European Strategy for Particle Physics

PARALLEL 8 / **DARK MATTER AND DARK SECTORS**

Accelerator-based probes

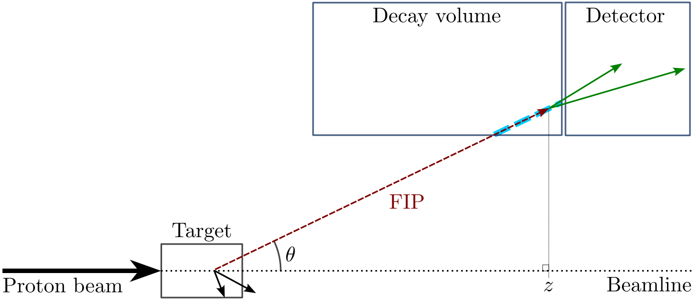
Maksym Ovchynnikov (CERN)

23-27 JUNE 2025 Lido di Venezia

Accelerator-based experiments I

Accelerator-based experiments

– Detectors outside the main collider experiments

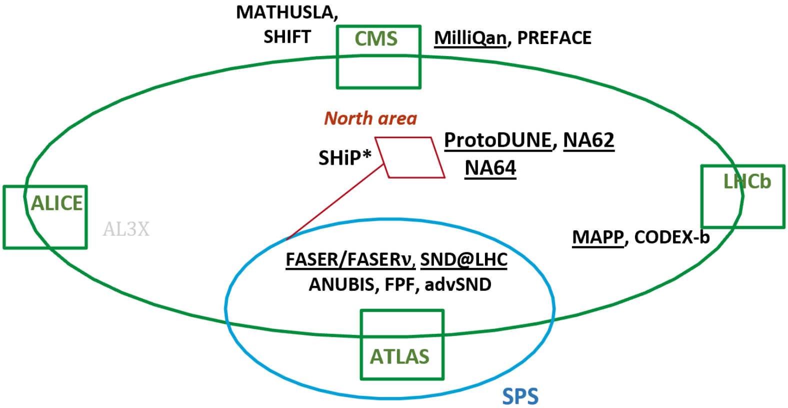


Classification

1. **Collision type:**
   - Collider-based (e.g., *FASER*)
   - Beam dump (e.g., *ProtoDUNE*)
2. **Signature:**
   - Scatterings (SND@LHC,. . .)
   - Decays (CODEX-b)
   - Missing energy (NA64,. . .)

Accelerator-based experiments II

3. **Beam type:**
   - $\boldsymbol{l = e, \mu}$ (NA64,LUXE,...)
   - $\boldsymbol{h = p, Pb}, \ldots$ (NA62,...)
4. **Location:**
   - CERN (MAPP,...)
   - Fermilab (DUNE,...)
   - DESY (LUXE)
   - ...



5. **Timeline:**
   - Associated with **existing** colliders/facilities ($<$ **20** years) (SHiP, ...)
   - Associated with **future** colliders/facilities (@FCC-hh, ILC-BD,...)

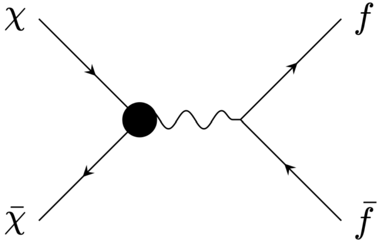
Models to be searched for: dark matter I

A minimal model to be explored at accelerator-based experiments:

$$\mathcal{L} = \overbrace{\mathcal{L}[V, \psi_{\text{SM}}]}^{\textbf{portal}} + \overbrace{\mathcal{L}_{V\chi\chi^*}}^{\textbf{interaction}} + \overbrace{\mathcal{L}_{h_d, V, \chi}}^{\textbf{gives mass}} \quad (1)$$

Mediator V, *DM particle* χ, *dark Higgs boson* h_d

- Typical production: freeze-out/freeze-in
- The simplest model (**elastic DM**):
  - Dark photon mediator A'
  - h_d is extra heavy and/or tiny-coupled
  - $\text{Br}(A' \to \chi\chi) = 1$



Models to be searched for: dark matter II

– Variation:

$$\mathcal{L}_{A'\chi\chi^*} \to \mathcal{L}_{A'\chi\chi'^*}, \quad \Delta \equiv \frac{m_{\chi'} - m_\chi}{m_\chi} > 0 \tag{2}$$

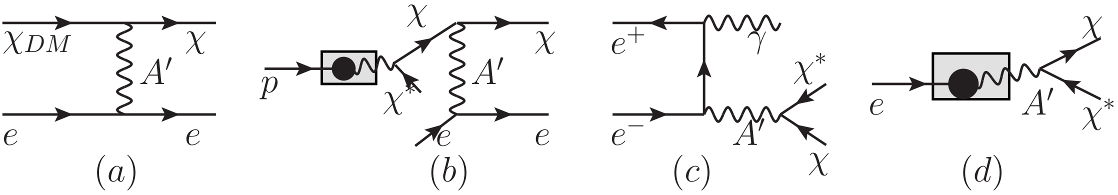
The DM is called **inelastic**

Even a tiny Δ makes probing with direct detection experiments impossible

$\chi + e \to \chi + e$ **becomes** $\chi + e \to \chi' + e$

[0101138], *[1901.09966]*

Models to be searched for: dark matter III



Quasi-elastic DM ($\boldsymbol{\Delta \ll 1}$) – signatures:

- (a): ~~Elastic scattering of DM $\boldsymbol{\chi}$ ($\boldsymbol{\Delta = 0}$)~~
- (b): Production at accelerators and subsequent scattering
- (c),(d): Production and subsequent (semi-)invisible signatures

Inelastic DM: missing energy or decays $\boldsymbol{\chi' \to \chi + \mathrm{SM}}$

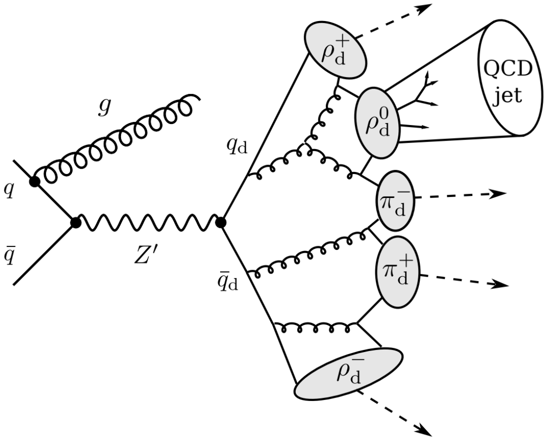
[1107.4580], [1810.01879],...

Models to be searched for: dark matter IV

Other models with distinct signatures

- **Millicharged particles**, constituting DM
  Multiple scatterings
- **Dark QCD**, with $\boldsymbol{\rho_d}, \boldsymbol{\pi_d}$ being DM
  Dark showers
- DM coupled via **inelastic dipole portal**
  Mono-photon
- ...

[1907.04346], [2301.05252], [1806.03310],...



Models to be searched for: portals I

“Portals” – lowest-dimensional gauge-invariant operators with LLPs:

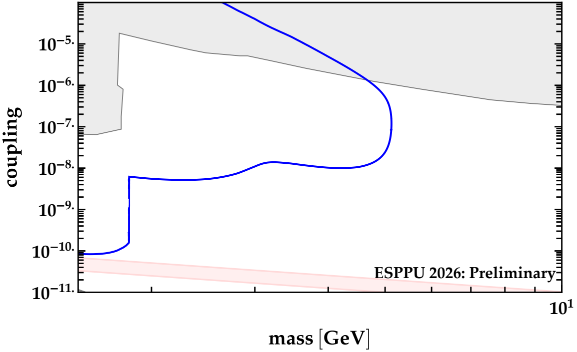
Model	**(Effective) Lagrangian**	**What it looks like**
HNL N	$Y\bar{L}\tilde{H}N + \text{h.c.}$	Heavy neutrino with interaction suppressed by $U \sim \frac{Y v_h}{m_N} \ll 1$
Higgs-like scalar S	$c_1 H^\dagger H S^2 + c_2 H^\dagger H S$	A light Higgs boson with interaction suppressed by $\theta \sim \frac{c_2 v_h}{m_h} \ll 1$
Vector mediator V	$-\frac{\epsilon}{2} B_{\mu\nu} V^{\mu\nu} + g V^\mu J_{\mu,B}$	A massive photon/vector meson with interaction suppressed by $\epsilon, g \ll 1$
ALP a	$c_G \frac{\alpha_s}{4\pi} a G^{\mu\nu} \tilde{G}_{\mu\nu} + \dots$	A $\pi^0/\eta/\eta'$-like particle with interaction suppressed by $\frac{f_\pi}{f_a} \ll 1$
...	...	...

Simplest signature – displaced decays

Exclusion potential I

Plots: details

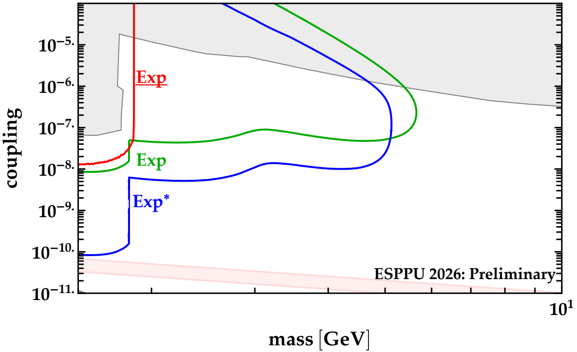
1. **Meaning of the plot**:
   - **Gray** domain – excluded parameter space
   - Domain defined by **colored** curves – to be excluded if nothing is found (**exclusion potential**)



Exclusion potential II

Plots: details

2. **Status of experiments:**
   - **exp**: proposal (e.g., FPF)
   - <u>**exp**</u>: currently running (e.g., NA62)
   - **exp***: approved/in construction (e.g., SHiP)
   - <u>**exp**</u>*: currently running, but the luminosity is to be approved (e.g., NA64 with high EoT)

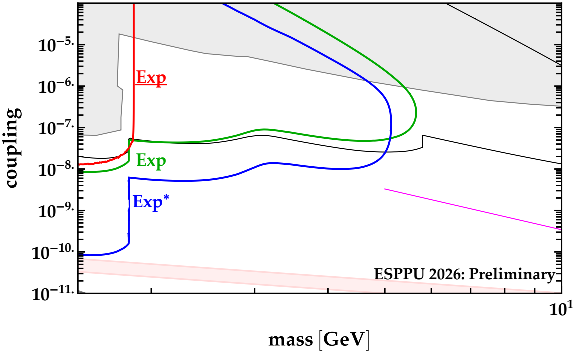


Exclusion potential III

Plots: details

3. **Collider searches:**
   - Thin **black** lines: probes from existing colliders (LHC, Belle II)
   - Thin **magenta** lines: probes from future colliders (FCC-XX, ILC)

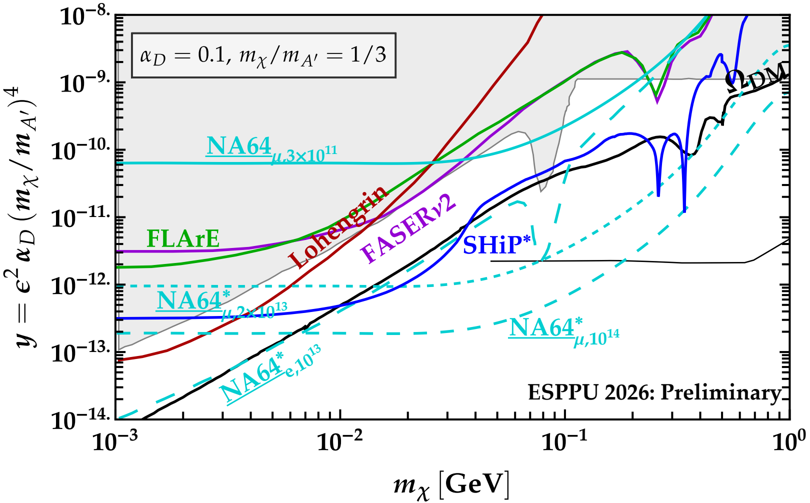
To be covered in Monica's talk



Exclusion potential IV

Quasi-elastic DM
$\Delta \approx 0$

- ***Missing energy* – *better for exclusion***: more parameter space, but limited information



- ***Scattering signature* – *better for discovery***: less parameter space but more information about interaction and kinematics

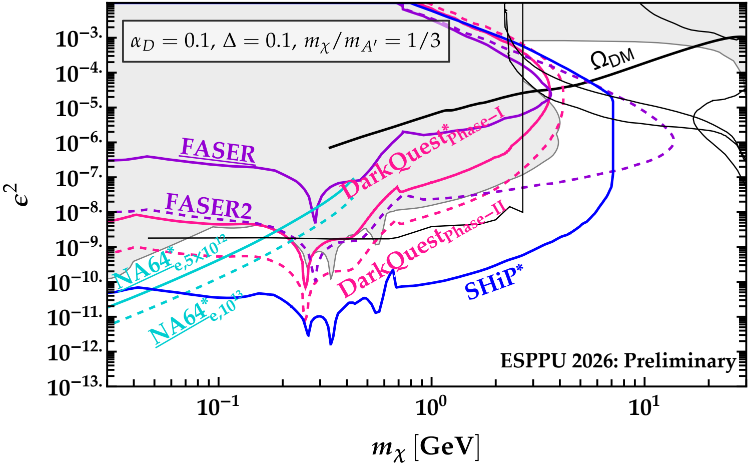
Exclusion potential V

Inelastic DM

- χ''s decay length:

$$c\tau_{\chi'}\gamma_{\chi'} \propto \frac{1}{\epsilon^2\Delta^5 m_{\chi'}^2}\left(\frac{m_{A'}}{m_\chi}\right)^4$$

- Reach of an individual experiment may heavily vary depending on $\Delta, m_\chi/m_{A'}$

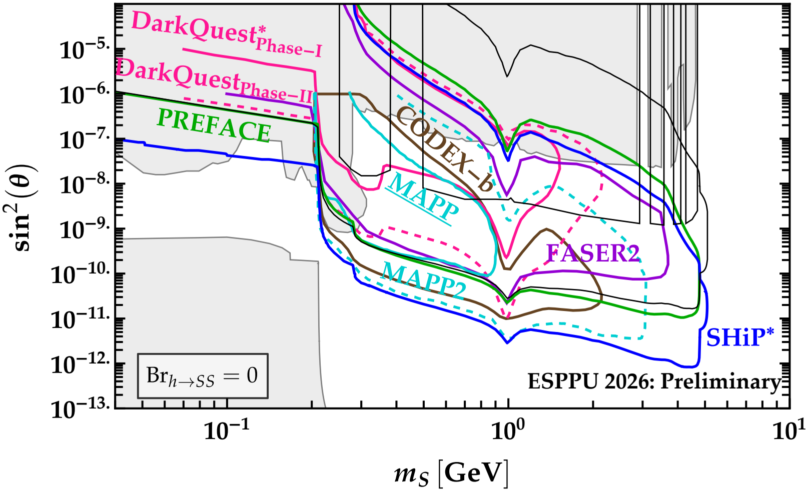


Exclusion potential VI

Higgs-like scalar

Case $\mathbf{Br}(h \to SS) = 0$

- Two couplings: $\theta m_h^2 hS$ and $c_2 hSS$
- Case $c_2 = 0$
- Well-probed at B factories



GeV mass range: large theor. uncertainties!

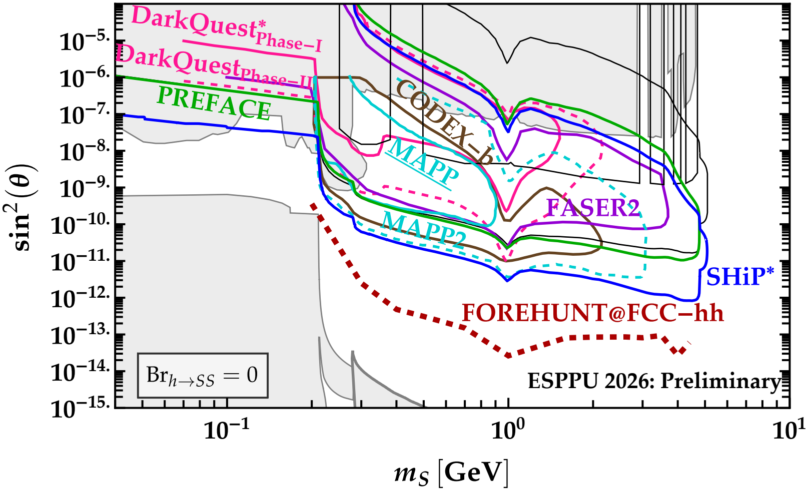
[2407.13587]

Exclusion potential VII

Higgs-like scalar

Case $\mathbf{Br}(h \to SS) = 0$

- Future FCC-hh-based experiments may significantly enhance the sensitivity to small couplings

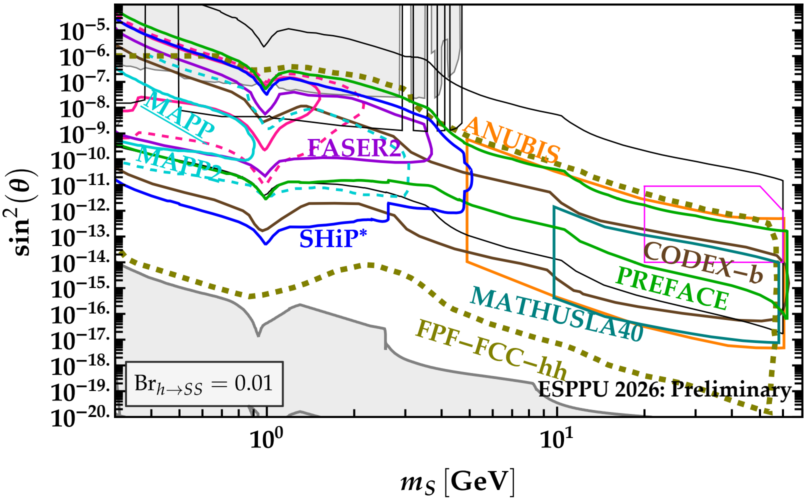


Exclusion potential VIII

Higgs-like scalar

Case $\mathbf{Br}(h \to SS) \neq 0$

- LHC/FCC-based experiments benefit from $h \to SS$
- B factories: induced $B \to X_s SS$, $B_s \to SS$

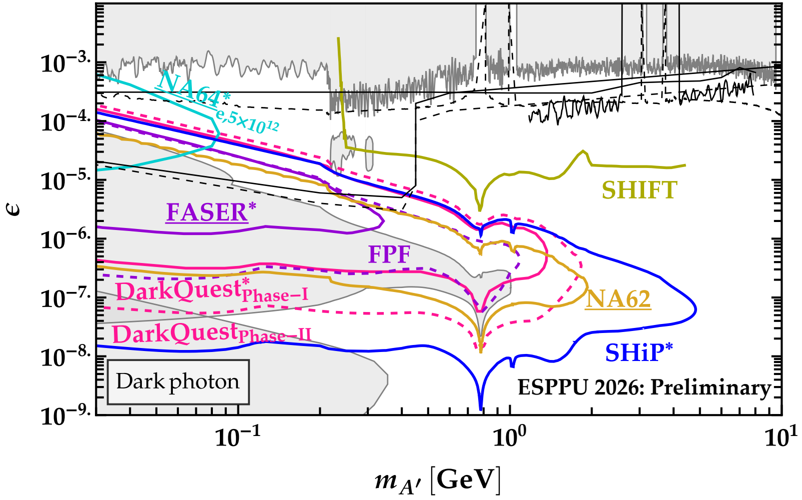


Collider probes: see $c\tau$ vs $Br(h \to SS)$ plot in Monica's talk

Exclusion potential IX

Dark photon

- Sensitivity is dominated by on-axis experiments



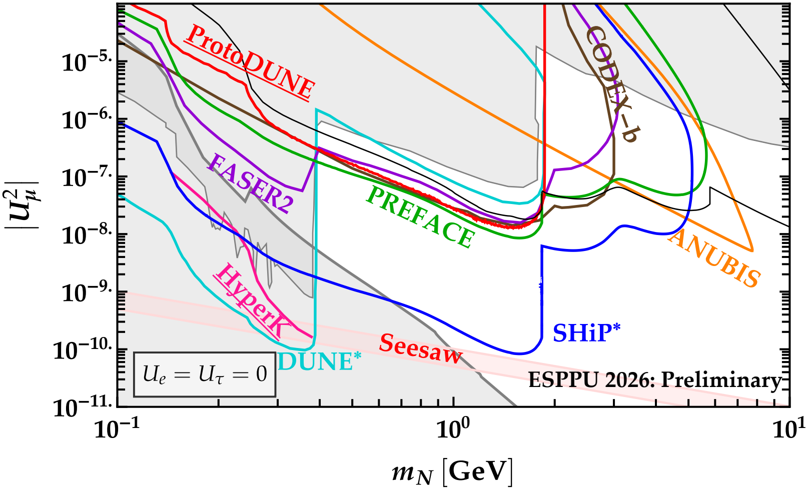
GeV mass range: large theor. uncertainties!

[2409.11096]

Exclusion potential X

HNL

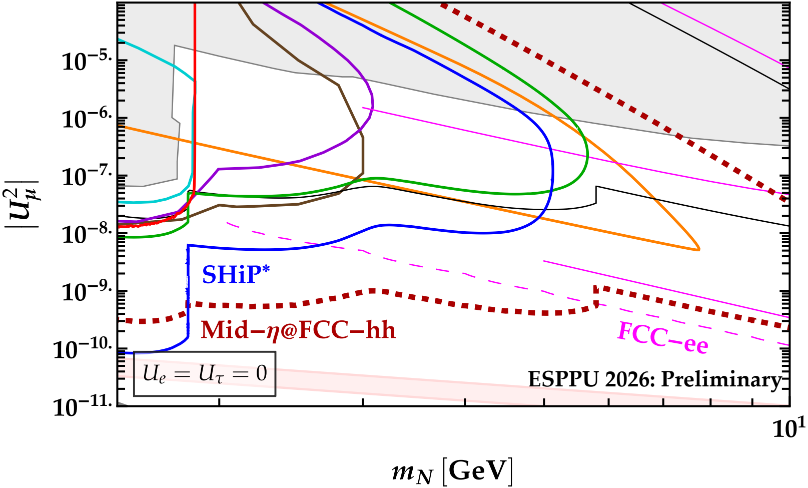
- Sensitivity comes from $\boldsymbol{K}, \boldsymbol{D}, \boldsymbol{B}, \boldsymbol{W}, \boldsymbol{Z}$ factories



Exclusion potential XI

HNL

- FCC-ee will complementarily probe the large mass region $m_N \gtrsim m_B$
- But the domain $m_N \lesssim m_B$ will remain underexplored

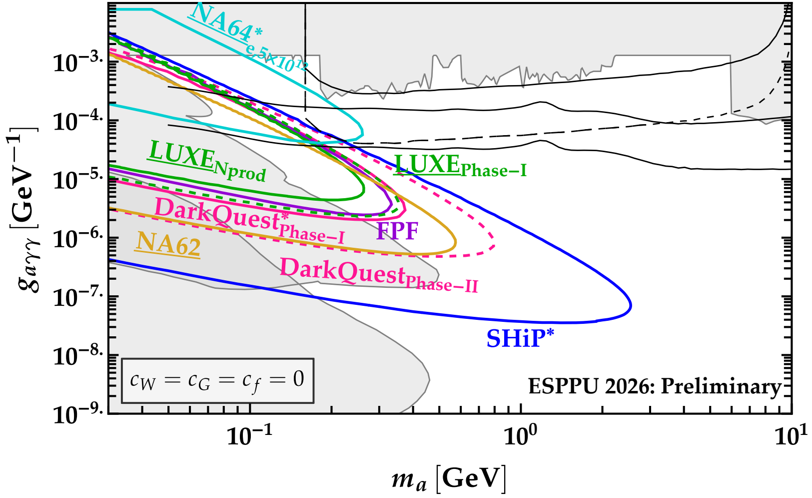


- **FCC-hh-based experiments**: significantly extend the SHiP reach for $m_D < m_N < m_B$

Exclusion potential XII

ALP (γ dominance)

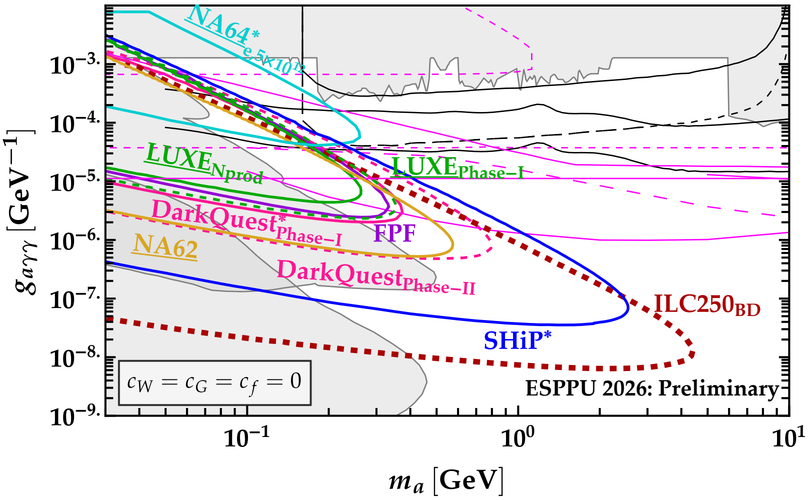
- Sensitivity is dominated by on-axis experiments
- In case of hadronic reach: similar potential, but sizeable theor. uncertainties *[2501.04525]*



Exclusion potential XIII

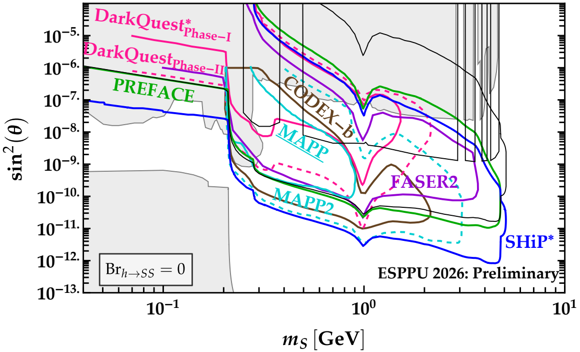
ALP (γ dominance)

- Future accelerator-based experiments may add a lot



Discovery potential?

- Accelerator-based experiments may probe orders of magnitude of unexplored parameter space
- $\mathcal{O}(1000)$ events may be observed in case of **discovery**

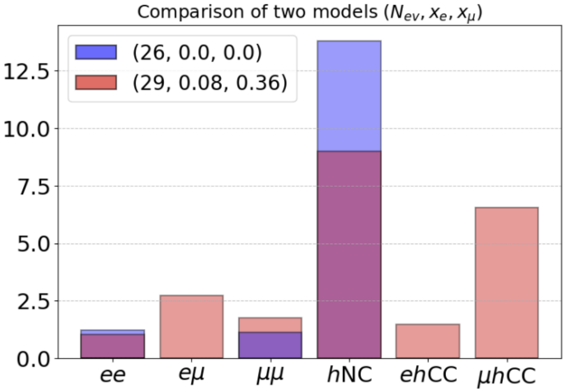


What is discovery potential?

Extracting information from simple signatures

Simple signatures – "mono"-events

- Reconstructing decay modes and kinematics ⇒ identifying particle's spin and decay operators
  ECAL+PID+magnetic field
- **HNL case as an example:**
  - Extracting mixing pattern
  - Checking consistency with neutrino oscillations
  - Resolving HNL-anti-HNL oscillations and measuring mass splitting

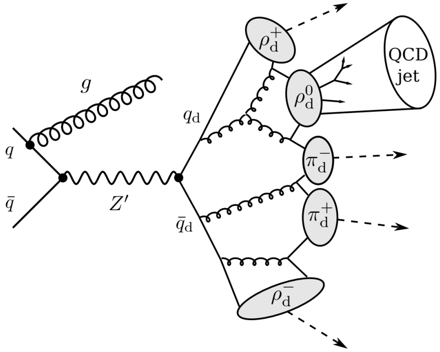


[1912.05520], [2312.05163]

What if simple signatures are not enough? I

Different models may have the same "mono"-events

- **Inelastic DM:**
  - Add $\boldsymbol{A'\chi'\chi'}$ vertex
    (vs models with $\boldsymbol{A'\chi'\chi}$ *only)*
  - Make $\boldsymbol{h_d}$ visible
    (vs Higgs-like scalars)
- **Portals:**
  - Dark QCD vs portals
    Dark pions vs ALPs, dark $\boldsymbol{\rho}$*s vs dark photons*
  - Mediators with/without quadratic coupling to SM
    LLPs $\boldsymbol{X}$ *with vs without* $\boldsymbol{hXX}$ *coupling*

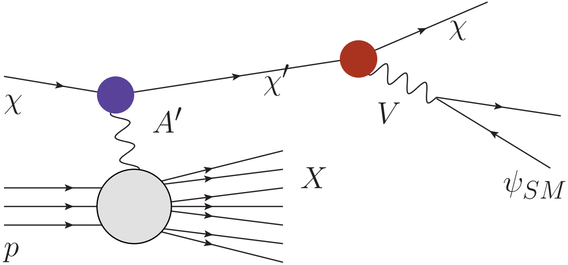


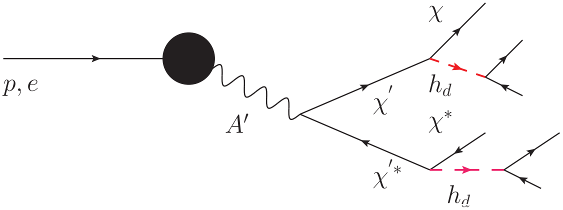
May be distinguished by production, but accelerator-based experiments (typically) do not see it!

Solution: "multi-bang" events I

n-decays:

- DM: decays $\boldsymbol{\chi^*\chi^*, \chi^* h_d, h_d h_d}$
- Portals: $\boldsymbol{SS, NN, n\rho_d/n\pi_d}$





Scatterings + decays:

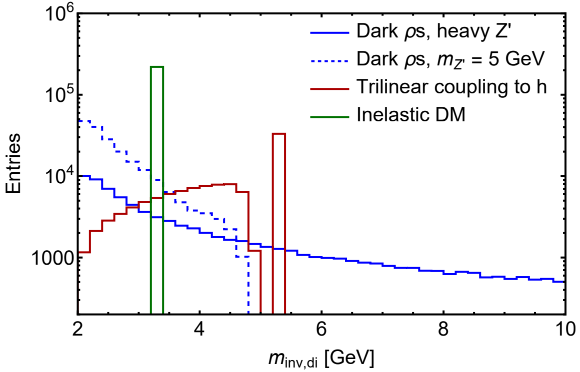
- DM: scatterings $\boldsymbol{\chi + p/e \to \chi' + X}$ followed by $\boldsymbol{\chi' \to \chi + \text{X'}}$
- Portals: neutrino upscattering + decay

[1707.08573], *[2012.08595]*, *[2312.14868]*, *[2503.01760]* *[2505.05663]*,...

Solution: "multi-bang" events II

n-decays as an example:

- Access to correlated distributions of the decaying particles: $c\tau, m_{\mathrm{inv}}$
- $m_{\mathrm{inv,di}}$: may allow identifying the production without seeing it



n-decays may be observed at experiments with large intensity

[2503.01760]+backup

Conclusions

- Accelerator-based experiments: great exploration power of dark matter and dark sector with mass $\boldsymbol{M < \Lambda_{\mathrm{EW}}}$
- Their landscape extends from today until decades forward
- Large intensity, different setups and detection techniques – a unique opportunity to search for various models
- Think not in terms of exclusion potential but discovery potential

Contributions from ESPP submissions

Used input:

273. 2026 EPPSU input from the ANUBIS Collaboration
199. CODEX-b...
23. Prospects and Opportunities with an upgraded FASER...
61. MATHUSLA...
19. The Forward Physics Facility...
92. The LUXE Experiment
145. SHiP...
235. Summary Report of the Physics Beyond Colliders...

81. Discovery potential of LHCb Upgrade II
118. The DUNE Science Program
275. Status of the International Linear Collider
44. Proposal for a shared transverse LLP detector for FCC-ee ...
250. Rich dark sectors
50. Searching for Light Dark Matter and Dark Sectors with the NA64...
46. Search for feebly interacting particles with the Lohengrin experiment at the ELSA accelerator

+ Communications with representatives of collaborations

Backup slides

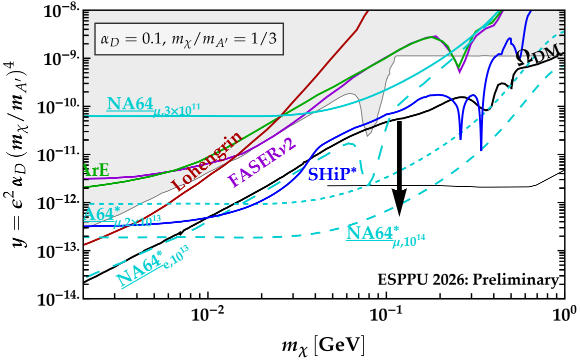
Relic target line

We know a little about

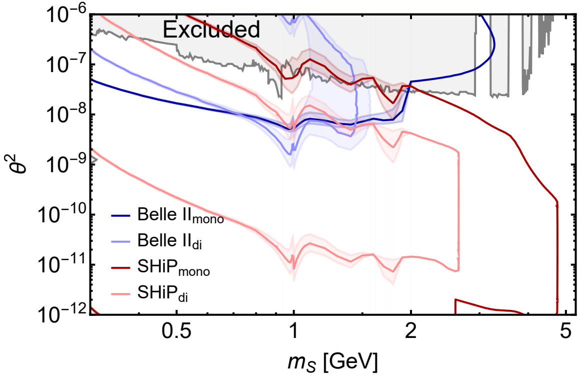
- The Early Universe before neutrino decoupling
- Properties of dark sector – interaction structure, particle content, etc.

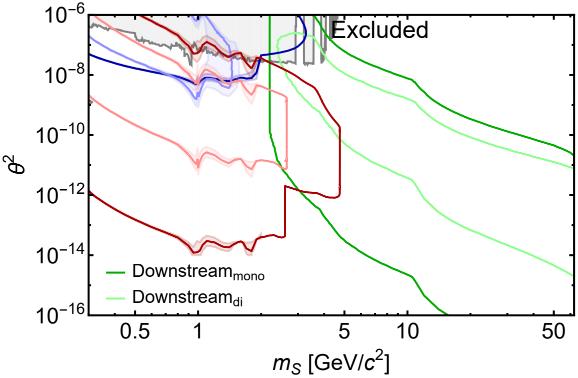
DM parameter space may be any

- Entropy dilution, "secret" interactions may heavily affect the abundance
- Do not concentrate on the relic target line



Di-decays: case studies I

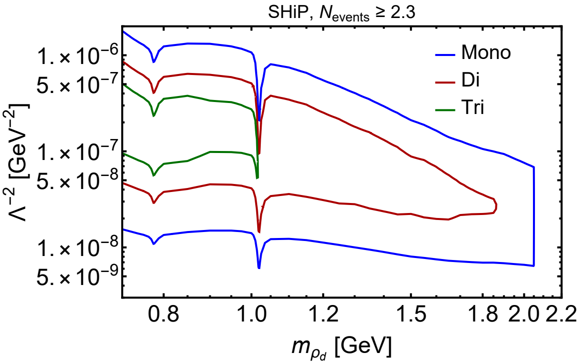




- **Example 1**: Higgs-like scalars with tri-linear coupling to $\boldsymbol{h}$

Di-decays: case studies II

- **Example 2**: Dark QCD with visibly decaying $\boldsymbol{\rho_d}$
- Smoking gun signature: di-tri-decays



To appear soon