Dark Matter search in ATLAS in $H \rightarrow \gamma\gamma + E_T^{miss}$ events: Run 1 results and Run 2 prospects

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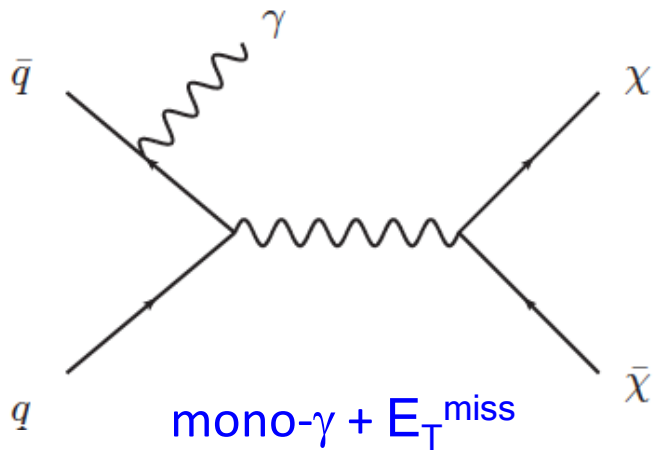
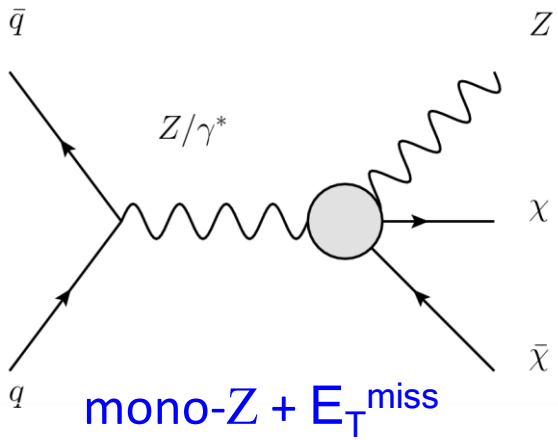
Motivation

- Mono-object + missing transverse momentum (E_T^{miss}) useful signatures for dark matter search, enabling (quasi)model-independent searches



mono-γ + E_T^{miss}



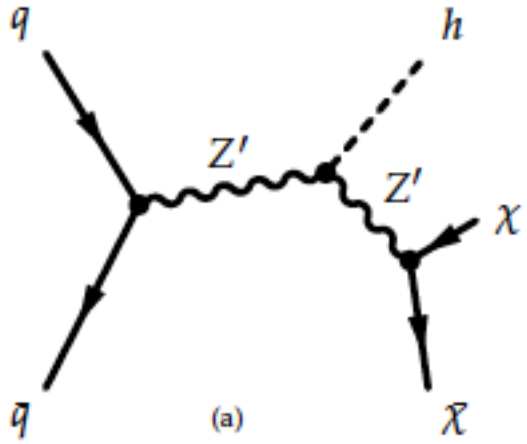
mono-Z + E_T^{miss}

- Following Higgs discovery, mono-Higgs production in association with dark matter pair provides very interesting final states
- Higgs decay modes without intrinsic E_T^{miss} are sensitive:

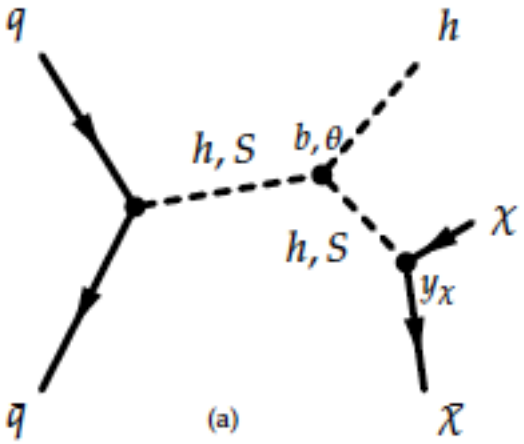
  $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow bb$
- Provide largely signature-based searches for BSM phenomena, DM being the most interesting one

Models of dark matter production with a Higgs

- **Effective field theory (EFT):** mediator assumed to be much heavier than collision energy
  - Can be 'integrated out' → model-independent searches
  - But suffers from validity issues as momentum transfers in LHC collisions become close to mass scale of mediator
- **Simplified models:** theories with explicit mediator
  - Search more model-dependent, but models valid at all energies



Z'_B mediator
arXiv:1312.2592



scalar mediator
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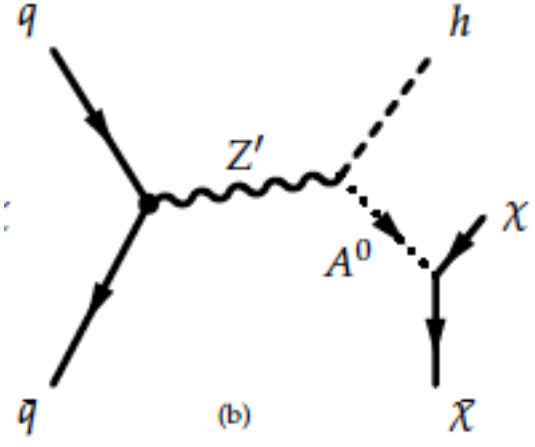


Z' mediator in 2HDM
arXiv:1402.7074

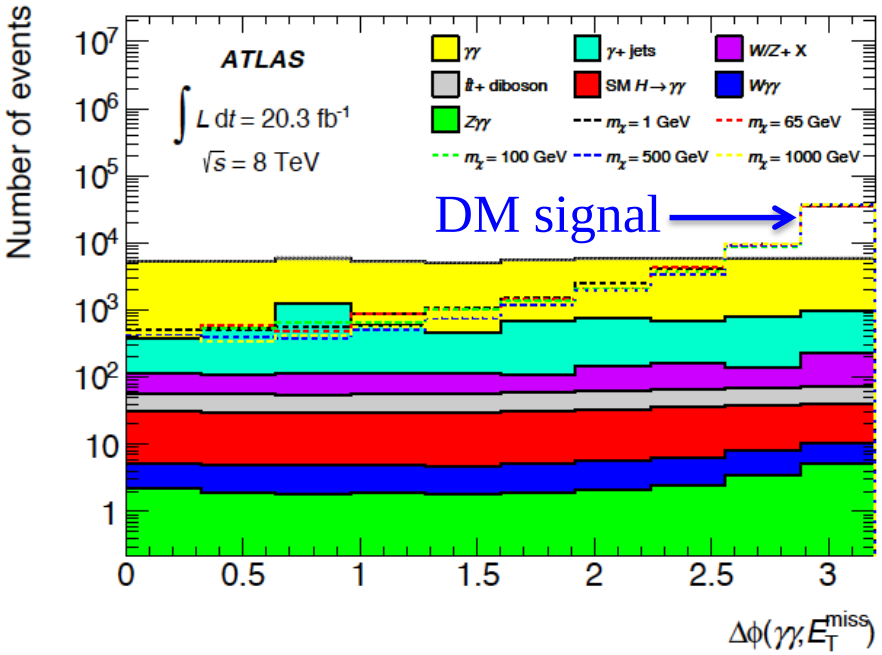
$H \rightarrow \gamma\gamma + E_T^{miss}$ search: Run 1

http://arxiv.org/abs/1506.01081

Submitted to PRL

Analysis overview

- $H \rightarrow \gamma\gamma$ branching fraction small ($2.3 * 10^{-3}$ @ 125 GeV), but very clean signature owing to good mass resolution
- At high E_T^{miss}, major background processes are:
  - Non-resonant $\gamma\gamma$ production: $\gamma\gamma$, $W\gamma\gamma$, $Z\gamma\gamma$
  - γ+jet with jet misidentified as γ
  - $W\gamma$ ($W \rightarrow e\nu$), $Z\gamma$ ($Z \rightarrow ee$) with e misidentified as γ
  - ZH with $Z \rightarrow \nu\nu$
  - WH with $W \rightarrow l\nu$



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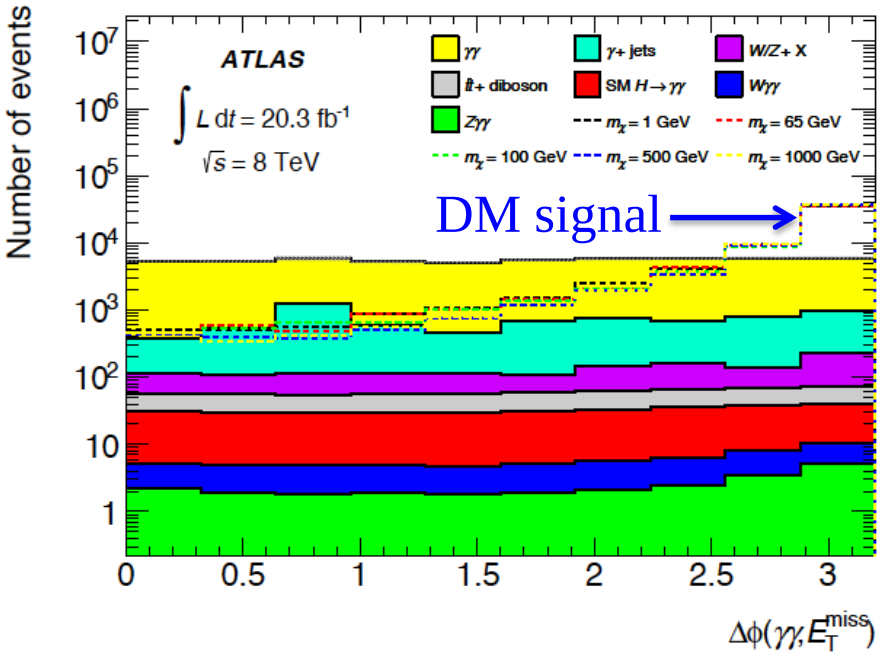


- Non-resonant backgrounds estimated from sidebands in $m_{\gamma\gamma}$ distribution
- Backgrounds from VH processes estimated from MC
- Statistical results derived from maximum likelihood fit to $m_{\gamma\gamma}$ distribution

Event triggering and photon selection

➢ Trigger

- Requires two photons, with E_T > 35 GeV and > 25 GeV

➢ Photon selection

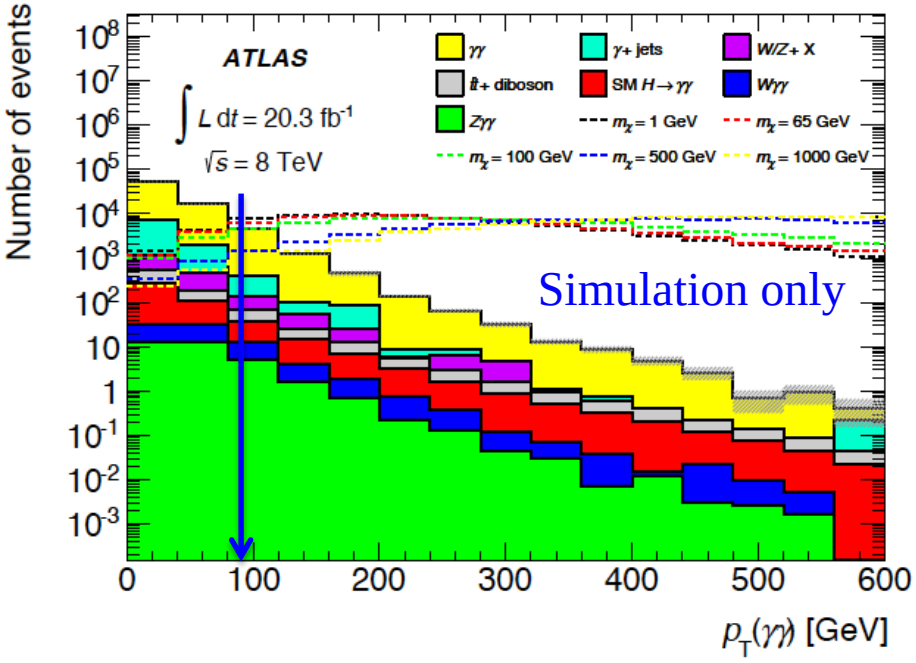
- Identification: each γ must satisfy identification criteria based on profile of energy deposit in first two layers of ATLAS EM calorimeter
- Fiducial volume: γ within $|\eta| < 2.37$, excluding $1.37 < |\eta| < 1.56$ which is not well-instrumented
- Calorimeter isolation: energy in cone $\Delta R = 0.4$ around γ cluster < 6 GeV
- Track isolation: Σp_T of tracks coming from $\gamma\gamma$ vertex with ΔR(track, cluster) < 0.2 must be < 2.6 GeV
- Scaled p_T requirement on each photon: $p_T(\gamma^{lead})/m_{\gamma\gamma} > 0.35$, $p_T(\gamma^{sublead})/m_{\gamma\gamma} > 0.25$

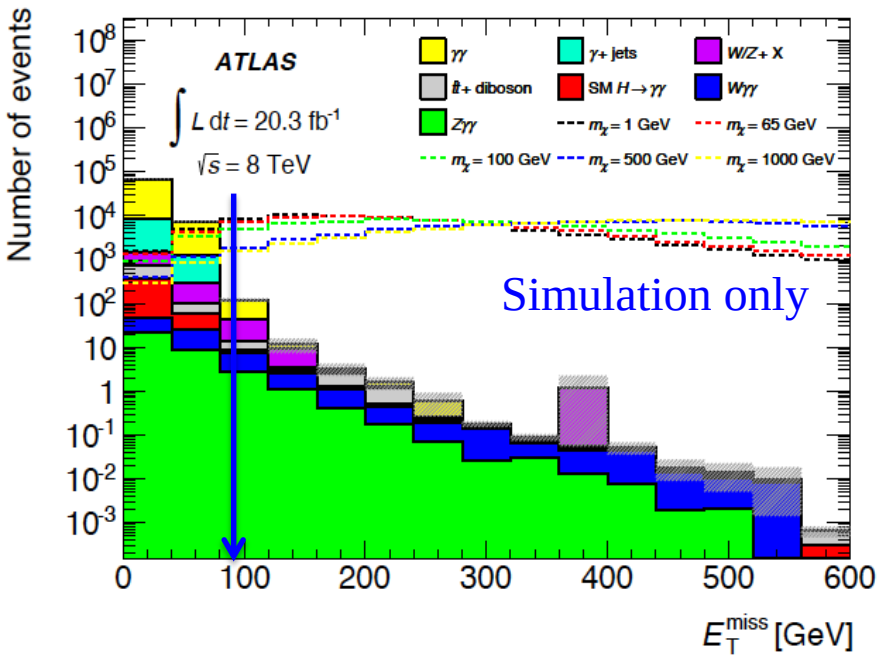
Event selection

- Diphoton invariant mass window: 105 GeV < $m_{\gamma\gamma}$ < 160 GeV
- $p_T^{\gamma\gamma}$ > 90 GeV
- E_T^{miss} > 90 GeV

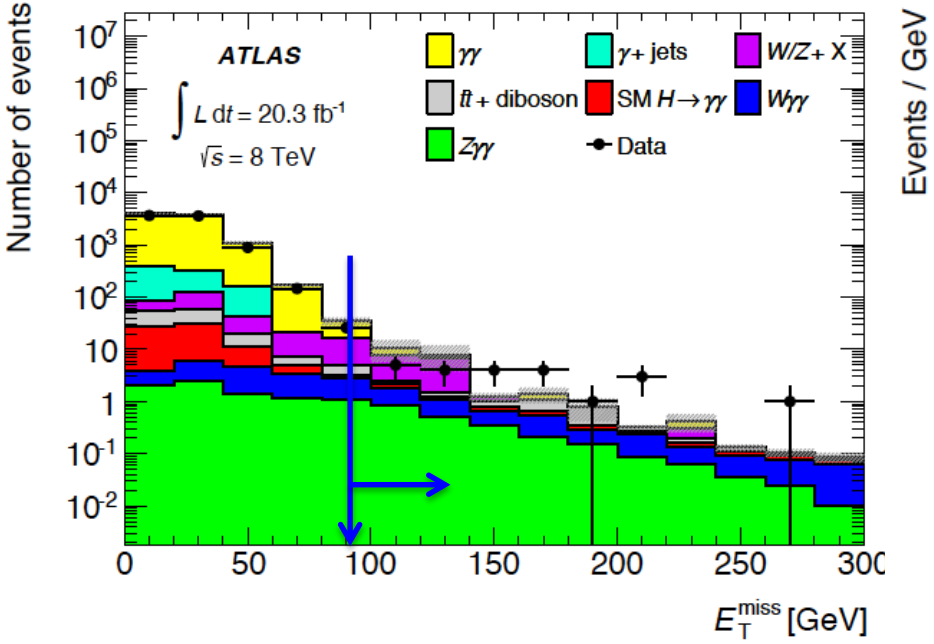
Optimized by maximizing sensitivity on dark matter production models

  - $p_T^{\gamma\gamma}$ and E_T^{miss} distributions for signal and bkgs within $m_{\gamma\gamma}$ window
  - Arbitrary signal normalization

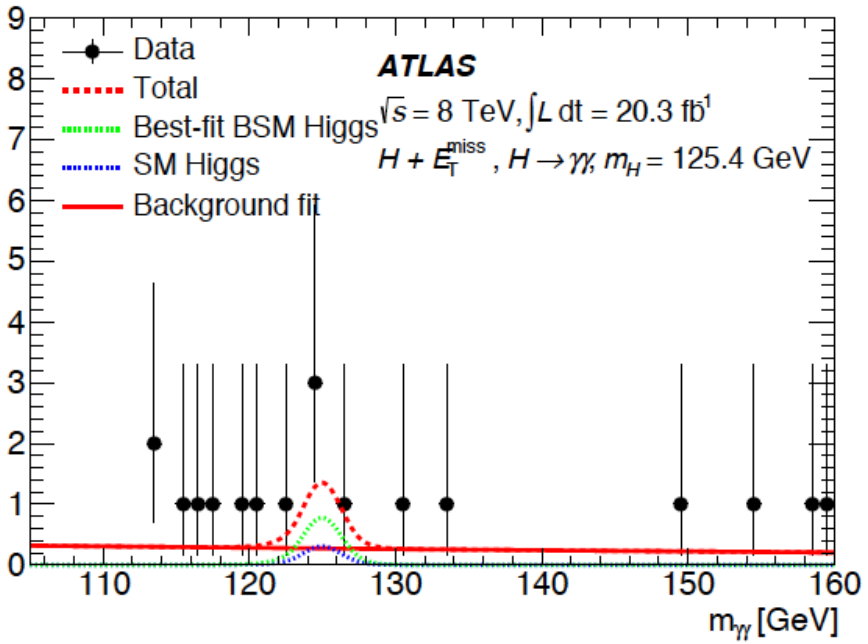




What is in data?



E_T^{miss} in $m_{\gamma\gamma}$ window, $p_T^{\gamma\gamma} > 70$ GeV



$m_{\gamma\gamma}$ after full selection

- No significant excess seen

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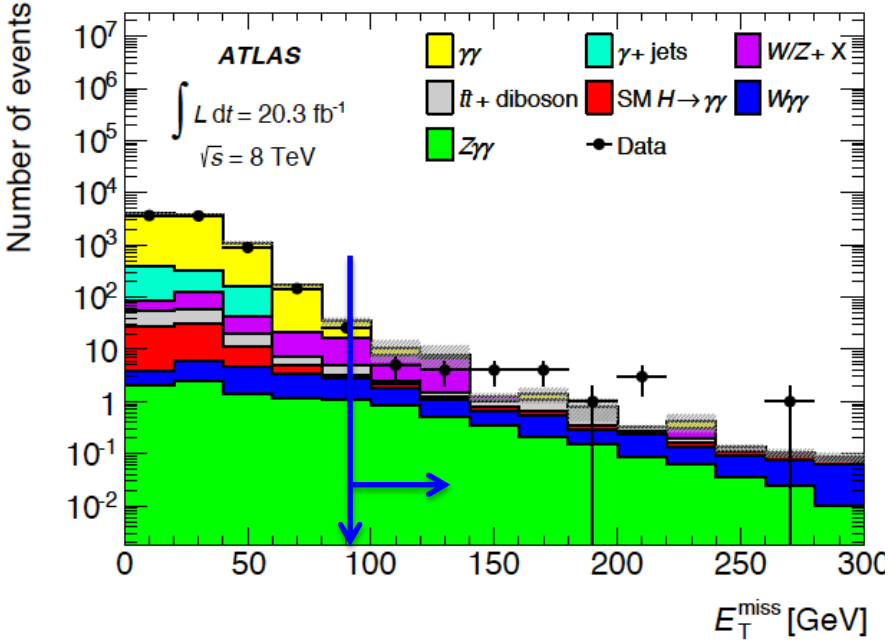
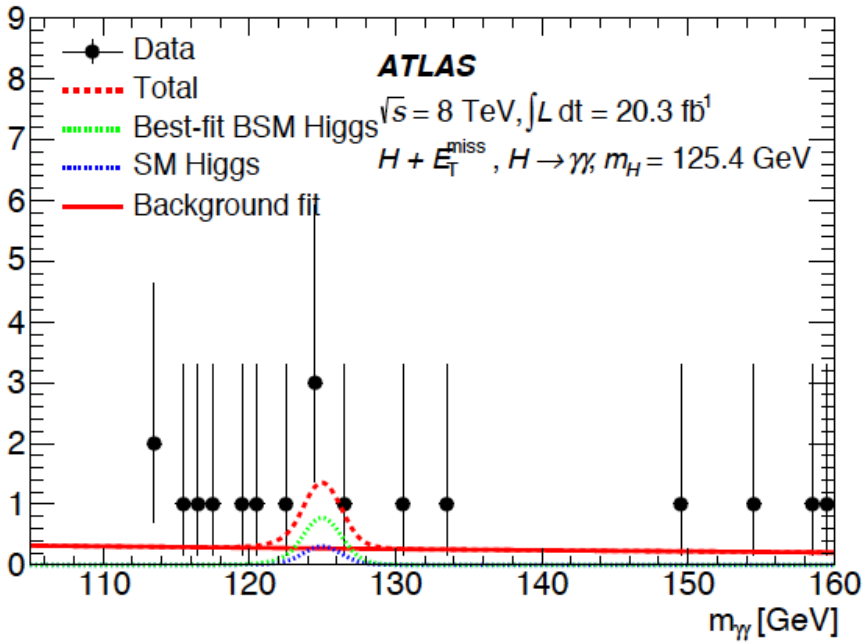


MET in $m_{\gamma\gamma}$ window, $p_T^{\gamma\gamma} > 70$ GeV



$m_{\gamma\gamma}$ after full selection

- No significant excess seen
- Parameterization of $m_{\gamma\gamma}$ spectra
  - Continuum bkg: exponential function
    - validated using simulated bkg samples and data in $m_{\gamma\gamma}$ sidebands
  - Signal and SM Higgs: double-sided Crystal Ball function

Systematic uncertainties

- Mainly on SM Higgs bkg, which is estimated from simulation

Experimental uncertainties

Source	Uncertainty (%)
Photon isolation	2.8
Photon ID	2.1
Jet energy scale, resolution, E_T^{miss} soft term	1.2
Photon energy scale	1.1
Photon energy resolution	0.2
Trigger	0.2
Luminosity	2.8

Total experimental uncertainty: ~5%

Theoretical uncertainties

- QCD scale
- PDFs
- Higgs decay branching fraction

Total theoretical uncertainty: ~6%

Model-independent exclusion limits

- Limits on fiducial cross section $\sigma * A$ of $H \rightarrow \gamma\gamma$ + E_T^{miss} events, including both SM and BSM components

  - A is fiducial acceptance, estimated at particle-level

- Limits on visible cross section $\sigma * A * \varepsilon$ extracted first: observed 95% CL upper limit is 0.39 fb

  - ε is reconstruction efficiency in fiducial region
  - estimated from signal simulation, variation is <10% across models
  - taken to be $\varepsilon = 56\%$

Model-independent exclusion limits

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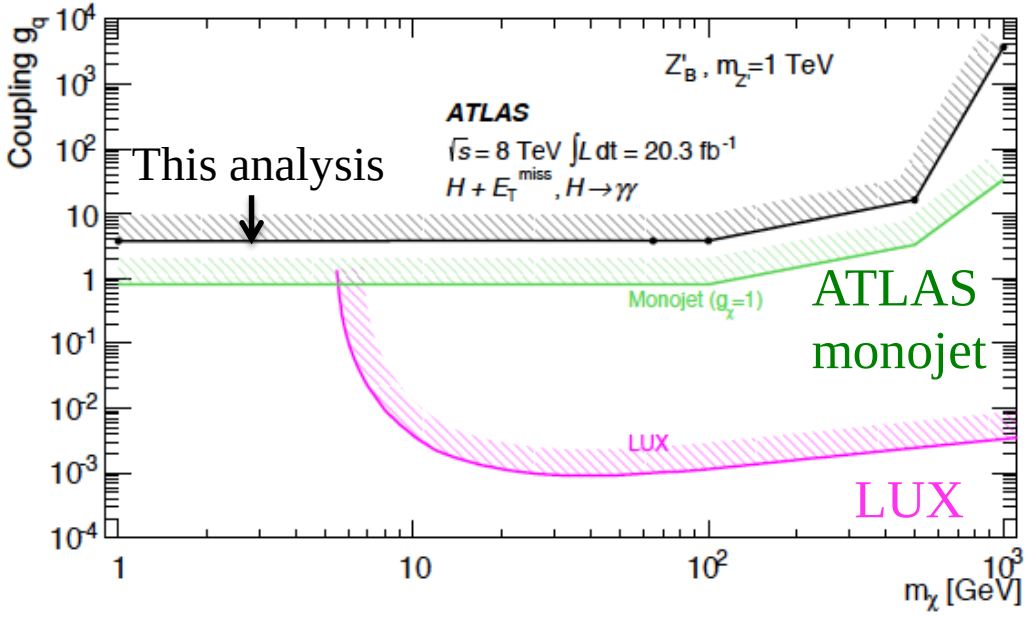
- Observed 95% CL upper limit on fiducial cross section: 0.70 fb

  - expected limit: 0.43 fb

- 1.4σ deviation from bkg-only hypothesis
- Limits applicable to any model predicting $H \rightarrow \gamma\gamma + E_T^{miss}$ events with similar reconstruction efficiency

Exclusion of model parameter space



Z' mediator:

- Limits on mediator-quark coupling as function of m_{DM}
- Region **above** curves excluded
- Significant constraint on models for m_{DM} < ~5 GeV
  - direct detection experiments have little sensitivity here

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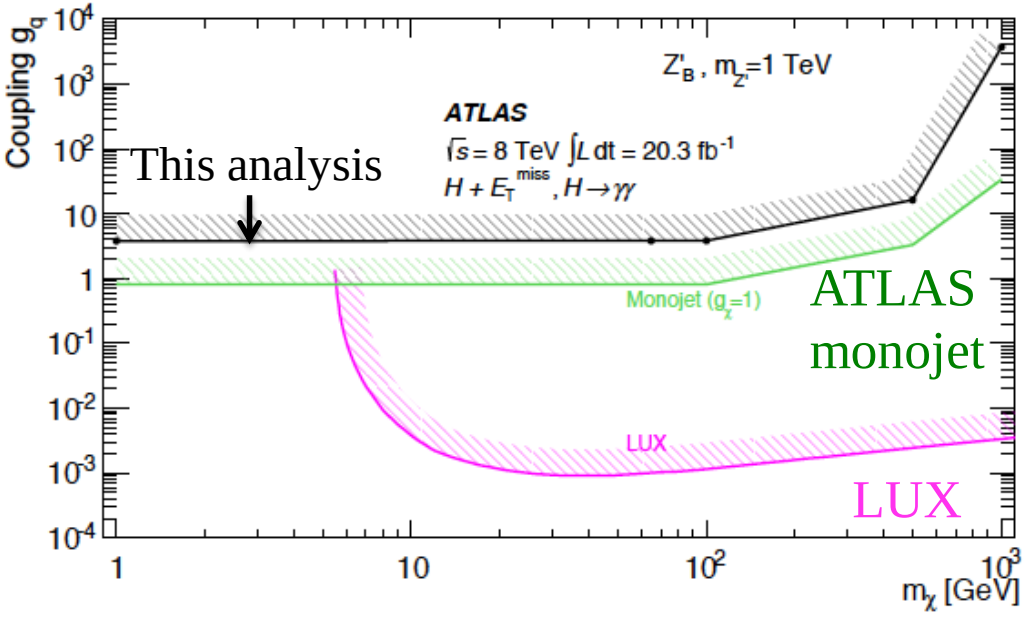

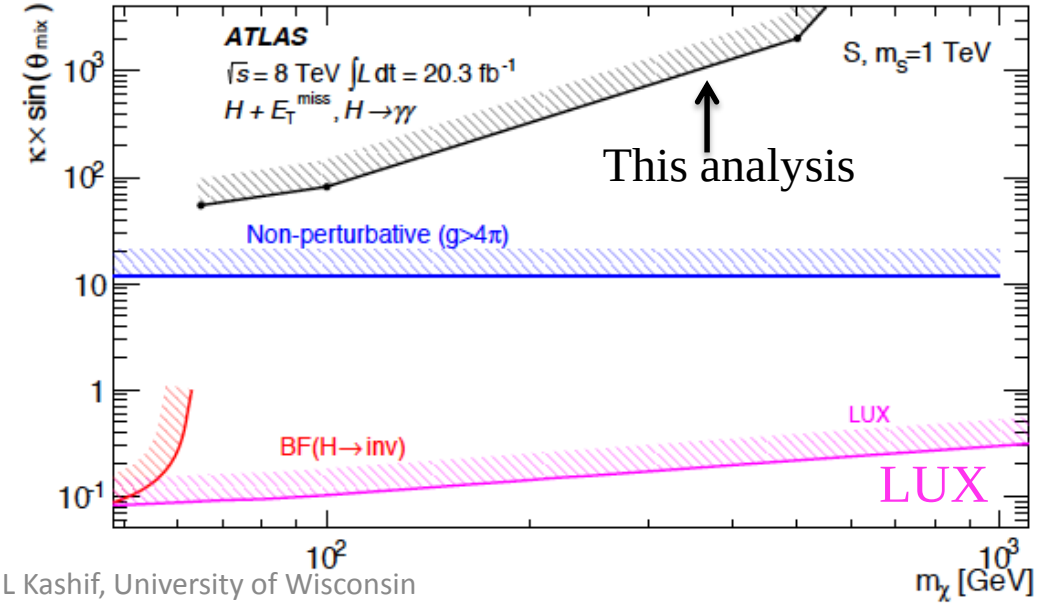

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Scalar mediator:

- Limits on mixing angle b/w heavy scalar and light Higgs, as function of m_{DM}
- Does not exclude a meaningful region of phase space with Run 1 data

$H \rightarrow \gamma\gamma + E_T^{miss}$ search: Run 2 prospects

Benchmark models

- Models for early DM searches in LHC Run 2 set out in the LHC Dark Matter Forum report:

  http://arxiv.org/pdf/1507.00966.pdf

- Trend is to move away from EFTs and focus on simplified models with light mediators

➢ Mono-Higgs searches to be interpreted in 3 simplified models:

- Vector mediator: leptophobic *Z'*
- Scalar mediator: heavy Higgs-like particle
- 2-Higgs-Doublet model containing *Z'* mediator

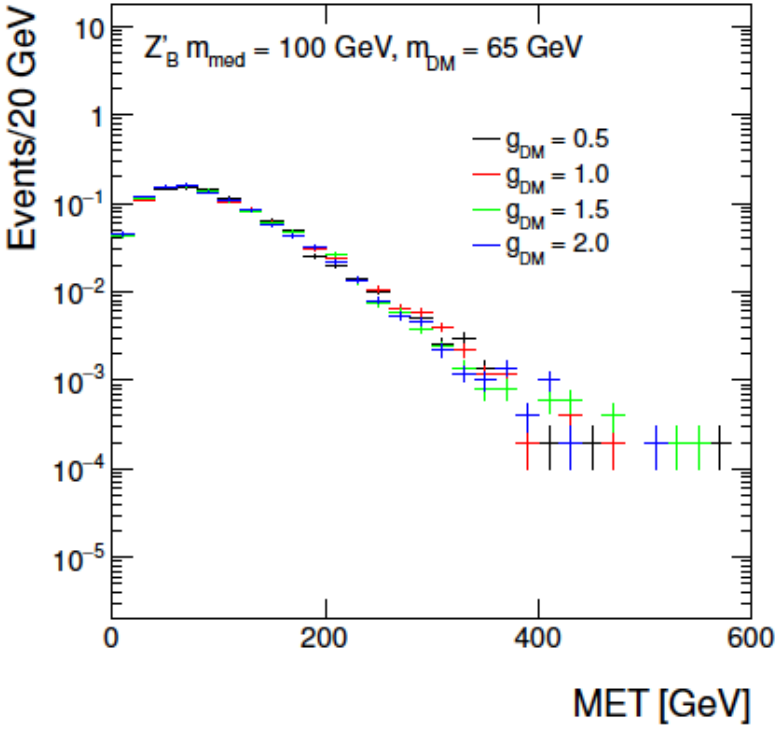
Mass scan for vector and scalar mediators

m_χ / GeV	M_{med} / GeV									
1	10	20	50	100	200	300	500	1000	2000	10000
10	10	15	50	100						10000
50	10		50	95	200	300				10000
150	10				200	295	500	1000		10000
500	10						500	995	2000	10000
1000	10							1000	1995	10000

Dependence of kinematics on model parameters

- Kinematics of mono-Higgs events insensitive to mediator couplings to either dark matter or SM sector
- For off-shell mediator, E_T^{miss} spectrum sensitive to dark matter mass

arXiv:1507.00966v1



DM-mediator coupling varied from 0.5 to 2.0 for fixed m_{DM}, m_{Med}

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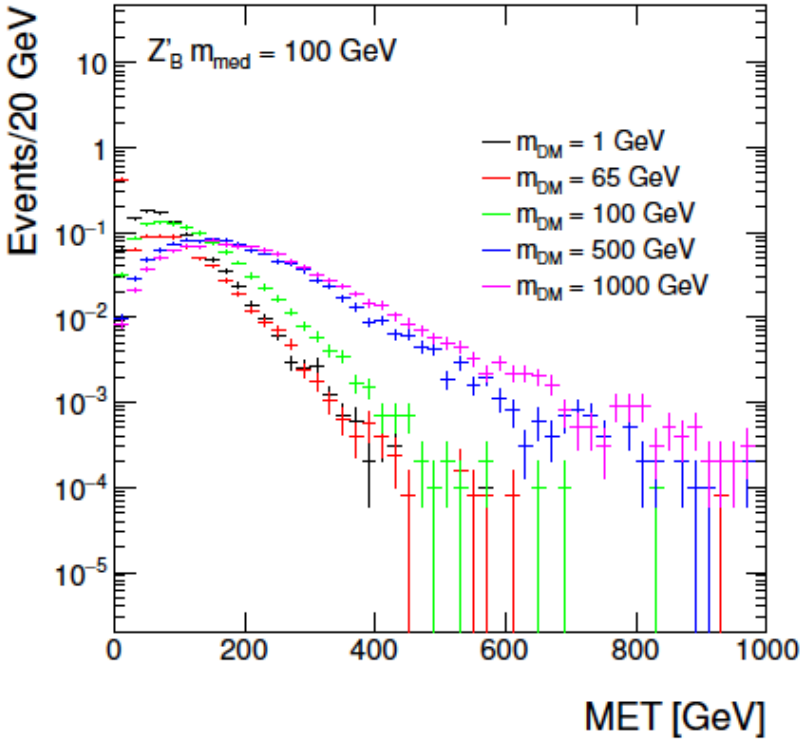

m_{DM} varied from 1 to 1000 GeV for fixed couplings, m_{Med}

Conclusion & outlook

- Mono-object final states with E_T^{miss} are powerful channels to search for new phenomena, dark matter being a prime example
- Mono-Higgs + E_T^{miss} channels probe new physics directly
- ATLAS search for dark matter in $H \rightarrow \gamma\gamma$ + E_T^{miss} using Run 1 data
- Model-independent limit on fiducial cross section: 0.70 fb at 95% CL

  - 1.4σ deviation from bkg-only hypothesis
- Limits also interpreted as exclusion of parameter spaces of dark matter production models

  - significant constraints on some models at low dark matter masses, where direct detection experiments have little sensitivity
- Vigorous program of mono-Higgs searches for LHC Run 2 underway

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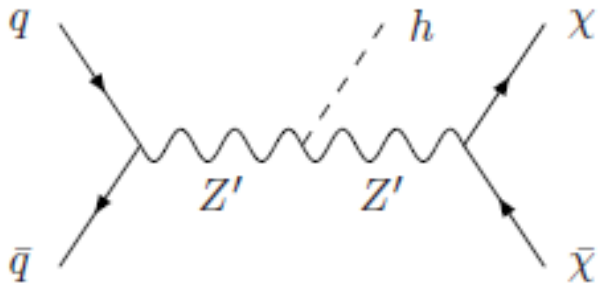
Higgs boson: major excitement of LHC Run 1 is now a promising tool to look for new physics!

Backup

Vector mediator model

- Production via *qq* annihilation
- Gauge extension of SM, baryon number transforms under a $U(1)_B$ symmetry
  - *Z'* is associated gauge boson

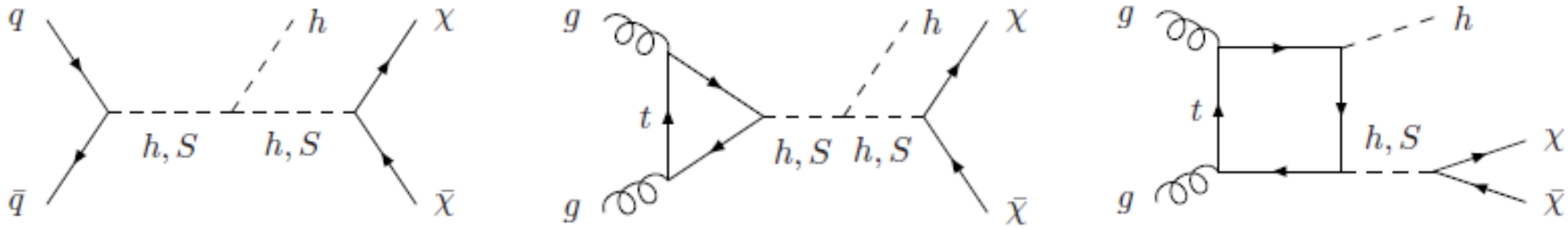


- $U(1)_B$ symmetry broken by a new baryonic Higgs, which couples to *Z'* and also mixes with SM Higgs with mixing angle θ
- Dark matter candidate is a stable baryonic state
- Leptophobic model, thus avoiding precision EW constraints

Model parameters:

m_{DM}, m_{med}
$\sin\theta$
mediator coupling to DM: g_χ
mediator coupling to fermions: g_f
h-Z'-Z' coupling: $g_{hZ'Z'}$

Scalar mediator model



- Production via *qq* annihilation or gluon fusion
- Scalar *S* mixes with SM Higgs with mixing angle θ, constrained by Run 1 Higgs measurements
- Yukawa-like coupling of *S* to both SM fields and DM

Model parameters:

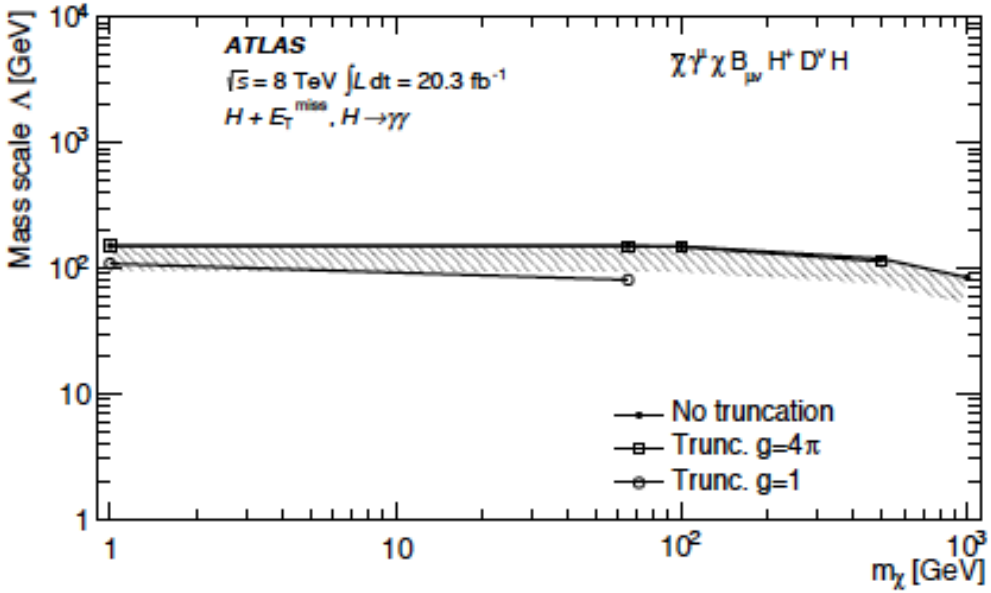
m_{DM}, m_{med}

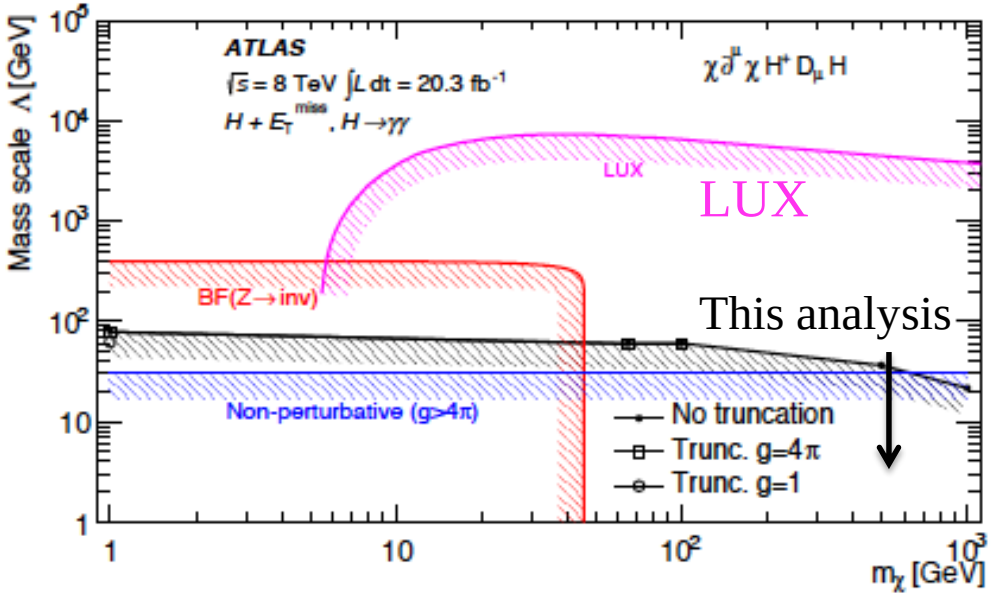
$\sin\theta$

mediator coupling to DM: y_χ

h-*S*-*S* coupling: g_b

Exclusion of EFT parameter space





- Limits on effective mass scale Λ of mediator, as function of m_{DM}

EFT validity and truncation:

- EFTs valid when momentum transfer Q_{tr} in event << mass scale of propagator
- This is not always the case at LHC energies
- Events with $Q_{tr}^2 >\sim g_1 g_2 \Lambda^2$ are in invalid region
  - g_1, g_2 propagator couplings to DM, SM
- Assuming $Q_{tr} = m_{\chi\chi}$, validity condition is

$$m_{\chi\chi}^2 < g_1 g_2 \Lambda^2$$

- Leave out simulated events that fail this condition