Dark Matter Searches at Colliders

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On behalf of ATLAS and CMS Collaborations

11th Patras Workshop on Axions, WIMPs and WISPs
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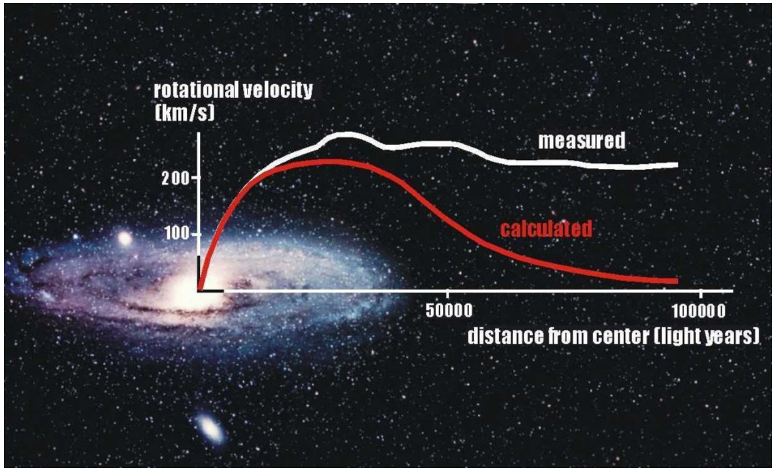
Outline

- Motivation for Dark Matter at colliders
- EFT and simplified models
- ATLAS and CMS Dark Matter searches
- Prospective for Run-II
- Conclusions

All ATLAS and CMS public results:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic
https://twiki.cern.ch/twiki/bin/view/CMSPublic

Motivation for dark matter

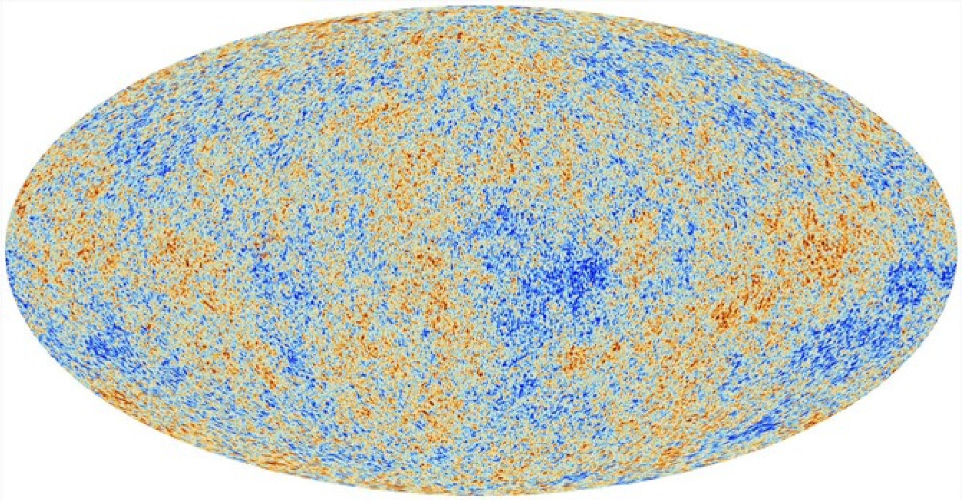


'Anomalous' galactic rotation curves

Gravitational lensing effect in deep field Hubble

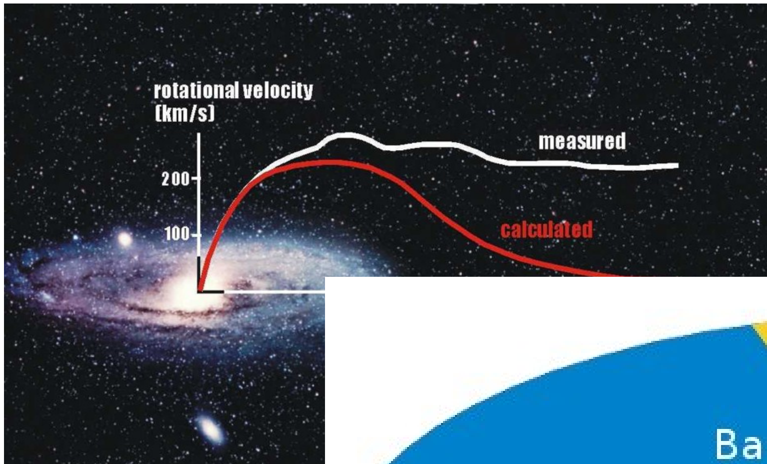
Should I really go through this slide?!

OK so dark matter exists and we all know it!

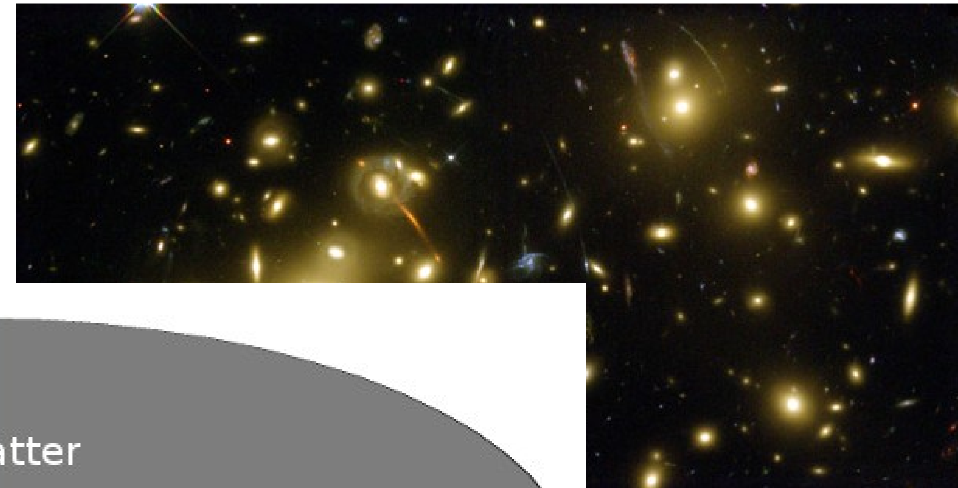


Planck 2013: Dark matter vs luminous matter from CMB anisotropy measurements

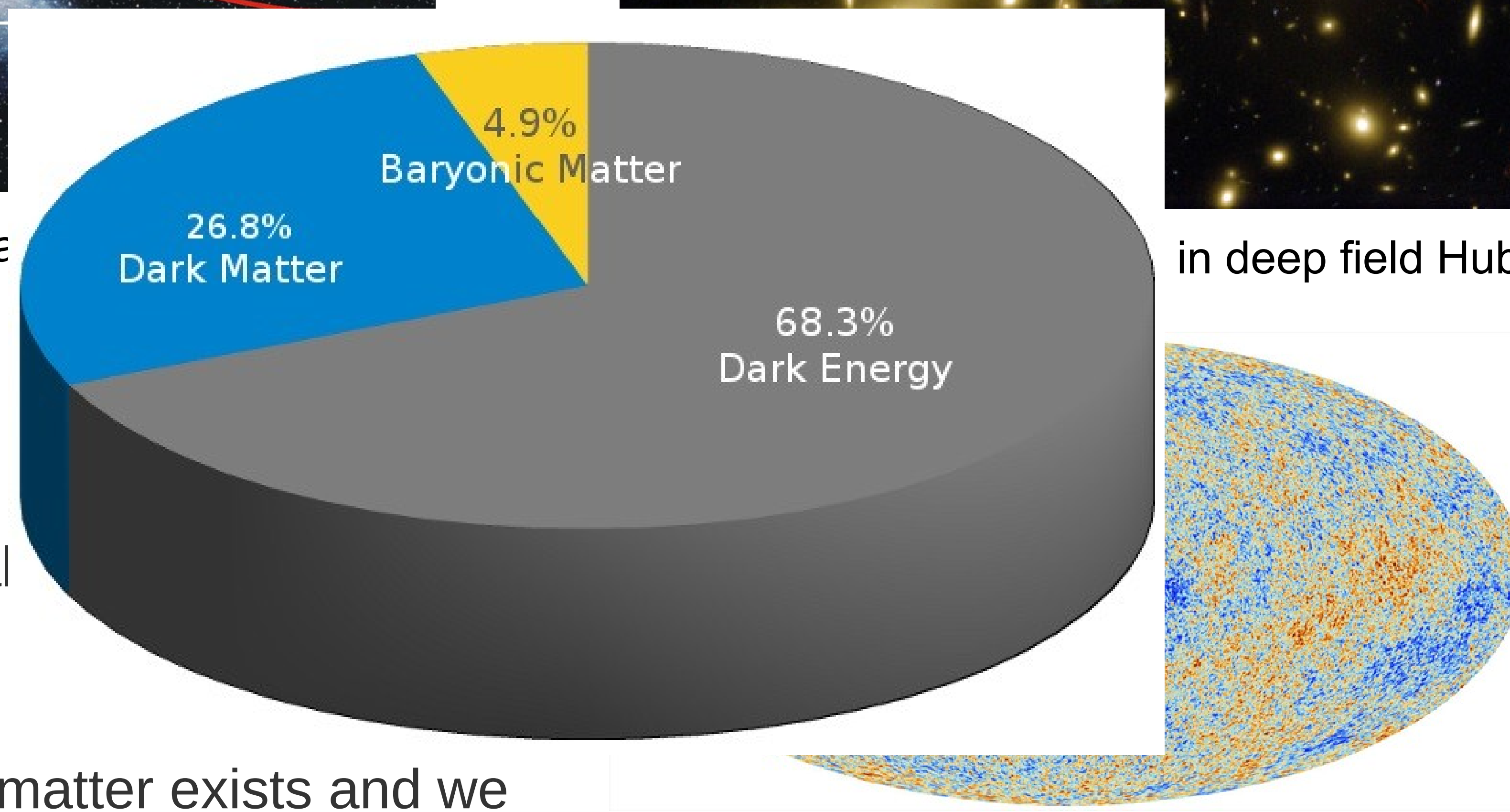
Motivation for dark matter



'Anomalous' ga



in deep field Hubble



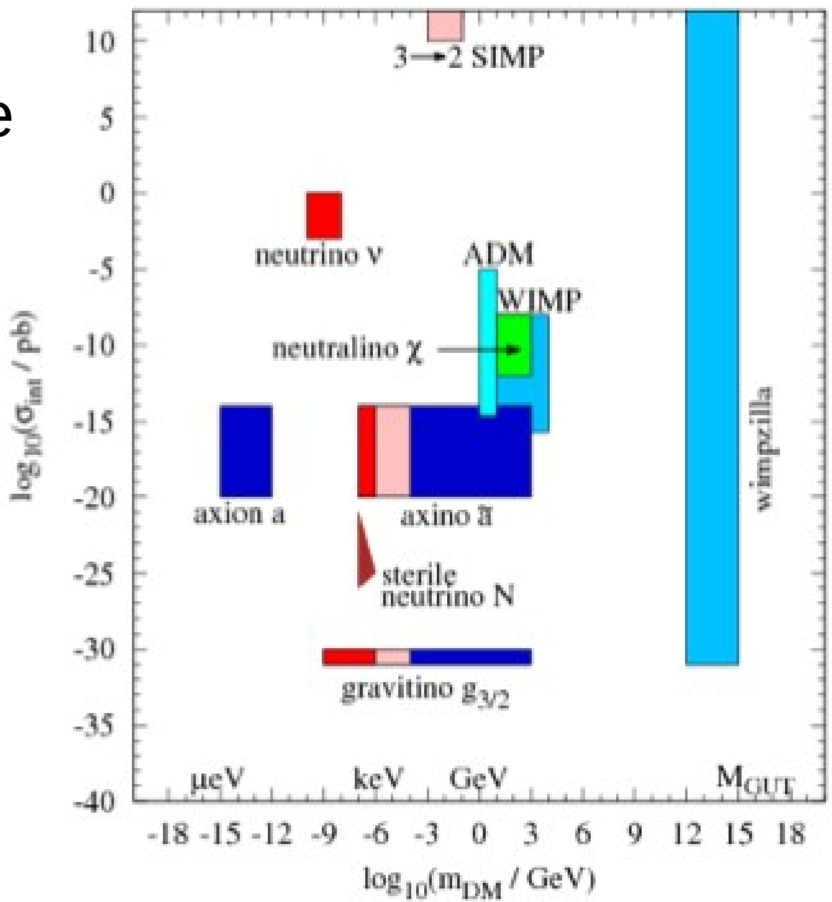
Should I real
slide?!

OK so dark matter exists and we all know it!

Planck 2013: Dark matter vs luminous matter from CMB anisotropy measurements

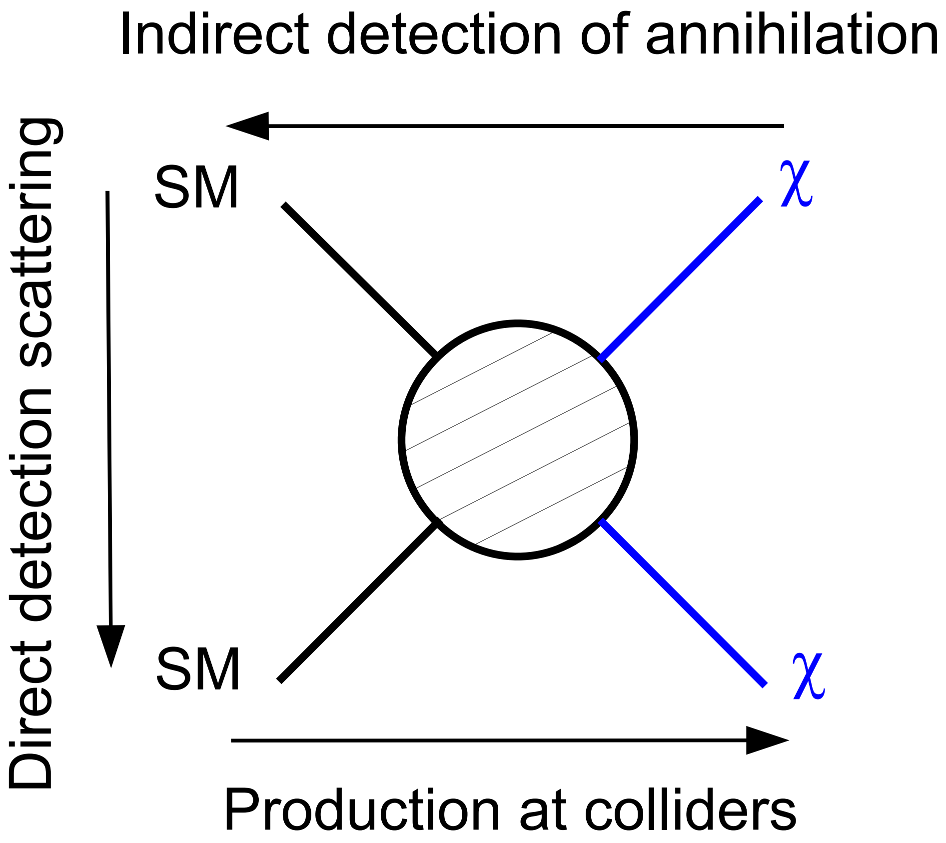
WIMP is “our” favourite candidate

- WIMP is even capable of doing a miracle
  - A cold thermal relic with weak scale mass (few GeV to few TeV) and interactions ($\langle\sigma v\rangle \approx 3 \times 10^{-26}$ cm^3/s)
  - Naturally accounts for the required relic abundance
  - The WIMP miracle!
- Other alternatives exist (axions, sterile neutrinos, etc) but they are not part of this talk. Also LHC SUSY searches involving missing transverse energy from LSP are not covered here.

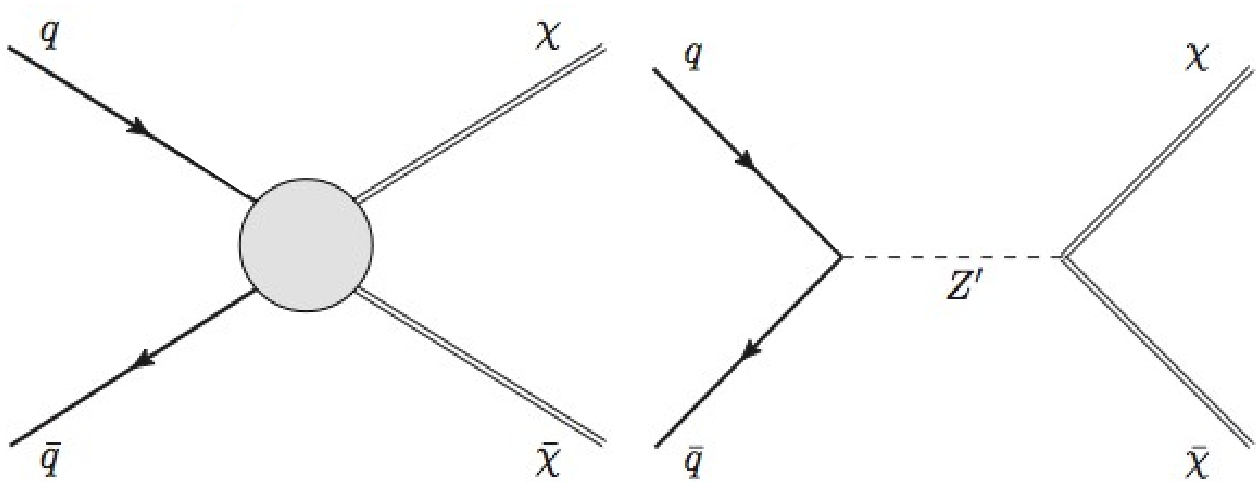


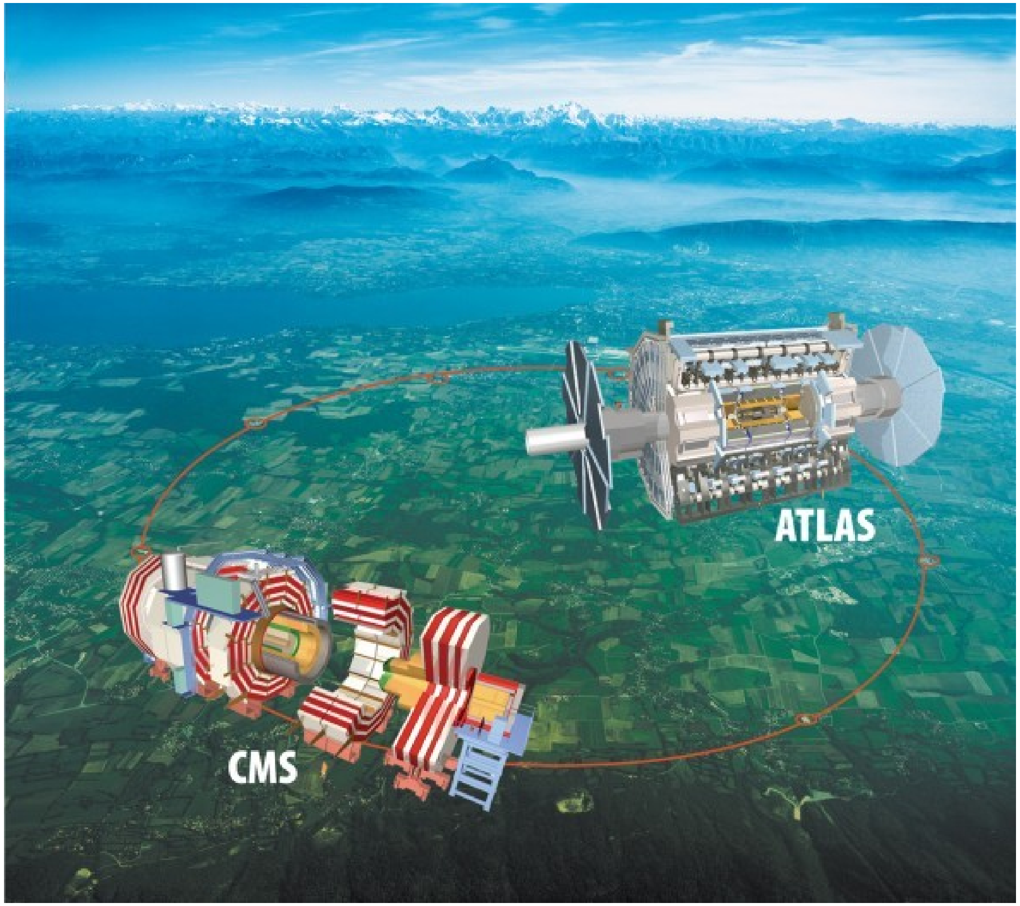
WIMP – SM interactions and detection

- Some kind of interaction is expected between WIMPs and SM particles
- Current experiments probe different scales:
  - Direct detection *O*(10 MeV)
  - Indirect detection *O*(100 GeV)
  - Colliders *O*(1TeV)
- They are complementary under some conditions



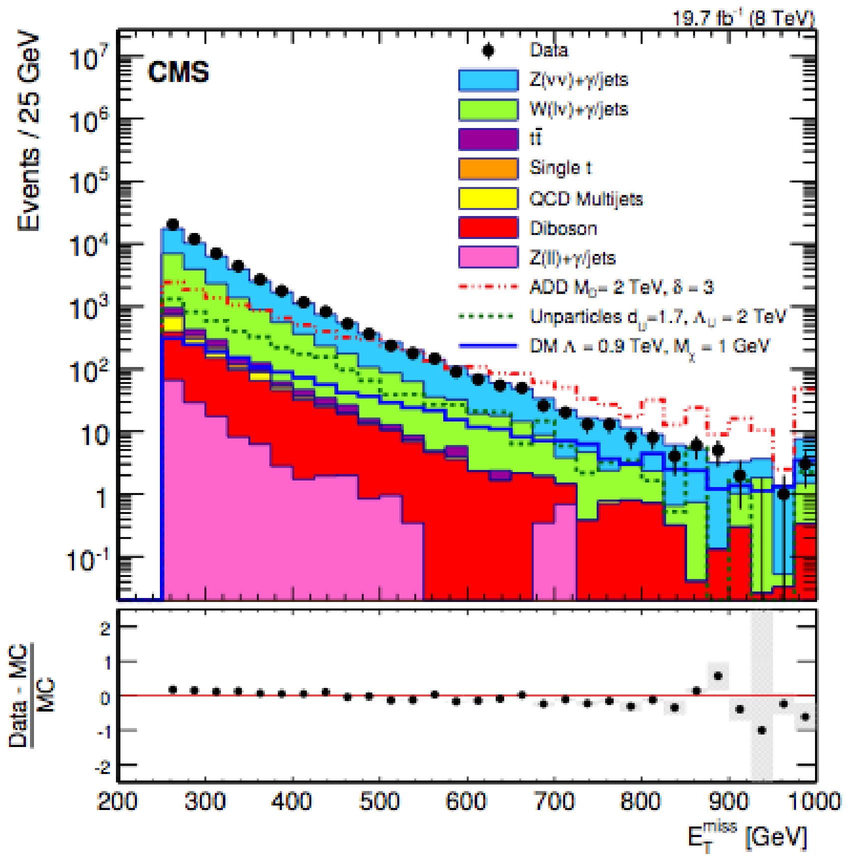
- EFT operators are convenient for representing DM - SM interactions with very few parameters: scale of the interaction M_* (or Λ) and DM mass, e.g. $L_{eff} = \frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
- These operators could arise from integrating out the heavy-mediator with mass $M_{\mathrm{med}} = \sqrt{g_{\mathrm{q}} g_\chi} M_\star$
- EFT approach is valid for a momentum transfer $Q_{\mathrm{tr}} < M_{\mathrm{med}}$
- Simplified models constitute a good alternative but involve additional parameters (mediator mass, couplings, and decay width)

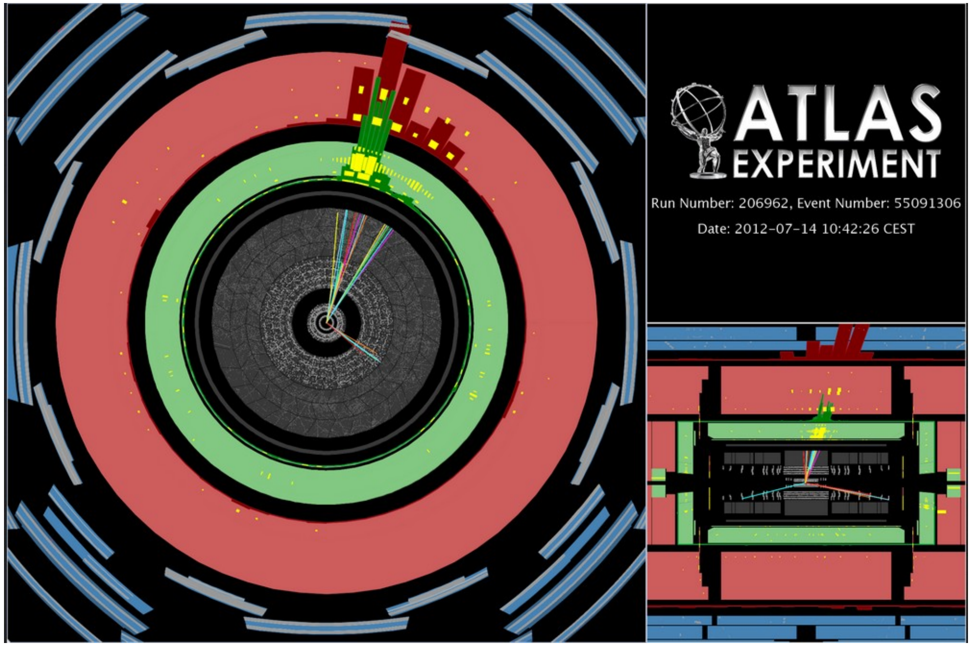




ATLAS and CMS are general-purpose experiments with nearly full solid angle coverage and excellent performance for tracking, calorimetry and muon spectrometer

- Dark Matter searches at ATLAS and CMS could be categorized in three main lines (not fully independent though):
  - Mono-X searches (X=boson)
  - DM with heavy flavour
  - Higgs to invisible searches in Higgs-DM portal models
- Results are interpreted using EFT (with or without truncation $Q_{\mathrm{tr}} < M_{\mathrm{med}}$) and using simplified models





Typical analysis strategy:

- Select events with high pT jet(s) and large transverse momentum
- Veto electrons/muons/(taus and tracks) to reject leptonic W/Z decays.
- Cut and count experiment at different pT and MET thresholds.

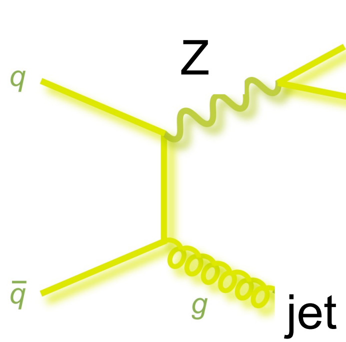
- Main backgrounds:

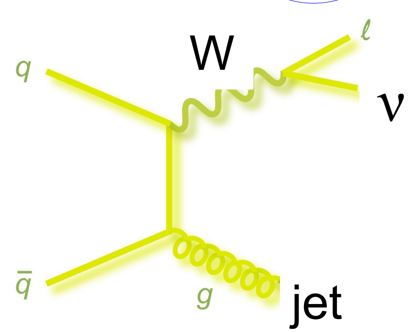
  Z(νν)+jets, W(lν)+jets with lost lepton
- Estimation of the EW background is based on leptonic W/Z control regions
- Transfer factor method:

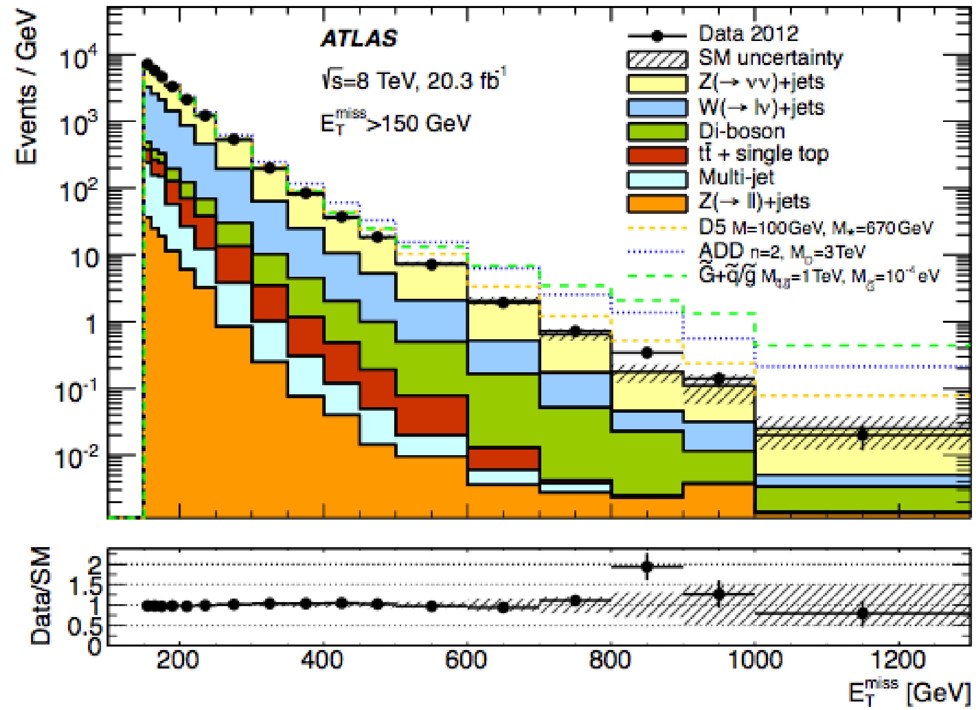
MC TF

$$N_{\mathrm{SR}}^{\mathrm{predicted}} = (N_{\mathrm{CR}}^{\mathrm{Data}} - N_{\mathrm{Bkg}}) \cdot C \cdot \frac{N_{\mathrm{SR}}^{\mathrm{MC}}}{N_{\mathrm{jet}/E_{\mathrm{T}}^{\mathrm{miss}}}^{\mathrm{MC}}}$$

Correction factor





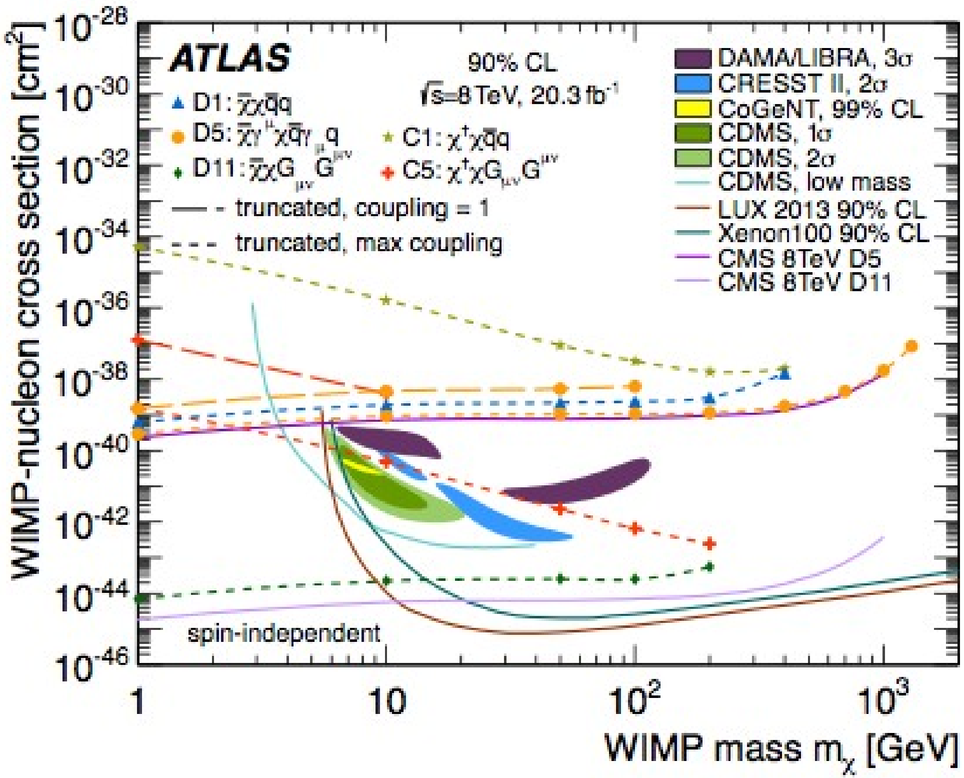


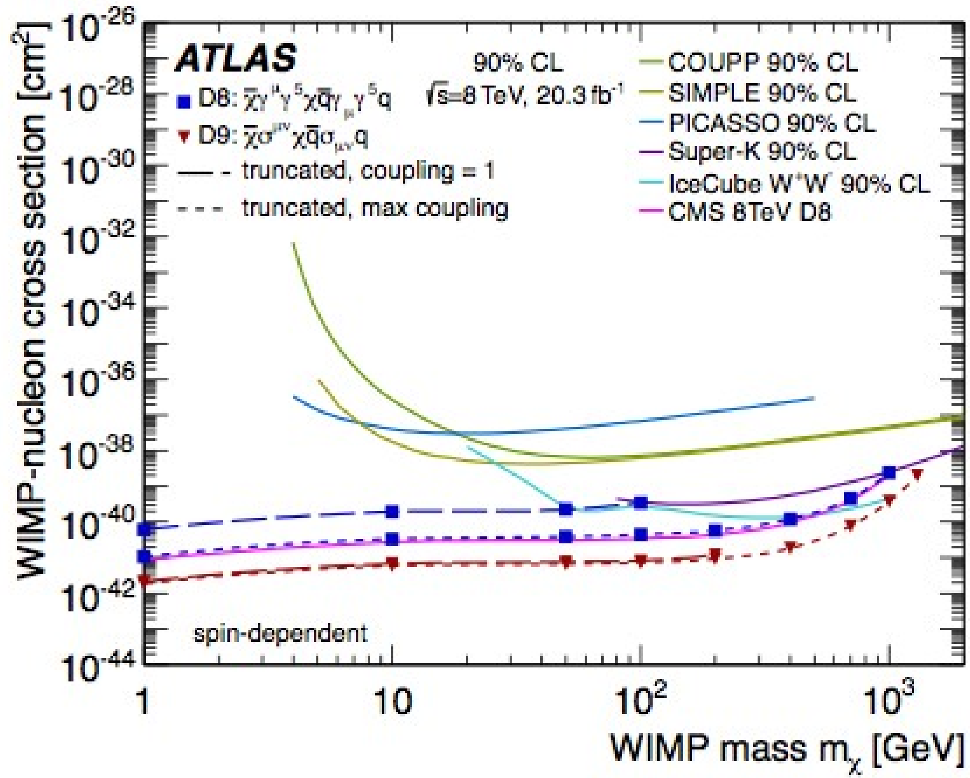
- Theoretical and experimental uncertainties largely cancel out in the TF
- Statistical uncertainties from CR usually take over the systematics (particularly at high MET)

Monojet EFT results

ATLAS: arXiv:1502.01518

CMS: arXiv:1408.3583



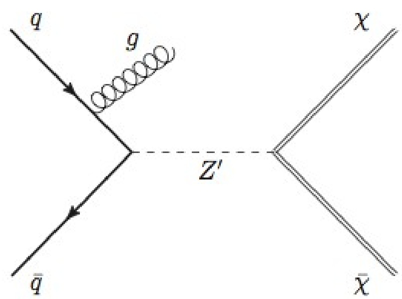


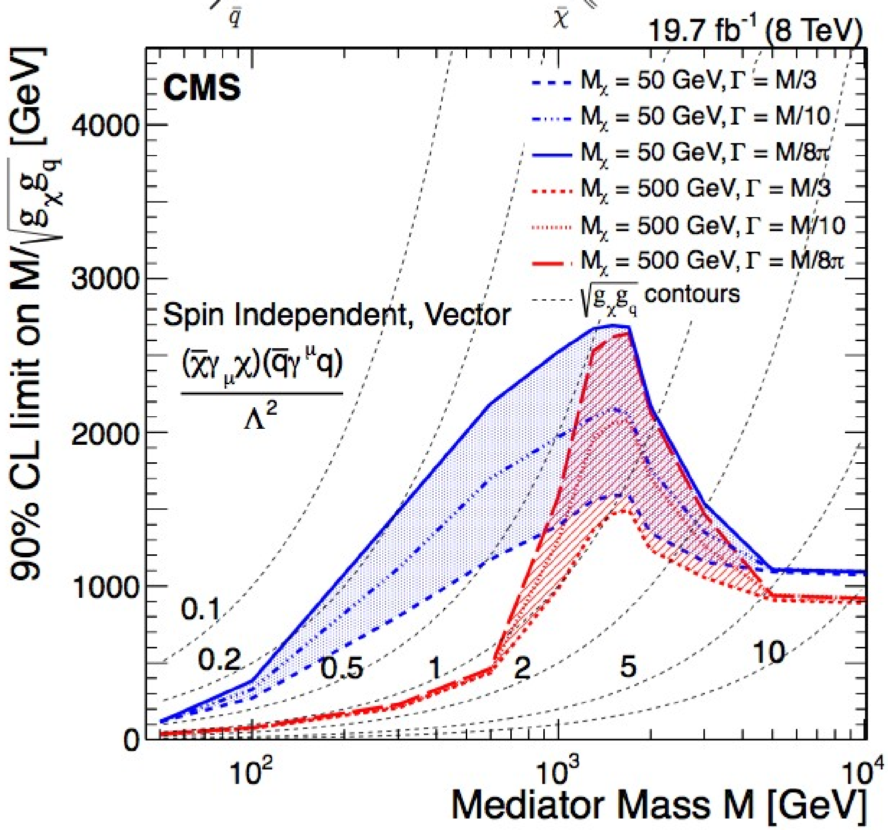
- Results are interpreted in terms of exclusion limits on WIMP-nucleon cross section
- ATLAS limits are done with the truncation $Q_{\mathrm{tr}} < M_{\mathrm{med}}$. Need agreement on common procedure.

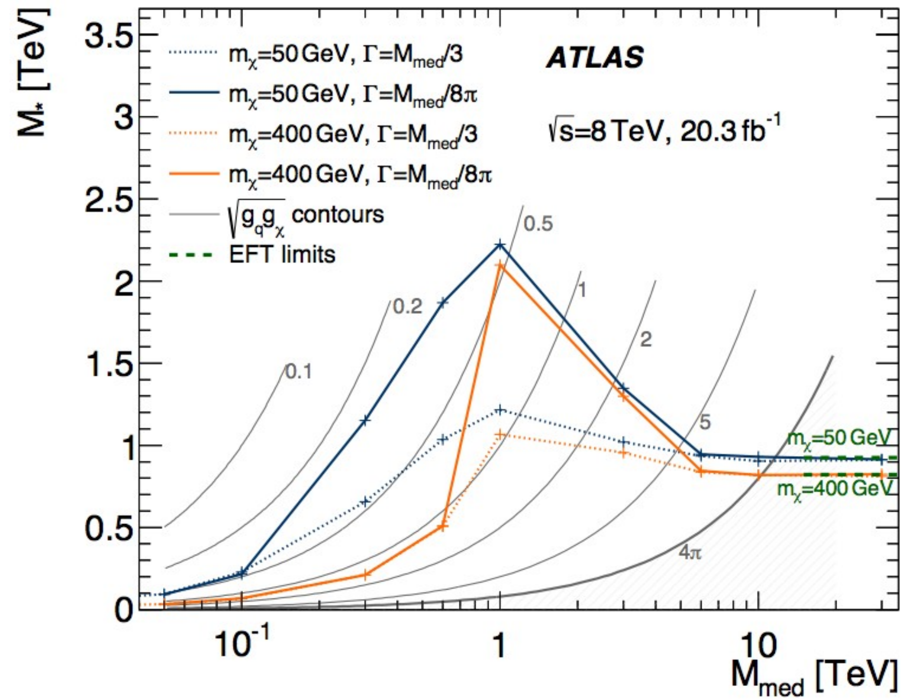
Monojet simplified model results

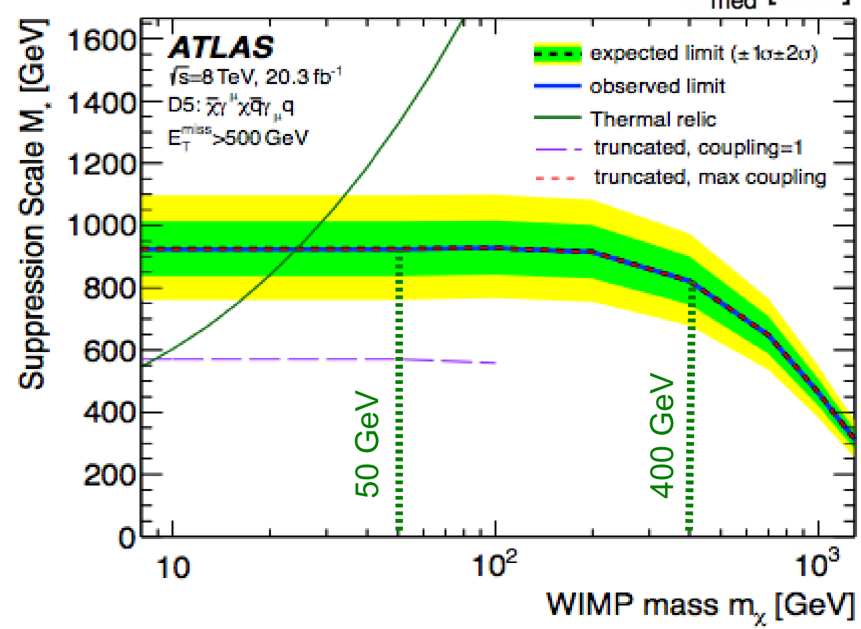
ATLAS: arXiv:1502.01518

CMS: arXiv:1408.3583







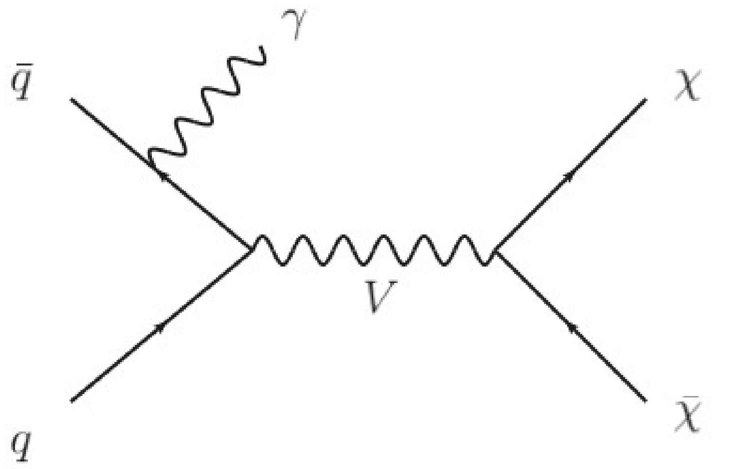


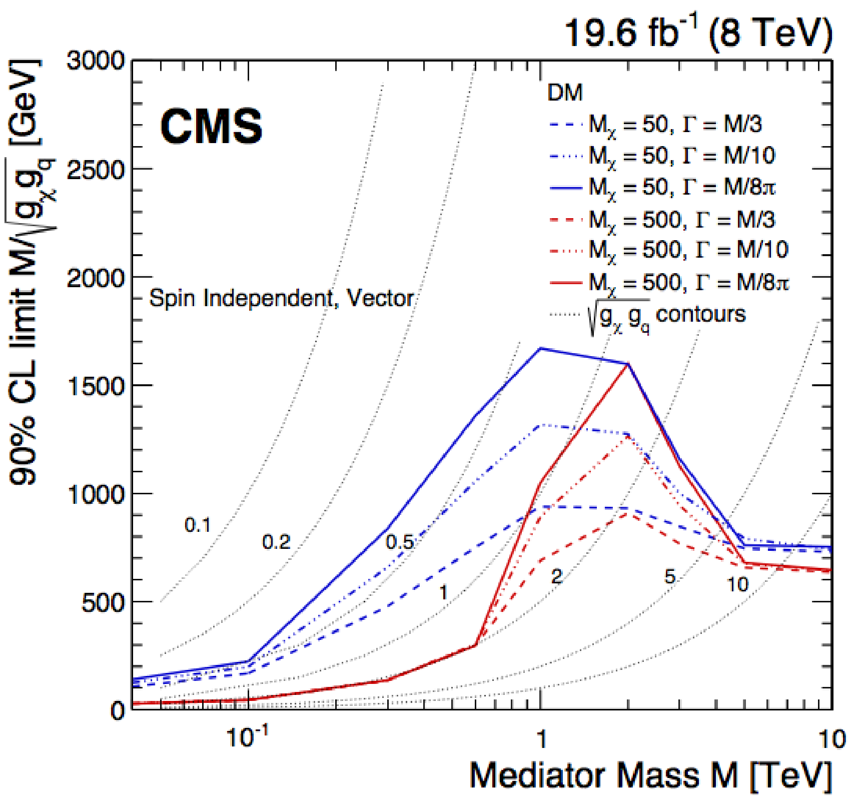
- Limits on M_* sensitive to mediator mass
- For $M_{med} > 5$ TeV, EFT limit of M_*~1 TeV is retrieved

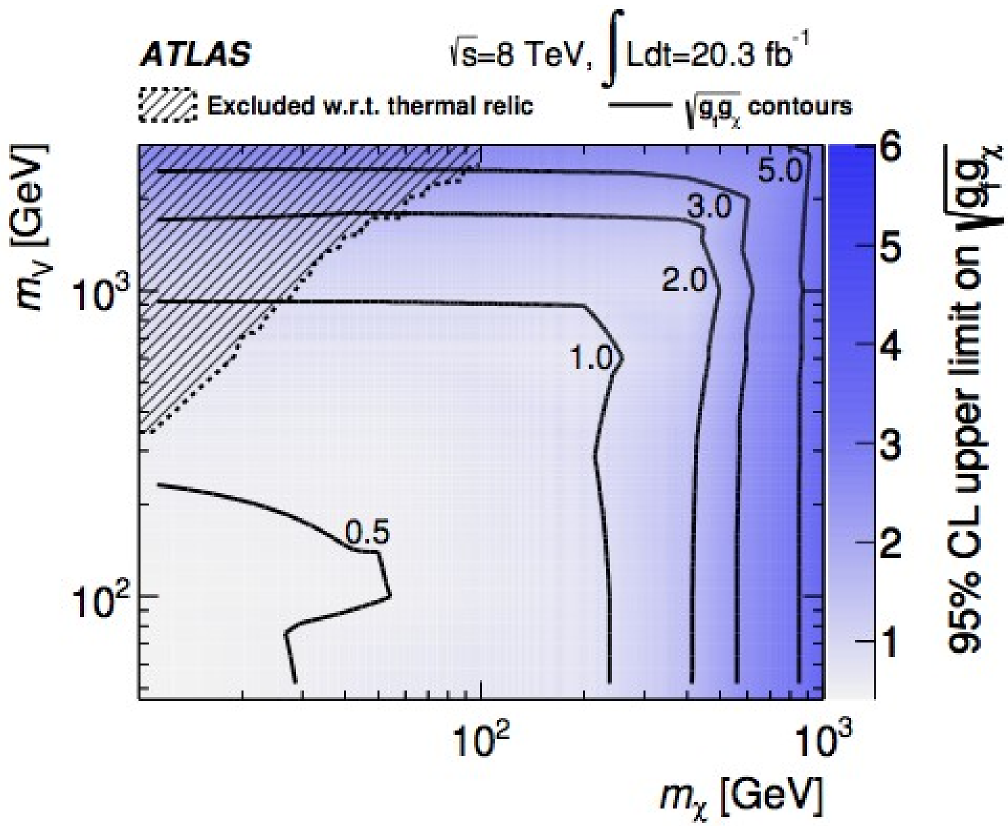
Monophoton simplified model results

ATLAS: PRD 91, 012008 (2015)

CMS: arXiv:1410.8812

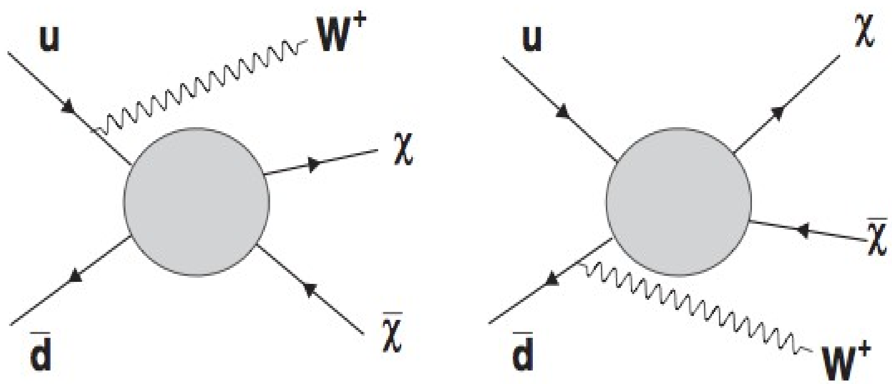


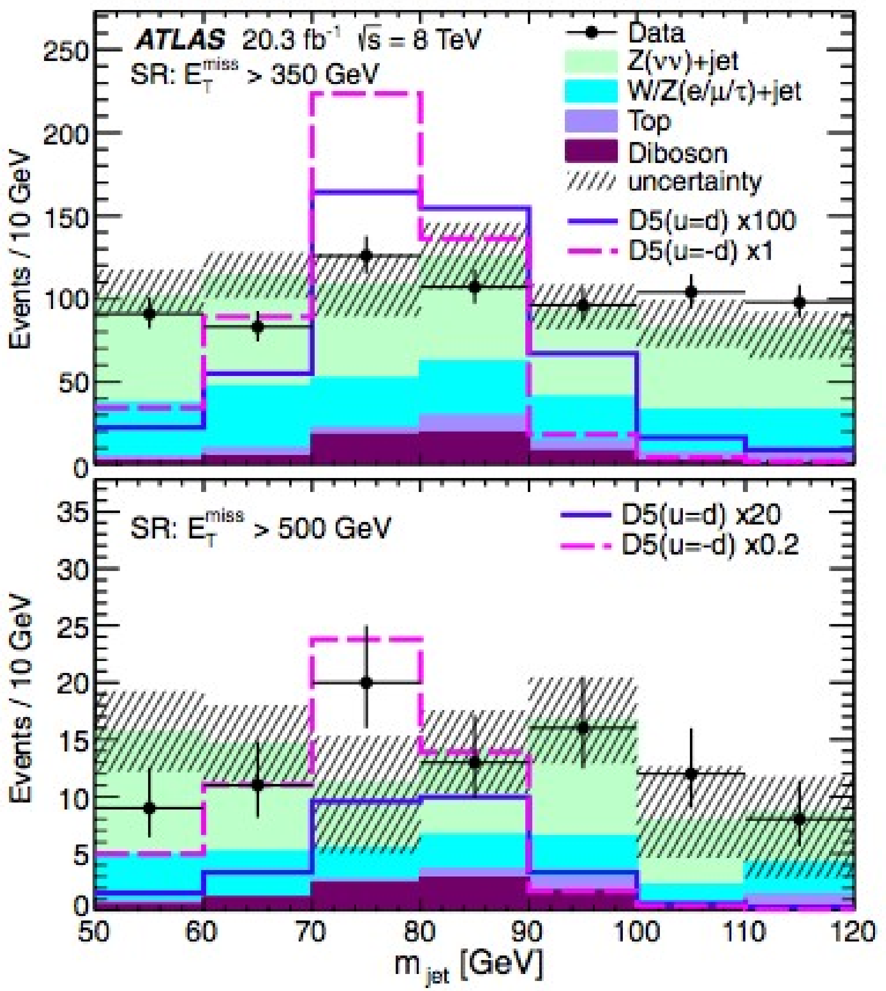




- Signal from photon emission in the initial state and large MET
- Background estimated from CR
- EFT results also available

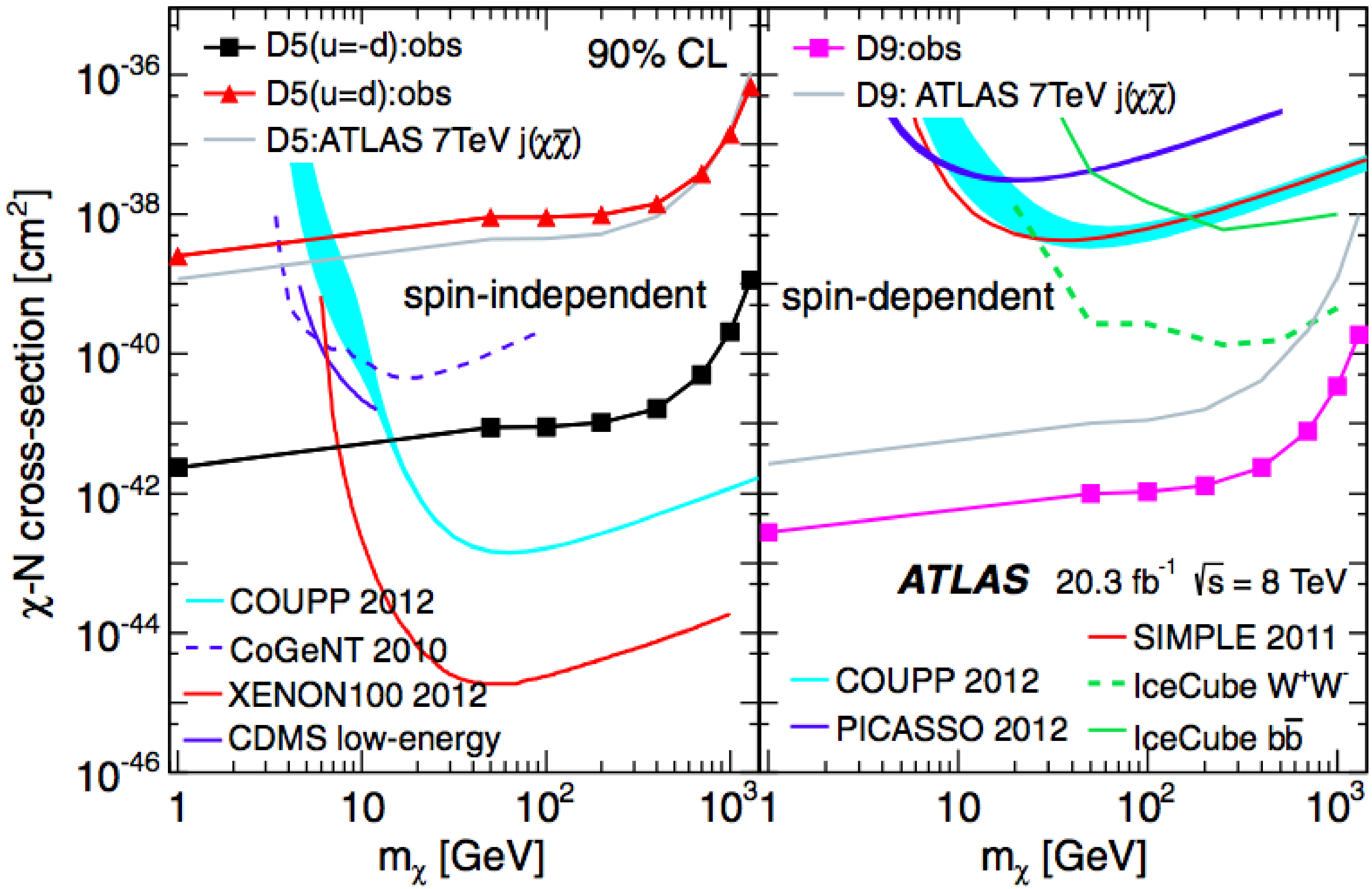
ATLAS: PRL 112, 041802 (2014)





- High boson pT with high missing transverse energy
- Boosted regime: use single fat jet ($\Delta R=1.2$) for W/Z → jj reconstruction
- Constructive and destructive interference in W diagrams play important role

MET+W/Z → hadrons limits

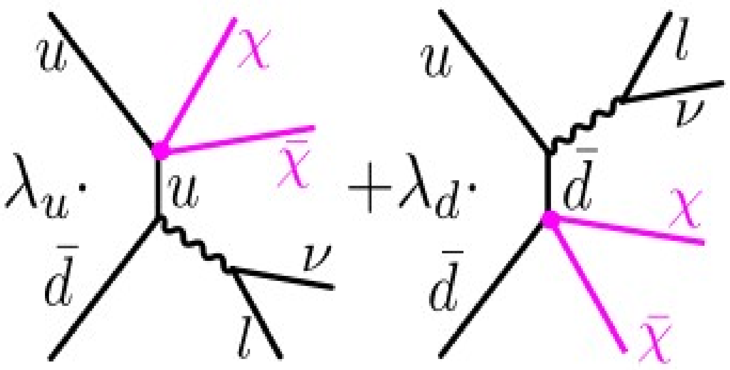


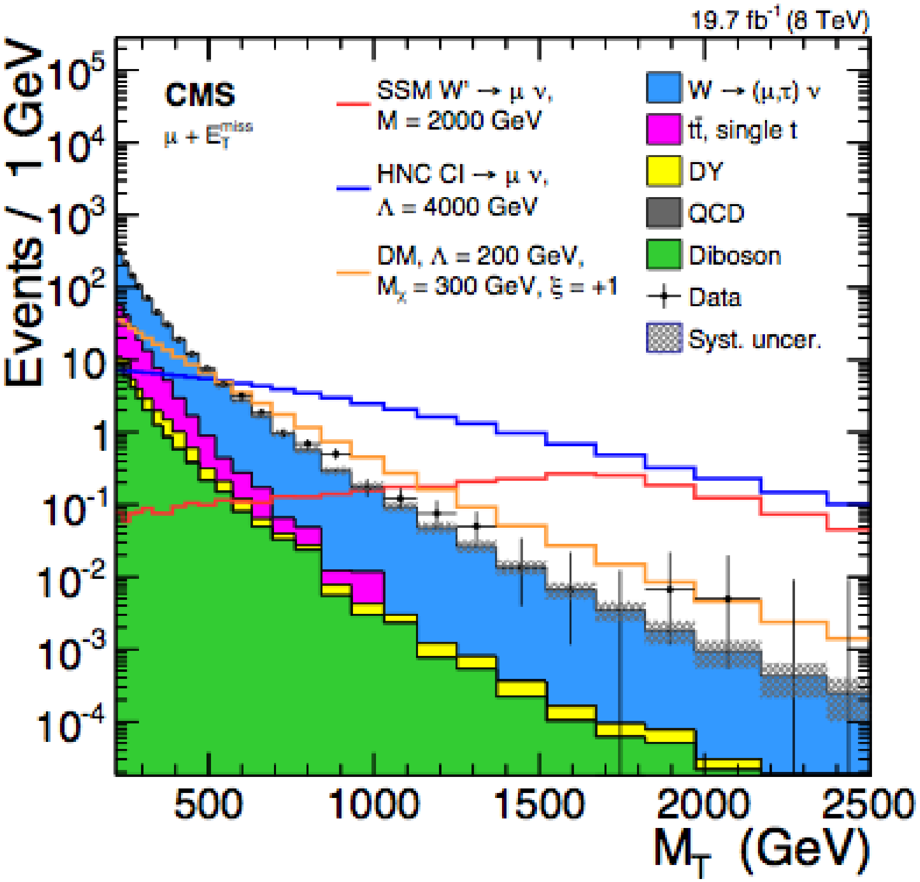
- Strong limits in the case of constructive interference.

MET+W/Z → leptons

ATLAS: PRD 90, 012004 (2014), JHEP 09 (2014) 037

CMS: arXiv:1408.2745



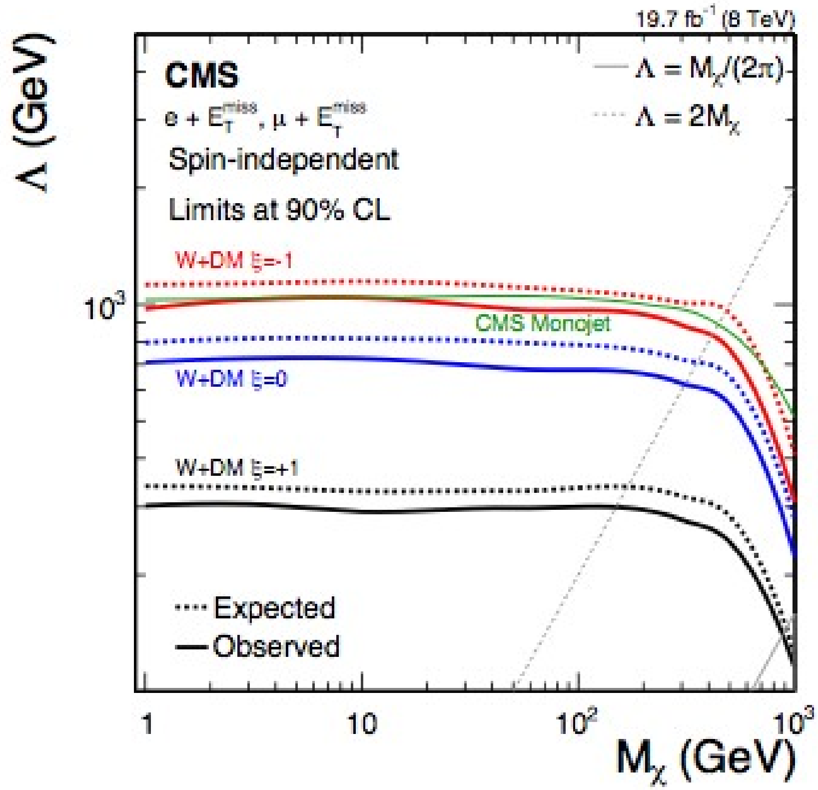


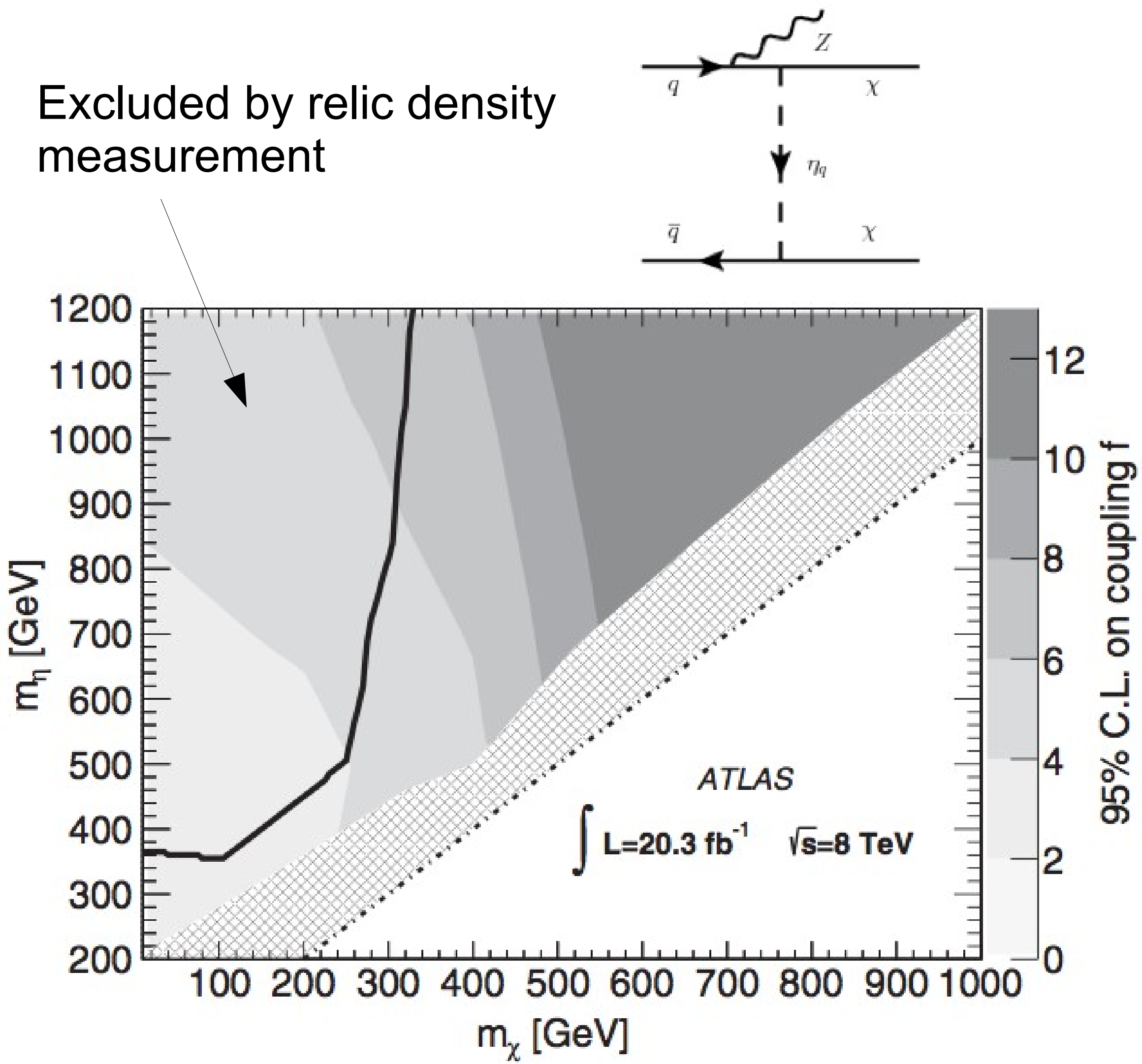
- Dark Matter production with W/Z-boson decaying to leptons
- Bosons recoil against the pair of dark matter → look for excess of events at high MET
- Use transverse mass M_T for W and invariant mass M_{ll} for Z as discriminant

MET+W/Z → leptons

ATLAS: PRD 90, 012004 (2014), JHEP 09 (2014) 037

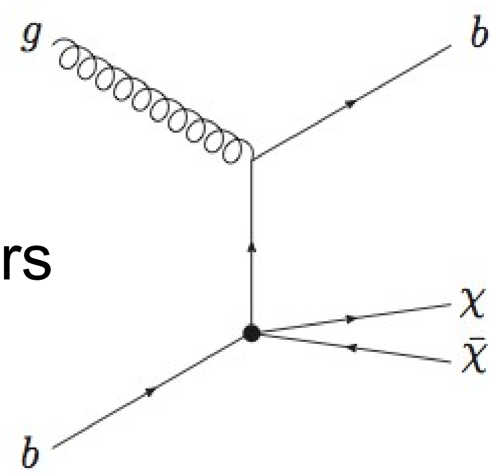
CMS: arXiv:1408.2745

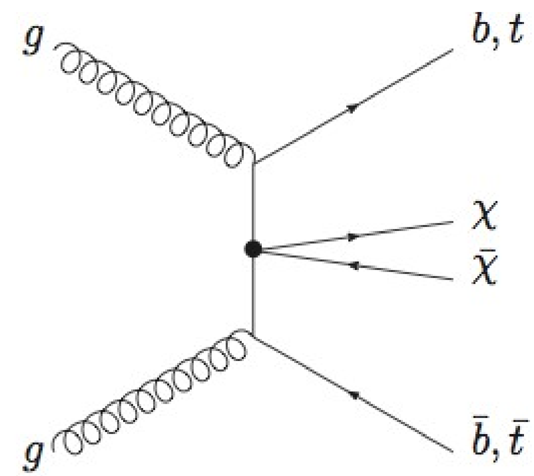




- Limits on the suppression scale as a function of dark matter mass
- Also simplified model limits in the scalar-mediator theory

DM with heavy flavour





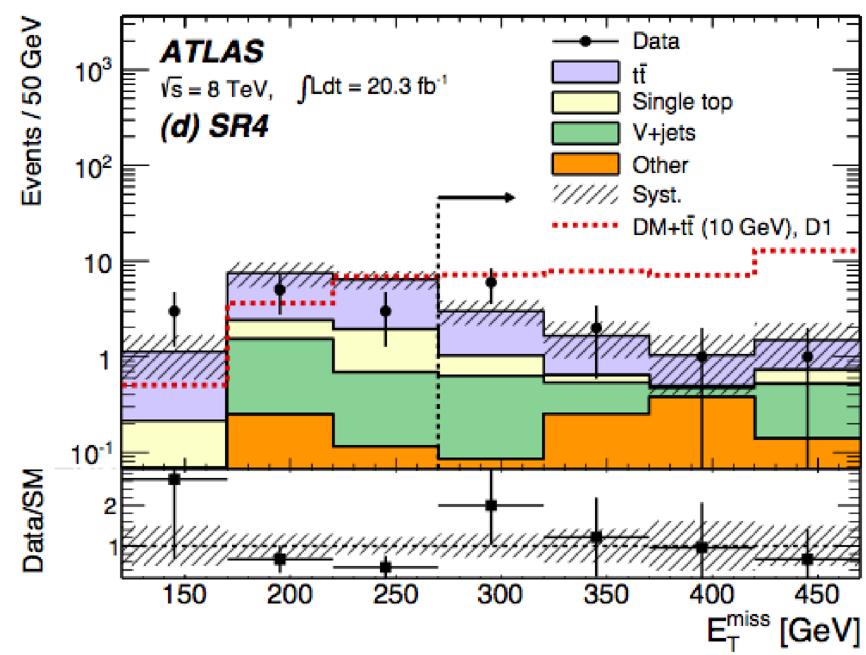
- Some EFT operators enhanced for heavy flavours

$$\mathcal{O}_{\text{scalar}} = \sum_q \frac{m_q}{M_*^N} \bar{q} q \bar{\chi} \chi,$$

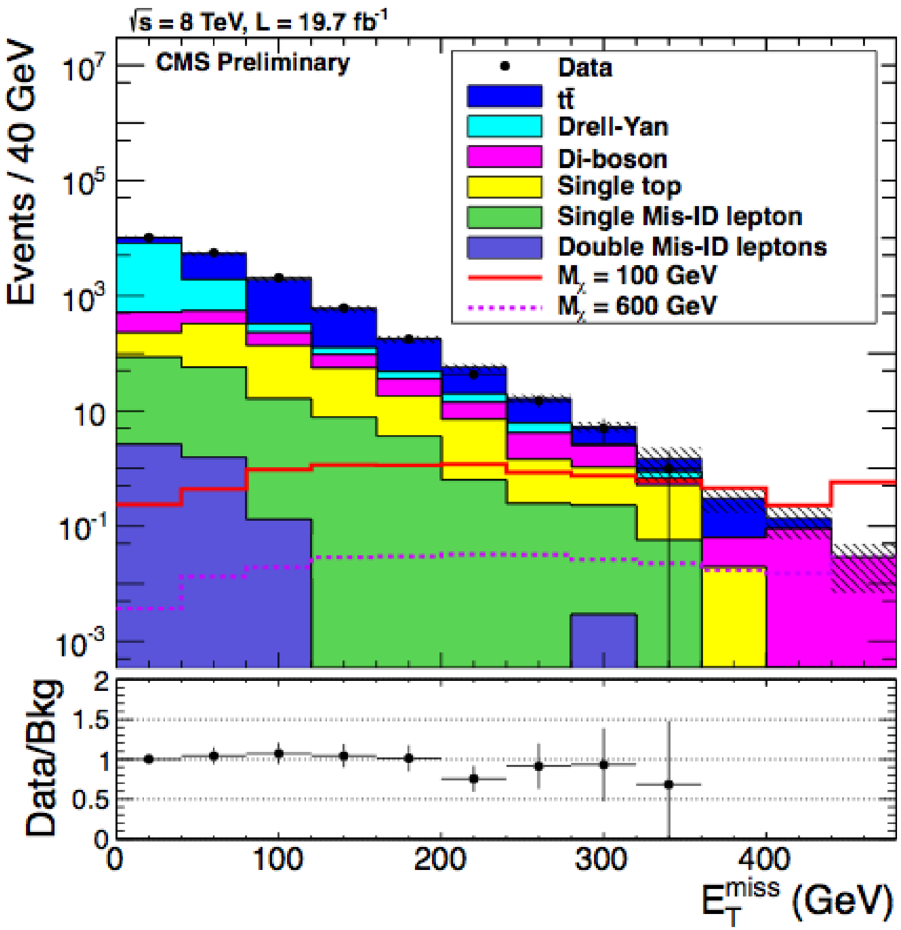
- May arise from from integrating out a scalar mediator with couplings proportional to quark mass m_q.

- Look for events with high MET and b-tagged jet(s)

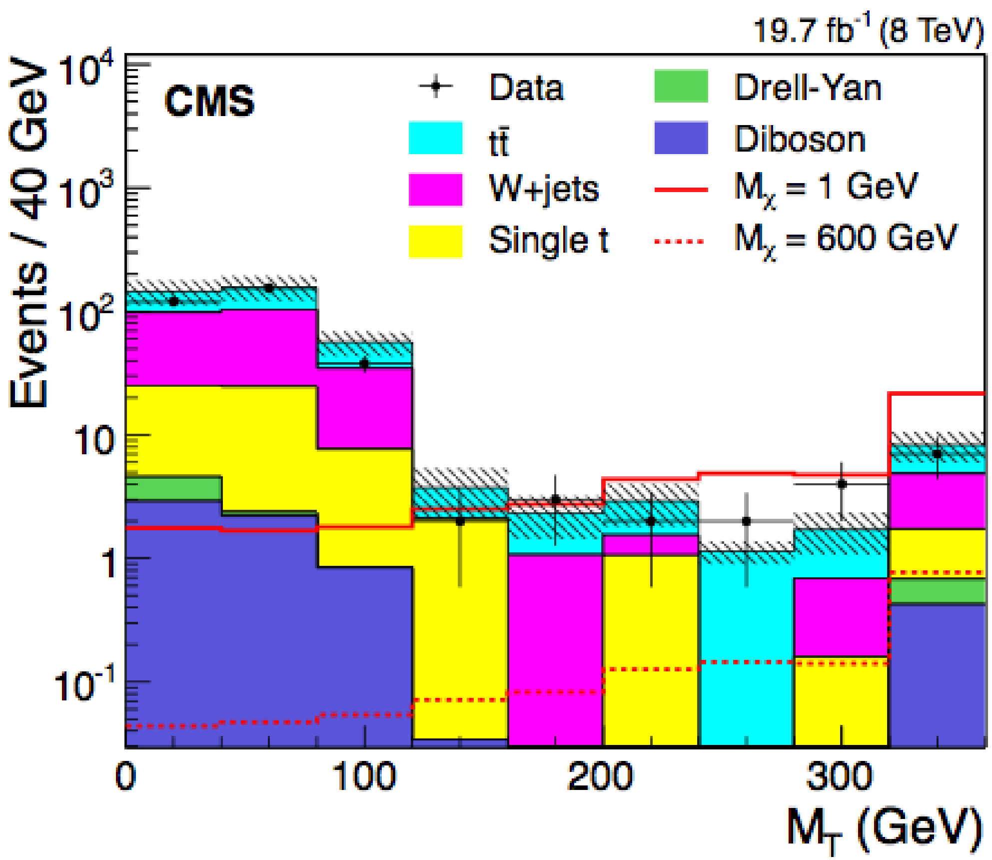
- Signal regions normalized from control regions



Full leptonic ttbar



Semi-leptonic ttbar



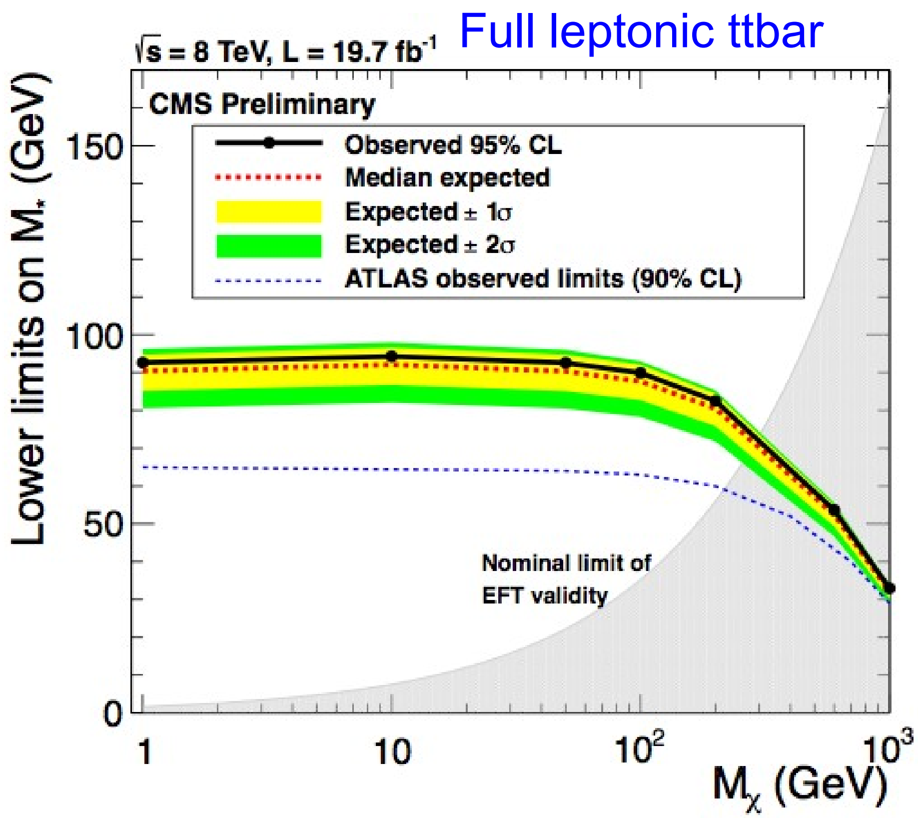
- Different analysis approaches for the different ttbar decay channels (all-hadronic, semi-leptonic and di-leptonic)

DM with heavy flavour

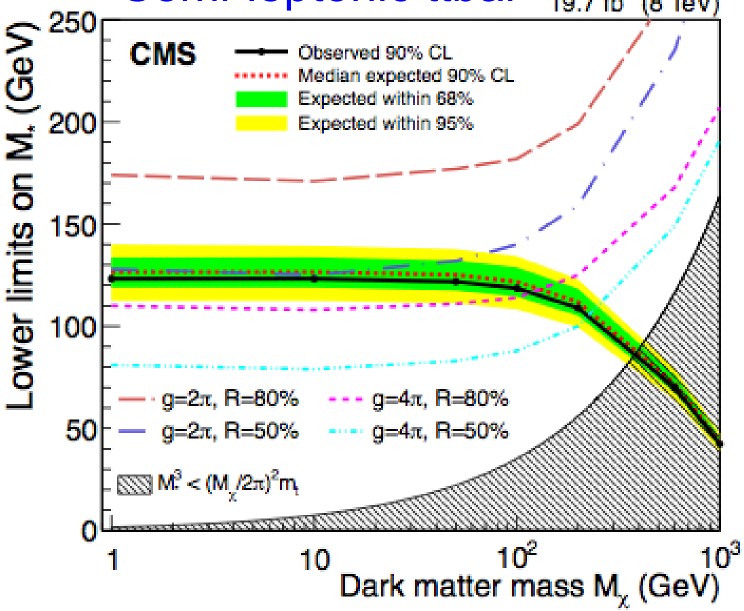
ATLAS: EPJ 75:92

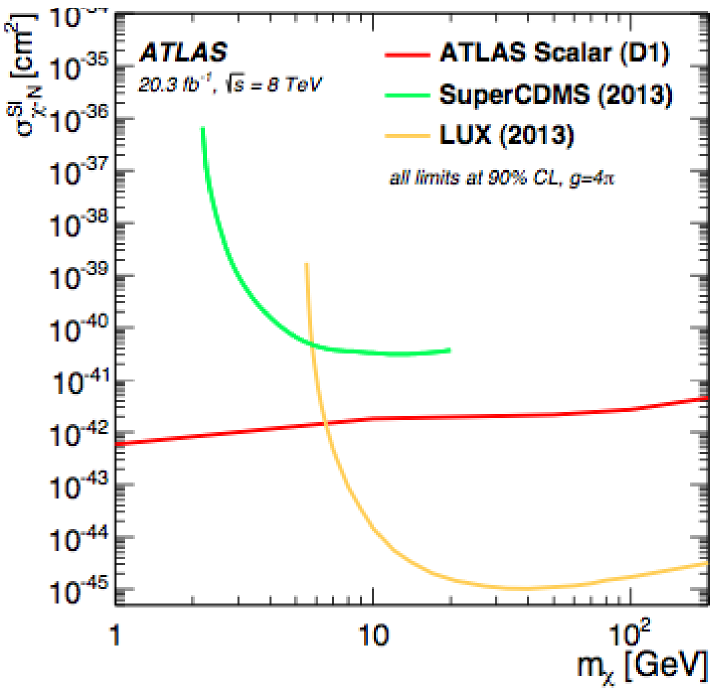
CMS: CMS-PAS-B2G-13-004, arxiv:1504.03198

Full leptonic ttbar



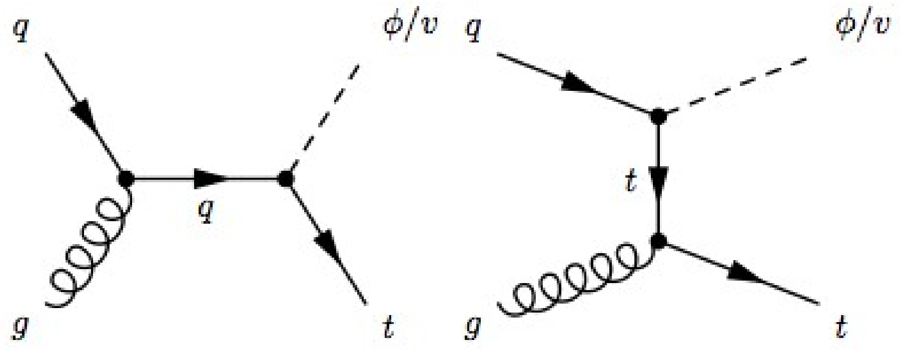
Semi-leptonic ttbar

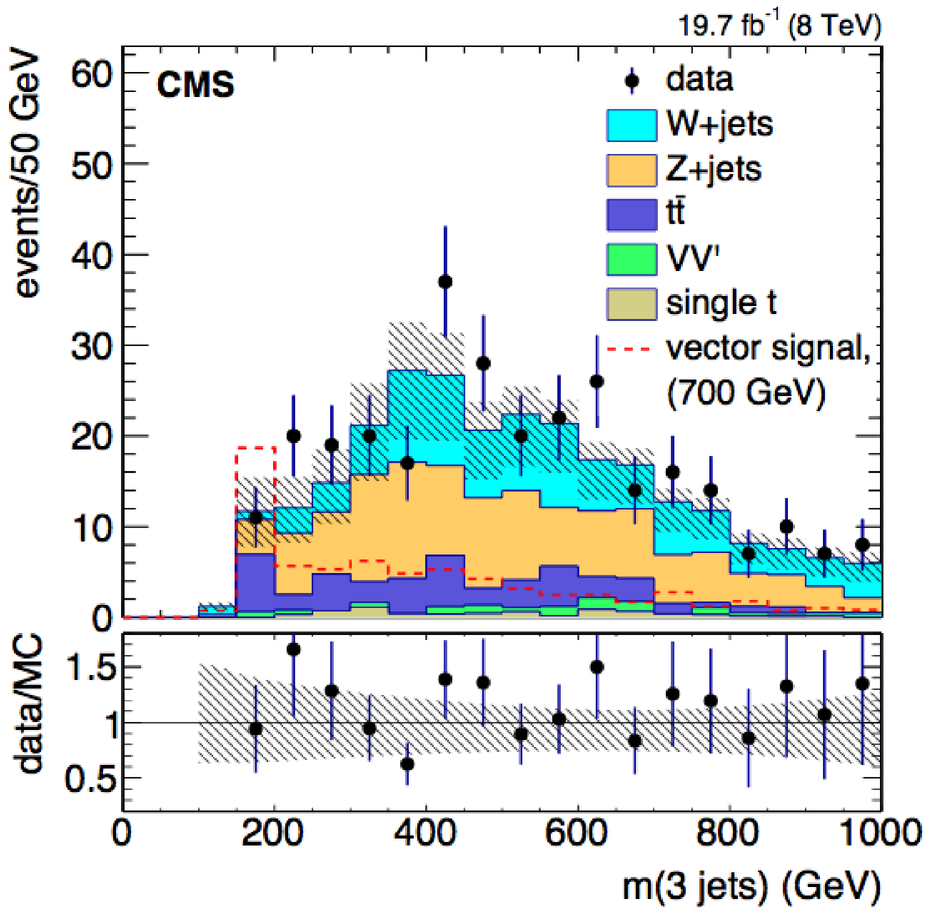


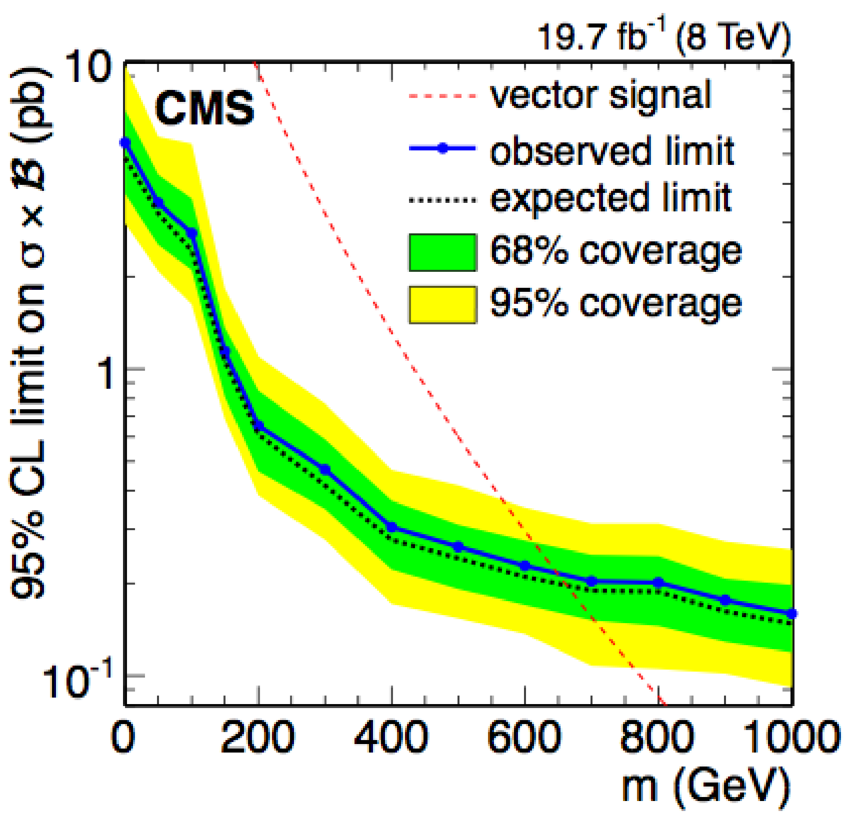


- Better limits from the semi-leptonic ttbar.
- Collider limits are competitive for DM mass below 10 GeV

- Single top+MET predicted by many BSM
- At least 3-jets with one b-tag



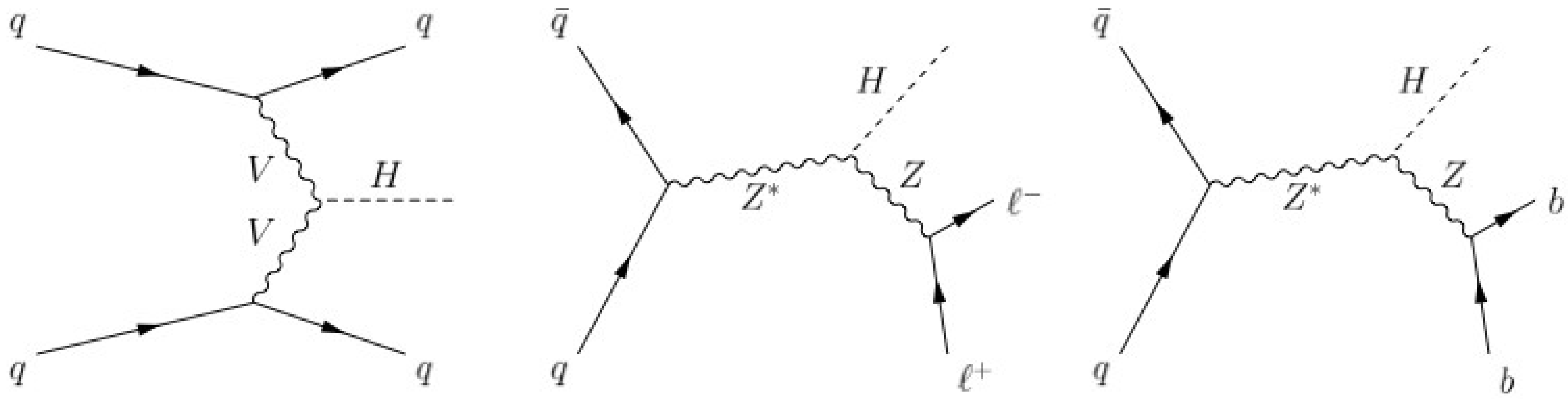




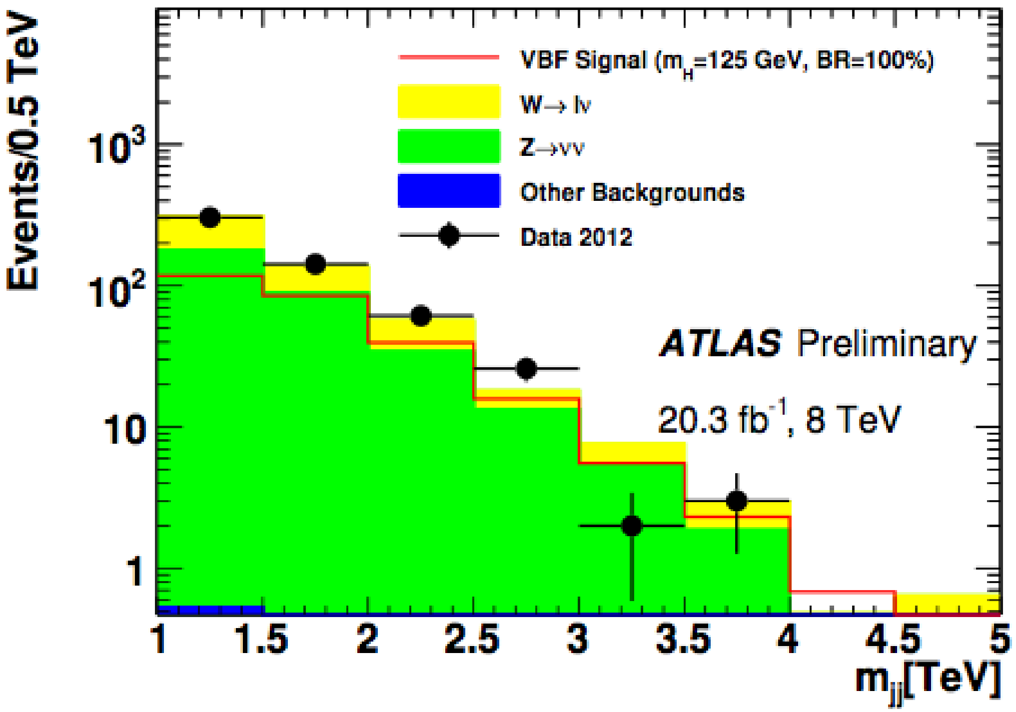
Invisible Higgs decay

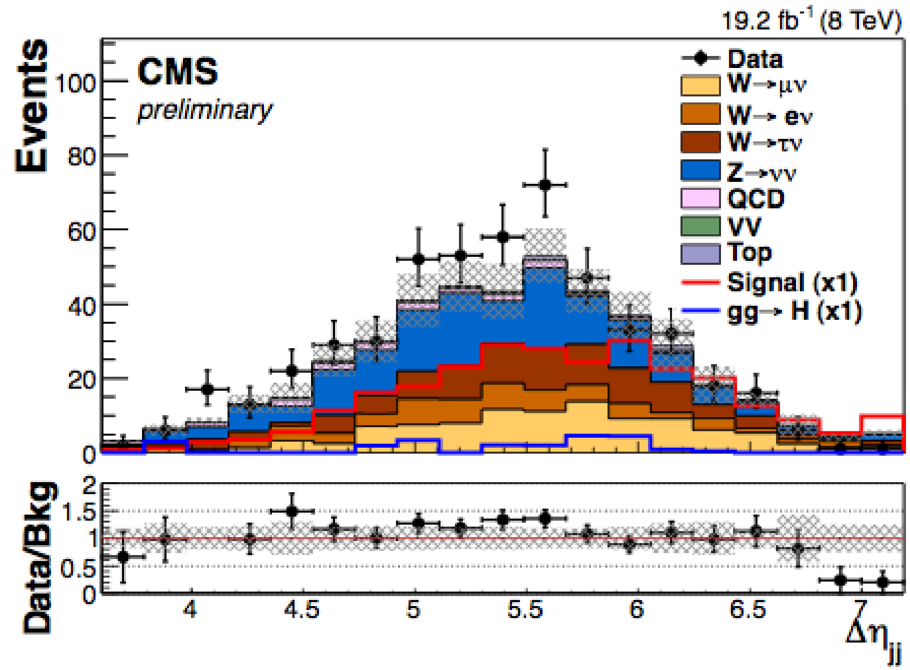
ATLAS: ATLAS-CONF-2015-004, arXiv:1504.04324, PRL 112, 201802

CMS: EPJC 74 (2014) 2980, CMS-PAS-HIG-14-038



- The discovery of the Higgs at a mass of 125 GeV opens the door for realistic searches for invisible Higgs decays
- The SM H → ZZ → νννν has a BR of 1.2×10^{-3}, below the sensitivity of current analyses
- However DM could have substantially large Yukawa couplings to Higgs leading to BR(H → invisible) much larger than predicted in SM (if DM mass < $m_H/2$)
- Vector boson fusion (VBF) and associated vector boson production (VH) with different topologies have been explored



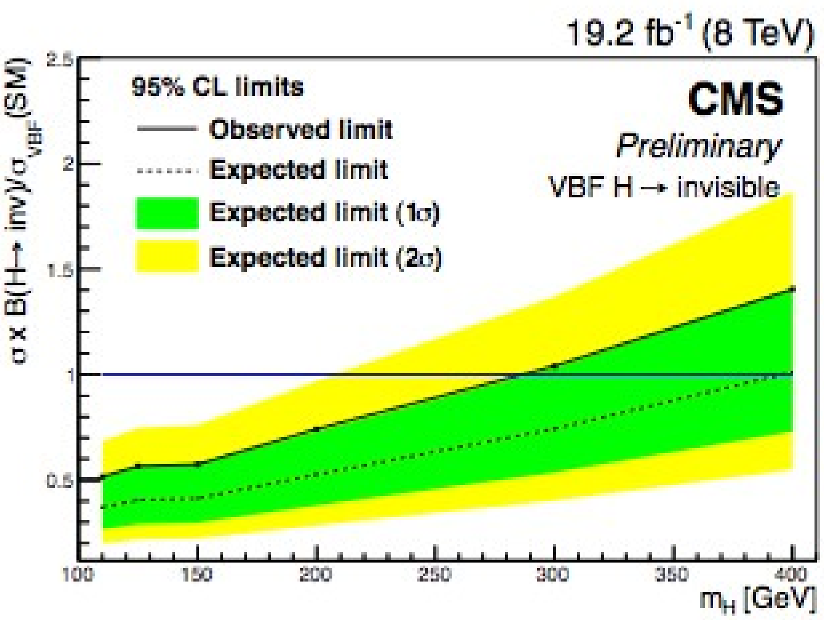


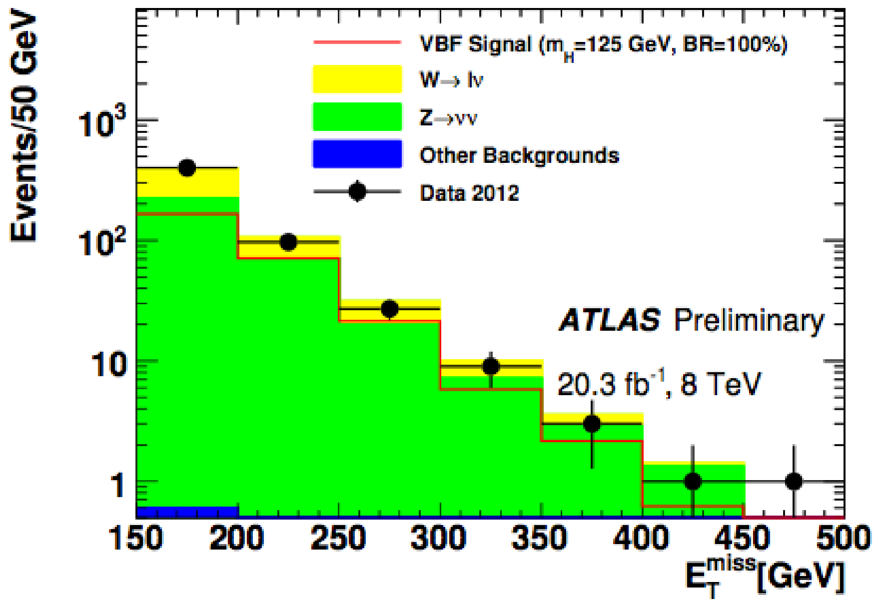
- Look for two forward jets with large invariant mass m_{jj} (above 1 TeV) and large η separation (typically $\Delta\eta_{jj}$ more than 3.5)
- Main background from V+jets and VBF EW production
- It is one of the most sensitive channels to look for invisible Higgs decays

VBF H → invisible

ATLAS: ATLAS-CONF-2015-004

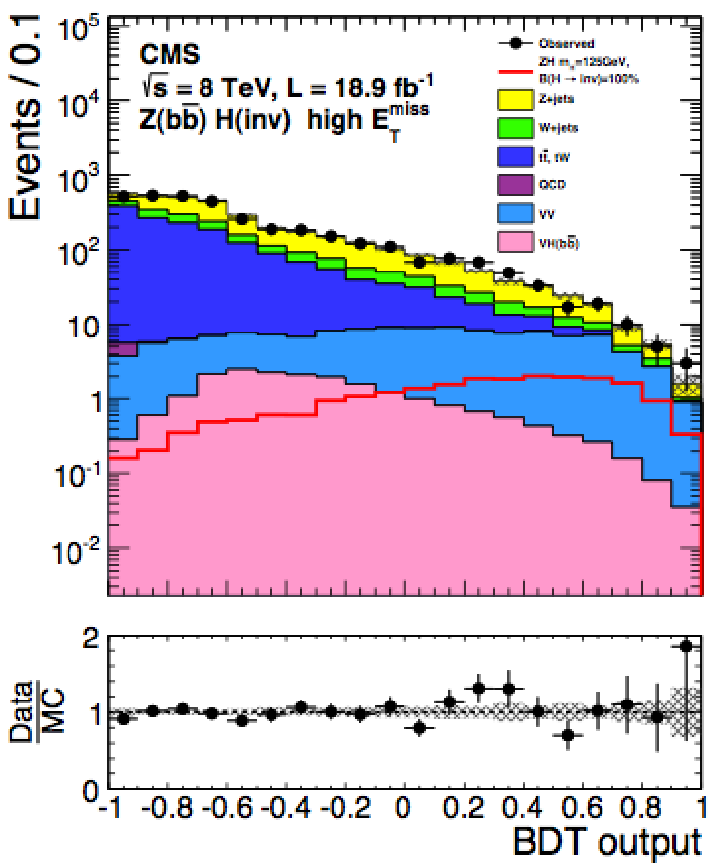
CMS: EPJC 74 (2014) 2980, CMS-PAS-HIG-14-038

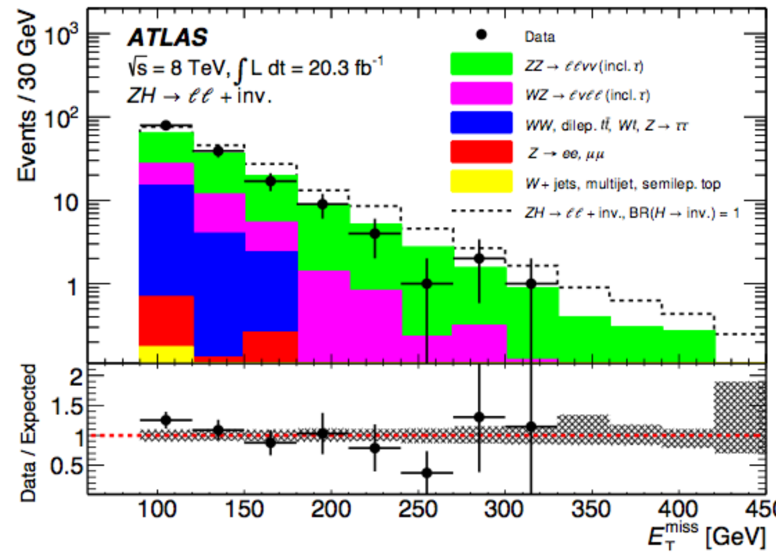


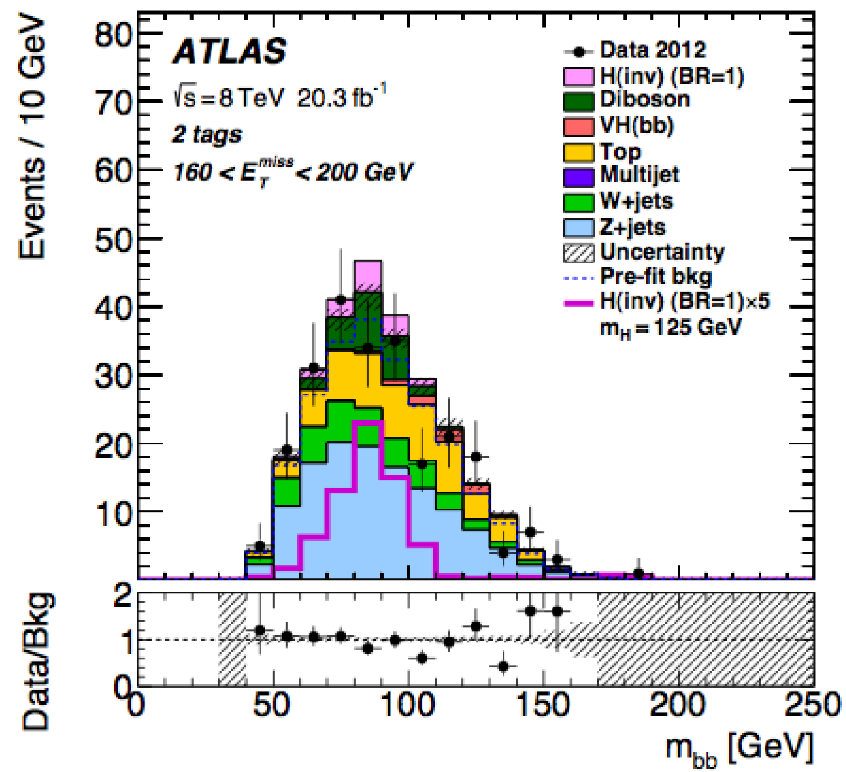


- Similar expected limits on BR(Higgs → invisible) between CMS (<35%) and ATLAS (< 29%) for m_H=125 GeV
- Observed: ATLAS <35%, CMS <47%
- Scan as a function of the Higgs mass assuming SM couplings.

- Hadronic and leptonic boson decays + large MET
- Use b-tagging and/or BDT to enhance H(Z → bb) signal



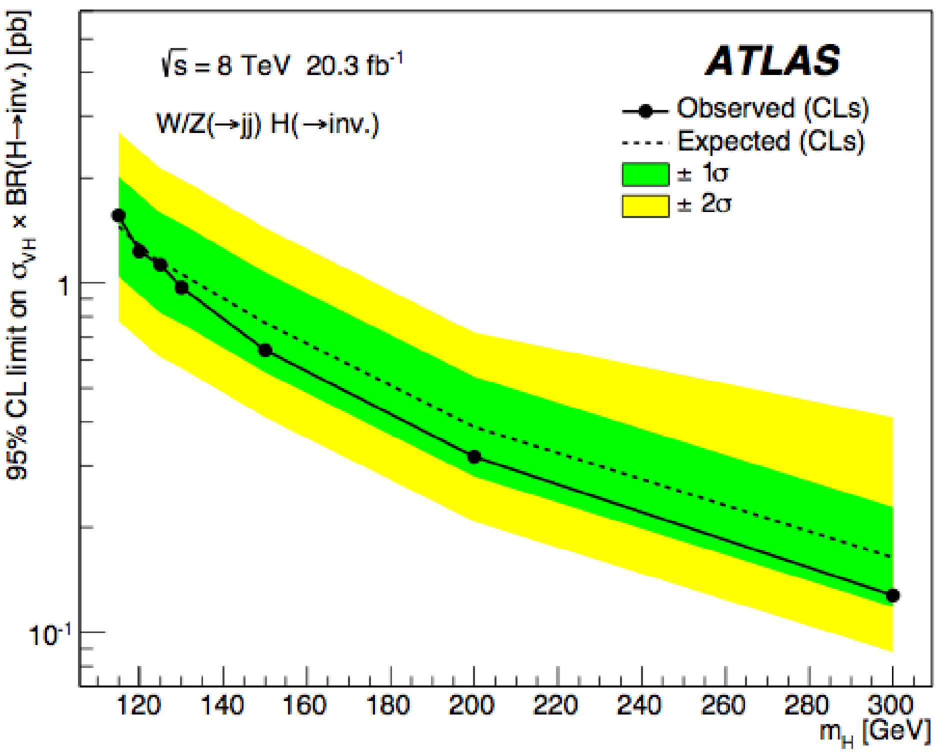


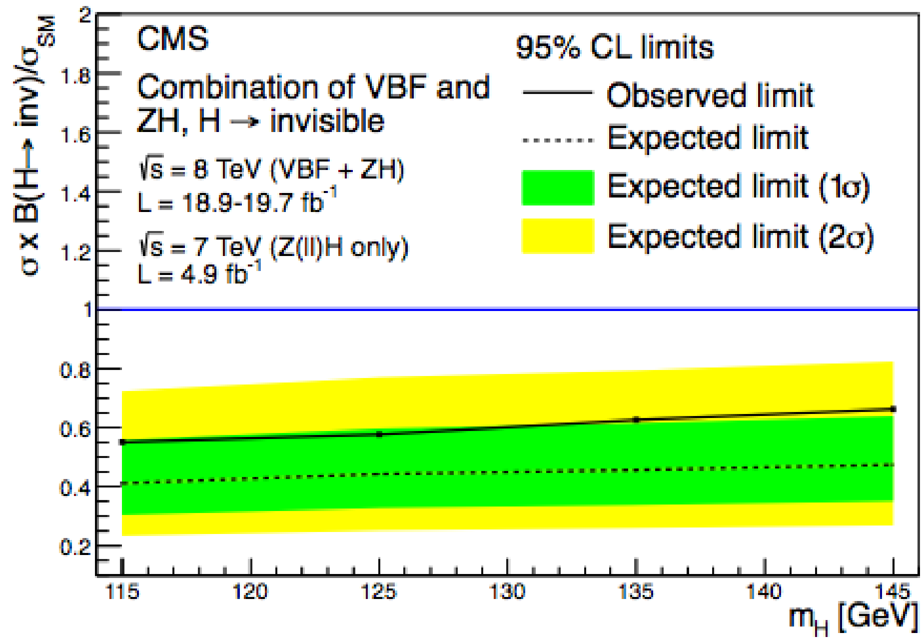


VH (H → invisible)

ATLAS: arXiv:1504.04324, PRL 112, 201802

CMS: EPJC 74 (2014) 2980

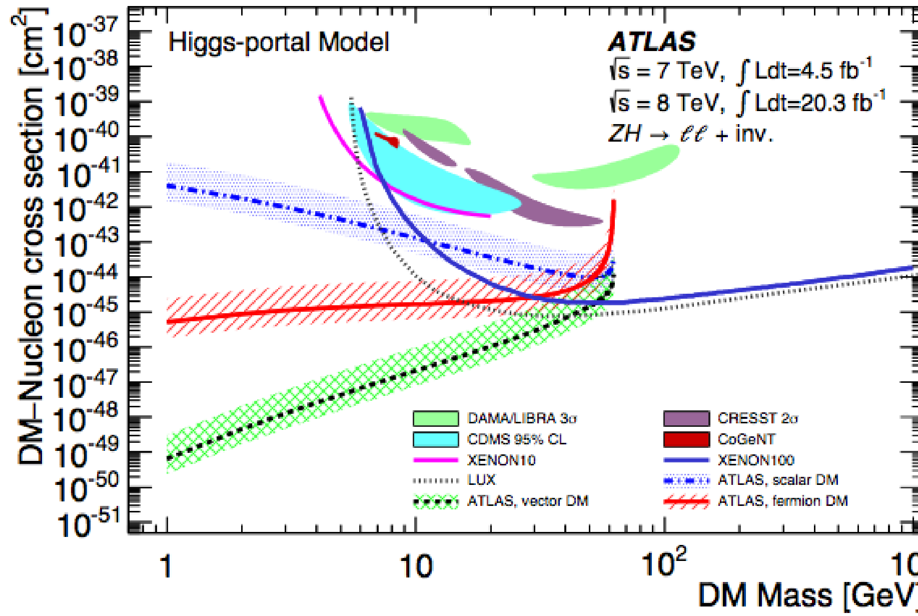




- Limit scan as a function of the Higgs mass assuming SM couplings.
- Limits on BR(Higgs → invisible) less stringent than VBF channel

DM-Higgs portal

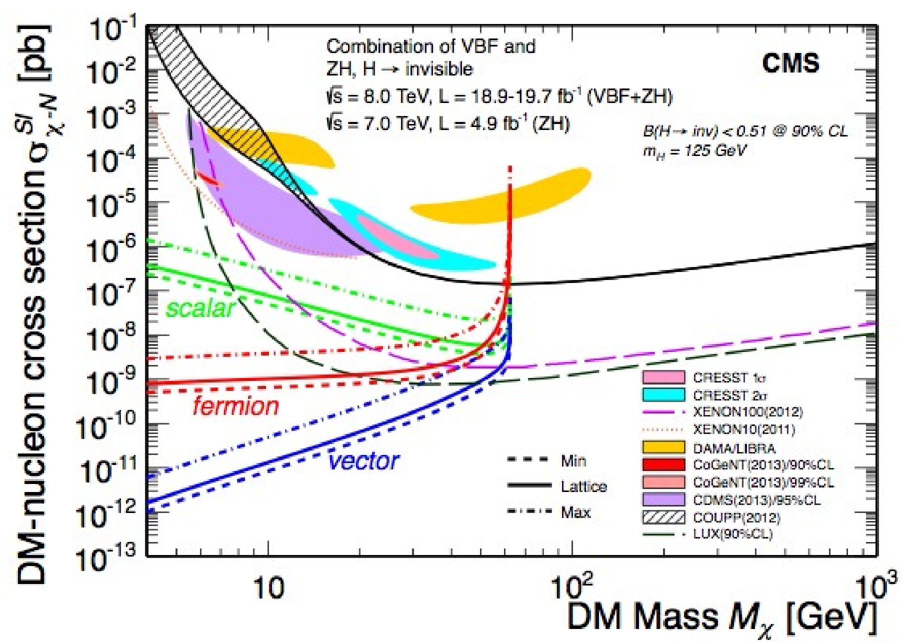
- If the DM particle has a mass below $m_H/2$ the invisible decay width of the Higgs can be directly translated to DM-nucleon spin independent cross section
- For DM masses below $m_H/2$ the collider limits are very competitive



$$\sigma^{\mathrm{SI}}_{\mathrm{S-N}} = \frac{4\Gamma_{\mathrm{inv}}}{m^3_{\mathrm{H}} v^2 \beta} \frac{m^4_{\mathrm{N}} f^2_{\mathrm{N}}}{(M_\chi + m_{\mathrm{N}})^2},$$

$$\sigma^{\mathrm{SI}}_{\mathrm{V-N}} = \frac{16\Gamma_{\mathrm{inv}} M^4_\chi}{m^3_{\mathrm{H}} v^2 \beta (m^4_{\mathrm{H}} - 4M^2_\chi m^2_{\mathrm{H}} + 12 M^4_\chi)} \frac{m^4_{\mathrm{N}} f^2_{\mathrm{N}}}{(M_\chi + m_{\mathrm{N}})^2},$$

$$\sigma^{\mathrm{SI}}_{\mathrm{f-N}} = \frac{8\Gamma_{\mathrm{inv}} M^2_\chi}{m^5_{\mathrm{H}} v^2 \beta^3} \frac{m^4_{\mathrm{N}} f^2_{\mathrm{N}}}{(M_\chi + m_{\mathrm{N}})^2}.$$

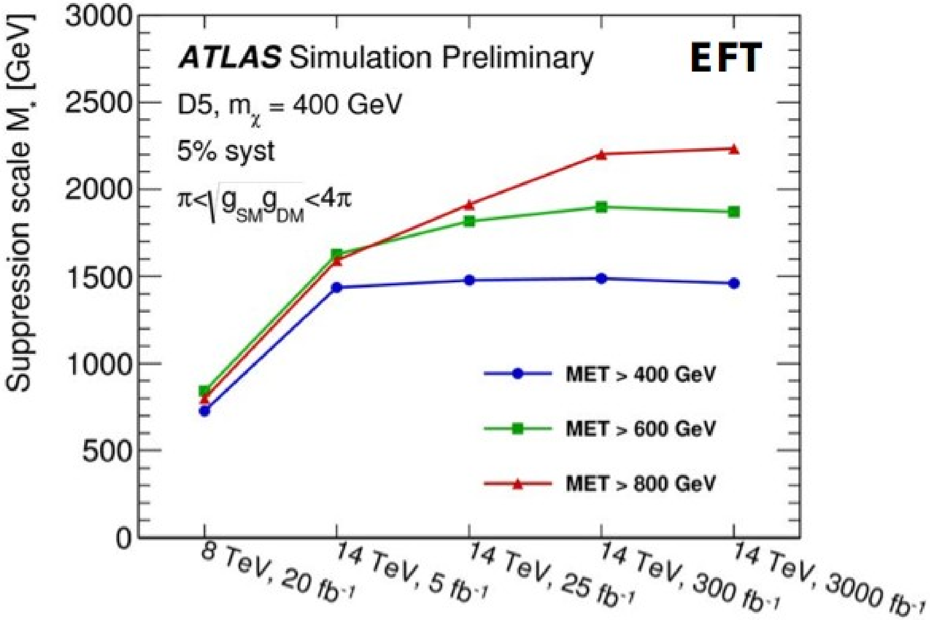


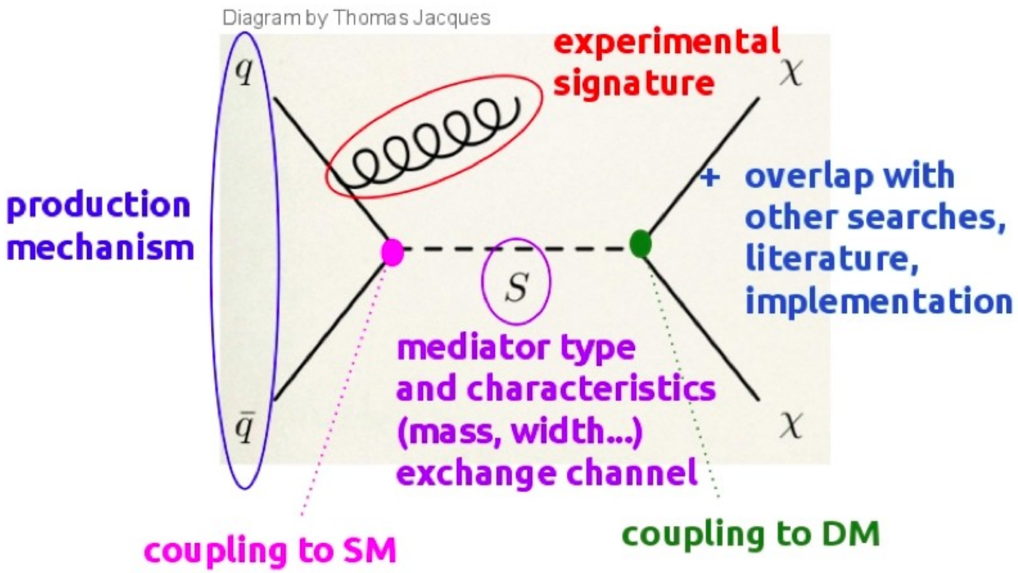
Prospects for Run-II dark matter searches

- Monojet analyses using similar strategies as in Run-I are expected to surpass previous limits with only 5/fb at 13 TeV
- Harmonization of DM searches ongoing within the ATLAS/CMS Dark Matter Forum

https://twiki.cern.ch/twiki/bin/view/LHCDMF/WebHome

Monojet selection



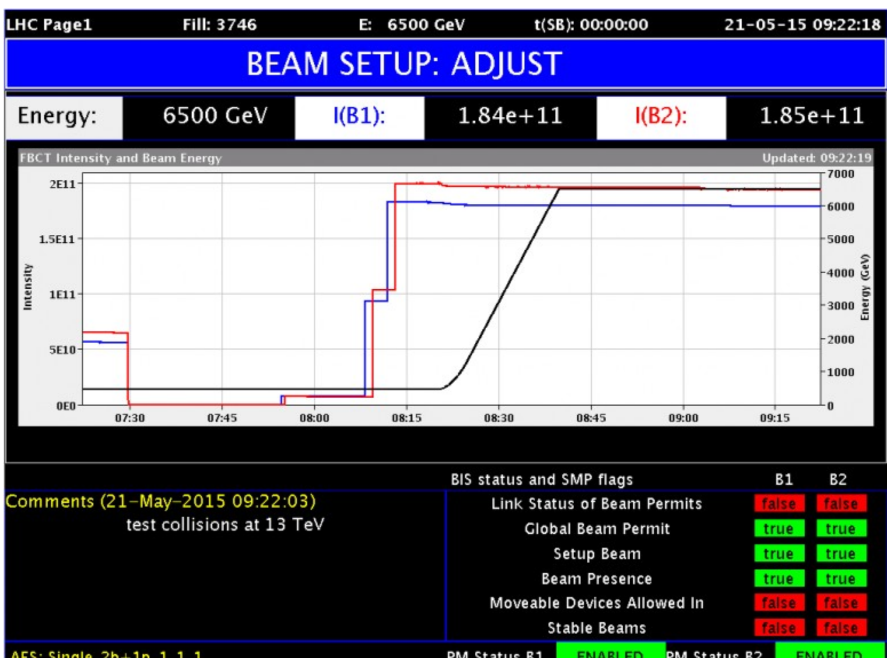


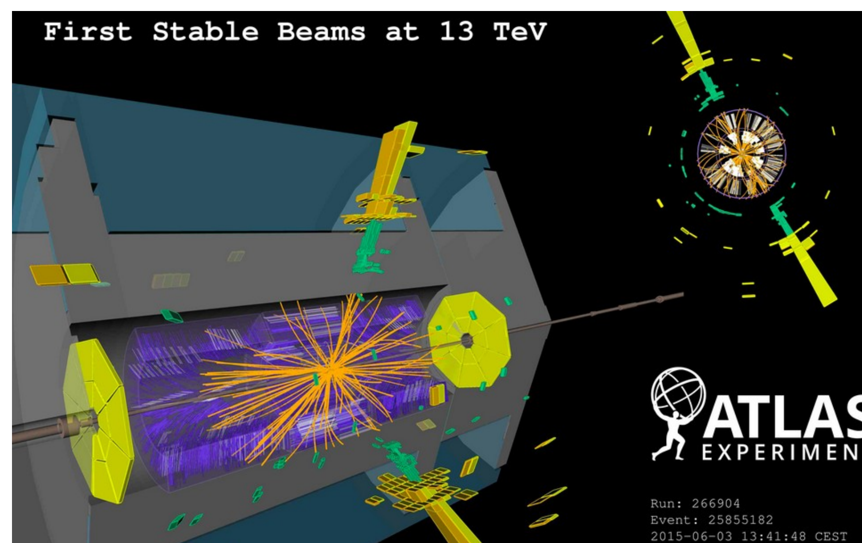
The Forum addresses:

- Set of prioritized simplified models
- Benchmark MC generation for common models (treatment of details, systematics, etc).
- Common procedure for EFT validity treatment

The LHC is up and running at 13 TeV!!

The CMS experiment team celebrated when the first collisions occurred





Conclusions

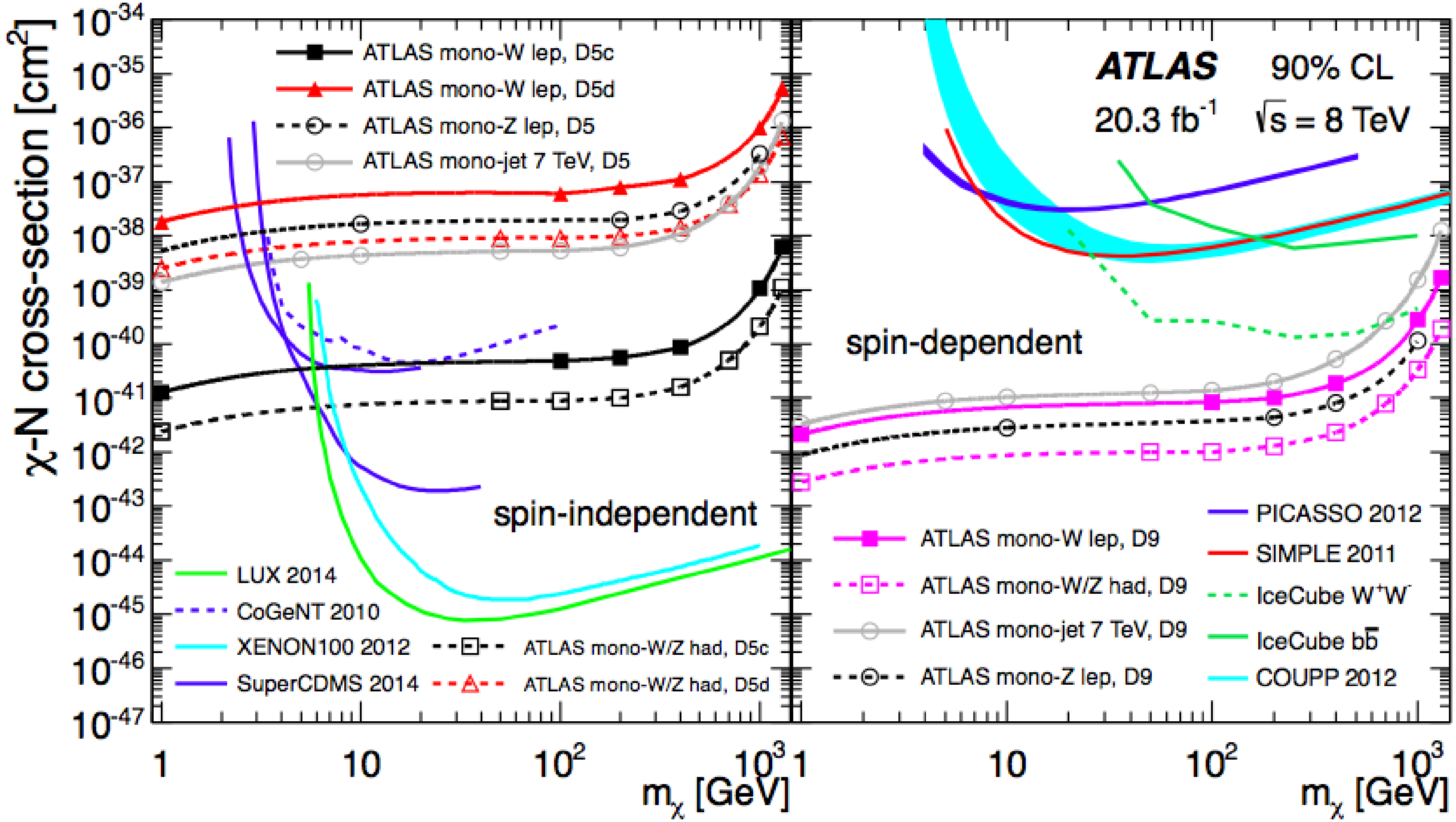
- Dedicated ATLAS and CMS dark matter searches using multiple final states.
- Interpretation of the results done in the context of EFT and simplified models.
- No signal discovered yet → complementary results to other Dark Matter experiments
- But run-II has just started... stay tuned!!

Additional material

MET+W/Z → leptons

ATLAS: PRD 90, 012004 (2014), JHEP 09 (2014) 037

CMS: arXiv:1408.2745



EFT operators

Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
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	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$