FUTURE CIRCULAR COLLIDER

International MUON Collider Collaboration

BSM @ 10 TeV pCM Colliders

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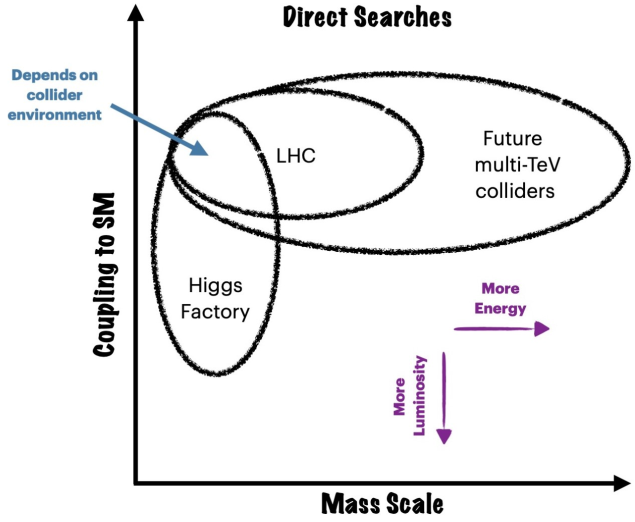
Introduction

- There is a strong motivation to push the energy frontier into the 10s of TeV range. As well as the **indirect** sensitivity to BSM accessed through high-precision measurements of high-mass/ rare processes (Higgs/Top/EW), target **direct** access to:
    - (WIMP) dark matter
    - Probe EWK baryogenesis and shape of Higgs potential.
    - Maximise sensitivity to broad range of BSM particles.

- Exploration is key, but all options would present significant **experimental** and **theoretical challenges** ⇒ **opportunities** for study in the coming years!

- Will focus on FCC-eh/hh and the muon collider, but note that arguments relevant for FCC could apply to a 100 TeV pp collider in the CEPC tunnel.



Strong complementarity: EF exploration could directly probe NP seen indirectly at e+e- Higgs factory

Assumptions in sensitivity projections

Lepton colliders: Projections are $m<\sqrt{s}/2$, with assumptions:

- Particles are pair produced
- Backgrounds are low
- High enough cross-section / luminosity

Need to be careful at higher energies when primary production mode would be VBF so particles produced at ranges of energies.

Hadron colliders: multiple approaches

1. Directly simulate collider beam, collision physics and detector response, and analyse resulting samples.
2. Extrapolate from LHC (run 2) using parton luminosity assuming reconstruction efficiencies, background rejection and signal-to-background ratios remain constant.

If you want to try this- check out the “collider reach” programme http://collider-reach.web.cern.ch/

A lot of assumptions here that should be tested- opportunities for future study!

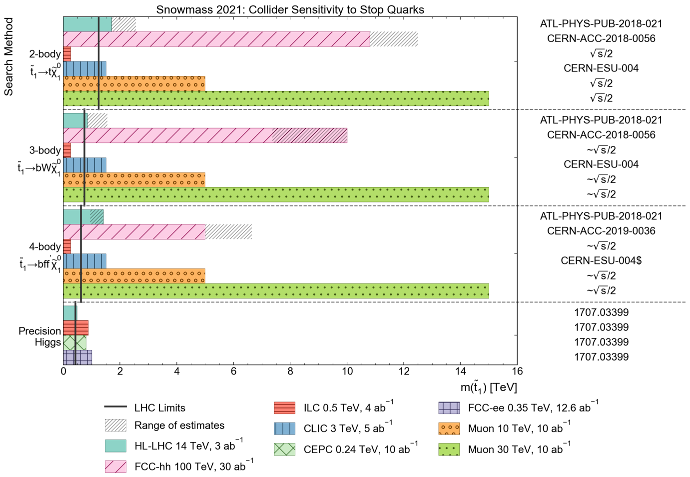
Benchmark collider scenarios

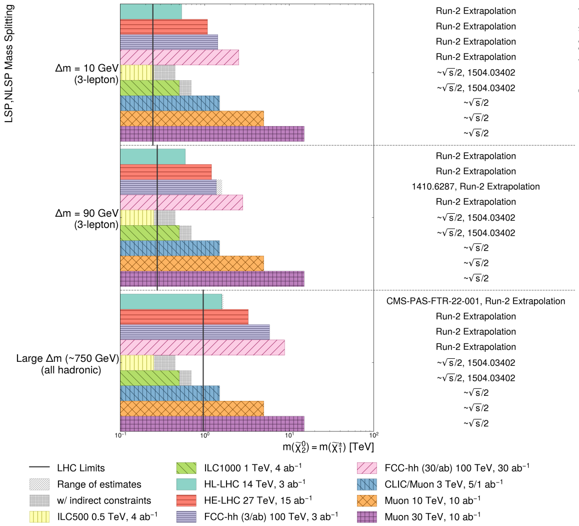
- Table taken from snowmass EF report: https://arxiv.org/abs/2211.11084
- For FCC-hh : some early studies look at impact of varying COM energy in 80-120 TeV range (little impact) but more planned.

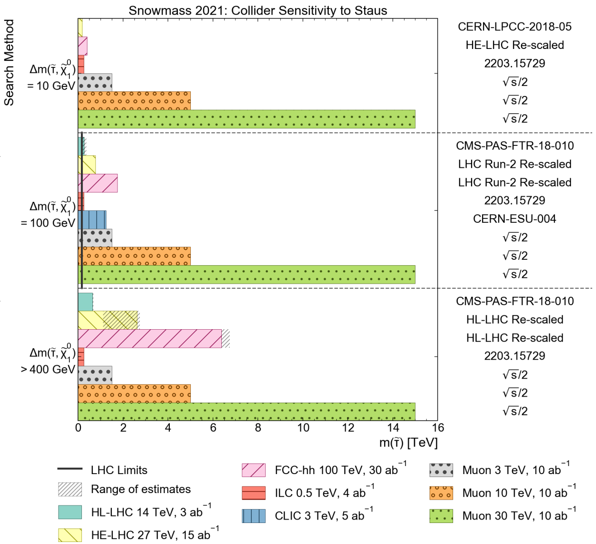
Collider	Type	$\sqrt{s}$ (TeV)	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	
HE-LHC	pp	27		15	
FCC-hh	pp	100		30	~20 years
SPPC	pp	75-125		10-20	
LHeC	ep	1.3		1	
FCC-eh		3.5		2	
CLIC	ee	1.5	±80/0	2.5	
		3.0	±80/0	5	
μ-collider	$\mu\mu$	3		1	~ 5 years
		10		10	~ 5 years

Case study: SUSY

- Strong-production processes – like top squarks, see in hh an advantage, as expected. Compressed scenarios better covered with muon collider - similar consideration for EWK sparticles including staus
- Consider 10 TeV muon and 100 TeV hh comparisons in the plots below







See Snowmass BSM report: https://arxiv.org/abs/2209.13128

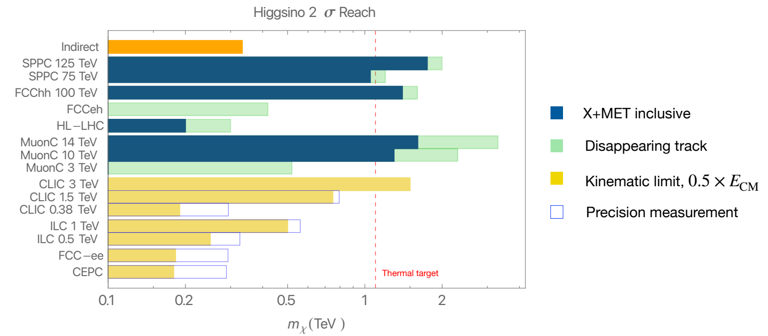
Case study: (minimal-WIMP) dark matter

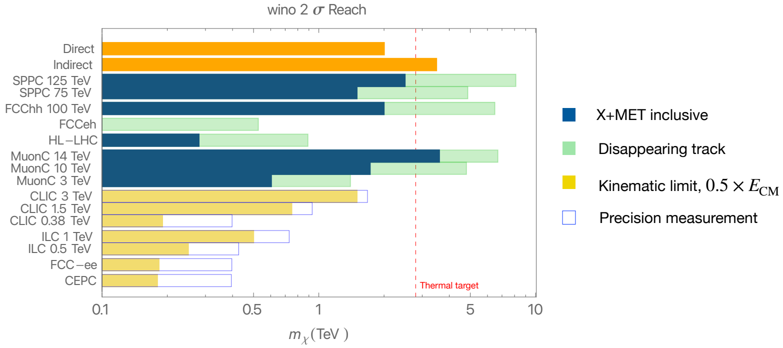
For minimal WIMP dark matter- EW multiplet with clear thermal targets.

For lepton colliders, X+MET analyses dominate at lower energies with disappearing track more sensitive at higher energies. Mono-muon and mono-W important at muon collider.

Sensitivity of disappearing track analysis strongly dependent on mass splitting and detector design.

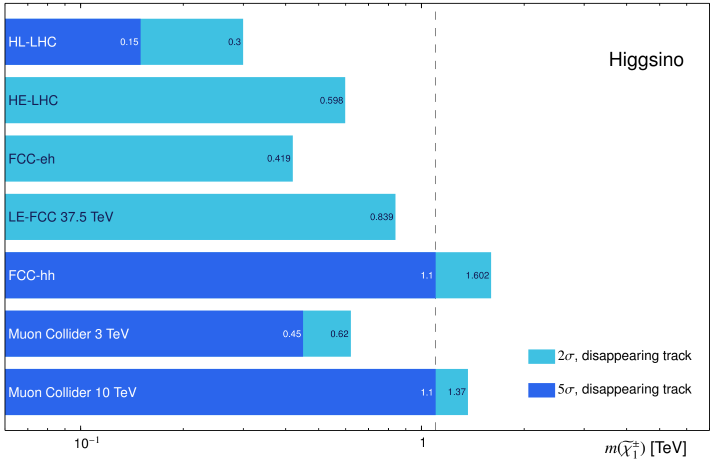
For both hh and muon colliders, key to study impact of pileup (mu~1000) and beam-induced backgrounds on tracking efficiency.



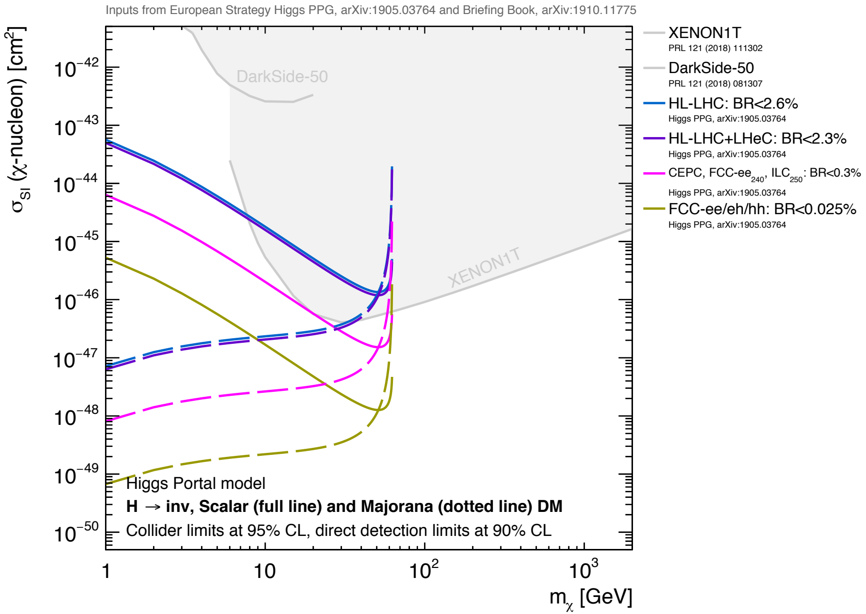


Case study: Dark matter

Closer look to disappearing track for Higgsinos- key to reach thermal targets

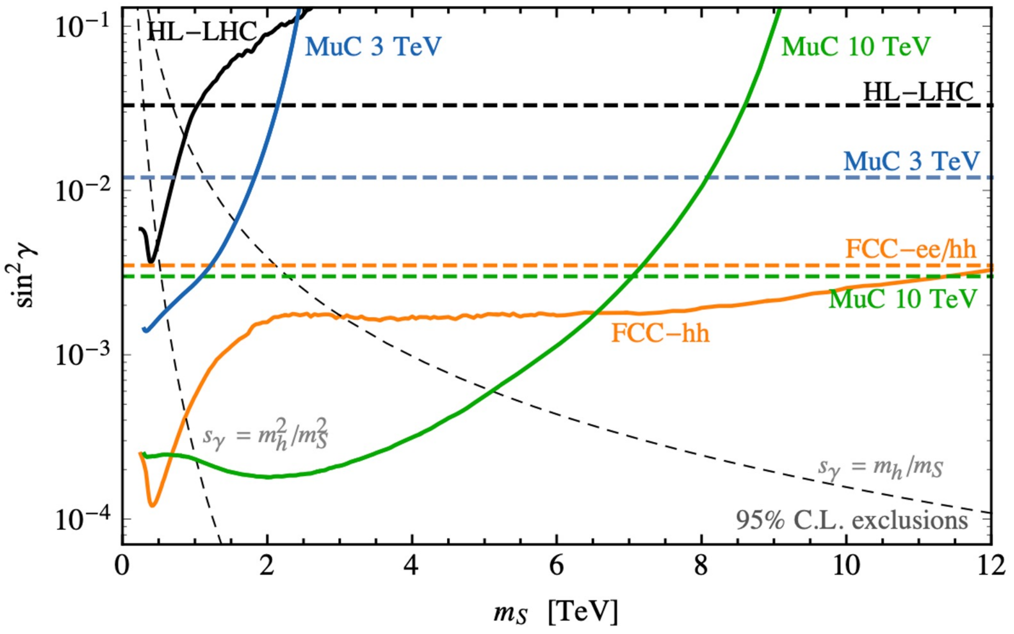


Constraints from Higgs->invisible



Early studies (https://arxiv.org/pdf/2303.14202) indicate μC competitive with FCC-hh through measuring forward muons in VBF. Result depends on ability to instrument the forwards region (tungsten nozzles).

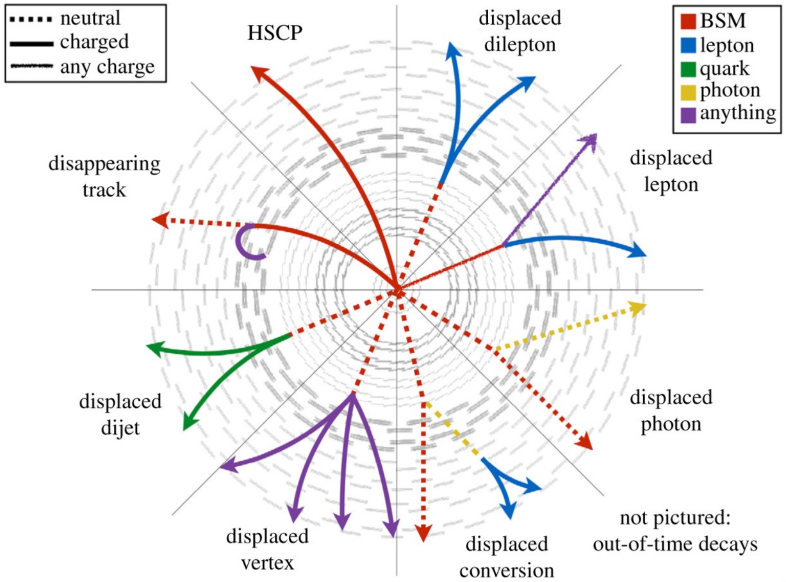
Case study: hidden sectors



- EF colliders have the potential to either indirectly (through higgs self coupling) or directly probe a first order EWPT through discovering new particles responsible.
- LH plot shows additional heavy singlet mixing with Higgs that could be detected through resonant di-Higgs production.

Long-lived particles @ future EF colliders

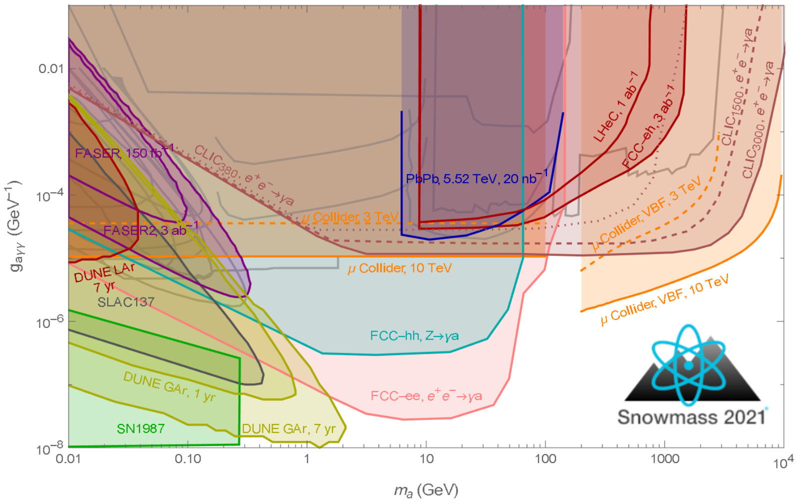
- Detector geometry choices that provide similar hermeticity for prompt particles can differ significantly in their ability to reconstruct LLPs → important to consider LLP searches when designing future detectors.
- Background rejection can be as important as signal acceptance.
- Also consider dedicated LLP detectors at future colliders (and whether to integrate their trigger/readout with GPDs).

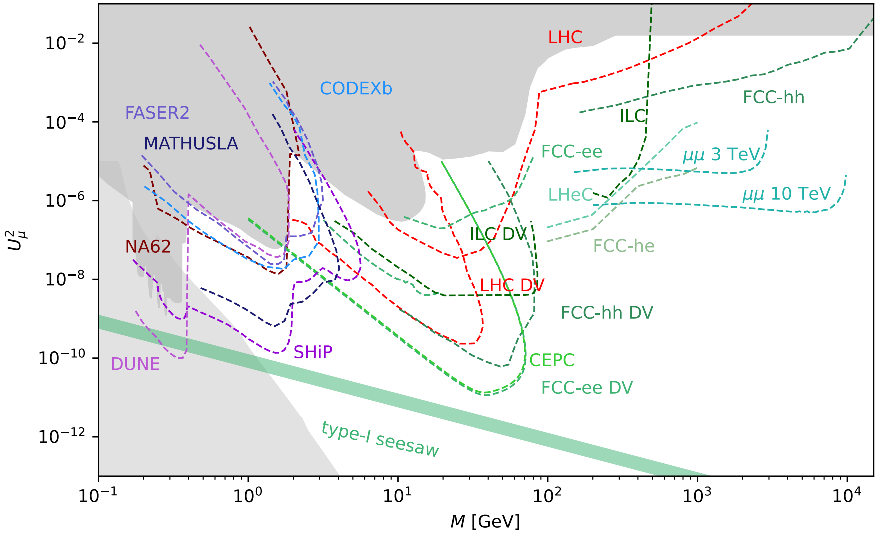


LLPs

- ALPs and HNLs- lots of complementarity between collider options

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



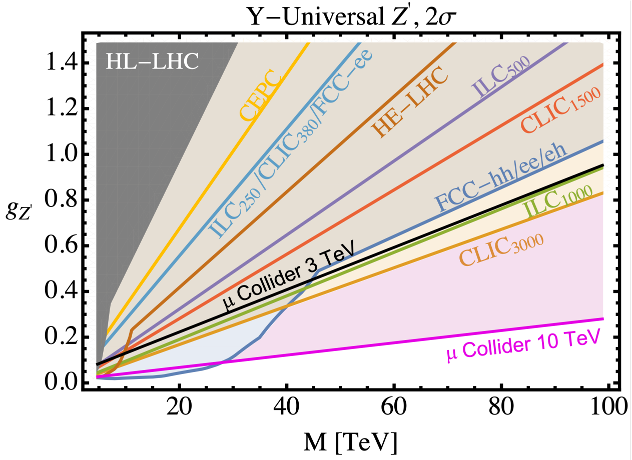


Case study: resonances

Taken from snowmass BSM report
https://arxiv.org/abs/2209.13128

Take Z' as "standard candle" .

Complementarity between pp and lepton colliders- FCC-hh has highest sensitivity for direct searches for masses < 28 TeV, muon collider can go to lower couplings and indirectly probe masses >100 TeV

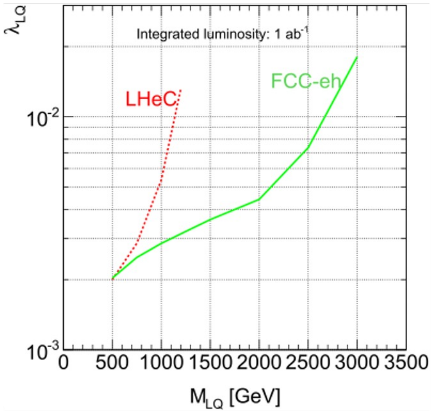


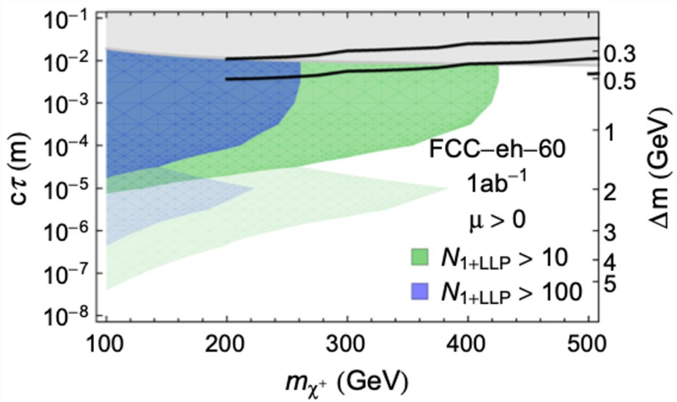
Machine	Type	√s (TeV)	∫L dt (ab^{-1})	Source	Z' Model	5σ (TeV)	95% CL (TeV)
HL-LHC	p p	14	3	R.H.	$Z'_{SSM} \to$ dijet	4.2	5.2
				ATLAS	$Z'_{SSM} \to l^+ l^-$	6.4	6.5
				CMS	$Z'_{SSM} \to l^+ l^-$	6.3	6.8
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	6
ILC250/ CLIC380/ FCC-ee	$e^+ e^-$	0.25	2	ILC	$Z'_{SSM} \to f^+ f^-$	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

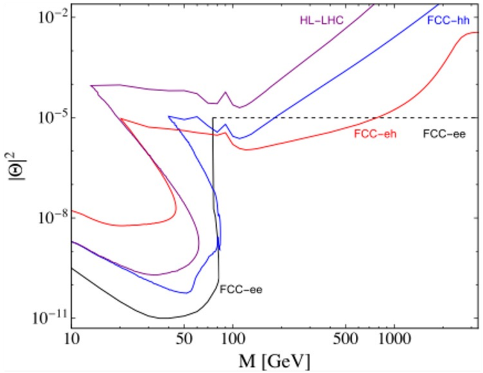
Increasing Z' Sensitivity

Complementarity between FCC-eh and hh- BSM

- Unique opportunities for leptoquark searches up to 3 TeV.
- Sensitivity to compressed supersymmetric scenarios that would elude discovery at FCC-hh.
- Novel charged current interactions for Heavy Neutral Lepton (HNL) discovery







Plots taken from vol. 1 of FCC CDR: https://fcc-cdr.web.cern.ch/

Hadron vs muon colliders: strengths and weaknesses

pp collisions:

- Favour QCD couplings → strongest sensitivity for strongly produced processes (i.e. squarks and gluinos).
- High luminosities enable study of rarer processes.

But:

- High theoretical uncertainties on proton PDFs at high energies- but expect significant theoretical development (EW bosons in PDFs).
- Large QCD backgrounds and challenging pileup- can we simulate mu~1000, including non-jet components, reliably? (it isn't integrated in current toolchain).

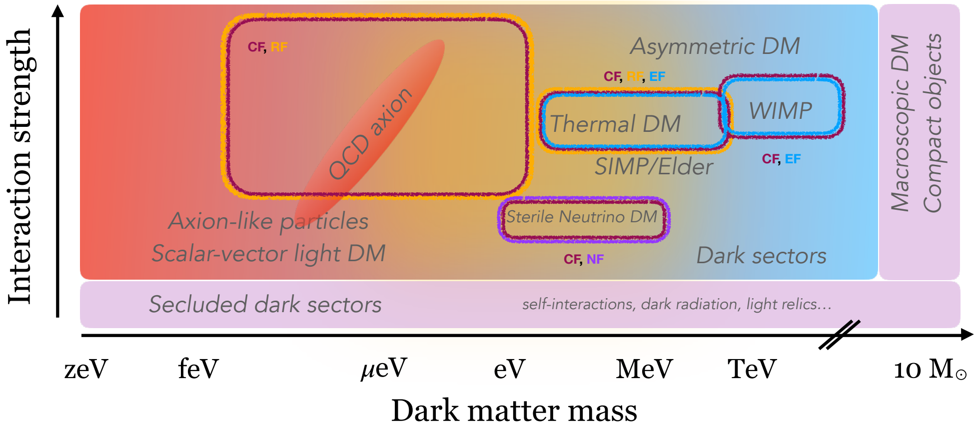
Muon collisions:

- Primary production mechanism VBF ⇒ favour BSM with EW couplings.
- Smaller theoretical uncertainties on (smaller) backgrounds.

But:

- Lower s-channel production cross-sections.
- Need to handle beam-induced backgrounds due to muon decay.

Complementarity beyond colliders



In-keeping with desires to "delve deep" and "search wide", 10 TeV pCM colliders provide strong complementarity to sensitivity achieved across neutrino physics, direct detection and through astrophysical/cosmological probes.

Similarly if gravitational wave signals indicative of 1st order PT in Early Universe were seen, EF searches could directly probe the new physics responsible.

Challenges/opportunities for further study.

- Reconstruction: highly boosted objects.
- For hadron colliders: how to model pileup ~1000. Can we build detectors in such extreme environments?
- Muon colliders: beam induced background requires careful study and restricts detector design (many projections rely on ‘precision’ associated with lepton collisions that could be compromised by BIB).
- For both colliders: new physics studies planned for next ESPPU (see next slide)

I.e. lots of areas where we could make key contributions!

The roadmap ahead: how to get involved

FCC-hh: dedicated kick-off meeting on 3rd September aiming to plan studies to feed into the ESPPU: https://indico.cern.ch/event/1439072/

- Dedicated efforts planned for new studies for ESPPU
- Opportunity to build on previous UK efforts towards FCC-hh under the FCC-UK umbrella (i.e. https://indico.cern.ch/event/1147914/ and https://indico.cern.ch/event/1254077/)

Muon collider: UK workshop in B'ham on July: https://indico.stfc.ac.uk/event/983/

- ESPPU studies run through IMCC (Tuesdays at 4 pm)

Great opportunity to get involved in either!

Conclusions

- 10 TeV pCM machines allow a broad exploration that could directly discover BSM physics linked to key questions about our universe- DM, EWPT as well as characterising NP discovered indirectly through precision measurements at a Higgs factory.
- Lots of complementarity between FCC-hh and a muon collider → a world where we could have both would be very exciting!
- Lots of opportunities to contribute to (new) studies for the ESPPU- please get in touch if interested!

“Every time we increase pCM 10-fold…

… we learn something entirely new!” (Christophe Englert, yesterday)

Back up

Adding an electron-proton collider to the FCC: FCC-eh

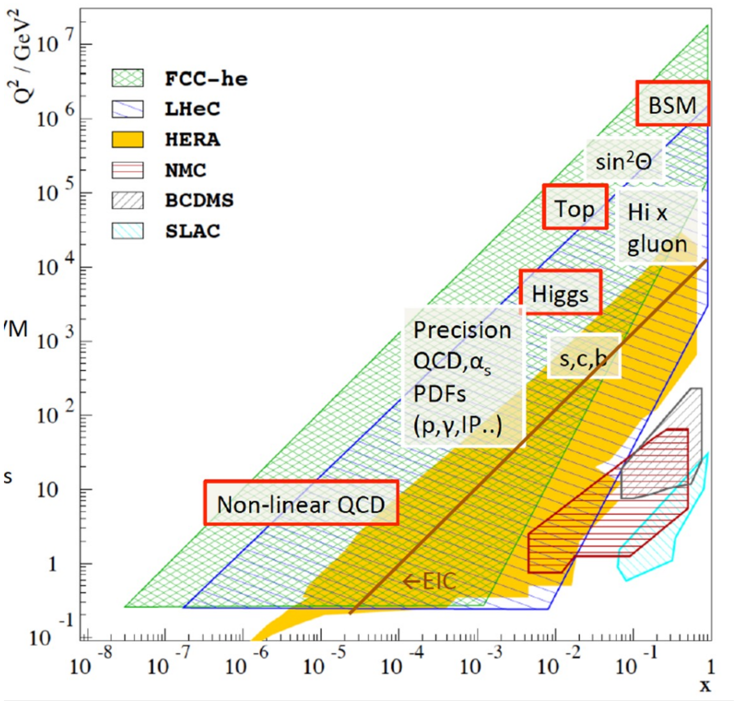
The **FCC-eh**:

E_e=60 GeV

50 TeV protons, √s = 3.5 TeV

Integrated luminosity: ~ 1-2 ab^{-1}

Concurrent ep + pp (eA + AA) operations



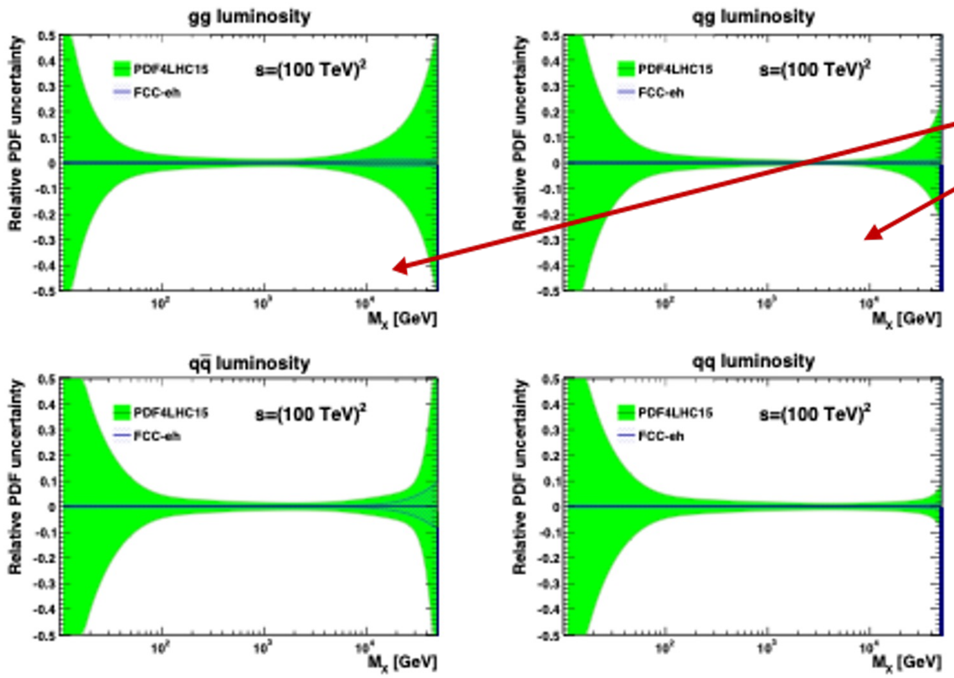
Physics complementarity FCC-hh/FCC-eh

- PDFs, strong coupling constant, low-x measurements
- W mass, top mass, on other precision measurements
- Higgs measurements with additional sensitivity
- Searches for new physics, including prompt and **long-lived new scalars from Higgs**, SUSY particles, heavy neutrinos, **dark photons and axions**
- High-energy and high-density measurements of heavy ion collisions

- Low pileup
- Low background
- But also lower production rate

Impact of FCC-eh on FCC-hh: PDF

•Complete unfolding of parton contents in unprecedented kinematic range: **u,d,s,c,b,t, xg**



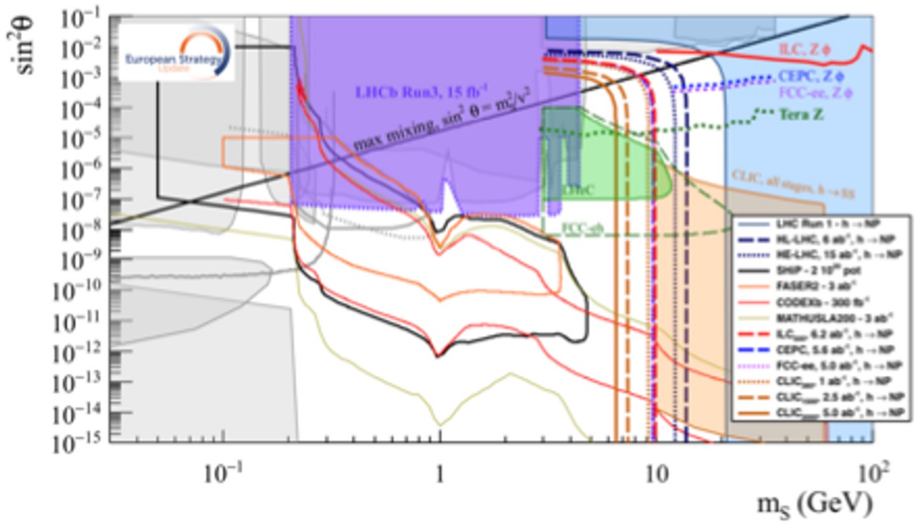
Range relevant for new heavy particles and where new physics can be!

Crucial for FCC-hh:

- Extension of high mass search range
- Non-linear low x parton evolution
- high precision relevant for Higgs measurements

LLP (2)

- Interpreting the results for a specific model, where lifetime and production rate of the LLP are governed by the scalar mixing angle.



Dark photons