Summary of discussions about collider sensitivity comparisons

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summarizing discussions with:

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Goals

Prepare **comparisons (i.e. dark matter summary plots)** of projected results from searches for WIMPs at future collider experiments

- Start from work done for European strategy for HL-LHC and other future colliders
- Potentially improve upon the (simplified/simple) models used there
- Depict coupling dependence

Connect these plots to other DM searches and Frontiers

- Rare/precision Frontier (RF): accelerator-based / fixed target experiments
- Cosmic Frontier (CF): direct detection and indirect detection
- Make comparisons between collider projections and searches at other frontiers

Will need to agree on benchmarks models and presentation of results with the other frontiers

Note also work ongoing in LHC Dark Matter WG to connect to Physics Beyond Colliders [Talk by P. Harris]

Make code publicly available and usable by others

Models, and what to do with them

Vector-mediated simplified model (LHC DM WG, arXiv:1507.00966)

- ff → mediator → ff (SM or DM)
- Extend to lower coupling values than considered by LHC
- Rescale to dark photon model (simple, for vector model with added photon couplings)

Scalar– and pseudo-scalar–mediated simplified models (LHC DM WG, arXiv:1507.00966)

- Use results from 2020 European Strategy, but keep in mind also other constraints from accelerator experiments on both vector and scalar models

Extended scalar sectors

- Many possibilities here, e.g. 2HDM+a used by LHC DM WG
- Do we need a narrower scope? e.g. simple "scalar portal" that has also a connection with the Higgs
    - Higgs portal
        - We have results for this ready from the European Strategy
    - Scalar portal mixing with the Higgs
        - Scalar singlet with Higgs mixing (arXiv:1607.06680)
- *In both cases, use Higgs to invisible constraints from direct searches and couplings*
- Further discussion ongoing with EF1 & EF2 (dedicated meeting planned later in the year)

Plot 1—DM mass vs mediator mass with alternate choices of coupling values

Many variations possible; at minimum

Version 1: vector model, without lepton couplings

Version 2: vector model, with lepton couplings

Version 3: vector model, with dark photon coupling

Version 4: DM WG scalar model (easy to make assuming no off-shell sensitivity)

+ other scalar possibilities

Aim to improve on European Strategy with rescaling to different (lower) coupling values

What we need from other groups (see B. Gao and K. Pachal's talk for more details)

Collider projections for each search channel ,$\sqrt{s}$ (can't rescale), and incoming particles/ polarization

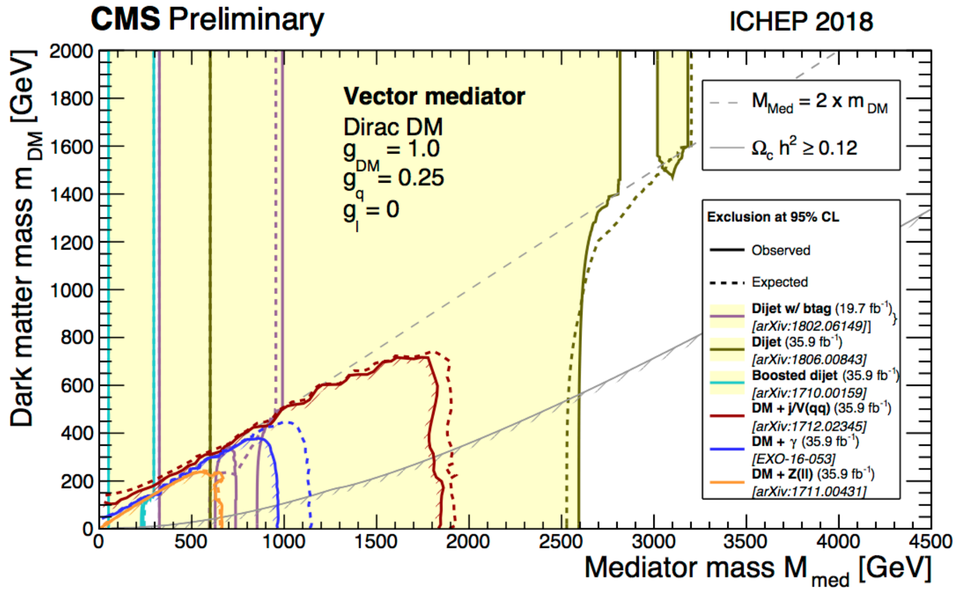
- Limits for different widths, where analysis is sensitive
- For "Mono-X" searches, care needed for grid of exclusion "depth" in the DM mass–mediator mass plane (in terms of exclusion of theory xsec, or mu) for a single coupling
- For dijet or dilepton searches, need limit vs coupling and mediator mass—can fix DM mass and rescale in interpretation

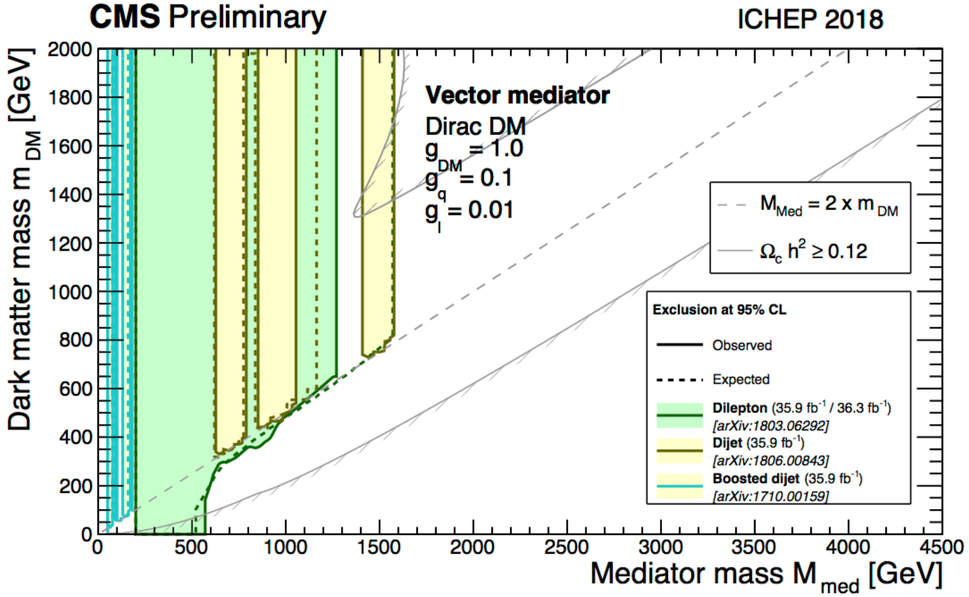
<u>Notes</u>

We don't know how to rescale searches for ttbar resonances

We'd need more help for the scalar treatment

For the dilepton searches, may be possible to find a parameterization that connects the coupling to the width—important to capture this dependence for dilepton search sensitivity





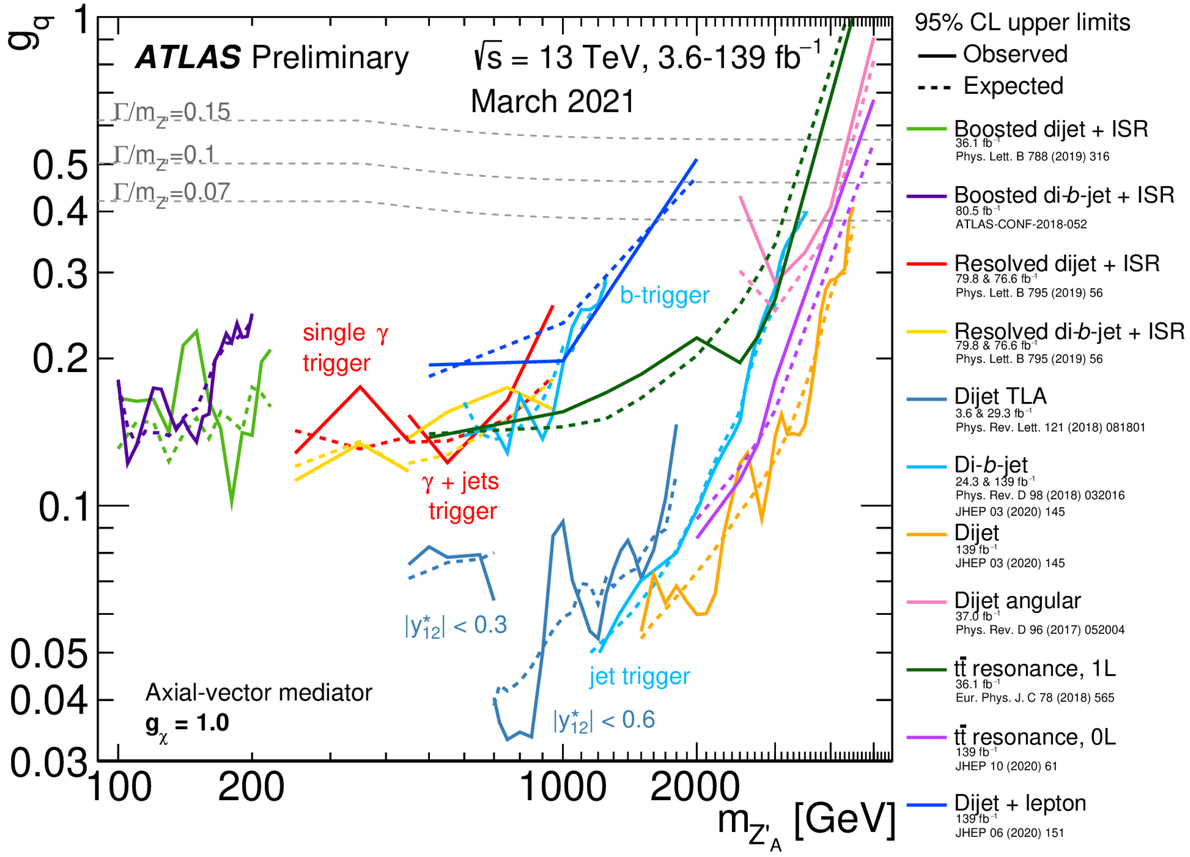
Plot 2—Vector mediator model, coupling vs mediator mass

From Plot #1 to plot #2 should be straightforward, except in the case of $t\bar{t}$ searches

Version 1: g_q vs mediator mass, with fixed DM mass and coupling to DM

Version 2: similar figure showing dependence on lepton coupling values

Version 3: dark photon coupling vs dark photon mass



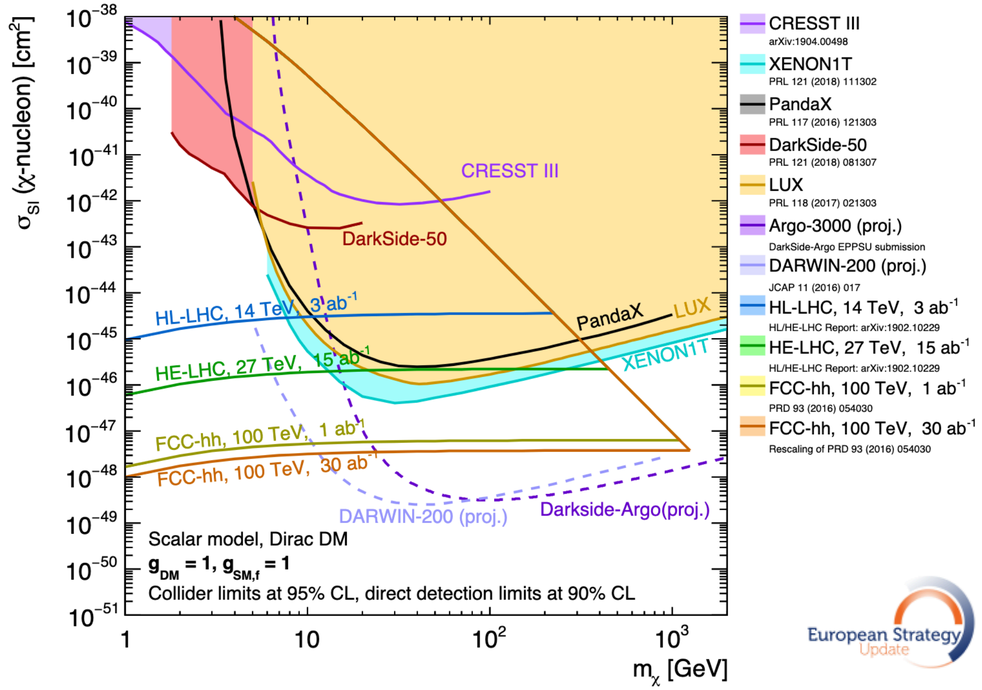
Plot 3– Collider and direct detection, with fixed coupling values

Version 1: scalar model

Version 2: vector model

These plots will need the following **caveats** in the captions:

- Intensity frontier experiments in RF06 can also play a role in constraining those models
- Collider plots do not assume the model reproduces the relic density

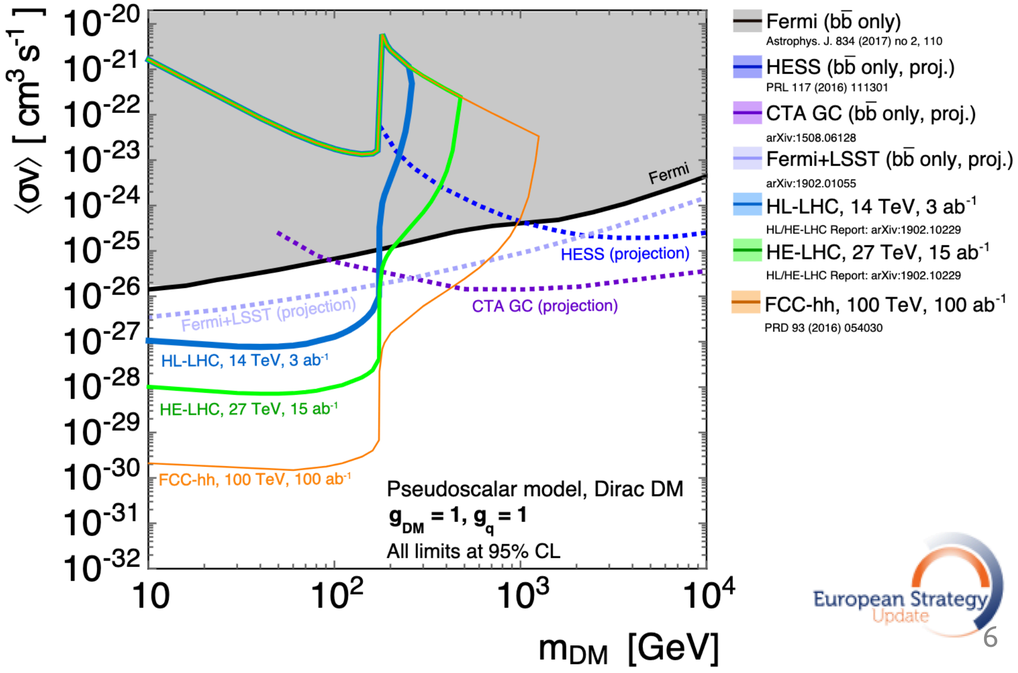


Plot 4–Collider and indirect detection, with fixed coupling values

Version 1: pseudo-scalar model

Version n: other scalar models?

Both following approaches described in arXiv:1603.04156 with code developed for European Strategy, but extend to show impact of varying couplings

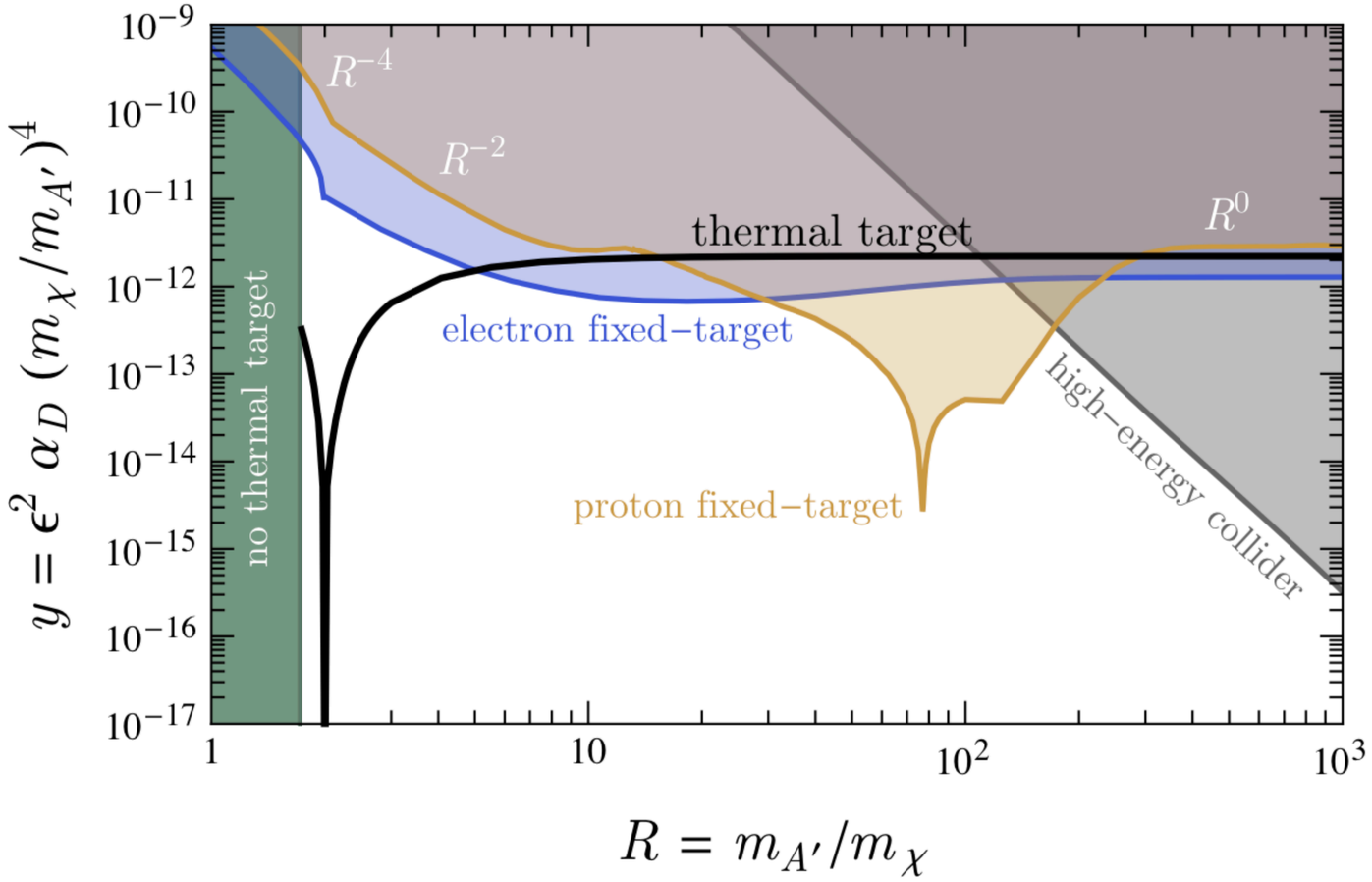


Plot 5—High energy colliders and low-mass experiments

Use the dark photon hypothesis, in collaboration with RF06 using DarkCast software.

Details to be discussed with RF06:

- what is already excluded in the high-energy region (> 10 GeV)?
- what is the role of the thermal target line?



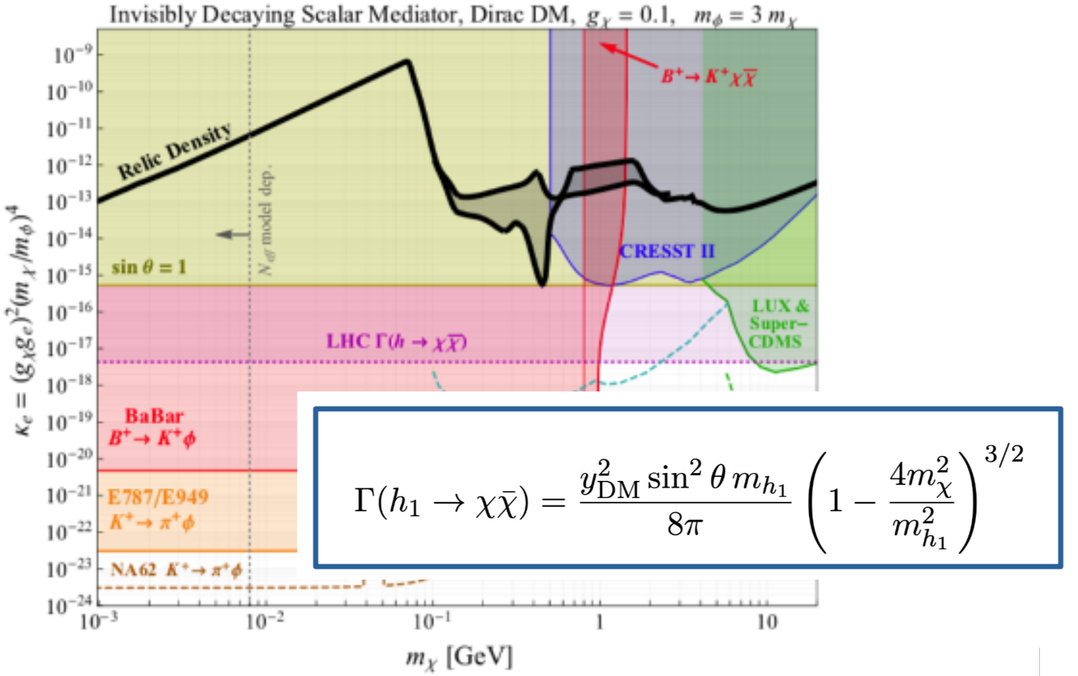
Plot 6&7— Scalar singlet with Higgs Mixing, Higgs Portal

Plot 6 **Higgs to invisible constraints for scalar portals with Higgs mixing**

- using "SMM" model (arXiv:1607.06680)
- Parameters: DM mass (x axis for plots), sinTheta (y axis for plots)
- Mass of the other scalar h_2 (can be fixed)

Discussion points

Start by preparing a plot that only uses Higgs to invisible direct searches, but need to understand the impact of Higgs coupling measurements on this model



$$\Gamma(h_1 \to \chi\bar{\chi}) = \frac{y_{\rm DM}^2 \sin^2\theta\, m_{h_1}}{8\pi}\left(1 - \frac{4m_\chi^2}{m_{h_1}^2}\right)^{3/2}$$

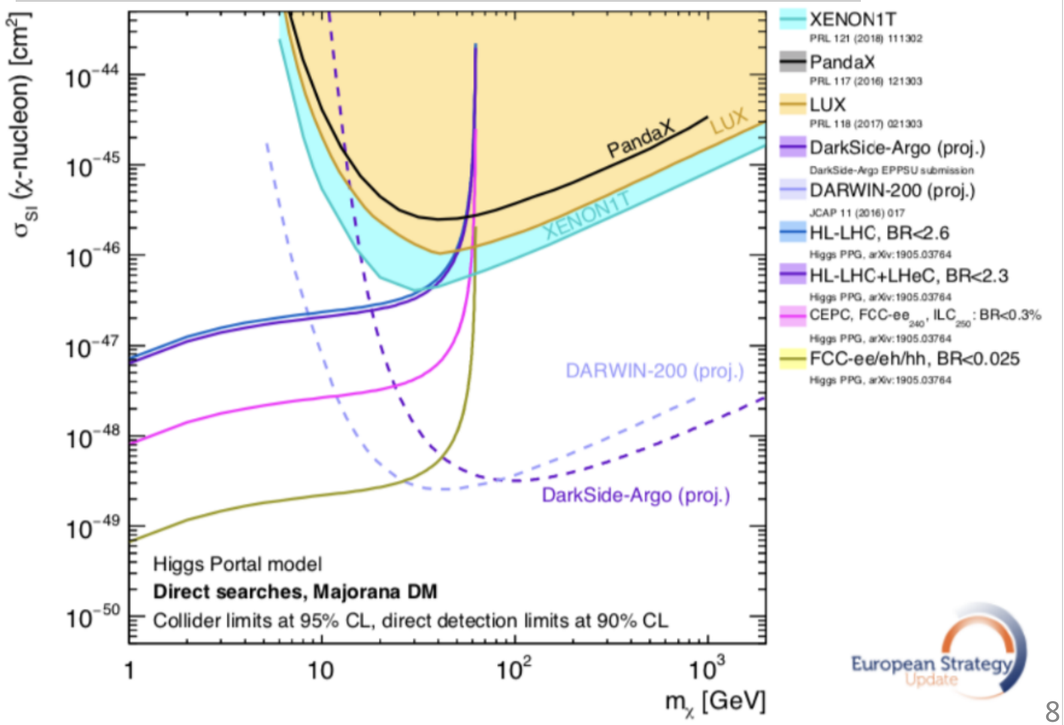
Plot 7 **Higgs portal (from Higgs to invisible and couplings)**

Discussion with Higgs Topical Groups

Most of the parameter space for this model is excluded if one assumes that the relic density is provided strictly by the model (but that need not be the case)

=> explicitly provide the region where the relic density is satisfied

How to compare lower-mass DM searches to high energy searches e.g. for vector like quarks or resonances, since the latter would be the UV completion of the lower mass DM models?



European Strategy Update

Analyses to include in these projections

The list of analyses from future colliders we can put on these plots

- Jet+MET
- Photon+MET
- ttbar + MET
- Di-jet / di-lepton
- Higgs…

The list of colliders the Energy Frontier would like to have

- HL-LHC
- FCC-eh, FCC-ee, FCC-hh
- CLIC
- CEPC
- ILC
- Muon collider

Snowmass 2021: EF Benchmark Scenarios

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
HL-LHC	pp	14 TeV		6
ILC	ee	250 GeV 350 GeV 500 GeV 1 TeV	±80/±30 ±80/±30 ±80/±30 ±80/±20	2 0.2 4 8
CLIC	ee	380 GeV 1.5 TeV 3.0 TeV	±80/0 ±80/0 ±80/0	1 2.5 5
CEPC	ee	M_Z $2M_W$ 240 GeV		16 2.6 5.6
FCC-ee	ee	M_Z $2M_W$ 240 GeV 2 M_{top}		150 10 5 1.5

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
FCC-hh	pp	100 TeV		30
LHeC FCC-eh	ep ep	1.3 TeV 3.5 TeV		1 2
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02
High energy muon-collider	$\mu\mu$	3 TeV 10 TeV 14 TeV 30 TeV		1 10 20 90

Note for muon-collider: It is important to note that the plan is not to run subsequently at the various c.o.m etc. These are reference points to explore and assess the physics potential and technology. The luminosity can be varied to determine how best to exploit the physics potential.

Other options to explore:

- Muon collider at a very high energy (>30 TeV?)[Need to consolidate g list of c.o.m. energies]
- FCC pp >200 TeV? and ~75 TeV documenting sensitivity loss
- Very high energy e+e- collider
- Other emerging ideas: γ-γ collider, C^3 e^+e^- collider [C3=Cool Copper Collider]

In order to include these, note that we need the corresponding future collider / EF working group to make the analysis projections.

Snowmass restart day: https://indico.fnal.gov/event/49756/sessions/19056/attachments/146606/187910/EF-Restart-Workshop-EF-Report-Plot-Table-Discussion1.pdf

Ingredients needed

[✔] Generator configuration for signal models

See Boyu+Kate's talk today

- MadGraph implementations from LHC DM WG / DMsimp

[ ] Future collider projections for each simplified model

- Extend to lower coupling values than considered by LHC
- Add lepton collider projections
- ff → mediator → ff (SM or DM)
- Rescale to dark photon model. Note that the vector model is equivalent to a dark photon model, but the couplings in the case of the dark photon have a fixed relationship with the dark photon massScalar and pseudo-scalar simplified model (LHC DM WG, arXiv:1507.00966)

[✔] Code to extrapolate from hadron collider limits on Lagrangian parameters to non-collider observables

- Extrapolation formulae to direct-detection xsec vs mDM and ID xsec-v vs mDM planes for most mediator models
- Based on recommendations of LHC DM WG
- Formulae relating "LHC DM vector" mediator model to dark photon model
- DarkCast

[ ] Code to extrapolate between hadron collider and lepton collider projections

[ ] Theory input for DD/ID plots including lepton colliders

(we can probably find a way to do this for dark photons but we need help for the rest)

References

Expressions of Interest from 2020

Taking future collider results and making varying-coupling plots in collider space (mDM vs mMed or g_q vs mDM)

- Varying coupling LOI with DM WG: https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF10_EF9_Andreas_Albert-094.pdf
- Summary plots LOI: https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF9_EF10-RF6_RF0-CF1_CF3_Boyu_Gao-160.pdf

Taking future collider results and overlaying them on top of accelerators, Direct detection and Indirect detection

- DM complementarity LOI: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF7-EF10_EF0-RF6_RF0-TF9_TF0-150.pdf

Past presentations

Collider scenarios foreseen by EF leadership: https://indico.fnal.gov/event/49756/sessions/19056/attachments/146606/187910/EF-Restart-Workshop-EF-Report-Plot-Table-Discussion1.pdf

EF restart workshop: EF10 summary https://indico.fnal.gov/event/49756/contributions/221944/attachments/146906/187903/20210902 - DM @ colliders - Snowmass EF Restart-2.pdf