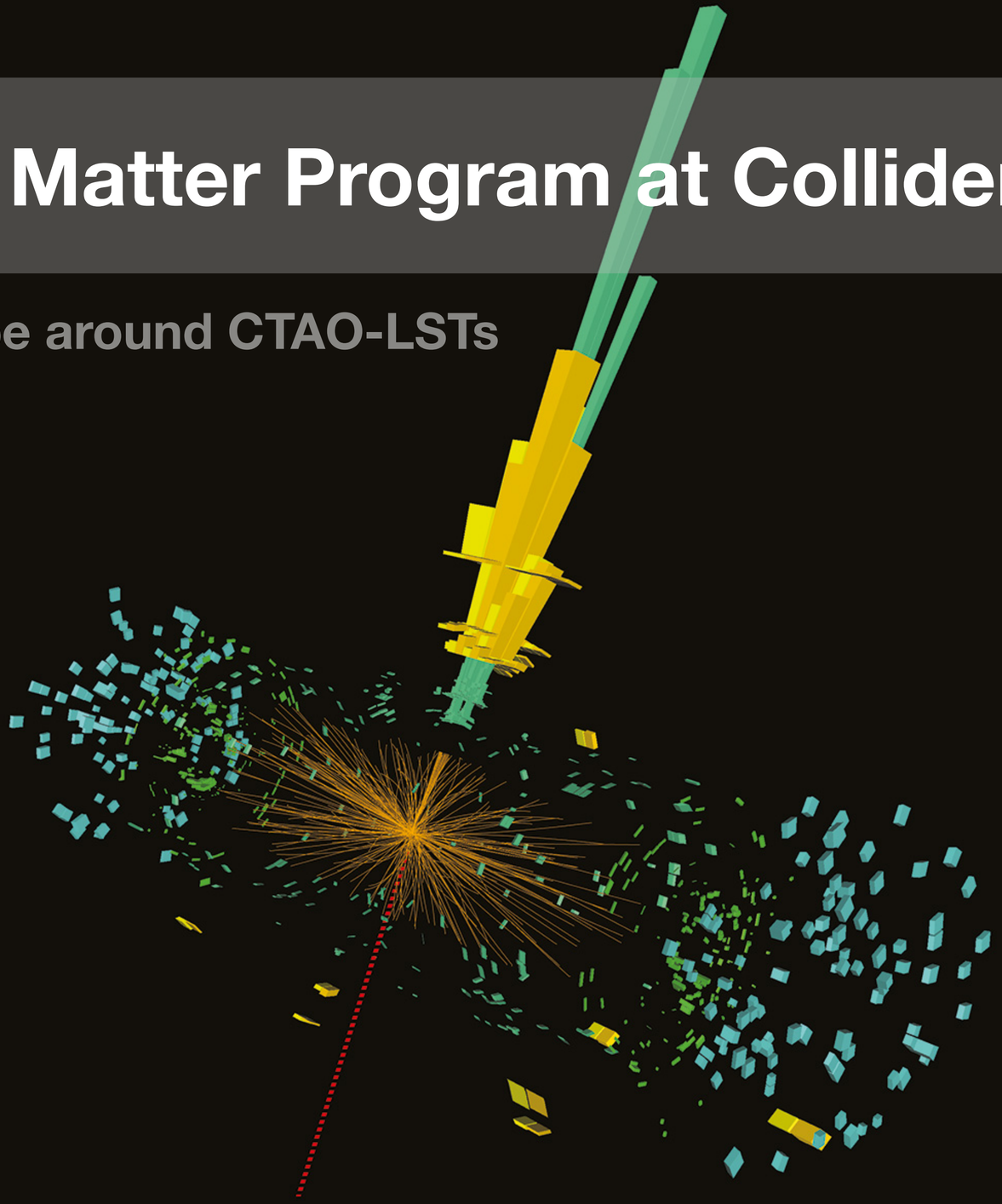
Dark Matter Program at Colliders

Landscape around CTAO-LSTs



From LHC to FCC

… and more



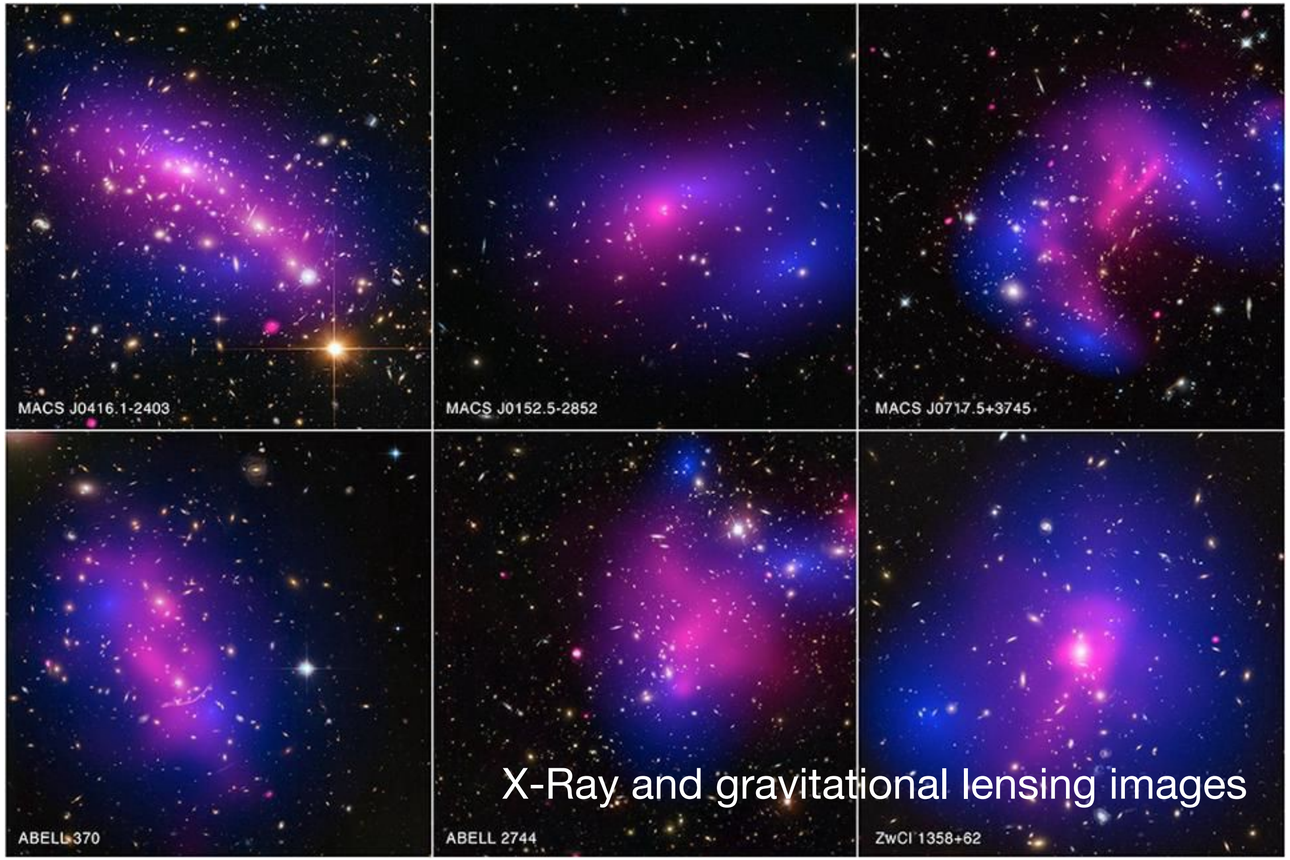
CTA Observatory, La Palma

LST sub-Array Inauguration
16 October 2026

MAX-PLANCK-INSTITUT FÜR PHYSIK

Marumi Kado

The Dark Matter Mystery



X-Ray and gravitational lensing images

Overwhelming evidences and known properties are through gravitation effects.

- Galaxy rotation curves
- CMB
- Large Scale Structure formation
- Galaxy cluster collisions
- …

What is it (or made of), how does it couple to SM and what is its mass?

The Range of Possibilities is Overwhelming!

10^{-23} eV

$100\ M_\odot$

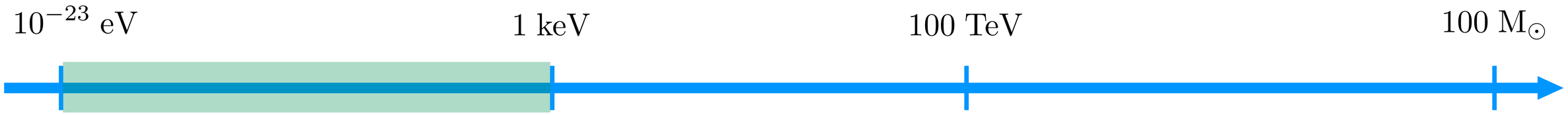
Galactic size wavelength

~90 orders of magnitude !!

Primordial Black Holes

or Exotic DM models

From Ultra- to Very-Low Masses



Galactic size wavelength

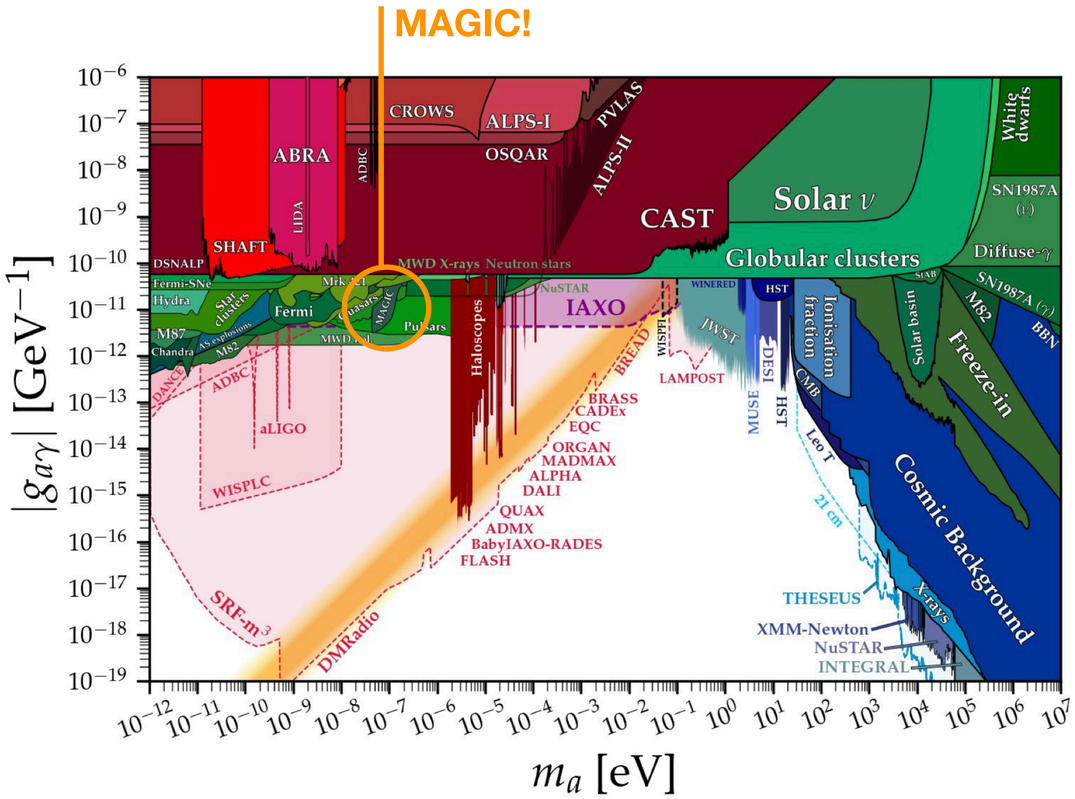
PBHs or Exotic DM models

- 10^{-22} eV de Broglie wavelength not lower than galactic size (in order for these structures to form), and constraints from PTAs, gravitational, and cosmological experiments.

- Below keV, DM should be bosonic **also** Particle physics motivated scenario (one of the three principal naturalness problem) Strong CP problem or the absence of nucleon EDM.

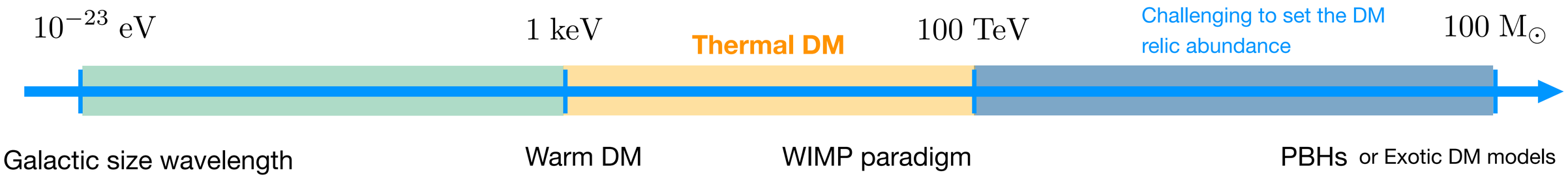
QCD Axion (non thermally produced) are viable DM candidates in the low mass regime.

Suite of Axion searches!

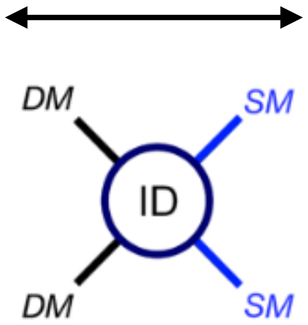


Search for wiggles in spectra of γ-rays (from ALP-photon mixing)

The Thermal Dark Matter Window



Thermal eq. before FO



Relic abundance

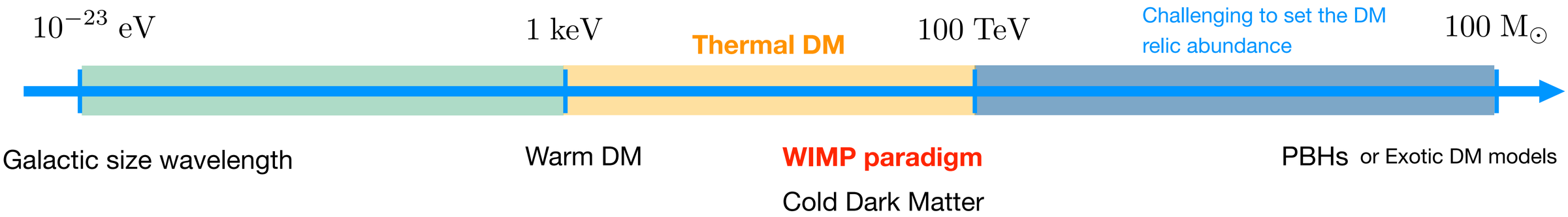
- For high masses >100 TeV challenging to set the DM relic abundance in tension with perturbative unitarity

$$\langle \sigma v \rangle \propto \frac{g_\chi^4}{m_\chi^2}$$

- Candidates in this mass range primordial Black Holes (PBHs) or exotic particle DM models

- Thermal Dark Matter is also bounded from below at ~keV “free streaming limit” where DM moves too fast to form small observed structures.

WIMP Cosmological Coincidence and Miracle



- **Coincidence of cosmological** scale and a DM mass at EWK scale 100 GeV and

$$\rho_{DM} = \rho_{obs}$$

$$n_{DM}\langle\sigma v\rangle \simeq H(T_{\rm fo})$$

$$\langle\sigma v\rangle \simeq 3\times 10^{-26}\ {\rm cm}^3/{\rm s} \qquad \Omega_{DM} \sim 0.1 \sim \frac{1}{{\rm M_{Pl}}\times <\sigma v>_{\rm Weak}}$$

- **The miracle** : SUSY postulated to address profound TH questions but provided the existence of a stable WIMP - the **Neutralino**!

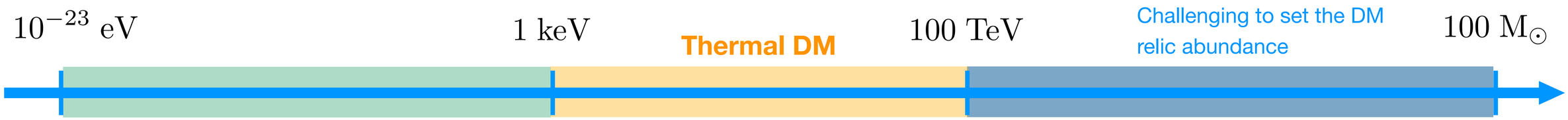
SUSY remains highly motivated

…strongly experimentally constrained, in particular by LHC

- Gauge hierarchy - naturalness problem
- Unification of couplings
- Local SUSY gravitino

DM candidate!

Direct Detection



Galactic size wavelength

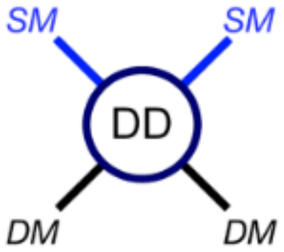
Warm DM

WIMP paradigm

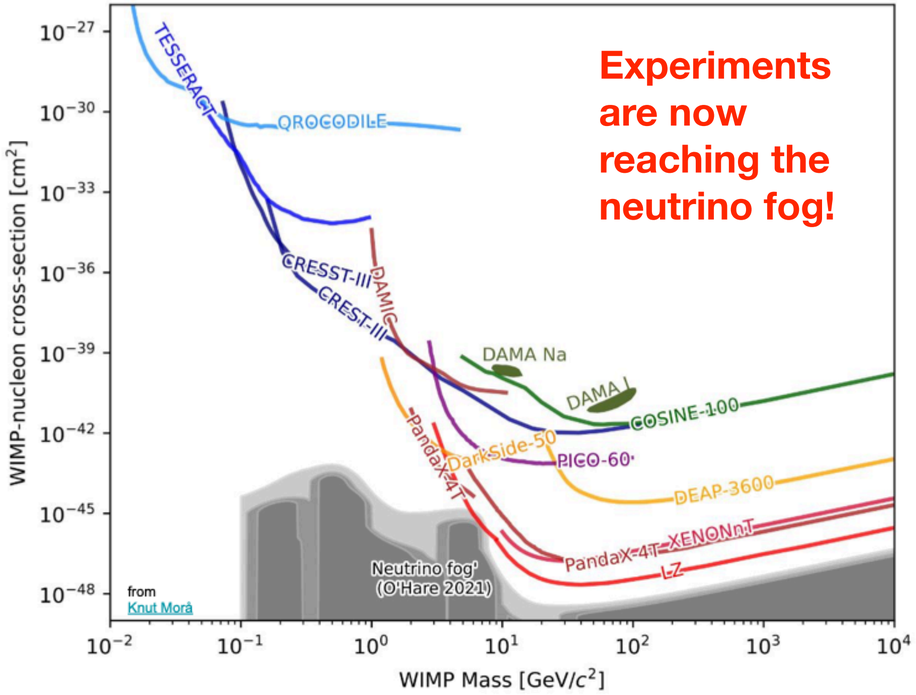
Cold Dark Matter

PBHs or Exotic DM models

Direct detection of DM from the local halo



Key aspect is that elastic cross section SI is coherent - scales with A^2



Nobel liquid have best overall sensitivity (in particular for SI processes - e.g. **Higgsino**)

PANDA-X



Xenon

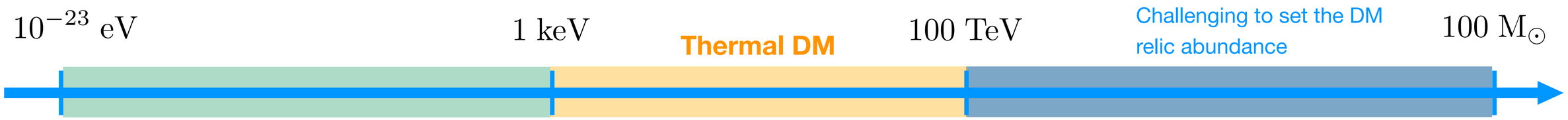


LZ



Pure electroweakino (**Bino** and **Wino**) would not give coherent scattering so **evade limits**.

Indirect Detection



Galactic size wavelength

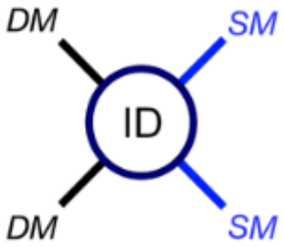
Warm DM

WIMP paradigm

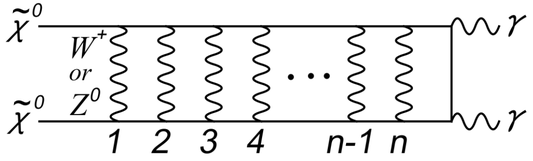
Cold Dark Matter

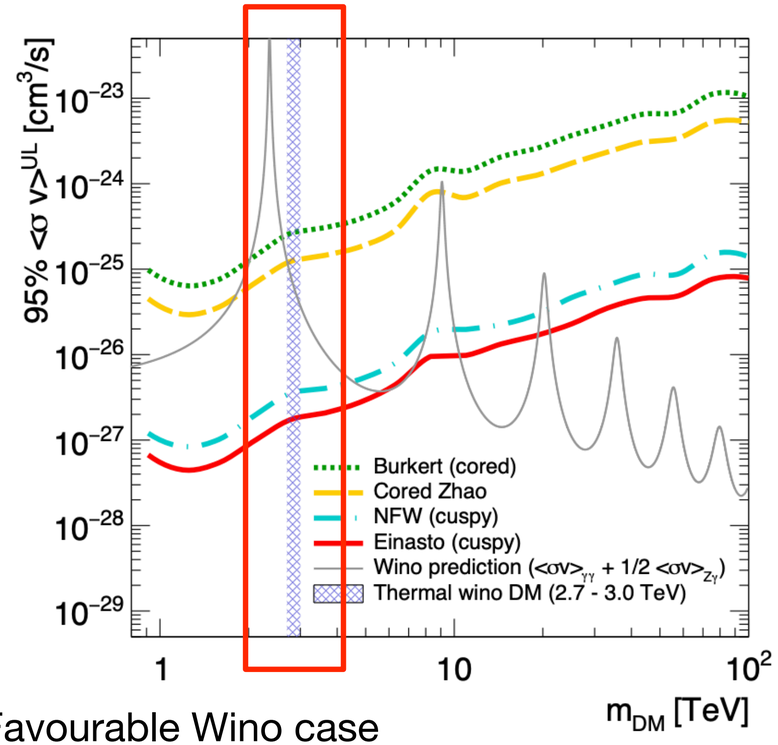
PBHs or Exotic DM models

Indirect detection of DM annihilation



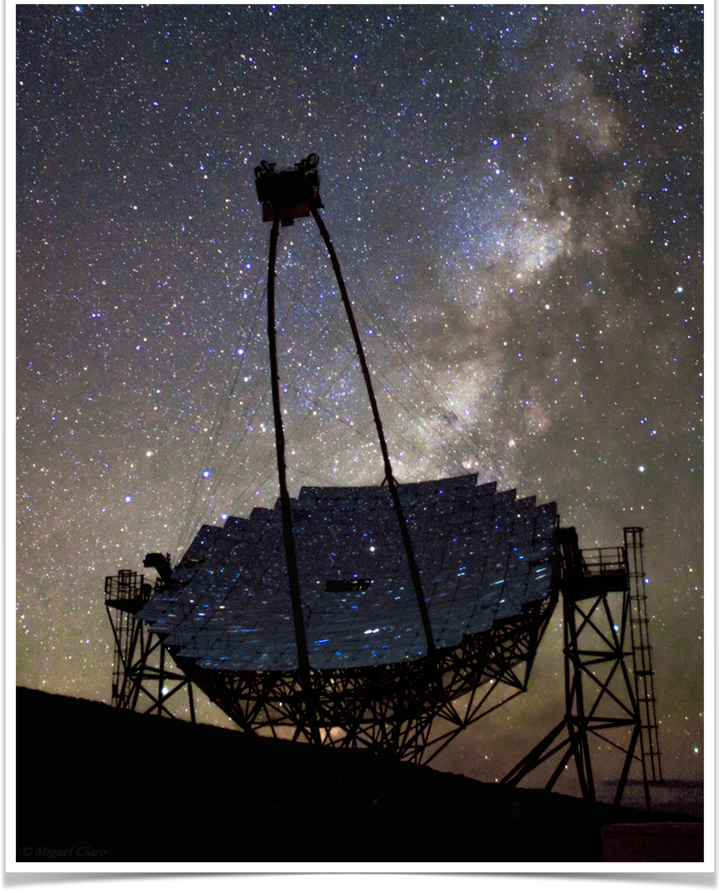
In some cases strong $\langle \sigma v \rangle$ enhancement - a NR advantage!



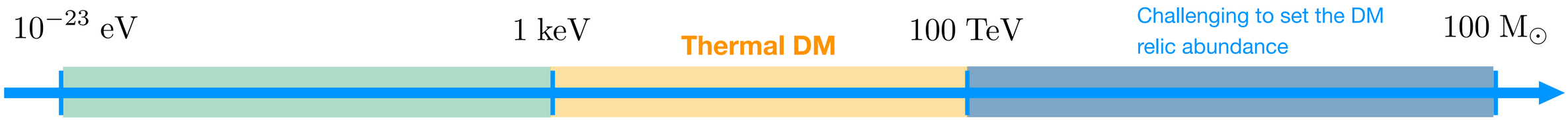


Favourable Wino case

Thermal relic fixes the mass of the pure state!



Dark Matter at Colliders



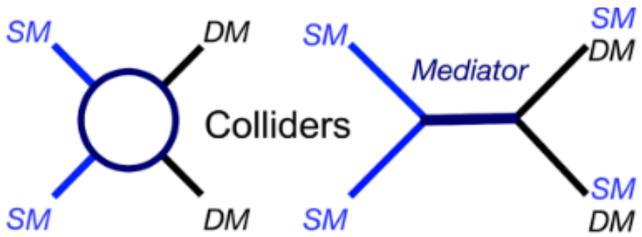
Galactic size wavelength

Warm DM

WIMP paradigm

Cold Dark Matter

PBHs or Exotic DM models



At colliders DM produced from SM providing opportunities to understand its detailed nature.

Requires casting a wide net to make sure that all possible final state scenarios are covered. TH guidelines are very important.

Three main approaches for DM searches:
(1) SUSY - (2) Generic DM - (3) Dark Sector

Typical event topologies have missing transverse momentum but not only!

Defining Moment for High Energy Collider Physics

Snowmass community study (2021) - link!

Exploring the Quantum Universe

The 2023 P5 report Link

A strong consensus on "pathway" for HEP

Immediate priority is HL-LHC!

Higgs factory (EW and HF**) precision**

Several options circular (FCC-ee and LEP3) or linear (LCF, CLIC)

(At least) **10 TeV pCOM collider**

Several options (pp, $\mu\mu$, ee or $\gamma\gamma$)

Which specific path to get there?

European Strategy for Particle Physics

CERN-ESU-2025-002
December 2025

Link

September 2024 community called to make a strategic decision

The next CERN flagship collider project is the FCCee

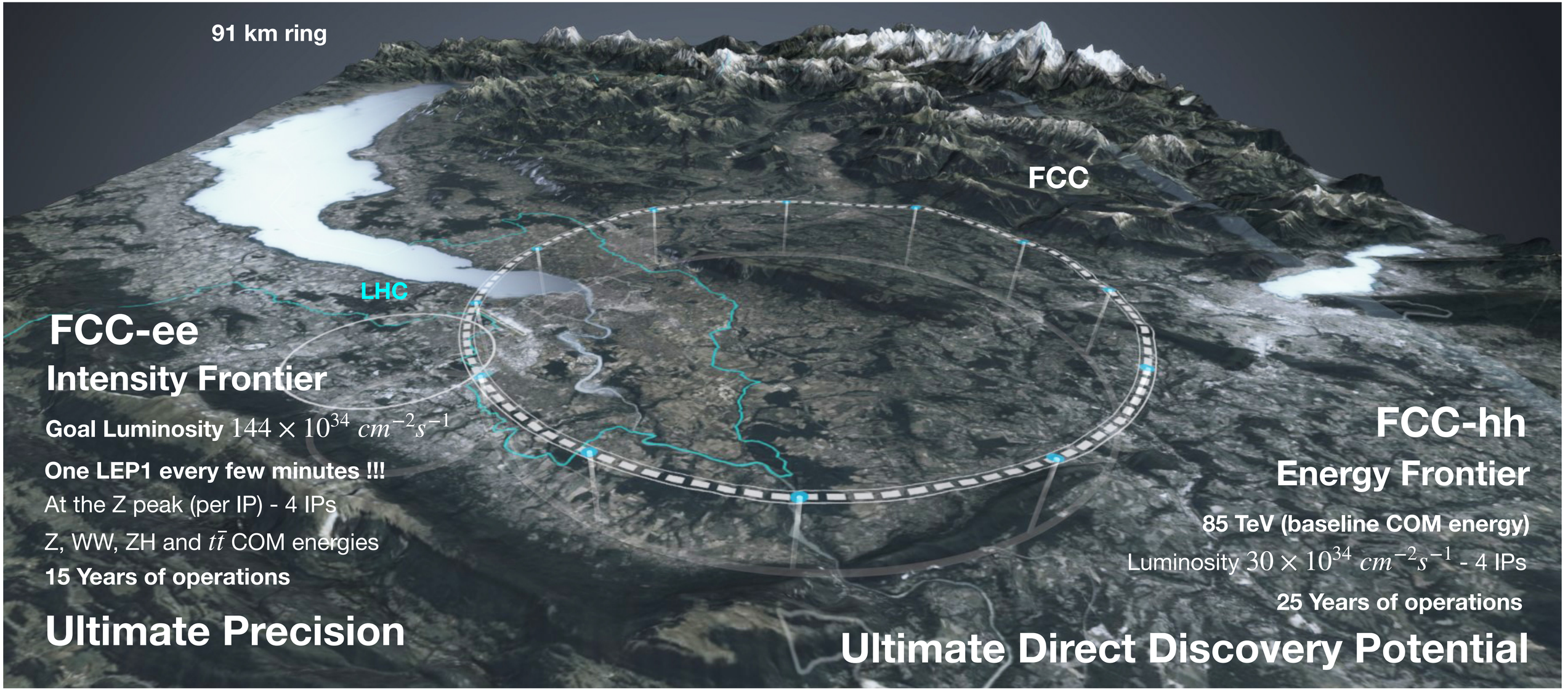
The chosen path: FCC-ee → FCC-hh

Immediate priority remains HL-LHC!

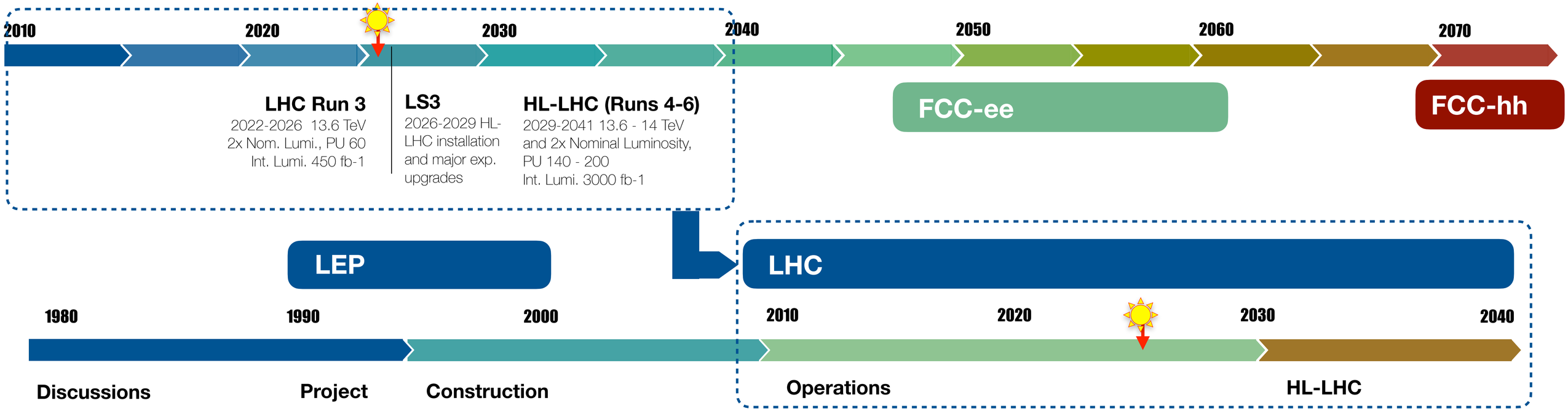
Decision by CERN Council expected in 2028

The Searches for Dark Matter, despite not being mentioned explicitly, are a pilar of the collider physics program!

A Scientific Mission for the 21st Century



A Scientific Mission for the 21st Century





The LHC is currently shut down. Teams will now dismantle 1.2 kilometres of the accelerator to install the new HiLumi LHC equipment. This will be connected to the

CERN [press release](#)

CERN bids farewell to the LHC and enters Long Shutdown 3

LHC completed at 13.6 TeV and entering the (inverse) attobarn era.

The Run 3 has ~330 fb^{-1} at 13.6 TeV **entering the attobarn era** with **0.5** ab^{-1} (per experiment)

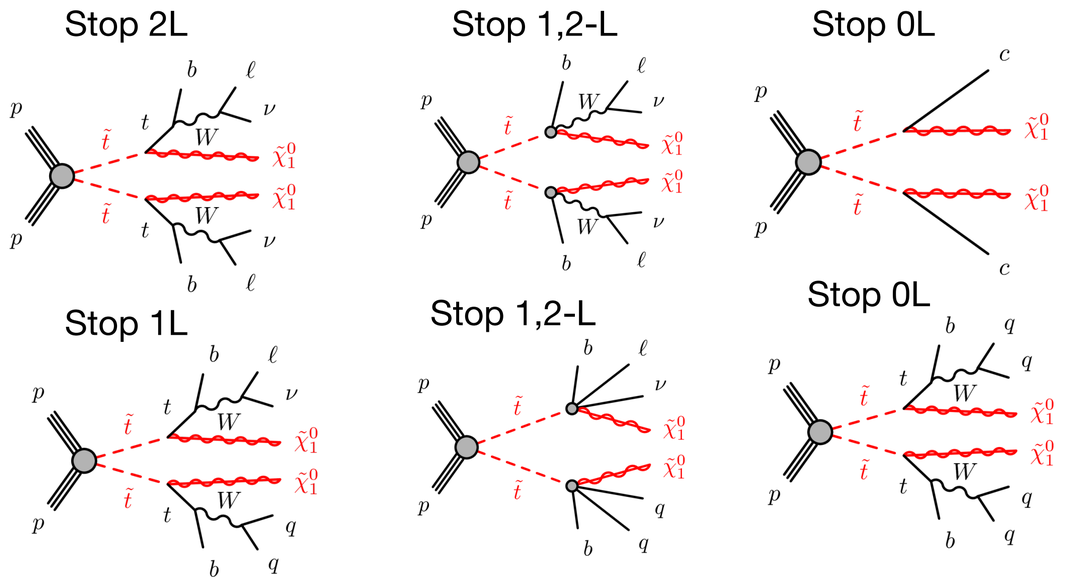
Experiments and the machine now in full swing in LS3 to ensure to restart in 2030.

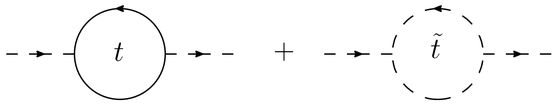
Natural Dark Matter at the LHC

Strong SUSY produced dark matter (throught squarks and gluinos)

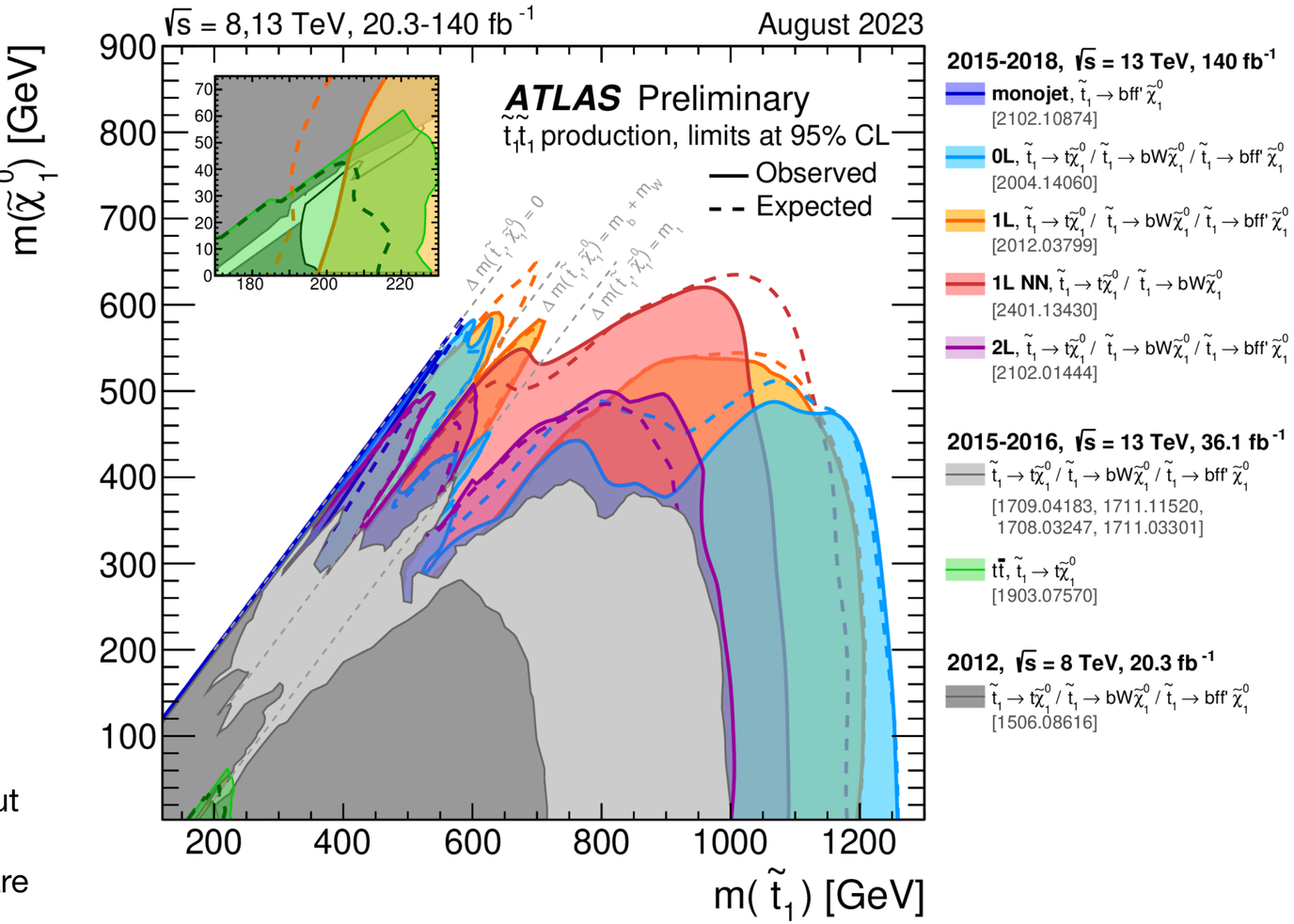
A fairly light top partner key to preserve naturalness

Stop searches (main channels)



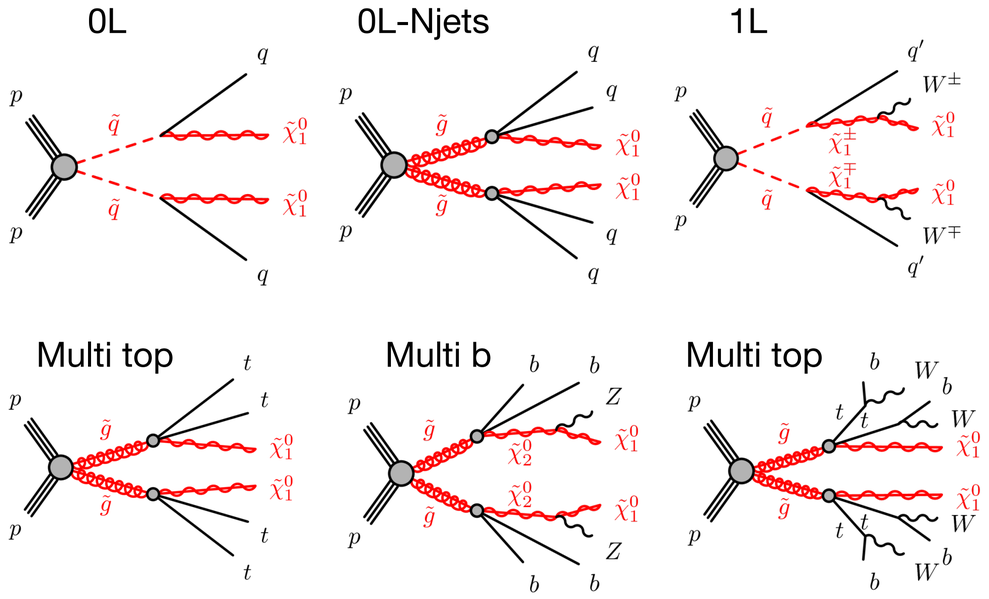


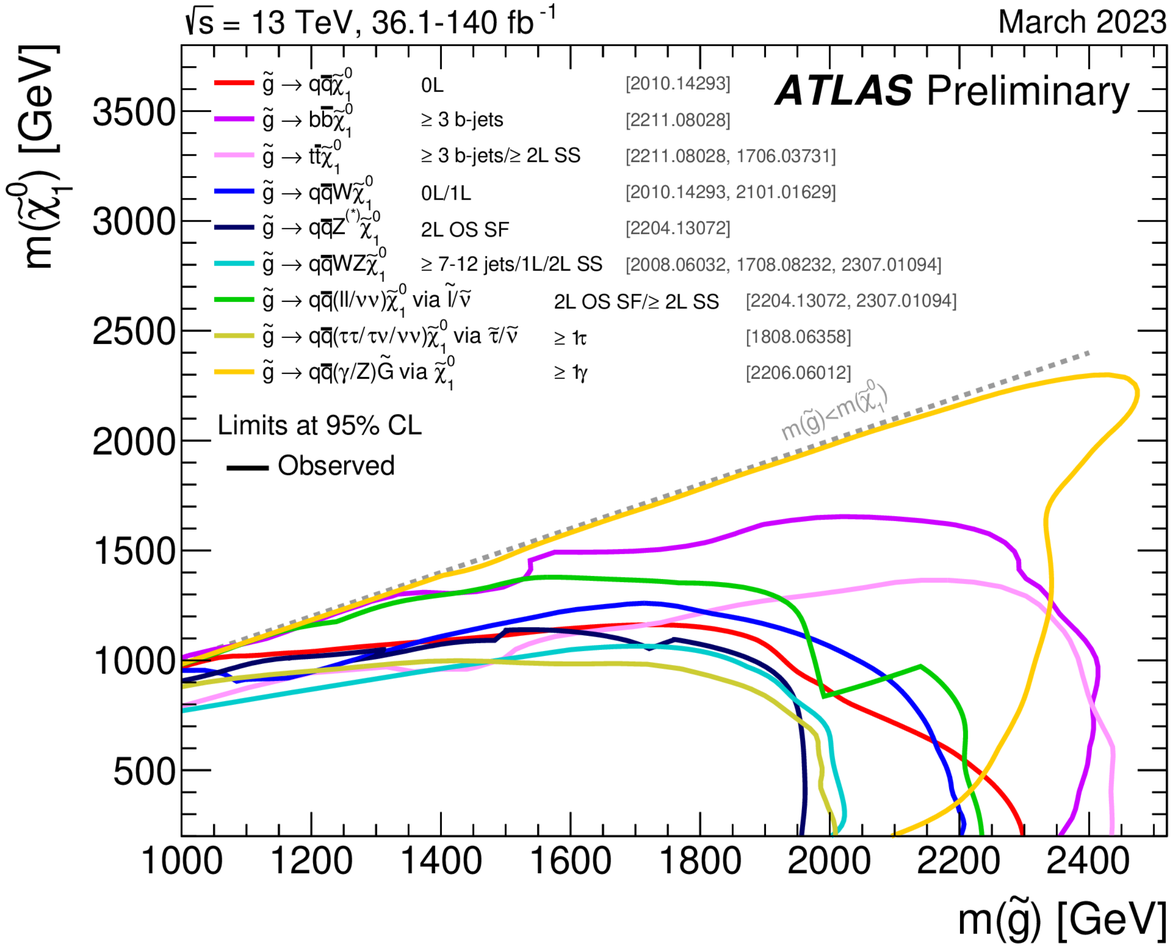
Not so natural SUSY: Stops > 1.2 TeV ~Tuning of factor **20**, but these exclusions are under specific conditions, and there are unexcluded corridors.



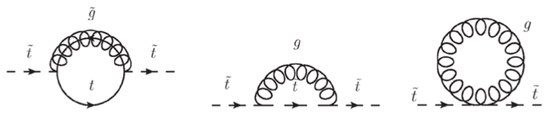
Natural Dark Matter at the LHC

Lighter squarks and gluinos searches (main channels)



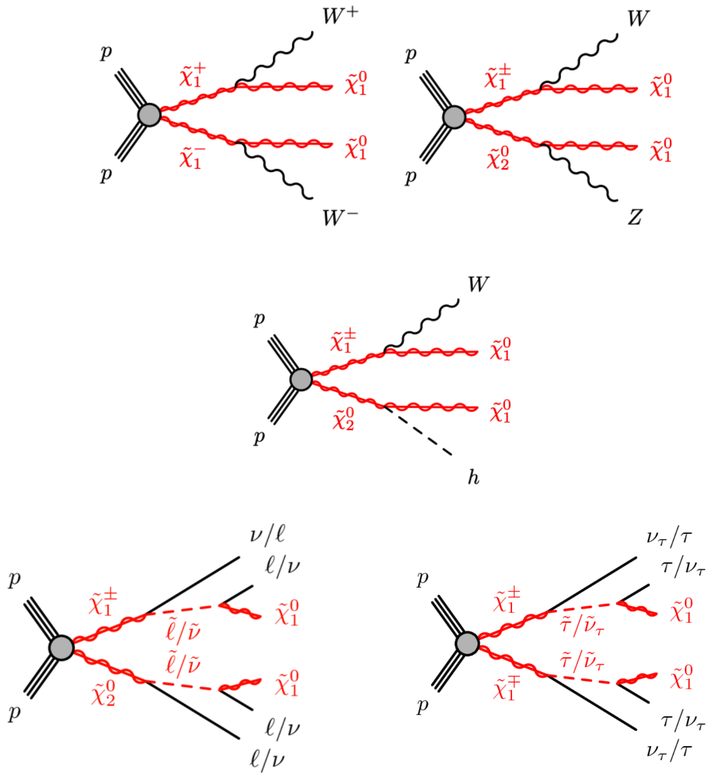


Stop also a scalar requires light gluinos to be light enough: for gluinos > 2.4 TeV ~tuning of Factor of **30**

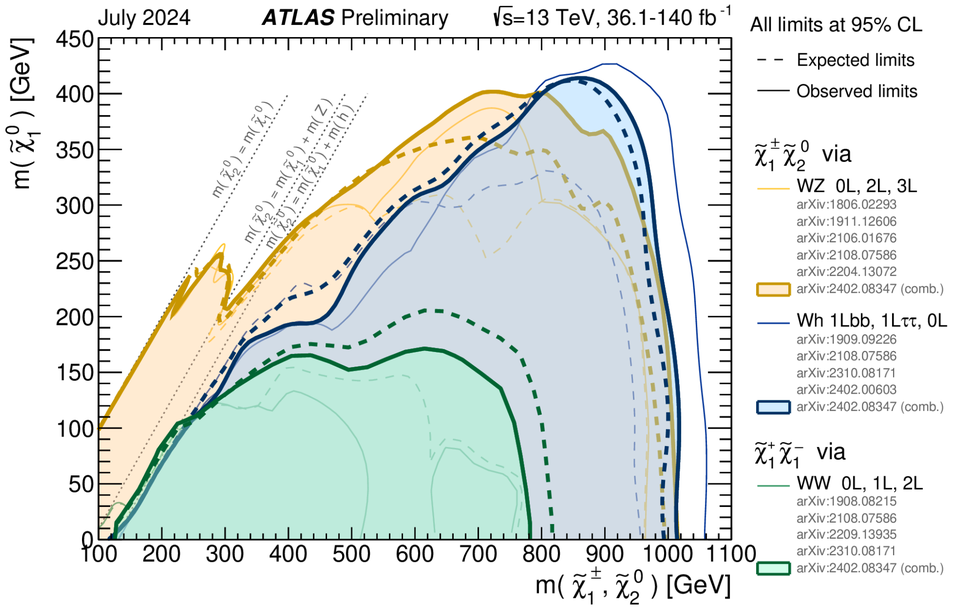


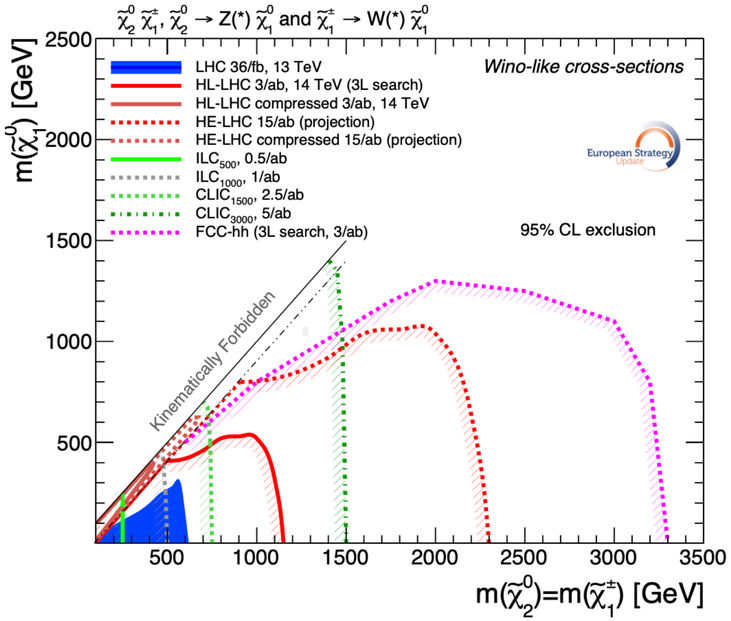
Electroweak-Produced Natural SUSY

Weak production of charginos, neutralinos and sleptons



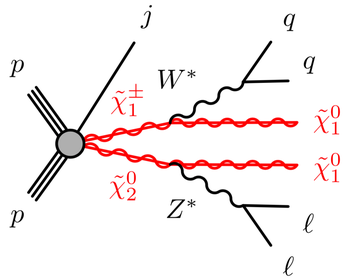
1 to 4 leptons (including taus) in the final state. Including decays to electroweak bosons.



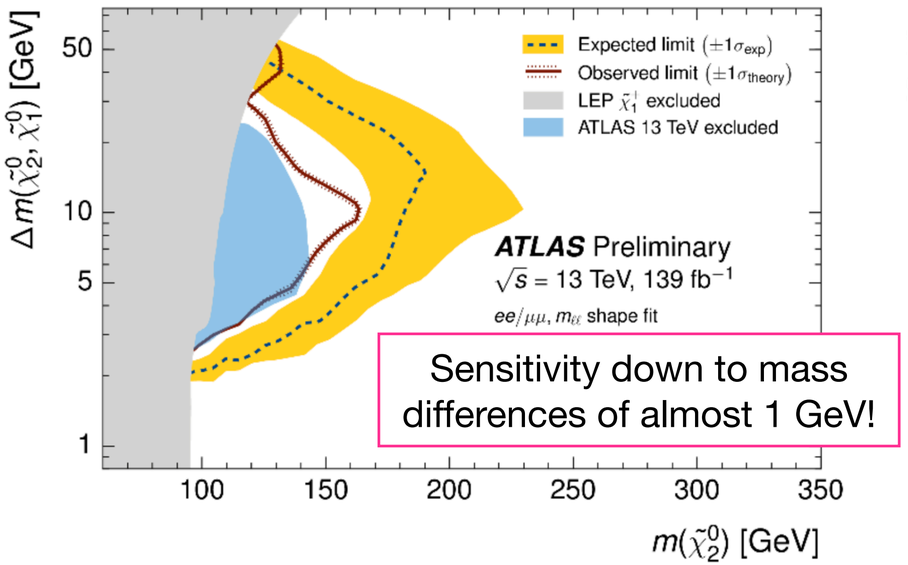


More Challenging (typical) Wino-like Cases

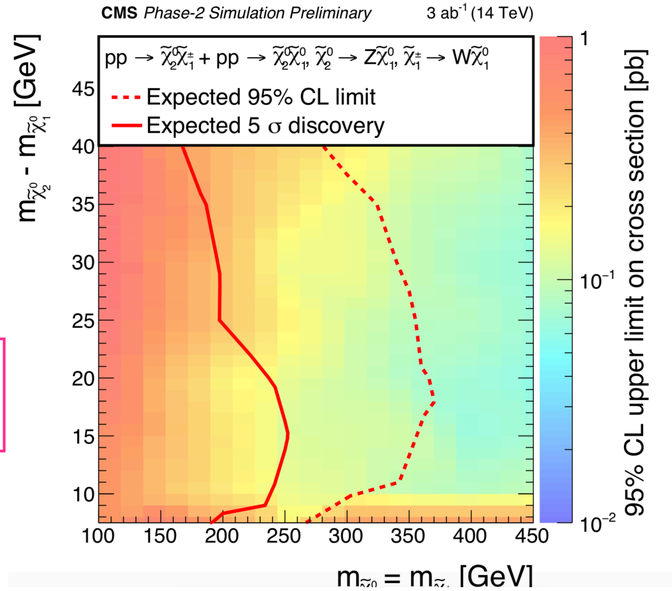
Weak production of charginos and neutralinos in compressed scenarios



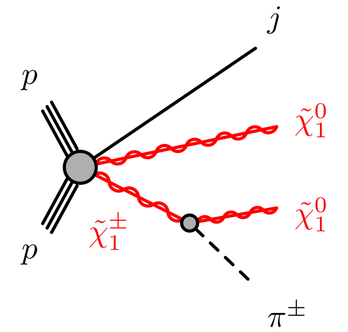
Example of boosting to find small mass differences.



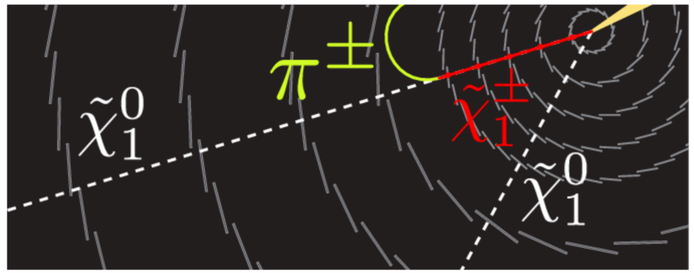
Sensitivity down to mass differences of almost 1 GeV!



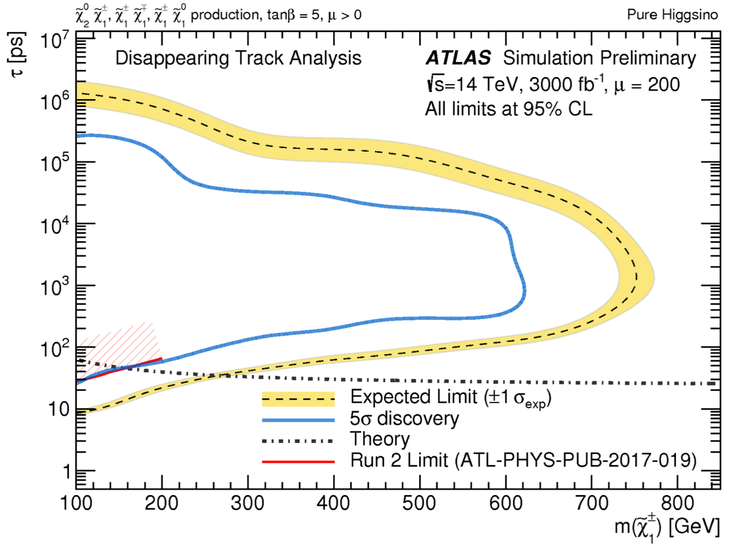
SUSY in highly compressed scenarios



Disappearing tracks topologies
(Uses MET Trigger - requires ISR jet)



Scenario where the charginos and neutralinos are almost degenerate (chargino has significant lifetime and is seen in the first layers of the ID).



Pushing the limits

Exploring further new physics possibilities at the LHC, at lower energies and smaller couplings through **unconventional signatures** at the LHC

(HL-) LHC

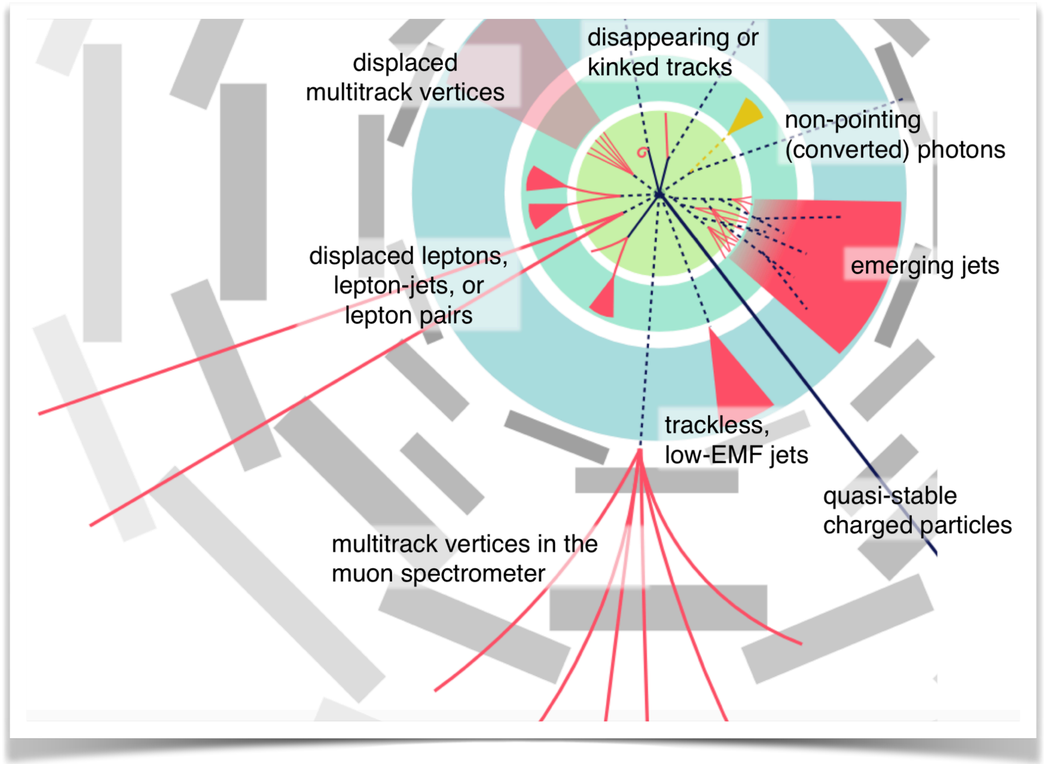
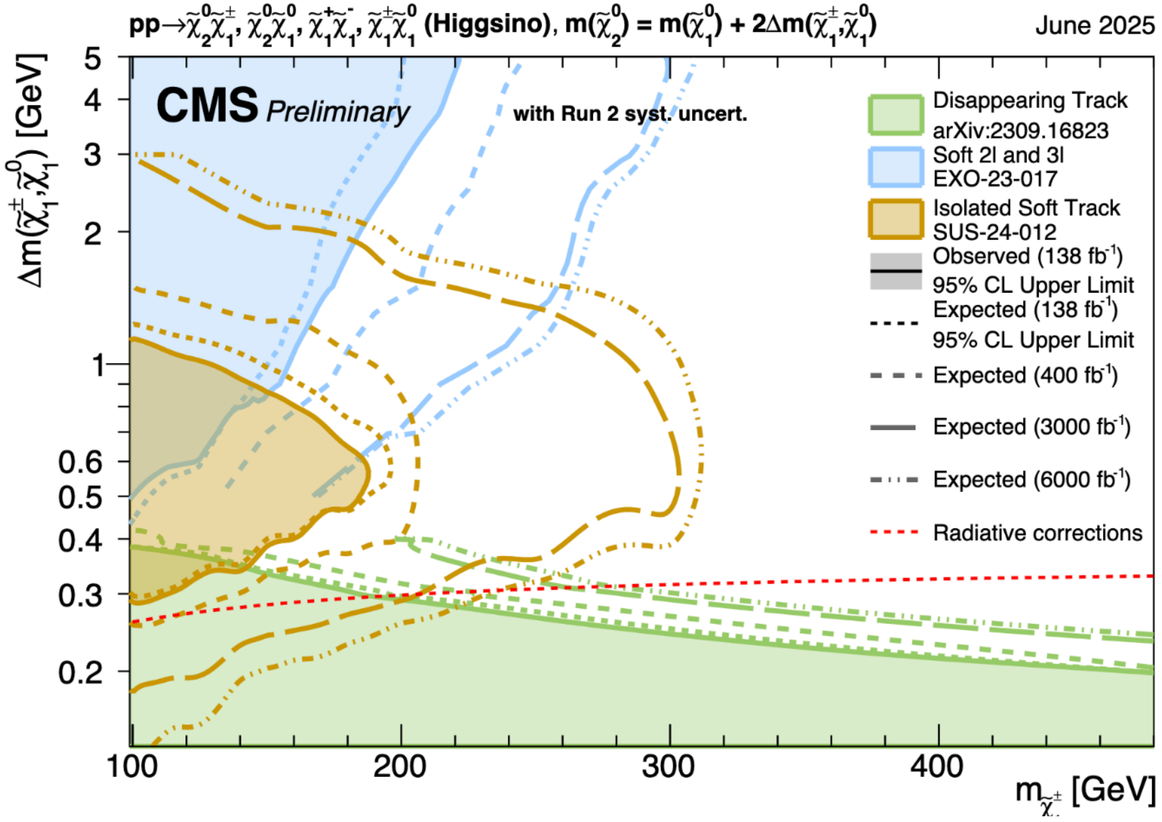


Image from H. Russell

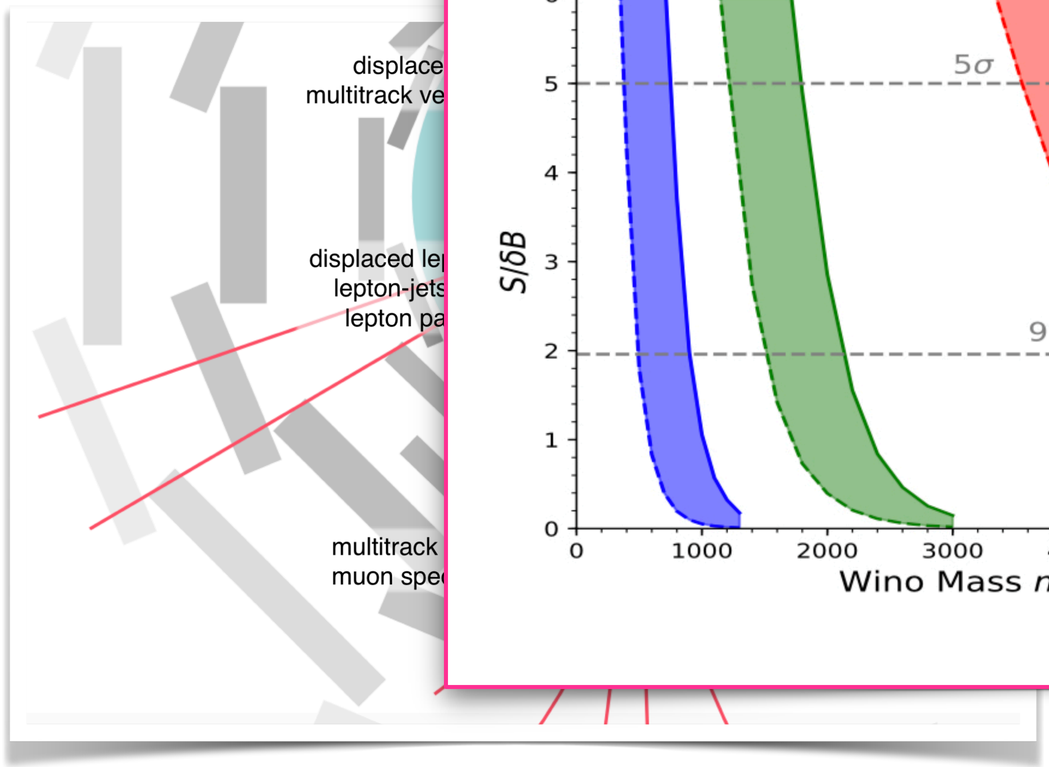


Unconventional signature also helped in setting lower on neutralinos covering the **nightmare compressed** SUSY scenarios!

Pushing the limits

Exploring further new physics possibilities at the LHC, at lower energies and smaller couplings through **unconventional signatures** at the LHC

(HL-) LHC



The FCC-hh will be able to bring **conclusive answers to thermal DM search!**

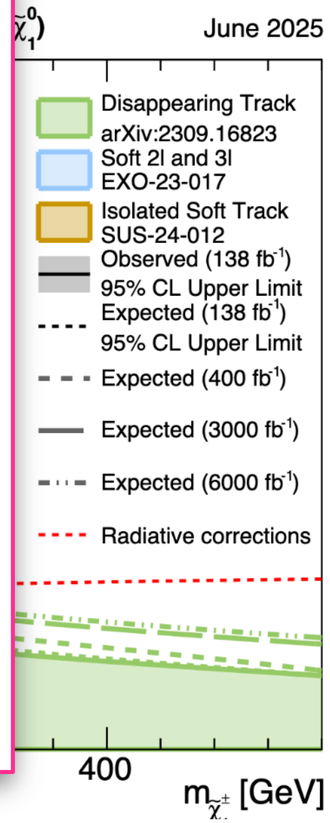


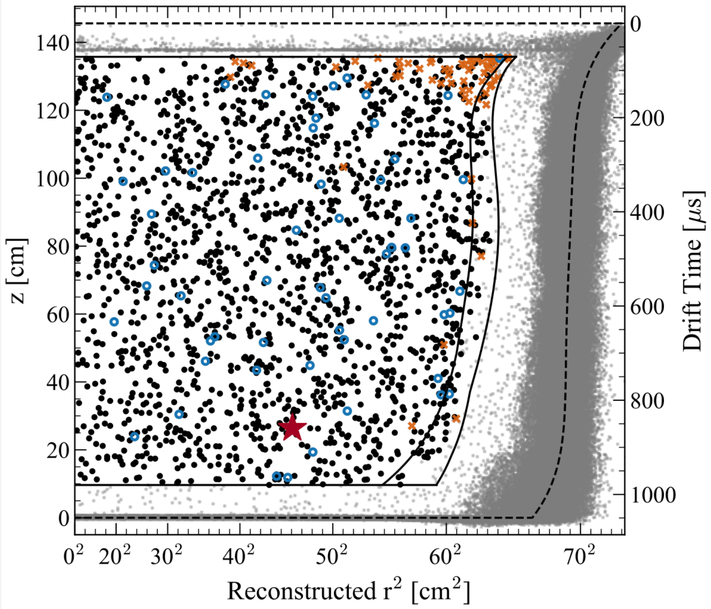
Image from H. Russell

Unconventional signature also helped in setting lower on neutralinos covering the **nightmare compressed** SUSY scenarios!

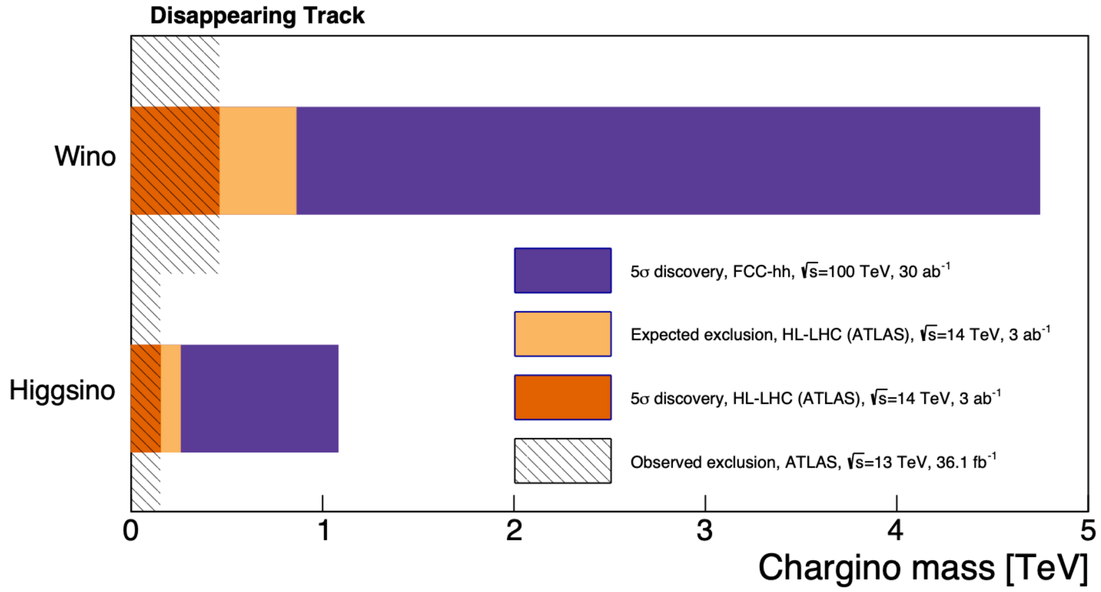
Hints of Inelastic DM in LZ?

LZ puzzling event: Imagine a 1 TeV Higgsino DM (link)





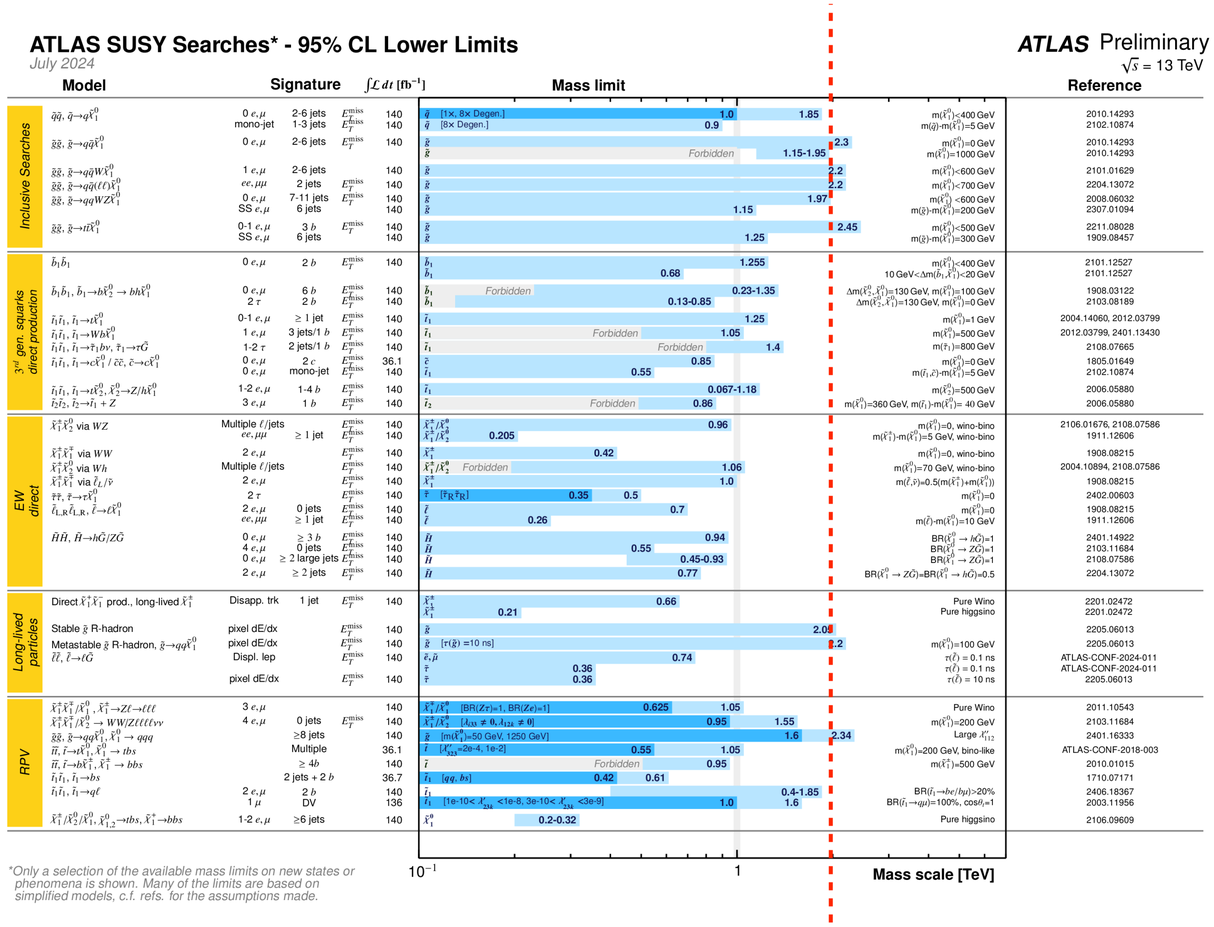
Higgsino above the fog? (Fan and Reece link)

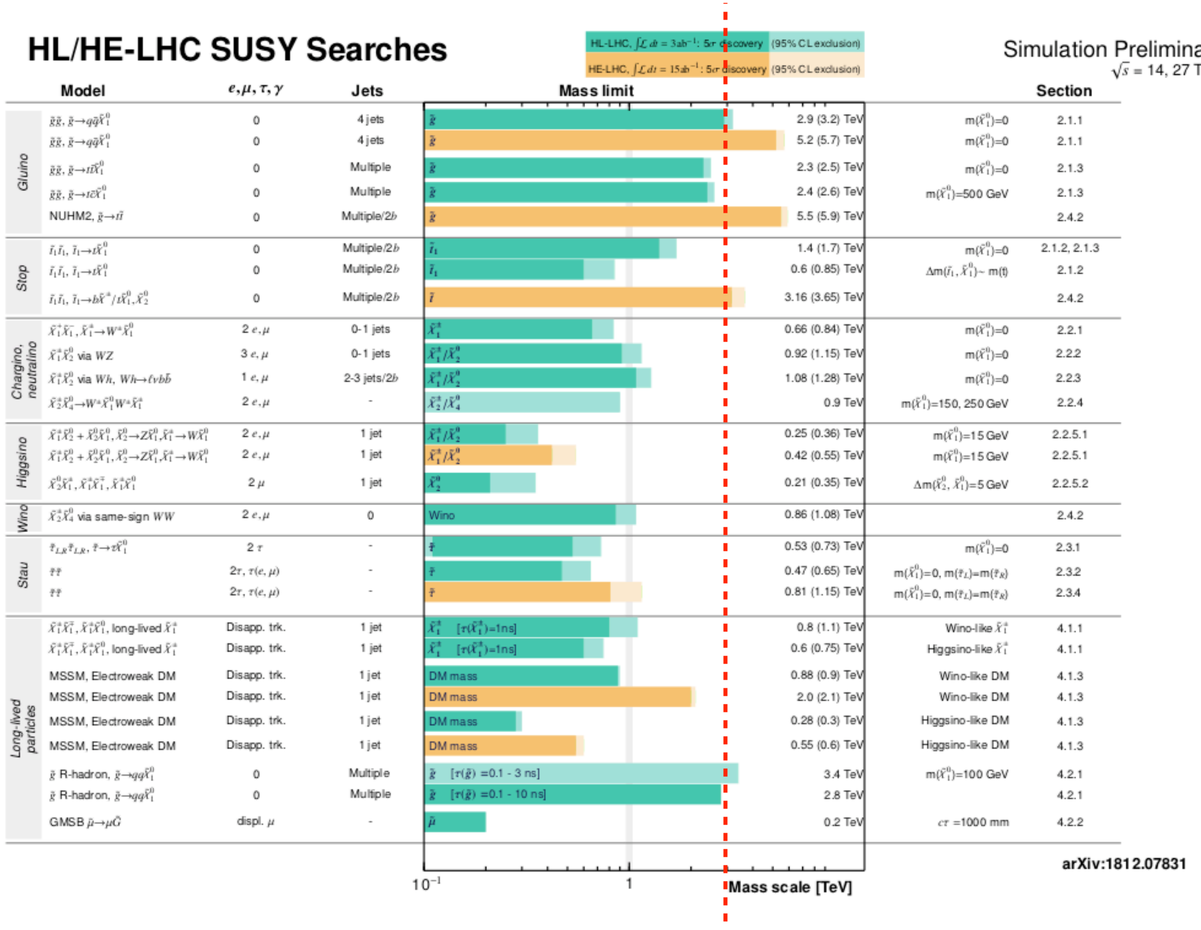


Wino and Higgsino DM discovery reach (M. Saito, R. Sawada, K. Terashi, S. Asai link)

Higgsino disfavoured by IceCube! (link) Other inelastic scenarios possible.

Very Large Number of SUSY Searches





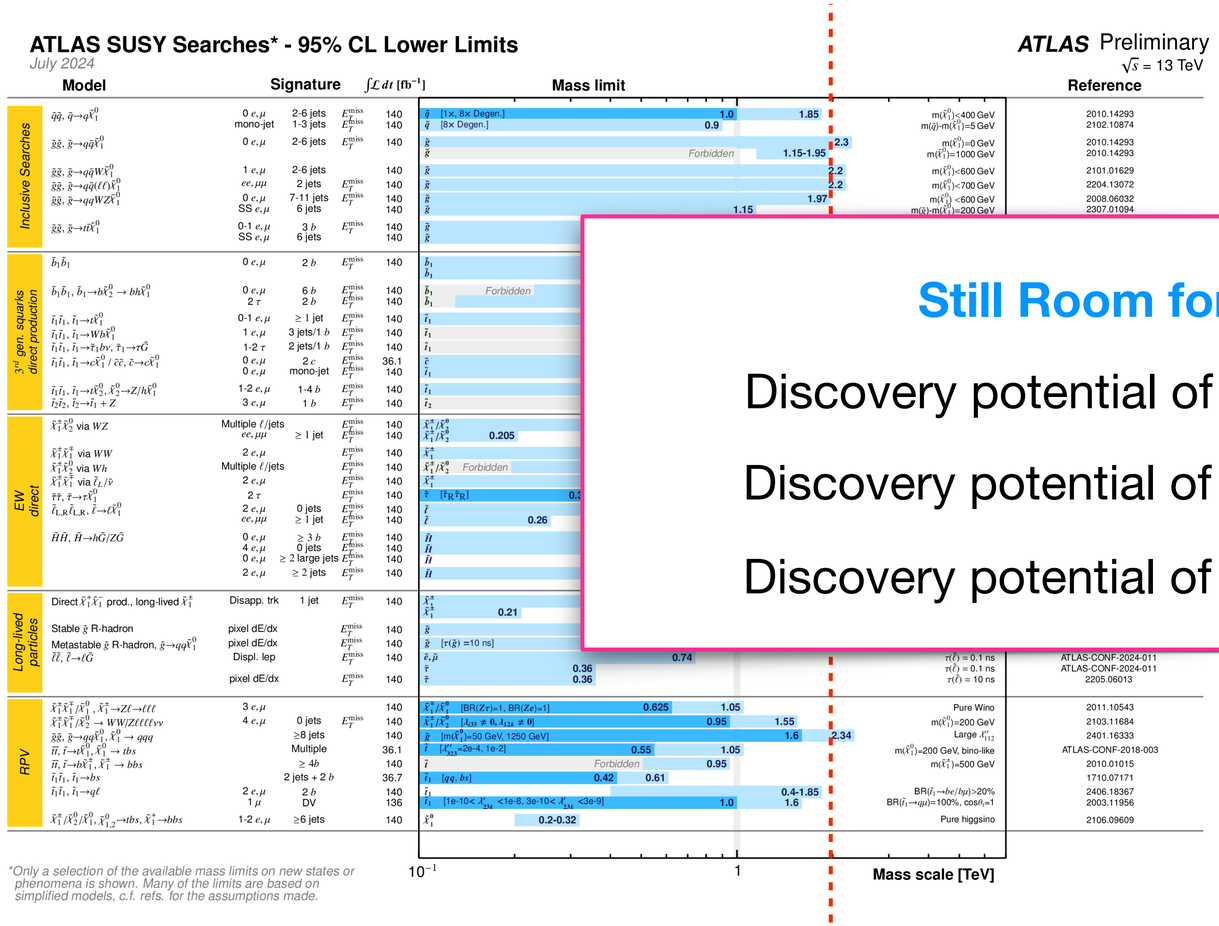
2 TeV

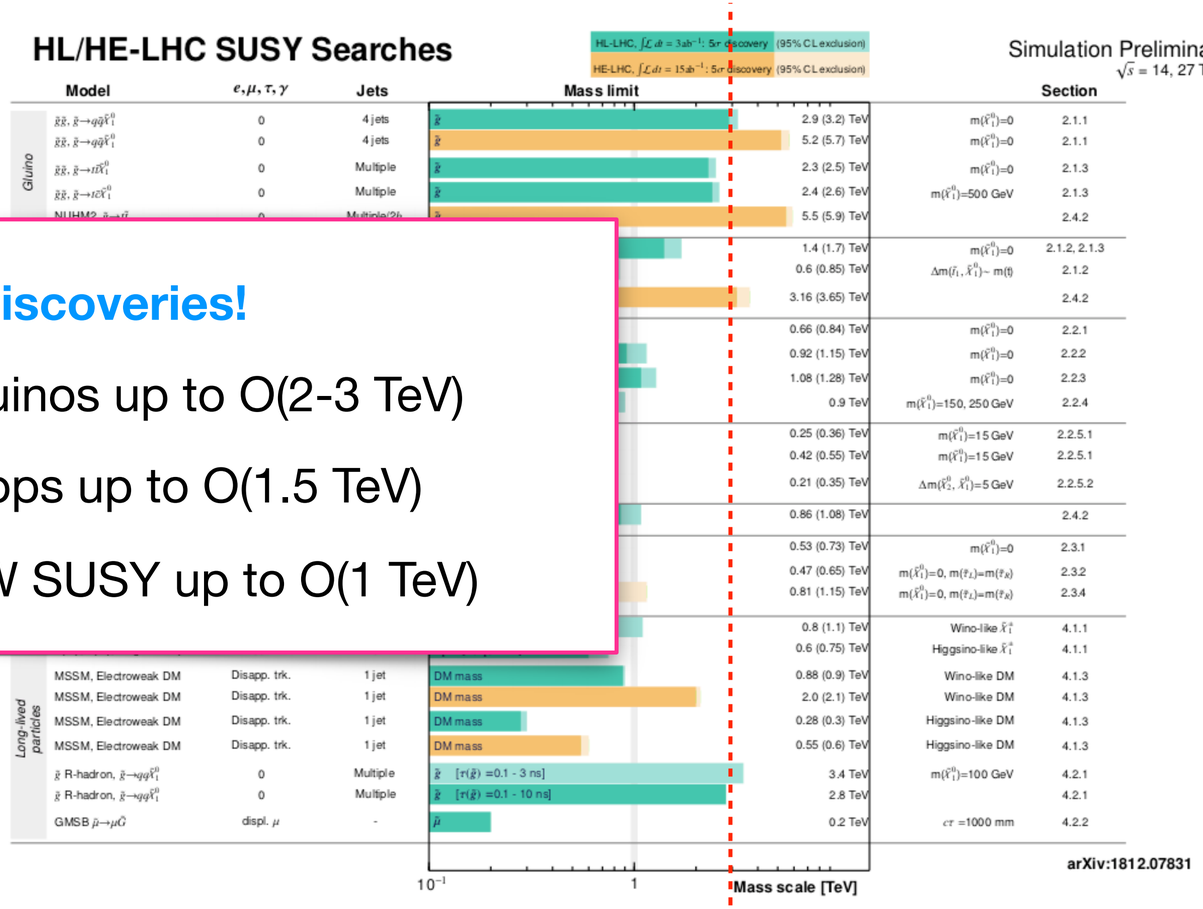
3 TeV

Example from ATLAS (similar for CMS)

HL-LHC YR
1812.07831

Very Large Number of SUSY Searches





Still Room for Discoveries!

Discovery potential of gluinos up to O(2-3 TeV)

Discovery potential of stops up to O(1.5 TeV)

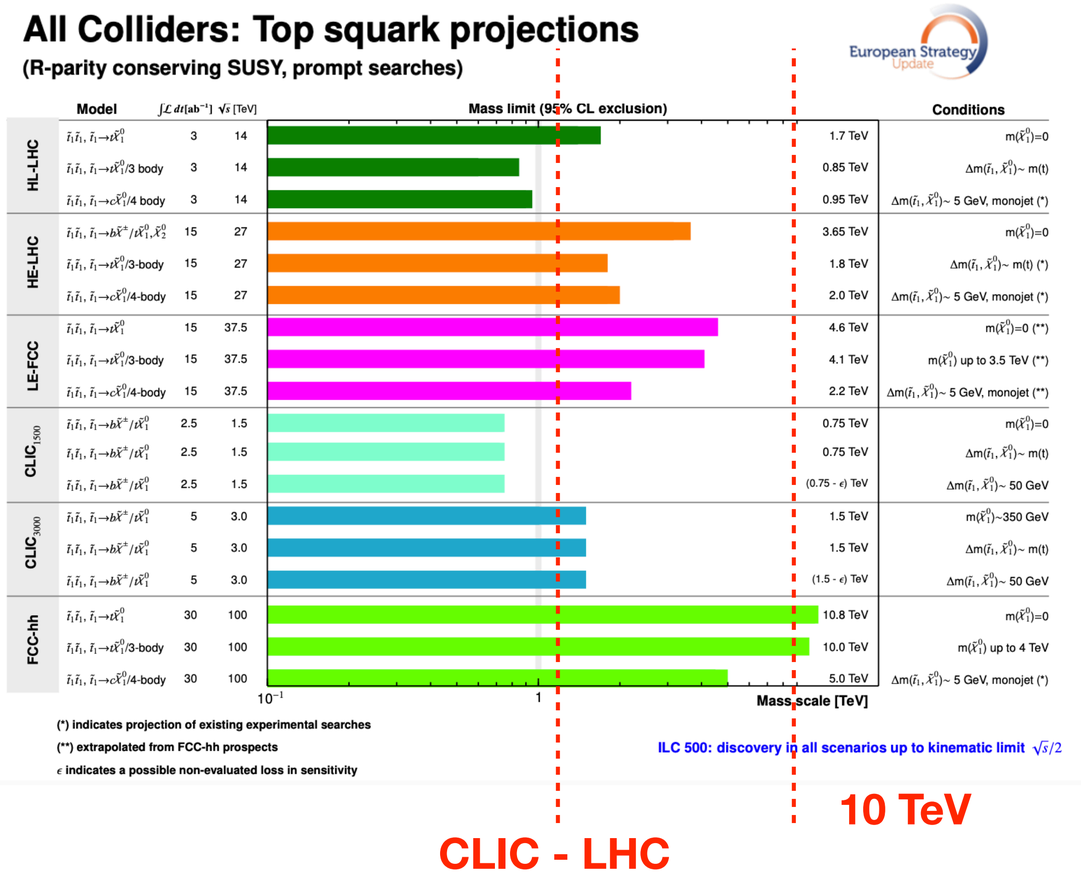
Discovery potential of EW SUSY up to O(1 TeV)

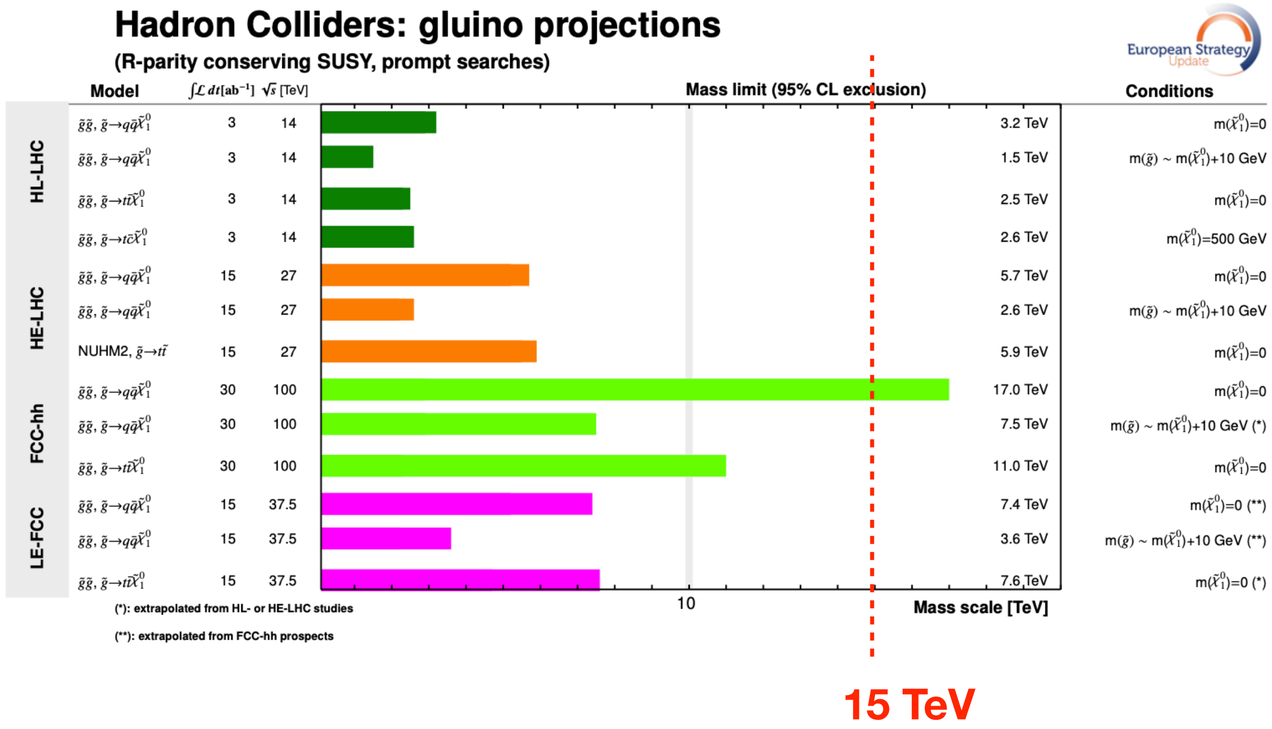
2 TeV **3 TeV**

Example from ATLAS (similar for CMS)

HL-LHC YR
1812.07831

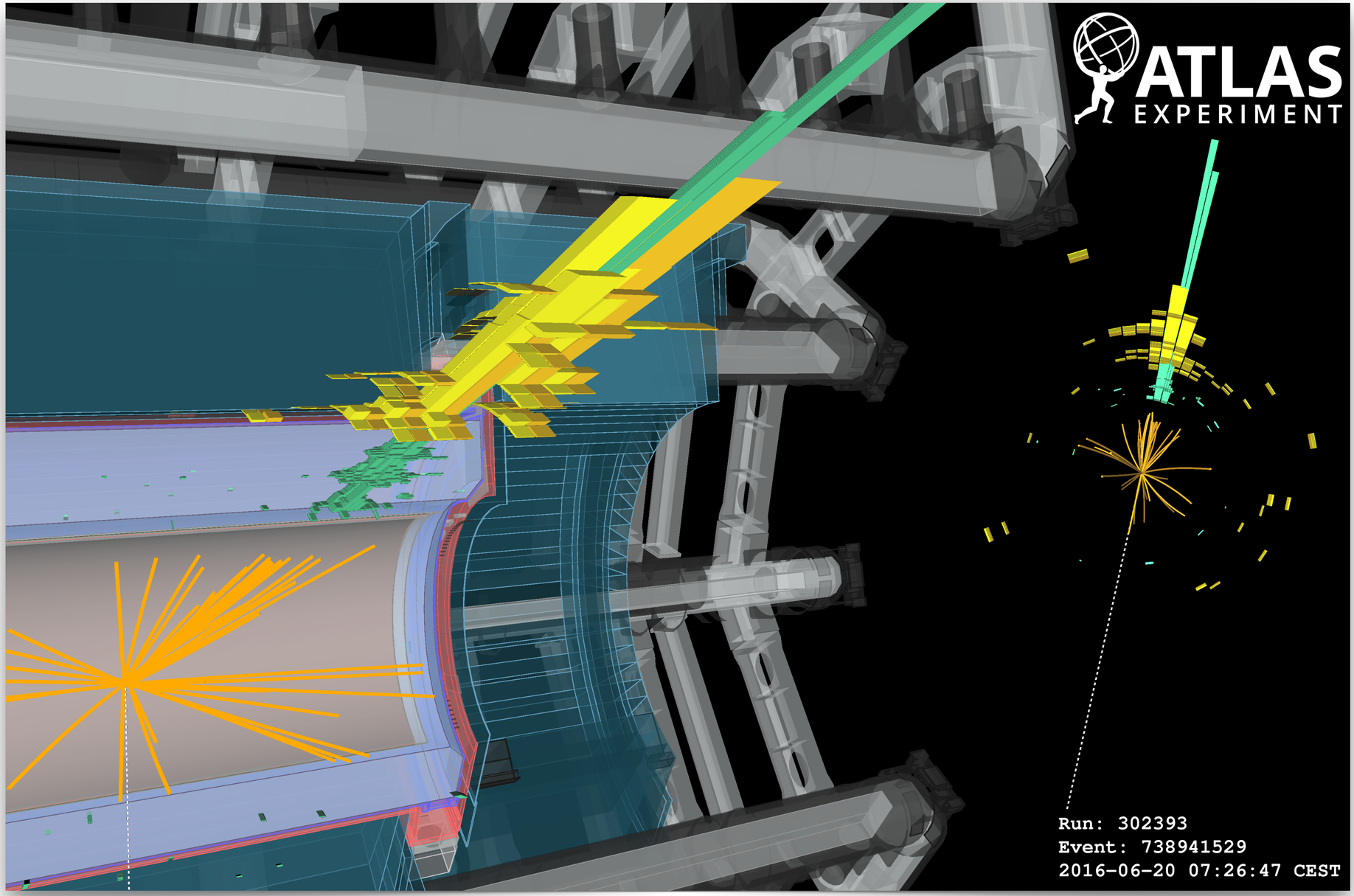
Projections at Future Hadron Collider



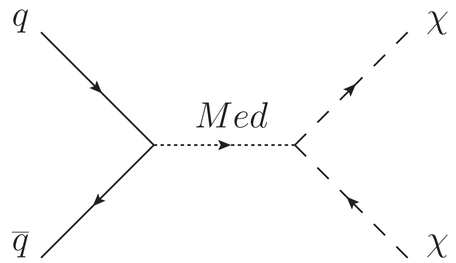


To go above the 10 TeV scale SUSY will require a future hadron collider (100 TeV) or a 10 TeV Parton COM energy machine.

Generic Searches for Dark Matter



Jet with pT of 1707 GeV. The ETmiss of 1735 GeV is shown as the white dashed line. No additional jets with pT above 30 GeV is found.



Simplified model approach: **Dark matter part. is a Dirac fermion** and s-channel production of DM particles.

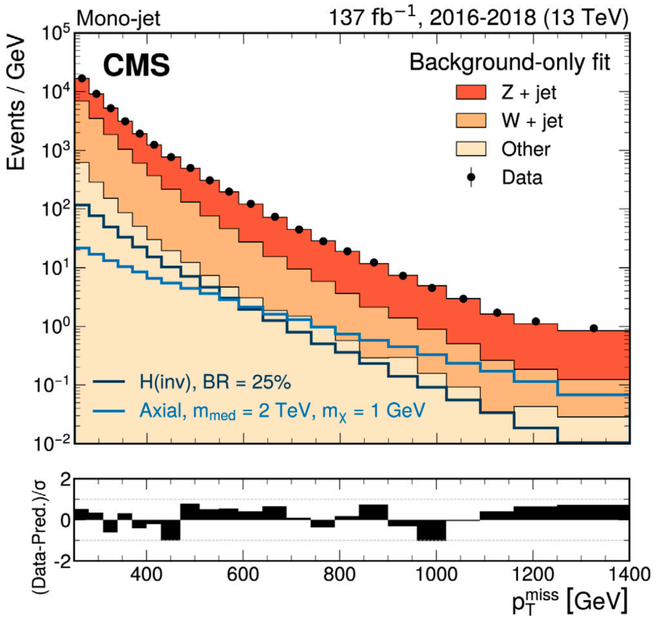
Model parameters:
- Couplings g_{DM} g_q
- Masses of DM mediator
- Nature of mediator

DM Forum benchmarks link

Generic Searches for Dark Matter

A wealth searches for DM at the LHC:

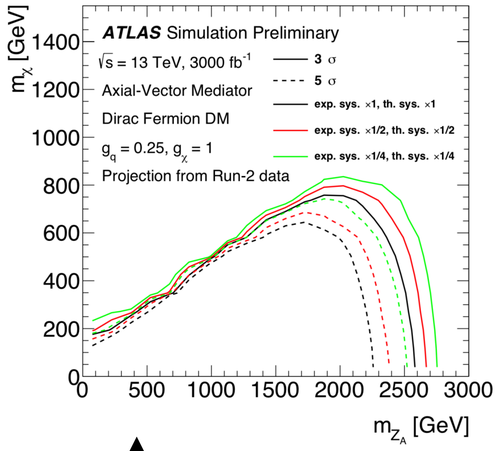
- Mono-jet, mono-V (leptonic and hadronic), Mono-Higgs (various modes), Mono-photon, Mono-top
- VBF-like signatures
- Associated production-like signatures
- Invisible Higgs searches

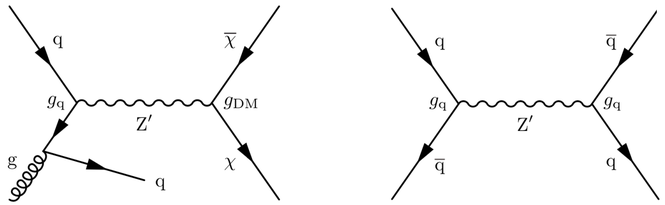


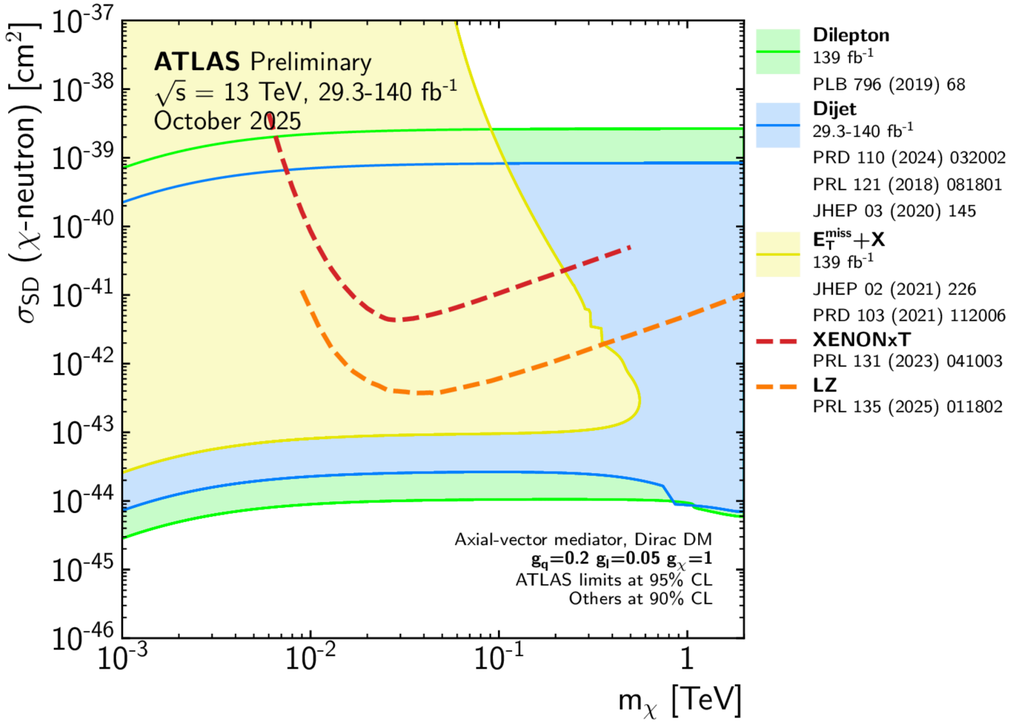
In all these channels, the background control as well as the resolution on the measurement of the MET are key!

Through simplified models also SM processes can be used to constrain DM

Example: interpretation in Axial Vector Mediator







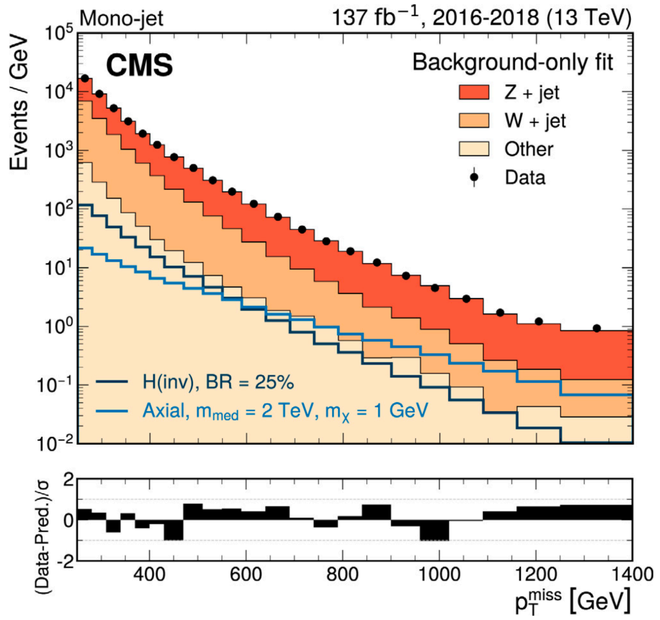
$$-Z'_\mu\left(g_{\mathrm{DM}}\,\bar{\chi}\gamma^\mu\gamma_5\chi + g_f\sum_f \bar{f}\gamma^\mu\gamma_5 f\right)$$

Interesting scenario limits impact of collider searches as the interaction in the non-relativistic limit is purely spin-dependent.

Generic Searches for Dark Matter

A wealth searches for DM at the LHC:

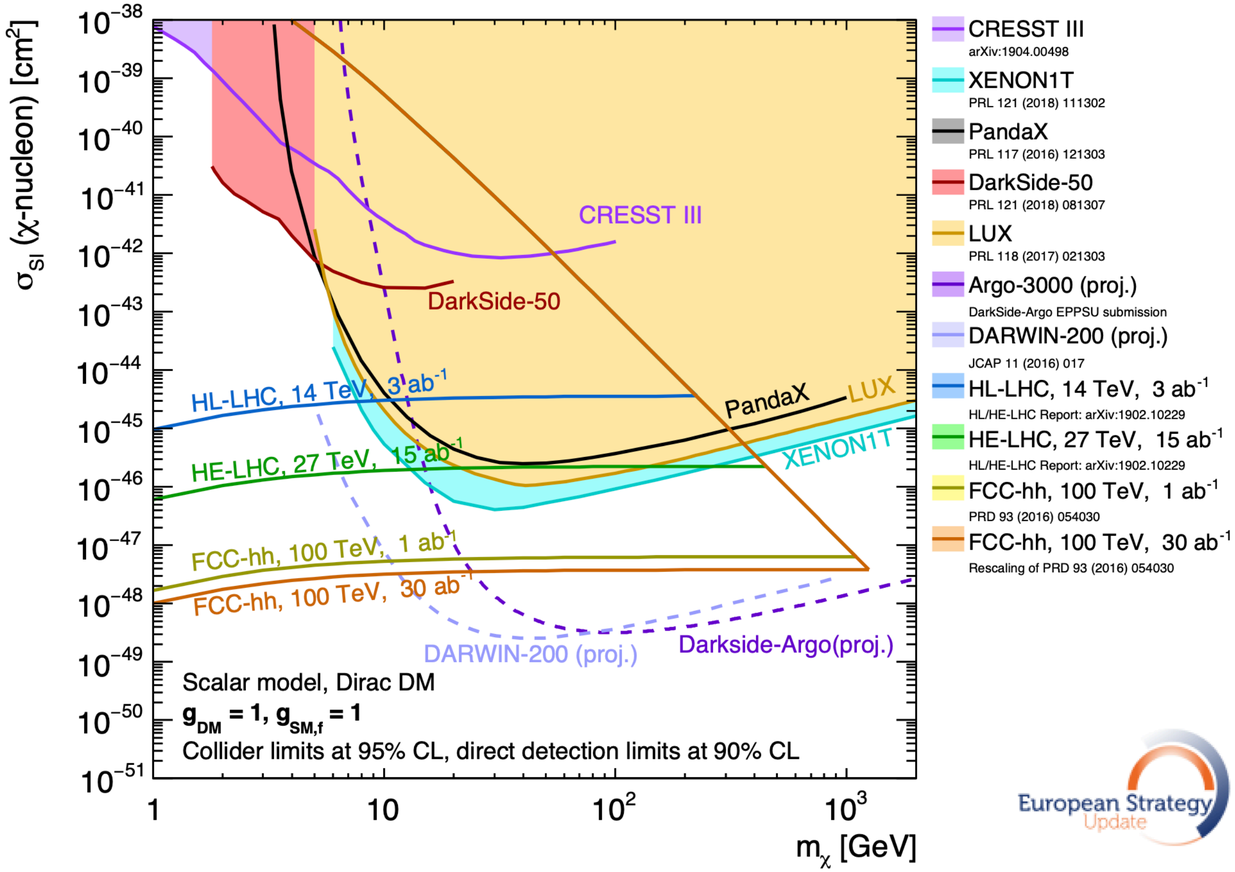
- Mono-jet, mono-V (leptonic and hadronic), Mono-Higgs (various modes), Mono-photon, Mono-top
- VBF-like signatures
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- Invisible Higgs searches



In all these channels, the background control as well as the resolution on the measurement of the MET are key!

Through simplified models also SM processes can be used to constrain DM

Scalar $\phi(g_{DM}\bar{\chi}\chi - g_f\sum_f y_f \bar{f}f/\sqrt{2})$

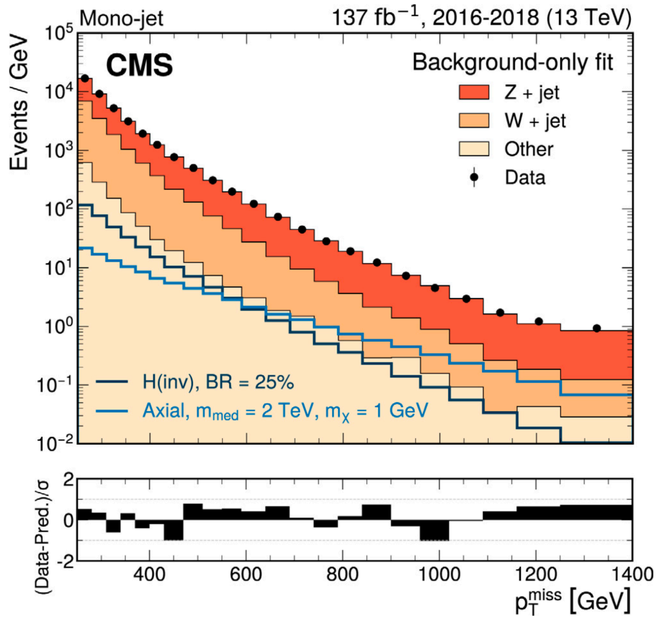


European Strategy Update

Generic Searches for Dark Matter

A wealth searches for DM at the LHC:

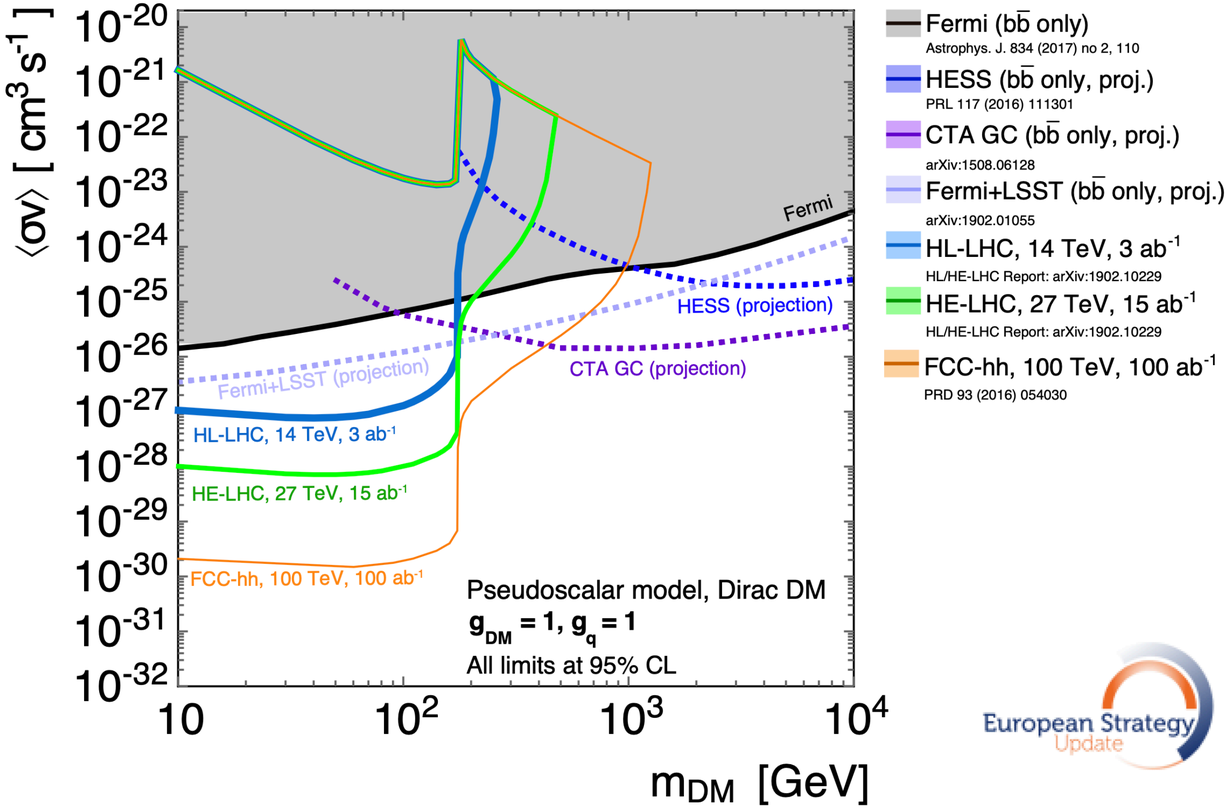
- Mono-jet, mono-V (leptonic and hadronic), Mono-Higgs (various modes), Mono-photon, Mono-top
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In all these channels, the background control as well as the resolution on the measurement of the MET are key!

Through simplified models also SM processes can be used to constrain DM

Pseudo-scalar $-ig_{\mathrm{DM}}\phi\bar{\chi}\gamma_5\chi - ig_q\frac{\phi}{\sqrt{2}}\sum_{q=u,d,s,c,b,t} y_q\bar{q}\gamma_5 q$



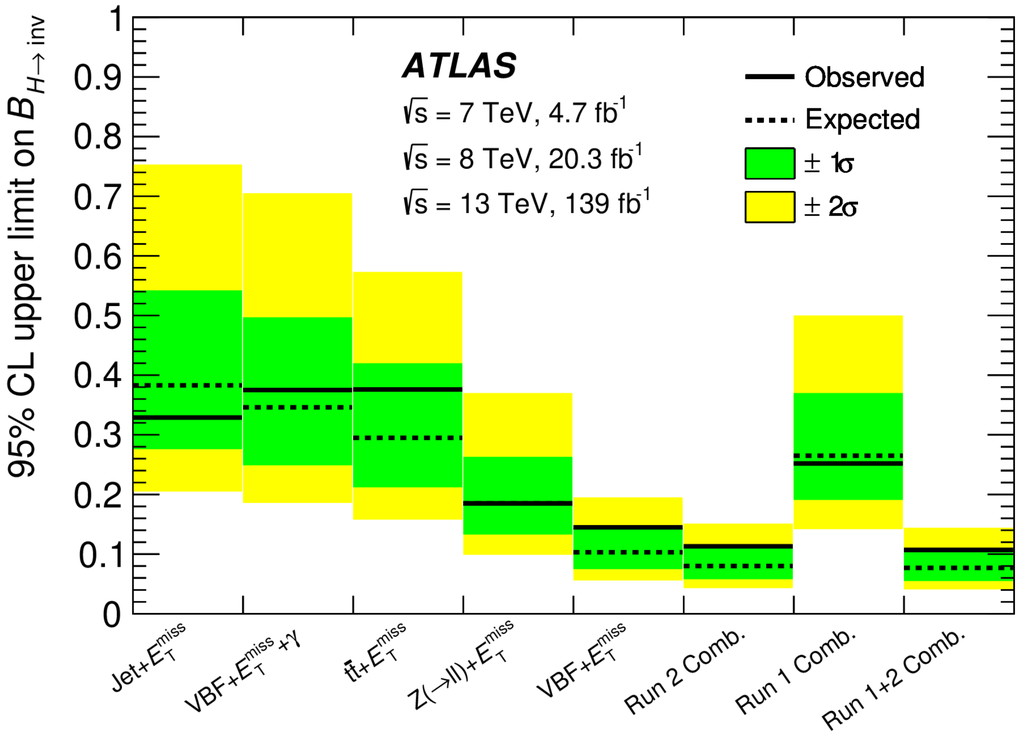
European Strategy Update

Essential Collider and CTAO ID complementarity to reveal nature of DM!

The Higgs portal and Invisible Higgs Decays

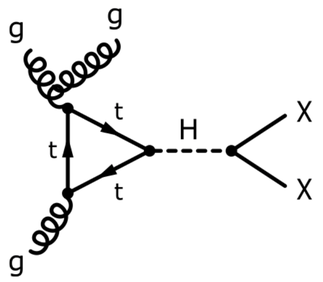
Searches for invisible decays of the Higgs boson in several channels!

To be precise: upper limit on the H→invisible branching of **0.107** (0.077) at the 95% CL

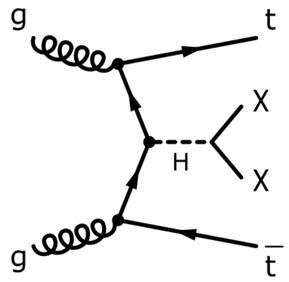


In the SM the H→invisible branching of **0.1%**

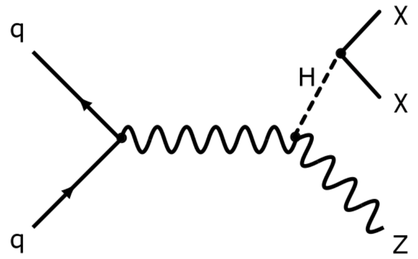
Monojet



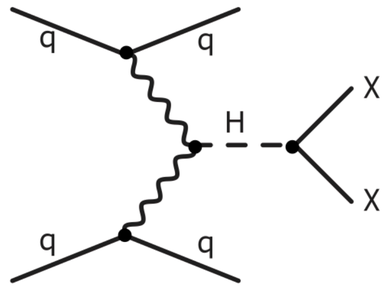
ttH



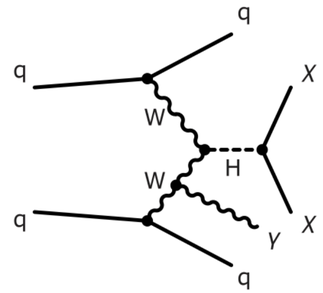
ZH



VBF



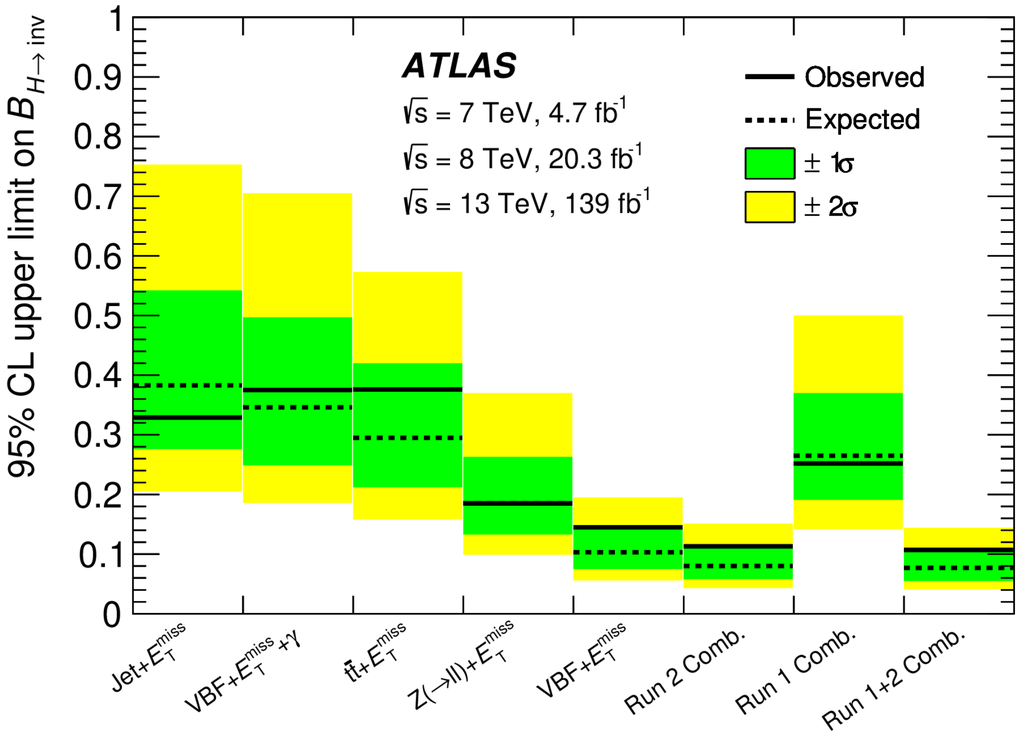
VBF-γ



The Higgs portal and Invisible Higgs Decays

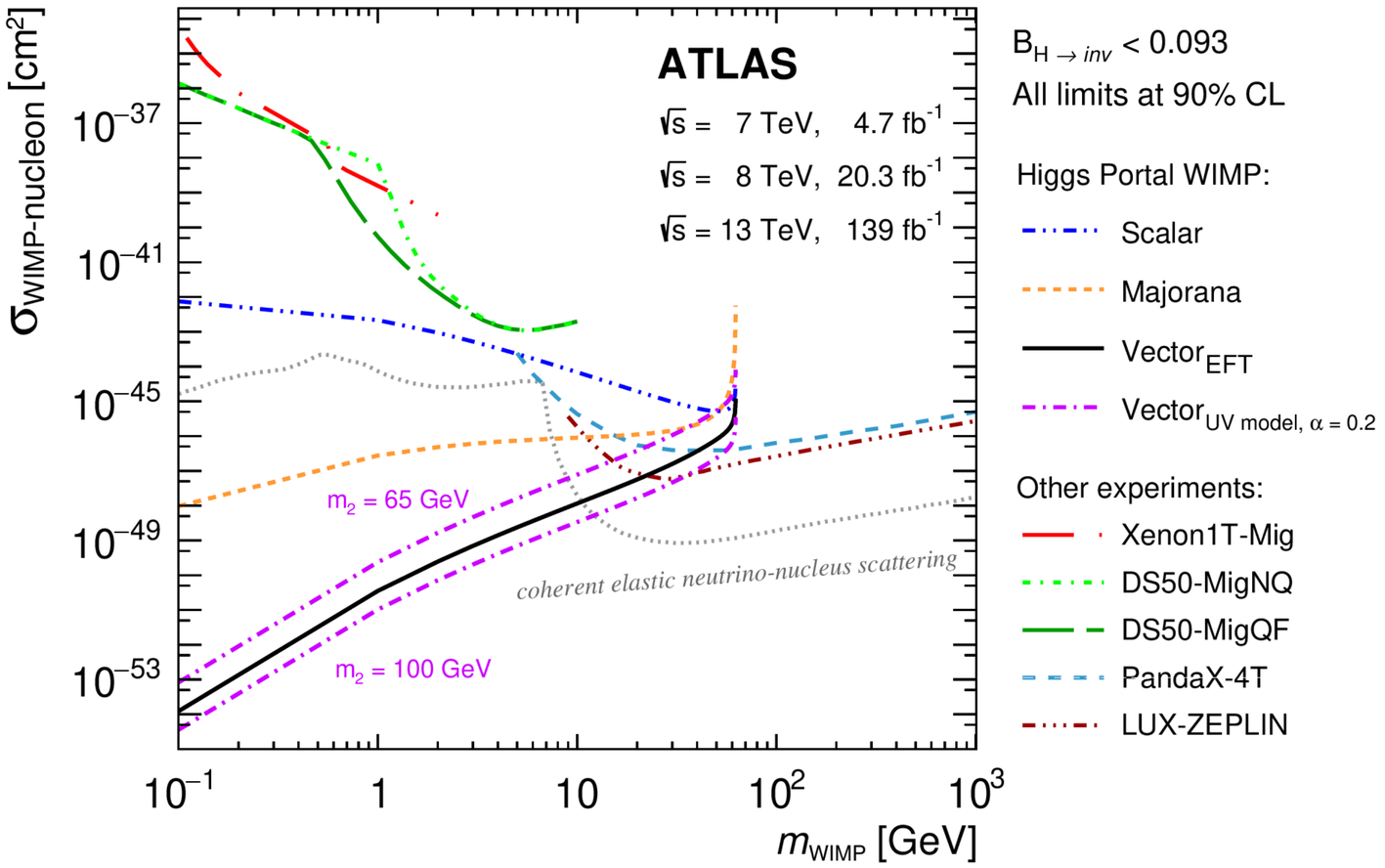
Searches for invisible decays of the Higgs boson in several channels!

To be precise: upper limit on the H→invisible branching of **0.107** (0.077) at the 95% CL



In the SM the H→invisible branching of **0.1%**

Current LHC limit 10% (90% CL)

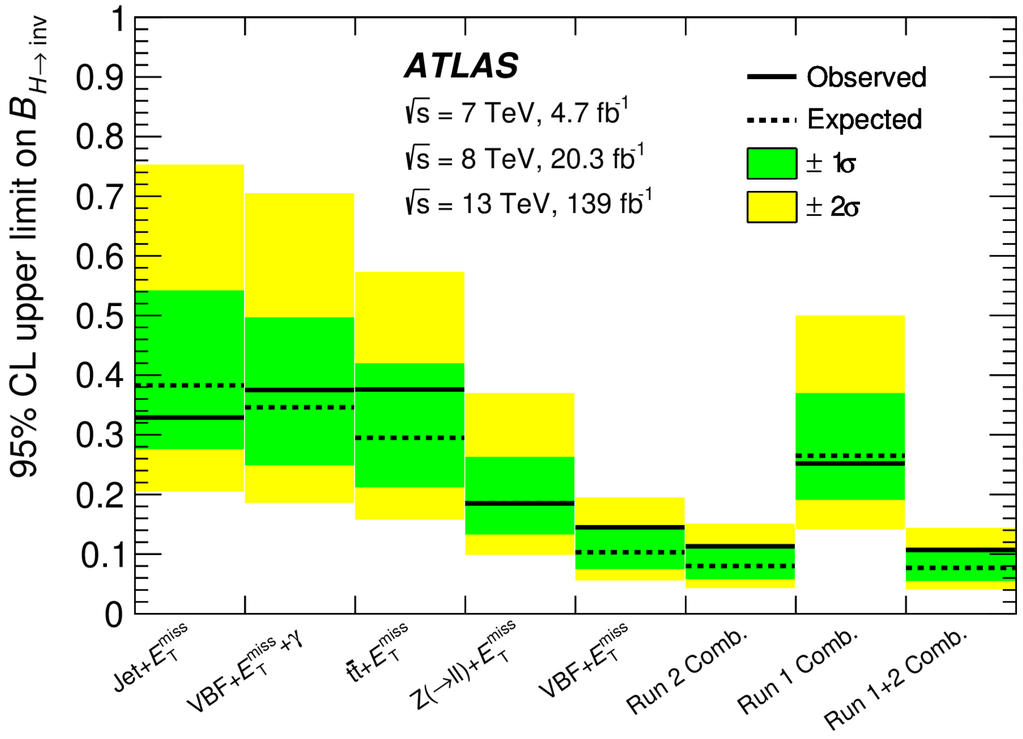


Expect to reach 2% level at HL-LHC!

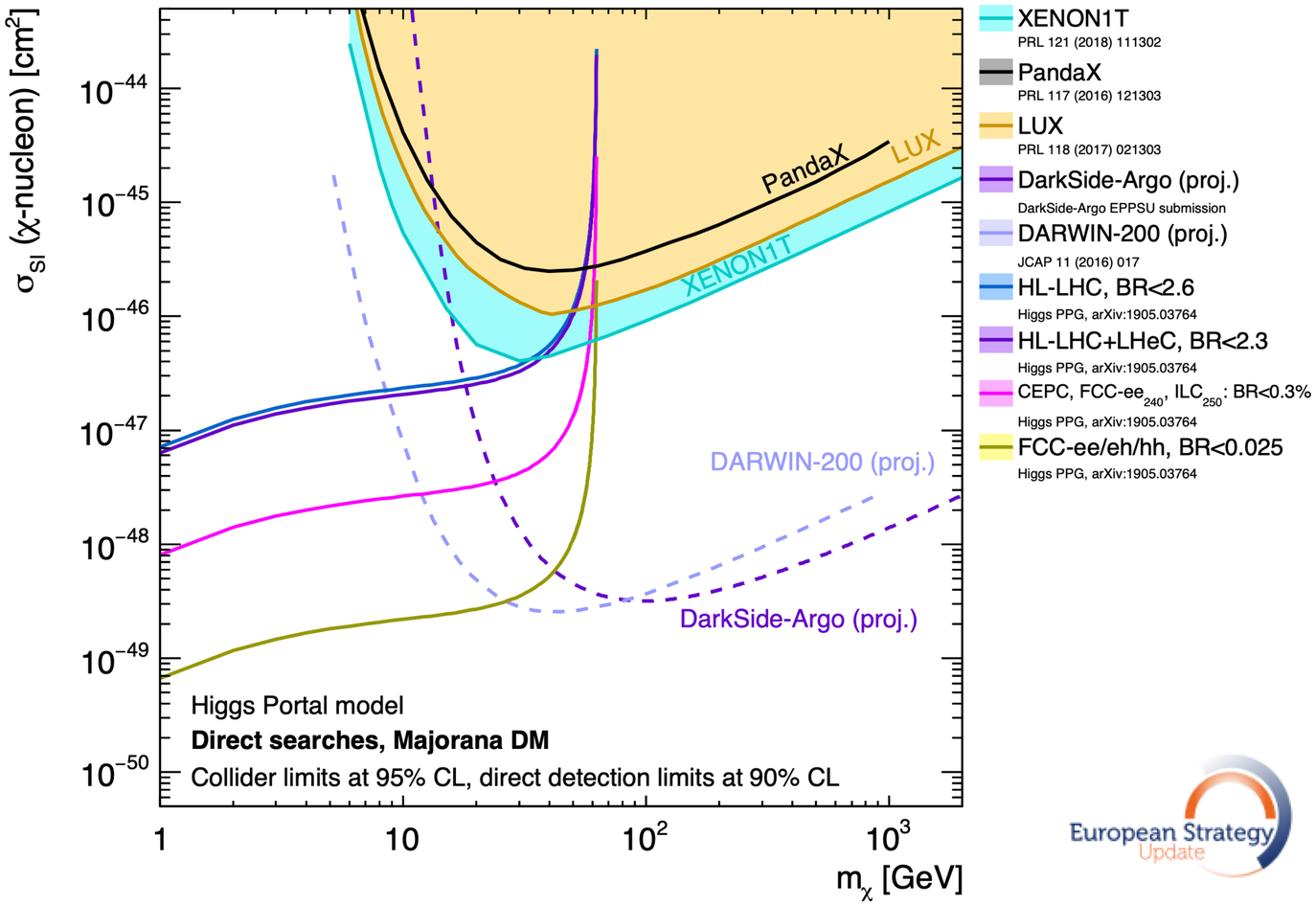
The Higgs portal and Invisible Higgs Decays

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In the SM the H→invisible branching of **0.1%**



European Strategy Update

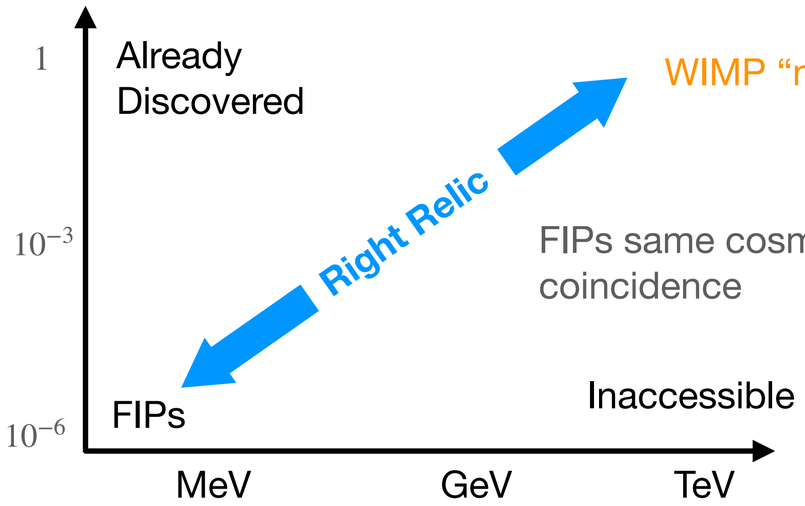
Should reach 0.3% level at FCC-ee and 0.02% with FCC-hh!

Dark Sector Searches

CMS-EXO-23-007

Feebly Interacting Particles - “the WIMPless miracle!”*

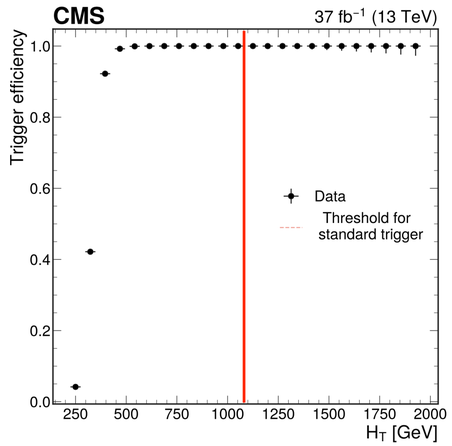
Initially motivated by Dark Matter to investigate small couplings!



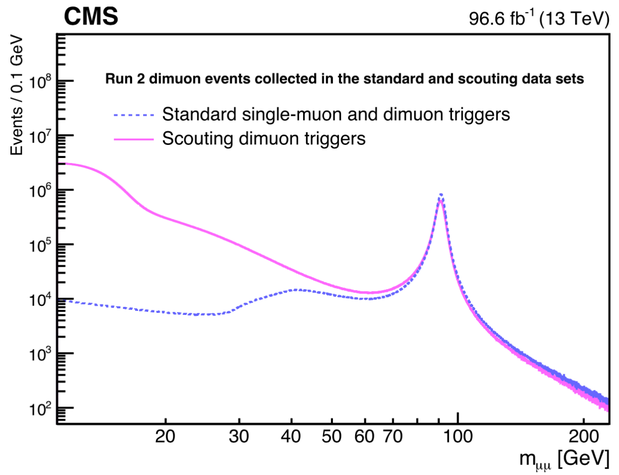
Scouting triggers: Selected L1 Triggers feed into stream with higher HLT rate and reduced content events for specific signatures (two streams: jets and muons).



Reconstruction of **muons** with thresholds down to $p_T > 3\,\mathrm{GeV}$



Reconstruction of **di-jets** with thresholds down to $p_T > 500\,\mathrm{GeV}$ instead of 1.1 TeV



Searches Bellow the EW Scale Into Dark Sectors

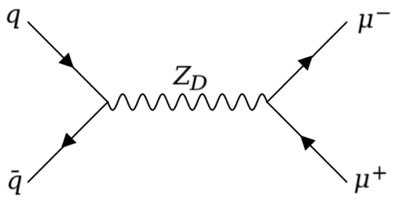
Low interaction strength requires high intensity,

*J. Feng ICHEP 26’

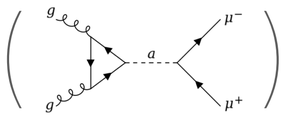
The Dark Photon Portal

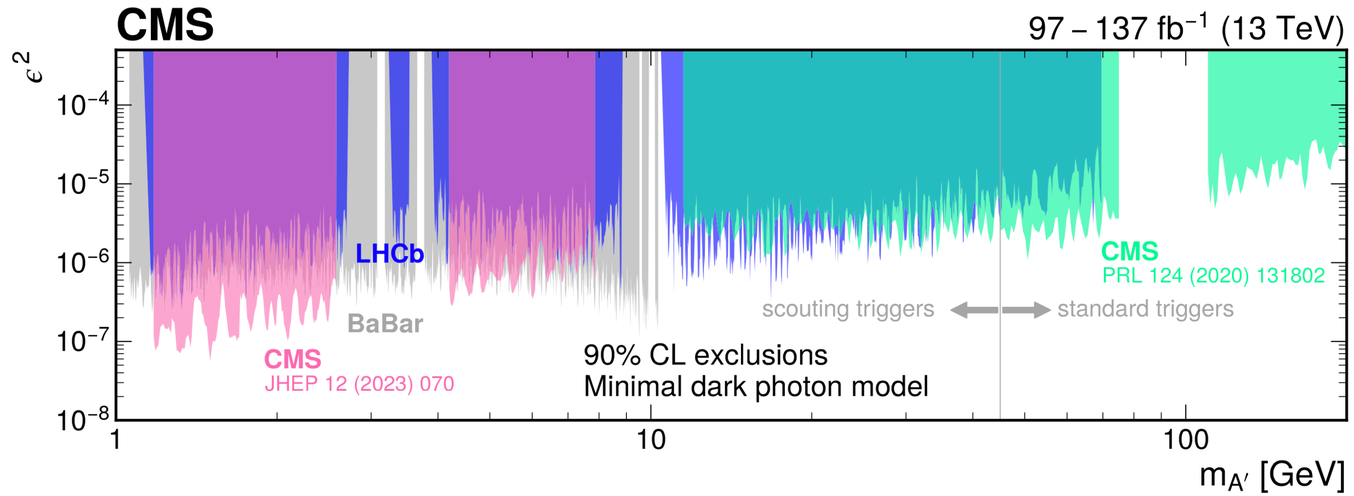
Searches for new **light vector particles** (Dark Photons) which mixes with the hypercharge field.

$$-\frac{\varepsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$$



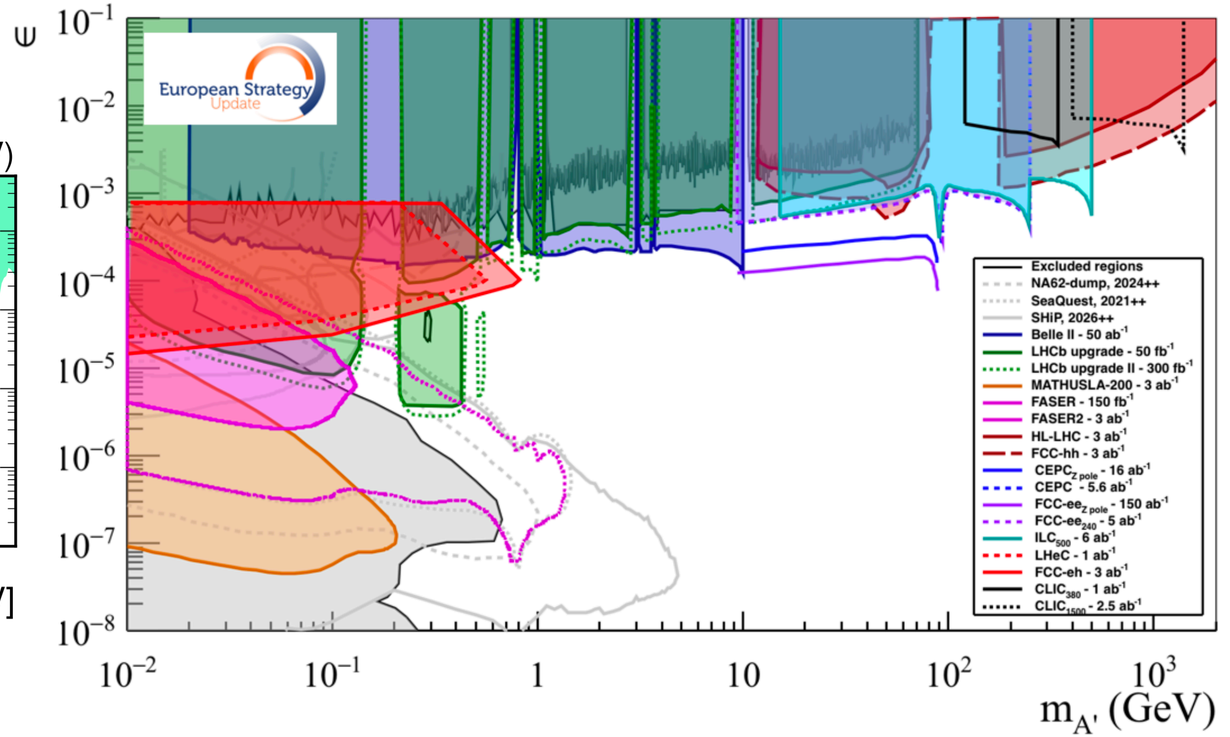
Also used in search for pseudo scalar case.





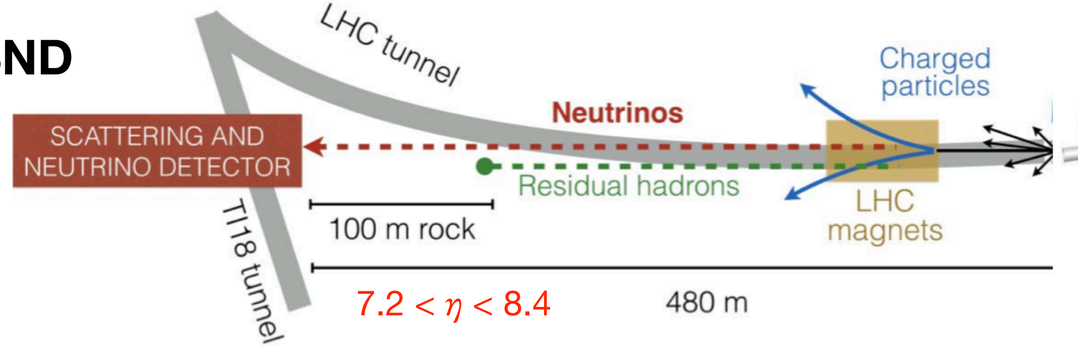
With scouting triggers CMS competitive with LHCb in the low mass range.

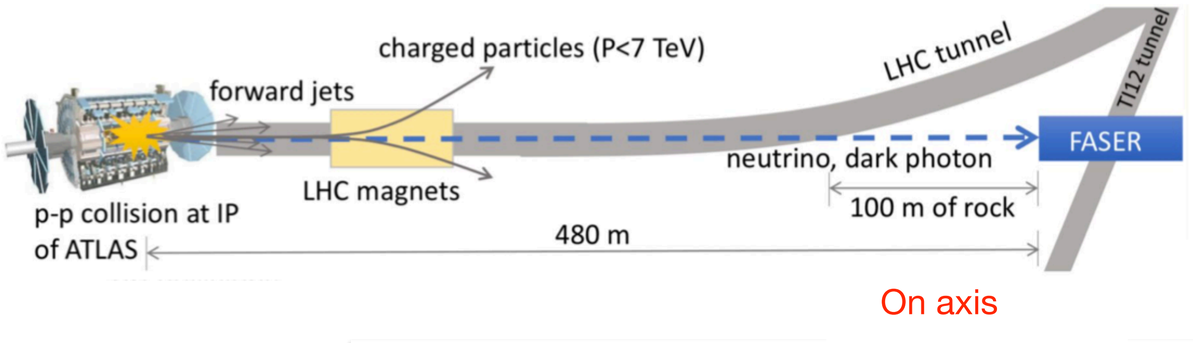
Beam dump experiment (SHiP) will provide sufficiently high intensity to explore very small coupling (but relatively low mass)



The birth of Collider Neutrinos (at the LHC) and more…

SND



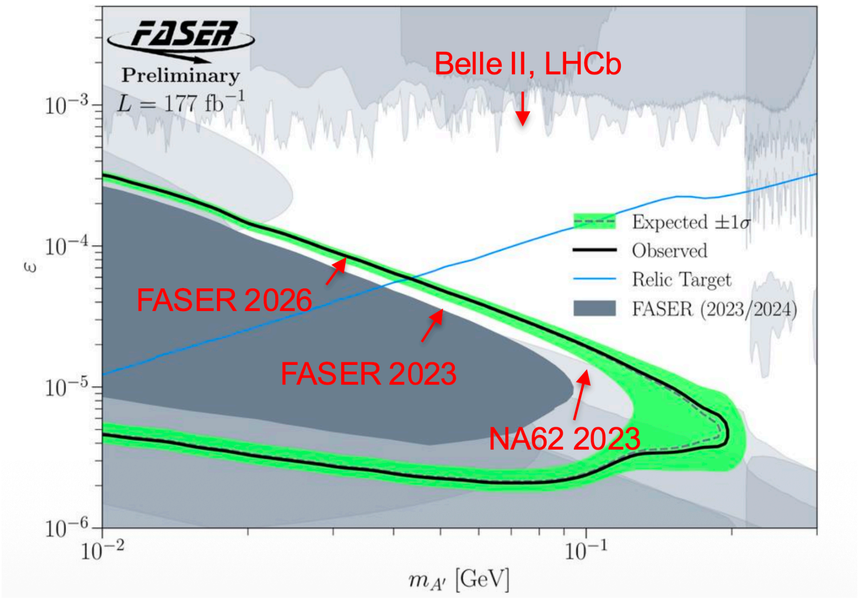


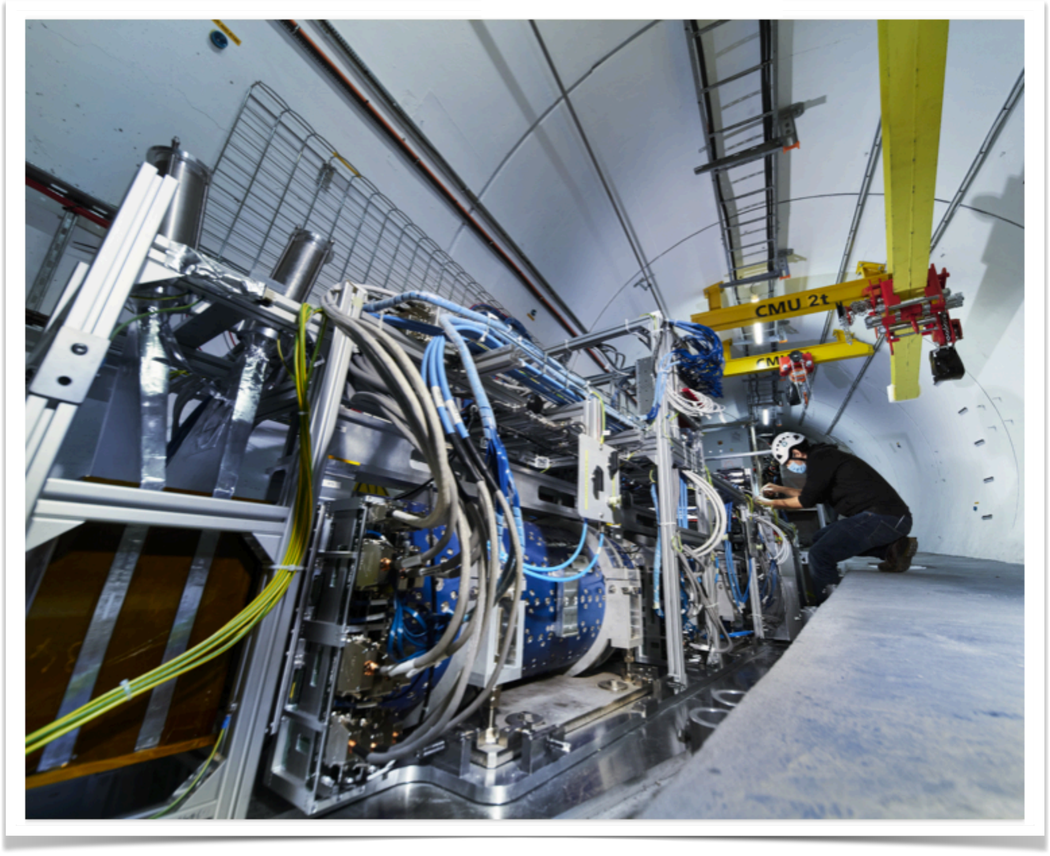
Faser-ν

Faser and SND experiments at LHC

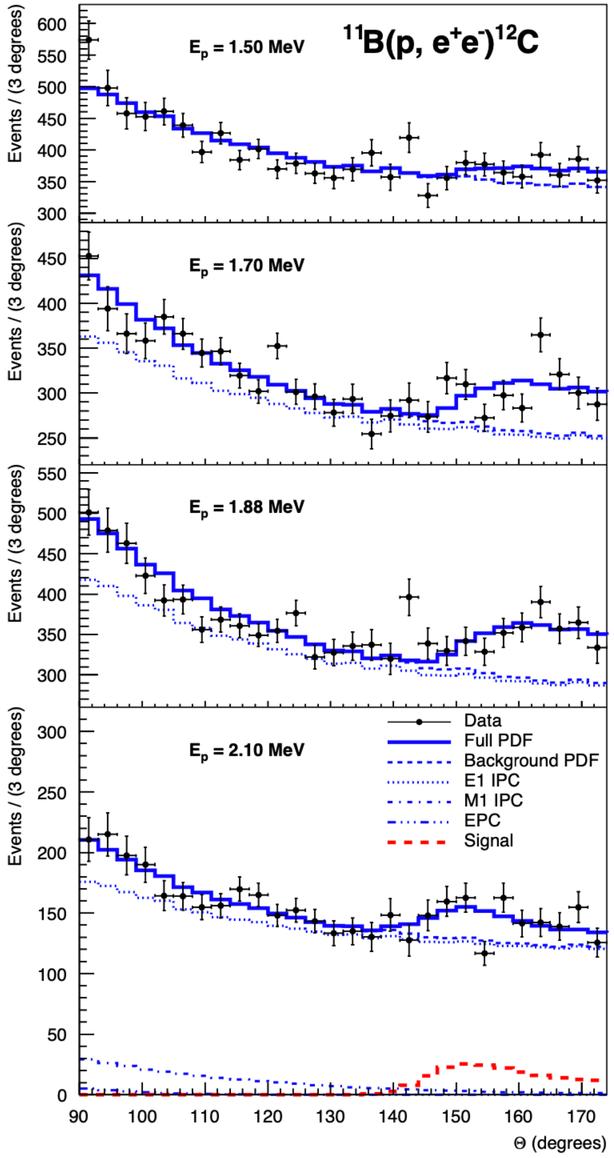
First observation and measurement of cross sections of electron and muon neutrino production at collider!

Latest FASER results on search for $A' \to e^+e^-$



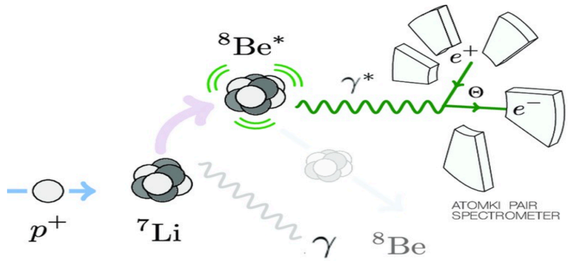


^8Be Anomaly and PADME



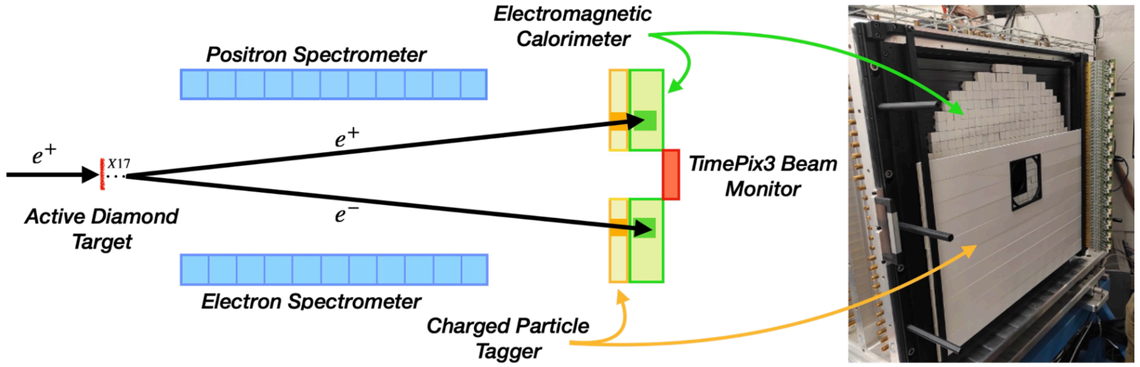
The ATOMKI institute observes the long standing ^8Be anomaly, observed also in ^4He and ^{12}C, i.e. a significant excess compatible with new particle of 17 MeV mass.

Significance of ~7σ



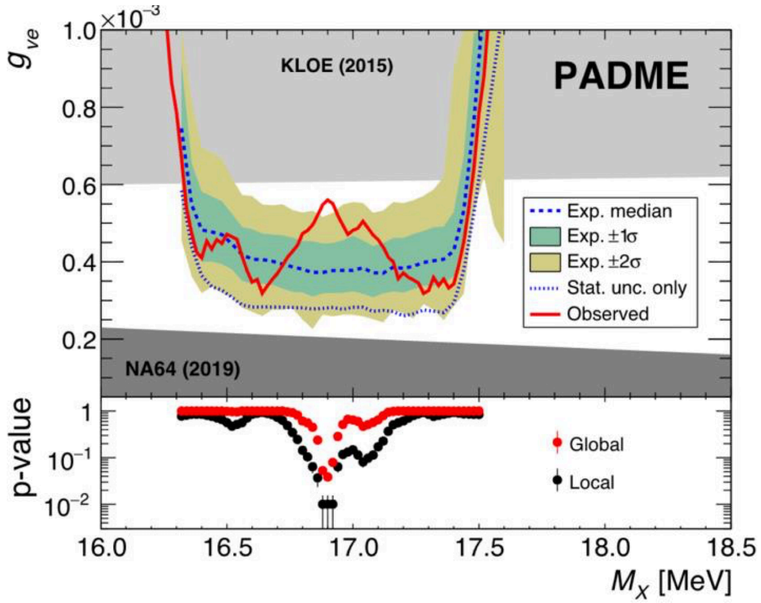
DAΦNE Beam Test Facility only facility with a positron beam at 282 MeV (yielding 17 MeV COM collisions w/ fixed electron!)

PADME experiment (**P**ositron **A**nnihilation into **D**ark **M**atter **E**xperiment)



There is a ~2σ excess seen at 17 MeV by PADME.

… also is a ~2σ exclusion by MEG II



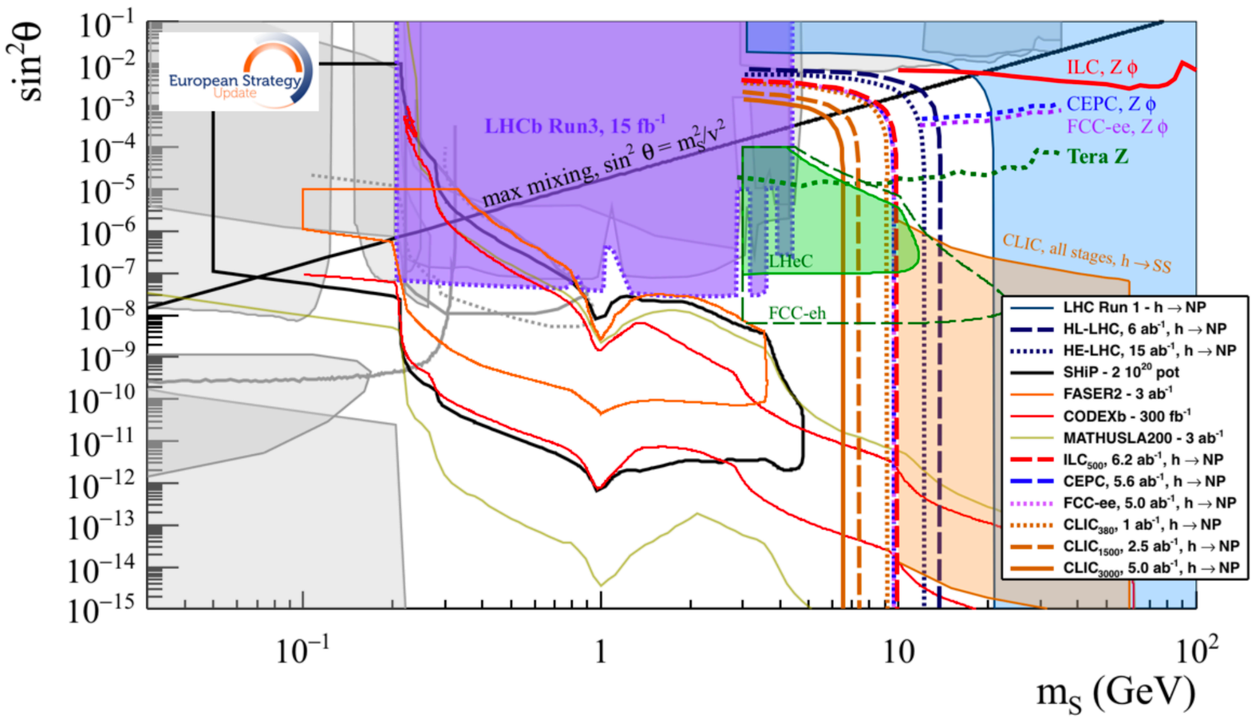
Scalar and HNL Portals

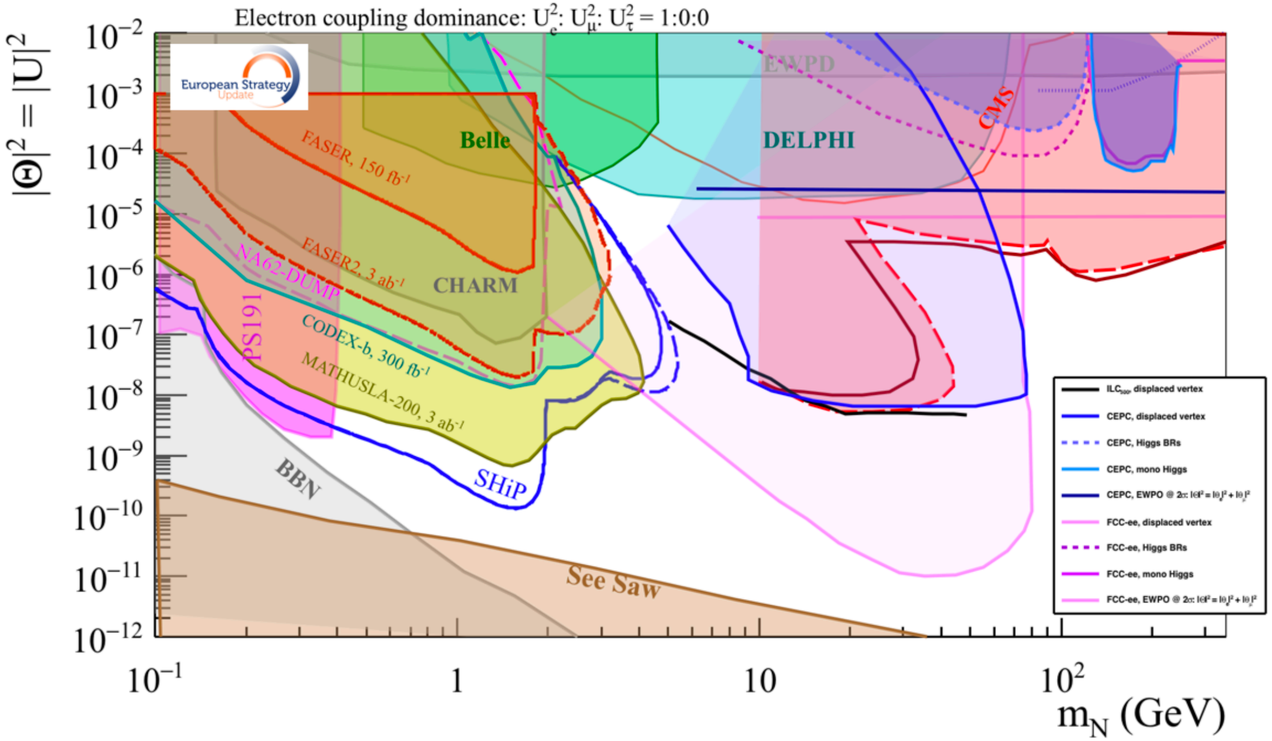
The scalar portal

$$(\mu S + \lambda_{HS} S^2) H^\dagger H$$

Searches for **new neutral fermions** (Heavy Neutral Leptons or Sterile Neutrinos) which mix with left handed SM fermions.

$$y_N L H N$$



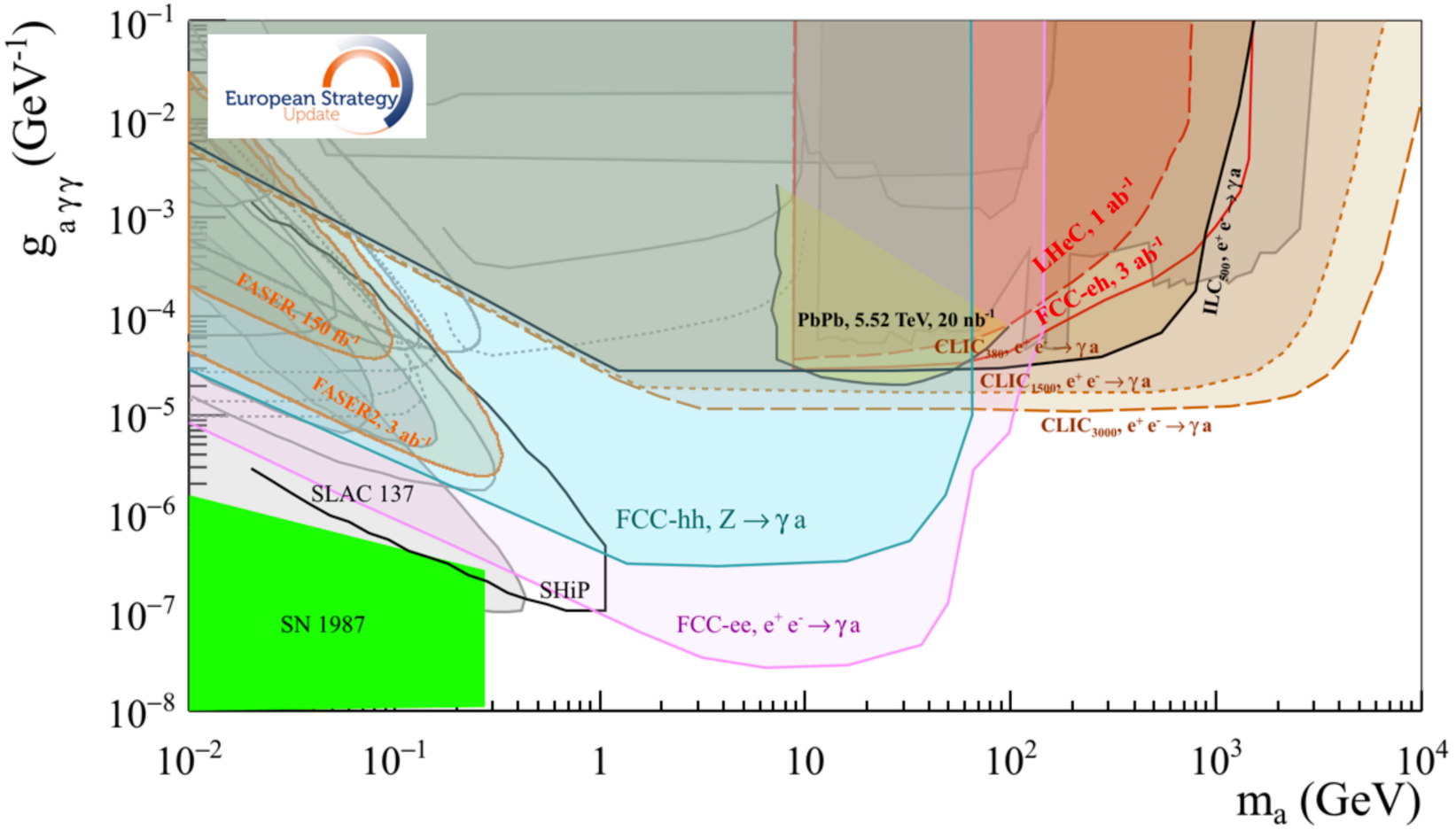


LHC covering higher mass range - FCC-ee high statistics covers lower masses (along with SHiP).

Axion Like Particles at Colliders

Searches for a light **pseudo-scalar particle (Axion or Axion like particle)** through Dimension-5 operators

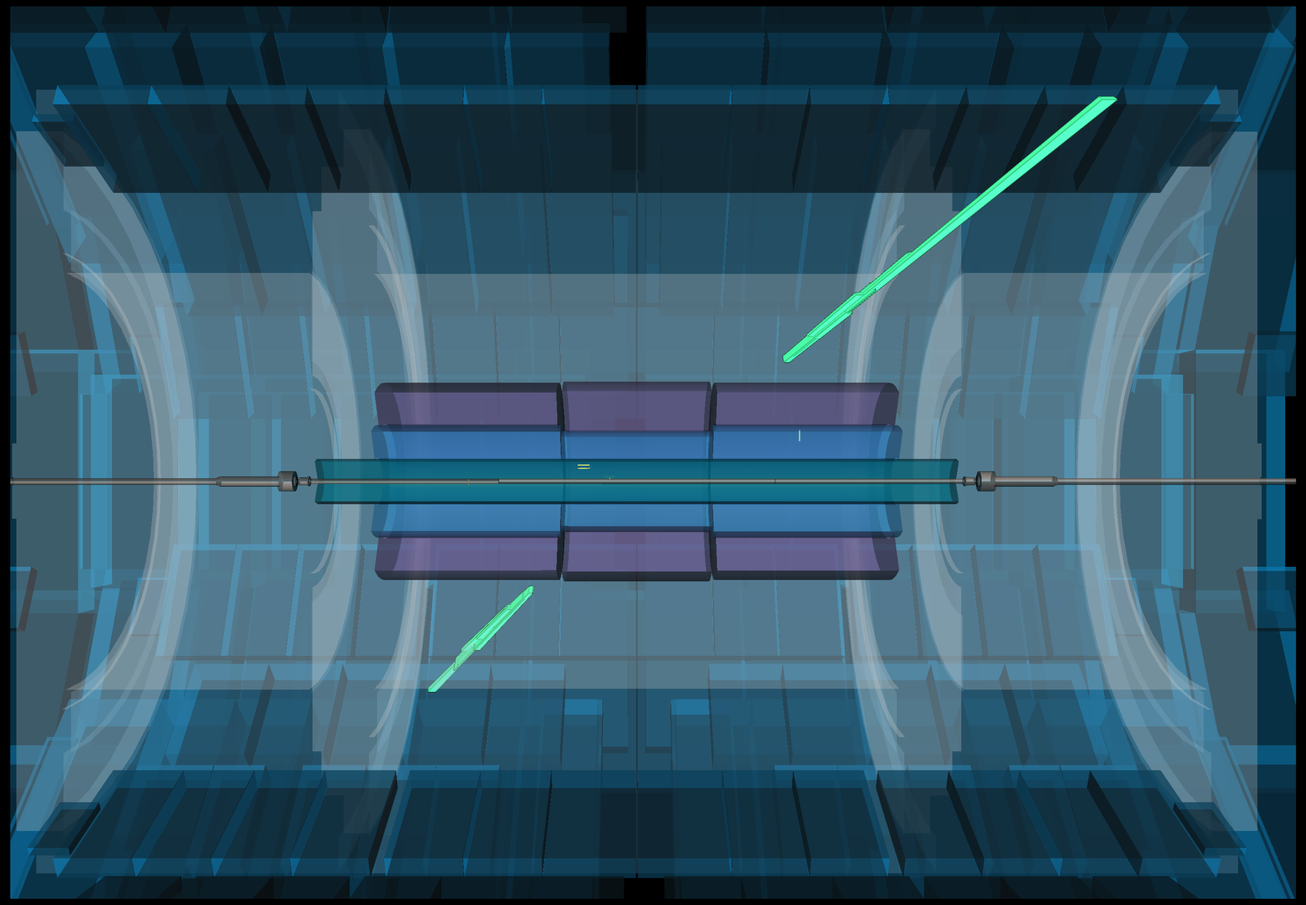
$$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu},\ \frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu},\ \frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$$



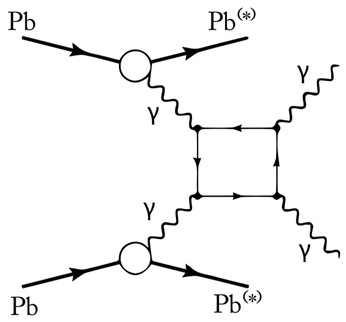
A Spectacular Heavy Ion Event

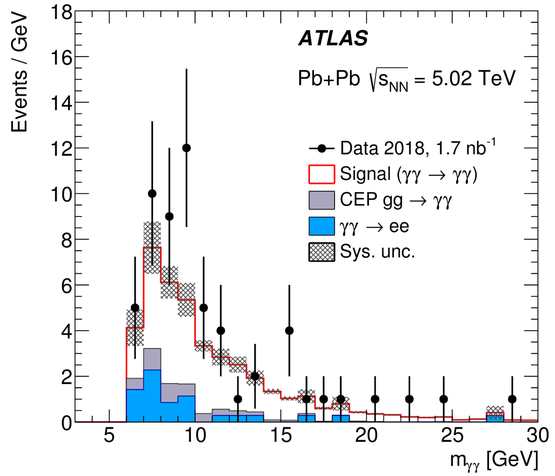
ATLAS EXPERIMENT

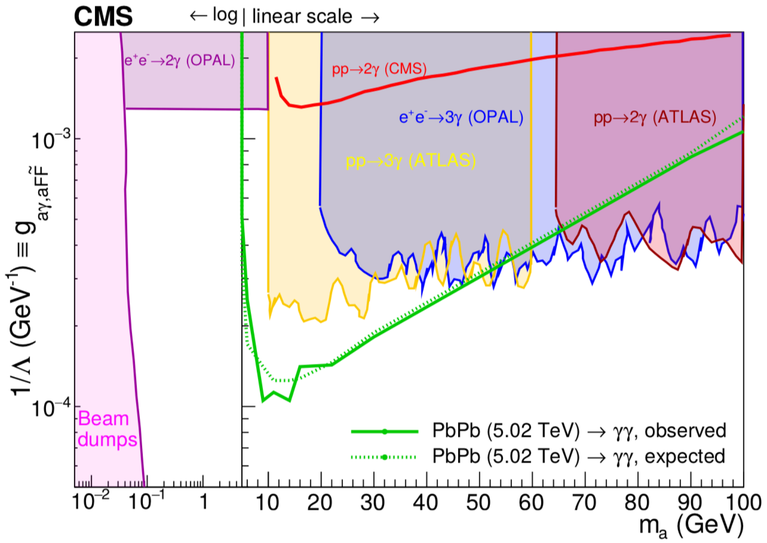
Run: 366994
Event: 453765663
2018-11-26 18:32:03 CEST



Observation of **Light-by-light scattering** (Central Exclusive Production)







Constraints on ALP (Axion Like Particles) assuming sole coupling to photons.

Conclusions



Colliders have a **very broad DM search program**, aiming at leaving no stone unturned, however search reach towards higher masses limited by available collider energy!

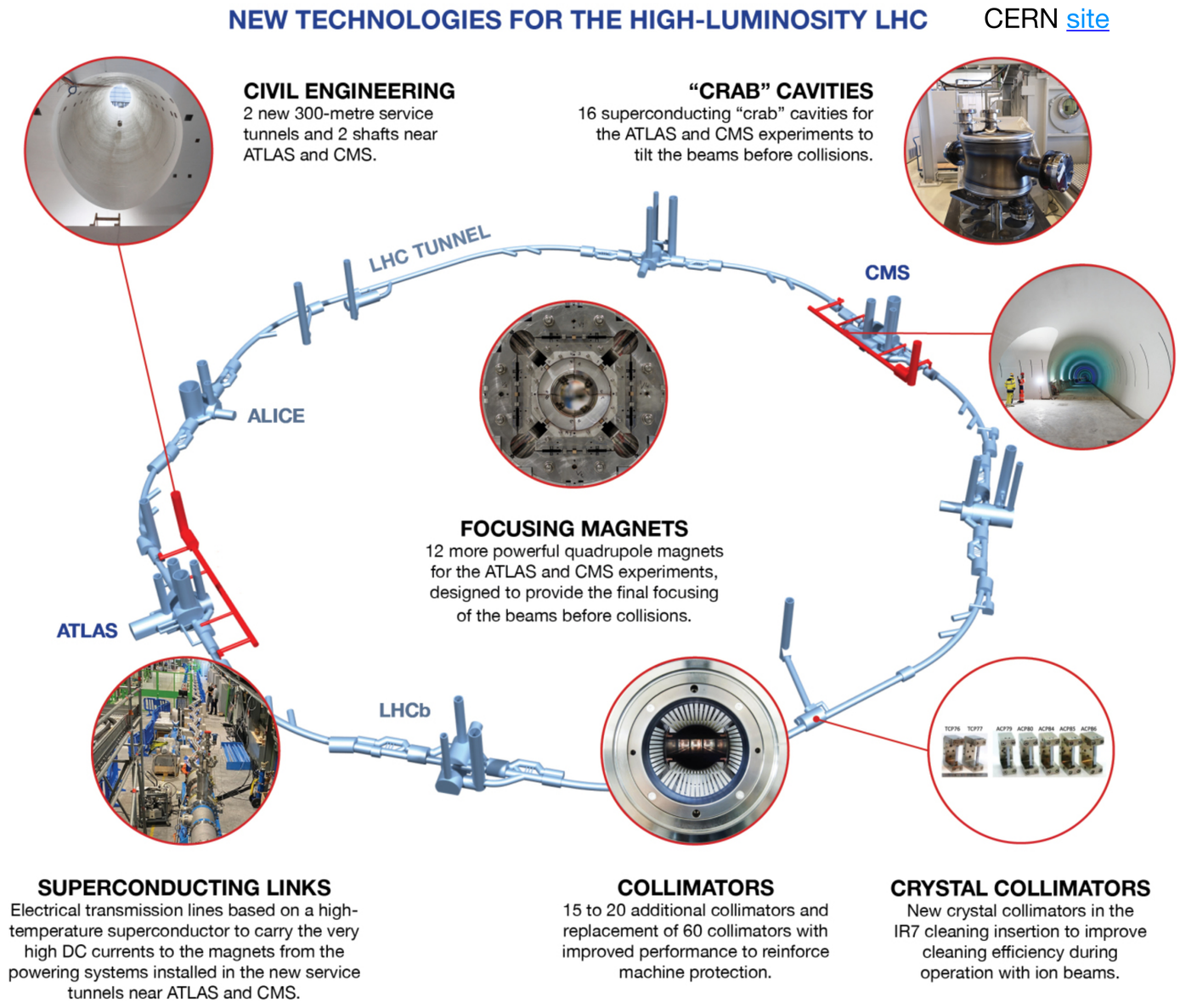
Beautiful synergy between collider, DD, and Cherenkov Telescopes to fully cover WIMP DM scenarios.

CTAO has a unique window of opportunity to uncover the nature of Dark Matter

Congratulations for the Construction of CTAO !

Backup

LHC Machine Towards Major LS3 Upgrades



CERN site

Front page of the CERN Courier says it all!



LS3 installation fully on track!

Nb_3Sn series magnets manufactured at Fermilab arrived at CERN! See CERN News.

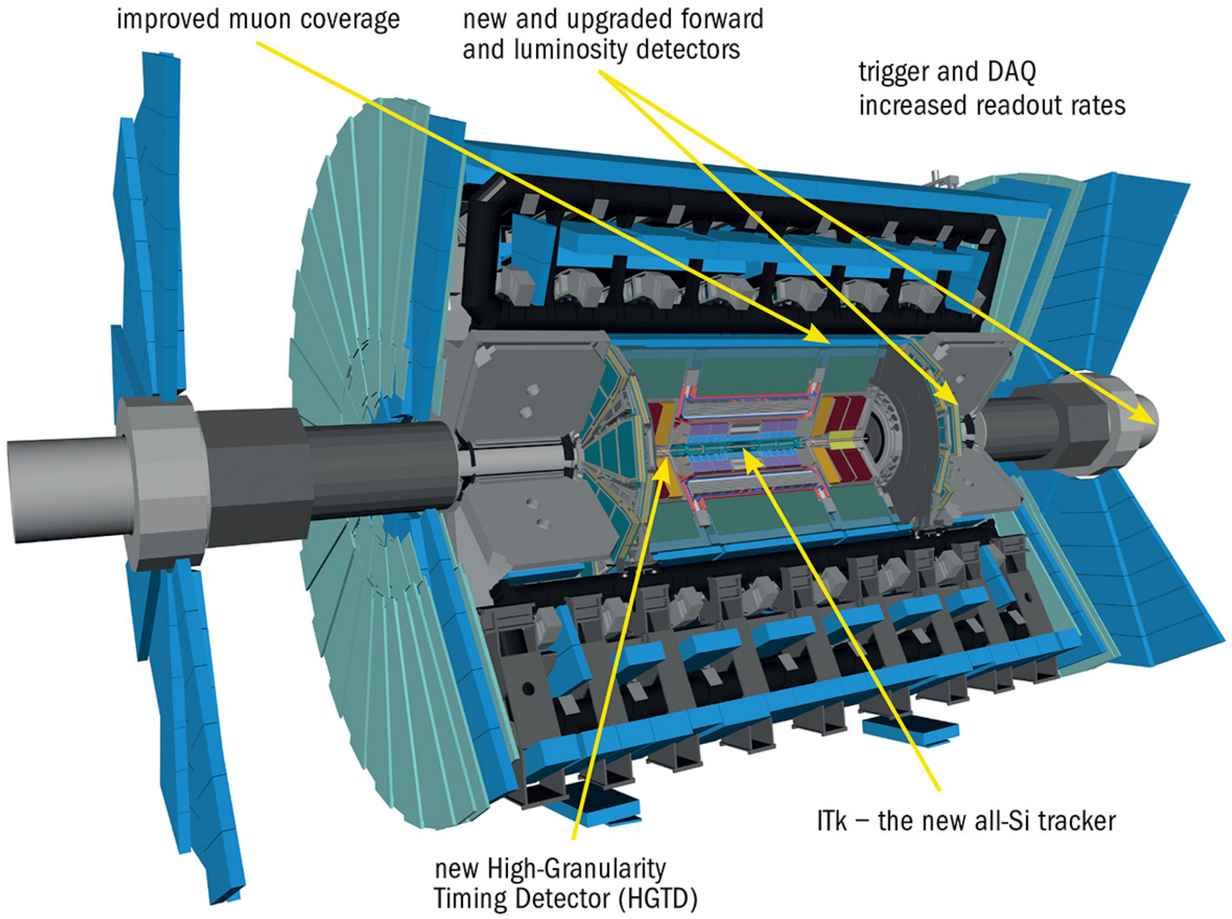


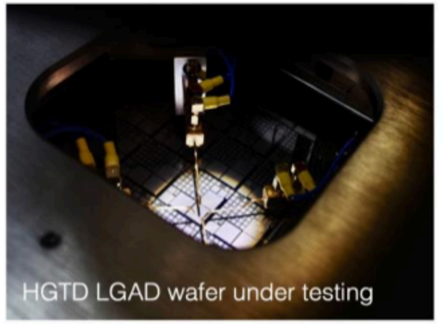
ATLAS Towards Major LS3 Upgrades

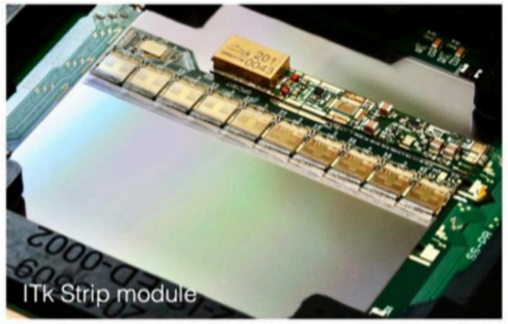
A new ATLAS for the high-luminosity era

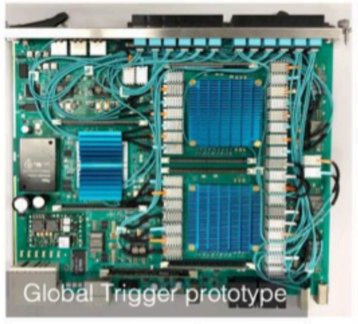
18 January 2023 | By Stefan Guindon, Christian Ohm, Caterina Vernieri

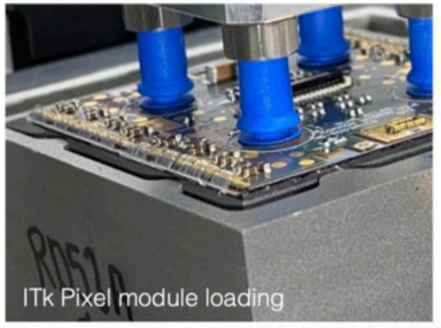
Feature link



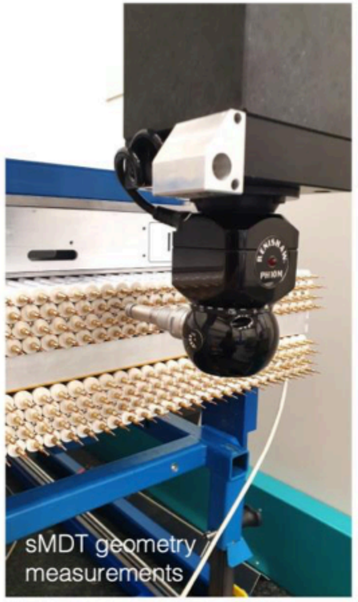

HGTD LGAD wafer under testing


ITk Strip module

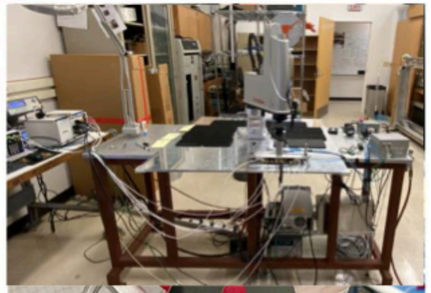

Global Trigger prototype


ITk Pixel module loading


Tony Weidberg and Georg Viehhauser with Strip L3 structure and


sMDT geometry measurements


ITk Pixel Inner System ring with modules




LAr ALFEv2 tests


and module

ATLAS Towards Major LS3 Upgrades

ACCELERATORS | FEATURE

CMS prepares for Phase II

9 January 2023

CERN Courier article link

Trigger/HLT/DAQ
- Track information in L1-Trigger
- L1-Trigger: 12.5 ms latency – output 750 kHz
- HLT output 7.5 kHz

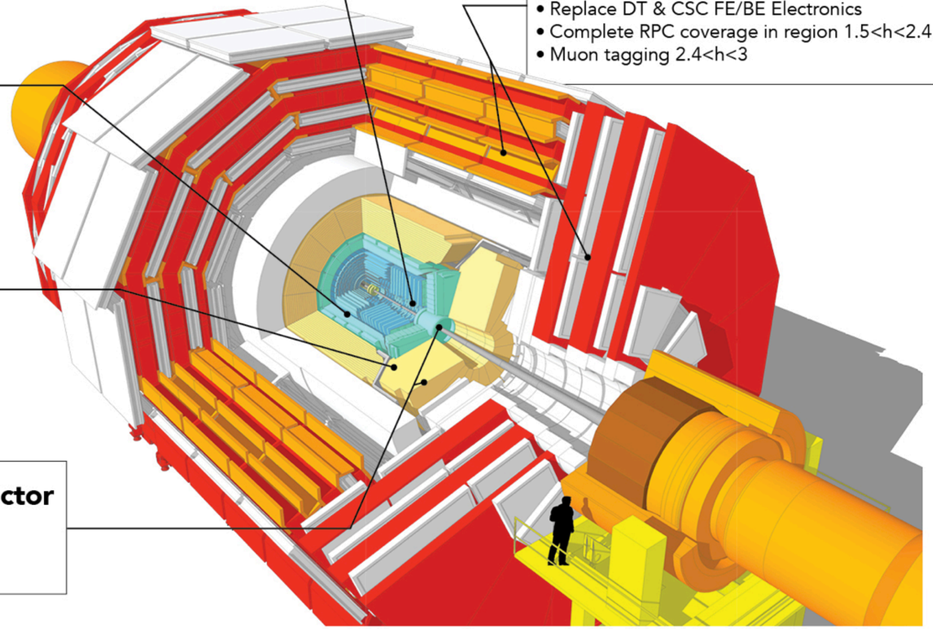
Barrel ECAL/HCAL
- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)

Muon Systems
- Replace DT & CSC FE/BE Electronics
- Complete RPC coverage in region 1.5<h<2.4
- Muon tagging 2.4<h<3

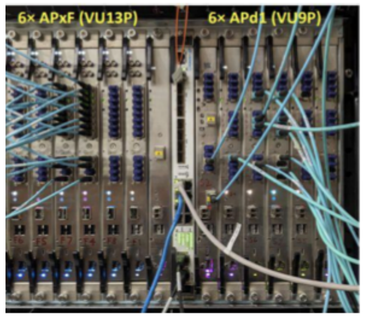
New Endcap Calorimeters
- Rad. tolerant – high granularity
- 3D capable

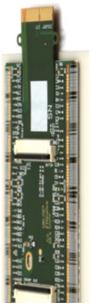
New Tracker
- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout (pT>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to h=4

MIP Precision Timing Detector
- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes

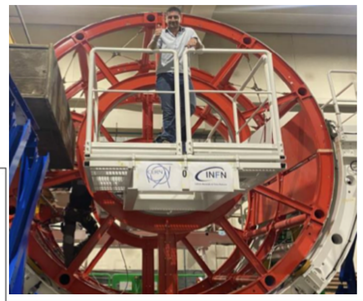


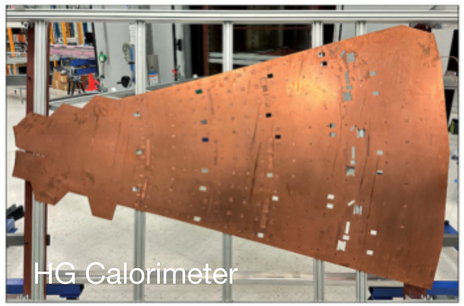
From CLASSE (Cornell)

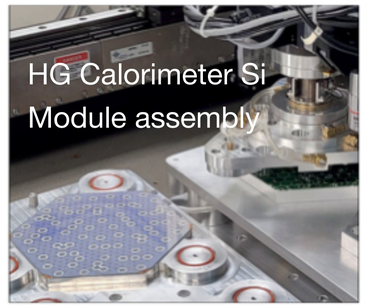




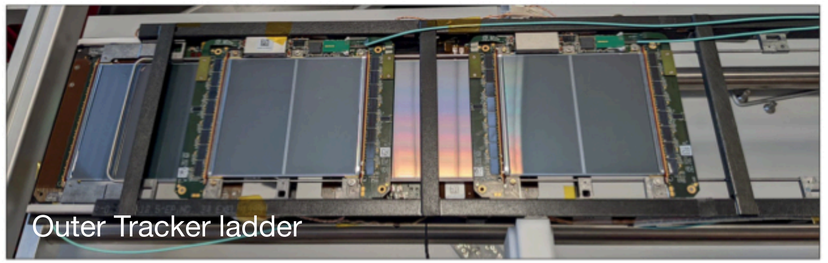




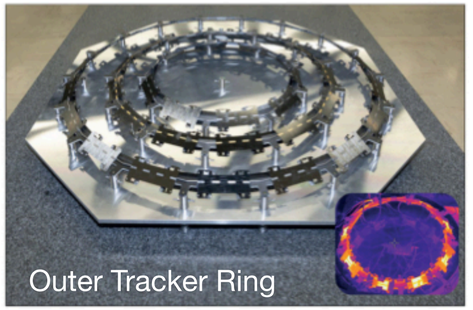






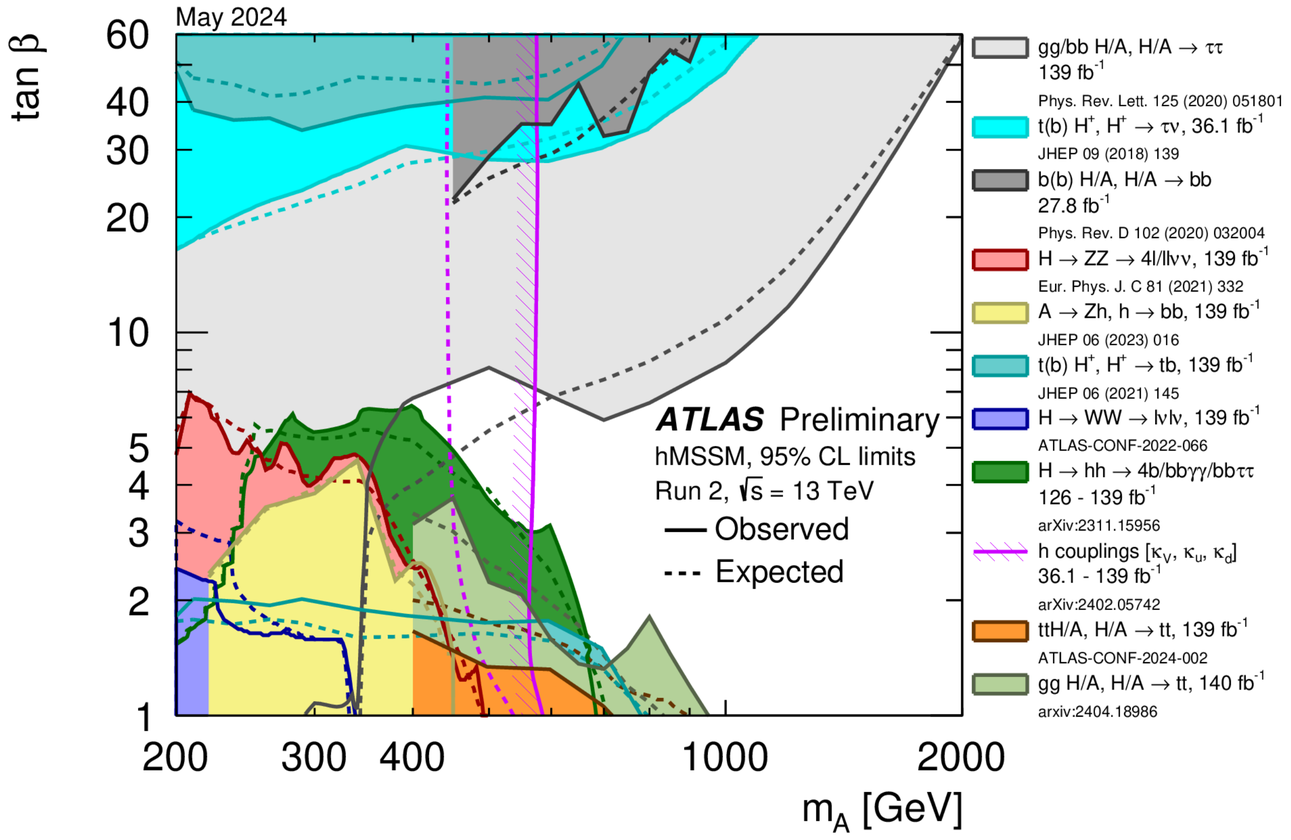






Reaching SUSY from its extended Higgs sector

The MSSM Higgs sector at tree level is governed by only two parameters (mA and tan β).



hMSSM: trade the value Mh = 125 GeV against the radiative corrections where the Higgs mass is used as proxy for the leading stop sector corrections.
[Maiani, Polosa, Djouadi et al. link]

SUSY could modify the couplings of the Higgs

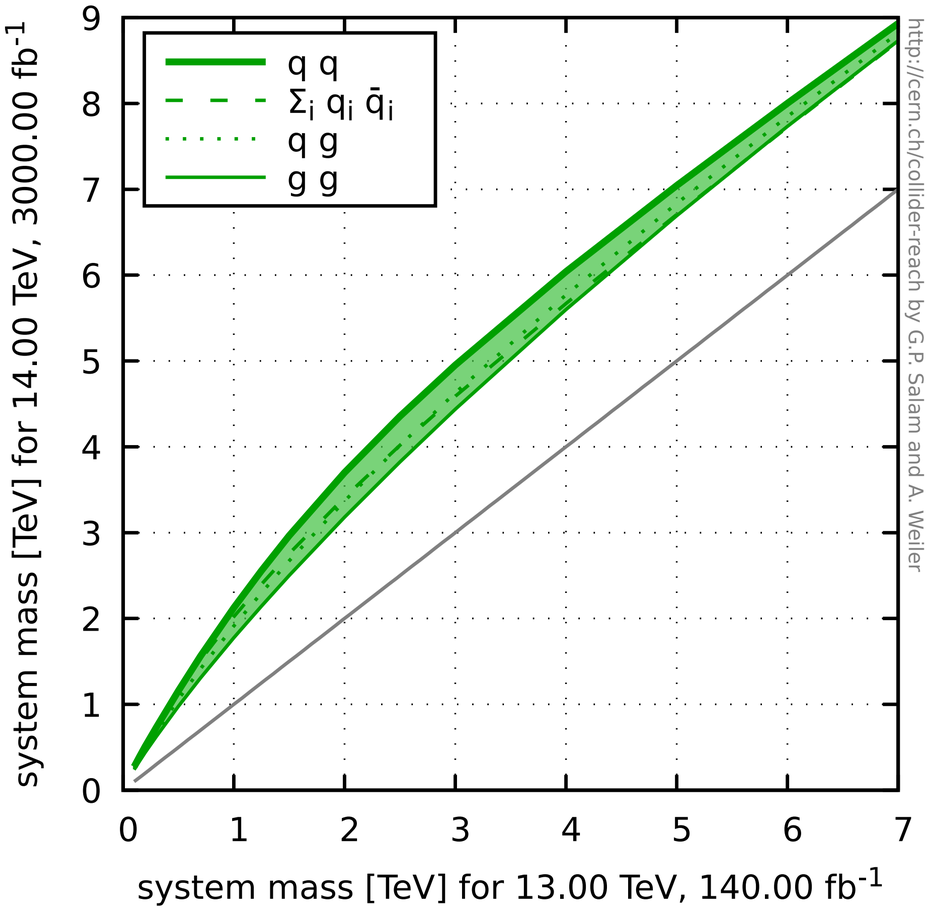
From the combination of all Higgs coupling measurements channels presented, mostly from constraints on up versus down Yukawa and coupling to vector bosons.

Direct searches for additional Higgs bosons (neutral and charged) have been performed:

- Neutral heavy Higgs to tau tau
- Charged Higgs to tau neutrino
- Heavy neutral Higgs to ZZ
- Charged Higgs to tb
- Heavy neutral Higgs to ZH
- Heavy Higgs boson to HH

Still Room for Discoveries at HL-LHC?

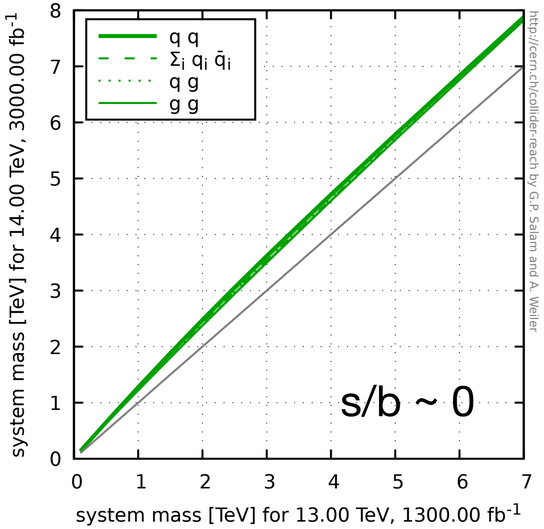
At HL-LHC still a factor of **effectively 20** in luminosity



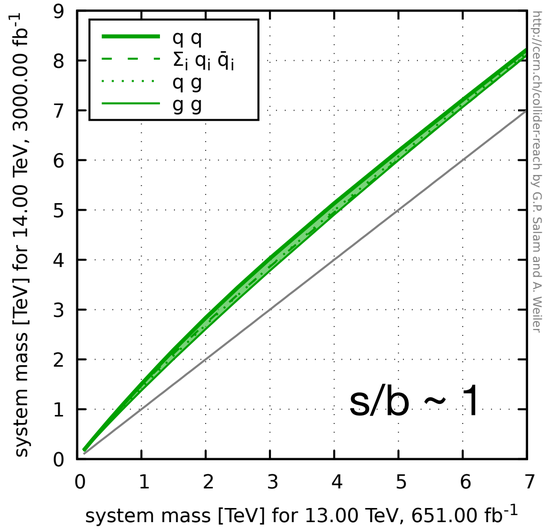
Still nearly up to 2 TeV of Exploration (exclusion)!!

Still room for discoveries w.r.t. Exclusions?

Depends on analysis purity (s/b)



Up to **~500 GeV improvement**

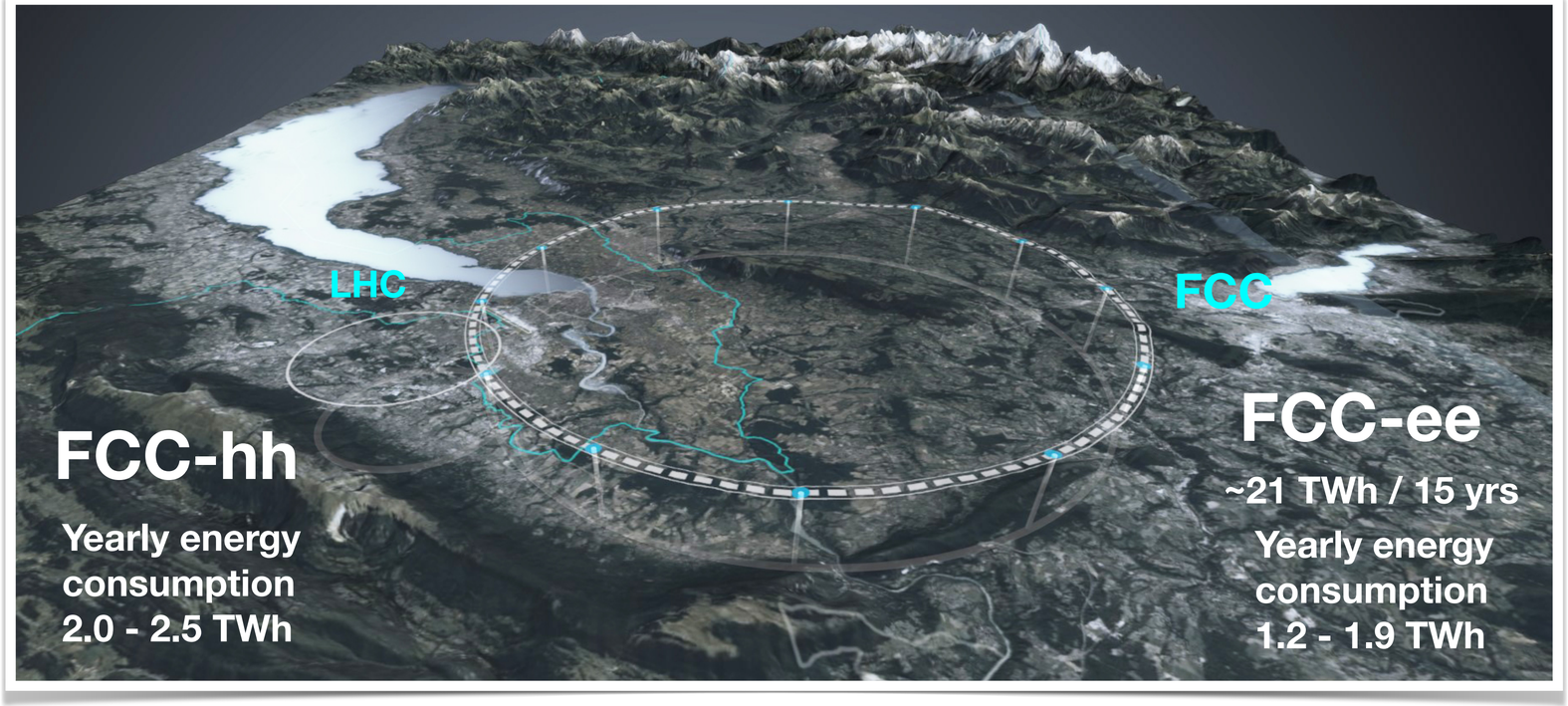


Up to **~1 TeV improvement**

Performance can be improved!

- New ideas and developments (e.g. ML techniques, Trigger, Scouting, etc…).
- **Improving precision and ancillary measurement!**

The FCC in a nutshell



FCC-ee Intensity Frontier

Ultimate Precision and discovery potential

Goal Luminosity $144 \times 10^{34}\ cm^{-2}s^{-1}$

One LEP1 every few minutes !!!

At the Z peak (per IP) - 4 IPs

Z, WW, ZH and $t\bar{t}$ COM energies

Continuous beams

No Pile Up

15 Years of operations

FCC-hh Energy Frontier

85 TeV (baseline COM energy)

Target luminosity 20ab^{-1}

14 T Nb_3Sn magnets

Luminosity $30 \times 10^{34}\ cm^{-2}s^{-1}$ - 4 IPs

PU / bunch crossing up to 1000!

Stored energy/beam 6.5 GJ (compared to 0.7 GJ at HL-LHC

25 Years of operations

Yearly electrical energy consumption **1.9 K < 2.5 TWh**

Magnet temperature **4.5 K < 2.0 TWh**

Possibly lower energy consumption and higher COM Energy with HTS!

… also an ion collider