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

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Elementary Particle Physics Seminar

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

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

Time ↓

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

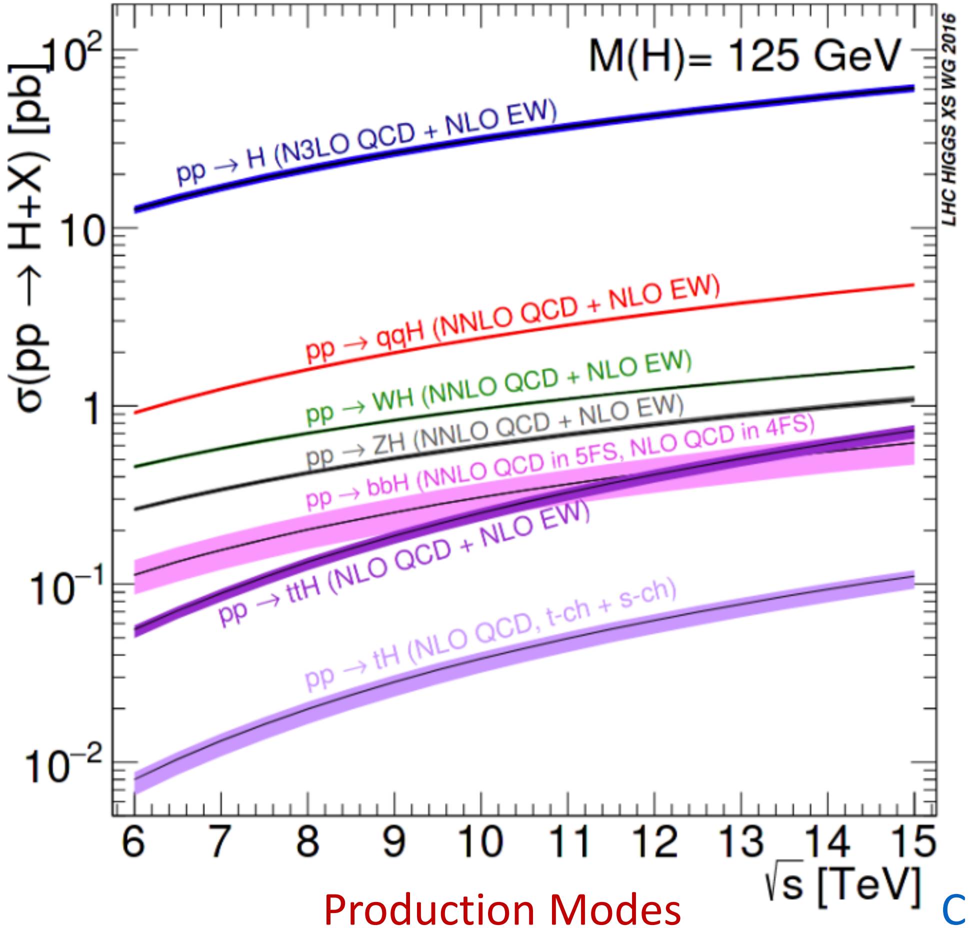
The Higgs Boson

- Higgs field gives mass to particles via the Higgs mechanism
  - Higgs boson coupling strength to fermions ∝ mass in the SM
    - Provides concrete predictions for fermion interactions
    - Only evidence for Higgs-quark couplings to-date is for the t- and b-quarks

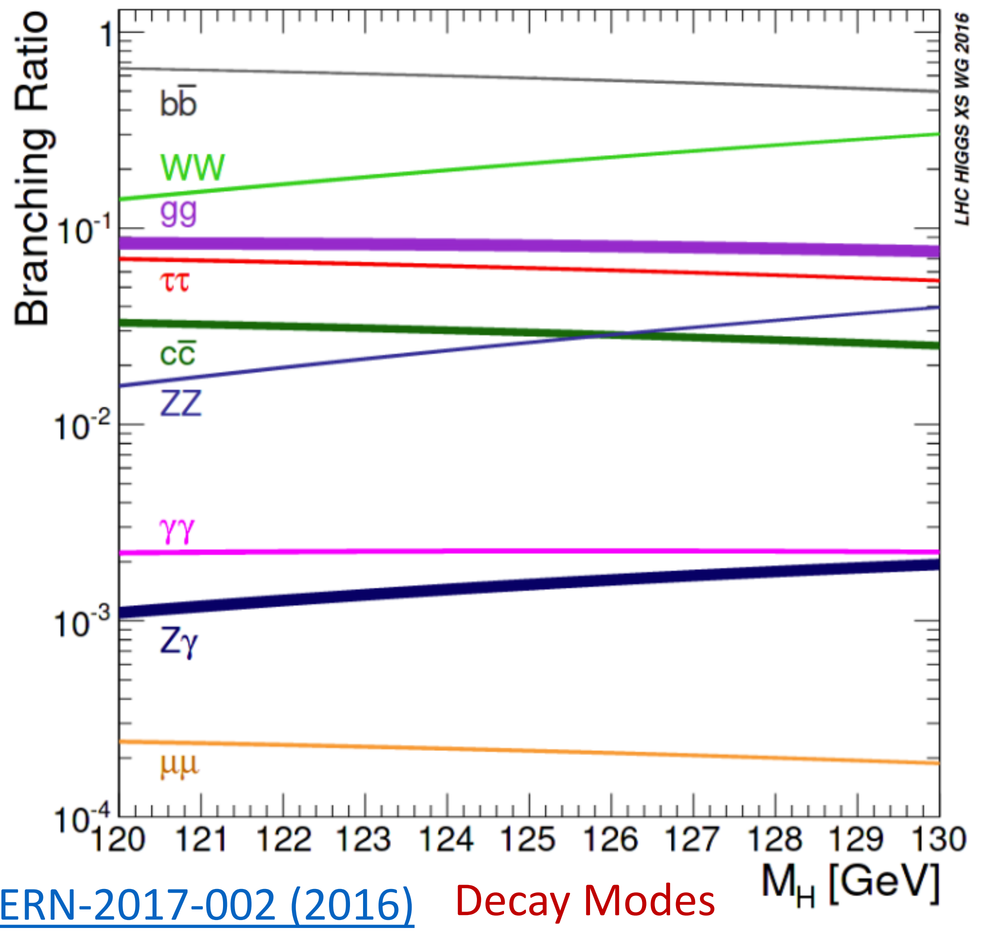
$v \approx 246$ GeV

Fermion couplings

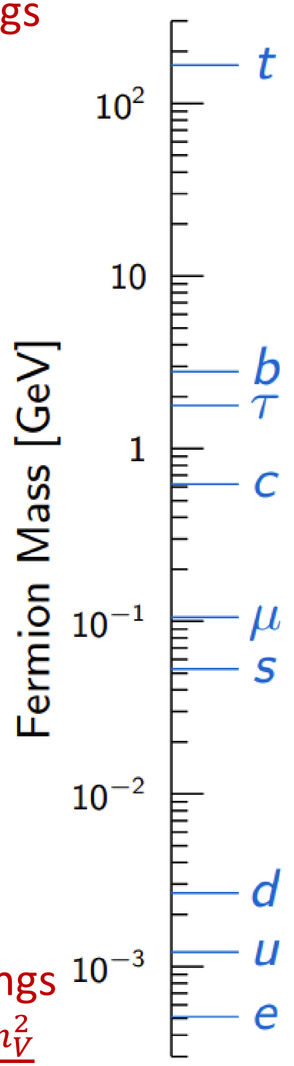
$$g_f^{SM} = \frac{m_f}{v}\sqrt{2}$$



Production Modes



[CERN-2017-002 (2016)](#) Decay Modes



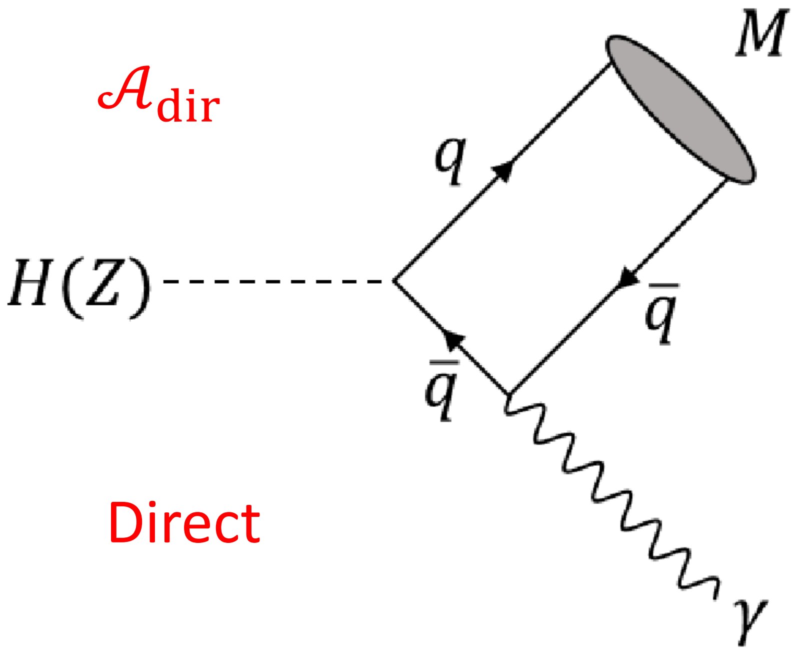
W/Z couplings

$$g_V^{SM} = \frac{2m_V^2}{v}$$

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

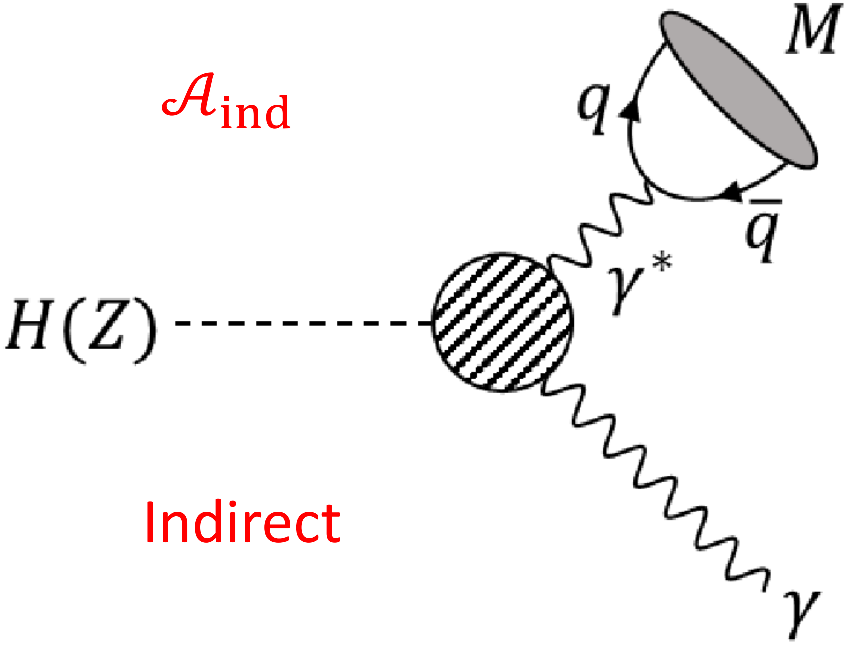
- Search for exclusive $H(Z) \to \mathcal{M}\gamma$ decays: $\mathcal{M}$ = vector mesons ($q\bar{q}$)
  - Two destructively interfering contributions to decay amplitude
  - Distinct signatures avoid large QCD backgrounds

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



Direct

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



Indirect

- ***H* decays:** probe magnitude and sign of quark Yukawa couplings
- ***Z* decays:** provide reference channels and tests of QCD factorisation
  - $1000 \times$ higher production rate of Z bosons at LHC compared to Higgs bosons: probe rarer decays

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

	SM expected branching fraction $\mathcal{B}(H/Z \rightarrow \mathcal{M}\gamma)$			
	Meson $\mathcal{M}$	H	Z	References
Heavy mesons (quarkonia) $q = b, c$	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]
Light mesons $q = s, d, u$	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]

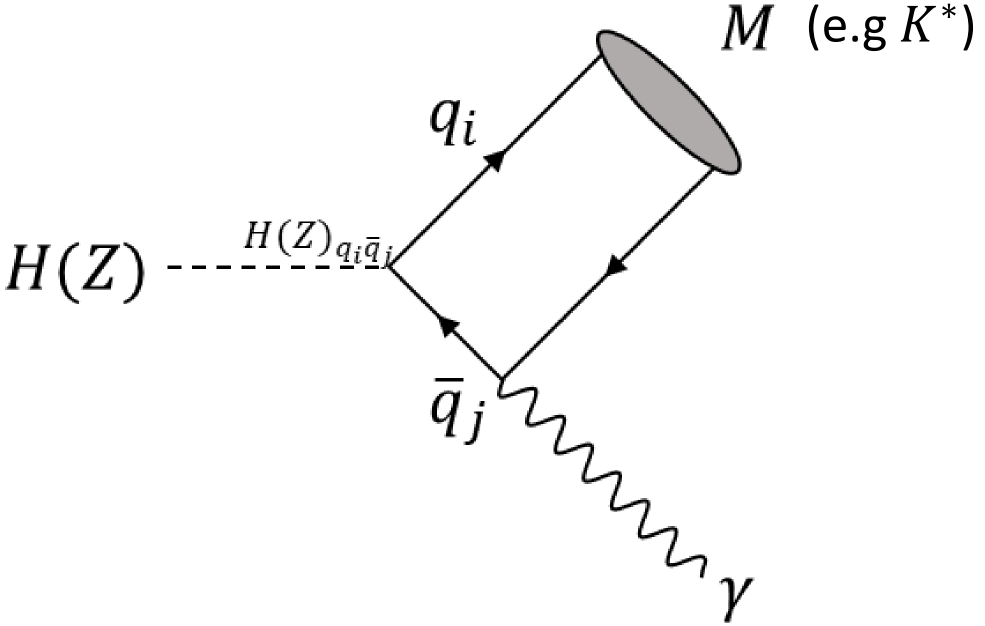
Theory Refs: 25: JHEP 08 (2015) 012, 27: Phys. Rev. D 95 (2017) 054018,
28: Phys. Rev. D 96 (2017) 116014, 29: Phys. Rev. D 97 (2018) 016009, 30: JHEP 04 (2015) 101

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

ATL-PHYS-PUB-2023-004

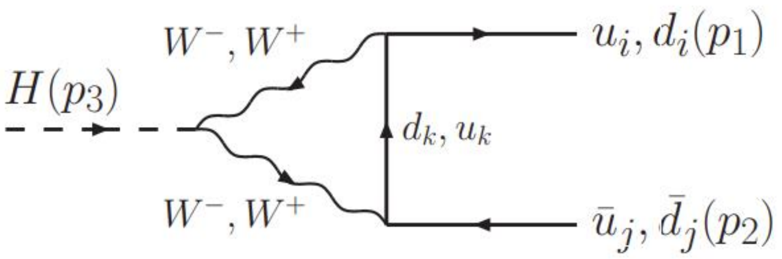
Flavour-Violating Radiative Decays of the Higgs and Z Bosons

- 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}

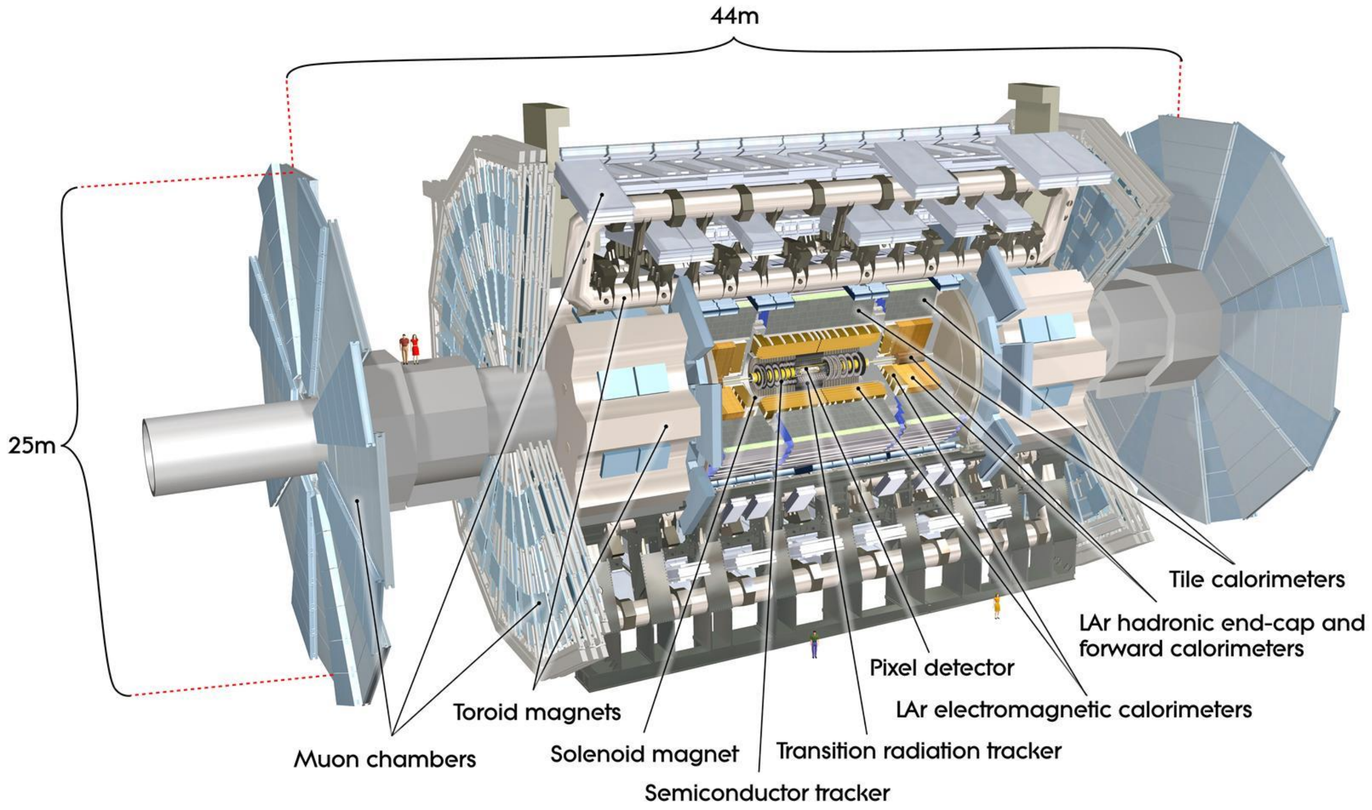
One-loop SM contributions to $H \to q_i\bar{q}_j$

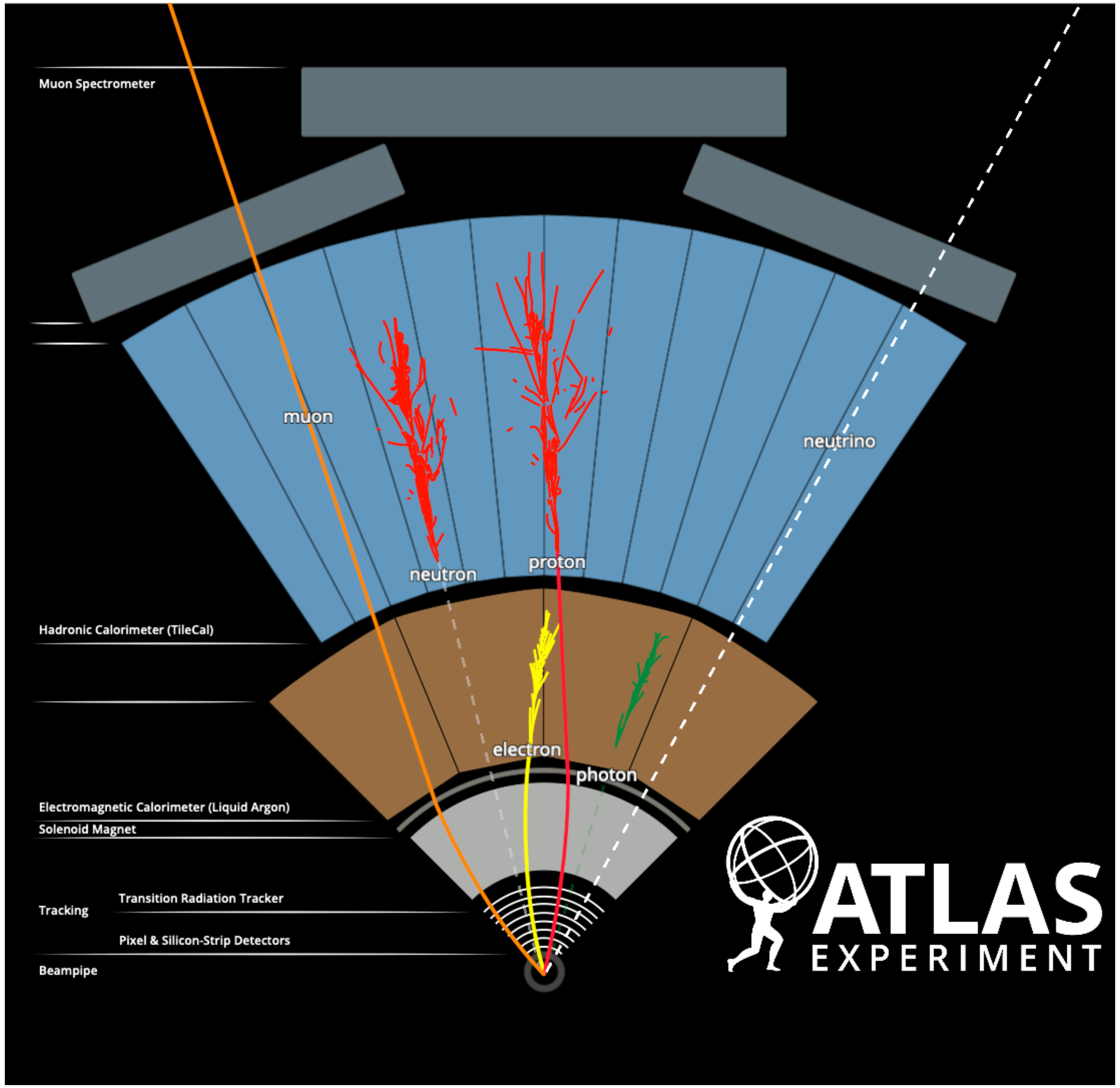
($H \to \mathcal{M}\gamma$ needs additional γ radiation + hadronisation)

- Similar signatures to the rare SM decays

The ATLAS Experiment

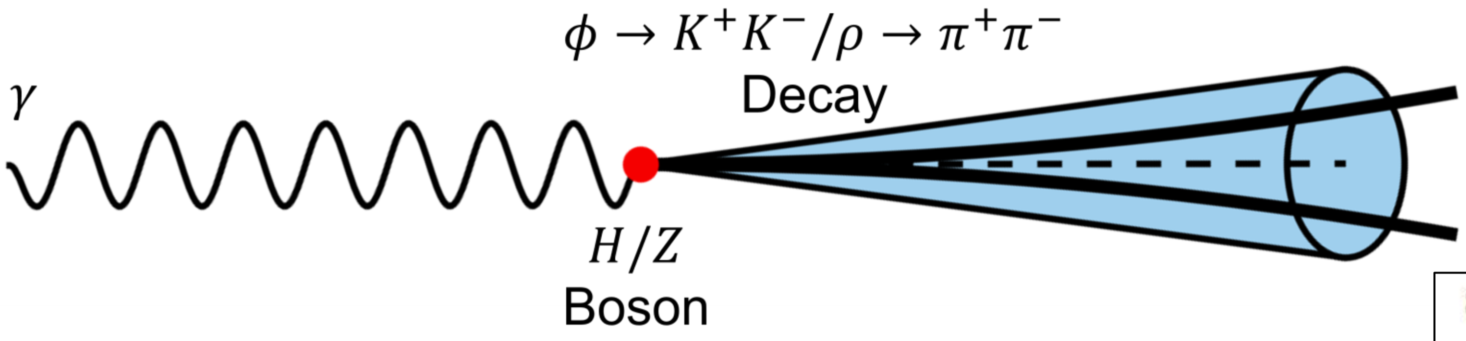
- General-purpose particle physics experiment at the LHC
  - 3k authors across 182 institutions in 42 countries





$H(Z) \rightarrow (\phi, \rho)\gamma$: 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**	***Z* decays**
$BR^{SM}_{H\rightarrow\phi\gamma} \approx 10^{-6}$	$BR^{SM}_{Z\rightarrow\phi\gamma} \approx 10^{-8}$
$BR^{SM}_{H\rightarrow\rho\gamma} \approx 10^{-5}$	$BR^{SM}_{Z\rightarrow\rho\gamma} \approx 10^{-9}$

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

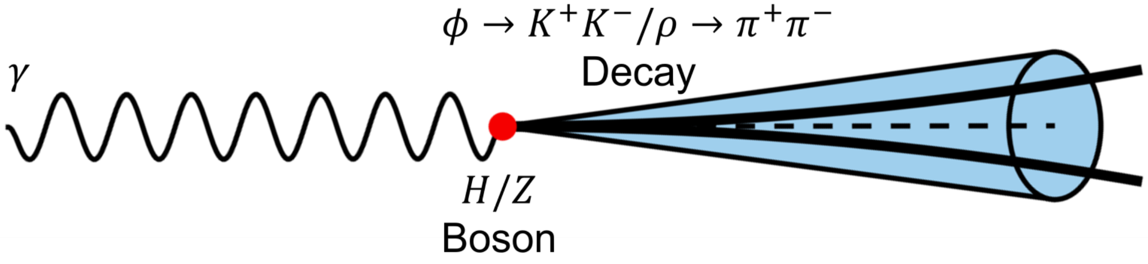
- Background from multi-jet and γ + jet sources
  - Non-parametric data-driven background model

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)

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

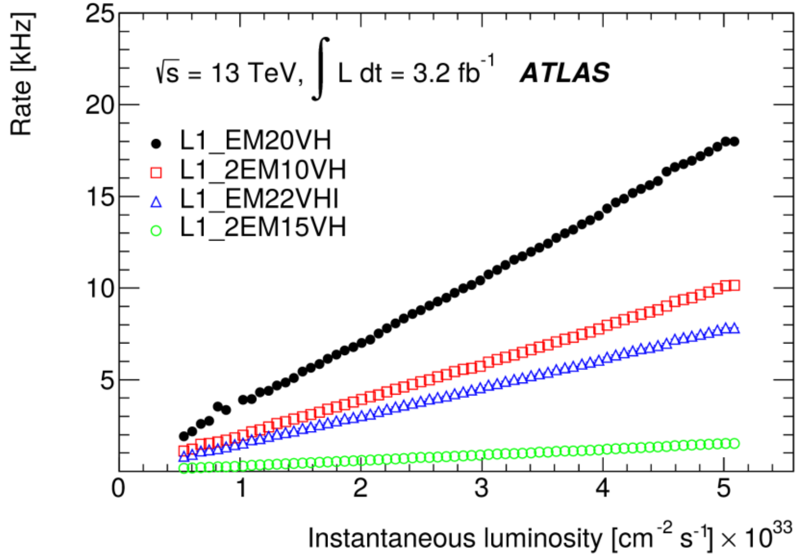
- ATLAS event rate ≈ 40 MHz – capture interesting interactions with a two-level system
  - Level-1 (L1): Hardware based trigger (40 MHz → 100 kHz)
  - Level-2/High-level Trigger (HLT): Software based trigger (100 kHz → 1 kHz for storage)

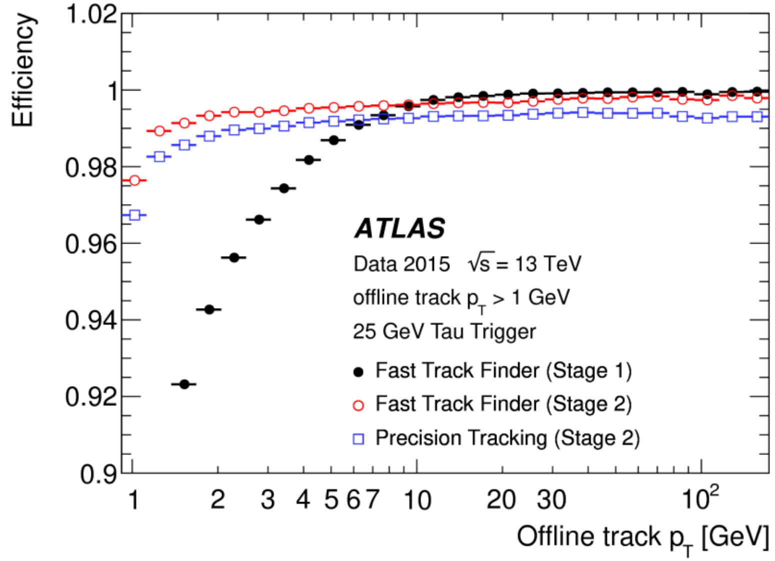


- $H(Z) \rightarrow (\phi, \rho)\gamma$ trigger strategy
  - L1: Isolated EM object
    - Lowest p_{T} unprescaled trigger
  - HLT: Collimated high-p_{T} track-pair consistent with ϕ/ρ mass recoiling against high-p_{T} photon
    - Capture meson decay using modified HLT τ-algorithms

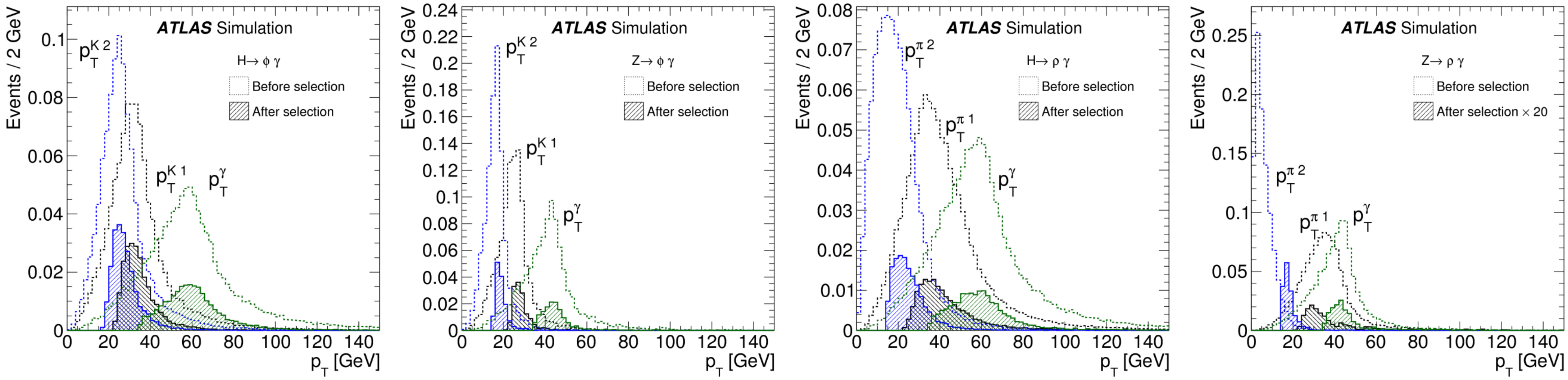
75% efficiency w.r.t offline selection

Eur. Phys. J. C 77 (2017) 317





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

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

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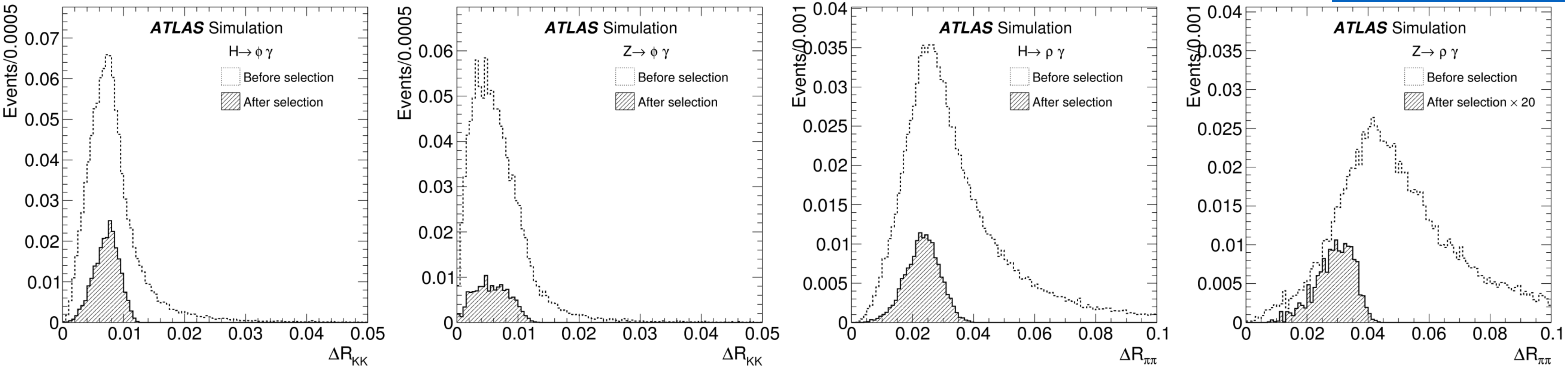
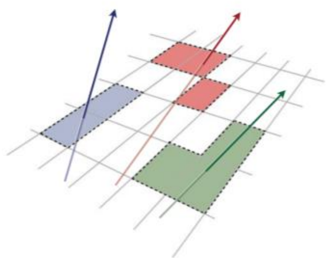
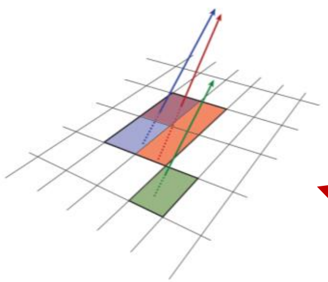


- Small opening angles between decay products
  - Particularly for $\phi \rightarrow K^+K^-$: tracking in dense environments



Single-Particle Clusters



Merged Clusters

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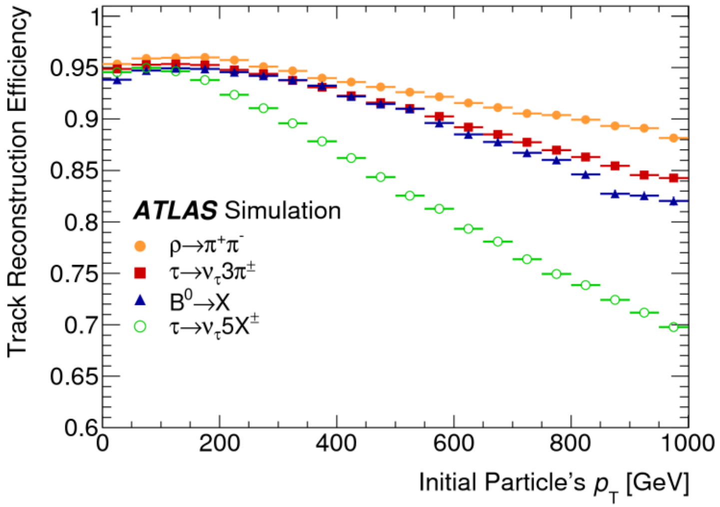
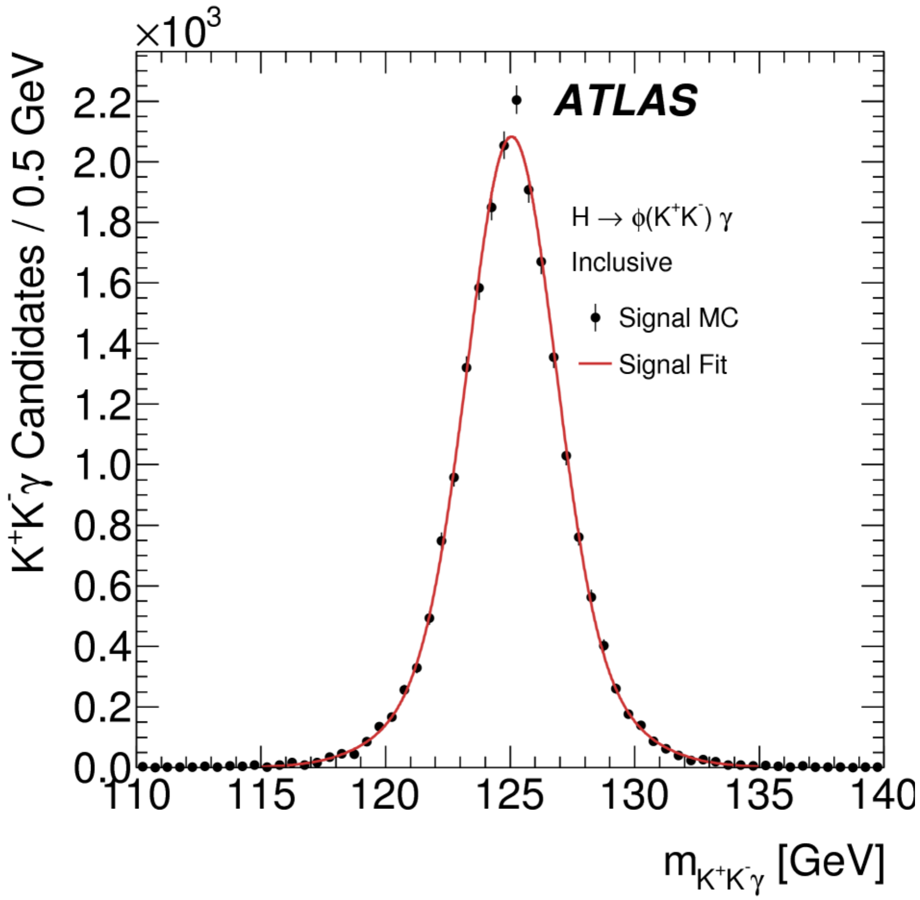
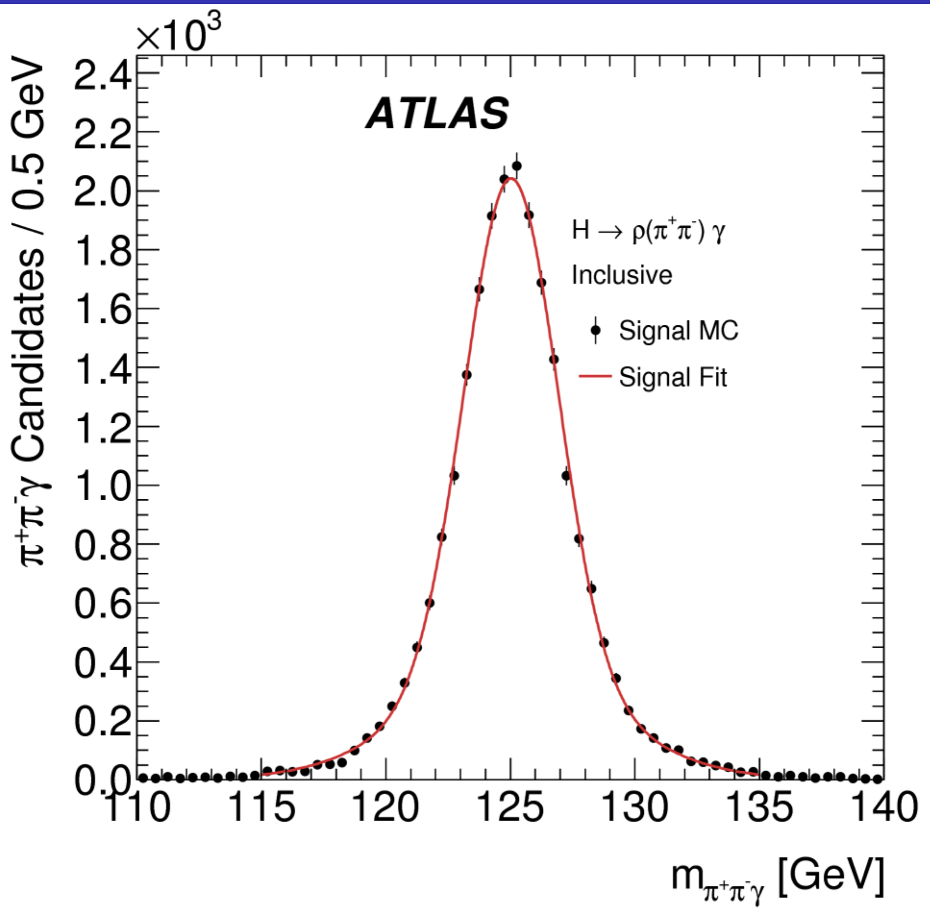


$H(Z) \to (\phi, \rho)\gamma$: Signal Modelling





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

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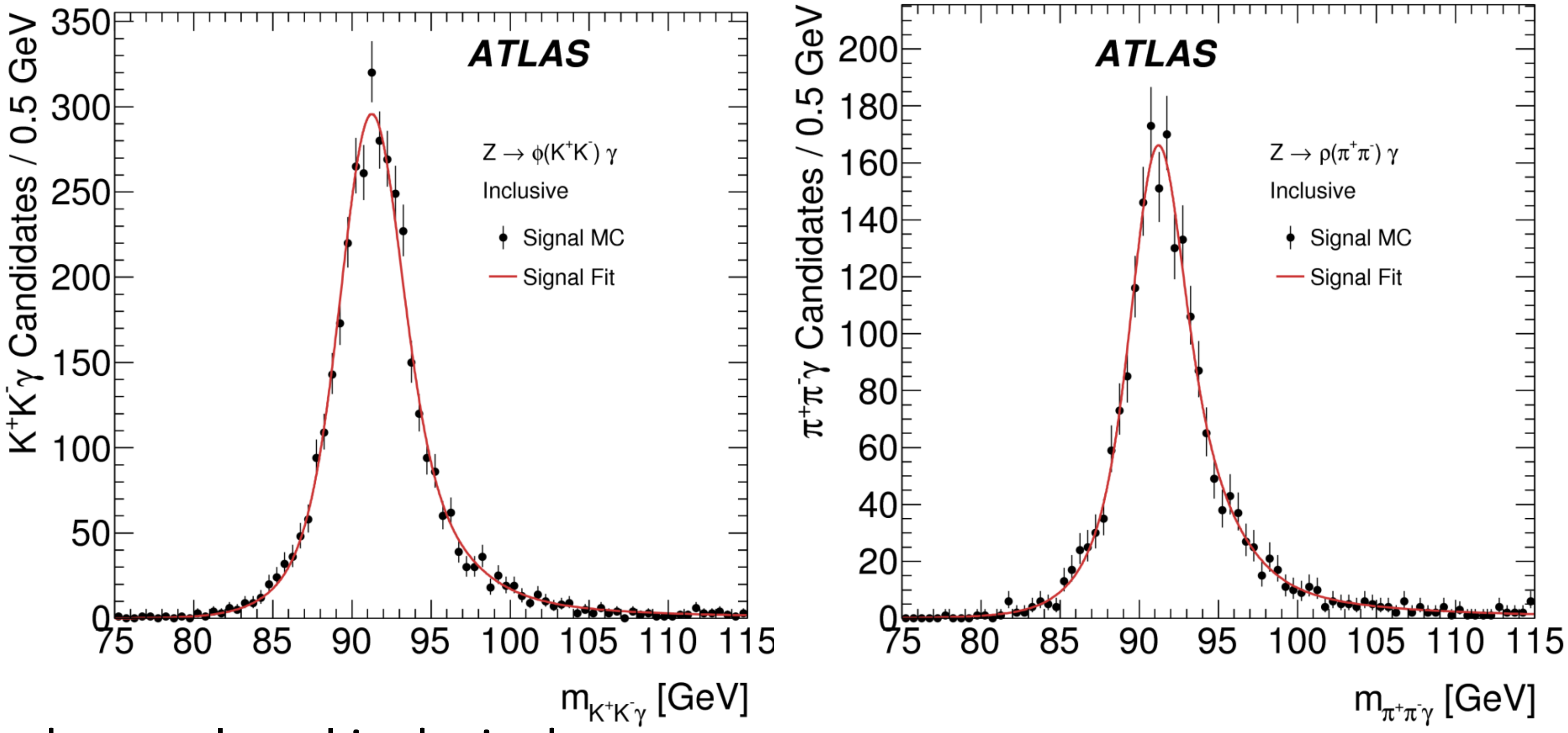
$H(Z) \rightarrow (\phi, \rho)\gamma$: Signal Modelling



- Z boson samples produced inclusively
  - Shape: (sum of two Voigtian distributions) $\times$ 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%

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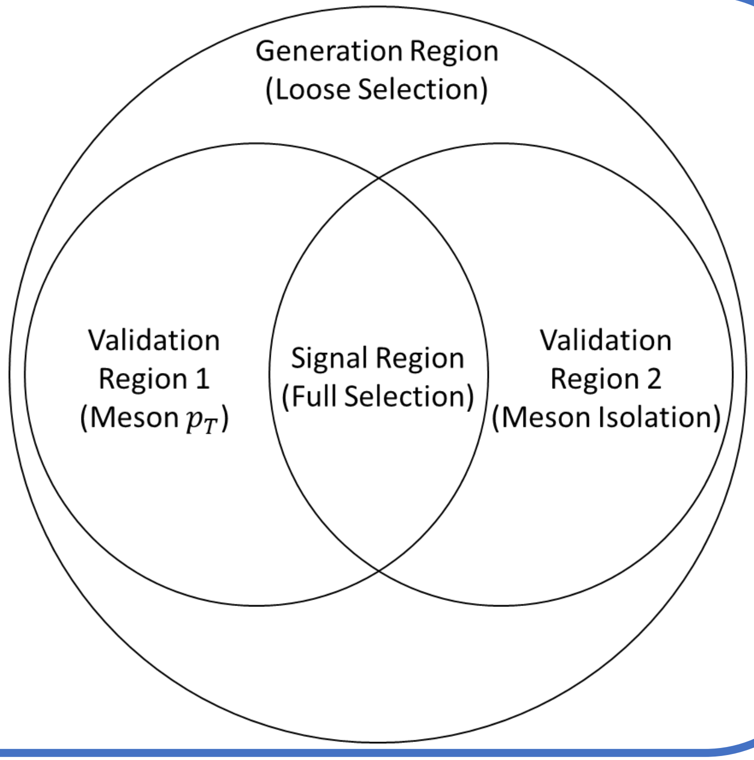
Aside: Non-Parametric Data Driven Background Modelling

- 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

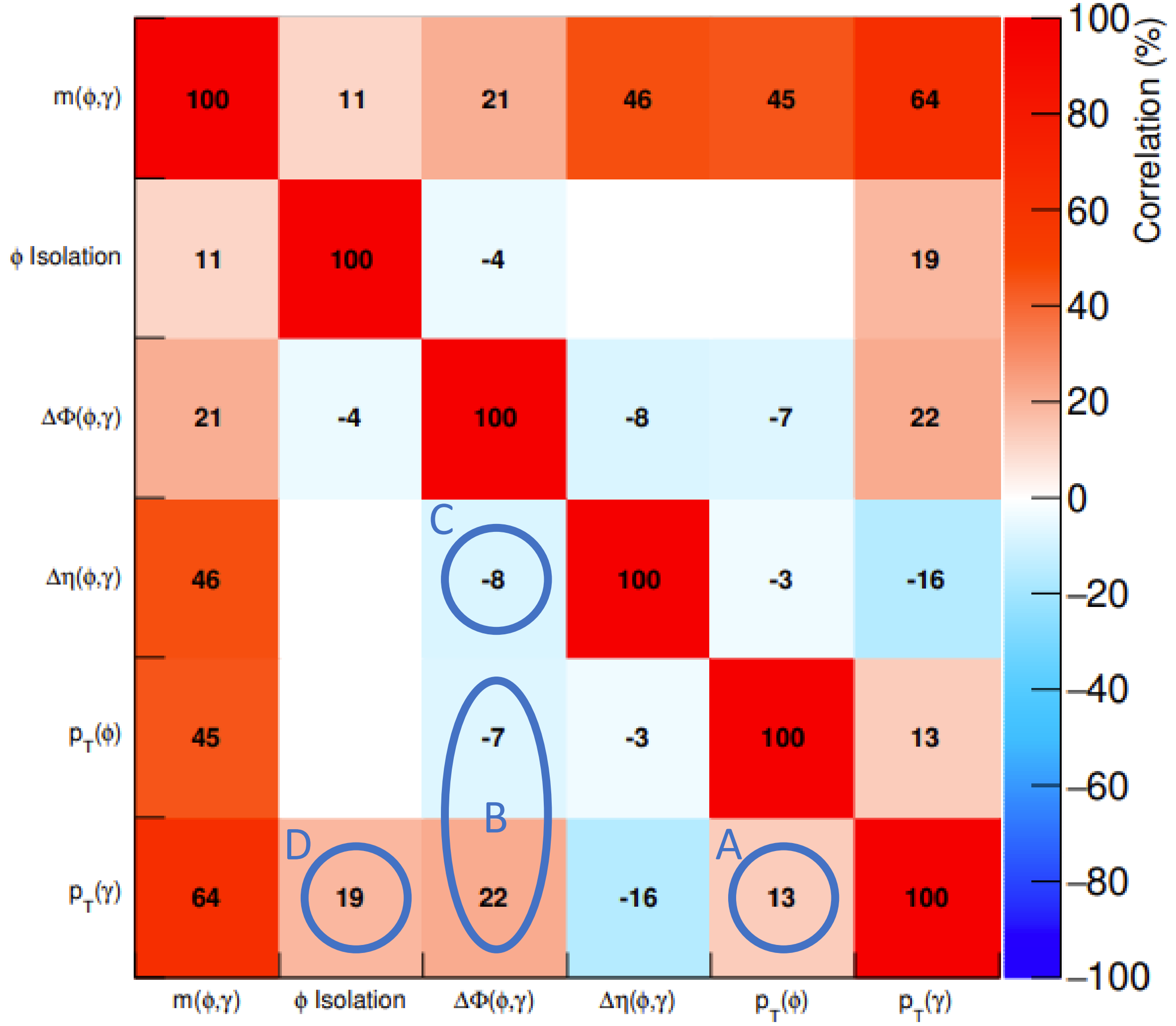
1. Model correlations in data in loose Generation Region
2. Sample pseudo-events (e.g 4-momenta) using model
3. Apply Validation Region selection to evaluate performance
4. Apply Signal Region selection and smooth for final model

	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



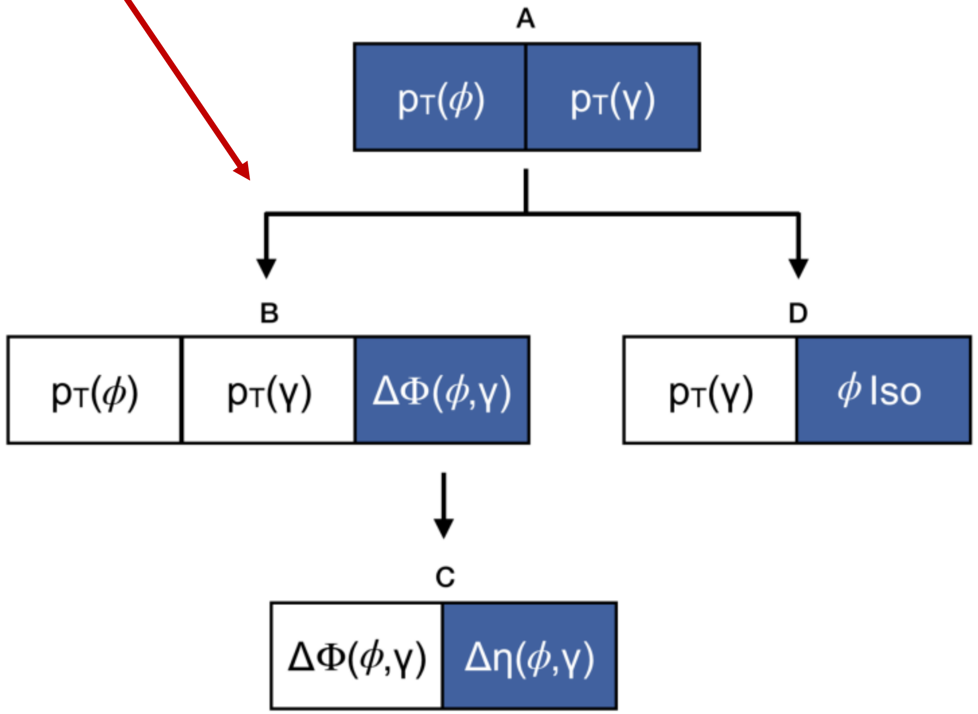
Non-Parametric Data Driven Model: Sampling Scheme 1

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



Correlations in "Data"

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

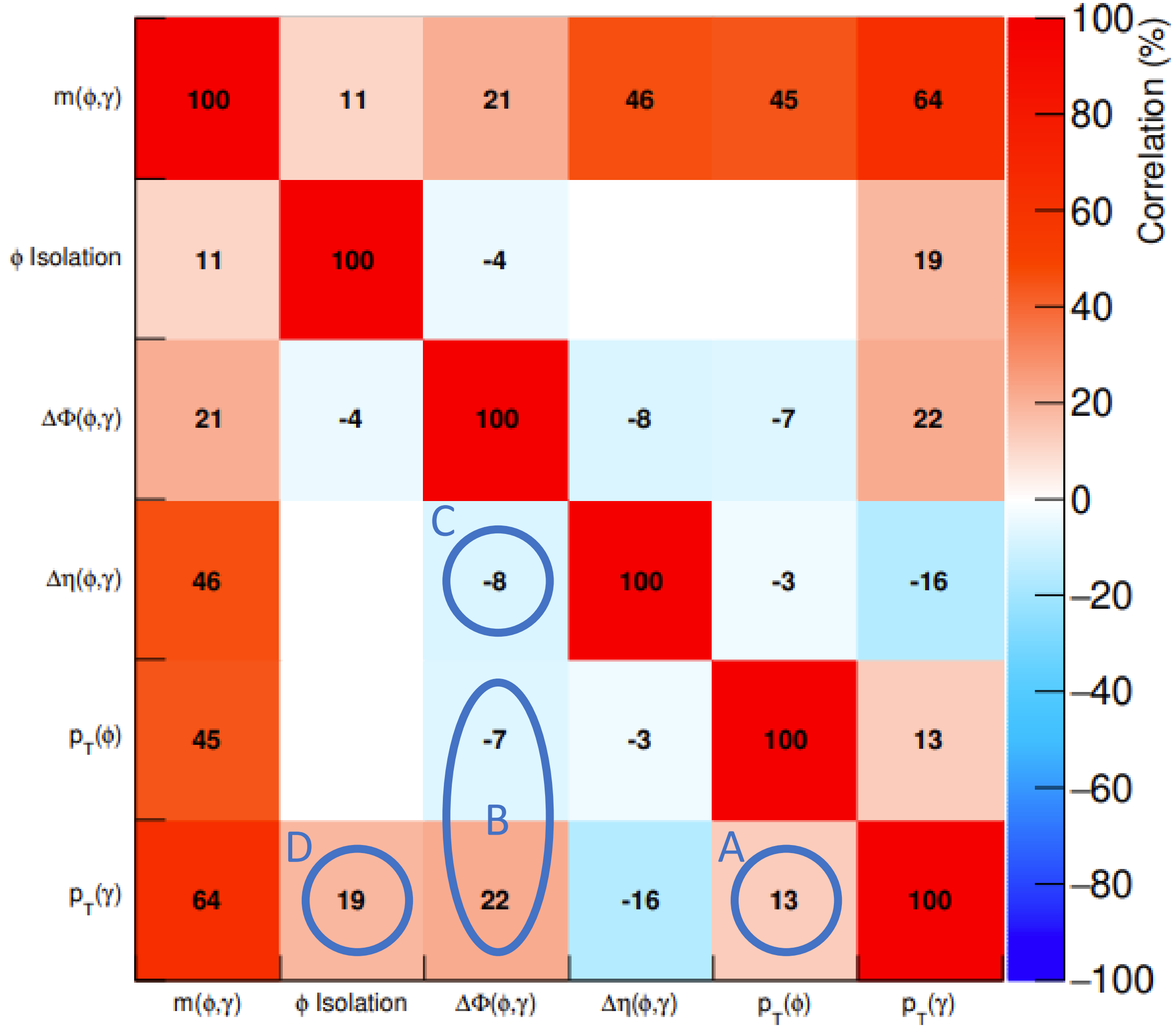


Sampling Scheme

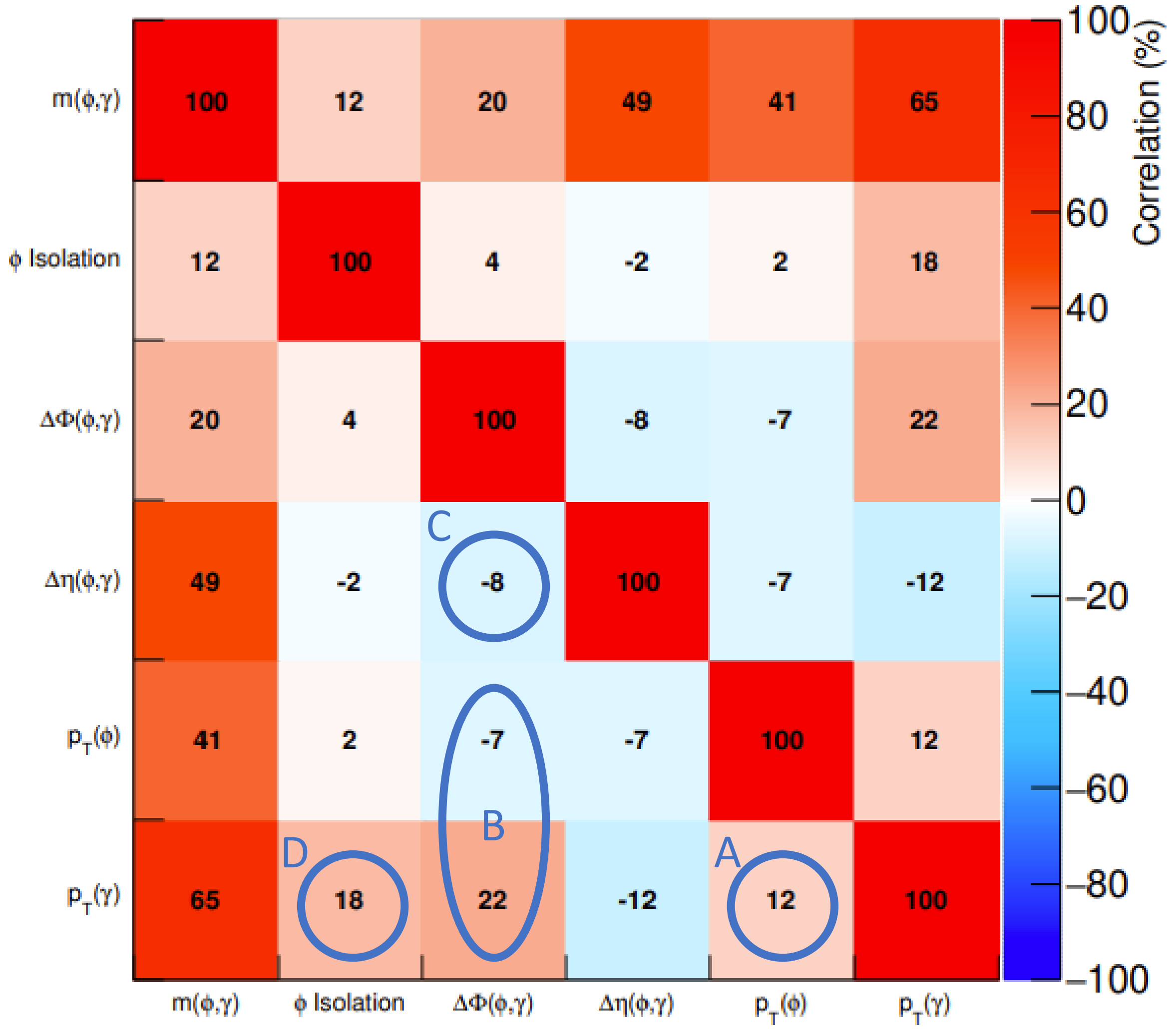
JHEP 10 (2022) 001

Non-Parametric Data Driven Model: Sampling Scheme 2

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



Correlations in "Data"



Correlations in Model

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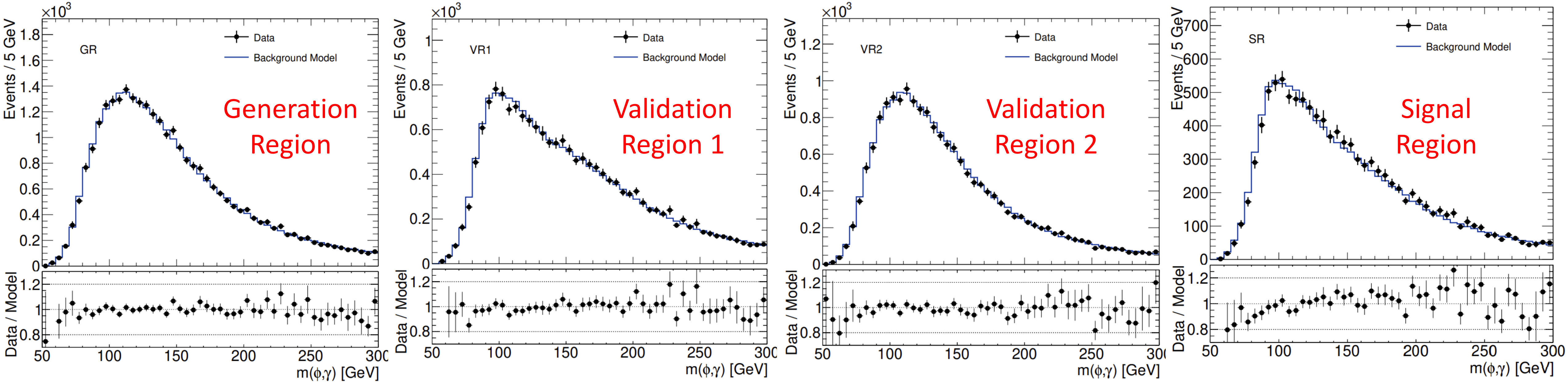
Non-Parametric Data Driven Model: Demonstration

- 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

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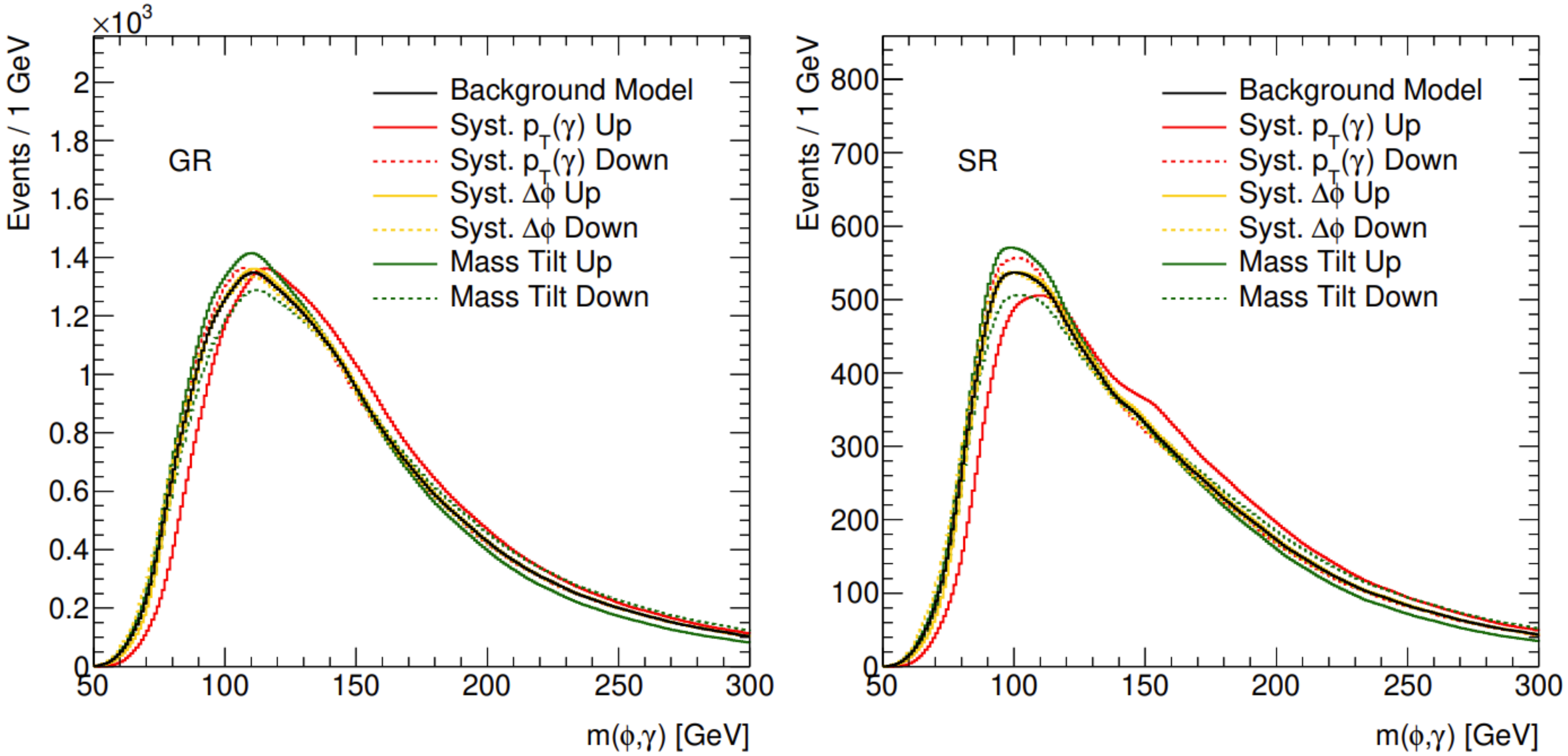
Non-Parametric Data Driven Model: Shape Systematics

- 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

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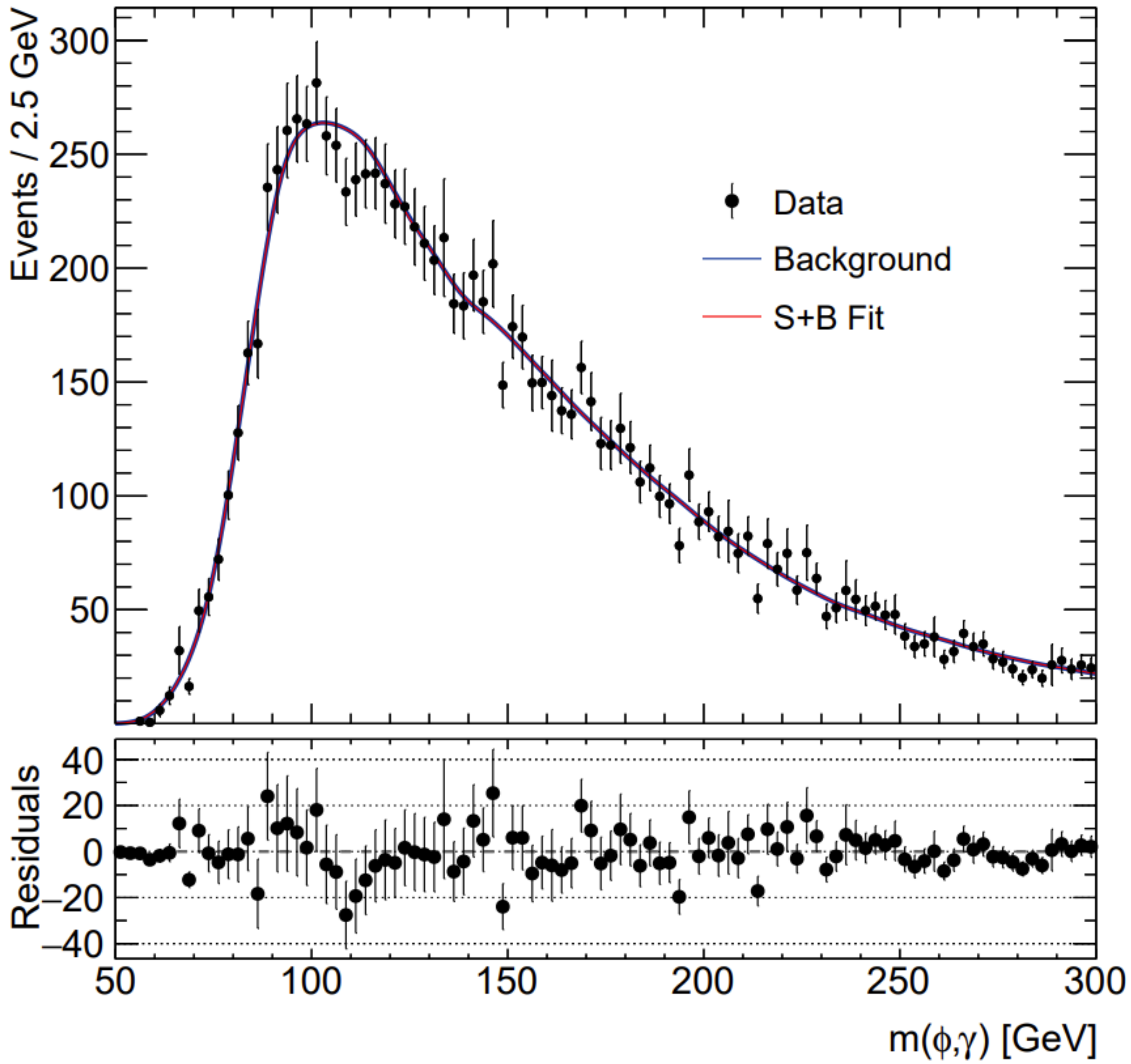
Non-Parametric Data Driven Model: Post Fit

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



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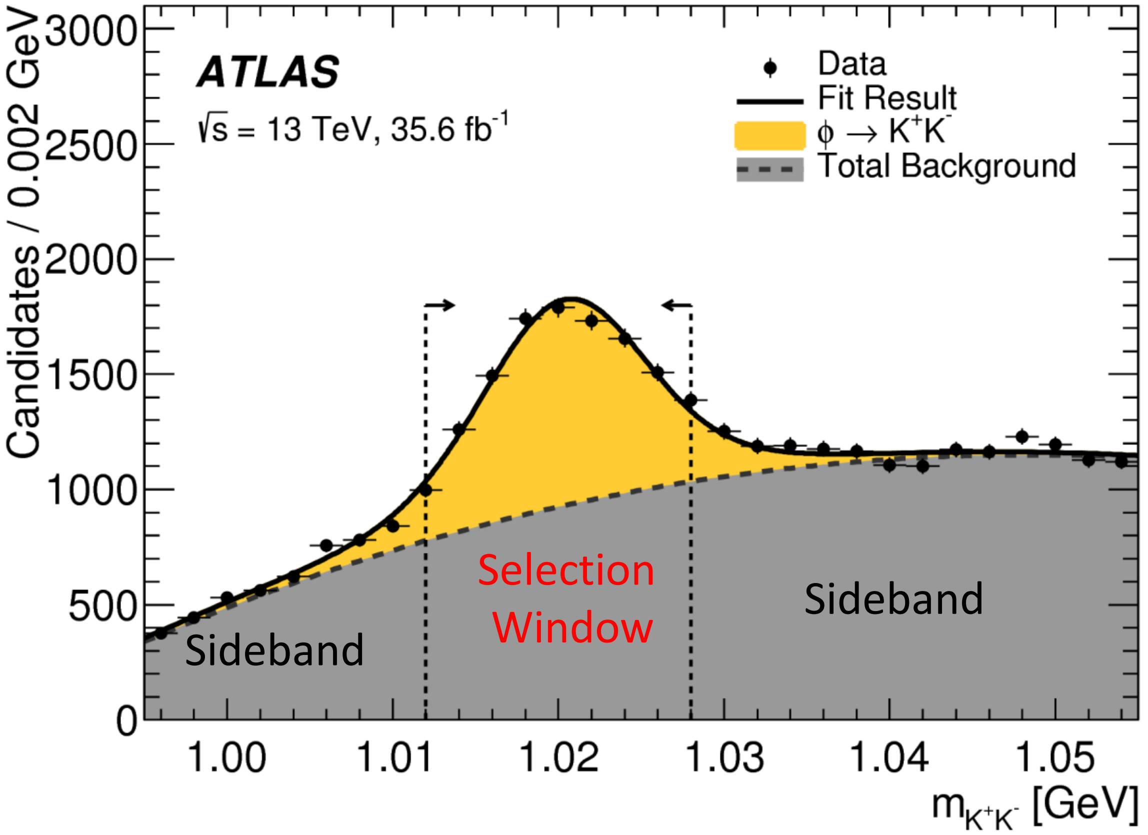
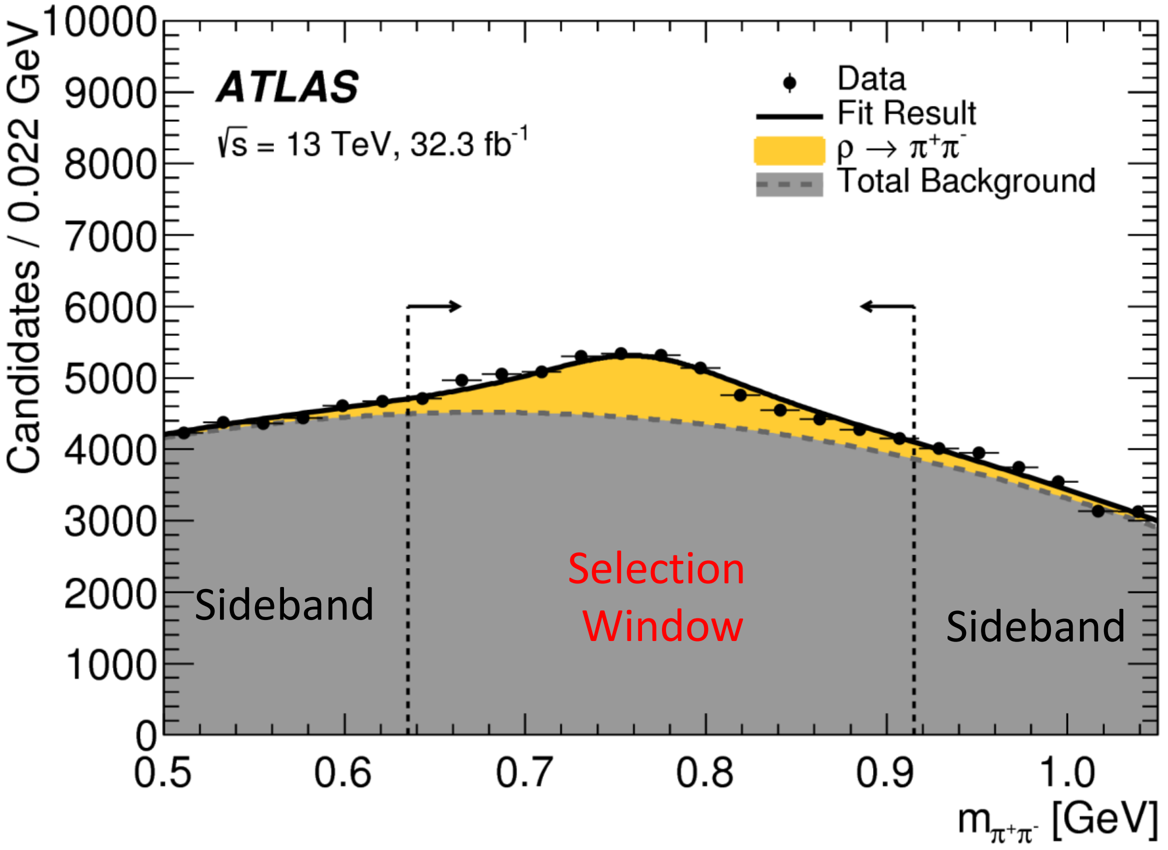
$H(Z) \rightarrow (\phi, \rho)\gamma$: Meson Reconstruction

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





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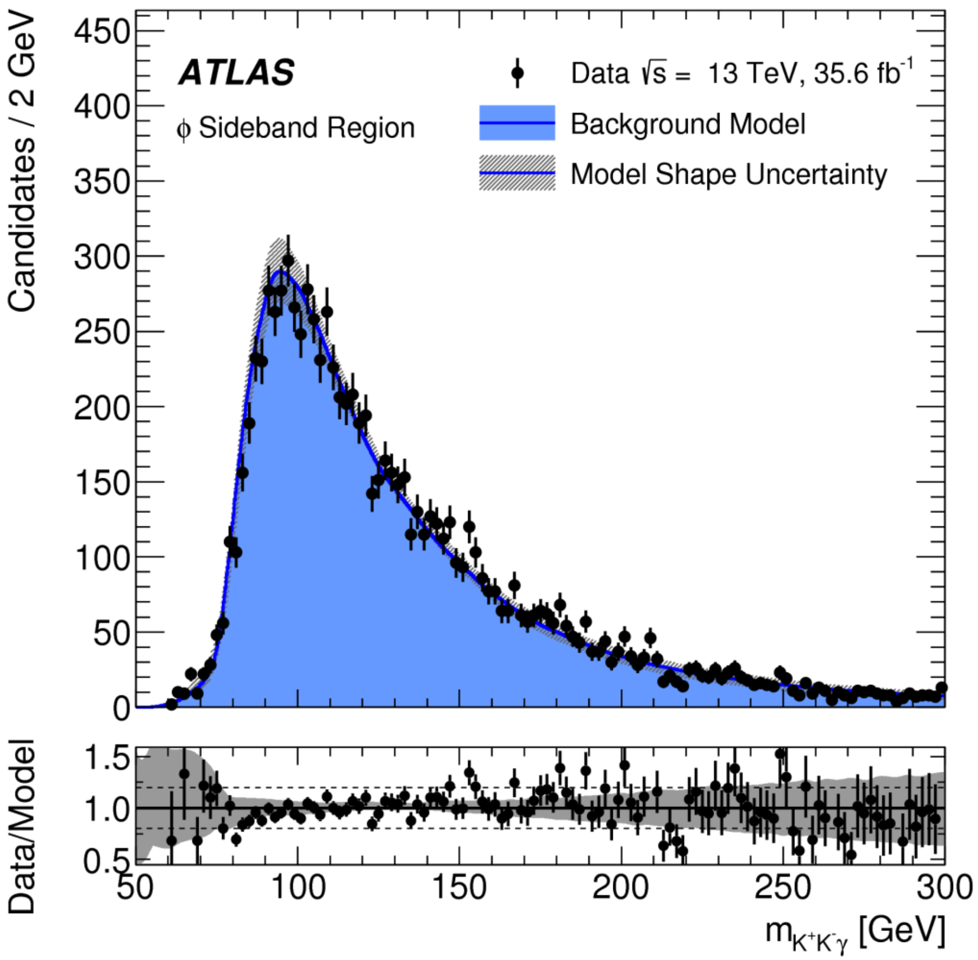
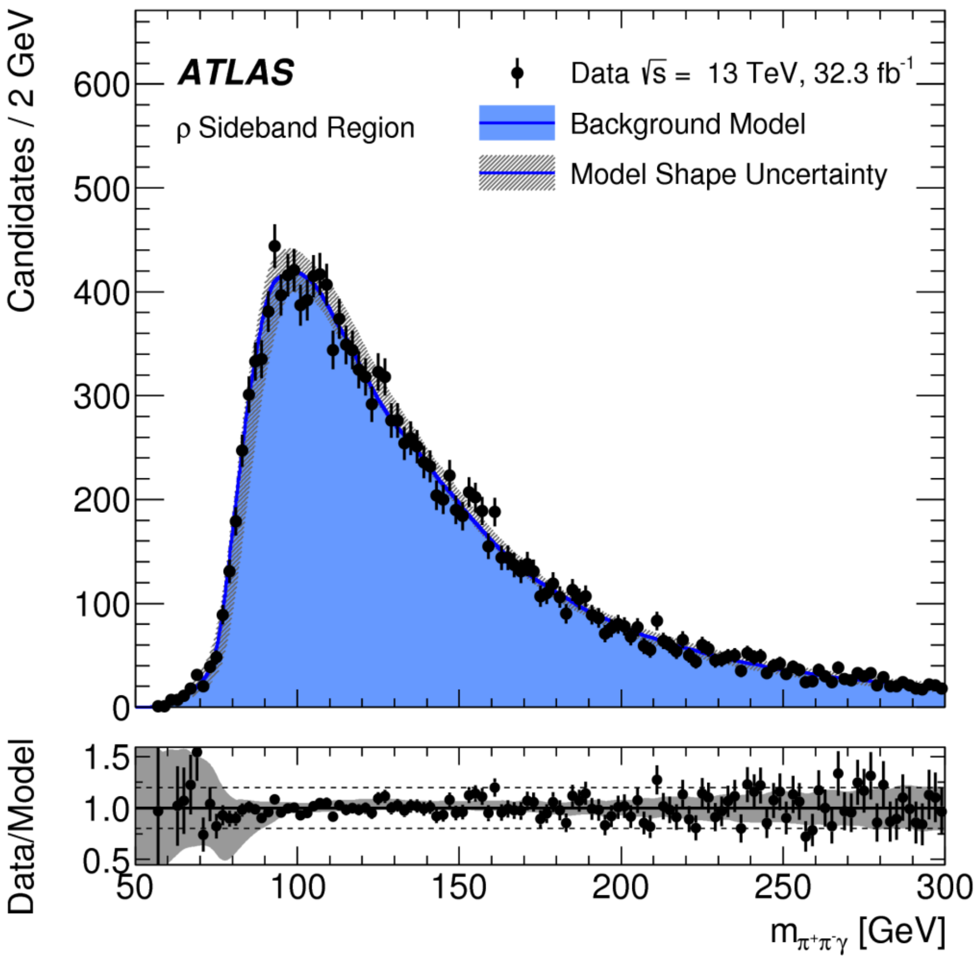
$H(Z) \to (\phi, \rho)\gamma$: Background Modelling

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



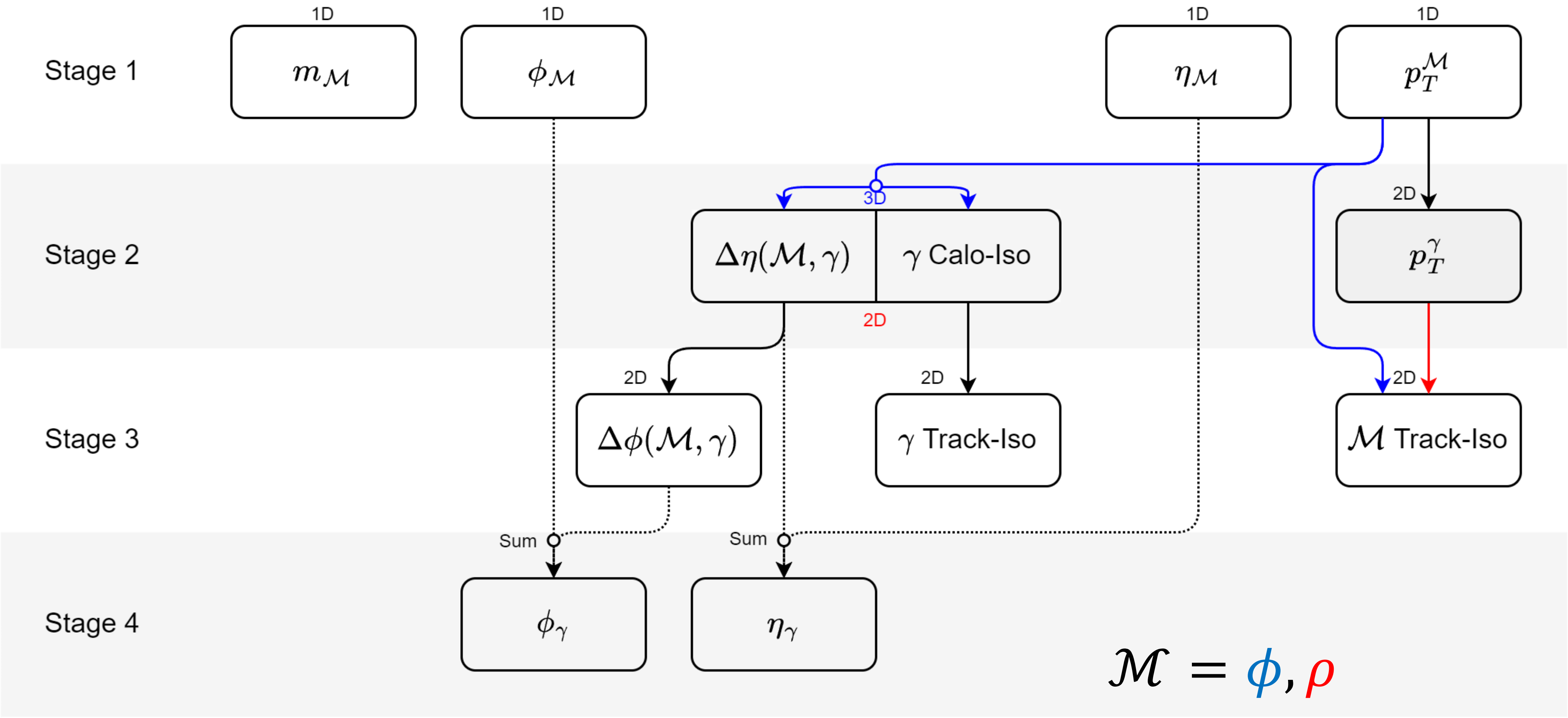


Background in ϕ/ρ-mass Sidebands (Pre-Fit)

[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 $\rho\gamma$



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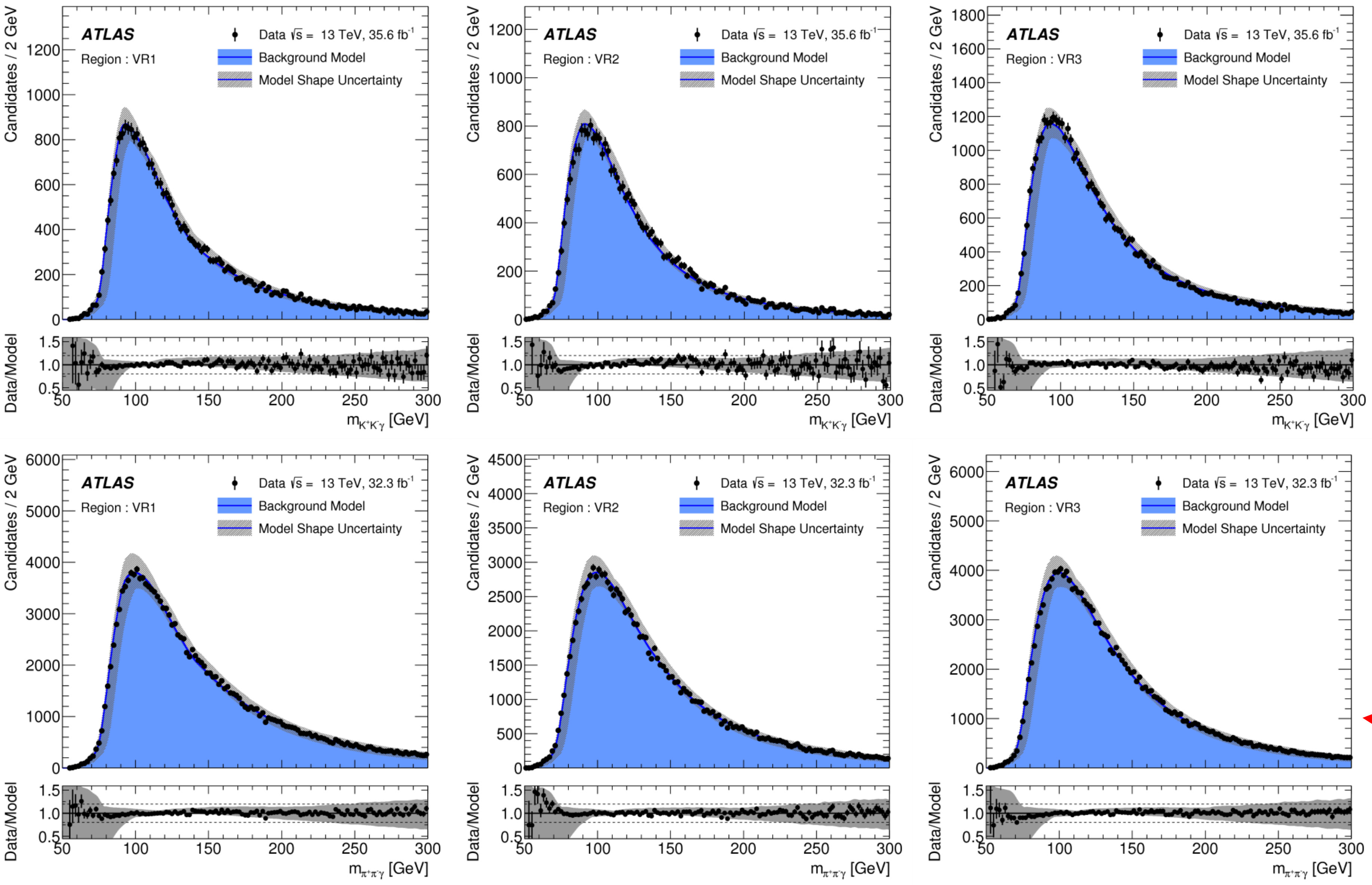
$H(Z) \to (\phi, \rho)\gamma$: Background Validation



- Freedom via shape systematics: mass-tilt, $\Delta\phi$-distortion, p_{T}-shift

$\phi\gamma$ Background Validation

$\rho\gamma$ Background Validation

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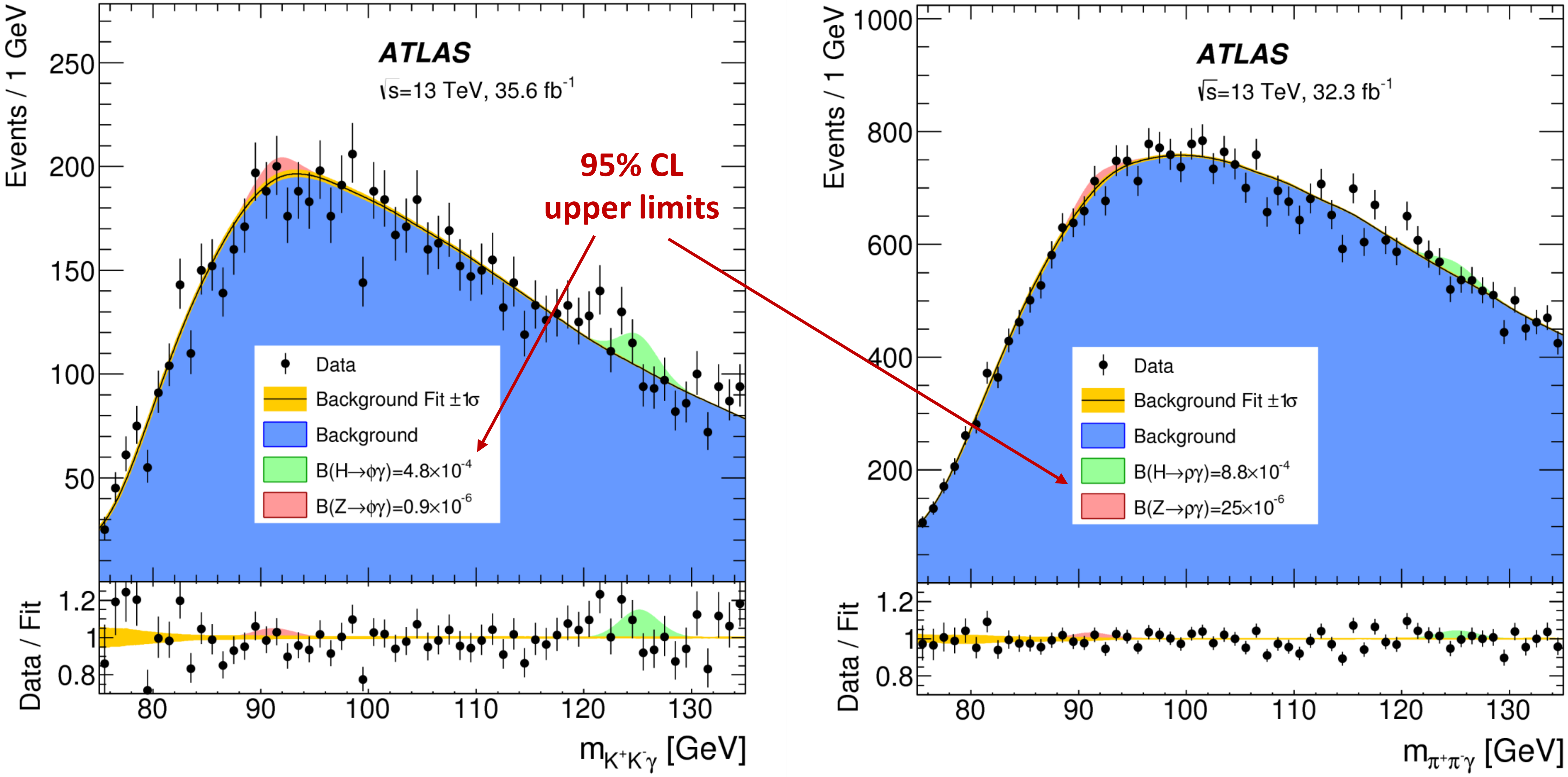
$H(Z) \rightarrow (\phi, \rho)\gamma$: Results

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



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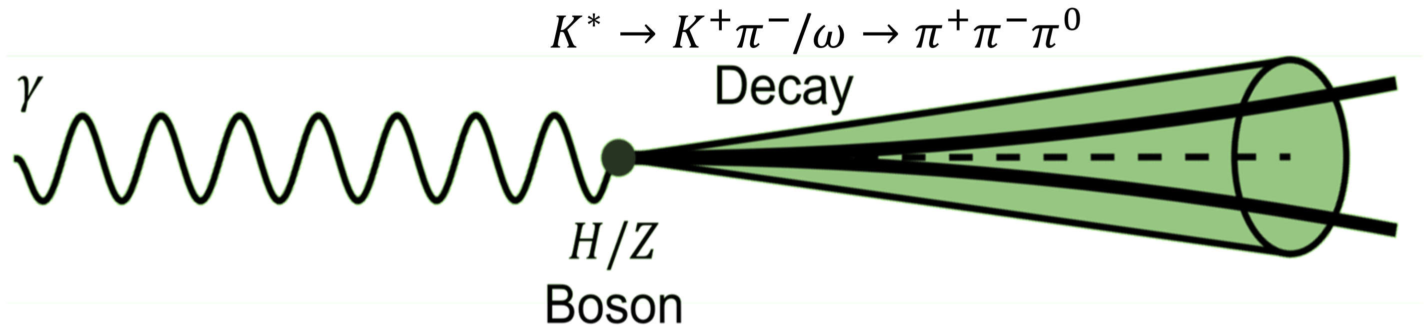
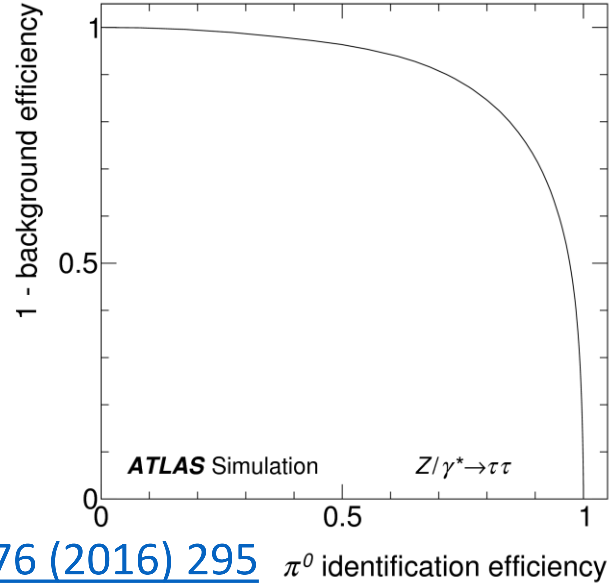
$H \to K^*\gamma$ and $H(Z) \to \omega\gamma$: Overview

- $H \to K^*(K^-\pi^+)\gamma$: d/s-quark flavour-changing coupling
  - Two tracks and a photon in final state
    - Two possibilities for K/π mass hypothesis – choose closest to K^*
- $H \to \omega(\pi^+\pi^-\pi^0)\gamma$: u/d-quark couplings
  - Two tracks, a photon **and a neutral pion** in final state
    - Use τ algorithms to reconstruct π^0 close to track-pair

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





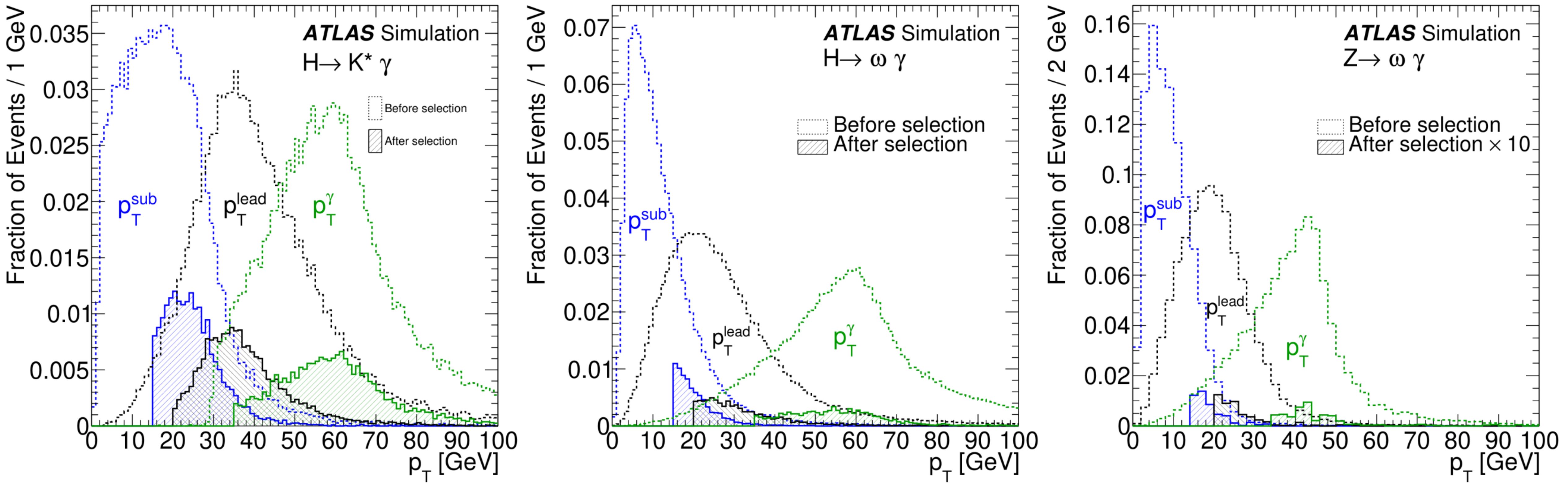
Eur. Phys. J C 76 (2016) 295

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

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

arXiv:2301.09938 - Submitted to PLB

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



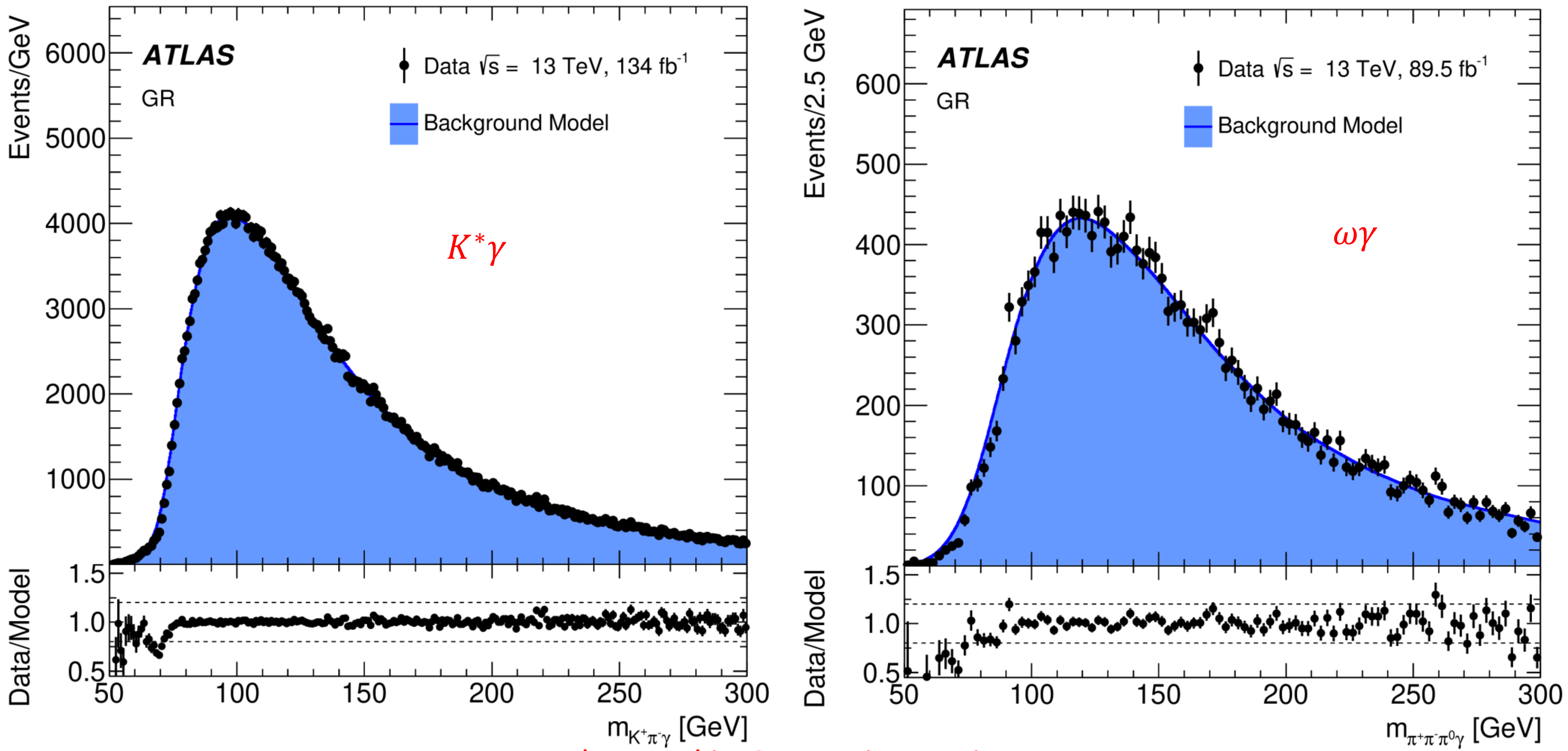
- Presence of π^0 in $H(Z) \to \omega\gamma$ reduces signal efficiency
- Shapes for $H \to K^*\gamma$ and $Z \to \omega\gamma$ same form as in $(\phi, \rho)\gamma$
  - $H \to \omega\gamma$ modelled with Gaussian + crystal-ball distribution

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

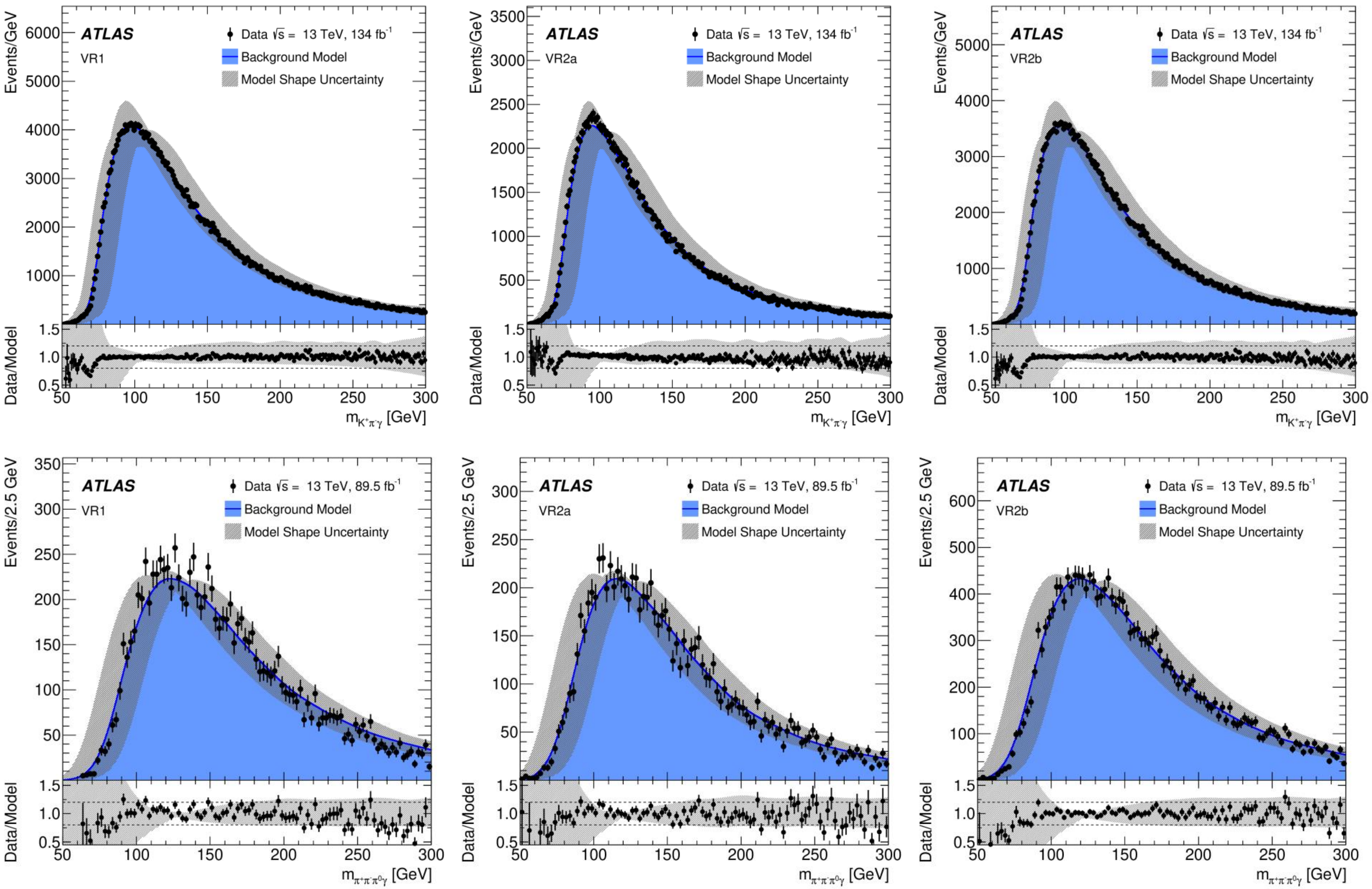
- Background is multi-jet and γ+jet sources – treat inclusively
  - Use non-parametric data-driven background model



Background in Generation Region

arXiv:2301.09938

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



- Freedom via shape systematics: mass-tilt, $\Delta\phi$-distortion, p_{T}-shift

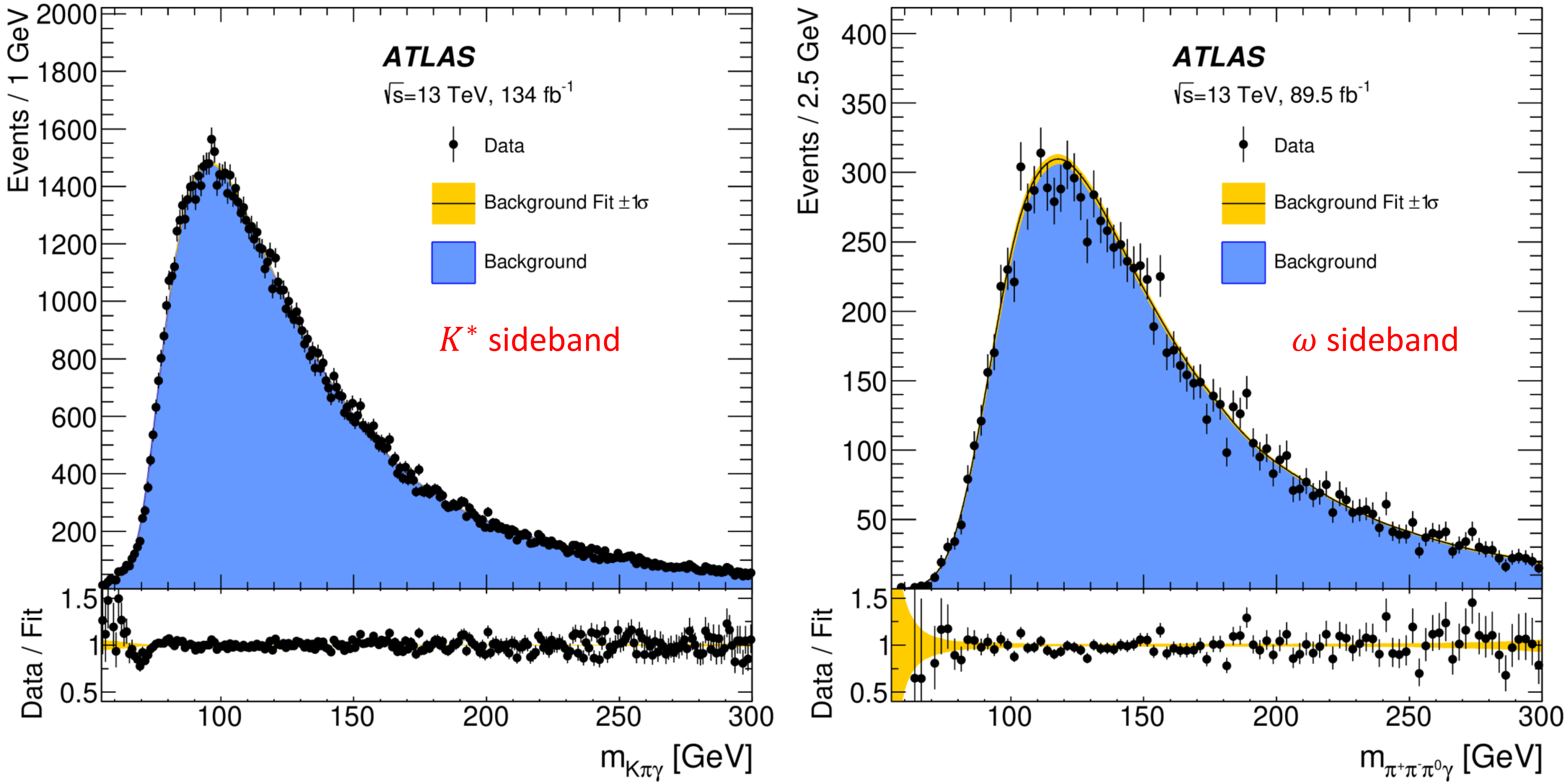
$K^*\gamma$ Background Validation

$\omega\gamma$ 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 $m(\pi^+\pi^-\pi^0\gamma)$

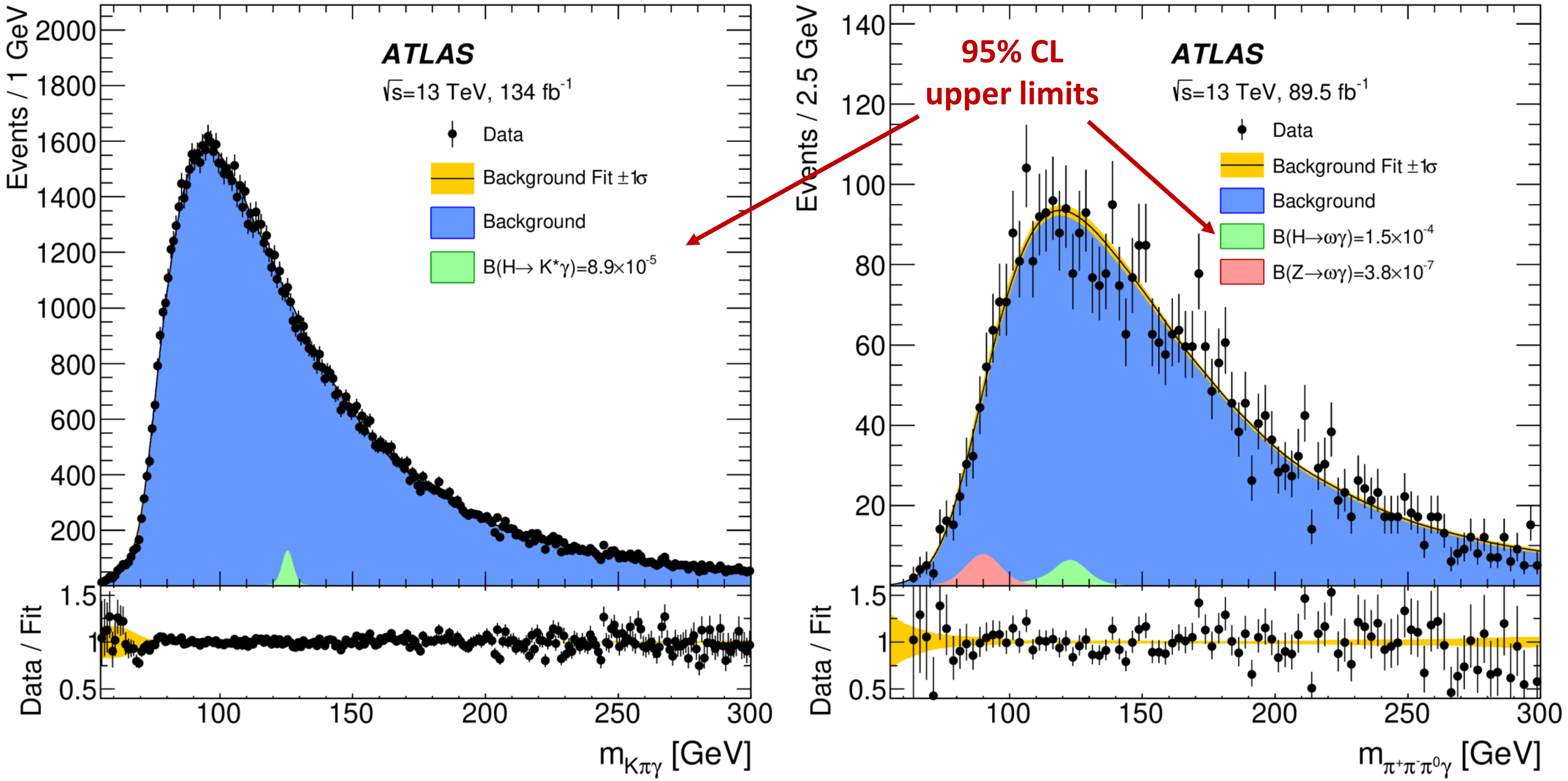


Background in Sidebands (Post-Fit)

arXiv:2301.09938

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

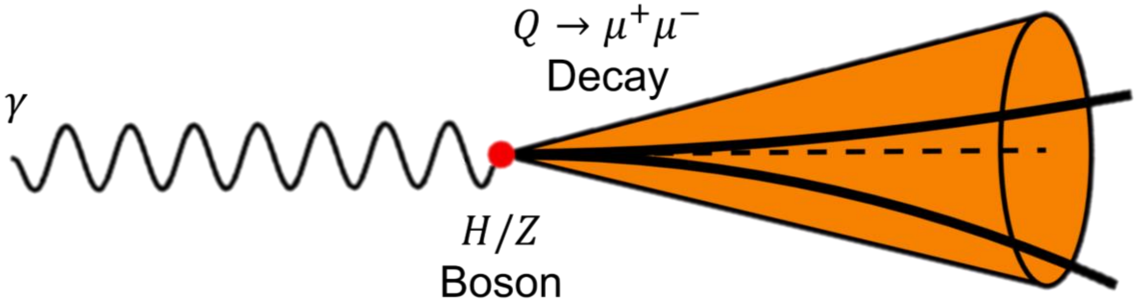
- Unbinned likelihood fit in $m(K^{\pm}\pi^{\mp}\gamma)$ and $m(\pi^+\pi^-\pi^0\gamma)$



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
  - 97% efficiency w.r.t offline
- Additional resonant $q\bar{q} \to \mu^+\mu^-\gamma$ background contribution
  - Use a **2D** fit in $m_{\mu^+\mu^-\gamma}$ vs $m_{\mu^+\mu^-}$

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

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

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

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

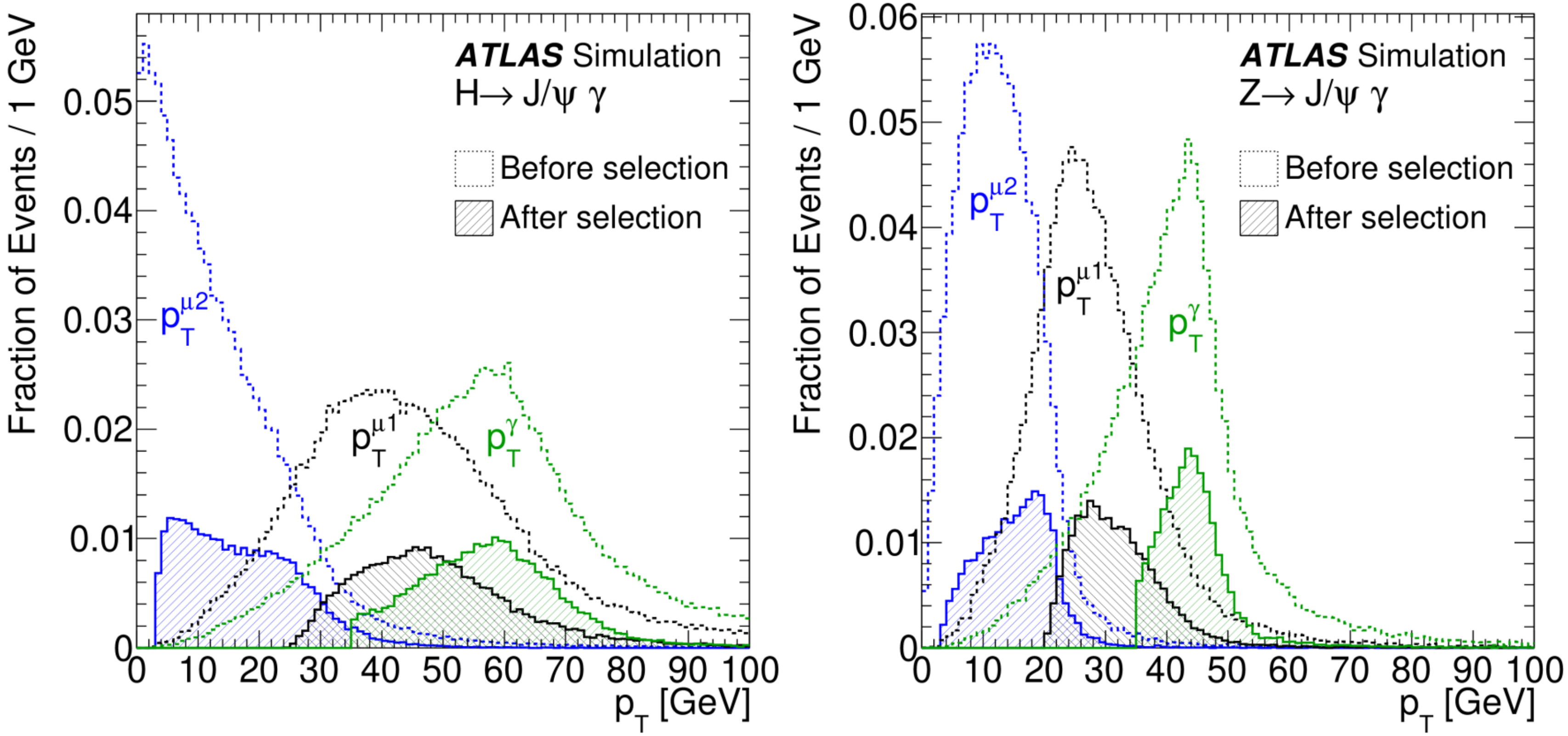
Phys.Lett.B 786 (2018) 134-155 – 2nd iteration

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)

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

arXiv:2208.03122

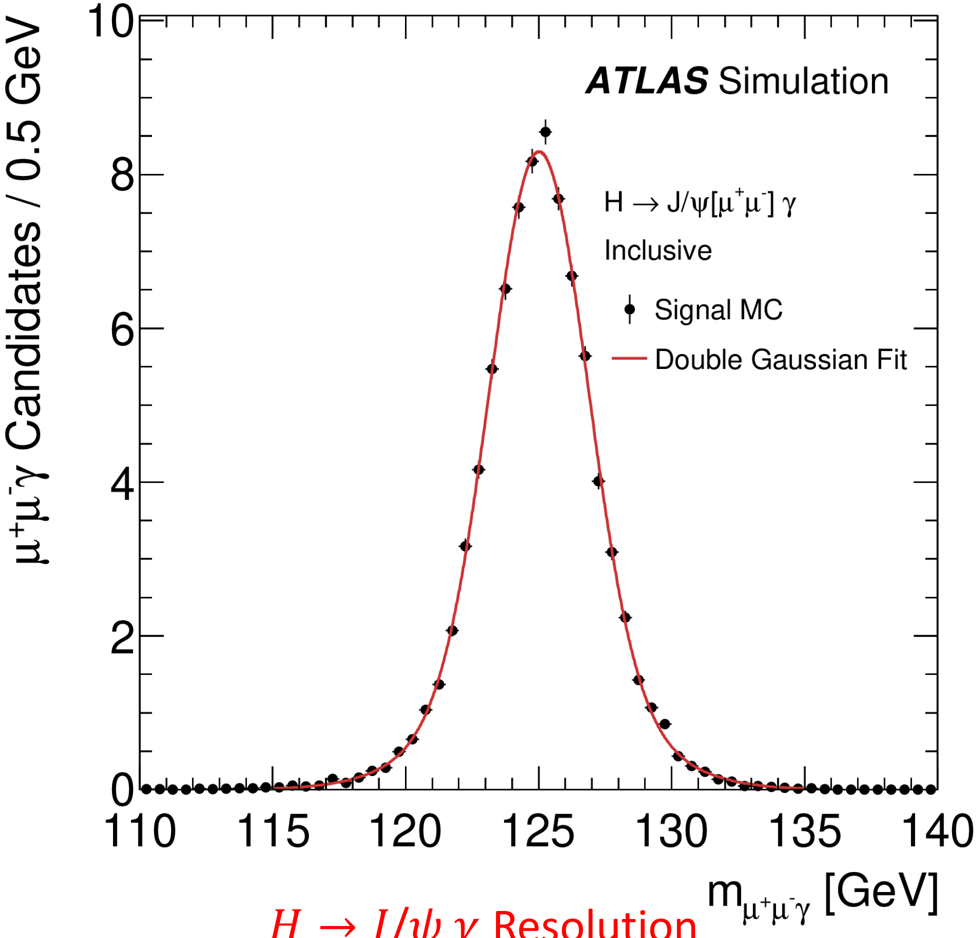


Generator-level p_{T} (J/ψ channels)

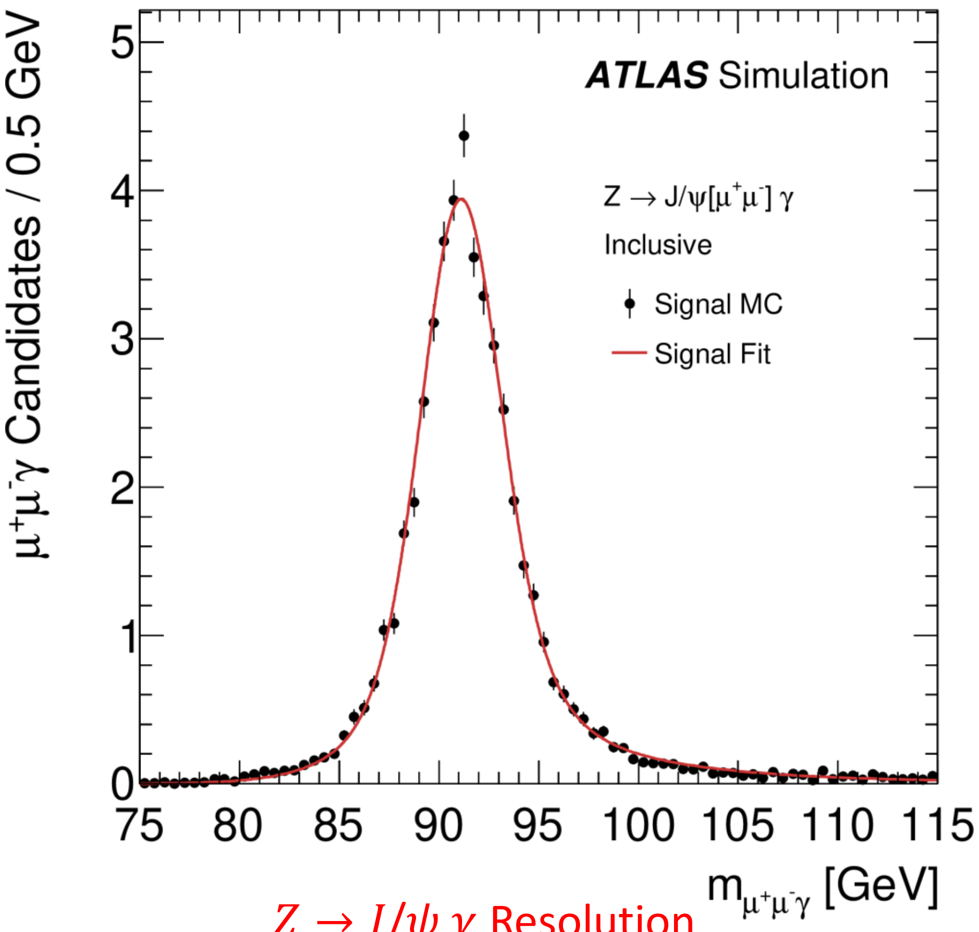
- Softer photon and muon p_{T} in Z decays leads to smaller signal efficiencies than for H decays
- Reject displaced vertices to avoid $b \to \psi(nS)$

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

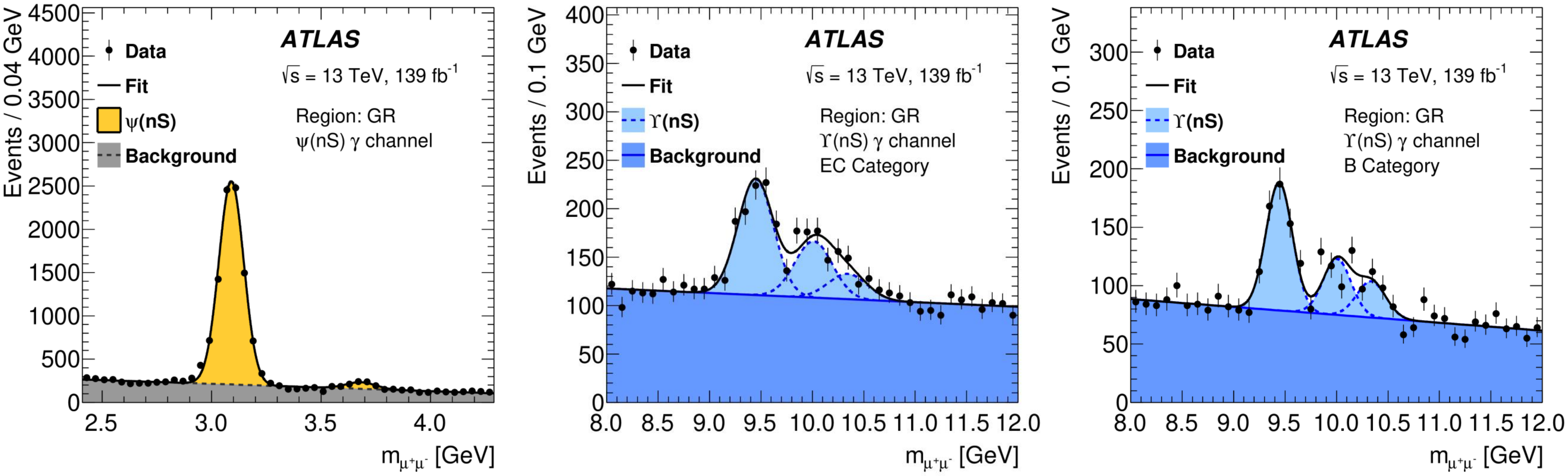
- Produce H samples by production mode
  - 2D Shape: Sum of two bivariate Gaussians
  - Resolution: $1.6 - 1.8\%$

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

arXiv:2208.03122

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

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

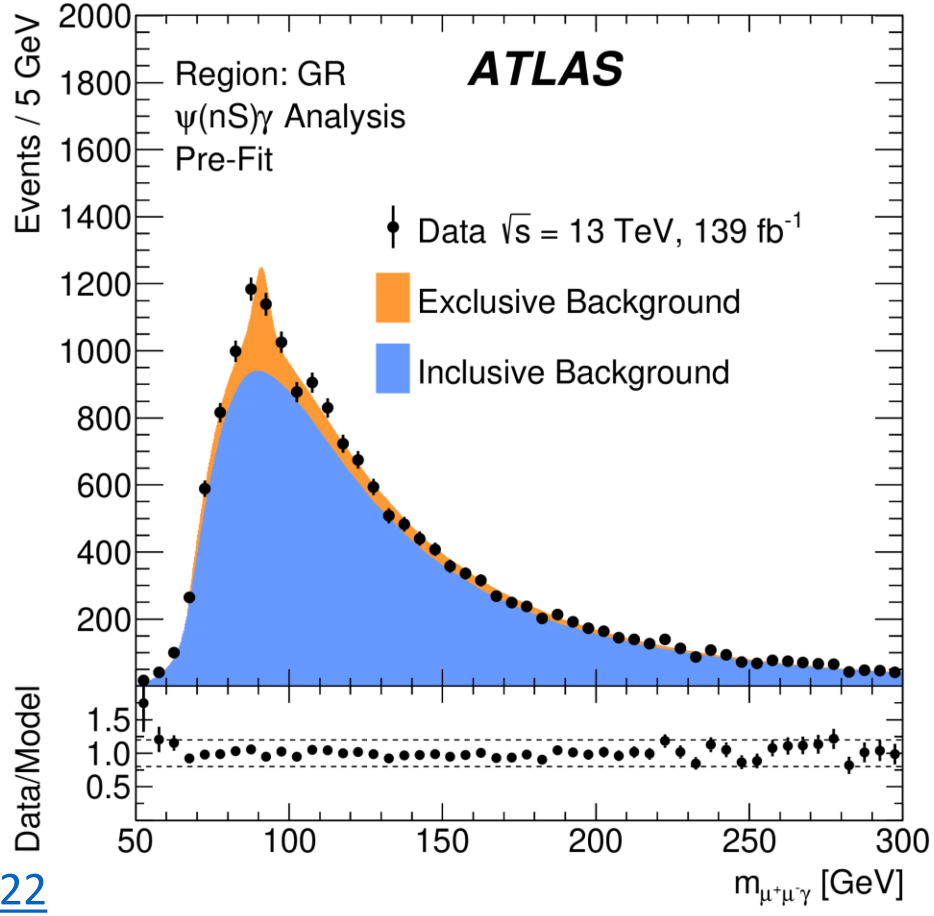


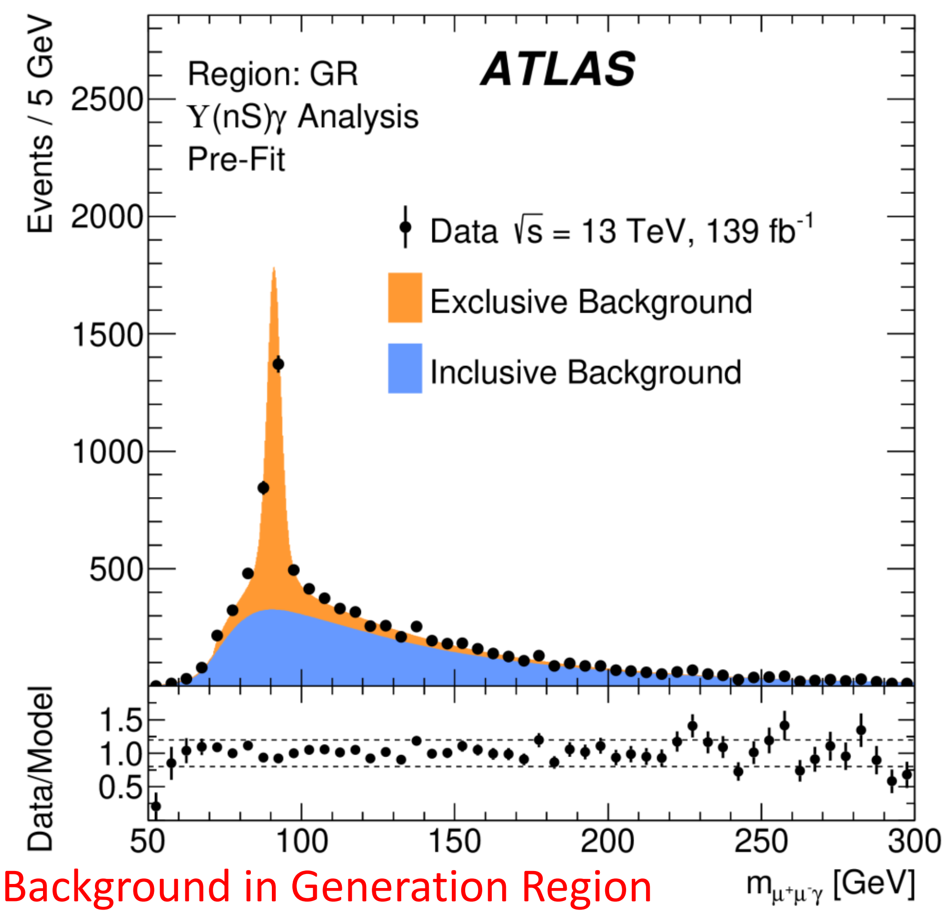
Meson Reconstruction in GR

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
  - Resonant in $m_{\mu^+\mu^-\gamma}$ but not in $m_{\mu^+\mu^-}$
- Inclusive background
  - Multi-jet and γ+jet sources with $Q/\mu^+\mu^-$ production
  - Non-parametric data-driven background model
  - Non-resonant in $m_{\mu^+\mu^-\gamma}$; mix of resonant/non-resonant in $m_{\mu^+\mu^-}$

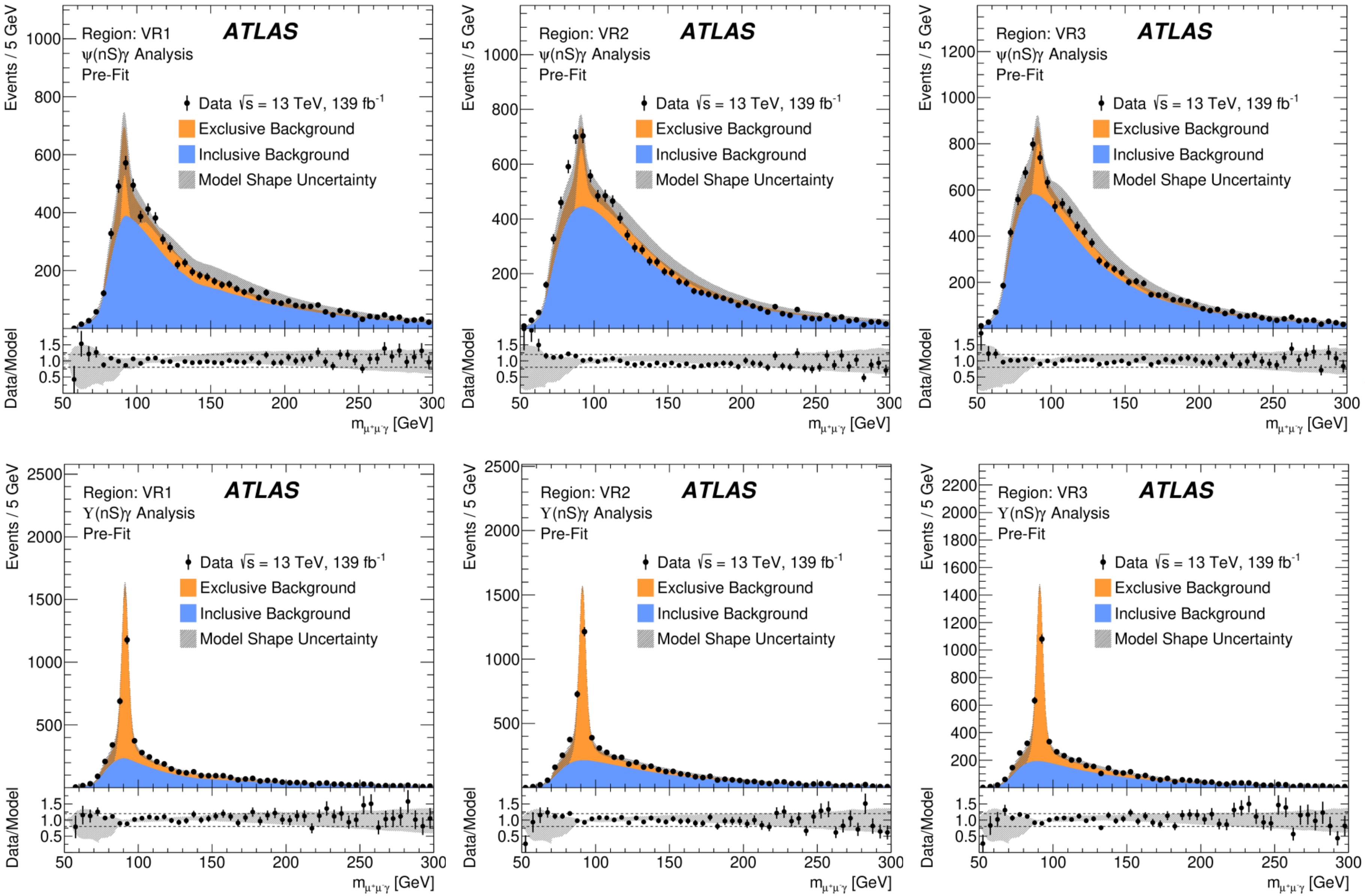




Background in Generation Region

arXiv:2208.03122

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



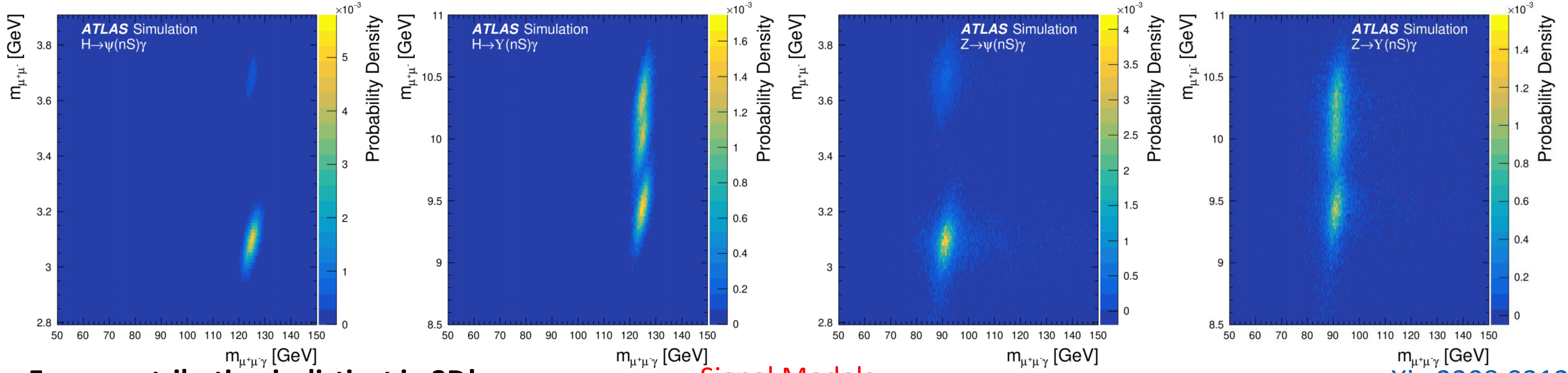
- Subtract exclusive contribution from data in GR to prepare for inclusive model
- Freedom via shape systematics: mass-tilt, $\Delta\phi$-distortion, p_{T}-shift

$\psi(nS)\gamma$ Background Validation

$\Upsilon(nS)\gamma$ Background Validation

arXiv:2208.03122

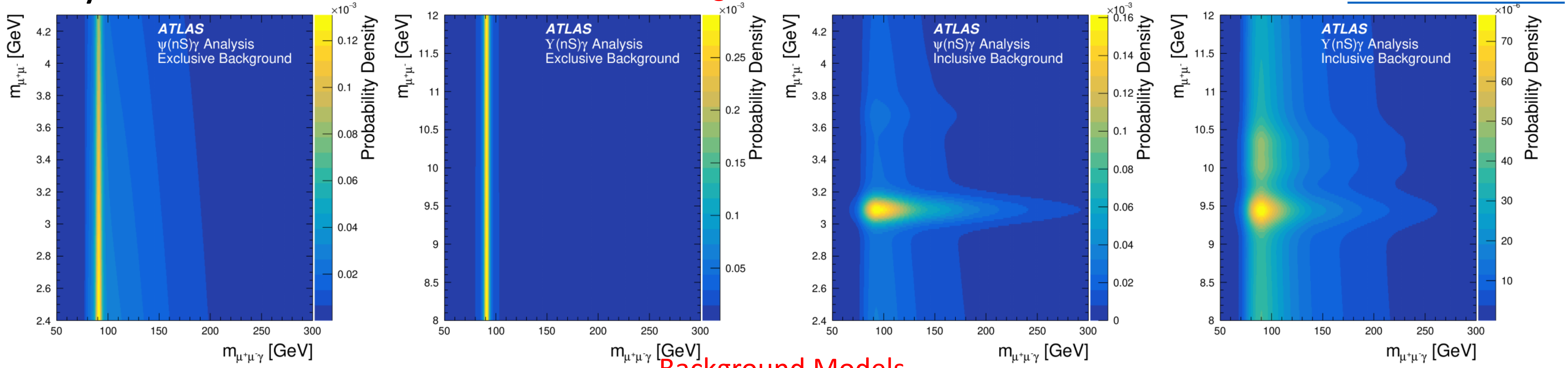
$H(Z) \rightarrow Q\gamma$: Three-body Mass Versus Dimuon Mass



Every contribution is distinct in 2D!

Signal Models

arXiv:2208.03122

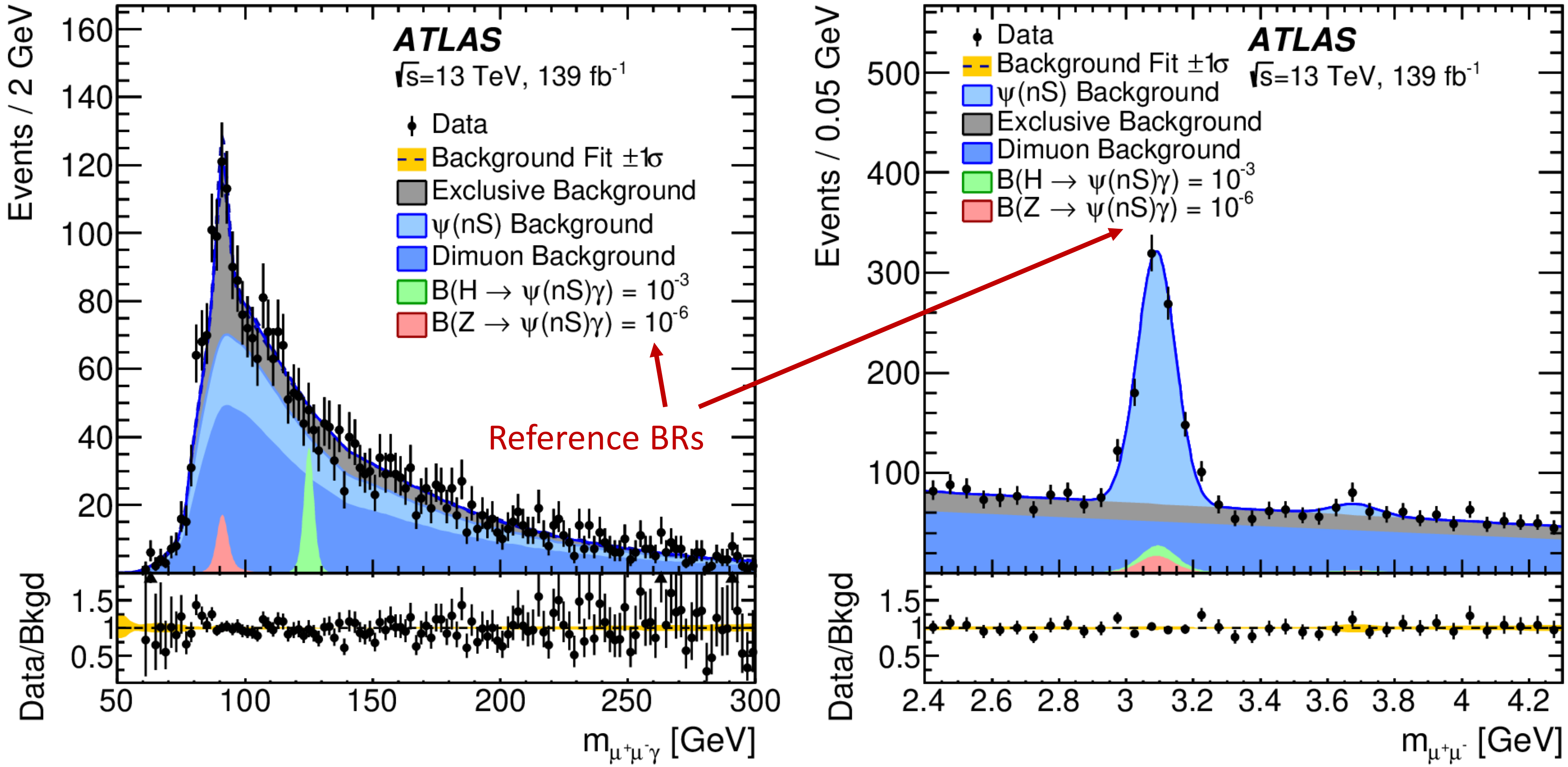


Background Models

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

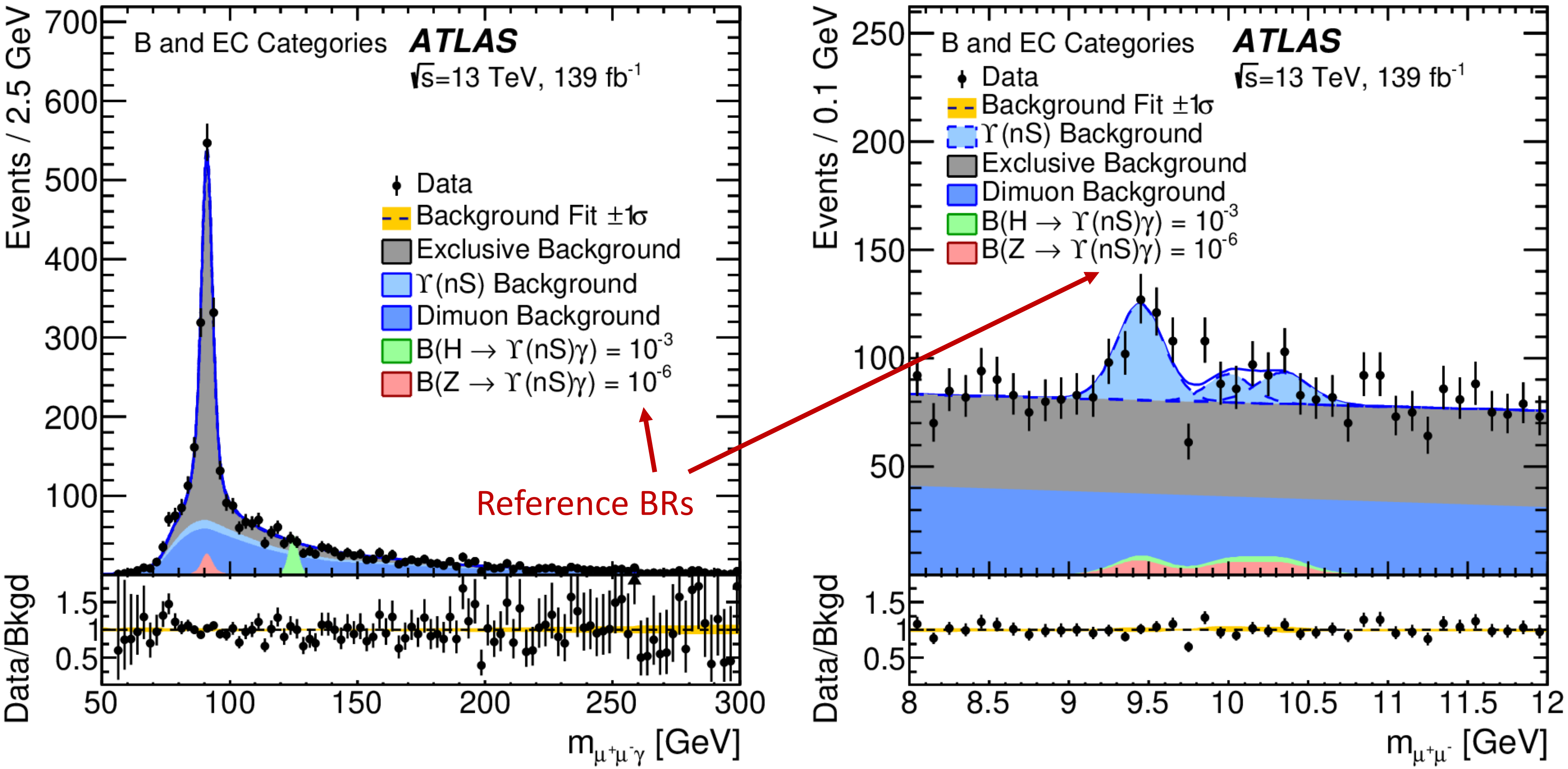
- Use **2D** unbinned likelihood fit in $m(\mu^+\mu^-), m(\mu^+\mu^-\gamma)$
  - Discriminates between **all** signal and background contributions
- $\psi(nS)\gamma$ analysis fit is performed in a single category

arXiv:2208.03122



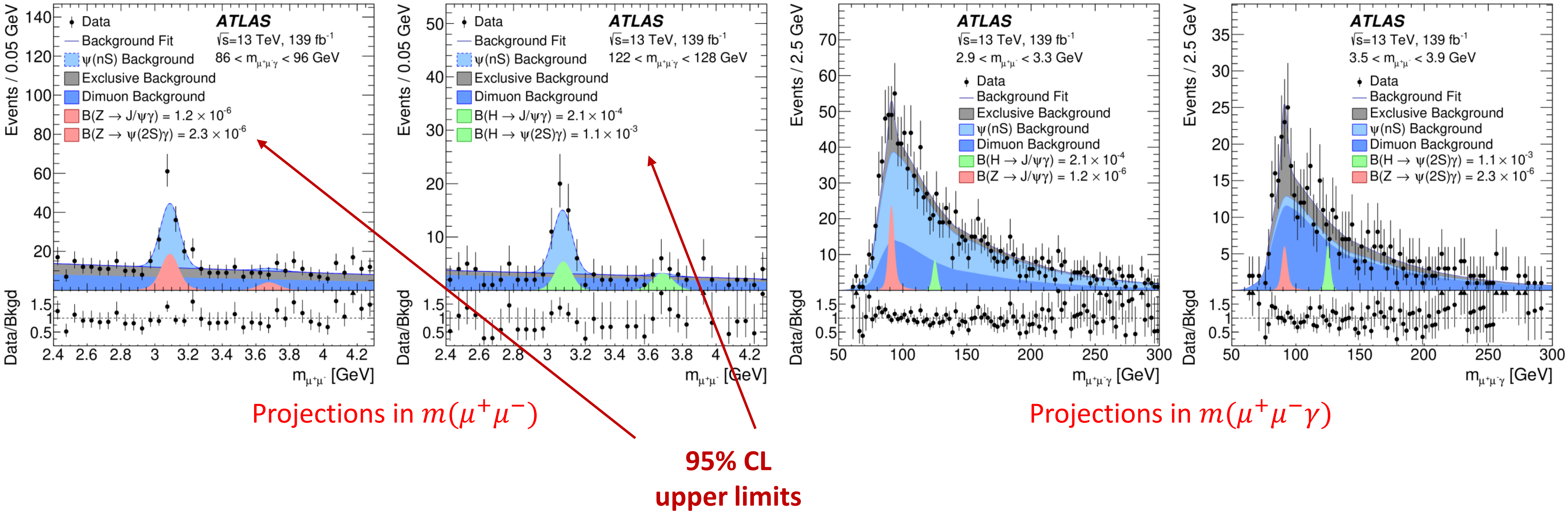
$H(Z) \rightarrow \Upsilon(nS)\gamma$: Inclusive Fit

- Use **2D** unbinned likelihood fit in $m(\mu^+\mu^-), m(\mu^+\mu^-\gamma)$ arXiv:2208.03122
  - Discriminates between **all** signal and background contributions
- $\Upsilon(nS)\gamma$ analysis fit is performed simultaneously in the barrel and endcap categories



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

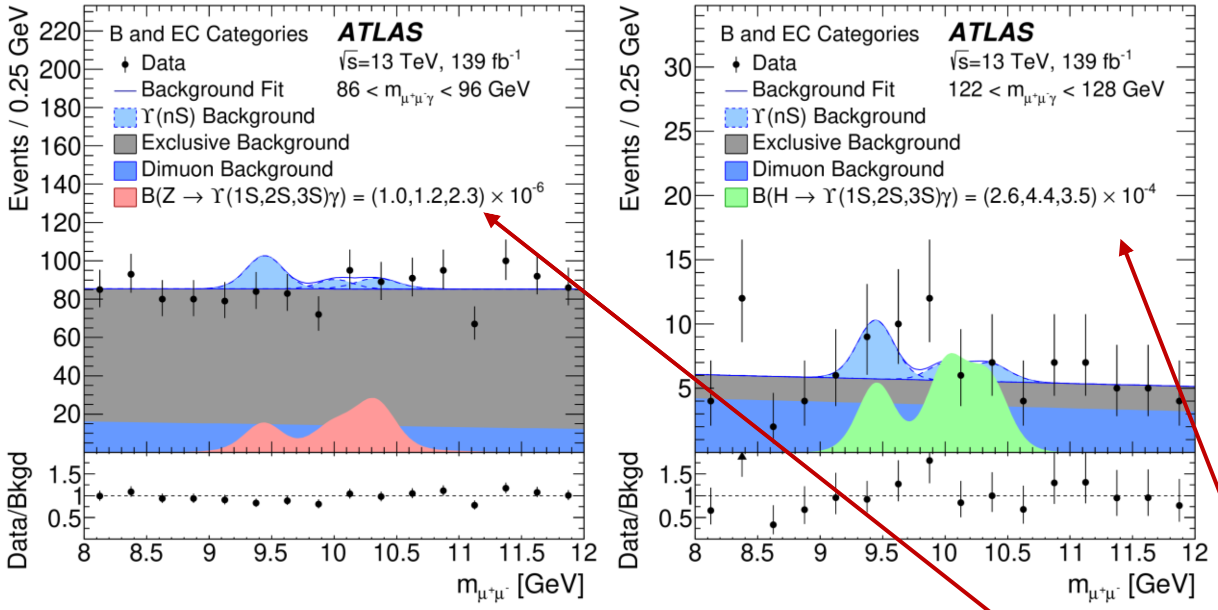
- Projection of fits fit near each signal resonance in each mass dimension



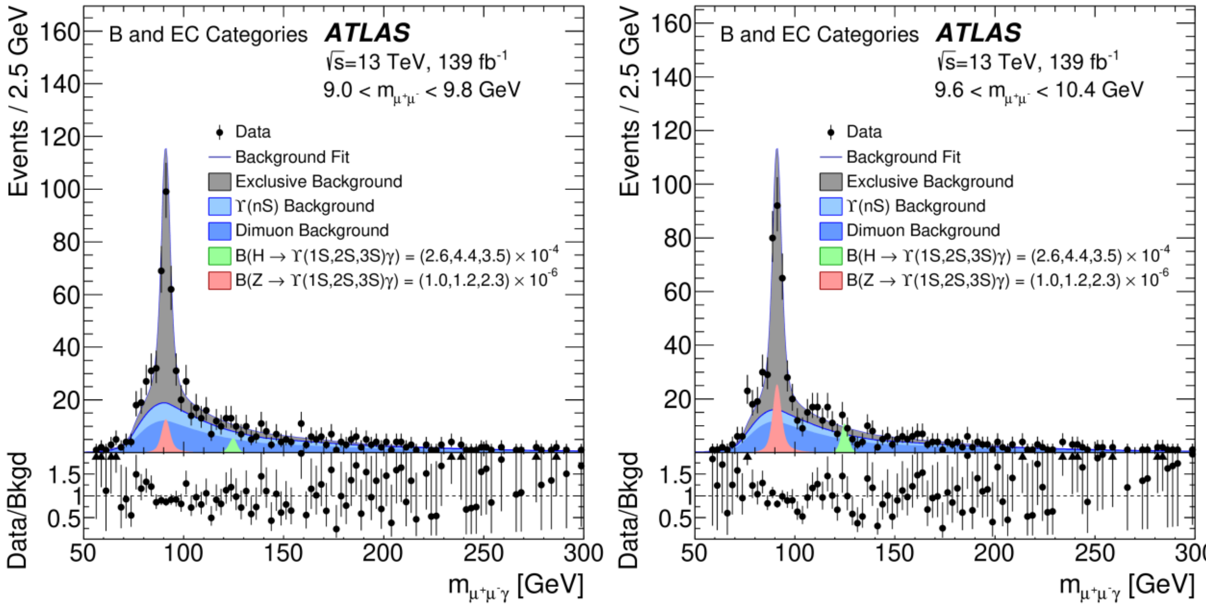
arXiv:2208.03122

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

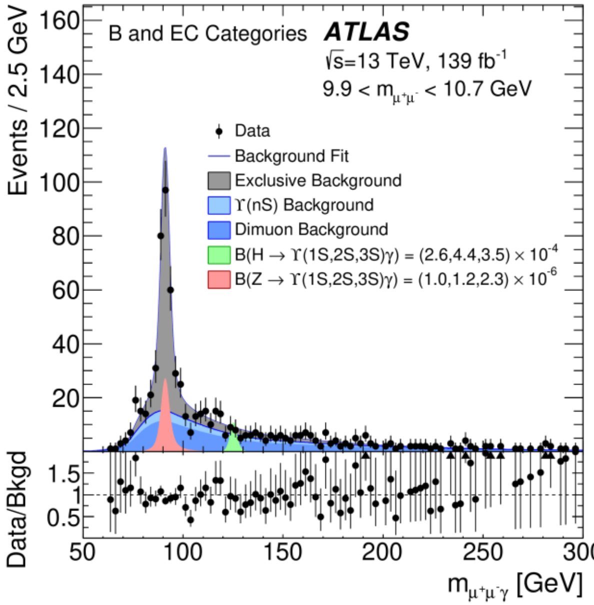
- Projection of fits fit near each signal resonance in each mass dimension



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



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



95% CL upper limits

arXiv:2208.03122

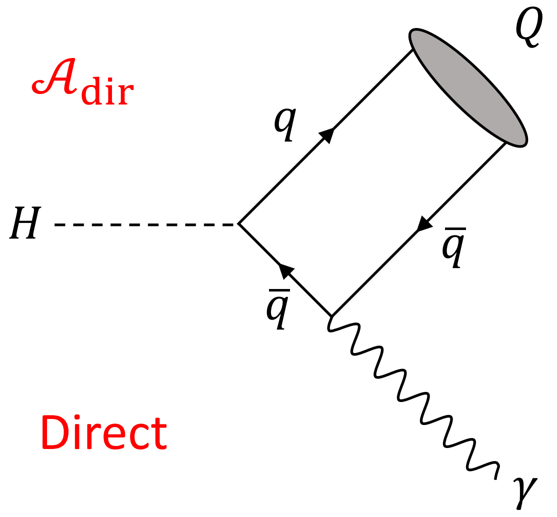
$H \rightarrow Q\gamma$: κ-Framework Interpretation

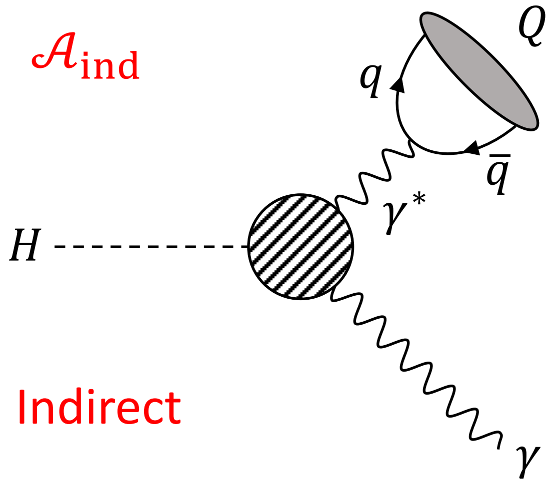
- κ_q coupling modifier: ratio of quark coupling g_q over the SM−expectation, $\kappa_q = \frac{g_q}{g_q^{SM}}$
- Combine with $H \rightarrow \gamma\gamma$ [§] to interpret in terms of $\kappa_{c,b}/\kappa_\gamma$:

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

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	$(-37, 40)$	$[-38, 40]$





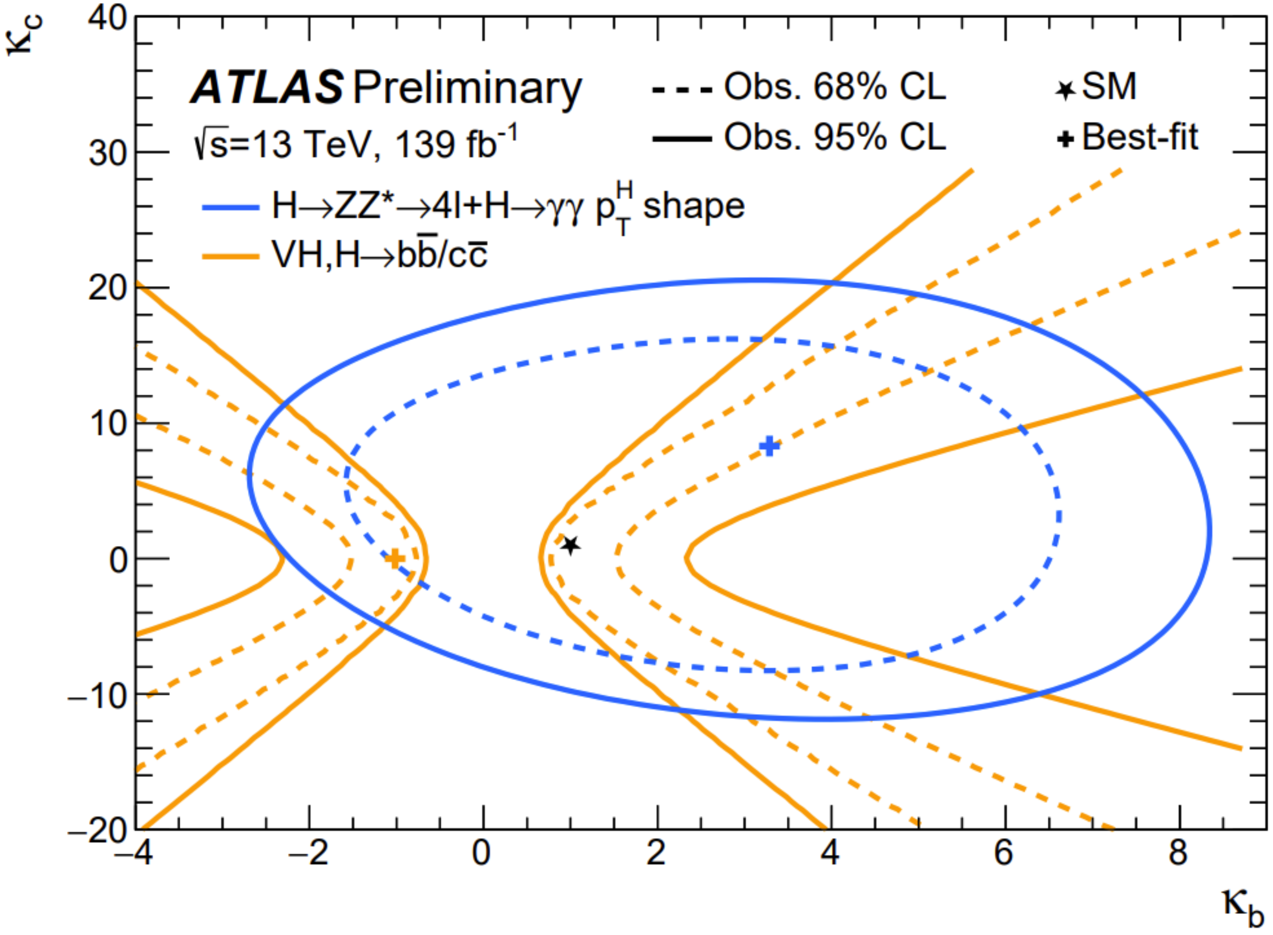
[§] ATLAS-CONF-2020-026

arXiv:2208.03122

Other κ-Framework Results

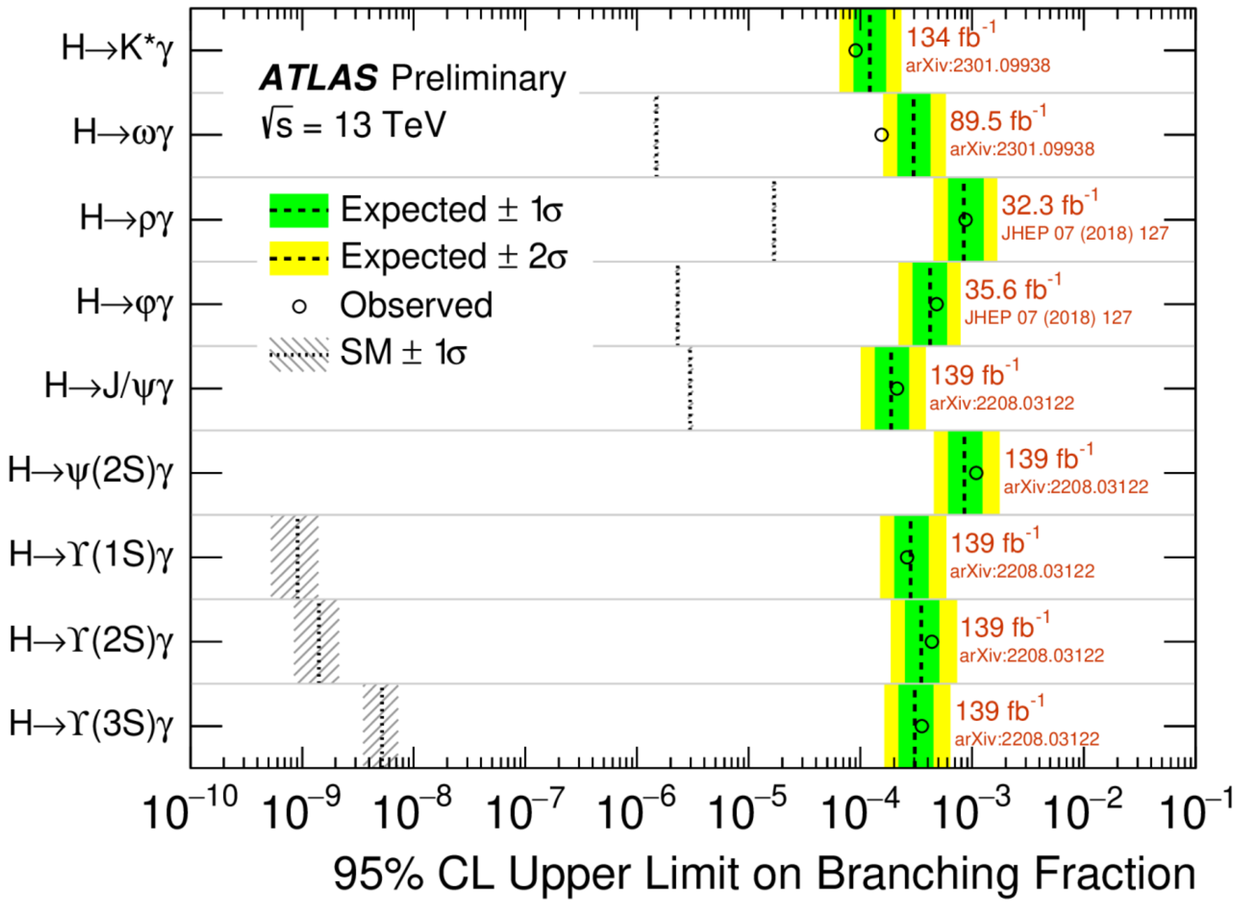
- κ-interpretation complements results from other searches
  - $H \to b\bar{b}$: Eur. Phys. J. C 81 (2021) 178
  - $H \to c\bar{c}$: Eur. Phys. J. C 82 (2022) 717
    - $|\kappa_c| < 8.5$ (12.4) @ 95% CL
    - $|\kappa_c/\kappa_b| < 4.5$ (5.1) @ 95% CL
  - Measurements of p_{T}^{H}: arXiv:2207.08615

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	$[-10.5,\ 18.0]$	$[-10.4,\ 16.6]$

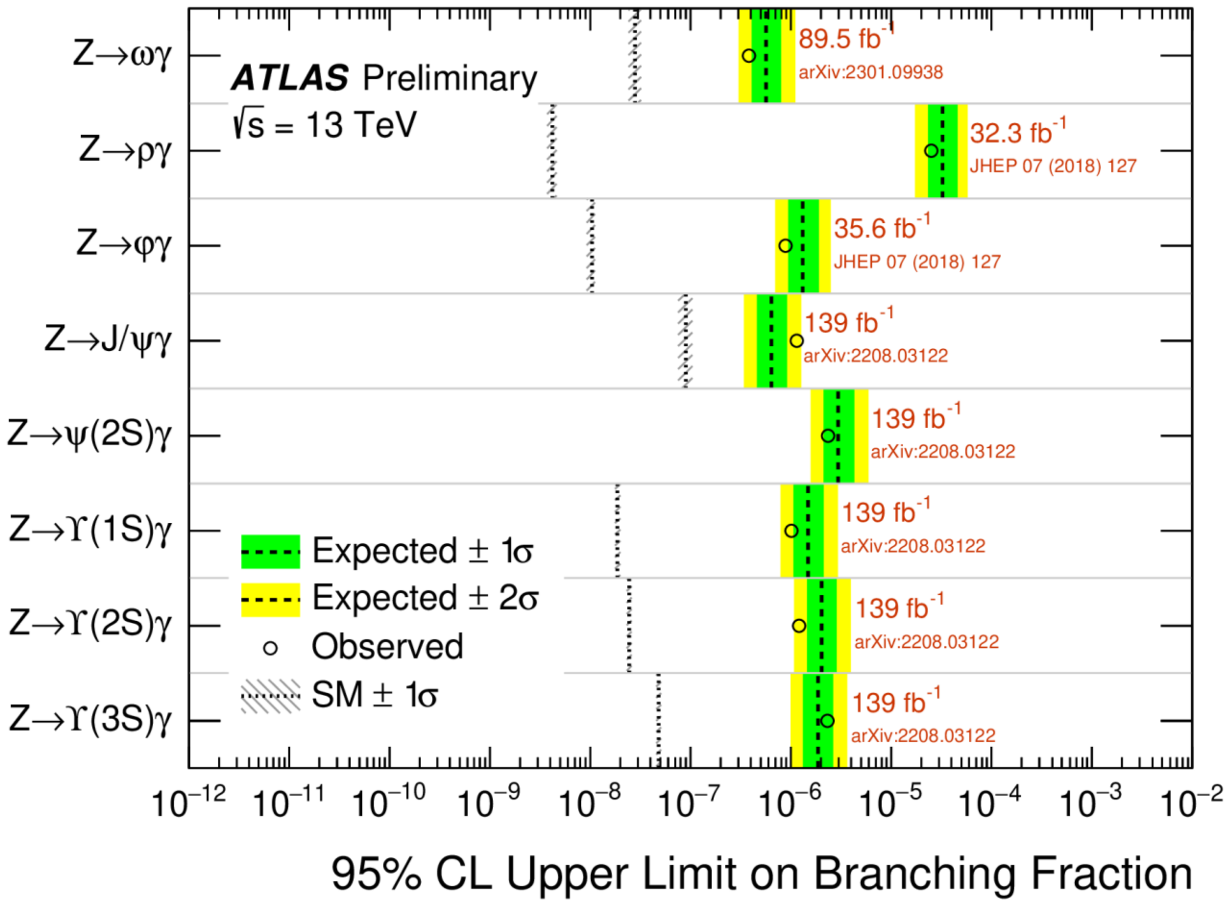


Summary of Exclusive $H(Z) \rightarrow M\gamma$ Search Results 2

ATL-PHYS-PUB-2023-004



Higgs Boson Decays (with SM Expectations)

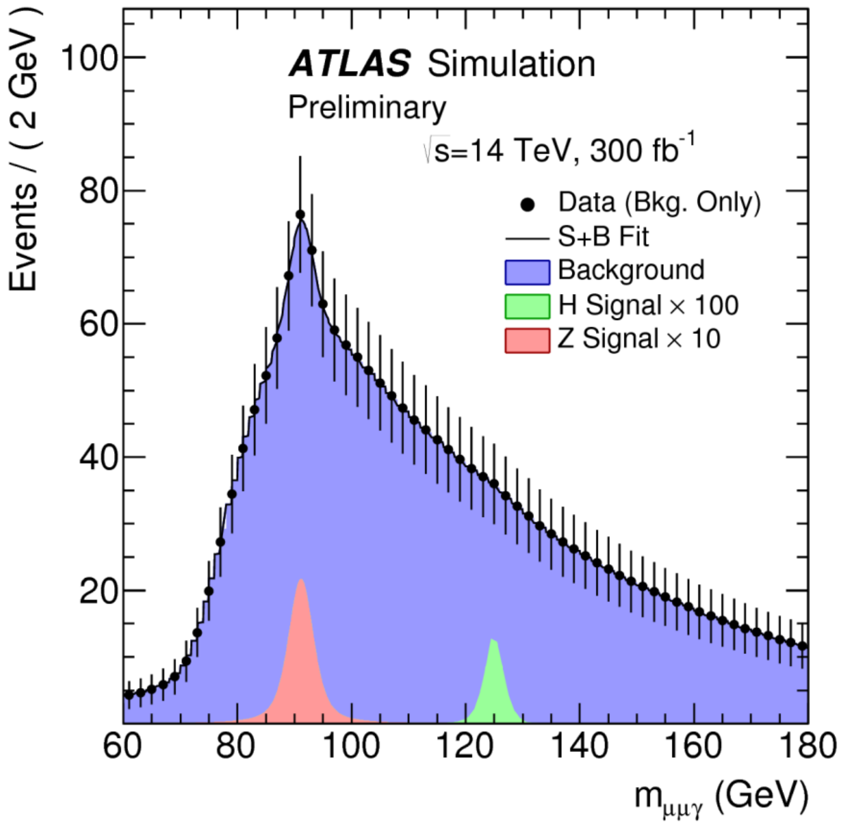


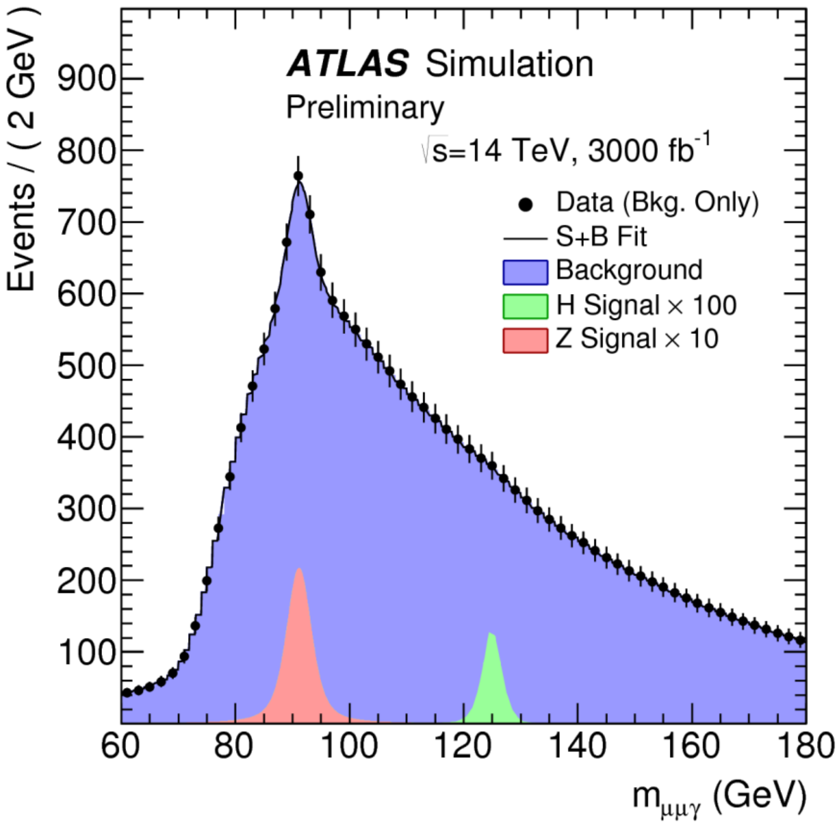
Z Boson Decays (with SM Expectations)

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

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

ATL-PHYS-PUB-2015-043

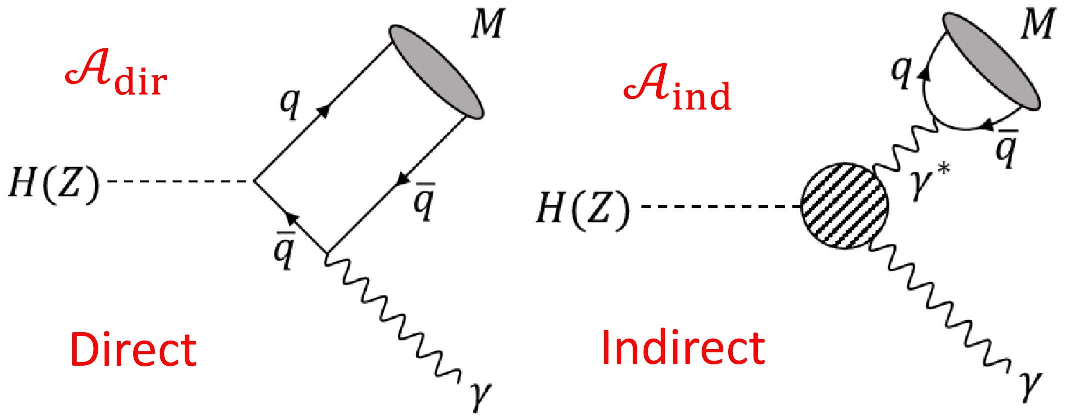




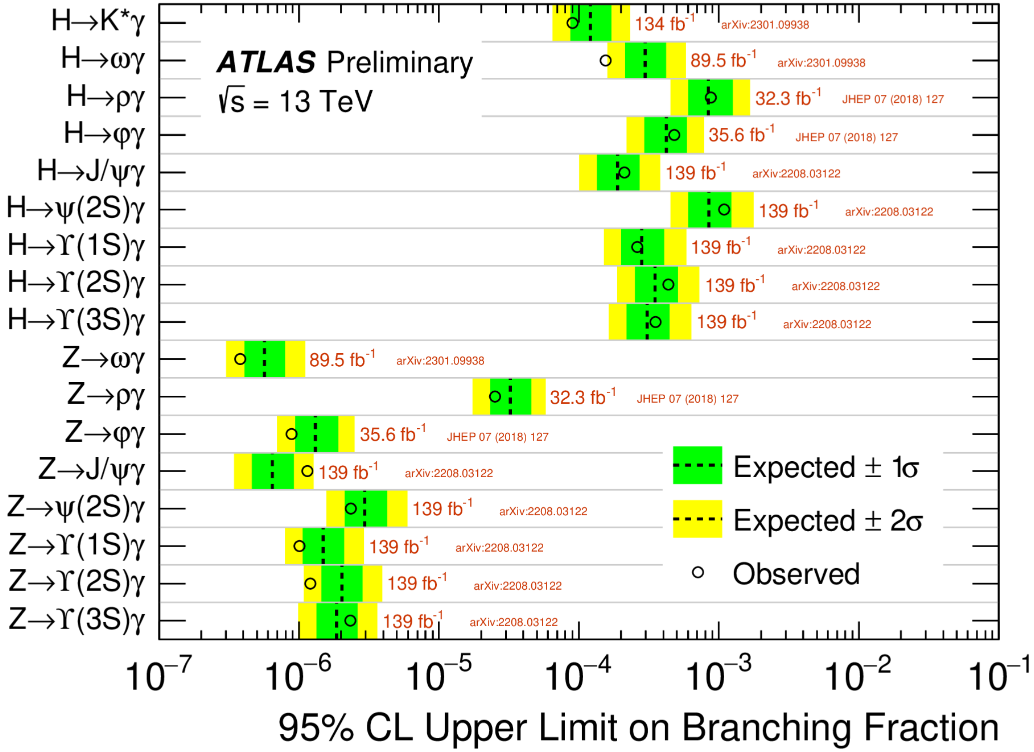
- Performed prospects study for $H(Z) \to J/\psi\,\gamma$ in 2015
  - Expected to reach $15 \times \mathrm{SM}$ and $4 \times \mathrm{SM}$ sensitivity respectively by HL-LHC (simple assumptions)
  - Room for improvement – but not far off!

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



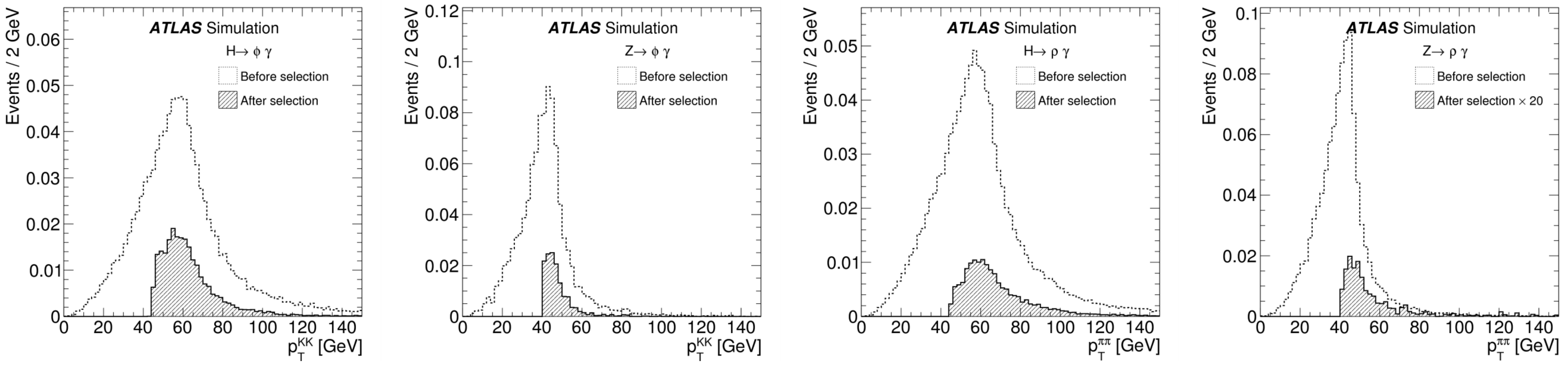
- $H(Z) \to (\phi, \rho)\gamma$: JHEP 07 (2018) 127
  - 2nd iteration of analysis
  - Published in JHEP (2018)
- $H(Z) \to \omega\gamma$ and $H \to K^*\gamma$: arXiv:2301.09938
  - 1st iteration of analysis
  - Submitted to PLB
- $H(Z) \to Q\gamma$: arXiv:2208.03122
  - 3rd iteration of analysis
  -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



ADDITIONAL SLIDES

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

- Meson p_{T} distributions for each signal decay



JHEP 07 (2018) 127

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

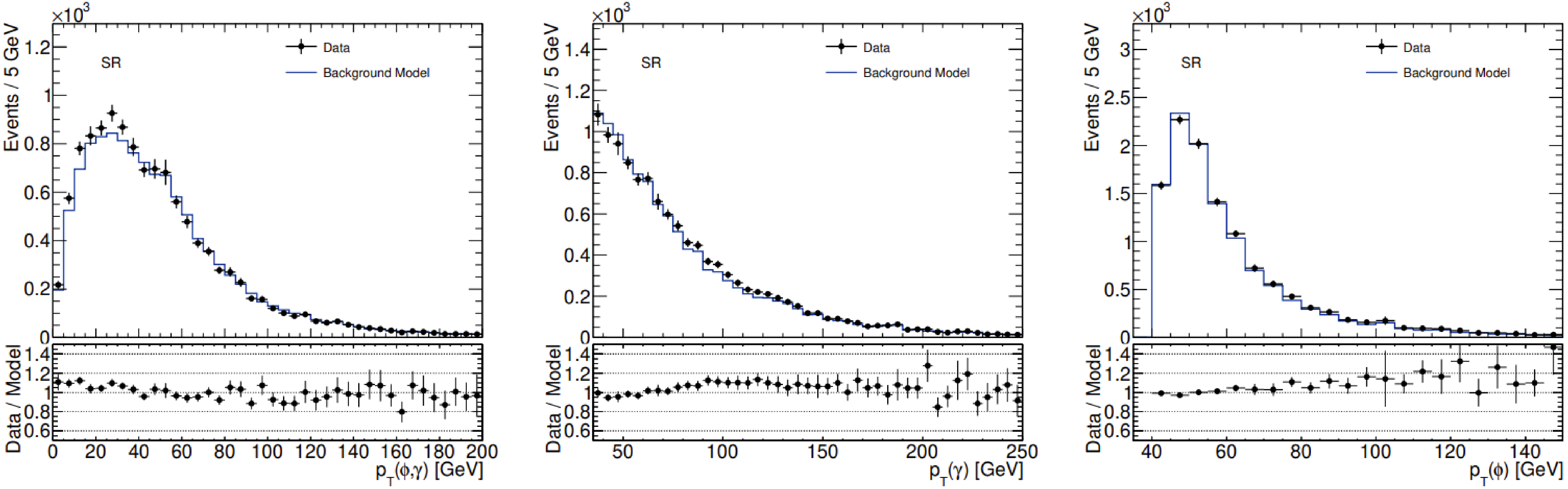
- Take into account relevant uncertainties on the total signal yield
  - Nuisance parameters with standard Gaussian constraints in maximum likelihood fit
  - Shape uncertainties found to be negligible

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

Non-Parametric Data Driven Model: Additional Variables 1

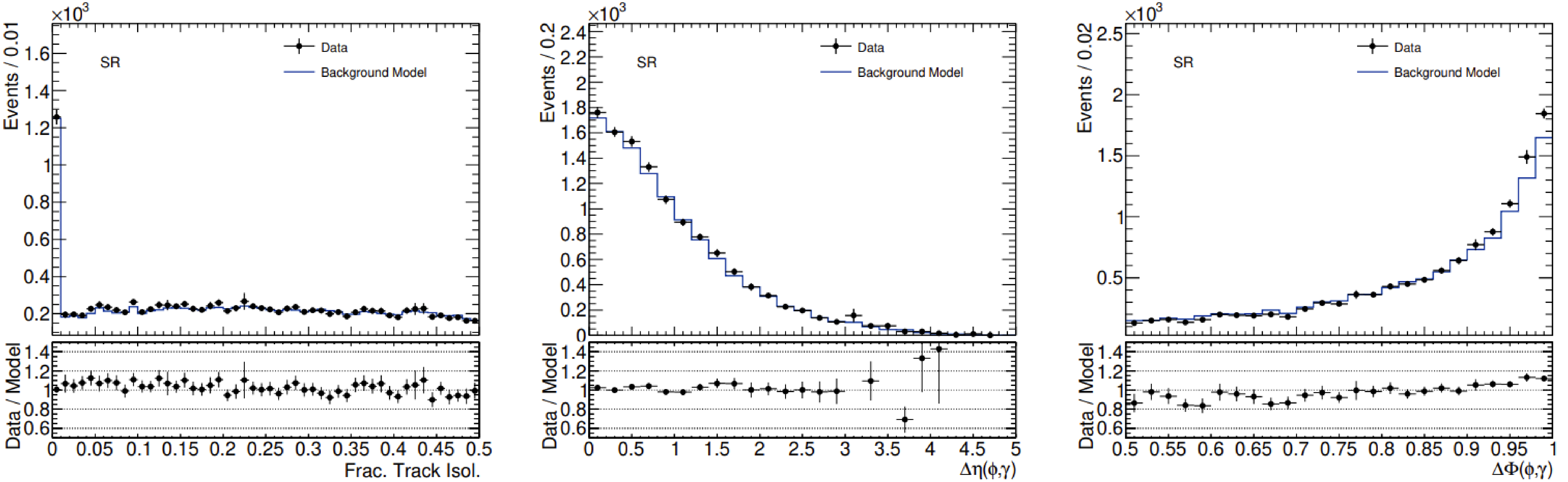
- Non-discriminant variables can also be used in model validation
  - Less important as not used in fit – but can help troubleshoot issues



JHEP 10 (2022) 001

Non-Parametric Data Driven Model: Additional Variables 2

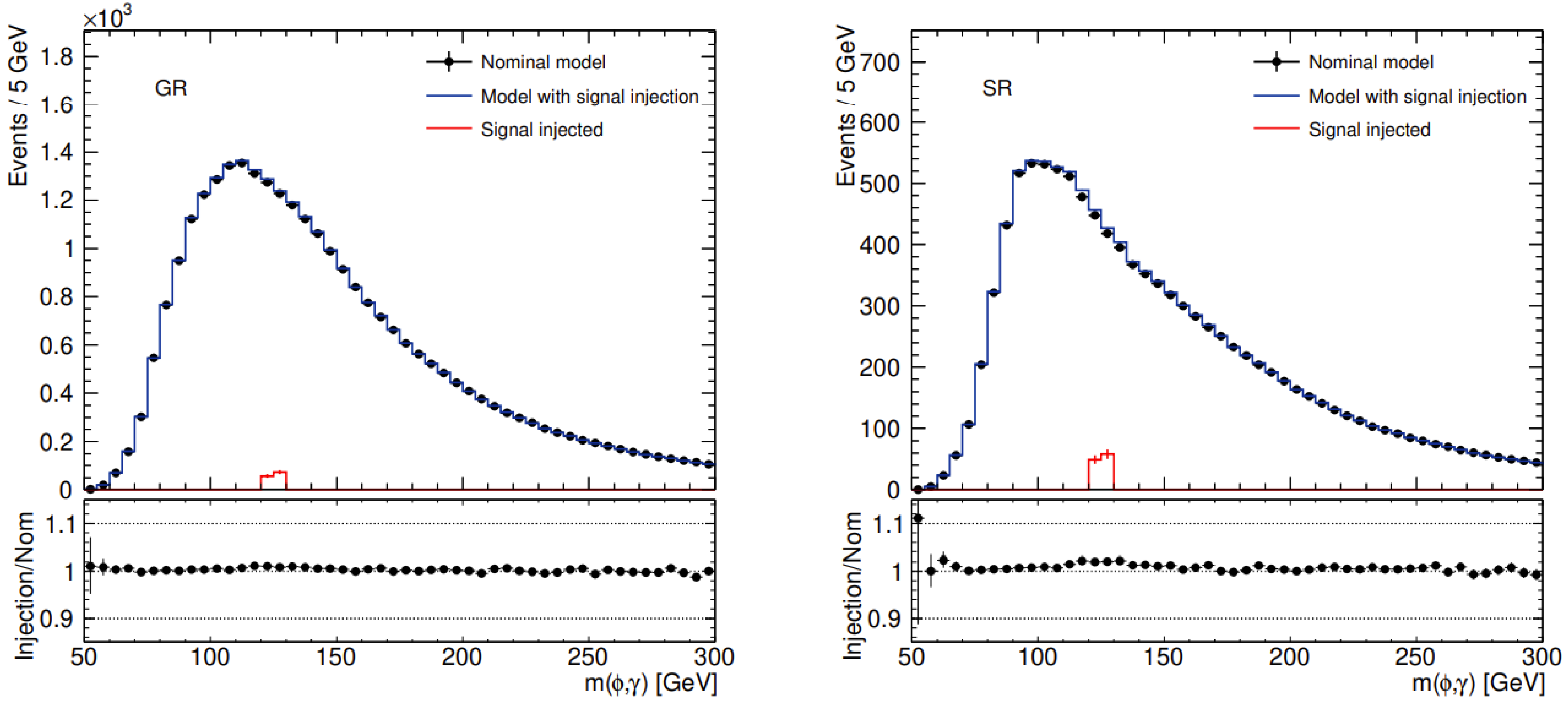
- Non-discriminant variables can also be used in model validation
  - Less important as not used in fit – but can help troubleshoot issues



JHEP 10 (2022) 001

Non-Parametric Data Driven Model: Signal Injection

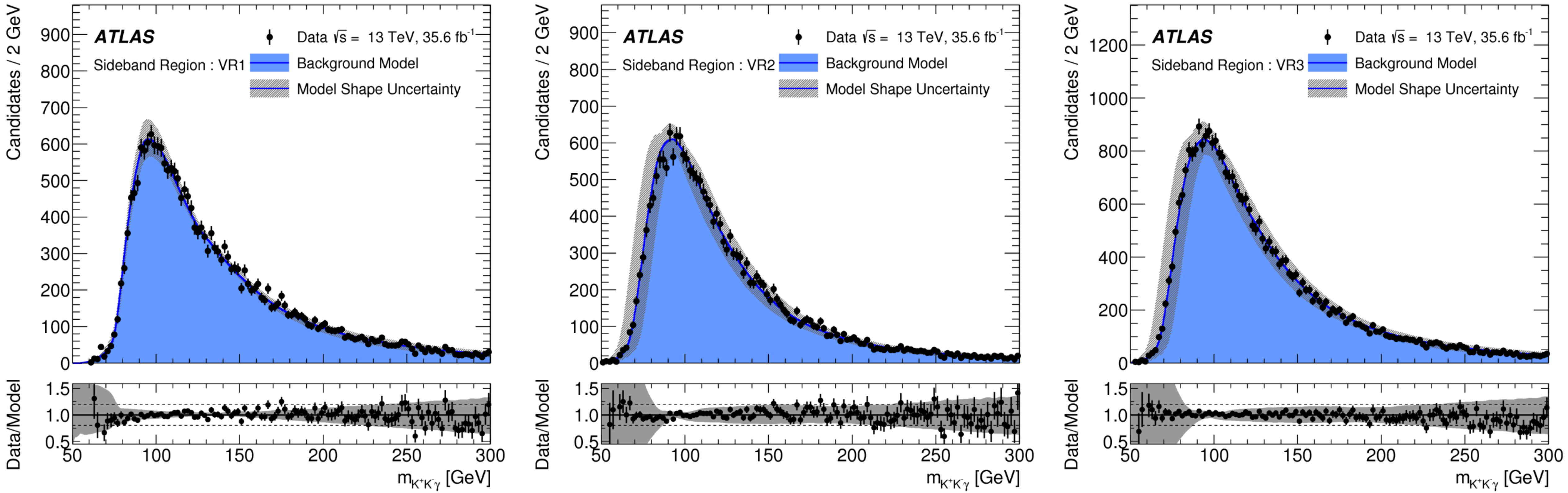
- Model is robust against signal contamination in GR
  - Injected 5.5σ worth of signal in GR to test this – change in model prediction near H signal in SR only $\sim 2\%$



JHEP 10 (2022) 001

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

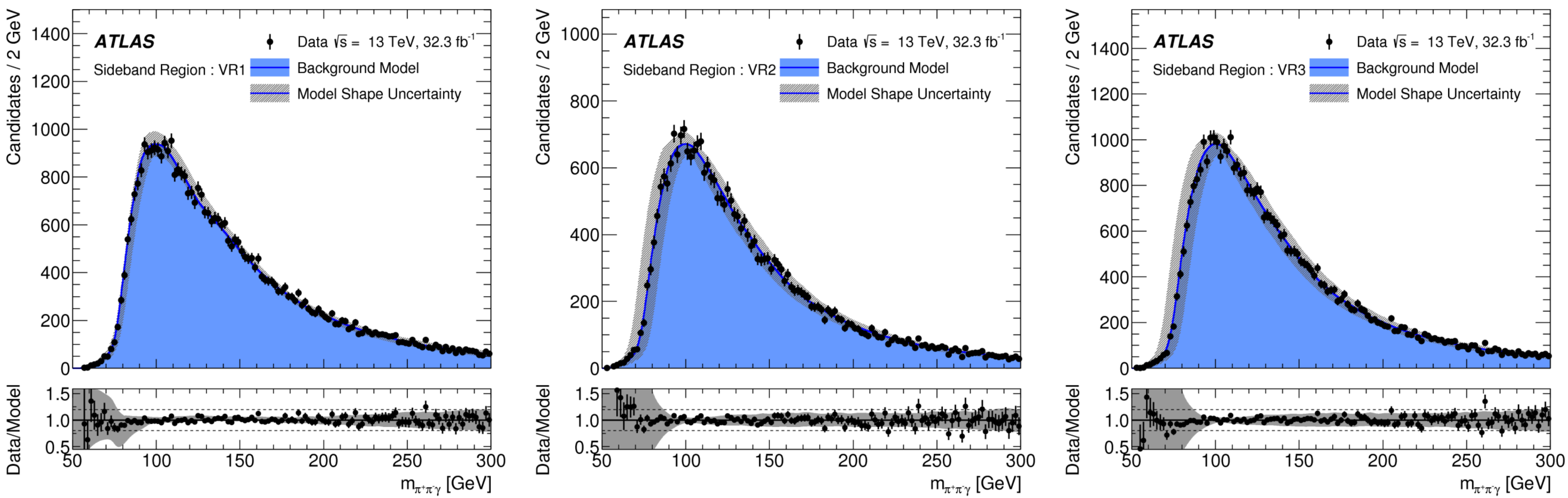
- Validation plots in $\phi\gamma$ sideband regions



JHEP 07 (2018) 127

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

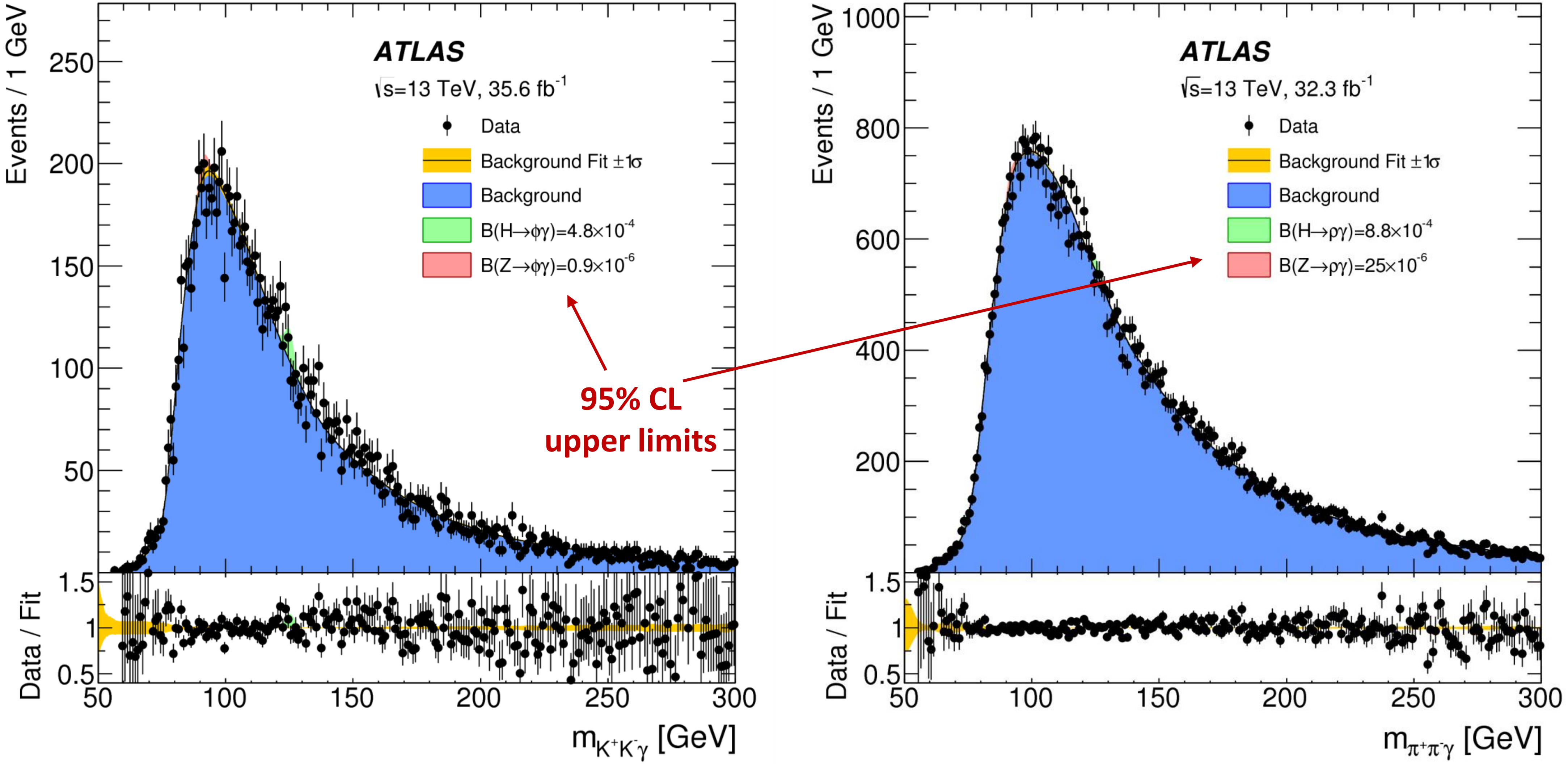
- Validation plots in $\rho\gamma$ sideband regions



JHEP 07 (2018) 127

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

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



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

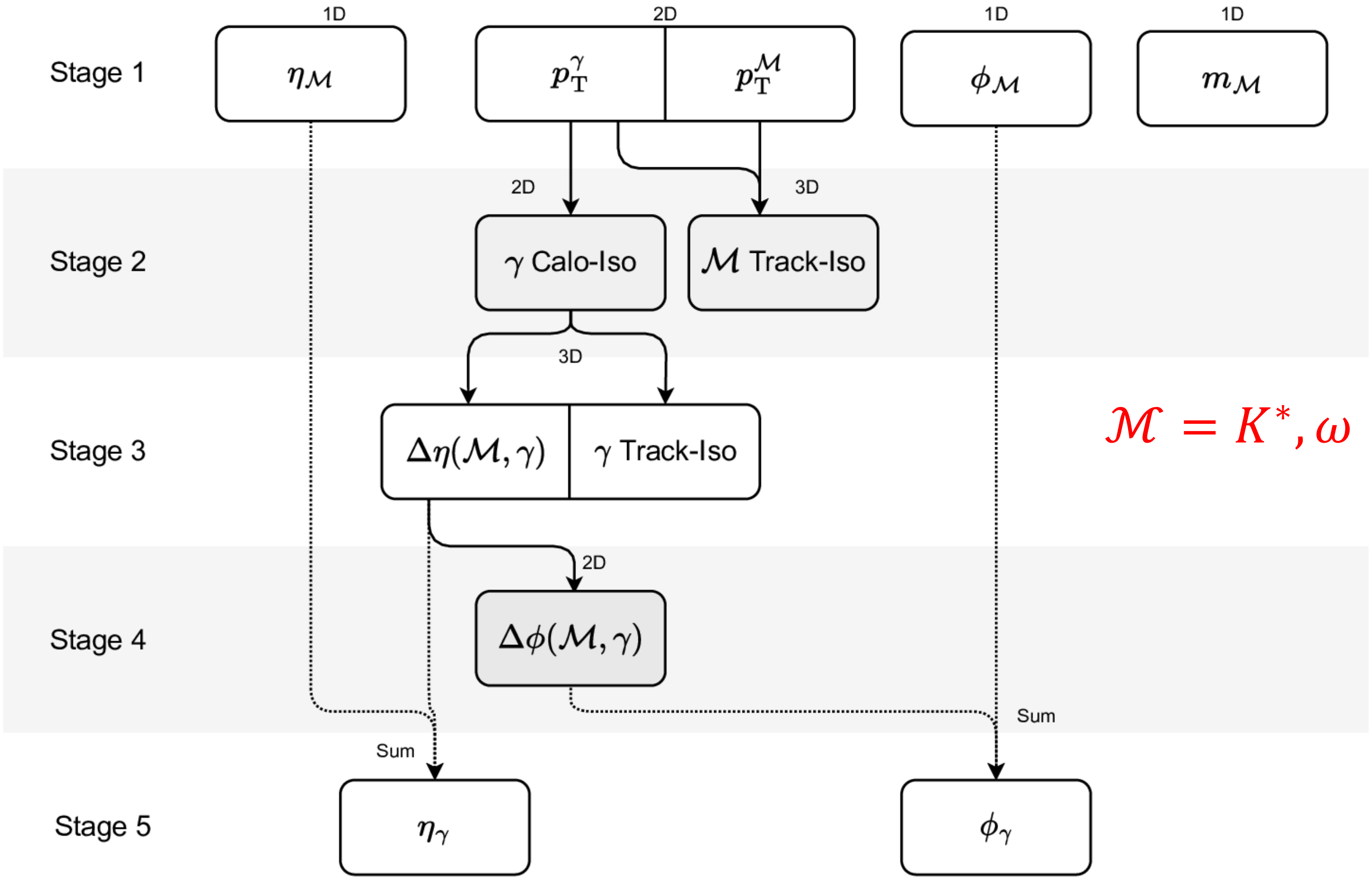
Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \rightarrow \phi\gamma)\,[10^{-4}]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \rightarrow \phi\gamma)\,[10^{-6}]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \rightarrow \rho\gamma)\,[10^{-4}]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \rightarrow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

$H \to K^*\gamma$ and $H(Z) \to \omega\gamma$: 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 $\mathcal{B} = 10^{-6}$
$H \to \omega\gamma$	115–135	681 (724 ± 16)	33 ± 4	–
$Z \to \omega\gamma$	80–100	385 (382 ± 17)	–	149 ± 13
$H \to K^*\gamma$	120–130	10474 (10550 ± 60)	163 ± 15	–

Observed and Expected Events

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

Observed and Expected Limits

arXiv:2301.09938

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

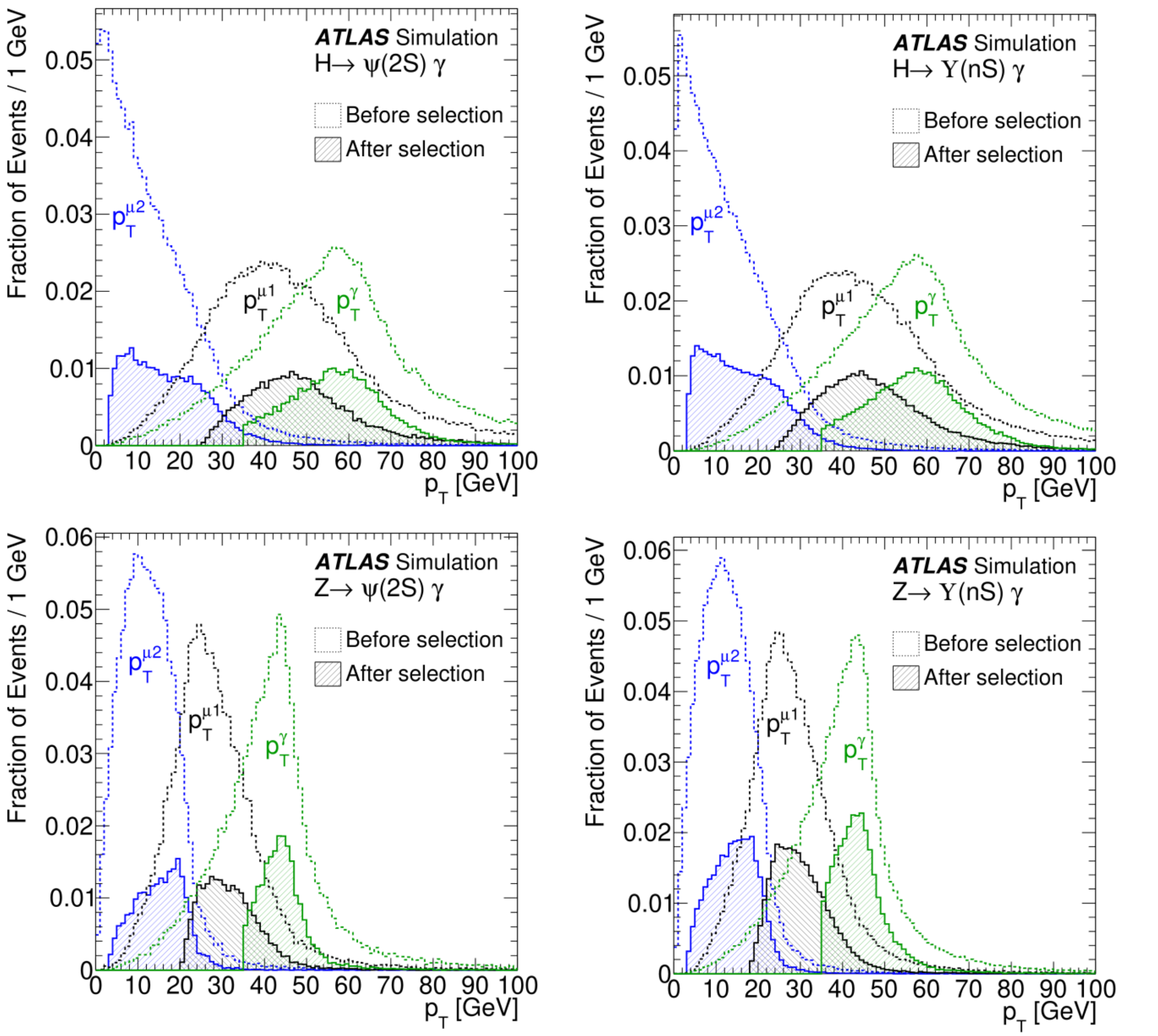
Red: Not applied in GR

Quarkonium	Composition	Mass [GeV]	Width [keV]	$\mathcal{B}(Q \to \mu^+\mu^-)$
J/ψ	$c\bar{c}$	3.10	92.9 ± 2.8	$(5.96 \pm 0.03)\%$
$\psi(2S)$	$c\bar{c}$	3.69	294.0 ± 8.0	$(0.80 \pm 0.06)\%$
$\Upsilon(1S)$	$b\bar{b}$	9.46	54.0 ± 1.3	$(2.48 \pm 0.05)\%$
$\Upsilon(2S)$	$b\bar{b}$	10.02	32.0 ± 2.6	$(1.93 \pm 0.17)\%$
$\Upsilon(3S)$	$b\bar{b}$	10.36	20.3 ± 1.9	$(2.18 \pm 0.21)\%$

arXiv:2208.03122

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

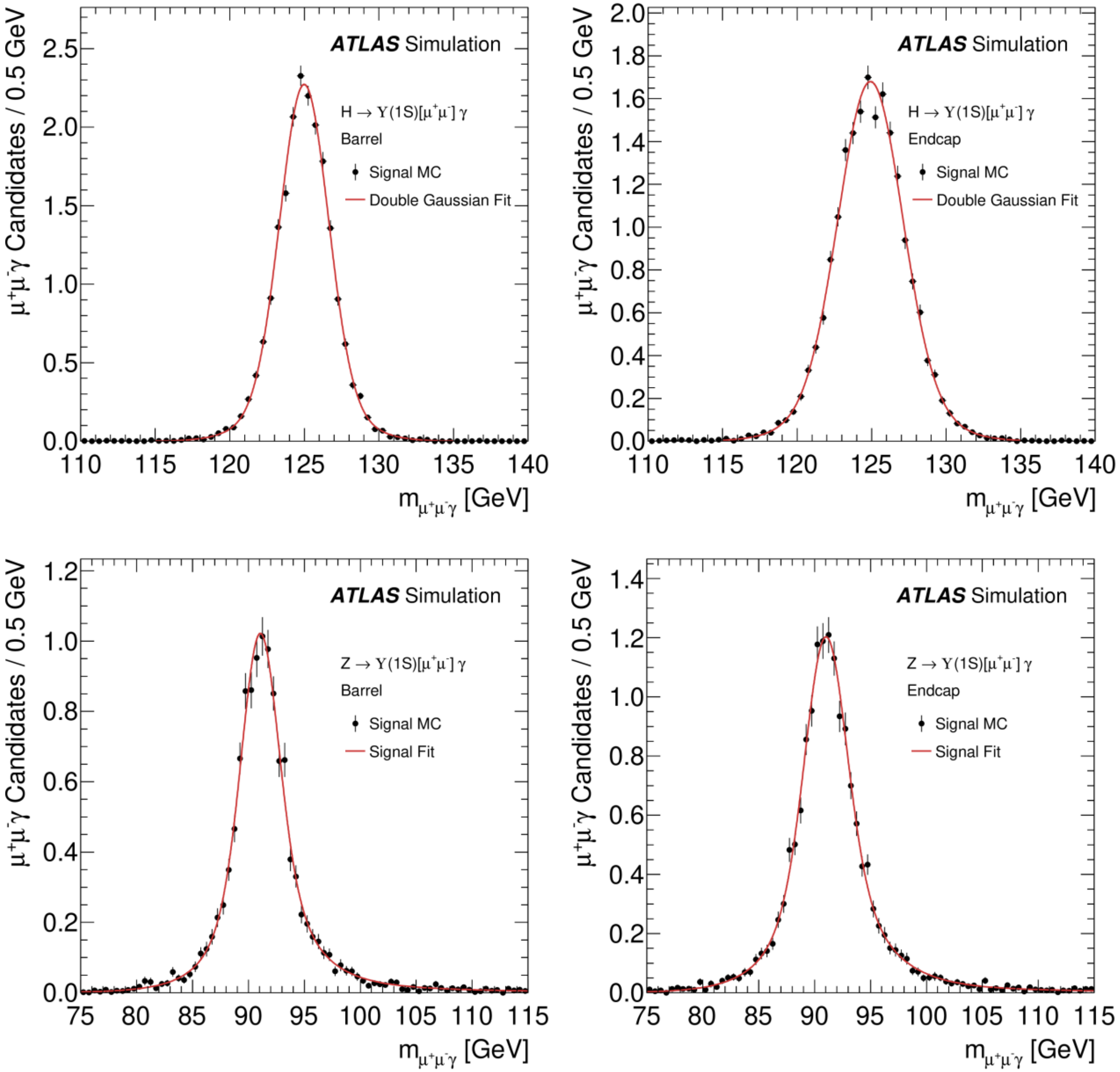
- Generator p_{T} plots for $\psi(2S)\gamma$ and $\Upsilon(nS)\gamma$ channels



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

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

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

- Define three VRs for $Q\gamma$

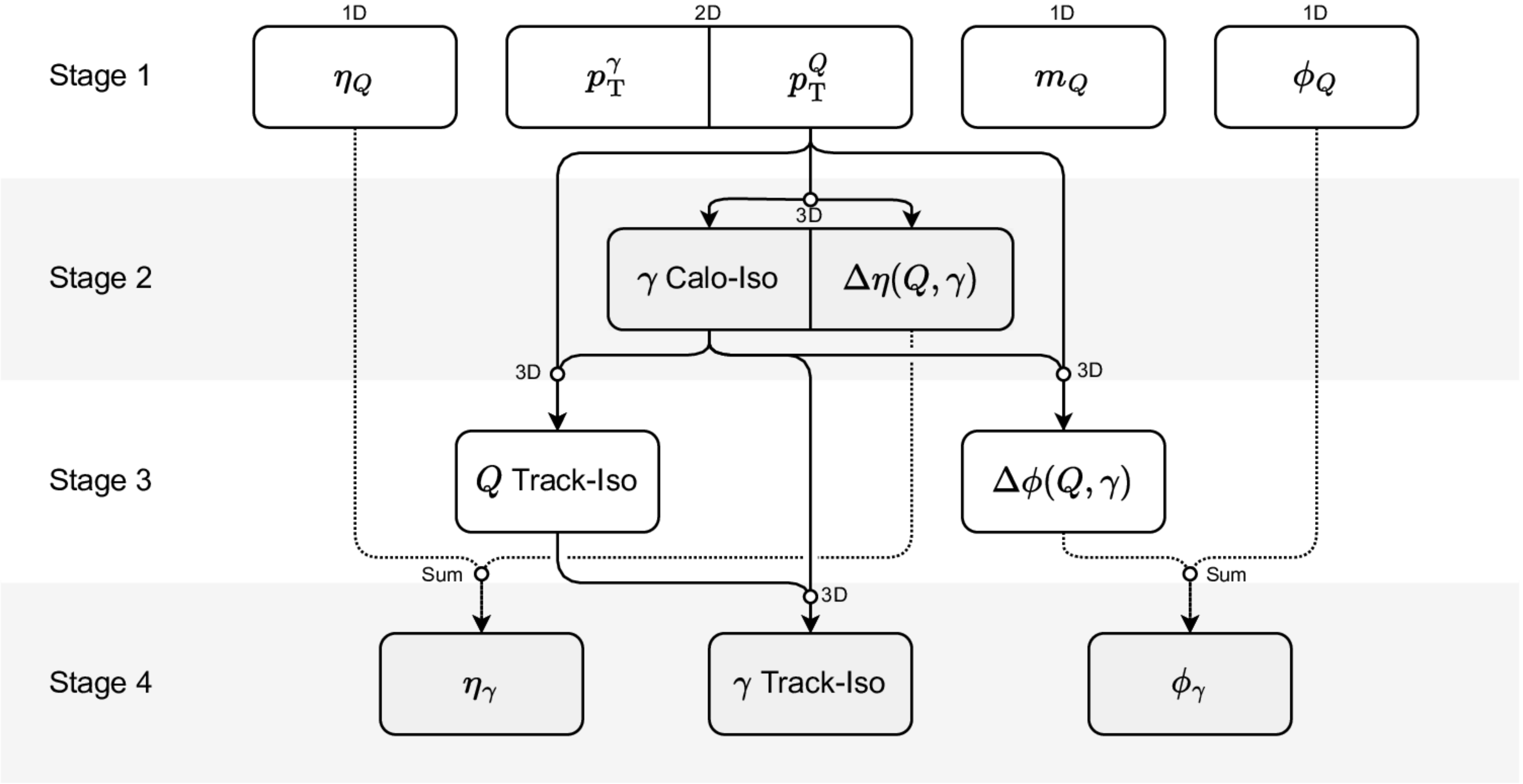
Region		$p_{\mathrm{T}}^{\mu\mu}$	Photon Isolation	Q Isolation
Generation Region	(GR)	> 30 GeV	Relaxed	Relaxed
Validation Region 1	(VR1)	Full	Relaxed	Relaxed
Validation Region 2	(VR2)	> 30 GeV	Relaxed	Full
Validation Region 3	(VR3)	> 30 GeV	Full	Relaxed
Signal Region	(SR)	Full	Full	Full

Region Definitions

arXiv:2208.03122

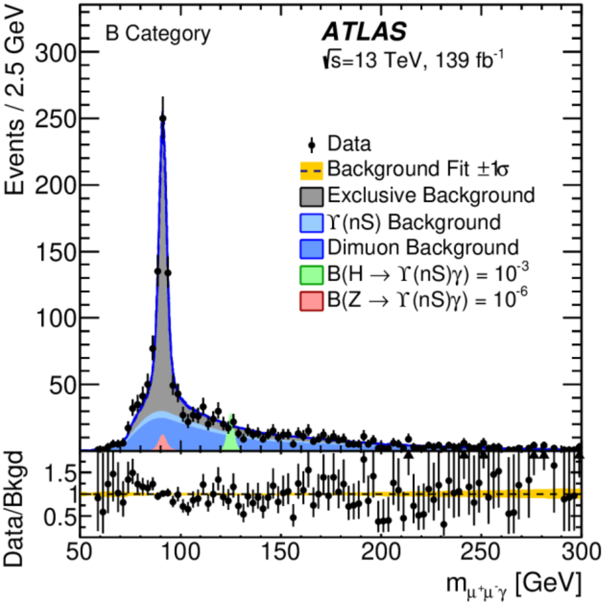
$H(Z) \to Q\gamma$: Ancestral Sampling Scheme

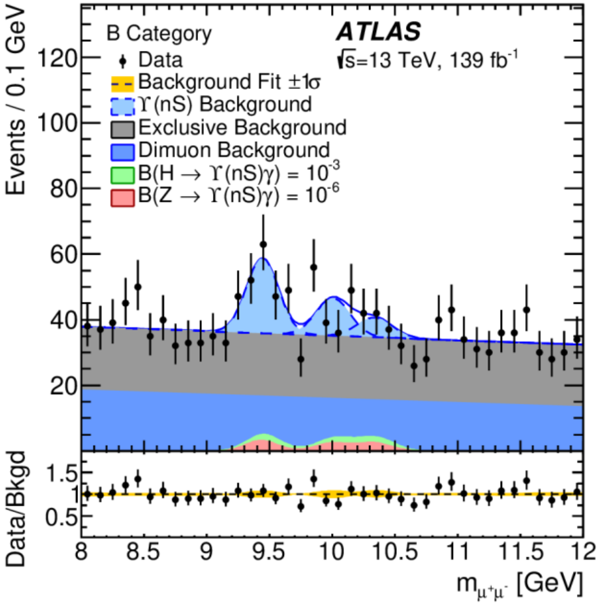
➤ Subtract exclusive background events from data in GR before generating inclusive model

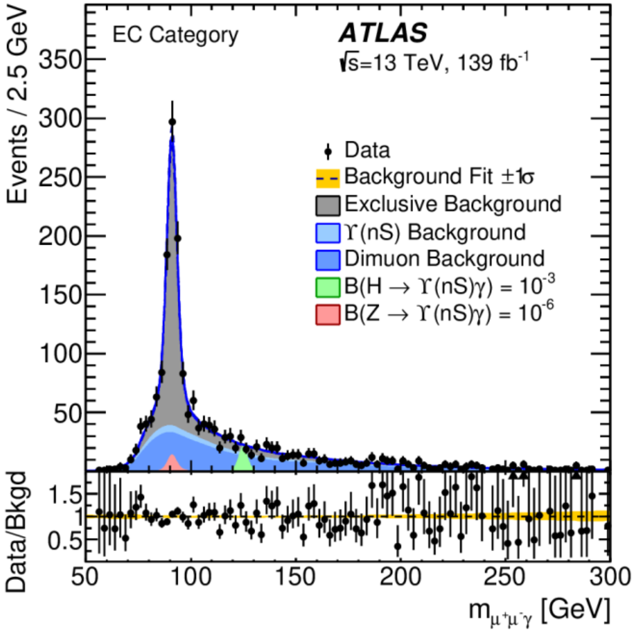


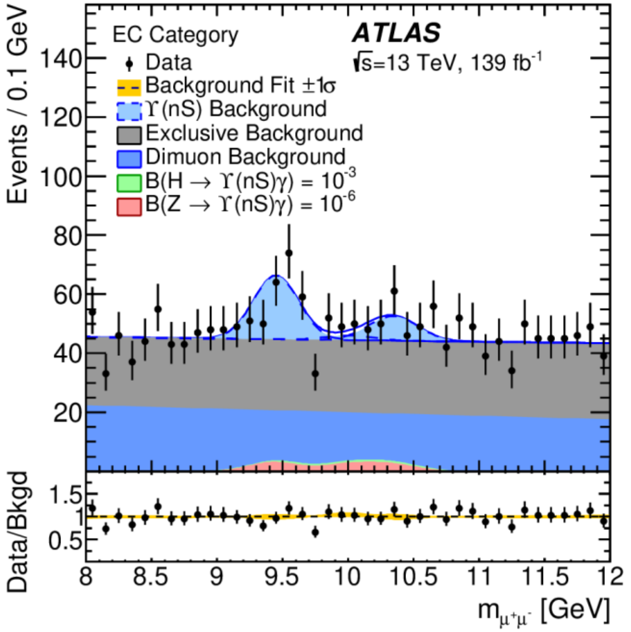
arXiv:2208.03122

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



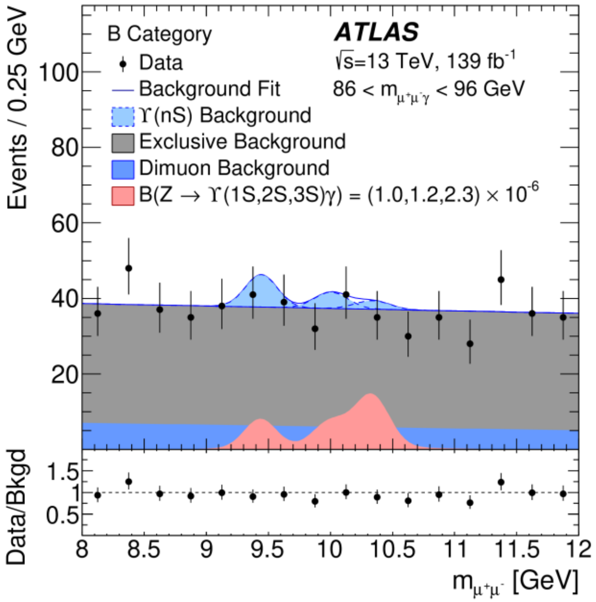


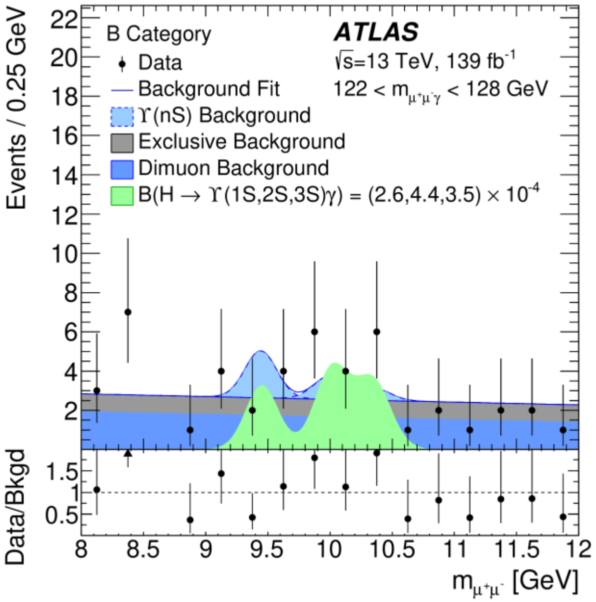


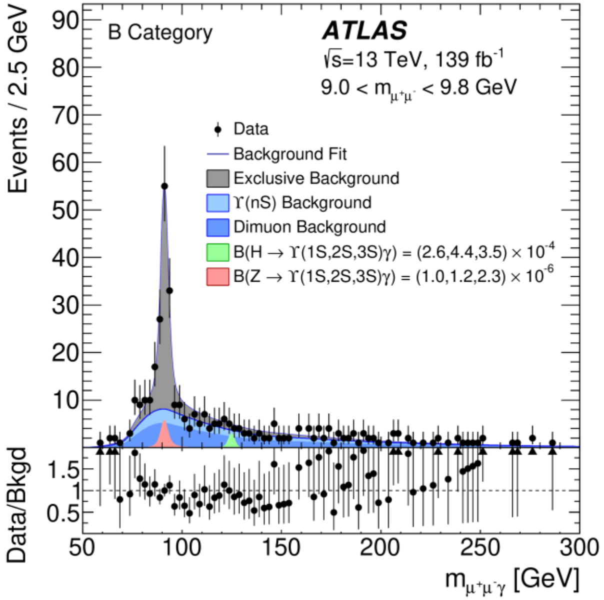


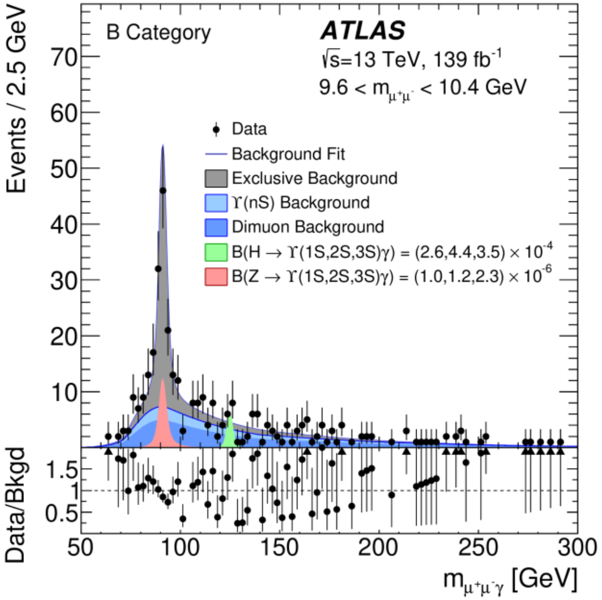
arXiv:2208.03122

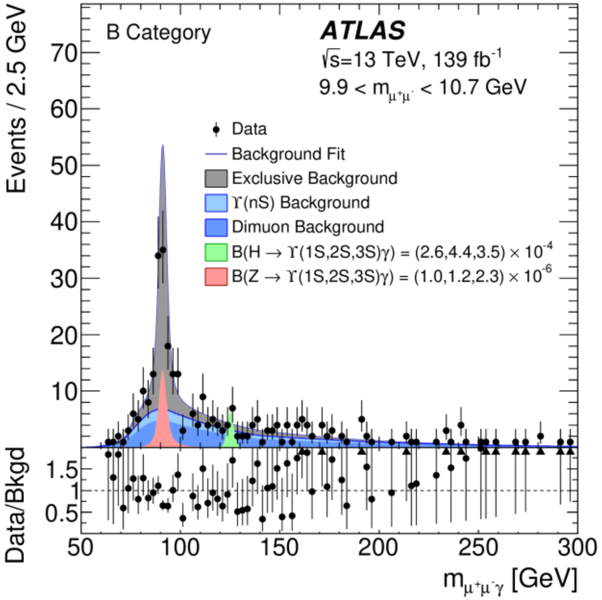
$H(Z) \rightarrow \Upsilon(nS)\gamma$: Barrel Category Projections





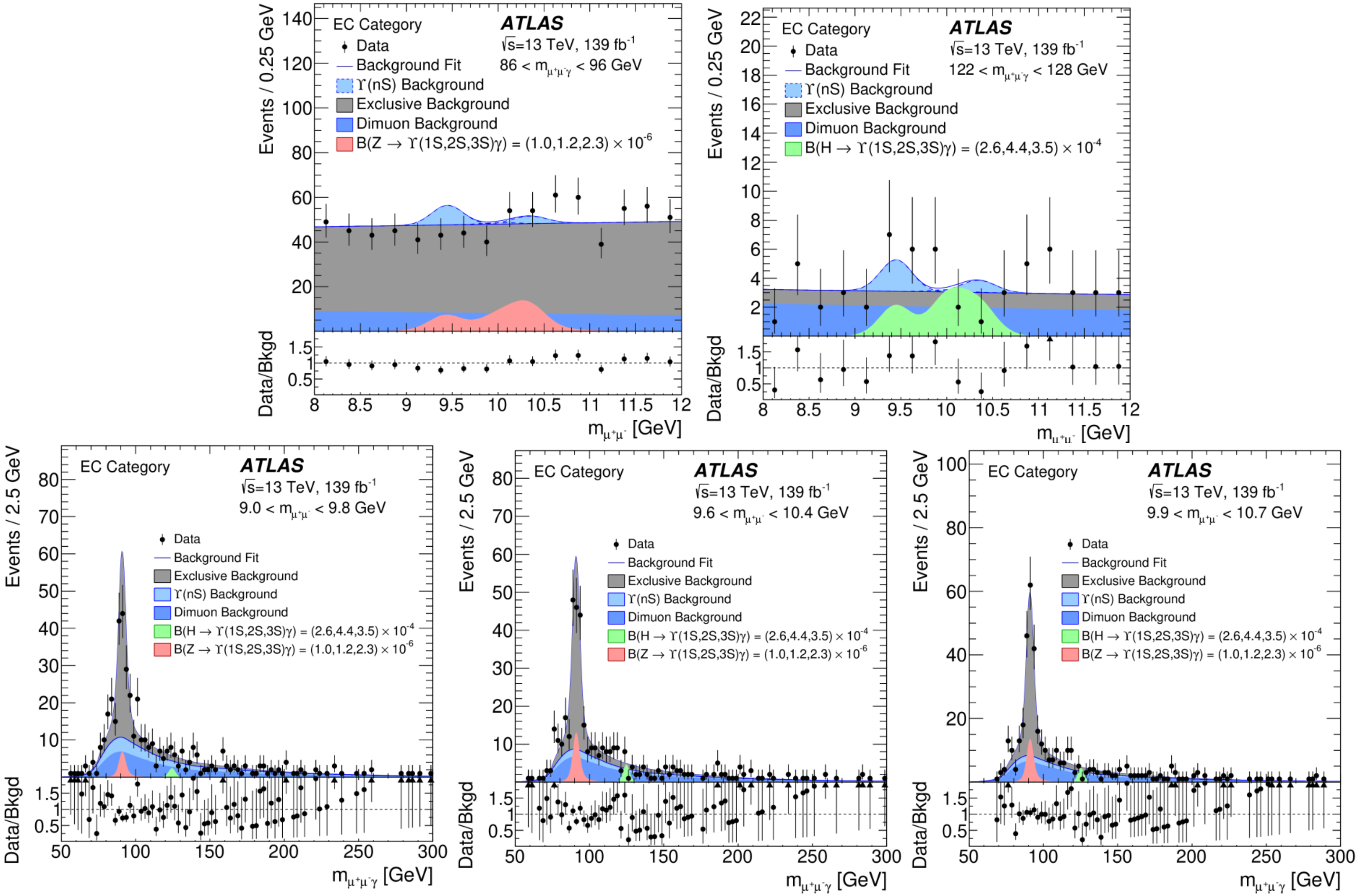






arXiv:2208.03122

$H(Z) \to \Upsilon(nS)\gamma$: 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	Higgs boson [10^{-4}] Observed	Z boson [10^{-6}] Expected	Z boson [10^{-6}] 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

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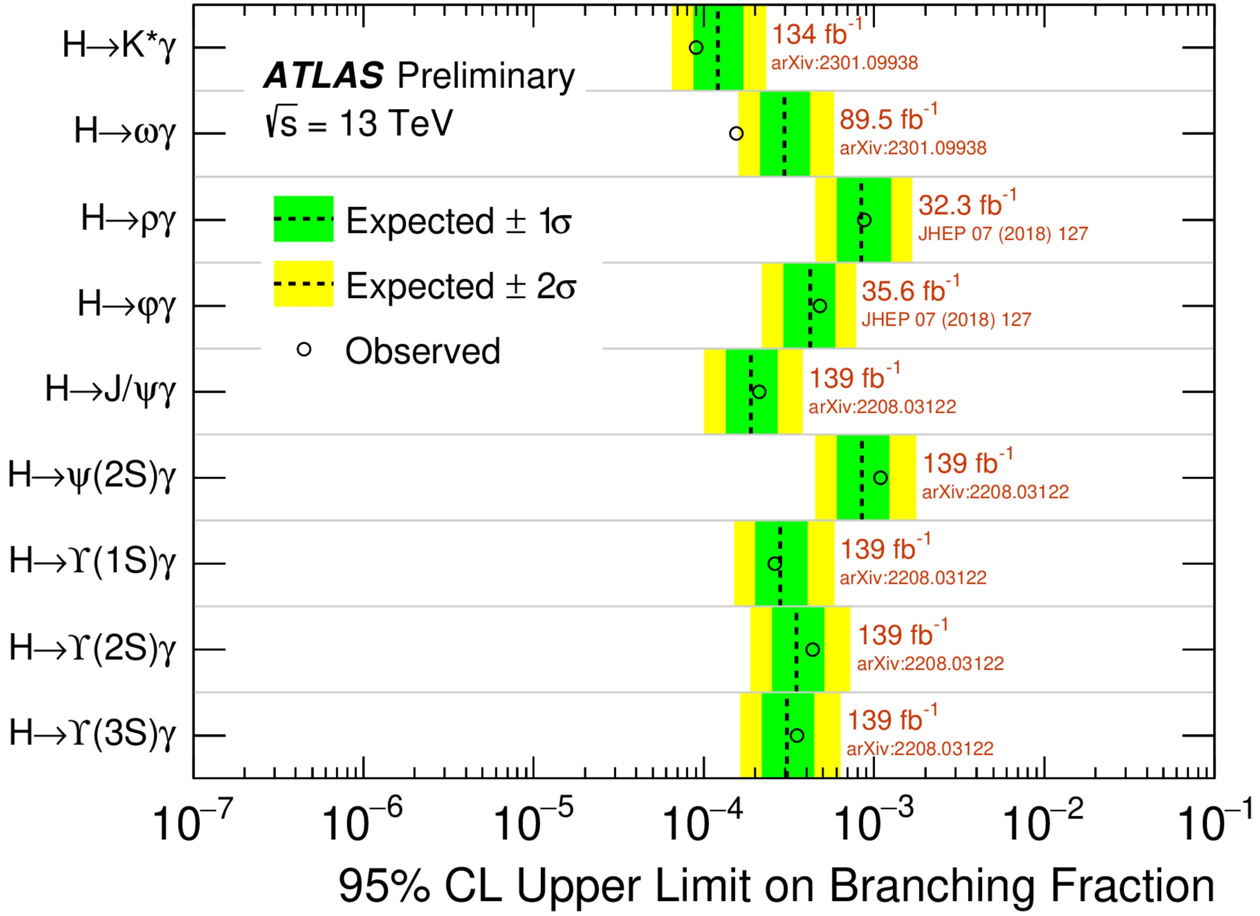
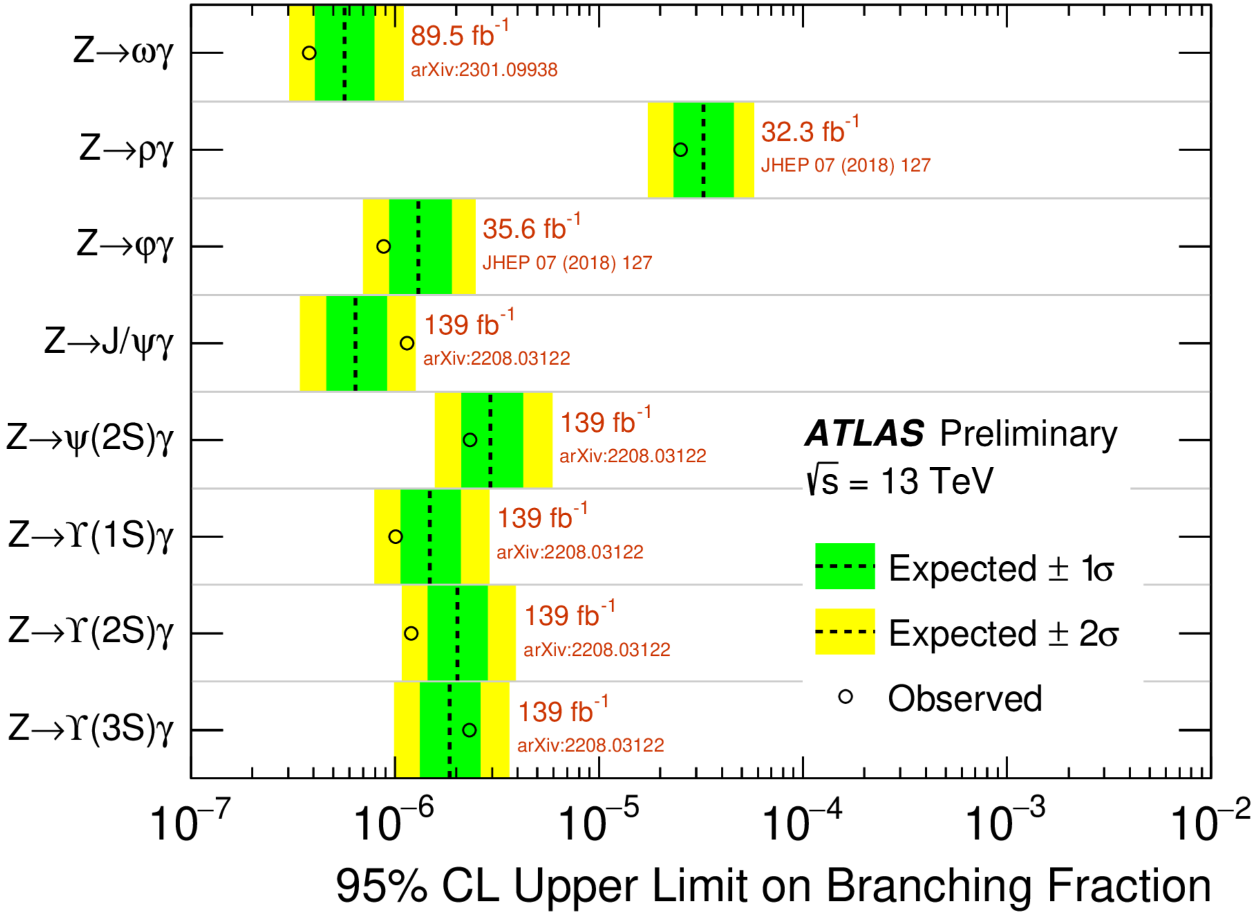


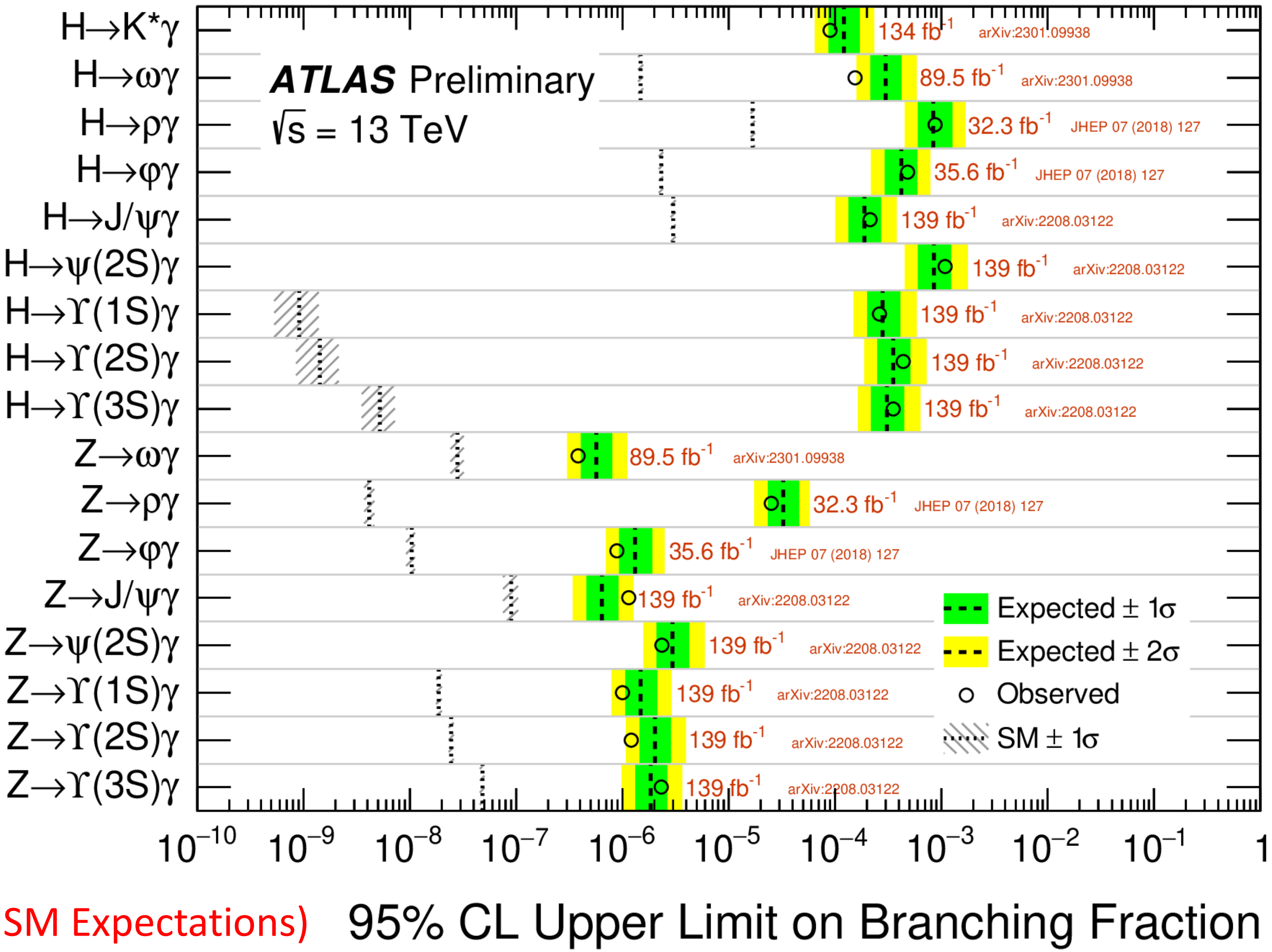
Higgs Boson Decays



Z Boson Decays

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

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



All Decays (with SM Expectations)

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

ATL-PHYS-PUB-2023-004