Exclusive Higgs and Z boson decays in ATLAS

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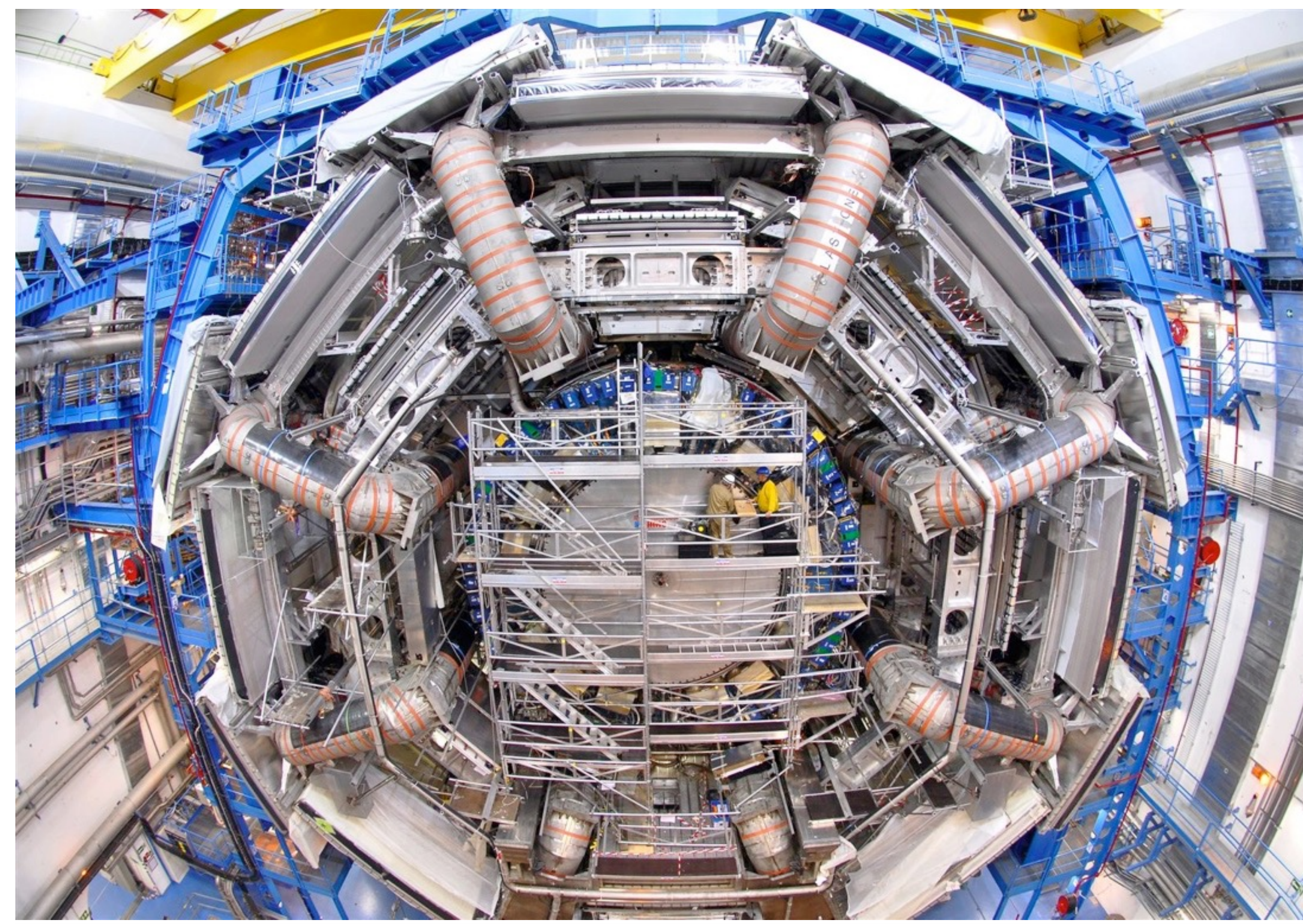


ATLAS experiment at CERN

Exclusive Higgs

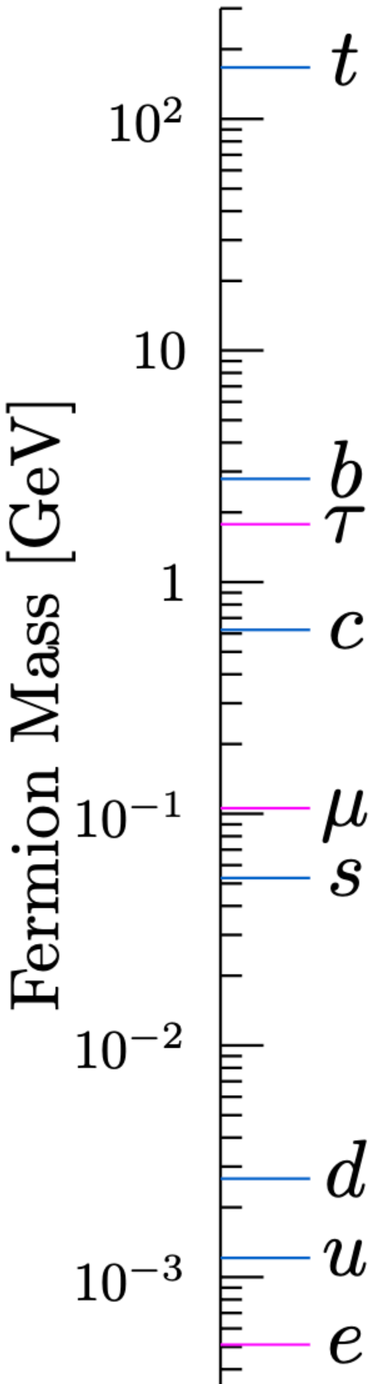
European Research Council
Established by the European Commission

Beauty 2023
July 3-7, Clermont-Ferrand, France

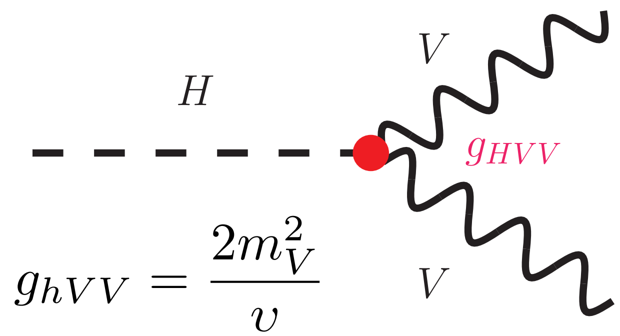
This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement no 714893 (ExclusiveHiggs)

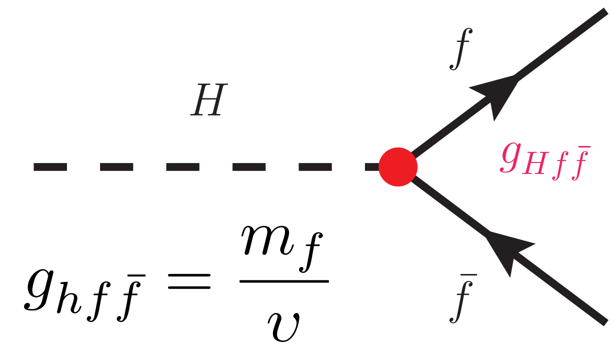
Higgs-fermion interactions: Yukawa couplings

- **Higgs interactions to vector bosons:** defined by electroweak symmetry breaking
- **Higgs interactions to fermions:** ad-hoc hierarchical Yukawa couplings $\propto m_f$



$\frac{m_e}{m_t} \approx 3 \times 10^{-6}$





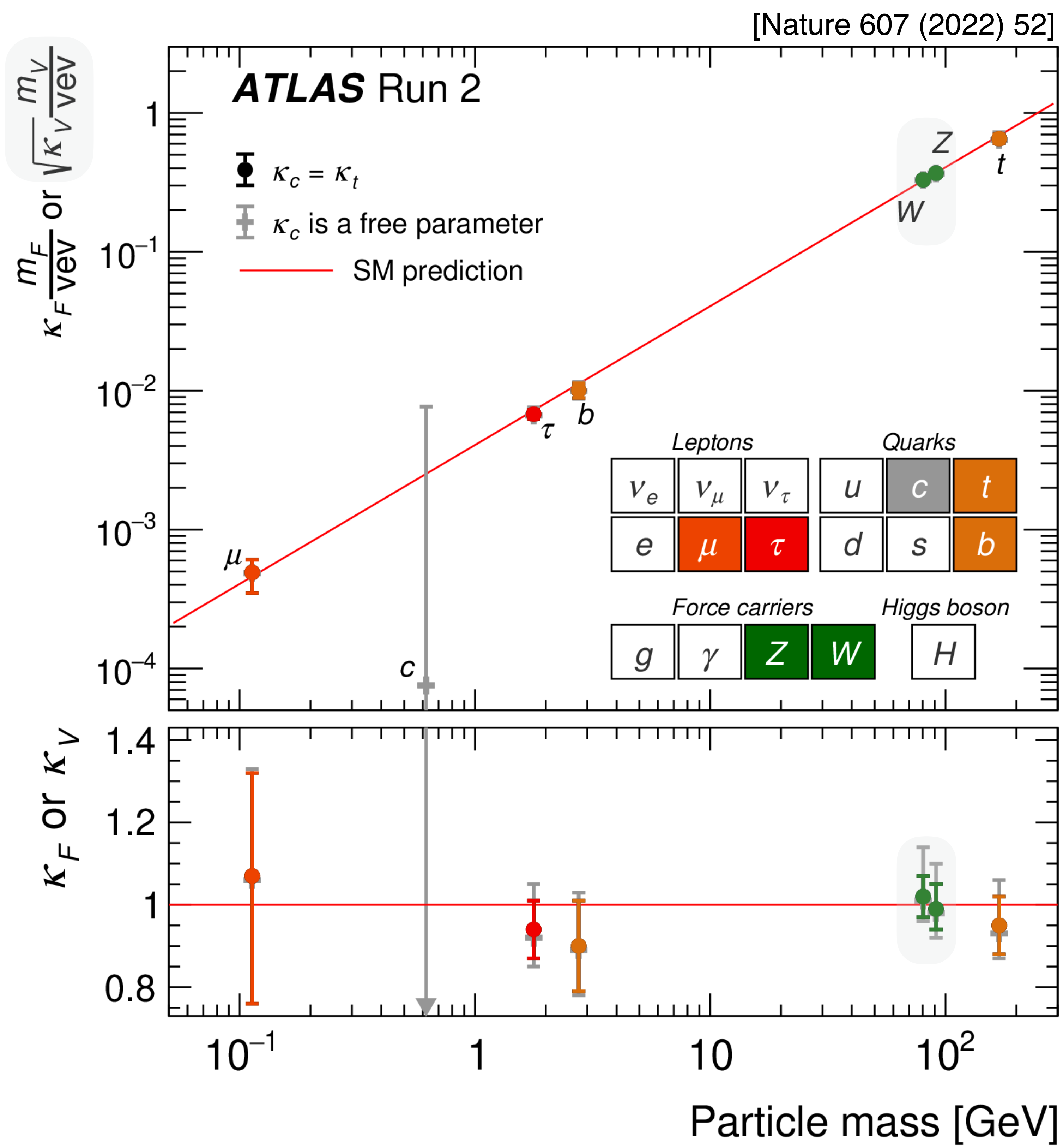
- ❑ Yukawa couplings **not** imposed by fundamental principle
- ❑ Probing fermion mass generation scale→independent task
- ❑ Fermion mass generation scale from **unitarity bounds**:

$$\Lambda \approx 23, 31, 52, 77, 84\ \text{TeV}_{\text{(b,c,s,d,u)}}$$

[Phys. Rev. Lett. 59, 2405 (1987); Phys.Rev. D71 (2005) 093009]

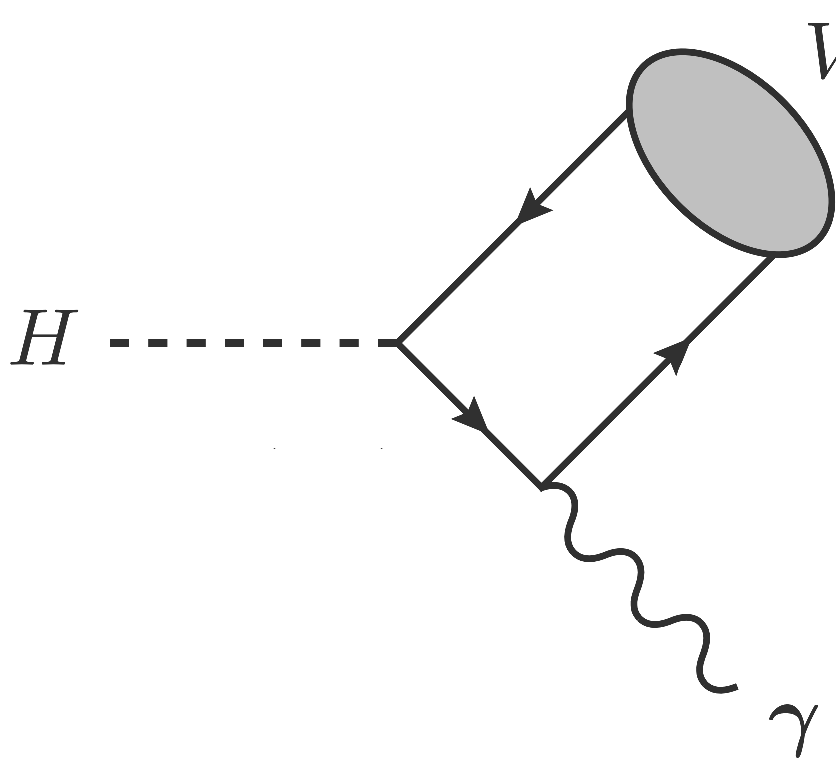
- ☑ Modified Higgs-fermion couplings in BSM scenarios
  - Concise summary in LHC Higgs WG YR4 [arxiv:1610.07922]
  - Effects suppressed $\mathcal{O}\left(1/\Lambda^2\right)$ or proportional to mixing angles with additional scalars.

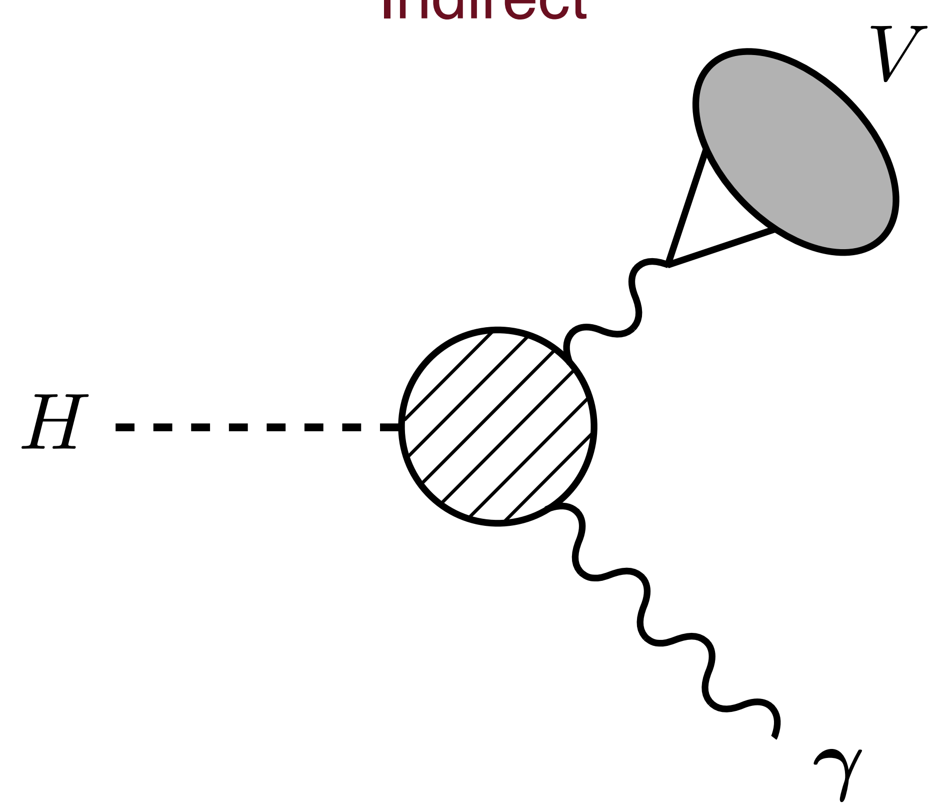
Higgs-fermion interactions: The story so far



Exclusive Decays h→Qγ

- **h→Qγ decays: clean probe** for Higgs-quark couplings for 1st/2nd generation quarks
  - Q is a vector meson or quarkonium state
- **Two amplitude contributions**
  - **Direct:** sensitivity to Higgs-quark couplings (magnitude + sign)
  - **Indirect:** insensitive to Higgs-quark couplings; (typically) larger than direct amplitude
  - **Destructive interference**





$$\Gamma(H \to J/\psi + \gamma) = \left|(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c\right|^2 \times 10^{-10}\ \mathrm{GeV}$$
$$\Gamma[H \to \Upsilon(1S) + \gamma] = \left|(3.33 \pm 0.03) - (3.49 \pm 0.15)\kappa_b\right|^2 \times 10^{-10}\ \mathrm{GeV}$$

"Indirect" "Direct"

Phys.Rev. D90 (2014) 11, 113010

Exclusive Decays h→Qγ

- Similar decays of W± and Z bosons: also rich physics programme
  - **Novel** precision studies of quantum chromo-dynamics
  - **W±/Z boson interactions with light quarks** not well covered at earlier facilities
  - **Discovery potential** for new physics processes
- Substantial **engagement from theory** on calculations and feasibility

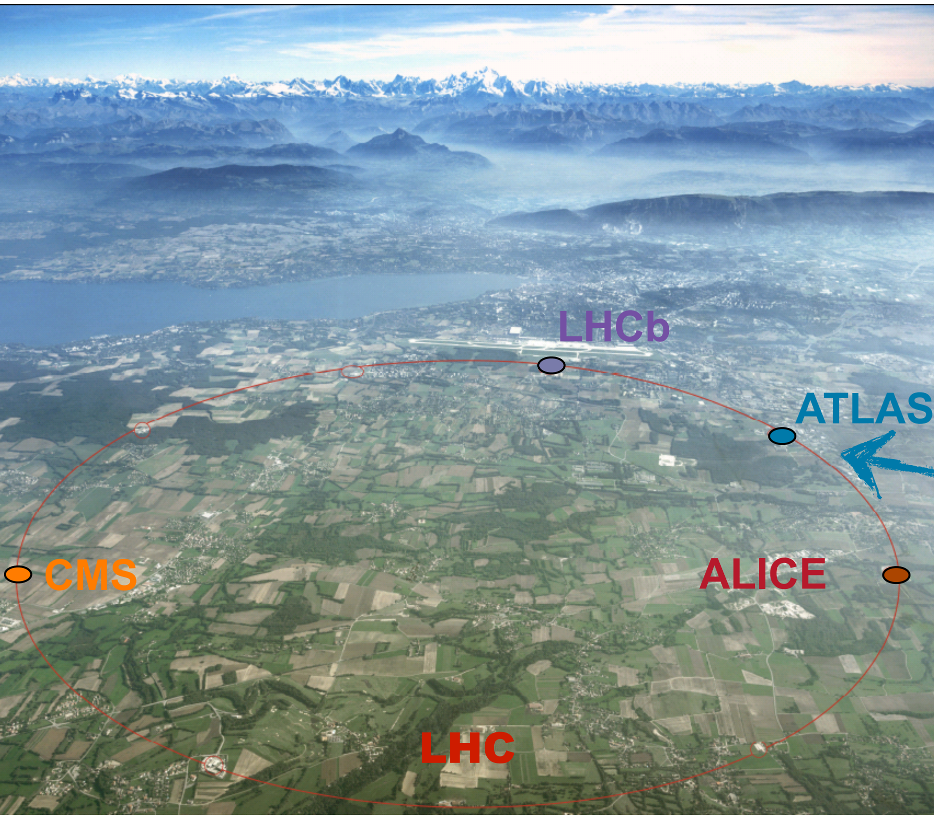
SM expected branching fraction $\mathcal{B}(H/Z \to \mathcal{M}\gamma)$			
Meson $\mathcal{M}$	H	Z	References
J/ψ	$(2.99^{+0.16}_{-0.15}) \times 10^{-6}$	$(8.96^{+1.51}_{-1.38}) \times 10^{-8}$	[27–29]
$\psi(2S)$	–	–	
$\Upsilon(1S)$	$(5.22^{+2.02}_{-1.70}) \times 10^{-9}$	$(4.80^{+0.26}_{-0.25}) \times 10^{-8}$	[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]

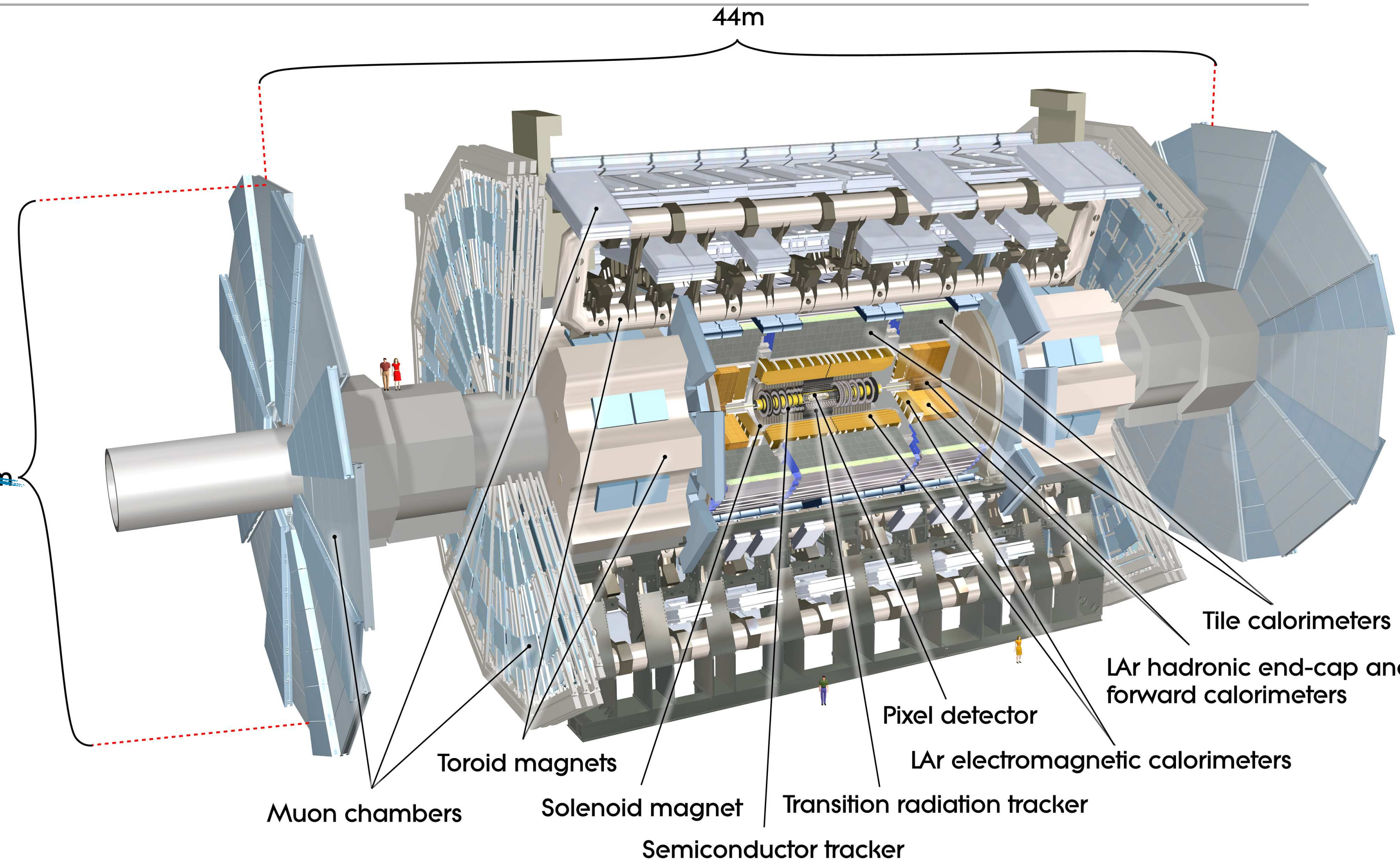
ATL-PHYS-PUB-2023-004

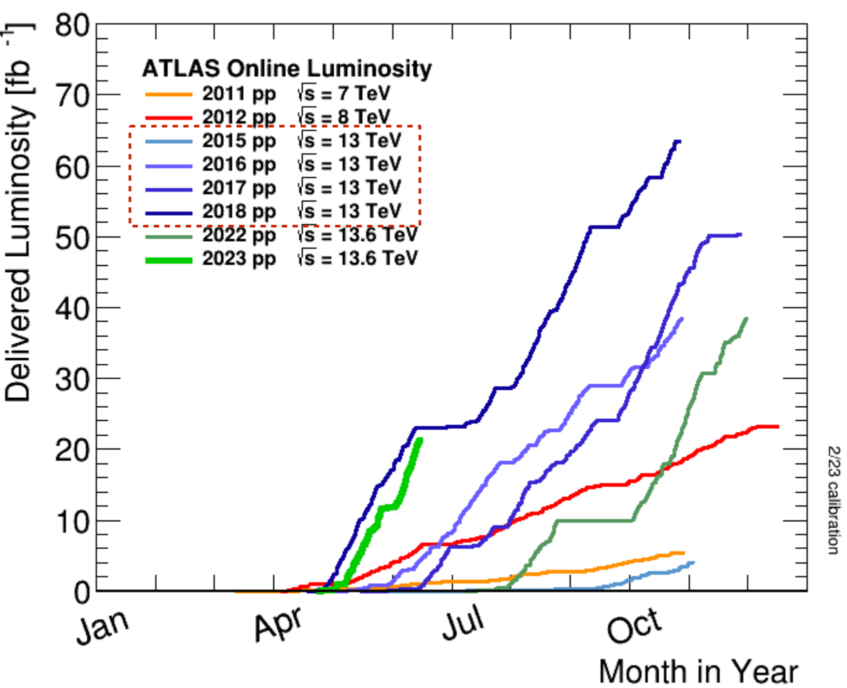
25: JHEP 1508 (2015) 012
27: PRD95 (2017) 054018
28: PRD96 (2017) 116014
29: PRD97 (2018) 016009
30: JHEP 04 (2015) 101

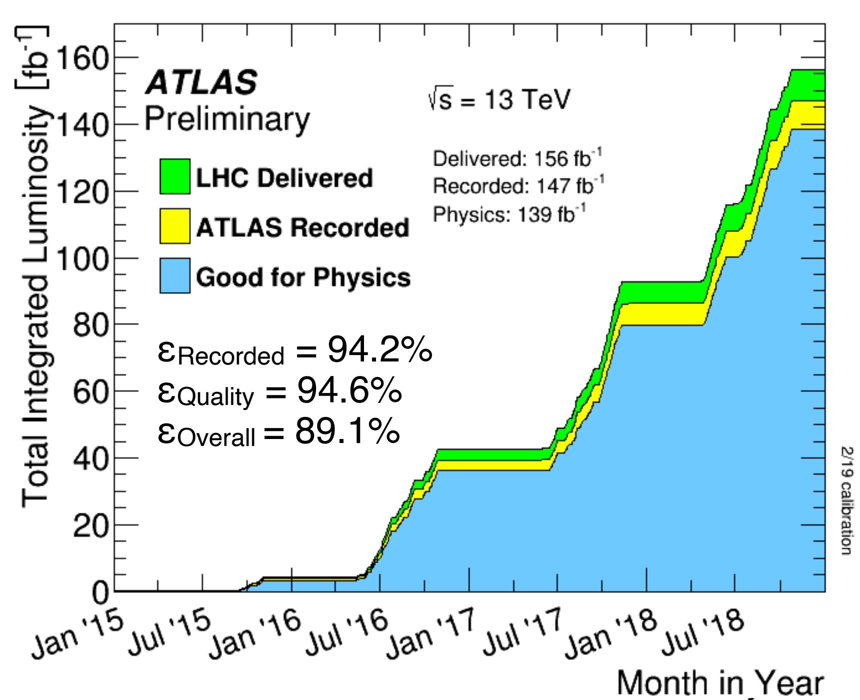
Not exhaustive list…

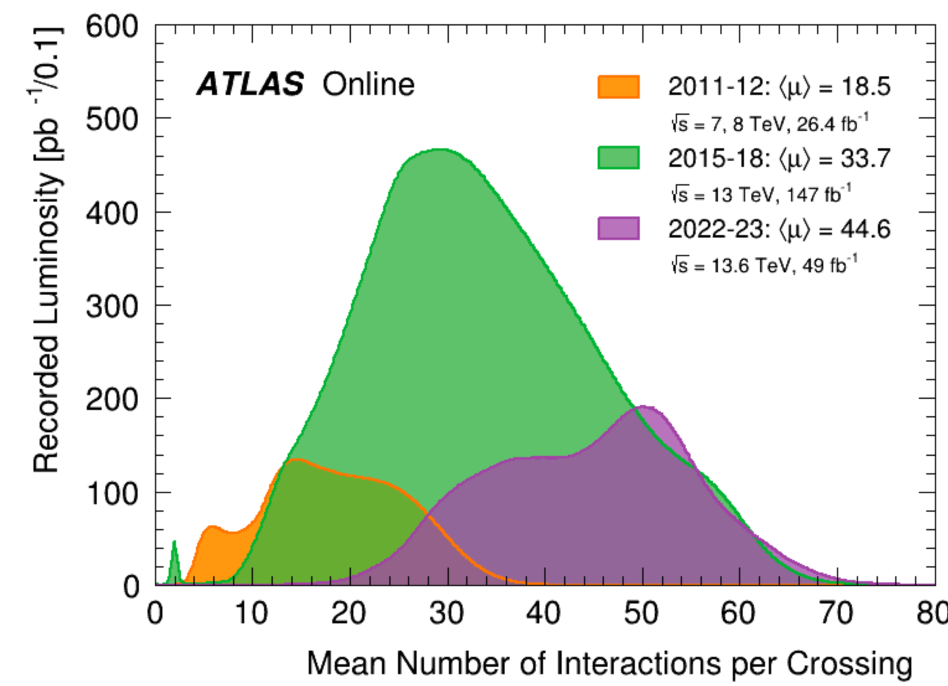
ATLAS, datasets, and pile-up











h/Z→J/ψγ, ψ(2S)γ, and Υ(nS)γ (n=1,2,3)

- **Di-muon + photon final state:** probes b- and c-quark Yukawa couplings
  - Dedicated photon + muon triggers (97% efficiency w.r.t offline selection)

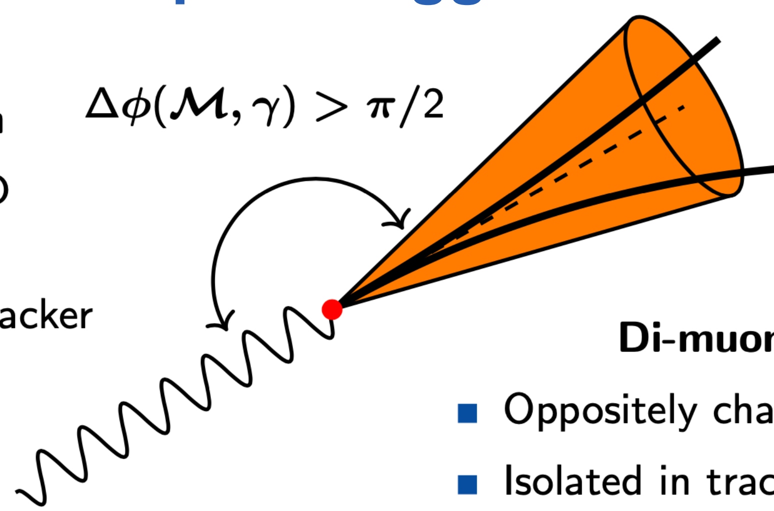
[Phys.Rev.Lett. 114 (2015) 12, 121801, Phys.Lett. B753 (2016) 341]

- **Run 1: Indication of non-universal quark-Higgs boson coupling**

[Phys.Rev. D92 (2015) 033016, JHEP 08 (2015) 012]

Photon Selection

- "Tight" photon ID requirements
- Isolated in both tracker and calorimeter

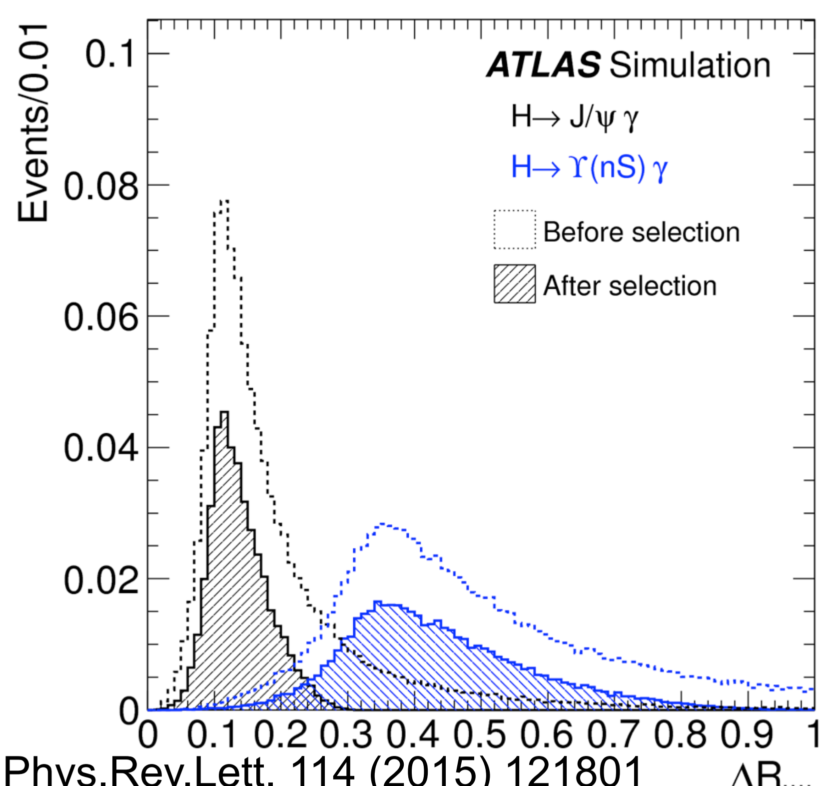


Di-muon Selection

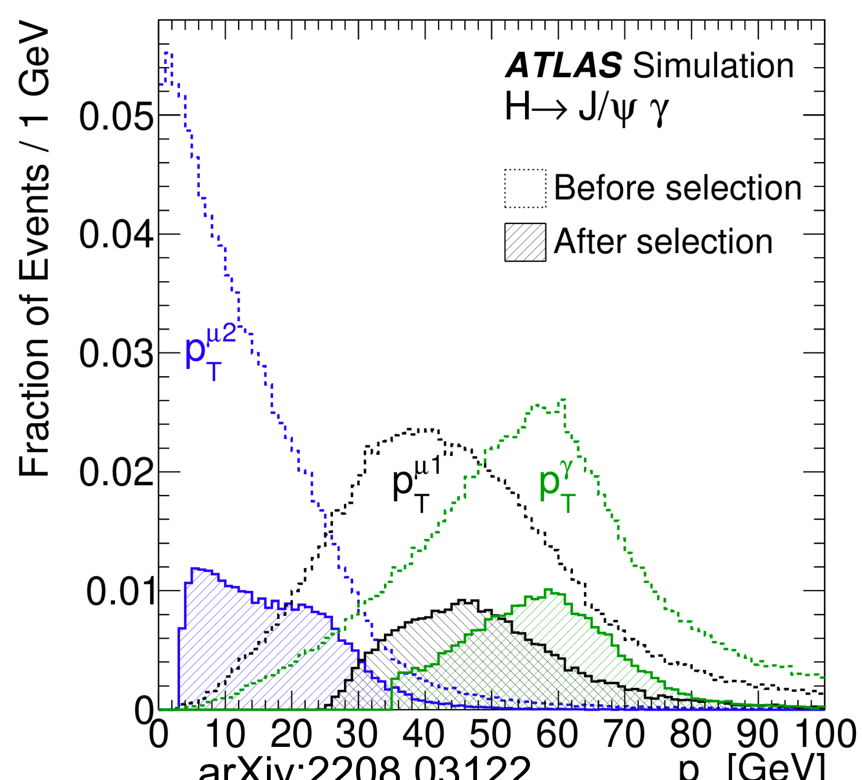
- Oppositely charged pair of muons
- Isolated in tracker (accounting for neighboring muon track)
- $p_T^{\mathcal{M}}$ requirement ($m_{\mathcal{M}\gamma}$-dependent)
- $L_{xy}/\sigma_{L_{xy}} < 3$ to reject $b \to \psi(nS)$

Signal $\mathcal{A}\times\epsilon$

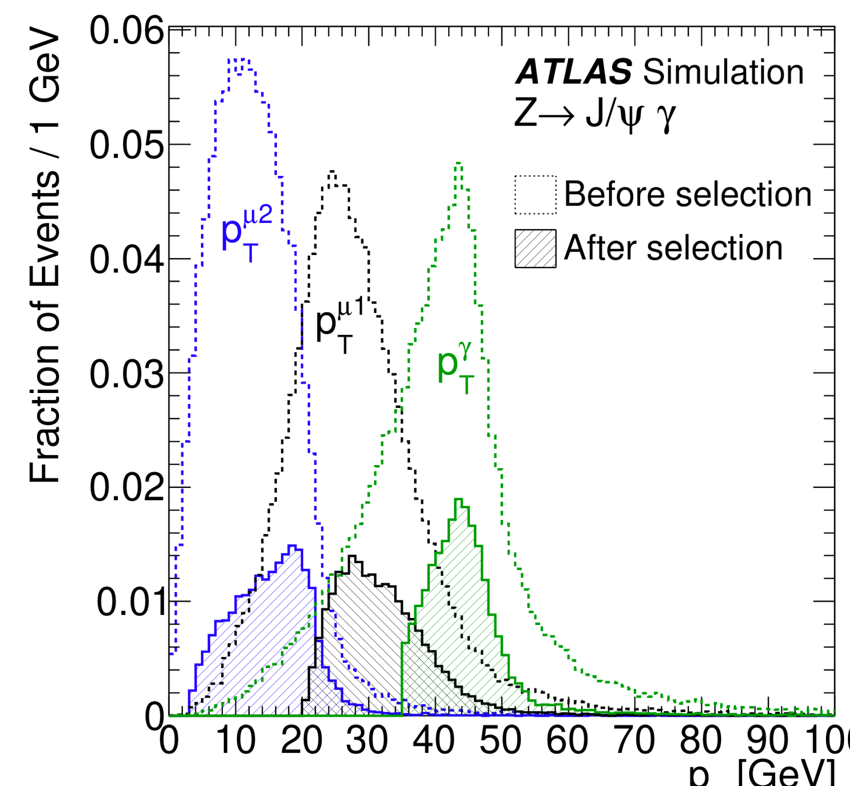
- h/Z→J/ψ(→μμ)γ ~19% (11%)
- h/Z→Υ(→μμ)γ ~ 21% (14%)



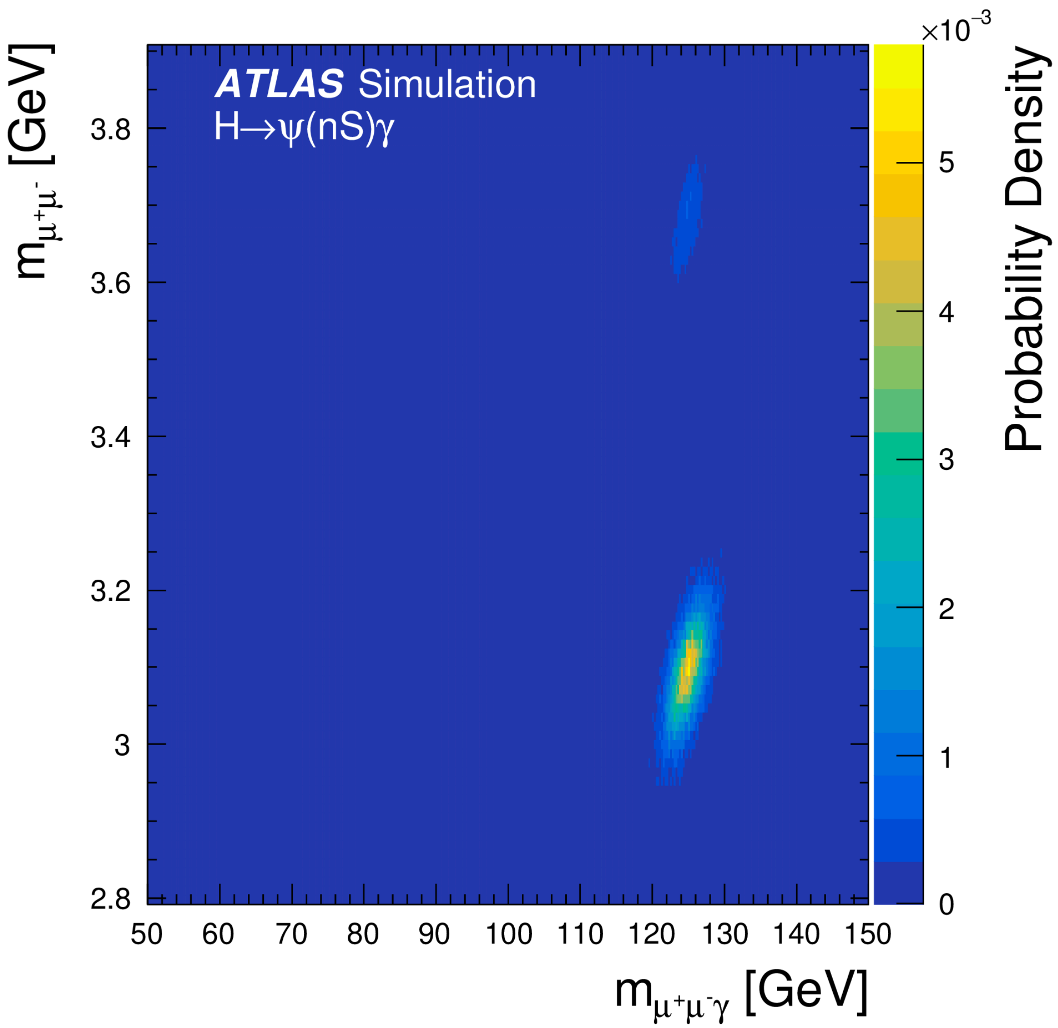
Phys.Rev.Lett. 114 (2015) 121801

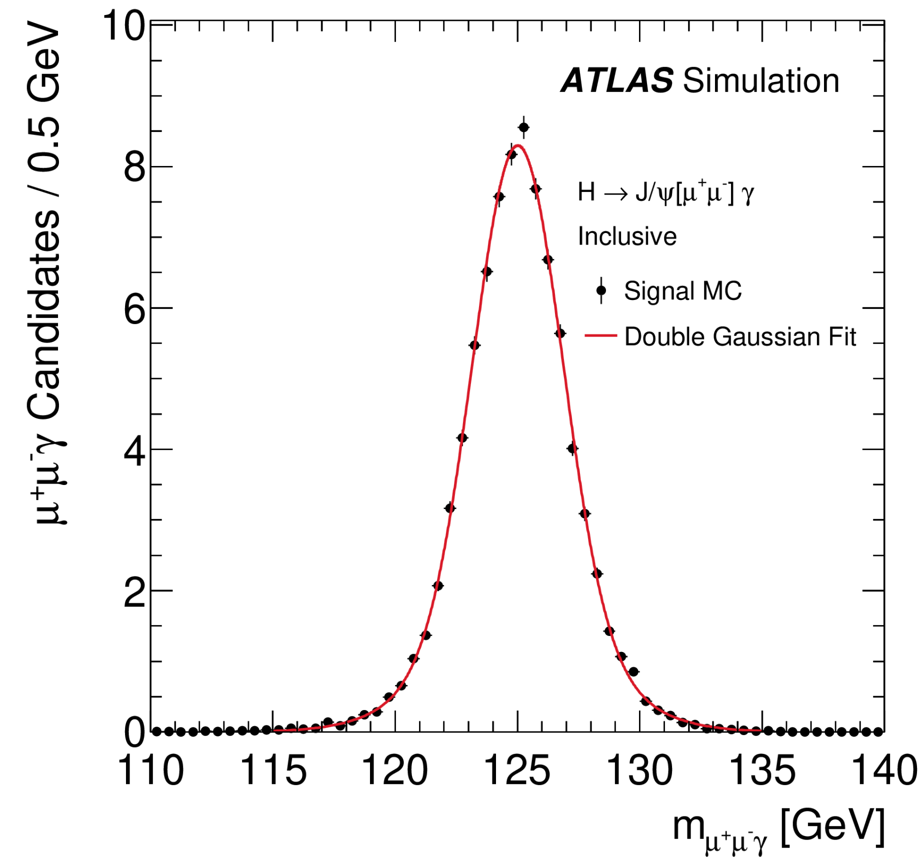


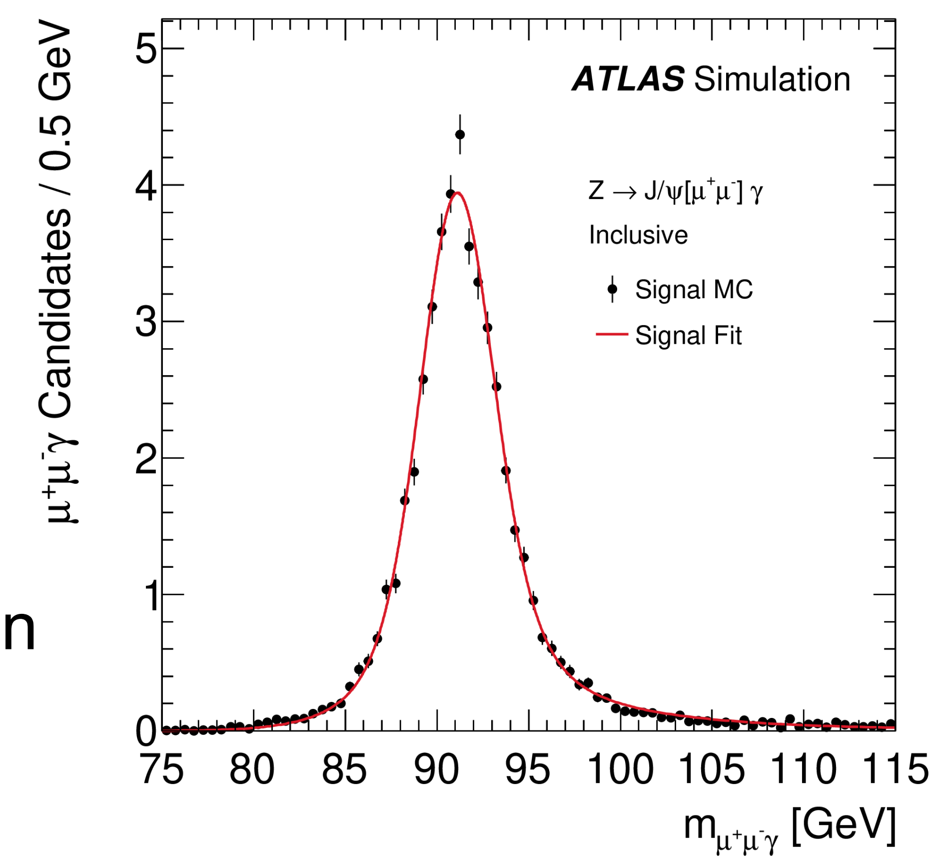
arXiv:2208.03122



h/Z→Qγ: Signal Model



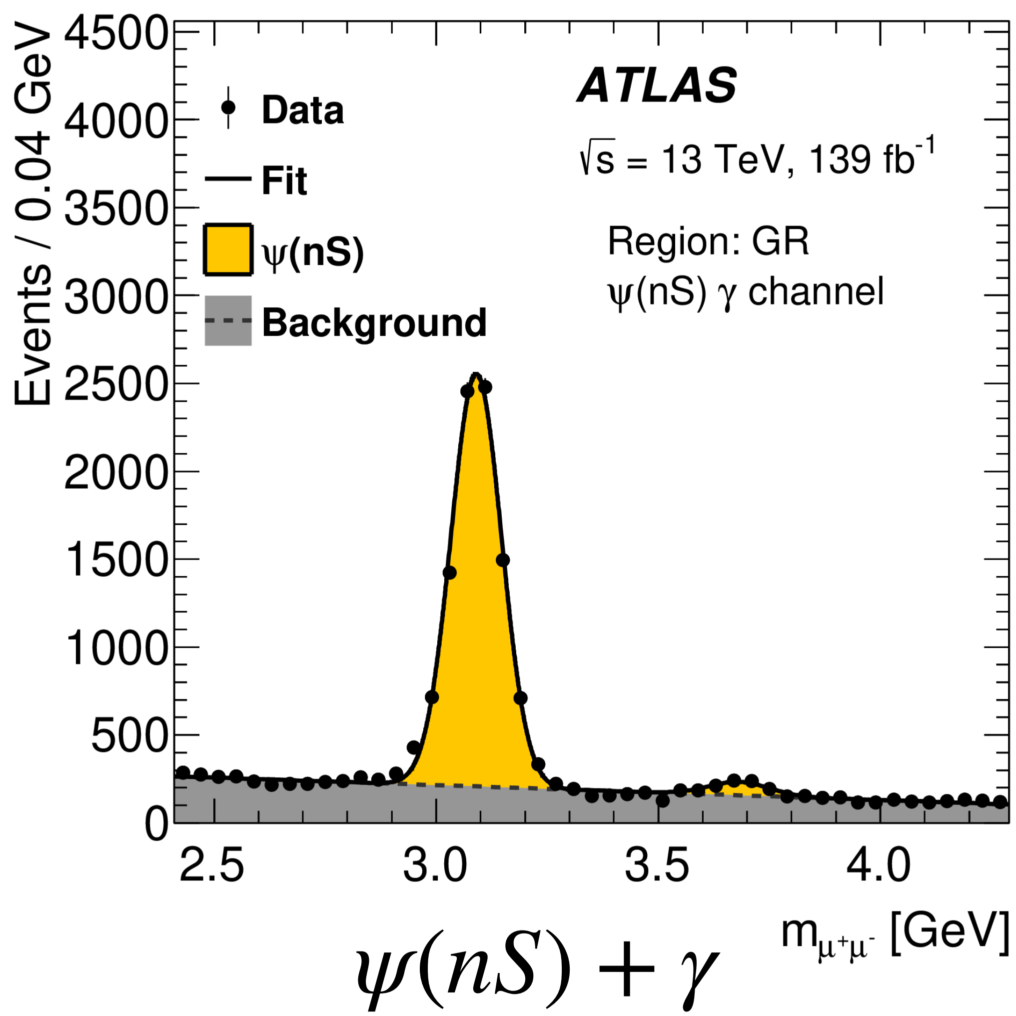


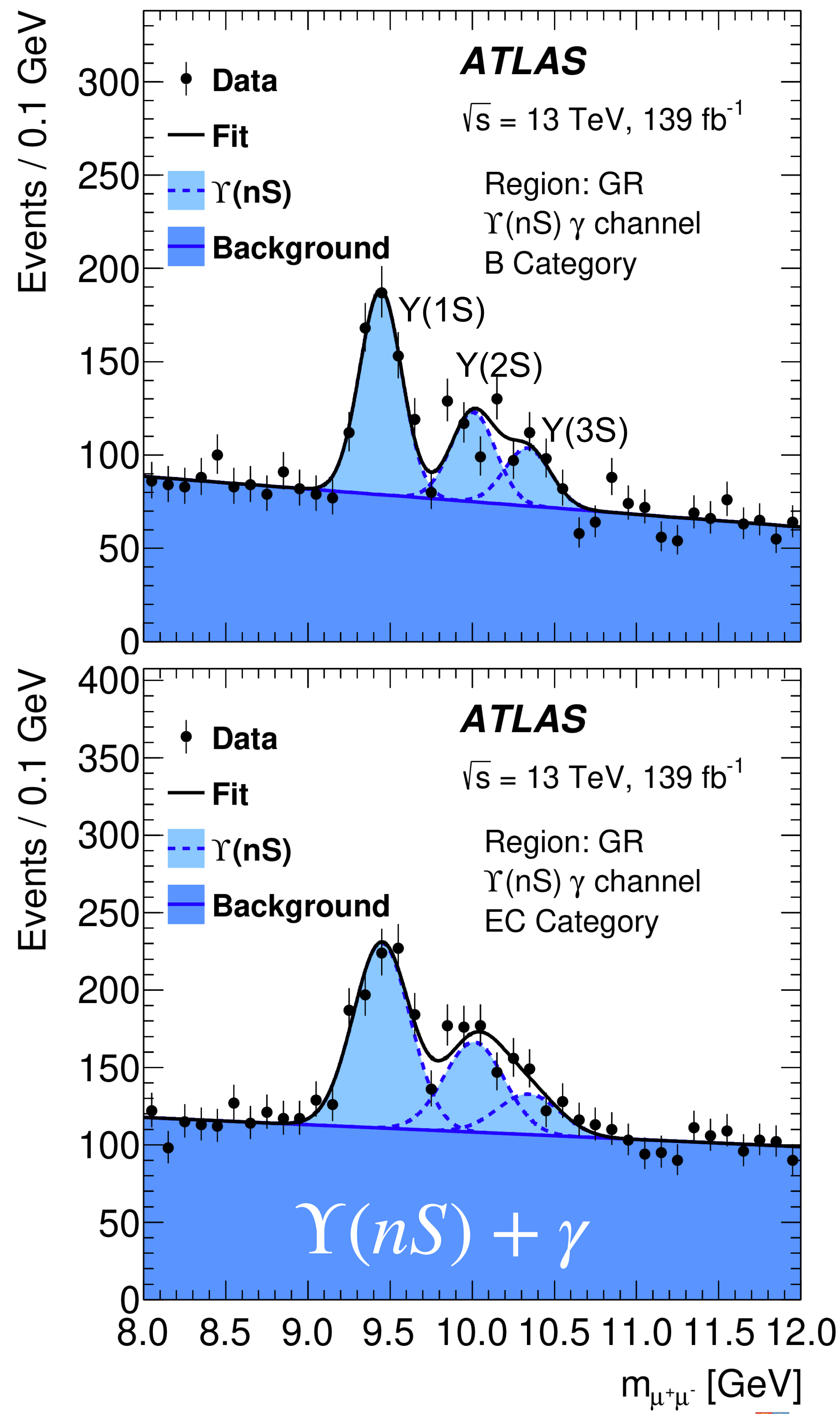


- Signal Modelling
  - 2D Shape: $(m_{\mu^+\mu^-\gamma}, m_{\mu^+\mu^-})$
  - Higgs boson: Sum of two bi-variate Gaussians
  - Z boson:
    (Double Voigt × Efficiency($m_{\mu^+\mu^-\gamma}$)) ⊗ Double Gaussian
- $m_{\mu^+\mu^-\gamma}$ resolution: 1.6−1.8%

arXiv:2208.03122

h/Z→Qγ: Mass Resolution

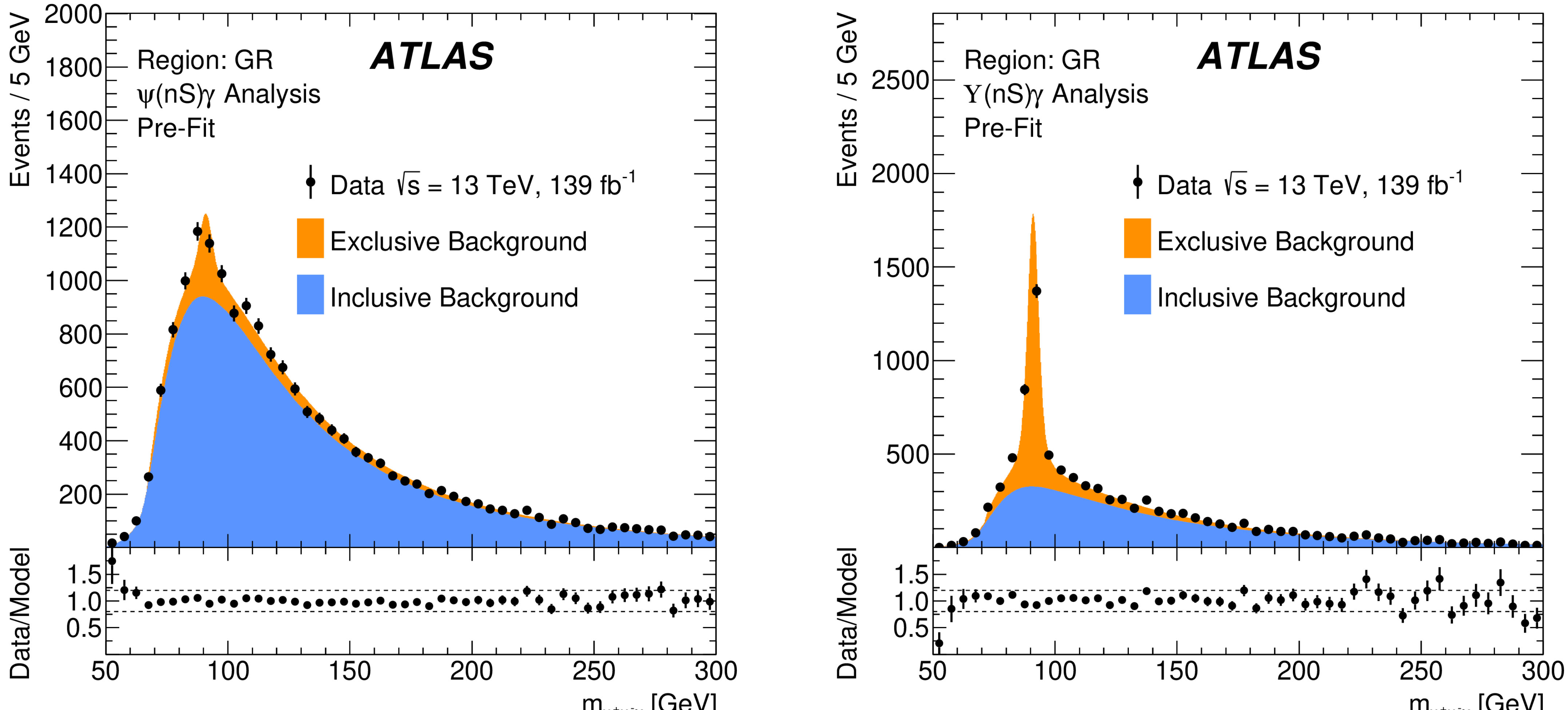




arXiv:2208.03122

h/Z→Qγ: Background

- **Two background sources**
  - **Exclusive**: $q\bar{q} \to \mu^+\mu^-\gamma$ Drell-Yan production
    - Fit to analytical model derived from simulation
    - Resonant in $m_{\mu^+\mu^-\gamma}$ but not $m_{\mu^+\mu^-}$
  - **Inclusive**: mixture of background contributions
    - Q+jet production with jet "seen" as γ
    - Combinatoric background: small contribution
    - Contribution from Q+γ production
    - Modelled with **non-parametric data-driven** method

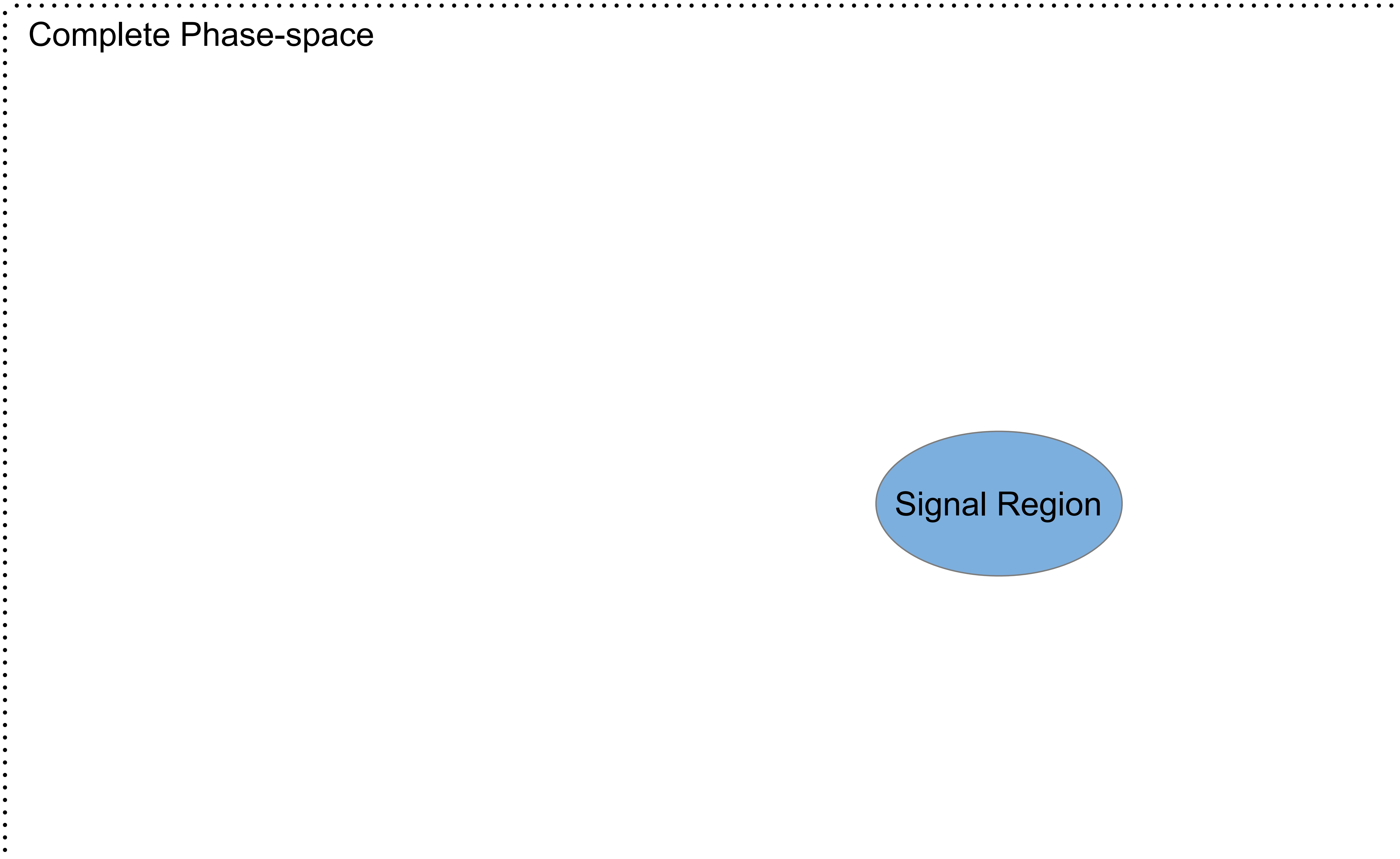


Non-parametric data-driven background model

Complete Phase-space

See also: JHEP 10 (2022) 001

Non-parametric data-driven background model



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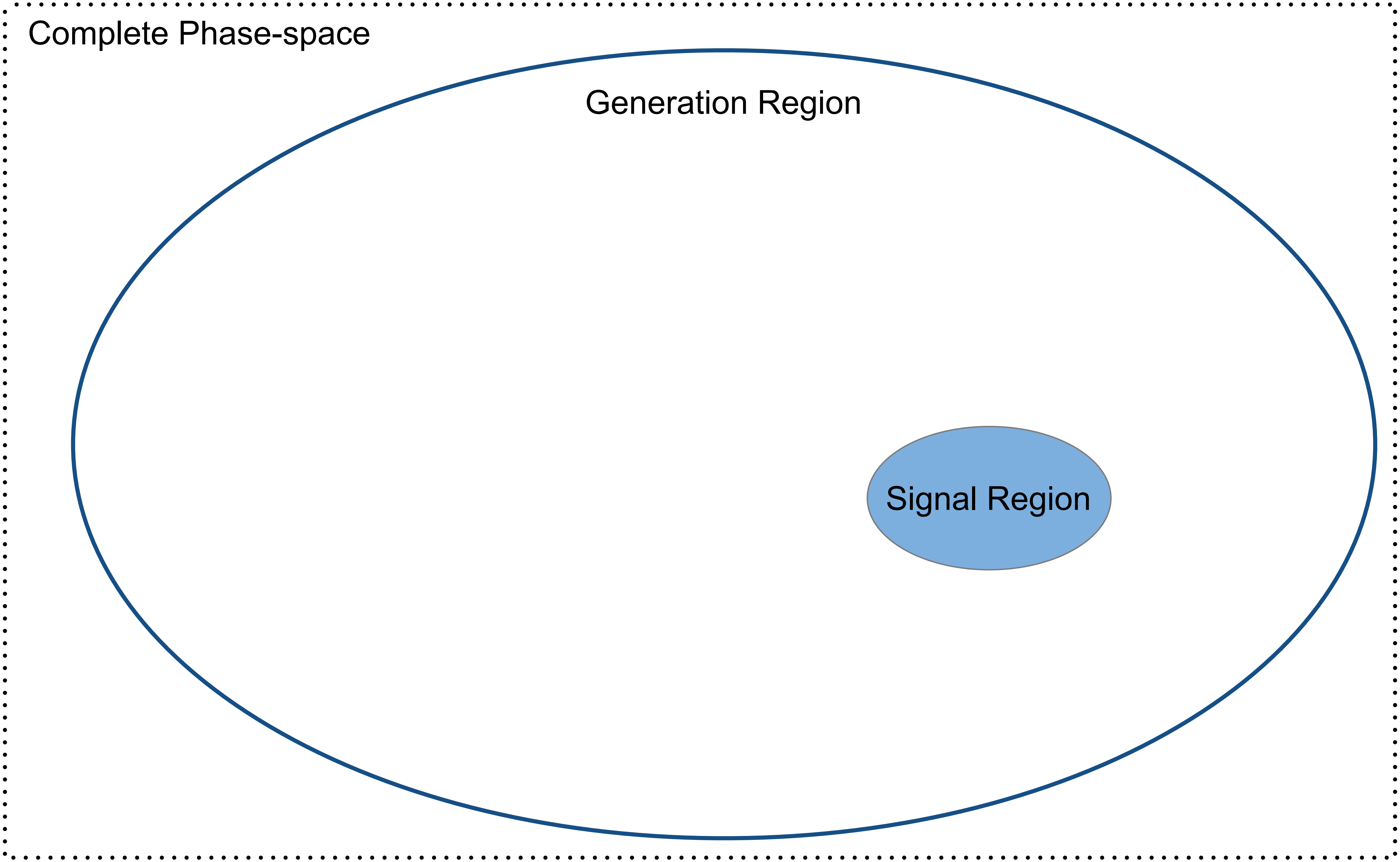
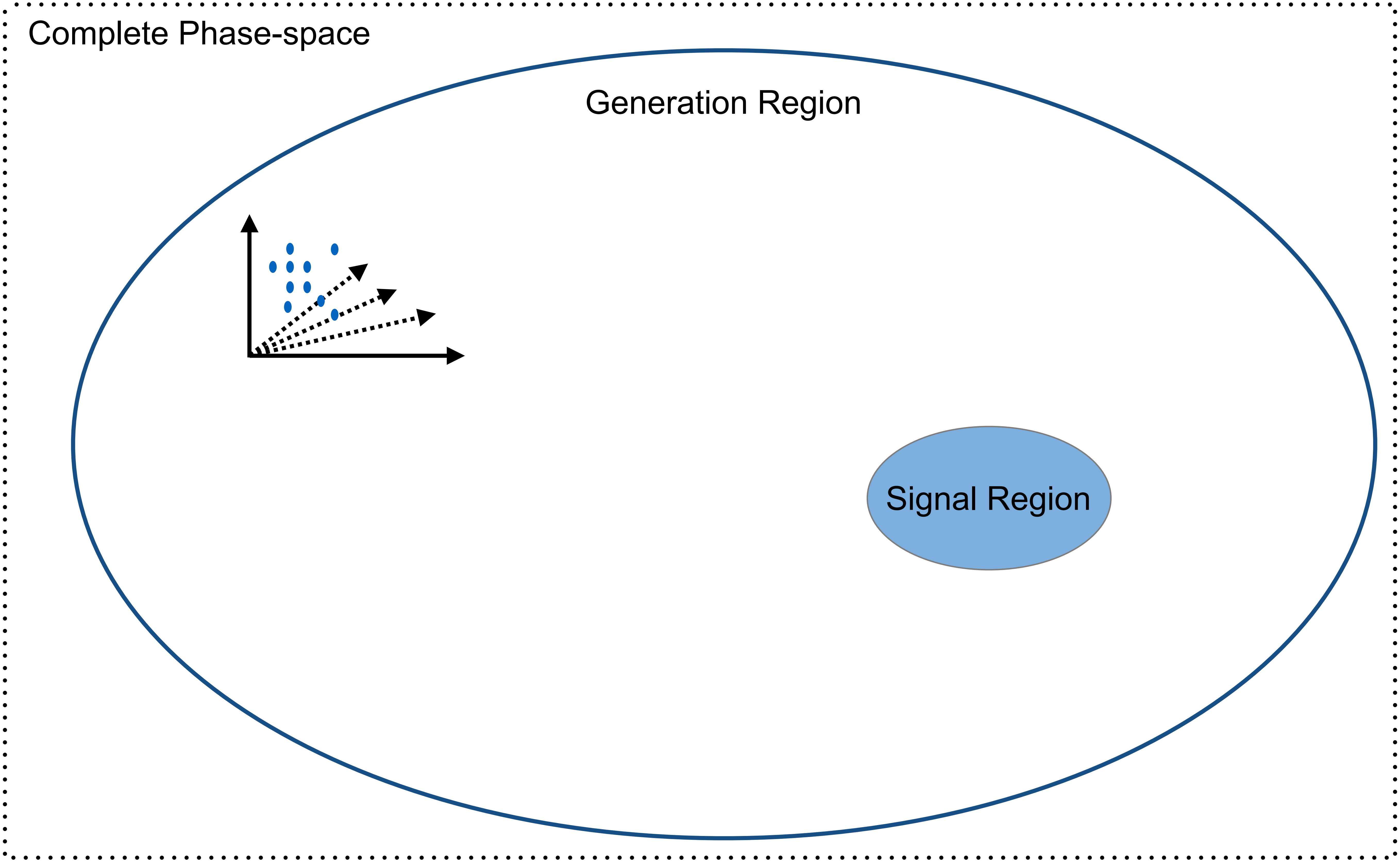
Non-parametric data-driven background model



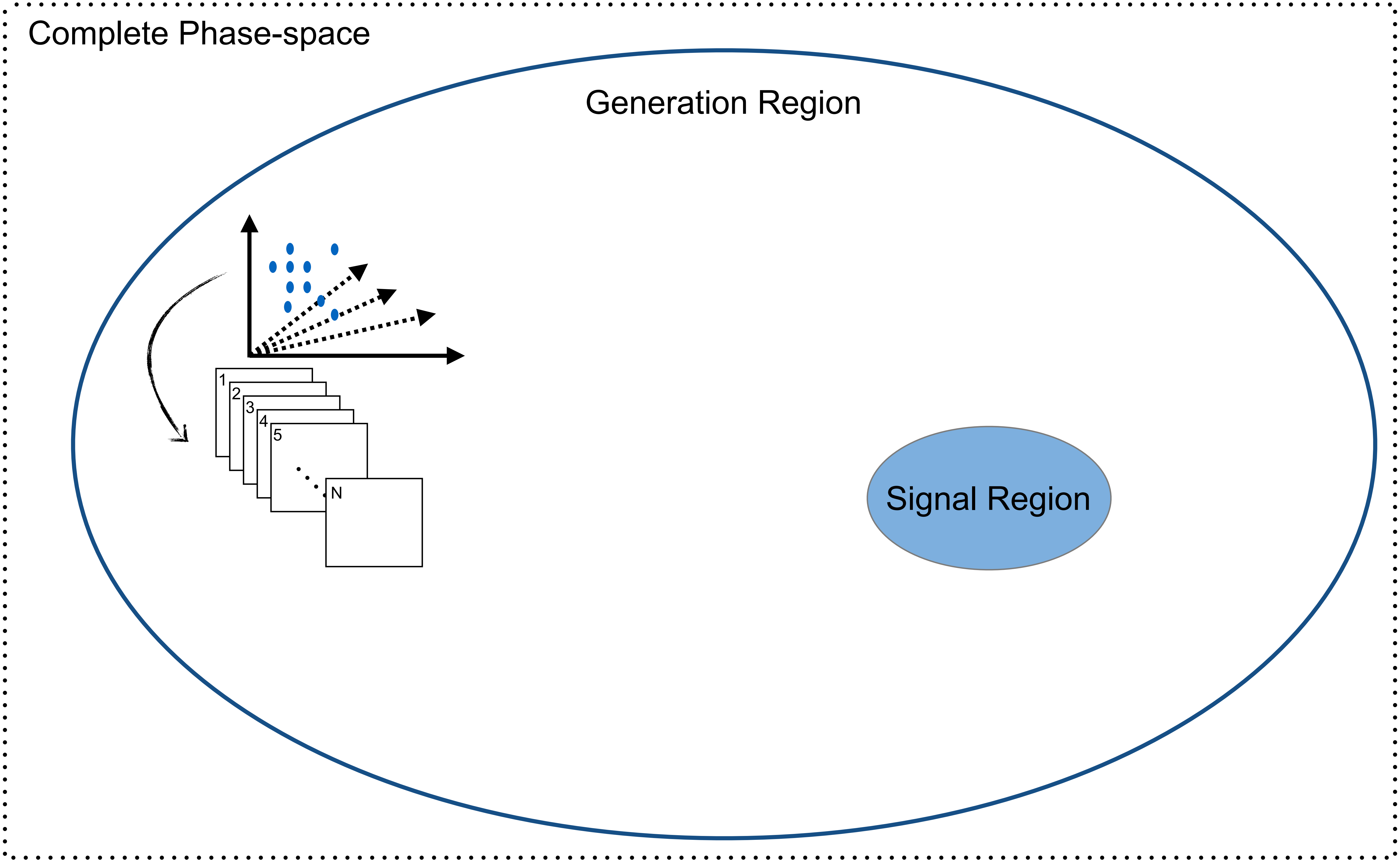
See also: JHEP 10 (2022) 001

Non-parametric data-driven background model



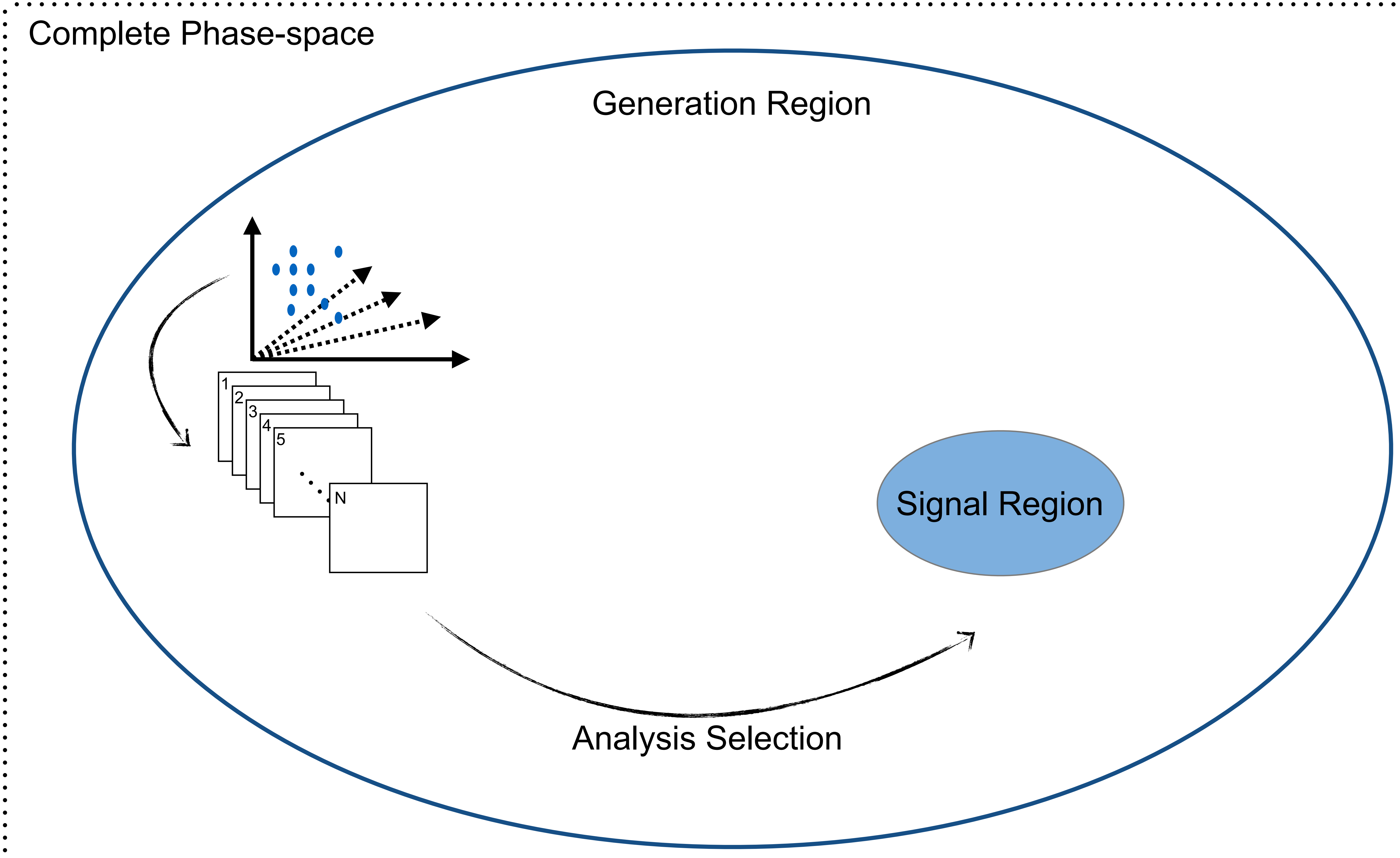
See also: JHEP 10 (2022) 001

Non-parametric data-driven background model



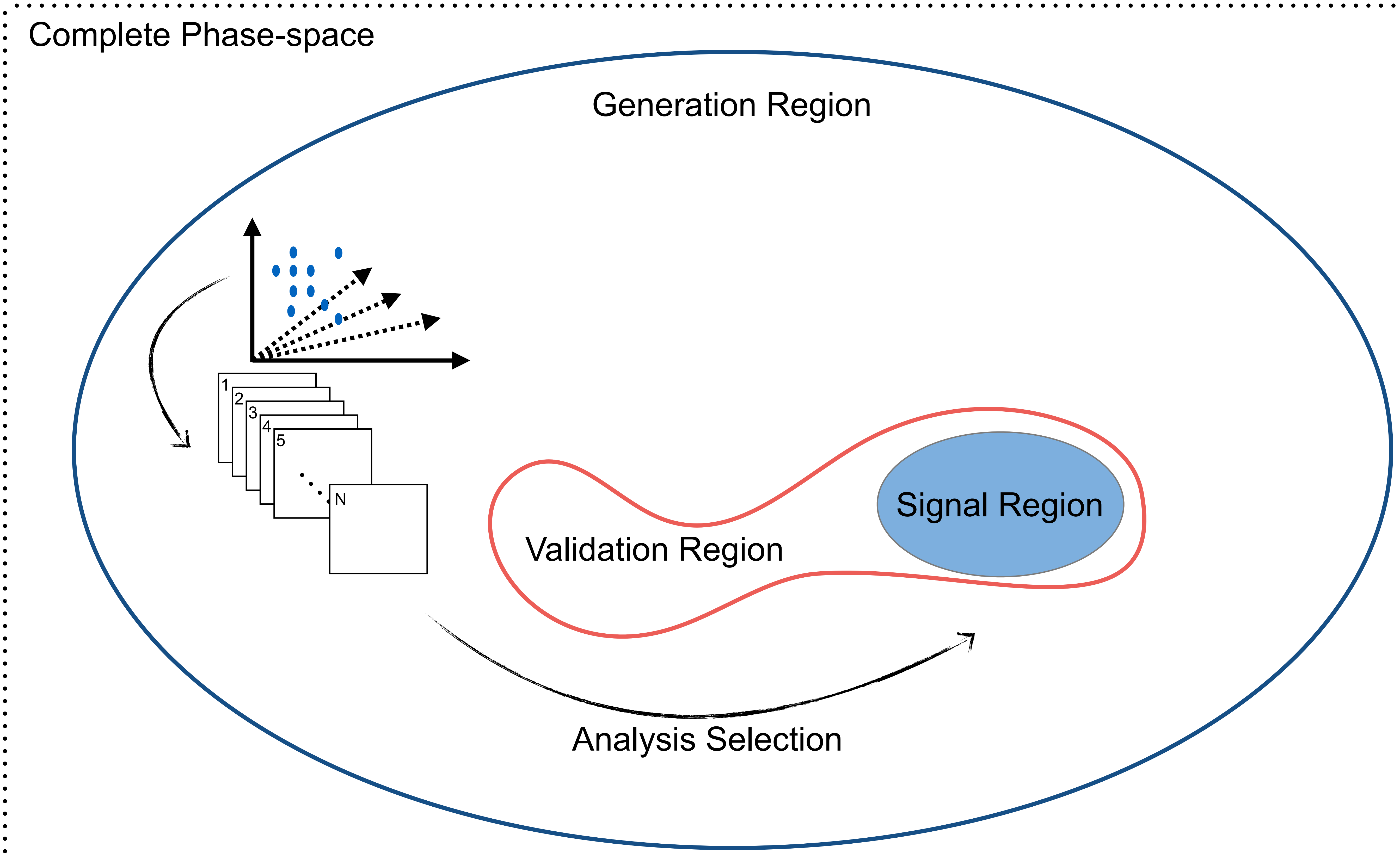
See also: JHEP 10 (2022) 001

Non-parametric data-driven background model



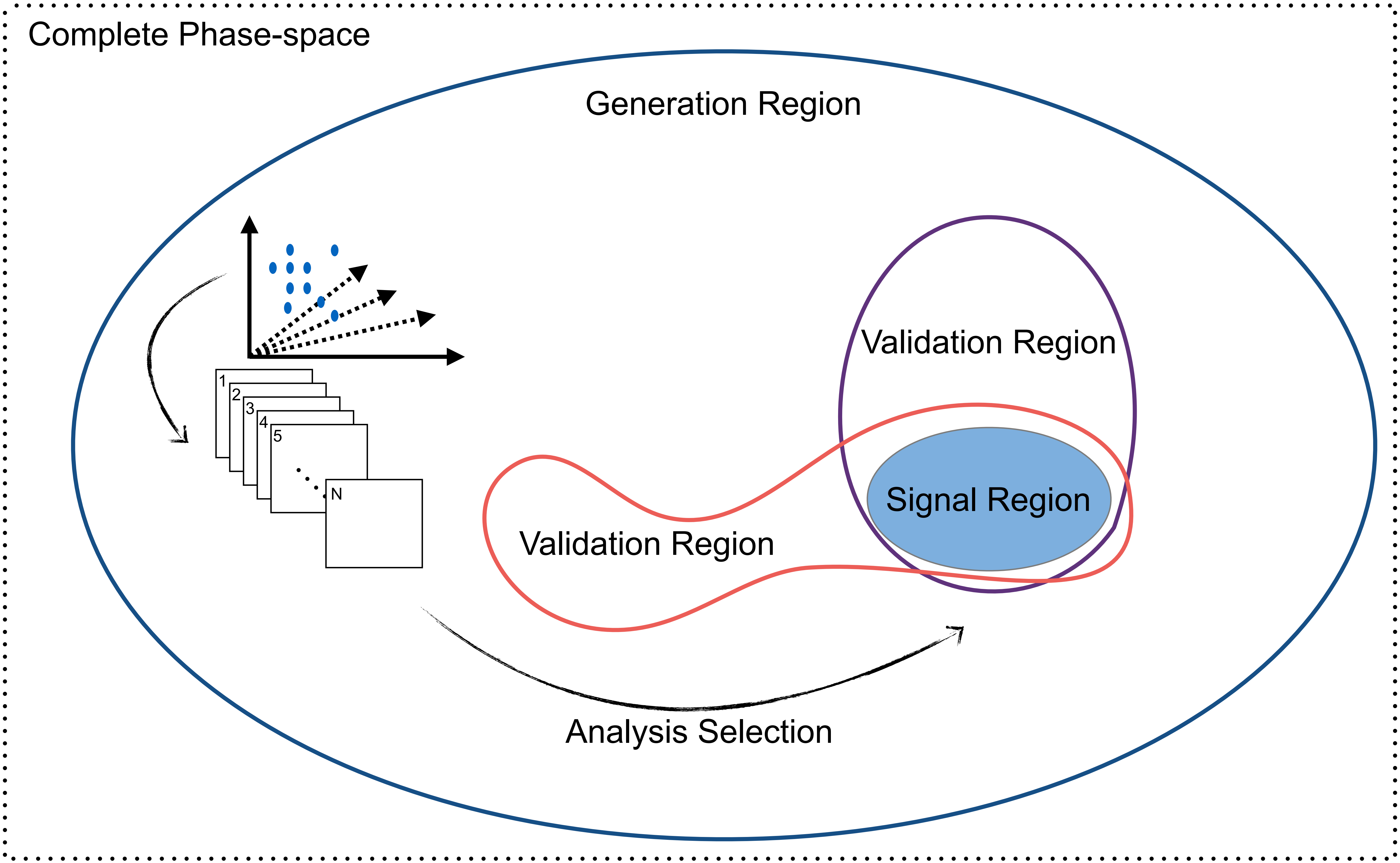
See also: JHEP 10 (2022) 001

Non-parametric data-driven background model



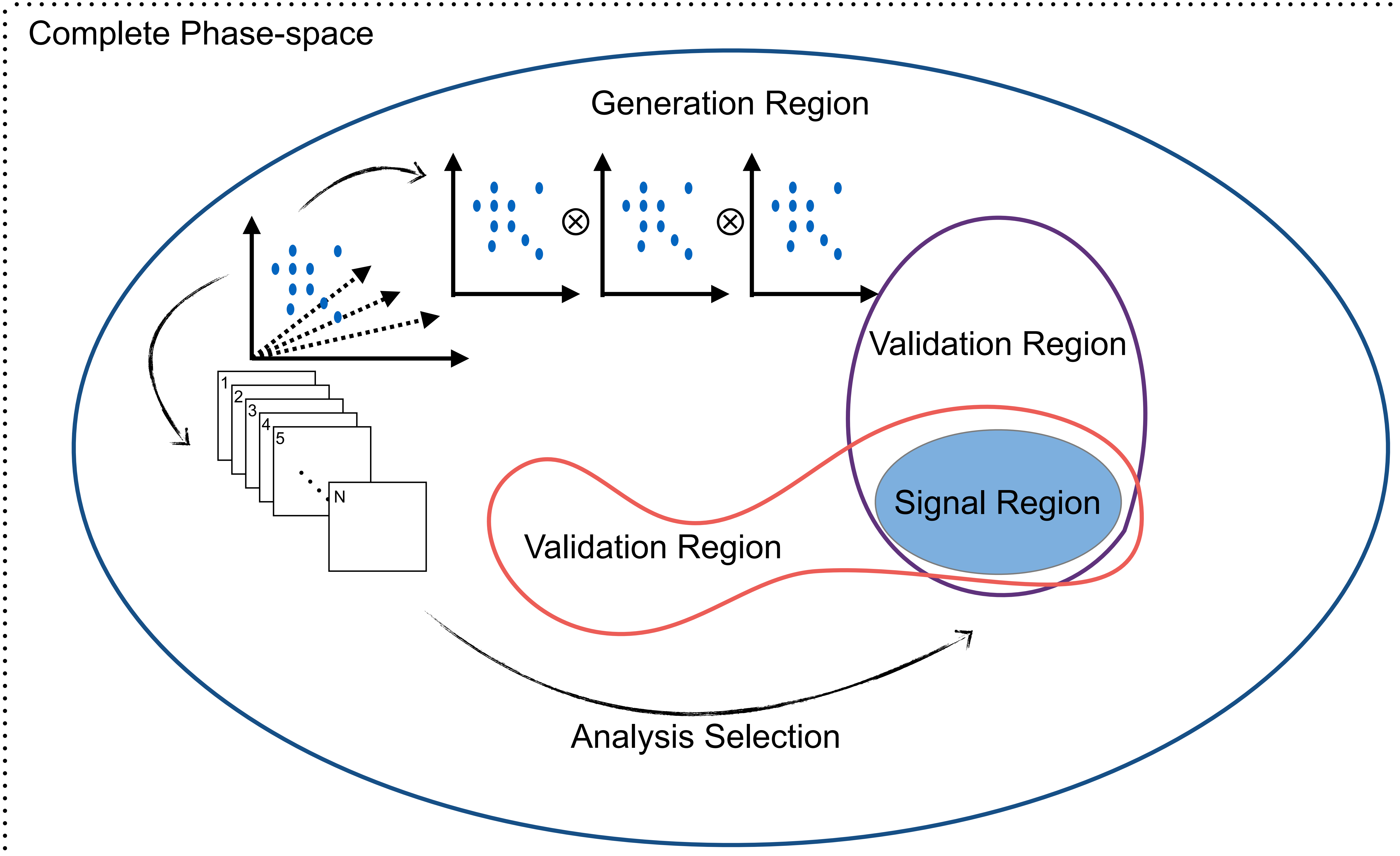
See also: JHEP 10 (2022) 001

Non-parametric data-driven background model



See also: JHEP 10 (2022) 001

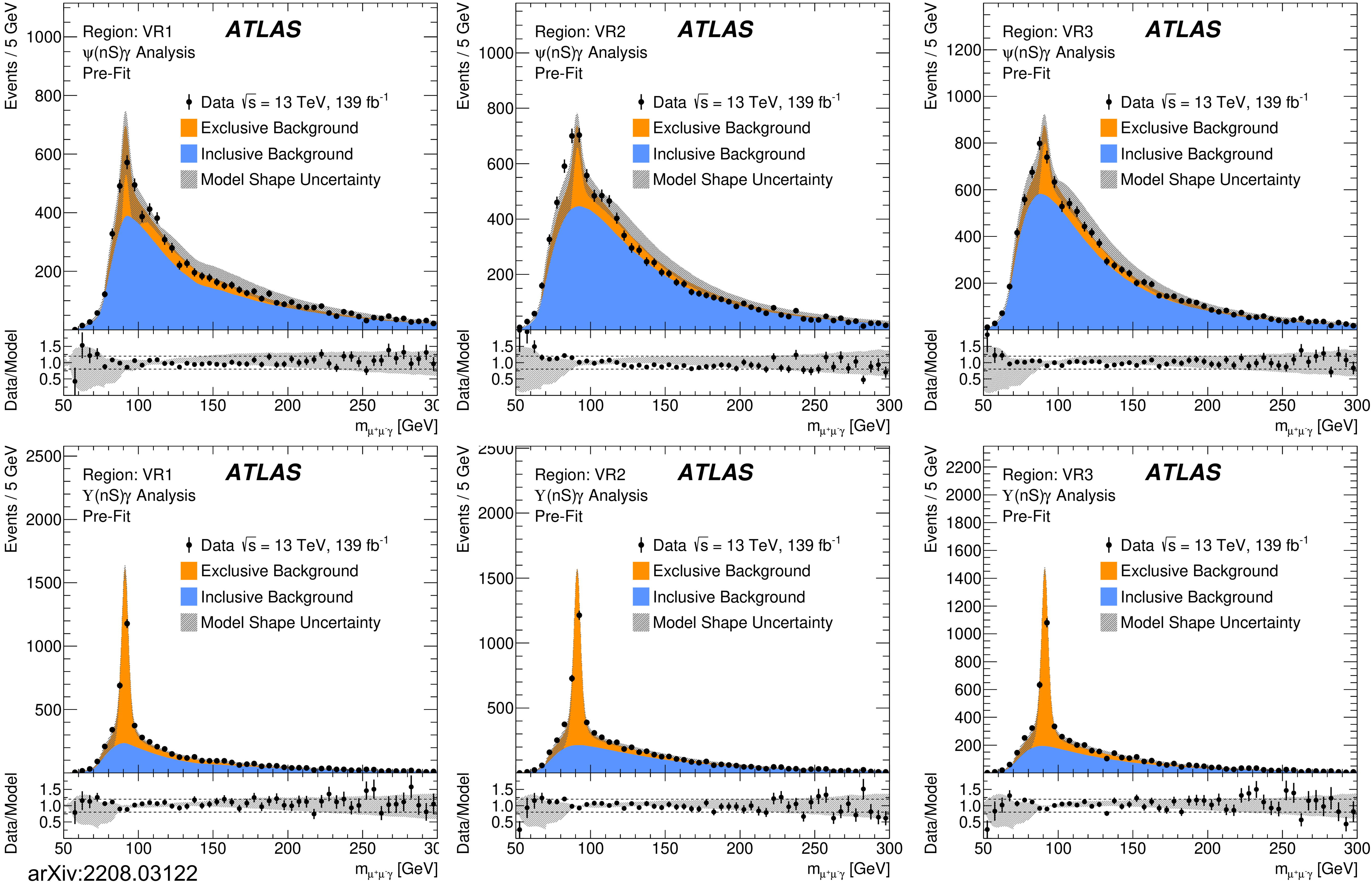
Non-parametric data-driven background model



See also: JHEP 10 (2022) 001

h/Z→Qγ: Validation

Region		$p_T^{\mu\mu}$	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



arXiv:2208.03122

h/Z→Qγ: Systematics

- **Signal Yield Uncertainty:** Several sources of systematic uncertainty on the h and Z signal yields are considered, all modelled by nuisance parameters in likelihood:

Source of systematic uncertainty	Signal yield uncertainty			
	$H \to \psi(nS)$	$H \to \Upsilon(nS)$	$Z \to \psi(nS)$	$Z \to \Upsilon(nS)$
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

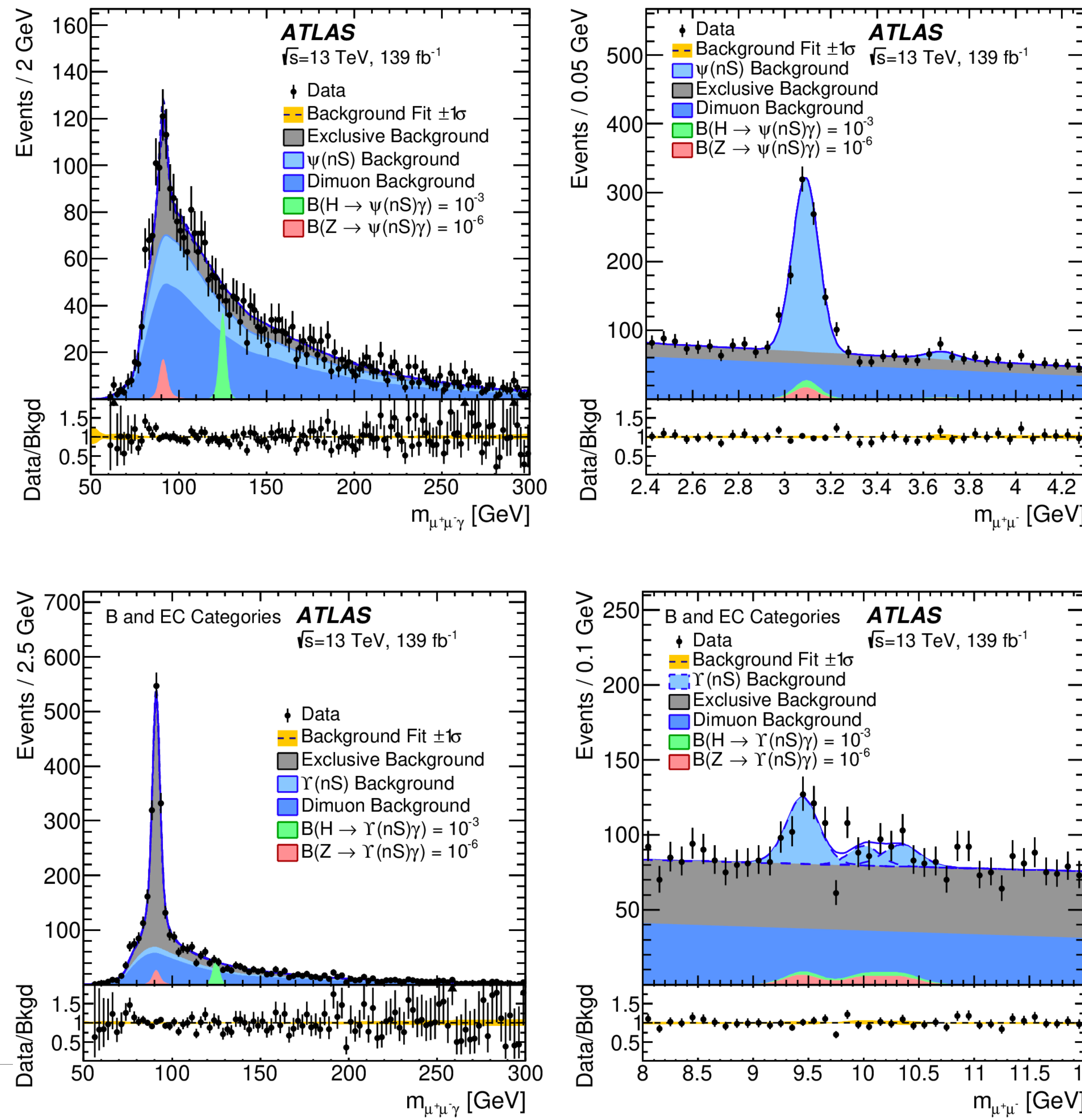
- **Background Shape Uncertainty:** Estimated from modifications to modelling procedure (e.g. shifting/warping input distributions), shape uncertainty included in likelihood as a shape morphing nuisance parameter

- **Analysis is statistics limited**

h/Z→Qγ: Results

- **Maximum Likelihood fit**
  - Two observables: $m_{\mu\mu\gamma}$, $m_{\mu\mu}$
- **Categorisation**
  - ψ(nS)γ: inclusive
  - Υ(nS)γ: two categories (B/EC)
- **No significant excess** above background observed
- **95% CL upper limits on BR**
  - Higgs boson: $\mathcal{O}(10^{-4})$

    (SM production cross-section assumed)
  - Z boson: $\mathcal{O}(10^{-6})$



Decay channel	Branching fraction: Higgs boson [10^{-4}] Expected	Higgs boson [10^{-4}] Observed	Z boson [10^{-6}] Expected	Z boson [10^{-6}] Observed
$J/\psi\,\gamma$	$1.9^{+0.8}_{-0.5}$	2.1	$0.6^{+0.3}_{-0.2}$	1.2
$\psi(2S)\,\gamma$	$8.5^{+3.8}_{-2.4}$	10.9	$2.9^{+1.3}_{-0.8}$	2.3
$\Upsilon(1S)\,\gamma$	$2.8^{+1.3}_{-0.8}$	2.6	$1.5^{+0.6}_{-0.4}$	1.0
$\Upsilon(2S)\,\gamma$	$3.5^{+1.6}_{-1.0}$	4.4	$2.0^{+0.8}_{-0.6}$	1.2
$\Upsilon(3S)\,\gamma$	$3.1^{+1.4}_{-0.9}$	3.5	$1.9^{+0.8}_{-0.5}$	2.3

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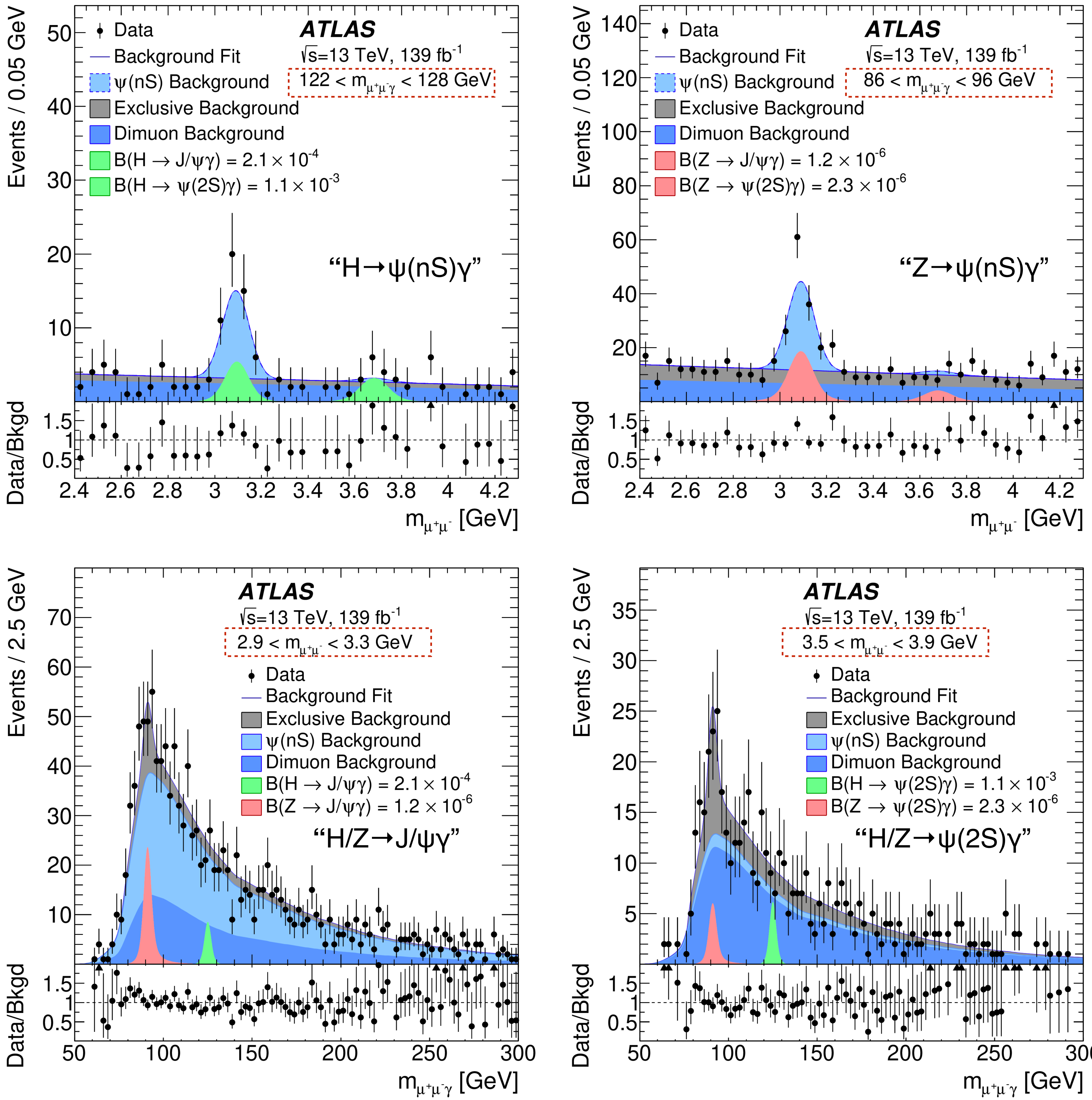
h/Z→ψ(nS)γ: Fit projections



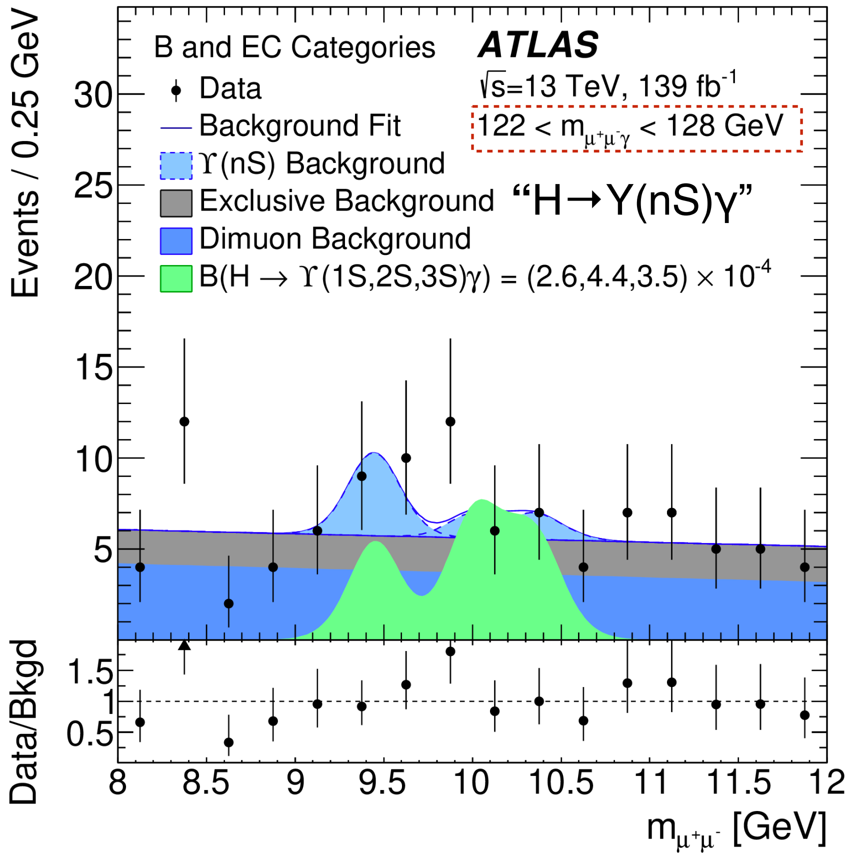
Projection in $m_{\mu\mu}$

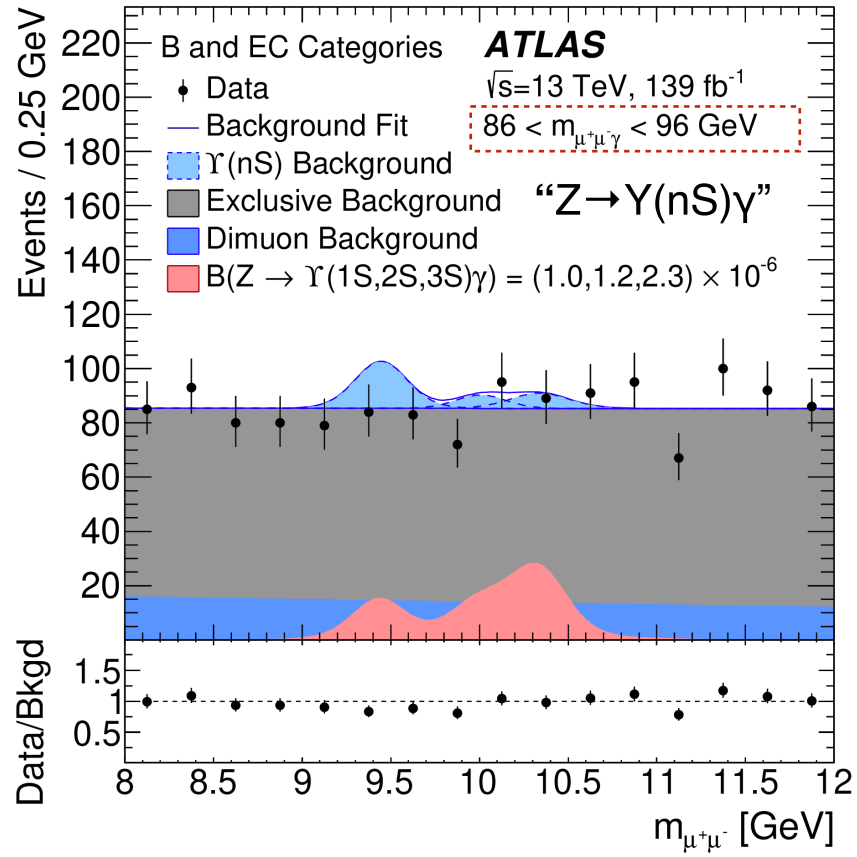
Projection in $m_{\mu\mu\gamma}$

arXiv:2208.03122

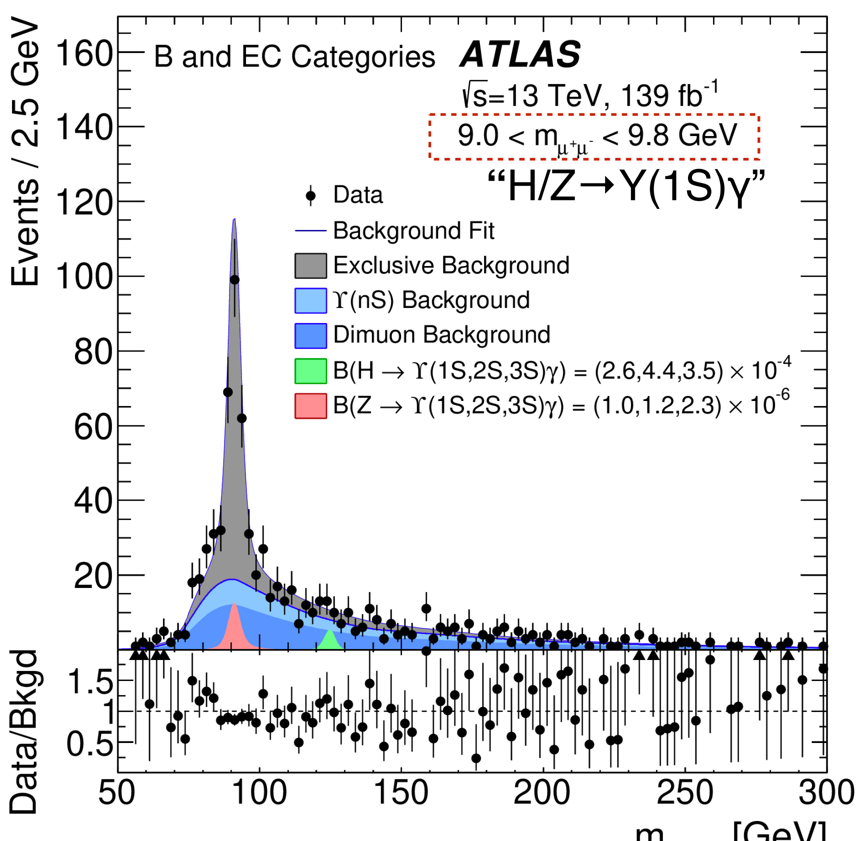
h/Z→Υ(nS)γ: Fit projections

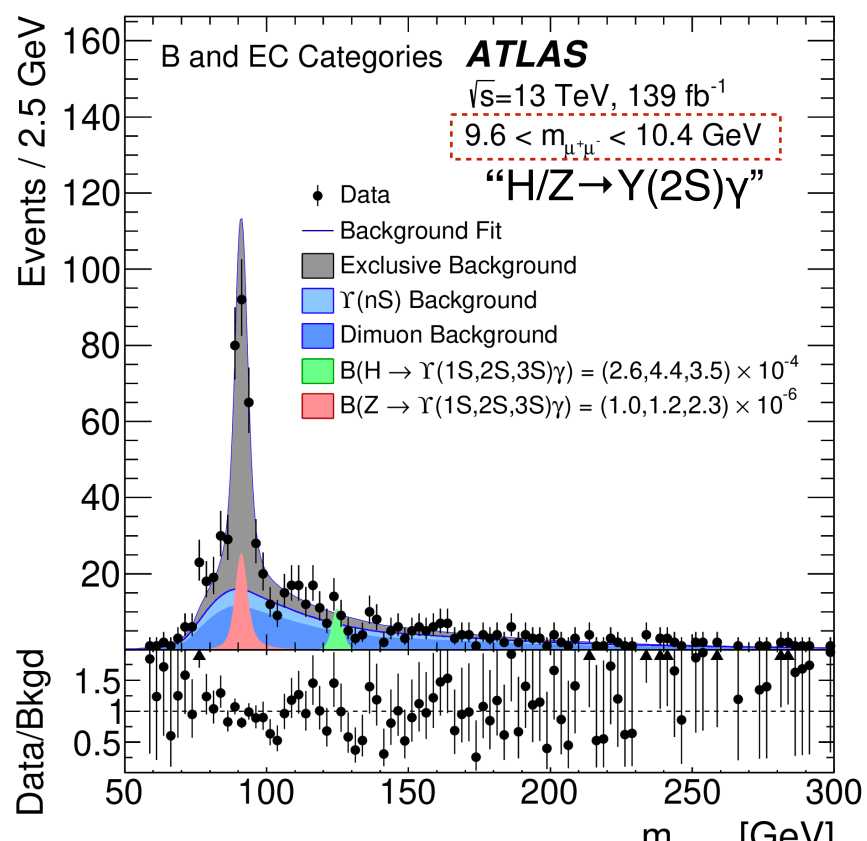
Projection in $m_{\mu\mu}$

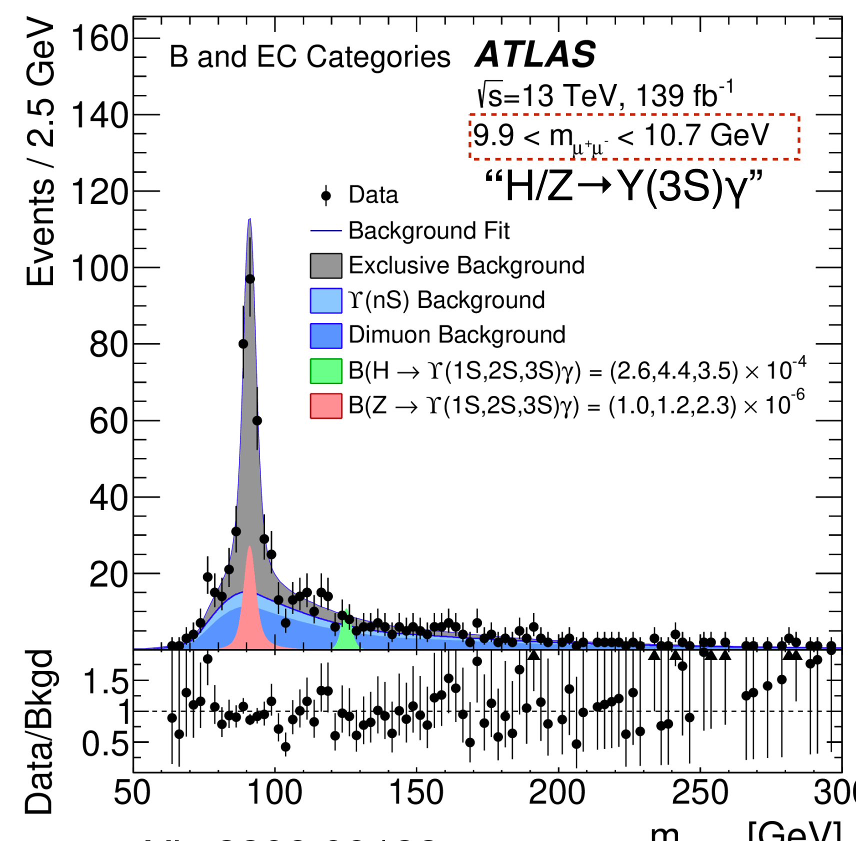




Projection in $m_{\mu\mu\gamma}$



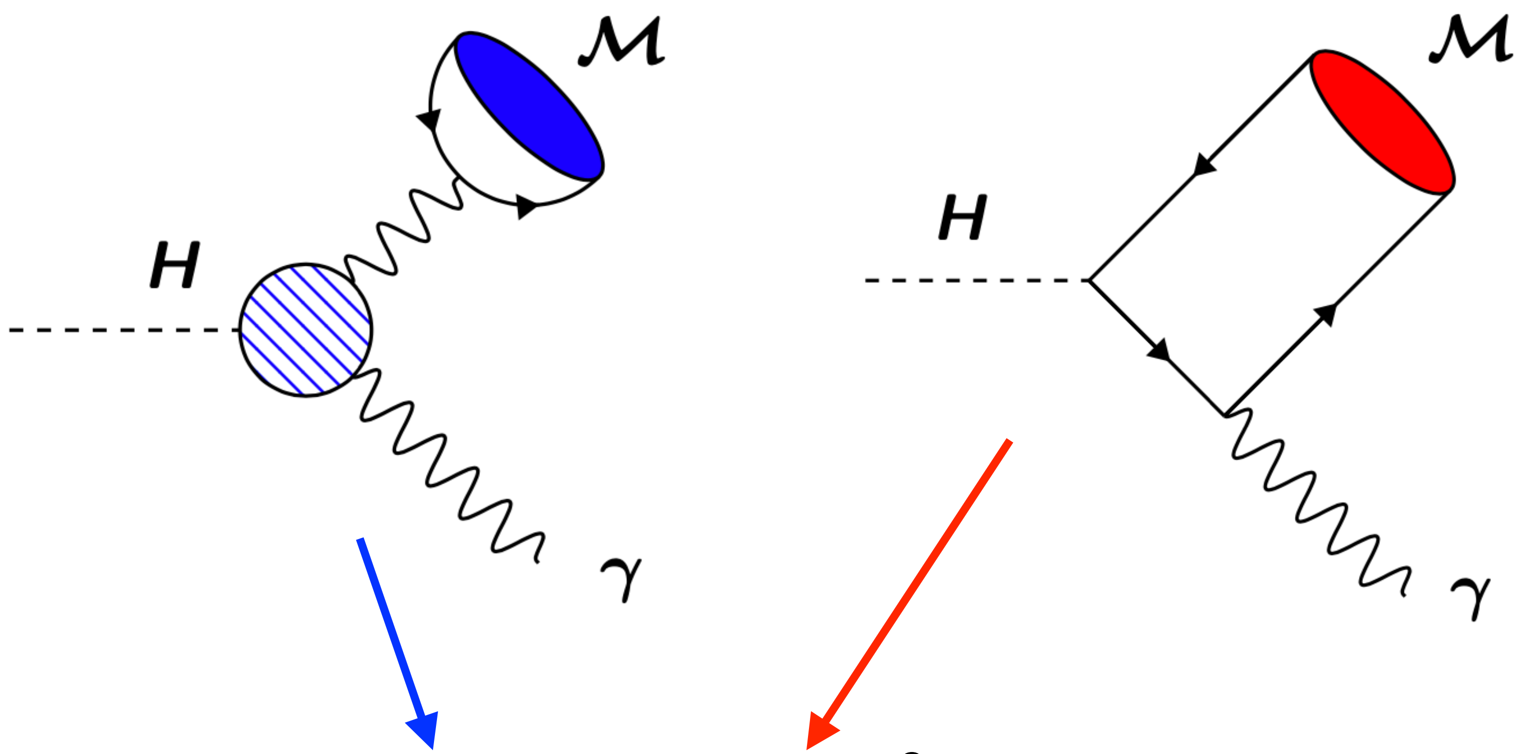




arXiv:2208.03122

h/Z→Qγ: κ-framework interpretation

- κ_q **coupling modifier**: ratio of quark coupling y_q over the SM-expectation $\kappa_q = \frac{y_q}{y_q^{SM}}$
- **Combine** with $H \to \gamma\gamma$[1] to remove Γ_H-dependence →constraints in κ_q/κ_γ



$$\frac{\mu_{h\to J/\psi\gamma}}{\mu_{h\to\gamma\gamma}} \approx \frac{\left|\mathscr{A}_{ind} + \frac{\kappa_c}{\kappa_\gamma}\mathscr{A}_{dir}\right|^2}{\Gamma^{SM}_{h\to J/\psi\gamma}}$$

$$\mu = \frac{(\sigma \times \mathscr{B})_{\text{obs}}}{(\sigma \times \mathscr{B})_{\text{SM}}}$$

Analysis	κ-ratio	Constraints	
		Expected	Observed
$H \to J/\psi\gamma$	κ_c/κ_γ	$(-123, 146)$	$[-136, 178]$
$H \to \Upsilon(nS)\gamma$	κ_b/κ_γ	$(-37, 40)$	$[-38, 40]$

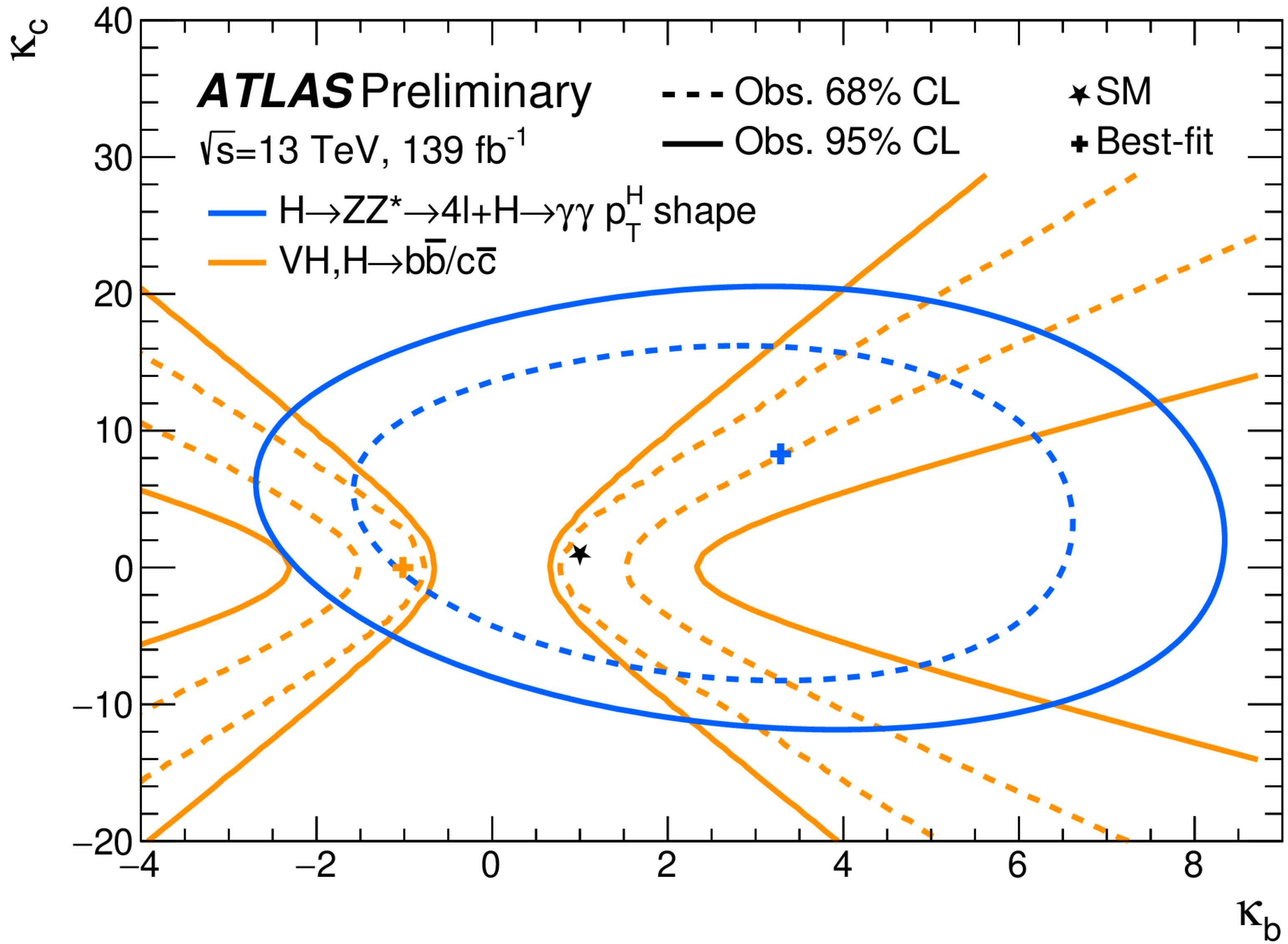
arXiv:2208.03122

[1]ATLAS-CONF-2020-026

Other κ-framework results

- **κ-framework interpretation 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]
    - $|\kappa_c| < 8.5\ (12.4)$ at 95% CL
    - $|\kappa_c/\kappa_b| < 4.5\ (5.1)$ at 95% CL
- Measurements of Higgs p_T
  [arXiv:2207.08615]

Channel	Parameter	Observed 95% confidence interval	Expected 95% confidence interval
$H \to ZZ^* \to 4\ell$	κ_b	$[-1.8,\ 6.4]$	$[-3.3,\ 9.3]$
	κ_c	$[-7.7,\ 18.3]$	$[-12.3,\ 19.2]$
$H \to \gamma\gamma$	κ_b	$[-3.5,\ 10.2]$	$[-2.5,\ 8.0]$
	κ_c	$[-12.6,\ 18.3]$	$[-10.1,\ 17.3]$
Combined	κ_b	$[-2.0,\ 7.4]$	$[-2.0,\ 7.4]$
	κ_c	$[-8.6,\ 17.3]$	$[-8.5,\ 15.9]$



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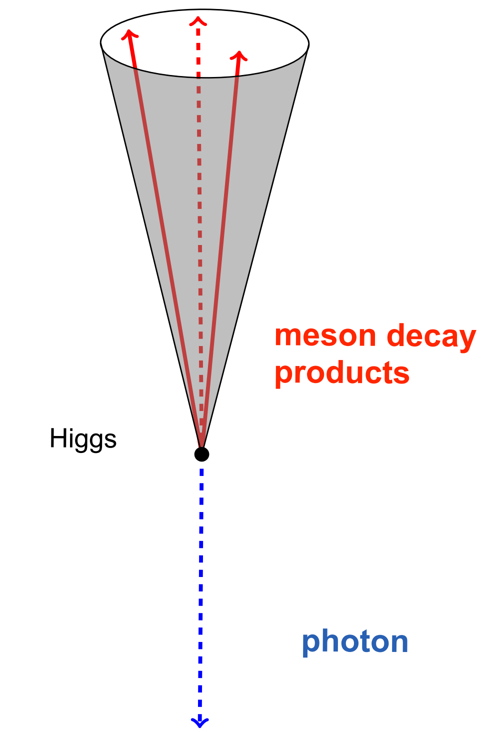
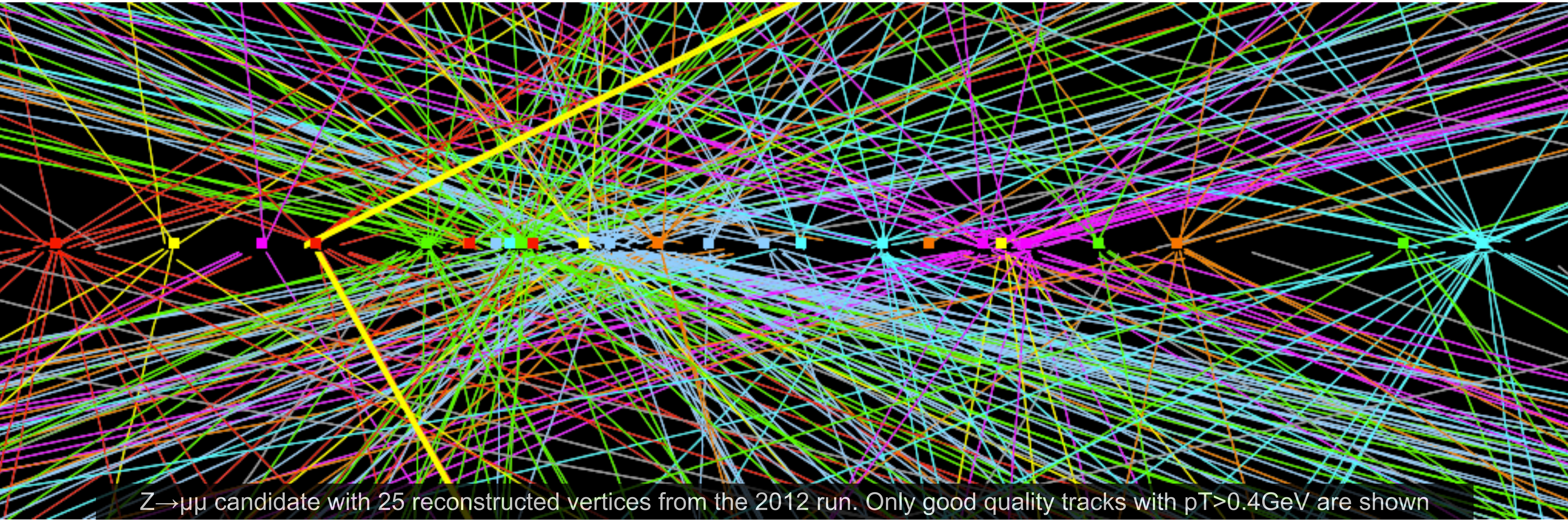
h/Z→ϕγ, ργ, ωγ, and h→K*γ: Analysis Strategy

- **Exclusive decays → distinct experimental signature**
  - Collimated isolated high-pT track pair recoils against high-pT isolated photon
- **Meson decays:**
  - $\phi \to K^+K^-$, BR=49%
  - $\rho \to \pi^+\pi^-$, BR~100%
  - $\omega \to \pi^+\pi^-\pi^0$, BR=89%
  - $K^* \to K^\pm\pi^\mp$, BR~100% ·········▸ First look for flavour-changing interactions in exclusive decays
- **Small opening angles between decay products**
  - Particularly for $\phi \to K^+K^-$
  - Tracking in dense environments

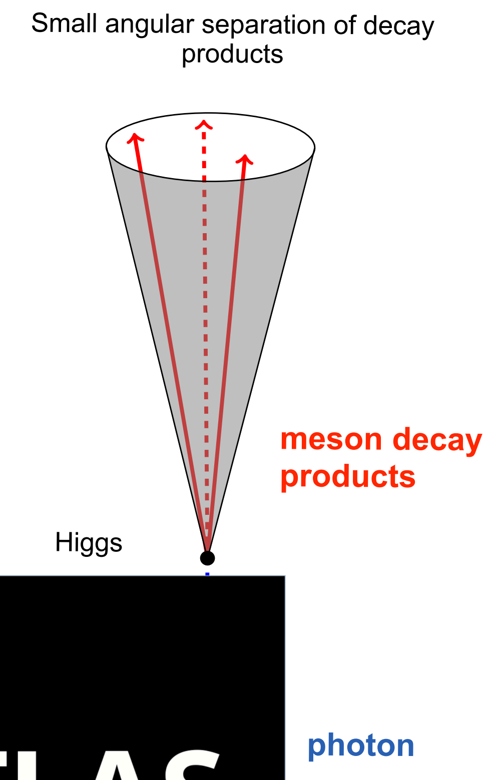


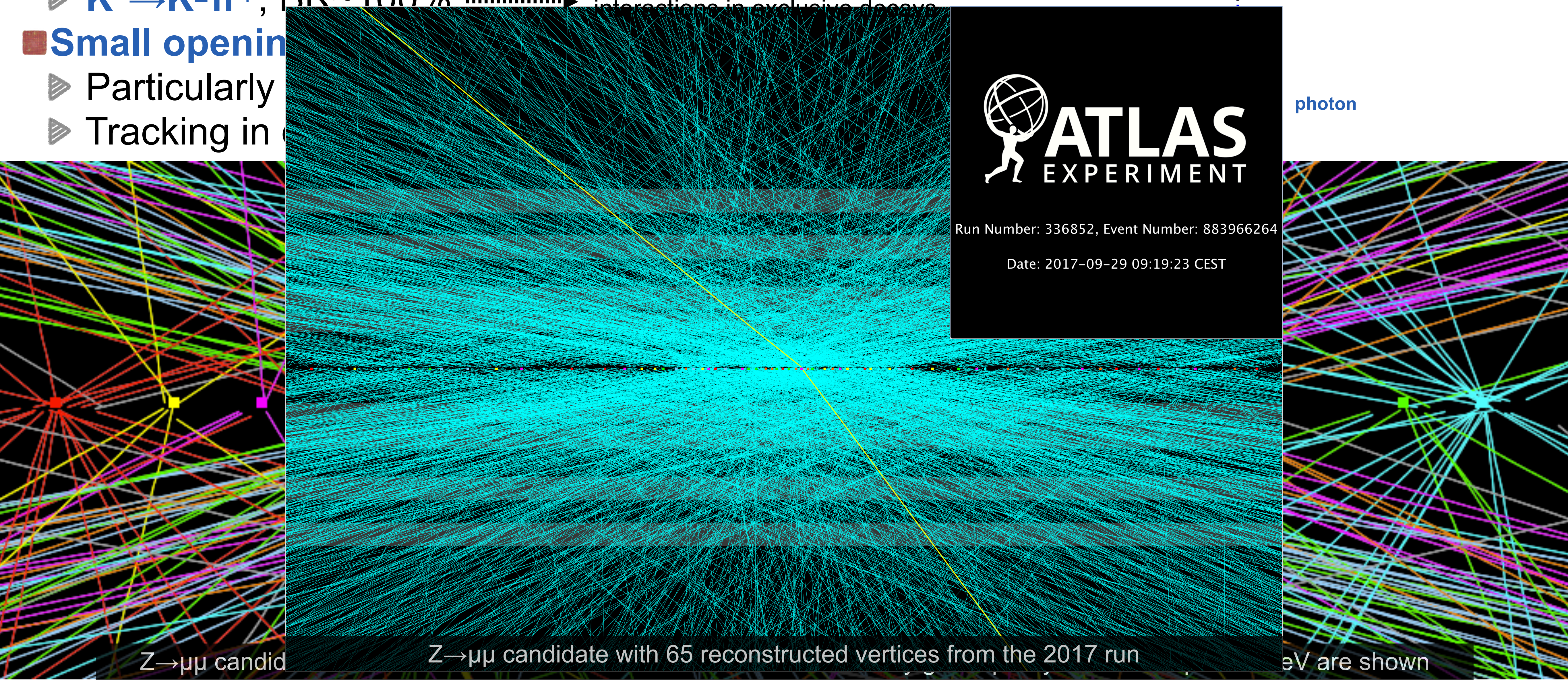


Z→μμ candidate with 25 reconstructed vertices from the 2012 run. Only good quality tracks with pT>0.4GeV are shown

h/Z→ϕγ, ργ, ωγ, and h→K*γ: Analysis Strategy

- **Exclusive decays → distinct experimental signature**
  - Collimated isolated high-pT track pair recoils against high-pT isolated photon
- **Meson decays:**
  - $\phi \to K^+K^-$, BR=49%
  - $\rho \to \pi^+\pi^-$, BR~100%
  - $\omega \to \pi^+\pi^-\pi^0$, BR=89%
  - $K^* \to K^\pm\pi^\mp$, BR~100% ······▶ First look for flavour-changing interactions in exclusive decays
- **Small openin**
  - Particularly
  - Tracking in



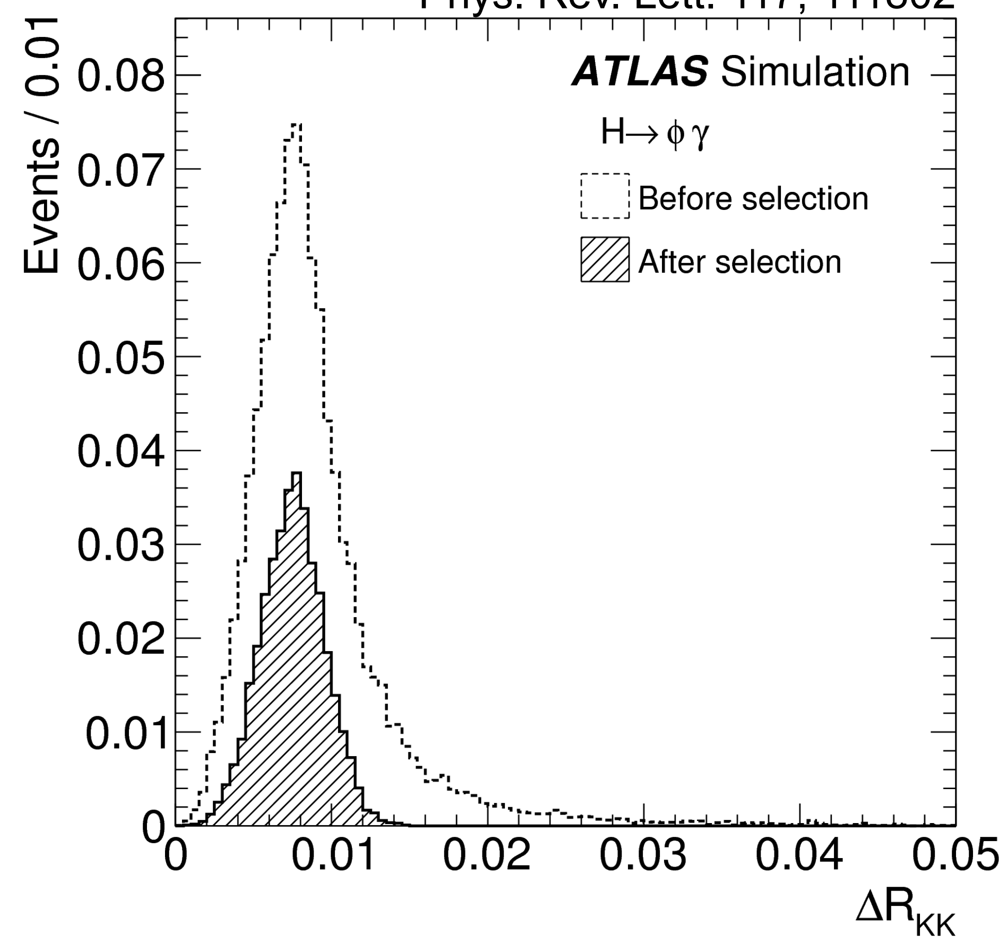


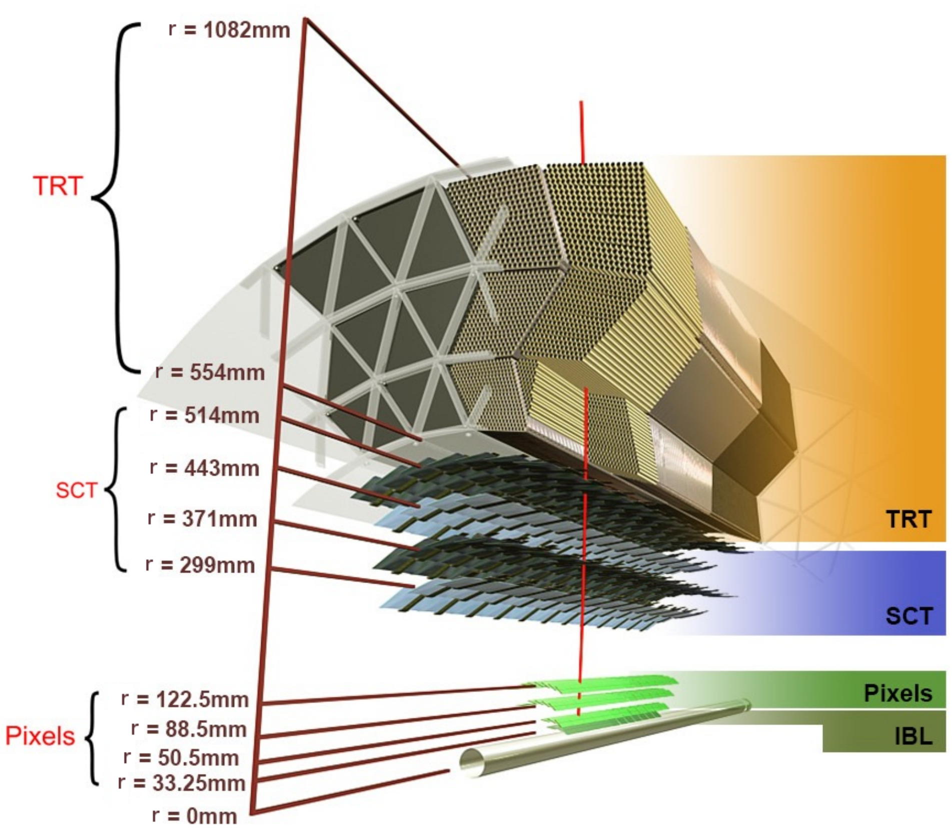
Z→μμ candidate with 65 reconstructed vertices from the 2017 run

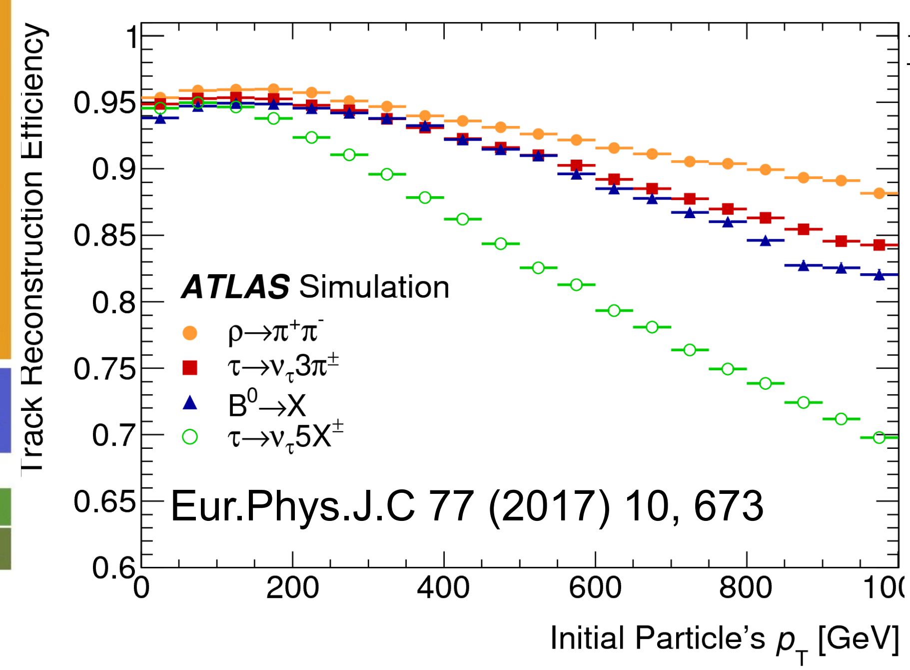
h/Z→ϕγ, ργ, ωγ, and h→K*γ: Analysis Strategy

- **Exclusive decays → distinct experimental signature**
  - Collimated isolated high-pT track pair recoils against high-pT isolated photon
- **Meson decays:**
  - **$\varphi \to K^+K^-$**, BR=49%
  - **$\rho \to \pi^+\pi^-$**, BR~100%
  - **$\omega \to \pi^+\pi^-\pi^0$**, BR=89%
  - **$K^* \to K^\pm\pi^\mp$**, BR~100%
- **Small opening angles between decay products**
  - Particularly for $\varphi \to K^+K^-$
  - Tracking in dense environments

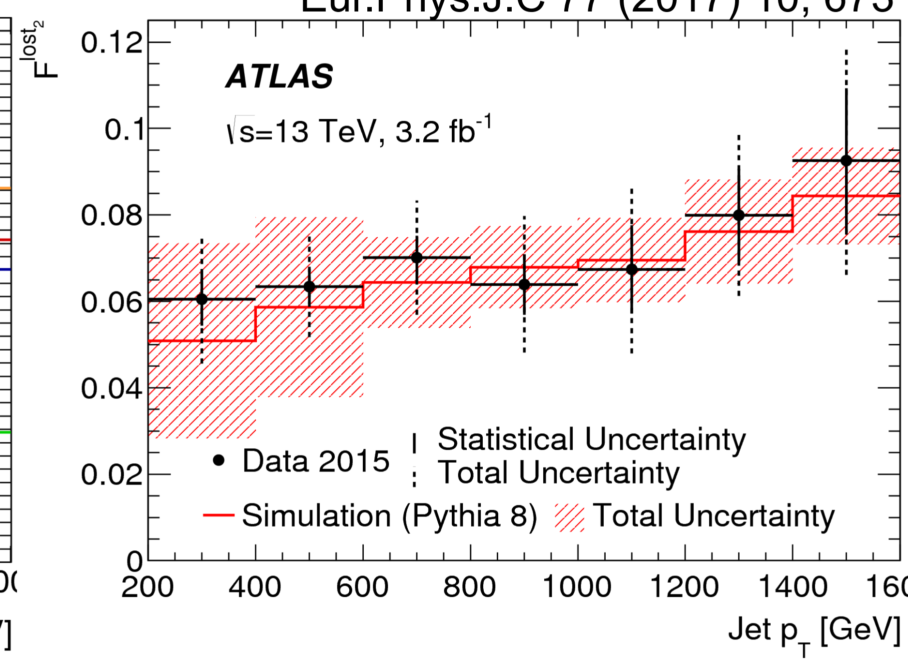
Phys. Rev. Lett. 117, 111802



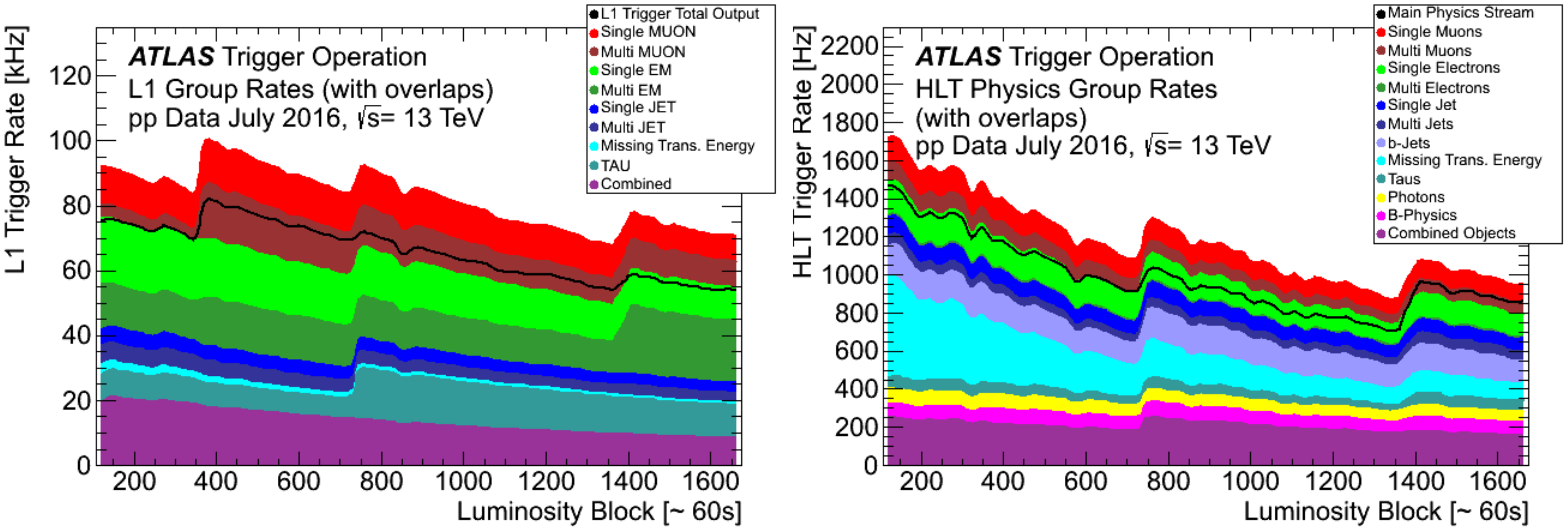




Eur.Phys.J.C 77 (2017) 10, 673

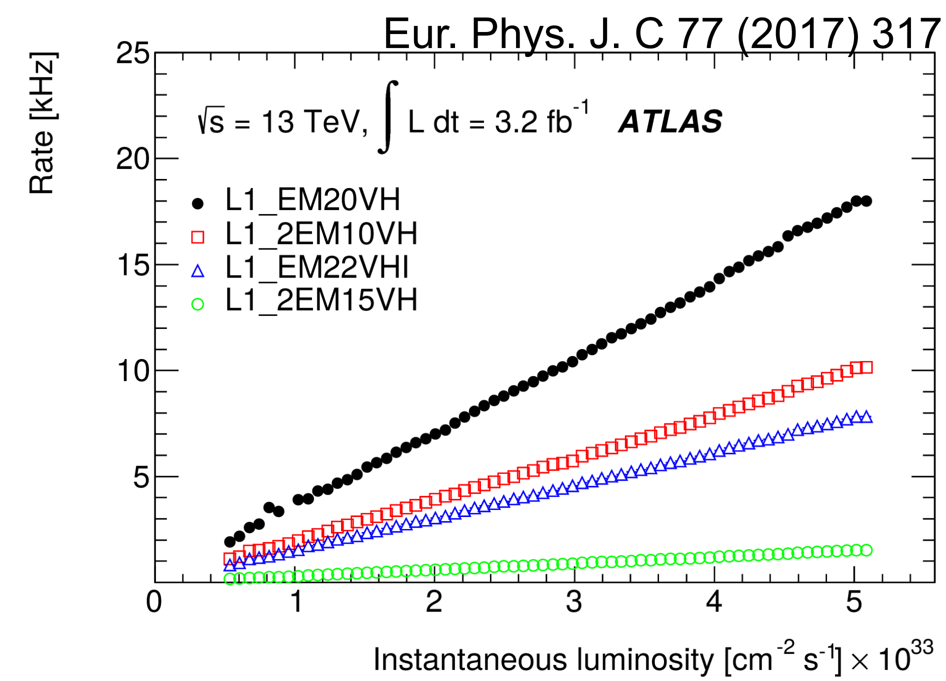


h/Z→ϕγ, ργ, ωγ, and h→K*γ: Trigger Strategy

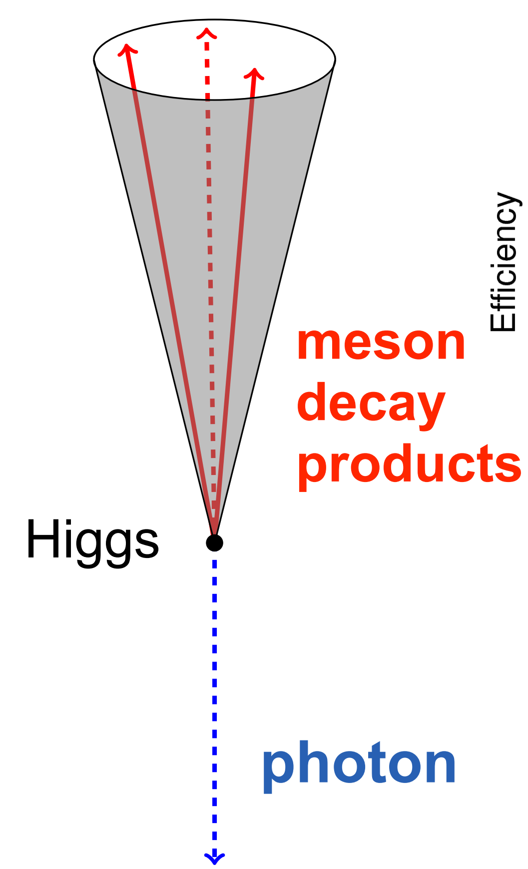


Trigger rates (July 2016) LHC fill with peak luminosity $1.02 \times 10^{34} cm^{-2}s^{-1}$ and <μ>= 24.2

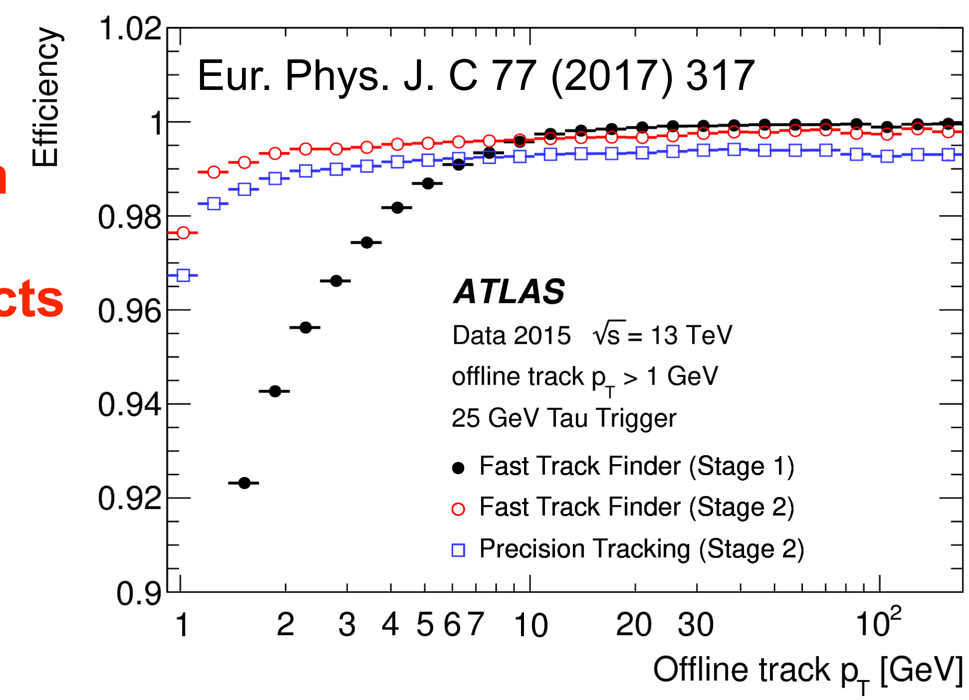
- **Two-level trigger system**
  - Level-1: Hardware-based
  - HLT: Software-based



Small angular separation
of decay products



- **Enabled by dedicated trigger items**
  - Modified τ-lepton algorithms
  - Efficiency w.r.t offline selection
    - φγ: ~75%
    - ργ: ~78%
- **Level-1**
  - Lowest pT unprescaled EM object
- **HLT**
  - Isolated di-track consistent with m_{Meson}
  - Photon



h/Z→ϕγ, ργ, ωγ, and h→K*γ: Results

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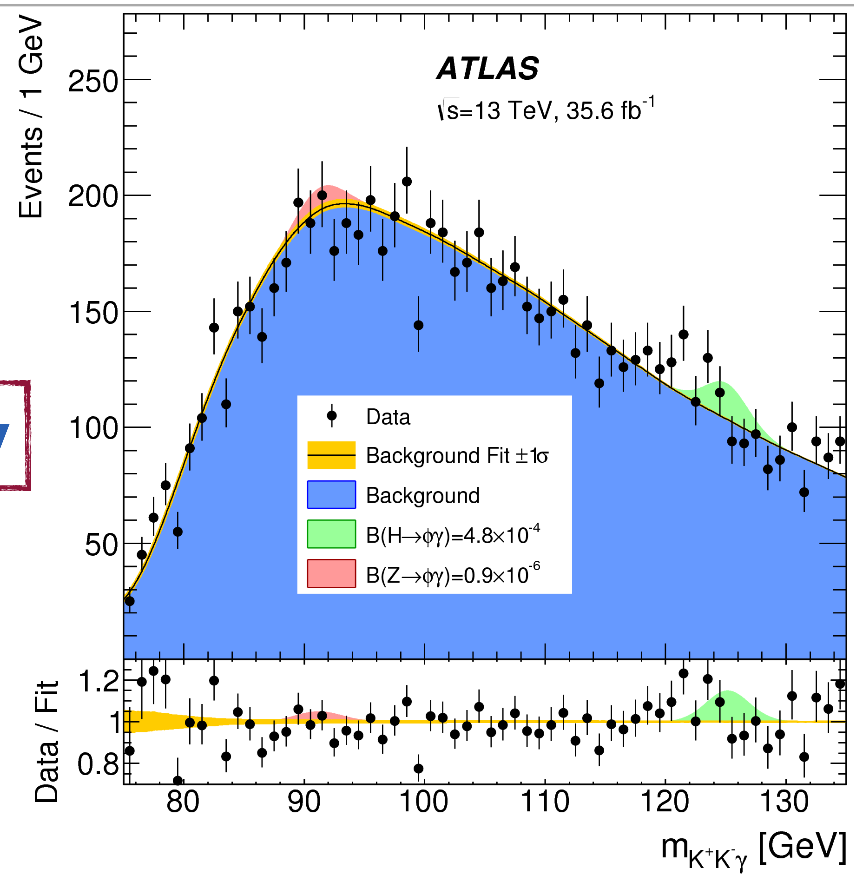
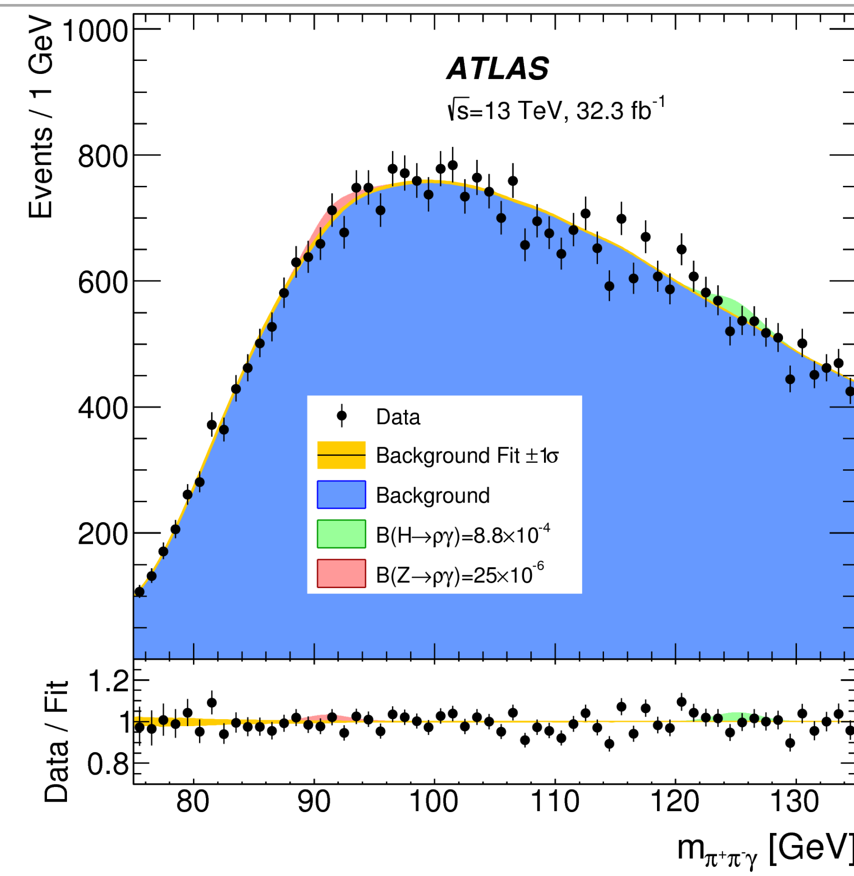
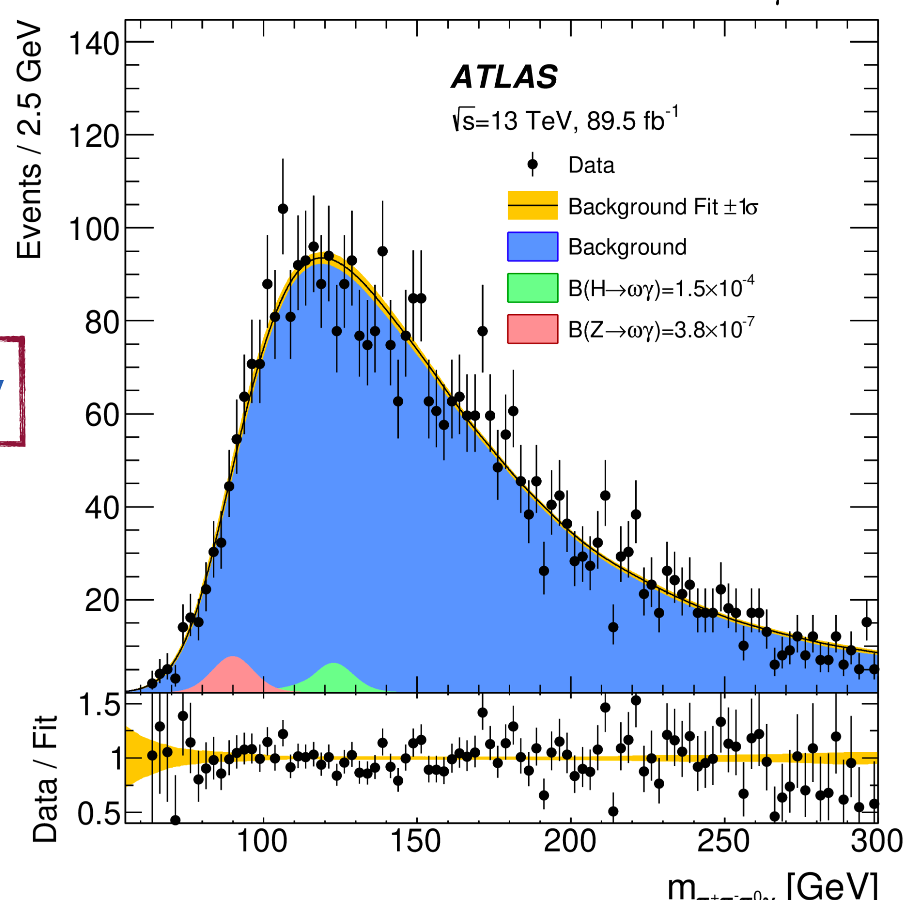
h/Z→φγ



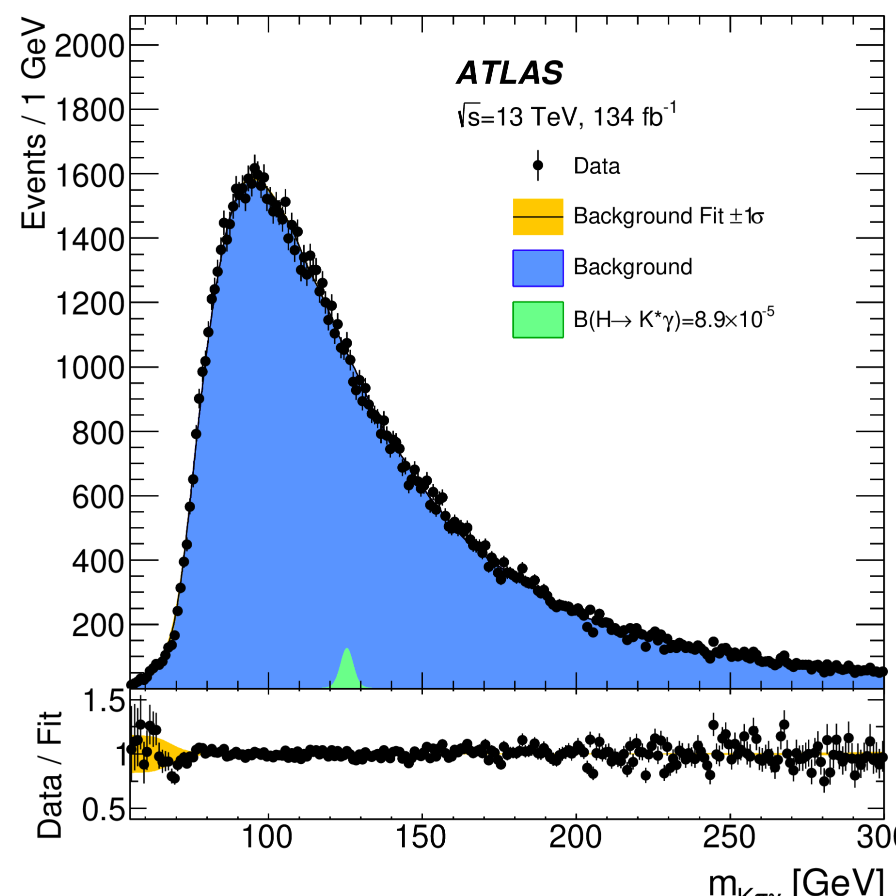
h/Z→ργ



h/Z→ωγ

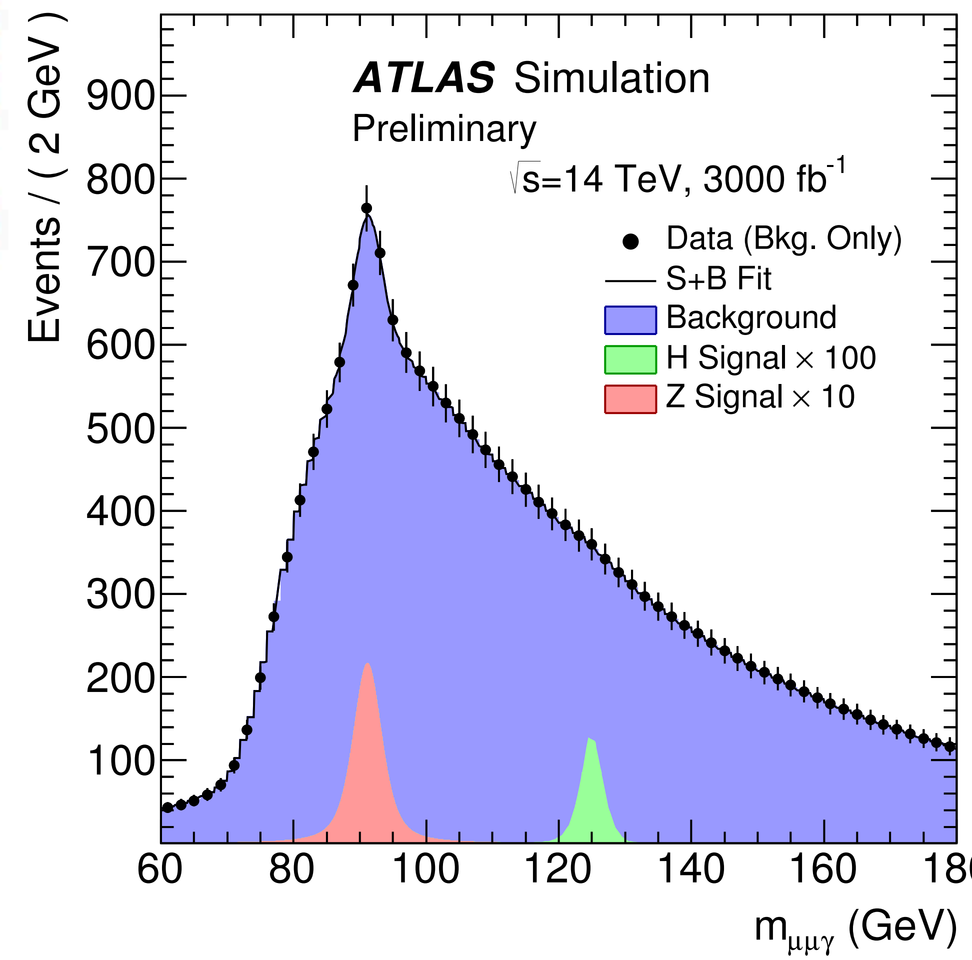


h→K*γ



arXiv:2301.09938

h/Z→Qγ: in the future



- HL-LHC is a Higgs boson factory
  - $\mathcal{O}$(200M) Higgs bosons produced
- HL-LHC projections for h/Z→J/ψγ
  - Simple and, relatively, clean final state
  - Small branching ratio, few events expected
  - At SM sensitivity h→μμγ_{FSR} contribution~3×h→J/ψγ
- Future colliders: leap in Higgs production
  - FCC-hh 100 TeV 20/ab: $\mathcal{O}$(15G) Higgs bosons

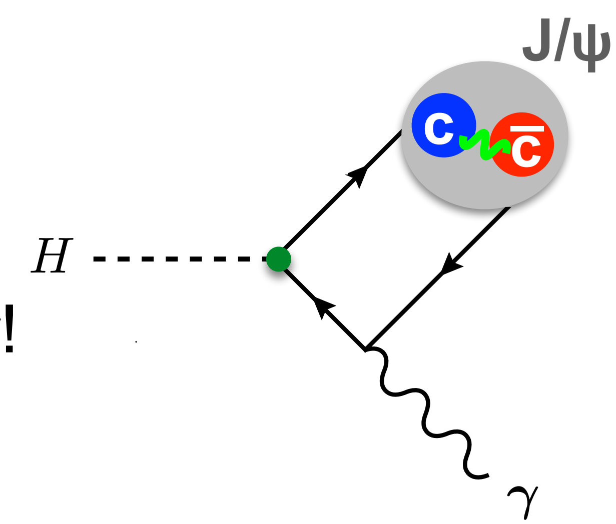
	Expected branching ratio limit at 95% CL		
	$\mathcal{B}(H \to J/\psi\gamma)\,[10^{-6}]$		$\mathcal{B}(Z \to J/\psi\gamma)\,[10^{-7}]$
	Cut Based	Multivariate Analysis	Cut Based
300 fb^{-1}	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
3000 fb^{-1}	55^{+24}_{-15}	44^{+19}_{-12}	$4.4^{+1.9}_{-1.1}$

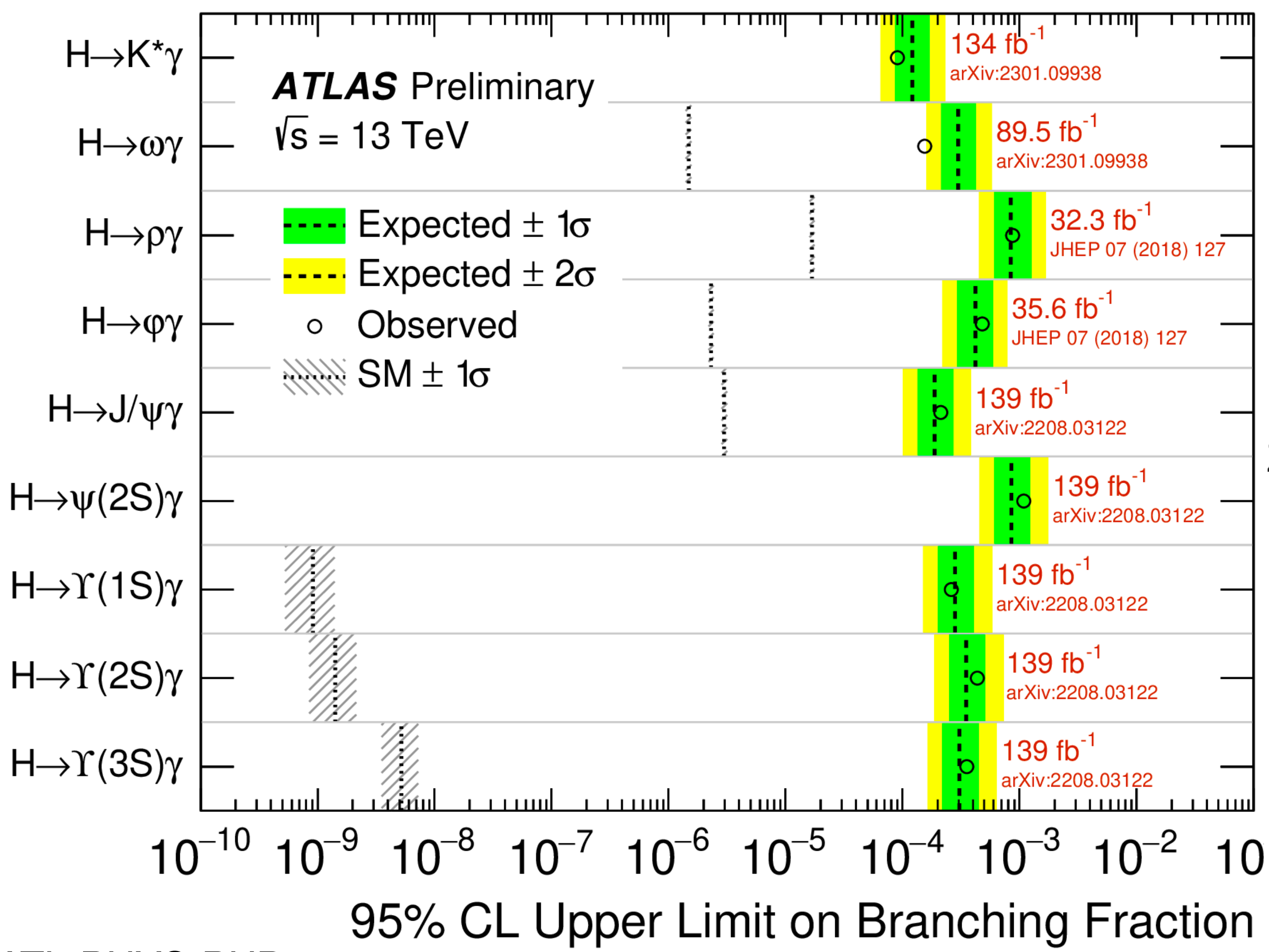
	Standard Model expectation	
	$\mathcal{B}(H \to J/\psi\gamma)\,[10^{-6}]$	$\mathcal{B}(Z \to J/\psi\gamma)\,[10^{-7}]$
	2.9 ± 0.2	0.80 ± 0.05

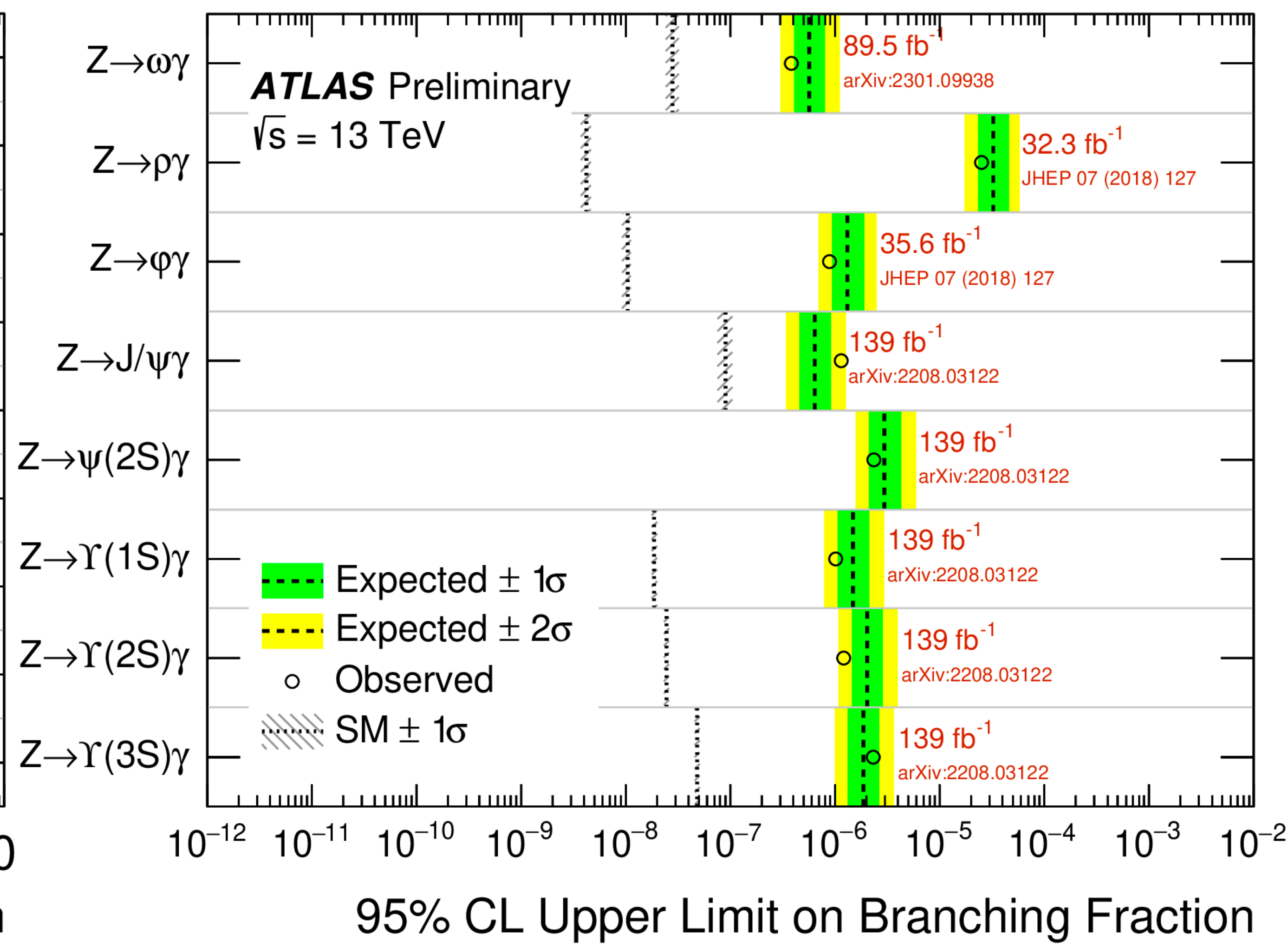
ATLAS-PHYS-PUB-2015-043

Summary

- **Higgs boson-fermion interactions is SM's least explored part**
  - New Physics could be hiding here!
- **Complementary approaches available:**
  - Exclusive decays, inclusive decays (e.g. charm tagging), Higgs boson kinematics, … A new field of study in the Higgs sector!
- **Exclusive decays**
  - Higgs boson: magnitude and sign of quark couplings
  - Z boson: reference channels + tests of QCD factorisation
  - New techniques: Dedicated triggers + non-parametric data-driven background models



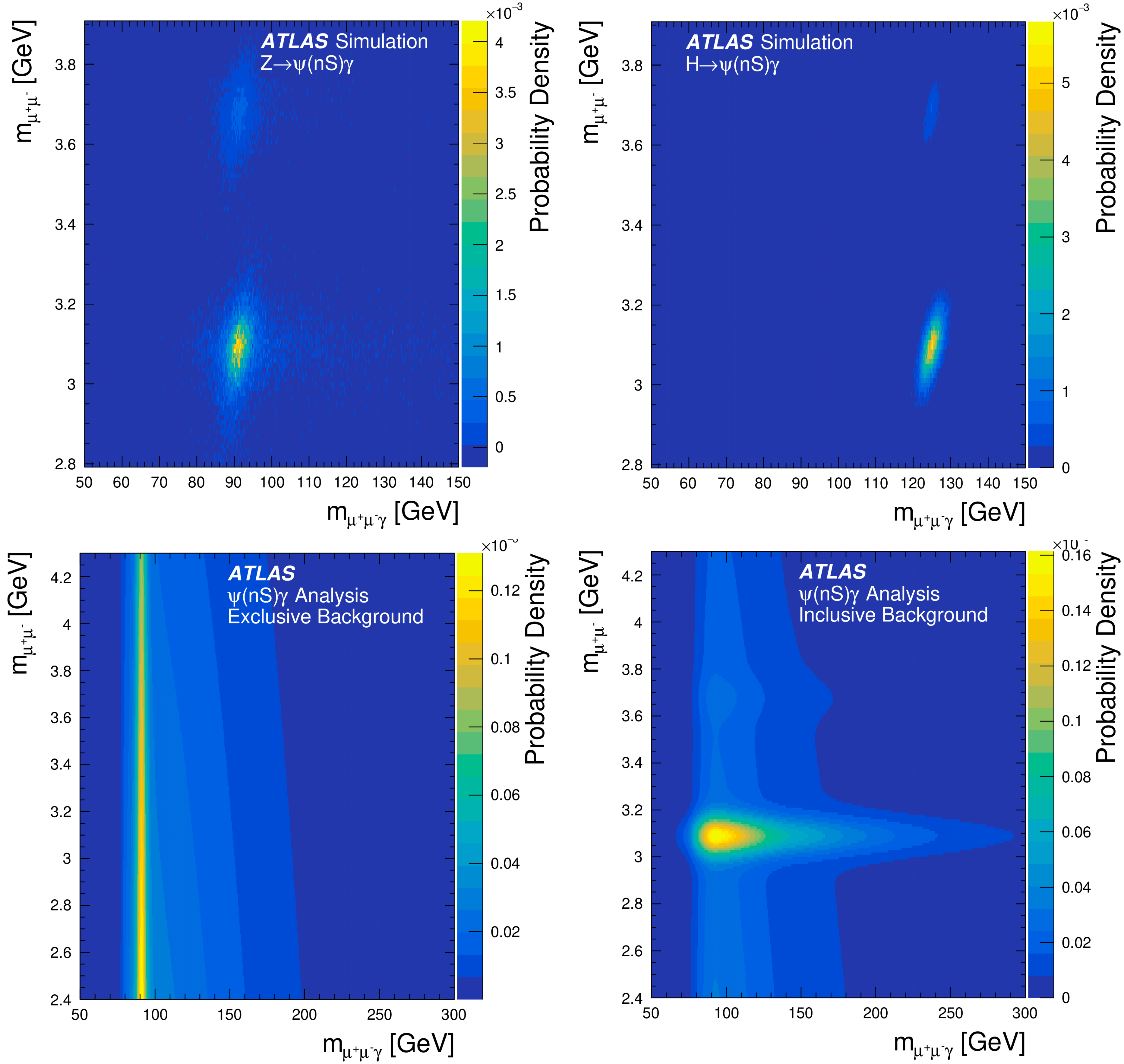




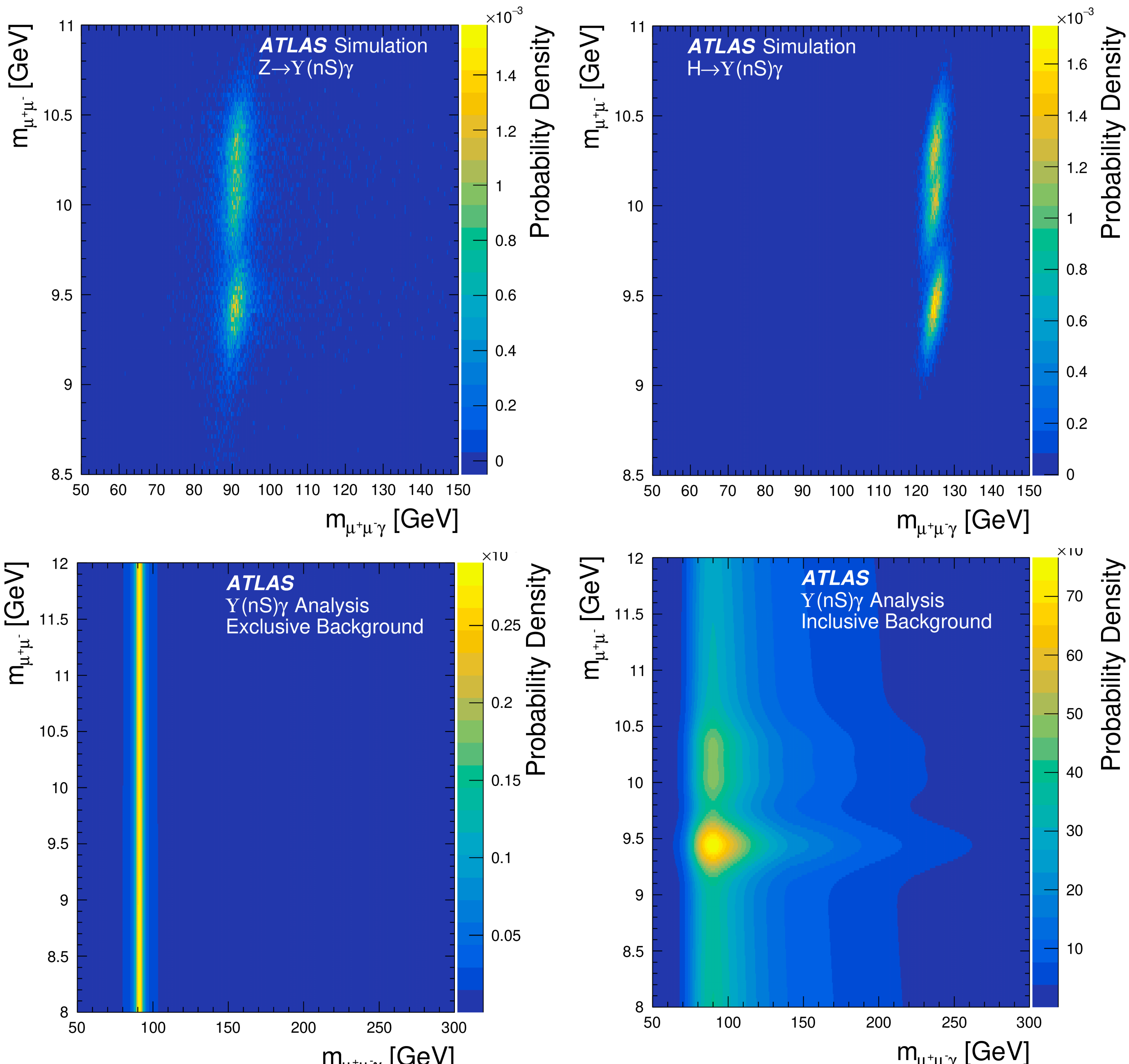
ATL-PHYS-PUB-2023-004

Additional Slides

h/Z→Qγ: Signal and Background Models



h/Z→Qγ: Signal and Background Models



h/Z→Qγ: Background Model