Searches for exotic decays of the Higgs boson as a window to the dark sector with ATLAS

CIPANP 2022
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On behalf of the ATLAS collaboration

Analyses covered

All full Run-2 analyses with 139/fb of data
Deep(er) dive of 4 searches

- Search for non-pointing/delayed photons
  $Zh \rightarrow ll\gamma\gamma$+MET [ATLAS-CONF-2022-017]

- Search for NMSSM Higgs from Zh production
  $Zh \rightarrow llbb$+METs [JHEP 01 (2022) 063]

- VBF search for higgs to invisible/dark photons
  $h \rightarrow \chi\chi$, $h \rightarrow \gamma_d\gamma$ [EPJC 82 (2022) 105]

- Dark sector Higgs decays
  $h \rightarrow Z_dZ_d \rightarrow llll$ [JHEP 02 (2022) 041]

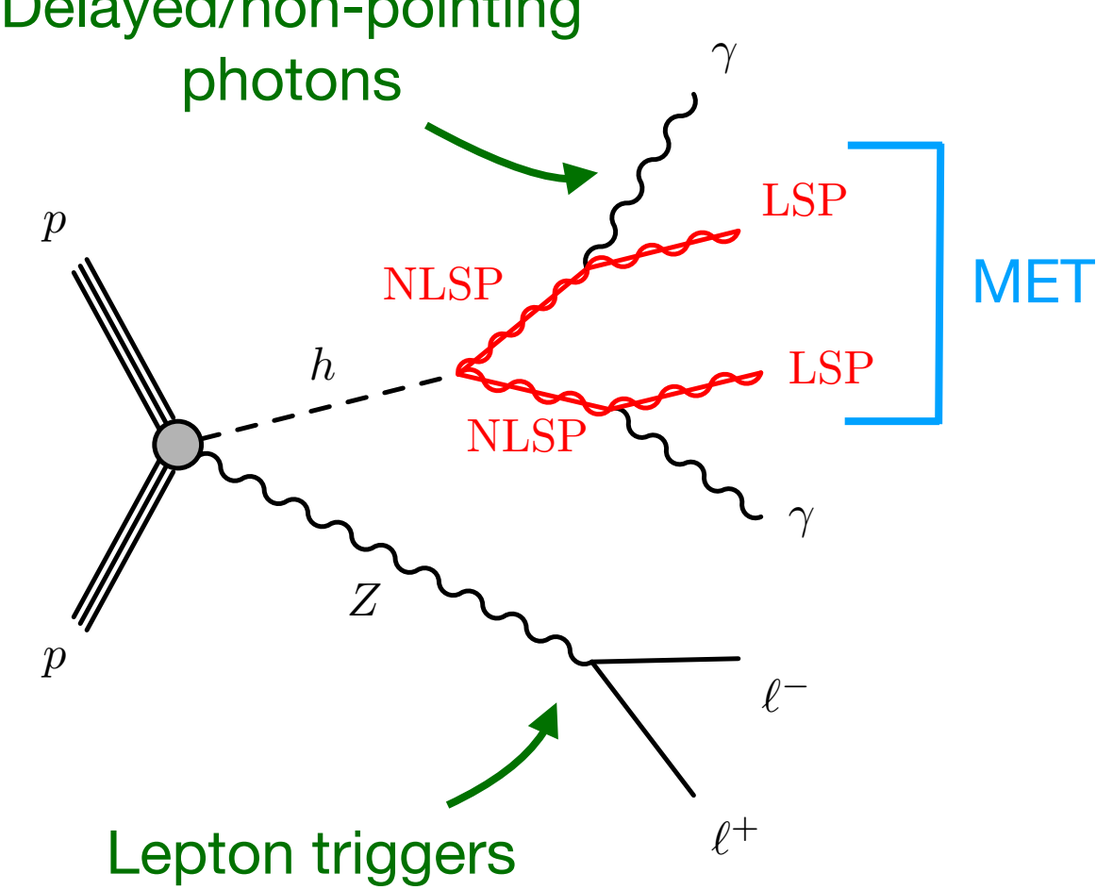
+ some bonus searches & results

Non-Pointing/Delayed photons

ATLAS-CONF-2022-017

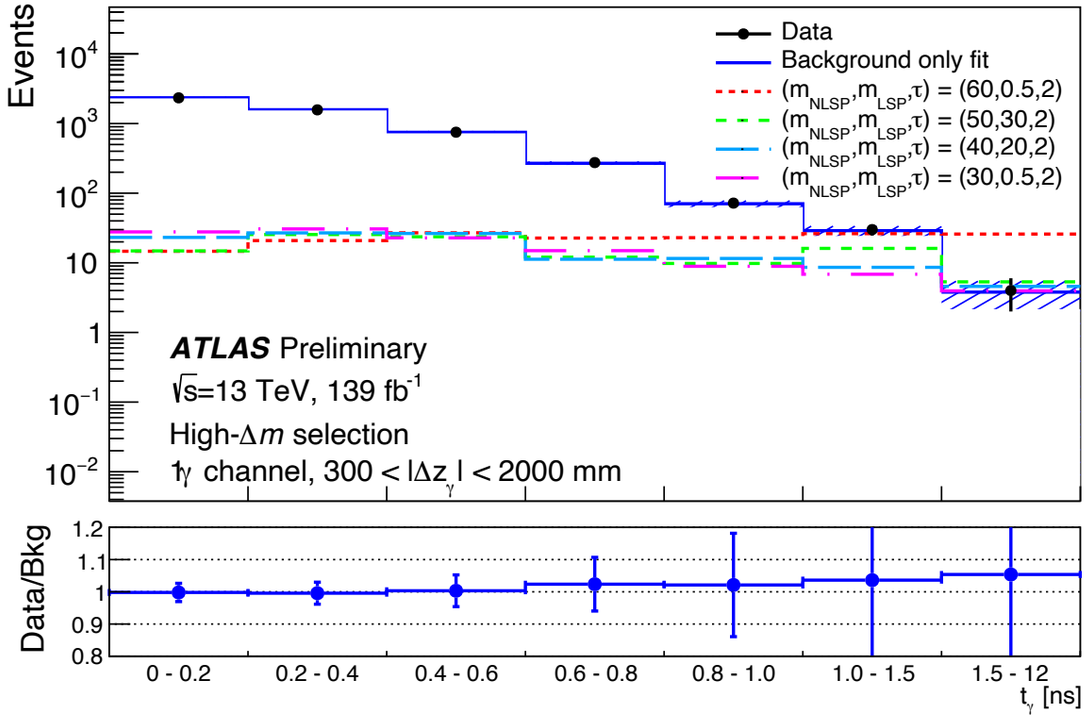
Non-Pointing/Delayed Photons Analysis

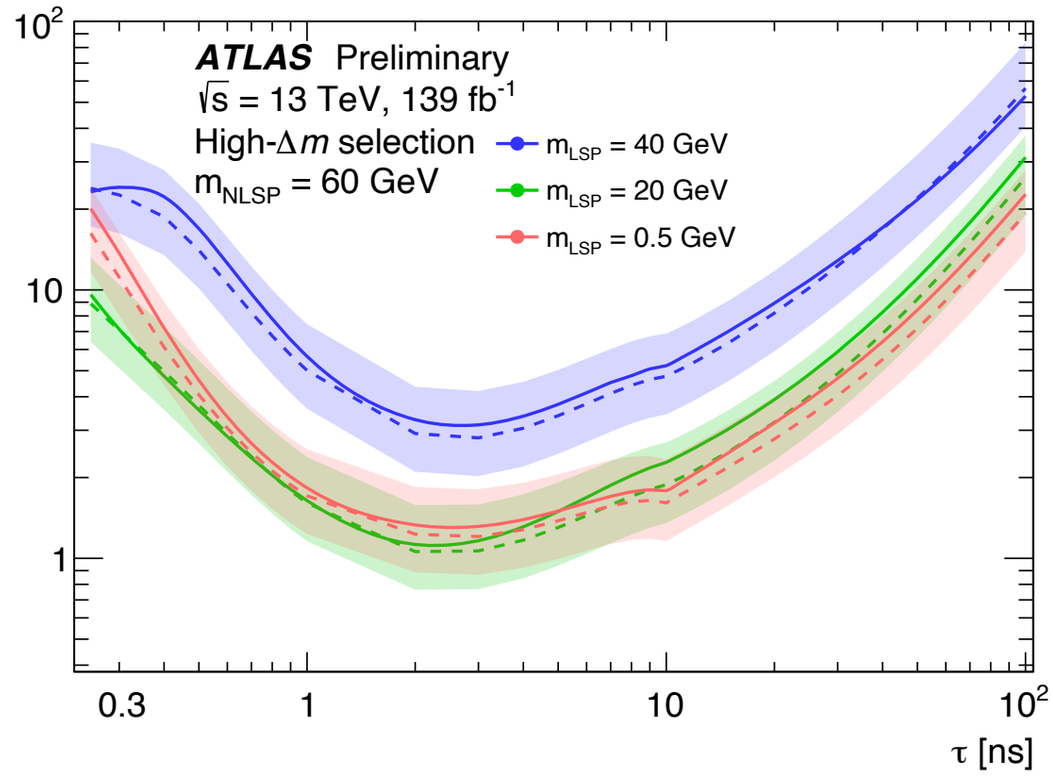
- Photons from the decays of a heavy long-lived particle (LLP) that are late with respect to bunch crossings, and don't point to the primary vertex
- Use precise Liquid Argon Calorimeter pointing and timing (unique to ATLAS)
  - Signal region = high MET, high timing, high pointing
  - Optimised separately for low- and high-LSP/NLSP splitting (LSP = Lightest SUSY Particle)
  - Fully data-driven background estimate used



Non-Pointing/Delayed Photons Results

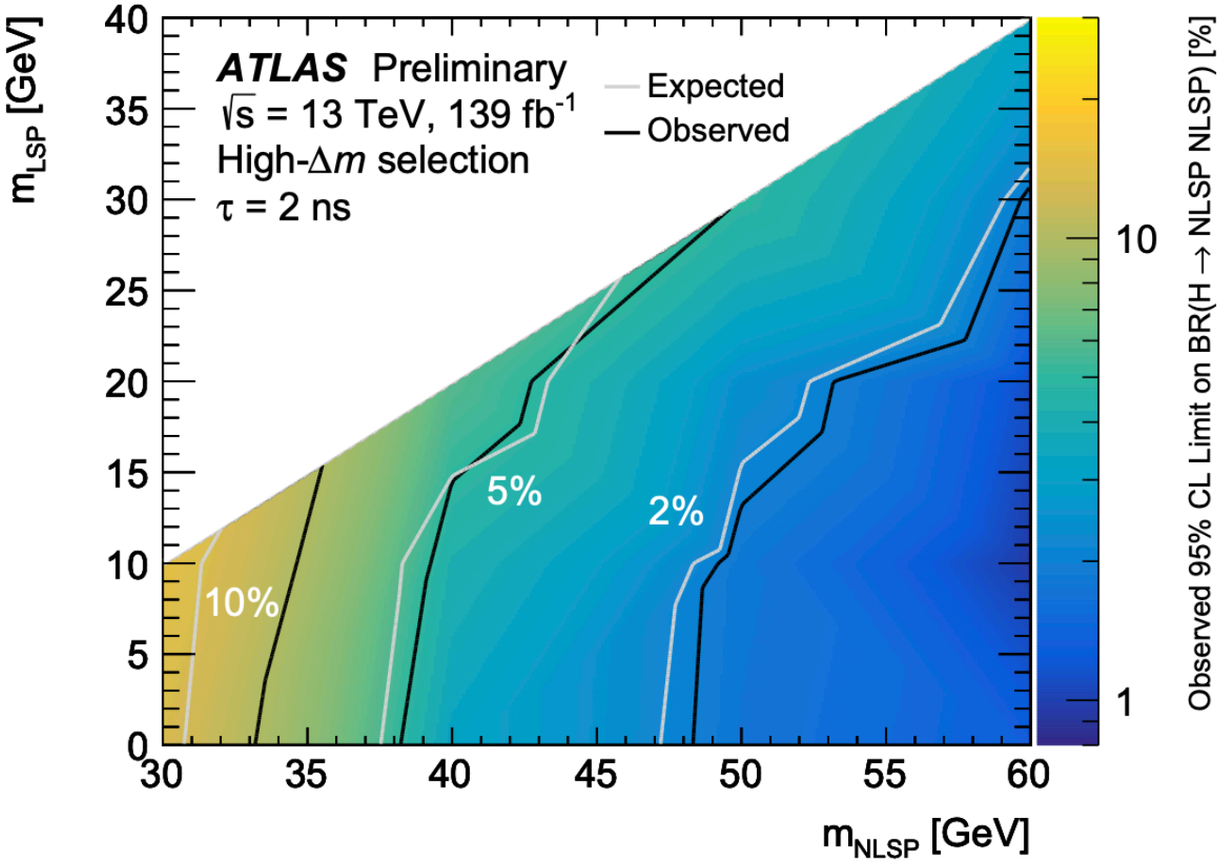
- Simultaneously fit photon timing data templates across 5 categories of photon pointing, separately for low- and high-mass splitting regions
- Result: no excess beyond the SM expectation, set limits on BR(h → 2 × NLSP)
  - As low as 1% for $\tau \sim 1$ ns and high LSP/NSLP mass splitting of ~40 GeV
  - First Run-2 sensitivity to this signature

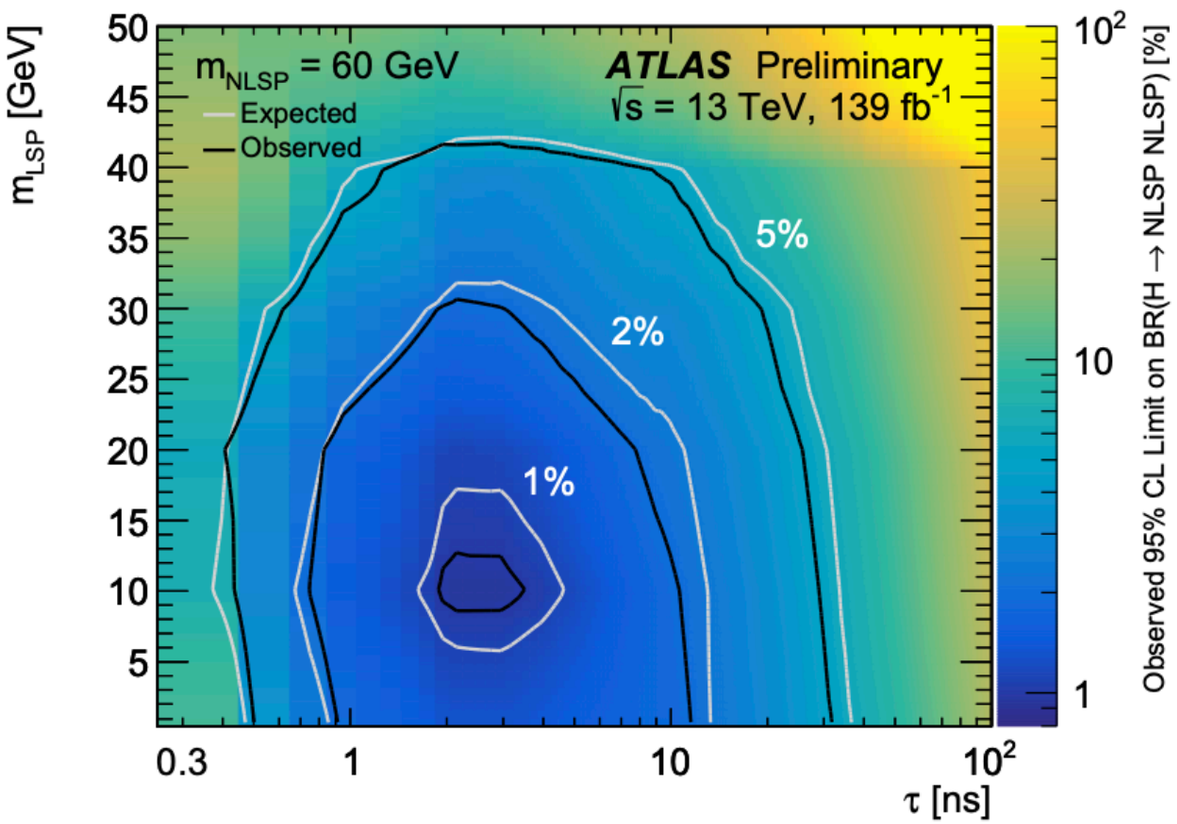




Non-Pointing/Delayed Photons Results

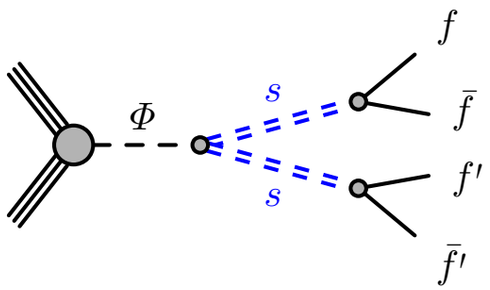
- Simultaneously fit photon timing data templates across 5 categories of photon pointing, separately for low- and high-mass splitting regions
- Result: no excess beyond the SM expectation, set limits on BR(h → 2 × NLSP)
  - Interpolated results show sensitivity across the m(LSP), m(NLSP), τ plane
  - First Run-2 sensitivity to this signature



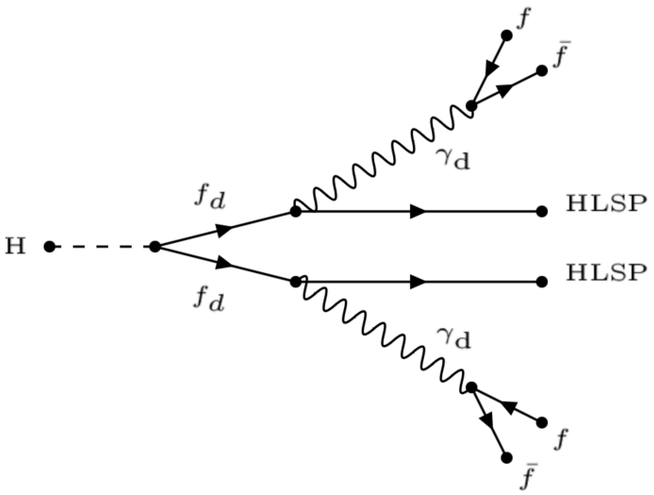


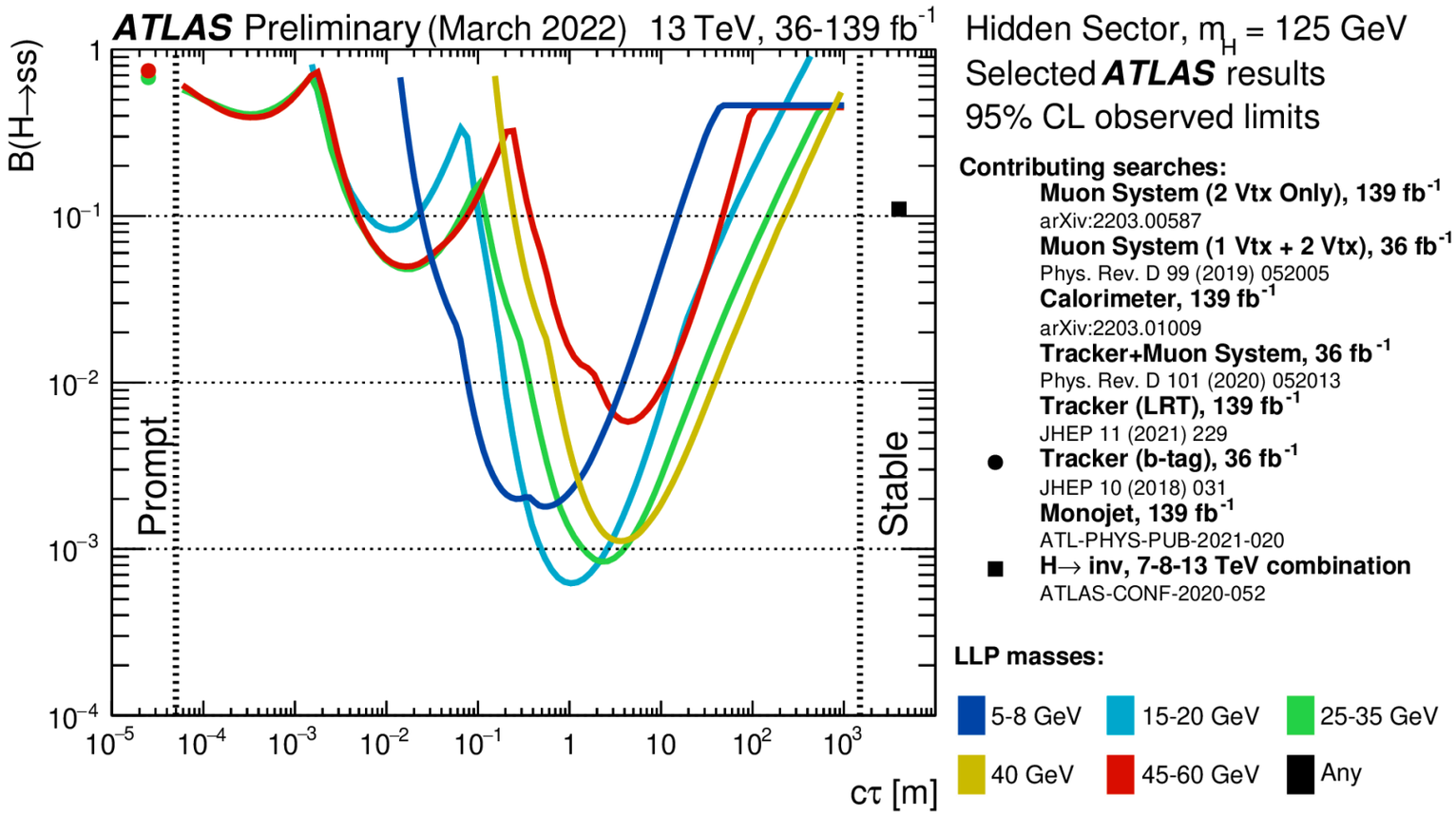
Other LLP Higgs portal searches

- Displaced jets in the calorimeter JHEP 06 (2022) 005



- Displaced leptons in the calorimeter / muon system arXiv:2206.12181





- Limit on 125 GeV mediator Higgs boson decaying to pair of scalars, shown in Higgs BR vs cτ
- Case where Higgs decays to a pair of long-lived neutral scalars
- Prompt and detector stable limits shown

Search for NMSSM Higgs from *Zh* production

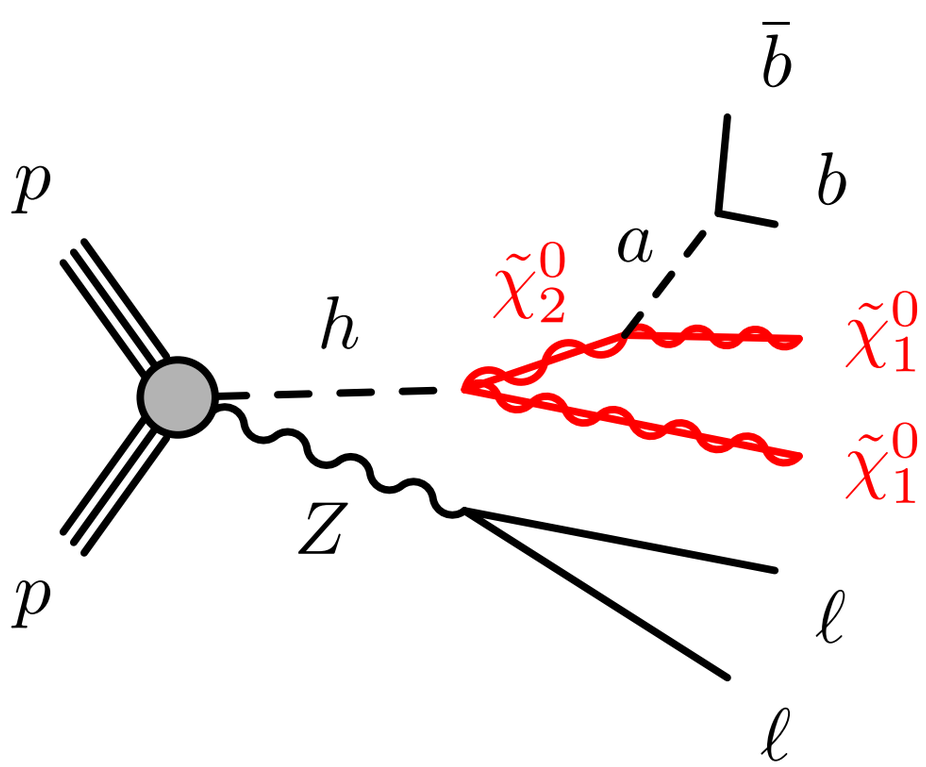
Zh→llbb+MET

JHEP 01 (2022) 063

Also see Christian's talks

Search for NMSSM Higgs from Zh production

- Up to ~21% of Higgs decays goes via undetected modes [PRD.101.012002]
- Searches for exotic decays of the Higgs is a high priority for ATLAS
- MSSM has 4 Higgs bosons, NMSSM introduces an 5th Higgs boson, *a,* that can alleviate the little hierarchy problem. Needs to be less massive than the 125 GeV Higgs boson.
- In Peccei-Quinn symmetry limit of the NMSSM, $h \to \tilde{\chi}_2^0 \tilde{\chi}_1^0$ dominates over $h \to aa$
- **Strategy**: Search for a peak in the dijet invariant mass distribution from $a \to b\bar{b}$

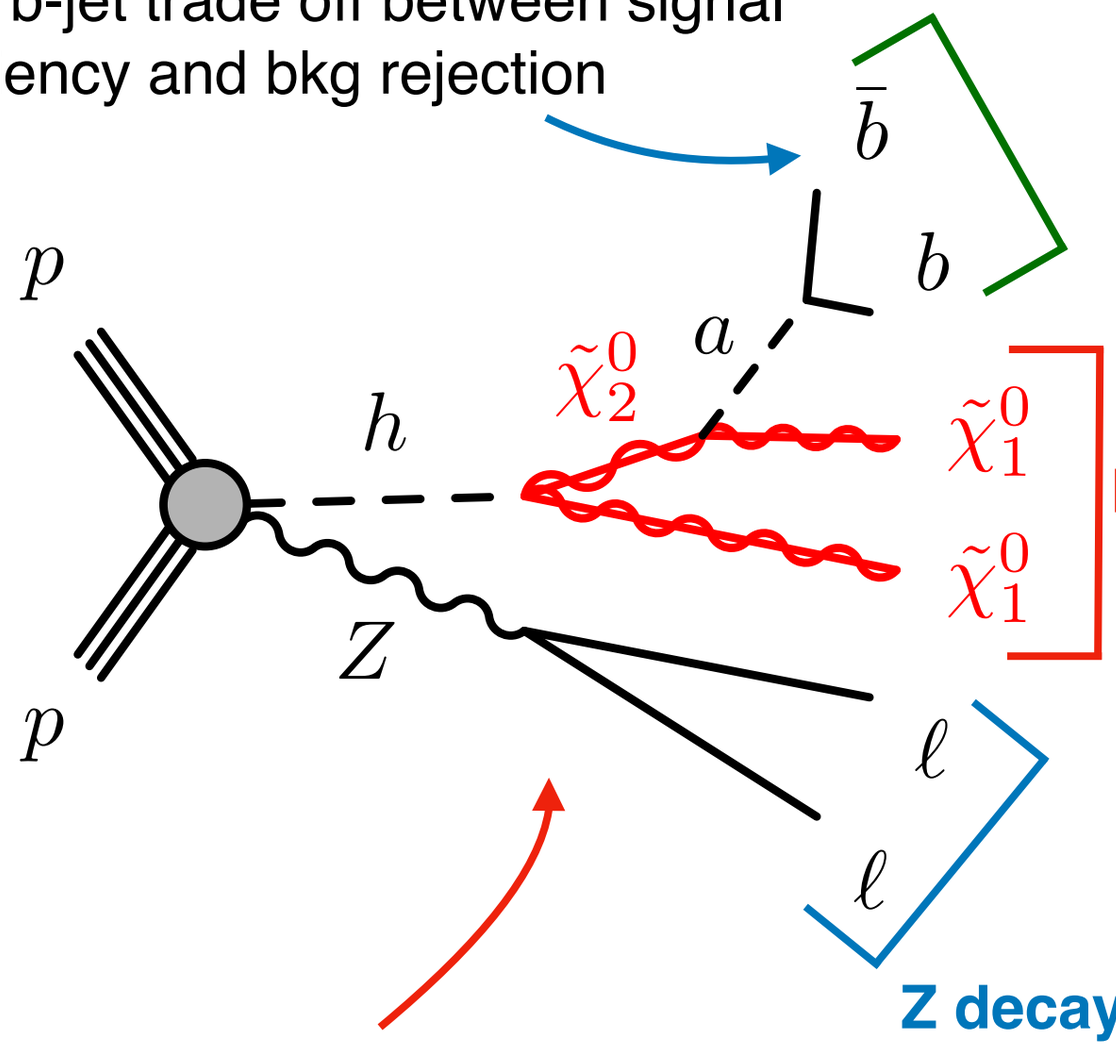


Overall selection

Jets
>= 2 jets, pT > 20 GeV
>= 1 b-jet
One b-jet trade off between signal efficiency and bkg rejection

Dijet mass
Key search variable
$20 < m_{jj} < 120$ GeV*

*Signal only in 20-60 GeV range, but there's a long tail due to extra jets mixed in with the dijet invariant mass.



MET > 100 GeV

Single Lepton trigger

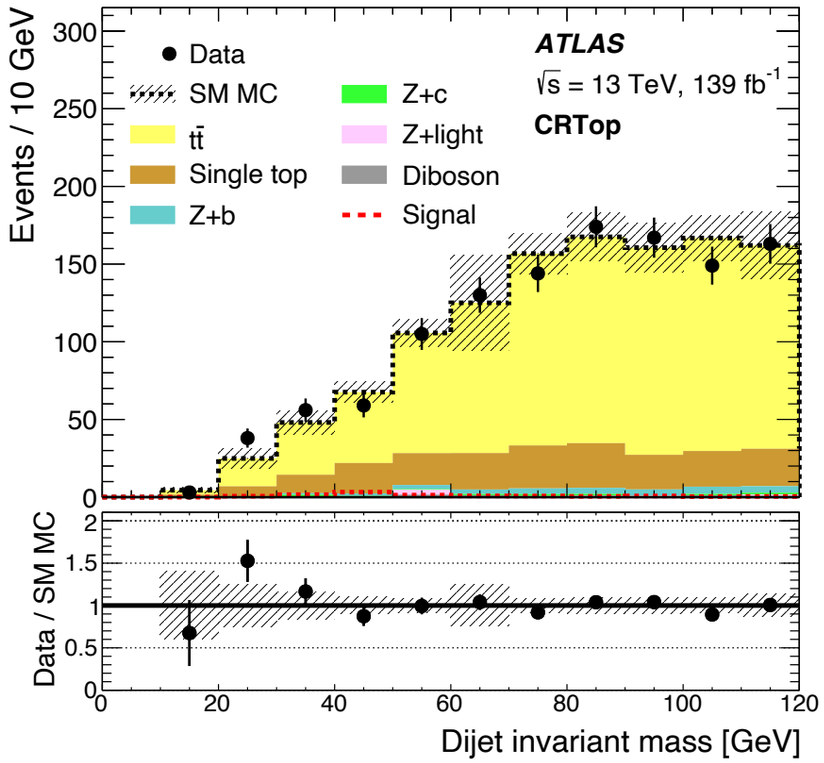
Z decay consistency
Z mass: $81 < m_{ll} < 101$ GeV
Exactly 2 leptons (veto events with more)

ttbar killer

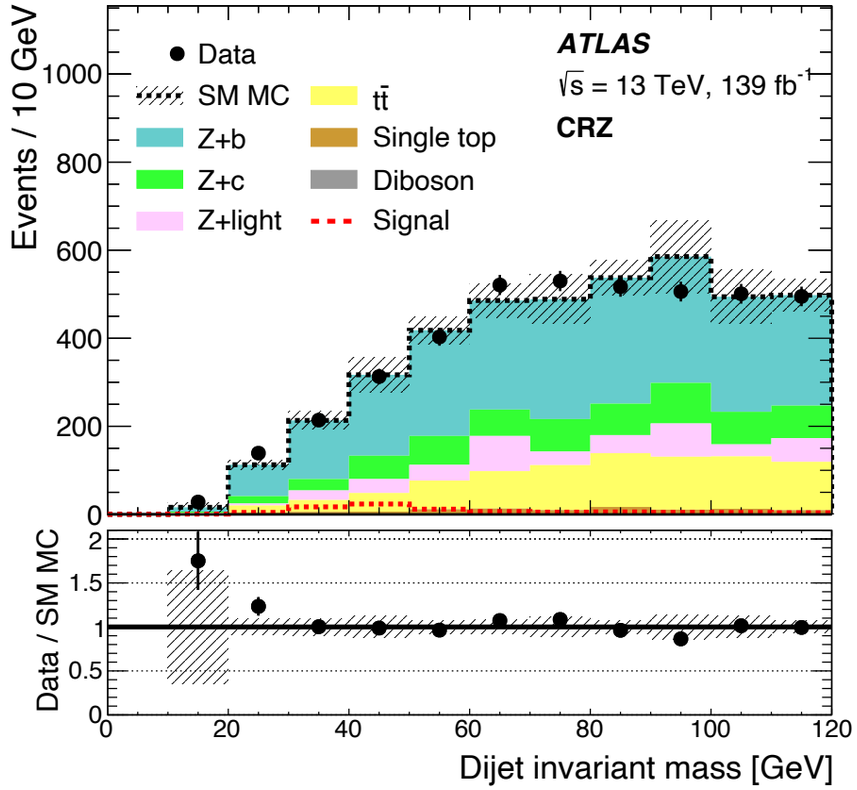
$$0.8 < \frac{p_{\mathrm{T}}^{jj} + E_{\mathrm{T}}^{\mathrm{miss}}}{p_{\mathrm{T}}^{\ell\ell}} < 1.2$$

Background Estimation

- Backgrounds, major: ttbar, Z+jets, minor: diboson, single top (Wt)
- Normalisation of major backgrounds extracted from fit to Control Region (CR)
- m_{jj} distribution: e.g. CRZ, non Z+jets contribution subtracted (~30%), giving "pure Z+jets" m_{jj} distribution. This shape then transferred to Signal Region (SR). Likewise for CRTop.
- Shape of m_{jj} for CRZ found to differ slightly from that in the SR (according to MC in the SR). Bin-by-bin correction factor applied.



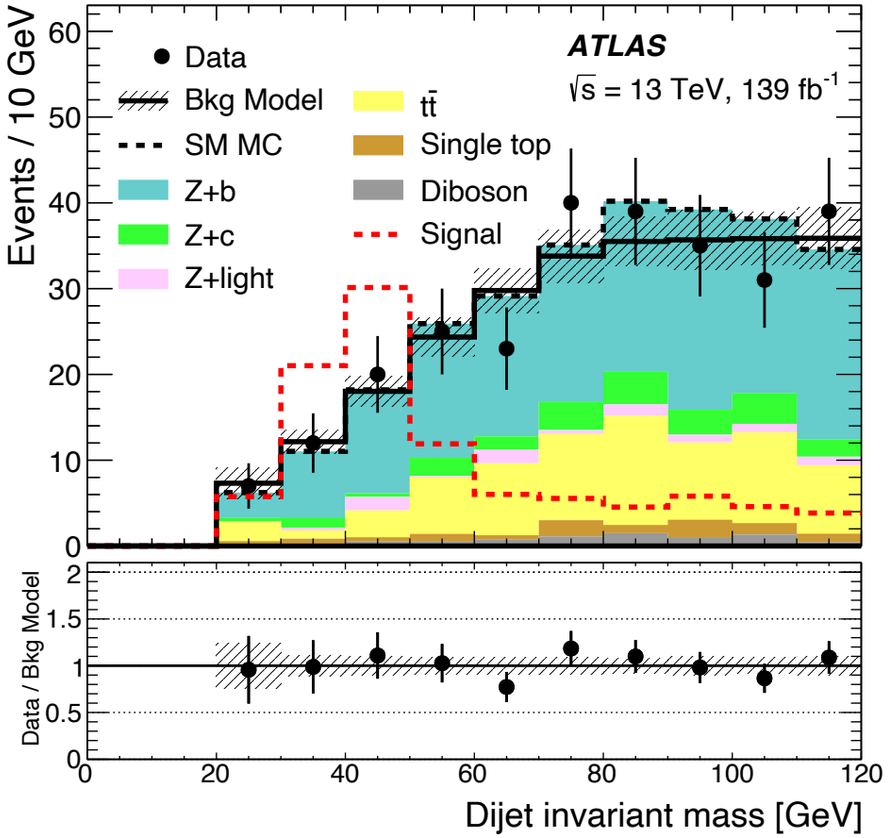
CRTop (ttbar)
same as SR except with 60 < MET < 100 GeV

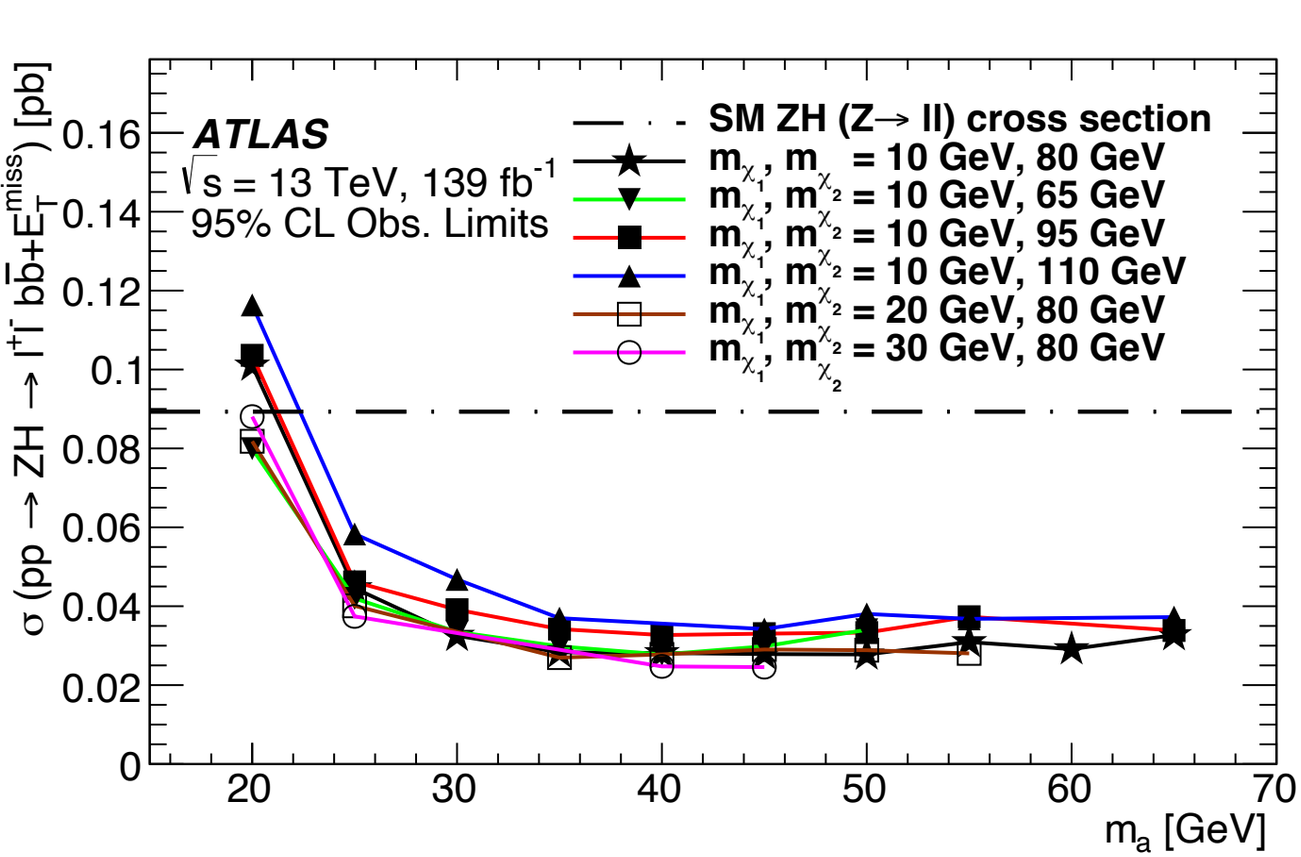


CRZ (Z+jet from heavy flavour)
same as SR except with 60 < MET < 100 GeV

Results

- Z+jets and ttbar backgrounds estimated from shapes taken from SR. Normalisation for each background taken from MC in the SR.
- Multi bin fit of mjj distribution done:
  - Background-only fit (fit to the SM background from — “is the data consistent with the SM?")
  - Fit with background+signal (to rule out BSM signal hypotheses)
- No significant excess seen over SM expectation
- Assuming SM Zh production, limits set on $BR(h \to \tilde{\chi}_2^0\tilde{\chi}_1^0 \to a\tilde{\chi}_1^0\tilde{\chi}_1^0 \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0)$, max limit of 31%





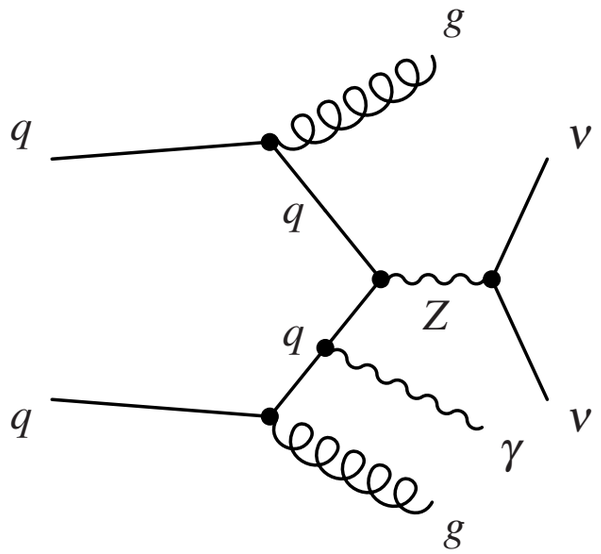
Vector Boson Fusion EW($Z\gamma \rightarrow \nu\nu$) measurement *and* Higgs to invisible/dark photons

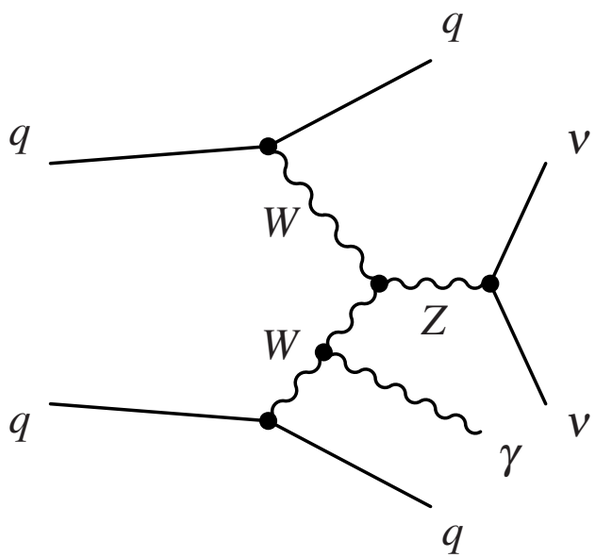
$h \rightarrow \chi\chi$, $h \rightarrow \gamma_d\gamma$

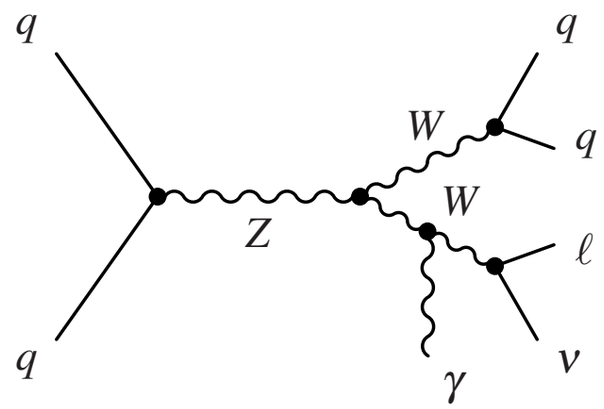
EPJC 82 (2022) 105

A measurement and a search

- Measurements of vector boson scattering can be a probe for BSM physics
- This paper: measurement of the electroweak production of two jets in association with a $Z\gamma$ pair, with the Z boson decaying into two neutrinos.
- **Signature**: two forward hadronic jets (from VBF), a photon and significant MET





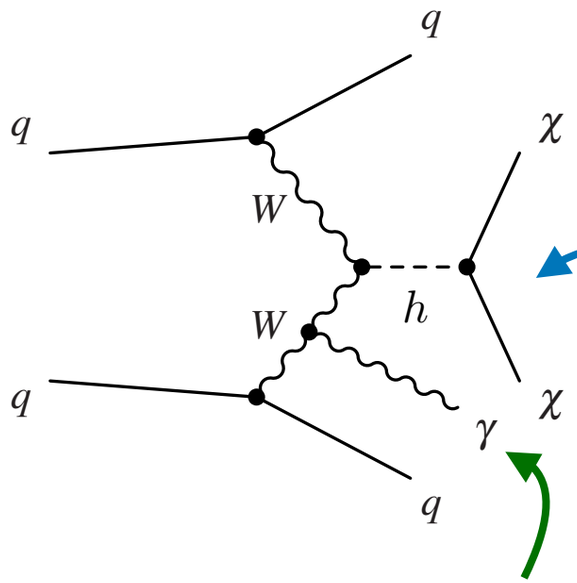


- **Strategy**: measure the EW $Z(\rightarrow \nu\nu)\gamma$ + jets, and once the SM process is understood, search for the Higgs decaying into invisible particles.
- Interpret search results in “Higgs portal” model and “dark photon” model that have the same final state.

Signals

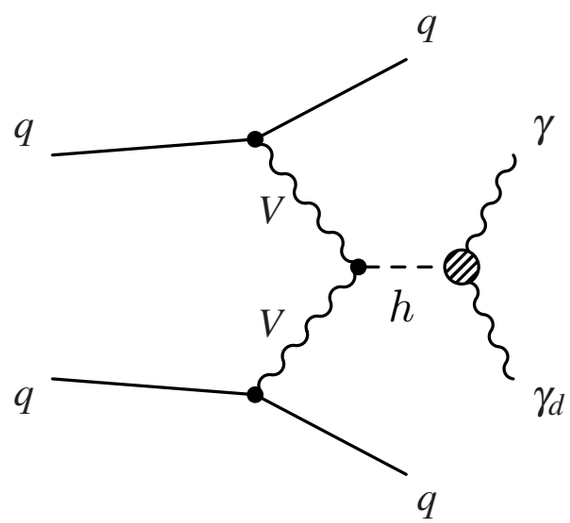
- **Signature**: two forward hadronic jets (from VBF), a photon and significant MET

Higgs portal model:
Introduce a dark matter candidate which behaves as a singlet under SM gauge symmetries.



Radiate photon from W
Improves background rejection and signal efficiency but lowers cross section

Dark photon model
Introduce a light/massless “dark photon”, coupled to Higgs through unbroken U(1) dark sector.



Event selection

Baseline selection applied for all scenarios, then extra specific cuts made for the measurement and each signal model.

VBF process: jets tend to be in different hemisphere of the detector & more forward than non-VBF processes.

Photons

- One photon with 15 < pT < 110 GeV (upper bound reduces from photon+jet background). $\Delta\phi(E_T^{\text{miss}}, \gamma) > 1.8$
- Photon centrality > 0.4: $C_\gamma = \left[-\frac{4}{(\eta_1 - \eta_2)^2}\left(\eta_\gamma - \frac{\eta_1 + \eta_2}{2}\right)\right]$ C_γ = 1 when photon between two VBF jets. 1/e = 0.38 when aligned w/ jet

Jets

- High pT (j_1 > 60 GeV, j_2 > 50 GeV), opposite hemispheres $\eta(j_1) \times \eta(j_2) < 0$. Well separated in eta: $|\Delta\eta_{jj}| > 3.0$, large invariant mass: $m_{jj} > 0.25$ TeV, not back-to-back in transverse plane: $\Delta\phi_{jj} < 2.5$
- Suppress contribution from strong $V\gamma$ + jets production with C3 (equivalent to Cγ for 3rd jet if there is one).

Veto events with leptons

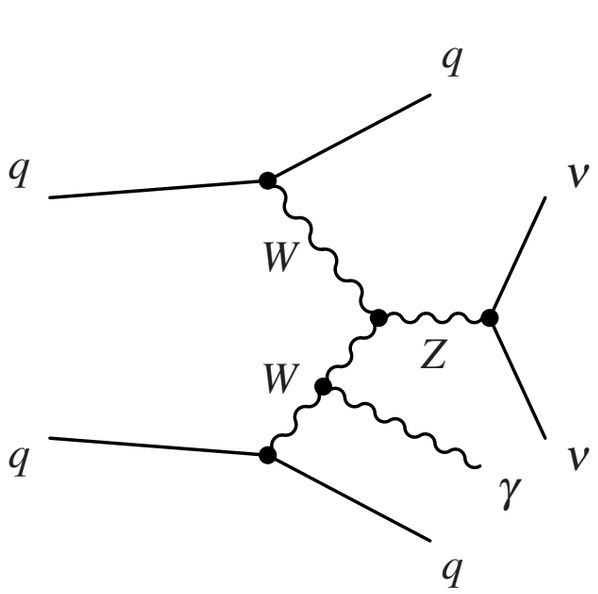
Background

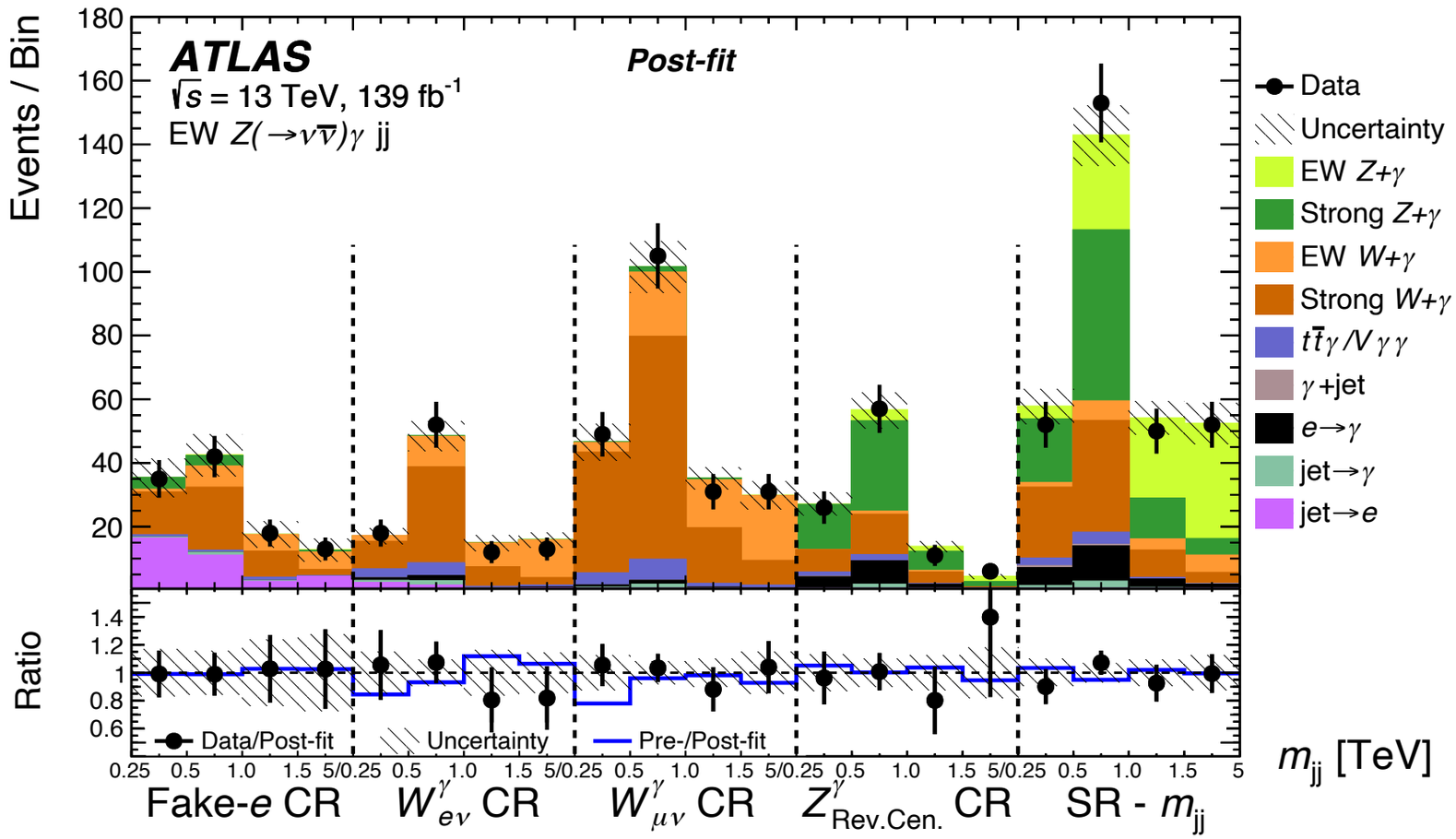
- Main backgrounds: strong $Z\gamma$, strong $W\gamma$
- CRs for $W(\rightarrow l\nu)\gamma$ + jets used to normalise that background, likewise CRs for $Z(\rightarrow \nu\nu)\gamma$ + jets events
- Jet → photon fake estimated with ABCD method (W/Z+jets in which one jet fakes a photon).
- Electron → photon fakes: Determined from the rates of Z boson reconstruction in eγ and e+e- final states . V small background for EW $Z\gamma$ + jets and Higgs → invisible, but more relevant for dark-photon.

Measurement results

- Fit to the 4 m_{jj} bins. EW $Z\gamma$ normalisation floating in the fit in the SR
- Measured fiducial cross-section: $\sigma^{\text{fid.}} = 1.31 \pm 0.20(\text{stat}) \pm 0.20(\text{syst})$ fb,
- > 5 sigma observation

New Observation





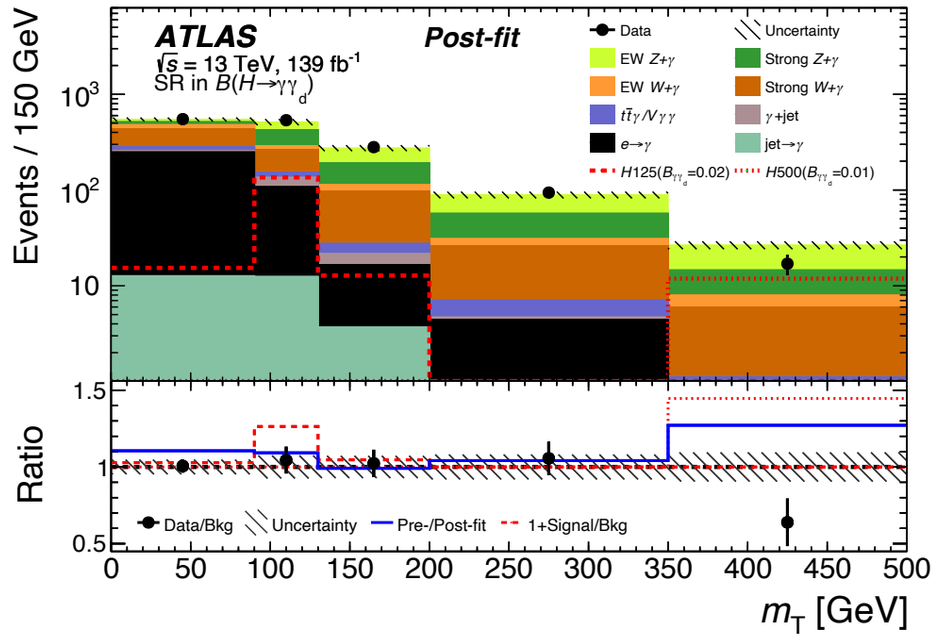
Search results

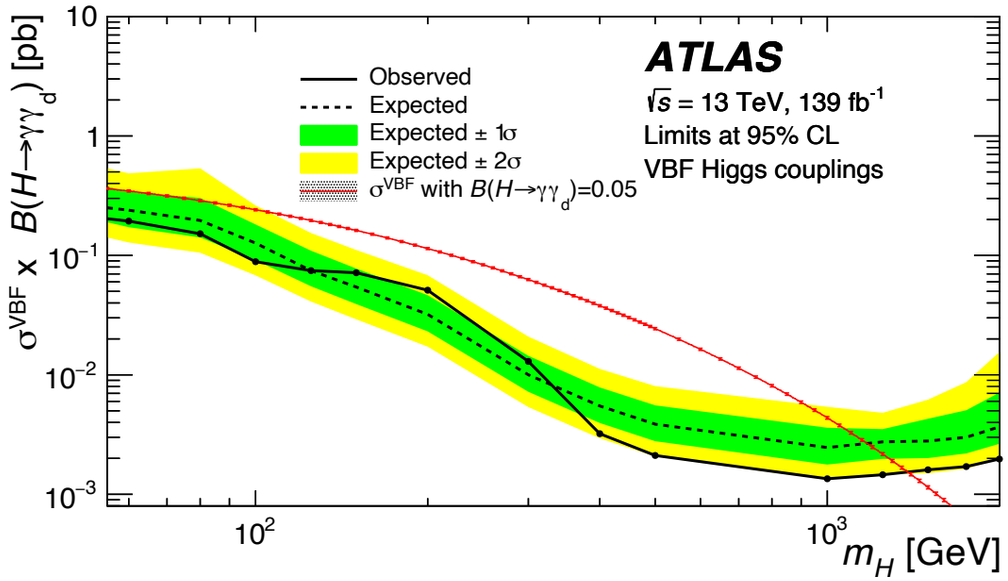
Invisible Higgs

- Train DNN, bin output score
- No excess observed, 0.37 observed UL on the branching ratio to invisible particles.
- Limit not the strongest but useful in combination

Dark Photon

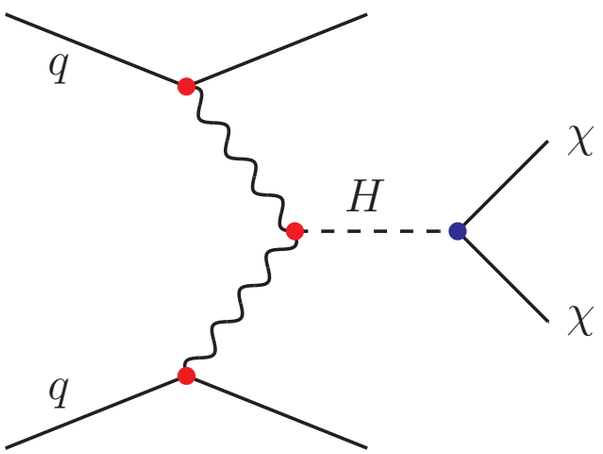
Limit up to 2 TeV: currently world's strongest



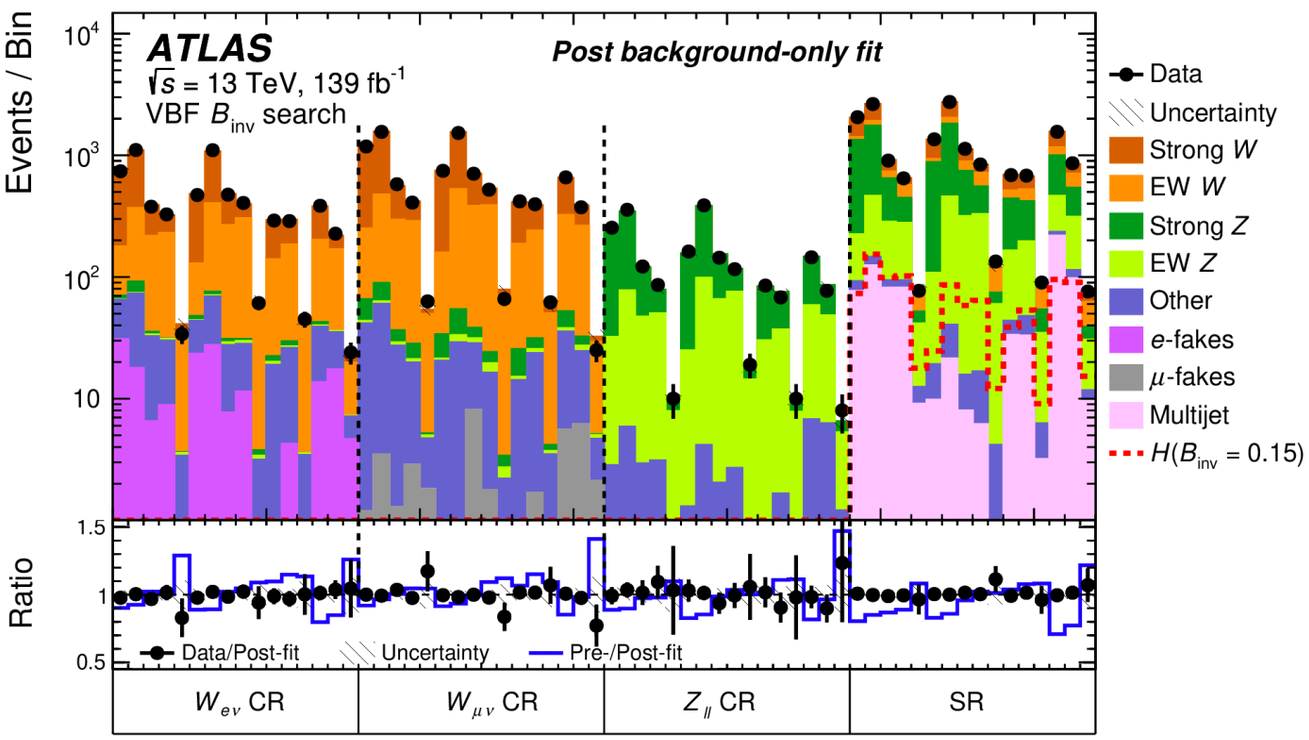


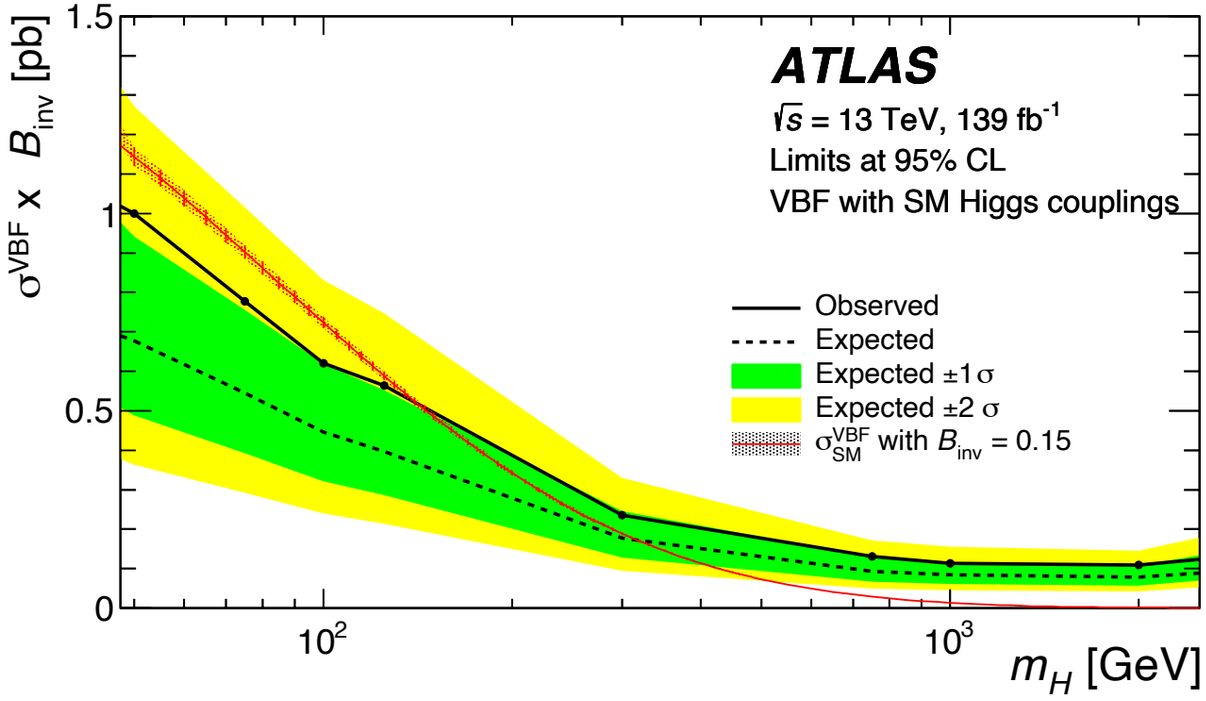
Bonus: Direct search for invisible Higgs: JHEP 08 (2022) 104

Higgs portal



- Same signature as previous search with similar backgrounds
- **Strategy**: target VBF process: wide rapidity gap, $\Delta\eta_{jj}$ & large invariant mass m_{jj}
- Additional selection on MET, jet centrality, VBF jet topology
- Signal yield extracted from binned likelihood fit to 16 search bins (jet multiplicity, m_{jj} $\Delta\phi_{jj}$)
- Z_{ll} and W_{lv} CRs to estimate main backgrounds Z(→νν)+jets, W(→lν)+jets





Upper limit on cross section x BR_{inv} for scalar mediator

Dark sector Higgs decays

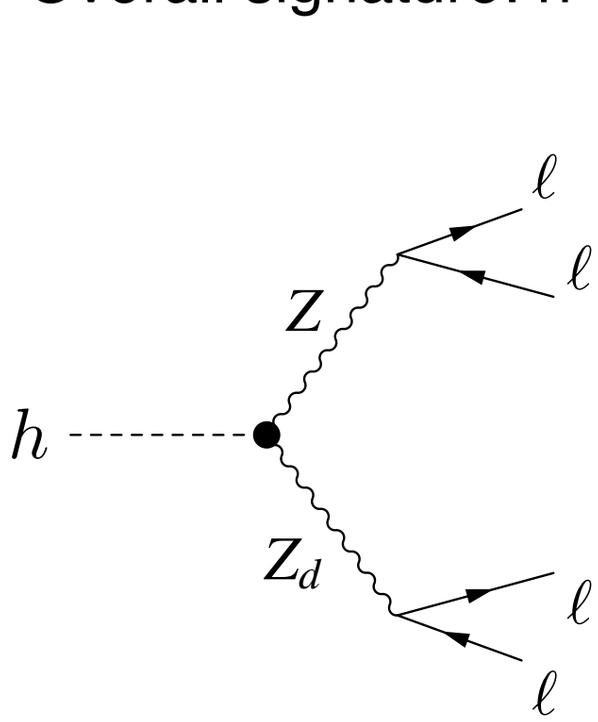
$h \rightarrow Z_d Z_d \rightarrow llll$

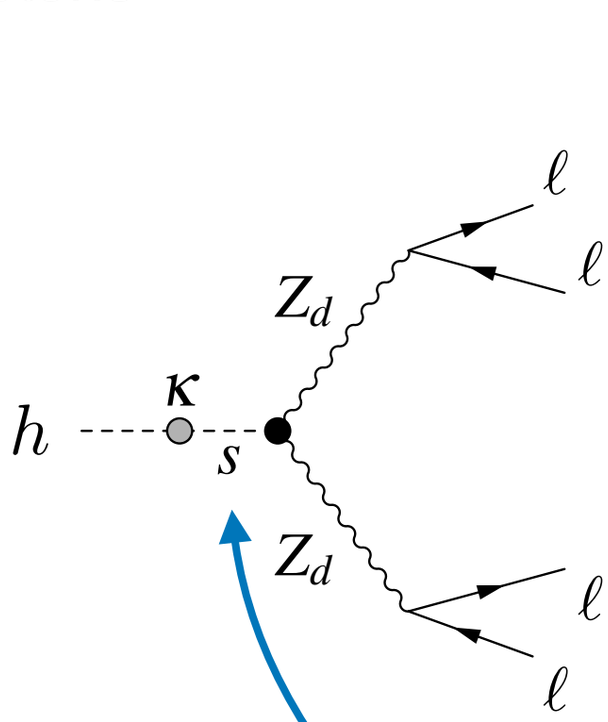
JHEP 03 (2022) 041

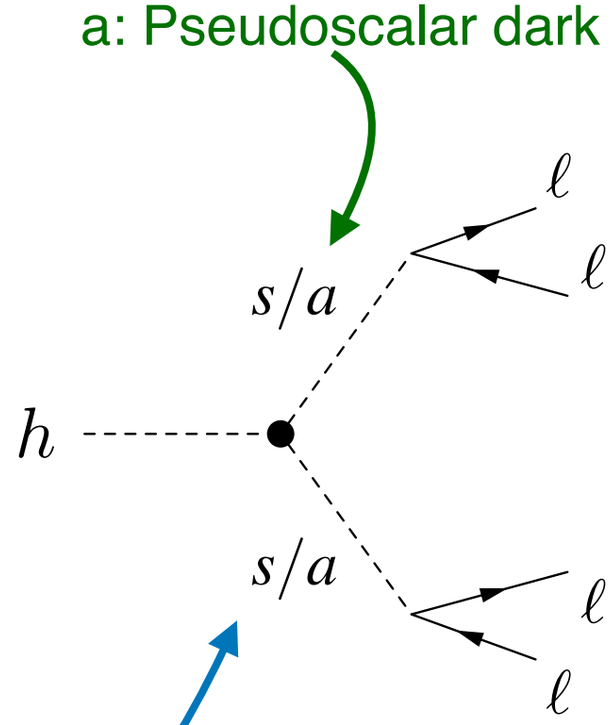
Also see Christian's talks

Higgs decay to new boson

- Many SM extensions include U(1) dark gauge symmetry with new gauge boson Z_d
- Mixes with SM Higgs and other gauge bosons.
- Gives rise to $h \to Z_d Z_d$ and $h \to Z Z_d$, Z_d decays ~30% to lepton pairs
- 4 lepton final state also sensitive to $h \to aa \to 4\mu$ if BR($a \to \mu\mu$) is significant
- Overall signature: $h \to XX \to 4$leptons







a: Pseudoscalar dark Higgs

s: dark Higgs boson (scalar)

$h \to Z_d Z_d / aa \to llll$

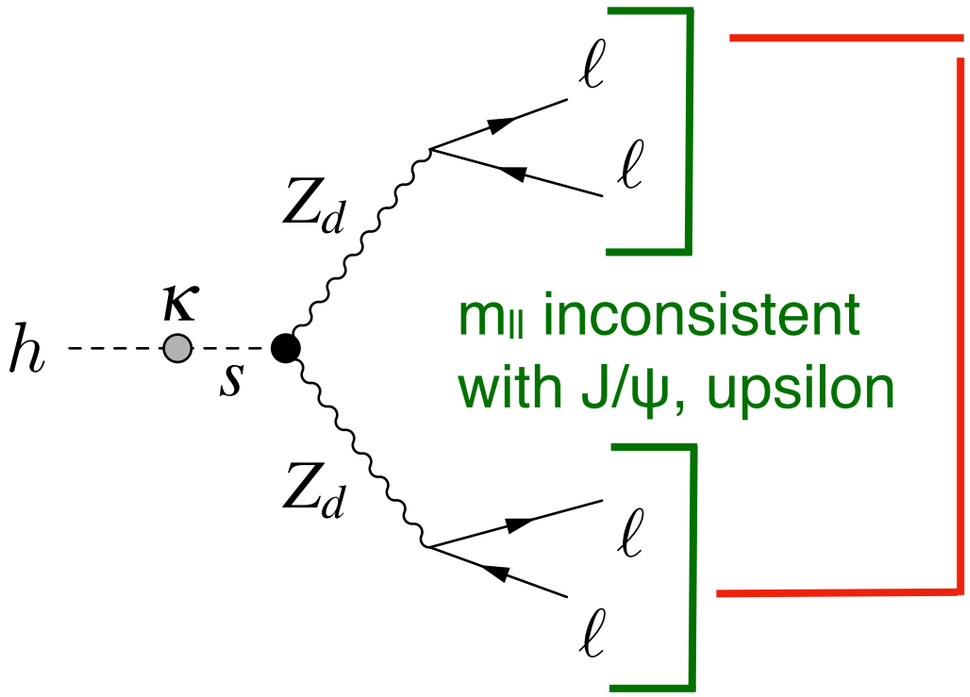
Selection

Two lepton pairs: (ee)(ee), (ee)(μμ), (μμ)(μμ)

Construct invariant mass pairs: m_{12}, m_{34}

m_{12} closest to m_Z: $|m_{12} - m_Z| < |m_{34} - m_Z|$

mass compatibility of pairs: $m_{12}/m_{34} > \sim 0.85$

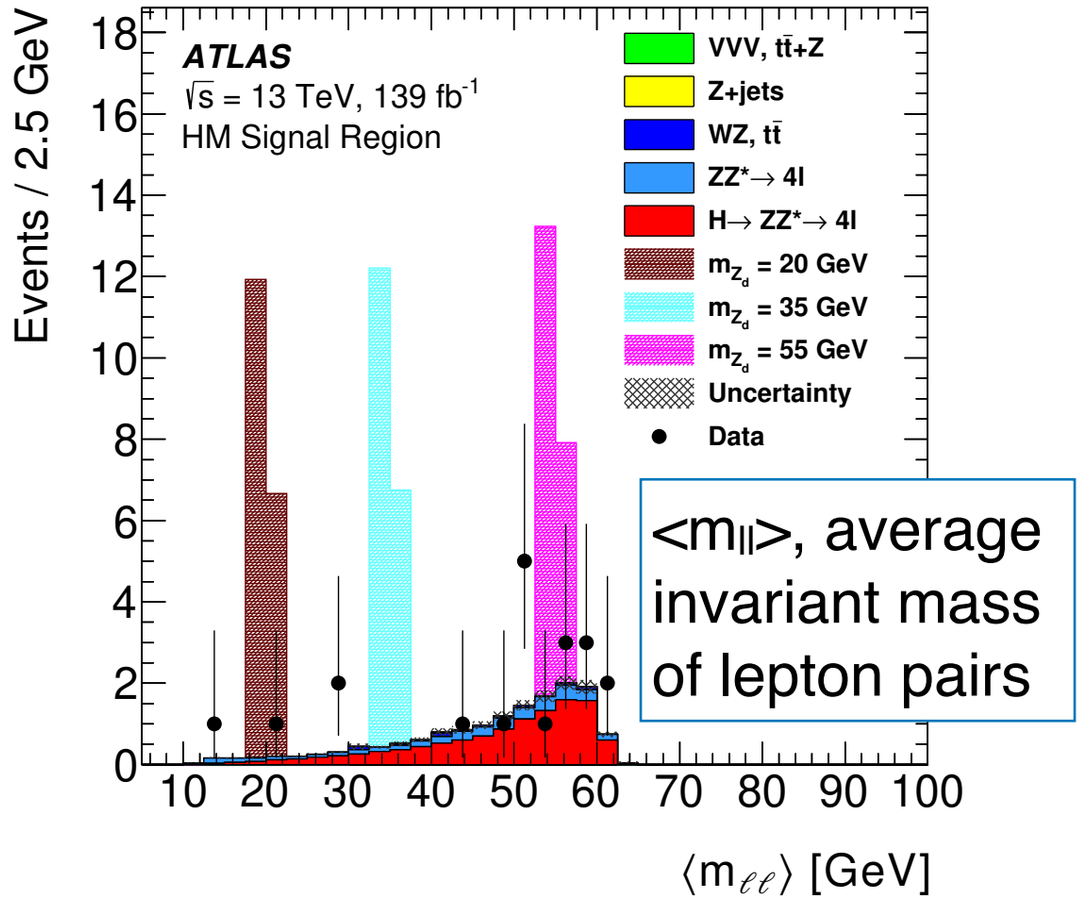


m_{ll} inconsistent with J/ψ, upsilon

m_{4l} consistent with m_h

Strategy: search for a peak in $\langle m_{ll} \rangle$

Main backgrounds: $h \to ZZ^*$ and ZZ^*

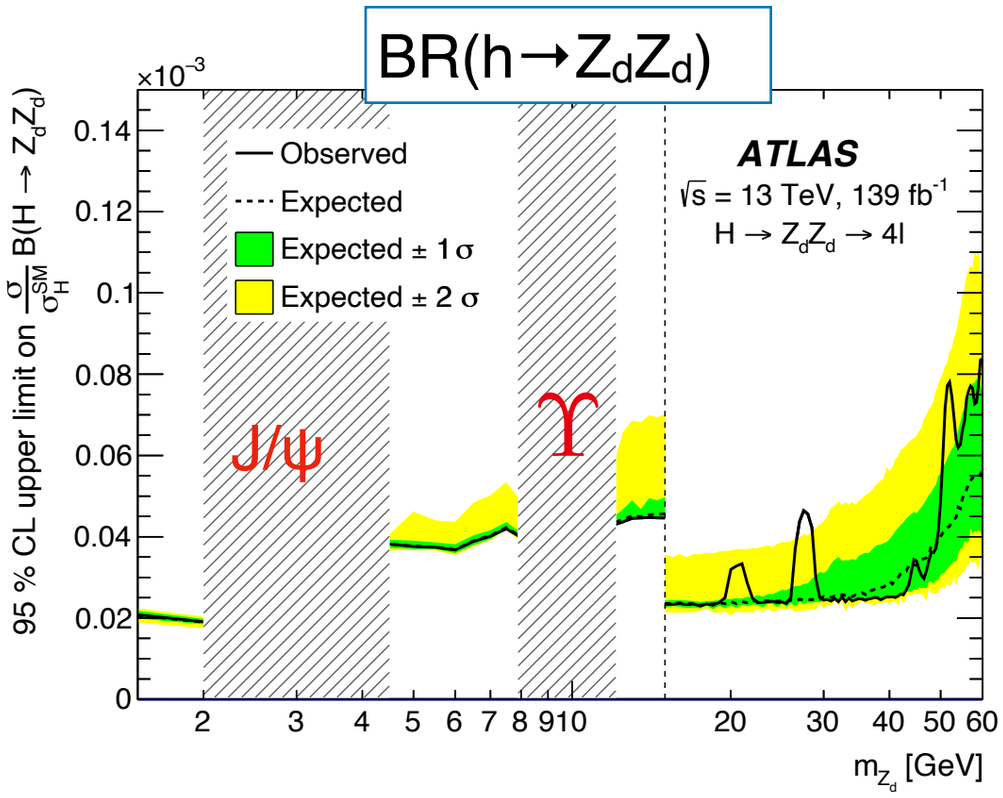


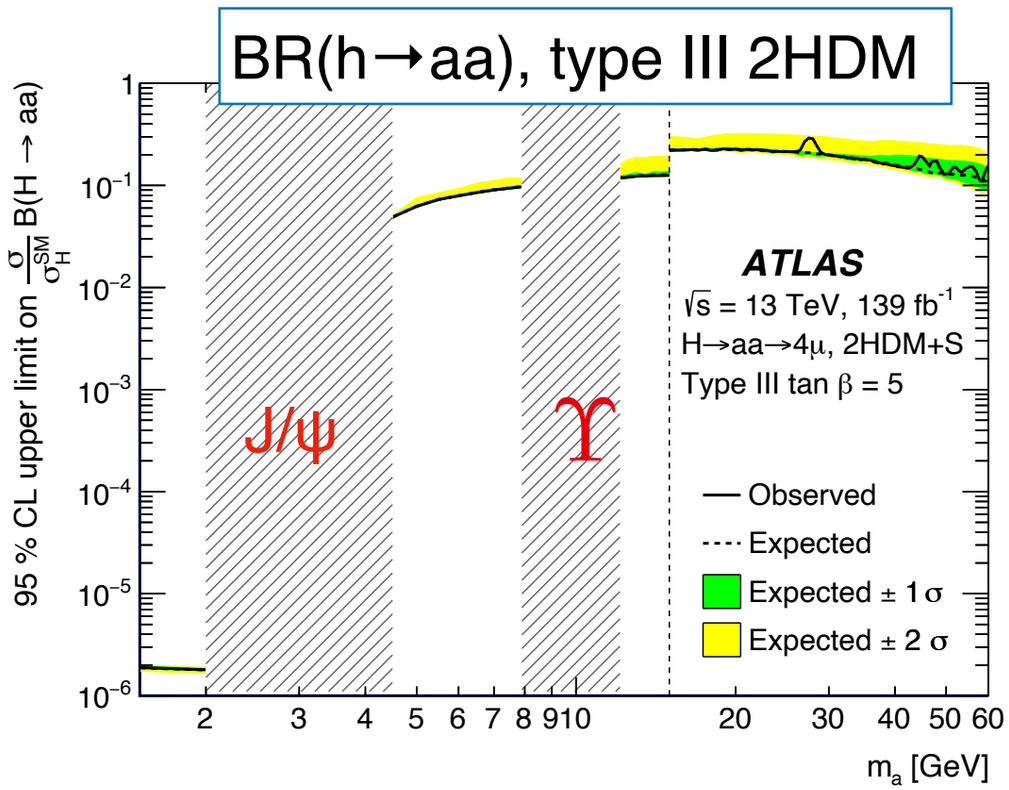
$\langle m_{ll} \rangle$, average invariant mass of lepton pairs

Consider only 4μ for $1 < m_X < 15$ GeV because electrons become difficult to separate at low pT

$h \to Z_d Z_d / aa \to llll$

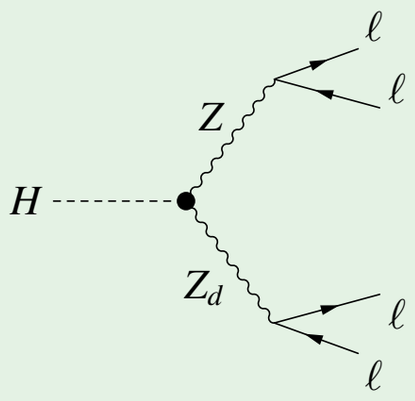
- Cross-section upper limits set on the different modes
- Significant improvement on previously set limits
- 2.5σ (local) excess in High mass $h \to Z_d Z_d$ channel around $m(Z_d) = 28$ GeV





$h \to ZZ_d \to llll$

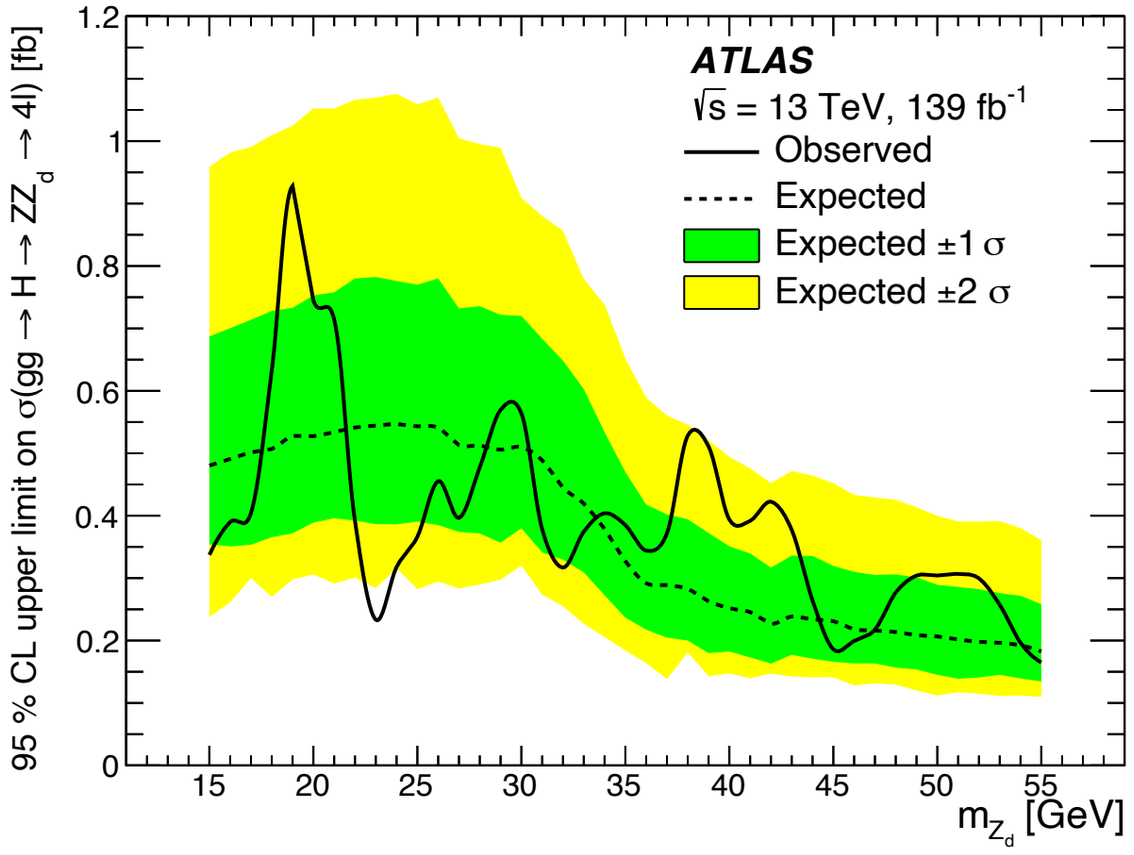
Two lepton pairs: (ee)(ee), (ee)(μμ), (μμ)(μμ)



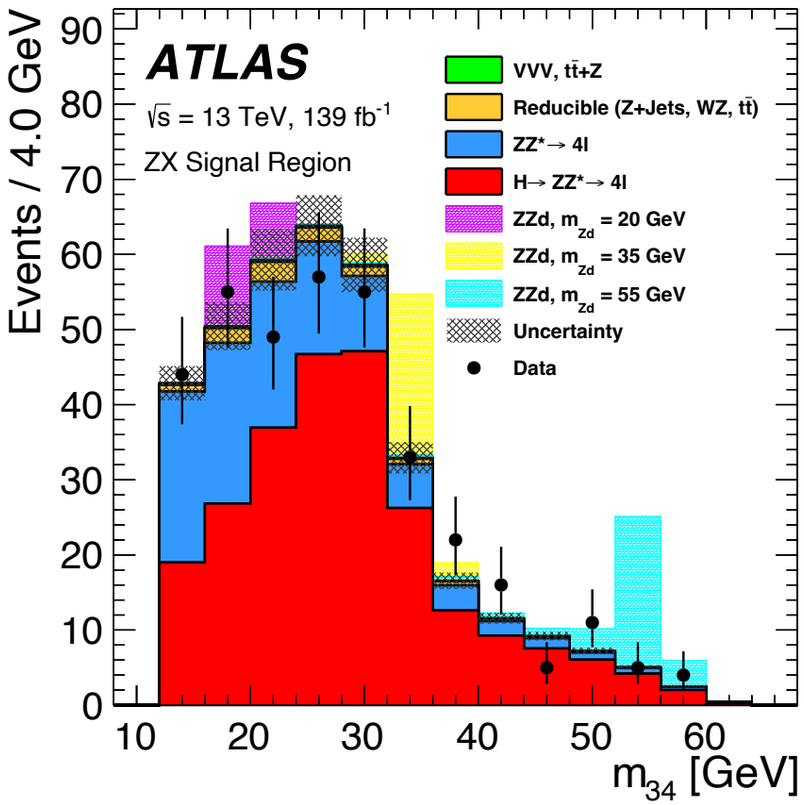
One pair (m_{12}) consistent with m_Z

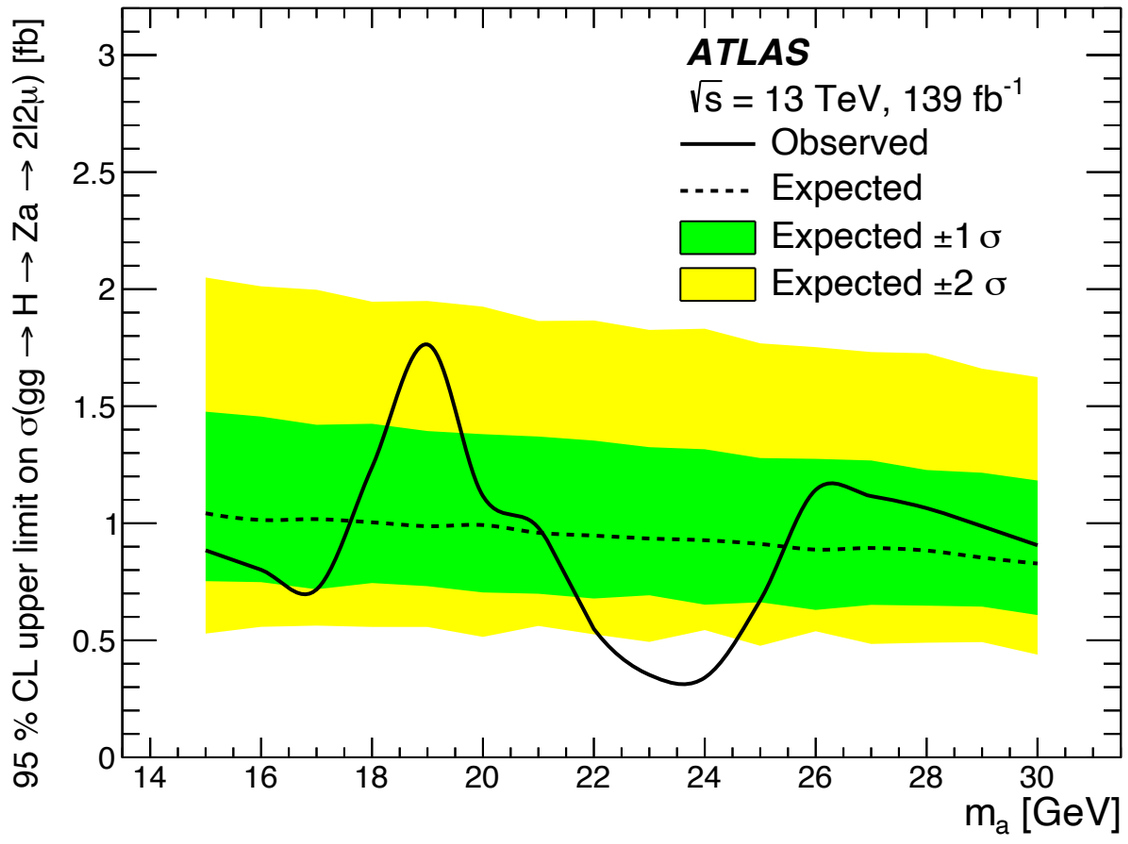
m_{4l} consistent with m_h

Strategy: look for peak in distribution of m_{34}



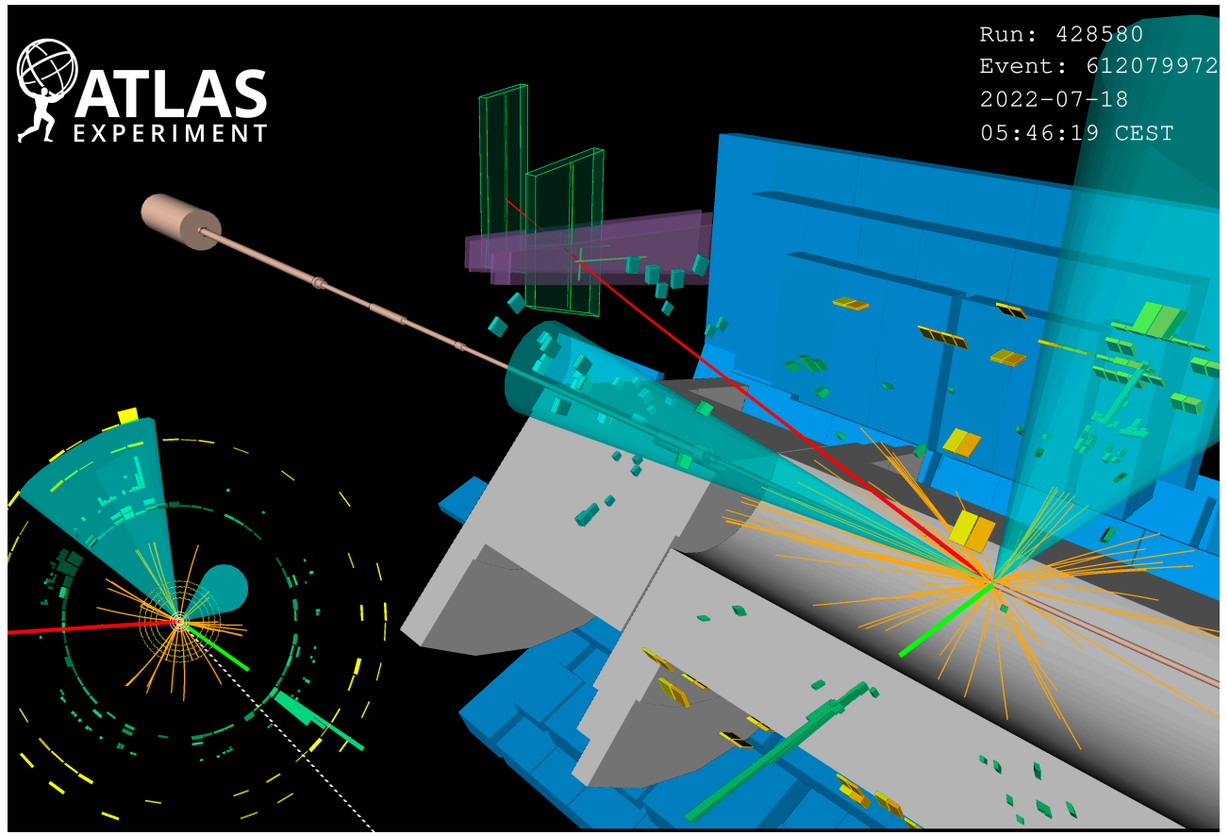
Main backgrounds: h→ZZ* and ZZ*





Summary

- Many searches for non-standard decays of the Higgs boson, with a wide reach:
  - long lived particles
  - Measurements and searches together
- No significant excess beyond SM prediction
  - 2.5σ local excess in High mass $h \to Z_d Z_d$ channel
- All results full Run-2, many will improve with more data
- Stay tuned for fresh results from Run-3



Thank you!

Direct search for invisible Higgs: JHEP 08 (2022) 104

- Results also interpreted as upper limits on the spin-independent WIMP-nucleon cross section using Higgs portal interpretations of B_{inv} at 90% CL vs m_{WIMP}.