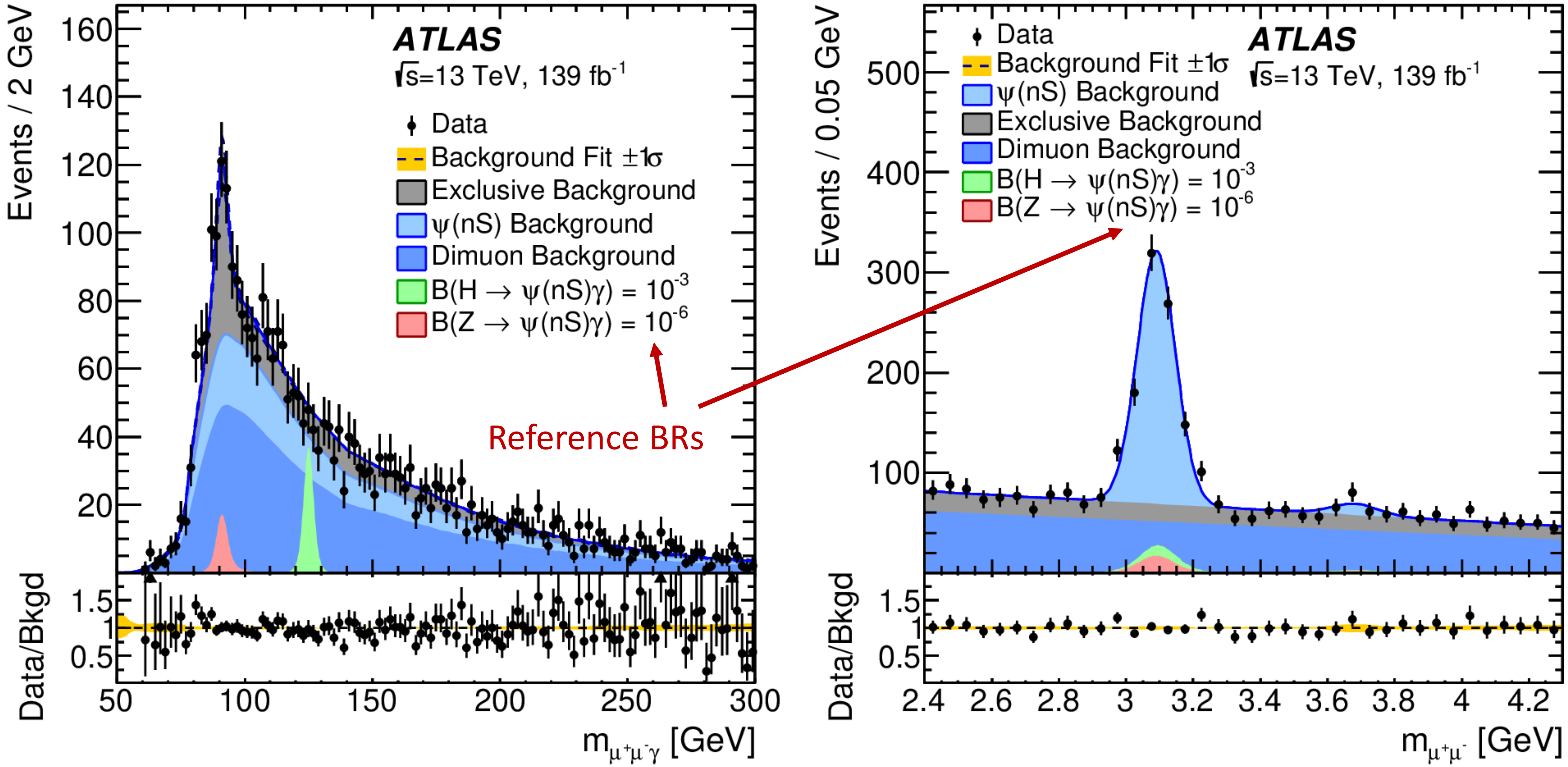


Background Models

$H(Z) \to \psi(nS)\gamma$: Inclusive Fit

arXiv:2208.03122

- Use **2D** unbinned likelihood fit in $m(\mu^+\mu^-), m(\mu^+\mu^-\gamma)$
  - Discriminates between **all** signal and background contributions
- $\psi(nS)\gamma$ analysis fit is performed in a single category

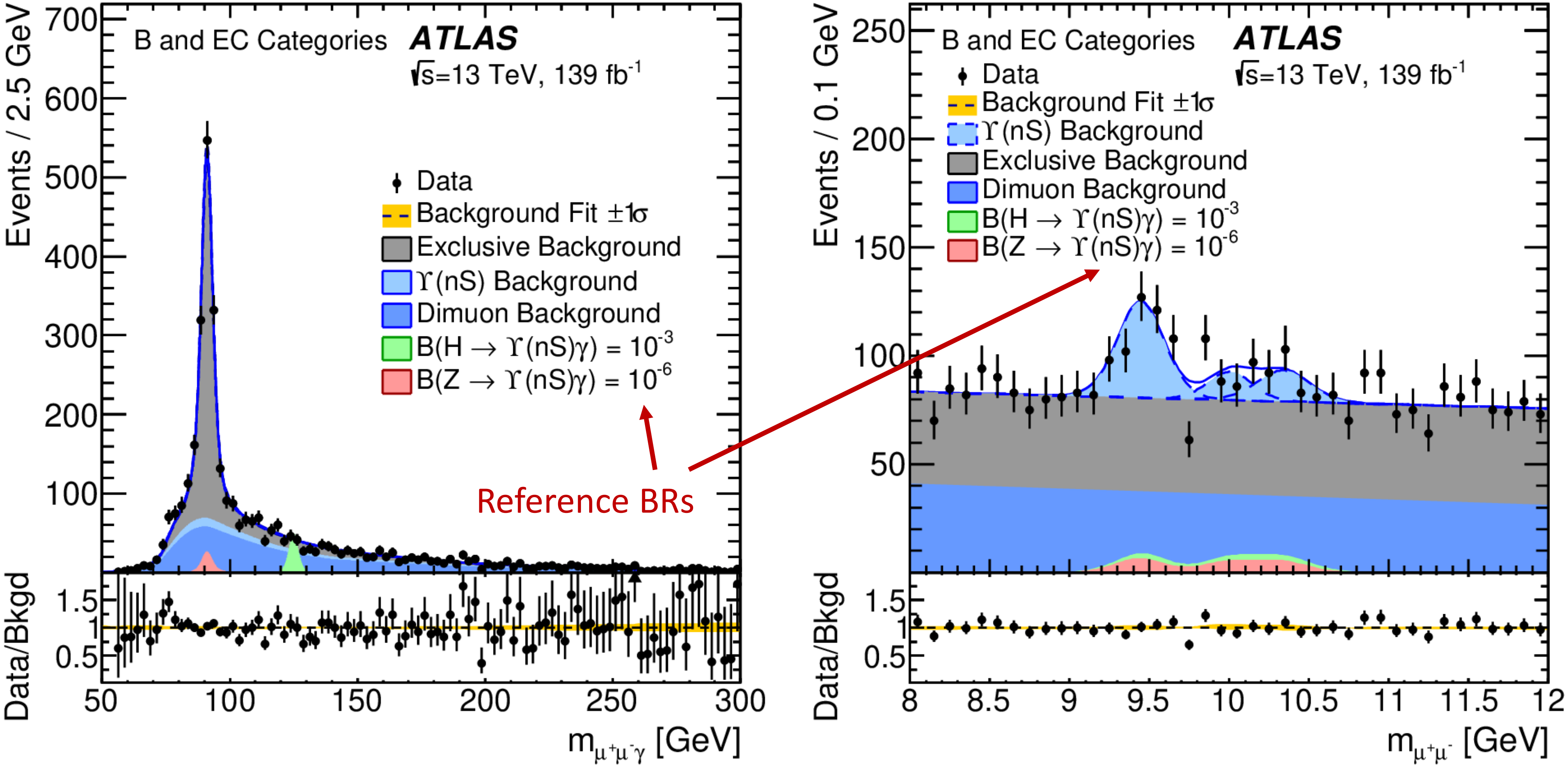


Reference BRs

$H(Z) \rightarrow \Upsilon(nS)\gamma$: Inclusive Fit

- Use **2D** unbinned likelihood fit in $m(\mu^+\mu^-), m(\mu^+\mu^-\gamma)$
  - Discriminates between **all** signal and background contributions
- $\Upsilon(nS)\gamma$ analysis fit is performed simultaneously in the barrel and endcap categories

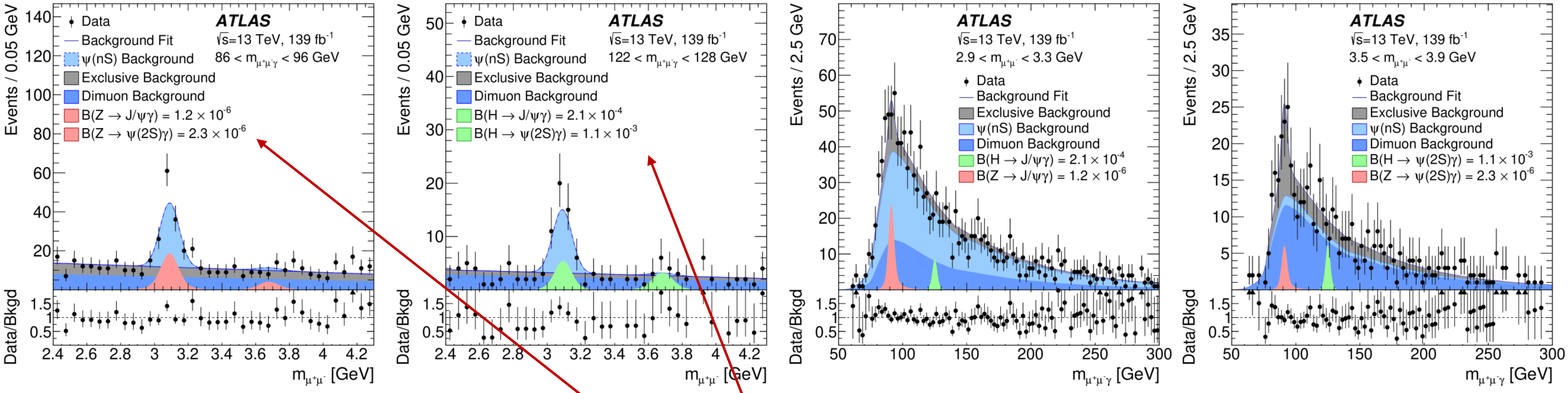
arXiv:2208.03122



Reference BRs

$H(Z) \to \psi(nS)\gamma$: Projection of Fit in Regions

- Projection of fits fit near each signal resonance in each mass dimension



Projections in $m(\mu^+\mu^-)$

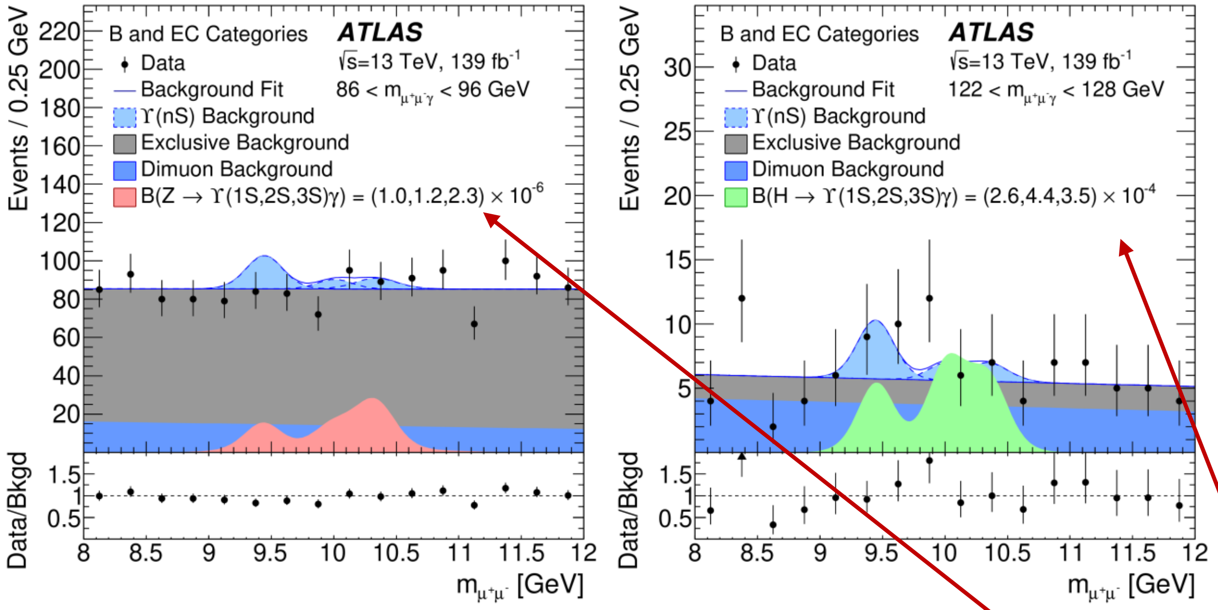
Projections in $m(\mu^+\mu^-\gamma)$

95% CL upper limits

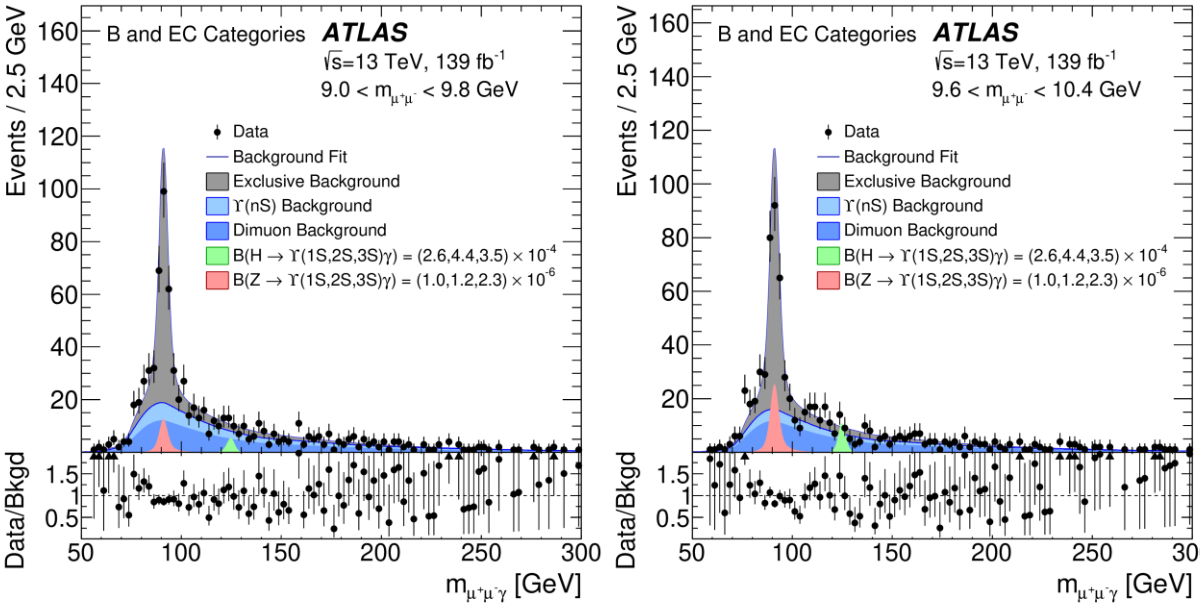
arXiv:2208.03122

$H(Z) \rightarrow \Upsilon(nS)\gamma$: Projection of Fit in Regions

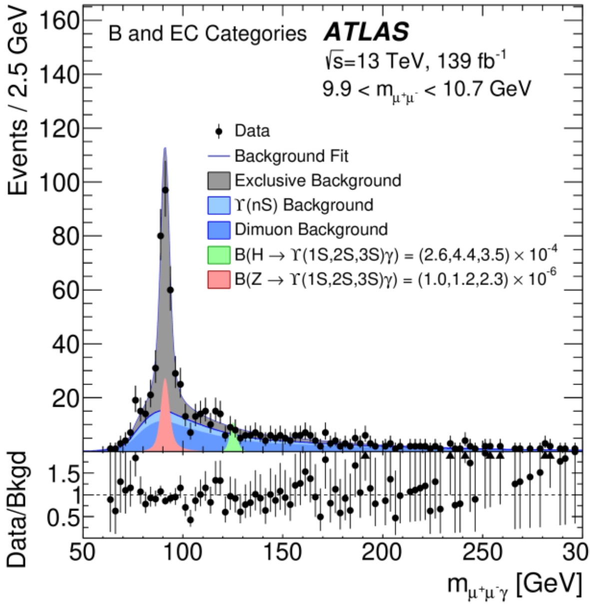
- Projection of fits fit near each signal resonance in each mass dimension



Projections in $m(\mu^+\mu^-)$



Projections in $m(\mu^+\mu^-\gamma)$



95% CL upper limits

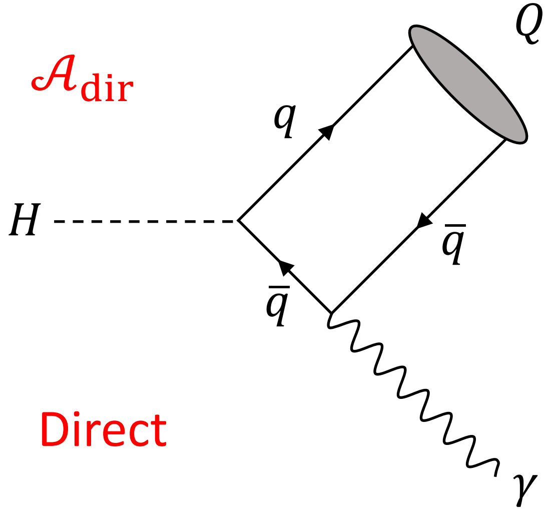
arXiv:2208.03122

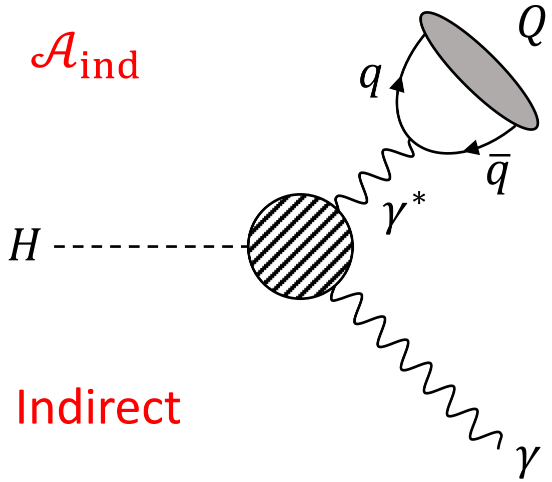
$H \rightarrow Q\gamma$: κ-Framework Interpretation

- κ_q coupling modifier: ratio of quark coupling y_q over the SM−expectation, $\kappa_q = \frac{y_q}{y_q^{\mathrm{SM}}}$
- Combine with $H \rightarrow \gamma\gamma$ § to interpret in terms of $\kappa_{c,b}/\kappa_\gamma$:

$$\frac{\mu_{H\rightarrow \mathrm{J}/\psi\,\gamma}}{\mu_{H\rightarrow\gamma\gamma}} \approx \frac{\left|\mathcal{A}_{\mathrm{ind}} + \frac{\kappa_c}{\kappa_\gamma}\mathcal{A}_{\mathrm{dir}}\right|^2}{\Gamma^{\mathrm{SM}}_{H\rightarrow \mathrm{J}/\psi\,\gamma}}$$

μ: observed rate normalised to SM rate





Analysis	κ Ratio	Expected Bounds	Observed Bounds
$H \rightarrow J/\psi\,\gamma$	κ_c/κ_γ	$(-123, 164)$	$[-136, 178]$
$H \rightarrow \Upsilon(nS)\gamma$	κ_b/κ_γ	$(-37, 40)$	$[-38, 40]$

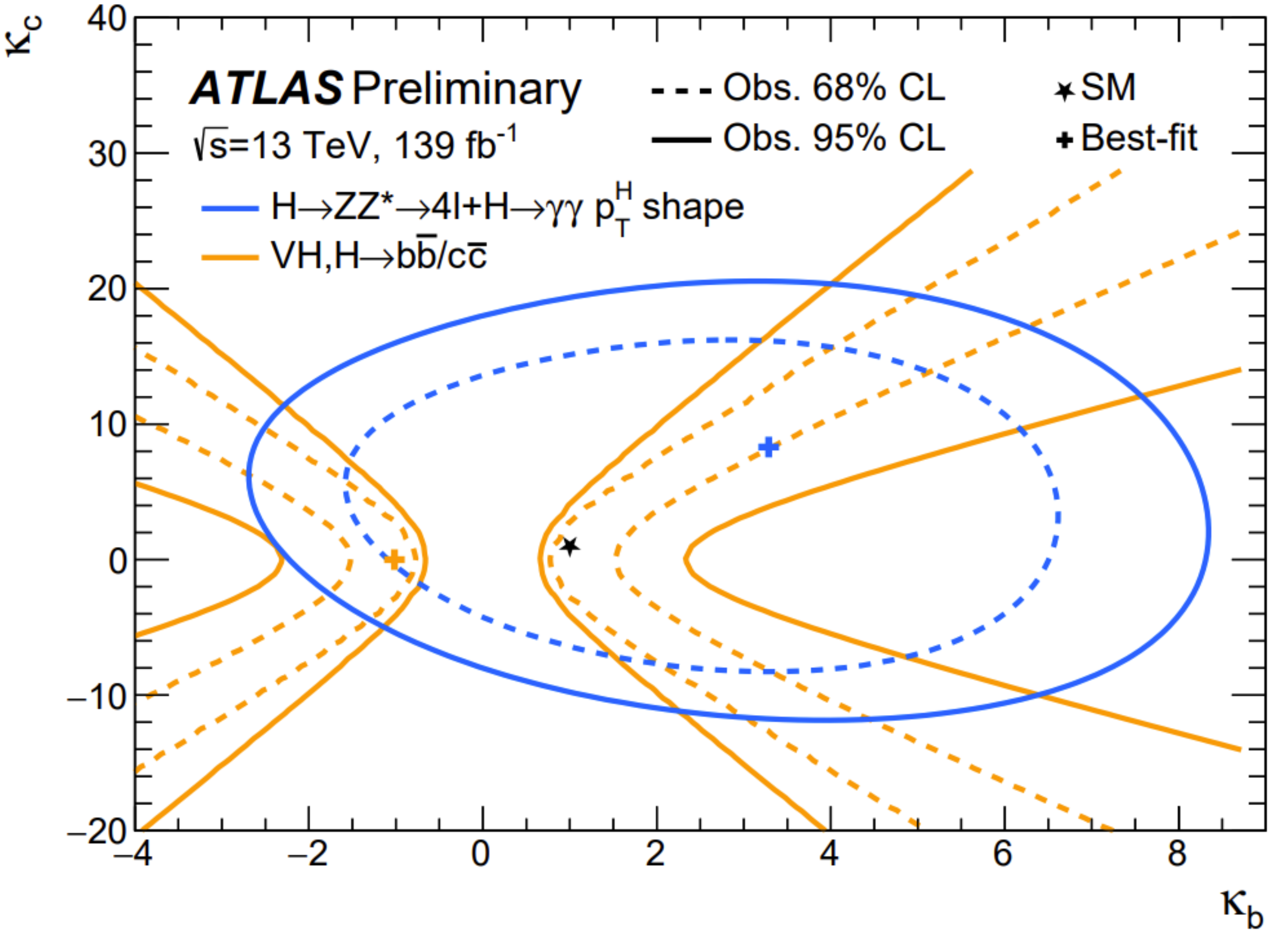
§ ATLAS-CONF-2020-026

arXiv:2208.03122

Other κ-Framework Results

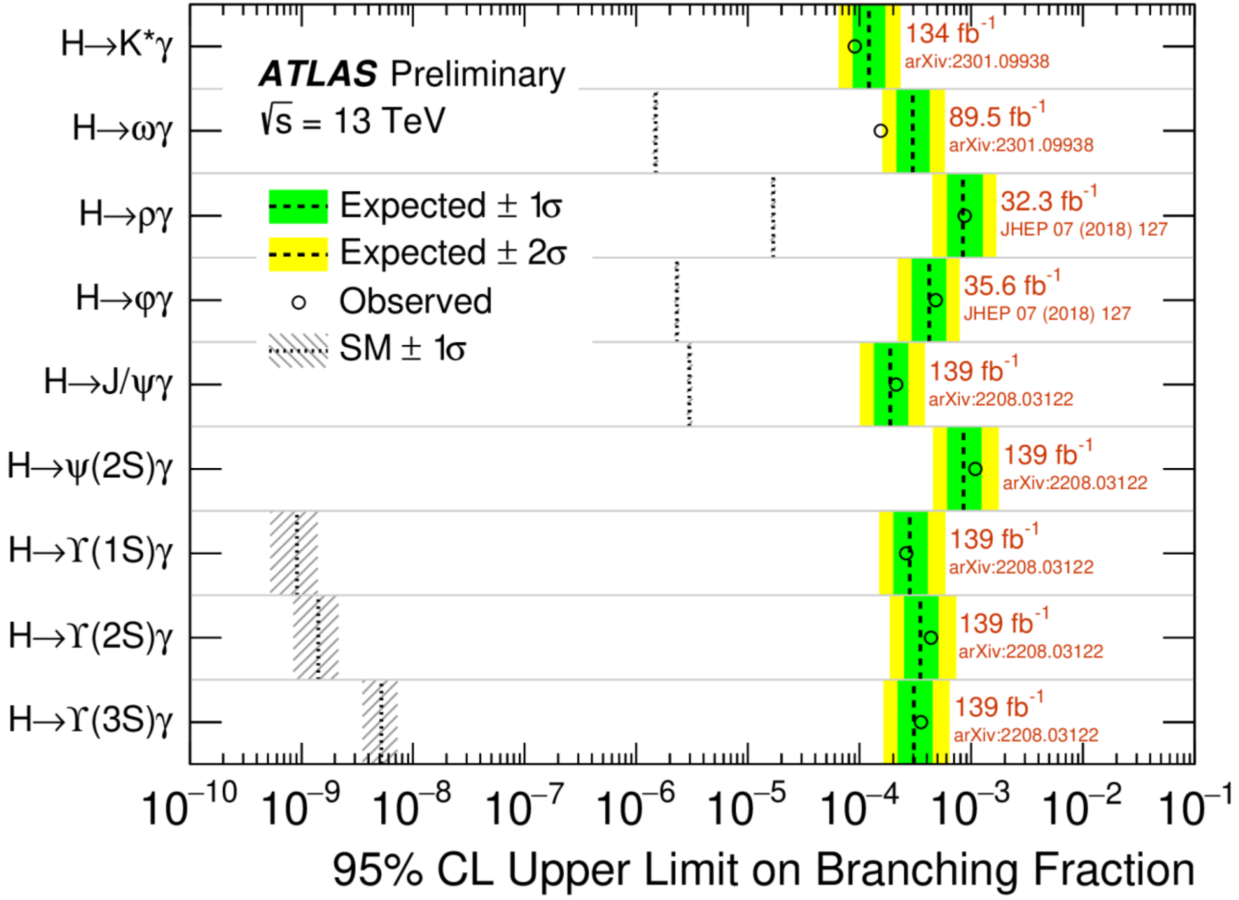
- κ-interpretation complements results from other searches
  - $H \to b\bar{b}$: Eur. Phys. J. C 81 (2021) 178
  - $H \to c\bar{c}$: Eur. Phys. J. C 82 (2022) 717
    - $|\kappa_c| < 8.5\ (12.4)$ @ 95% CL
    - $|\kappa_c/\kappa_b| < 4.5\ (5.1)$ @ 95% CL
  - Measurements of p_{T}^{H}: arXiv:2207.08615

Channel	Parameter	Observed 95% confidence interval	Expected 95% confidence interval
$H \to ZZ^* \to 4\ell$	κ_b	$[-2.1,\ 6.1]$	$[-3.6,\ 9.3]$
	κ_c	$[-9.4,\ 18.5]$	$[-14.3,\ 19.6]$
$H \to \gamma\gamma$	κ_b	$[-3.8,\ 10.2]$	$[-2.8,\ 8.0]$
	κ_c	$[-14.5,\ 18.9]$	$[-12.1,\ 17.8]$
Combined	κ_b	$[-2.3,\ 7.3]$	$[-2.2,\ 7.4]$
	κ_c	$[-10.5,\ 18.0]$	$[-10.4,\ 16.6]$

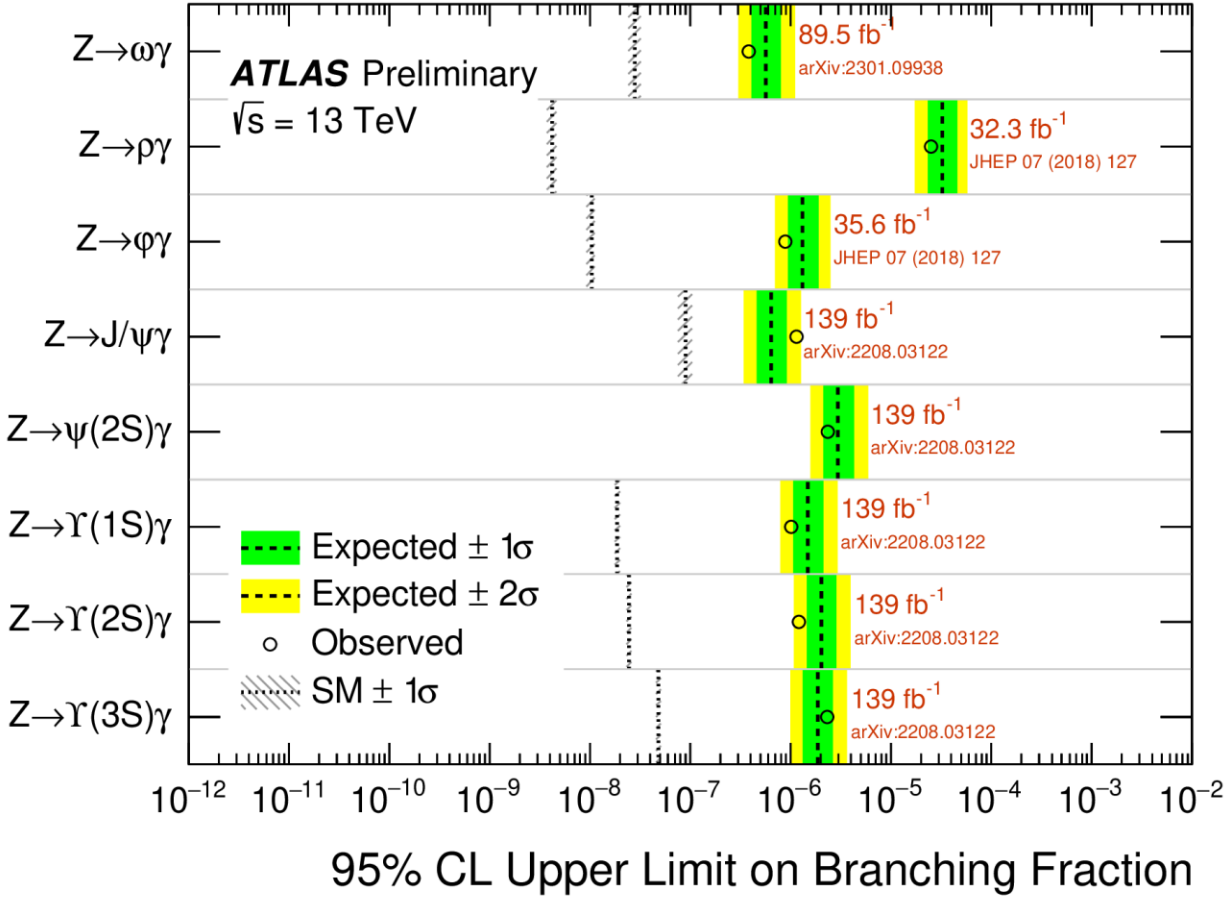


Summary of Exclusive $H(Z) \rightarrow M\gamma$ Search Results 2

ATL-PHYS-PUB-2023-004



Higgs Boson Decays (with SM Expectations)

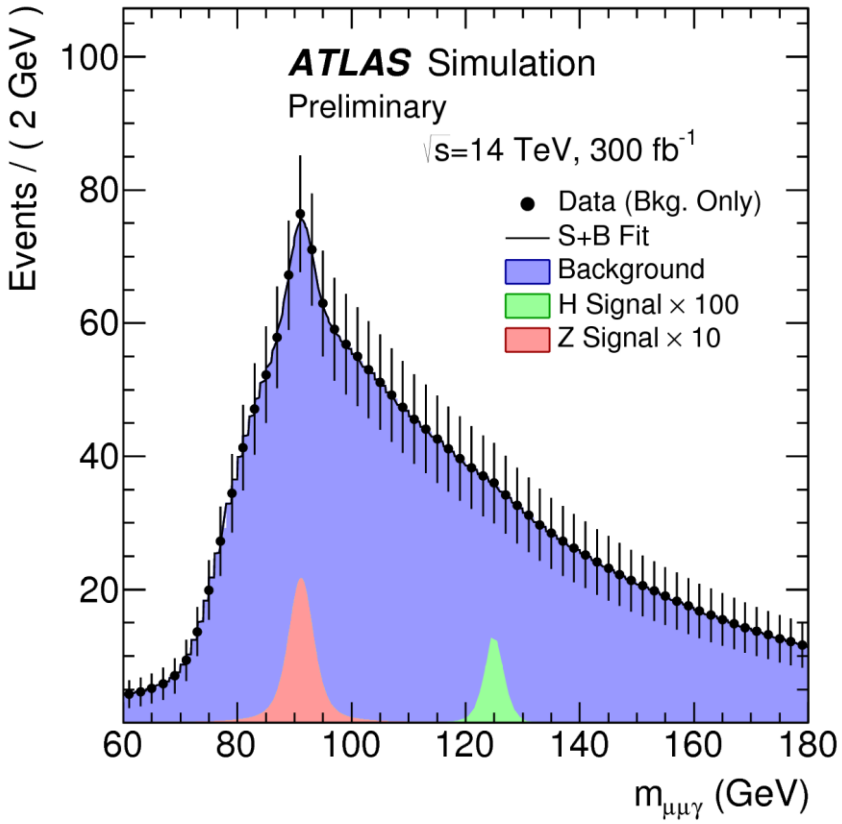


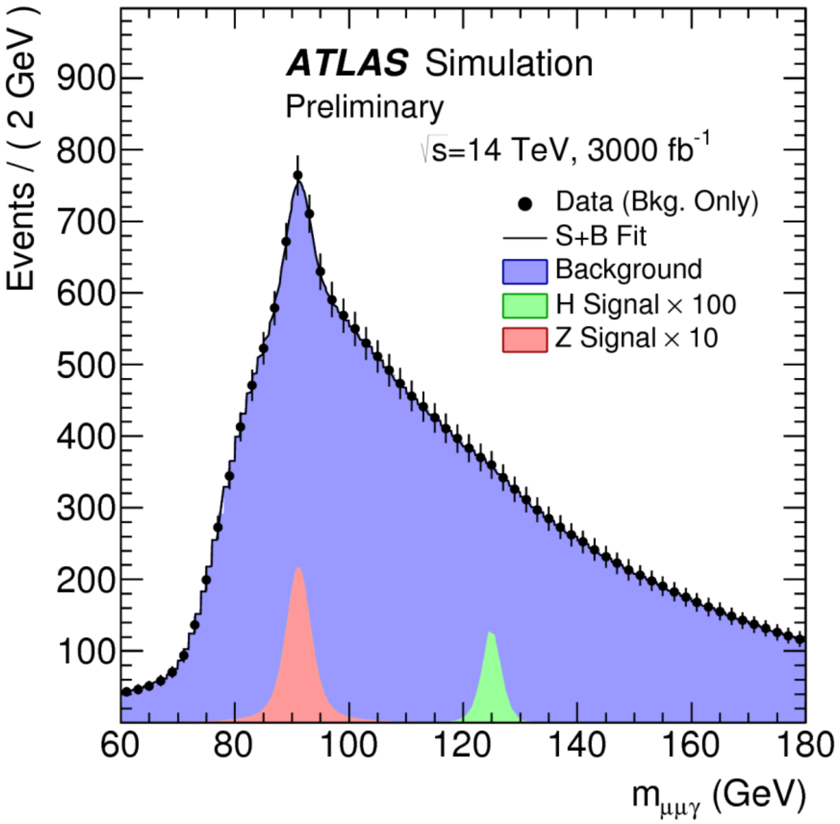
Z Boson Decays (with SM Expectations)

- ATLAS has the most stringent limits on each of these decay channels

Prospects for Exclusive $H(Z) \rightarrow M\gamma$ Searches

ATL-PHYS-PUB-2015-043

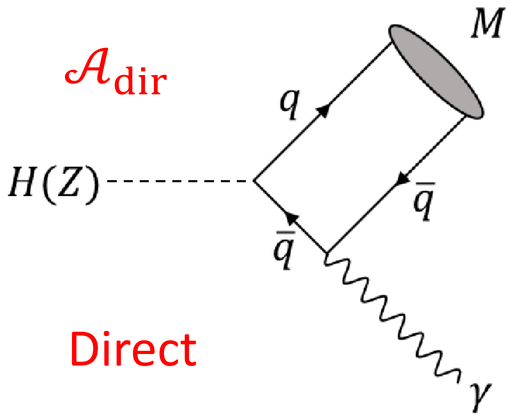


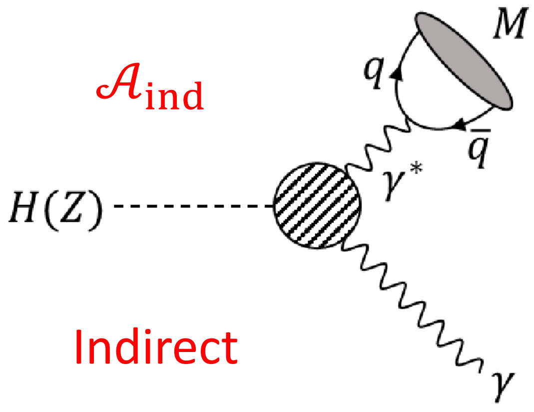


- Performed prospects study for $H(Z) \rightarrow J/\psi\,\gamma$ in 2015
  - Expected to reach $15 \times \mathrm{SM}$ and $4 \times \mathrm{SM}$ sensitivity respectively by HL-LHC (simple assumptions)
  - Room for improvement – but not far off!

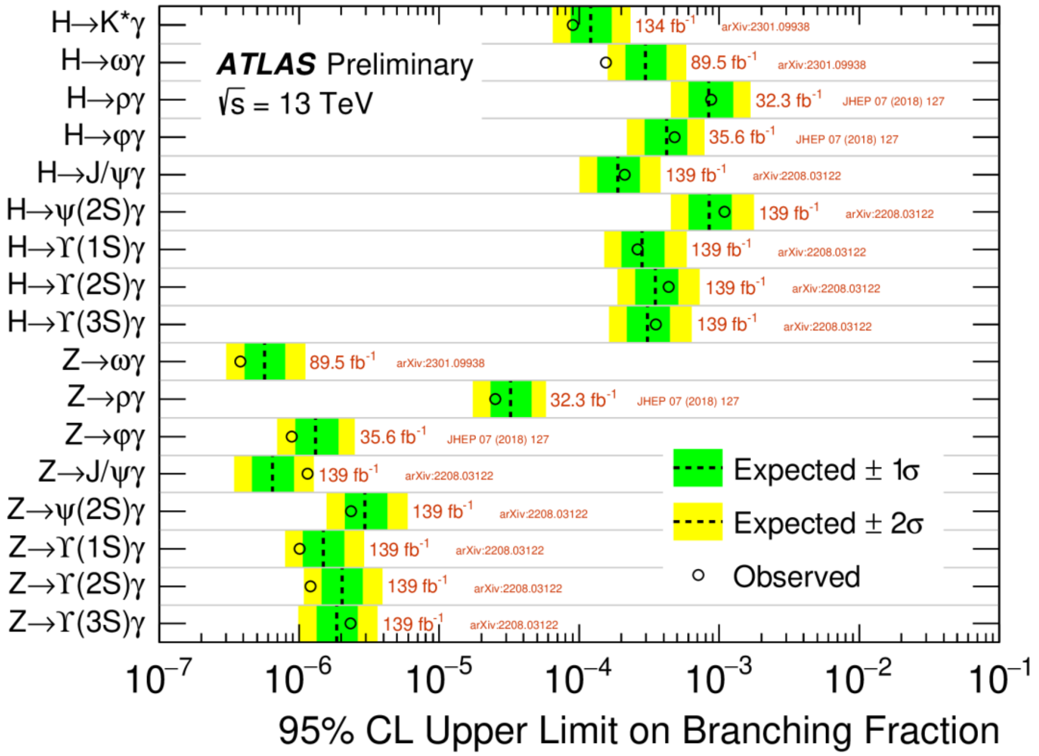
Summary

- **ATLAS Searches for exclusive $H(Z) \to \mathcal{M}\gamma$ decays**
  - H decays: magnitude and sign of quark couplings
  - Z decays: reference channels + tests of QCD factorisation
  - Dedicated triggers capture decays
  - Non-parametric data-driven model for the backgrounds
    - Procedure: JHEP 10 (2022) 001





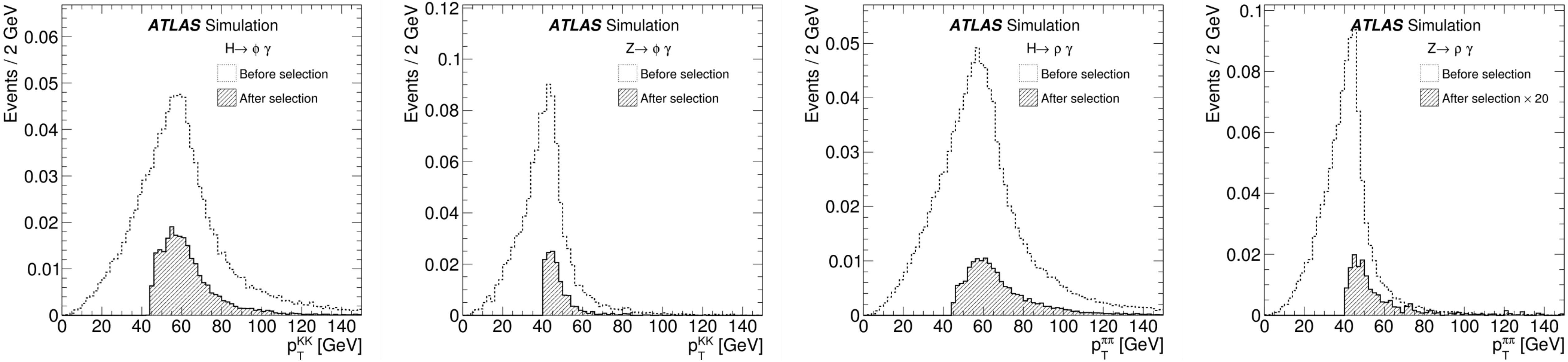
- $H(Z) \to (\phi, \rho)\gamma$: JHEP 07 (2018) 127
  - 2nd iteration of analysis
  - Published in JHEP (2018)
- $H(Z) \to \omega\gamma$ and $H \to K^*\gamma$: arXiv:2301.09938
  - 1st iteration of analysis
  - Submitted to PLB
- $H(Z) \to \mathcal{Q}\gamma$: arXiv:2208.03122
  - 3rd iteration of analysis
  - Accepted by EPJ C
- Summary of results: ATL-PHYS-PUB-2023-004



ADDITIONAL SLIDES

$H(Z) \rightarrow (\phi, \rho)\gamma$: Signal Acceptance

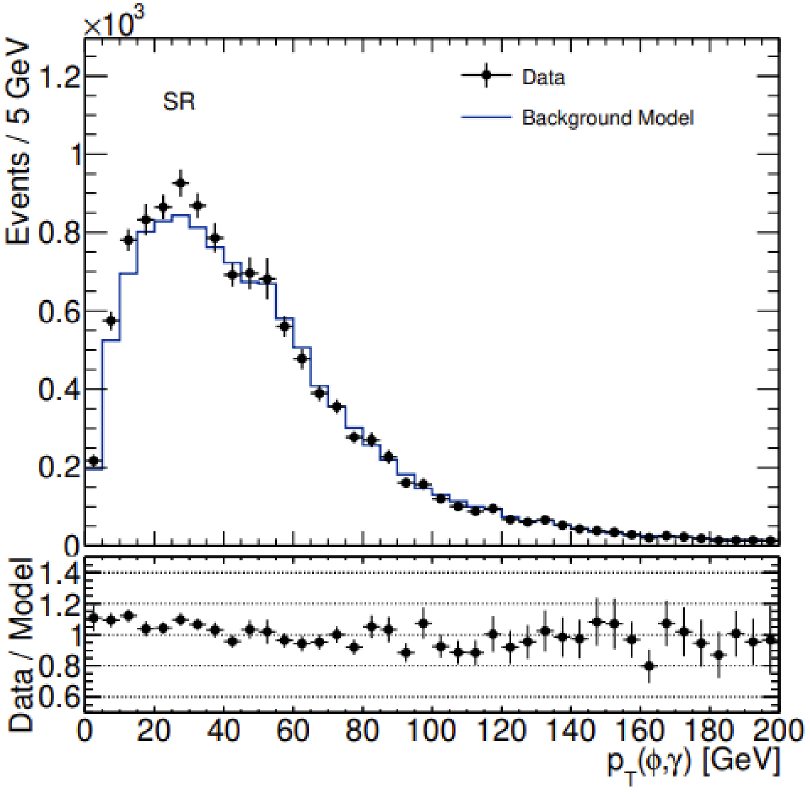
- Meson p_{T} distributions for each signal decay

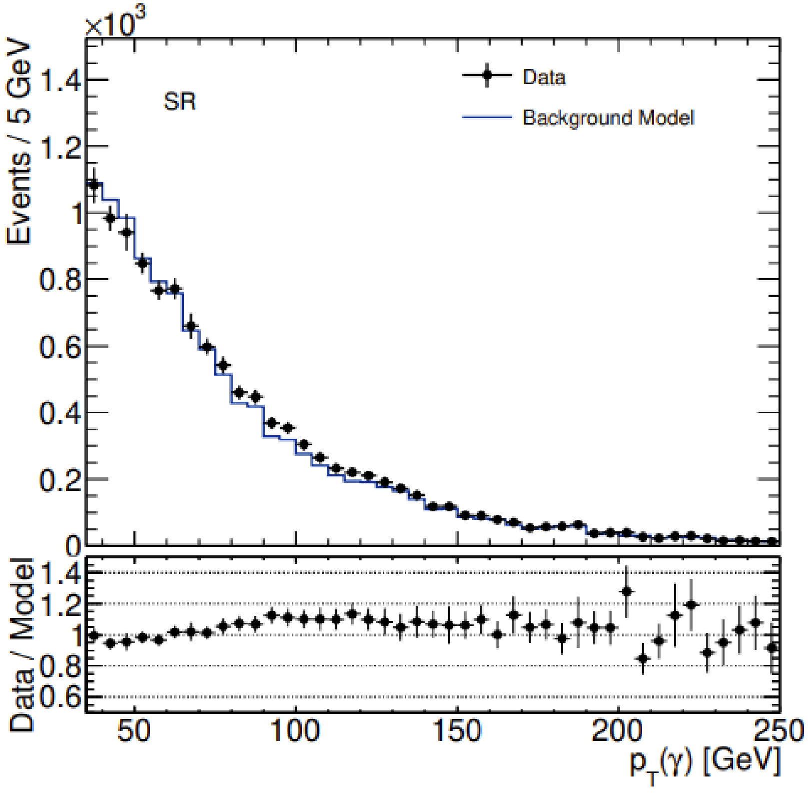


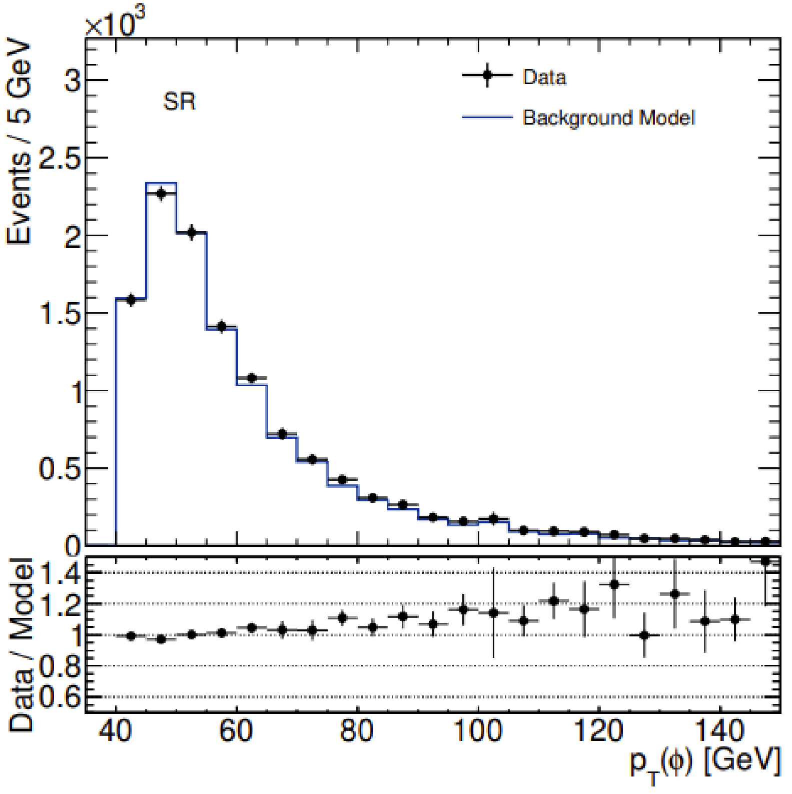
JHEP 07 (2018) 127

Non-Parametric Data Driven Model: Additional Variables 1

- Non-discriminant variables can also be used in model validation
  - Less important as not used in fit – but can help troubleshoot issues



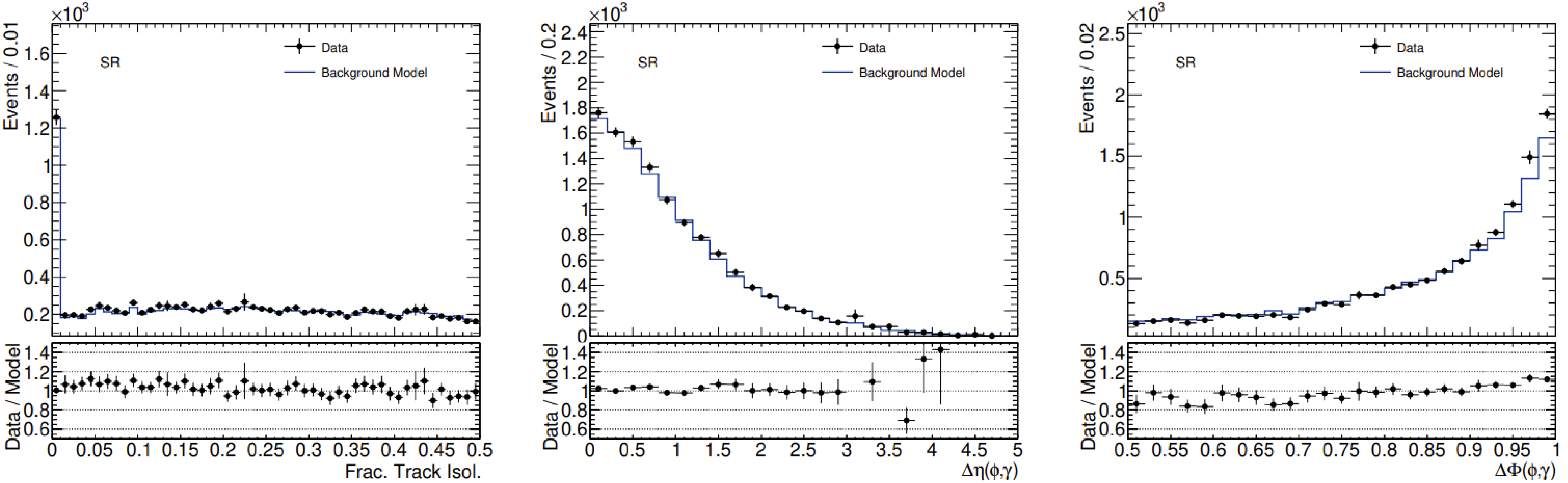




JHEP 10 (2022) 001

Non-Parametric Data Driven Model: Additional Variables 2

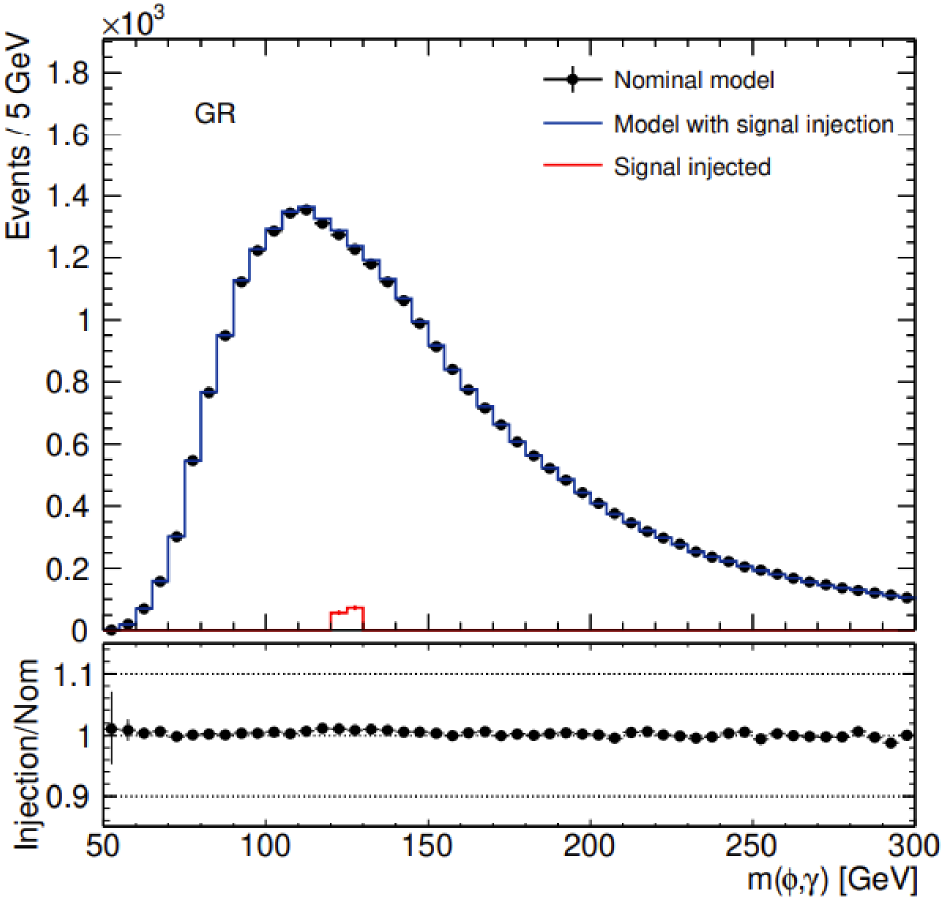
- Non-discriminant variables can also be used in model validation
  - Less important as not used in fit – but can help troubleshoot issues

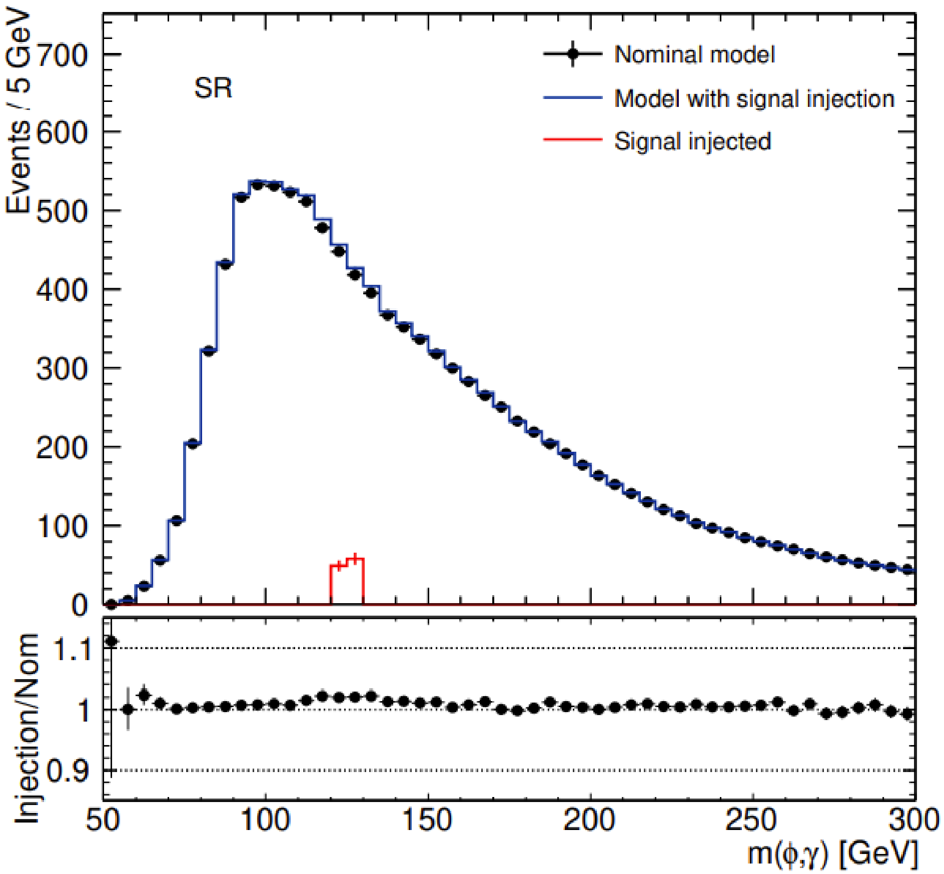


JHEP 10 (2022) 001

Non-Parametric Data Driven Model: Signal Injection

- Model is robust against signal contamination in GR
  - Injected 5.5σ worth of signal in GR to test this – change in model prediction near H signal in SR only $\sim 2\%$

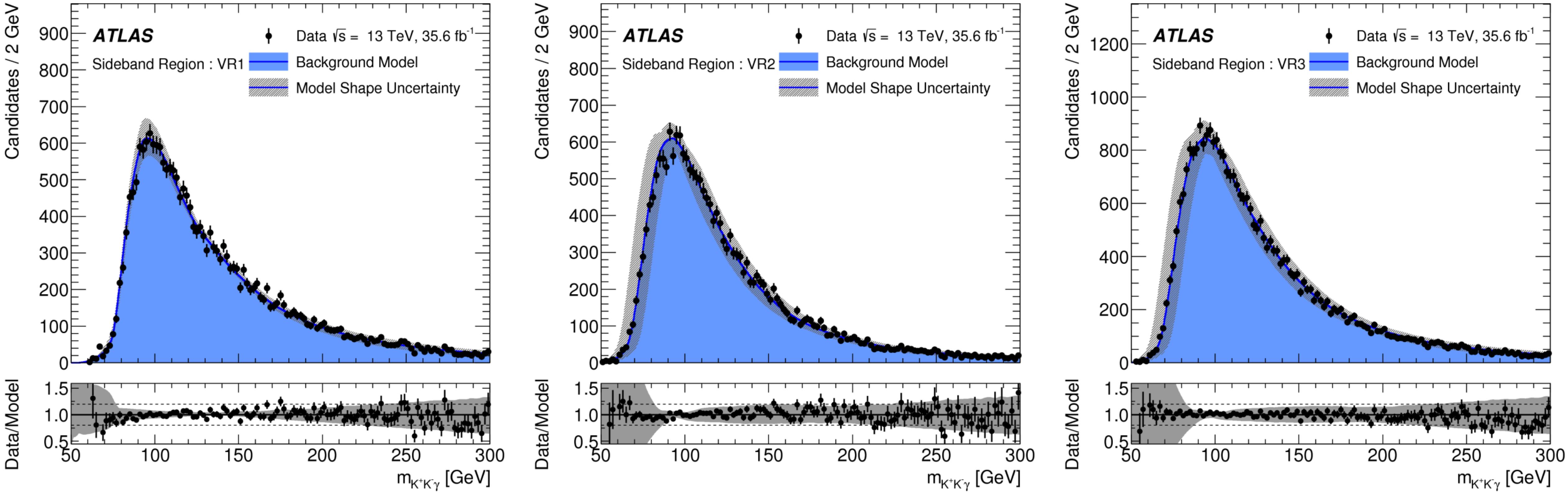




JHEP 10 (2022) 001

$H(Z) \rightarrow (\phi, \rho)\gamma$: Sideband Background Validation

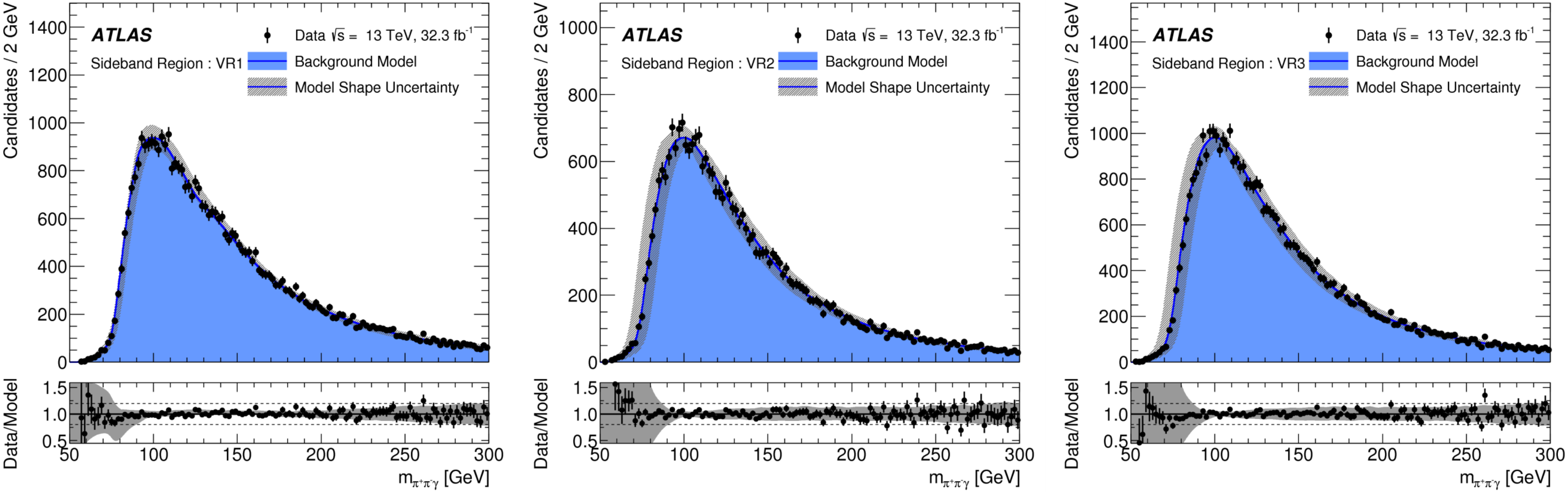
- Validation plots in $\phi\gamma$ sideband regions



JHEP 07 (2018) 127

$H(Z) \rightarrow (\phi, \rho)\gamma$: Sideband Background Validation

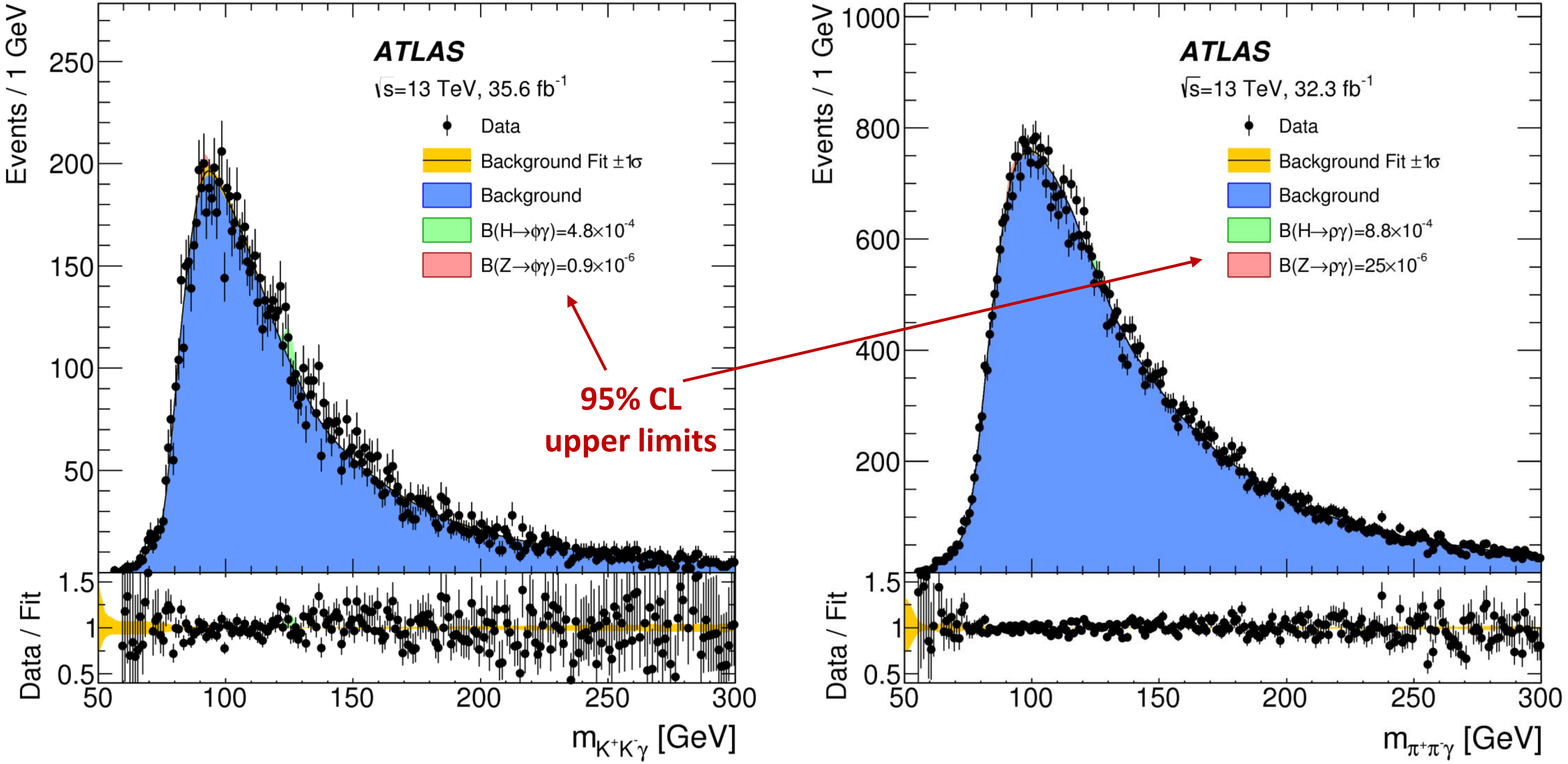
- Validation plots in $\rho\gamma$ sideband regions



JHEP 07 (2018) 127

$H(Z) \rightarrow (\phi, \rho)\gamma$: Results (Full Mass Range)

- Unbinned likelihood fit in $m(K^+K^-\gamma)$ and $m(\pi^+\pi^-\gamma)$



95% CL upper limits

JHEP 07 (2018) 127

$H(Z) \rightarrow (\phi, \rho)\gamma$: Limits and Observed Events

- Unbinned likelihood fit in $m(K^+K^-\gamma)$ and $m(\pi^+\pi^-\gamma)$

	Observed yields (Mean expected background)					Expected signal yields	
	Mass range [GeV]					H	Z
	All	81–101		120–130		$[\mathcal{B} = 10^{-4}]$	$[\mathcal{B} = 10^{-6}]$
$\phi\gamma$	12051	3364	(3500 ± 30)	1076	(1038 ± 9)	15.6 ± 1.5	83 ± 7
$\rho\gamma$	58702	12583	(12660 ± 60)	5473	(5450 ± 30)	17.0 ± 1.7	7.5 ± 0.6

Observed and Expected Events

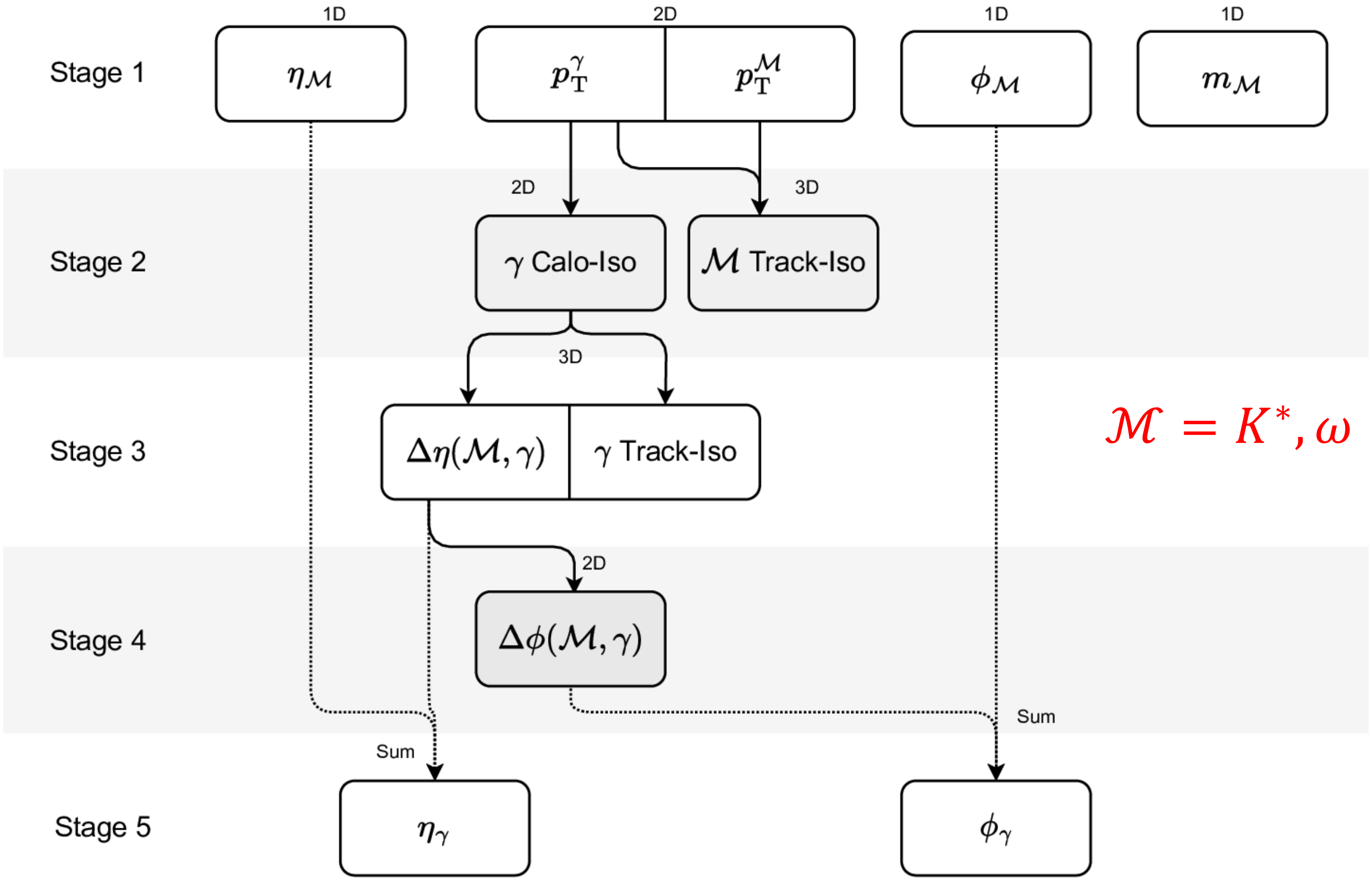
Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \rightarrow \phi\gamma)\,[\,10^{-4}\,]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \rightarrow \phi\gamma)\,[\,10^{-6}\,]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \rightarrow \rho\gamma)\,[\,10^{-4}\,]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \rightarrow \rho\gamma)\,[\,10^{-6}\,]$	33^{+13}_{-9}	25

Observed and Expected Limits

JHEP 07 (2018) 127

$H \to K^*\gamma$ and $H(Z) \to \omega\gamma$: Ancestral Sampling Scheme

- Important correlations differ compared to $H(Z) \to (\phi, \rho)\gamma$ searches: adapt sampling scheme

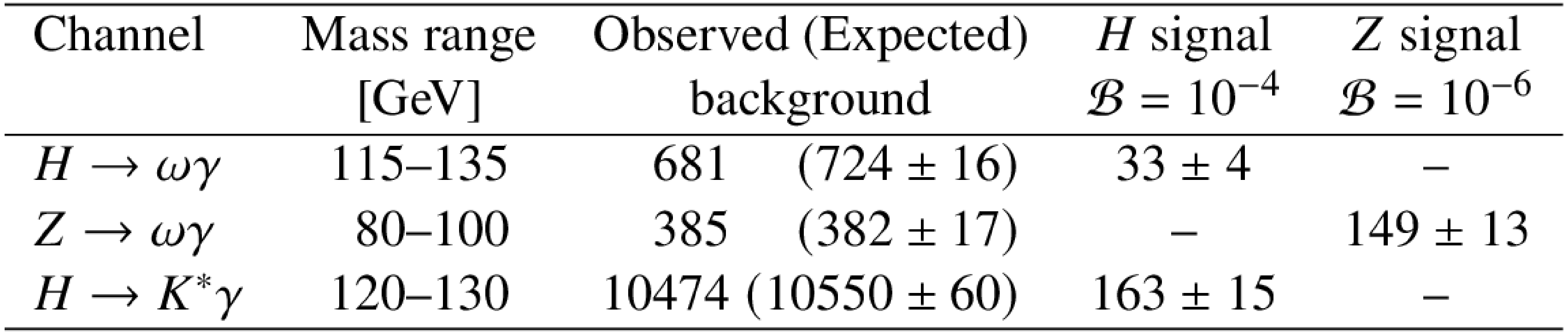


$\mathcal{M} = K^*, \omega$

arXiv:2301.09938

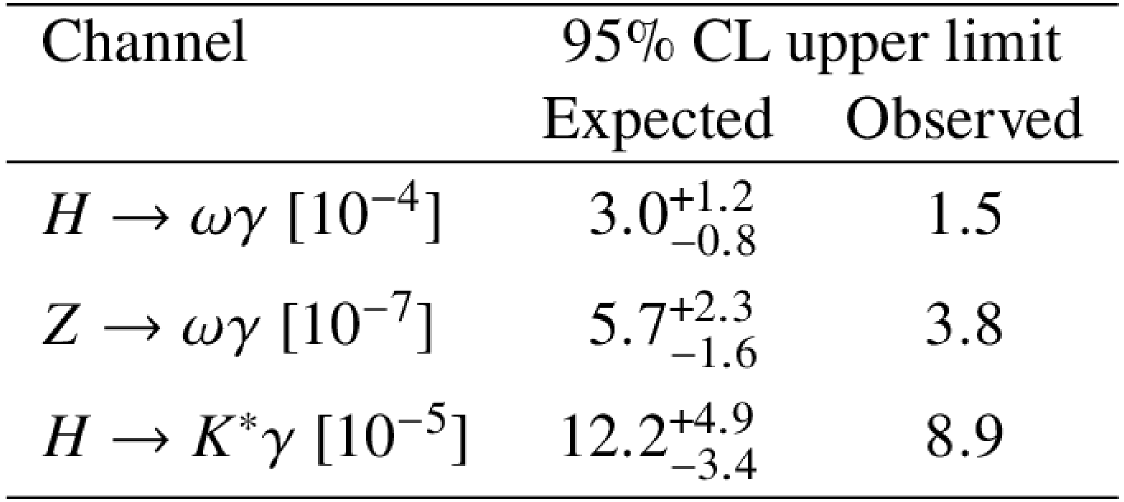
$H \rightarrow K^{*}\gamma$ and $H(Z) \rightarrow \omega\gamma$: Limits and Observed Events

- Unbinned likelihood fit in $m(K^{\pm}\pi^{\mp}\gamma)$ and $m(\pi^{+}\pi^{-}\pi^{0}\gamma)$



Channel	Mass range [GeV]	Observed (Expected) background	H signal $\mathcal{B} = 10^{-4}$	Z signal $\mathcal{B} = 10^{-6}$
$H \rightarrow \omega\gamma$	115–135	681 (724 ± 16)	33 ± 4	–
$Z \rightarrow \omega\gamma$	80–100	385 (382 ± 17)	–	149 ± 13
$H \rightarrow K^{*}\gamma$	120–130	10474 (10550 ± 60)	163 ± 15	–

Observed and Expected Events



Channel	95% CL upper limit	
	Expected	Observed
$H \rightarrow \omega\gamma\ [10^{-4}]$	$3.0^{+1.2}_{-0.8}$	1.5
$Z \rightarrow \omega\gamma\ [10^{-7}]$	$5.7^{+2.3}_{-1.6}$	3.8
$H \rightarrow K^{*}\gamma\ [10^{-5}]$	$12.2^{+4.9}_{-3.4}$	8.9

Observed and Expected Limits

arXiv:2301.09938

$H(Z) \rightarrow Q\gamma$: Selection

- Selection defined largely by trigger thresholds, geometry constraints, and recommended working points
  - Variable $p_{\mathrm{T}}^{\mu^+\mu^-}$ threshold optimised based on $S/\sqrt{B}$ near H and Z signal peaks

Photon Selection:

- $p_{\mathrm{T}}^{\gamma} > 35$ GeV
- $|\eta^{\gamma}| < 2.37$ and outside transition region $1.37 < |\eta^{\gamma}| < 1.52$
- Tight quality
- $\Delta\phi(Q,\gamma) > \pi/2$
- Photon isolation

Meson Selection:

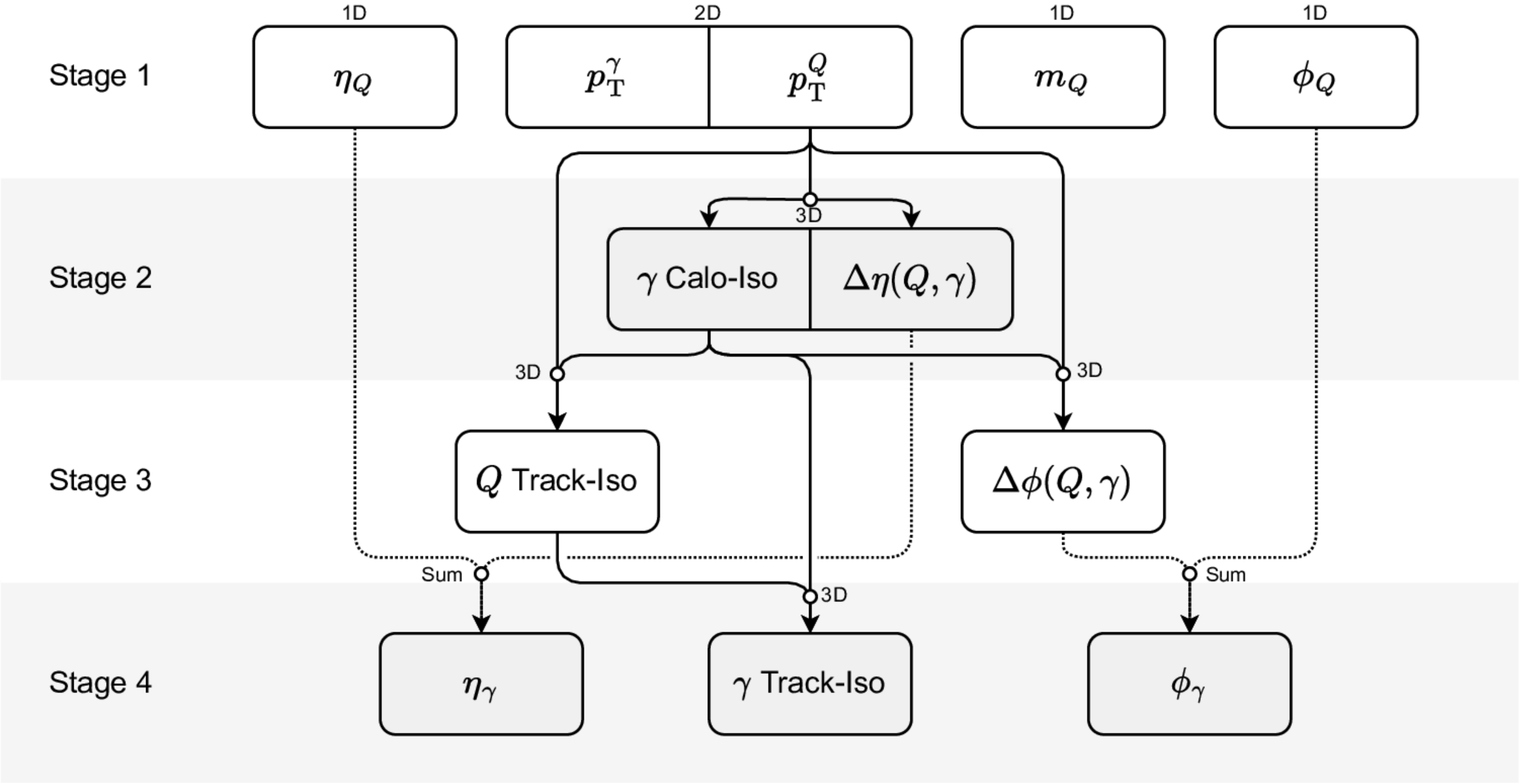
- $p_{\mathrm{T}}^{\mathrm{lead}} > 18$ GeV; $p_{\mathrm{T}}^{\mathrm{sublead}} > 3$ GeV
- $|\eta^{\mu}| < 2.5$
- Oppositely charged muons
- Medium quality
- $m(\mu^+\mu^-)$ near meson mass
- Transverse decay length significance $|L_{xy}/\sigma_{L_{xy}}| < 3$
- $p_{\mathrm{T}}(\mu^+\mu^-)$ cut varies with $m(\mu^+\mu^-\gamma)$
- Muon isolation

Red: Not applied in GR

arXiv:2208.03122

$H(Z) \to Q\gamma$: Ancestral Sampling Scheme

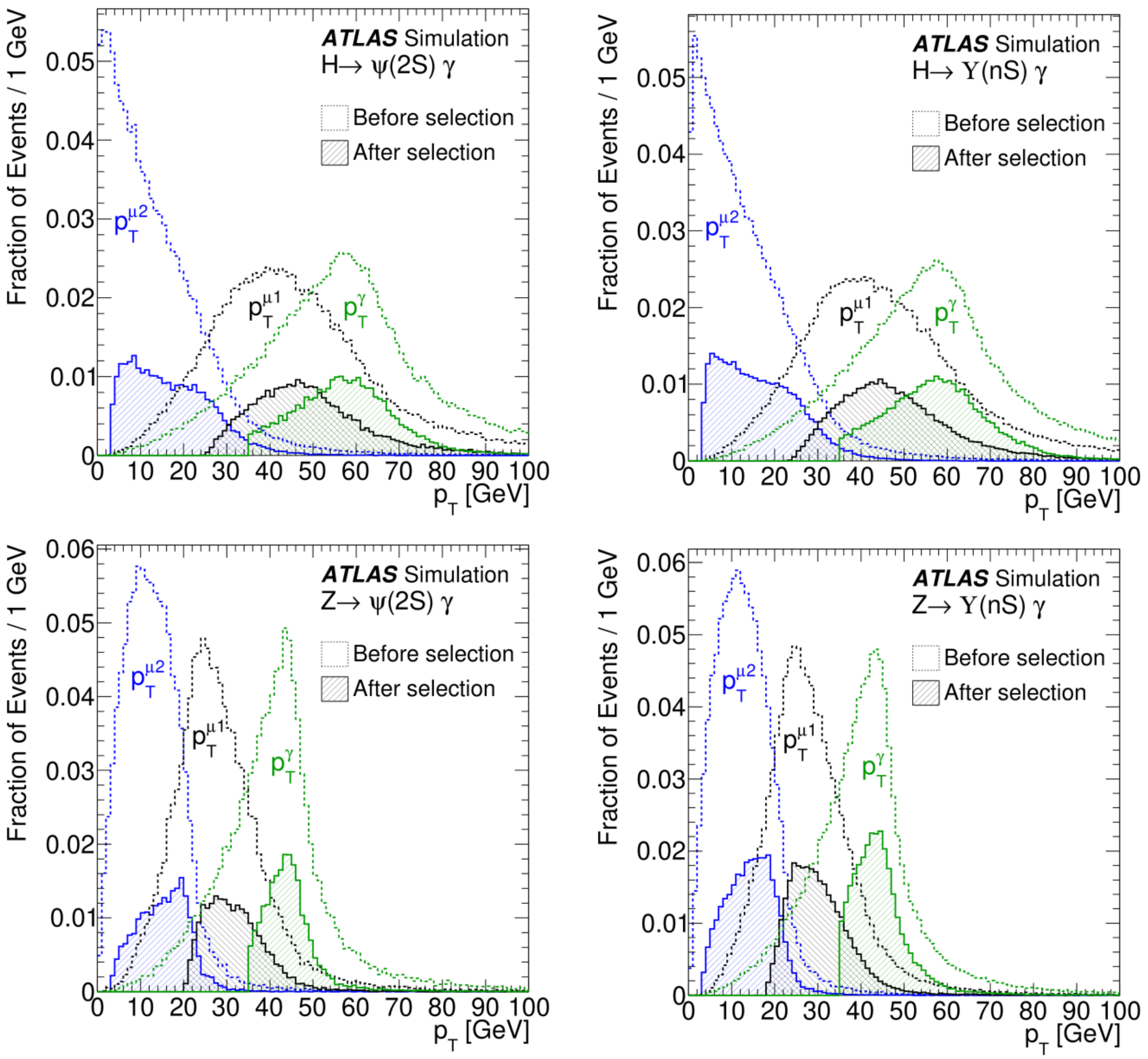
- Subtract exclusive background events from data in GR before generating inclusive model



arXiv:2208.03122

$H(Z) \rightarrow Q\gamma$: Signal Efficiency

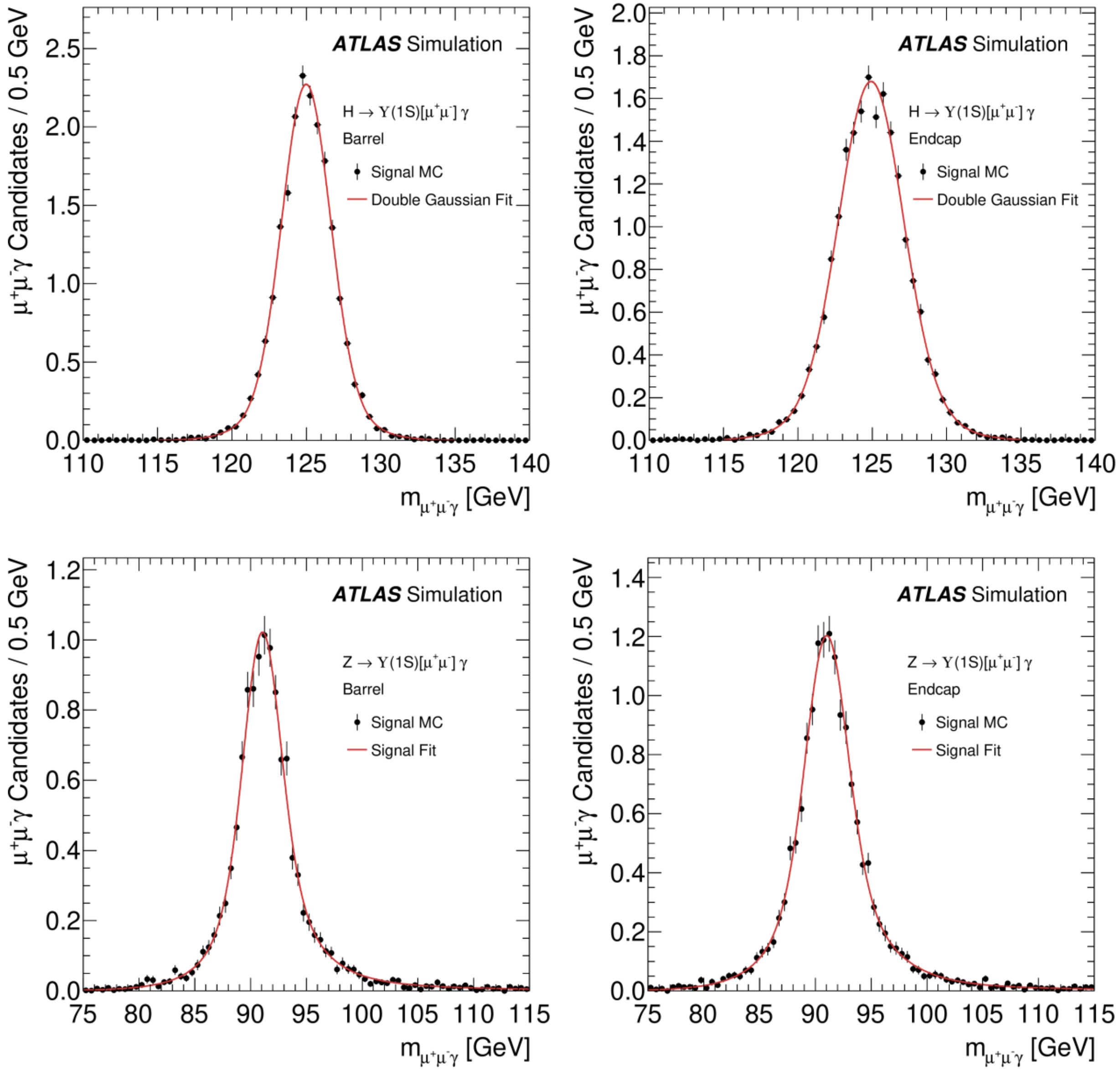
- Generator p_{T} plots for $\psi(2S)\gamma$ and $\Upsilon(nS)\gamma$ channels



arXiv:2208.03122

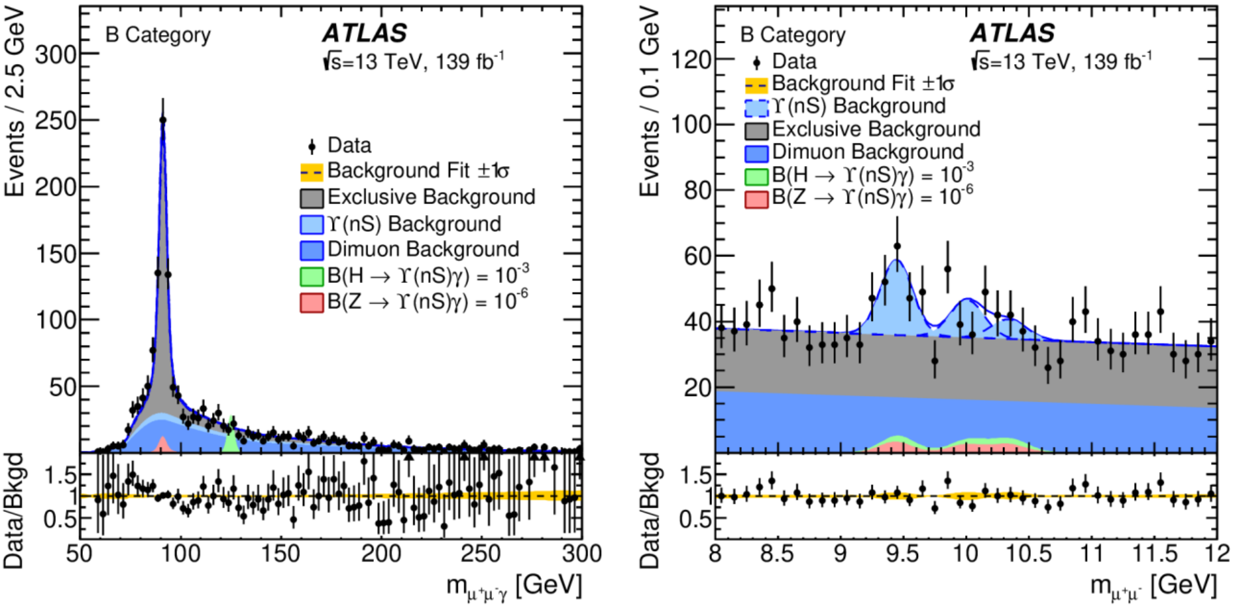
$H(Z) \rightarrow Q\gamma$: Signal Modelling and Resolution

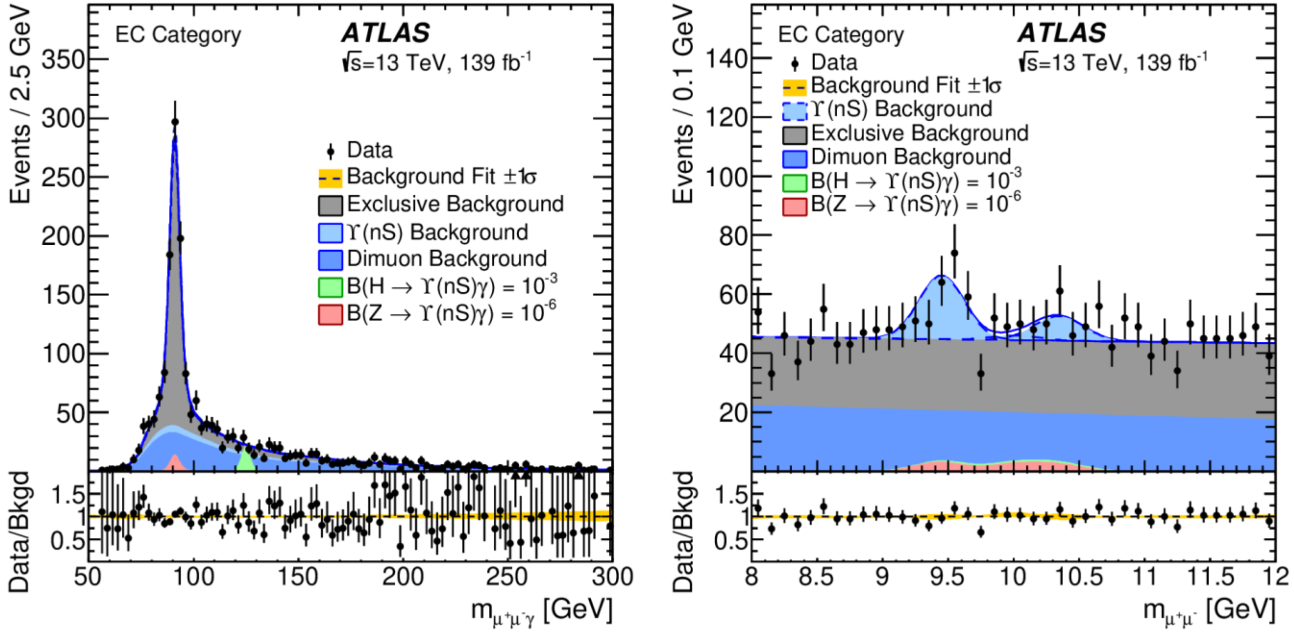
- Signal resolution plots for $\Upsilon(1S)\gamma$ channels in B and EC categories



arXiv:2208.03122

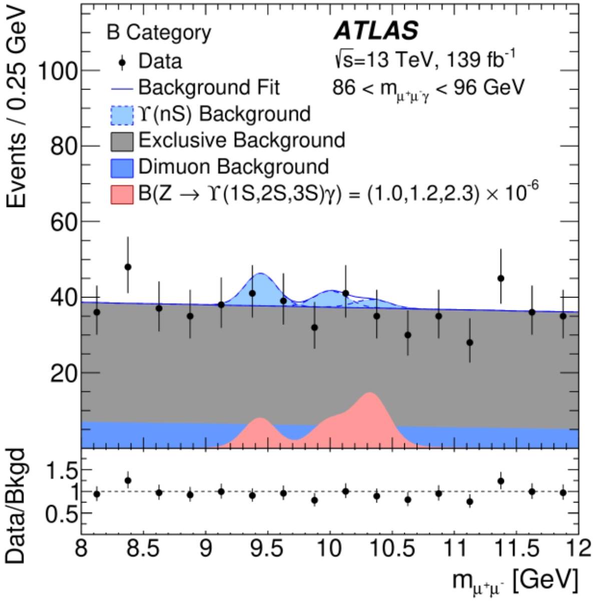
$H(Z) \to \Upsilon(nS)\gamma$: Fit in Separate B and EC Categories

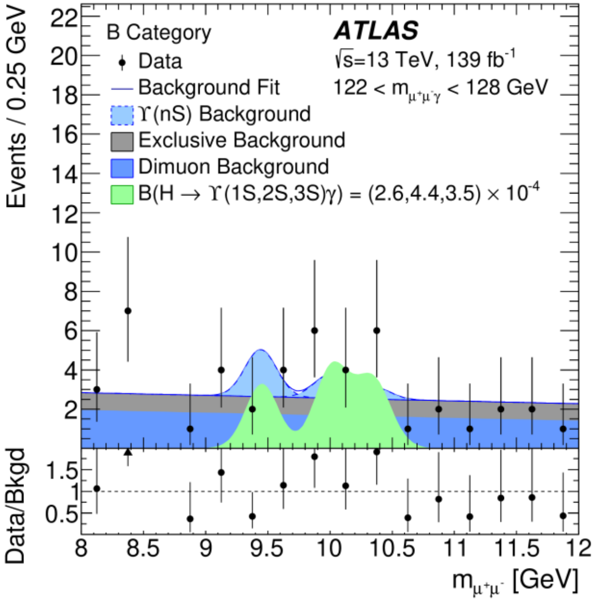


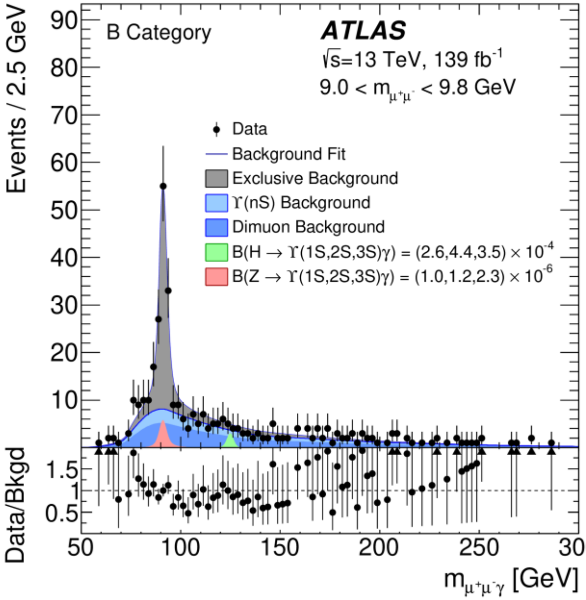


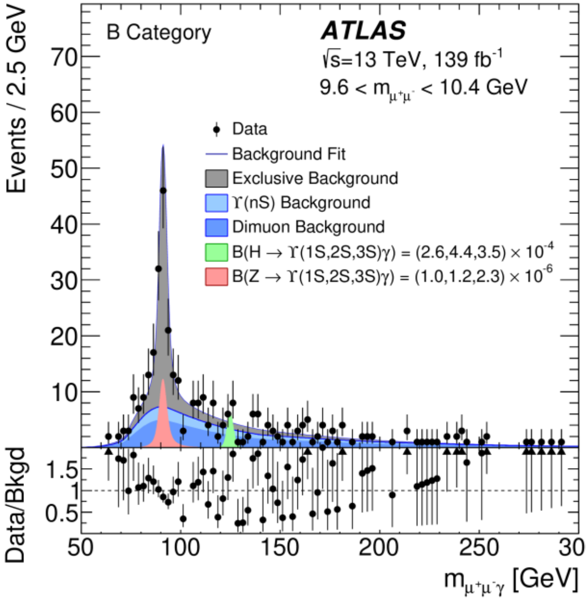
arXiv:2208.03122

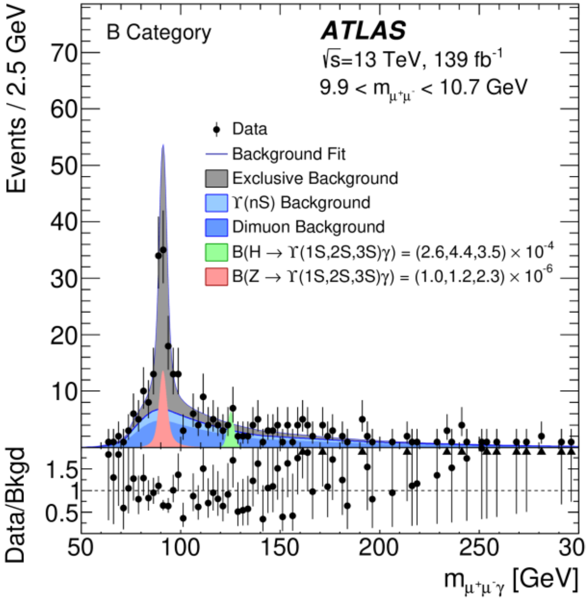
$H(Z) \rightarrow \Upsilon(nS)\gamma$: Barrel Category Projections





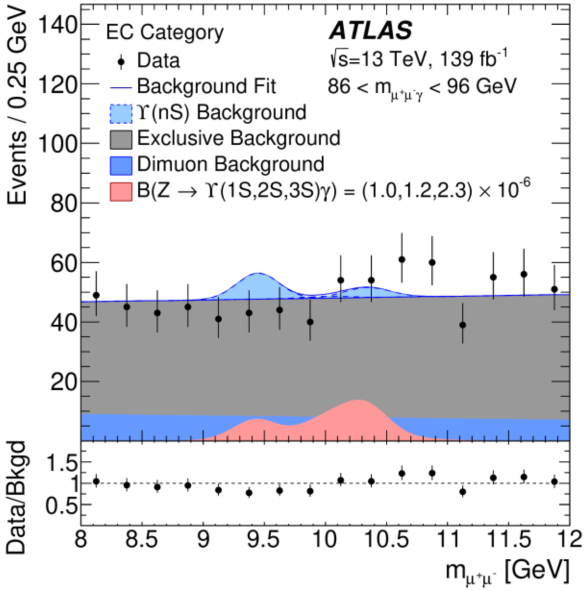


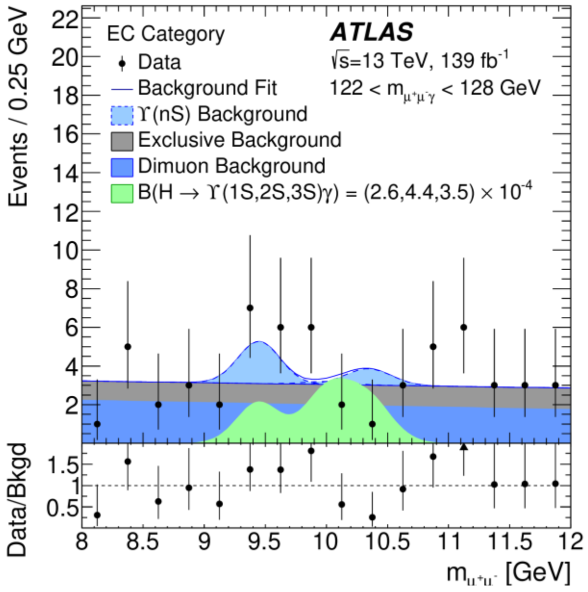


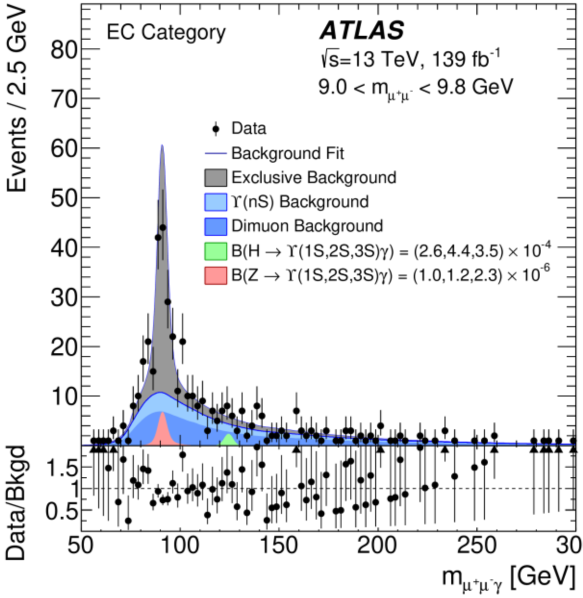


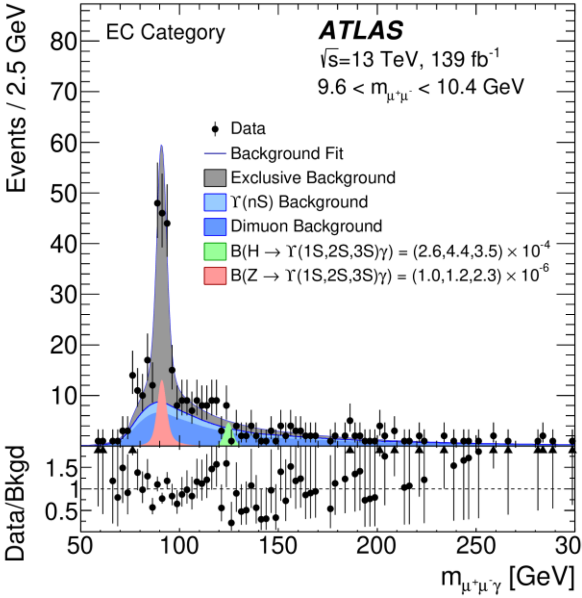
arXiv:2208.03122

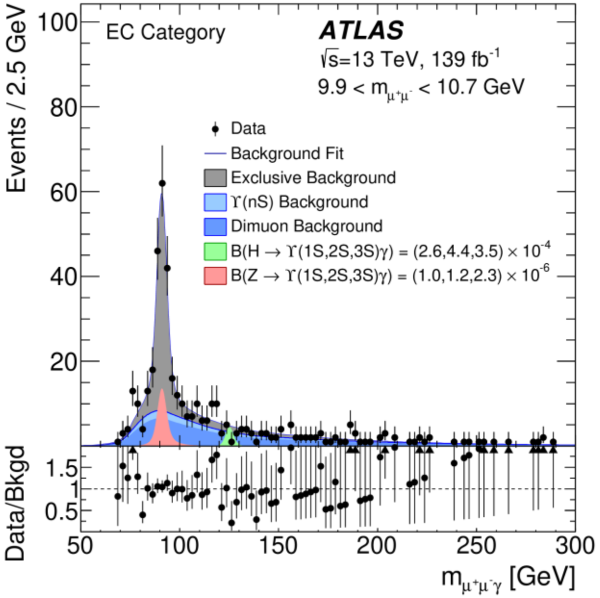
$H(Z) \rightarrow \Upsilon(nS)\gamma$: Endcap Category Projections





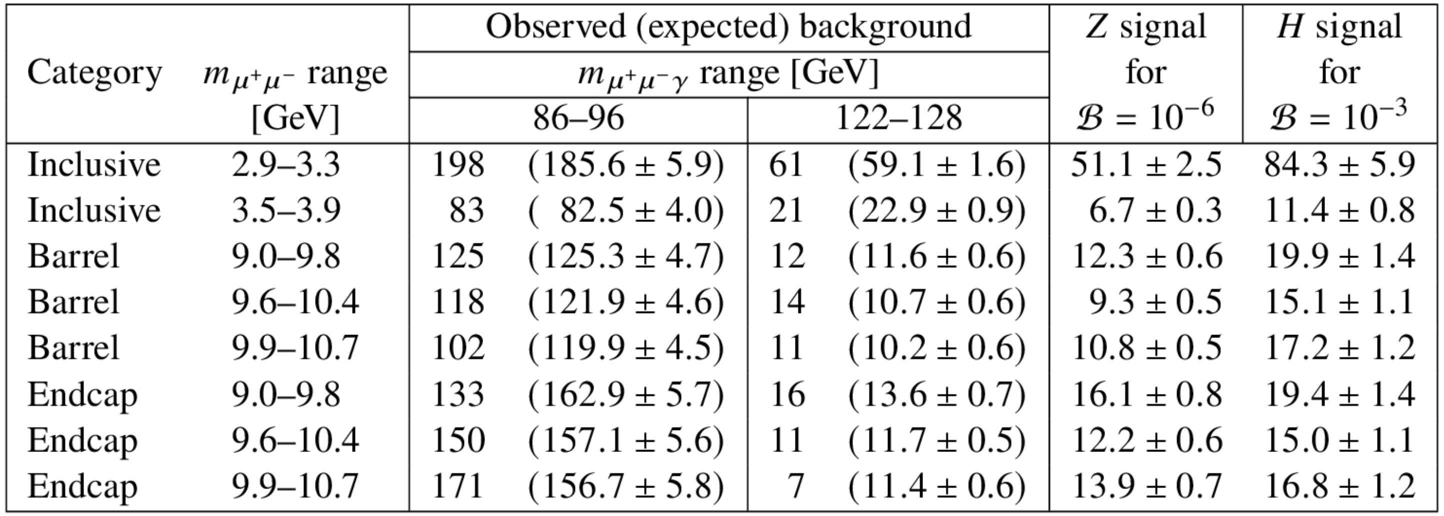






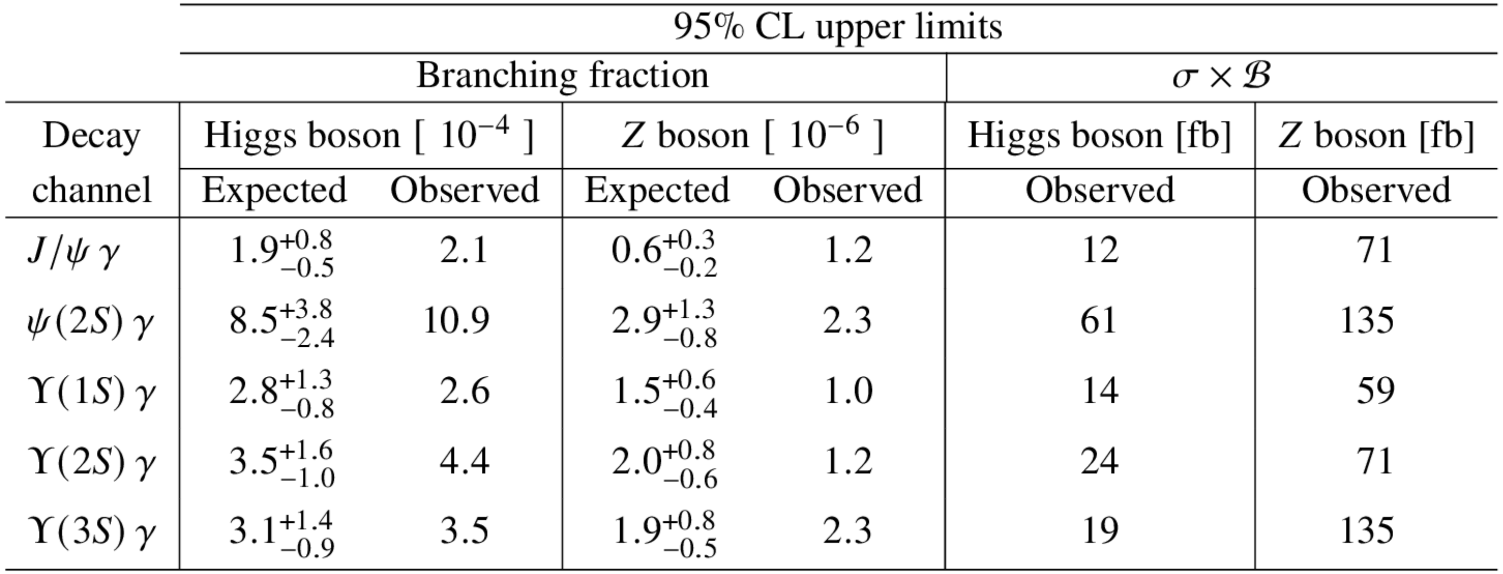
arXiv:2208.03122

$H(Z) \to Q\gamma$: Limits and Observed Events



Category	$m_{\mu^+\mu^-}$ range [GeV]	Observed (expected) background $m_{\mu^+\mu^-\gamma}$ range [GeV] 86–96		122–128		Z signal for $\mathcal{B} = 10^{-6}$	H signal for $\mathcal{B} = 10^{-3}$
Inclusive	2.9–3.3	198	(185.6 ± 5.9)	61	(59.1 ± 1.6)	51.1 ± 2.5	84.3 ± 5.9
Inclusive	3.5–3.9	83	(82.5 ± 4.0)	21	(22.9 ± 0.9)	6.7 ± 0.3	11.4 ± 0.8
Barrel	9.0–9.8	125	(125.3 ± 4.7)	12	(11.6 ± 0.6)	12.3 ± 0.6	19.9 ± 1.4
Barrel	9.6–10.4	118	(121.9 ± 4.6)	14	(10.7 ± 0.6)	9.3 ± 0.5	15.1 ± 1.1
Barrel	9.9–10.7	102	(119.9 ± 4.5)	11	(10.2 ± 0.6)	10.8 ± 0.5	17.2 ± 1.2
Endcap	9.0–9.8	133	(162.9 ± 5.7)	16	(13.6 ± 0.7)	16.1 ± 0.8	19.4 ± 1.4
Endcap	9.6–10.4	150	(157.1 ± 5.6)	11	(11.7 ± 0.5)	12.2 ± 0.6	15.0 ± 1.1
Endcap	9.9–10.7	171	(156.7 ± 5.8)	7	(11.4 ± 0.6)	13.9 ± 0.7	16.8 ± 1.2

Observed and Expected Events



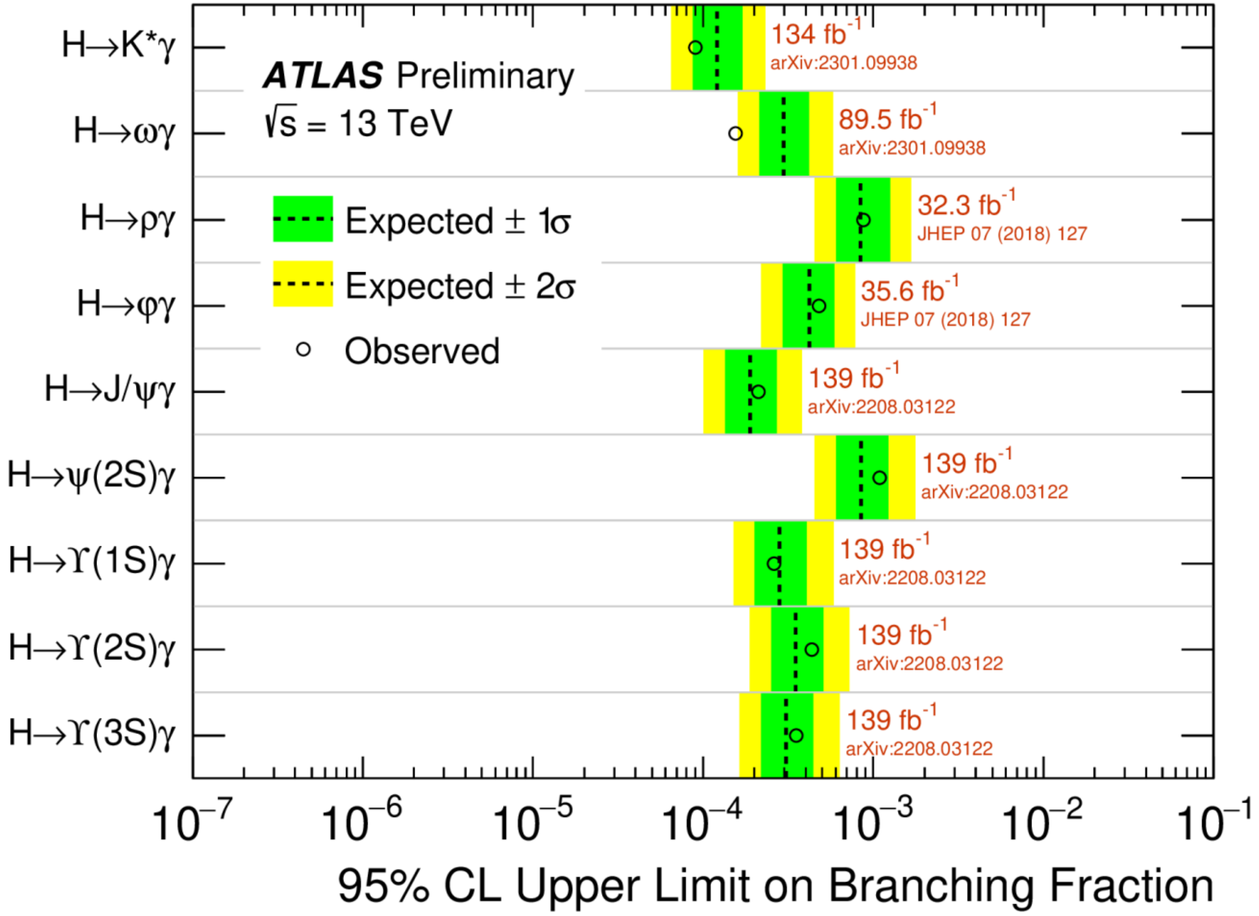
	95% CL upper limits					
	Branching fraction				$\sigma \times \mathcal{B}$	
Decay channel	Higgs boson [10^{-4}] Expected	Observed	Z boson [10^{-6}] Expected	Observed	Higgs boson [fb] Observed	Z boson [fb] Observed
$J/\psi\,\gamma$	$1.9^{+0.8}_{-0.5}$	2.1	$0.6^{+0.3}_{-0.2}$	1.2	12	71
$\psi(2S)\,\gamma$	$8.5^{+3.8}_{-2.4}$	10.9	$2.9^{+1.3}_{-0.8}$	2.3	61	135
$\Upsilon(1S)\,\gamma$	$2.8^{+1.3}_{-0.8}$	2.6	$1.5^{+0.6}_{-0.4}$	1.0	14	59
$\Upsilon(2S)\,\gamma$	$3.5^{+1.6}_{-1.0}$	4.4	$2.0^{+0.8}_{-0.6}$	1.2	24	71
$\Upsilon(3S)\,\gamma$	$3.1^{+1.4}_{-0.9}$	3.5	$1.9^{+0.8}_{-0.5}$	2.3	19	135

Observed and Expected Limits

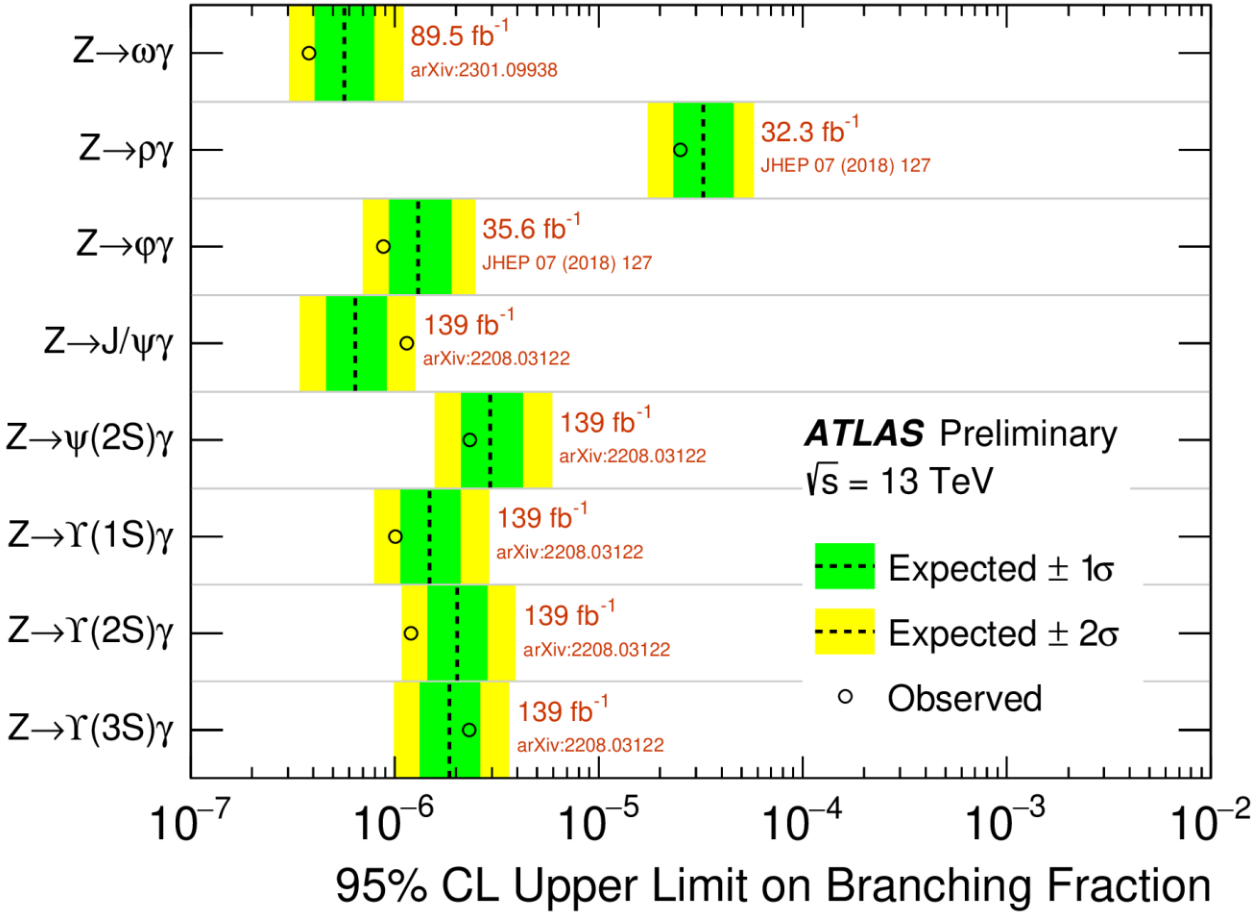
arXiv:2208.03122

Summary of Exclusive $H(Z) \to M\gamma$ Search Results 1

ATL-PHYS-PUB-2023-004



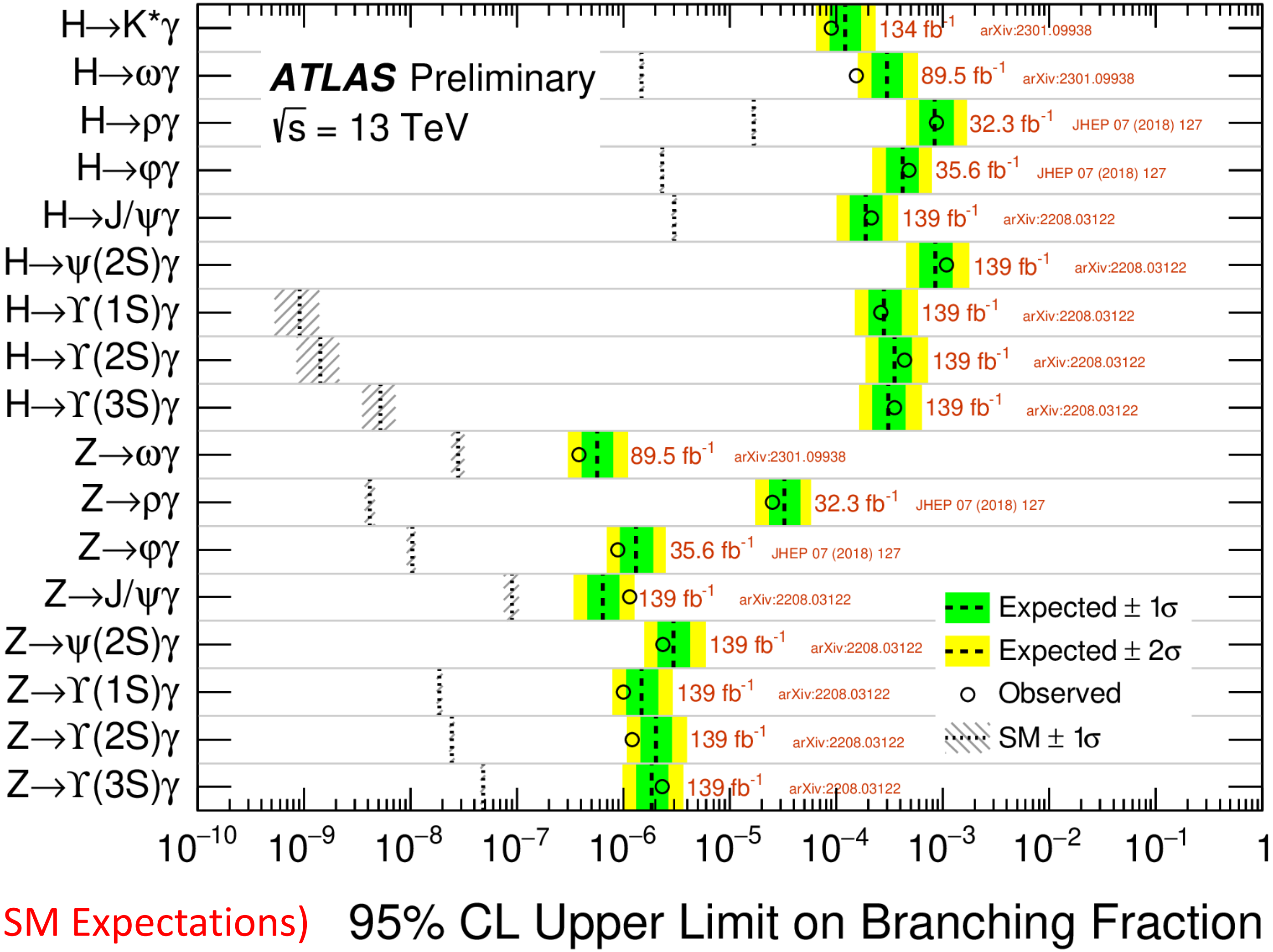
Higgs Boson Decays



Z Boson Decays

- ATLAS has the most stringent limits on each of these decay channels

Summary of Exclusive $H(Z) \rightarrow M\gamma$ Search Results



All Decays (with SM Expectations)

- ATLAS has the most stringent limits on each of these decay channels

ATL-PHYS-PUB-2023-004