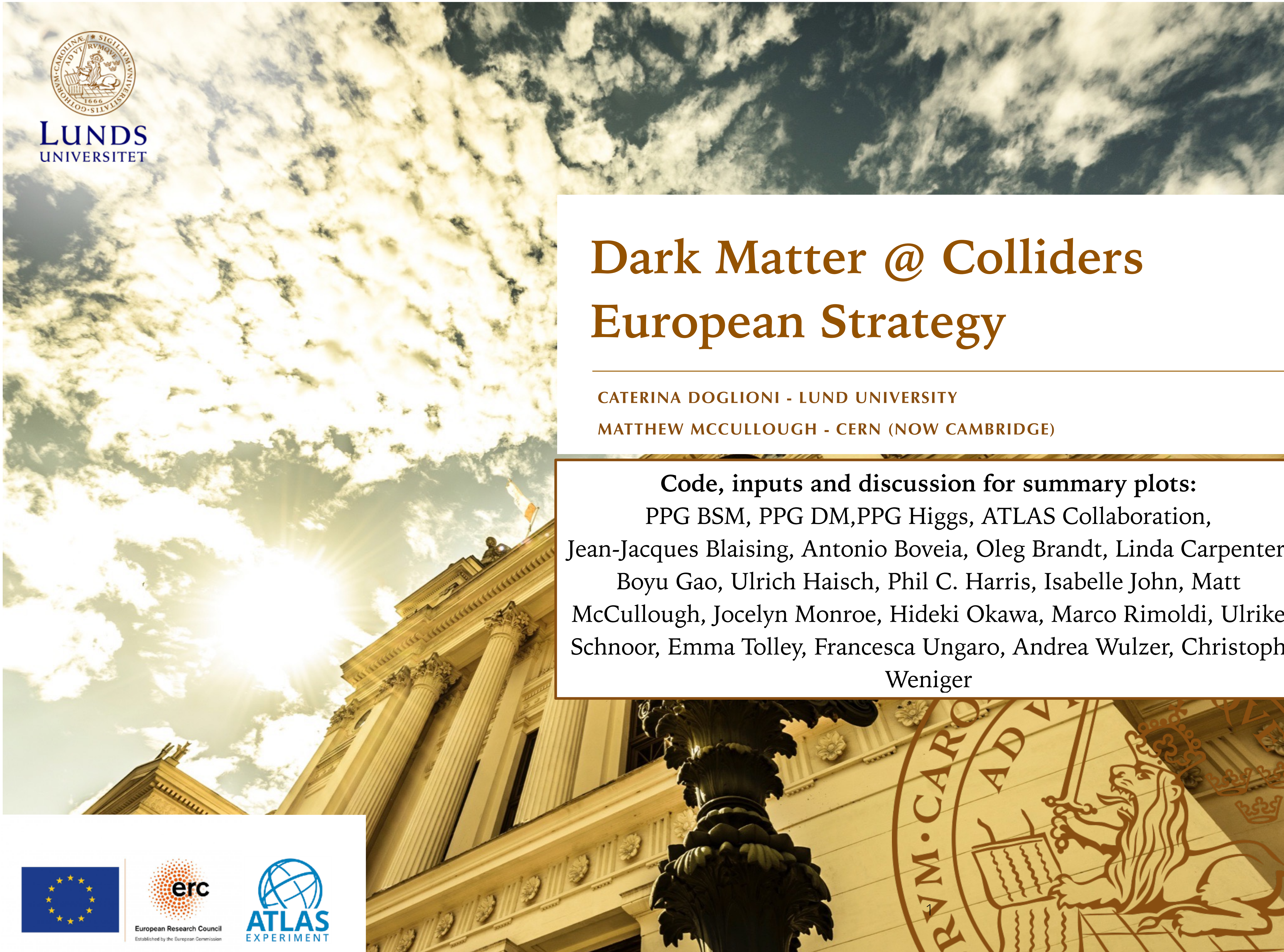


LUNDS UNIVERSITET

Dark Matter @ Colliders European Strategy

CATERINA DOGLIONI - LUND UNIVERSITY

MATTHEW MCCULLOUGH - CERN (NOW CAMBRIDGE)

Code, inputs and discussion for summary plots:
PPG BSM, PPG DM,PPG Higgs, ATLAS Collaboration, Jean-Jacques Blaising, Antonio Boveia, Oleg Brandt, Linda Carpenter, Boyu Gao, Ulrich Haisch, Phil C. Harris, Isabelle John, Matt McCullough, Jocelyn Monroe, Hideki Okawa, Marco Rimoldi, Ulrike Schnoor, Emma Tolley, Francesca Ungaro, Andrea Wulzer, Christoph Weniger

European Research Council
Established by the European Commission

ATLAS EXPERIMENT

Outline of this talk

Introduction: the **European Strategy** effort and structure for DM@(future) colliders

Choice of **benchmarks** and **projections**

- Wino/Higgsino dark matter
- Higgs decays to invisible particles
- Simplified models: generic vector/scalar mediators
- A brief look at dark photons (visible/invisible decays)

- Collider DM **results in context**
  - Benchmark models and **relic** density
  - Comparison of future colliders and **direct/indirect detection**

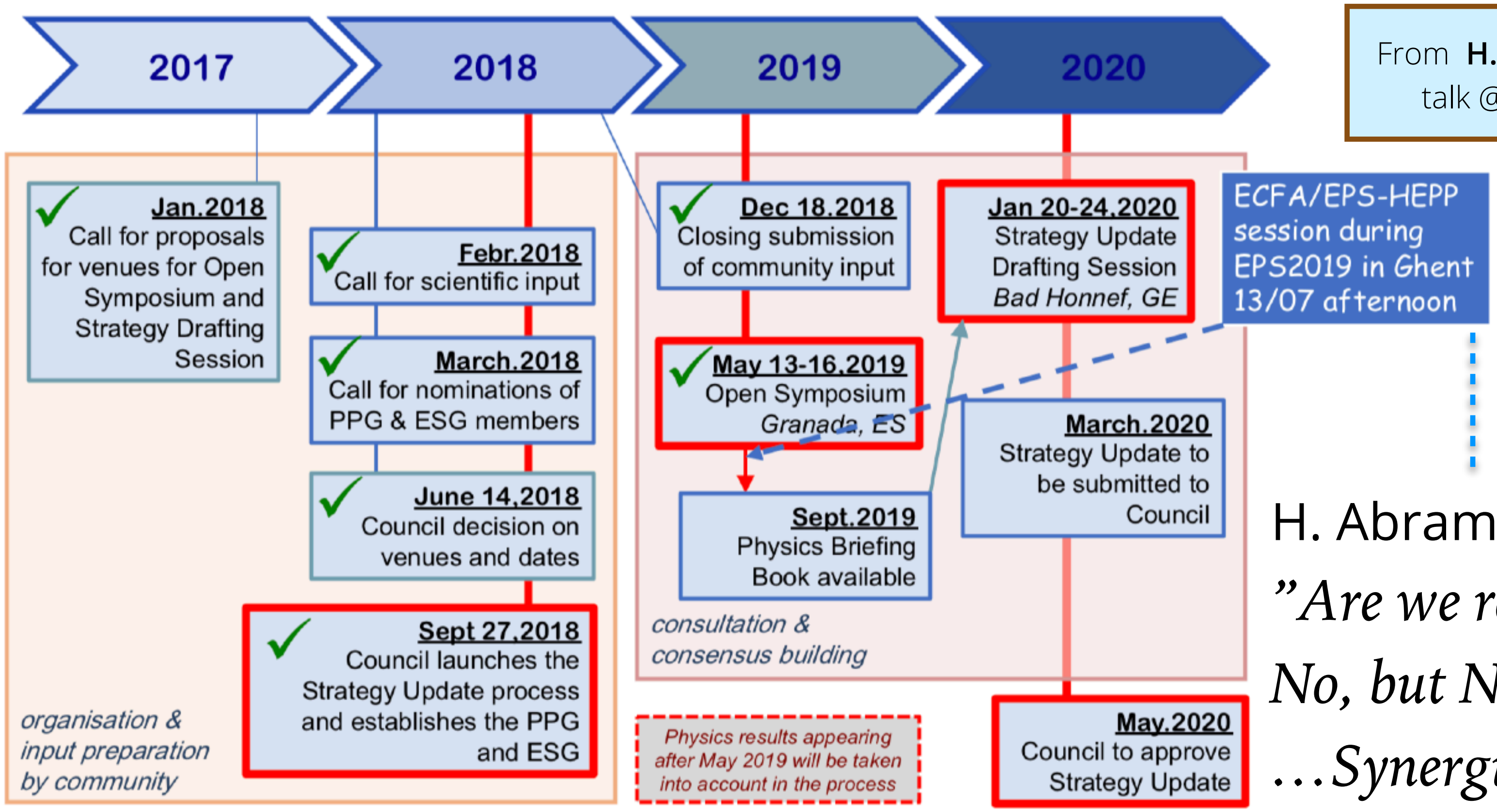
Open points for discussion

Plots and material (unless otherwise specified)
coming from Briefing Book of European Strategy of Particle Physics

Context: update of the European Strategy of Particle Physics

https://europeanstrategyupdate.web.cern.ch/about

> The European Strategy for Particle Physics provides a clear prioritisation of European ambitions in advancing the particle physics science. The Strategy is due to be updated by May 2020 to guide the direction of the field to the mid-2020s and beyond.



From **H. Abramowicz**'s talk @ EPSHEP'19

H. Abramowicz, 2019/07/13:

"Are we ready to recommend a future facility in Europe?"

No, but National Inputs [recommend]:

…Synergies with Astroparticle Physics" → dark matter!

Submissions to the European Strategy

Guidelines

In order to submit input, you need to have a registered account at CERN.
If you do not have one please fill in the form under
https://account.cern.ch/account/Externals/RegisterAccount.aspx

1. **Main document:** Please prepare a pdf file containing a cover page (title, abstract, name of the contact person and his/her e-mail address) and a comprehensive and self-contained description of the proposed input (maximum 10 pages). This document should address (when applicable) the scientific context, objectives, methodology, readiness and expected challenges.
2. **Addendum:** Please also prepare a pdf file containing information on the following topics (where relevant): interested community, timeline, construction and operating costs, computing requirements. The name of this pdf file should be as follows: "*Addendum-NN.pdf*", where NN is the file-name of your main document.
3. **Submitting input**: Select the "Submit input" tab and then click on the "Submit new abstract" button and upload both the main document and the addendum following the instructions in the "Attachments" field. Once submitted, both documents will be passed on to the Physics Preparatory Group (PPG) and the European Strategy Group (ESG), and made public in January 2019 for consideration before the Open Symposium from 13-16 May 2019. Please copy the abstract of your input into the field labelled "Content". Please also indicate one or more submission themes (tracks) to which your input relates:
   - *Large experiments and projects*
   - *National road maps*
   - *Accelerator Science and Technology*
   - *Beyond the Standard Model at colliders (present and future)*
   - *Dark matter and dark sector (accelerator and non-accelerator dark matter, dark photons, hidden sector, axions)*
   - *Instrumentation and computing*
   - *Electroweak physics (physics of the W, Z, H bosons, of the top quark, and QED)*
   - *Flavour Physics and CP violation (quarks, charged leptons and rare processes)*
   - *Neutrino physics (accelerator and non-accelerator)*
   - *Strong interactions (perturbative and non-perturbative QCD, DIS, heavy ions)*
   - *Other (communication, outreach, strategy process, technology transfer, individual contributions,…)*

Submitted Input

160 / 160 | Enter #id or search string

5. A European Data Science Institute for Fundamental Physics
Instrumentation and com...
In order to facilitate the deployment of modern data science technologies (e.g., Deep Learning) into theoretical and experimental research in high energy physics, we suggest that the creation of a European Data Science Institute for

112. A European Strategy Towards Finding Axions and Other WISPs
Dark matter and dark sec...
Since the last update of the European strategy on particle physics (ESPP) the interest in hypothetical very weakly interacting slim particles, dubbed WISPs,

57. A high precision neutrino beam for a new generation of short baseline experiments
Neutrino physics (accele...
The current generation of short baseline neutrino experiments is approaching intrinsic source limitations in the knowledge of flux

70. A memorandum by the Global Neutrino Network as input to the update of the European Strategy for Particle Physics
Neutrino physics (accele...
The Global Neutrino Network is an association of the neutrino telescope projects targeting the investigation of cosmic and atmospheric neutrinos in the energy range from GeV to beyond PeV. The main scientific objectives are the

143. A New QCD Facility at the M2 beam line of the CERN SPS
Strong interactions (pert...
This document summarises the physics interest, sensitivity reach and competitiveness of a future general-purpose fixed-target facility for Particle Physics research. Based upon the versatile M2 beam line of the CERN SPS, a great

110. A next-generation LHC heavy-ion experiment
Strong interactions (pert...
The present document discusses plans for a compact, next-generation multi-purpose detector at the LHC as a follow-up to the present ALICE experiment. The aim is to build a nearly massless barrel detector consisting of truly cylindrical

..and many more here

Context: structure of the European Strategy

Physics Planning Groups / chapters of the Briefing Book:

Electroweak Physics (physics of the W, Z, H bosons, of the top quark, and QED)	Keith Ellis	Beate Heinemann
Flavour Physics and CP violation (quarks, charged leptons and rare processes)	Belen Gavela	Antonio Zoccoli
→ Dark matter and Dark Sector (accelerator and non-accelerator dark matter, dark photons, hidden sector, axions)	Marcela Carena	Shoji Asai
Accelerator Science and Technology	Caterina Biscari	Lenny Rivkin
→ Beyond the Standard Model at colliders (present and future)	Gian Giudice	Paris Sphicas
Strong Interactions (perturbative and non-perturbative QCD, DIS, heavy ions)	Krzysztof Redlich	Jorgen D'Hondt
Neutrino Physics (accelerator and non-accelerator)	Stan Bentvelsen	Marco Zito
Instrumentation and Computing	Xinchou Lou	Brigitte Vachon

H. Abramowicz - EPS-HEP 2019

Dark Matter and Dark Sector Parallel Sessions, May 13-14, 2019

Monday afternoon

Session 1 (1.5 hours) – Introduction and Synergies - Scientific Secretary: K. Zurek
- Talk 1: Dark Sectors and DM Models: from Ultralight to Ultraheavy (25+5) H.Murayama (Berkeley and Tokyo)
- Talk 2: Dark Matter Direct Detection Searches (25+5) J. Monroe (London)
- Talk 3: Indirect DM Detection Overview (15+5) C. Weniger (Amsterdam)

Session 2 (2.5 hours) – DM at Colliders (joint w/ BSM) Scientific Secretaries: C.Doglioni (Lund), M.McCullough (CERN)
- Talk 4: How can/will Direct and Indirect DM Searches guide DM Searches at Accelerators? (25+5) M. Lisanti (Princeton)
- Talk 5: Theory: DM at Colliders (25+5) M. McCullough (CERN)
- Talk 6: Experiment: DM at Colliders (25+5) C. Doglioni (Lund)
- Discussion for Sessions 1 and 2 (60) All

Tuesday afternoon

Session 3 (1.5 hours) – Axions/ALPs - Scientific Secretaries: J.Jaeckel (Heidelberg), B.Doebrich (CERN)
- Talk 7: Ultra-light DM (ALPS) Theory and Overview (25+5) P. Agrawal (Harvard)
- Talk 8: ALPs: Lab Searches (15+5) A. Lindner (DESY)
- Talk 9: ALPs: Helioscope Searches (15+5) I. Irastorza (Zaragoza)
- Discussion for Axions/ALPs (30) All

Session 4 (2.5 hours) – Fixed Target/Beam Dump - Scientific Secretaries: G.Krnjaic (Fermilab), K.Petridis (Bristol)
- Talk 10: Theory and Overview (25+5) C. Frugiuele (Weizmann)
- Talk 11: Lepton Beams: LDMX@eSPS (NA64++ AWAKE ++) (12+3) R. Poettgen (Lund)
- Talk 12: Proton Beams: SHiP@BDF QCD (12+3) E. Graverini (EPFL)
- Talk 13: General Perspective (15+5) C. Vallee (Marseille)
- Discussion for Fixed Target/Beam Dump (70) All

Big Questions

1) How do we search for DM, depending on its properties?
What are the main differences between light Hidden Sector DM and WIMPs?
How broad is the parameter space for the QCD axion?

2) What are the most promising experimental programs, approved or proposed, to probe the different DM possibilities in a compelling manner?

3) How to compare results of different experiments in a more model-independent way?

4) How will direct and indirect DM Detection experiments inform/guide accelerator searches and vice-versa?

M. Carena and Shoji Asai - Granada Symposium, 2019

Context: structure of the European Strategy

Working Groups / chapters of the Briefing Book:

Electroweak Physics (physics of the W, Z, H bosons, of the top quark, and QED)	Keith Ellis	Beate Heinemann
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Instrumentation and Computing	Xinchou Lou	Brigitte Vachon

H. Abramowicz - EPS-HEP 2019

Topics in BSM

1) Electroweak breaking dynamics and resonances (EWSB/NewR)
Andrea Wulzer (CERN) & Juan Alcaraz (CIEMAT)
Composite Higgs, top partners, particles associated with EW symmetry breaking, heavy Z' and W'

2) Supersymmetry (SUSY)
Andreas Weiler (TUM) & Monica D'Onofrio (Liverpool)
Collider searches, motivations for supersymmetry after the LHC, unexplored corners, new models

3) Extended Higgs sectors & High-energy flavor dynamics (Ext-H/FD)
Veronica Sanz (Sussex) & Philipp Roloff (CERN)
Two Higgs doublets, singlets, new particles accompanying the Higgs, leptoquarks, particles related to flavour dynamics at the EW scale, rare top decays

4) Dark matter (DM)
Matthew McCullough (CERN) & Caterina Doglioni (Lund)
Collider searches, simplified models, comparisons with direct/indirect searches

5) Feebly-interacting particles (FIPs)
Gilad Perez (Weizmann) & Gaia Lanfranchi (INFN, Frascati)
Long-lived particles, right-handed neutrinos at the EW scale, dark photons at colliders, dark scalar/relaxion, ALPs at colliders

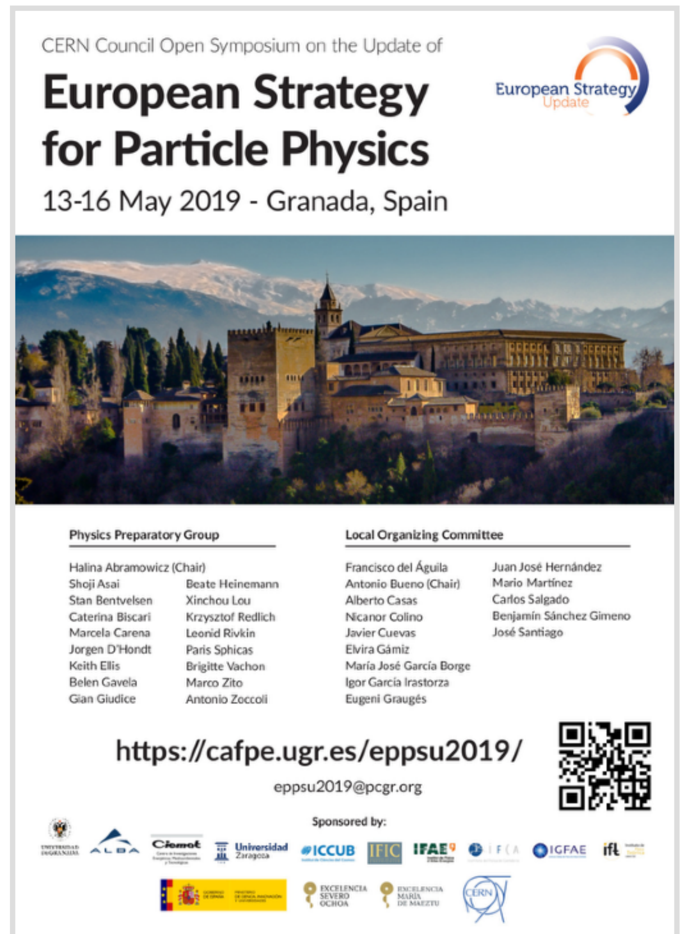
- **The four big questions for BSM (@colliders):**
  - To what extent can we tell whether the Higgs is fundamental or composite?
    - EWSB/NewReson, SUSY
  - Are there new interactions or new particles around or above the electroweak scale?
    - EWSB/NewReson, SUSY, Ext-H/FlavorDyn, DM, FIPs
  - What cases of thermal relic WIMPs are still unprobed and can be fully covered by future collider searches?
    - DM, FIPs, SUSY
  - To what extent can current or future accelerators probe feebly interacting sectors?
    - FIPs, SUSY

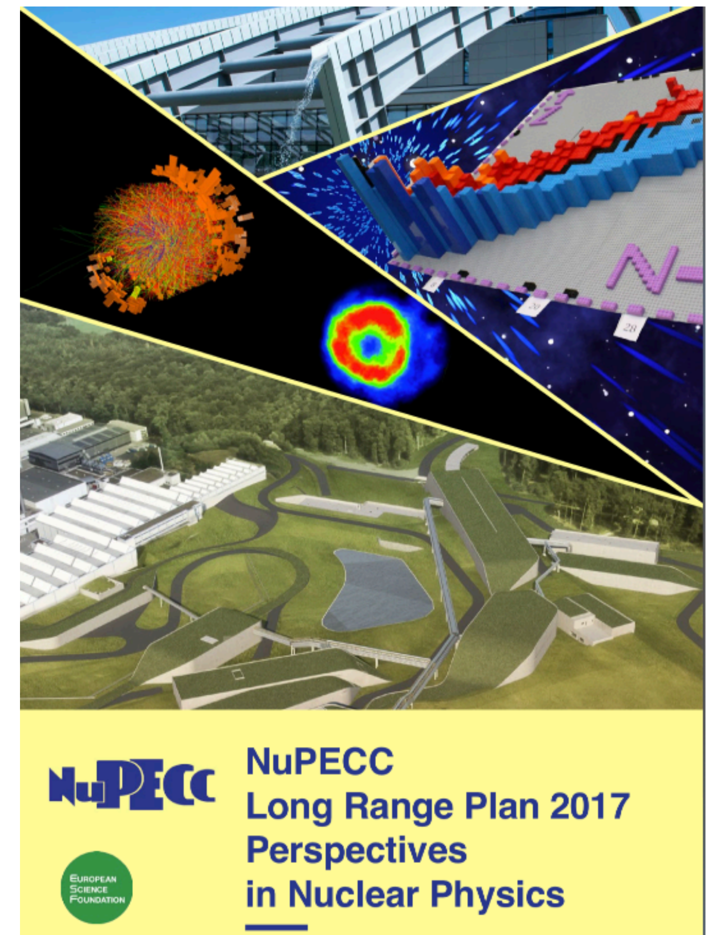
G. Giudice and P. Sphicas - Granada Symposium, 2019

European visions: APPEC, ECFA, NuPECC

More info in this talk

Astroparticle (APPEC) Particle (ECFA) Nuclear physics (NuPECC)





Astroparticle, particle and nuclear physics in Europe have **strategies and plans** that **recognize the importance of synergies** between the different fields

Benchmarks of choice (for WIMP DM)

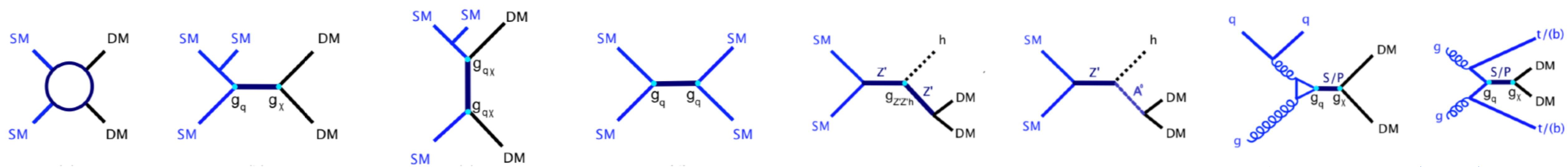
See talk by S. Chang

European Strategy "big question"

What cases of thermal relic WIMPs are still unprobed and can be covered by collider searches?

Problem: unable to cover all cases!

- Large number of model possibilities for WIMPs, even limiting to the simplest models (see e.g. LHC Dark Matter Forum/WG documents)



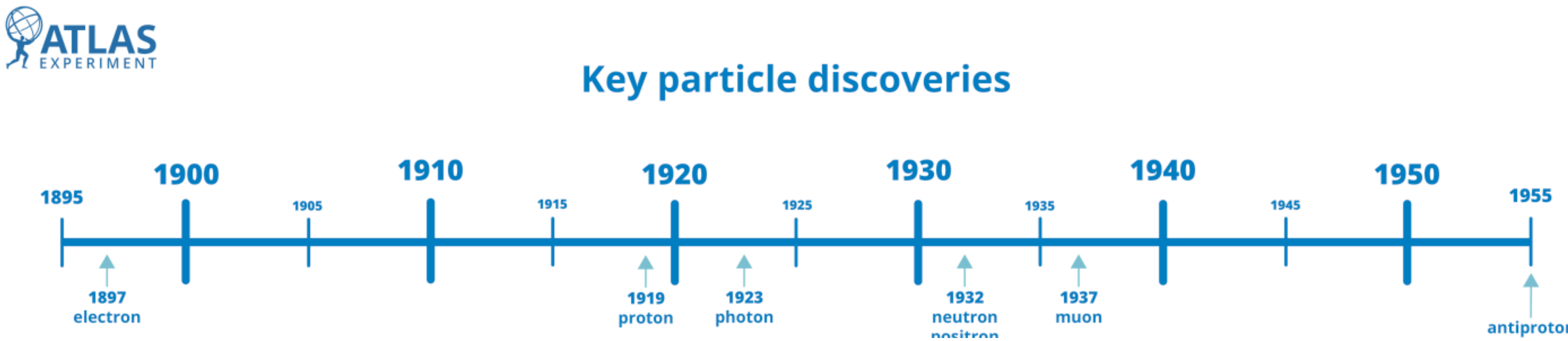
Ann.Rev.Nucl.Part.Sci. 68 (2018) 429-459

- Any benchmarks chosen will be **only examples -** what to choose and why?
  - **Wino/Higgsino DM:** simple extension of SM portals within SUSY framework
  - **Higgs portal DM:** newly discovered Higgs, simple interaction
  - **Simplified models of vector/scalar-mediated DM:**
    - Vector/axial vector: visible and invisible signatures
    - Scalar: cross-sections are small → good future collider probes

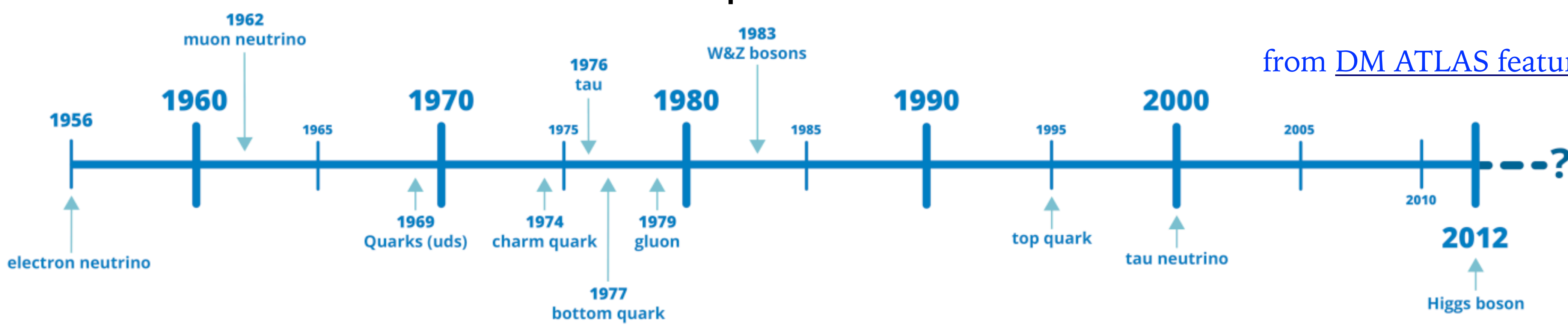
Choice of benchmarks

https://abstrusegoose.com/406

"Why comparing future colliders using such simple models?"
"Do we think DM is all made of a single WIMP model?" (not necessarily…)



- **Lesson from SM**: most common particles discovered first



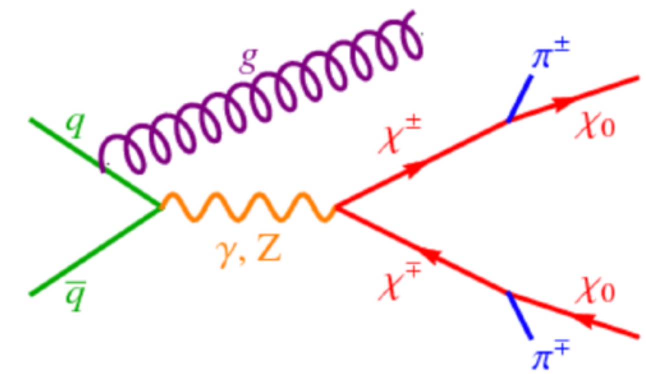
from DM ATLAS feature

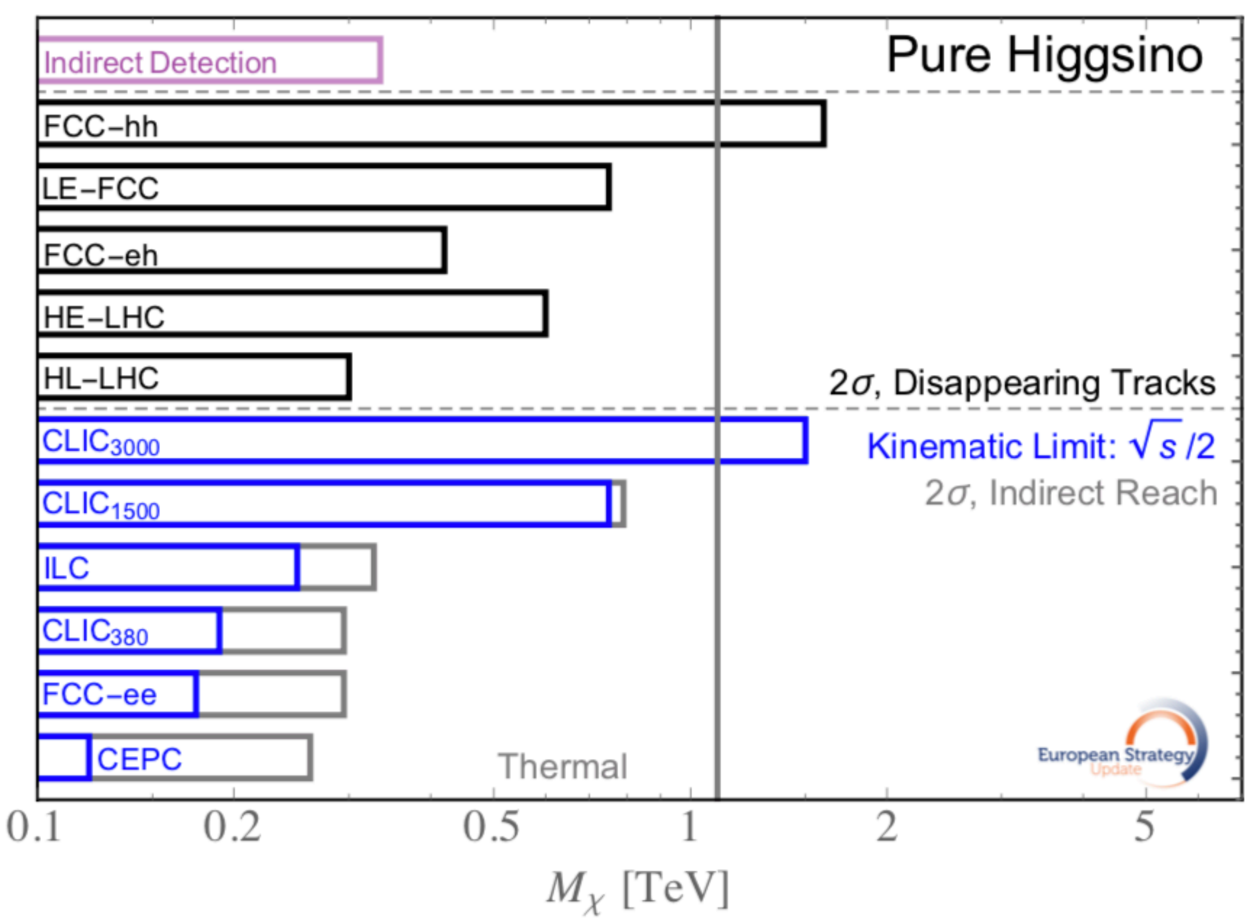
- Even simple models can encapsulate **relevant experimental characteristics** representing wider classes of theories

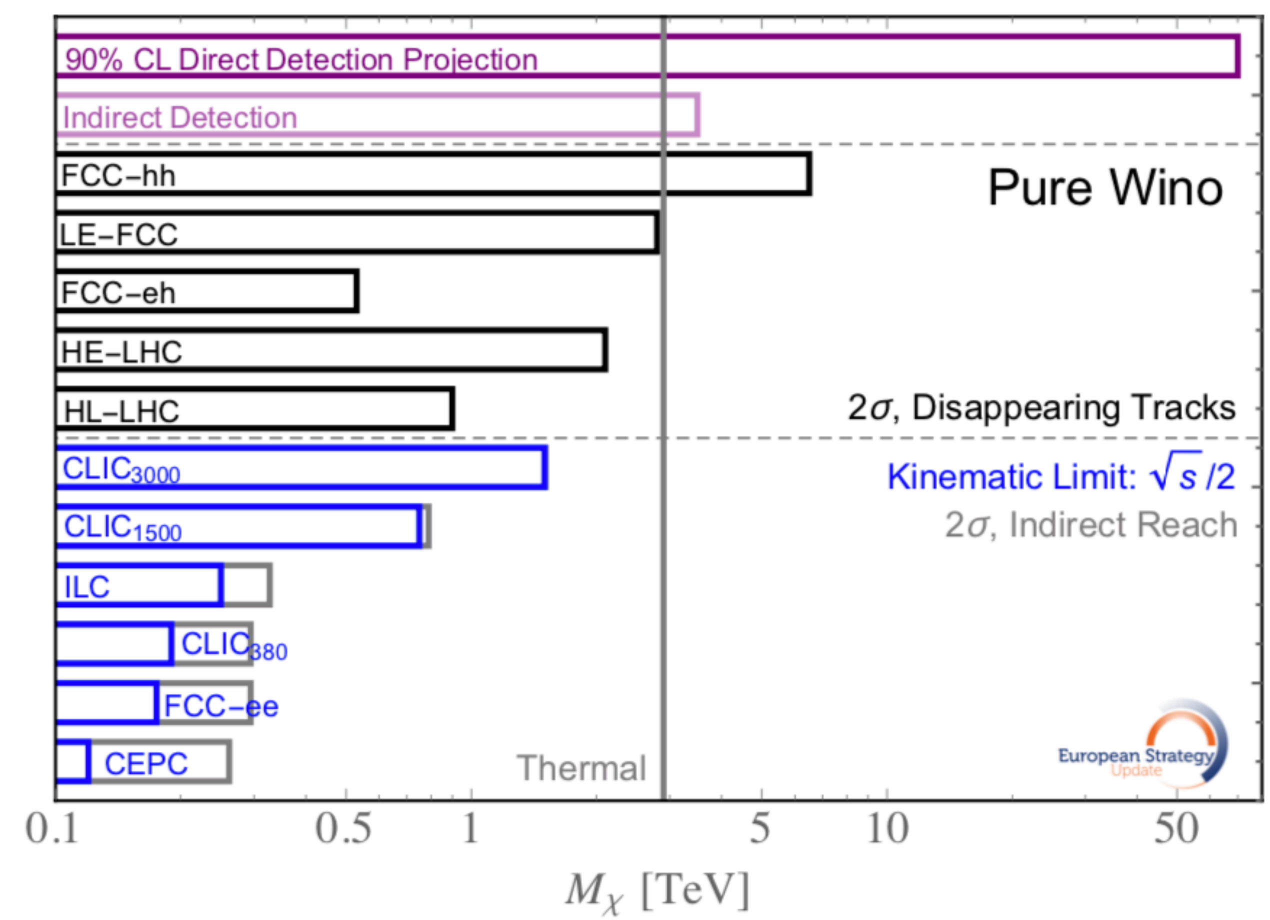
Results for Wino/Higgsino models

arXiv:1802.04097, arXiv:0706.4071, arXiv:1705.04843

- Viable **thermal relic WIMP candidate** in SUSY: lightest neutralino - pure Wino/Higgsino
  - Also standalone model of ”minimal DM”

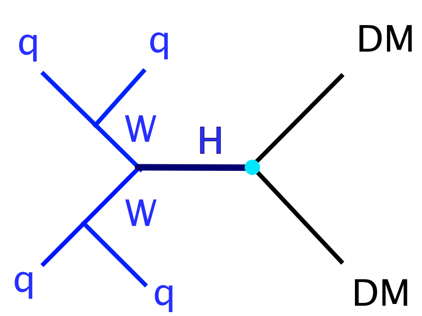


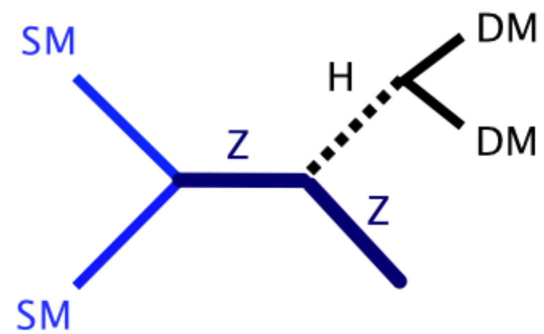




Higgs portal: direct searches and coupling fits

Higgs to invisible constraints
interpreted as **Higgs Portal** models





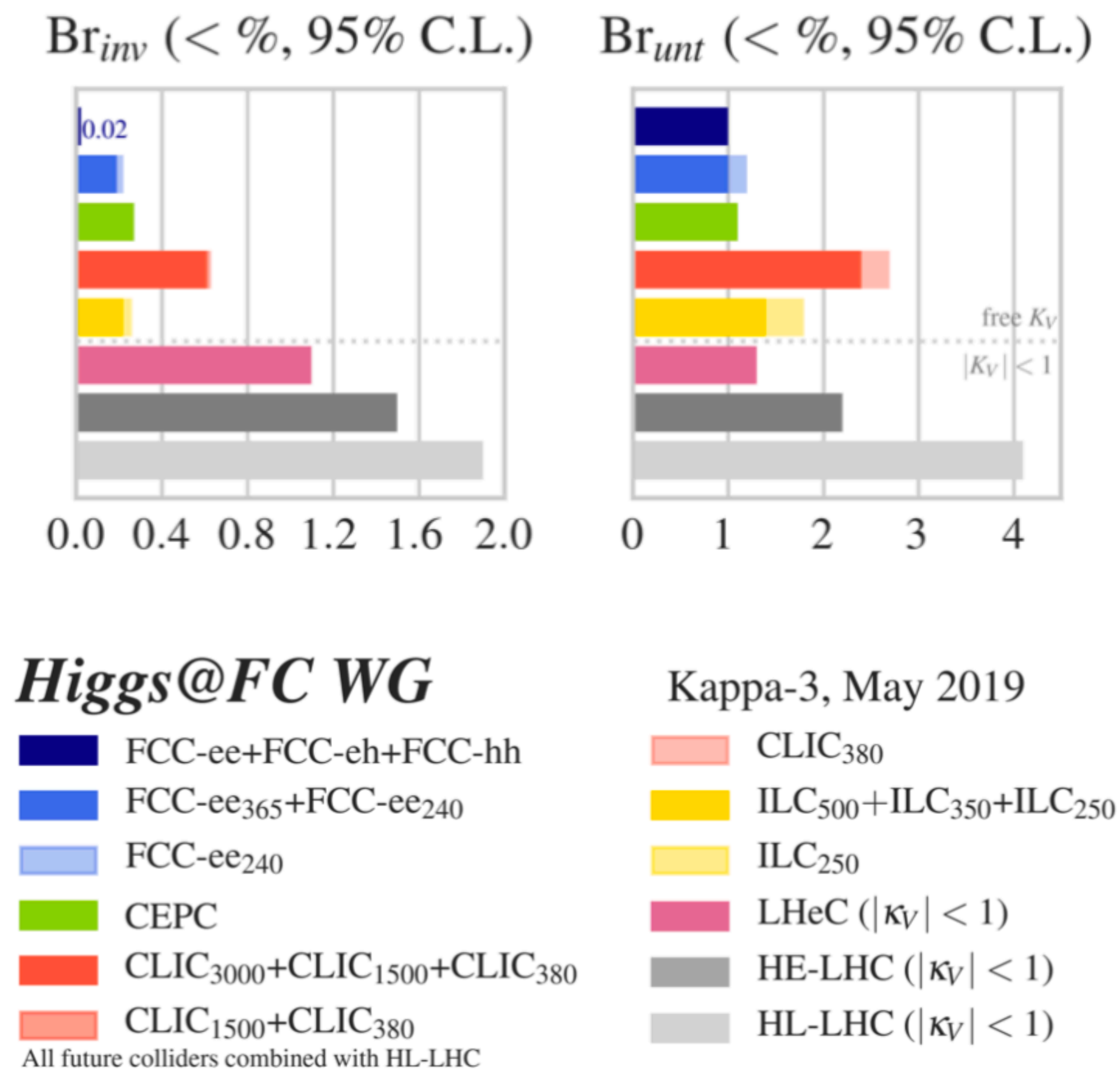
arXiv:1905.03764 used for plots used for plots

Collider	95% CL upper bound on BR_{inv} [%]		
	Direct searches	kappa-3 fit	Fit to BR_{inv} only
HL-LHC	2.6	1.9	1.9
HL-LHC & HE-LHC		1.5	1.5
FCC-hh	0.025	0.024	0.024
HL-LHC & LHeC	2.3	1.1	1.1
CEPC	0.3	0.27	0.26
$FCC\text{-}ee_{240}$	0.3	0.22	0.22
$FCC\text{-}ee_{365}$		0.19	0.19
ILC_{250}	0.3	0.26	0.25
ILC_{500}		0.22	0.22
$CLIC_{380}$	0.69	0.63	0.60
$CLIC_{1500}$		0.62	0.41
$CLIC_{3000}$		0.61	0.30

LHeC 5.5 (2-sigma, no syst.)
HE-LHeC 3.4 (2-sigma, no syst.)
FCC-eh 1.7 (2-sigma, no syst.)

Precision Higgs Physics at High-Energy Electron-Proton Colliders, LHeC Higgs Study Group, G.~Azuelos et al, in preparation.

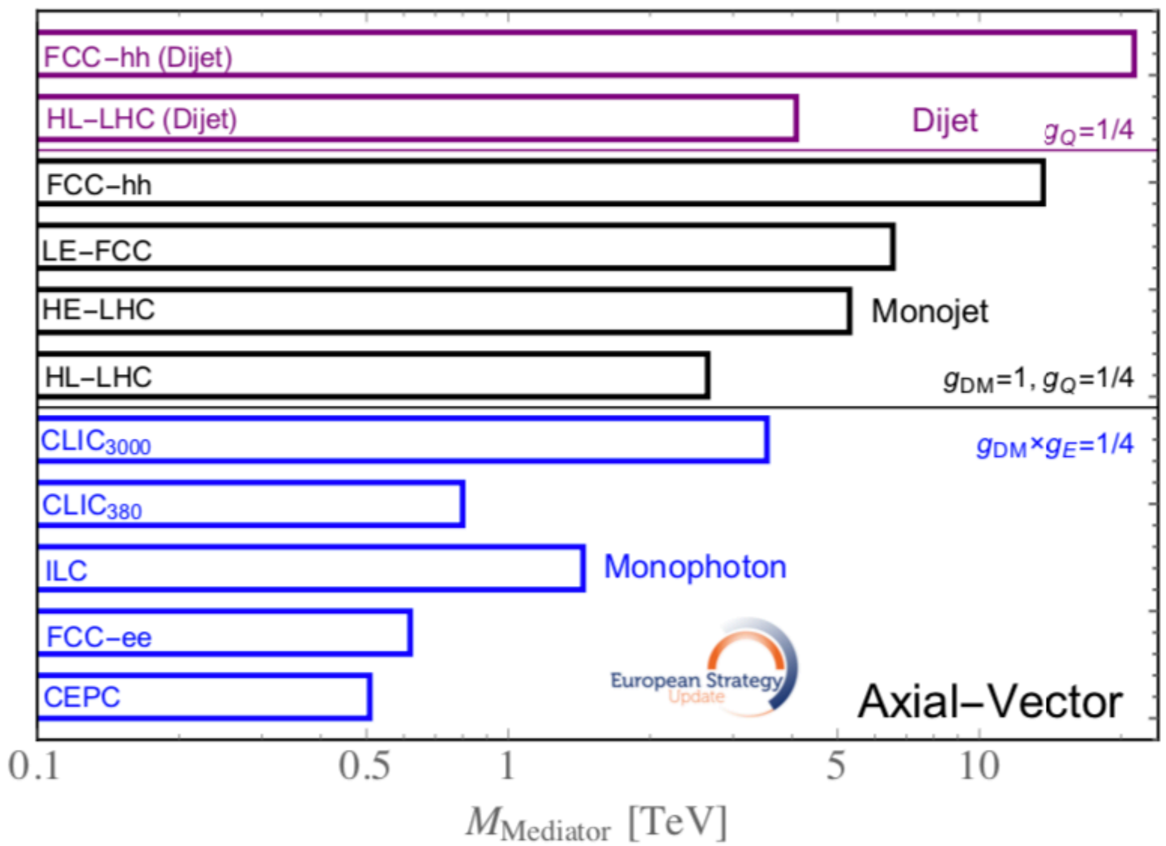
arXiv:1903.03616



Results for simplified models: vector/scalar

Axial vector

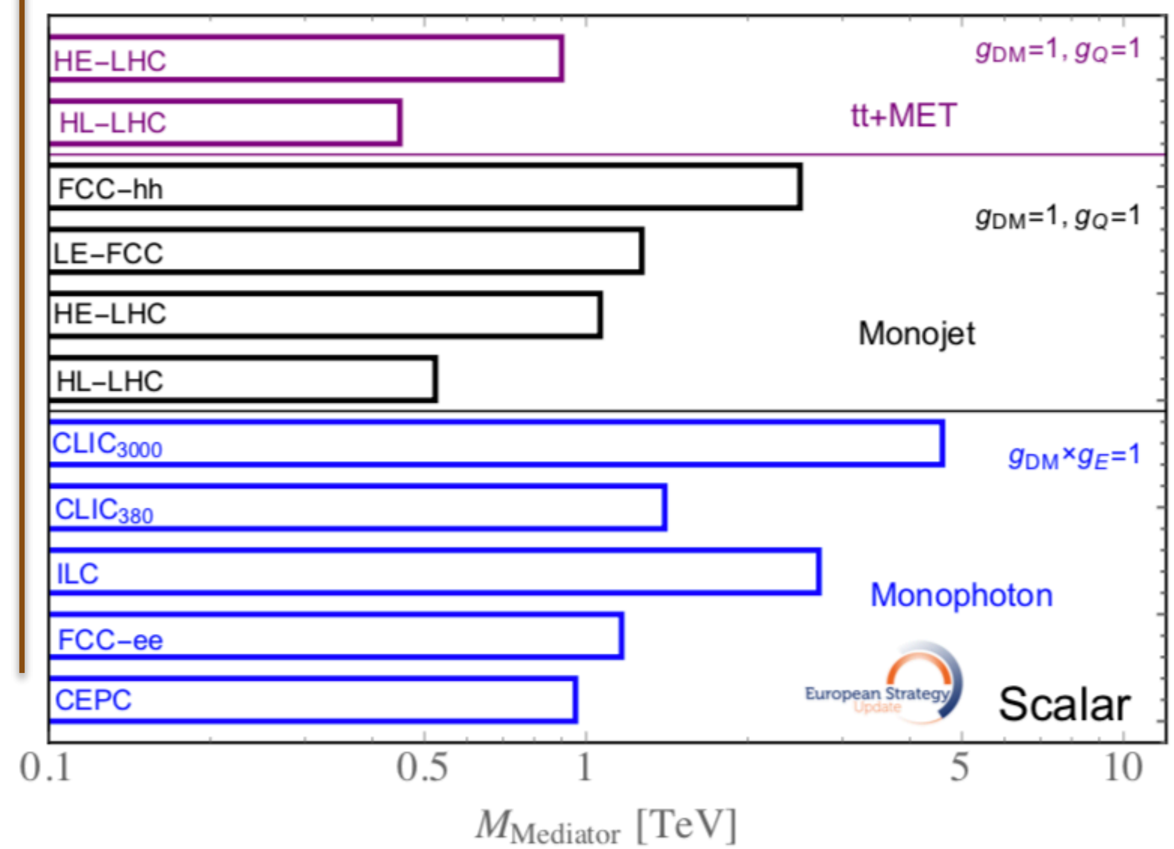
$$\mathcal{L}_{\text{axial-vector}} = -g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu\gamma_5\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma_5 q$$



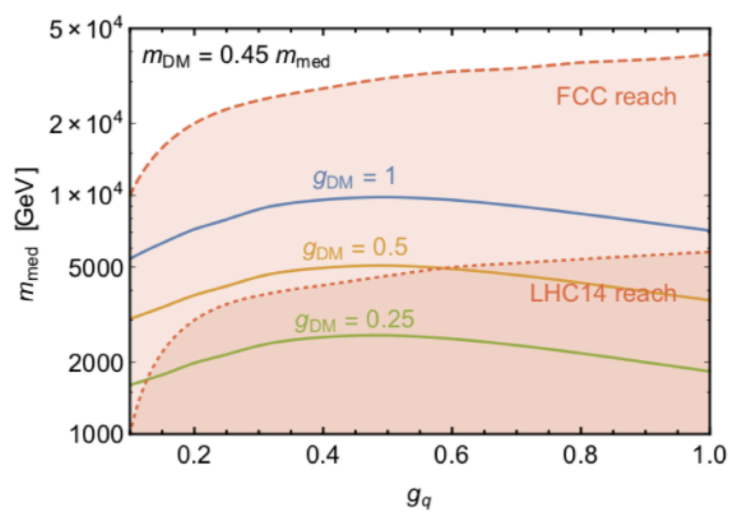
Scalar/(pseudoscalar)

Yukawa couplings

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



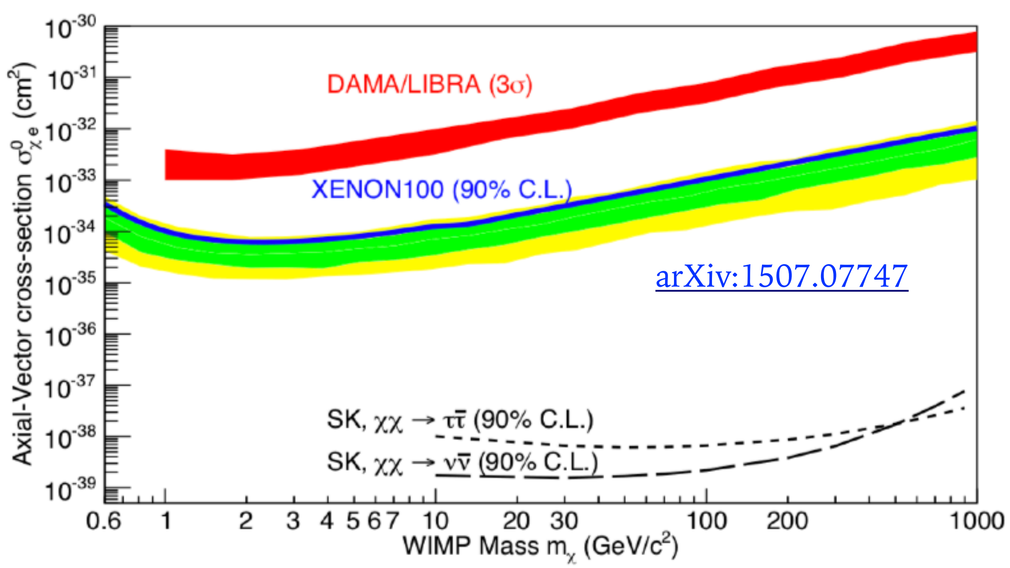
Note: strong constraints from visible searches are coupling-dependent



Scalar mediator, comparison of lepton colliders

- No summary plot for scalar mediator and lepton colliders
- In order to compare to DD, one would need:
  1) quark couplings (DM-nucleon interaction)
  2) model-dependent statement for quark/lepton coupling ratio
  → only **compare mediator/EFT reach at fixed mDM** with the same coupling assumptions

Example of DD reach for leptophilic DM model



Scalar mediator, fermion couplings = 1, gDM = 1, m_{DM}=1 GeV

- **ILC** (@ 90% CL): [M. Habermehl's thesis]
  - sqrt(s)=250 GeV, 2/ab : **1250 GeV**
  - sqrt(s)=500 GeV, 4/ab: **2710 GeV**

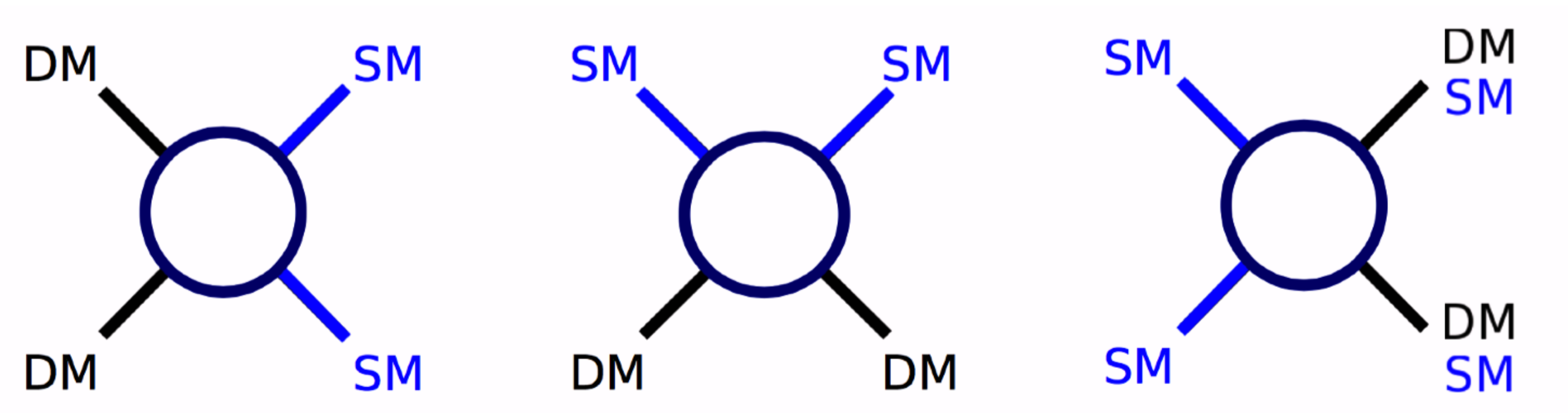
  (@95% CL, 10/ab): about 150 GeV lower
- **CLIC** (@95% CL, 5/ab, no beam polarization):
  [private communication with U. Schnoor, J. J. Blasing, A. Wulzer, CLIC Collab.]
  - sqrt(s)=3000 GeV: **4600 GeV**
- **CEPC** results w/o systematics also available: [arXiv:1903.12114]

Collider, direct and indirect detection

European Strategy "big question"

How will Direct and Indirect DM Detection experiments inform/guide accelerator searches and vice-versa?

- Why we need complementarity:
  - DD/ID can discover DM with cosmological origin



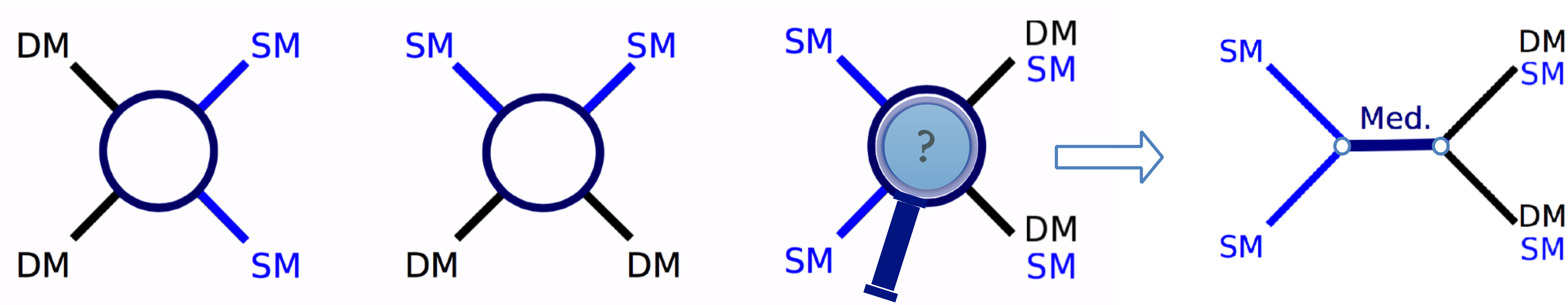
Indirect Detection Direct Detection Particle Colliders

Collider, direct and indirect detection

European Strategy "big question"

How will Direct and Indirect DM Detection experiments inform/guide accelerator searches and vice-versa?

- Why we need complementarity:
  - DD/ID can discover DM with cosmological origin
  - Colliders can produce DM and probe the dark interaction



Indirect Detection Direct Detection Particle Colliders

Complementarity of DM experiments

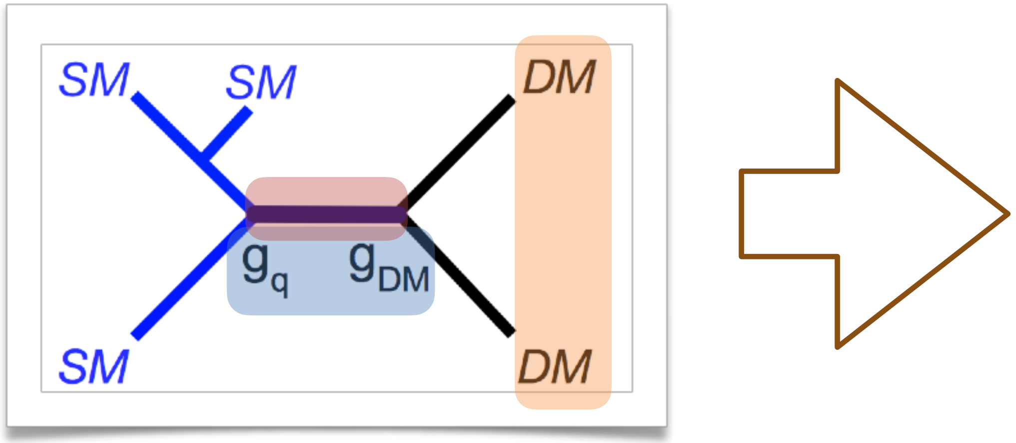
See talk by T. Tait

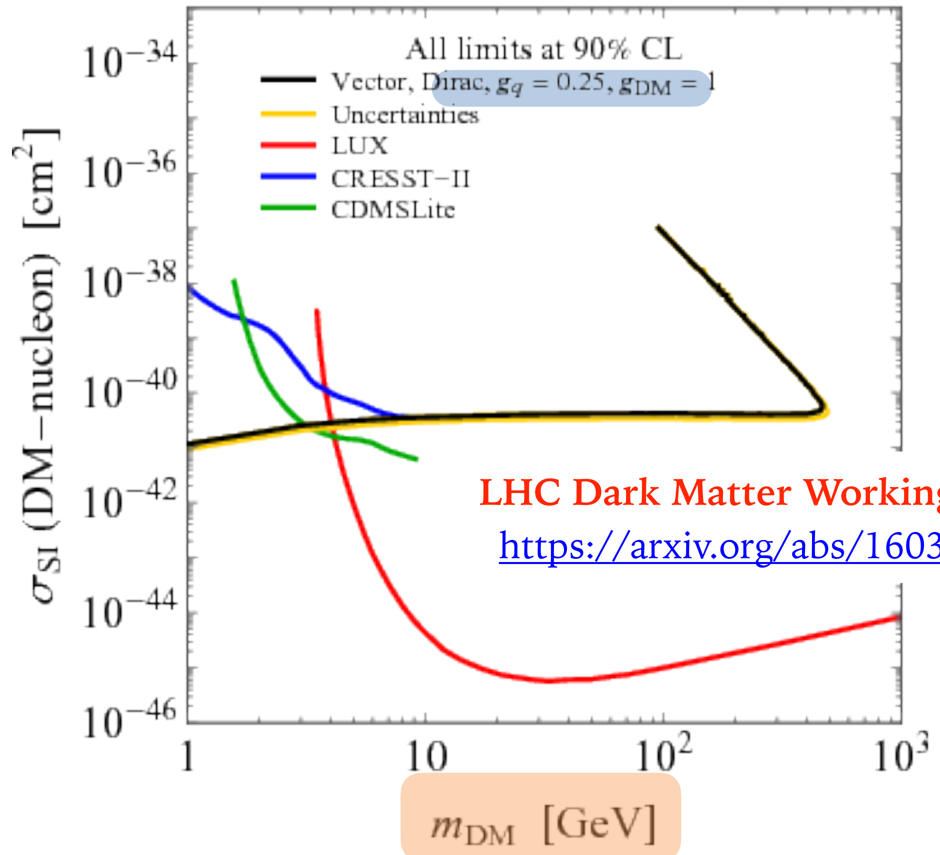
European Strategy "big question"

How do we compare results of different experiments ~~in the most model independent way possible?~~

Comparisons are possible only in the context of a model

Essential to **fully specify model/parameters** and **be aware of limitations**





LHC Dark Matter Working Group
https://arxiv.org/abs/1603.04156

For more thoughts on upper bounds to collider sensitivity: arXiv:1810.07705 and DMWG meeting June 2017

Complementarity of colliders with direct (indirect) detection performed **within the chosen benchmark models & parameters**

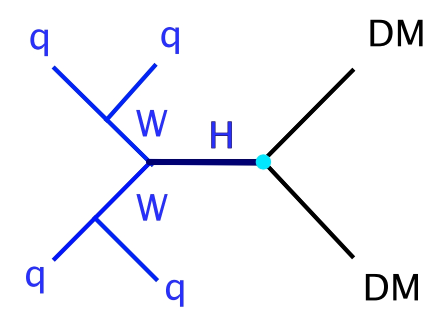
Higgs portal, plot for direct searches

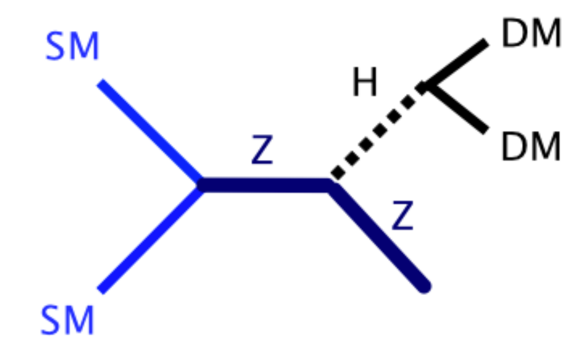
- Limits on BR can be translated to limits in the DM-nucleon plane

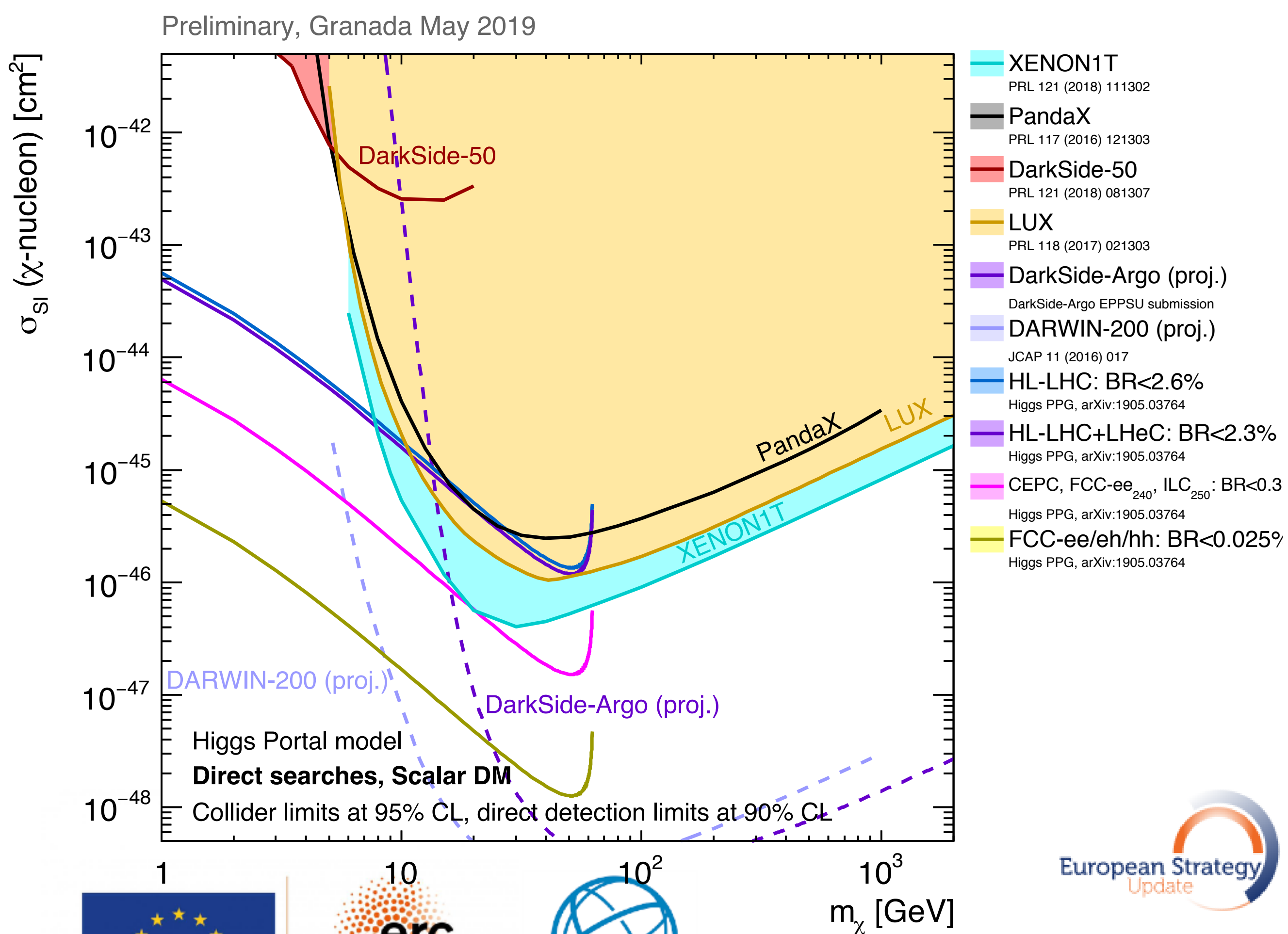
$$\sigma_{\chi N} = \Gamma_{\text{inv}} \frac{8 m_N^4 f_N^2}{v^2 \beta m_h^3 (m_\chi + m_N)^2} g_\chi\left(\frac{m_h}{m_\chi}\right), \qquad (15)$$

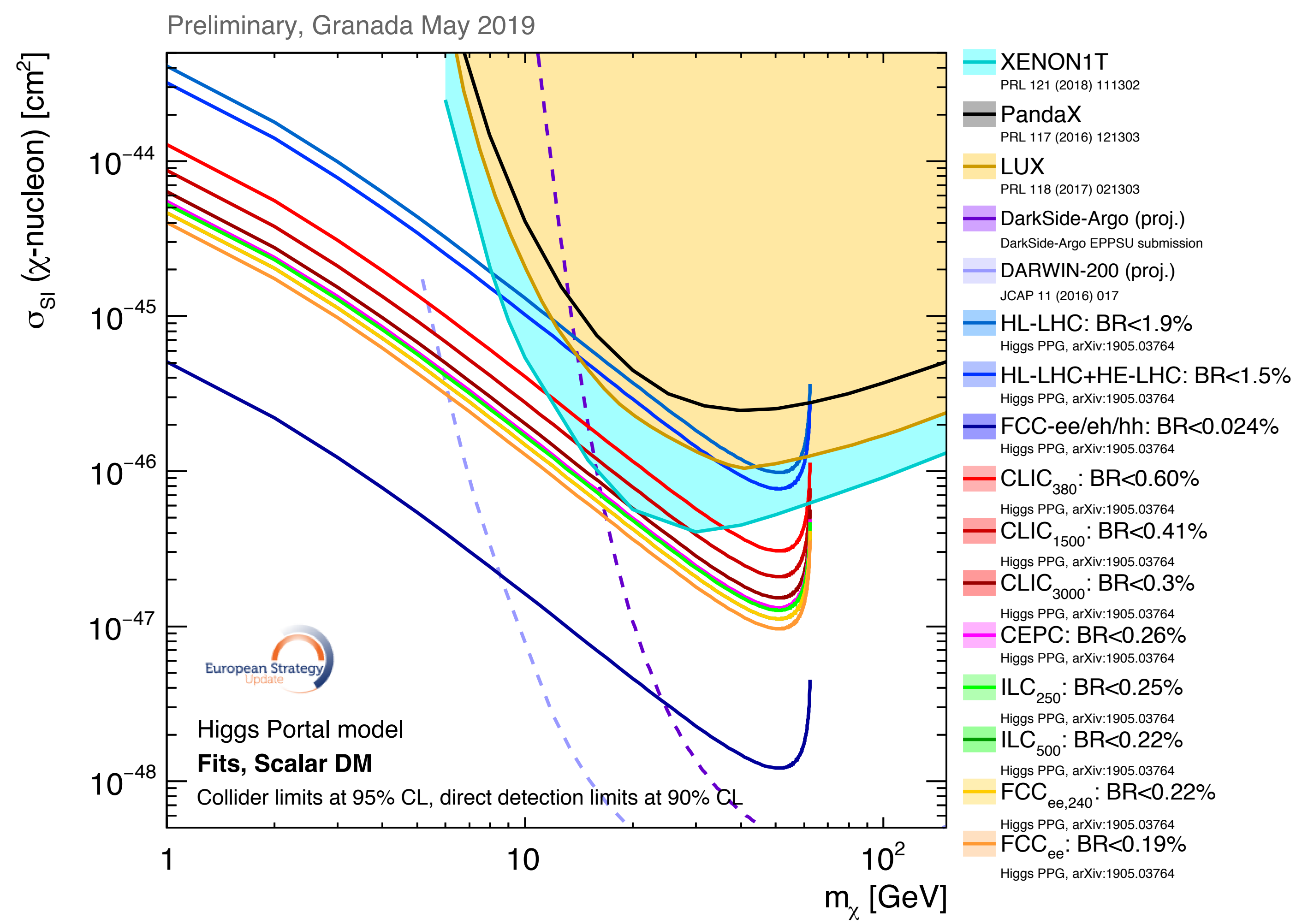
arXiv:1708.02245

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









Scalar mediator, hadron colliders and direct detection

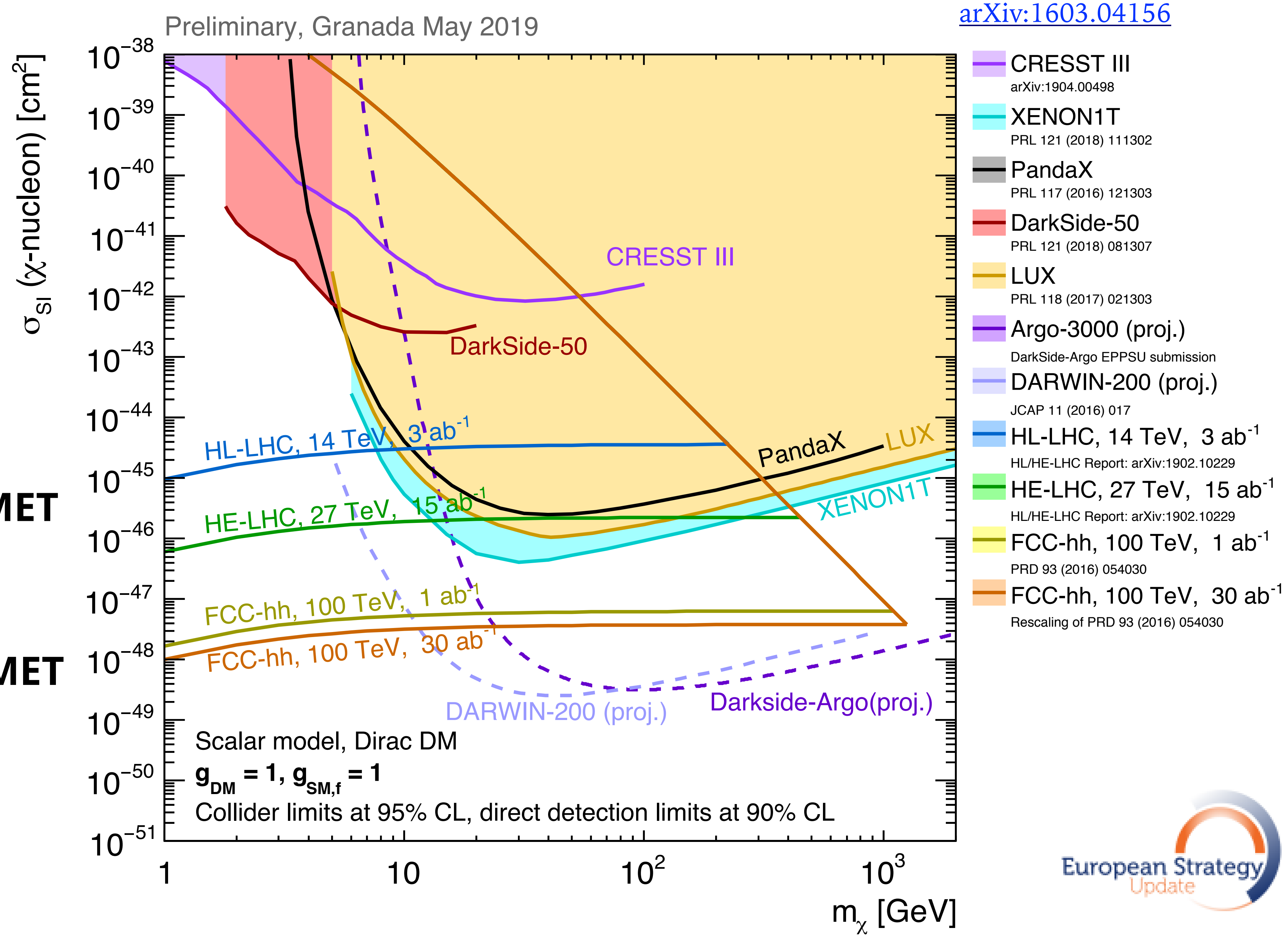
- Limits on scalar mediator mass/scale can be translated to limits in the DM-nucleon plane

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

arXiv:1603.04156

ttbar+MET

V/jet+MET



European Research Council
Established by the European Commission

European Strategy Update

Scalar mediator, hadron colliders and direct detection

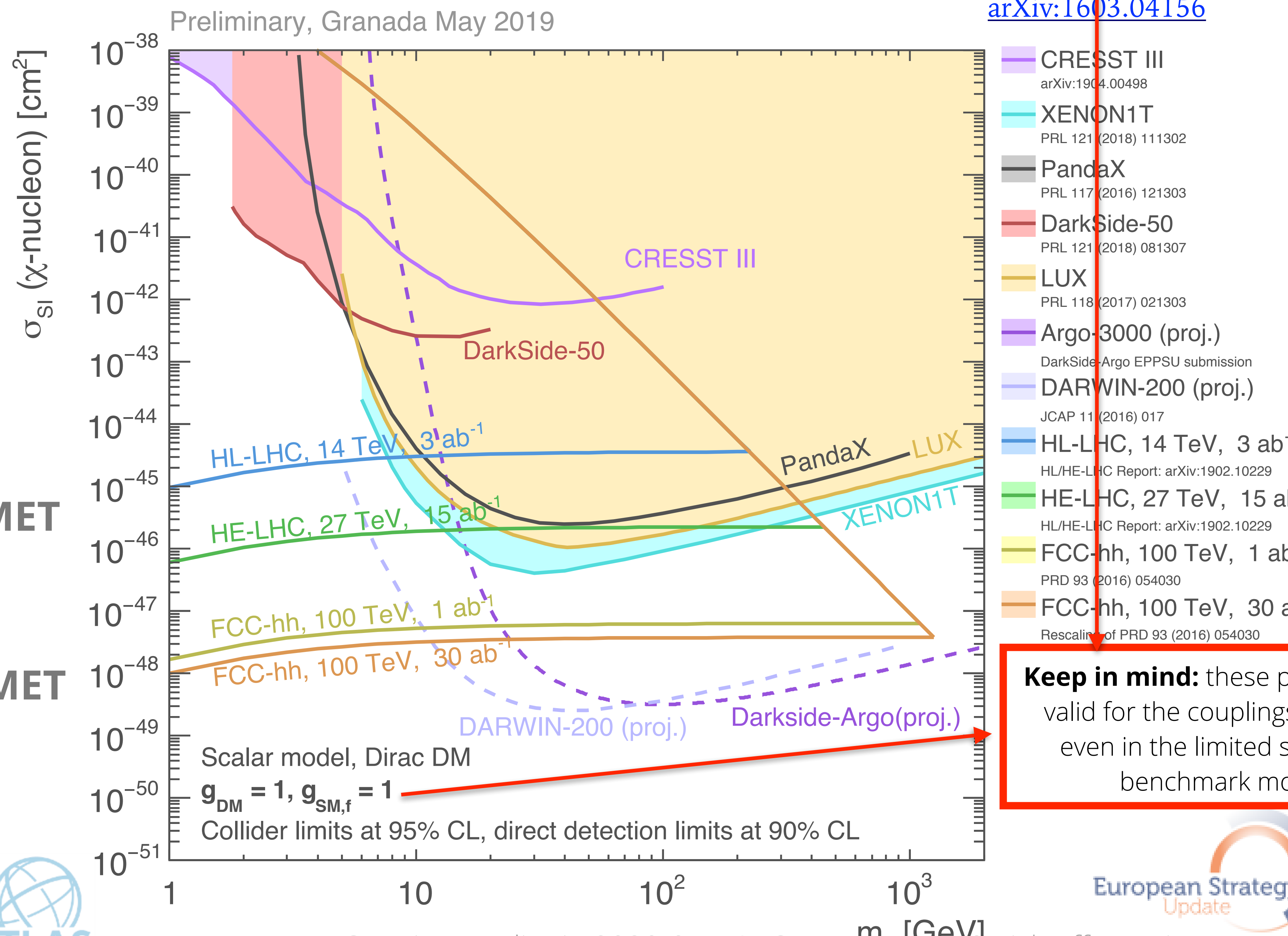
- Limits on scalar mediator mass/scale can be translated to limits in the DM-nucleon plane

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

arXiv:1603.04156

ttbar+MET

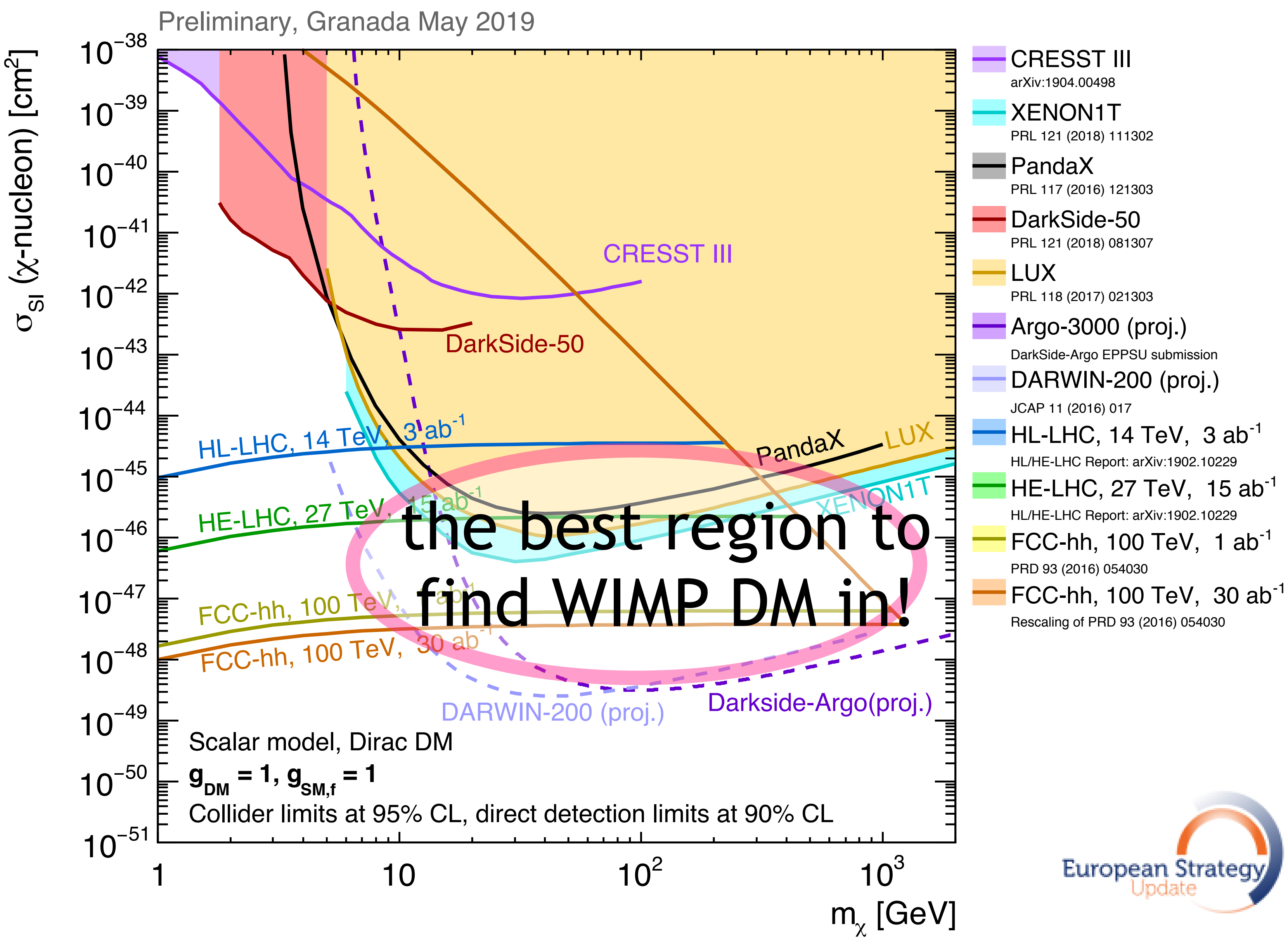
V/jet+MET



Keep in mind: these plots are only valid for the couplings specified, even in the limited space of a benchmark model!

Complementarity in summary plots

Synergy = complementary reach for future colliders and direct detection



- **Collider discovery** of invisible particle needs **confirmation of cosmological origin** from DD/ID
- **DD/ID discovery** needs collider **understanding of nature of interaction**
- A **future collider program** that increases sensitivity to invisible particles **coherently with DD/ID** serves these purposes
- **Other experiments** looking for **invisible particles and their mediators** may also be able to reach these regions

- Synergies with also in **non-WIMP DM, for DD and beam dump experiments**

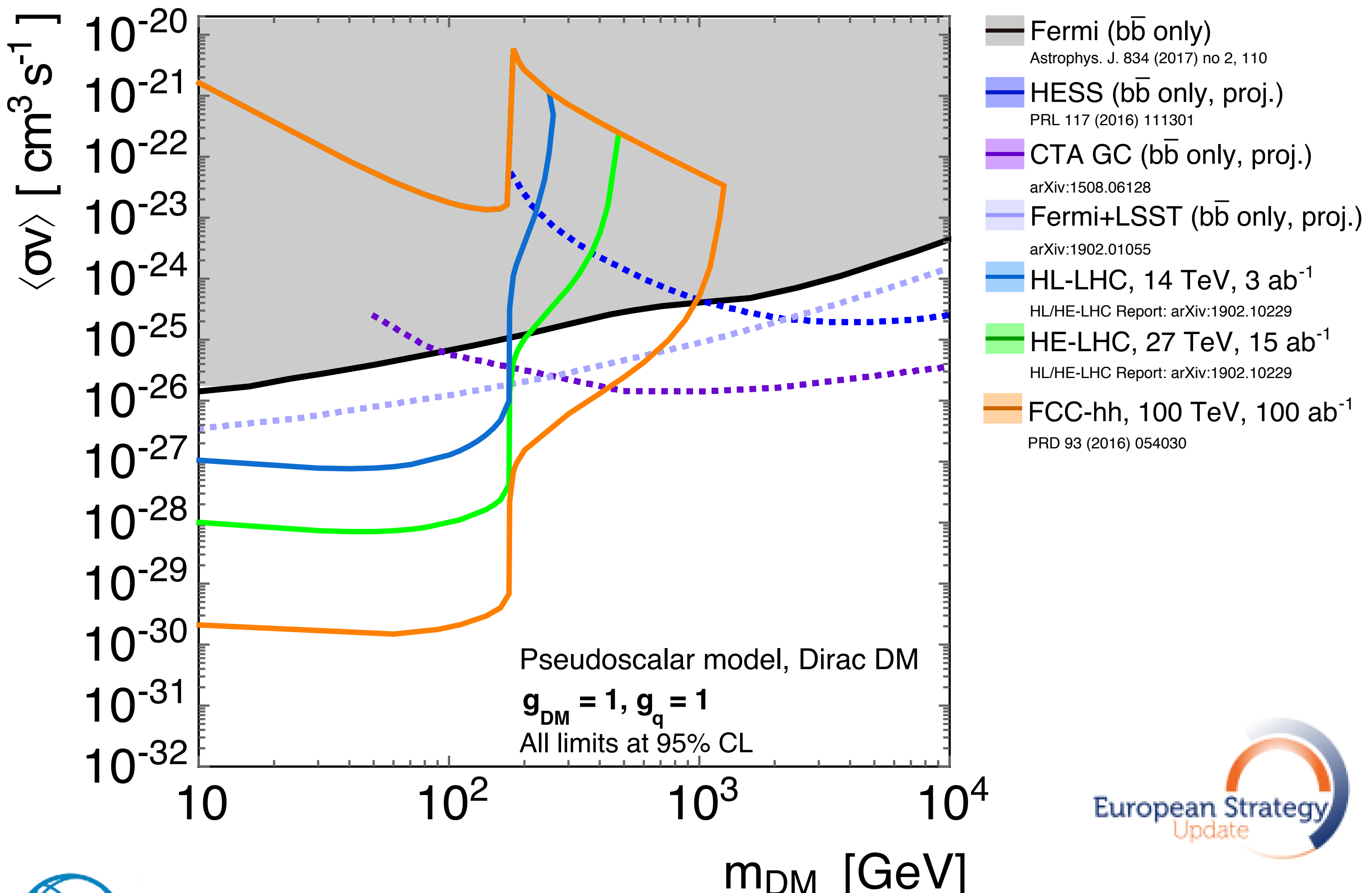
Indirect detection plots with pseudoscalar mediator

- Collider limits on pseudoscalar mediator mass/scale can be translated to limits in the velocity-avg DM annihilation plane

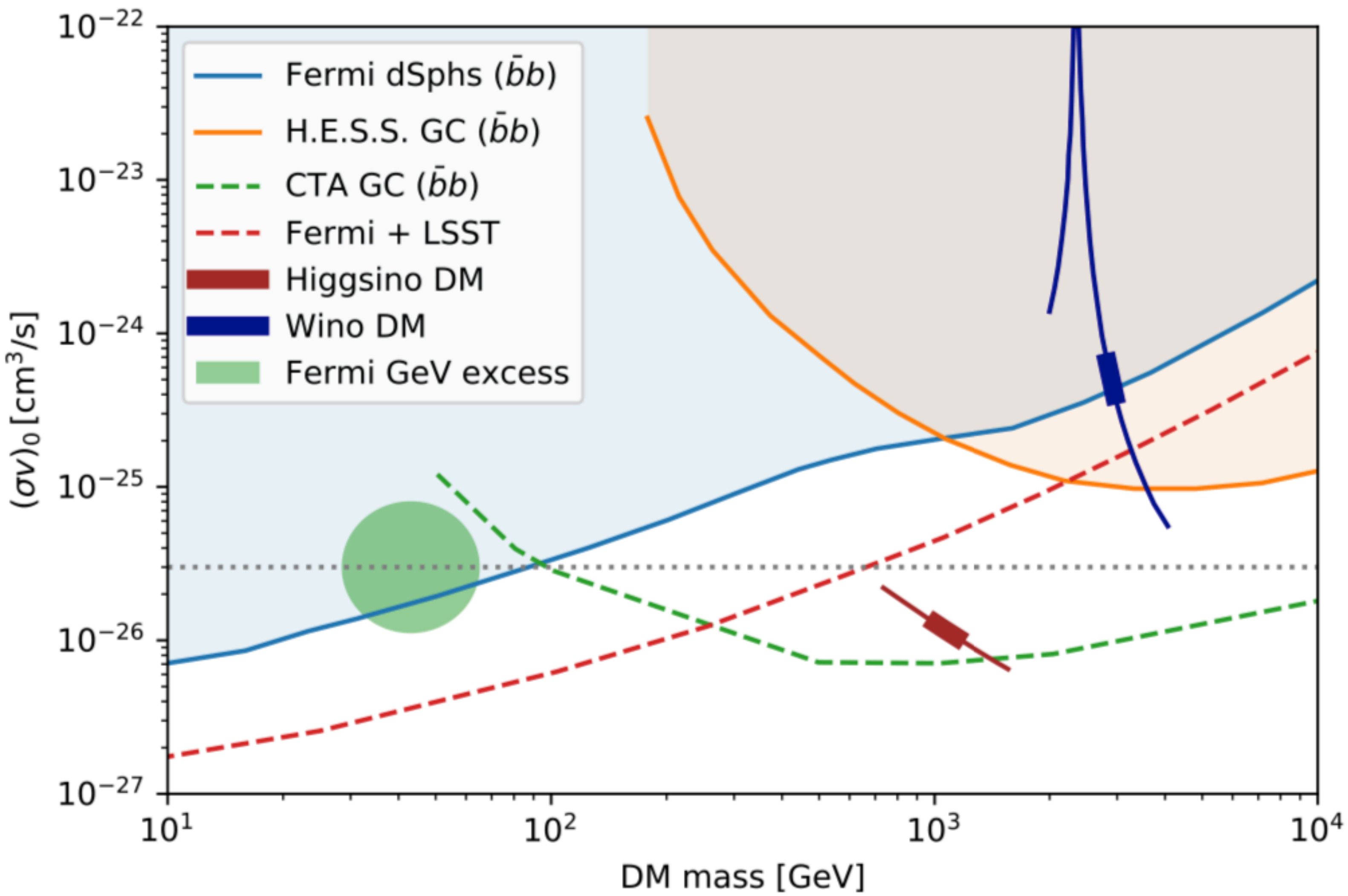
$$\langle \sigma v_{\rm rel} \rangle_q = \frac{3 m_q^2}{2\pi v^2} \frac{g_q^2 g_{\rm DM}^2 m_{\rm DM}^2}{(M_{\rm med}^2 - 4m_{\rm DM}^2)^2 + M_{\rm med}^2 \Gamma_{\rm med}^2} \sqrt{1 - \frac{m_q^2}{m_{\rm DM}^2}}$$

$$\langle \sigma v_{\rm rel} \rangle_g = \frac{\alpha_s^2}{2\pi^3 v^2} \frac{g_q^2 g_{\rm DM}^2}{(M_{\rm med}^2 - 4m_{\rm DM}^2)^2 + M_{\rm med}^2 \Gamma_{\rm med}^2} \left| \sum_q m_q^2 f_{\text{pseudo-scalar}} \left(\frac{m_q^2}{m_\chi^2} \right) \right|^2$$

arXiv:1603.04156



Indirect detection plots with Higgsino/Wino

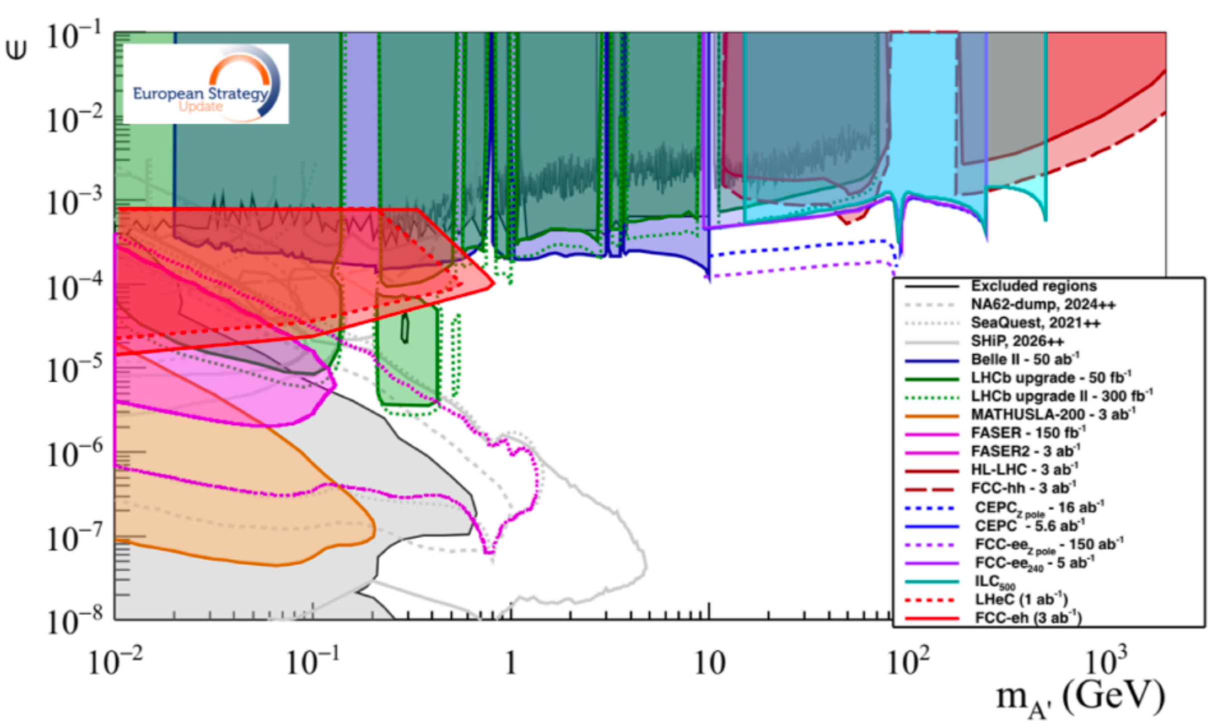


As shown in Chapter 8, Wino DM can also be probed with the FCC-hh [443] and LE-FCC, while slightly lighter Wino-like dark matter would be already accessible for HE-LHC [443] and CLIC$_{3000}$ [345].

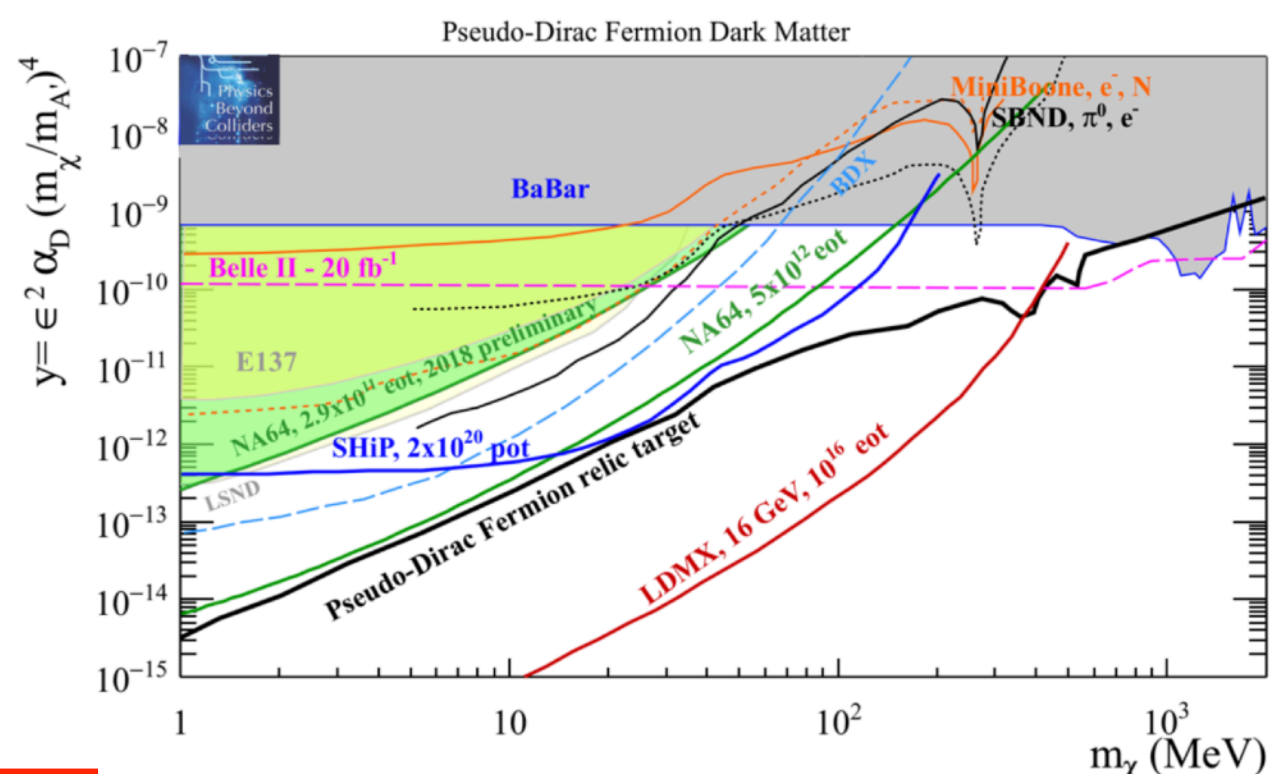
Light DM prospects (a quick overview)

- Four benchmark models for **dark sector** searches:
  - Dark photon, Heavy Neutral Lepton, Dark Higgs, Axion-like particle
- Benchmark with thermal dark matter interpretation: dark photon (invisible decays) → **complementarity of collider and non-collider experiments**

Visible dark photon decays



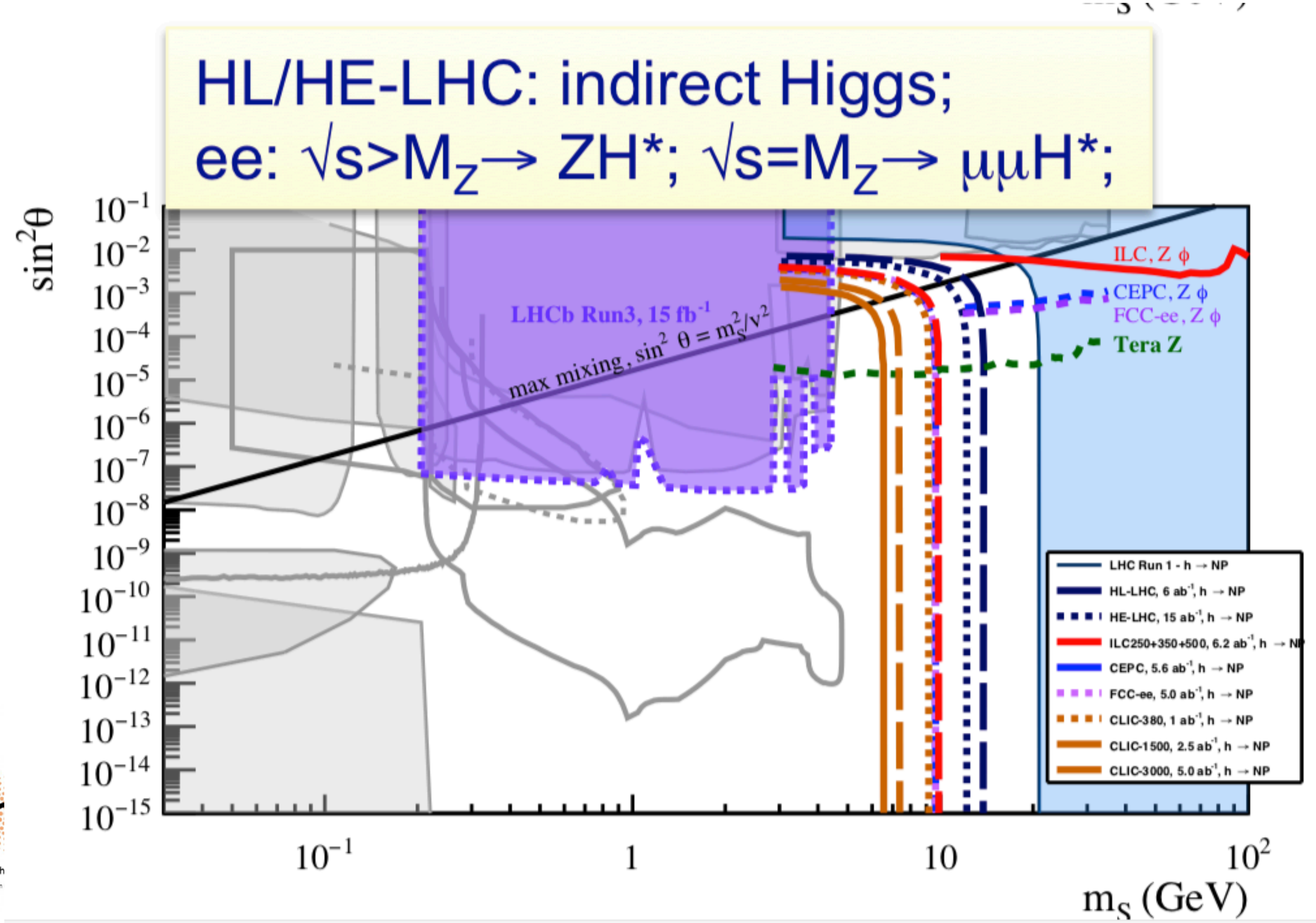
Invisible dark photon decays



Note: HL-LHC and FCC projections assume 8 TeV trigger thresholds…essential to think of future collider detectors, trigger & DAQ together with physics

Light DM prospects (a quick overview)

- Four benchmark models for **dark sector** searches:
  - Dark photon, Heavy Neutral Lepton, Heavy Higgs, Axion-like particle
- Dark Higgs portal sensitivity comparisons of future colliders

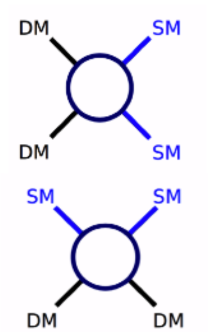


European Research

Conclusions & outlook (from European Strategy)

Huge progress planned on **DD and ID front**

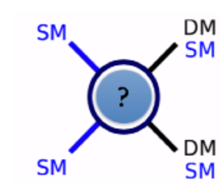
Future colliders can follow: essential **complementarity** between



cosmological origin
DD/ID/astrophysics

and

nature of the DM-SM interaction
colliders(/beam dumps)



This talk covered **simple models** used for comparison and contextualization

- SM-DM interactions mediated by **Higgs boson / EW bosons (SUSY)**
- SM-DM interactions mediated by **new BSM particle**

Strengths in WIMP searches both in **future (lepton and) hadron** options:

- combined FCC program shows best sensitivity to benchmarks
  - still, needs complementary experiments (DM != WIMP only)
- lepton colliders can also probe large parts of phase space thanks to precision environment

Next 10 years: hope for **concerted effort (including tools & foundations)**
between DD/ID/colliders/other experiments
to **discover and understand** a possible **particle nature of DM**

Open points from the European Strategy experience

(to be taken up for Snowmass? We decide together!)

On **benchmarks:**

- Missing in terms of signatures & benchmark models:
  - t-channel simplified models (only s-channel considered)
  - Long lived collider signatures beyond disappearing track (connections to EF8 and EF9)
    - Also the hardest to make projections for without a precise detector simulation

On **comparison plots with DD/ID/other experiments:**

- Can we have an open discussion on how to improve those plots together with Cosmic & Underground frontier? E.g.
- Current ESG DM summary plots only show hadron colliders, how to add lepton colliders?
- Showing a single simplified model / o(1) coupling is not representative, how to improve?
- How to display effect of uncertainties?
- Can we solve the "can colliders go below 1 GeV WIMP" question?
- Do we also want to compare to direct detection for minimal DM models (Wino/Higgsino)?
- …many other points came up during the discussions with DM & dark sector European Strategy convenors (Marcela Carena and Shoji Asai), to be continued

Closing remarks

How to make the most of the European Strategy for Snowmass

- Remember that the **purpose and organization** of the two efforts is different
  - As members of the Snowmass community,
    we are encouraged to come up with **our own big questions**
  - More of this in today & future **discussion session**

- We want to build upon what we have learned, without duplicating work…
- …but we want to **fill the gaps**, if any
  - This is a great time to **update studies** and **start new ones**!

Form for interest in the group: [link]

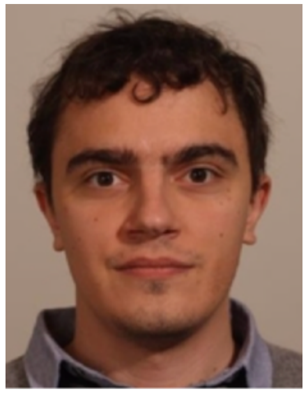
- can be used to inject ideas and topics into this group
- could be useful if you have ideas and are looking for collaborators
- does not substitute Letters of Intent, but could be seen as an informal step towards those

Thanks for your attention
(and thanks to the junior physicists who worked on many of those European Strategy plots)!

CLICdp projections:
Ulrike Schnoor (CERN)

with Andrea Wulzer, Philipp Roloff, Jean-Jacques Blaising

Scalar projections:
Marco Rimoldi (DESY)



with Francesca Ungaro, Hideki Yukawa, Oleg Brandt

Direct Detection:
Isabelle John (Lund)

with CD, Emma Tolley, Antonio Boveia, Jocelyn Monroe

Indirect Detection:
Boyu Gao (OSU)

with Emma Tolley, Linda Carpenter, Antonio Boveia, Christoph Weniger

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Backup slides

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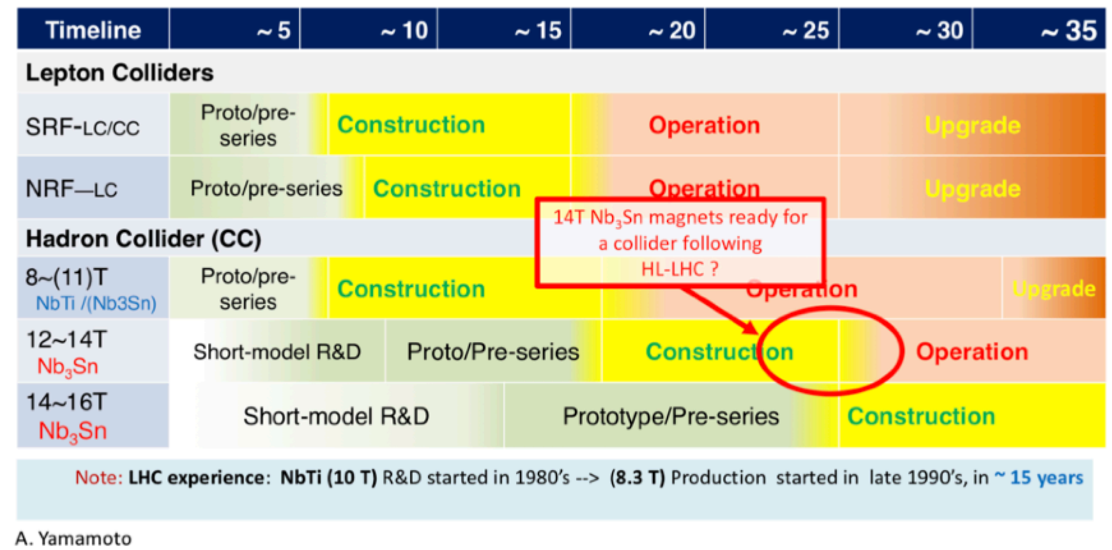
Accelerators

A (tentative) timeline of future colliders

V. Shiltsev's talk @ Granada
https://arxiv.org/abs/1905.03764

- Technology for lepton colliders ready earlier than for high-energy hadron colliders
- Example: magnets & accelerators

From **C. Biscari**'s talk @ EPSHEP'19



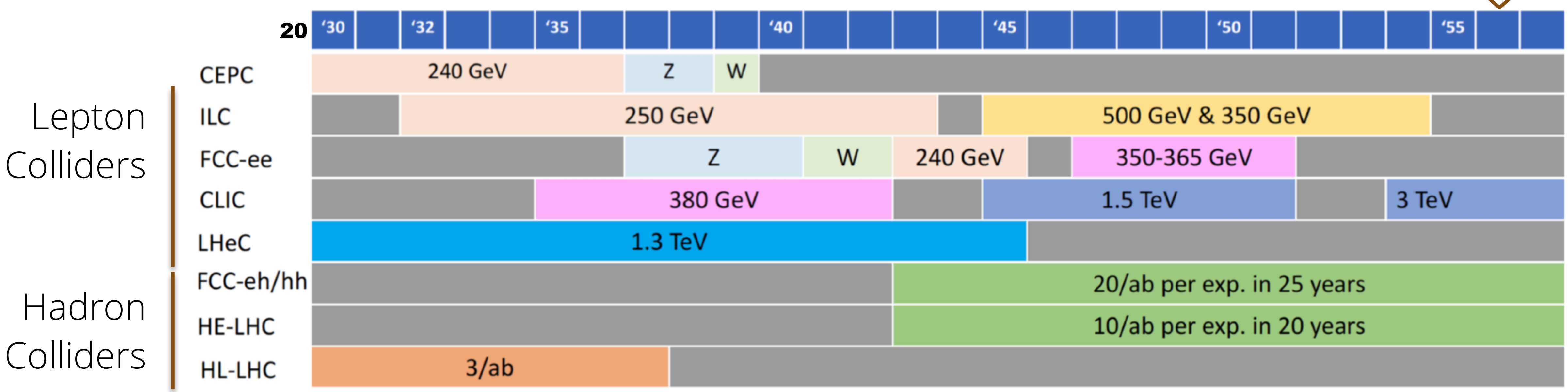


Figure 13. Sketch of timeline of various collider projects starting at the "earliest start time" stated in the respective documents. For FCC-eh/hh this figure assumes that it is not preceeded by FCC-ee. If it comes after FCC-ee it would start in the early 2060s.

Input scenarios for colliders, from Higgs PPG

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	$\pm80/\pm30$	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	$\pm80/\pm30$	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	$\pm80/\pm30$	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	$\pm80/0$	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	$\pm80/0$	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	$\pm80/0$	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

https://arxiv.org/abs/1905.03764

Full programs include earlier versions / CoM energies

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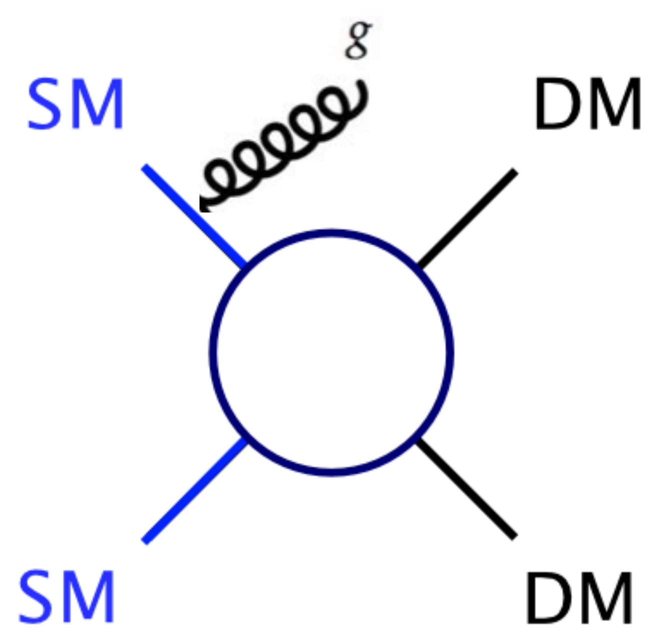
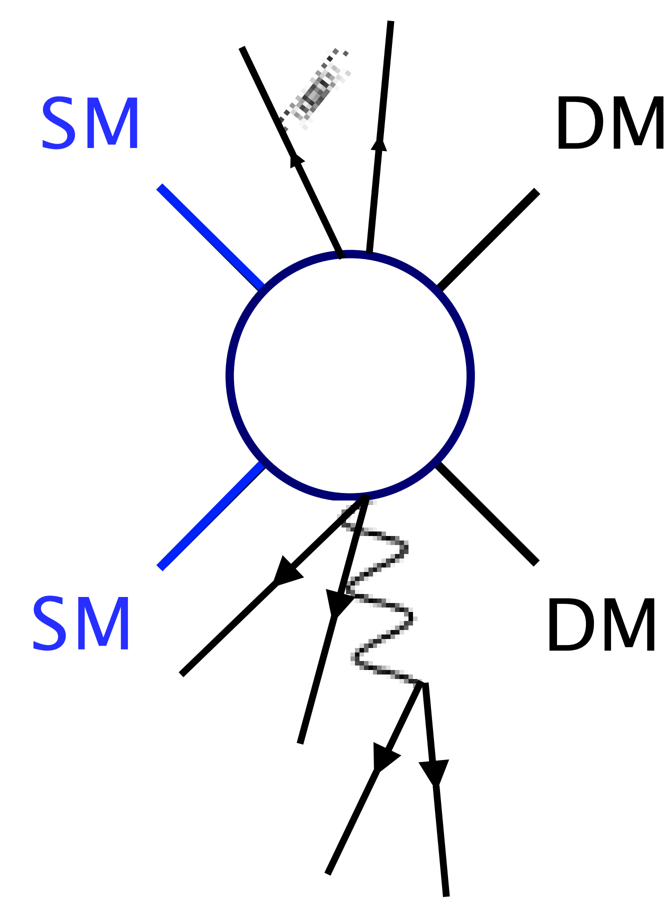
Benchmarks and searches

Broad categories of searches for DM@colliders

Generic searches ⟷ More specific searches





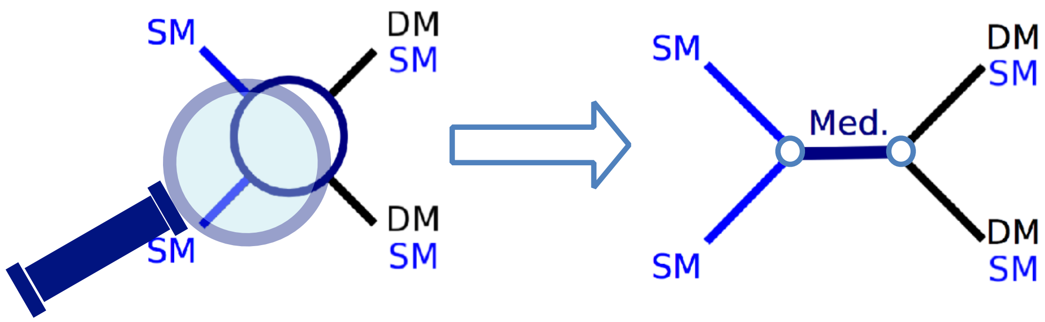
→ the way we think of benchmark models **influences searches**

34

Many different benchmarks for collider searches

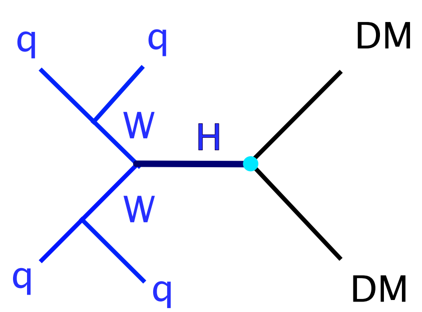
Simple models ⟷ More complex/complete models

Simple DM mediation



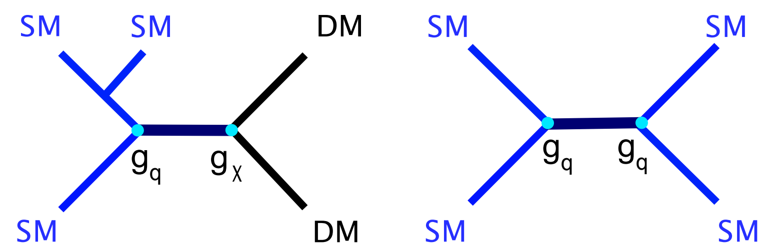
SM mediator

- **Z/Higgs** portals

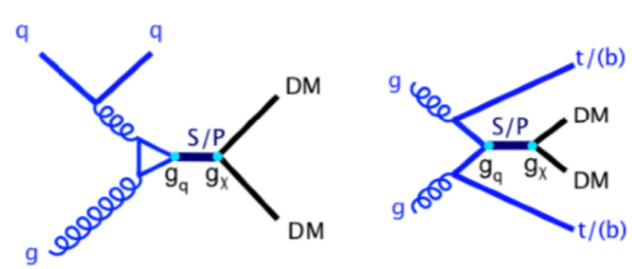


Beyond-SM mediator

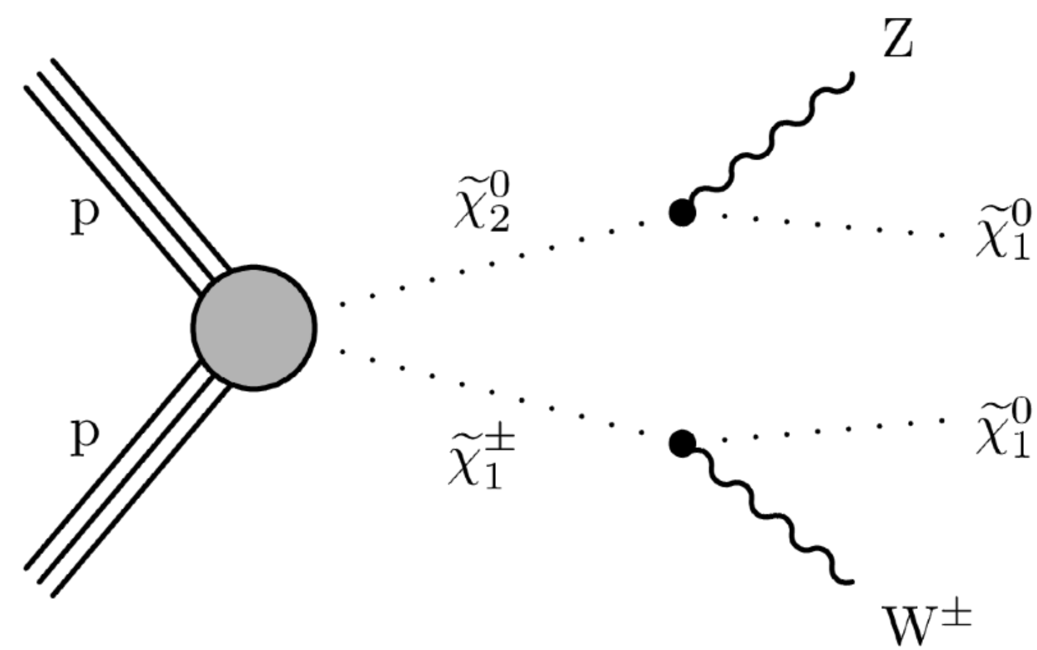
- **Vector-like** mediator



- **Scalar-like** mediator and Two Higgs Doublet Models



Supersymmetry: Wino/Higgsino



(*Simplified model* diagram)

[JHEP 03 (2018) 160](#)

A. Weiler and M. D'Onofrio's talks @ Granada

Also: DM models with long-lived particles

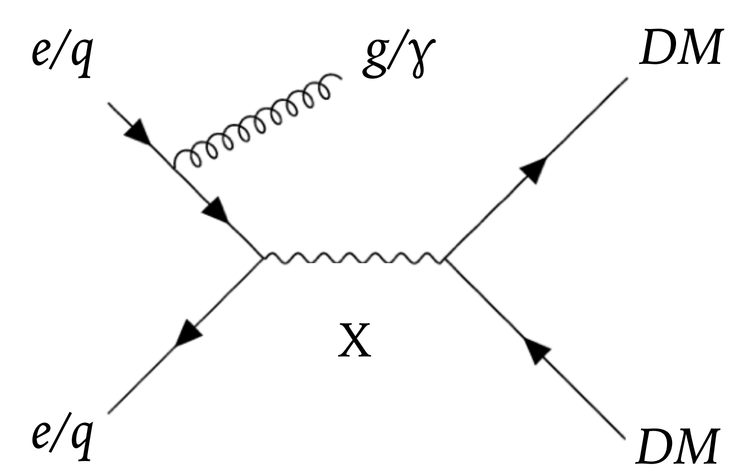
G. Perez and G. Lanfranchi's talks @ Granada

R. Poettgen and A. Vallier's talks @ Granada

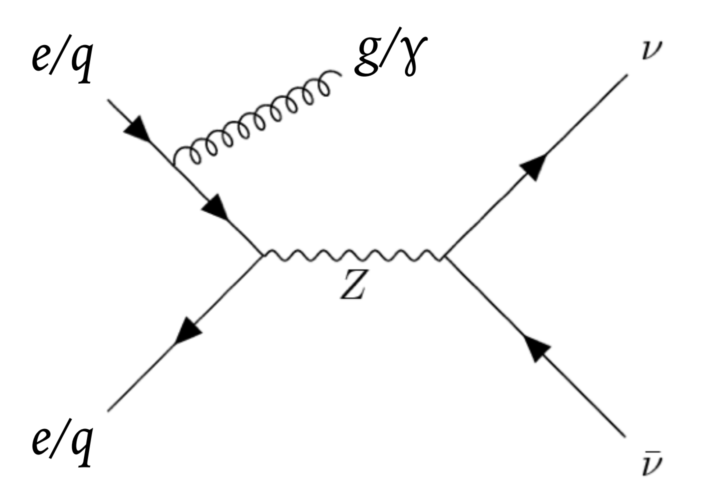
Searches for DM @ colliders ("MET searches")

Process of interest:
invisible (**DM**) particles
produced in association with
radiated **recoiling SM particle**

example DM process



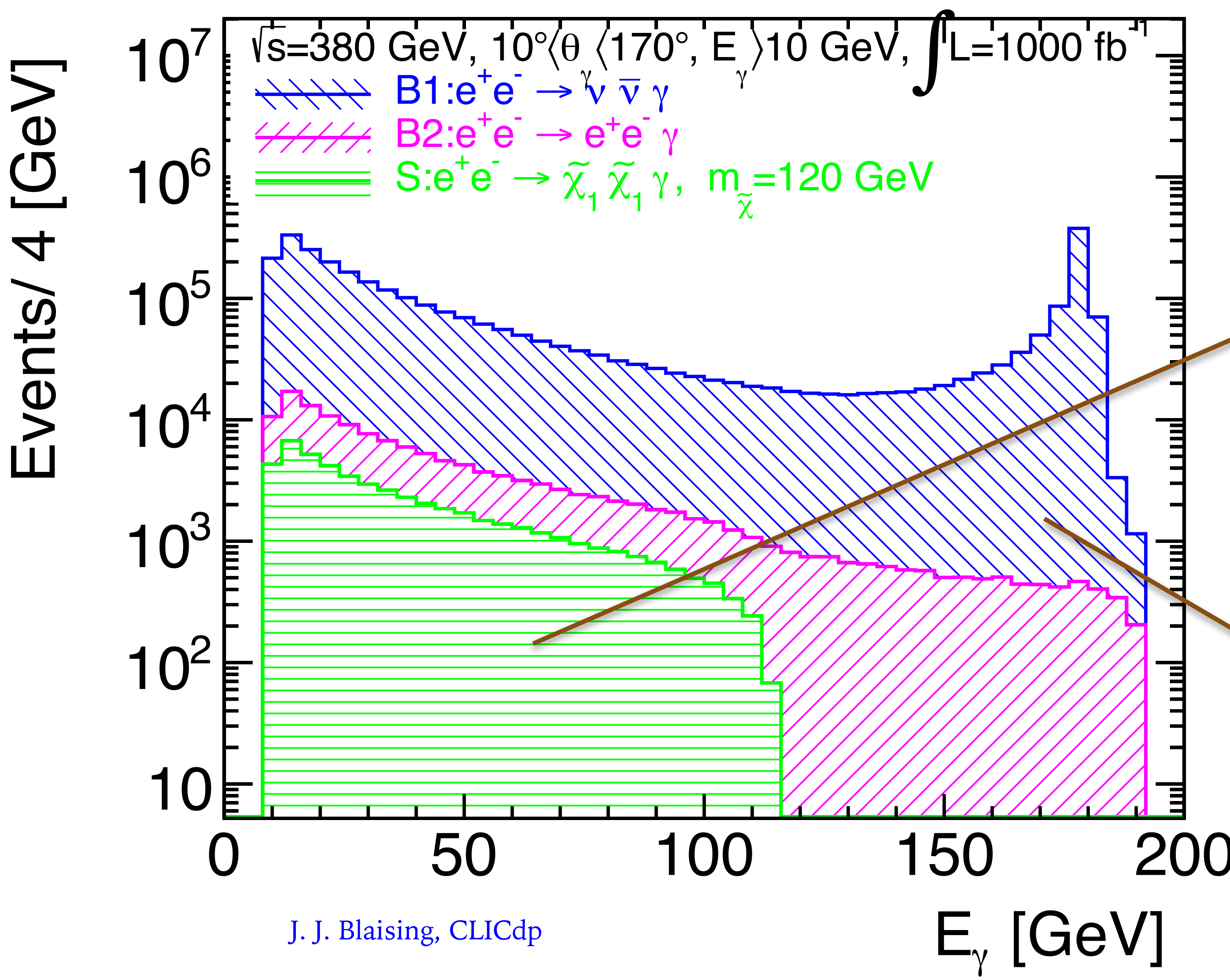
Production of invisible particles
is common in the SM:
backgrounds **need precise estimation**

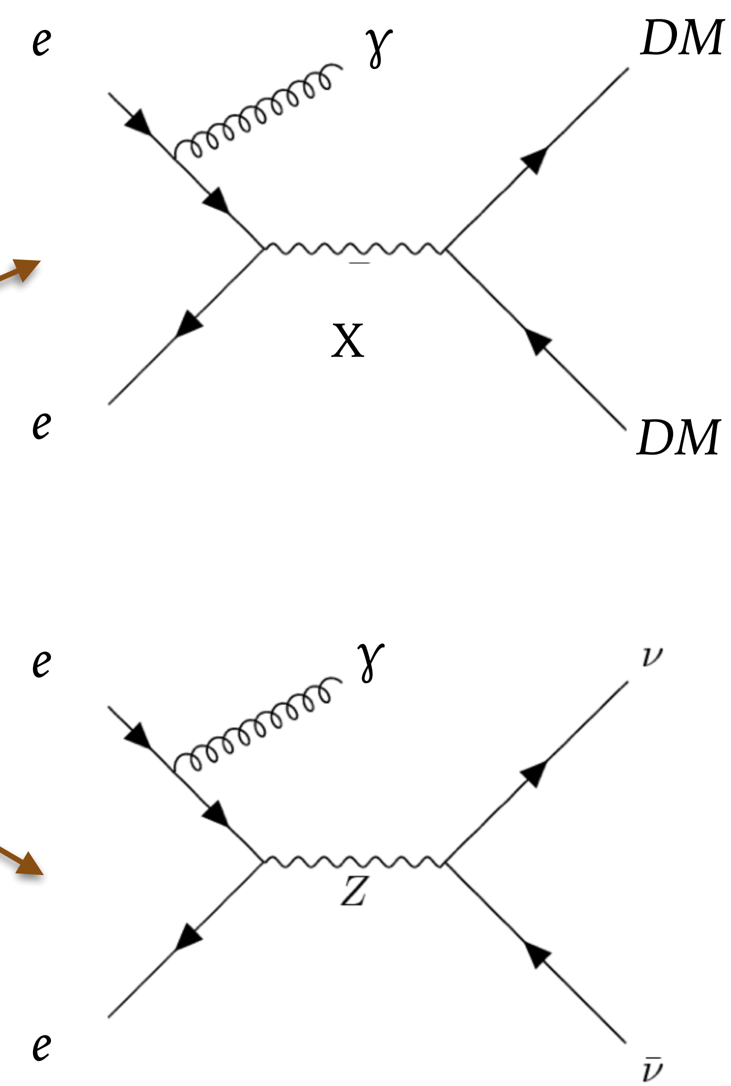


↑

input from theory/precision machines

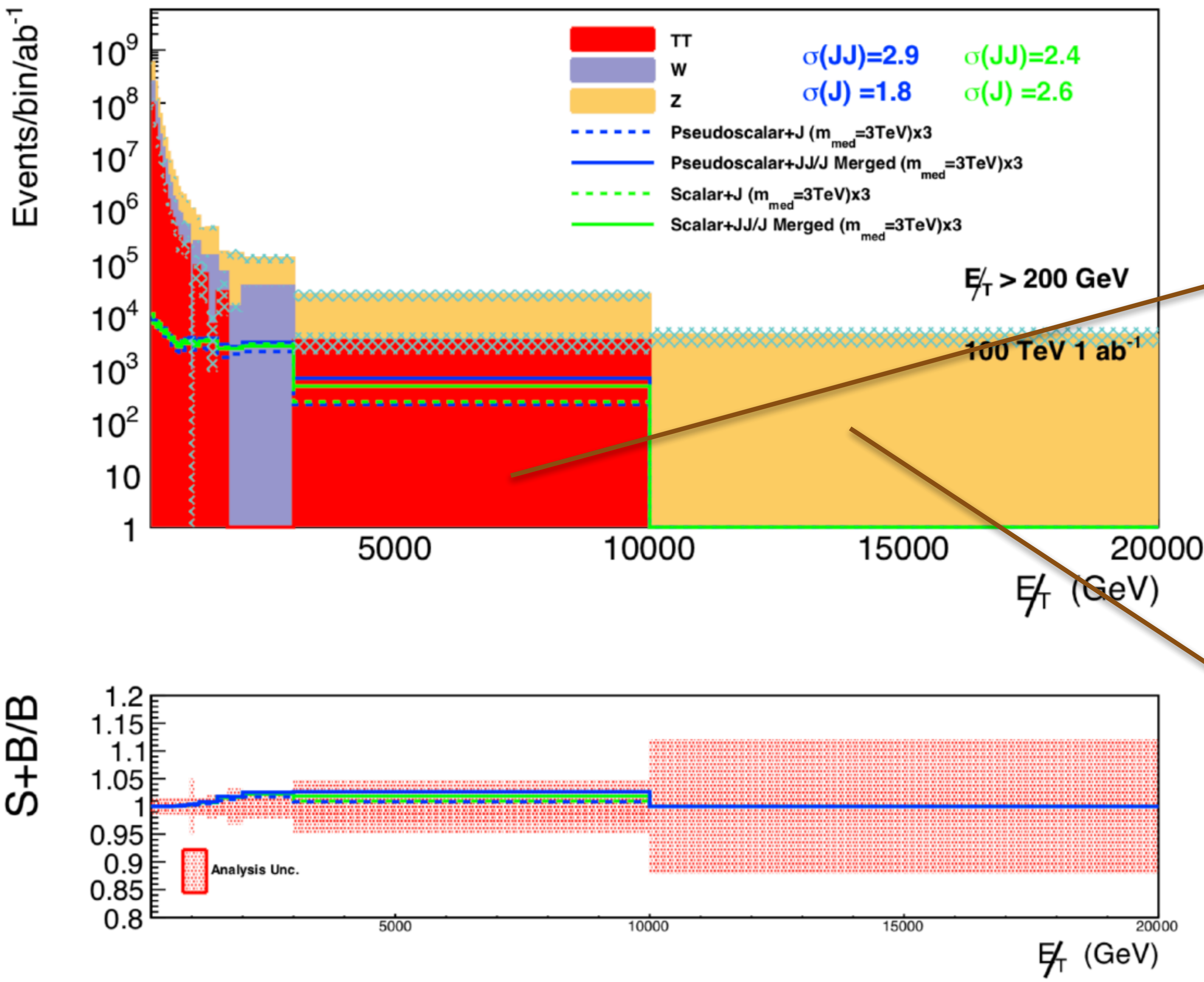
Searches for DM @ lepton colliders



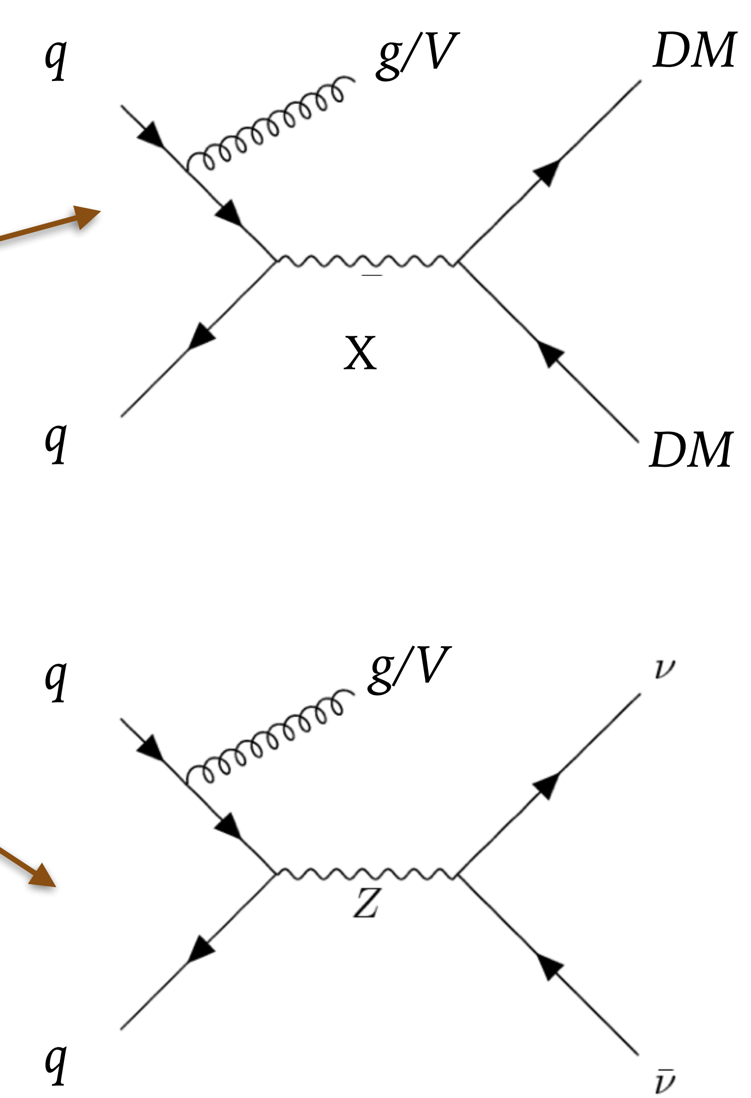


+ other backgrounds, e.g. W t-channel…

Searches for DM @ hadron colliders

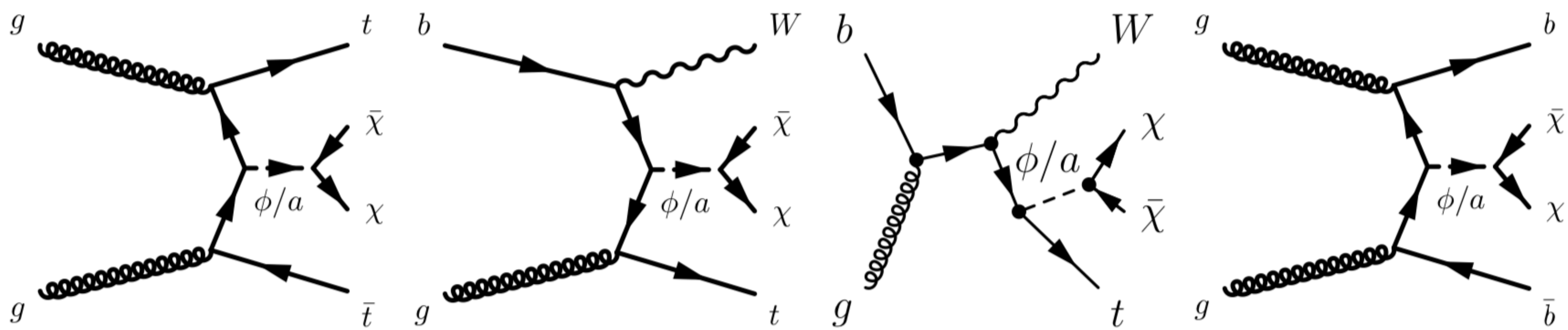


arXiv:1509.02904

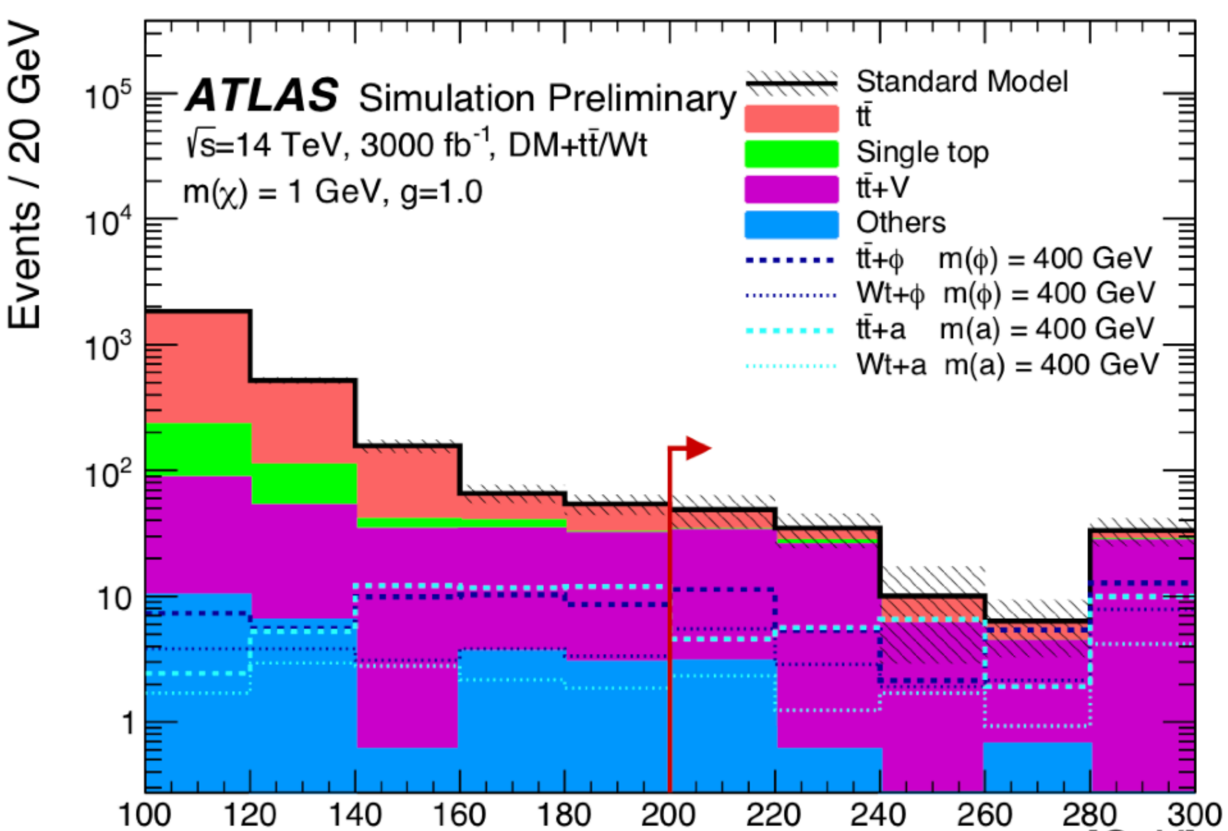


+ other backgrounds, e.g. W, top

Searches for DM @ hadron colliders - with heavy quarks



(a) DM+$t\bar{t}$ (b) DM+Wt (c) DM+Wt (d) DM+$b\bar{b}$



[arXiv:1902.10229 and ATL-PHYS-PUB-2018-036]

More sophisticated searches when using other objects to discriminate signal/background

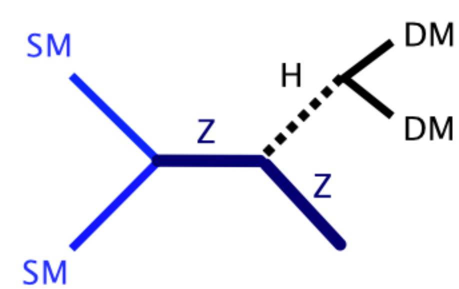
e.g. stransverse mass M_{T2} for semi-invisible decays

Visible decays of the mediator relevant in all cases
—> connection with EF03/EF09

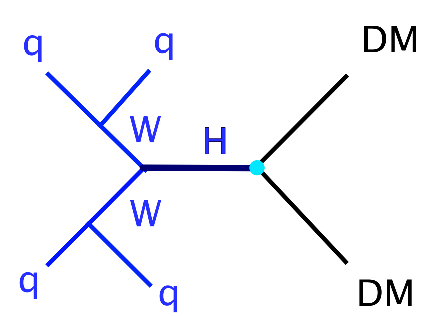
Searches for DM using other signatures

"MET+X" searches also include the following signatures:

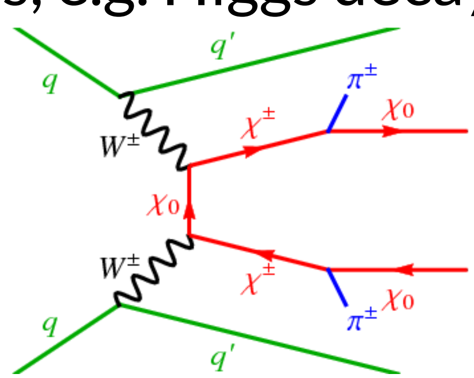
- "**Intermediate" radiation** (e.g. Higgs-strahlung)
    - MET = DM
    - X = decay products of the particle that radiated the DM mediator



- **Vector Boson Fusion**
    - MET = DM
    - X = forward jets



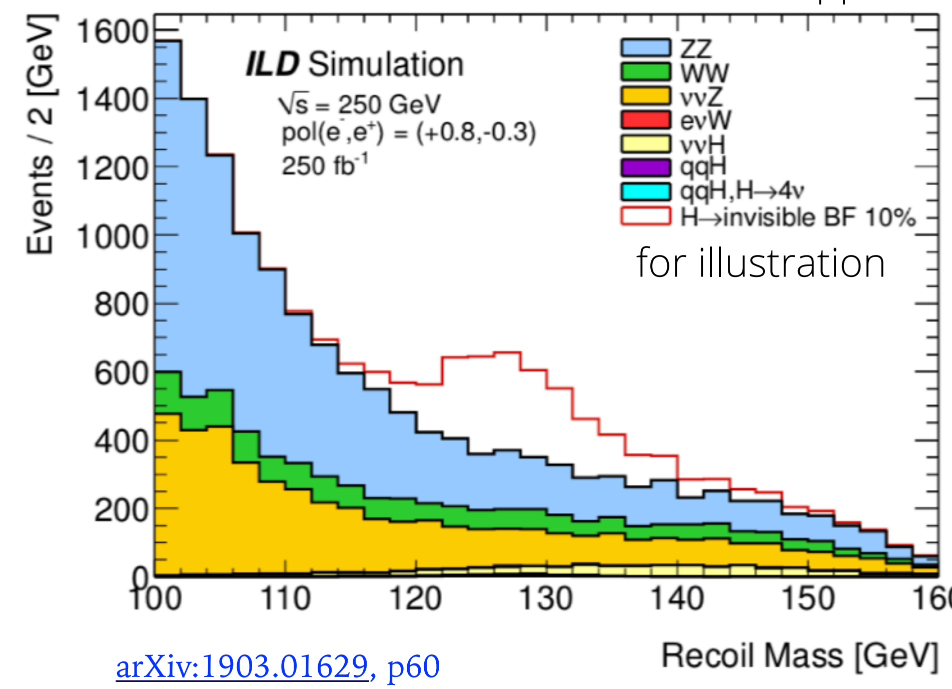
Sensitive to a variety of models, e.g. Higgs decays to DM (see later), pure WIMP triplet,



arXiv:1902.10229 and ATL-PHYS-PUB-2018-038

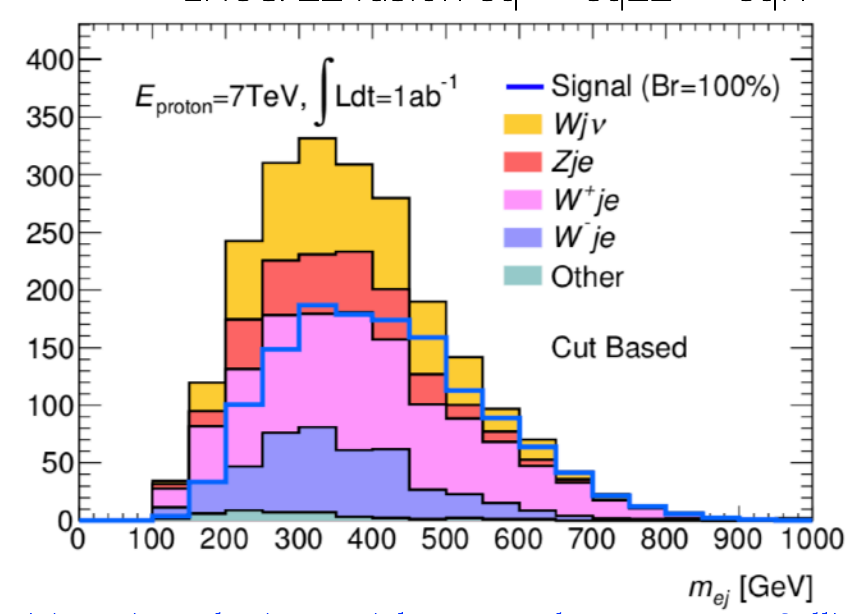
+ others…

ILC: H→inv., Z→qq



arXiv:1903.01629, p60

LHeC: ZZ fusion eq → eqZZ → eqH



Precision Higgs Physics at High-Energy Electron-Proton Colliders, LHeC Higgs Study Group, G.~Azuelos et al, in preparation.

Higgs portal model

arXiv:1903.03616

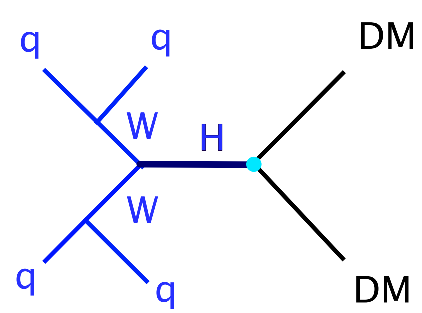
$$\Delta\mathcal{L}_\chi = -\frac{1}{2}M_\chi\bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\bar{\chi}\chi\,.$$

$$\Delta\mathcal{L}_S = -\frac{1}{2}M_S^2S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HSS}\Phi^\dagger\Phi S^2\,,$$

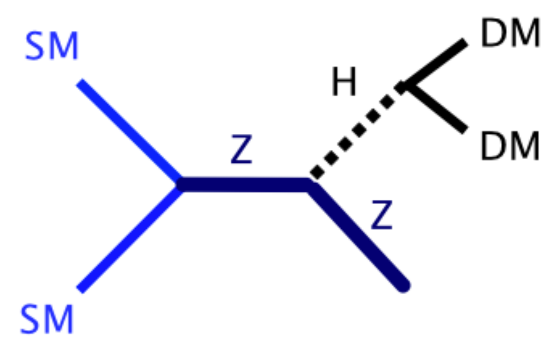
Lambda for fermion EFT: assumed 1 TeV

- Different kinds of dark matter
  - Majorana fermion DM
  - Scalar DM
  - Vector DM: would need more advanced UV completion, not covered here, see e.g. arXiv:1512.06853

- How to detect invisibly decaying Higgs:
  - **directly** (MET searches)



VBF signature



Higgs-strahlung signature

  - **indirectly** (deviation of SM coupling through fits, using κ-framework)
    - including only σ x Branching Ratio (BR) measurements/ratios, no high-pT Higgs keeping SM BR fixed, only allow invisible BR to float in the fit (subtracting SM)
- Drawing from work by Higgs Physics Planning Group (PPG), arXiv:1905.03764

BSM mediators, Dirac DM

Vector/axial vector mediators

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q\,,$$

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma_5 q\,.$$

Scalar/pseudoscalar mediators

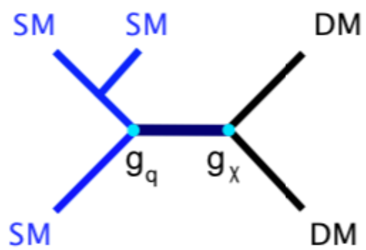
Yukawa couplings

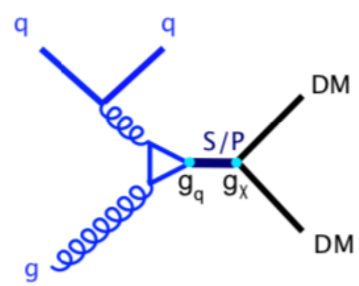
$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}} \phi \bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q\,,$$

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

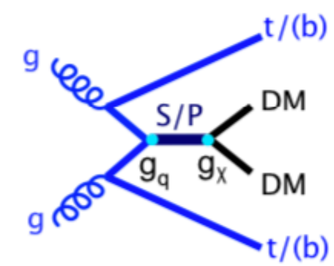
arXiv:1603.04156 & references

- How to detect new scalar mediators of DM:
  - **invisible decays** (MET searches)



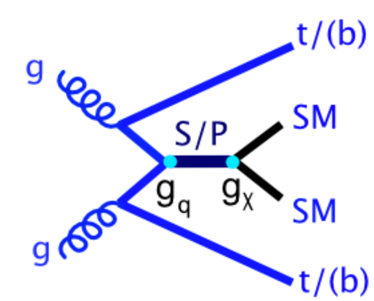


Vector & scalar: mono-jet or mono-photon searches



Scalar: also in association with heavy flavor quarks (also: single top, Wt signatures)

  - **visible decays of mediators back to SM**
    - especially relevant in case of dijet/dilepton decays
    - also 2HDM+pseudoscalar (HL-LHC benchmark)



4-top signatures

arXiv:1902.10229 and ATL-PHYS-PUB-2018-036

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Results

BSM scalar mediator

Yukawa couplings

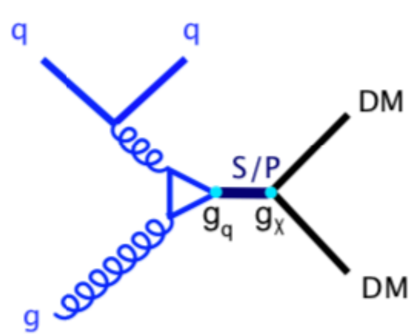
$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}}\phi\bar{\chi}\chi - g_q\frac{\phi}{\sqrt{2}}\sum_{q=u,d,s,c,b,t} y_q\bar{q}q\,,$$

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

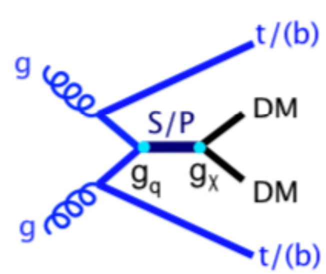
arXiv:1708.02245 & references

Also includes lepton couplings, requiring quark couplings for DD comparisons

- How to detect new scalar mediators of DM:
  - **invisible decays** (MET searches)



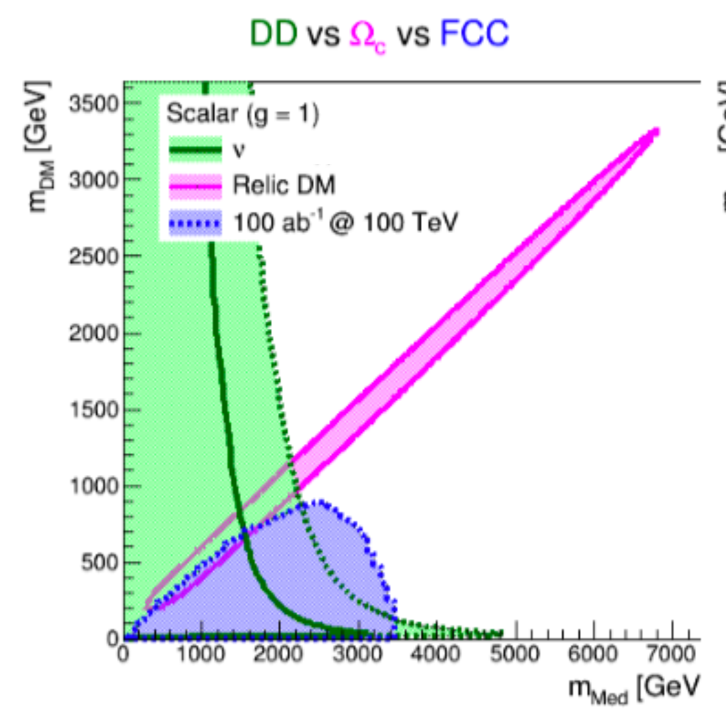
Mono-jet search
(or mono-photon)



In association with heavy flavor quarks
(also: single top, Wt signatures)

- Dark matter type considered:
  - Dirac fermion DM

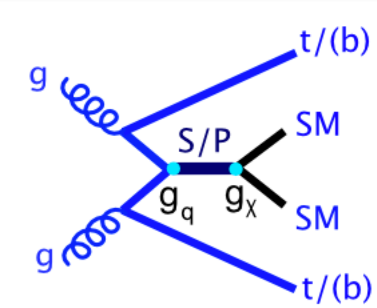
Relic density: not entirely probed



arXiv:1606.00947

- **visible decays of scalar/pseudoscalar mediators**
  - especially relevant in case of 2HDM+pseudoscalar (HL-LHC benchmark)

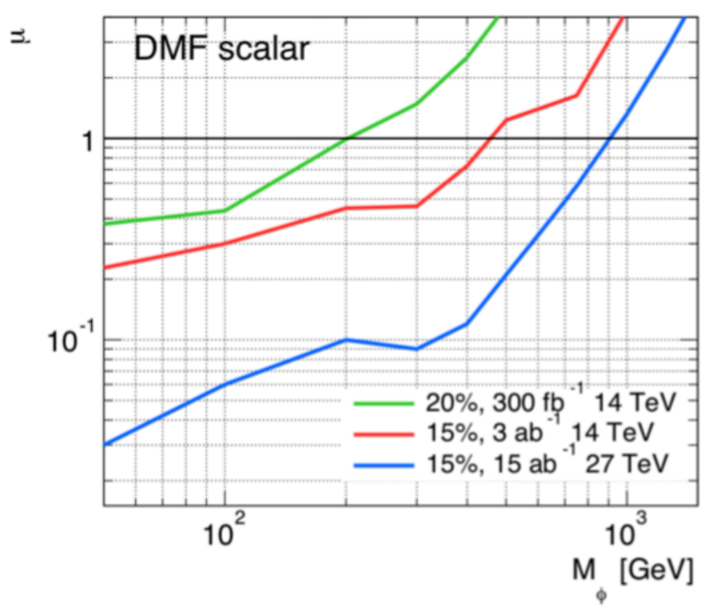
arXiv:1902.10229 and ATL-PHYS-PUB-2018-036



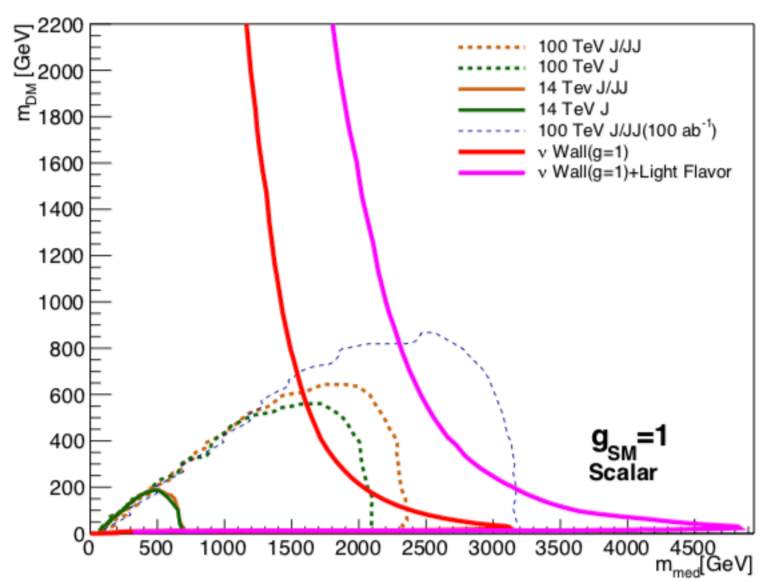
4-top signatures

Results for scalar mediators

Hadron colliders

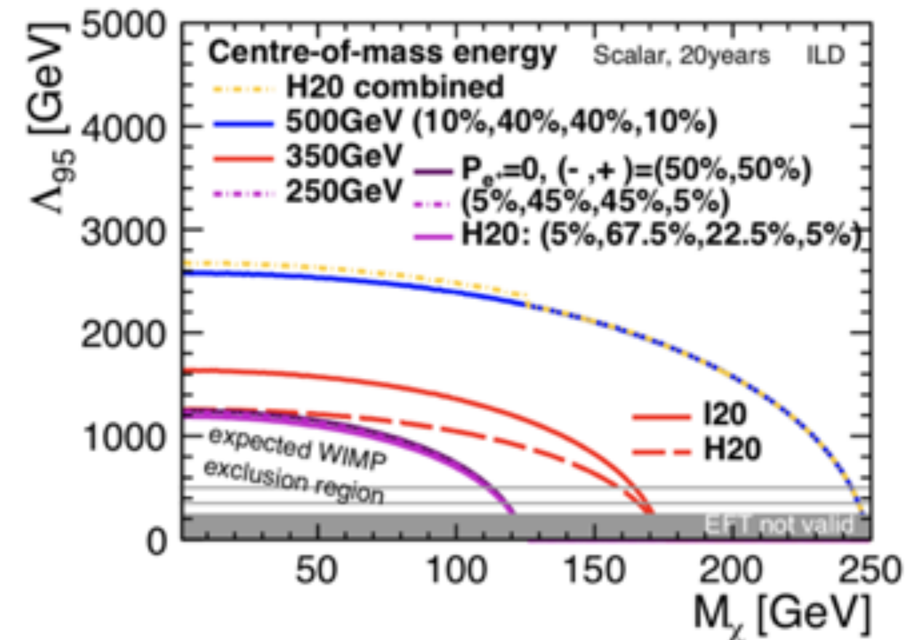


arXiv:1902.10229, p71

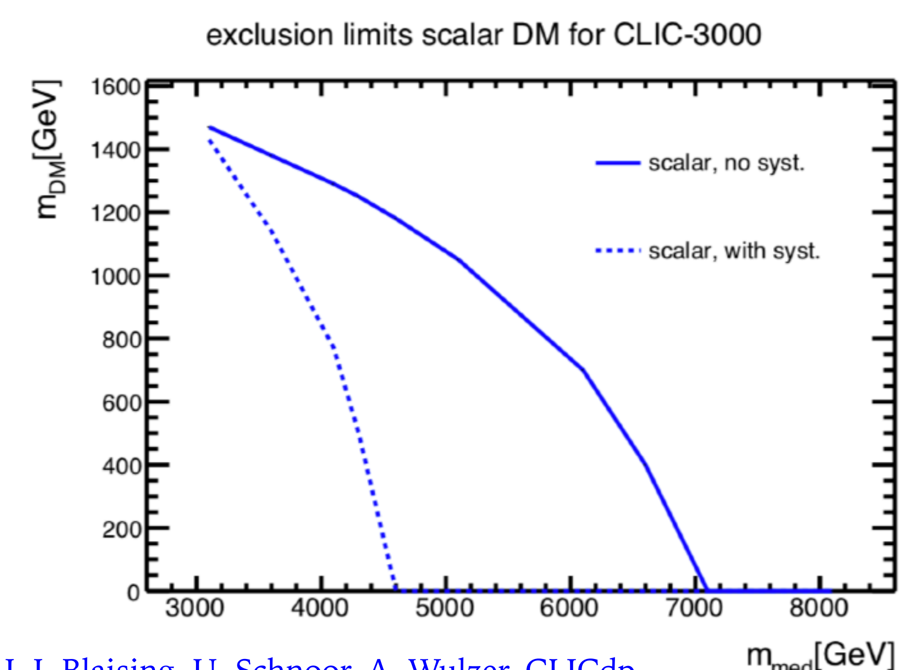


arXiv:1509.02904

Lepton colliders



M. Habermehl's PhD thesis



J. J. Blaising, U. Schnoor, A. Wulzer, CLICdp

Inputs for scalars, HE-LHC and HL-LHC

https://cds.cern.ch/record/2650173/files/report-2.pdf

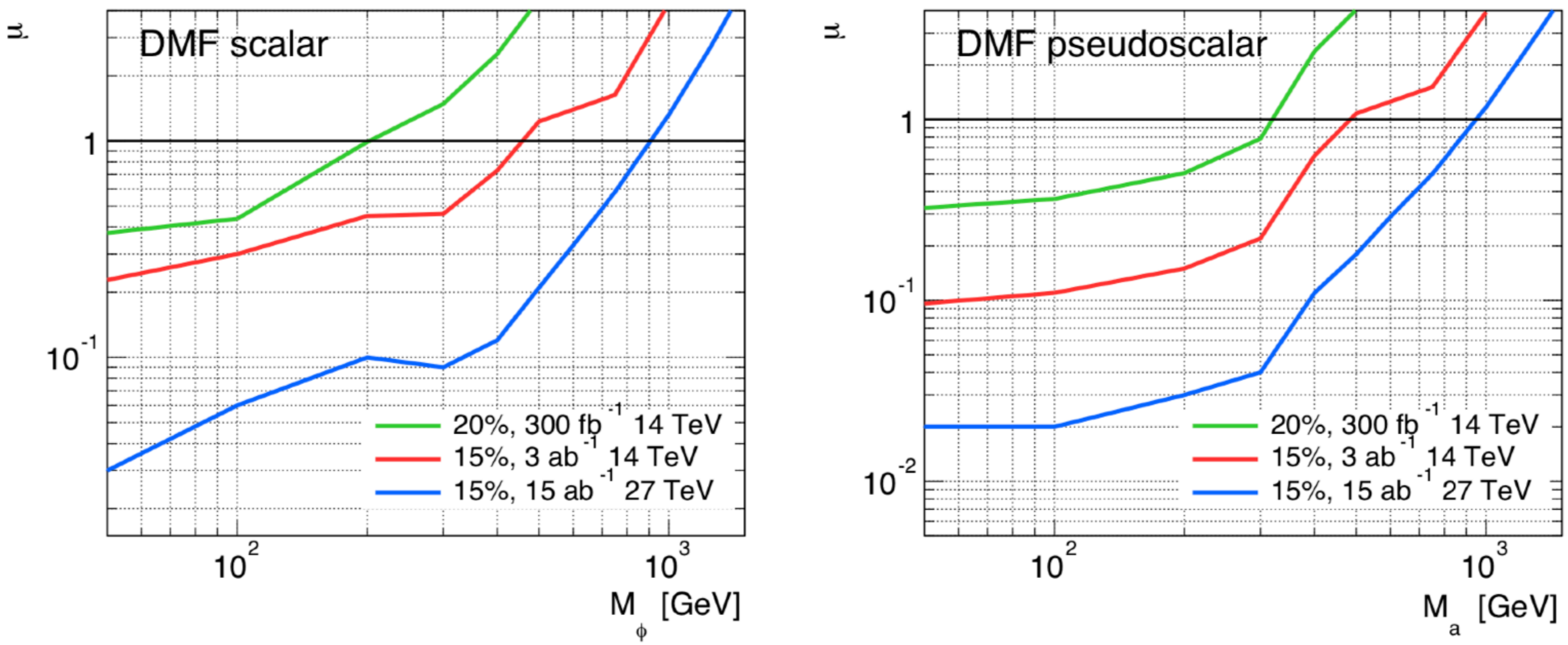
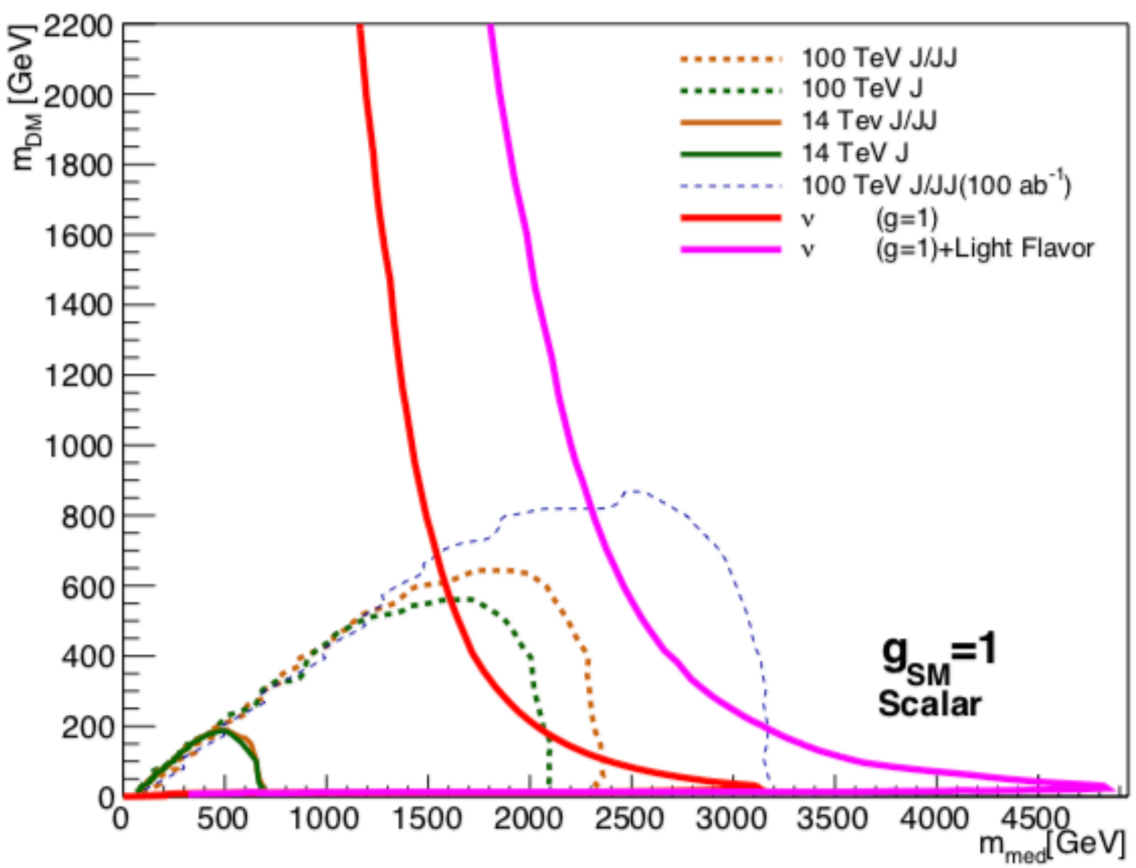
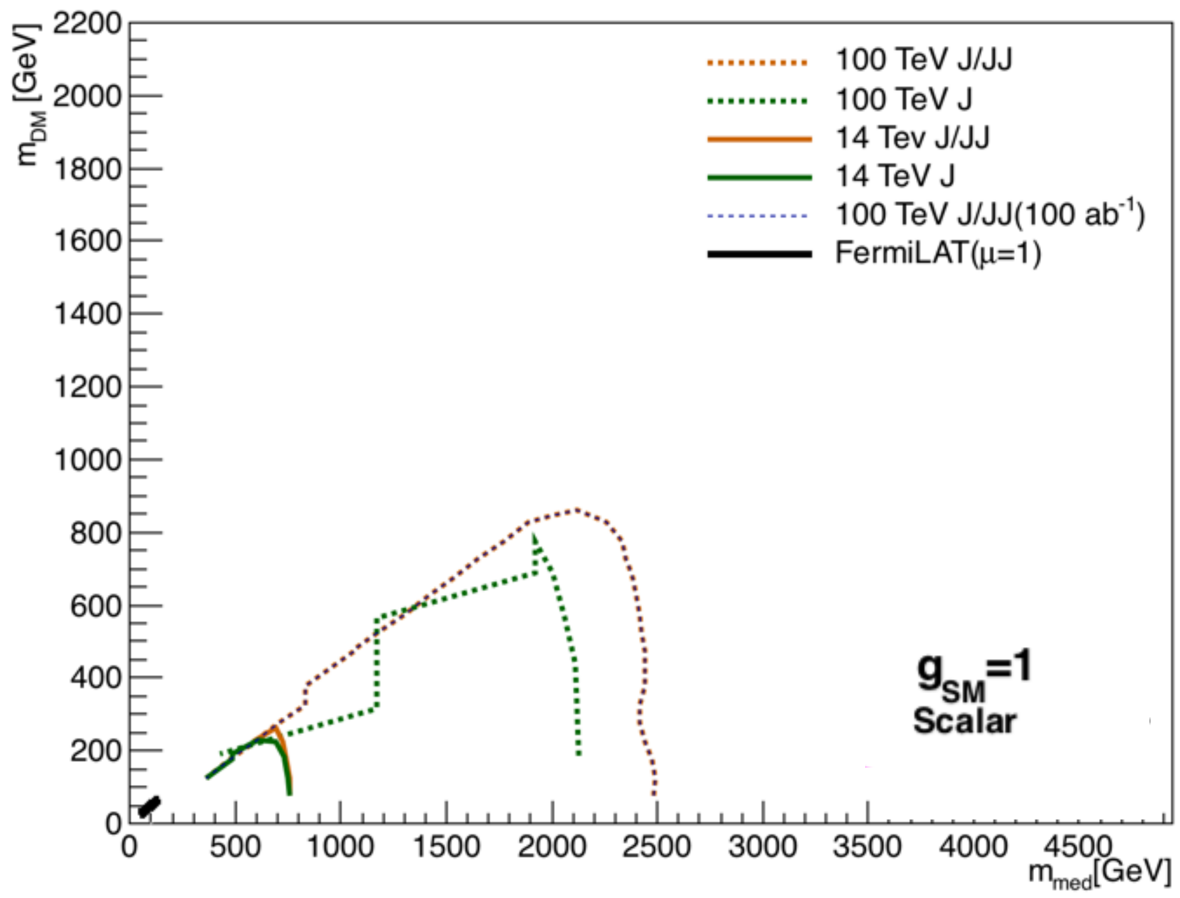


Fig. 3.2.4: Values of the signal strength μ that can be excluded at 95% C.L. as a function of the mass for DMF scalar (left) and pseudoscalar (right) mediators. The reach with $300\,\text{fb}^{-1}$ (LHC Run-3) and $3\,\text{ab}^{-1}$ (HL-LHC) of $\sqrt{s} = 14\,\text{TeV}$ data is given for a 5-bin shape fit with 20% (green curves) and 15% (red curves) errors. A hypothetical shape-fit scenario based on $15\,\text{ab}^{-1}$ of $\sqrt{s} = 27\,\text{TeV}$ of data (HE-LHC) and 15% systematics is also shown (blue curves).

Inputs from luminosity-scaled FCC-hh



Phil Harris, luminosity rescaling



mediator limit @ 100/fb: 3200 GeV

mediator limit @ 30/fb: 2500 GeV

Example: systematics for Higgs to invisible (ILC)

Akimasa Ishikawa, slides from ILC meeting 2014

Systematic	From 2016 data	This analysis
e-ID	1%(gsf)$\oplus$1%(idiso)	1%
μ-ID	1%(reco)$\oplus$1%(id)$\oplus$0.5%(iso)	0.5%
e-veto	0.6%(gsf)$\oplus$1.5%(idiso)	1%
μ-veto on QCD V+jets	5%(reco)$\oplus$5%(id)$\oplus$2%(iso)	2%
μ-veto on EWK V+2jets	10%(reco)$\oplus$10%(id)$\oplus$6%(iso)	6%
τ-veto	1–1.5% for QCD–EWK	0.5–0.75%
b-tag-veto	0.1% (sig) 2% (top)	0.05% (sig) 1% (top)
JES	14%(sig) 2%(W/W) 1%(Z/Z)	4.5%(sig) 0.5%(W/W) 0.2%(Z/Z)
Lumi	2.5%	1%
QCD multijet	1.5%	1.5%
Theory on W/Z ratio	12.5%	7%
ggH normalisation	24%	20%
QCDscale_qqH	$^{+0.4\%}_{-0.3\%}$	$^{+0.4\%}_{-0.3\%}$
QCDscale_accept_qqH	2%	1%
pdf_qqbar	2%	1%
pdf_accept_qqbar	1%	1%
QCDscale_ggH2in	40%	20%
QCDscale_YR4_ggH	$^{+4.6\%}_{-6.7\%}$	$^{+2\%}_{-4\%}$
pdf_gg	3.2%	1.5%
UEPS	16.8%	9%

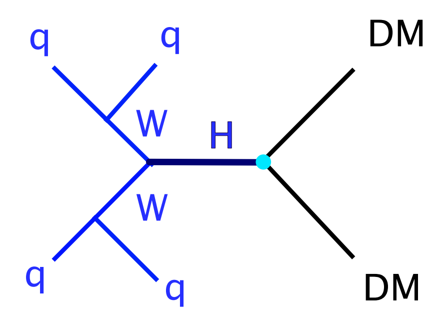
Higgs portal, plot for direct searches

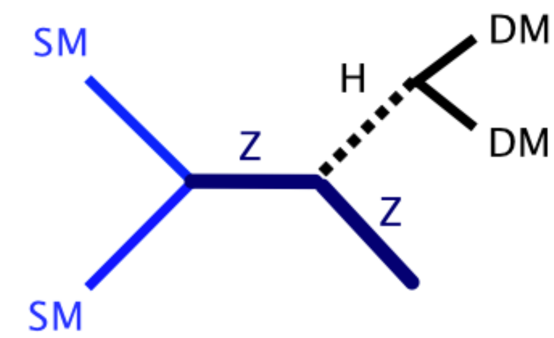
- Limits on BR can be translated to limits in the DM-nucleon plane

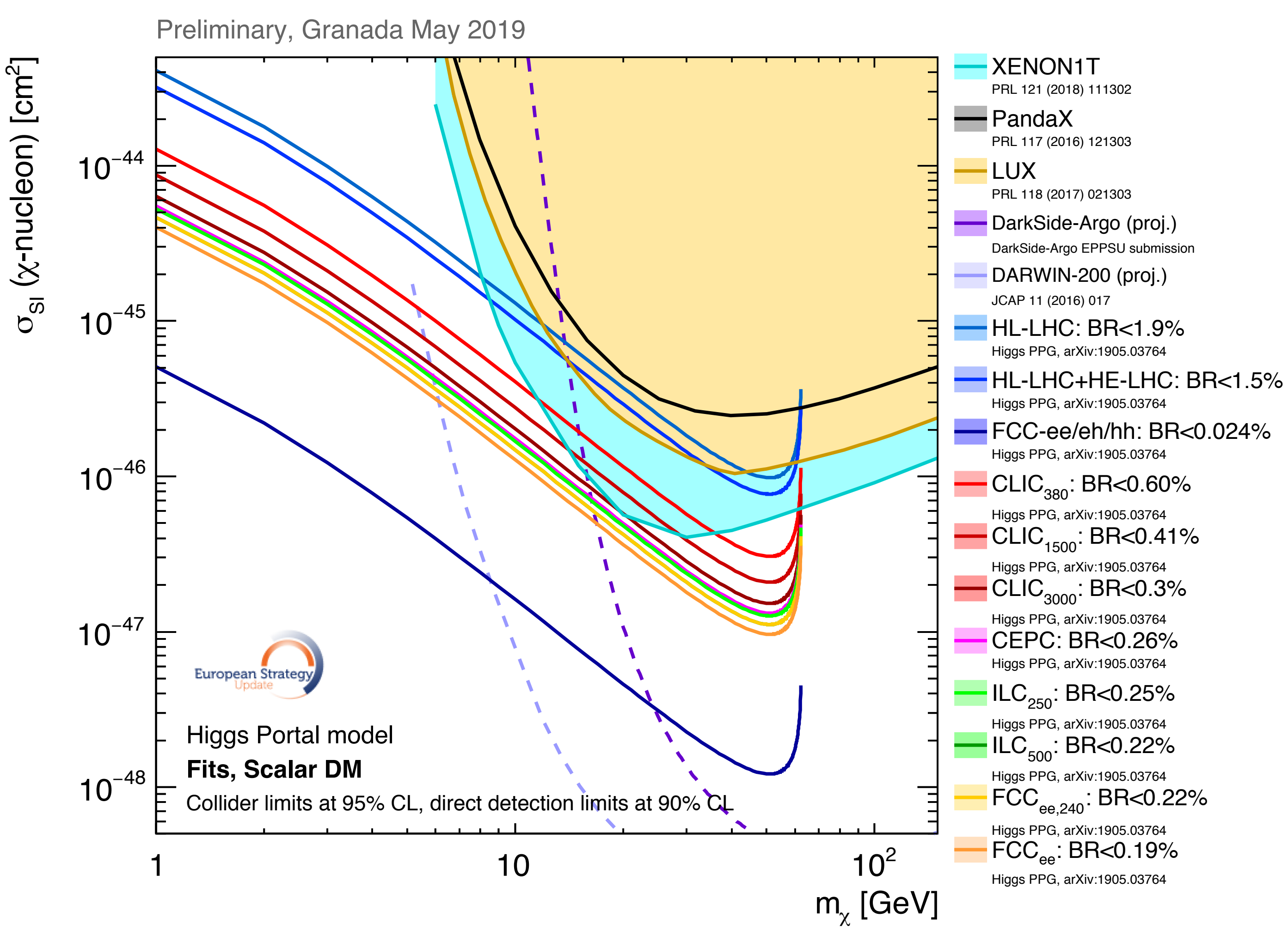
$$\sigma_{\chi N} = \Gamma_{\rm inv} \frac{8 m_N^4 f_N^2}{v^2 \beta m_h^3 (m_\chi + m_N)^2} g_\chi\left(\frac{m_h}{m_\chi}\right), \qquad (15)$$

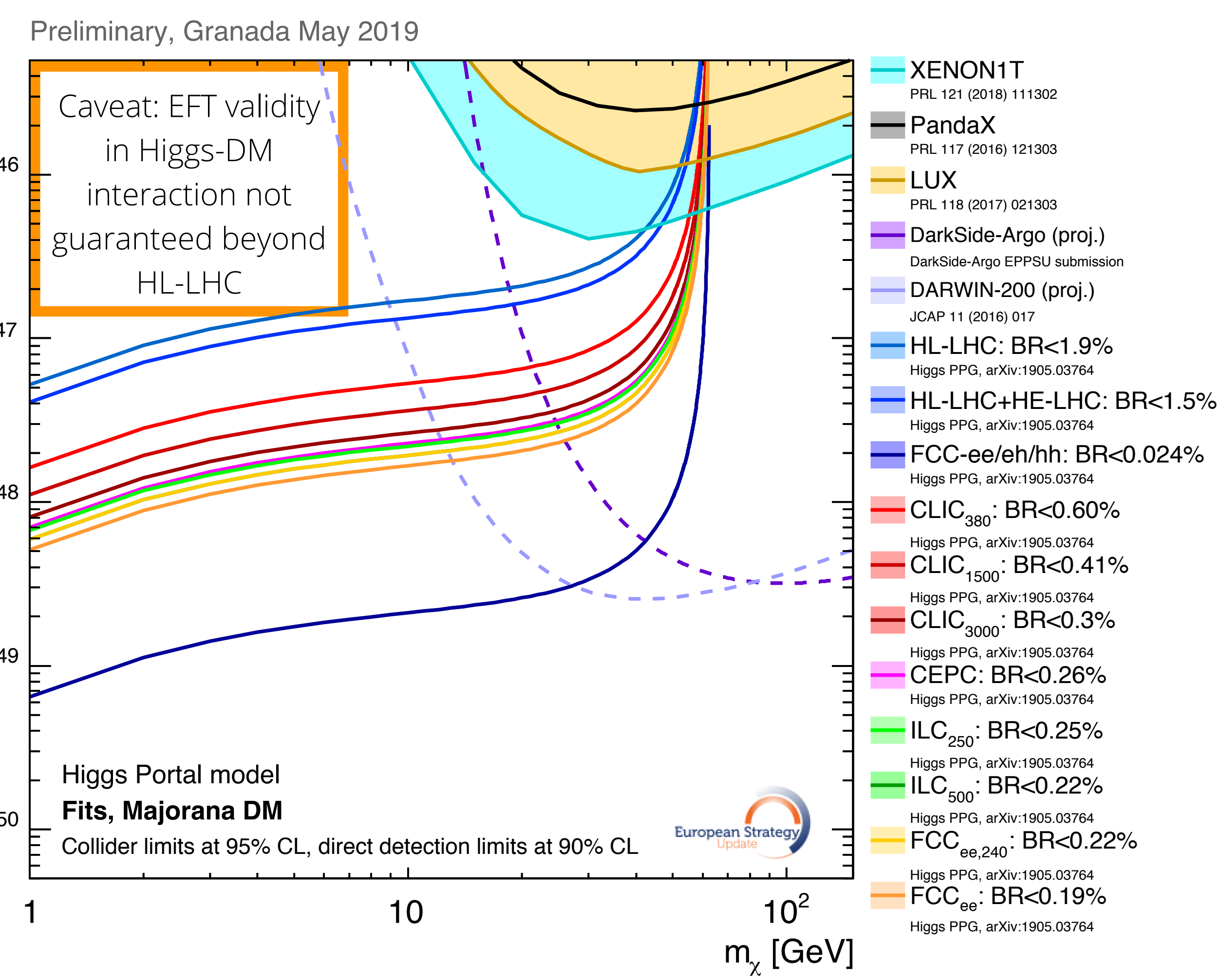
arXiv:1708.02245

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







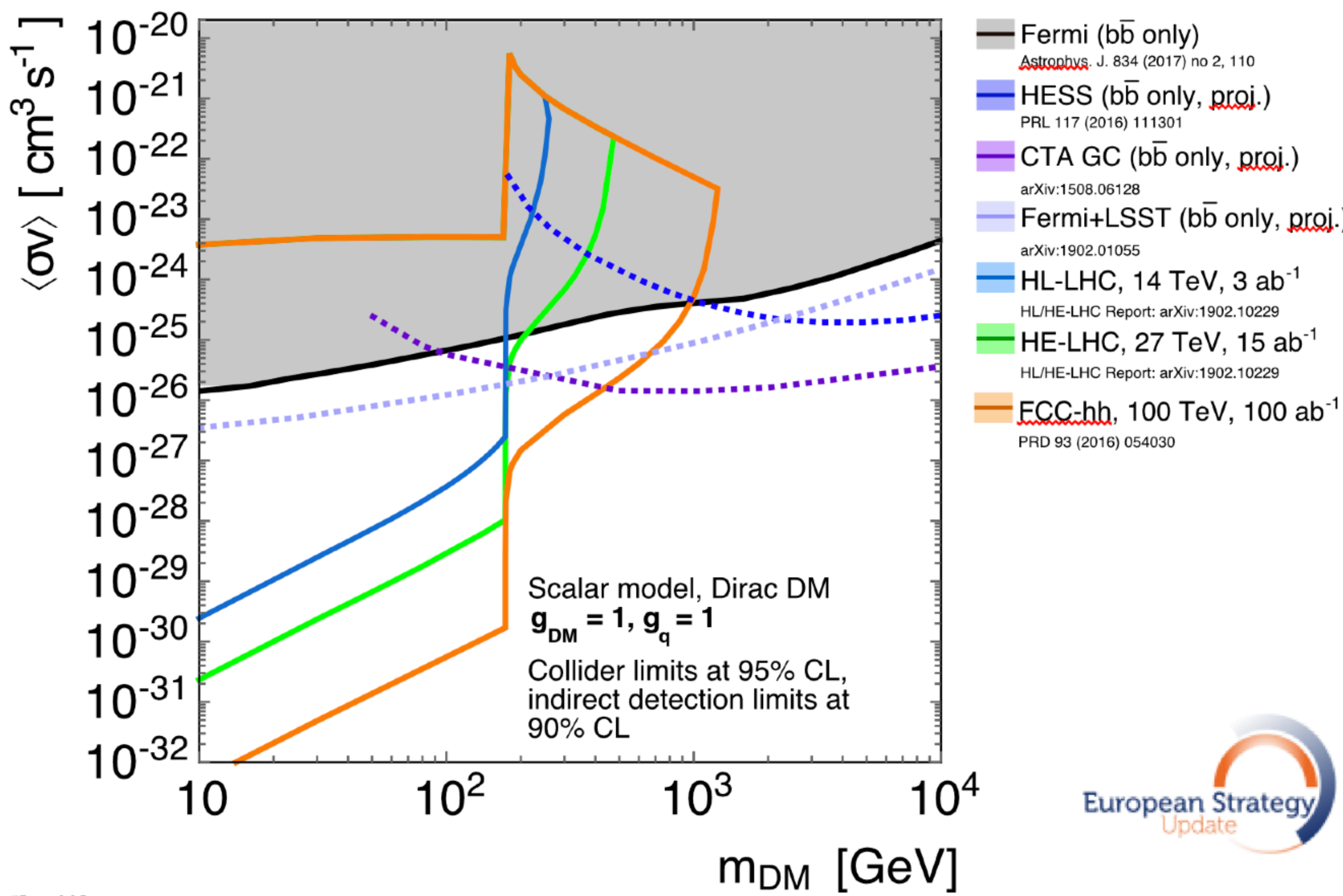


Indirect detection plots, without gluon contribution

- Limits on pseudoscalar mediator mass/scale can be translated to limits in the velocity-averaged DM annihilation plane

$$\langle \sigma v_{\rm rel} \rangle_q = \frac{3 m_q^2}{2\pi v^2} \frac{g_q^2 g_{\rm DM}^2 m_{\rm DM}^2}{(M_{\rm med}^2 - 4 m_{\rm DM}^2)^2 + M_{\rm med}^2 \Gamma_{\rm med}^2} \sqrt{1 - \frac{m_q^2}{m_{\rm DM}^2}}$$

arXiv:1603.04156



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Uncertainties

Uncertainties on DD for comparison to colliders

- DD is subject to astrophysical uncertainties, how much does it matter when comparing to collider searches? Note: collider searches have uncertainties too!

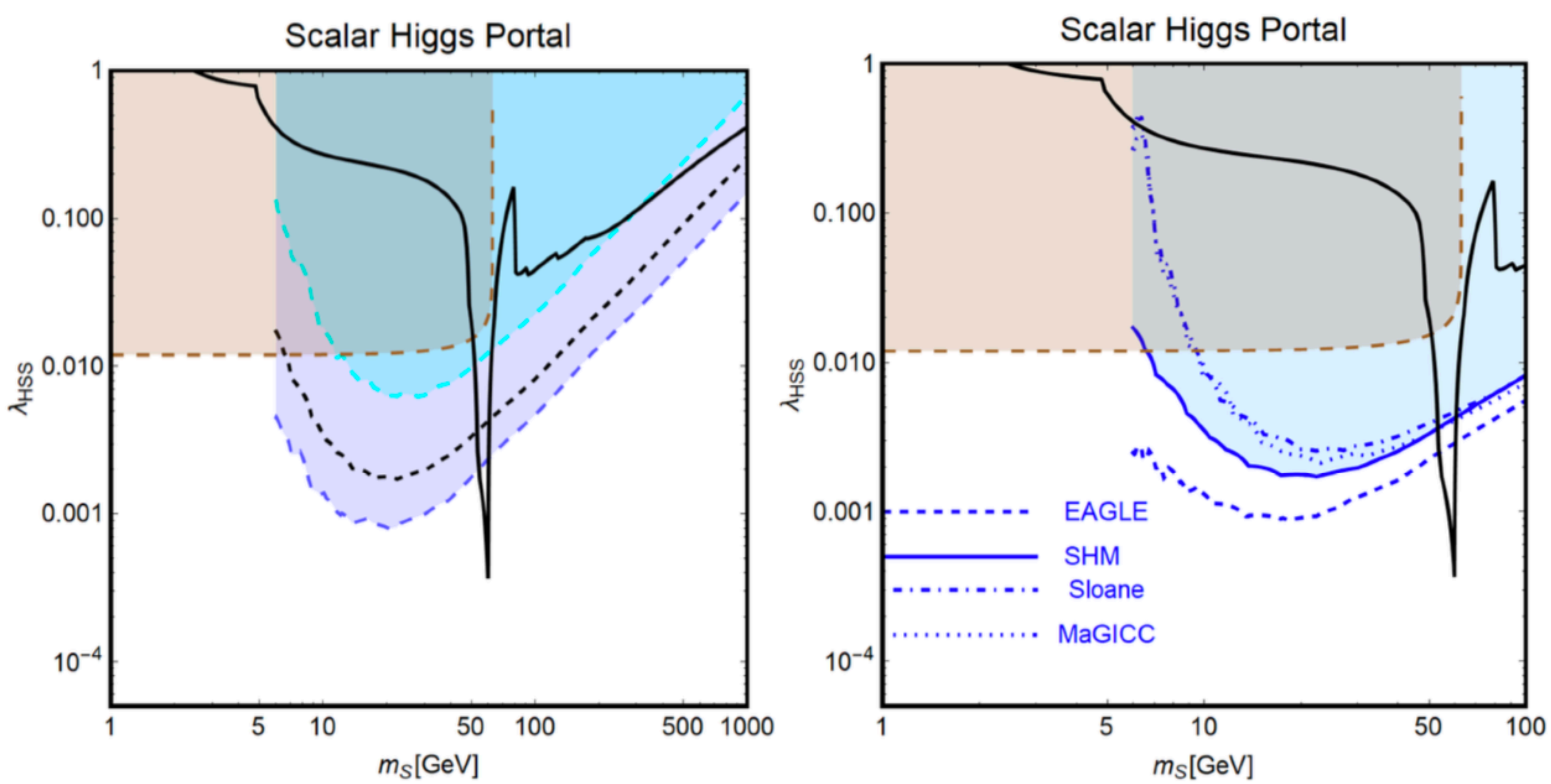


Figure 21: Impact on direct detection constraints of deviations from the SHM. In the left panel, shown is the effect of varying the astrophysical inputs, as performed in Ref. [302]. The blue region between the dashed cyan and blue lines represent the variation of the XENON1T exclusion bound with the astrophysical inputs while the black solid lines represent the limit adopting the SHM. In the right panel, the conventional excluded region above the solid blue line is compared with cases in which the DM distribution adopted in the SHM is replaced by the outcome of the hydrodynamical simulations indicated in the plot [291]. In both panels, together with the direct detection excluded regions, we show the (black) isocontour of the correct DM relic density according to the WIMP paradigm and the excluded regions by the invisible width of the Higgs boson.

arXiv:1903.03616

European Research Council

Uncertainties on DD for comparison to colliders

- DD is subject to astrophysical uncertainties, how much do they matter when comparing to collider searches? Note: collider searches have uncertainties too!

Isabelle John, Lund University Master's thesis in preparation

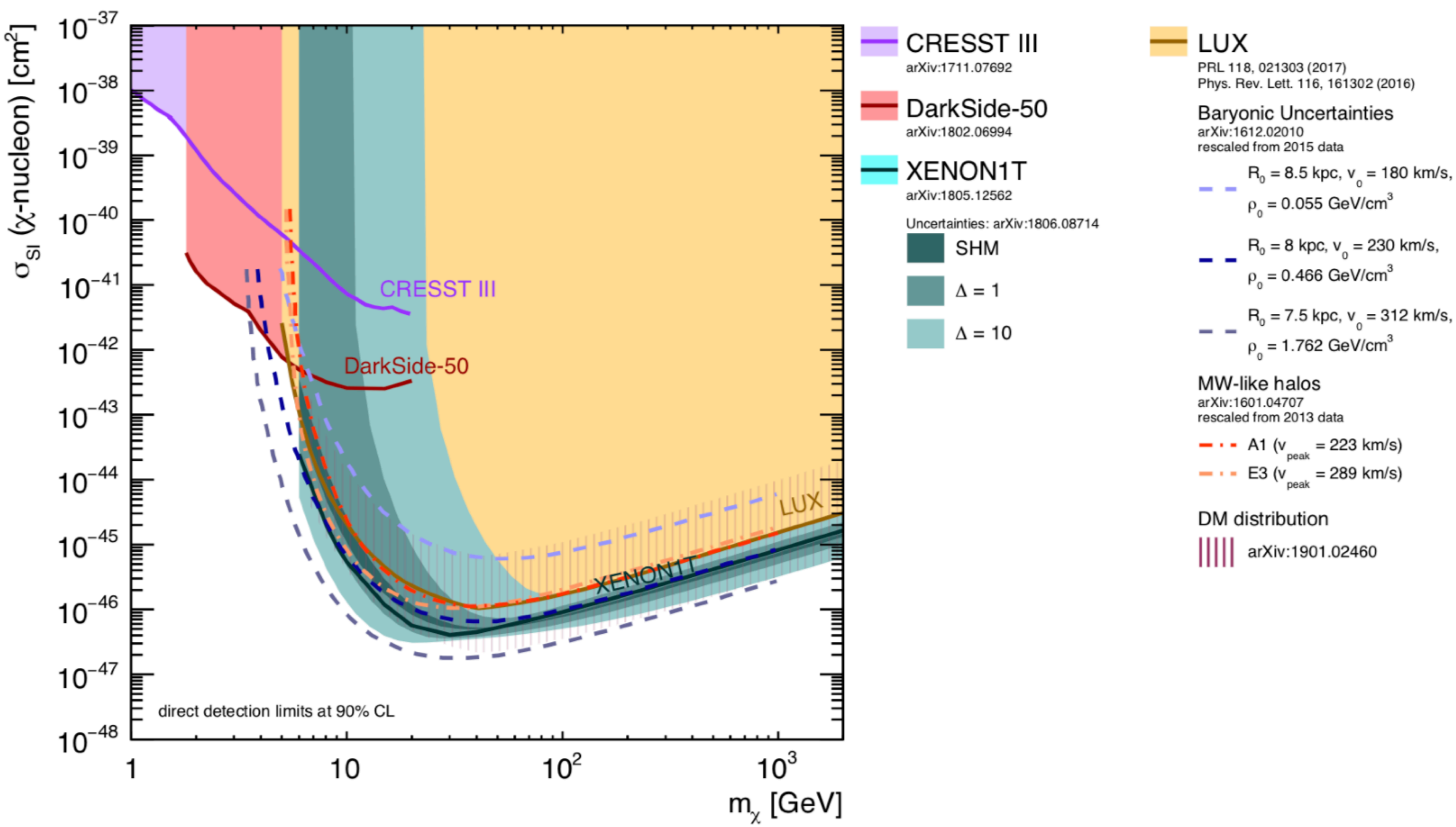


Figure 5.1: Exclusion plot with direct detection searches, including all deviations and uncertainty bands for direct detection limits.

Relic density

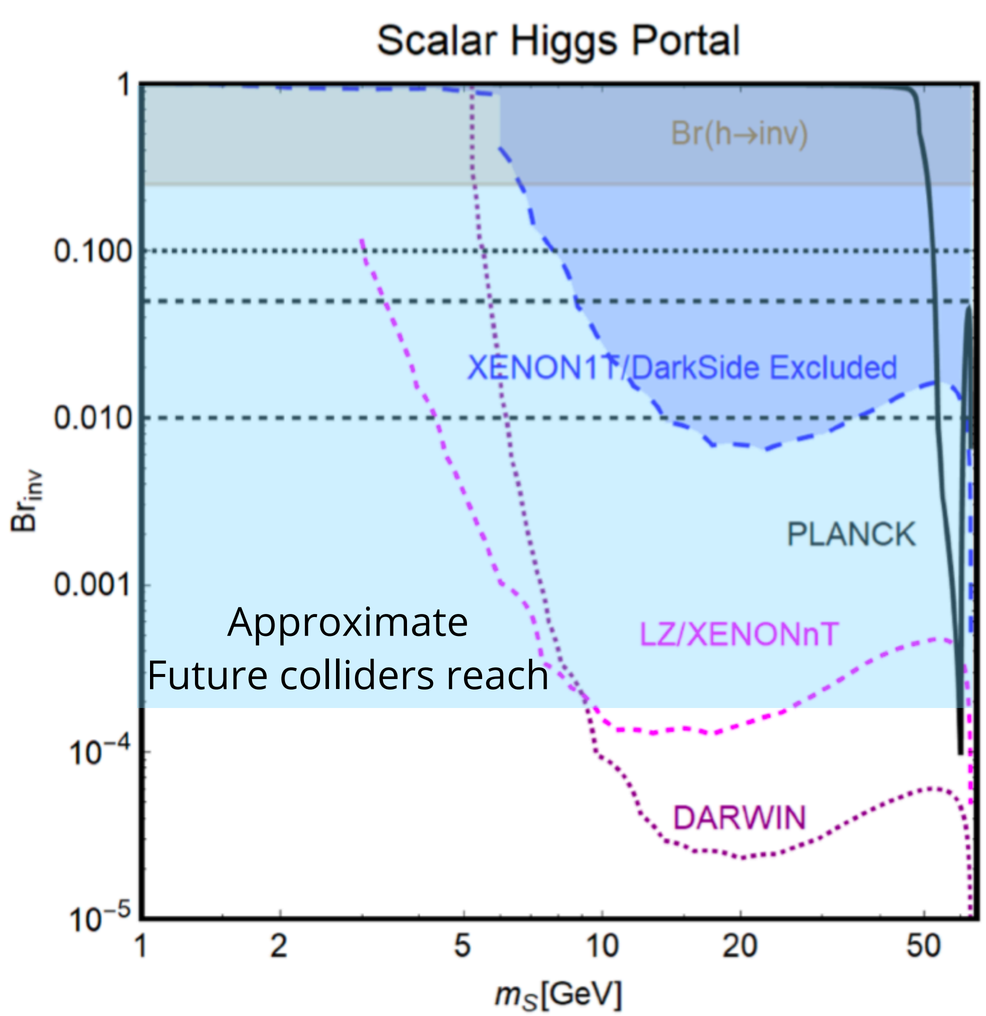
Collider reach and relic density

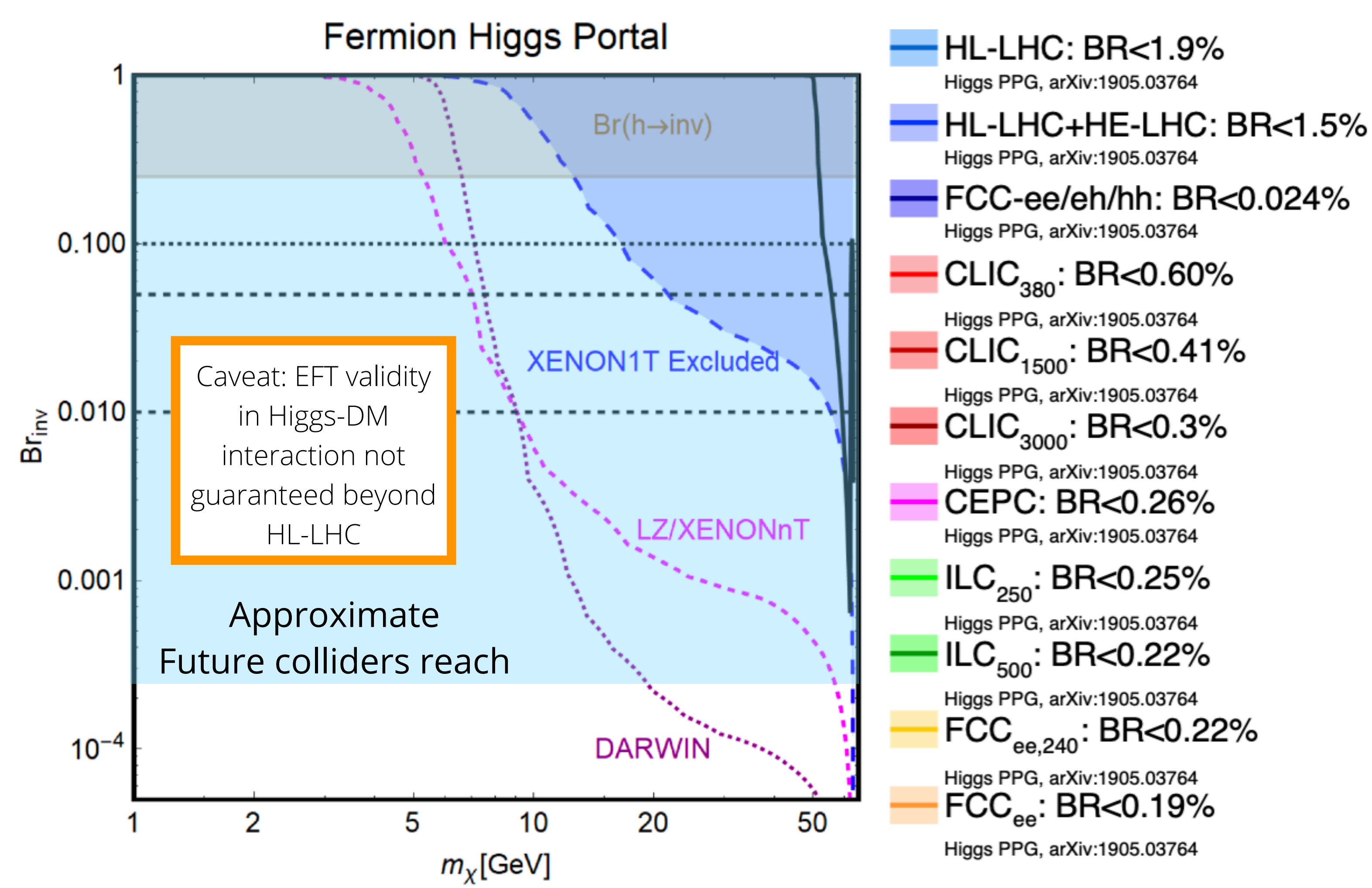
See talk by A. Kvellerstad

European Strategy "big question"

What cases of thermal relic WIMPs are still unprobed and can be covered by collider searches?

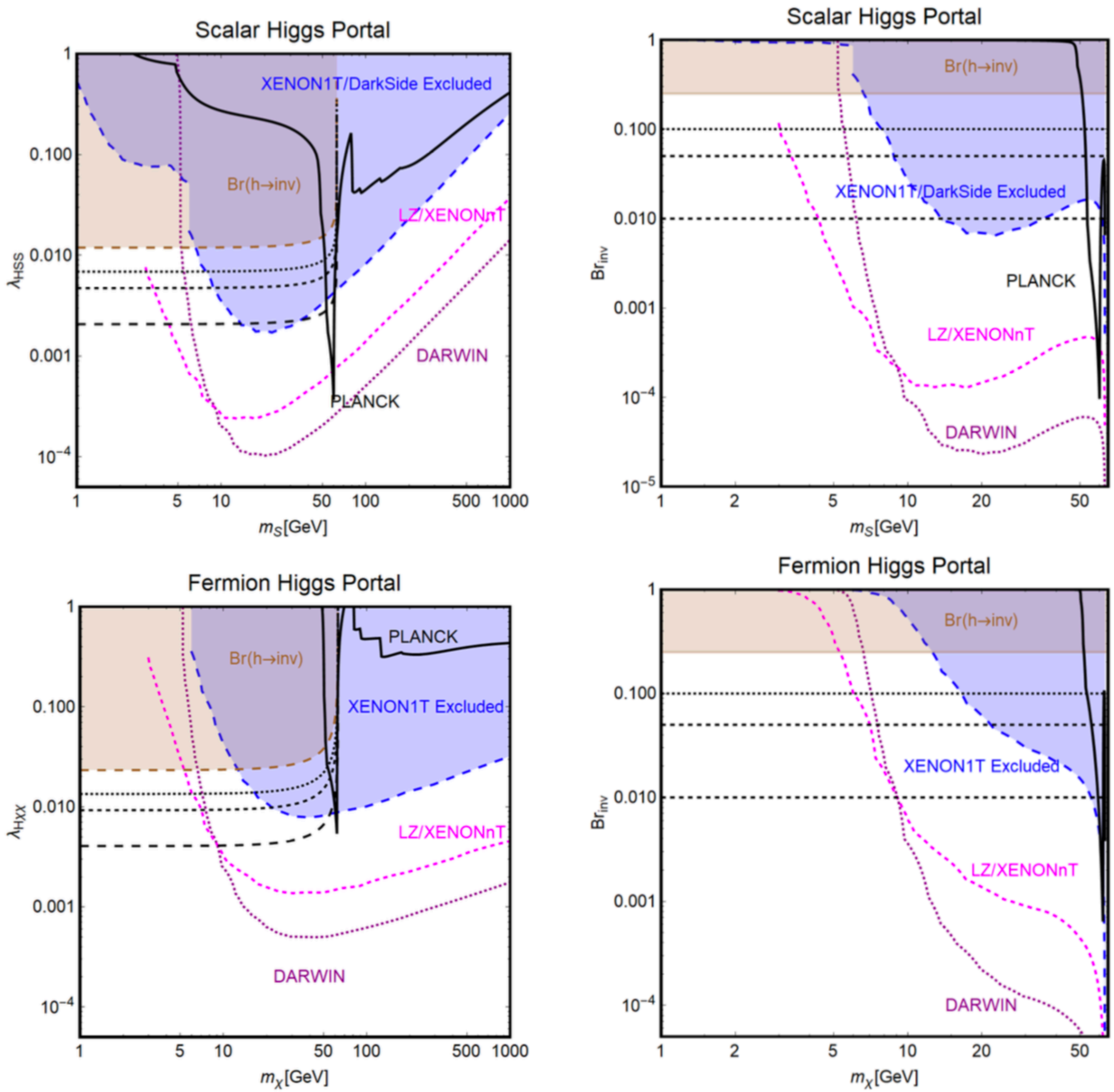
- Very simple model, so careful with taking relic density at face value
- If Higgs portal is to make up 100% of DM, can exclude using DD and colliders





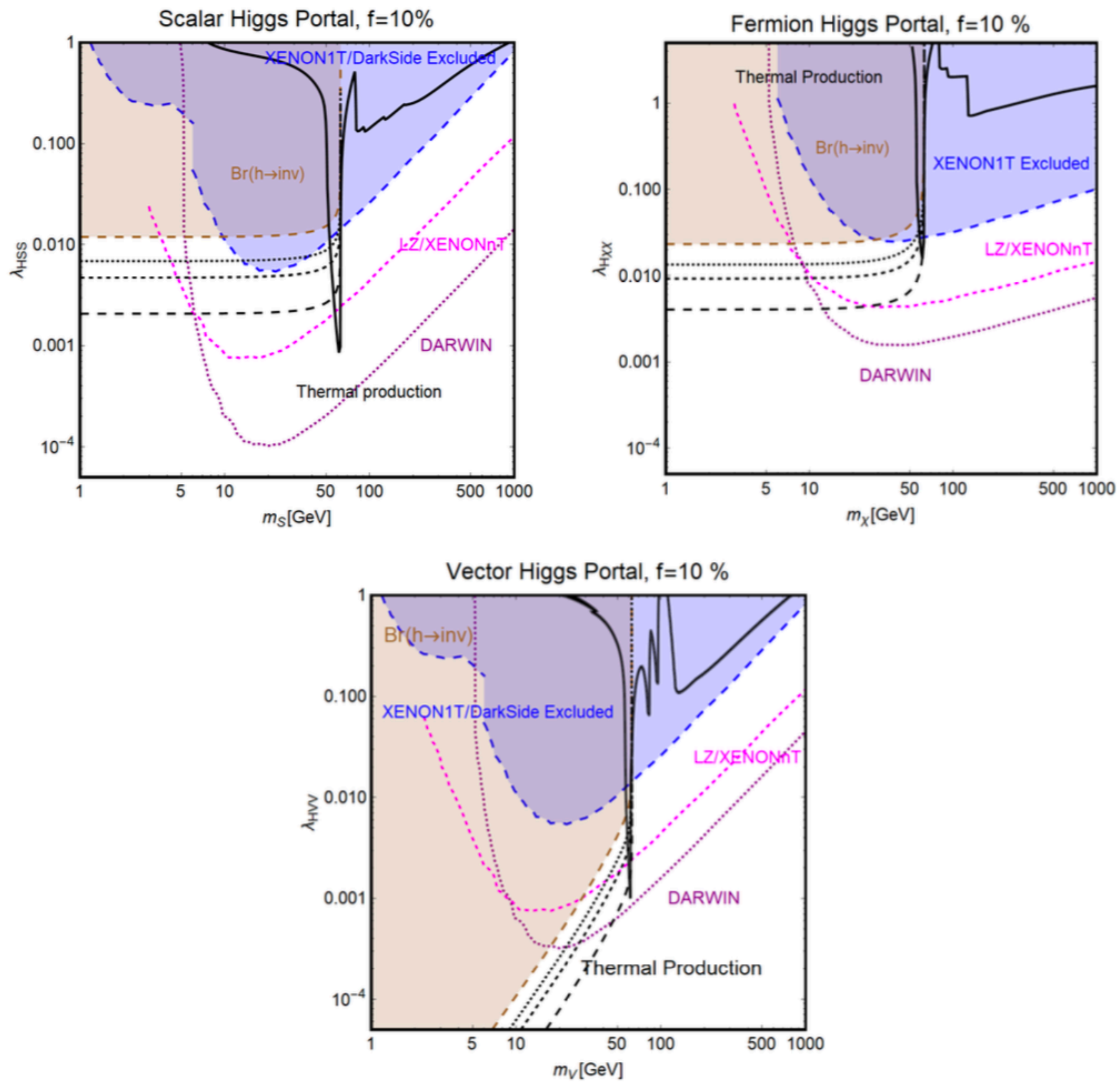
arXiv:1903.03616

Higgs portal and relic density, beyond $m_H/2$



arXiv:1903.03616

Alternative relic density scenario



arXiv:1903.03616

Figure 22: The same as the left column of Fig. 19 but assuming that the WIMP DM candidate contributes only a fraction $f = 10\%$ of the total DM component of the Universe. In contrast to Fig. 19, the black isocontours have been labelled as "thermal production" since they do not correspond to the experimentally favored value of the relic density.

Relic density and FCC-hh, simplified models

https://arxiv.org/pdf/1606.00947.pdf

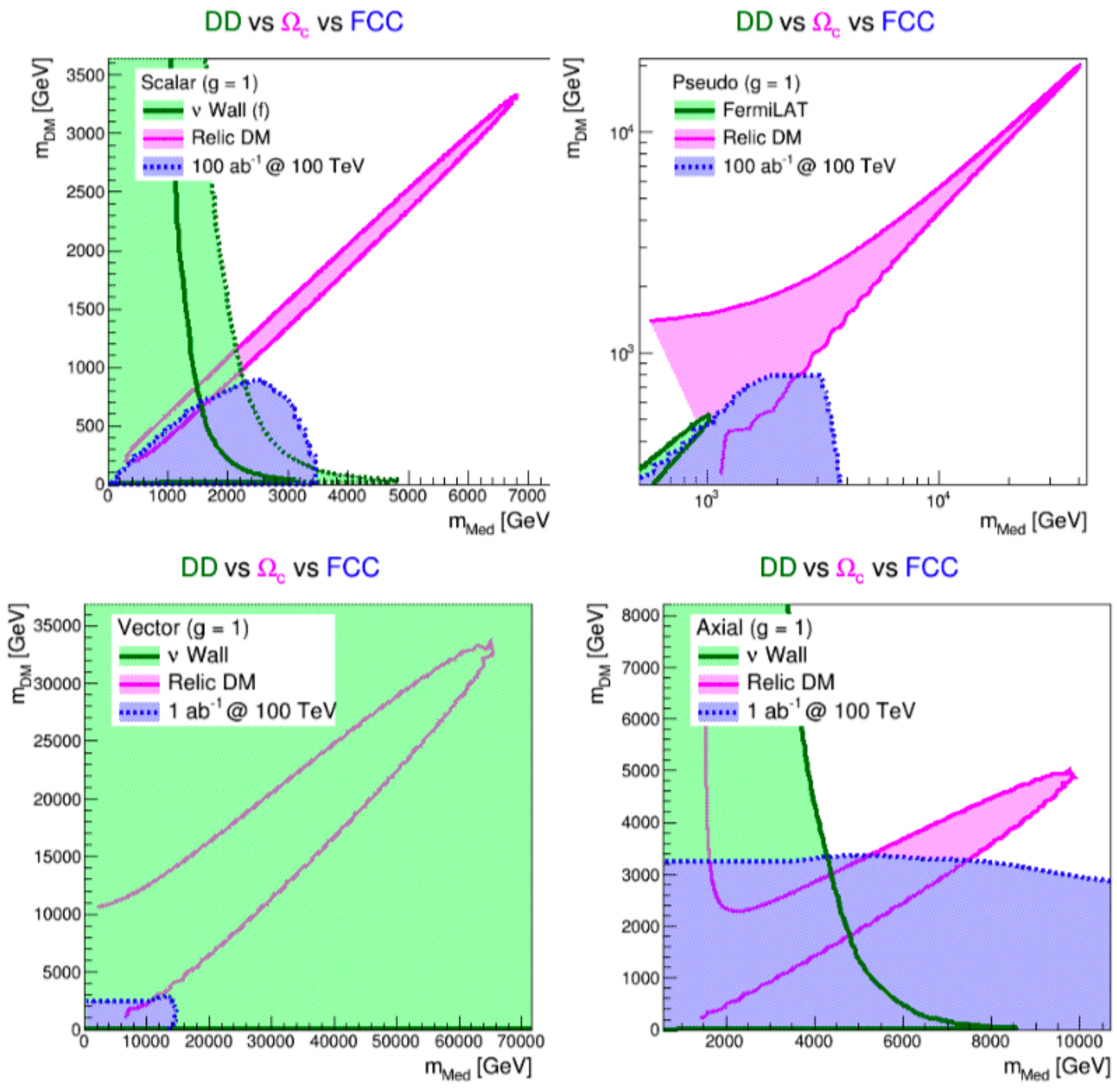


Fig. 60: Mass limits for scalar mediator models (top left panel), pseudo-scalar models (top right panel), vector models (bottom left panel), and axial models (bottom right panels) at 100 TeV colliders. The neutrino wall affecting the direct detection experiments is green for all plots expluding the pseudo-scalar mediator, where the projected indirect detection limit using FERMI-LAT and HESS projections data [308] is shown. The relic density is additionally computed all allowed mediator and DM masses are contained within the relic density lines.