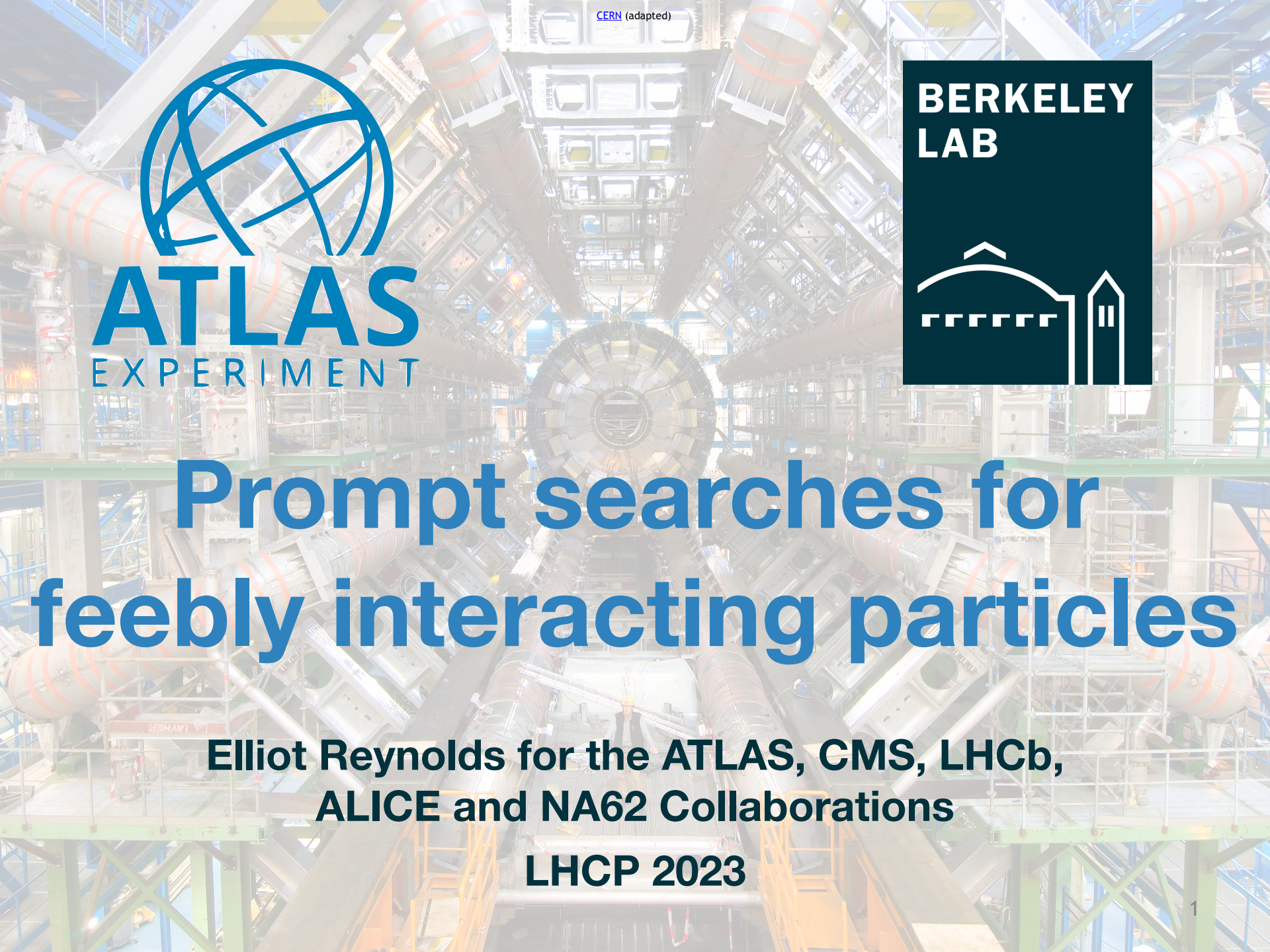


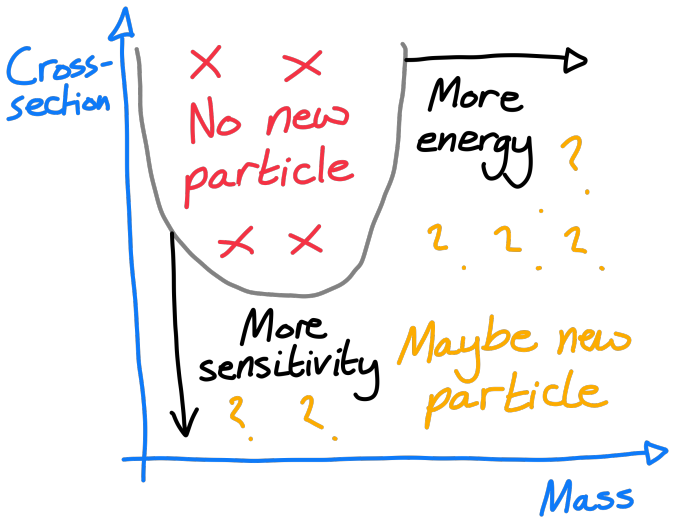
Prompt searches for feebly interacting particles

Elliot Reynolds for the ATLAS, CMS, LHCb, ALICE and NA62 Collaborations

LHCP 2023

Introduction

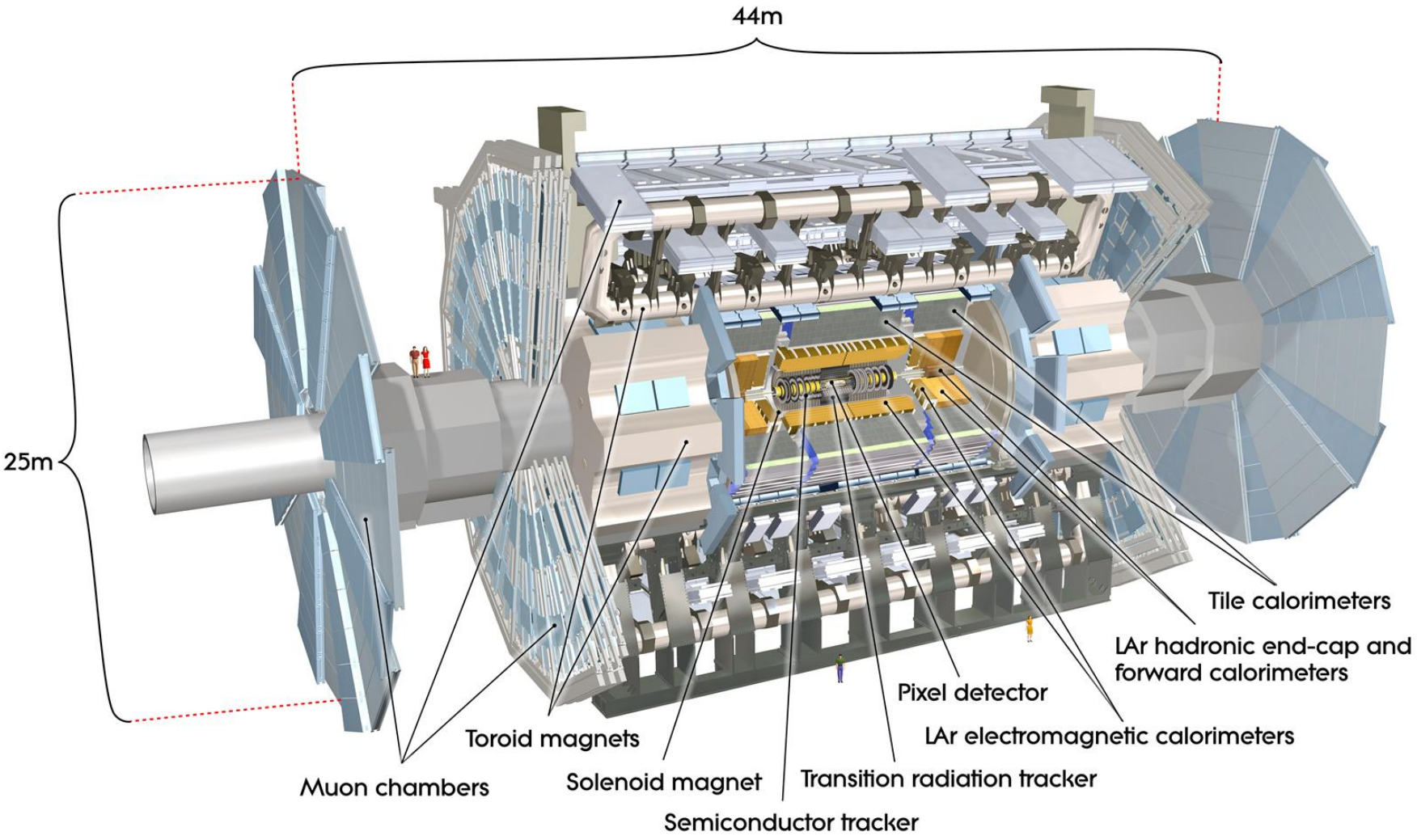
- No fundamental particles observed so far at the LHC, other than the Higgs boson
- New particles could be discovered by probing higher energies or lower cross-sections
- The LHC has been running near its maximum energy since 2015, and it is ~50 years before much higher energy collisions are expected
- Searches for weaker couplings becoming more important
- The small Higgs width means even small Higgs–BSM couplings can manifest as large branching fractions
- Colliders provide a good probe at the ~GeV scale and above
- Lower energy experiments, e.g. beam dumps, are sensitive at lower masses



Models

- Many BSM models predict feebly interacting particles (FIPs), e.g. Higgs bosons, dark photons, axions/axion like particles (ALPs), heavy neutral leptons…
- Extended Higgs sectors (e.g. 2HDM+S) introduce additional Higgs bosons, and are present in various models (e.g. supersymmetry)
- FIPs can interact with the Standard Model (SM) via portal particles, which often kinematically mix with a SM boson
  - Dark sectors containing dark matter (DM) can couple weakly to the SM through portals
- Majorana neutrinos from "see-saw" models can explain the small neutrino masses
- Axions/ALPs can solve the strong CP problem, and provide a DM candidate
- Models with FIPs can also potentially explain the $g-2$ anomaly

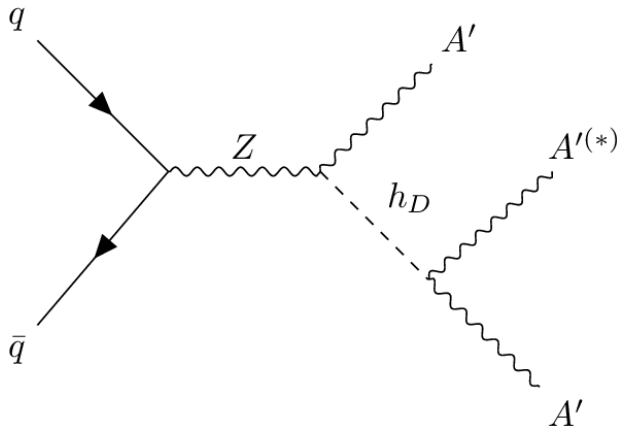
ATLAS


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

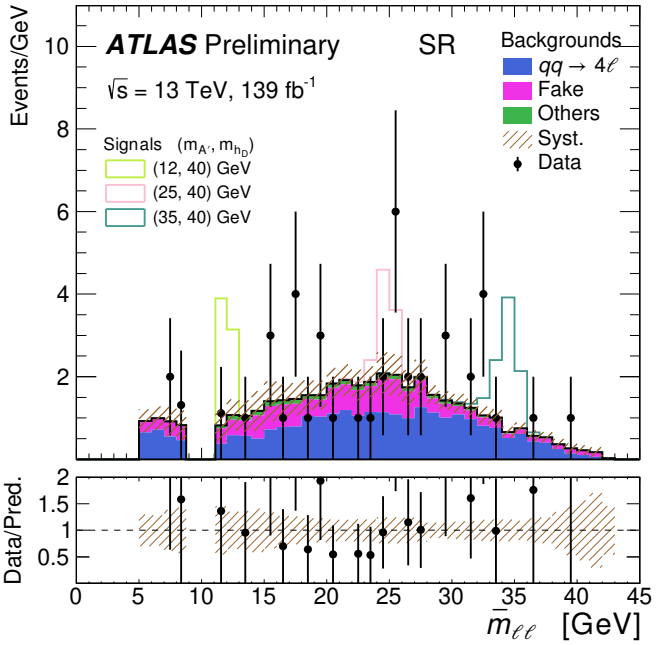
ATLAS

$Z \to A'h_d, h_d \to A'A'^{(*)}$

ATLAS-CONF-2023-016

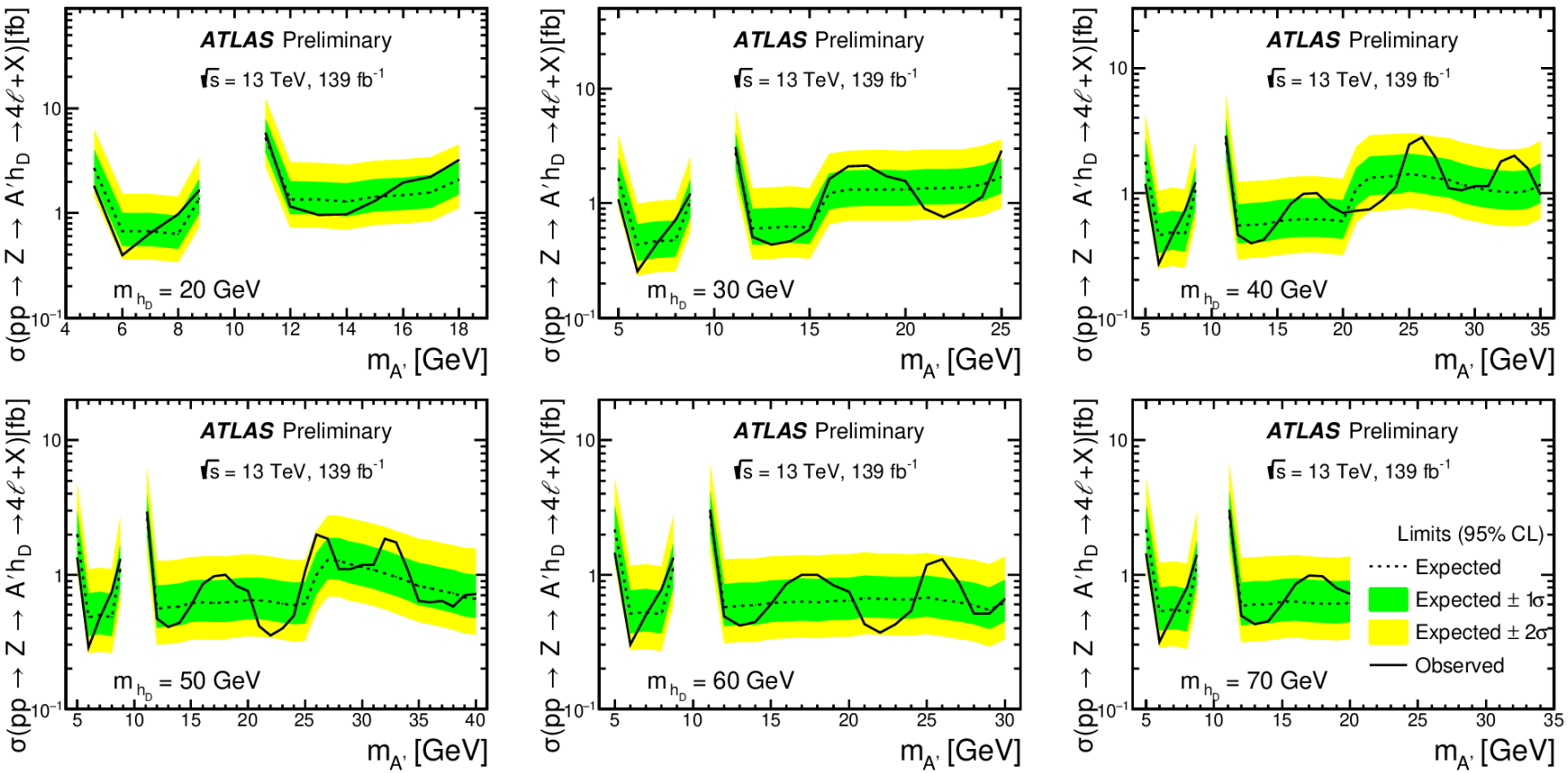


- **Target signal:** dark photon A'
- **Signature:** two $A' \to \ell^+\ell^-$ decays
- **Triggers:** single-ℓ & multi-ℓ
- **Selection overview:** ≥ 2 SF OS lepton pairs; $m_{4\ell} < m_Z - 5$ GeV; $m_{\ell_3\ell_4}/m_{\ell_1\ell_2} > 0.85$
- **Main backgrounds (models):**
  - $qq \to 4\ell$ (MC & CR)
  - fake leptons (fake-factor method)
- **Categorisation:** SR & $qq \to 4\ell$ CR
- **Discriminant:** mean di-ℓ mass
- **Dominant uncertainties:** data stats



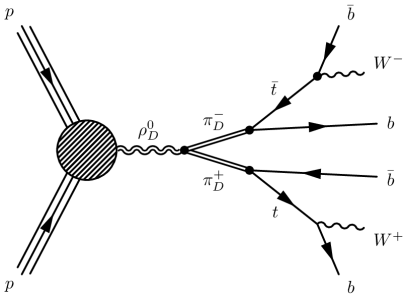
$Z \to A'h_d, h_d \to A'A'^{(*)}$

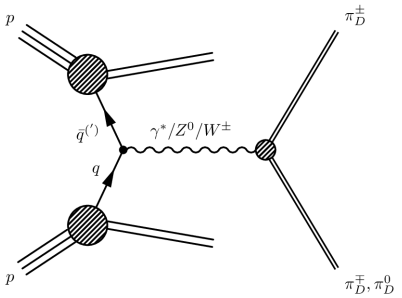
- Covers significantly wider A' and h_d mass ranges than previous searches, e.g. PRL 108 (2012) 211801 and PRL 114 (2015) 211801



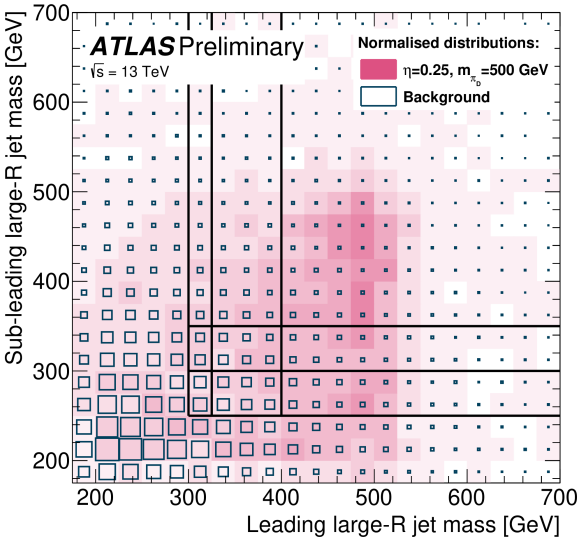
ATLAS-CONF-2023-016

$\pi_D^{\pm}\pi_D^{0,\pm} \rightarrow 2t2b,3t1b$

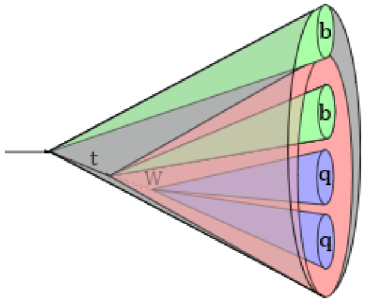




ATLAS-CONF-2023-021

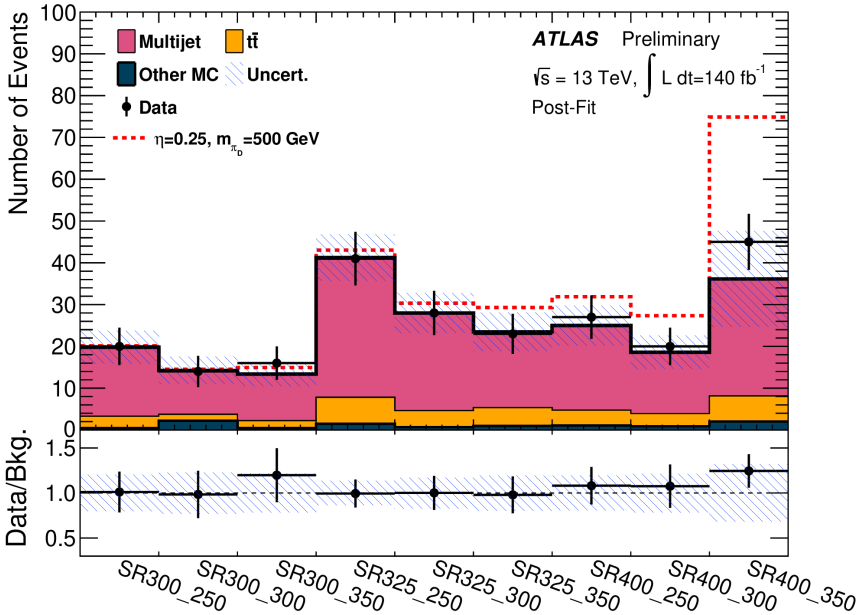


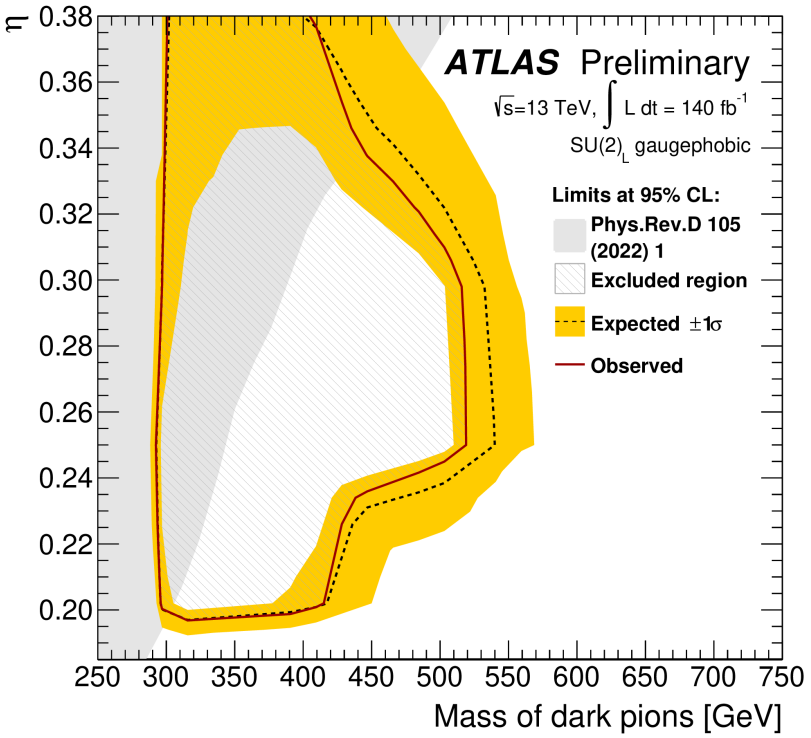
- **Target signal:** dark pions π_D
- **Signature:** 8–10 jets with ≥ 4 b-jets
- **Triggers:** $H_{\mathrm{T}} = \Sigma |p_{\mathrm{T}}^{\mathrm{jet}}|$
- **Selection overview:** ≥ 2 large-radius jets with masses > 250 GeV & > 300 GeV for π_D, 2 b-jets with $\Delta R < 1$, & $m_{bb}/p_{\mathrm{T},bb} > 0.25$
- **Main background (model):**
  - multiple QCD jets (4D ABCD estimate)
- **Categorisation:** 9 SRs based on m_{jet} values



$\pi_D^{\pm}\pi_D^{0,\pm} \rightarrow 2t2b,3t1b$

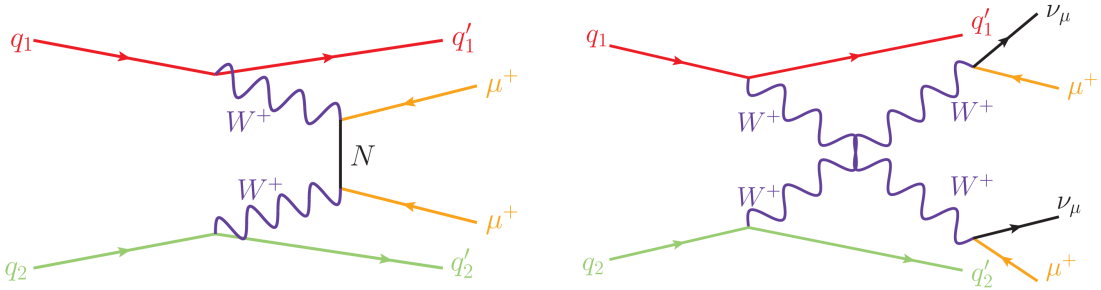
- **Discriminant:** event yields in 2D m_{jet} regions
- **Dominant uncertainties:** multi-jet background estimation and data stats
- First dedicated π_D search!





ATLAS-CONF-2023-021

VBS Heavy Majorana Neutrinos



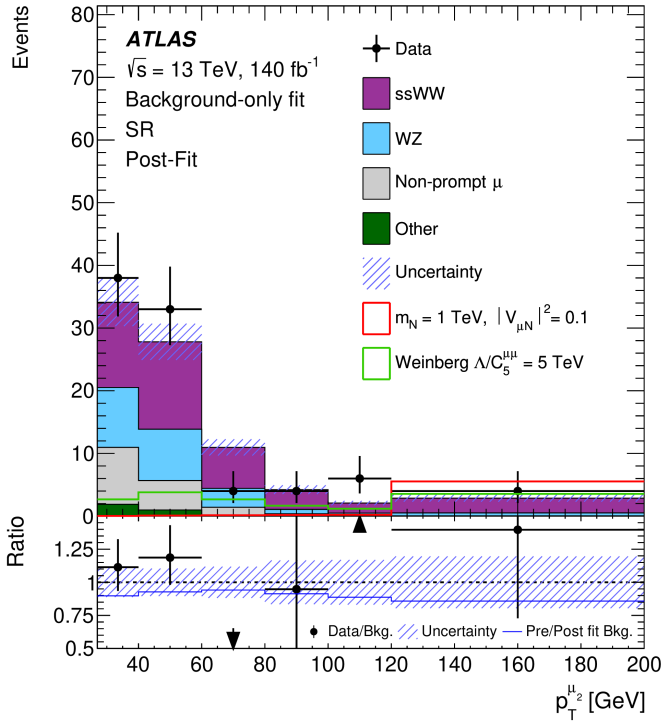
- **Target signal:** Majorana neutrino N exchange, with Weinberg Operator and Phenomenological Type I "see-saw" interpretations
- **Signature:** vector boson scattering (VBS), giving $\mu^{\pm}\mu^{\pm}$ + VBS jets
- **Triggers:** single-μ
- **Selection overview:** same-sign di-μ & ≥ 2 jets; $m_{jj} > 300$ GeV & $\Delta\eta_{jj} > 4$; b-jet & $E_{\mathrm{T}}^{\mathrm{miss}}$ vetos
- **Main backgrounds (models):**
  - $WWjj$ (MC with CR)
  - WZ (MC with CR)
- **Categorisation:** SR, $ssWW$ CR & ZZ CR

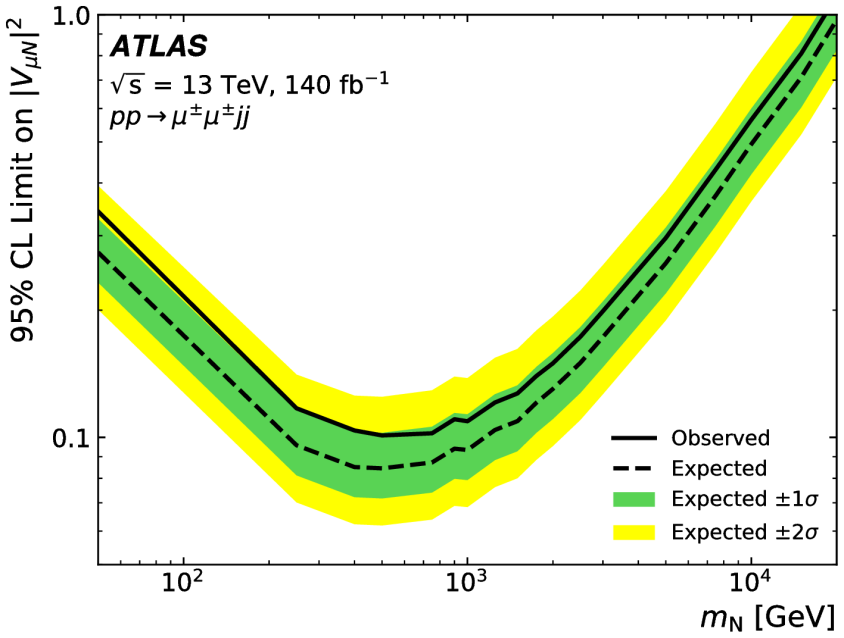
EXOT-2020-06

VBS Heavy Majorana Neutrinos

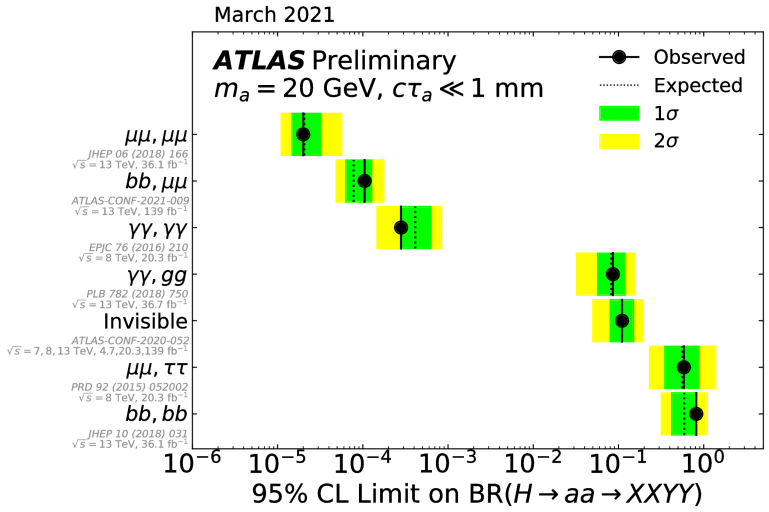
- **Discriminant:** sub-leading jet p_T
- **Dominant uncertainties:** data stats
- $|m_{\mu\mu}| < 16.7$ GeV (13.1 GeV exp)
- This analysis provides world leading sensitivity to TeV-scale m_N, and complimentary sensitivity neutrinoless double beta decay

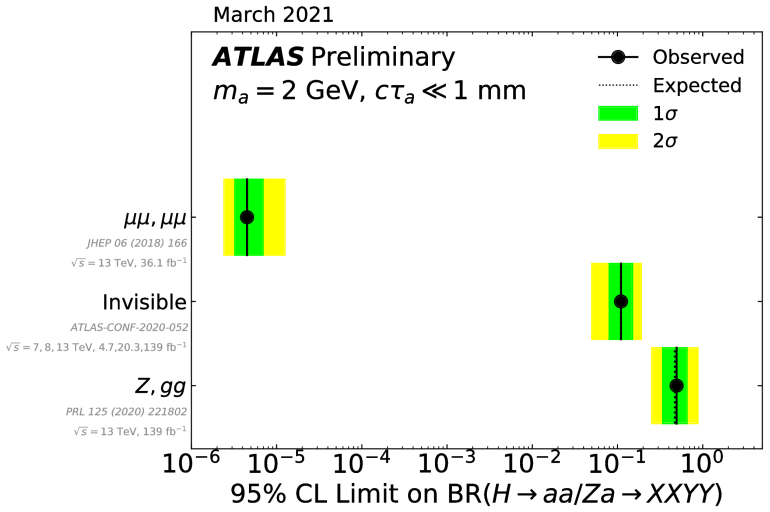
EXOT-2020-06

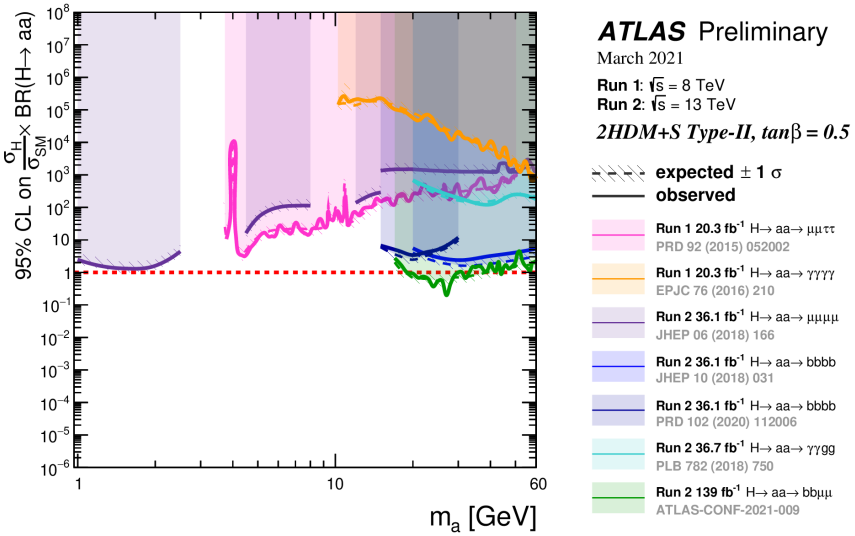


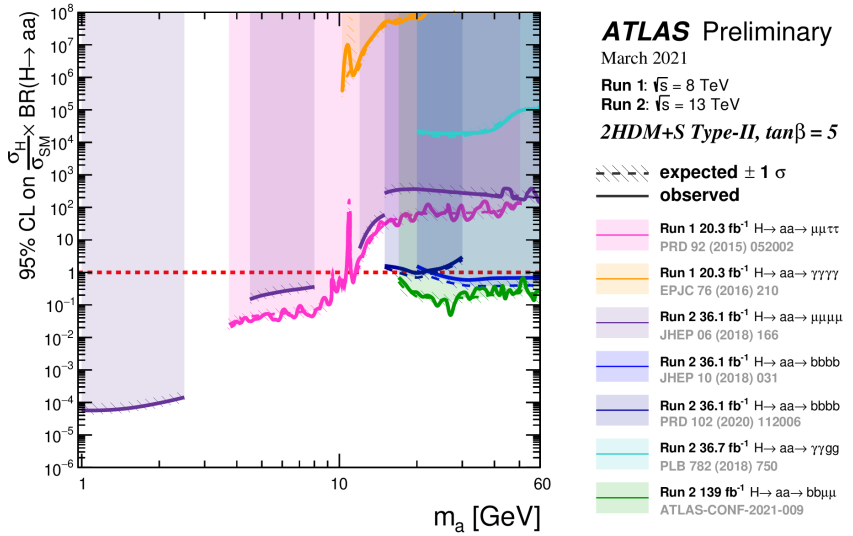


Exotic Higgs Decays Summary





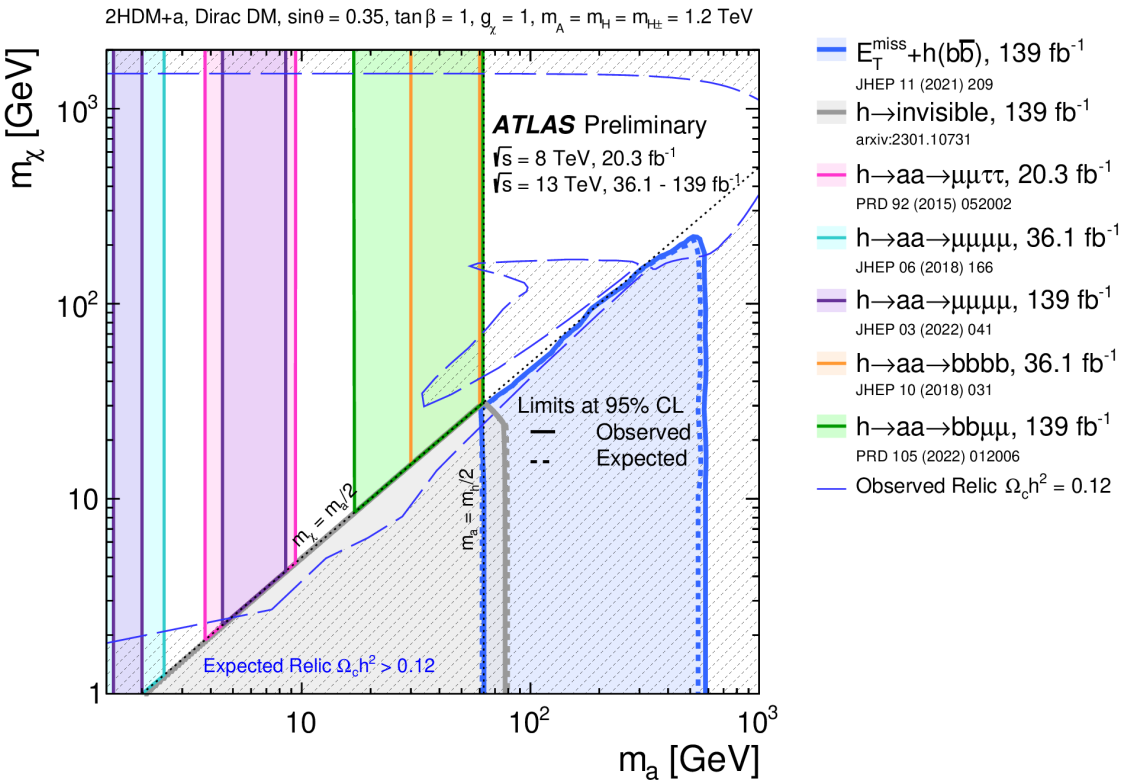




ATL-PHYS-PUB-2021-008

2HDM+a DM Comb/Summary

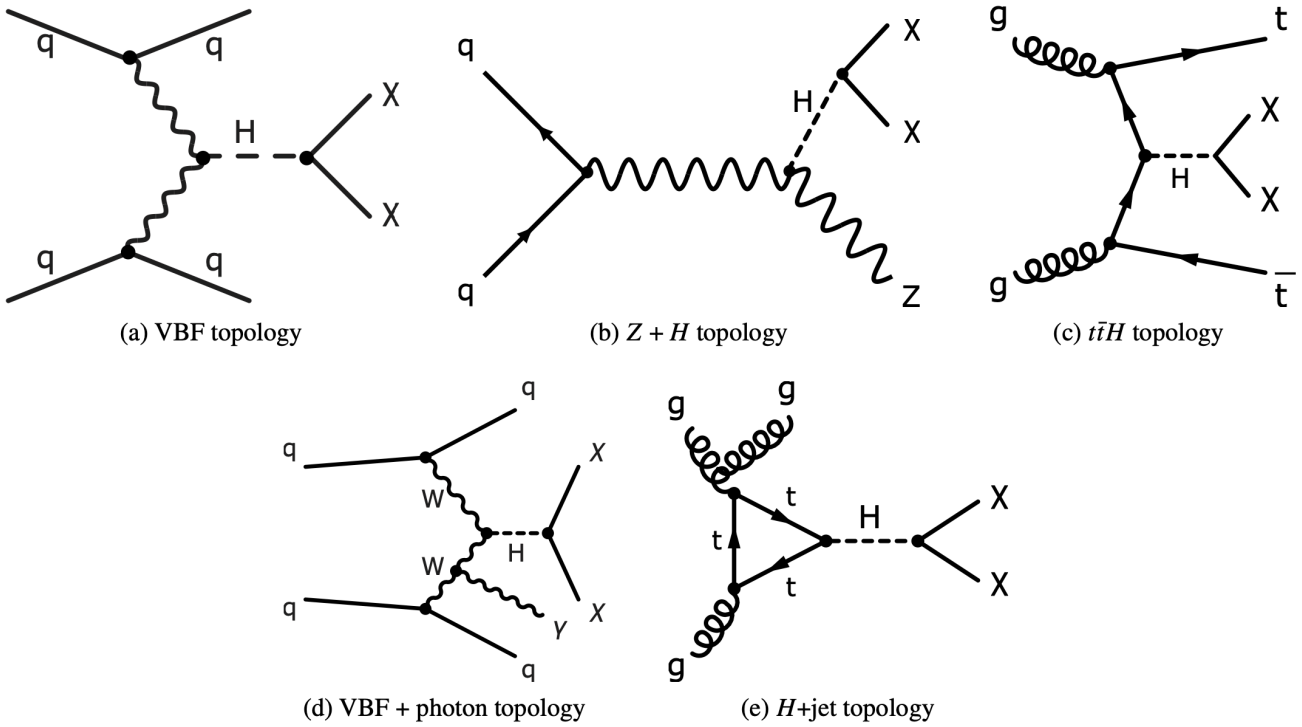
- 2HDM+a is an important DM model, with 14 free parameters
- 3 analyses are combined, and 7 more included in the summary
- Several benchmark scenarios are considered, e.g.:



EXOT-2018-64

Higgs to invisible combination

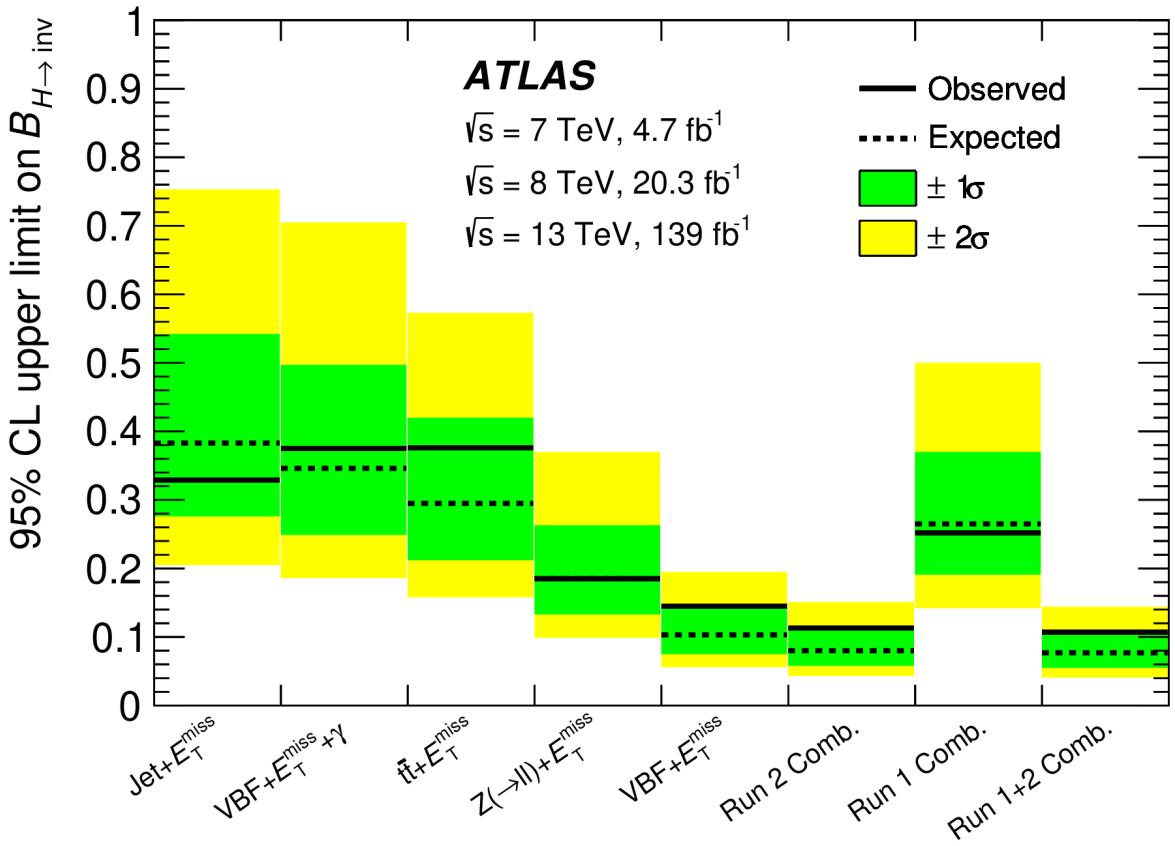
- The portal between the dark sector and the SM can be the Higgs boson, which can make decays of the Higgs to DM possible



arXiv:2301.10731 [hep-ex]

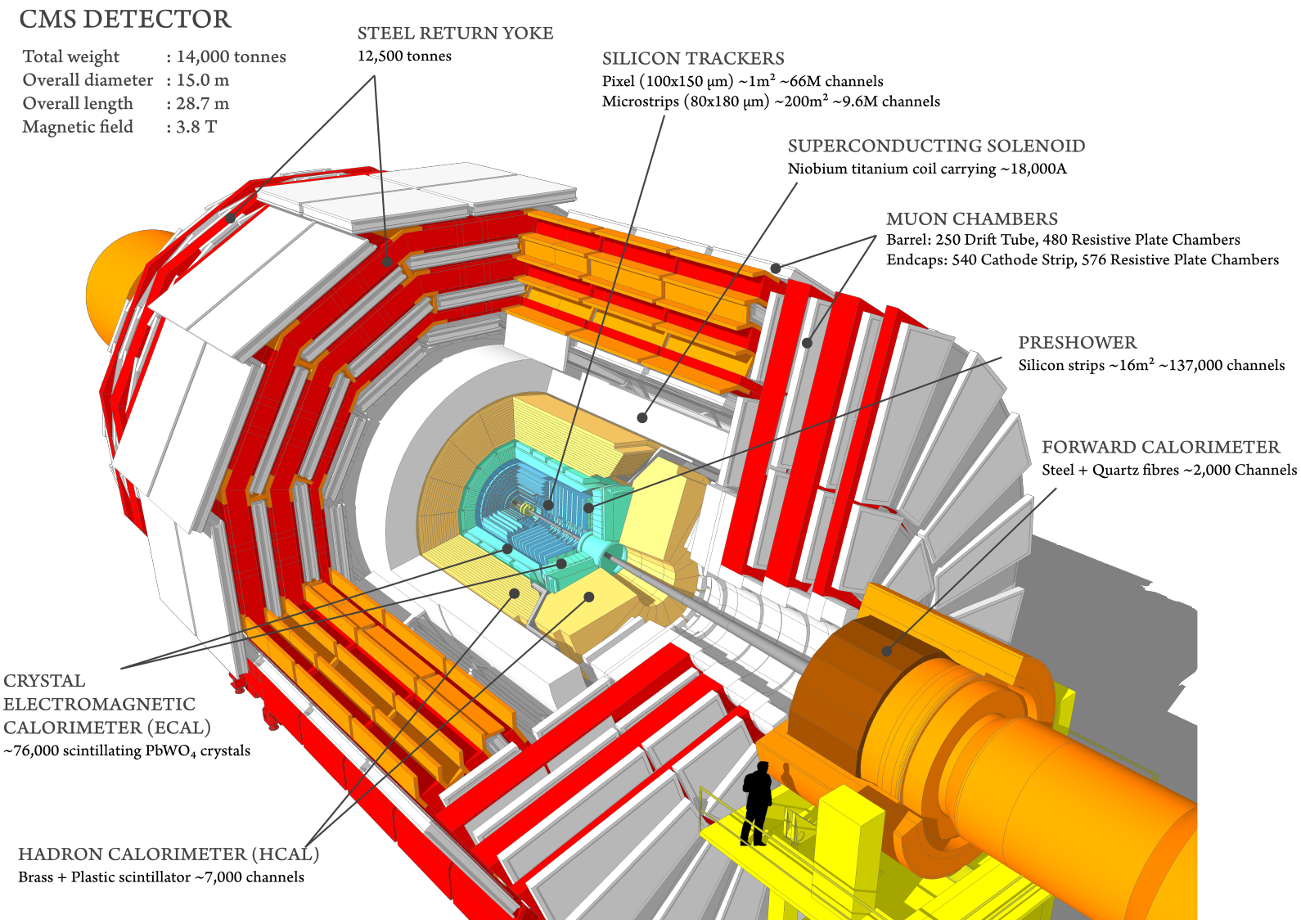
Higgs to invisible combination

- **95% CL upper limit:** $\mathcal{B} < 10.7\,\%\ (7.7\%)$
  - Most stringent upper limit to date!



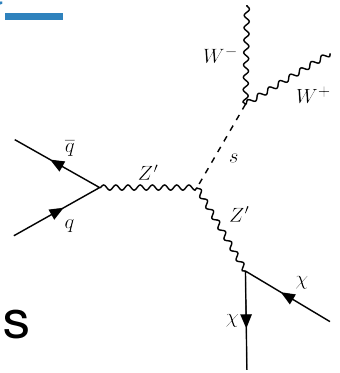
arXiv:2301.10731 [hep-ex]

CMS


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~1m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

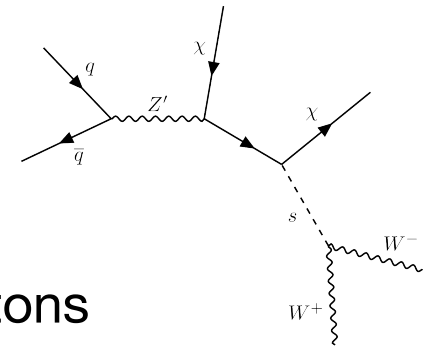
CMS

$Z' \to s\chi\chi,\ s \to W^+W^-$



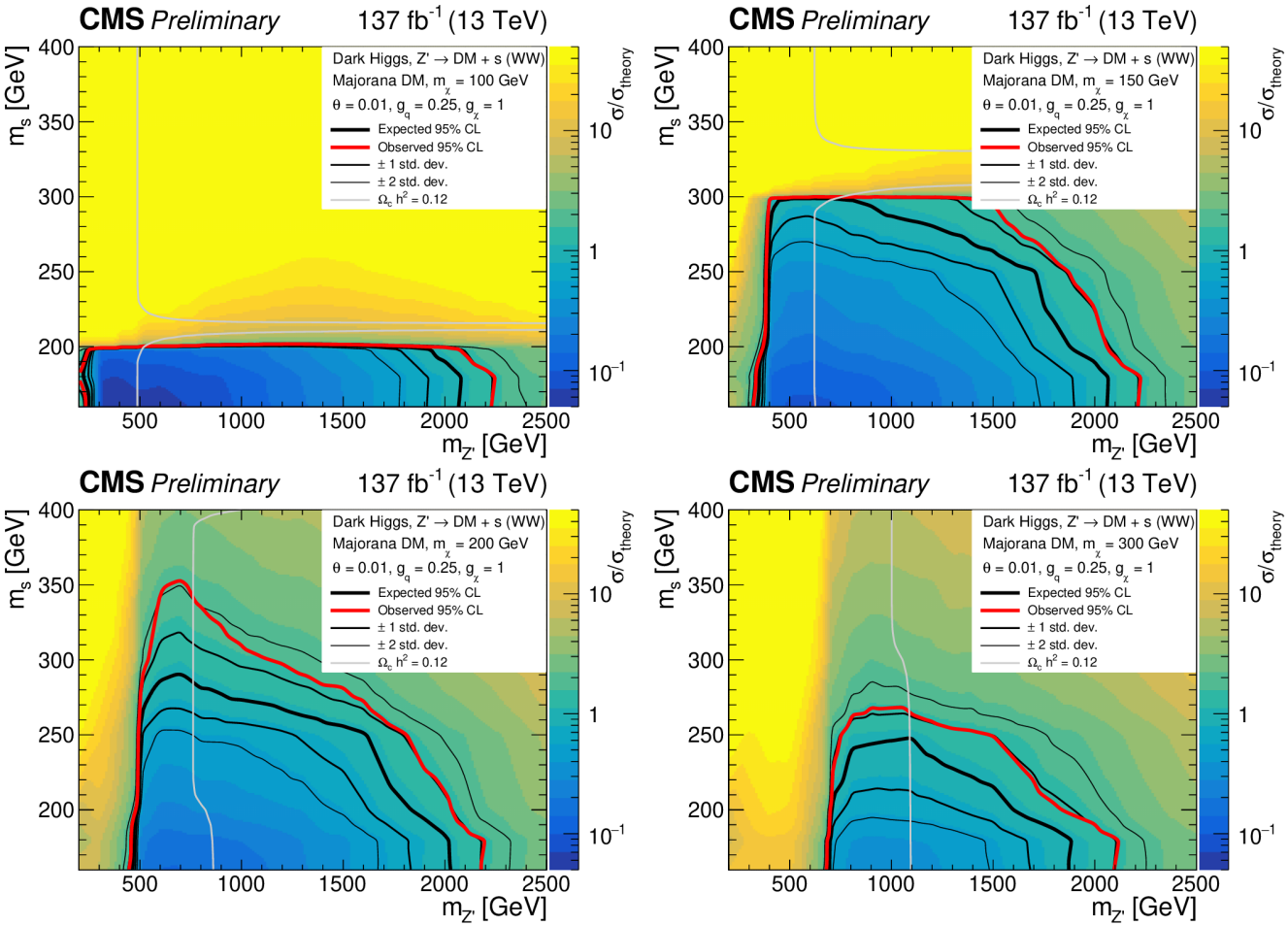
CMS-PAS-EXO-21-012

- **Target signal:** DM produced via dark Z and dark Higgs
- **Signature:** W^+W^- + MET, with at least one leptonic W decay
- **Channels:** di-leptonic & semi-leptonic
- **Triggers:** single-ℓ & di-ℓ
- **Selection overview:** MET requirements & b-vetos
  - **Di-leptonic channel:** 2 opposite-flavour OS leptons
  - **Semi-leptonic channel:** 1 ℓ & ≥ 2 jets
- **Categorisation:** di-leptonic channel has 3 $\Delta R_{\ell\ell}$ categories
- **Main backgrounds (models):**
  - **Di-leptonic channel:** tW, $t\bar{t}$, & WW (MC+CRs)
  - **Semi-leptonic channel:** W + jets, tW & $t\bar{t}$ (MC+CRs)



$Z' \to s\chi\chi, s \to W^+W^-$

- **Discriminants:** transverse mass of subleading lepton and MET, and $m_{\ell\ell}$ in di-leptonic channel, and BDT in semi-leptonic channel

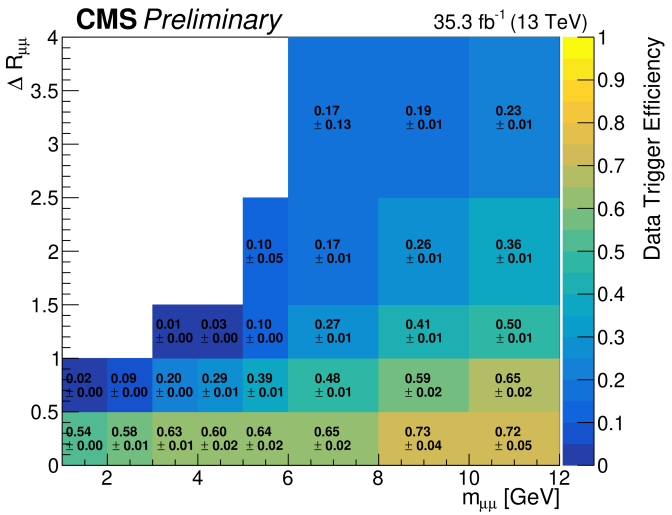


CMS-PAS-EXO-21-012

$X \to \mu\mu$

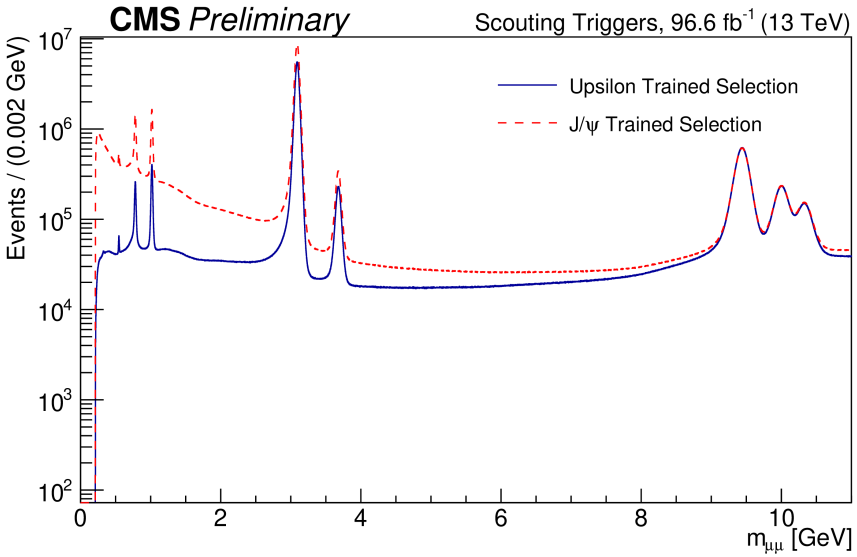
- **Target signal:** generic $X \to \mu^+\mu^-$, m_X: [1.1, 2.6] or [4.2, 7.9] GeV
  - Model independent, 2HDM+S and Z_D interpretations
- **Triggers:** di-μ scouting triggers write subset of event to disk
  - Event rates up to 2 kHz ($\sim 4 \times$ standard di-μ triggers)
- **Selection overview:** ≥ 2 BDT-based high-level trigger muons with $p_T > 4$ GeV & $|\eta| < 1.9$
  - Additional high-p_T selection with μ & di-μ p_T requirements
- **Signal model:** DSCB+Gaussian
- **Background model:** smooth functions

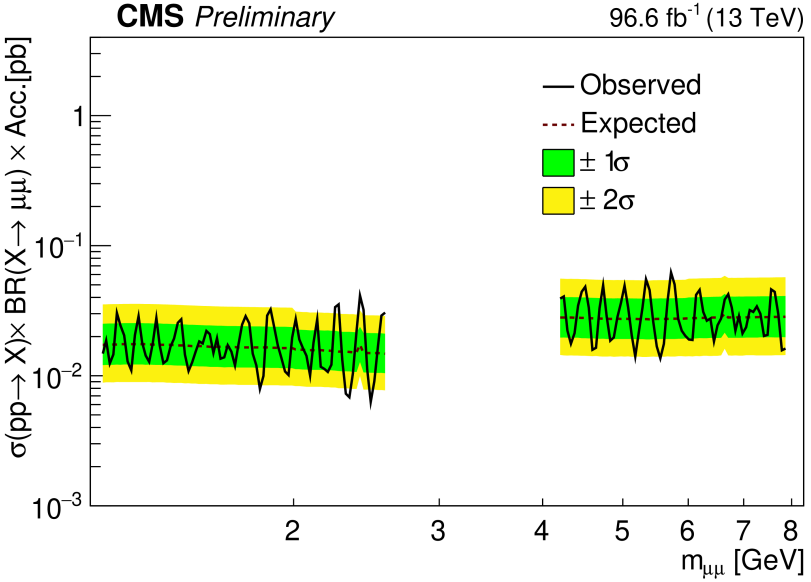
CMS-PAS-EXO-21-005



$X \rightarrow \mu\mu$

- **Discriminant:** di-μ mass

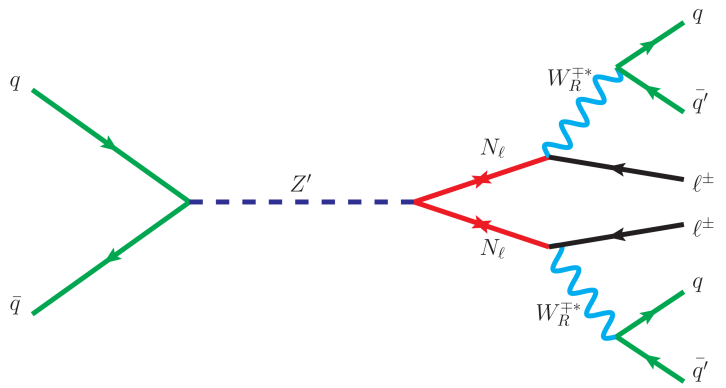




CMS-PAS-EXO-21-005

$Z' \to N_\ell N_\ell \to \ell^\pm \ell^\pm 4q$

- **Target signal:** $Z' \to N_\ell N_\ell$ decays from a "see-saw" mechanism in a left-right symmetry model
- **Signature:** 2 SS ℓ & 4 jets
  - A focus on $m_{N_\ell} \ll m_{Z'}$
- **Channels:** di-e & di-μ
- **Triggers:** di-e/γ & single-μ

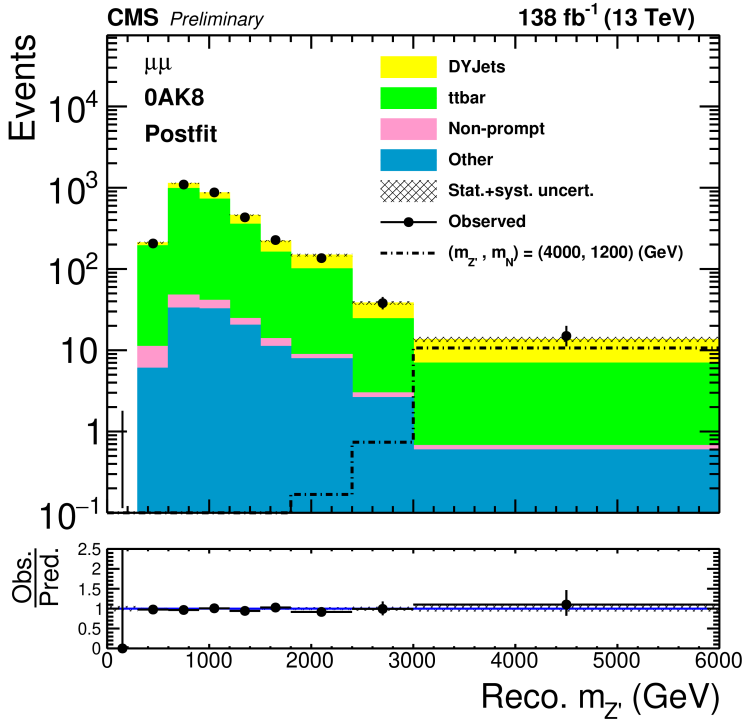


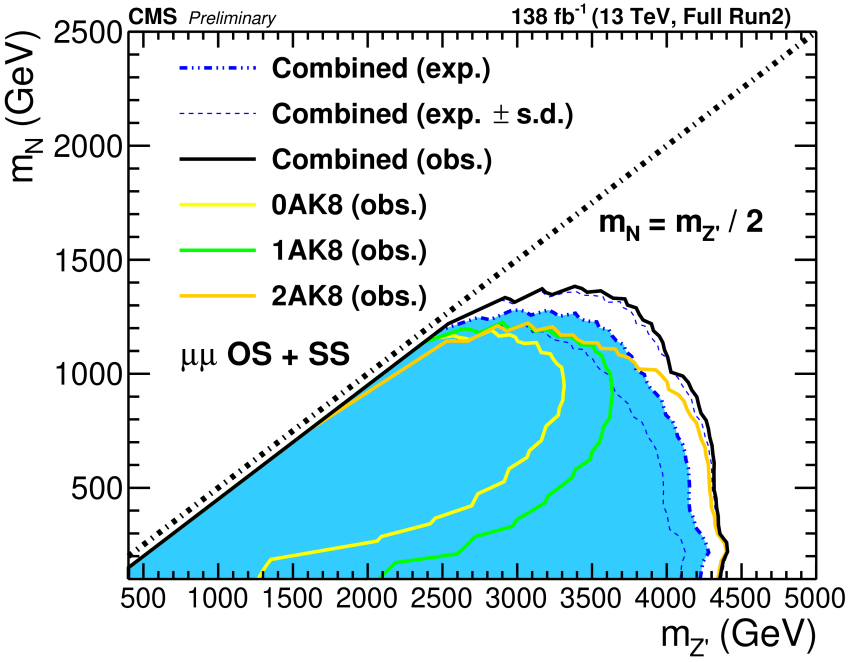
- **Selection overview:** 2 same flavour "loose" ℓ & ≥ 2 jets; $m_{\ell\ell} > 150$ GeV; N_ℓ mass difference minimised in matching
- **Categorisation (per channel):** 0 AK8 jets, 2 ℓ & ≥ 4 AK4 jets SR; 1 AK8 jet, ≥ 1 ℓ & ≥ 2 AK4 jets SR; ≥ 2 AK8 jets SR; $t\bar{t}$ CR; & Z CR
- **Main backgrounds (models):** $t\bar{t}$ & Drell-Yan/Z (both MC with data-driven corrections and CRs)

CMS-PAS-EXO-20-006

$Z' \to N_\ell N_\ell \to \ell^\pm \ell^\pm 4q$

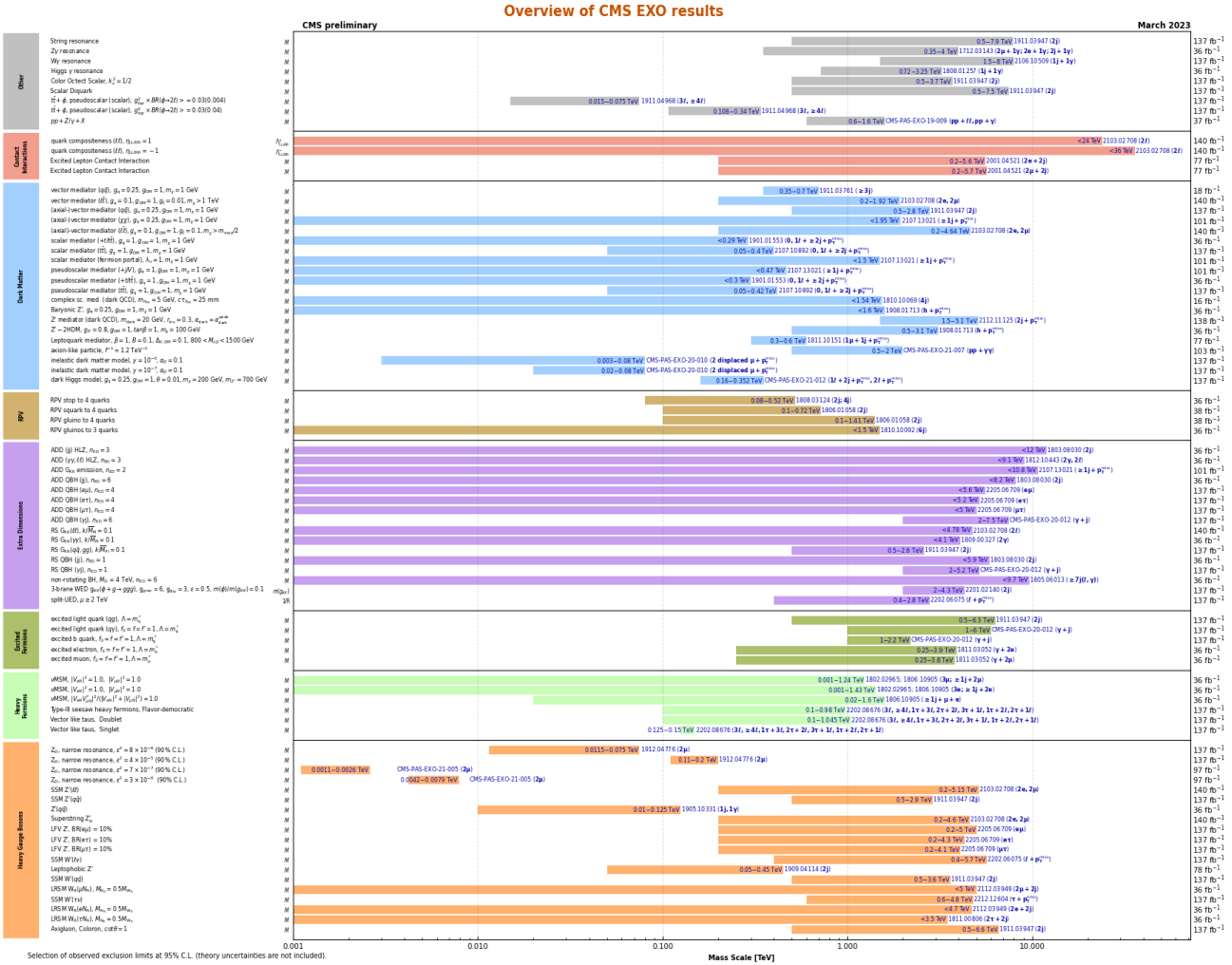
- **Discriminant:** $m_{Z'}$
- Most stringent direct limits on $m_{Z'}$—m_{N_ℓ} plane to date





CMS-PAS-EXO-20-006

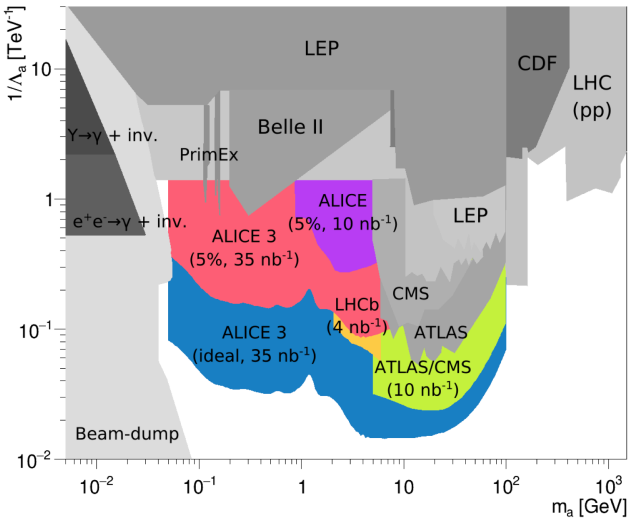
Exotica Results Summary



[CMS Exotica Public Plots]

Summary

- The LHC pushes the energy frontier, but can also probe lower cross-sections via FIP searches
- Various recent FIP searches were presented, but many less-recent searches exist
- ATLAS also performed a semi-visible jets search (see Sukanya's talk), and a variety of exotic Higgs decays searches (see Rocky's talk)
- Many searches stats limited → Run 3 & HL-LHC should be exciting!
- New LHCb results on the way!
- ALICE 3 will have sensitivity to ALPs
- NA62 has various less-recent FIP results:
  - Phys. Lett. B 807 (2020) 135599
  - JHEP 3 (2021) 58
  - Phys. Lett. B 816 (2021) 136259
  - JHEP 2 (2021) 201



Thanks for listening!

Any questions?