Searches for FIPs with prompt particles

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For ATLAS, CMS, LHCb, NA62 collaborations

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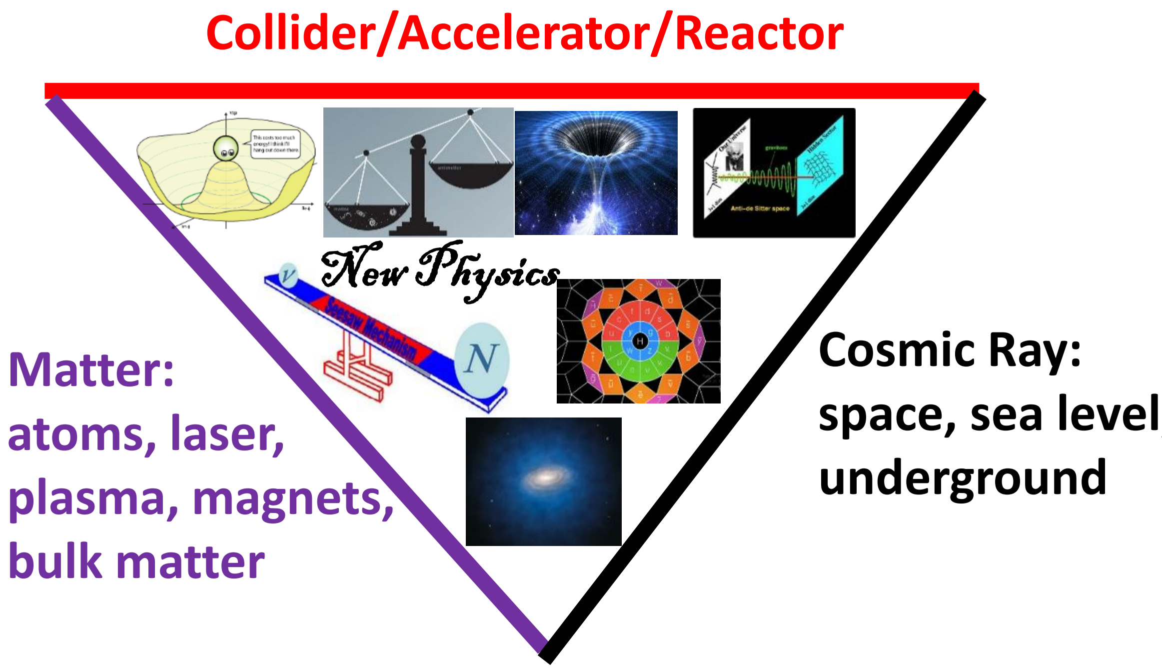
Searches for Feebly Interacting Particles

- ❖ Null search results so far at EW/TeV scale
- ❖ Growing interests in lower scales with very weak couplings ➔ FIPs (aka dark sectors)
- ❖ Motivated for many BSM phenomena and connection with astrophysics
- ❖ Diverse experimental probes

ATLAS, CMS, LHCb, Belle-II, BES-III, NA48/2, NA62/64, KLOE2, HPS, APEX, MicroBooNE, DarkQuest, T2K-ND280, g-2, Phenix, A1, HADES, … *



CAST (Helioscopes), ADMX (Haloscopes), ALPS (Light shining through walls), Atomic clocks, GPS.DM, GNOME, QUAX, … *

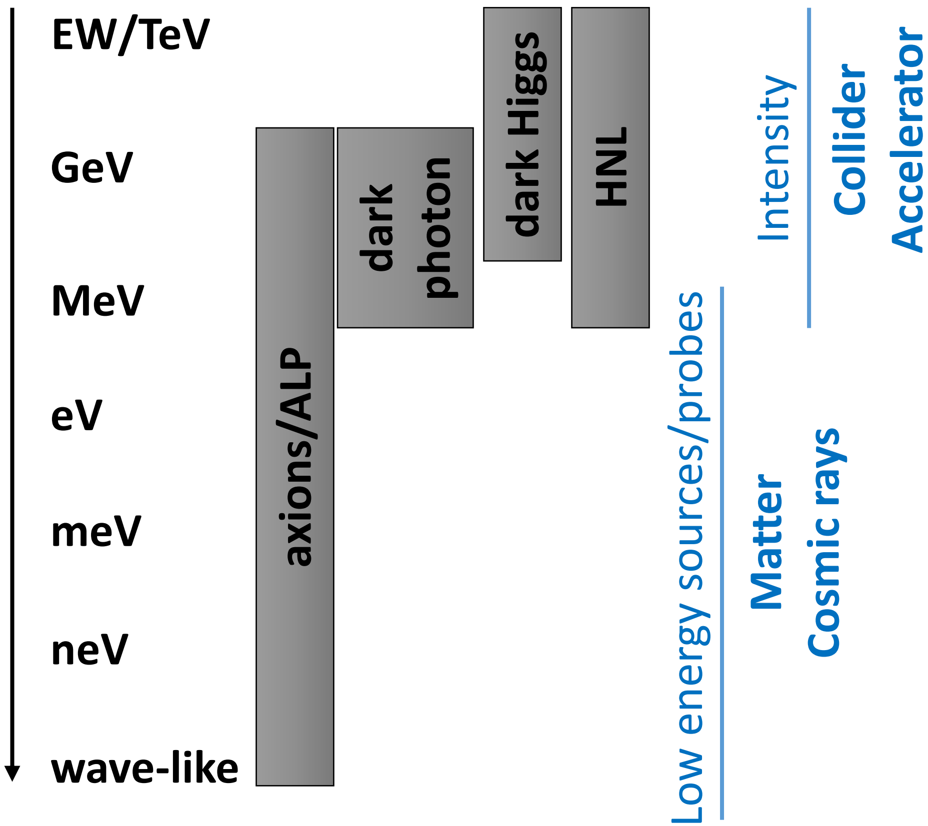
* Disclaimer: list of experiments for demonstration purpose, certainly missing many

FIPs and Detection

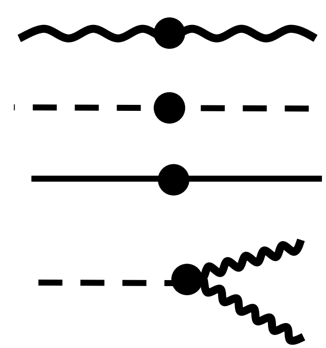
Assumptions of different spin-CP natures

Leading candidates: **dark photons** (vector), **dark Higgs** (scalar), **axions/ALP** (pseudoscalar), **heavy neutral leptons/HNL** (fermion) …

Broad range of possible masses or couplings



- ❖ Detectable signals due to mixing or coupling with SM particles



- ❖ Prompt (focus of this talk) or displaced final states depending on couplings, parameter spaces, etc.

Models to constrain

Simplified models and parameters:

$-\frac{\varepsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$

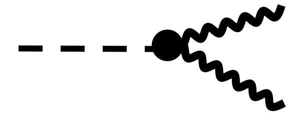
Dark photon:
$m_{A'}$: mass
ε: mixing parameter between dark U(1) and SM
α_D: dark U(1) coupling
…

$(\mu S + \lambda_{HS}S^2)H^\dagger H$

Dark Higgs:
m_S: mass
θ: mixing parameter between dark Higgs and SM
…

$y_N LHN$

HNL:
m_N: mass
U_α: mixing parameter between SM leptons and HNL
…



$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi$

Axions/ALP:
m_a: mass
f_a: axion decay constant
$g_{a\gamma}$: axion-photon coupling (as an example)
…

Ref: Annu. Rev. Nucl. Part. Sci. 2021.71:279-313

Other relevant models/scenarios:

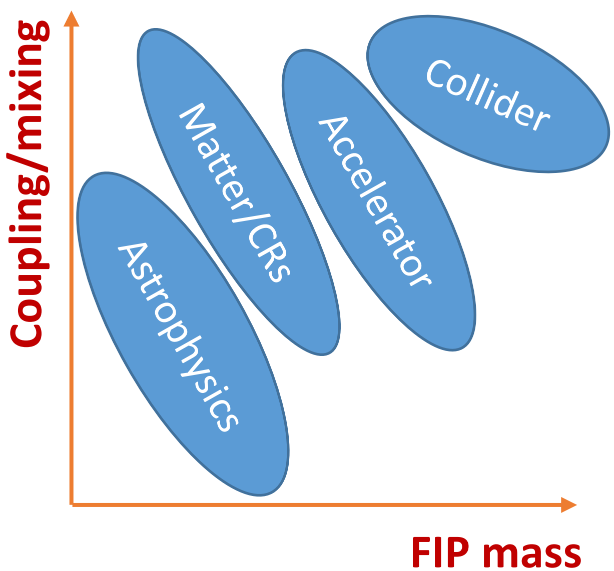
- Extended models embedding one or several of these FIPs
- BSM particles sharing similarity, such as dark Z *

* dark Z differs from dark photon in the way that dark Z also couples with SM neutral currents (ambiguities exist in using the term, depending on the context)

Disclaimer: will mostly use labels A' for dark photon, Z_D for dark Z, S for dark Higgs, N for HNL, a for axions or ALPs

Experimental Overview

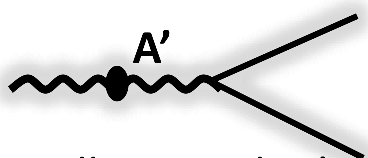
- Not yet positive results on FIP searches
- Pushing further exclusions on parameter spaces
- Complementarity among experiments



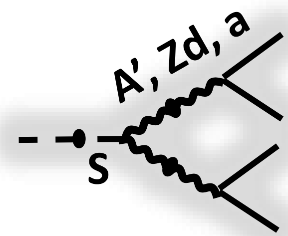
Collider/accelerator prompt final states

Partially illustrated below:

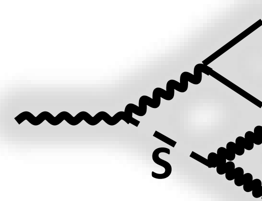
χ is DM particle



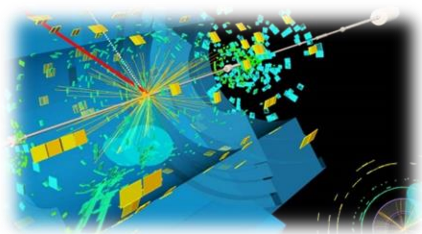
Drell-Yan with A'

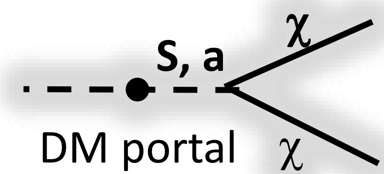


H or S decays → A', Zd, a

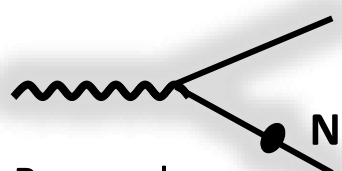


Dark sector with S

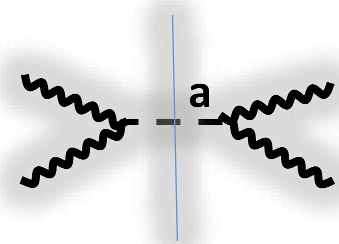




DM portal with S, a



Boson decays → HNL



Photons with a

Landscape of Recent Results to Cover

100 MeV — 1 GeV — 10 GeV — 100 GeV — TeV

[HNL] NA62
with >10^{12} kaons
PLB807(2020)135599
PLB816(2021)136259

[HNL] LHCb 7-8TeV pp 3fb^{-1}, W decays
EPJC81(2021)248

[A'] CMS 13TeV pp 137fb^{-1}, dimuon
PRL124(2020)131802

[HNL] ATLAS
13TeV pp 139fb^{-1}, leptons + jets
arXiv:2202.02039 , EPJC81(2021)218

[A',S] LHCb 13TeV pp 5fb^{-1}, dimuon PRL124(2020)041801, JHEP10(2020)156

[HNL] CMS 13TeV pp ~140fb^{-1}, leptons + jets
arXiv:2112.03949, CMS-PAS-EXO-20-006, CMS-PAS-EXO-21-003, CMS-PAS-EXO-20-011

[A',S,Z_D] ATLAS,CMS 13TeV pp ~140fb^{-1},
H→4l arXiv:2110.13673 , EPJC82(2022)290

[A',S] ATLAS,CMS 13TeV pp ~140fb^{-1},
H→inv arXiv:2202.07953, PLB829(2022)137066
EPJC82(2022)105, arXiv:2201.11585

a.k.a. Exotic Higgs decays searches, more here ATL-PHYS-PUB-2021-008

[S] ATLAS, CMS 13TeV pp ~140fb^{-1}, diboson
PRL126(2021)121802 , CMS-PAS-EXO-20-013, ATLAS-CONF-2022-029

[ALP,S] NA62
Kaon/Pion decays
JHEP02(2021)201,
JHEP03(2021)058
JHEP06(2021)093

[ALP] ATLAS 13TeV pp 139fb^{-1},
H→bbX, PRD105(2022)012006,
JHEP01(2022)063

[ALP] CMS 13TeV pp 132fb^{-1},
H→4γ CMS-PAS-HIG-21-003

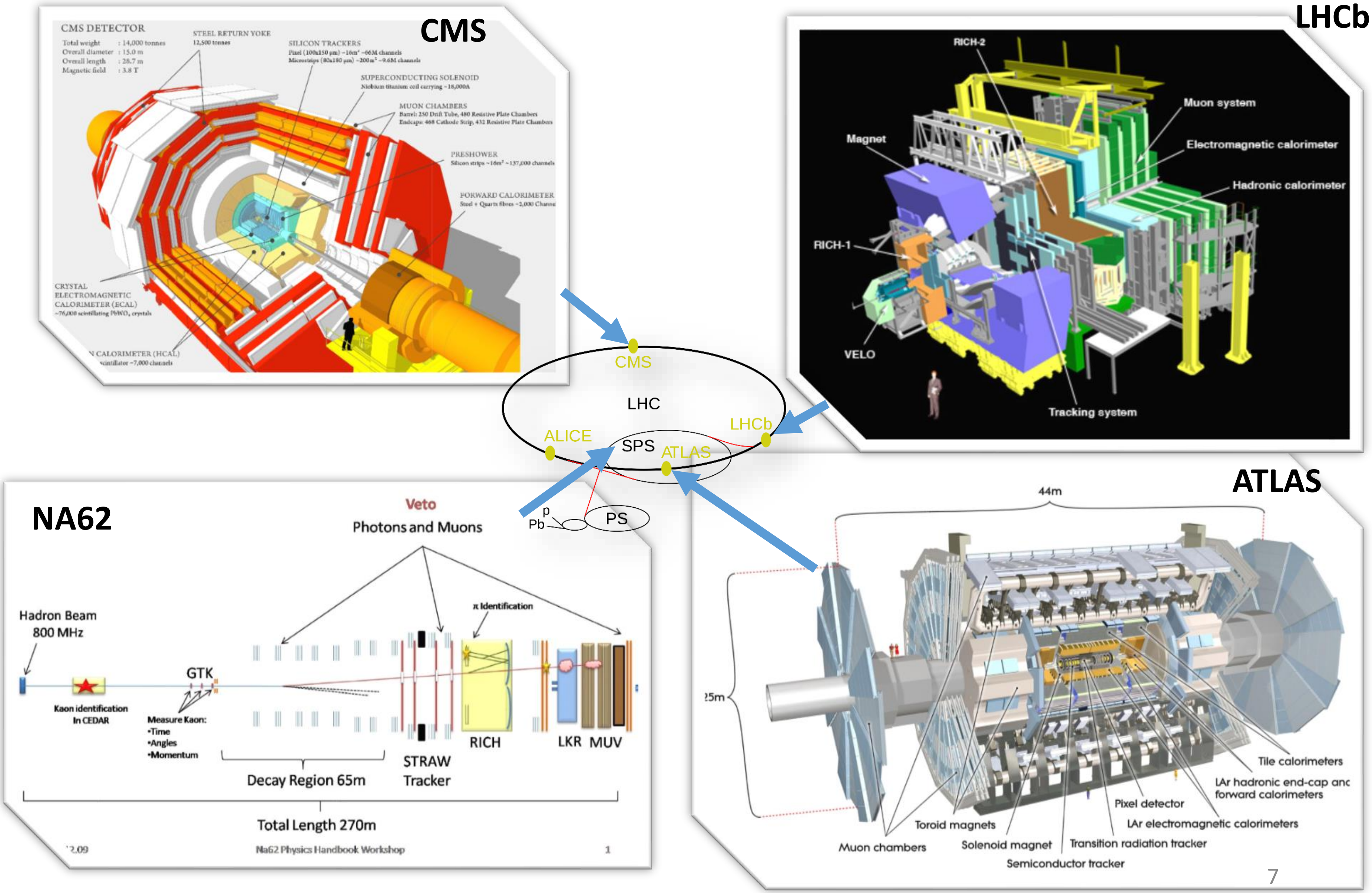
[ALP] CMS 13TeV pp 136fb^{-1}, H→2 merged γ
CMS-PAS-HIG-21-016

[ALP] ATLAS 13TeV pp 139fb^{-1}, diphoton
ATLAS-CONF-2022-018

[ALP] ATLAS 13TeV pp 139fb^{-1}, 2HDMa with mono-X ATLAS-CONF-2022-012, ATLAS-CONF-2021-036

[ALP] ATLAS 13TeV PbPb 2fb^{-1}, light-by-light scattering JHEP03(2021)243

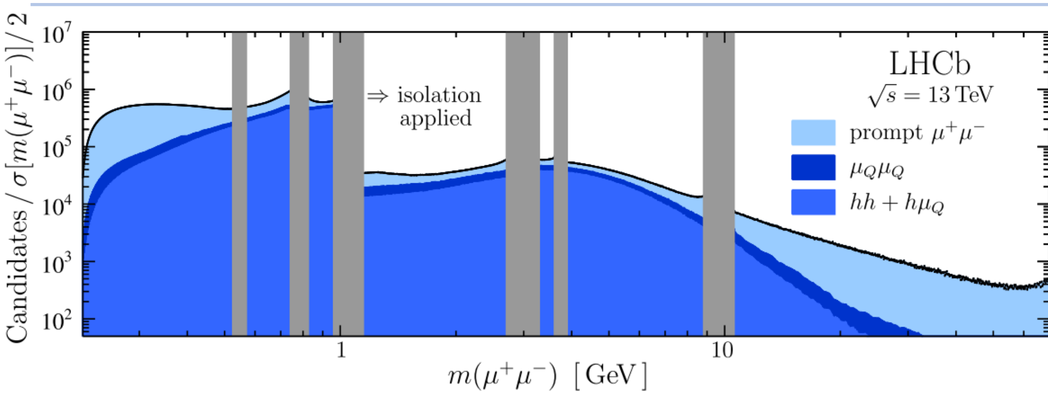
Apparatus

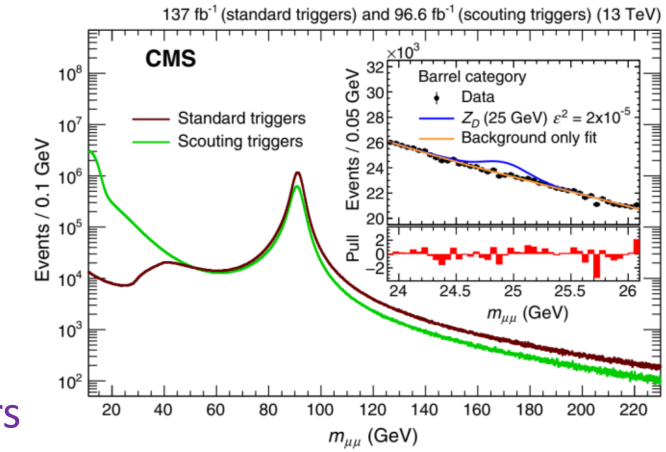

CMS
CMS DETECTOR
STEEL RETURN YOKE
SILICON TRACKERS
SUPERCONDUCTING SOLENOID
MUON CHAMBERS
PRESHOWER
FORWARD CALORIMETER
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
LHCb
RICH-2
Magnet
Muon system
Electromagnetic calorimeter
Hadronic calorimeter
RICH-1
VELO
Tracking system
CMS
LHC
ALICE
SPS
ATLAS
LHCb
p
Pb
PS
NA62
Veto
Photons and Muons
Hadron Beam
800 MHz
π Identification
GTK
Kaon identification
In CEDAR
Measure Kaon:
•Time
•Angles
•Momentum
RICH
LKR
MUV
STRAW
Tracker
Decay Region 65m
Total Length 270m
Na62 Physics Handbook Workshop
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

Dark bosons (A’, Z_D, S)

Precision Search: Two Muons

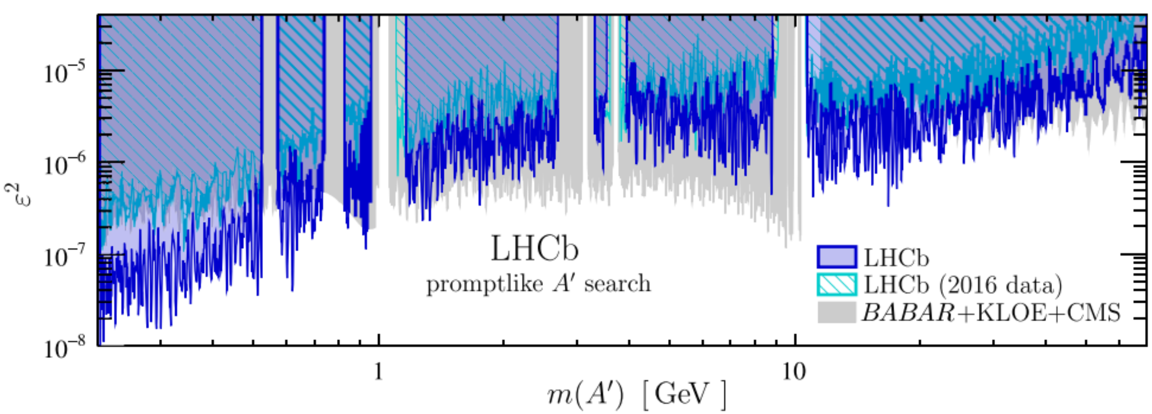
PRL124(2020)041801 PRL124(2020)131802

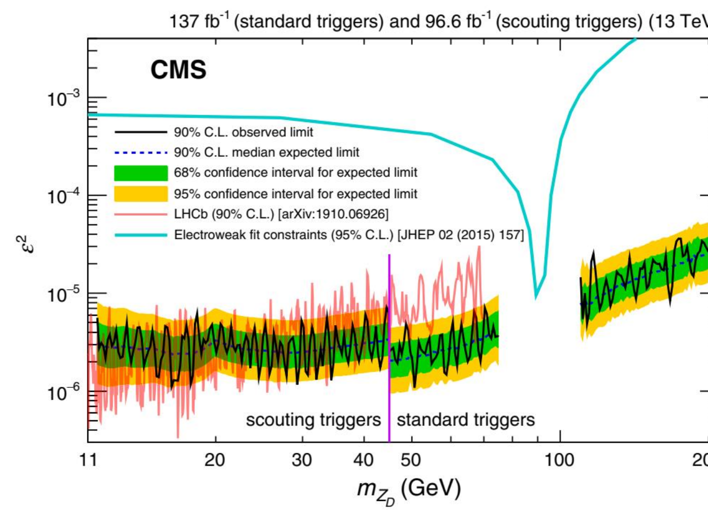




Examine small masses via low thresholds, special triggers

➔ Hunt for narrow A' bumps





Most stringent constraints on $(\varepsilon^2, m_{A'})$ in sub-GeV and beyond 10 GeV

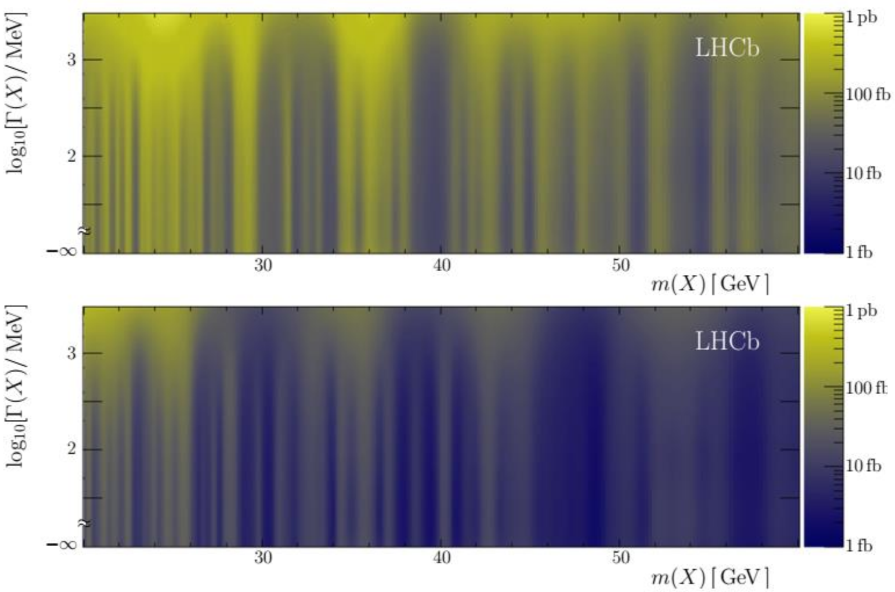
More on Two Muons

JHEP10(2020)156

Main sensitivity factors: data statistics, detector resolution, model kinematics, efficiencies

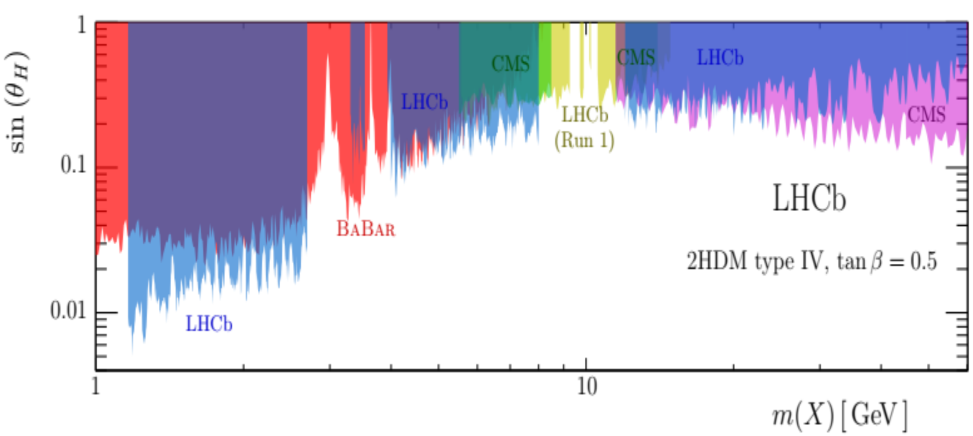
Go beyond constraining simplified A' models

e.g., Model independent σ limits as a function of mass, width



top for σ(X→μμ), bottom for σ(X→μμ+b)

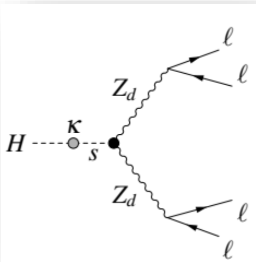
e.g., constraints on 2HDM model (pseudoscalar mass and mixing with H)

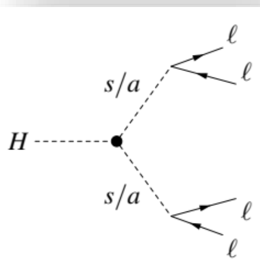


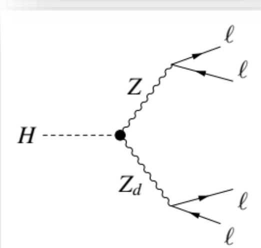
H → four leptons

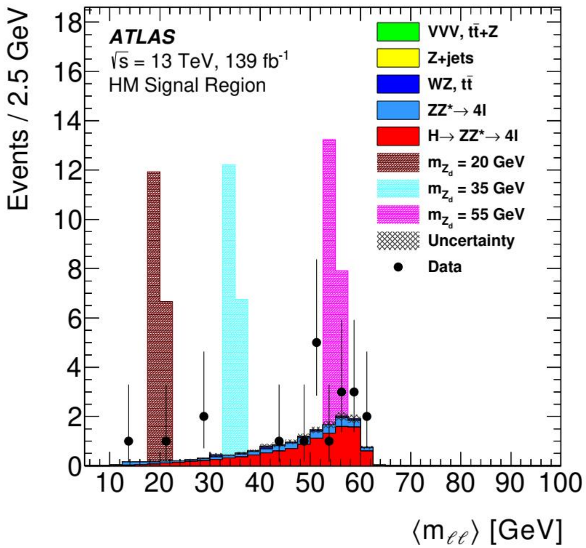
arXiv:2110.13673 , EPJC82(2022)290

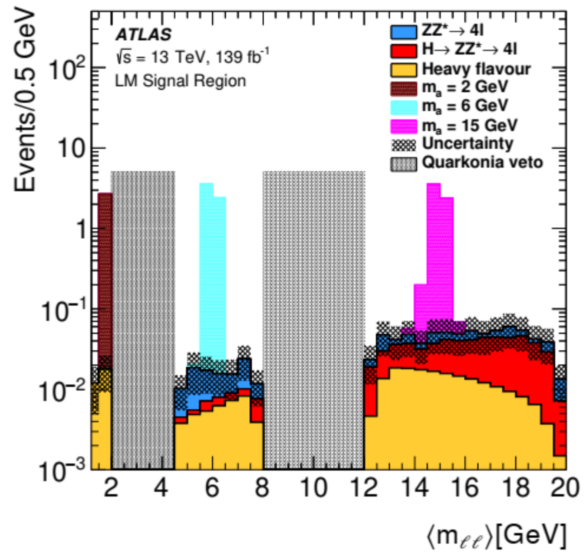
Higgs factory + Clean 4l final state + Rich diagram topology → **Unique probe**





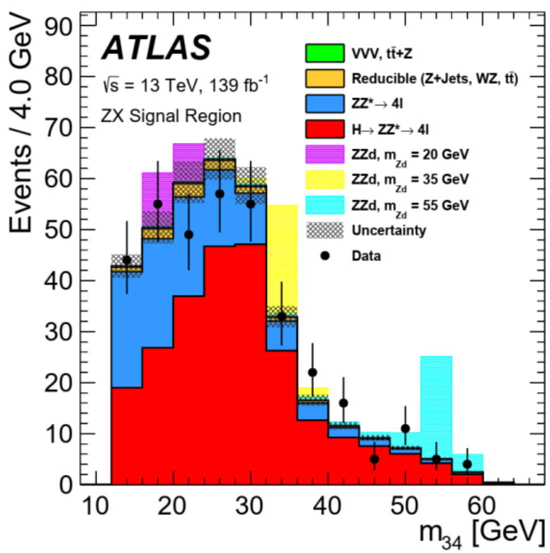






H→XX

H→ZX



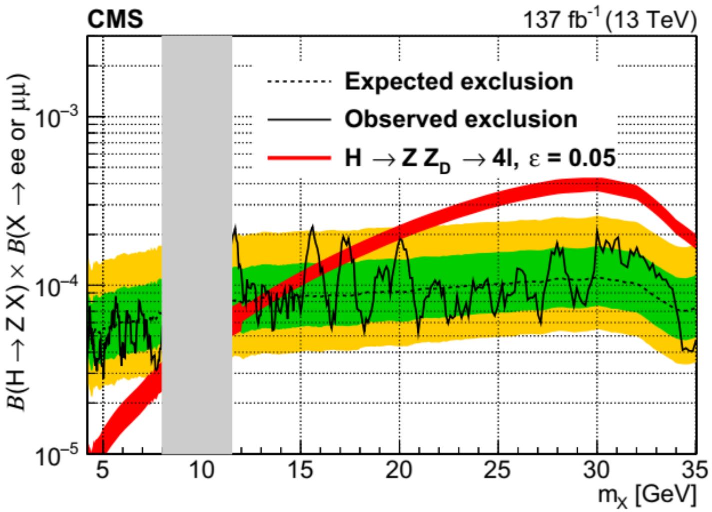
Bump hunting via lepton pair mass

Data statistics, acceptance, efficiencies are keys

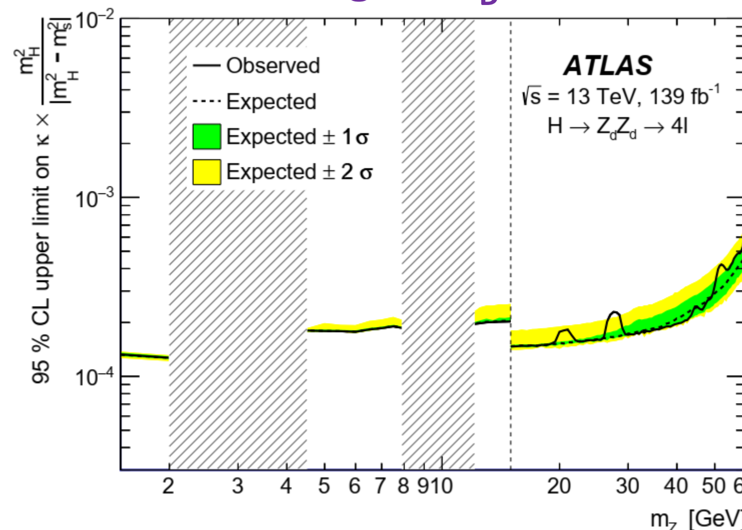
H → four leptons

arXiv:2110.13673 , EPJC82(2022)290

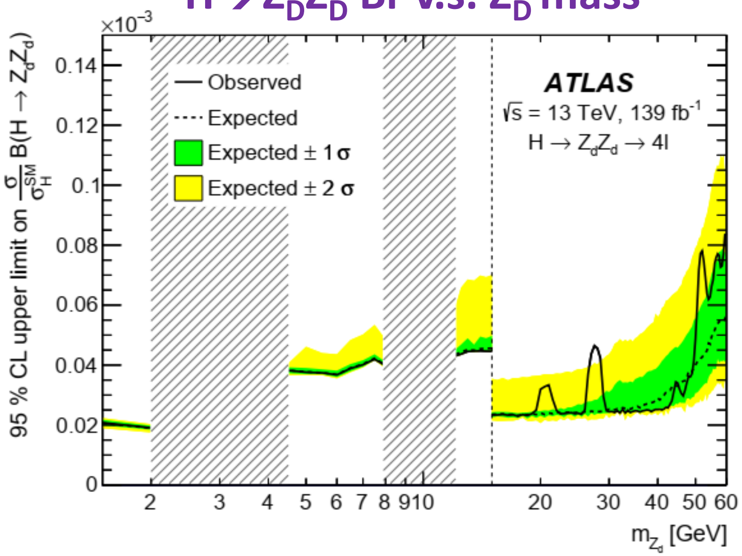
H→ZZ$_D$ Br v.s. Z$_D$ mass



S mixing v.s. Z$_D$ mass

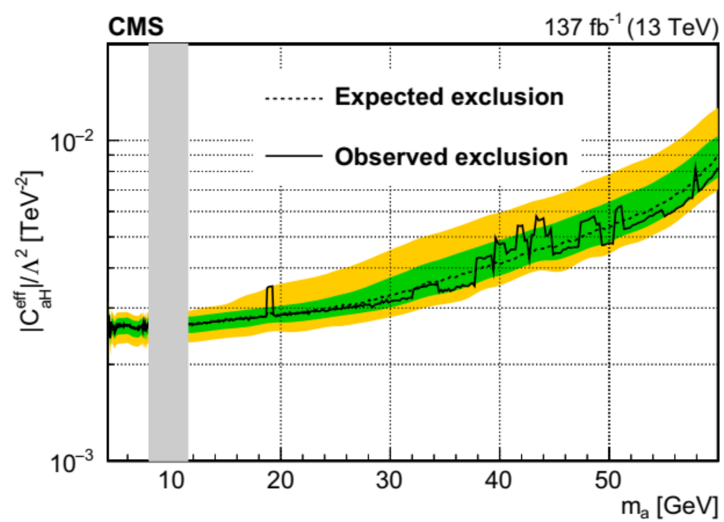


H→Z$_D$Z$_D$ Br v.s. Z$_D$ mass



Unique constraints between GeV-EW scales for FIPs-Higgs models

ALP-H coupling v.s. mass



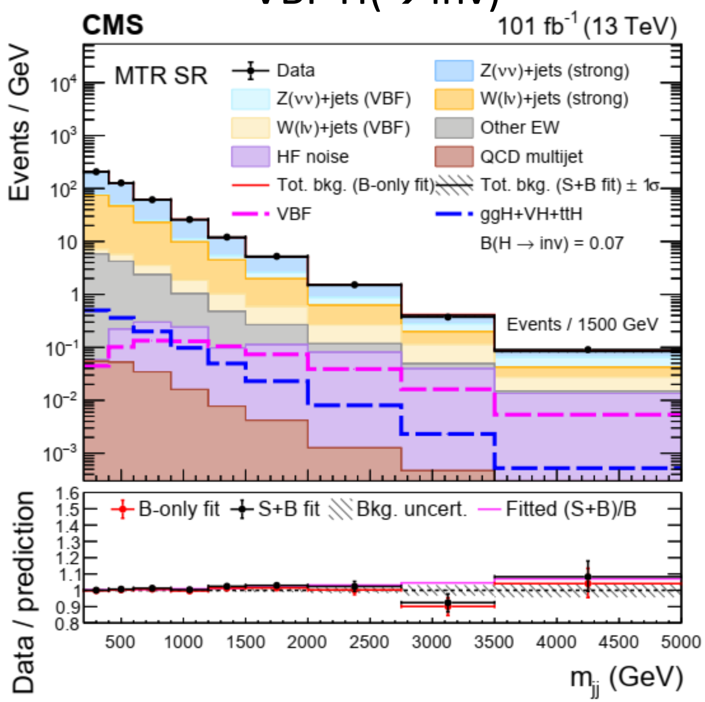
H → invisible

arXiv:2202.07953, PLB829(2022)137066 EPJC82(2022)105, arXiv:2201.11585

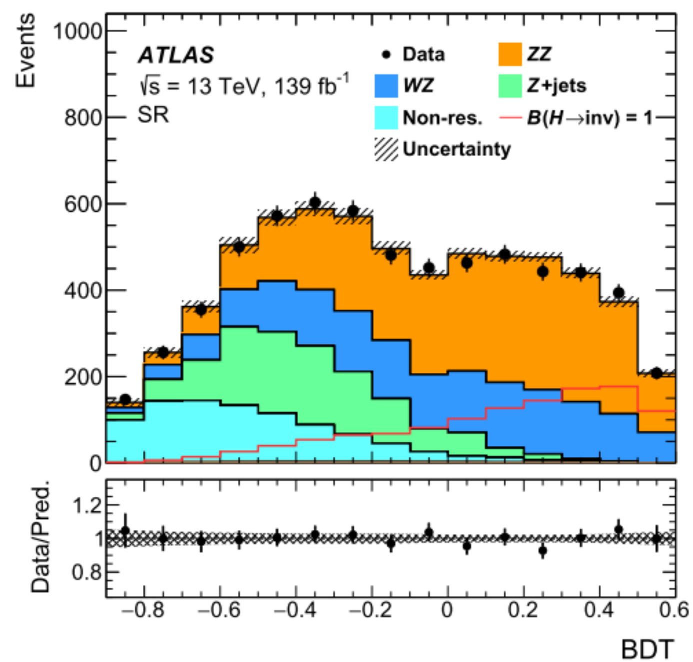
Utilize high sensitivity channels, e.g.,
VBF H(→inv), Z(ll)H(→inv), …

Can directly constrain dark Higgs models
not yet frequently reported from exp. papers

VBF H(→inv)



Z(ll)H(→inv)



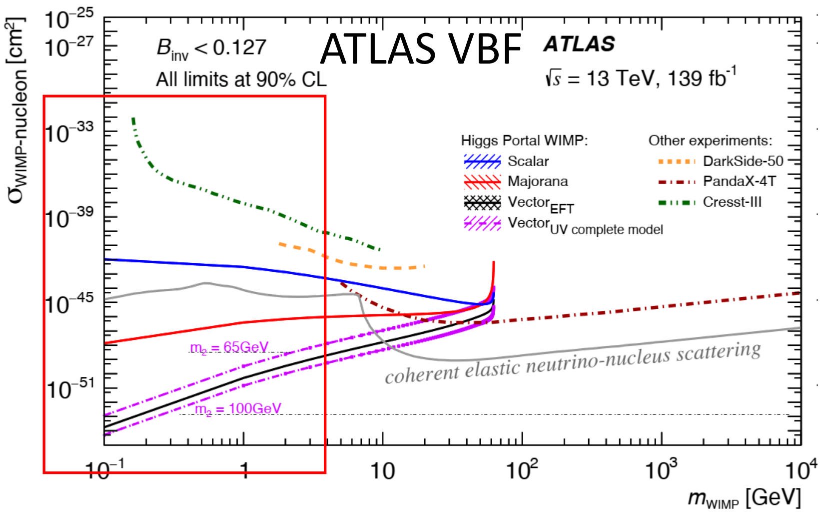
Search relying on precise understanding of kinematic shapes
all matters to sensitivity: modelling, backgrounds, MVA, …

H → invisible

arXiv:2202.07953, PLB829(2022)137066 EPJC82(2022)105, arXiv:2201.11585

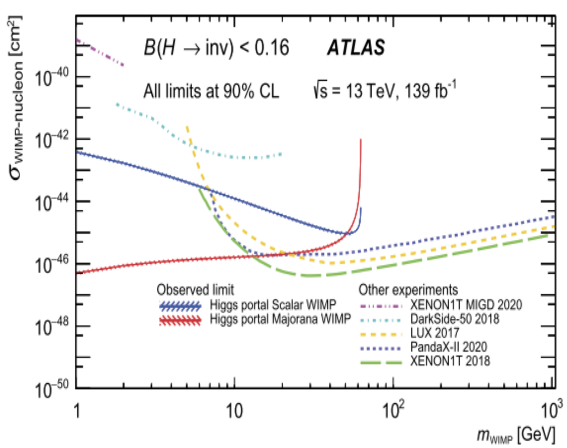
Individual channels show Br(H→inv) < 14-20% at 95% CL; Results are systematics dominated

Typical re-interpretation into WIMP DM-n σ

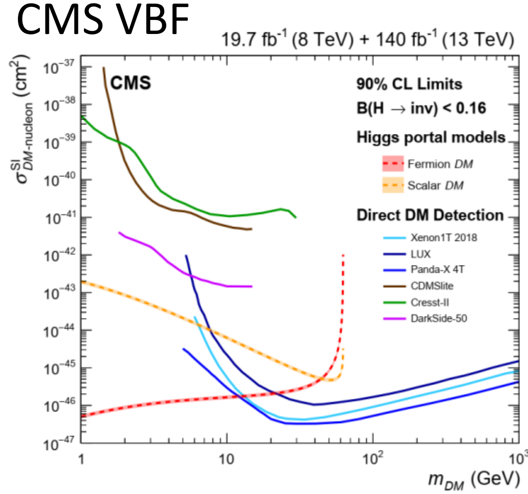


Competitive at low mass WIMP DM

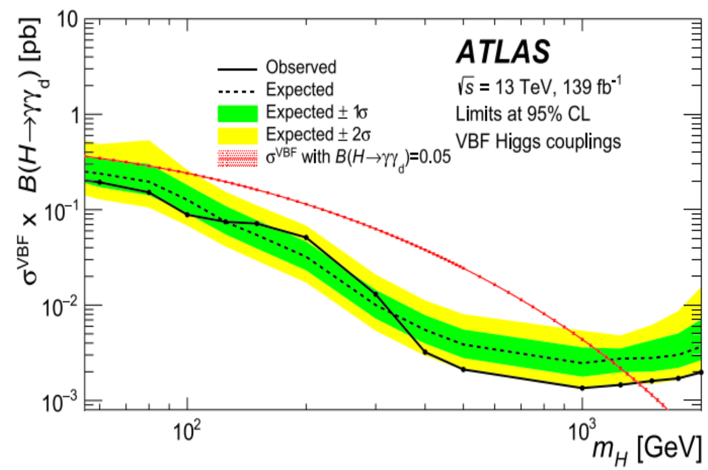
ATLAS ZH



CMS VBF



Also probing rarer channels, e.g., VBF H(→inv) + γ

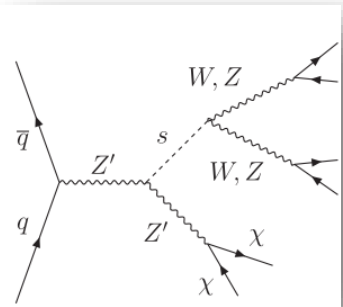


Not only constraints on H→inv, but also on **invisibly decaying dark photons**

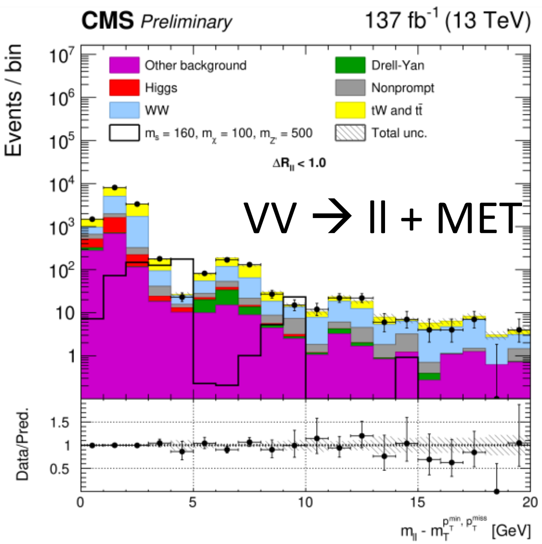
S → diboson

PRL126(2021)121802 , CMS-PAS-EXO-20-013, ATLAS-CONF-2022-029

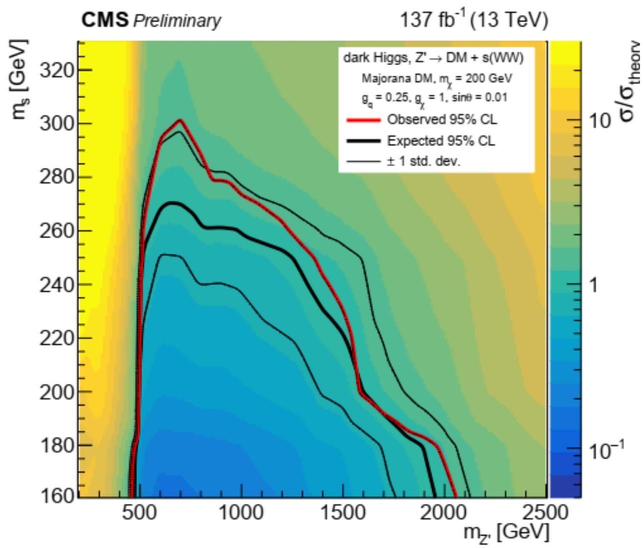
Extended models with new vector (Z') and EW-scale S decaying to diboson



Example kinematic distribution



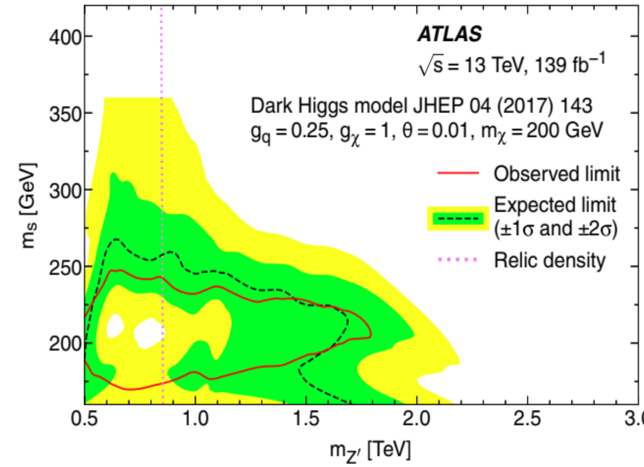
CMS: ll + MET



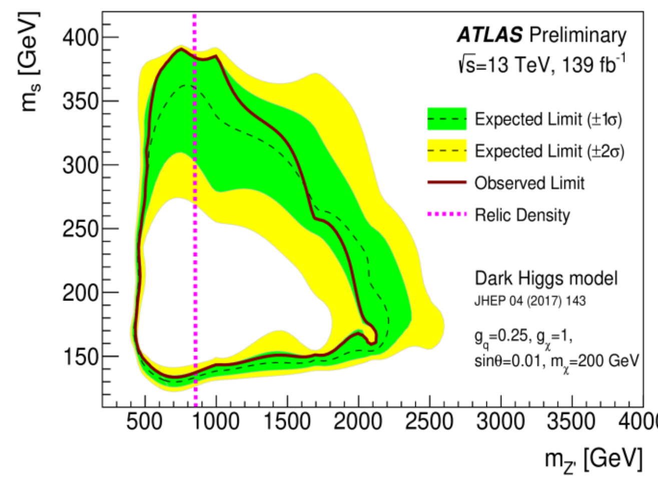
2D mass exclusions:

exploring a new territory of EW-scale dark Higgs

ATLAS: jets + MET



ATLAS: l + MET + qq

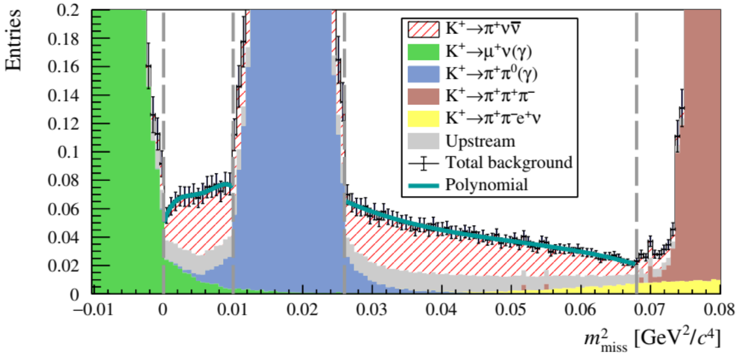


Axion-Like Particles

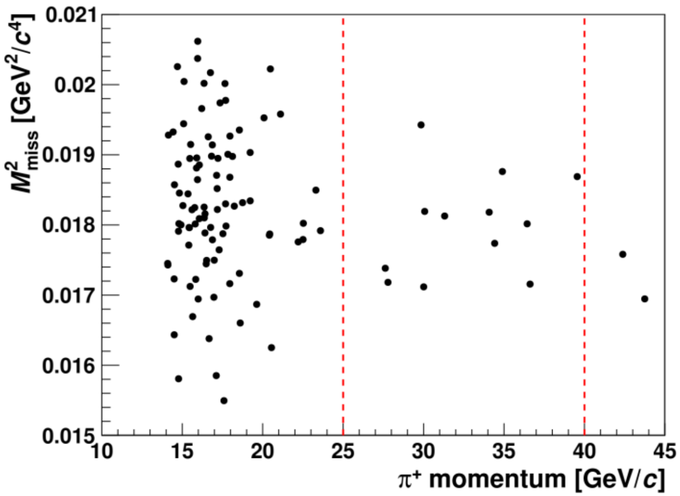
From kaon, pion decays NA62

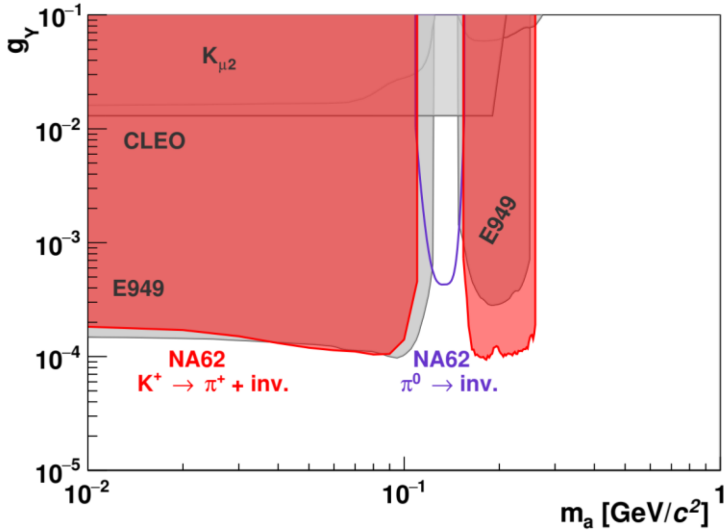
JHEP02(2021)201, JHEP03(2021)058, JHEP06(2021)093

$K^+ \rightarrow \pi^+$ + inv. (without π^0 peak)

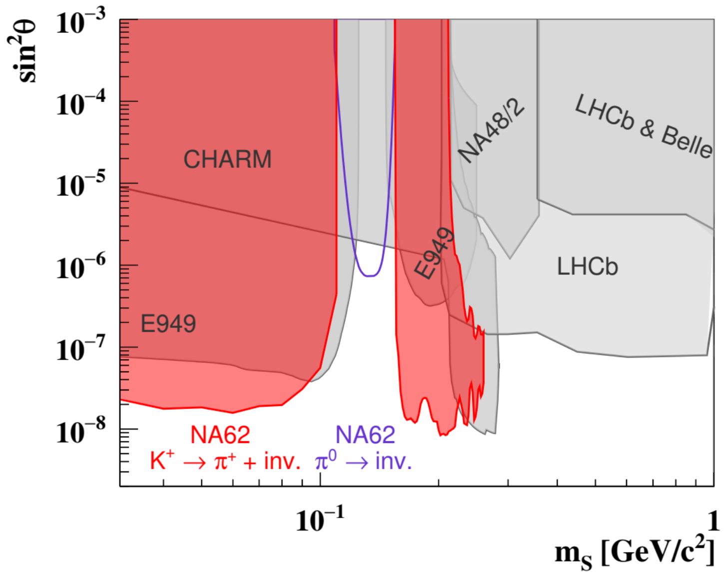


$K^+ \rightarrow \pi^+$ + inv. (focus on $\pi^0 \rightarrow$ inv.)





ALP coupling vs mass



Dark Higgs mixing vs mass

Leading constraints among lower energy experiments

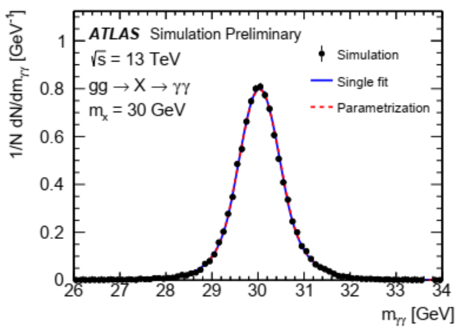
gg to a to $\gamma\gamma$

ATLAS-CONF-2022-018

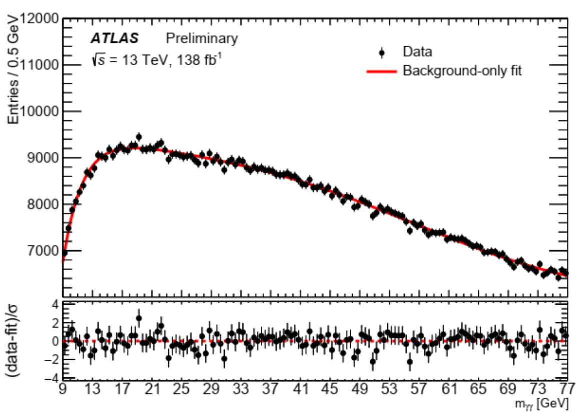
Assume ALPs couple to both g and γ

Utilize boosted $\gamma\gamma$ to reach lower mass, with advantage of a smooth background shape

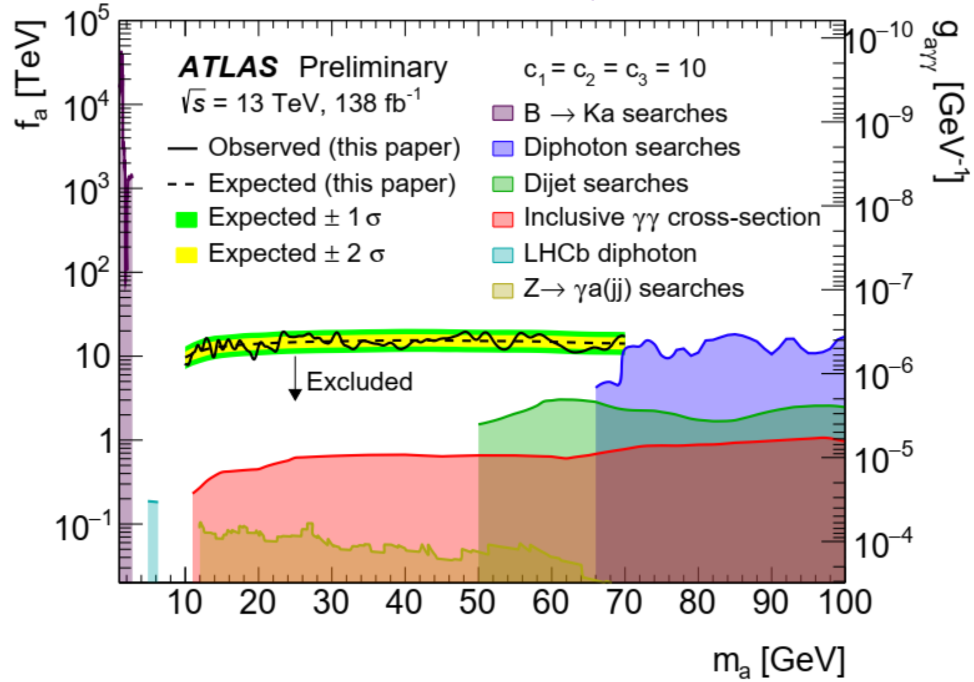
Signal



Background-only fit



Constraints on f/g v.s. m_a



Significant improvement to 10-70 GeV range;

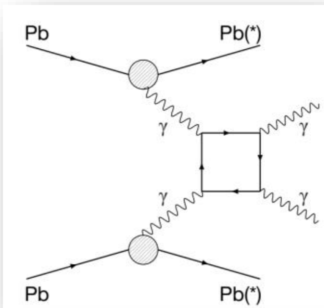
Filled the gap below 65 GeV for direct searches

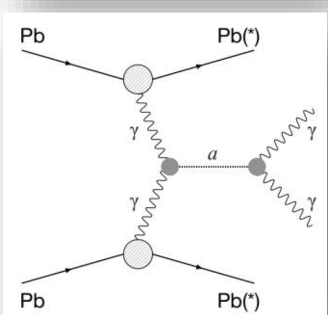
ALPs in Light-by-light Scattering

JHEP03(2021)243

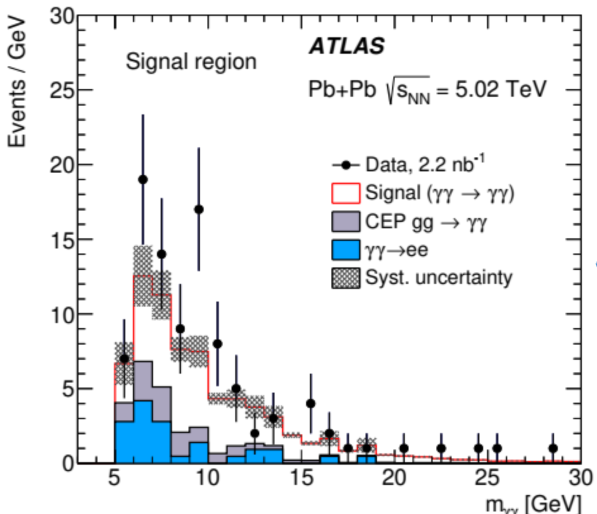
Light-by-light scattering

a rare EM process + an ideal process for pure a-γ couplings



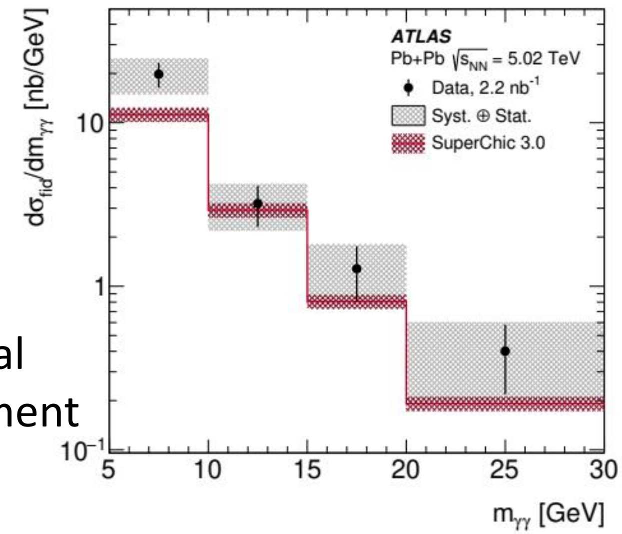


Great enhancement of photon flux via Pb+Pb collisions

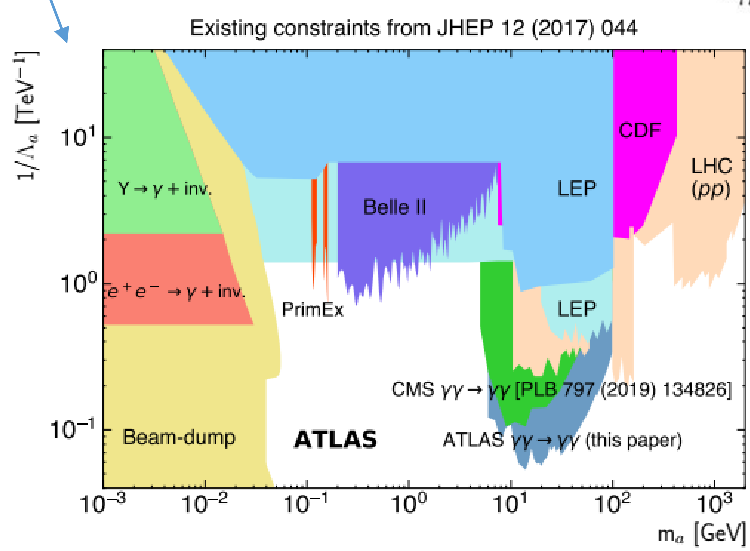


Achieved good S/B via "zero-track" feature

Differential measurement



Most stringent constraints to pure a-γ couplings at 10-30 GeV range

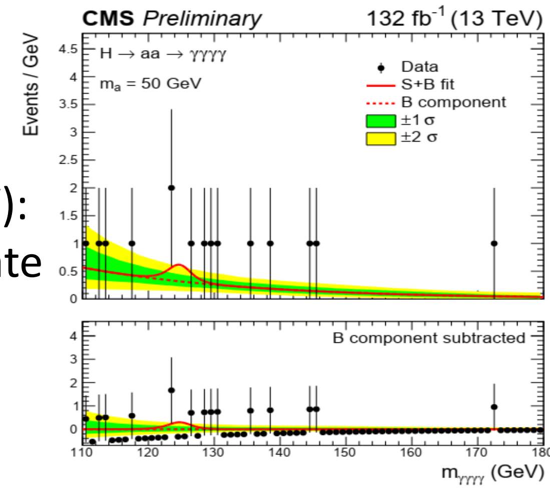


ALPs in H to 4γ decay

CMS-PAS-HIG-21-016, CMS-PAS-HIG-21-003

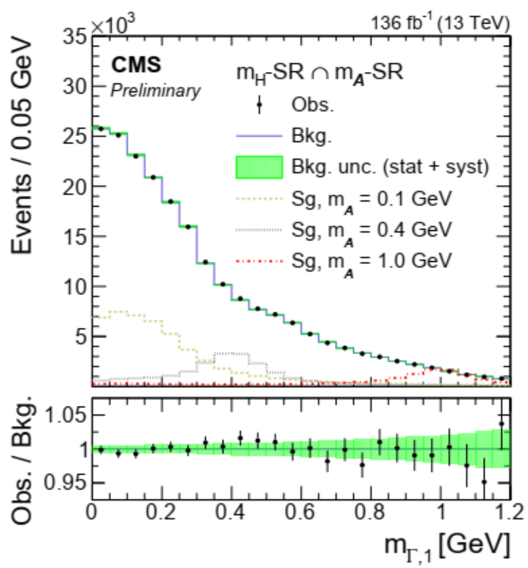
Exploit the unusual final states with novelty

Larger m_a (15-60 GeV): four separate photons



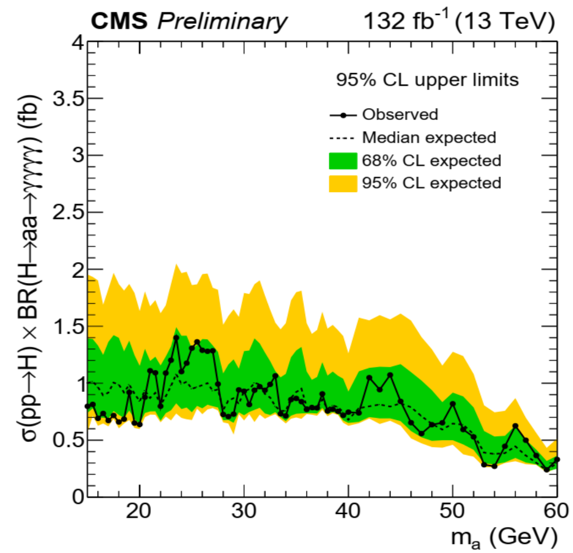
Cleanness via MVA

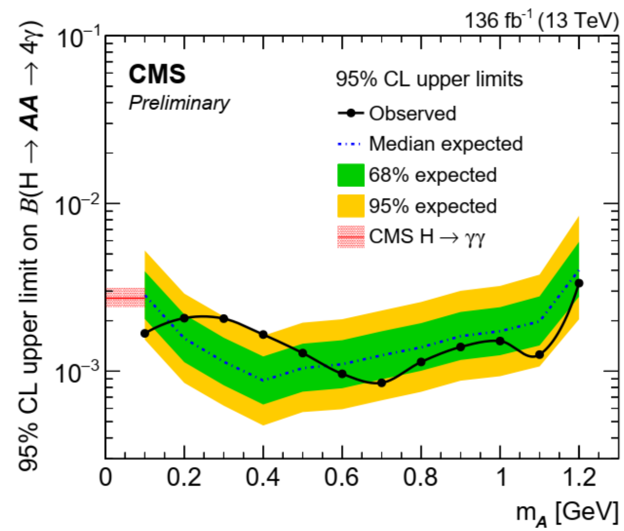
Small m_a (0.1-1.2 GeV) two merged photons



Merged photon via MVA

σ or Br constraints





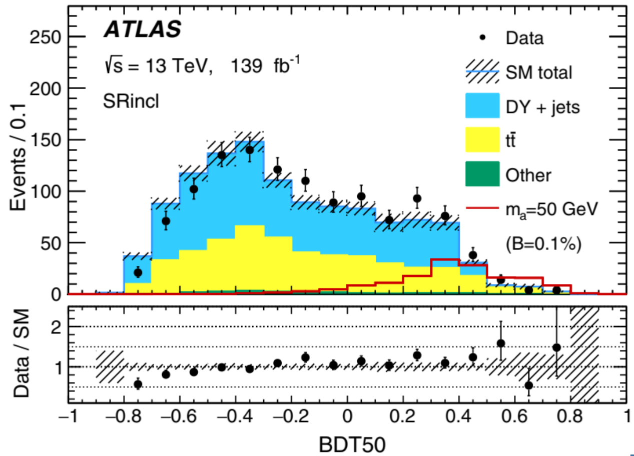
ALPs with H → 4 fermions

PRD105(2022)012006, JHEP01(2022)063

Exploit the fermion sector from H decays

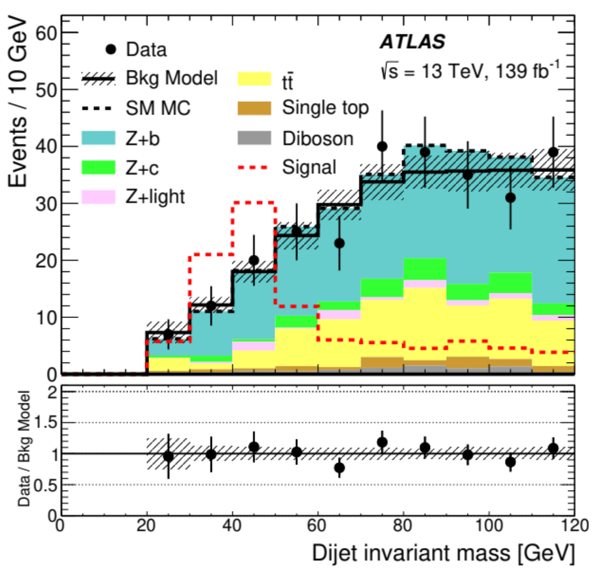
H→aa →bbμμ

Fits to improve mass reso. + MVA

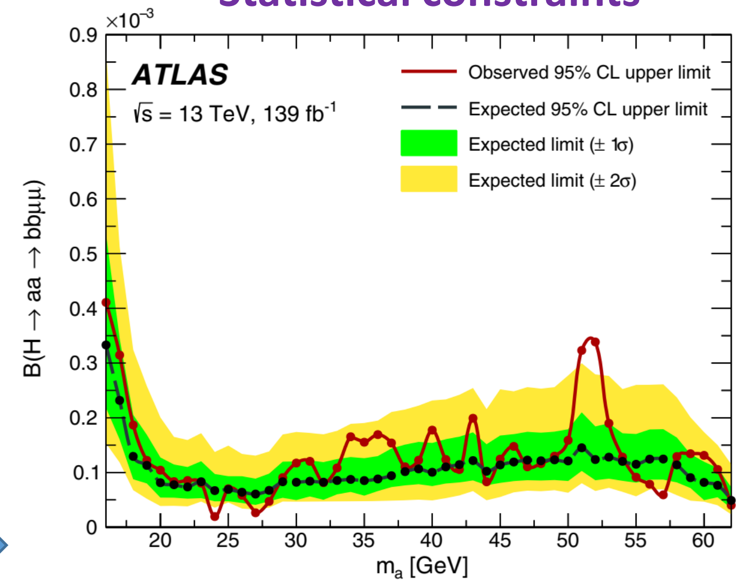


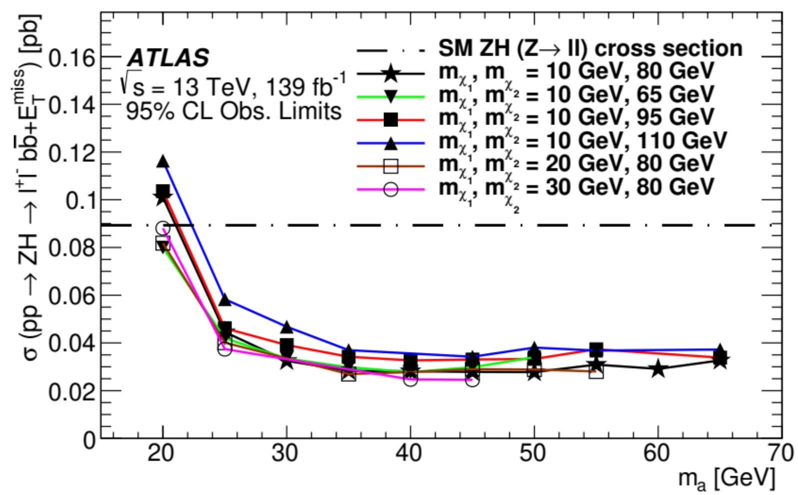
ZH→ll+ a(→bb) +MET

Consider a scenario with NMSSM (e.g., with neutralinos)



Statistical constraints

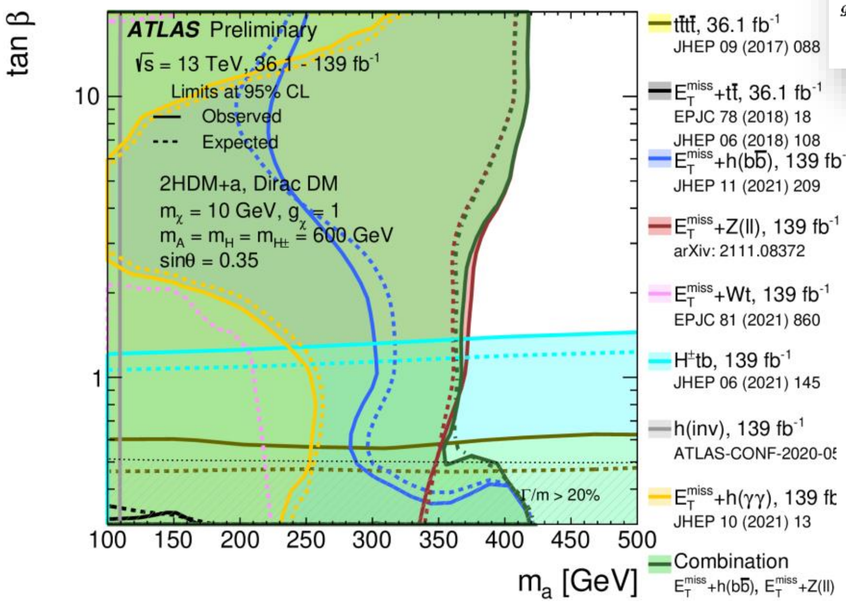




2HDM+a Searches

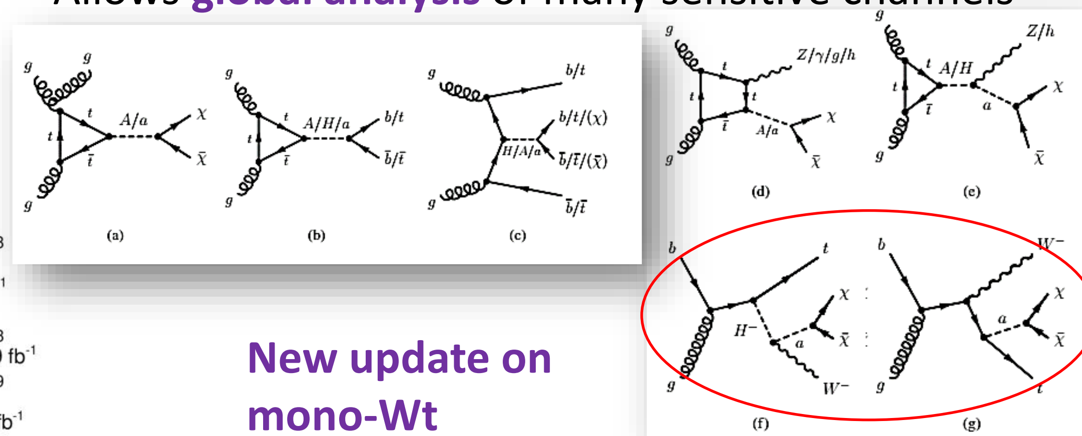
ATLAS-CONF-2021-036, ATLAS-CONF-2022-012

A "complete" model for collider DM searches **based on 2HDM**, with a **pseudoscalar a coupling to DM**
(see LHC DM White Paper)

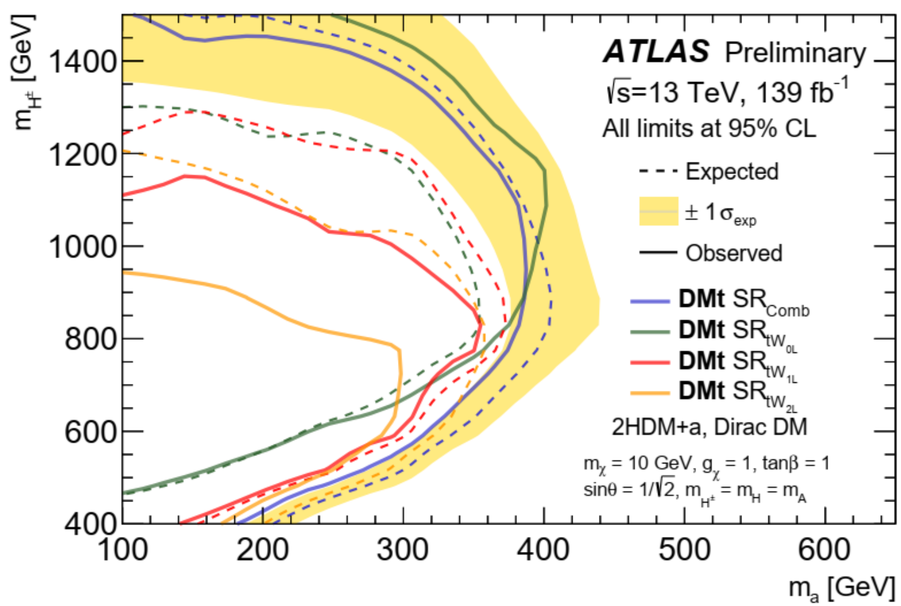


More parameters and more assumptions made in scanning

Allows **global analysis** of many sensitive channels



New update on mono-Wt



Not covered here:
ATLAS results on mono-γ/j JHEP02(2021)226, PRD103(2021)112006 also directly constrains a, h_D

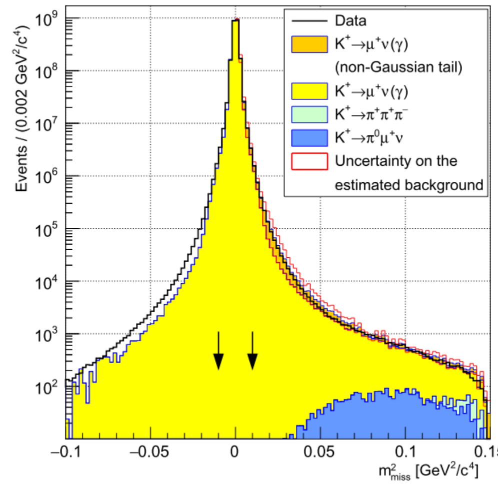
Heavy Neutral Leptons

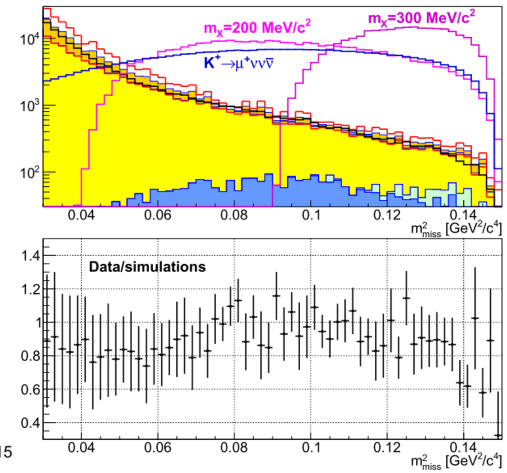
Kaon decays with NA62

PLB807(2020)135599
PLB816(2021)136259

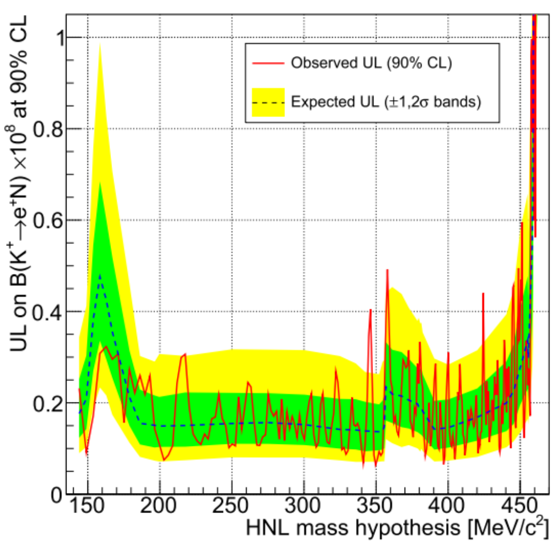
K→e/μ + N

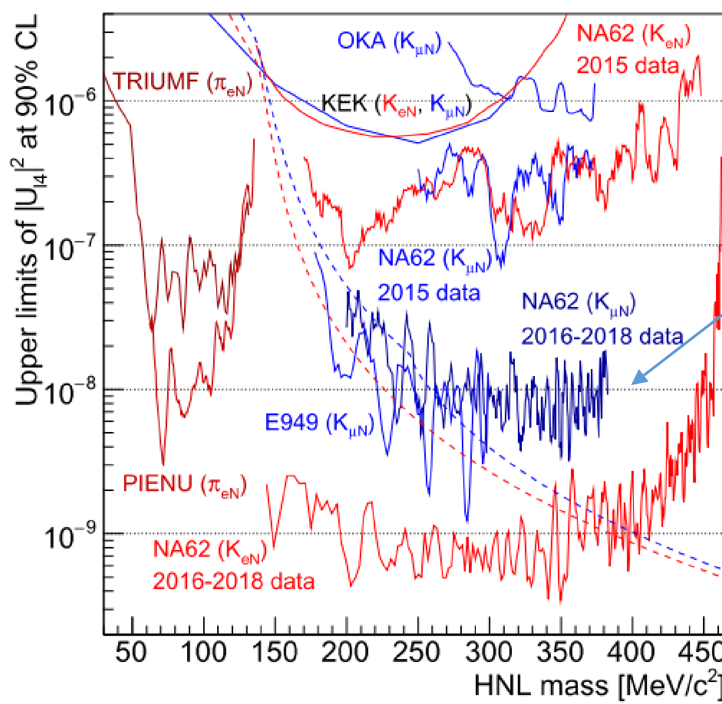
- ✓ Rely on **missing mass** measurement to explore heavier nature of N
- ✓ Precision tail analysis, range of O(100) MeV
- ✓ Resolution, statistics are keys





Derived the **Br limits**





μ

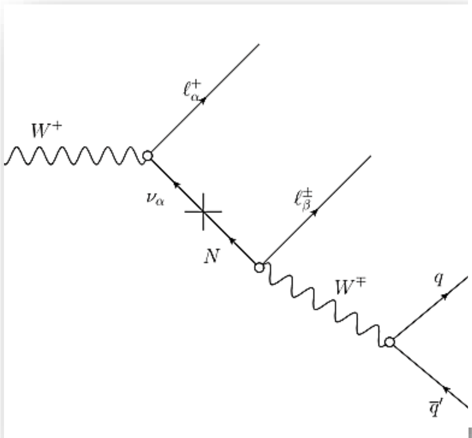
e

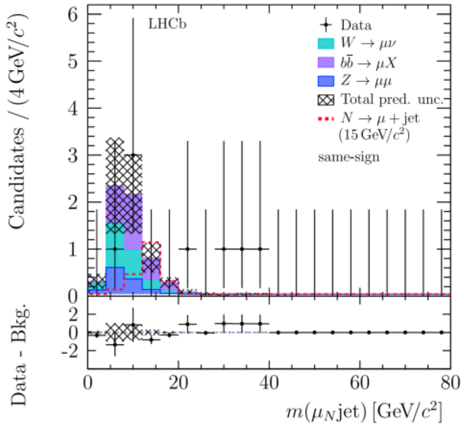
Most stringent constraints to U parameters at O(100) MeV

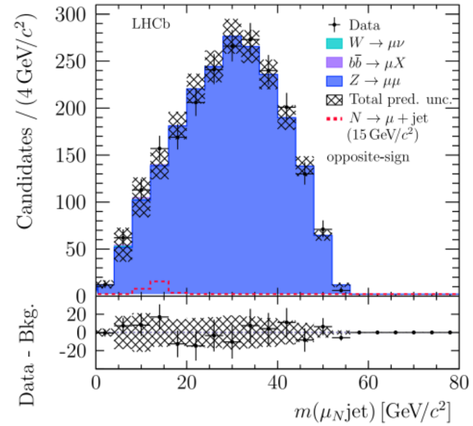
W decays

EPJC81(2021)248

Assume further decays of N to lepton and jets

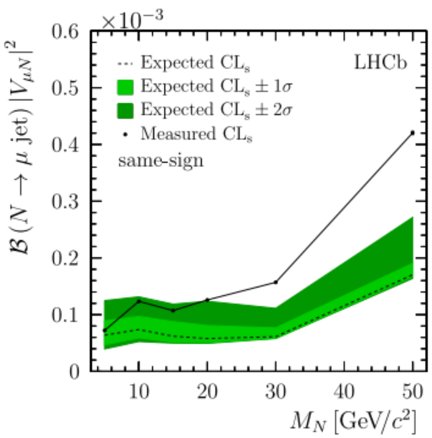


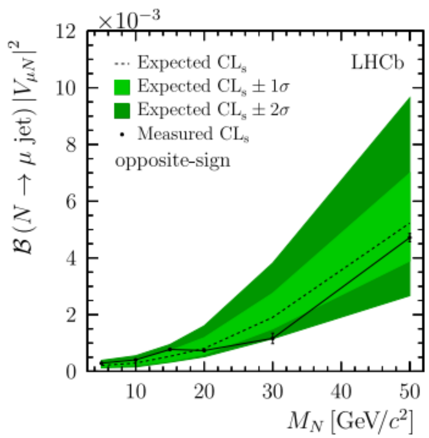




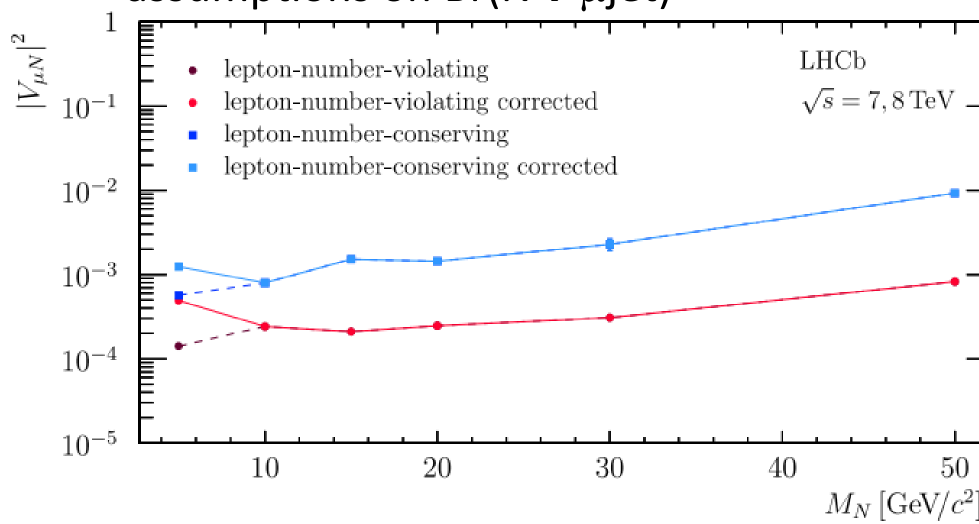
Rely on MVA to define SR: **same-sign** and **opposite-sign** dimuons + jets

Limits on **Br(N→μjet) x U parameter**



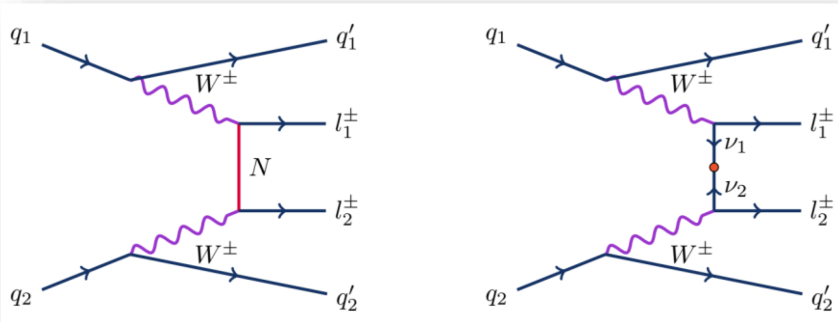


Limits on **U parameter only** with assumptions on Br(N→μjet)



Higher-scale with leptons and jets

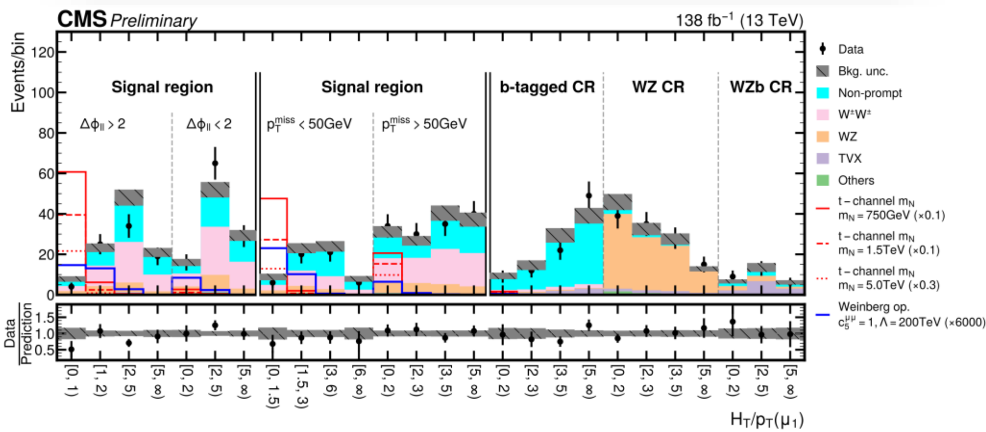
CMS-PAS-EXO-21-003

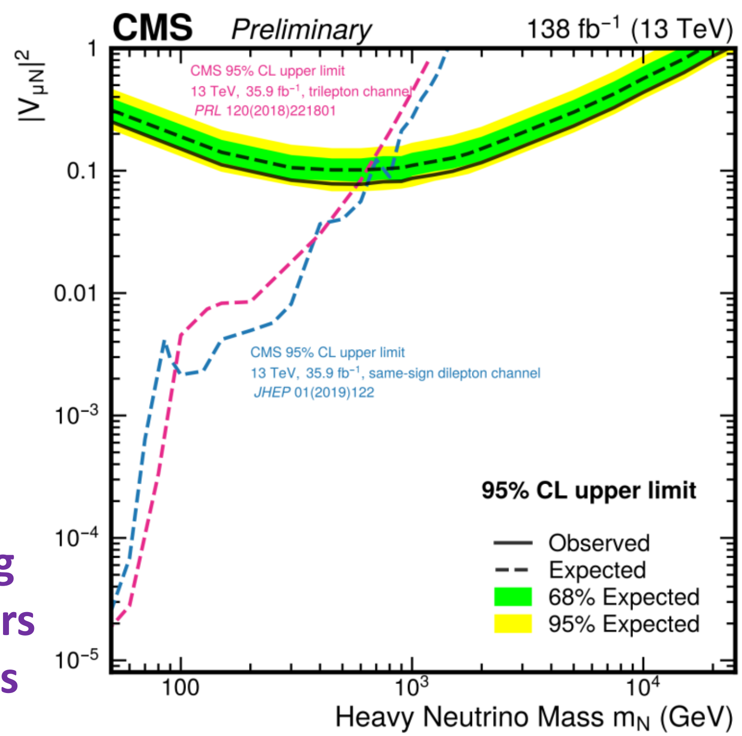


Collider version of "0νββ decay"

➔ Utilize the VBF process and look for same-sign dilepton

➔ Probe HNL above EW scale, as well as Weinberg operator $C_5^{\ell\ell'}$





Signature with small MET/hadronic activities

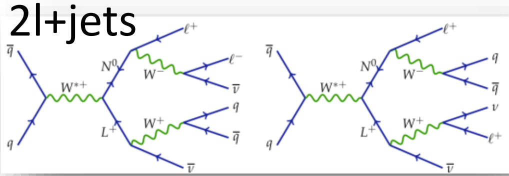
Constraining U parameters to TeV scales

Higher-scale with leptons and jets

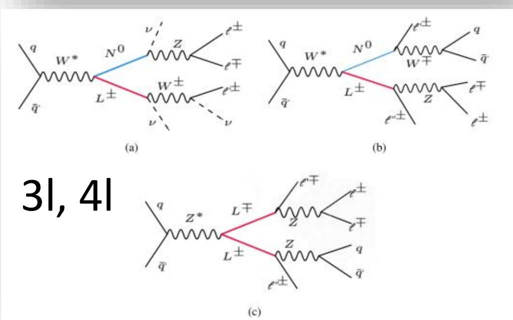
arXiv:2202.02039 , EPJC81(2021)218

Probe HNL in Type-III see-saw

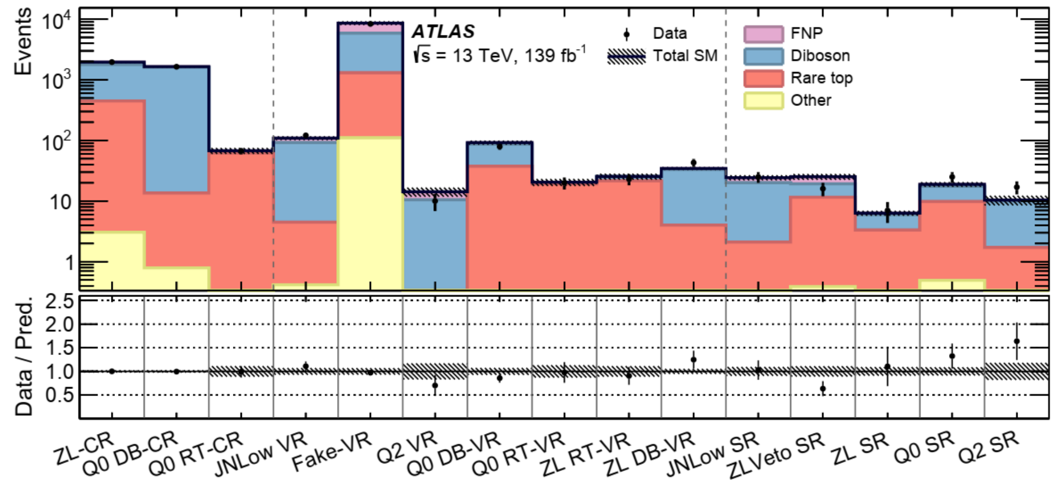
2l+jets



3l, 4l

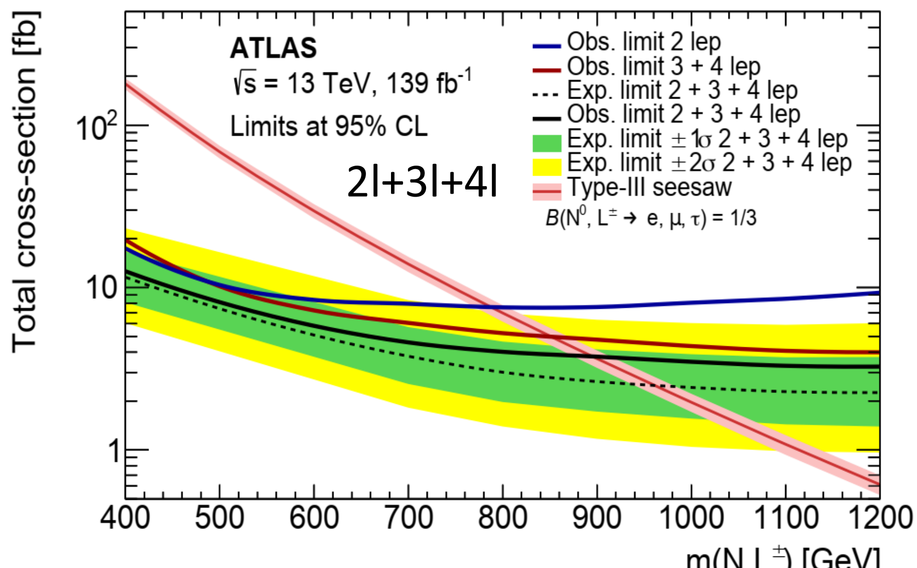


Complex final states: example for 3l, 4l



Limits on production σ

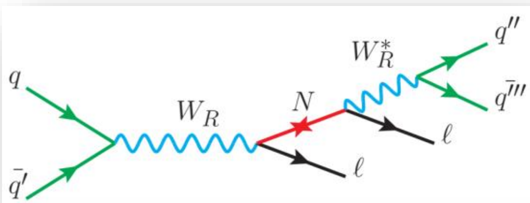
Strong constraints with adding 3l, 4l in addition to 2l channels

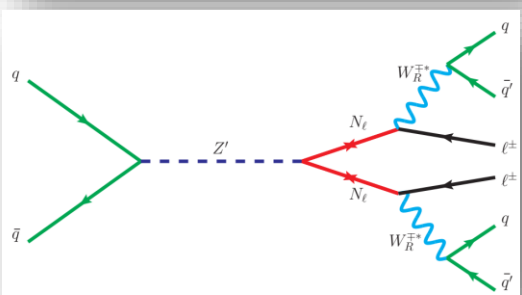


Higher-scale N with leptons and jets

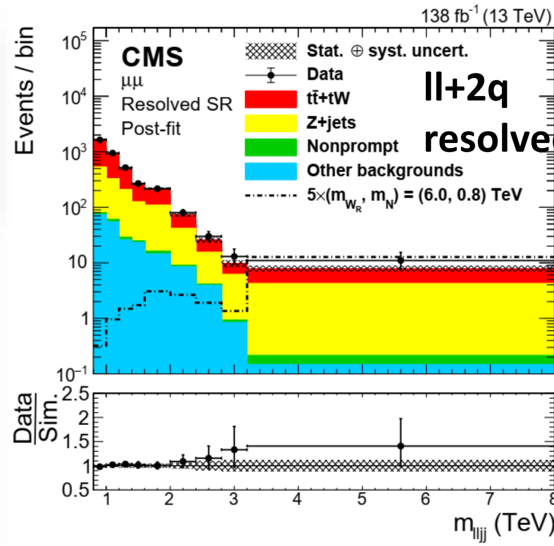
arXiv:2112.03949,
CMS-PAS-EXO-20-006,

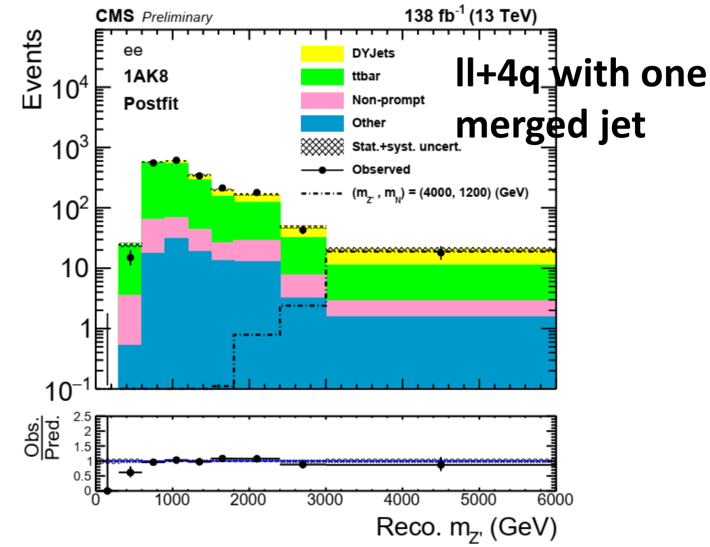
Probe HNL in LR models

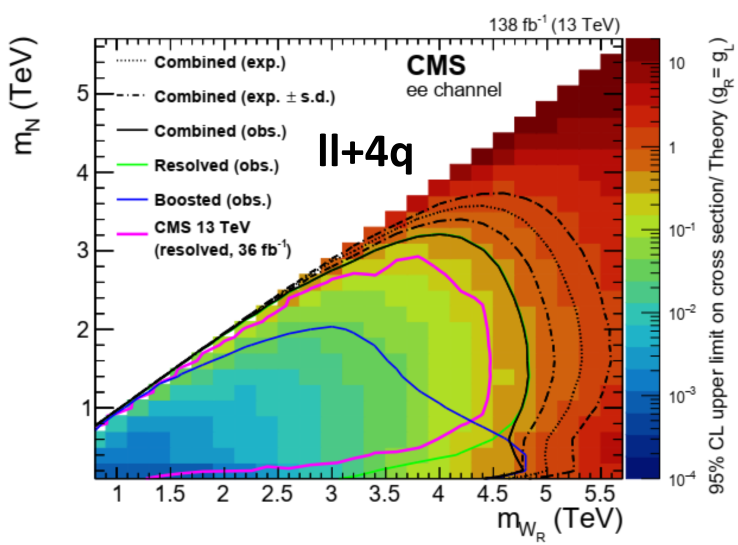


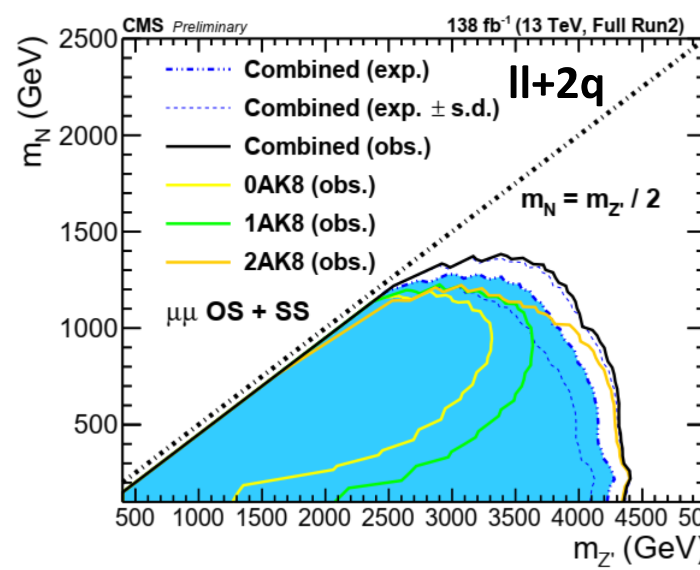


Combing resolved and boosted final states







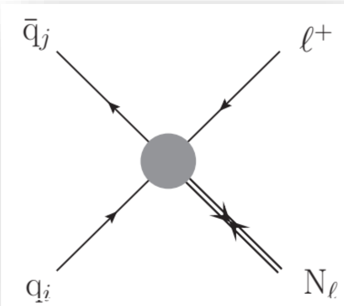


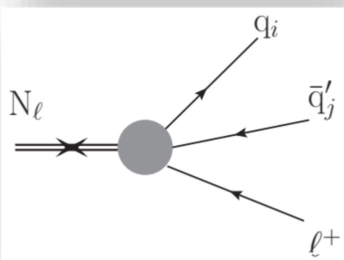
2D mass constraints: sensitivity to TeV regime

Higher-scale N with leptons and jets

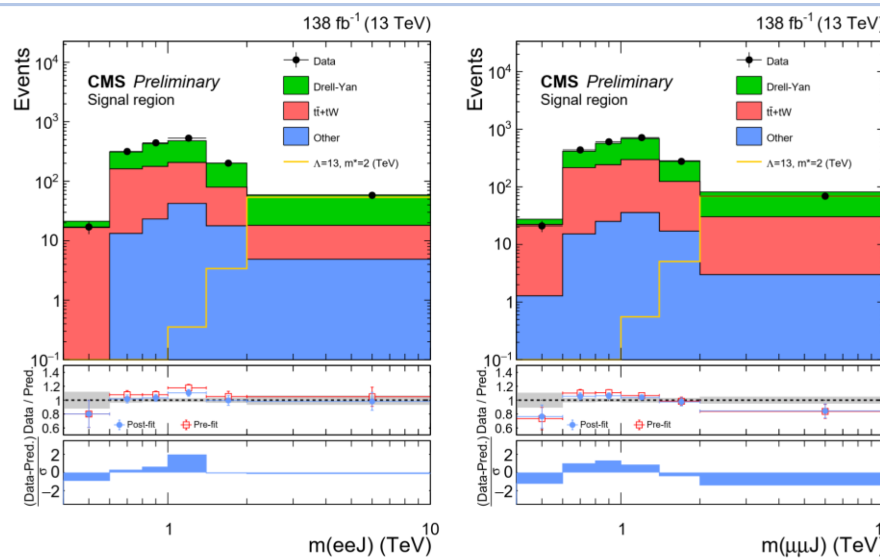
CMS-PAS-EXO-20-011

Probe HNL in composite models with ll + merged J

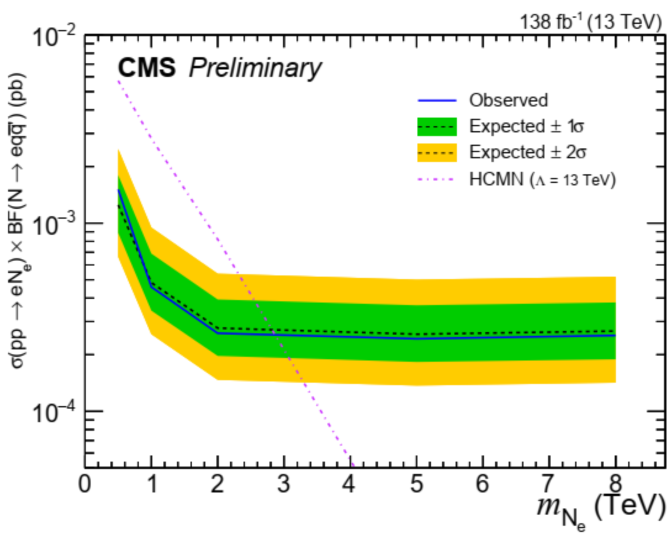


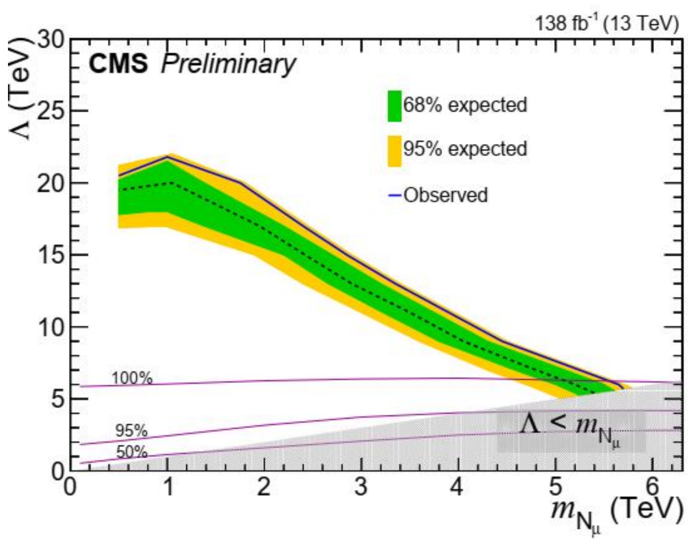


Parameters to constrain: contact interaction scale Λ, and m_N



Invariant mass of (ll+J)





Constraints to σ x Br, and CI scale

➔ **highest reach in mass constraints for N currently at LHC**

Summary

- **Discussed recent searches at ATLAS, CMS, LHCb, and NA62 for FIPs with prompt final states**
  - Covered a broad mass-scale from 100 MeV to TeV and with model variations from simplified to more complete ones
  - Still null results, statistical constraints improve further
  - Complementarity between different experiments, channels, etc.
  - LHC has given leading sensitivities in relevant searches

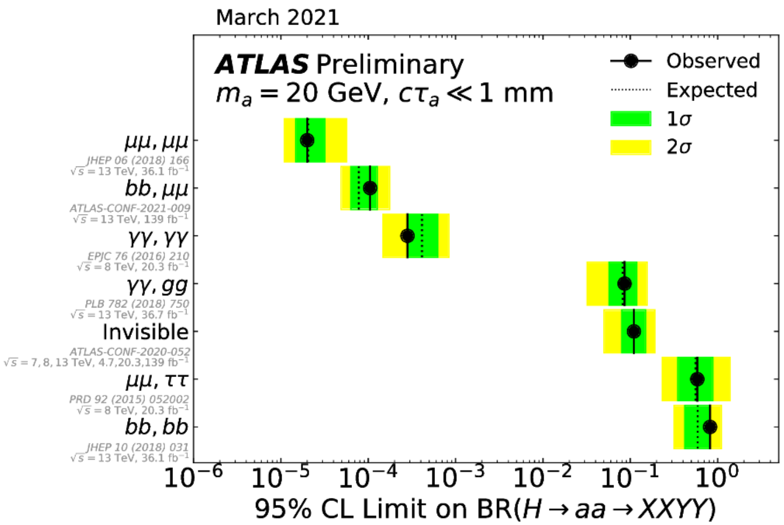
- **Future at the LHC**
  - Run-3 and HL-LHC will provide **enlarged datasets**, **revolutionized understanding of SM backgrounds**, and **new capabilities** (with new detector installation), to probe the feebly interacting phenomena

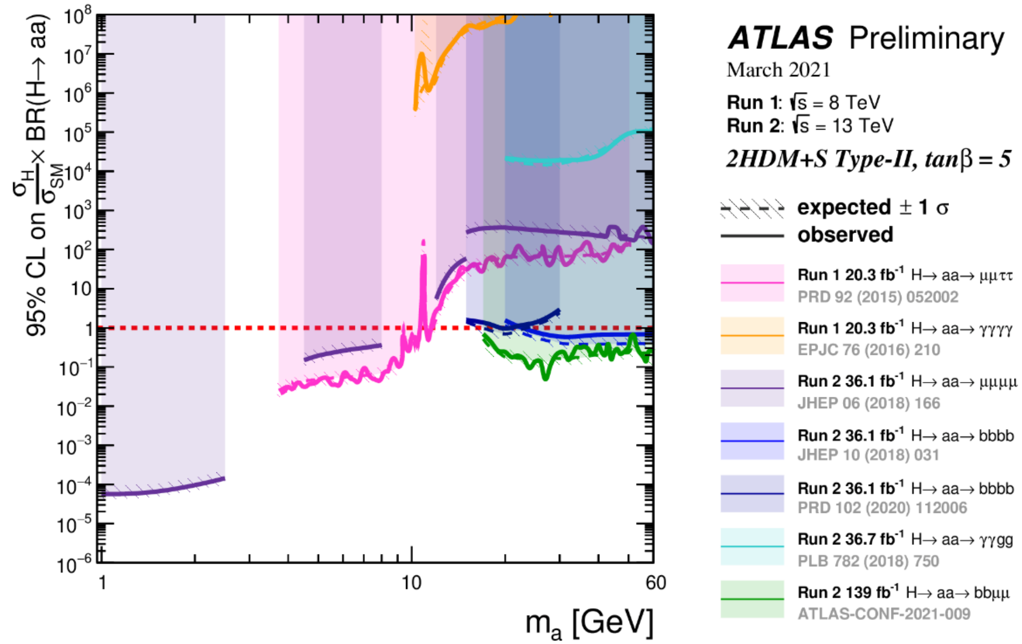
Thank you for your attention!

Backup

H→aa→4 objects Summary

❖ https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-008/





Nice overview of probing a through H→4 object decays!