Recherche directe de matière noire auprès des collisionneurs

Matthias Saimpert (CEA Irfu/DPhP)

Journée SFP Champs & Particules 2024
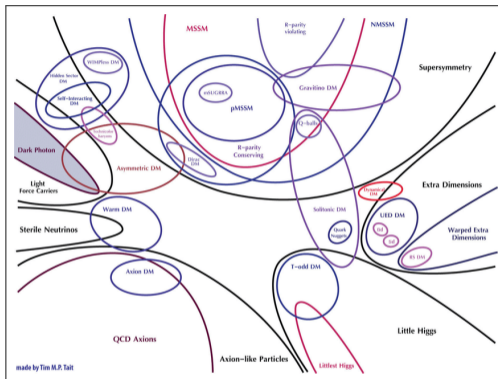
Jeudi 21 Mars 2024

Models for Dark Matter

- Cosmological evidence for **dark matter (DM),** but no experimental hints on its nature
- Searching for **weakly-interating massive particles (WIMP)** w/ minimal assumptions
  is one of the main approaches pursued w/ the ATLAS & CMS detectors at the LHC → focus of this talk
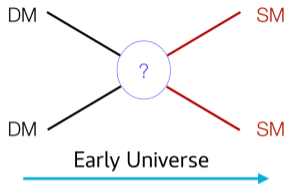
Overview

1. **Models & Signatures at the LHC**

2. **Results on simplified models (ATLAS & CMS)**
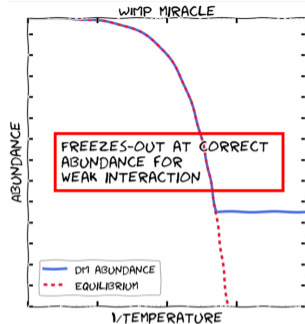
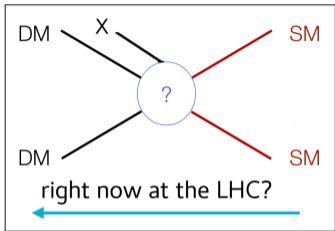**3.** **Other models & Experiments**

1. Models & Signatures at the LHC

WIMP hunting at colliders

- WIMP abundance set by thermal freeze-out
  - weak interaction ($< \sigma v > \sim 10^{-26}$ cm^{3}s^{-1})
  - $M_\chi \sim$ 1-1000 GeV $\rightarrow \Omega_c h^2 \sim 0.12$

WIMP hunting at colliders

right now at the LHC?

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  $M_\chi \sim$ 1-1000 GeV $\to \Omega_c h^2 \sim 0.12$

- **"mono-X" signatures at LHC**
    - proton collisions (quarks & gluons)
    - X = jet, γ, Z, W, ... $\to$ visible recoil
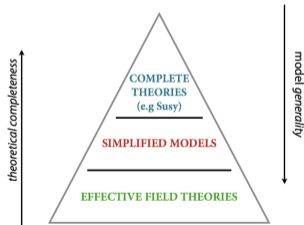   - missing momentum in transverse plane (E_T^{miss})
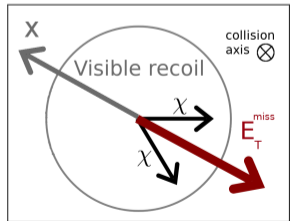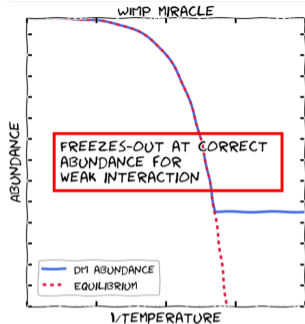
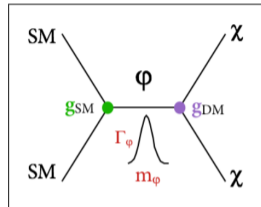# Common benchmark 'simplified' models at the LHC

Phys.Dark Univ. 27 (2020) 100371

- **WIMP DM + mediator**
  - free parameters: m_ϕ, m_χ, g_{SM}, g_{DM}, Γ_ϕ
  - already rich phenomenology
  - models classified w.r.t spin/CP of mediator and DM,
    $\rightarrow$ special case: mediator = Higgs boson
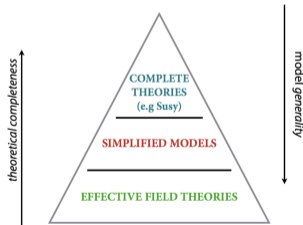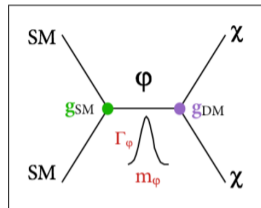
Common benchmark 'simplified' models at the LHC

Phys.Dark Univ. 27 (2020) 100371

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- "Less simplified" model: 2 Higgs Doublet + a   PDU 27 (2020) 100351
- Under development: DM + t-channel mediator   EPJC 80 (2020) 5, 409

Common benchmark 'simplified' models at the LHC

Phys.Dark Univ. 27 (2020) 100371

- **WIMP DM + mediator**
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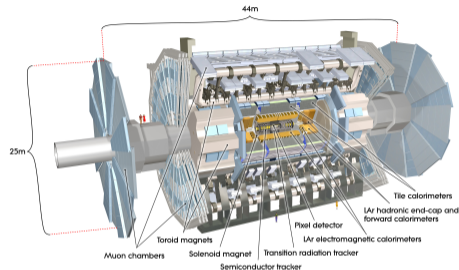- Other (non-WIMP) simplified models:
  - dark higgs   JHEP 04 (2017) 143,
  - unconventional signatures,
    e.g. strongly-interacting dark sectors   JHEP 11 (2017) 196
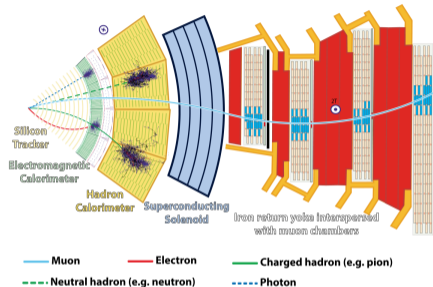 - dark photons, axion-like particles, ...
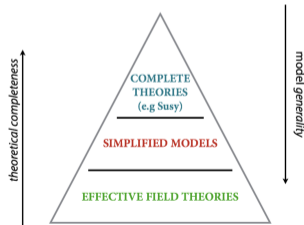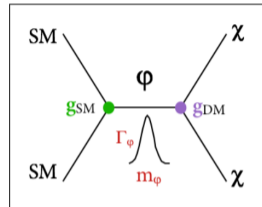
The ATLAS & CMS detectors at the LHC
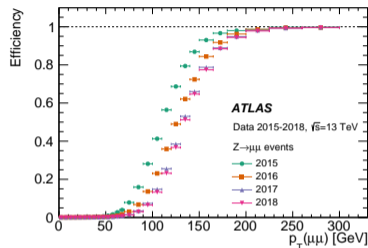
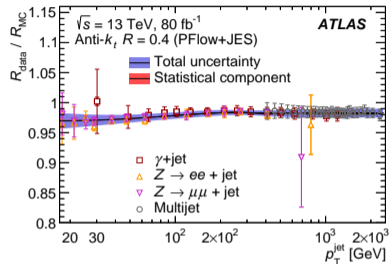**ATLAS detector overview**

Particle identification at CMS

- Results shown today based on LHC proton-proton collisions at $\sqrt{s}$ = 13 TeV

- Very large dataset collected by ATLAS/CMS during **Run 2 (2015-2018)** $\rightarrow$ 139 fb^{-1}
  - 7.7M Higgs, 275M top quarks, 2800M Z bosons, ...

- Multi-purpose, **high efficiency/acceptance detectors**
  - excellent online/offline reconstruction performance

The ATLAS & CMS detectors at the LHC

E_T^{miss} trigger JHEP 08 (2020) 80

Jet energy scale Eur. Phys. J. C 81 (2021) 689

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E_T^{miss} reconstruction at the LHC
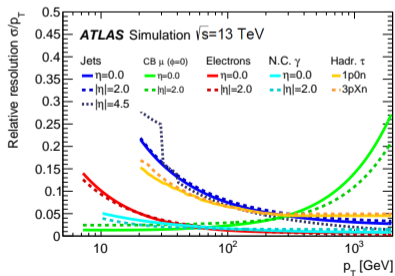
ATLAS: arXiv:2402.05858   CMS: JINST 14 (2019) P07004

$$\mathbf{E}_T^{miss} = (E_x^{miss}, E_y^{miss}),$$
$$E_T^{miss} = |\mathbf{E}_T^{miss}| = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2},$$
$$\phi^{miss} = \tan^{-1}(E_y^{miss}/E_x^{miss}).$$

$$\mathbf{E}_T^{miss} = -\underbrace{\sum_{\substack{\text{selected} \\ \text{electrons}}} \mathbf{p}_T^e}_{\mathbf{E}_T^{miss,e}} - \underbrace{\sum_{\substack{\text{accepted} \\ \text{photons}}} \mathbf{p}_T^\gamma}_{\mathbf{E}_T^{miss,\gamma}} - \underbrace{\sum_{\substack{\text{accepted} \\ \tau\text{-leptons}}} \mathbf{p}_T^{\tau_{had}}}_{\mathbf{E}_T^{miss,\tau_{had}}} - \underbrace{\sum_{\substack{\text{selected} \\ \text{muons}}} \mathbf{p}_T^\mu}_{\mathbf{E}_T^{miss,\mu}} - \underbrace{\sum_{\substack{\text{accepted} \\ \text{jets}}} \mathbf{p}_T^{jet}}_{\mathbf{E}_T^{miss,jet}} - \underbrace{\sum_{\substack{\text{unused} \\ \text{tracks}}} \mathbf{p}_T^{track}}_{\mathbf{E}_T^{miss,soft}}$$

hard term   soft term

ATLAS Simulation √s=13 TeV

- Proxy to **undetected particle kinematics** based on the conservation of the momentum in the transverse plane

- Uses all the reconstructed high-level objects in the events + non-associated tracks (ATLAS) or particle-flow object (CMS)
  - resolution depends on event topology

- Online E_T^{miss} also available for event triggering

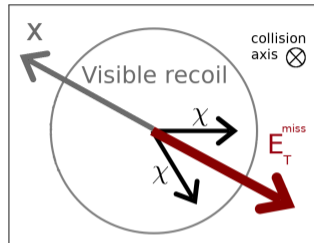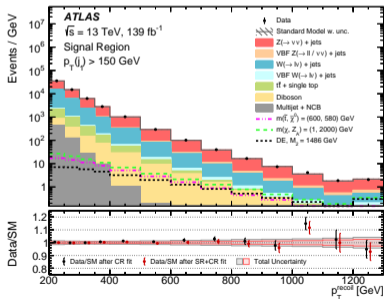# 2. Results on simplified models (ATLAS & CMS)

Mono-jet search

ATLAS: Phys. Rev. D 103 (2021) 112006 – **'precision search'**

- **Signal region (SR) selection**
  - $E_T^{miss} > 200$ GeV – E_T^{miss} trigger
  - up to 4 jets well separated from E_T^{miss}
 - leading jet pT > 150 GeV, no lepton

SR: no excess over background predictions

Visible recoil *X* here is: up to 4 jets

Mono-jet search

Signal region (SR) selection

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- leading jet pT > 150 GeV, no lepton

Background: $Z(\to \nu\nu)$, $W(\to \ell\nu)$ + jets

- constrained in control regions (CR) w/ leptons
- use of state-of-the-art W/Z+jets predictions EPJC 77, 829 (2017)
- total background uncertainty: 2-4%,

SR: no excess over background predictions
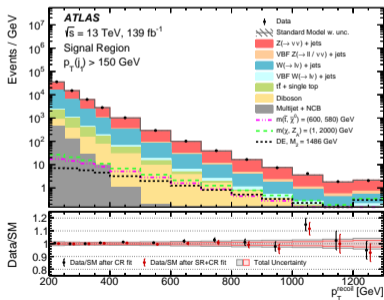
example of CR for $Z \to \mu\mu$
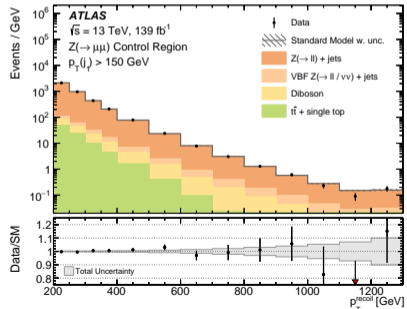
ATLAS mono-jet event display
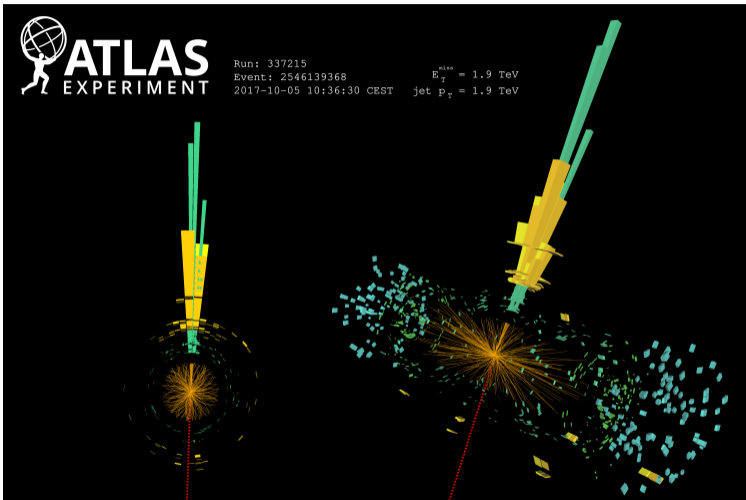
other mono-X (ATLAS): mono-γ, mono-V, mono-Z, ... similar analyses were performed by CMS. No excess found.
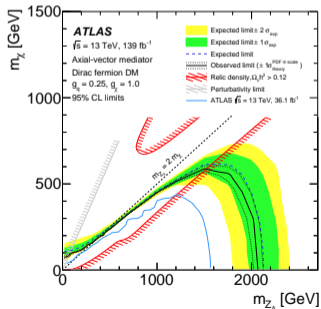
ATLAS mono-jet search results

ATLAS: Phys. Rev. D 103 (2021) 112006   CMS: JHEP 11 (2021) 153 – **'precision search'**
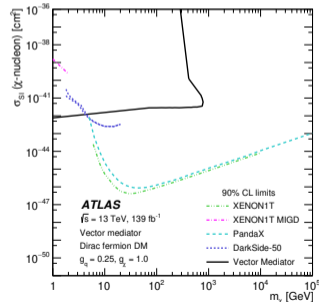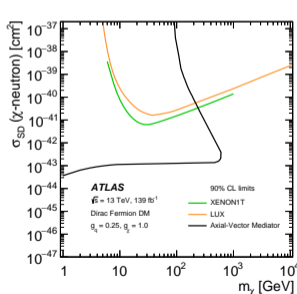
- **Various interpretations:**
  - DM mediated by axial vector $Z_A \to$ comparison w/ direct detection
  - SUSY, e.g. squark pair production with $\tilde{q} \to q + \tilde{\chi}^0$
  - other dark sector models: ATL-PHYS-PUB-2021-020
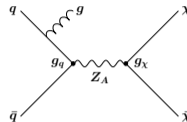
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ATLAS: Phys. Rev. D 103 (2021) 112006 CMS: JHEP 11 (2021) 153 – '**precision search**'

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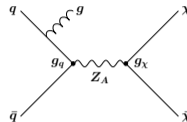
axial vector mediator interpretation

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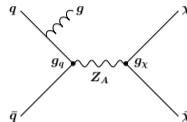
axial vector mediator interpretation
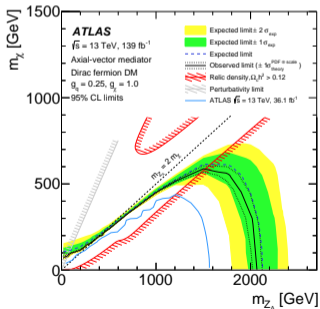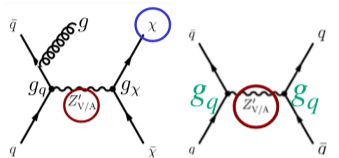
(model-dependent) comparison w/ direct detection

# Interplay w/ resonant searches

mono-jet search vs resonant search

- **Resonant search for mediator particle**
- Look for bump in mass spectra: jj, $\ell\ell$, ...
- Sensitivity at 'low' mass typically limited by trigger threshold
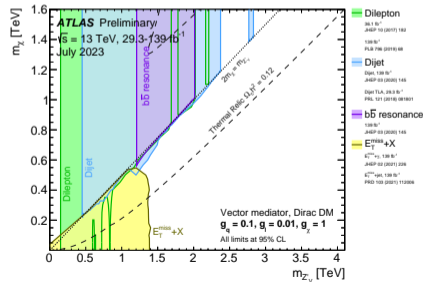 (for dijet, $m < 2$ TeV)

Interplay w/ resonant searches

ATLAS DM Summary plots: ATL-PHYS-PUB-2023-018

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mono-jet search vs resonant search
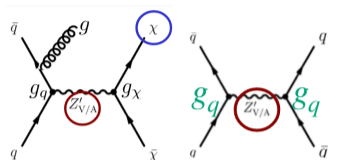
- **Complementarity with mono-X searches**

Z_A w/ large coupling to quarks
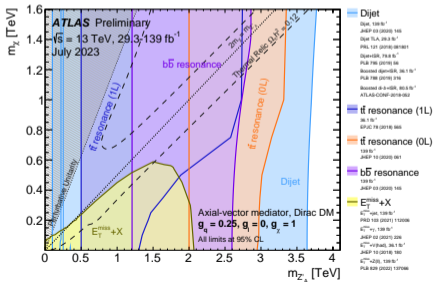
Z_V w/ small coupling to quarks and leptons

Dark matter searches w/ third generation

- **spin-0 mediator** under minimal flavour violation hypothesis → Yukawa-like couplings ∝ fermion mass
- leading channels: $b\bar{b} + E_T^{miss}$, $t\bar{t} + E_T^{miss}$ and $t(W) + E_T^{miss}$

Dark matter searches w/ third generation
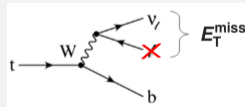
ATLAS: arXiv:2402.16561 (2024),   EPJC 83 (2023) 603,   EPJC 83 (2023) 503,   JHEP 05 (2021) 093

- **spin-0 mediator** under minimal flavour violation hypothesis → Yukawa-like couplings $\propto$ fermion mass
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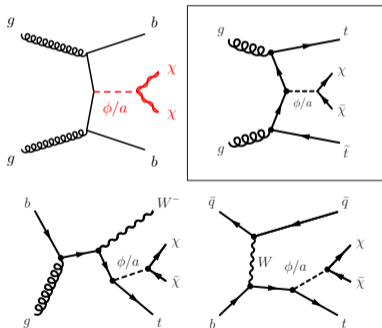
- **Signal region (SR) selection in $t\bar{t} + E_T^{miss}$ searches**
    - large E_T^{miss}, 2 b-tagged jets, & 0, 1 or 2 leptons
    - additional cuts to remove main backgrounds

- **Main backgrounds**
    - 0-lepton: $t\bar{t}$ incl. a top quark decay w/ an undetected lepton

    - 2-lepton: irreducible $t\bar{t}Z(\to \nu\nu)$
    - 1-lepton: mix

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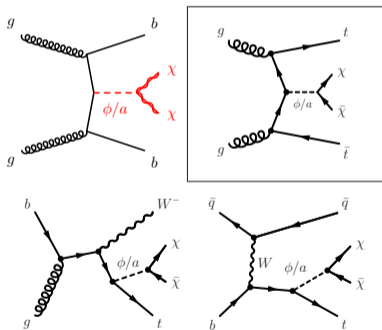
(one of) main challenge in 0-lepton analysis:
rejection of top quark decays with an undetected lepton
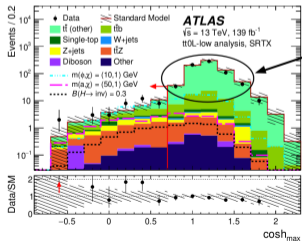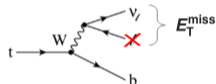
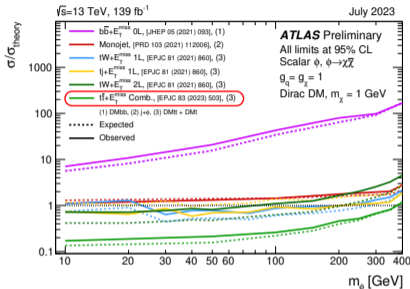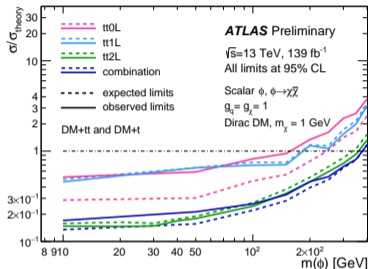Top reconstructed assuming E_T^{miss} = W boson pT

Dark matter with spin 0 mediator - results

ATLAS: EPJC 83 (2023) 503, ATL-PHYS-PUB-2023-018 [CMS equivalent: EPJC 81 (2021) 11, 970]

- $t\bar{t} + E_T^{miss}$ **searches** drive the sensitivity to spin 0 mediators w/ Yukawa-like couplings, no excess found.
    - $m_\phi > 370$ GeV for coupling $g = 1$
   - coupling $g < 0.17$ if $m_\phi = 10$ GeV

- results for both scalar and pseudo-scalar mediators available
- 2-lepton channel dominates the sensitivity and is statistically-limited

Searches for H→ invisible decays

ATLAS: Nature 607, 52 (2022)   CMS: Nature 607, 60 (2022)

- **SM Higgs boson** as spin 0 mediator
- SM Higgs production (Yukawa-like + HVV couplings) is assumed
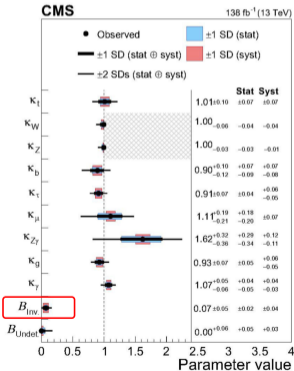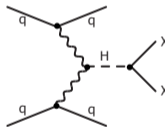- Enter global Higgs measurement combination
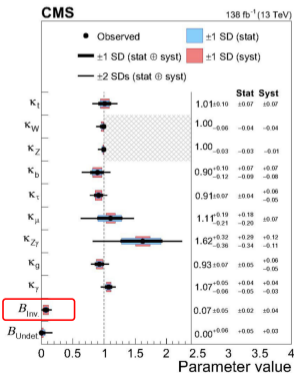
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Most sensitive channel: "vector boson fusion" (VBF) + E_T^{miss}

- **Signal region (SR) selection**
  - 2 jets with large $\Delta\eta$ and m_{jj}
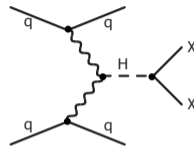 - $E_T^{miss} > 160$ GeV – E_T^{miss} trigger
  - no lepton

VBF + E_T^{miss} analysis

- **Background: $Z(\to \nu\nu)$, $W(\to \ell\nu)$ + 2 jets**
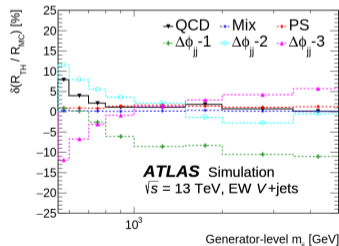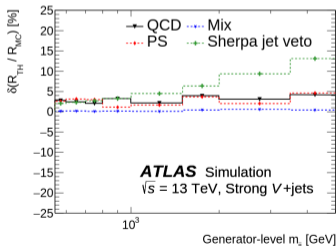 - constrained in control regions w/ leptons
  - use of dedicated W/Z + 2 jets predictions in VBF phase space (ATLAS) JHEP 01 (2023) 070
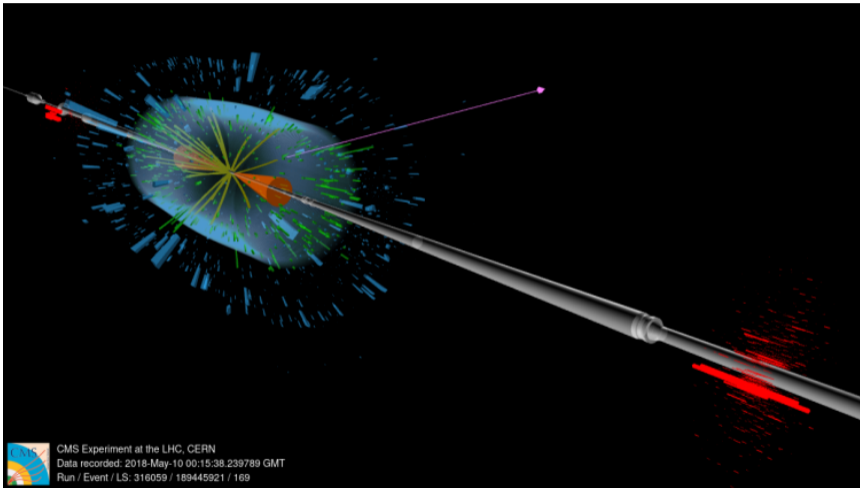 - total background uncertainty: $\sim$ 5%,

example SR
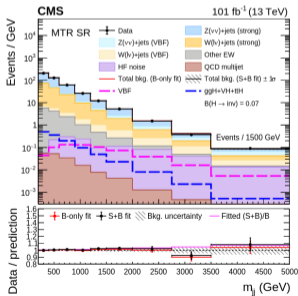
V+jets theory uncertainties (ATLAS)

No significant excess observed over background predictions.
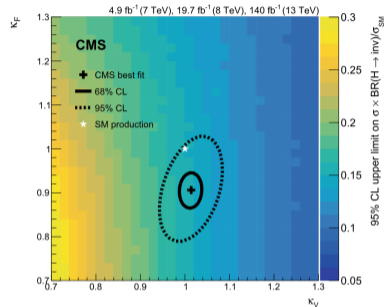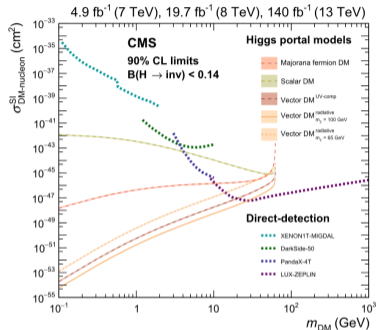
CMS VBF + E_T^{miss} event display

interactive version
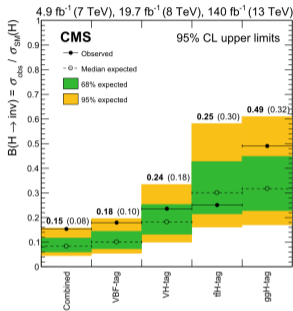
H→ invisible results

- **Sensitivity to BR($H \to$ inv.) $> 10\%$, driven by VBF + E_T^{miss} and V + E_T^{miss}**
  - stable if best fitted Higgs couplings (κ_F, κ_V) assumed instead of SM

- $t\bar{t}$ + E_T^{miss} subleading but still statistically-limited
- Complementary to direct detection experiments

3. Other models & Experiments

New generation of signal models at the LHC

ATLAS DM Summary plots: ATL-PHYS-PUB-2023-018

- **2HDM+a model:** pseudo-scalar mediator UV-complete extension   CERN-LPCC-2018-02
  - new signatures: mono-H, $t(W) + E_T^{miss}$, ...
- **Secluded dark sector:** dark photons, dark Higgs, sterile neutrino, ALP   JHEP 04 (2017) 143
  - new signatures: $VV + E_T^{miss}$, ...
- **Unconventional signatures:** strongly-interacting dark sector JHEP 06 (2022) 156 ; PLB 848 (2024) 138324
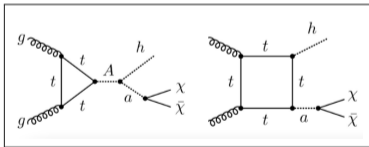 - new signatures: semi-visible jets, displaced jet/leptons, ...
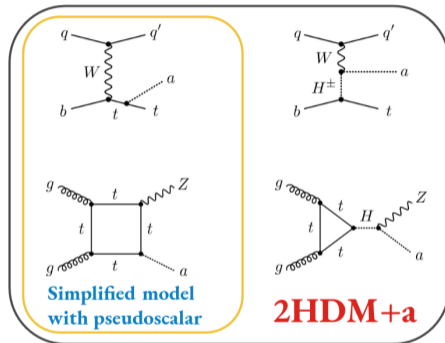

2HDM+a
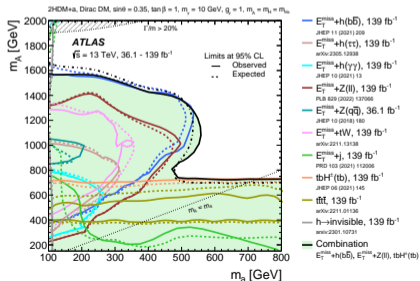
Dark Higgs
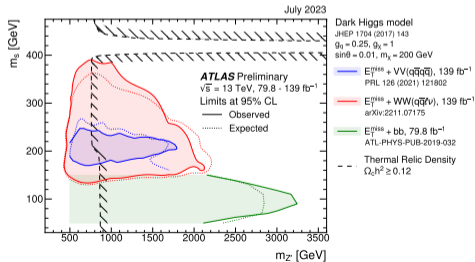
Less simplified: "2 Higgs doublet + a" Model (2HDM+a)

- Next-to-simplest simplified **pseudoscalar model** being gauge-invariant and renormalisable

- New particles: H, $H^{\pm}$ (scalars), A, a (pseudoscalars)

- Additional contributions via $H/H^{\pm}$ resonant diag.

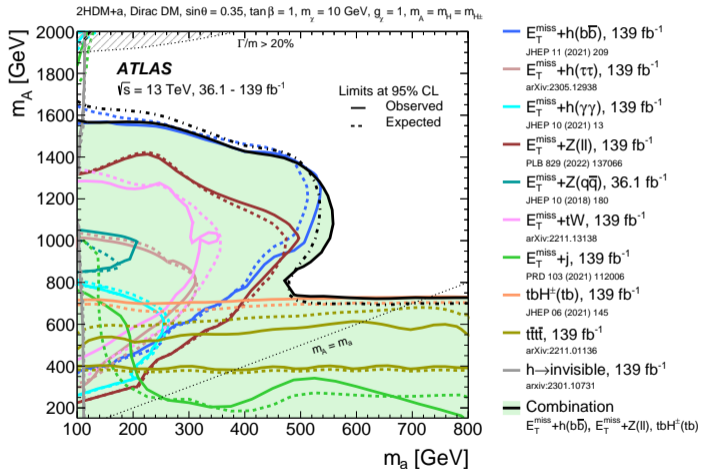- New signatures via A resonant diagrams

new signature: mono-H channel

additional contributions to mono-Z and mono-top

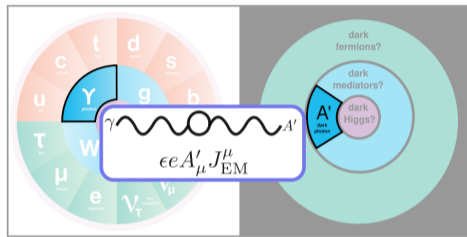# Less simplified: "2 Higgs doublet + a" Model (2HDM+a)

ATLAS DM Summary plots: ATL-PHYS-PUB-2023-018

Toward the intensity frontier: secluded dark sector

- **DM is not a single particle**
  but a sector incl. many several states

- Limited number (usually one) dark sector particles
  interact with SM via kinetic mixing

- 4 Portals defined in JPG 47 (2020) 1, 010501
 - dark photon
  - dark Higgs
 - sterile neutrino
  - axion-like particles

dark photon model

$$\mathcal{L} \supset \begin{cases} -\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H, & \text{Higgs portal} \\ y_n L H N, & \text{neutrino portal} \\ \frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu}, & \text{axion portal.} \end{cases}$$
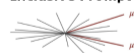
← Portals to the dark sector
Symmetry 2022, 14(7), 1299

LHCb highlights

- 5.5 fb^{-1} of proton-proton collisions at 13 TeV with low pileup

- asymmetric detector to study CPV and rare decays of heavy flavor hadrons

- DM search program incl. light DM or mediators (0.1-50 GeV) coupled to 2nd/3rd generation
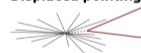
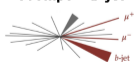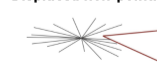dark photon to $\mu\mu$ decays: PRL 124 (2020) 4, 041801   JHEP 10 (2020) 156
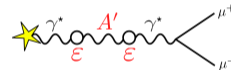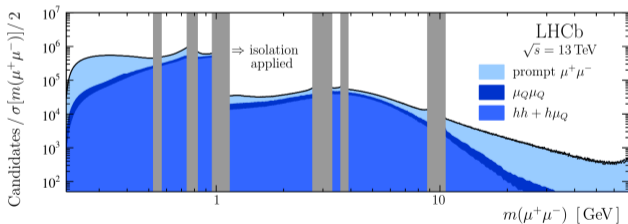

Full reconstruction in the trigger → no data prescale factors

Belle 2 highlights

Belle 2 Physics Book: PTEP 2019 (2019) 12, 123C01   Z' search: PRL 130 (2023) 23, 231801

$e^+e^- \to \mu^+\mu^- Z'; Z' \to invisible$

- Asymmetric e^+e^- collision near the $\Upsilon(4S)$ peak B-factory, $\sqrt{s} = 10.58$ GeV, unprecedented luminosity

- DM search program incl. light DM or mediators (0.1-10 GeV) coupled to 2nd/3rd generation

- More results to come
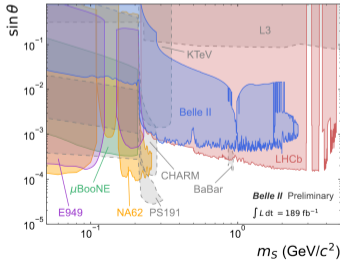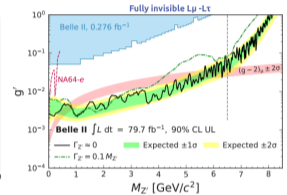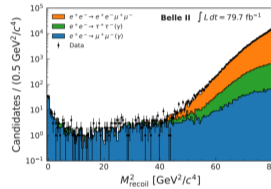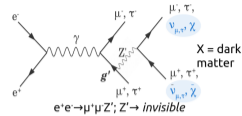
← long-lived scalar in $b \to s$ transitions: PRD 108 (2023) L111104
similar models probed by LHCb

$B^+ \to K^+ S$
$B^0 \to K^{*0} (\to K^+\pi^-) S$ $S \to ee/\mu\mu/\pi\pi/KK$
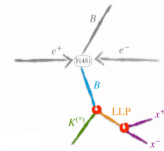
Summary

- **DM searches at colliders mostly guided by WIMP simplified models**
  - single mediator   → mono-X
 - Higgs portal   → H to invisible
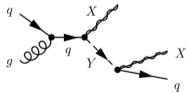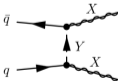 - toward UV-completion   → 2HDM+a

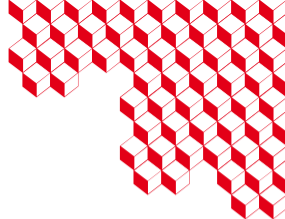- **Large parameter space explored, no hint so far**
  - sensitivity model-dependent but complementary to direct detection

- **In parallel, models beyond the WIMP paradigm also explored**
  - dark higgs, dark photon, axion-like particles, strongly-interacting dark sectors, ...

- **Possible focus for the LHC Run 3: t-channel simplified mediator models**
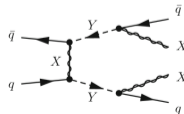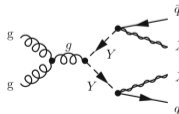
Merci pour votre attention

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