Search for Dark Matter with ATLAS and CMS

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On behalf of the ATLAS and CMS collaborations

57th Rencontres de Moriond
LaThuile, Italy
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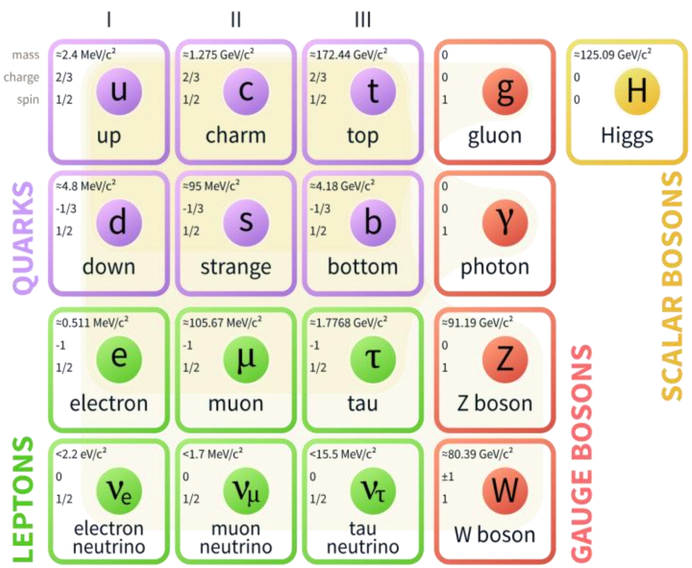
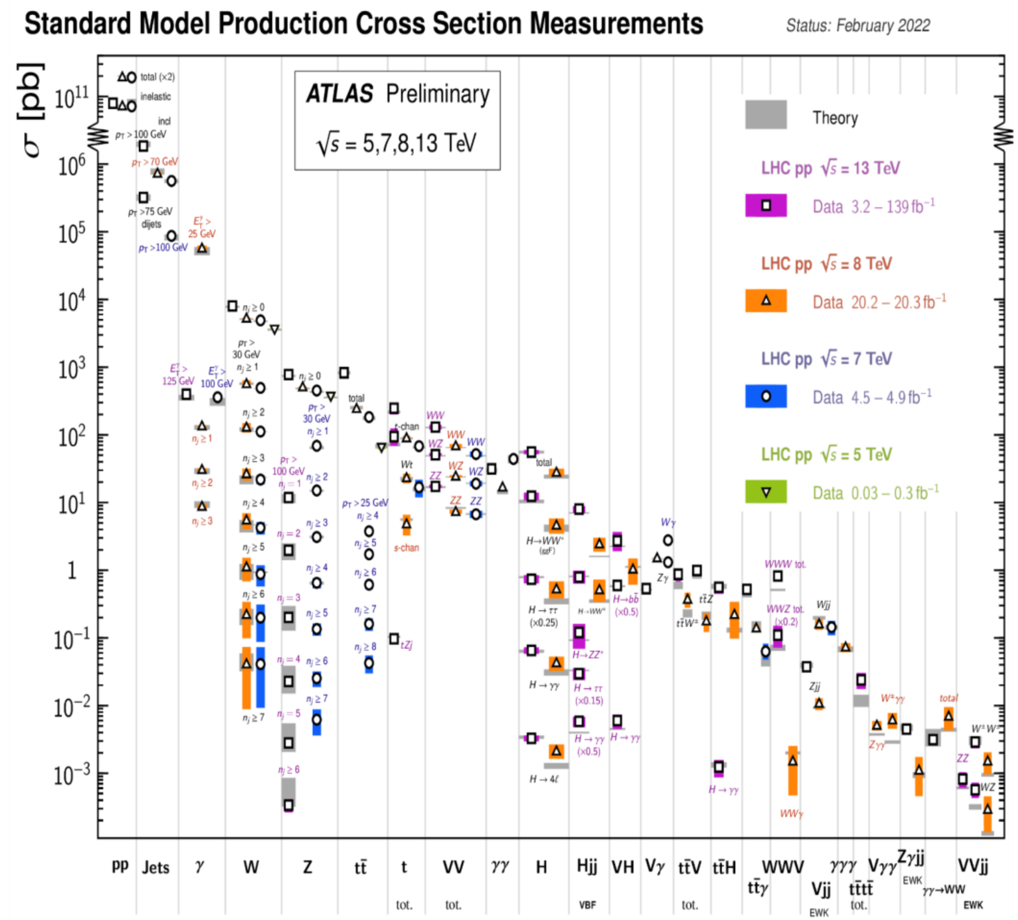
Introduction

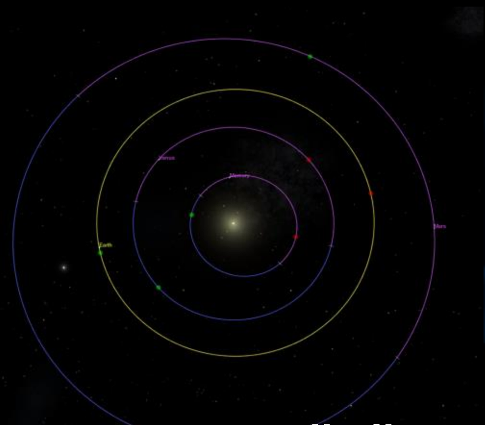


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

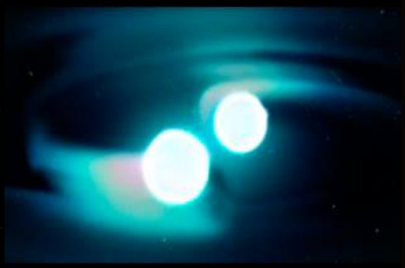
The Standard Model is working as expected



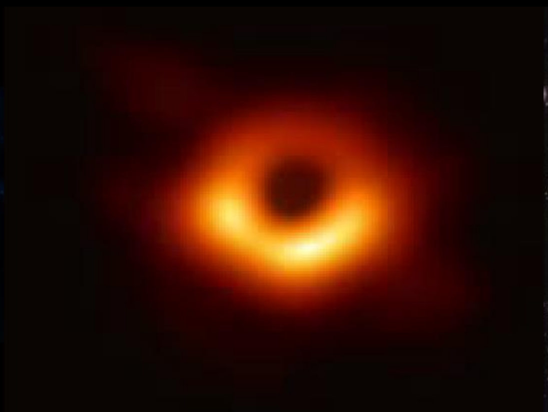
Introduction



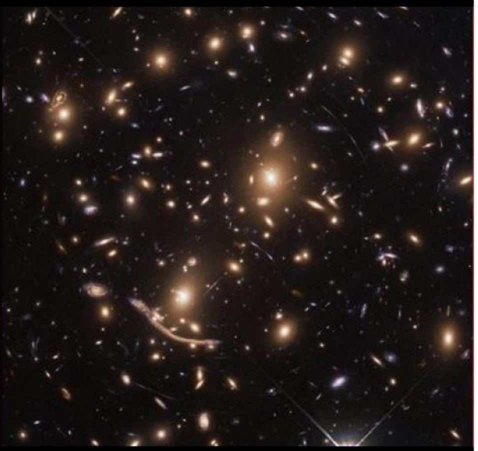
Mercury Perihelion



Gravitational waves



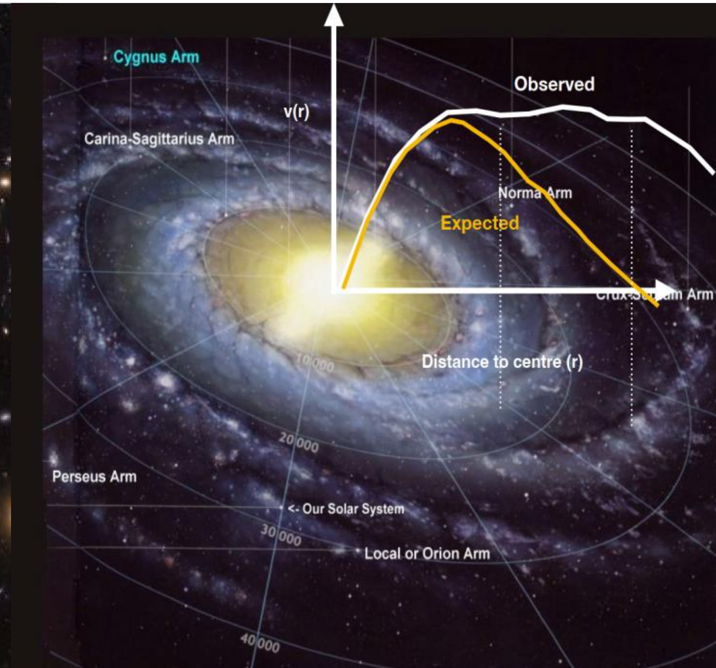
BH horizon



Einstein rings

General gravity seems to work ☺
BUT!

3 Main issues from observations:



Missing mass

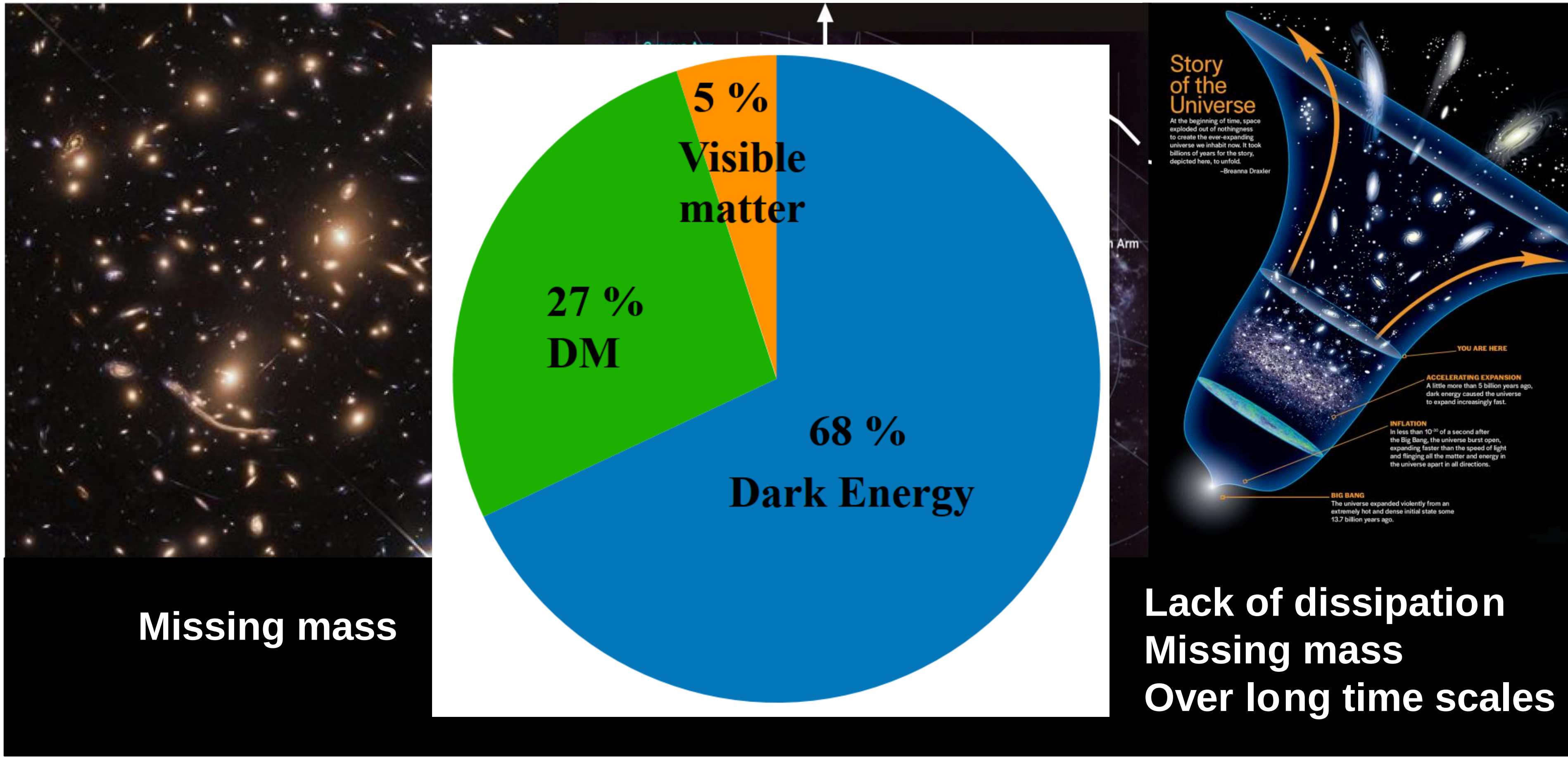
Missing mass
Lack of dissipation

Lack of dissipation
Missing mass
Over long time scales

Missing Mass ⇒**Dark Matter**

"Inferred" through its gravitational interactions

3 Main issues from observations:



Most of the Universe seems to be **dark**!

~**5%** of (SM) interacting matter!

The quest for Dark Matter

The physics that we know cannot explain observations and the formation of the objects that we know $\Rightarrow$ Major paradigm shift

Solutions

- **Modify Gravity** (astro-ph/0403694, astro-ph/0505519). **Hard!**

- **Add Mass/particles**
  - Production/annihilation cross sections need to explain relic density
  - New particles could be light / heavy but with small interactions with SM particles

WIMP hypothesis

- Many models predict such a weakly interacting massive particle
- SM-DM interact via mediator
- Might be produced in high energy pp collisions at the LHC
- Possible searches for both DM particles and mediators

The quest for Dark Matter

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Solutions

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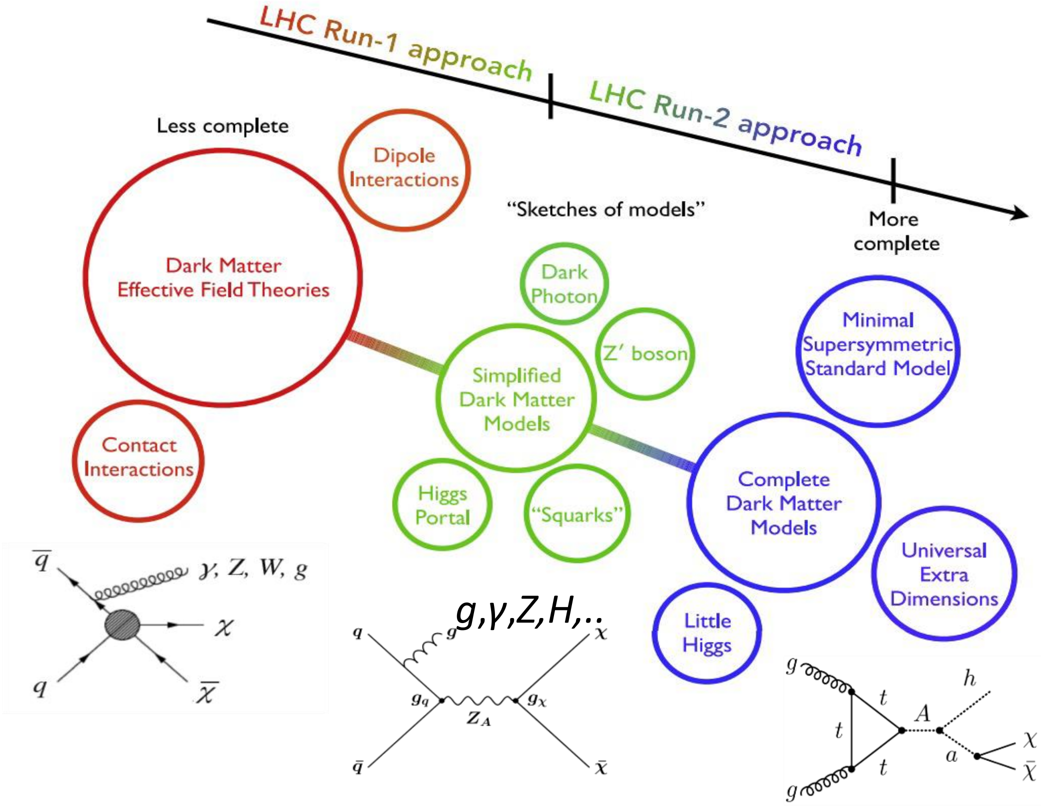
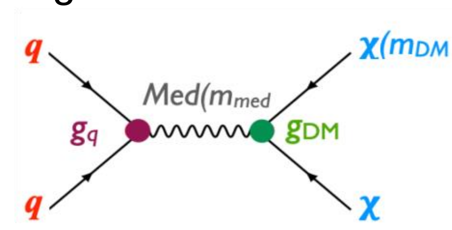
Most models provide some kind of WIMPs

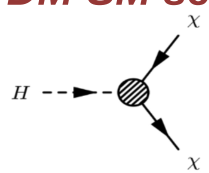


Dark Matter Models

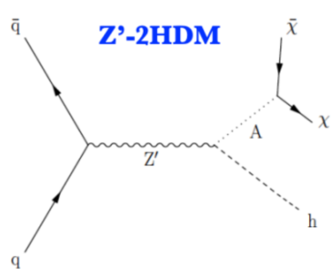
- **Simplified models:**
  - Describe the essential features of a variety of DM signals through a minimal set of parameters. (**LHC DM Forum arXiv:1507.00966**)
  - Parameters:
    - ✓ Mediator: Spin, Mass ***(M_{med}),***
    - ✓ ***DM mass*** ***(M_{DM})***
    - ✓ Mediator coupling to DM ***(g_{DM}),*** quarks ***(g_q),*** leptons ***(g_ℓ)***

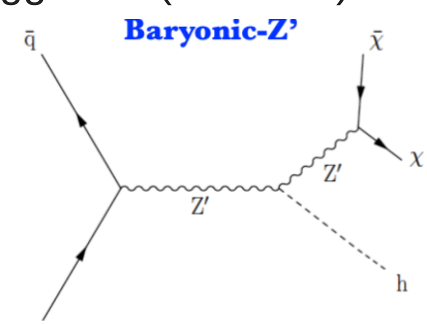


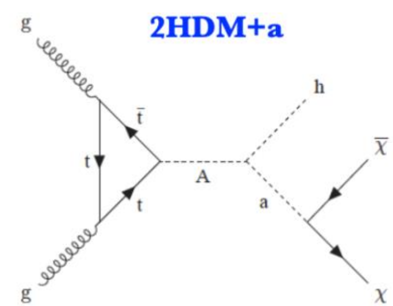
- **Higgs Portal**
  - ***Higgs boson mediates the DM-SM sectors. Parameters: $m\chi$, χ-spin***



- **Extended Higgs sector**
  - More complete models (more free parameters and better sensitivity) involving several Higgs-like (or scalar) bosons 2HDM+a, Dark Higgs,…



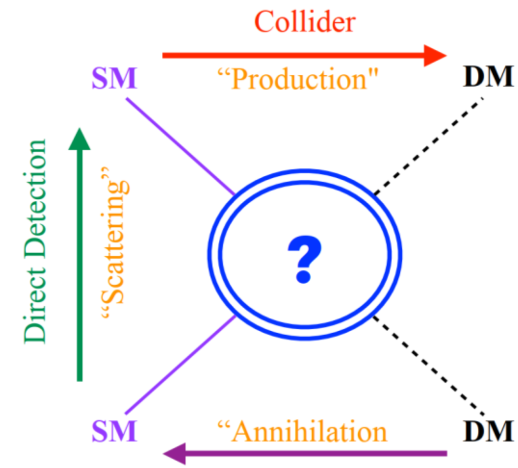




- **SUSY**
  - Provides good candidate for DM: Lightest supersymmetric particle (LSP). But Model-dependent limits.

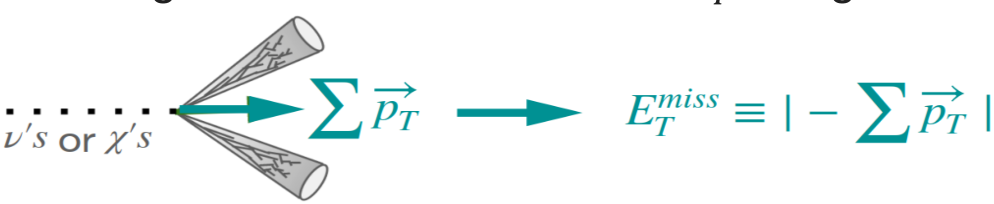
Dark Matter @ the LHC

- Searches at colliders could be complementary to Direct (DD) and indirect (ID) detection
- Favourite candidate: WIMP: heavy (?), stable

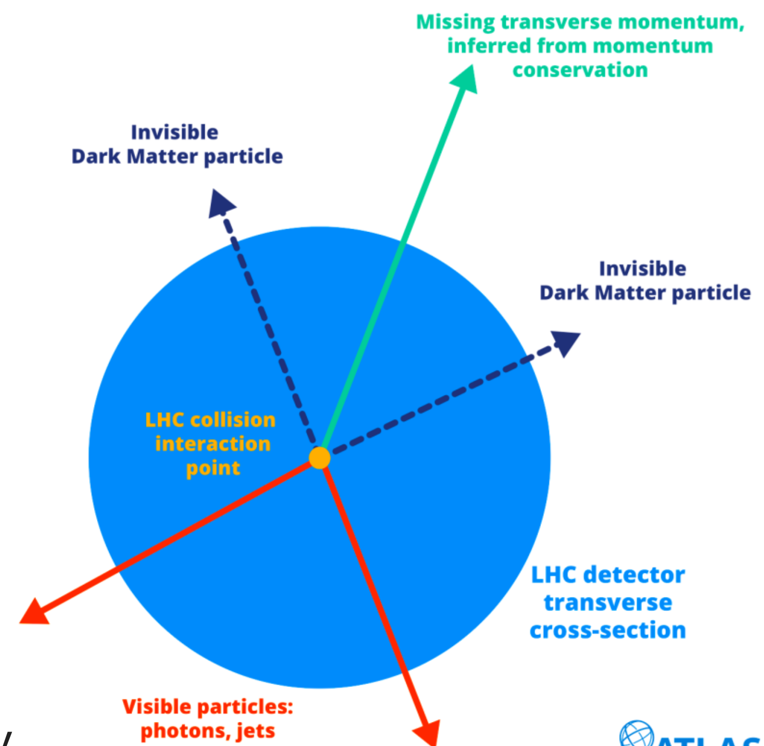


General collider strategy

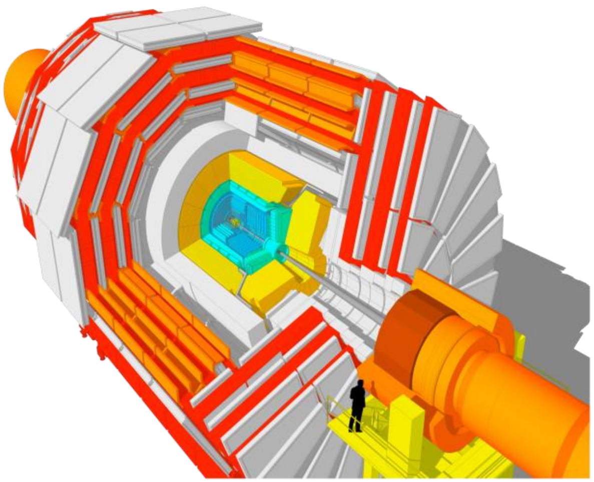
- DM does not interact with the apparatus ⇒ Final states with undetected particles
- Creates a transverse momentum p_T imbalance
- Missing transverse momentum E_T^{miss} signature

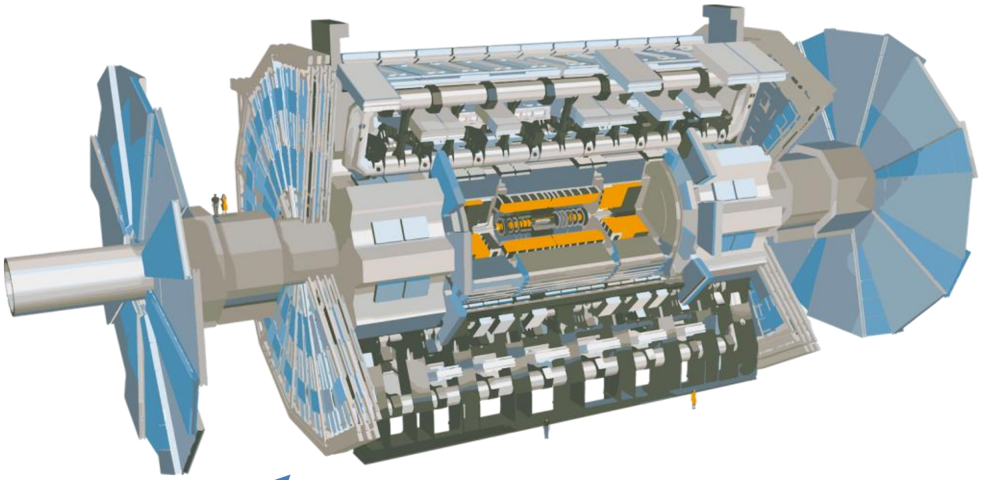


- Precise measurements needed to identify and reject sources of anomalous high E_T^{miss} (noise, beam halo, Energy resolution…)
- SM particles provide trigger and event topology



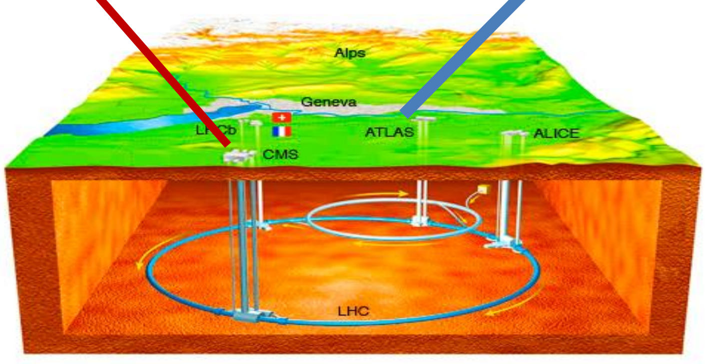
The ATLAS and CMS detectors at the LHC





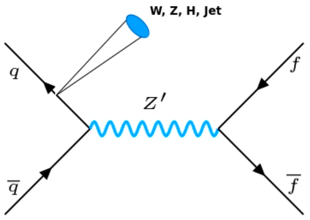
21m long, 15m high, weighs 14000 tons

46m long, 25m high, weighs 7000 tons

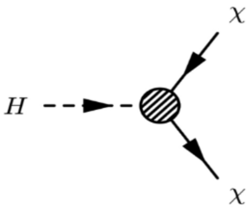


This talk

- Mono-X searches
  - Examples
  - DM summary plots

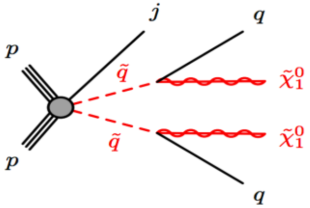


- Higgs portal
  - Invisible



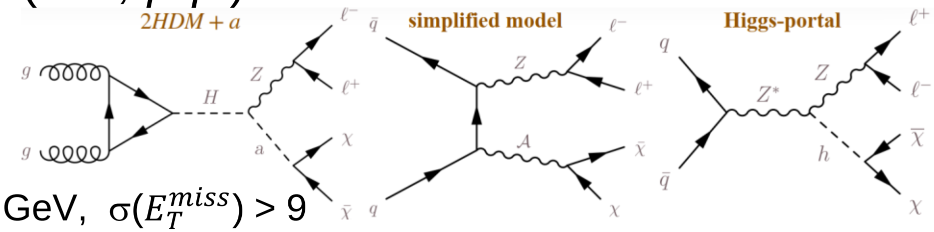
- Non-WIMP searches
  - Semi-visible Higgs decays
  - Dark Higgs
  - Dark jets

- What about SUSY?



Mono-Z: Z($\rightarrow\ell\ell$)+E_T^{miss}

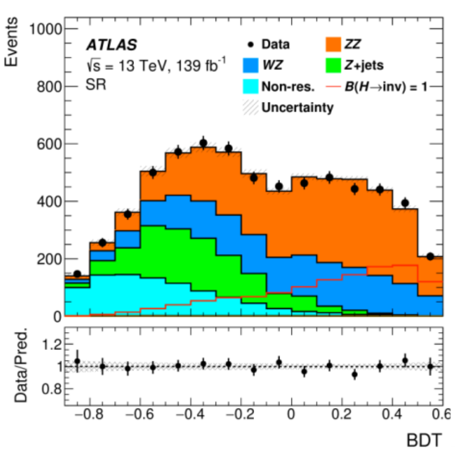
- Final state: Two opposite-charge leptons (e^+e^-, $\mu^+\mu^-$)
- Trigger: 1,2 leptons
- Signal region defined with:
  ✓ATLAS: $m_{\ell\ell} \in$ [76,106] GeV, $\Delta R_{\ell\ell}$ < 1.8. E_T^{miss} > 90 GeV, $\sigma(E_T^{miss})$ > 9
  ✓CMS: similar selections plus $p_T^{\ell\ell}$ > 60 GeV, E_T^{miss} > 80 GeV
- Dominant background: ZZ and WZ
  3ℓ, 4ℓ CRs to constrain WZ/ZZ, eμ CR to constrain tt, WW

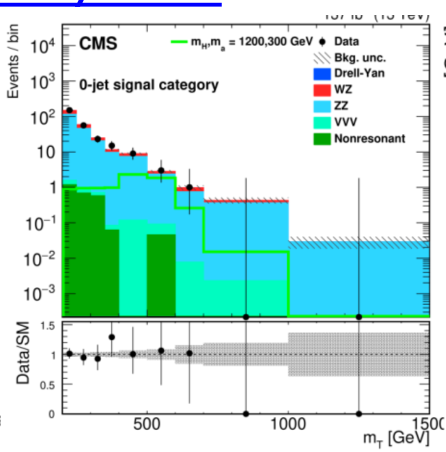


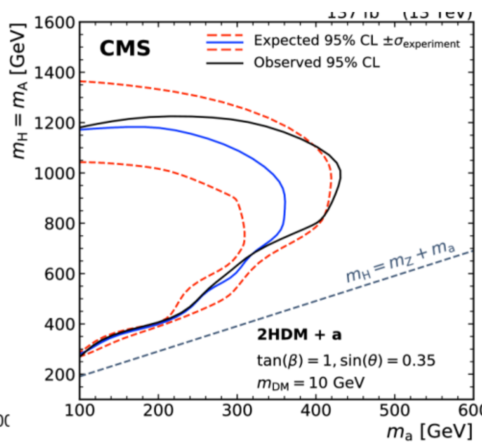
Interpretation in '2*HDM+a'*, simplified DM model (spin-1 mediator), Higgs-portal

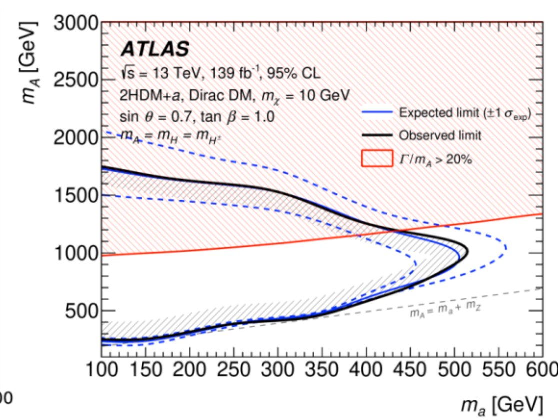
Phys. Lett. B 829 (2022) 137066

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



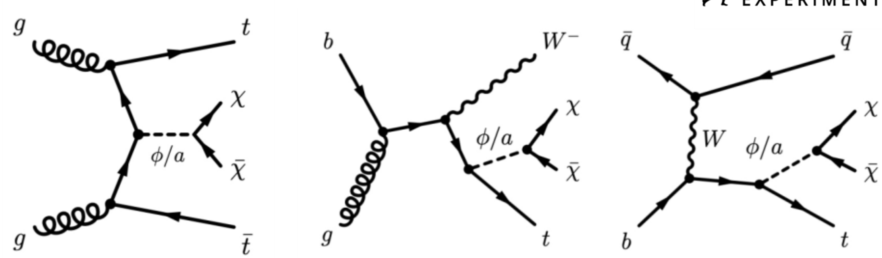






tt, tW, tq + E_T^{miss}

- Focus on DM with spin-0 mediator
- Combination of 0, 1, & 2 lepton searches
- Dominant background: tt, W/Z+jets
- Signal Region:
  0,1 *e / μ, 1 b-jet,* E_T^{miss} > 250 GeV, large-R jets with W-tagging or two small-R jets for hadronic W candidate
- Discriminant: depend on target signature: mT, BDT…
- Set limits on σ/σ_{theory} vs. $m_{\phi(a)}$

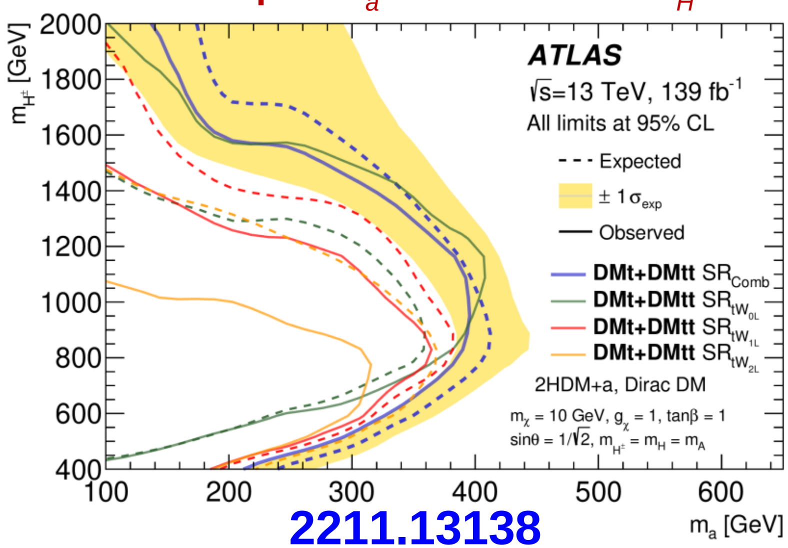


Invisible Higgs interpretation

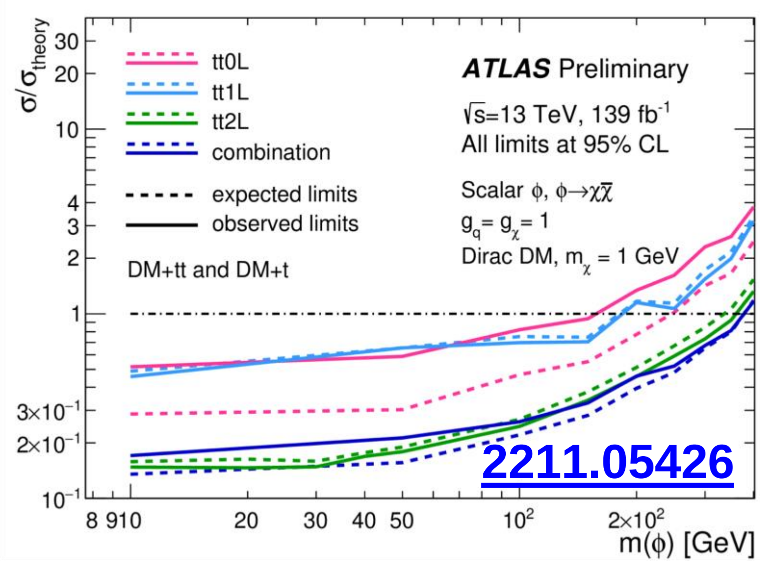
Analysis	Best fit $\mathcal{B}_{H\to inv}$	Observed upper limit	Expected upper limit
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$
tt2L	$-0.09^{+0.22}_{-0.20}$	0.39	$0.42^{+0.18}_{-0.12}$
$t\bar{t}H$ comb.	$0.08^{+0.16}_{-0.15}$	0.40	$0.30^{+0.13}_{-0.09}$

Model excluded up to m_a = 370 GeV and $m_{H^\pm}$ = 1500 GeV

tW + DM



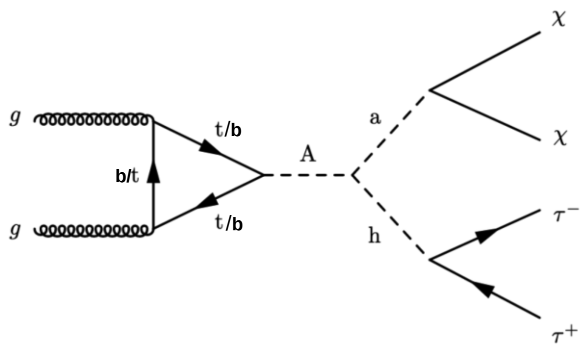
[2211.13138](https://arxiv.org/abs/2211.13138)

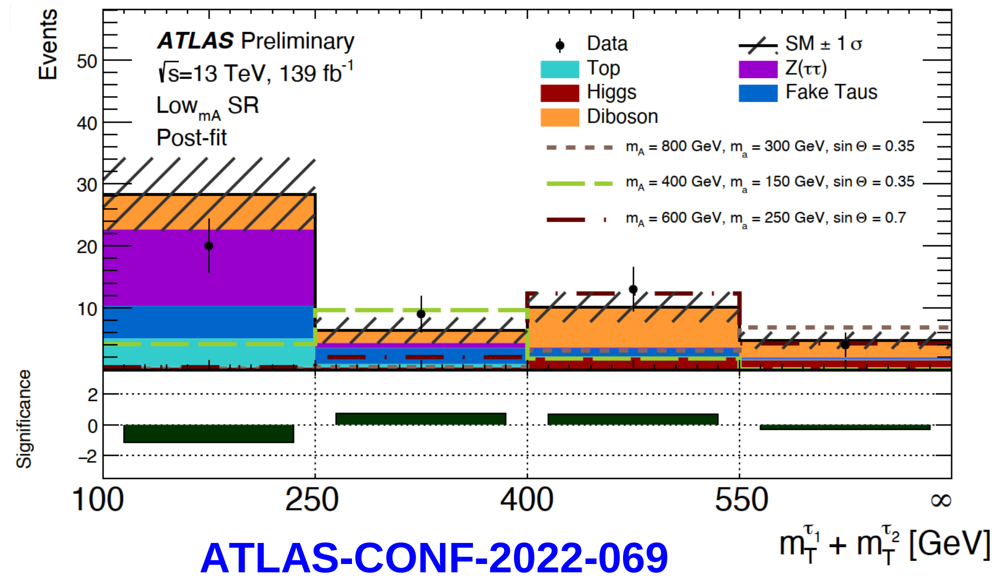


[2211.05426](https://arxiv.org/abs/2211.05426)

tt + DM

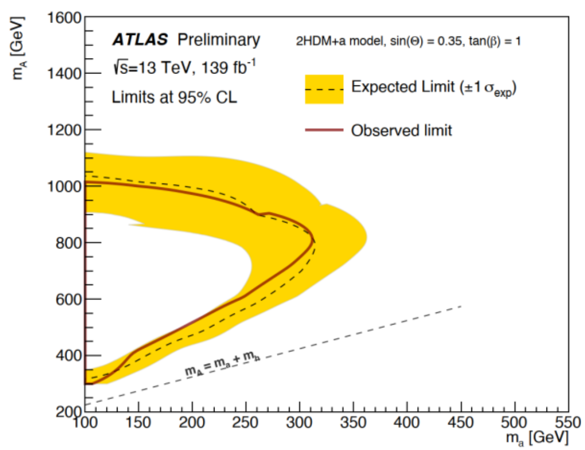
Mono-Higgs: h($\rightarrow\tau_{had}\tau_{had}$) + E_T^{miss}

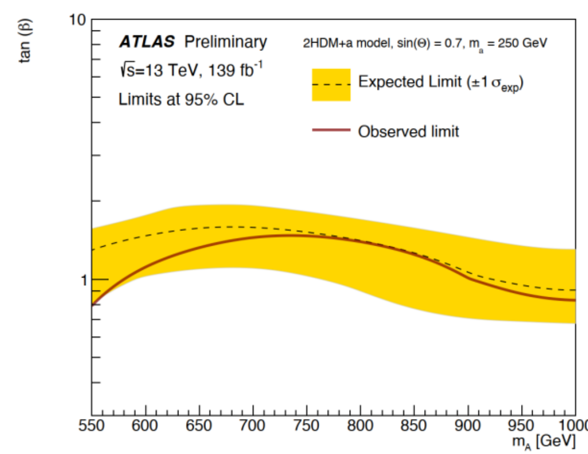




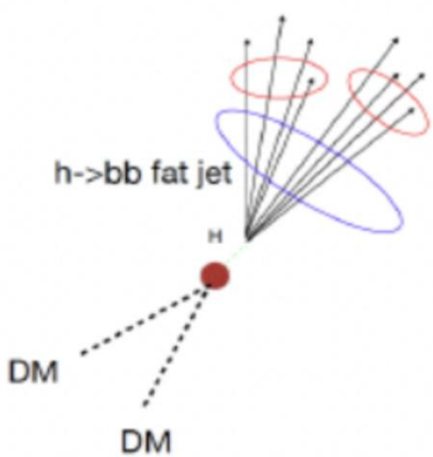
ATLAS-CONF-2022-069

- di- τ_{had} + E_T^{miss} trigger
- Dominant background: VV, VH, tt, V+jets
- Lepton & b-jet veto
- Data driven for fake factor jet $\rightarrow\tau_{had}$
- Discriminant variable: Sum of τ -lepton transverse masses
- Strong dependance on mA
- Model-independent limits on BSM signal for every bin, σ_{vis} < 0.04 − 0.08 fb.





Mono-Higgs searches

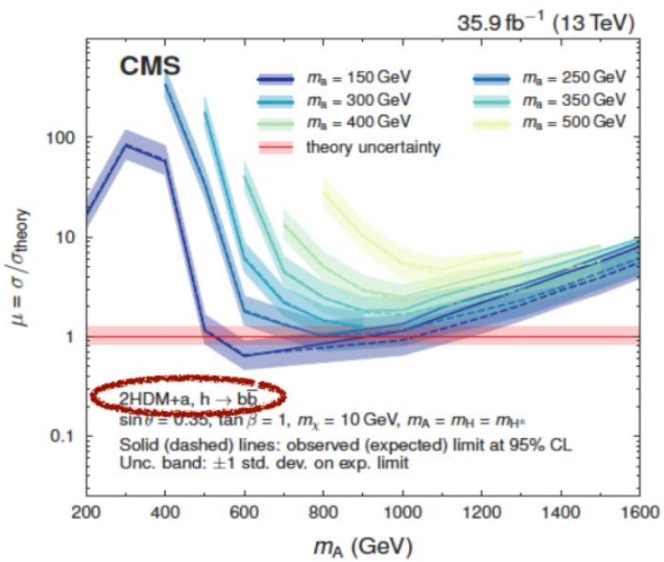


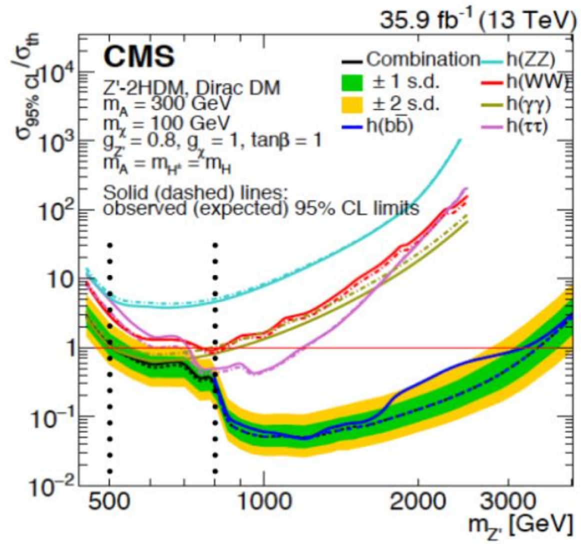
H→bb	most sensitive
2HDM+a	CA15 jets
Baryonic-Z’	CA15 jets
Z’-2HDM	AK8 jets

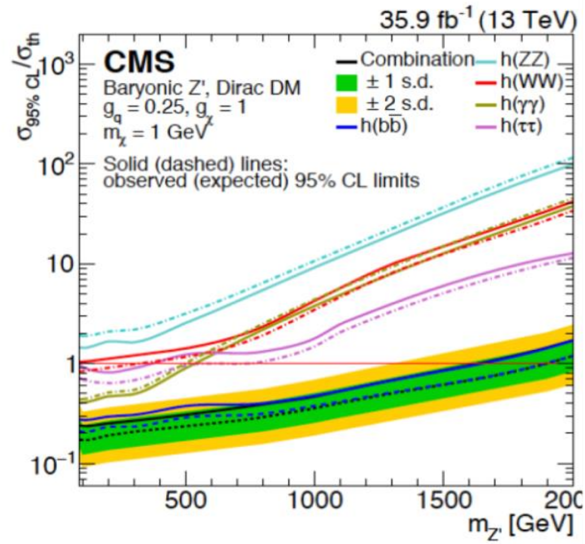
Decay channel	Final state or category
$h \rightarrow bb$	AK8 jet (Z'-2HDM) CA15 jet (Baryonic Z')
$h \rightarrow \gamma\gamma$	$p_T^{miss} \in 50$–$130\,GeV$ $p_T^{miss} > 130\,GeV$
$h \rightarrow \tau\tau$	$\tau_h\tau_h$ $\mu\tau_h$ $e\tau_h$
$h \rightarrow WW$	$e\nu\mu\nu$
$h \rightarrow ZZ$	$4e$ 4μ $2e2\mu$

JHEP03(2020)025

Final states orthogonal to each other



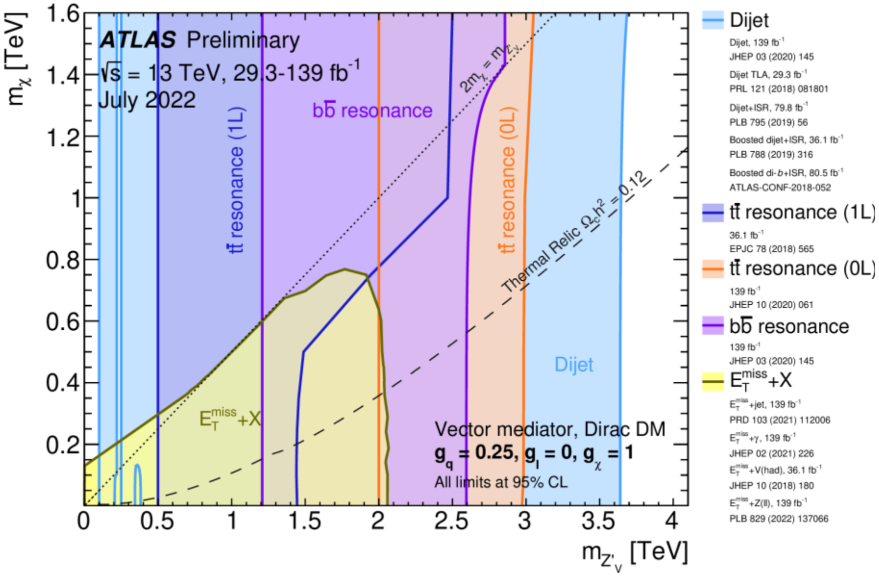


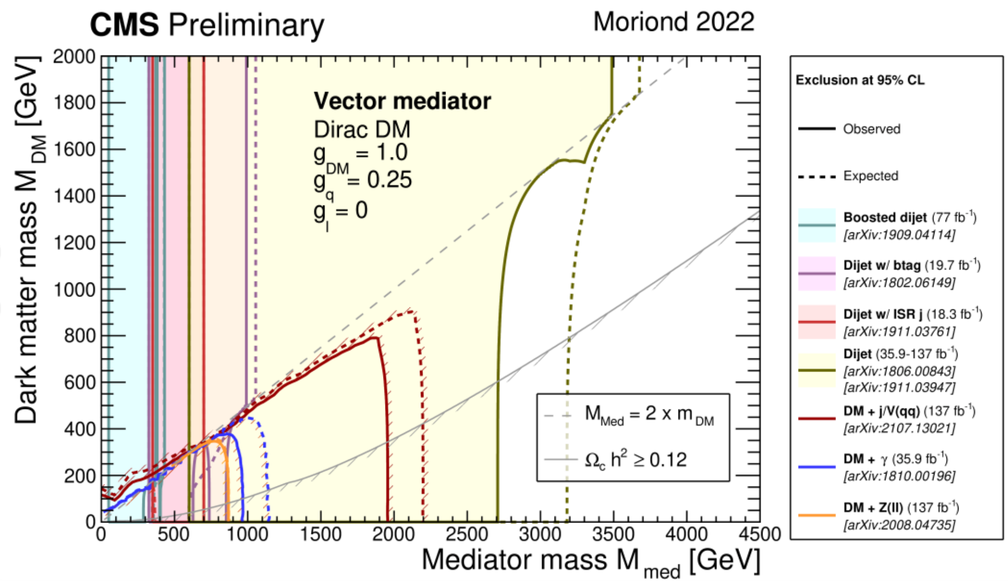


DM summary

ATLAS DM Summary: **[ATL-PHYS-PUB-2022-036]**
CMS DM Summary: **[Exotica Summary plots]**

Vector Mediator in Simplified Models

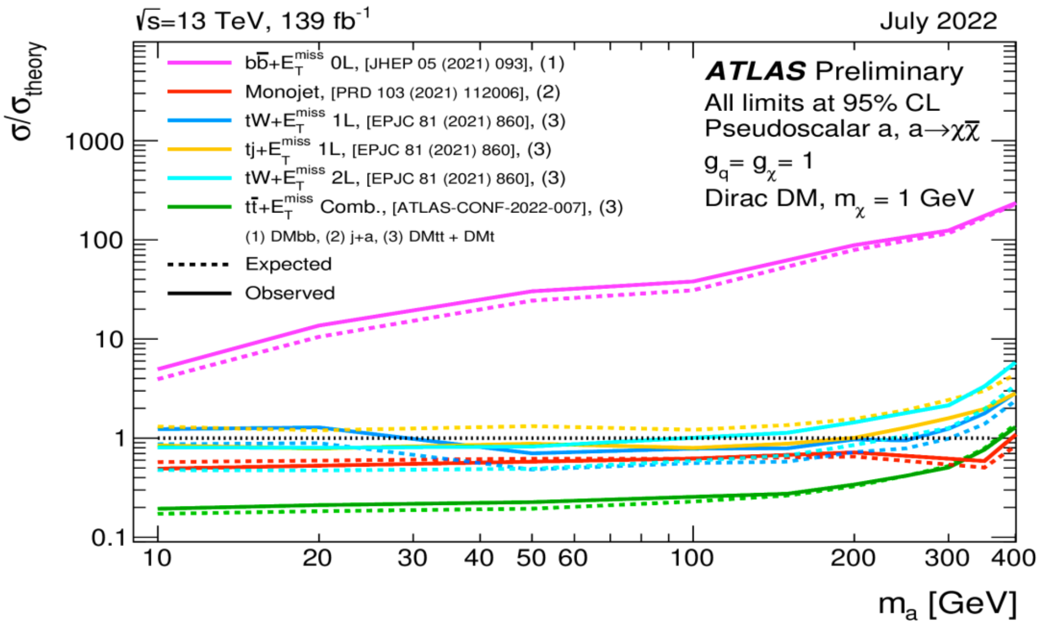


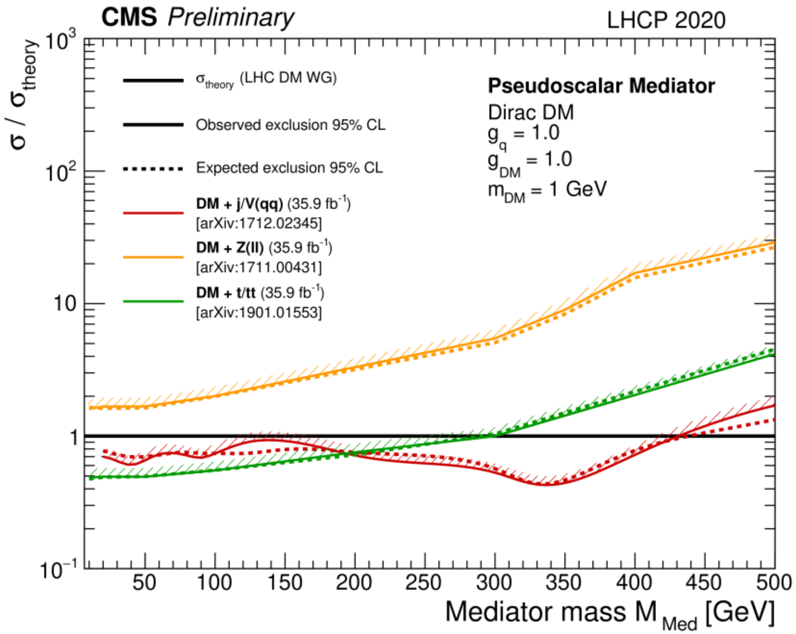


Exclusions depend on coupling parameters
Mediator searches in dijet resonances largely dominant.

DM summary

Pseudo-Scalar Mediator in Simplified Models



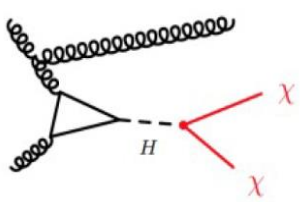


Combination of H → *invisible* searches

- Higgs boson as a mediator between SM and DM sectors
- SM BR(h→inv) = 0.1% from h → ZZ*→4ν
- Invisible Higgs decay would increase BR(h→inv) w-r-t SM predictions

- Assume SM Higgs production, with different event topologies

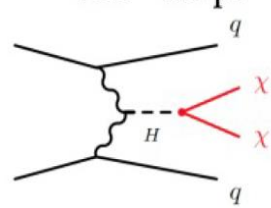
ggF ~49 pb



Select on high pT ISR jet

[Phys. Rev. D 103, 112006 (2021)](#)

VBF ~3.8 pb



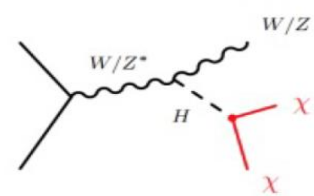
Select on forward jets in opposite hemispheres

[JHEP 08 (2022) 104](#)

Also VBF + γ + E_t^{miss}

[Eur. Phys. J. C82 (2022) 105](#)

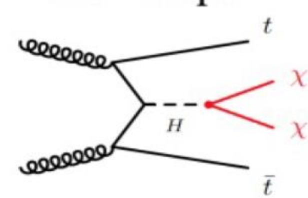
VH ~2.3 pb



Select on lep. or had. decay of Z or W

[Phys. Lett. B 829 (2022) 137066](#)

ttH ~0.5 pb

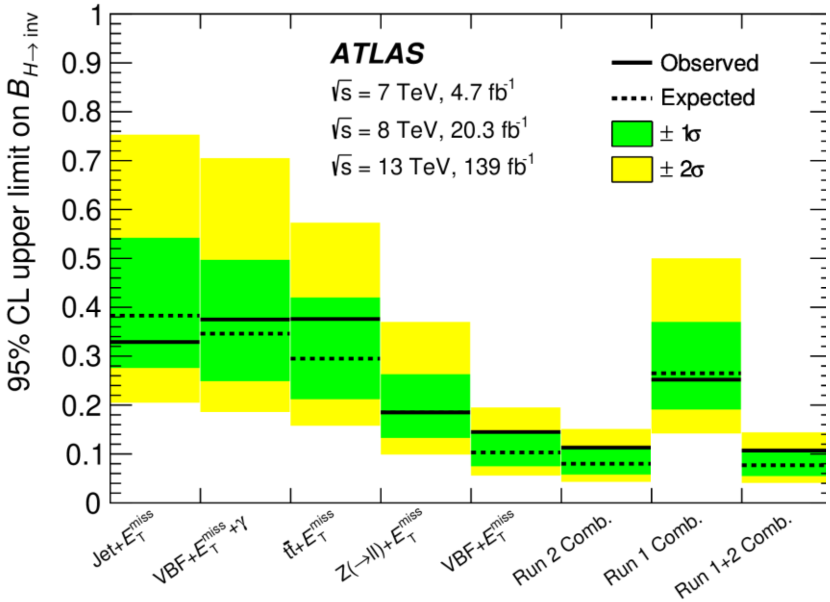


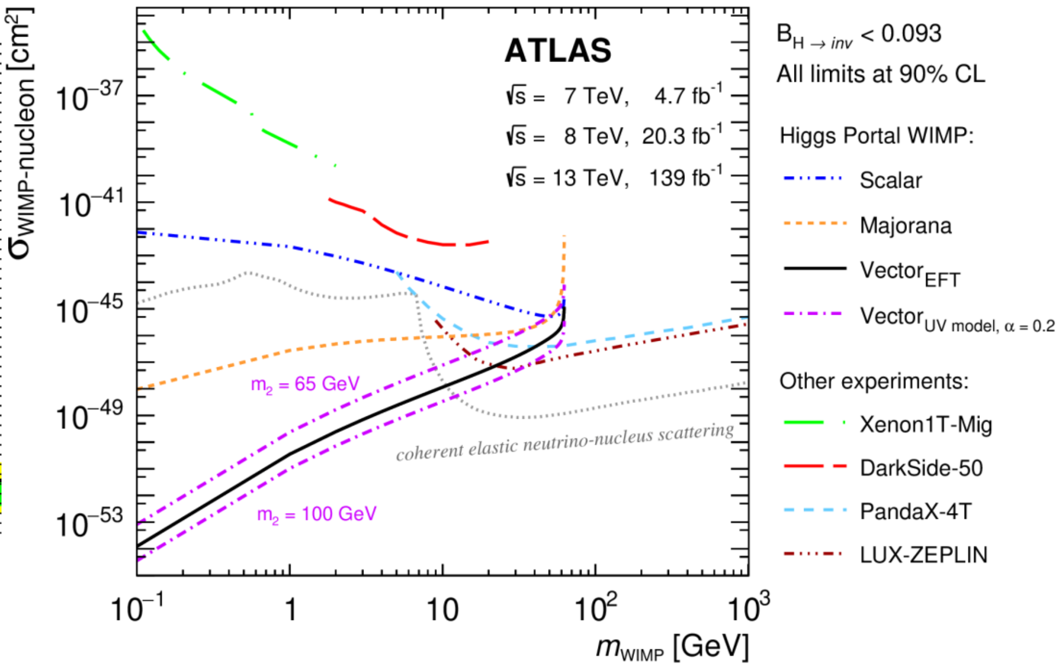
Select on $t\bar{t}$

[2211.05426](#)

Combination of H → *invisible* searches

arXiv:2301.1073





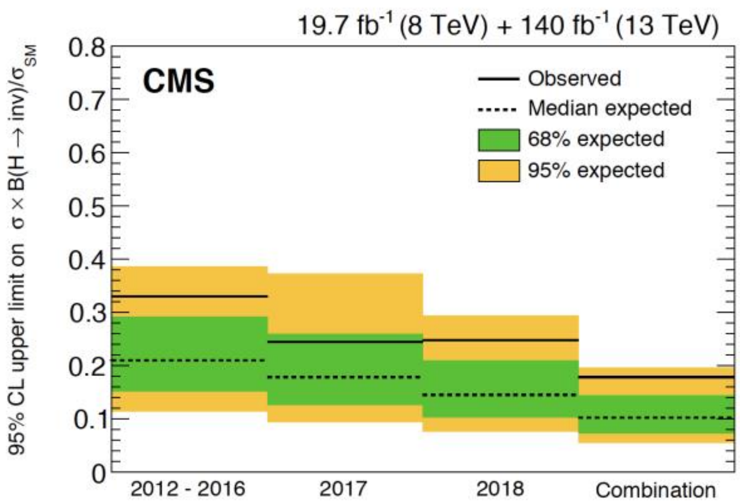
- Full Run-2 H→inv combination BR(H→inv) < 0.107 (0.077) @ 95% C.L

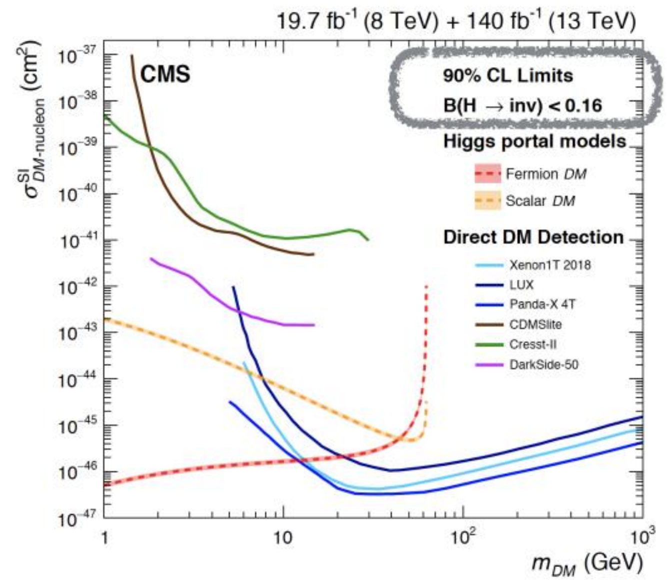
- Interpret in **Higgs portal** models to set limits on WIMP-nucleon cross section at 90% CL
- Complementary to direct searches

Combination of H → *invisible* searches

PRD.105.092007

- Combination of Run 1 and Run2
  - **95% CL** upper limit on the in **BR (H→invisible) < 0.18 (0.10)**

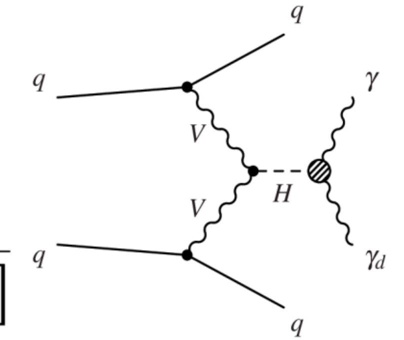




Constraints are compatible with SM H → invisible branching ratio.

Constraints on spin independent DM-neucleon cross-section

Dark photon in VBF $H \rightarrow \gamma + E_T^{miss}$



- Final state: isolated γ, E_T^{miss}, 2 forward jets
- Trigger: single γ (ATLAS, CMS), E_T^{miss} (CMS)
- Dominant Background: $W(\rightarrow \ell\nu)(+\gamma)$+*jets*, $Z(\rightarrow \nu\nu)(+\gamma)$+*jets*
- Discriminant Variable:

$$m_T(\gamma, E_T^{miss}) = \sqrt{2 p_T^{\gamma} E_T^{miss} \left[1 - \cos(\phi_\gamma - \phi_{E_T^{miss}})\right]}$$

- ATLAS/CMS searched for $\gamma+\gamma_d$ decay *from both SM Higgs or BSM Higgs-like bosons.*

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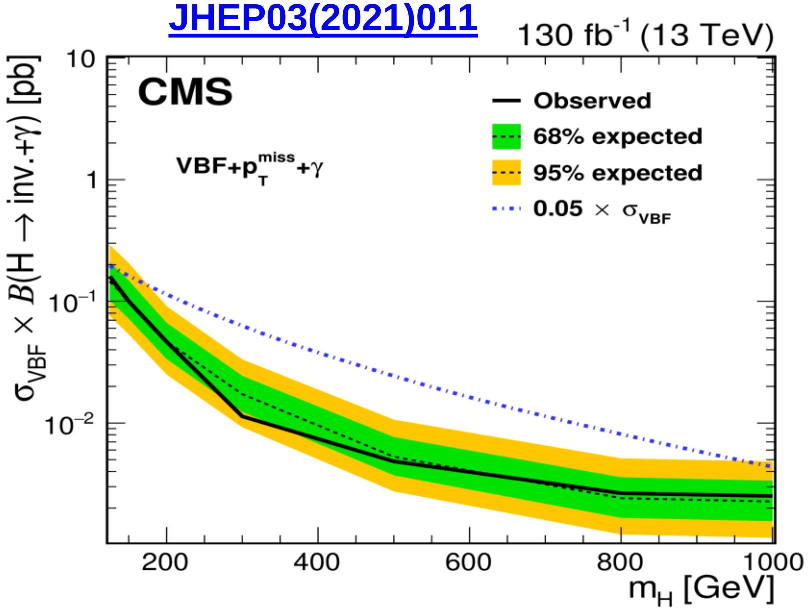

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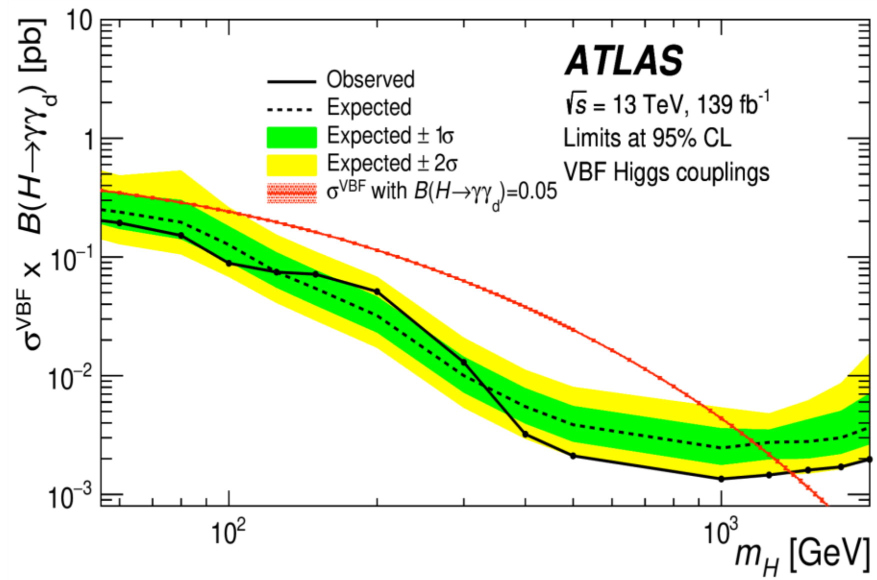
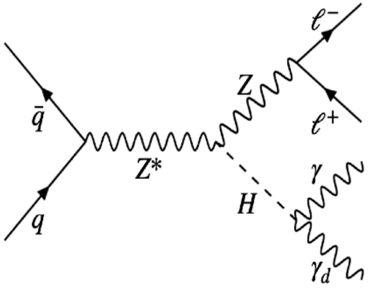
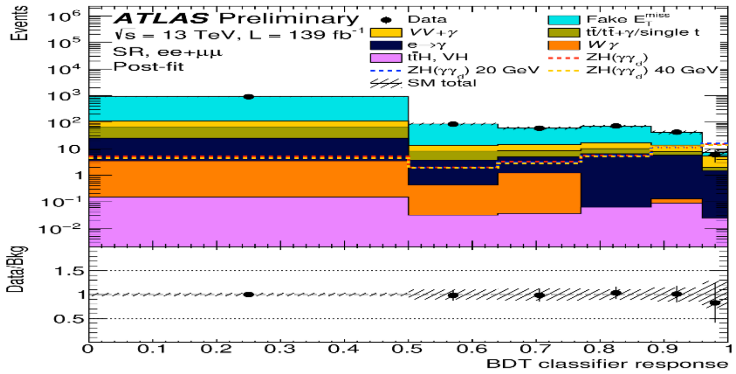
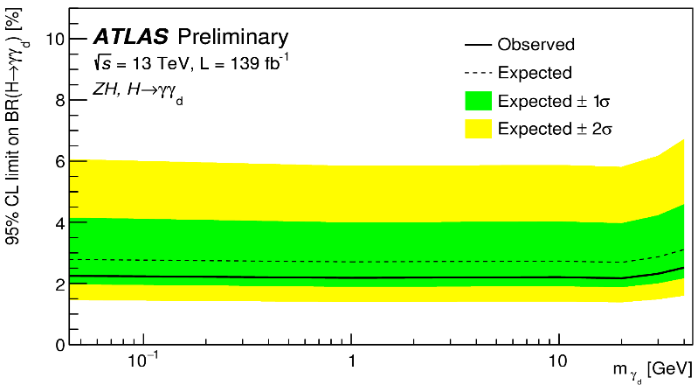


Dark photons in $\ell^+\ell^- + \gamma + E_T^{miss}$

- Signal from SM ZH, Z→ $\ell^+\ell^-$, H→ $\gamma\gamma_d$, undetected dark photon → E_T^{miss}
- Background estimation:
  - Fake E_T^{miss}: Zγ+jets, Z+jets. Data driven
  - e → γ: fake photon. VV, VVV. Data driven fake factor
  - top, VVγ, Wy, Higgs. MC estimated with validations in CR
- Binned BDT classifier to enhance signal sensitivity







2212.09649

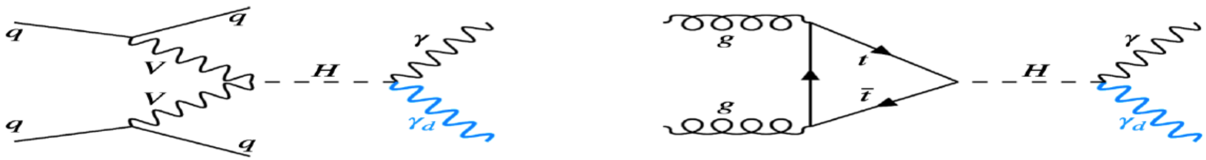
The observed (expected) upper limits on BR(H→ $\gamma\gamma_d$) are at the level of **2.3% (2.8%)** for massless γ_d, and **2.5% (3.1%)** for mass (γ_d) of 40 GeV.

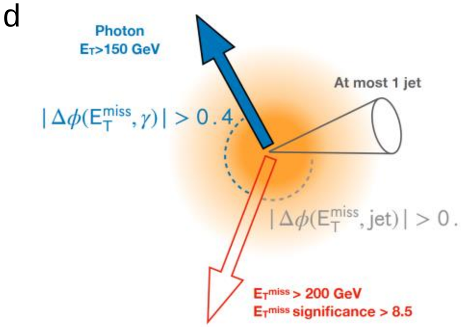
The first limit on low mass γ_d from H→ $\gamma\gamma_d$ at the LHC

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

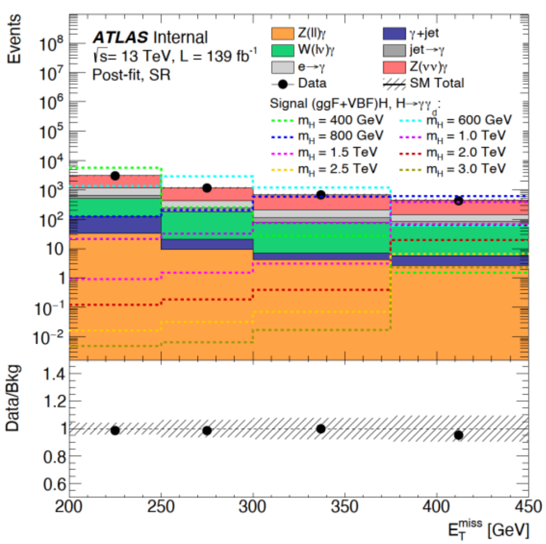
More searches for dark photons

- **What about BSM Higgs**? ⇒ Searches for high-mass $\gamma + E_T^{miss}$ resonances
- Final state with ggF and VBF production modes, with H→ $\gamma\gamma_d$





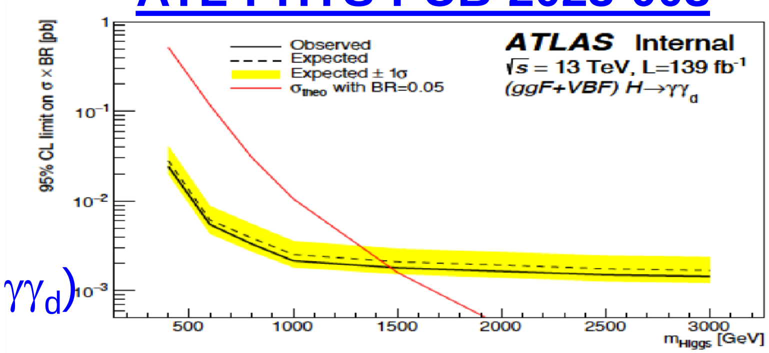
- E_T^{miss} trigger limits the reach for low masses.
- Analysis optimized in E_T^{miss} bins defining 4 SR for maximum sensitivity
- Main background: Z(→νν)γ, W(→lν) γ, Fake γ from e or jets
- Independents results for ggF (first at the LHC) and VBF, + combination



No excess w-r-t SM

limits on σ x BR(H→ $\gamma\gamma_d$)

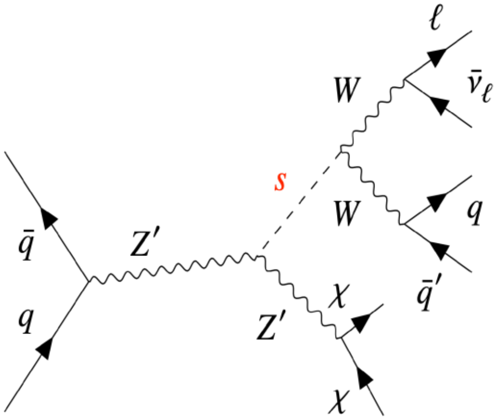
ATL-PHYS-PUB-2023-003



Improved results w-r-t existing VBF analysis

Most stringent exclusion at high mass $\gamma + E_T^{miss}$ resonances

Dark Higgs Models: $s(W^+W^-) + E_T^{miss}$

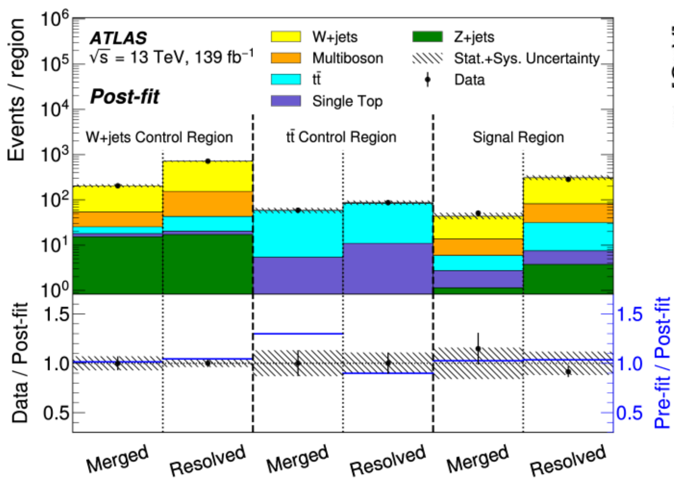


- Signature $s \rightarrow WW \rightarrow \ell\nu$+qq
- E_T^{miss} or single trigger
- Discriminant variable m_s^{min}
- Dominant Background:
- W+jets: Constra*ined using a CR with large* $\Delta\phi(W_{had}, \ell)$
- ttbar: Constrained using a CR with a CR 2 b-quarks jets

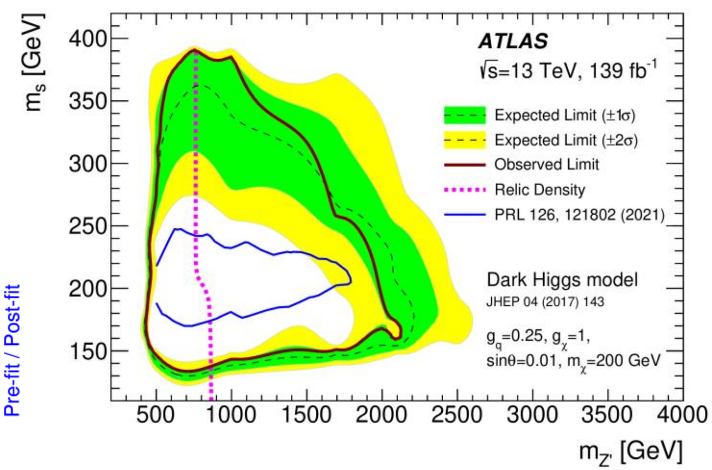
[arXiv:2211.07175](https://arxiv.org/abs/2211.07175)

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 *> 200 GeV*   At least 1 large-R jet



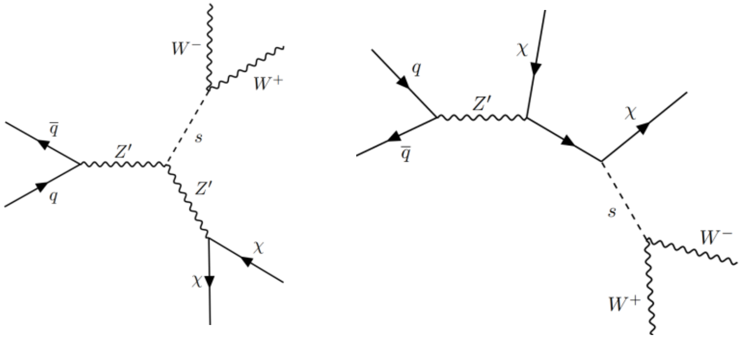
Dark Higgs model limit in the ($m_{Z'}$, m_s) plane.



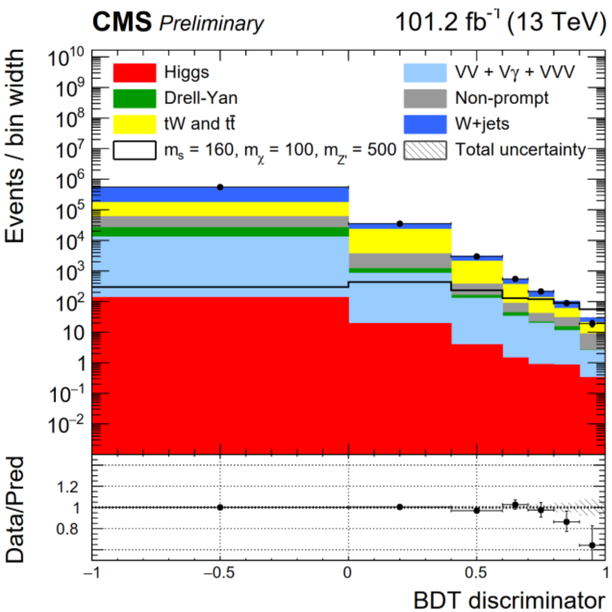
Dark Higgs Models: $s(W^+W^-) + E_T^{miss}$

- Signature $s \to WW \to \ell\nu + \ell\nu$ / $\ell\nu$+qq
- Discriminant variable:
- Dilepton:

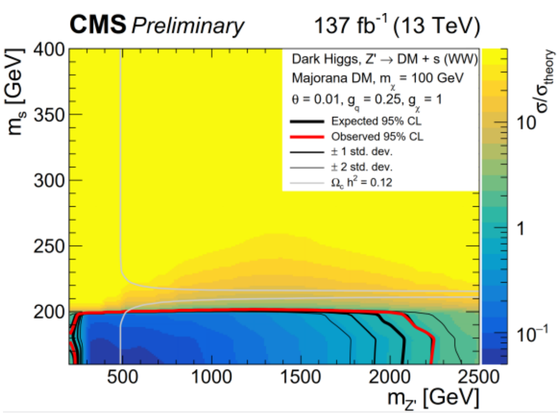
$$m_T^{\ell\,\min, p_T^{\rm miss}} = \sqrt{2 p_T^{\ell\,\min} p_T^{\rm miss} \left[1 - \cos\Delta\phi(\vec{p}_T^{\,\ell\,\min}, \vec{p}_T^{\,\rm miss})\right]},$$

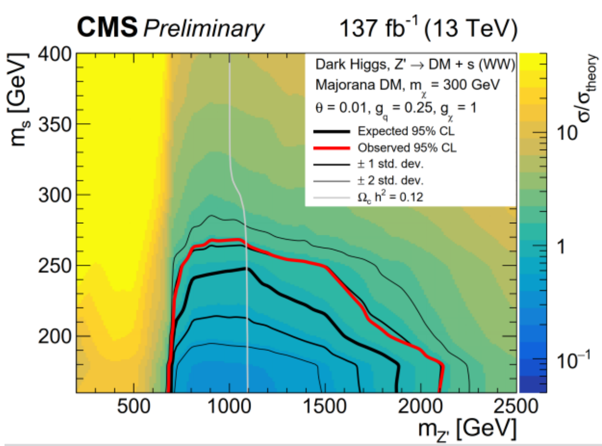


- Semi-leptonic:
- BDT based on `13 variables with S/B max. sensitivity
- Background CR regions for ttbar/tW, WW, DY, W+jets
- SR for Semi-leptonic optimized for 2016 and 2017-18



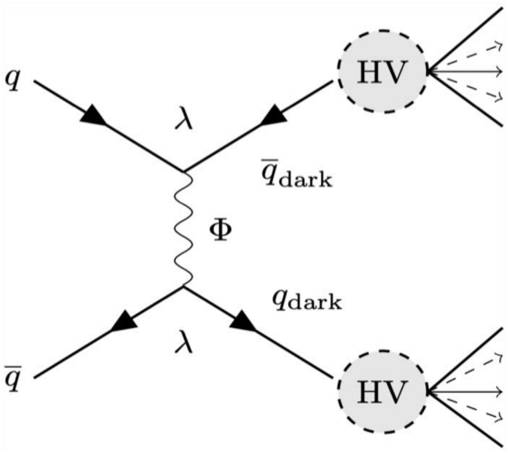
CMS-PAS-EXO-21-012



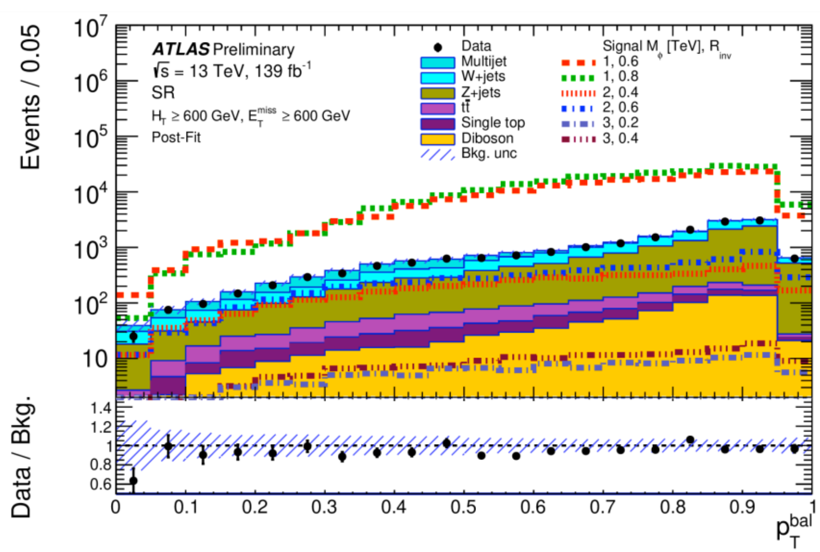


Semi-Visible jets

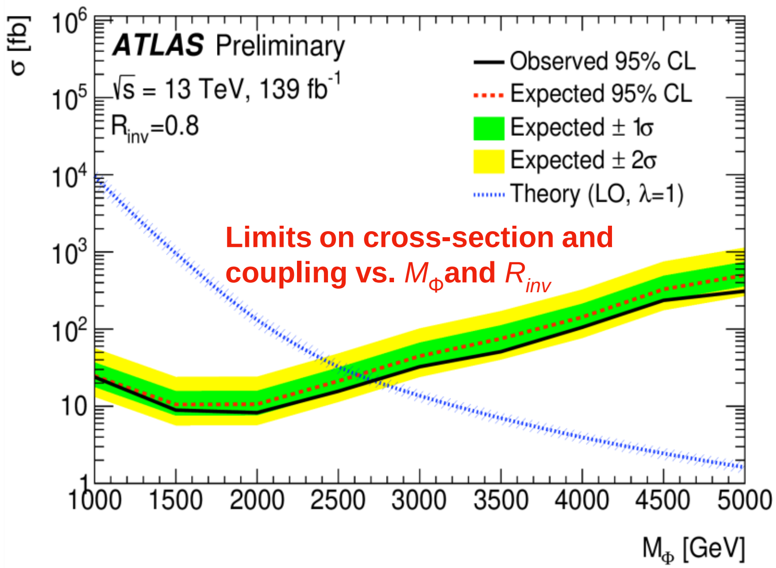
- Signature $s \rightarrow WW \rightarrow \ell\nu + \ell\nu$ / $\ell\nu$+qq
- Signal Region
  - 2 semi-visible jets (SVJs), Leading/sub-leading jet p_T> 150/30 GeV
  - ≥1 additional jet to suppress multijet background
  - Veto e, μ, and ≥2 b-tags to suppress other backgrounds
  - High $H_T = \Sigma_{jets} p_T$ and high E_T^{miss} > 600 GeV close to a jet
- Discriminant variables: p_T balance and $|\Phi_{max} - \Phi_{min}|$



Exclusion of mediator masses up to 2.7 TeV

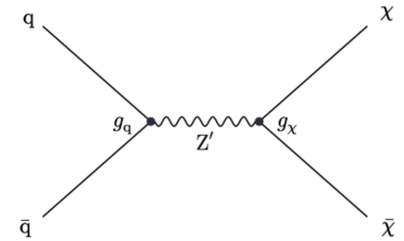


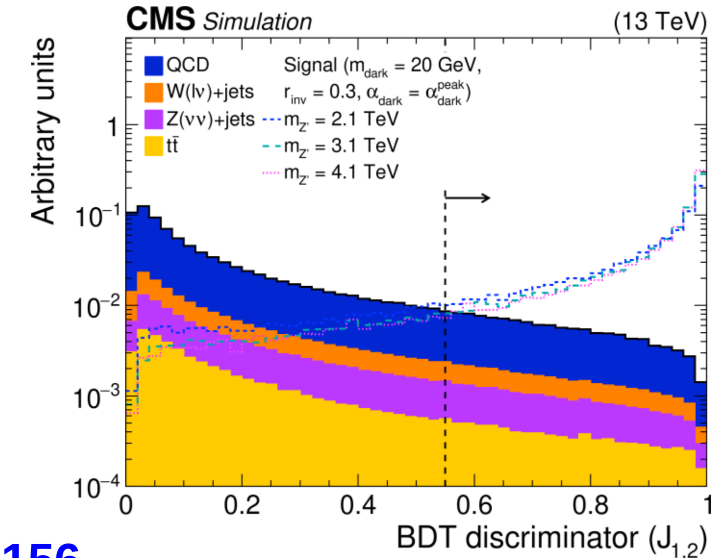
ATLAS-CONF-2022-038

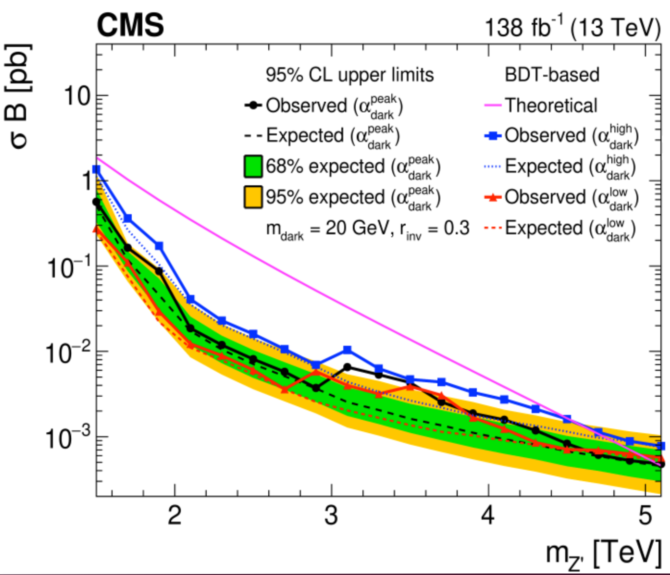


Semi-Visible jets

- The scalar mediator Z' acts as a SM-DS portal
- **Signature:** 1 jet aligned to the E_T^{miss} direction
- **Backgrounds:** QCD multijet, rejected by $R_T = p_T^{miss}/m_T > 0.15$ and this reject t-channel as well
- 2 Signal Regions
  - Low R_T: $0.15 < R_T < 0.25$
  - High R_T: $R_T > 20{,}25$
  - High $H_T = \Sigma_{jets} p_T$ and $E_T^{miss} > 600$ GeV close to a jet
- Discriminant variables: m_T and E_T^{miss}







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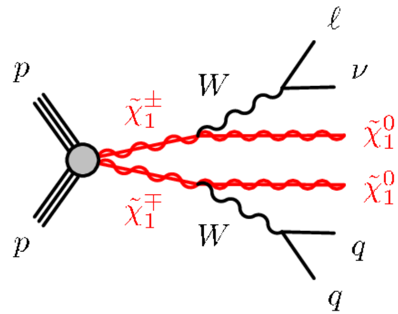
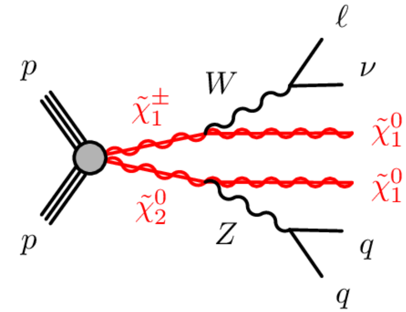
- Excluding $1.5 \leq m_{z'} \leq 5$ TeV for $r_{Inv} = 0.3$
- Excluding $0.01 \leq r_{Inv} \leq 0.77$ TeV for $m_{dark} = 20$ GeV
- Small excess around $m_{z'} = 3.5$ TeV with no real significance ($\sim 2\sigma$ local)

Searches for Electroweakinos

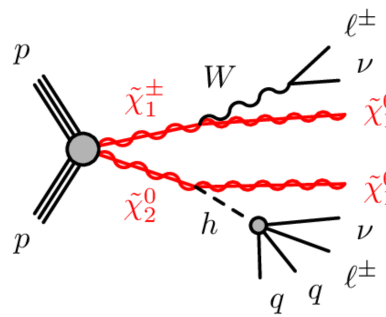
Examples of searches for direct neutralino/chargino production

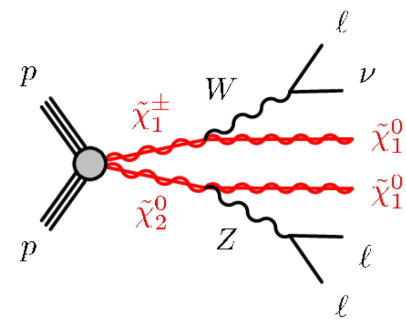
- **Lepton+jet**
  [ATLAS-CONF-2022-059]



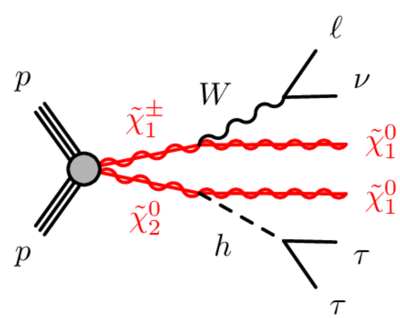


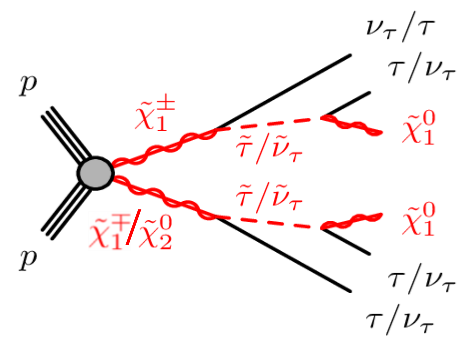
- **Same-sign/trilepton**
  [ATLAS-CONF-2022-057]





- **Di-tau**
  [ATLAS-CONF-2022-042]

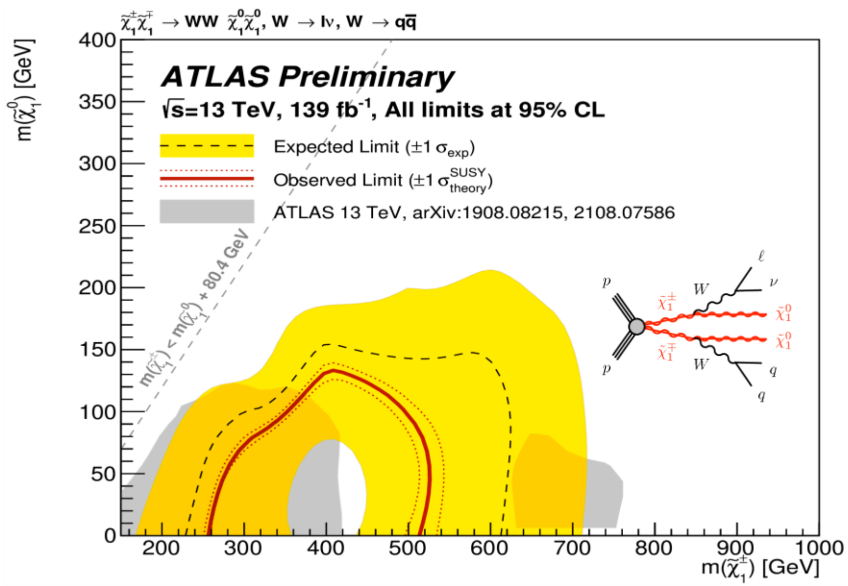


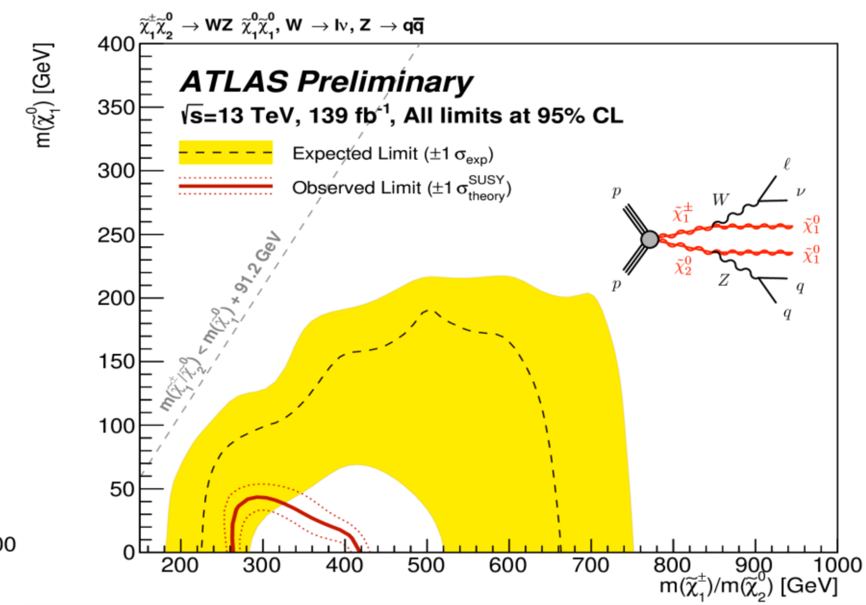


Electroweakinos in 1ℓ2J

- Single lepton trigger
- Dominant background: V+jets, VV
- Signature: 1 isolated lepton, at least two jets, and missing transverse energy

[ATLAS-CONF-2022-059]

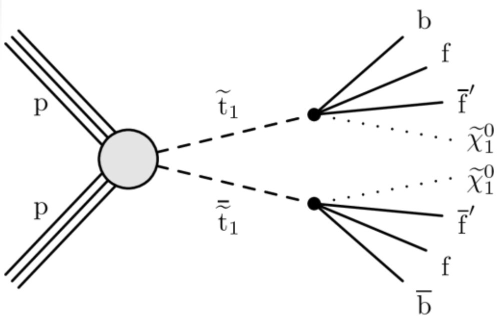




- WW: chargino masses 260-520 GeV can be excluded (for a massless neutralino)
- WZ: degenerate chargino/neutralino masses 260-420 GeV can be excluded (for a massless neutralino

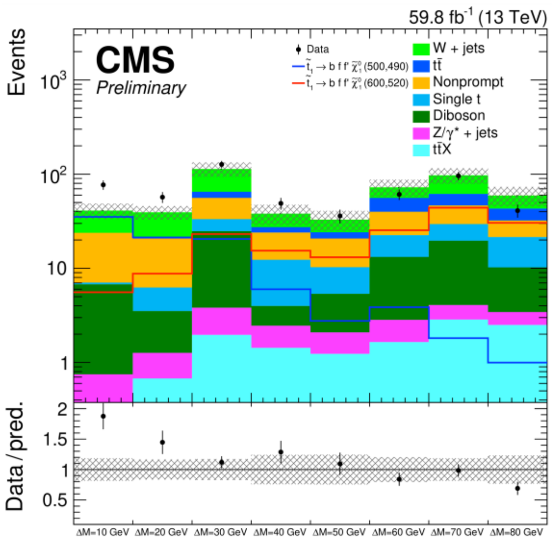
top squark in 1ℓ2J

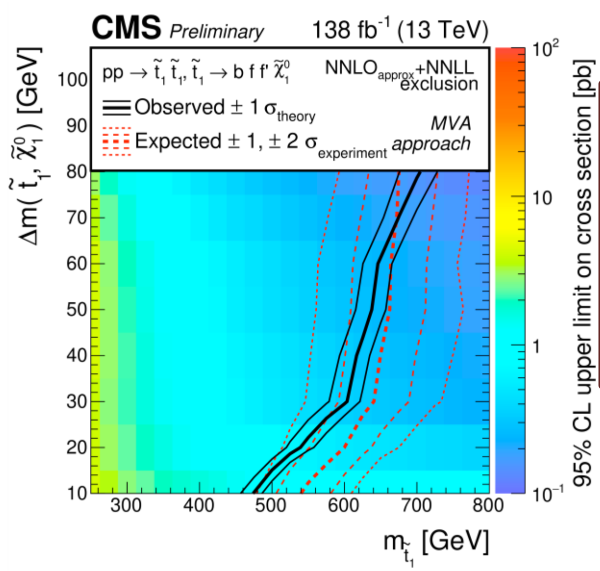
- Four-body decay of the $\tilde{t}_1$: $bff'\chi_1^0$
- **Signature:** high p_T^{jet}, significant E_T^{miss} and low $p_T^{e||\mu}$
- Signal selected based on a multivariate approach (BDT) adapted to the $m(\tilde{t}_1) - m(\tilde{\chi}_1^0)$ mass difference that should not exceed the W boson mass.
- Leading background processes ($W + jets$, $t\bar{t}$) are determined from data.



Exclusion limits on the production cross section as a function of the and masses under the assumption of simplified models

CMS-PAS-SUS-21-003





- 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

Conclusion

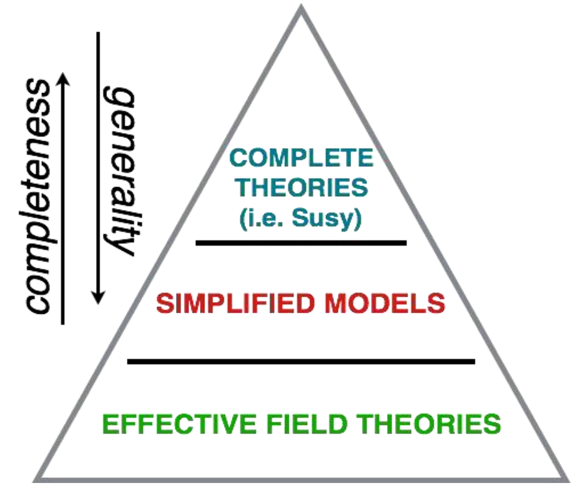
- **Extensive list of results on searches for DM signals**
- **Both ATLAS and CMS experiments probed a wide range of final states and models**
- **Large Run 2 datasets + improvements in analysis techniques, background modeling and estimation led to more stringent exclusions**
- **Still no sign from DM production at the LHC**
- **Ongoing Run 3, with expected double integrated luminosity could open a new era in DM searches**
  - **More precision to investigate existing “excesses”**
  - **Higher statistics to explore rare processes for potential anomalies**
  - **Possibility to identify not yet covered phase-space**
  - **New unexplored search strategies**

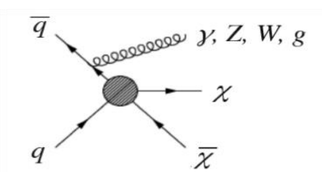
Backup

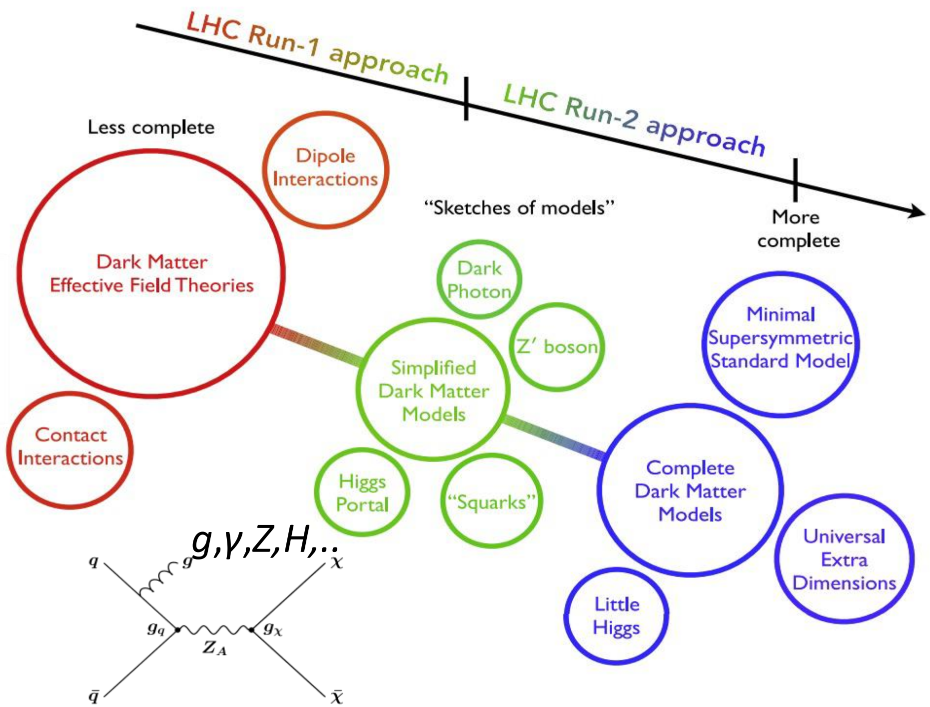
Dark Matter Models

Need to balance between generality and completeness

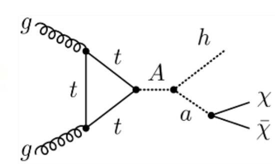
- Simplified Models are used as guidance
- Few free parameters:
  - Masses, Couplings / lifetimes
  - Nature of BSM particles
  - Easy visualization and comparisons between
  - experiments







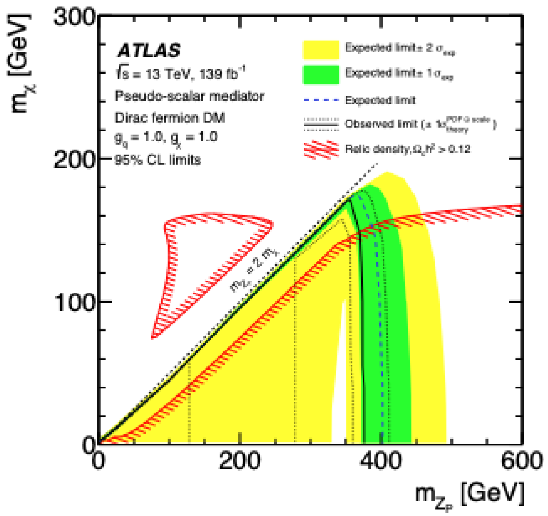
Most models provide some kind of Weakly interacting massive particles (WIMPs)



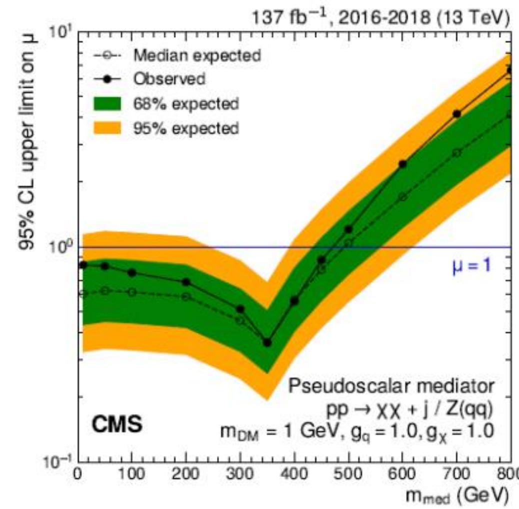
Monojet comparison ATLAS-CMS

ATLAS-EXOT-2018-06
CMS-EXO-20-004

Pseudo-scalar mediator



Exclude m_{med}< 376 GeV

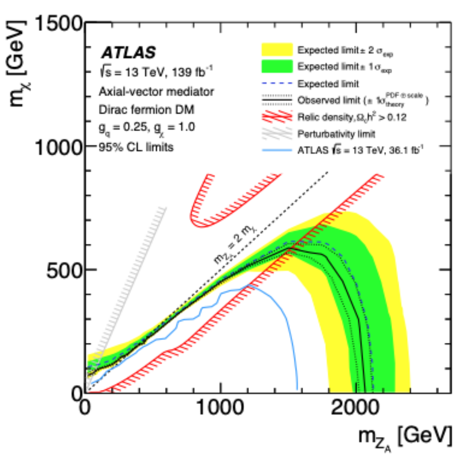


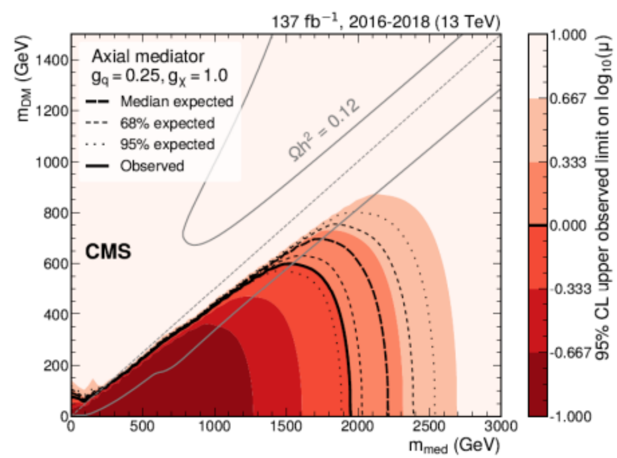
Exclude m_{med} < 470 GeV (490 GeV expected).

CMS has significantly better limits in pseudo-scalar mass exclusion

1

Axial-vector mediator





CMS and ATLAS pretty much similar limits for spin-1, exclude mediator mass upto 1.95 (2.1) TeV, for CMS(ATLAS), respectively

- CMS produces exclusion in coupling which ATLAS doesn't