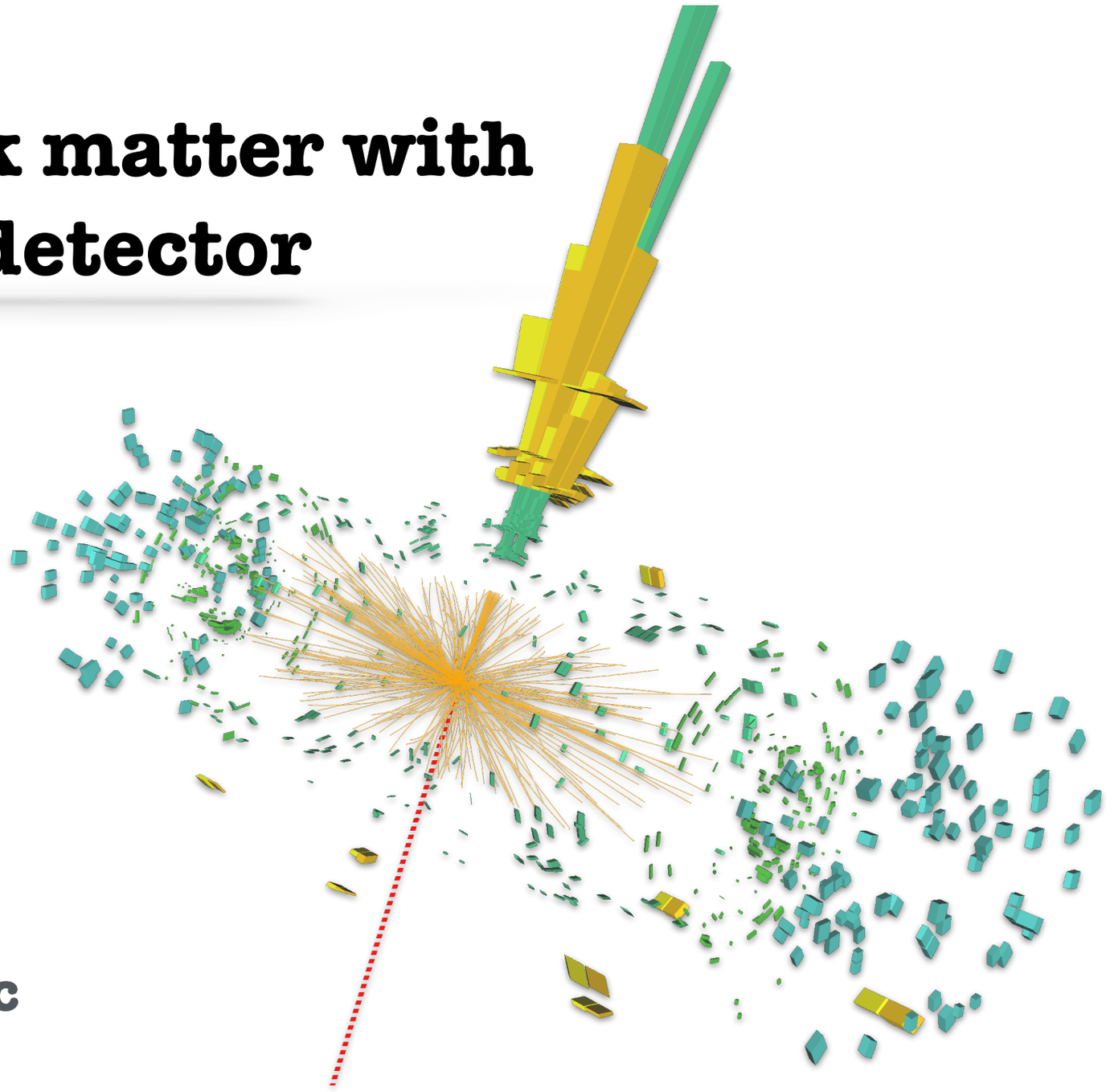
LEPTON PHOTON 2021 MAN

30th International Symposium on Lepton Photon Interactions at High Energies

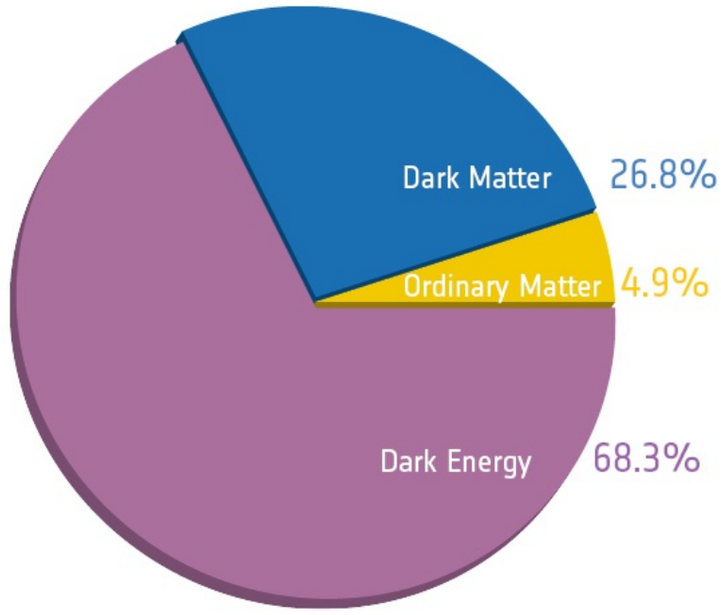
Searches for dark matter with the ATLAS detector

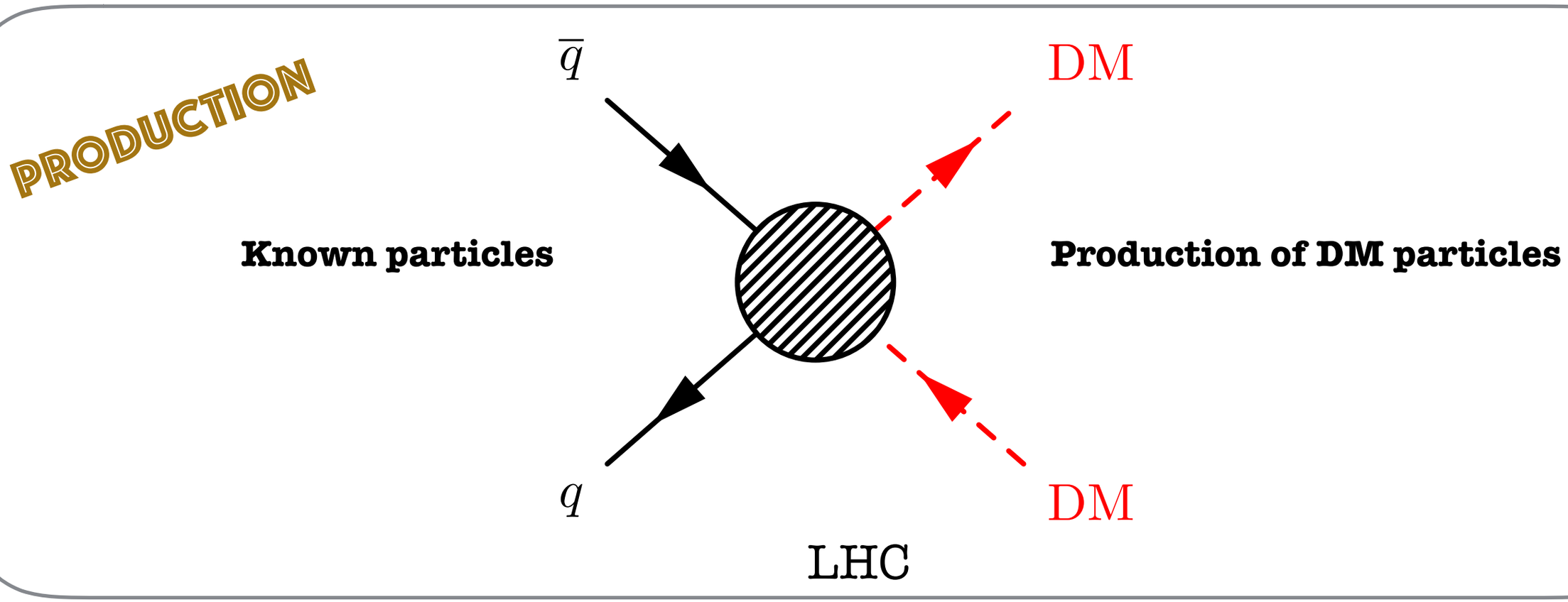


Danijela Bogavac
(CERN)
on behalf of the ATLAS Collaboration

Introduction

- **Standard Model (SM)** is a very successful theory and has been found to be in agreement with experimental measurements, but it can only explain 5% of the energy density in the Universe
- **Dark Matter (DM)** constitutes the dominant component of the total matter in the Universe
- **Weakly interacting massive particles** χ (**WIMPs**) are the most popular candidates for **DM** and **can be produced in collisions at the Large Hadron Collider (LHC)**





Introduction

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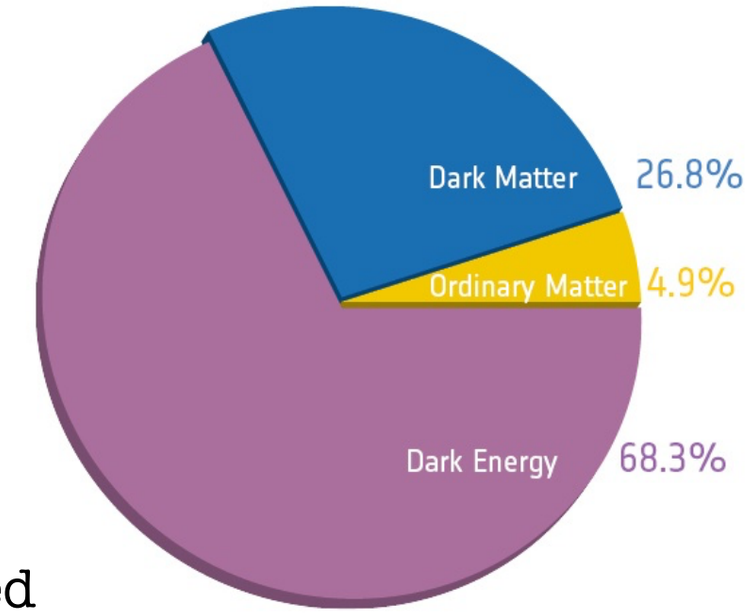
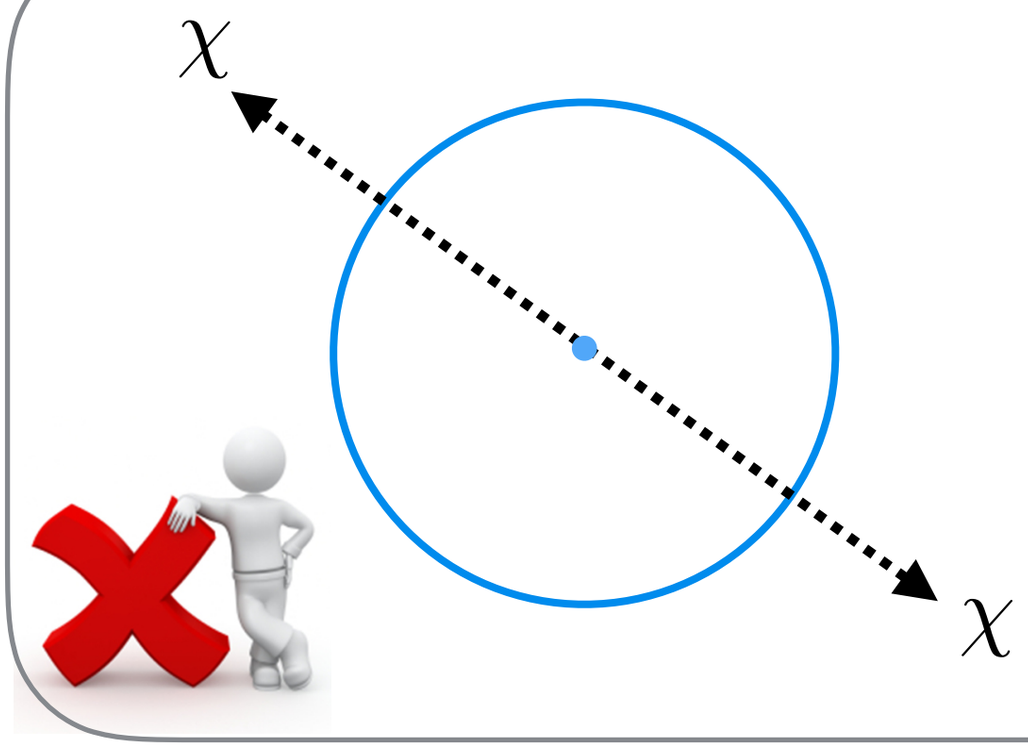
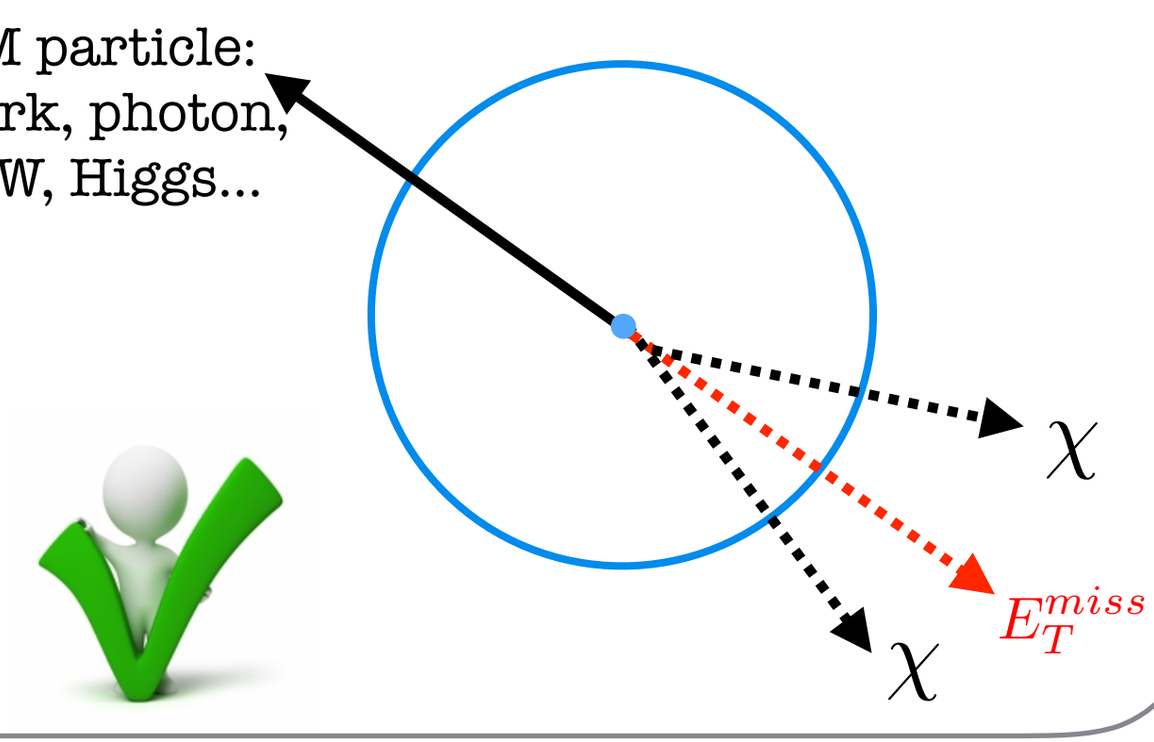
- **Dark Matter (DM)** constitutes the dominant component of the total matter in the Universe
- **Weakly interacting massive particles** χ (**WIMPs**) are the most popular candidates for **DM** but **can't be observed directly** at the Large Hadron Collider. A **SM** particle is needed to recoil against **DM** candidates



DETECTION



SM particle:
quark, photon,
Z, W, Higgs...



Recent ATLAS searches for dark matter with

- **ATLAS** has a broad program of searches for **Dark Matter candidates**

Individual searches

- E_T^{miss}+Jet — Phys. Rev. D 103, 112006 (2021)
- E_T^{miss}+s(WW) — Phys. Rev. Lett. 126 (2021) 121802
- E_T^{miss}+Z(ll) — arXiv:2111.08372
- VBF+E_T^{miss}+γ — arXiv:2109.00925
- E_T^{miss}+tW — Eur. Phys. J. C 81 (2021) 860
- E_T^{miss}+γ — JHEP 02 (2021) 226
- E_T^{miss}+h(bb) — JHEP 11 (2021) 209
- E_T^{miss}+bjets — JHEP 05 (2021) 093
- E_T^{miss}+1L+jets — JHEP 04 (2021) 174
- E_T^{miss}+2L+jets — JHEP 04 (2021) 165

Combinations and summaries

- Simplified models — ATL-PHYS-PUB-2021-045
- Higgs portal — ATLAS-CONF-2020-052
- 2HDM+a — ATL-PHYS-PUB-2021-045

ATLAS public twiki page: link here

Subset of Dark Matter searches with the ATLAS detector in this talk, please also see:

- Federico Meloni (talk): “Overview on Dark Matter searches at colliders and fixed target experiments”
- Giordon Holtsberg Stark (talk): “Searches for Supersymmetry with the ATLAS detector”
- Eloisa Arena (poster): “Search for associated production of a Z boson with an invisibly decaying Higgs boson or dark matter candidates with the ATLAS detector using full Run-II Data at LHC”

Signal models

Same signature can be sensitive to various models such as:

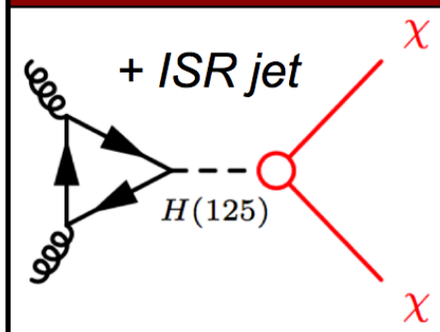
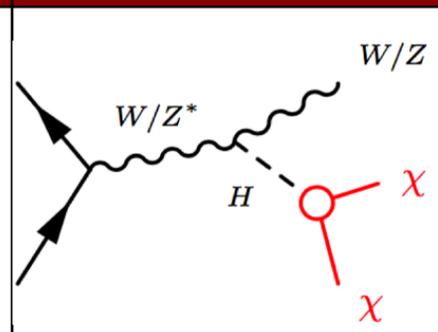
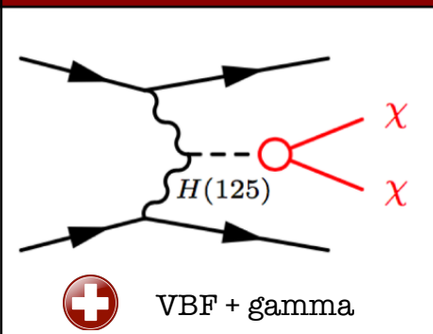
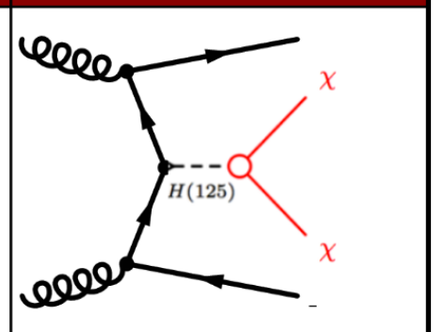
Higgs portal

According to the Standard Model, the probability of Br(H → 4 ν) ~ 0.1 %

- **Higgs boson** ⇛ mediator between SM and DM particles
- Detection requires for the Higgs to recoil against a visible system + E_T^{miss}

All four main production modes of the Higgs boson are used:

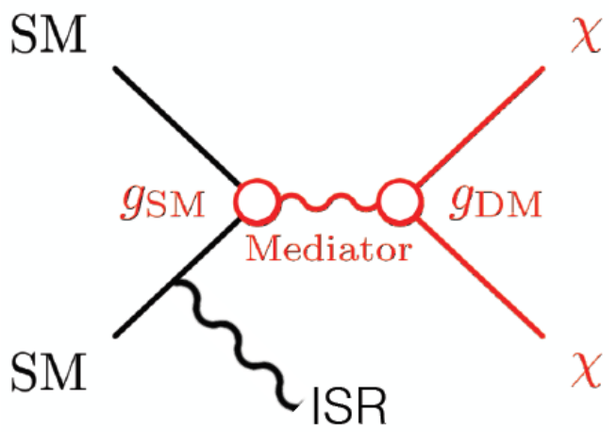
gluon-gluon fusion (ggF), associated production with a vector-boson (VH), Vector-Boson Fusion (VBF) and tt pair (ttH)

ggF H [49 pb]	VH [2.3 pb]	VBF H [3.8 pb]	ttH [0.09 pb]
			

Simplified DM model: E_T^{miss}+X

"Direct" searches

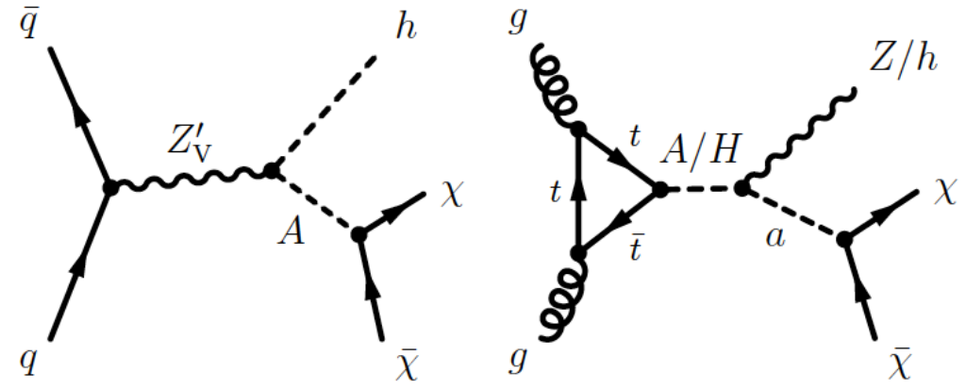
using ISR or associated production



Extended Higgs sector

Two-Higgs-doublet Model extended

with a vector boson Z' or a pseudoscalar A which mediates the interaction between SM and DM

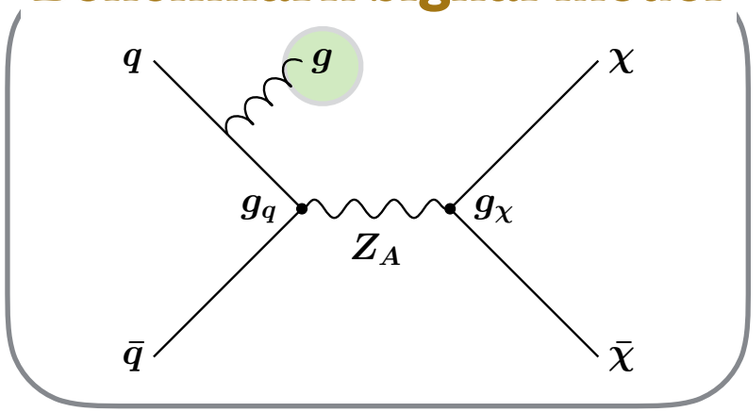


E_T^{miss} + Jet

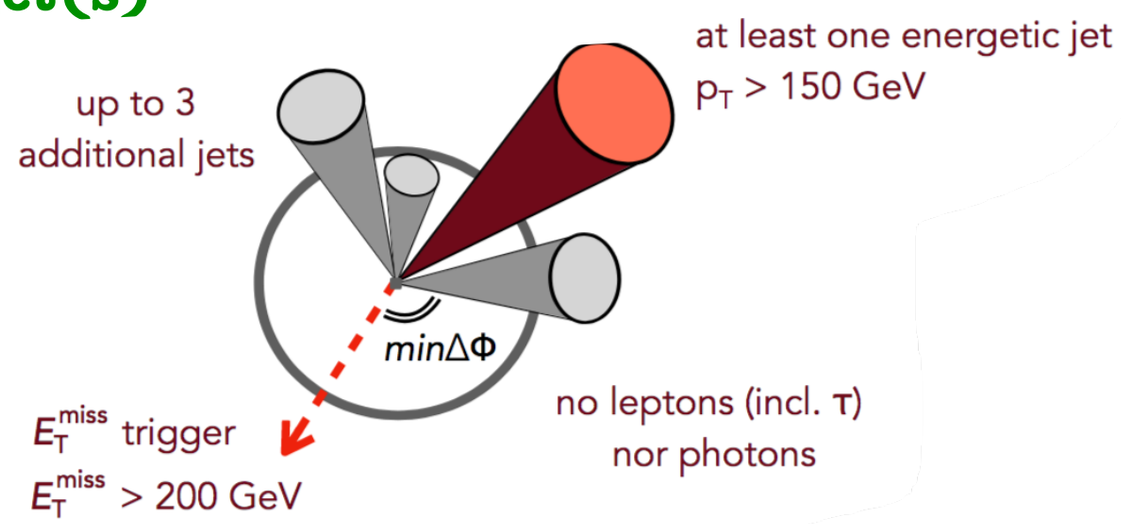
Phys. Rev. D 103, 112006 (2021)

- Dark Matter produced in association with **jet(s)**

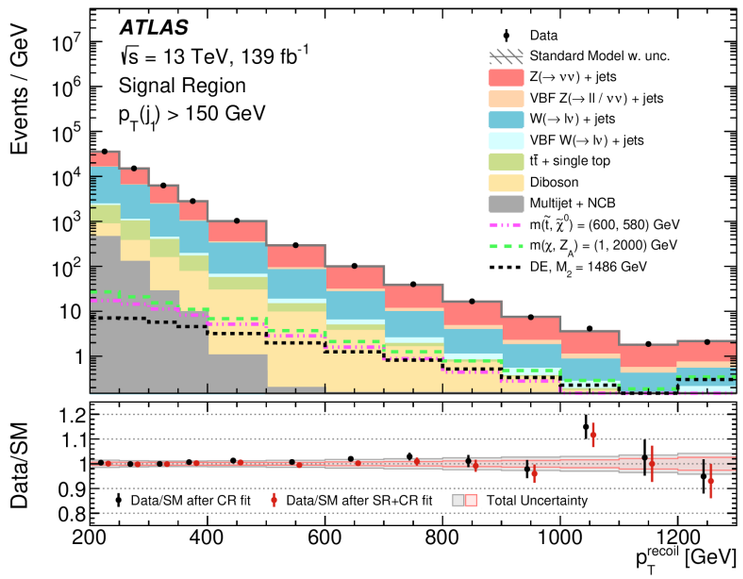
Benchmark signal model



Event selection



- **This signature is sensitive to a wide range** of other Beyond Standard Model theories: supersymmetry, dark energy, Higgs invisible, large extra dimensions, axion-like particles
- **Z/W+jets and top-related backgrounds** constrained using Monte Carlo simulation normalized to data in the control regions defined with leptons
- **Z/W+jets Monte Carlo predictions** reweighed to account for high order corrections following Eur. Phys. J. C 77, 829 (2017)



Good agreement with the SM prediction

Reached high precision in the background prediction uncertainty: **1.5%** at low E_T^{miss} and **4.2%** in the TeV regime

Inclusive Signal Region

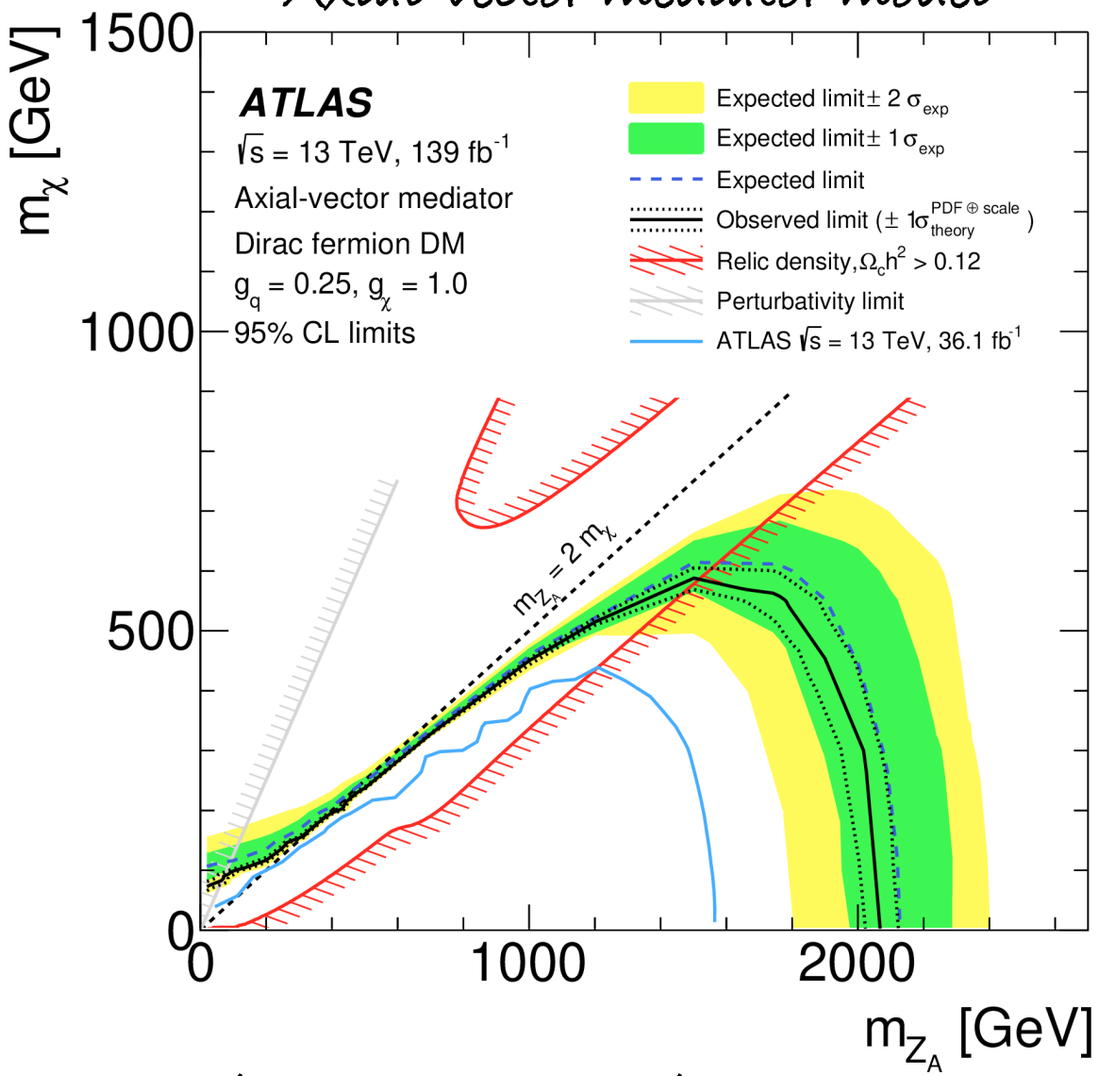
Region	Predicted		Observed
IM0	3 120 000 ± 40 000	1.5%	3 148 643
IM1	1 346 000 ± 16 000		1 357 019
IM2	597 000 ± 8000		604 691
IM3	286 000 ± 4000		290 779
IM4	146 400 ± 2300		149 743
IM5	45 550 ± 1000		46 855
IM6	16 800 ± 500		17 397
IM7	7070 ± 240		7194
IM8	3180 ± 130		3208
IM9	1560 ± 80		1545
IM10	720 ± 60		807
IM11	407 ± 34		394
IM12	223 ± 19	4.2%	207

E_T^{miss} + Jet

Phys. Rev. D 103, 112006 (2021)

No significant excess? Set limits and constrain parameter space for DM models!

Axial-vector mediator model

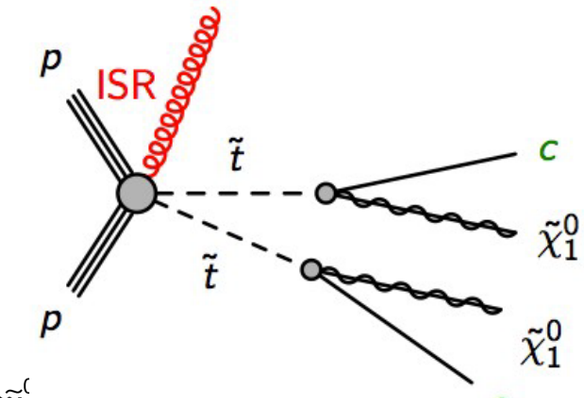


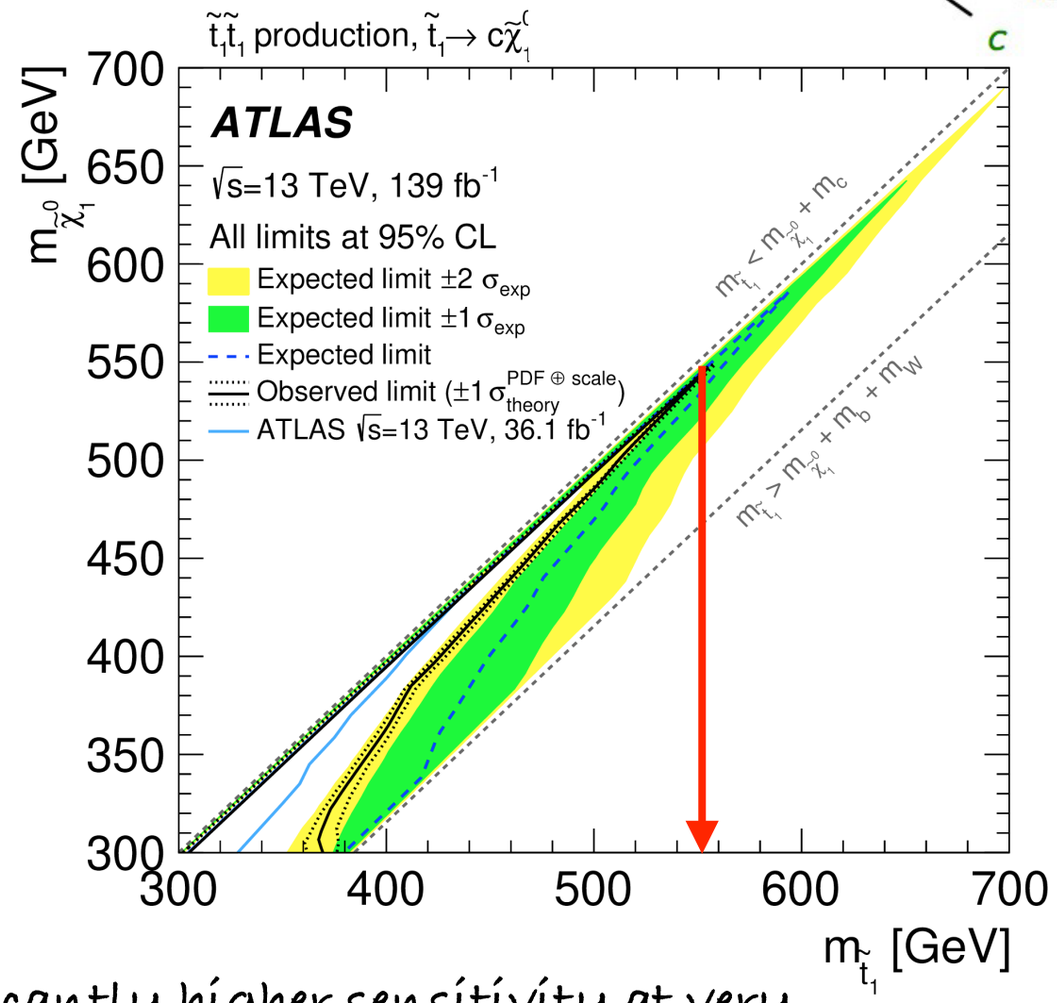
In the region $m_{ZA} > 2m_\chi$, mediator masses up to about 2.1 TeV are excluded for $m\chi$=1 GeV

Invisible Higgs model

- Observed limit: 0.34
- Expected limit: $0.39^{+0.16}_{-0.11}$

compressed supersymmetric model





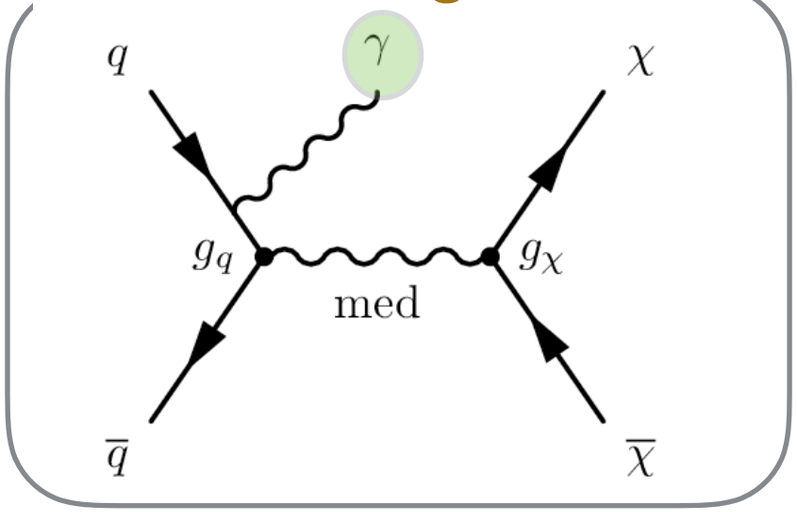
Significantly higher sensitivity at very low stop–neutralino mass difference

E_T^{miss}+Photon

JHEP 02 (2021) 226

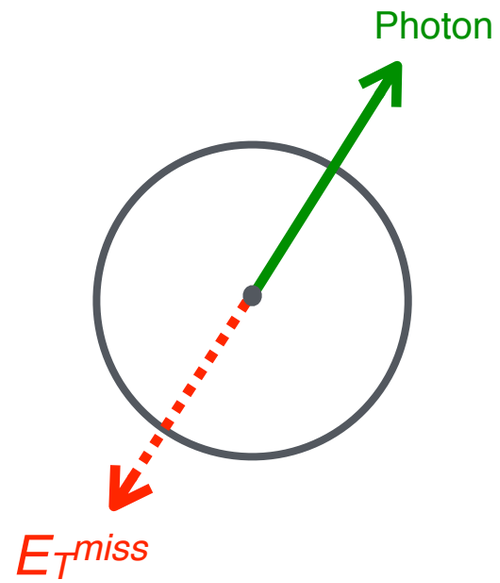
- Dark Matter produced in association with a **photon**

Benchmark signal model



Event selection

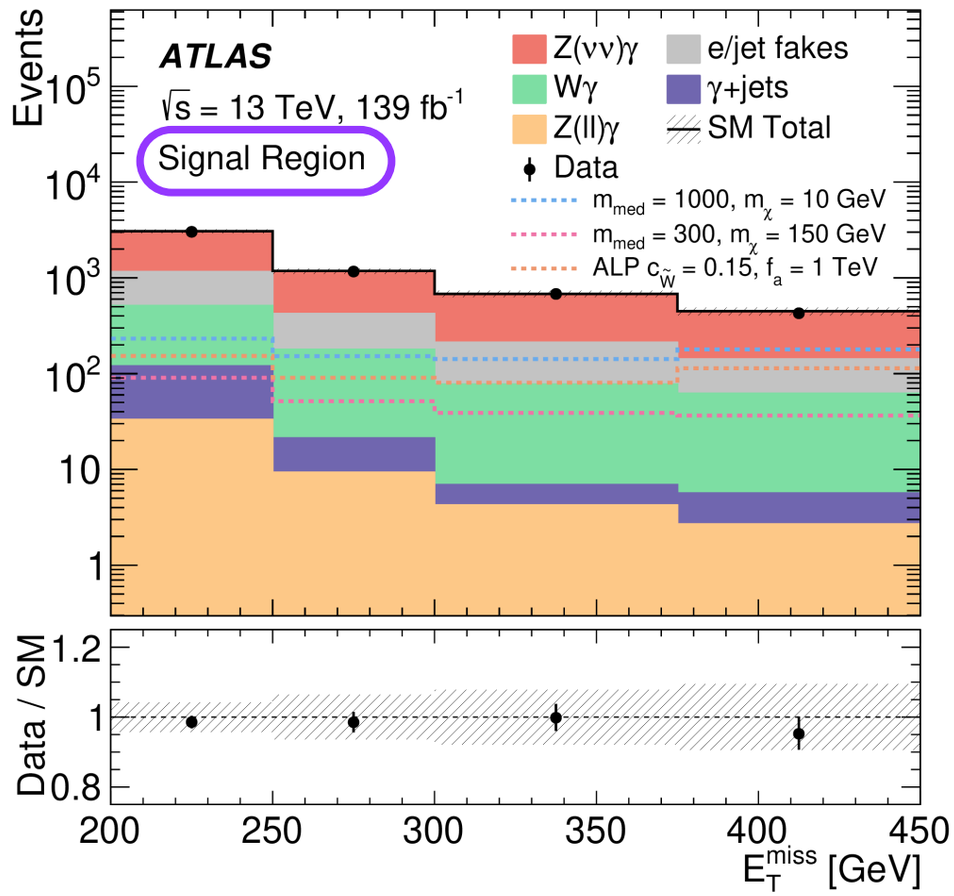
- Relative clean final state
- High p_T **photon** to trigger the events
- High E_T^{miss} as a discriminating variable



Strategy:

- **signal region** defined with a photon, 0/1 jet and different E_T^{miss} ranges: 200 GeV, 250 GeV, 300 GeV and 375 GeV
- **dominant backgrounds** (Z+γ, W+γ, γ+jets) estimated in the dedicated control regions defined with leptons (Z+γ, W+γ) or at low E_T^{miss} (γ+jets)
- fake background estimated via data driven methods

Good agreement with the SM prediction



E_T^{miss}+Photon

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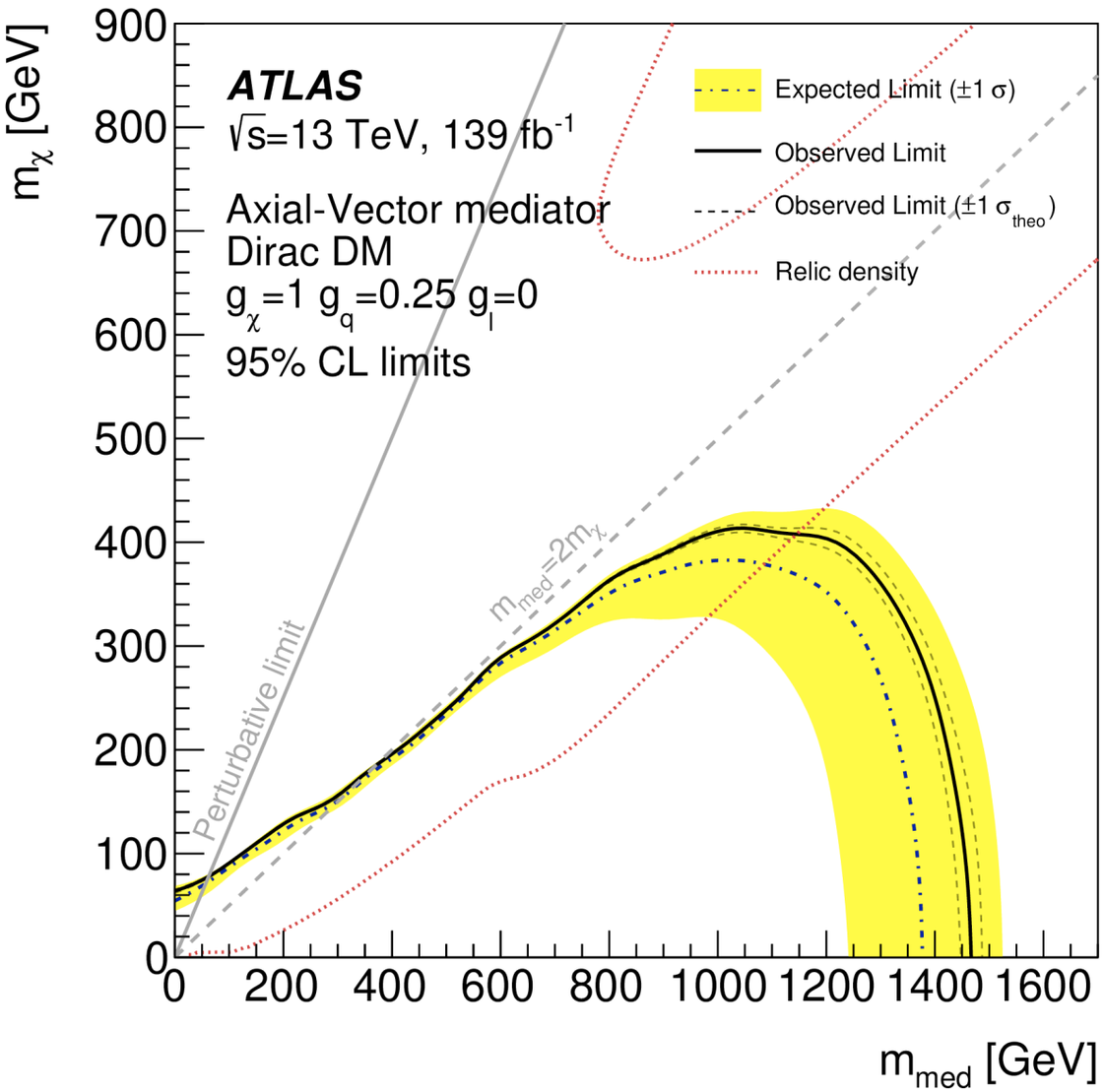
No significant excess? Set limits and constrain parameter space for DM models!

Axial-vector mediator



Observed (expected) limit:

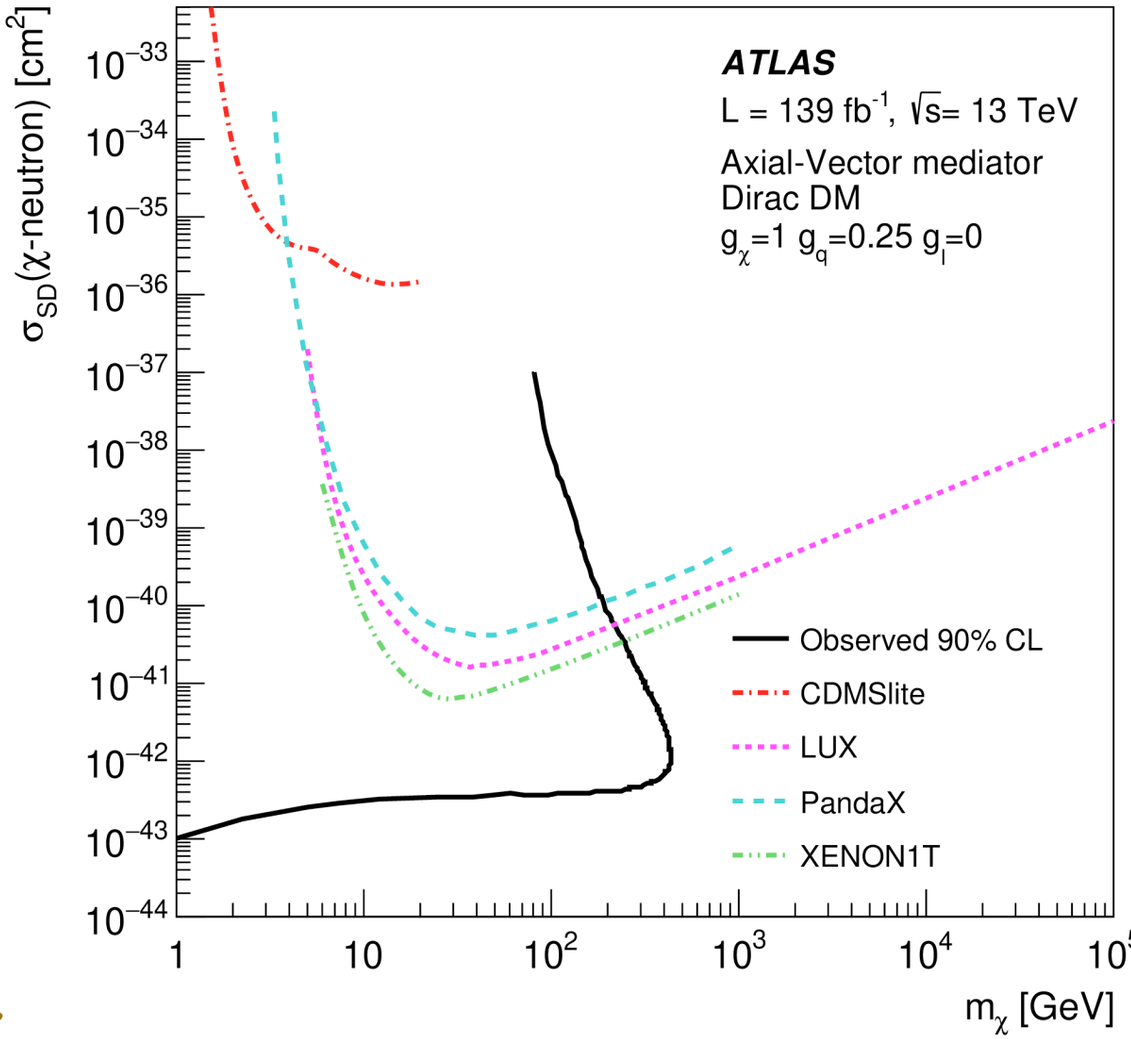
1.46 TeV (1.37 TeV) for very light DM candidates

Comparison to direct detection experiments

Axial-vector mediator

⇩

Spin dependent interaction



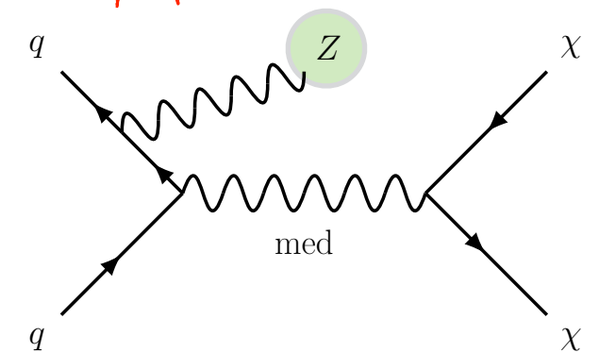
E_T^{miss} + Z(ll)

arXiv:2111.08372

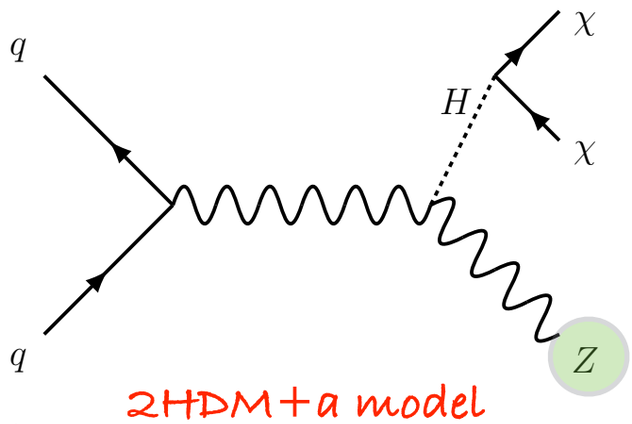
- Dark Matter produced in association with a **Z boson** decaying leptonically

Signal models

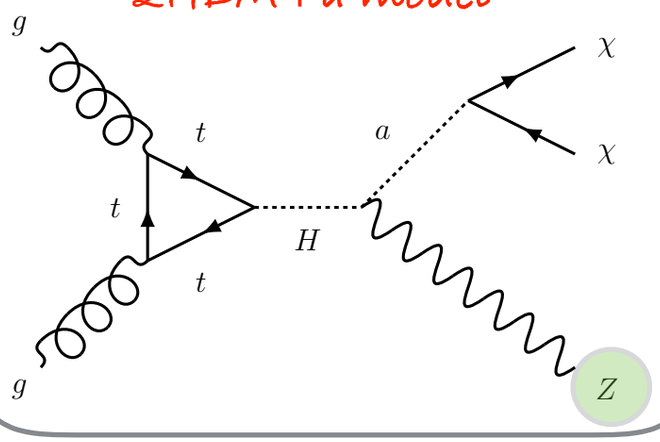
Simplified DM model



Associated production of a Higgs boson and a Z boson



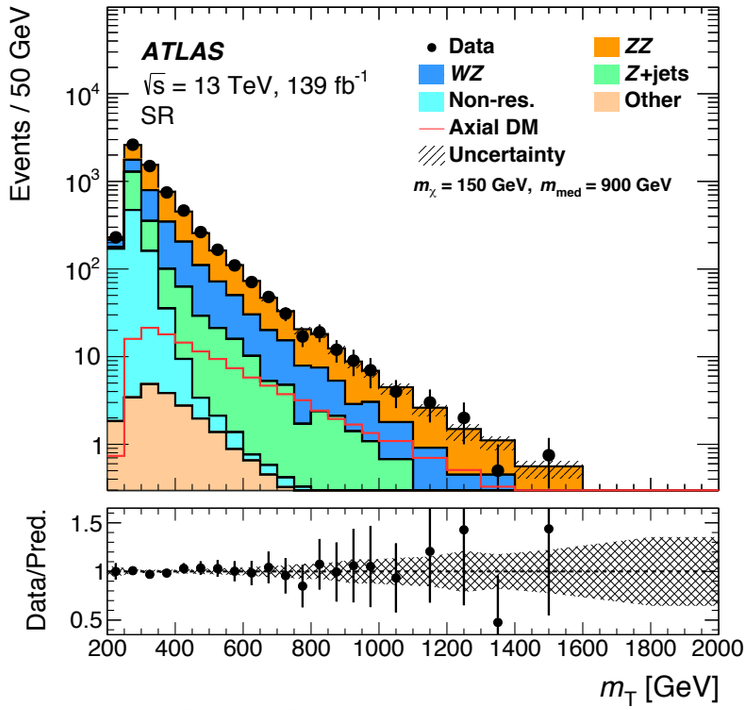
2HDM+a model

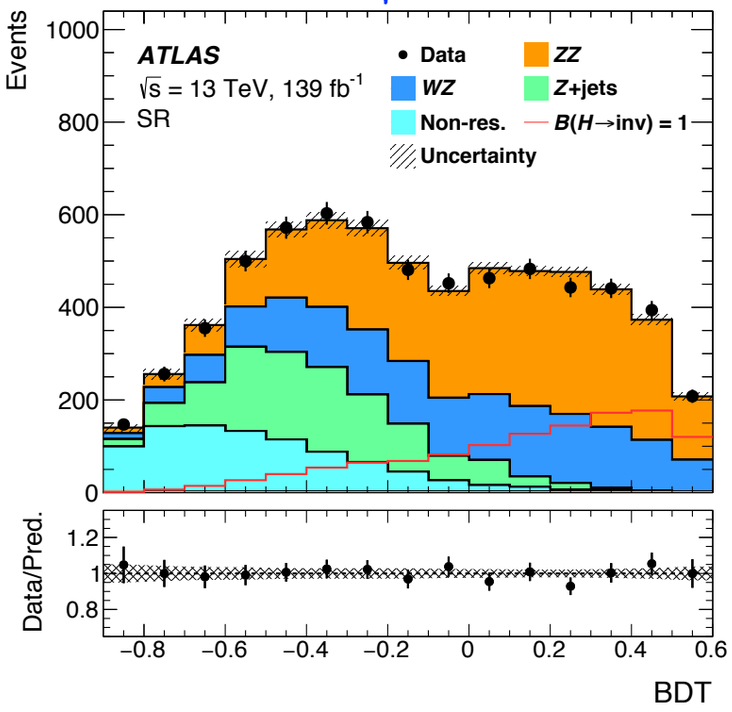


Strategy:

- targeting events with a **pair of high-p_T leptons** (ee or μμ) and **large E_T^{miss}**
- 76 GeV < m_{ll} < 106 GeV ➜ consistent with a Z boson
- **ZZ** background estimated in a control region containing exactly 4 leptons, while **WZ** is normalized to data in the 3L control region
- For the simplified DM and 2HDM+a models, transverse mass distribution (m_T) is used in the maximum-likelihood fits, while a BDT is used to improve the sensitivity of the Higgs to invisible search

Good agreement with the SM prediction

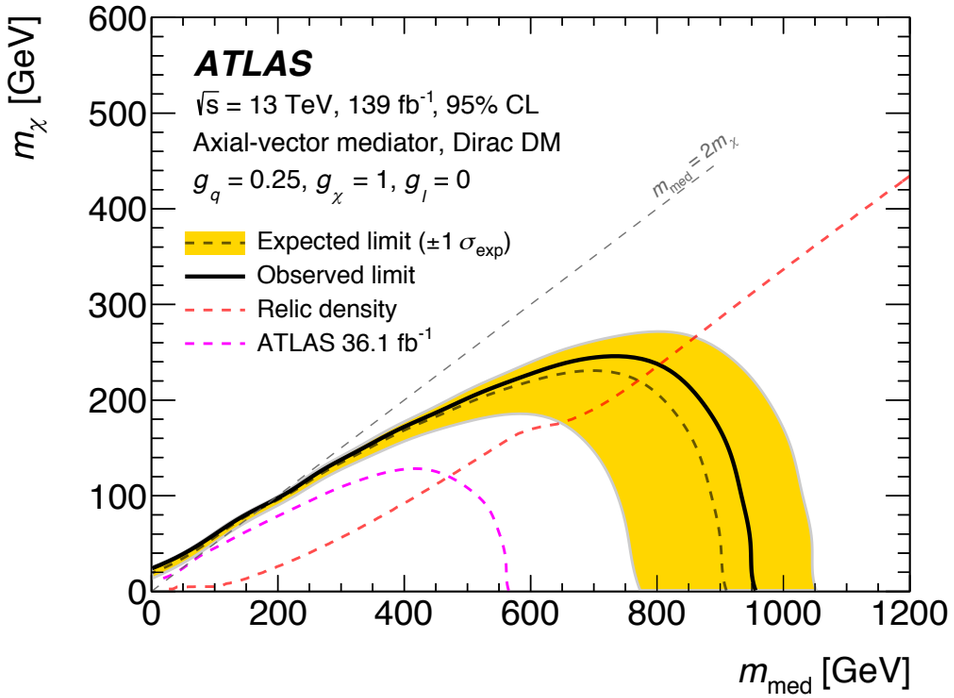




E_T^{miss} + Z(ll)

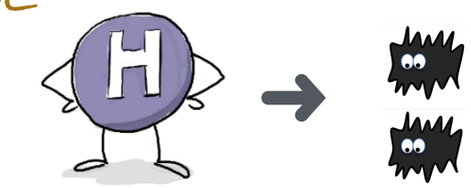
arXiv:2111.08372

95% CL limits on axial-vector mediator model



Observed (expected) upper limit on the invisible Higgs boson branching ratio at 95% CL

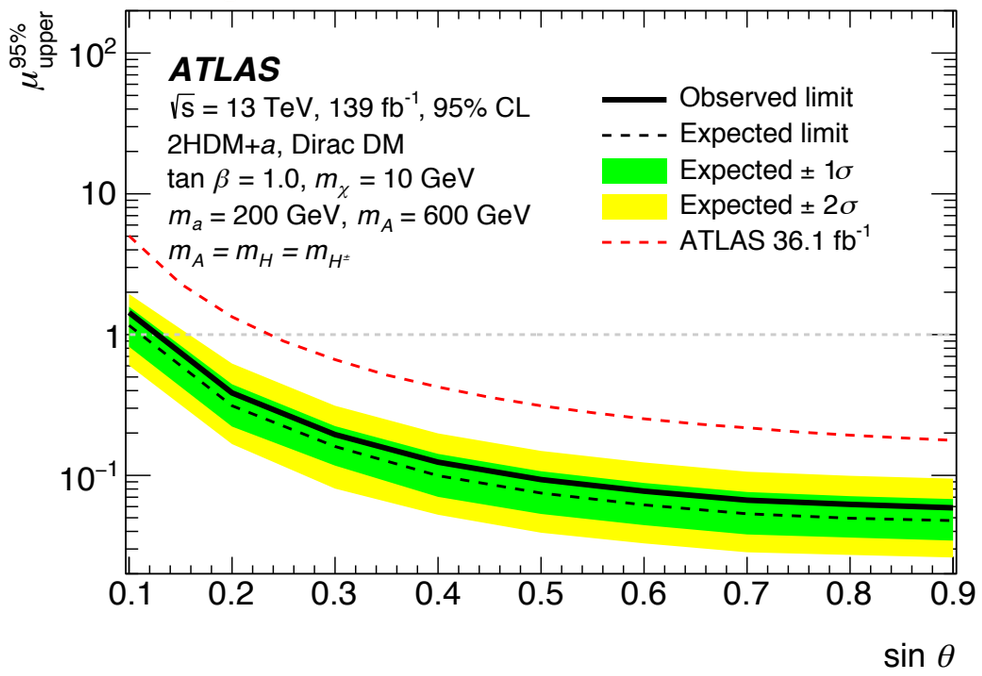
- Observed limit: 0.19
- Expected limit: 0.19

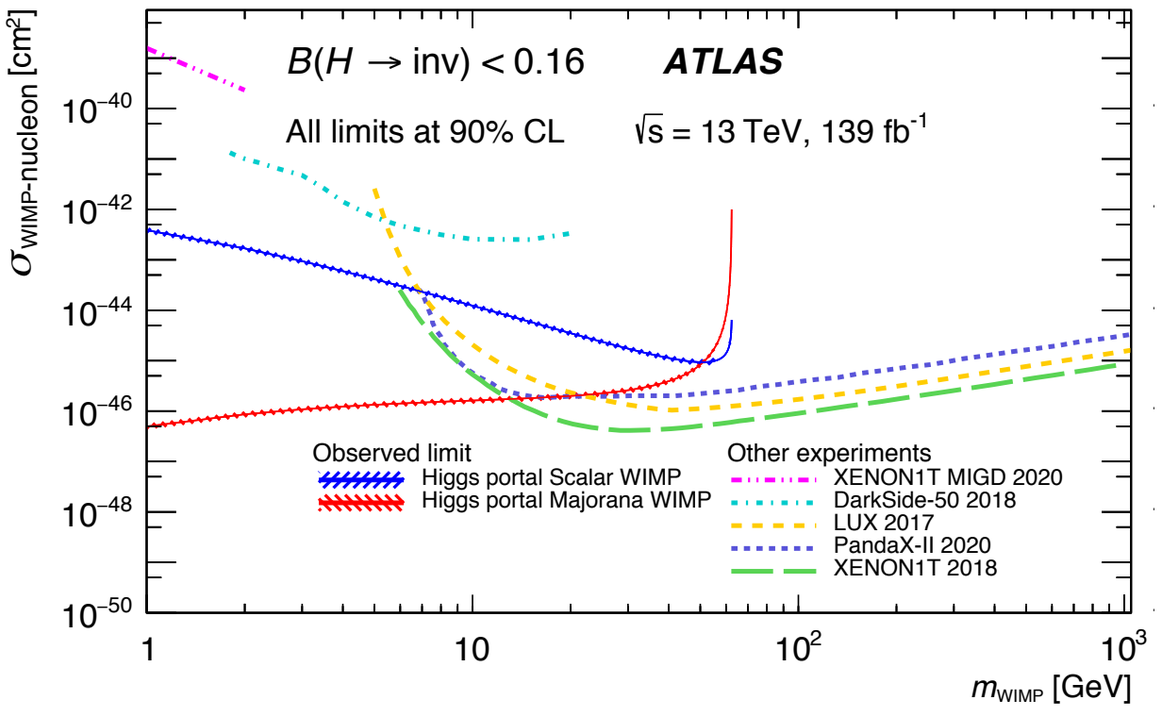


Comparison to direct detection experiments

90% CL is used, which corresponds to B(H→inv)=16%

95% CL limits for 2HDM+a model



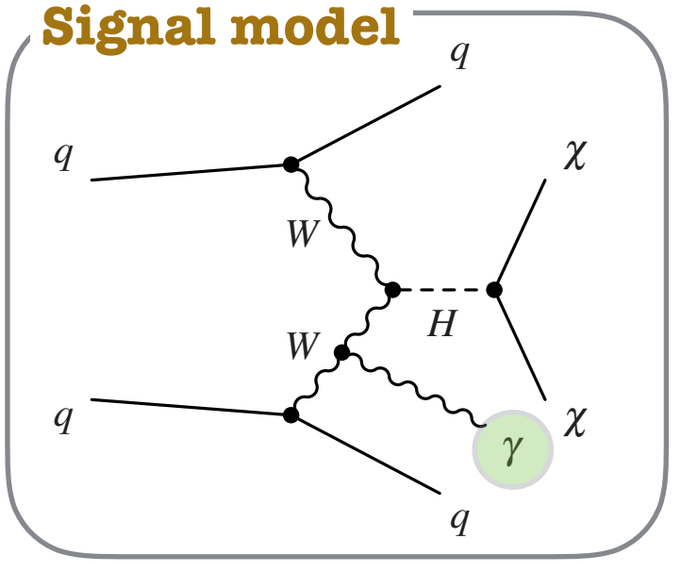


E_T^{miss} + VBF+γ

arXiv:2109.00925

Search for invisible decay of Higgs produced by Vector Boson Fusion (VBF) with a **photon**

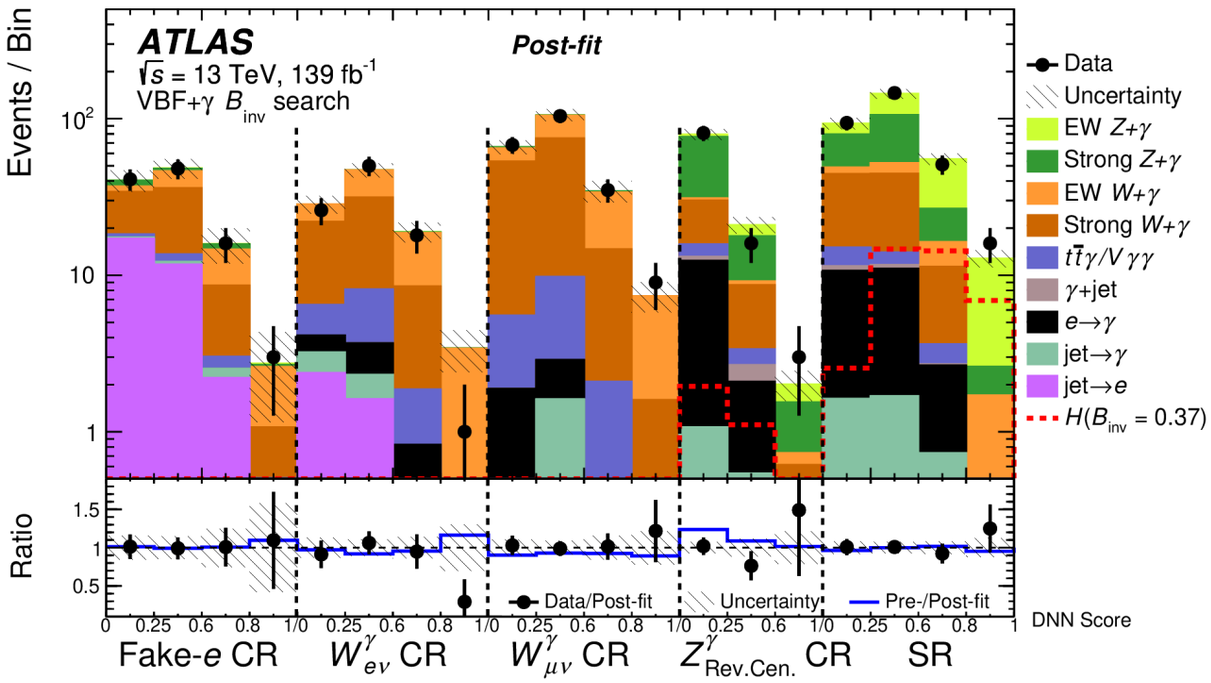
Signal model



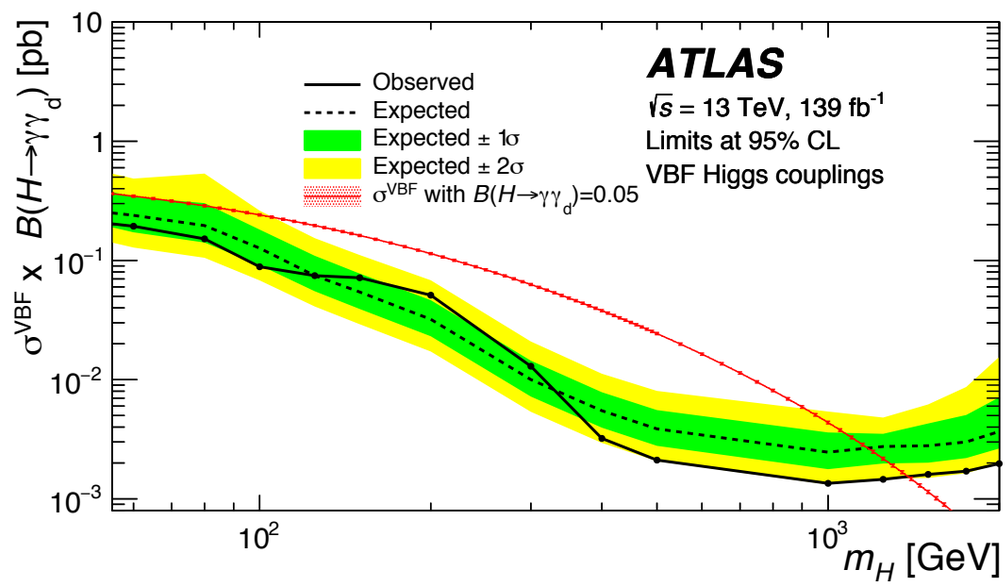
Strategy

- Selecting events with a photon, two jets with a rapidity difference $|\Delta\eta_{jj}| > 2.5$ and high E_T^{miss}
- **Main backgrounds:** Z(νν)+jets and W(lν)+jets with lost lepton estimated in the control regions defined with a lepton(s)
- **Additional background:** Z+jets & W+jets in which one of the jets is misreconstructed as a photon, photon+jet
- DNN output scope used in the maximum-likelihood fit to the observed data

Good agreement with the SM prediction

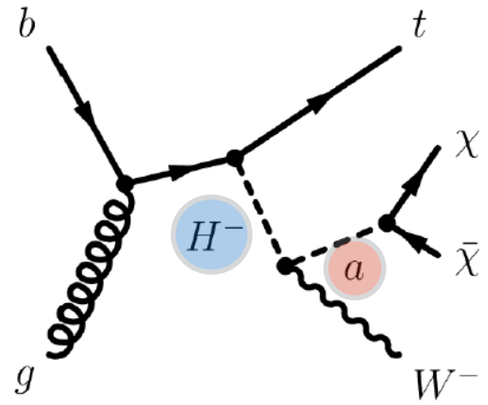


95% CL upper limit on the Higgs boson production cross-section times branching ratio to $\gamma\gamma_d$



arXiv:2011.09308

t + E_T^{miss}



- **2 Higgs Double Models** - with charged heavy Higgs particle ($H^{\pm}$) & pseudo-scalar (a) that couples to Dark Matter
- **Final states** with E_T^{miss}, a different number of leptons, jets/ b-jets are used to define signal regions
- **Main backgrounds** *tt*, W+jets, *tt*Z, WZ are estimated in the control regions defined using discriminating variables:

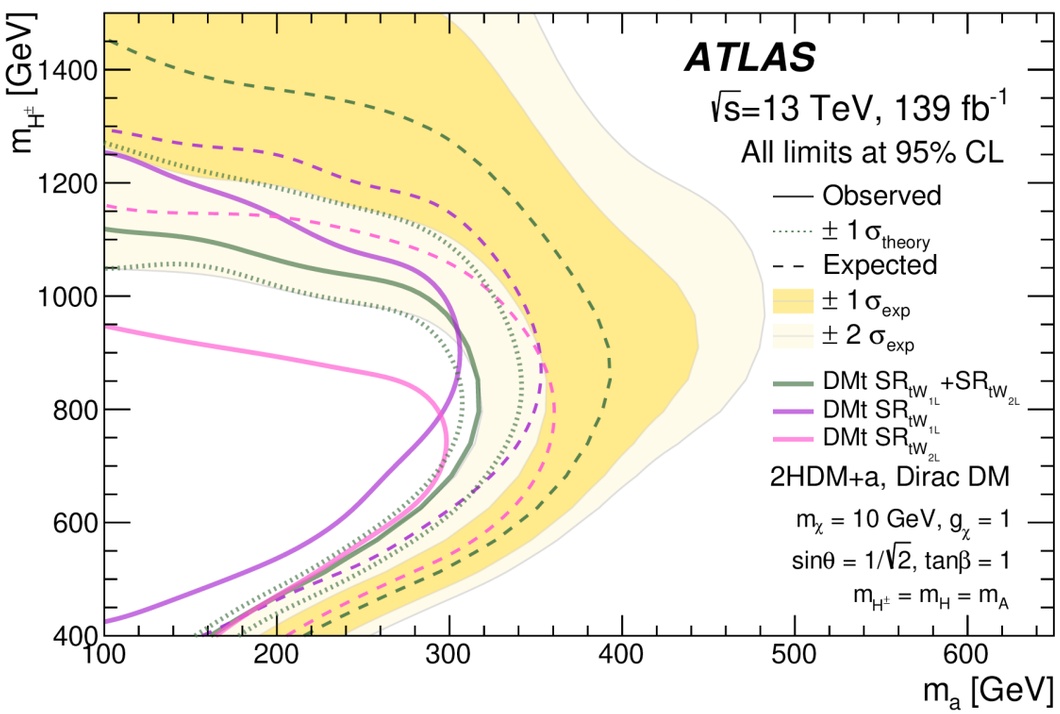
  ➜ transverse mass and similar variables defined with b-jets

$$m_{\mathrm{T}}^{\mathrm{lep}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} \left(1 - \cos\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})\right)}$$

➜ asymmetric stransverse mass, E_T^{miss}, m$_W$, m$_{ll}$, lepton/b-jet separation

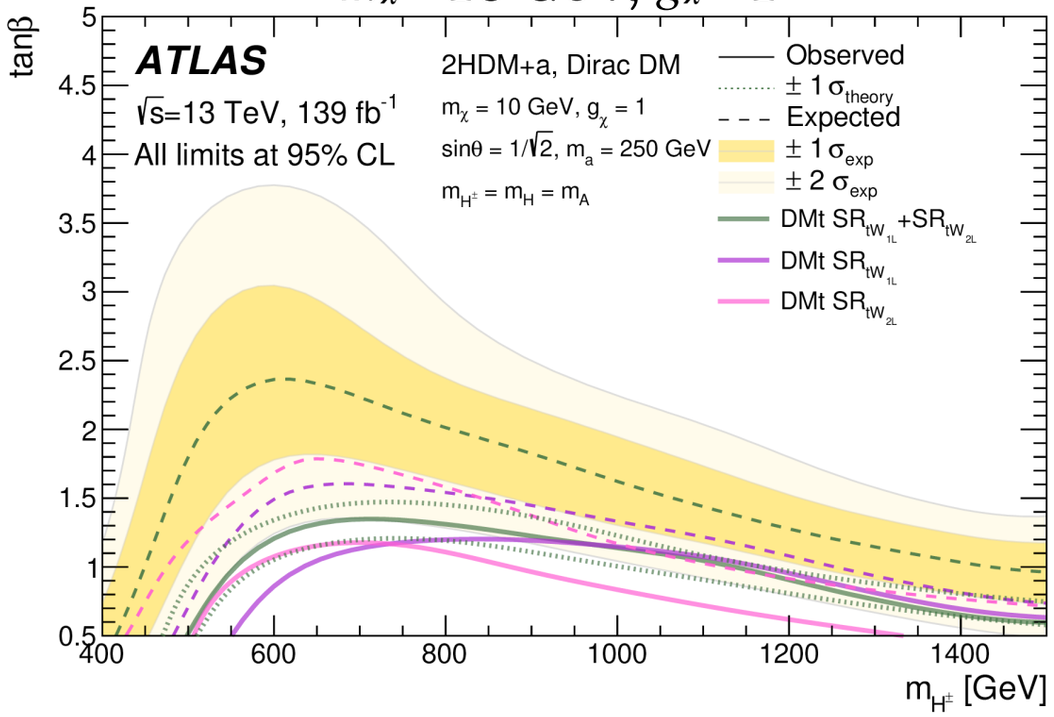
Charged Higgs vs Pseudo-scalar (a)

m_χ= 10 GeV, g_χ= 1



tanβ vs Charged Higgs ($H^{\pm}$)

m_χ= 10 GeV, g_χ= 1



E_T^{miss} + h(bb)

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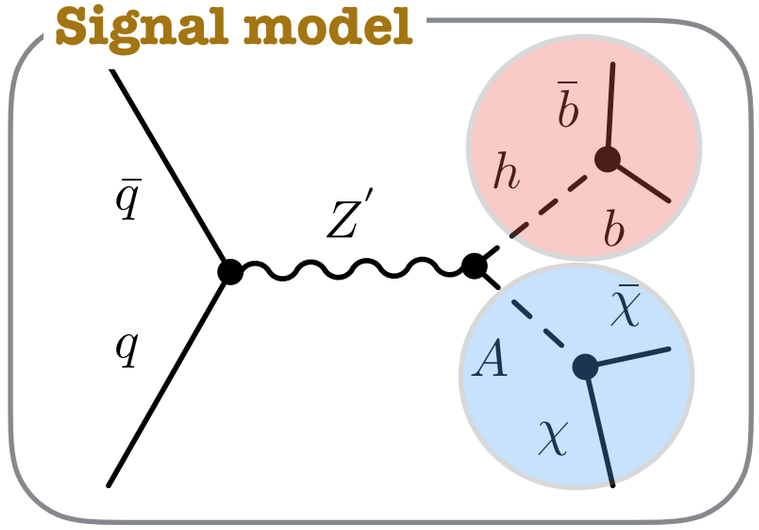
- Associated production of **Dark Matter** and a Higgs boson (**h → bb**)

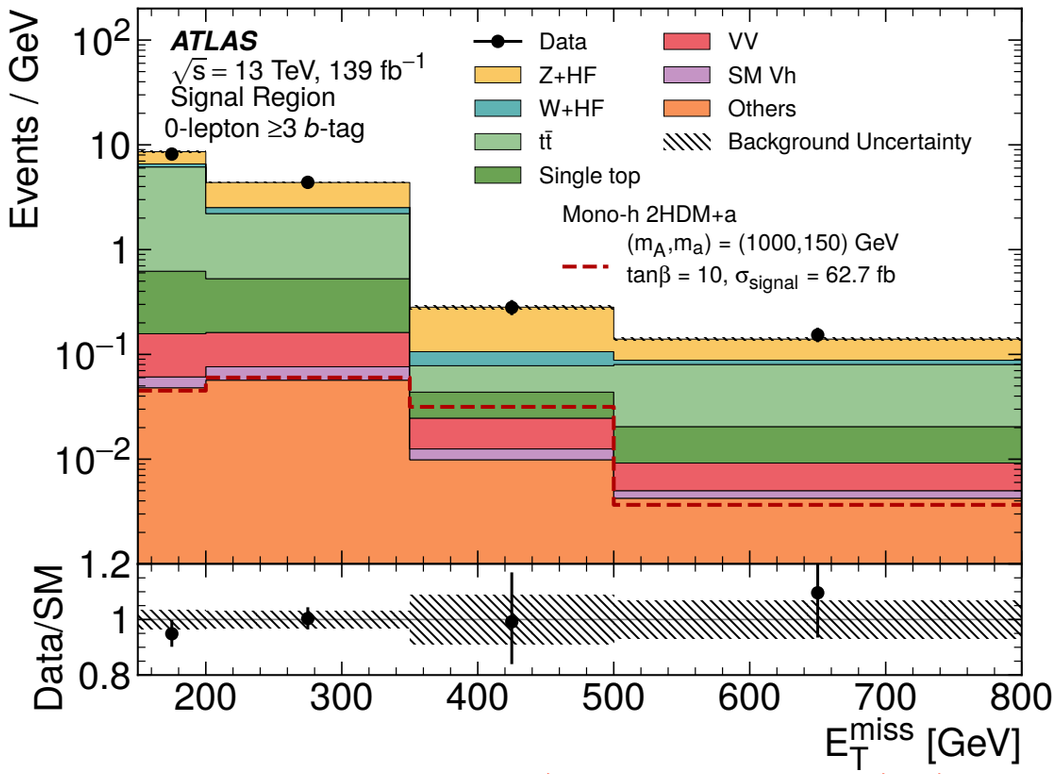
Signal model



Strategy:

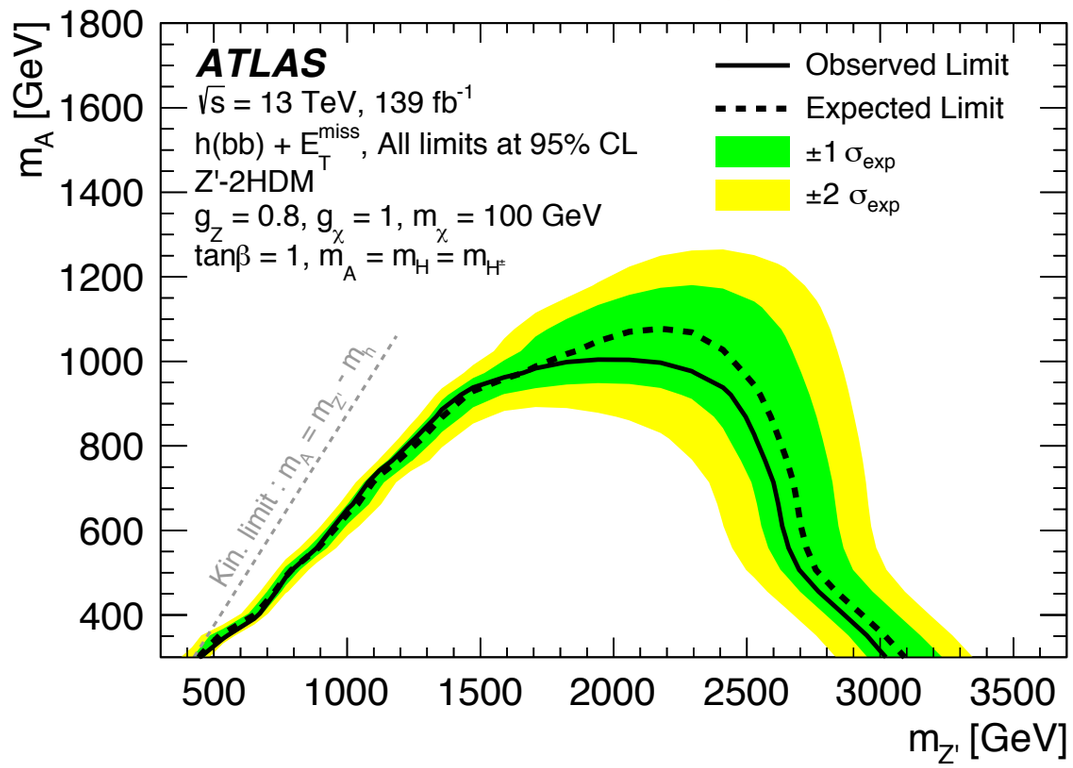
- selecting events with E_T^{miss} > 150 GeV and Higgs boson decay products
- two topologies: **resolved** (pair of separated jets) and **boosted** (single large-radius jet), depending on the Higgs boson momentum
- Discriminating variables: E_T^{miss} and dijet/large-R jet mass
- Z/W+jets and top-related backgrounds estimated in the control regions defined with 1/2 leptons

Signal Region



Good agreement with the SM prediction

Exclusion limit @ 95% CL



Combinations and summaries

Higgs portal

Simplified DM models

2 Higgs Double Models+a

Higgs portal

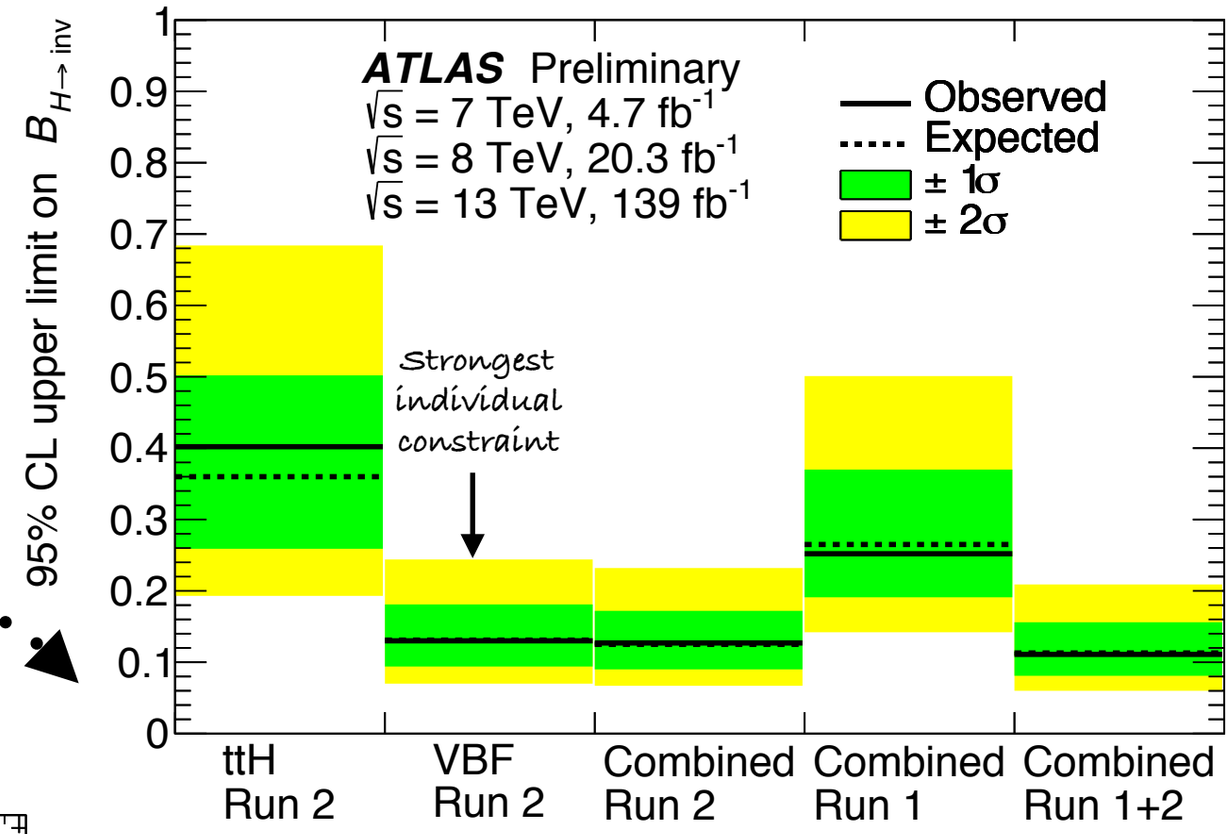
ATLAS-CONF-2020-052

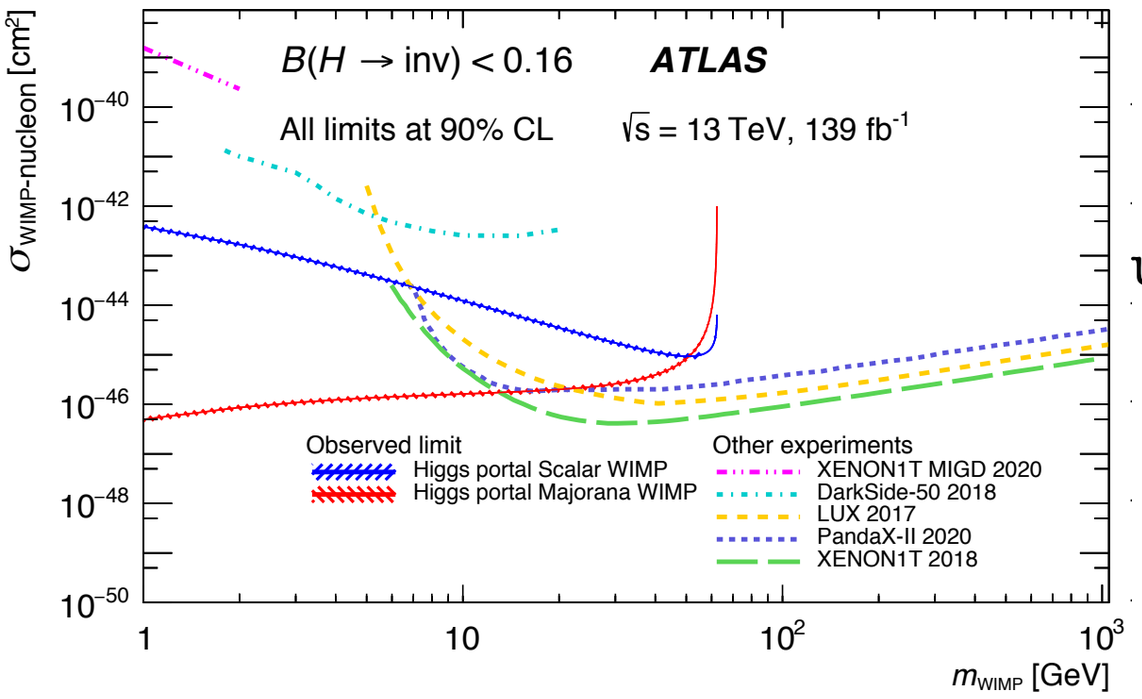
Statistical combination:

E_T^{miss}+VBF

tt+E_T^{miss} (2L and 0L + high E_T^{miss})

Run 1 (E_T^{miss}+VBF; E_T^{miss}+Z(ll); E_T^{miss}+W/Z)





Comparison to direct detection experiments

upper limits at 90% CL on the spin-independent WIMP-nucleon scattering cross-section to the observed exclusion limit

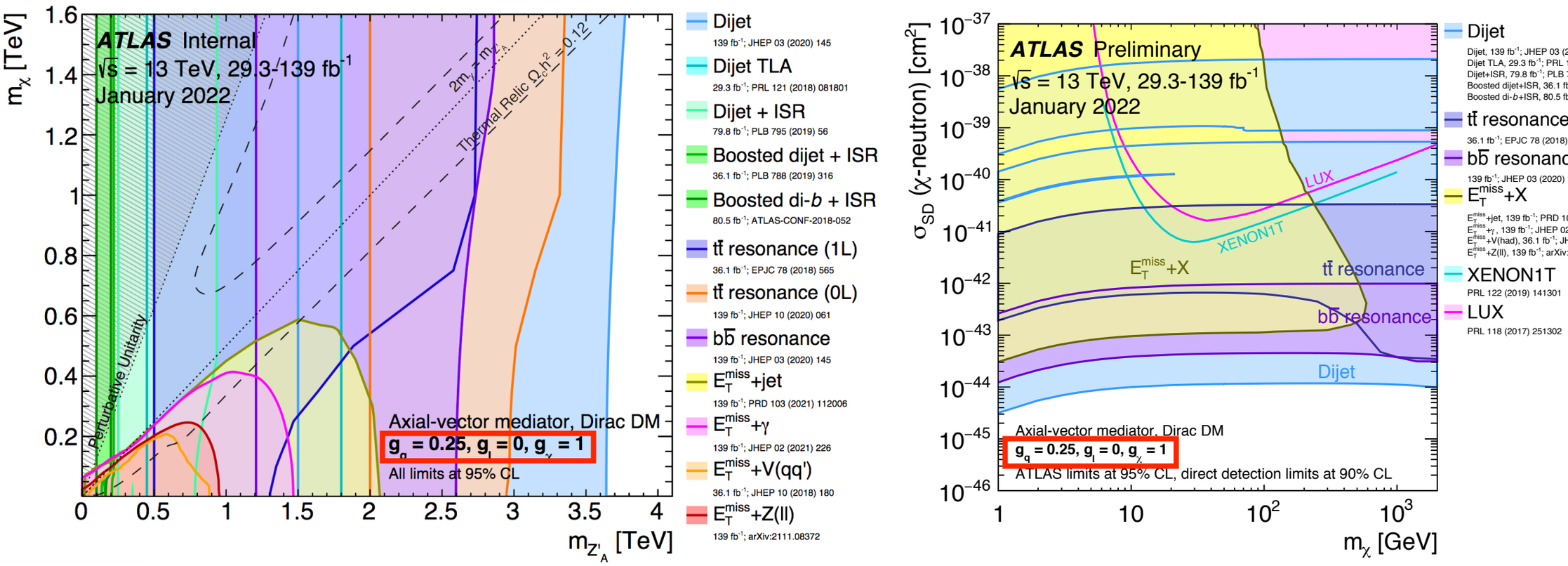
Final Run 2 will include more channels:

- E_T^{miss}+ Z(ll): Upper limits on Br(H→inv) = 19%
- E_T^{miss}+VBF+γ: Upper limits on Br(H→inv) = 37%

Simplified DM models

Axial-vector mediators

- E_T^{miss}+jet is the most sensitive channel among E_T^{miss}+X searches
- Upper limits on scattering cross-section compared with direct detection results



- Sensitivity of collider searches
  - comparisons different for different coupling values!
- Similar results for vector mediators
- Similar comparisons are produced for “different spin hypotheses”

2HDM+a models

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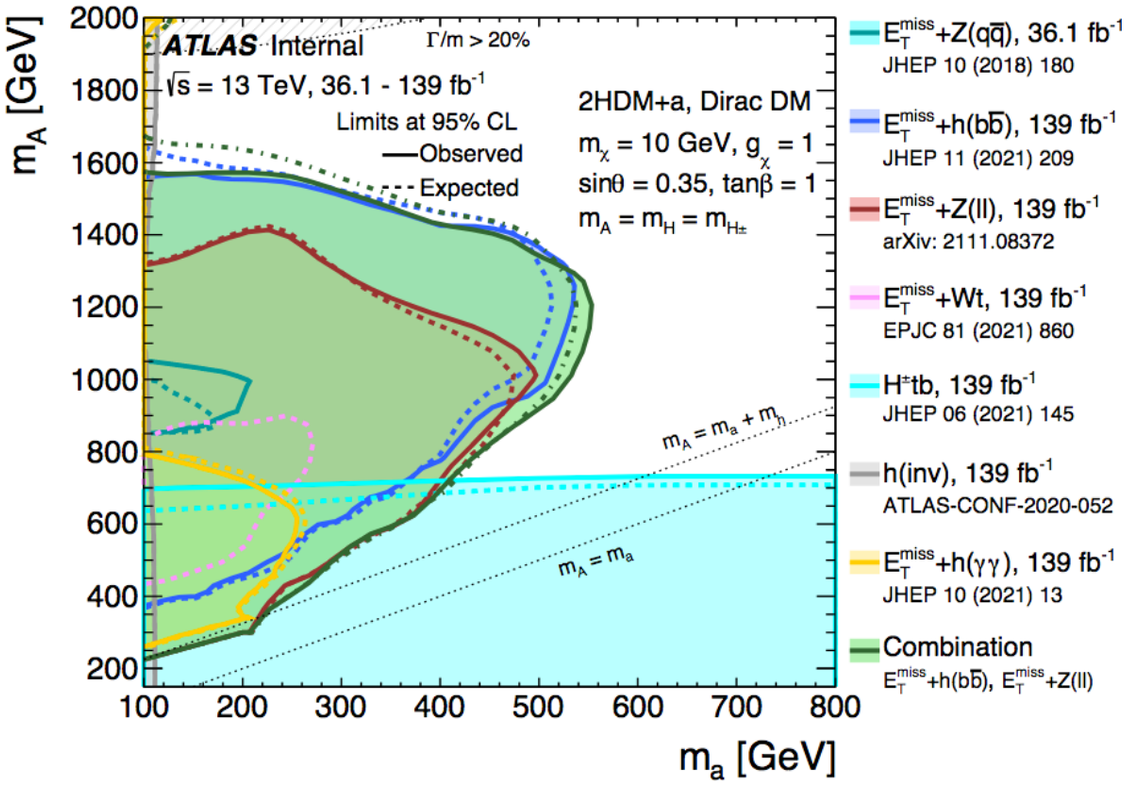
PUTTING IT ALL TOGETHER

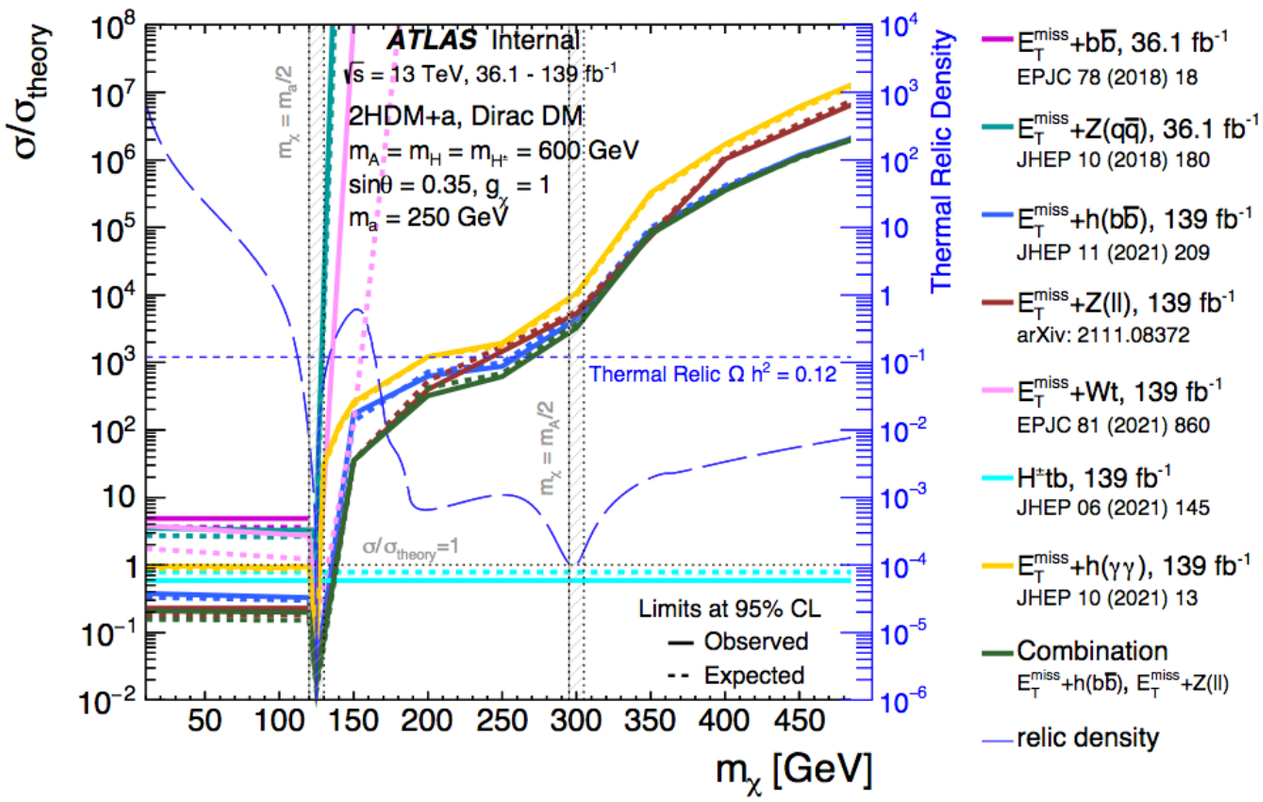
Exclusion sensitivity dominated by E_T^{miss}+h(bb) and E_T^{miss}+Z(ll)

H to invisible used to set limits on very low values of m_a

sinθ = 0.35



m(χ) scan



- Additional channels: $H^{\pm}tb$ and E_T^{miss}+Wt
- Statistical combination of E_T^{miss}+h(bb) and E_T^{miss}+Z(ll)

HL-LHC

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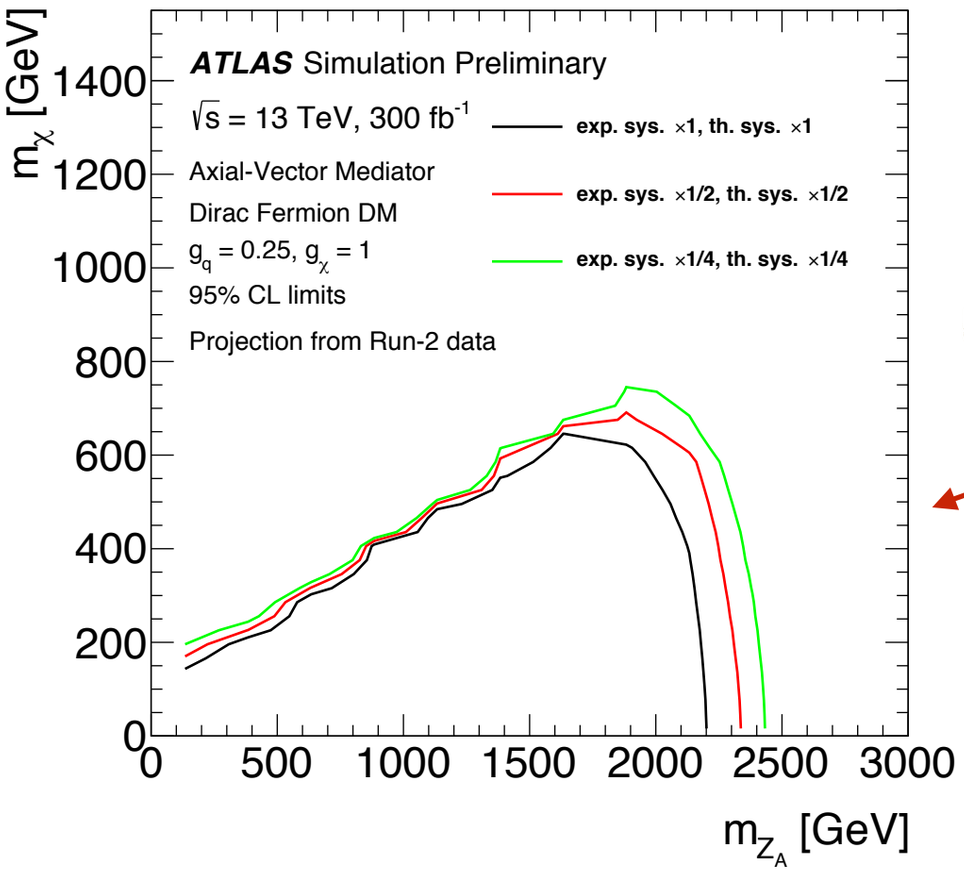
High Luminosity Large Hadron Collider (HL-LHC) will achieve the instantaneous luminosity **by a factor of 5 larger than the LHC nominal value around 2027**

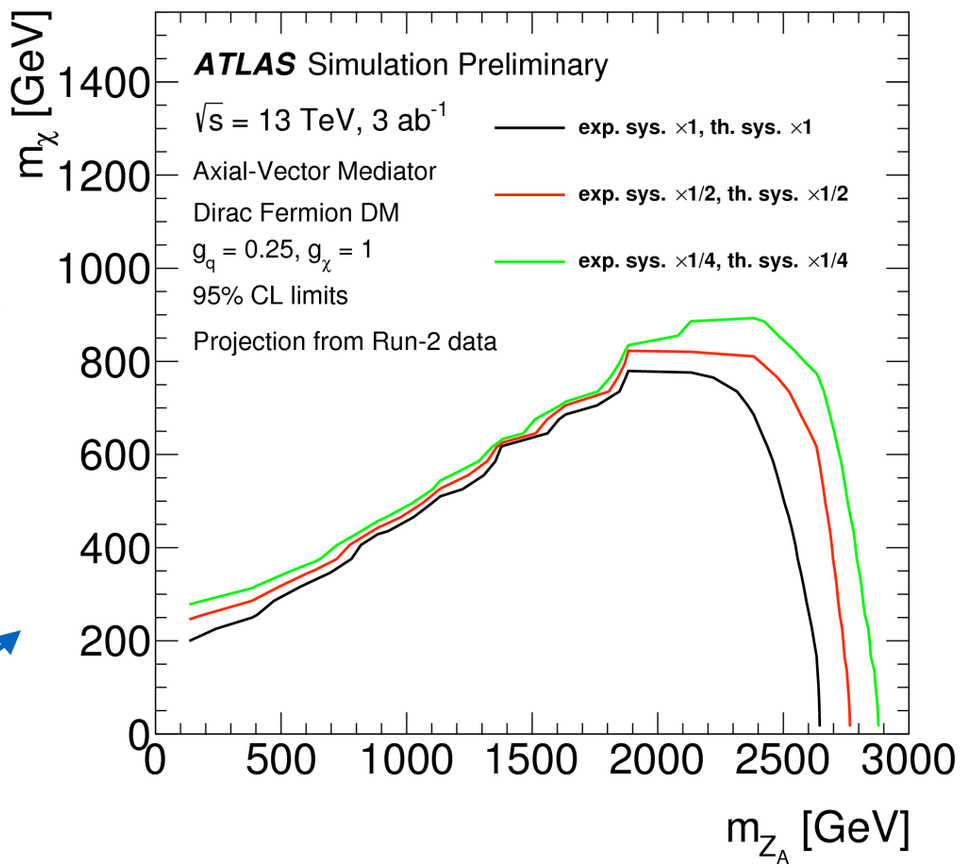
- expected number of collision per bunch crossing will increase up to 200

E_T^{miss} + Jet is a key channel for the search for dark matter

- The **sensitivity prospectives** are evaluated by extrapolating simulated results obtained by the ATLAS search based on 36 fb^{-1} of pp collisions at a center-of-mass energy of 13 TeV to integrated luminosities of **300 fb^{-1}** and **3000 fb^{-1}**
- Impact of different systematic uncertainty scenarios on the sensitivity
  - standard (black), reduced by a factor 2 (red), and 4 (green)



Sensitivity projections @ integrated luminosities of 300 fb^{-1} and 3000 fb^{-1}



Summary

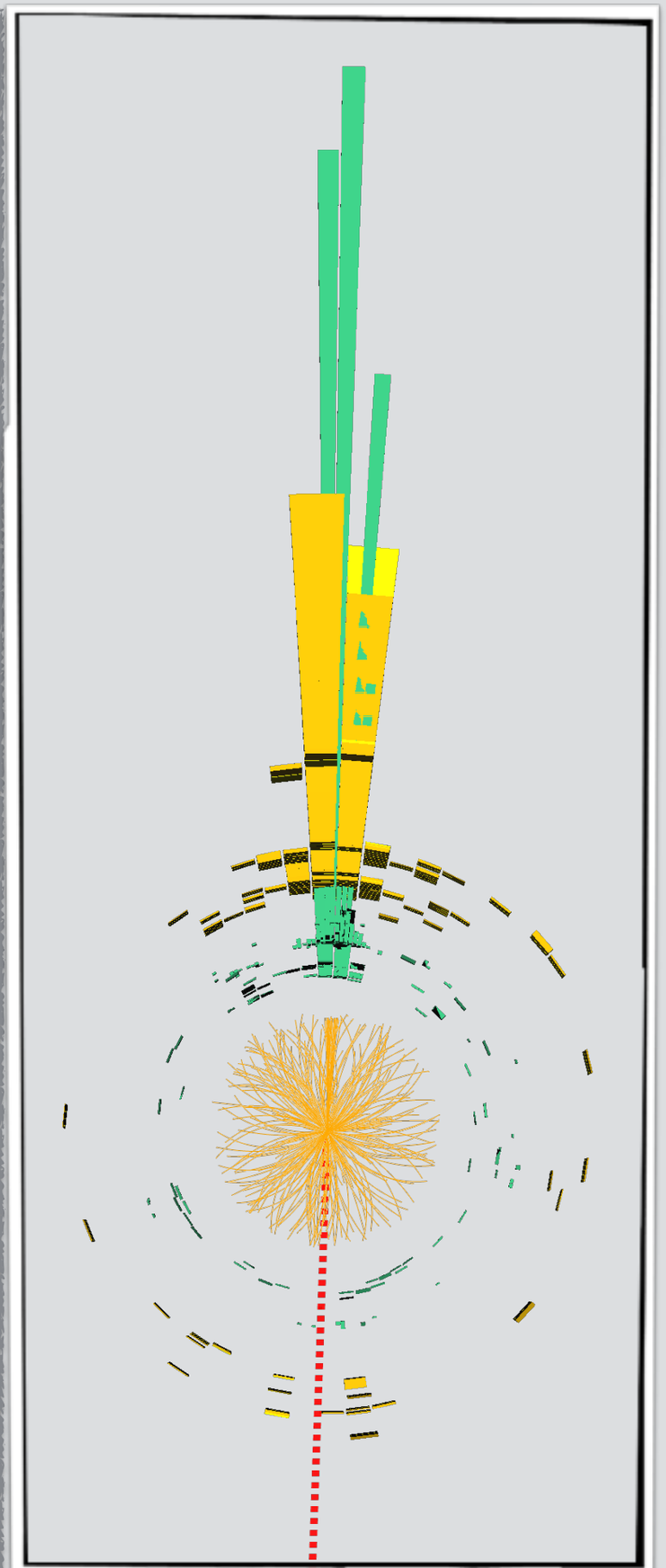
- The nature of the Dark Matter remains **one of the main questions** in particle physics
- **ATLAS** has a broad program of searches for Dark Matter candidates
- **Run II** searches mainly focus on simplified models
- **Subset of Dark Matter searches with the ATLAS detector** presented in this talk

A lot more results... but ...

ATLAS public twiki page: link here

- **Run 3** will double the dataset (~350 fb^{-1} to be delivered)
- **Full HL-LHC** program will extend significantly the reach (one order of magnitude more data!)

THANK YOU FOR YOUR ATTENTION!



Backup: E_T^{miss} + Jet

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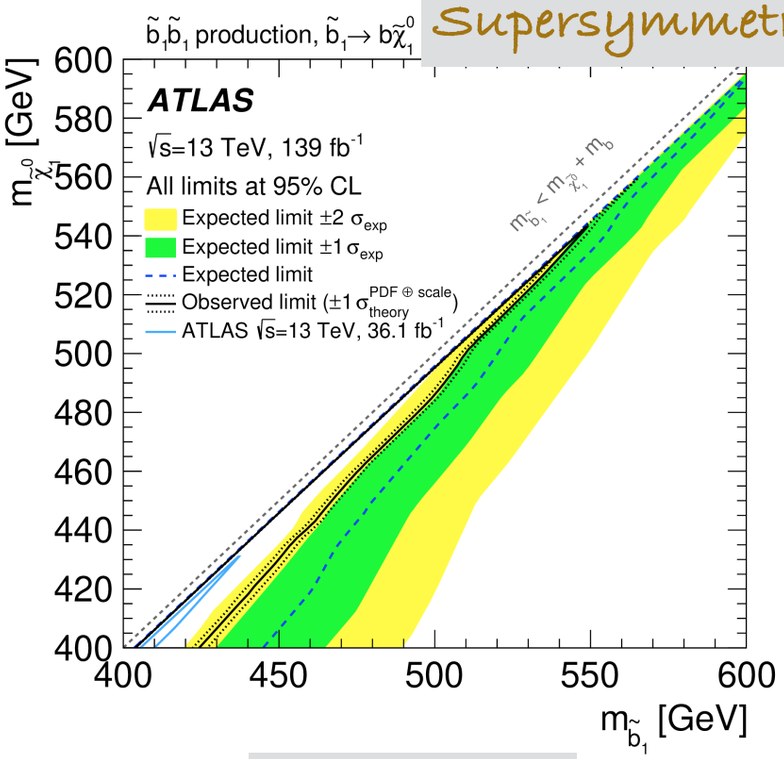
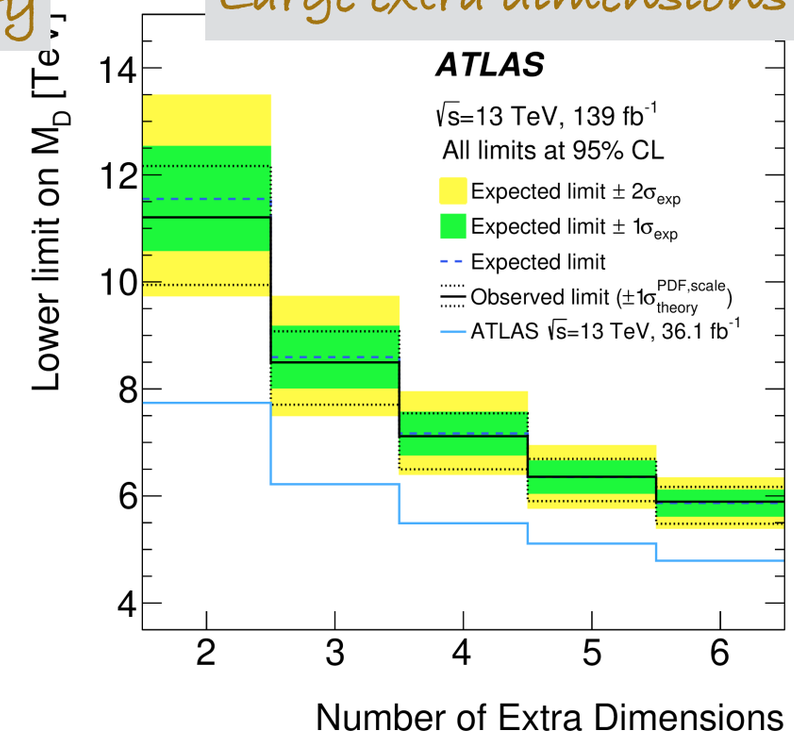
Supersymmetry



Large extra dimensions

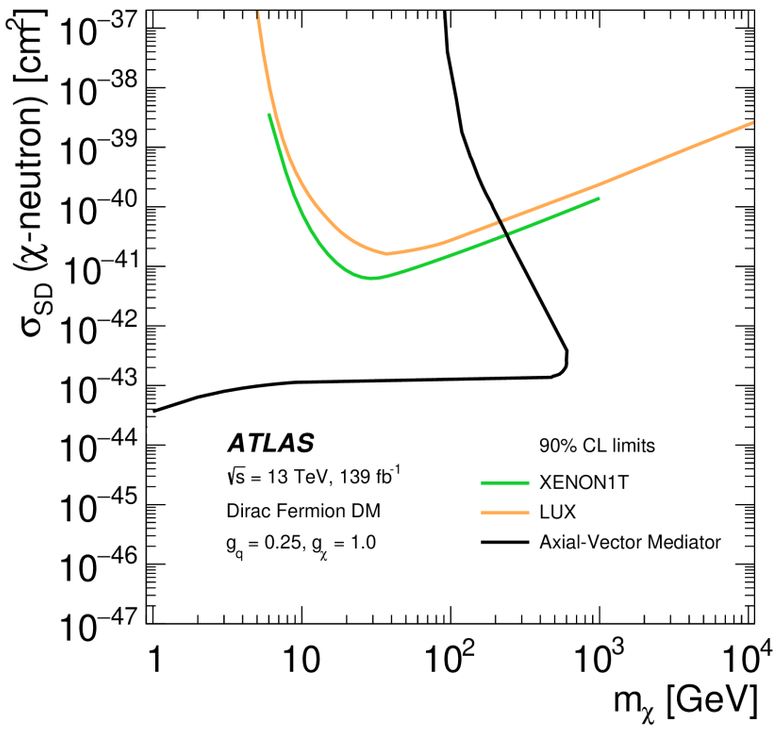


Comparison to direct detection experiments

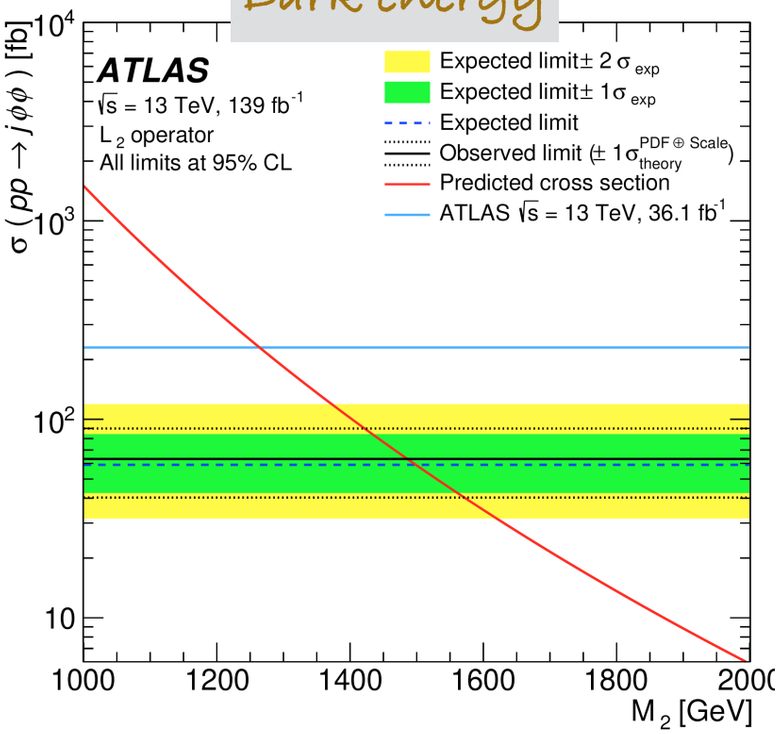
Axial-vector mediator

⇩

Spin dependent interaction



Dark energy



Axion-like particle