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ATLAS and CMS Dark Matter Searches: Results and Future Opportunities

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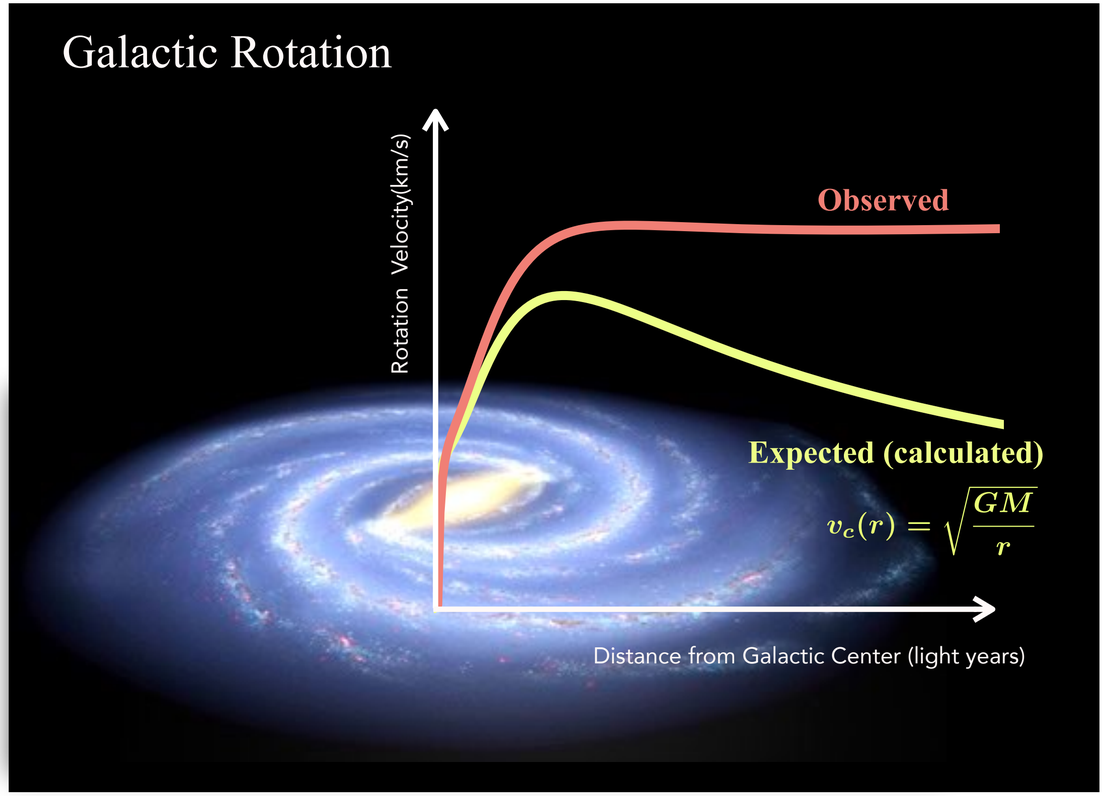
On behalf of the ATLAS and CMS collaborations

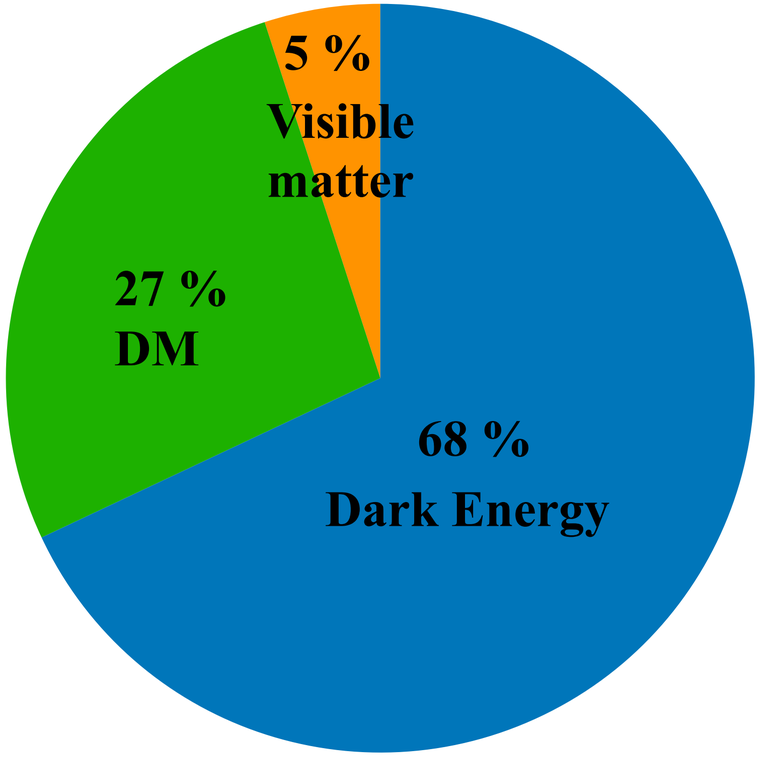
Dark Matter

Long-standing evidences for Dark Matter (DM) from astronomical observations and gravitational effects:

- Galactic rotation curves
- Gravitational lensing
- Cosmic Microwave Background anisotropies, …



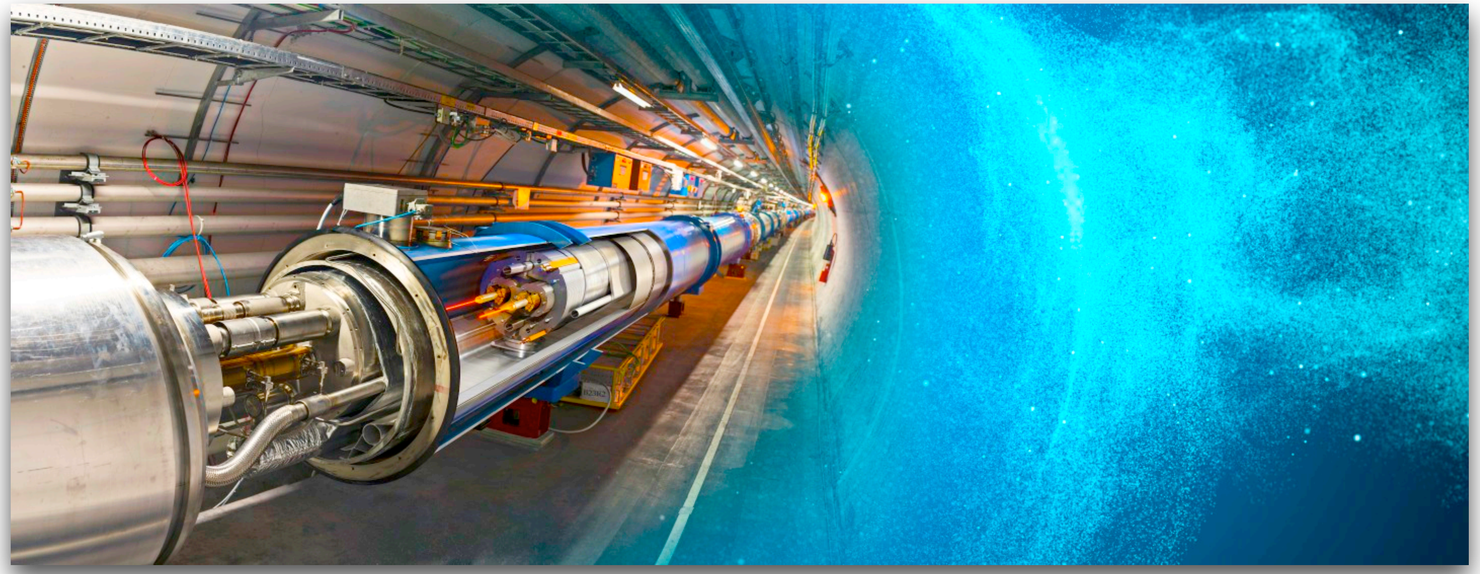
The estimated matter-energy content in the universe is:

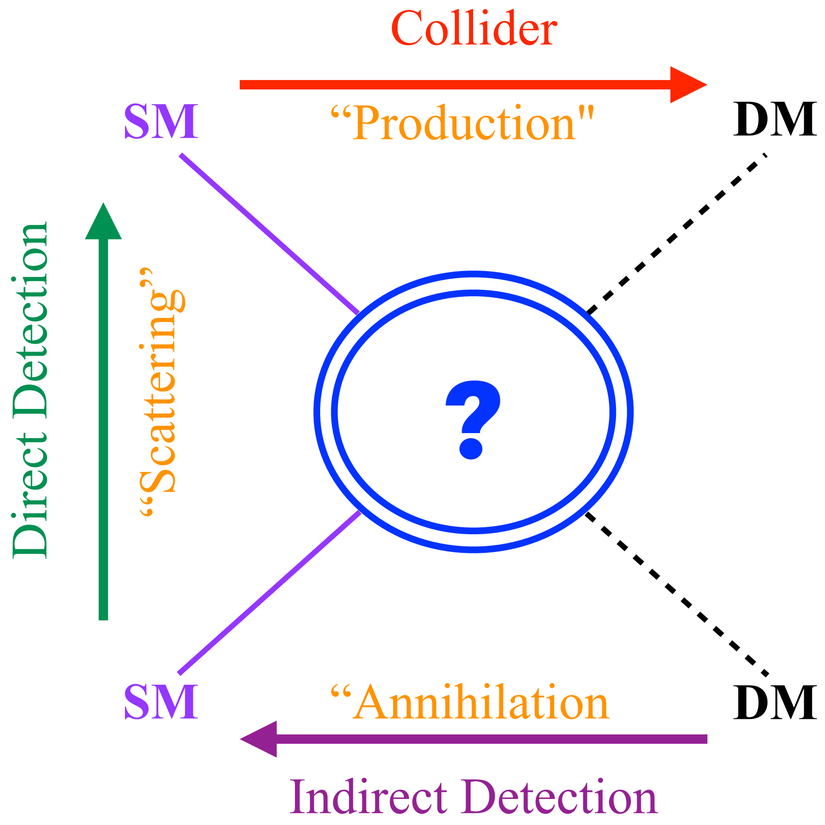


Dark Matter Detection

DM-SM weak interaction enables different searches:

- **Indirect Detection (ID)**: products from DM annihilation (HESS, IceCube, ..)
- **Direct Detection (DD)**: nuclear recoils from DM-nuclei scattering (XENON, SNOLAB)
- **Colliders**: DM production in high-energy collisions (LHC)

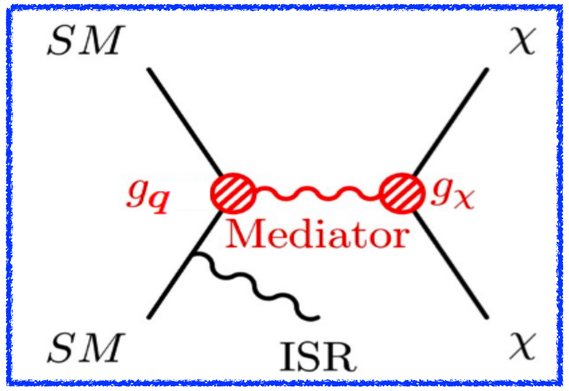




- Directly probes the DM production mechanism.
- Complementary to DD and ID searches.

Dark Matter Models at the LHC

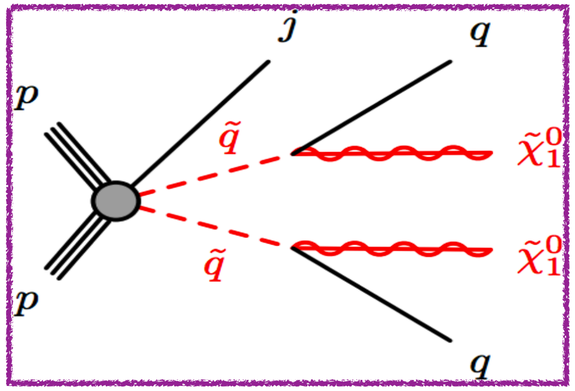
Simplified models



SM-DM boson mediator:

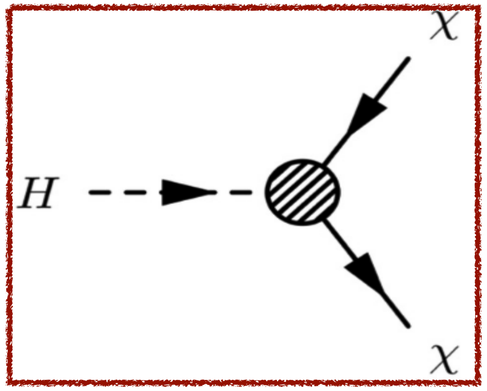
- Spin-0: Scalar (S) or pseudo-scalar (a)
- Spin-1:
  Vector (V/Z') or axial-vector (A)
- Minimal set of parameters:
  M_χ, $M_{mediator}$, g_χ, g_q, g_ℓ

SUSY



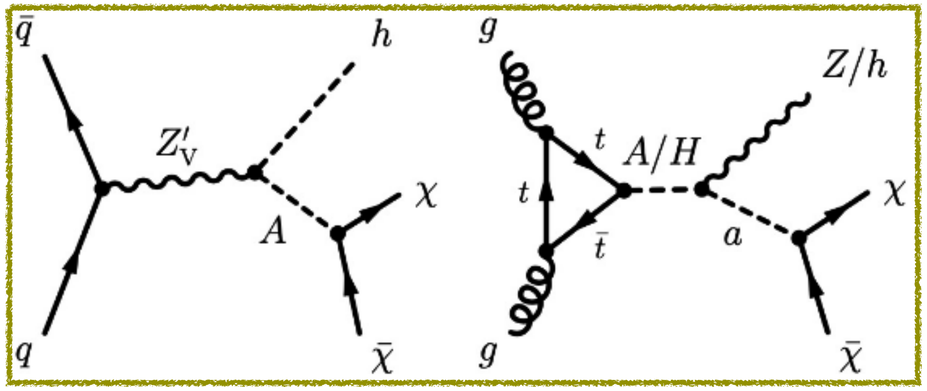
- Provides good candidate for DM
- R-parity conservation
- Lightest supersymmetric Particle (LSP)
- Model-dependent limit on DM candidate

Higgs portal



- Higgs boson mediates DM-SM interaction:
  $H \rightarrow invisible$
- Parameters: m_χ, χ spin

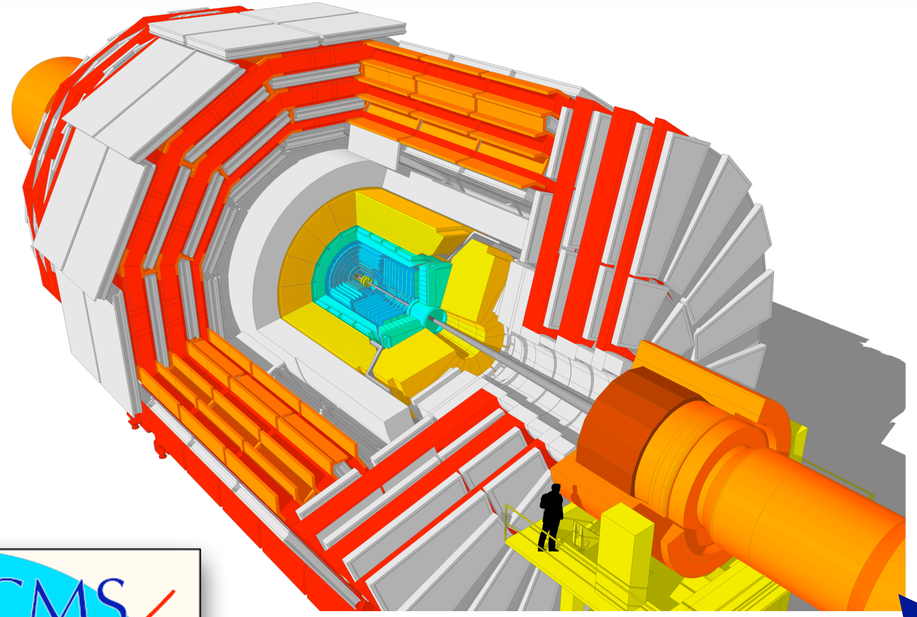
Extended Higgs sector



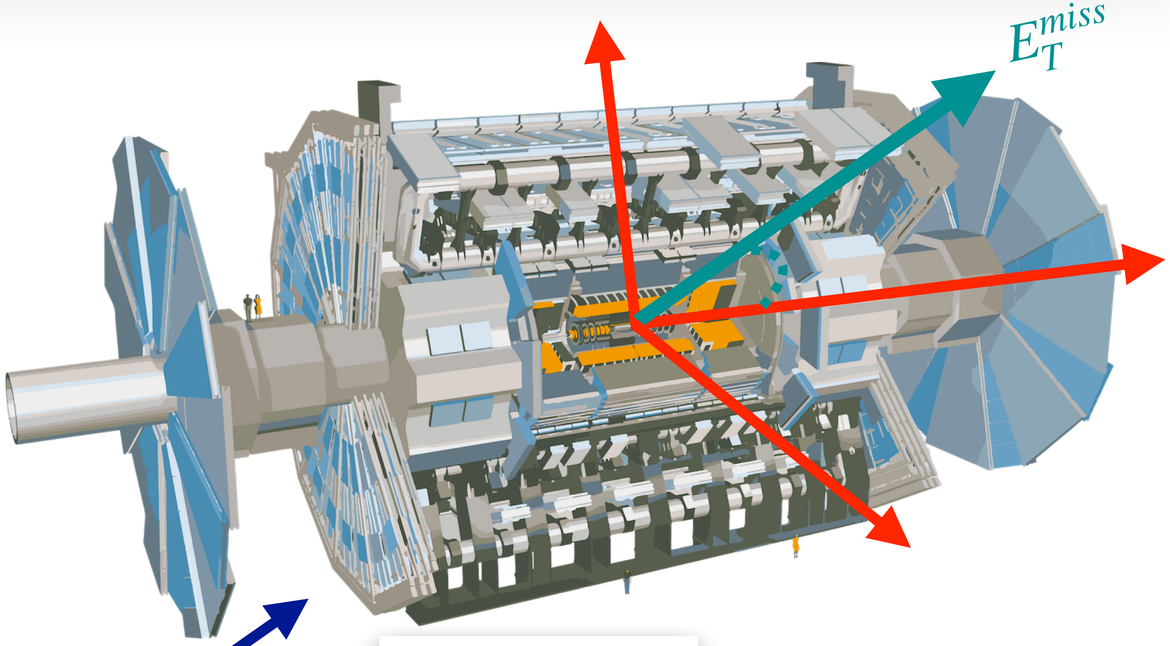
- More complete models (more free parameters and better sensitivity) involving several Higgs-like (or scalar) bosons: 2HDMa, Dark Higgs, ..

ATLAS and CMS

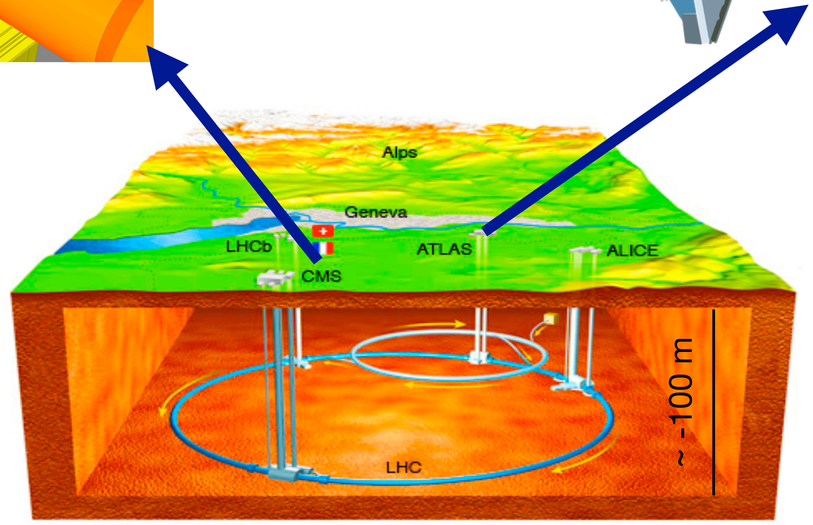
p-p LHC Run 2: Center of mass energy $\sqrt{s} = 13\ TeV$, integrated luminosity 139 (137) fb^{-1} for ATLAS (CMS)



21m long, 15m high,
weighs 14000 tonnes



46m long, 25m high,
weighs 7000 tonnes

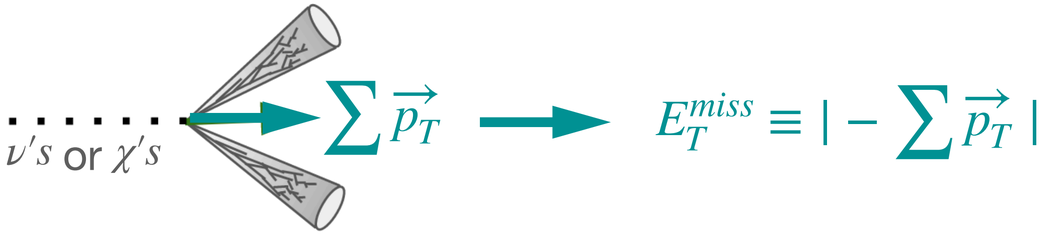


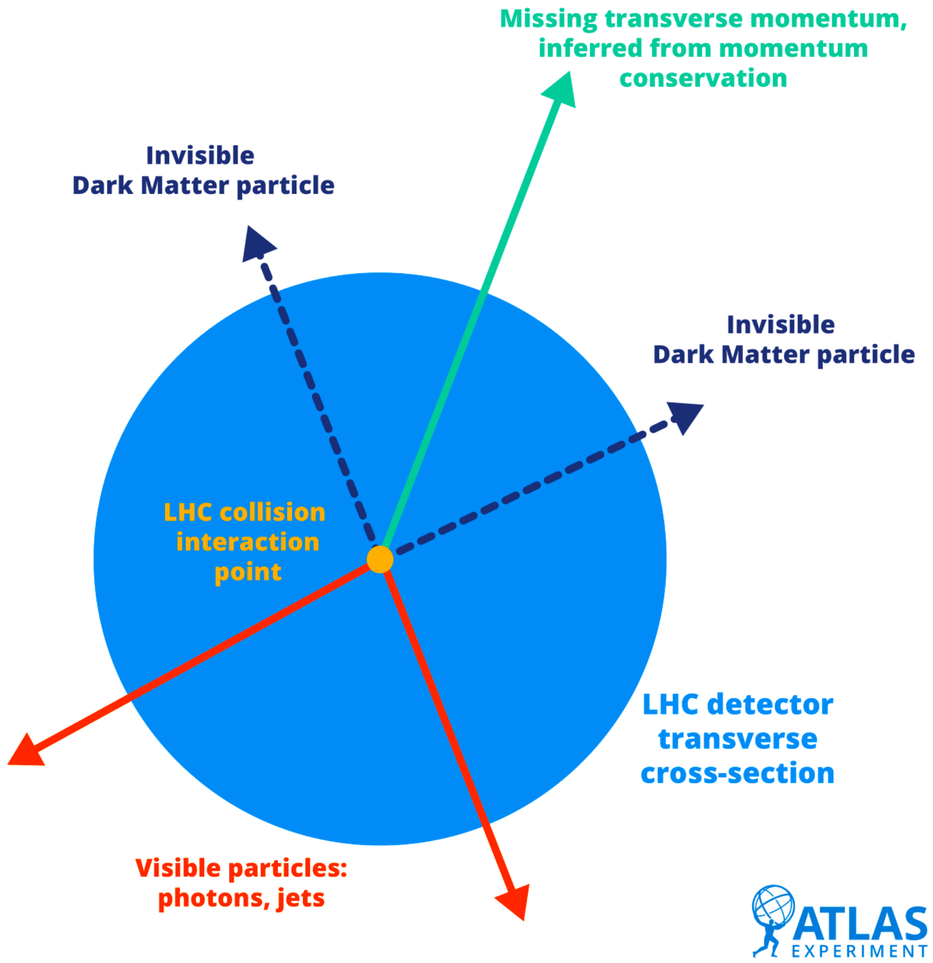
Dark Matter at the LHC

At the LHC experiments (ATLAS and CMS):

- DM makes an important part of the LHC search program
- DM does not interact with the apparatus.
  - Final states with undetected particles.
  - Creates a transverse momentum p_T imbalance

    => Detected as **Missing transverse energy** E_T^{miss}.
- Favourite collider DM candidate: WIMP
  - Weakly interacting, heavy, & stable
  - Naturally accounts for observed relic density (WIMP Miracle)

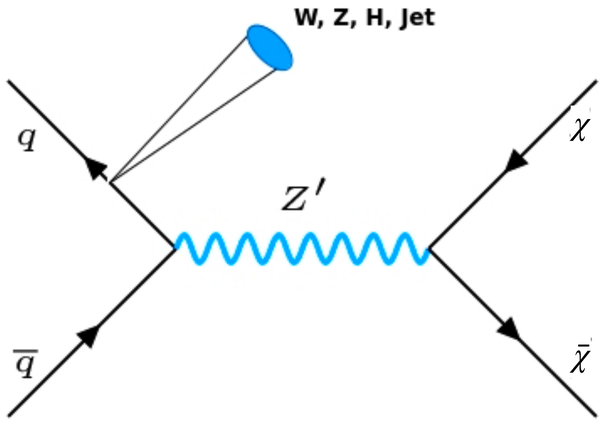




ATLAS and CMS Dark Matter Searches: Results

Disclaimer: focusing only on the most recent results.
More results are included in the backup slides.

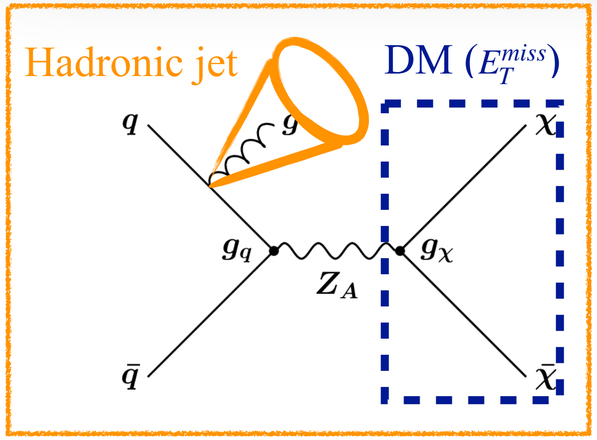
MonoX searches: $X + E_T^{miss}$



$jet + E_T^{miss}$

ATLAS: Phys. Rev. D 103 (2021) 112006

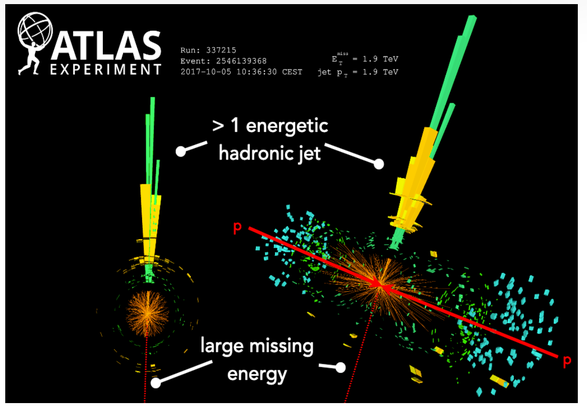
Inclusive signature sensitive to a wide range of New Physics theories



Main Backgrounds

- ✓ Dominant contribution from $Z(\rightarrow \nu\nu) + jets$ and $W(\rightarrow \ell\nu) + jets$
  - ➡Constrained in 1/2 ℓ regions
  - ➡Shapes modelled by state-of-the-art MC simulation: **NNLO QCD+ NLO EW**
- ✓ 5 Control Regions (CR) in the fit: $W(e\nu)$, $W(\mu\nu)$, $Z(ee)$, $Z(\mu\mu)$, $t\bar{t} + single\ t$
- ✓ Total background uncertainty: 2-4%

$jet + E_T^{miss}$ events displays

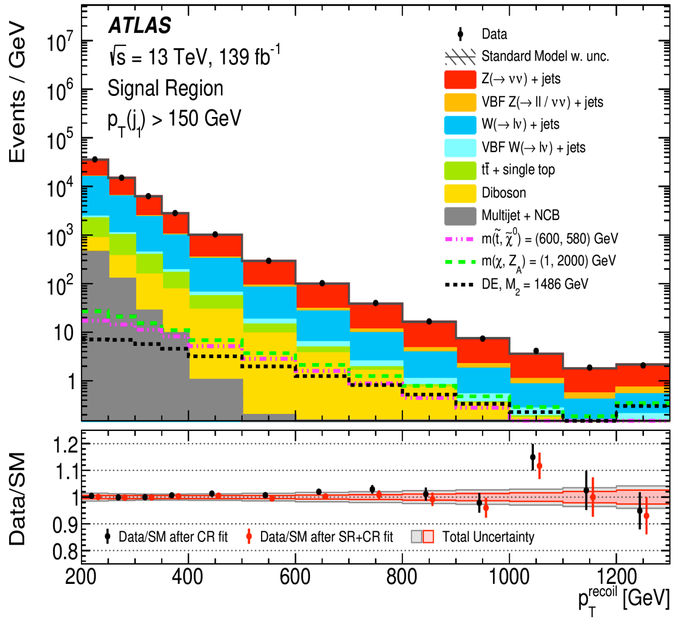


'simplified DM model'

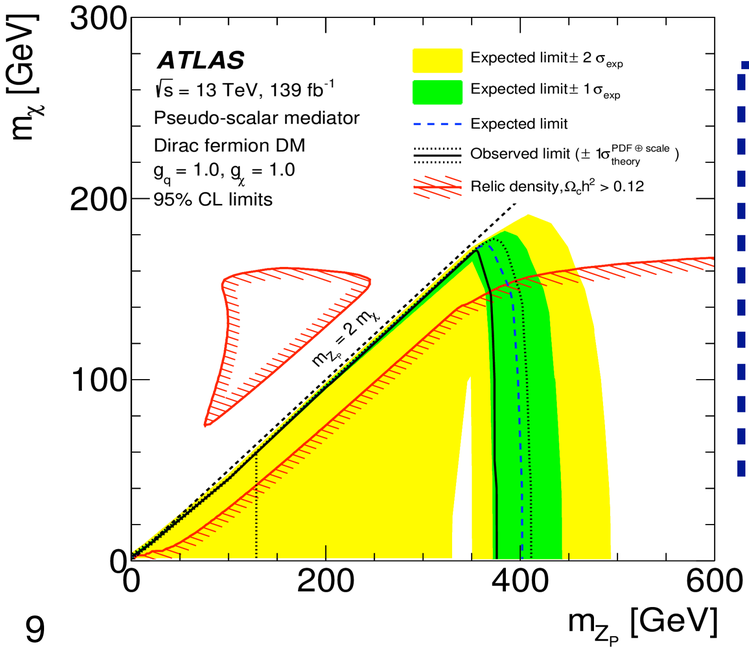
Signal Region (SR)

- E_T^{miss} triggered events
- $E_T^{miss} > 200$ GeV for
- Up to 4 jets well separated from E_T^{miss}
- Require jet from ISR with $p_T > 150$ GeV and $|\eta| < 2.4$
- Veto leptons and photon

Simultaneous fit to p_T^{recoil}



Limit on Pseudo-scalar mediator

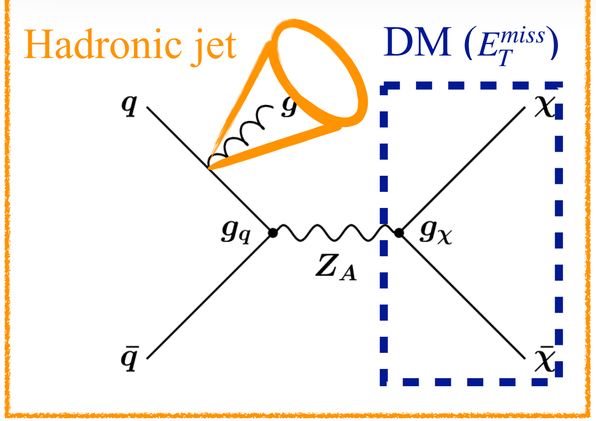


Various interpretations: model dependent & independent limits on (WIMPs, squark pair production, extra dimensions, scalar dark energy, invisible Higgs, ALPs) are included in the paper.

$jet + E_T^{miss}$

CMS: JHEP 11 (2021) 153

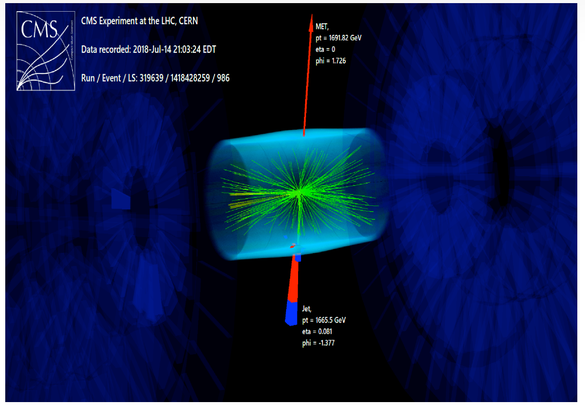
Inclusive signature sensitive to a wide range of New Physics theories



Main Backgrounds

- ✓ Dominant contribution: $Z(\rightarrow \nu\nu) + jets$, $W(\rightarrow \ell\nu) + jets$ and $\gamma + jets$
  - ➡Constrained in 3 CRs: 1ℓ, 2ℓ and $1\,\gamma$.
- ✓ QCD Multi-jet: **Data-Driven**
- ✓ Signal includes also $V(had) + E_T^{miss}$

$jet + E_T^{miss}$ events displays

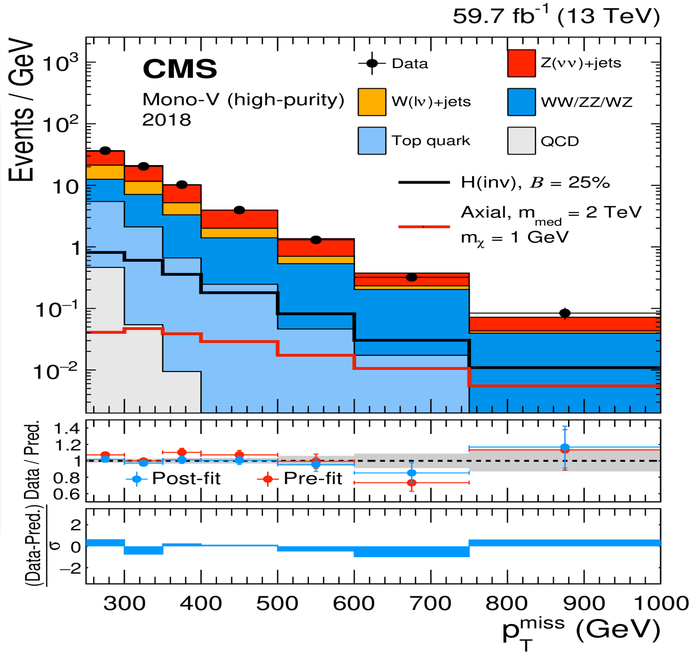


'simplified DM model'

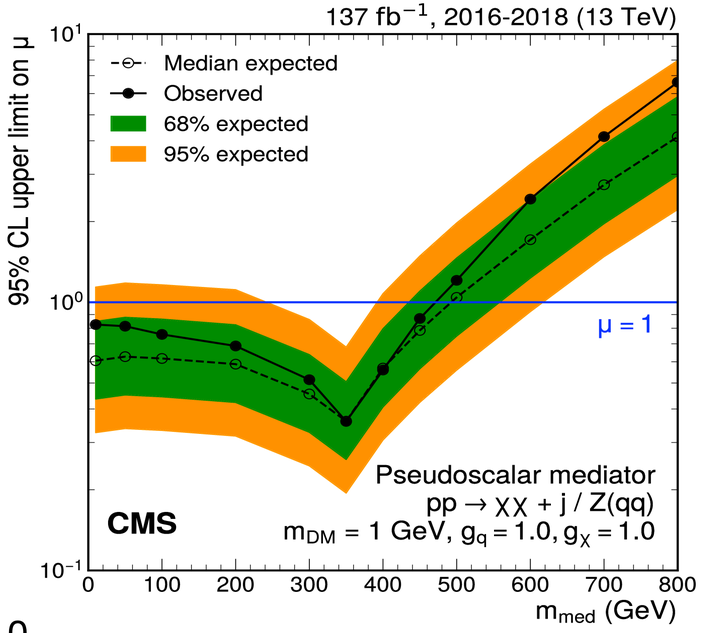
Signal Region (SR)

- E_T^{miss} triggered events
- $E_T^{miss} > 250$ GeV for
- Up to 4 jets well separated from E_T^{miss}
- Require jet from ISR with $p_T > 100$ GeV and $|\eta| < 2.4$
- Veto leptons and photon

Simultaneous fit to p_T^{miss}



Limit on Pseudo-scalar mediator



Various interpretations: Limits on dark matter particle production in the context of simplified models with vector mediator and axial-vector mediator are included in the paper.

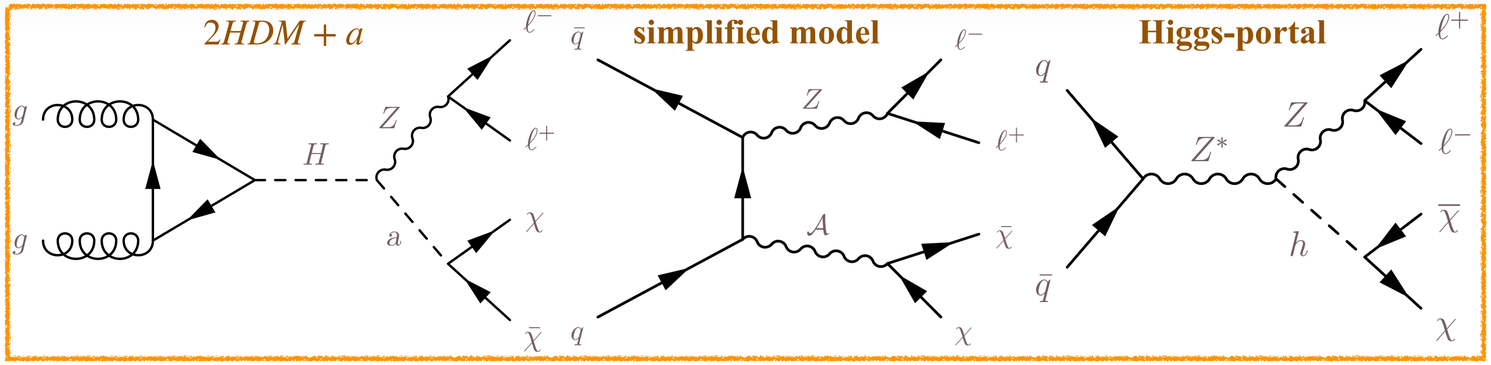
$Z(\rightarrow ll) + E_T^{miss}$

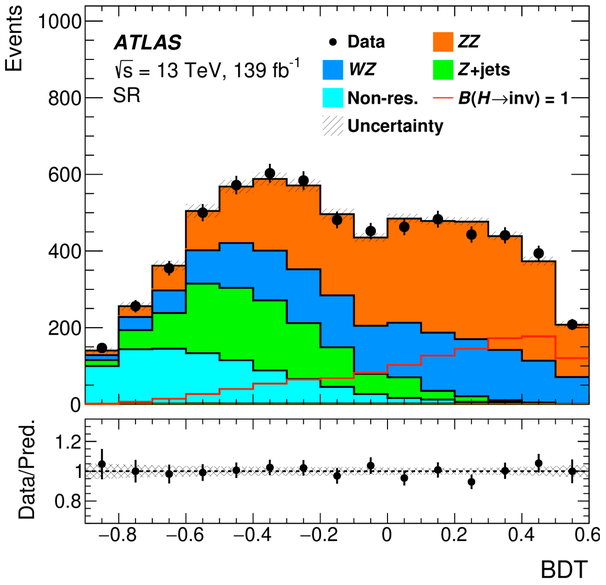
ATLAS: Phys. Lett. B 829 (2022) 137066

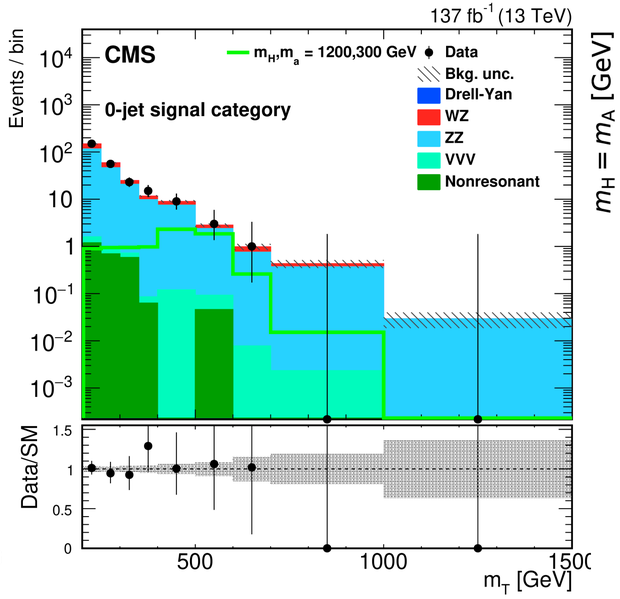
CMS: Eur. Phys. J. C 81 (2021) 13

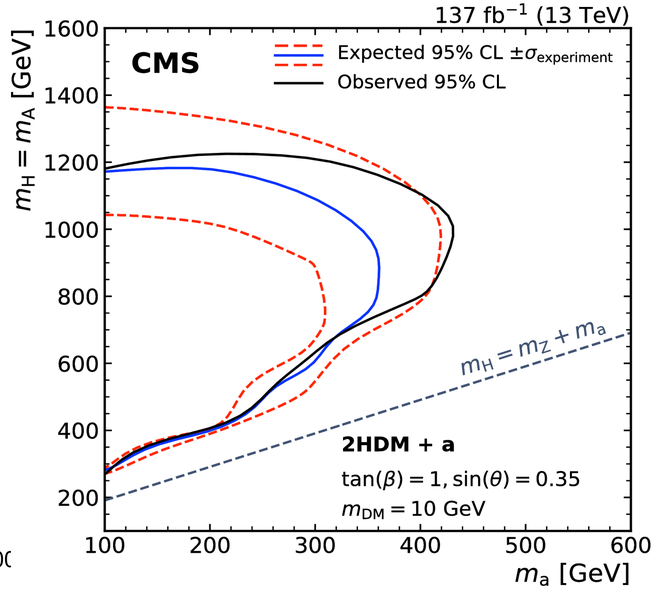
'2*HDM* + *a*, simplified DM model (spin-1 mediator), Higgs-portal'

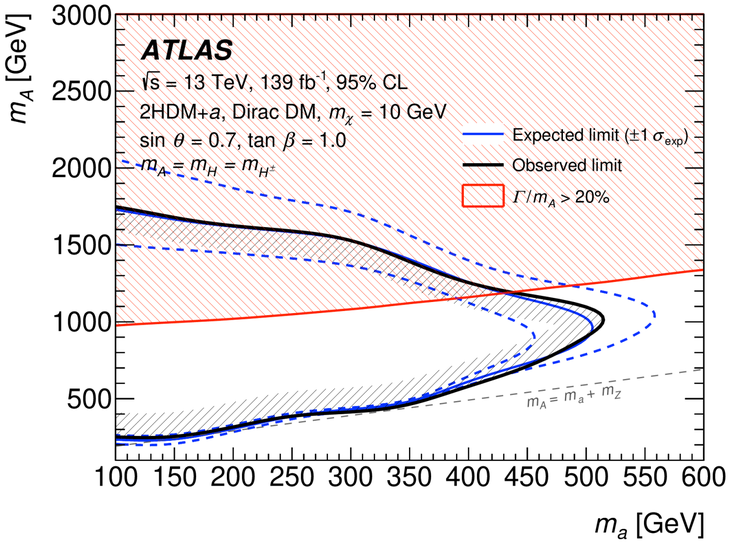
- ✓ **Signature:** 2 SFOC leptons + E_T^{miss}
- ✓ **Trigger:** 1/2 leptons
- ✓ **Dominant background:** SM $qq \rightarrow ZZ$.
  - 3ℓ, 4ℓ CRs used to constrain WZ/ZZ predictions
  - emu CR to constrain non-resonant (ttbar, WW) processes
- ✓ **SR**: $|m_{\ell\ell} - m_Z| < 15$ GeV, $E_T^{miss} > 80$ (90) GeV for CMS (ATLAS), $\Delta R < 1.8$ and $p_T^{\ell\ell} > 60$ GeV (CMS to reject DY).











Single top + E_T^{miss}

ATLAS:ATLAS-CONF-2022-036

Simplified DM model

✓**Trigger:** E_T^{miss}

✓**Dominant background**:

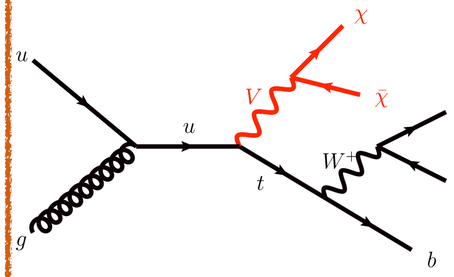
- $t\bar{t}$ and Z/W+jets →constrained in CRs

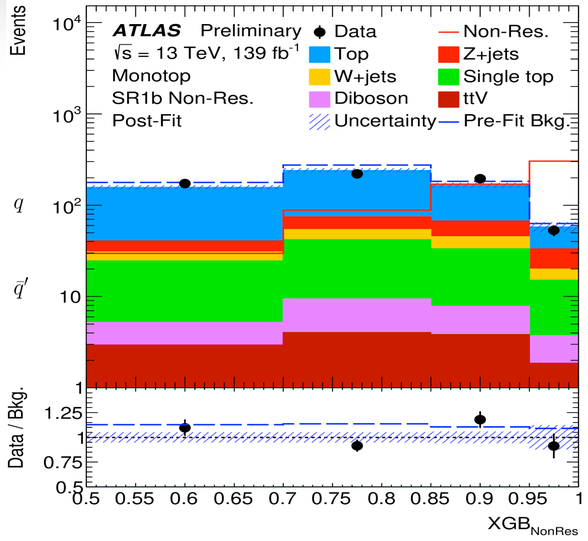
✓**SR**:

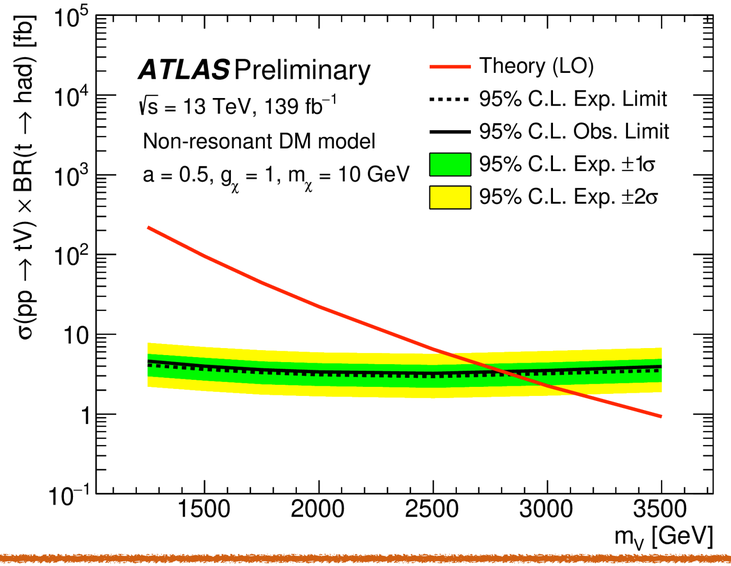
- 0ℓ.
- $E_T^{miss} \geq 250$ GeV.
- ≥ 1 boosted Large-R jet associated to the top quark.
- $\Delta\phi_{min}(E_T^{miss}, small - Rjet) > 0.2$

✓**BDT** (XGBoost) is used to discriminate signal/ background (E_T^{miss} based variables and ΔR_{max} among the most important features in the training)

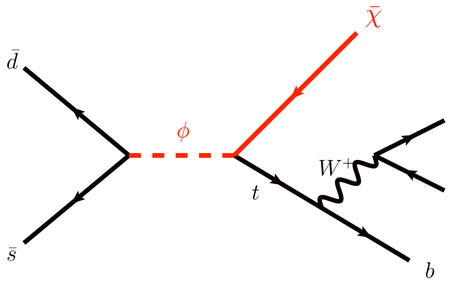
Non-resonant

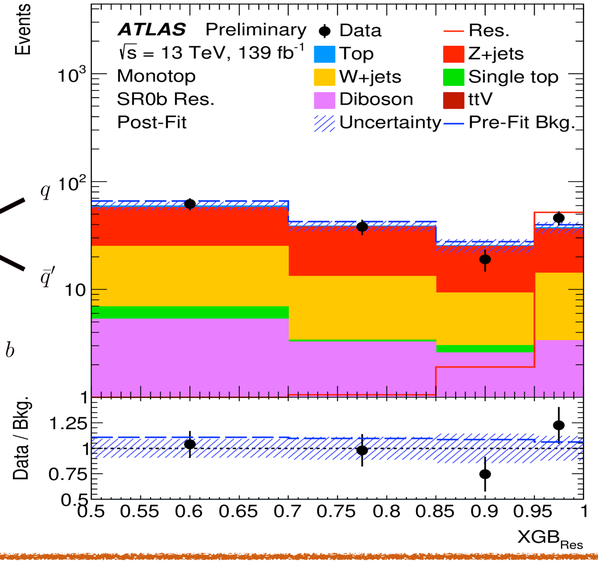


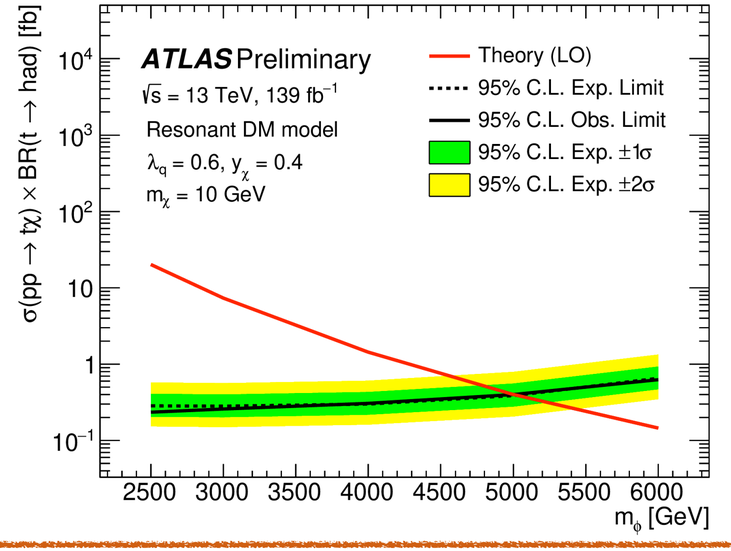




resonant







'2*HDM* + *a*, mediator search'

✓**Trigger:** E_T^{miss}

✓**Dominant background**:

- $t\bar{t}$, Z/W+jets and $t\bar{t}Z$ →constrained in CRs

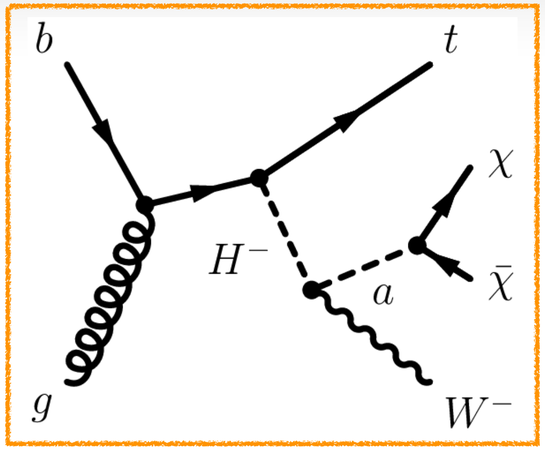
✓**SR**: 0-1 electrons/muons, 1 b-jet, $E_T^{miss} \geq 250$ GeV. Large-R jets with W-tagging or two small-R jets for hadronic W candidate.

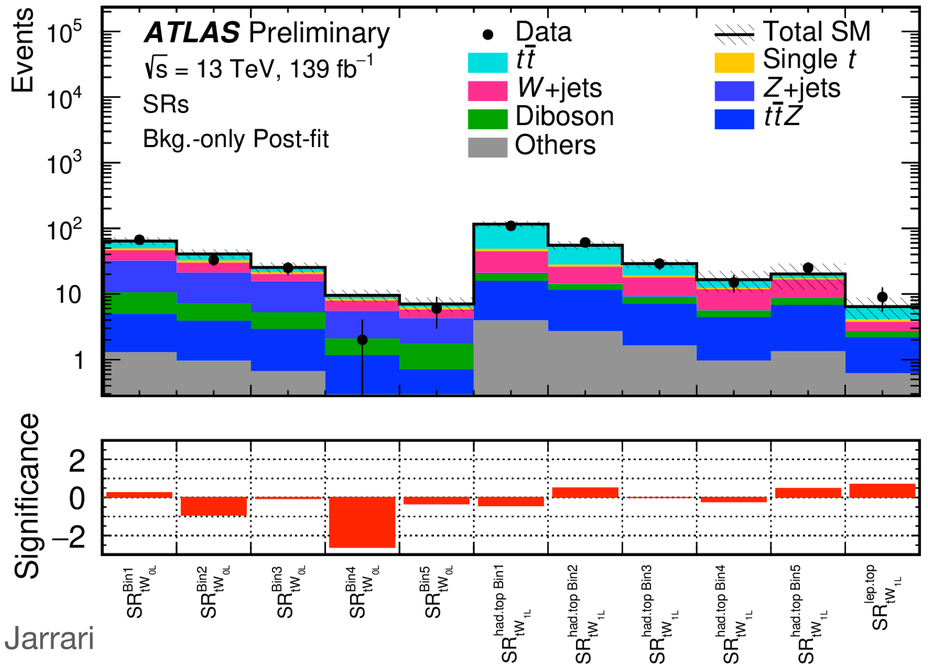
✓**Discriminators** depend on the target signature: m_T, BDT, ..

✓6 CRs, 6 VRs: $t\bar{t}$ ($tW_{0\ell}$, $tW_{1\ell}$), single t, $V + jets$ and $t\bar{t}Z$

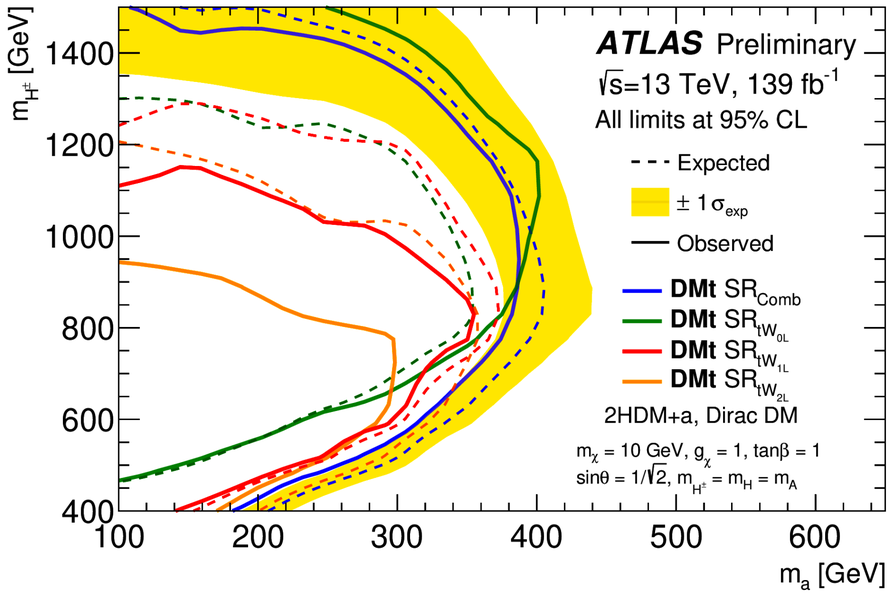
✓ Fit to data under the background-only hypothesis yields to measure the normalization of the main backgrounds.

✓Results provided for separate and combined 0, 1 and 2 lepton selections





Model excluded up to m_a= 350 GeV and $m_{H^\pm}$ = 1500 GeV



$H(\rightarrow bb) + E_T^{miss}$

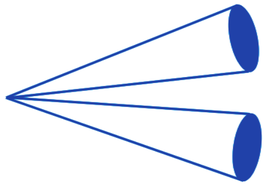
ATLAS: JHEP 11 (2021) 209

'$2HDM + a$, $2HDM + Z'$, Z'_B'

- ✓ **Trigger:** E_T^{miss}
- ✓ **Dominant background:** $V + (HF)$ *jets* (constrained in CR1 (1 muon) and CR2 (2 leptons))
  $t\bar{t}$ (suppressed by a cut on the missing energy significance S<5)

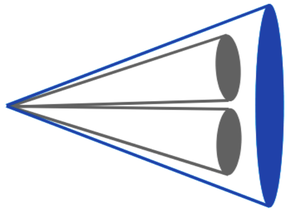
Resolved topology

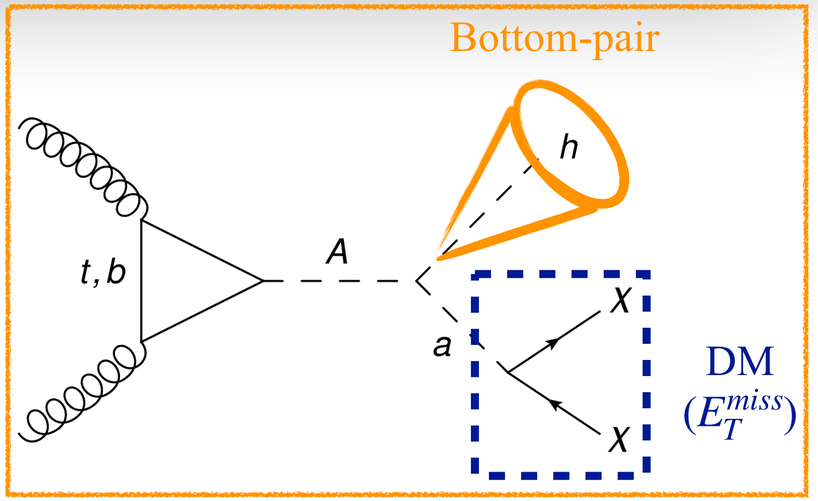
$150 < E_T^{miss} < 500$ GeV
$50\ GeV < m_h < 280\ GeV$
At least 2 small-R jets

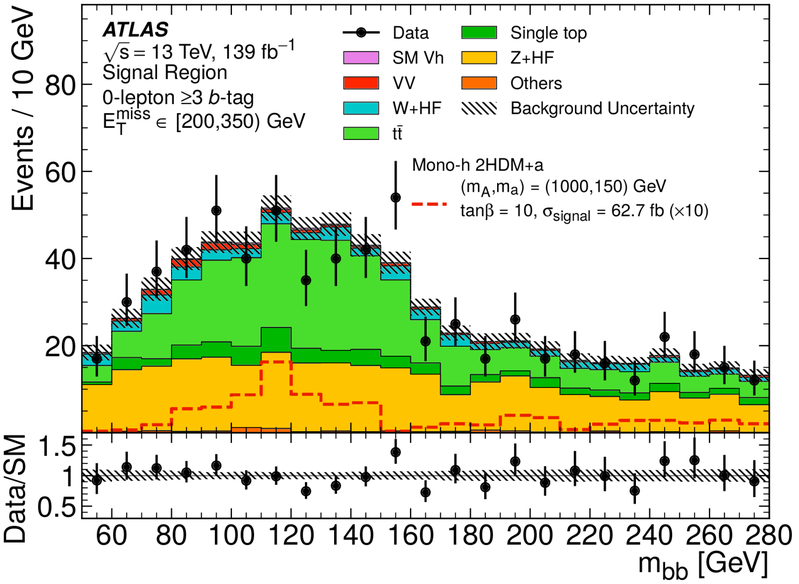


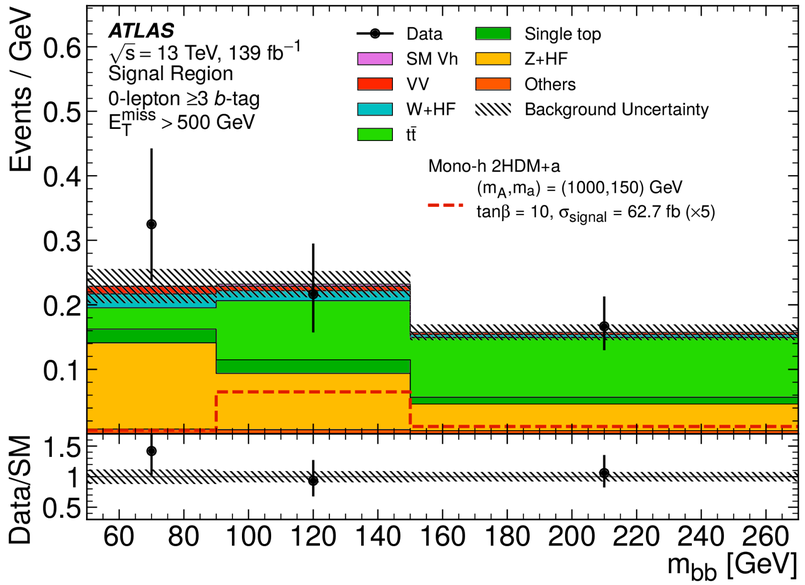
Merged topology

$E_T^{miss} > 500$ GeV
$50\ GeV < m_h < 270\ GeV$
At least 1 large-R jet



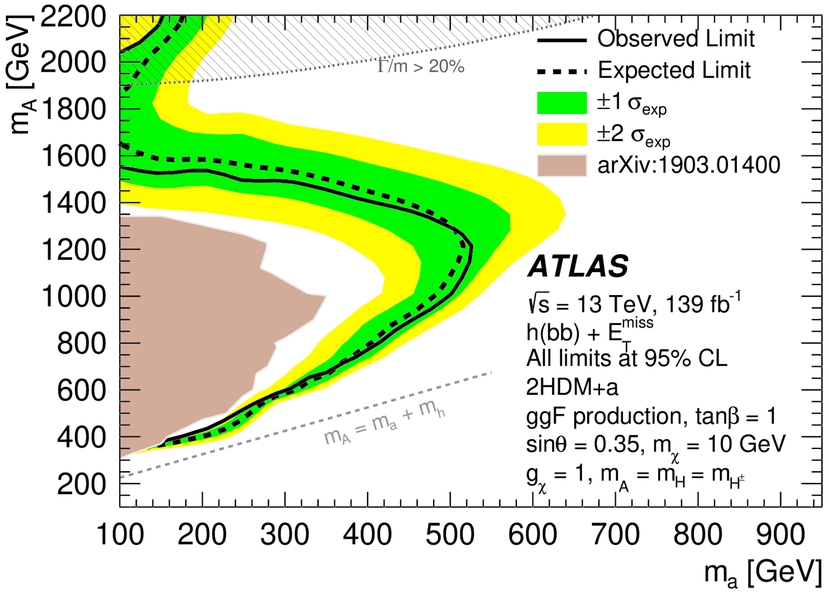






$H(\rightarrow bb)$ recoiling against large E_T^{miss}

Limits set on a variety of models: 2HDM+a, …

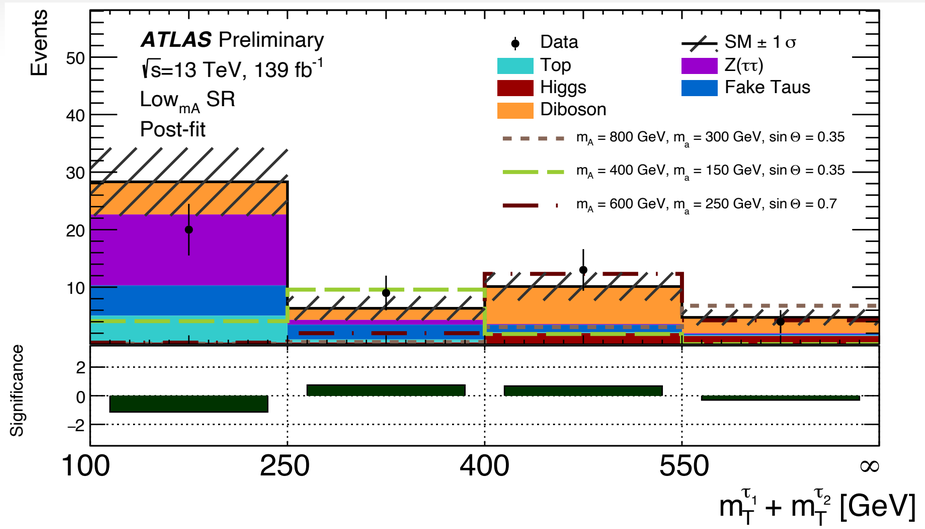


$h(\tau_{had}\tau_{had}) + E_T^{miss}$

ATLAS:ATLAS-CONF-2022-069

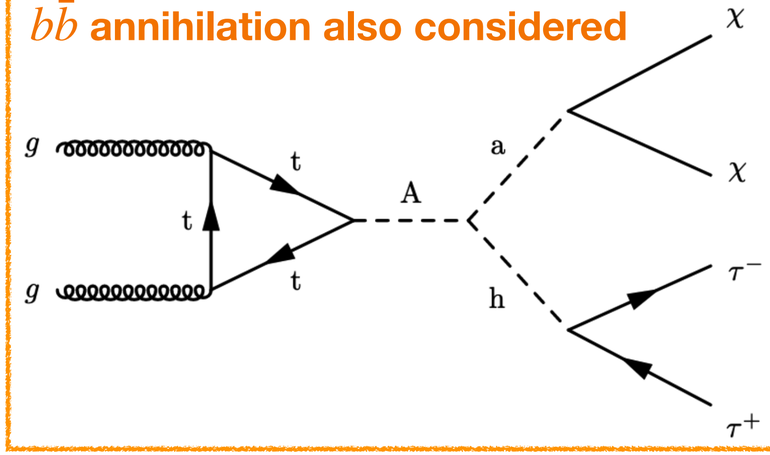
'2HDM + a' Search for a new charged Higgs decay mode supported by numerous theoretical models.

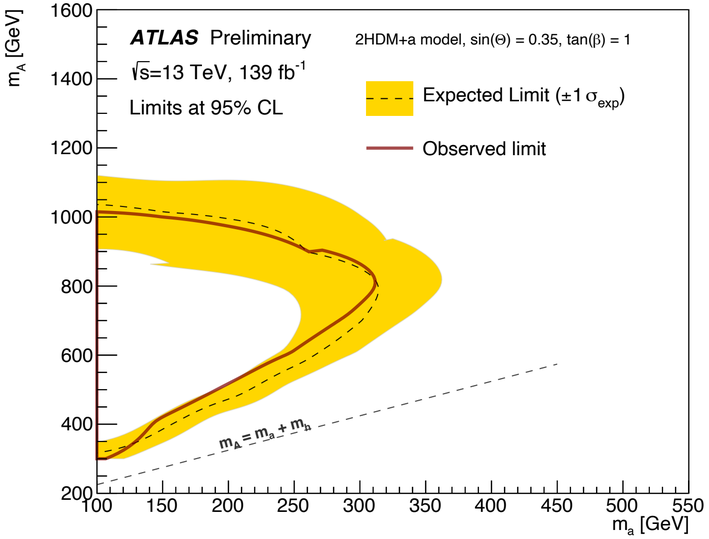
- ✓ **Trigger:** di-$\tau_{had} + E_T^{miss}$
- ✓ **Discriminant variable:** Sum of τ -lepton transverse masse
- ✓ Dominant background: VV, VH, $t\bar{t}$, $V + jets$.
  - Lepton and b-jet veto applied.
  - Fake τ estimated using the Data-driven fake factor method.
  - CRs for $Z + jets$, $t\bar{t}$ and 4 VRs.
- ✓ Strong kinematics dependence on m_A
- ✓ DM candidate mass of 10 GeV
- ✓ Model-independent limits on BSM signal for every bin, $\sigma_{vis} < 0.04 - 0.08$ fb.

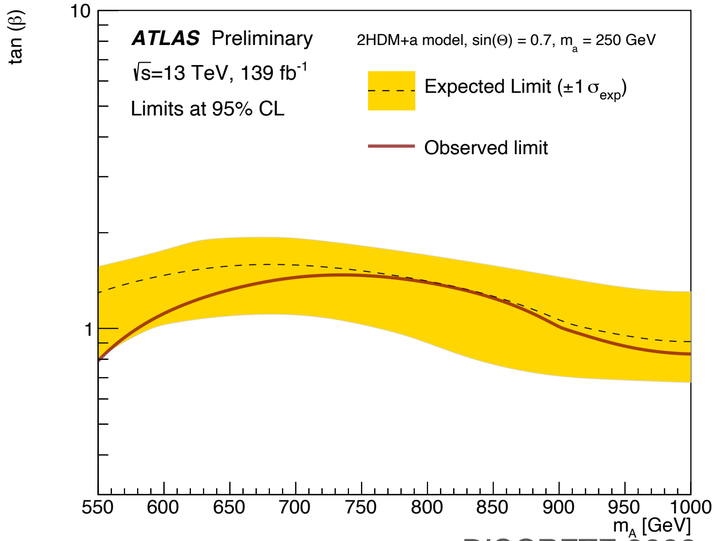


Scans in m_A vs m_a and $\tan(\beta)$ vs m_A.

$b\bar{b}$ annihilation also considered







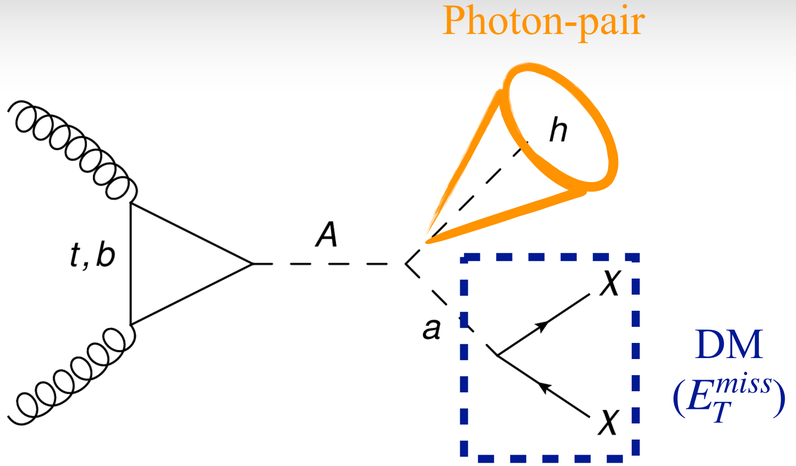
$H(\rightarrow \gamma\gamma) + E_T^{miss}$

ATLAS: JHEP 10 (2021) 13

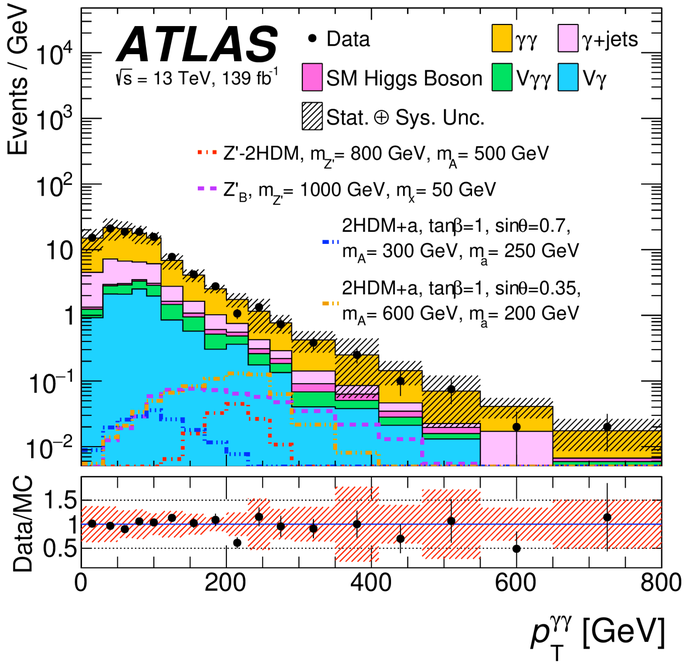
'$2HDM + a$, $2HDM + Z'$, Z'_B'

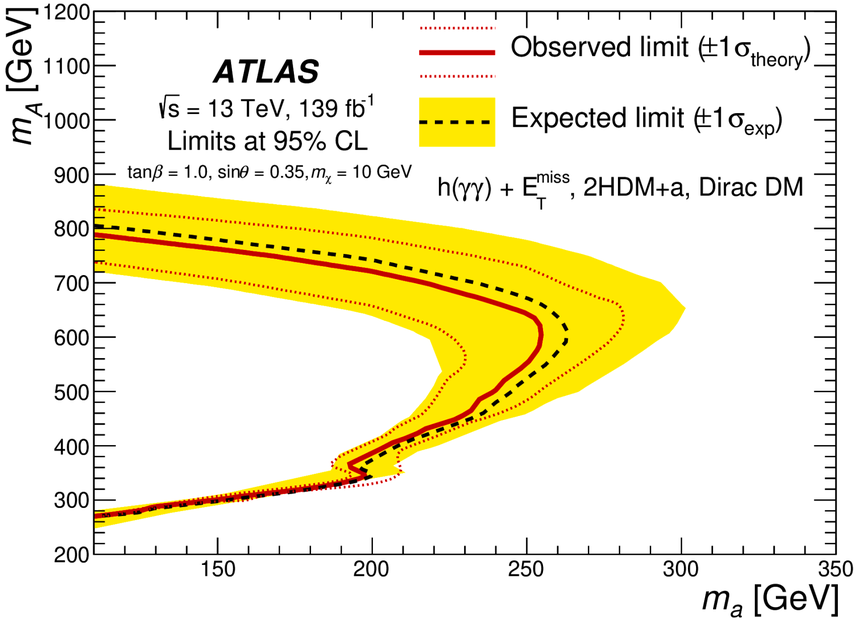
- ✓ **Signature:** 2 photon + E_T^{miss}
- ✓ **Trigger:** Diphoton
- ✓ **Dominant background:** SM Higgs boson, QCD-induced non-resonant diphoton ($\gamma\gamma$, $V_{\gamma\gamma}$)
- ✓ **BDT** (XGBoost) used to discriminate signal/ non-resonant diphoton background
- ✓ **SRs**: $105 < m_{\gamma\gamma} < 160$ GeV and $E_T^{miss} > 90$ GeV

Category	E_T^{miss} requirement	BDT score range
High E_T^{miss} BDT tight	$E_T^{miss} > 150$ GeV	$0.950 <$ BDT score < 1
High E_T^{miss} BDT loose	$E_T^{miss} > 150$ GeV	$0.694 <$ BDT score < 0.950
Low E_T^{miss} BDT tight	$E_T^{miss} < 150$ GeV	$0.864 <$ BDT score < 1
Low E_T^{miss} BDT loose	$E_T^{miss} < 150$ GeV	$0.386 <$ BDT score < 0.864



$2HDM + a$



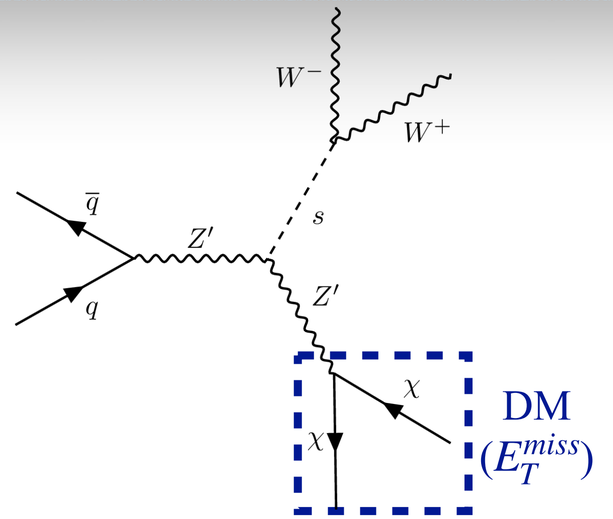


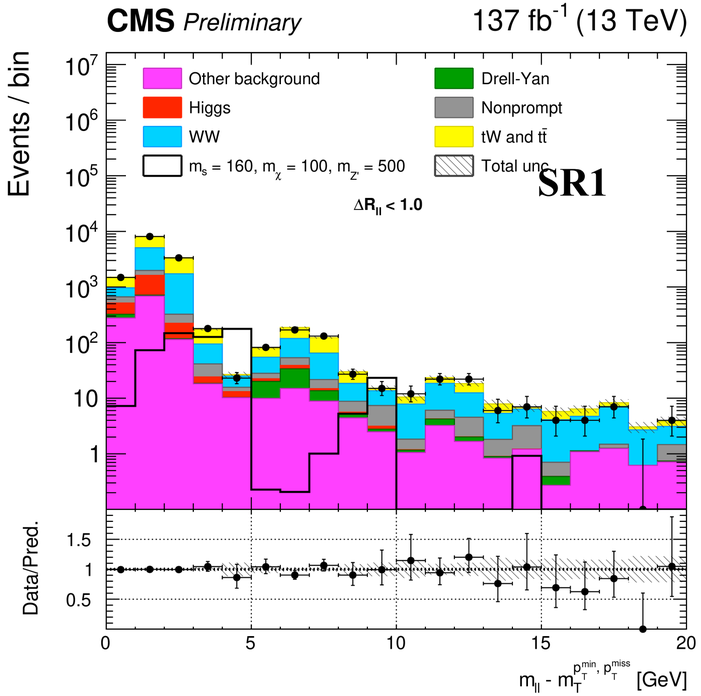
$s(W^+W^-) + E_T^{miss}$

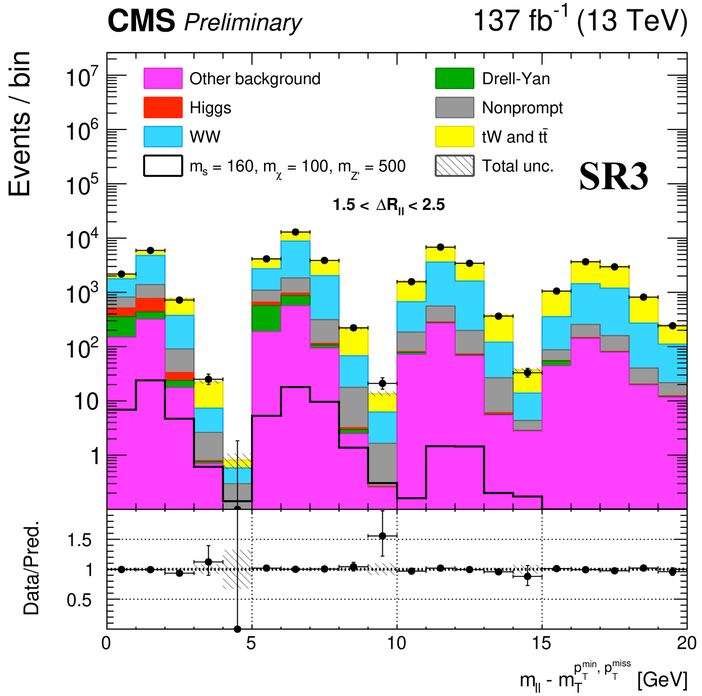
CMS: CMS-PAS-EXO-20-013

'Dark Higgs model'

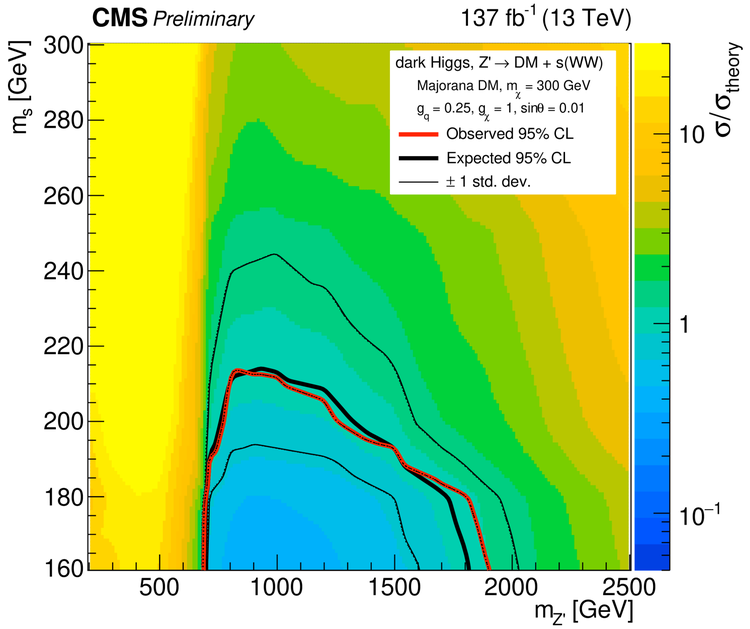
- ✓ **Signature:** $s \rightarrow WW$ (2 charged leptons DFOC to suppress Drell-Yan)
- ✓ **3 SRs:** SR1 ($\Delta R_{\ell\ell} < 1.0$ high boost), SR2 ($1.0 < \Delta R_{\ell\ell} < 1.5$ medium boost), SR3 ($1.5 < \Delta R_{\ell\ell} < 2.5$ low boost)
- ✓ **Trigger:** 1/2 leptons
- ✓ **Dominant background:** W^+W^-, $t\bar{t} + tW$ and Drell-Yan (constrained in CRs enriched in these events by investing some the SR cuts [N b-jets, $\Delta R_{\ell\ell}$ and $m_T^{\ell\ell,p_T^{miss}}$])







Dark Higgs model limit in the $(m_{Z'}, m_s)$ plane.

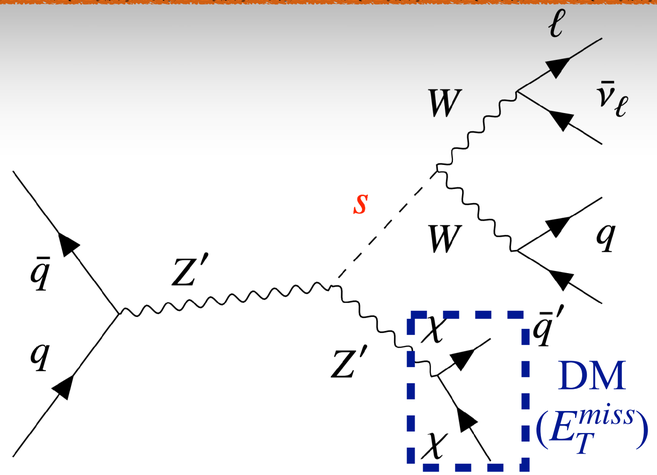


$s(W^+W^-) + E_T^{miss}$

ATLAS:ATLAS-CONF-2022-029

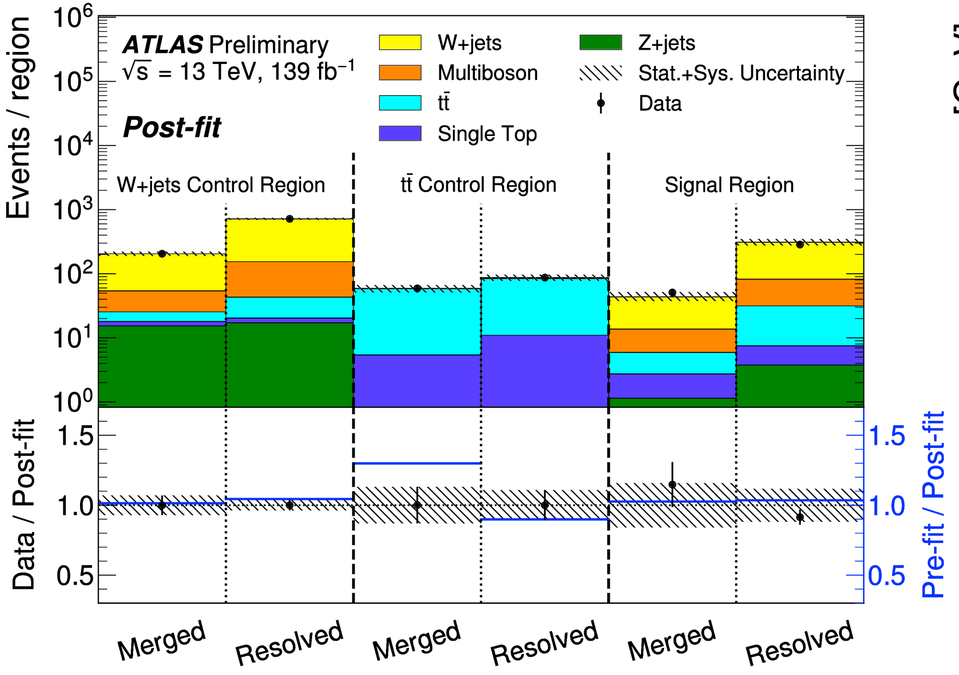
'Dark Higgs two-mediator DM model'

- ✓ **Signature:** $s \to WW \to \ell\nu q\bar{q}'$ (1 charged lepton)
- ✓ **Trigger:** E_T^{miss} or single muon
- ✓ **Discriminant variable:** m_s^{min}
- ✓ **Dominant background:** $W + jets$ (constrained in a CR requiring a large $\Delta\phi(W_{had}, \ell)$)
  $t\bar{t}$ (constrained in a CR requiring at least two b-quark jets)

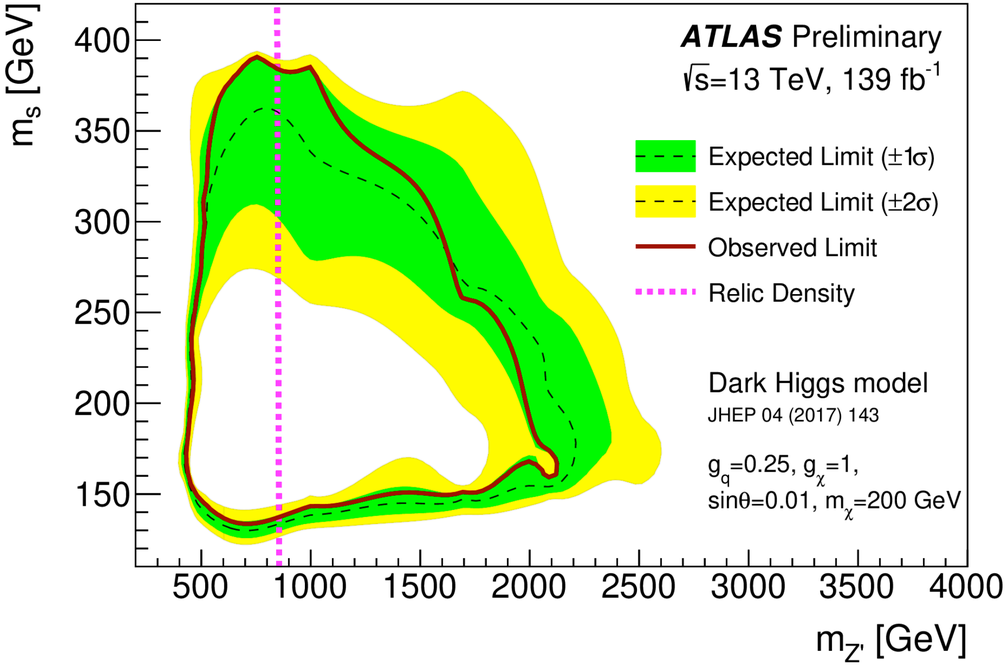


Resolved topology
$E_T^{miss} > 250$ GeV
$m_T > 200$ GeV
At least 2 small-R jets

Merged topology
$E_T^{miss} > 200$ GeV
$m_T > 220$ GeV
At least 1 large-R jet



Dark Higgs model limit in the $(m_{Z'}, m_s)$ plane.



$VBF, H \rightarrow invisible$

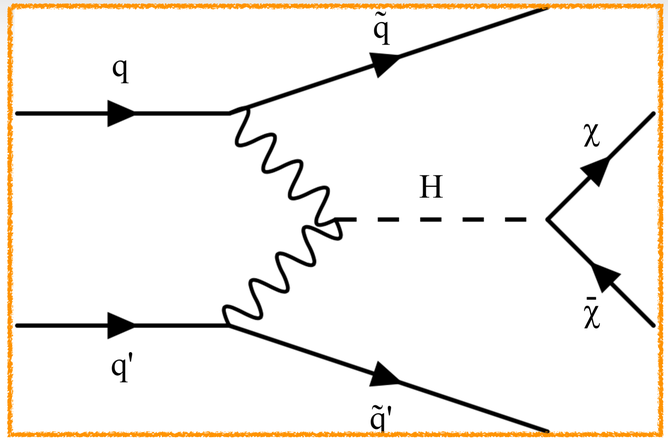
CMS:Phys. Rev. D 105 (2022) 092007

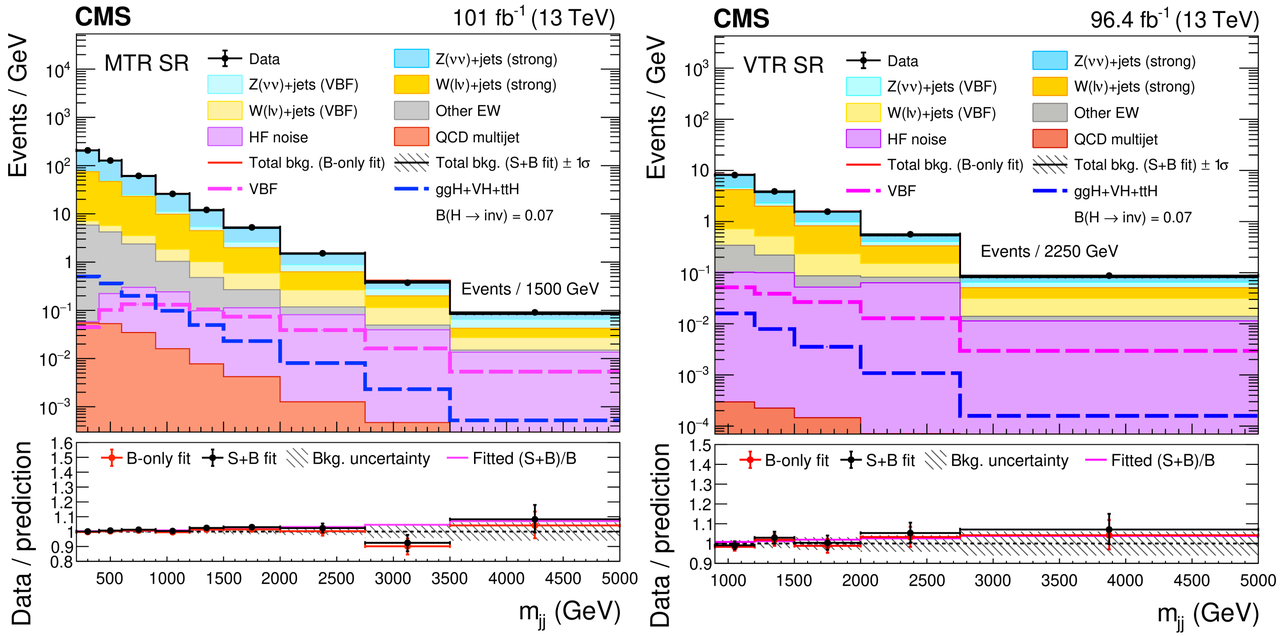
Higgs Portal, most sensitive $H \rightarrow invisible$ channel

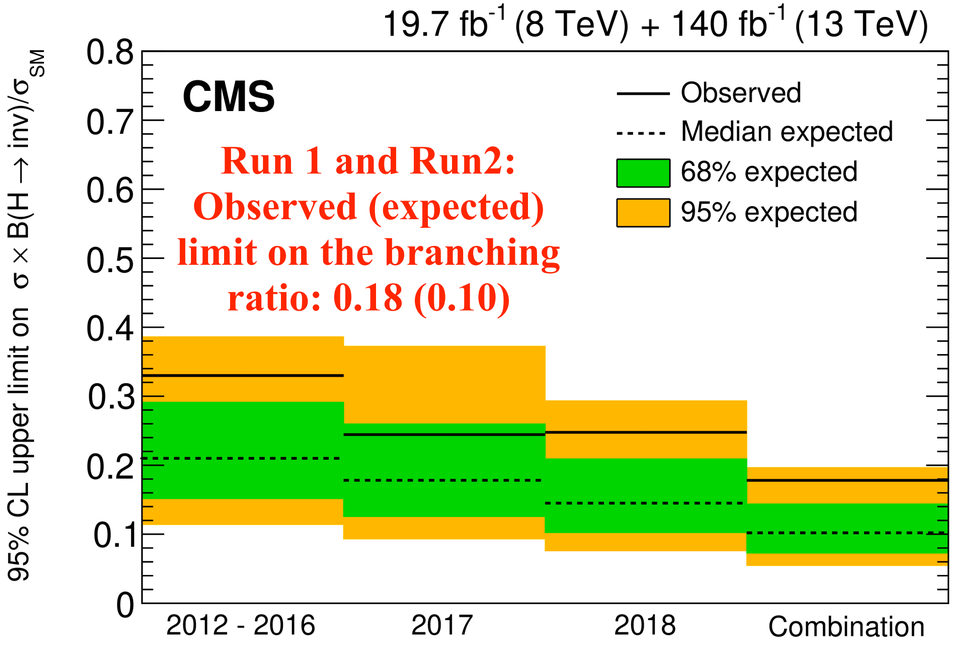
- ✓ **Signature:** Vector-Boson Fusion VBF [large $\Delta\eta_{jj}$ and m_{jj}. Small $\Delta\phi_{jj}$]
- ✓ **Dominant background**: $Z \rightarrow \nu\nu$, $W \rightarrow \ell\nu$, *multijet*
- **SR:** Two different trigger strategies

  MTR: missing momentum triggered region: $E_T^{miss} > 250$ GeV, $m_{jj} > 200$ GeV

  VTR: VBF jets triggered region: $160 < E_T^{miss} \leq 250$ GeV, $m_{jj} > 900$ GeV



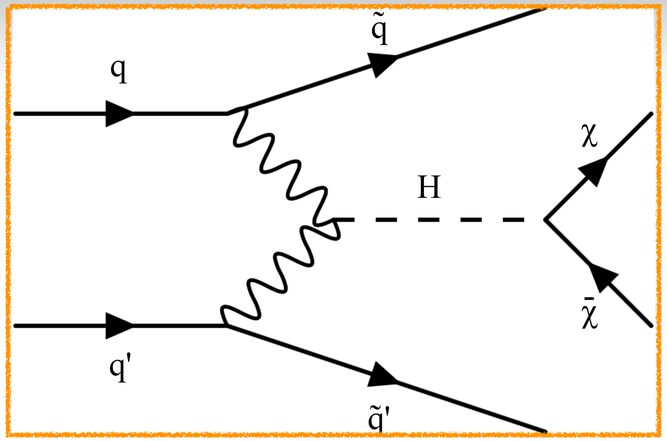




$VBF, H \rightarrow invisible$

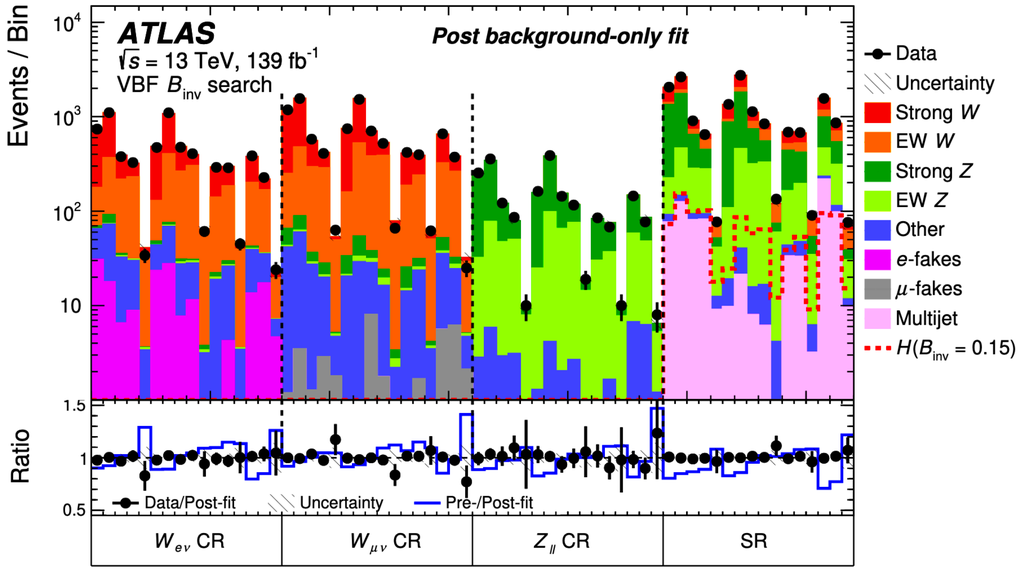
ATLAS:JHEP08(2022)104

Higgs Portal, most sensitive $H \rightarrow invisible$ channel

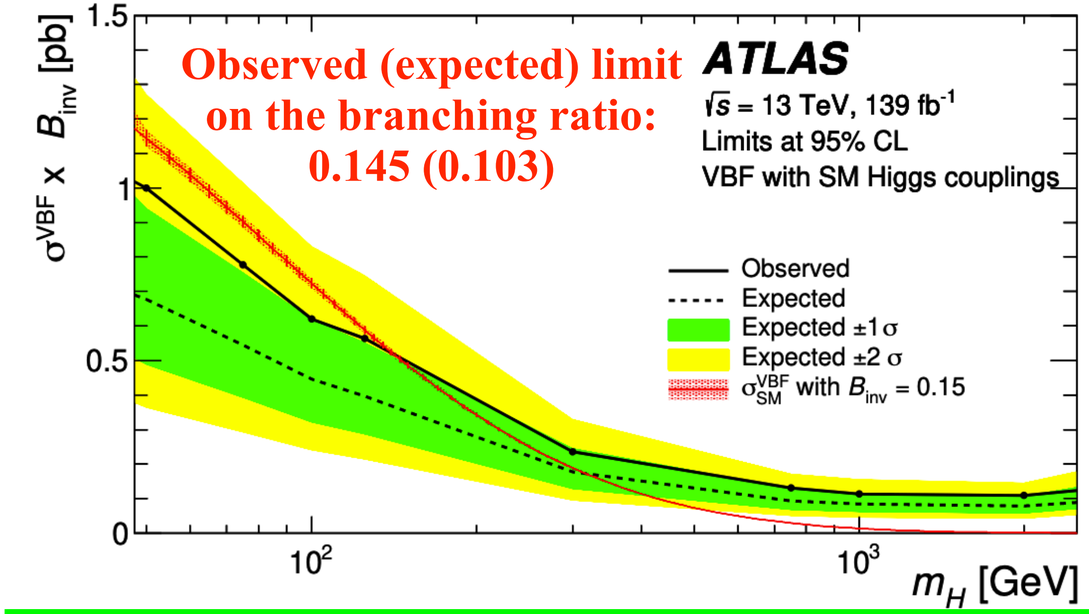


- ✓ **Signature:** Vector-Boson Fusion VBF [large $\Delta\eta_{jj}$ and m_{jj}. Small $\Delta\phi_{jj}$]
- ✓ **SR:** $E_T^{miss} \geq 160$ GeV. 2, 3 or 4 jets with $p_T > 25$ GeV.

  Leading/Subleading jet: $p_T > 85/\ 50$ GeV ($\Delta\phi_{jj} < 2$, $m_{jj} > 0.8$ TeV)
- ✓ **Trigger:** E_T^{miss}(SR), 1/2 leptons ($V + jets$ CR) and single-jet (QCD multi-jet)
- ✓ **Dominant background:** $Z \rightarrow \nu\nu$, $W \rightarrow \ell\nu$, *multijet*
- ✓ Strong and ewk $V + jets$ correction: State-of-the art precision achieved thanks to the double ratio $R_{TH}^{Z/W}/R_{MC}^{Z/W}$



No excess over
Standard Model predictions



NEW $H \rightarrow invisible$ combination in the backup: page 51

Summary /combination results

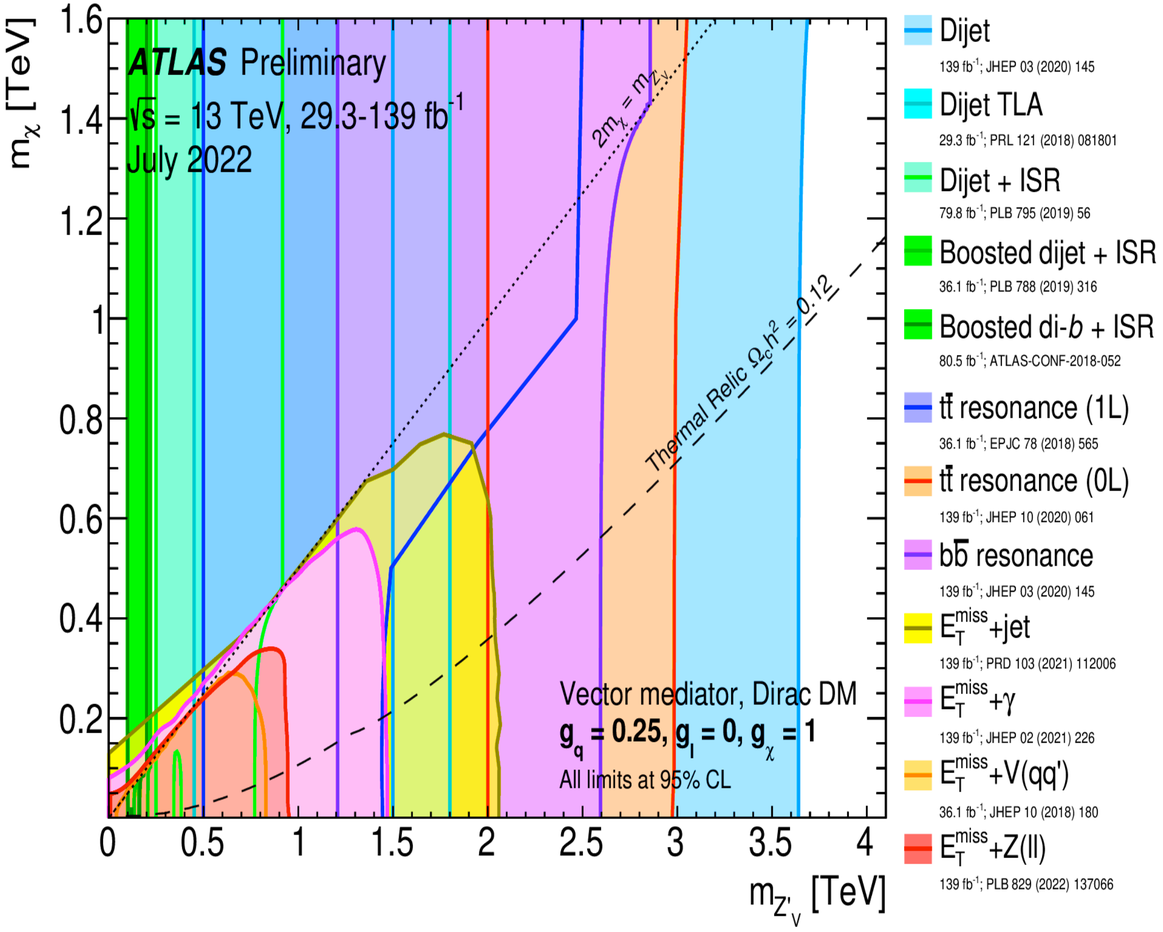
DM Summary Plots

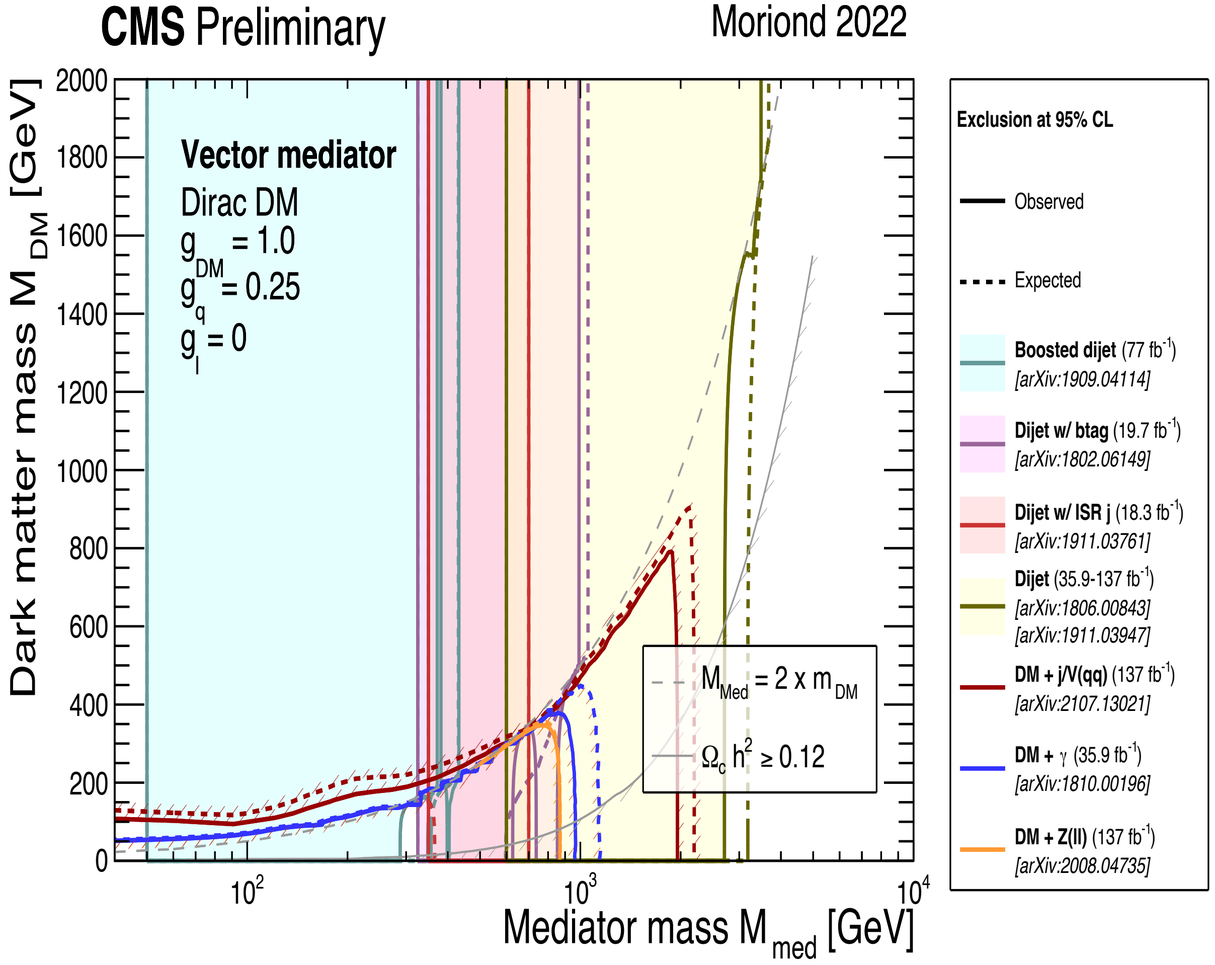
ATLAS: ATL-PHYS-PUB-2022-036

CMS: DM_summary_plots

Simplified DM model

Vector





More combinations in the backup slides

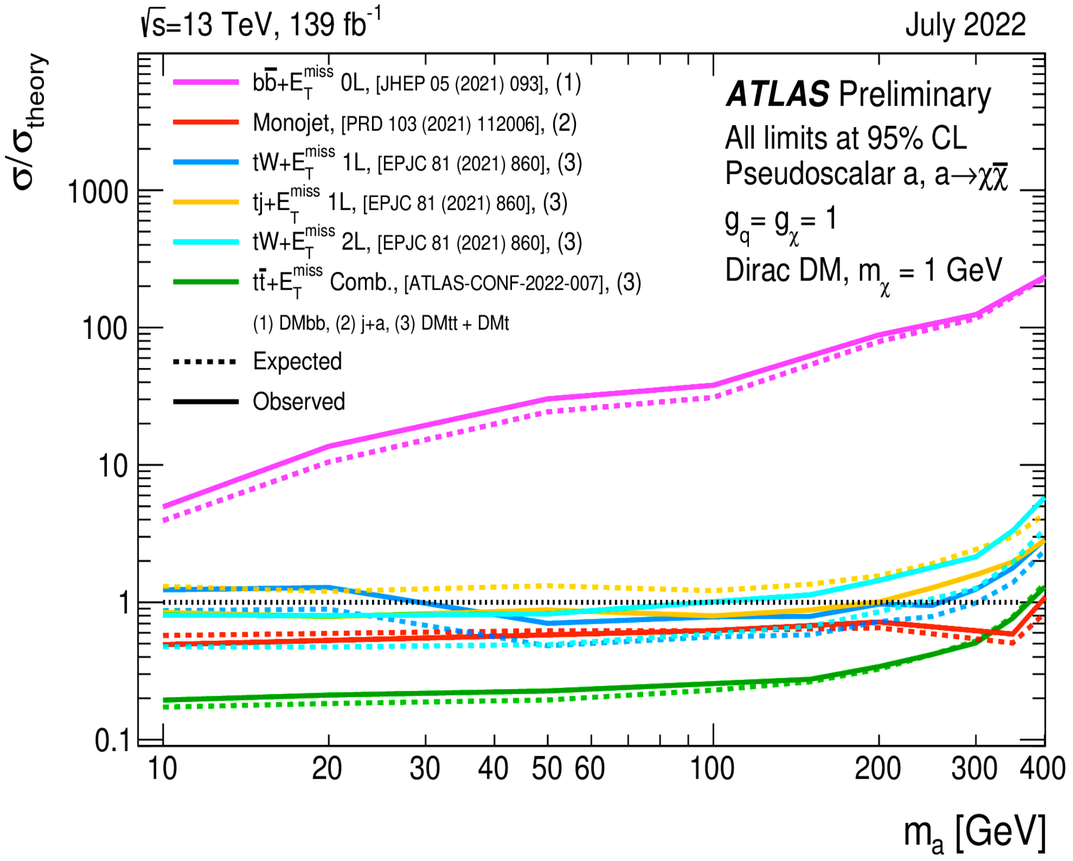
DM Summary Plots

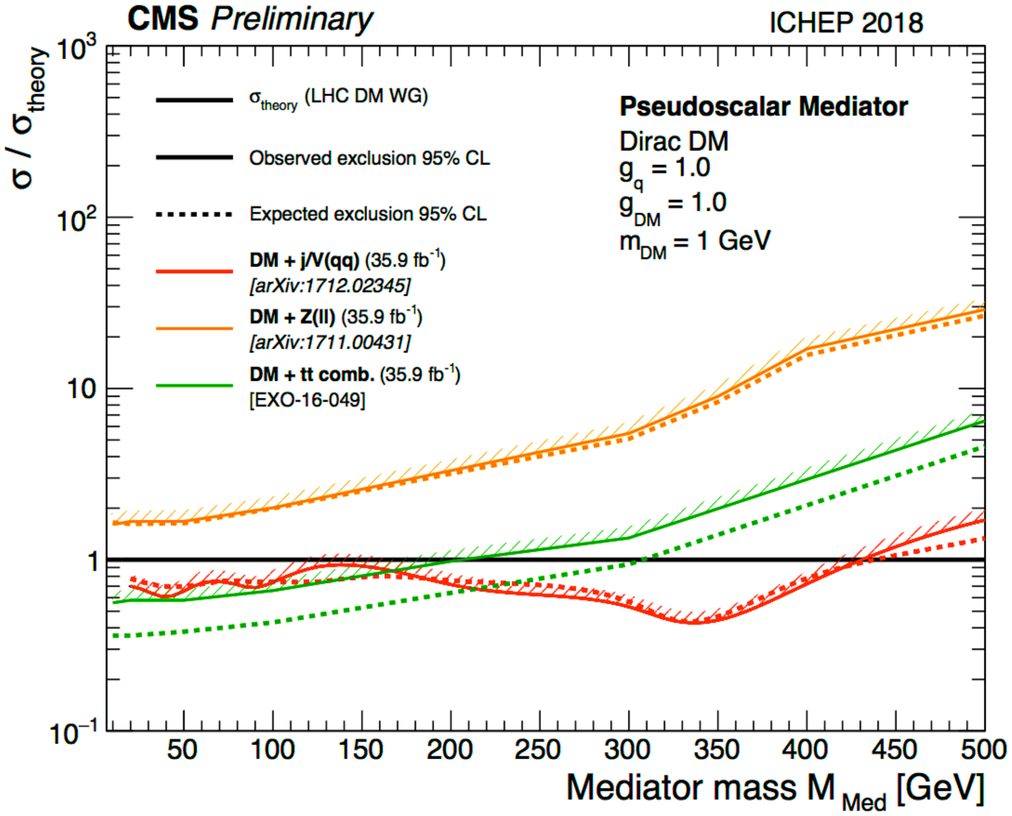
ATLAS: ATL-PHYS-PUB-2022-036

CMS: DM_summary_plots

Simplified DM model

Pseudo-scalar mediator





More combinations in the backup slides

DM Summary Plots

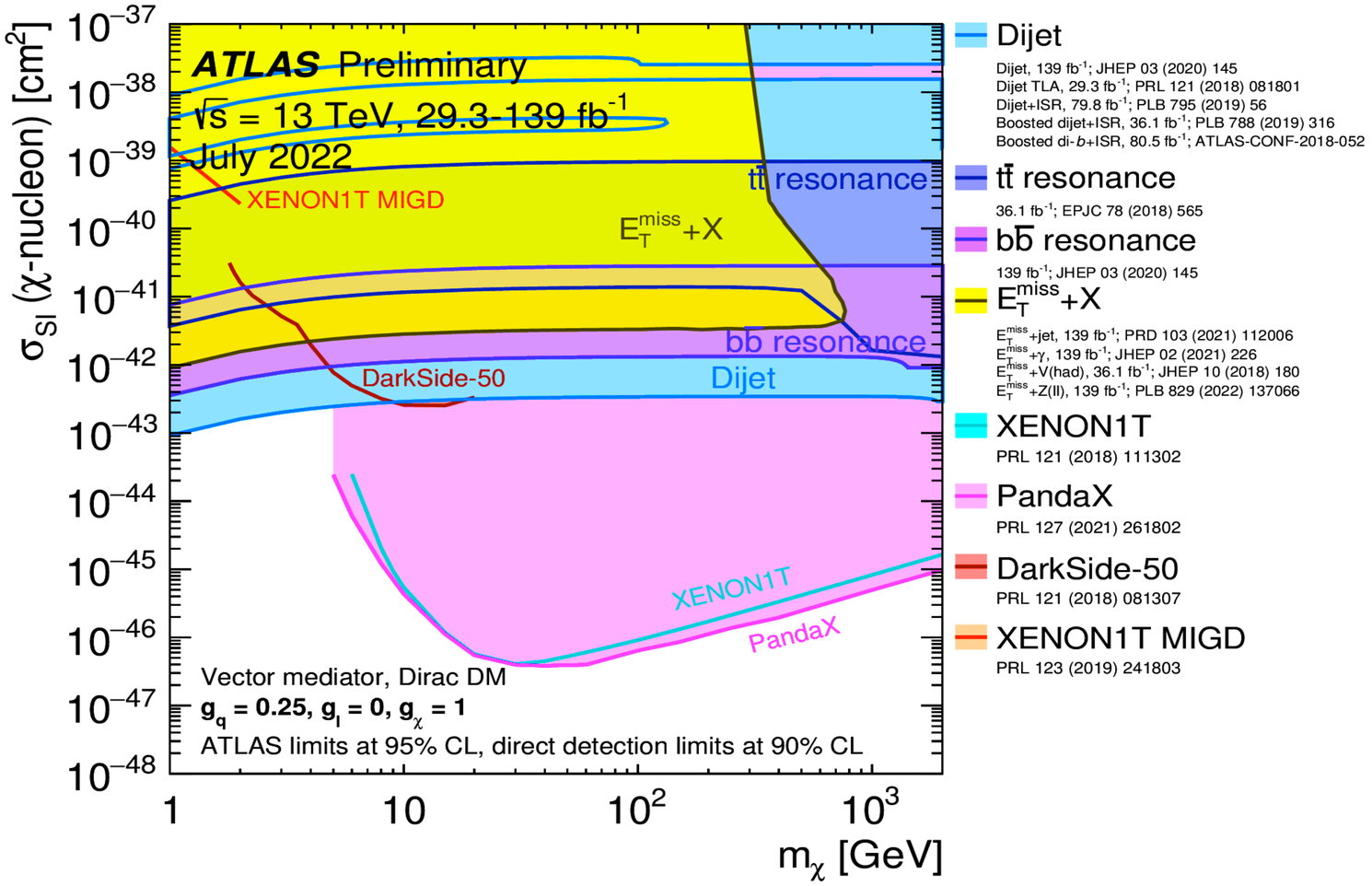
ATLAS: ATL-PHYS-PUB-2022-036

Simplified DM model

Combination with DD experiments

ATLAS results are also used to extract limits on the DM-nucleon cross-section with a better exclusion limits at lower dark matter masses.

Direct detection has better exclusion limits for the spin-independent nucleon cross-section

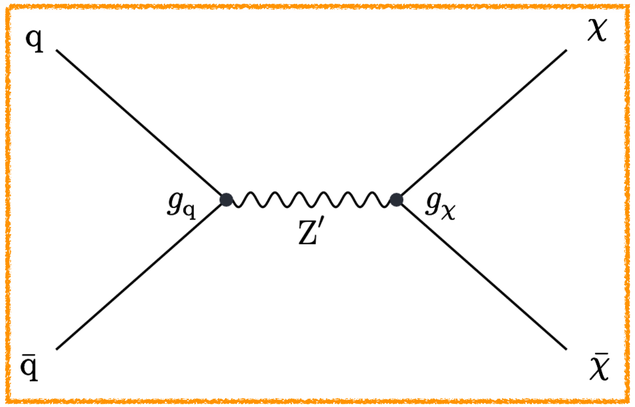


non-WIMP DM candidates

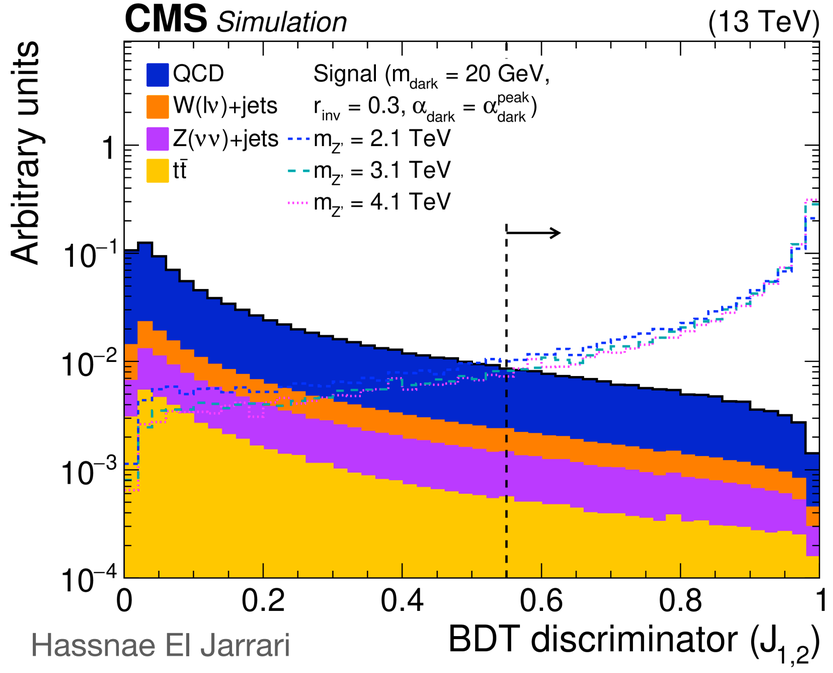
Semi-visible jets

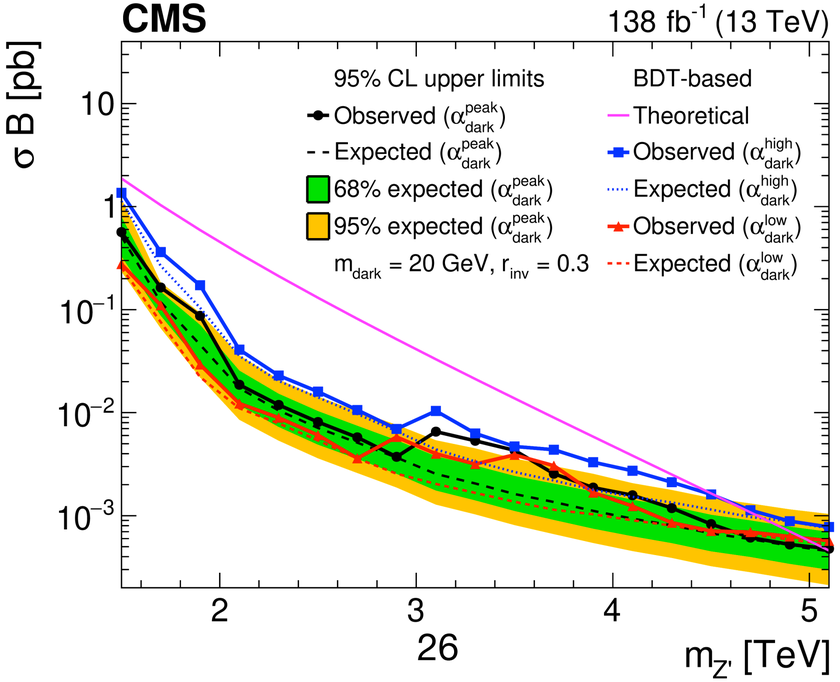
CMS: JHEP 06 (2022) 156

Strongly-interacting dark sector Dark quarks form bound dark hadron states



- ✓ **Signature:** 1 jet aligned to the E_T^{miss} direction → Previous searches for jets+E_T^{miss} not sensitive.
- ✓ The scalar mediator (Z') acts as a SM-DS portal
- ✓ **Trigger:** jet
- ✓ BDT used to tag semivisible jets and define a high purity category.
- ✓ **Sensitive variables**: Di-jet transverse mass m_T and E_T^{miss}
- ✓ **Dominant background:** QCD multijet, rejected by $R_T = p_T^{miss}/m_T > 0.15$ and this reject t-channel as well
- ✓ **SR:** 2 are defined (low-R_T: $0.15 < R_T \leq 0.25$ and high-R_T: $R_T > 0.25$). Focus on s-channel



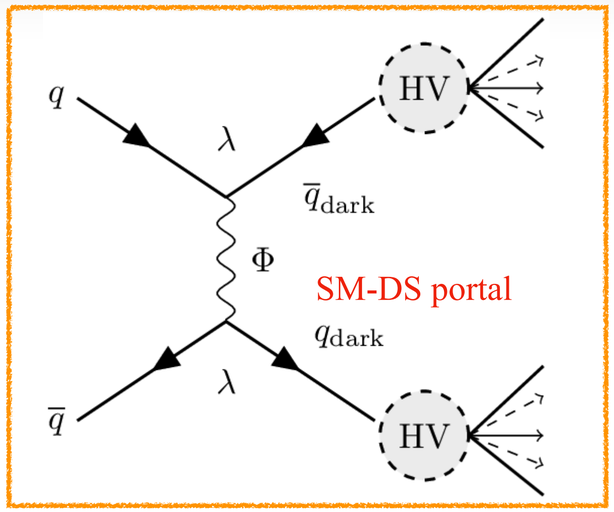


- Large improvement vs analysis without BDT identification of semi-visible jets
- Excluding $1.5 \leq m_{z'} \leq 5$ TeV for $r_{Inv} = 0.3$
- Excluding $0.01 \leq r_{Inv} \leq 0.77$ TeV for $m_{dark} = 20$ GeV
- Small excess around $m_{z'} = 3.5$ TeV with no real significance ($\sim 2\sigma$ local)

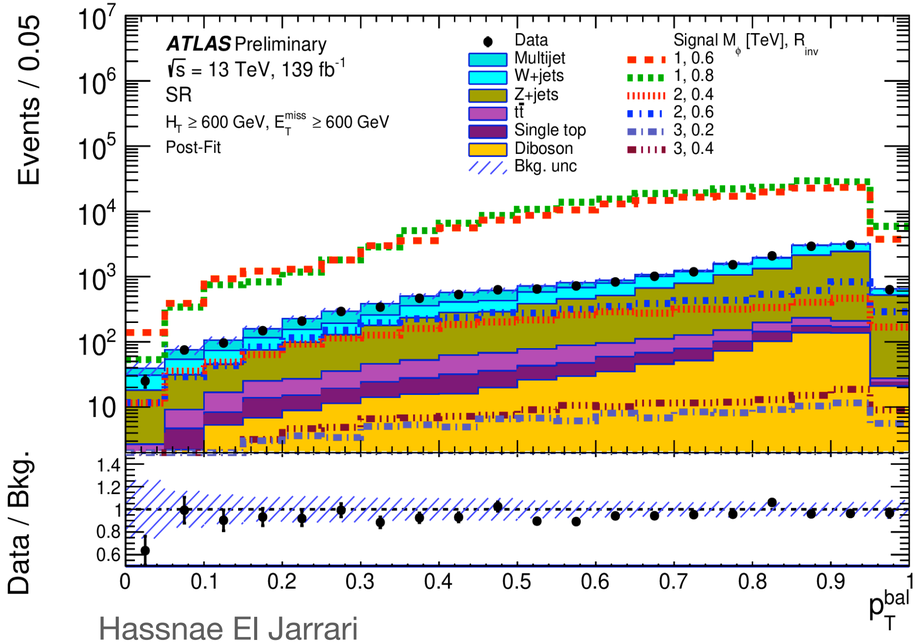
Semi-visible jets

ATLAS: ATLAS-CONF-2022-038

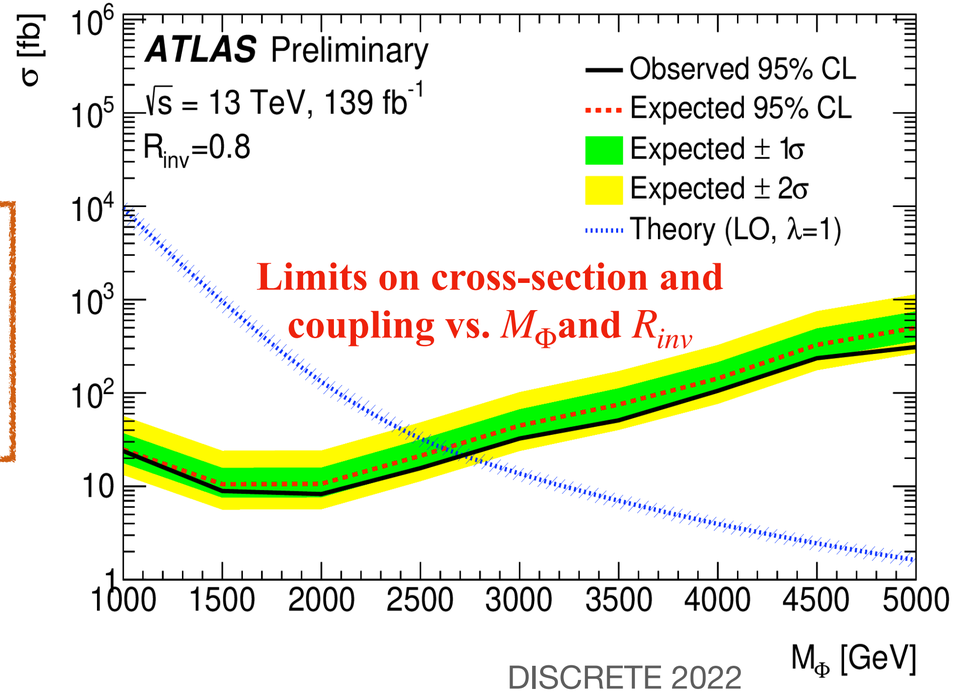
Strongly-interacting dark sector



- ✓ ***t*-channel**: to probe a broad class of non-resonant signals and reach higher masses
- ✓ **Trigger:** E_T^{miss}
- ✓ **CR:** 1L, 1L1B and 2L control regions
- ✓ **Discriminant variables:** p_T balance and $|\Phi_{max} - \Phi_{min}|$
- ✓ **SR:** 2 semi-visible jets (SVJs), Leading/sub-leading jet $p_T > 150/30$ GeV
  - ≥1 additional jet to suppress the **dominant** multijet background
  - Veto e, μ, and ≥2 b-tags to suppress other backgrounds
  - High $E_T^{miss} > 600$ GeV and $H_T = \sum_{jets} p_T > 600$ GeV



- ✓ **mediator masses up to 2.7 TeV can be excluded**
- ✓ **Upper limits on the coupling strength**



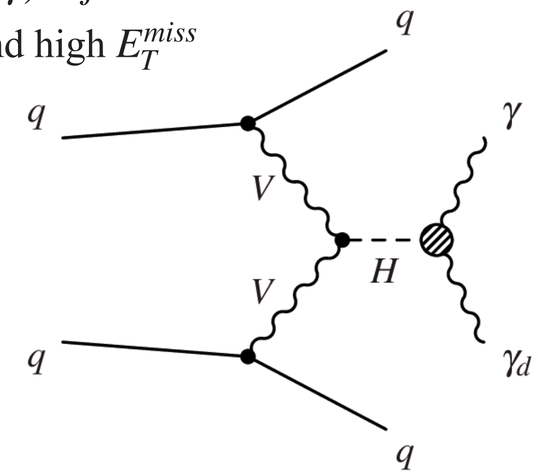
Dark Photons (VBF)

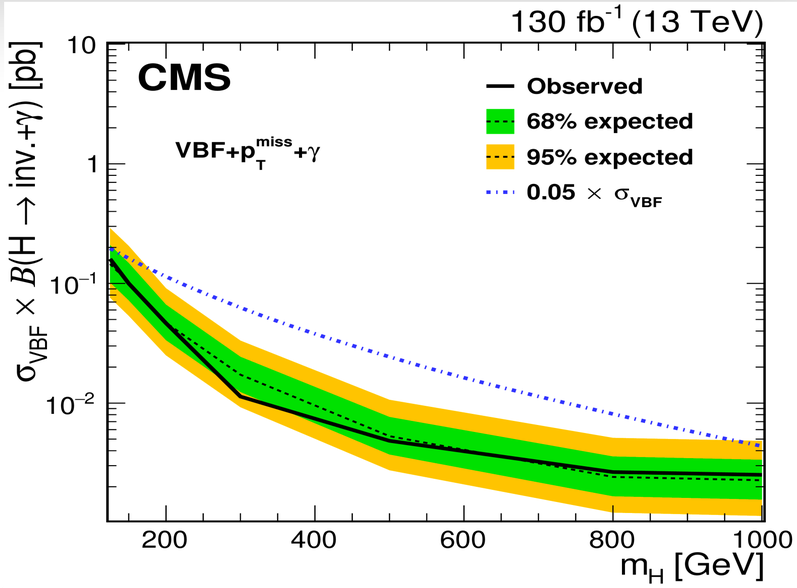
ATLAS: Eur. Phys. J. C 82 (2022) 105

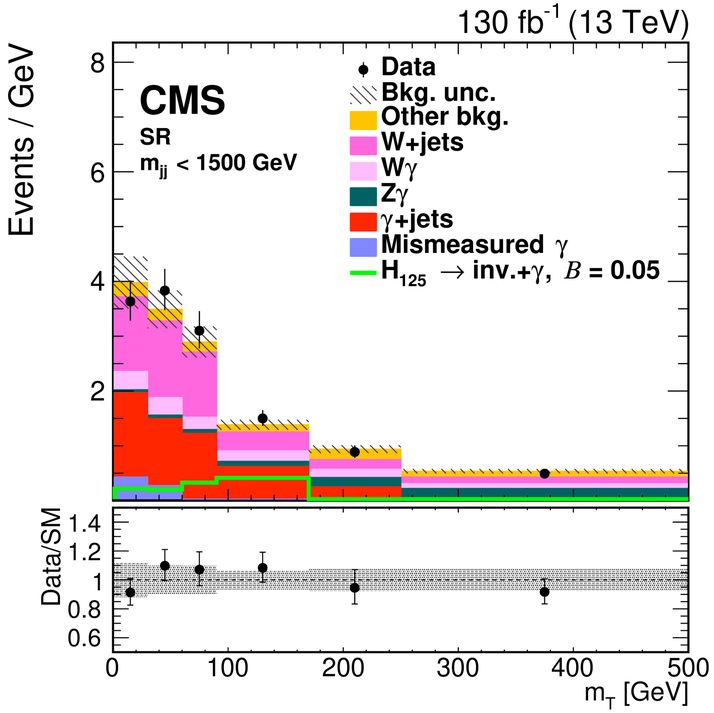
CMS: JHEP 03 (2021) 011

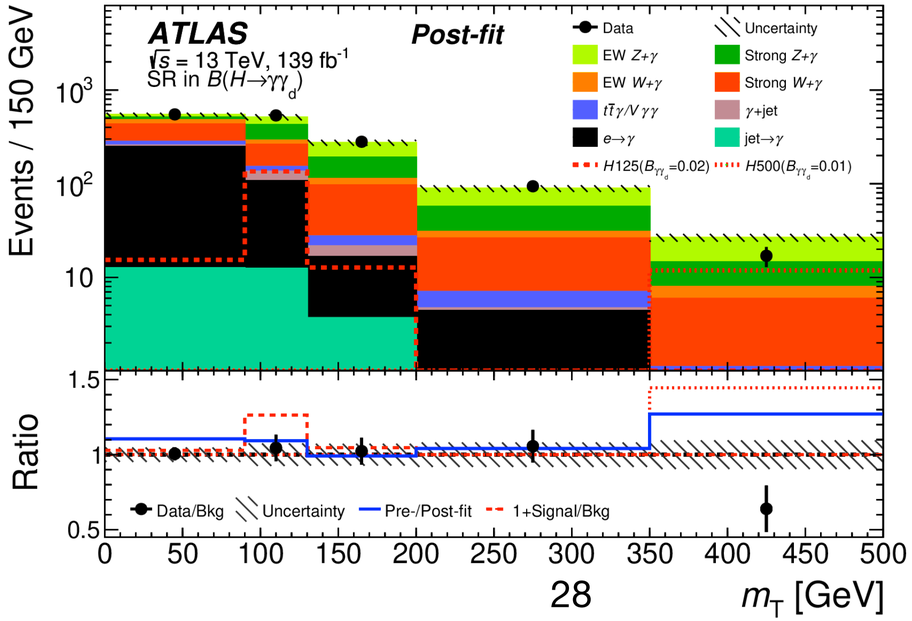
- ✓ **Trigger:** single-photon (ATLAS, CMS)+ E_T^{miss} (CMS)
- ✓ **Dominant background:** $W(\rightarrow \ell\nu)(+\gamma) + jets$ and $Z(\rightarrow \nu\nu)(+\gamma) + jets$
- ✓ **SR:** Selecting events with a photon, two jets with $|\Delta\eta_{jj}| > 2.5$ and high E_T^{miss}

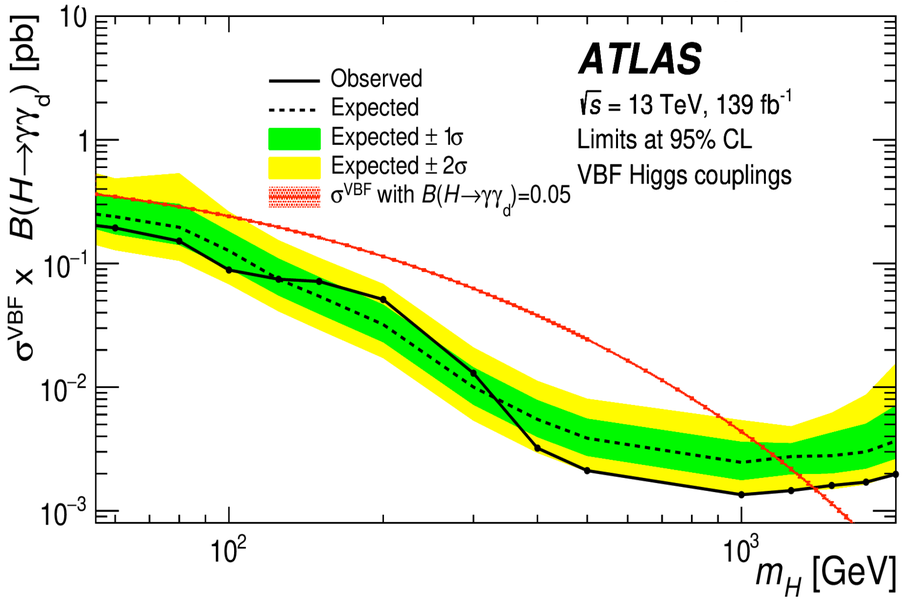
$$m_{\mathrm{T}}(\gamma, E_{\mathrm{T}}^{\mathrm{miss}}) = \sqrt{2 p_{\mathrm{T}}^{\gamma} E_{\mathrm{T}}^{\mathrm{miss}} \left[1 - \cos(\phi_{\gamma} - \phi_{E_{\mathrm{T}}^{\mathrm{miss}}})\right]}$$









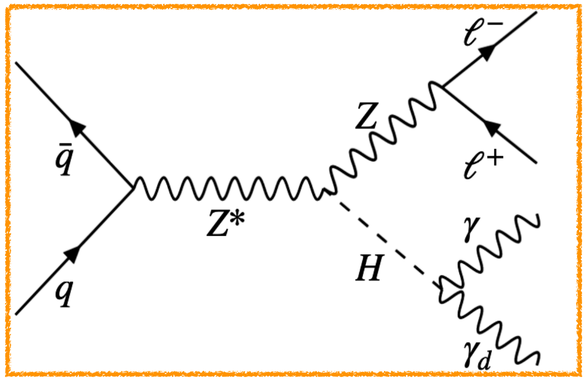


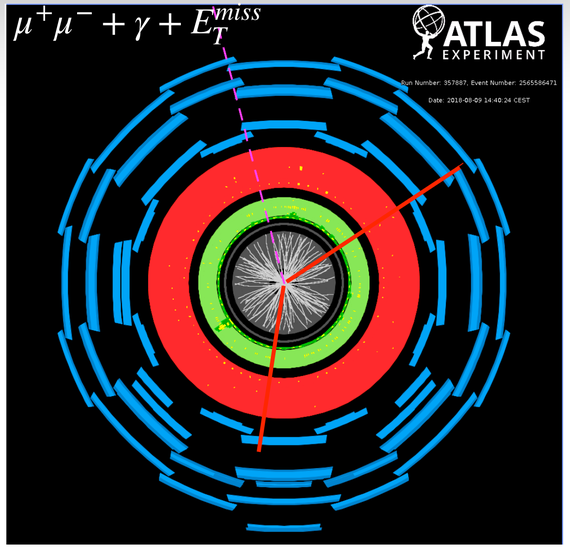
Dark Photons (ZH)

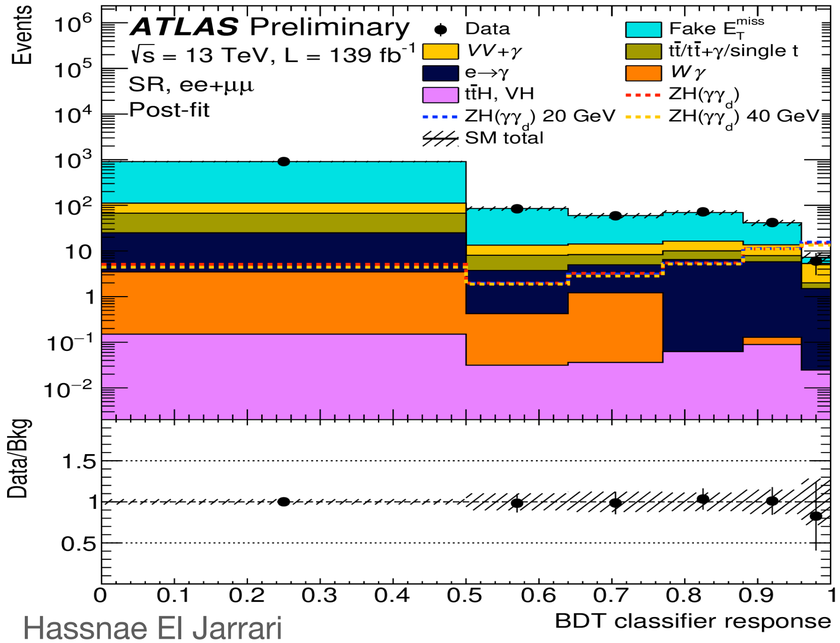
ATLAS:ATLAS-CONF-2022-064

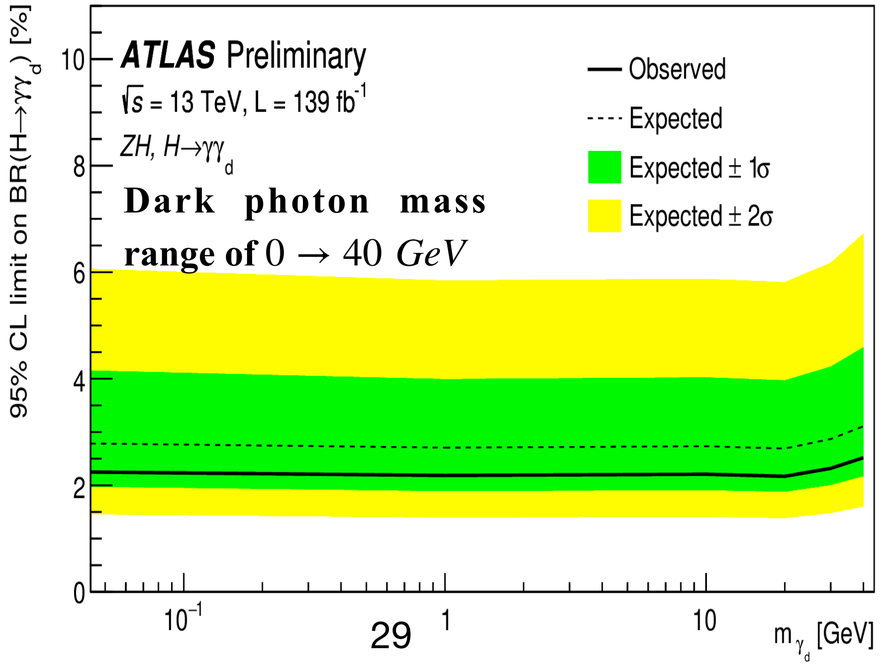
CMS:JHEP 10 (2019) 139

- ✓ **Signal**: ZH, $Z \to \ell^+\ell^-$ and $H \to \gamma\gamma_d$ (undetected dark photon $\to E_T^{miss}$).
- ✓ **BDT** classifier response (XGBoost) is used to enhance the analysis sensitivity using 6 input variables.
- ✓ Background estimation:
  - ✳ **Fake E_T^{miss}**: $Z\gamma + jets$, $Z + jets$ ⇒ Data-driven ABCD
  - ✳ $e \to \gamma$ ***fake***: VV, VVV ⇒ Data-driven fake rate and probe-electron CR
  - ✳ ***top***: MC, with 20% systematic uncertainty from the ***top*** **VR** (>=1 b-tag).
  - ✳ $VV\gamma$: MC normalised to data in the $VV\gamma$ **CR** (enhanced in $WZ\gamma$ ($3\ \mu + 1\gamma$)).
  - ✳ $W\gamma$, ***Higgs***: pure MC.





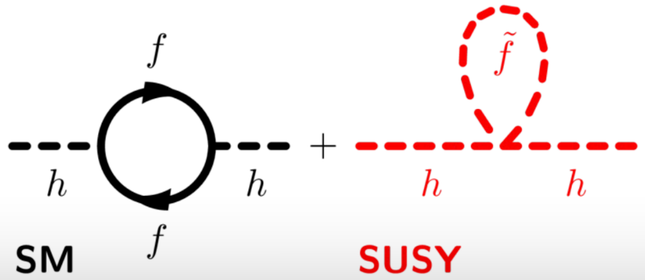




Observed (expected) exclusion limits at 95% CL on the BR(H → $\gamma\gamma_d$) as a function of the dark photon mass:
are found to be within the [2.19-2.52]% ([2.71-3.11]%) range.

Observed (expected) LHC Limits on BR(H → $\gamma\gamma_d$) for massless dark photons:

Production	ZH	VBF
ATLAS	**2.3 (2.8)%**	1.8 (1.7)%
CMS	4.6 (3.6)%	3.5 (2.8)%



SUSY as a DM generator

Remember that supersymmetry can be a dark matter model as well.

R-parity conservation requires an even number of SUSY particles in each interaction.

Therefore, Lightest Supersymmetric Particles (LSP) must be stable => DM candidate!

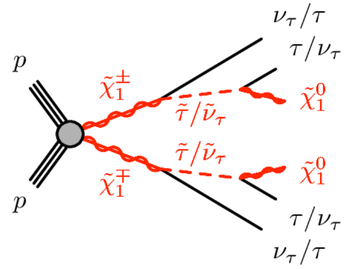
May induce non-trivial signals in detectors

Electroweak di-tau

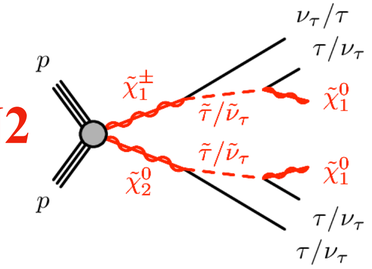
ATLAS:ATLAS-CONF-2022-042

- Chargino/neutralino pair production decaying to LSP via stau using ≥ 2 tau final states
- Categorised into chargino-chargino(C1C1)/ chargino-neutralino(C1N2), same-sign(SS)/ opposite-sign(OS) and high-mass(HM)/ low-mass(LM) channels

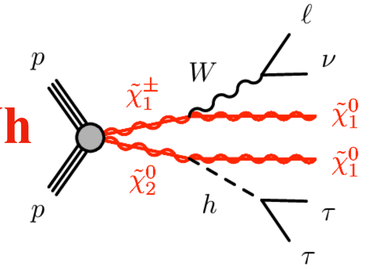
C1C1

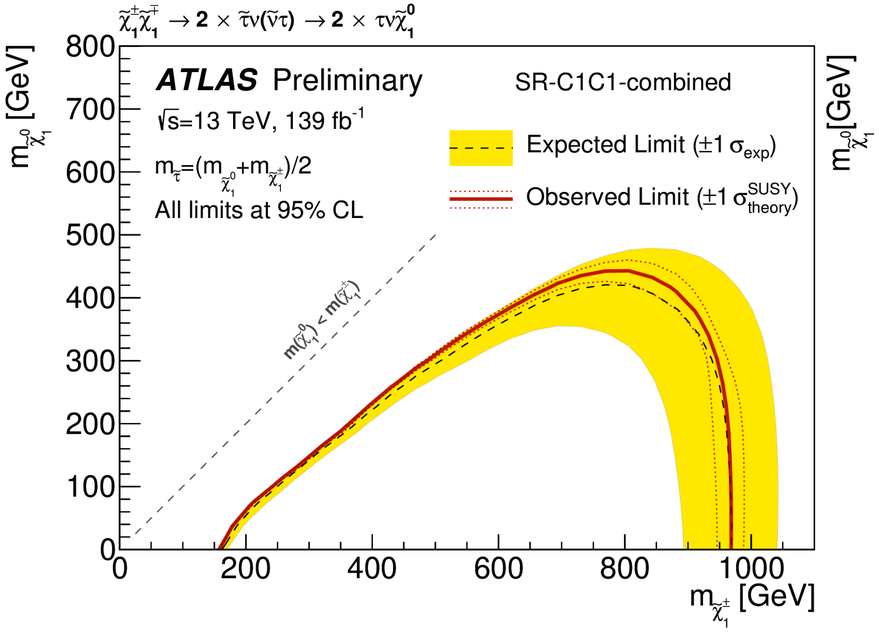


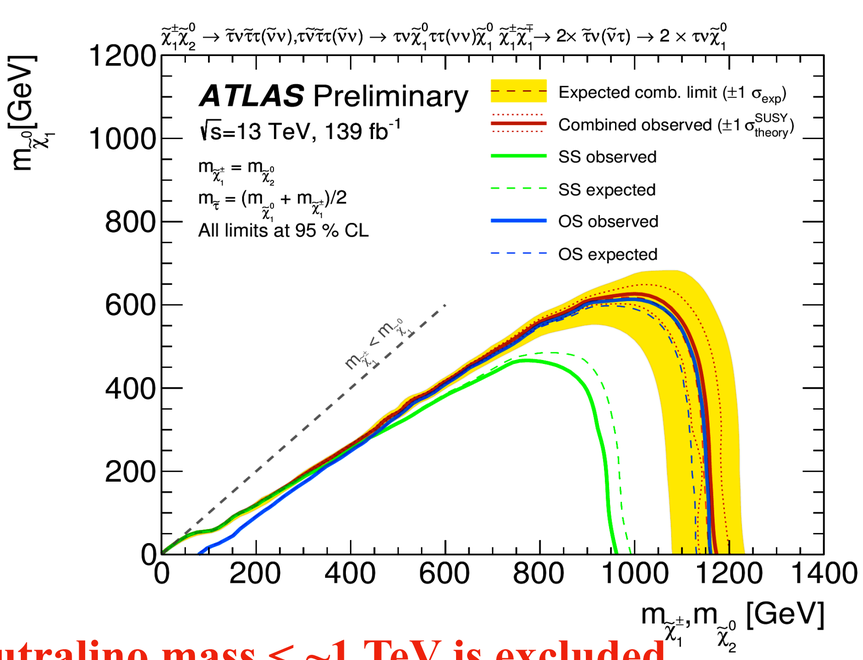
C1N2

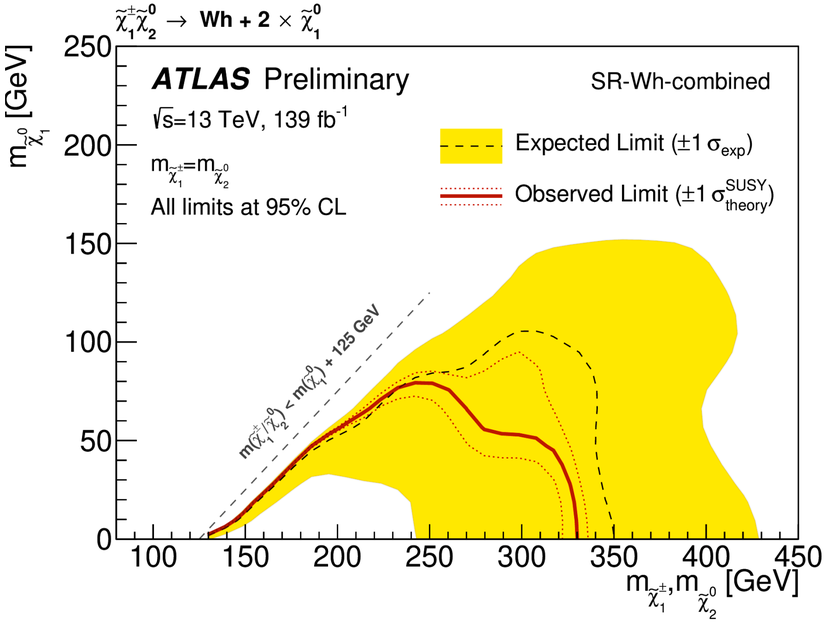


Wh









C1C1/C1N2: Chargino/neutralino mass < ~1 TeV is excluded

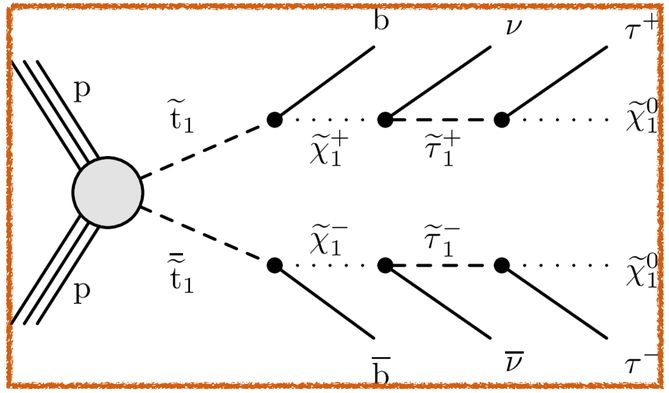
Wh: < ~300 GeV is excluded

➡ Using as assumption: $m_{\tilde{\tau}} = (m_{\tilde{\chi}_1^{\pm}} + m_{\tilde{\chi}_1^0})/2$

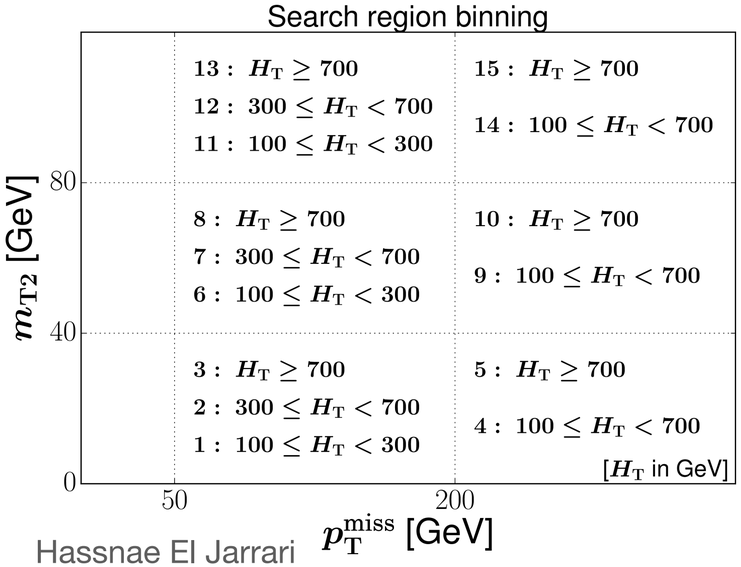
top squark di-tau

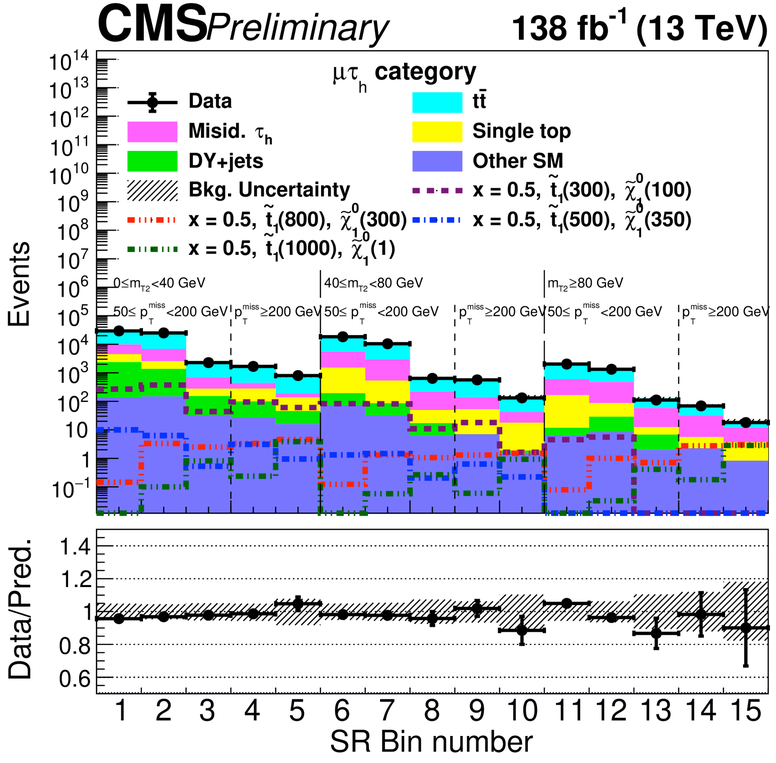
CMS: CMS-PAS-SUS-21-004

- Highly sensitive to high $tan(\beta)$ and higgsino-like scenarios.
- Exclusion limits on top squark and lightest neutrino masses under the assumption of simplified models.

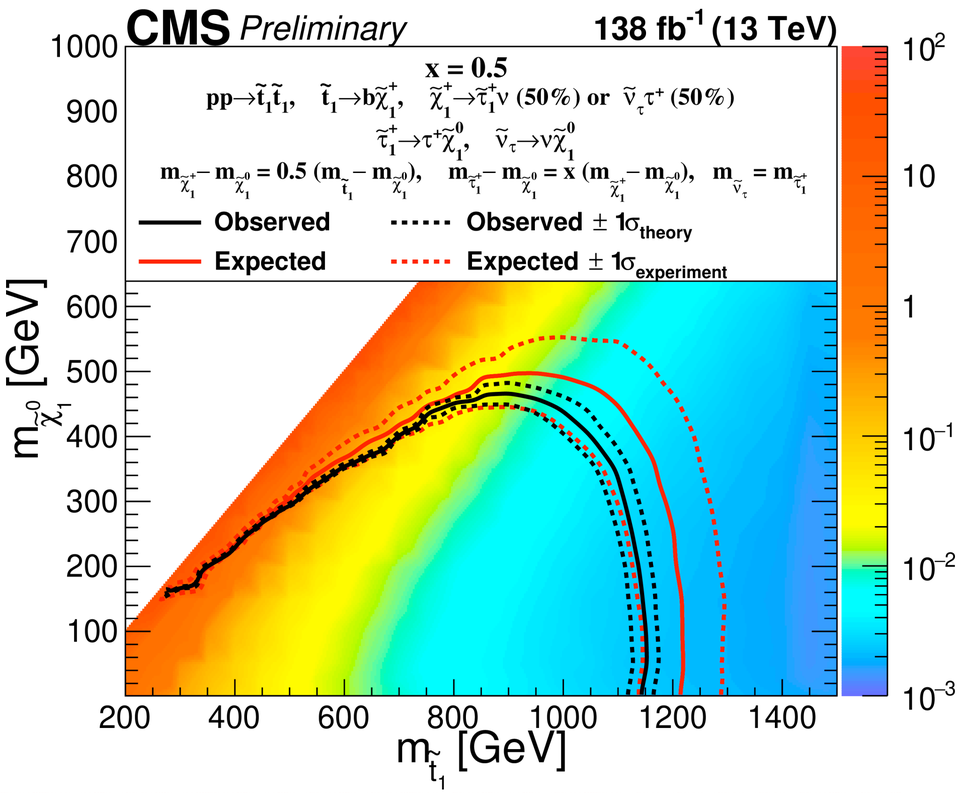


- 15 bin signal region
- 3 categories: $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$





Results also available for x=0.25 and x=0.75



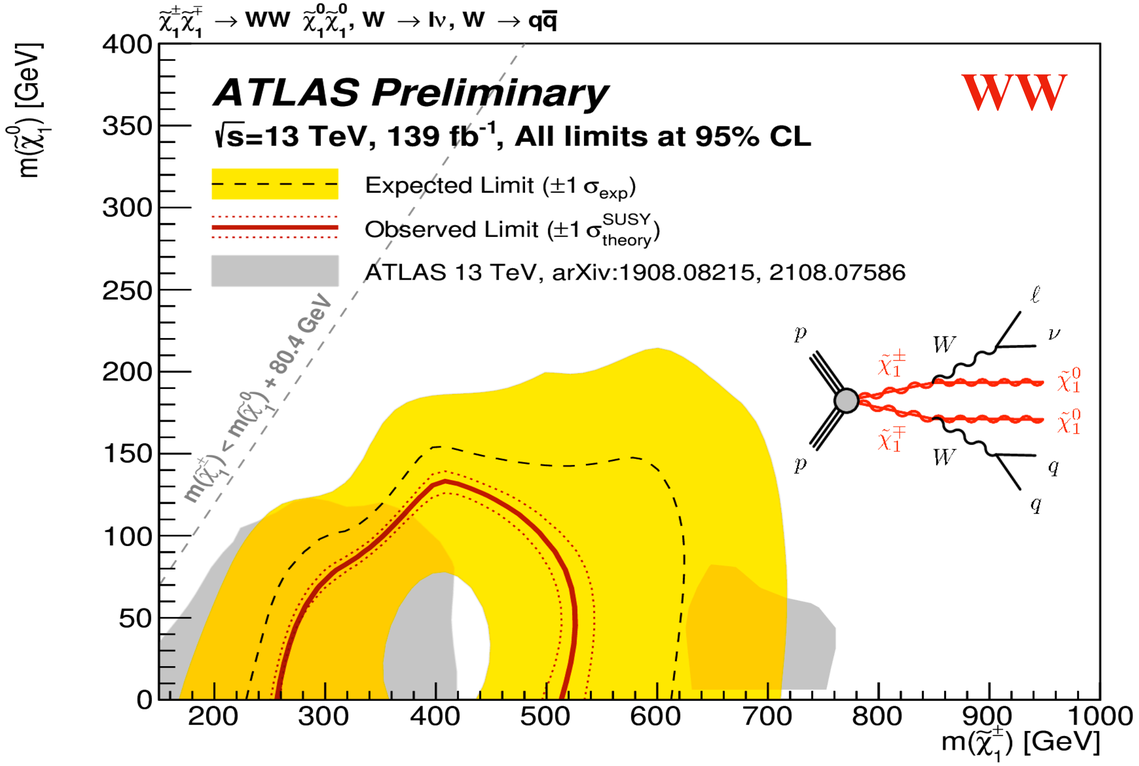
- Exclusion of top squark masses up to 1150 GeV for a nearly massless neutralino (1GeV LSP).
- LSP masses up to 450 GeV excluded for a top squark mass of 900 GeV.

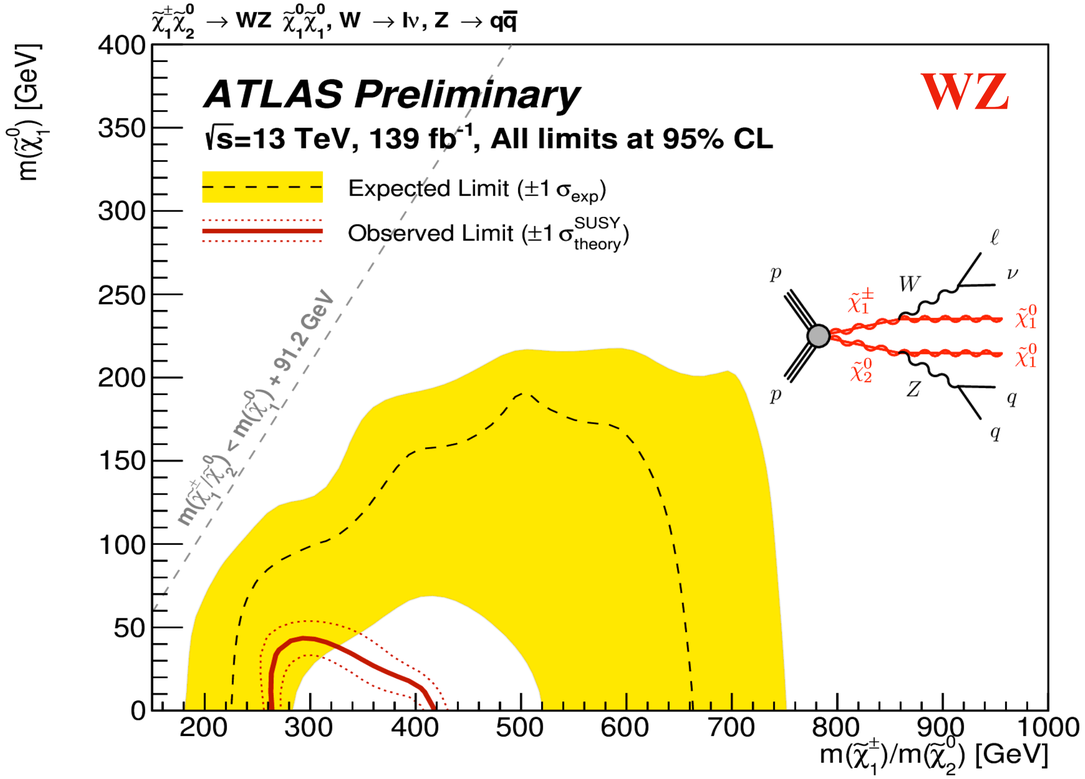
Best sensitivity for such signal model

Electroweak 1ℓ2J

ATLAS:ATLAS-CONF-2022-059

- ✓ **Trigger:** single lepton
- ✓ **Dominant background:** $W + jets$ and VV
- ✓ **Signature:** single isolated lepton, at least two jet, and missing transverse energy.





✓**WW: chargino masses 260-520 GeV can be excluded (for a massless neutralino).**

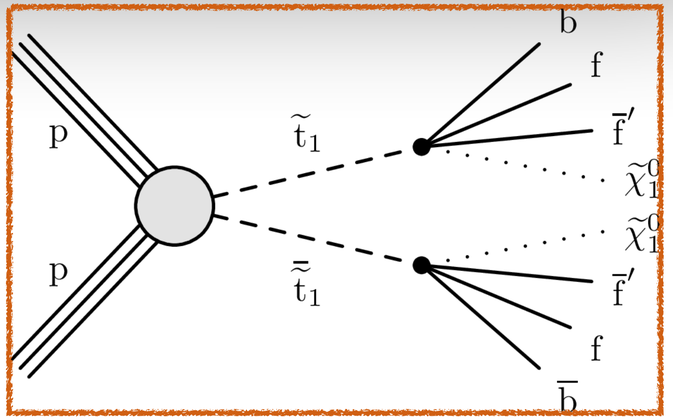
✓**WZ: degenerate chargino/neutralino masses 260-420 GeV can be excluded (for a massless neutralino).**

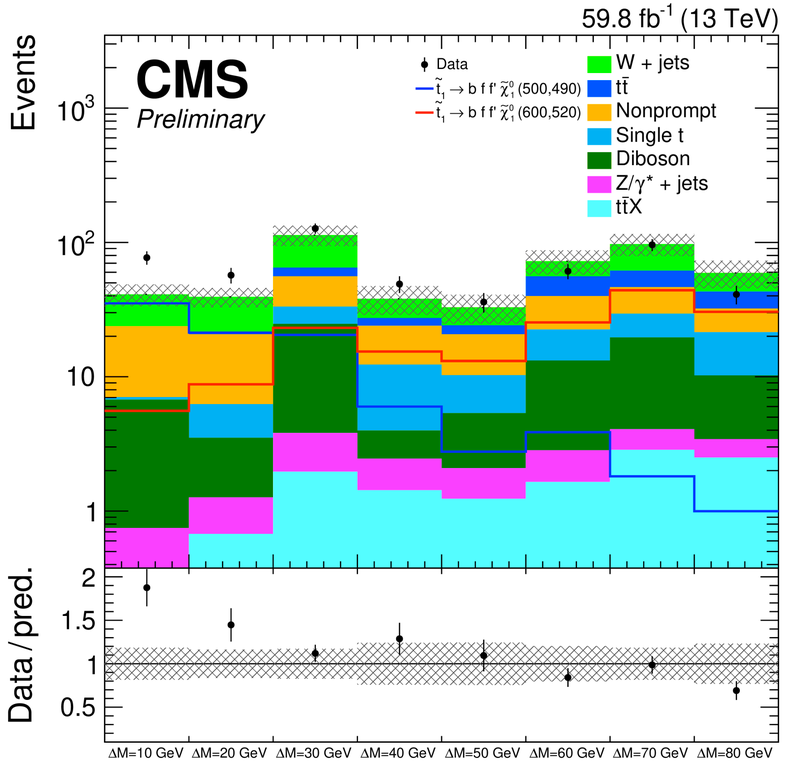
Best sensitivity in 1L2J

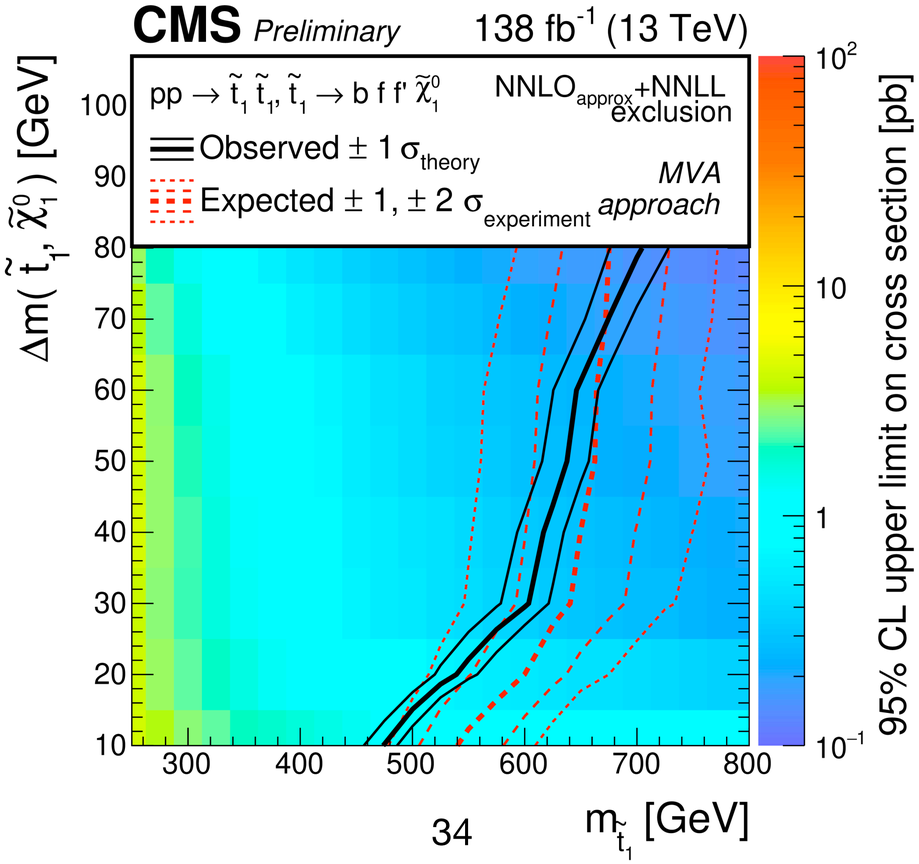
top squark in 1ℓ2J

CMS:CMS-PAS-SUS-21-003

- Four-body decay of the $\tilde{t}_1$: $b\mathrm{f}\bar{\mathrm{f}}'\tilde{\chi}_1^0$
- **Signature:** high p_T^{jet}, significant E_T^{miss} and low $p_T^{e||\mu}$
- Signal selected based on a multivariate approach (BDT) adapted to the $m(\tilde{t}_1) - m(\tilde{\chi}_1^0)$ mass difference that should not exceed the W boson mass.
- Leading background processes ($W + jets$, $t\bar{t}$) are determined from data.







- Exclusion limits on the production cross section as a function of the $\tilde{t}_1$ and $\tilde{\chi}_1^0$ masses under the assumption of simplified models.

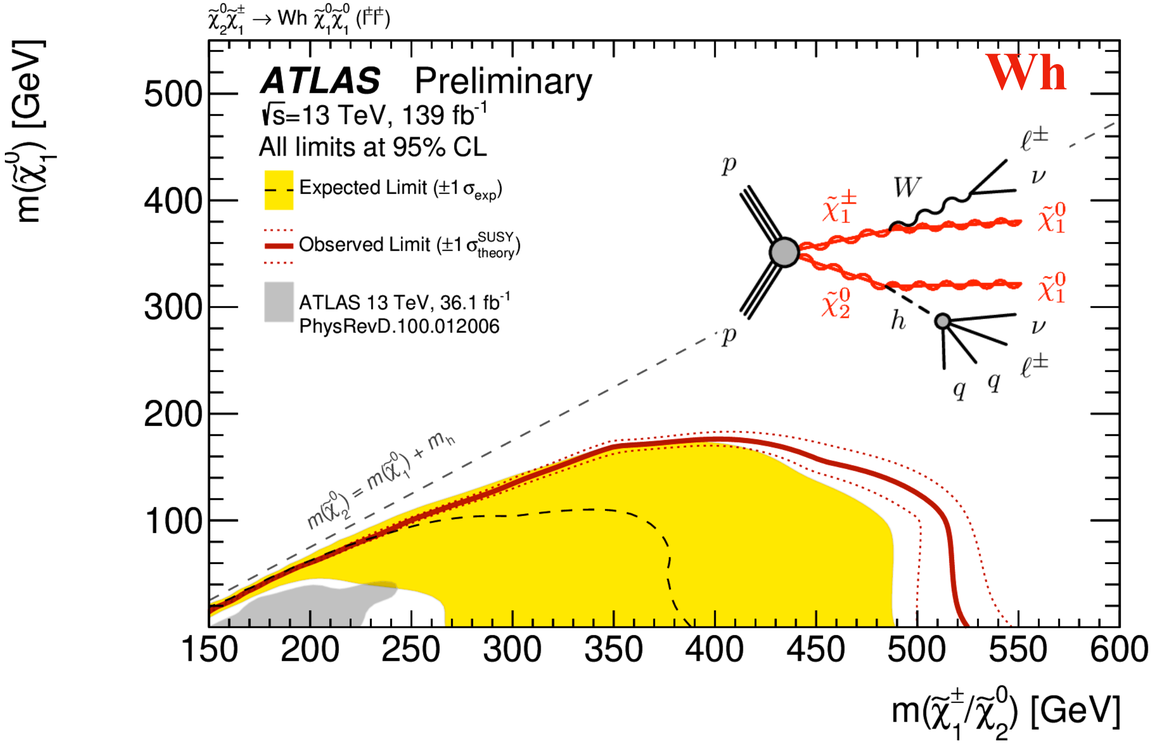
- top squark masses excluded depending on the $\Delta m = m(\tilde{t}_1) - m(\tilde{\chi}_1^0)$ mass difference.
- Δm = 10 GeV => up to 480 GeV excluded, Δm = 80 GeV => up to 700 GeV

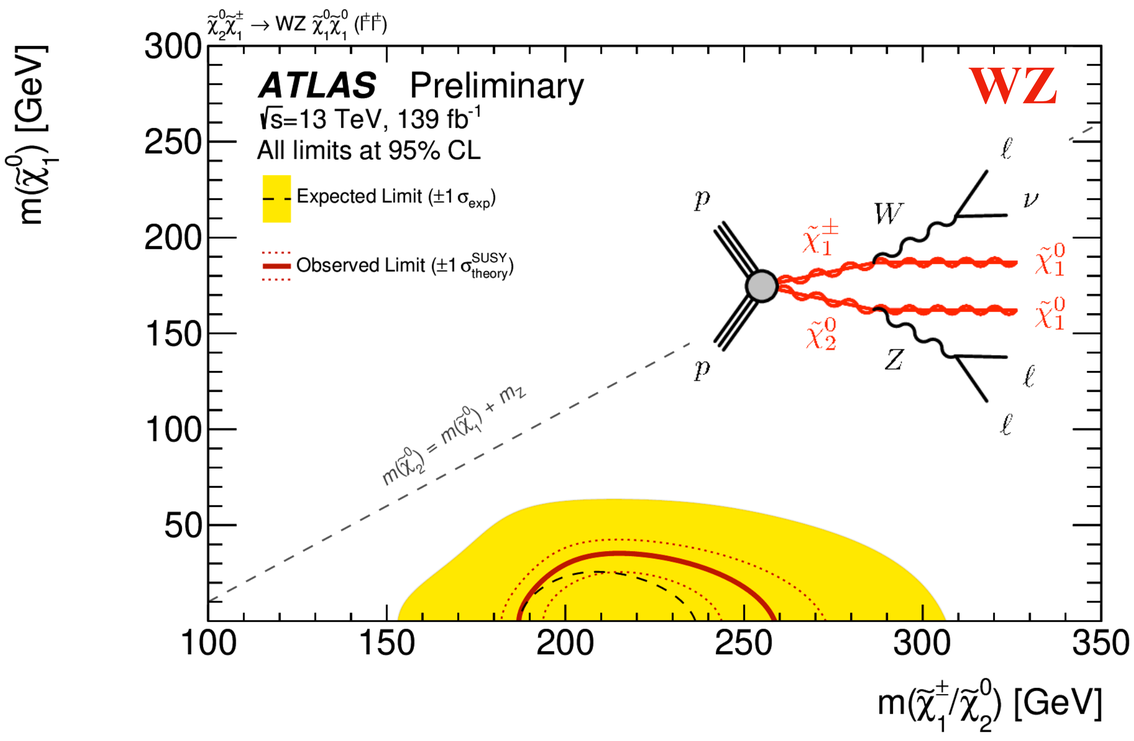
Best sensitivity for such signal model

Electroweak 2-SS-lepton

ATLAS:ATLAS-CONF-2022-057

- ✓ **Trigger:** di-lepton+ E_T^{miss}
- ✓ **Dominant background:** *WW* and *WZ*
- ✓ **Signature:** Wino-bino production with ***W h*** or ***W Z*** bosons (a pair of isolated light leptons (same sign), $m_{jj} < 350$ GeV (to reduce *WW*))



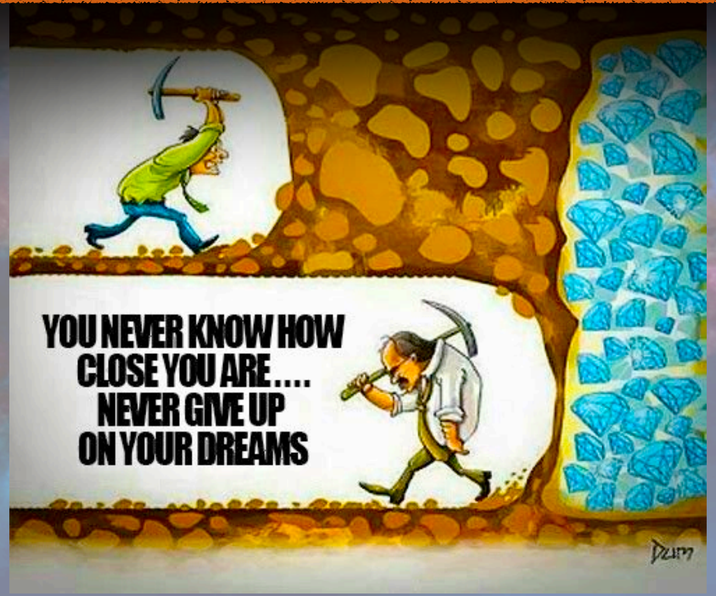


✓**wino masses up to 525 GeV and 260 GeV are excluded (for Wh and WZ respectively).**

✓**Higgsino masses smaller than 440 GeV are excluded**

Best sensitivity in 2-SSL

ATLAS and CMS Dark Matter Searches: Future Opportunities

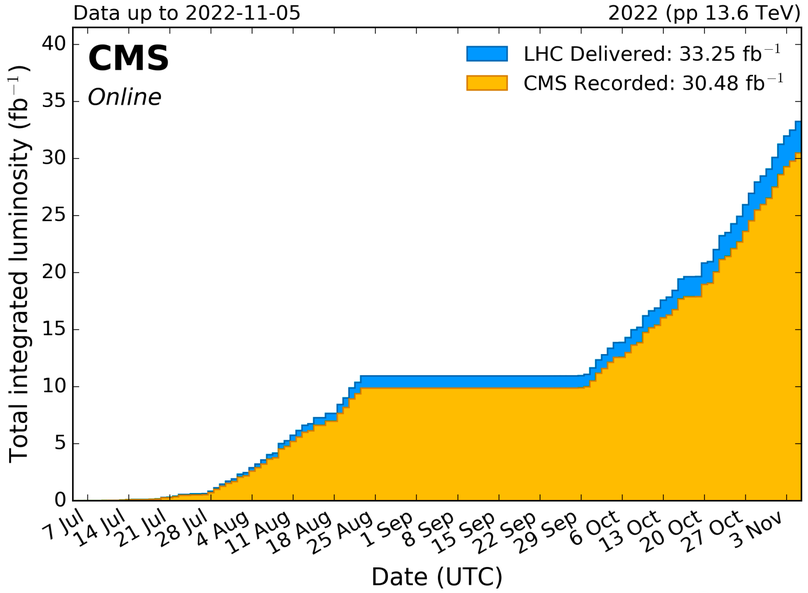


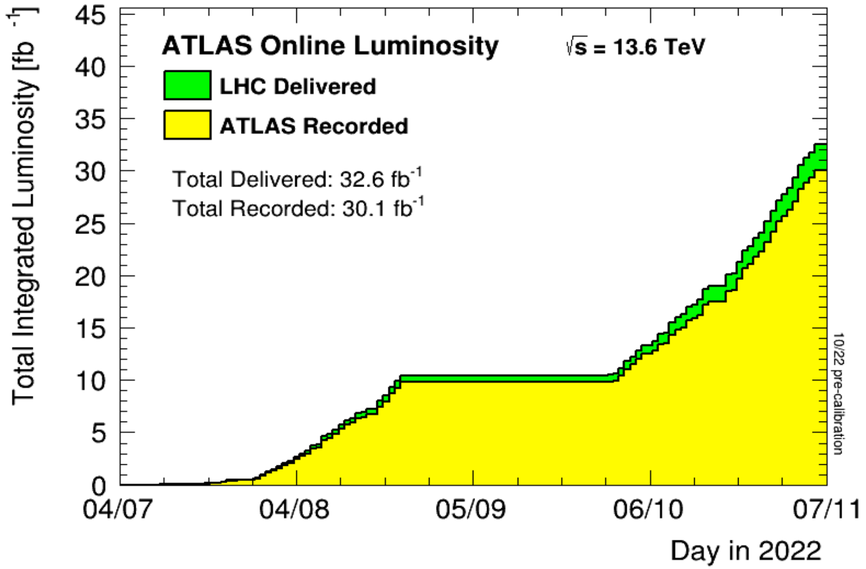
The LHC Timelines

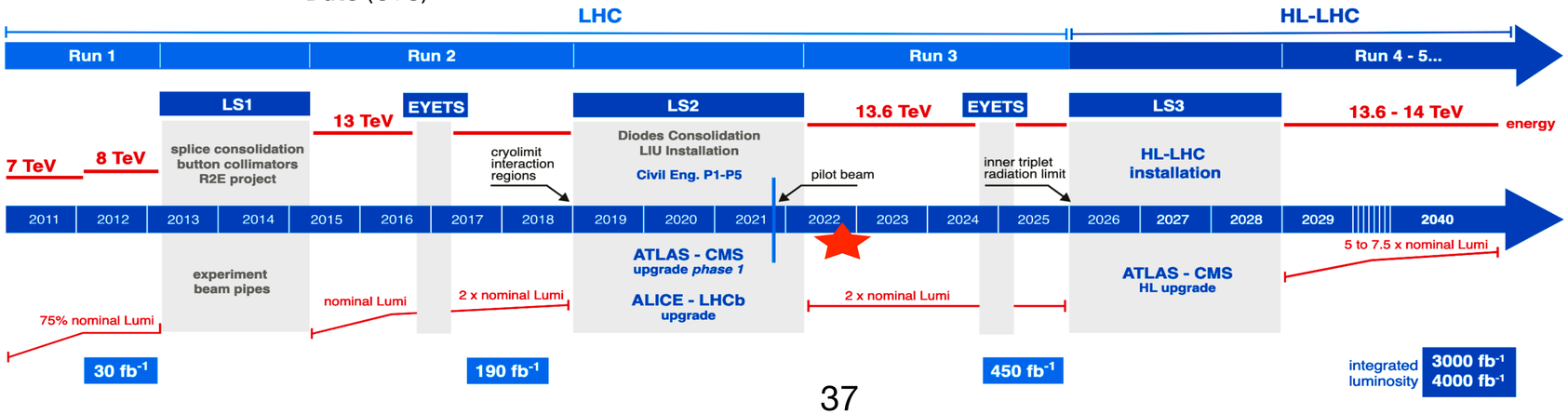
LHC $\sqrt{s} = 13.6$ TeV RUN3 is ongoing.

➡ Higgs production rate ($\sigma * L$) 7% larger than Run2.

➡ Total ~50M Higgs to be produced by the end of RUN3.







★ You are here

HL-LHC operation foreseen from 2029 to achieve >3000/fb.

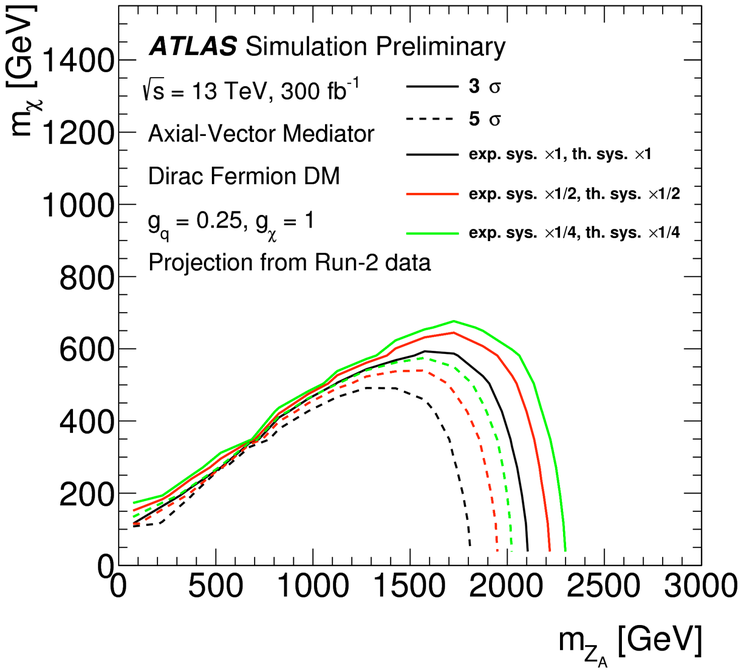
Future improvement

ATLAS: ATL-PHYS-PUB-2018-043

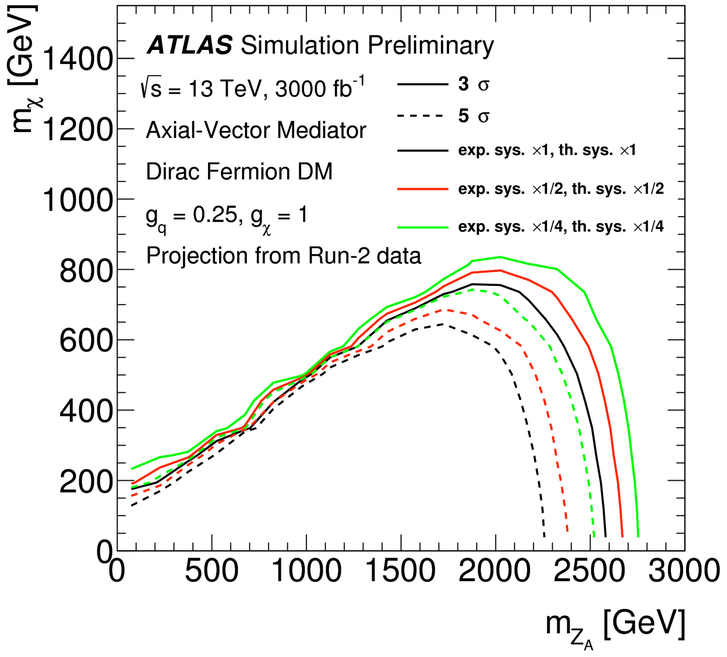
CMS: CMS-PAS-FTR-18-016

- Extrapolation from current results to 300 fb^{-1} (Run2+Run3) and 3000 fb^{-1} (HL-LHC) show the reach in DM searches
- Impact of different systematic uncertainties scenarios was investigated

Run2+Run3



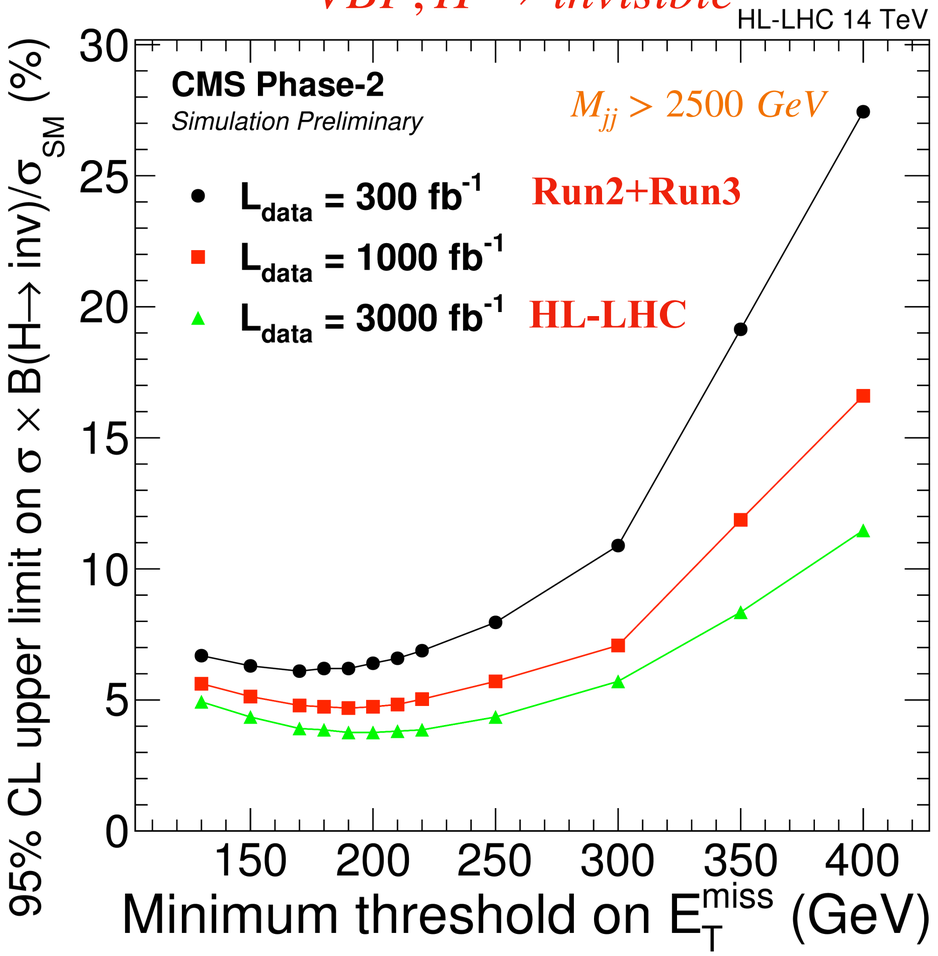
HL-LHC



Mono-jet search (one of the most systematic-limited DM analyses):

Expected 3σ (solid) and 5σ (dashed) discovery contours on the (m_χ,m_{ZA}) mass plane

$VBF, H \rightarrow invisible$

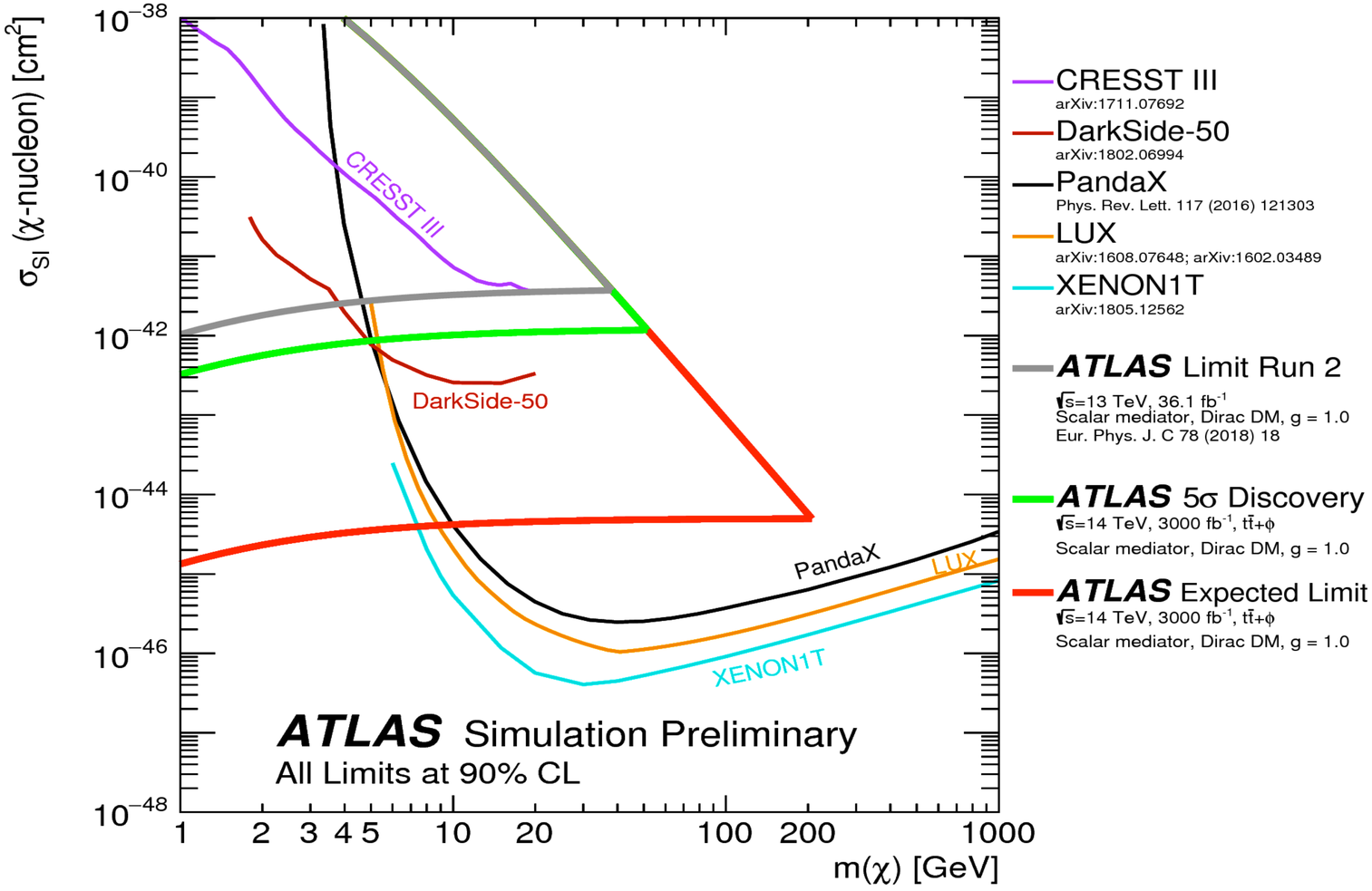


Future improvement in HL-LHC

ATL-PHYS-PUB-2022-018

Heavy quarks:

Comparison of the spin-independent DM-nucleon cross-section as a function of DM mass, to the DD experiments

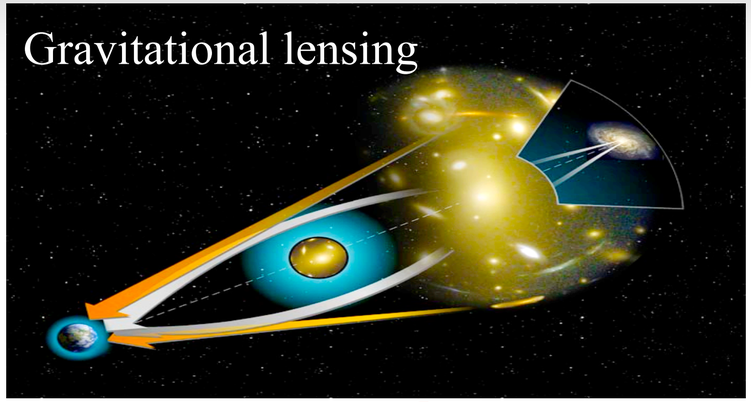


Conclusion

- Both astrophysical and terrestrial searches are needed to uncover a complete dark matter model.
- Many signatures were explored thanks to excellent detector performance
- Wide range of parameter space investigated by ATLAS and CMS, no hint so far
- No significant excess of events above SM background prediction with the current LHC Run 2 data.
- Observed complementarity with non-collider DM searches.
- ATLAS and CMS ATLAS underwent several upgrades during the Long Shutdown 2.
- All legacy and upgraded components (re)commissioned using splashes and pp collision data
- The LHC delivered the stable proton-proton collisions at 13.6 TeV, on July 5, starting Run 3
- Stay tuned for new Run 3 ATLAS and CMS results

Thank you

Dark Matter

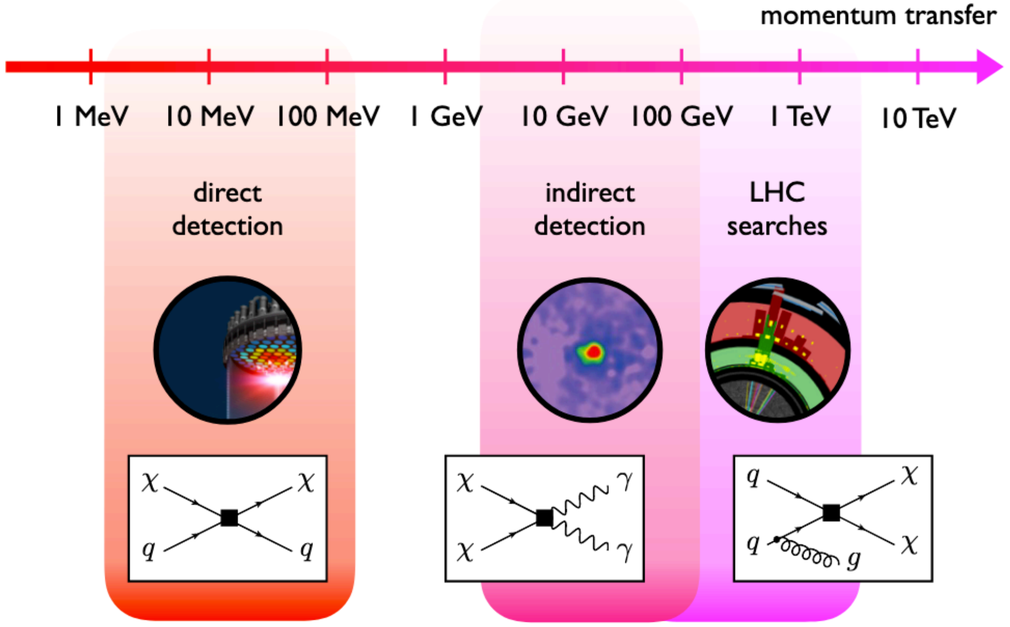


What do we know about DM ?

- Stable
- Massive
- Non-baryonic
- Electrically neutral
- No SM candidate
- 85% of all matter in the Universe
- Sensitive to gravitational interactions

Dark Matter Detection

Range of momenta probed in DD,
ID experiments and LHC searches



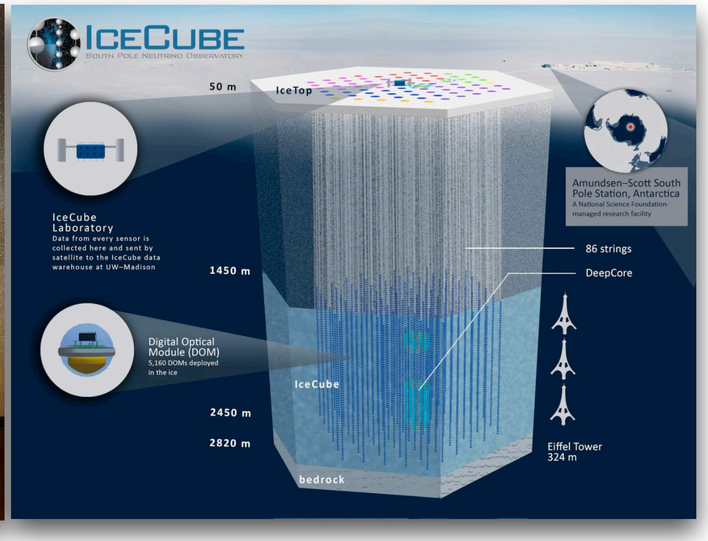
arXiv:1810.09420

Dark Matter Detection

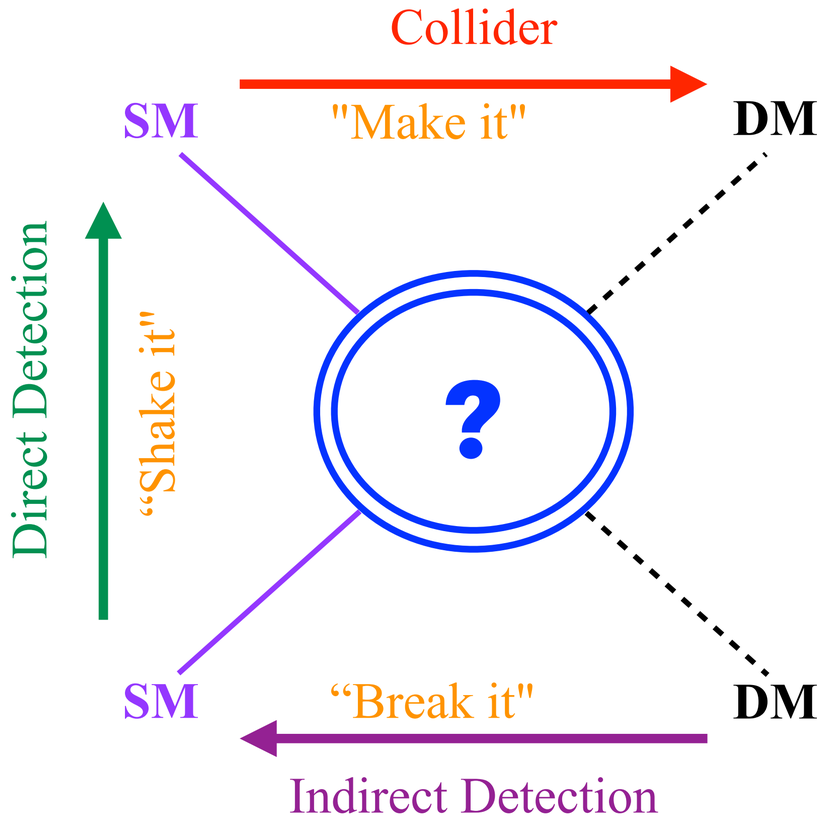
DM-SM weak interaction enables different searches:

- **Indirect Detection (ID)**: products from DM annihilation

HESS



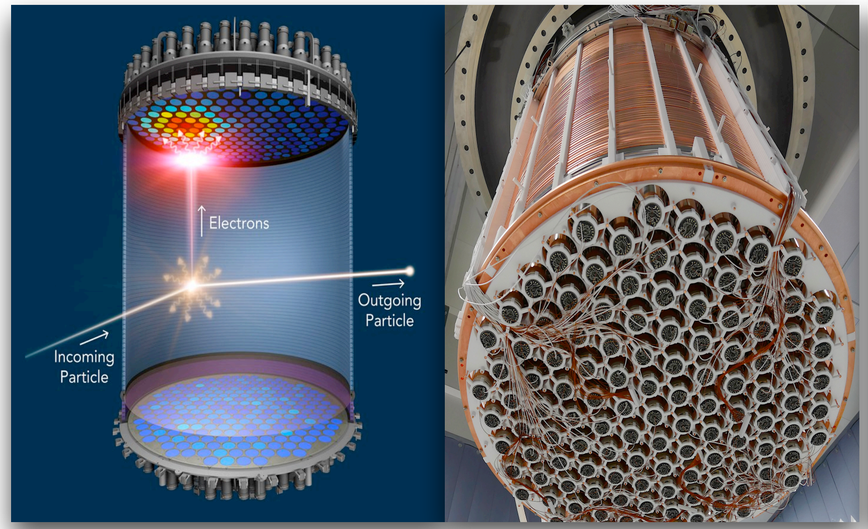
IceCube



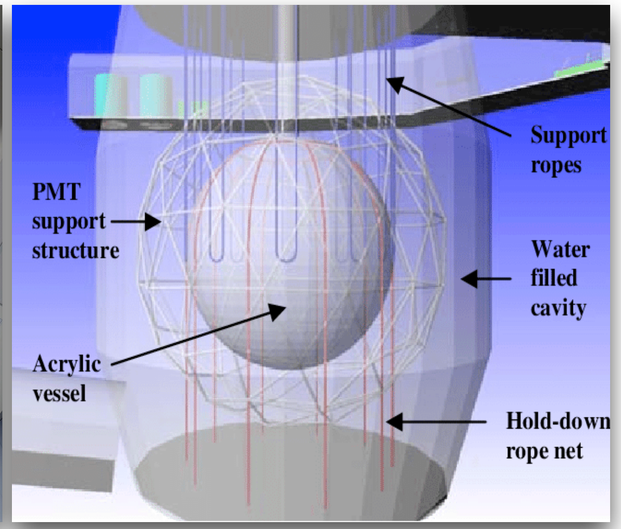
Dark Matter Detection

DM-SM weak interaction enables different searches:

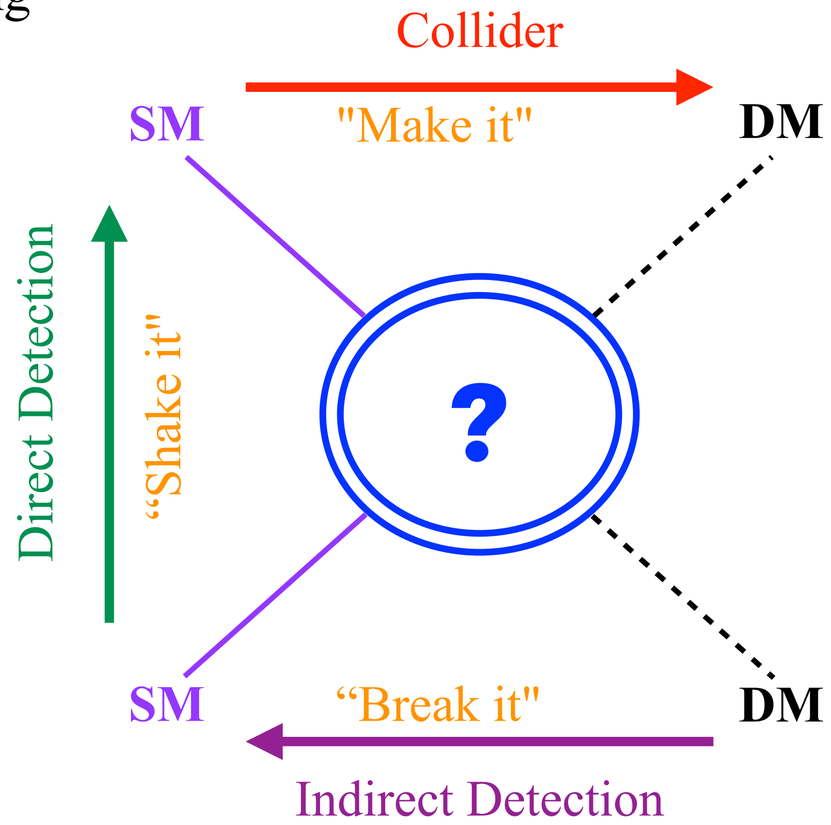
- **Indirect Detection (ID)**: products from DM annihilation
- **Direct Detection (DD)**: nuclear recoils from DM-nuclei scattering



XENON



SNOLAB

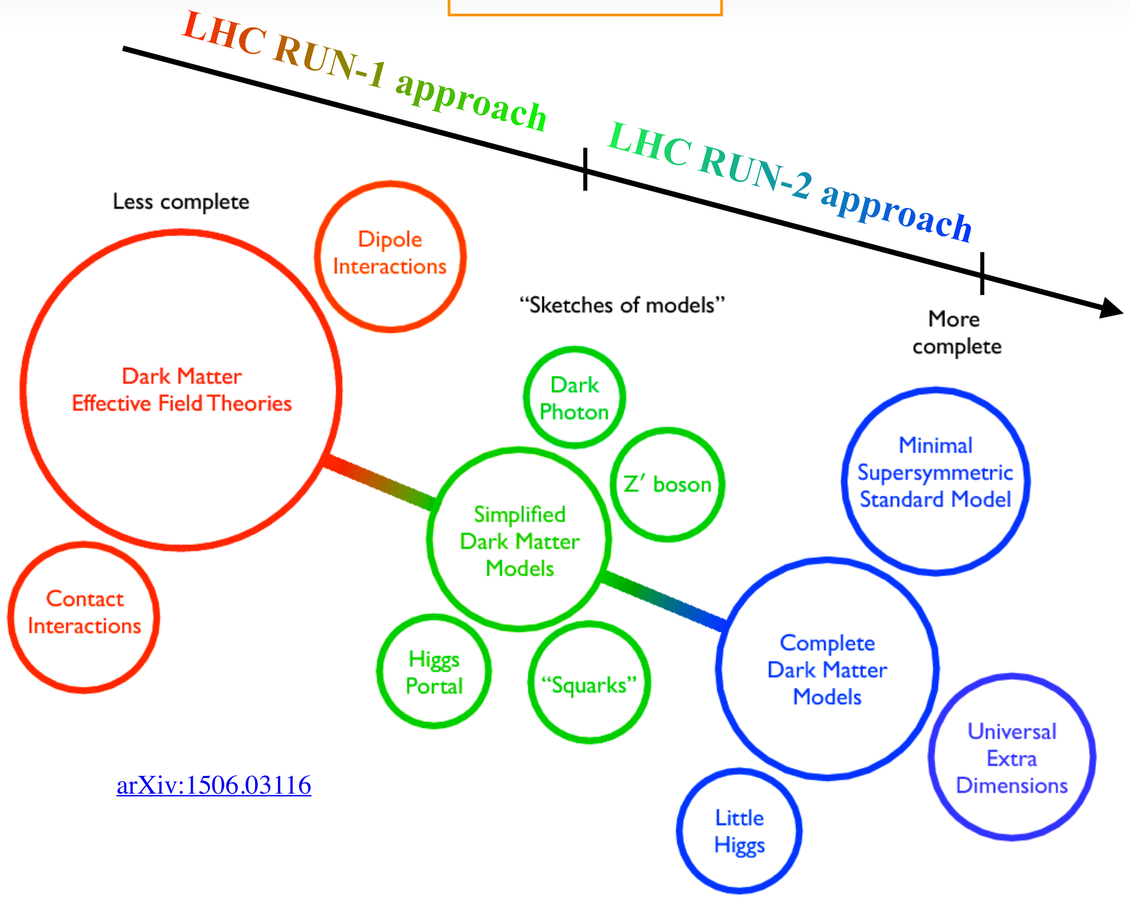


Dark Matter Models

Theories of Dark Matter

By Tim Tait

At the LHC



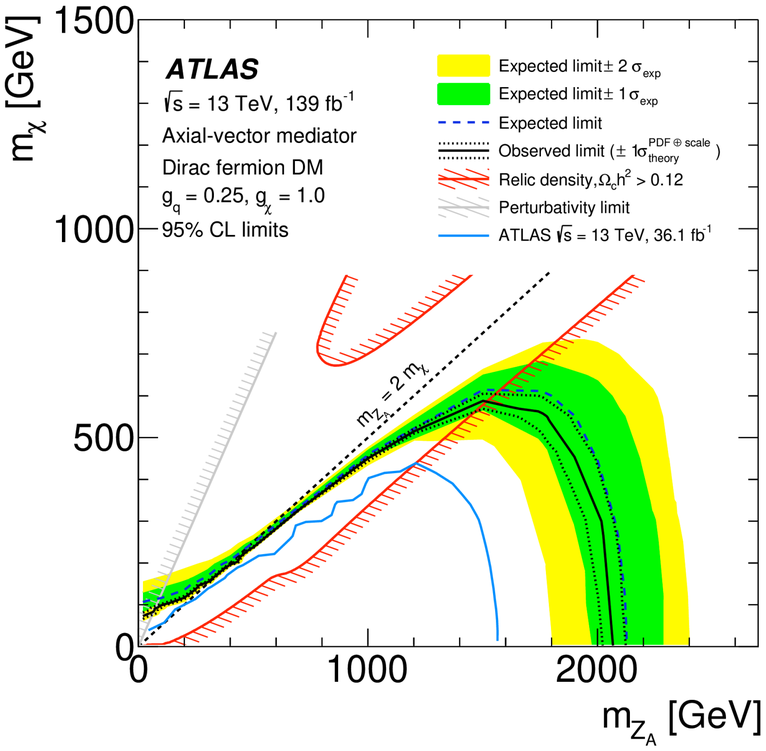
arXiv:1506.03116

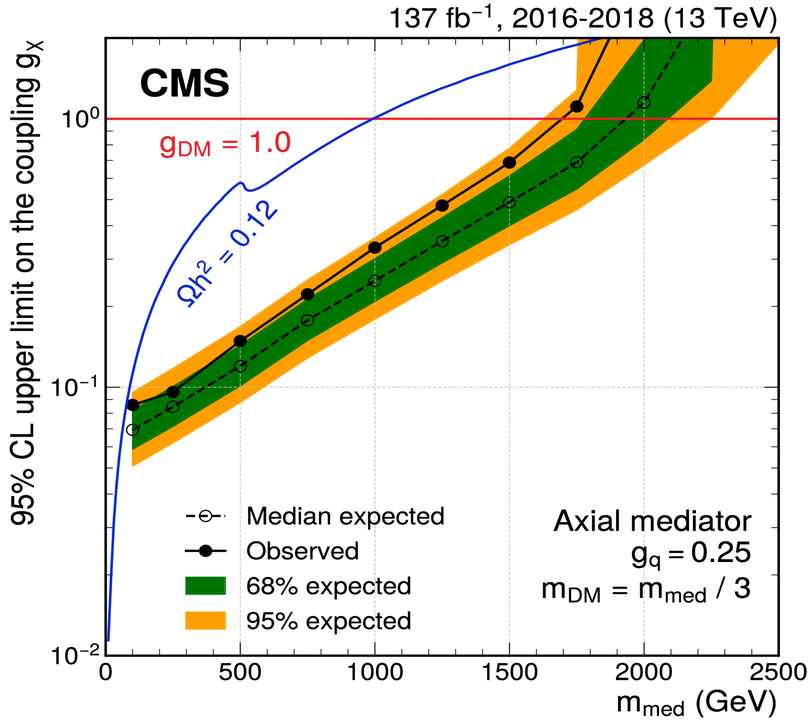
Perhaps a new dark sector consisting of many DM particles

Most models provide some kind of WIMPs

- ✓ Additional background from t, $t\bar{t}$, VV and Multijet (**data-driven jet-smearing**)
- ✓ CMS: Additional background from t, $t\bar{t}$, VV (**MC simulation**)

Limit on Axial-vector

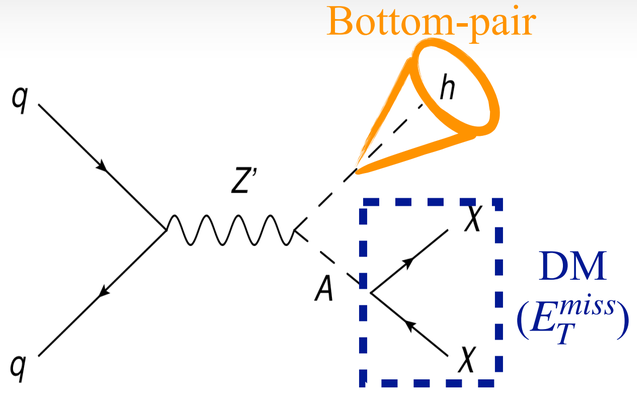


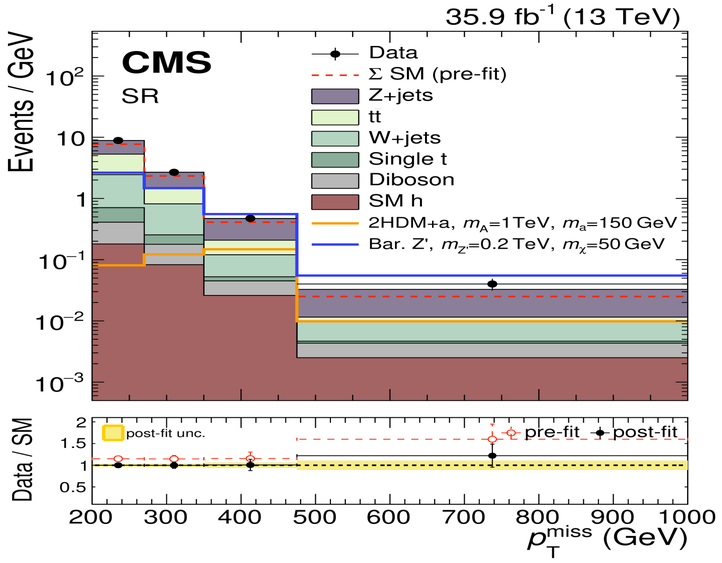


$H(\rightarrow bb) + E_T^{miss}$

CMS: EPJC 79 (2019) 280

'$2HDM + a$, $2HDM + Z'$, Z'_B'

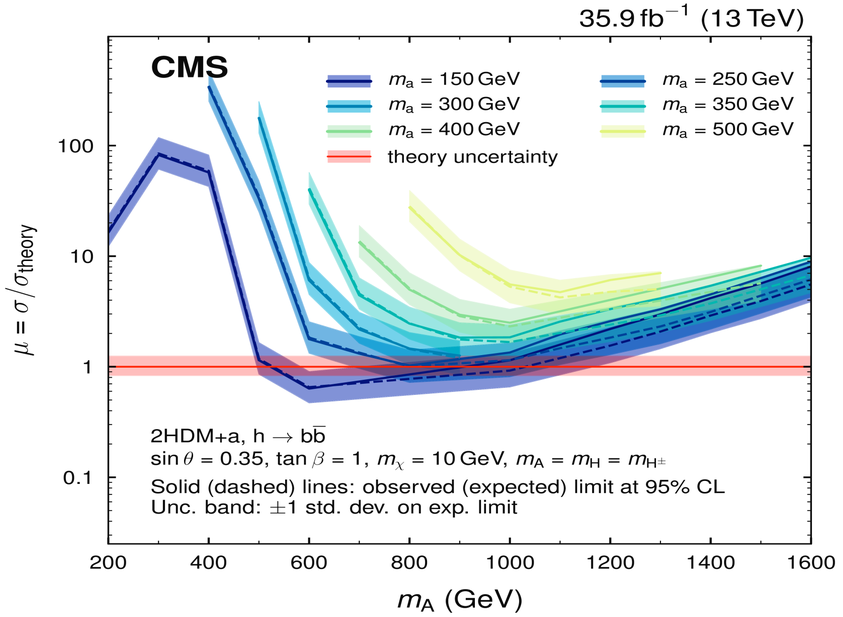




The data are in agreement with the post-fit SM predictions

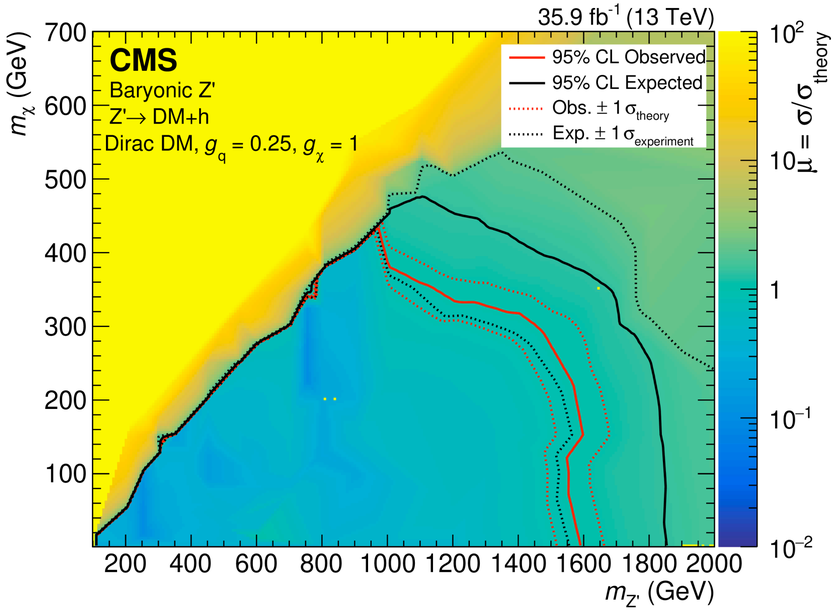
SR

- E_T^{miss} triggered events. $E_T^{miss} > 200$ GeV
- Double-b tag. Veto leptons and photon
- jet $p_T > 200$ GeV and $|\eta| < 2.4$



Upper limits for the 2HDM+a on the signal strength modifier: $\mu = \sigma/\sigma_{theory}$ as a function of m_A

Region	Main background process
Signal	Z+jets, $t\bar{t}$, W+jets
Single-lepton	W+jets, $t\bar{t}$
Single-lepton, b-tagged	$t\bar{t}$, W+jets
Dilepton	Z+jets

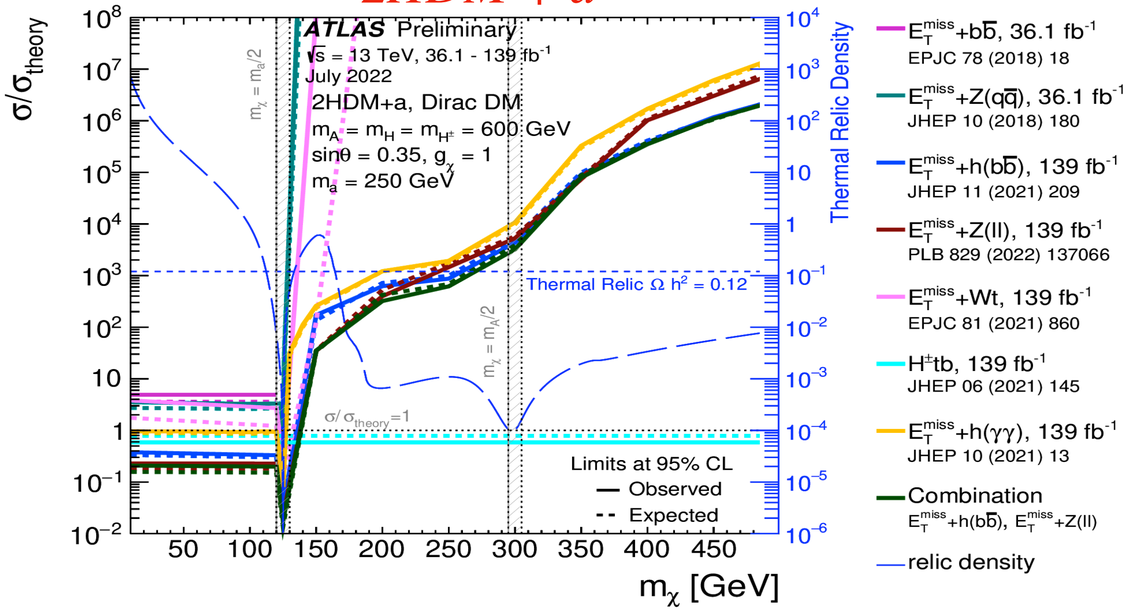


Upper limits for the Baryonic Z' model on the signal strength modifier: $\mu = \sigma/\sigma_{theory}$ as a function of $m_{Z'}$

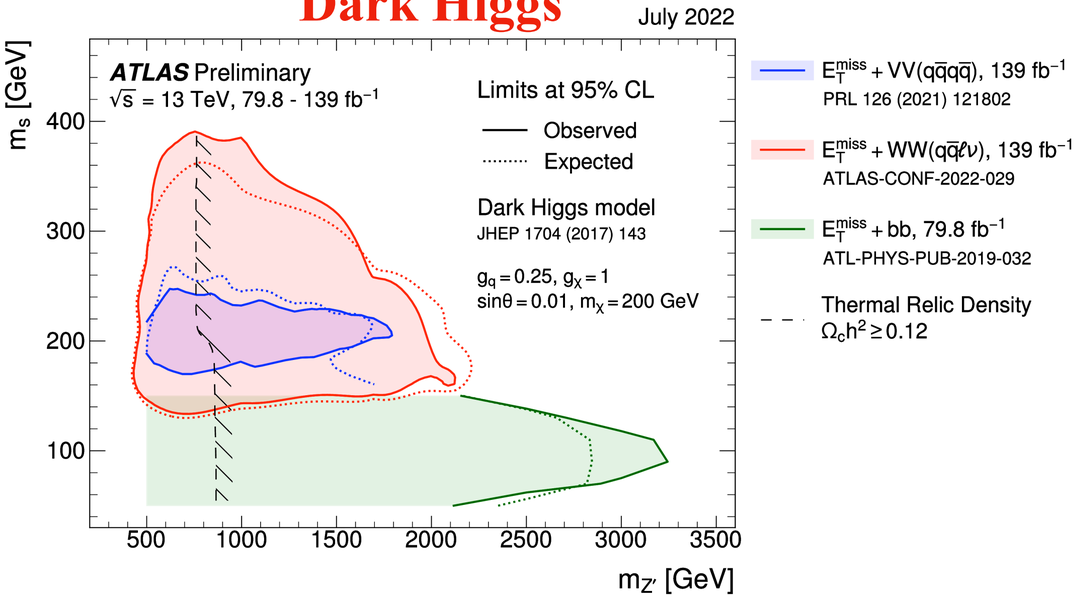
DM Summary Plots

ATLAS: ATL-PHYS-PUB-2022-036

2HDM + a



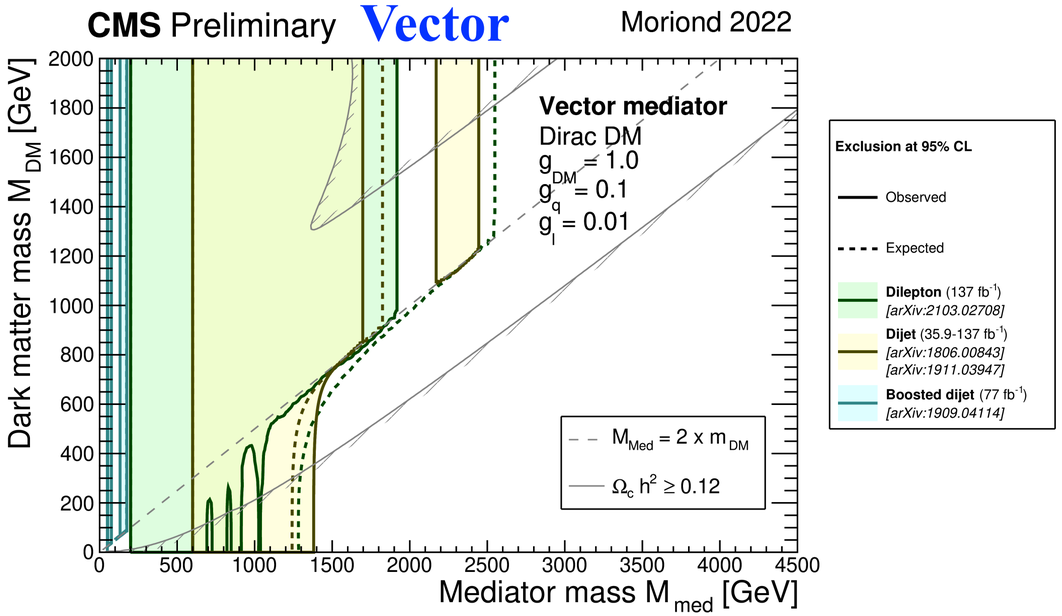
Dark Higgs

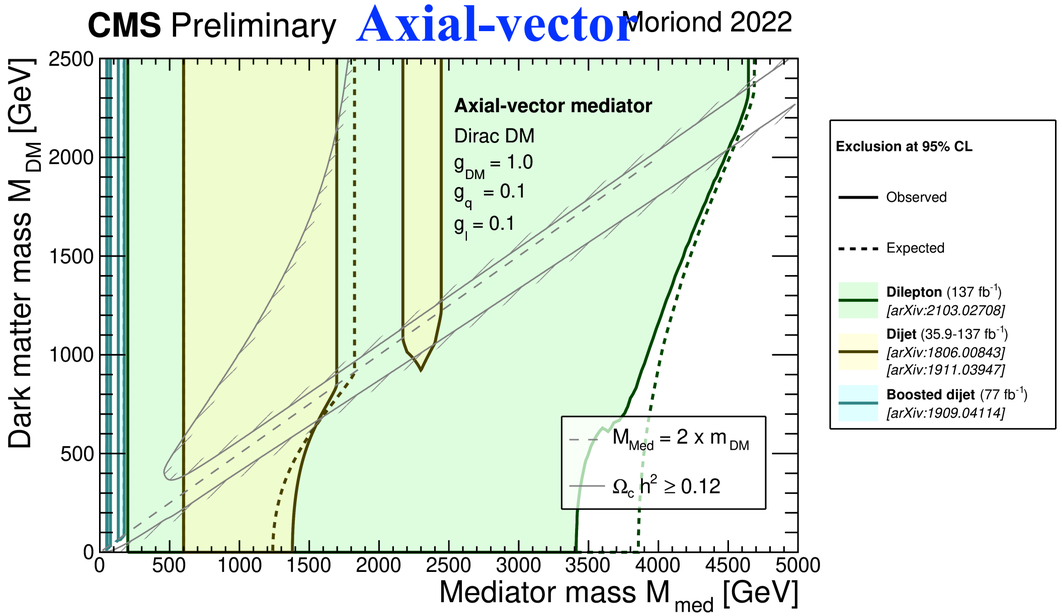


DM Summary Plots

CMS: DM_summary_plots

Simplified DM model





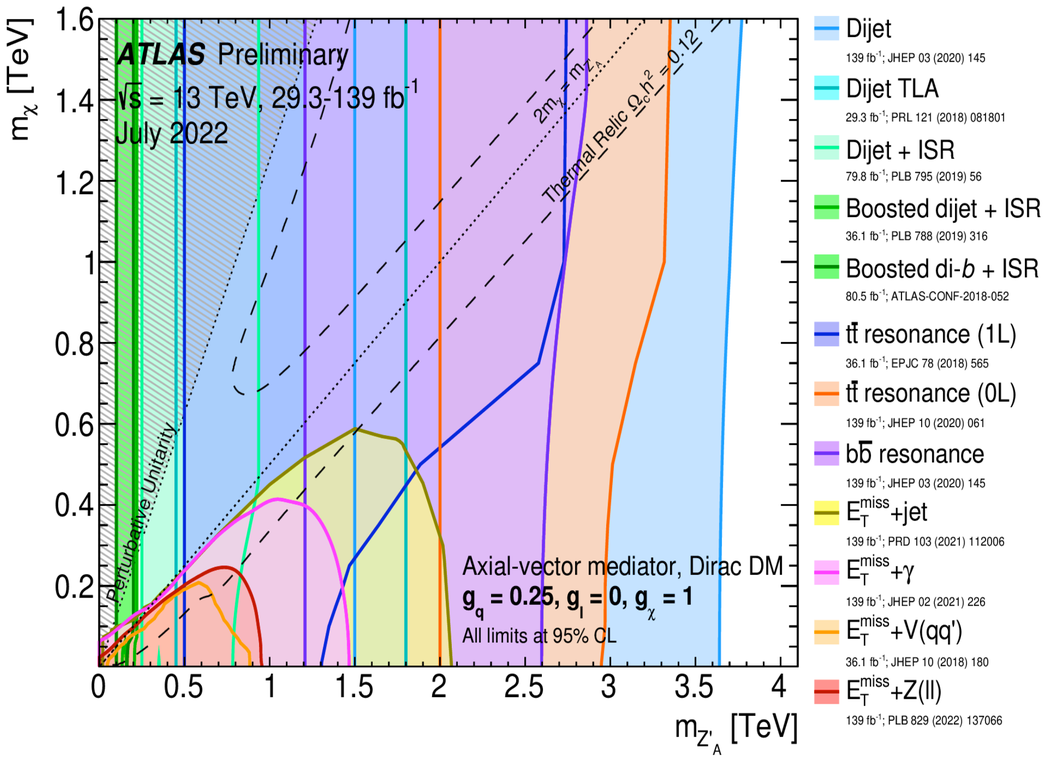
DM Summary Plots

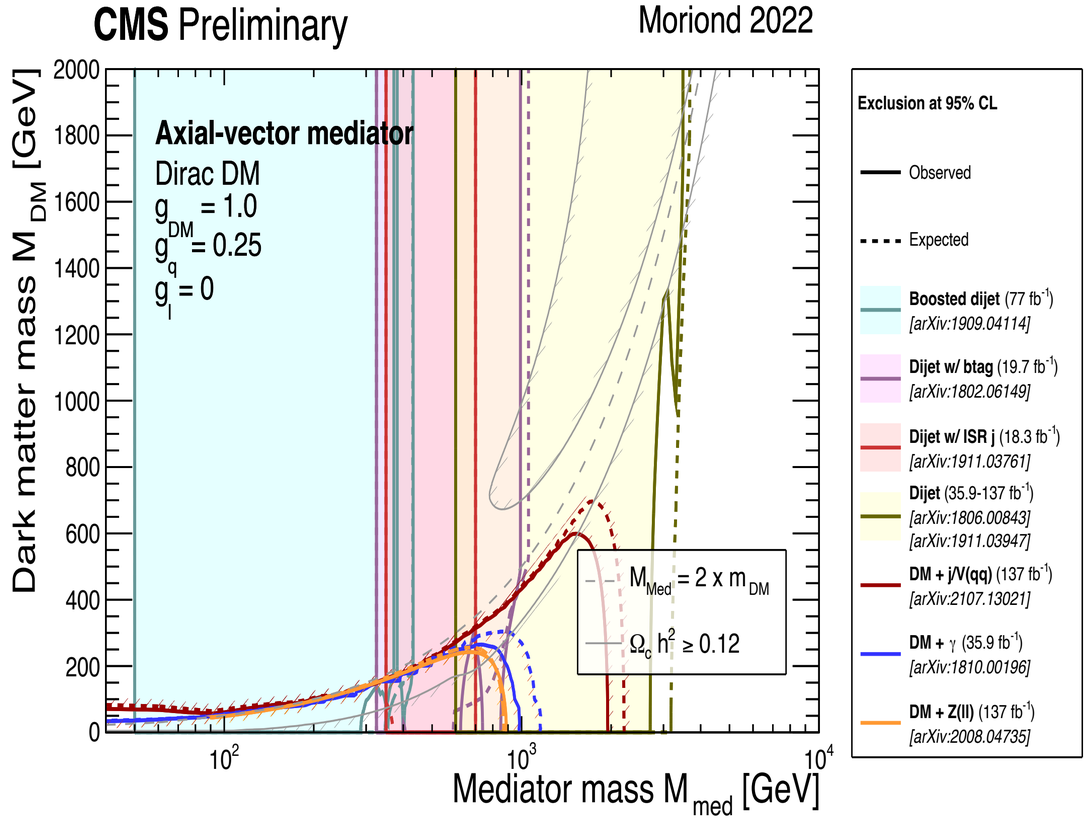
ATLAS: ATL-PHYS-PUB-2022-036

CMS: DM_summary_plots

Simplified DM model

Axial-vector



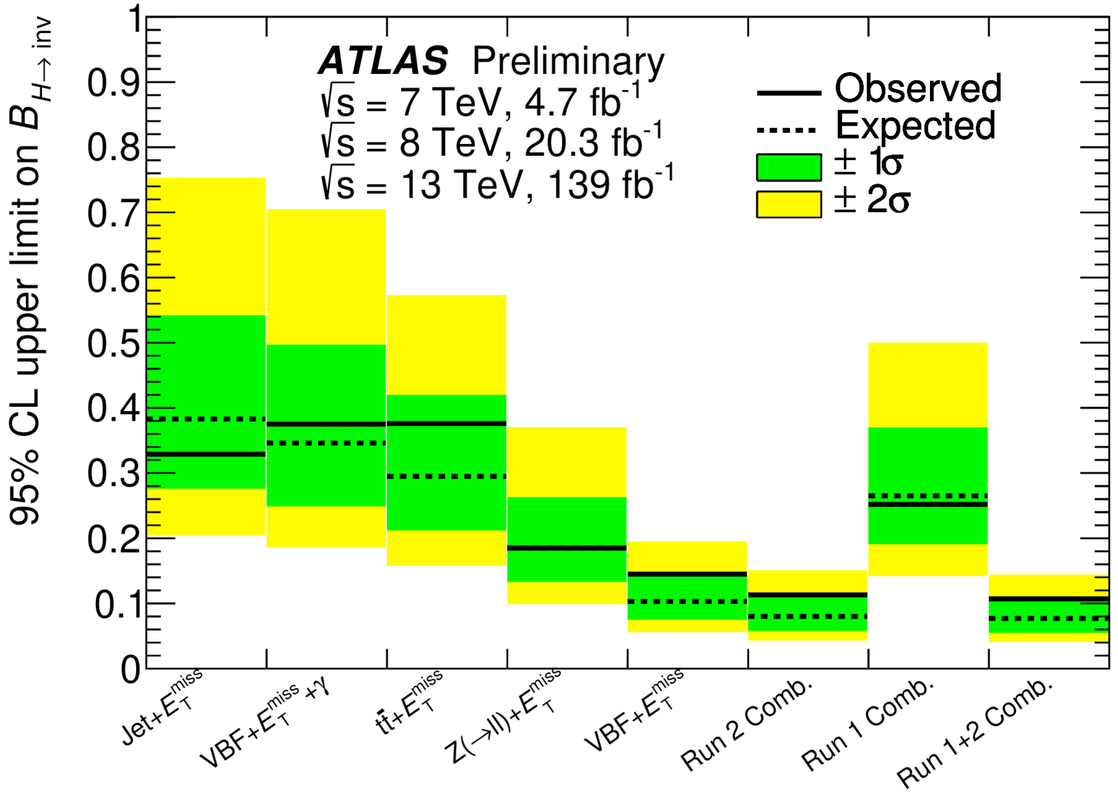


$H \rightarrow inv$ combination

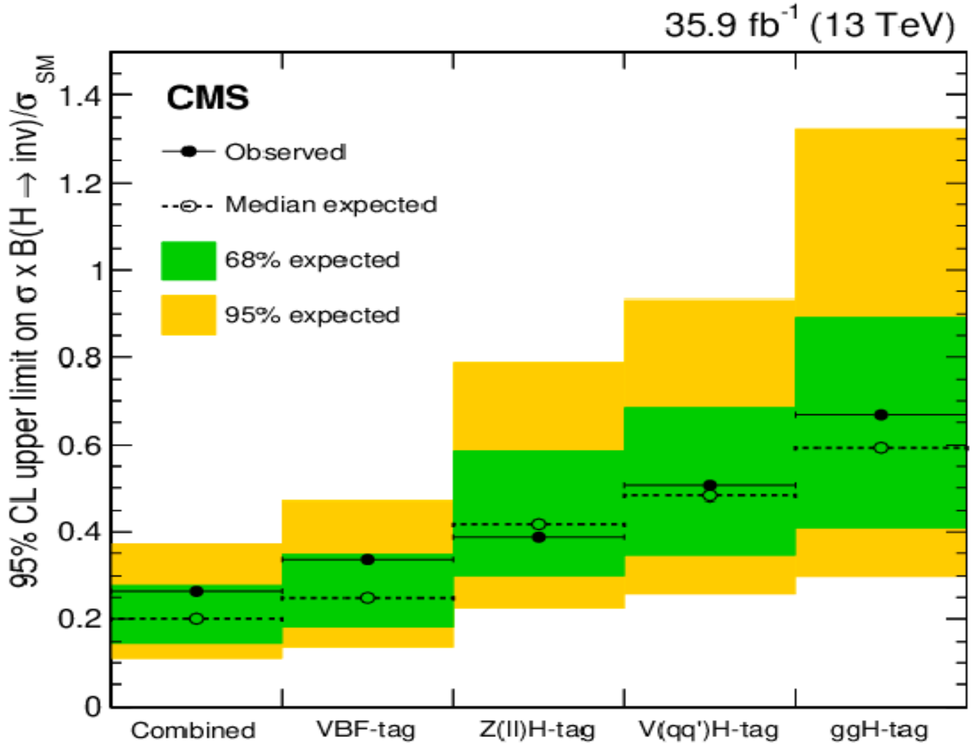
ATLAS: HIGG-2021-05

CMS: Phys. Lett. B 793 (2019)520

Higgs portal



ATLAS full Run-2 data:
BR(H→ inv) < 11 % (11% exp)



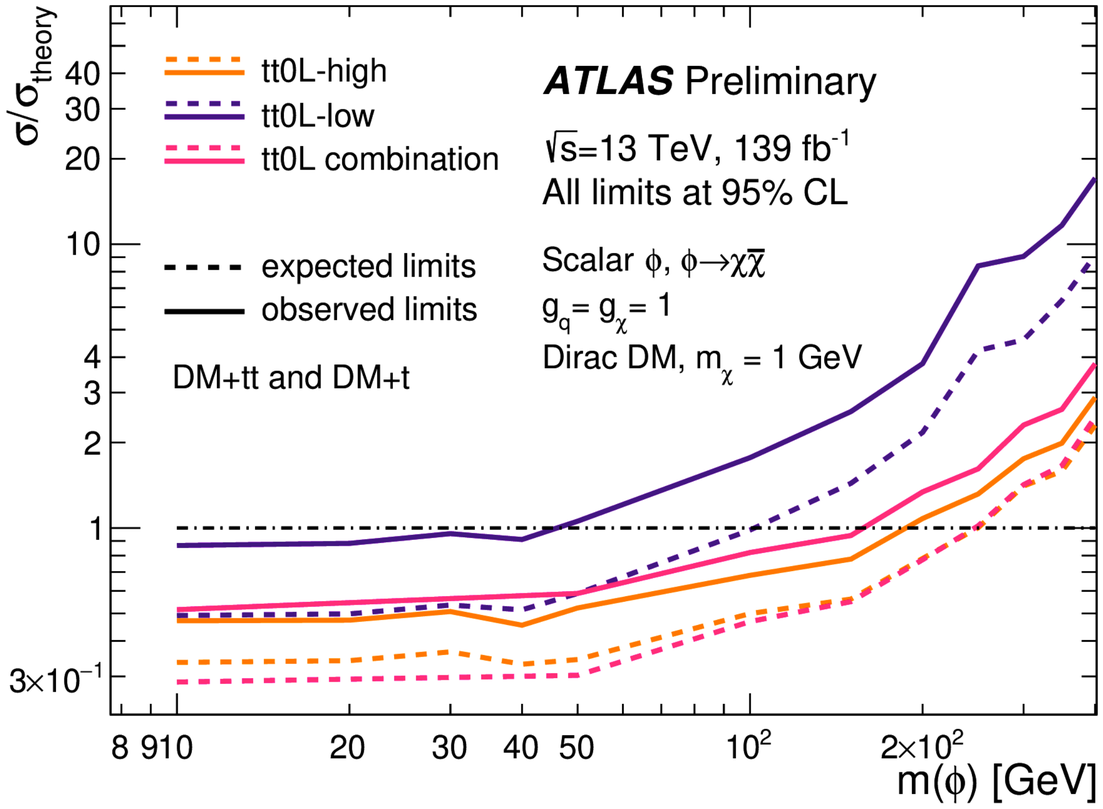
CMS 2015 + 2016 data : BR(H→ inv) < 19% (15% exp)
Full Run-2 data Hinv VBF : BR (H→inv) < 18% (10%)

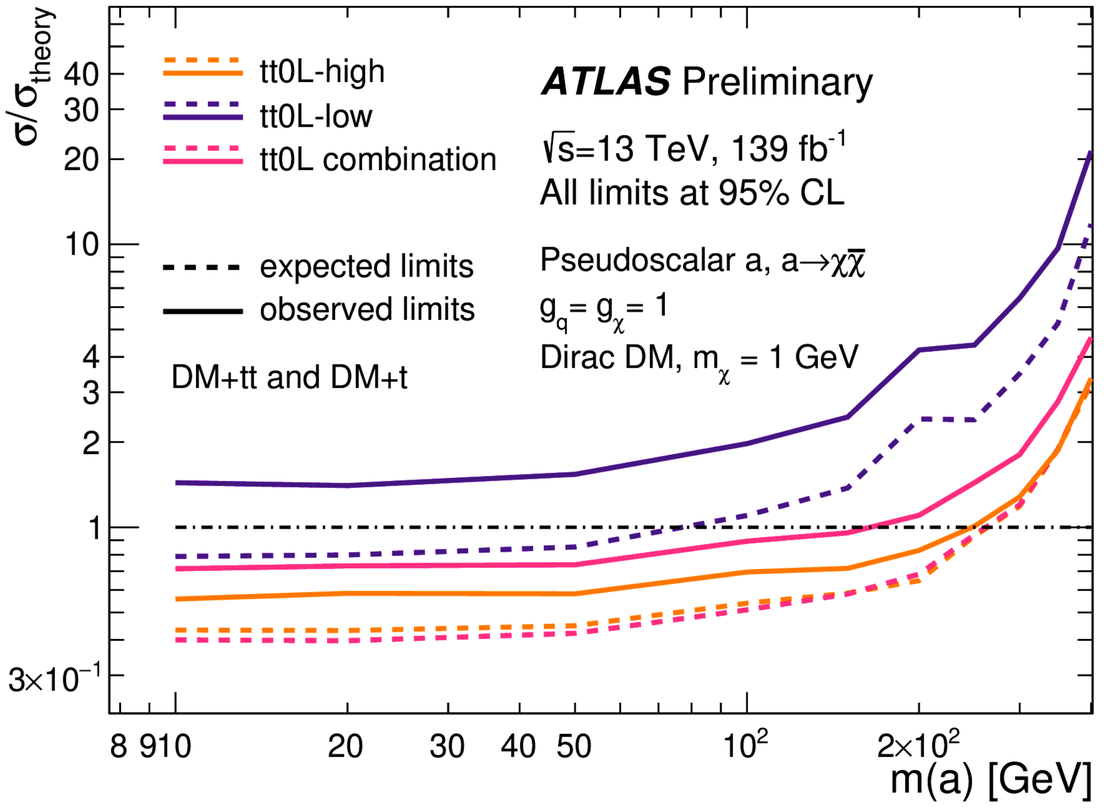
NEW

WIMP +($t/t\bar{t}$) combination

ATLAS: ATLAS-CONF-2022-007

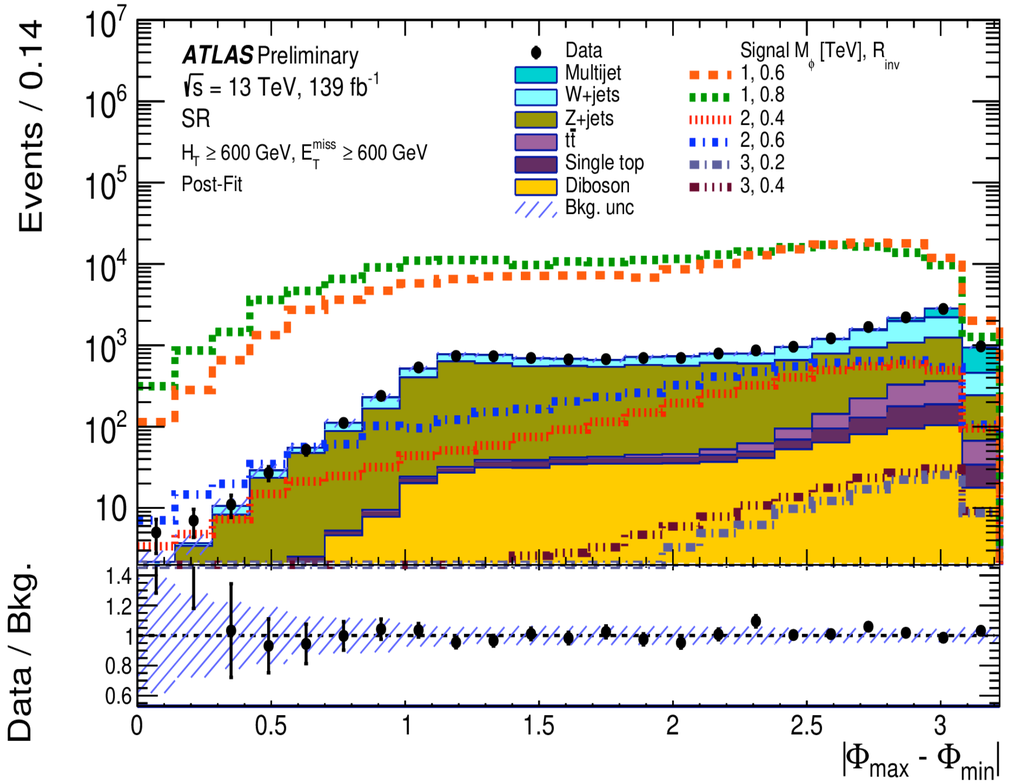
Simplified model

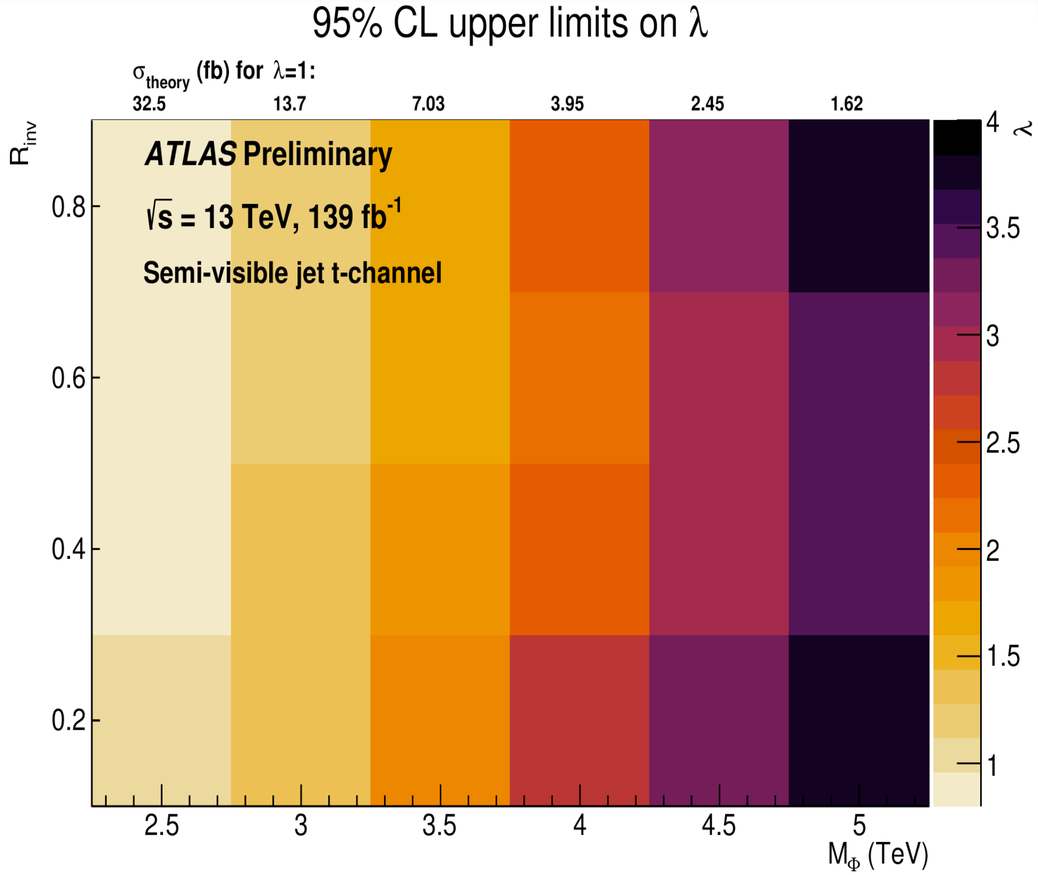




Semi-visible jets

ATLAS: ATLAS-CONF-2022-038





Improvements in Run-3 trigger

ATL-PHYS-PUB-2022-018

- **L1Calo**: Finer-granularity LAr Calorimeter ===> better resolution and background rejection
- **New ATCA**-based Feature Extractors:
  - ✓ eFEX: sophisticated clustering algorithms and isolation ===> Better e, y, tau ID
  - ✓ jFEX : jet reconstruction algorithms ===> jet, ETmiss, had-decaying taus
- **L1Muon**
  - ✓ New Small Wheel (1.3<|η|<2.7) ===> improve fake muons rejection
  - ✓ New RPC detectors: RPC-BIS78 (1.0<|η|<1.3) ===> between barrel and endcap
  - ✓ Coincidences between TGC and NSW/RPC-BIS78. New L1 Muon endcap logic
- **HLT**: Large radius tracking, Faster track reconstruction, Better pile-up suppression, New triggers for unconventional signatures.