# Searches for Dark Matter Production with Mono-objects and MET in ATLAS

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on behalf of the

**ATLAS Collaboration**

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# Dark Matter searches

- Experimental evidence for Dark Matter
  - DM accounts for 24% of matter-energy content of the Universe (WMAP/Planck).
  - Galactic rotation curves
  - Bullet Cluster
  - …



- Direct and indirect DM detection
  - model assumptions
  - kinematic limitations
- DM production at the LHC
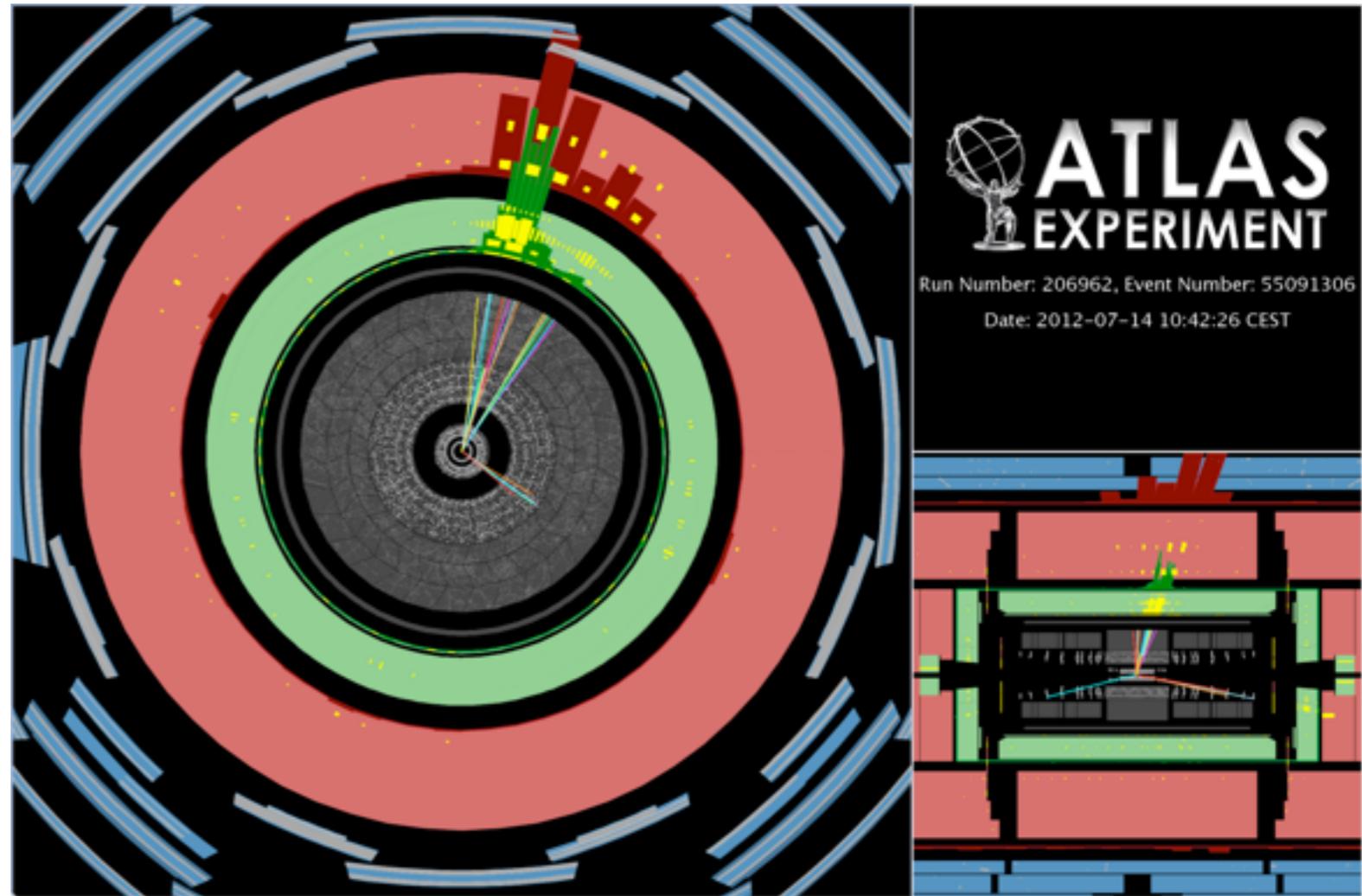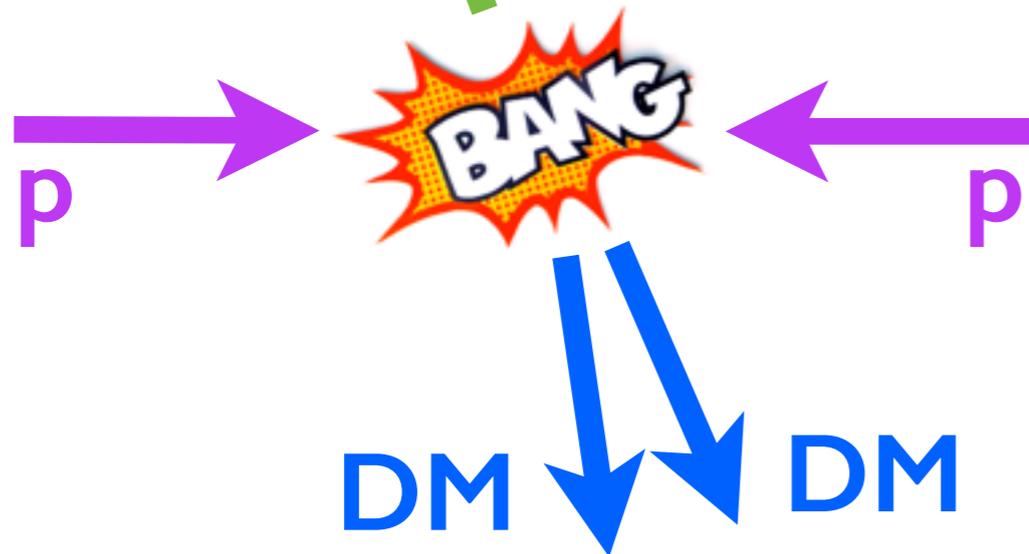  - independent of astrophysical assumptions
  - sensitive to light DM particles
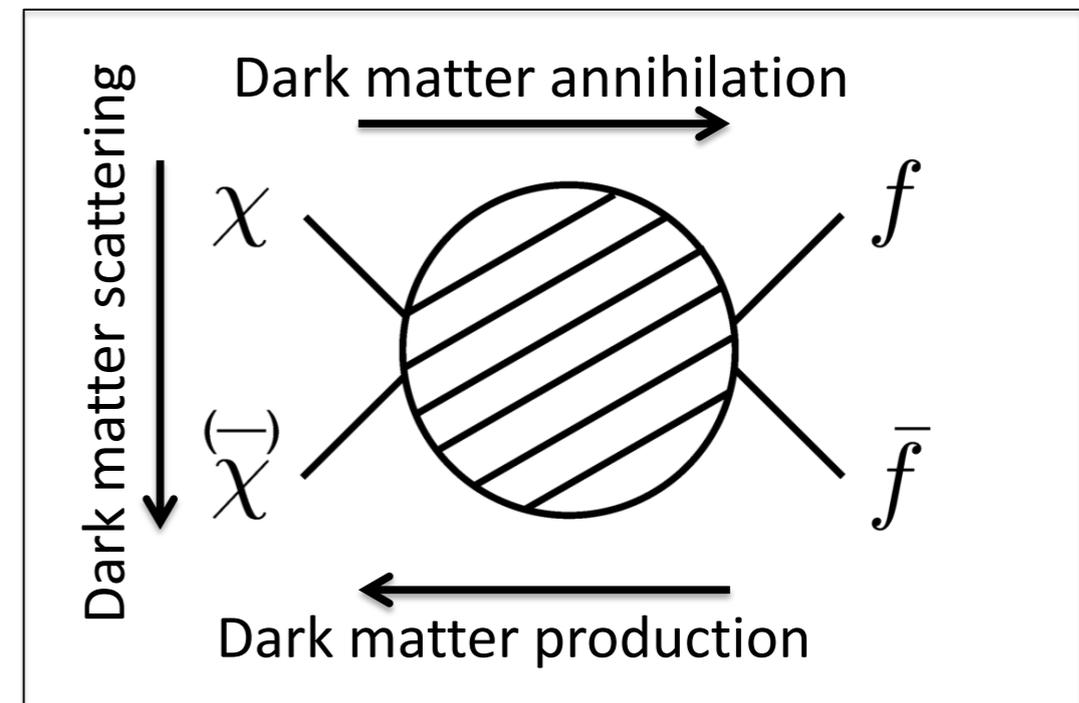
# DM production at the LHC
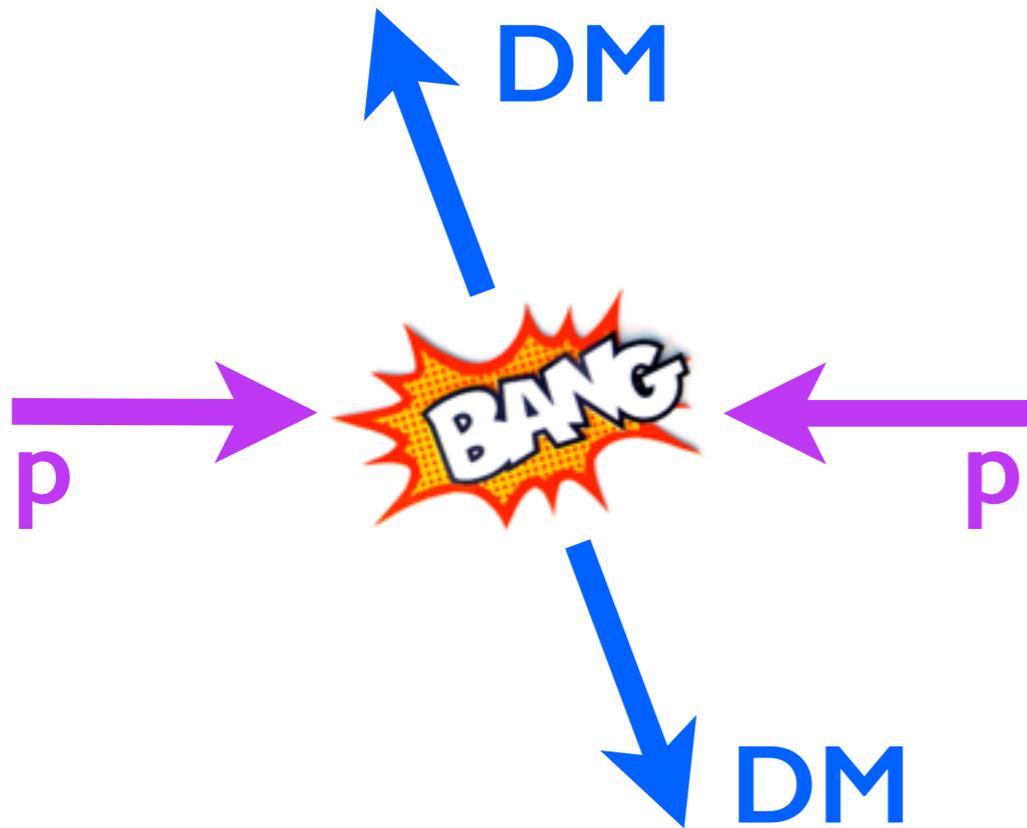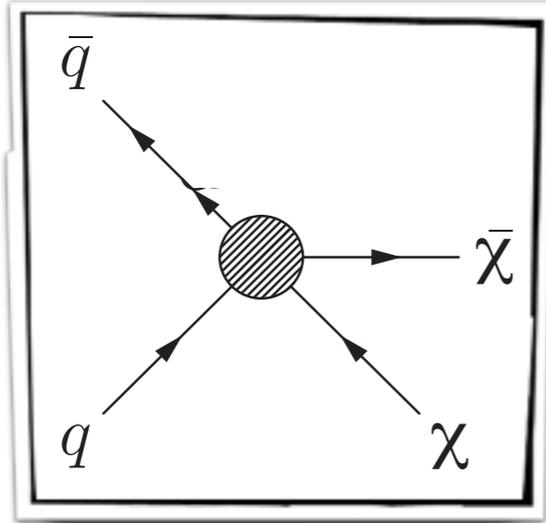
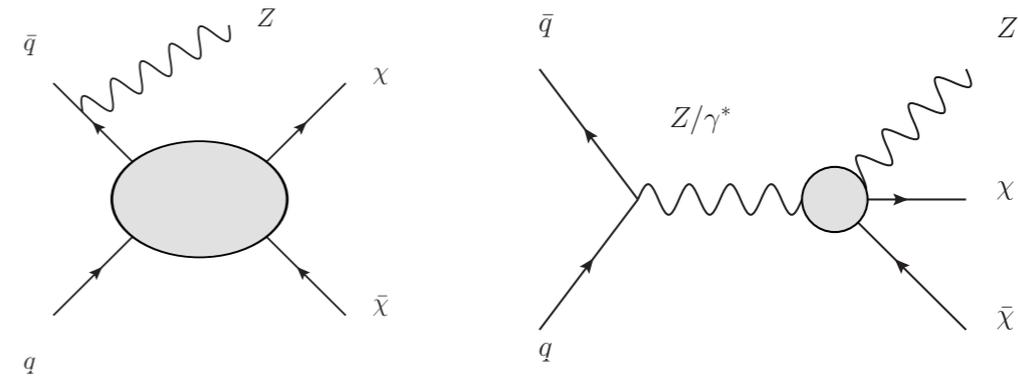# DM production at the LHC



jet, γ, W, Z, ...

p → BANG ← p

DM ⬇ ⬇ DM
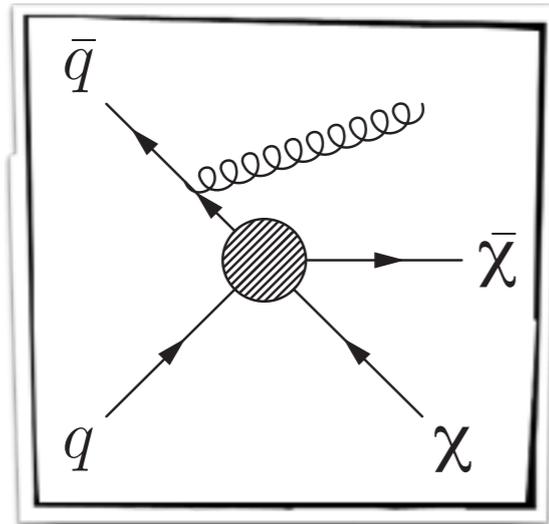


mono-jet event from 7 TeV data

JHEP 1304 (2013) 075

# mono-X searches



## Effective Field Theory

- simple benchmark models
  - couplings to quarks and gluons
  - couplings to vector bosons
- only two free parameters: $m_\chi$, suppression scale M*
- validity concerns at the LHC energies

| Name | Initial state | Type | Operator |
|------|---------------|------|----------|
| D1 | $qq$ | scalar | $\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$ |
| D5 | $qq$ | vector | $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ |
| D8 | $qq$ | axial-vector | $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$ |
| D9 | $qq$ | tensor | $\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ |
| D11 | $gg$ | scalar | $\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G_{\mu\nu}^a)^2$ |

## Simplified models

- UV-complete
- s-channel or t-channel
- parameters: $m_\chi$, mediator mass and width, couplings
- Higgs-portal DM
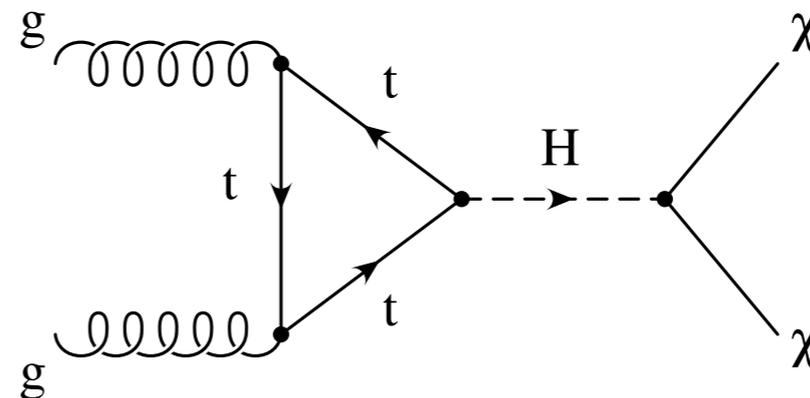
# mono-jet

## Event selection
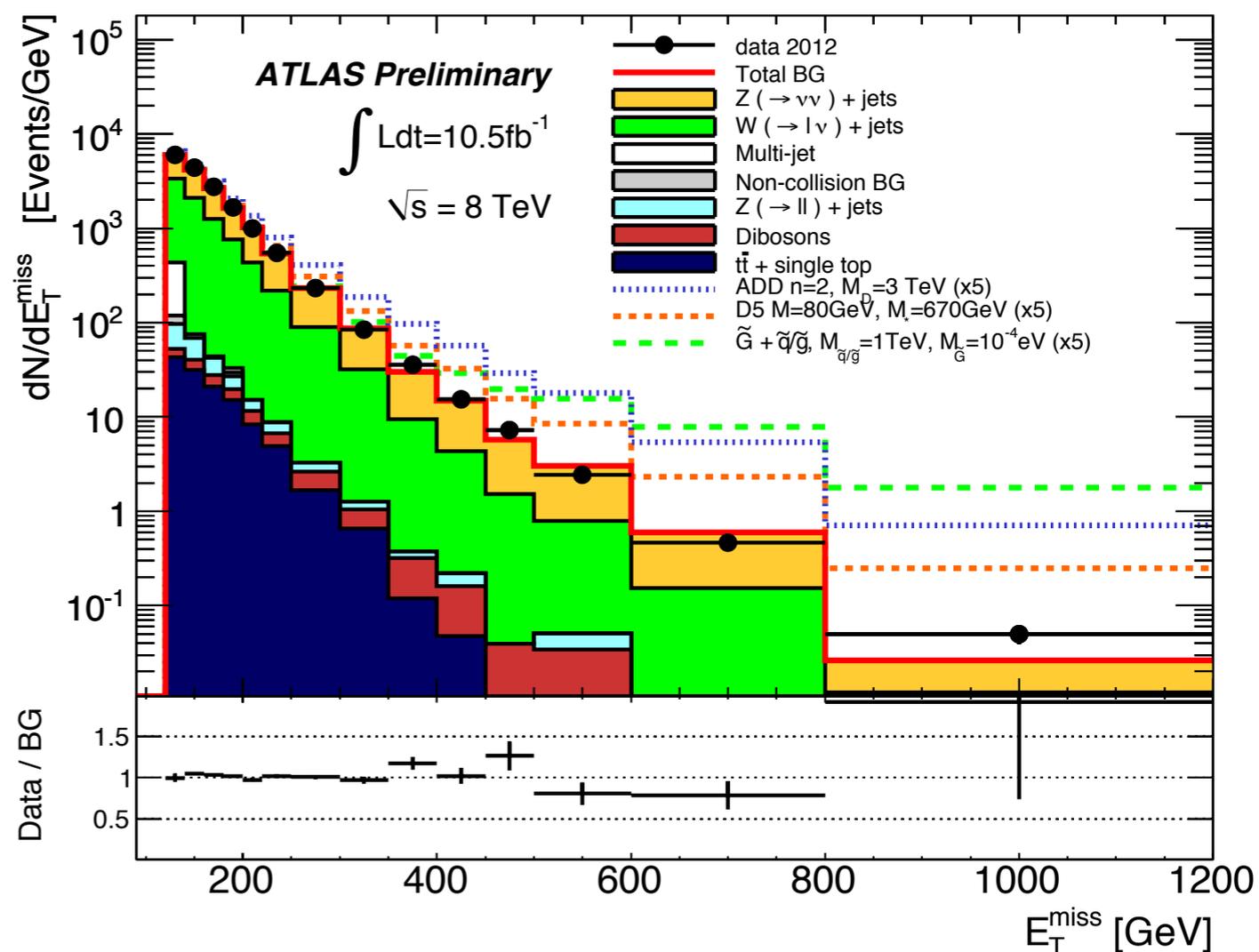
- central jet $|\eta| < 2.0$

- electron veto (pT > 20 GeV)

- muon veto (pT > 7 GeV)

- at most two jets (pT > 30 GeV)

- $\Delta\varphi$(jet, MET)>0.5

- signal region (SR) defined by symmetric cuts on the leading jet pT and MET > 120, 220, 350, 500 GeV

## Dominant backgrounds

- Zνν from Zℓℓ and Wℓν control region (CR)
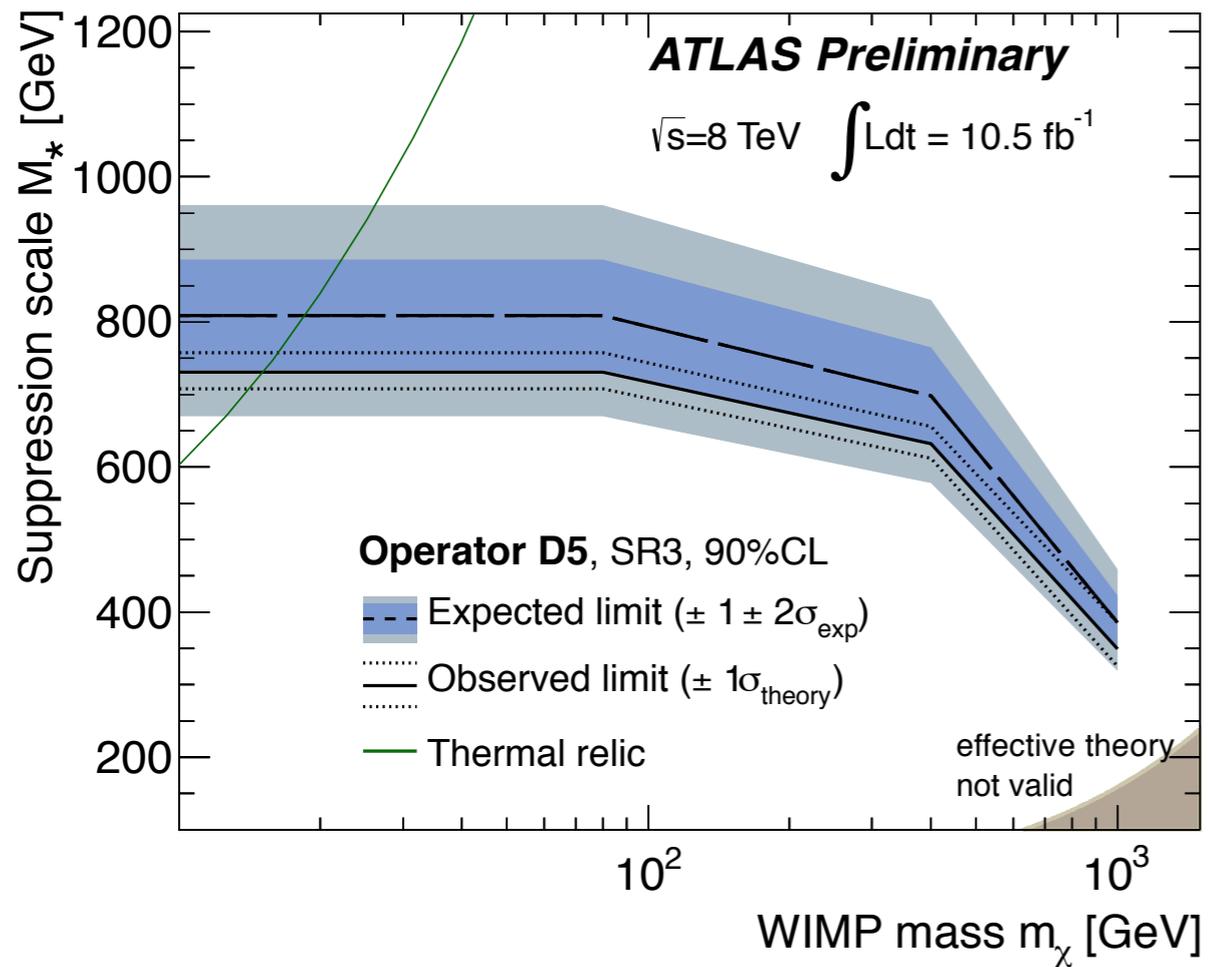
- Wℓν from Wℓν CR

## Uncertainties

- limited CR statistics
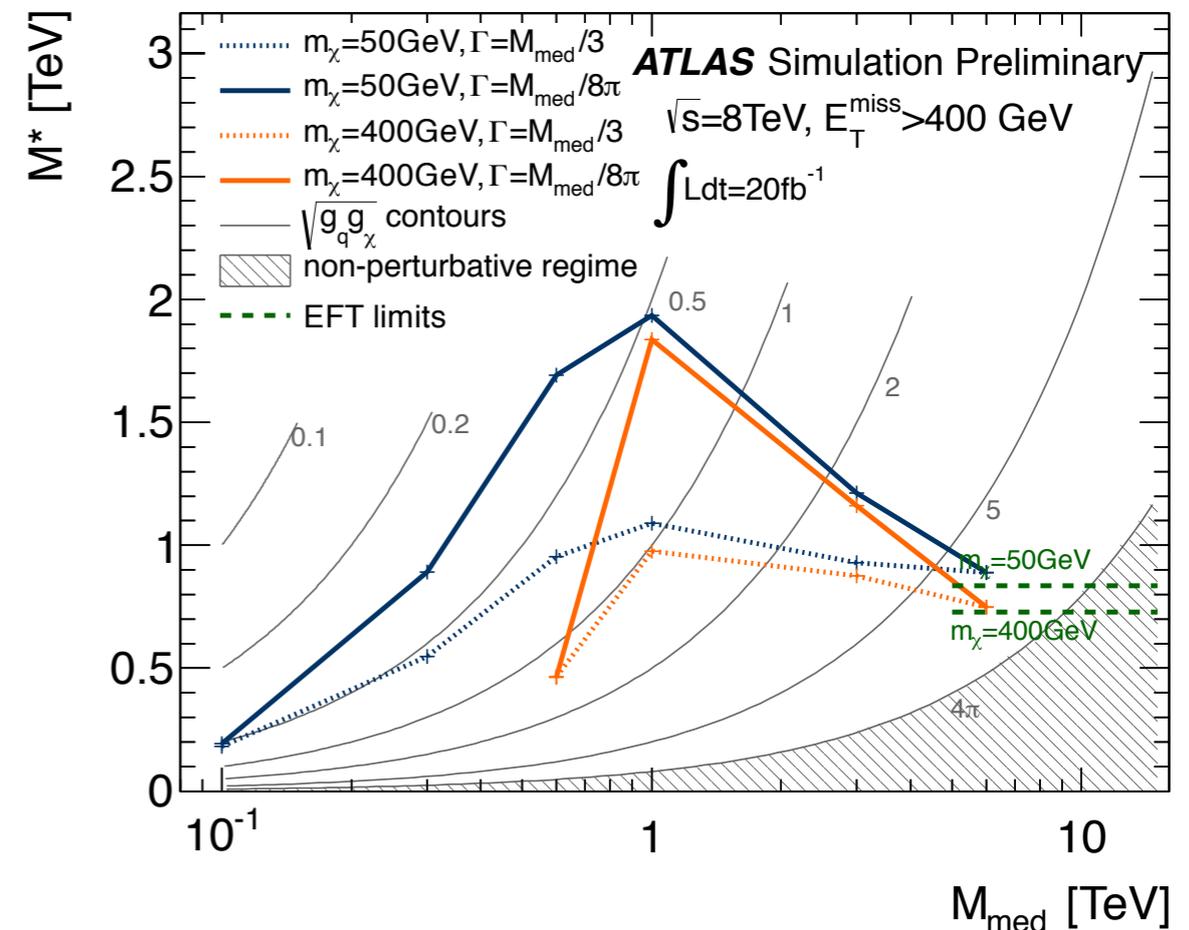
- uncertainty 3.4 to 17%

# mono-jet

## ATLAS-CONF-2012-147

- Limits on the suppression scale of the EFT operators are set assuming full EFT validity.
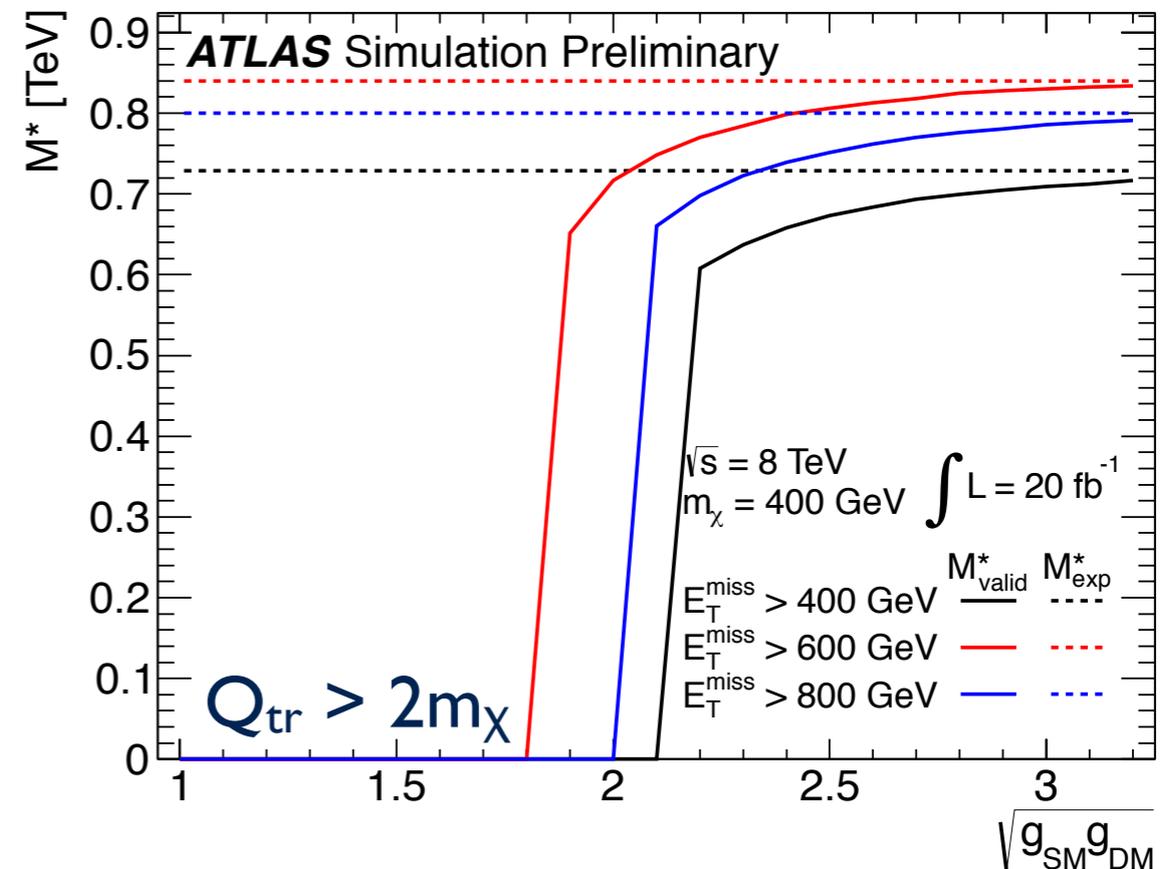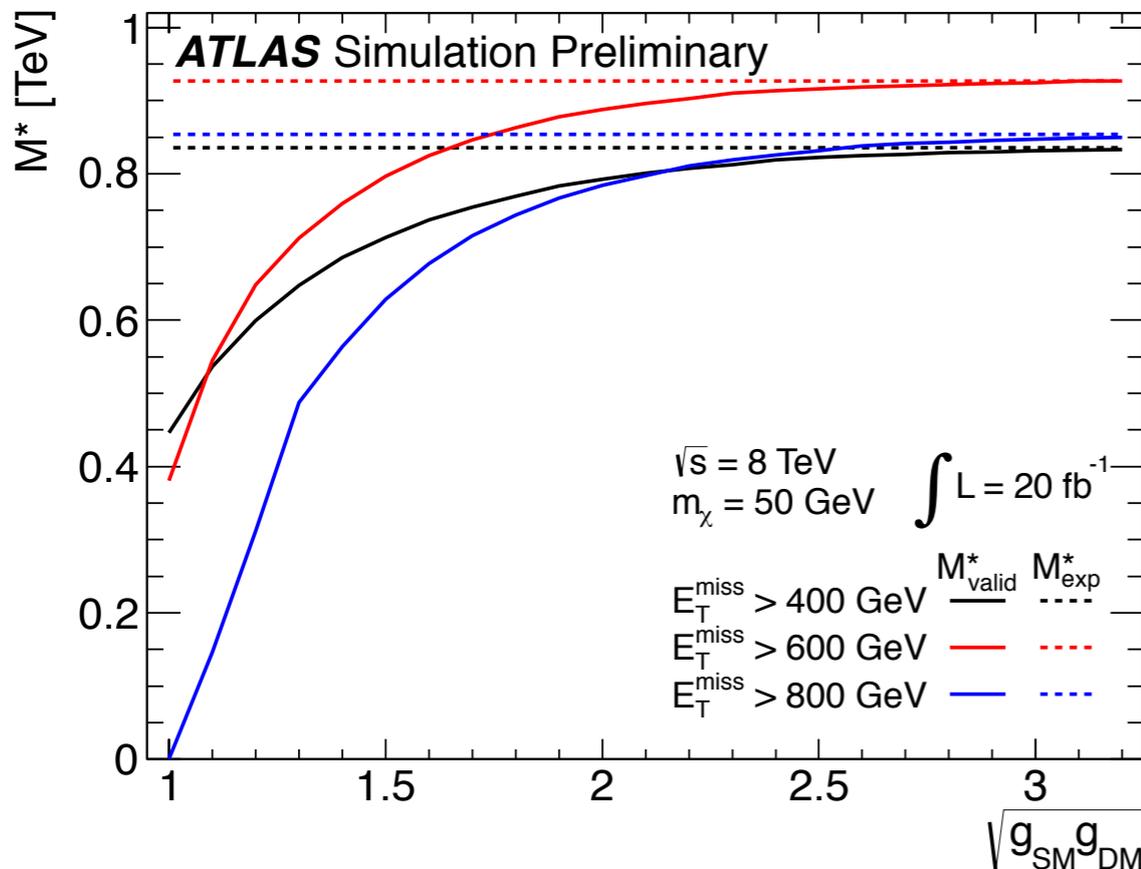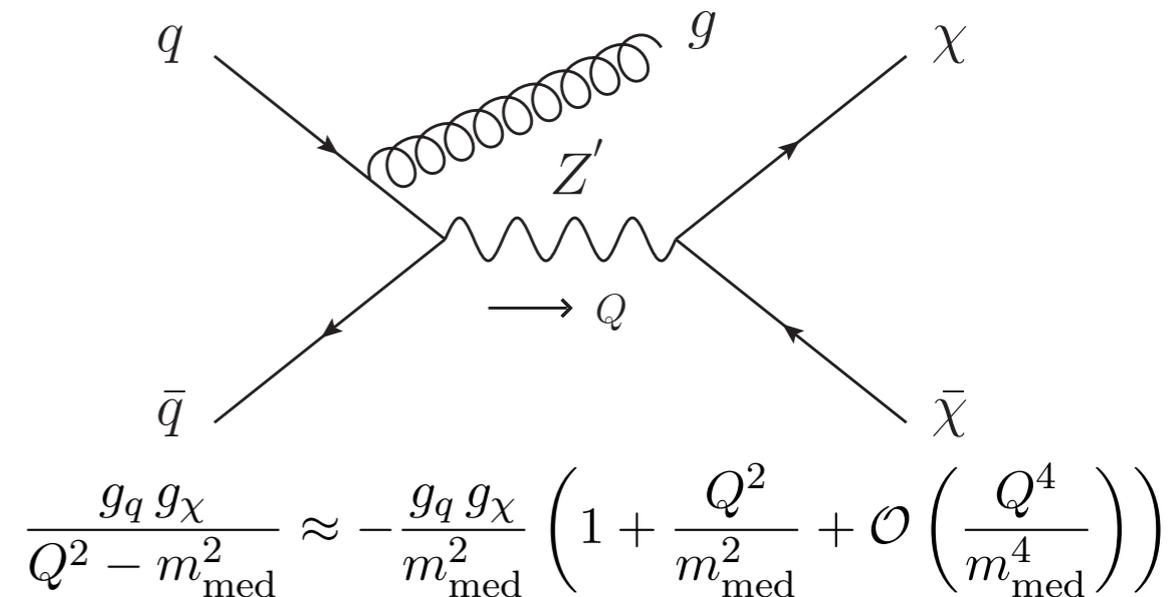


## ATL-PHYS-PUB-2014-007

- Simplified models with Z'-like mediators reveal that
  - EFT limits are conservative in the resonant region.
  - EFT limits are not valid for light mediators.

# EFT validity

- Minimum requirement for EFT being a valid approximation of models is $Q_{tr} < M_m$

- Not all events gene at the LHC energie

- As a consequence,

- For D5, the EFT approach is fully valid for $\sqrt{g_q\, g_\chi} \gtrsim \pi$.

$$\frac{g_q\, g_\chi}{Q^2 - m_{med}^2} \approx -\frac{g_q\, g_\chi}{m_{med}^2}\left(1 + \frac{Q^2}{m_{med}^2} + \mathcal{O}\left(\frac{Q^4}{m_{med}^4}\right)\right)$$

# mono-Z($\ell\ell$)

arXiv:1404.0051 (accepted by PRD)

## Event selection

- two opposite sign leptons, $67 < m\ell\ell < 106$ GeV

- 3rd lepton veto (pT > 7 GeV)

- |MET - pT$\ell\ell$| / pT$\ell\ell$ < 0.5

- $\Delta\varphi$(pT$\ell\ell$, MET) < 2.5

- $\Delta|\eta\ell\ell|$ < 2.5

- jet veto (pT > 25 GeV)

- SR defined by MET > 150, 250, 350, 450 GeV

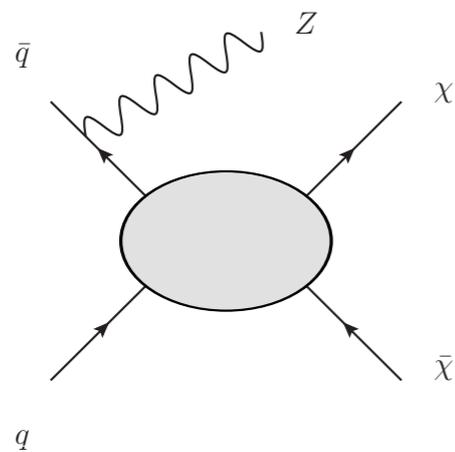## Uncertainties

- 35% theory uncertainty on background

## Dominant backgrounds

- ZZ$\rightarrow\ell\ell\nu\nu$ taken from MC (validated in ZZ$\rightarrow\ell\ell\ell\ell$ CR)

- WZ->$\ell\nu\ell\ell$ taken from MC

- WW and top from e$\mu$ CR
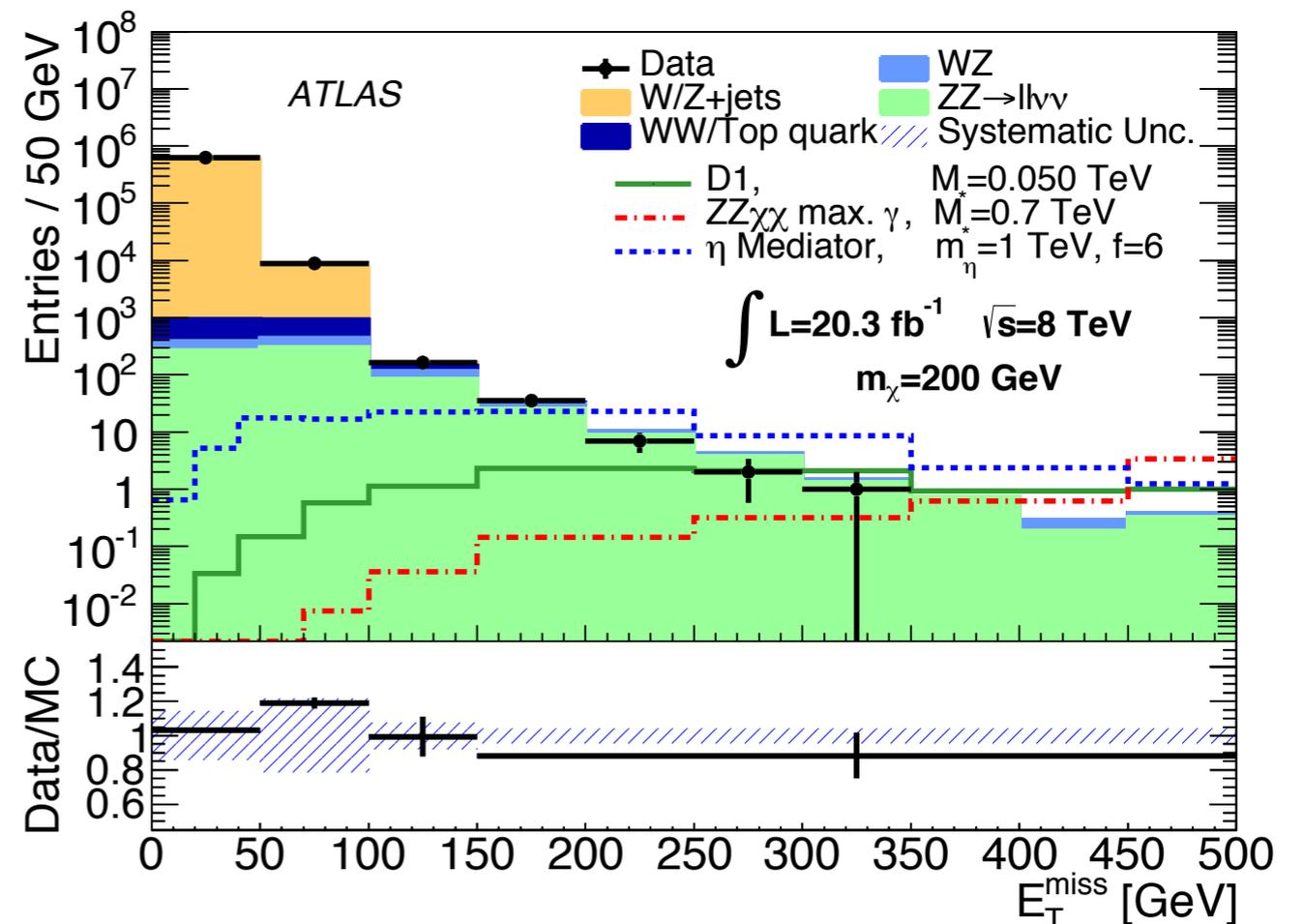
# mono-Z($\ell\ell$)
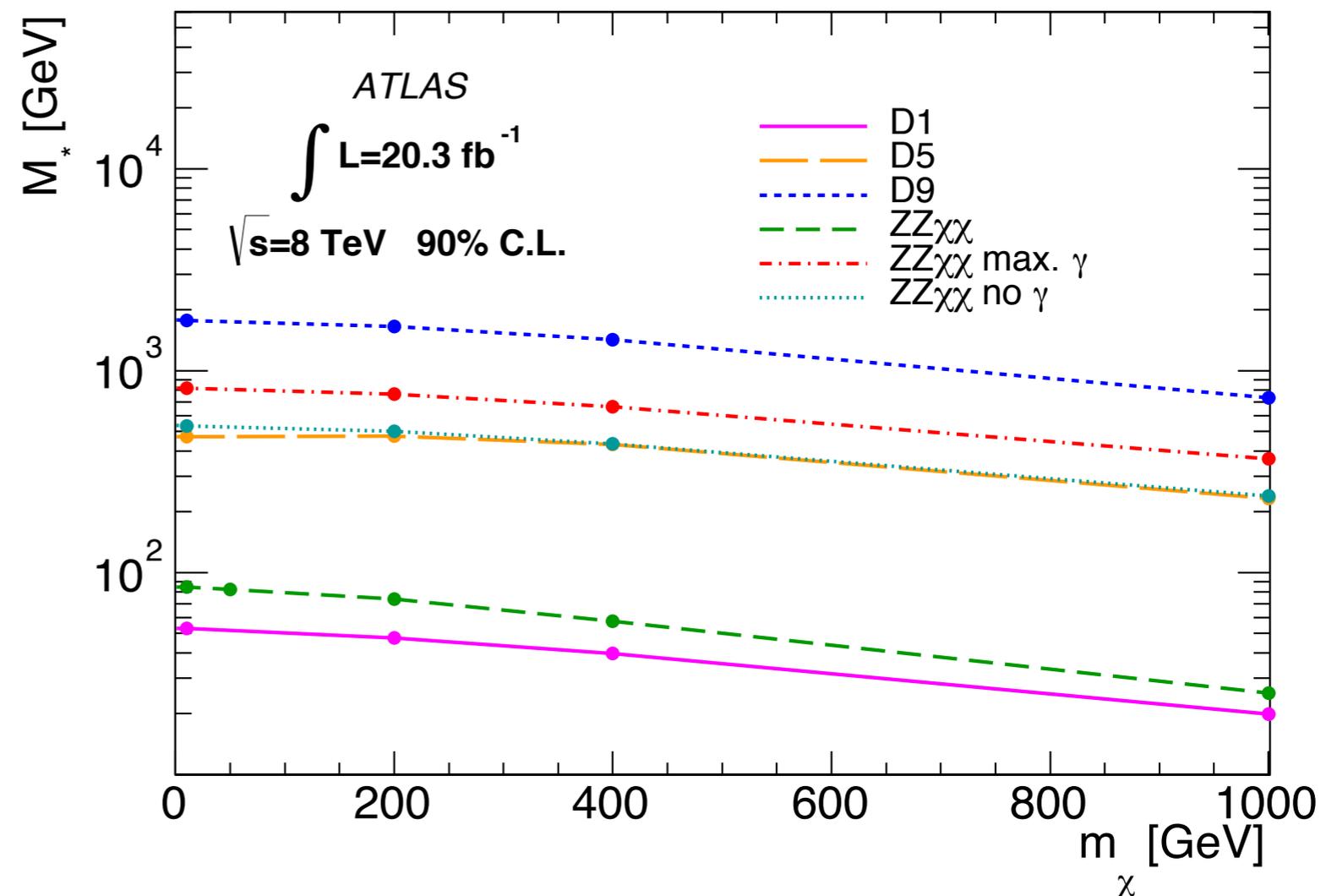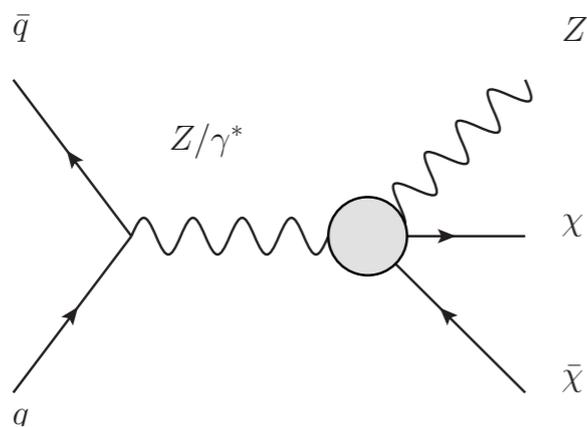
- dimension-5 operators
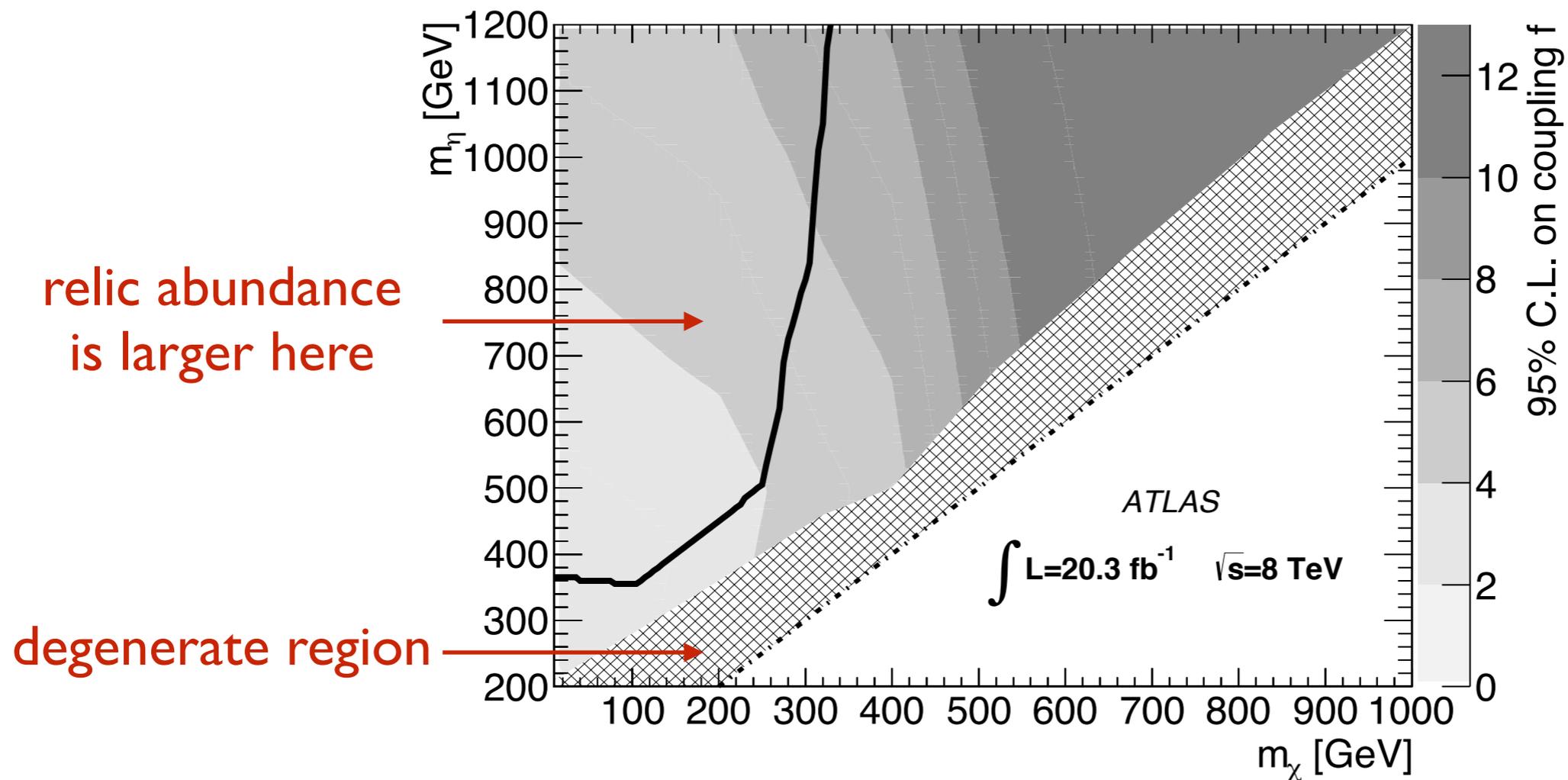
  - not as sensitive as other mono-X channels



- dimension-7 operators

  - unique sensitivity to ZZ$\chi\chi$ and $\gamma$*Z$\chi\chi$ coupling

# mono-Z($\ell\ell$)

- Simplified model: t-channel with a scalar coloured mediator $\eta$
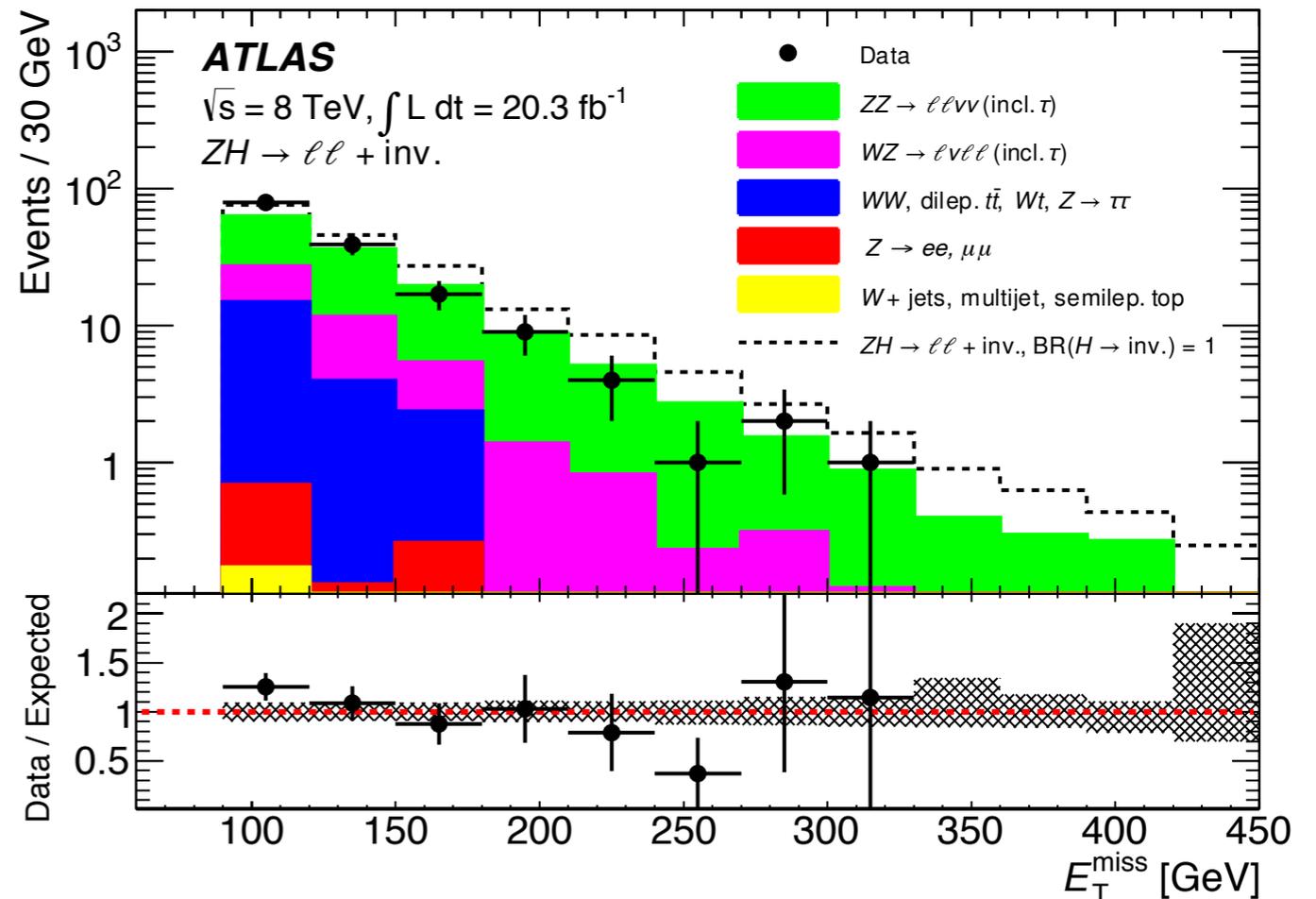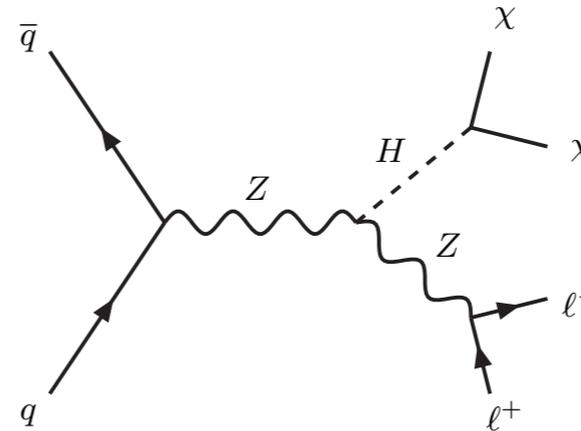- Upper limits on the coupling strength in the $m_\chi$-$m_\eta$ plane

# ZH(→invisible)

## Event selection

- two opposite sign leptons, $67 < m\ell\ell < 106$ GeV

- 3rd lepton veto (pT > 7 GeV)

- $|MET - pT\ell\ell| / pT\ell\ell < 0.2$

- $\Delta\varphi(MET, pTmiss) < 0.2$

- $\Delta\varphi\ell\ell < 1.7$

- $\Delta\varphi(Z, MET) > 2.6$

- jet veto (pT > 25 GeV)

- MET > 90 GeV

# ZH(→invisible)
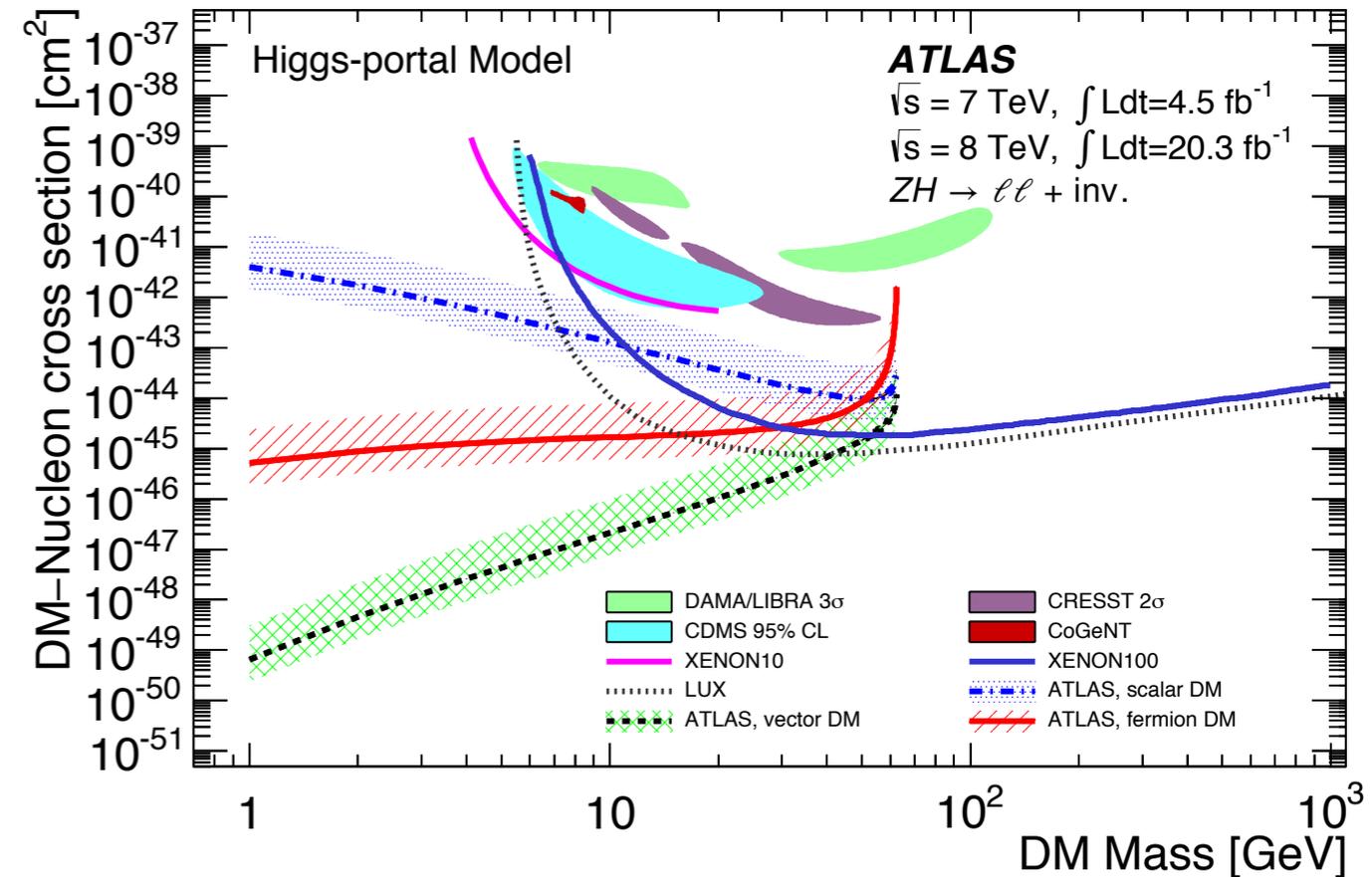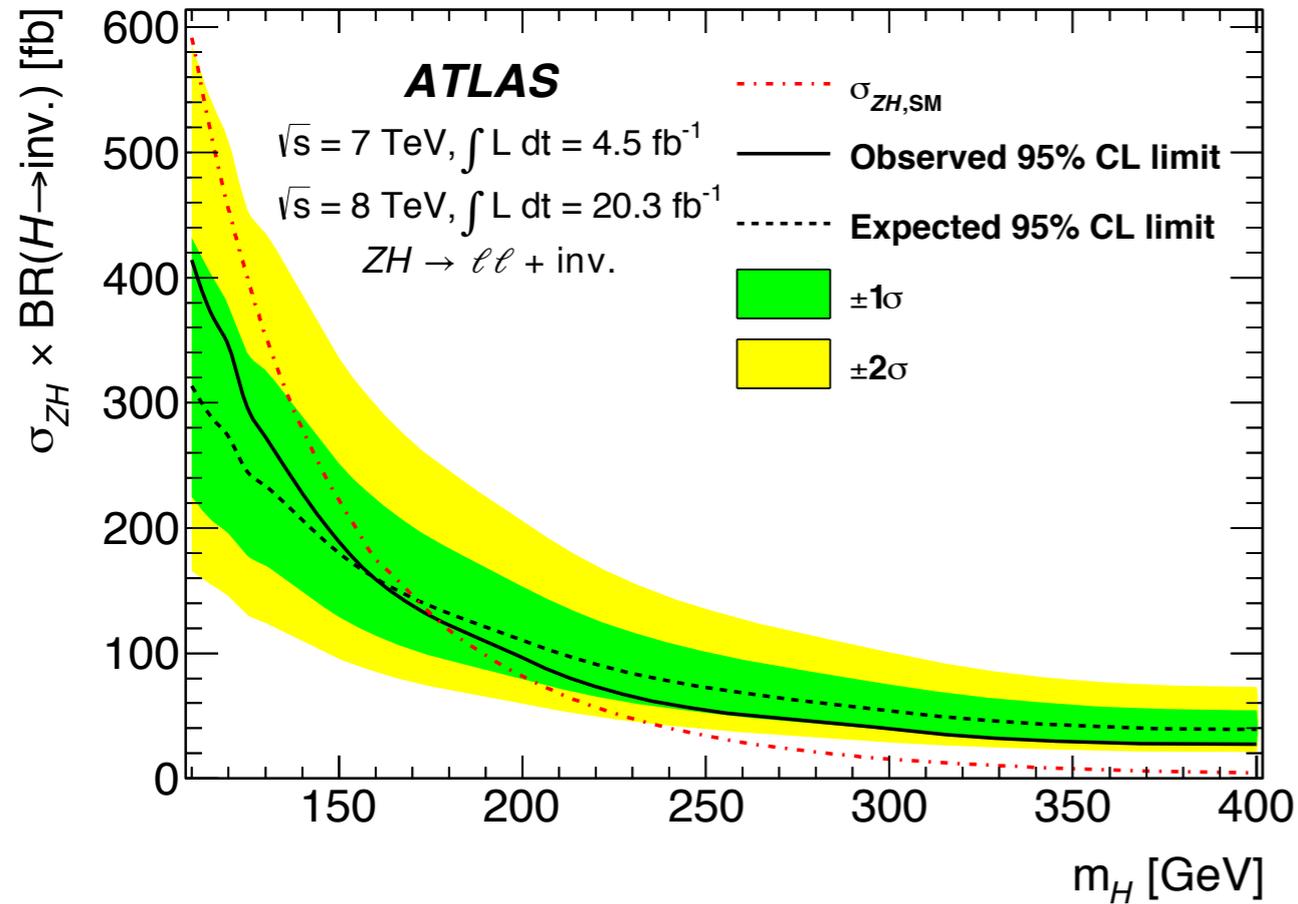


- BR(H→inv) = 75% observed (63% expected)
- Higgs portal Dark Matter interpretation
  - scalar, vector and fermion DM
  - sensitive to DM with $m_X < m_H/2$

# mono-W/Z(qq)

## Event selection

- large R=1.2 Cambridge-Aachen jet
  pT > 250 GeV, |η| < 1.2,
  50 < m < 120 GeV, √y > 0.4

- at most one extra light jet
  pT > 40 GeV, |η| < 4.5
  away from the fat jet (dR > 0.9)
  and MET (dφ > 0.4)

- lepton and photon veto
  (pT > 10 GeV)

- SR defined by
  MET > 350, 500 GeV

## Dominant backgrounds

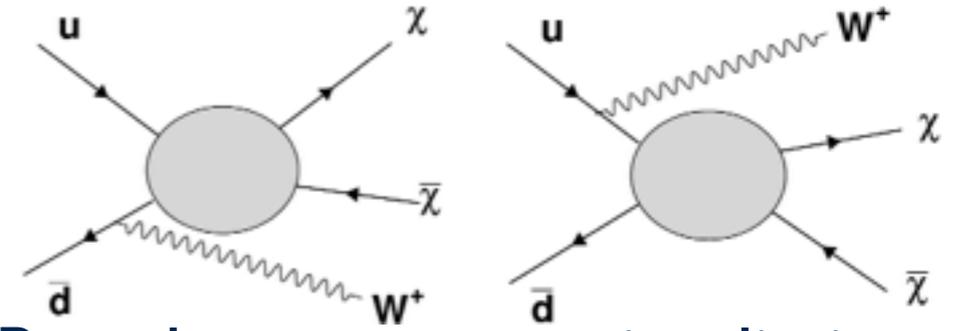- Zνν+jets, W/Z from CR
  (inverted muon veto)

## Uncertainties

- limited CR statistics

- MC theory uncertainties

- C-A jet energy scale/resolution
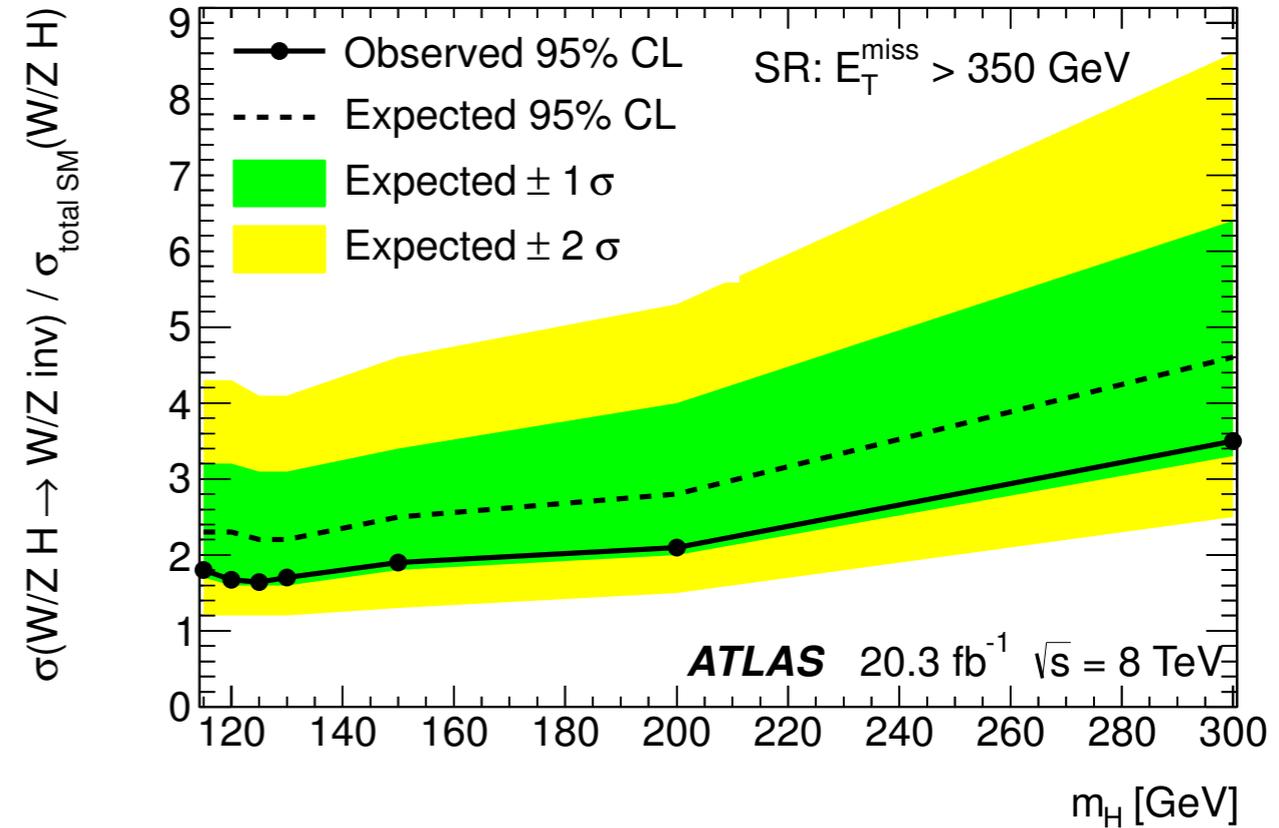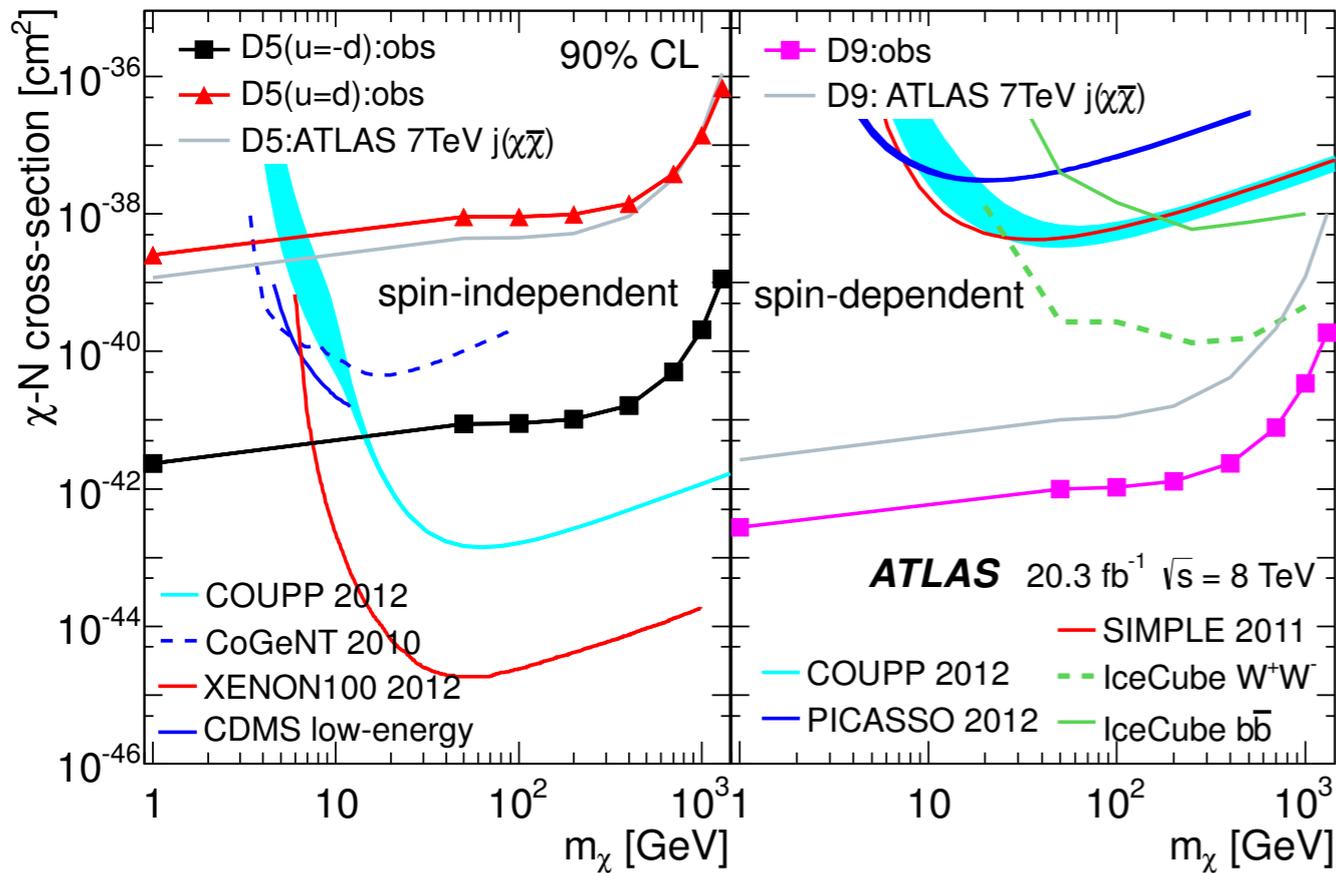
- total uncertainty 7-13%
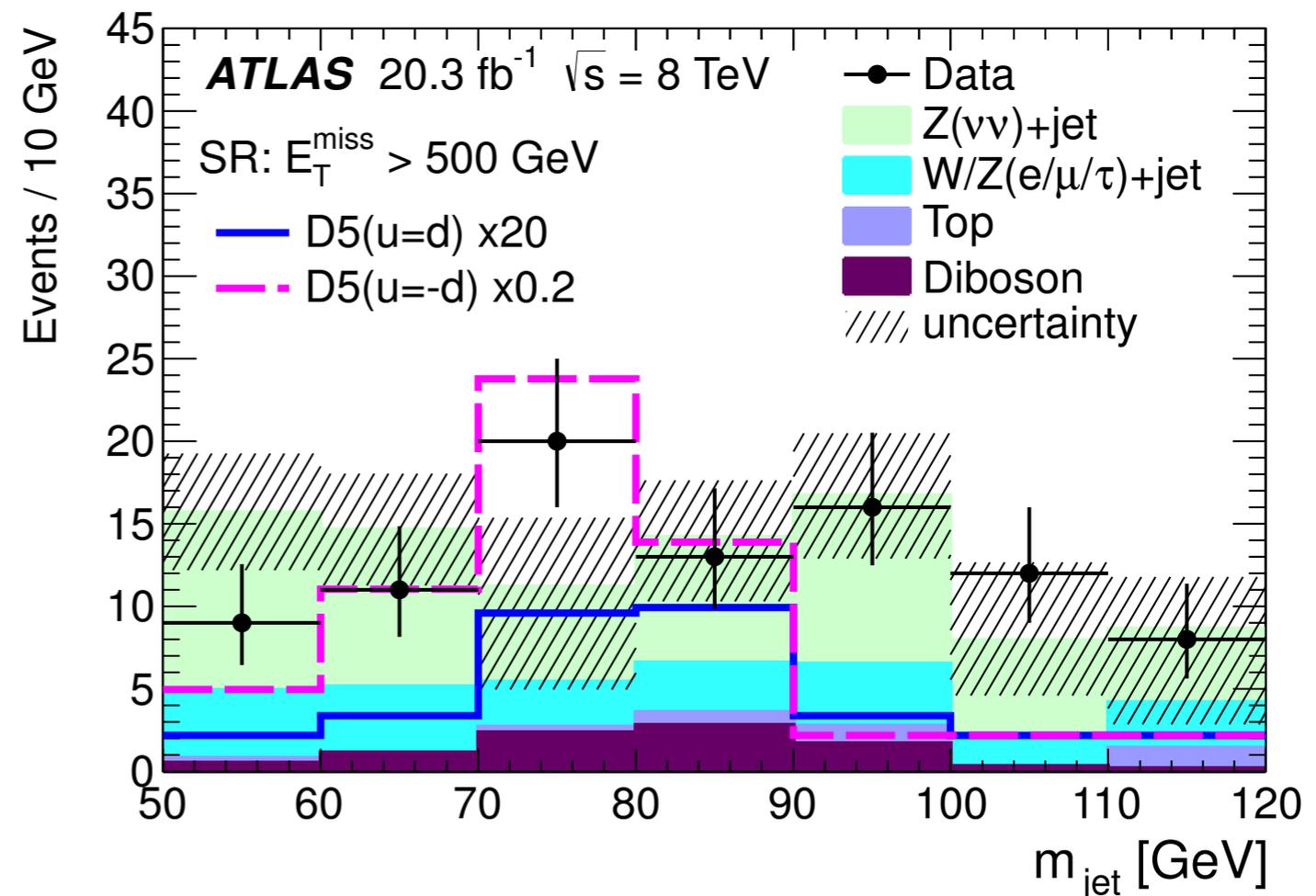
# mono-W/Z(qq)

- Sensitive to the sign of the DM couplings to up and down quarks.

  - $C(u) = C(d)$    destructive interference
  - $C(u) = -C(d)$    constructive interference



➡ Order of magnitude improvement on the WIMP-nucleon cross section limits.

  - $M^* > \sim 2$ TeV for D5 constructive mode.



- $\sigma(H \rightarrow \text{inv})/\sigma_{\text{total}} = 1.2$ observed (2.2 expected)

# mono-W($\ell\nu$)
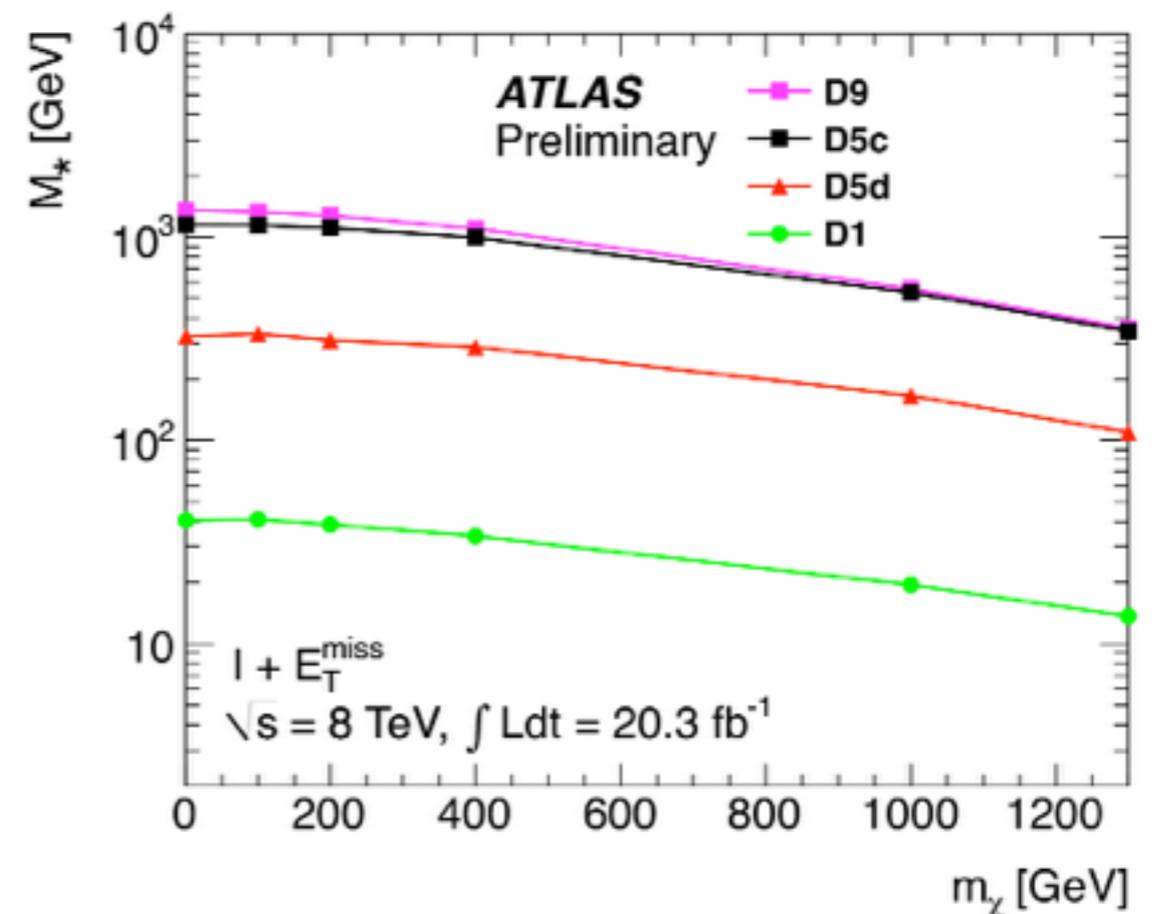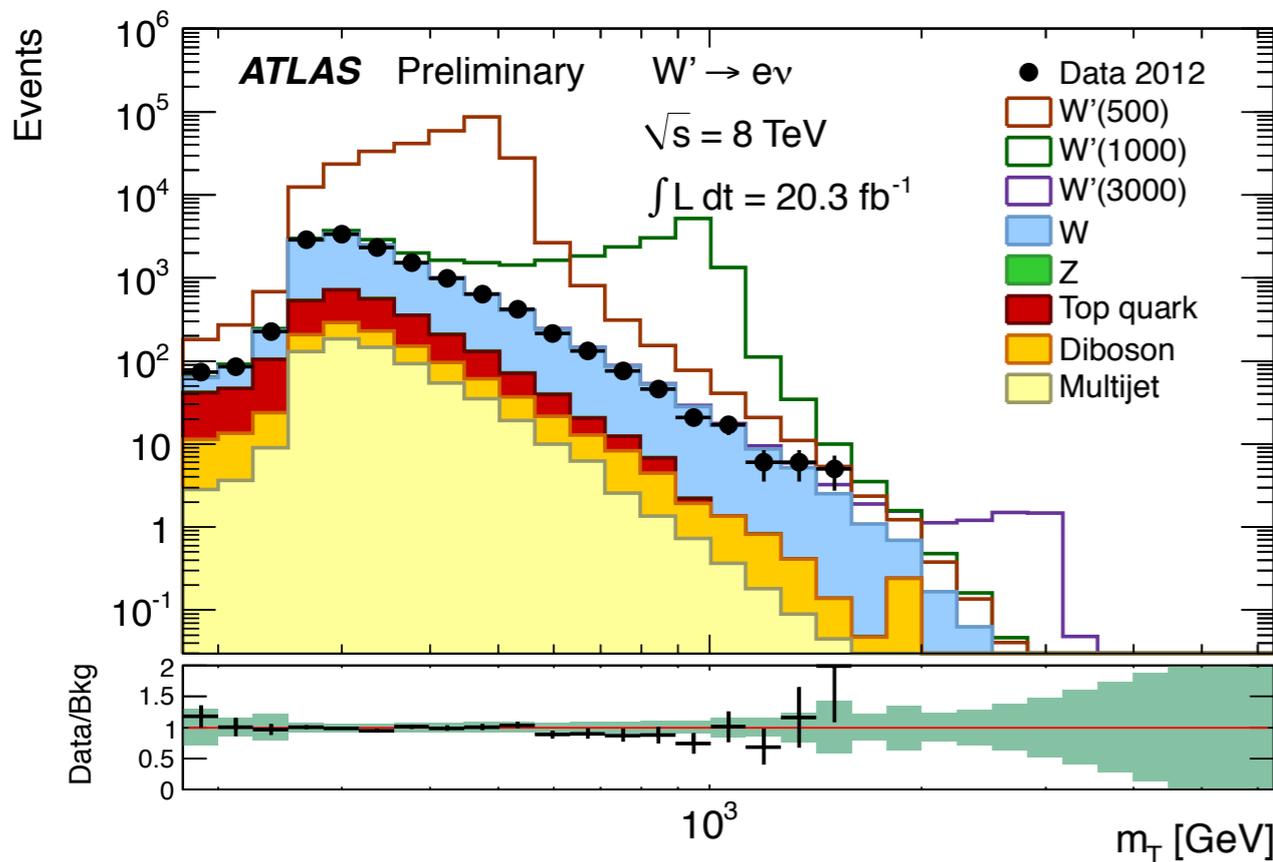
## Event selection

- one isolated lepton
  - electron:   pT, MET>125 GeV
  - muon:       pT, MET>45 GeV
- SR defined by cuts on $m_T(\ell, \text{MET})$

# mono-jet prospects @ 14 TeV

## Event selection

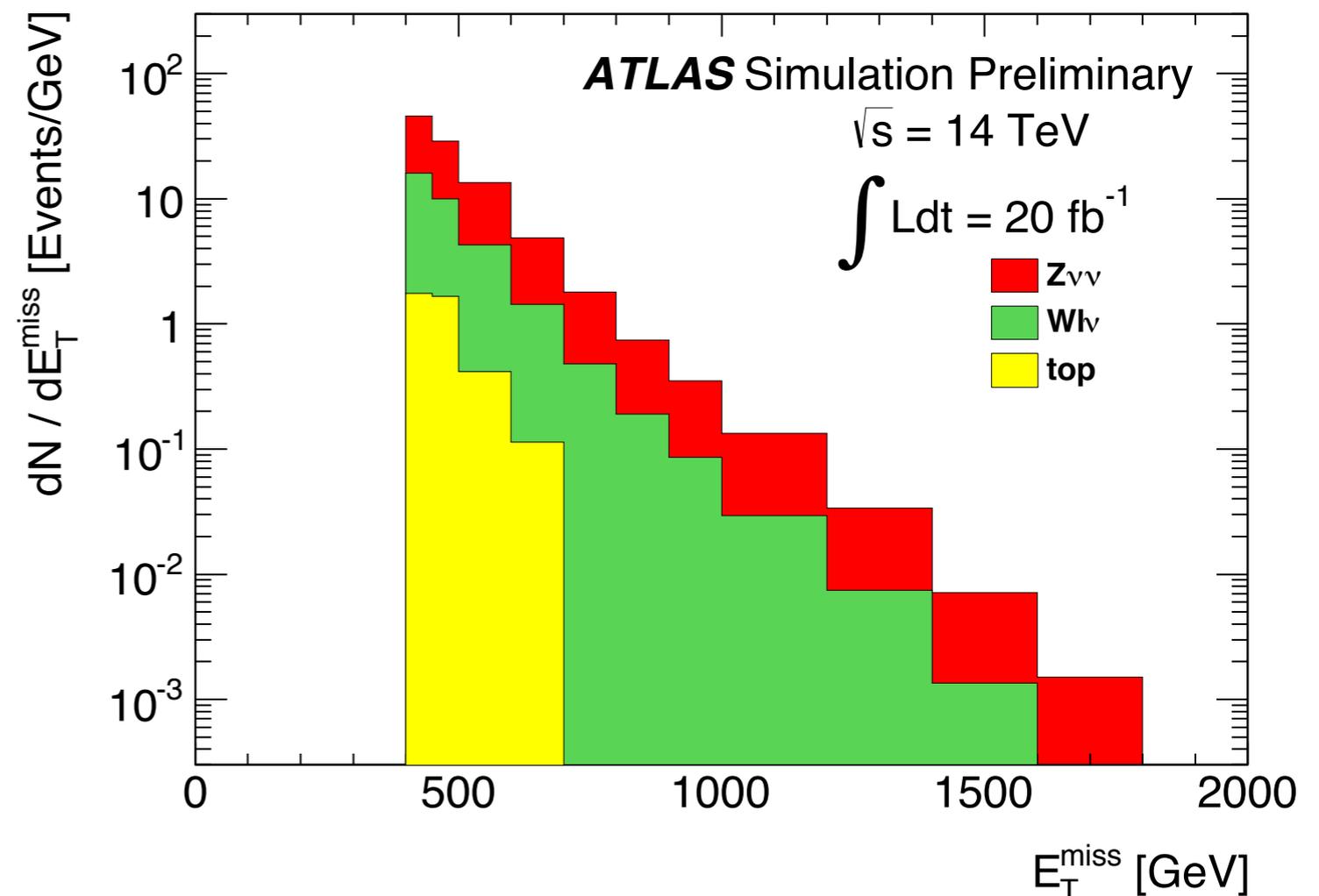- leading jet pT > 300 GeV

- $\Delta\varphi$(jet, MET) > 0.5

- electron and muon veto

- at most two jets

    - pT > 30 GeV @ 8 TeV

    - pT > 50 GeV @ 14 TeV

- SR defined by
  MET > 400, 600, 800 GeV

## Backgrounds
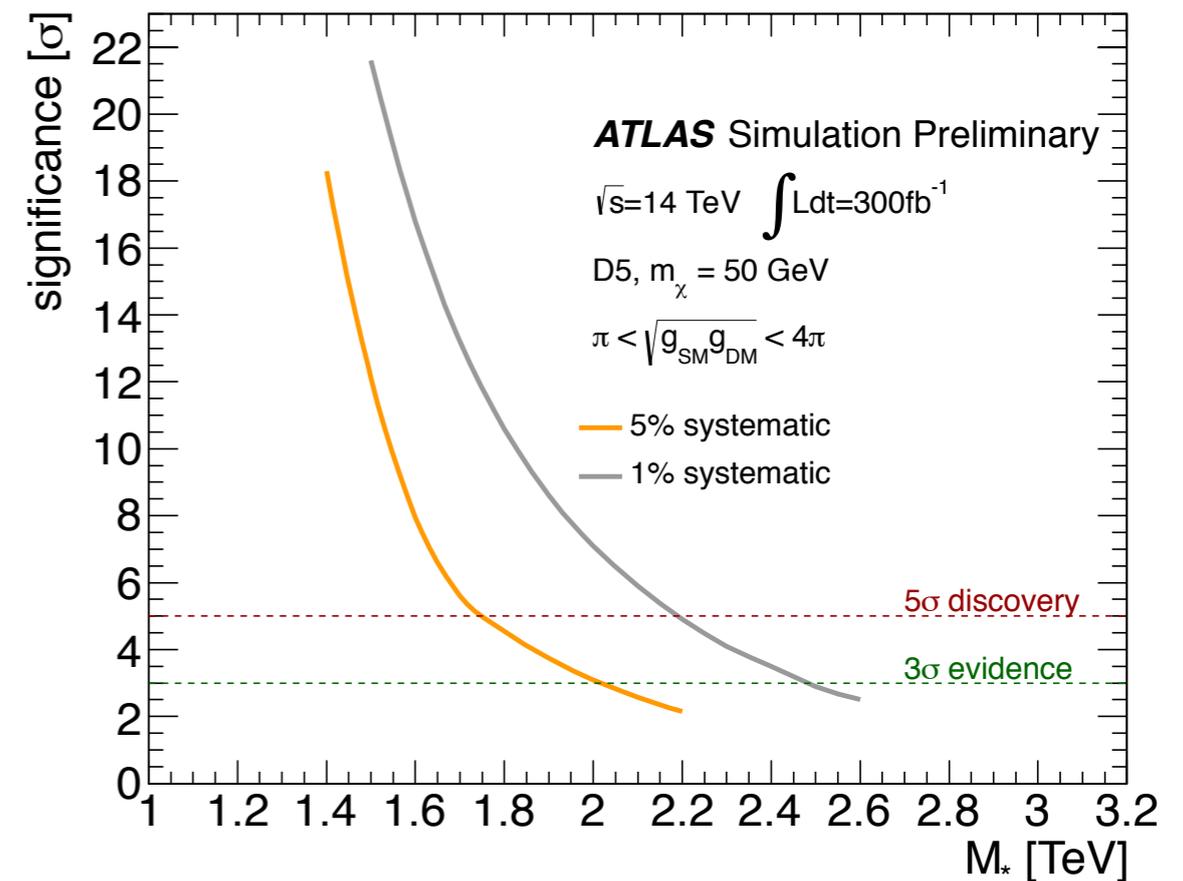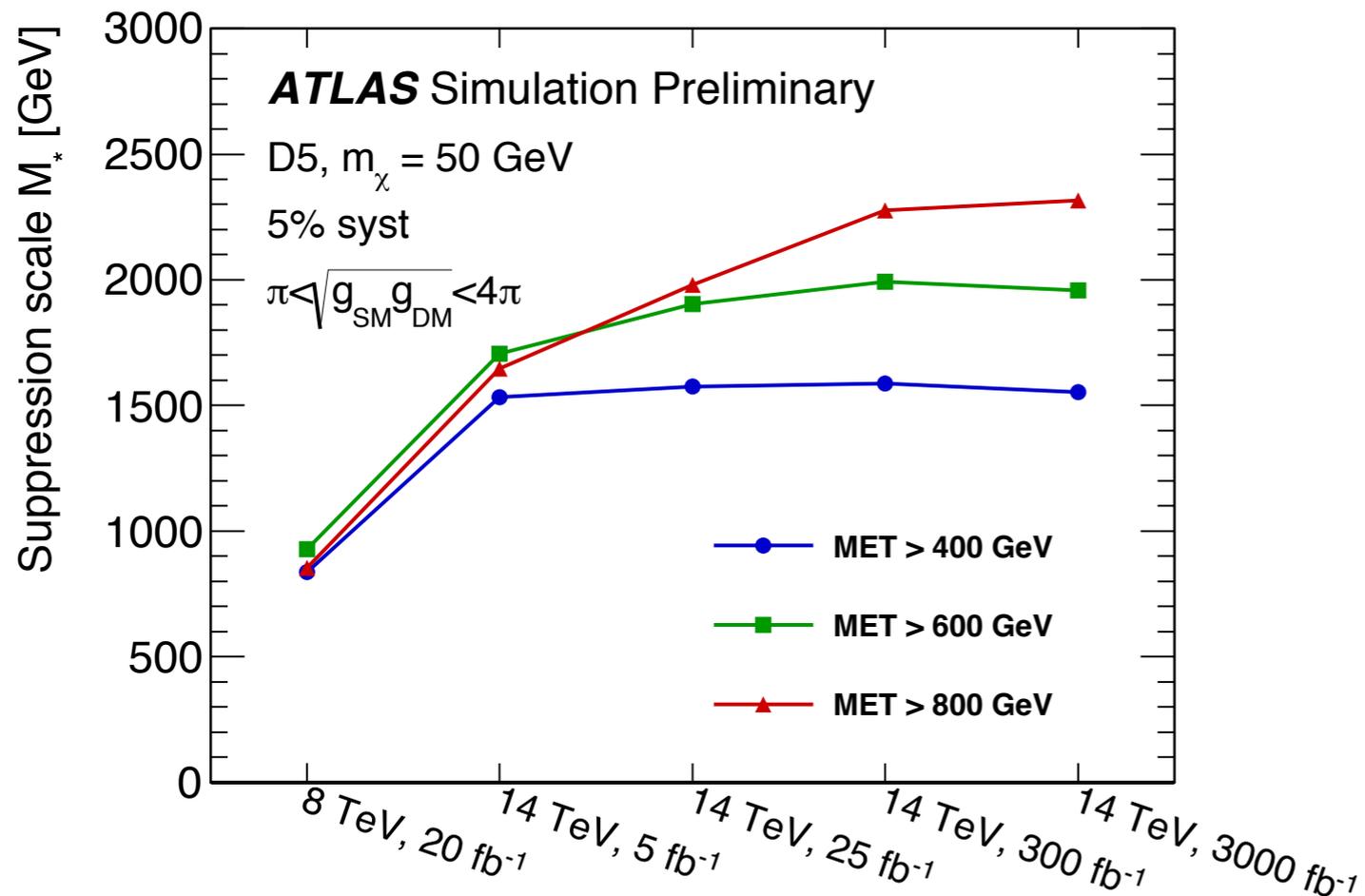
- pure MC study

## Systematic uncertainties

- 5% reasonable expectation for early Run-II

- 1% ultimate goal for HL-LHC

# mono-jet prospects @ 14 TeV

- Already first data from Run-II will bring improvements in sensitivity to DM.
  - Exclusion limits can be improved by factor of 2 with first few fb⁻¹.
  - 5σ discovery potential for M* ~ 1.7 TeV with 300 fb⁻¹.

# Summary

- ATLAS has probed various mono-X + MET final states in order to search for Dark Matter.

- Good agreement between data and Standard Model expectations are observed in all cases.

- Limits are set using Effective Field Theories and Simplified Models.

- Preliminary projections of DM @ 14 TeV in the mono-jet final states suggest the first data from Run-II will significantly increase sensitivity.

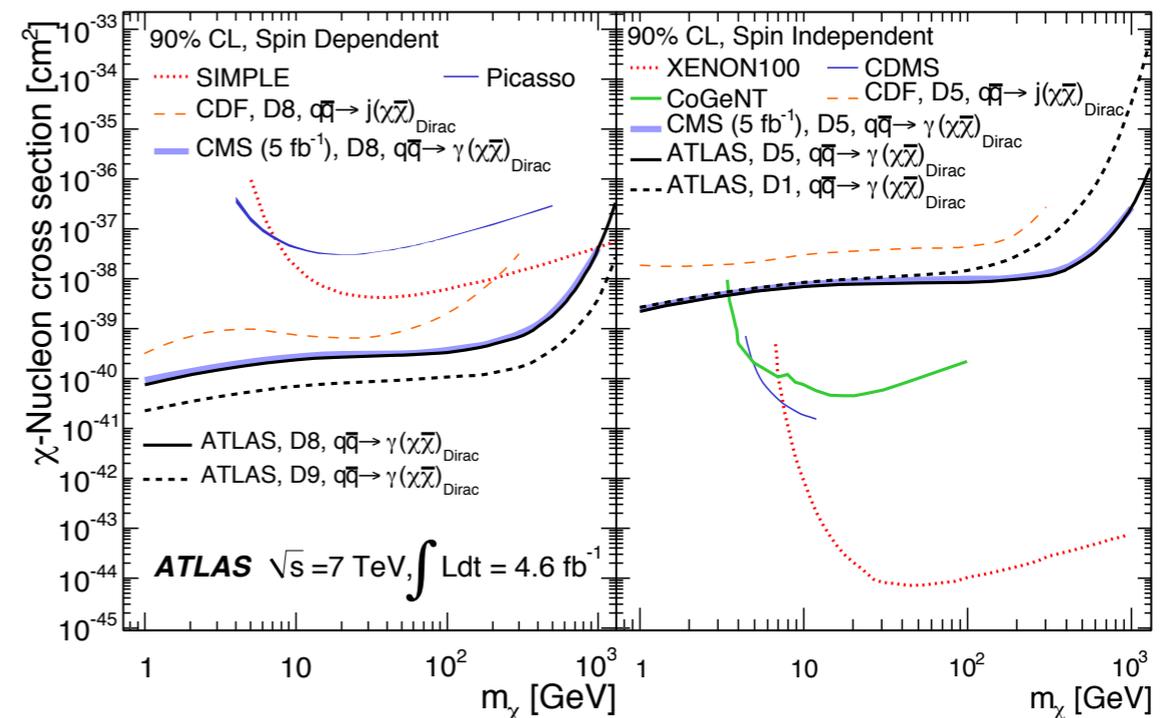# extra material
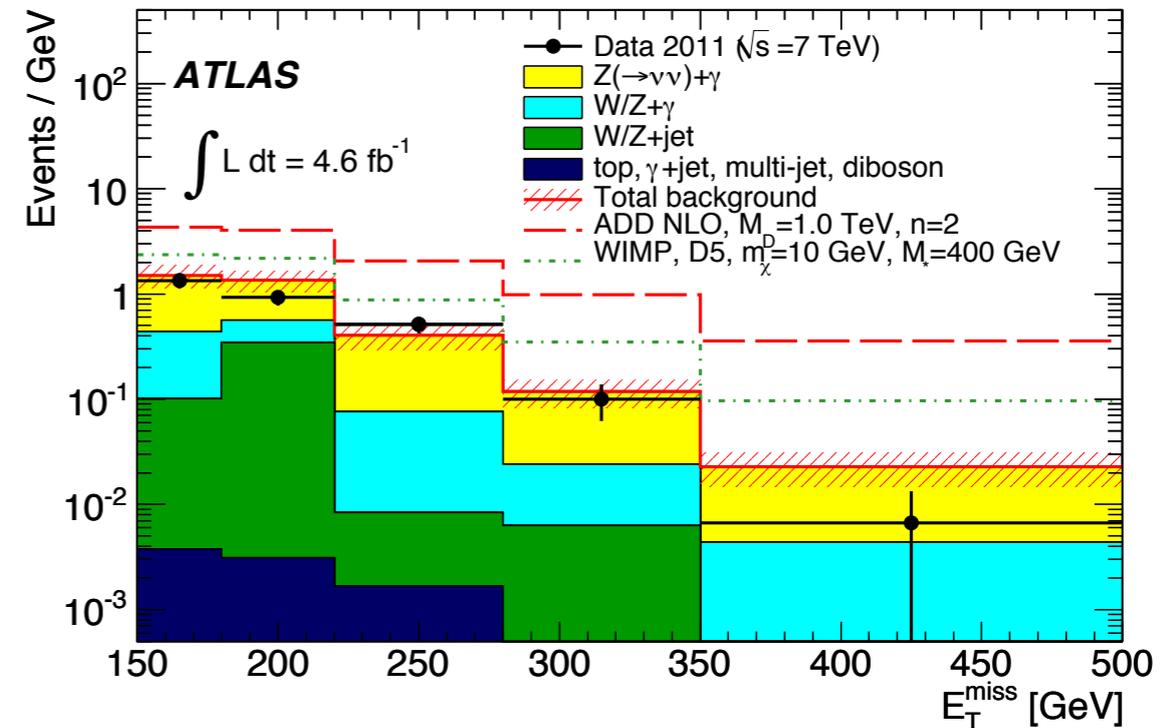
# mono-photon

## Event selection

- photon pT > 150 GeV

- at most 1 jet (pT > 30 GeV)

- MET > 150 GeV

## Dominant backgrounds

- $Z\nu\nu+\gamma$ and $W\ell\nu+\gamma$ from CR

## Uncertainties

- photon/jet energy scale, MET

- showering and hadronization

- statistics in CR

- total uncertainty 15%

# mono-jet