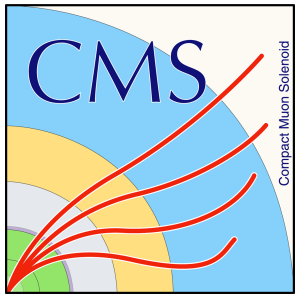
# Search for Dark Matter and Unconventional Signatures at the LHC




**Lailin Xu（徐来林）**

University of Sci. & Tech. of China

**CLHCP 2021**

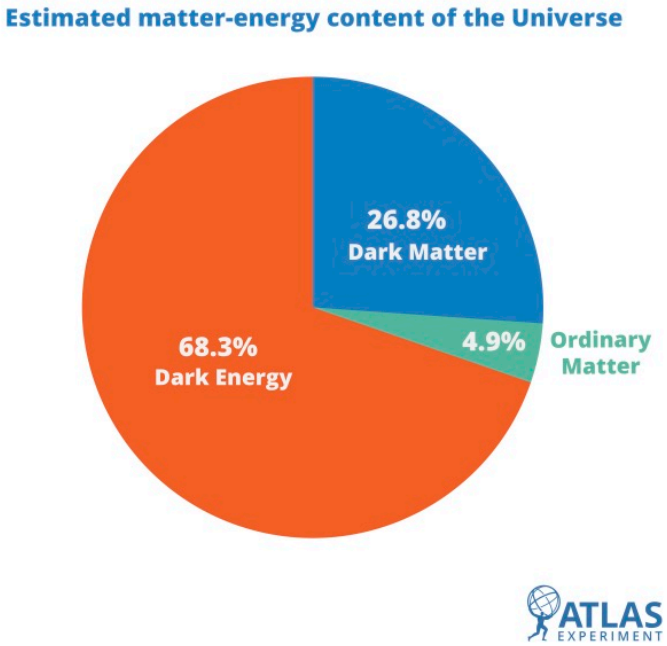
2021.11.25-28, Nanjing (online)

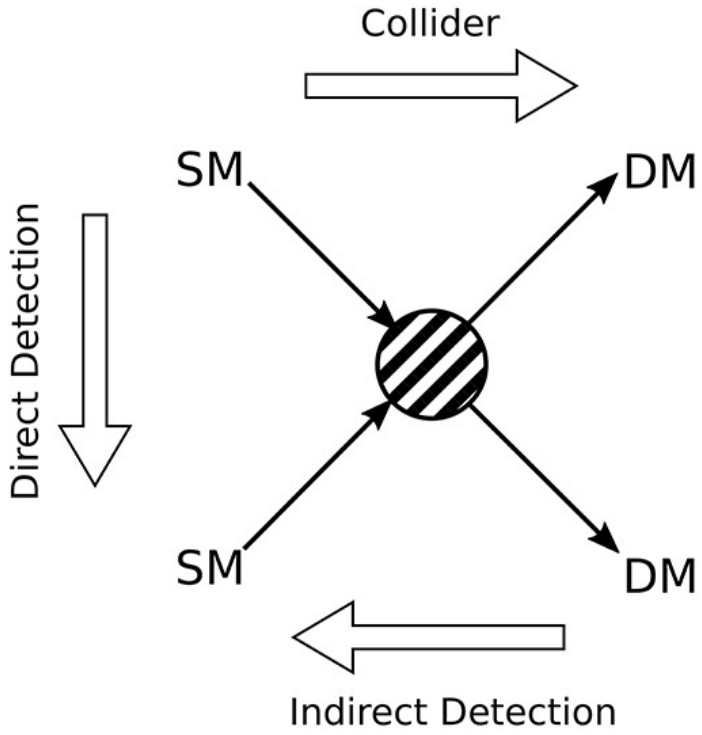


# Search for Dark Matter

# Dark matter searches at the LHC

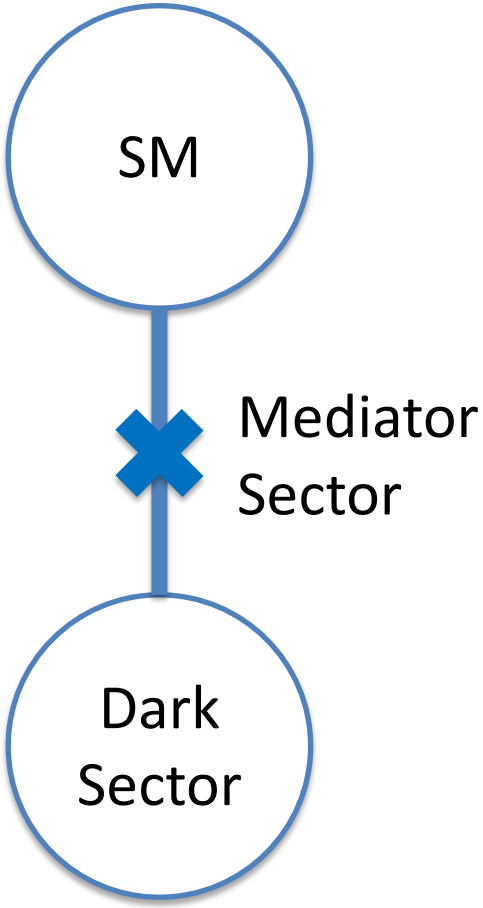
- Long history of dark matter searches in the particle physics community
- Collider experiments at the energy frontier provide a complementary approach to search for DM particles (WIMP)
- One of the flagship physics programs at the LHC



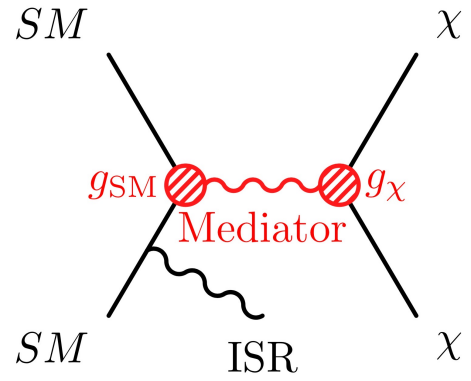
# Dark matter searches at the LHC

- Benchmark simplified DM models
  - Assume WIMPs are Dirac fermions

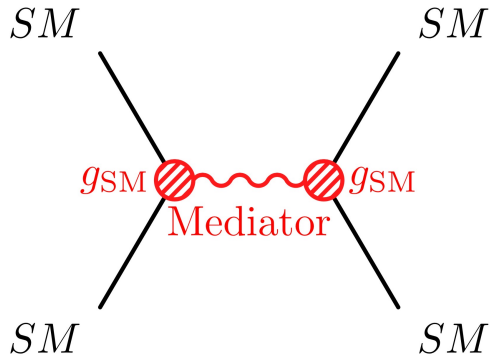



**S-channel mediators**

Mono-X searches

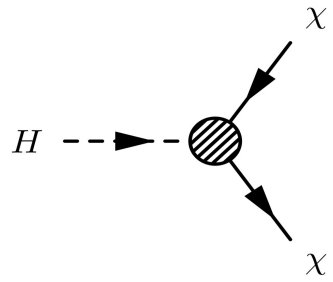



Resonance searches



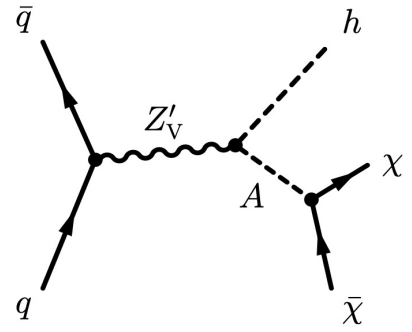

**Higgs portal**

Invisible Higgs searches

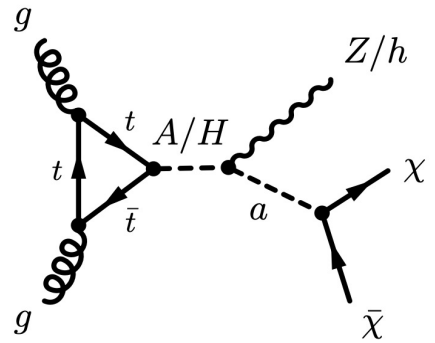



**Extended Higgs sectors**

Two-Higgs-doublet Model extended with a **vector boson Z'** or a **pseudoscalar a** which mediates the interaction between SM and DM




2HDM+Z'




2HDM+a

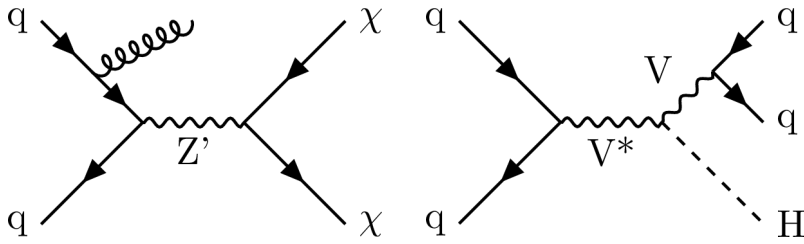
# Recent DM search results

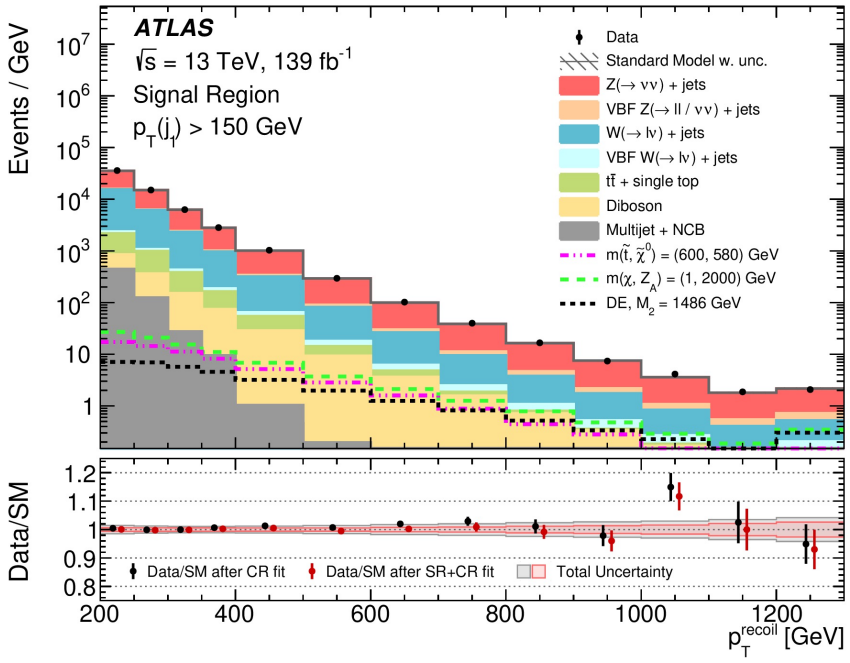
- ATLAS
  - Mono-jet and H→invisible: PRD 103 (2021) 112006
  - Mono-Z(ll) and ZH(→invisible): arXiv:2111.08372
  - Mono-H(bb): arXiv:2108.13391
  - Mono-H($\gamma\gamma$): arXiv:2104.13240
  - VBF H$\gamma$ with H→invisible: arXiv:2109.00925
  - tt+$E_T^{miss}$ : JHEP 04 (2021) 165
  - bb+ $E_T^{miss}$ : JHEP 05 (2021) 093
  - 2HDM+pseudoscalar combination: ATLAS-CONF-2021-036
- CMS
  - Mono-jet: arXiv:2107.13021
  - Mono-s(WW): CMS-PAS-EXO-20-013

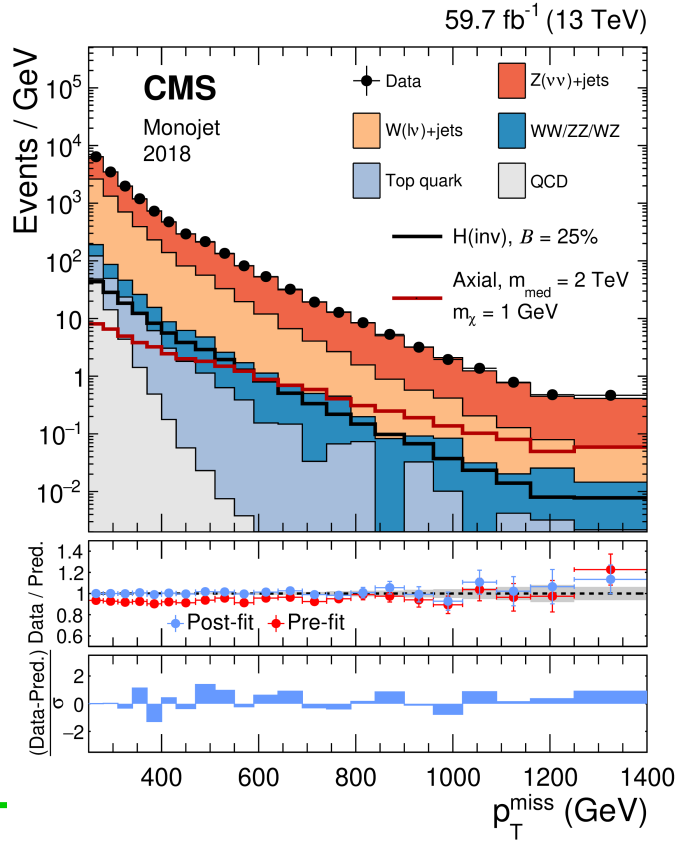
# Mono-jet/V(had)

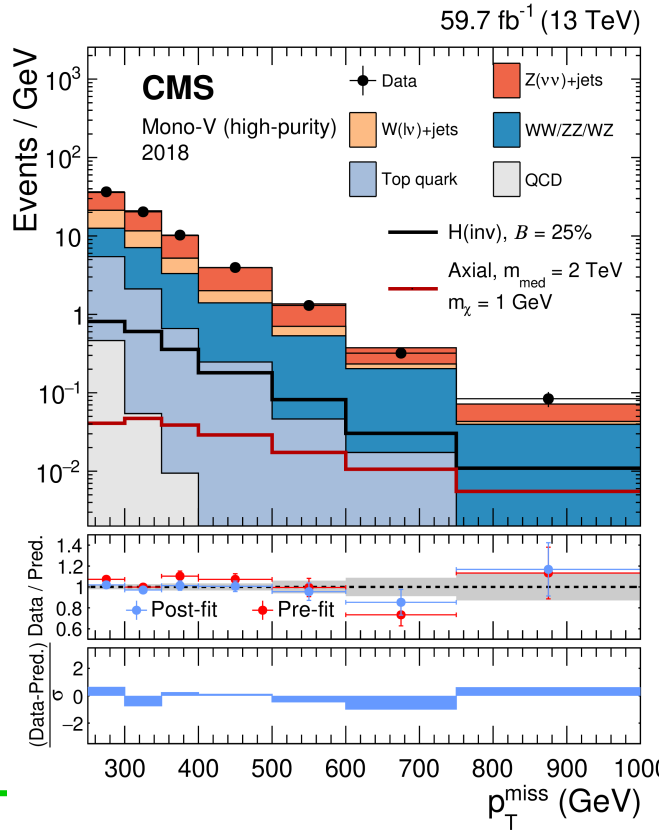
**ATLAS**: PRD 103 (2021) 112006
**CMS**: arXiv:2107.13021

- Using events with energetic jets and large $p_T^{miss} > 250$ GeV
- CMS: also slit into mono-V and mono-jet categories
  - Mono-V(had): one large-R jet with boson tagging requirement
- Main backgrounds constrained using data control regions
  - Z→νν, W →lν, $\gamma$+jets



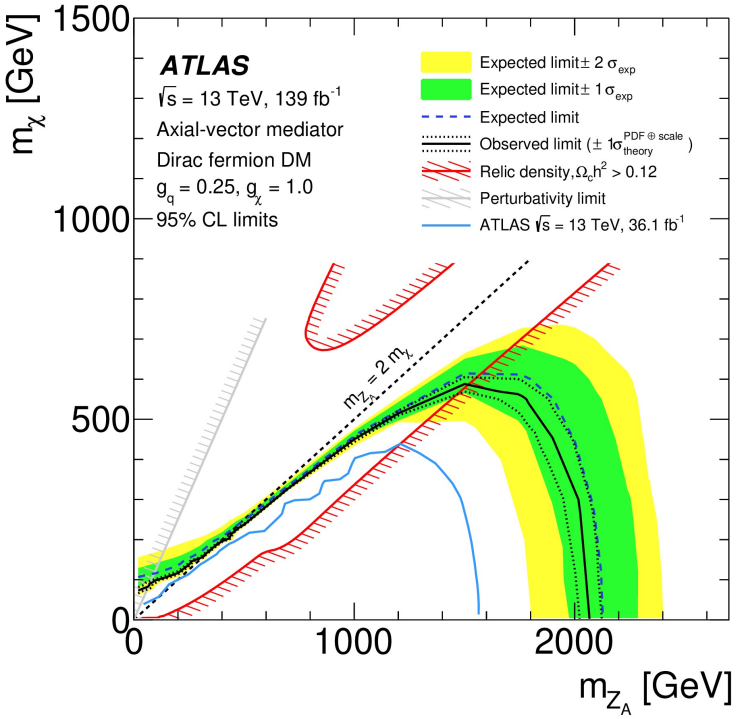



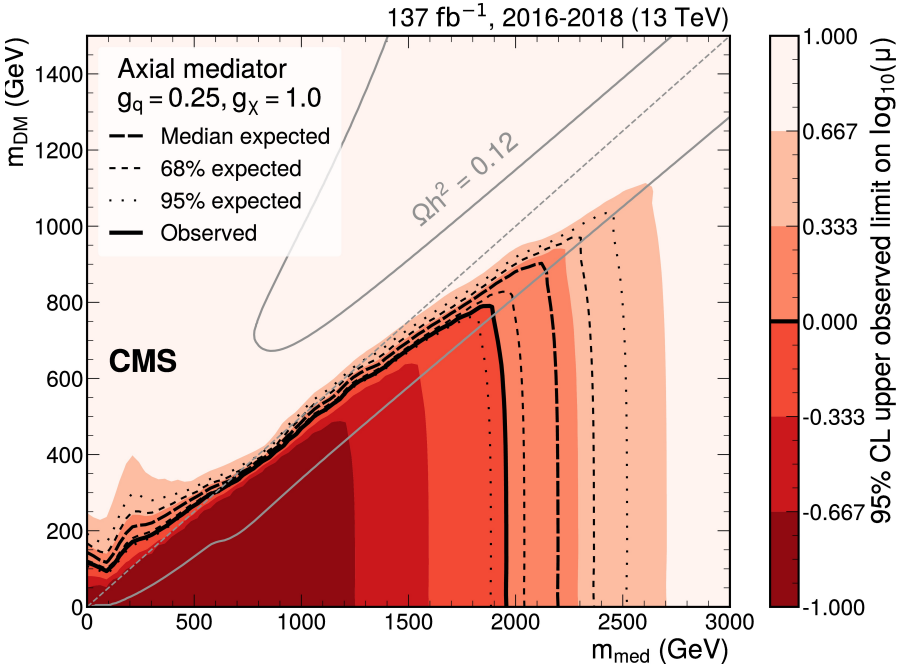
# Mono-jet/V(had)

**ATLAS**: PRD 103 (2021) 112006
**CMS**: arXiv:2107.13021

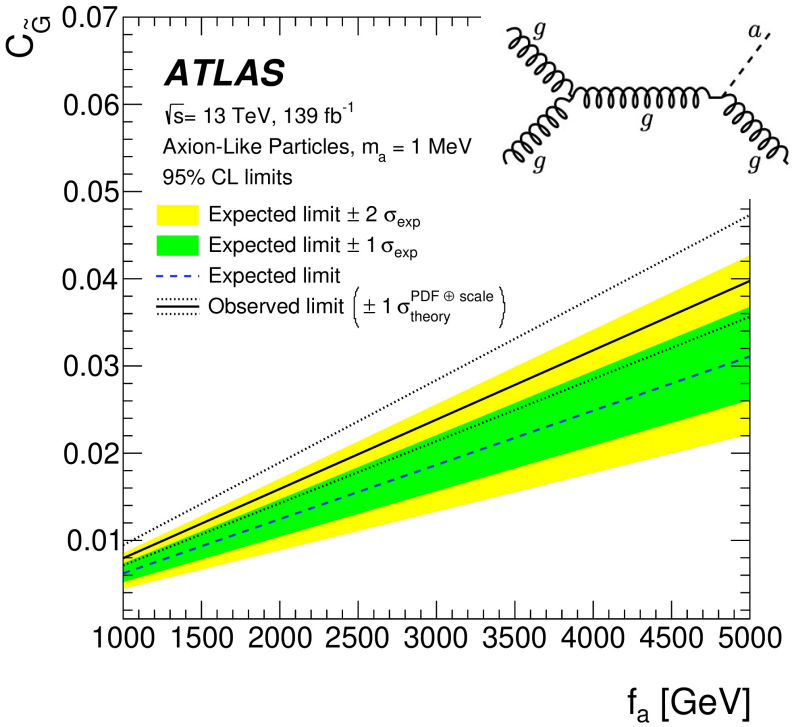
- Results are interpreted for Vector, Axial mediator and Fermion portal models
  - And also other BSM models: large extra dimensions, SUSY, leptoquarks, Axion-like particles etc

Axial-vector mediator DM



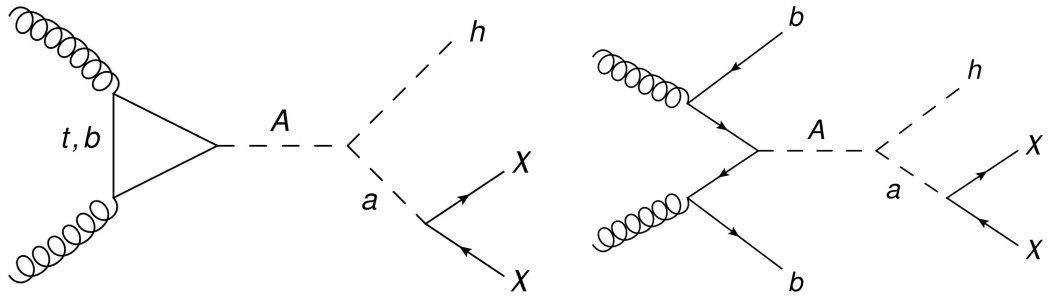

Axion-like particles (**ALP**s)
→ Also popular candidates of DM



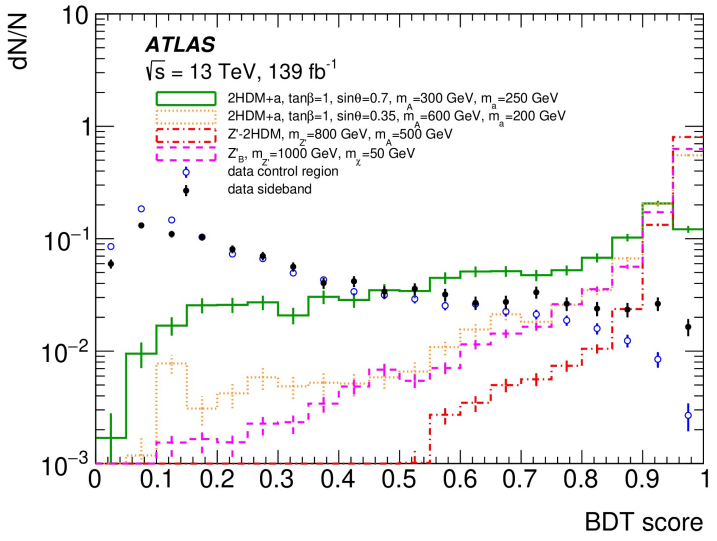
# Mono-H, bb and $\gamma\gamma$

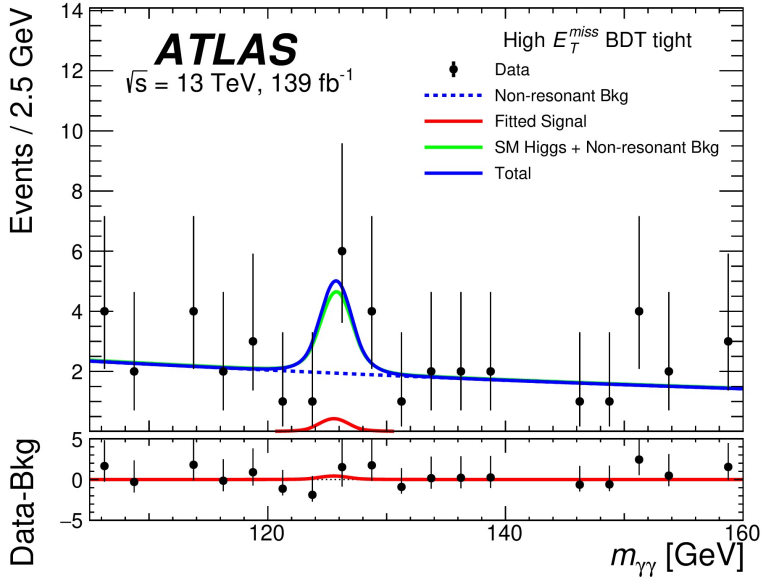
**ATLAS**: arXiv:2108.13391
JHEP 10 (2021) 13

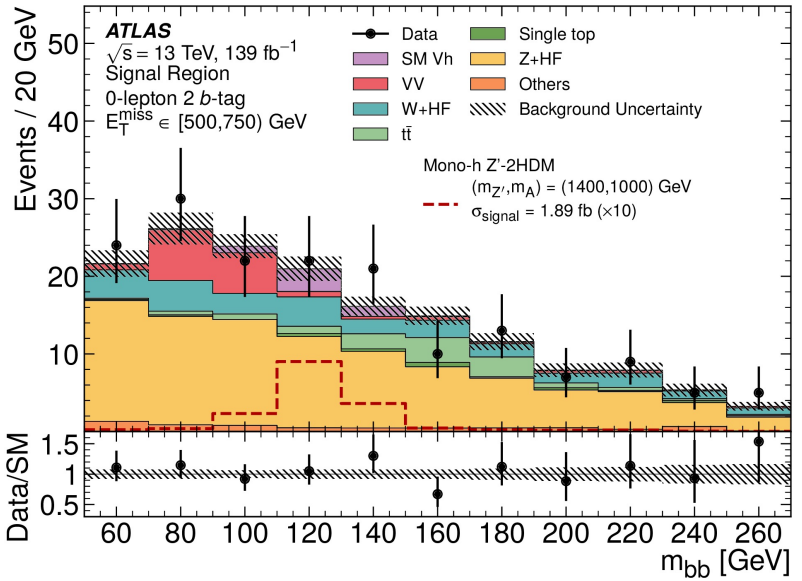
- Using the SM Higgs boson to probe DM
- Benchmark signal model: extended Higgs sectors
  - 2HDM+Z' vector
  - 2HDM+a pseudoscalar




- Reconstructed Higgs mass ($m_{bb}, m_{\gamma\gamma}$) in different signal regions to probe the DM signal
  - **H→bb**: different $E_T^{miss}$ bins, boosted and resolved, 2-b-tagged and 3-b-tagged
  - **H→$\gamma\gamma$**: different BDT bins



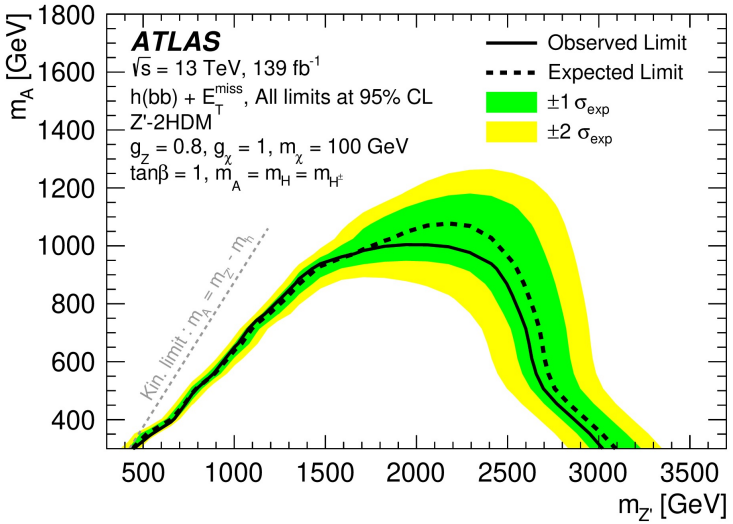



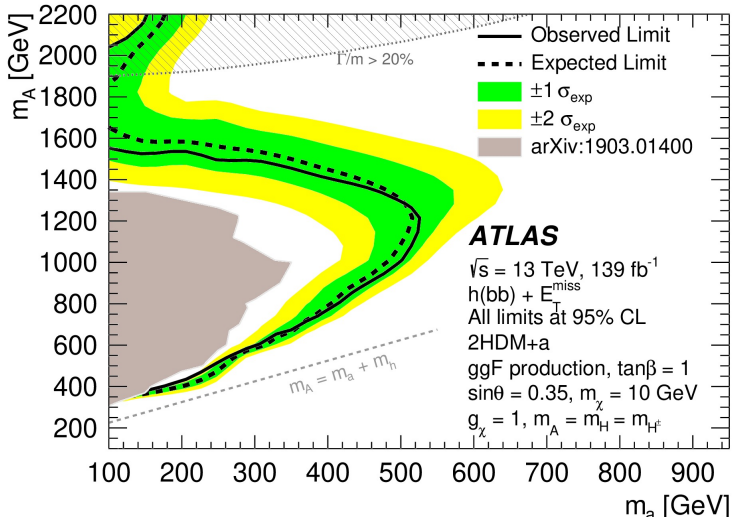
# Mono-H, bb and $\gamma\gamma$

**ATLAS**: arXiv:2108.13391
JHEP 10 (2021) 13

- Interpretations

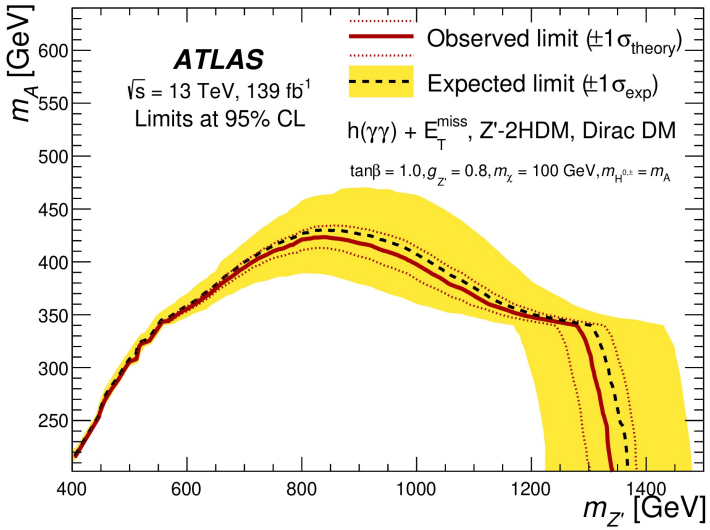



**H→bb**

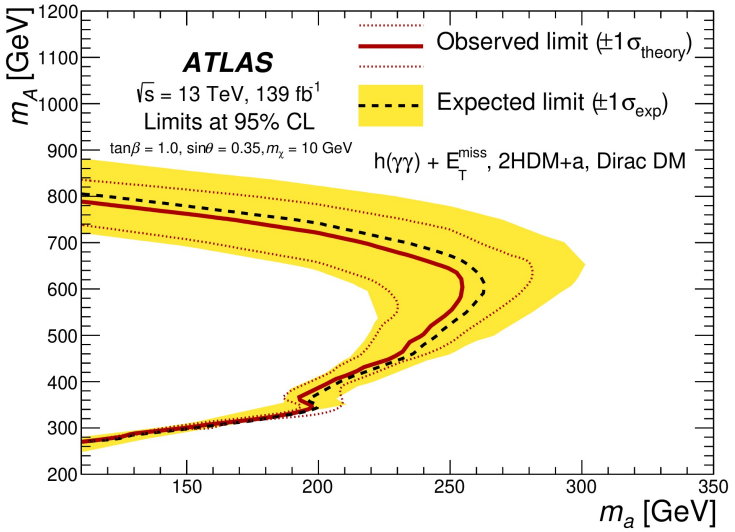



**2HDM+Z'**

**2HDM+a**




**H→$\gamma\gamma$**

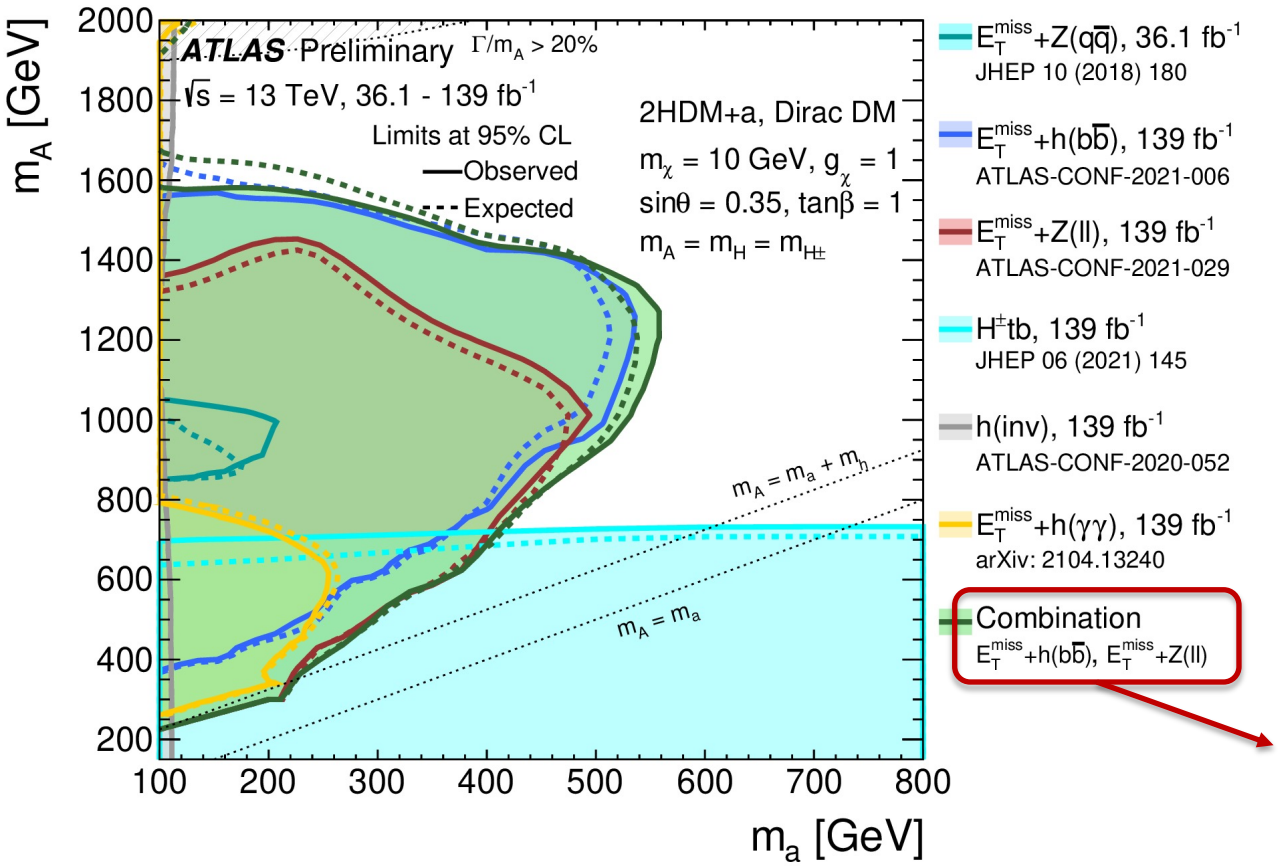


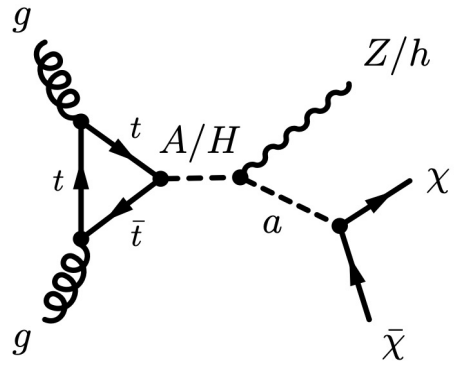

Complementary sensitivity of the two channels

# Combined/summary results: 2HDM+a

ATLAS-CONF-2021-036

$(m_a, m_A)$ scan, sinθ = 0.35




Mono-H(bb) and mono-Z(ll) are statistically combined

Excellent complementarity of different final states

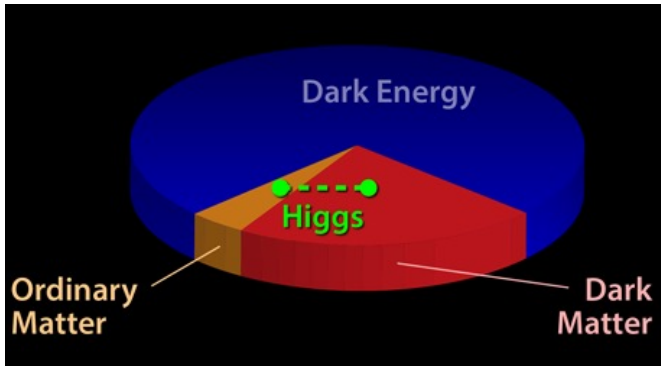
# Higgs portal

- The SM Higgs as a portal to connect the SM and the Hidden Sector
- Invisible decays of the SM Higgs boson
  - Best sensitivity is from VBF

ATLAS-CONF-2020-052

| Analysis | $\sqrt{s}$ [TeV] | Int. luminosity [fb$^{-1}$] | Best fit $\mathcal{B}_{H\to\text{inv}}$ | Observed upper limit | Expected upper limit | Reference |
|---|---|---|---|---|---|---|
| Run 2 VBF | 13 | 139 | $0.00^{+0.07}_{-0.07}$ | 0.13 | $0.13^{+0.05}_{-0.04}$ | [42] |
| Run 2 $t\bar{t}H$ | 13 | 139 | $0.04^{+0.20}_{-0.20}$ | 0.40 | $0.36^{+0.15}_{-0.10}$ | This document |
| Run 2 Comb. | 13 | 139 | $0.00^{+0.06}_{-0.07}$ | 0.13 | $0.12^{+0.05}_{-0.04}$ | This document |
| Run 1 Comb. | 7, 8 | 4.7, 20.3 | $-0.02^{+0.14}_{-0.13}$ | 0.25 | $0.27^{+0.10}_{-0.08}$ | [36] |
| Run 1+2 Comb. | 7, 8, 13 | 4.7, 20.3, 139 | $0.00^{+0.06}_{-0.06}$ | 0.11 | $0.11^{+0.04}_{-0.03}$ | This document |

| Br(Hinv): obs/exp | ATLAS | CMS | Ref. |
|---|---|---|---|
| mono-jet | 34% (39%) | 27.8% (25.3%) | CMS: arXiv:2107.13021 |
| mono-Z(ll) | 19% (19%) | 29% (25%) | ATLAS: arXiv:2111.08372<br>CMS: *EPJC 81 (2021) 13* |
| VBF H(inv)γ | 37% (34%) | | ATLAS: arXiv:2109.00925 |




Best constraint from VBF Hinv
ATLAS: 13% @ 95% CL
(CMS: 17%)
ATLAS 2020 Combination: 11%

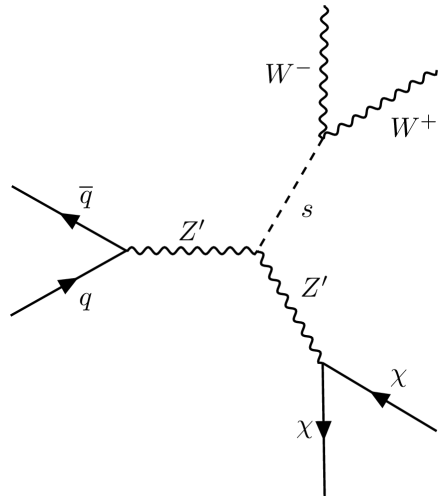
mono-jet: ggF H→inv, V(→qq)H(inv)
mono-Z(ll): ZH(inv)

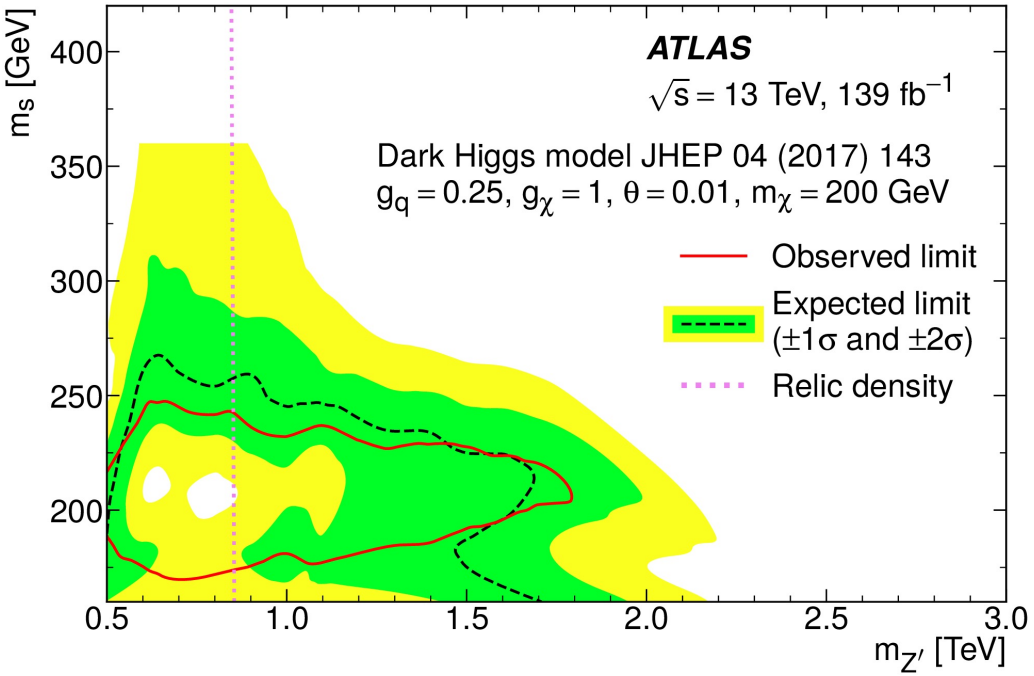
*For VBF Hinv, see Vukasin's talk*
*For mono-Z(ll), see Chuanshun's talk*
*For VBF H(inv)γ, see Han Cui's talk*

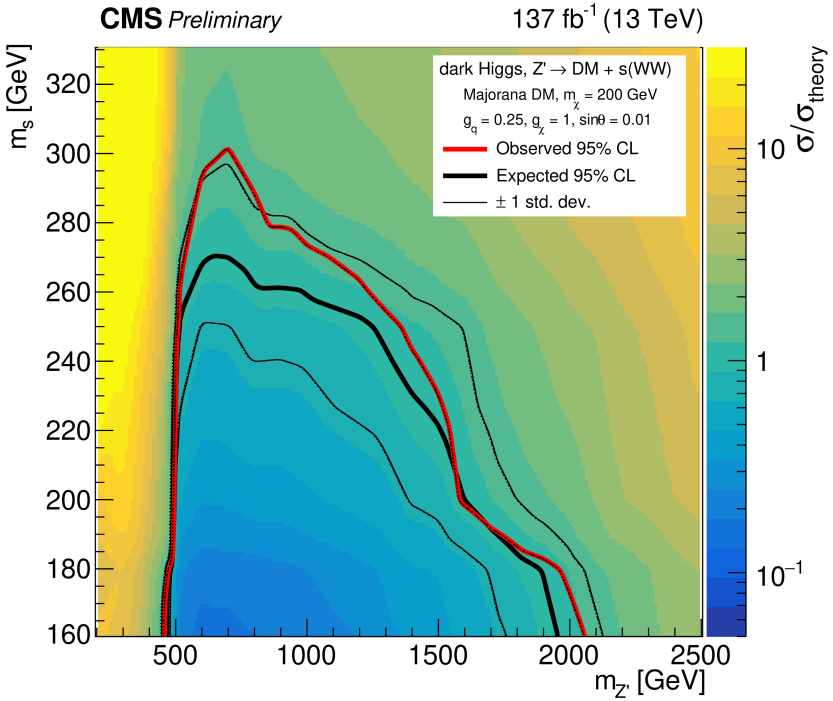
# Mono-s(WW)

ATLAS: PRL126 (2021) 121802
CMS: CMS-PAS-EXO-20-013

- Dark Higgs model: Dark Matter particle acquire mass through their interaction with a dark Higgs boson
  - Model parameters: mediator Z' mass, $m_s$, couplings $g_q$, $g_x$, mixing sinθ
- ATLAS: s→VV fully hadronic
- CMS: s→WW fully leptonic



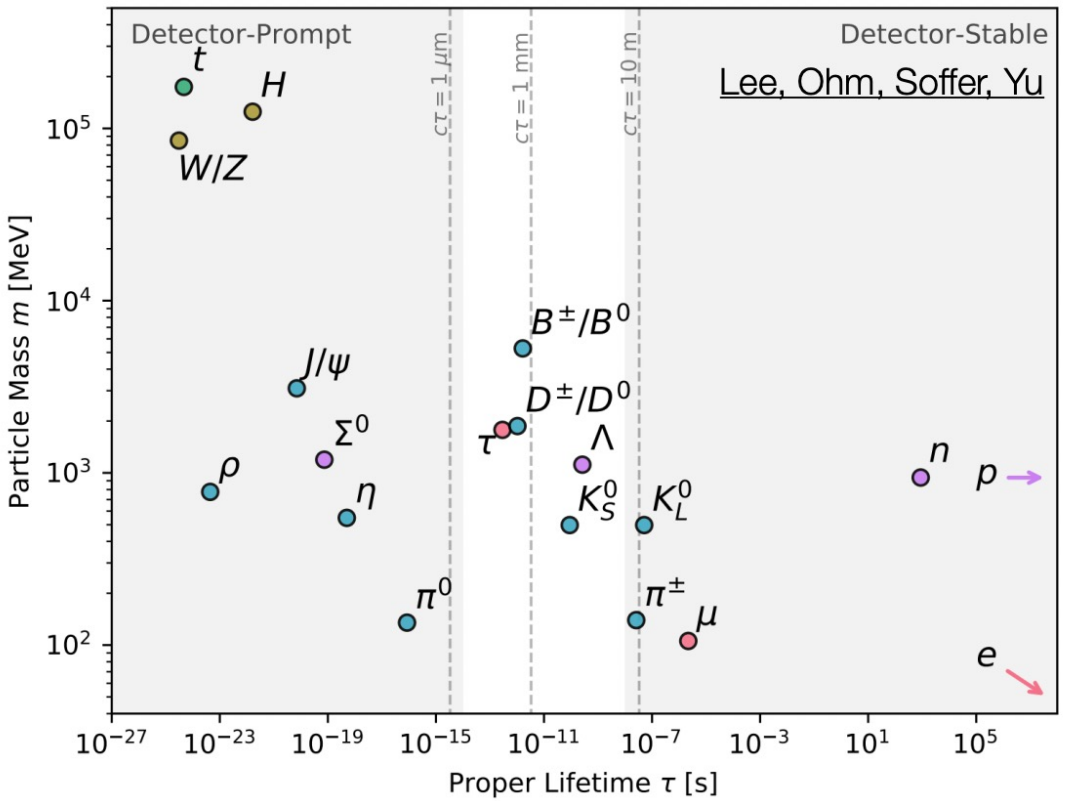



# Search for Unconventional Signatures

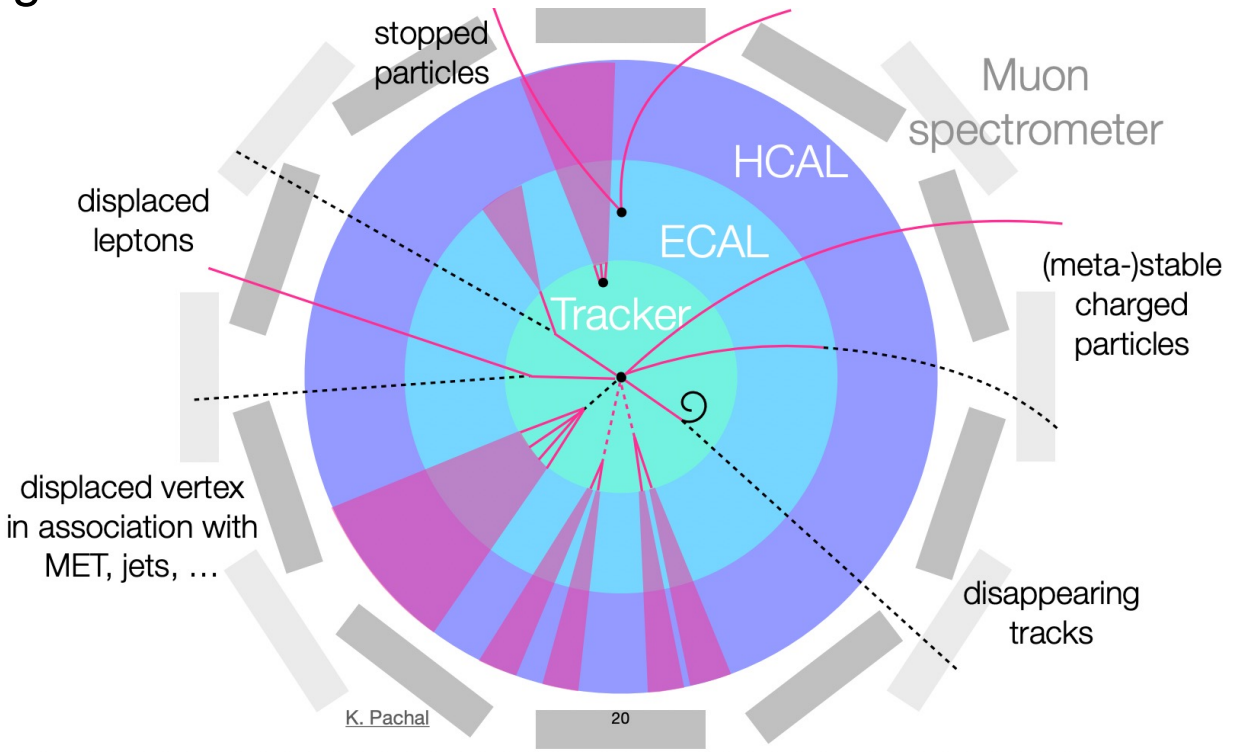
# Unconventional signatures: why?

- No evidence of BSM particles yet from experimental searches, which are mostly based on "conventional" scenarios
- BSM could still be hiding
  - Unexplored phase space
  - Unconventional signatures
- Unconventional signatures come from
  - Small couplings → long lifetime
  - Limited phase space
  - Decays via heavy particles
- Long-lived particles (LLP) exist in many theories
  - SUSY: R-parity violating, Compressed, Folded
  - Heavy Neutrinos
  - Dark Sectors i.e. via Higgs portals, Quirky Little Higgs
  - Nature (SM) displays a wide spectrum of lifetimes



# Long-lived particles

- Experimentally give rise to a diverse set of unusual signatures and unusual backgrounds
- Typically require
  - Customized triggers
  - Non-conventional, tailored reconstruction / tagging tools
- Many complementary signatures
  - Direct detection:
    - Anomalous energy loss and/or low velocity
    - A disappearing track
  - Indirect detection of displaced decays
    - Non-prompt final-state jets, photons, leptons



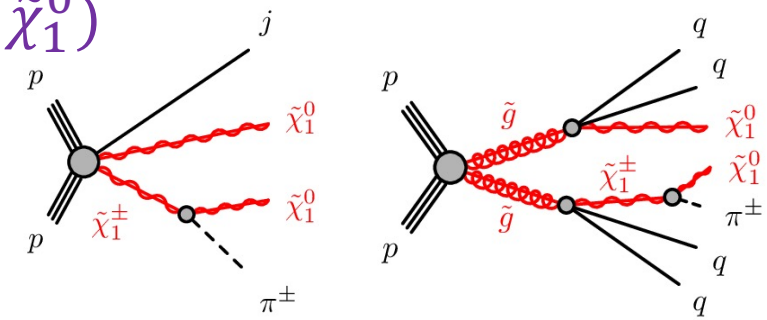
# Recent LLP search results

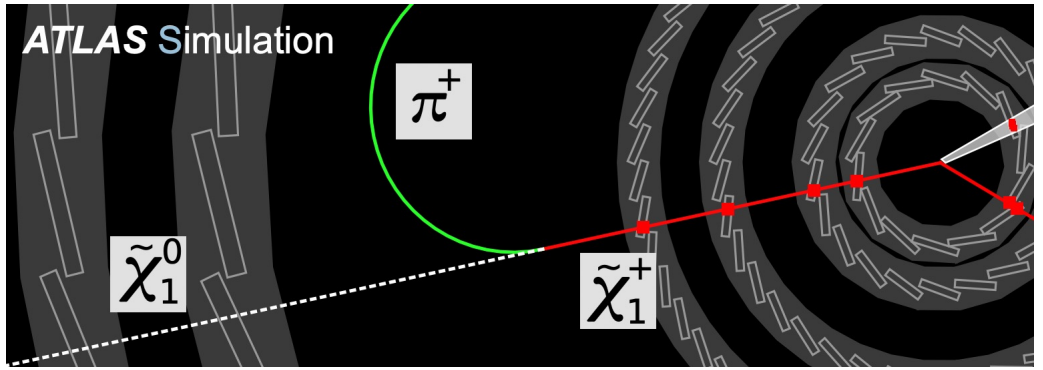
- ATLAS
  - Disappearing tracks: ATLAS-CONF-2021-015
  - Displaced jets: ATLAS-CONF-2021-032
  - Associated Z(ll)H(→displaced jets): arXiv:2107.06092
  - Stopped LLPs: *JHEP 07 (2021) 173*
- CMS
  - Displaced leptons: arXiv:2110.04809
  - Displaced jets: arXiv:2107.04838
  - Displaced vertices: arXiv:2104.13474
  - Associated Z(ll)H(→displaced jets): arXiv:2110.13218

# Disappearing tracks

**ATLAS**: ATLAS-CONF-2021-015

- Search for long-lived charginos: small mass splitting $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$
  - $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 + \pi^{\pm}$ from EWK and QCD production
  - $\tilde{\chi}_1^{\pm}$ is long-lived and leaves hits (tracklets) in the Inner Track
  - $\tilde{\chi}_1^0$ escapes the detector
  - $\pi^{\pm}$ is too soft to be reconstructed
- Event selections
  - $E_T^{miss}$ triggers
  - Specialized pixel tracklet reconstruction



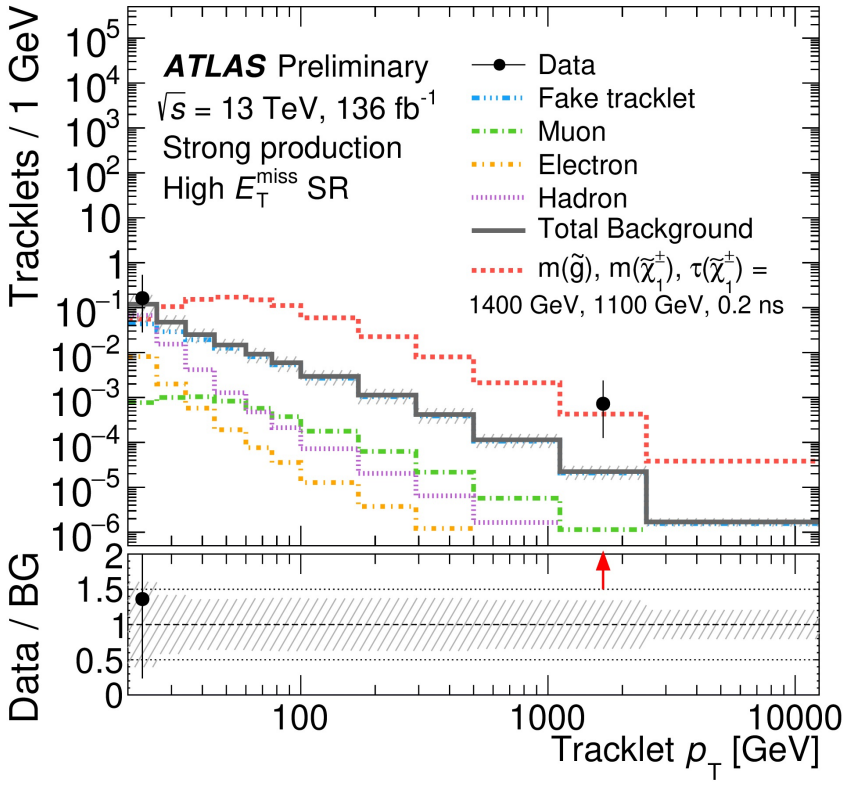

| Signal region | Electroweak production | Strong production |
|---|---|---|
| Number of electrons and muons | 0 | |
| Number of pixel tracklets | $\geq 1$ | |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV] | $> 200$ | $> 250$ |
| Number of jets ($p_{\mathrm{T}}$> 20 GeV) | $\geq 1$ | $\geq 3$ |
| Leading jet $p_{\mathrm{T}}$ [GeV] | $> 100$ | $> 100$ |
| Second and third jet $p_{\mathrm{T}}$ [GeV] | – | $> 20$ |
| $\Delta\phi_{min}^{\mathrm{jet}-E_{\mathrm{T}}^{\mathrm{miss}}}$ | $> 1.0$ | $> 0.4$ |

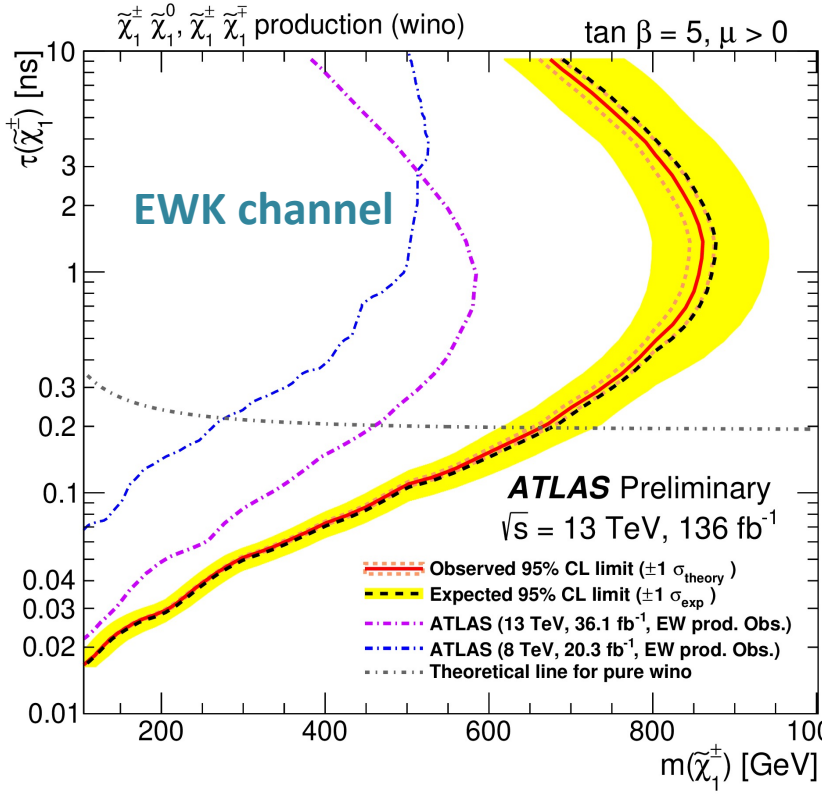
- Two signal regions to target the EWK and QCD production modes
- Discriminant: the pixel tracklet $p_T$ spectrum

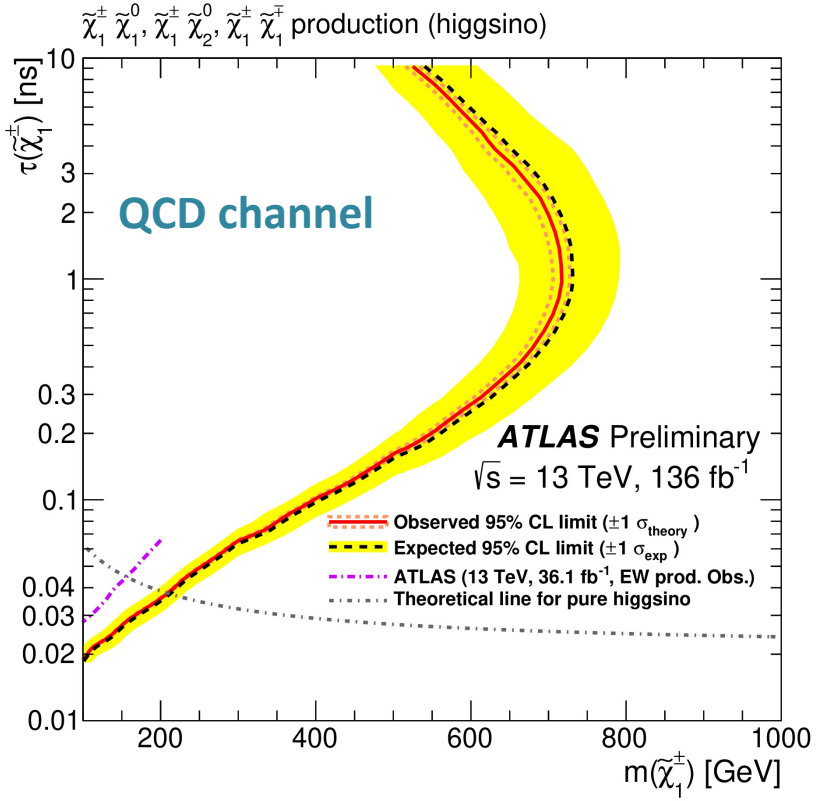
# Disappearing tracks

**ATLAS**: ATLAS-CONF-2021-015

- Data-driven background estimates:
  - Templates from dedicated control regions
  - Normalization using fit to tracklet $p_T$ spectrum
- Most stringent limits on pure winos or higgsinos so far



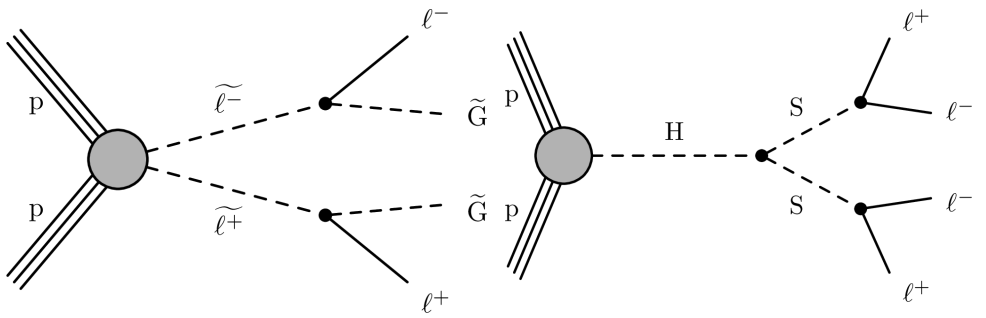



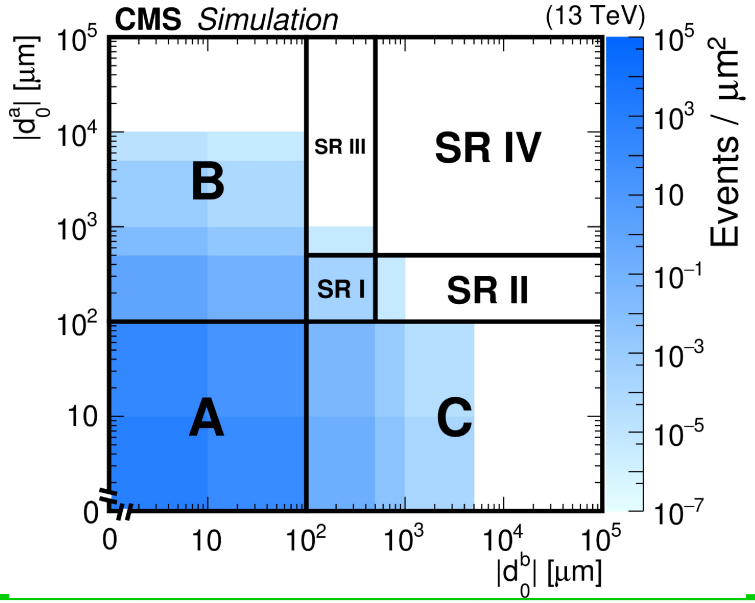



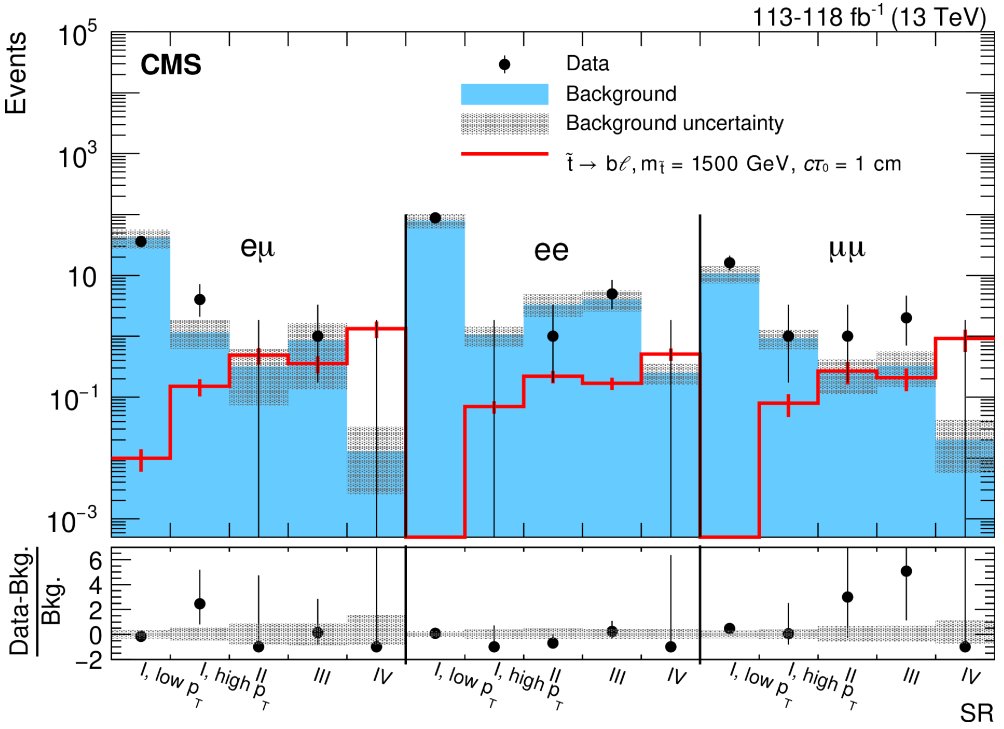
# Displaced leptons

CMS: arXiv:2110.04809

- Inclusive search for LLPs that decay to e,μ in pixel tracker
  - ≥ 2 isolated leptons, 0.01 < $|d_0|$ < 10 cm
  - no constraints on missing energy, jets, etc
- Sensitive to several models with non-prompt leptons
  - SUSY RPV $\tilde{t} \to b\tilde{l}$, $\tilde{t} \to d\tilde{l}$, GMSB $\tilde{l} \to l\tilde{G}$
  - Exotic Higgs decay: H→SS with S→ll
- Backgrounds estimated from data in prompt lepton regions (ABCD)



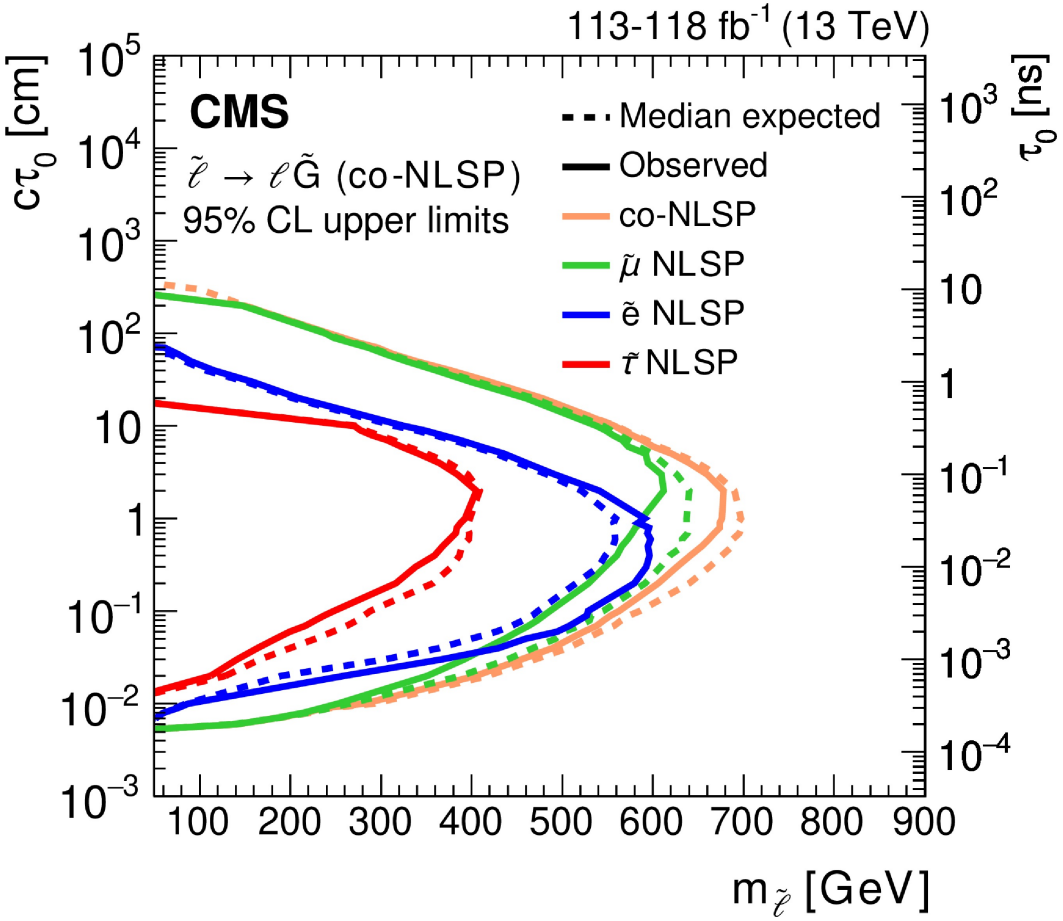



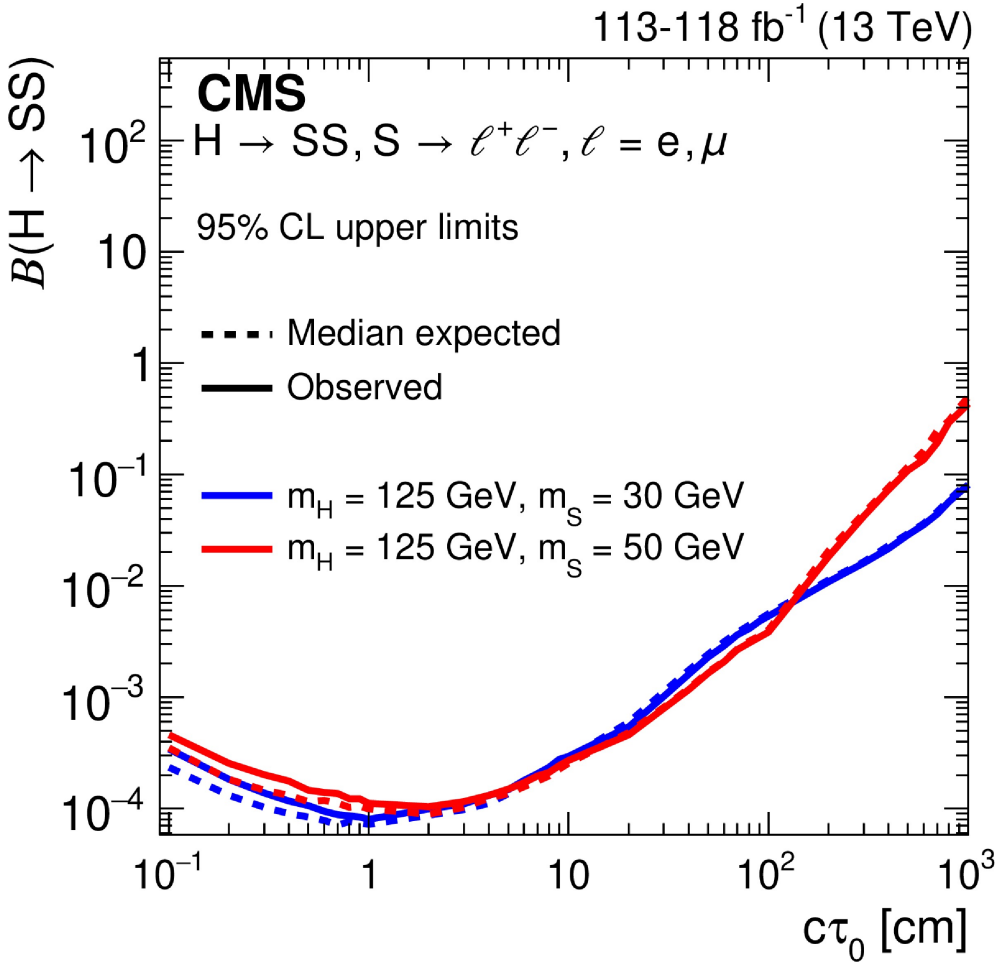
# Displaced leptons

CMS: arXiv:2110.04809

- Interpretations



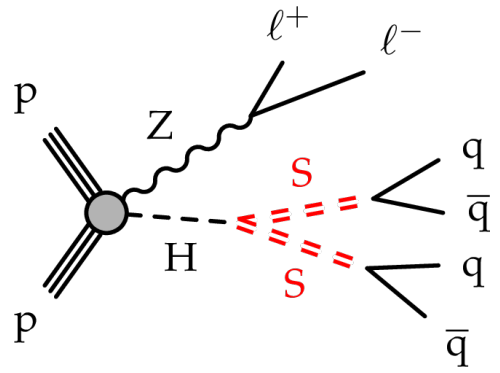

Most sensitive results for **s-leptons** with $c\tau_0 < 0.8$ cm

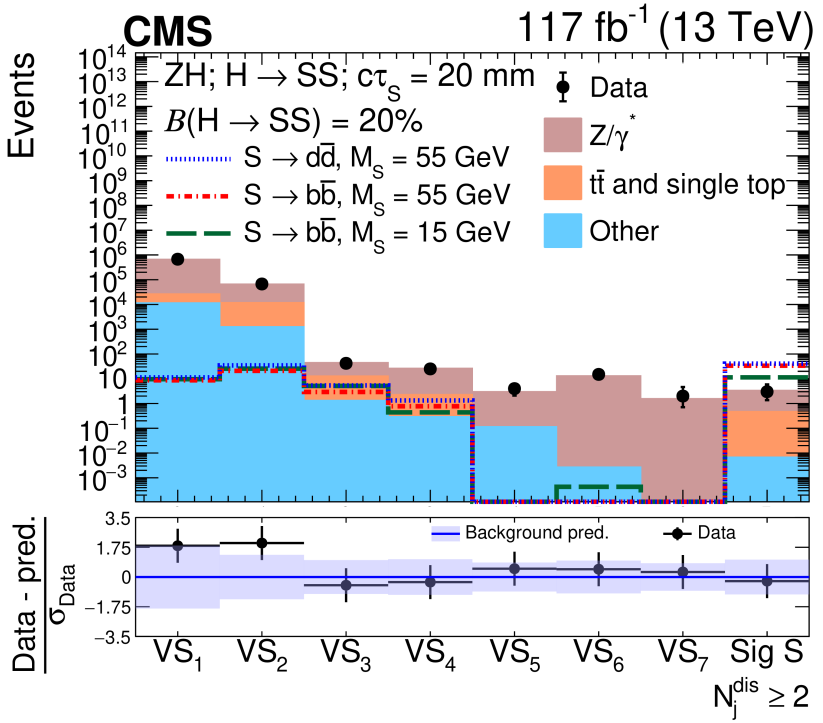



Most sensitive results for $0.1 < c\tau_0 < 1000$ cm

# Associated production of LLPs with a Z boson

- Prompt leptons from Z→ll provide an effective trigger
  - Sensitive to events with low-$p_T$ jet
  - SM ZH production with H decaying into long-lived scalar particles
- ATLAS: arXiv:2107.06092
  - Use "large-radius tracking" to reconstruct displaced vertices (DV)
  - Look for 2 DVs in the inner tracker
  - The DVs are required to be associated with different jets
- CMS: arXiv:2110.13218
  - Use dedicated tagging variables to select displaced jets ($N_j^{dis}$)
- Control samples with < 2 DVs are used to estimate the background

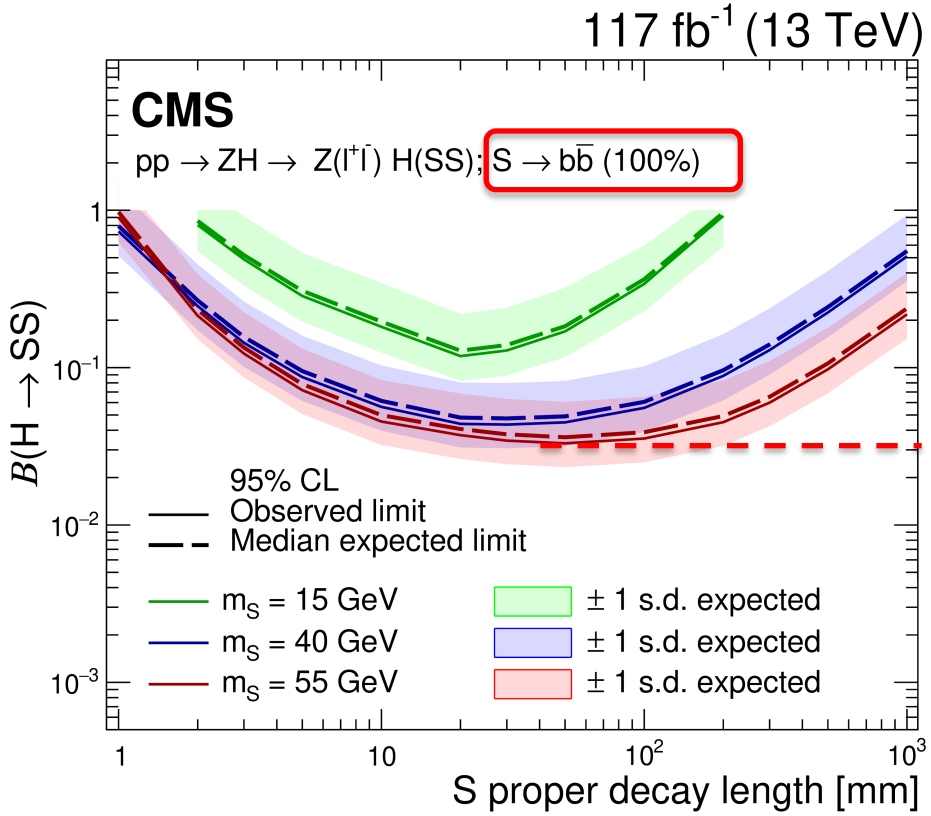


# Associated production of LLPs with a Z boson

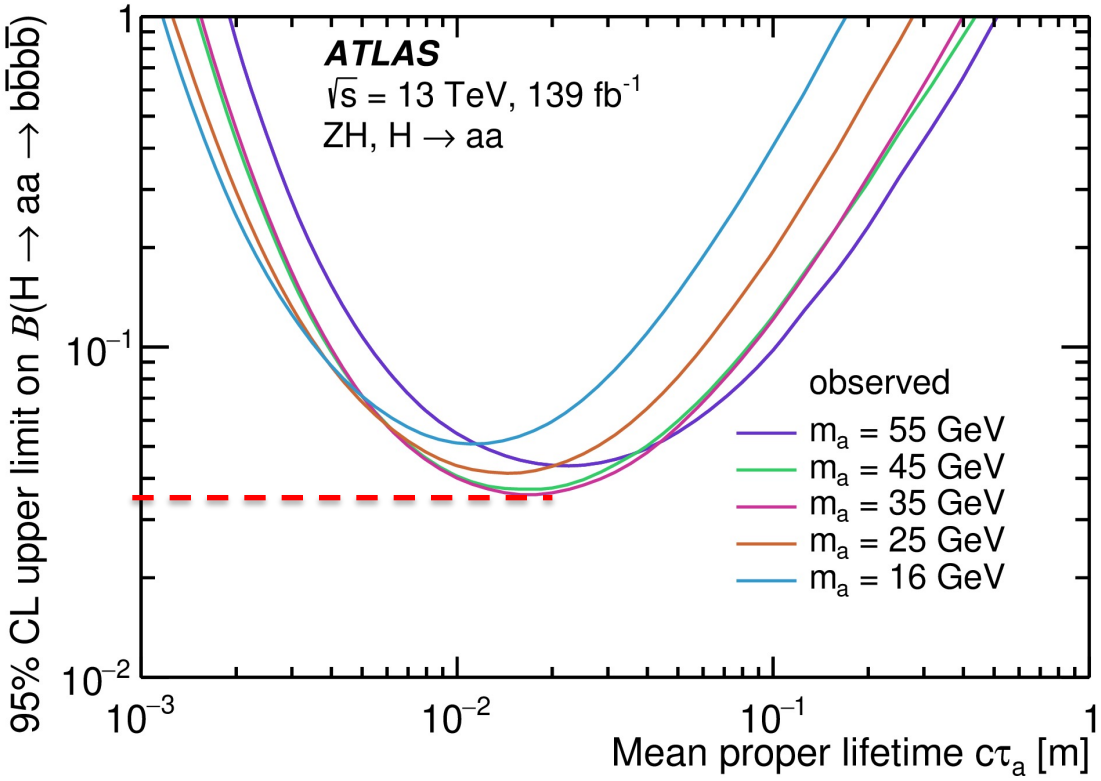
- Interpretations: limits on Br(H→SS)

arXiv:2110.13218




arXiv:2107.06092

ATLAS assumes Br(S→bb) = 100%

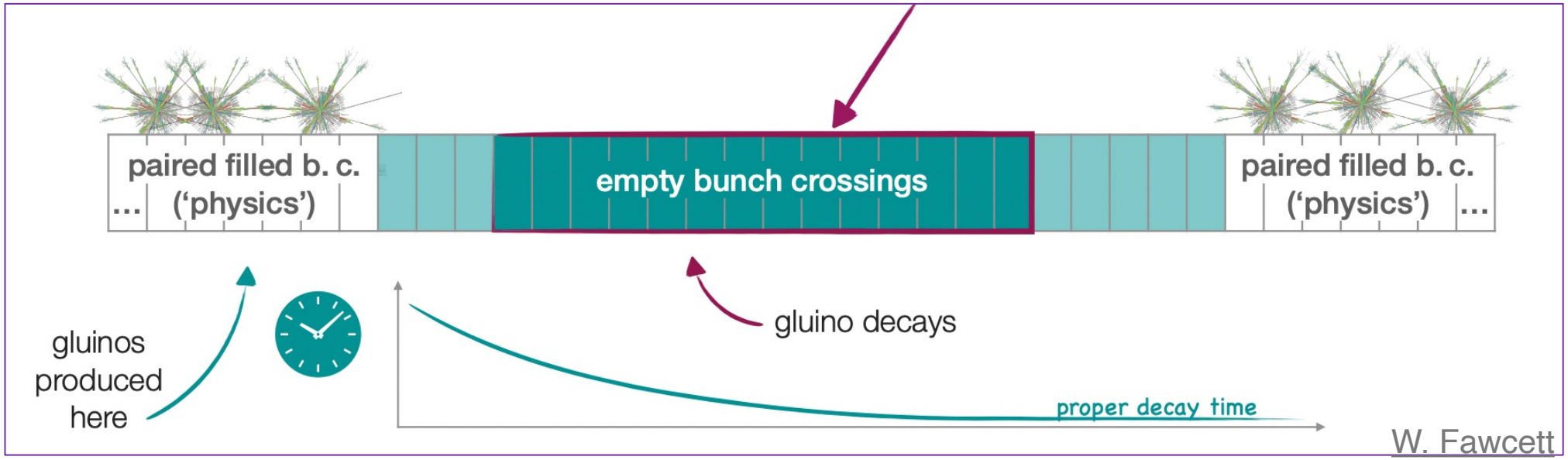


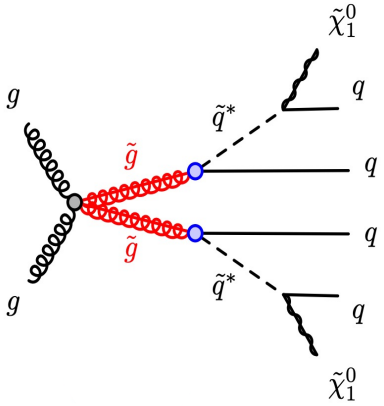
# Stopped LLPs

ATLAS: *JHEP 07 (2021) 173*

- Search for LLPs which have come to rest within the ATLAS calorimeters and decay at a later time when no pp collisions occur
- Search strategy: trigger on jets produced in empty bunch crossings(BX)
  - A clean environment to identify delayed decays
  - 298 hours in 2017, 281 hours in 2018 → 111 $fb^{-1}$ data

Benchmark signal:
SUSY gluino R-hadrons

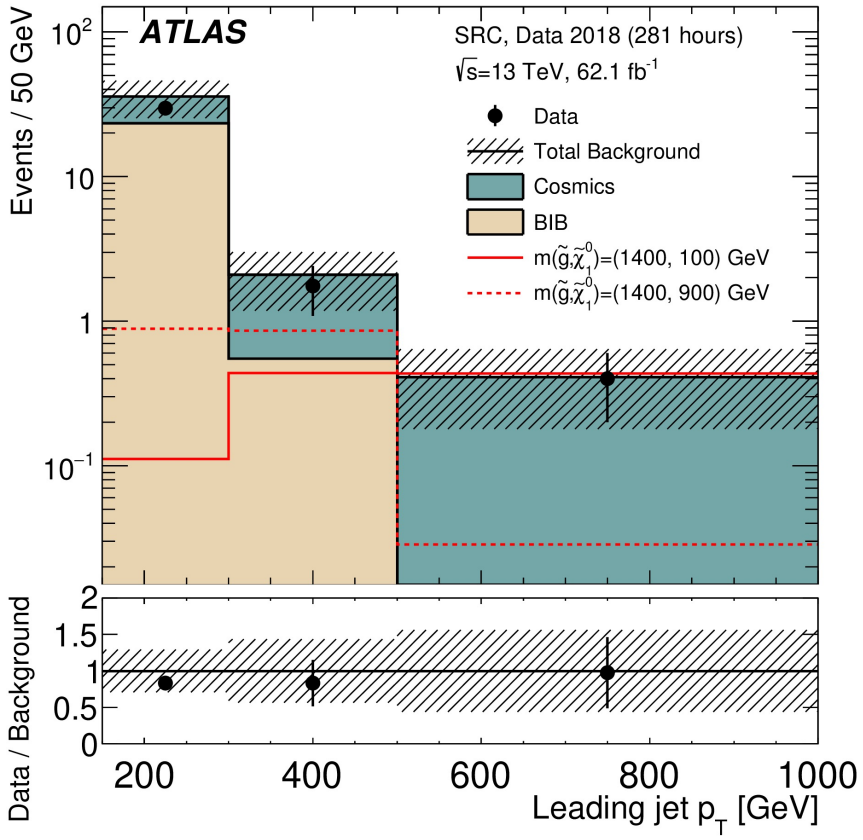


# Stopped LLPs

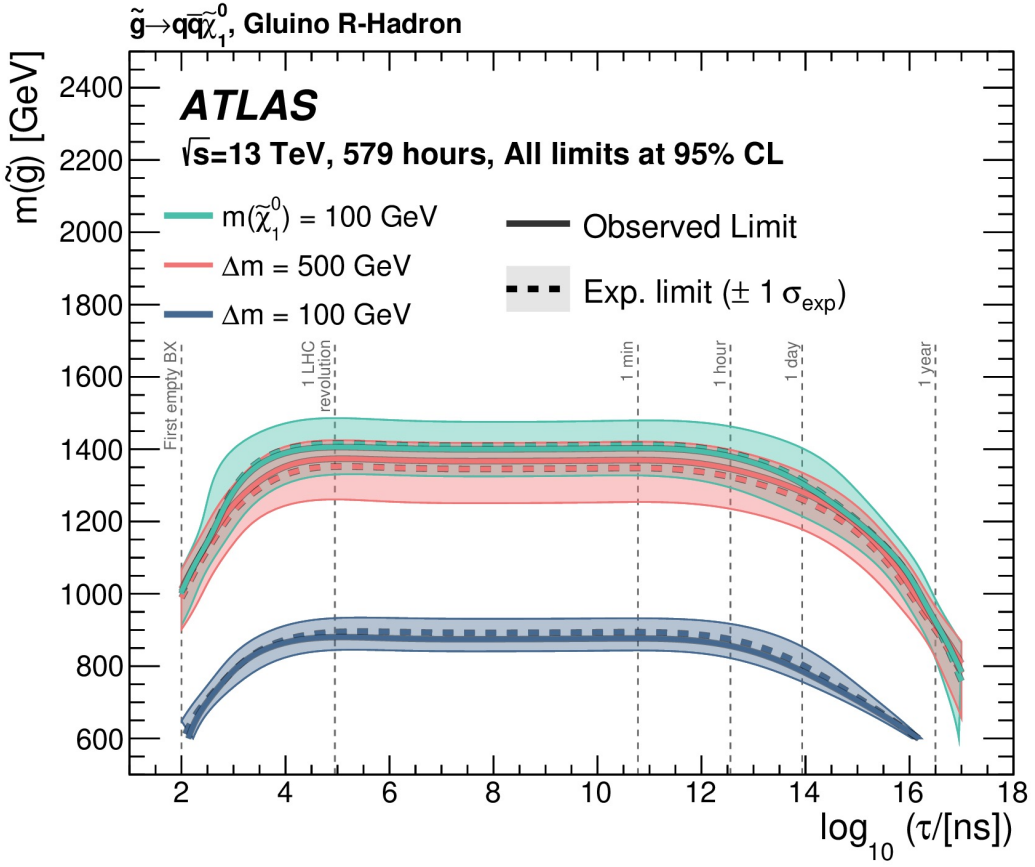
ATLAS: *JHEP 07 (2021) 173*

- Non-collision backgrounds: cosmics, beam induced background (BIB)
  - Jet $p_T$ templates extracted from data control regions




- Interpretations

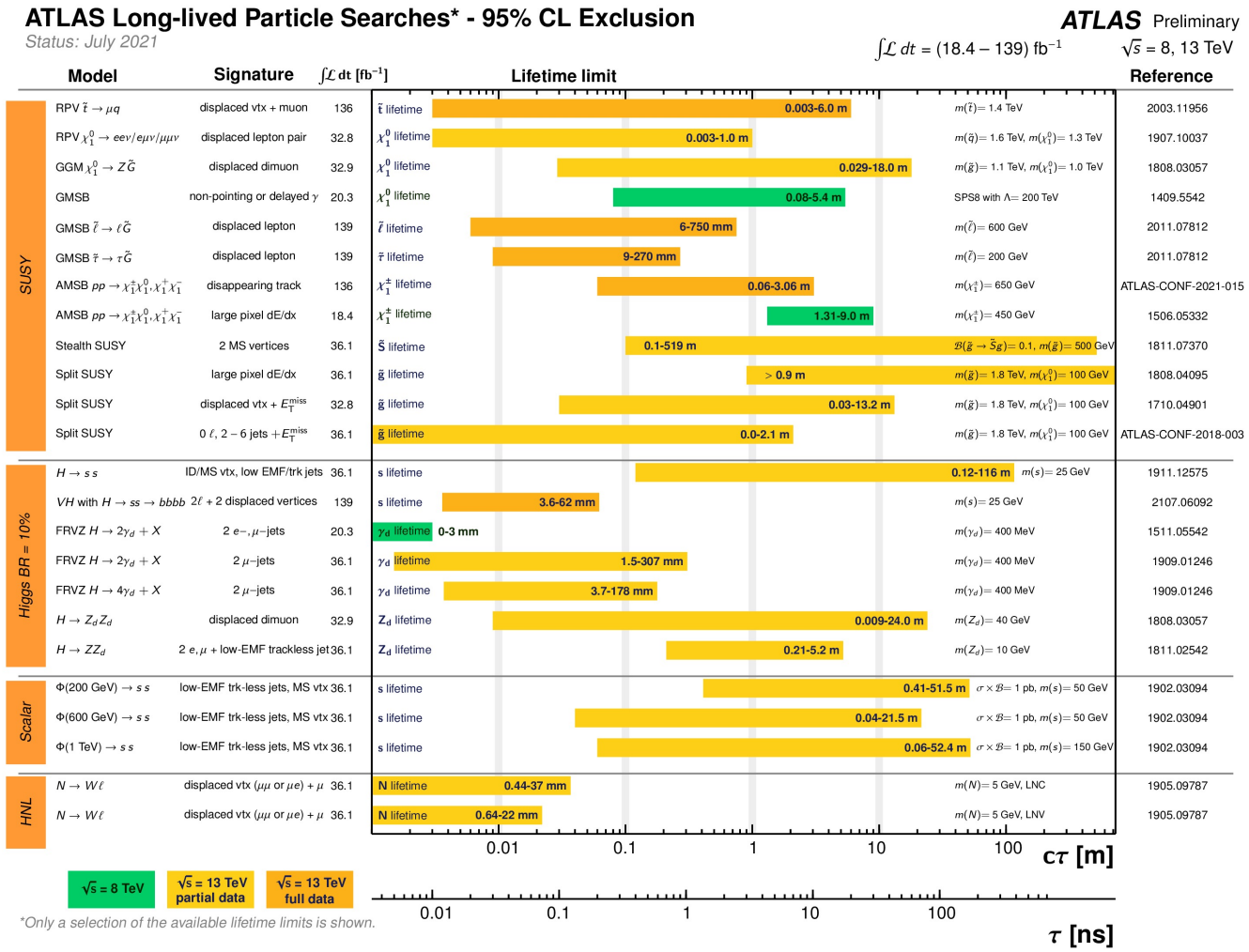
Exclude gluinos $m_{\tilde{g}} \leq 1.4$ TeV, 10 $\mu$s < $c\tau_{\tilde{g}}$ <1 day



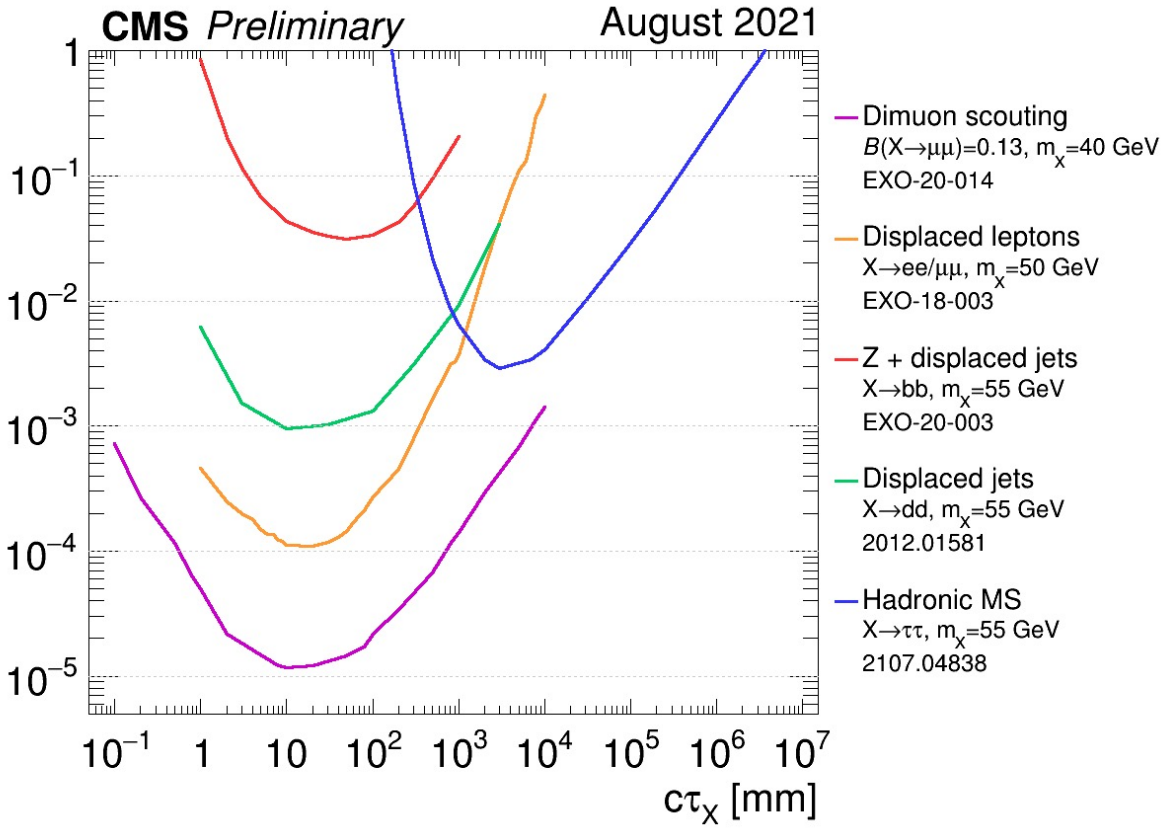
# Summary of LLP searches

ATL-PHYS-PUB-2021-033

## New particle lifetimes




## Exotic Higgs decay to LLPs with displaced jets




CMS

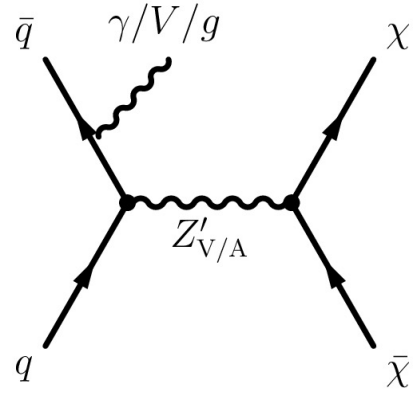
# Summary

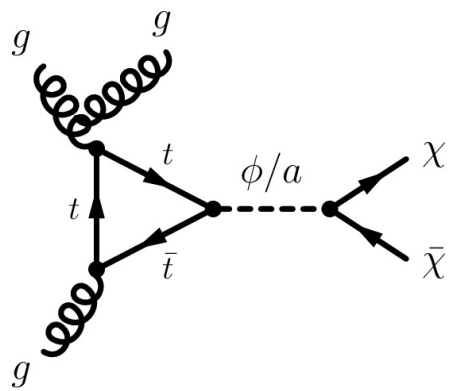
- LHC experiments are harvesting exciting new results on searches for Dark Matter and Unconventional Signatures
- DM
  - Conventional signatures exploited:
    - mono-X, resonances, H → invisible
  - Complementary to non-collider/direct searches
- Unconventional Signatures
  - Novel experimental techniques to search for long-lived particles
    - Disappearing tracks, displaced jets/leptons/vertices, stopped particles, etc
- No significant excess found and stringent constraints on various BSM models
- More searches are in progress with full Run 2 data (stay tuned!)
  - Looking forward for Run-3 and beyond

# Backup

# *s*-channel mediator models

- Model overview
  - Free parameters:
    - The DM mass $m_{DM}$
    - The mediator mass $M_{med}$
    - The coupling $g_{DM}$ of a mediator-DM-DM vertex
    - The coupling $g_q$ universal to all mediator-quark-quark vertices
    - The coupling $g_l$ universal to all mediator-lepton-lepton vertices
  - Mediator types:
    - Spin-0: scalar, pseudo-scalar
    - Spin-1: vector, axial-vector




- Rich phenomenology and complementary experimental signatures
  - Invisible searches: X+MET final states (mono-X)
  - Visible searches: resonance

LHC DM Working Group recommendations:
Phys. Dark Univ. 26 (2020) 100371
Phys. Dark Univ. 27 (2020) 100365
Phys. Dark Univ. 26 (2019) 100377

# 2HDM+pseudo-scalar

- 2HDM+pseudo-scalar Dark Matter model (U. Haisch et al JHEP05(2017)138)
  - New class of simplified models in a UV-complete, renormalizable and gauge invariant framework
  - Pseudo-scalar mediators($a \to \chi\chi$): advantage of avoiding constraints from Direct Detection experiments
  - Recommended by the LHC DM Working Group

**LHC Dark Matter Working Group: Next-generation spin-0 dark matter models**
*Phys.Dark Univ.* 27 (2020) 100351

- Phenomenology
  - Type-II 2HDM coupling structure
  - 14 in total, reduced to 5 with some assumptions: $m_a$, $m_A$, $m_\chi$, **tanβ, sinθ**
    - $m_a$ : mass of the pseudoscalar
    - **θ**: mixing between ***a*** and ***A***
    - $m_\chi$: mass of the DM particle

**2HDM**
CP-even: ***h***(*SM*), ***H***
CP-odd: ***A***
Charged bosons: $H^{\pm}$

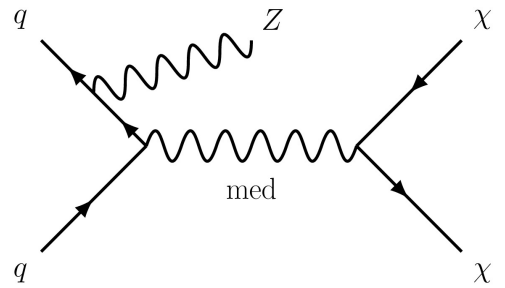


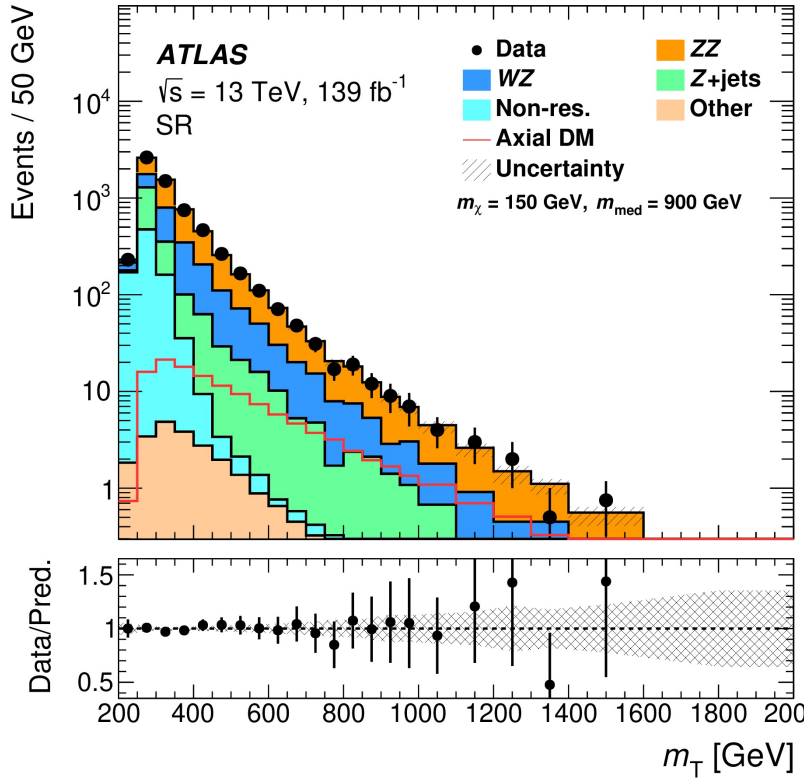
pseudo-scalar mediator: ***a***

# Mono-Z(ll)

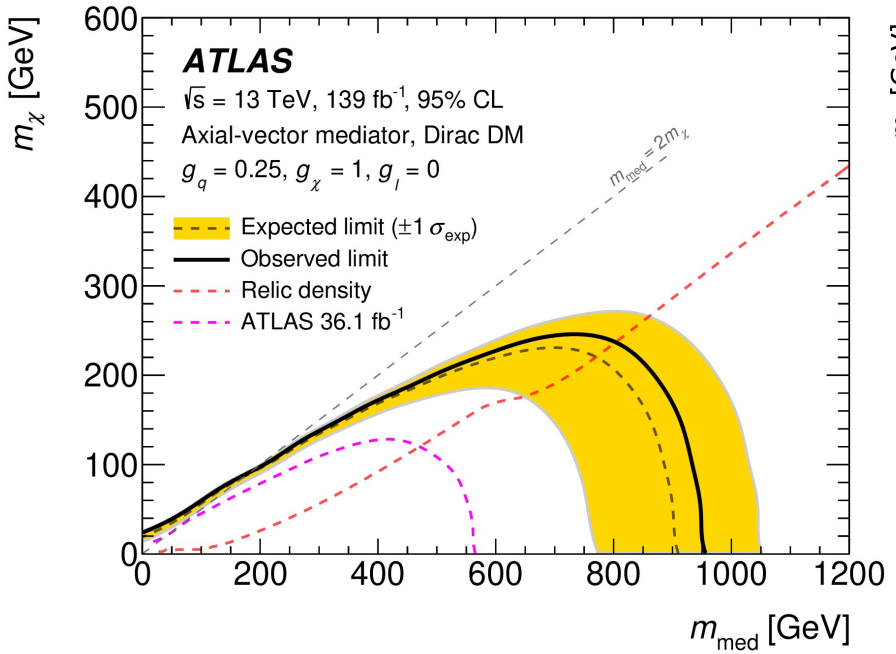
**ATLAS**: arXiv:2111.08372
**CMS**: *EPJC 81 (2021) 13*

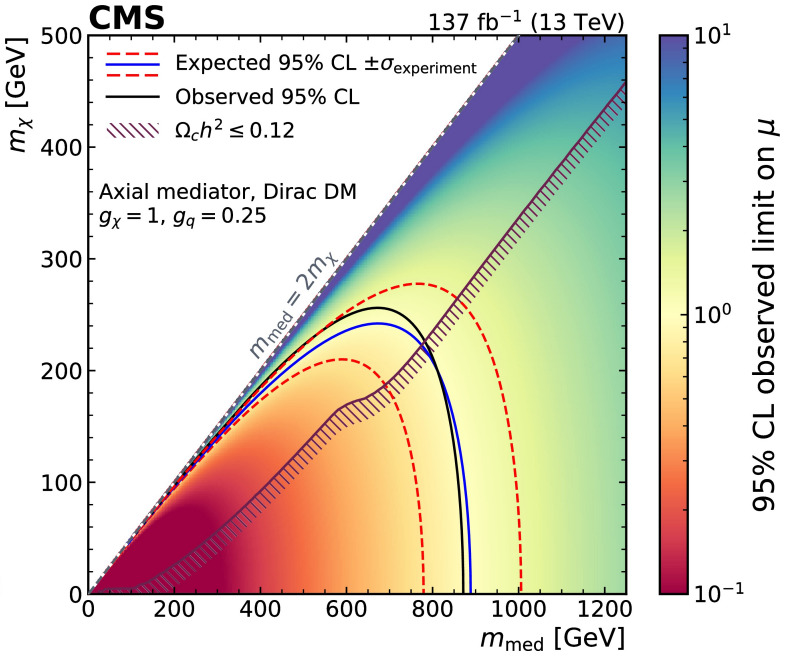
- Moderate $E_T^{miss}$ cut with lepton triggers
- Sensitive to various DM models and invisible Higgs




Axial-vector mediator



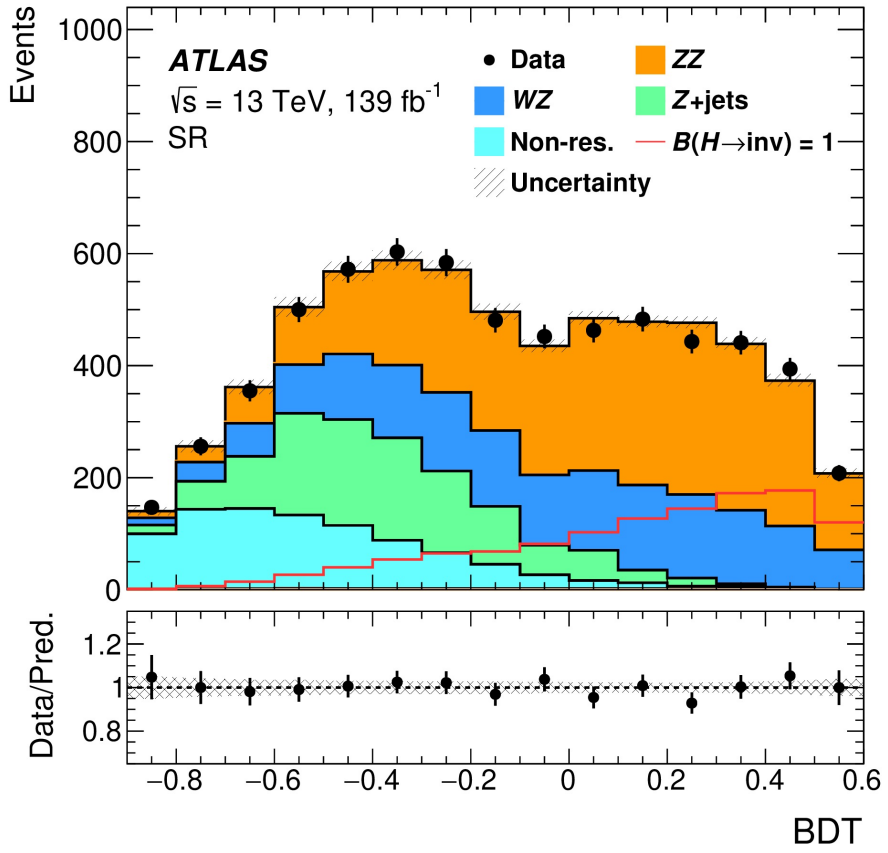
# Z(→ll)H(inv)

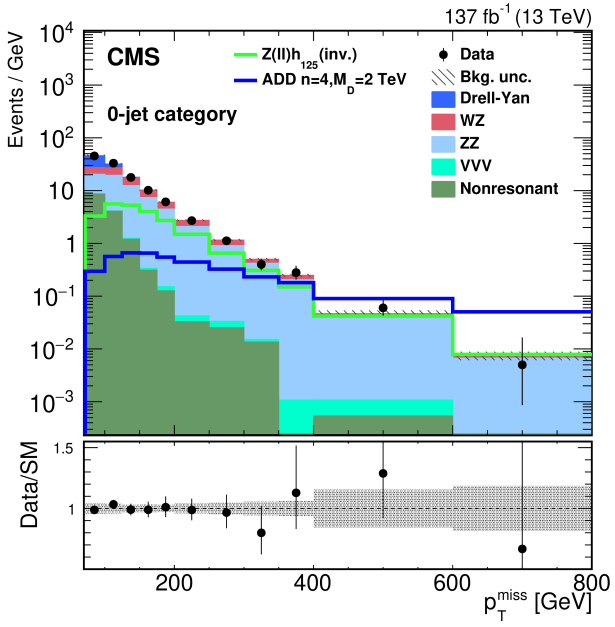
arXiv:2111.08372

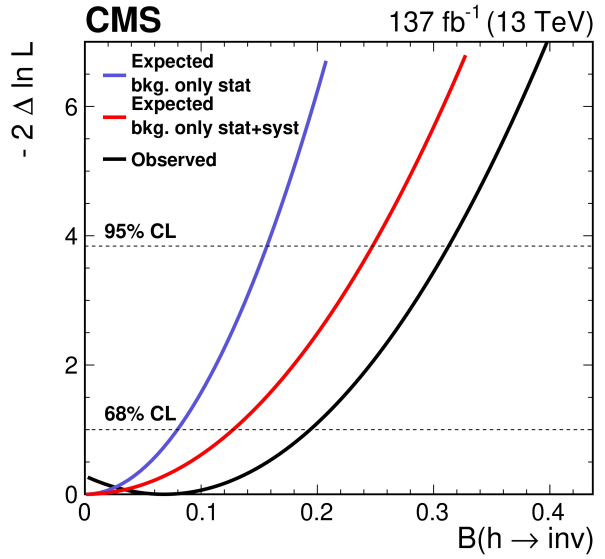
- With full Run-2 data

Br($H \rightarrow$ inv) < 19% @ 95% CL for both observed and expected

**CMS** Z(ll)Hinv: *EPJC 81 (2021) 13*
29% (25% expected) @ 95% CL



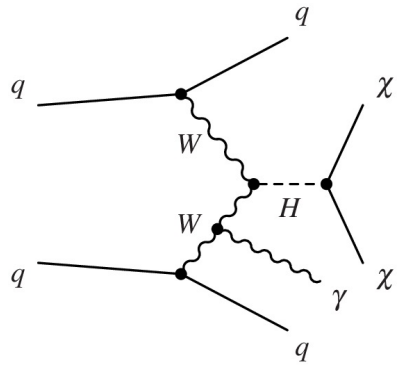



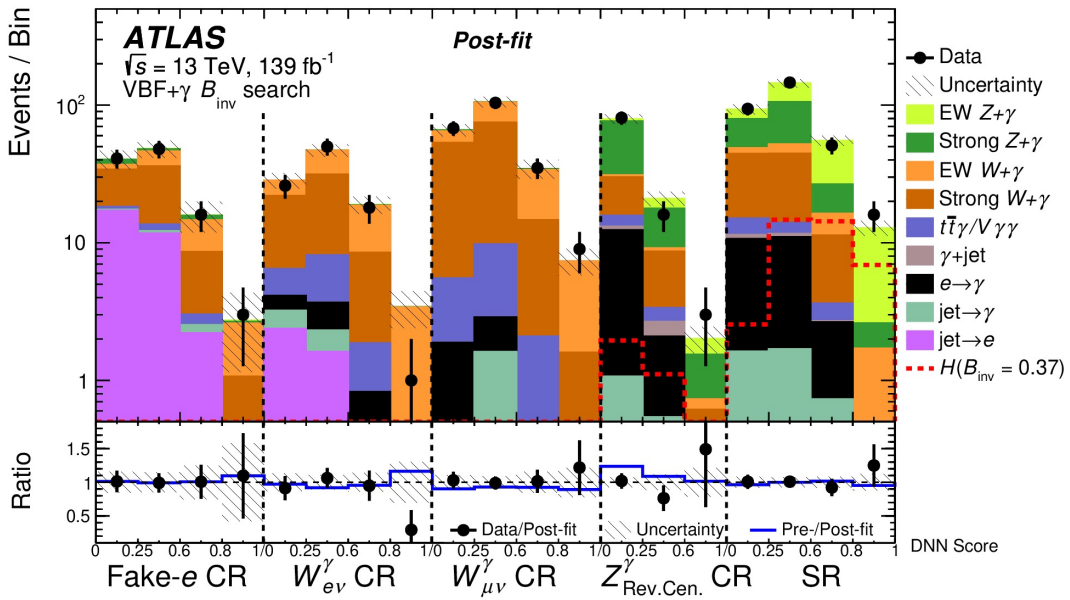



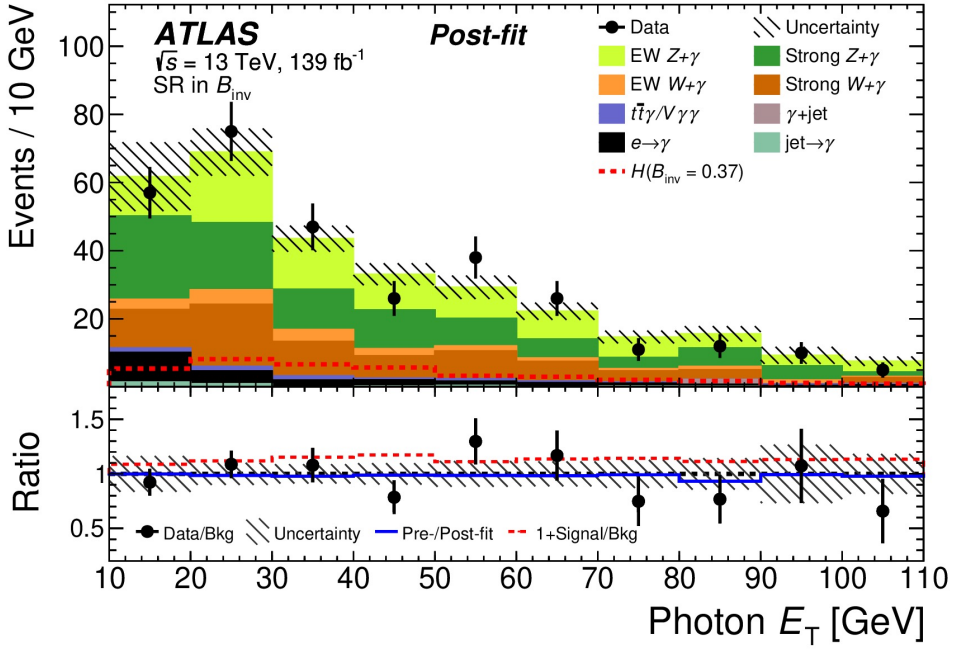
# VBF Hγ with H→invisible

**ATLAS**: arXiv:2109.00925

- Experimental signatures: two forward jets + $\gamma$ + large $E_T^{miss}$
- First search of H→inv in this final state
- Dominant background: V$\gamma$ +2j (QCD and EW)
  - Various control regions (W$\gamma$, Z$\gamma$, Fake) used in the simultaneous fit
- DNN discriminant used to extract the H→inv signal




Observed(expected) upper limits:
Br($H \rightarrow$ inv) < 37% (34%)
@ 95% CL

*See more details in Han Cui's talk*

# Direct detection limits

- Translation of the ($m_{DM}$, $M_{med}$) limits to ($m_{DM}$, $\sigma_{SI/SD}$) limits
  - A vector and scalar mediator lead to a SI interaction
  - A axial-vector and pseudo-scalar mediator induce SD interactions
    - Pseudo-scalar interaction has additional velocity-suppression in the non-relativistic limit

**Vector**

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2$$

**Axial-vector**

$$\sigma^{\rm SD} \simeq 2.4 \times 10^{-42}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2$$

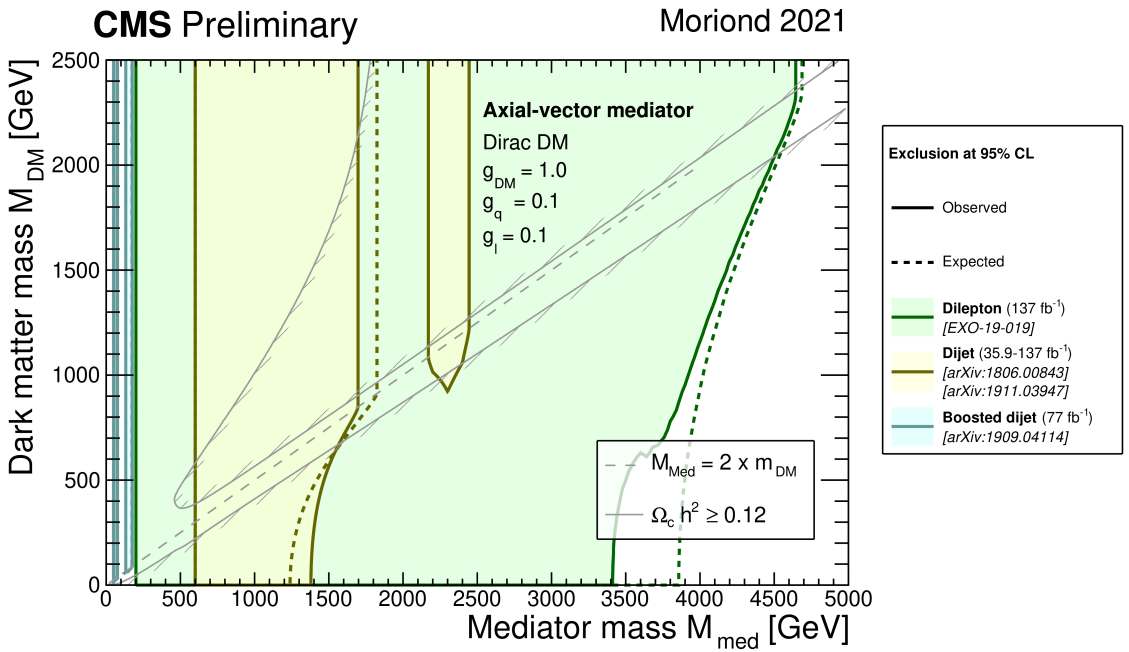
**Scalar**

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-43}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{1}\right)^2 \left(\frac{125\,{\rm GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2$$

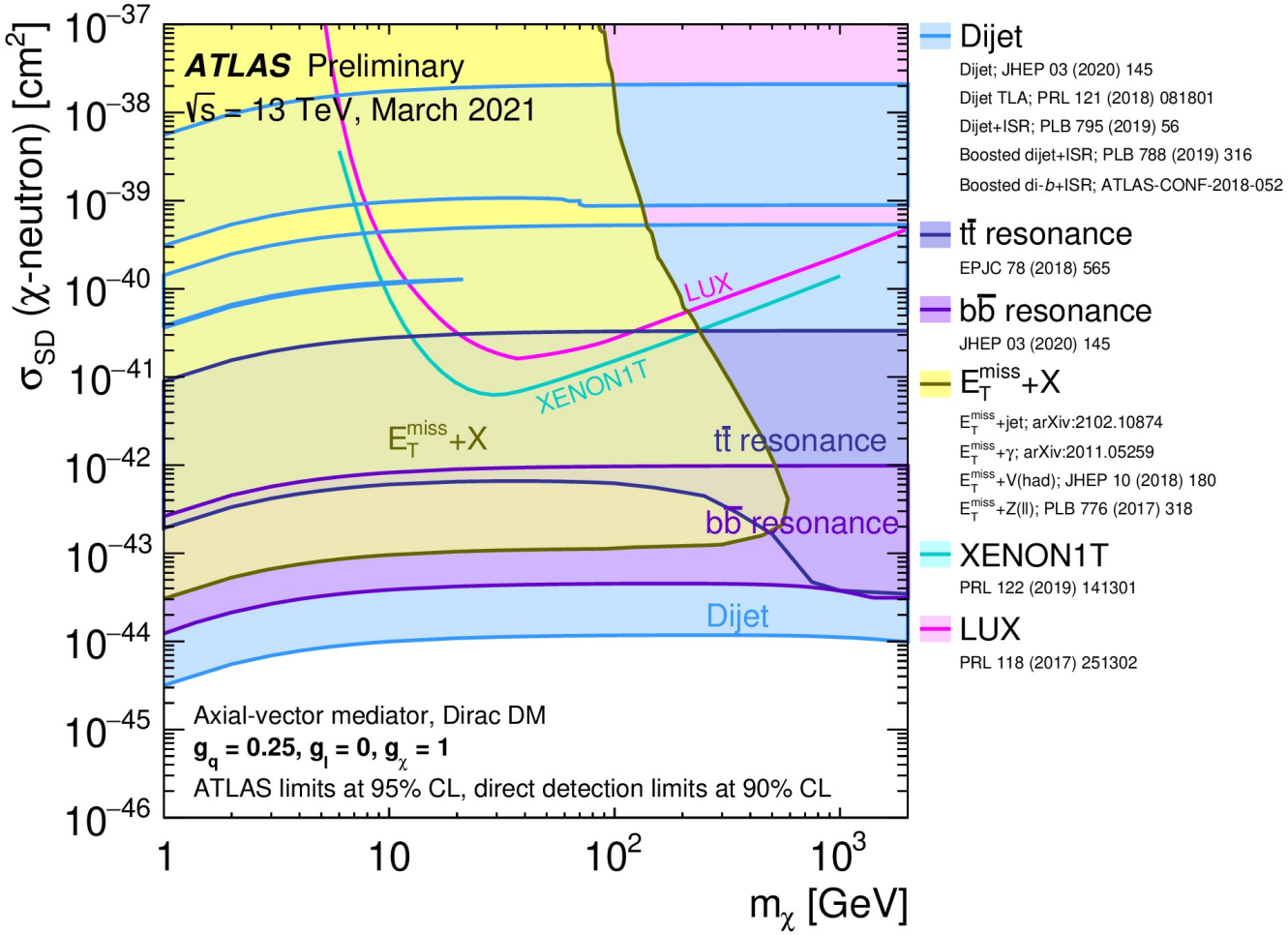
Phys. Dark Univ. 27 (2020) 100365

# Direct detection limits: *s*-channel mediators

## Axial-vector mediator




## Axial-vector mediator, leptophobic
## Spin-dependent



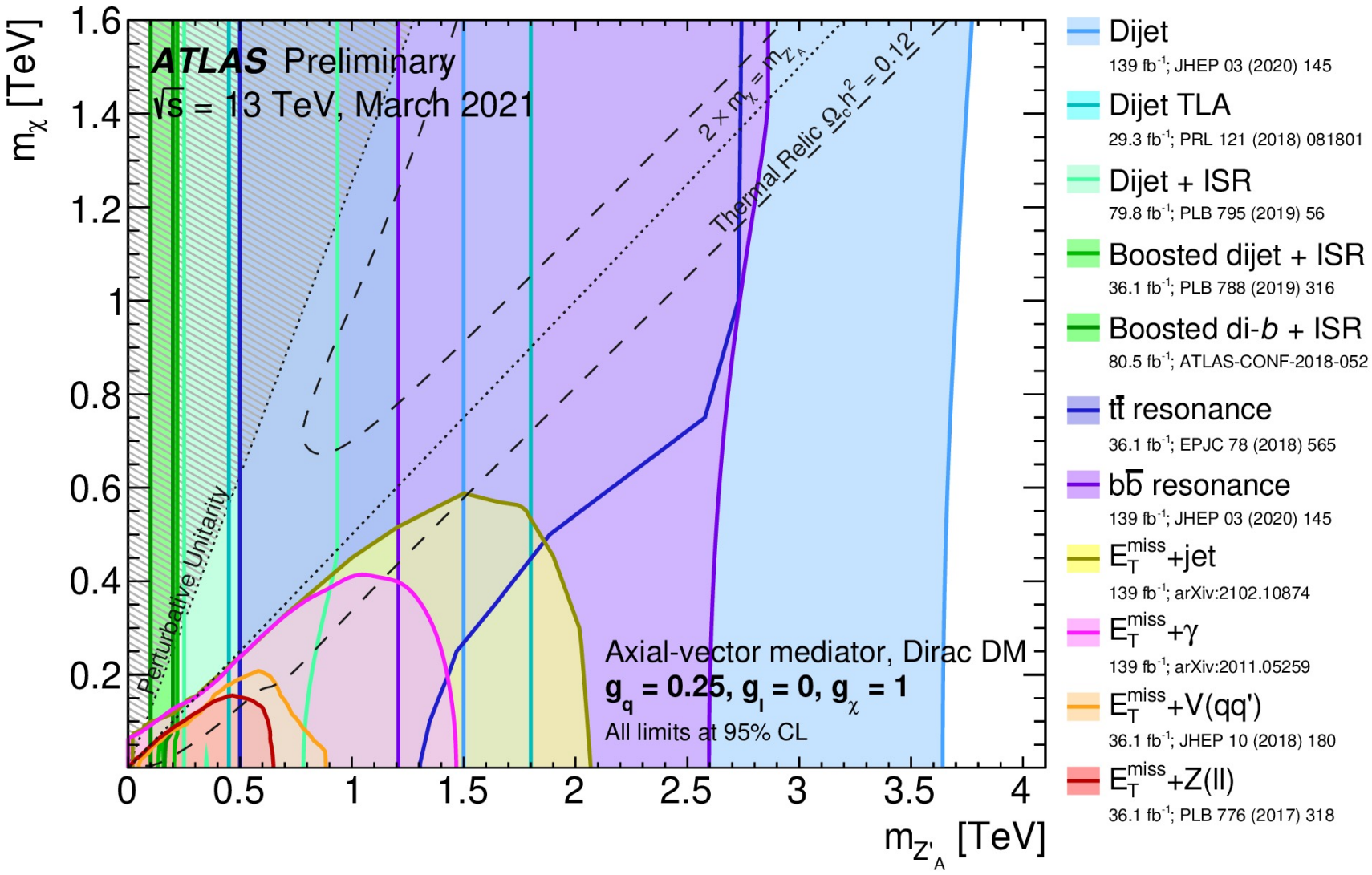

*Interpretations for other models can be found at:*

ATL-PHYS-PUB-2021-006

CMS link

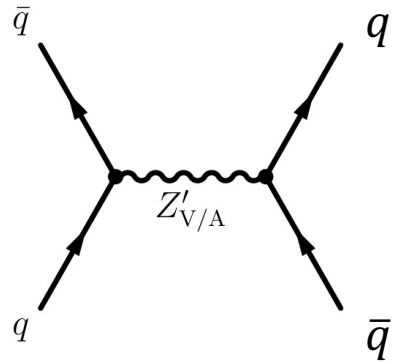
Dominant sensitivities from the LHC

# Summary of *s*-channel results



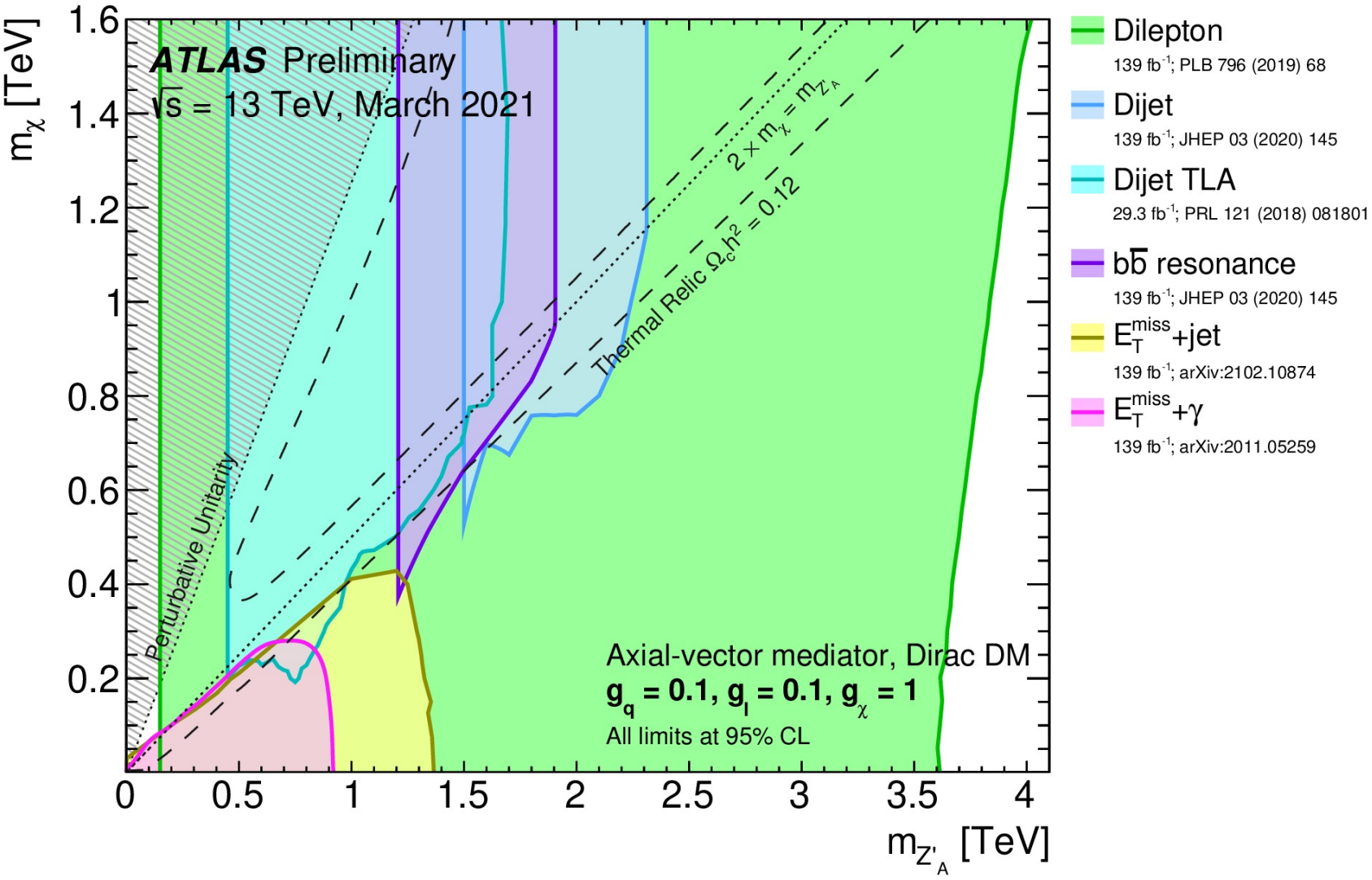

- Dijet — 139 fb$^{-1}$; JHEP 03 (2020) 145
- Dijet TLA — 29.3 fb$^{-1}$; PRL 121 (2018) 081801
- Dijet + ISR — 79.8 fb$^{-1}$; PLB 795 (2019) 56
- Boosted dijet + ISR — 36.1 fb$^{-1}$; PLB 788 (2019) 316
- Boosted di-*b* + ISR — 80.5 fb$^{-1}$; ATLAS-CONF-2018-052
- $t\bar{t}$ resonance — 36.1 fb$^{-1}$; EPJC 78 (2018) 565
- $b\bar{b}$ resonance — 139 fb$^{-1}$; JHEP 03 (2020) 145
- $E_T^{miss}$+jet — 139 fb$^{-1}$; arXiv:2102.10874
- $E_T^{miss}$+γ — 139 fb$^{-1}$; arXiv:2011.05259
- $E_T^{miss}$+V(qq') — 36.1 fb$^{-1}$; JHEP 10 (2018) 180
- $E_T^{miss}$+Z(ll) — 36.1 fb$^{-1}$; PLB 776 (2017) 318

Leptophobic axial-vector mediator
$g_l = 0$, $g_q = 0.25$




ATL-PHYS-PUB-2021-006

# Summary of *s*-channel results




Dilepton
139 fb$^{-1}$; PLB 796 (2019) 68

Dijet
139 fb$^{-1}$; JHEP 03 (2020) 145

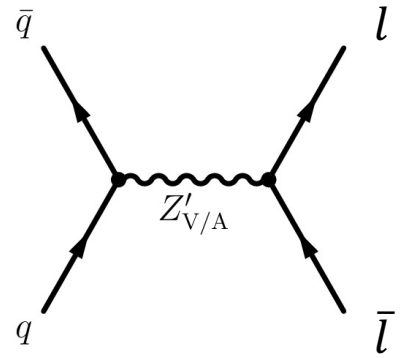
Dijet TLA
29.3 fb$^{-1}$; PRL 121 (2018) 081801

$b\bar{b}$ resonance
139 fb$^{-1}$; JHEP 03 (2020) 145

$E_T^{miss}$+jet
139 fb$^{-1}$; arXiv:2102.10874

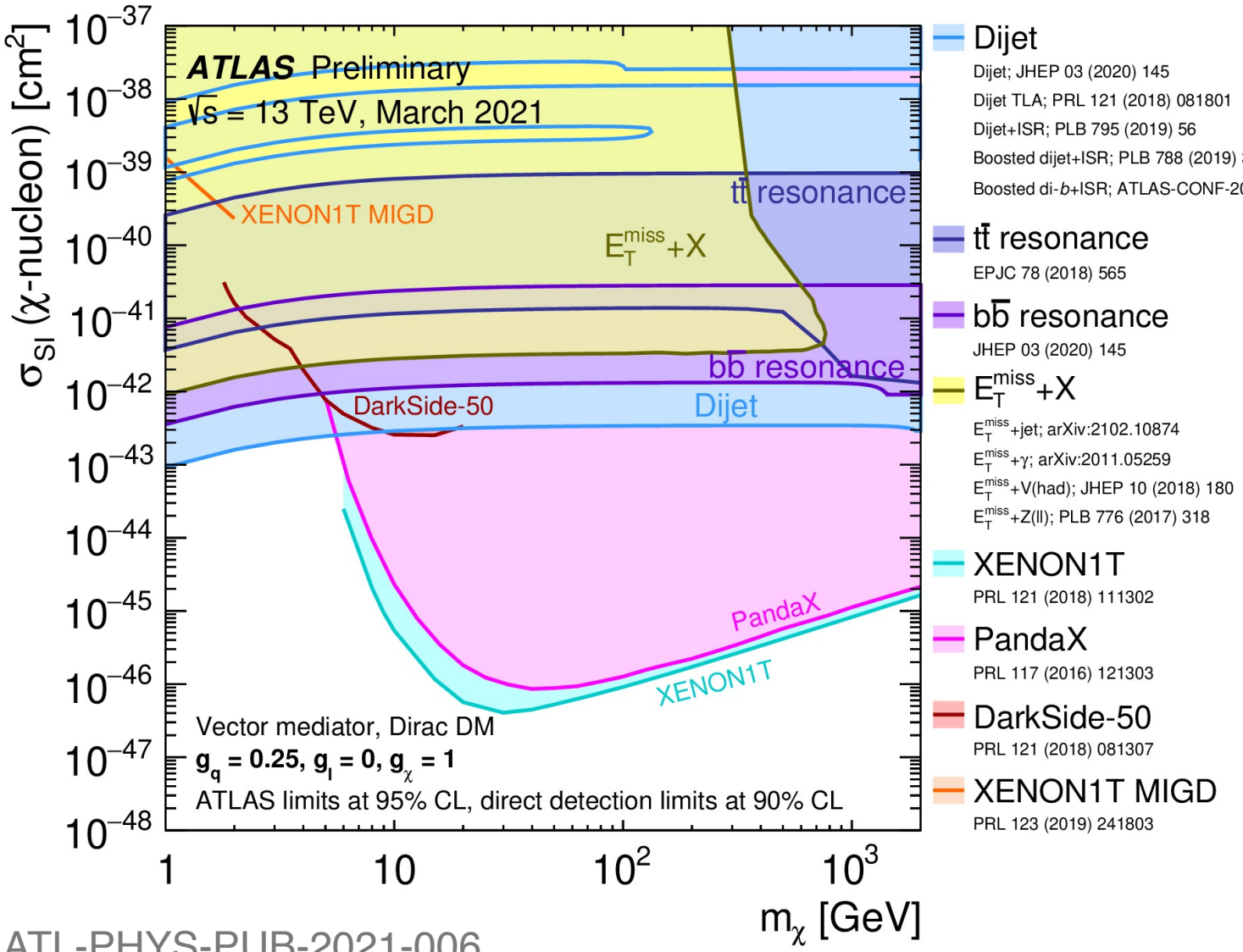
$E_T^{miss}+\gamma$
139 fb$^{-1}$; arXiv:2011.05259

Leptophilic axial-vector mediator
$g_l = g_q = 0.1$




ATL-PHYS-PUB-2021-006

# Direct detection limits




ATL-PHYS-PUB-2021-006

Vector mediator, leptophobic
Spin-independent

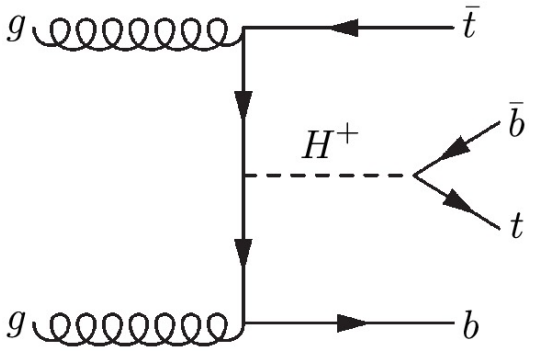
Good complementarity:
LHC: low $m_\chi$
DD: high $m_\chi$

Latest PandaX(arXiv:2107.13438) results not included yet

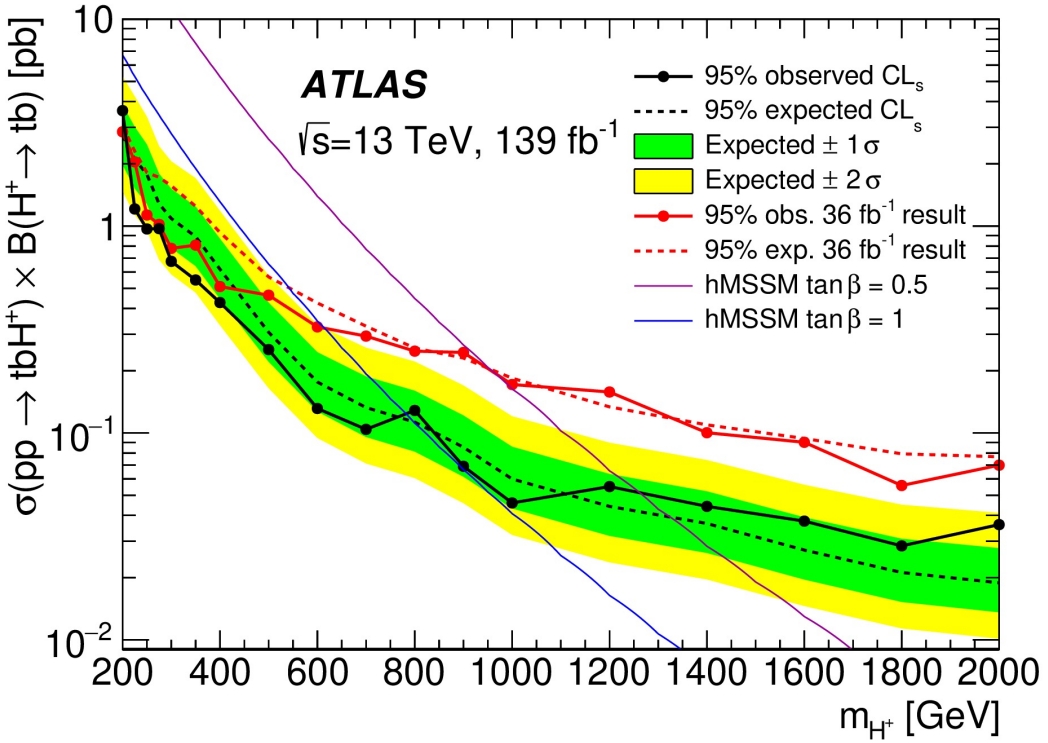
# $H^+tb$

JHEP 06 (2021) 145

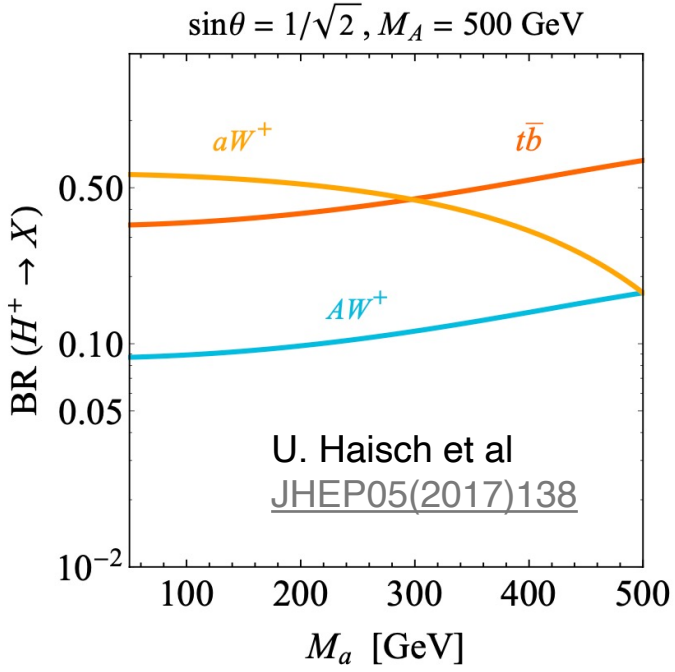
- The original analysis was targeted for 2HDM (hMSSM and $M_h^{125}$)
- Reinterpreted to 2HDM+a
  - Similar event kinematics between 2HDM-II and 2HDM+a
  - Simple cross-section X branching ratio rescaling




The same process predicted in both 2HDM-II and 2HDM+a



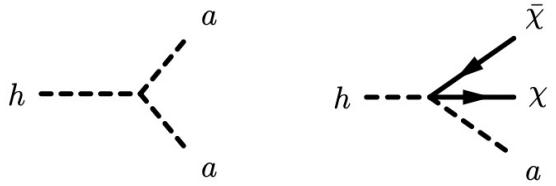

Additional decay $H^+ \rightarrow aW^+$ in 2HDM+a



# Invisible Higgs

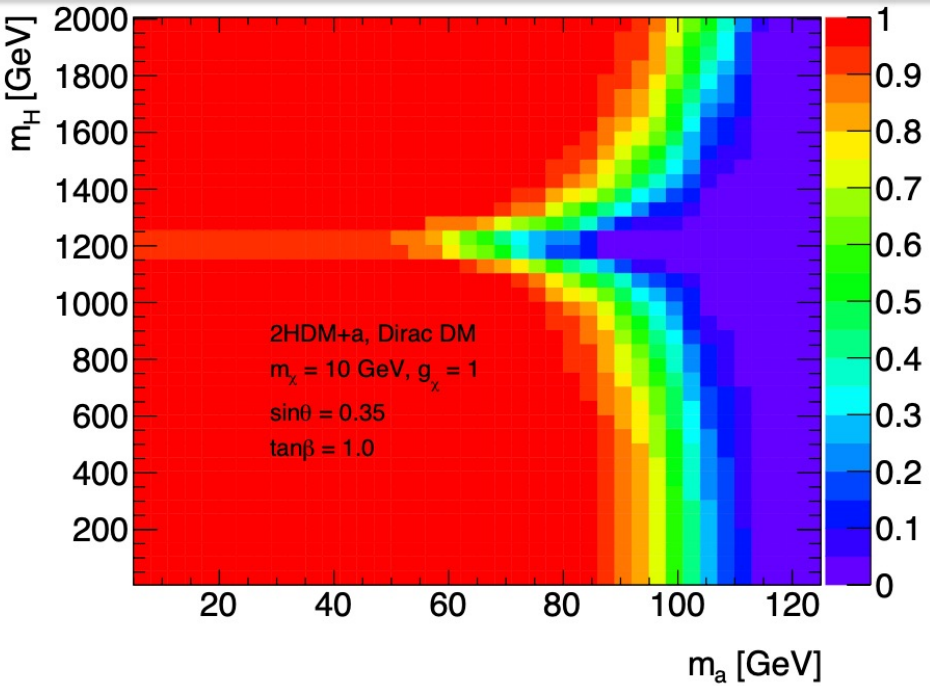
- Contributions to h → invisible in 2HDM+a:
  - For $m_a < \frac{m_h}{2}$ , on-shell: h→ aa, a →$\chi\chi$
  - For $\frac{m_h}{2} < m_a < m_h$, 3-body decay: h→ a$\chi\chi$ and h→ a$ff$

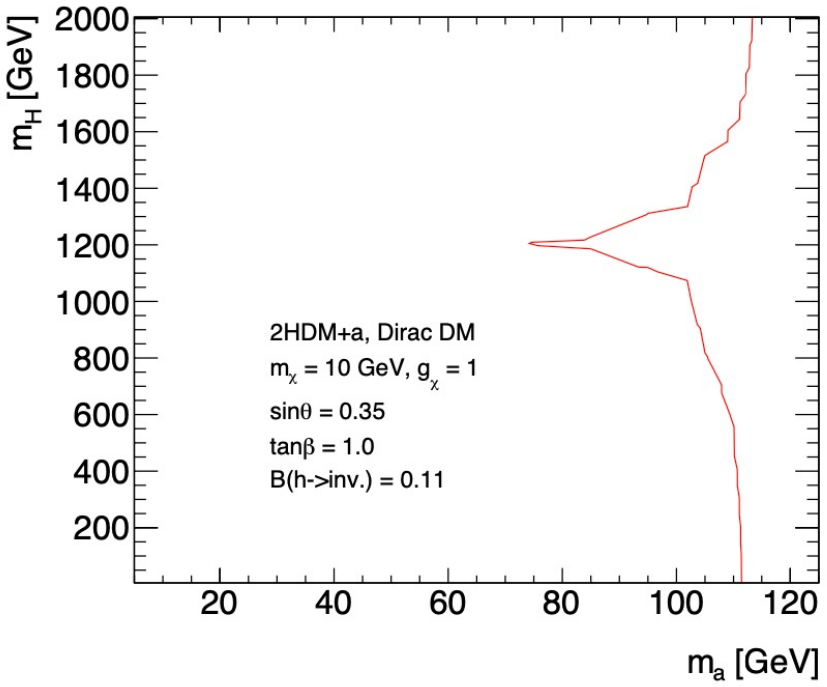
For small $m_\chi$, Br(a →$\chi\chi$) = 100%



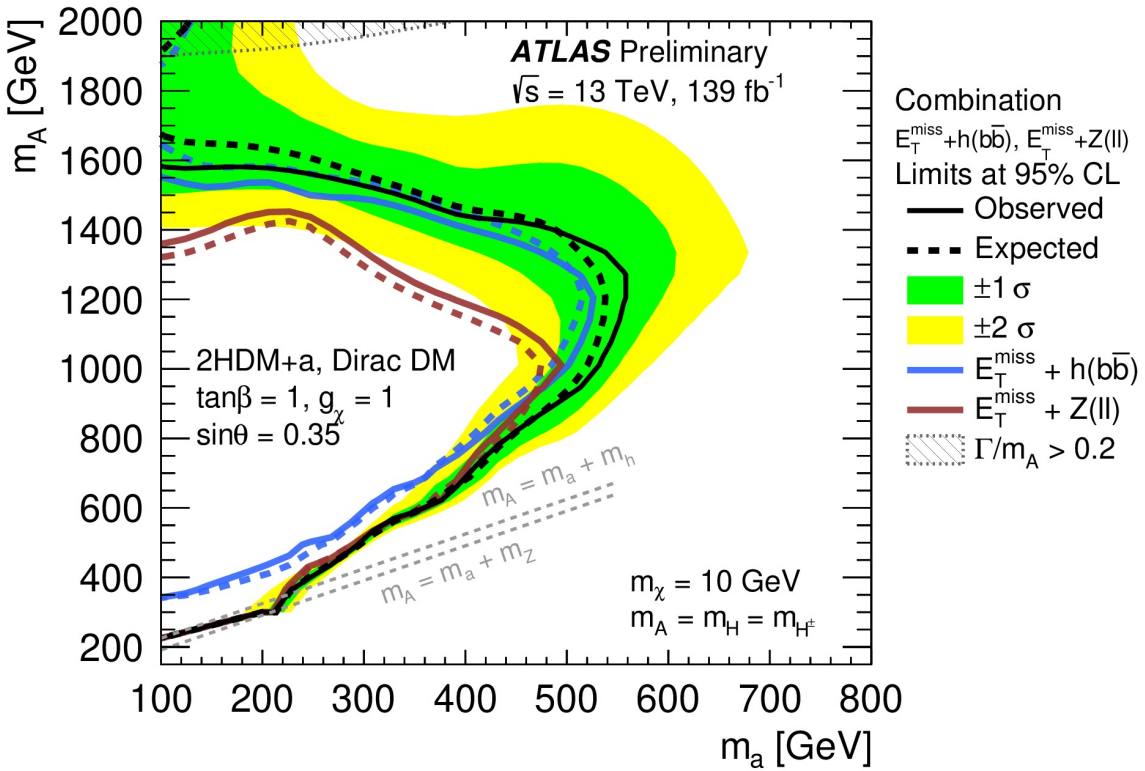

$$\mathrm{Br}(\mathrm{h} \to \mathrm{invisible}) = \frac{\Gamma^{2HDM+a}}{\Gamma^{2HDM+a} + \Gamma^{\mathrm{SM}}}$$ in 2HDM+a

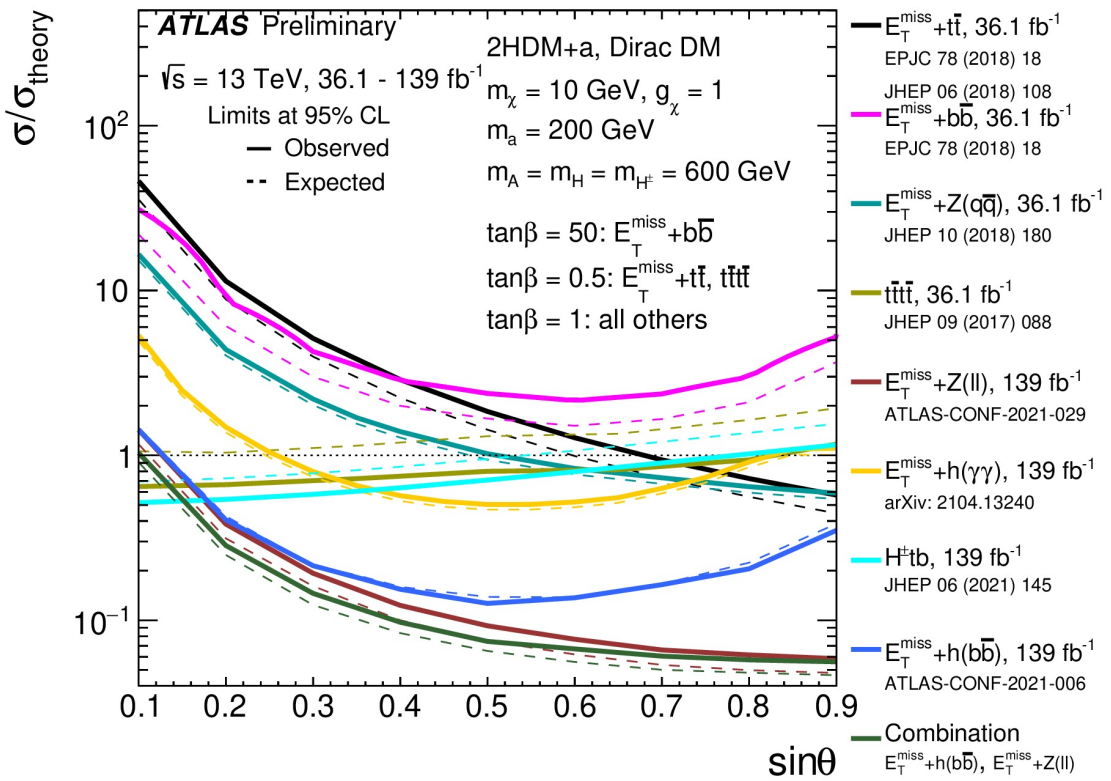
Exclusion contour by imposing Br($H$ → inv) < 11% @ 95% CL



# Combined/summary results: 2HDM+a

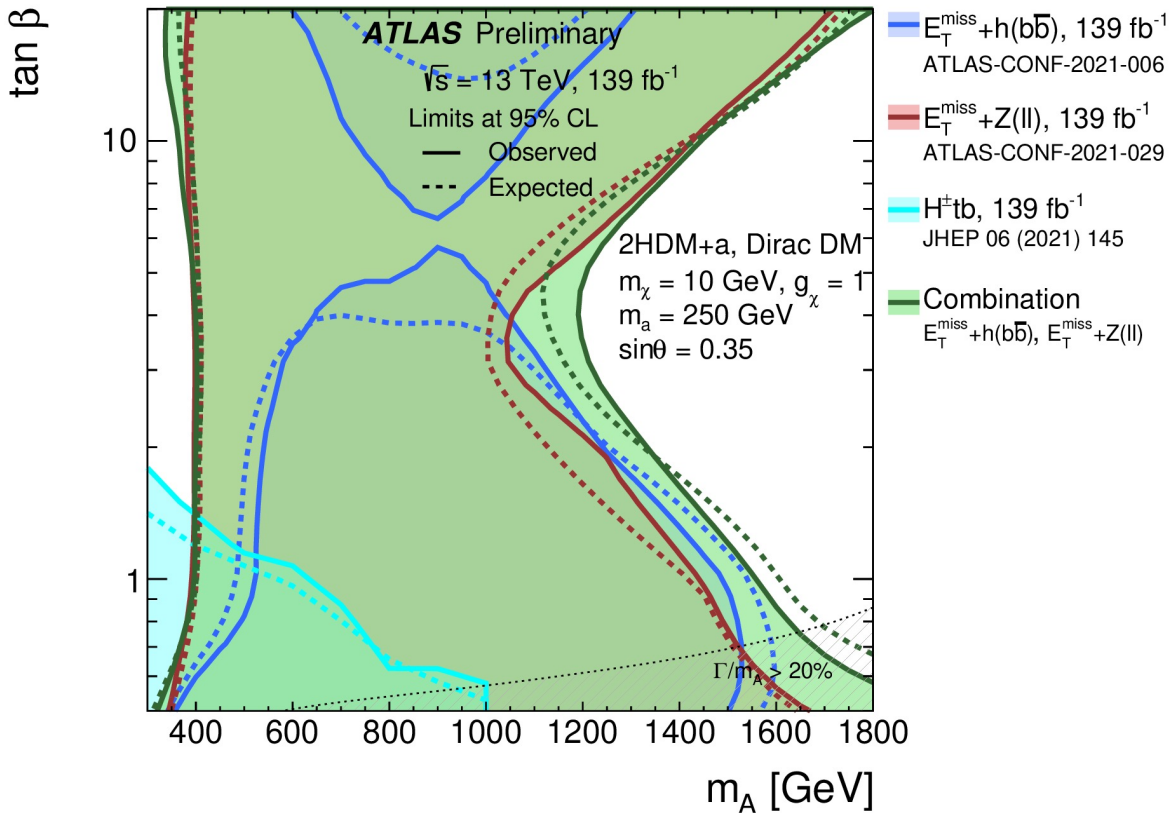


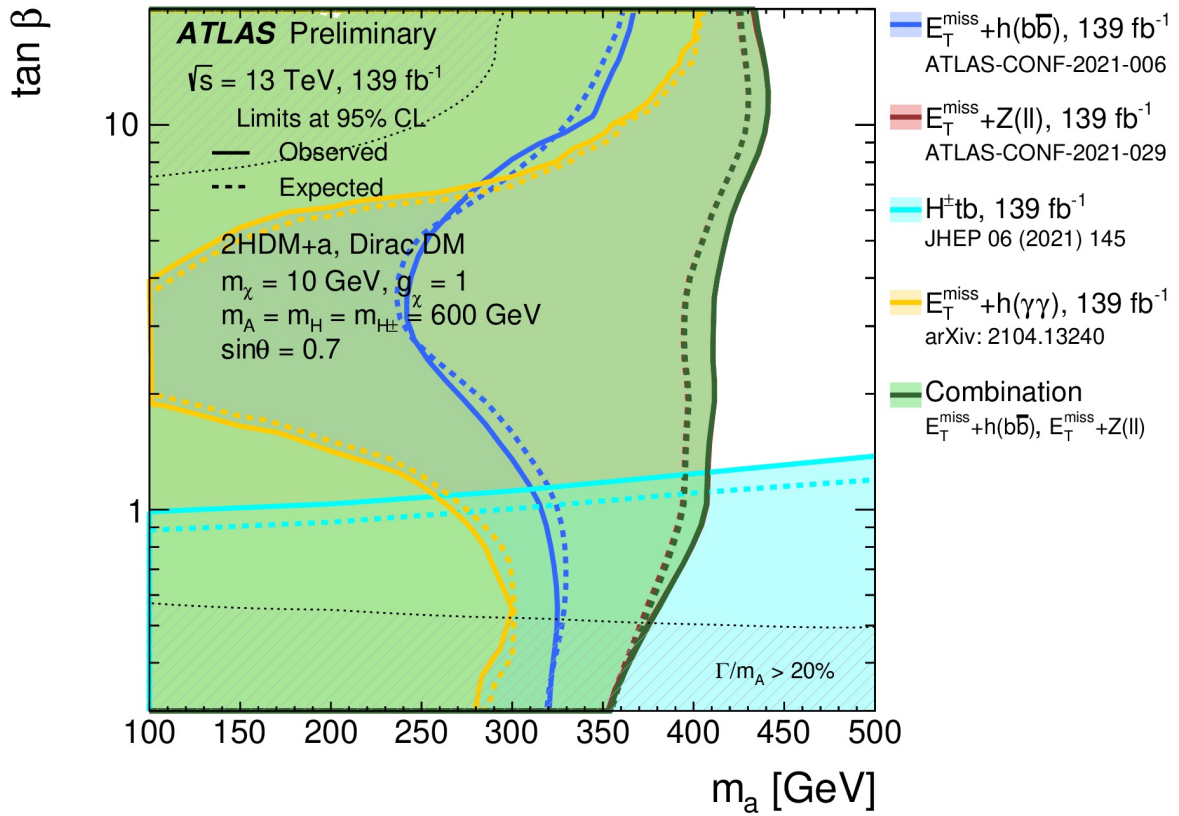
# Combined/summary results

ATLAS-CONF-2021-036

**($m_A$, tanβ)** scan, sinθ = 0.35



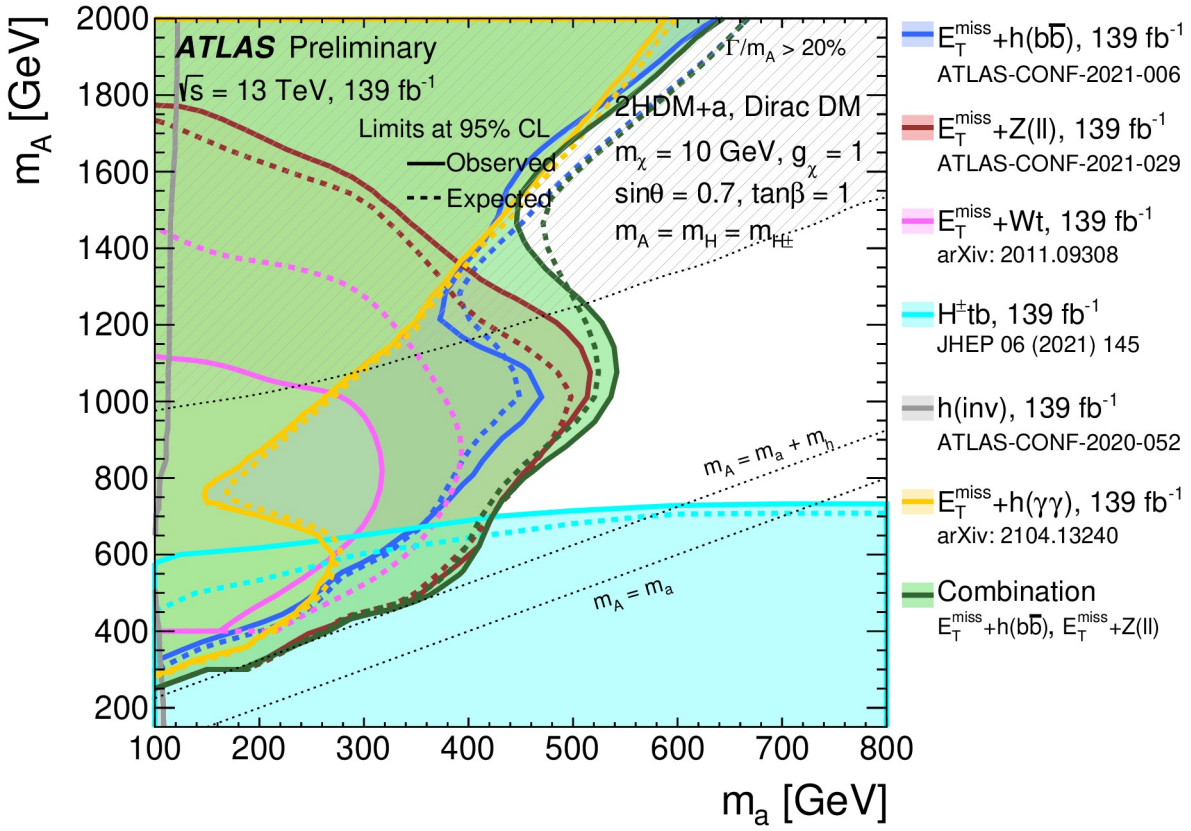

**($m_a$, tanβ)** scan, sinθ = 0.7

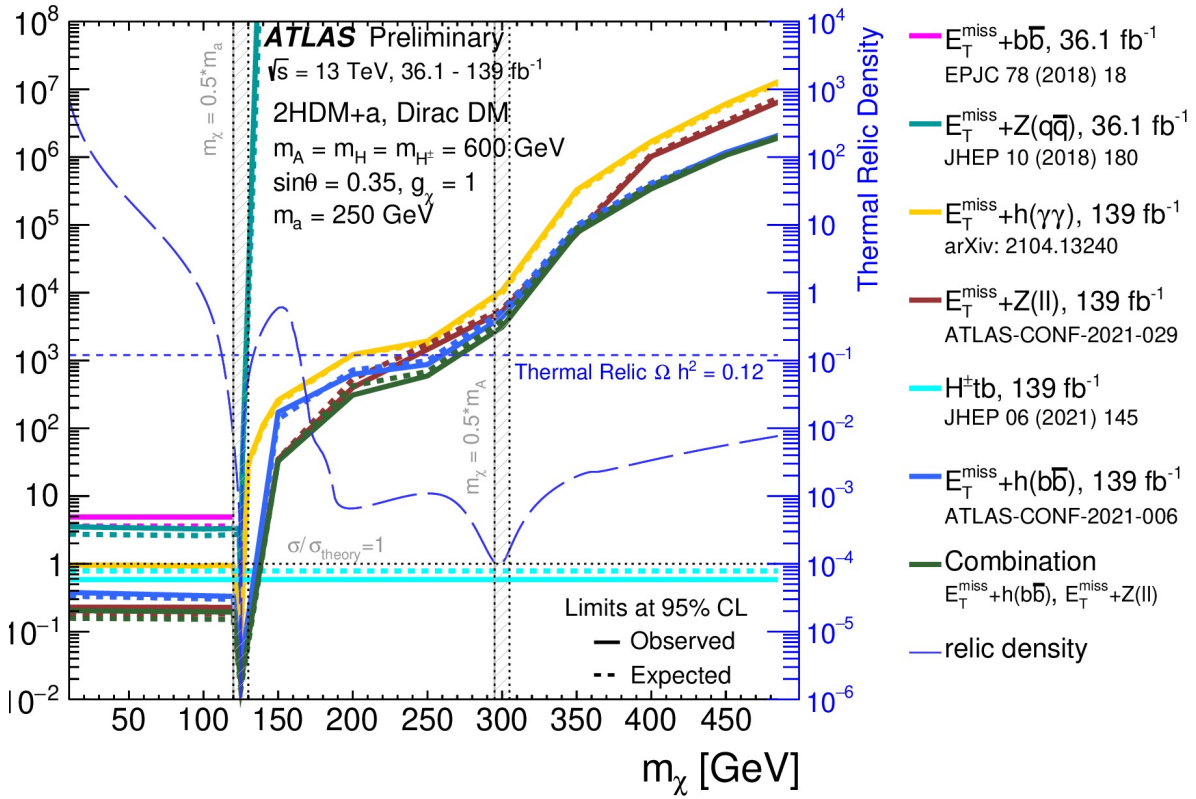


# Combined/summary results

ATLAS-CONF-2021-036

$(m_a, m_A)$ scan, sinθ = 0.7



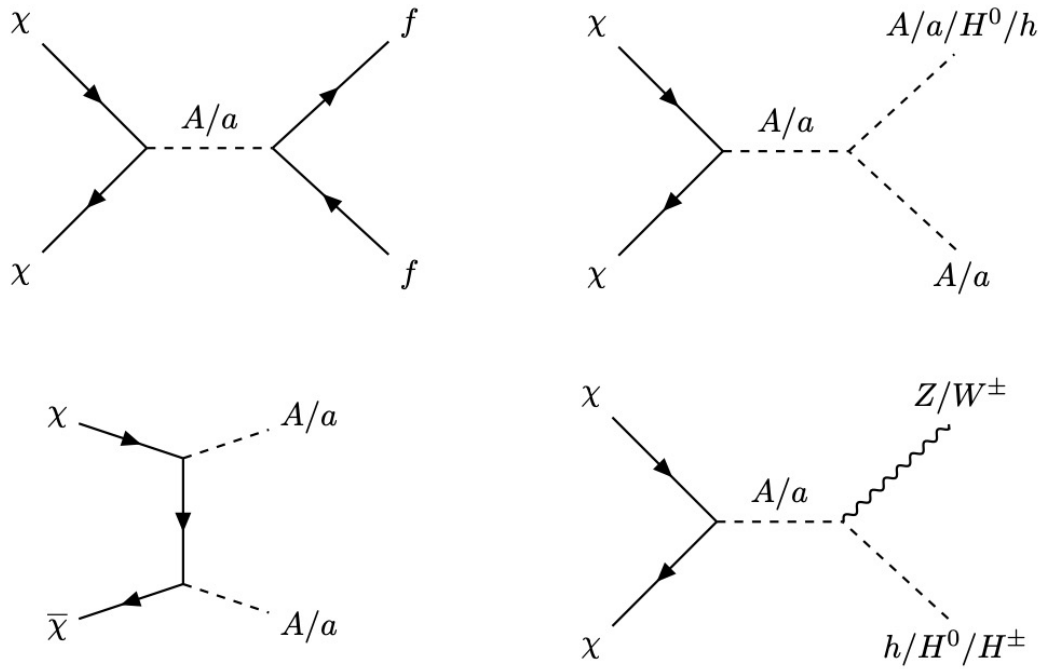




$m_a$ = 250 GeV

a→ $\chi\chi$ forbidden for $m_\chi > 0.5 * m_a$

# Relic density in 2HDM+a

*Phys.Dark Univ.* 27 (2020) 100351



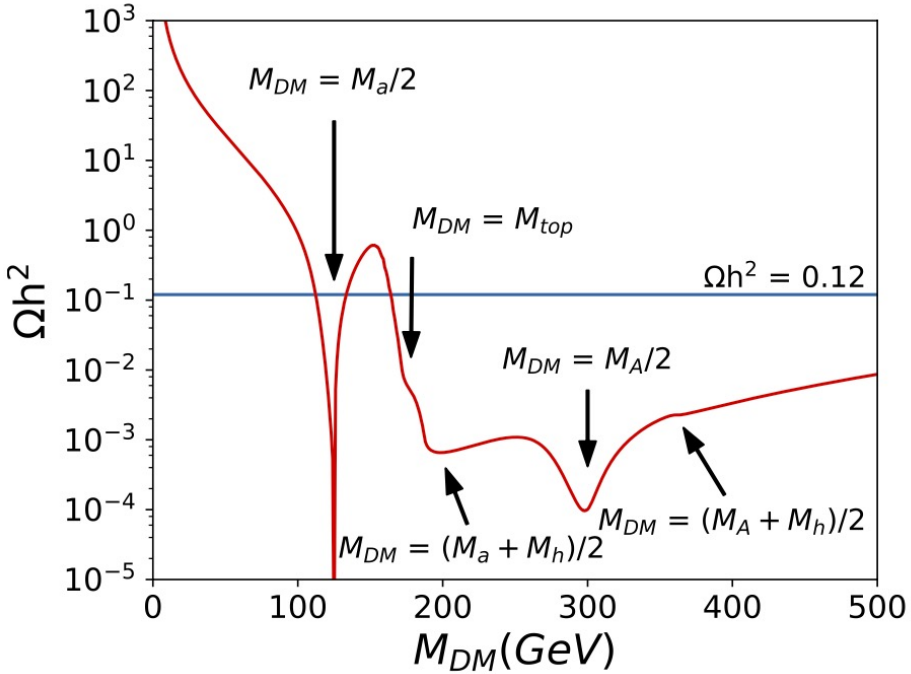
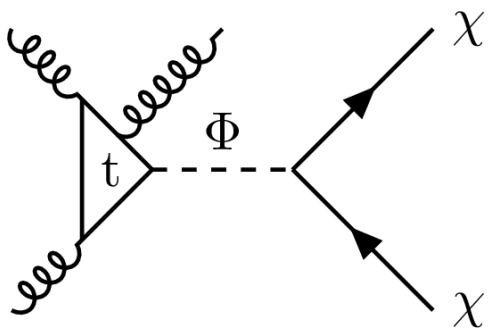



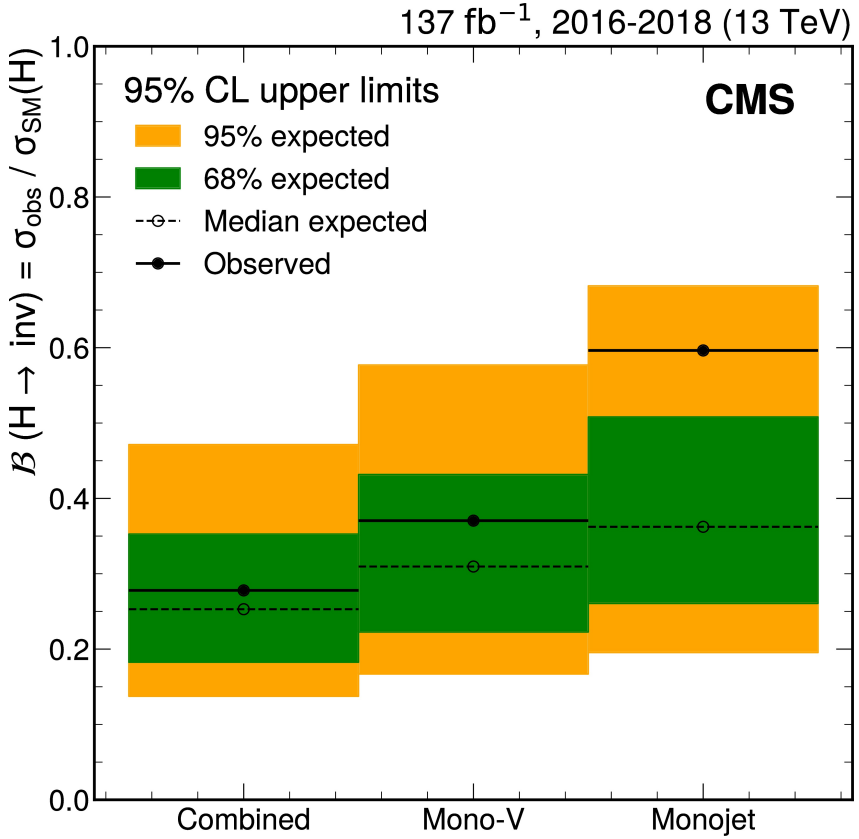

**Figure 25**: Tree-level annihilation diagrams of DM in the 2HDM+a model. Annihilation into pairs of SM fermions ($f$), spin-0 states ($h, H, A, a$) and a spin-0 particle and a EW gauge boson ($HZ$ and $H^{\pm}W^{\pm}$) are possible in the alignment limit.

# Mono-jet H(invisible)

arXiv:2107.13021

- Sensitive to ggF H(→inv) and V(qq)H(→inv)

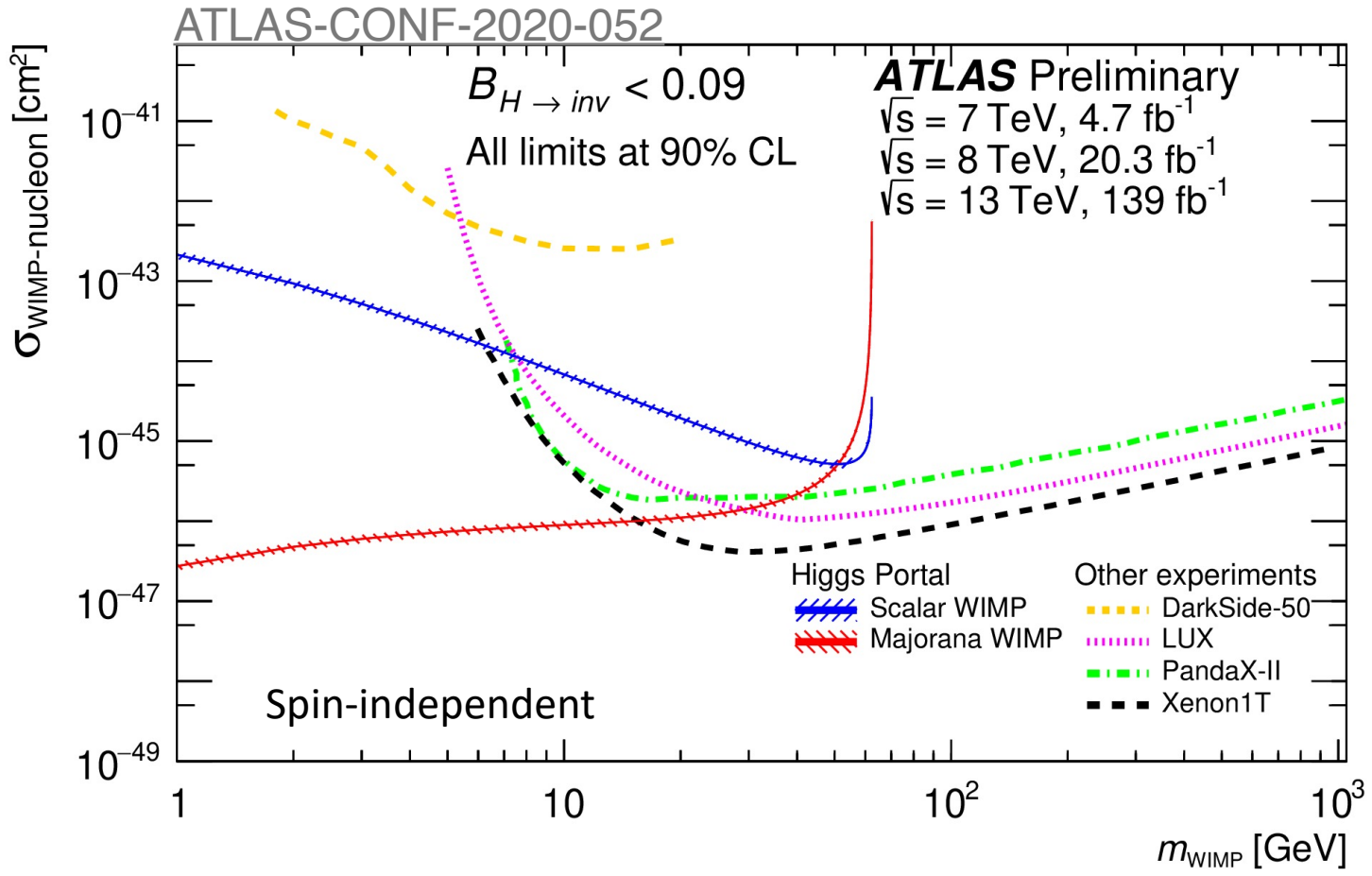


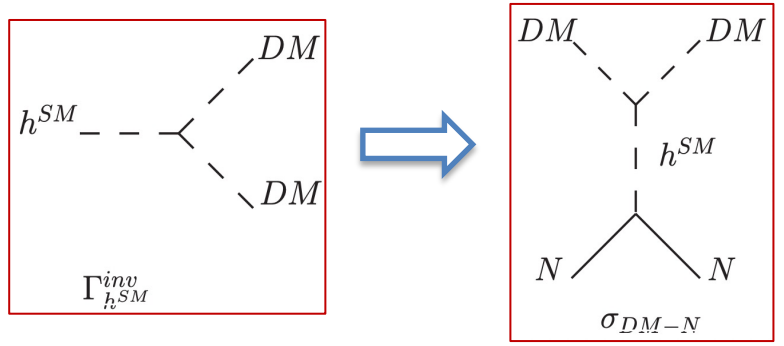



# Direct detection limits: invisible Higgs

- Translate the limit on Br(H→inv) to $\sigma_{WIMP\text{-}N}$ in the Effective Field Theory approach

$$\Gamma_H^{\text{inv}} = \frac{\text{Br}(H \to \text{inv})}{1 - \text{Br}(H \to \text{inv})} \cdot \Gamma_H^{\text{SM}}$$




**Scalar WIMP**

$$\Gamma^{\text{inv}}_{H\to SS} = \frac{\lambda^2_{HSS} v^2 \beta_S}{64\pi m_H},$$

$$\sigma^{\text{SI}}_{SN} = \frac{\lambda^2_{HSS}}{16\pi m_H^4} \frac{m_N^4 f_N^2}{(m_S + m_N)^2},$$

**Fermion WIMP**

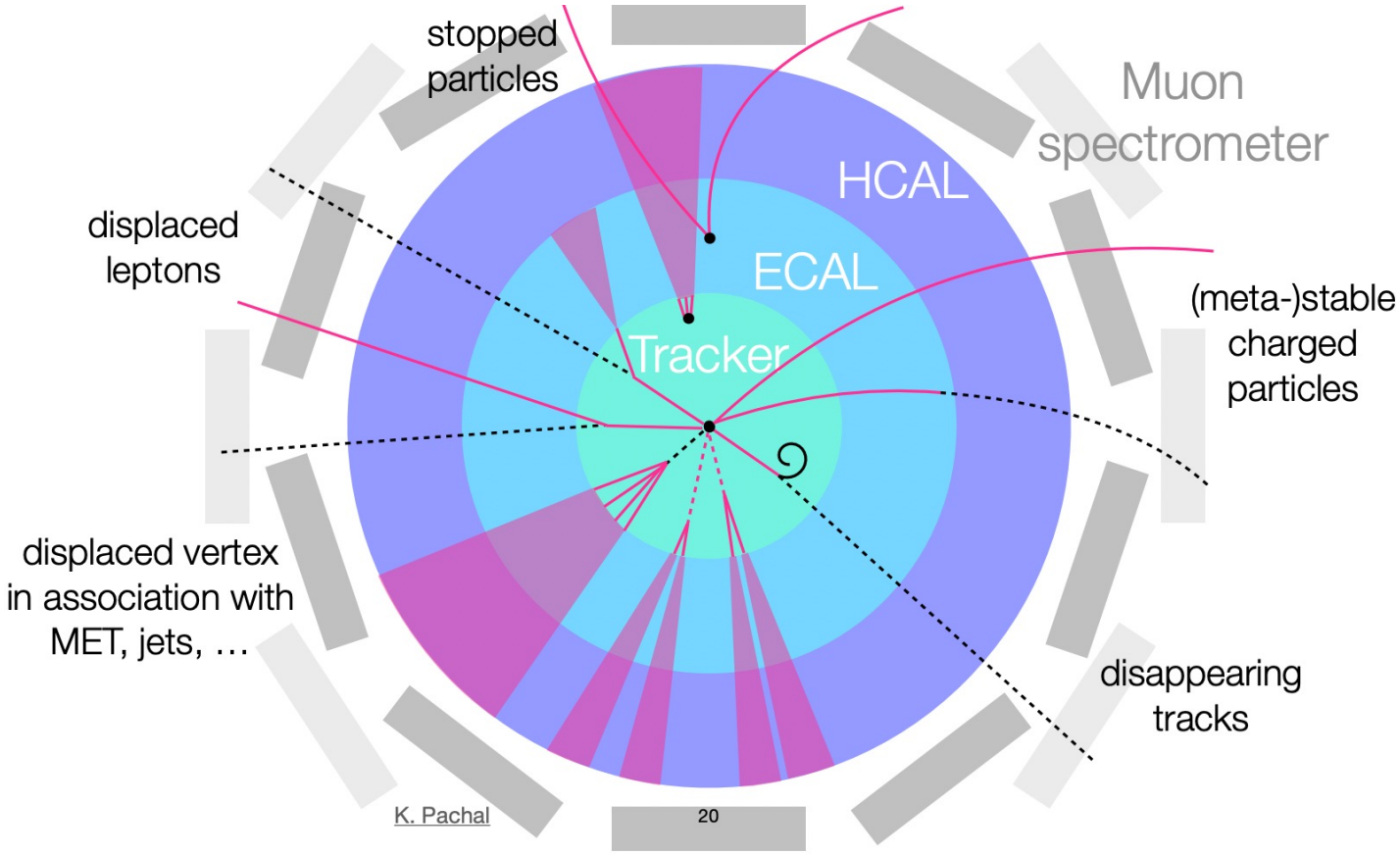
$$\Gamma^{\text{inv}}_{H\to ff} = \frac{\lambda^2_{Hff} v^2 m_H \beta_f^3}{32\pi\Lambda^2}$$

$$\sigma^{\text{SI}}_{fN} = \frac{\lambda^2_{Hff}}{4\pi\Lambda^2 m_H^4} \frac{m_N^4 m_f^2 f_N^2}{(m_f + m_N)^2}$$

# Unconventional signatures: what?

- Experimental definition: a customized reconstruction is needed
  - Long-lived particles (LLP): proper lifetime range that detectors not designed for
  - q≠e: highly ionizing particles

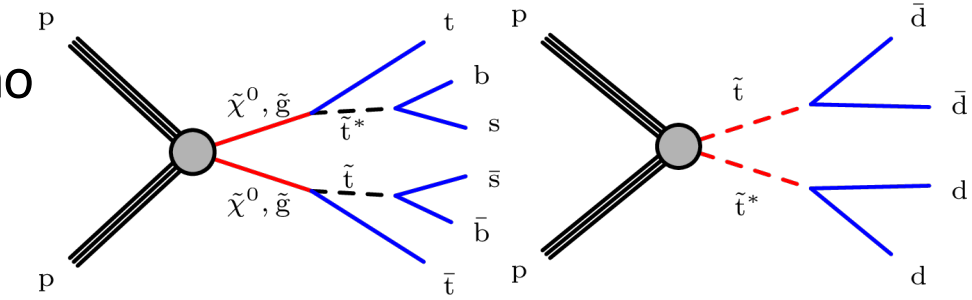
- Disappearing tracks
- Displaced leptons/jets/vertices
- Stopped particles



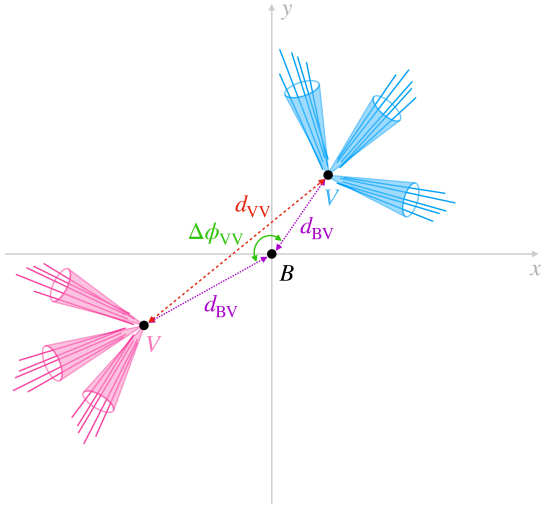
# Displaced vertices

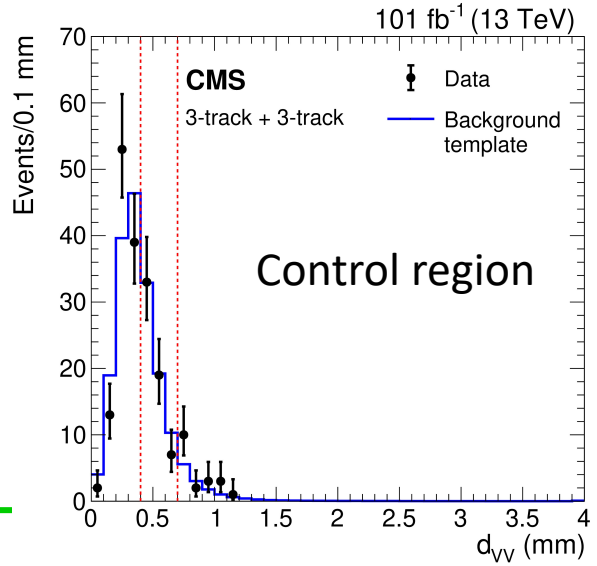
CMS: arXiv:2104.13474

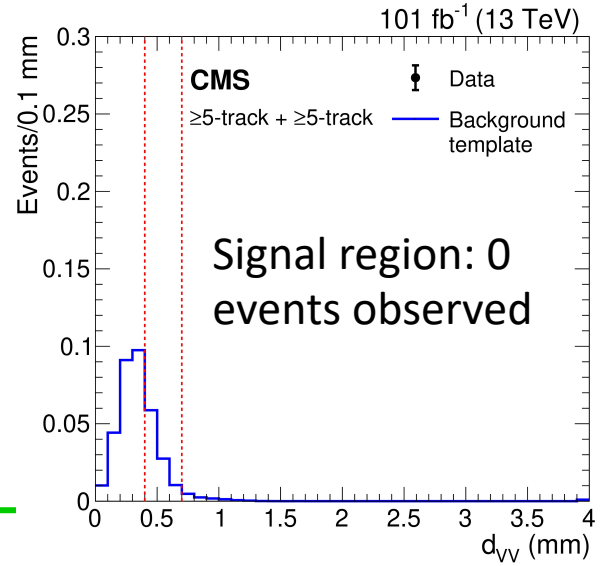
- Targets pairs of LLPs with $0.1 < c\tau < 100$ mm, decays into at least two jets, resulting in a final state with two displaced vertices
  - Multijet signal model: SUSY RPV long-lived neutralino/gluino
  - Dijet signal model: s-top quarks




- Search strategy:
  - Select events that contain at least two vertices each with $\geq 5$ tracks
  - Background template obtained from one-vertex events and validated in two-vertex control regions
  - Discriminant: distance between two vertices in the x-y plane ($d_{VV}$)



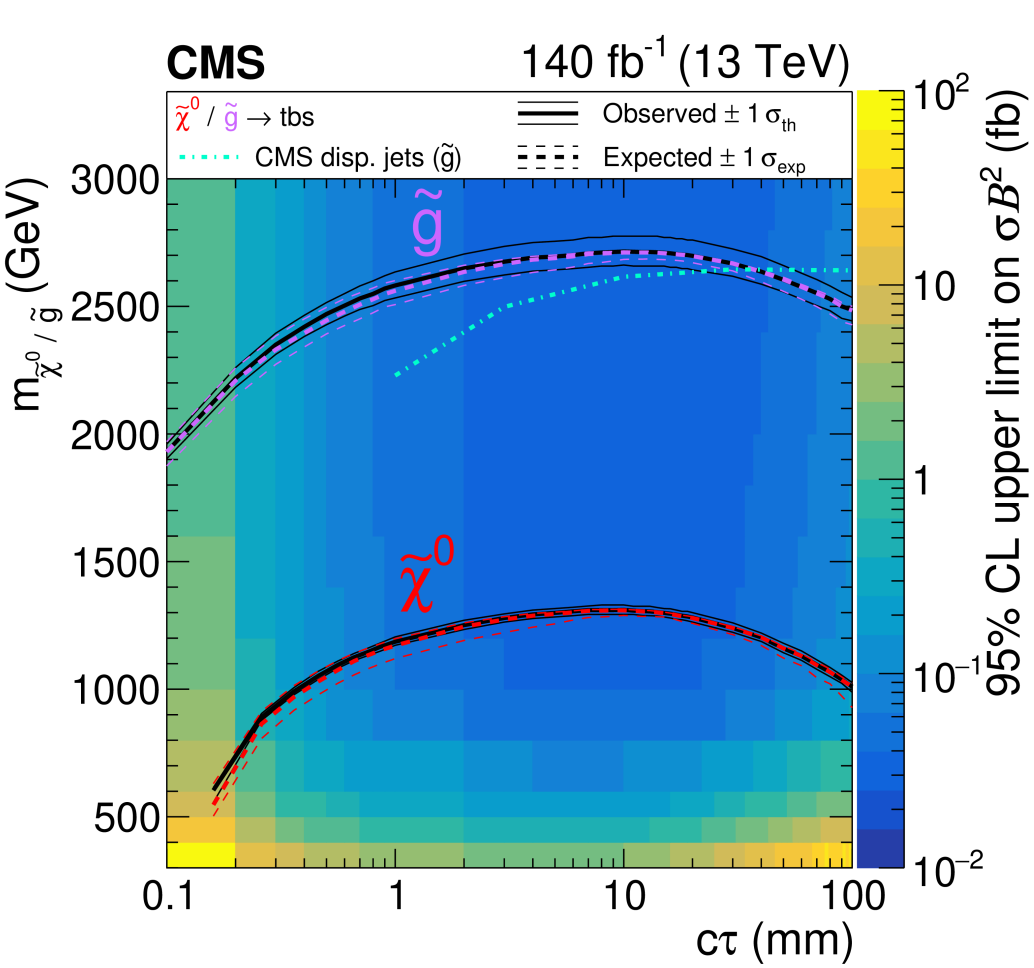



# Displaced vertices

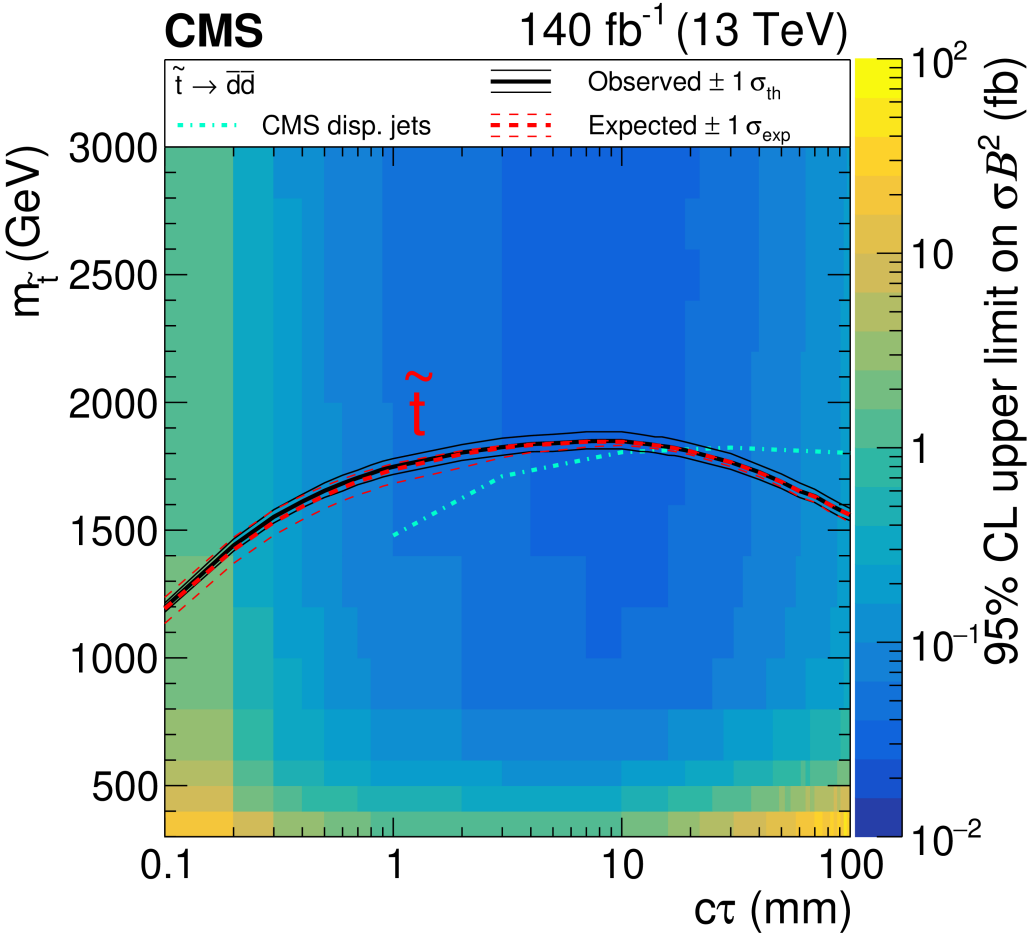
CMS: arXiv:2104.13474

- Interpretations

Long-lived neutralino/gluino



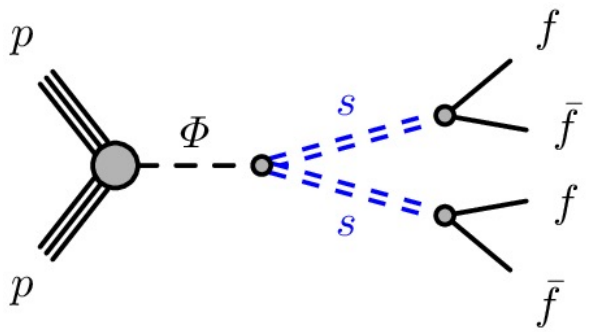

Long-lived s-top



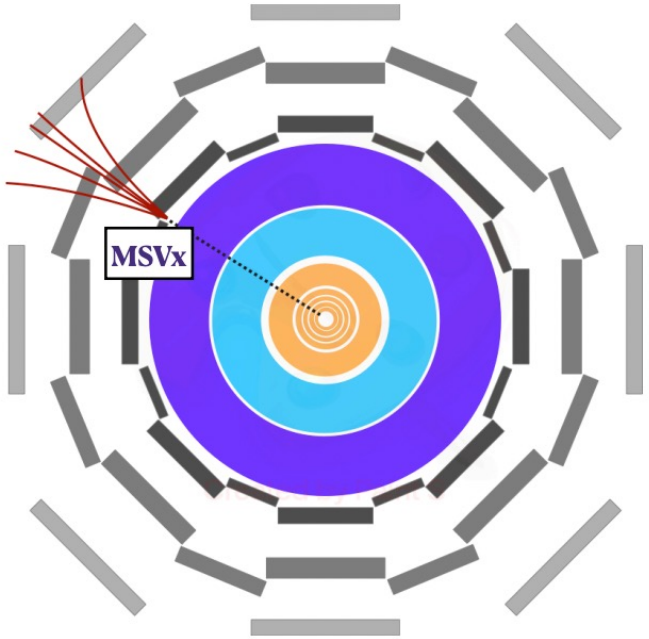
# Displaced jets

ATLAS: ATLAS-CONF-2021-032
CMS: arXiv:2107.04838

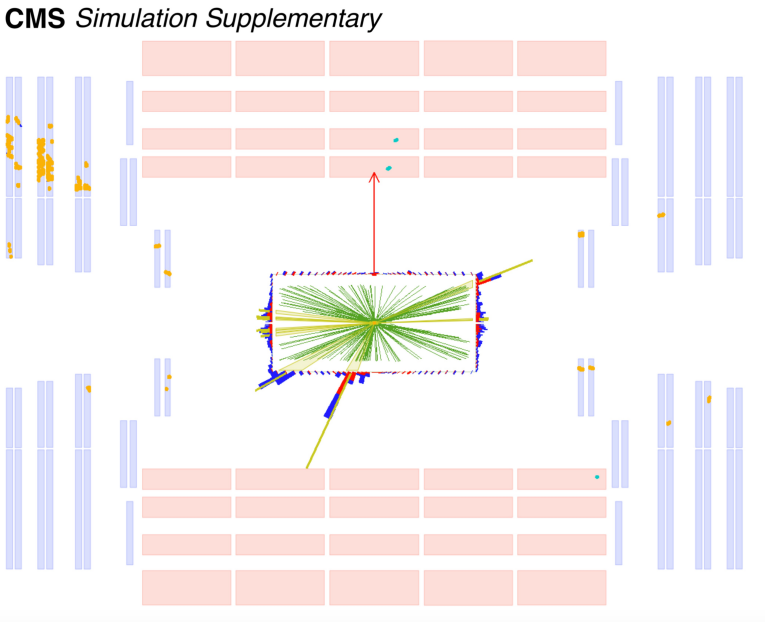
- Search for neutral LLPs decay into SM particles in the muon spectrometer
- ATLAS: look for pairs of displaced multi-trk vertices (DVs) in MS (barrel and endcap)
  - Hidden Abelian Higgs Model
- CMS: endcap $\mu$ detector used as a sampling calorimeter to identify showers produced by decays of LLPs
  - 2HDM with $m_\Phi$=125 GeV




ggF production of a SM-like Higgs scalar




ATLAS: a dedicated algorithm is used to reconstruct DVs in the MS

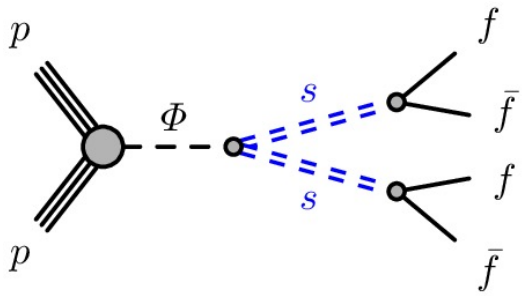



CMS endcap muon detectors: Interleaved detector planes + yoke steel layers

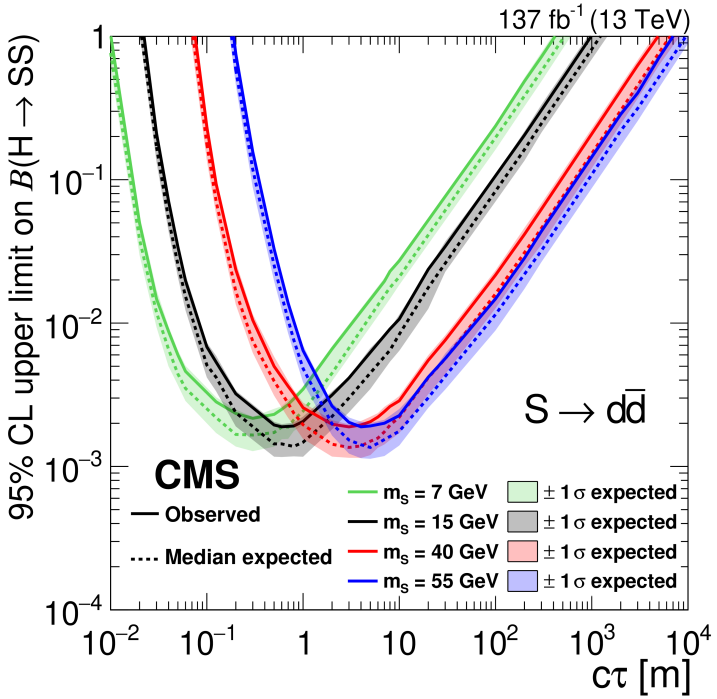
# Displaced jets

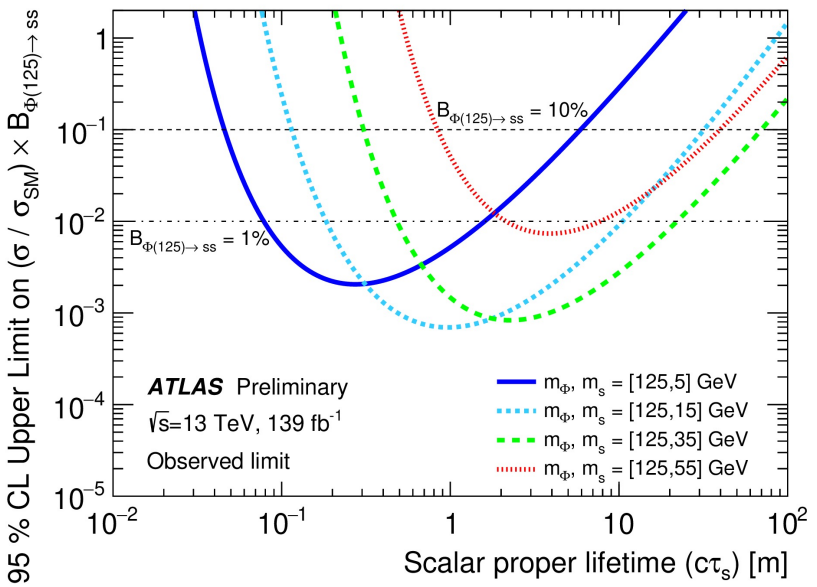
**ATLAS**: ATLAS-CONF-2021-032
**CMS**: arXiv:2107.04838

- Interpretations
  - ATLAS: 2D ($m_\Phi$, $m_S$)
  - CMS: 1D scan of $m_S$ with $m_\Phi$=125 GeV

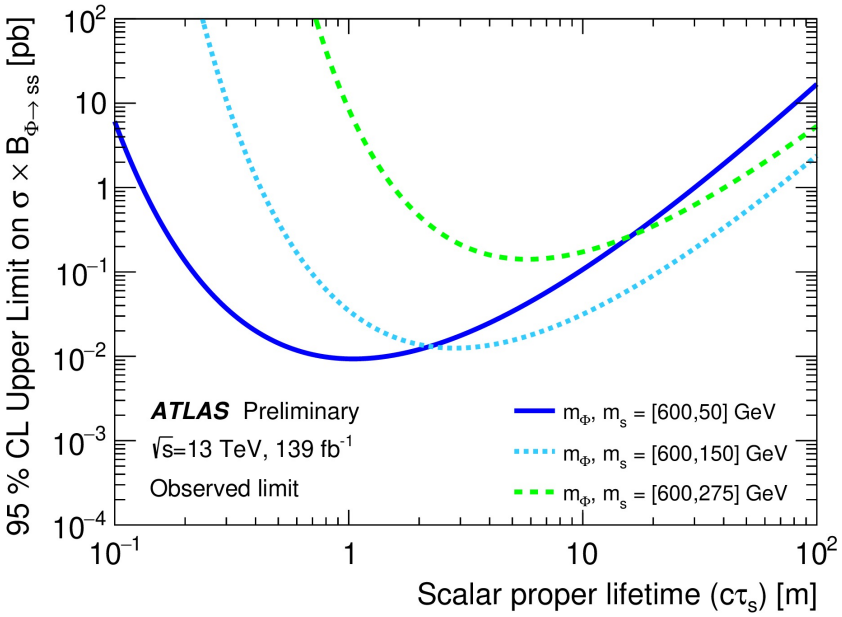



$m_\Phi$=125 GeV



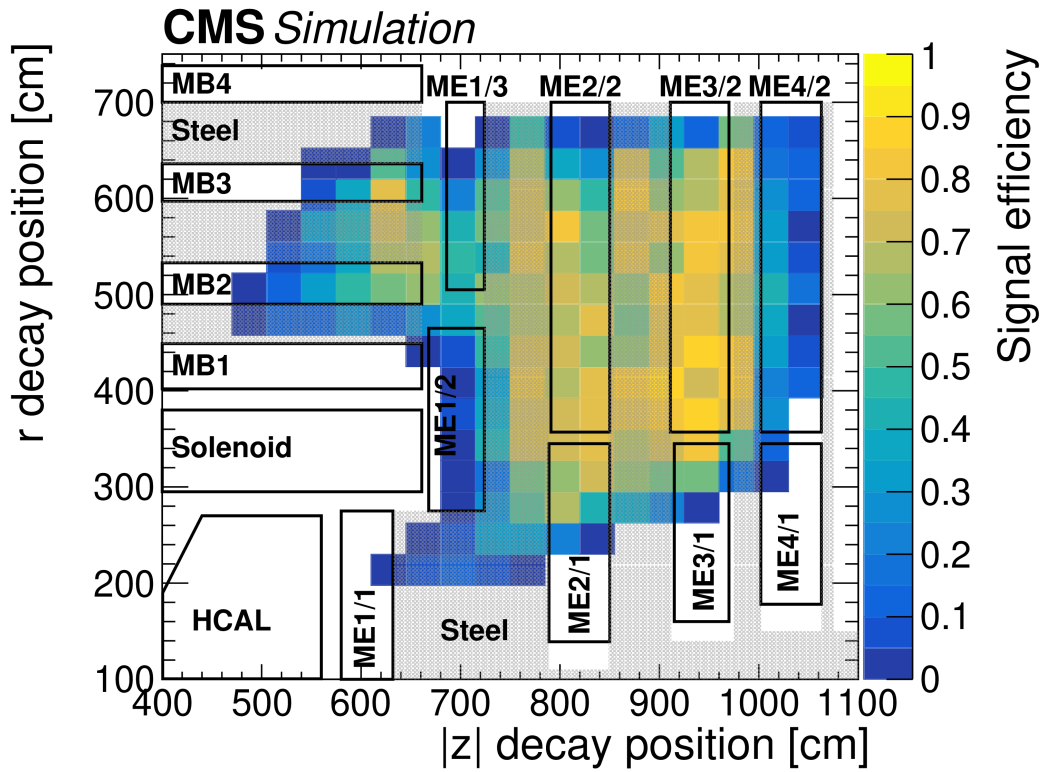




$m_\Phi \neq$125 GeV



# CMS displaced jets

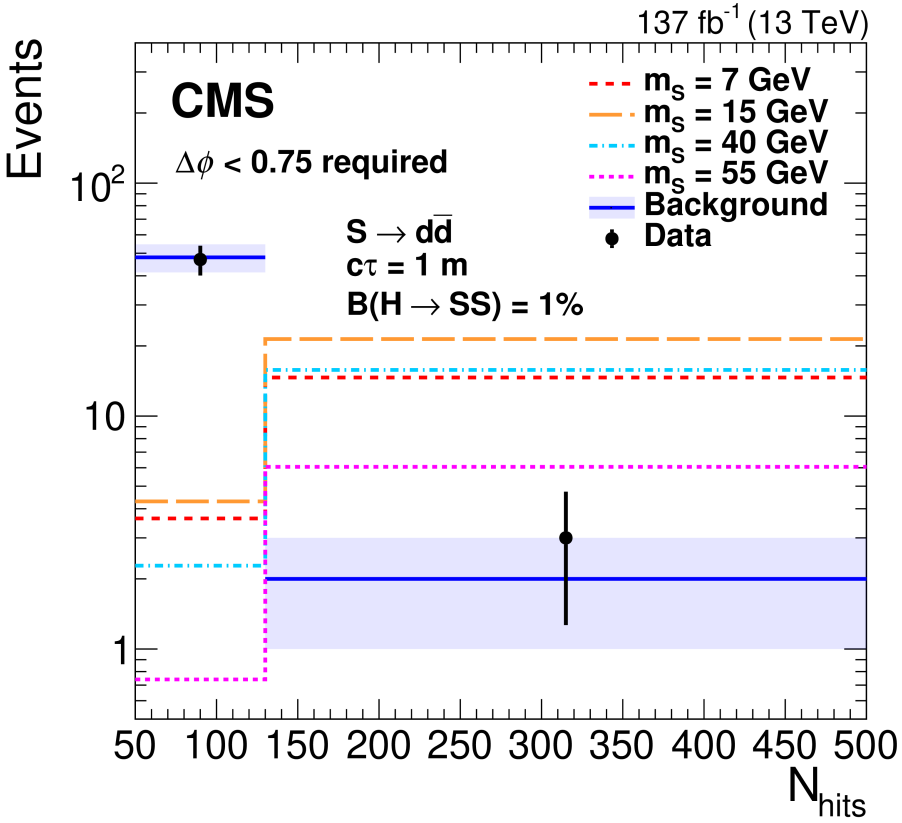
arXiv:2107.04838



# Displaced jets

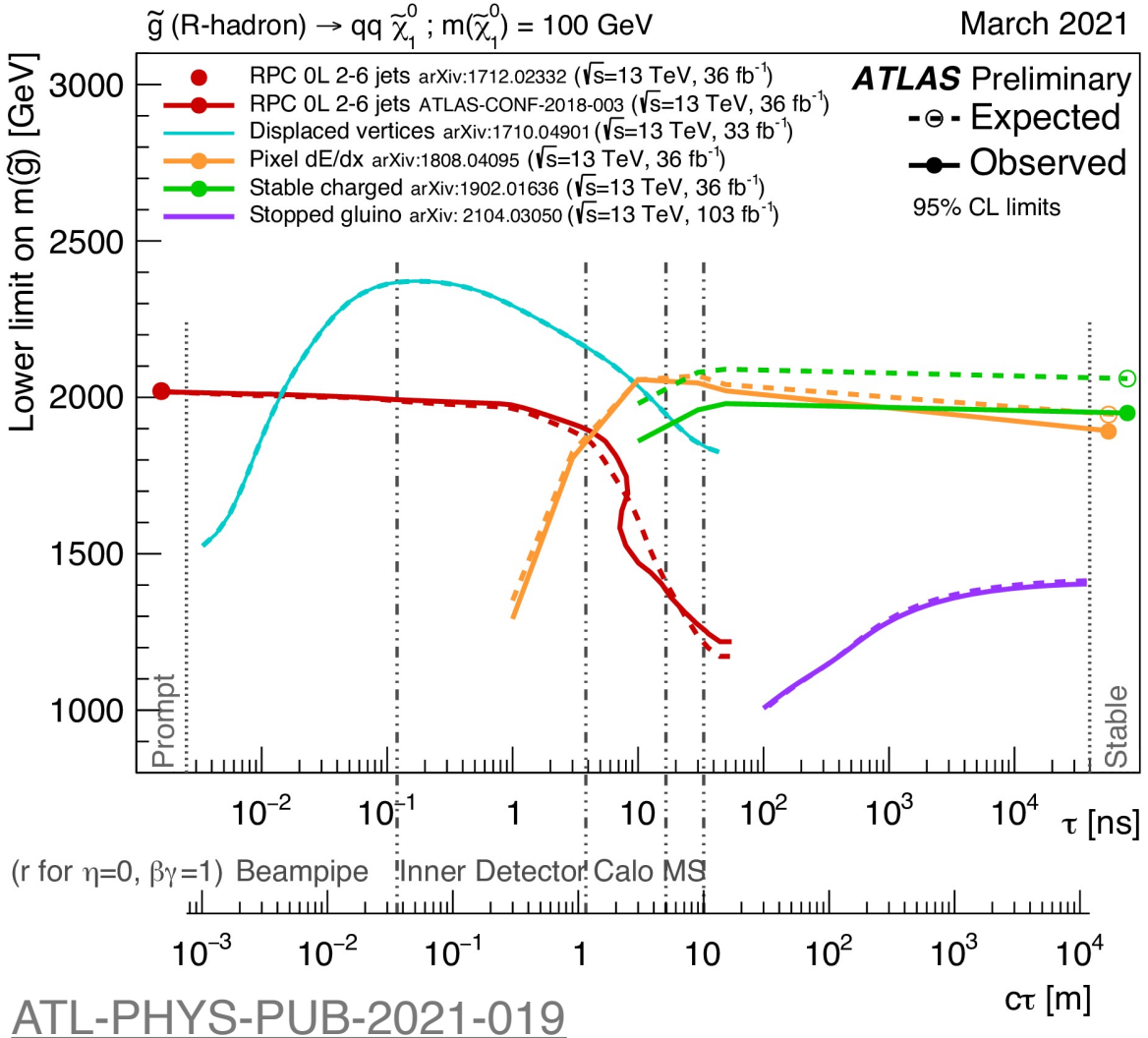
**ATLAS**: ATLAS-CONF-2021-032
**CMS**: arXiv:2107.04838

- Main background:
  - ATLAS: punch-through jets, non-collision backgrounds
  - CMS: SM LLPs through pileup interactions ($K_L^0$)
  - Data-driven estimate
- Results
  - ATLAS: No events observed, expected bkg: 0.35 ±0.05
  - CMS: 3 events observed, expected bkg: 2.0 ± 1.0

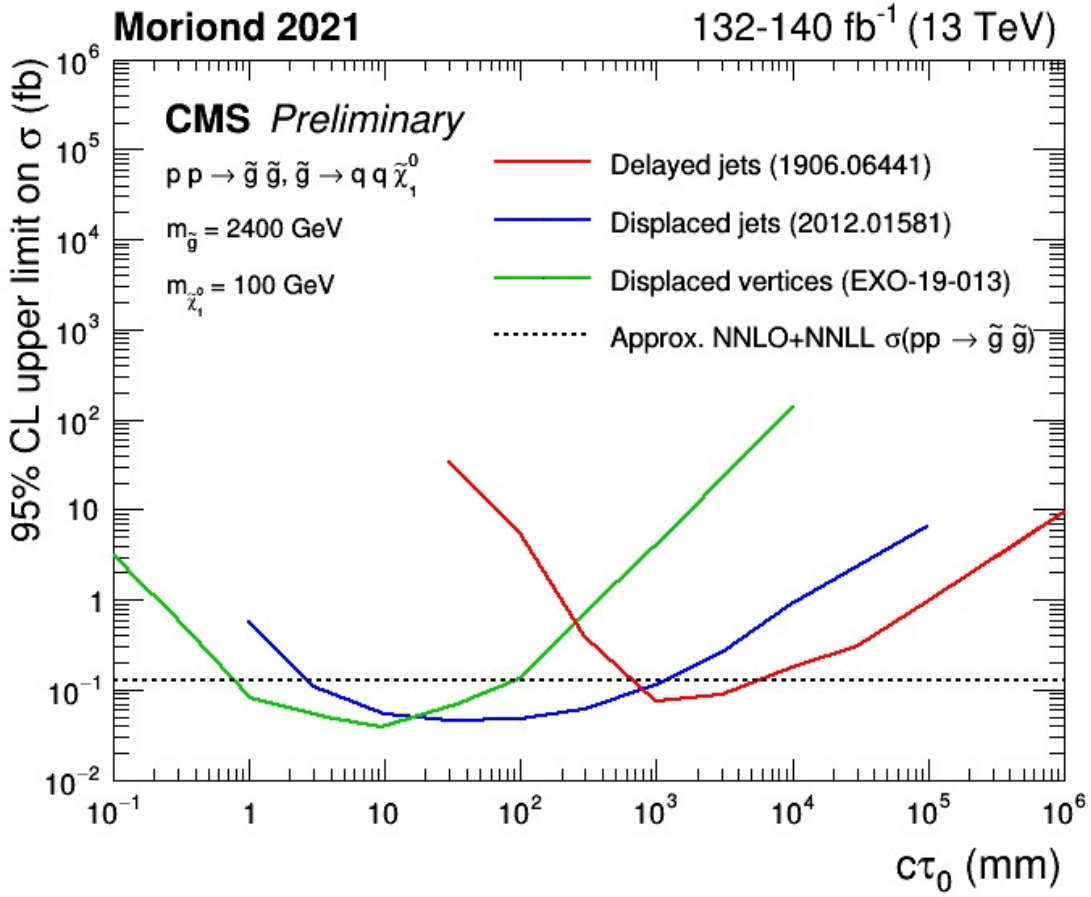


# LLPs

- Split-SUSY gluino




ATL-PHYS-PUB-2021-019




CMS

# Recent LLP searches at LHCb

- LHCb is capable to study LLPs down to relatively low masses
  - So far only within VELO
- LLPs → μ + jets: arXiv:2110.07293
  - mSUGRA RPV $\tilde{\chi}_1^0 \to \mu^{\pm} q_i q_j$
- LLPs → $e^{\pm}\mu^{\mp}\nu$ EPJC 81 (2021) 261
- HNL $W^+ \to \mu^+\mu^{\pm}$jets: EPJC 81, 248 (2021)

