Search for non-standard and rare decays of the Higgs boson with the ATLAS detector

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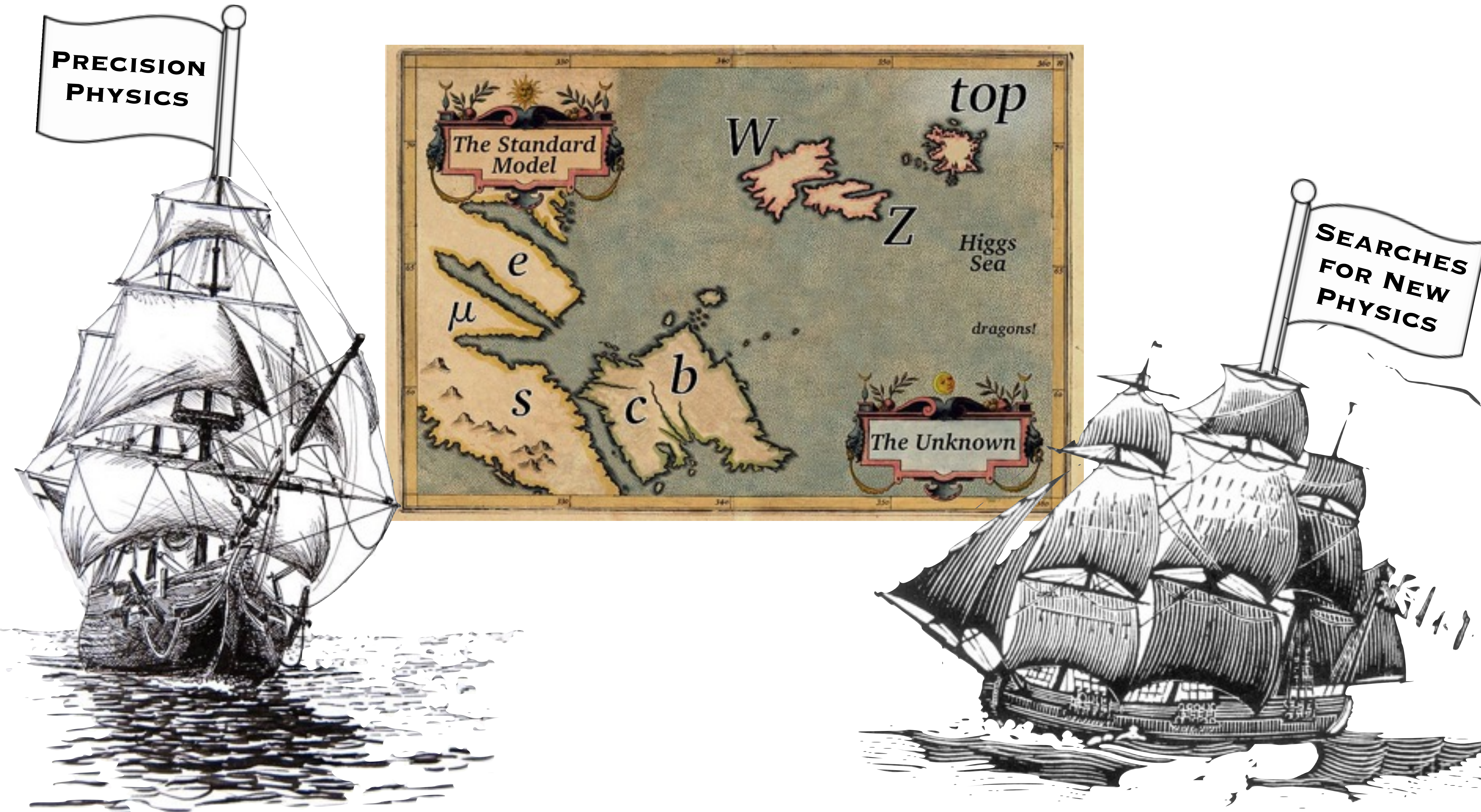
on behalf of the ATLAS Collaboration

2nd September 2017

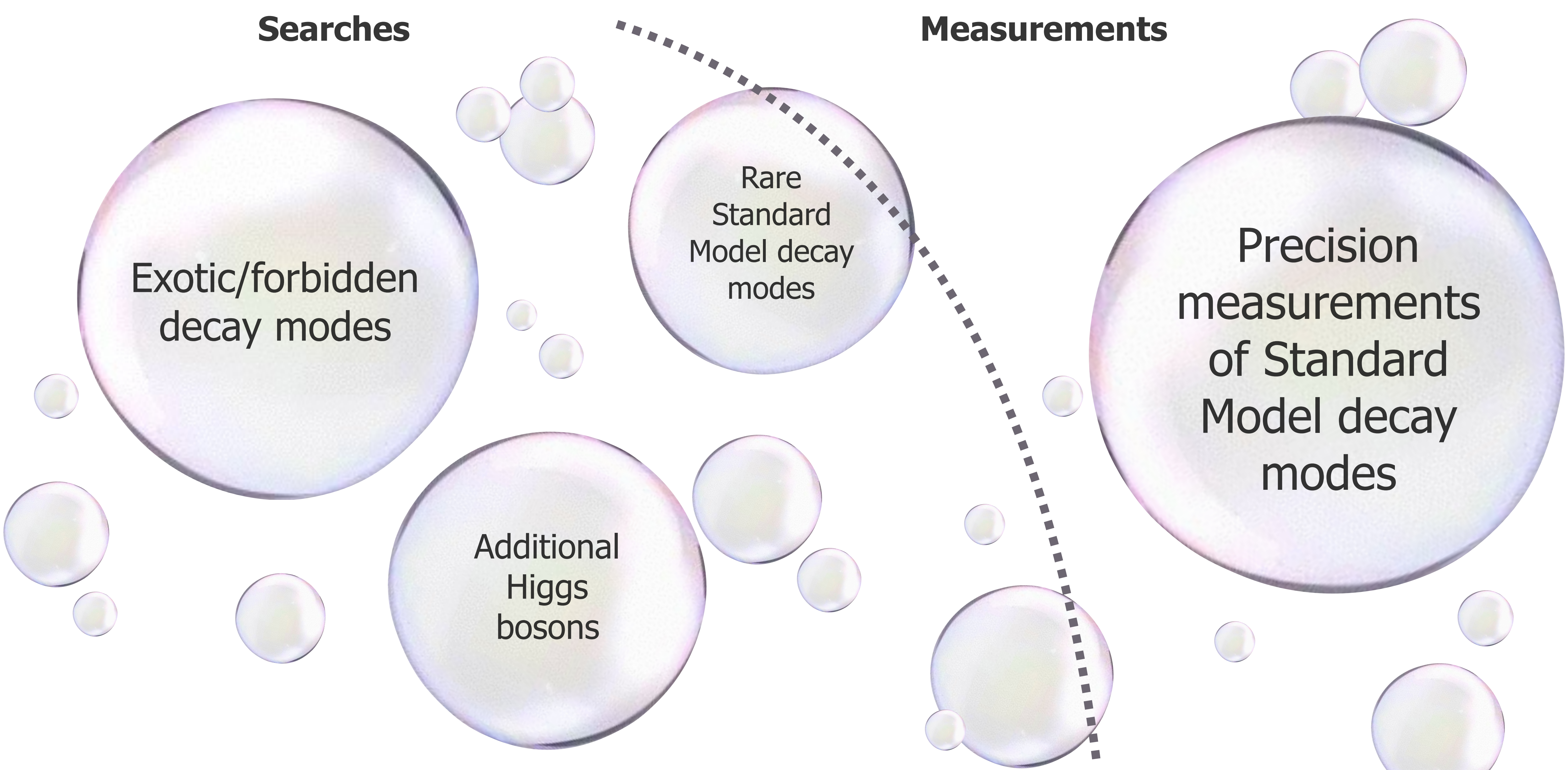
Introduction

- Standard Model still leaves plenty of unanswered questions.
  - Likely to be an effective field theory (i.e. the limit at currently accessible energy regimes of a more fundamental theory with new degrees of freedom).



The Higgs as a Portal to New Physics

- Higgs boson is (still) new territory - may provide a portal into new physics.
  - Many allowed decay modes not measured accurately (if at all).
  - New decay modes or deviations from SM predictions would be a sign of new physics.



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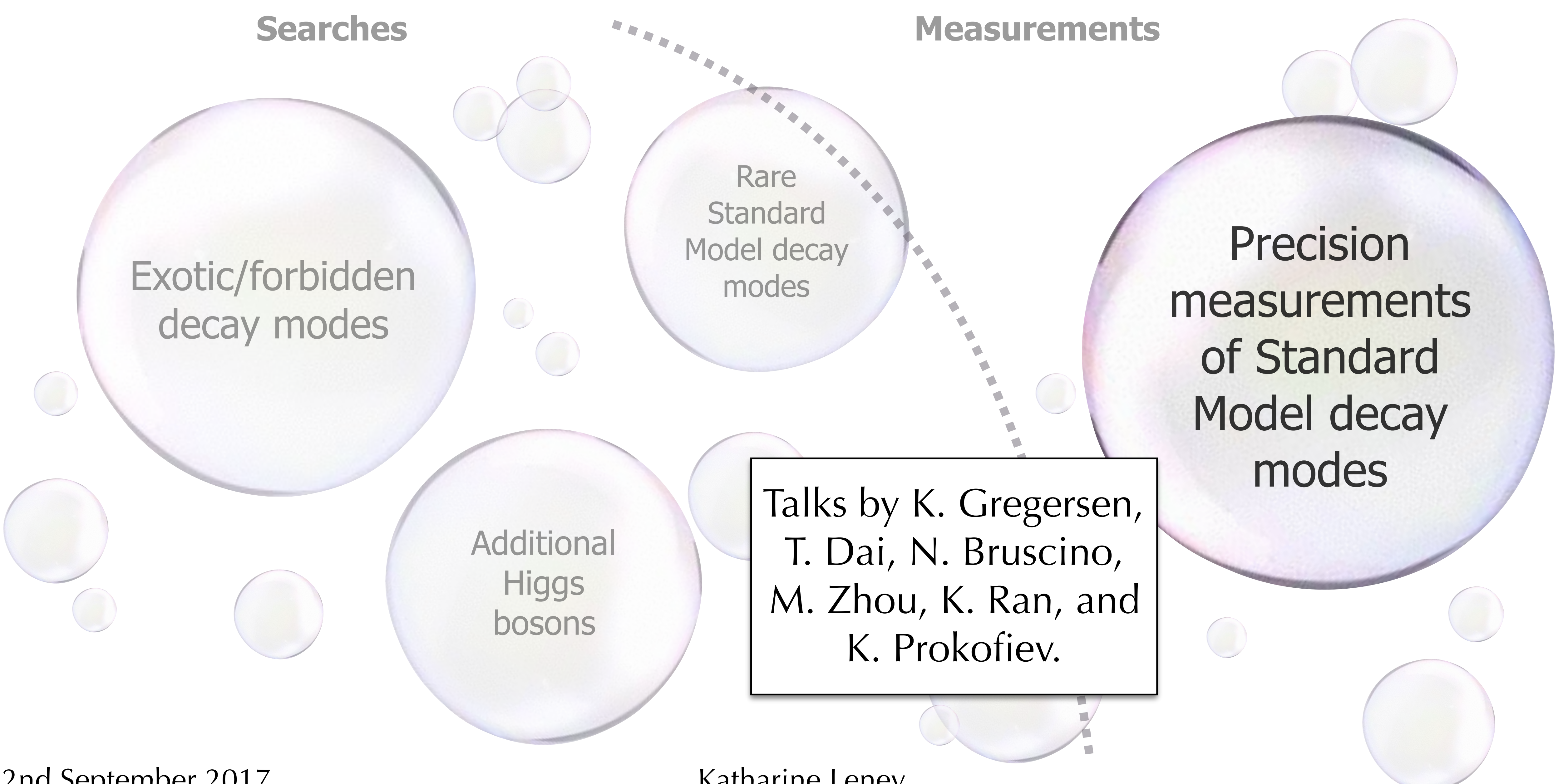

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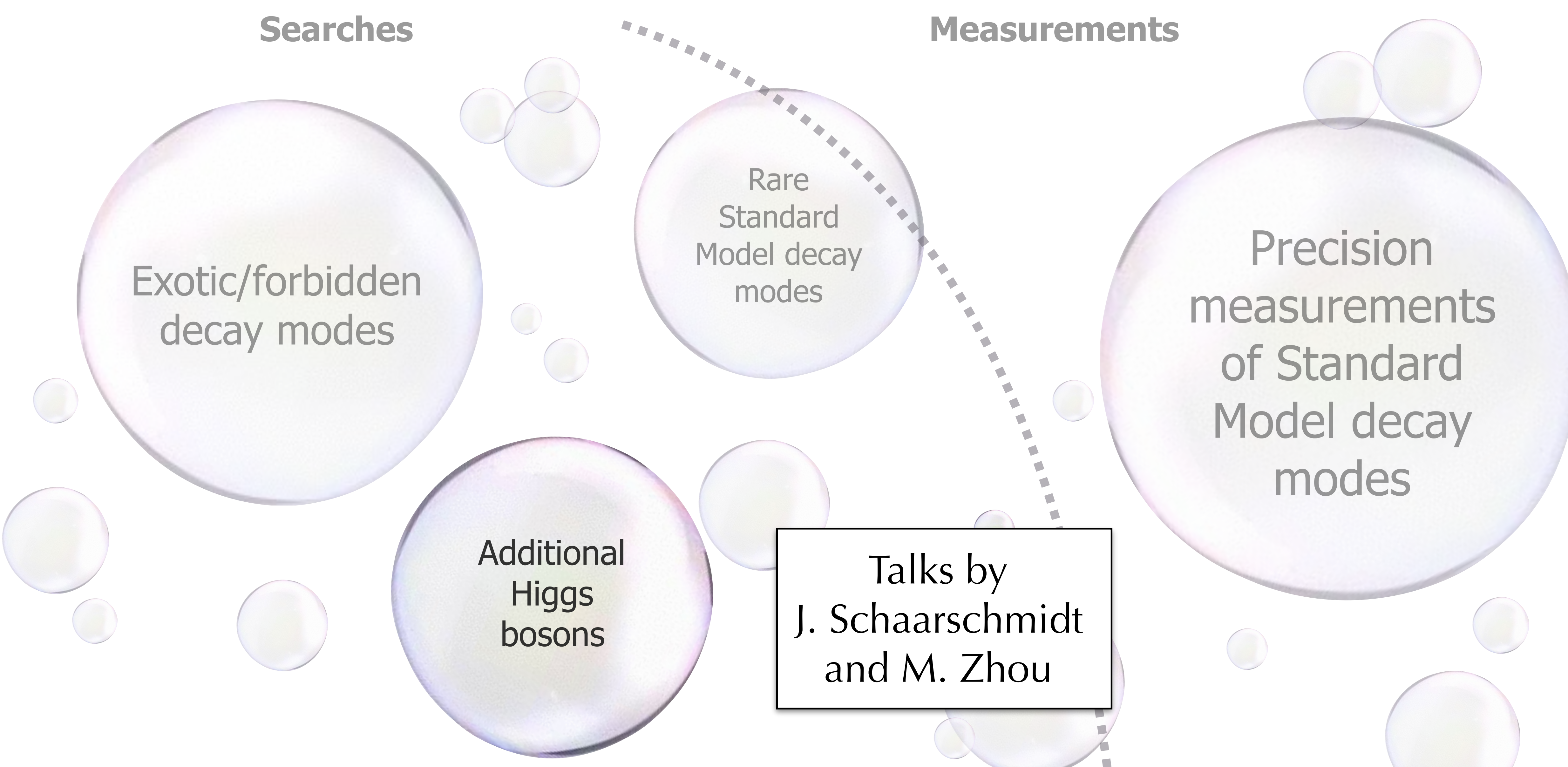

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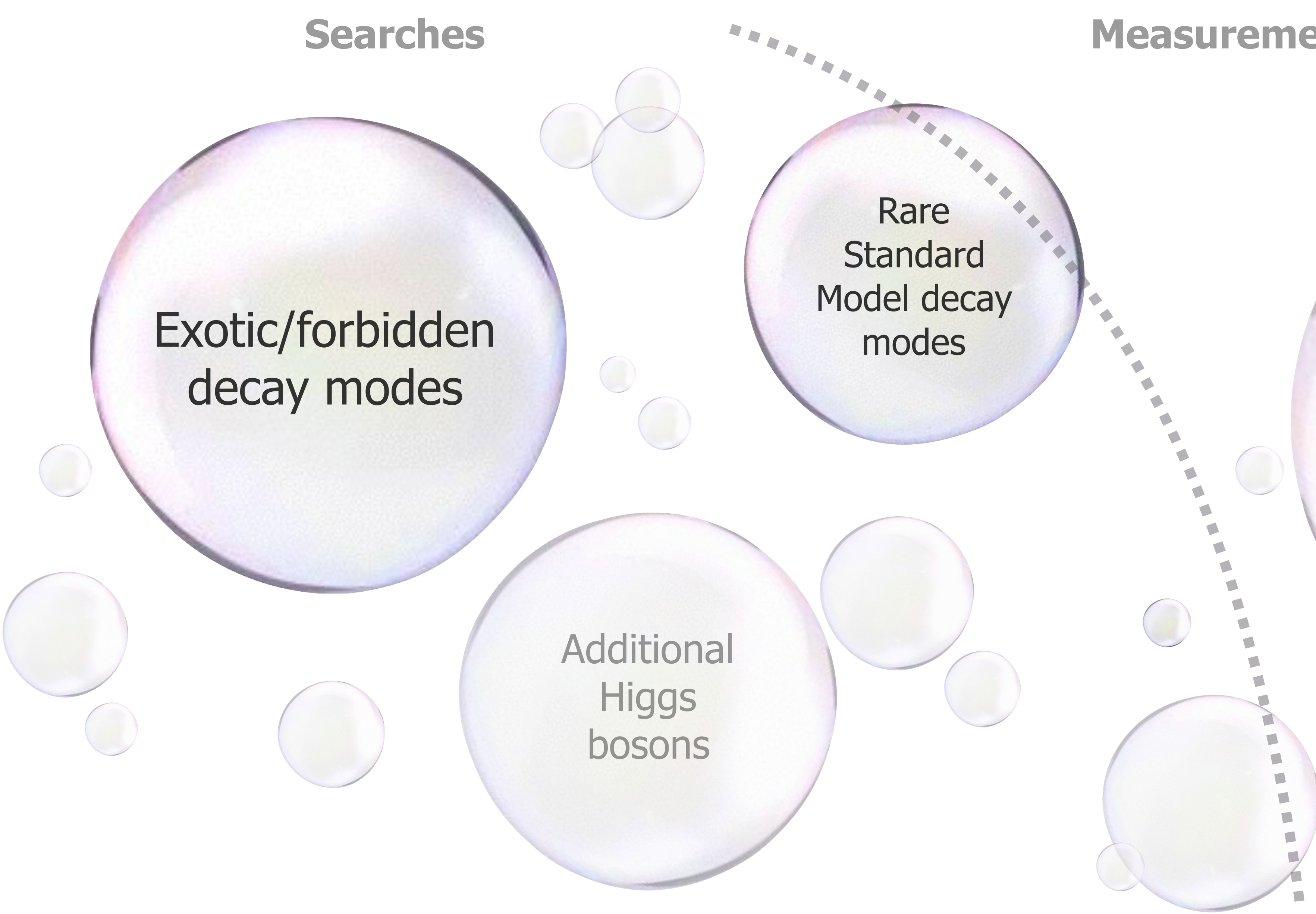


This talk

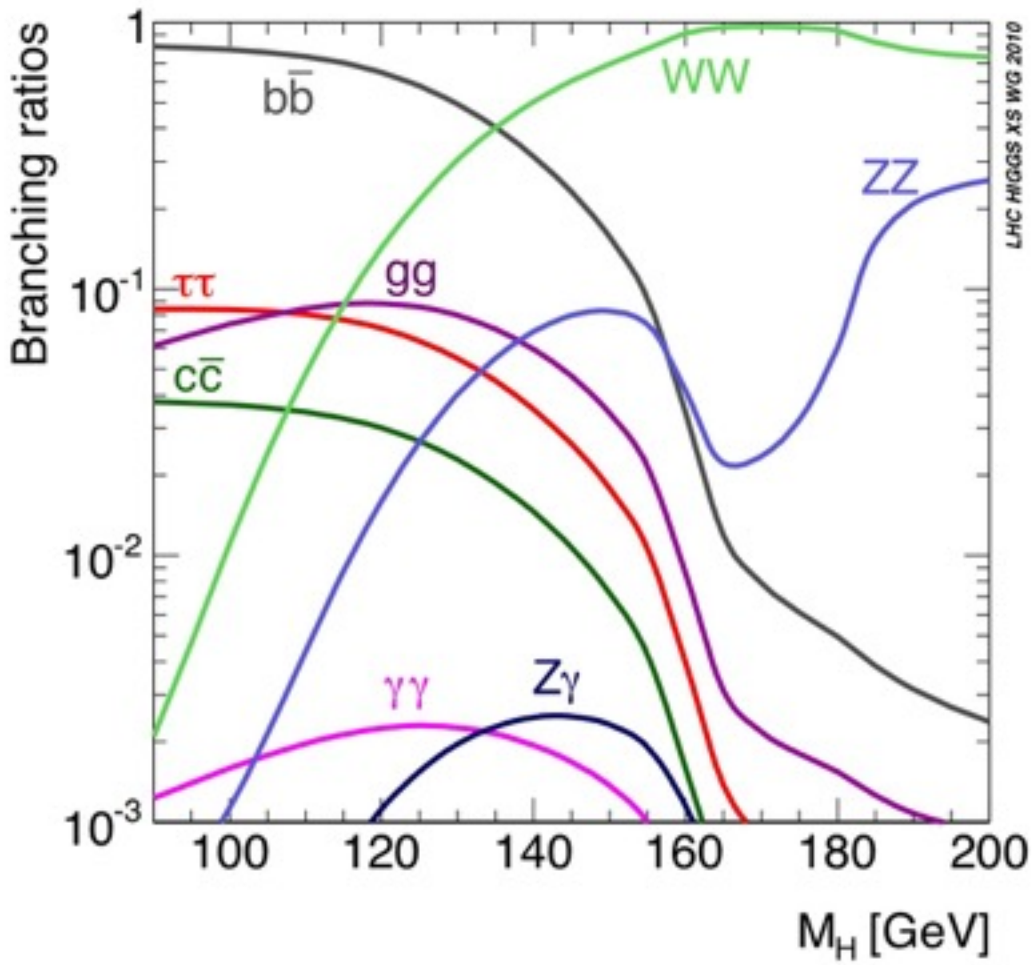
- $H \to Z\gamma$
- $H \to \varphi\gamma/\rho\gamma$
- $H \to Z_{(d)}Z_d \to 4\ell$
- ZH ($H \to$ invisible)

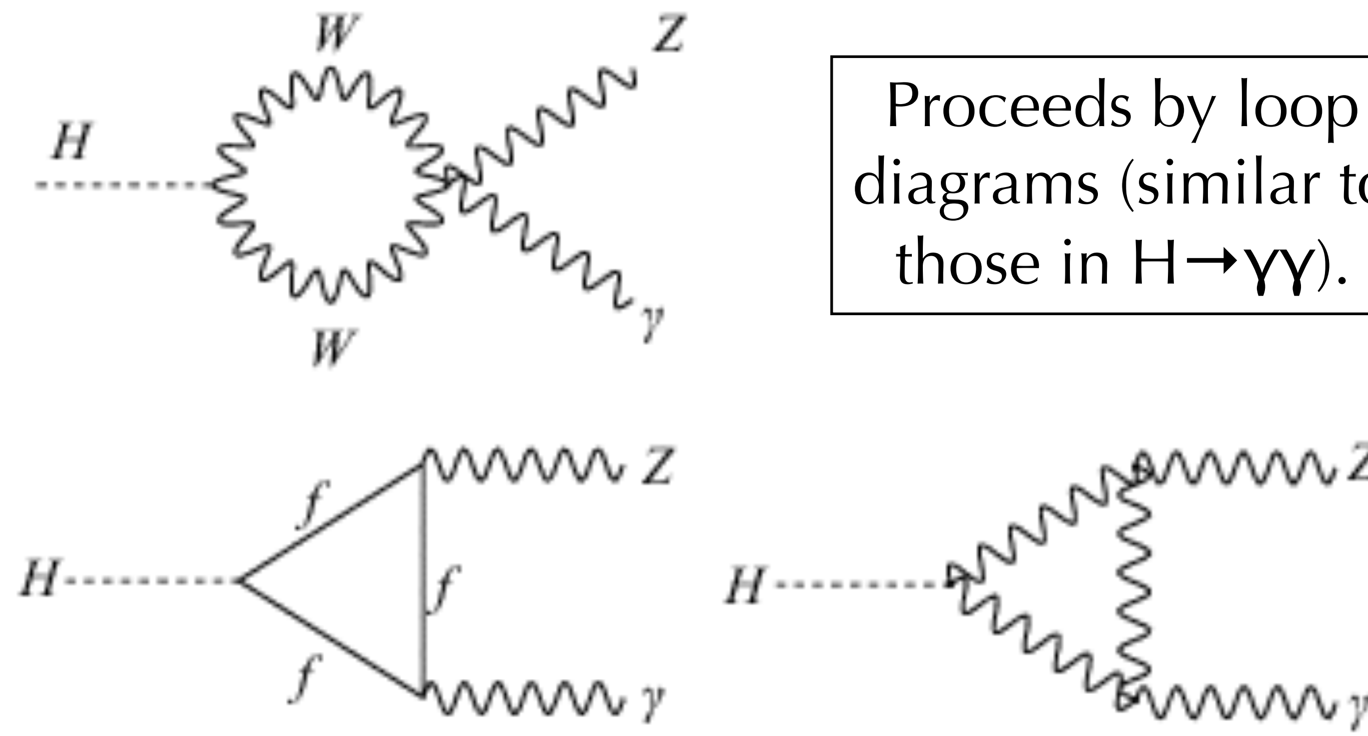
NOT in this talk

- $H \to \mu\mu$ (covered by K. Gregersen yesterday)

H→ Zγ

arXiv:1708.00212
submitted to JHEP





Proceeds by loop diagrams (similar to those in H→γγ).

- Similar branching ratio to H→γγ, but lower sensitivity because of BR(Z→ℓℓ).
- H→Zγ branching ratio can deviate from SM predictions if:
  - H is a neutral scalar of different origin.
  - H is a composite state.
  - In models with additional colourless charged scalars, leptons or vector bosons coupled to the Higgs boson and exchanged in the H→Zγ loop.

$H \rightarrow Z\gamma$

arXiv:1708.00212
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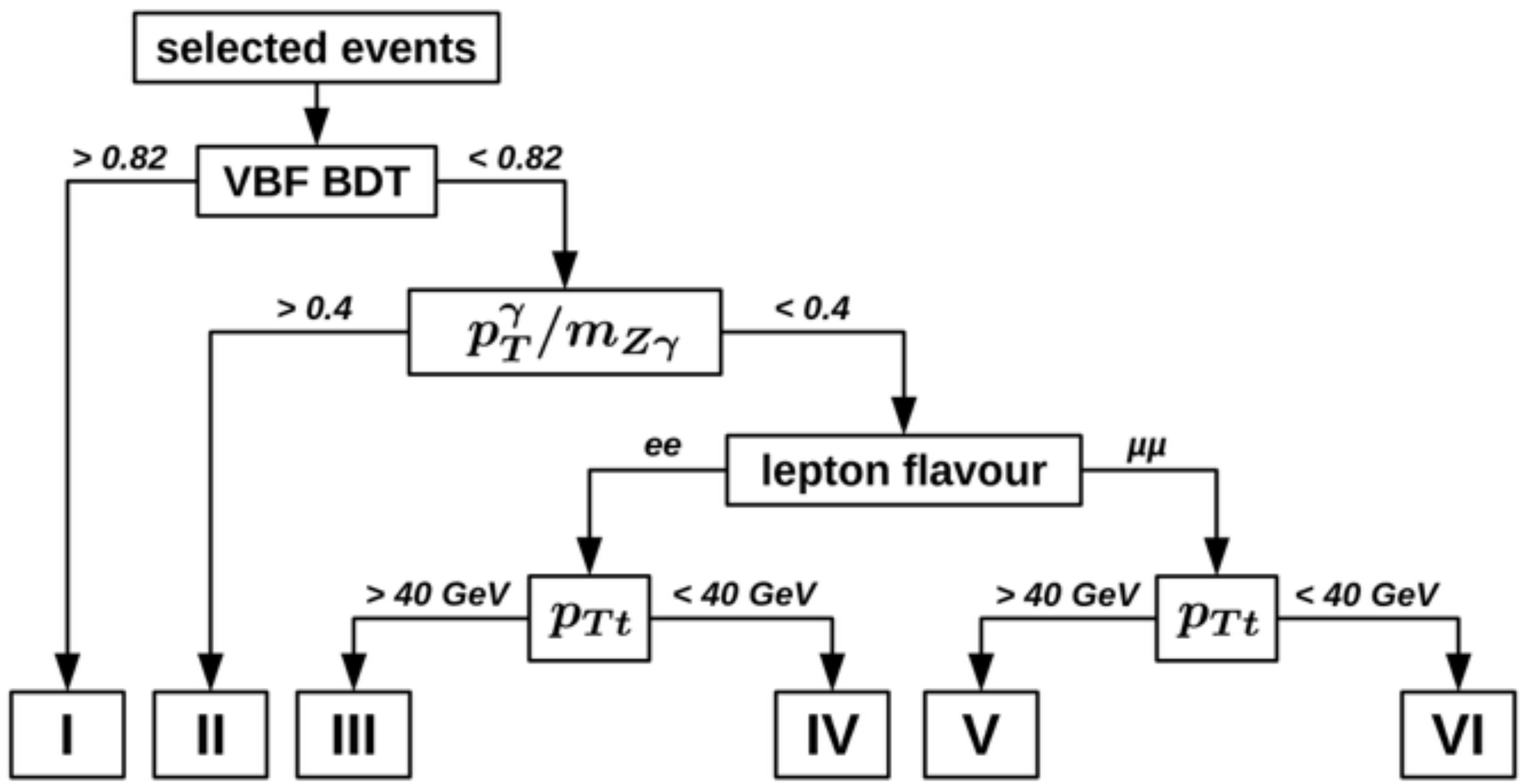
- Consider scenarios where:
  - H is SM Higgs boson (m_H = 125.09 GeV).
  - "H" is some new resonance (300 GeV < m_H < 2.4 TeV) → J. Schaarschmidt's talk.
- Select events with two same-flavour opposite-sign leptons and one photon.
- Optimise to select events produced by gluon-fusion and VBF production.
  - VBF events required to have two jets with large $\Delta\eta$ and selected using BDT.
- Events separated into six categories:



H→ Zγ

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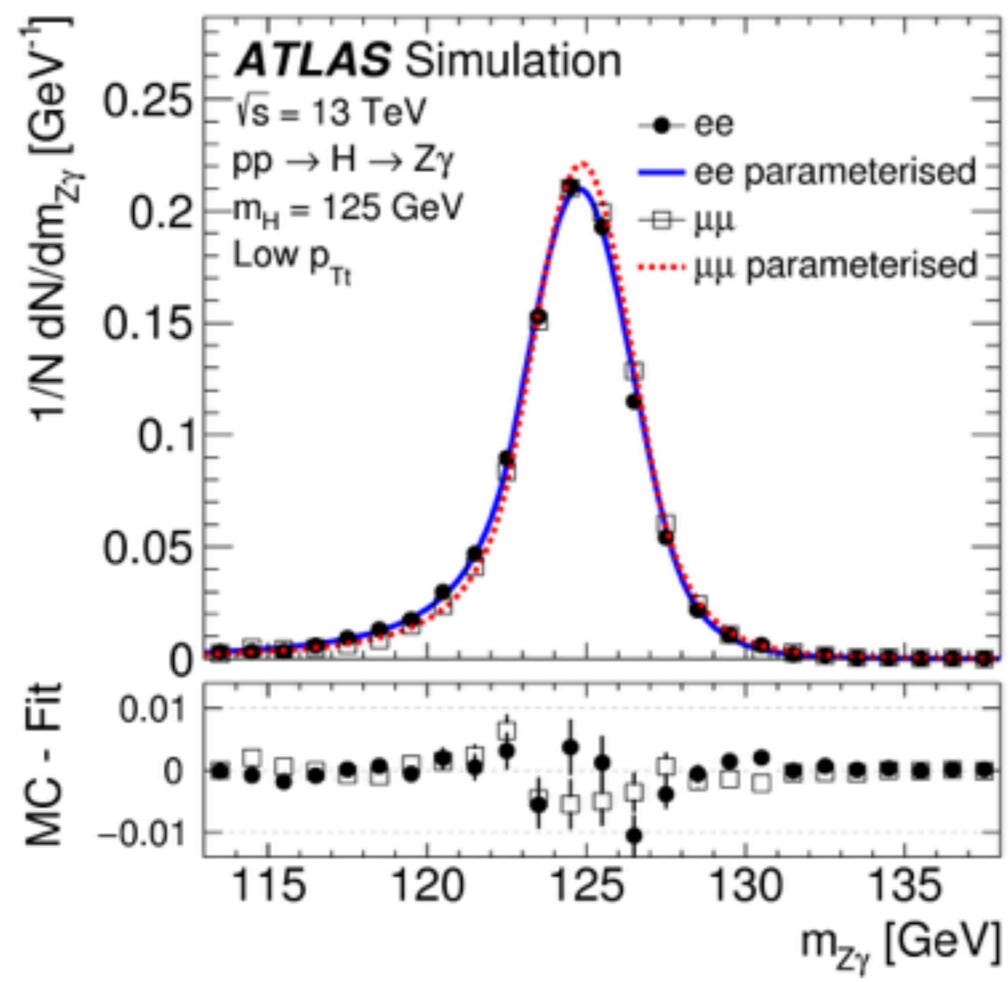
- Signal extracted by signal+background fit to m(Zγ).
  - Good mass resolution is essential.
  - Constrained kinematic fit applied to reconstruct 4-momenta of $Z\rightarrow\ell\ell$ candidates, improving m(Zγ) resolution.
- Signal modelled by a double-sided Crystal Ball function.



Main Backgrounds
Non-resonant Zγ production
Z+jets (jet is mis-identified as a γ)

- Background shape taken from Z+γ (fast) simulation.
  - Z+jets contribution (< 20% in all categories) estimated using data-driven methods in region with looser γ isolation applied.
  - Bernstein polynomials used to fit smoothly-falling background spectrum.

$H \rightarrow Z\gamma$

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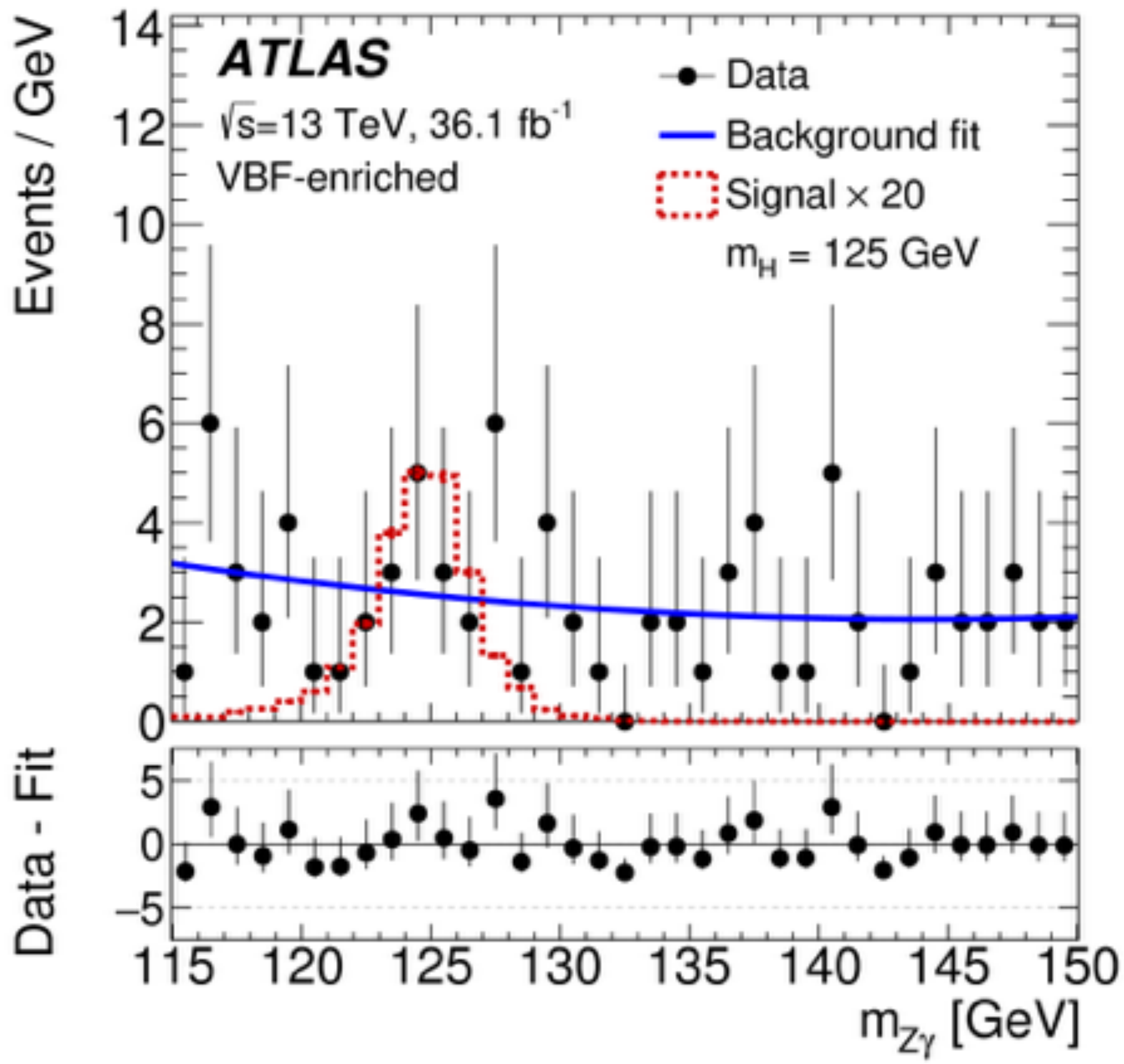
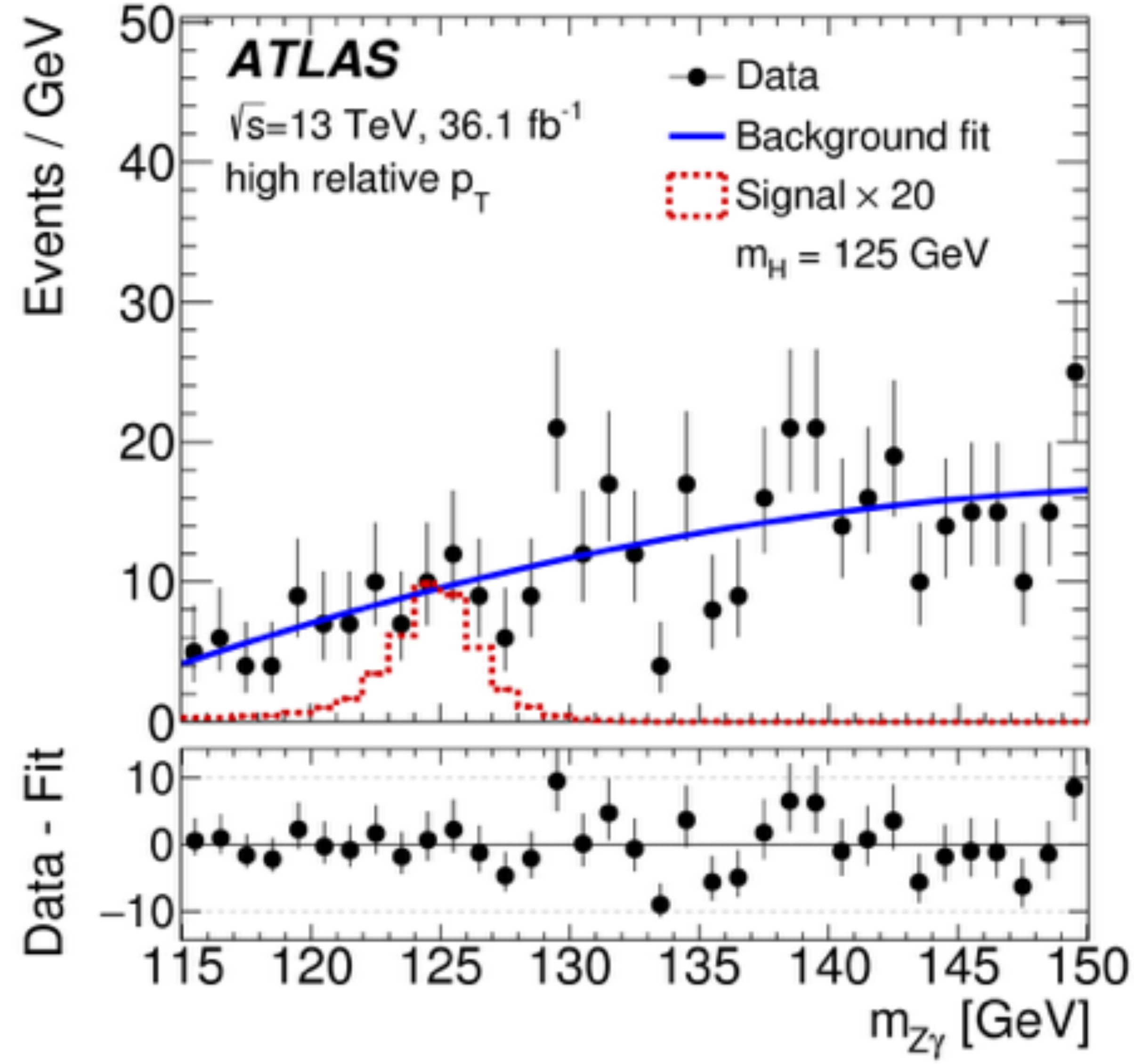




95% C.L. upper limit	Expected without $H \rightarrow Z\gamma$	Expected with $H \rightarrow Z\gamma$	Observed
$\frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$	4.4	5.2	6.6

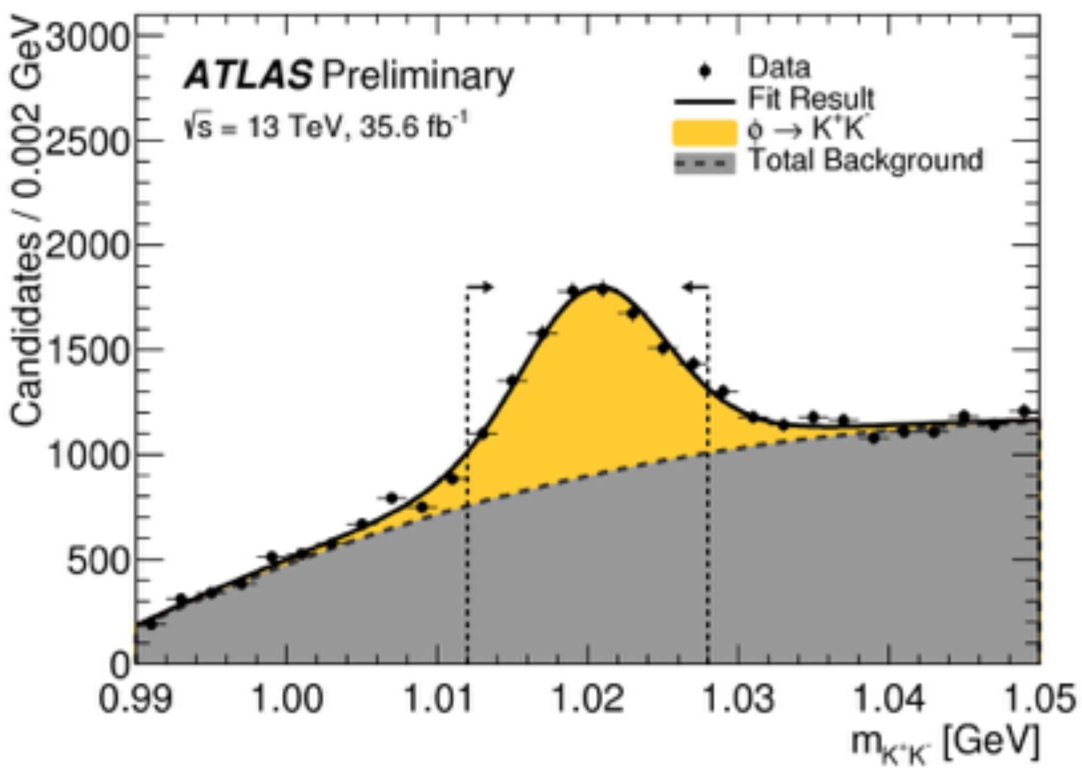
$H \rightarrow \varphi\gamma$, $H \rightarrow \rho\gamma$

Probe the Higgs boson couplings to light quarks

$H \rightarrow \varphi\gamma$

$BR(H \rightarrow \varphi\gamma) = (2.31 \pm 0.11) \times 10^{-6}$

Reconstruct $\varphi\gamma \rightarrow K^+K^-\gamma$

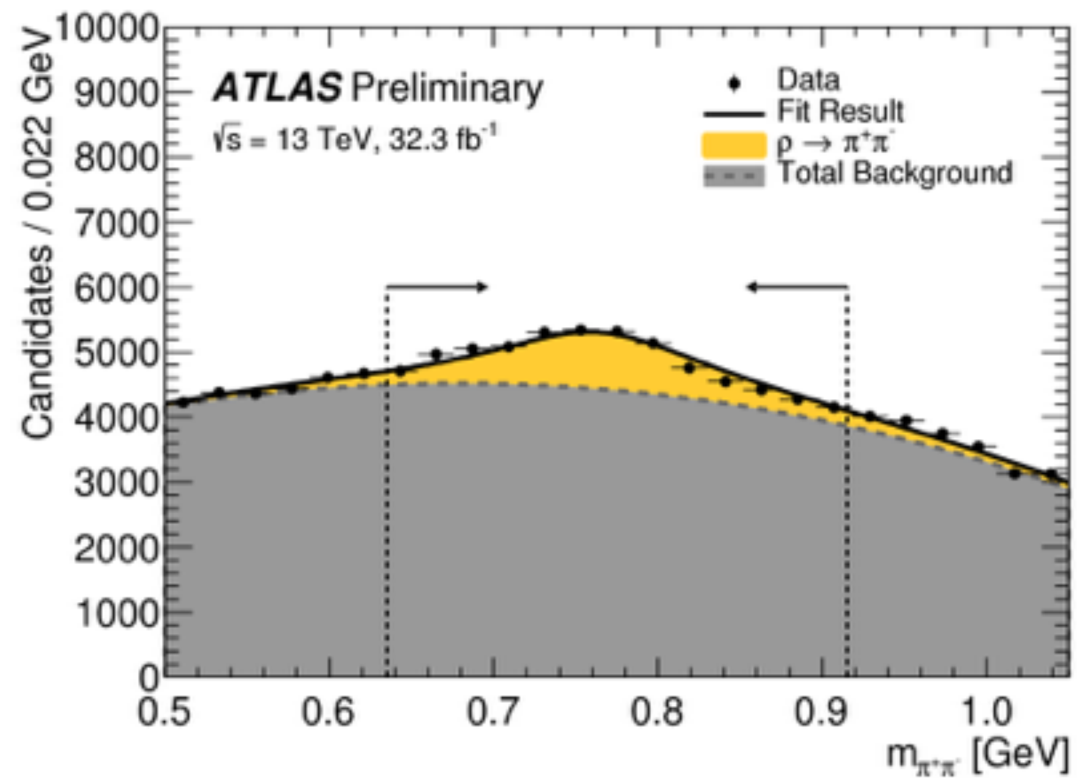


$BR(\varphi \rightarrow K^+K^-) = (48.9 \pm 0.5)\%$

$H \rightarrow \rho\gamma$

$BR(H \rightarrow \rho\gamma) = (1.68 \pm 0.08) \times 10^{-5}$

Reconstruct $\rho\gamma \rightarrow \pi^+\pi^-\gamma$



$BR(\rho \rightarrow \pi^+\pi^-) = \sim 100\%$

- Require two high p_T isolated tracks consistent with φ/ρ mass recoiling against high p_T γ.
- Cut on p_T of φ/ρ dependent on three body invariant mass.

$H \to \phi\gamma$, $H \to \rho\gamma$

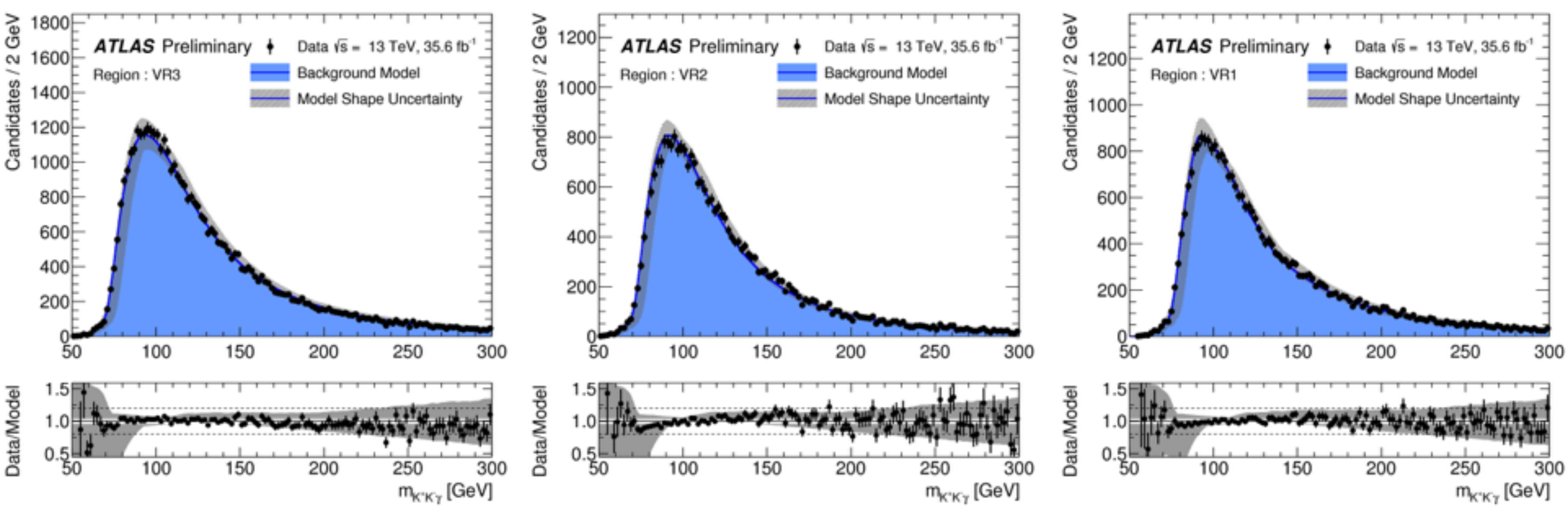
ATLAS-CONF-2017-057

- Backgrounds estimated using templates derived from data to describe kinematic distributions.
  - $K^+K^-\gamma$ and $\pi^+\pi^-\gamma$ events selected in data, with looser isolation and $p_T(\phi,\rho)$ requirements.
  - PDFs constructed to describe distributions of relevant variables.

Main Backgrounds
Inclusive γ+jet
Multi-jet

- Model validated in validation regions by adding:
  - Meson p_T requirement (VR1).
  - γ isolation (VR2).
  - Meson isolation requirement (VR3).

Further validation in mass sidebands



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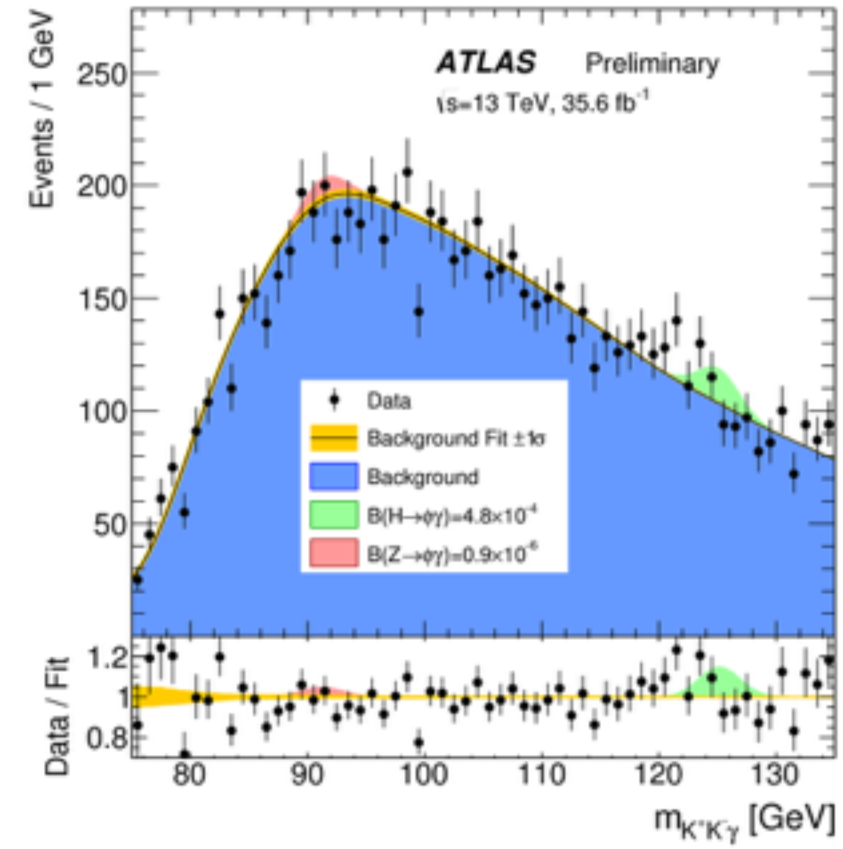
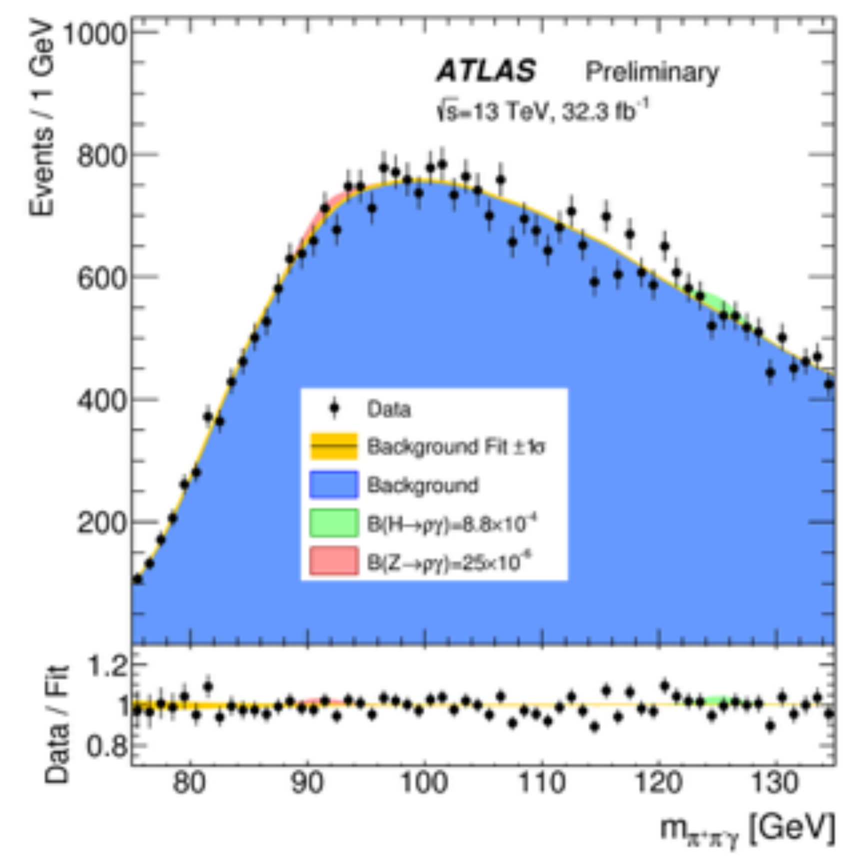
H→ φγ, H→ργ

- No significant excess above background.
- Set limits on Z decays to φγ and ργ as well as Higgs.
- Un-binned maximum likelihood fit used to extract limits.

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

- Significant improvement (1 to 2 orders of magnitude) over previous Run 2 result
  - Phys. Rev. Lett. 117, 111802 (2016)





H→Invisible

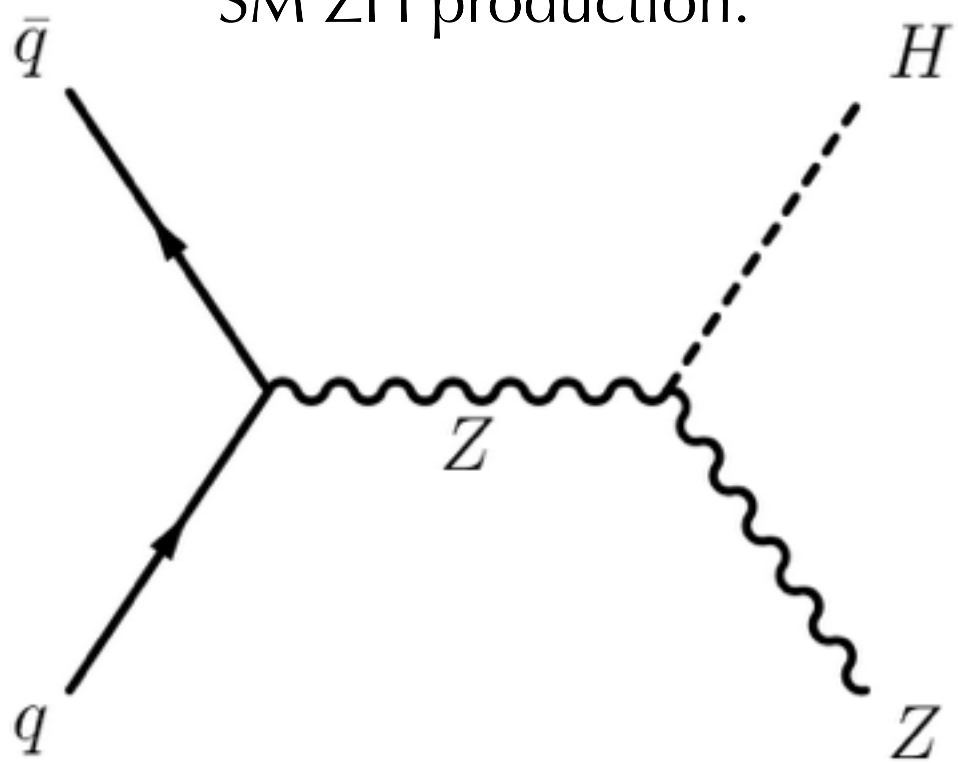
ATLAS-CONF-2017-040

- Search for $pp \rightarrow ZH \rightarrow \ell\ell + E_T^{miss}$.
  - Clean signature, thanks to $Z \rightarrow ee, \mu\mu$ decay.
  - Large missing energy from invisible Higgs decay.

Standard Model

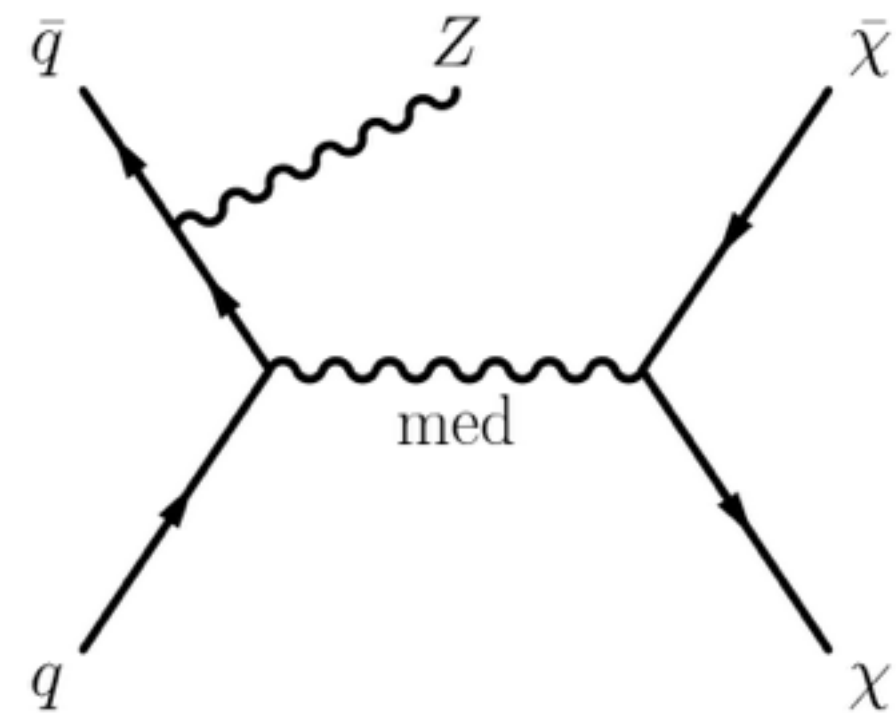
$BR(H \rightarrow ZZ \rightarrow \nu\nu\nu\nu) = 1.06 \times 10^{-3}$.

Set limit on $BR(H \rightarrow \text{invisible})$ assuming SM ZH production.



Dark Matter

BSM axial-vector mediator and decay to WIMP pair.



Same signature if Higgs decays to neutralinos, graviscalars in extra-dimension models, majorons etc.

- Select events with two e or μ, compatible with coming from Z, and large E_T^{miss}.

H→Invisible

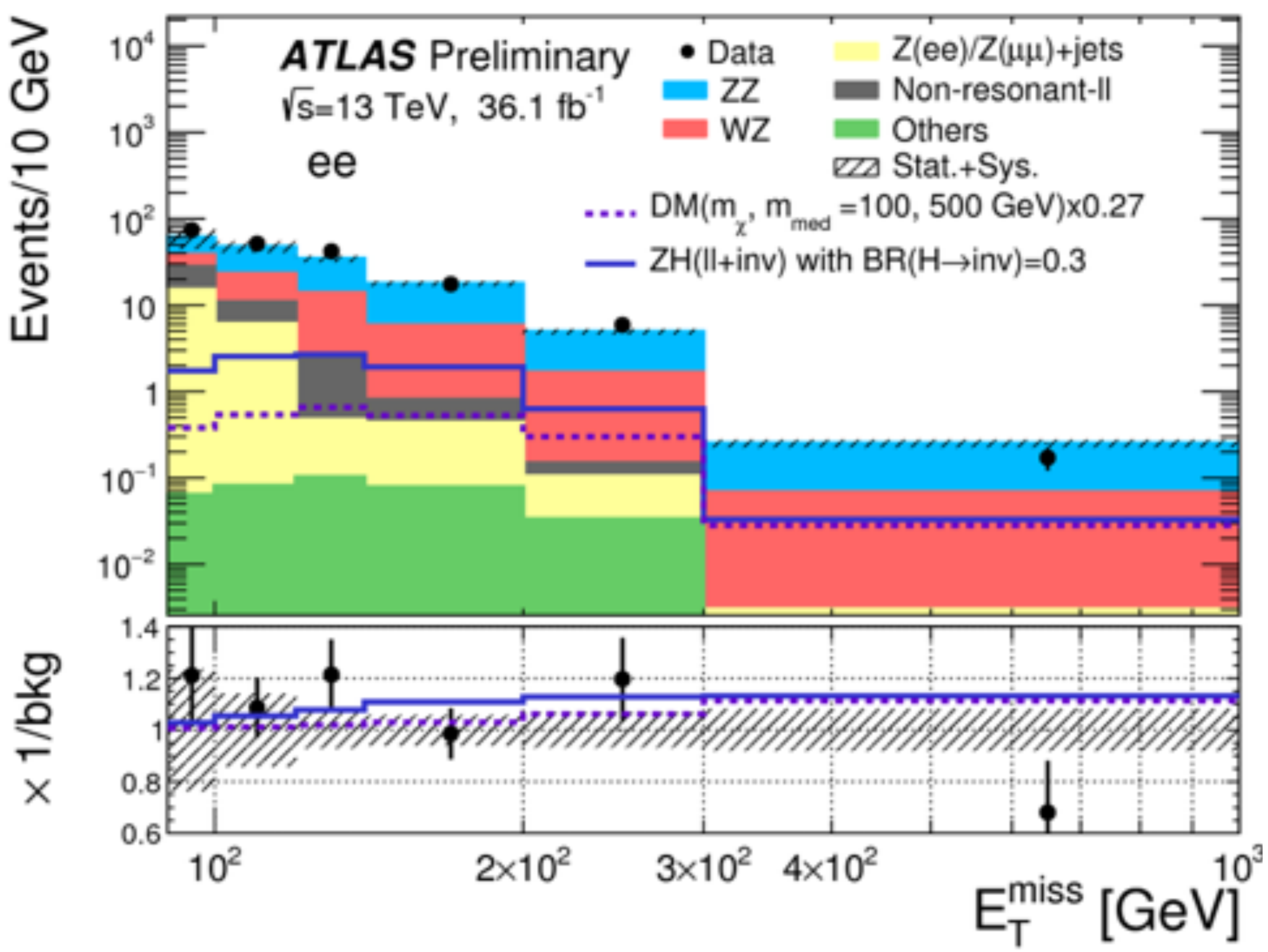
ATLAS-CONF-2017-040

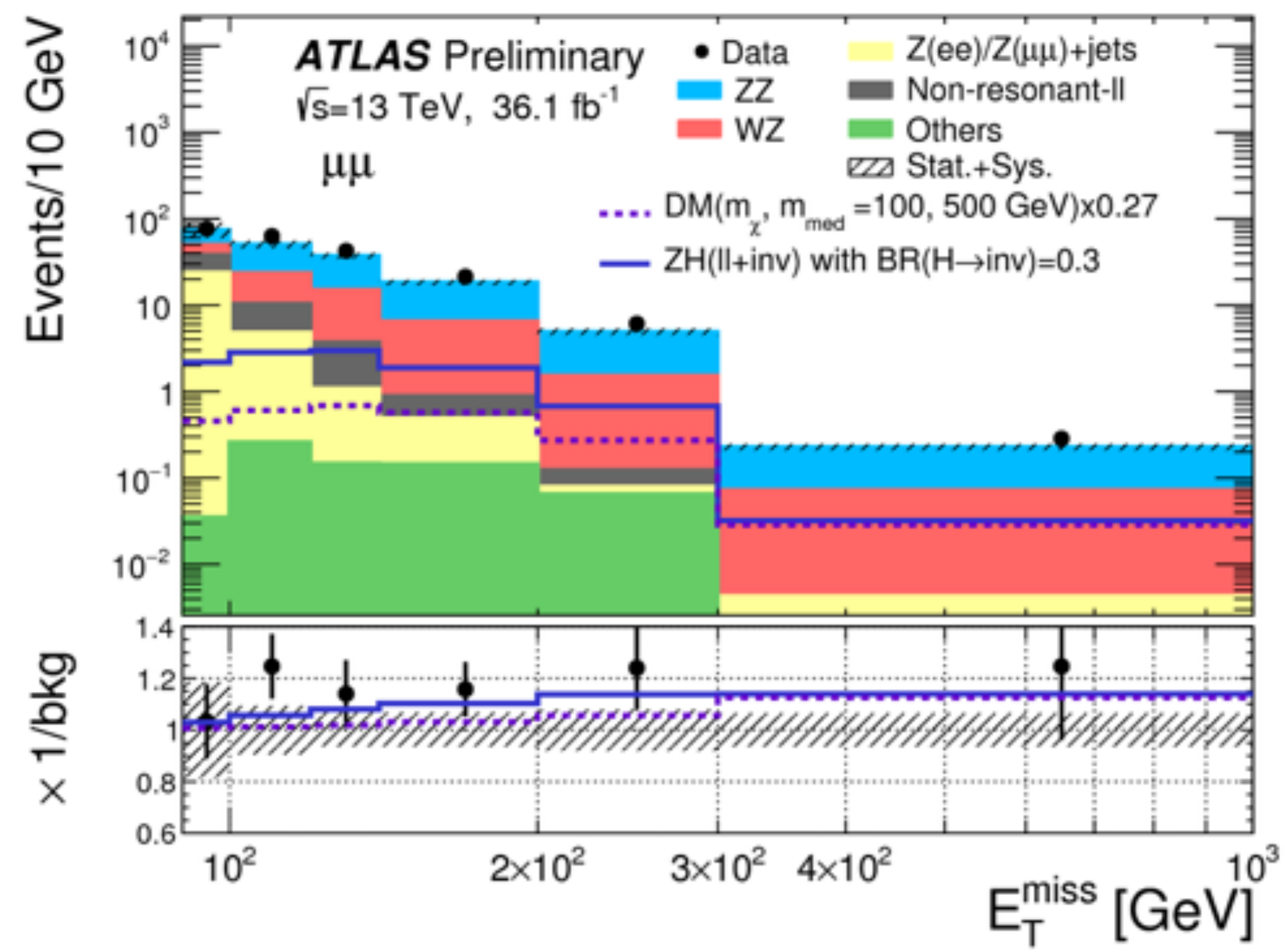
Main Backgrounds

ZZ: Estimated from simulation.

WZ: Shape from MC, scale derived in 3ℓ region.

Z+jets: "ABCD" method using E_T^{miss} and H_T/E_T^{miss}.

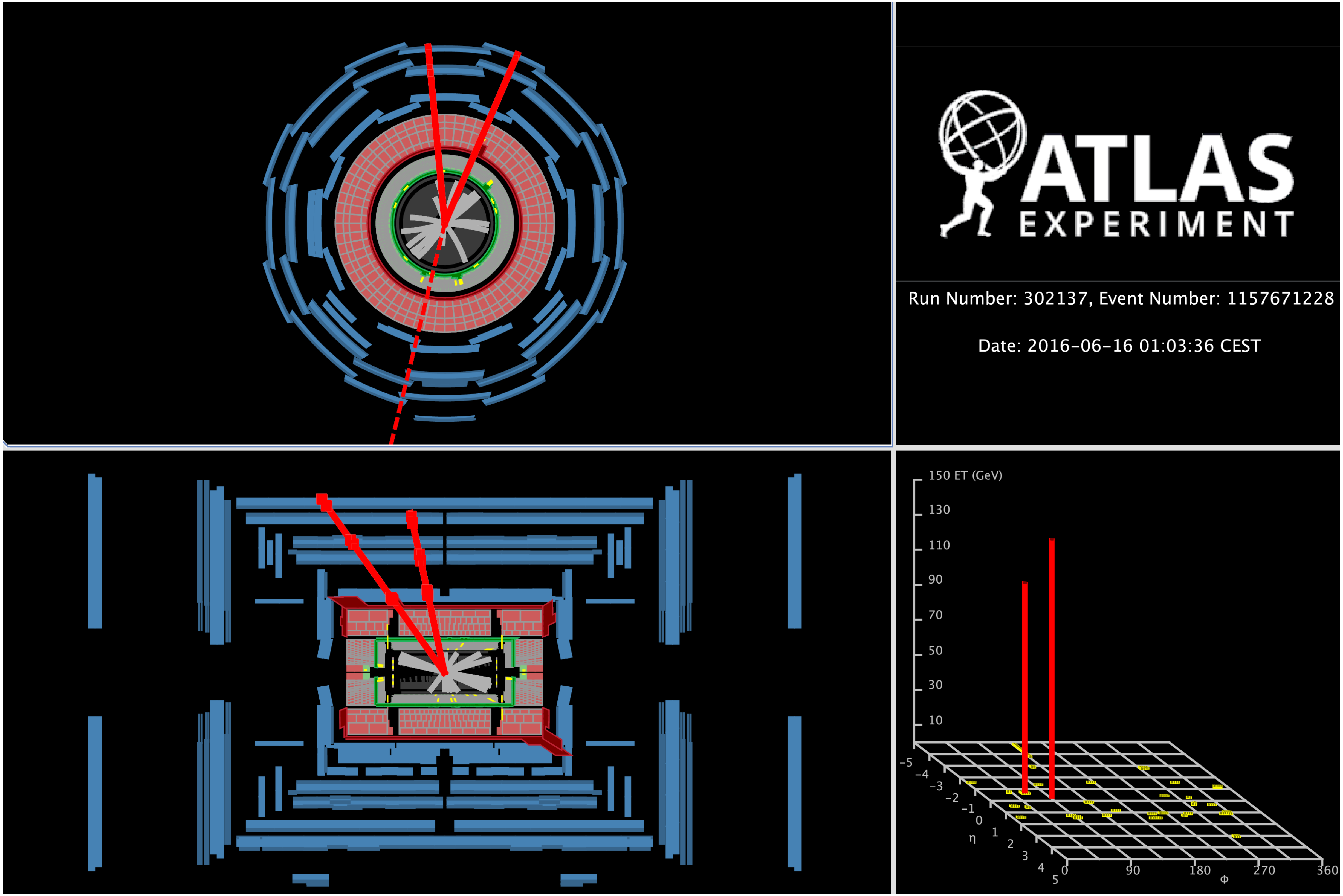




- Look for excess in E_T^{miss} spectrum.
  - No significant excess wrt SM background.
  - Small excess (2.2σ) in μμ channel → 1.5σ in combination.

H→Invisible

ATLAS-CONF-2017-040



H→Invisible

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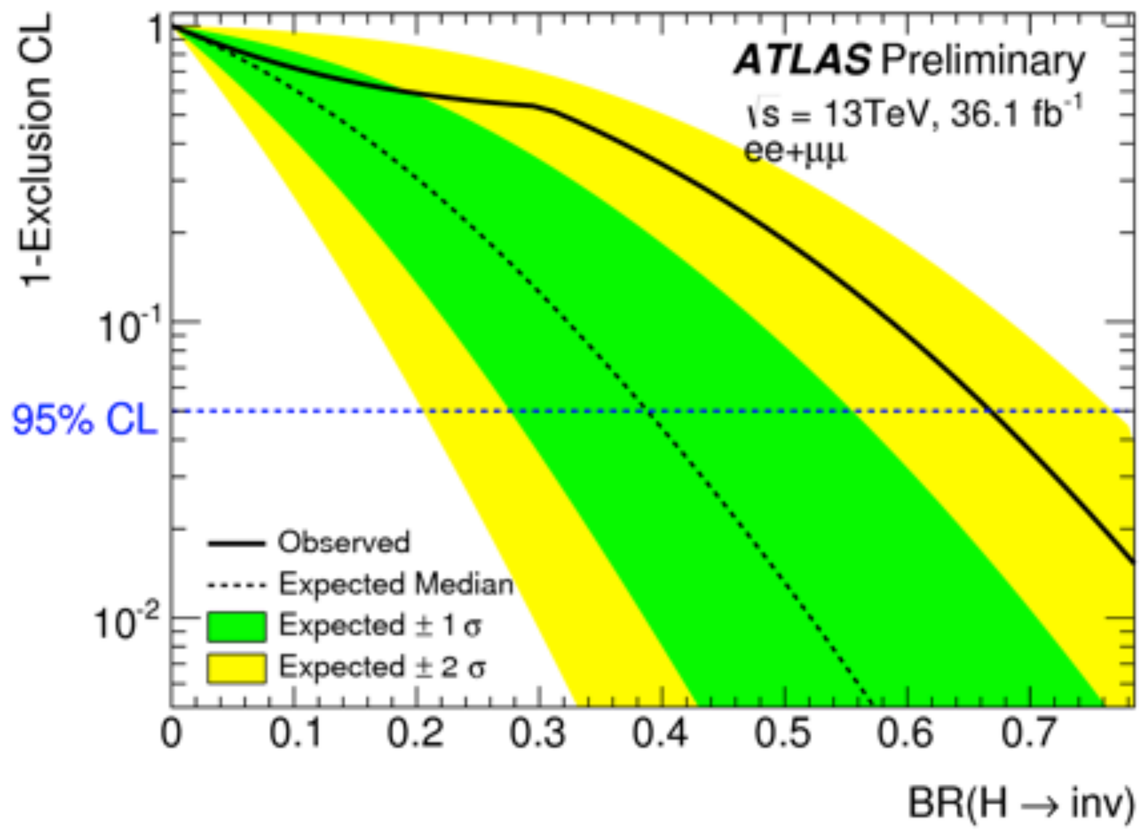
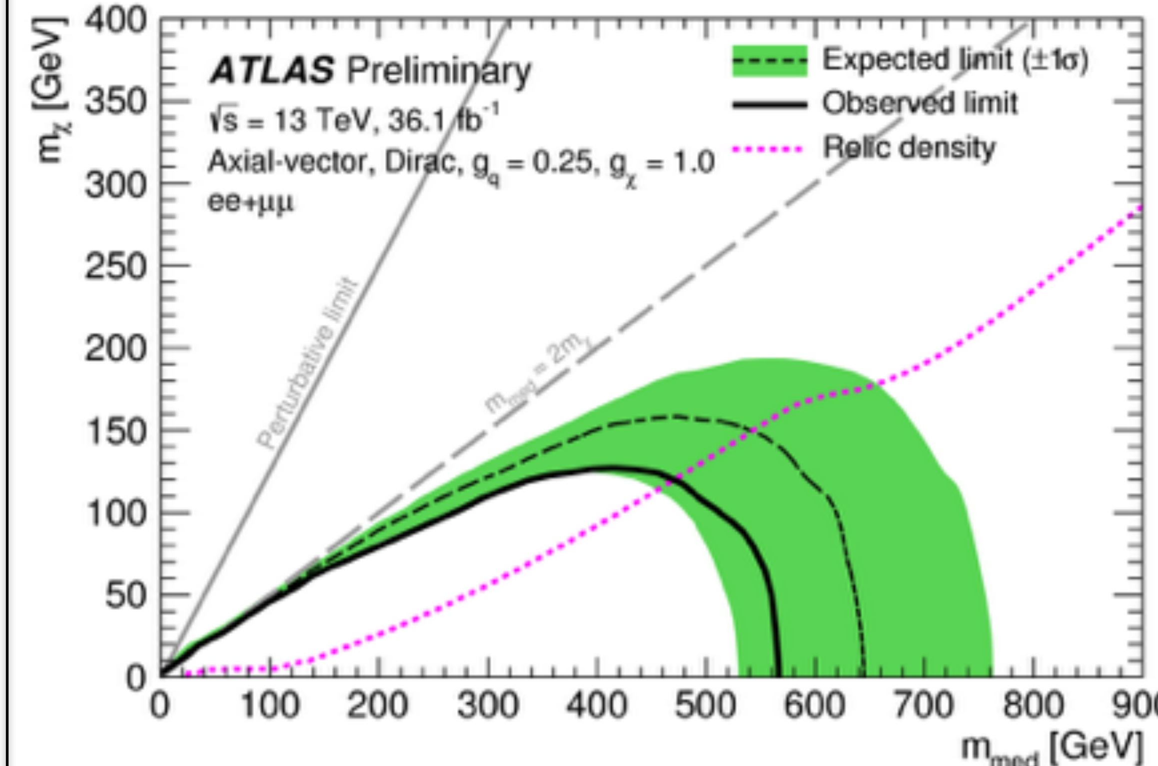
Standard Model



- Set limit on BR(H→invisible), assuming SM ZH cross section.
  - Observed (expected) limit of 67% (39%) at 95% CL.
  - Run 1 results were 75% (62%) .

Dark Matter



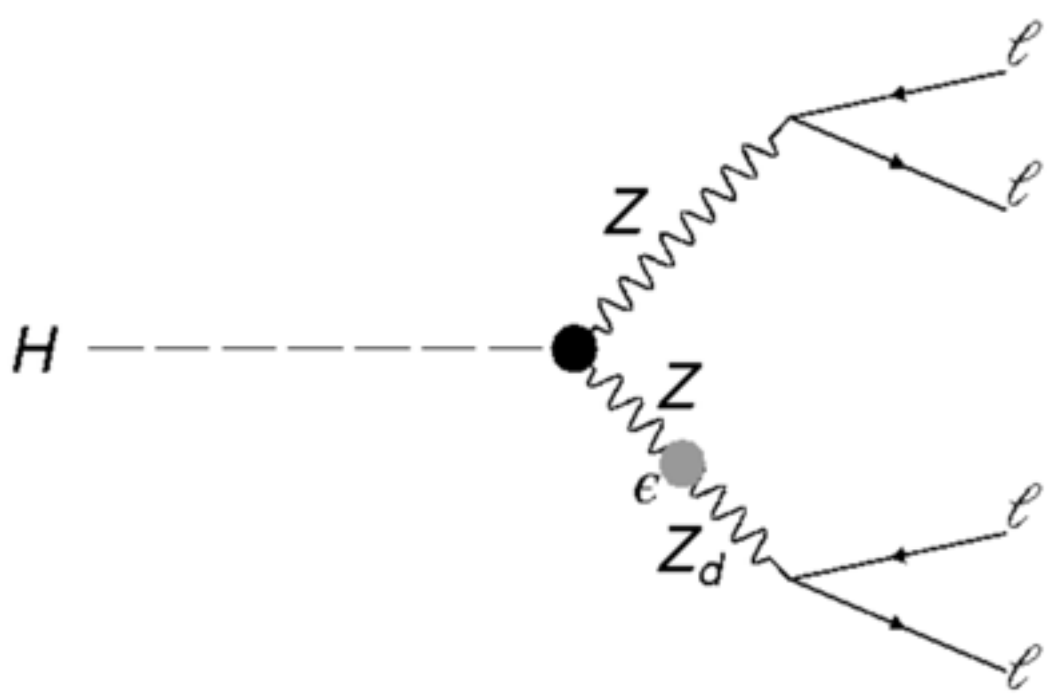
- Set limits in 2D plane of m_χ and m_{med}.
  - DM model assumes an axial-vector mediator, fermionic WIMPs, and a specific scenario of the coupling parameters ($g_\chi = 1$, $g_q = 0.25$).
  - Mediators excluded for m_{med} up to 560 GeV.
  - WIMPs excluded for m_χ up to 130 GeV.

$H \to Z_{(d)}Z_d \to 4\ell$, $H \to aa \to 4\mu$

ATLAS-CONF-2017-042

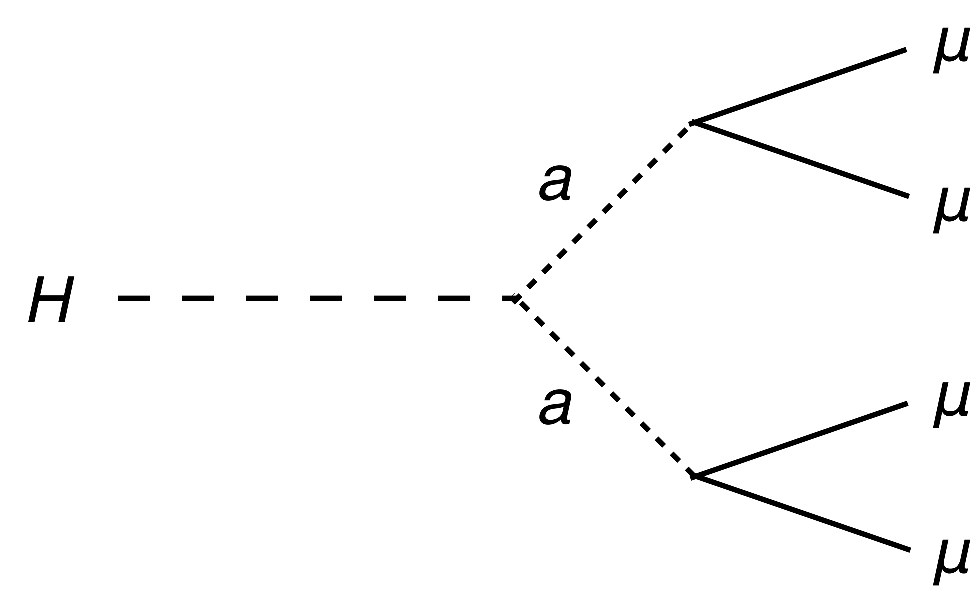
$H \to Z_{(d)}Z_d \to 4\ell$

125 GeV Higgs boson decays to BSM vector boson, Z_d, predicted in $U(1)_d$ dark-sector extensions of the SM.



$H \to aa \to 4\mu$

125 GeV Higgs boson decays to pseudoscalar boson, *a*, predicted in BSM models with two Higgs doublets and an additional singlet scalar field.



- Events with four light leptons (e/μ) are selected.
  - Only 4μ channel considered for $H \to aa$ channel, since *a* couples to mass.

$H \to Z_{(d)}Z_d \to 4\ell$, $H \to aa \to 4\mu$

ATLAS-CONF-2017-042

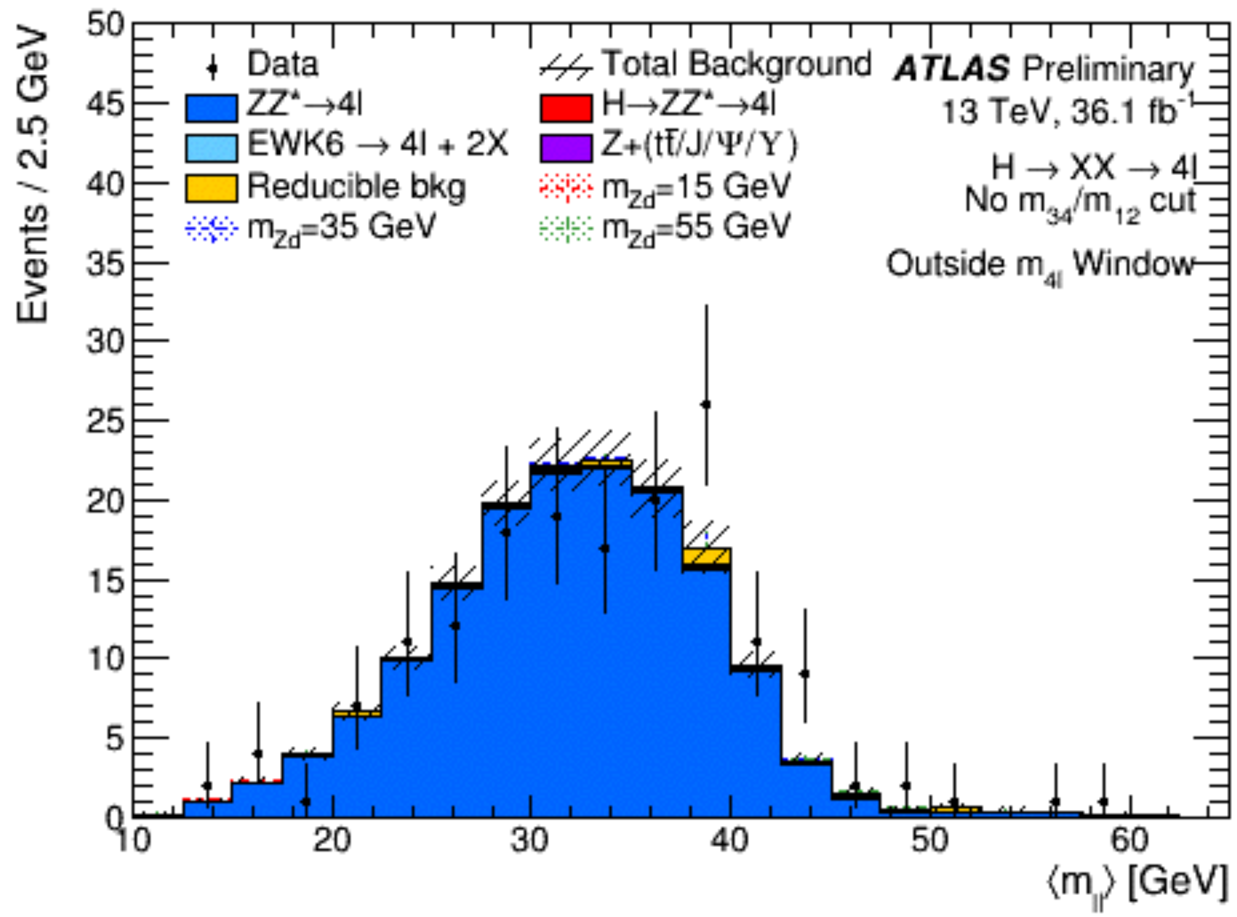
- For each event, consider four-lepton quadruplets in all possible permutations of pairs of same-flavour opposite-sign leptons.
  - $H \to Z_dZ_d$ and $H \to aa$ channels: dilepton pairs with smallest mass difference are selected.
  - $H \to ZZ_d$ channel: select combination with leading dilepton pair invariant mass closest to the Z mass.
  - Dilepton masses compatible with J/ψ and $\Upsilon(1,2,3S)$ are not allowed.

Main Backgrounds

$ZZ^* \to 4\ell$

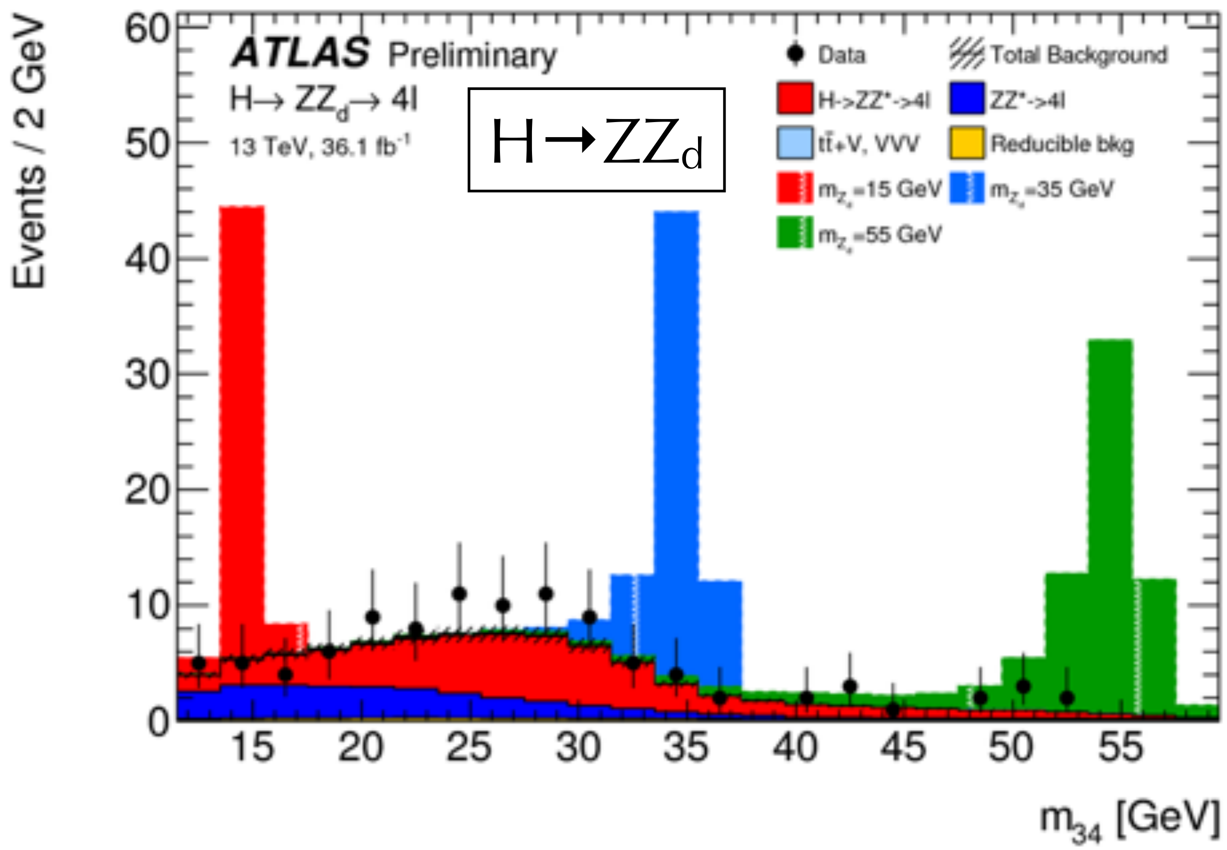
$H \to ZZ^* \to 4\ell$

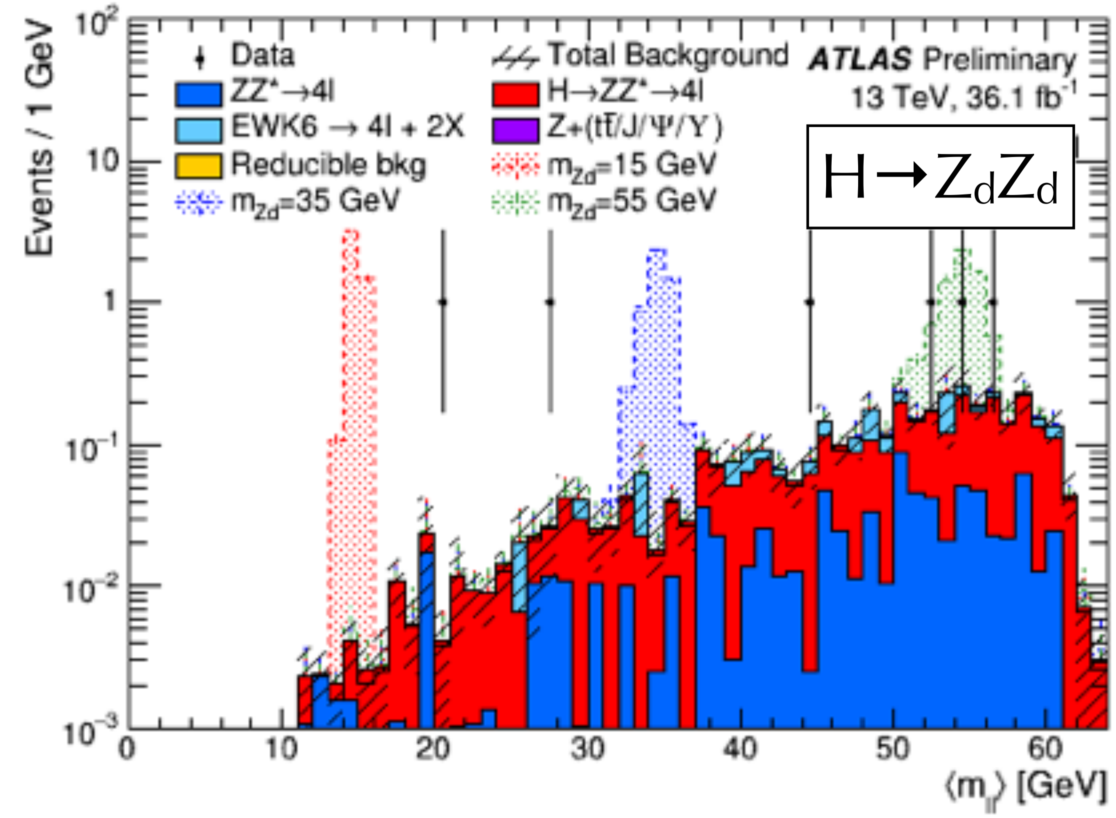
- Dominant backgrounds estimated using simulation.
- Validated in four mass sideband regions dominated by $H \to ZZ^*$, non-resonant ZZ^* or mis-paired $4e/4\mu$ events.

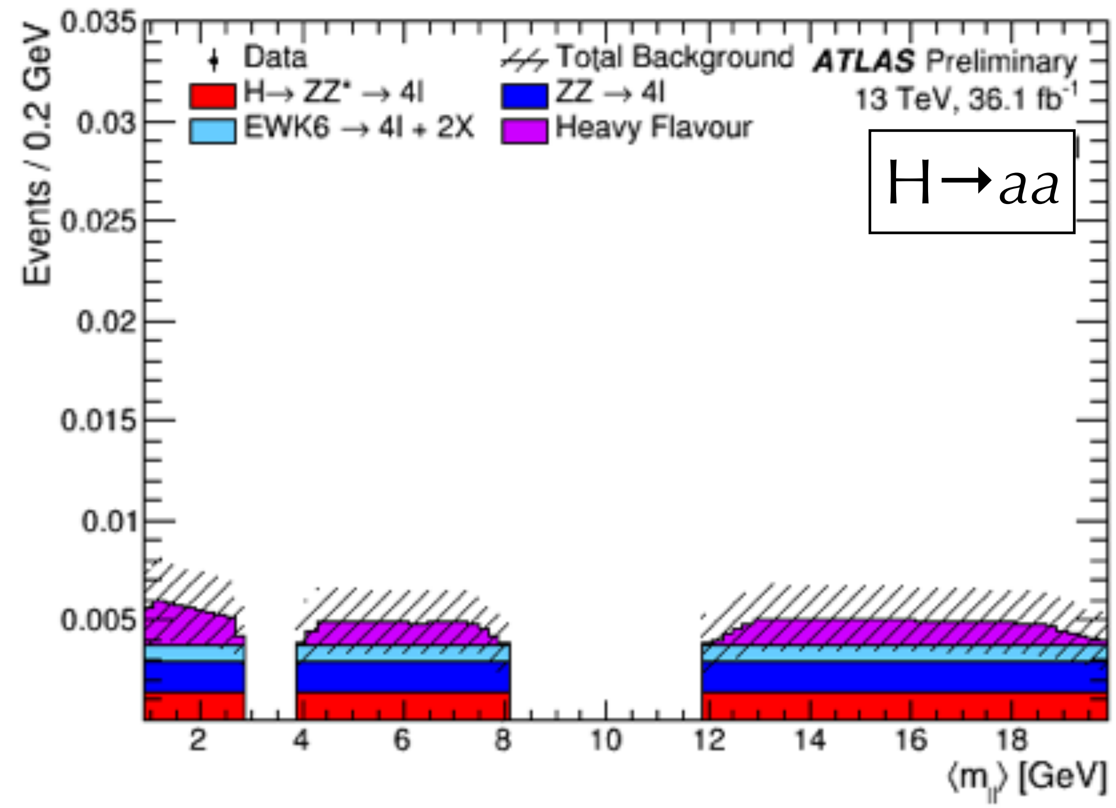


$H \rightarrow Z_{(d)}Z_d \rightarrow 4\ell$, $H \rightarrow aa \rightarrow 4\mu$

ATLAS-CONF-2017-042





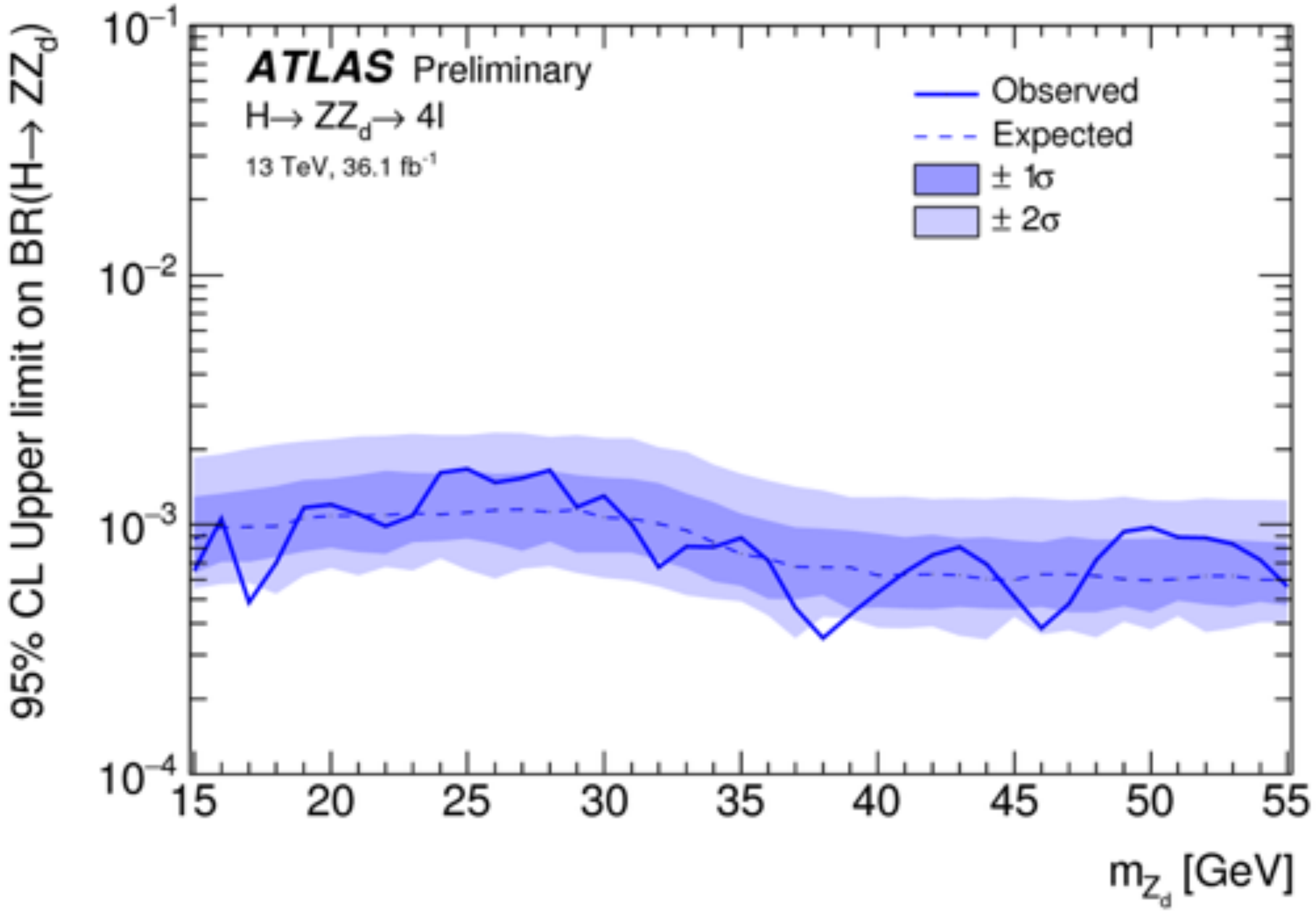


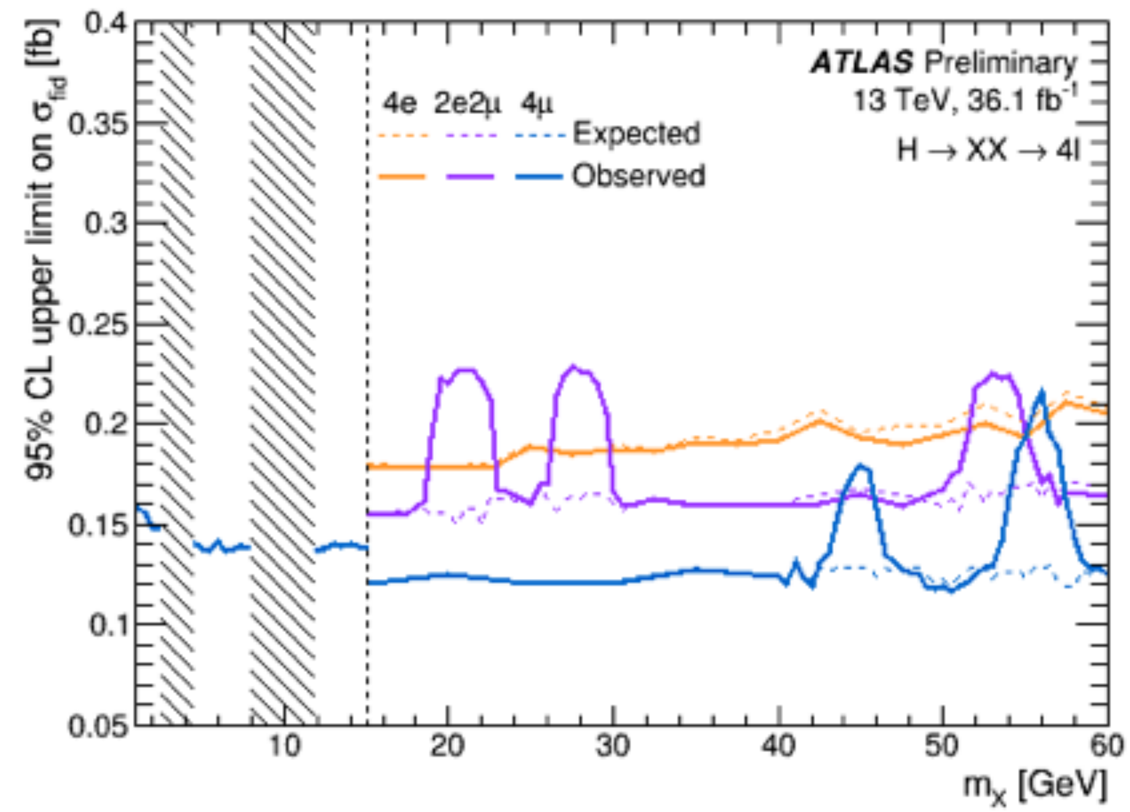
- Mass of intermediate boson(s) used as observable.
- No significant excess observed in any channel.
  - Largest deviation from SM prediction caused by single event passing $H \rightarrow Z_dZ_d$ selection with $\langle m_{\ell\ell} \rangle$ ~20 GeV.
  - 3.8σ local (2.8σ global) significance.

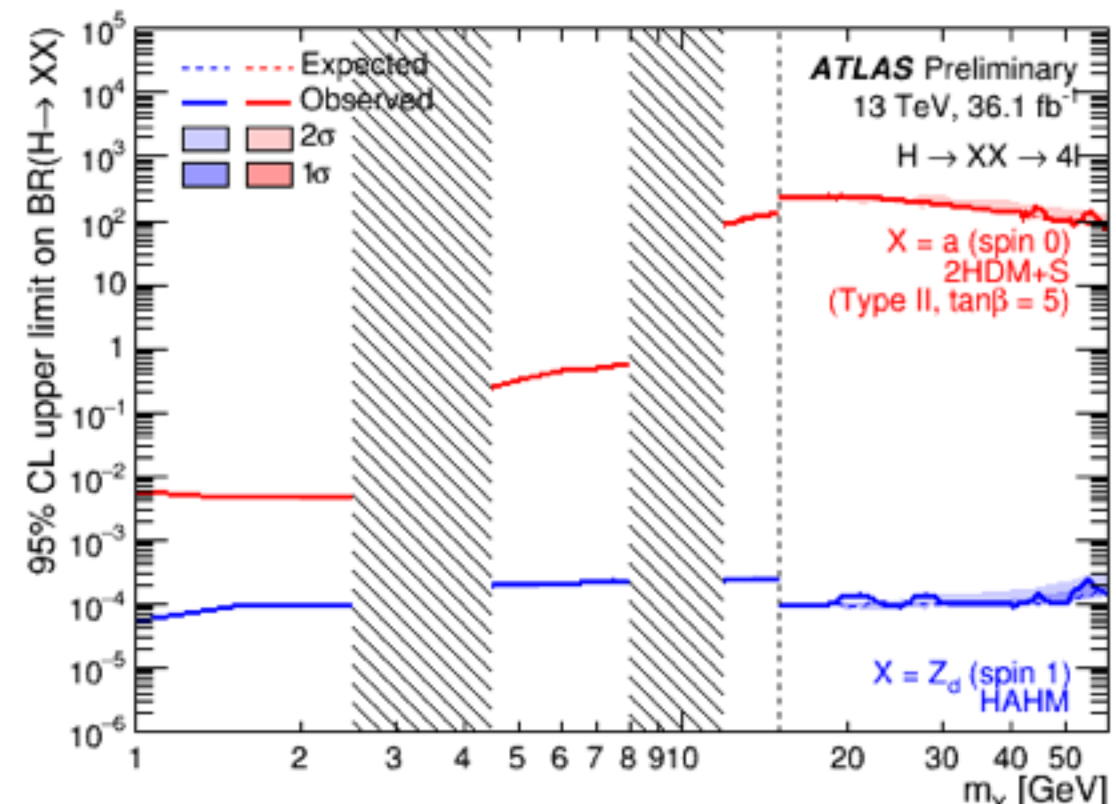
$H \to Z_{(d)}Z_d \to 4\ell$, $H \to aa \to 4\mu$

ATLAS-CONF-2017-042

- Limits placed on:
  - Model-independent $\sigma \times$ BR of $H \to XX \to 4\ell$ process.
  - BR($H \to ZZ_d$)
  - BR($H \to Z_dZ_d$)
  - BR($H \to aa$).







Exotic and Rare Higgs Decay Modes: Latest ATLAS Results

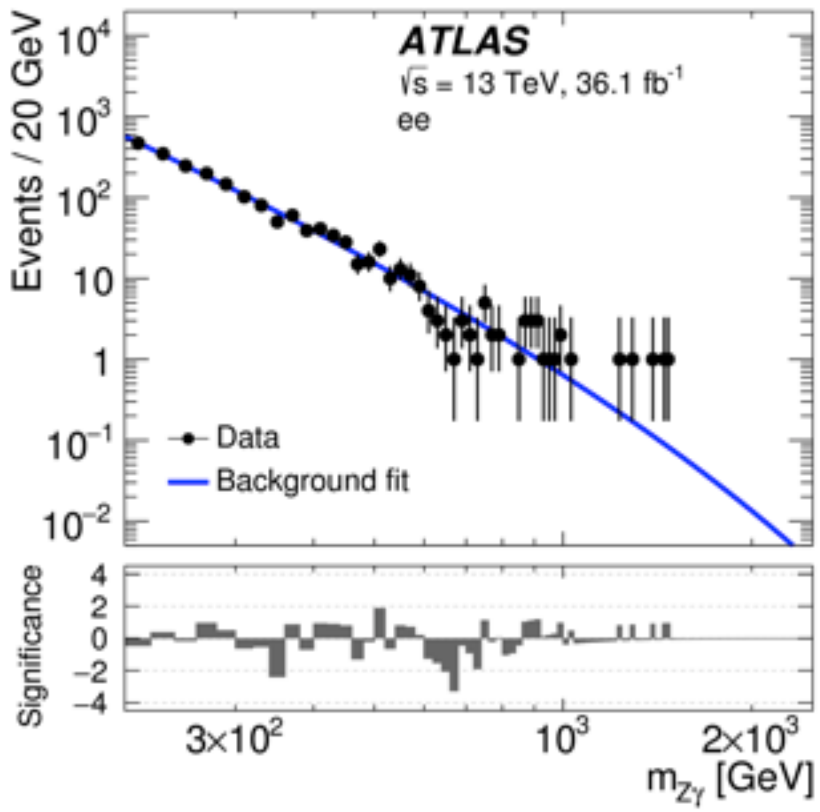
- Higgs boson discovery opens up a new portal to searching for new physics.
  - Either by looking for deviations from SM predictions, or by direct searches.
  - Many rare Higgs decays have not been observed yet.
- Wide variety of measurements and searches have been performed by ATLAS in this field.
  - Only most recent ATLAS results shown today.

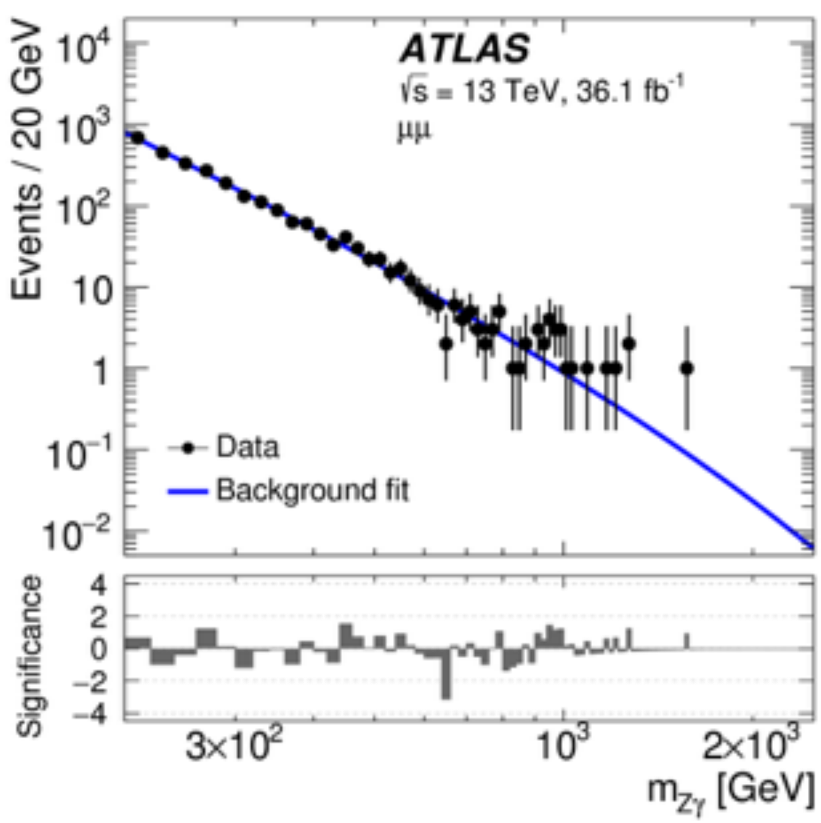
$H \rightarrow Z\gamma$	arXiv:1708.00212, submitted to JHEP
$H \rightarrow \varphi\gamma/\rho\gamma$	ATLAS-CONF-2017-057
$H \rightarrow$ Invisible	ATLAS-CONF-2017-040
$H \rightarrow ZZ_d/Z_dZ_d \rightarrow 4\ell$ **$H \rightarrow aa \rightarrow 4\mu$**	ATLAS-CONF-2017-042

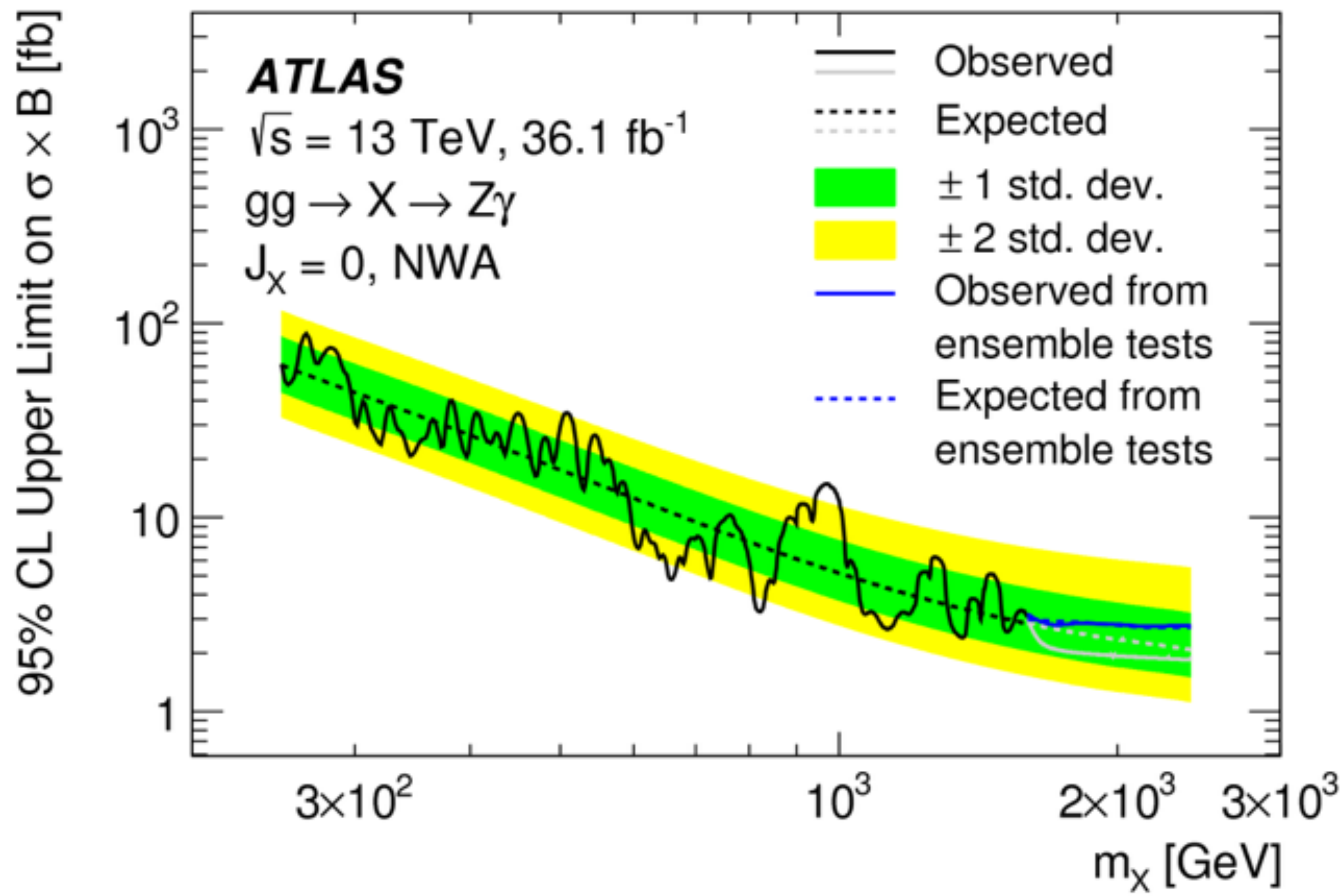
All ATLAS Higgs results can be found here:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

Back Up

H→ Zγ (Resonance Search)







- No significant excess observed in any channel.
  - Largest deviation from SM prediction observed around mX = 960 GeV.
  - Corresponds to a local excess of 2.7σ.
  - Translates to global significance of 0.8σ.

H→ φγ, H→ργ

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

$H \rightarrow Z_{(d)} Z_d \rightarrow 4\ell$, $H \rightarrow aa \rightarrow 4\mu$

Validation regions

Invert $m_{14,32}$ cut	Targets 4e and 4μ events that have been mis-paired
High mass selection, invert m_{12} < 64 GeV cut	Targets ZZ* production with 115 < $m_{4\ell}$ < 130 GeV
High mass selection, invert 115 < $m_{4\ell}$ < 130 GeV cut	Targets non-resonant ZZ production
Low mass selection, invert 120 < $m_{4\ell}$ < 130 GeV cut	Targets non-resonant ZZ production