BSM Report

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EF09: Tulika Bose (U Wisconsin-Madison), Zhen Liu (Minnesota), Simone Pagan Griso (LBL)
EF10: Caterina Doglioni (Lund), LianTao Wang (Chicago), Antonio Boveia (Ohio State)

EF BSM Report

BSM Report available at: [Report v2]

Implemented/responded to inputs and suggestions in v0, v1 from earlier Google doc and various review processes; continue to revise/update

A big thank you to everybody who gave us comments.

Additional comments and suggestions highly welcome! [Google doc]

Thanks all for the excellent EF (BSM) and xF sessions

	Energy Frontier and Related Sessions			Room loca
	Date	Session Name	Time Slot in PS	Room (ma
Monday	7-18	EF Higgs and BSM I	8am-noon	332 HUB
	7-18	XF: Report of the Accelerator Frontier Impleme	3:35pm-5pm	
Tuesday	7-19	XF DM Complementarity	8am-noon	220 Kane
	7-19	XF Energy Frontier Theory	8am-noon	175 JHN
	7-19	EF Plenary - Lepton Colliders	3:35pm-4:58pm	120 Kane
Wednesday	7-20	EF BSM II - non DM	8am-10 am	220 Kane
	7-20	XF Long Lived Particles	10am-noon	340 HUB
Thursday	7-21	EF DM Discussion	10am-12pm	110 Kane
	7-21	XF Flavor anomalies and exotics at colliders	8am-10am	241 Kane
	7-21	XF CLFV and heavy states	10am-12pm	231 MGH
	7-21	XF Flavor anomalies & exotics (RF-EF-TF)	10am-12pm	241 MGH
Friday	7-22	EF BSM IV	8am-9am	102 JHN
	7-22	EF BSM V	9am-10am	022 JHN
	7-22	NF-EF Cross-cutting issues	8am-10am	
	7-22	combined EF/AF report discussion	10am-12pm	022 JHN
Saturday	7-23	EF Discussion and Summaries (ie EF plenary)	8am-noon	130 Kane
	7-23	EF Plenary talks - Physics on the Energy Fronti	2pm-3:30pm	130 Kane
Sunday	7-24	XF: AF Future Colliders R&D Program Initiative	10am-noon	120 Kane
Monday	7-25	Panel: Physics Highlights from the Frontiers	8:00-9:30am	130 Kane
Tuesday	7-26	Panel: Large Exp./Facilities & timelines	9:00-10:00am	130 Kane
Tuesday	7-26	Panel: Mid/Small Exp./Facilities & timelines	10:30-11:30am	130 Kane

Intro and layout of the BSM report

- Introduction has a brief summary of BSM motivations…
  - **Direct observations:** DM, Matter-Antimatter Asymmetry, Anomalies, Existence of gravity, Cosmological tensions
  - **Theoretical Motivations:** Naturalness, Flavor structure of SM, Lightness of neutrinos, Strong CP violation, Desire for grand unified theory
  - **Exploring the unknown:** Maintaining a wide open view
- Above motivations most relevant to Energy Frontier are then expanded in two sections:

II. Experimental guidance & motivation
  A. Dark Matter
  B. Anomalies in Indirect Measurements (g-2, m_W, etc)
  C. General Exploration

III. Theoretical guidance & motivation
  A. Naturalness
  B. Higgs and Electroweak Symmetry Breaking
  C. Composite Higgs and Extra Dimensions
  D. Supersymmetry (SUSY)

Intro and layout of the BSM report (con't)

- This is followed by a brief discussion of methods and collider scenarios
- And then sections discussing search targets / signatures and projections

Model specific explorations (EF08)

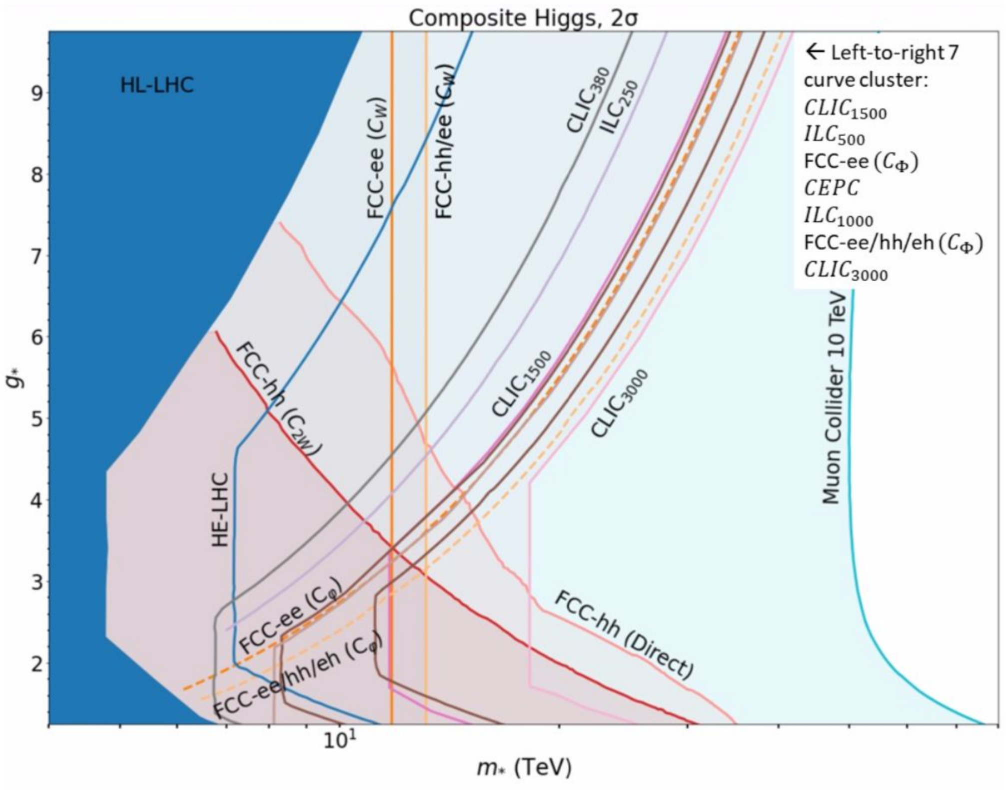
Sections

- Compositeness and Extra Dimensions
- Supersymmetry
- Leptoquarks (briefly discussed in report, not in these slides)

Main Goal: Compare sensitivity to representative established models for

- Discovery and exclusion reach at lepton and hadron colliders
- Indirect constraints from precision collider measurements vs. direct collider searches

Compositeness



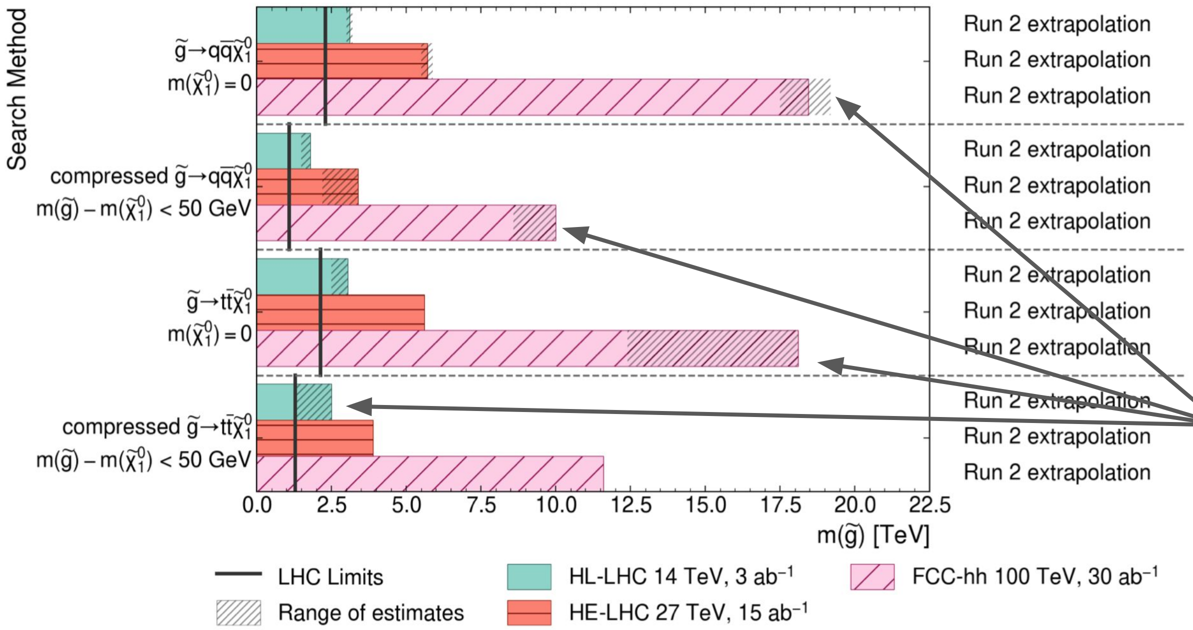
Interpret in framework of toy strongly coupled model.

Largely the same as European Strategy Report

Added muon collider from snowmass white paper (https://arxiv.org/abs/2202.10509)

Compares indirect reach in various colliders to direct reach for an example triplet ρ vector resonance in FCC-hh

SUSY Gluino

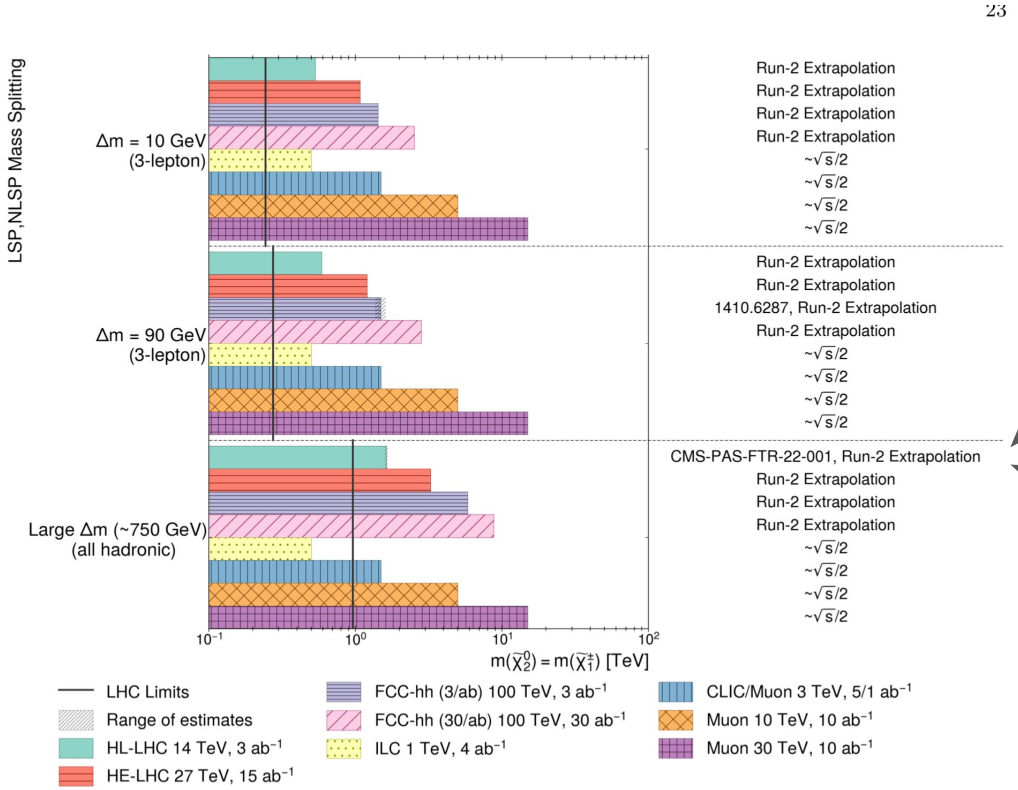


Decay and mass-splitting scenarios chosen to highlight differences in sensitivity for conspicuous signature from massless LSP and challenging signature from compressed spectra

Hash indicates comparison of dedicated study to collider reach tool

Tables in appendix give list of all source papers

SUSY: Wino-Bino Scenario



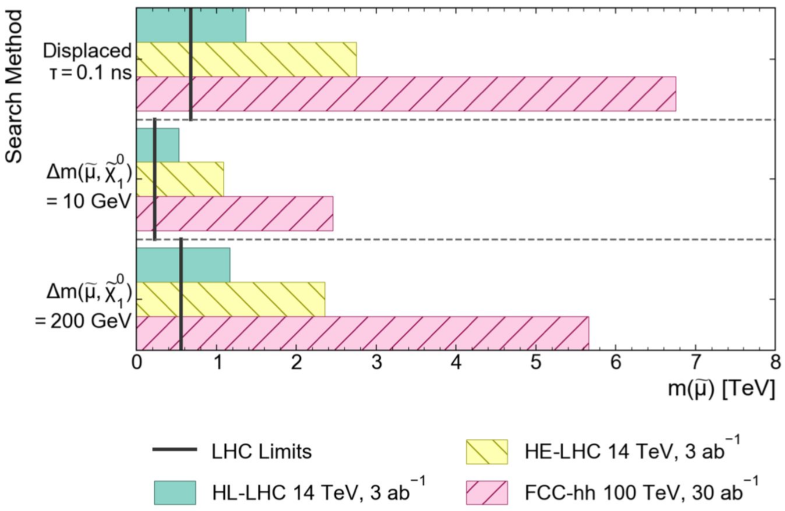
Added all hadronic search which covers particularly large ΔM

Note: CMS dedicated study and collider reach extrapolation give nearly identical result

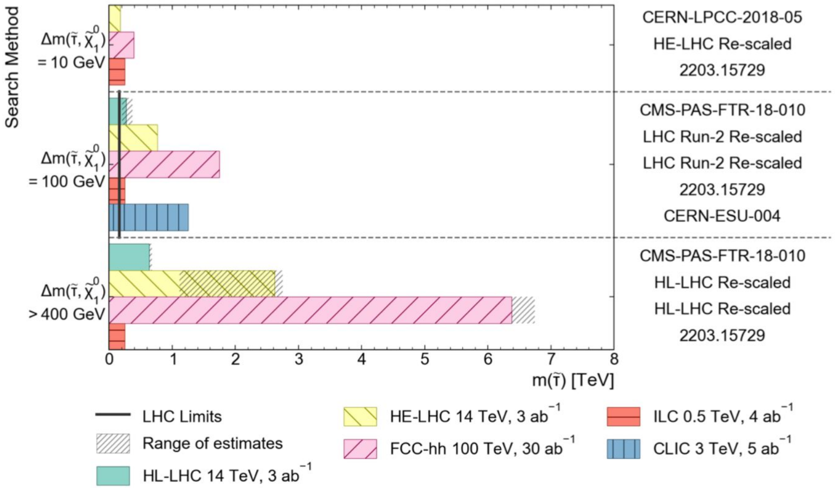
SUSY Sleptons

New compared to European strategy, particularly relevant to g-2 and DM thermal production (e.g. stau-coannihilation)

Smuon



Stau

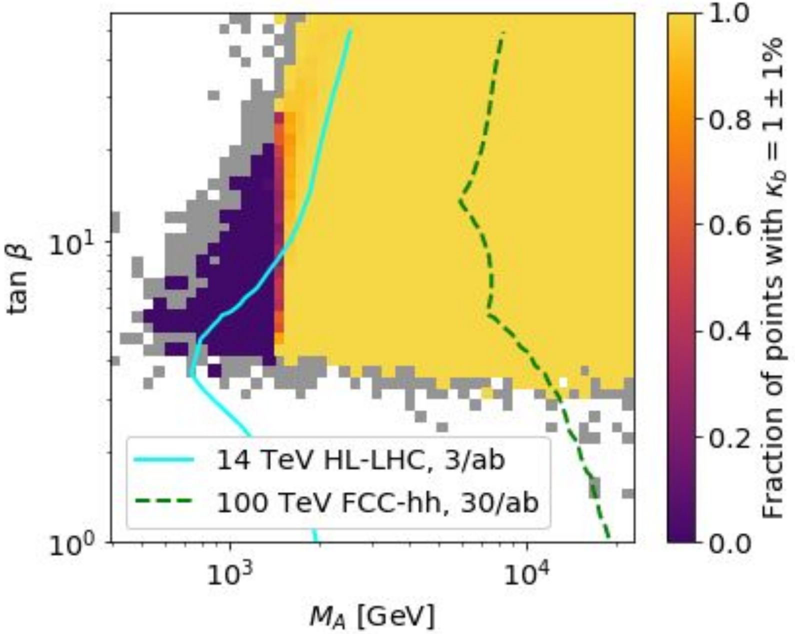


We require input on acceptable assumptions for adding additional lepton collider lines

- Dedicated stau at ILC study shows √s/2 sensitivity is good assumption even at very low ΔM

SUSY pMSSM scan

- Perform Markov chain MC-based scan of 19-parameter pMSSM to (i) quantify sensitivity beyond simplified models and (ii) allow comparison of direct searches and indirect sensitivity through precision Higgs measurements.
- Only precision constraints on pMSSM come from ~0.5% measurement of Hbb coupling (FCC-ee/eh/hh, CLIC1500, ILC1000).
- These constraints are ~comparable to direct search for pseudoscalar Higgs at HL-LHC.



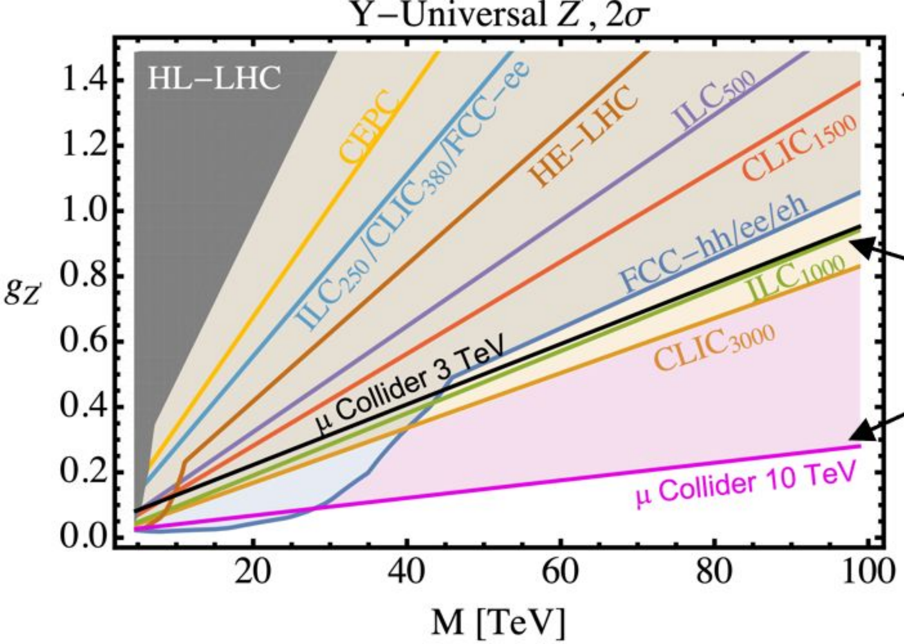
General BSM explorations (EF09)

Sections

- New Bosons and Heavy Resonances
- New Fermions
- Long-Lived Particles
- Other signatures (anomaly detection, extreme dark-sector motivated signatures, … not discussed in this presentation)

Main Goal:

- Provide assessment of potential for high-energy exploration
- Emphasize and maximize flexibility of colliders in exploring unexpected signatures now and in the future



95%CL at all colliders

European Strategy Briefing Book arXiv:1910.11775

μ Collider Physics Summary arXiv:2203.07526

Robert M. Harris
Fermilab

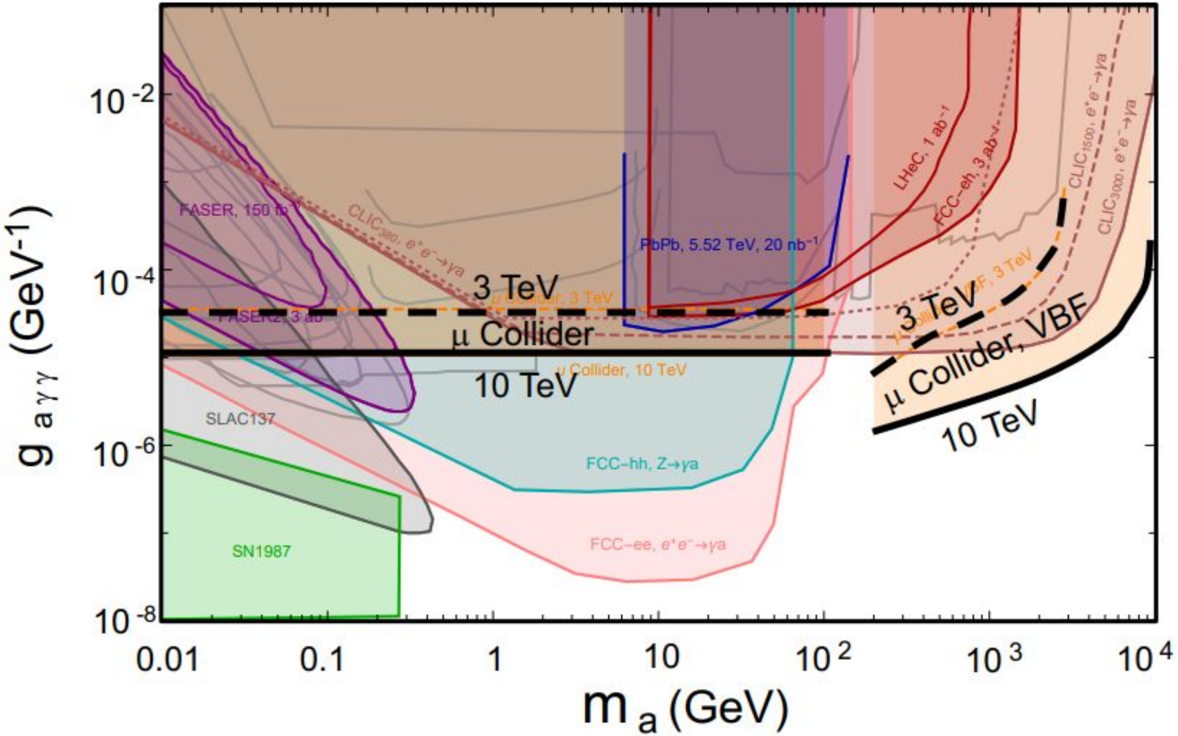
Felix Yu
Johannes-Gutenberg University of Mainz

- Z' with universal coupling $g_{Z'}$ to all SM fermions, ideal for collider comparisons.
  - Lepton colliders have an edge at large masses where only indirect effects can be measured
  - Hadron colliders provide best sensitivity at lower masses via direct observation of bumps.
- Muon collider results, new for Snowmass 2021, show impressive sensitivity
  - 3 TeV μ collider competitive with indirect searches using contact interactions at FCC-hh
  - 10 TeV μ collider most sensitive for M_Z' > 28 TeV, uniquely probes M_Z' > 100 TeV.

- ALP produced in association or via VBF decays to diphotons with coupling $g_{a\gamma\gamma}$
- For m_a < 100 GeV, FCC is best, but HL-LHC heavy-ions will explore first.
- For m_a > 200 GeV, 10 TeV μ Collider is best

Robert M. Harris
Fermilab

Felix Yu
Johannes-Gutenberg University of Mainz

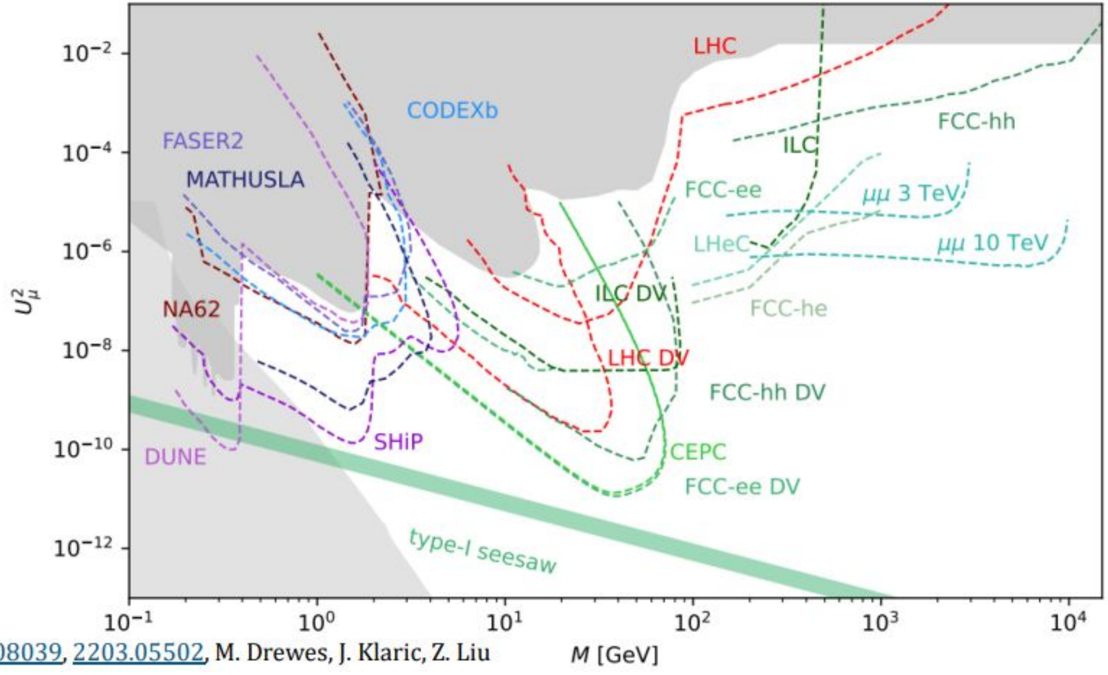


95% CL at all colliders

Whitepapers: FCC arXiv:2203.06520, μCollider: arXiv:2203.07261, arXiv:2203.05484

New Fermions: e.g., Heavy Neutral Leptons

Further divided in neutral / charged leptons, heavy quarks and other exotic signals



2203.08039, 2203.05502, M. Drewes, J. Klaric, Z. Liu

Three main messages:

- Auxiliary experiments in the timescale of HL-LHC can be extremely sensitive (more in RPF report)
- Importance of high luminosity (FCC-ee reaches far down in mixing due to the ~10^{12} Z bosons produced in the Z run)
- Higher energy colliders reach higher masses

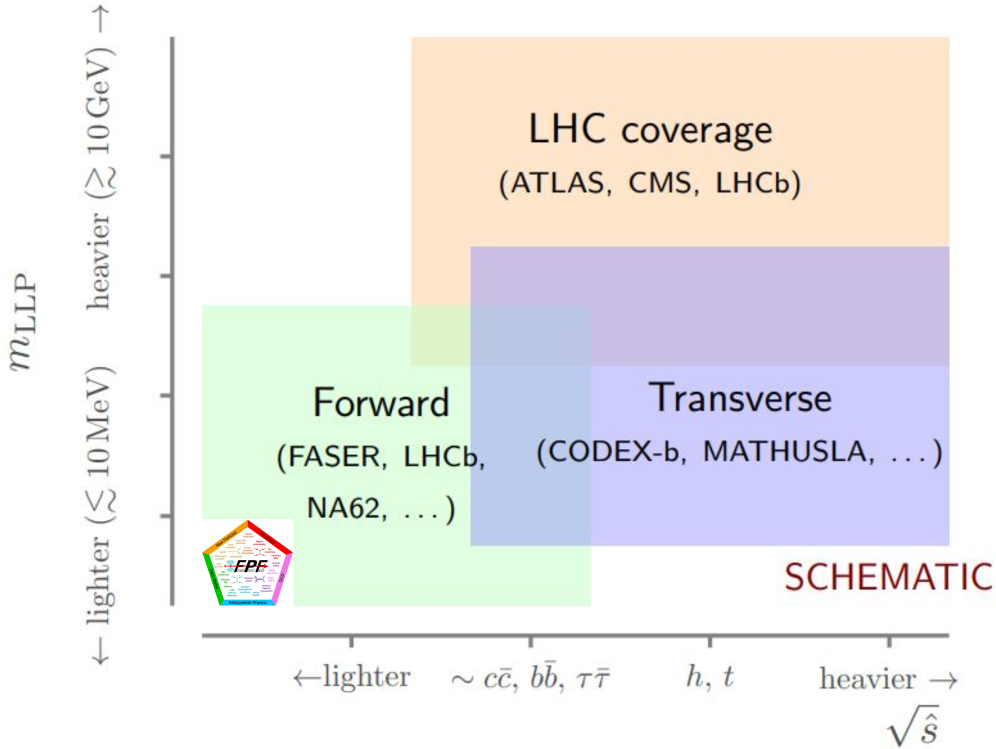
Various models motivate specific regions of this plane, and make the regions expected to be probed by these experiments well motivated

Long-Lived Particles

Naturally arising through weak couplings, compressed mass spectra, …

Care in detector design is needed to maximize reach for long-lived signatures

- Dedicated section discussing interplay with instrumentation frontier and future detector requirements
- Some emphasis on near-term projects that can enhance HL-LHC capability

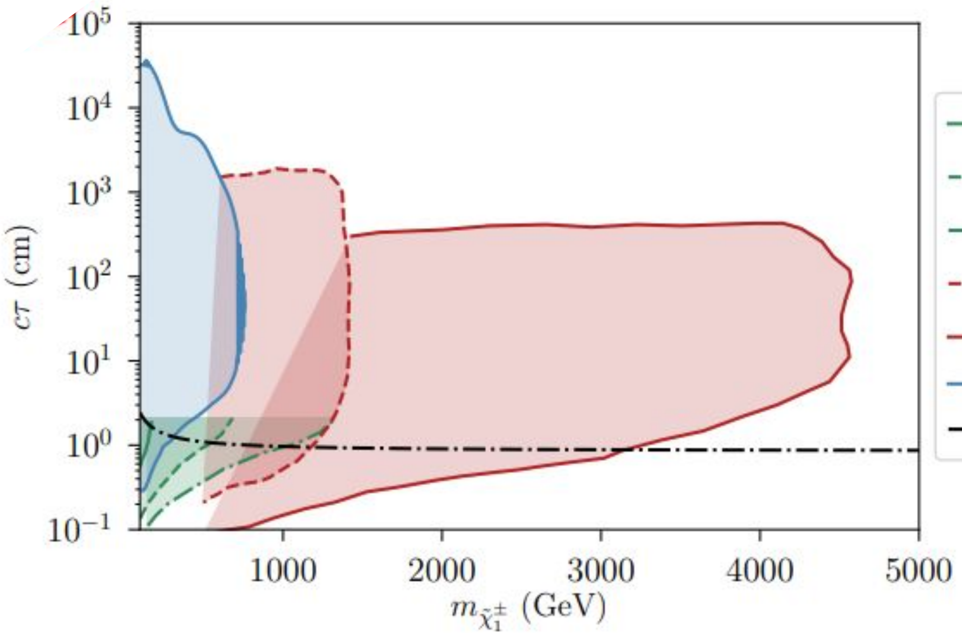


Charged LLPs

Electrically charged LLPs can have two main signatures: disappearing tracks and heavy stable charged particles (HSCPs)

Focus on disappearing tracks, to show improvements at HL-LHC and future colliders

Disappearing track (Higgsino) sensitivity estimates, as function of mass and lifetime



Juliette Alimena** (CERN)

Simon Knapen** (LBNL)

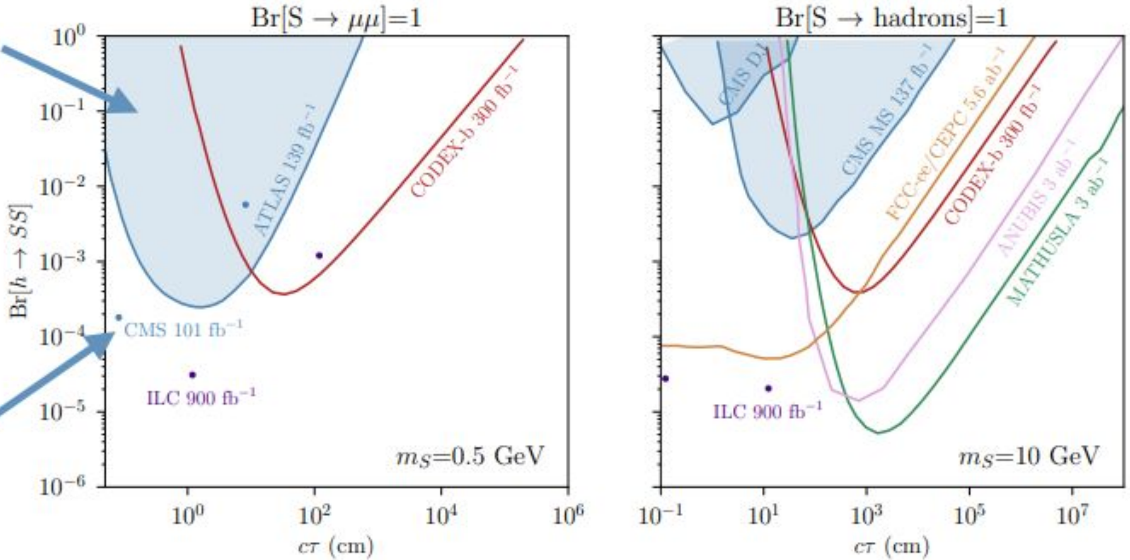
Light LLPs

"Light" = hard to trigger on or need auxiliary detector

LLPs produced in Higgs decays (Higgs as window to new physics)

lepton jet search

Scouting search



Would love to have LHC projections!

- Included strongest searches that we were comfortable extrapolating
- Sometimes only two lifetime points were available
- Mathusla study for left hand panel under way
- Several HL-LHC projections available, but already outperformed by existing analysis

Juliette Alimena** (CERN)

Simon Knapen** (LBNL)

Dark matter at colliders (EF10)

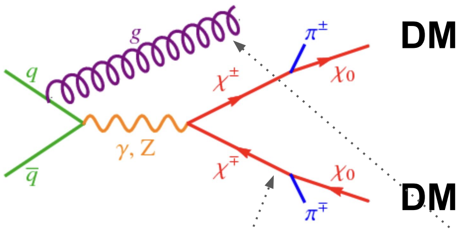
Sections

- Testing the simplest / minimal WIMP and its extensions
- Testing DM with the Higgs boson
- Simplified models of dark matter
- Beyond WIMPs: dark matter portals and other models

Main Goals:

- Discuss DM interpretations of future collider projections
- Prepare the ground for a discussion of dark matter complementarity with other Frontiers (especially Cosmic, Rare Processes & Precision, Theory & Neutrino)
    - Dark matter complementarity: dedicated session at Seattle CSS (Tuesday morning, 19/07/2022 8:30 am) and report to be compiled afterwards

How can we best test the minimal WIMP paradigm?

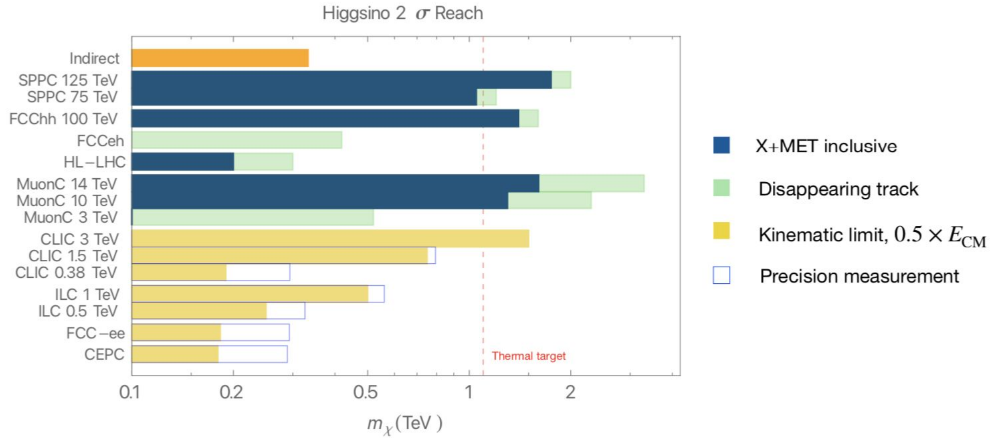


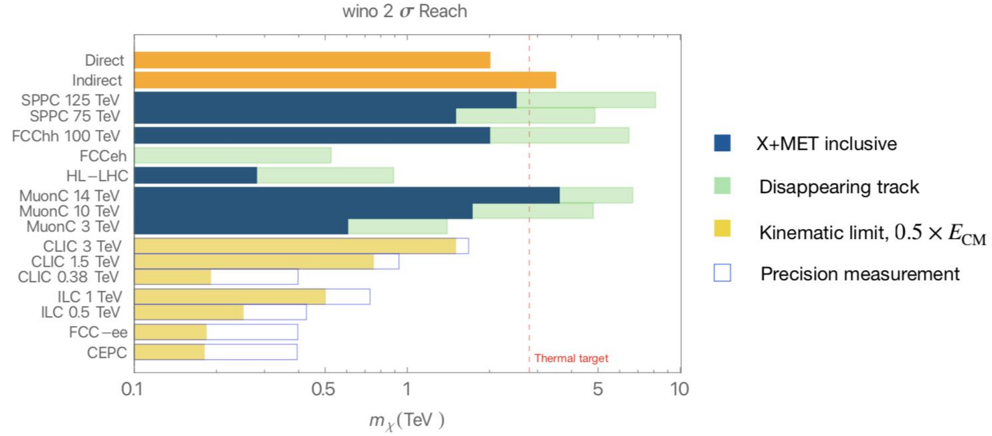
Signatures: **disappearing track, X+MET**

Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV

Higgsino
Wino

Reaching the **thermal target** (where model produces correct relic abundance): **complete coverage** for minimal WIMP candidate for **FCC complex and muon collider**



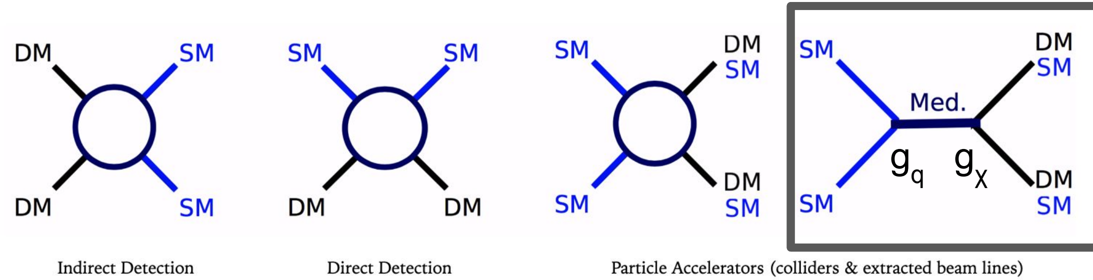


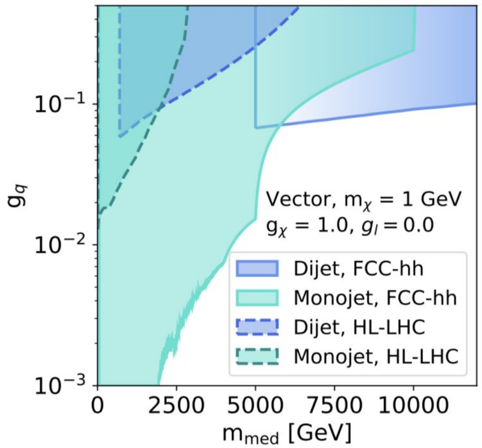
DM simplified models

Models with BSM mediator (Z') used in European Strategy, to highlight collider strength in **probing the dark interaction**

- Significant update from European Strategy: rescale results to arbitrary couplings
  - Useful to display dependence on choices when comparing to CF/RPF

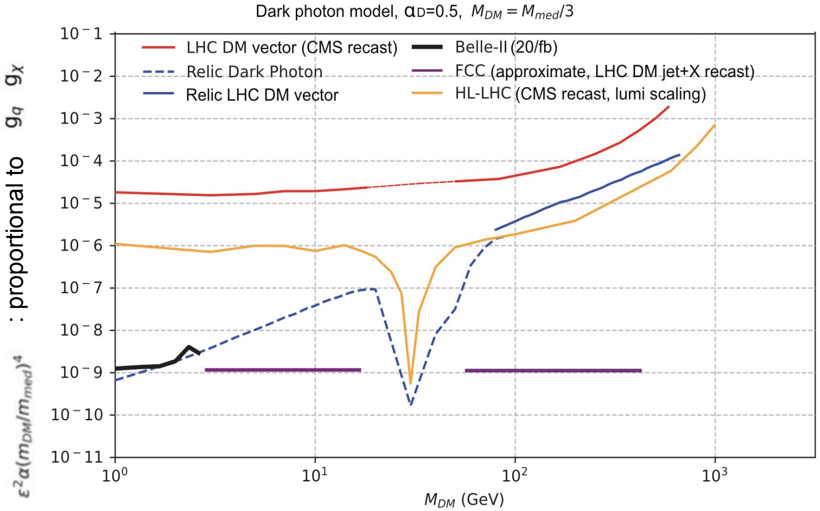
- Inputs from HL-LHC / FCC-hh (possibly also adding lepton colliders) show a **much extended reach in masses and couplings**





Simultaneous discovery in area covered by both visible and invisible searches **elucidates DM-SM interaction**

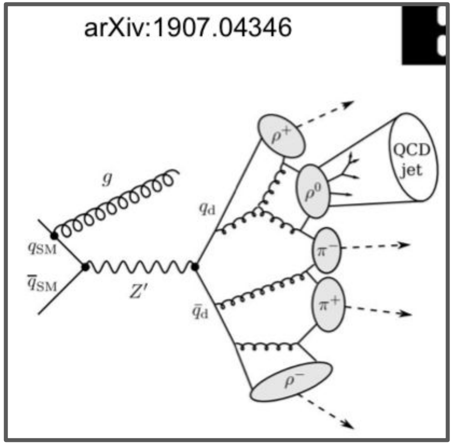
Concrete "minimal" benchmark shared with RPF: **dark photon**



HL-LHC and future colliders (lepton colliders as well, even if not shown) needed to reach the **thermal relic milestone**

Beyond-WIMP benchmarks and facilities for DM at colliders (new for Snowmass)

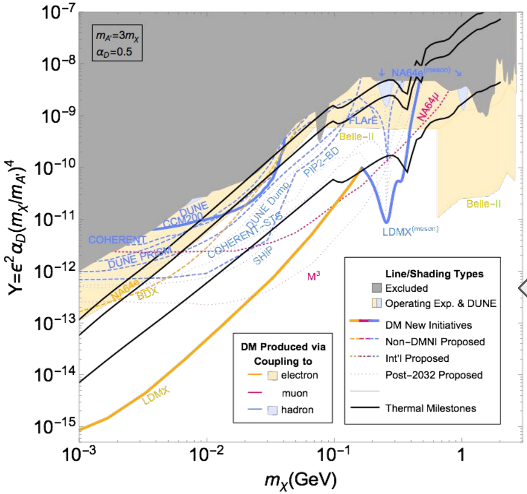
Extensive study of non-abelian QCD-like theories with dark confinement in dark showers project
→ **stable dark hadron** is DM candidate, within different detector signatures of ***dark showers***

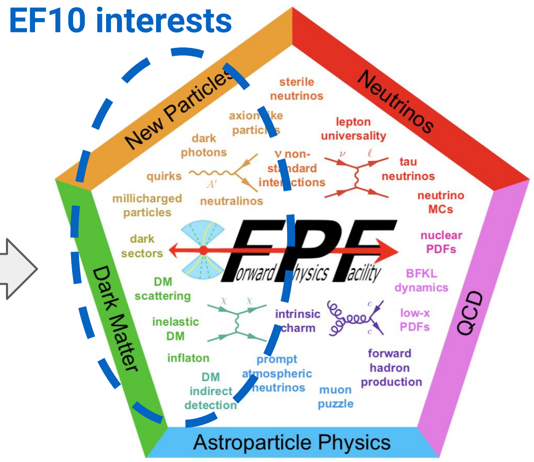


→ Work to **connect** those models to **cosmology** is encouraged

Facilities with smaller experiments **co-located at colliders** (example: the **Forward Physics Facility** for HL-LHC):

- Make the most of civil engineering at future colliders
- **Maximise the physics potential** e.g. with "dark matter beams" in the forward region
    - Many different dark matter models within reach





Dark matter complementarity: synergies with other Frontiers

Session on Tuesday 19/07 [agenda]: **interim conclusions**

- Understanding the particle nature of Dark Matter is one of the most important topics in HEP across all frontiers: CF, EF, RF, NF, IF, TF
- Several highly compelling targets for minimal models are accessible in the next decade, by future CF/RF/IF experiments & colliders
- This motivates the strategy to *delve deep* and *search wide* for DM, across all frontiers
- Discovering DM requires projects at multiple scales, from large facilities to medium and small projects
- Cross frontier support for theory, computing, and R&D to identify and pursue the next targets (*key point for future colliders*)
    - As well as broad support for the dark matter new initiatives process for identifying small projects.

Conclusion (0)

BSM:

- Vibrant
- Evolving
- What is possible

EF a central player in our BSM exploration

A wide net of thousands of different searches and observables!

We echo EF report conclusions strongly.

Conclusions (1)

Immediate future: **High Luminosity LHC**

- Fully realize its physics potential

Many points and cases:

- LHC has been tremendously successful
    - Huge BSM parameter space explored since LHC startup (e.g. Z’-->ll reach > 5 times from 12 years ago, access to compressed spectra and other complex topologies)
- An exciting program for HL-LHC taking advantage of:
    - BSM discovery potential from Lumi
    - BSM discovery potential from Upgrades (e.g., precision timing, new triggers)
    - BSM discovery potential from auxiliary detectors (e..g, FASER, FPF, Codex-b, MATHUSLA)
    - Improvements in analysis techniques/computing (e.g. jet-substructure, scouting, trigger-level analyses, anomaly detection)

Conclusions (2)

Intermediate future: **A Higgs factory (~< 1 TeV)**

- Explore the Higgs in depth
    - Precision Higgs
    - Higgs BSM (exotic) decays
- Higher Energy for direct BSM
- Higher Intensity (also Z-pole, ttbar) for precision SM
    -

Longer term: **A multi-TeV discovery machine (hadron, muon or e+e-/gamma-gamma collider)**

- “Broad BSM”:
    - model coverages
    - different aspects (particles properties) of a theory
- The scale push (un)naturalness considerations
- Thermal target WIMP (Higgsino, Wino, ..)
- Hidden sectors
- New heavy states
- Need strong R&D such that - when the time comes - we are READY to build the comprehensive discovery machine.

Conclusions

BSM:

- Vibrant
- Evolving
- What is possible

EF a central player in our BSM exploration.

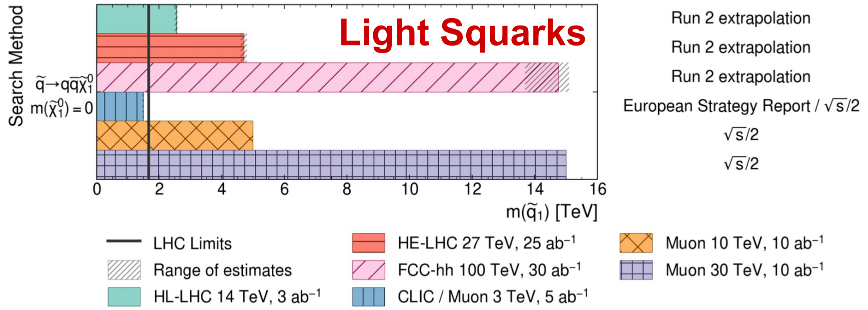
A wide net of thousands of different searches and observables.

We echo EF report conclusions strongly.

Deep synergy and complementarities with all other frontiers: TF, CompF, IF, NF, CF, RF…

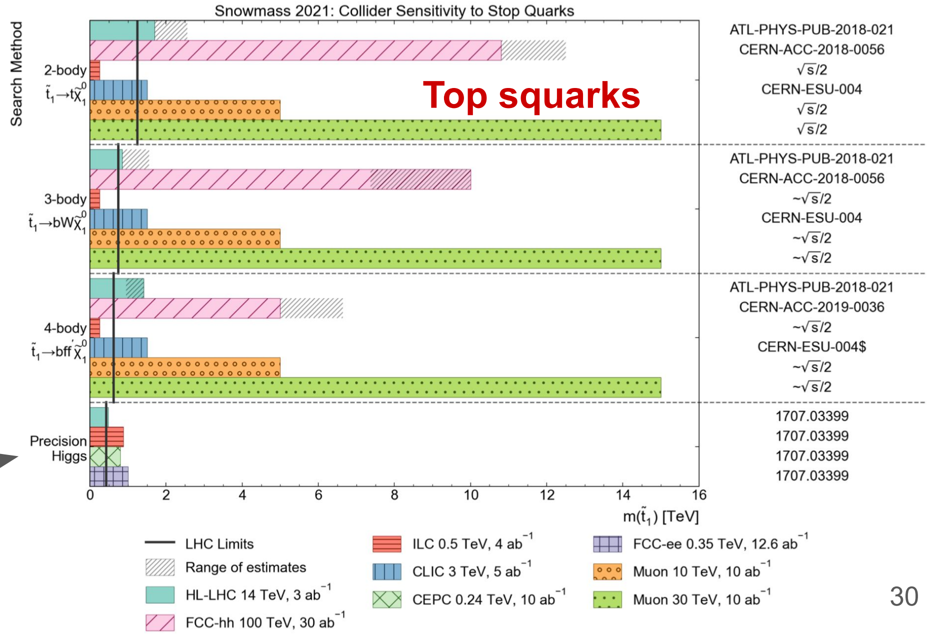
Backup slides

SUSY: squarks



Decay and mass-splitting scenarios chosen to highlight complementarity between

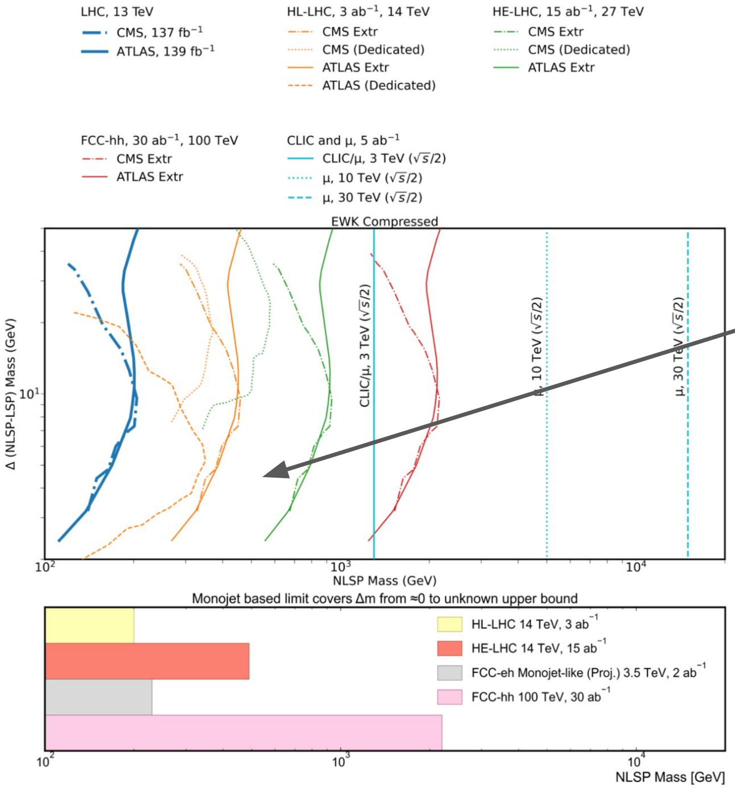
- lepton colliders - complete exclusion reach for compressed spectra
- hadron colliders - excellent discovery reach for low mass LSP



Lepton colliders generally assumed to be limited by energy (based on dedicated studies for several models)

Indirect reach based on precision Higgs

SUSY: (Compressed) Higgsino



Some in consistency in Run-2 extrapolation vs dedicated studies, but might be related to simplified binning for dedicated study

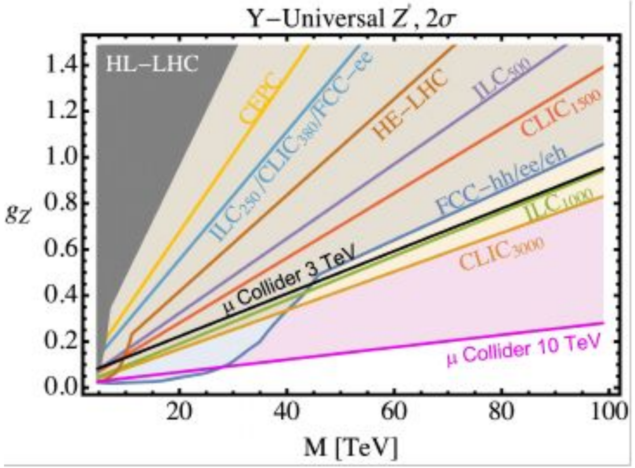
Caveat: Lepton colliders assumed to be √s/2 limited, which

- might not be appropriate for very small ΔM
- might depend on specific collider

NB: dependence on ΔM of monojet reach is not quantified in any studies – probably at least a few GeV.

Standard-candle: Z’

Minimal model that can be identified
by production/decay couplings and mass



Machine	Type	√s (TeV)	∫L dt (ab^{-1})	Source	Z’ Model	5σ (TeV)	95% CL (TeV)
HL-LHC	p p	14	3	R.H.	$Z'_{SSM} \to$ dijet	4.2	5.2
				ATLAS	$Z'_{SSM} \to l^+ l^-$	6.4	6.5
				CMS	$Z'_{SSM} \to l^+ l^-$	--	6.8
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	6
ILC250/ CLIC380/ FCC-ee	$e^+ e^-$	0.25	2	ILC	$Z'_{SSM} \to f^+ f^-$	4.9	7.7
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	7
HE-LHC/ FNAL-SF	p p	27	15	EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	11
				ATLAS	$Z'_{SSM} \to e^+ e^-$	12.8	12.8
ILC	$e^+ e^-$	0.5	4	ILC	$Z'_{SSM} \to f^+ f^-$	8.3	13
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	13
CLIC	$e^+ e^-$	1.5	2.5	EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	19
Muon Collider	$\mu^+ \mu^-$	3	1	IMCC	$Z'_{Univ}(g_Z'=0.2)$	10	20
ILC	$e^+ e^-$	1	8	ILC	$Z'_{SSM} \to f^+ f^-$	14	22
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	21
CLIC	$e^+ e^-$	3	5	EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	24
FCC-hh	p p	100	30	R.H.	$Z'_{SSM} \to$ dijet	25	32
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	35
				EPPSU	$Z'_{SSM} \to l^+ l^-$	43	43
Muon Collider	$\mu^+ \mu^-$	10	10	IMCC	$Z'_{Univ}(g_Z'=0.2)$	42	70
VLHC	p p	300	100	R.H.	$Z'_{SSM} \to$ dijet	67	87
Coll. In the Sea	p p	500	100	R.H.	$Z'_{SSM} \to$ dijet	96	130

Increasing Z’ Sensitivity

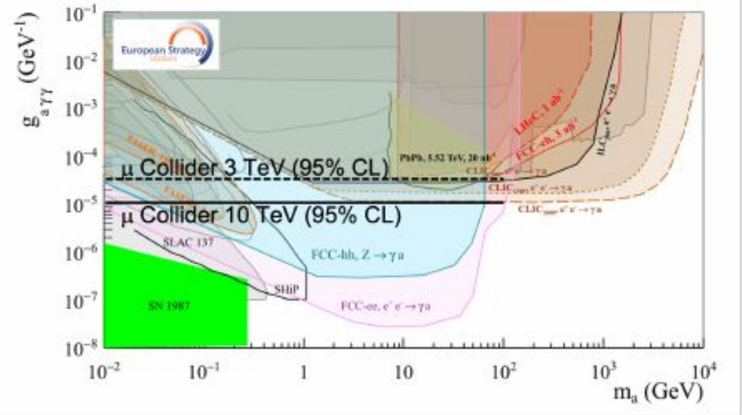
- Several choices possible depending on Z’-charge assignment to SM particles
- Combines direct (resonance) and indirect (angular and mass distributions) observables

Other resonant searches

Out of several more case-studies, two highlights:

Axion-like particles

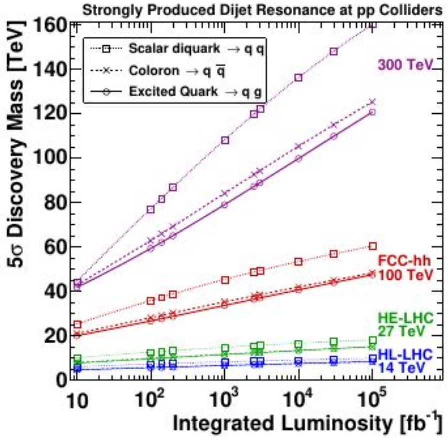
- Prompt or long-lived signatures
- Focus on coupling with photons
- Different couplings can invoke rich studies

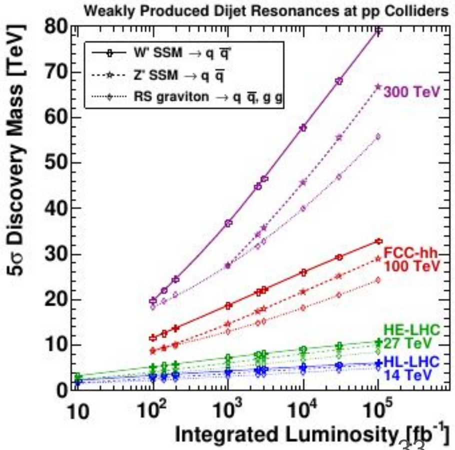


Preliminary plot: being re-made including more results & style updates

Di-jets resonances at hadron colliders

- including dependence on luminosity & energy





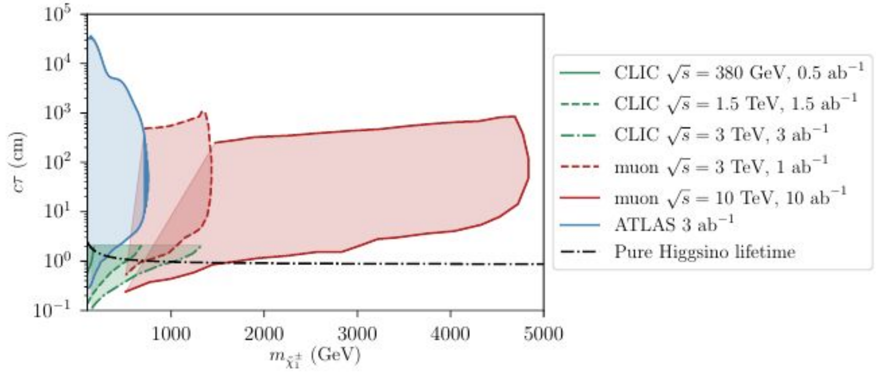
Long-Lived Particles @ future colliders

Explicit survey of exemplary signatures highlighting critical capabilities

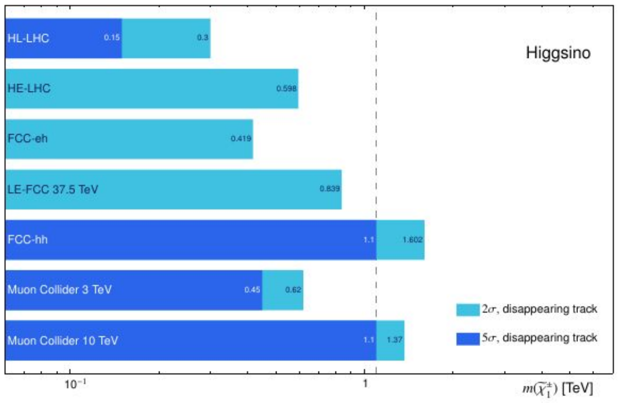
One highlight here: a BSM charged particle with macroscopic lifetime

- Most classic example: chargino state in SUSY (e.g. Wino or Higgsino)

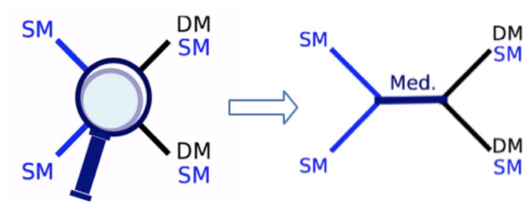
Some coverage of future colliders, used to exemplify the need of various approaches



For "natural" lifetime of a pure Higgsino, more results available -> "disappearing track" signature

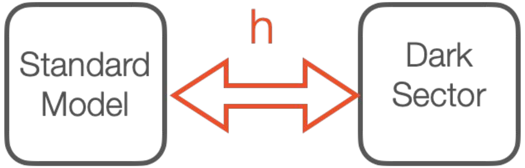


Why/how to search for DM at colliders



- Colliders can create DM particles in **controlled conditions**
  - Best suited to **investigate the SM-DM interaction**
- Experiments detect **WIMP DM** as **invisible** particles,
  but also the **visible** decays of the **mediators** of the DM-SM interaction
  and **other** kinds of **DM** through **non-standard** detector signatures
  - BSM report work in terms of DM@Colliders: reinterpretation of model-specific and model-agnostic results (e.g. SUSY searches, resonances…), but also specific searches for invisible particles
- EF collider DM searches need **complementary** searches from Cosmic Frontier, but also Rare Processes & Precision/Neutrino Frontiers
  - Dark matter complementarity: dedicated session at Seattle CSS (Tuesday morning, 19/07/2022 8:30 am) and report to be compiled afterwards

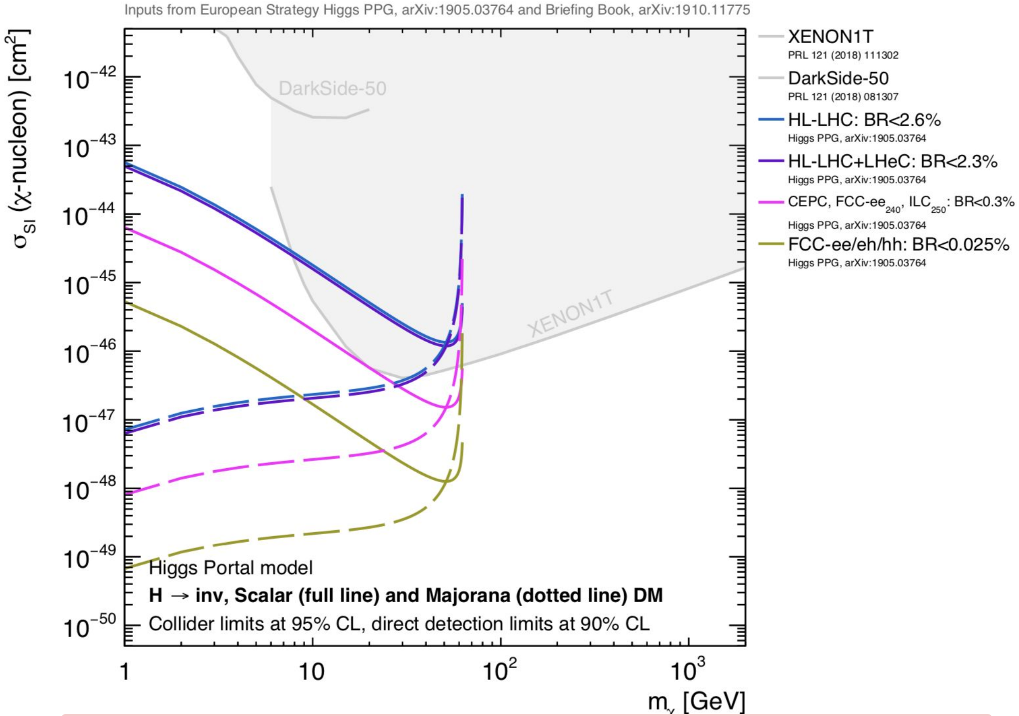
Higgs portal models



Minimal renormalizable model of DM mediation, only need to add DM to SM

Searches: extra **Higgs to invisible** decays, **Higgs couplings** deviations

Reaching the **SM sensitivity for Higgs to invisible decays BR**
($H \rightarrow ZZ \rightarrow 4\nu$, 0.01%)
is possible for **FCC complex**
(BR > 0.023% , fits)



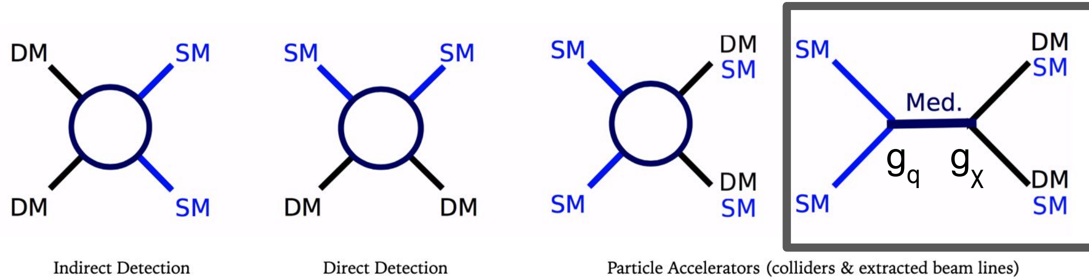
Theory+experiment suggestion to extend Higgs portal plots including DD to DM masses below 1 GeV, (based on analysis of UV-complete models)
To be discussed at Seattle CSS

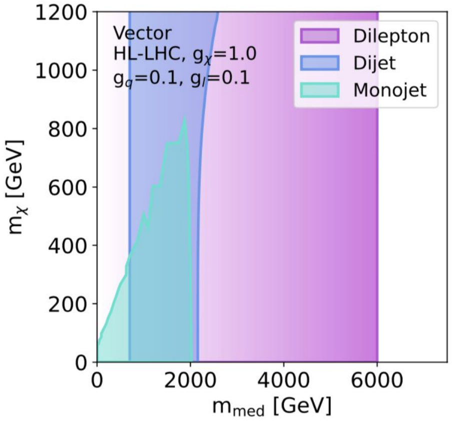
K. Assamagan et al:: “Higgs Portal Dark Matter Interpretation: review of EFT approach and UV-complete models” arXiv: 2107.01252

DM simplified models

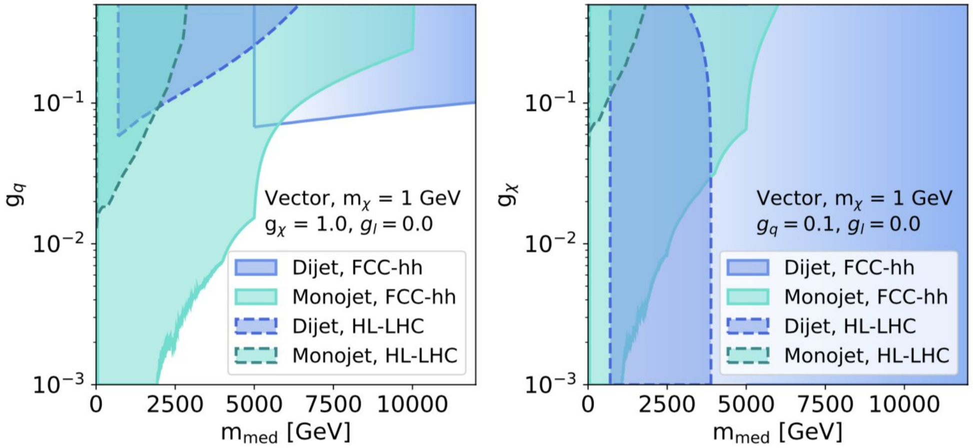
Models with BSM mediator (Z') used in European Strategy, to highlight collider strength in **probing the dark interaction**

- Significant update from European Strategy: rescale results to arbitrary couplings
  - Useful to display dependence on choices when comparing to CF/RPF
- Inputs from HL-LHC / FCC-hh (possibly also adding lepton colliders) show a **much extended reach in masses and couplings**





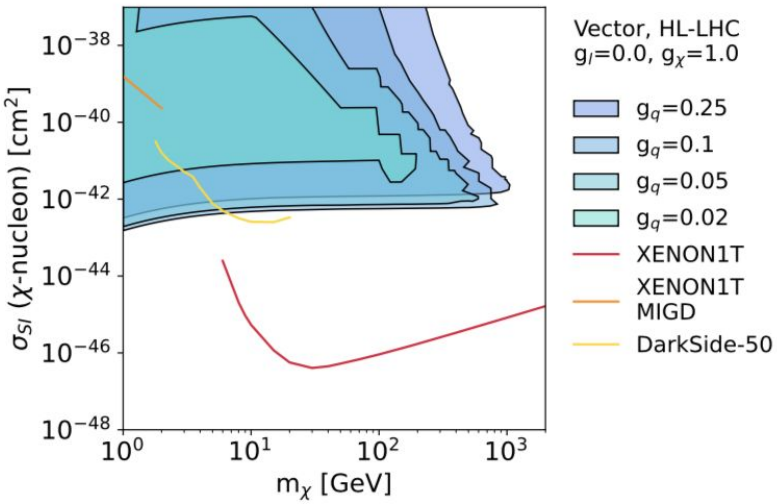
Visible & invisible mediator searches contribute to discovery potential

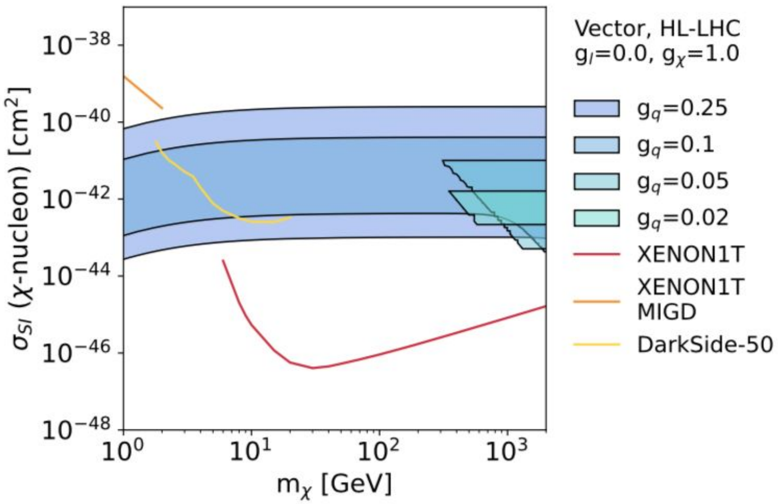


Simultaneous discovery in area covered by both visible and invisible searches gives information on DM-SM interaction

Complementarity with the Cosmic Frontier

Within the context of a simple model, can now show **coupling dependence of collider results in direct detection plane**





Monojet (invisible mediator decays): stronger results for lower mediator-SM couplings, then covered area shrinks around the minimum coupling collider is sensitive to

Dijet (visible mediator decays): same as monojet, but much stronger effect as mediator-SM coupling in both production and decay

Also available in BSM report: plots showing dependence on *mediator/DM mass ratio*
→ see next slide for a concrete theoretically consistent benchmark derived from vector mediator results

Dark showers WG and semi-visible jets

EF10 Focus Topic #2:
Beyond WIMP

Dark showers project LOI contacts and organizers: Suchita Kulkarni, Marie-Helene Genest, talk link

Goals of this theory + experiment working group / common whitepaper:

- Phenomenological studies of QCD-like & other benchmarks
- Defined reasonable assumptions and parameter scans
- Suggest new search strategies

Tools: common code and model repository, shared meetings and presentations, facilitating development of new Pythia release for the community

Meetings since 2020: literature survey and experimental reviews, connection to broader community (e.g. participation in LLP WG joint sessions including discussions about astrophysics), well-attended tutorials.

S. Kulkarni, M. H. Genest et al, "Theory, phenomenology, and experimental avenues for dark showers: a Snowmass 2021 report", arXiv:2203.09503

Table 3 summarises our current benchmarks.

Regime	N_c, N_f	Λ_v [GeV]	**Q**	m_{π_v} [GeV]	m_{ρ_v} [GeV]	Stable dark hadrons	Dark hadron decays
$m_{\pi_v} > m_{\rho_v}/2$	3,4	10	(-1,2,3,-4)	17	31.77	All π_v	$\rho_v^0 \to q\bar{q}$ $\rho_v^\pm \to \pi_v^\pm q\bar{q}$
$m_{\pi_v} < m_{\rho_v}/2$	3,3	5	Various	3	12.55	$0/1/2\pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$
	3,3	10	Various	6	26	$0/1/2\ \pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$
	3,3	50	Various	30	125.5	$0/1/2\ \pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$

New signatures push the development of **new variables and methods** to be used at present and future colliders

Example: development of new variables and neural networks for semi-visible jets (dark showers with visible and invisible particles intertwined)

H. Beauchesne, G. Grilli di Cortona, "Event-level variables for semivisible jets using anomalous jet tagging", arXiv:2111.12156

Minimal dark photons

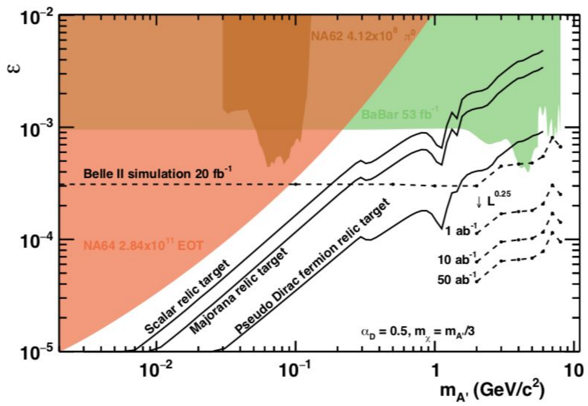
Dark boson (dark photon):
New vector-mediator-like particle connecting SM and dark sector

- Much smaller couplings than WIMP mediator models
- Can decay to visible SM particles …or new invisible ones
- Invisible particles from decay can be DM candidates
- No other particles besides γ_D and DM → *minimal* dark photon model

Dark photon can be ***connected to vector simplified model*** *from LHC Dark Matter Working Group → monojet projections can be reinterpreted*

- Even minimal dark sector models (e.g. dark U(1)) require new particles for UV consistency → new present/future collider signatures (T. Rizzo, 2202.02222)
- Experimental opportunities in the Forward Physics Facility (J. Feng et al, 2203.05090)

EF10 Focus Topic #2:
Beyond WIMP

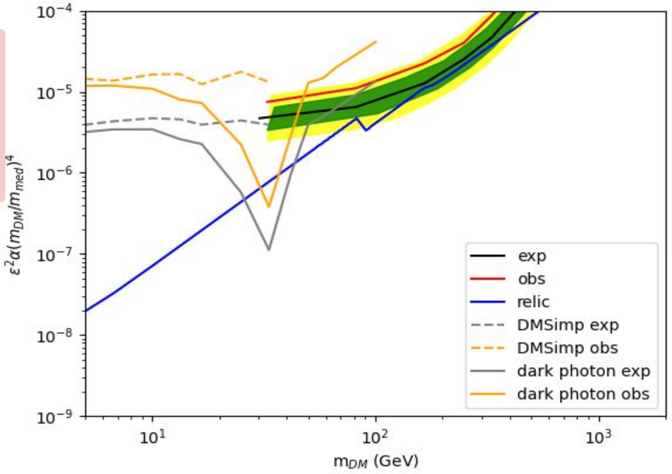


Belle-II projection for invisible dark photon decays

Belle-II Collaboration "Belle II physics reach and plans for the next decade and beyond"

Upgraded-LHCb updates for visible dark photon decays

D. Craik et al. "LHCb future dark-sector sensitivity projections for Snowmass 2021", arXiv:2203.07048



P. Harris, K. Pachal, J. Greaves et al. reinterpreting monojet analysis for invisible decays of dark photon, in preparation

(work ongoing in collaboration between DMWG & Physics Beyond Colliders)

Low/high mass particles in DM models

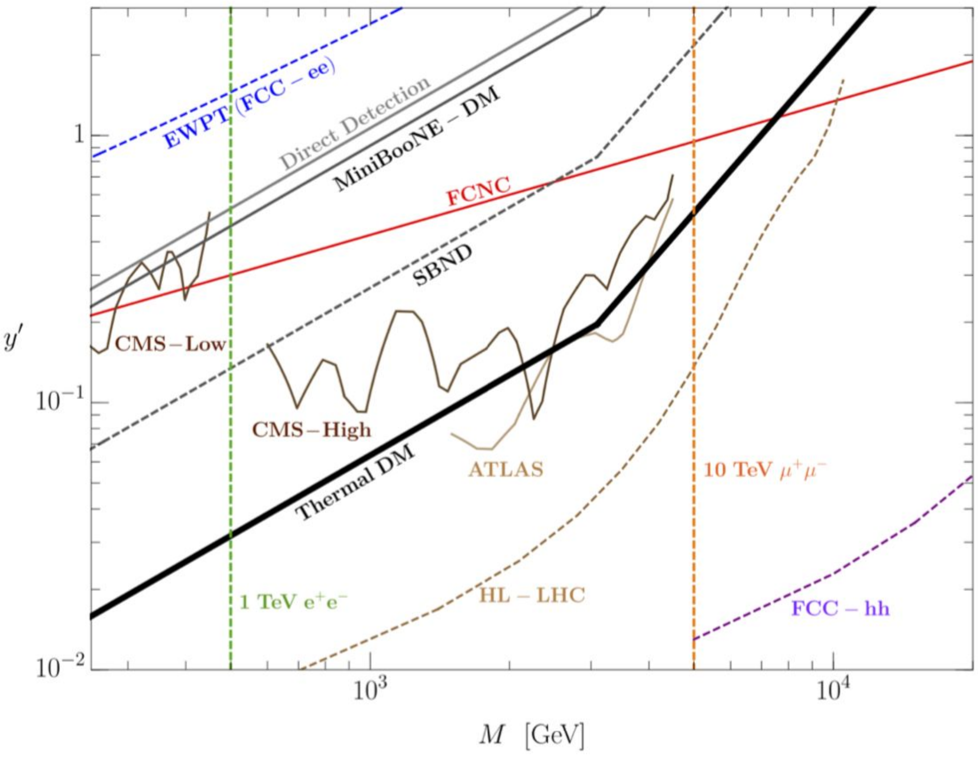
Most "portal" models of **light dark matter** (dark photon, dark Higgs) require **new high mass particles** to be theoretically self-consistent

Colliders can **discover** directly the **high-mass particles**, complementing discoveries at e.g. accelerator experiments

Example of **dark scalar mediator** model preferentially coupling to up-type quarks:

- **thermal DM** target can be reached with **HL-LHC**
- **lighter mediator** masses (< 1 TeV) still of interest for future colliders → need **non-standard data-taking techniques** (lower trigger thresholds)

New particle coupling to SM



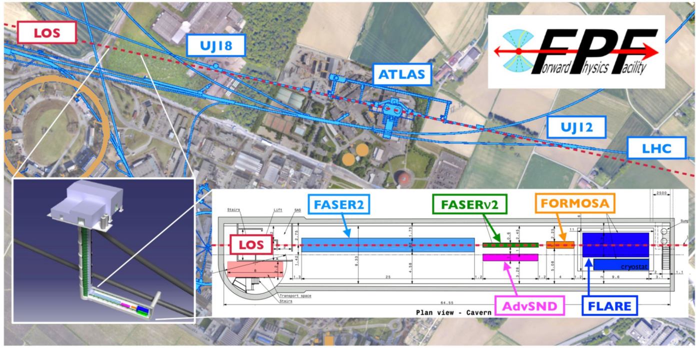
New particle mass

Dark sector experimental opportunity: Forward Physics Facility

EF10 Focus Topic #2:
Beyond WIMP

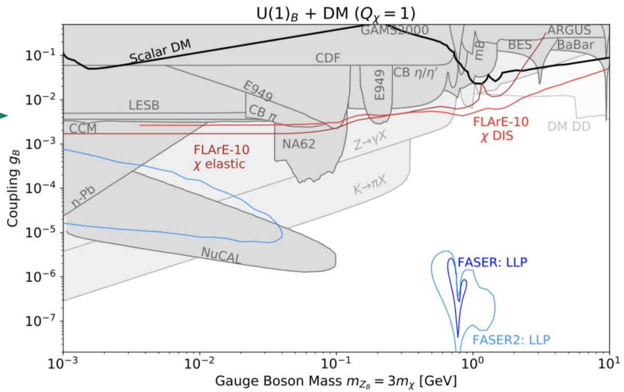
Establishing **new tunnels and related civil engineering** necessary for future collider physics program → how to maximise physics reach during construction?

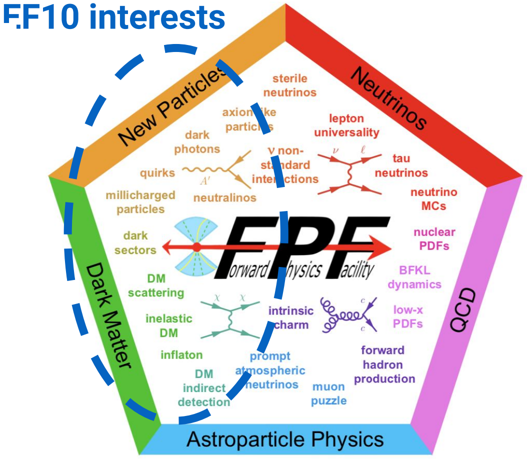
Following the example of LHC experiments (e.g. FASER/FASER-v), build dedicated tunnels / facilities to host complementary smaller experiments: [Forward Physics Facility](), **HL-LHC focused**



Many different BSM physics cases for dark matter and dark sectors in forward physics, e.g.:

- Mediators to invisible particles
- Dark photons
- Long-lived particles
- Millicharged particles

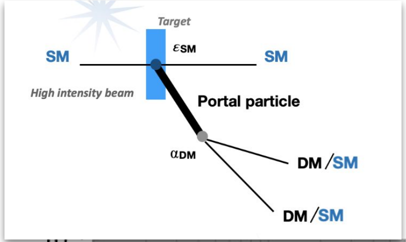


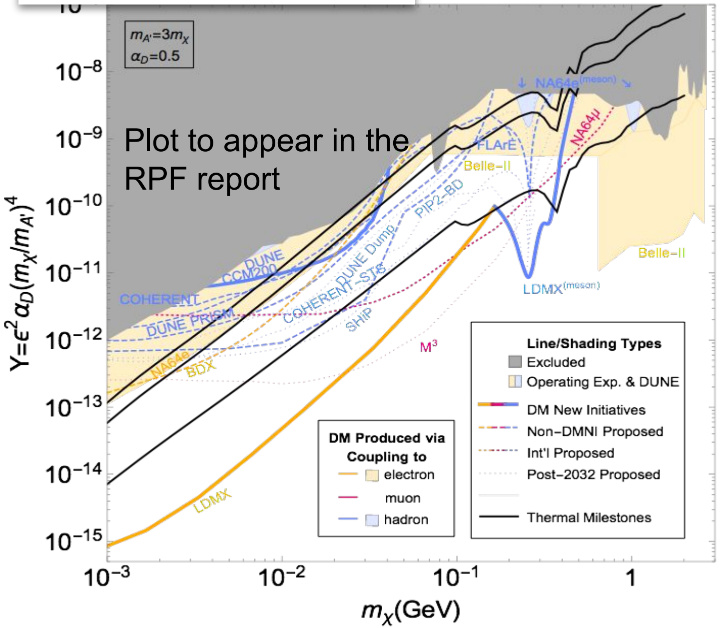


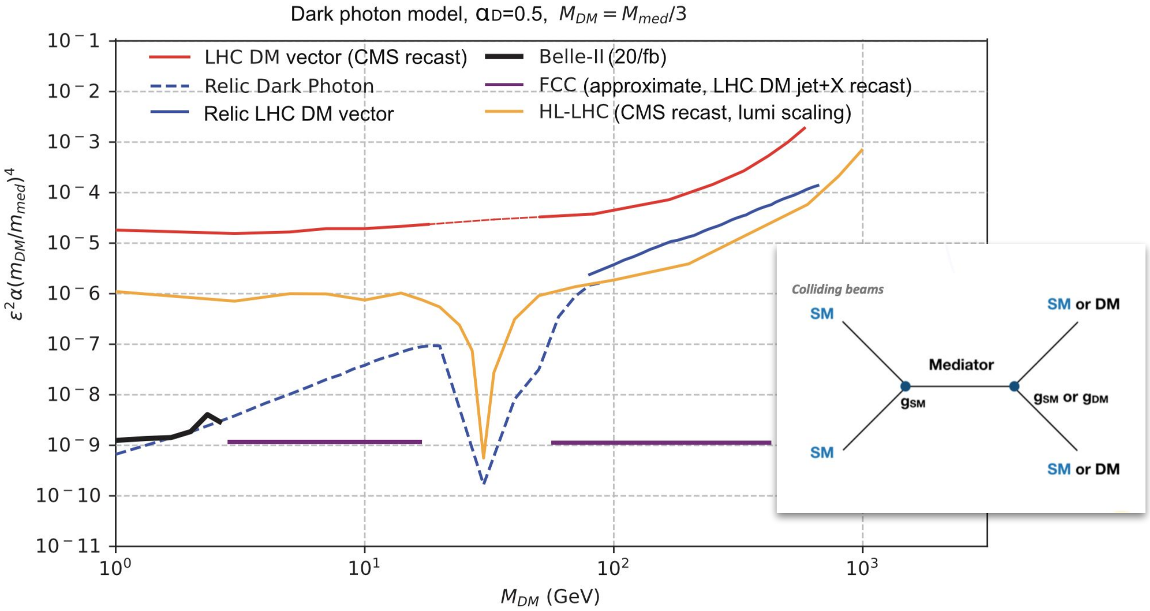
Jonathan Feng et al.: Forward Physics Facility Whitepaper, arXiv: 2203.05090

Complementarity with the Rare Processes & Precision Frontier

Dark photon = minimal theoretically-consistent vector mediator model for thermal DM production, chosen by RPF as benchmark → connects **light DM at accelerators** and **heavier DM at colliders**



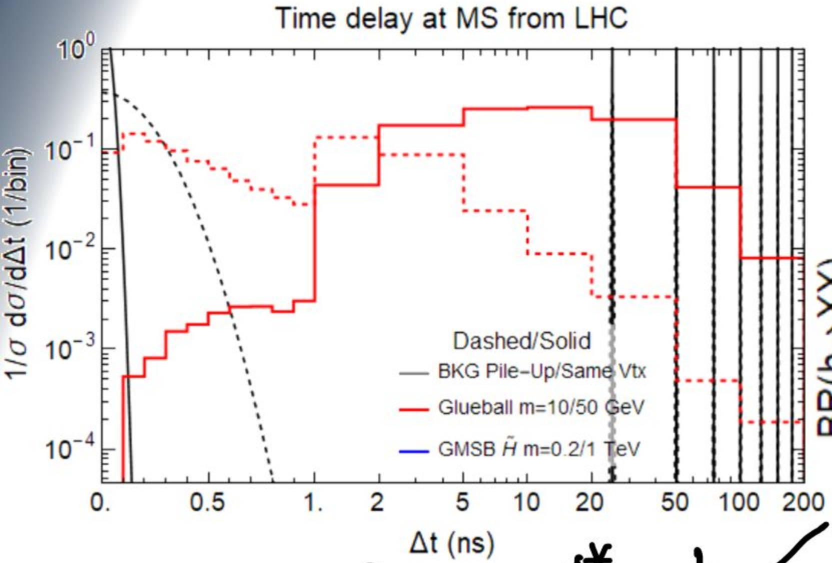


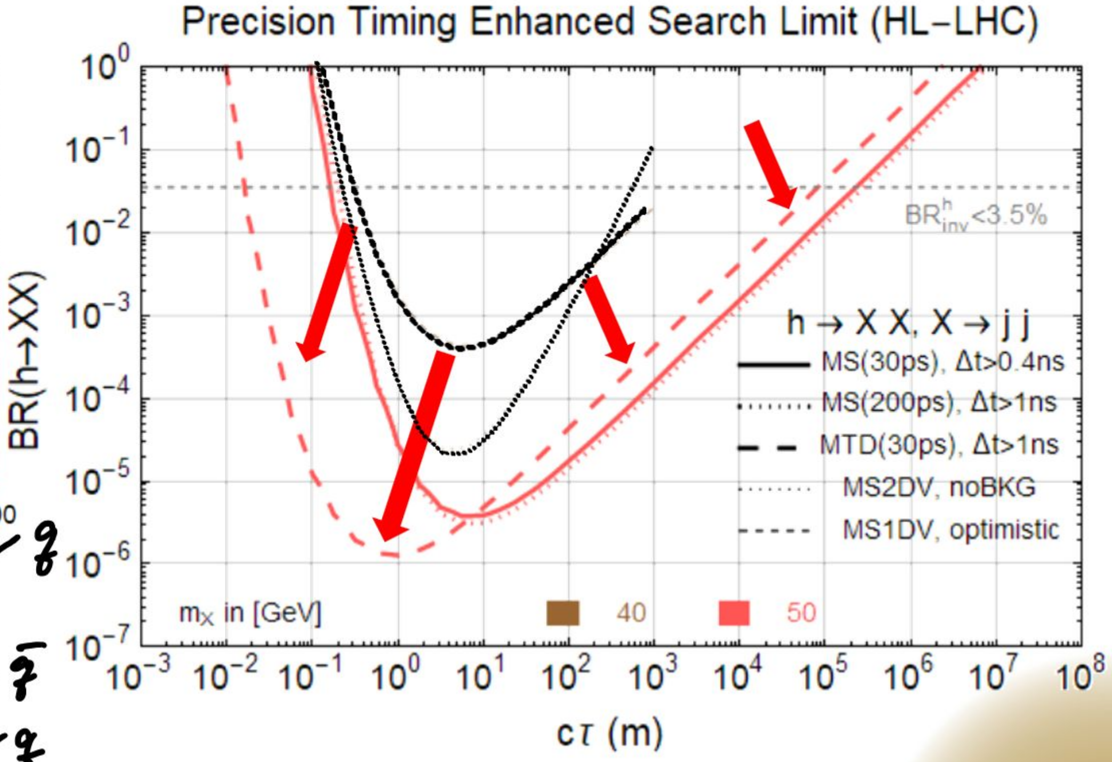


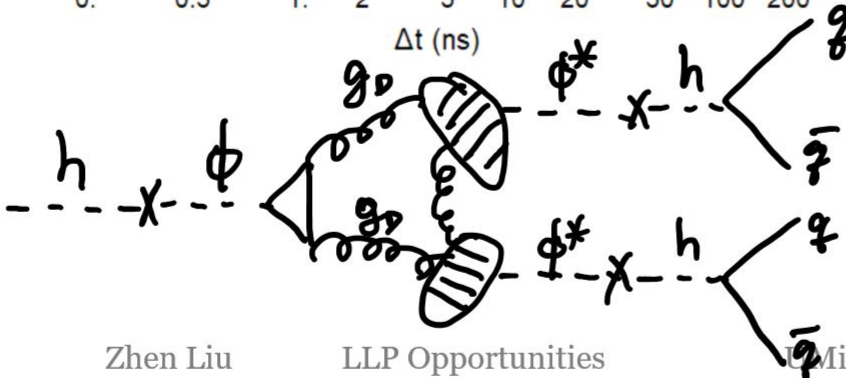
HL-LHC and future colliders (lepton colliders to be added) needed to reach the **thermal relic milestone**

J. Liu, ZL, LT Wang, 1805.05957

Late comers will be spotted easily: Higgs decays



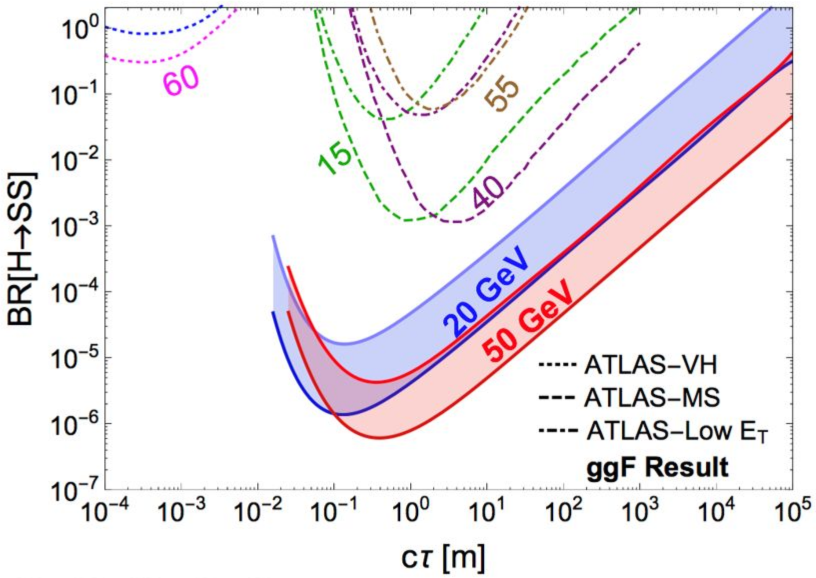


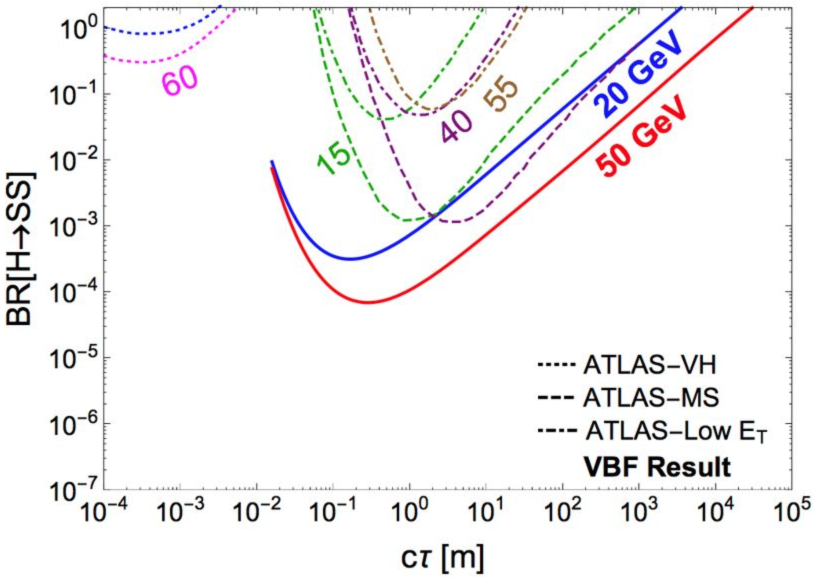


Projected sensitivity for HL-LHC

With a similar (in concept but different in details) vertexing selection as the previous axion example

- ggF result: with/without high H_T trigger requirement
- VBF result: standard VBF trigger





Compositeness and Extra Dimensions

Two classes of signatures possible in both extra dimensions and compositeness

1. New resonances, either Kaluza Klein (KK) or strong QCD-like excitations.
   - We consider this largely covered by the SUSY searches. E.g. KK makes new states for each SM particle much like SUSY. Relative comparisons of sensitivity (strong/weak production, compressed and otherwise) are similar.
   - QCD-like excitation can also be like Z’ (ρ…)
2. EFT operators for impact of higher energy physics integrated out (particularly relevant for strongly interaction new physics

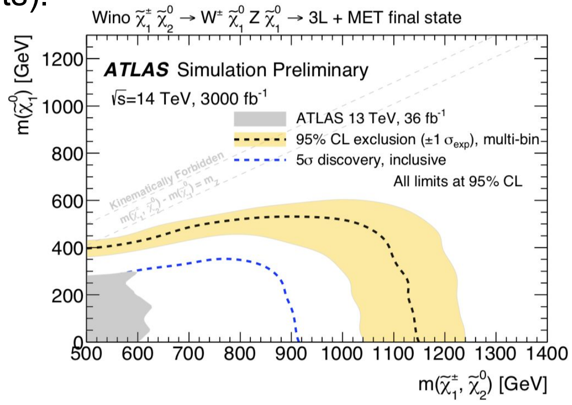
SUSY

Studies focus on R-parity conserving simplified models

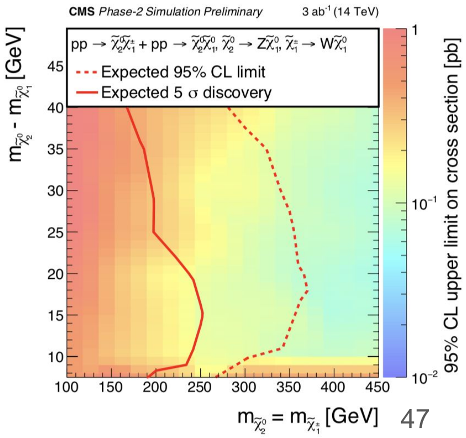
- Again main goal is to compare sensitivity, but there are subtleties. Simplified models often assume unrealistic 100% BR, but then combining several analyses can recover much of the loss (e.g. chargino-neutralino to WZ vs WH)
- There is not a complete set of reach estimate using simulated samples and analysis. We often used the collider reach tool (http://collider-reach.web.cern.ch/collider-reach/) to extrapolate Run-2 results.
  - Where a dedicated study is available, we compare it to the collider reach estimate to understand the broad reliability (see later plots).

In general

- Lepton colliders are energy limited: 95% CL exclusion and 5σ discovery reach is similar
- Hadron colliders are lumi / S/√B limited: exclusion reach severely limited for high background models



(a) ATLAS Wino-Bino HL-LHC sensitivity



(b) CMS Higgsino HL-LHC sensitivity