UNIVERSITY OF CAMBRIDGE

ATLAS EXPERIMENT

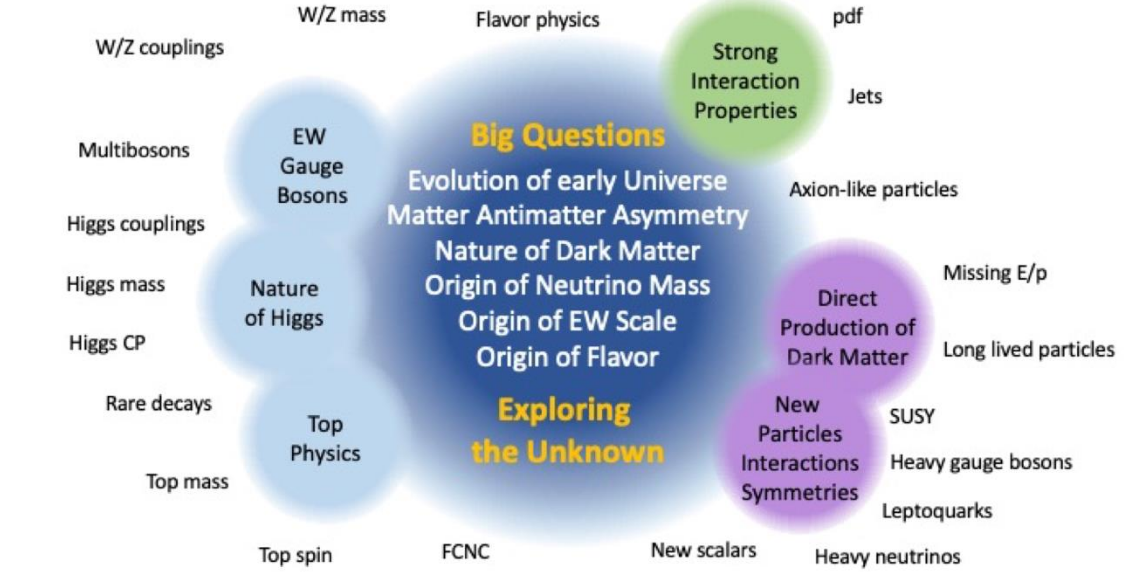
FUTURE CIRCULAR COLLIDER

Beyond the Standard Model Physics at the LHC and beyond…

Dr Sarah Williams, University of Cambridge

Introductions: big questions in particle physics

Image credit: snowmass energy frontier report



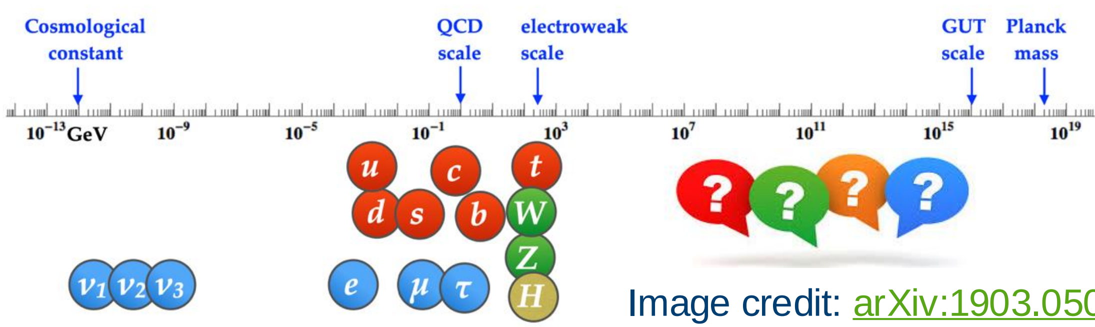
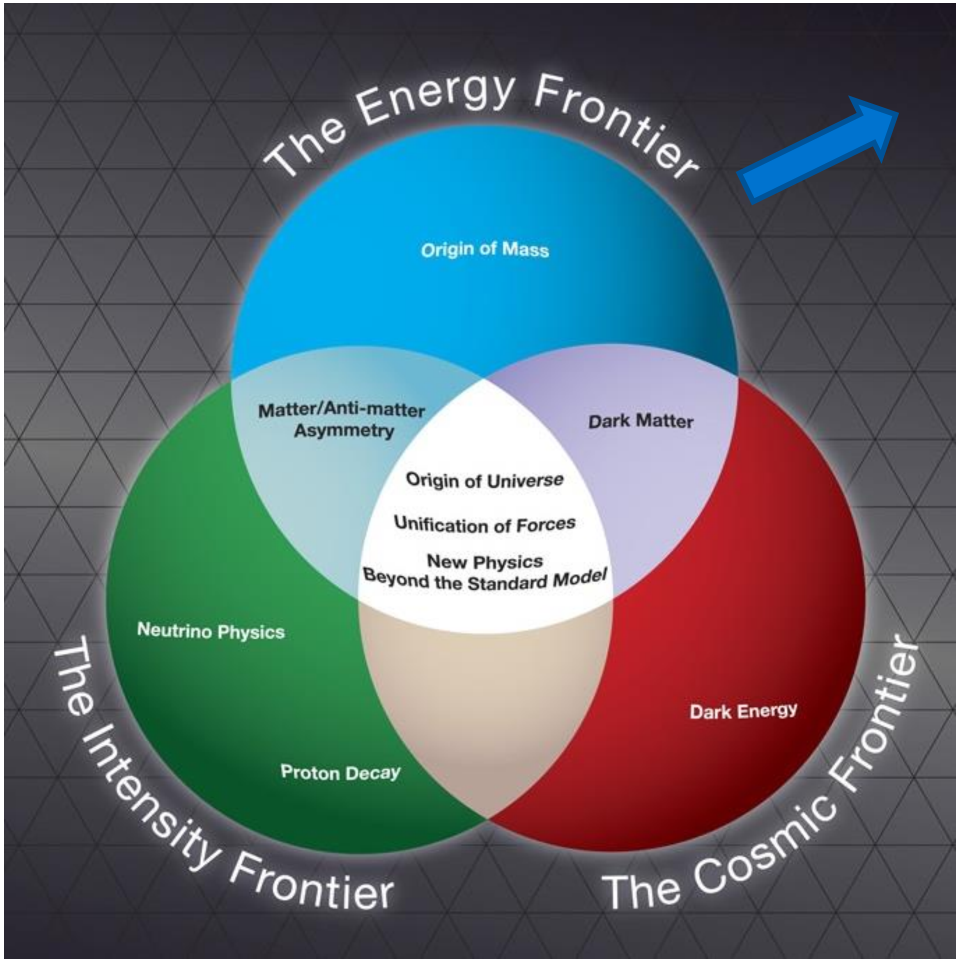


Image credit: arXiv:1903.05063

- Outstanding questions about nature/our universe could be solved through uncovering new physics at particle colliders.
- Unlike the Higgs discovery, we no longer have a clear idea of the (energy) scale at which it might appear.
- (Maximally) exploring the unknown is key…

Probing BSM @ Colliders

Image credit: https://science.osti.gov/hep/About/Vision-for-HEP



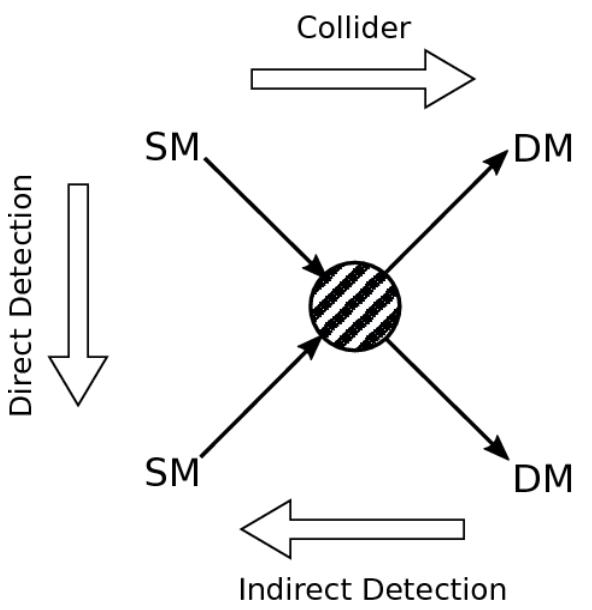
Try to create new heavy particles or test high-energy phenomena using high-energy particle accelerators.

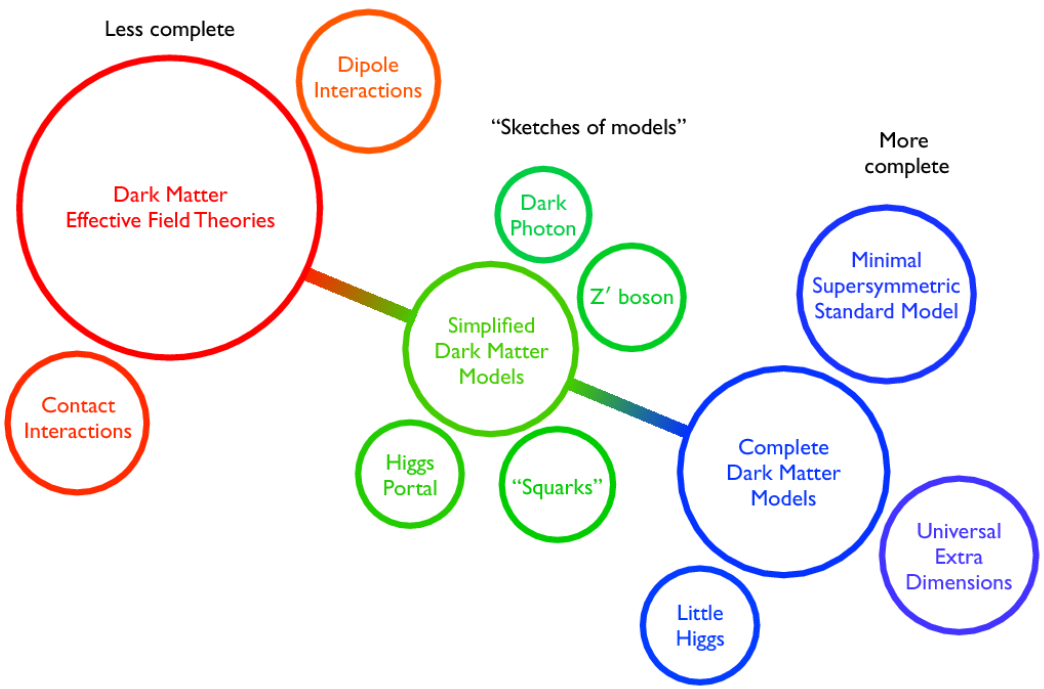
- Direct searches for new Beyond-the-Standard Model (BSM) particles.
- Precise measurements of SM processes which provide indirect sensitivity to BSM and enable (particle-level) comparisons to state-of-the-art theory predictions.

BSM models- dark matter as a case study

Image credit: arXiv:1712.01391

Image credit: arXiv:1506.03116





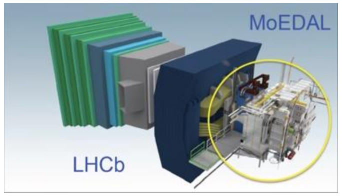
By assuming some generic interaction between Standard Model particles and Dark Matter, we could get production in colliders.

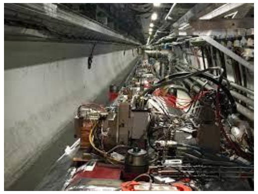
When designing/ interpreting searches, range of approaches from "effective field theories" (EFTs), to "simplified models" or more "complete" theories…

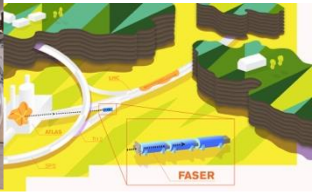
The Large Hadron Collider @ CERN

https://home.cern/science/experiments

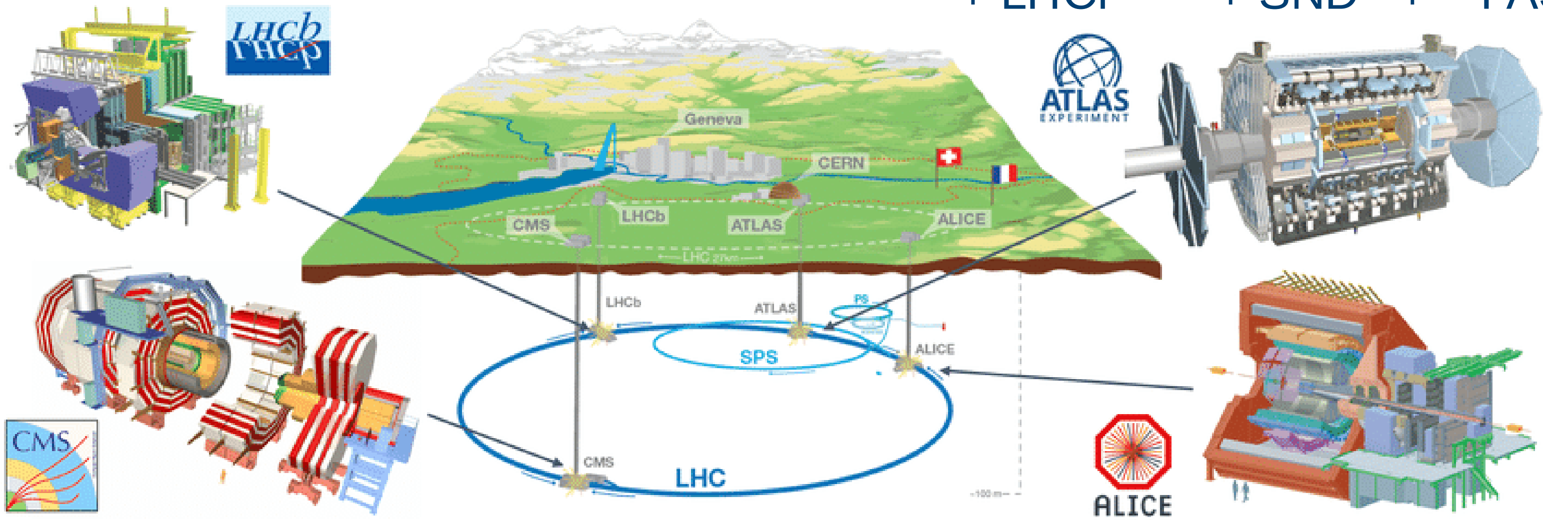
+ MoEDAL-MAPP



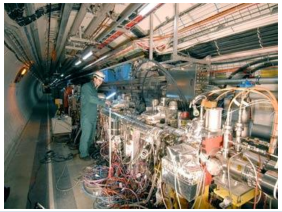




+ LHCf + SND + FASER



+ TOTEM



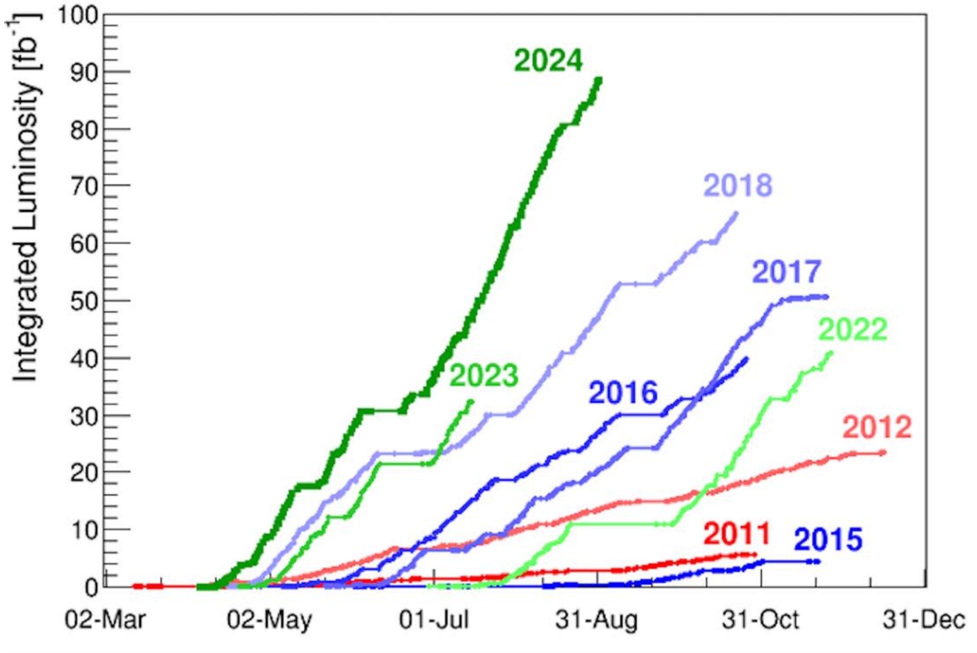
Will focus on ATLAS results and projections today!

Reasons for positivity

- LHC ~ doubled its design luminosity in run 2 and has continued to break luminosity records into run 3 (ongoing now).

- Developments in Machine Learning (ML) and analysis techniques are enabling us to analyse our data in increasingly sophisticated ways.

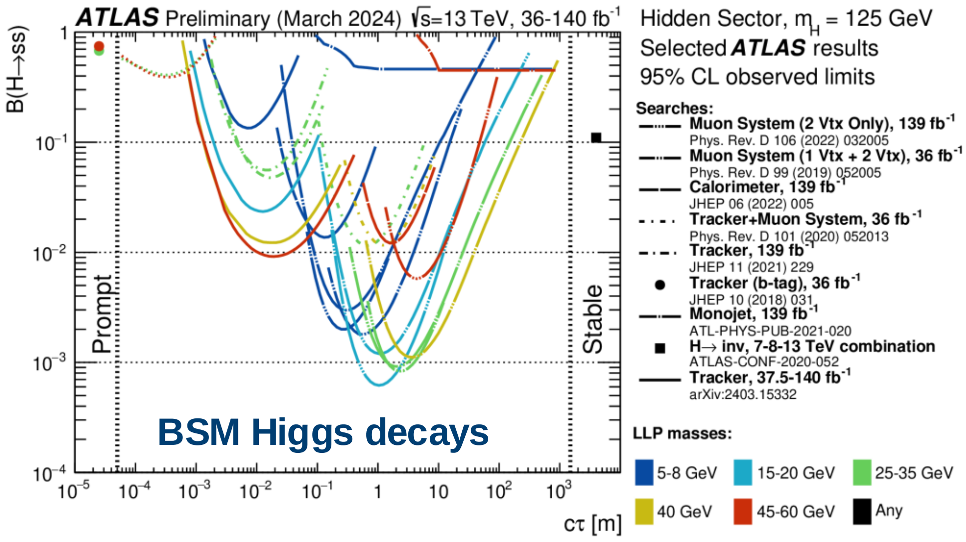
- The increasing data-set sizes are enabling us to probe previously unexplored SM processes and BSM scenarios

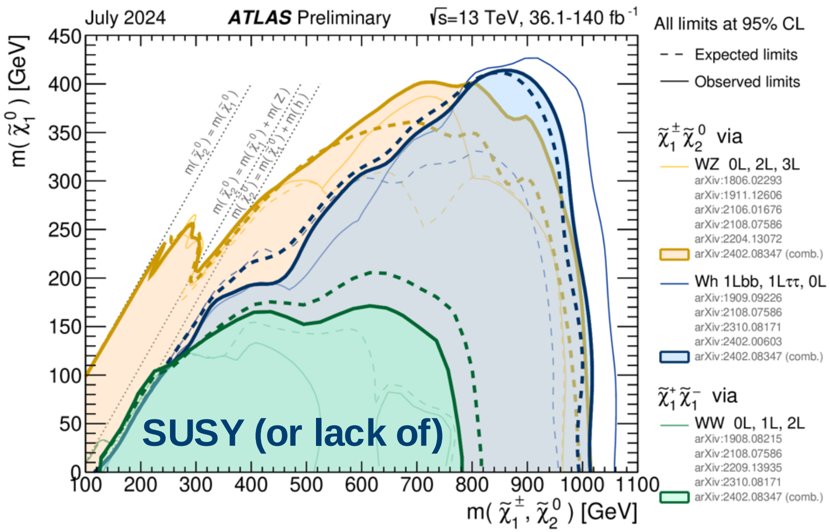


And the best is yet to come…

What do we know now? (BSM @ the LHC)

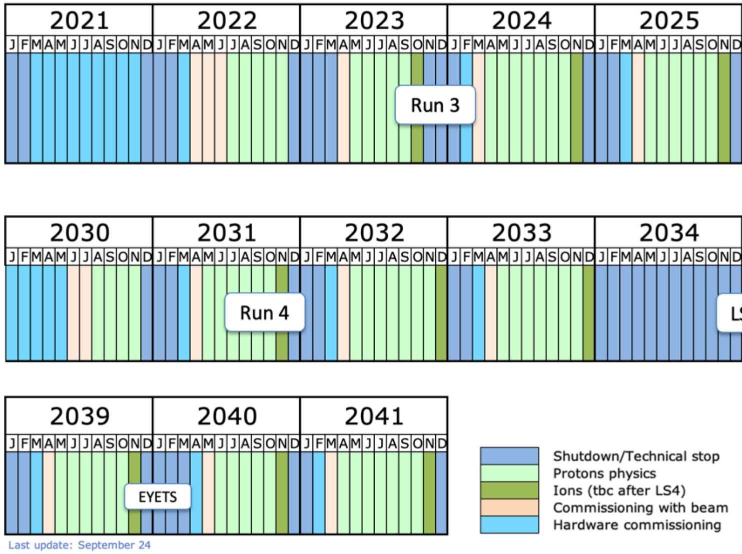
After a broad an extensive search programme, no significant deviations from SM predictions have been seen in run 2 searches





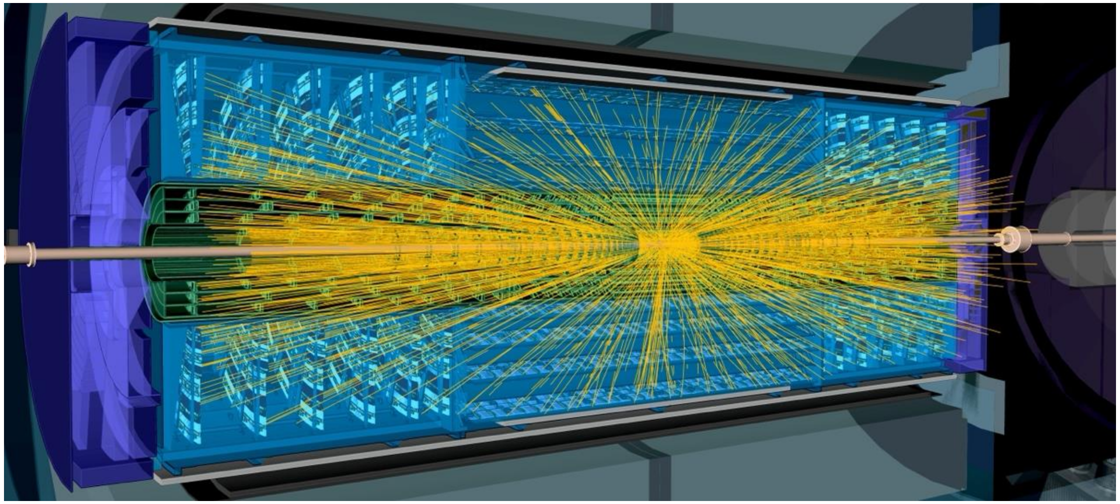
…plus observations of new (previously unexplored) SM processes, and improved precision on (differential) measurements…

High-Luminosity LHC upgrades



Left: current schedule for the LHC accelerator complex- aim to deliver 3000 fb^{-1} by 2041!

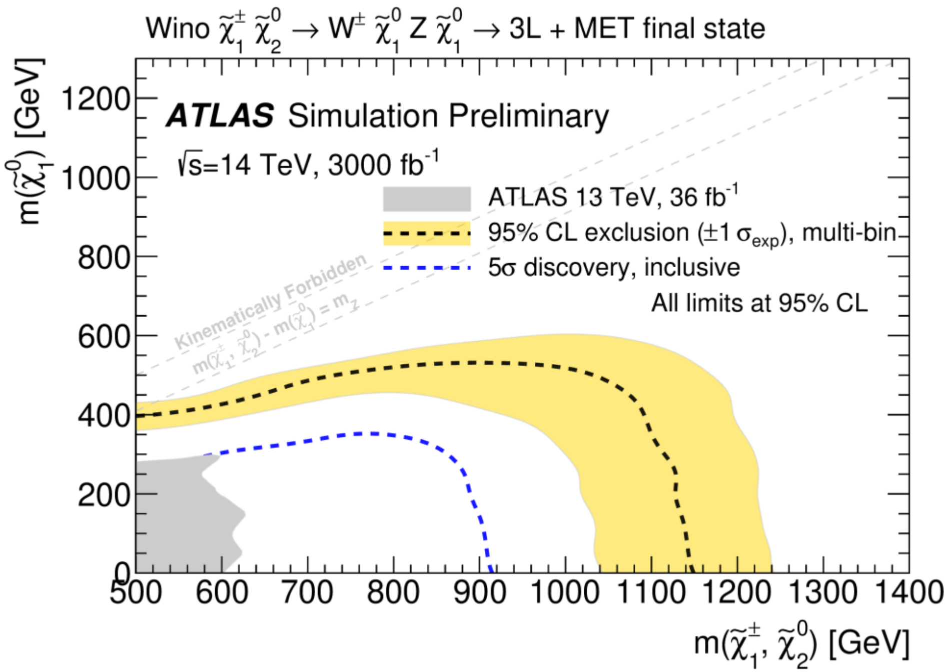
Right: Simulation of a typical HL-LHC event in the upgraded ATLAS tracker with a pileup of ~ 200 interactions per bunch crossing.



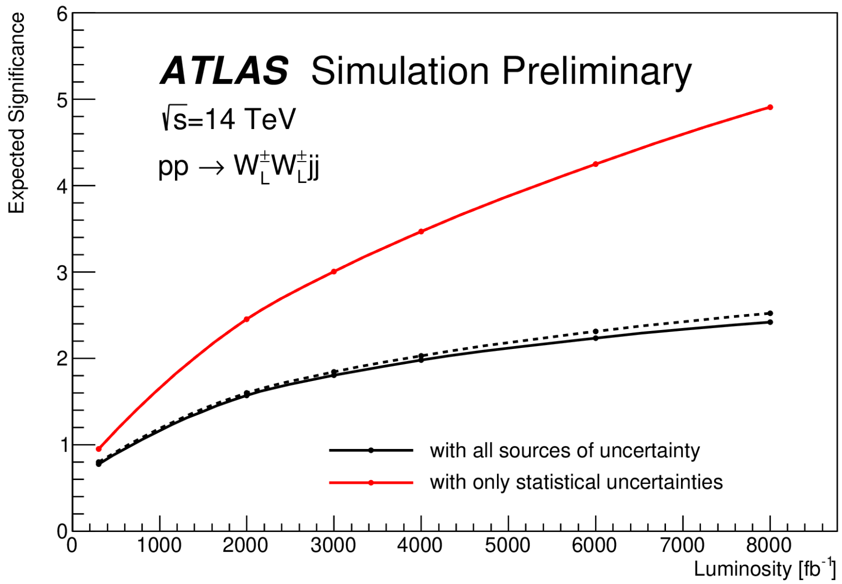
What could we know in ~ 15 years?

This could be an hour-long talk on its own!

Increased statistics (x 10) will significantly extend sensitivity to BSM

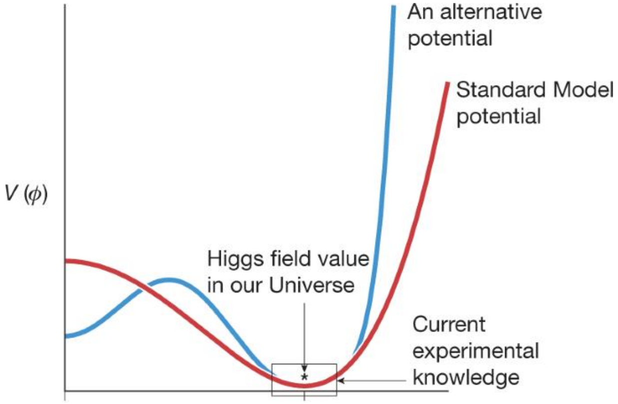


…plus studies of rare Higgs decays and SM processes



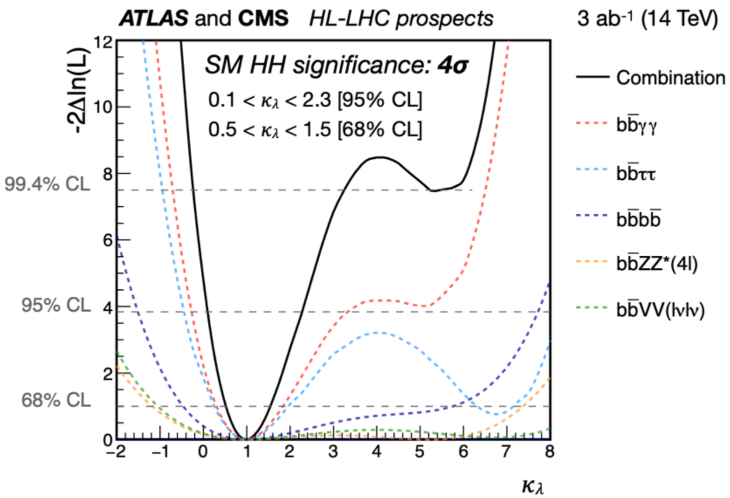
Projections often rely on extrapolations from run 2 searches- we should expect these to improve with innovations in reconstruction and analysis techniques….

Targeting the Higgs self coupling



$$V_{SM}(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \rightarrow \frac{1}{2}m_H^2h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 \ldots$$

After EWSB the quartic term gives 3-higgs and 4-higgs self-interaction vertices which can be accessed through di-Higgs production- a key target for the (HL-)LHC.



arXiv:1902.00134

Key message:

- BSM physics could modify HH rate/ kinematics.
- Innovative analysis approaches mean that run 2 results continue to exceed early projections.

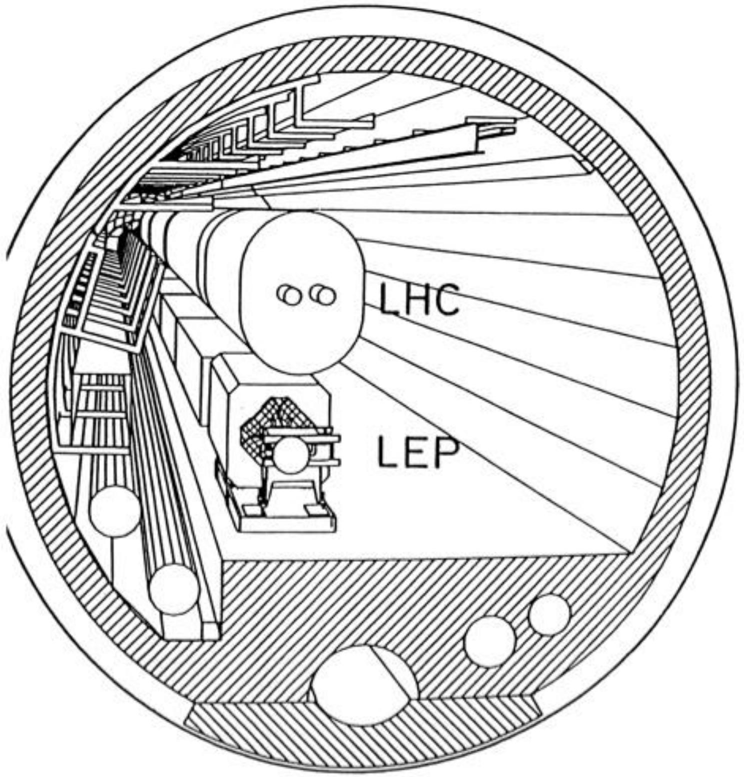
Timescales in particle physics

…are long…

1984: LHC proposed
1995: LHC approved
2012: Higgs discovery

ECFA-84-085-V-2

ECFA 84/85
CERN 84-10
5 September 1984



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

11. SUMMARY AND CONCLUSIONS

A theoretical consensus is emerging that new phenomena will be discovered at or below 1 TeV. There is no consensus about the nature of these phenomena but it is interesting that many of the ideas which have been suggested can be tested in experiments at an LHC. Although many, if not all, of these ideas will doubtless have been discarded, disproved or established by the time an LHC is built, this demonstrates the potential virtues of such a machine.

22 years later in 2006…

The European strategy *for particle physics*

Particle physics stands on the threshold of a new and exciting era of discovery. The next generation of experiments will explore new domains and probe the deep structure of space-time. They will measure the properties of the elementary constituents of matter and their interactions with unprecedented accuracy, and they will uncover new phenomena such as the Higgs boson or new forms of matter. Long-standing puzzles such as the origin of mass, the matter-antimatter asymmetry of the Universe and the mysterious dark matter and energy that permeate the cosmos will soon benefit from the insights that new measurements will bring. Together, the results will have a profound impact on the way we see our Universe; *European particle physics should thoroughly exploit its current exciting and diverse research programme. It should position itself to stand ready to address the challenges that will emerge from exploration of the new frontier, and it should participate fully in an increasingly global adventure.*

http://council-strategygroup.web.cern.ch/council-strategygroup/

To put this in context...?

1984

My parents

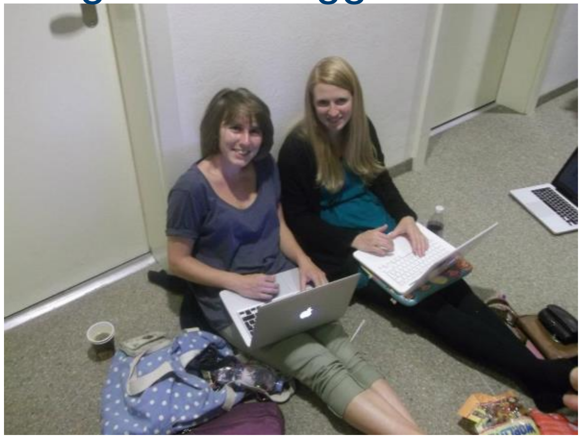
I have only been involved in a small part of the LHC journey…

1995

SW- aged 7

2012

Queuing for the Higgs seminar

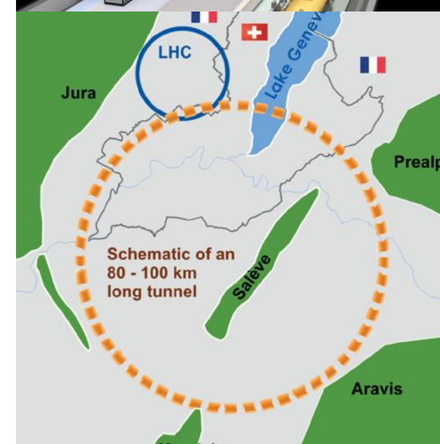


Looking ahead: what should come after the HL-LHC?

In the aftermath of the Higgs discovery, lots of discussion on what machine should follow the LHC…

What should come after the LHC?

- e^+e^- machine?
  - Linear collider?
    - **CLIC** (CERN?)
    - **ILC** (Japan?)
    - **HALHF** (??)
    - **C³** (??)
  - Circular collider?
    - **CepC** (China)
    - **FCC-ee/hh** (CERN)
- Hadron collider?
  - **FCC-ee/hh** (CERN)
- Muon collider?



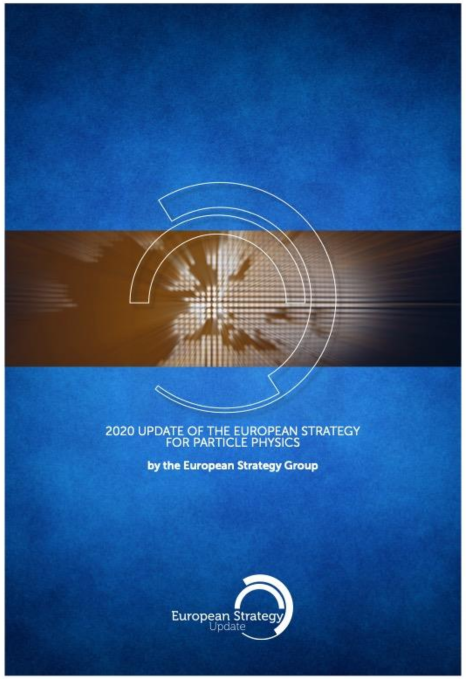
We can't do everything - a coherent global strategy is key!

The 2020 European Strategy Update

Following ~ 2 years of conensus gathering within the community, the ESU made several key recommendations to the community:

1. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy

2. Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage



Following the 2020 ESU, the FCC feasibility study was launched in 2021, aiming to provide input by 2025 to feed into the next ESU (coming soon)…

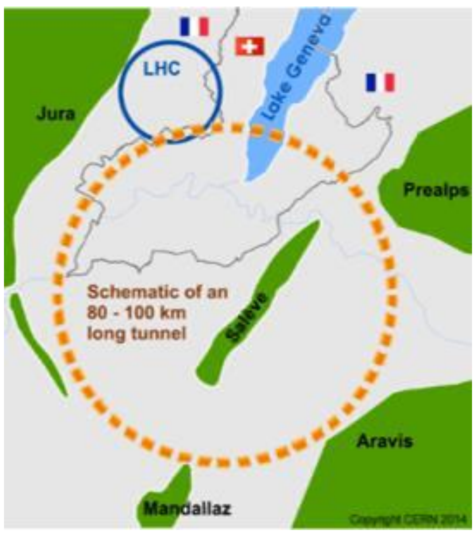
Integrated FCC programme

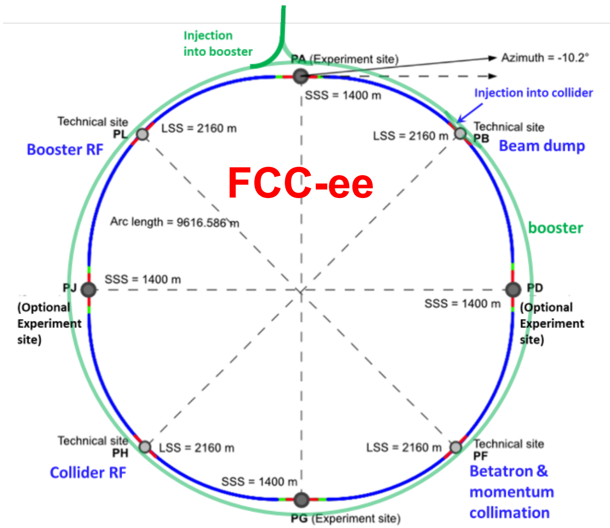
Taken from slides by M. Benedikt at FCC week.

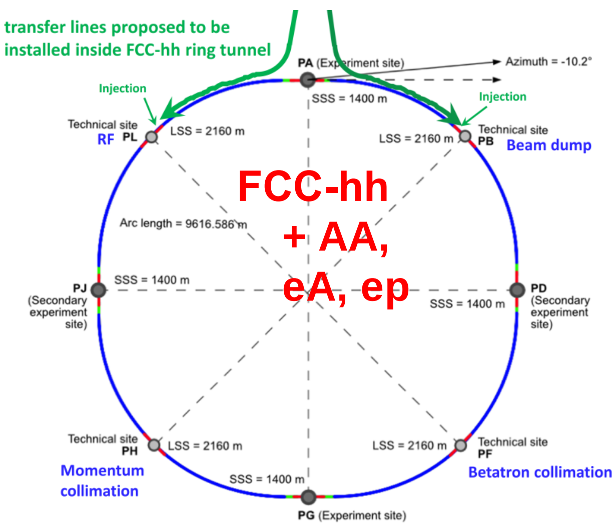
Comprehensive long-term programme maximises physics opportunities at the intensity and energy frontier:

1. FCC-ee (Z, W, H, $t\bar{t}$) as high-luminosity Higgs, EW + top factory.

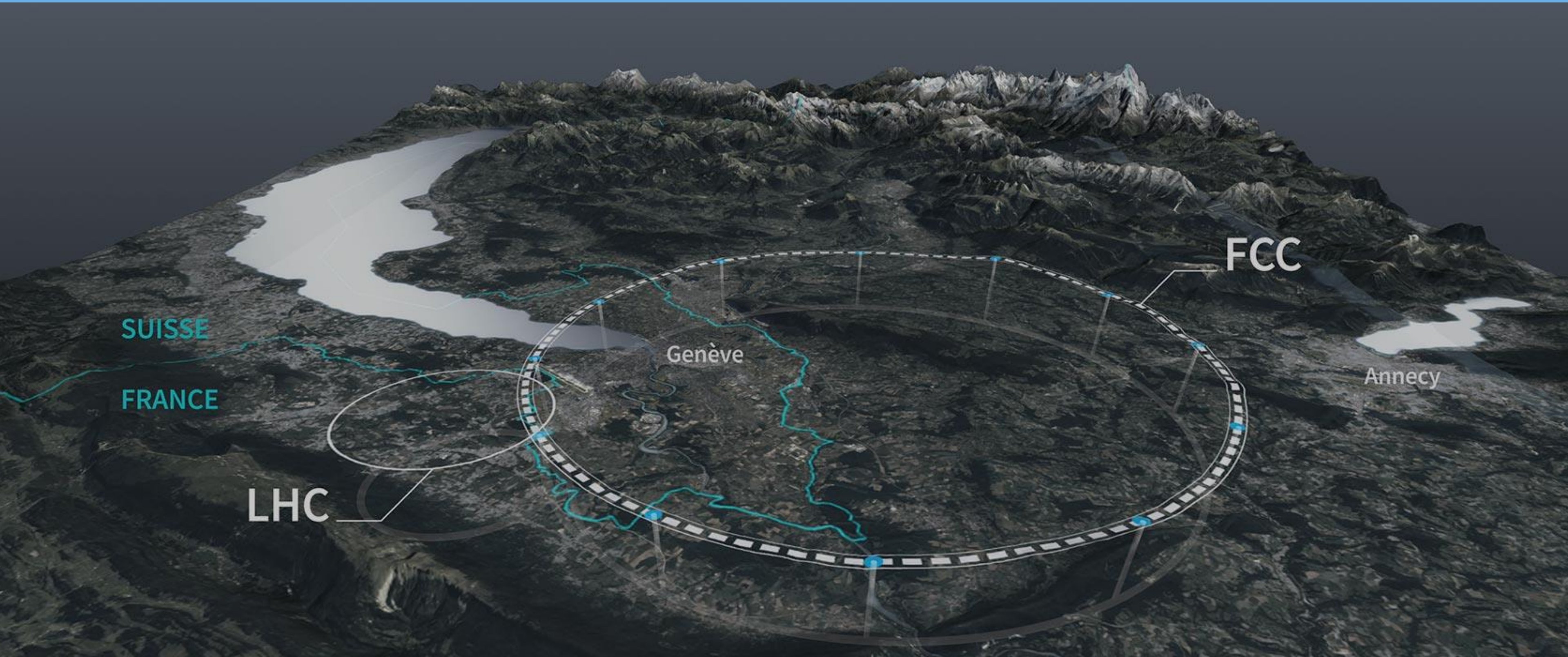
2. FCC-hh (~ 100 TeV) to maximise reach at the energy frontier, with pp, AA and e-h options (FCC-eh).







Synergies in the FCC programme



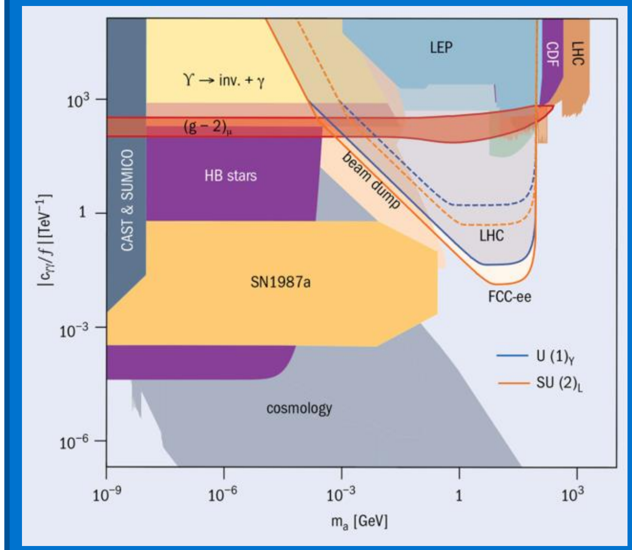
Integrated programme combines precision at the intensity frontier (FCC-ee) giving indirect sensitivity to a multitude of NP as well as unique direct sensitivity to low-mass and weakly interacting BSM physics, with discovery potential at the energy frontier (FCC-hh) that will furtger extend the precision achieved at FCC-ee!

FCC-ee and -hh synergies – BSM searches

See slides by G. Salam at FCC week

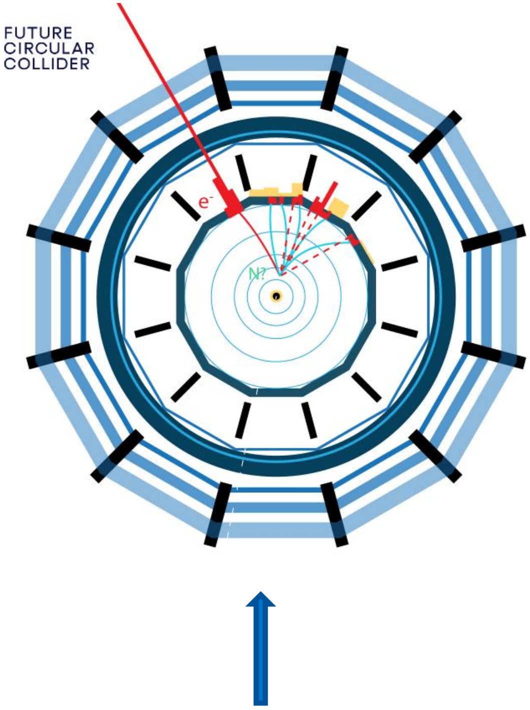
Direct FCC-ee sensitivity

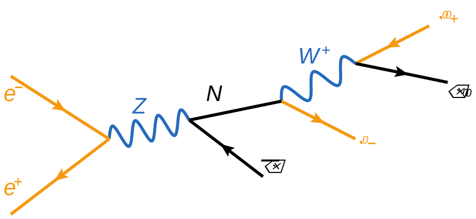
- HNLs
- Alps
- Exotic Higgs decays



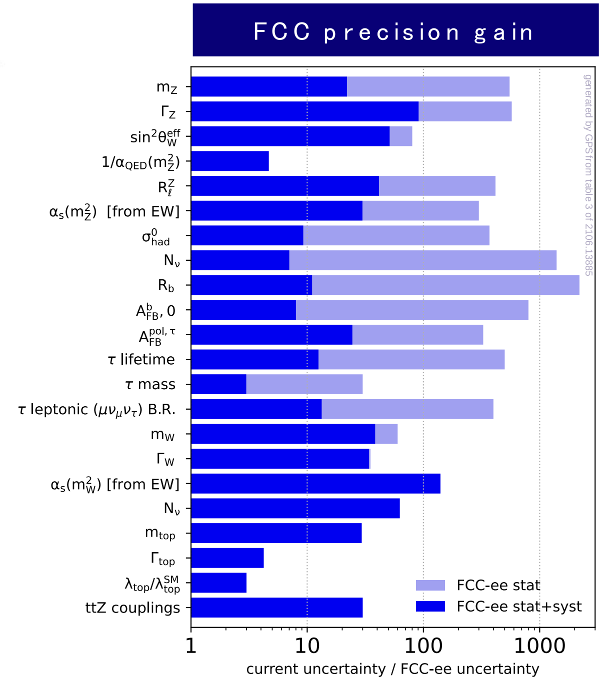
m_a: ALP mass, $c_{\gamma\gamma}$: ALP-photon coupling

FUTURE CIRCULAR COLLIDER





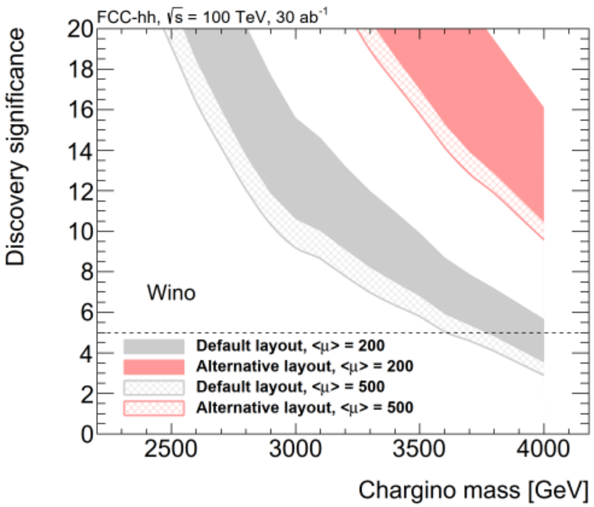
…plus **indirect access** to a range of BSM phenomena through ultra-precise measurements of SM parameters…

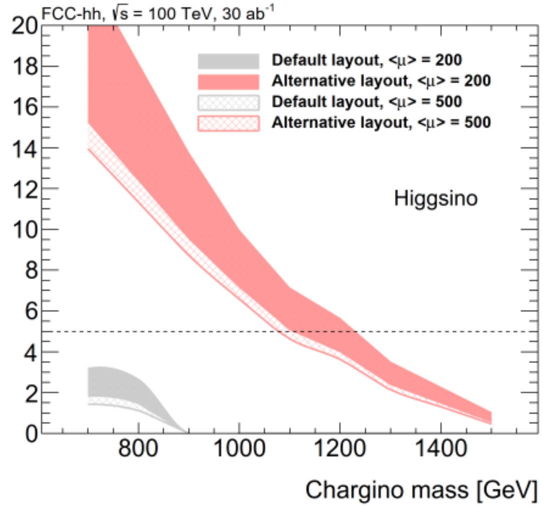


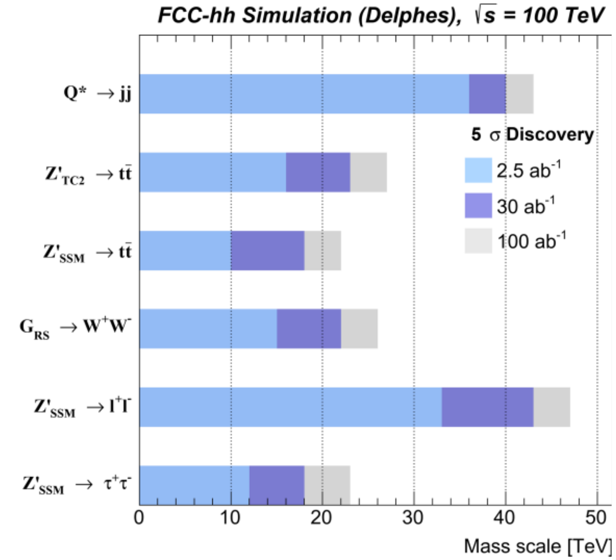
FCC-ee and -hh synergies - BSM searches

More details in FCC TDR and ESU submissions here

FCC-hh sensitivity to direct NP







Cover full mass range for discovery of WIMP dark matter candidates

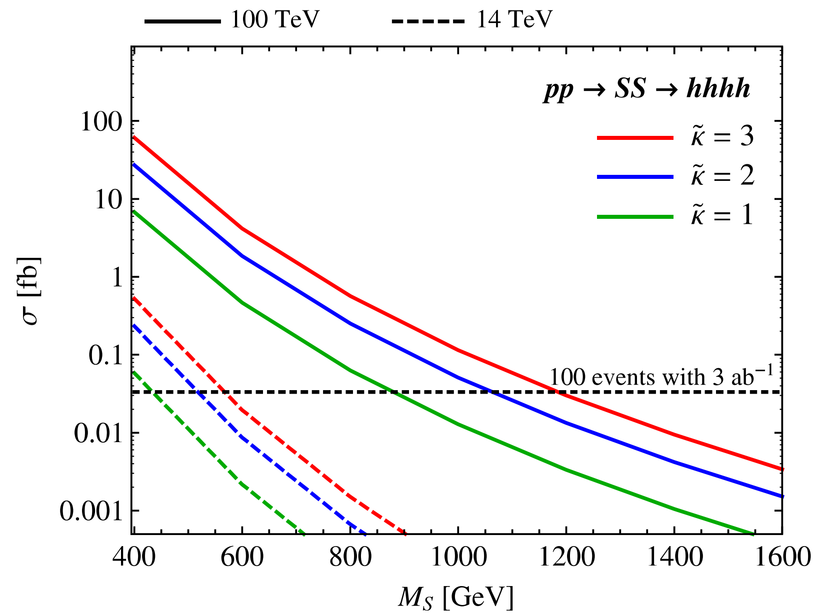
Substantial discovery reach for heavy resonances

In summary- exciting possibilities to discover/characterize NP that could be indirectly predicted through precision measurements at FCC-ee

Higgs coupling @ FCC-hh

https://arxiv.org/abs/1511.06495

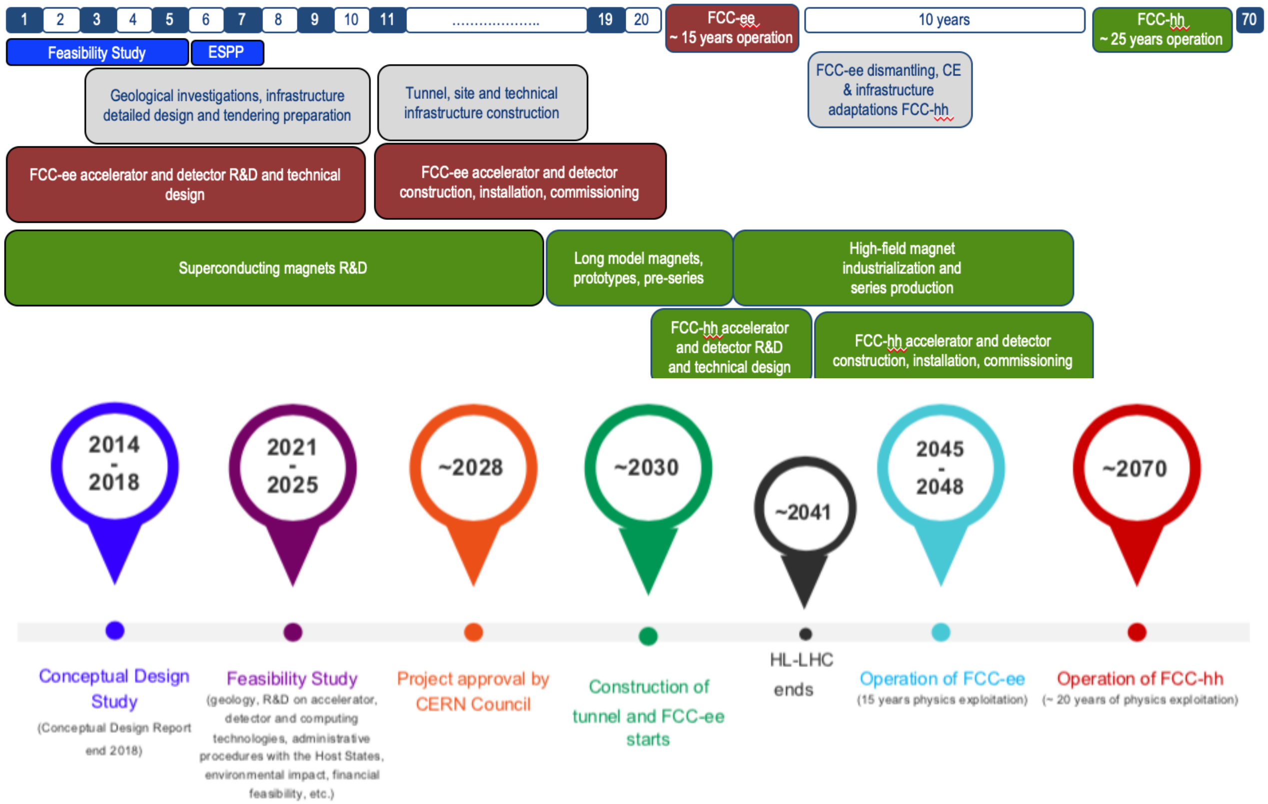
collider	Indirect-h	hh	combined
HL-LHC [40]	100-200%	50%	50%
ILC_{250}/C^3-250 [31, 33]	49%	–	49%
ILC_{500}/C^3-550 [31, 33]	38%	20%	20%
ILC_{1000}/C^3-1000 [31, 33]	36%	10%	10%
$CLIC_{380}$ [35]	50%	–	50%
$CLIC_{1500}$ [35]	49%	36%	29%
$CLIC_{3000}$ [35]	49%	9%	9%
FCC-ee [36]	33%	–	33%
FCC-ee (4 IPs) [36]	24%	–	24%
FCC-hh [41]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [39]	-	15-30%	15-30%
μ(10 TeV) [39]	-	4%	4%



New physics required for a strong first order phase transition (needed for EWK baryogenesis) either by directly discovering new states (which can't be too much heavier than the Higgs) or through O(1) deviations in the Higgs self-coupling (which will be measured to ~ 10%).

FCC timelines

Taken from slides by F. Gianotti at FCC week.



Based on **technical schedule**, FCC-ee operation could start in 2040 or earlier.

More **realistic schedule**, accounting for past experience of building colliders, approval timelines, HL-LHC operation…

Obvious comment: long timescales mean that ECR engagement is key- get involved in the upcoming European Strategy discussions!

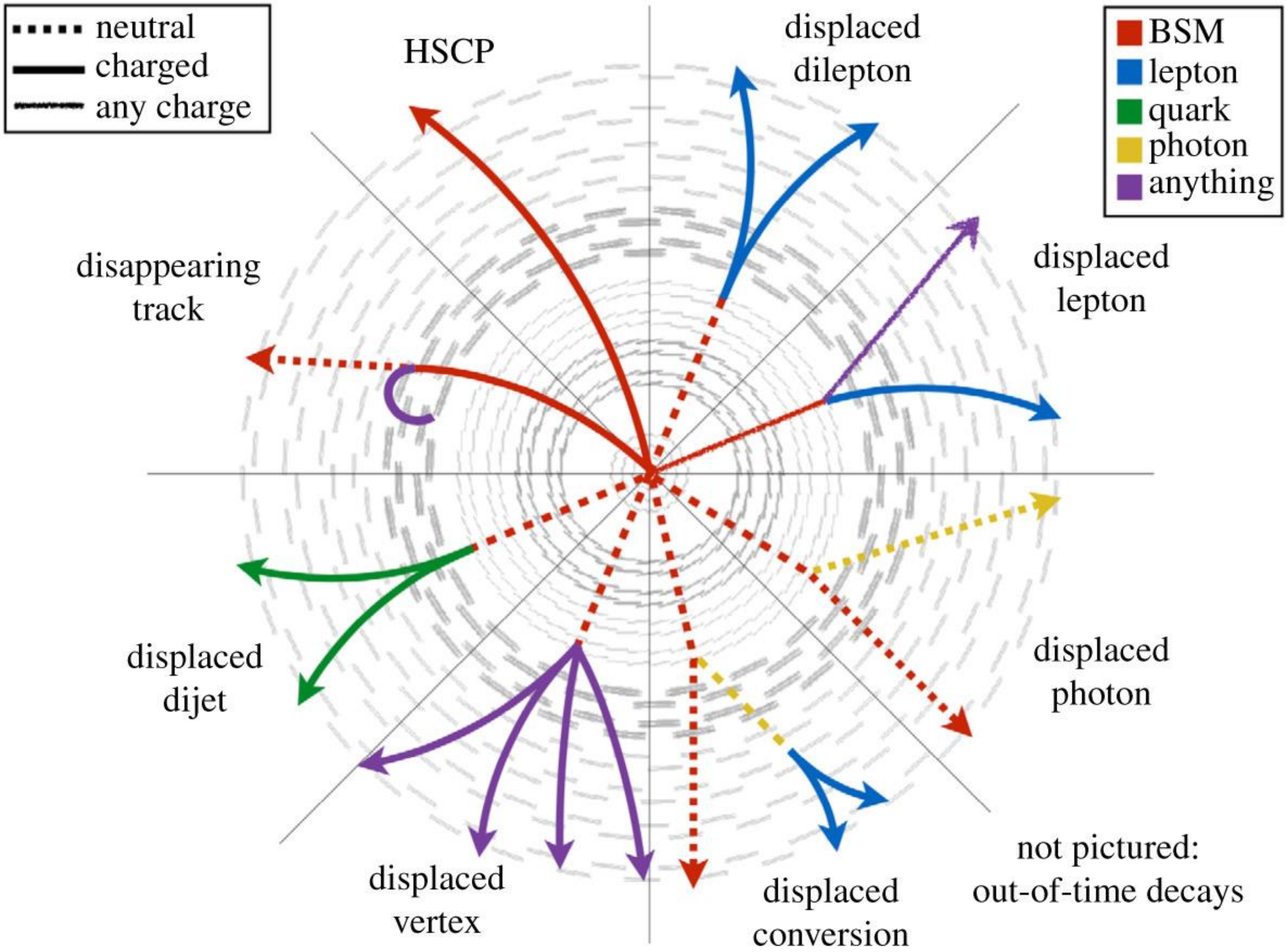
Conclusions/outlook

- We have an exciting route ahead with great opportunities to discovery/constrain BSM @ the LHC and beyond.
- Decisions on future (post-HL-LHC) colliders will happen soon- get involved in the discussions (both in Sweden and beyond)
- Thank you for having me here in Uppsala- it has been a great meeting!



Backup

Long-lived particles in central detectors

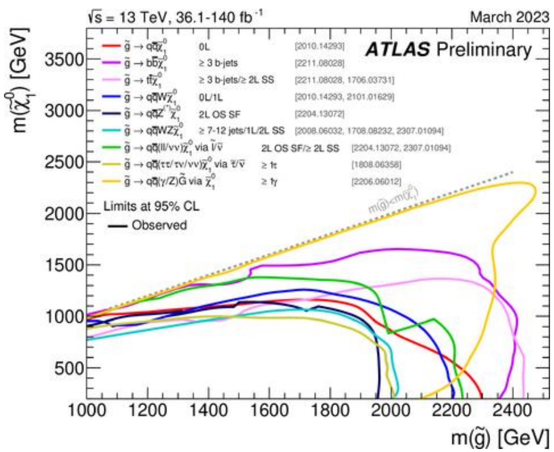


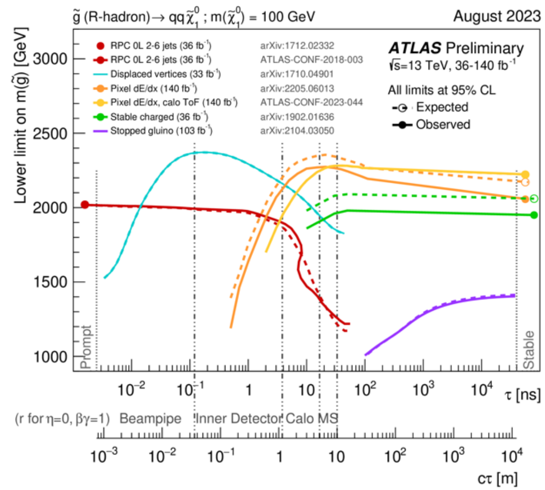
Long-lived particles that are semi-stable or decay in the sub-detectors are predicted in a variety of BSM models and lead to a range of unconventional signatures:

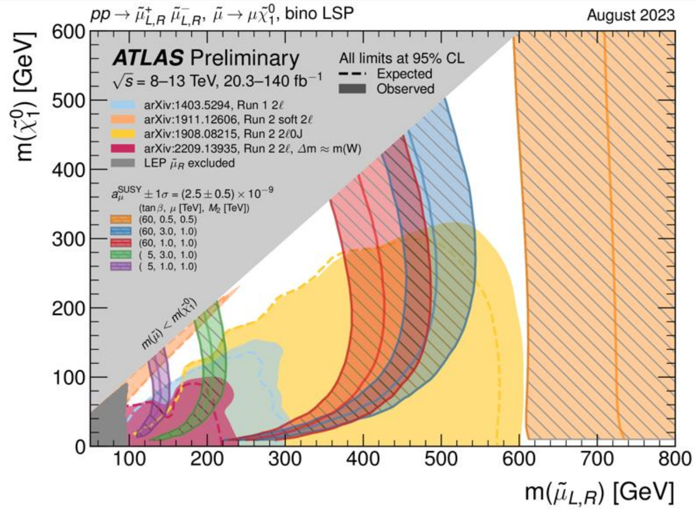
- RPV SUSY
- Dark photons
- ALPs
- Dark sector models

(More) ATLAS run 2 SUSY summary plots

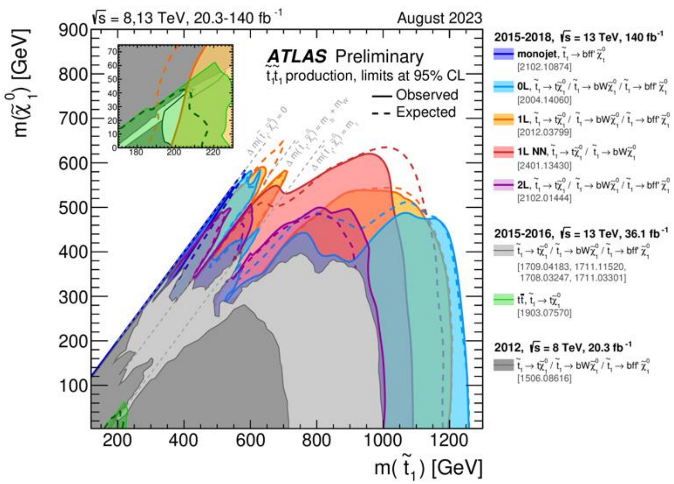
ATL-PHYS-PUB-2023-005

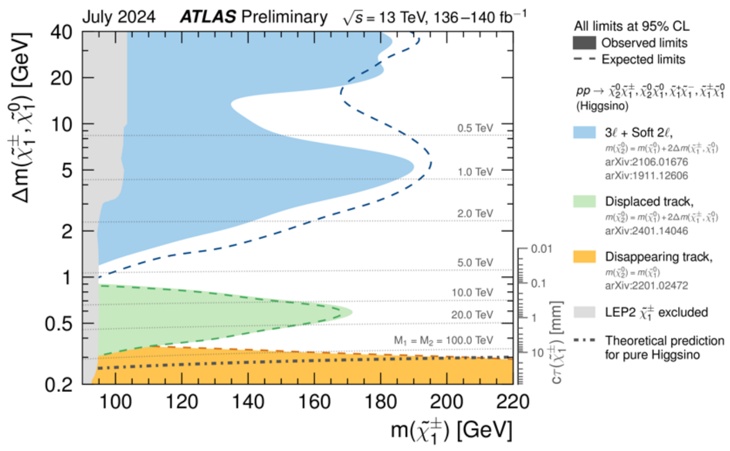




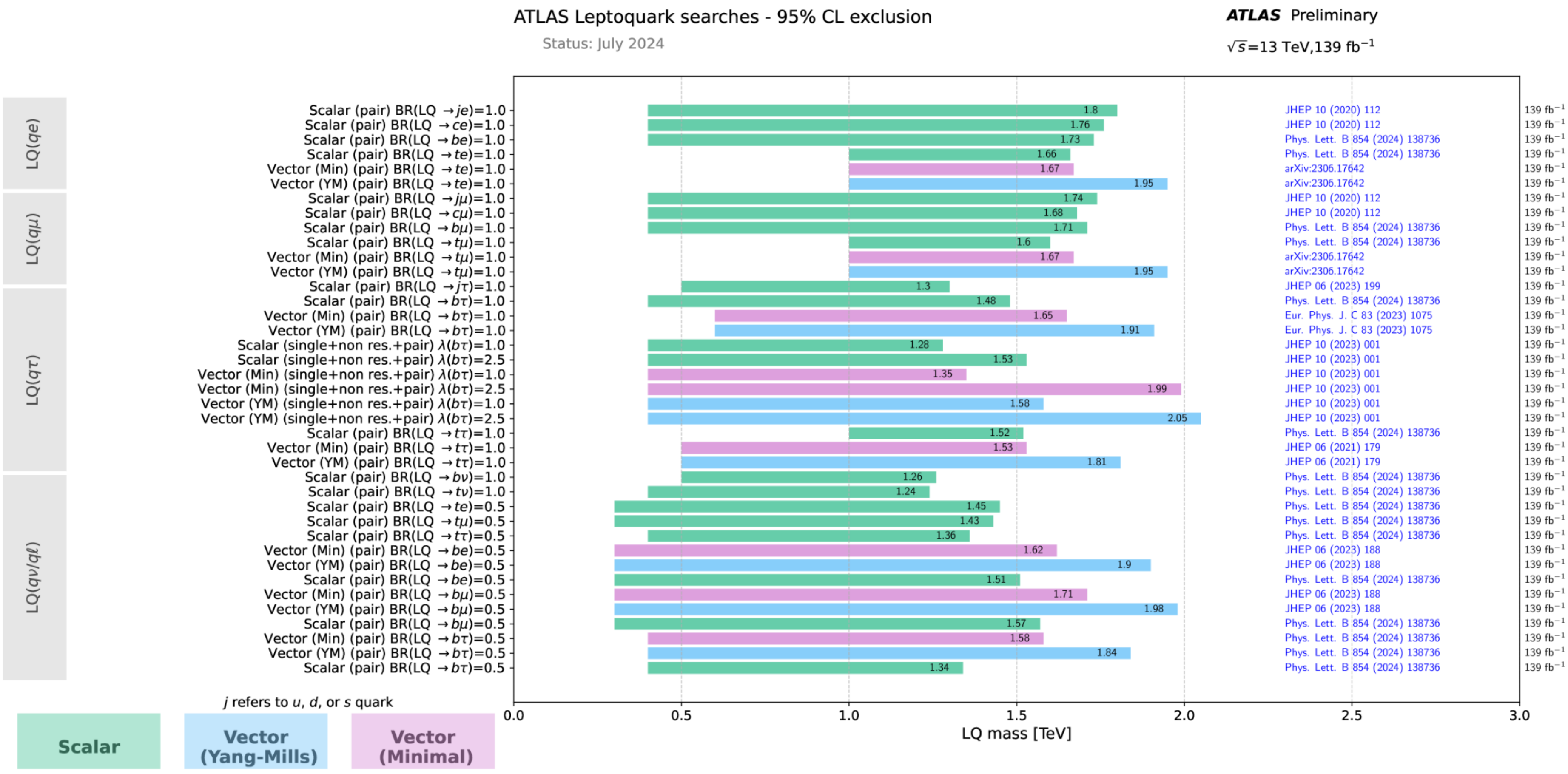


Impressive to see so many channels now contributing to summary plots!

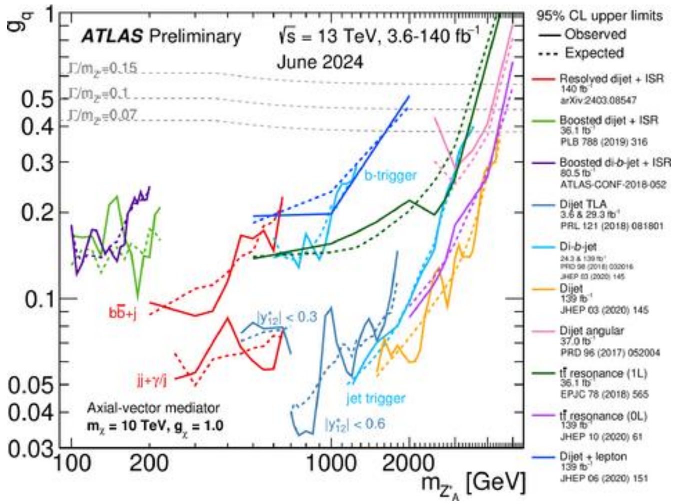


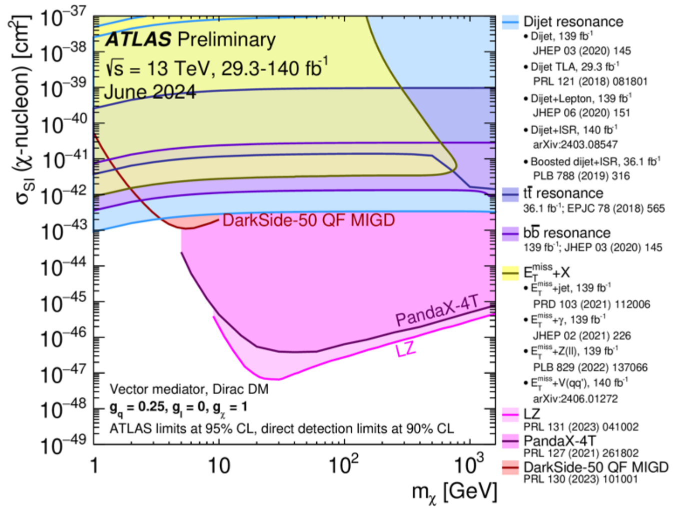


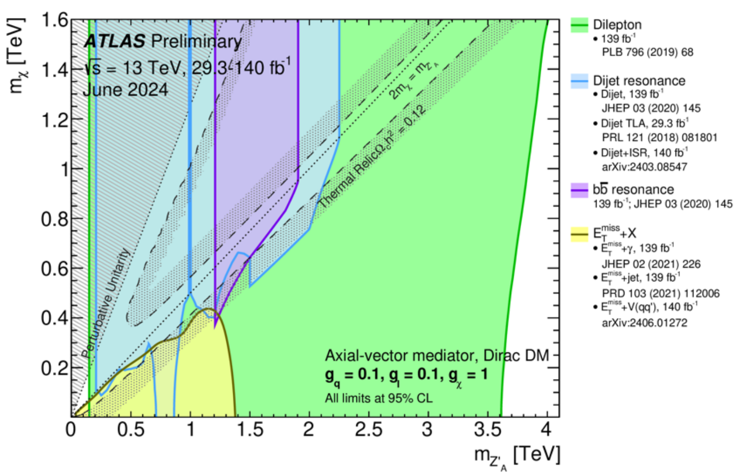
ATLAS run 2 leptoquark summary plot

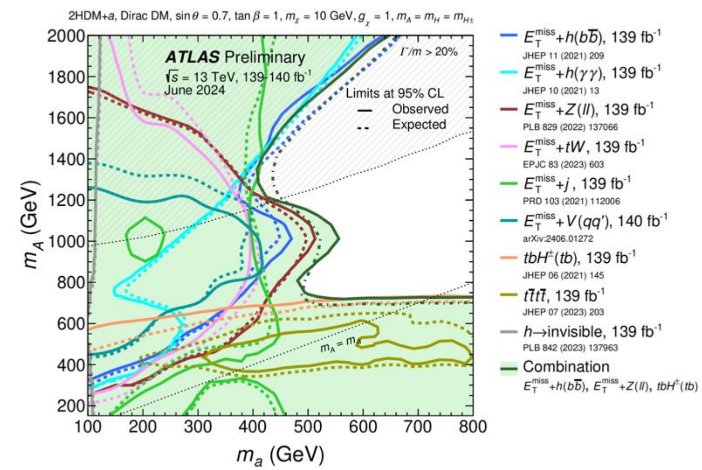


ATLAS run 2 dark matter summary plots



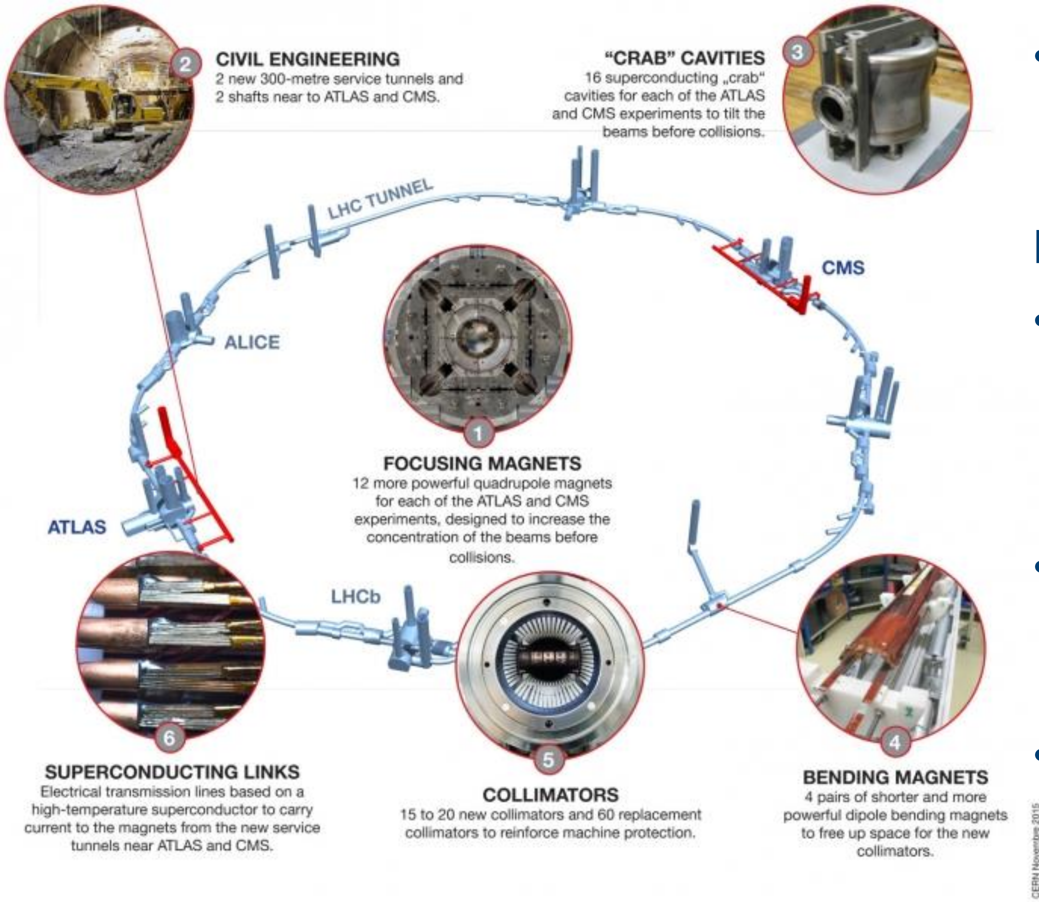






HL-LHC upgrade

Key point: this is the next future collider!



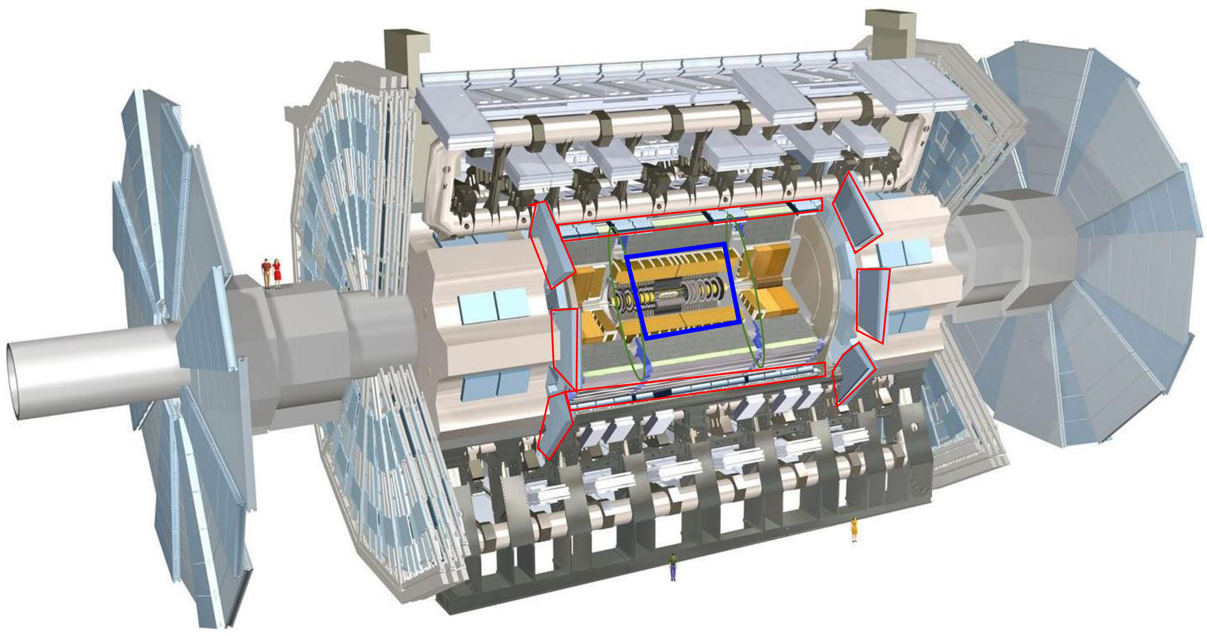
- Scheduled upgrade to increase integrated luminosity to 5 x the design value.

Key innovations include:

- Cutting edge 11-12 T niobium-tin superconducting quadrupoles for focusing the beam (target 140 interactions per BC)
- SC crab cavities for "tilting the beam" to give better overlap of crossing bunches.
- New technology for beam collimation – needed to protect SC elements from quenching.

ATLAS upgrade

Diagram taken from slides by Tony Affolder at Lepton-Photon 2021



Upgraded Trigger and Data Acquisition System

- Single Level Trigger with 1 MHz output
- Improved 10 kHZ Event Farm

Electronics Upgrades

- On-detector/off-detector electronics upgrades of LAr Calorimeter, Tile Calorimeter & Muon Detectors
- 40 MHz continuous readout with finer segmentation to trigger

High Granularity Timing Detector (HGTD)

- Precision time reconstruction (30 ps) with Low-Gain Avalanche Detectors (LGAD)
- Improved pile-up separation and bunch-by-bunch luminosity

New Muon Chambers

- Inner barrel region with new RPCs, sMDTs, and TGCs
- Improved trigger efficiency/momentum resolution, reduced fake rate

New Inner Tracking Detector (ITk)

- All silicon with at least 9 layers up to $|\eta| = 4$
- Less material, finer segmentation

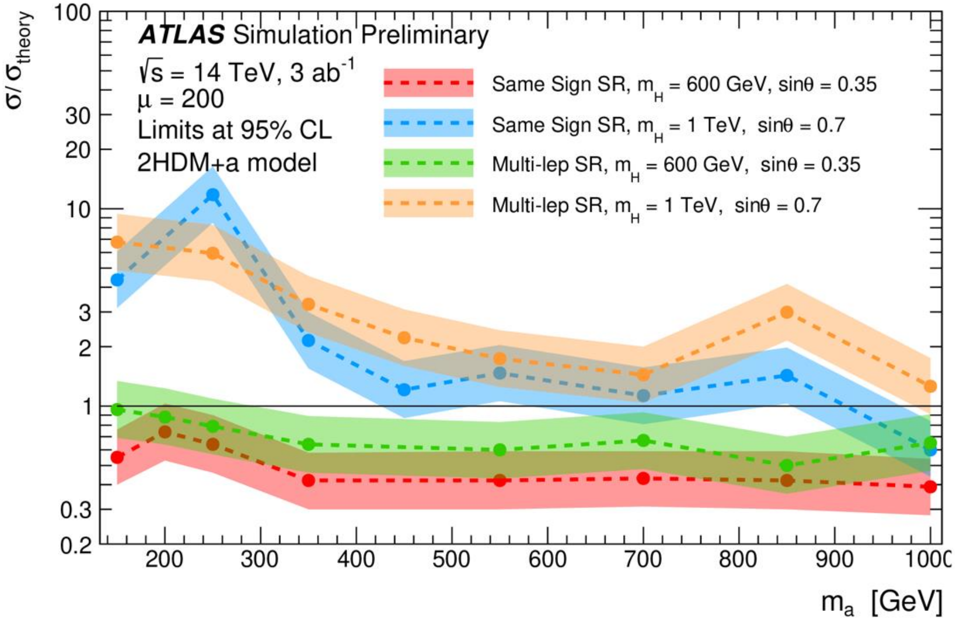
Additional small upgrades

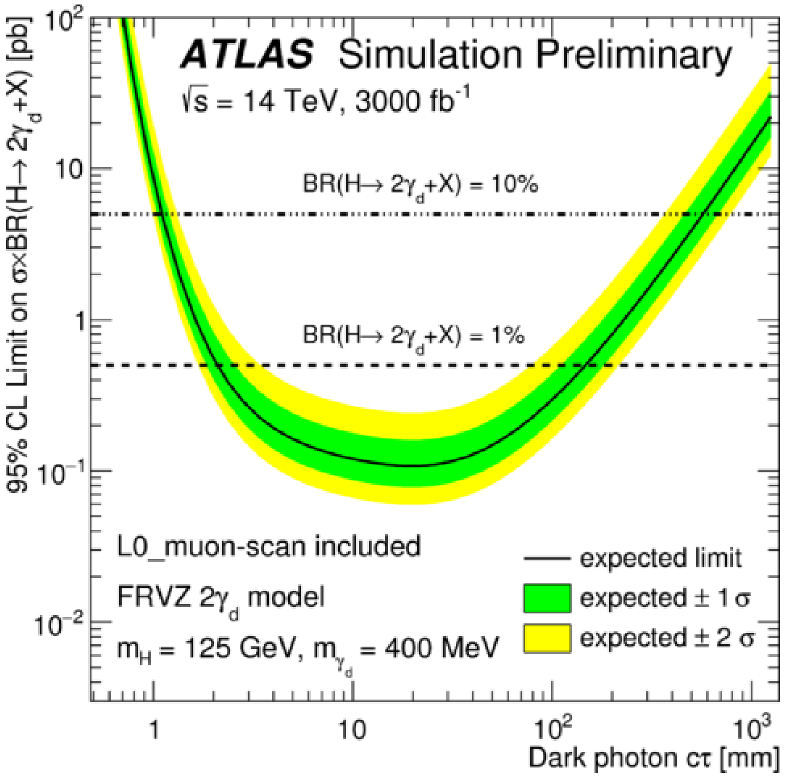
- Luminosity detectors (1% precision)
- HL-ZDC (Heavy Ion physics)

Needs to cope with much higher pileup (<mu>~140) with strong constraints on readout and radiation hardness.

Additional HL-LHC projections

For more details see ATLAS + CMS Snowmass white paper





Projected upper limits on 2HDM+a as a function of the pseudoscalar mass.

Projected limits on dark photon production

Integrated FCC programme

Taken from slides by F. Gianotti at FCC week.

	$\sqrt{s}$	L /IP ($cm^{-2} s^{-1}$)	Int L/IP/y (ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV Z 160 WW 240 H ~365 top	182×10^{34} 19.4 7.3 1.33	22 2.3 0.9 0.16	2-4 experiments Total ~ 15 years of operation
pp **FCC-hh**	100 TeV	$5\text{-}30 \times 10^{34}$ 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb **FCC-hh**	$\sqrt{s_{NN}}$ = 39TeV	3×10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep **Fcc-eh**	3.5 TeV	$1.5\ 10^{34}$	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb **Fcc-eh**	$\sqrt{s_{eN}}$ = 2.2 TeV	$0.5\ 10^{34}$	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

FCC-ee:
- Ultra-precise measurements of EW/ Higgs + top sectors of SM -> indirect sensitivity to BSM.
- Unique flavour opportunities
- Direct sensitivity to feebly interacting particles (LLPs)

FCC-hh:
- High-statistics for rare Higgs decays and 5% measurement of Higgs self interaction.
- Unprecedented direct sensitivity to BSM.

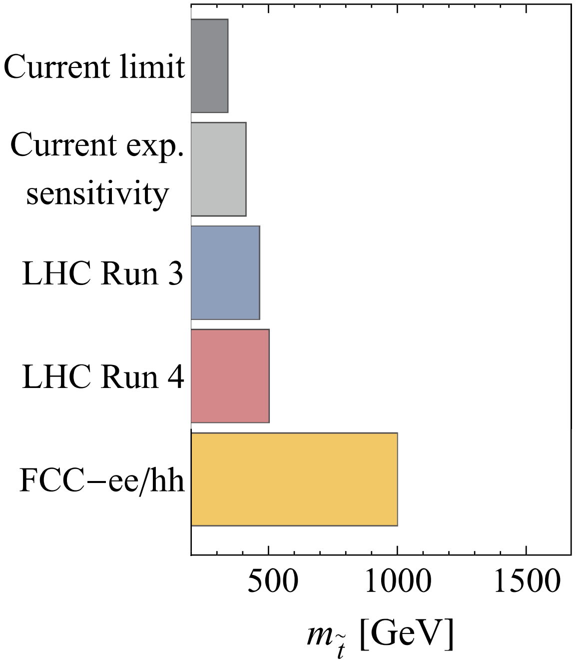
FCC-eh:
- Energy-frontier ep collisions provide ultimate super-microscope to fully resolve hadron structure and empower physics potential of hadron colliders.
- Very precise measurements of Higgs/top and EW parameters in synergy with ee and hh.

FCC-ee BSM snapshot

Taken from FCC Snowmass submission

1. Indirectly discover new particles coupling to the Higgs or EW bosons up to scales of $\Lambda \approx 7$ and 50 TeV.
2. Perform tests of SUSY at the loop level in regions not accessible at the LHC.
3. Study heavy flavour/tau physics in rare decays inaccessible at the LHC.
4. Perform searches with best collider sensitivity to dark matter, sterile neutrinos and ALPs up to masses ≈ 90 GeV.

Image credit: FCC CDR



Projected 2σ indirect reach from Higgs couplings on stops.

Physics landscape at FCC-ee

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
"boosted" B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau \nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau \tau$
$B \to K^* \nu \nu$
$B_s \to \varphi \nu \nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

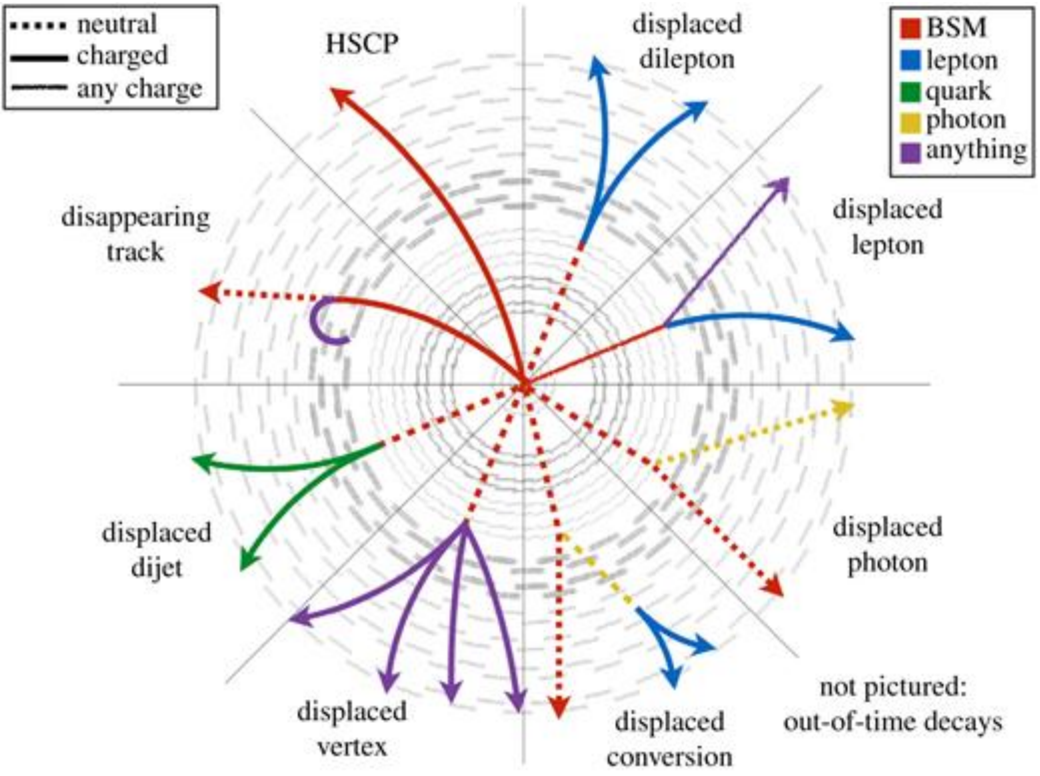
Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

- Broad landscape of physics opportunities which include direct and indirect sensitivity to new physics.
- Unique sensitivity to feebly interacting particles and LLPs means we are in an exciting position to design detectors with these scenarios in mind.

FCC-ee case study: LLPs



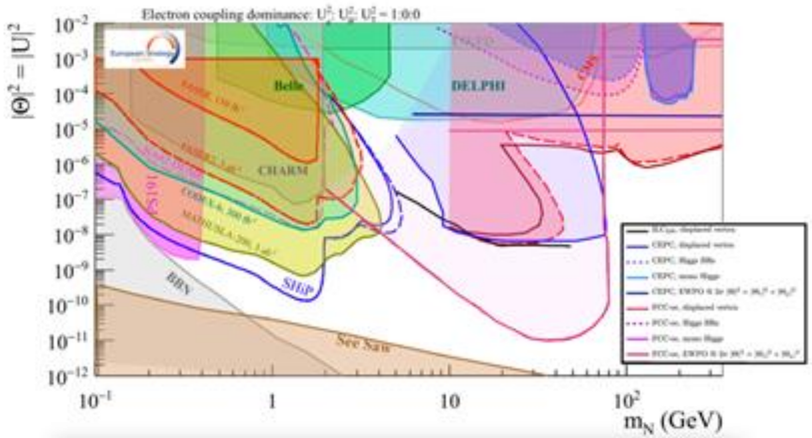
LLPs that are semi-stable or decay in the sub-detectors are predicted in a variety of BSM models:

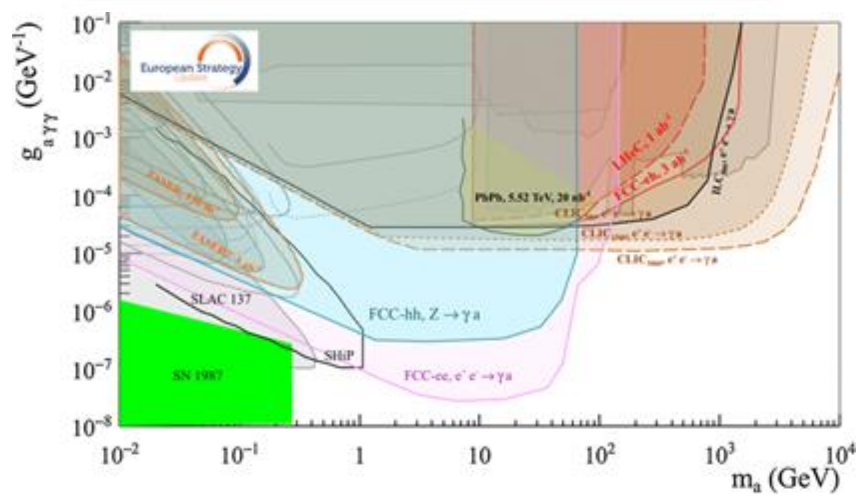
- Heavy Neutral Leptons (HNLs)
- RPV SUSY
- ALPs
- Dark sector models

The range of unconventional signatures and rich phenomenology means that understanding the impact of detector design/performance on the sensitivity of future experiments is key!

LLPs @ FCC-ee

- Targeting precision measurements of EWK/Higgs/top sector of SM.
- Unique sensitivity to LLPs coupling to Z or Higgs.
    - No trigger requirements.
    - Excellent vertex reconstruction and impact parameter resolution can target low LLP lifetimes (this can drive hardware choices).
    - **Projections often assume background-free searches** (should check these assumptions).



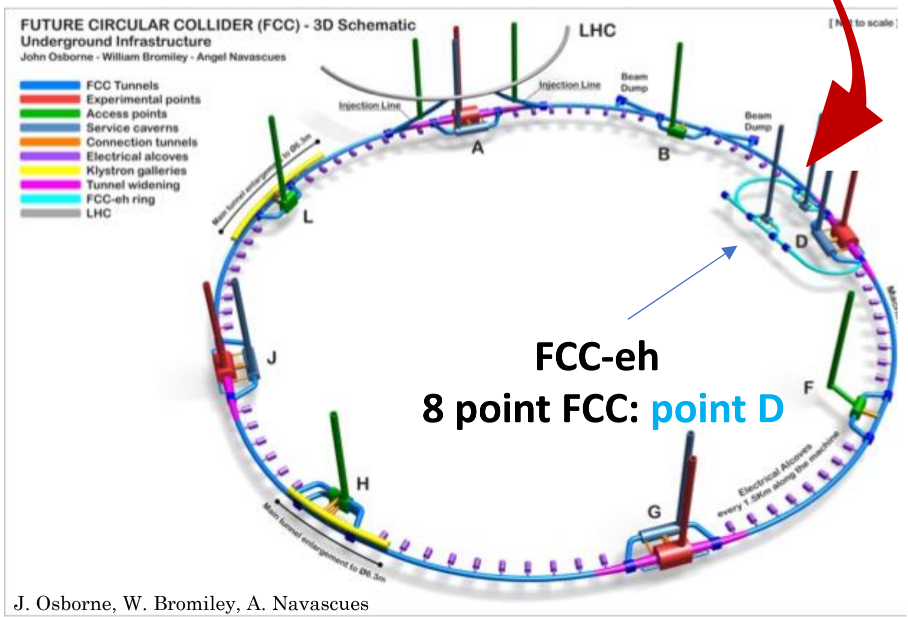


FCC-eh

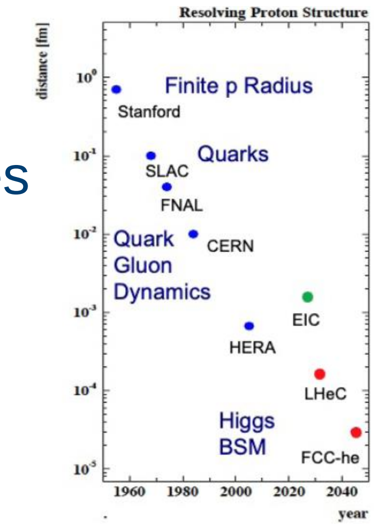
For a nice review of electron-hadron colliders (including EIC) see https://cds.cern.ch/record/2811194

Novel use of Energy Recovery Linac (ERL) technology that will be demonstrated with the PERLE ERL demonstrator

FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh



Use of ERL technologies a key step towards improving sustainability whilst maintaining high luminosities.

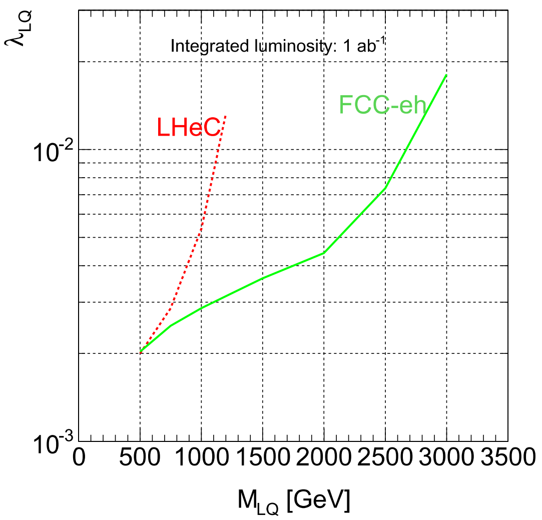


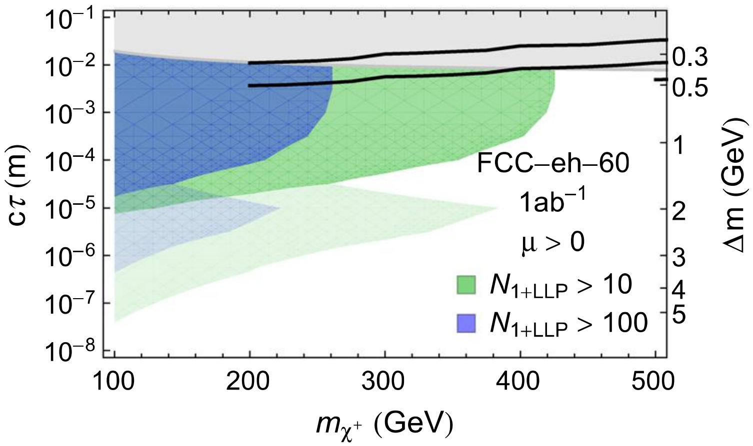
Relatively keen environment associated with e-p collisions provides a new window to discover new physics…

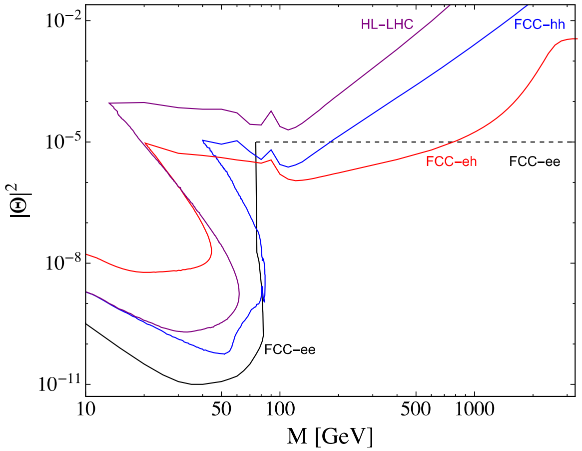
Taken from slides by J. D"Hondt at FCC week

FCC-eh BSM snapshot

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







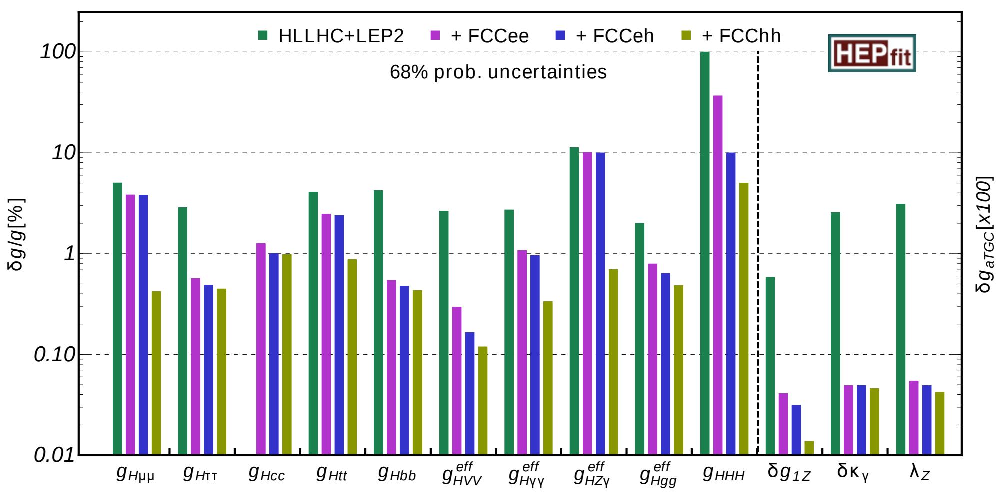
Plots taken from vol. 1 of FCC CDR: https://fcc-cdr.web.cern.ch/

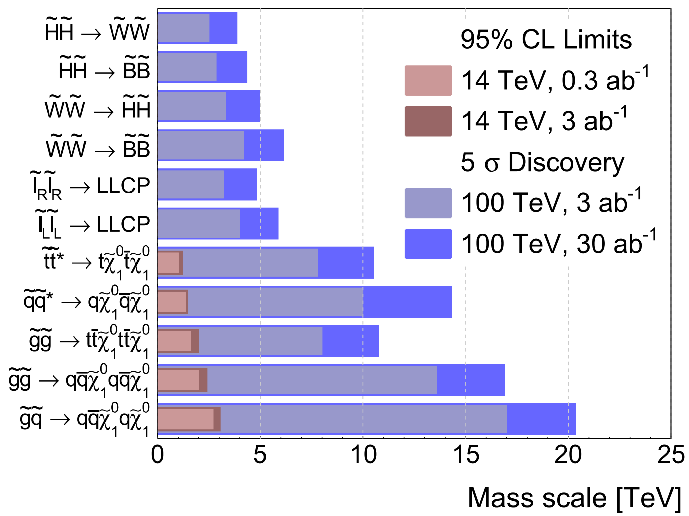
FCC-hh BSM snapshot

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

1. Direct discovery potential up to ~50 TeV.
2. Precision measurement of Higgs self coupling.
3. Conclusively test the WIMP dark matter paradigm.

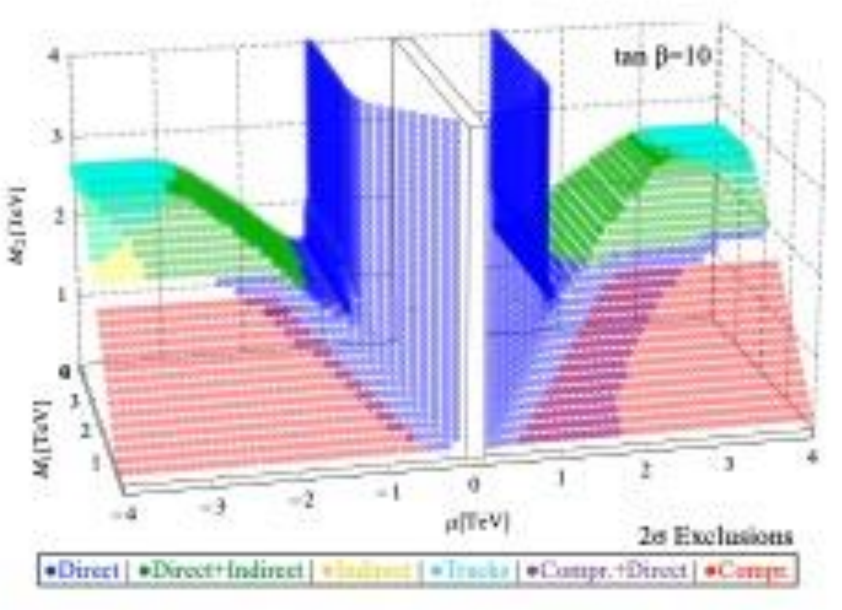
Plus: further indirect probes through rarer/higher mass Higgs processes.





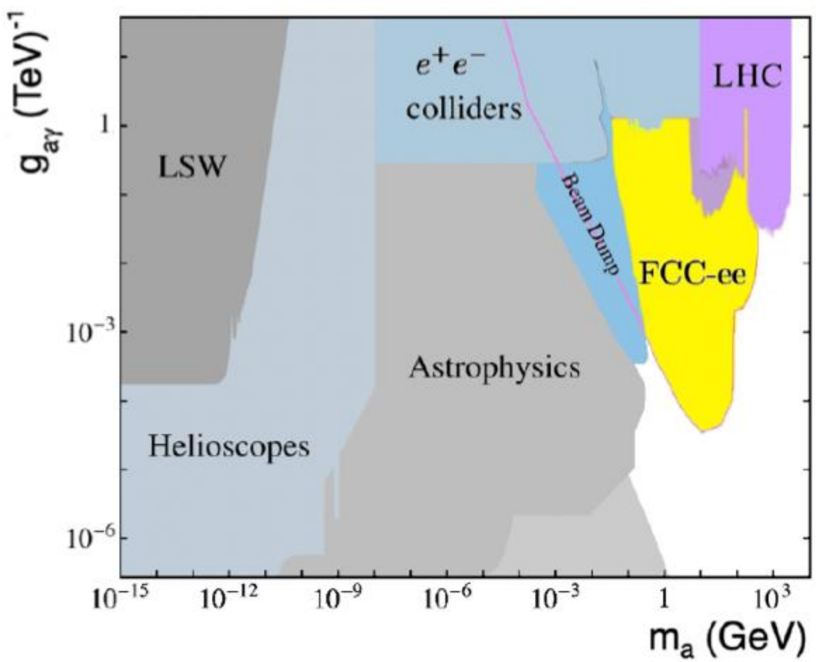
Dark matter complementarity…

… between direct/indirect detection and collider searches…



Full coverage of thermal surface in MSSM (image credit: arXiv:1606.00947)

… between collider, non-collider searches + astrophysical constraints…



ALP sensitivity (FCC-ee focussed)