BSM Searches at Future Colliders

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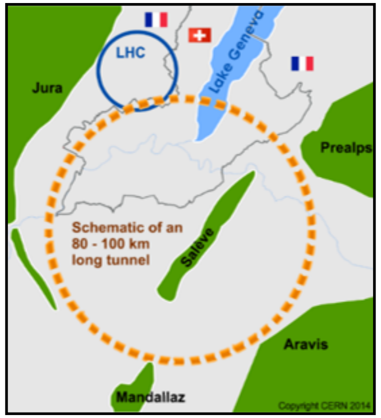
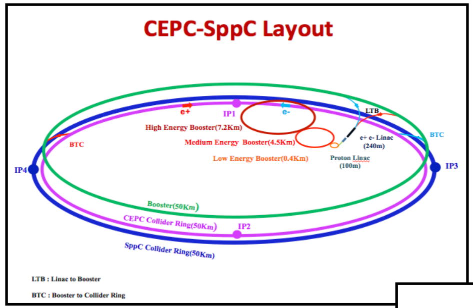
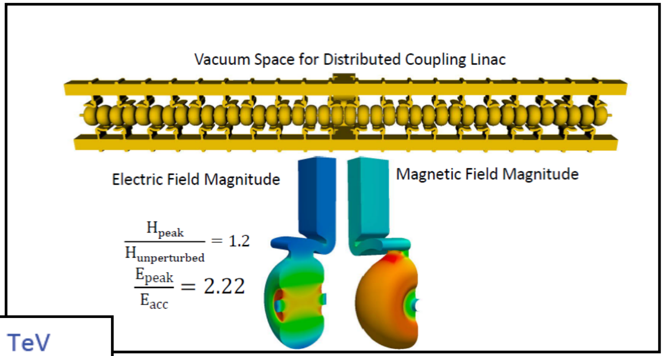
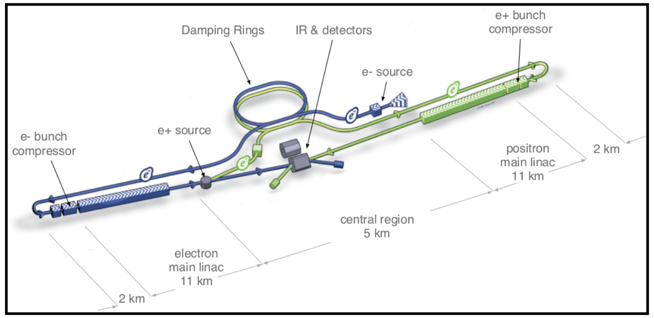
DESY Future Colliders Day

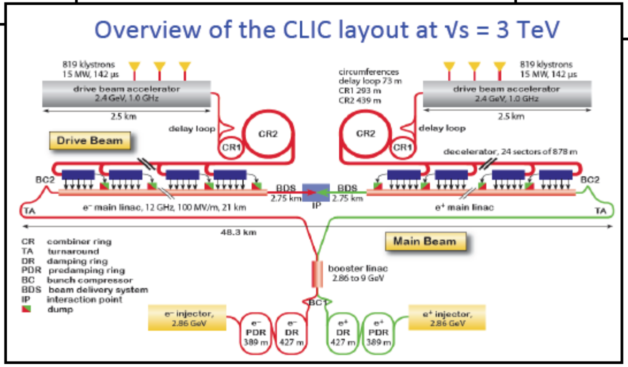
November 11, 2024











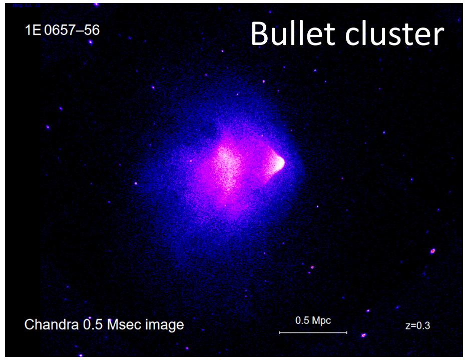
Philosophy of this Talk

- I was asked to discuss **BSM searches at future colliders**
- In particular, focus on **comparing different colliders** and what we can do at **different energies**
- Highlight any **controversies** that may exist
- My strategy: present the main points & summary plots from the **Snowmass Energy Frontier BSM report** (arXiv:2209.13128)
  - Updated plots where available (and other more recent inputs)
  - Combines EF08 (Model-specific explorations), EF09 (More general explorations), and EF10 (Dark matter at colliders)
- **If I missed an update**, please ping me and I will correct the slides!
- Trying to show the **breadth of BSM opportunities** available at future colliders, so perhaps light on the details

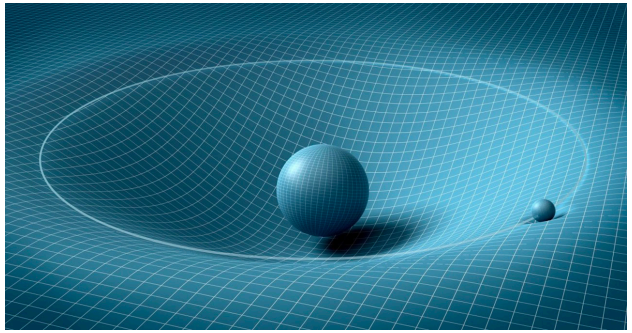
Future Colliders & New Physics

- Future colliders will provide **unique opportunities** to learn more about **how nature works**
- In **EVERY** Higgs/top/electroweak/flavor factory and multi-TeV collider, we will be able to **probe new physics** beyond the SM very well through **direct** and **indirect** searches
- There's **no other way** besides colliders to explore the **Higgs** boson!

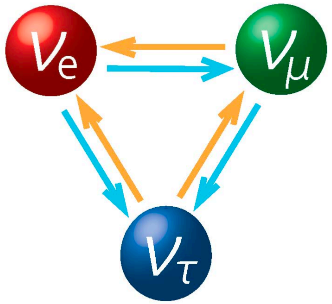
(Particle) nature of dark matter?



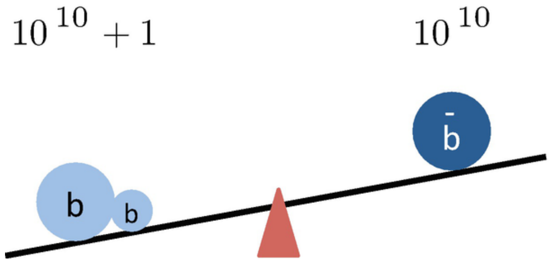
Incorporate gravity into a consistent theory?



How do neutrinos have mass?



Why more matter than antimatter?



Benchmark Collider Scenarios

- Classify colliders into **2 main categories**:
  - Higgs factories & multi-TeV colliders
  - Arbitrary distinction: just to organize the benchmark scenarios
- **Higgs factories** - lepton colliders with $\sqrt{s}$ < 1 TeV that will substantially improve the Higgs-boson precision physics reach beyond the HL-LHC
- **Multi-TeV colliders** - lepton and hadron colliders with $\sqrt{s}$ > 1 TeV

Higgs Factory Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C^3 c.o.m almost similar	ee	250 GeV	$\pm 80/\pm 30$	2
		350 GeV	$\pm 80/\pm 30$	0.2
		500 GeV	$\pm 80/\pm 30$	4
		1 TeV	$\pm 80/\pm 20$	8
CLIC	ee	380 GeV	$\pm 80/0$	1
CEPC	ee	M_Z		60
		$2M_W$		3.6
		240 GeV		20
		360 GeV		1
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2\ M_{top}$		1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

Multi-TeV Collider Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HE-LHC	pp	27 TeV		15
FCC-hh	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh		3.5 TeV		2
CLIC	ee	1.5 TeV	$\pm 80/0$	2.5
		3.0 TeV	$\pm 80/0$	5
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10

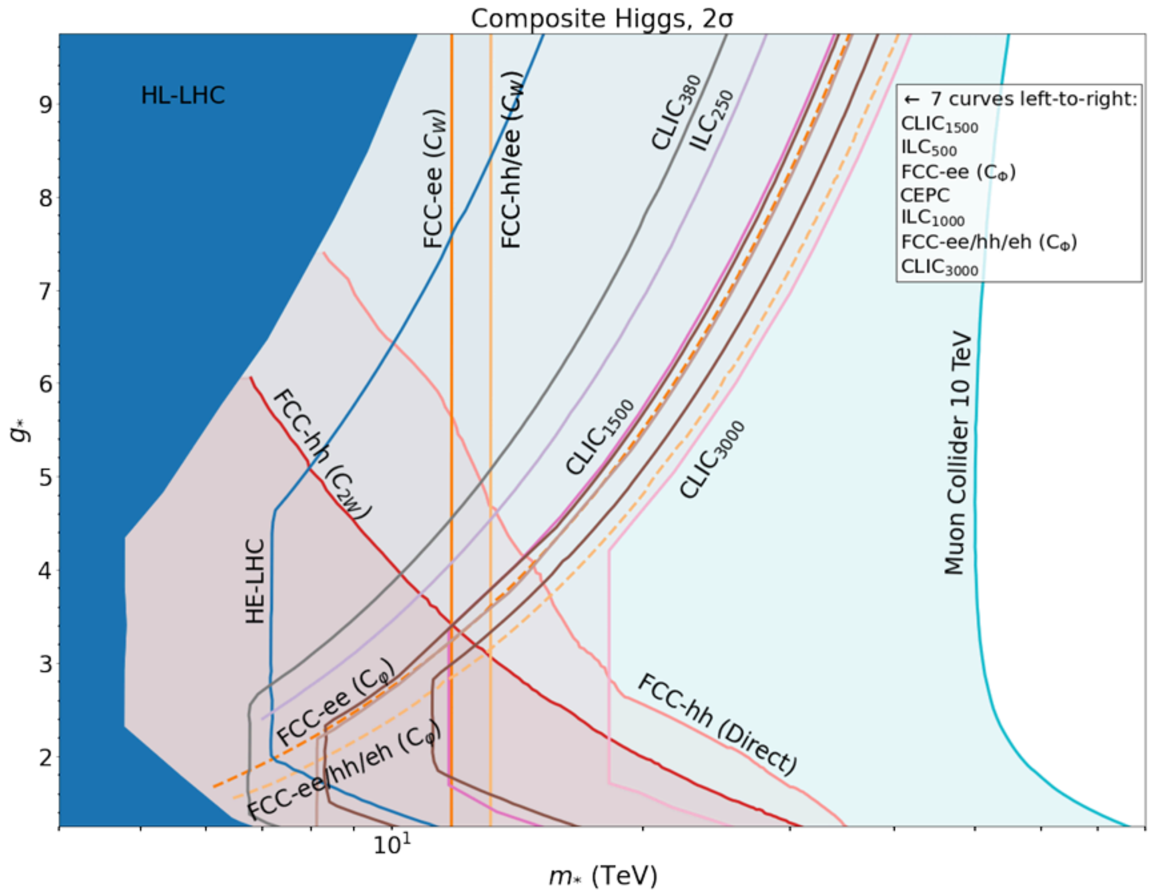
Physics Scenarios

- Composite Higgs
- SUSY
- New Particles and Heavy Resonances
- Axion-Like Particles
- Heavy Neutral Leptons
- Dark Matter & Dark Sectors
- Hidden Valleys & Dark QCD
- Long-Lived Particles

Composite Higgs

- Composite Higgs models: Higgs boson is a bound state of new strong interactions, has a finite size
  - Minimal Higgs mechanism for EWSB is extended by new confining degrees of freedom that ameliorate the gauge hierarchy problem in the SM
- 125 GeV Higgs scalar: mixture of a fundamental scalar boson and a composite meson of the confining group
- FCC (ee and hh/ee) sensitivity to CW is almost independent of g_*

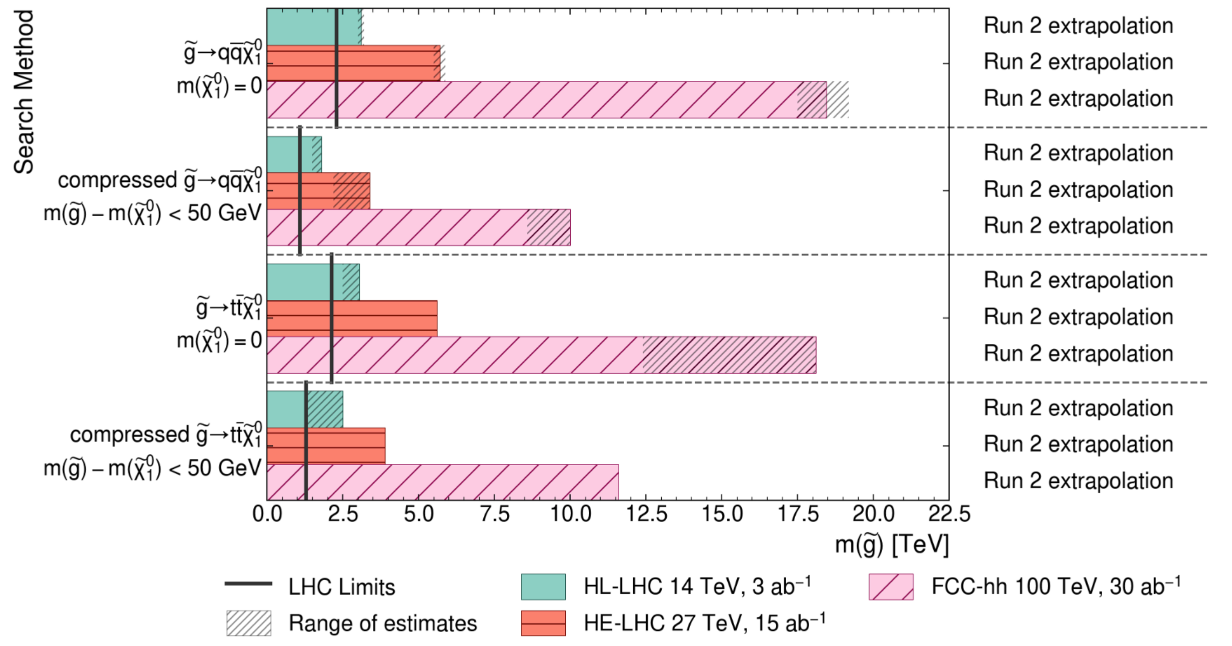
Exclusion (2σ) Sensitivity



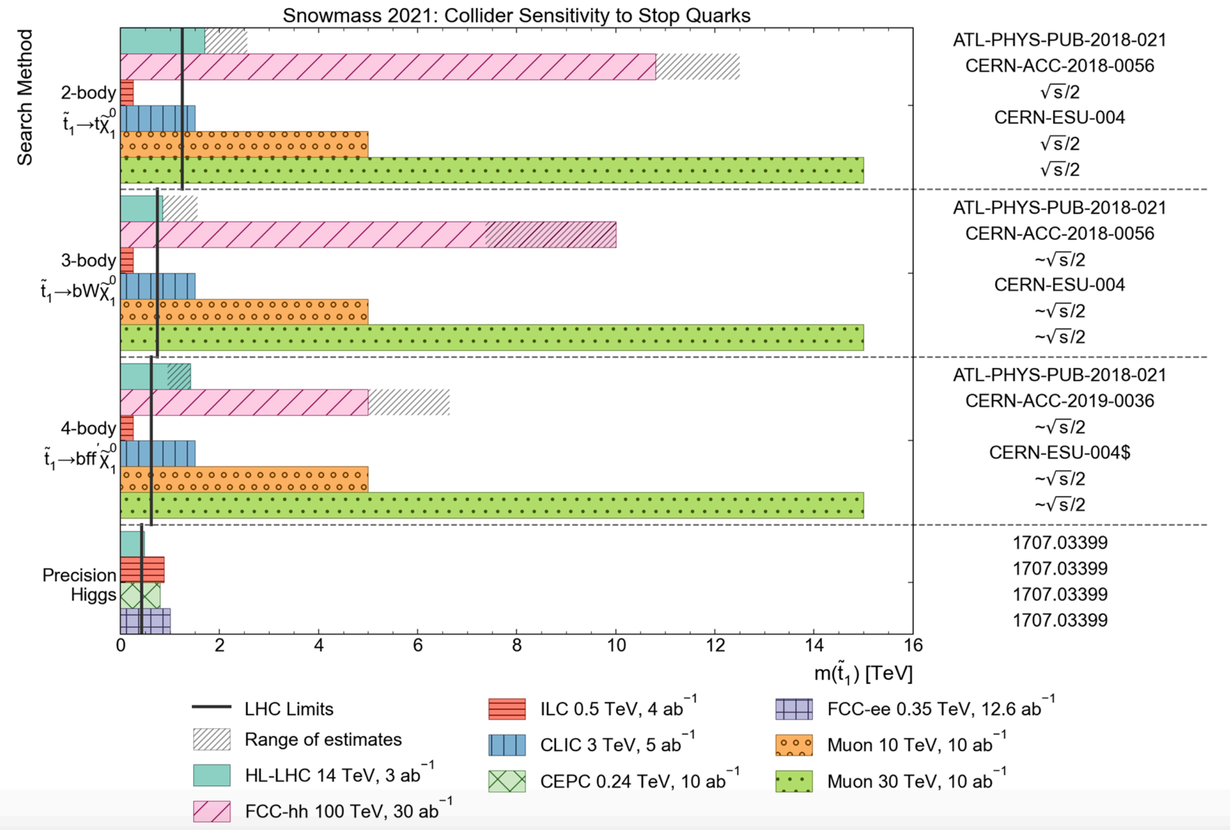
SUSY (I)

- Many results for future colliders shown in the context of the MSSM
- Various decay chains are lumped into a single multijet + pTmiss signature

Gluino 95% CL expected exclusion



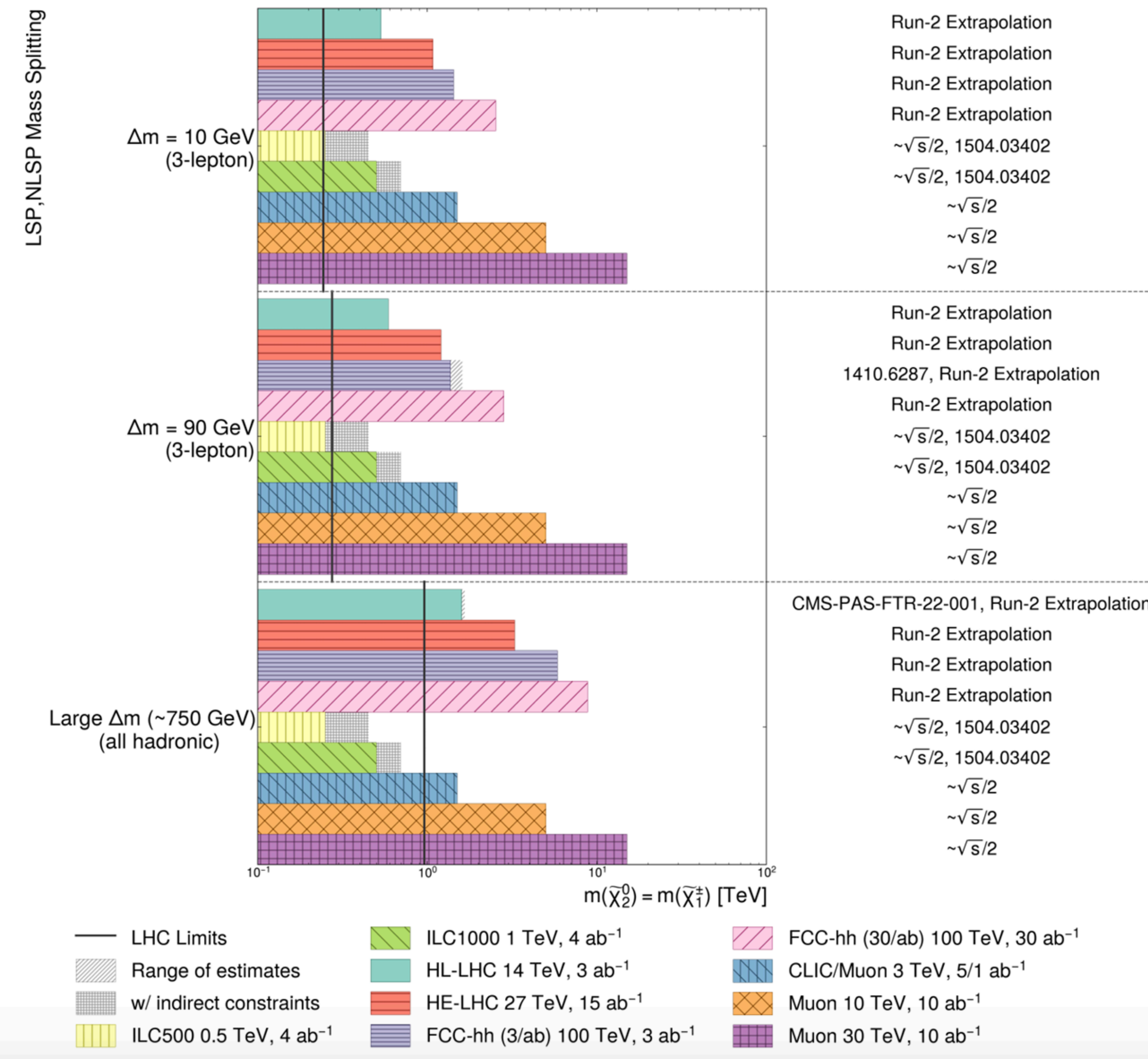
Stop 95% CL expected exclusion



SUSY (II)

- Larger mass splittings
- Wino Bino coupling for production
- Lightest chargino and next-to-lightest neutralino are produced as a pair
- Can then decay, resulting a WZ or Wh + pTmiss final state

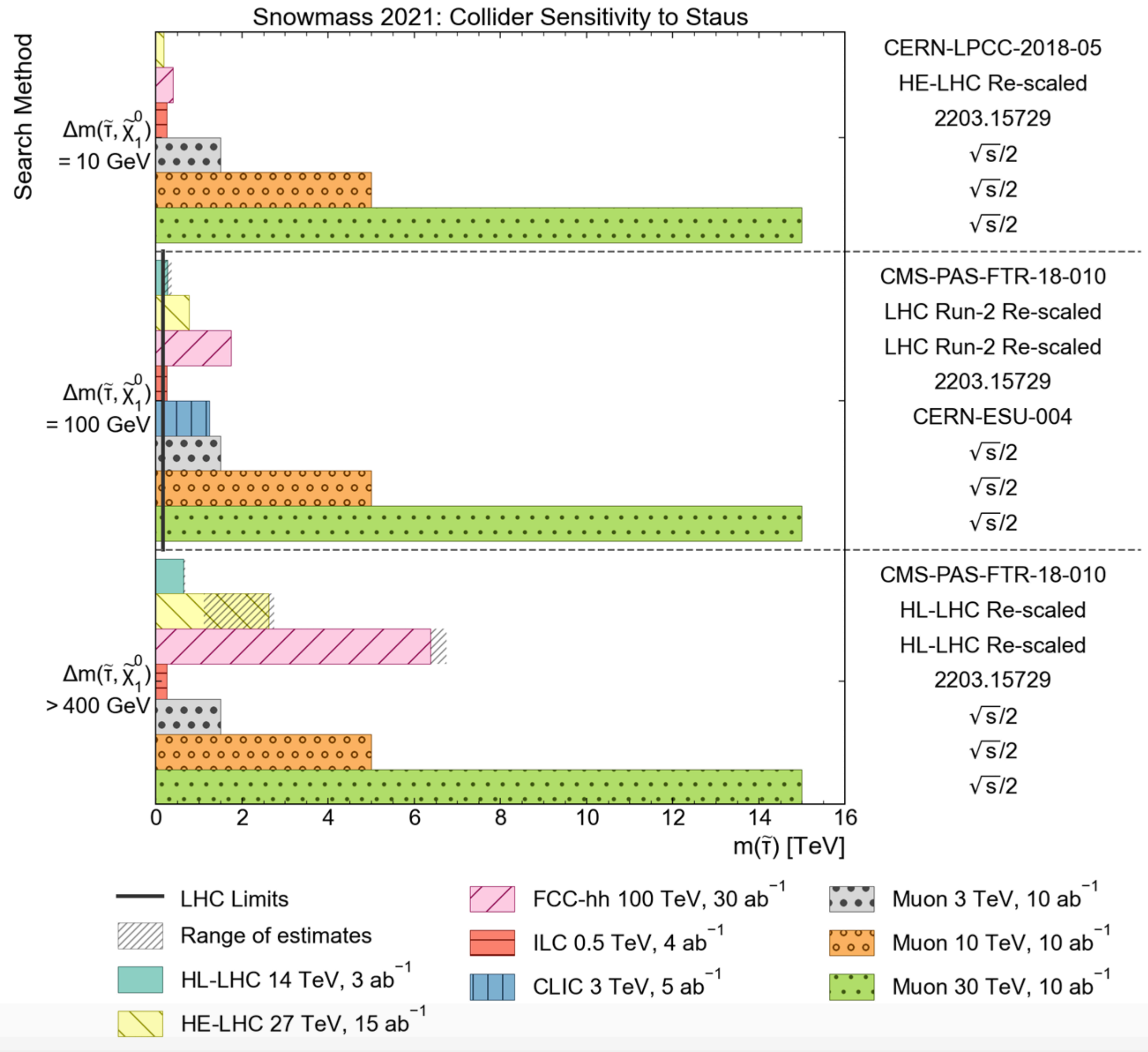
Wino NLSP bino LSP 95% CL expected exclusion



SUSY (III)

- Large amount of stau parameter space will not be probed even by the HL-LHC
- Lots of possibilities for stau searches at future colliders

Stau 95% CL expected exclusion



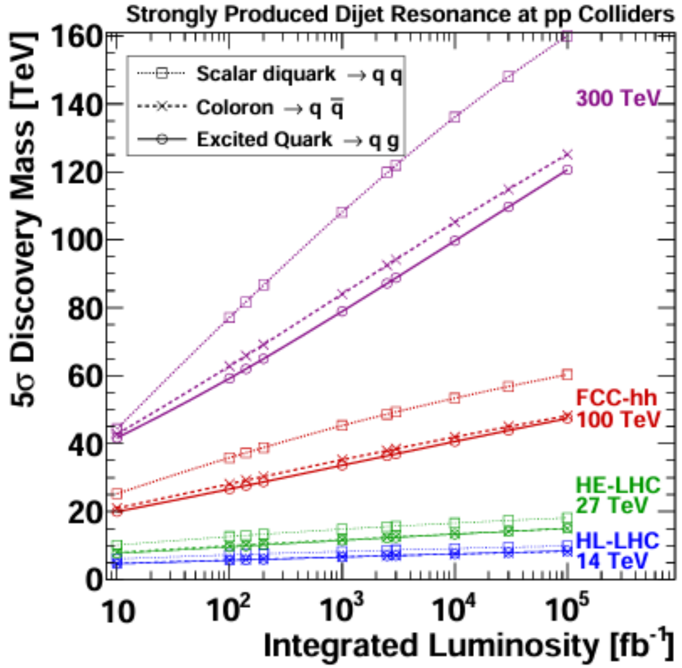
New Bosons and Heavy Resonances

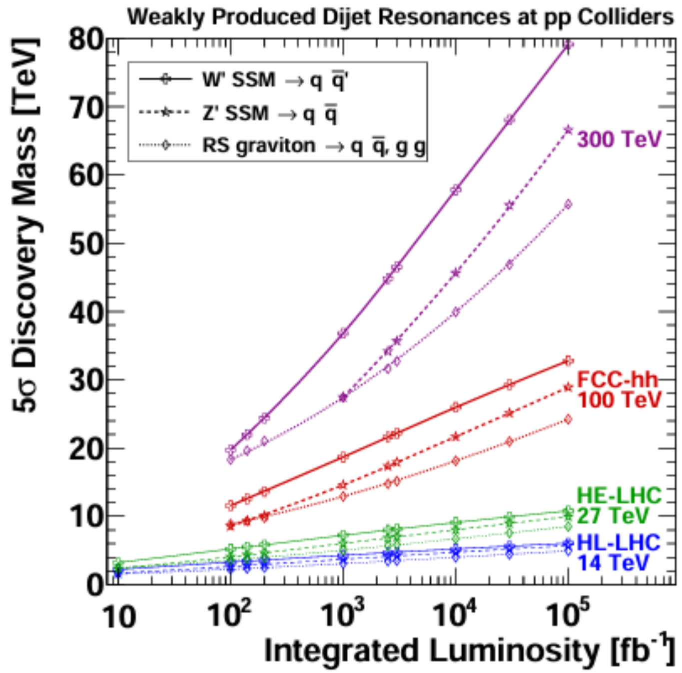
- 5σ discovery and 95% CL exclusion of SSM Z' model and universal Z' model with a coupling $g_{Z'} = 0.2$
- Obvious correlation that higher center of mass collider energy affords higher reach in Z' mass
- The two Z' model benchmarks have very comparable results: underlying charge assignments of SM fermions to the Z' currents only differ by O(1) factors
- Table illustrates both the power of lepton colliders for indirect discovery of new physics, and the subsequent necessity of a hadron collider to directly produce and confirm that new physics

Machine	Type	√s (TeV)	∫L dt (ab^{-1})	Source	Z' Model	5σ (TeV)	95% CL (TeV)
HL-LHC	p p	14	3	R.H.	$Z'_{SSM} \rightarrow$ dijet	4.2	5.2
				ATLAS	$Z'_{SSM} \rightarrow l^+ l^-$	6.4	6.5
				CMS	$Z'_{SSM} \rightarrow l^+ l^-$	6.3	6.8
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	6
ILC250/ CLIC380/ FCC-ee	$e^+ e^-$	0.25	2	ILC	$Z'_{SSM} \rightarrow f^+ f^-$	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	$Z'_{SSM} \rightarrow e^+ e^-$	12.8	12.8
ILC	$e^+ e^-$	0.5	4	ILC	$Z'_{SSM} \rightarrow f^+ f^-$	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	$Z'_{SSM} \rightarrow f^+ f^-$	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.	$Z'_{SSM} \rightarrow$ dijet	25	32
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	35
				EPPSU	$Z'_{SSM} \rightarrow l^+ l^-$	43	43
Muon Collider	$\mu^+ \mu^-$	10	10	IMCC	$Z'_{Univ}(g_{Z'}=0.2)$	42	70
VLHC	p p	300	100	R.H.	$Z'_{SSM} \rightarrow$ dijet	67	87
Coll. In the Sea	p p	500	100	R.H.	$Z'_{SSM} \rightarrow$ dijet	96	130

Dijet Resonances

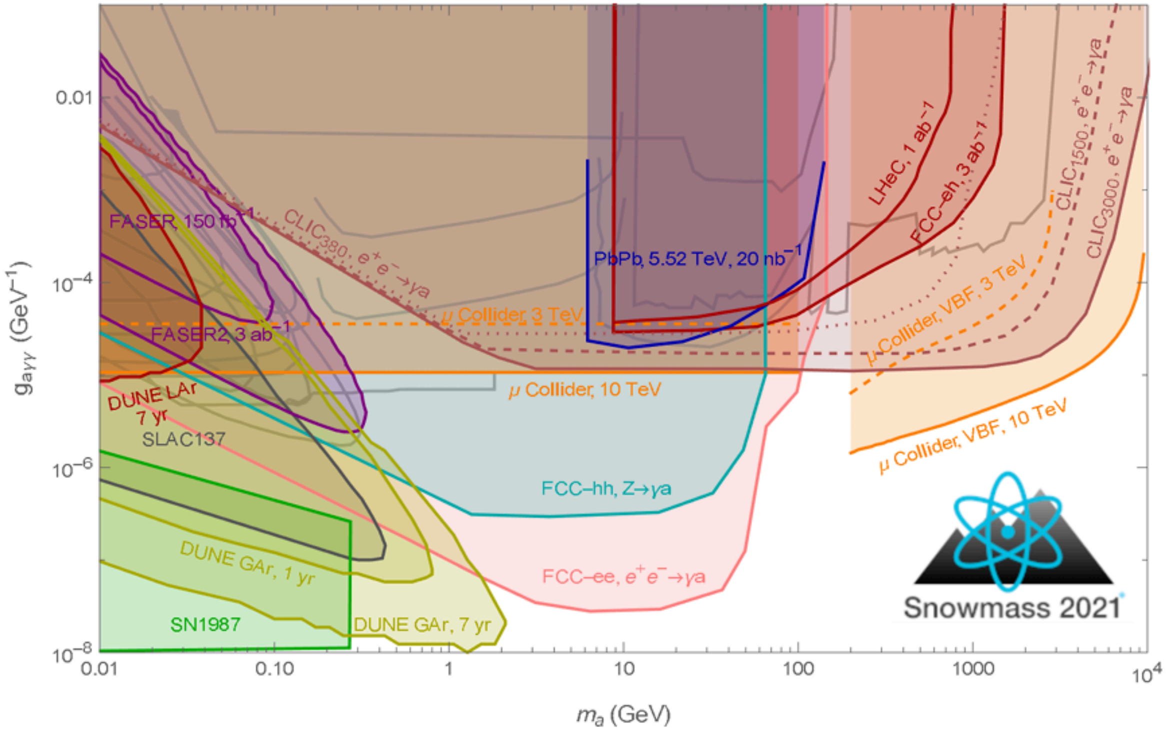
- pp→X→2jets: essential benchmark of discovery capability of pp colliders
- Sensitive to a variety of BSM models at the highest mass scales
- Strongly produced models: scalar diquarks, colorons, and excited quarks
- Weakly produced models: W’, Z’, and Randall-Sundrum gravitons



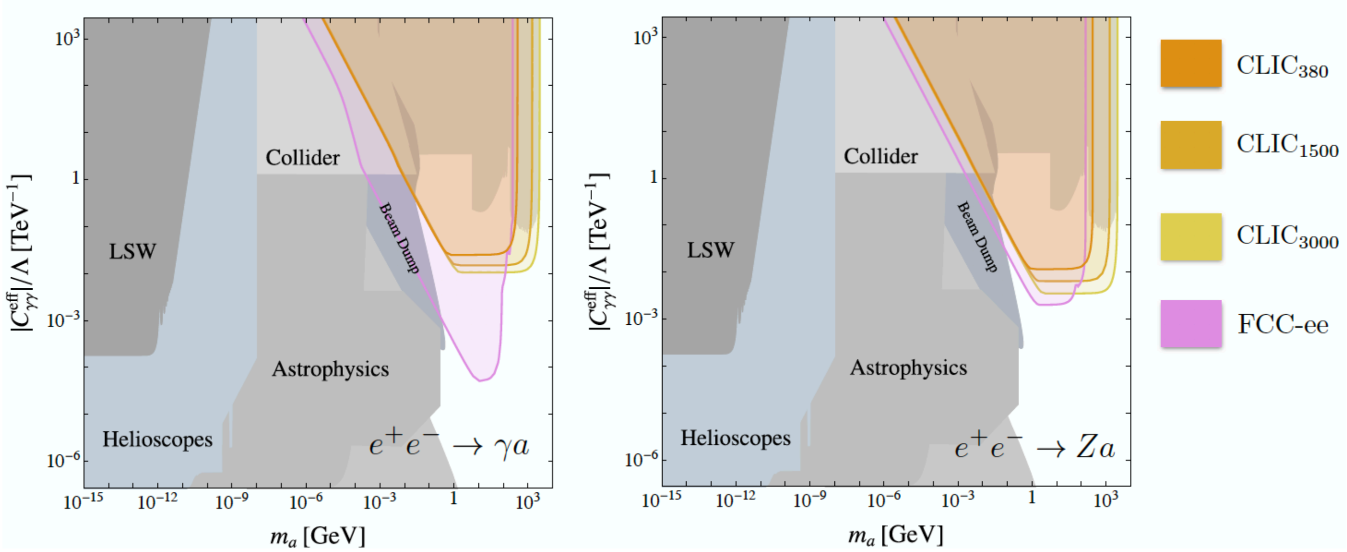


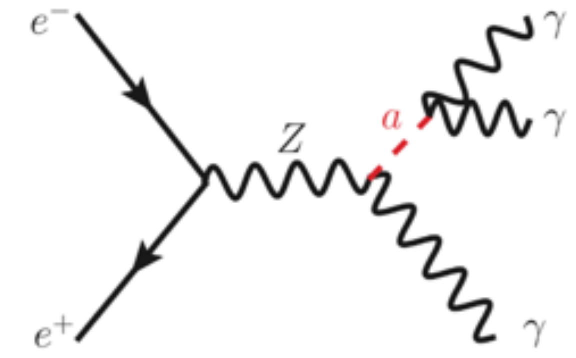
Axion-Like Particles (ALPs)

- Axion-like Particles (ALPs) are pseudoscalars in models with spontaneously broken global symmetries
- At the FCC-ee:
    - Orders of magnitude of parameter space accessible
    - Especially sensitive to final states with at least 1 photon



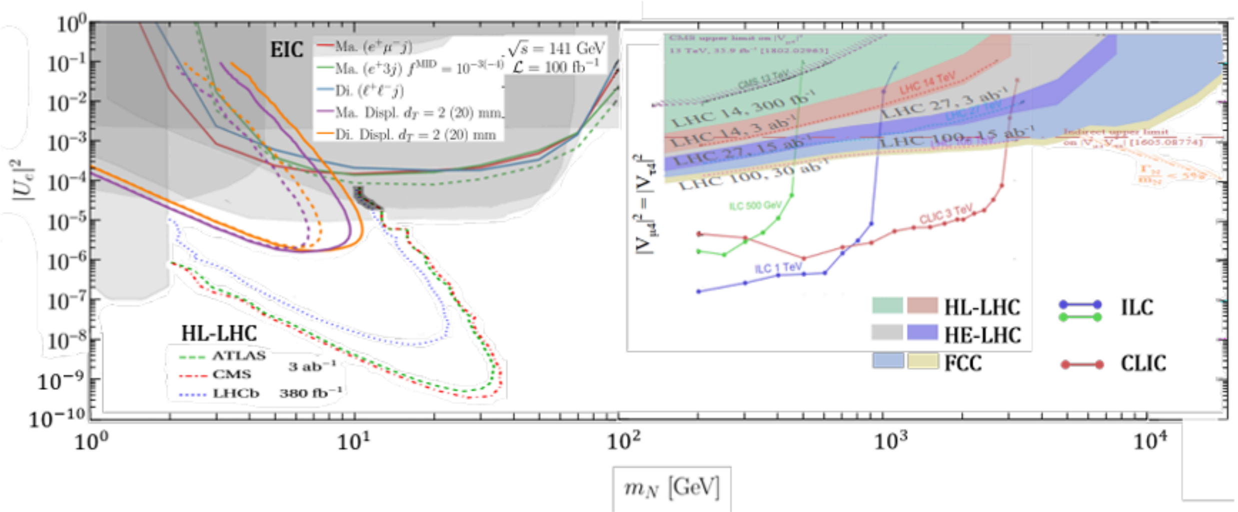
[arXiv:1808.10323](https://arxiv.org/abs/1808.10323), [arXiv:2108.08949](https://arxiv.org/abs/2108.08949)

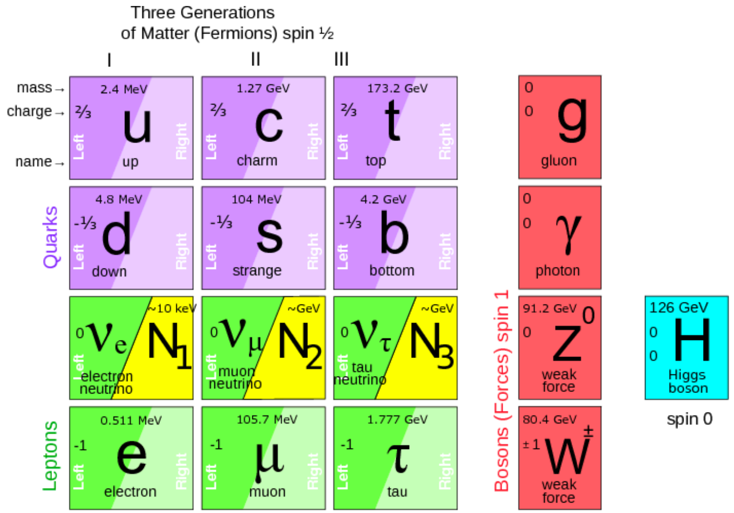


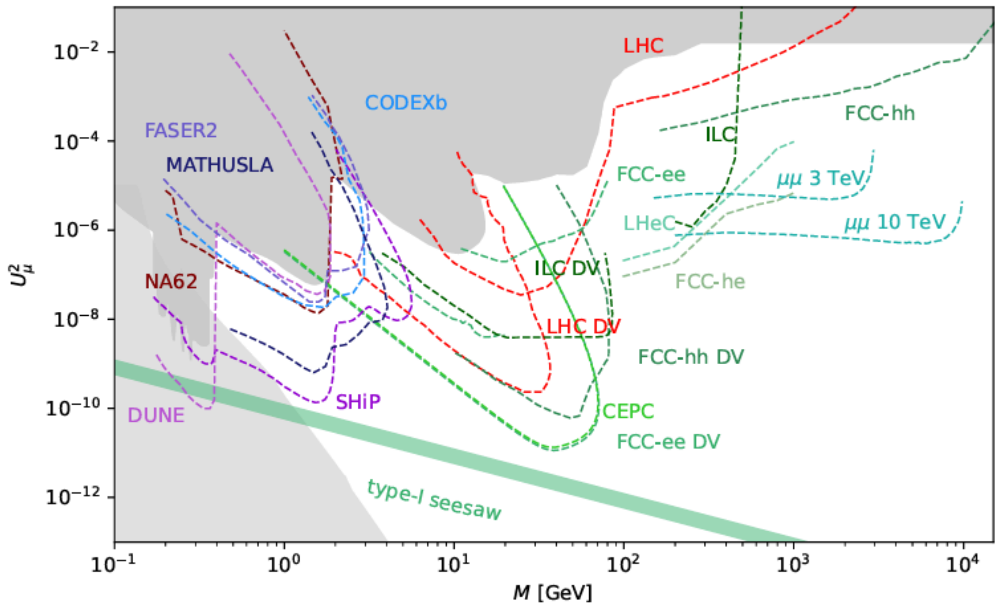


Heavy Neutral Leptons: Type I Seesaw/ HeavyN Simplified Model

- **Sterile neutrinos** with **very small mixing** with active neutrinos
- Could provide answers to some open questions of the SM: Neutrino masses, Baryon asymmetry, Dark matter
- Type I Seesaw models: singlet HNL is added to the SM

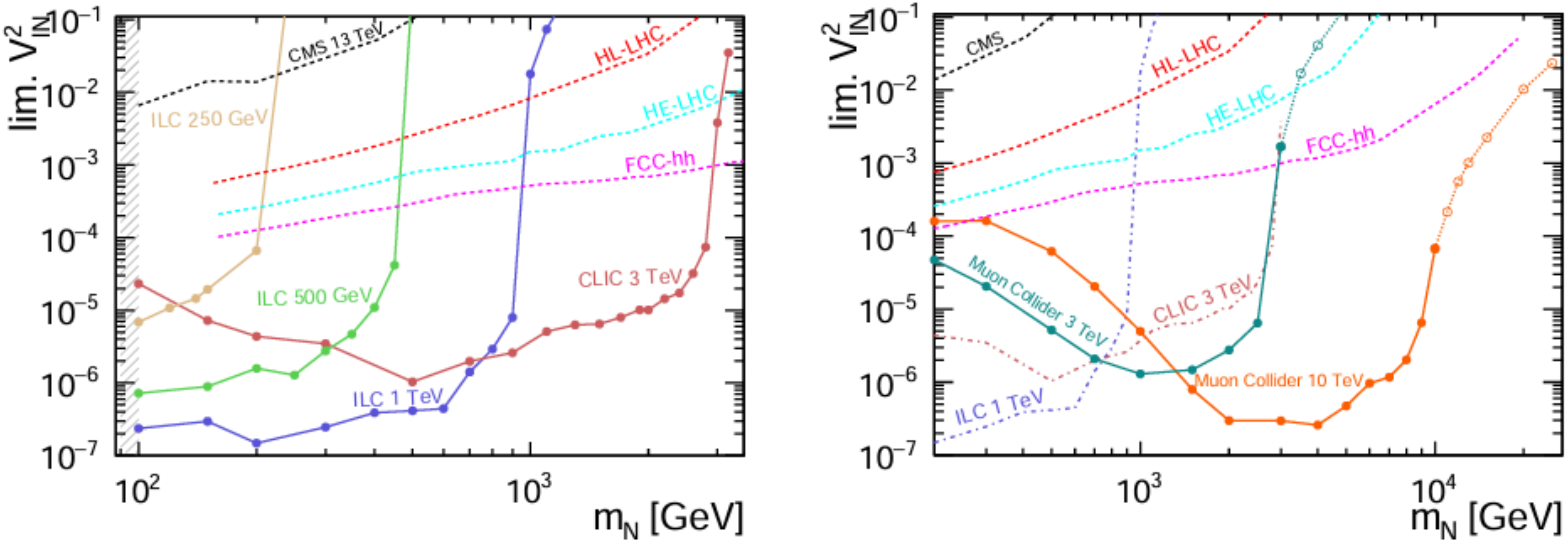






Updates to previous slide (after the talk)

https://inspirehep.net/literature/2751618



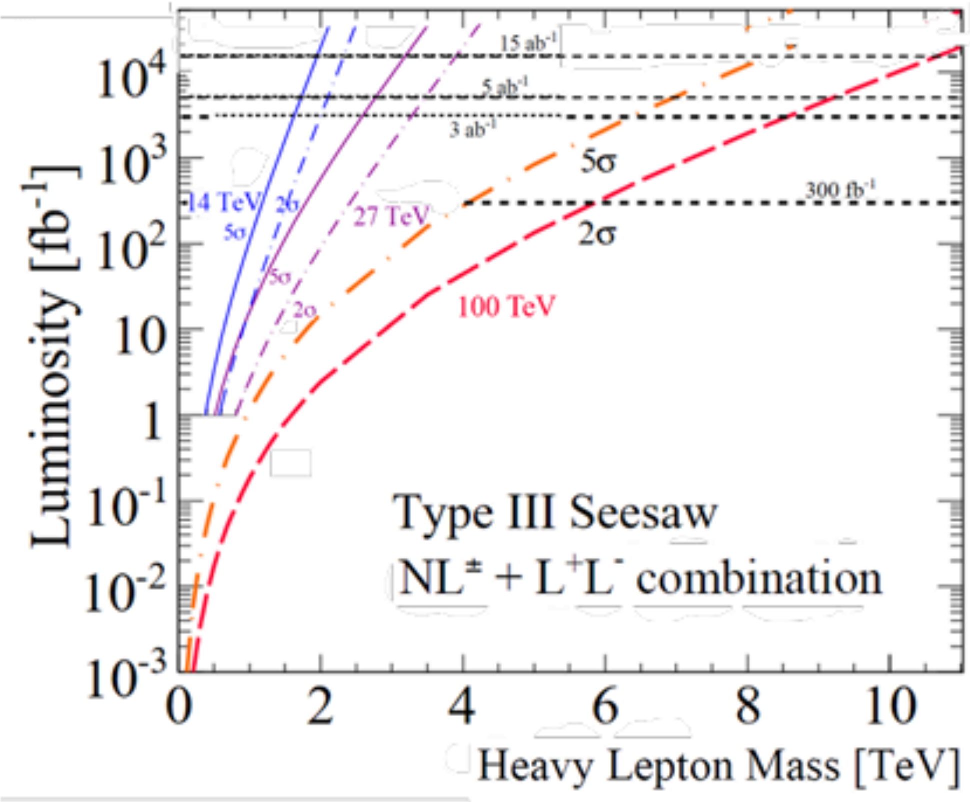
Expected limits on the coupling V^2_{lN} for e^+e^- colliders (left) and the Muon Collider (right).

Off-shell HNL production: mass reach over the whole range exceeds the one from FCC-hh

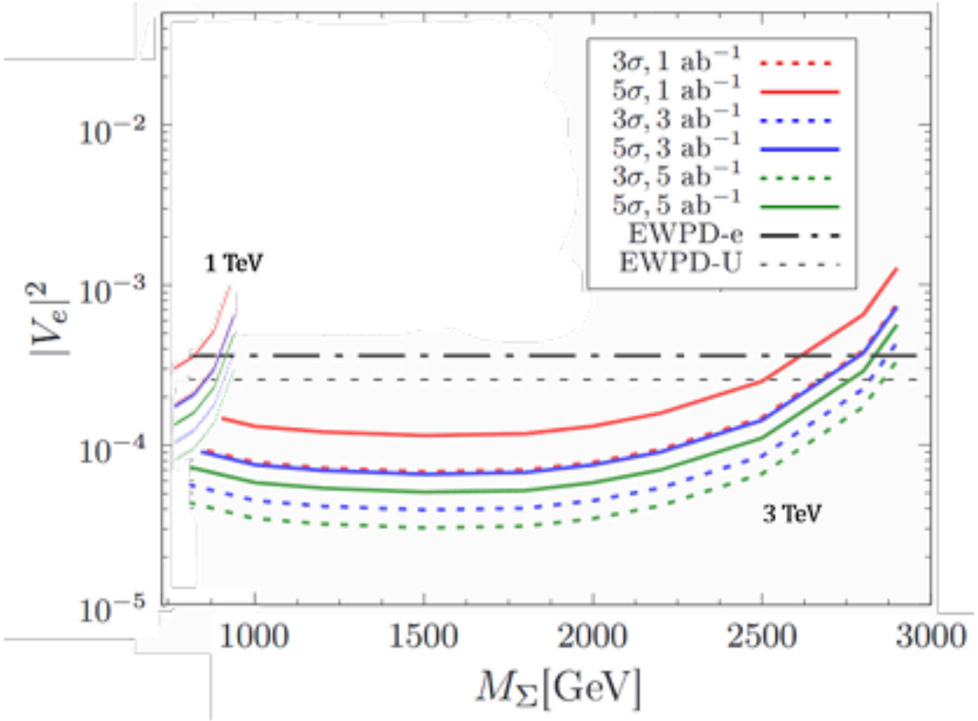
Heavy Neutral Leptons: Type III Seesaw

- Type III Seesaw: triplet of heavy leptons is added to the SM (one of is neutral)

Hadron Colliders



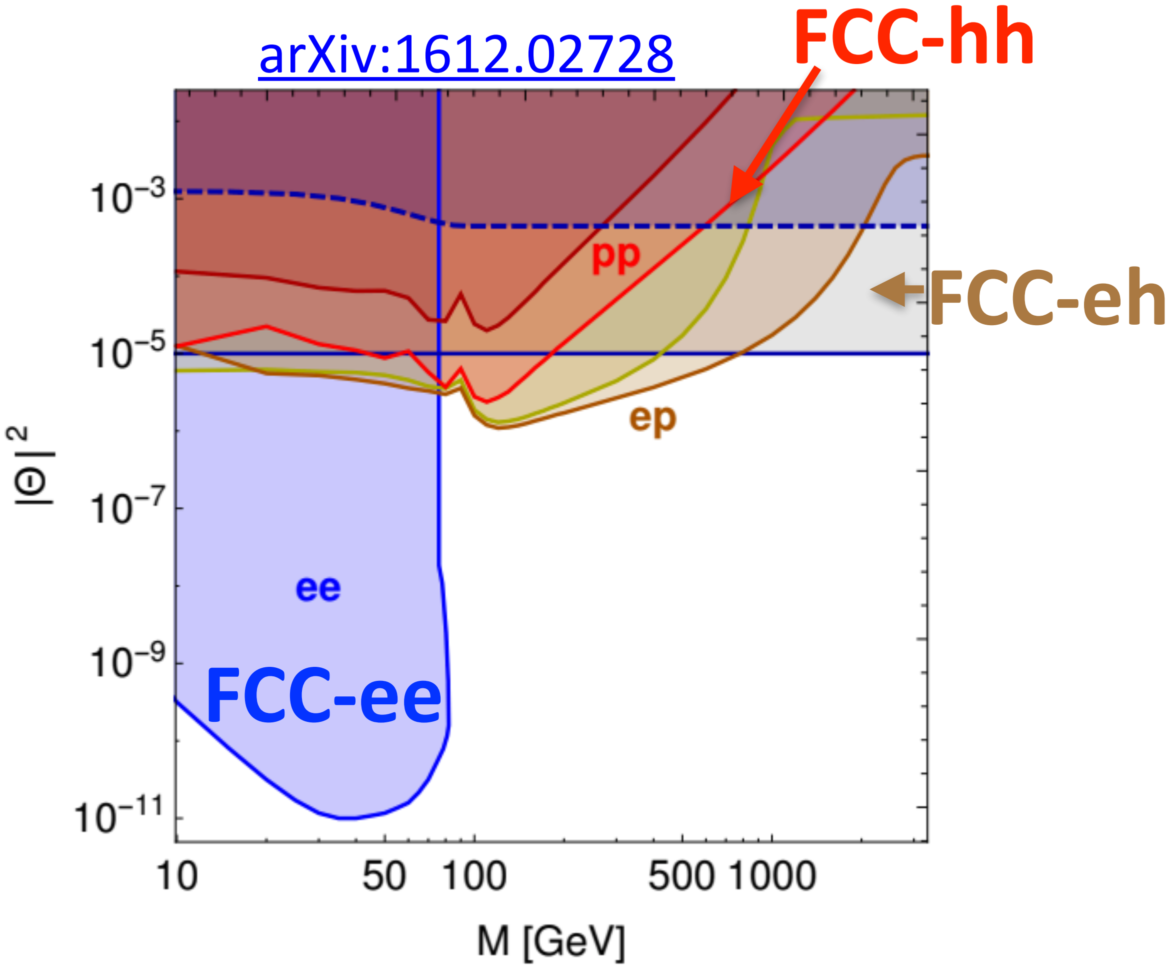
Lepton Colliders



Heavy Neutral Leptons: 3 Stages of the FCC

- **The three different stages of the FCC are complementary**
- Provides a unique potential to discover HNLs

arXiv:1612.02728



FCC-ee

- Direct search for single HNL production in W/Z decays
  - Sensitive to couplings down to 10^{-11} for M < W mass

FCC-hh

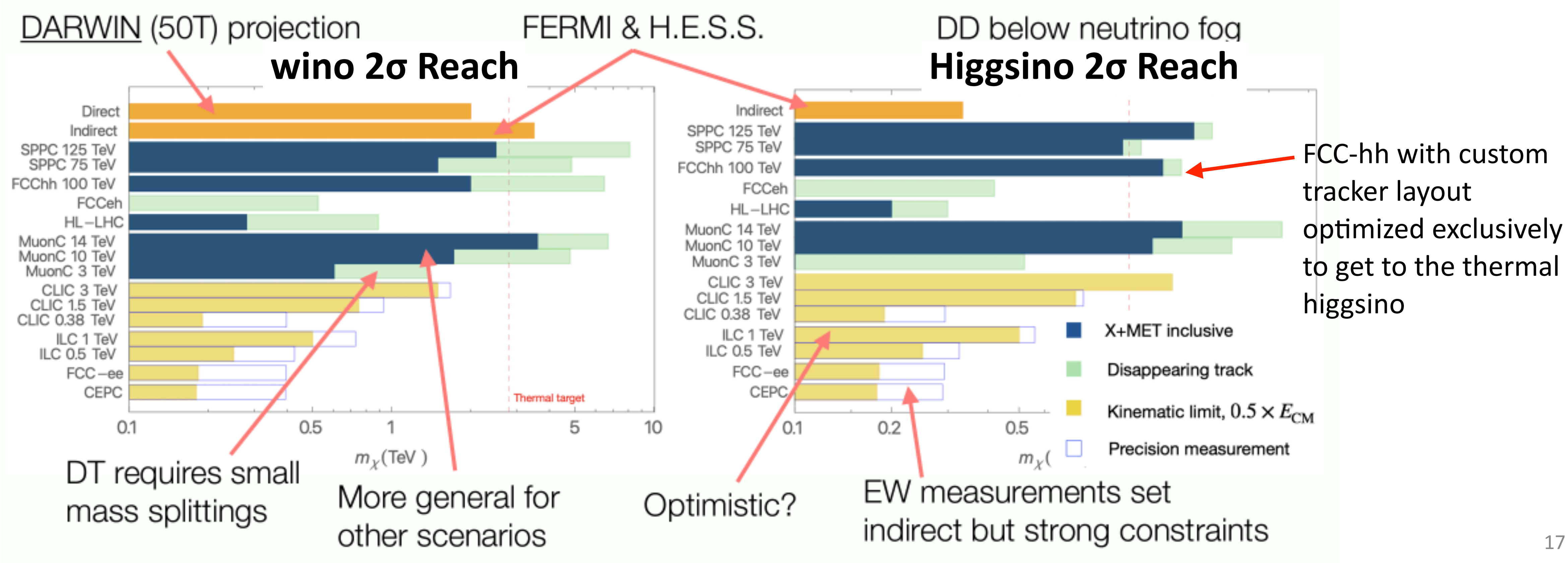
- Direct search for single HNL production in W/Z decays
- Can explore LNV and LFV
- Can test HNLs with masses up to ~2 TeV

FCC-eh

- Can extend the reach of the FCC-hh up to ~2.7 TeV in mass
- Best reach above W mass
- Sensitive to LFV and LNV signatures

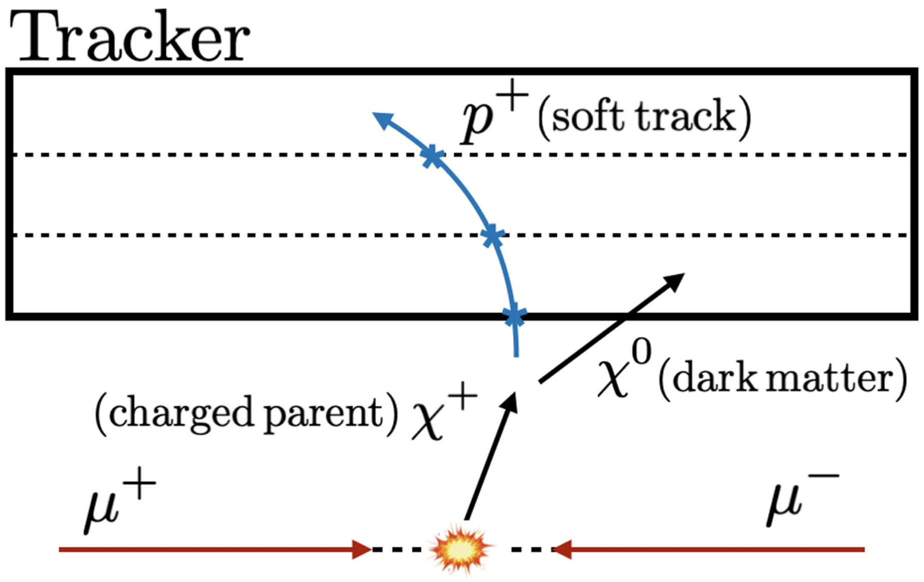
Minimal Dark Matter (I)

- **WIMP scenario**: DM is Higgsino or wino
- SM gauge couplings fix the interactions, so DM mass is the only free parameter and the thermal DM predictions are simple
- **Reaching thermal target** is not easy, but possible at some colliders

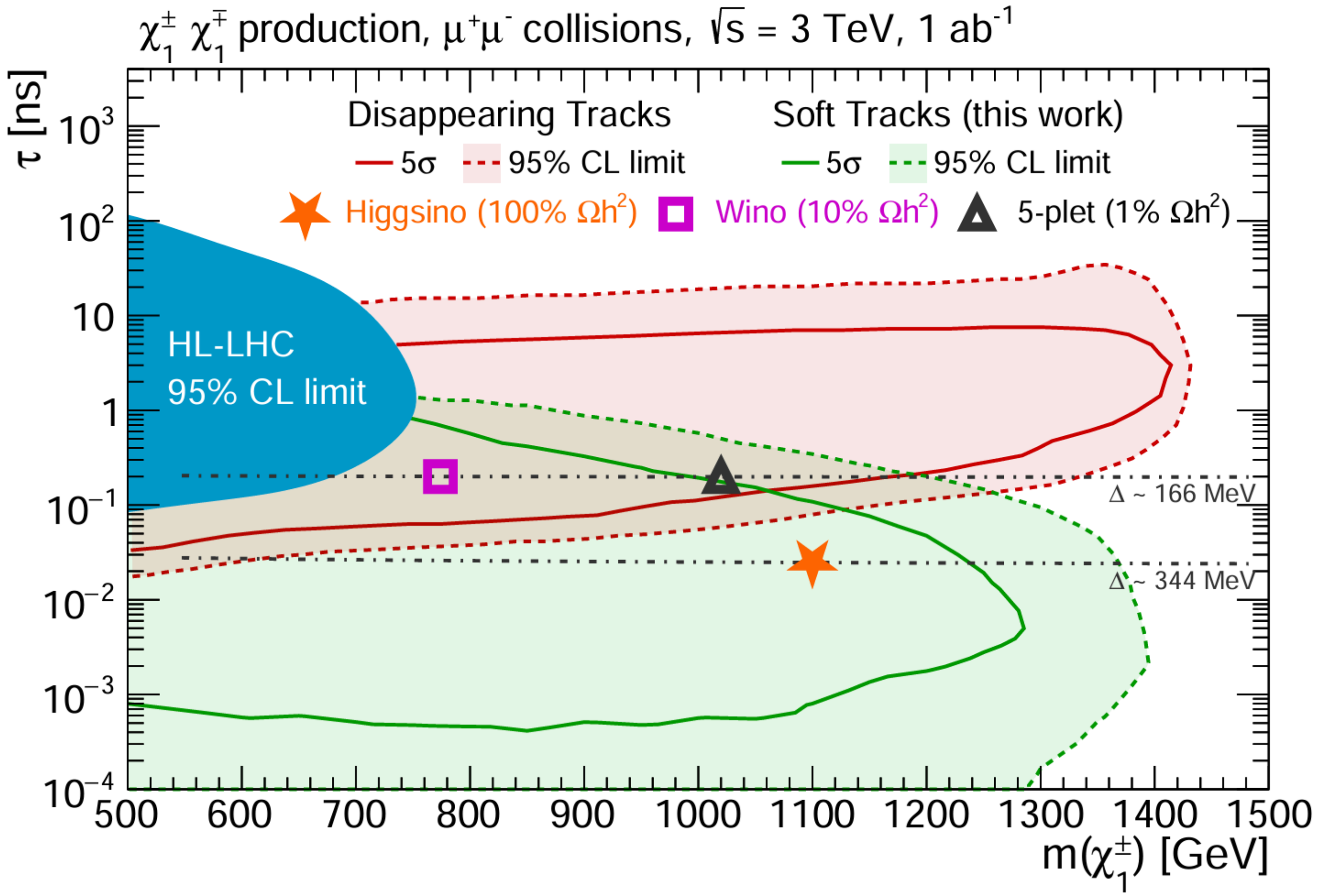


Minimal Dark Matter (II)

- Previous slide and this one:
- One powerful signature is disappearing tracks
- A 3 TeV muon collider can discover the thermal higgsino looking for soft pions

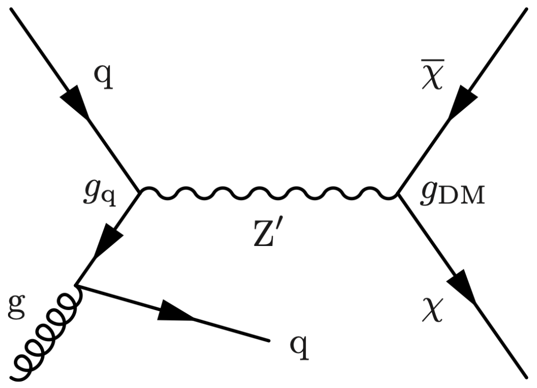


https://arxiv.org/abs/2405.08858

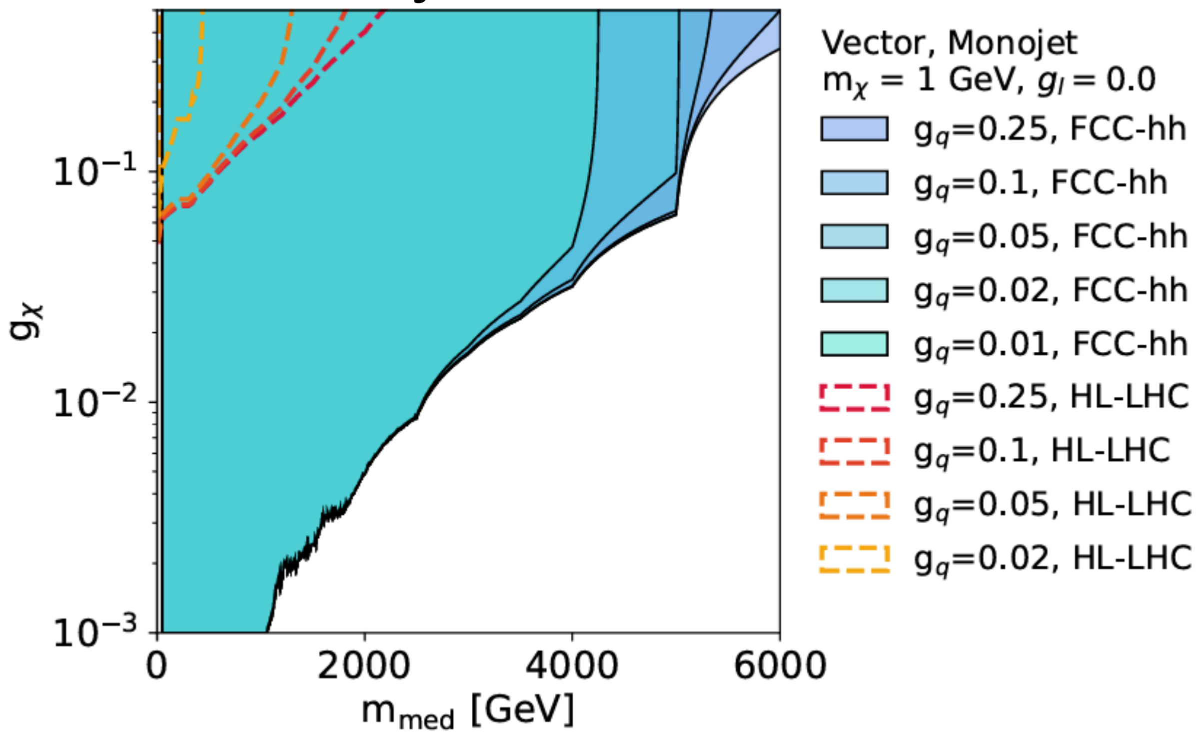


DM in Spin-1 Vector Portal

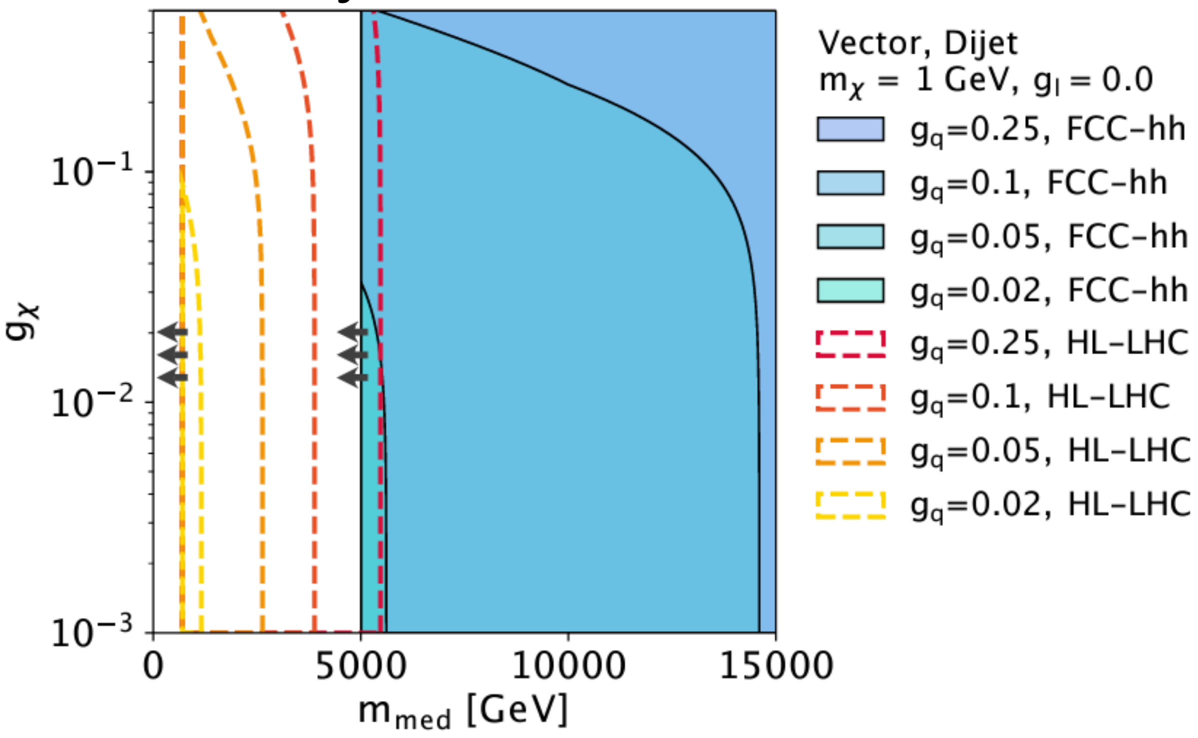
- Vector (and axial-vector) mediators arise from a broken U(1) symmetry, with couplings to the SM and the dark sector
- Limits for vector mediator on g_χ at HL-LHC and FCC-hh
- m_χ = 1 GeV and g_l = 0.0



Monojet searches

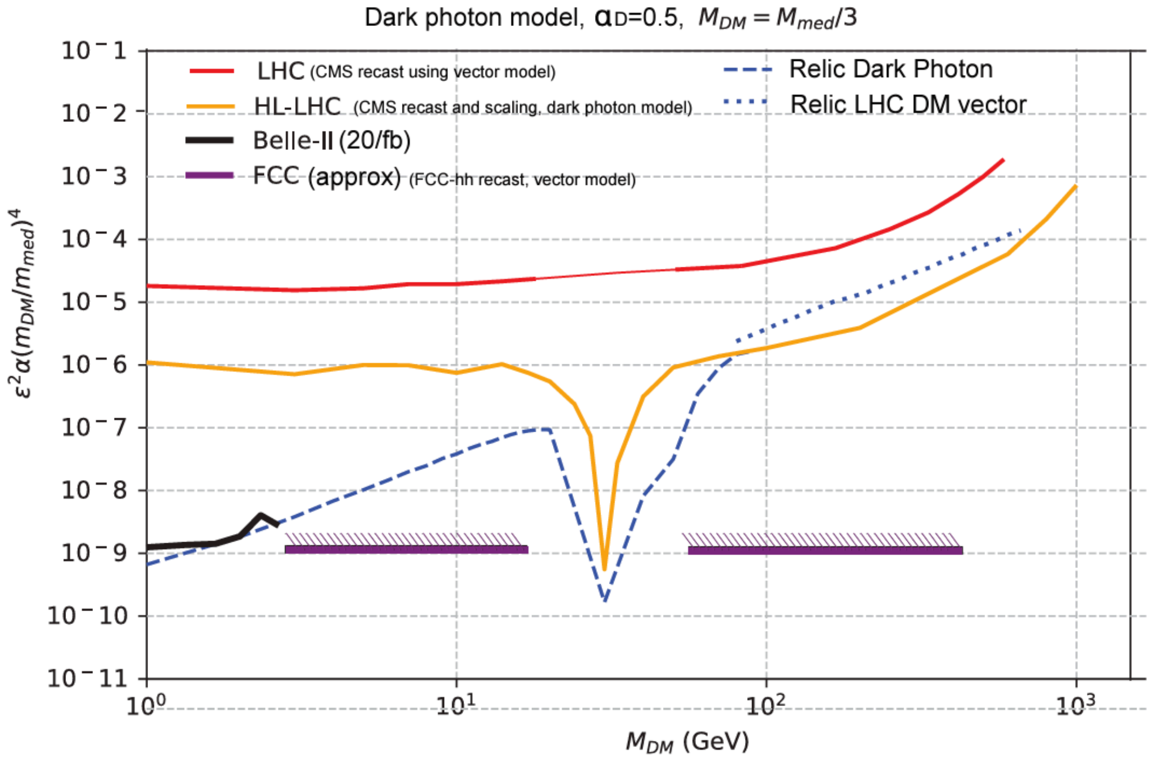


Dijet searches



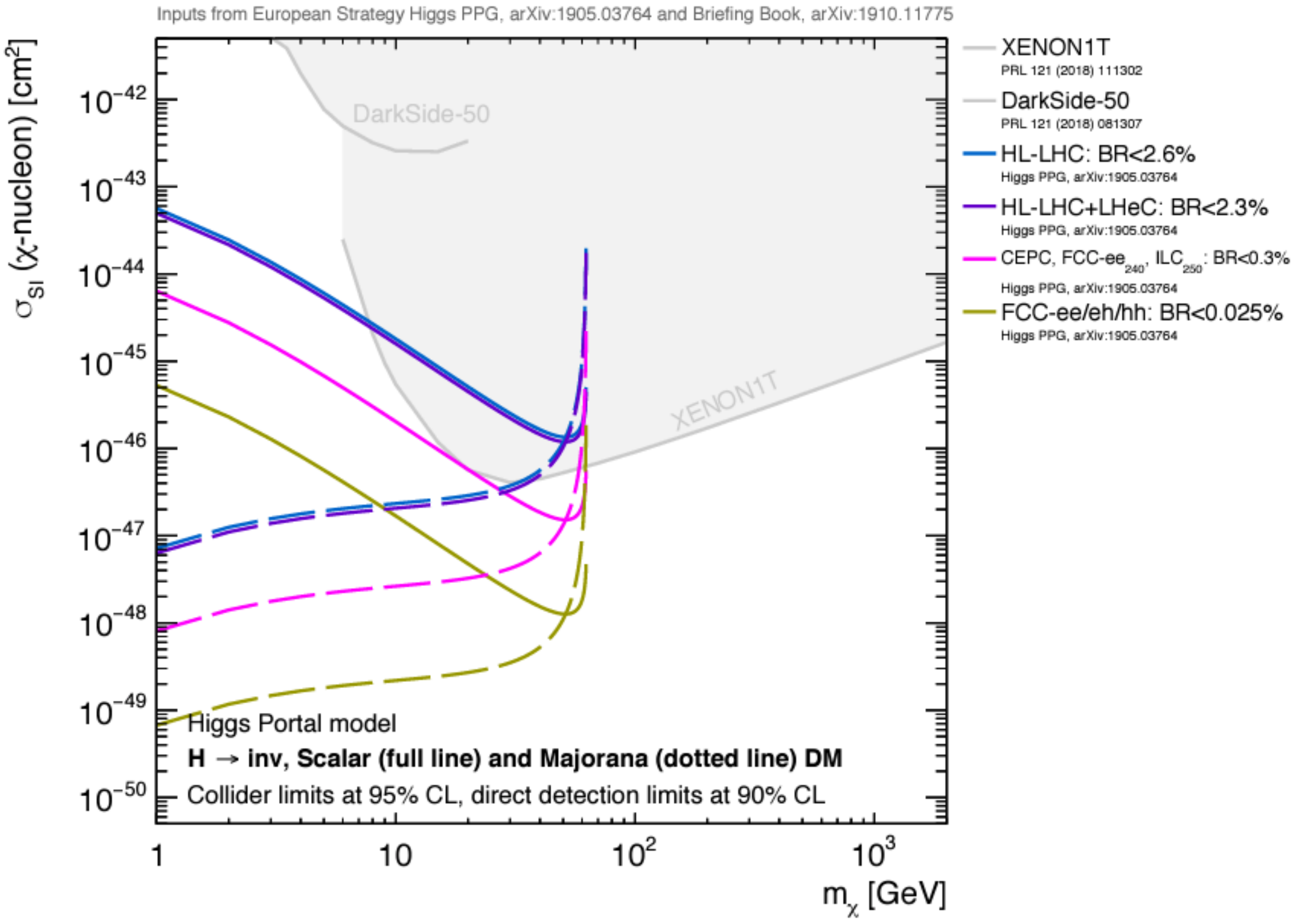
DM in Spin 1 Dark Photon Portal

- Portal particle has very small vector couplings with SM particles, induced by kinetic mixing with the SM photon
- $\alpha_D = 0.5, M_{DM} = M_{Med}/3$
- Lower energy experiments at accelerators and high energy colliders can cover together a number of well-motivated scenarios where the model can produce the entirety of the relic DM
- HL-LHC dataset is needed to reach a sensitivity to the thermal relic milestone for DM masses > 100 GeV
- FCC-hh is needed to cover the full range of DM masses



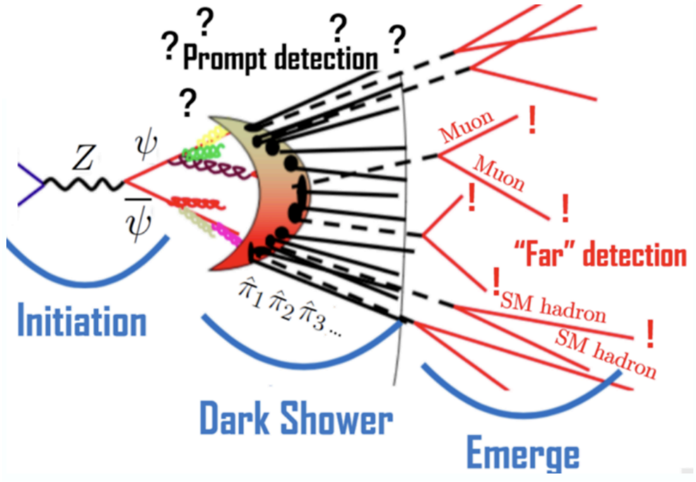
DM in Spin 0 Higgs Portal

- Simplified model with 125 GeV Higgs boson decaying to scalar or Majorana invisible DM particles
- Compares H —> inv sensitivity with current DD limits
- Collider limits at 95% CL and current DD limits at 90% CL

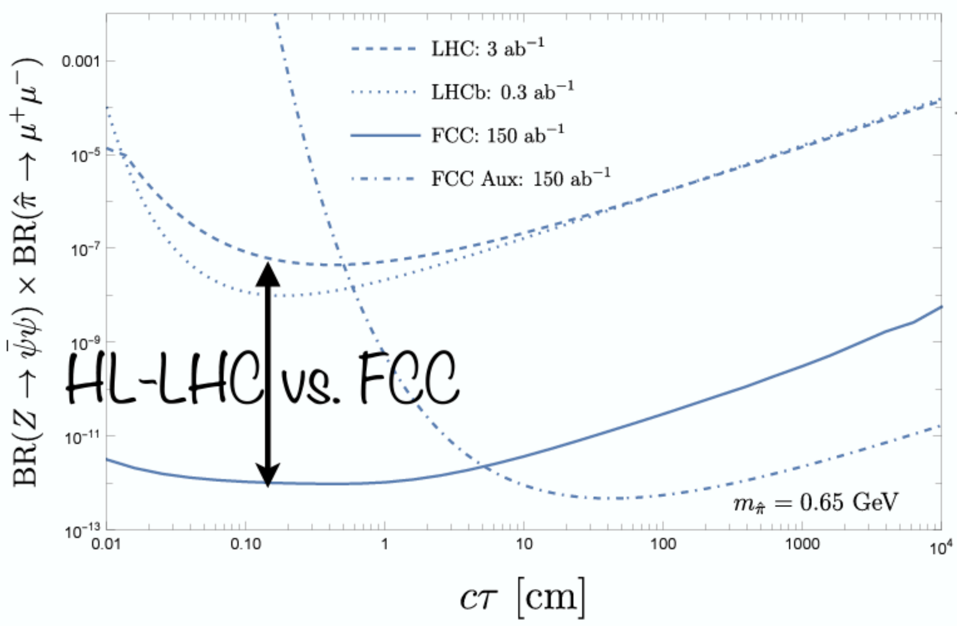


Hidden Valleys, Dark QCD, Dark Showers

- **Hidden valleys**: dark sector model with rich dynamics at low energy scales, and accessible at colliders at high energy scales
- **Dark QCD**: Simple hidden valley scenario with an additional broken U'(1) gauge group
- **Rich phenomenology available:** dijets, multijets, semivisible jets, emerging jets, etc.
- I haven't seen Dark QCD summary plots comparing different future colliders
- A study for the FCC: JHEP 04 (2024) 081 and 2408.13304
- **Needs more attention, IMHO!**

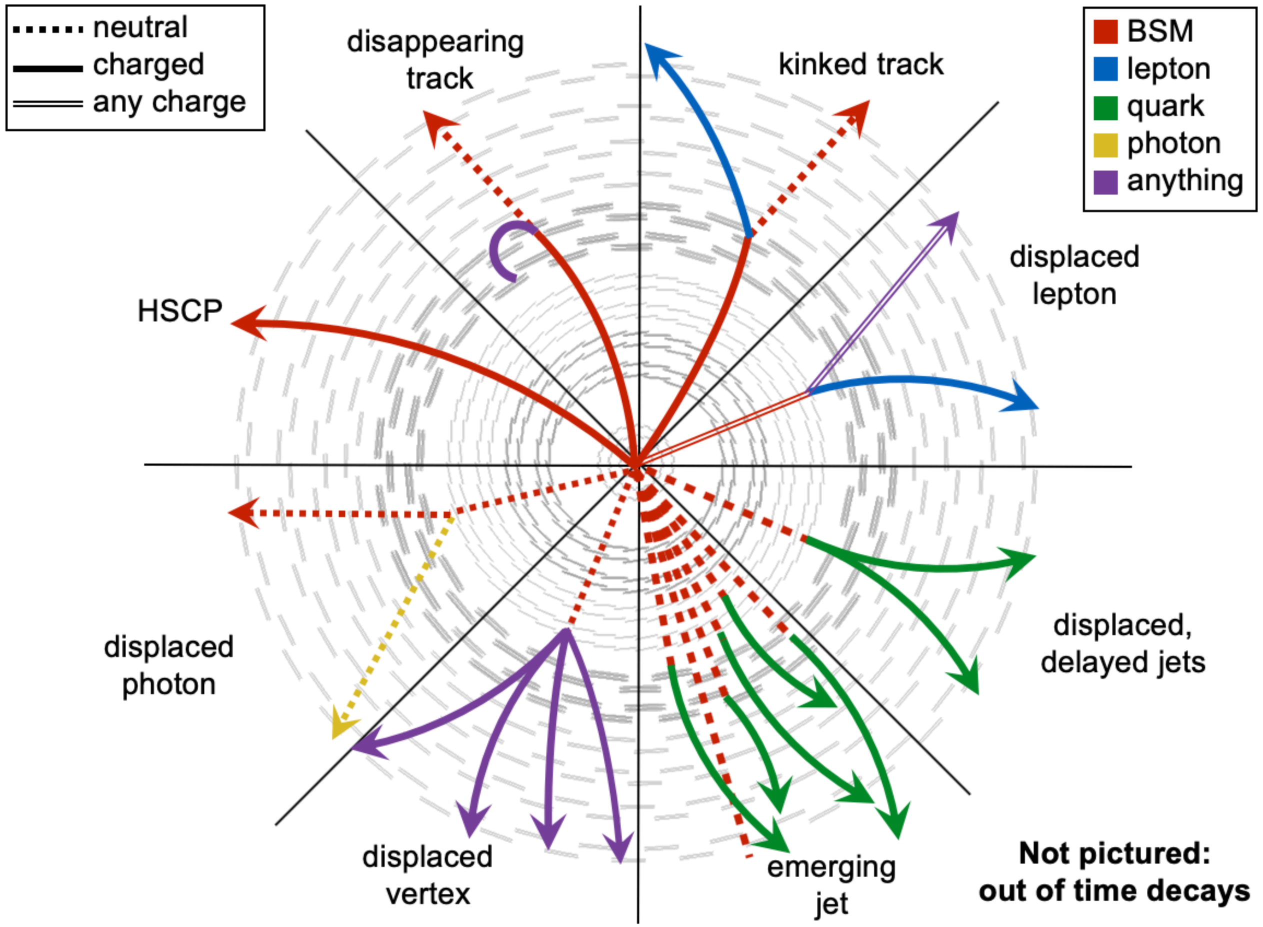


Talk at ECFA Workshop Overflow Session



Long-Lived Particle Searches

- Design **signature-driven** searches with a wide variety of final states and lifetimes
- **Challenges of the LHC:** main detectors, triggers, offline reconstruction not designed for displaced particles
- **Big opportunity to do something different at future colliders!**
- Can design **general-purpose detectors with LLPs in mind!**



Dedicated LLP Detectors at Future Facilities?

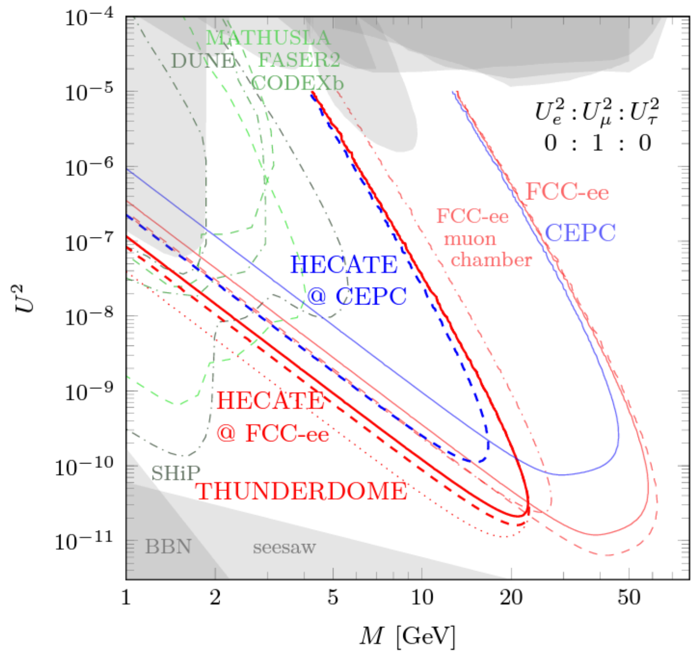
Opportunities for new, creative designs!

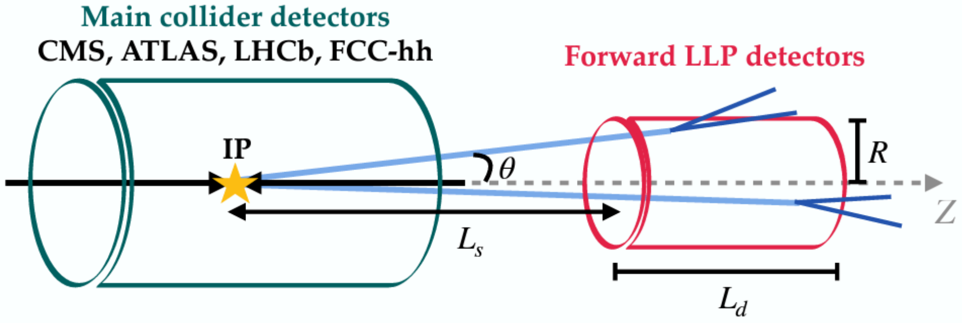
Lepton collider ideas:

- **HECATE** (EPJC 81 (2021) 546 / arXiv:2011.01005)
  - Instrument cavern walls with scintillators or RPCs
- **Study at ILC** (PRD 107 (2023) 076022 / arXiv:2202.11714)
  - Conclude that ILD still does better for LL ALPs

Hadron collider ideas:

- **DELIGHT** (PRD 106 (2022) 095018 / arXiv:2111.02437)
  - Transverse detector
- **FORESEE** (PRD 104 (2021) 035012 / arXiv:2105.07077)
  - Numerical package to simulate sensitivity of far-forward detectors
- **Study at FCC-hh for FIPs from B mesons:** arXiv:2204.01622
- **FOREHUNT** (arXiv:2306.11803)
  - Forward detector





Summary: BSM & Higgs Factory

- Precision measurements of Higgs properties: sensitive to BSM (regardless of production)
- Clean, large sample of Higgs bosons: provide unique access to exotic Higgs decays (could be challenging at hadron colliders)
- Can see most new direct production processes below $\sqrt{s}/2$ and have indirect sensitivity to higher energy scales
- Large lumi at lower energies (Z pole, ttbar, WW thresholds) can also provide high-precision measurements which indirectly constrain new physics

Summary: BSM & Multi-TeV Collider

- In the longer term, a multi-TeV machine will provide the largest and most comprehensive increase in the BSM discovery reach of the energy frontier
- Thermal WIMP target could be reached for minimal WIMP candidates (e.g., Higgsino- and Wino-like models with no other relevant particles)
- A discovery machine would push constraints on the Higgs-mass scale naturalness by the square of the increase in energy reach (potentially two orders of magnitude beyond the HL-LHC)
- Could open up access to new hidden sectors by producing a substantially higher mediator mass or probing even smaller couplings

Summary

- Future colliders have rich potential: Direct and indirect sensitivity to new physics
- Many interesting signals: new resonances, Heavy Neutral Leptons, hidden sectors, axion-like particles, exotic Higgs decays, SUSY, long-lived particles, and more
- Many interesting models to probe, but also diverse set of detector signatures
- We now have the opportunity to design detectors and algorithms with unusual signatures (LLPs, dark showers, ….) in mind
- Plenty of phase space to explore! Let’s make sure we don’t miss new physics!

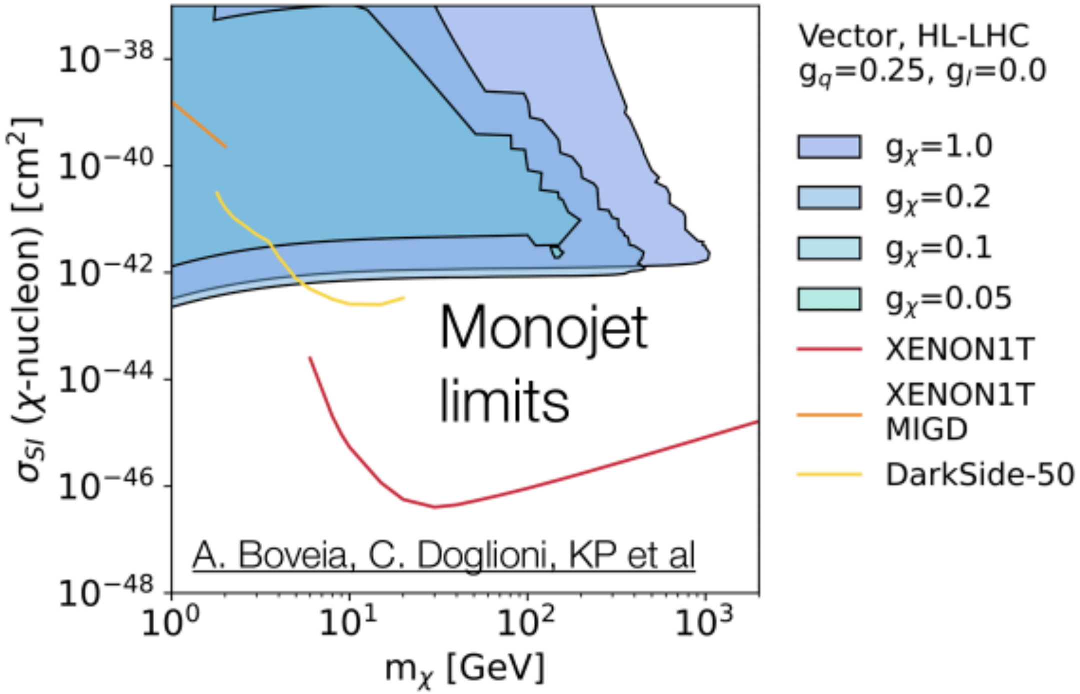
Backup

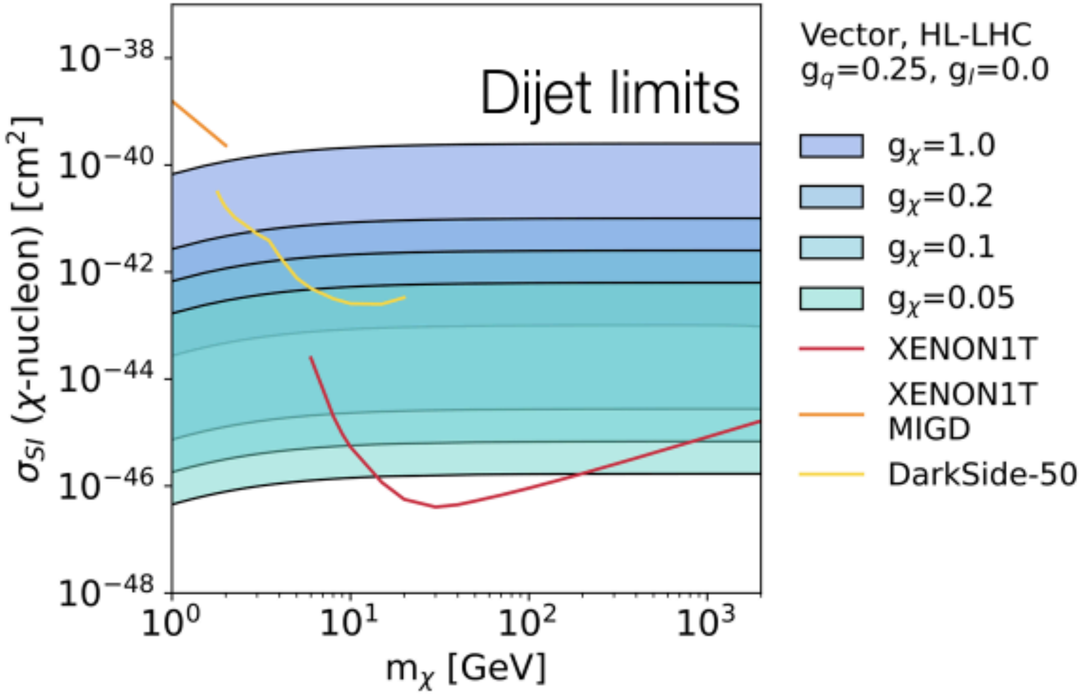
Summary: BSM & HL-LHC

- **Expansion of the current LHC program through:**
  - A factor of 20 enhancement of the Run 2 integrated luminosity
  - New detector capabilities (extension of the tracking coverage to the forward regions, pico-second-precision timing detectors, extended trigger systems,…)
  - New data collection/reconstruction/analysis techniques (jet substructure, ML, data scouting & parking, and automated anomaly detection…)
  - New auxiliary detectors
- **Example sensitivities:**
  - Increase SUSY particle reaches by a factor of 1.5 to 2
  - Order of magnitude increase in sensitivity to dark photon coupling
  - Factor of 4 improvement in the Higgs to invisible branching ratio

Kate Pachal (TRIUMF)

https://indico.triumf.ca/event/526/contributions/6000





These are the type of projections we usually show from ATLAS and CMS

Couplings take explicit values

Mediator mass absorbed into y axis variable

Implication: no constraint on mediator mass

Points with strong collider limits have high mediator mass to DM mass ratio

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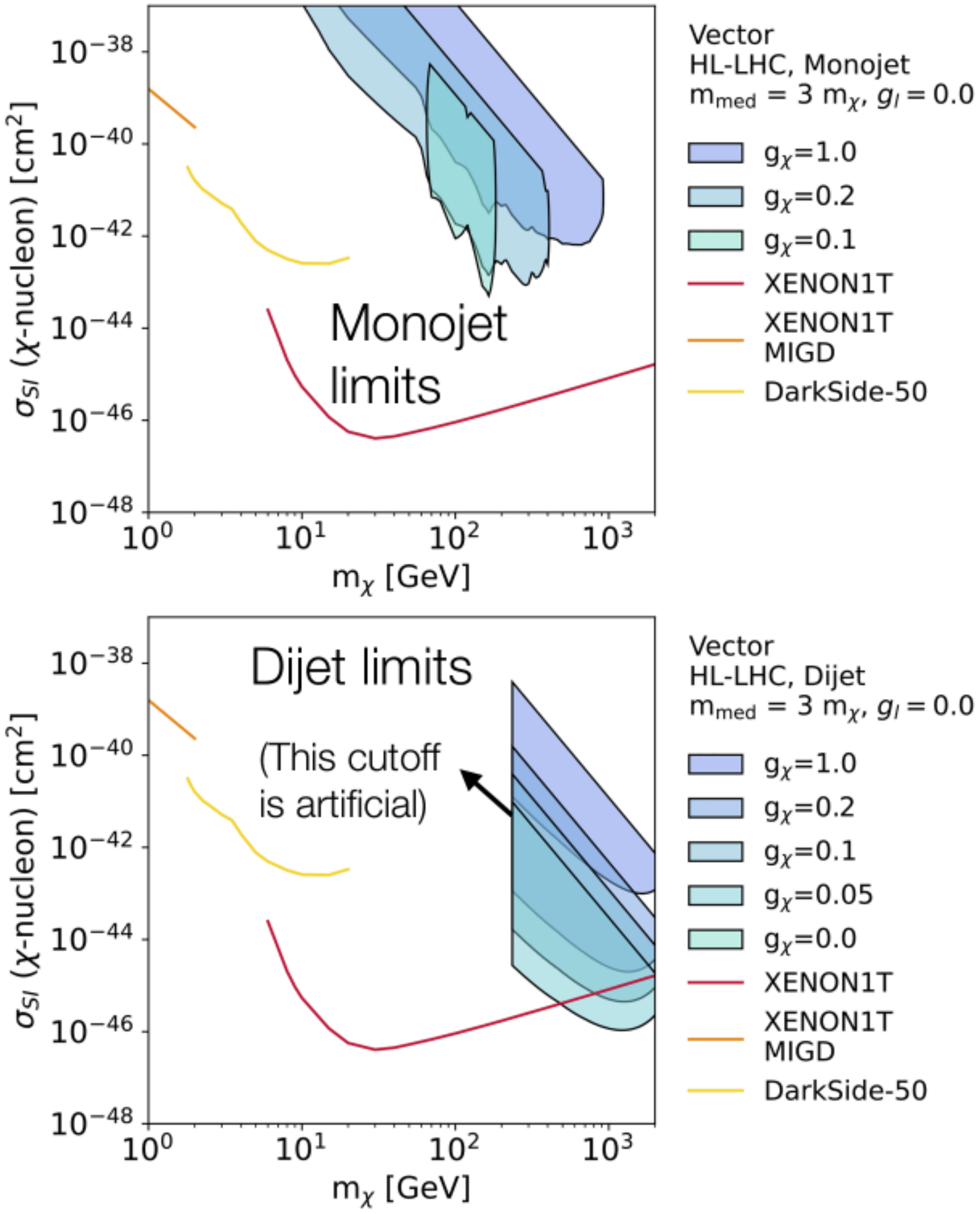


Same concept, different projection into two dimensions

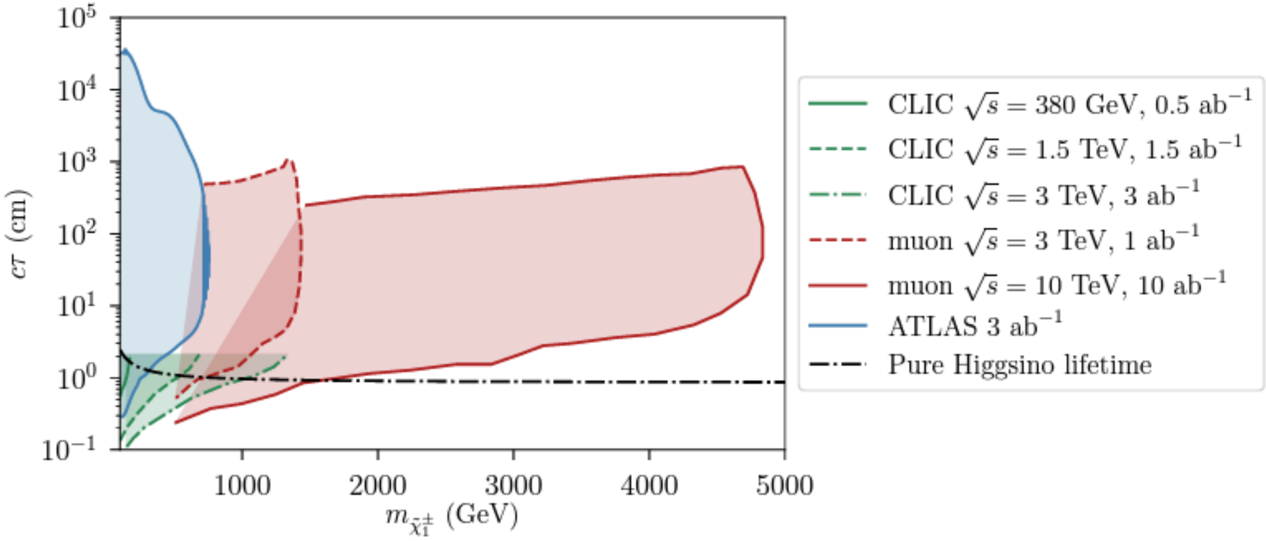
Now ratio between mediators is fixed and g_q is absorbed into y axis

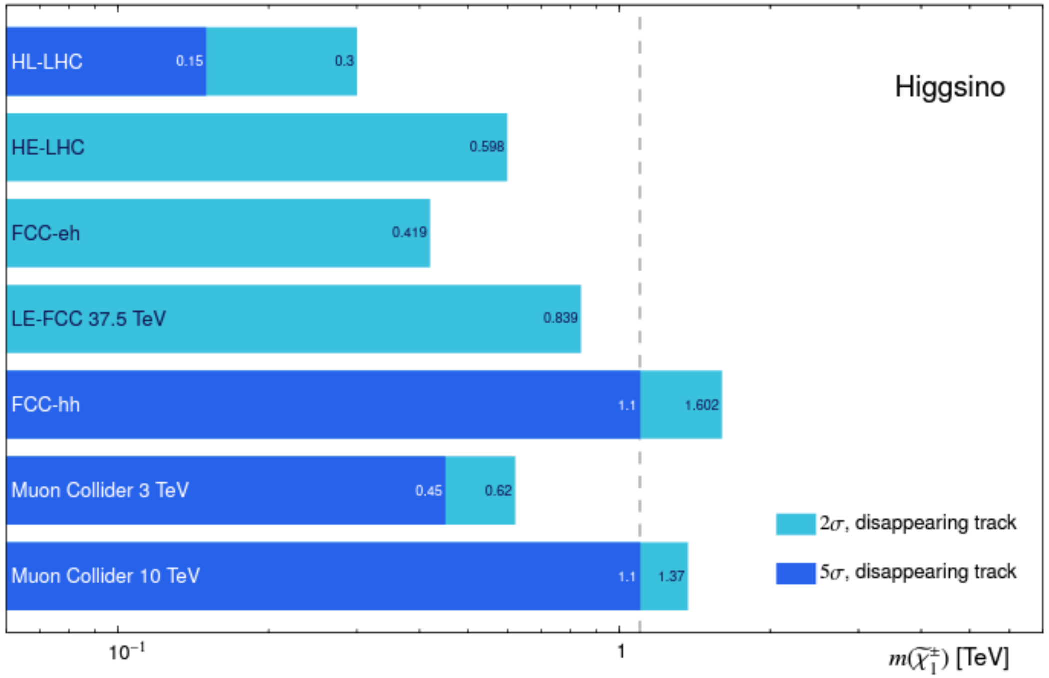
Colliders have unique strengths in accessing heavy mediators

Direct detection has unique strengths in accessing small couplings

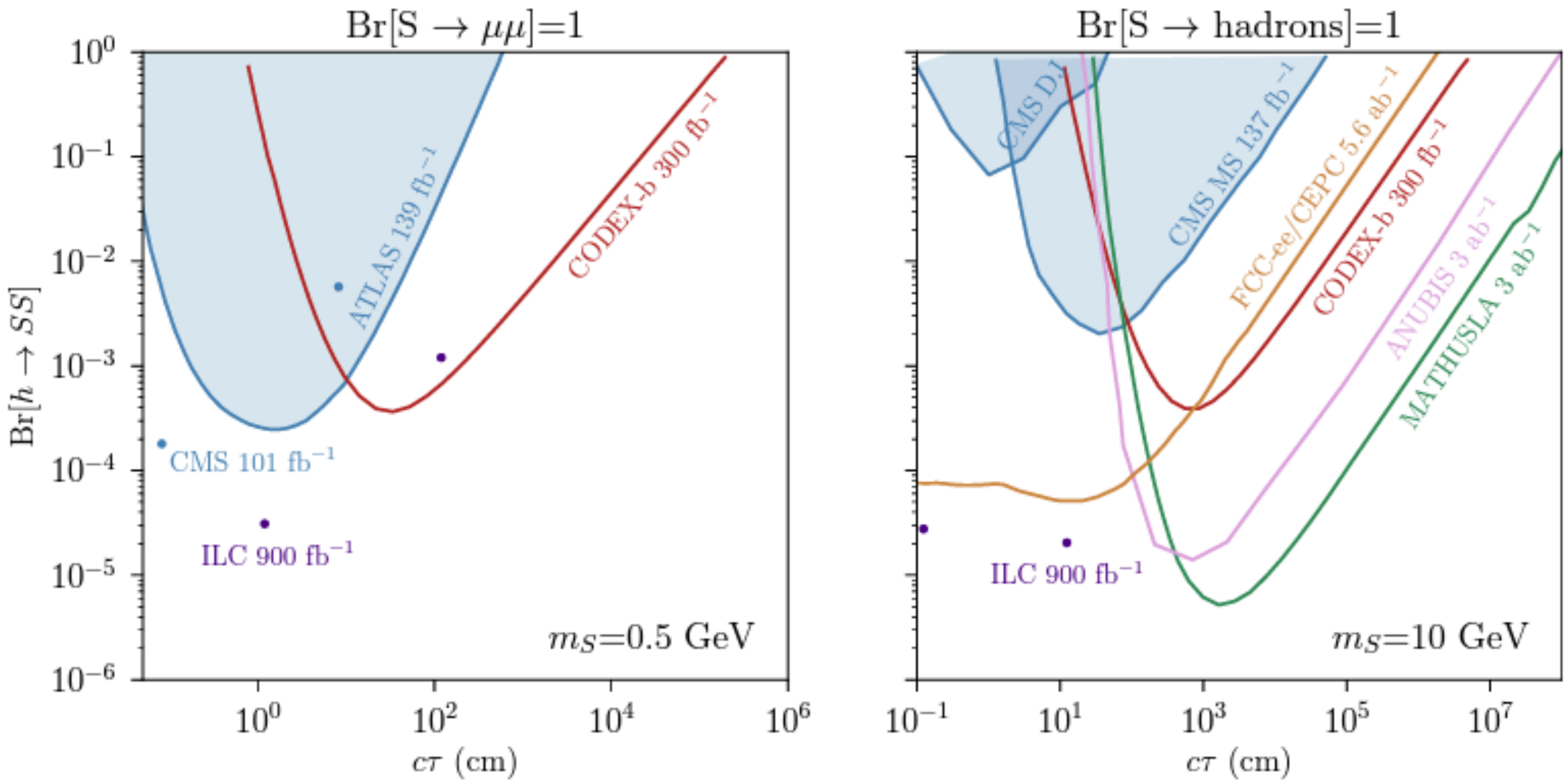
Must present both for complete picture

Disappearing Tracks





Low Mass Displaced Vertices



High Mass Displaced Vertices