European Strategy for Particle Physics

PARALLEL 8 / **DM and DS**

DM and DS at colliders and interplay with major future facilities

Monica D'Onofrio (University of Liverpool)

Credits to many people – in particular members of the DM&DS and BSM groups

Input documents

- Out of 277 submissions scrutinised by the Dark Matter and Dark Sectors group, **114** were found to contain material relevant to the DMS area.
- Submissions focusing on major collider facilities (and references therein) have been considered, as well as dedicated submissions underlining the impact of collider searches on the dark matter & dark sector theme – list of most relevant given below (in no particular order):

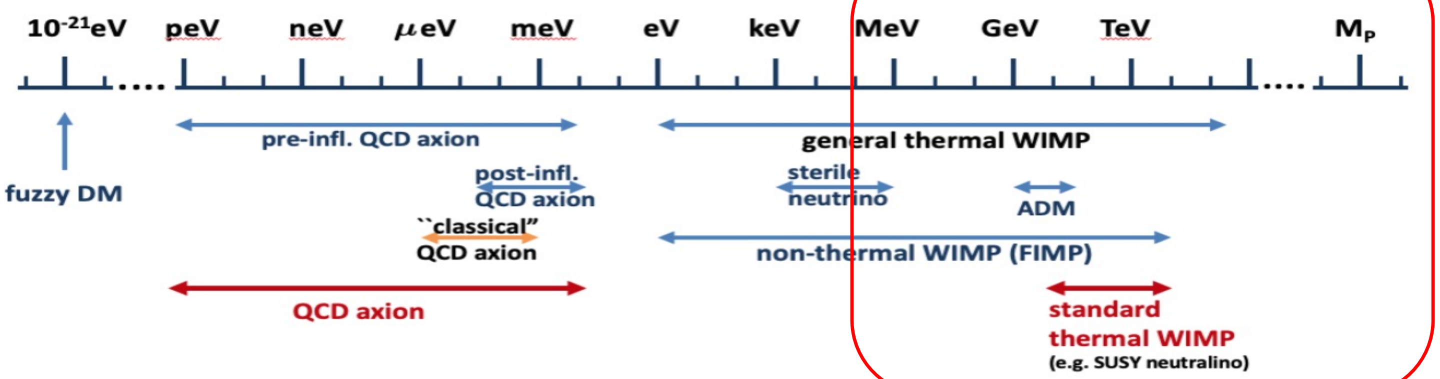
#77: Discovery potential of LHCb Upgrade II
#195: The Muon Collider
#74: The Compact Linear e+e- Collider (CLIC)
#176: LEP3: A High-Luminosity e+e− Higgs & Electroweak Factory in the LHC Tunnel
#65: Future Opportunities with Lepton-Hadron Collisions
#201: The Large Hadron electron Collider (LHeC) as a bridge project for CERN
#144: The Circular Electron Positron Collider (CEPC)
#204: Prospects in Electroweak, Higgs and Top physics at FCC
#133: The ECFA Higgs/Electroweak/Top Factory Study

#132: A Linear Collider Vision for the Future of Particle Physics
#106:Enhancing European Cooperation in the Search for Dark Matter
#229 : Prospects in BSM physics at FCC
#64: Input from the ALICE Collaboration
#260: Dark Matter Complementarity: from the Snowmass process to the EPPSU
#228: The FCC integrated programme: a physics manifesto
#214: Prospects for physics at FCC-hh
#159: Highlights of the HL-LHC physics projections by ATLAS and CMS

- Strong interplay with submissions on accelerator-based facilities, direct and indirect detections
  - See lists in dedicated talks in this session
- National facilities and other submissions also mentioning relevance of dark matters – not listed

Dark matter @ colliders

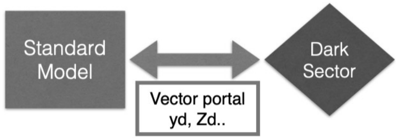
- Many **models**, classification by **mass range**:



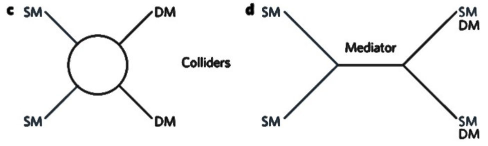
Relevant for this talk - inputs for ESPP 2026 preliminary plots in back-up

Ultralight DM: Axion, ALPs, Dark Photon (Z')

Light DM: ALPs, Z' (Dark Photon), Freeze-In Dark Matter



Heavy DM: Wino & Higgsino (WIMPs), portals to EWK (e.g. Higgs Portal), Scalar and Pseudoscalar mediator simplified models (O1 and velocity-dependent)



Exotica: Dark Showers, Dark Compact Objects (PBH + Exotic Compact Objects)

Projects and main targets

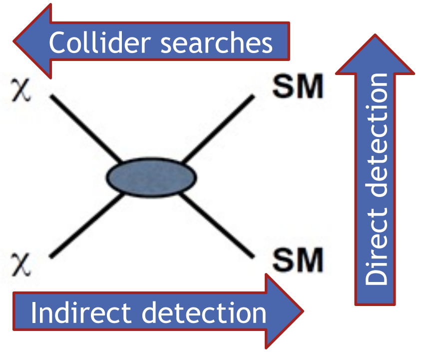
A non-exhaustive list of targeted models at main collider facilities

HL-LHC: Heavy DM, Higgs Portal, Long-Lived Particles (LLP) in dark sector, ALPs etc
FCC (ee/hh): WIMP, Higgs portal, LLP, ALPs, DP - minimal, heavy, light DM
Linear Collider: WIMPs, Simplified Models
CLIC: Minimal DM, ALPs
Muon Collider: Minimal DM, Portals, ALPs
LEP3: similar to other e+e-
Lepton-Hadron (LHeC/FCC-eh): ALPs, Dark Photons, LLP
CEPC: WIMPs, Scalar and lepton portal, Simplified Models

__Note:__ in several cases, prospects are as in ESPP2020/Snowmass; where no prospects are available but there is potential, this is indicated

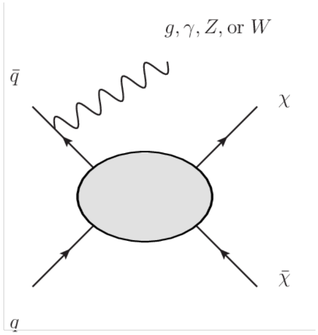
Complementary to **direct*** and **indirect*** detections, as well as **accelerator-based*** programme (for which colliders are, by nature, instrumental)

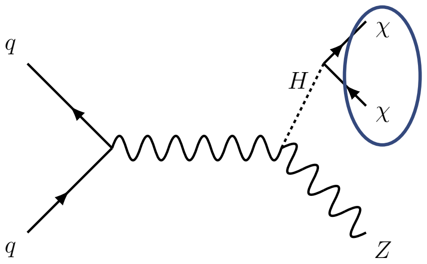
* See other contributions in this session



Heavy Dark Matter

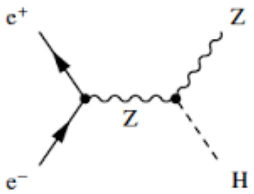
- Mass m_{DM}: **O(GeV) → 10 TeV scale**, collider searches naturally focus on models with sizeable coupling to SM particles
  - for m_{DM} ~ EW scale → classical WIMP candidates: **Higgsino, Wino** (SUSY or not)
  - *OR* portal to EW physics → **Higgs** or **other portals** (scalar or axial-vector simplified models)
- Dark and stable → **missing transverse energy** signatures



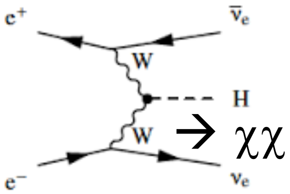


- Recoiling against SM particles
- Produced through mediators

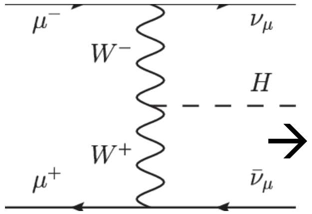
or from Higgs decays (Higgs portal)



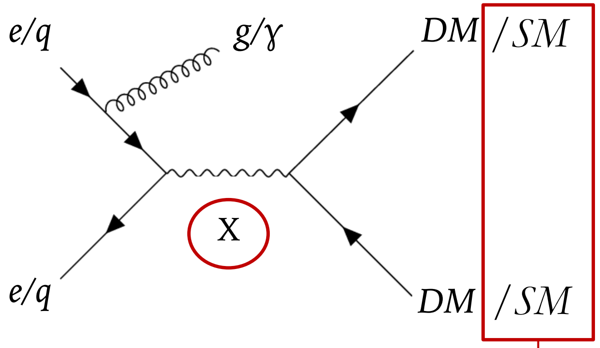
→ χχ

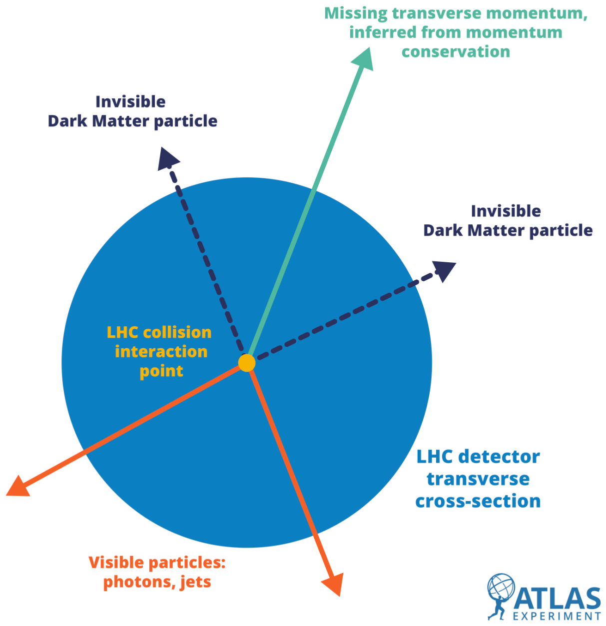


→ χχ



→ χχ

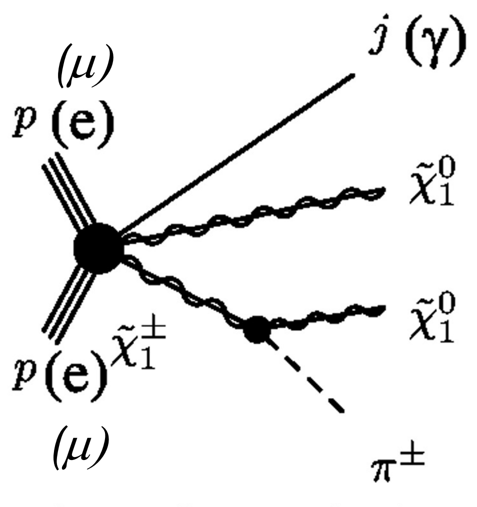


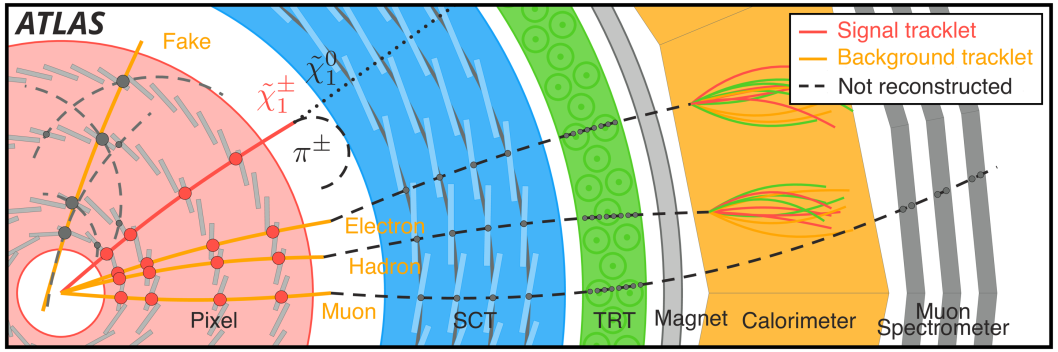


Note: depending on coupling, mediators can decay back in SM particles → resonance signatures

Heavy Dark Matter

- Mass m_{DM}: O(GeV) → 10 TeV scale, collider searches naturally focus on models with sizeable coupling to SM particle
  - for m_{DM} ~ EW scale → classical WIMP candidates: Higgsino, Wino (SUSY or not)
  - *OR* portal to EW physics → **Higgs** or **other portals** (scalar or axial-vector simplified models)
- But also – specialized techniques such as "disappearing tracks"
  - Higgsino and Wino models predict very compressed 'triplet', with lowest mass particle being the DM candidate
  - 'heavier' partners decay through emission of a pion

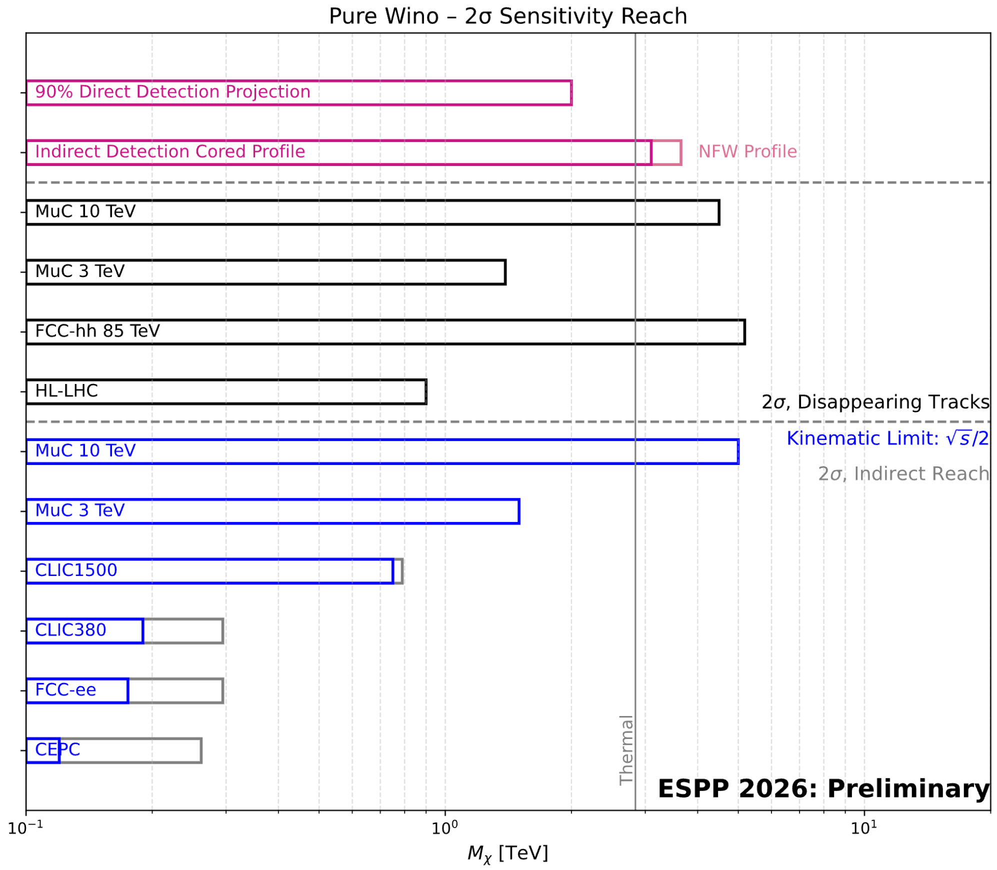




- Short "tracklet" + additional jet(s), especially at hadron colliders
- Charged stubs + photon at lepton colliders (but also "soft" tracks)

Wino and higgsino (1)

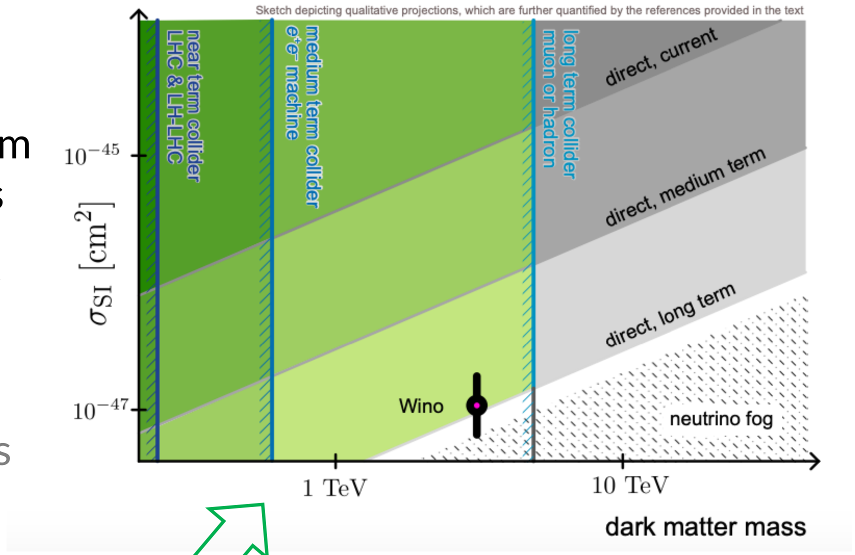
- DM part of a Dirac fermion doublet (Higgsino) or of a Majorana fermion triplet (Wino)
  - In SUSY, superpartners of the SM Higgs/gauge bosons [see back-up]
  - Very predictive models: requiring relic density under the assumption of a standard cosmology with thermal freezeout of the DM → m_{DM} ~ **2.8 TeV** for the Wino case, and ~ **1.1 TeV** for the Higgsino case



WINO

- ✓ **FCC-hh** (also with lower com energy) **reaches** wino mass
- ✓ Similar to MuonC @10 TeV
- ✓ e+e- also sensitive through modification of propagators [see more in back-up]

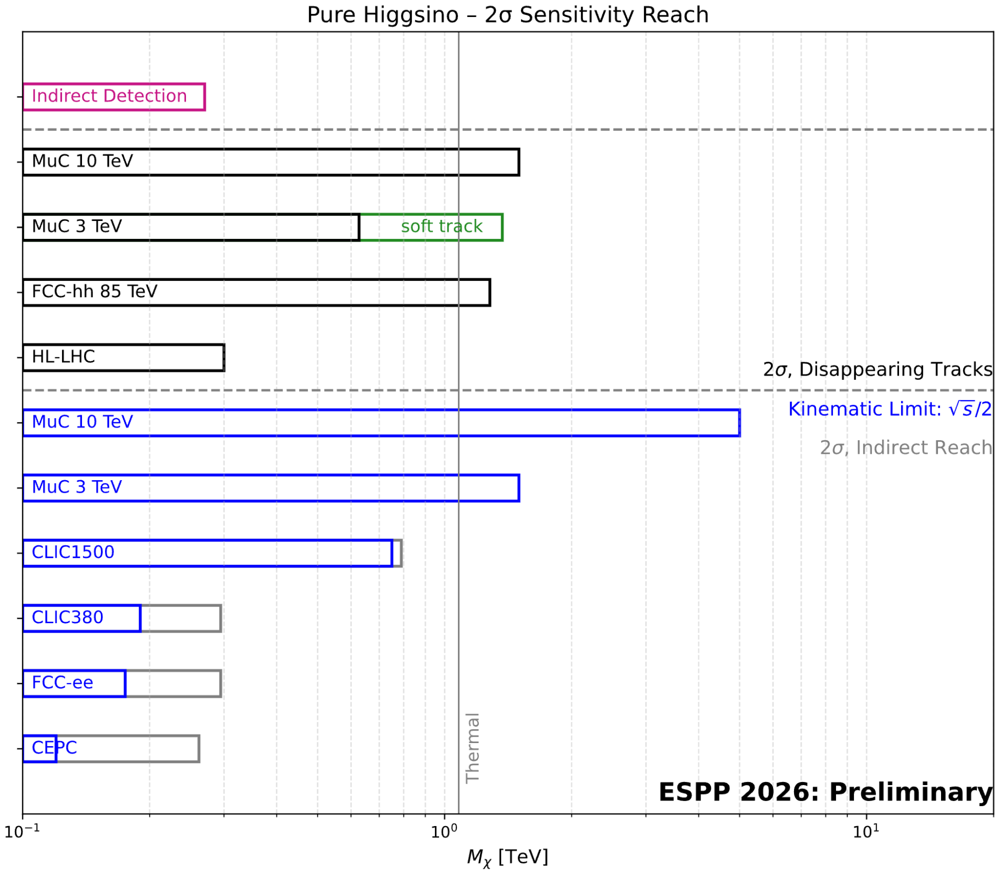
#260: Dark Matter Complementarity



Direct detection projections: close to colliders reach but also to neutrino fog region – difficult
Indirect detection: 3.65 TeV at 95% CL for NFW profile (CTA and SWGO). Cored profile: 3.1 TeV (Private comm)

Wino and higgsino (2)

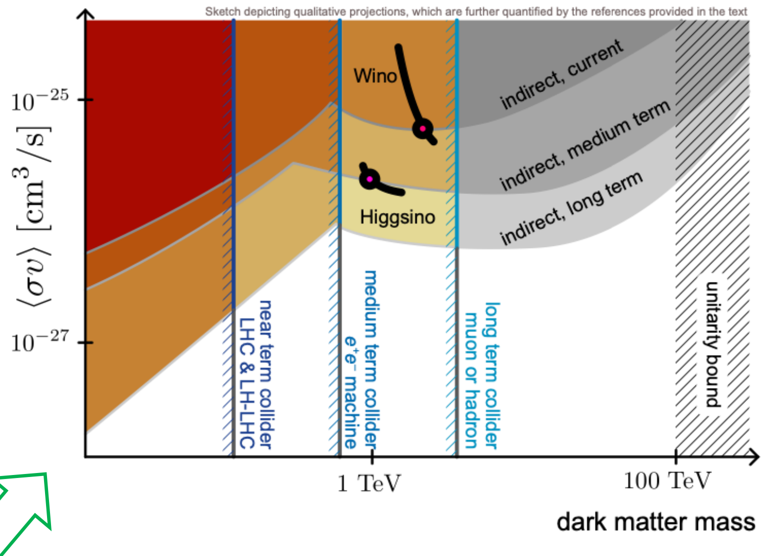
- DM part of a Dirac fermion doublet (Higgsino) or of a Majorana fermion triplet (Wino)
  - In SUSY, superpartners of the SM Higgs/gauge bosons [see back-up]
  - Very predictive models: requiring relic density under the assumption of a standard cosmology with thermal freezeout of the DM → m_{DM} ~ **2.8 TeV** for the Wino case, and ~ **1.1 TeV** for the Higgsino case



HIGGSINO

- ✓ **FCC-hh reaches** higgsino mass
- ✓ MuonC and CLIC @ 3 TeV can also **reach** higgsino mass

#260: Dark Matter Complementarity

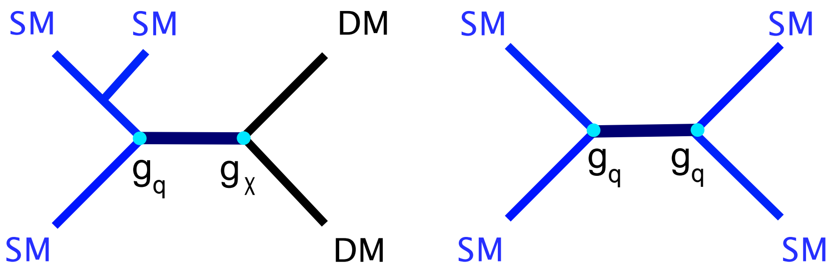


Direct detection projections: still far from colliders reach (in neutrino fog region) – very difficult
Indirect detection: [current] 270 GeV at 95% CL (Fermi γ-ray data) – **[prospects]** reach 1.1 TeV Higgsino mass with CTAO
Role of hadron/muon colliders is crucial if discovered

Simplified models: axial-vector mediators (1)

- Simplified models are good benchmarks to compare diverse signatures and facilities
  - DM interacts with SM through coupling with a (axial-vector) mediator

Ref: 1810.12238

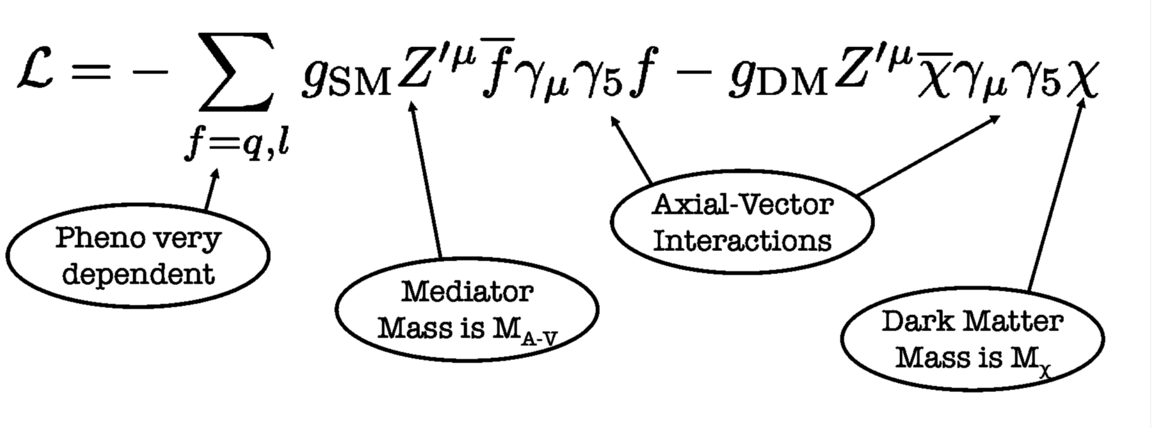


Typical signatures:
- **E_T^{Miss}+X (i.e. monojet, mono-γ, ..)**
- Di-jet/di-lepton resonances

interpretation → depend on g_{DM} and $g_{SM(l,q)}$

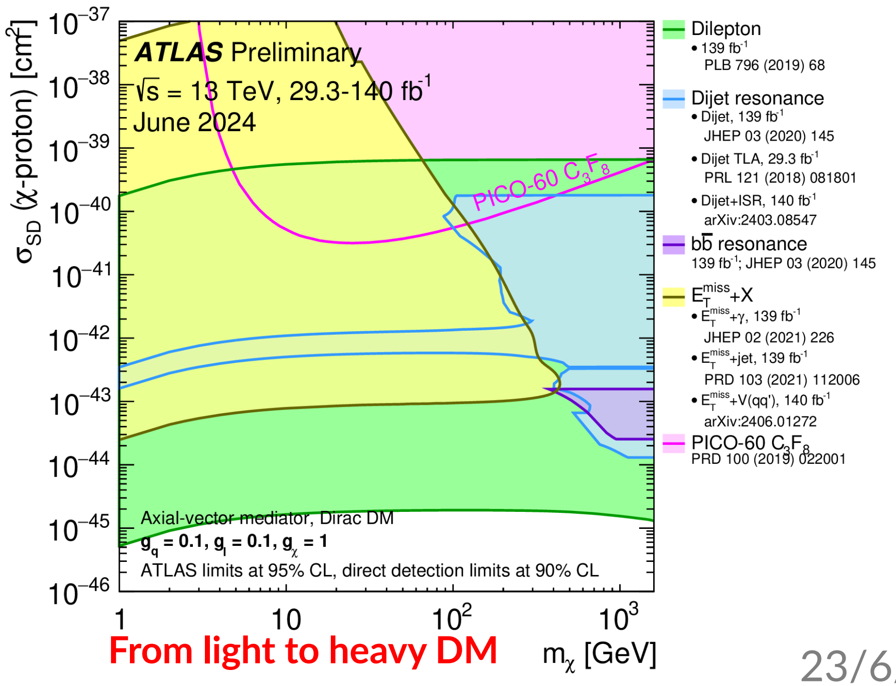
Widely considered since ES2020:

$$\mathcal{L} = -\sum_{f=q,l} g_{\rm SM} Z'^{\mu} \bar{f}\gamma_\mu\gamma_5 f - g_{\rm DM} Z'^{\mu}\bar{\chi}\gamma_\mu\gamma_5\chi$$



Matthew Mccullough, Granada 2019

Example of current results

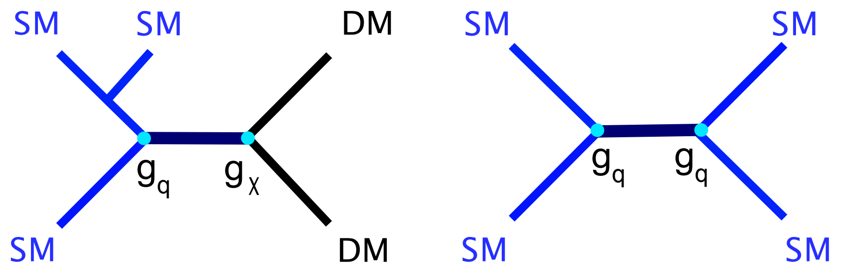


From light to heavy DM

Simplified models: axial-vector mediators (2)

- Simplified models are good benchmarks to compare diverse signatures and facilities
  - DM interacts with SM through coupling with a (axial-vector) mediator

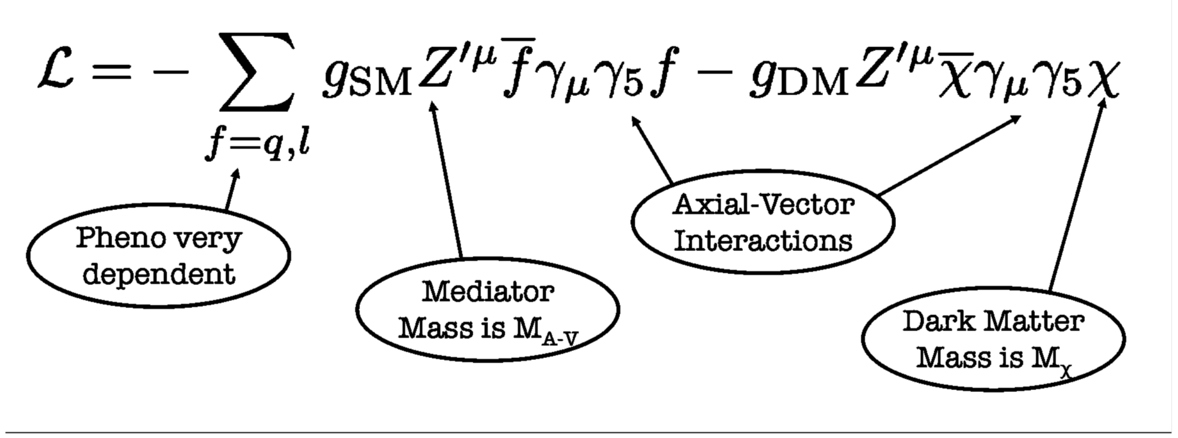
Ref: 1810.12238



Typical signatures:
- E_T^{Miss}+X (i.e. monojet, mono-g, ..)
- **Di-jet/di-lepton/di-X resonances**

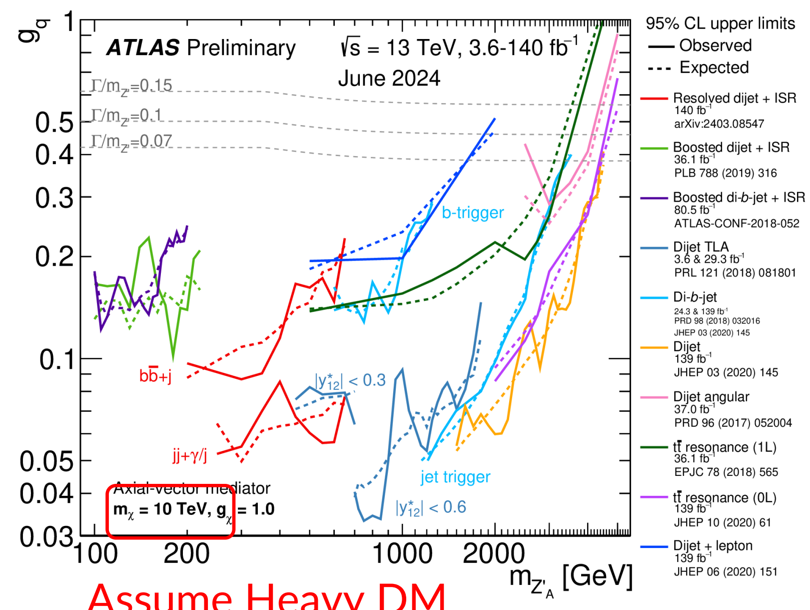
interpretation → mediator mass, g_{SM} for fixed m_{DM}

Widely considered since ES2020:



Matthew Mccullough, Granada 2019

Example of current results

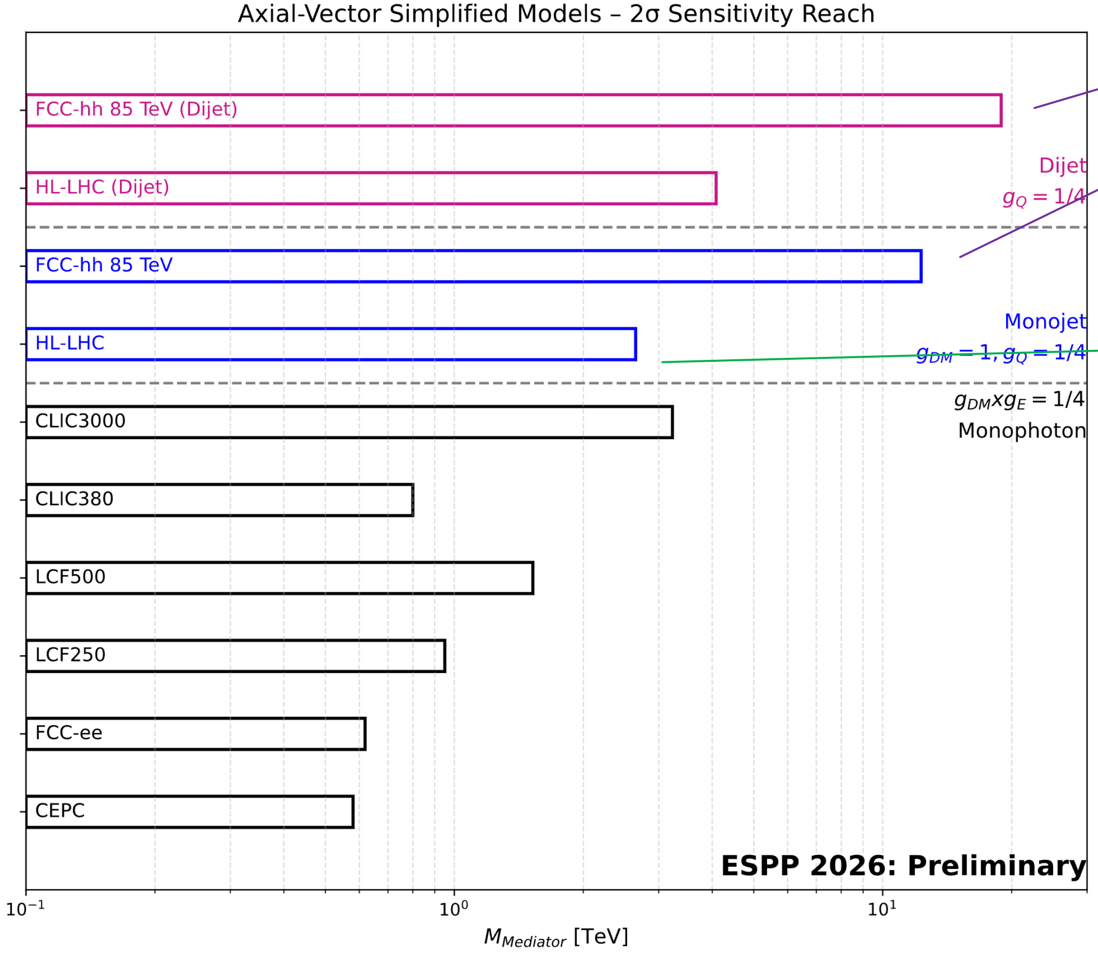


Assume Heavy DM

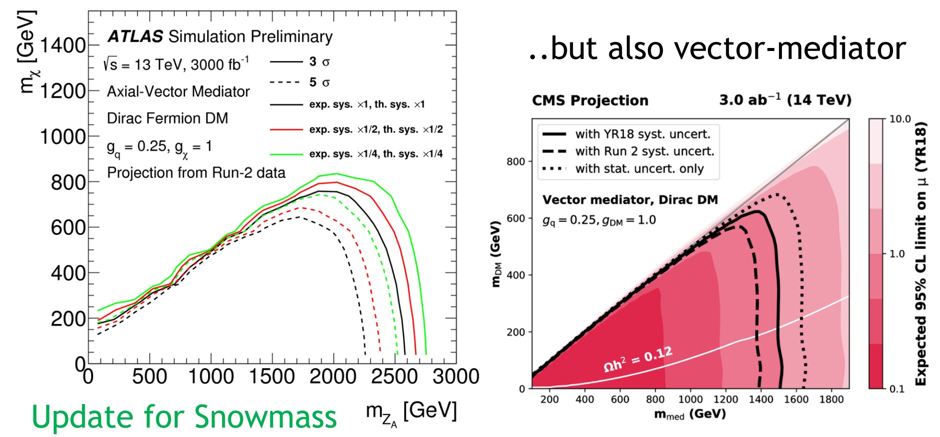
Simplified models: axial-vector mediators (3)

- Assumption → Light dark matter (m_{DM} = 1 GeV)

$$g_{\rm DM} = 1\ ,\ g_{\rm SM} = 0.25$$



FCC-hh rescaled for **85 TeV**
[for 100 TeV see FCChh prospects].



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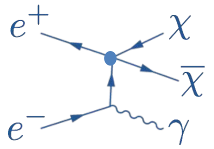


→ lepton-couplings only (g_{SM}=g_l)

Muon Collider not (yet) in this plot: mono-γ but also mono-W reach also available (see back-up)

Simplified models: scalar mediators – BSM (1)

- Simplified models are good benchmarks to compare diverse signatures and facilities
  - DM interacts with SM through coupling with a (**scalar**) mediator

Yukawa couplings

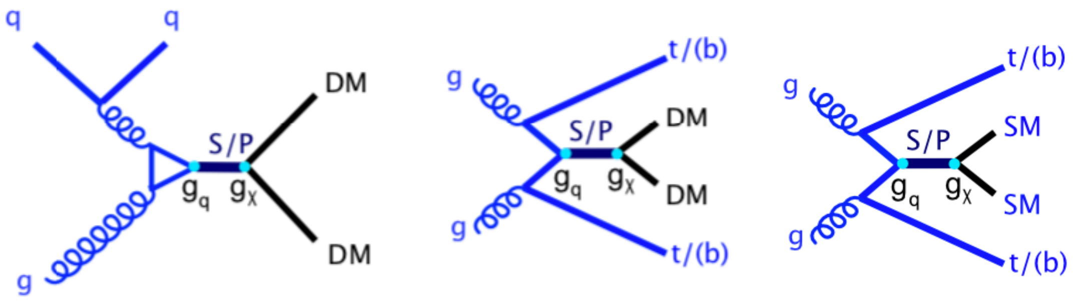
$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}}\phi\bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q \,,$$

$$\mathcal{L}_{\text{pseudo-scalar}} = -i g_{\text{DM}}\phi\bar{\chi}\gamma_5\chi - i g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}\gamma_5 q \,,$$

arXiv:1708.02245 & references

Benchmarks as in ES2020/Snowmass
Caterina Doglioni, Granada 2019

- **Signatures at colliders**
  - **Mono-jet/mono-photon** but also E_T^{Miss} associated to top and b-quarks, or **4 tops *e.g.*** relevant in 2HDM models –HL-LHC improvements → EPSS2026 update,



Ref: 1810.12238

- Can be translated into limits in the DM-nucleon plane to evaluate interplays with DD

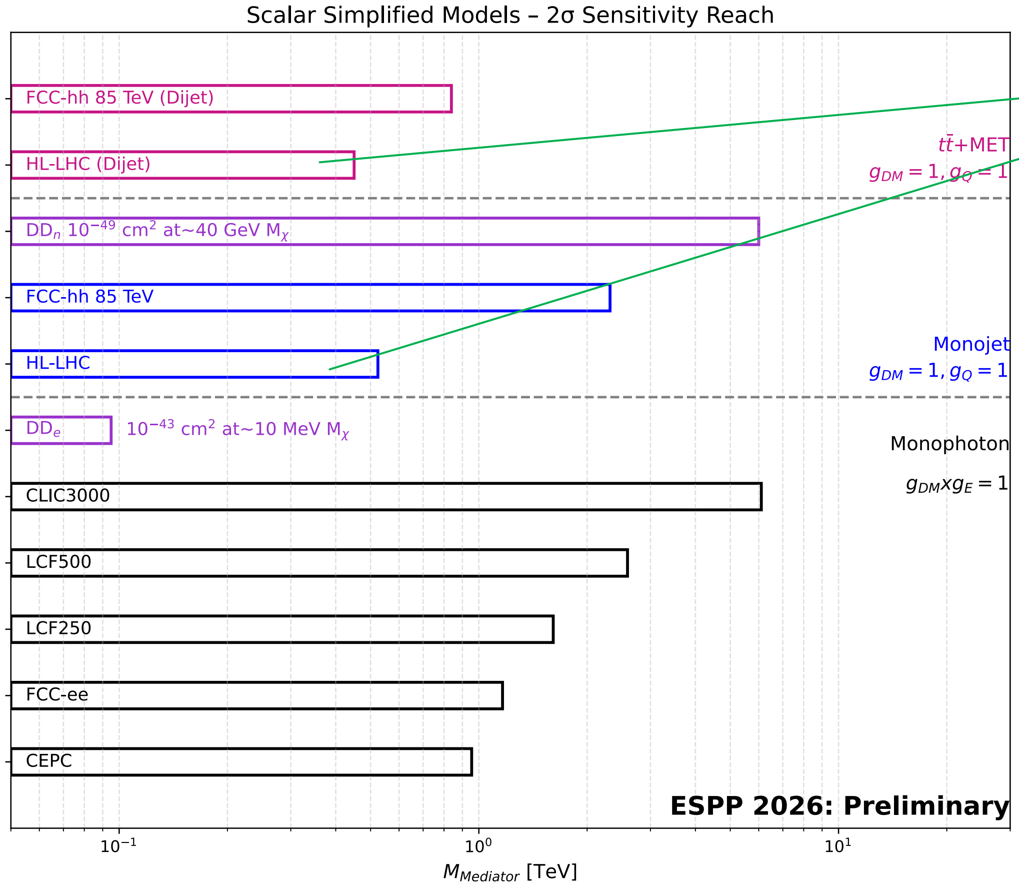
$$\sigma_{\text{SI}} \simeq 6.9 \times 10^{-43}\ \text{cm}^2 \cdot \left(\frac{g_q g_{\text{DM}}}{1}\right)^2 \left(\frac{125\ \text{GeV}}{M_{\text{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \text{GeV}}\right)^2 .$$

Caveat: strong model-dependence!

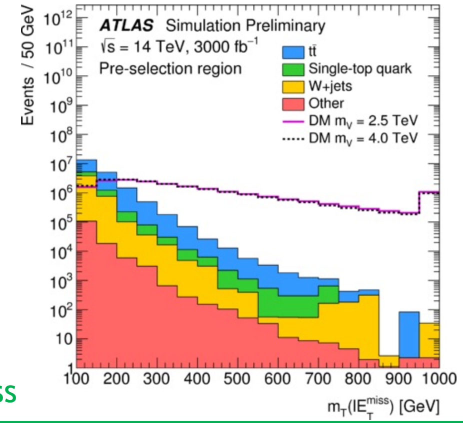
Simplified models: scalar mediators – BSM (2)

- Assumption → Light dark matter (m_{DM} = 1 GeV) for colliders

$g_{DM} = 1, g_{SM,f} = 1$



No new updates, but signatures like mono-top (new) can also add to sensitivity



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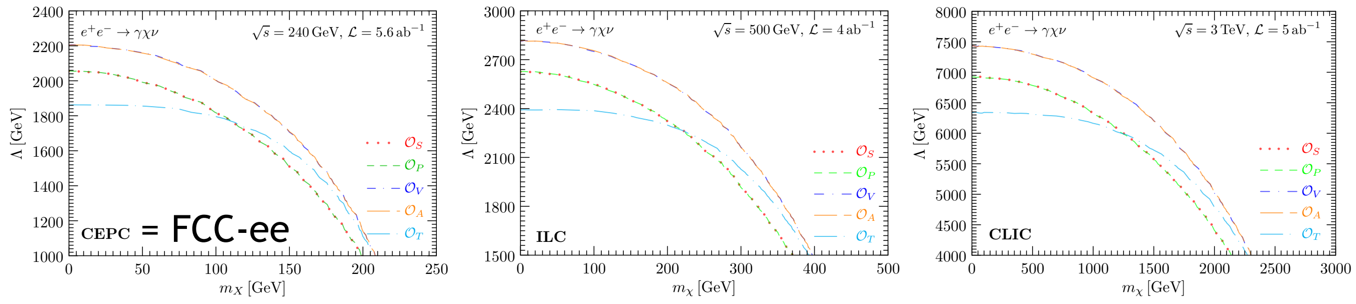
Update for Snowmass

FCC-hh rescaled for **85 TeV** [for 100 TeV see FCChh prospects]

Updates from https://arxiv.org/pdf/2306.00657



$DD_{n,e}$: **max** reach for XLZD 1000, OSCURA (nucleon, e respectively)
Note different assumptions of DM mass

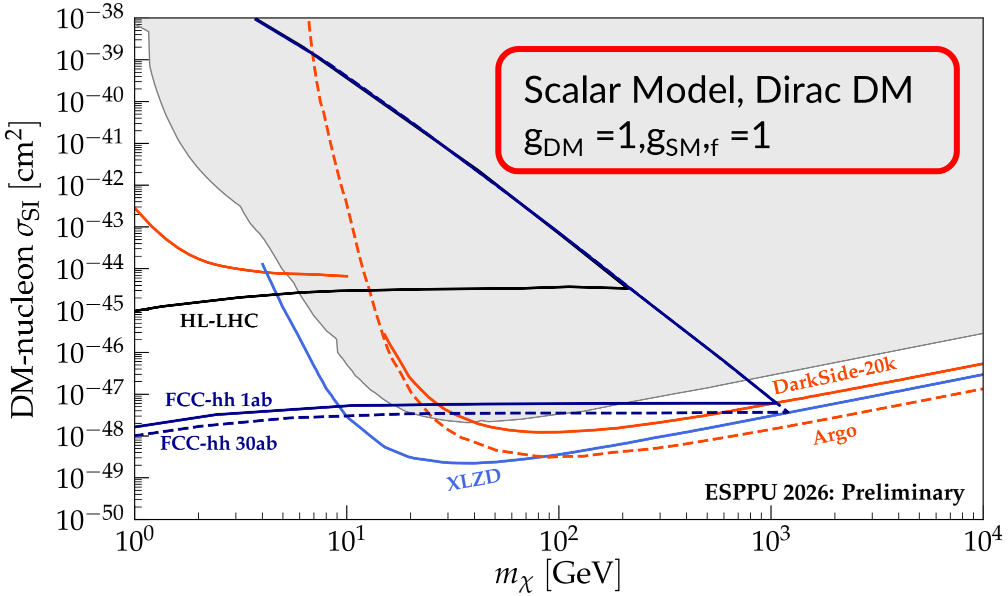
Muon Collider not (yet)in this plot: mono-γ/W reach in back-up

Simplified models: scalar mediators – BSM (3)

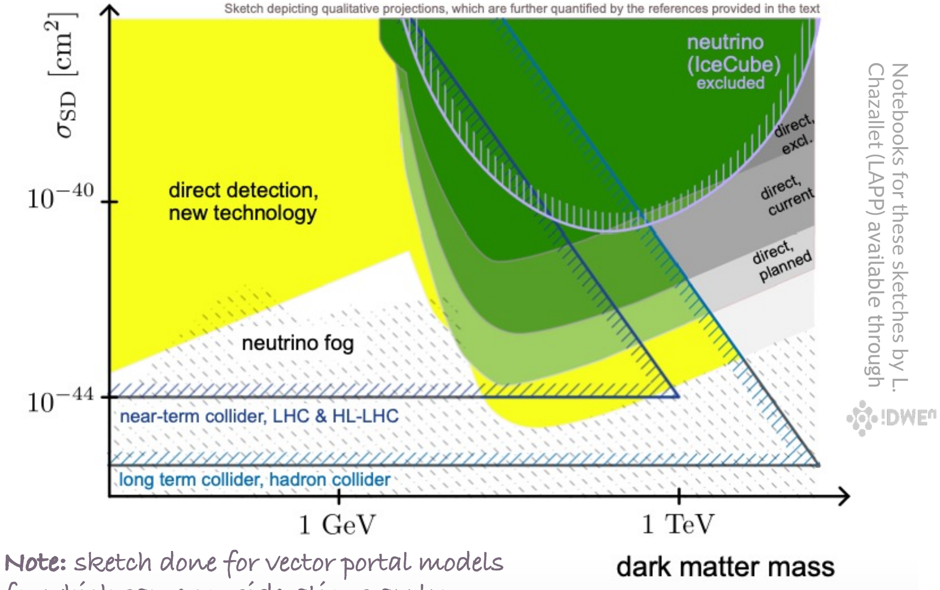
- Limits can be translated in DM-nucleon cross section constraints
  - Validity within the chosen benchmark models & parameters
  - No major updates on the colliders side wrt ES2020 but updates in DD (current and potential)

tt+MET

V/j+MET



Future colliders sensitive to models with mediators decaying to **lighter DM candidates** as well as possibly reaching DM masses up to a TeV from the decays of multi-TeV- mass mediators.

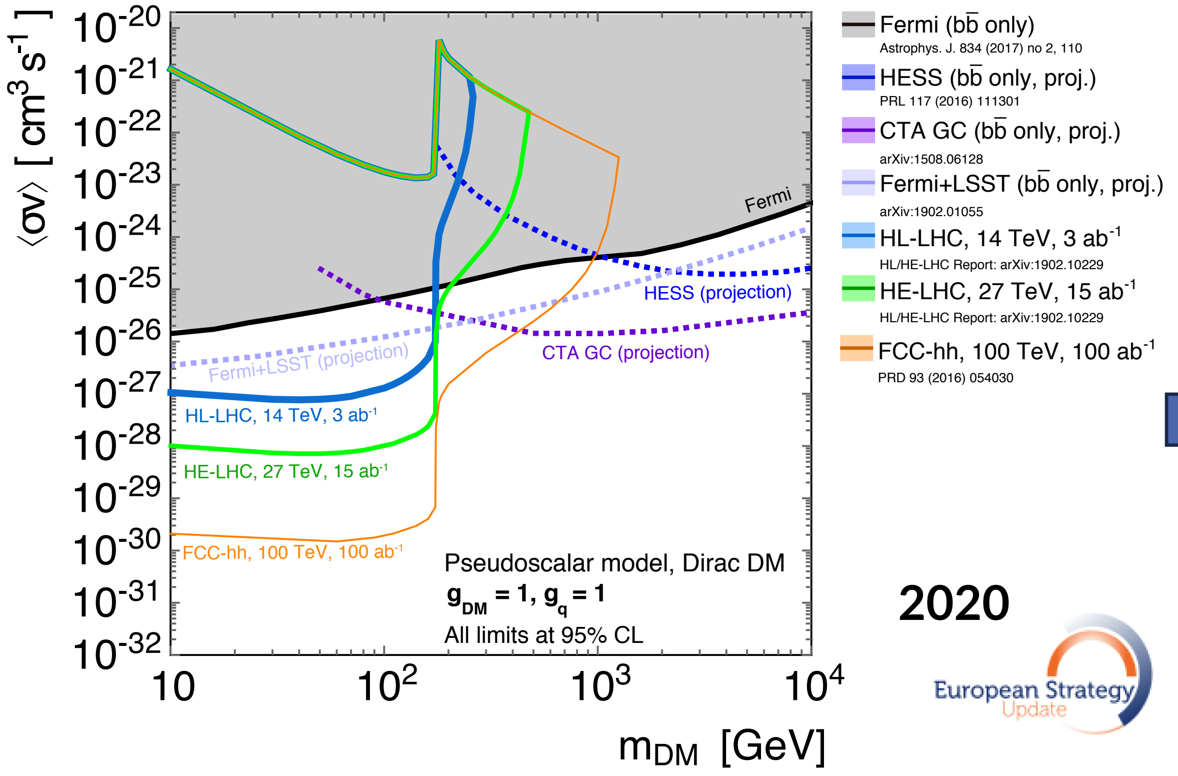


Note: sketch done for vector portal models for which same considerations apply

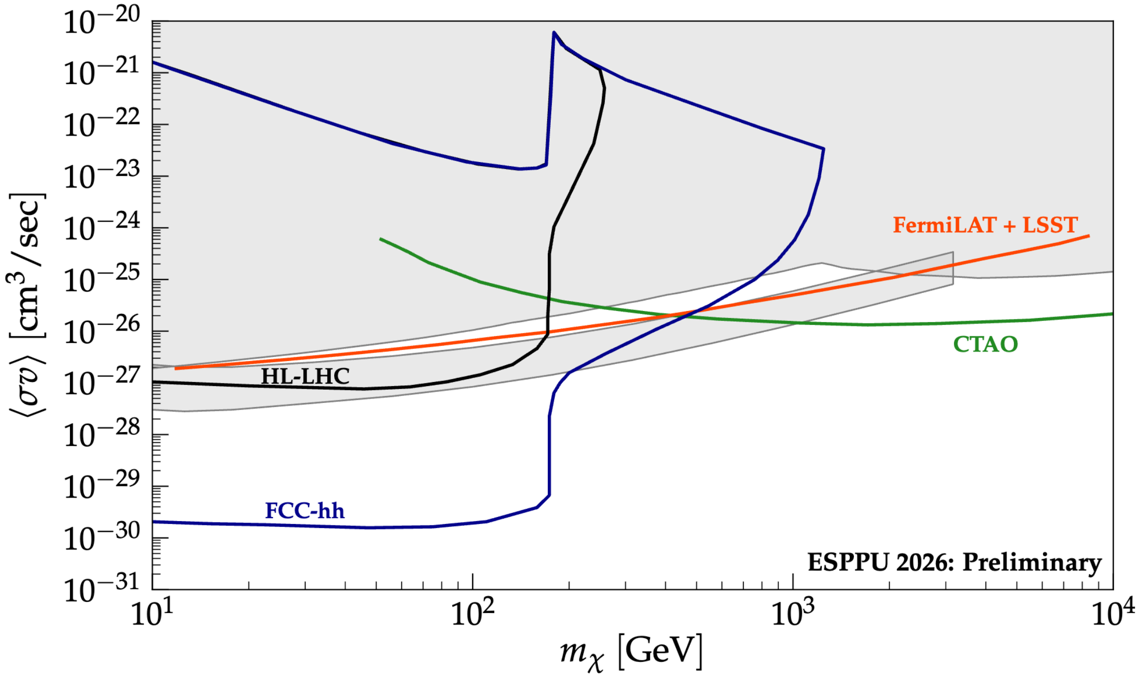
Lepton colliders not included as would require translation in terms of quark-gluon coupling → sensitivity to **DM-electron interactions** could be considered – see Paolo's talk

Simplified models: scalar mediators – BSM (4)

- Further interplays with indirect detection
  - velocity-averaged annihilation cross section <σv> mapped to multiple values of LHC mediator mass–m_{DM} pairs.
- collider searches have better sensitivity for DM masses below the top mass (here considering pseudoscalar mediators) → **complementary** to indirect searches which are more powerful for higher m_{DM} (No major updates on the colliders side wrt ES2020/Snowmass but several updates in indirect detection)



2020

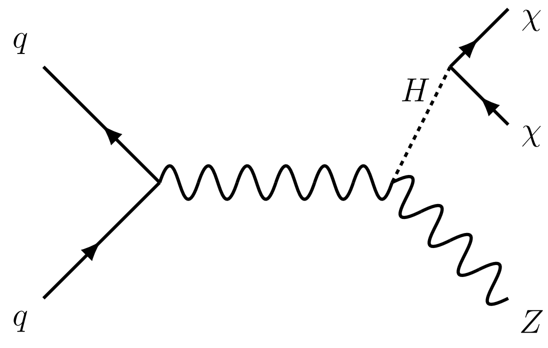


New: 2025

Details on ID constraints in back-up

Higgs portal models

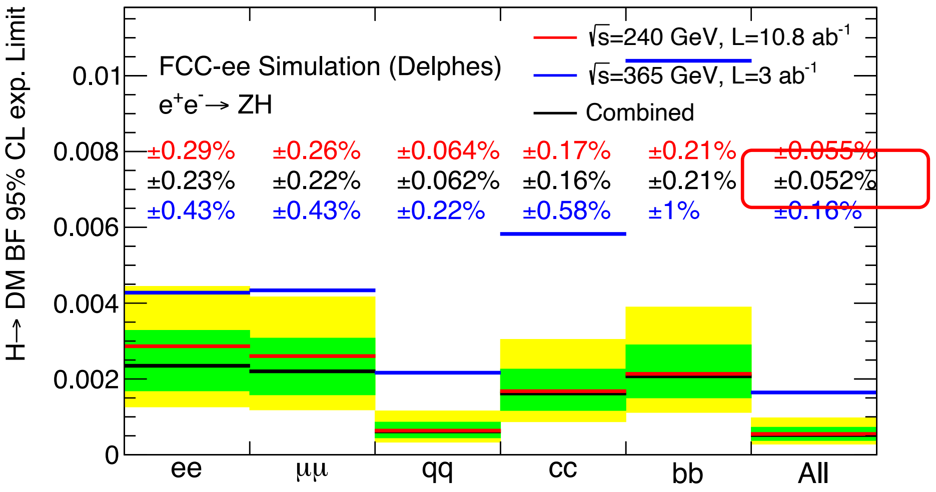
- Translate Higgs to invisible BR into DM-nucleon constraints. Results for BR of Higgs to invisible
  - HL-LHC: **2.5%** from ES2020 Higgs report
    - **0.9%** reach combining ATLAS+CMS for 6 ab^{-1} to be confirmed [see back-up]
  - ILC: **0.16%** combining 900 fb^{-1} per each polarisation at sqrt(s) = 250 GeV.
  - FCC-ee: **0.052%** combining 240 and 365 GeV results
  - FCC-hh: **0.02%** for 100 TeV (to be rescaled for 84 TeV)
  - Muon collider: **0.046% -** with 1% relative uncertainty on resolution



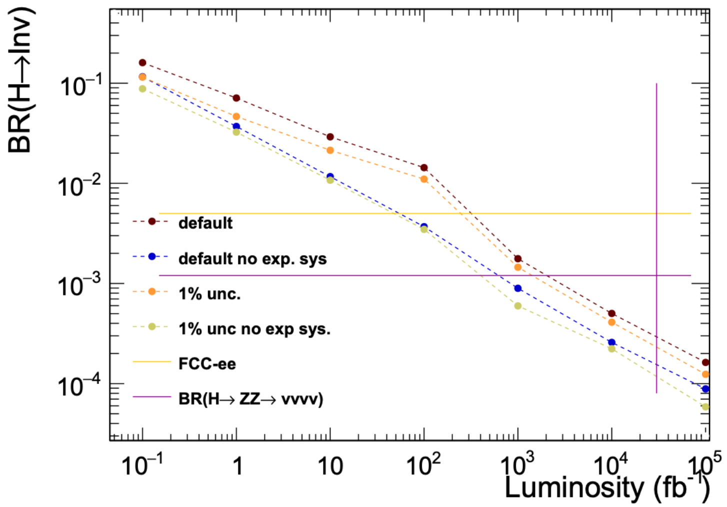
ILC ele/μ and hadron channels and combination

Channel	80% $e^-_L e^+_R$ 30%	80% $e^-_R e^+_L$ 30%	Combined
Electron	1.12%	0.35%	0.33%
Muon	0.77%	0.29%	0.27%
Hadron	0.42%	0.31%	0.25%
Combined	0.35%	0.18%	0.16%

FCC-ee



FCC-hh



Higgs portal models: interplays with DD

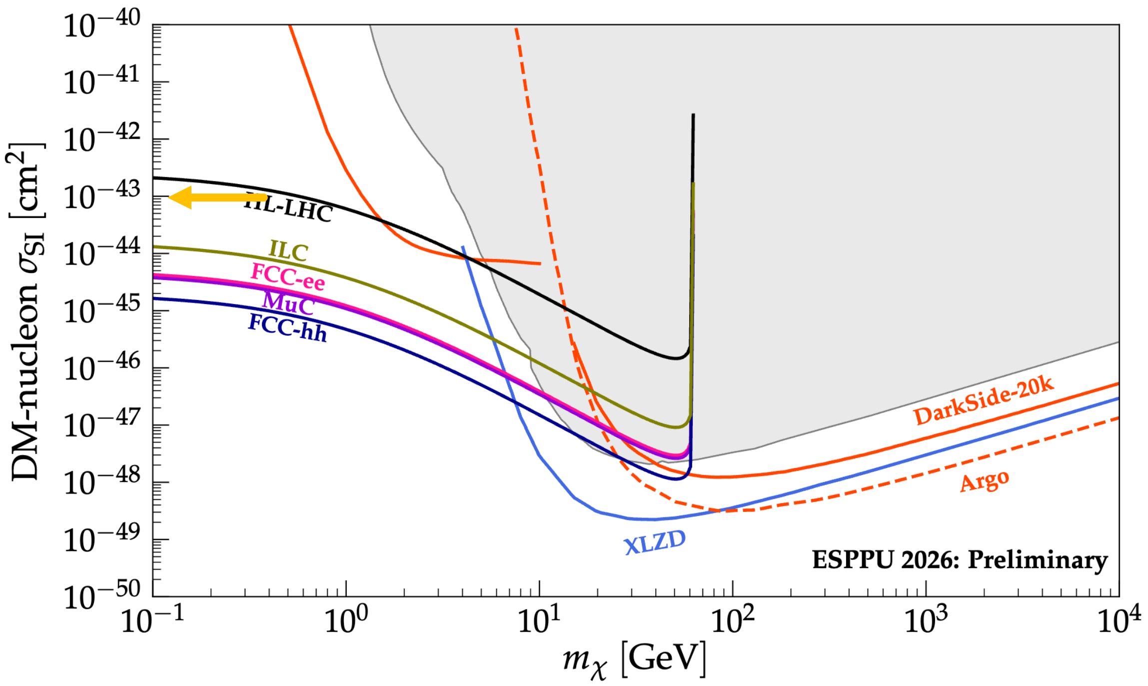
- Translated Higgs to invisible BR into DM-nucleon constraints
  - Nuclear form factor f_N = 0.326

$$\sigma_{\chi N} = \Gamma_{\rm inv} \frac{8 m_N^4 f_N^2}{v^2 \beta m_h^3 (m_\chi + m_N)^2} g_\chi\left(\frac{m_h}{m_\chi}\right), \qquad (15)$$

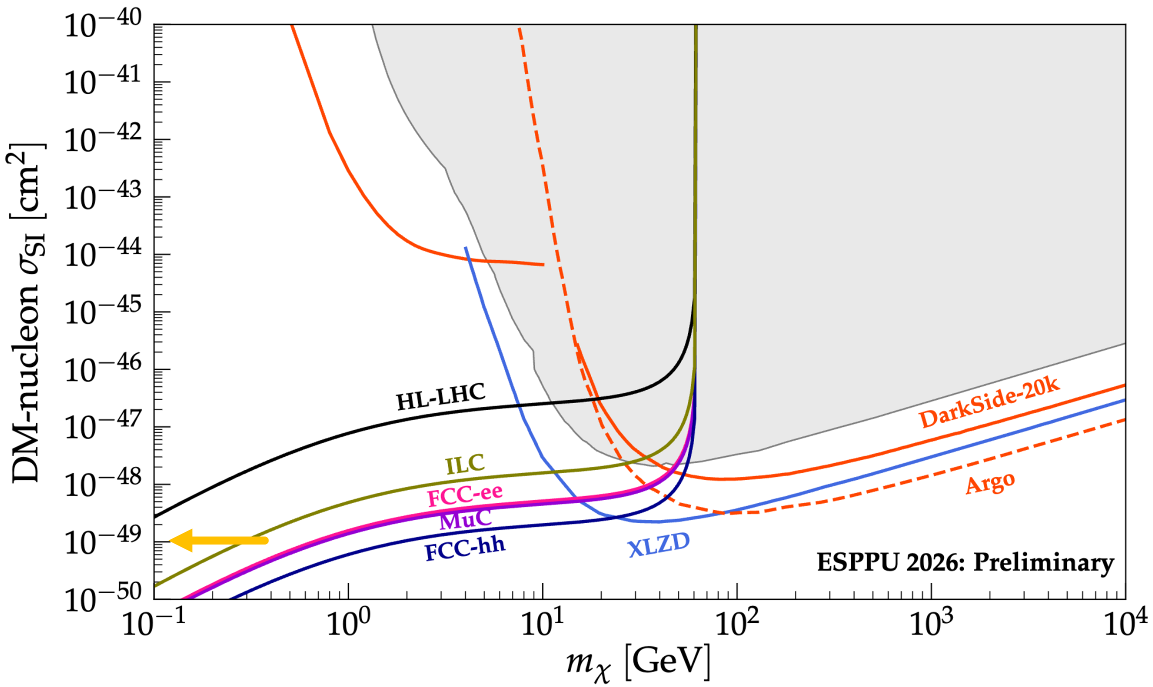
arXiv:1708.02245

where $g_S(x) = 1$,
$g_f(x) = 2/(x^2 - 4),\ \beta = \sqrt{1 - 4m_\chi^2/m_h^2},\ v = 246\,\text{GeV}$

Higgs Portal - Scalar DM



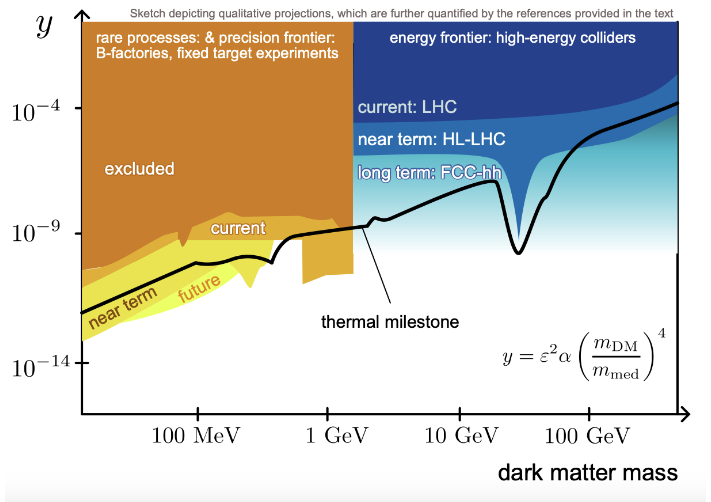
Higgs Portal - Majorana DM

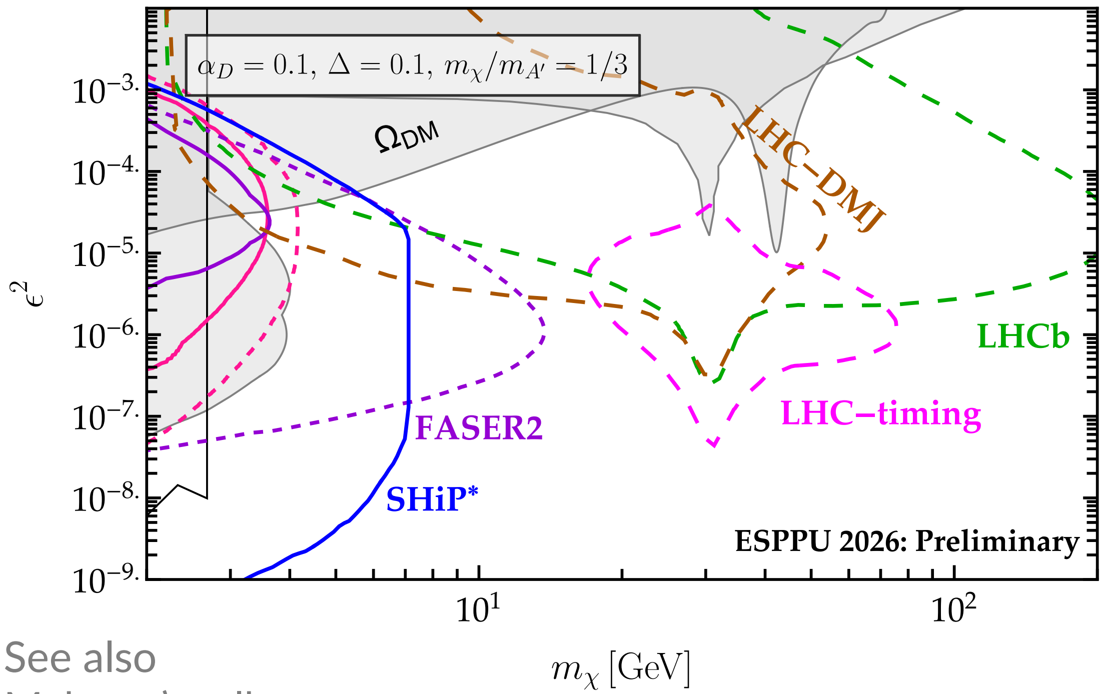


Change if BR HL-LHC: 2.5%→0.9% [also in back-up]

From heavy to light DM - interplays

- Complementarities with accelerator-based experiments, rare processes and precision measurements (*ie* B-factories) in several models, depending on m_{DM}
- Examples: quasi-elastic DM and **inelastic DM**

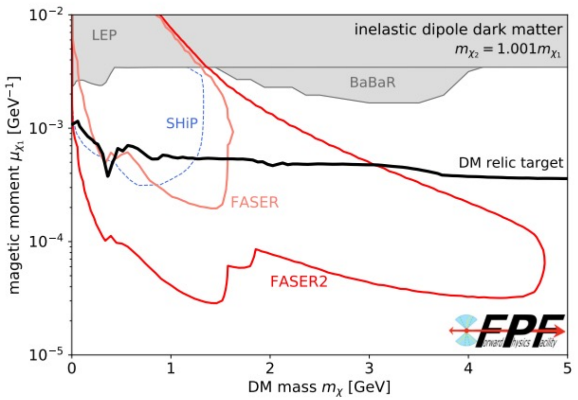




See also Maksym's talk

Further sensitivity for inelastic-DM of colliders possible!

→ Signatures with moderate/low E_T^{miss} or long-lived particles
https://arxiv.org/pdf/1810.01879



→ Sensitivity depends on assumptions of the model

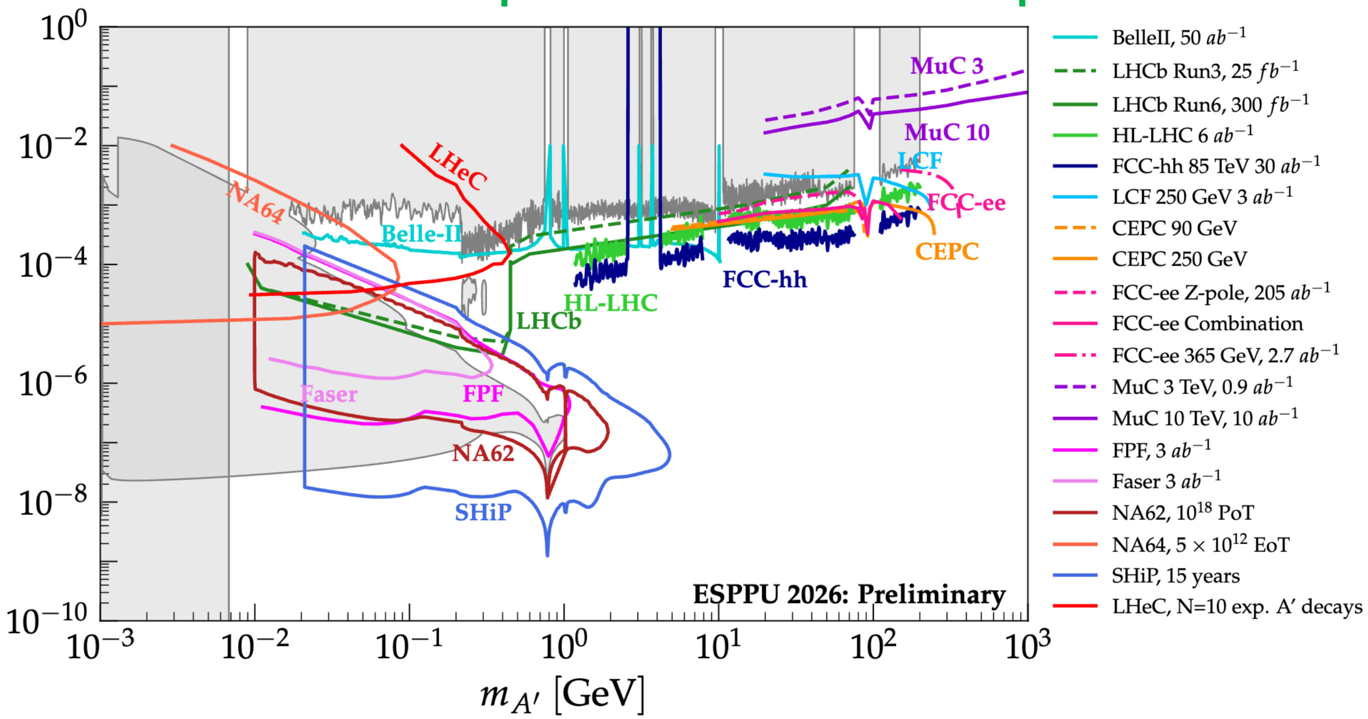
Beyond this, relevant interplays are in Dark Sectors → LLP

(see Yohei's introduction and back-up for portal models definition)

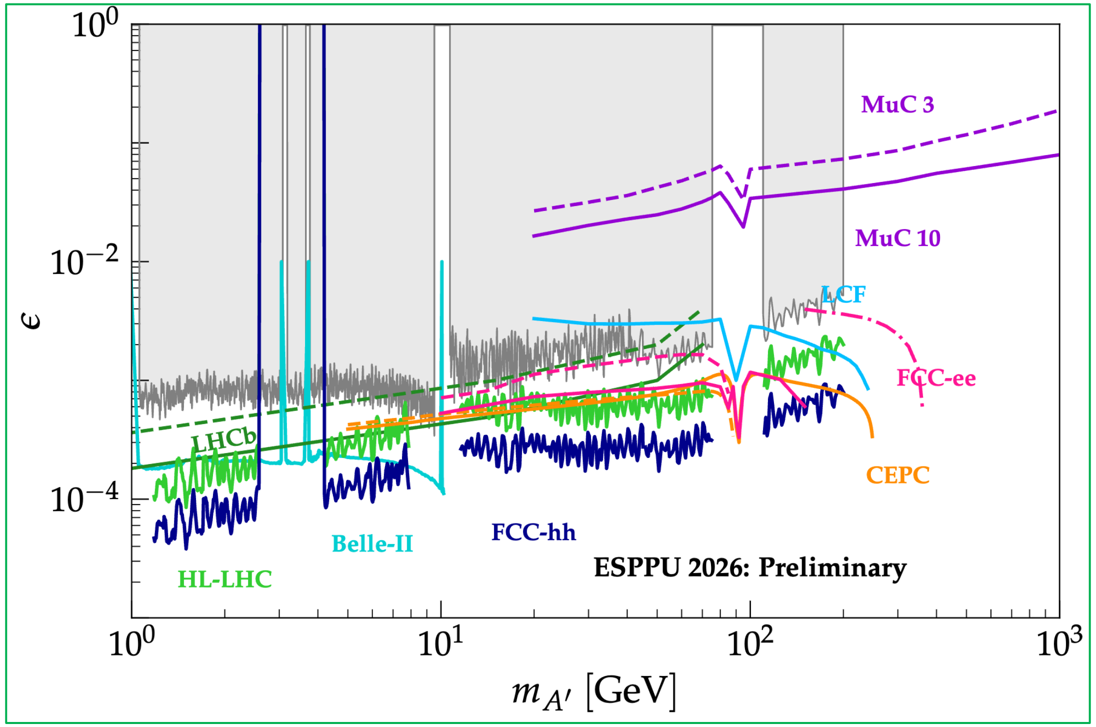
Minimal models: Dark photons

$\mathcal{L} = \mathcal{O}_{\rm SM} \times \mathcal{O}_{\rm dark} : \ \epsilon B_{\mu\nu} F'^{\mu\nu}$

- Colliders sensitivity mainly in **medium-coupling** region
  - Lowest mass ranges: LHCb, Belle-II (also at higher mass), LHeC
  - High-mass ranges: reach down to 10^{-4} coupling ε at FCC-hh, e/μ colliders reach higher mass/lower ε



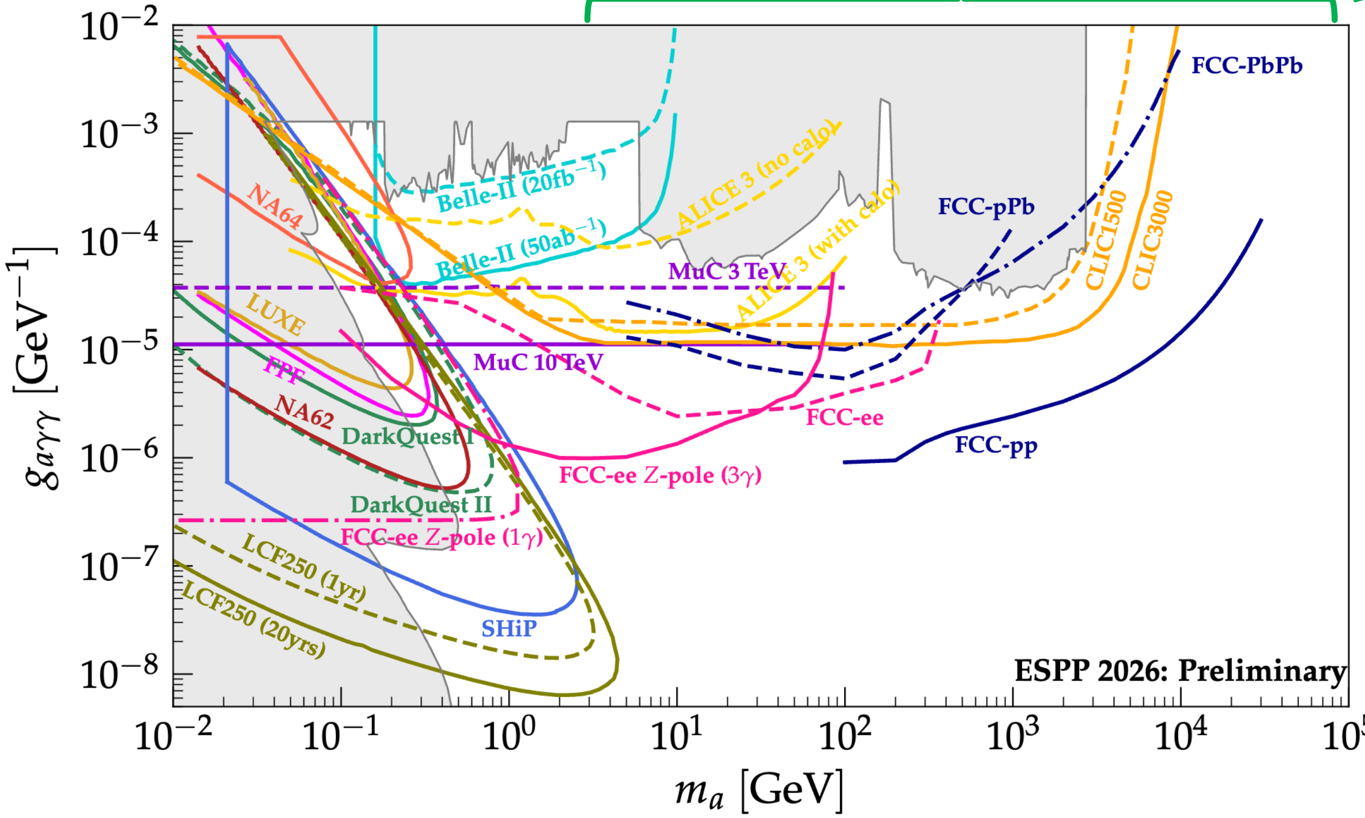
High-mass region



Minimal models: ALPs

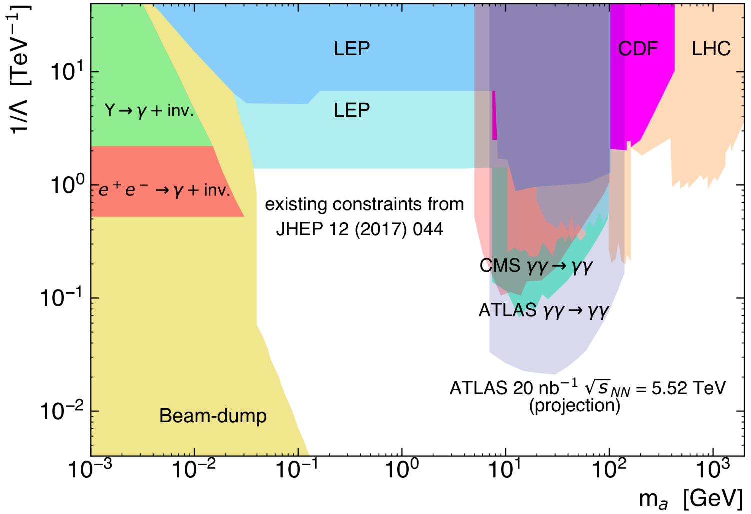
$\mathscr{L} = \mathscr{O}_{\rm SM} \times \mathscr{O}_{\rm dark} : aF\tilde{F}$

- ALPs searches at colliders very diverse depending on couplings
  - Here, focus on coupling $g_{a\gamma\gamma}$ in units of GeV^{-1} vs mass
  - Z-pole ($e^+e^- \to Z \to \gamma a$) analyses at FCC-ee reach lower couplings
  - Muon Collider searches assume invisible decays
  - emphasis on light-by-light scatterings ($\gamma\gamma \to a \to \gamma\gamma$)

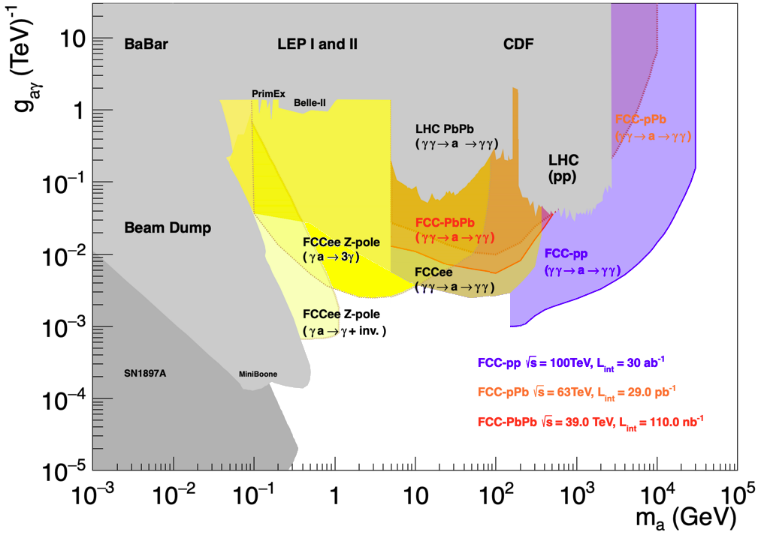


Heavy Ion searches (UPC)

Example of LHC Run 3 and Run 4 prospects



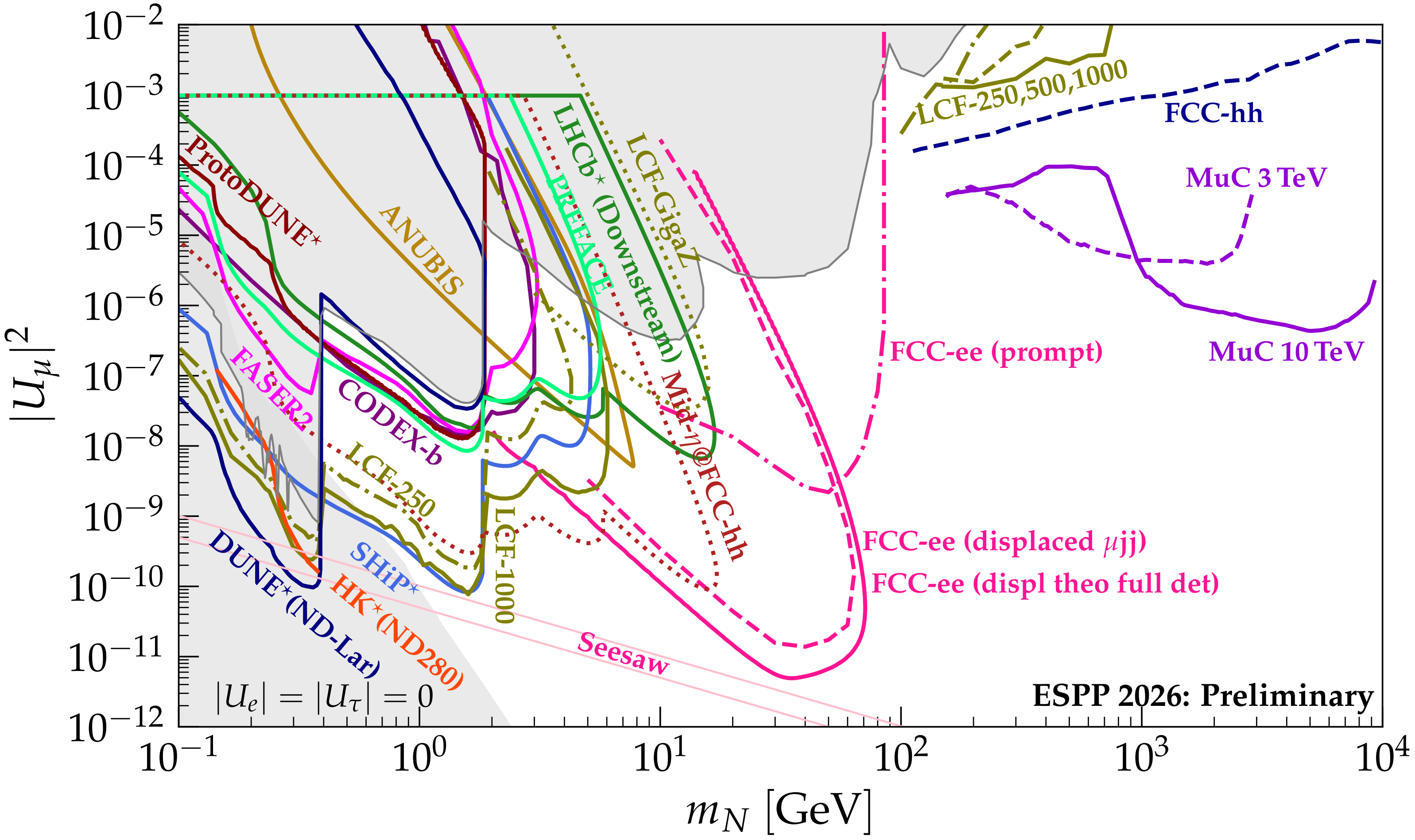
FCC BSM prospects



Minimal models: Heavy Neutral Leptons

$\mathscr{L} = \mathscr{O}_{\rm SM} \times \mathscr{O}_{\rm dark} : LHN_R$

- Sensitivity and analysis techniques depends on lepton-mixing assumptions
  - Consider case of **muon-dominance** (HNLs mixing solely to the muon neutrinos)



Strongest reach below W mass threshold through μνν and μjj searches at FCC-ee [see Fig.29 https://arxiv.org/pdf/2505.00272]

MuC covers high mass scenarios

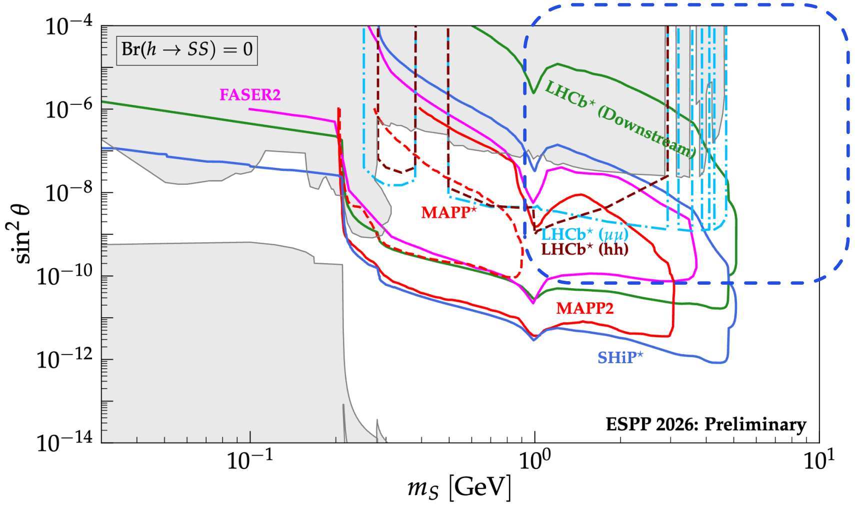
Electron-dominance or equal e-μ dominance also explored in past studies, with complementarities of ee-ep-pp facilities

[Discovery potential for HL-LHC, FCC in back-up]

Minimal models: Dark scalars

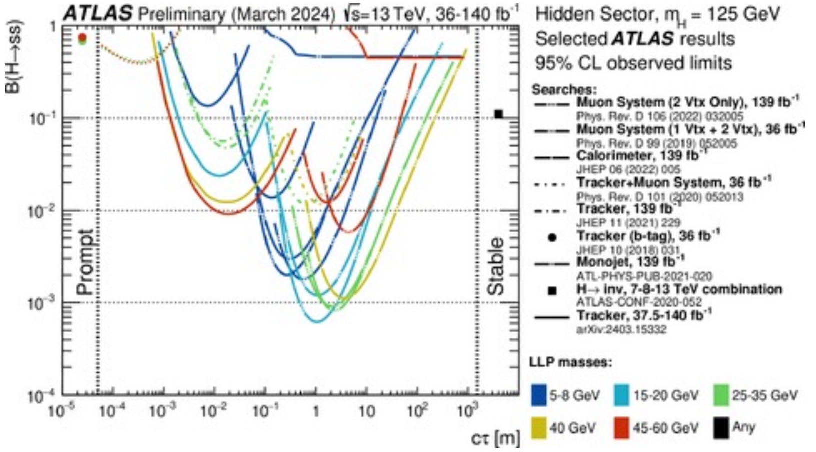
$\mathscr{L} = \mathcal{O}_{\rm SM} \times \mathcal{O}_{\rm dark} : |H|^2 S, |H|^2 S^2$

- Higgs-like scalar S with the mixing h_S and tri-linear h_{SS} interactions with the Higgs
  - Impact of collider searches mostly at high $\sin^2\theta$ and/or high mass



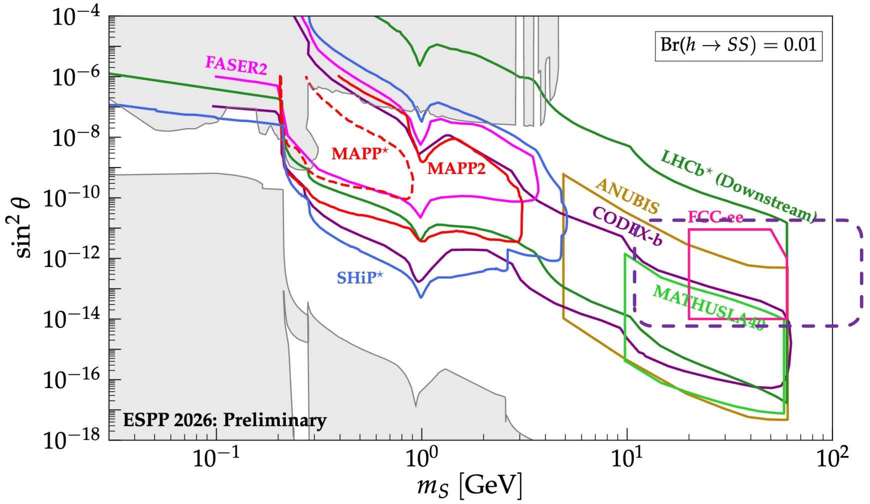
If BR (H→SS) non-zero
Sensitivity depends on lifetime/coupling

Current LHC →

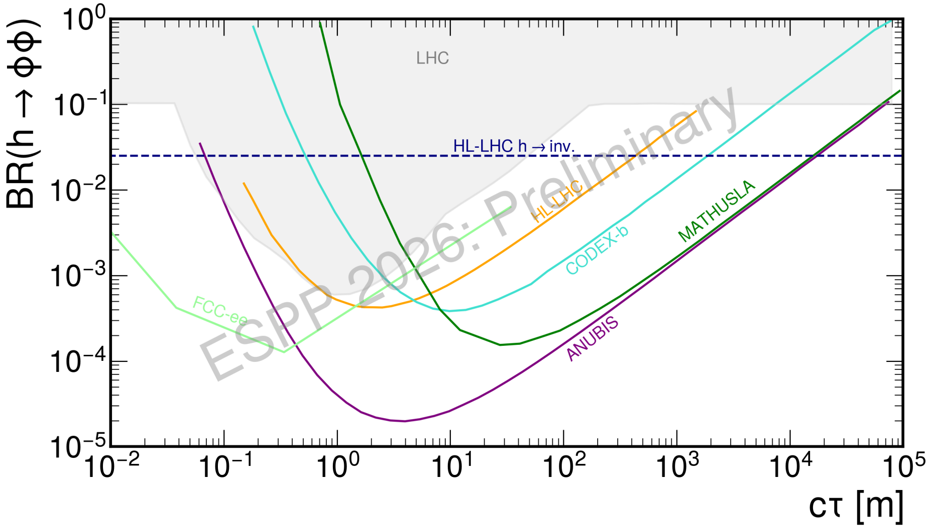


Partial projections for **future colliders (FCC-ee)** sensitivity:

Dependence on h→SS BR



more updates to be possibly included

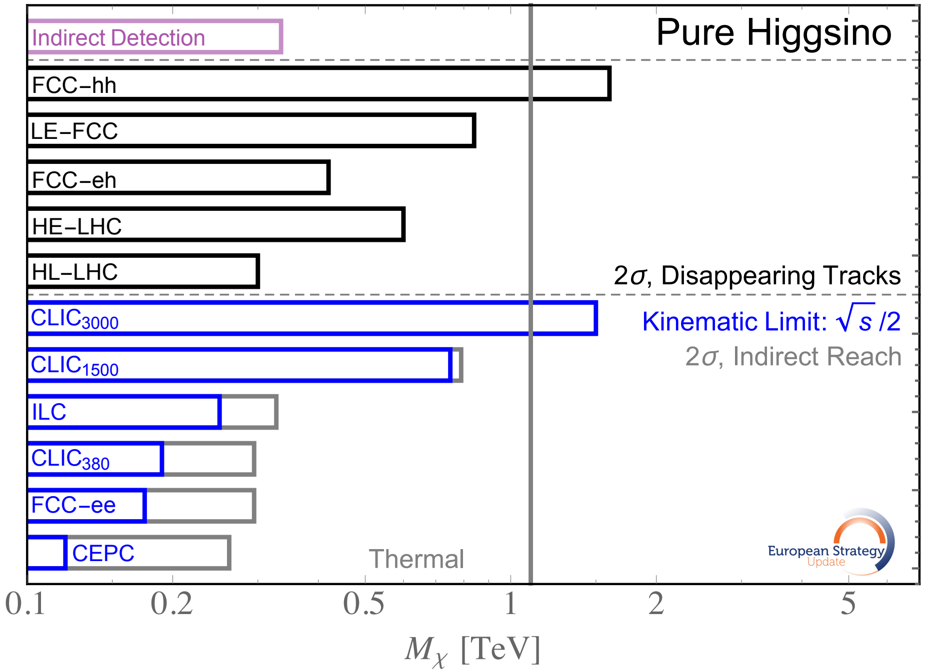


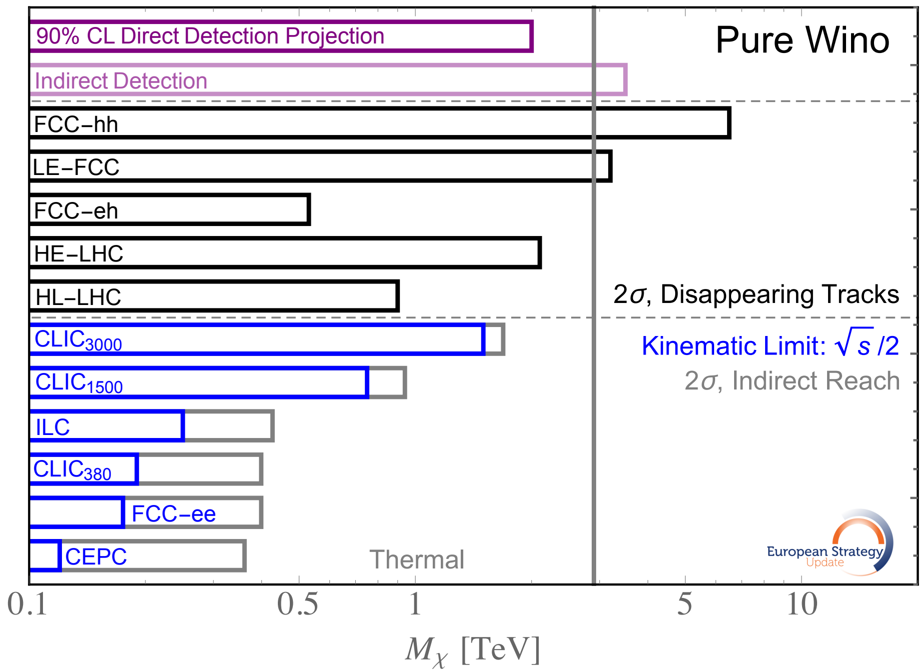
Summary

- Understanding the nature and origin of dark matter remains one of the fundamental challenges of HEP and beyond
- Colliders offer the possibility of producing DM in controlled conditions, as such maximizing the chances for discovery and understanding of its properties and new physics related to this
- Strong interplay with direct and indirect detection, as well as with accelerator-based experiments, with clear complementarities despite model-dependencies to be taken into account
- Exploiting further and better these complementarities remain a key objective of the community

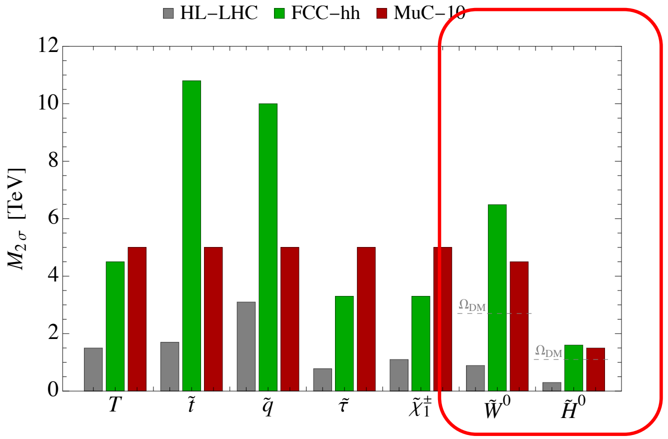
Back up

Wino and higgsino – comparison with ES2020

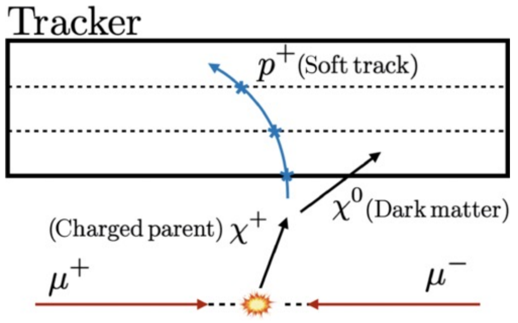




Muon Collider update studies
ES2026 submission (ref from Snowmass)

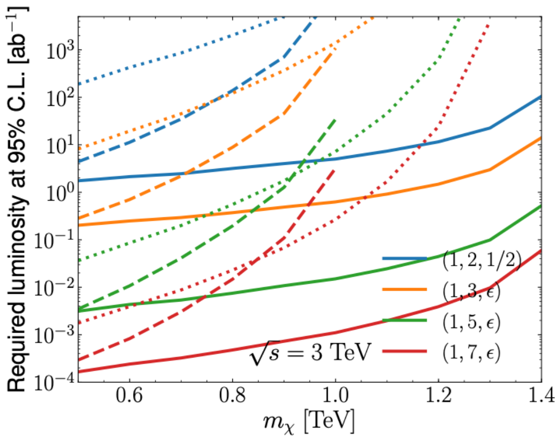


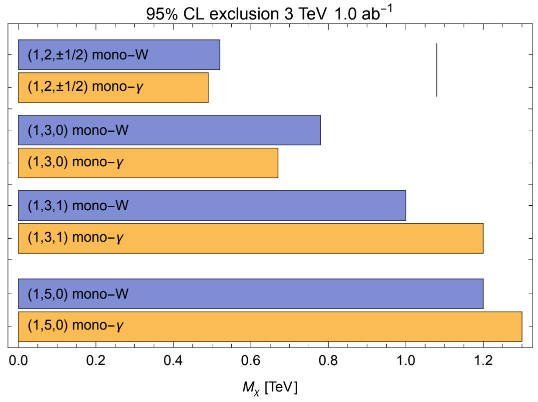
..and soft-track analysis

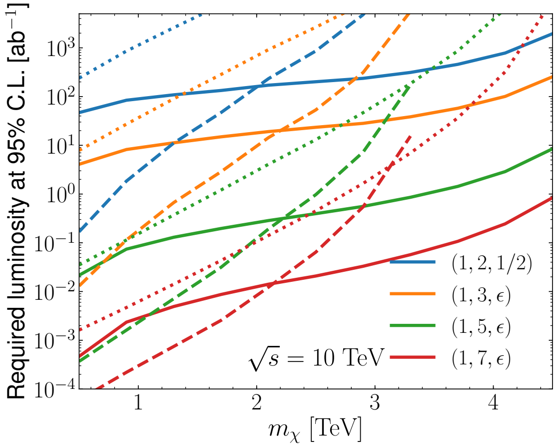


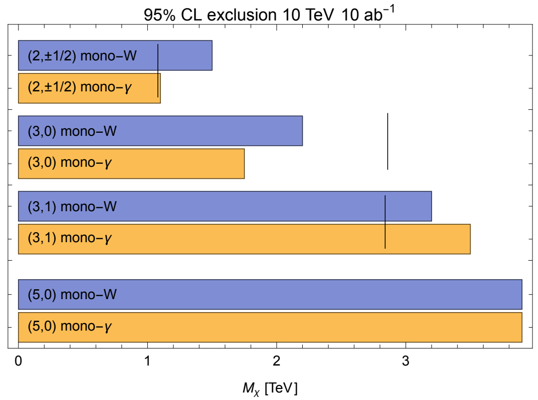
Muon Collider – mediators

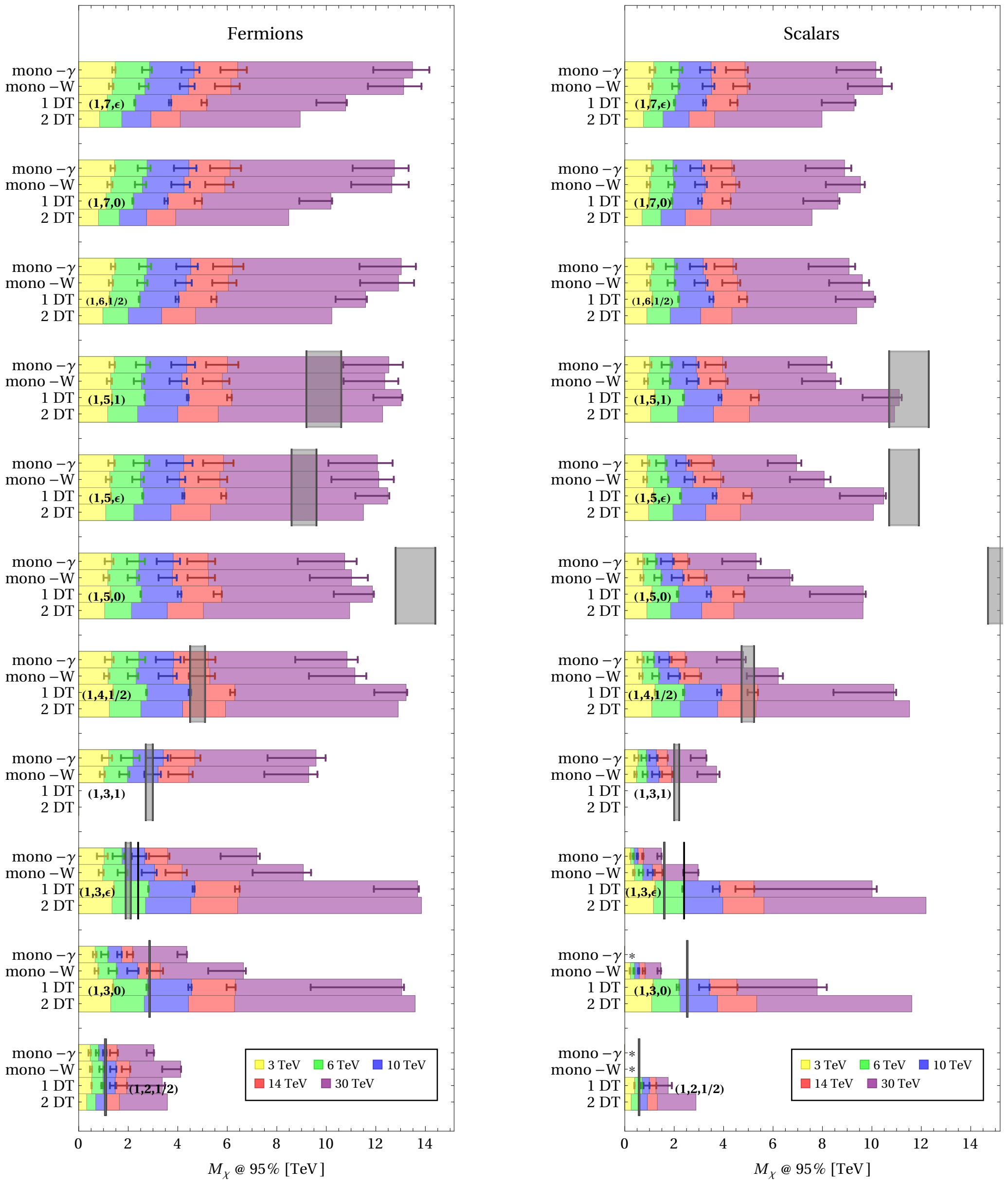
- From: https://arxiv.org/pdf/2303.08533







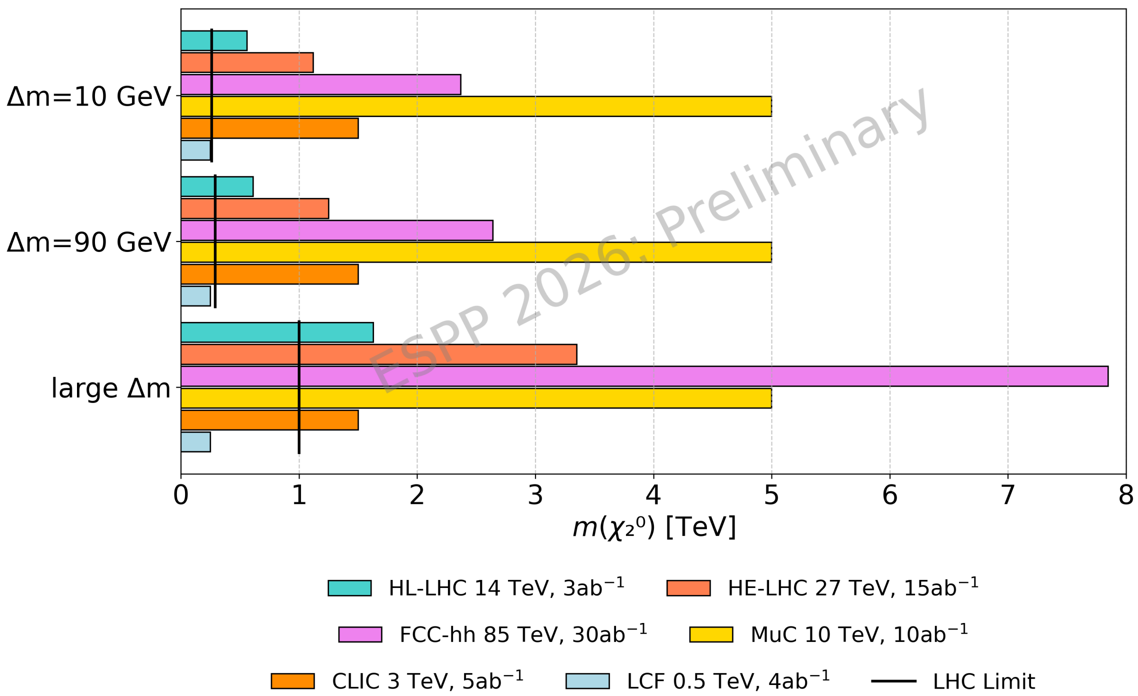




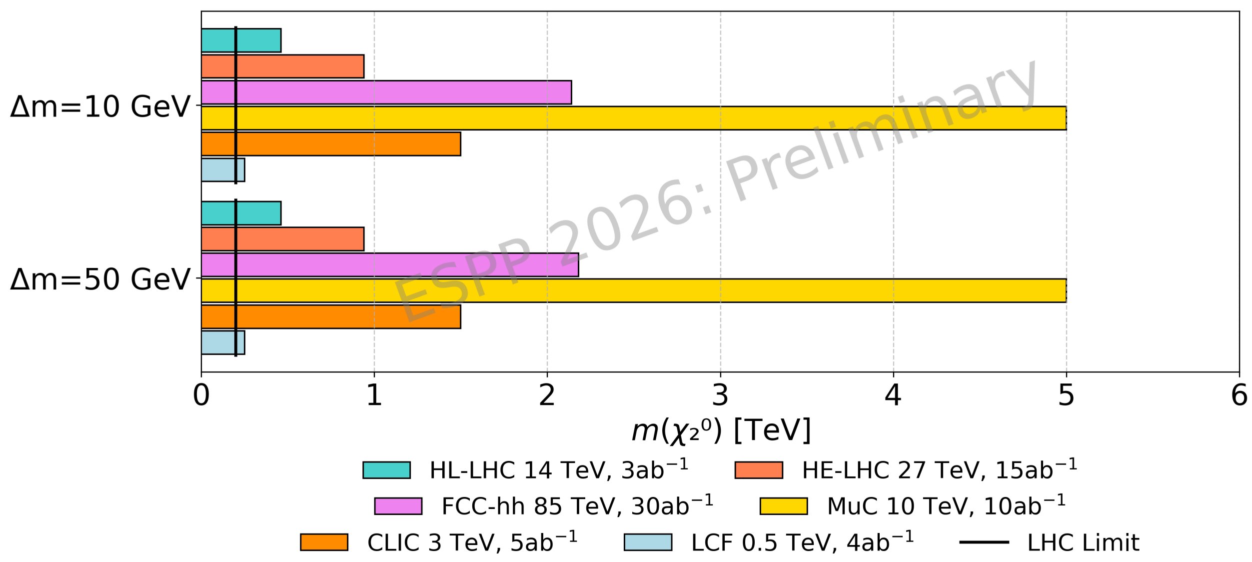
SUSY higgsino and wino-like scenarios

- DM part of a Dirac fermion doublet (Higgsino) or of a Majorana fermion triplet (Wino)
- In SUSY, these are the superpartners of the SM Higgs/gauge bosons
  - Lightest neutralino is the dark matter candidate
  - Depending on the mass hierarchy of the triplet (assuming chargino = next-to-lightest neutralino), sensitivity (and analysis techniques) differ:

Wino-bino scenarios

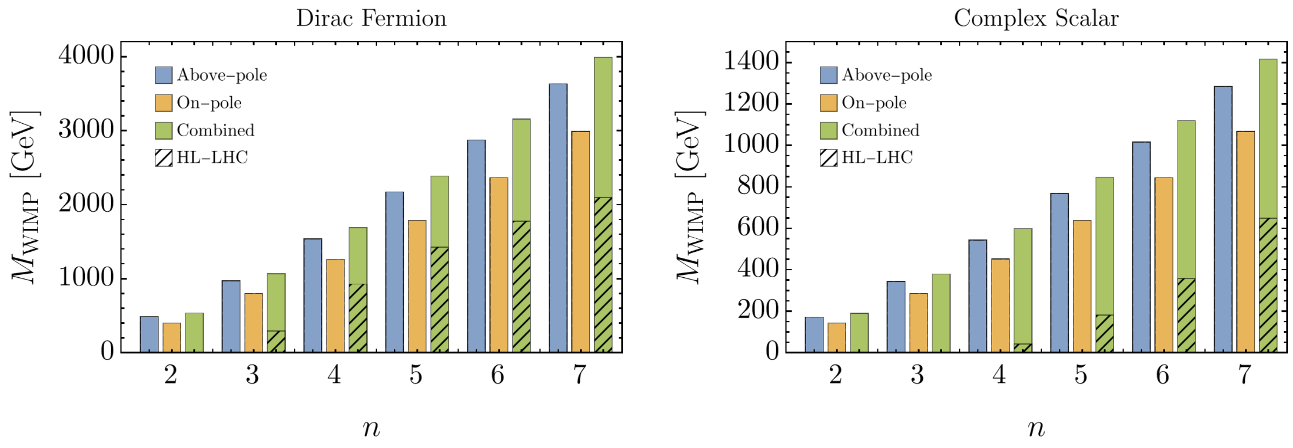


Higgsino scenarios



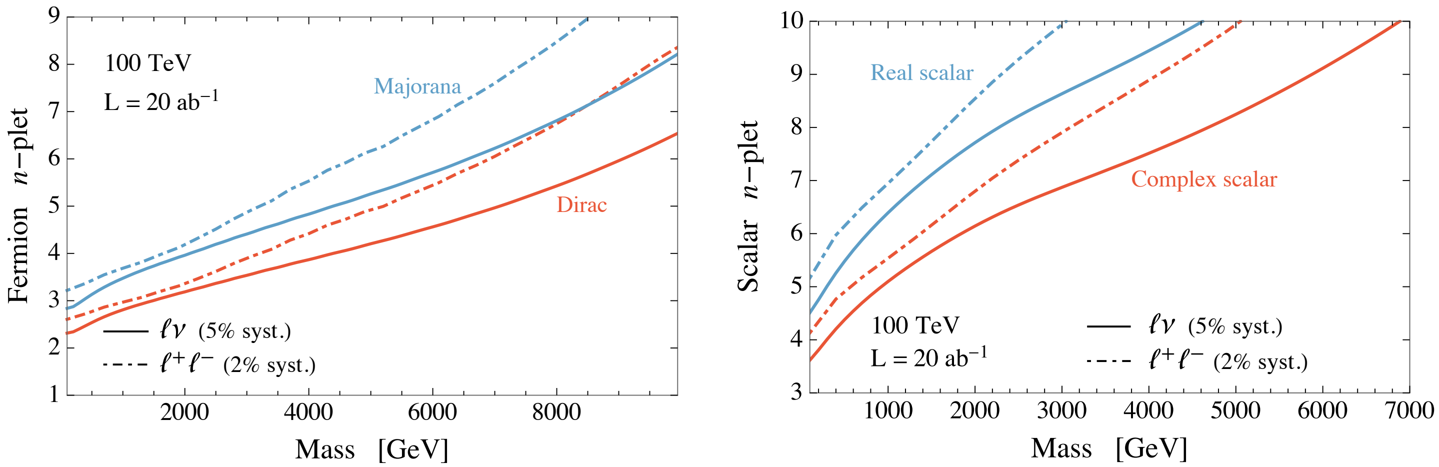
More on WIMPs sensitivity

- Sensitivity from indirect probes at e+e- and hh colliders → 1-loop, energy-enhanced corrections to EW gauge boson propagators (W, Y parameters) – from #229 : Prospects in BSM physics at FCC



FCC-ee sensitivity to W, Y at the 10^{-5} level (from precision EW measurements at the Z pole and from e+e− → f̄f processes)

Sensitivity to TeV-scale WIMPs



Even better **FCC-hh** sensitivity to W, Y through DY high-energy studies

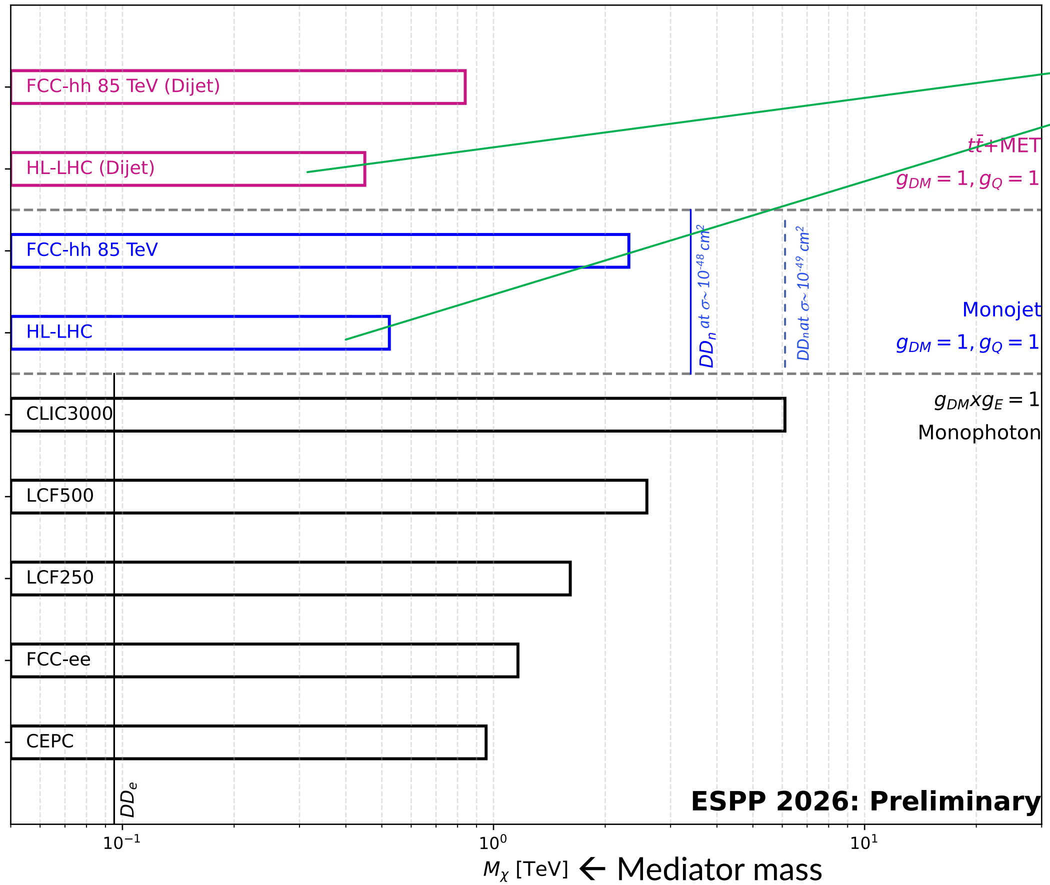
WIMP mass can be probed!

Simplified models: scalar mediators – BSM (2)

- Assumption → Light dark matter (m_{DM} = 1 GeV)

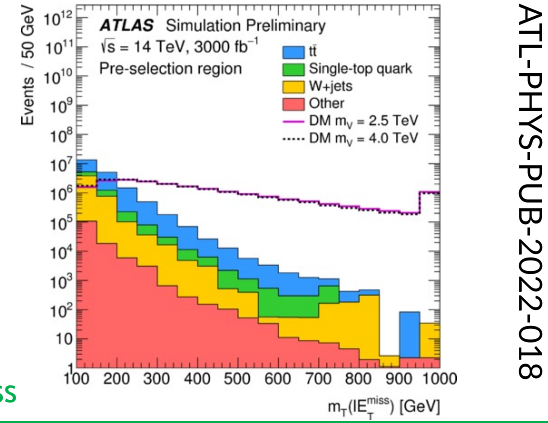
$g_{DM} = 1, g_{SM,f} = 1$

Scalar Simplified Models – 2σ Sensitivity Reach



DD $_{n,e}$: max reach for XLZD 1000, OSCURA (nucleon, e respectively)

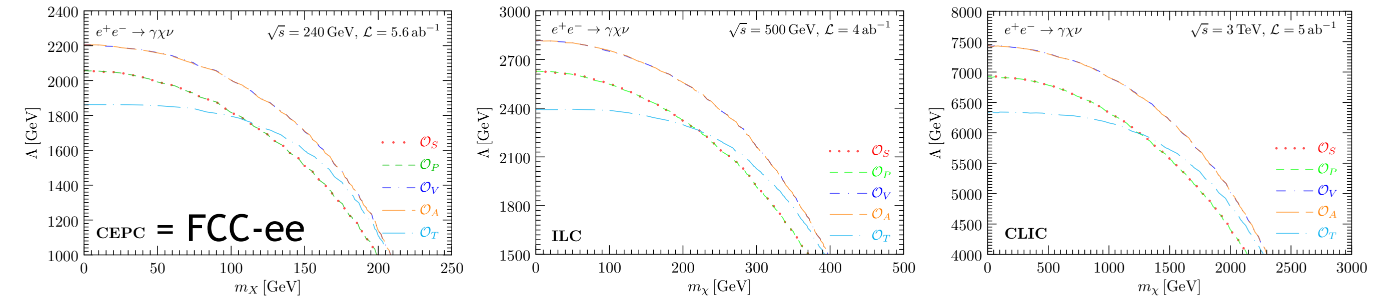
No new updates, but signatures like mono-top (new) can also add to sensitivity



Update for Snowmass

FCC-hh rescaled for **85 TeV** [for 100 TeV see FCChh prospects]

Updates from https://arxiv.org/pdf/2306.00657



Muon Collider not (yet)in this plot: mono-γ/W reach in back-up

Higgs portal models: interplays with DD

- Translated Higgs to invisible BR into DM-nucleon constraints
  - Nuclear form factor $f_N = 0.326$

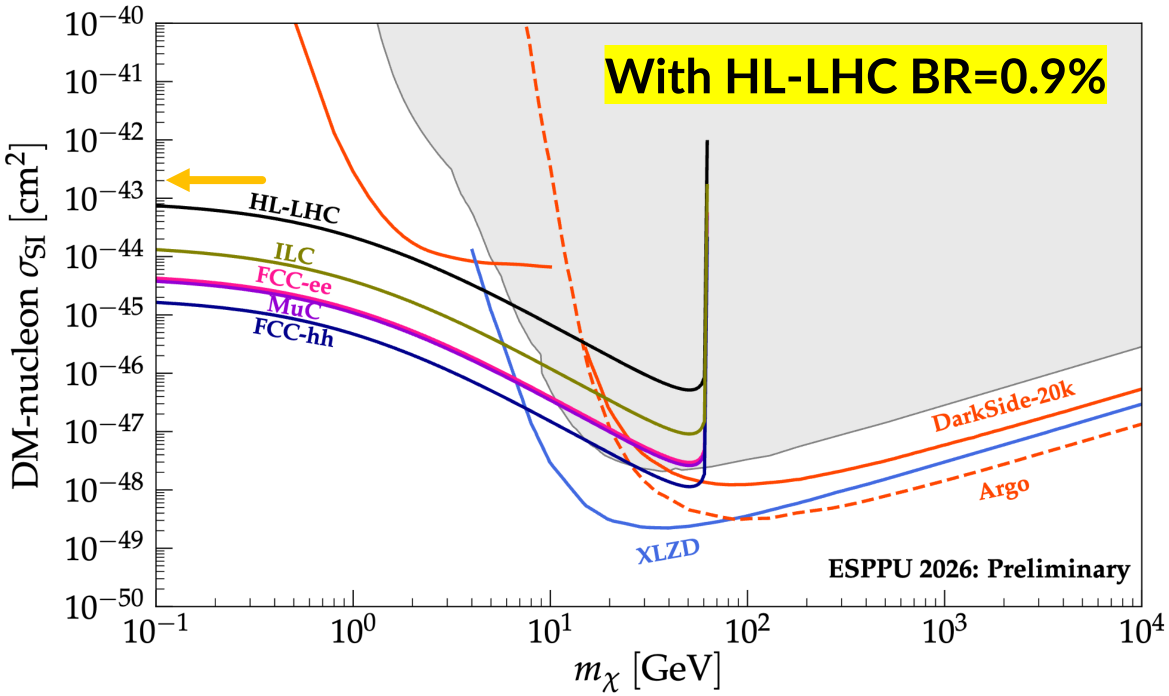
$$\sigma_{\chi N} = \Gamma_{\text{inv}} \frac{8 m_N^4 f_N^2}{v^2 \beta m_h^3 (m_\chi + m_N)^2} g_\chi \left(\frac{m_h}{m_\chi} \right), \qquad (15)$$

arXiv:1708.02245

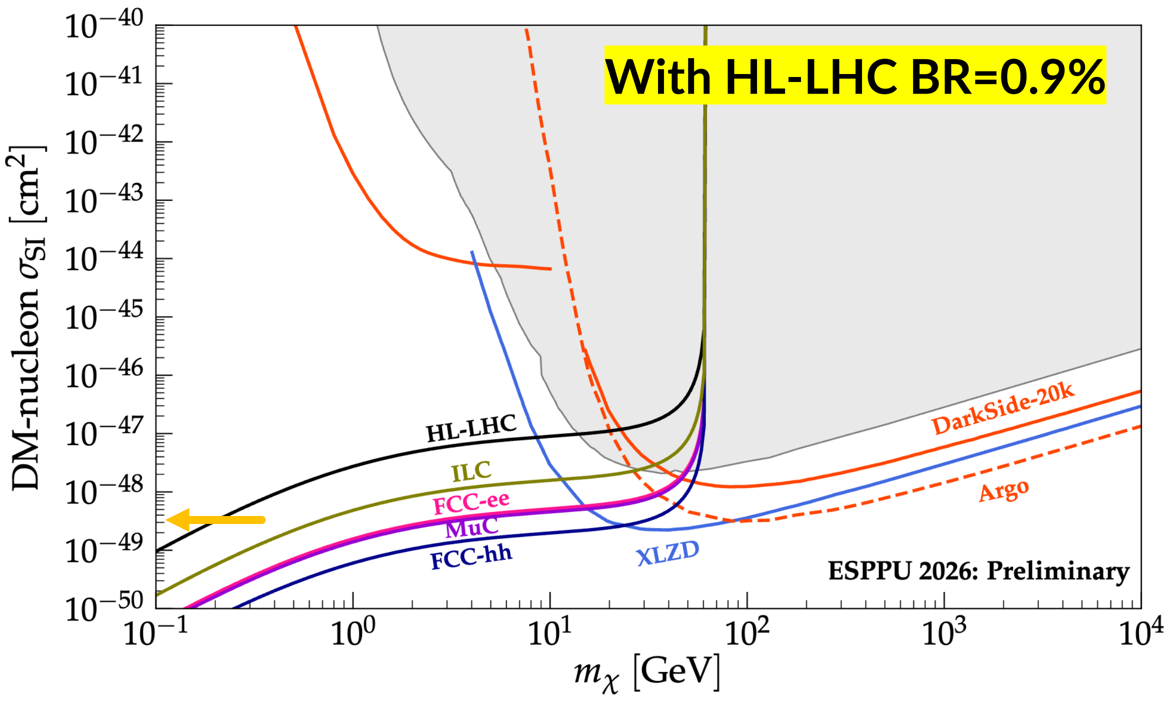
where $g_S(x) = 1$,

$$g_f(x) = 2/(x^2 - 4), \ \beta = \sqrt{1 - 4m_\chi^2/m_h^2}, \ v = 246\,\text{GeV}$$

Higgs Portal - Scalar DM

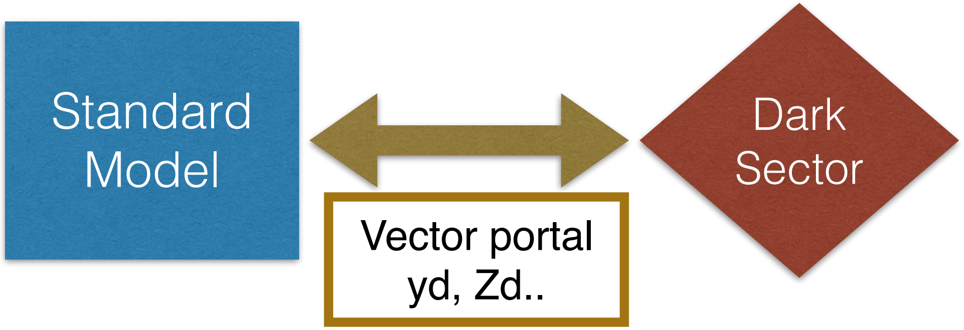


Higgs Portal - Majorana DM



DM in hidden sector: Long-Lived particles

- Dark sector **weakly coupled** with ordinary matter → can search for DM "sister" particles
  - e.g. dark photons, dark higgses, axions-like particles etc (DM candidate might be heavy, or decoupled)



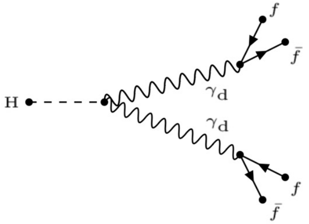
Several mechanisms theorized to define SM-DS couplings

"Minimal" models

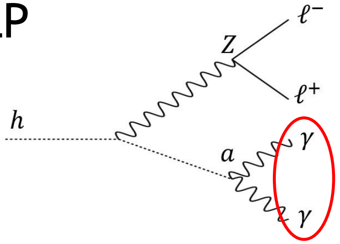
Portal	Coupling
Vector (Dark Vector, A_μ)	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Fermion (Sterile Neutrino, N)	$y_N LHN$

"Non-Minimal" models - e.g. DS coupled through the higgs

γ_D (Dark photon)

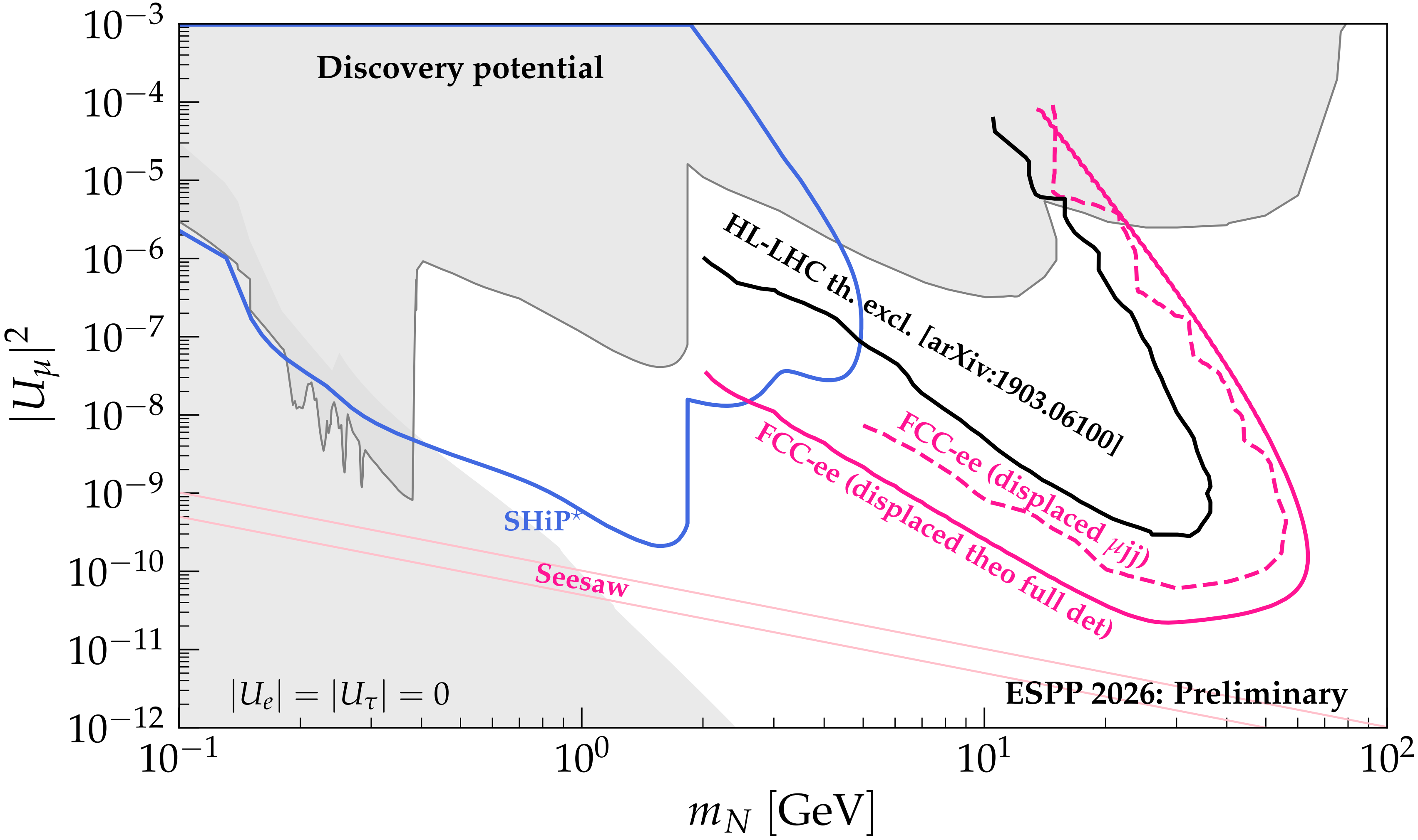


ALP



[several searches discussed in many publications]

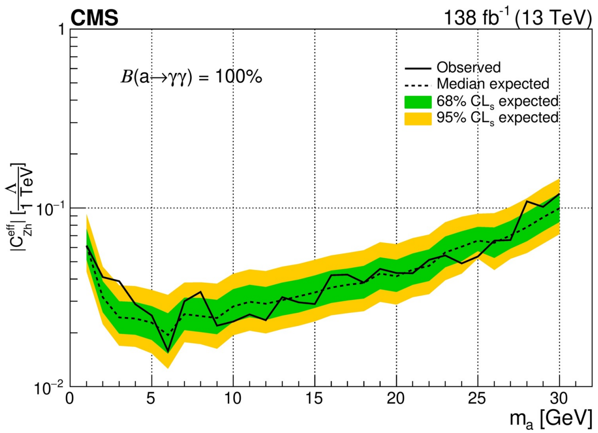
HNL: discovery potential

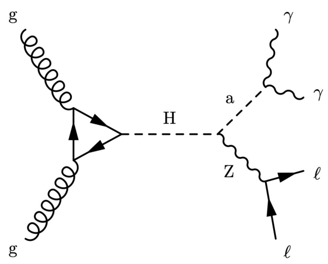


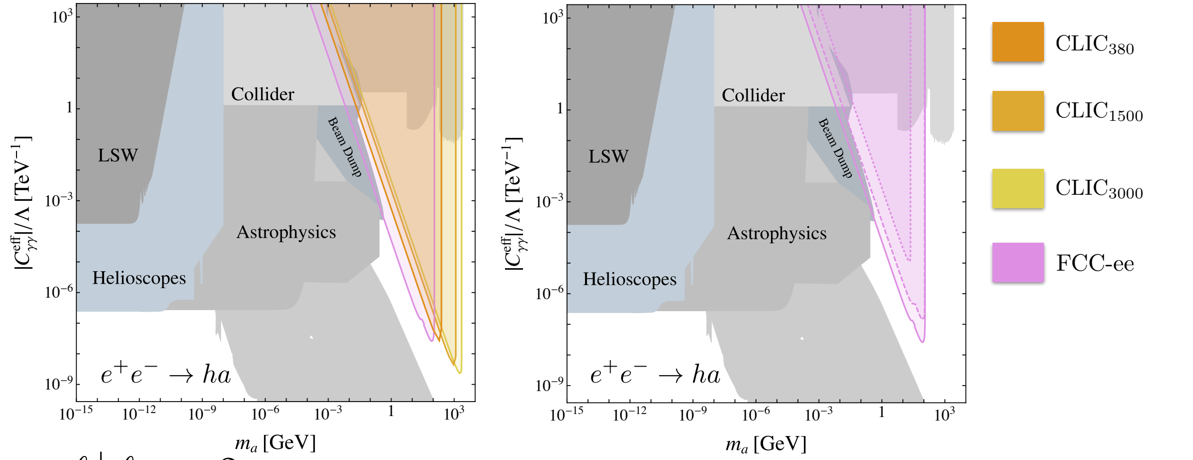
A word on non-minimal models: example

- Non-minimal portal models – ALPs might result from Z or Higgs bosons decays

$e^+e^- \to ha \to b\bar{b}\gamma\gamma$ https://arxiv.org/abs/1808.10323

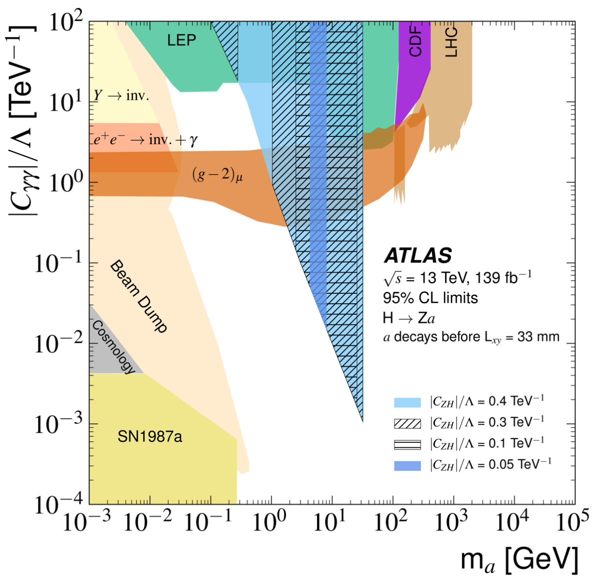


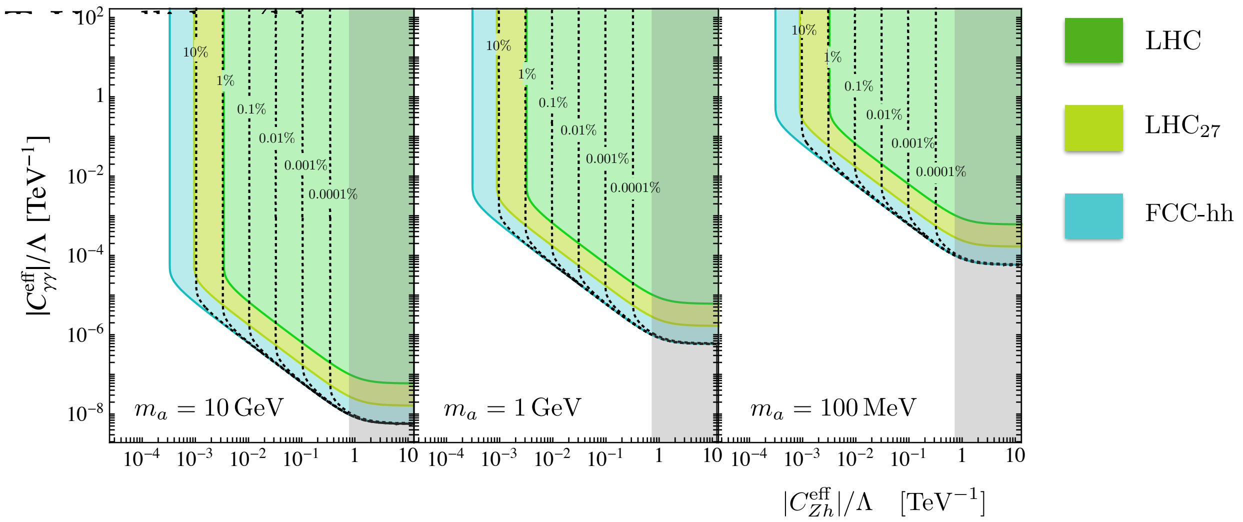




$h \to Za \to \ell^+\ell^- + 2\gamma$

Recent ATLAS and CMS results





WIMPs details: Wino and Higgsino

- Inputs almost unchanged from the briefing book 2019 (Fig 8.14 and 8.15 in https://arxiv.org/abs/1910.11775v2), or Snowmass 2021, except for:
- **Higgsino - Wino:**
  - Higgsino: Indirect det. **270 GeV** at 95% CL for NFW - Reference is https://arxiv.org/pdf/2207.10090
    - Credit: Joshua W. Foster, Yujin Park, Benjamin R. Safdi, Yotam Soreq, Weishuang Linda Xu, Nick Rodd, Christopher Dessert
  - Wino: Indirect det. 3.65 TeV at 95% CL for NFW profile from Fig 20 and 22 from https://arxiv.org/pdf/2405.13104.Cored Profile (Core): 3.1 TeV - Private communication
  - Muon Collider have been updated based on inputs from Federico Meloni based on Fig. 20.0.1 in https://arxiv.org/abs/2504.21417. A more sophisticated analysis based on soft tracks allows for a more stringent limit, and is overlayed to the 1DT result. (Note that the soft tracks limit only dominates for Higgsinos, so it is not included in the wino plot.)
  - FCC-hh from Fig 5 in https://www.arxiv.org/pdf/1901.02987, rescaled to 80 TeV by the authors. Scenario considered: Alternative Layout, optimistic pileup = 200 with time information (which assumes background reduction rate to be the same for optimistic and pessimistic pileup scenarios).
- **Relic abundance lines:**
  - Wino relic density with NLO Sommerfeld https://arxiv.org/pdf/2009.00640
    - This paper derives the thermal line at **2.842 TeV**. It also provides an LO value that 2.886 TeV.
  - Higgsino relic density: https://arxiv.org/pdf/2205.04486
    - The relevant value is the 2_{1/2} entry in Table 1: **1.08 +/- 0.02 TeV**
- **(more on) Indirect detection:**
  - One source of wino limits is from this work: https://arxiv.org/pdf/2405.13104. However, this requires reconstructing HESS efficiencies, which come with uncertainties. Note that this corrects an issue with the HESS analysis, which is a factor of 8 too strong. Wino is done in Fig 20 and 22. Instead, we quote numbers from a study done looking for wino annihilation in the Fermi data. The paper will come out in a few weeks, so for now this is coming from private communication.

WIMPs details: Axial Vector/Scalar

- Inputs almost unchanged from the brifing book 2019 (fig 8.14 and 8.15 in https://arxiv.org/abs/1910.11775v2), or Snowmass 2021, except for:
- **Axial Vector/ Scalar:**
  - FCC-hh scaled to 84 TeV
  - ILC updates results provided via private communication with Jenny List. Mass scale limits come from mono-photon analysis and are based on Eur.Phys.J.C 81 (2021) 10, 955 (arXiv:2107.11194) including systematic uncertainties.
- **For Higgs portals:**
  - Higgs to inv BRs from direct searches:
    - HL-LHC: 2.5% as taken from https://e-publishing.cern.ch/index.php/CYRM/article/view/952/769 N.B: There is an additional study (Phil Harris) that indicates 0.9% at 6 ab^{-1}. To be confirmed.
    - FCC-hh: 2 x 10^{-4} numbers from Phil Harris at sqrt(s) = 100 TeV
    - ILC: 0.16% combining 900 fb-1 per each polarisation at sqrt(s) = 250 GeV. Number from Table 8 in https://arxiv.org/pdf/2203.08330. NB: not blessed yet by the collaboration.
    - FCC-ee: 0.052% from https://repository.cern/records/9b128-qqc43
    - Muon Collider: 4.6 x 10 e-4 with 1% relative uncertainty on resolution from https://arxiv.org/pdf/2411.00096, which is referenced in the Muon Collider Input ID 207

Heavy DM indirect limits: details

- **Heavy_DM_ID_limits**
  - Current limits:
    - Fig.1 left in https://arxiv.org/pdf/2108.13646; annihilation into 100% bb; combined limits of LAT and IACTs observations of dwarf galaxies
    - Upper and lower limits of band in Fig. 4 left bb annihilation of 2202.03076; limits from radio image of the LMC with ASKAP
    - Fig. 8 top left bb, Einasto annihilation of 2207.10471; HESS analysis of 546h observations of the Galactic center
  - Future projections:
    - Fig.14 left bb of https://arxiv.org/pdf/2007.16129; CTAO sensitivity for GC observations
    - Fig. 19 of 1802.01055 bb; Projected sensitivity to dark matter annihilation combining LSST discoveries of new Milky Way satellites, improved spectroscopy of these galaxies, and continued FermiLAT observations

Inelastic DM: details - colliders

The model

This is the model of dark photons A coupled to a dark matter candidate χ and a heavier state χ'. The interaction Lagrangian of the model is (see, e.g., https://arxiv.org/pdf/1908.07525)

$$L = -\frac{\epsilon}{2\cos(\theta_W)} V_{\mu\nu} B^{\mu\nu} + g_D V^{\mu} \bar{\chi}' \gamma_{\mu} \chi + \text{h.c.},$$

where $V_{\mu\nu}$ is the dark photon field strength, and $B^{\mu\nu}$ is the $U(1)_Y$ field strength.

The non-zero mass splitting between χ, χ' allows to escape the direct detection constraints. The main signatures are "invisible" events like $e^+e^- \to \gamma + \text{inv}$ at Belle II and displaced decays $\chi' \to \chi + \text{SM}$ at beam dump and collider-based experiments.

The model's parameters are $m_V, m_\chi, \alpha_D, \epsilon, \Delta$, where $\alpha_D = g_D^2 / 4\pi$ and $\Delta \equiv (m_{\chi'} - m_\chi) / m_\chi$. To show 2D plots with parameter space, α_D, m_χ / m_V, and Δ are fixed; their values are chosen in a way such that dark photon predominantly decays into a $\chi\chi'$ pair. The commonly considered choice is $\alpha_D = 0.1$ (subject to a simple rescale) and $m_\chi = m_A / 3$. For Δ, the collected curves assume $\Delta = 0.1$.

For the beam-dump and collider-based experiments, results may significantly vary depending on Δ (as the decay width of χ' scales with Δ^5).

The sensitivity is given in terms of m_χ in GeV and ϵ^2.

- LHC sensitivities: estimate taken from https://arxiv.org/pdf/1810.01879.

Dark photons: details

- **Model description**
  - Dark photons A′ are massive vector particles with the Lagrangian

$$L = -\frac{\epsilon}{2\cos(\theta_W)} F_{\mu\nu} B^{\mu\nu}$$

, where $B_{\mu\nu}$ is the SM $U(1)_Y$ field, and $\epsilon \ll 1$ is the coupling.

  - For the masses mA′≪mZ, A′ interacts as a massive photon, with the coupling suppressed by ϵ.
    - **Issue** - theoretical uncertainties in the production of dark photons with mass O(1) GeV.
- **Available sensitivities**
  - Belle II: (the curve "VisibleDarkPhoton_50invab.txt")
  - SHiP: sensitivity in the plane mA′ [GeV]−ϵ2 (taken from the SHiP ESPP submission).
  - NA62: Production mode: Bremsstrahlung + meson mixing + light meson decays (without time-like form factor)
    - Projections based on Fig. 7 in arXiv:2502.04241, updated to 10^{18} PoT
  - NA64: Fig. 3 top right of the NA64 input to ESPP (e−Z→e−ZA′→e+e-), Bremsstrahlung production + visible decay, taken from https://arxiv.org/abs/2305.01715
  - Faser 2: Fig.4.4 in arxiv:2203.05090
  - LHCb: Run 3 and Run 4 projections for inclusive A′→e+e- from Fig.1 in LHCb Snowmass projection
  - Belle II: Fig.11 in arxiv:2207.06307
  - Muon Collider: Fig. 6 in arxiv:2412.09681 (gZ>>gD) Muon Collider production modes: associated production + Brem.

Dark photons: details

- **Available constraints – colliders**
  - FCCee - Private Communication. Available also data from Fig. 6 in arxiv:2412.09681 - FCC-ee: associated production + Z decays to Z' at the Z pole (ZH should be rescaled to 10 ab^{-1})
  - CEPC: Fig 8 in arxiv.org:1503.07209. Resonant production with ISR (radiative return)
  - HL-LHC is rescaled from CMS dark photon results (scouting plus offline trigger strategies, JHEP 12 (2023) 070 and PRL 124 (2020) 131802)
  - FCC-hh is rescaled from CMS dark photon results (scouting plus offline trigger strategies, JHEP 12 (2023) 070 and PRL 124 (2020) 131802). Cross section ratio are averaged over the mass interval and have been computed by Tim Cohen.
  - ILC 250 GeV 3ab^{-1}: The plot is an update from Figure 123 in the ECFA report: https://indico.cern.ch/event/1439855/contributions/6461549/attachments/3045922/5381868/ECFA_HETFactories_Backup_FullReport_indicov1.pdf. It includes updated luminosity and doing a likelihood ratio weighting of the two polarisations.
  - LHeC: Fig. 5 top left (Pt(X)>5 GeV, N=10 expected dark photon decay. Zero background assumed.
- **Available constraints – accelerator-based**
  - NuCal, CHARM: computed using the approach of https://arxiv.org/abs/2409.11096 ($m_{A'}$ [GeV]−ϵ)
  - LHCb, NA48, Orsay, NA64 - taken from the FORESEE repository.
  - SN+cosmo: taken from 2502.01731 + to cite the future overview papers ("The Heavy Dark Photon Handbook: Cosmological and Astrophysical Bounds", A. Caputo, F. D'Eramo, Jaeyoung Park, Seokhoon Yun, "The Dark Photon: a 2025 Perspective", A. Caputo & R. Essig, Encyclopedia for Particle Physics 2025)
  - FASER: provided by Roshan Mammen and Felix Kling; basically, 27 fb^-1 + 57 fb^-1 curves from https://arxiv.org/pdf/2308.05587, https://arxiv.org/pdf/2410.10363
  - SHIFT: taken from https://arxiv.org/abs/2406.08557
  - DarkQuest: taken from https://arxiv.org/abs/2203.08322
  - FASER@HL-LHC: provided by Roshan Mammen and Felix Kling

ALPs: details

- **Model and conventions** $L = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$
  - We are using the Lagrangian:

  and plotting the coupling $g_{a\gamma\gamma}$ in units of GeV^{-1} against the mass m_a in units of GeV.
  - Things to be careful of/make clear:
    - Some regions assume the ALP is invisible (i.e. decays outside the detector or decays into unknown invisible particles), which may not be a good assumption for some mass/coupling ranges
  - The FCC-ee Z pole regions assume that $C_{WW}=0$
- **FCC sensitivities**
  - **Z pole ($e^+e^- \to Z \to \gamma a$)**
    - note that these regions are always under the assumption that $C_{WW}=0$ (see p3 of https://arxiv.org/pdf/2502.08411). Darker yellow region labelled "FCCee Z-pole" from the FCC feasibility study fig 30 (p43) https://arxiv.org/pdf/2505.00272. Original ref https://arxiv.org/pdf/2502.08411.
    - FCC-ee mono-photon is the lighter yellow region labelled "FCCee Z-pole" from the FCC feasibility study fig 30 (p43) https://arxiv.org/pdf/2505.00272. Original ref https://arxiv.org/pdf/2502.08411.
    - Both original datafiles are using a different Lagrangian

    than our convention above, as given in https://arxiv.org/pdf/2502.08411 Equation (2.1): $L = \frac{e^2}{\Lambda} C_{\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$
    - They present the limits on $C_{\gamma\gamma}\Lambda[TeV^{-1}]$. So the conversion to our conventions is: $g_{a\gamma\gamma}[GeV^{-1}]=10^{-3}\times 4e^2 C_{\gamma\gamma}\Lambda[TeV^{-1}]$.
  - **$\gamma\gamma \to a \to \gamma\gamma$**
    - FCC-ee and FCC-Pb: all these regions (i.e. all not labelled Z pole) are from the FCC feasibility study fig 30 (p43). The FCC-ee constraints here come from the original ref 2310.17270, while the FCC-hh and heavy ion constraints refer to a paper "in preparation". File received from Patricia Rebello Teles (patricia.rebello.teles@cern.ch). The definition of the coupling is as in https://superchic.hepforge.org/superchic4.2.pdf process (68) page 19 (i.e same as our conventions).

ALPs: details (2)

- **Muon collider**
  - *the bound is simply a straight line, bounds given here*: Figure 20.3.2 of https://arxiv.org/abs/2504.21417, which originally comes from https://arxiv.org/pdf/2111.13220 Digitising these: gaγγ<1.06×10^{-2}TeV^{-1} (95%CL, 10TeV muon collider), and gaγγ<3.60×10−2TeV−1 (95%CL, 3TeV muon collider), for the mass range 2.5MeV<ma<100GeV.
  - **NB this assumes an invisible ALP
- **ALICE**
  - From Figure 76 (p126) of https://arxiv.org/pdf/2211.02491, which cites https://arxiv.org/pdf/1607.06083 for the procedure. Received from Andrea Dainese (andrea.dainese@pd.infn.it). In the file names, "ideal" is the case with calorimeter and "eff" is the case with 5% photon efficiency without calorimeter (conversion reconstruction in the tracker).
- **Belle II**
  - This is the projection region from Fig 10 (p34) of https://arxiv.org/pdf/2207.06307, originally taken from https://arxiv.org/abs/1709.00009.
- **ILC and CLIC**
  - Many of these same as in previous briefing book, which had regions for ILC-500, CLIC-380, CLIC-1500 and CLIC-300
  - New in this year's update is a projection for an ILC-250 beam dump mode - this is in Figure 44 of the Linear Collider Vision input, and comes from Fig 2 of https://arxiv.org/pdf/2009.13790.
- **Beam dump and collider-based sensitivities**
  - Definition of the ALP coupling gaγγ adopted for the sensitivities: $L = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$
  - The sensitivities below are in the plane ma in GeV - gaγγ in GeV−1.
  - NA62-dump, NA64, LUXE-Nprod, FPF, DarkQuest - taken from 2310.17726, Fig. 27 (Belle II, FPF - already confirmed that the sensitivities are up-to-date).
  - SHiP - taken from the Collaboration.

HNL: Details

- Simplified benchmark model: HNLs N with the mixing solely to the muon neutrinos. The mixing is given by the mixing angle U_μ (BC7).
- For the realistic models with non-trivial coupling pattern, the probes of most of the experiments would look very similar to the benchmark one.
- **Available sensitivities**
  - MATHUSLA40, ANUBIS, FASER2, SHiP: taken from https://arxiv.org/abs/2505.00947
  - Downstream@LHCb: taken from https://arxiv.org/abs/2312.14016
  - FCC-ee: provided by Giacomo Polesello, based on https://arxiv.org/pdf/2505.00272. There are three curves. The meaningful choice is "optimistic" (corresponding to the dashed green line of Fig. 29), as the setup and technologices (and hence efficiencies, etc.) are not yet completely fixed.
  - ILC: provided by Filip Zarnecki, based on https://arxiv.org/abs/2312.05223, and reevaluated in the single flavor dominance. The results are obtained for the ILC (in Japan) running scenarios assuming total of 2 ab^-1 at 250 GeV, 4 ab^-1 at 500 GeV and 8ab^-1 at 1TeV. Input exists also for the electron coupling (BC6).
  - ILC beam dump mode: provided by Yasuhito Sakaki, based on https://arxiv.org/abs/2206.13523, beam energy: 125, 500 GeV, (also Giga-Z option); number of electrons on target: 4×10^{22}. Input exists also for electron (BC6) and tau (BC8) couplings.
  - DUNE, HL-HLC and FCC-hh are taken from https://www.hep.ucl.ac.uk/~pbolton/plots.html#id151
  - FCC-hh-based experiments: Mid-eta setup from https://arxiv.org/pdf/2204.01622, computed for the muon mixing and s=84 TeV.
  - FCC-eh and LHeC limits not included as targeting a different BC scenarios – to be added
  - PREFACE: taken from https://arxiv.org/abs/2502.14598

Dark scalar: details

- Higgs-like scalar S with the mixing hS and tri-linear hSS interactions with the Higgs boson:

$$L = H^{\dagger}H(c_1S^2 + c_2S) \Rightarrow L_{\text{eff}} = \theta m_h^2 hS + \frac{\alpha}{2}hSS$$

  - The tri-linear coupling α is fixed by setting Br(h→SS). Widely adopted choices (https://arxiv.org/abs/1901.09966):
  - **BC4 model**: Br(h→SS)=0; **BC5 model**: Br(h→SS)=0.01

- ## Available sensitivities
  - SHiP: taken from https://arxiv.org/abs/2504.06692v1
  - MATHUSLA40, ANUBIS, FASER2, MAPP, MAPP2, CODEX-b: taken from https://arxiv.org/abs/2505.00947
  - Downstream@LHCb: taken from https://arxiv.org/abs/2503.23087, https://arxiv.org/abs/2505.00947
  - FOREHUNT@FCC-hh: taken from https://arxiv.org/abs/2306.11803
  - FPF@FCC-hh: taken from https://arxiv.org/abs/2409.02163
  - DarkQuest: taken from https://arxiv.org/abs/2203.08322
  - PREFACE: taken from https://arxiv.org/abs/2502.14598

- ## Higgs -> LLP
  - Simplified model based on the Higgs-like scalar S in which S is a long-lived particle produced in Higgs decays. Sensitivities of various collider experiments are shown in the plane of cτ and BR(h→ϕϕ), where ϕ is the light scalar mass eigenstate.
  - Limit curves for ANUBIS, CODEX-b, MATHUSLA, HL-LHC (ATLAS), and the current LHC exclusion are taken from the PBC submission (2505.00947). The limit for FCC-ee is obtained by rescaling the 20 GeV benchmarks from 2412.10141 to obtain a limit as function of branching ratio.