# LATEST RESULTS FROM THE MONO-X CHANNELS

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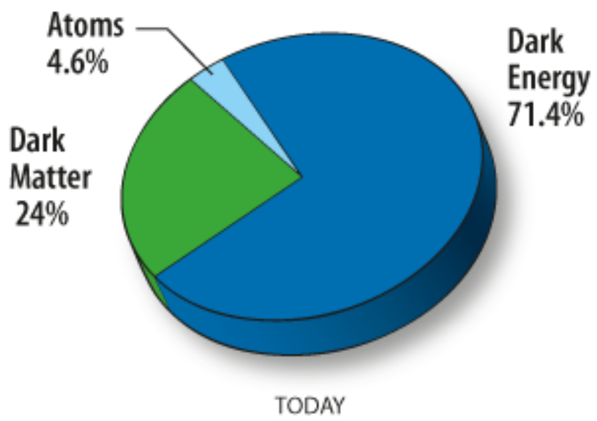
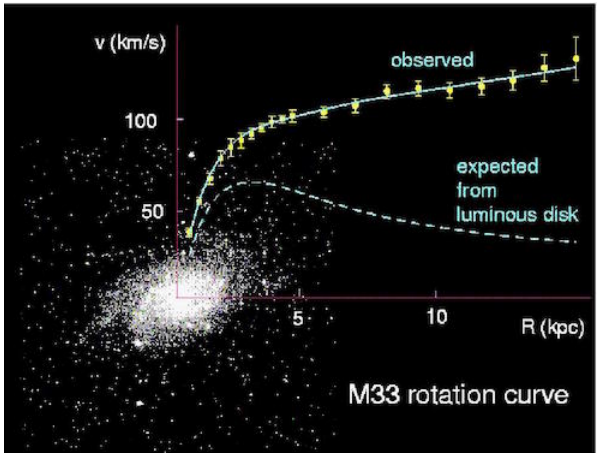
DM@LHC 2016 in Amsterdam

# Dark Matter Searches at LHC

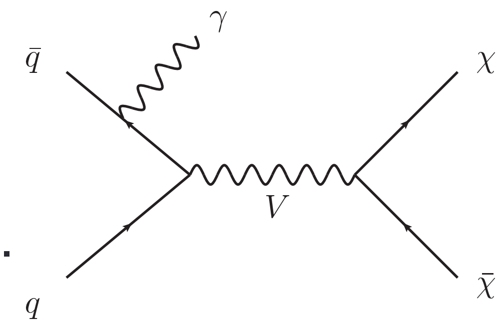
- Dark Matter (DM) exists ← cosmological observations.
- Particle nature of DM is completely unknown.
- LHC may be able to produce DM particles, but detectors (ATLAS or CMS) cannot detect them (MET).
- We need a SM particle recoil against DM to trigger the events → mono-X (+ MET) searches.



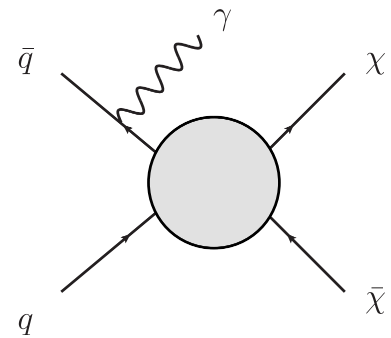



# Mono-X models

- Full theory to predict dark matter particles: SUSY, Extra Dimensions, etc:
  - George Redlinger's talk on SUSY searches.
- Simplified Models:
  - One DM and one mediator particles in addition to SM.
  - Five parameters:
    - DM mass, mediator mass, mediator width, mediator SM coupling, mediator DM coupling.



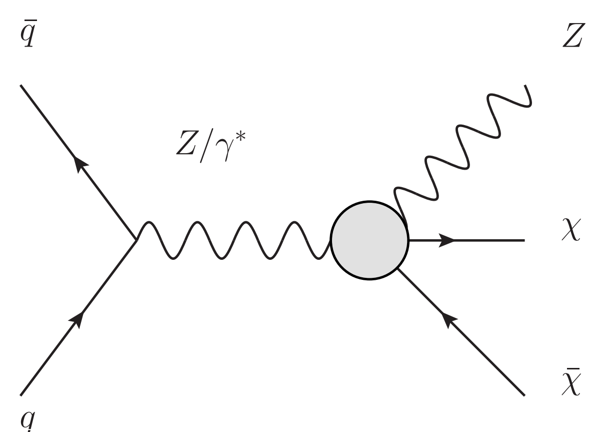

- Effective Field Theory (EFT) models.
  - The mediator is integrated out.
  - Two parameters (less model dependent):
    - DM mass, effective energy scale.
  - Variety of operators: D5 (vector), D6 (axialvector) etc.
  - Valid only where "momentum transfer $Q$ < mediator mass".
    - This can be a problem in Run2 (higher energy, 13 TeV).



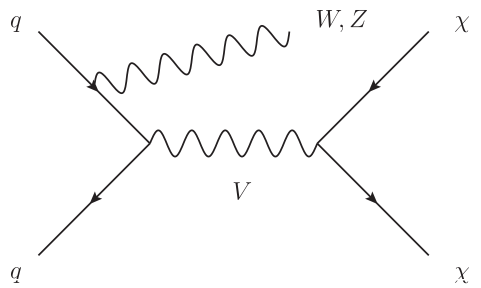
# Mono-X channels

- X = Vector Boson or Higgs are covered.
  - Highlights are on 13 TeV analysis (all ATLAS at this moment)
- Mono-photon
  - Low background.
- Mono-Z or mono-W
  - Z can be emitted from mediator in t-channel.
  - Hadronic decay mode → larger cross section
  - Leptonic decay mode → cleaner signature.
- Mono-H
  - No ISR (Initial State Radiation) Higgs.
  - H can be emitted from mediator in s-channel.
  - H -> bb decay mode → larger cross section.
  - H -> γγ decay mode → clean signature.
- VVxx (HHxx) contact interaction is unique.
- Other mono-X:
  - Mono-jet: Andreas Korn's talk.
  - Mono-heavy quark(s): Alberto Zucchetta's talk.

| | | |
|---|---|---|
| Mono-photon | 8 TeV | ATLAS: arXiv:1411.1559[hep-ex]<br>CMS: arXiv:1410.8812 |
| | 13 TeV | ATLAS: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2015-05/ |
| Mono-Z/W (hadr) | 8TeV | ATLAS: arXiv:1309.4017[hep-ex]<br>CMS: CMS PAS EXO-12-055 |
| | 13 TeV | ATLAS: ATLAS-CONF-2015-080 |
| Mono-Z(ll) | 8 TeV | ATLAS: arXiv: 1404.0051[hep-ex]<br>CMS: arXiv: 1511.09375 |
| Mono-W(lv) | 8 TeV | ATLAS: arXiv:1407.7495[hep-ex]<br>CMS: arXiv:1408.2745[hep-ex] |
| Mono-H(bb) | 8 TeV | ATLAS: arXiv:1510.0621[hep-ex] |
| | 13 TeV | ATLAS: ATLAS-CONF-2016-019 |
| Mono-H(gamgam) | 8 TeV | ATLAS: arXiv:1506.01081[hep-ex] |
| | 13 TeV | ATLAS: ATLAS-CONF-2016-011 |



# Simplified model parameters in Run2

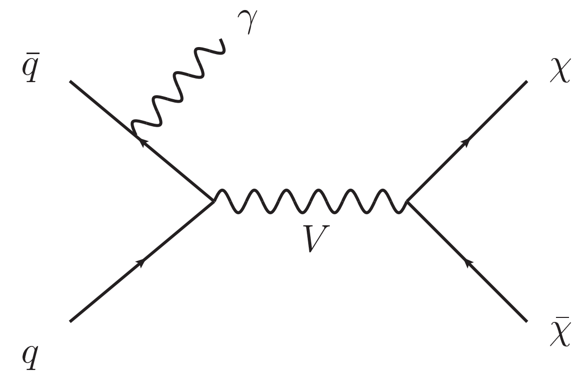



- Based on the Dark Matter Forum recommendation (arXiv:1507.00966 [hep-ex]).
- Dark matter: Dirac particles.
- Mediator: Vector, Axialvector, Scalar or Pseudoscalar particles.
- Mediator width: minimal width = sum of contributions from DM and quarks lighter than a half of the mediator mass.
- S-channel coupling constants:
  - Coupling to DM: $g_{DM} = 1.0$
  - Coupling to SM: universal to all quarks.
    - Vector and Axialvector: $g_{SM} = 0.25$ (larger values are constrained by dijet searches, also to keep the mediator width narrow).
    - Scalar and Pseudoscalar: $g_{SM} = 1.0$
- T-channel couplings: $g_{DM} = g_{SM} = 0.1 - 7$

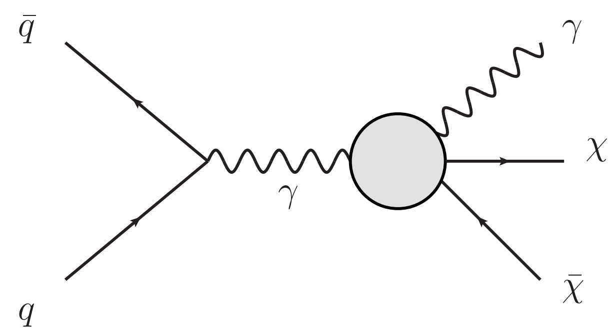
13 TeV

# Mono-photon Signal simulation

- Simplified model
  - Axial vector mediator
    - Higher cross section than scalar.
    - Corresponds to spin-dependent interaction
    → Direct detection has lower sensitivity.




- γγXX contact interaction
  - EW coupling: $k_1 = k_2 = 1.0$
  - Suppression scale: $\Lambda = 3.0$ TeV



13 TeV

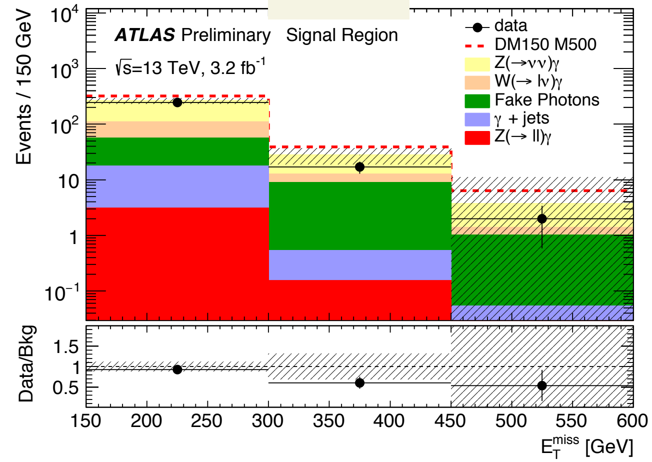
# Mono-Photon Results

- ATLAS: 13 TeV, 3.2 fb$^{-1}$

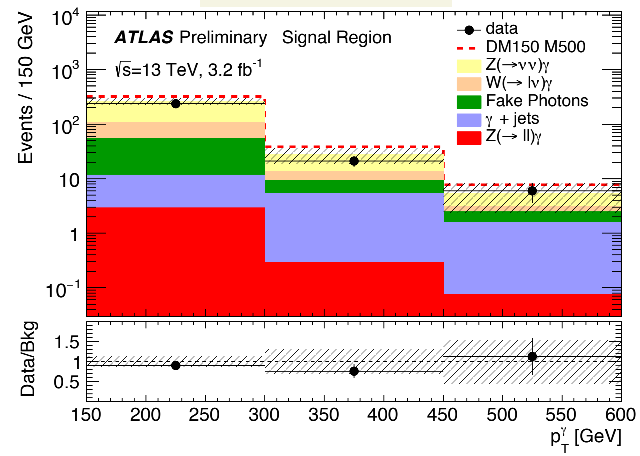
| | SR | 1muCR | 2muCR | 2eleCR | PhJetCR |
|---|---|---|---|---|---|
| Observed events | 264 | 145 | 29 | 20 | 214 |
| Fitted background | 295 ± 34 | 145 ± 12 | 27 ± 4 | 23 ± 3 | 214 ± 15 |
| $Z(\to \nu\nu) + \gamma$ | 171 ± 29 | 0.15 ± 0.03 | 0.00 ± 0.00 | 0.00 ± 0.00 | 8.6 ± 1.4 |
| $W(\to \ell\nu) + \gamma$ | 58 ± 9 | 119 ± 17 | 0.14 ± 0.04 | 0.11 ± 0.03 | 22 ± 4 |
| $Z(\to \ell\ell) + \gamma$ | 3.3 ± 0.6 | 7.9 ± 1.3 | 26 ± 4 | 20 ± 3 | 1.2 ± 0.2 |
| $\gamma$ + jets | 15 ± 4 | 0.7 ± 0.5 | 0.00 ± 0.00 | 0.03 ± 0.03 | 166 ± 17 |
| Fake photons from electrons | 22 ± 18 | 1.7 ± 1.5 | 0.05 ± 0.05 | 0.00 ± 0.00 | 5.8 ± 5.1 |
| Fake photons from jets | 26 ± 12 | 16 ± 11 | 1.1 ± 0.8 | 2.5 ± 1.3 | 9.9 ± 3.1 |
| Pre-fit background | 249 ± 29 | 105 ± 14 | 23 ± 2 | 19 ± 2 | 209 ± 50 |

- Statistical error 9%
- Systematic error 11%
  - Main systematic error: Electron and Jet fake rate.
- Dominant background:
  - Z(νν)+γ, W(lν)+γ
  - Fake electrons and jets
  - Estimated from CR (control regions)

MET



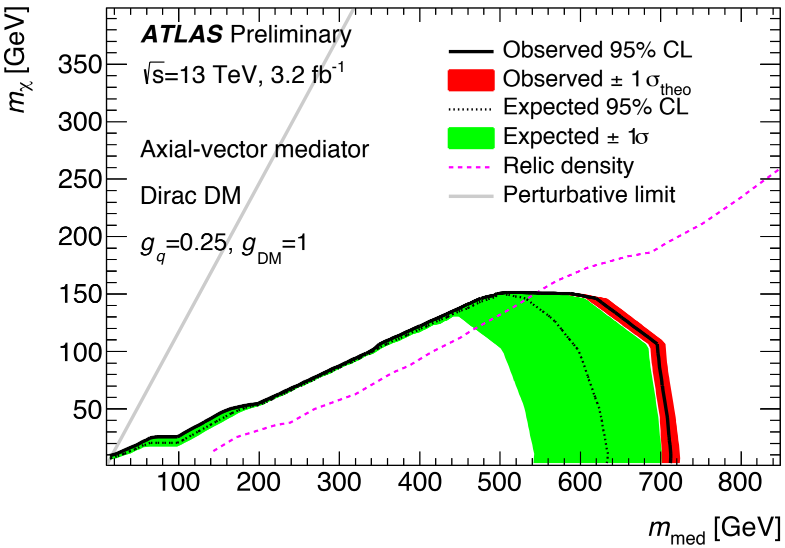

Photon $p_T$



# Mono-Photon Limits

- Simplified model

13 TeV

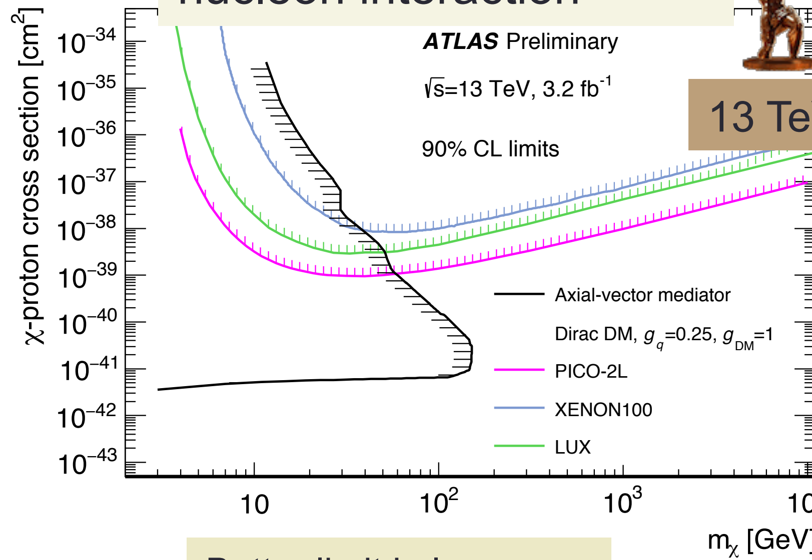



$M_{med}$ up to 710 GeV
and
$M_{\chi}$ up to 150 GeV
are excluded

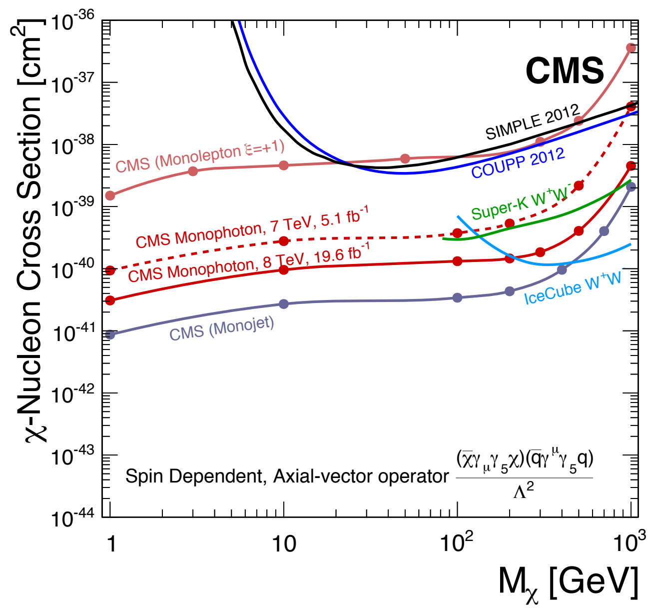
Truncated = non-valid region is removed

Spin dependent DM-nucleon interaction

13 TeV



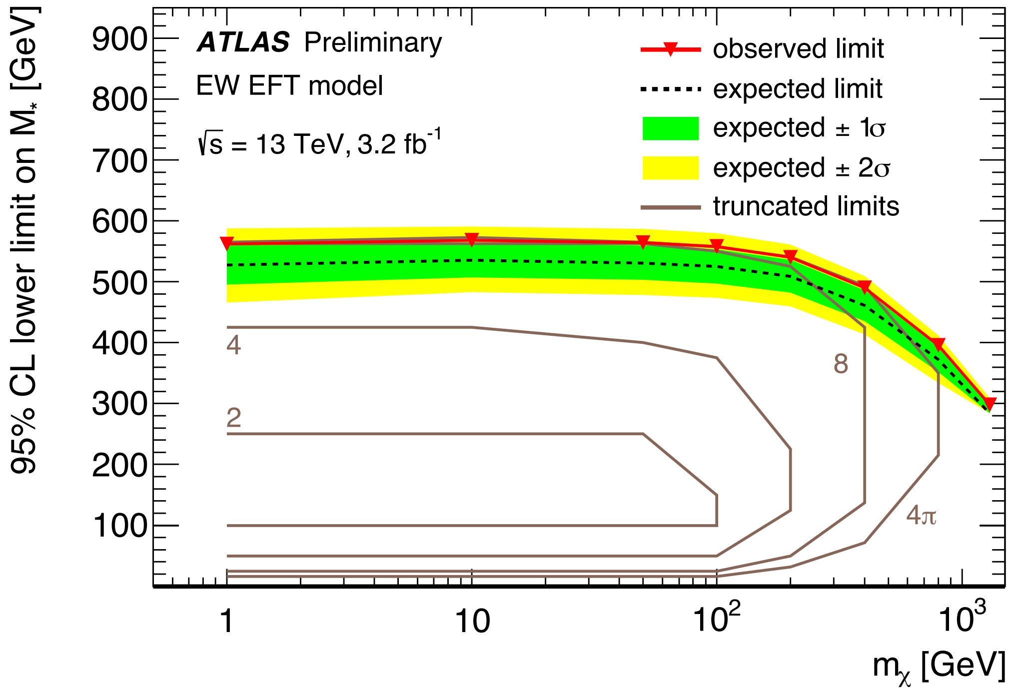

Better limit in low mass




8 TeV
19.6 $fb^{-1}$
EFT model

# Mono-Photon Limits

- γγXX contact interaction (EFT)




13 TeV

M* up to 570 GeV is excluded

Truncated = EFT non-valid region is removed

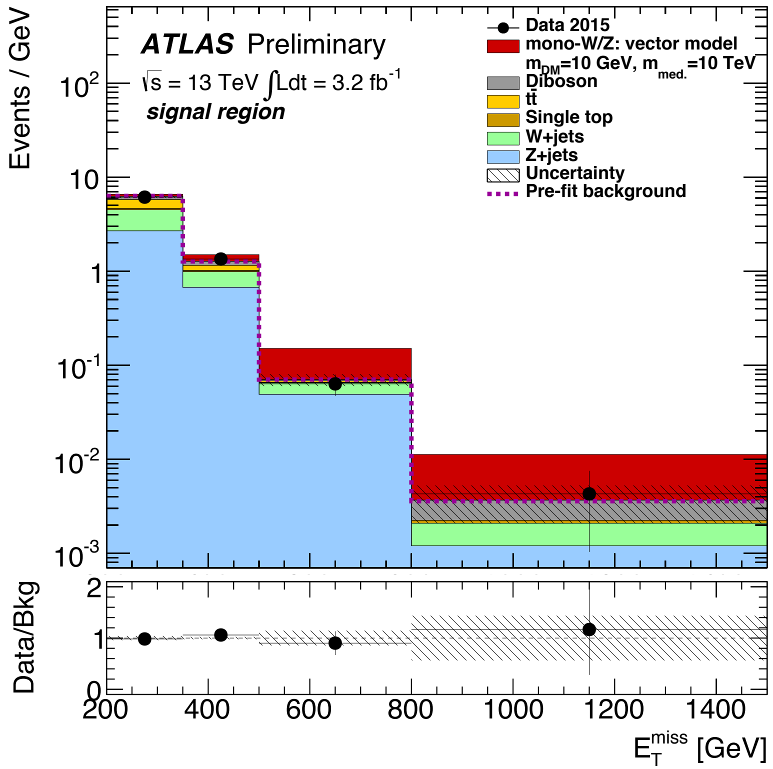
13 TeV

# Mono-W/Z (hadronic) Results

- ATLAS: 13 TeV, 3.2 fb$^{-1}$

| Process | events |
|---|---|
| $Z$+jets | $519 \pm 31$ |
| $W$+jets | $326 \pm 22$ |
| $t\bar{t}$ and single-top | $217 \pm 18$ |
| Diboson | $88 \pm 12$ |
| Total Background | $1150 \pm 30$ |
| Data | 1143 |

- Main systematic error:
  - Modeling of large-R jets 5 – 10%
- Main background:
  - Z+jets, W+jets, ttbar
  - One muon and two muon control region was used.

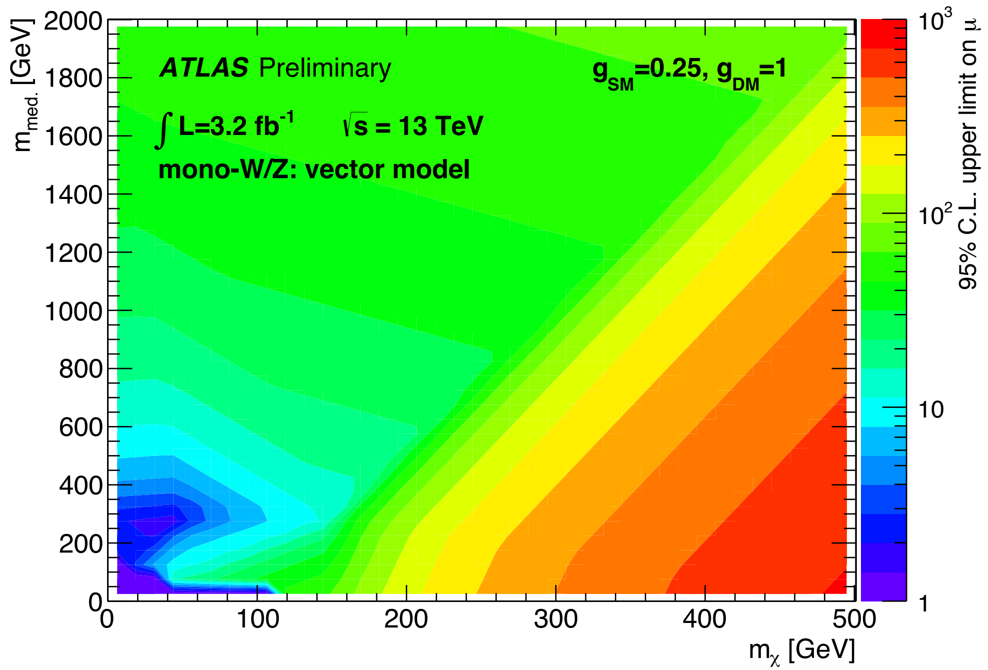


# Mono-W/Z (hadronic) Limits

- Simplified model (vector mediator):

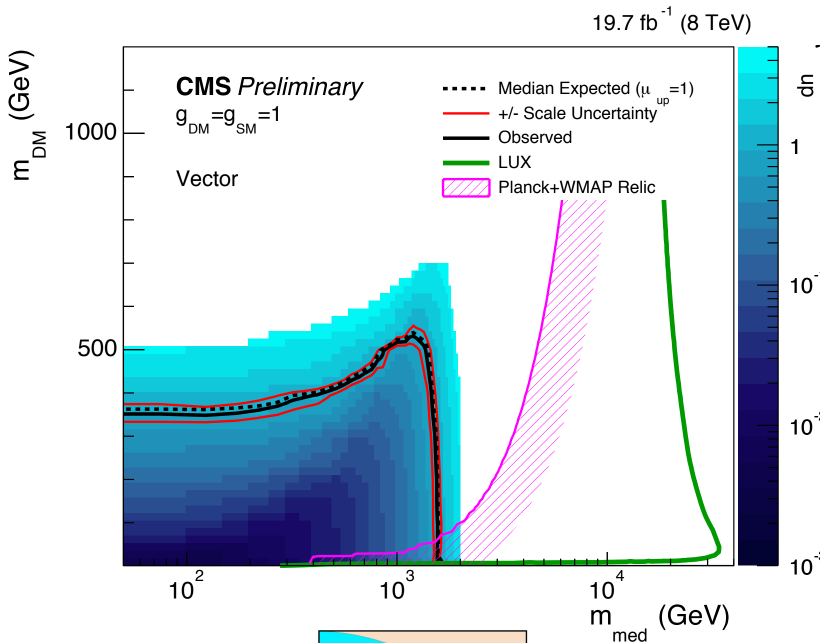
Signal strength limits

13 TeV




Exclusion contour

8TeV
19.7fb-1

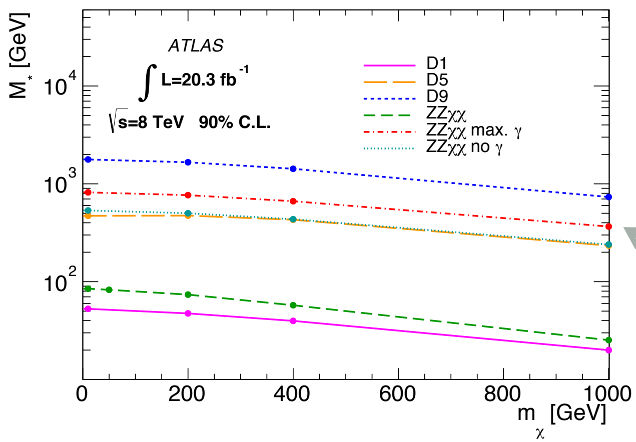


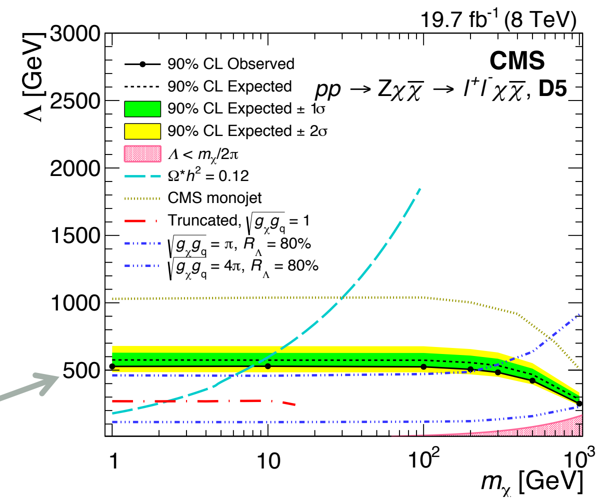

CMS limits are stronger?

8 TeV, ~20 $fb^{-1}$

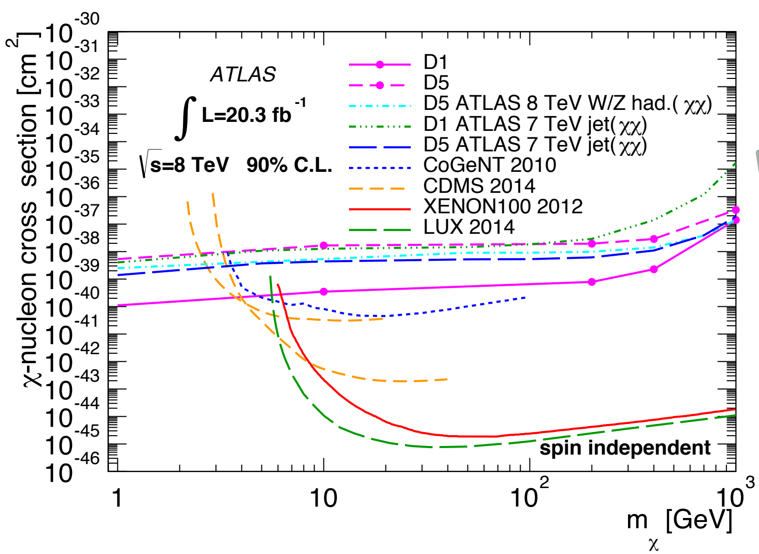
# Mono-Z(ll) Limits

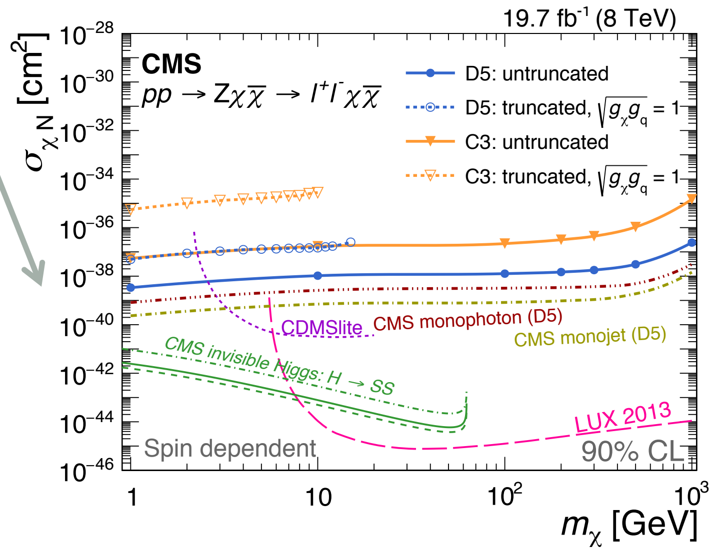
- 8 TeV, ~20 $fb^{-1}$; Limits on EFT:




D5
(Vector-like)

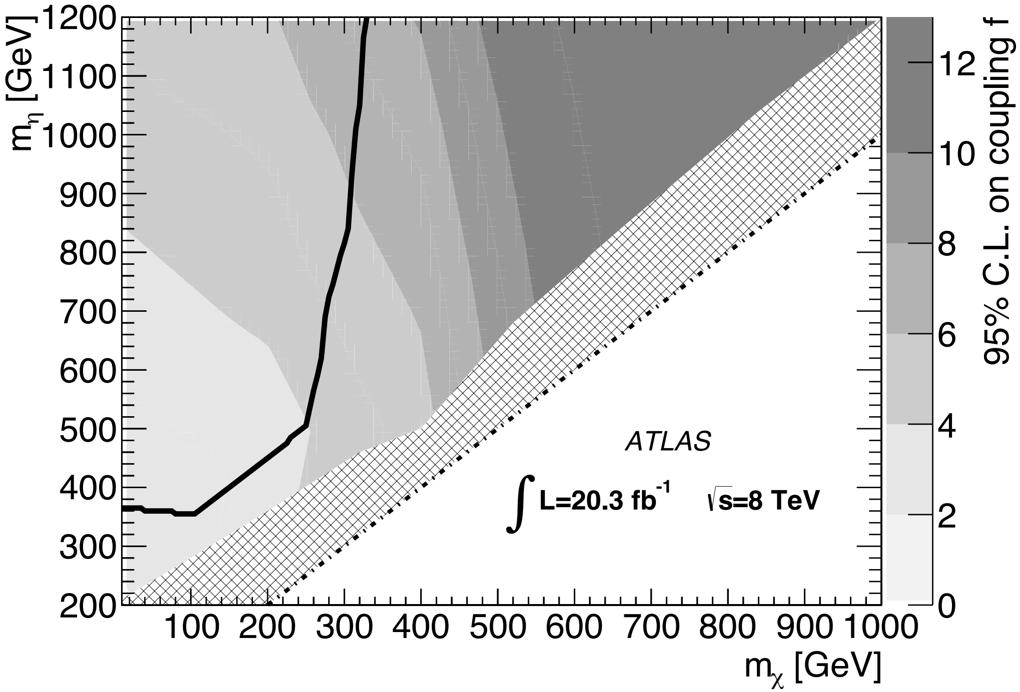


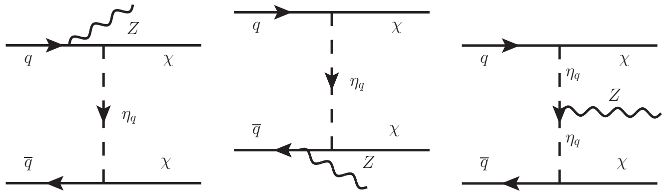
8 TeV

# Mono-Z(ll) Limits

- Simplified model



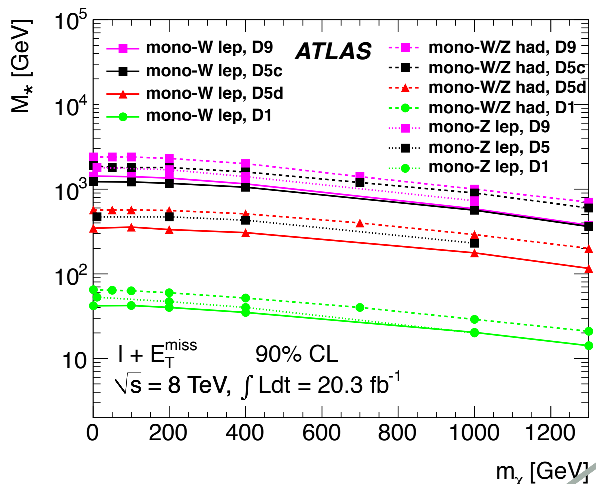

- Scalar mediator η
- Scalar DM χ
- $g_{DM} = g_{SM} = f$
- The t-channel are included

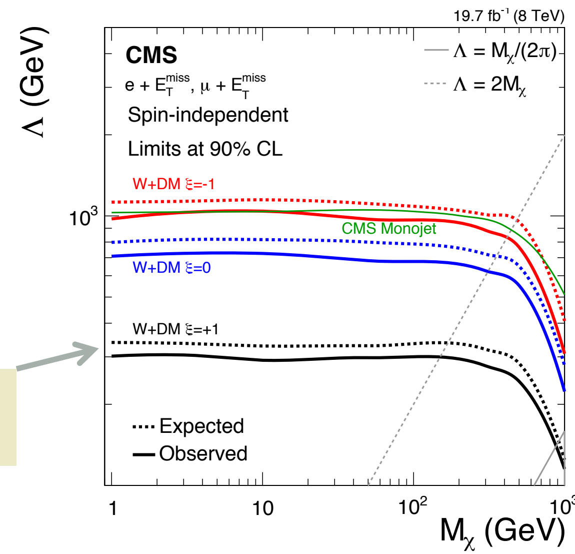


8 TeV

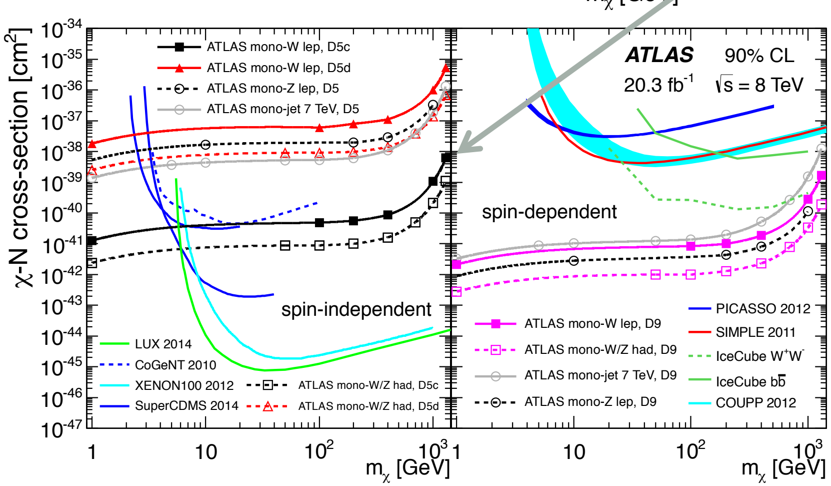
# Mono-W(lv) Limits

- 8 TeV, ~20fb-1; Limits on EFT:



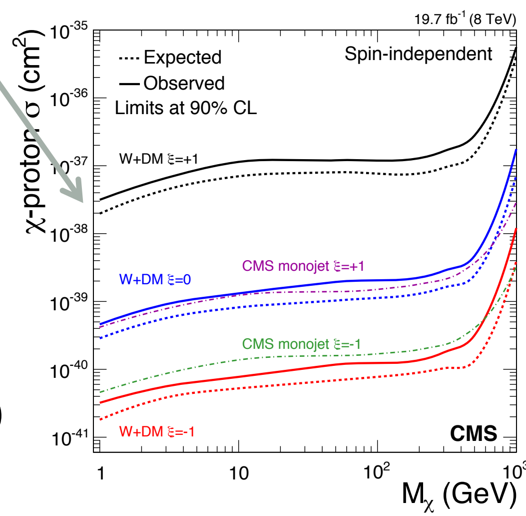




Vector-like D5d (destructive)

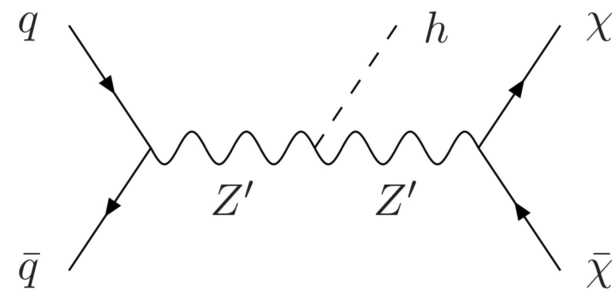



D5c (constructive): SU(2) gauge invariance violation.

$$\frac{1}{\Lambda^2}\,(\overline{\chi}\gamma^{\mu}\chi)\,(\overline{u}\gamma_{\mu}u + \xi\overline{d}\gamma_{\mu}d)$$

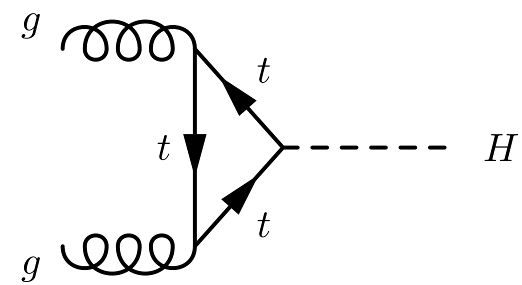


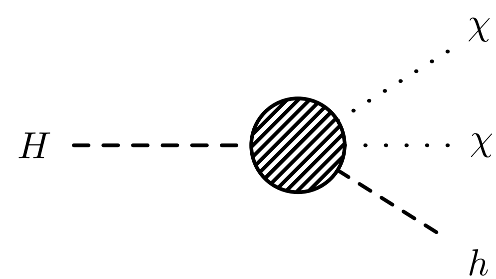
# Mono-H Signal simulation (1)



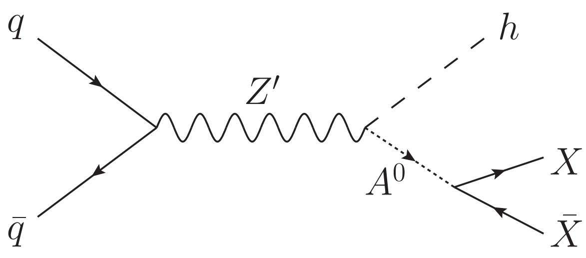

- Simplified model
  - Vector mediator Z’, with mass $m_{Z'}$
  - $g_{DM}$ = 1.0, $g_q$ = 1/3
  - Z’-Higgs coupling: $g_{Z'} = m_{Z'}$
  - Baryonic Higgs – SM Higgs mixing: sinθ=0.3
- Heavy scalar model
  - Heavy scalar H, with mass $m_H$
  - Lagrangian:

$$\mathcal{L}_H = -\frac{1}{4}\,\beta_g\,\kappa_{hgg}^{\mathrm{SM}}\;G_{\mu\nu}G^{\mu\nu}H + \beta_V\,\kappa_{hVV}^{\mathrm{SM}}\;V_\mu V^\mu H$$



# Mono-H Signal simulation (2)




- Two Higgs Doublet Model (2HDM)
  - Vector mediator Z', with mass $m_{Z'}$
  - Pseudo-scalar Higgs boson A, with mass $m_A$
  - DM mass fixed: $m_{DM}$ = 100 GeV
  - The ratio of the v.e.v. of two doublets: tanβ=1
  - SM Higgs – heavy scalar Higgs mixing angle α=β-π/2

(SM Higgs h, heavy scalar H, pseudo-scalar A, charged scalars $H^+$ and $H^-$ are the 5 Higgs bosons after symmetry breaking.)

13 TeV

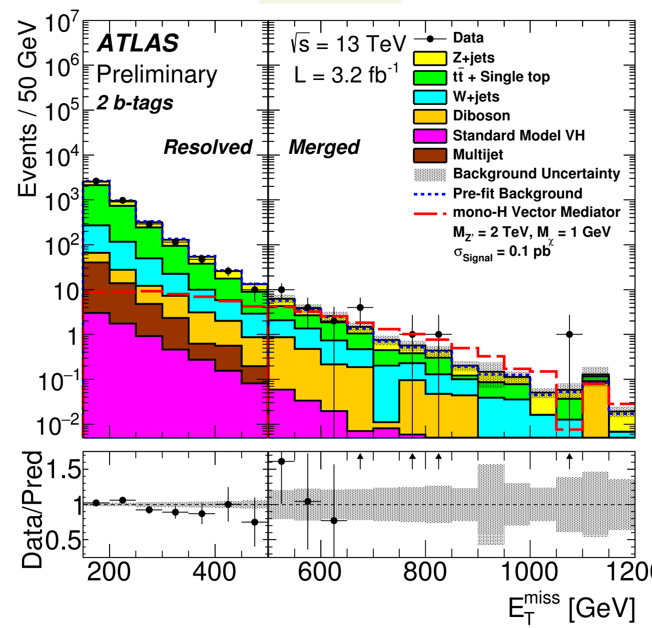
# Mono-H(bb) Results

NEW

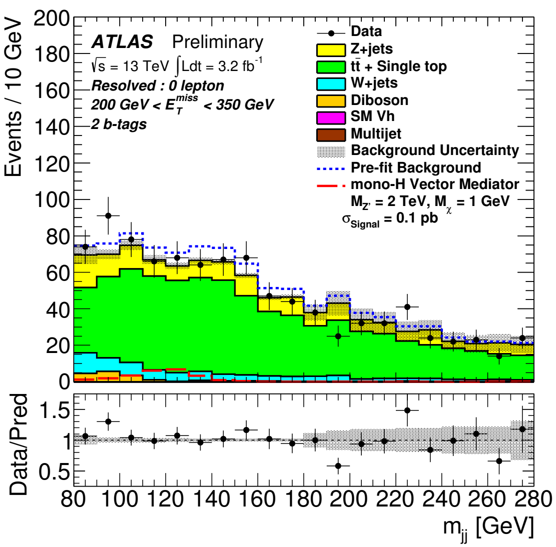
- ATLAS 13 TeV, 3.2 $fb^{-1}$; 4 signal regions:

| $E_T^{miss}$ (GeV) | Resolved | | | Merged |
|---|---|---|---|---|
| | 150–200 | 200–350 | 350–500 | >500 |
| $Z + jets$ | 258.52 ± 26.81 | 171.24 ± 13.13 | 14.63 ± 1.21 | 3.80 ± 0.44 |
| $W + jets$ | 94.78 ± 27.79 | 70.14 ± 21.67 | 7.51 ± 2.42 | 2.48 ± 0.71 |
| $t\bar{t}$ & Single top | 1444.38 ± 44.39 | 656.02 ± 24.51 | 30.76 ± 1.41 | 4.83 ± 0.88 |
| Multijet | 21.38 ± 9.96 | 10.89 ± 5.08 | 0.58 ± 0.27 | – |
| Diboson | 17.84 ± 1.62 | 18.73 ± 0.98 | 2.53 ± 0.22 | 1.20 ± 0.12 |
| $SMVh$ | 2.77 ± 1.30 | 2.78 ± 1.40 | 0.46 ± 0.23 | 0.15 ± 0.08 |
| Tot. Bkg. | 1839.68 ± 33.12 | 929.80 ± 19.63 | 56.47 ± 2.08 | 12.47 ± 1.27 |
| Data | 1830 | 942 | 56 | 20 |
| Exp. Signal | 80.15 ± 7.95 | 244.53 ± 17.76 | 160.58 ± 11.56 | 149.28 ± 33.67 |

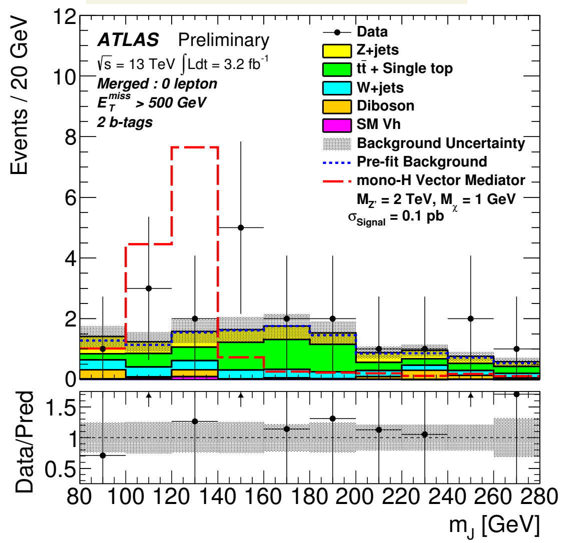
MET




Resolved, 2 b-tag




Merged, 2 b-tag




- Stat error 20.5%
- Systematic error 10.3%
- Main background:
  - Z+jets, W+jets, ttbar
  - Estimated from 1and 2 lepton CR

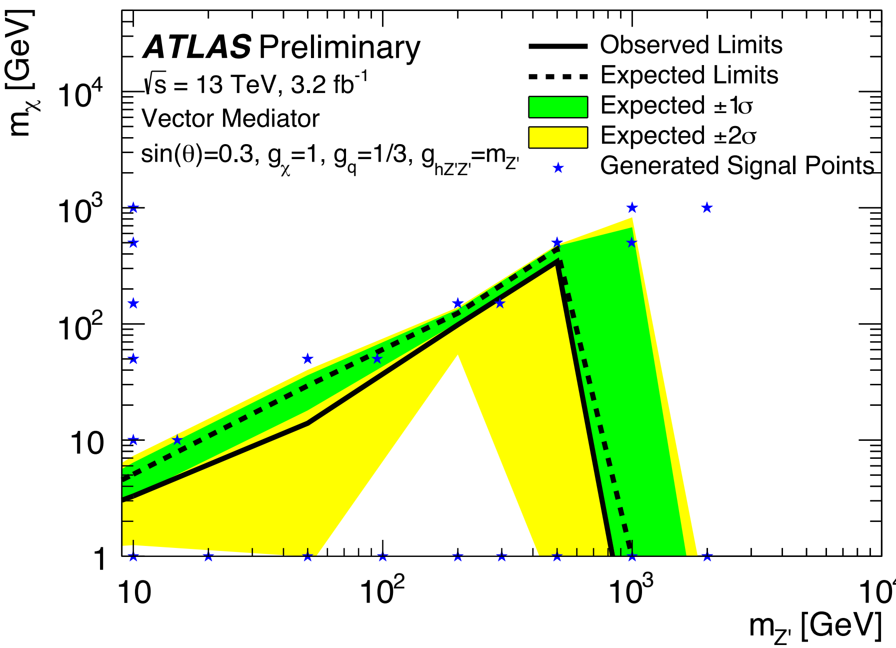
13 TeV

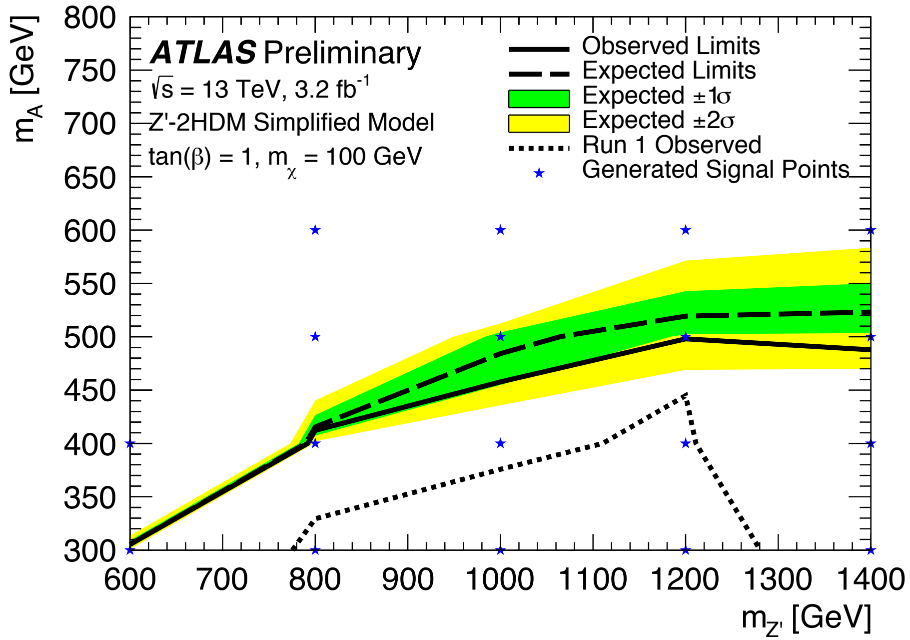
# Mono-H(bb) Limits

NEW

- Simplified model

2HDM



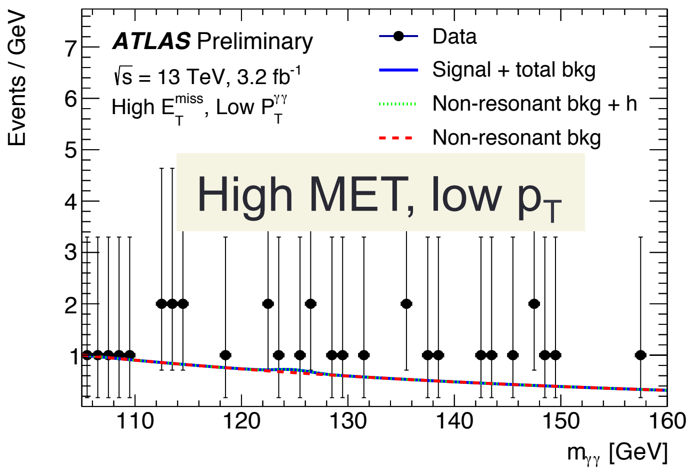

$m_{Z'} < 900$ GeV is excluded.

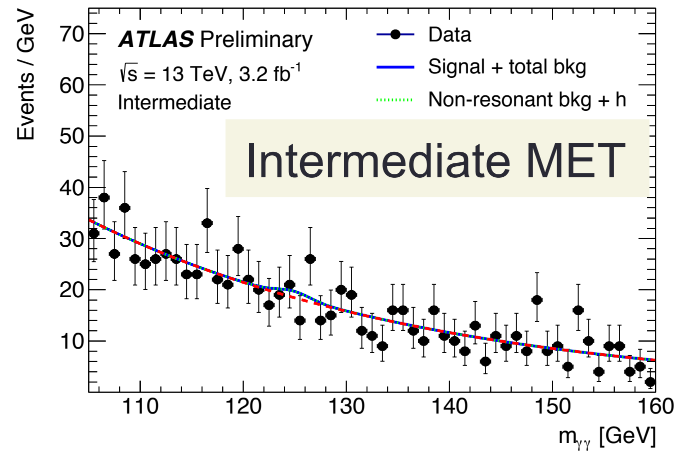
$m_A < 500$ GeV is excluded.

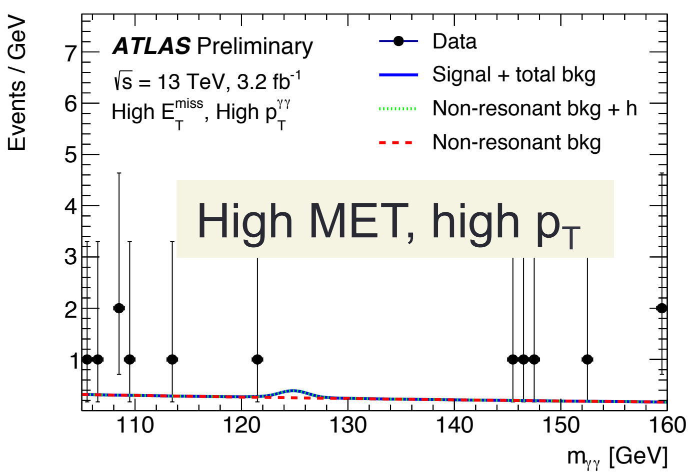
13 TeV

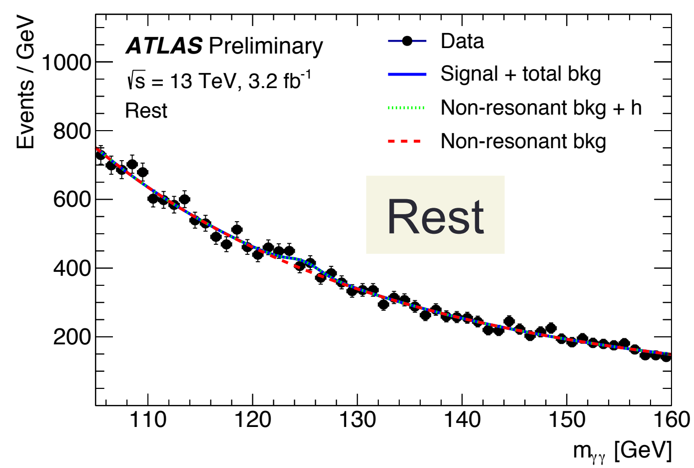
# Mono-H(γγ) Results

- ATLAS 13 TeV, 3.2 $fb^{-1}$ ; 4 signal regions



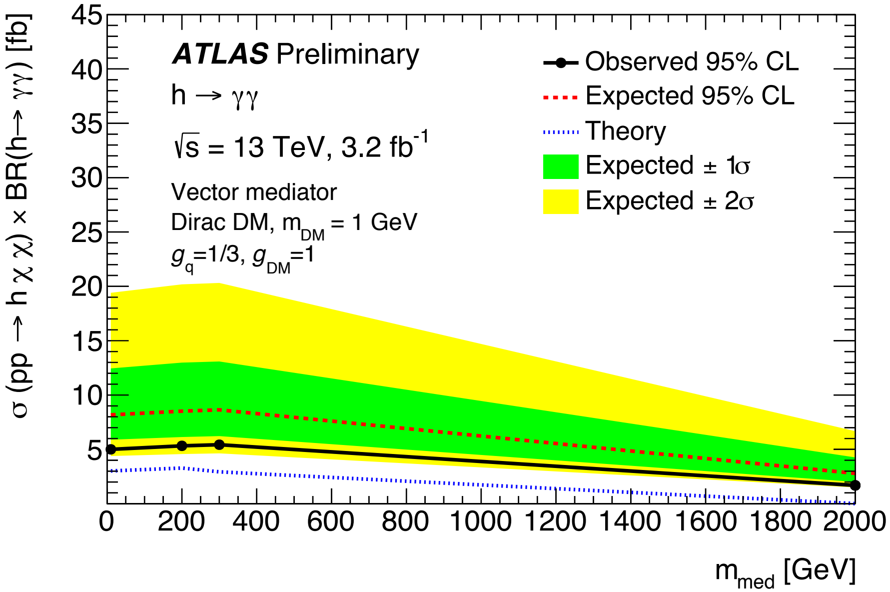




- Signal and background are parameterized.
- Statistical error dominant.

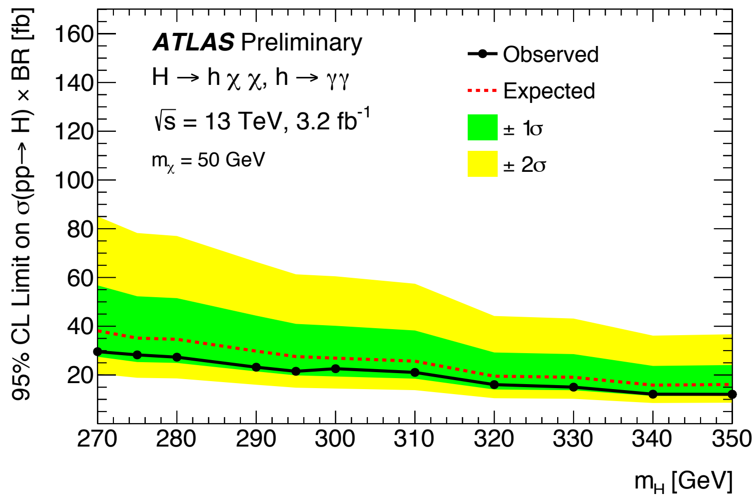
13 TeV

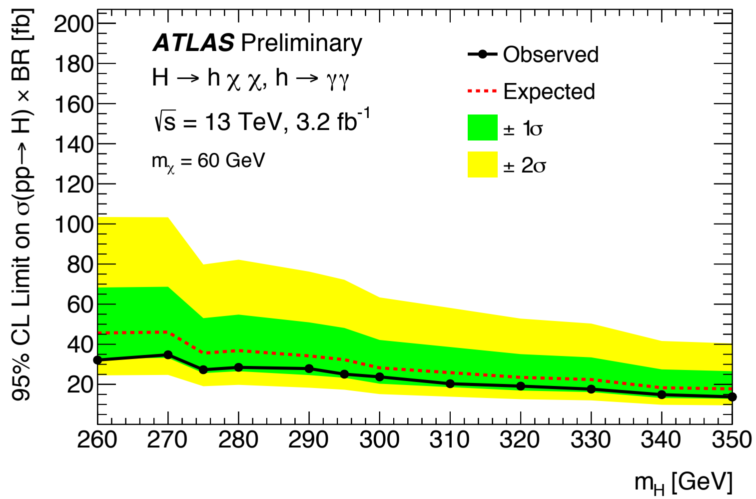
# Mono-H(γγ) Limits

- Simplified model:




Heavy scalar model:



# Conclusions

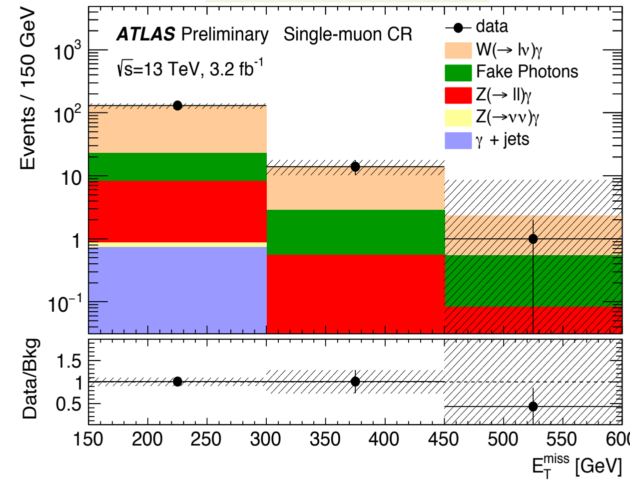
- Mono-γ/Z/W/H dark matter searches were presented for ATLAS and CMS.
- These are
  - Clean channels.
  - No-ISR processes are possible.
- Simplified models are the main focus in Run2 (13 TeV).
- Mediator mass exclusion
  - Mono-photon: 710 GeV
  - Mono-H(bb): 900 GeV
- Better exclusion at low mass than direct detection experiments.

13 TeV

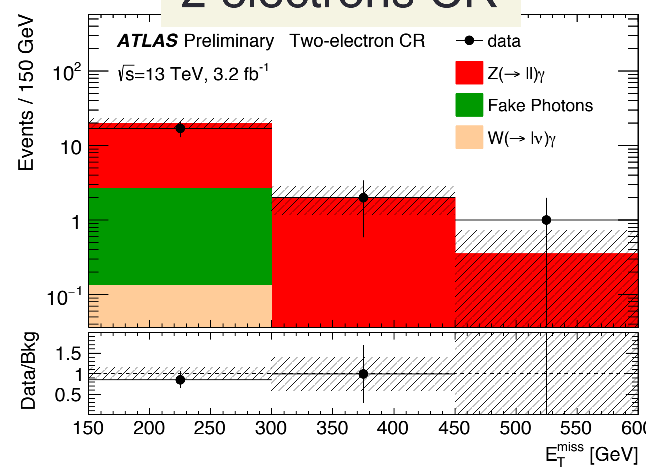
# Backup: Mono-Photon event selection and background estimation

- 13 TeV, 3.2 $fb^{-1}$
- Event selection:
  - Photon trigger with threshold of $p_T$ > 120 GeV.
  - Well reconstructed and isolated photon:
    - $p_T$ > 150 GeV, |η| < 2.37.
    - |z| < 0.25 m (suppress beam induced photons) .
  - MET > 150 GeV.
  - Δφ(γ,MET) > 0.4 (back to back).
  - Lepton veto (suppress W/Z events).
  - Rejects events with more than 1 jet.
- Low background:
  - Z(νν)+γ (irreducible): simulation normalized in two leptons control region.
  - W(lν)+γ and Z(ll)+γ with missing lepton(s): simulation normalized in single muon and two leptons control regions.
  - γ+jets with missing jets: simulation normalized in low MET control region.
  - W/Z + jets, top, diboson:
    - Fake photon from leptons: determine electron-to-photon misidentification factor with Z(ee) sample -> apply it to e+MET sample.
    - Fake photon from jets: ABCD method with photon ID and isolation.

1 muon CR




2 electrons CR



13 TeV

# Backup: Mono-W/Z(hadronic) Event Selection and Backgrounds

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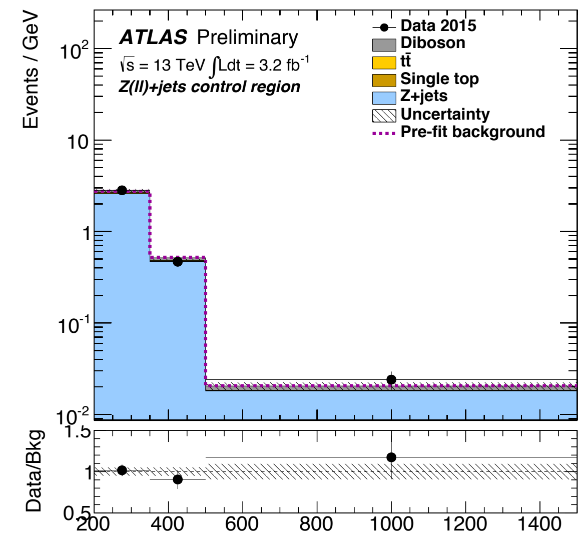
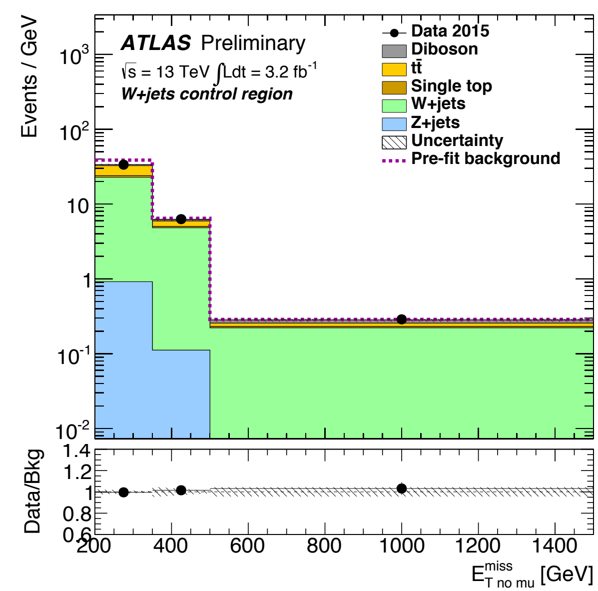
- 13 TeV, 3.2 fb$^{-1}$, MET trigger
- Event Selection
  - W or Z candidate = large-R jet
  - MET > 250 GeV, and track based MET: p-MET > 30 GeV
  - Min[Δφ(MET,jets)] > 0.6 : no jets near MET
  - Δφ(MET,p-MET) < π/2: track MET align to MET
  - Lepton veto
- Background estimation
  - Two muons CR: Z+jets
  - One muon and no b-tagged track jets CR: W+jets
  - One muon and b-tagged track jets CR: ttbar



13 TeV

# Backup: Mono-H(bb) Event Selection

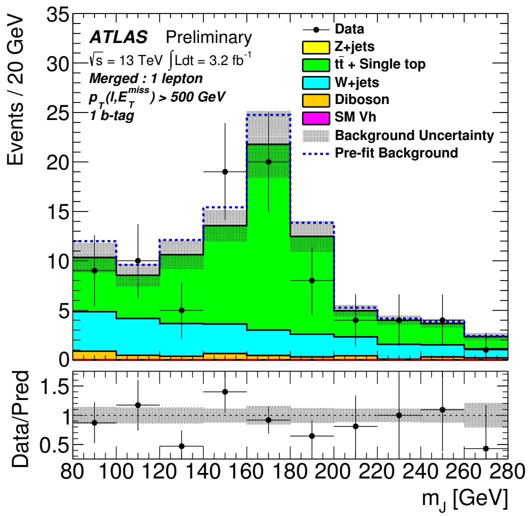
- 13 TeV, 3.2 $fb^{-1}$, MET trigger.
- MET > 150 GeV, and track based MET: p-MET > 30 GeV
- Lepton veto (no isolated electron or muon with pT>7GeV)
- H candidate:
  - Two small-R jets ($j_1$ and $j_2$) in resolved region (MET<500GeV)
    - Leading jet $p_T$ > 45 GeV
  - One large-R jet in merged region (MET>500GeV)
  - 1 or 2 b-tagged jet(s).
- Resolved region : cuts to suppress multi-jets background
  - min[$\Delta\varphi$(MET,jets)] > 20 deg: No jets near MET.
  - $\Delta\varphi$(MET,p-MET) < 90 deg: MET and track MET align.
  - $\Delta\varphi$(MET,Higgs) > 120 deg: MET and H go back-to-back.
  - $\Delta\varphi(j_1,j_2)$ < 140 deg: Two jets are not back-to-back.

13 TeV

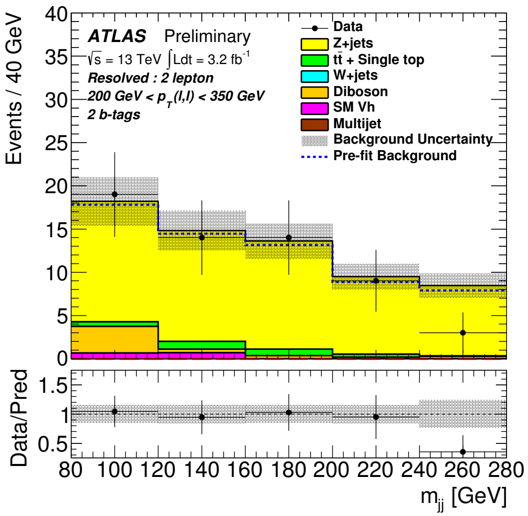
# Backup: Mono-H(bb) Background Estimation

- W+jets and ttbar with missing lepton: One-muon control region.
- Z+jets with missing leptons: Two-lepton control region
- Multi-jet background (resolved region): data-driven method. Derived from multi-jet dominant region.

One-muon CR, Merged, 1 b-tag




Two-lepton CR, Resolved, 2 b-tag



13 TeV

# Backup: Mono-H(bb) Systematic errors

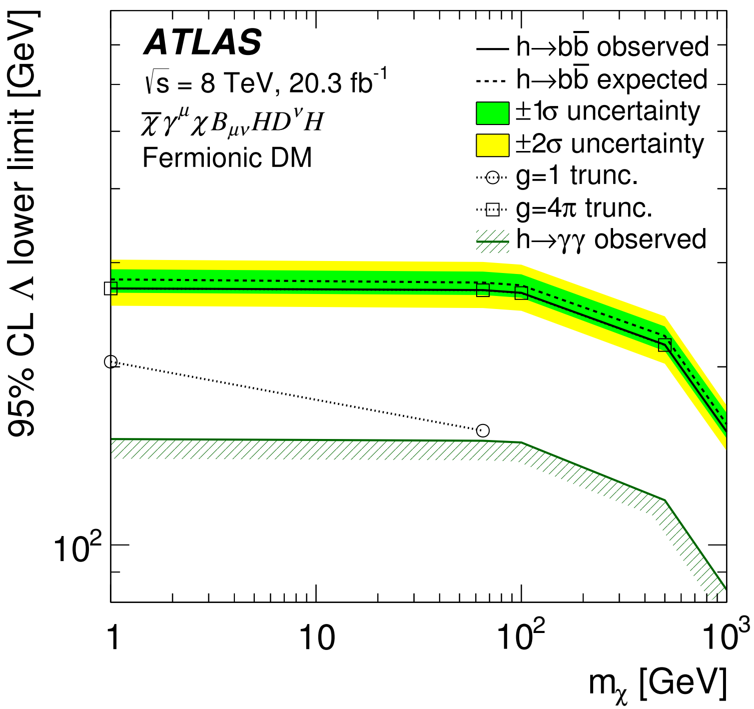
- Systematic errors

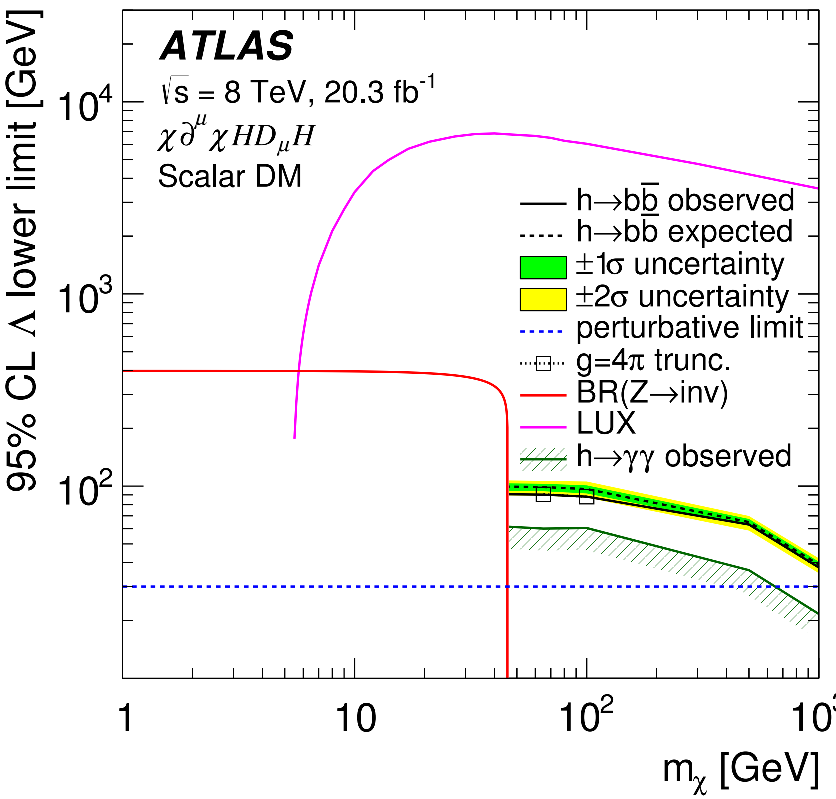
| Source of uncertainty | Impact (%) |
|---|---|
| Total | 23.0 |
| Statistical | 20.5 |
| Systematic | 10.3 |
| Experimental Uncertainties | |
| $b$-tagging | 6.6 |
| Luminosity | 4.4 |
| Jets+$E_T^{miss}$ | 2.8 |
| Leptons | 0.4 |
| Theoretical and Modeling Uncertainties | |
| Top | 5.1 |
| $Z$+jets | 3.4 |
| Signal | 2.6 |
| $W$+jets | 1.5 |
| Diboson | 0.6 |
| Multijet | 0.5 |
| $VH$ | 0.4 |

8 TeV

# Backup: Mono-H(bb) Limits

- EFT limits




$$\frac{1}{\Lambda^2}\chi^{\dagger}\partial^{\mu}\chi H^{\dagger}D_{\mu}H \quad \text{(Scalar DM, dimension-6)}$$

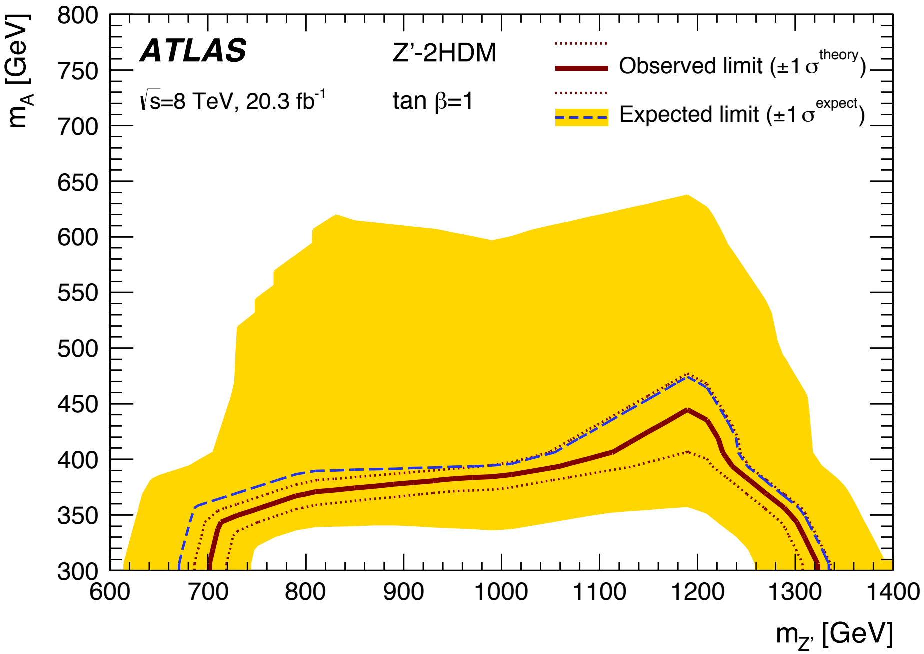
$$\frac{1}{\Lambda^4}\bar{\chi}\gamma^{\mu}\chi B_{\mu\nu}H^{\dagger}D^{\nu}H \quad \text{(Fermionic DM, dimension-8)}$$

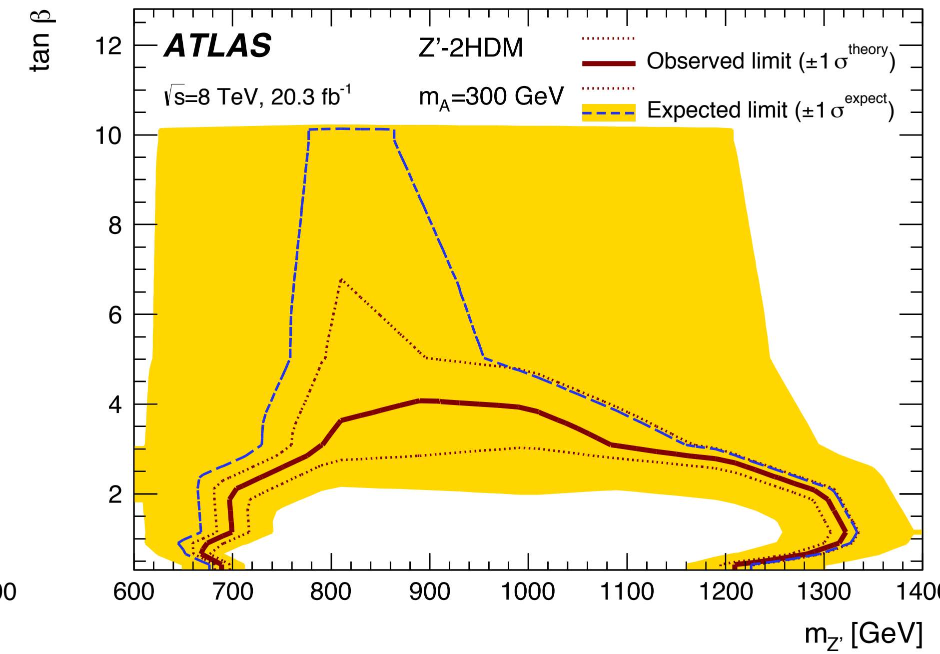
Direct detection and Z->inv. shows stronger limits

8 TeV

# Backup: Mono-H(bb) Limits

- 2HDM limits




(b) $m_{Z'} - \tan\beta$

mA = 300 GeV,
mZ' = 700 - 1300 GeV
is excluded

13 TeV

# Backup: Mono-H(γγ) Event selection and Backgrounds

- 13 TeV, 3.2 fb$^{-1}$, photon trigger.
- Event selection:
  - H candidate = two isolated photons with pT > 25 GeV, |η| < 2.37
    - H mass window [105 GeV, 160 GeV]

| Category | $E_T^{miss}$ [GeV] | $p_T^{hard}$ [GeV] | $p_T^{\gamma\gamma}$ [GeV] |
|---|---|---|---|
| High $E_T^{miss}$, high $p_T^{\gamma\gamma}$ | $> 100$ | - | $> 100$ |
| High $E_T^{miss}$, low $p_T^{\gamma\gamma}$ | $> 100$ | - | $\leq 100$ |
| Intermediate $E_T^{miss}$ | $> 50$ and $\leq 100$ | $> 40$ | - |
| Rest | - | - | $> 15$ |

- Signal and background are parameterized:
  - Signal : a double sided Crystal Ball (DSCB) function
  - Background:
    - An analytical function is chosen from background MC samples.
    - Evaluated by fitting to background dominant data.

13 TeV

# Backup: Mono-H(γγ) Systematic errors

- Systematic errors:

| Source | Maximum uncertainty (%) |
|---|---|
| **Experimental** | |
| Luminosity | 5 |
| Trigger efficiency | 0.4 |
| Vertex selection | 3.6 (Intermediate), 20 (High $E_T^{miss}$) |
| Photon identification efficiency | 2.8 |
| Photon energy scale | 1 |
| Photon energy resolution | 2 |
| Photon isolation efficiency | 4 |
| $E_T^{miss}$ reconstruction | 1 (Rest), 20 (Intermediate and High $E_T^{miss}$) |
| Pile-up reweighting | 4.5 |
| **Theoretical** | |
| QCD scale uncertainty of ggH $p_T$ spectrum | 10 - 20 |
| Modelling of ggH $E_T^{miss}$ spectrum | 25 |
| PDF | 9 |
| MPI | 1 (Intermediate), 50 (High $E_T^{miss}$) |
| BR($h \to \gamma\gamma$) | 4.9 |