Dancing in the dark

Exploring dark sectors at colliders, present and future

Rebeca Gonzalez Suarez (Uppsala University) - Helsinki Cosmology seminar

- High energy physics studies the Universe at its smaller distances → the building blocks of matter
- As a discipline, it started with the study of cosmic rays but today we use particle accelerators
- Our current best tool is the **Large Hadron Collider, at CERN in Geneva**

- The LHC is a particle accelerator and collider
  - Collides protons and heavy ions, up to 13.6TeV
- 27 km in circumference, 100 m underground
- Superconducting magnets steer the particles around the ring
  - 1.9 K (-271.3°C), colder than the 2.7 K (-270.5°C) of outer space
- It has four collision points and on each on them there is a detector


CMS
LHC
LHC
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Prevessin
ALICE
LHCb
ATLAS
CERN
Meyrin
1 km


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LHCb
> 5,000 people each
CMS
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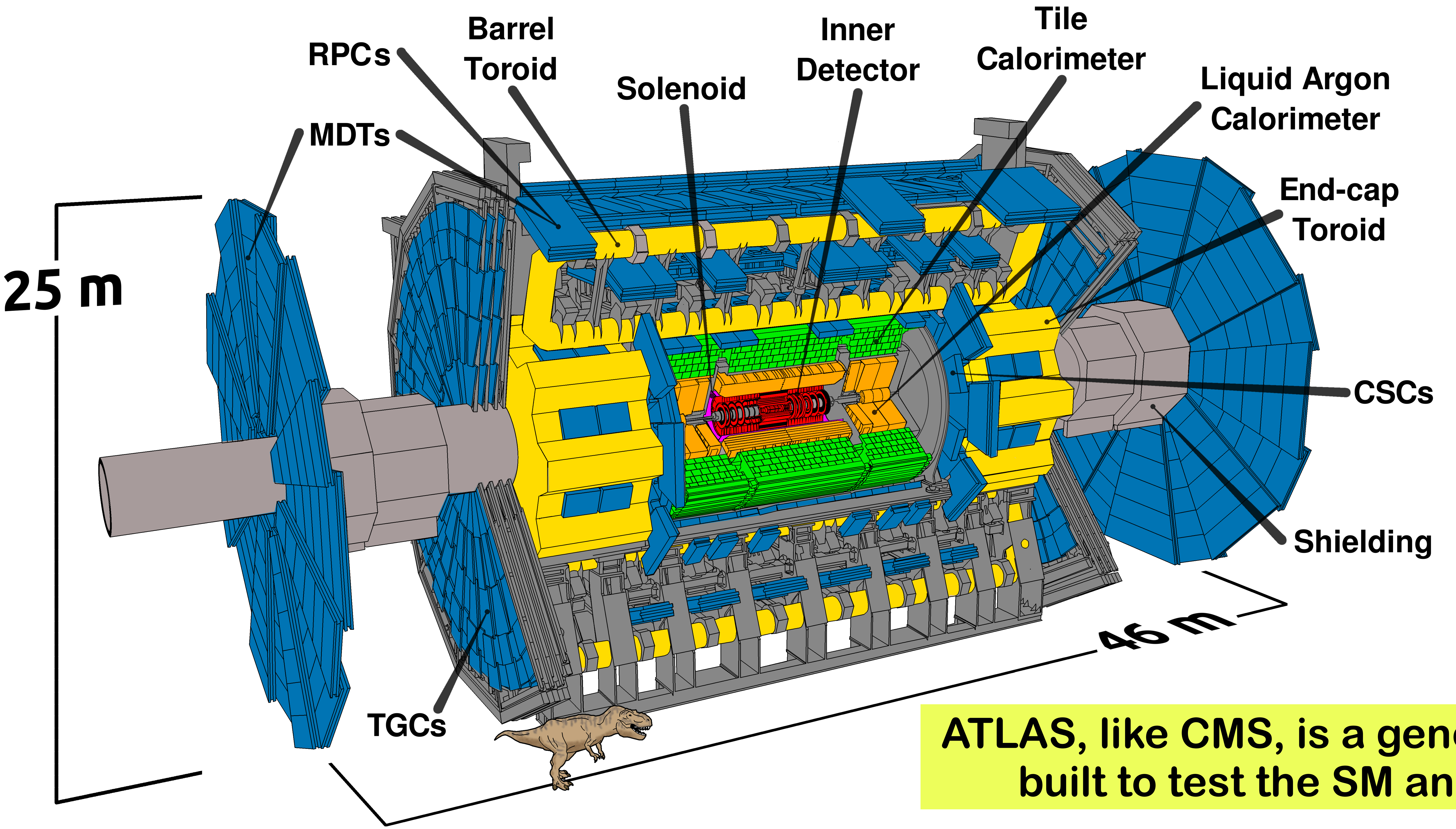
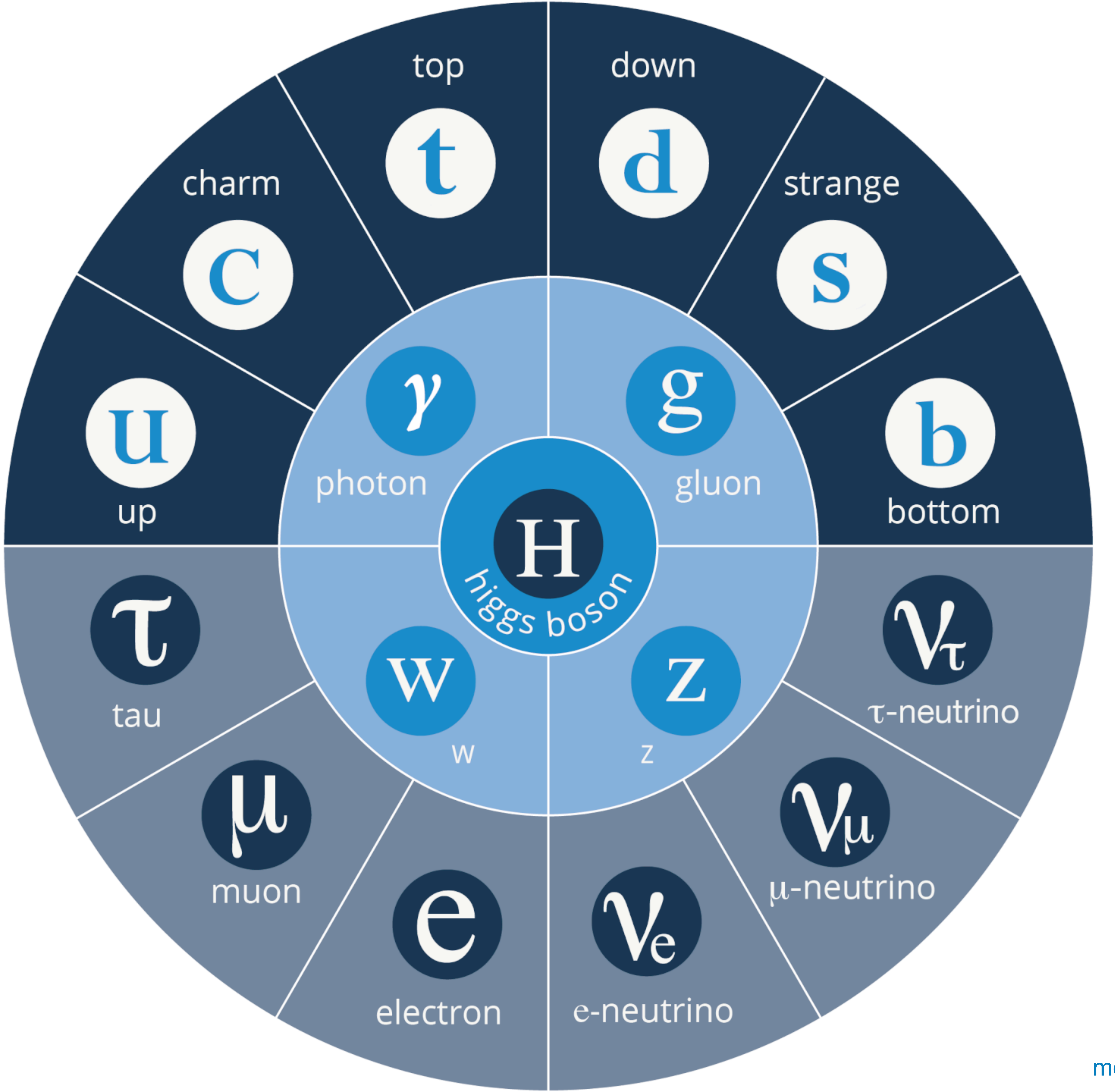
LHCb
ALICE

46 m long, 25 m high, 25 m wide
7000 t of weight
3000 authors, 1200
studetns, 182 institutions, 42 countries



ATLAS, like CMS, is a general-purpose detector, built to test the SM and find new physics

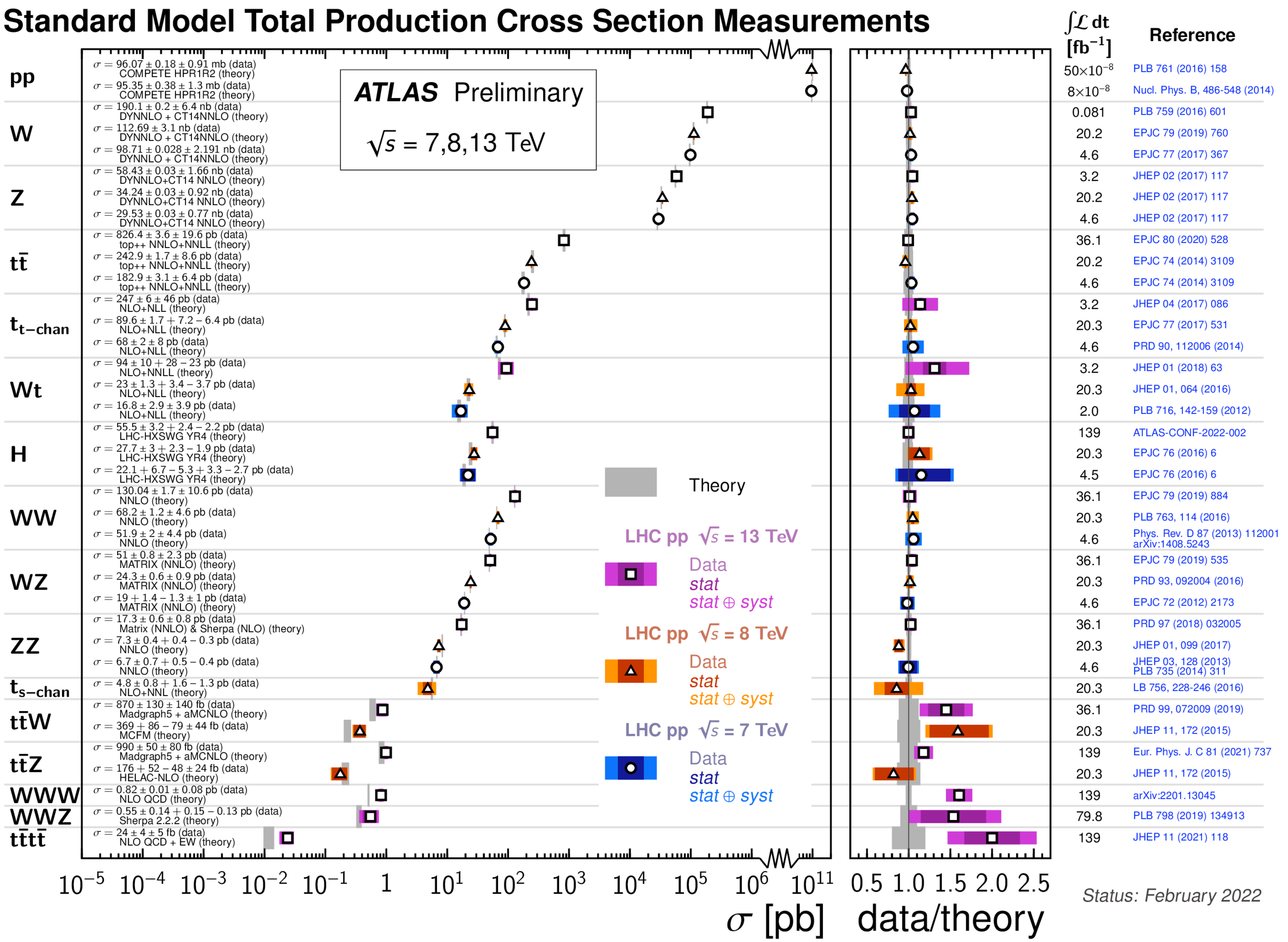


- These are all the **elementary particles** found so far, that cannot be broken into smaller pieces

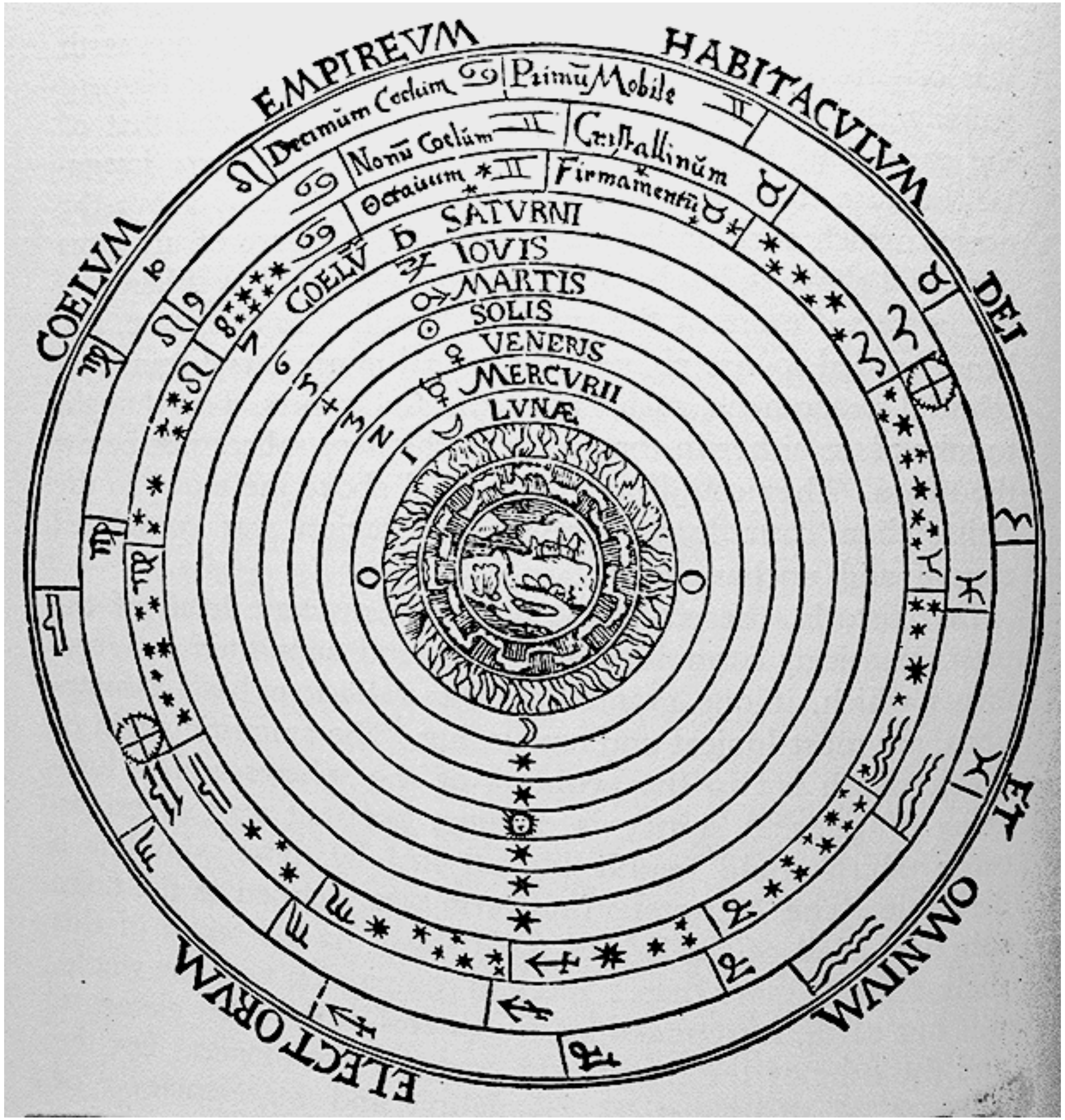
- What we know about them, including the **forces** that act among them, conforms **the standard model of particle physics**

The situation

- After decades, the standard model has been thoroughly tested
  - It is robust and provides extremely precise predictions
- It works really great



But in the past we had examples of predictive, scientific models that worked great while being inherently wrong.



The Aristotelian Ptolemaic system was remarkably plausible and powerful as a scientific theory but it was known that it had some “imperfections” (some of them required some fine tuning)

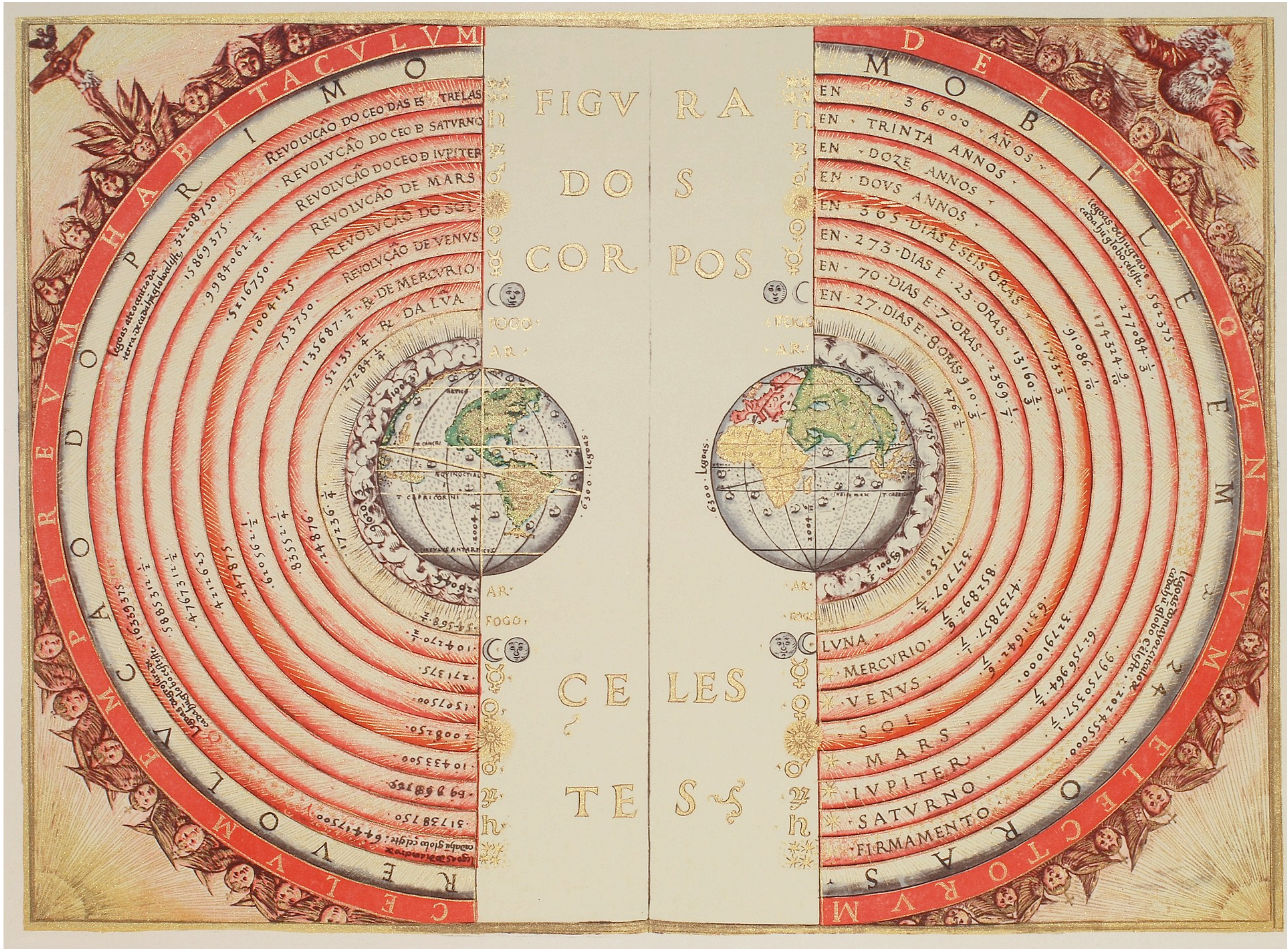
Our model

Does have some “imperfections”

- Neutrinos seem to have masses but the SM does not contemplate them
- The masses of the other particles are weird
- The SM cannot describe some really important effects
    - **Dark matter, dark energy, gravitation**
- It has tuning and hierarchy problems…

- [x] Higgs boson
- [ ] SUSY
- [ ] Extra dimensions
- [ ] Dark matter origins
- [ ] Dark energy origins
- [ ] Compositeness
- [ ] Technicolour
- [ ] New gauge bosons
- [ ] Right-handed neutrinos
- [ ] Mini black holes

Leon Lederman’s speculative laundry list for the LHC
Nature Review Article: “Beyond the standard model with the LHC” (2007)



This model was canon from the year 150 until the 16th century

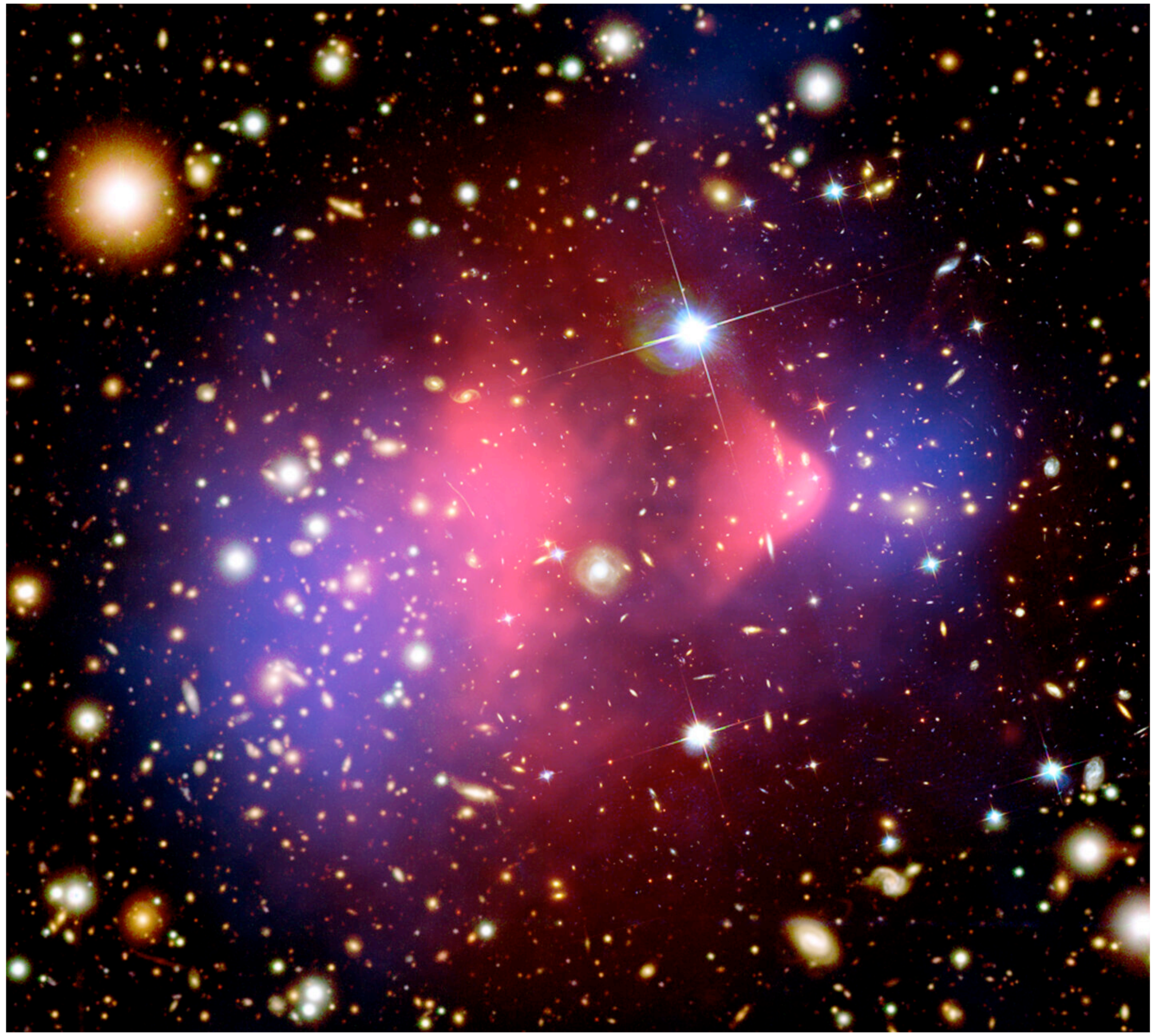
The goal is not to take so long this time around!

How do we start?

Let's pick one question

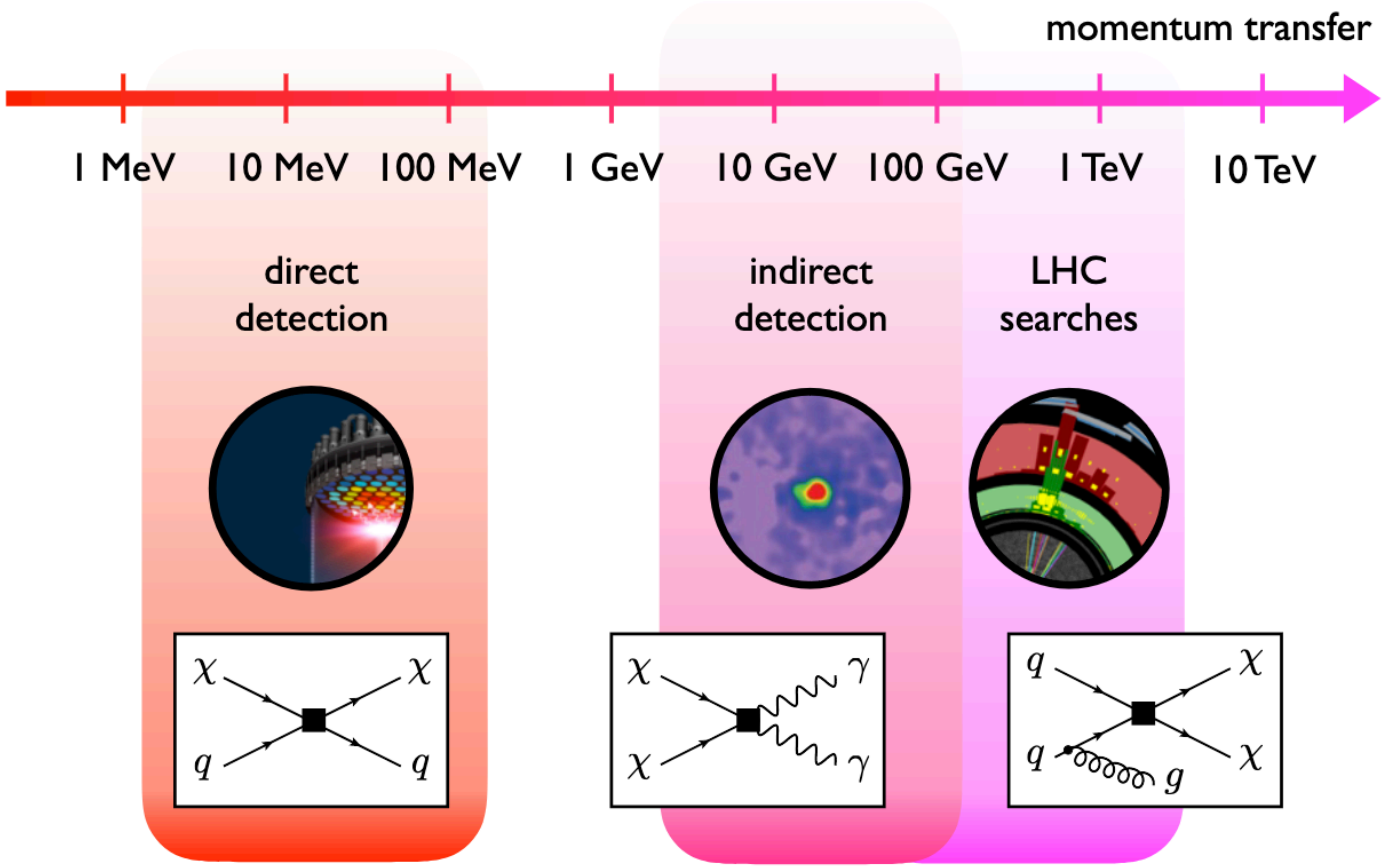
Dark matter is a good one, ⅘ of the matter in the Universe

- That dark matter exists is a well-established experimental fact
  - rotation curves of galaxies, dynamical evidence (e.g. the Bullet cluster and the variations in the Cosmic Microwave Background (CMB)), and the large-scale structure of the universe
    - Cannot be explained by Modified Newtonian Dynamics
- Seems like DM only interacts via gravity (so far!)



How to find dark matter?

Three complementary approaches

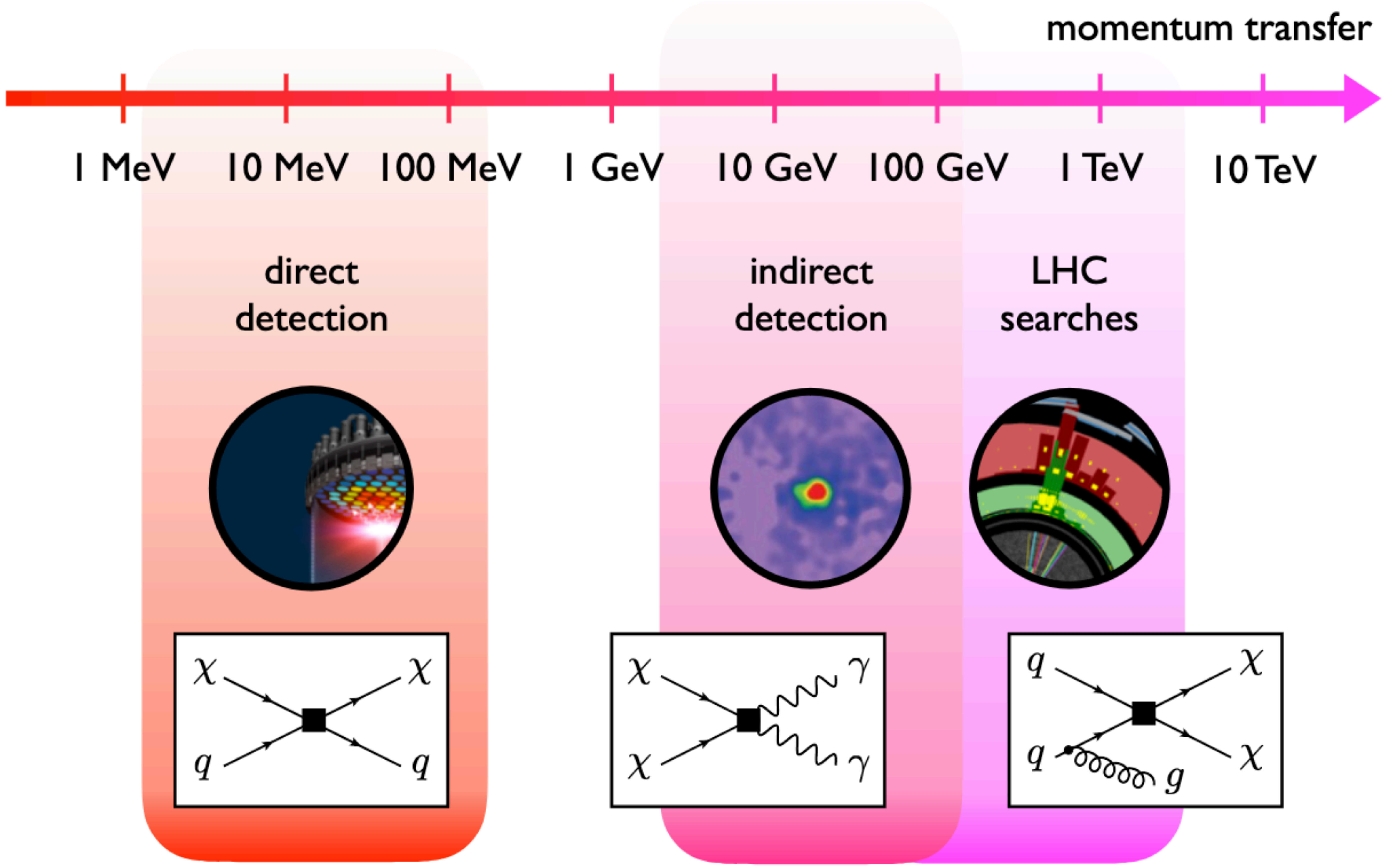


Range of momenta probed in DD experiments, ID experiments and LHC searches

- Direct detection experiments: scattering between DM and nuclei targets in underground laboratories
- Indirect detection experiments: Looking for fluxes of gamma-rays, cosmic-rays, neutrinos, anti-matter originated from dark matter annihilation
- Collider experiments

How to find dark matter?

Three complementary approaches



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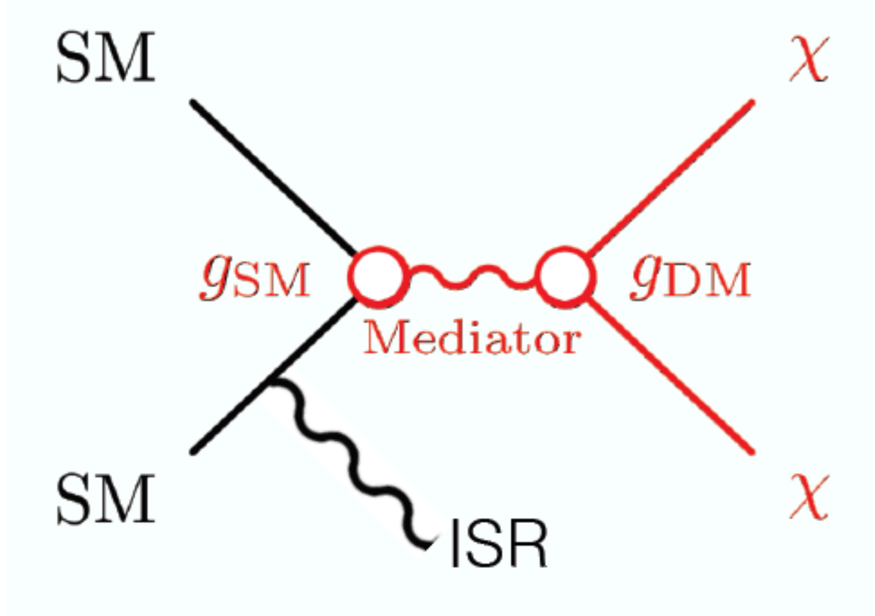
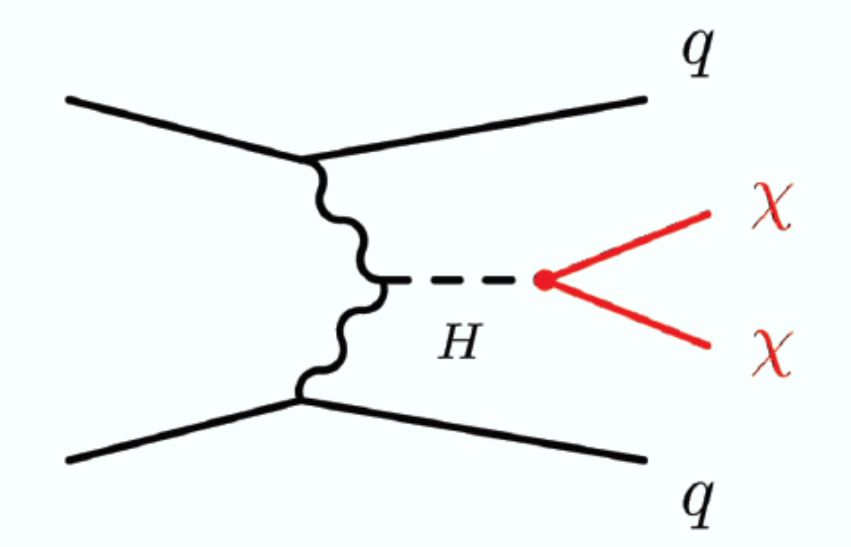
- Indirect detection experiments: Looking for fluxes of gamma-rays, cosmic-rays, neutrinos, anti-matter originated from dark matter annihilation
- Collider experiments **This talk!**

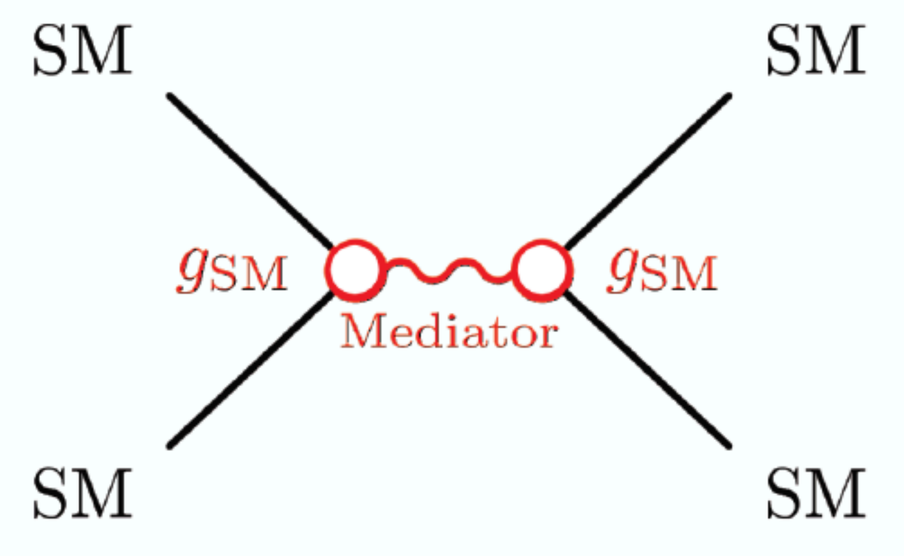
At the LHC

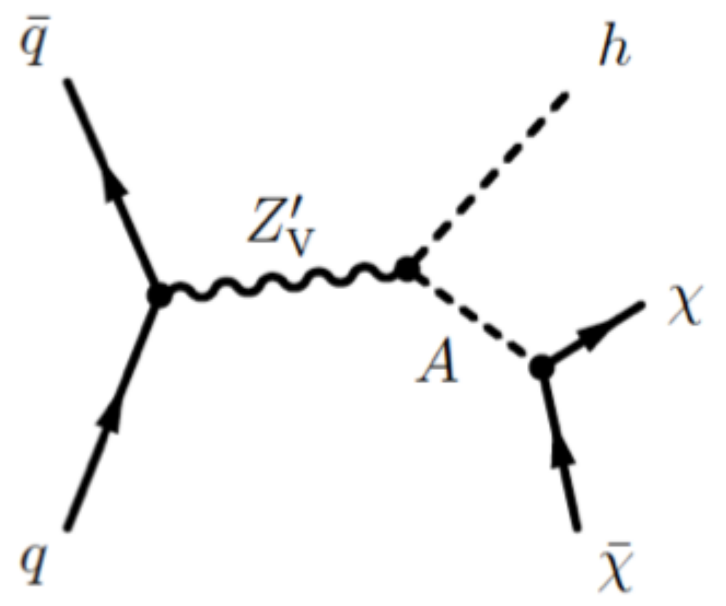
There are many options to explore and many different searches

- Three complementary philosophies, increased complexity: EFT, simplified models, complete models (SUSY, pMSSM)
- Broad general categories:
  - MET + X: monojet, mono-Z…
  - Higgs to invisible: DM could enhance Higgs boson decays to invisible (0.1% in the SM)
  - Bump hunt for mediator decays to fermions
  - Searches for two Higgs doublet models

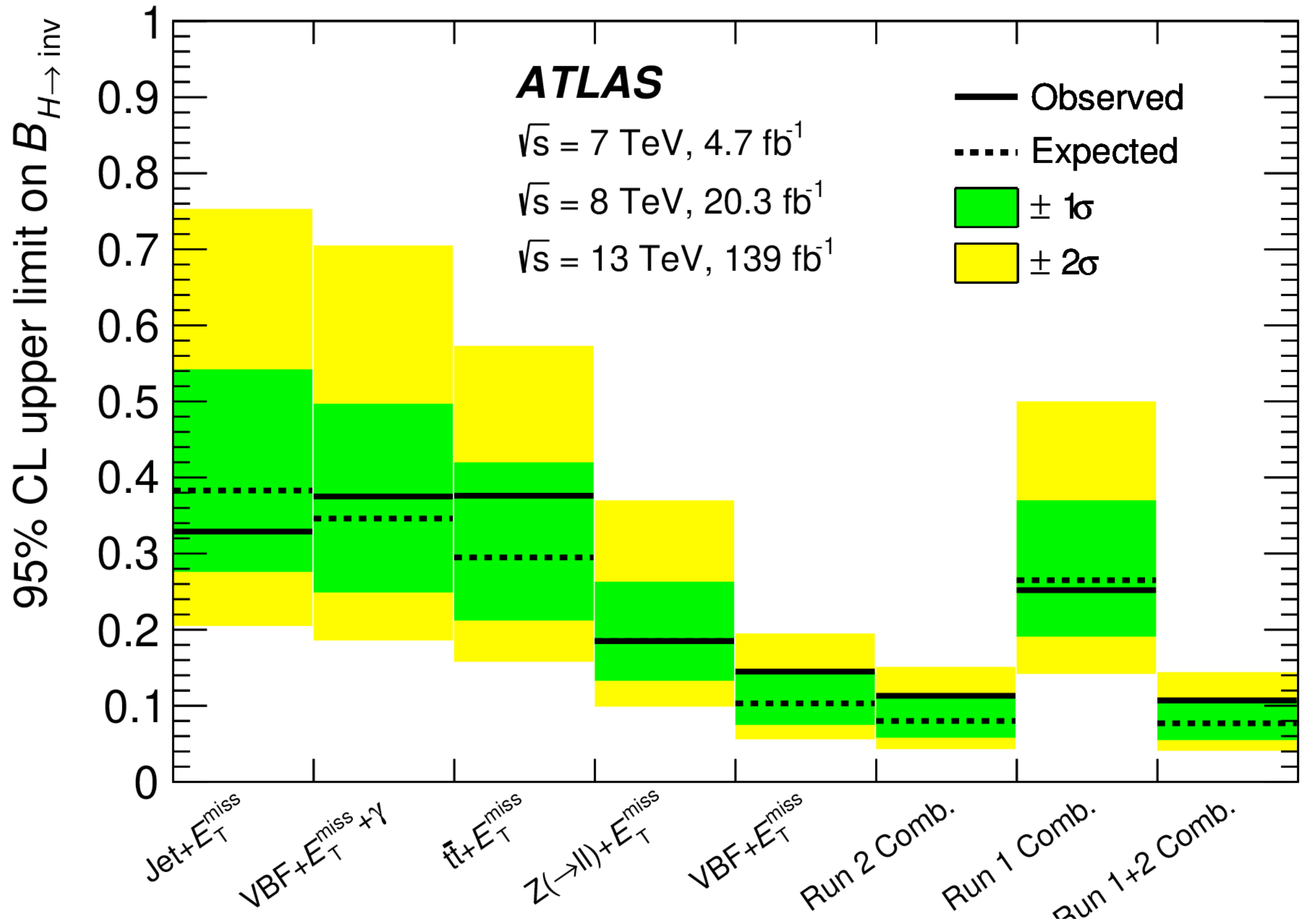


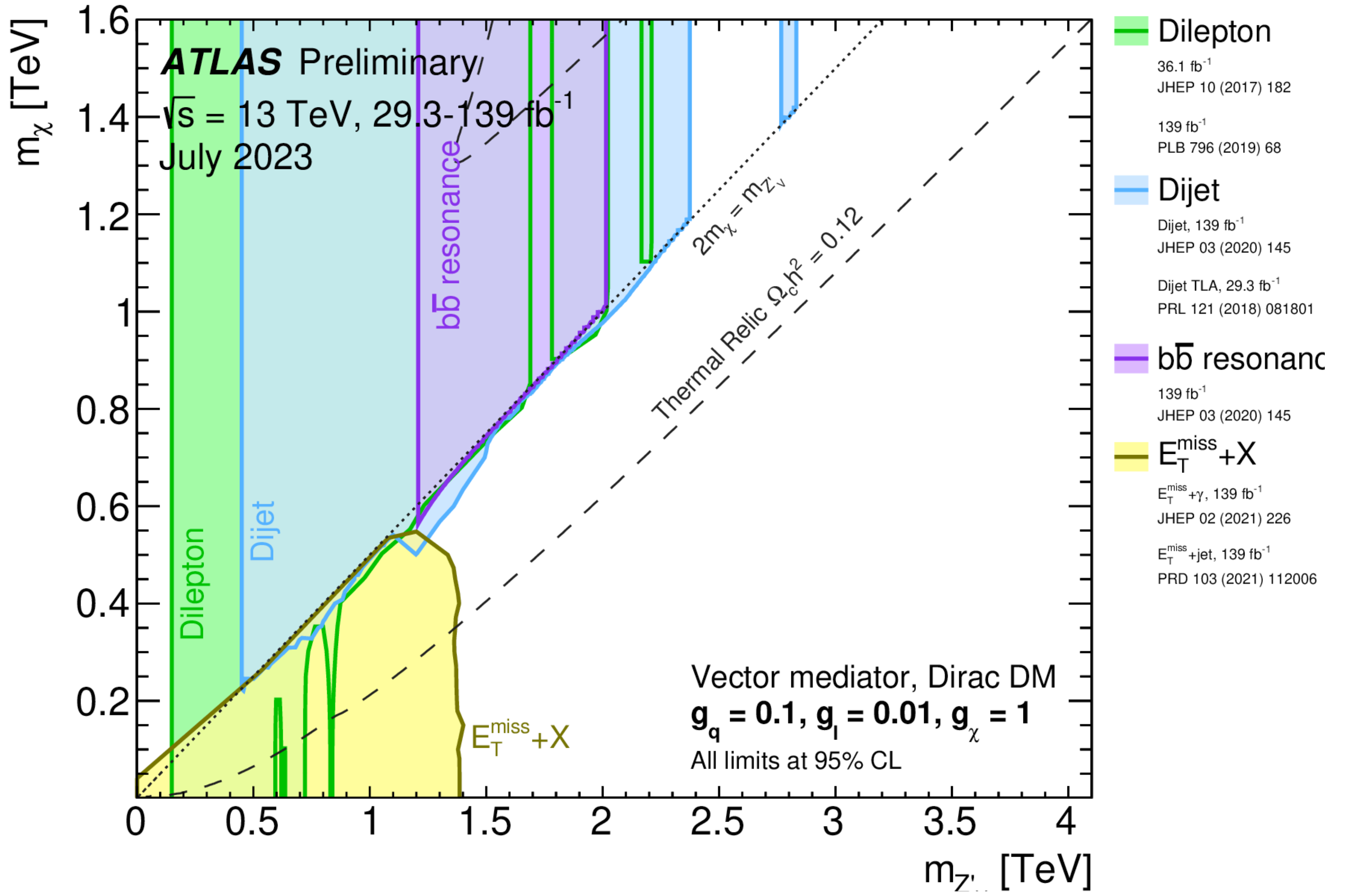


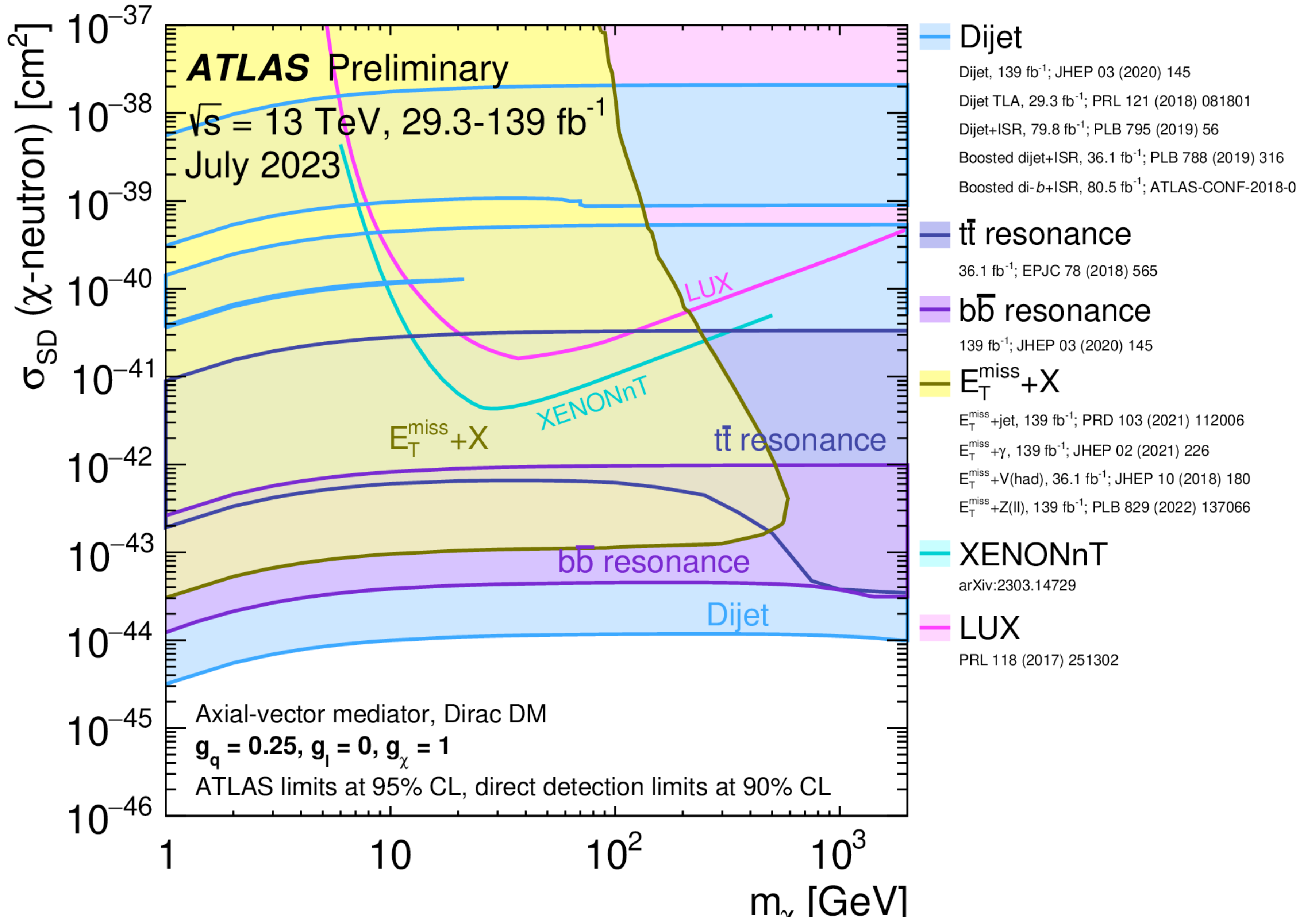


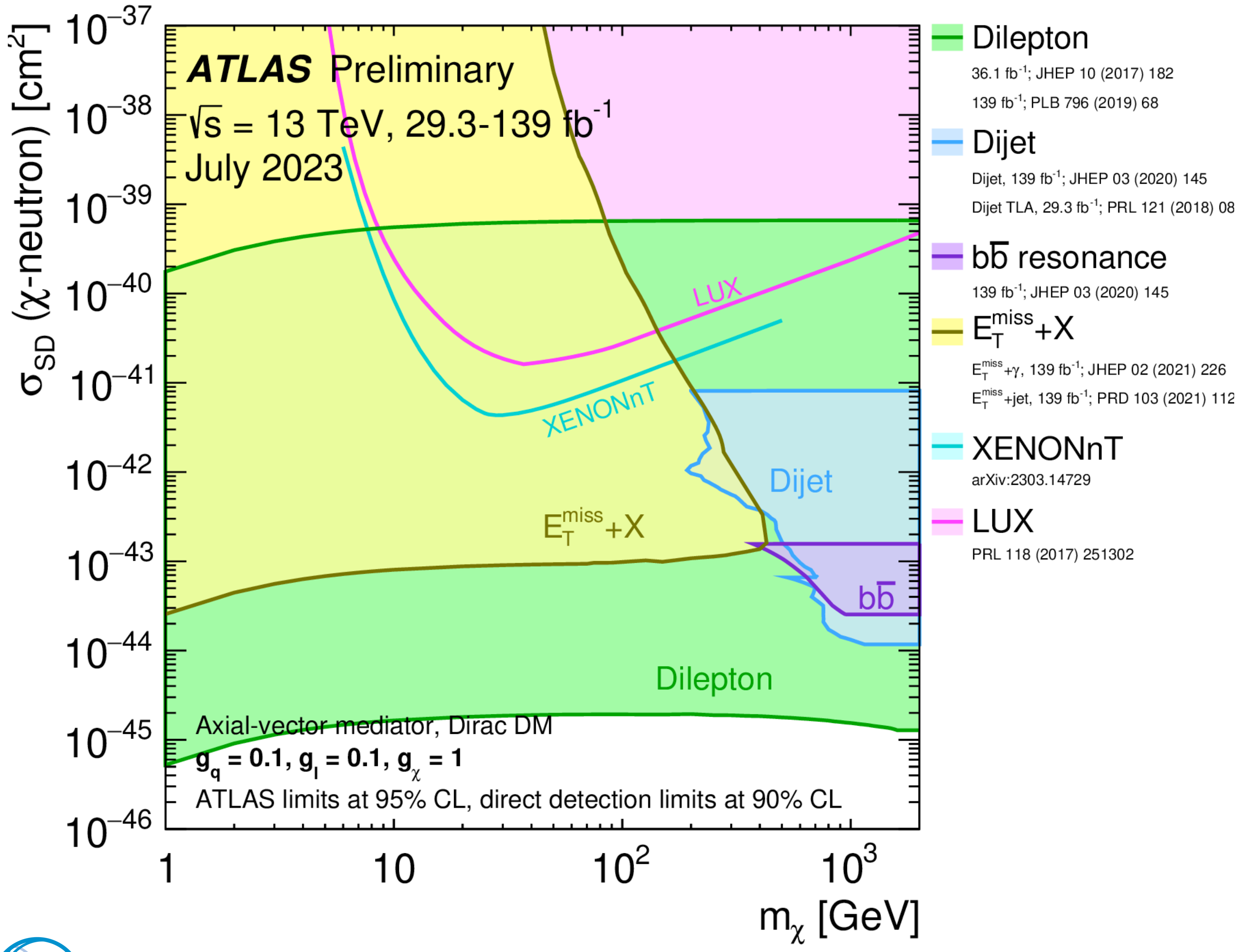


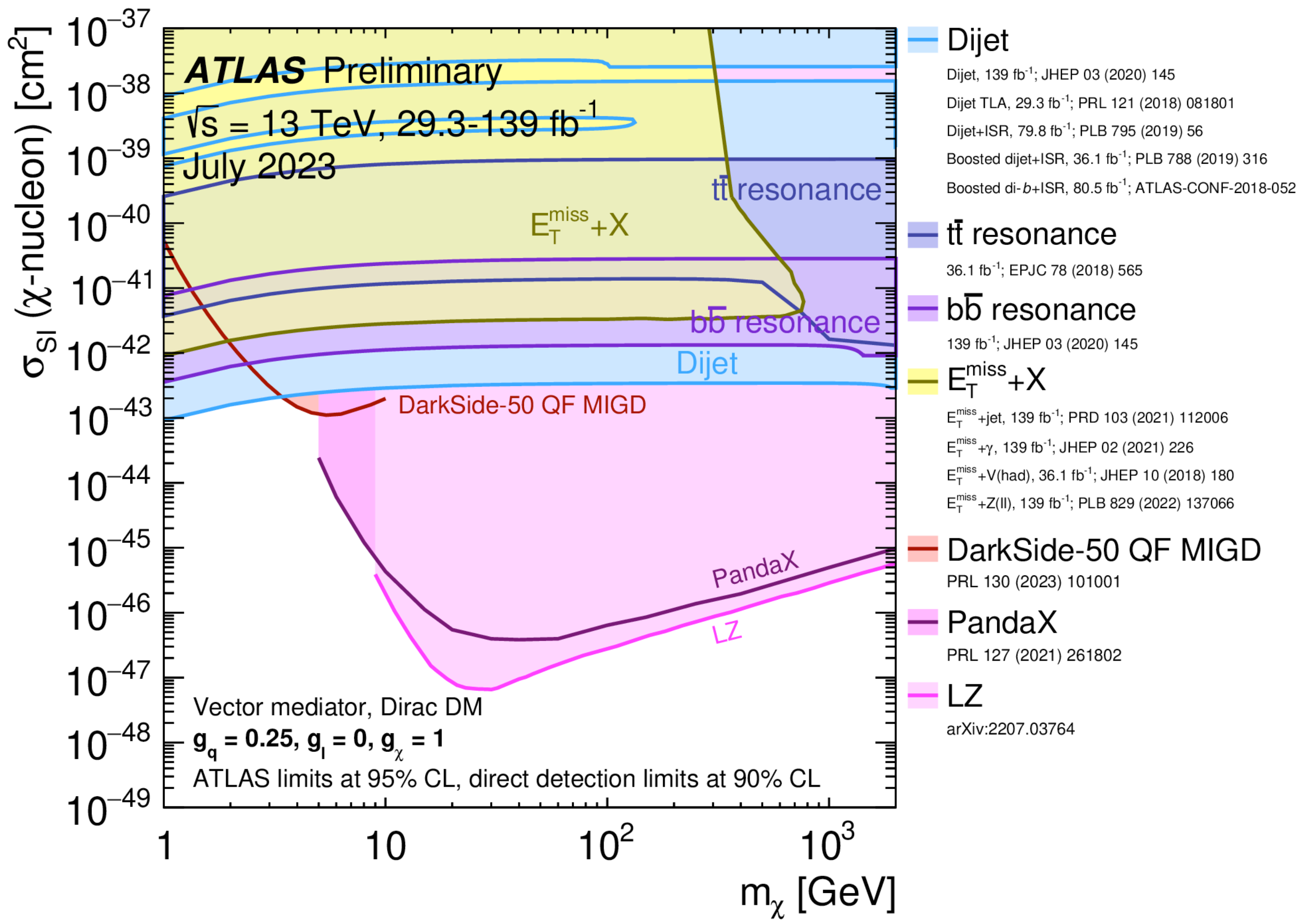
But those searches so far are not finding anything

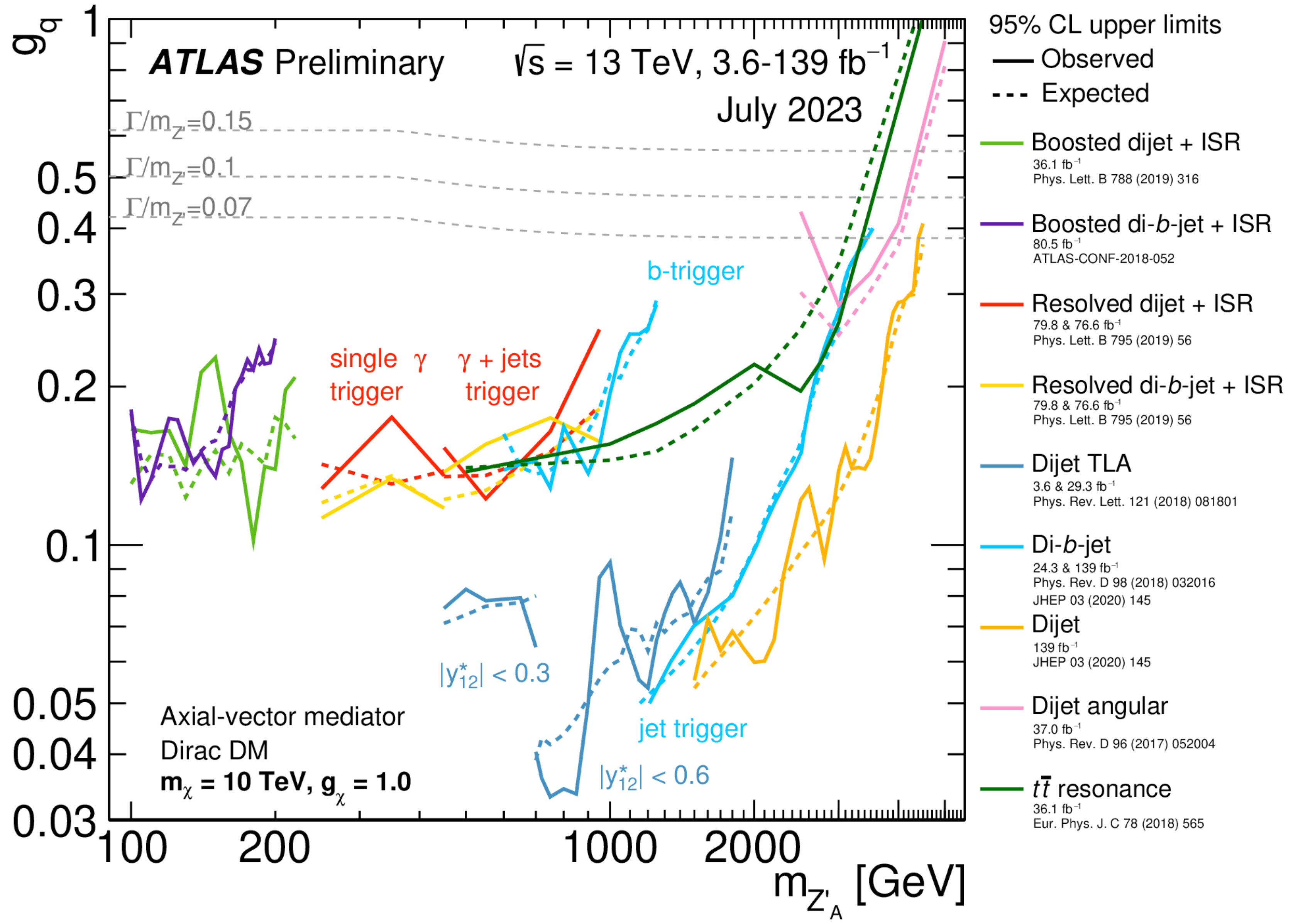












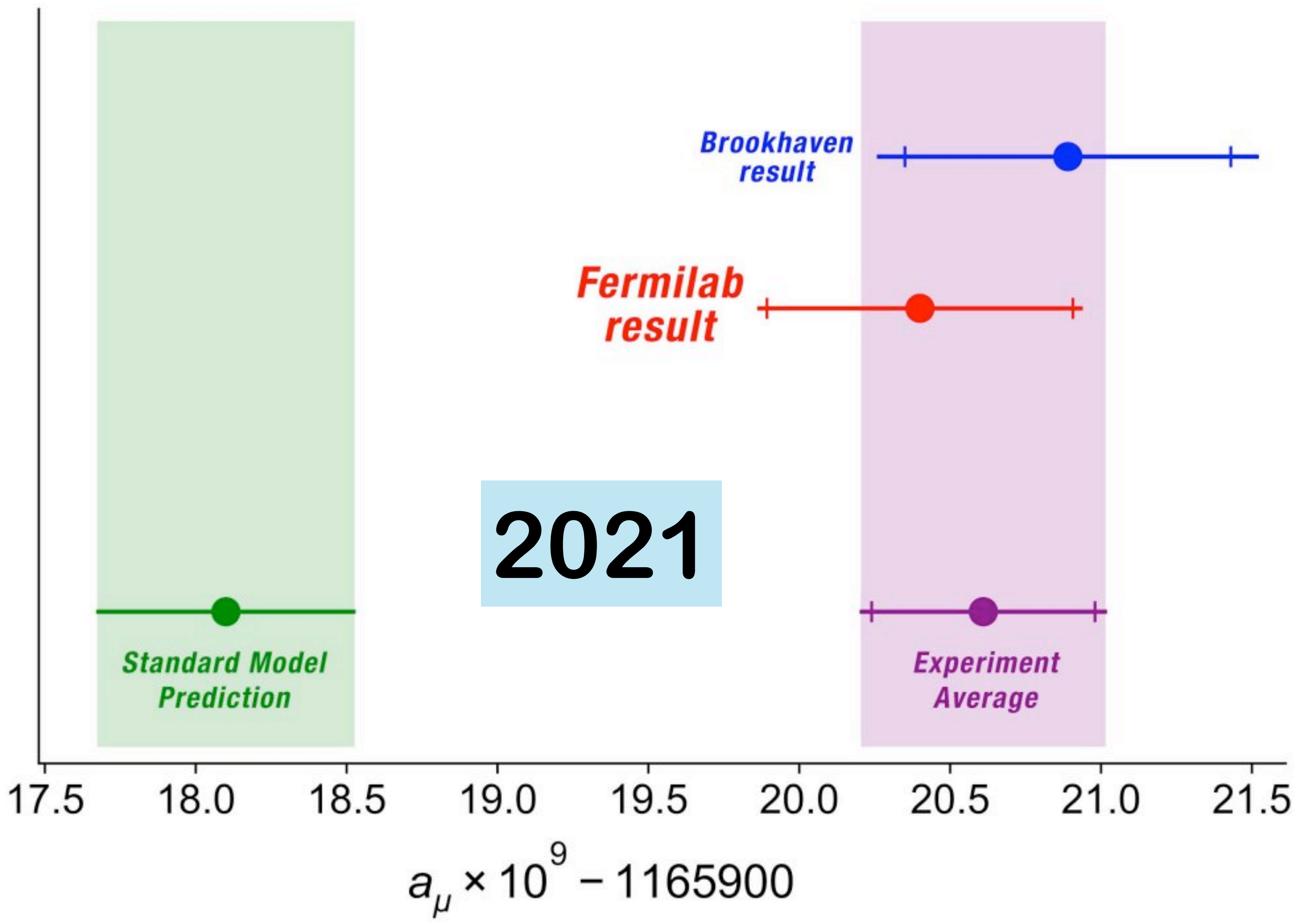
ATL-PHYS-PUB-2023-018 HIGG-2021-05

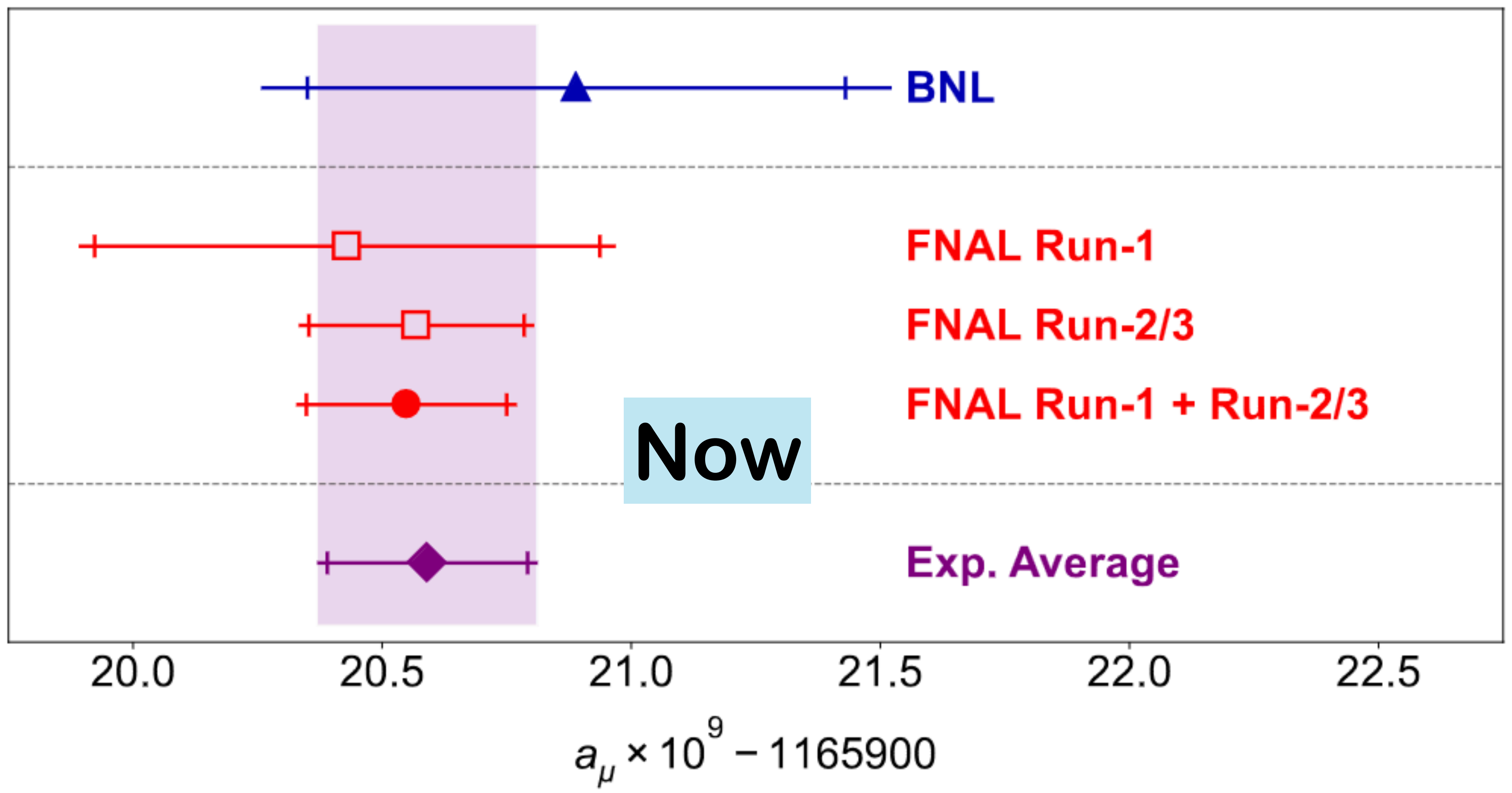
This is just ATLAS and only a very small fraction!

Time to look for alternatives

Dark sectors

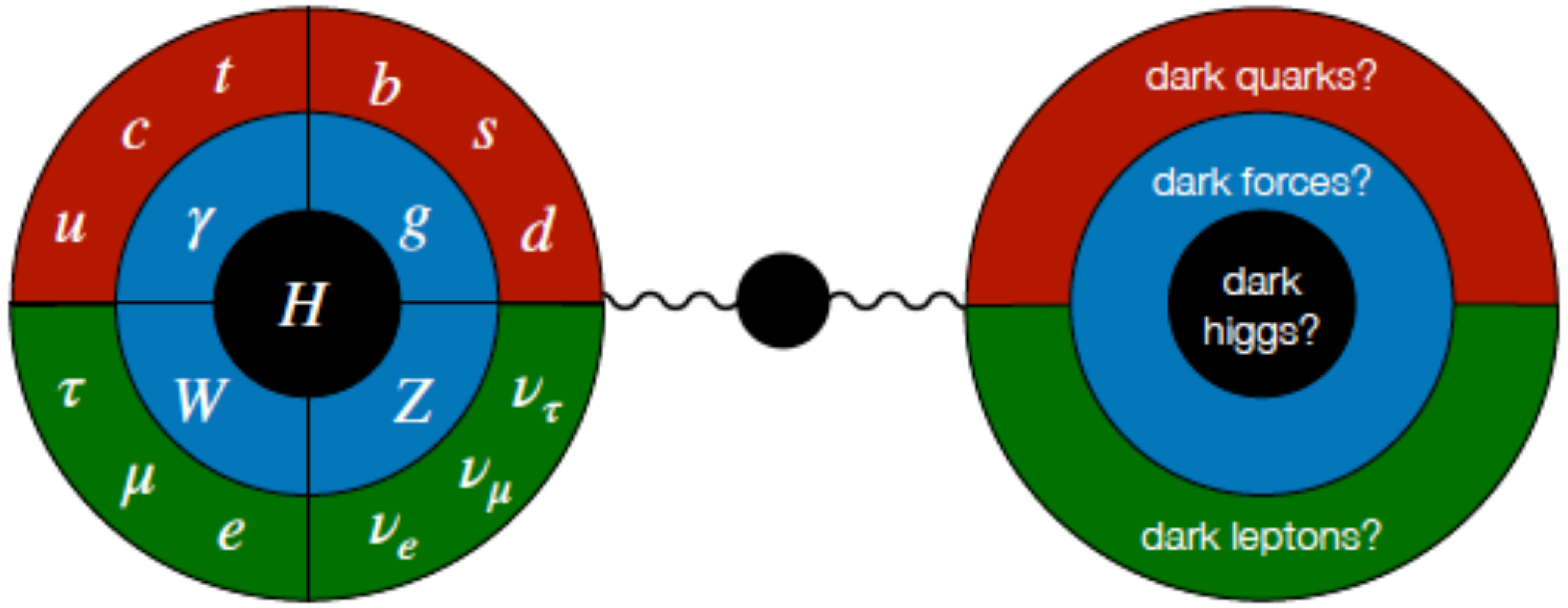
- Hidden sectors that mix almost imperceptibly with the SM and contain new, invisible particles and forces.
  - Could explain dark matter and other open questions in the field
  - Theoretically well-motivated and supported by effects like the muon g-2 anomaly





arXiv:2308.06230
5.2σ discrepancy

How do they look like



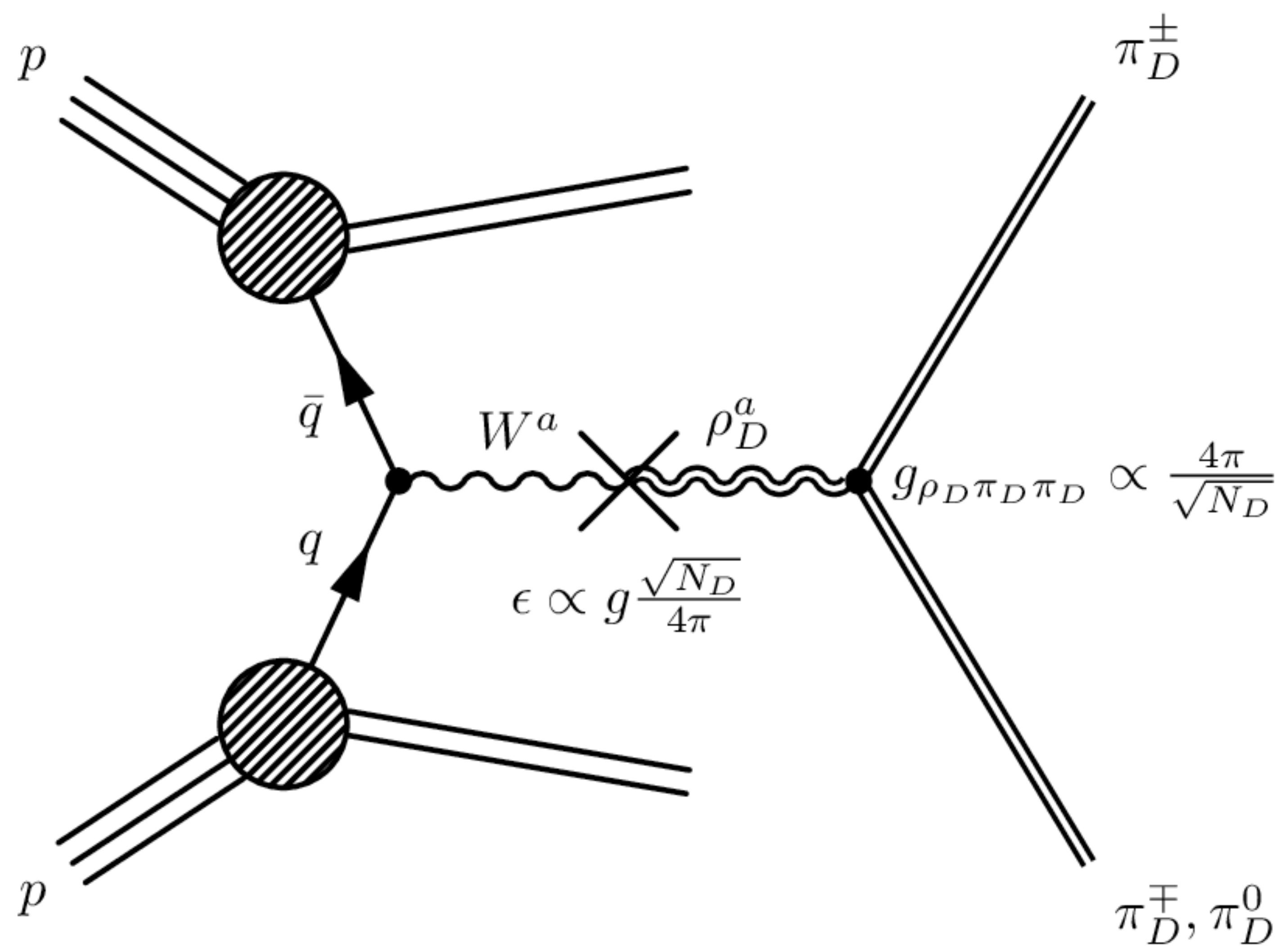
- Dark sectors typically include:
  - a **stable particle** (fundamental or composite), that could be a DM candidate; one or more **mediator particles** coupled to the SM via neutral portal
    - The spin of the mediator defines the portal: vector (e.g. dark photon), fermion (e.g. sterile neutrino), pseudoscalar, or scalar (e.g. Higgs portal)
- Often produce **non-mainstream experimental signatures, challenging to reconstruct or even detect** at colliders! (Which means that their potential is not yet full exploited)
  - **Long-lived particles, dark showers**…
  - Or **multiple top quarks with boosted jets**, like for example…

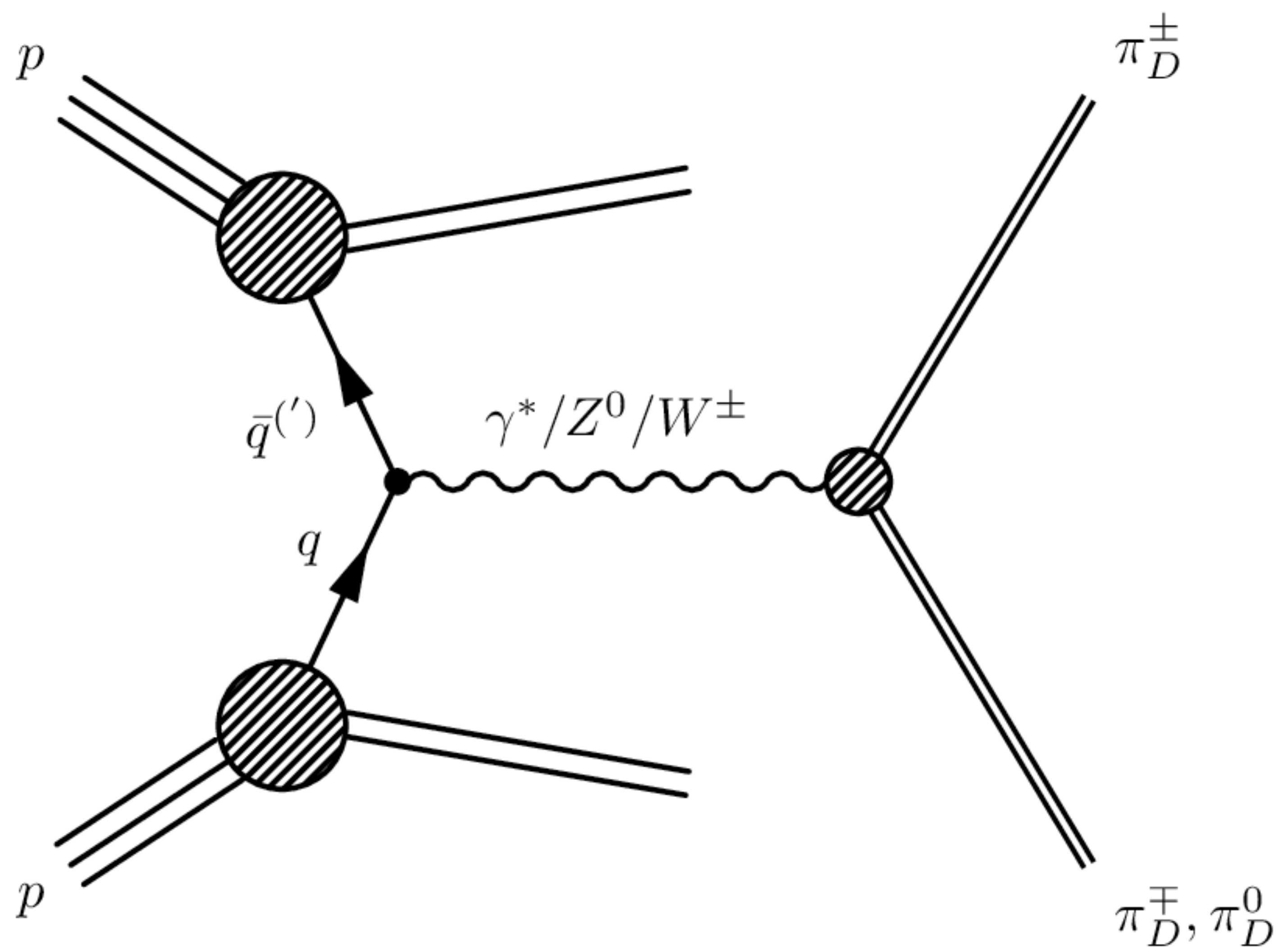
CONF note public (April)
ATLAS-CONF-2023-021

Work in progress in ATLAS

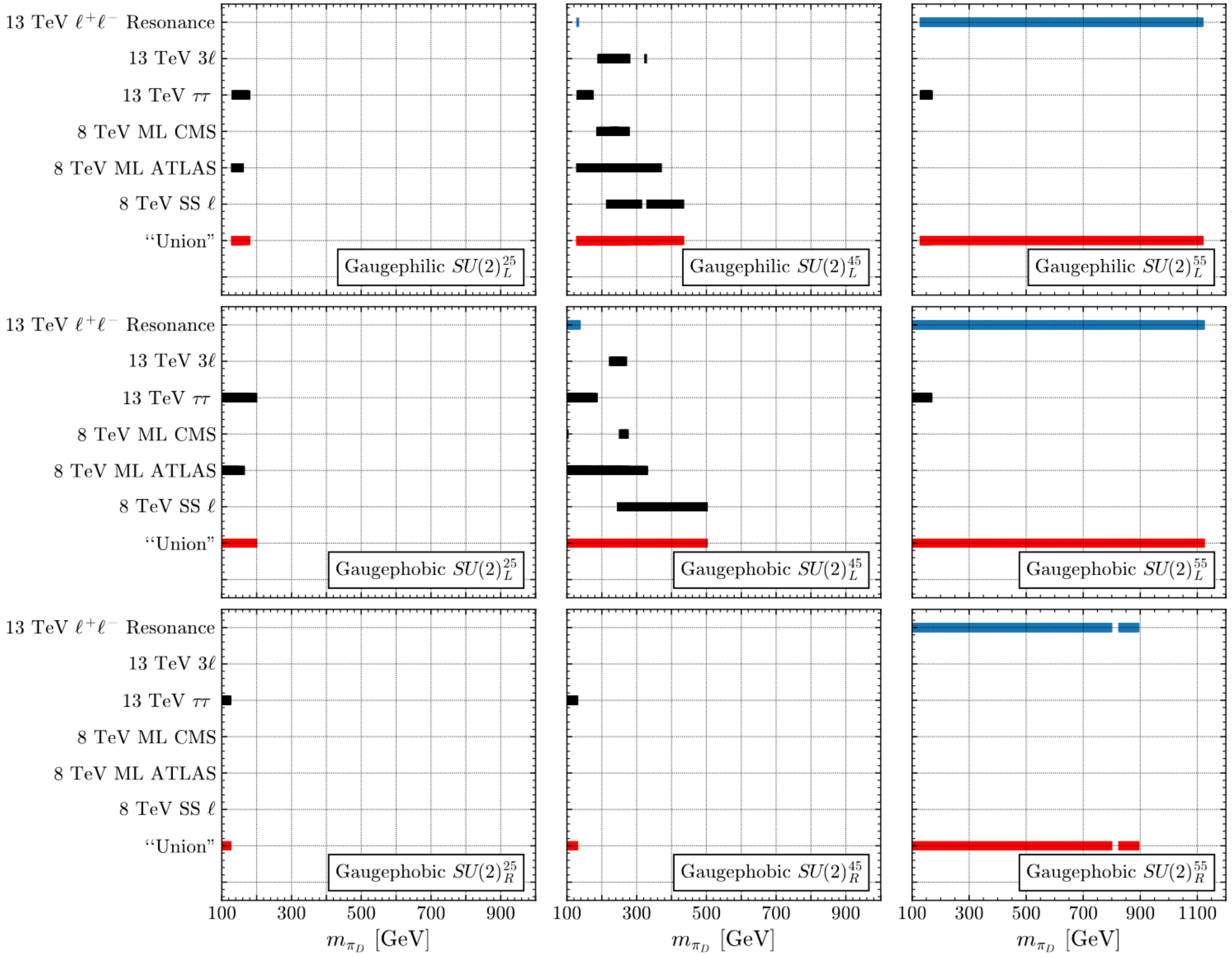
Searches for dark mesons in tttb and ttbb final states

- Higgs portal model of stealth dark matter → arXiv:1809.10184 arXiv:1809.10183
  - Dark mesons originating from strongly-coupled, SU(2) dark flavour-conserving models, decaying gaugephobically to pure SM final states containing top and bottom quarks





Why did we pick this model?


13 TeV $\ell^+\ell^-$ Resonance
13 TeV 3ℓ
13 TeV $\tau\tau$
8 TeV ML CMS
8 TeV ML ATLAS
8 TeV SS ℓ
"Union"
Gaugephilic $SU(2)^{25}_L$
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Gaugephilic $SU(2)^{55}_L$
Gaugephobic $SU(2)^{25}_L$
Gaugephobic $SU(2)^{45}_L$
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100 300 500 700 900
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m_{π_D} [GeV]
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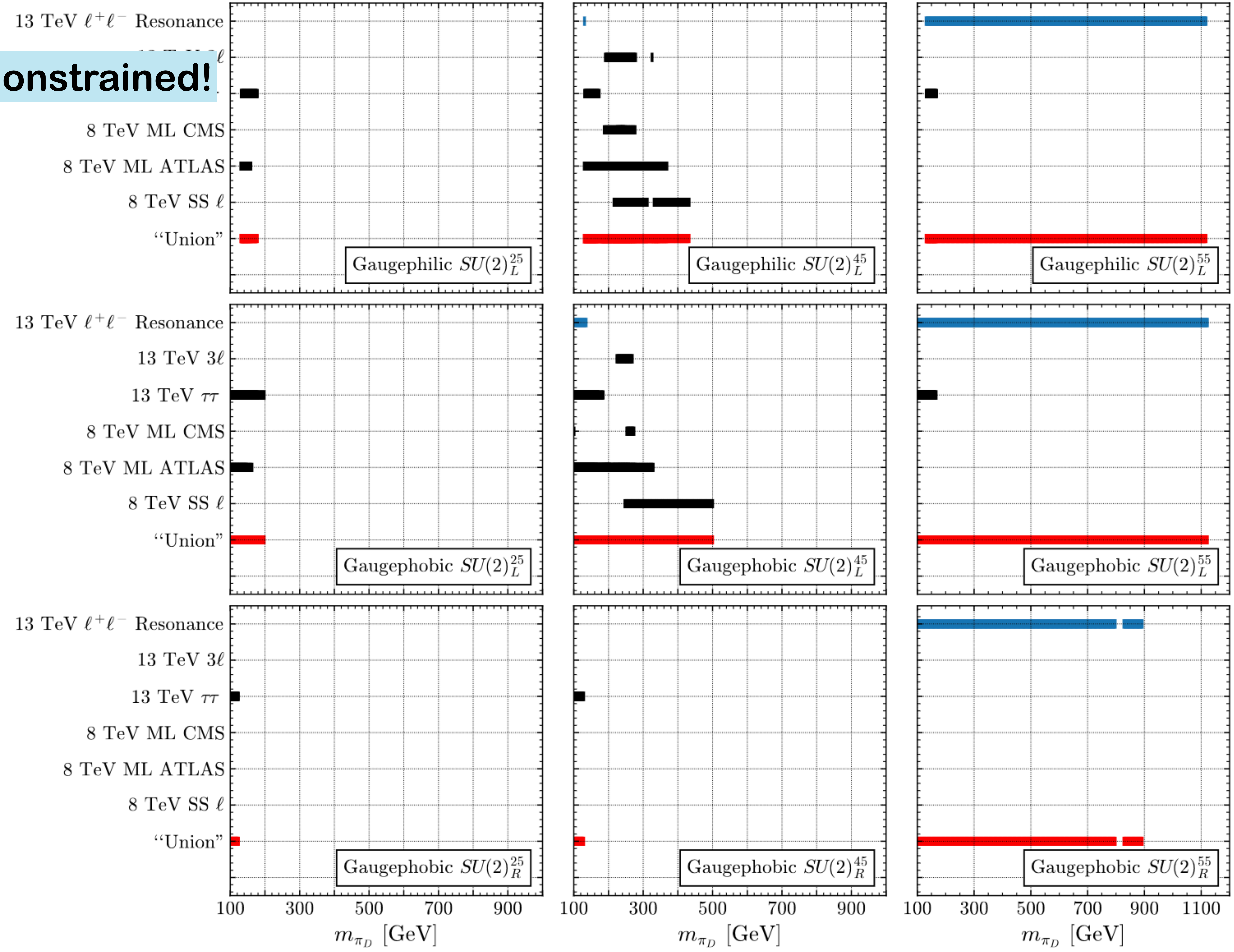
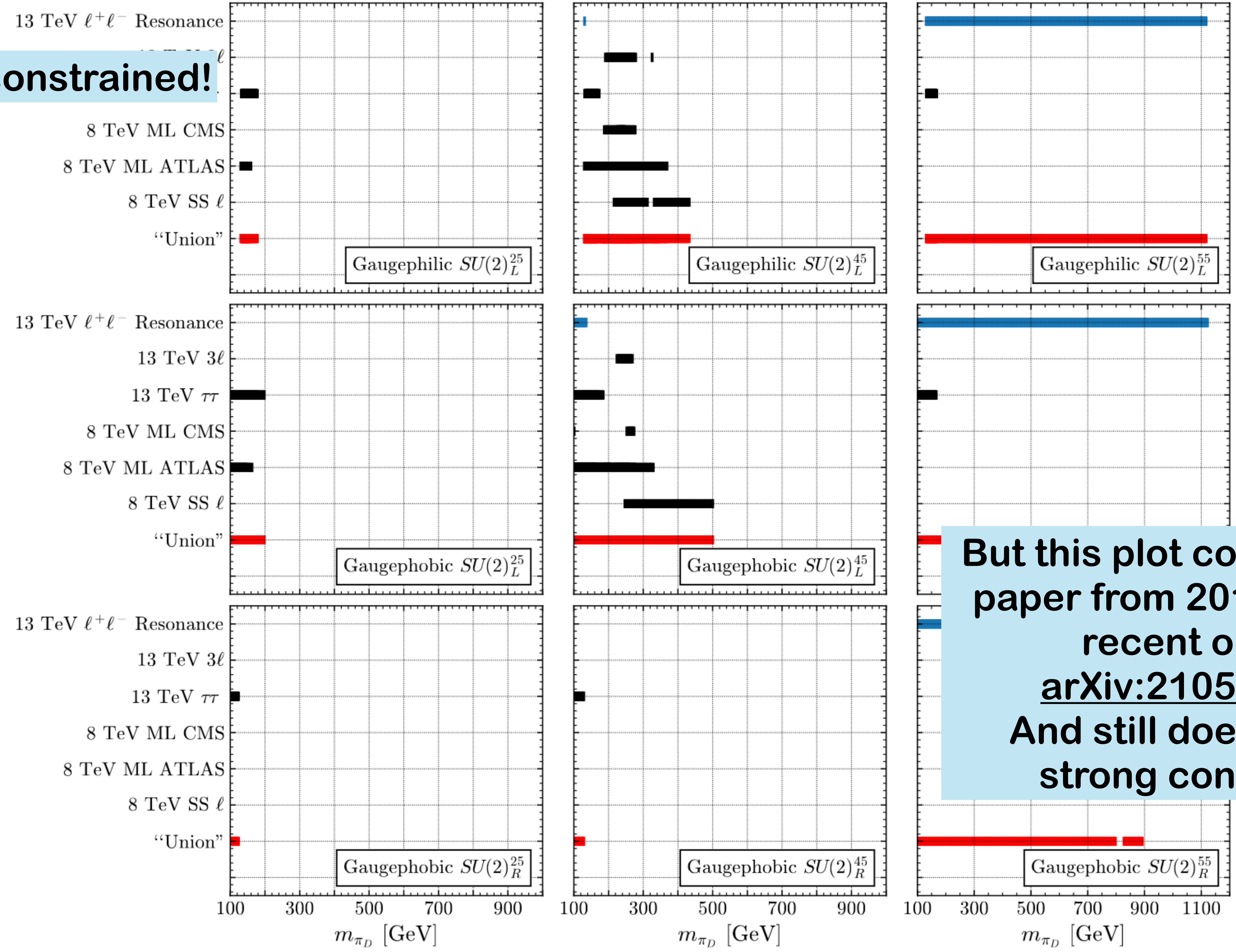
Almost unconstrained!



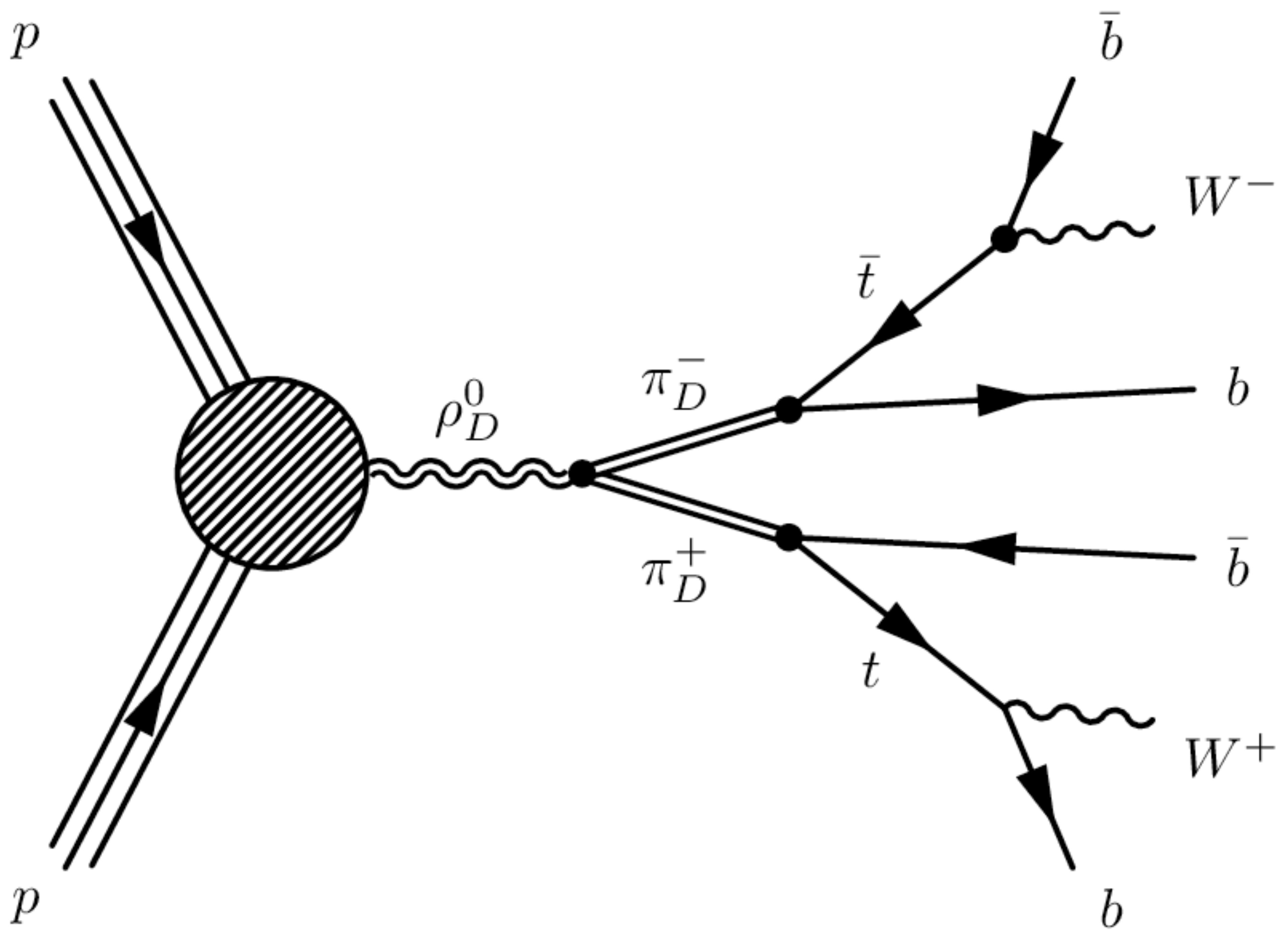
Almost unconstrained!



But this plot comes from a paper from 2018. A more recent one is arXiv:2105.08494
And still does not set strong constrains

It is admittedly painful

Challenging final state

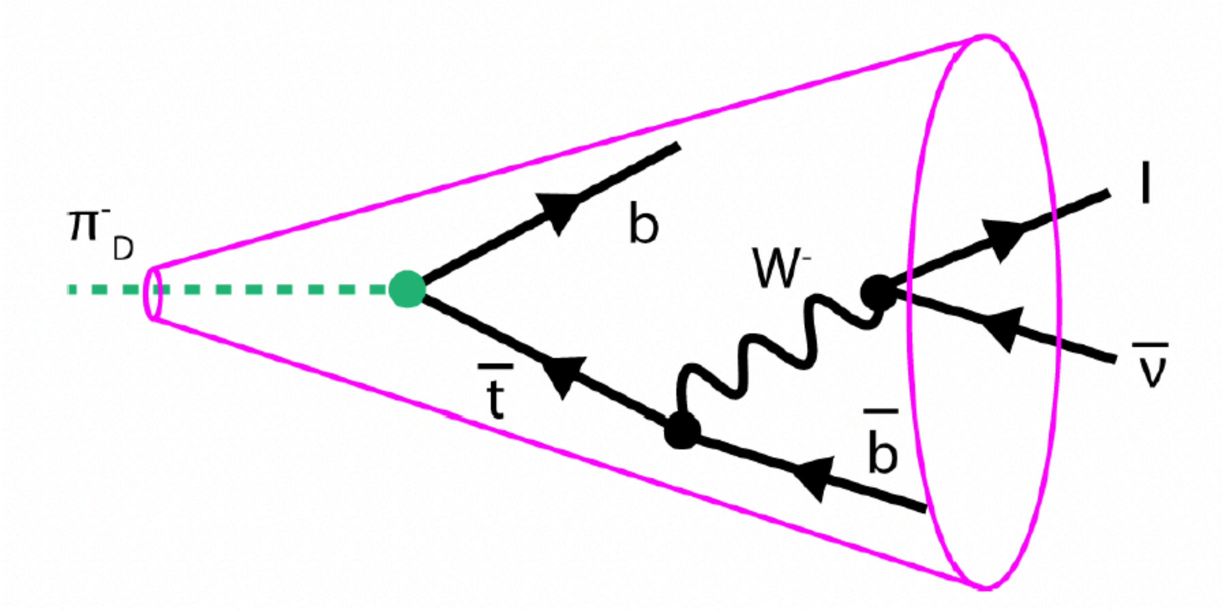


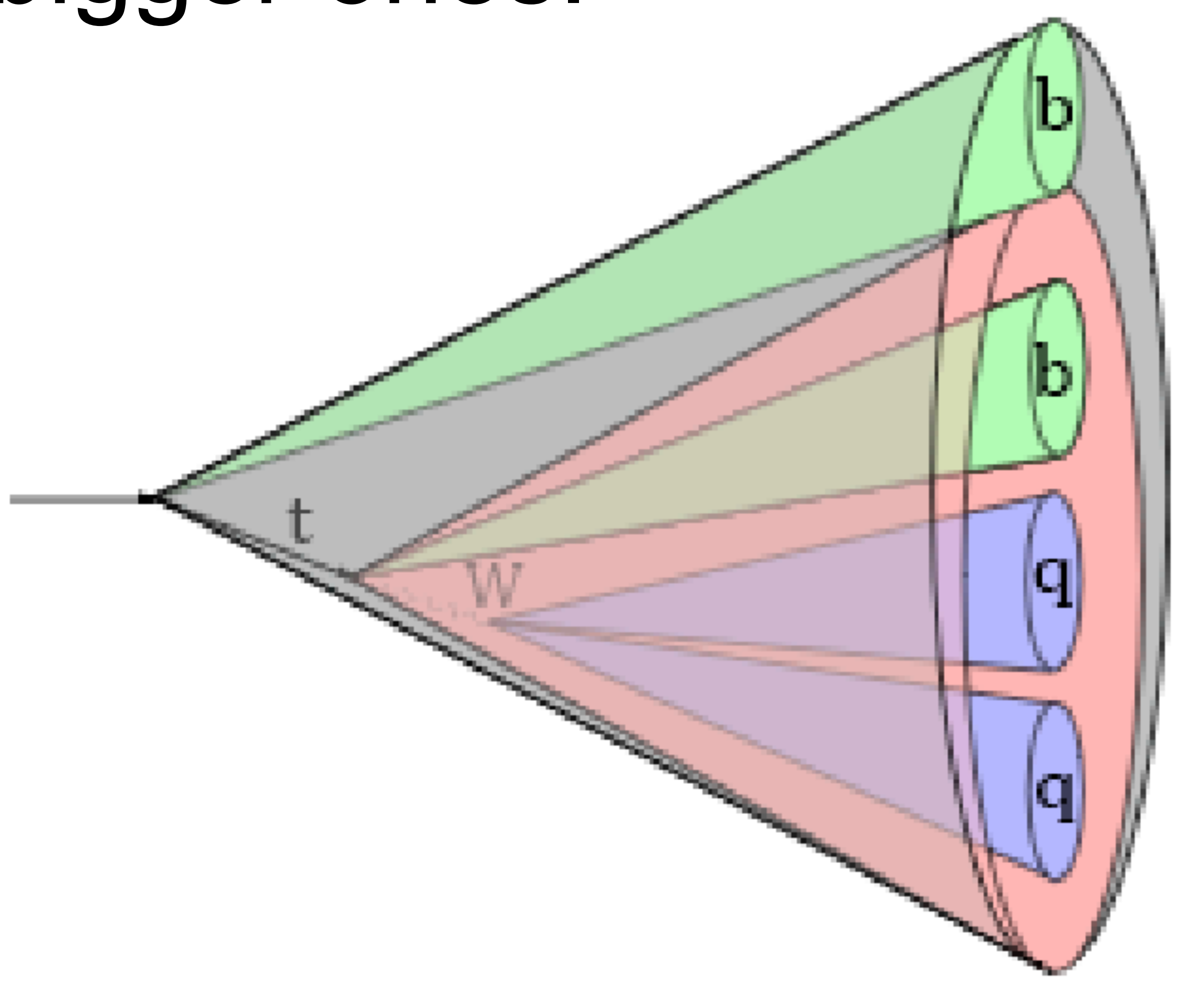
- Large ttbb background that is very difficult to model
- Set of tiny signals with varying kinematics across the grid
- Extreme phase space with many jets that depends heavily on b-tagging and jet reconstruction
- Affected by top p_T modelling issues
- A lot can be learn from ttH, H→bb and tttt (SM and BSM)

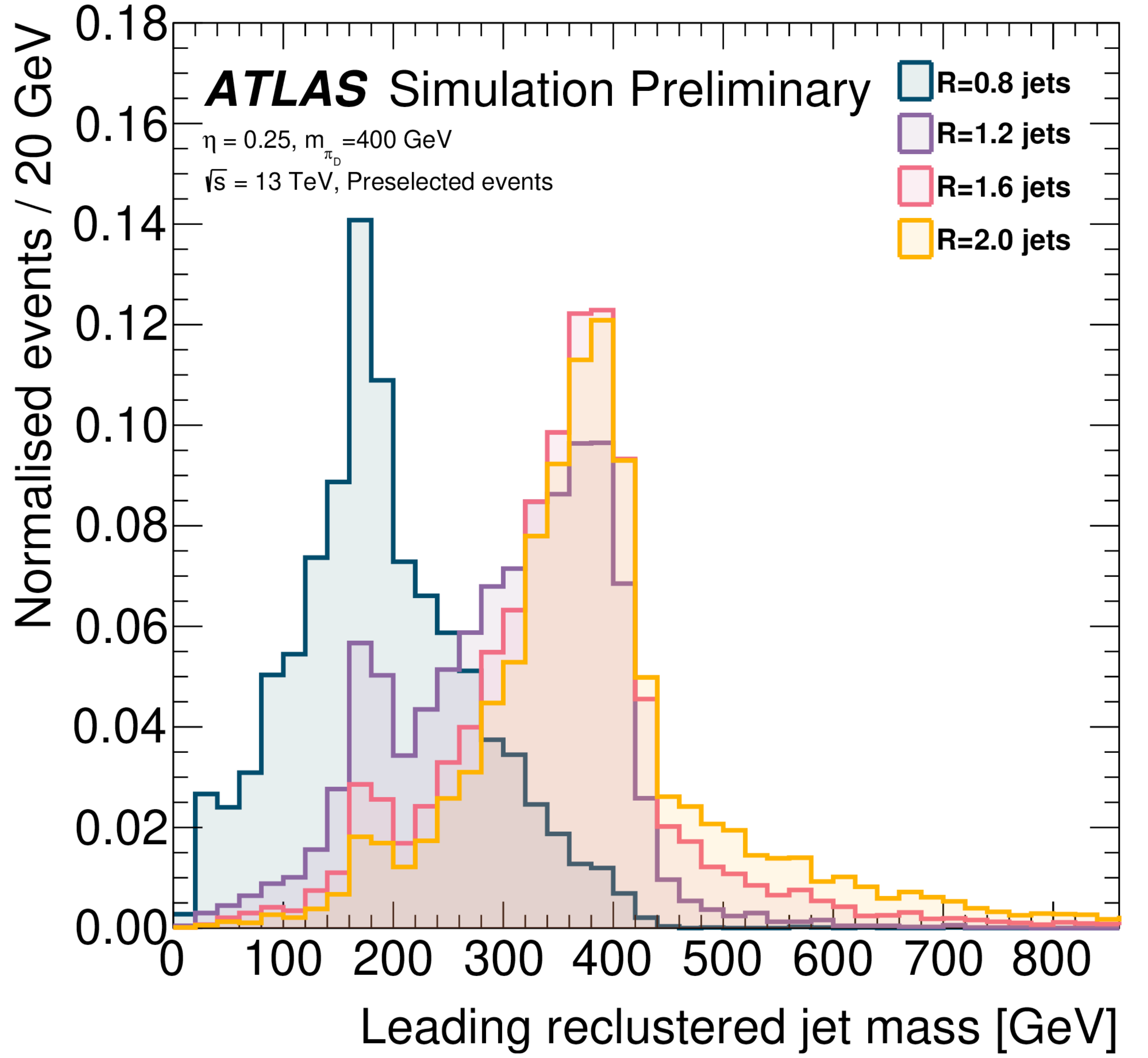
It is also very fun*!

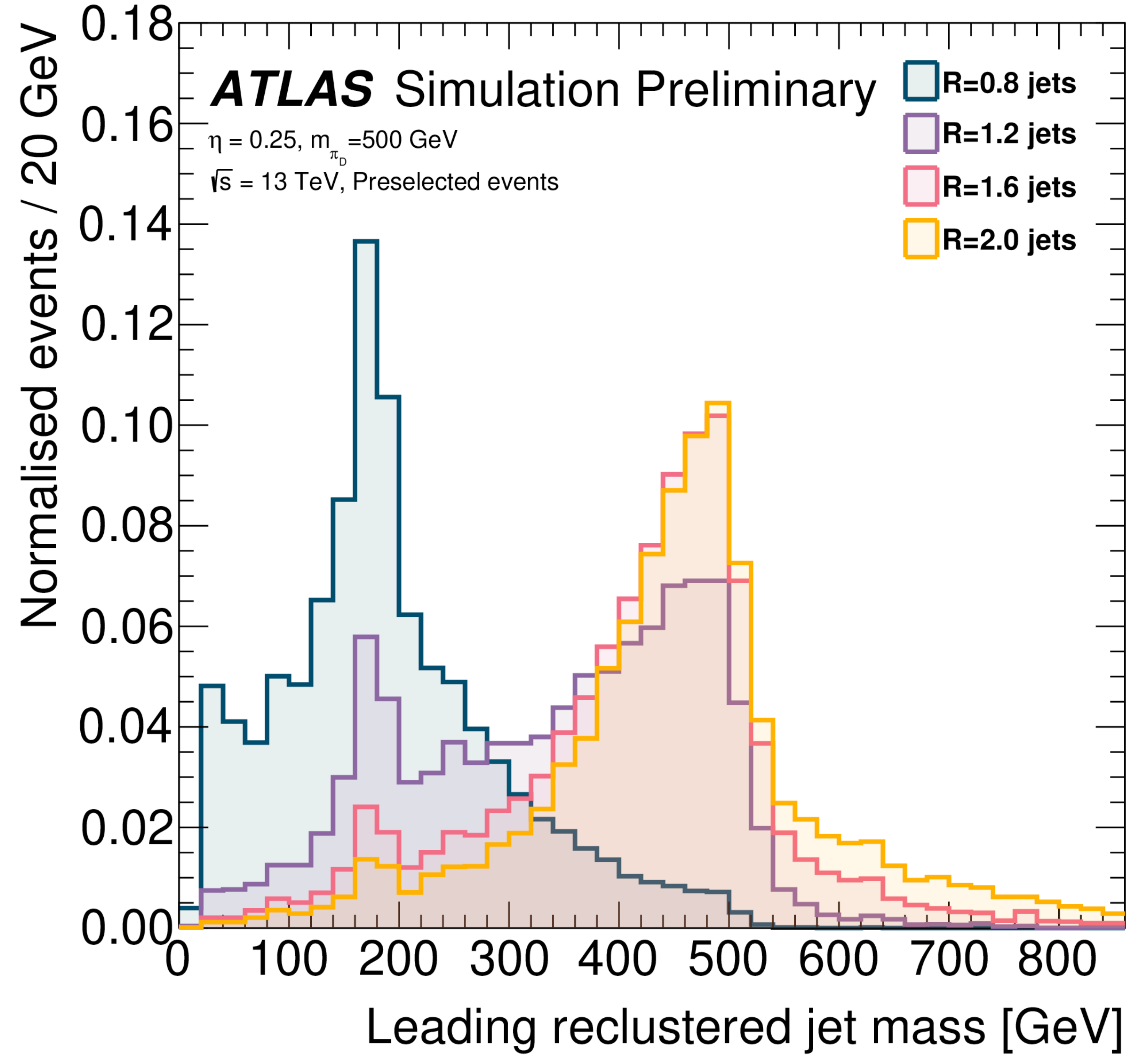
(* for an experimental physicist)

- Boosted jets with substructure that give us some information about the original dark mesons.
- We recluster regular jets/leptons into bigger ones.









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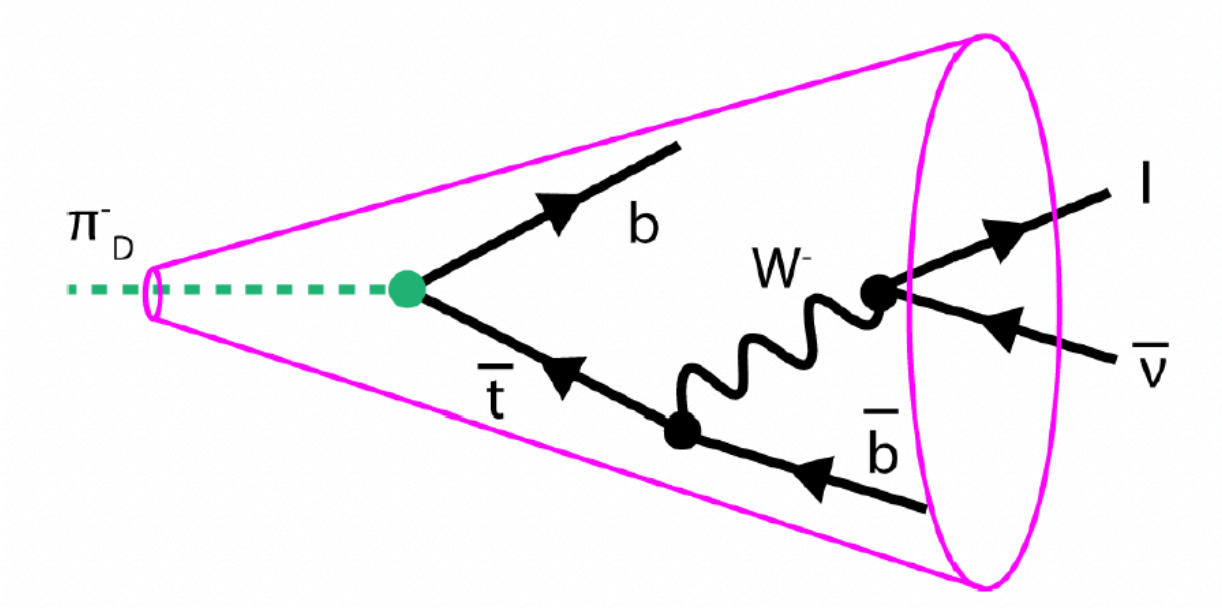
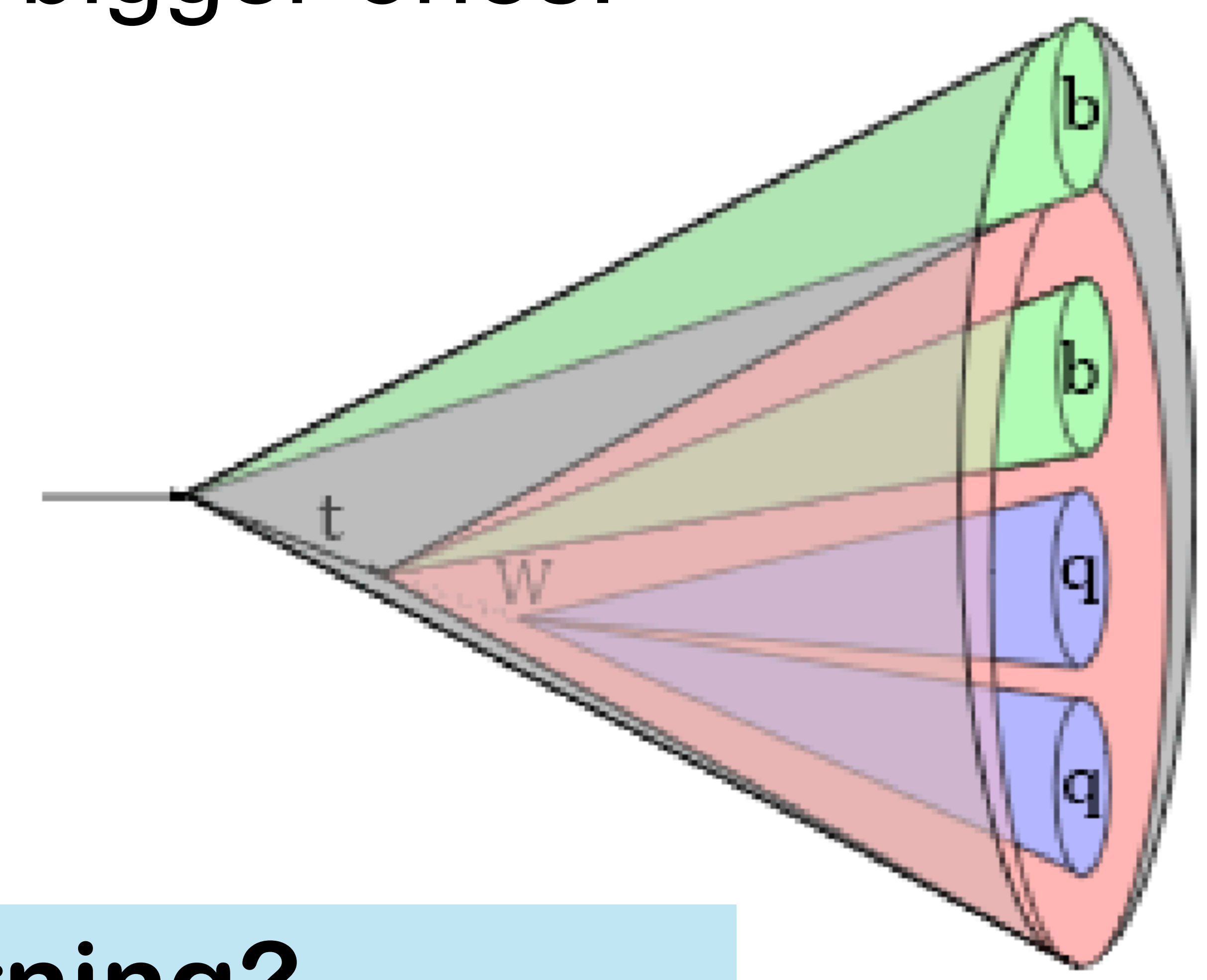
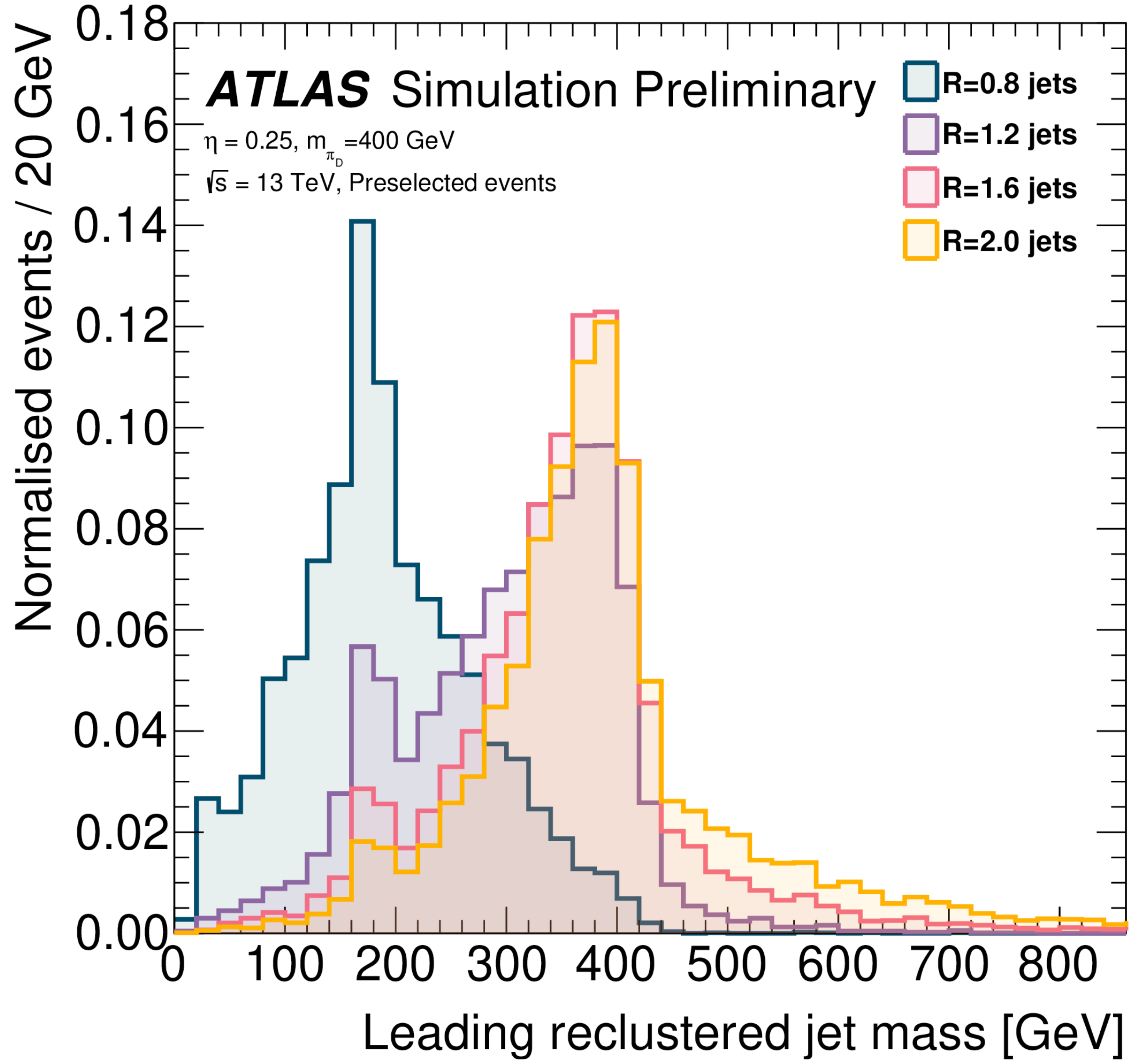
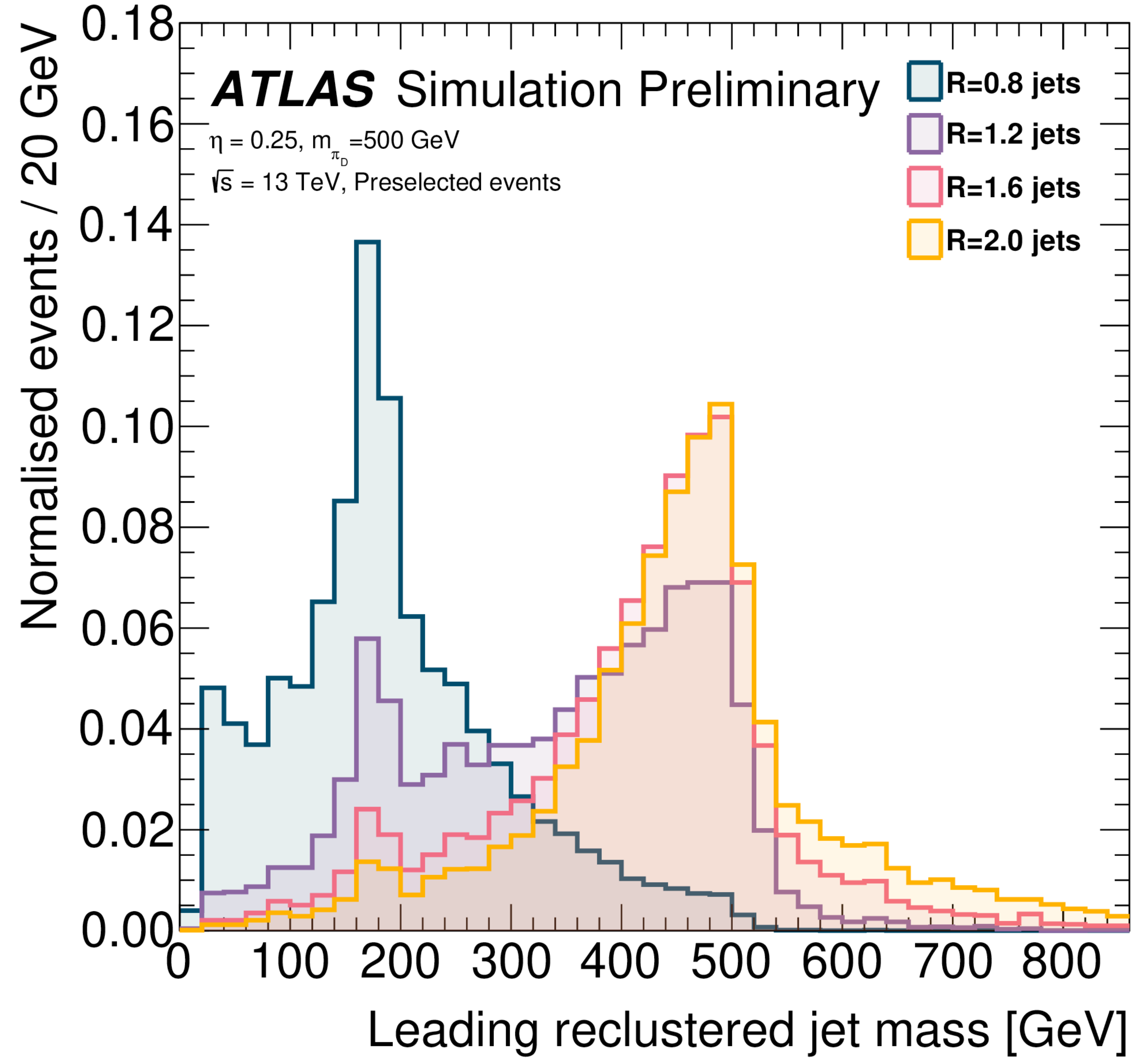




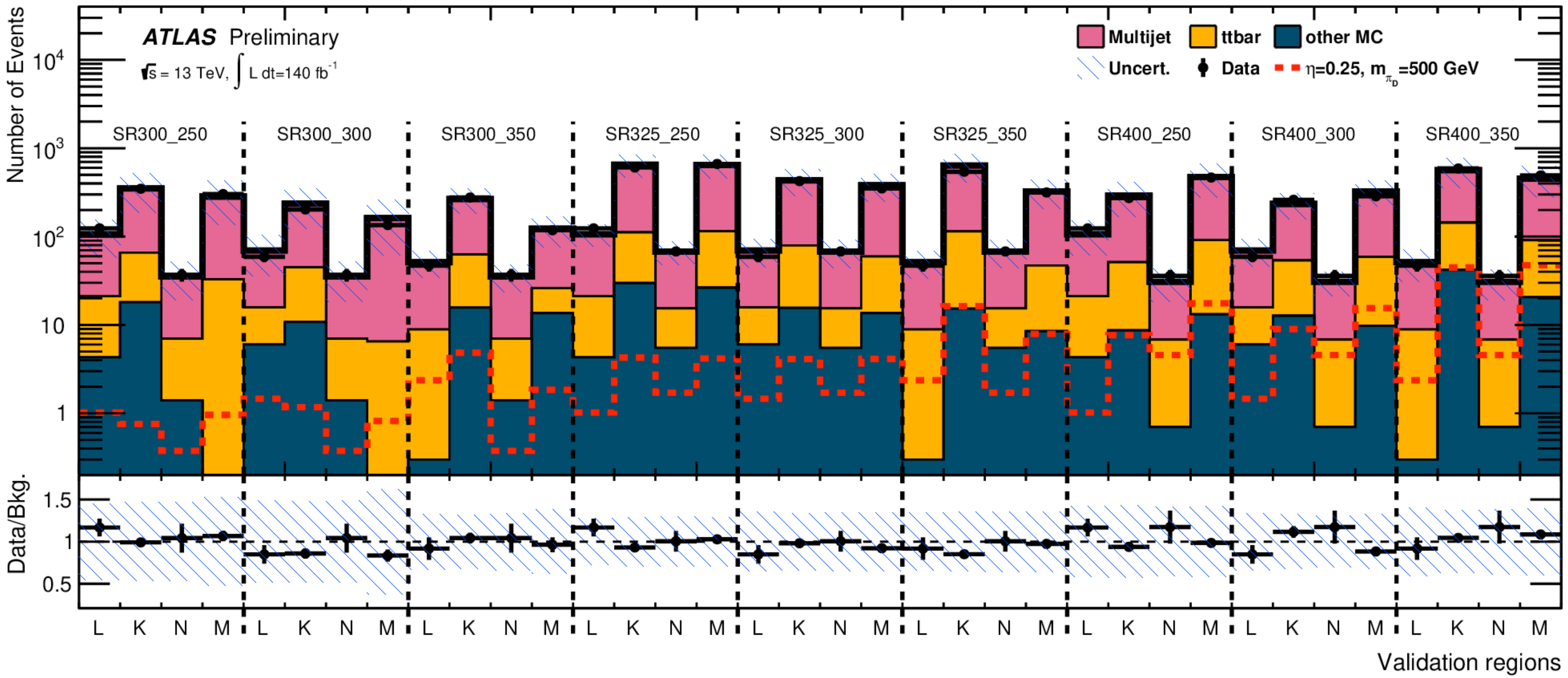




A place for Machine Learning?
Certainly yes! We are testing/want to do a few things, from signal extraction to jet taggers

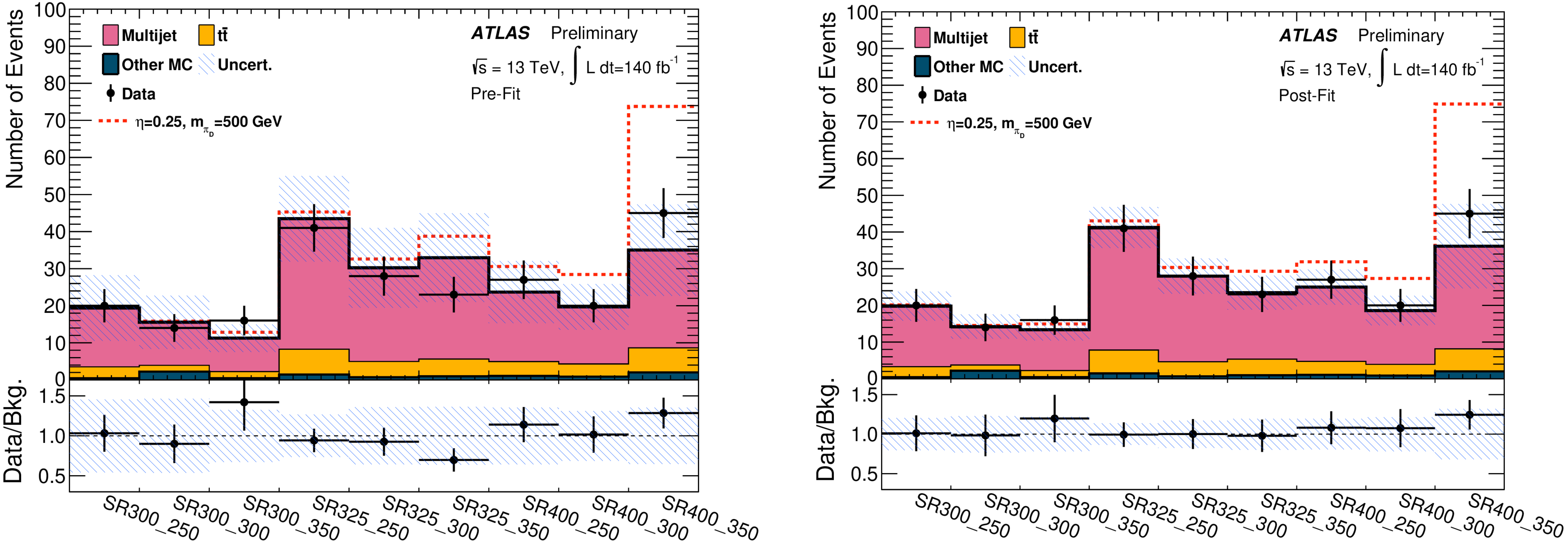
What are we doing with it?

- Full Run 2 data (140 fb^{-1}, 13 TeV) analysis, in all hadronic (CONF note) and 1-lepton final states (ongoing)
- The agreement in validation regions is very reasonable



Regions defined by number of jets, jet masses, angular variables and other kinematics

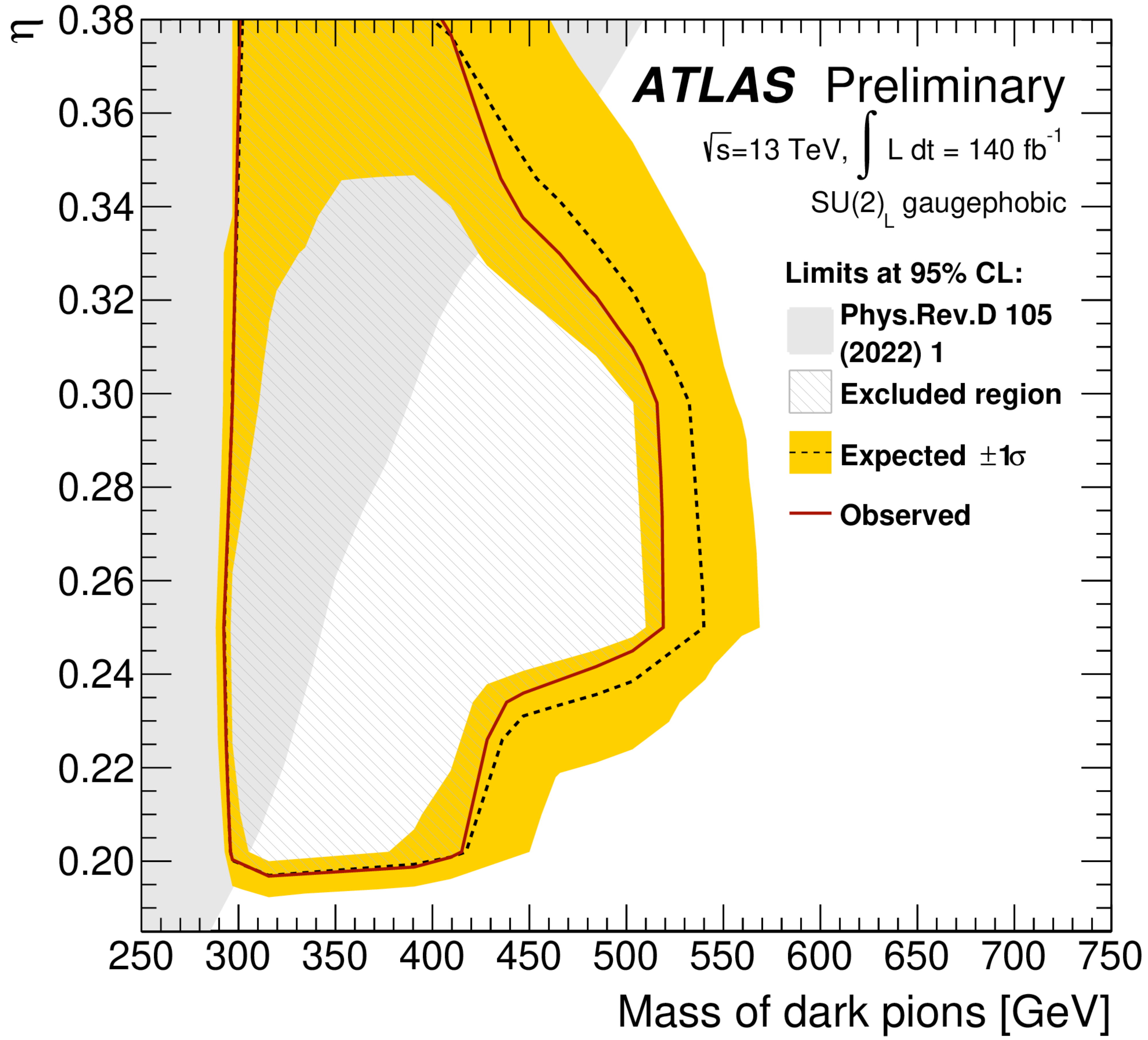
And we see no excess in the signal regions so far



Bins are named by their region in the 2D leading and sub-leading large-R jet mass [GeV] phase space

Results

A nice chunk excluded



- We scan the two dimensional signal space of dark pion masses ($m_{\pi D}$) and dark rho masses ($m_{\rho D}$)
  - The dark pion mass range 280 GeV < $m_{\pi D}$ < 522 GeV is excluded for signals with $\eta = m_{\pi D}/m_{\rho D} = 0.25$
  - For $\eta = 0.35$ dark pions in 280 GeV < $m_{\pi D}$ < 434 GeV are excluded

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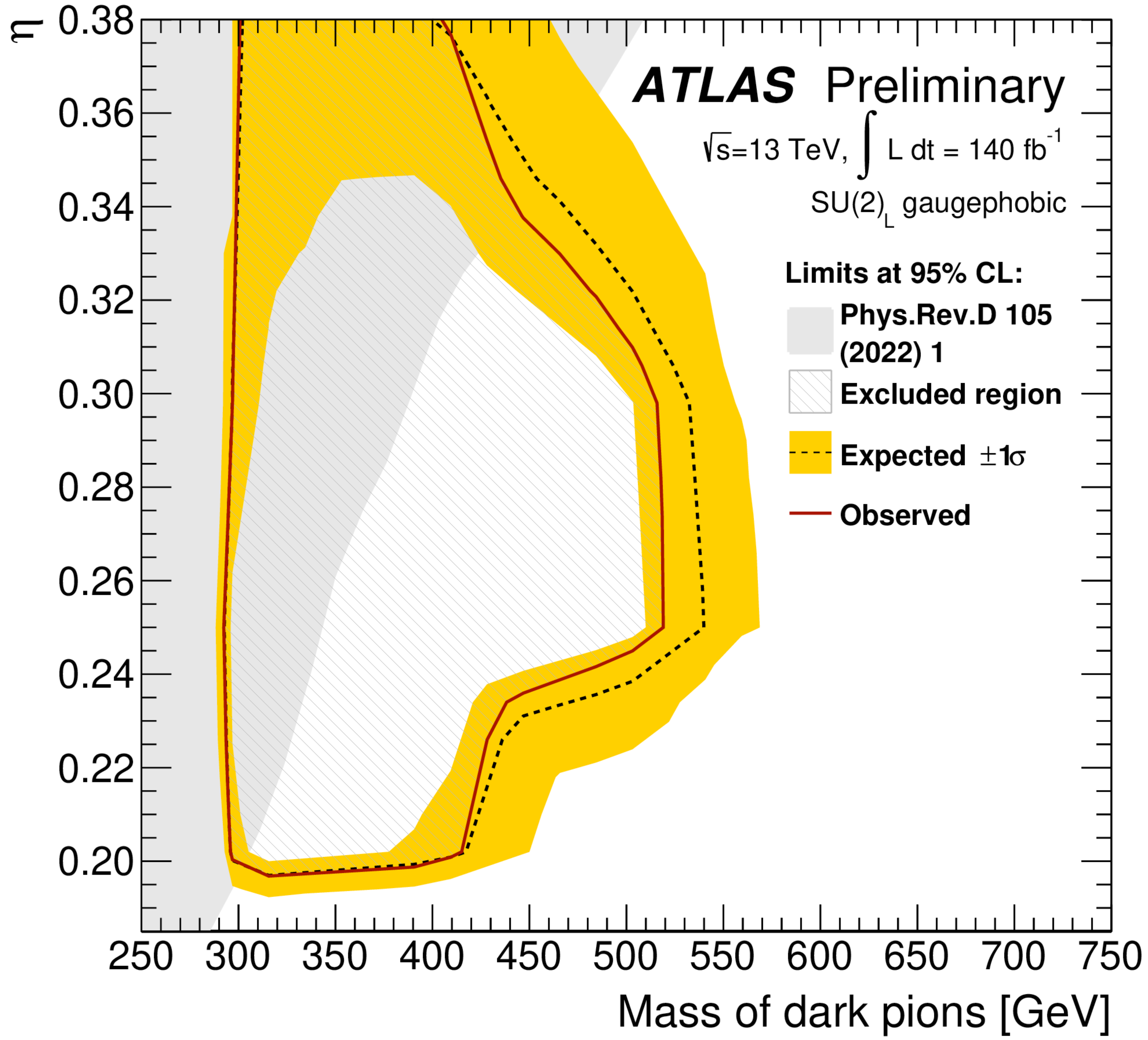
A nice chunk excluded



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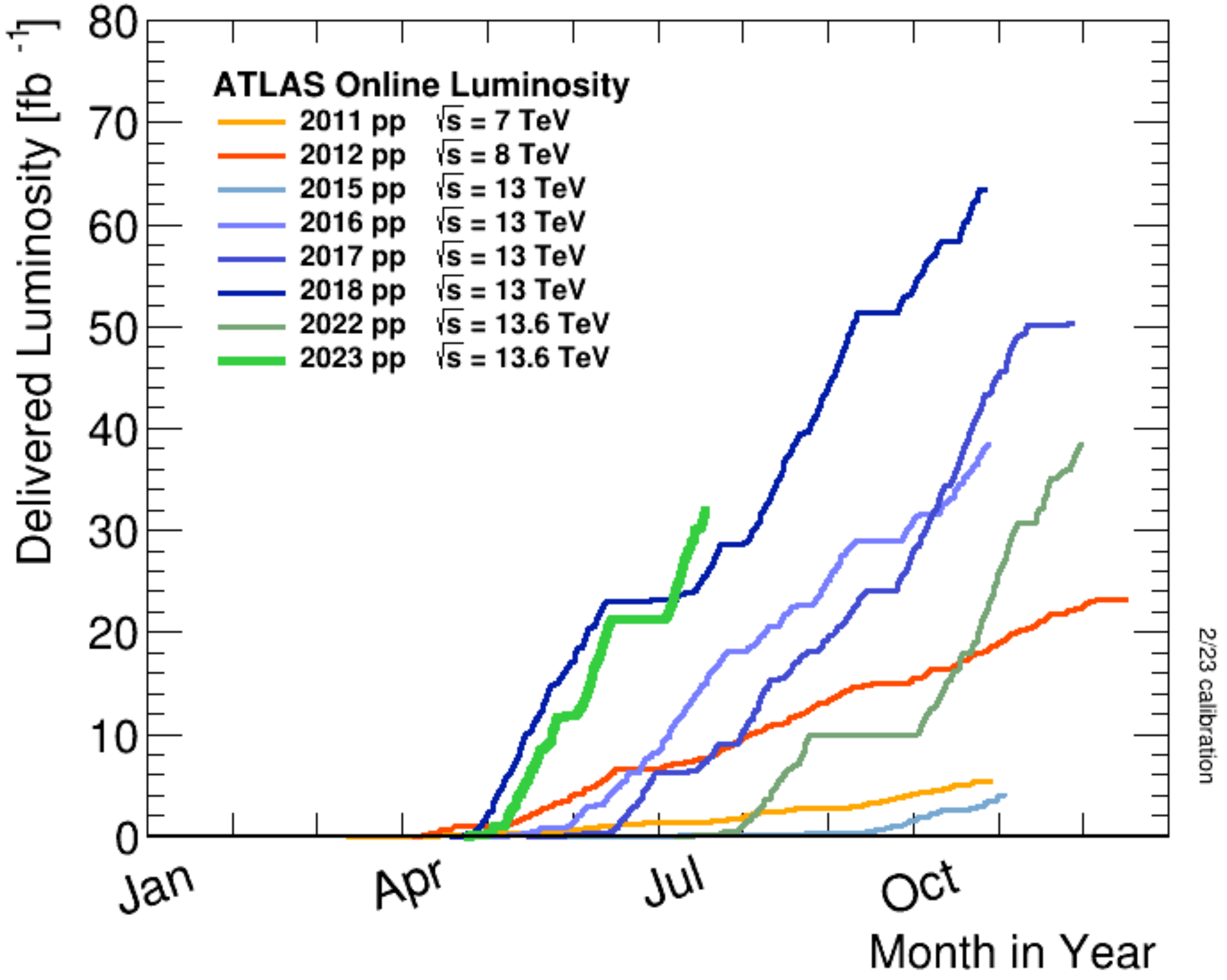
Stay tuned for the paper!

Back to the LHC in general

The LHC Run-3

Started last year



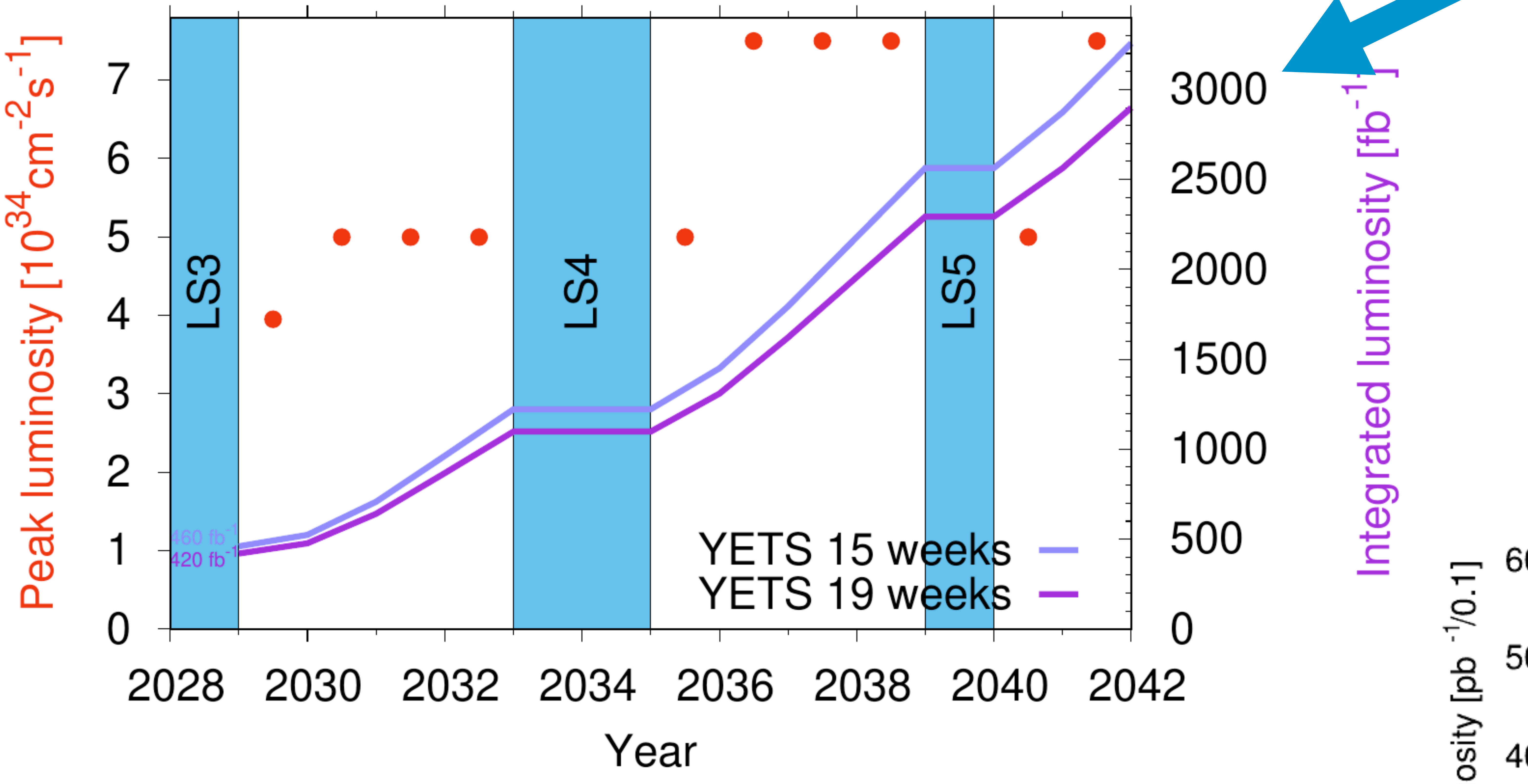
- **Run-1 pp dataset:** 5fb^{-1} at 7TeV / 20fb^{-1} at 8TeV
- **Run-2 pp dataset:** 140fb^{-1} at 13TeV
- **Run-3 target:** 250fb^{-1} (2022-2025)
  - **Maybe not a big boost for dark sector searches but a good time to test methods and tools**
  - Small increase of collision energy: 13.6TeV
  - Close to **70fb^{-1} recorded**

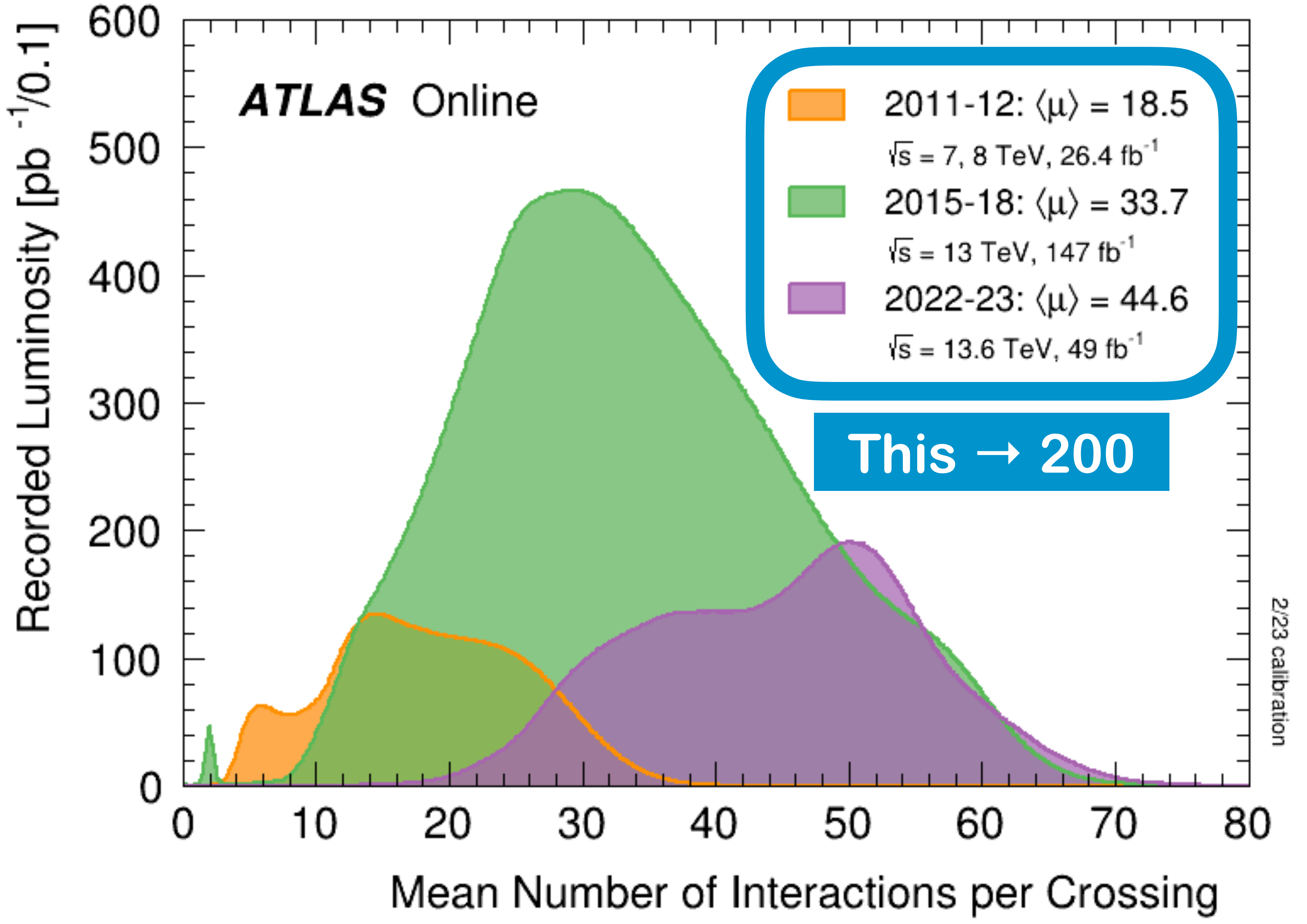
But the the Run-3 is the LHC's last

The High-Luminosity upgrade will follow

Quite the timescale

https://hilumilhc.web.cern.ch/

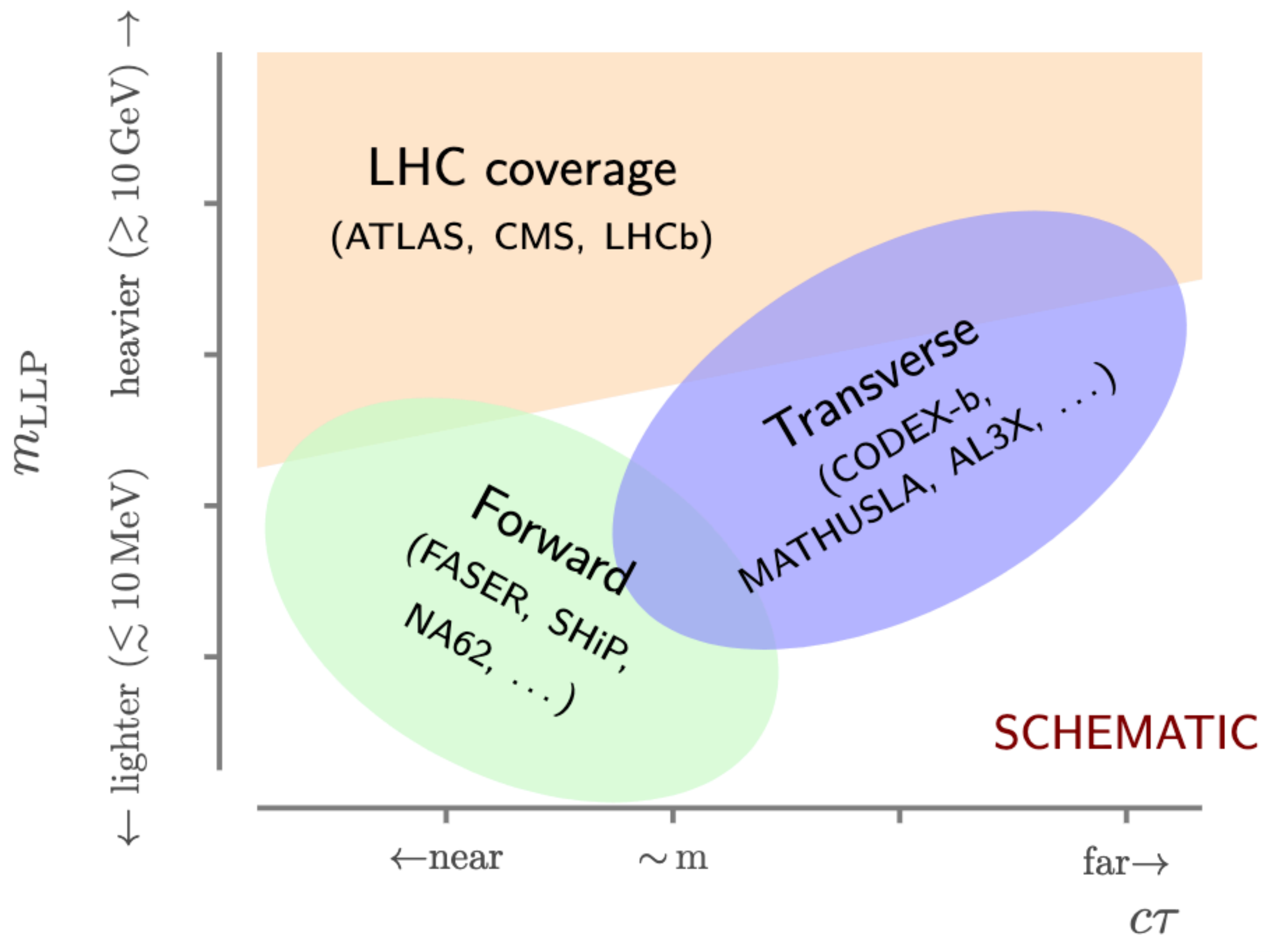


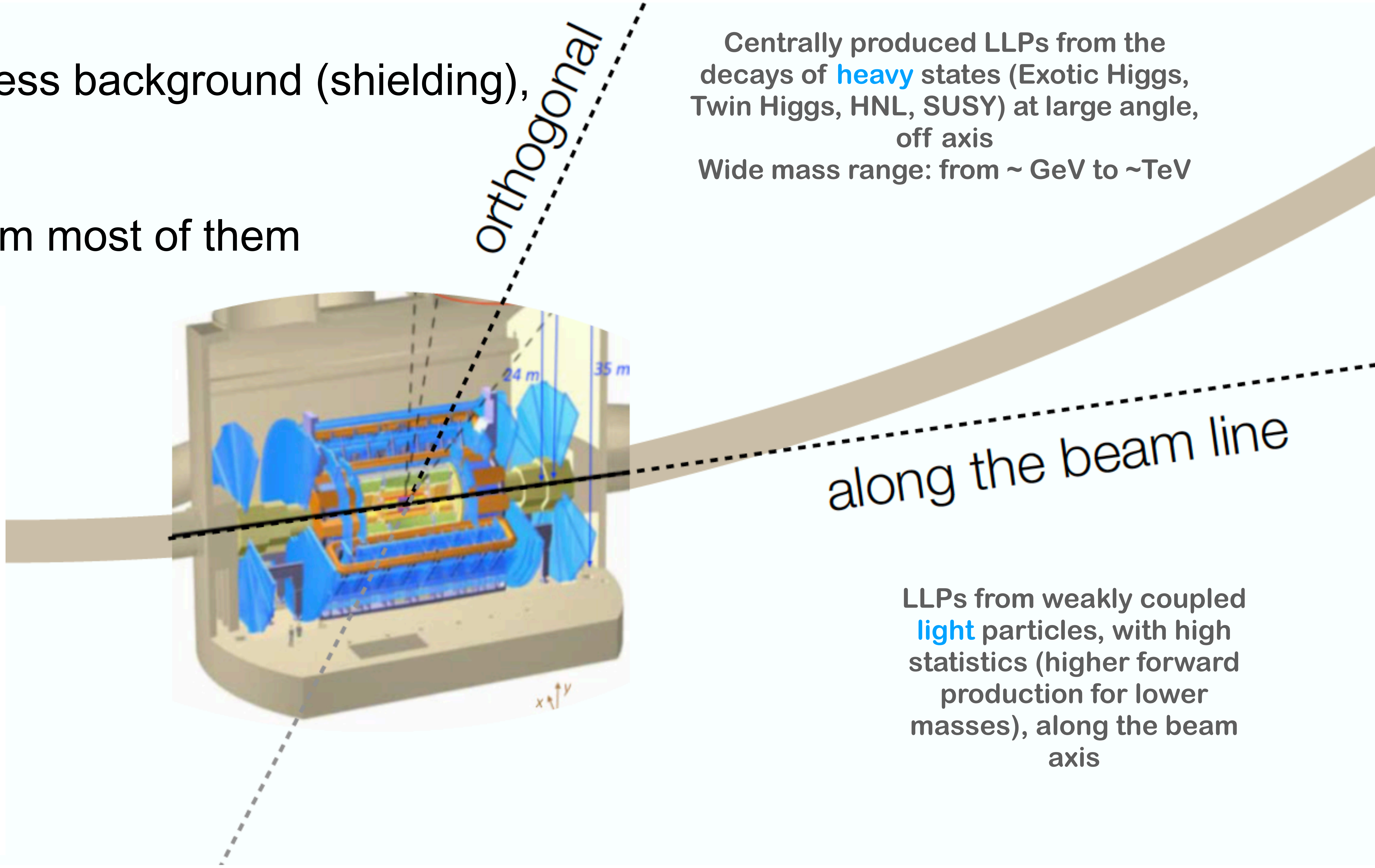


A lot of luminosity (**good** for dark sectors) but a LOT of pileup too with no increase of center of mass energy (**bad** in general)

Thinking outside the LHC detectors

- We can supplement them with **external detectors**
- Access to longer decay lengths, less background (shielding), easy trigger (or trigger-less)
  - Dark sectors a prime target from most of them





Centrally produced LLPs from the decays of **heavy** states (Exotic Higgs, Twin Higgs, HNL, SUSY) at large angle, off axis
Wide mass range: from ~ GeV to ~TeV

LLPs from weakly coupled **light** particles, with high statistics (higher forward production for lower masses), along the beam axis

There are many experiments

Proposed or running

- And they tend to either directly target dark sectors or have at least sensitivity to some of them:
  - dark photons, dark Higgs, HNLs, ALPs.....

Running

Proposed

AL3X ANUBIS

SHADOWS FACET

FORMOSA

Your experiment here

And then?

And then? Then we don’t know

We need to decide what we want to build

First: what do we have?

- A relatively new particle that is quite special, our newest **exploration tool**
- Decades of collider expertise to build on top of
- **The largest community we ever had**
- A few options on the table: linear/circular, hadron/lepton(ee/μμ)
- Priorities

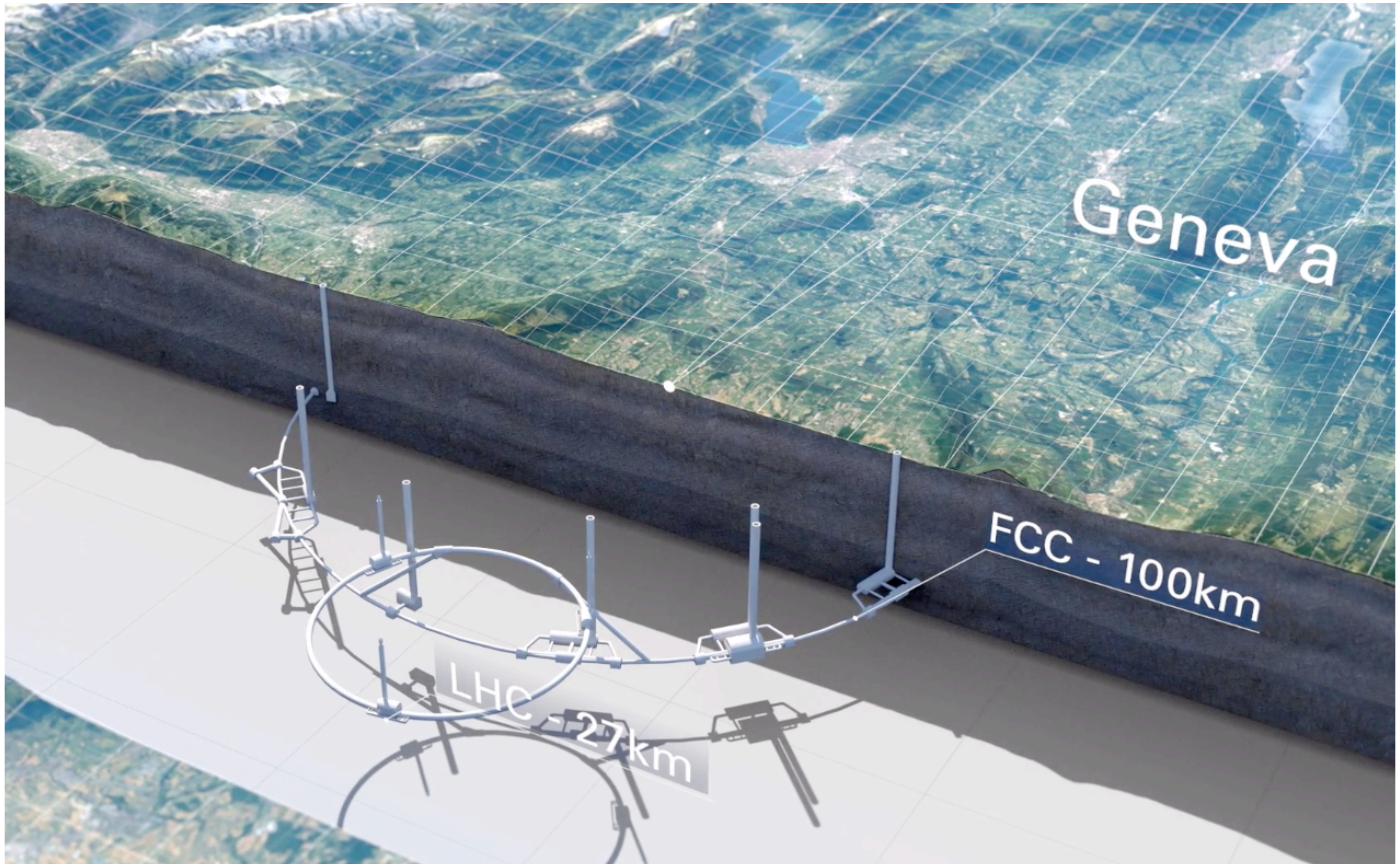
2020 European Strategy Update
"An electron-positron Higgs factory is the highest-priority next collider.
For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."
(European Strategy Update brochure)

Snowmass 2021
"The intermediate future is an e+e- Higgs factory, either based on a linear (ILC, C3) or circular collider (FCC-ee, CepC).
In the long term EF envision a collider that probes the multi-TeV scale, up or above 10 TeV parton center-of-mass energy (FCC-hh, SppC, Muon Coll.)"
(Energy Frontier Plenary by Alessandro Tricoli)

“I believe FCC is the best project for CERN’s future, we need to work together to make it happen“ - Fabiola Gianotti, FCC Week London, 5th June 2023

What is FCC?

Future Circular Collider at CERN



- Linked to the LHC accelerator chain
- Implemented in stages, one e+e- precision machine, followed by a high-energy hadron collider

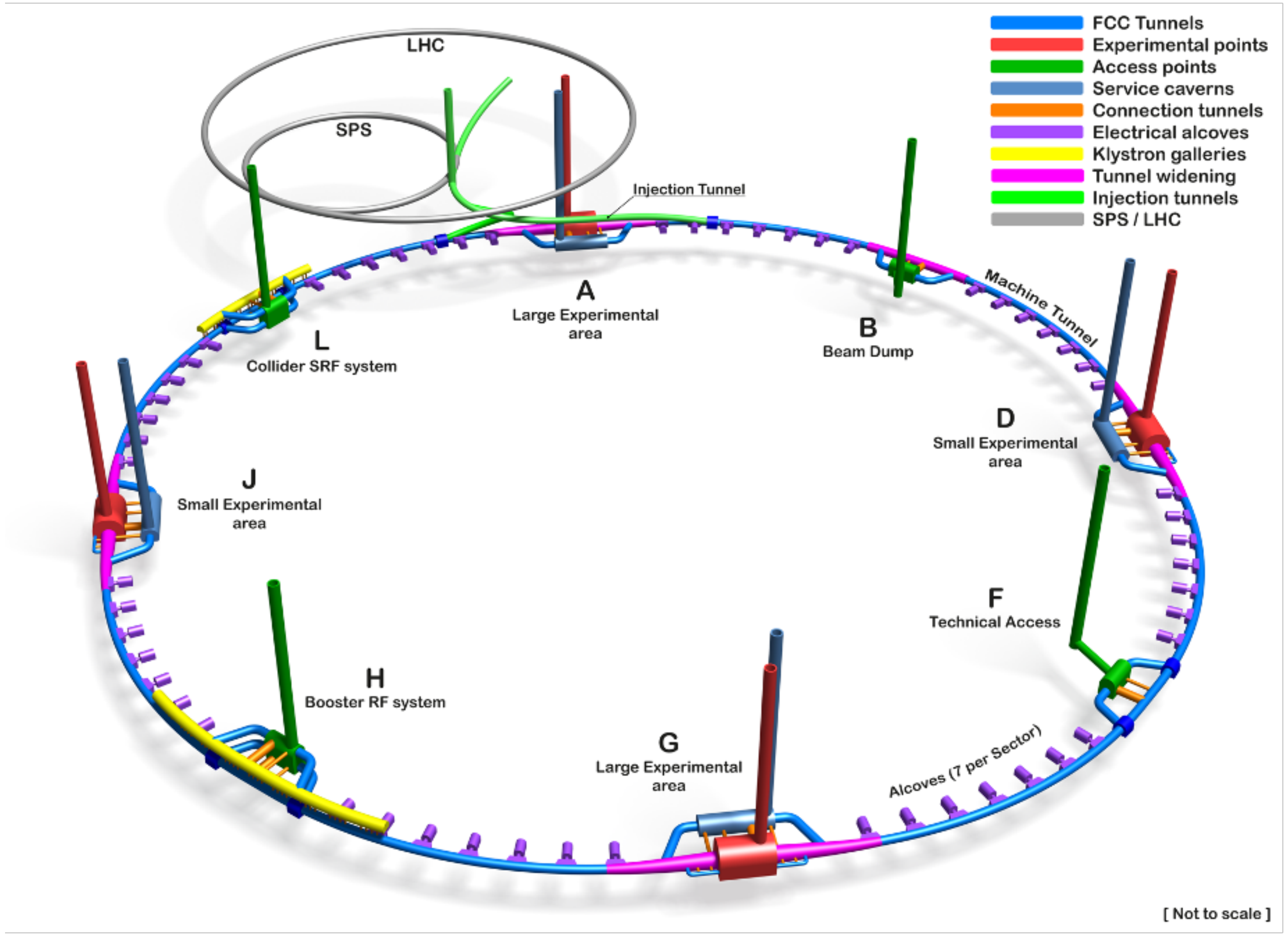
The FCC program covers two frontiers

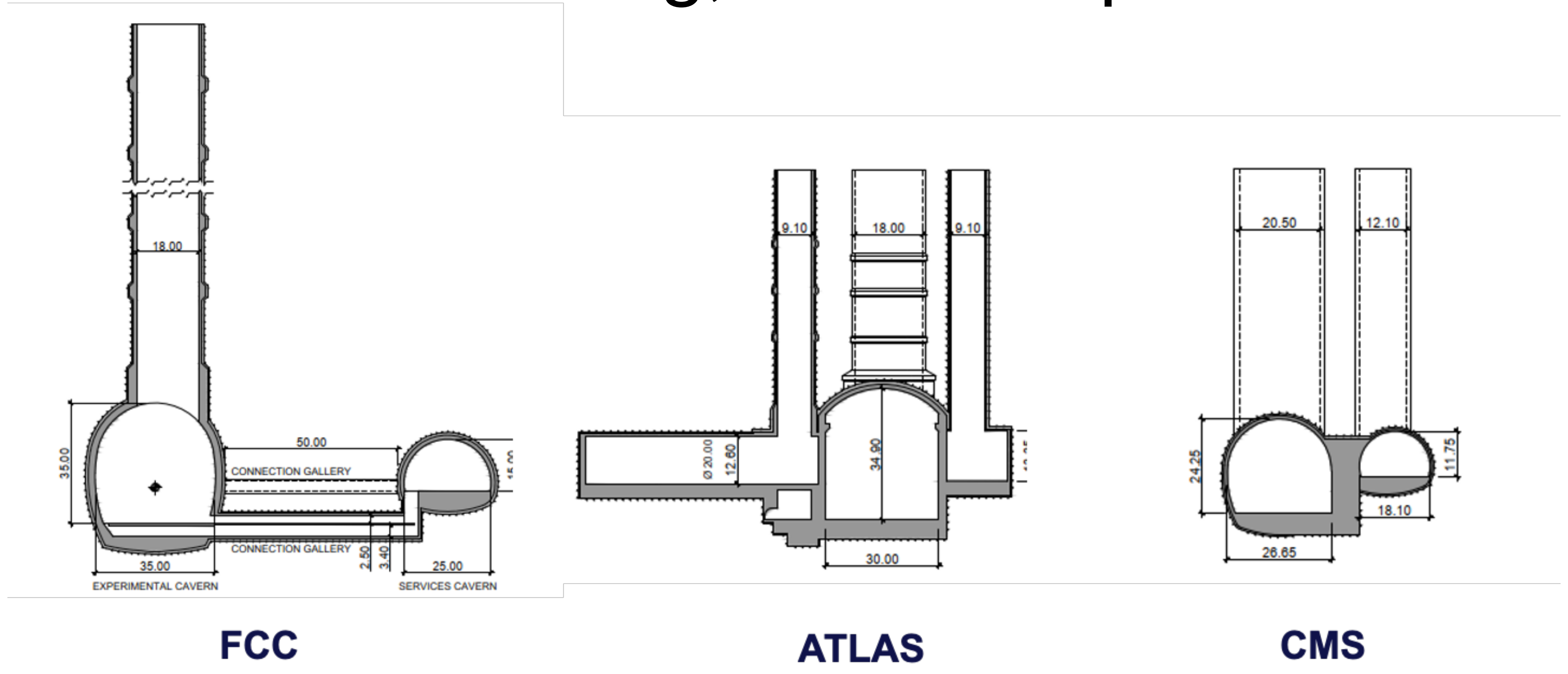
- **INTENSITY FRONTIER Precision** (electron-positron)
  - **1st stage collider, FCC-ee:** electron-positron collisions 90-360 GeV
  - Construction: 2033-2045 / Physics operation: 2048-2063
  - Stress-test the SM limits → Indirect / low mass BSM sensitivity
- **ENERGY FRONTIER Discovery** (hadron-hadron)
  - **2nd stage collider, FCC-hh:** proton-proton collisions at ≥ 100 TeV
  - Construction: 2058-2070 / Physics operation: ~ 2070-2095
  - Maximizing potential for BSM discovery → Direct / high mass BSM sensitivity

Strength

In shared infrastructure

- Making use of the current acceleration chain
- Using one tunnel (and one set of caverns) for both stages
  - Following LEP-LHC model
  - 90.7 km ring, 8 surface points



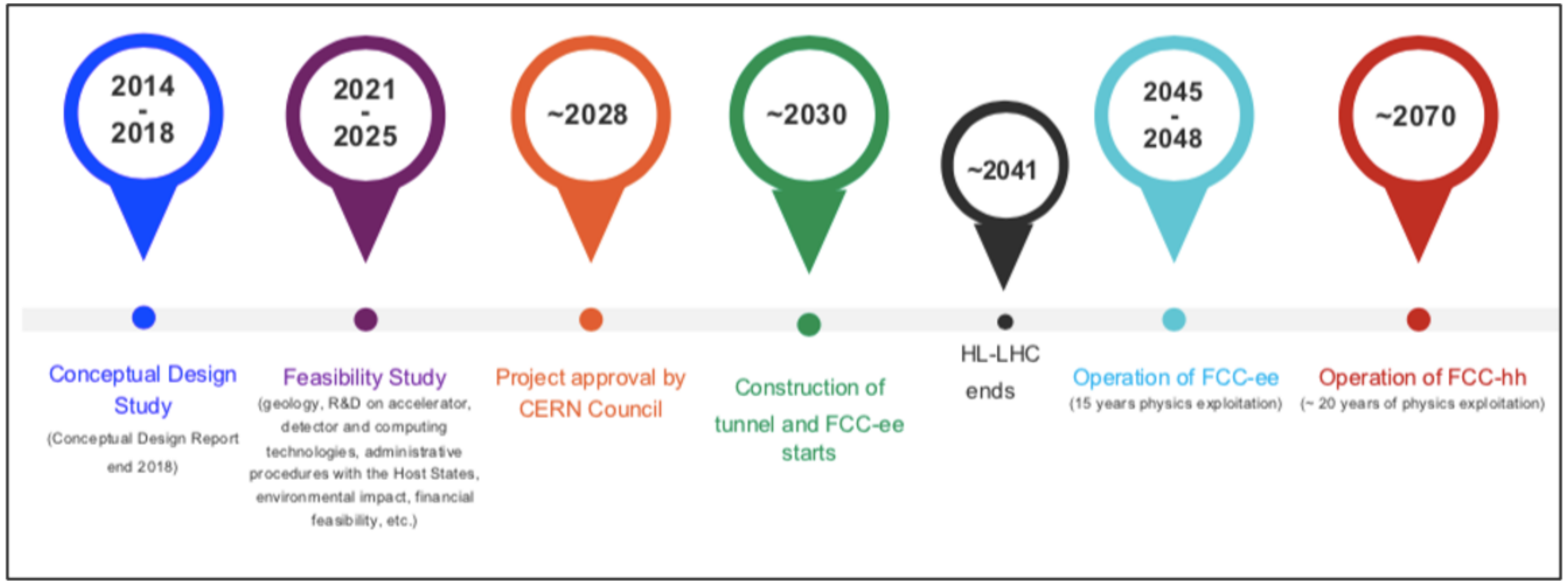


- **4 Experimental areas** 2 large (> ATLAS) & 2 small (~CMS)
- Deepest shaft: 400m
- Average shaft depth: 243m

Strength

Surprise!

In size and timescale



- FCC-ee technology is mature → construction in parallel to HL-LHC operation
- Physics a few years after the HL-LHC (2045-2048)
  - Continuity for multiple generations of high energy physicists guaranteed
  - Only proposed facility that can accommodate the size of the CERN community
- Two-stage approach
  - Allows to **spread the cost** of the (more expensive) FCC-hh over more years
  - **20 years of R&D work towards affordable magnets**
  - Optimization of overall investment by reusing civil engineering and large part of the technical infrastructure

Strength

In physics potential

	$\sqrt{s}$	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 x 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	5-30 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb **FCC-hh**	$\sqrt{s_{NN}}$ = 39TeV	3 x 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

Could be 20 years
Baseline now 4 IPs

The LHC is targeting 32 years now, so 25 may be pessimistic

F. Gianotti

	Z pole (90)	H pole (125)?	WW (160)	ZH (240)	tt (365)
Years	8	5	2	3	5
Events	8T	8k	300M	2 M	2 M

M. Selvaggi

- FCC-ee: **highest luminosities at Z, W, ZH of all proposed Higgs and EW factories**; indirect discovery potential up to ~70 TeV, options for direct BSM searches for feebly interacting particles

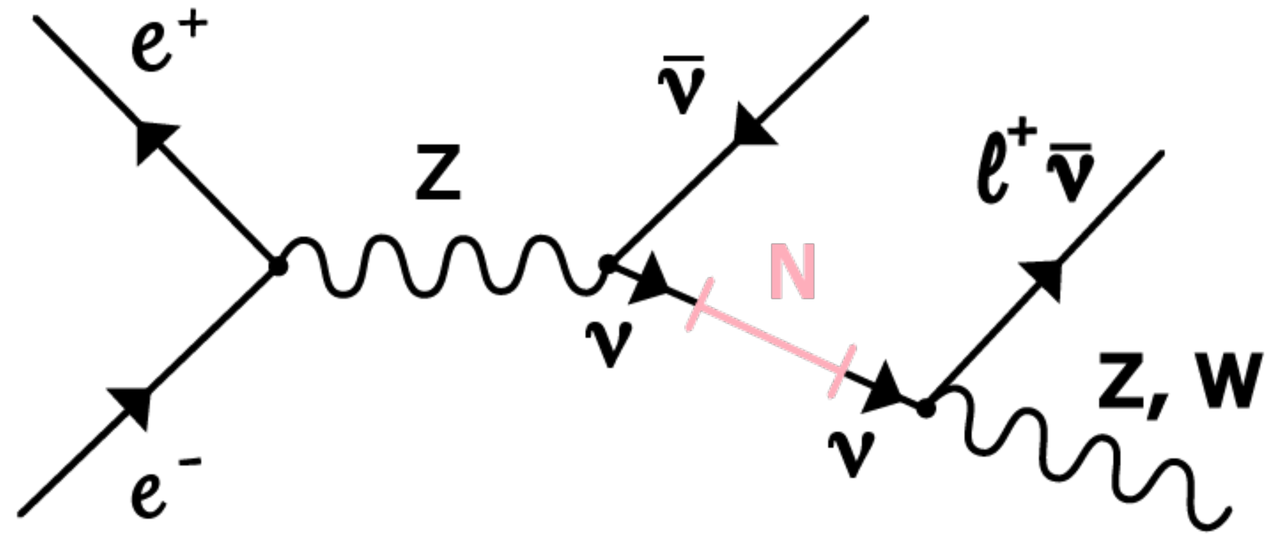
DARK SECTORS!

- FCC-hh: **direct exploration of next energy frontier (~x10 LHC)** and unparalleled measurements of low-rate and “heavy” Higgs couplings (ttH, HH)
  - heavy-ion collisions and, possibly, ep/e-ion collisions

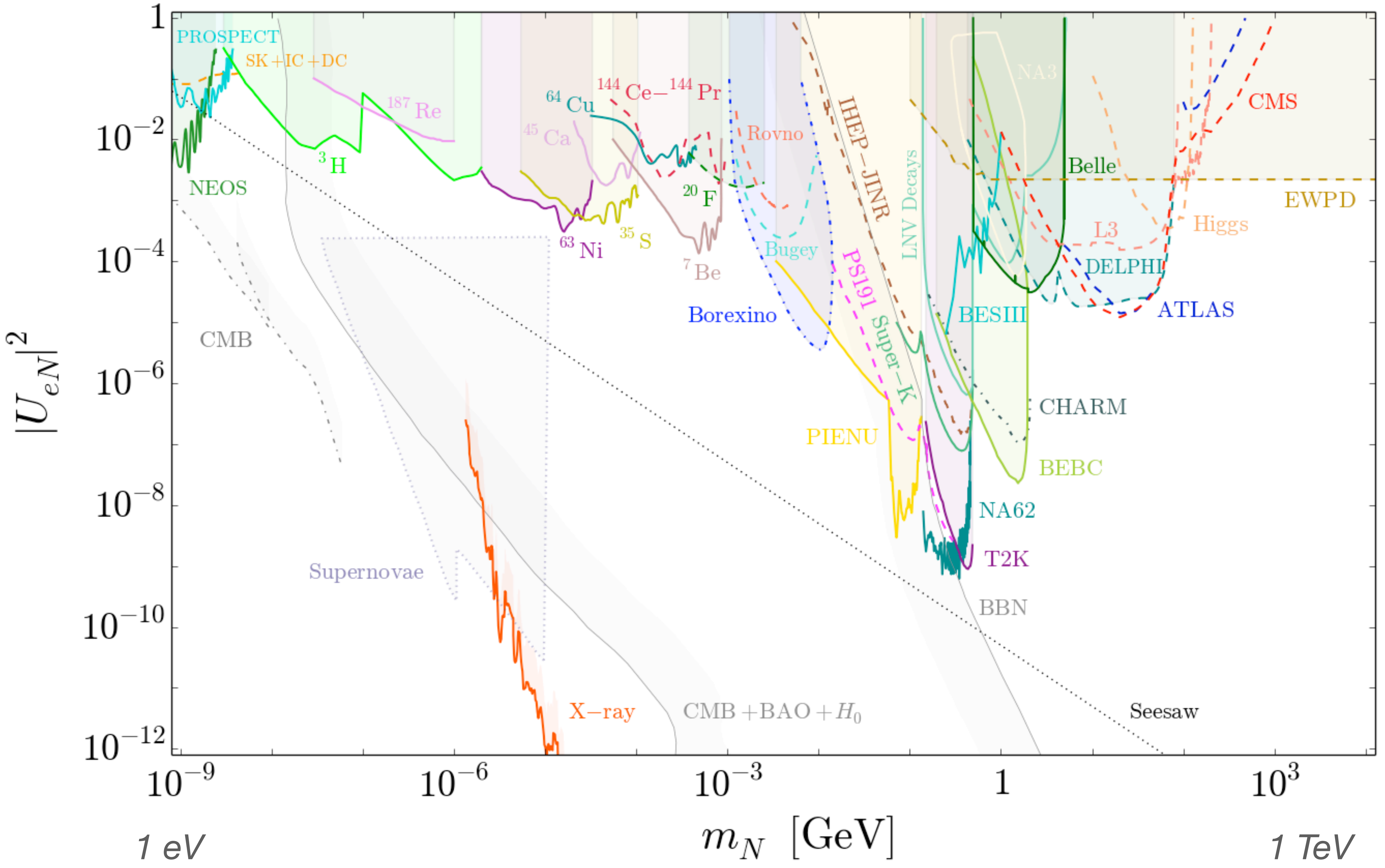
My favourite BSM options at FCC-ee

1- Heavy Neutral Leptons (HNLs)

Right-handed, sterile, heavy neutrinos



- Pdg: Dirac or Majorana fermions with sterile neutrino quantum numbers, that are heavy enough to not disrupt the simplest Big Bang Nucleosynthesis bounds and/or unstable on cosmological timescales
- Typical masses ~MeV and above
- Searches generically set bounds on the mixing between the HNL and active neutrinos and the HNL mass
  - Low mixing = long-lived



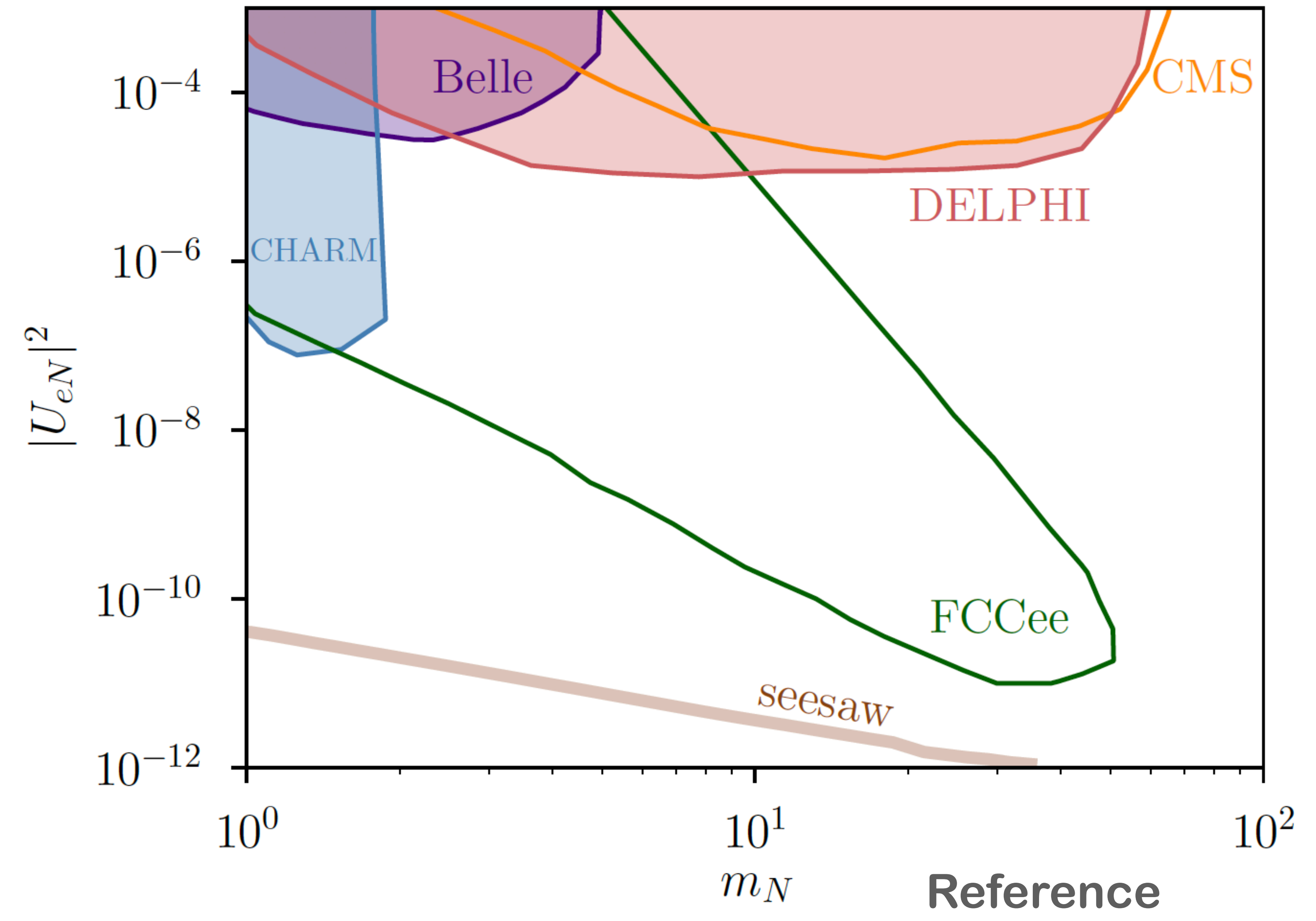
Current constraints on the electron neutrino-sterile neutrino mixing $|V_{eN}|^2$ as a function of the sterile neutrino mass m_N [Ref]

Solves three questions for the price of one

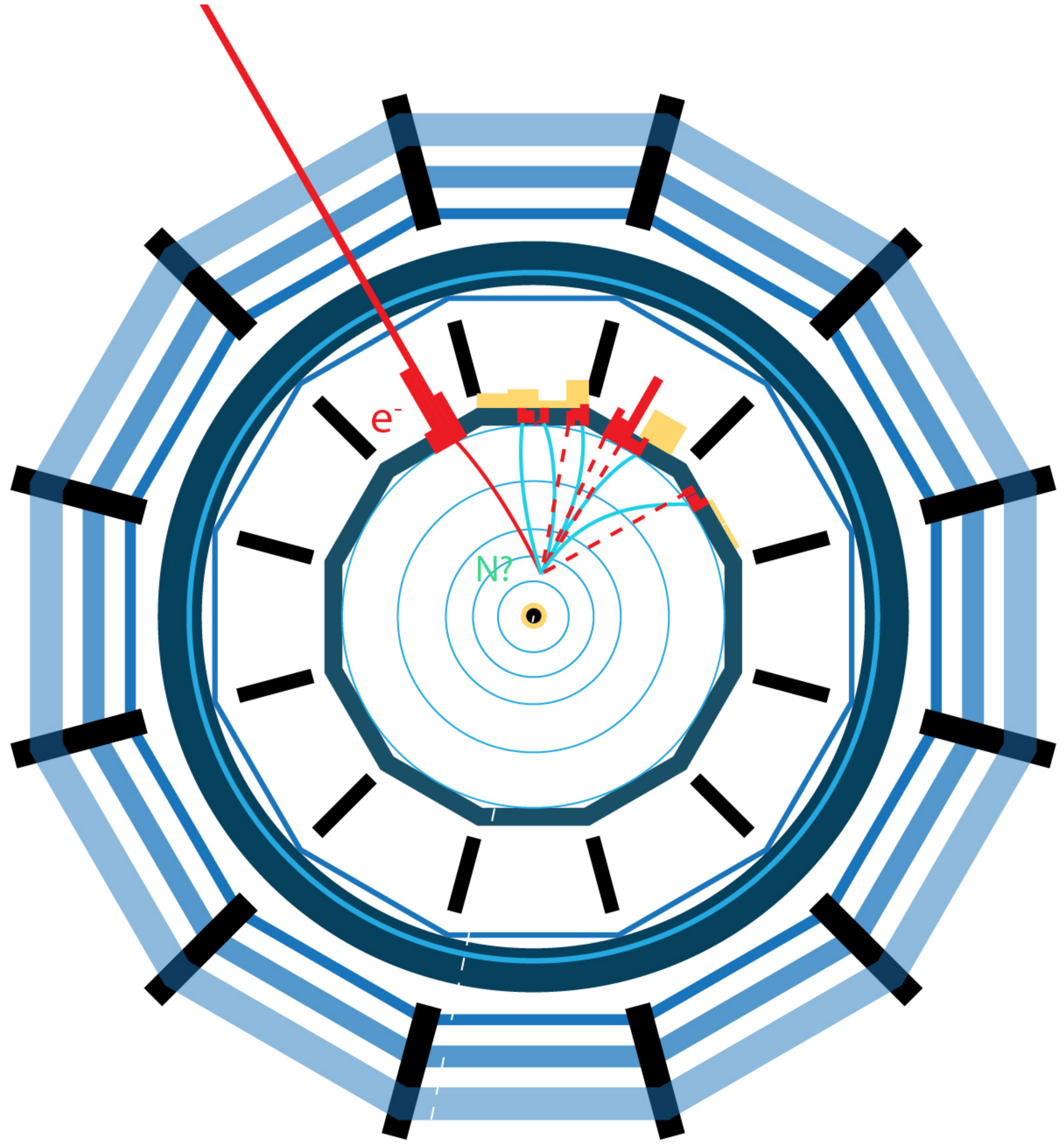
- The simplest way for the SM to incorporate **neutrino masses**
  - To introduce new “right-handed” neutrinos → new HNL
- If these neutrinos follow the see-saw mechanism → neutrinos will be their own antiparticle
  - Bonus solution: **matter-antimatter unbalance of the Universe**
- In the “vMSM”, the extension of the Minimal SM (SMS) in the neutrino sector, adding three right-handed neutrinos
  - The lightest sterile neutrino with mass the keV range → **dark matter!**

Flagship of BSM at FCC-ee

- The FCC-ee will offer an **unbeatable reach at the Z-Pole run**
- Working towards a complete sensitivity analysis implemented in FCC software → Displaced and prompt

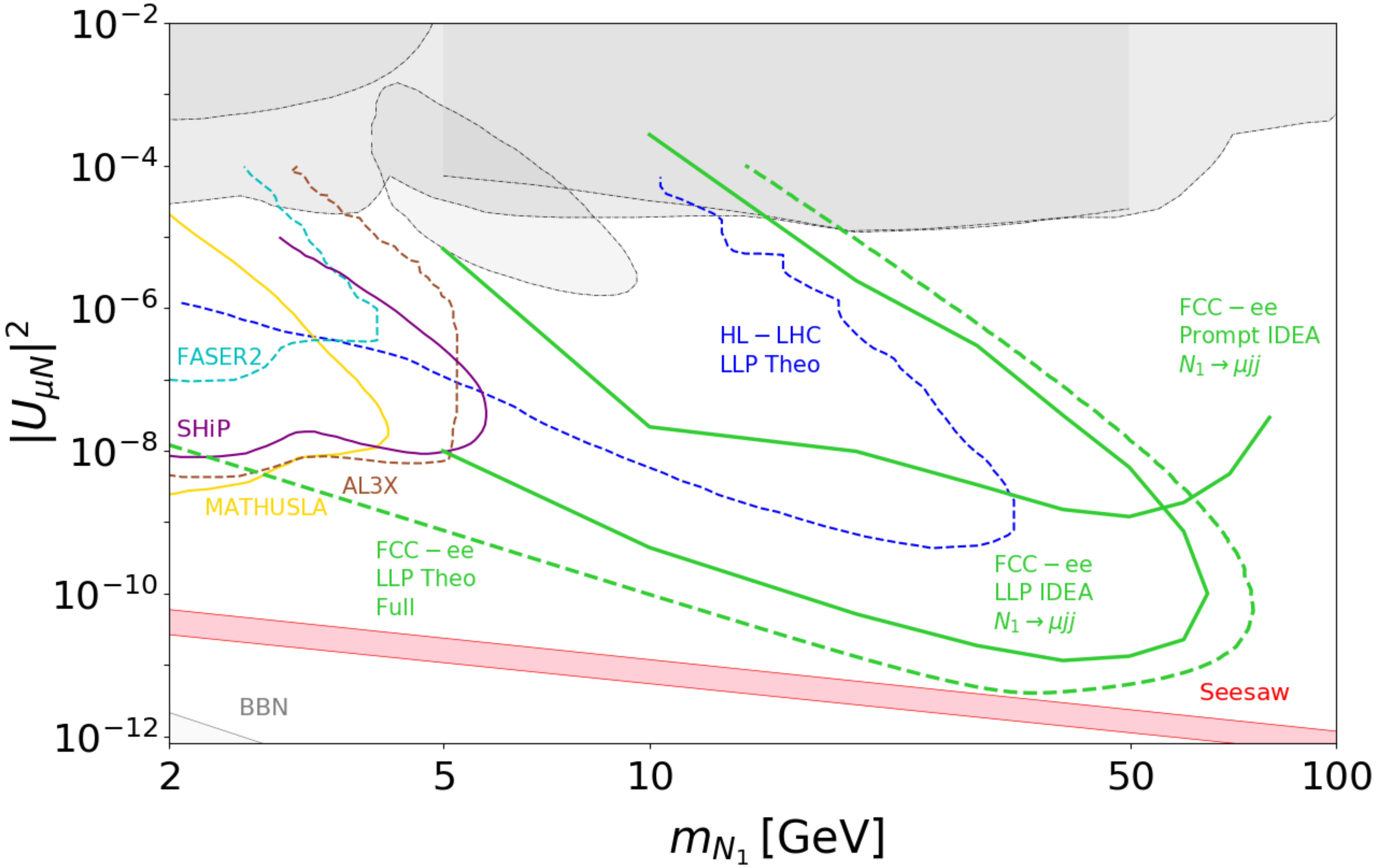


Reference



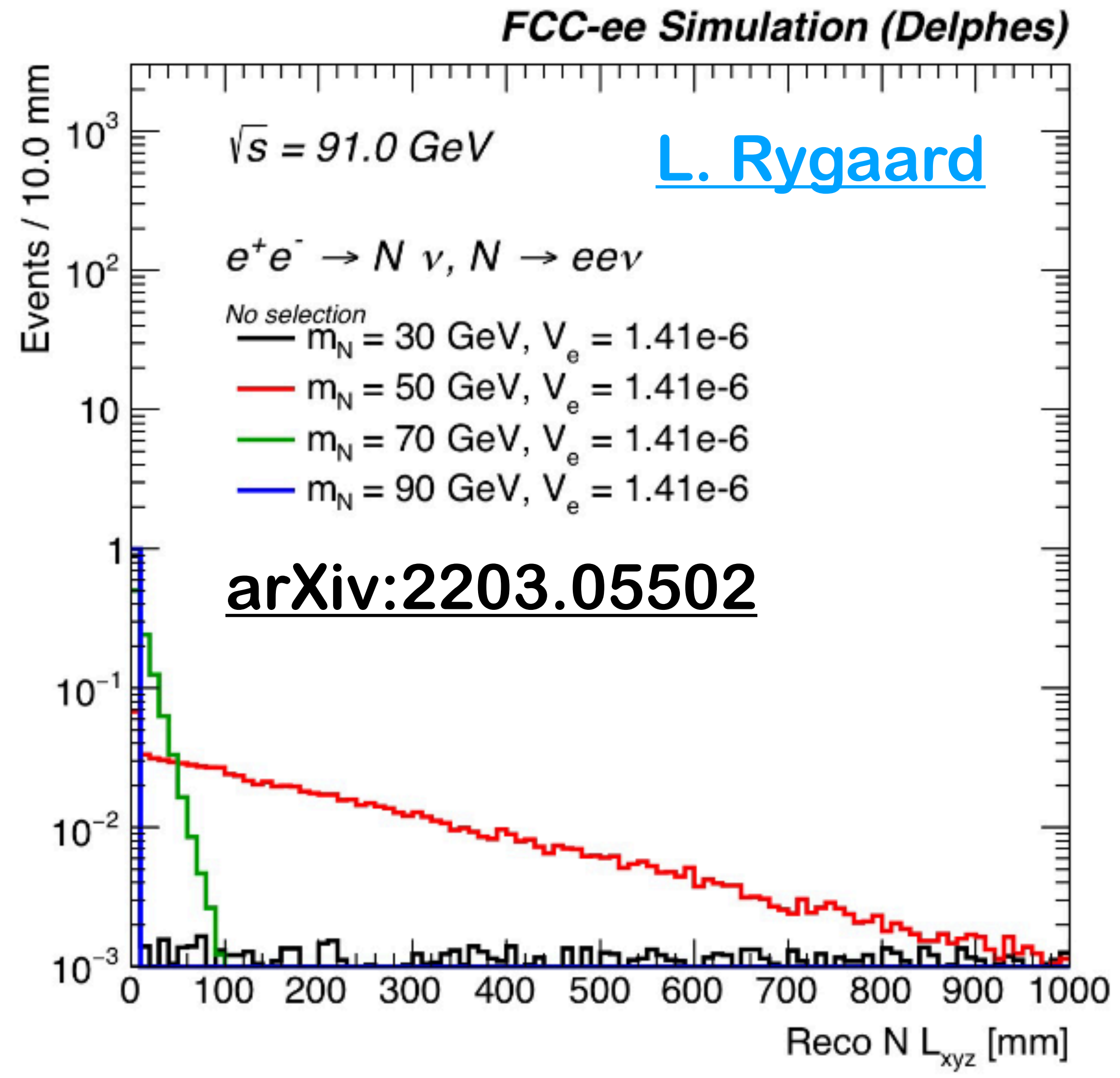
- Large Snowmass effort:
  - arXiv:2203.05502, arXiv:2203.08039, arXiv:2209.13128
- Internal note for midterm report:
  - https://new-cds.cern.ch/records/wnd8t-1k526

Experimental sensitivity studies



- HNL discovery possible over a mass range beyond the reach of specialised LLP detectors being developed, and for much smaller couplings than the ones to be covered at the HL-LHC
- A large part of the area favoured by the seesaw model would be covered for masses below 60-70 GeV

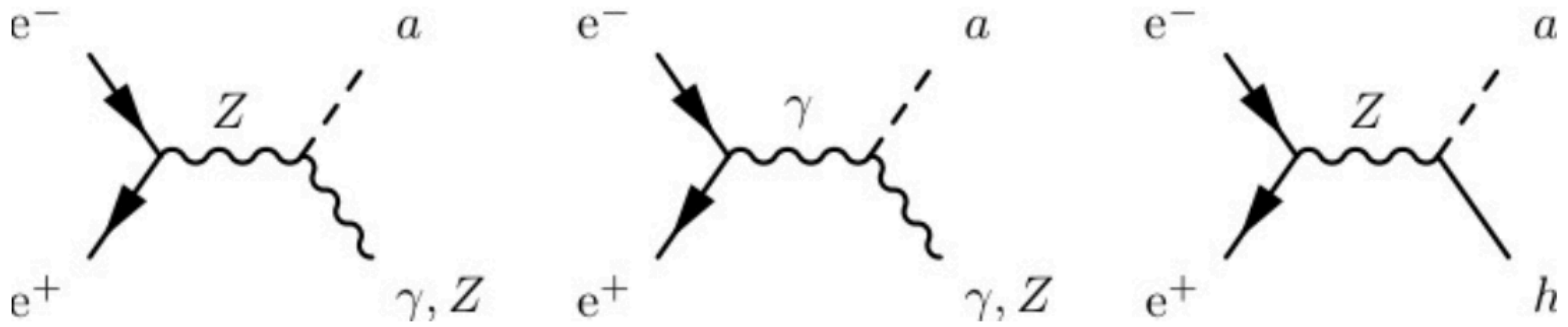
Master theses: Sissel Bay Nielsen, Rohini Sengupta, Lovisa Rygaard, Tanishq Sharma, Dimitri Moulin



Reconstruction-level three-dimensional decay length of the N

2. ALPs

Axion-like particles



- Pseudo-scalar particles predicted by BSM models with a spontaneously broken global symmetry (notably string theory), versatile in terms of mass and SM couplings
  - they could be dark matter candidates in certain regions
  - In others: dark sector mediators
  - Feeble interaction → long-lived

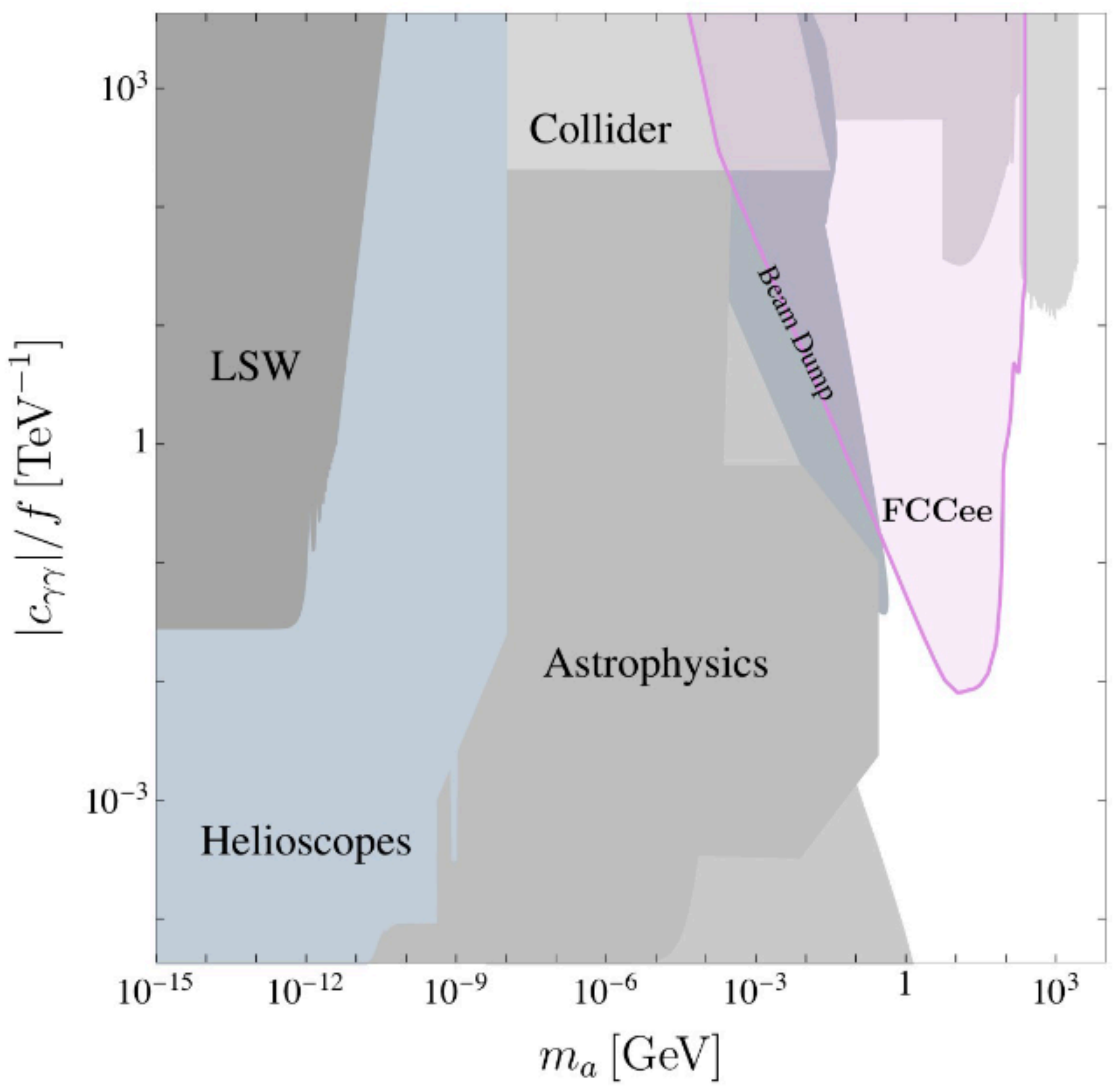
Pseudo-scalar Portal

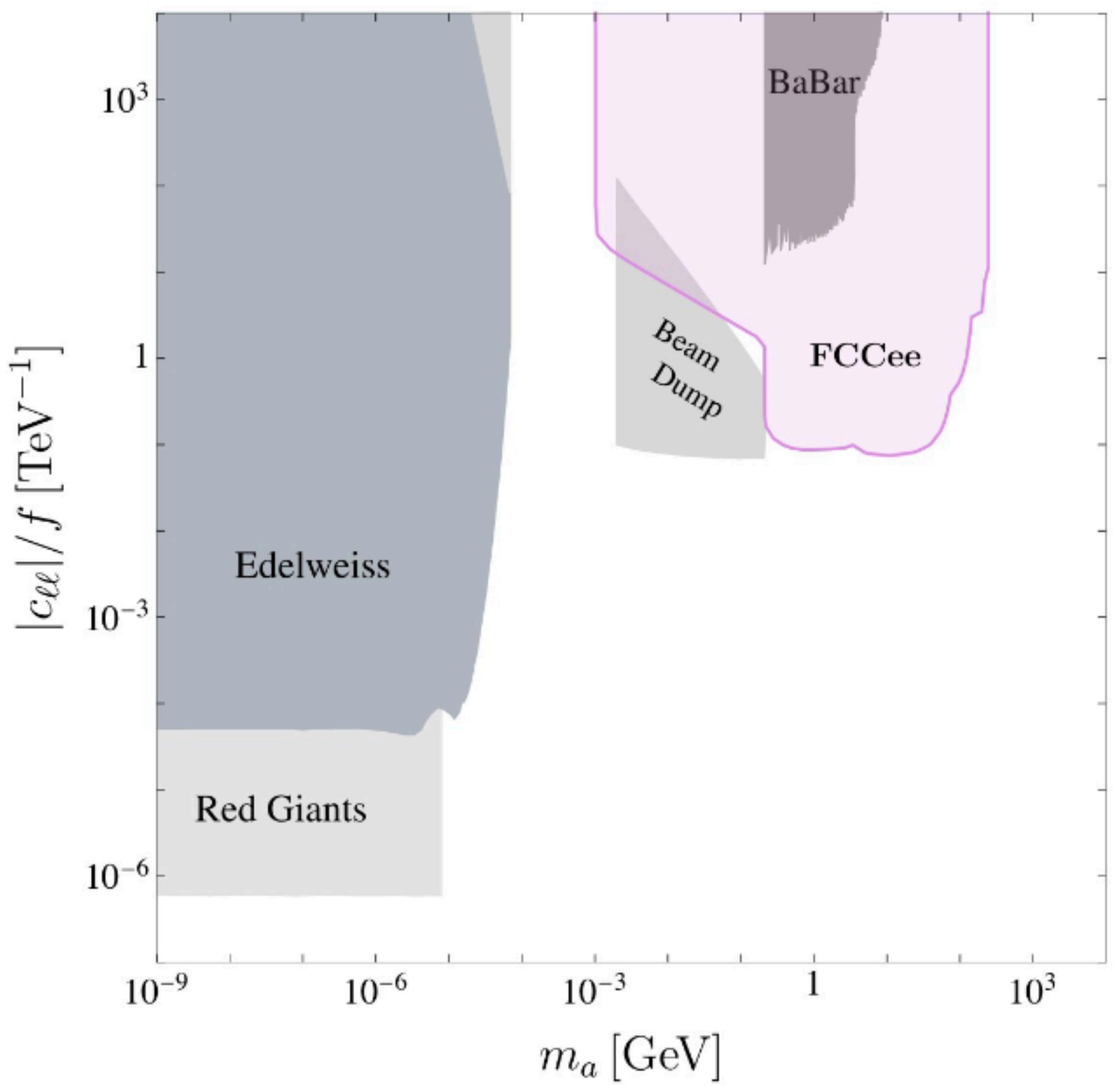
FCC-ee for ALPs

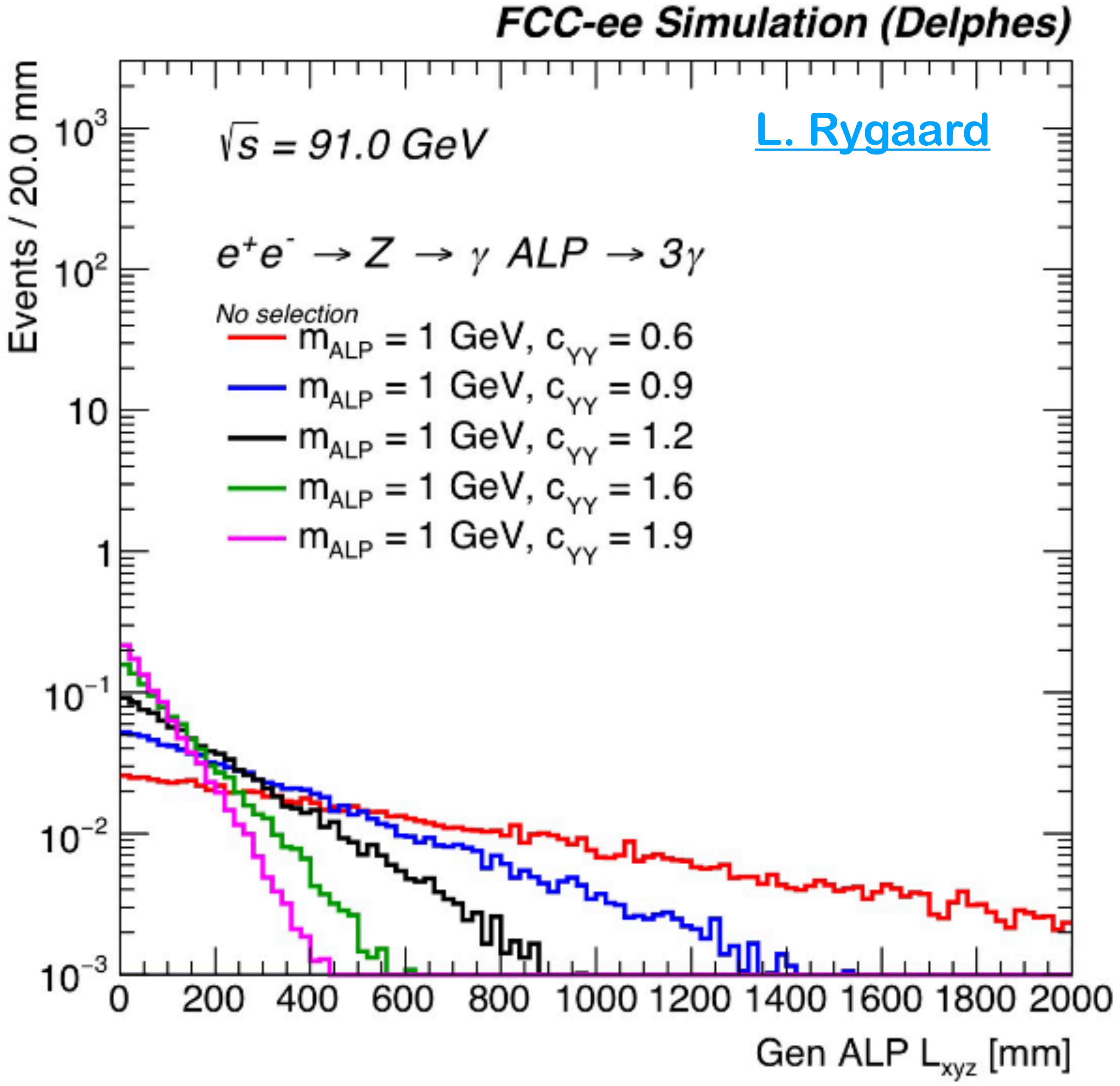
FUTURE CIRCULAR COLLIDER

arXiv:2203.05502

- Specially sensitive final states at FCC-ee of ALPs produced with photons
  - Calorimetry crucial to study this signature
- First generation studies with FCC software available





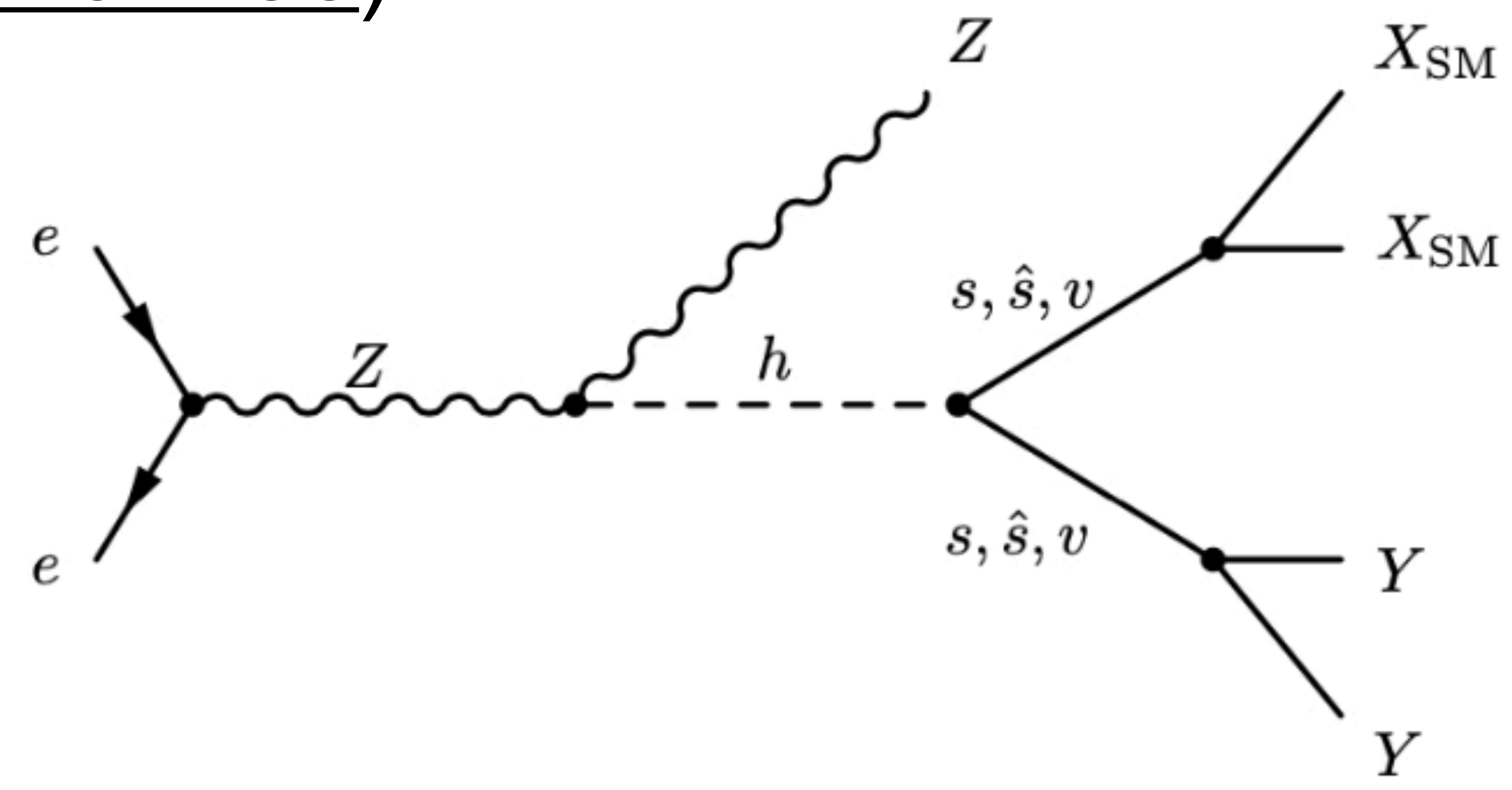


Truth-level decay length of the ALP

3. The Higgs boson
To be more precise, its decays

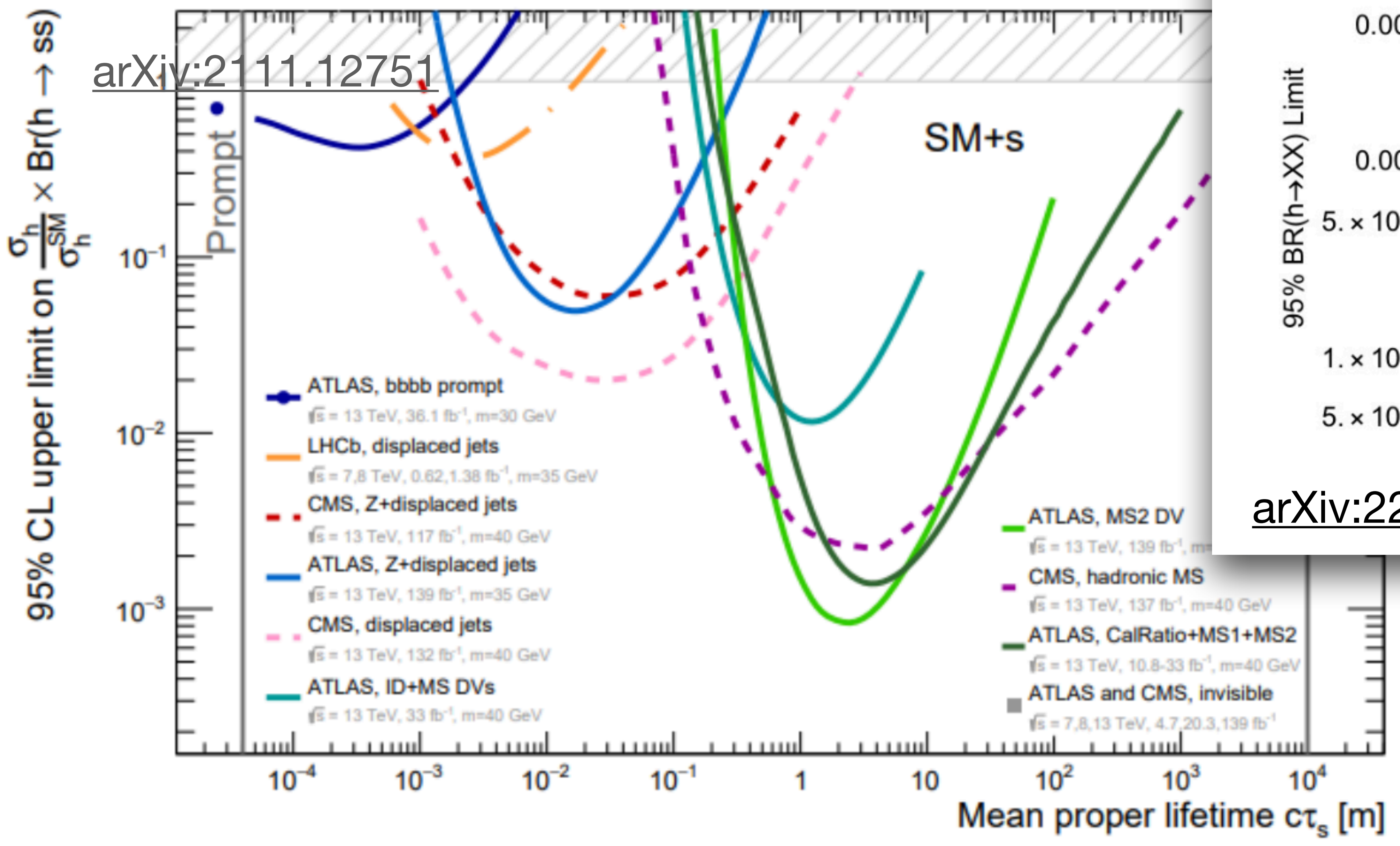
- We are still getting to know the Higgs boson, the LHC is the only place to study it (for now)
- So far it looks SM-like but it still could be exotic and provide us with indications of what lies beyond the SM
- Exotic Higgs decays to long-lived particles are possible and present in many models:
  - SM extensions with scalars/fermions/vectors, MSSM, NMSSM, Hidden Valleys, Twin Higgs (arXiv:1312.4992, arXiv:1812.05588, arXiv:1712.07135)

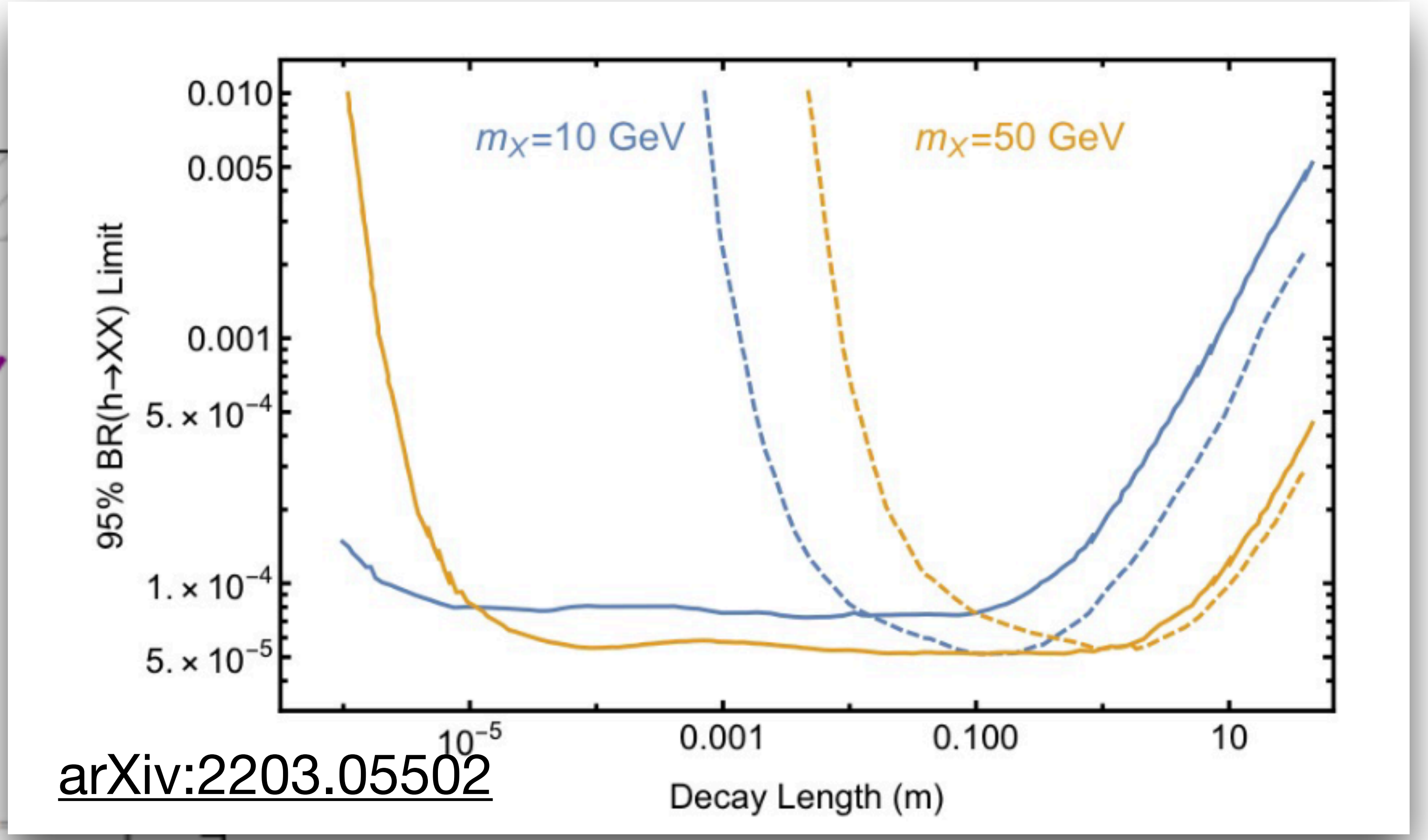
Higgs Portal

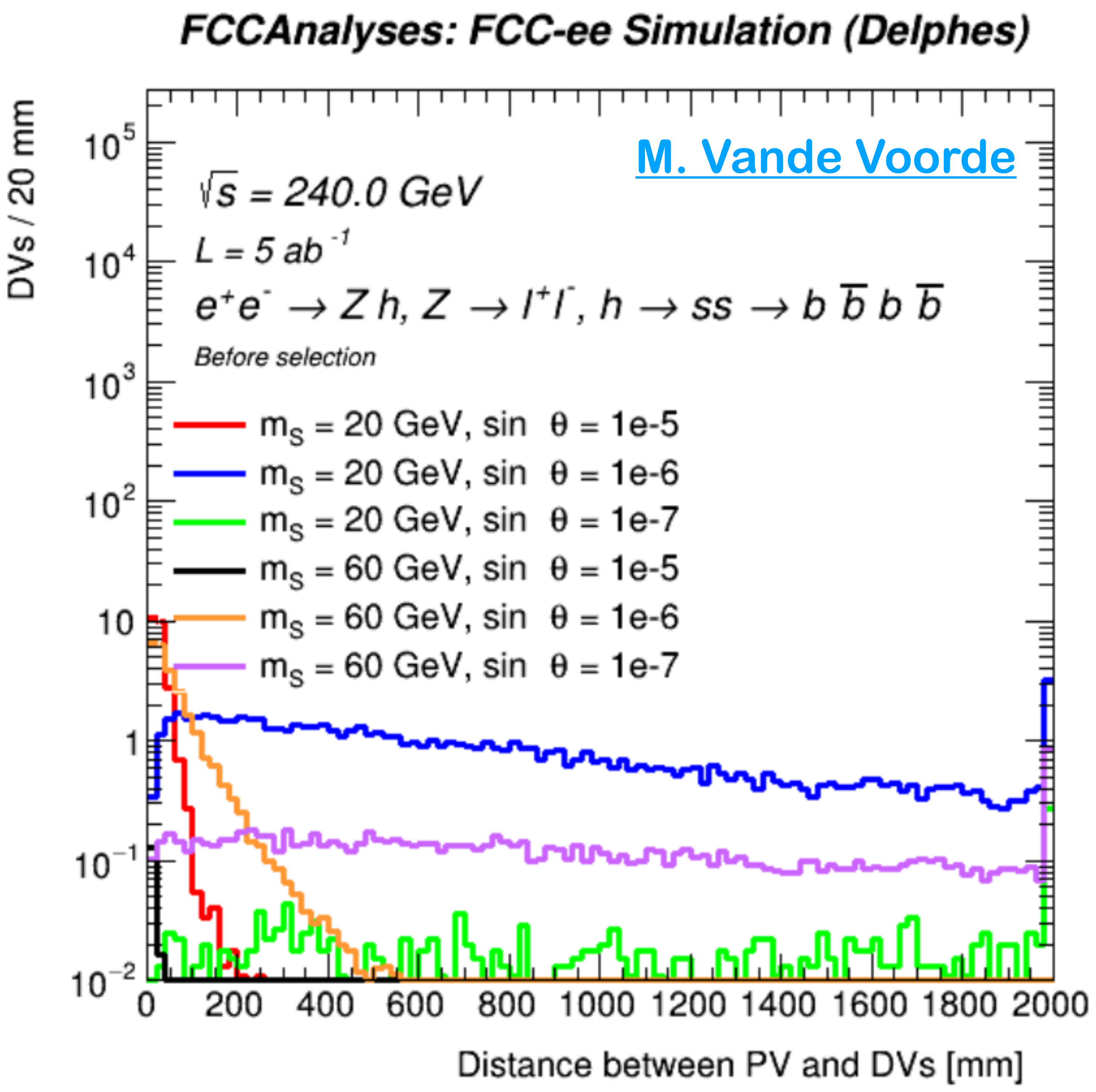


We are also working on that!

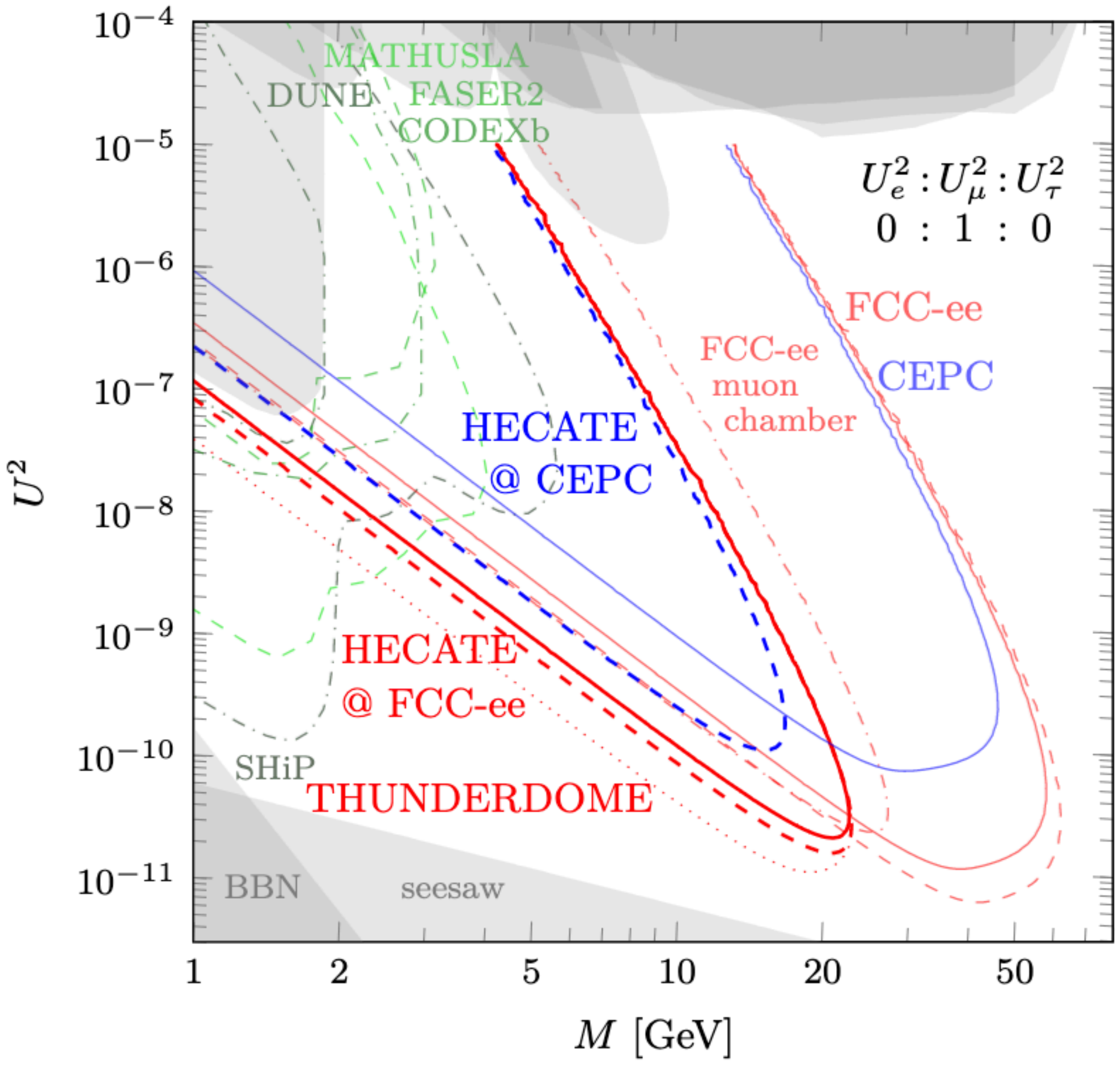
- Experimental studies ongoing with a SM + S model (arXiv:1312.4992, arXiv:1412.0018)
- Long-lived scalars for sufficiently small mixing between the Higgs and the scalar
- Note for midterm report: https://doi.org/10.17181/xgyvv-xfd72







Extra detectors



- Following the example of the LHC we can also propose additional experiments for future colliders
- FCC-ee will have much bigger detector caverns than needed (to use them further for FCC-hh)
- We could install extra instrumentation at the cavern walls
- HECATE: A long lived particle detector concept for the FCC-ee or CEPC: arXiv:2011.01005
- What about a **Forward Physics Facility at FCC?**

Far Detectors
arXiv:1911.06576
for ALPs at FCC-ee, CepC
arXiv:2201.08960

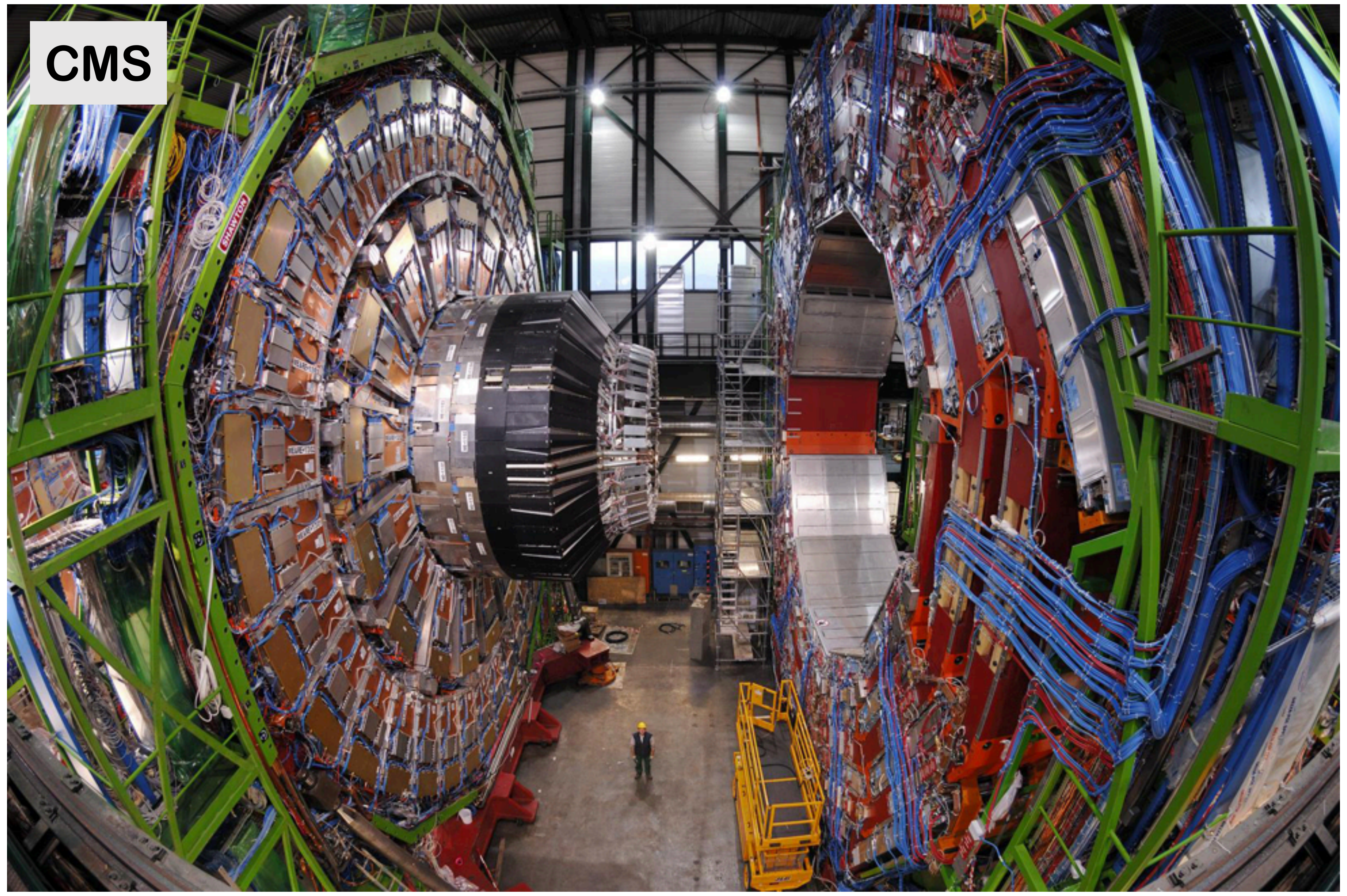
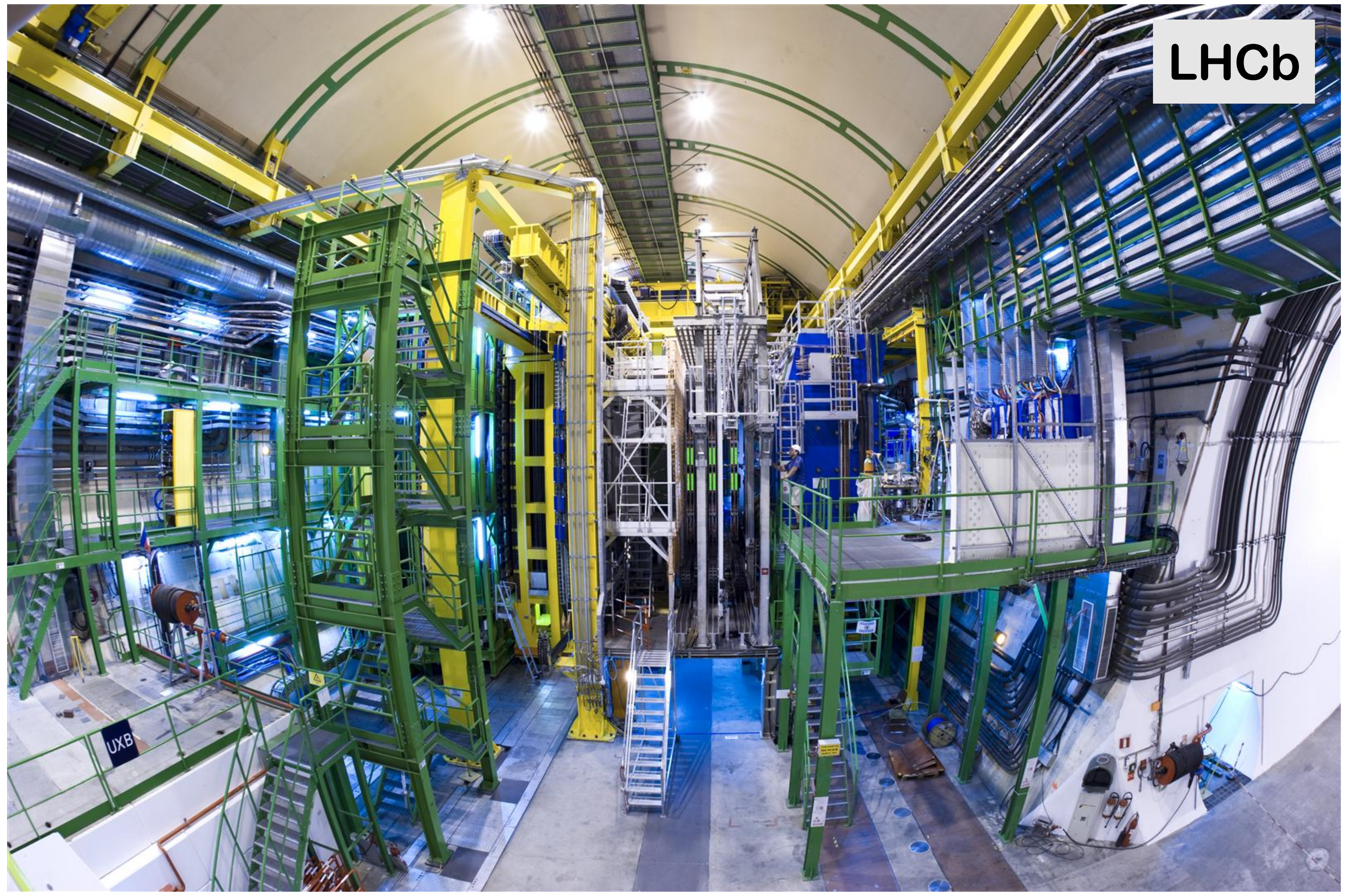
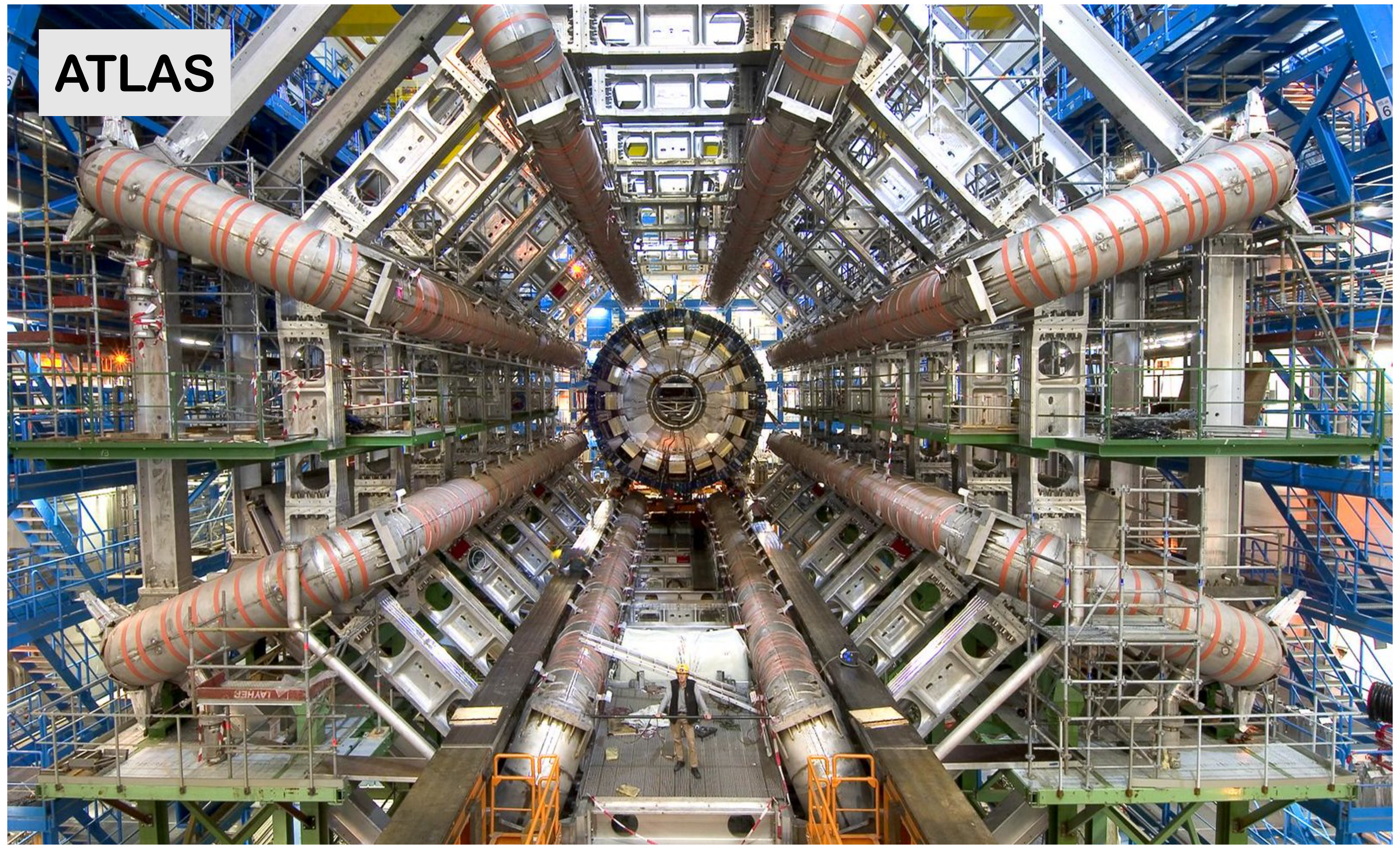
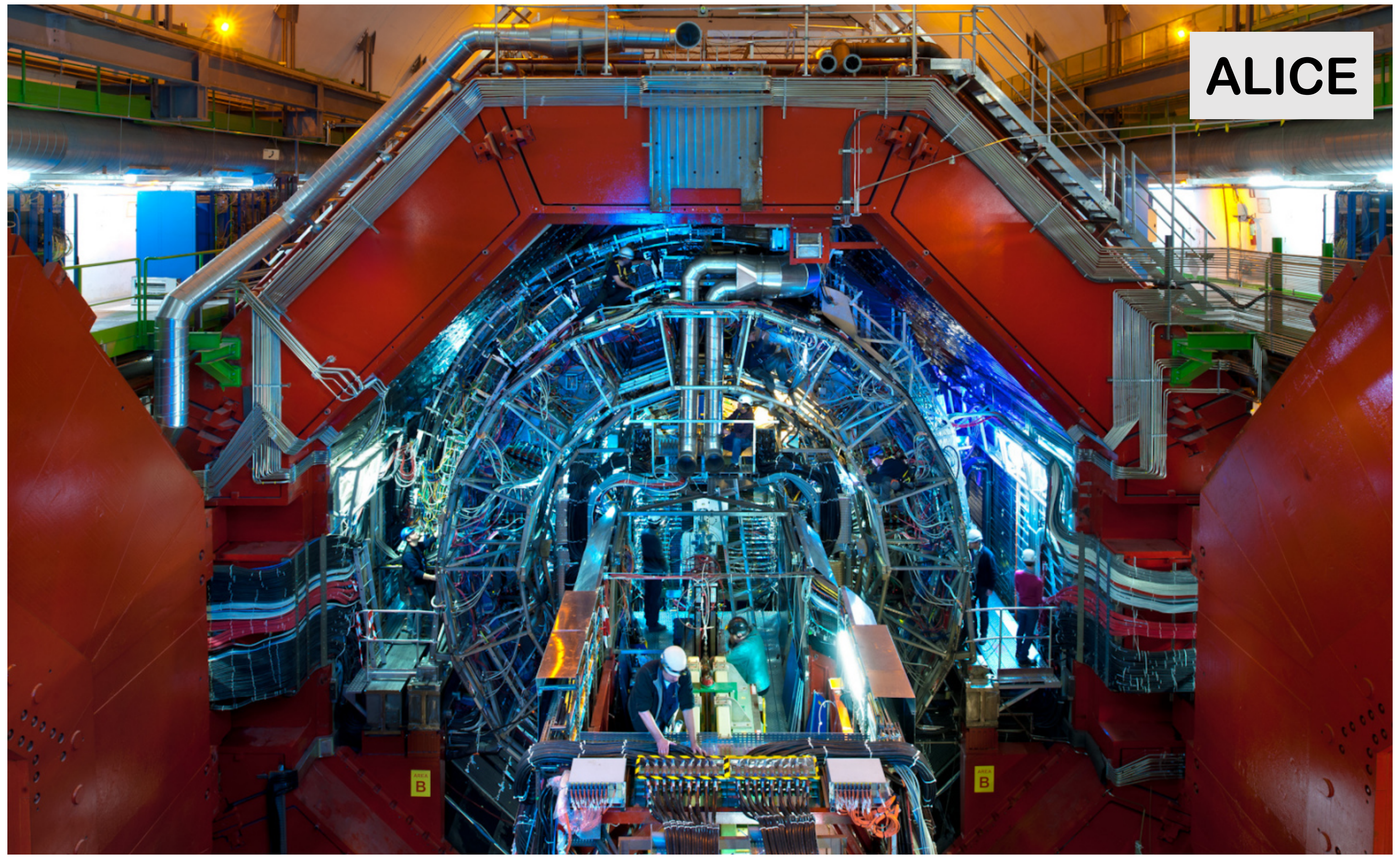
Summary

- Dark sectors: powerful alternative and complement to searches for dark matter at colliders
  - Can address the **lack of obvious BSM signals** → providing accessible new areas for BSM to hide
  - Are connected to other interesting physics questions such as neutrino masses
  - Display **unconventional experimental signatures** that offer us the opportunity to think outside the box
    - **Innovation:** in methods and experimental setups
- Searches ongoing at the LHC experiments + variety of **additional experiments** ongoing/ proposed to complement them at collision points, or using beam dumps
- At **future Higgs factories** (FCC-ee) dark sector searches could hold the key to new physics: HNLs, ALPs, exotic decays of the Higgs boson

Thank you!

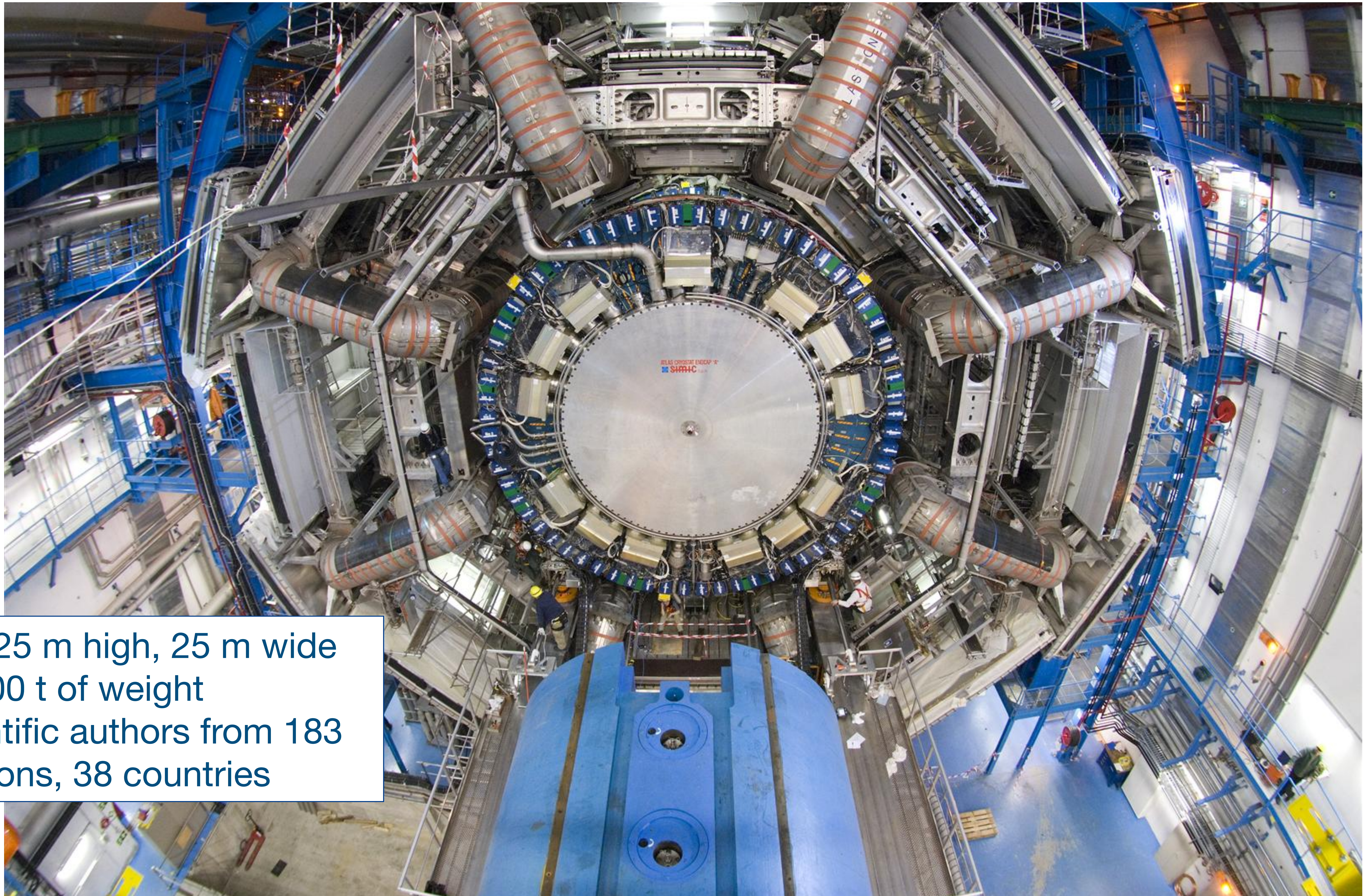
"This project is supported from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754."

Backup


CMS

LHCb

ATLAS

ALICE

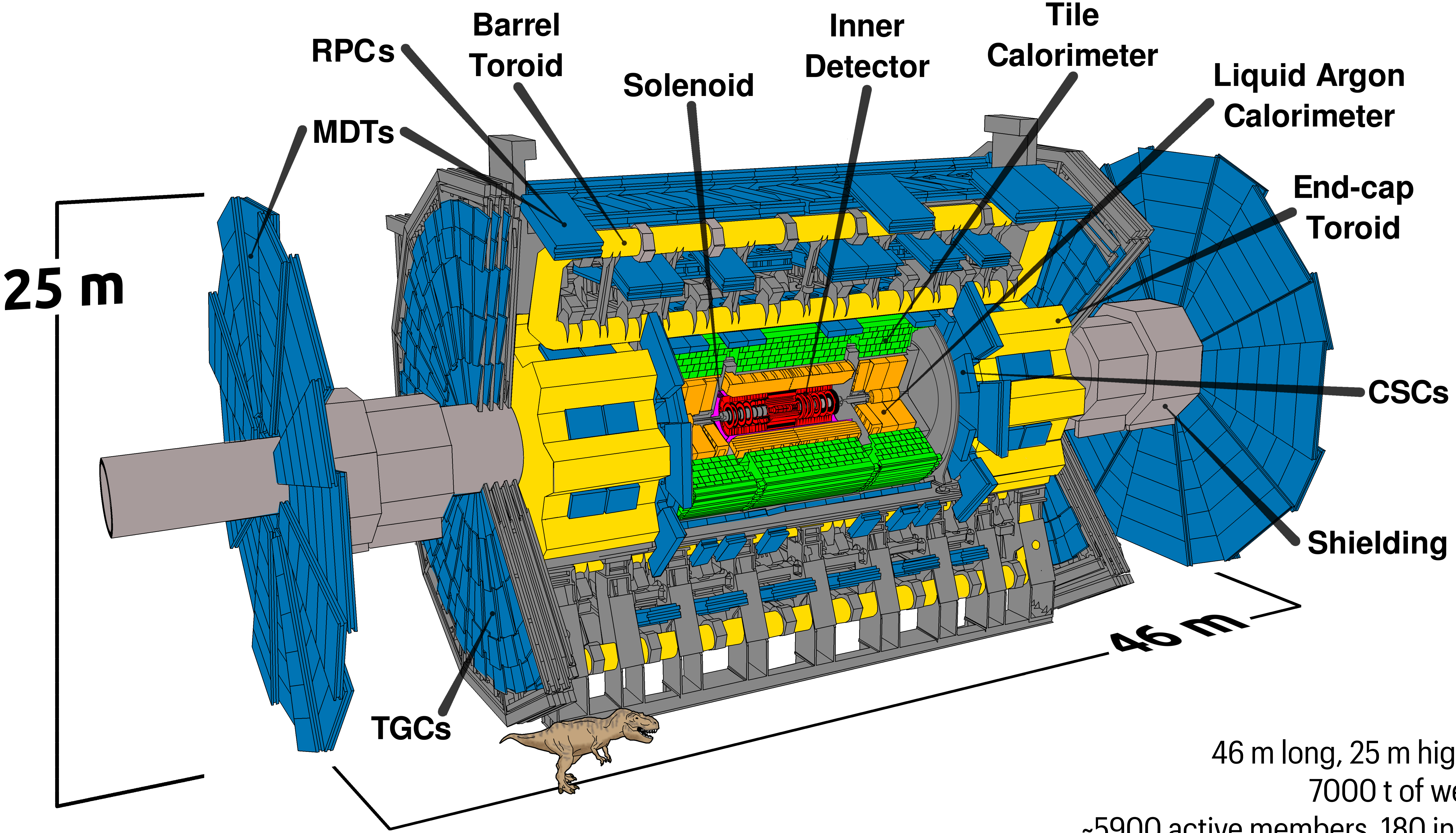
The ATLAS Experiment

ATLAS is the biggest of the LHC experiments

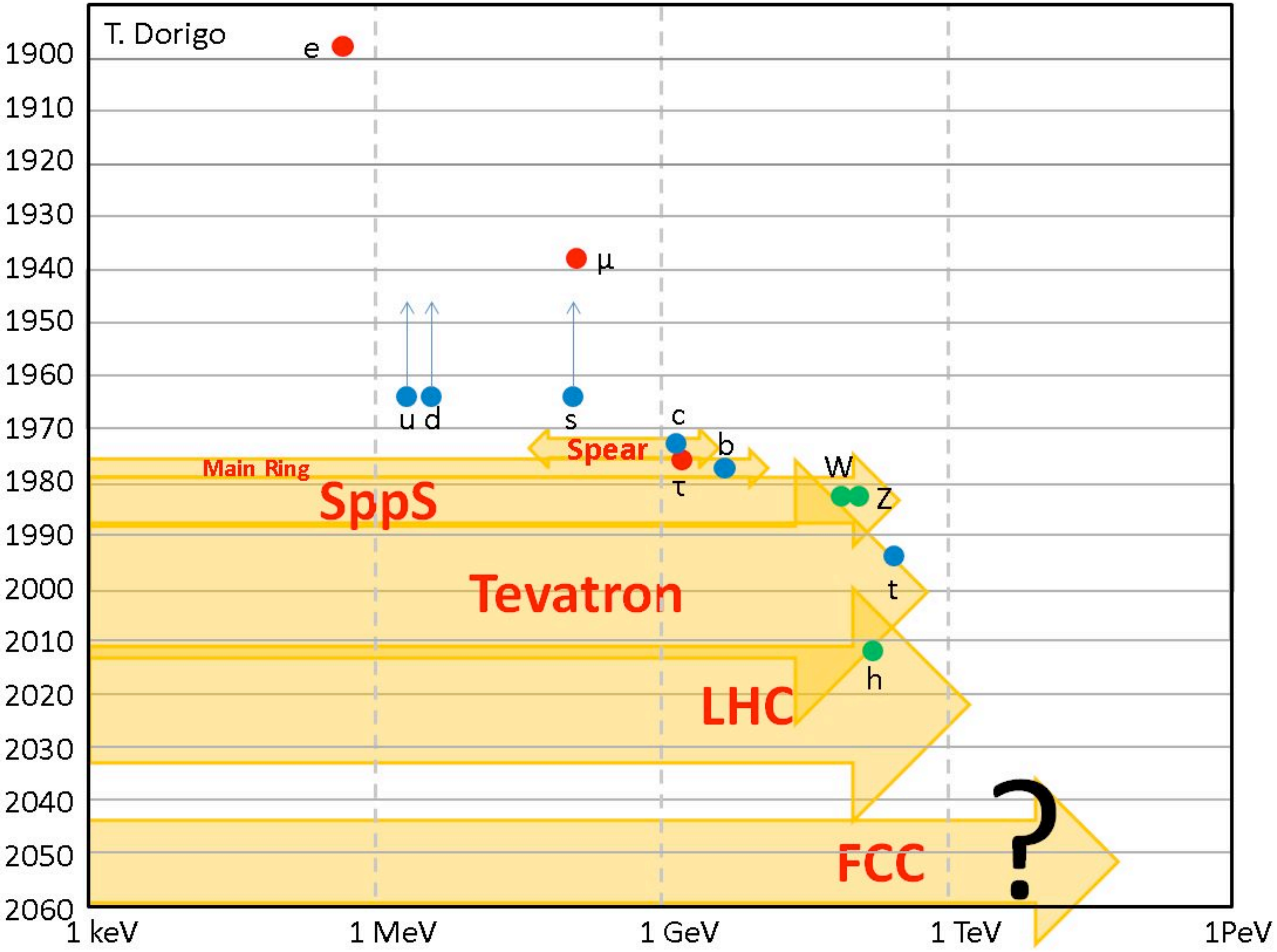


46 m long, 25 m high, 25 m wide
7000 t of weight
~3000 scientific authors from 183 institutions, 38 countries

ATLAS EXPERIMENT



46 m long, 25 m high, 25 m wide
7000 t of weight
~5900 active members, 180 institutions, 40 countries


T. Dorigo
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
1 keV
1 MeV
1 GeV
1 TeV
1PeV
e
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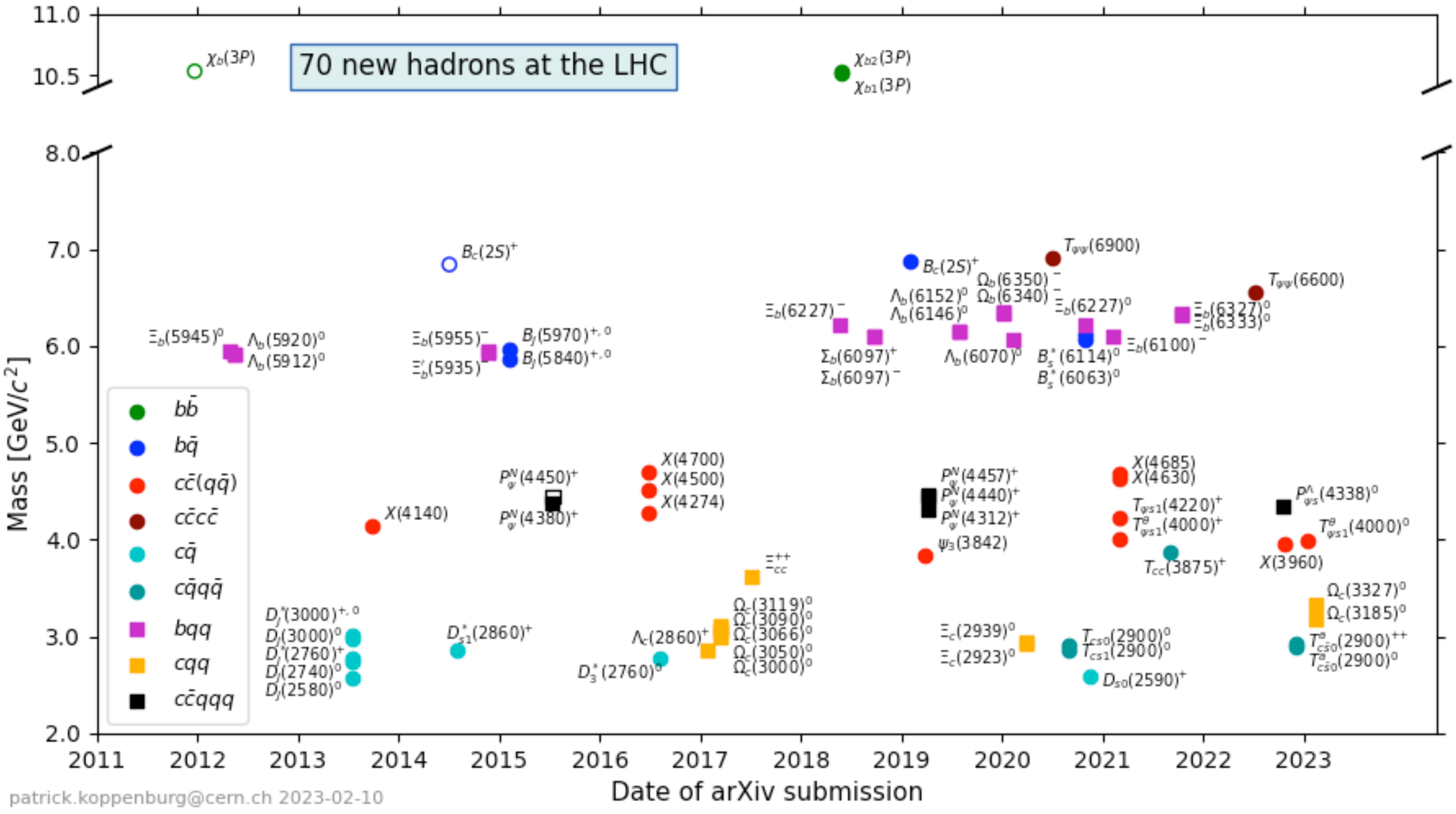
t
h
Main Ring
SppS
Spear
Tevatron
LHC
FCC
?


70 new hadrons at the LHC
Mass [GeV/c^2]
Date of arXiv submission
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
11.0
10.5
8.0
7.0
6.0
5.0
4.0
3.0
2.0
$b\bar{b}$
$b\bar{q}$
$c\bar{c}(q\bar{q})$
$c\bar{c}c\bar{c}$
$c\bar{q}$
$c\bar{q}q\bar{q}$
bqq
cqq
$c\bar{c}qqq$
$\chi_b(3P)$
$\chi_{b2}(3P)$
$\chi_{b1}(3P)$
$B_c(2S)^+$
$T_{\psi\psi}(6900)$
$T_{\psi\psi}(6600)$
$\Xi_b(5945)^0$
$\Lambda_b(5920)^0$
$\Lambda_b(5912)^0$
$\Xi_b(5955)^-$
$\Xi_b'(5935)^-$
$B_J(5970)^{+,0}$
$B_J(5840)^{+,0}$
$\Xi_b(6227)^-$
$\Sigma_b(6097)^+$
$\Sigma_b(6097)^-$
$\Lambda_b(6152)^0$
$\Lambda_b(6146)^0$
$\Omega_b(6350)^-$
$\Omega_b(6340)^-$
$\Lambda_b(6070)^0$
$\Xi_b(6227)^0$
$B_s^*(6114)^0$
$B_s^*(6063)^0$
$\Xi_b(6100)^-$
$\Xi_b(6327)^0$
$\Xi_b(6333)^0$
$X(4140)$
$P_\psi^N(4450)^+$
$P_\psi^N(4380)^+$
$X(4700)$
$X(4500)$
$X(4274)$
$P_\psi^N(4457)^+$
$P_\psi^N(4440)^+$
$P_\psi^N(4312)^+$
$\psi_3(3842)$
$X(4685)$
$X(4630)$
$T_{\psi s1}(4220)^+$
$T^\theta_{\psi s1}(4000)^+$
$T_{cc}(3875)^+$
$P^\Lambda_{\psi s}(4338)^0$
$T^\theta_{\psi s1}(4000)^0$
$X(3960)$
Ξ_{cc}^{++}
$D_J^*(3000)^{+,0}$
$D_J(3000)^0$
$D_J^*(2760)^+$
$D_J(2740)^0$
$D_J(2580)^0$
$D^*_{s1}(2860)^+$
$\Lambda_c(2860)^+$
$D_3^*(2760)^0$
$\Omega_c(3119)^0$
$\Omega_c(3090)^0$
$\Omega_c(3066)^0$
$\Omega_c(3050)^0$
$\Omega_c(3000)^0$
$\Xi_c(2939)^0$
$\Xi_c(2923)^0$
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$T_{cs1}(2900)^0$
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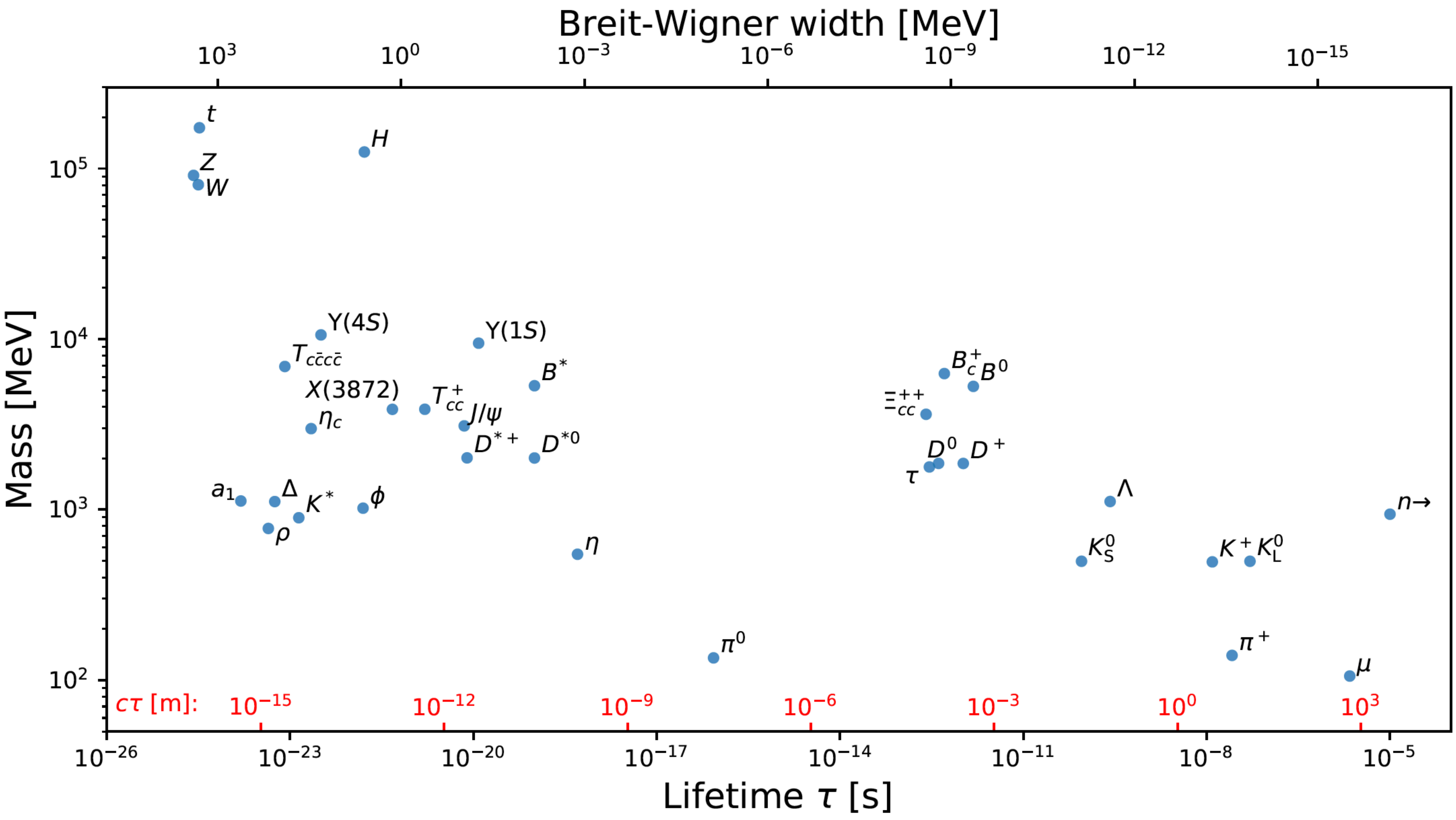
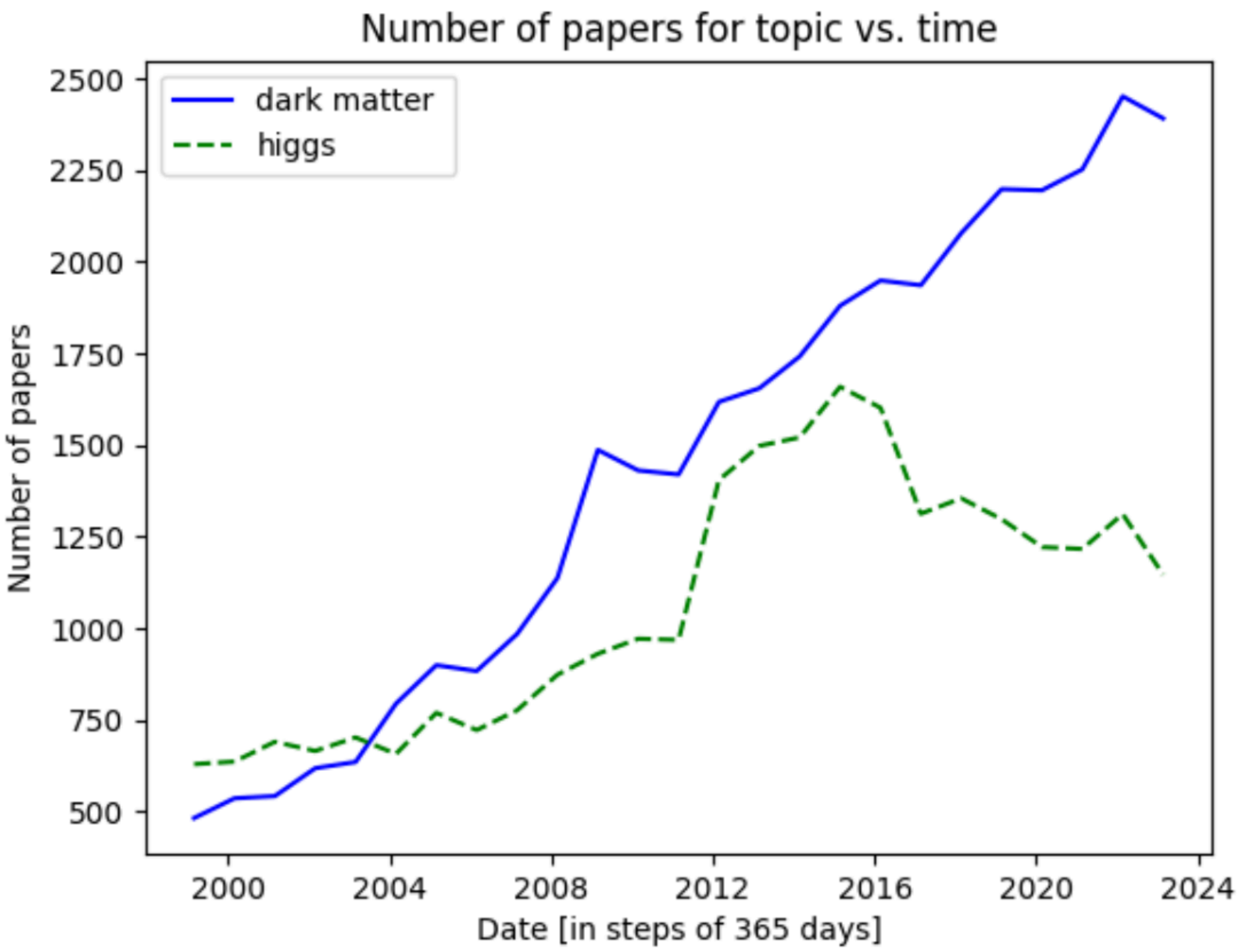
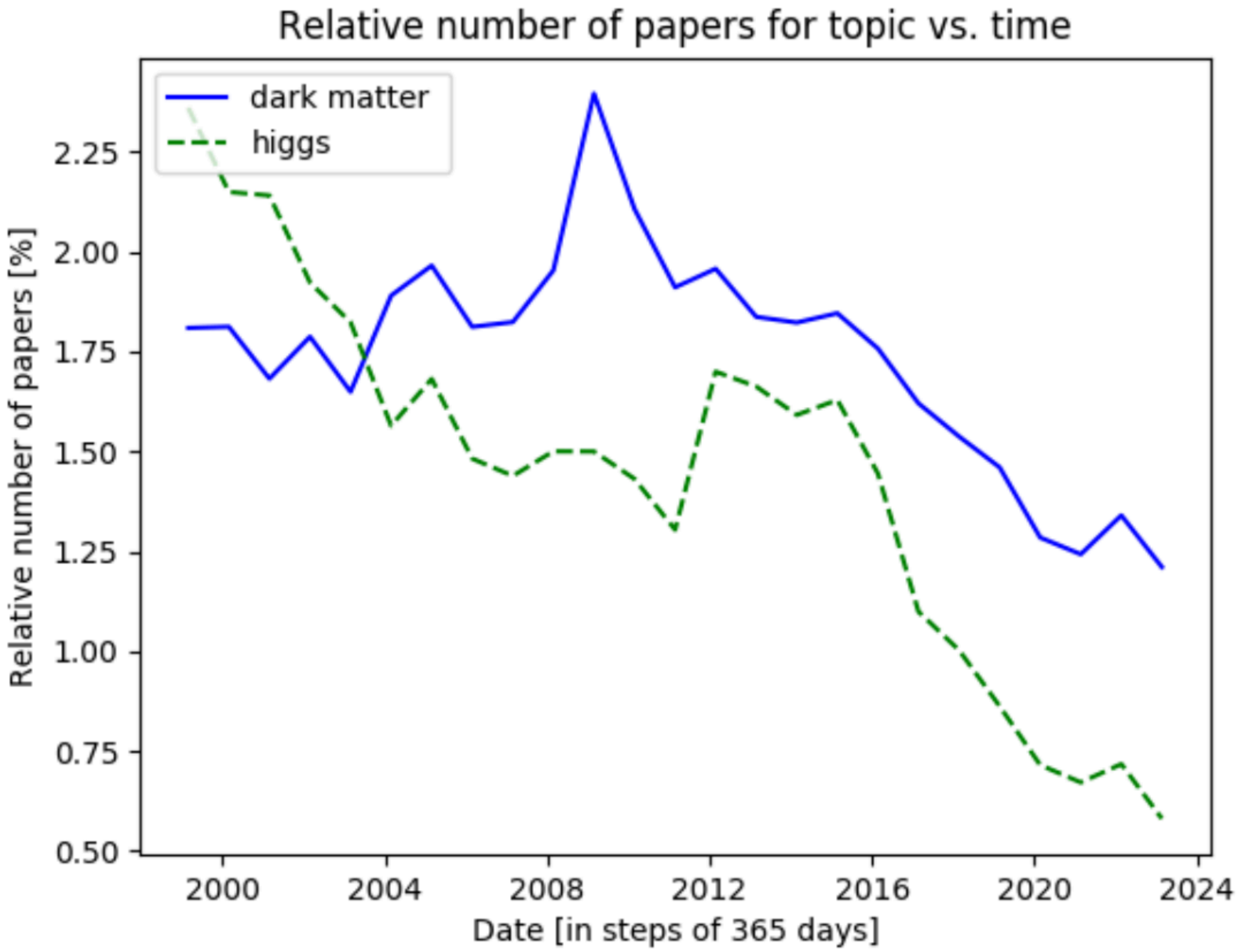
$\Omega_c(3185)^0$
$T^a_{c\bar{s}0}(2900)^{++}$
$T^a_{c\bar{s}0}(2900)^0$
patrick.koppenburg@cern.ch 2023-02-10



Courtesy of Patrick Koppenburg



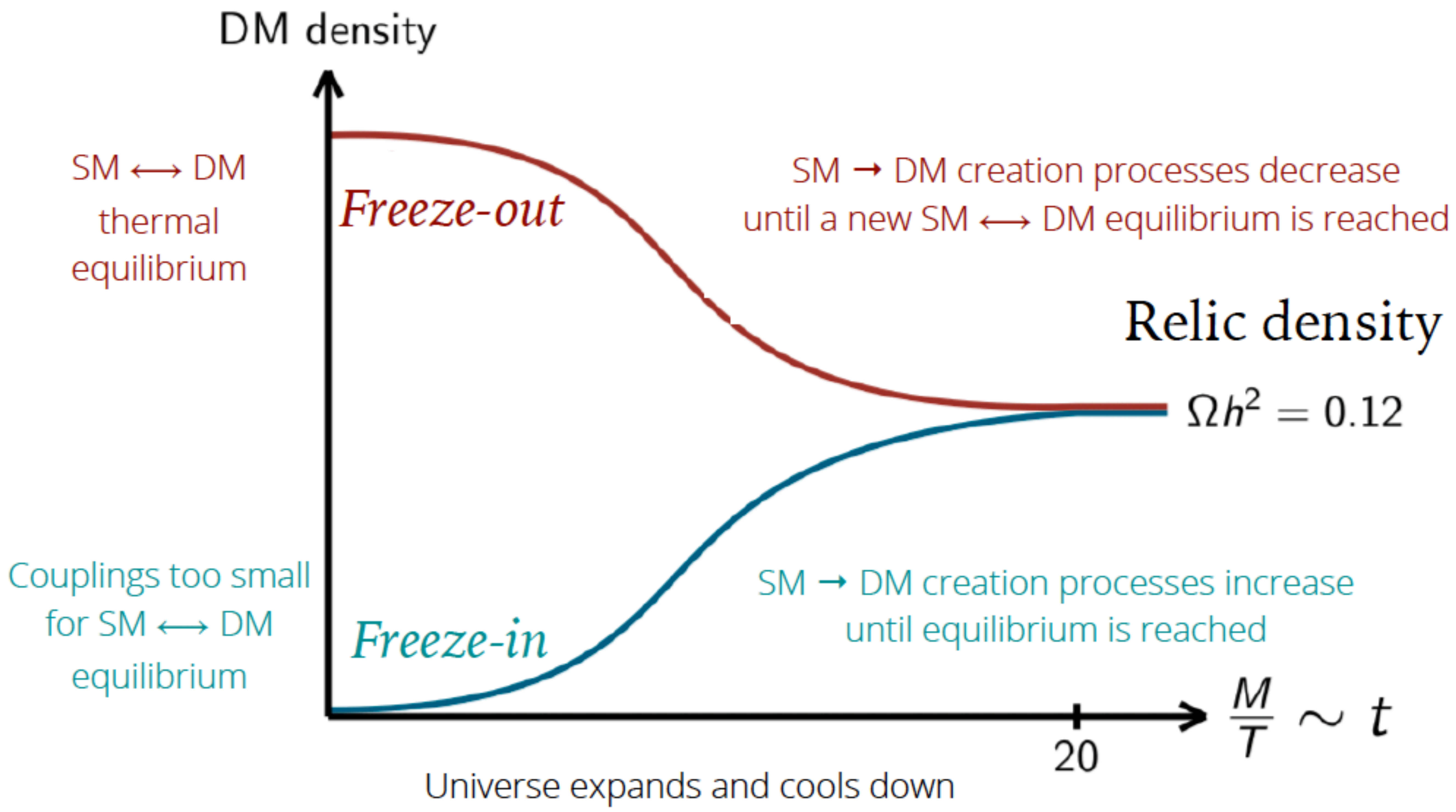
https://benty-fields.com/trending Idea from Caterina Doglioni

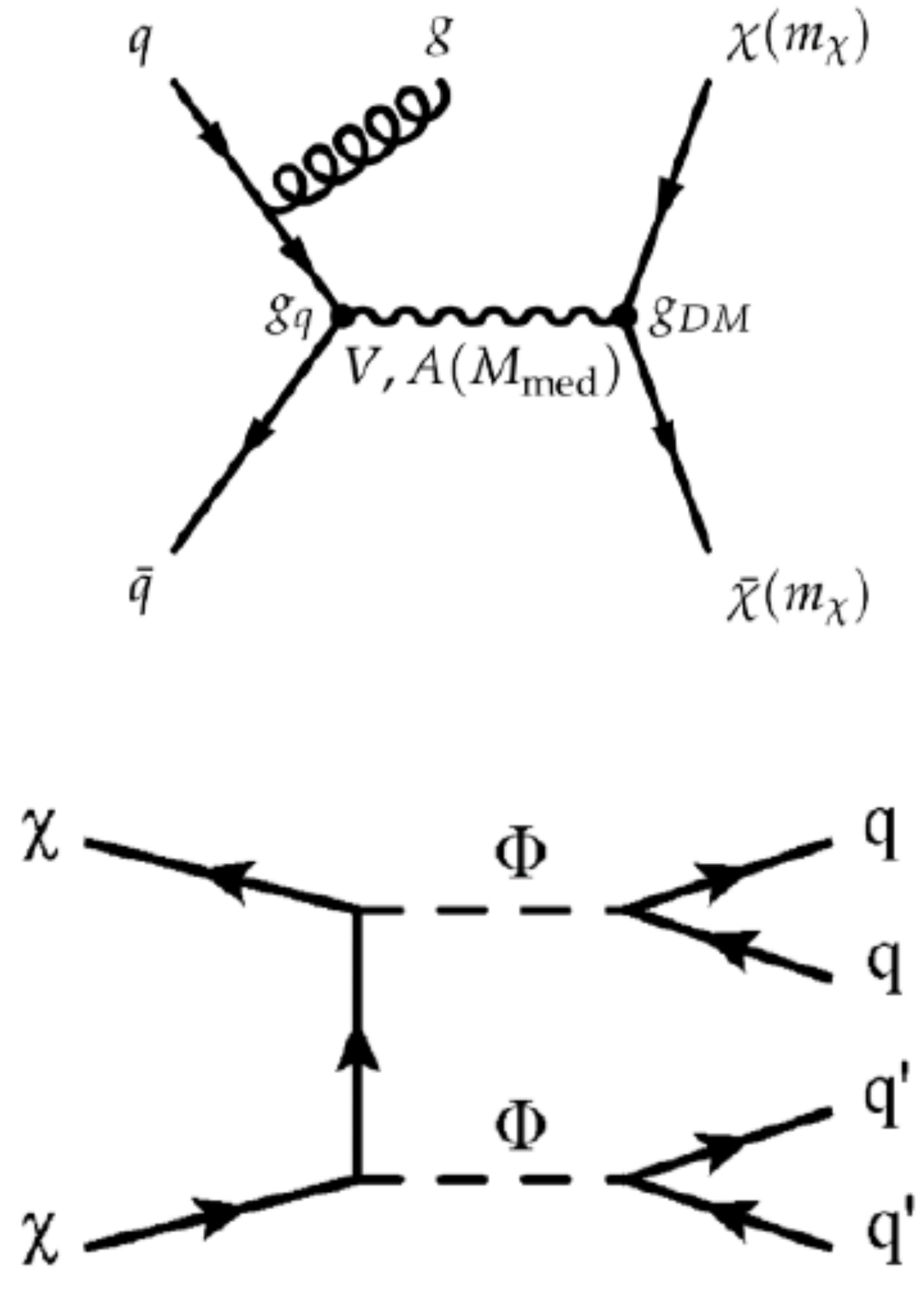


https://benty-fields.com/trending Idea from Caterina Doglioni

How did the relic density come to be?

From Caterina Doglioni

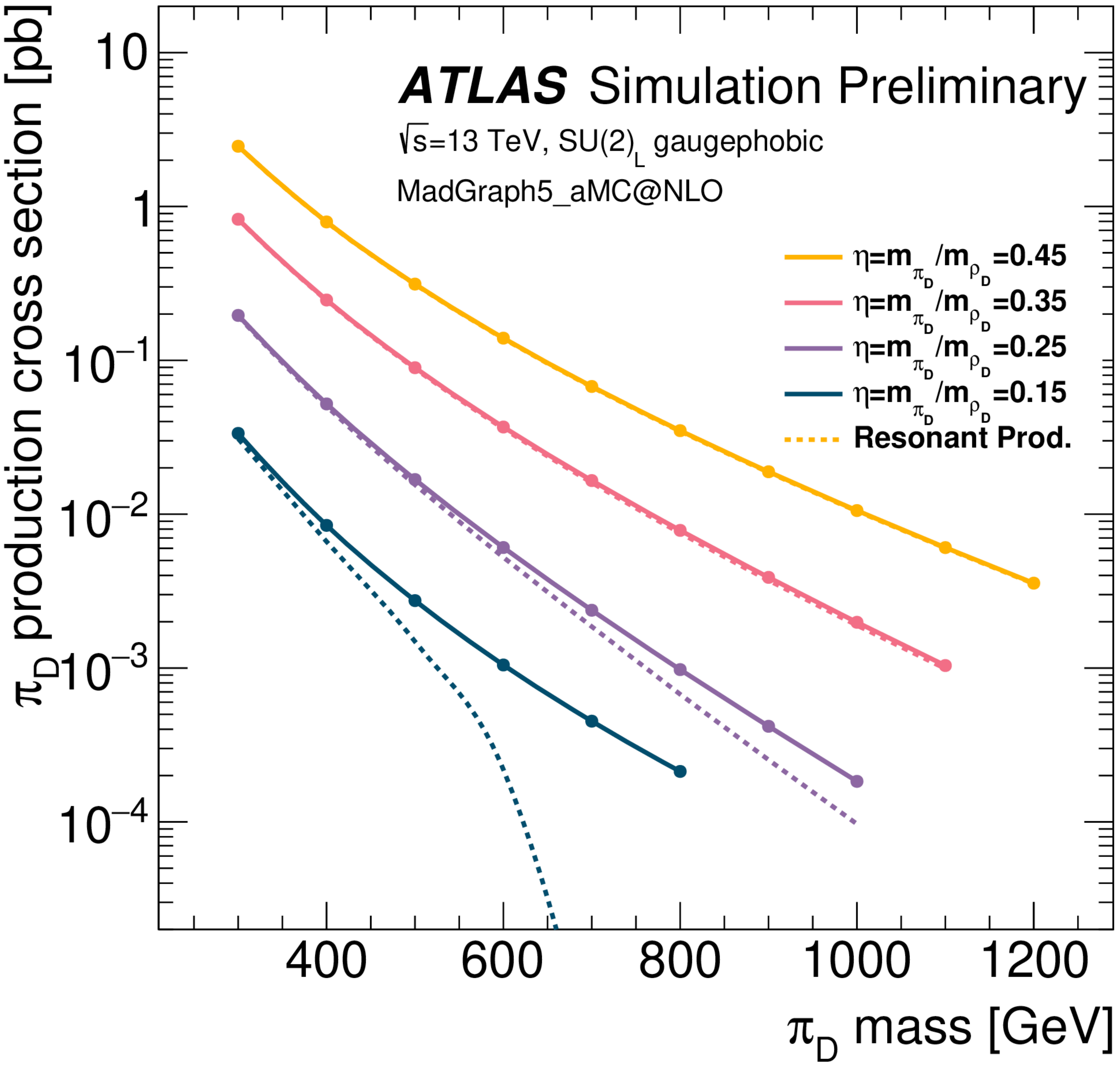


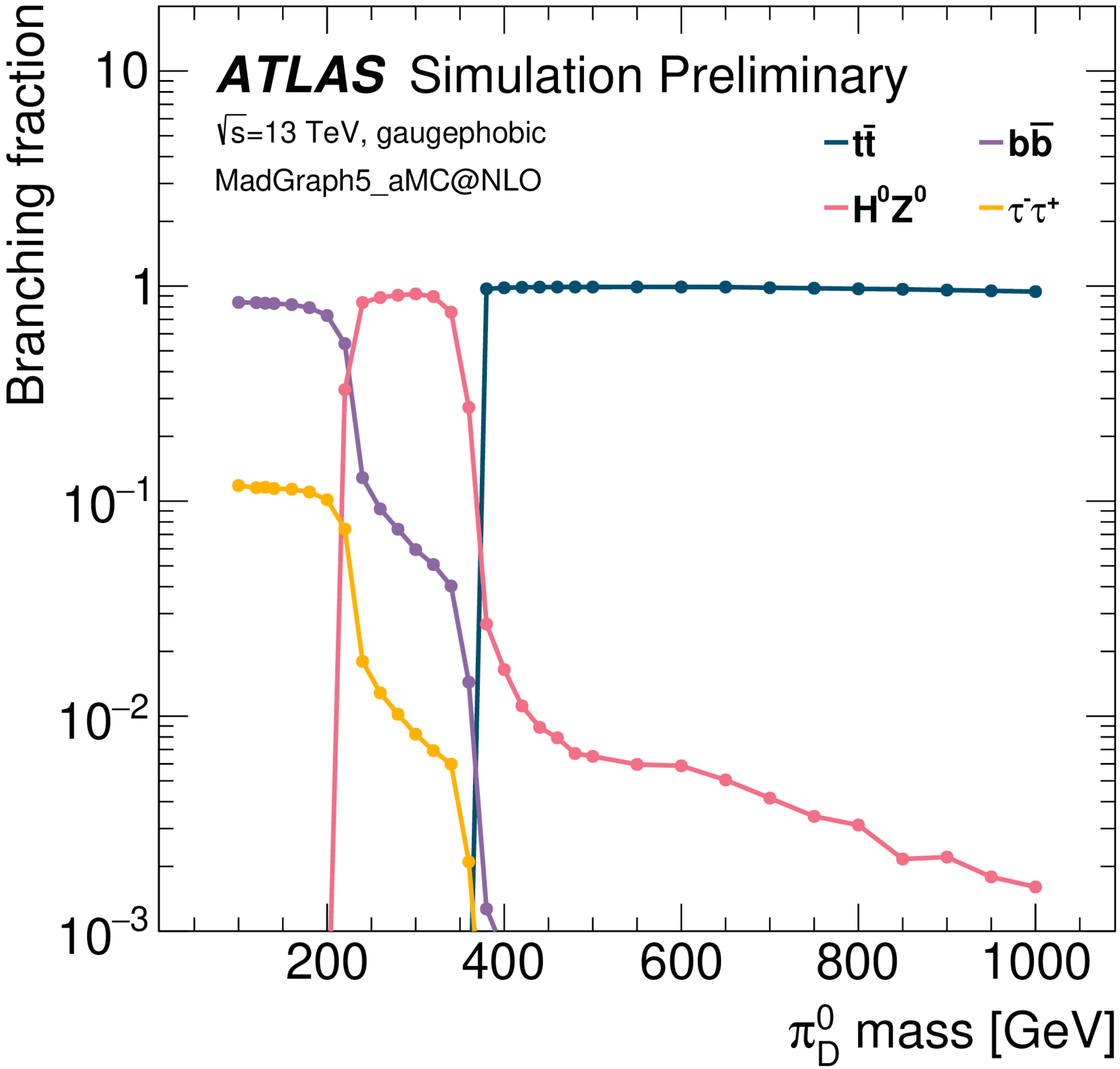


Examples of DM ⟷ SM processes

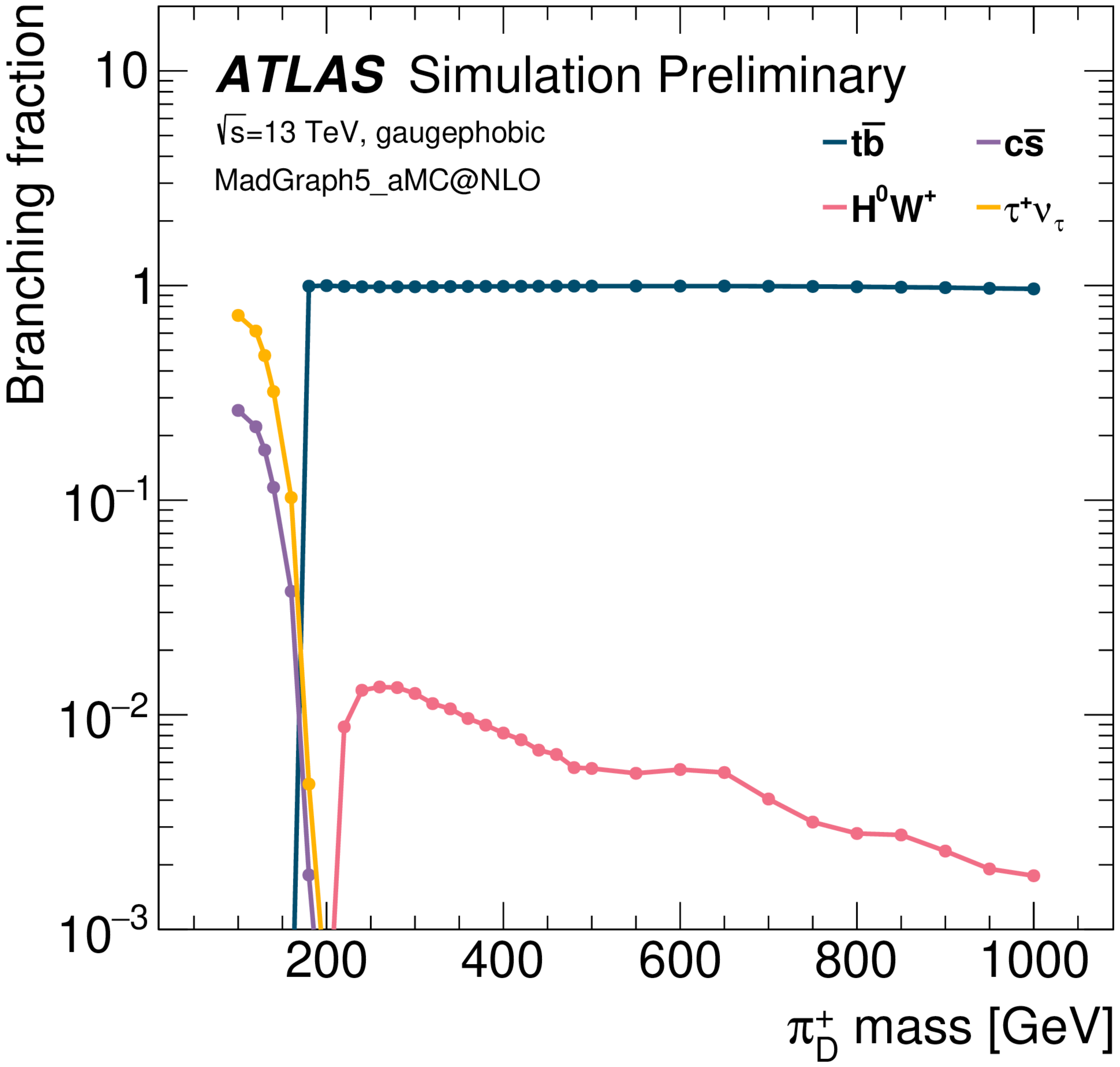
Isabelle John's thesis

Note: simplified picture, for a more complete one see https://arxiv.org/abs/1706.07442


ATLAS Simulation Preliminary
√s=13 TeV, SU(2)L gaugephobic
MadGraph5_aMC@NLO
η=mπD/mρD=0.45
η=mπD/mρD=0.35
η=mπD/mρD=0.25
η=mπD/mρD=0.15
Resonant Prod.
πD production cross section [pb]
πD mass [GeV]
10
1
10−1
10−2
10−3
10−4
400
600
800
1000
1200



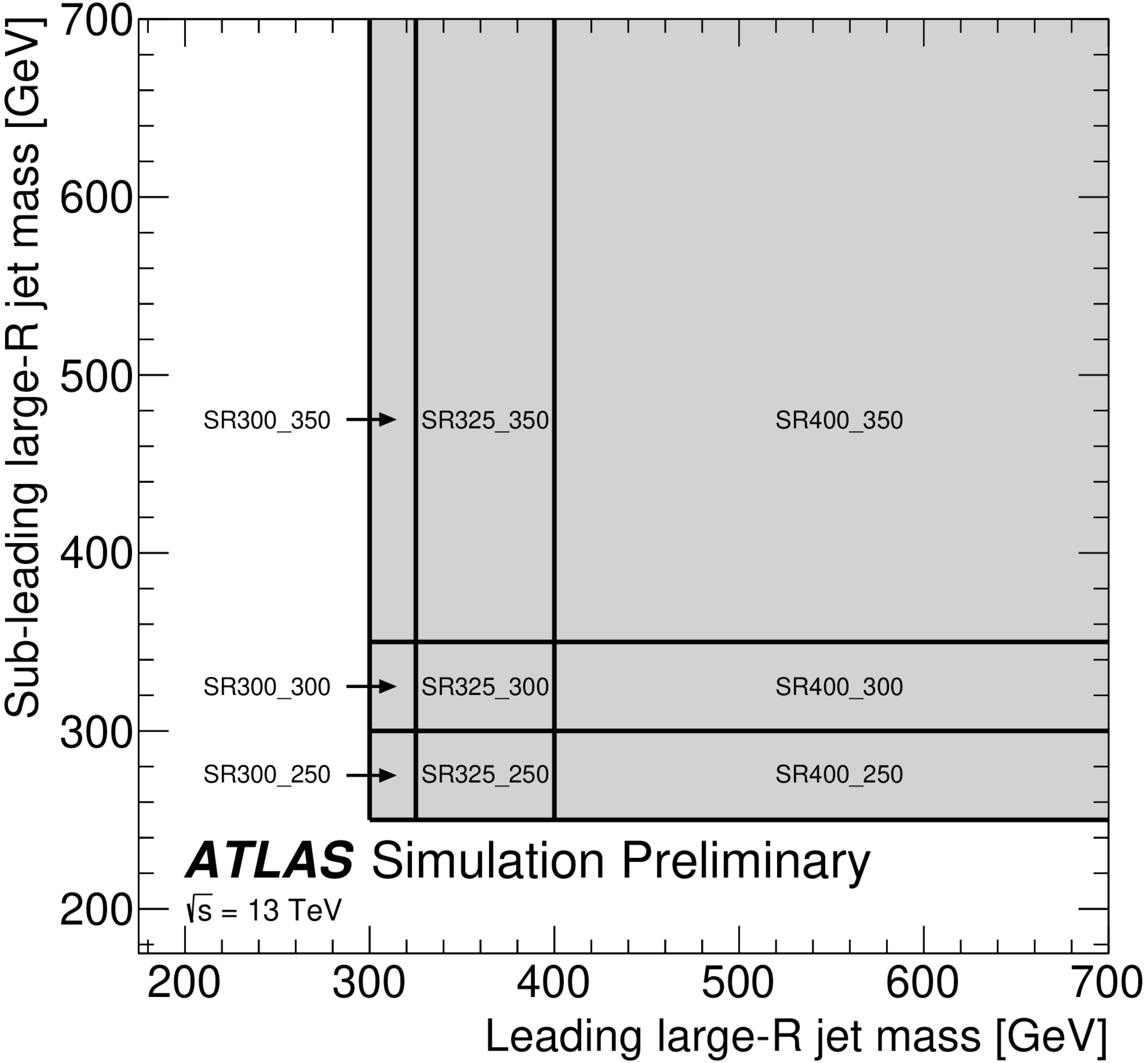
ATLAS Simulation Preliminary
√s=13 TeV, gaugephobic
MadGraph5_aMC@NLO
$t\bar{t}$
$b\bar{b}$
H^0Z^0
$\tau^-\tau^+$
Branching fraction
10
1
10^{-1}
10^{-2}
10^{-3}
200
400
600
800
1000
π_D^0 mass [GeV]



ATLAS Simulation Preliminary
√s=13 TeV, gaugephobic
MadGraph5_aMC@NLO
$t\bar{b}$
$c\bar{s}$
H^0W^+
$\tau^+\nu_\tau$
Branching fraction
10
1
10^{-1}
10^{-2}
10^{-3}
200
400
600
800
1000
π_D^+ mass [GeV]

	Mass	Charged Current	Neutral Current
gaugephilic	$m_{\pi_D} \lesssim 150$ GeV	$b\bar{b}\tau\nu$	$\tau^+\tau^-\nu\bar{\nu}$
	150 GeV $\lesssim m_{\pi_D} \lesssim$ 200 GeV	$b\bar{b}t\bar{b}$	$t\bar{t}b\bar{b}$
	200 GeV $\lesssim m_{\pi_D} \lesssim$ 450 GeV	$Z\,h\,t\bar{b}$	$t\bar{t}b\bar{b}$
	$m_{\pi_D} \gtrsim 450$ GeV	$h\,h\,Z\,W^+$	hhW^+W^-
gaugephobic	$m_{\pi_D} \lesssim 150$ GeV	$b\bar{b}\tau\nu$	$\tau^+\tau^-\nu\bar{\nu}$
	150 GeV $\lesssim m_{\pi_D} \lesssim$ 220 GeV	$b\bar{b}t\bar{b}$	$t\bar{t}b\bar{b}$
	220 GeV $\lesssim m_{\pi_D} \lesssim$ 350 GeV	$Zht\bar{b}$	$t\bar{t}b\bar{b}$
	$m_{\pi_D} \gtrsim 350$ GeV	$t\bar{t}t\bar{b}$	$t\bar{t}b\bar{b}$

Table 2: Phenomenological regions for collider signatures. The charged and neutral current columns show the SM particles for the dominant branching ratios.



SR300_350
SR325_350
SR400_350
SR300_300
SR325_300
SR400_300
SR300_250
SR325_250
SR400_250
ATLAS Simulation Preliminary
√s = 13 TeV
Sub-leading large-R jet mass [GeV]
Leading large-R jet mass [GeV]
200
300
400
500
600
700

	Tag	Variable	Tag selection	Anti-tag selection
Both large-R jets		$m_{bb}/p_{\mathrm{T},bb}$	> 0.25	
Leading large-R jet	bb_1	$\Delta R\,(j, b_2)$	< 1.0	≥ 1.0
Sub-leading large-R jet	bb_2	$\Delta R\,(j, b_2)$	< 1.0	≥ 1.0
Leading large-R jet	$\pi_{D,1}$	$m_{\mathrm{jet,R=1.2}}$	$[300 - 325\,GeV,$ $325 - 400\,GeV,$ $> 400\,GeV]$	$\leq 300\,GeV$
Sub-leading large-R jet	$\pi_{D,2}$	$m_{\mathrm{jet,R=1.2}}$	$[250 - 300\,GeV,$ $300 - 350\,GeV,$ $> 350\,GeV]$	$\leq 250\,GeV$

Leading large-R jet

Sub-leading large-R jet

	$\not{\pi}_{D,1}\not{bb}_1$	$\pi_{D,1}\not{bb}_1$	$\not{\pi}_{D,1}bb_1$	$\pi_{D,1}bb_1$
$\pi_{D,2}bb_2$	J	K	L	S
$\not{\pi}_{D,2}bb_2$	B	D	H	N
$\pi_{D,2}\not{bb}_2$	E	F	G	M
$\not{\pi}_{D,2}\not{bb}_2$	A	C	I	O

	SR300_250	SR300_300	SR300_350
Non-closure uncertainty	40%	45%	1.4%
Stat. uncert. on k-factors	37%	35%	39%
Total Multijet Uncertainty	55%	57%	39%

	SR325_250	SR325_300	SR325_350
Non-closure uncertainty	16%	28%	28%
Stat. uncert. on k-factors	29%	29%	29%
Total Multijet Uncertainty	33%	40%	41%

	SR400_250	SR400_300	SR400_350
Non-closure uncertainty	34%	3.2%	29%
Stat. uncert. on k-factors	37%	38%	38%
Total Multijet Uncertainty	51%	38%	48%

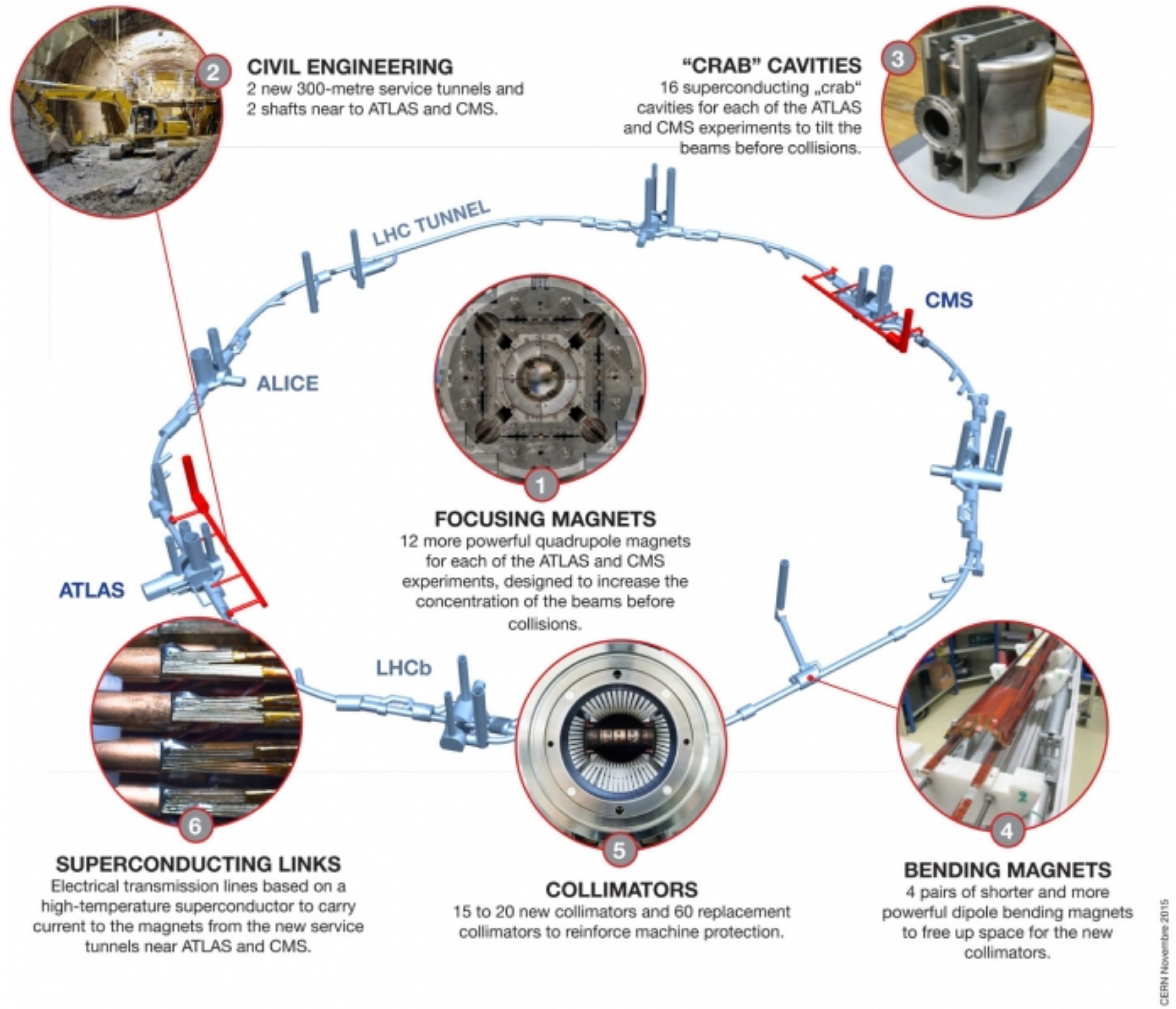
Post-fit event yields in all nine signal mass bins. The quoted uncertainties contain statistical and systematic components.

	SR300_250	SR300_300	SR300_350
V+jets	0.00±0.00	2.0±0.9	0.28±0.06
Single top	0.12±0.07	0.00±0.03	0.00±0.00
$t\bar{t}+X$	0.30±0.04	0.21±0.09	0.17±0.04
$t\bar{t}$	3±2	1.6±1.1	1.8±0.8
Multijet	16±4	10±4	11±3
Total SM	20±4	14±3	13±3
Data	20	14	16

	SR325_250	SR325_300	SR325_350
V+jets	0.7±0.6	0.12±0.18	0.19±0.16
Single top	0.4±0.1	0.12±0.13	0.27±0.15
$t\bar{t}+X$	0.4±0.1	0.4±0.1	0.50±0.07
$t\bar{t}$	6±4	4±2	4±2
Multijet	33±7	23±5	18±5
Total SM	41±6	28±5	23±5
Data	41	28	23

	SR400_250	SR400_300	SR400_350
V+jets	0.7±0.6	0.00±0.00	1.2±0.3
Single top	0.00±0.00	0.5±0.1	0.11±0.02
$t\bar{t}+X$	0.34±0.07	0.40±0.07	0.7±0.1
$t\bar{t}$	4±2	3.1±2.5	6±4
Multijet	20±5	15±5	28±12
Total SM	25±5	19±4	36±11
Data	27	20	45

https://hilumilhc.web.cern.ch/





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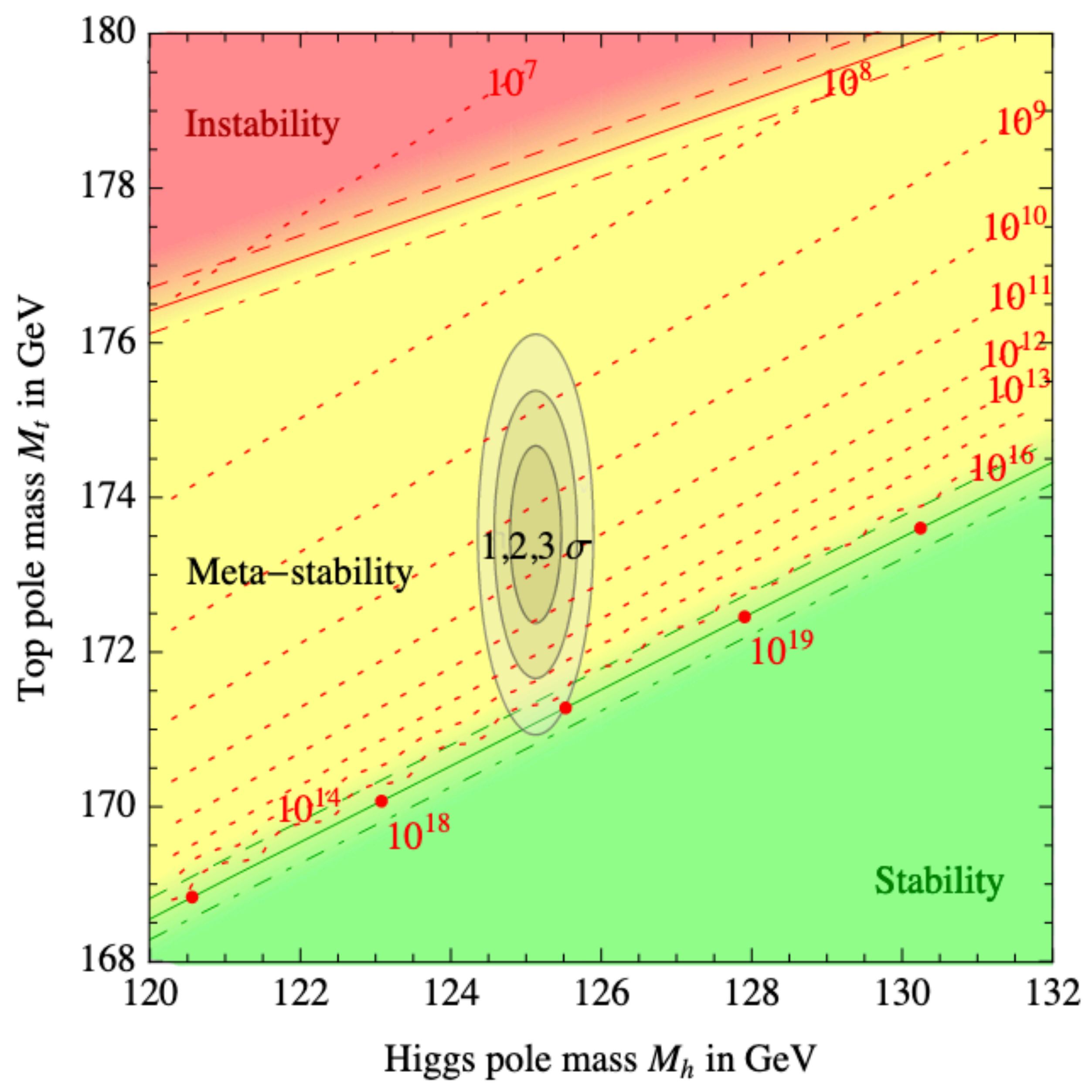

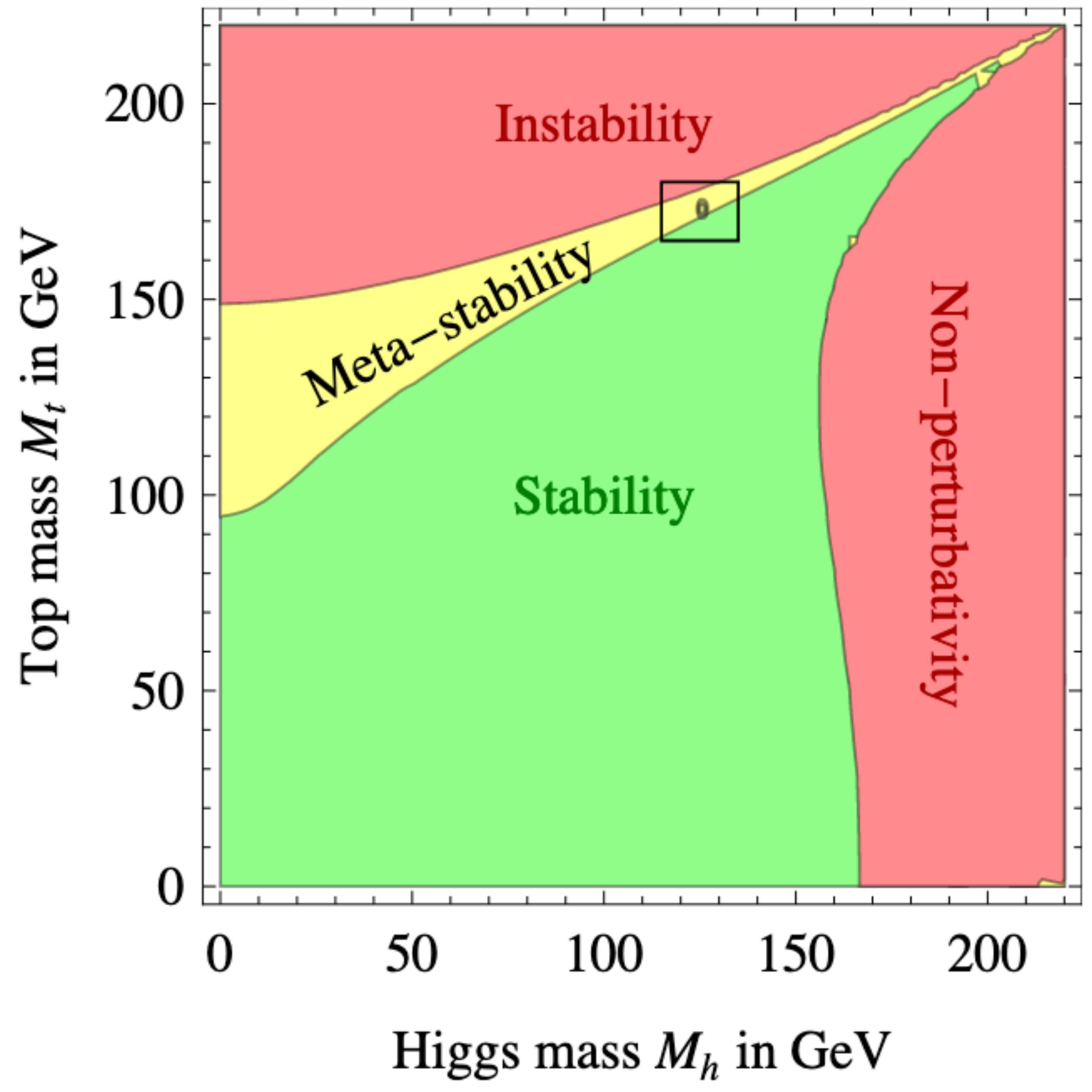

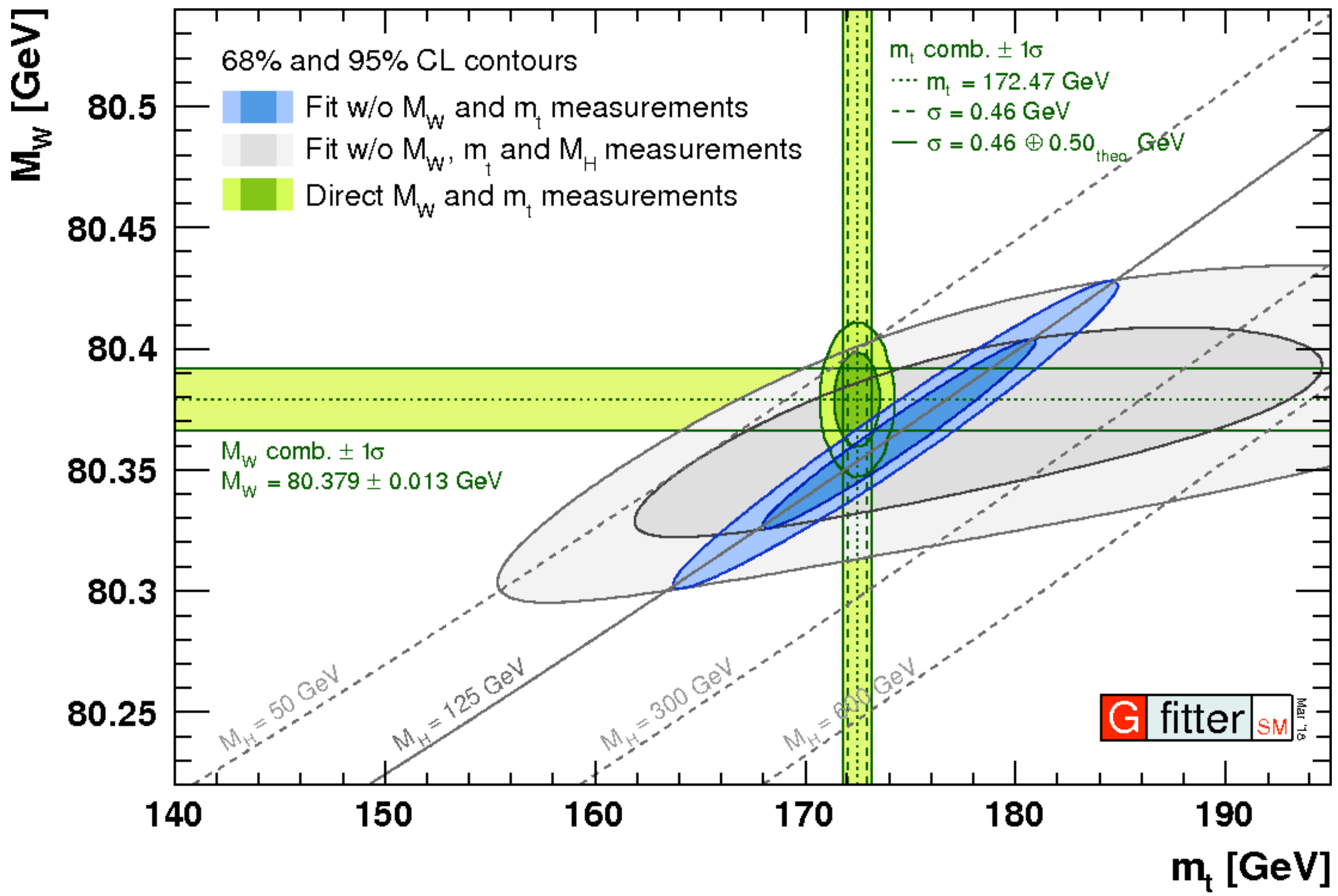

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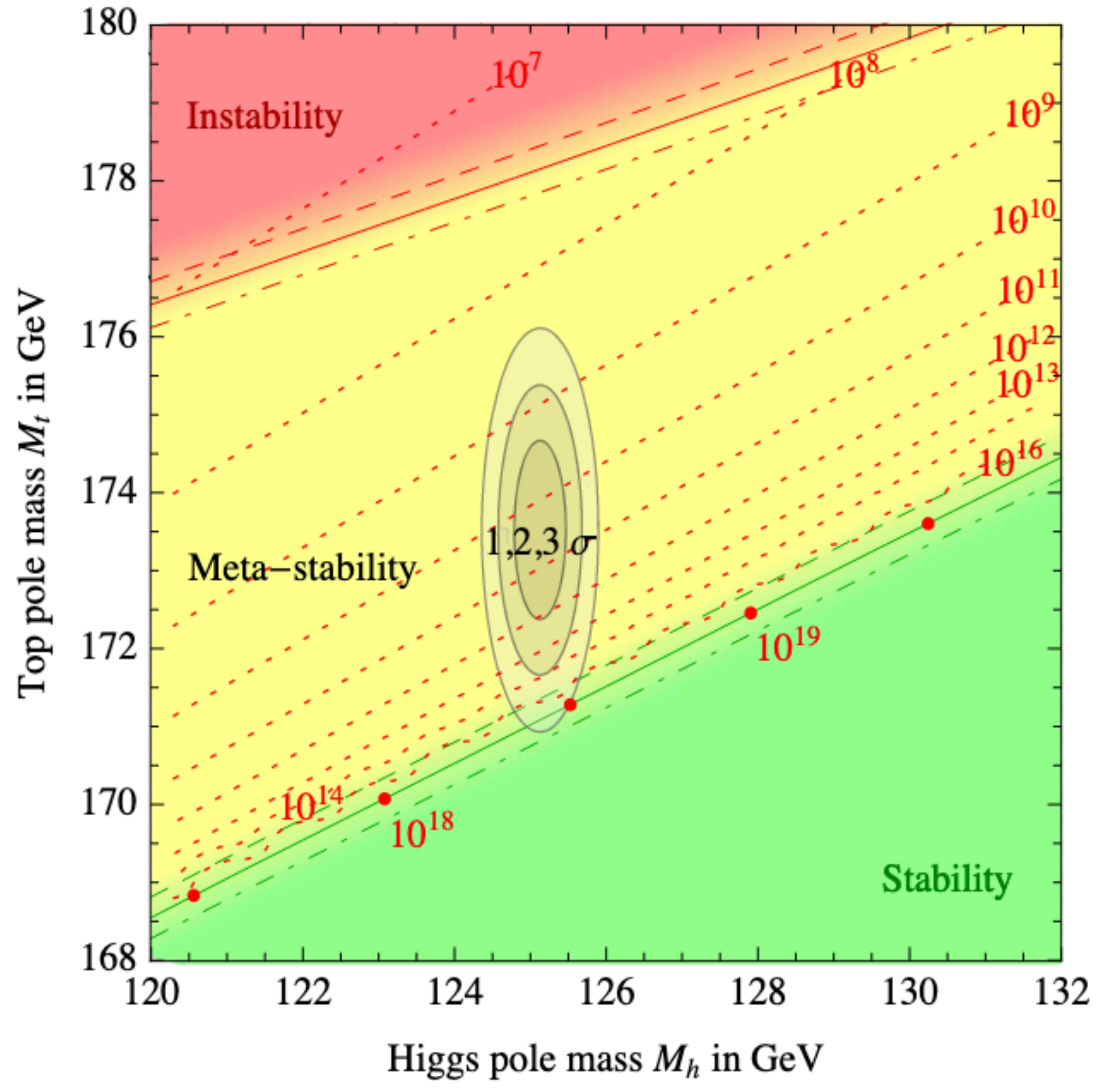

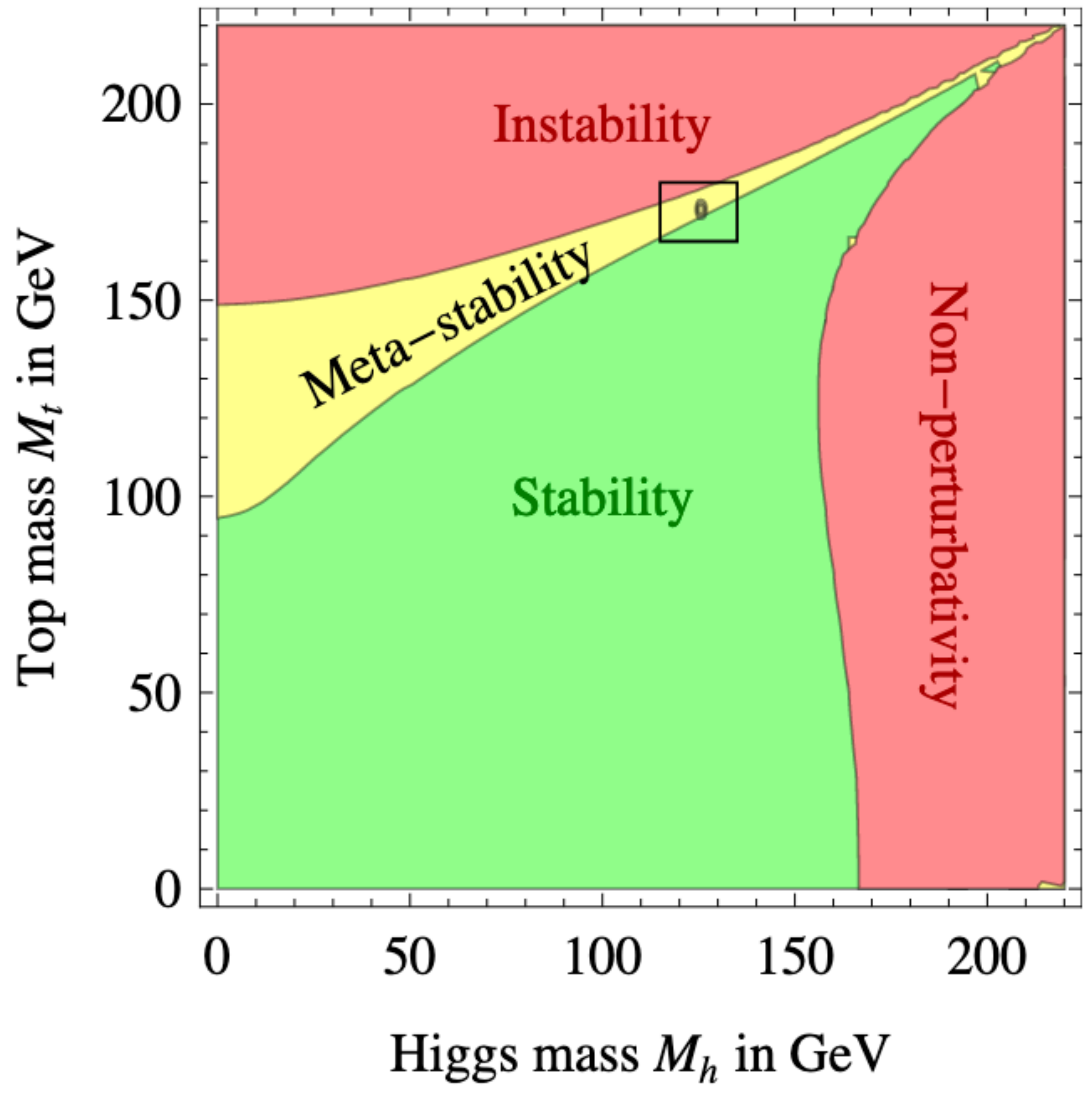

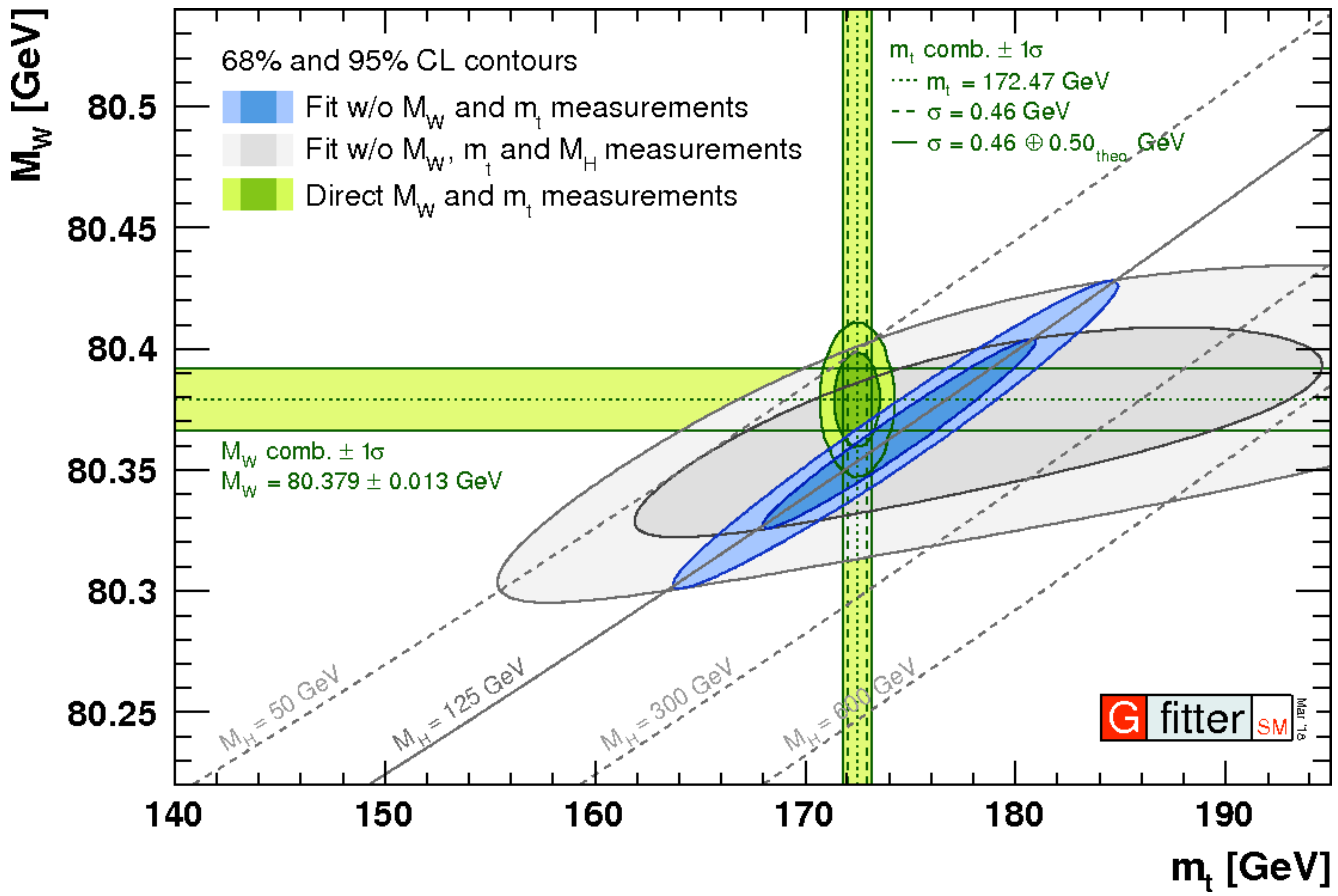

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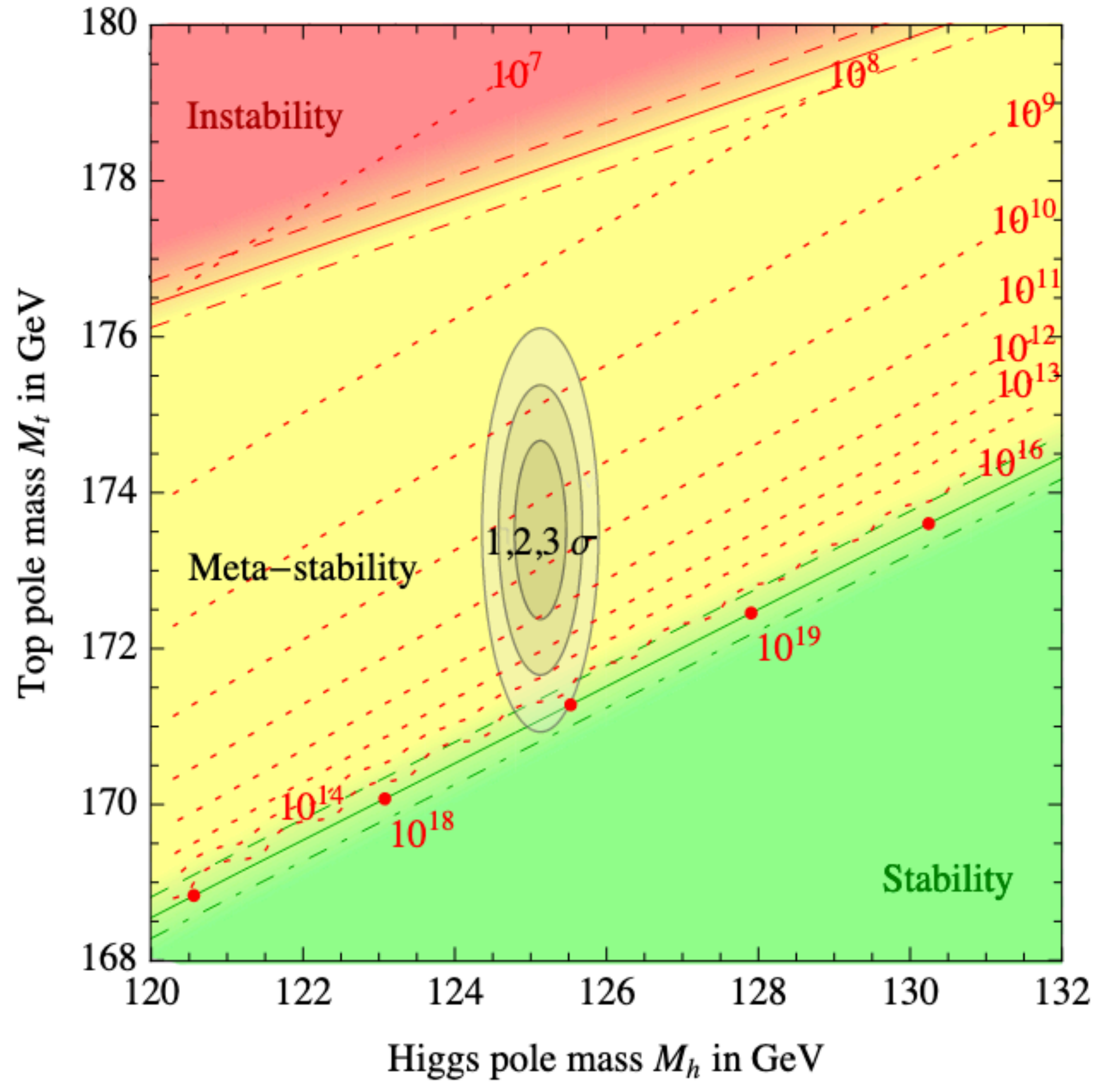

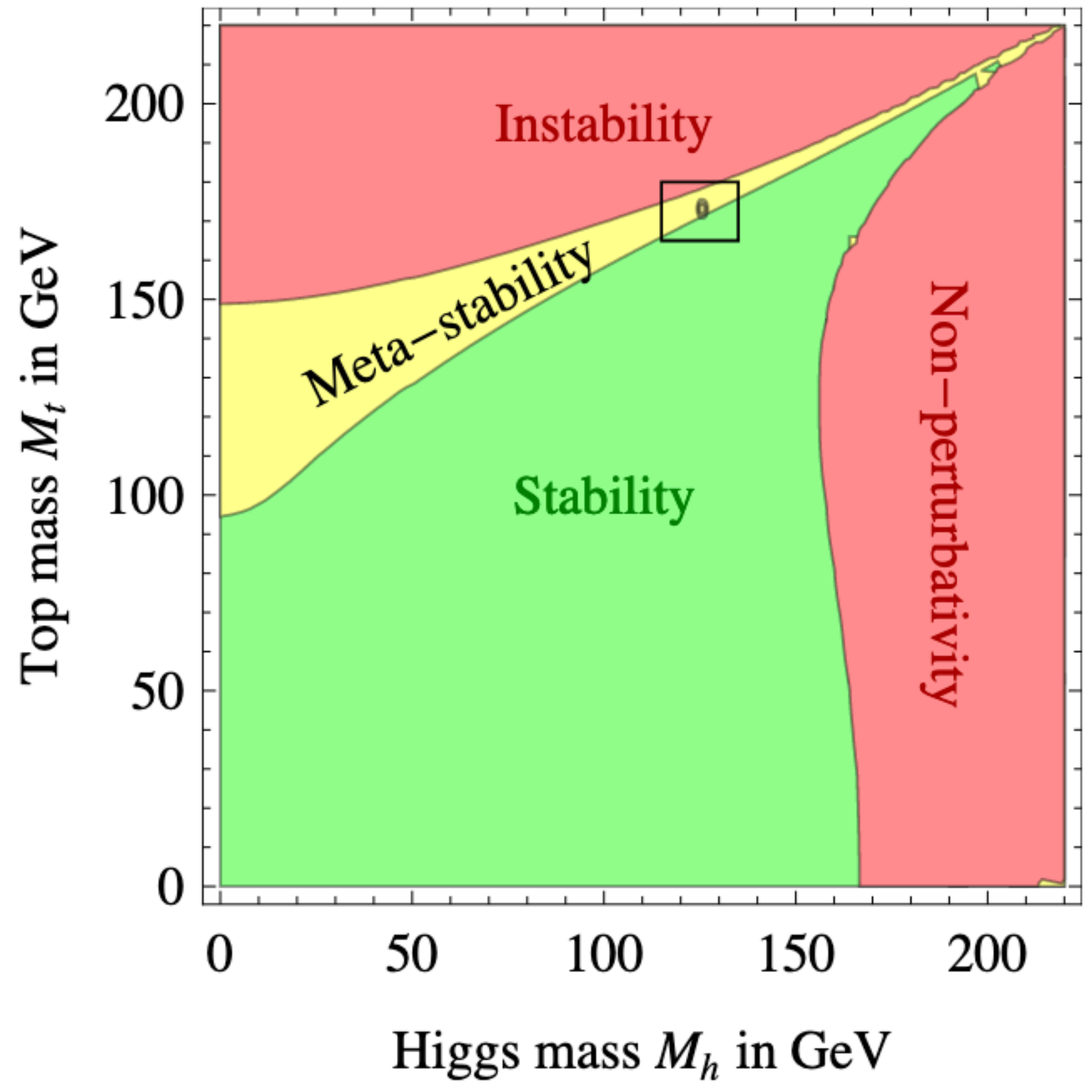

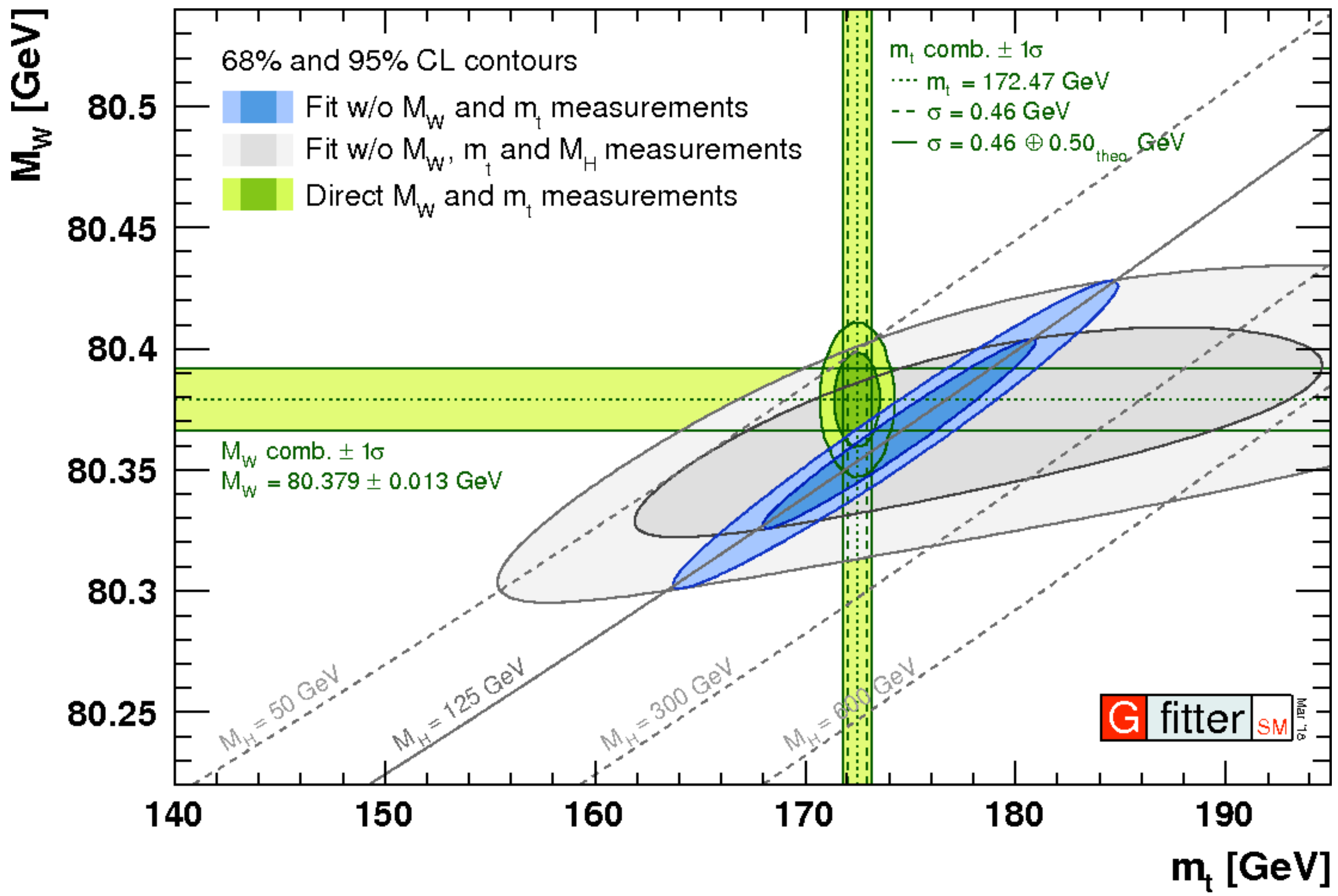

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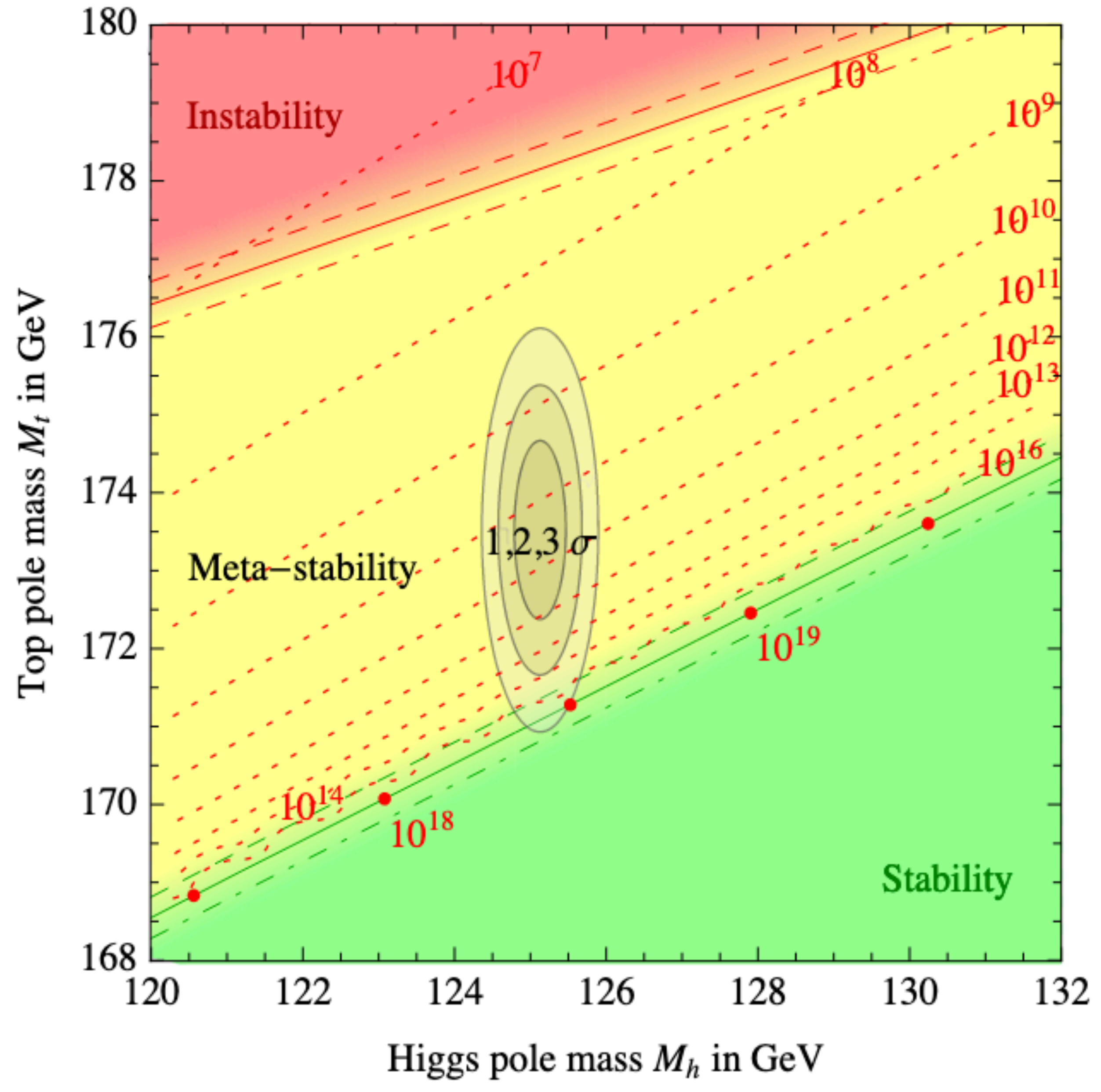

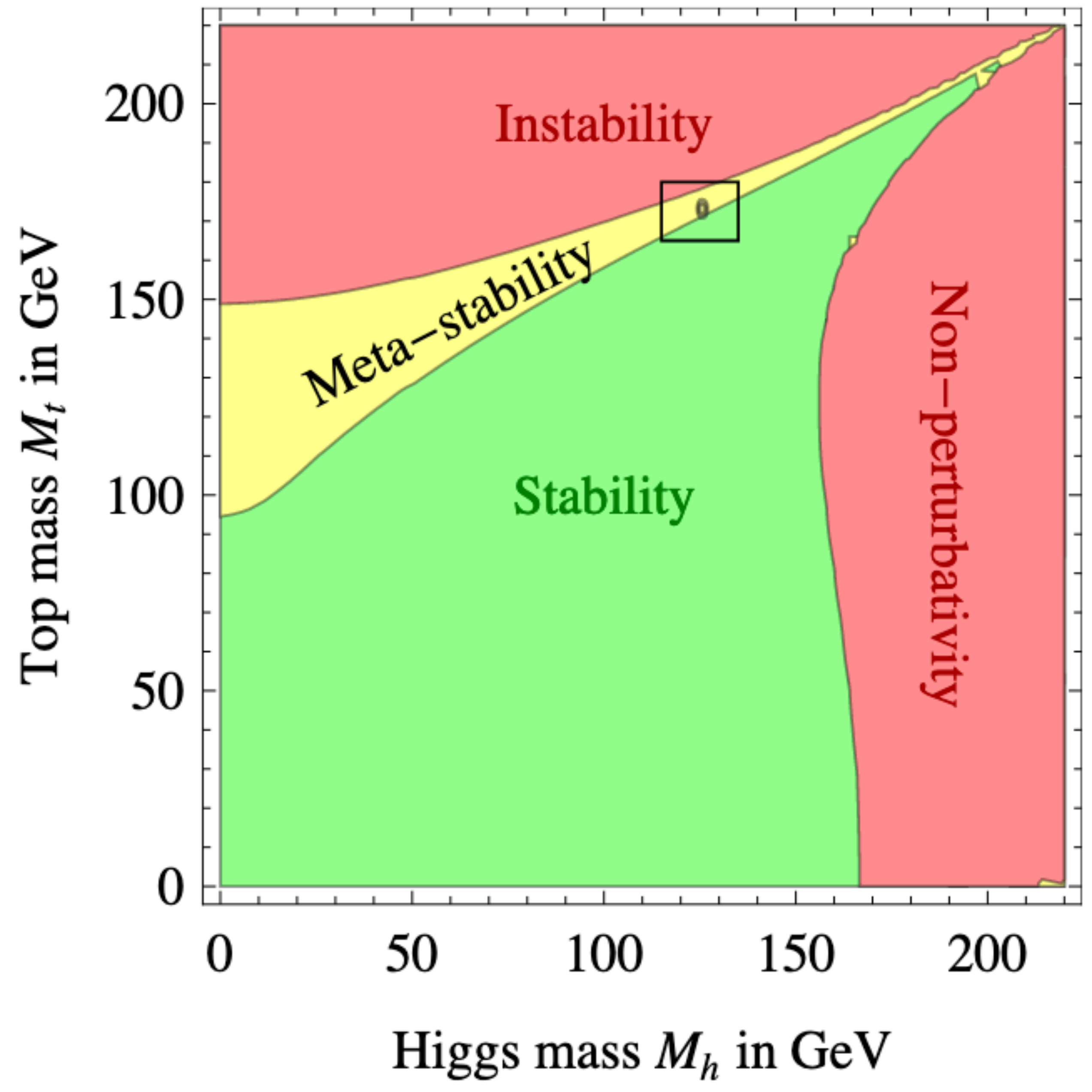

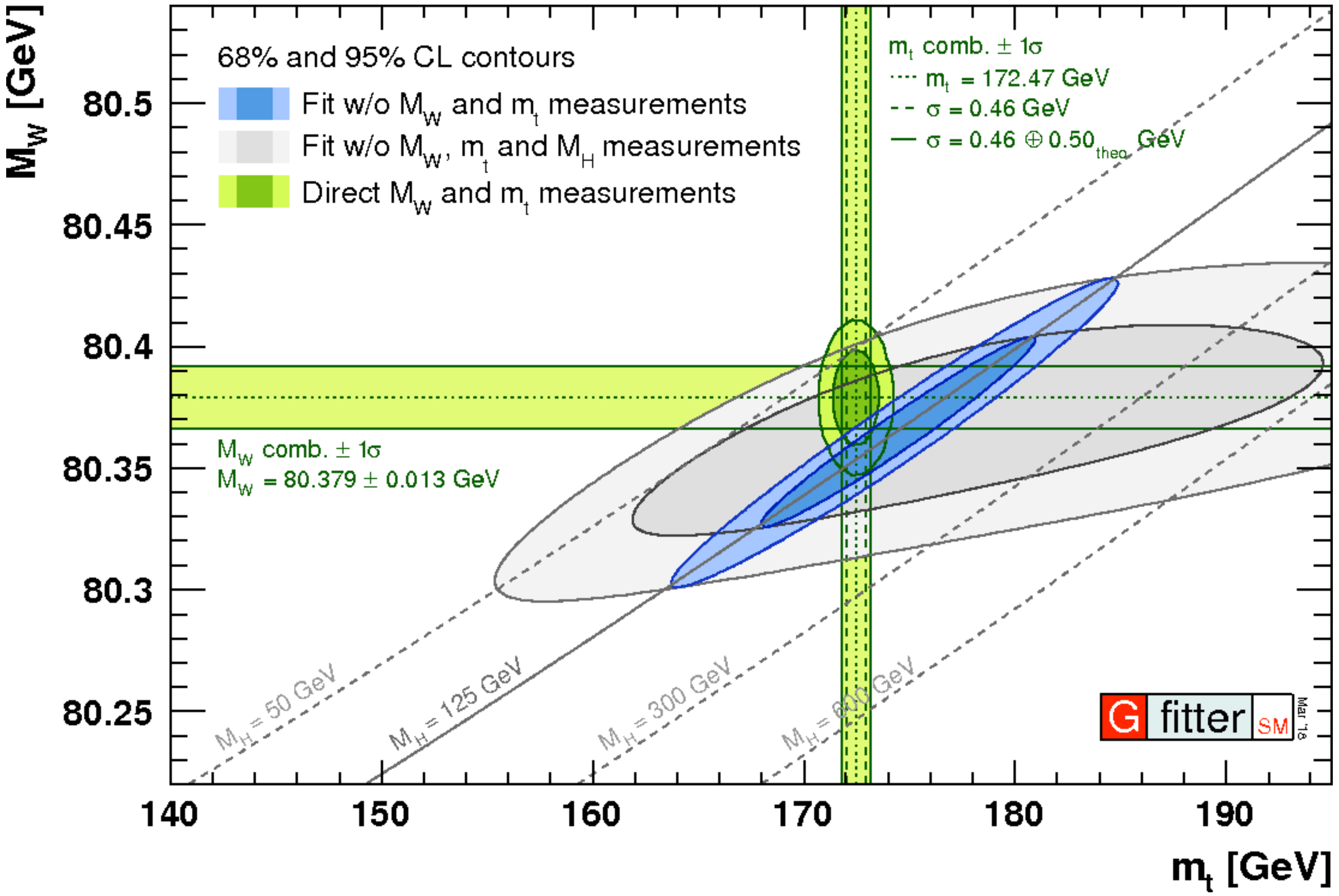

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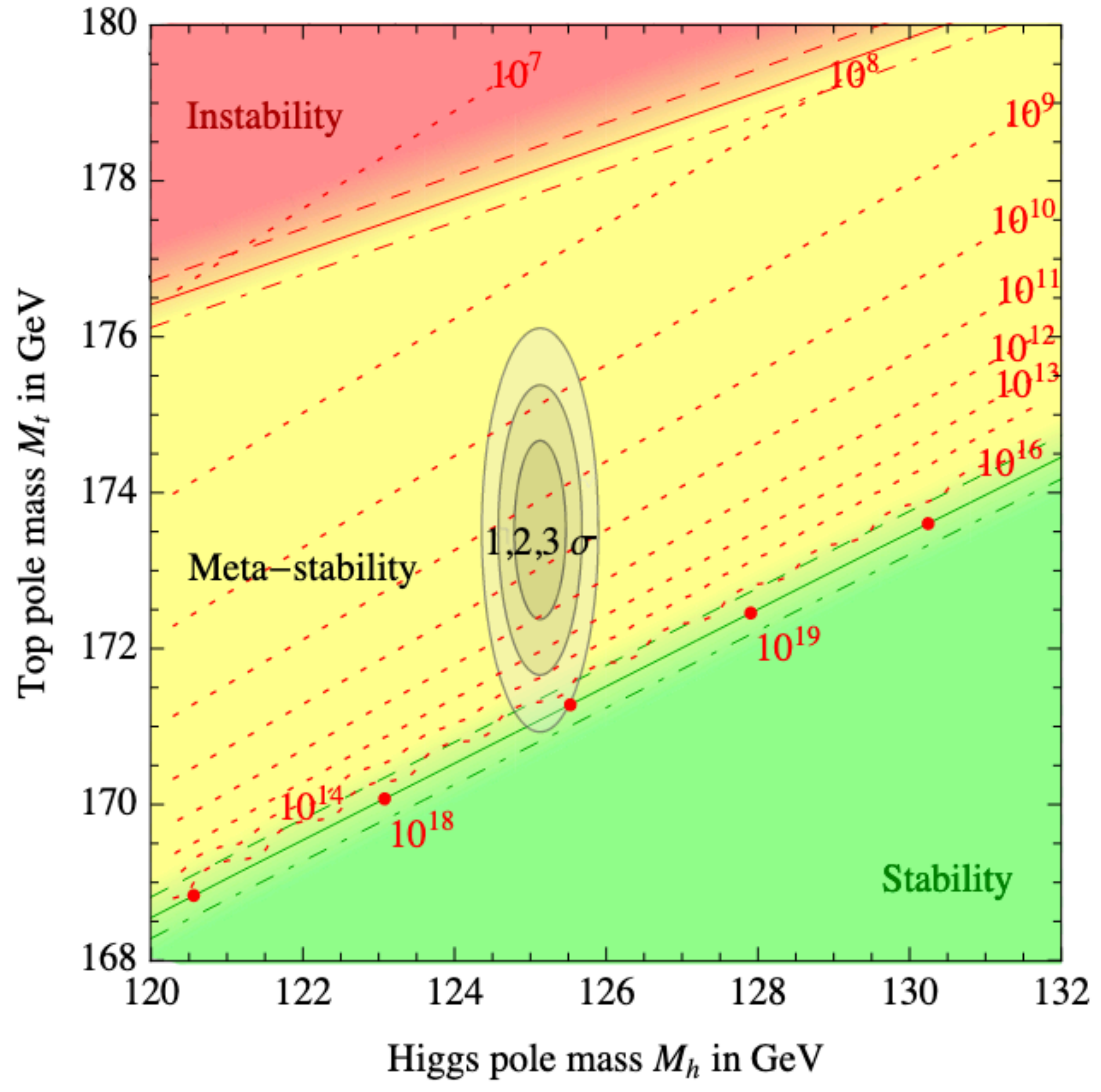

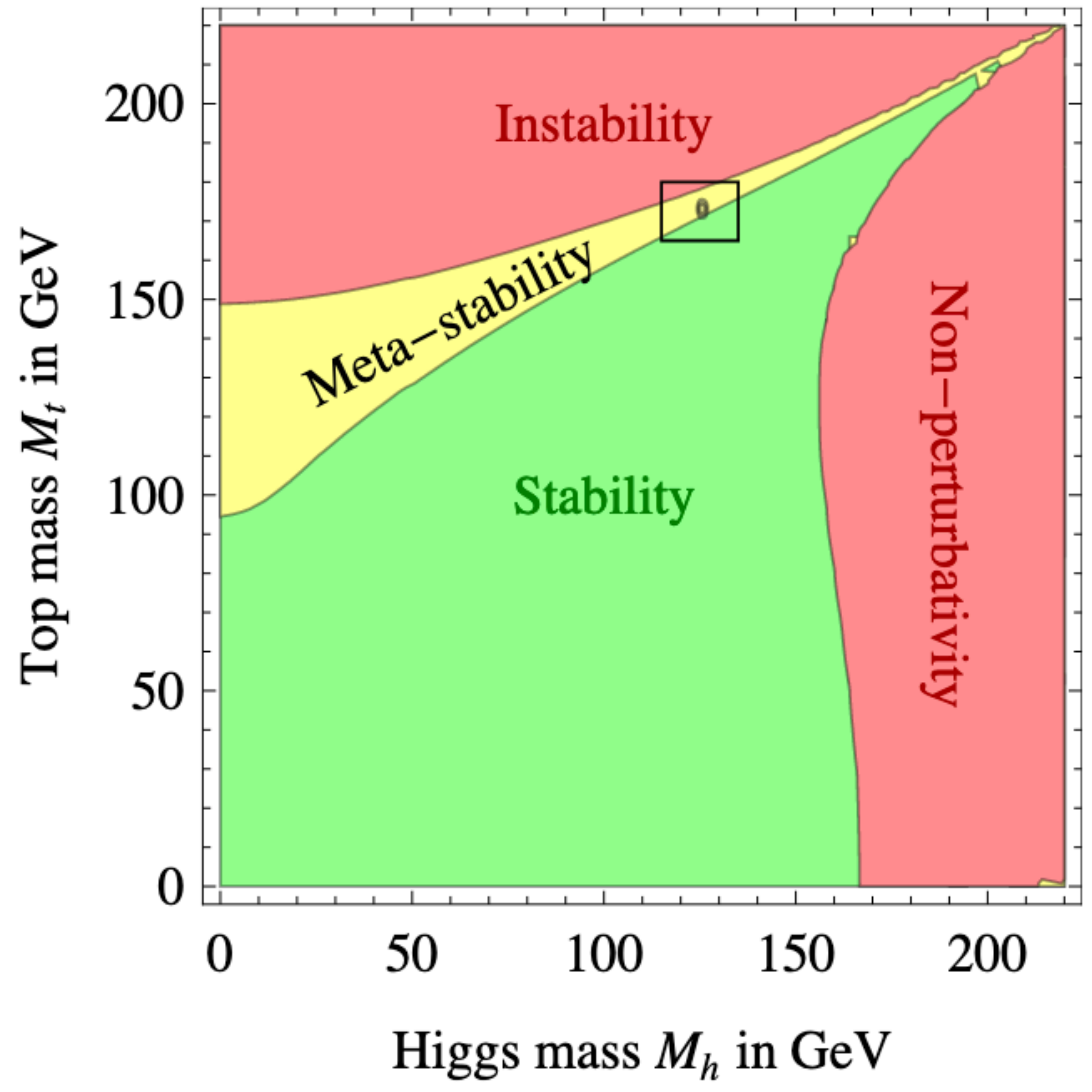

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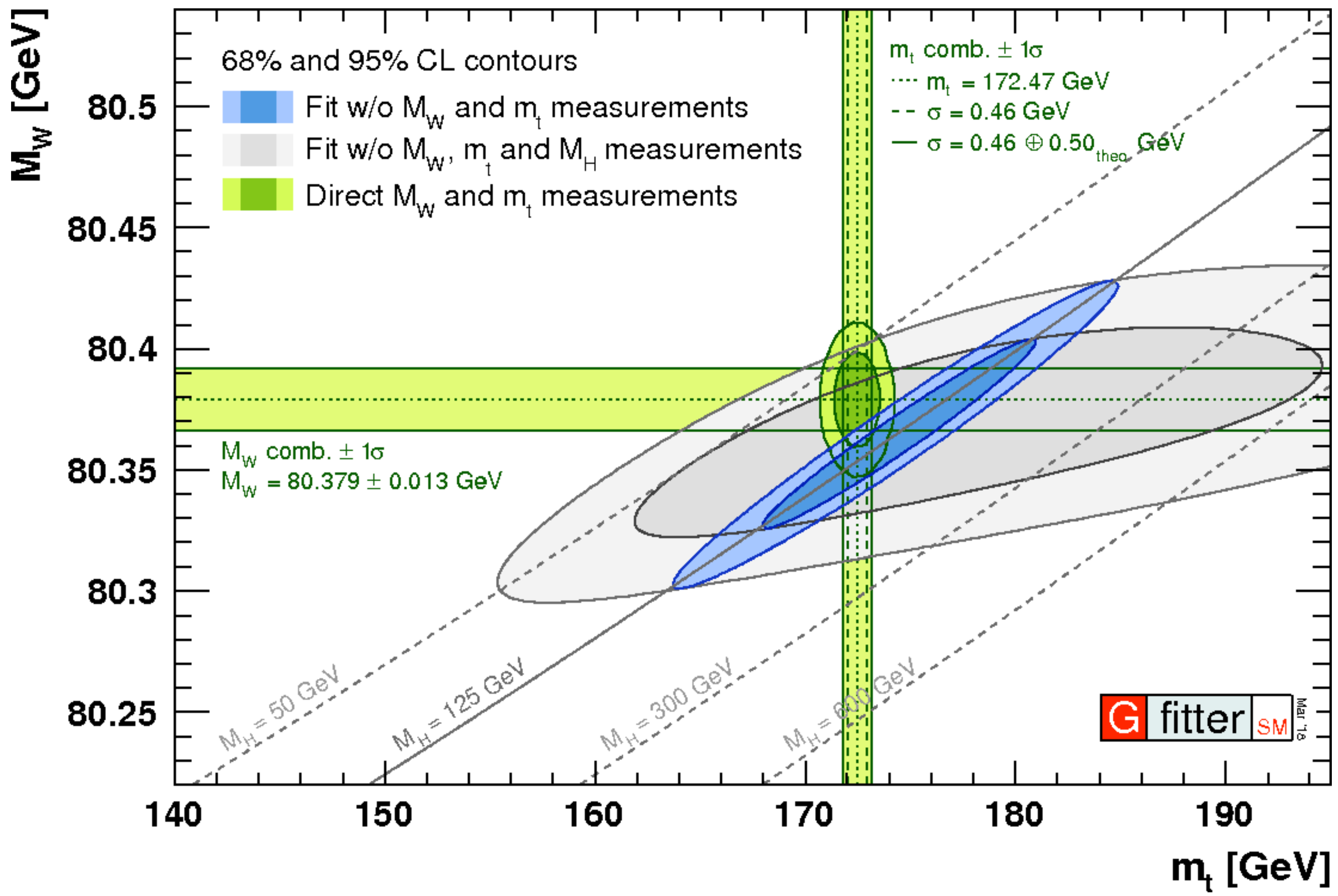

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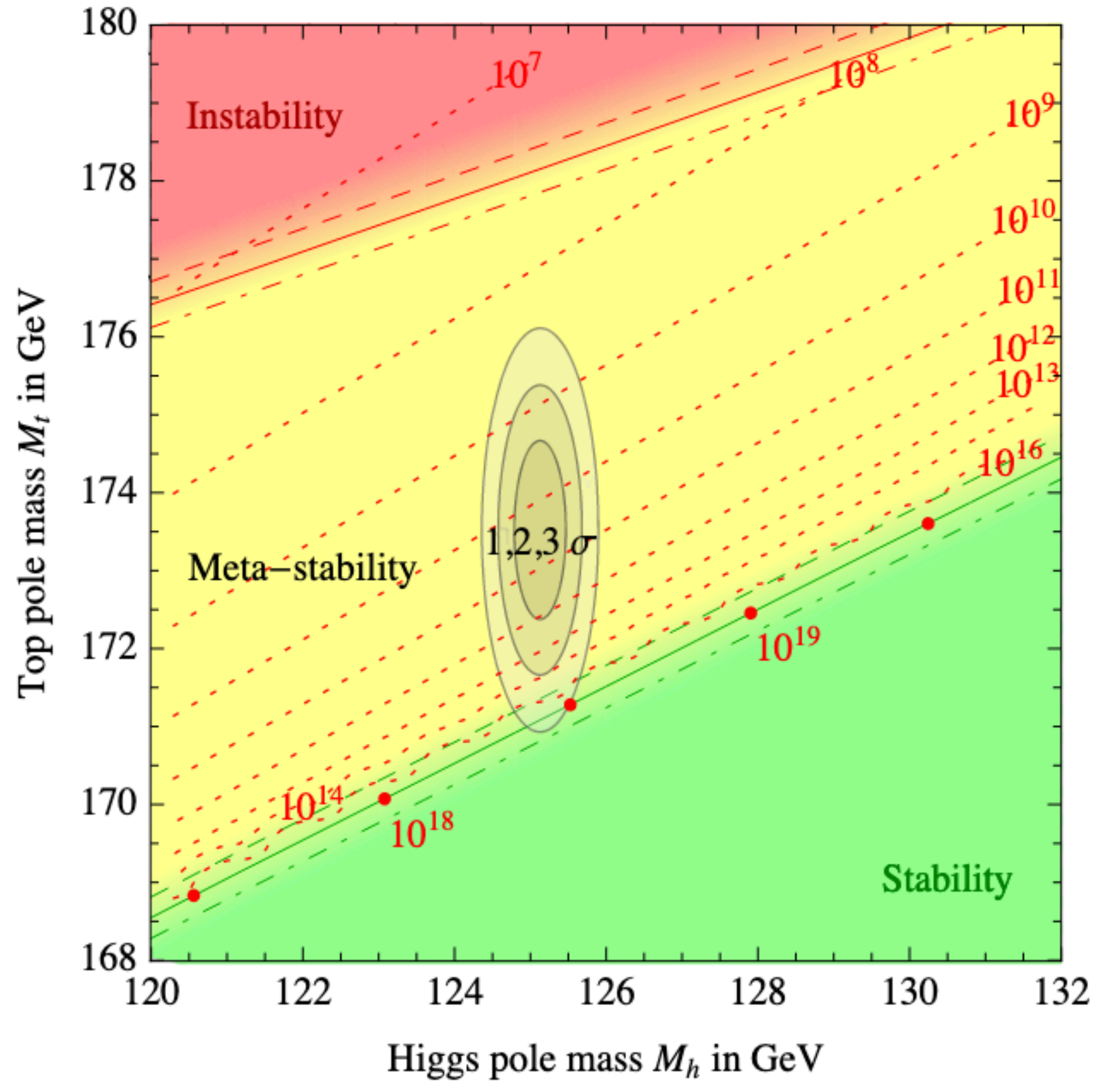

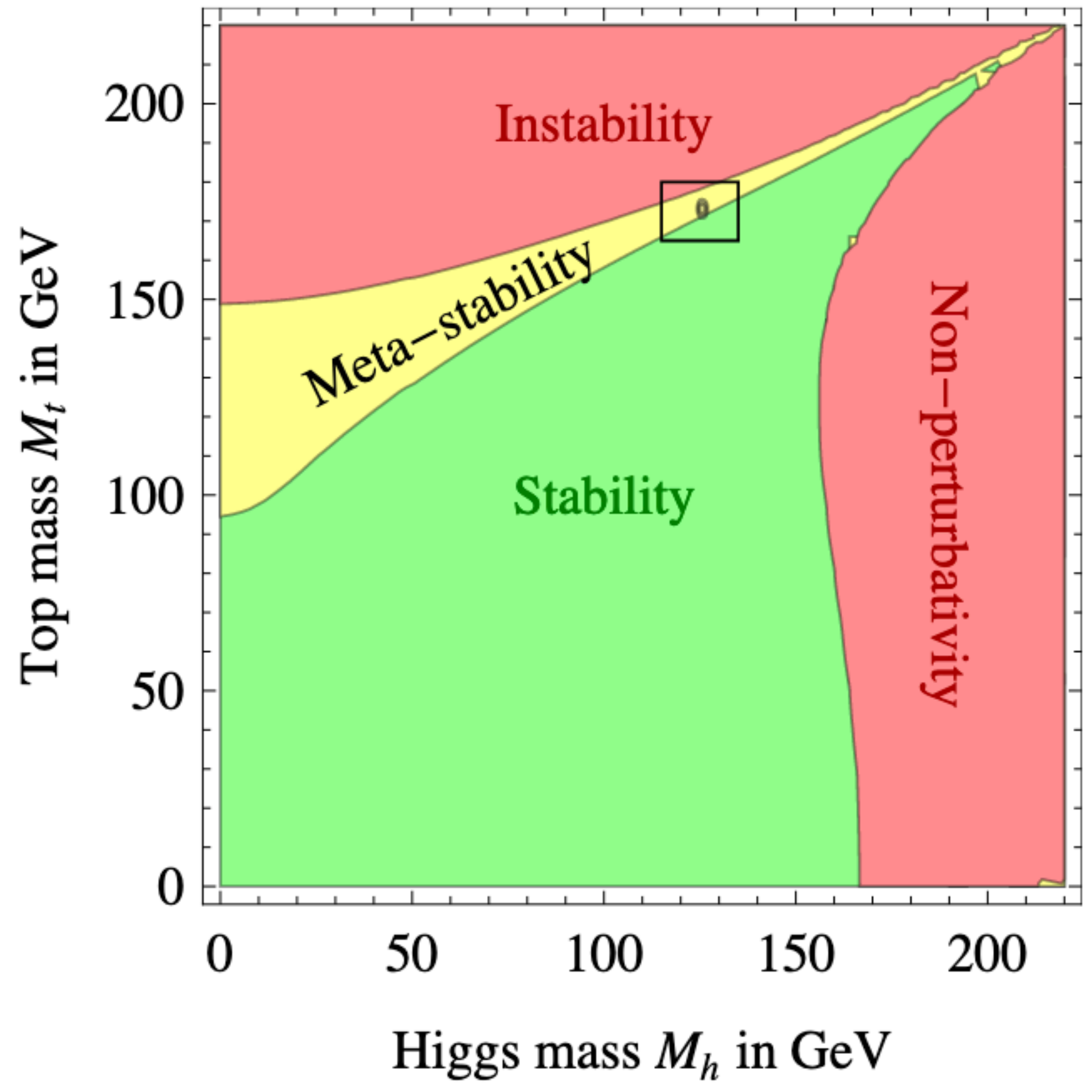

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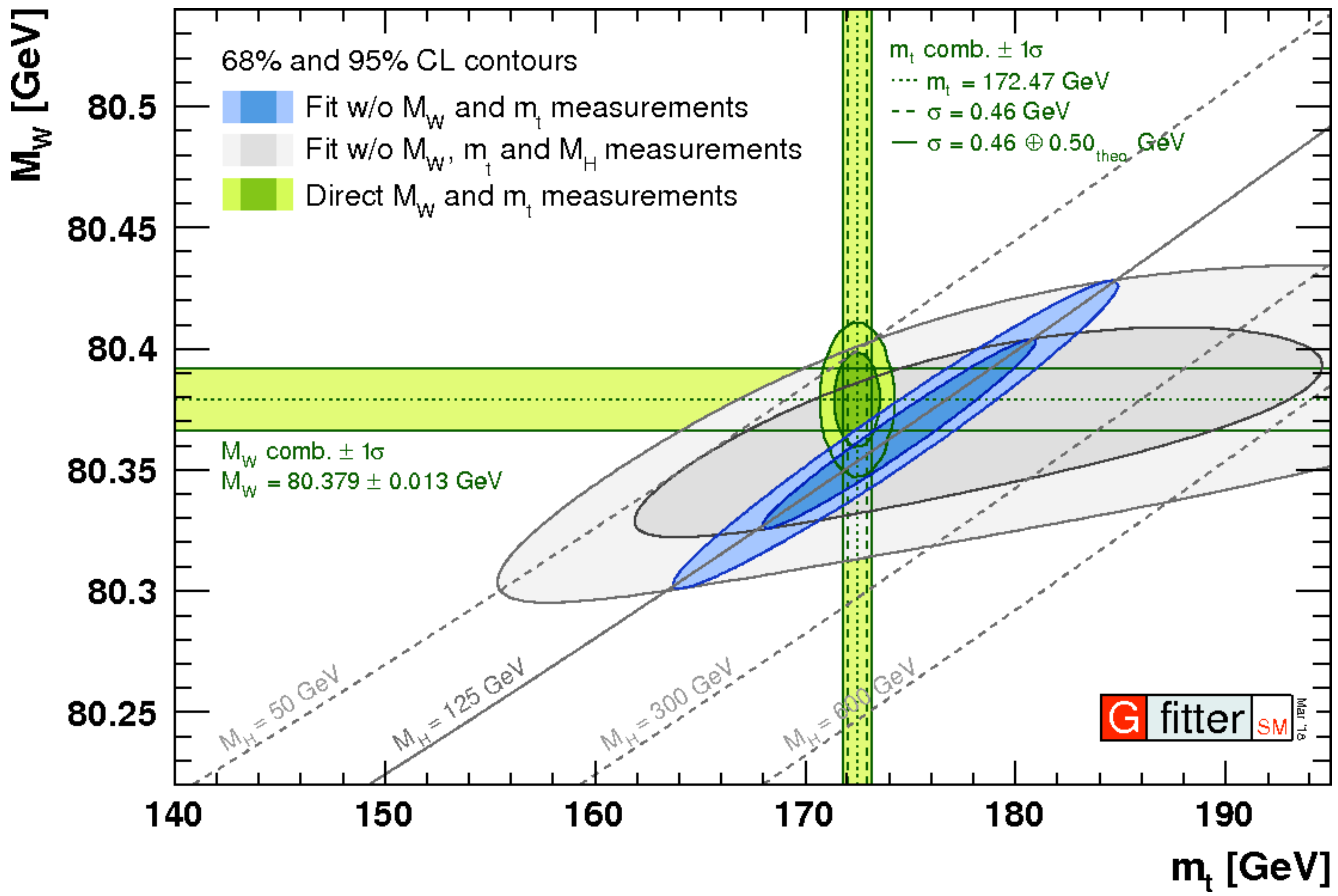

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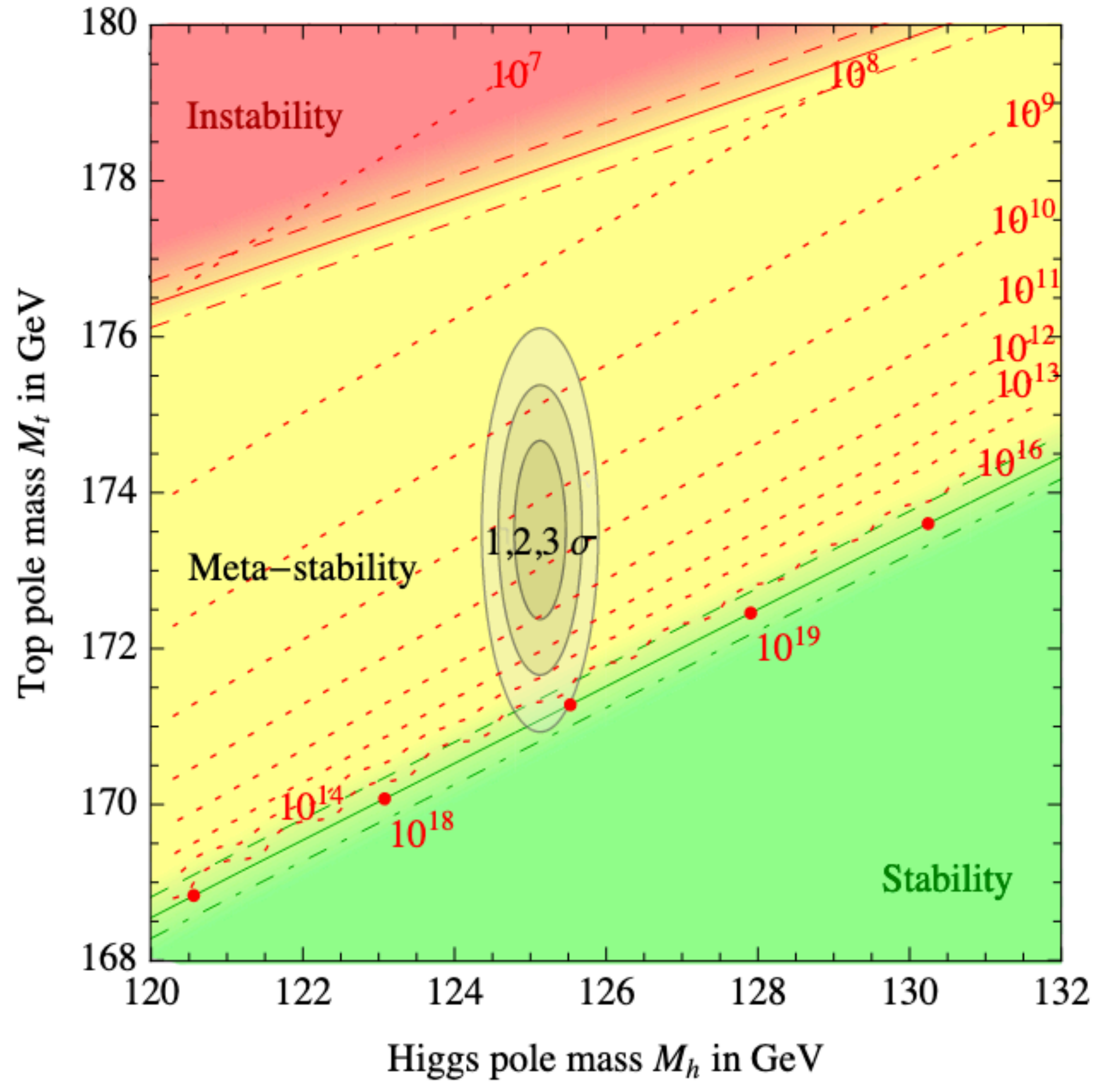

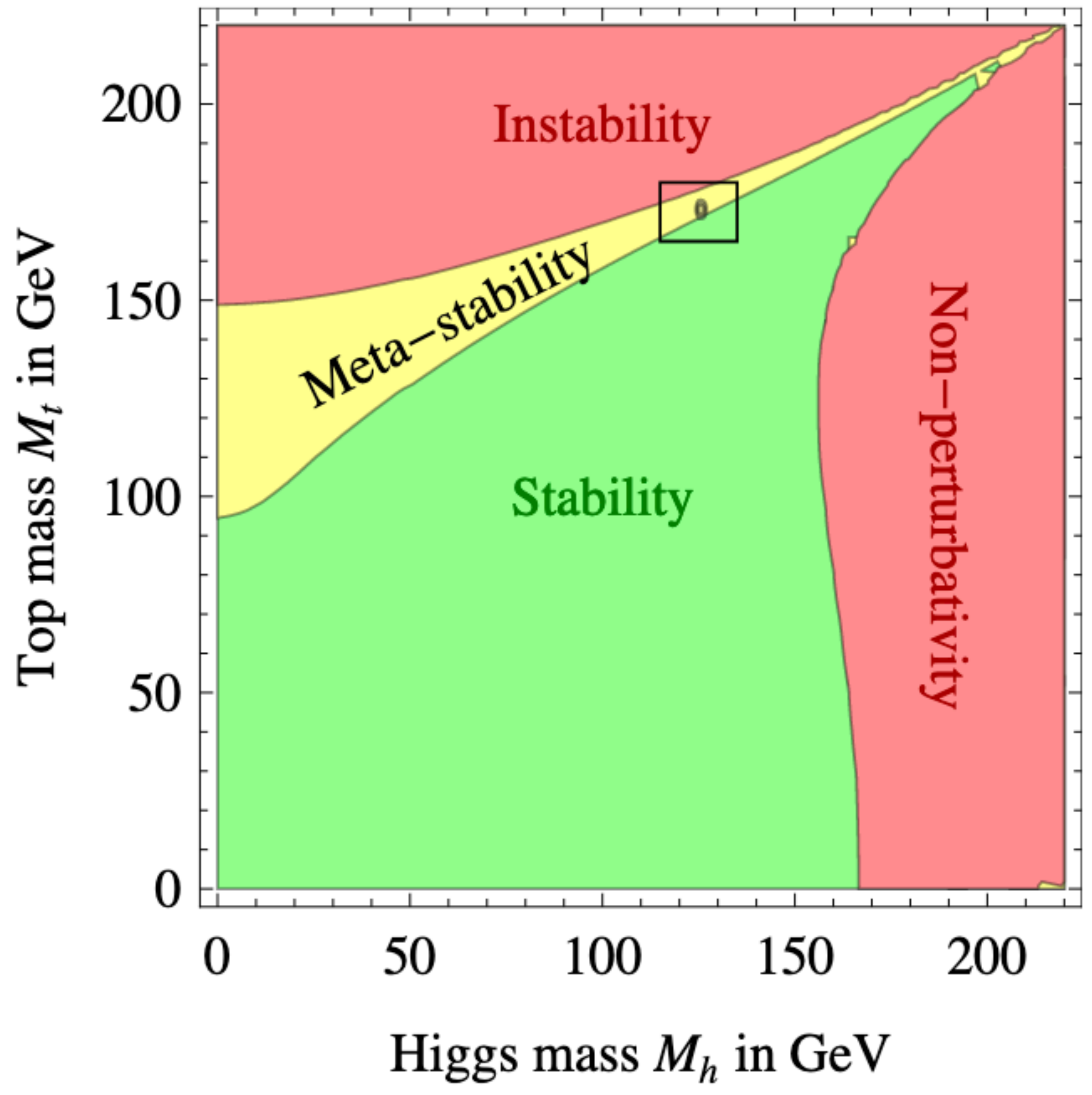

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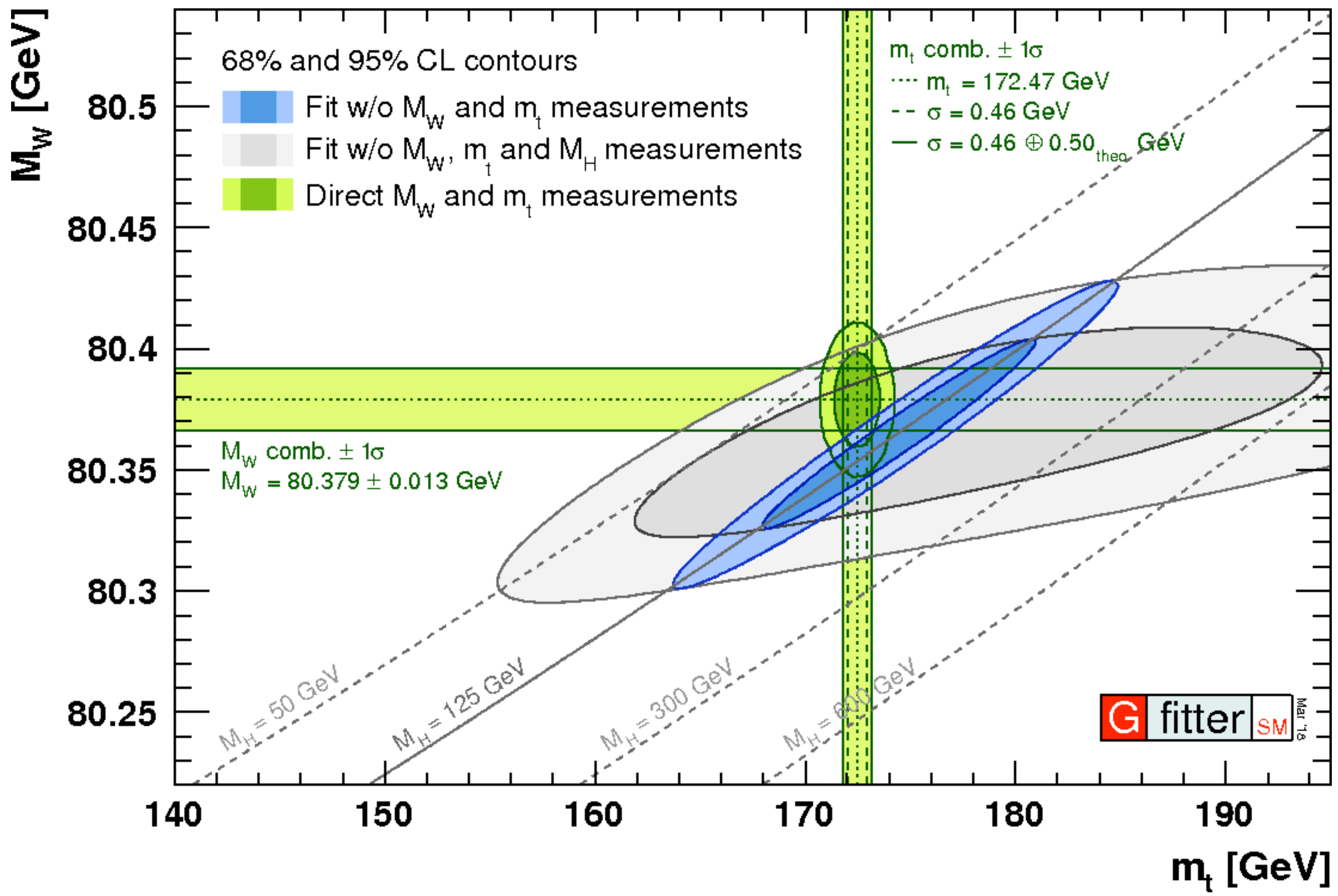

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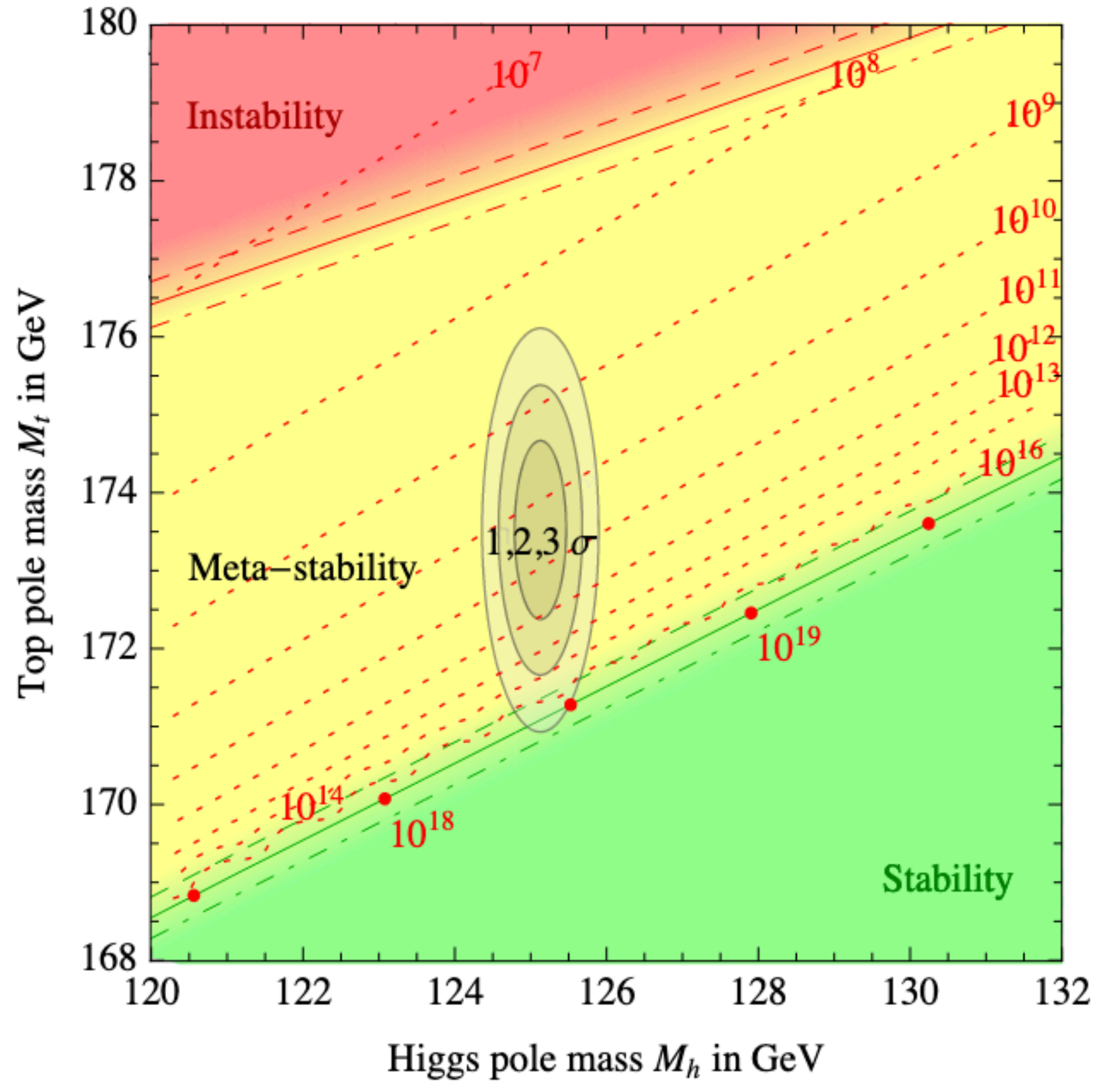
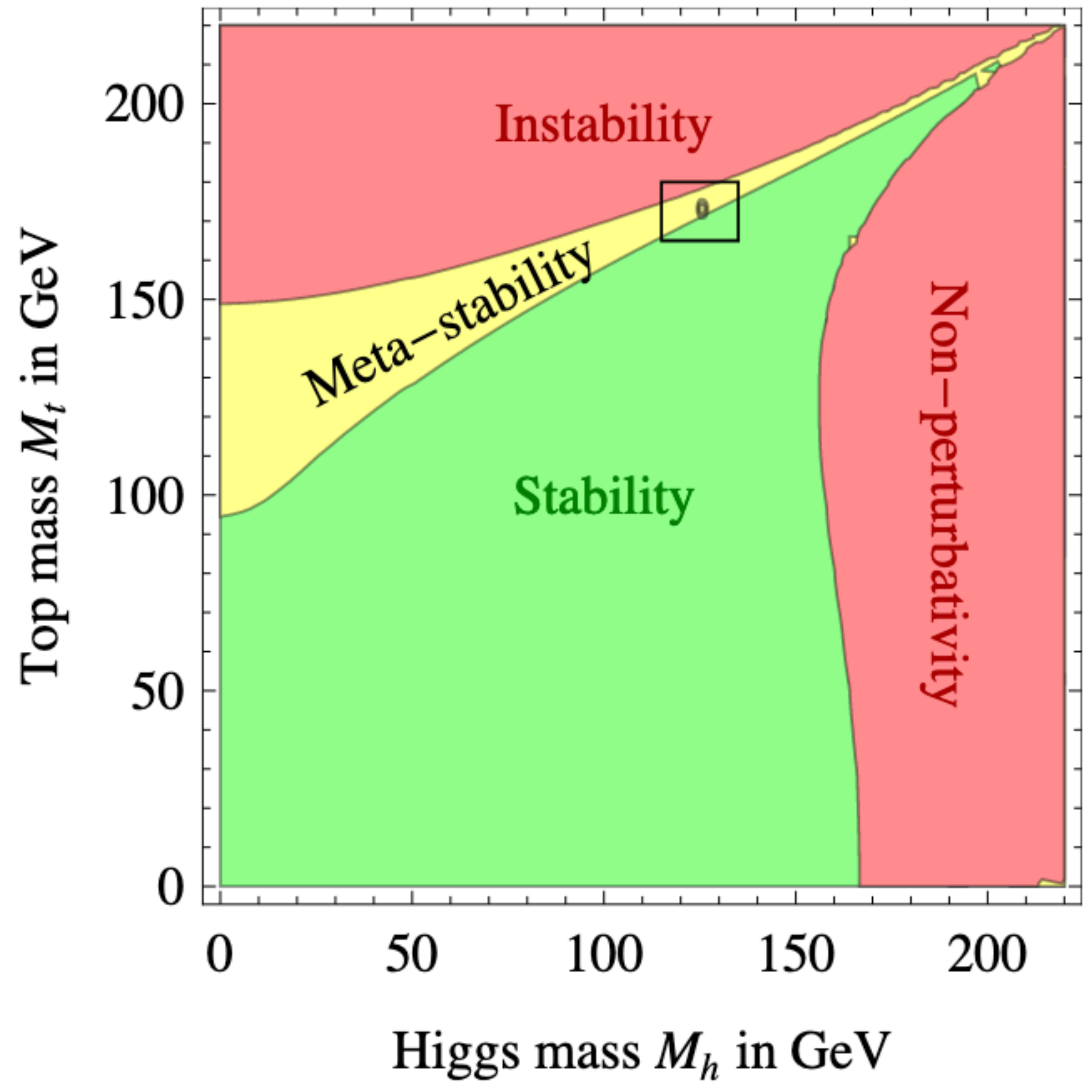
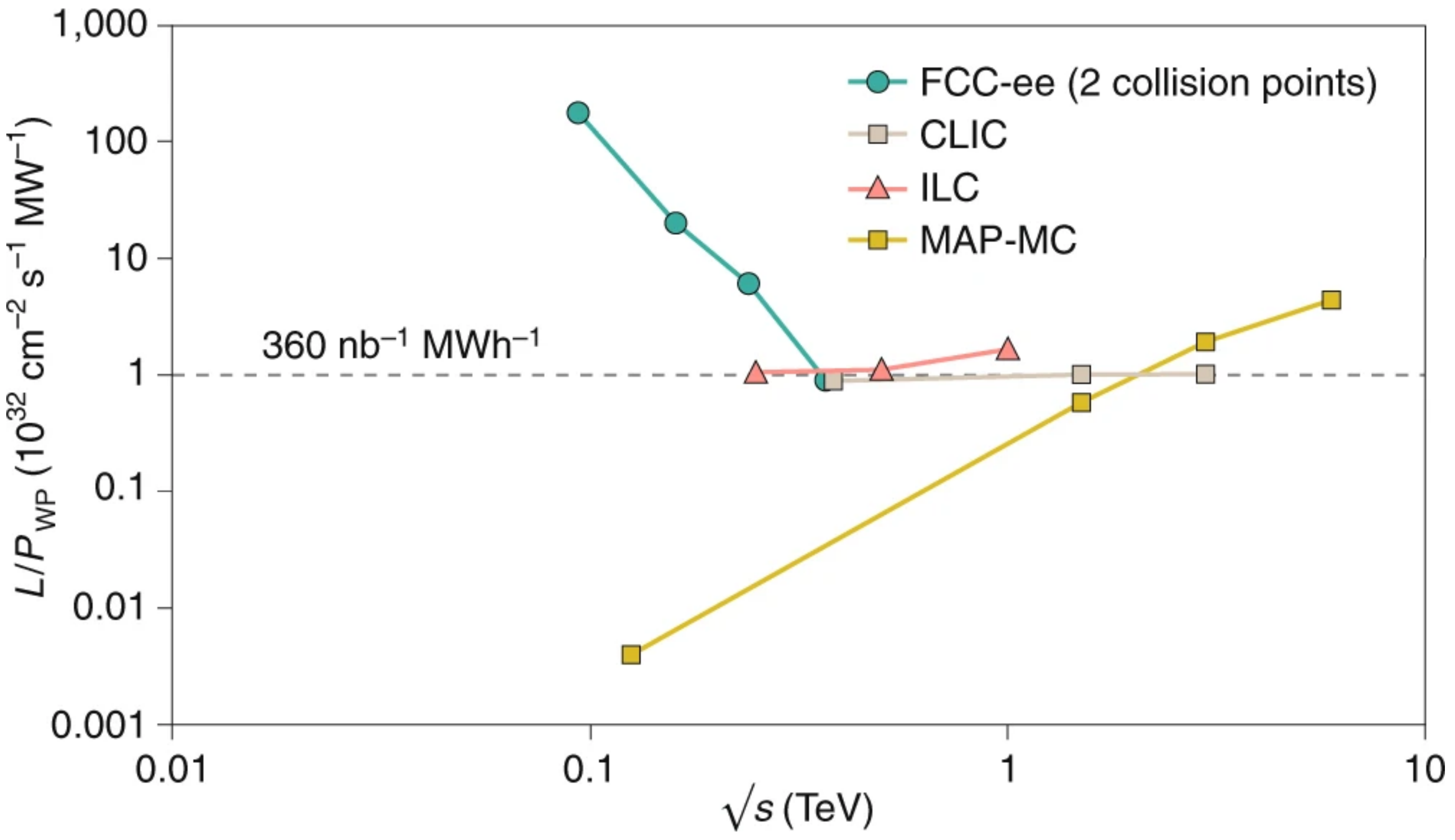




It took us 60 years to find it, but we will be learning from it for at least 60 years more!


LHC
SWITZERLAND
FRANCE
FCC
100 KM LONG
100 km Circumference

FCC-ee



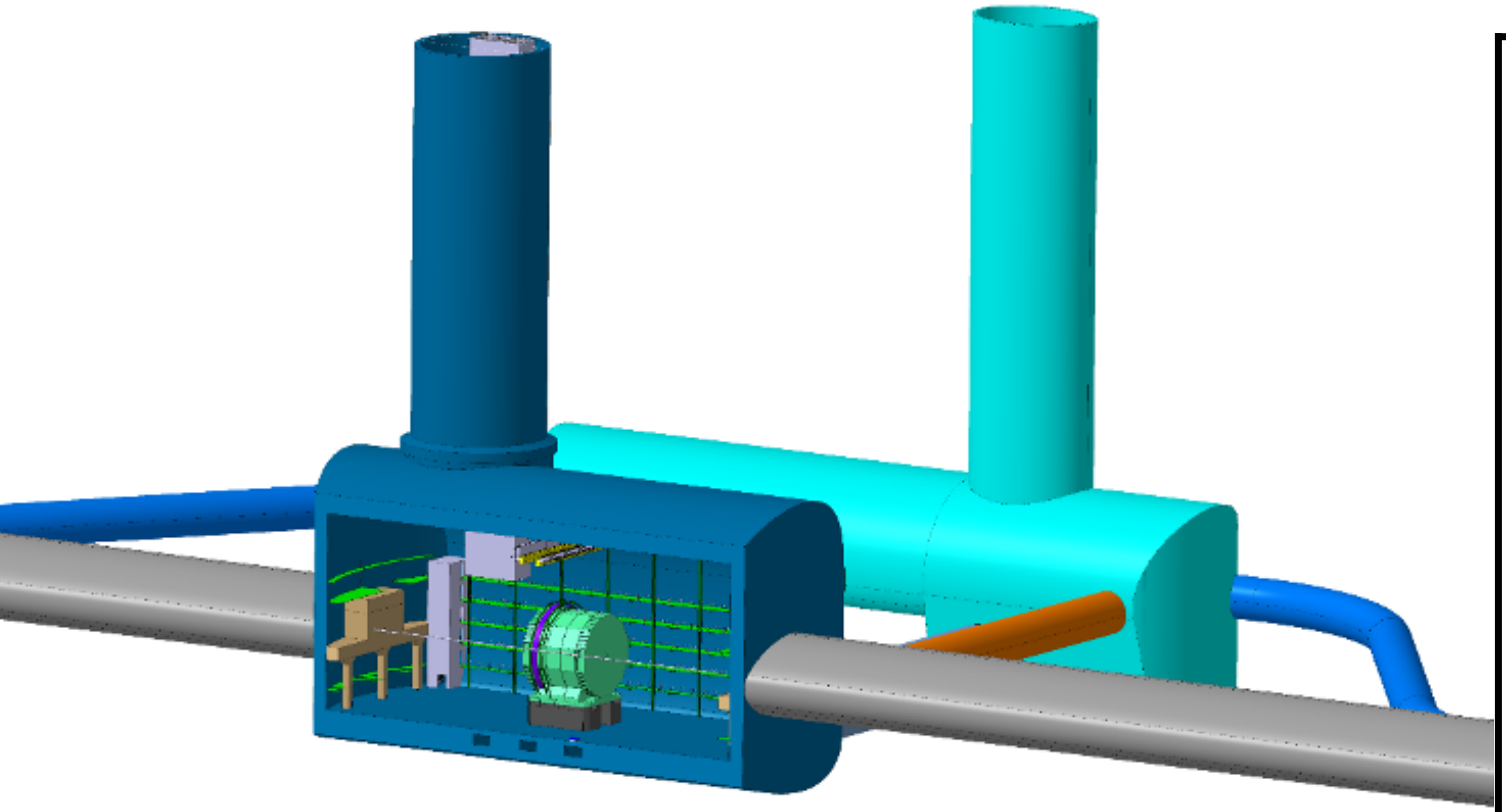
- Great energy range for the heavy particles of the Standard Model
- Complementarity with hadron (LHC, FCC-hh) and linear colliders
- combining successful ingredients of several recent colliders → highest luminosities & energies

The FCC-ee will be implemented in stages as an electroweak, flavour, and Higgs factory to study with unprecedented precision the Higgs boson, the Z and W bosons, the top quark, and other particles of the Standard Model

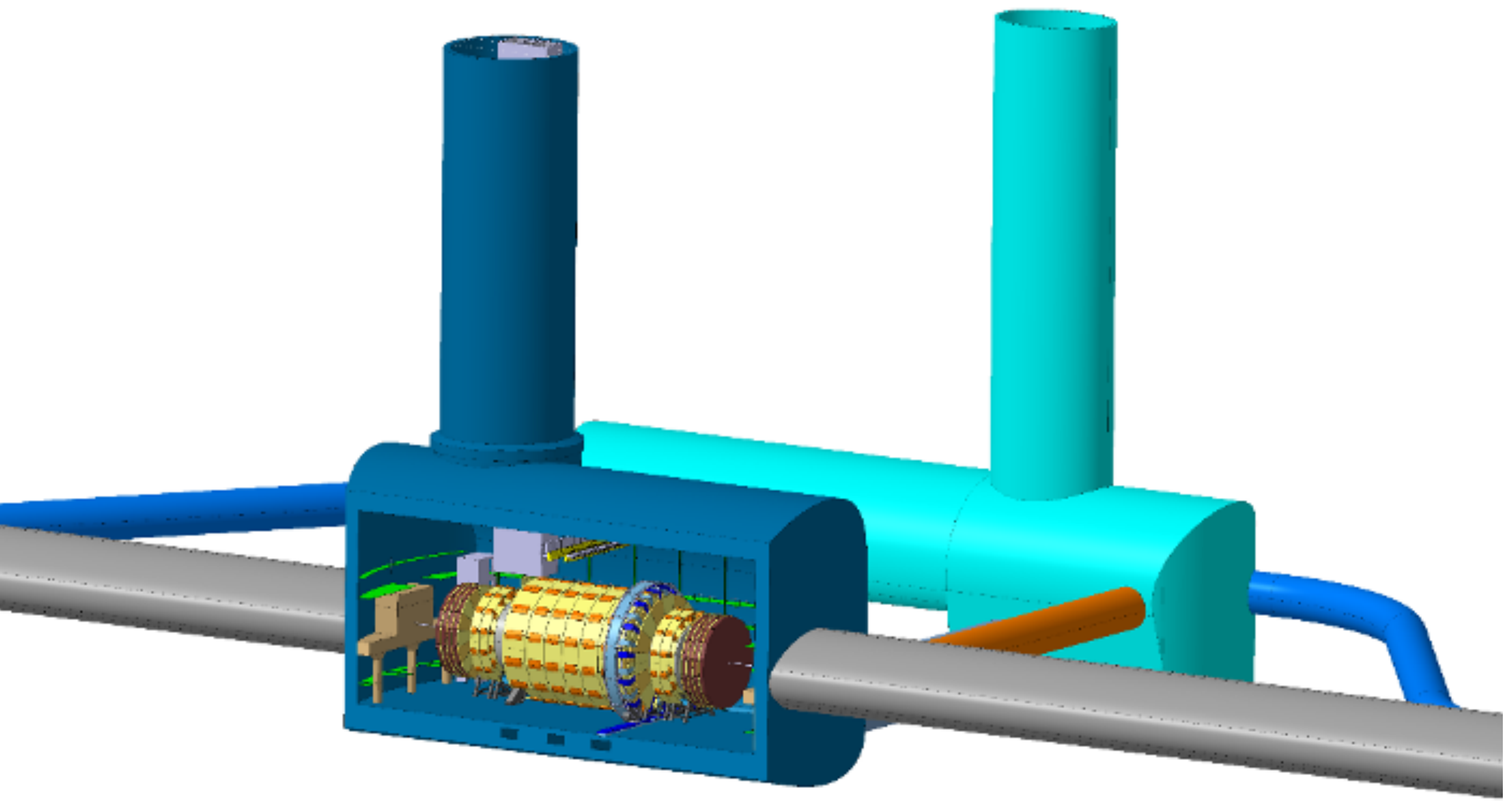
Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics	
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays	LEP x 10^5
FCC-ee-W	2	158-162	12	10^8 WW events	LEP x $2 \cdot 10^3$
FCC-ee-H	3	240	5	10^6 ZH events	Never done
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events	Never done

Detector requirements
from physics - M. Selvaggi

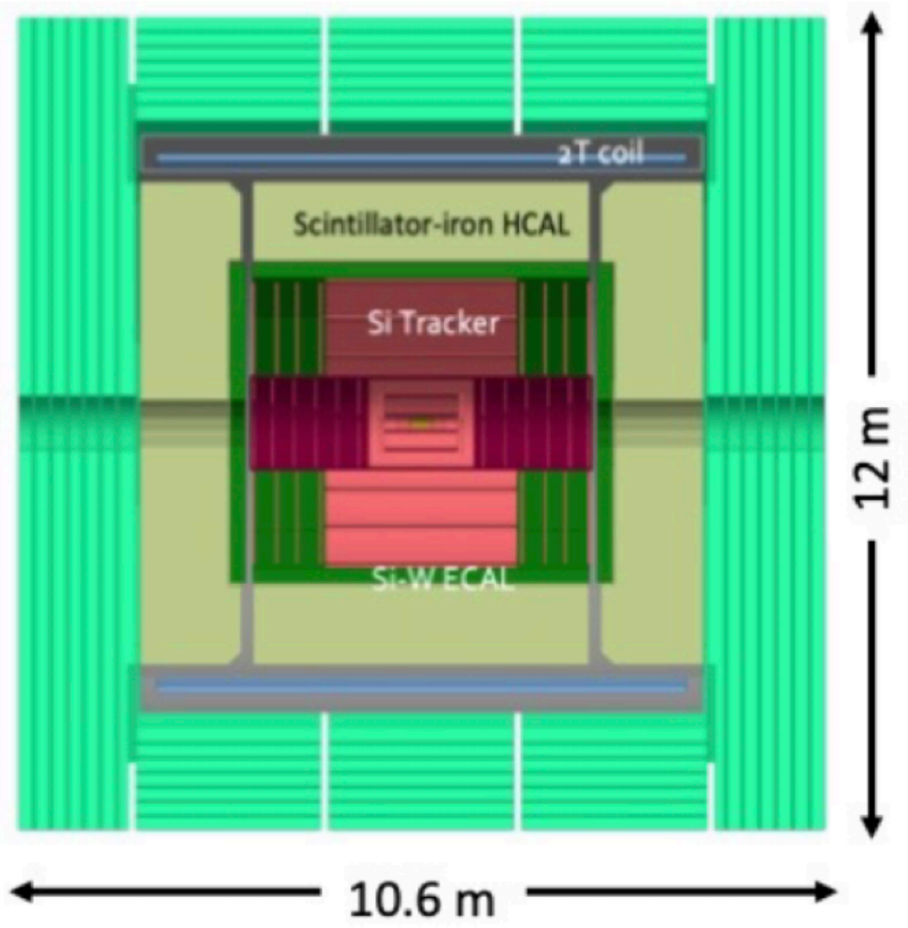
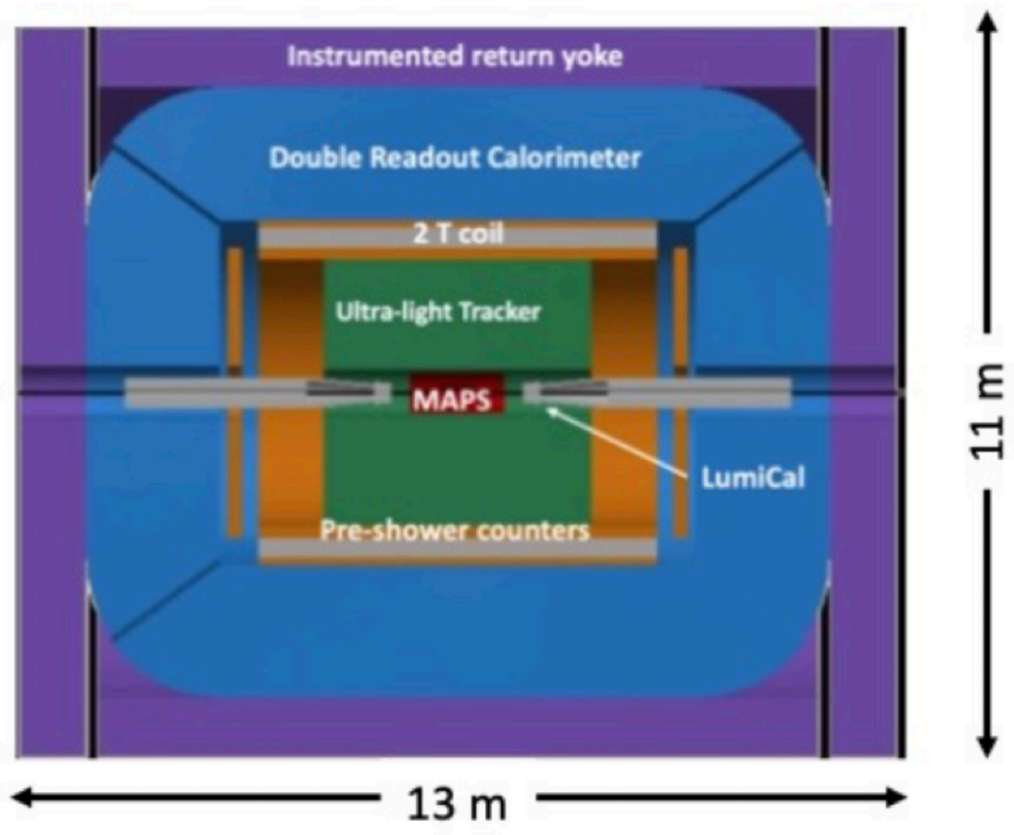
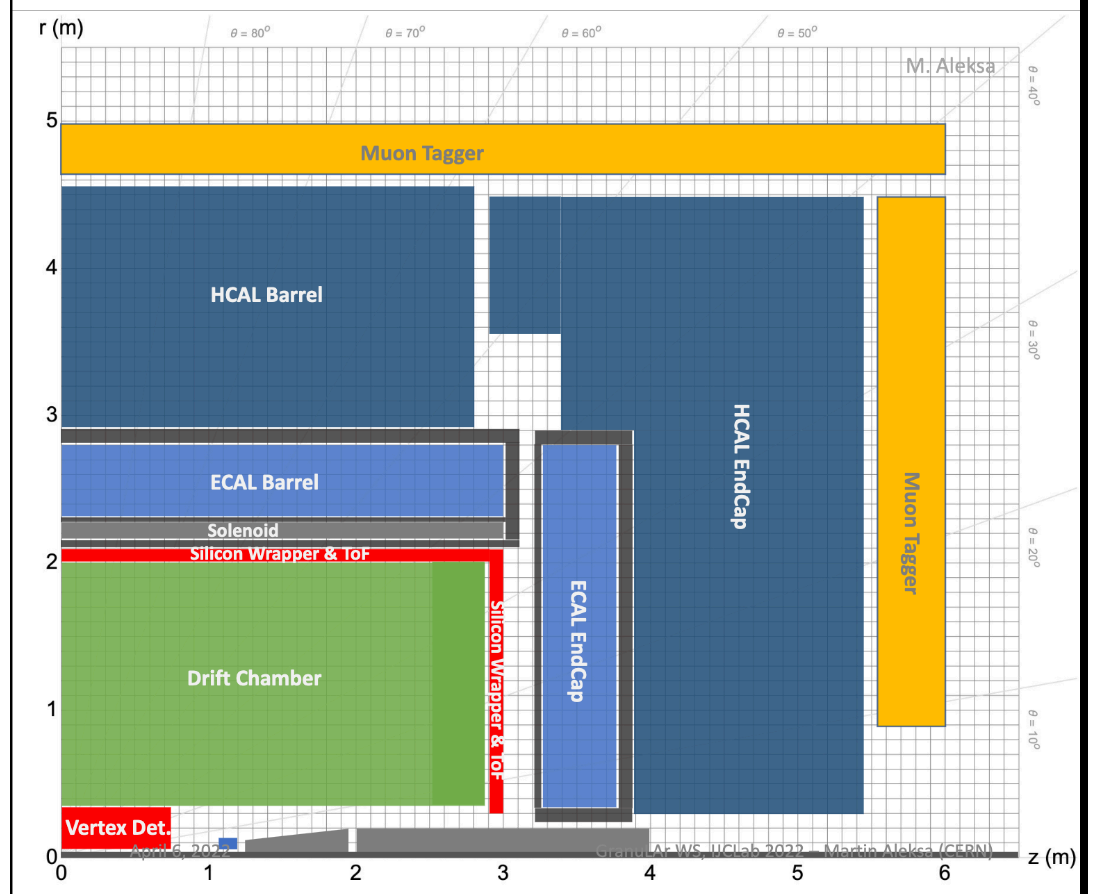
Detector concepts



FCC-ee

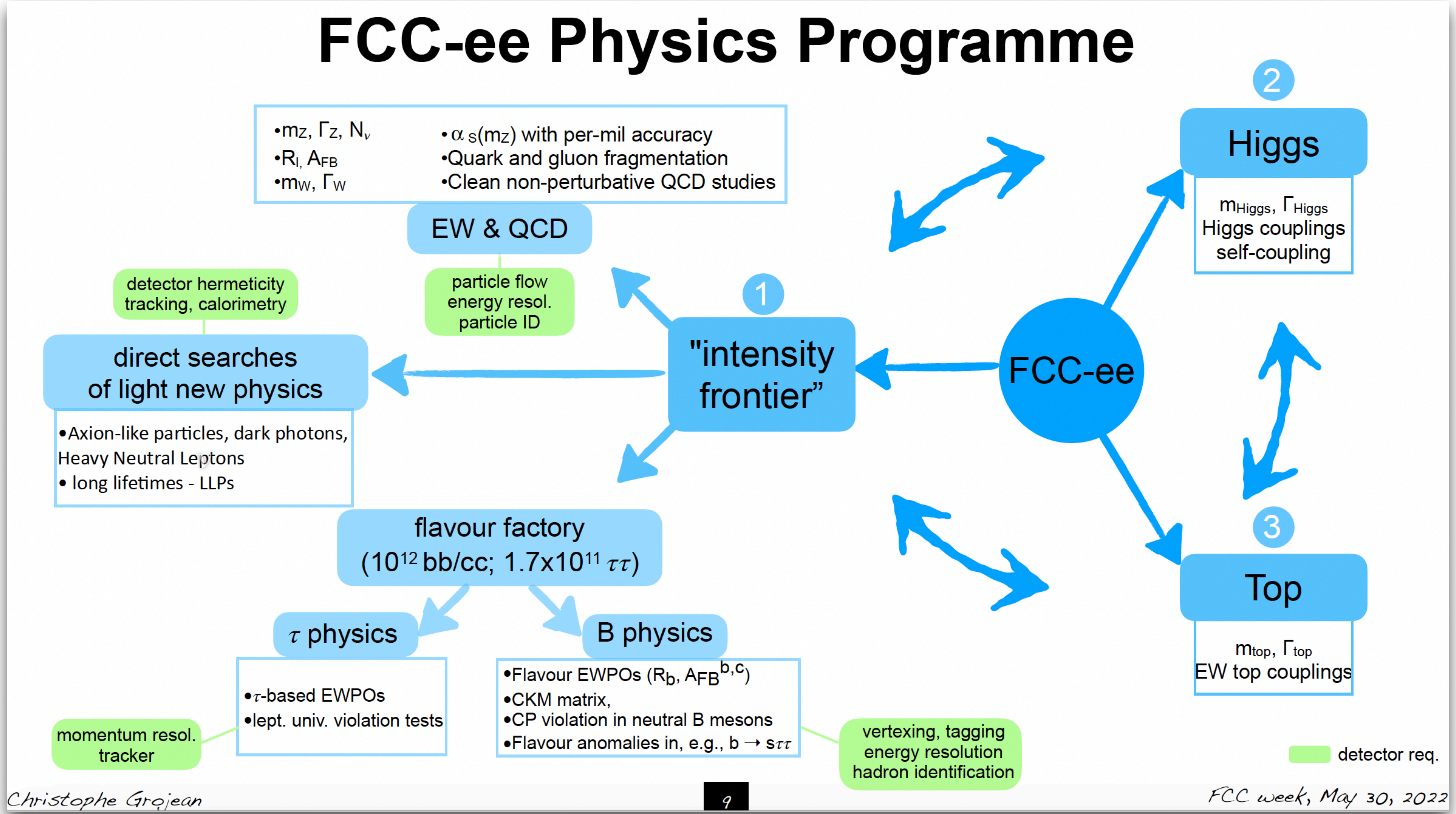


FCC-hh

CLD	IDEA	??
		
Based on CLIC detector design, arXiv:1911.12230 Full silicon vertex detector and tracker 3D-imaging highly-granular calorimeter system Coil outside calorimeter system	Innovative, possibly cheaper than CLD https://pos.sissa.it/390/819 Baseline in many ongoing studies Silicon vertex detector Short-drift, ultra-light wire chamber Dual-readout calorimeter Thin and light solenoid coil inside calorimeter system	New! Still unnamed! GranuLAr WS, IJCLab 2022 – Martin Aleksa Highly granular noble-liquid calorimeter Thin 2T solenoid in the calorimeter cryostat.

More complementary options possible (4 IP!) → Can we optimize detector designs for the complete physics program? Yes! opportunities to contribute

"FCC physics case: the once, the now and the future" - Christophe Grojean

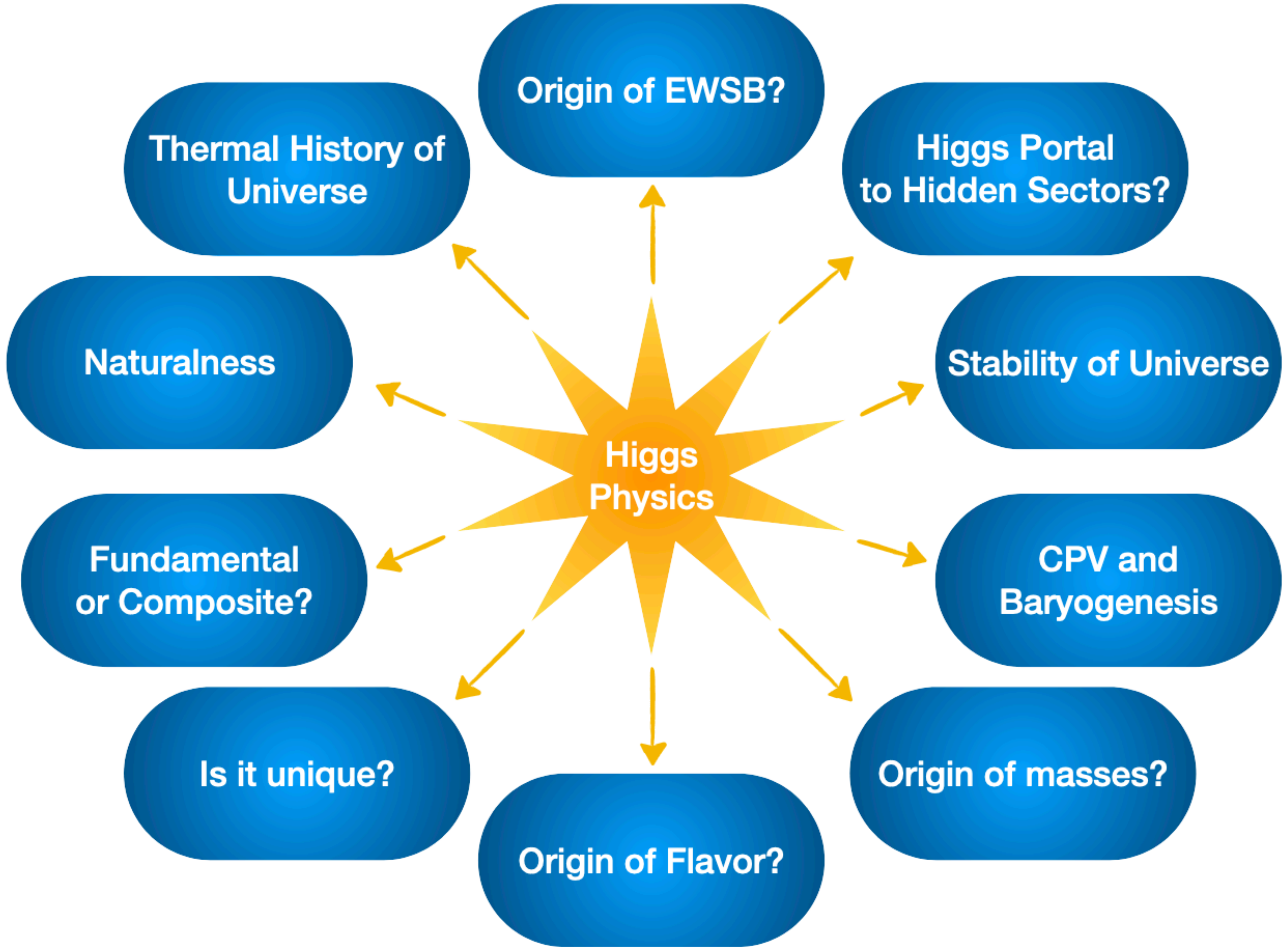


HET factory physics

J. de Blas, FCC week 2023

H is for Higgs

- FCC-ee is primarily a Higgs factory
- The Higgs is connected to central questions in HEP
- BSM scenarios dealing with these questions typically introduce modifications in the Higgs properties
- Indirect tests of new physics

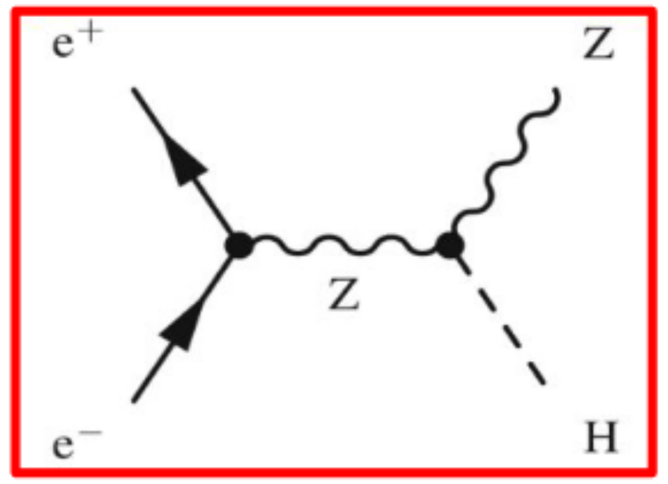


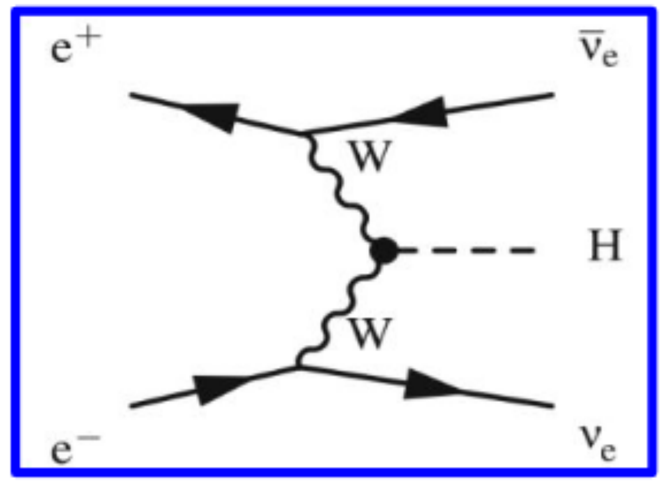
arXiv:2209.07510

Giant step forward in precision

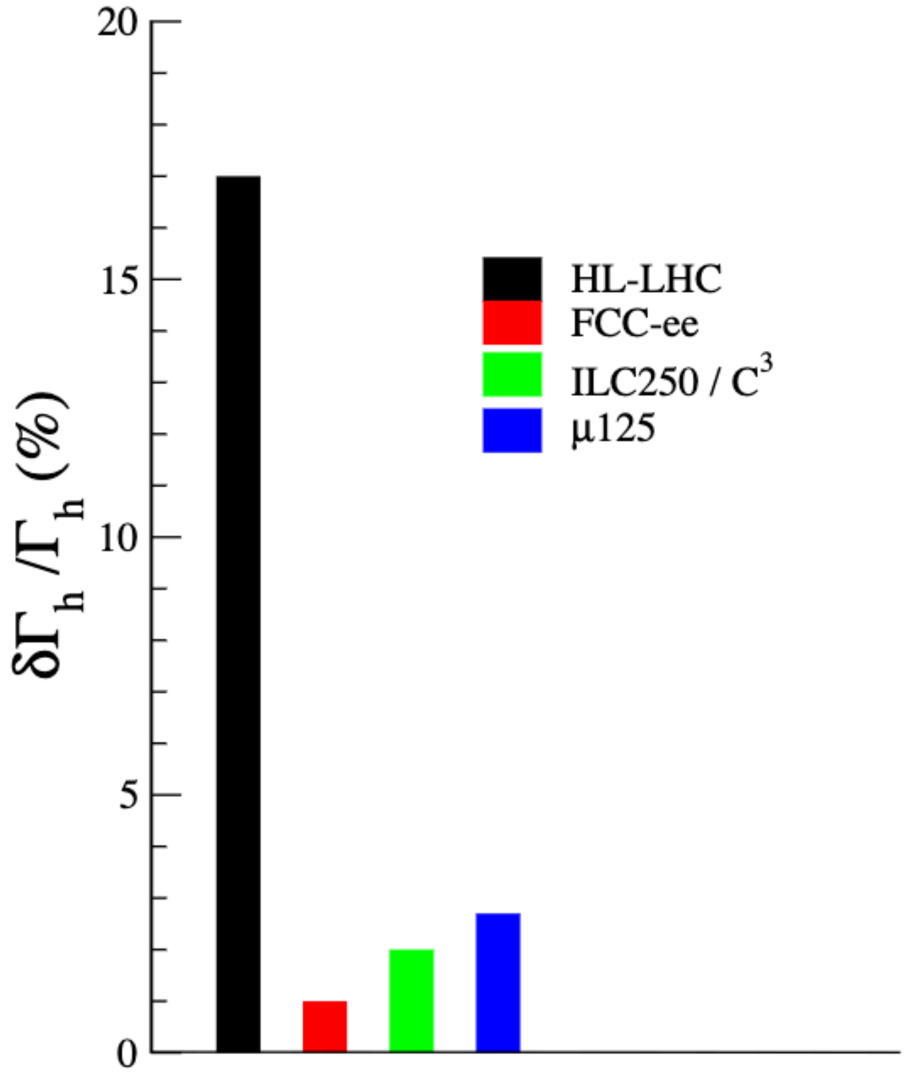
Wednesday session in the FCC week 2023

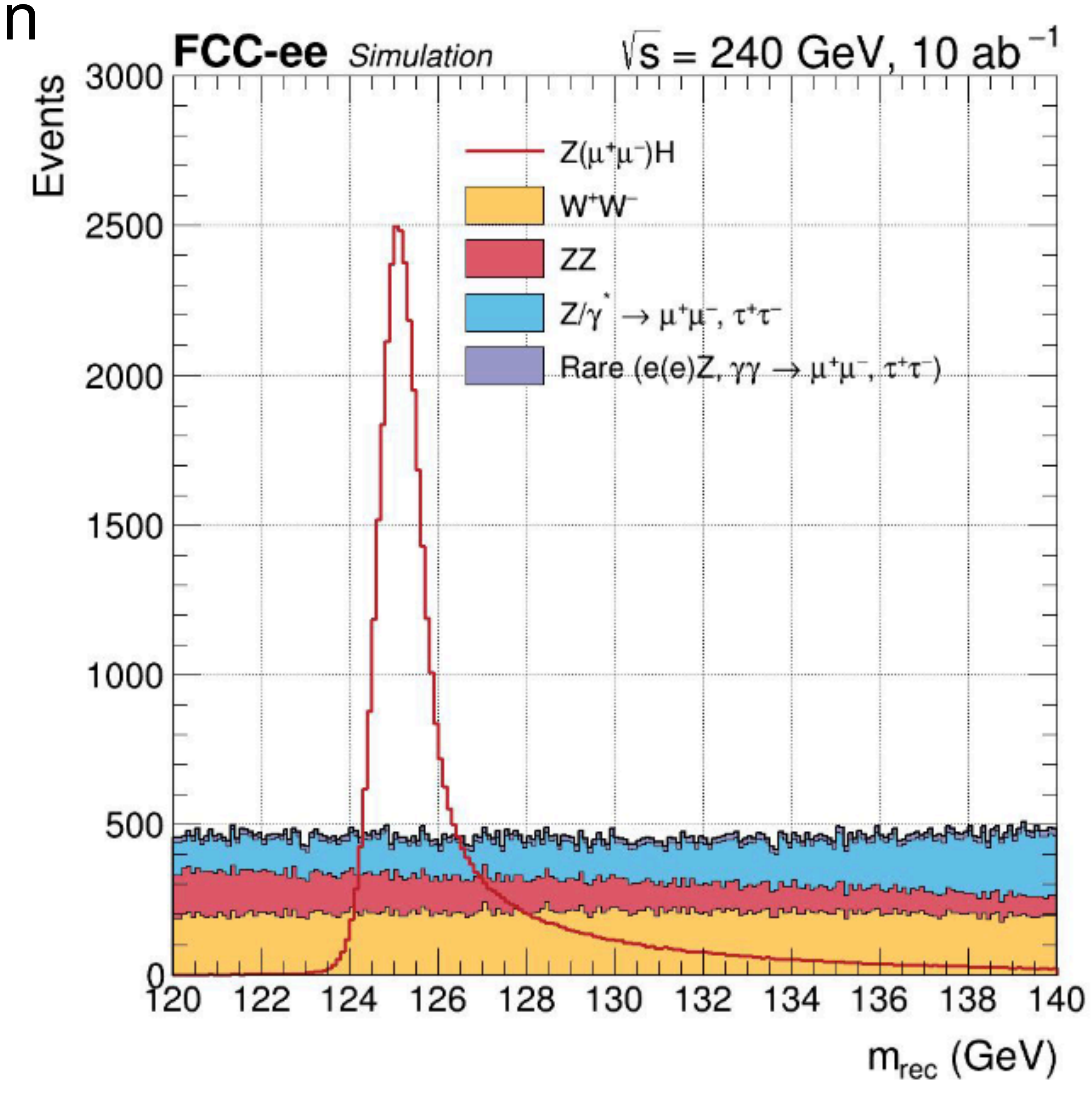
- x10 precision
- Recoil mass method for ZH production
  - Measurement of σ_{ZH} ⇒ Absolute measurement of HZZ interaction
  - Precise Higgs mass O(MeV) and width determination <1%





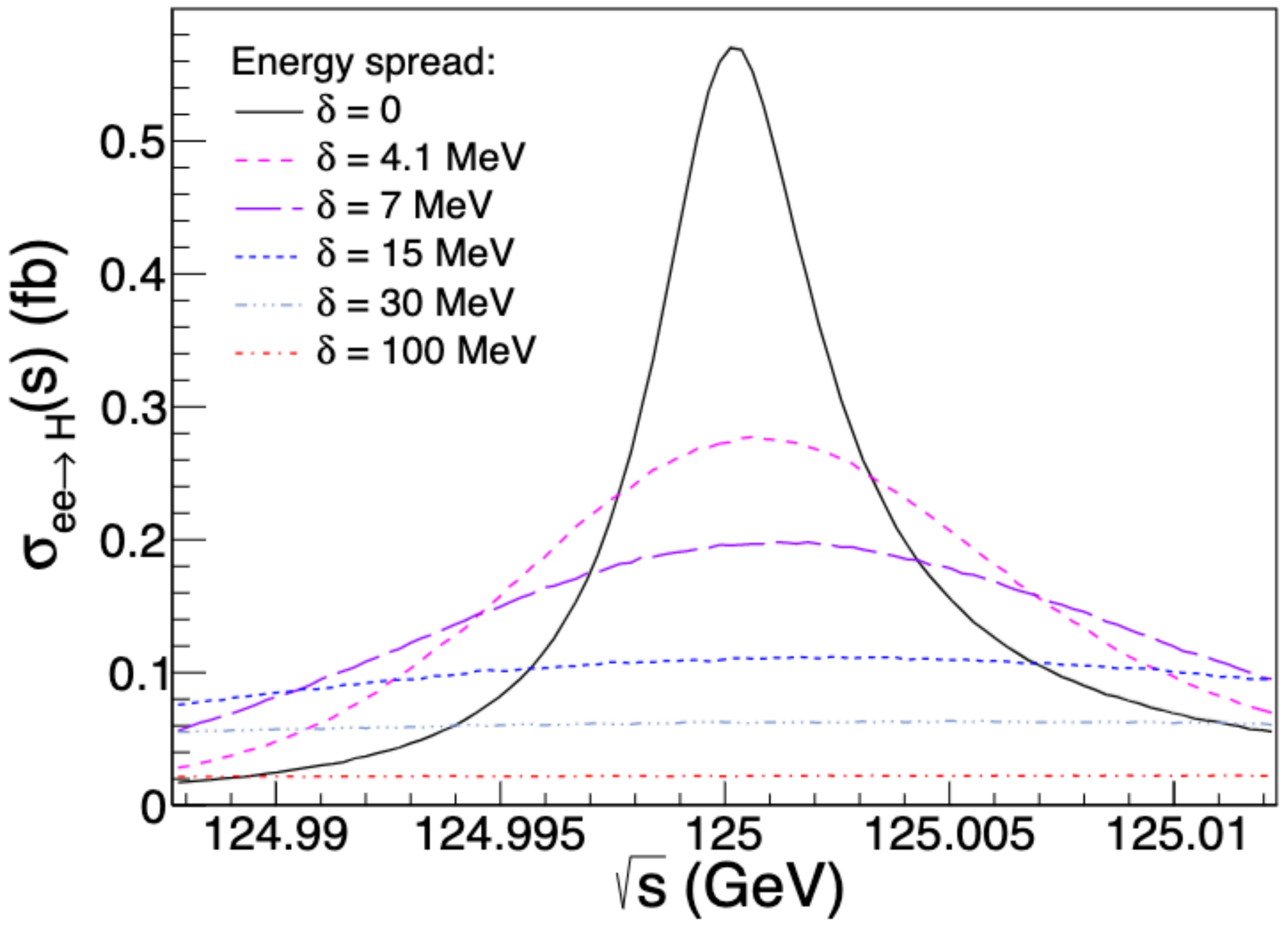
Total Higgs production @ FCC-ee (baseline – 4 IP)		
Threshold	ZH production	VBF production
240 GeV / 10 ab^{-1}	2 M	50 k
365 GeV / 3 ab^{-1}	0.4 M	0.1 M

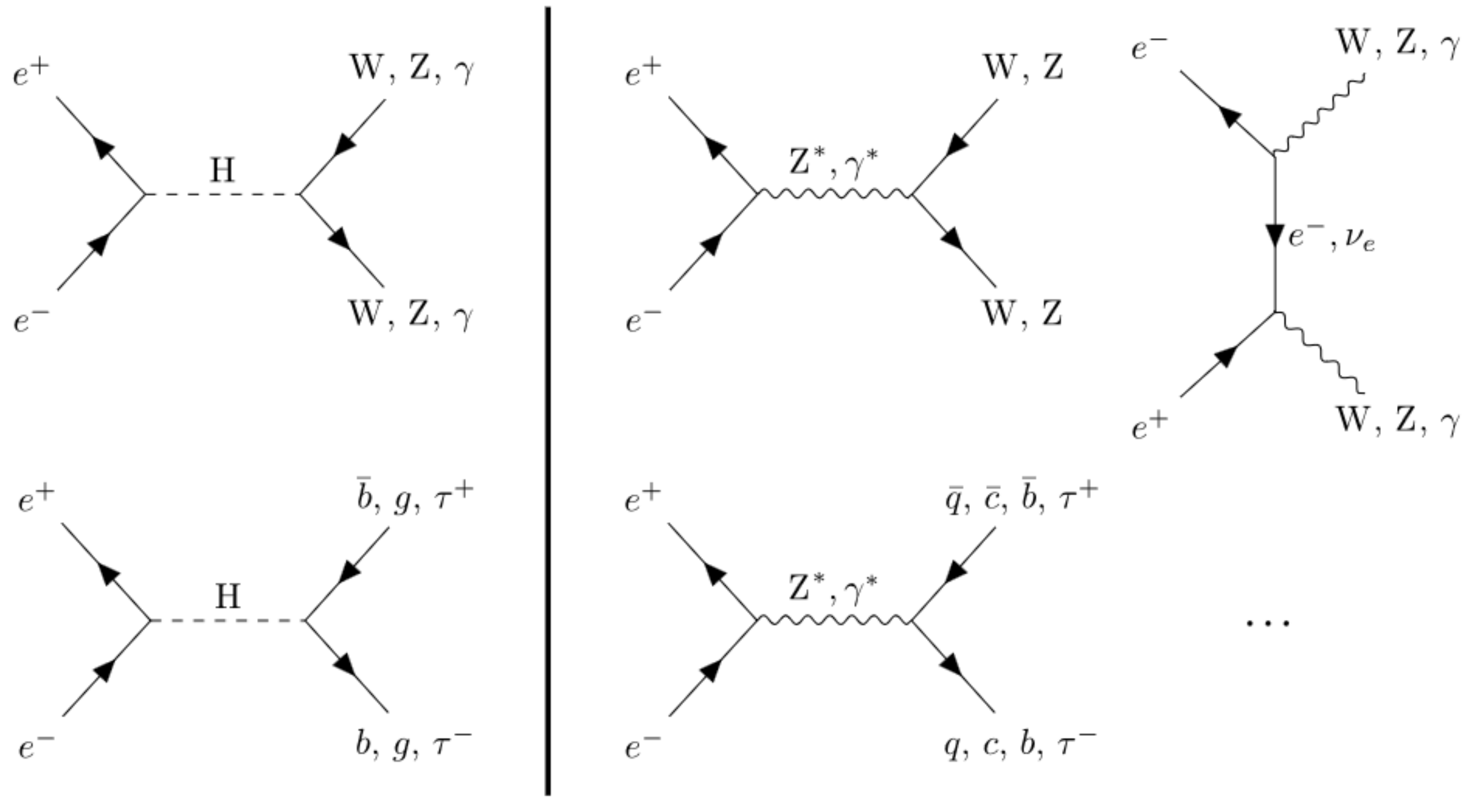


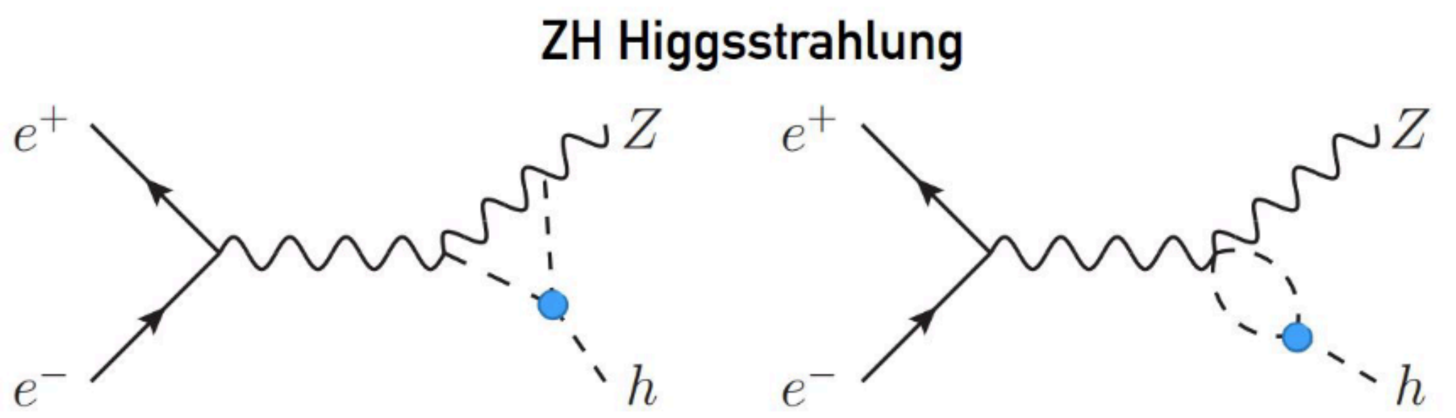


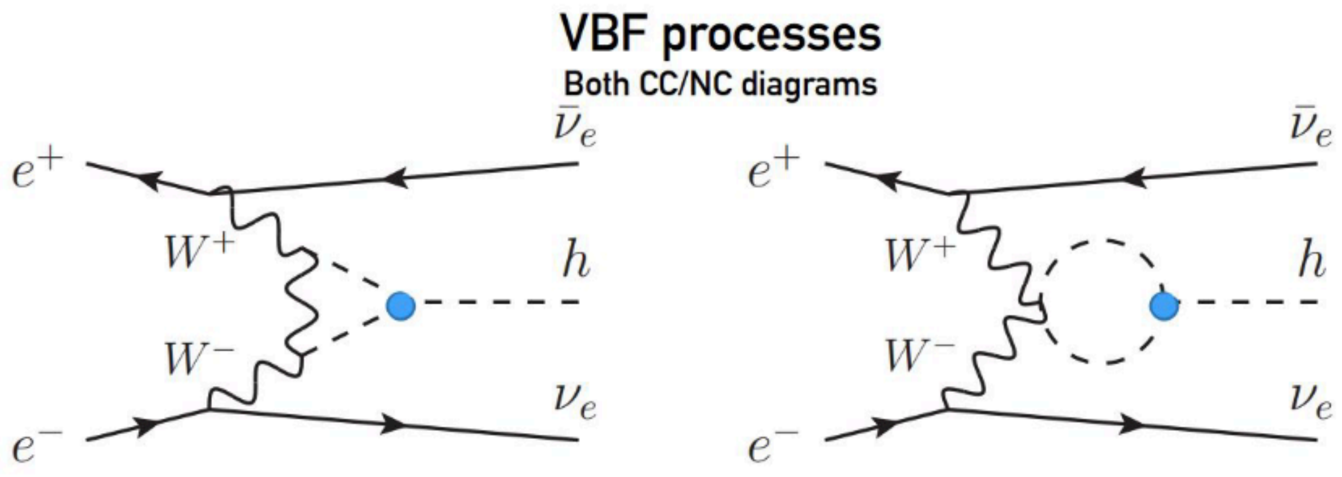
Per-mil level in couplings

- Thorough determination of couplings with high precision
  - fermions/gluons: O(≦1%)
  - Invisible O(30%)
- Access to interactions not easy/impossible at HL-LHC:
  - c guaranteed
  - s, e (unique challenge, using s-channel and beam monochromatization at √s = 125 GeV) within reach
- Indirect determination of self-coupling









- **pp:** statistics + e+e- precision measurements+ large dynamic range
  - sub-% measurement of rare decay modes
  - ≲5% measurement of the trilinear self-coupling
  - d > 4 EFT operators up to scales of several TeV
  - search for multi-TeV resonances decaying to H, Higgs sector extensions

Profound test of the SM

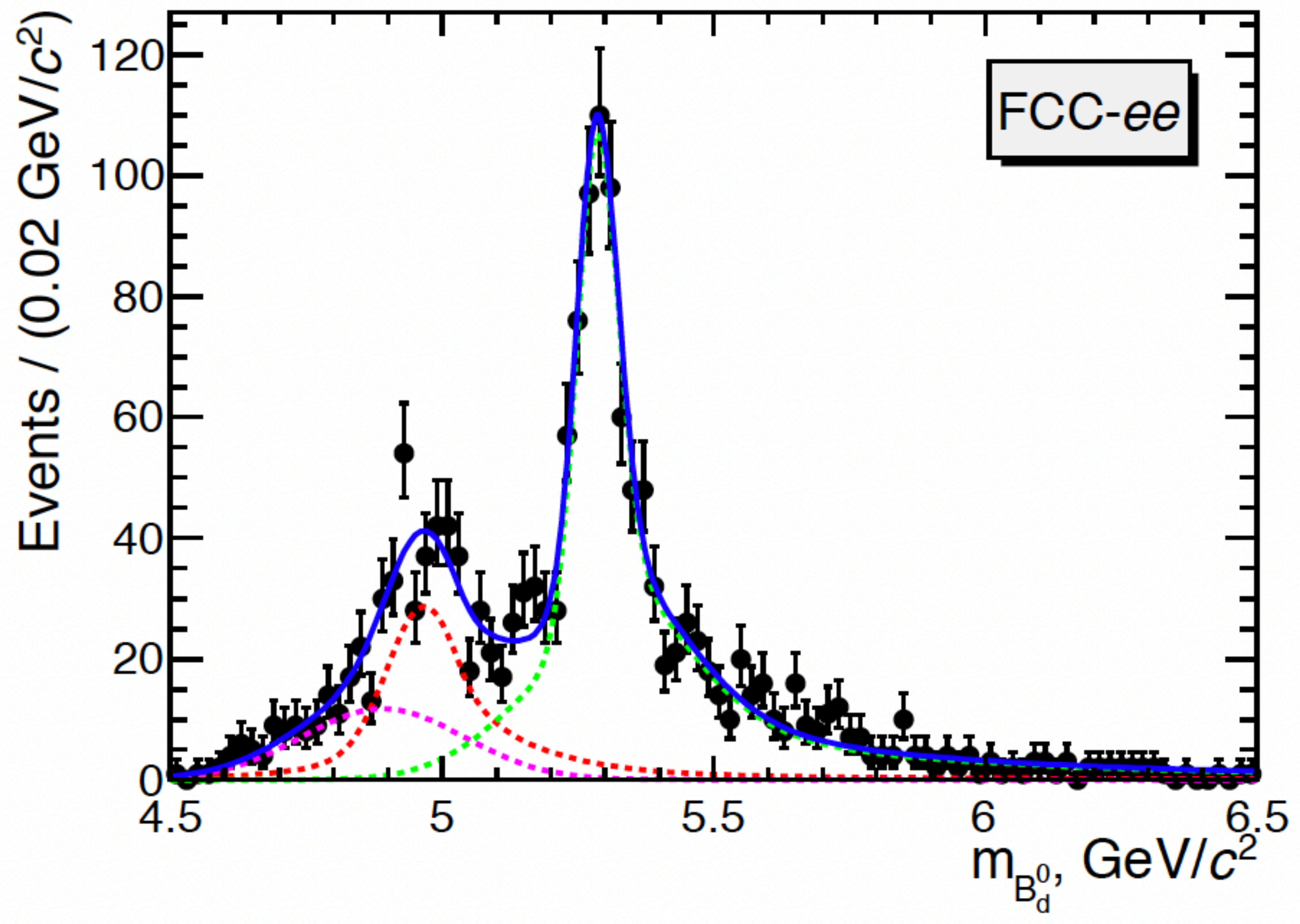
Precision electroweak - Christoph Paus

- O(10^5) larger statistics than LEP at the Z peak and O(10^3) at WW threshold
- Re-measurement 3 orders of magnitude more precisely: m_Z, $\alpha_{QED}(m_Z)$, …
- Severe constraints from pseudo observables
- Limiting factors to tackle now: Lumi, Energy calibration of the beam, experimental uncertainties (but mostly theory), fitting methods for pseudo observables

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	4	100	From Z lineshape scan; beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	4	25	From Z lineshape scan; beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	$0.2 - 1.0$	Ratio of hadrons to leptons; acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	$1,196 \pm 30$	0.1	$0.4 - 1.6$	From R_ℓ^Z above
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons; stat. extrapol. from SLD
$\sigma^0_{\rm had}$ ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross section; luminosity measurement
N_ν ($\times 10^3$)	$2,996 \pm 7$	0.005	1	Z peak cross sections; luminosity measurement
$\sin^2\theta_W^{\rm eff}$ ($\times 10^6$)	$231,480 \pm 160$	1.4	1.4	From $A_{FB}^{\mu\mu}$ at Z peak; beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	$128,952 \pm 14$	3.8	1.2	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1.3	b-quark asymmetry at Z pole; from jet charge
A_e ($\times 10^4$)	$1,498 \pm 49$	0.07	0.2	from $A_{FB}^{{\rm pol},\tau}$; systematics from non-τ backgrounds
m_W (MeV)	$80,350 \pm 15$	0.25	0.3	From WW threshold scan; beam energy calibration
Γ_W (MeV)	$2,085 \pm 42$	1.2	0.3	From WW threshold scan; beam energy calibration
N_ν ($\times 10^3$)	$2,920 \pm 50$	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
$\alpha_S(m_W^2)$ ($\times 10^4$)	$1,170 \pm 420$	3	Small	From R_ℓ^W

Flavour

- FCC-ee could be a powerful and competitive probe of flavour physics beyond current experimental programs
- Tera-Z run of the FCC-ee 15x Belle's stats (more with 4IPs) → covering the full program of LHCb & Belle II and compete favorably everywhere
- All b-hadron species available, potential for excellent secondary vertex reconstruction
- Large tau production, boost



Flavour physics - Jernej F. Kamenik

Wednesday session in the FCC week 2023

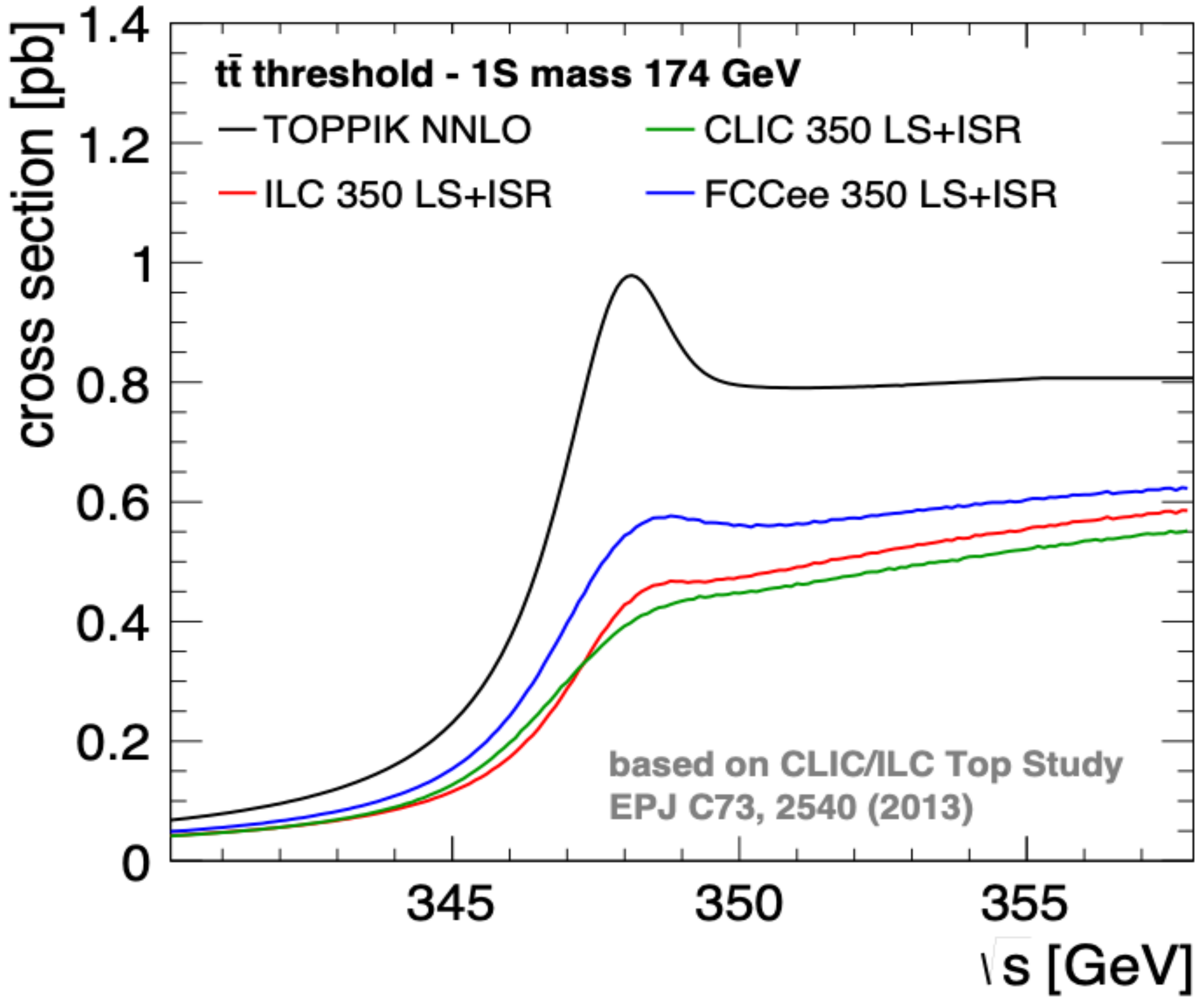
Top

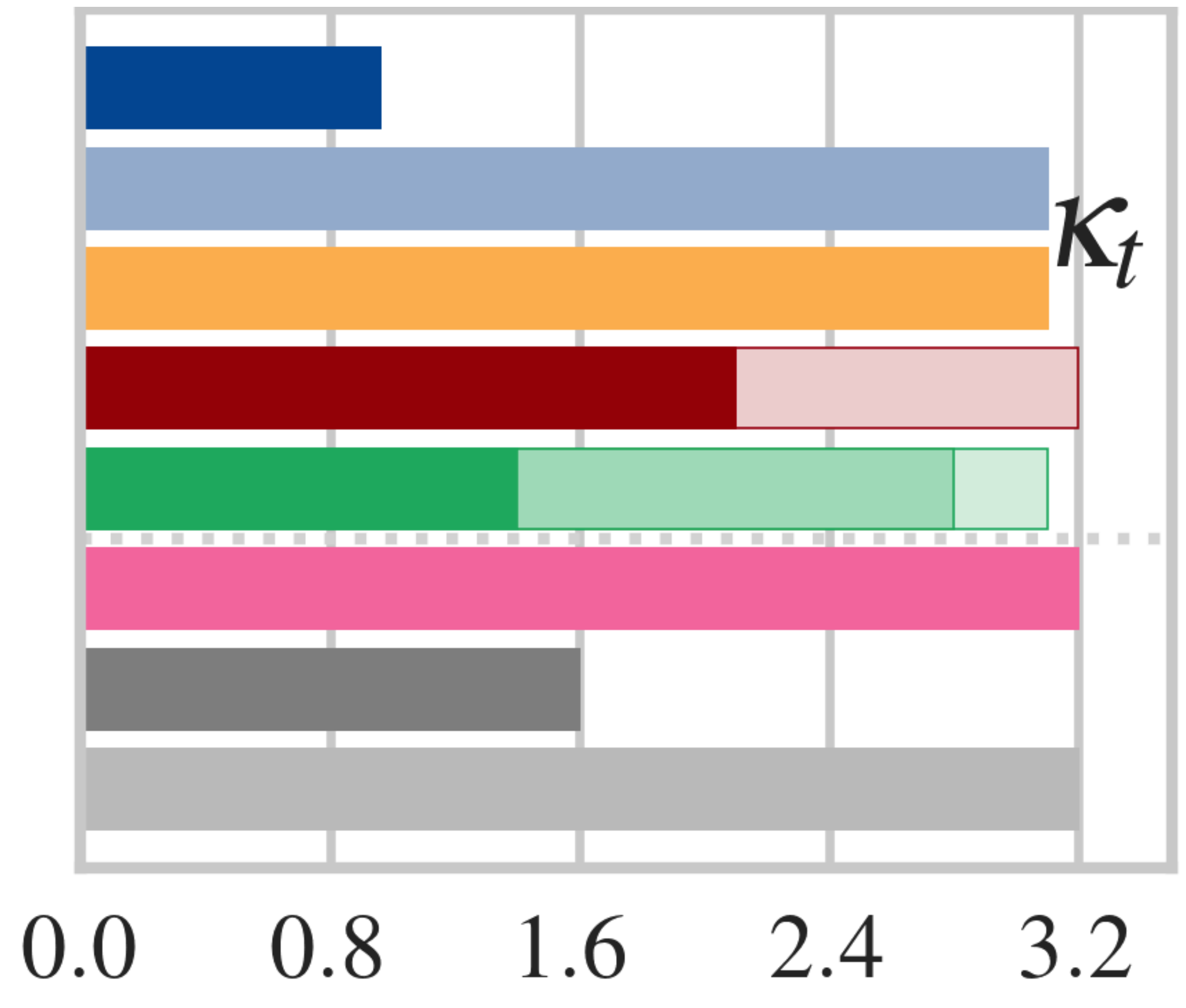
Less explored, opportunities

- Less explored areas in scope of FCC-ee,-hh include flavour studies using top decays, spectroscopy, quarkonium physics & flavor conversion at high-p_T

- FCC-ee: Threshold region allows most precise measurements of top mass, width, and estimate of Yukawa coupling

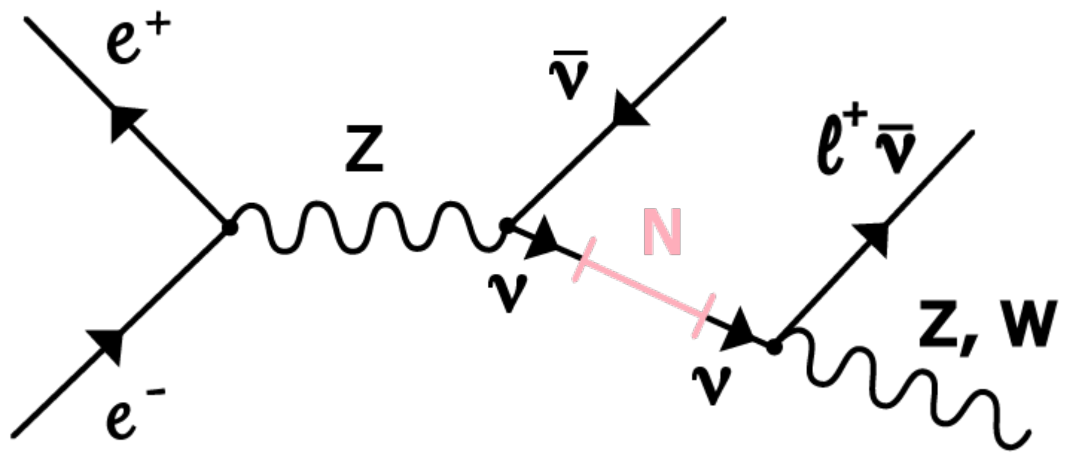
- FCC-hh: Incredible potential with very challenging reconstruction



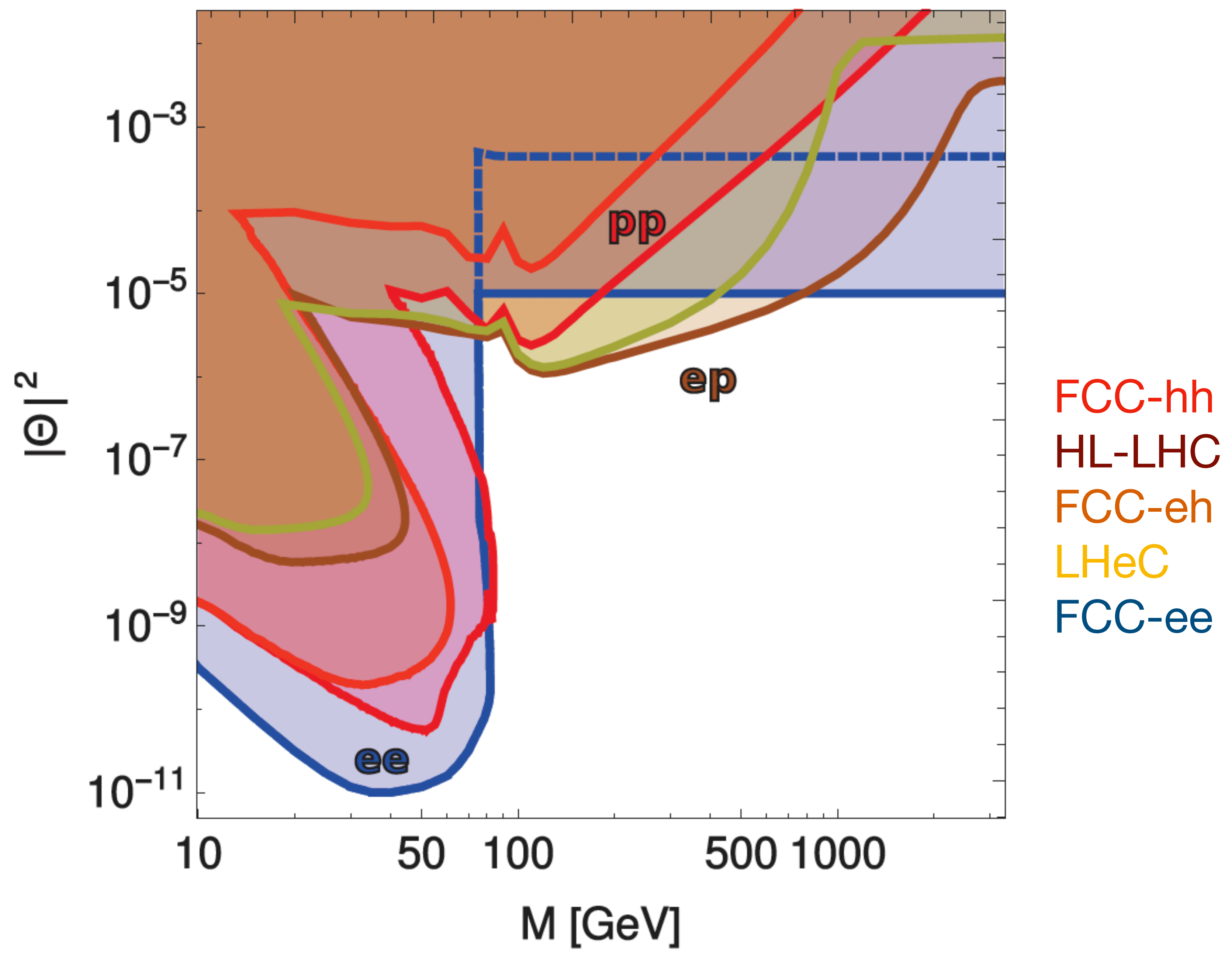


Complementarity

Across stages



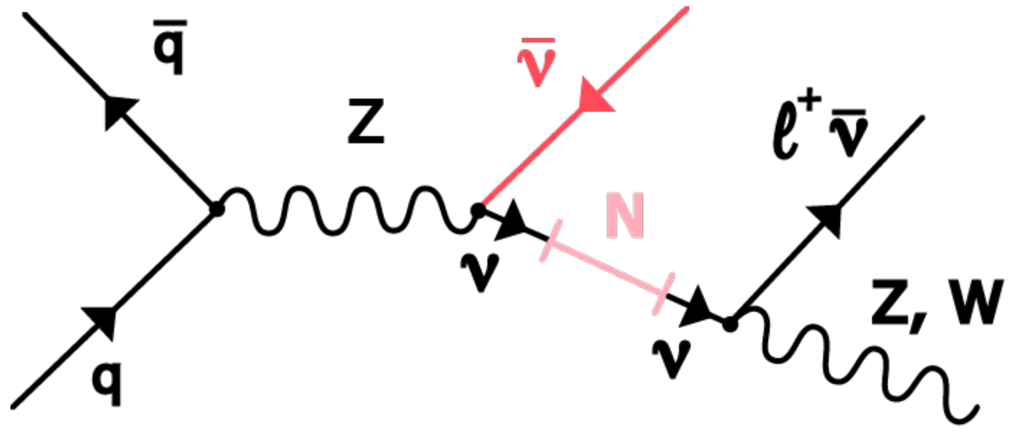
arXiv:1612.02728

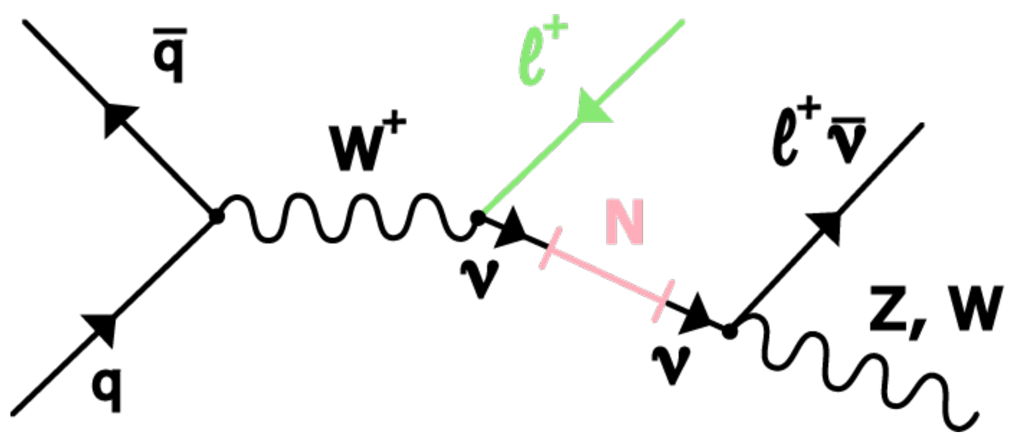


FCC-ee
Indirect constrains from precision SM measurements
Direct search: single HNL production in Z decays
Sensitive to 10^{-11} for M below the W mass

FCC-hh
Direct search: single HNL production in W/Z decays
Lepton Number Violation, Lepton Flavor Violation
can test heavy neutrinos with masses up to ~2 TeV

FCC-eh
Can extend the reach of the FCC-hh up to ~2.7 TeV
Best reach above W mass
Sensitive to LFV and Lepton-Number-violation signatures





Complementarity is the key word, also in Higgs physics, top physics, and other new physics searches

All this comes at a cost

More important than money

- While in some metrics, like energy consumption or carbon footprint per Higgs boson, FCC-ee is the most effective collider (due to the large luminosity) arXiv:2208.10466, FCC is a very large machine that will have an important environmental impact
- Sustainability is a key aspect of project
  - All designs and R&D are focused on energy savings to reduce the power demand and the energy consumption
  - Accelerator technologies (cavities, magnets...) will be designed with a focus on energy savings.
  - Other focus: reduction of water intake and treatment or reuse of excavated materials
  - FCC includes renewable energy supply

Energy and sustainability issues - Jean-Paul Burnet

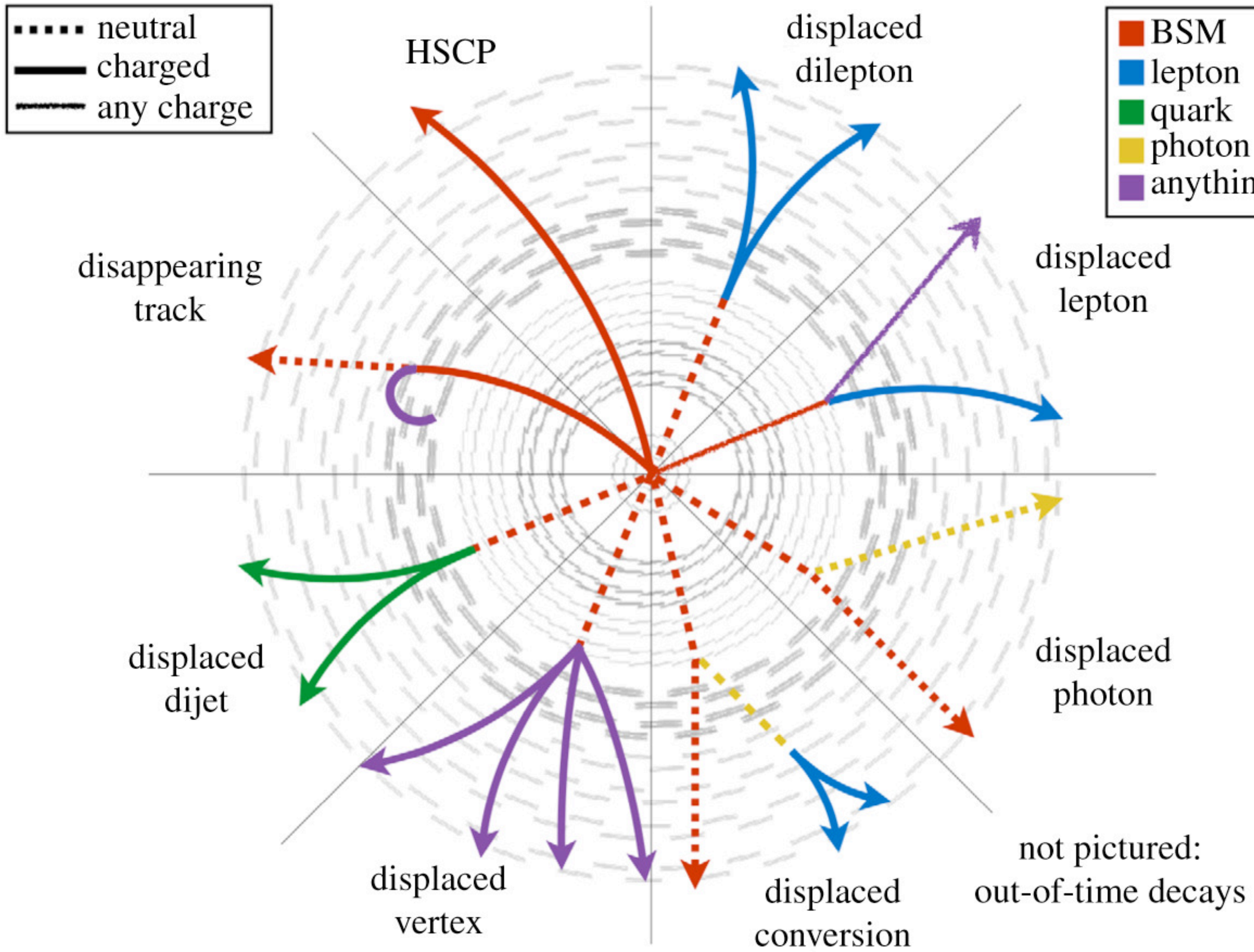
Power during, in MW	Z	W	H	TT
shutdown	30	33	34	41
Technical stop	67	78	81	108
Downtime	67	78	81	108
Commissioning	144	163	177	233
Machine Development	96	121	147	231
Beam operation	222	247	273	357

Time to do the work to

Minimize impact on environment (Energy, CO2 and water footprint, emissions, waste etc…) and availability of resources (e.g. less materials extracted)

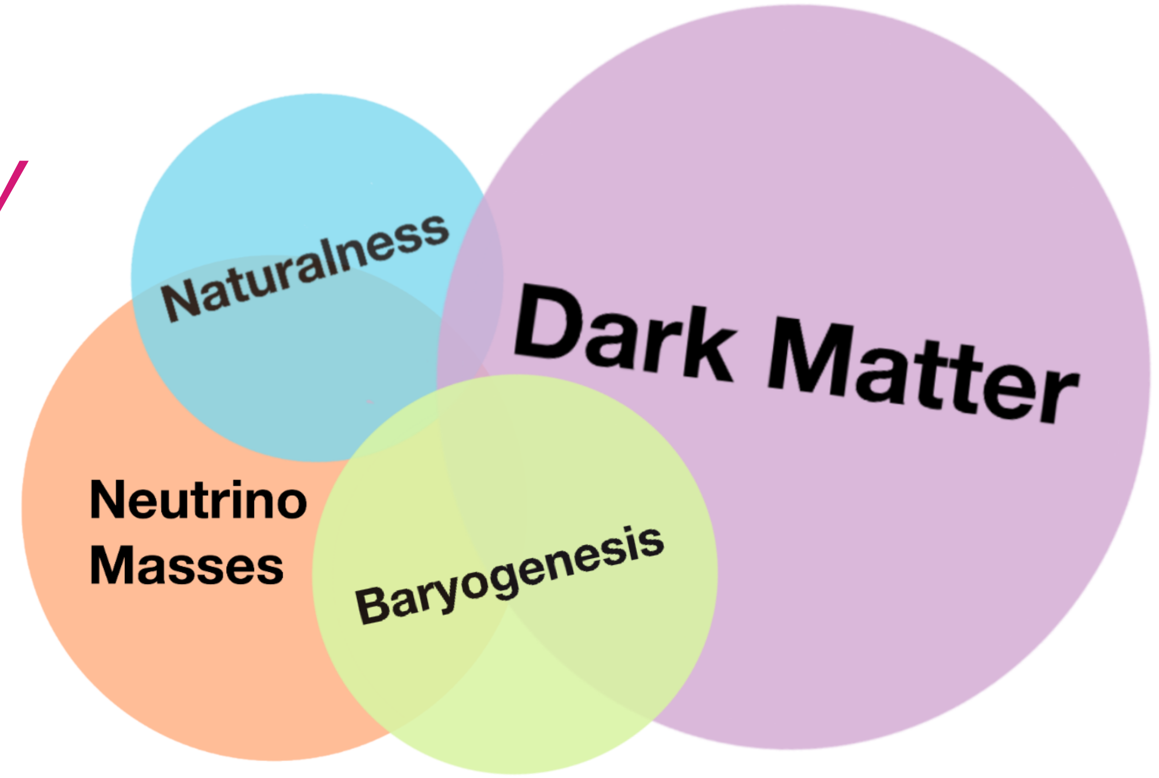
Maximize not only physics but the value returned to society (included but not limited to training, technology and knowledge transfer)

What is a long-lived particle?



- Long-lived particles is an **umbrella term** to cover new particles that we have not discovered yet, with lifetimes long enough to travel measurable distances inside the detectors before decaying, long enough to have non-standard experimental signatures

Theoretically, their presence is strongly motivated

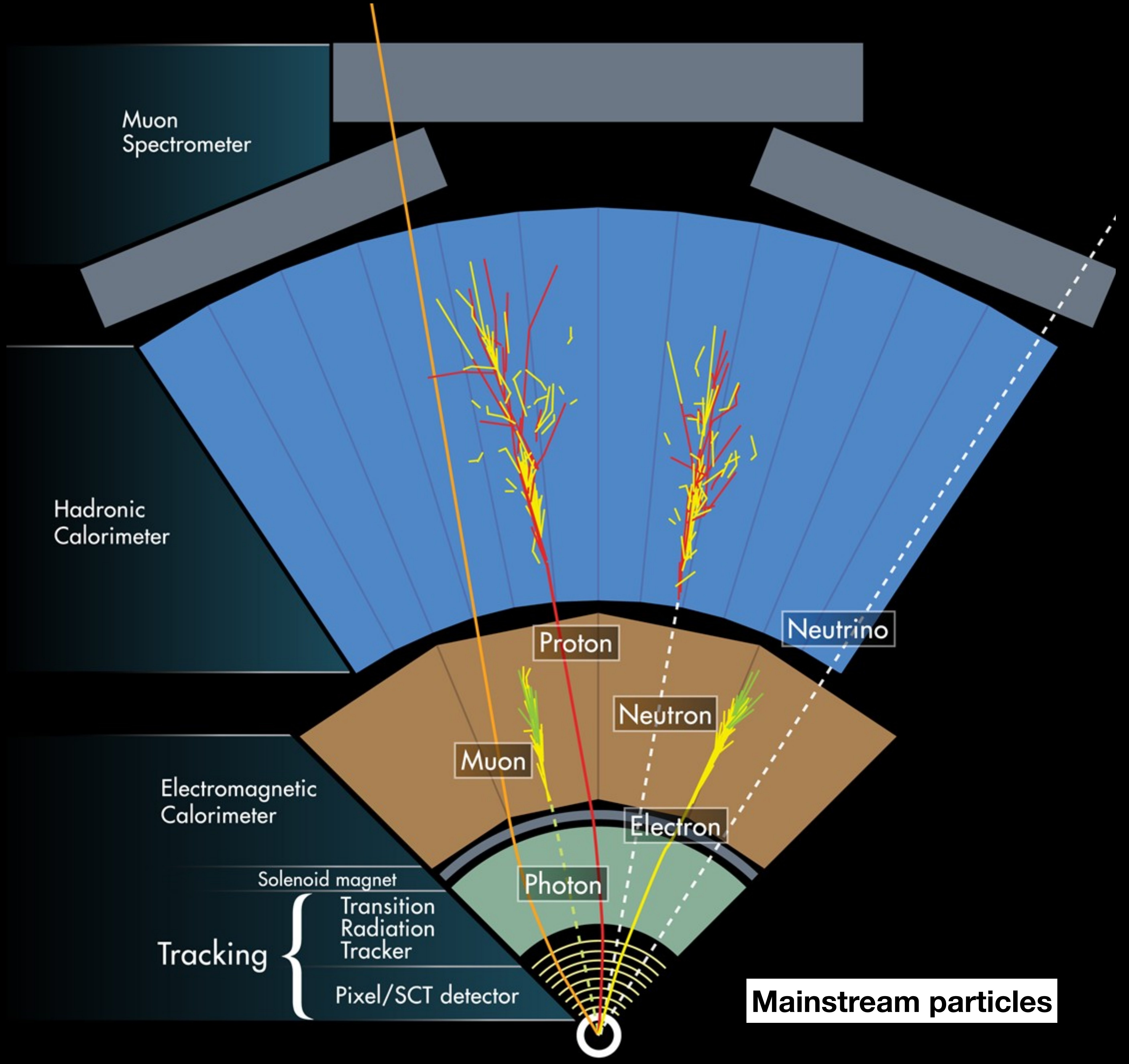


Detecting particles

At high-energy colliders

- As we reach higher and higher energies, we gain access to more massive particles
  - That in turn are shorter and shorter-lived

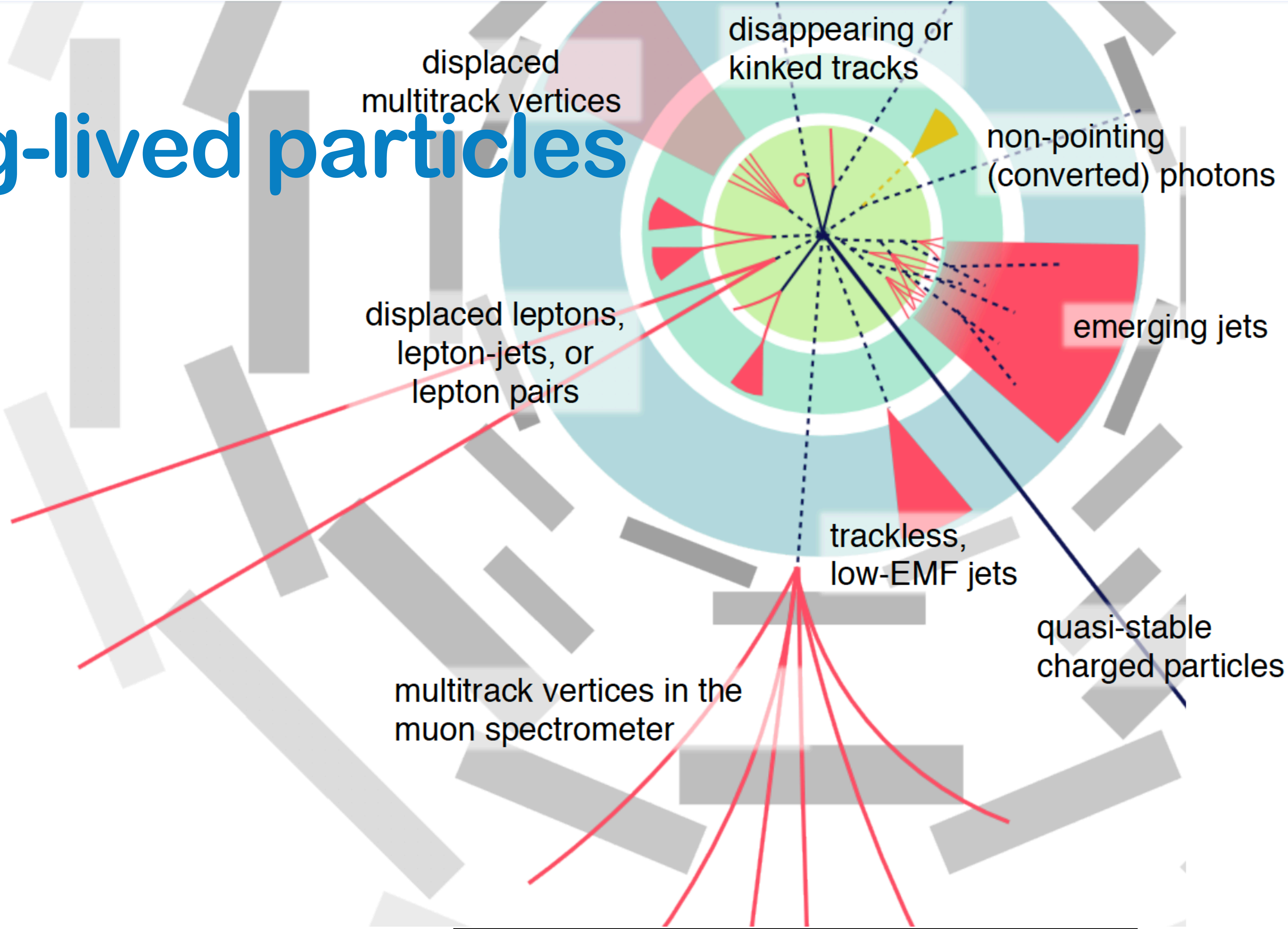
Our detectors, trigger, and reconstruction are optimized for that!



Figures by Heather Russell

Detecting Long-lived particles

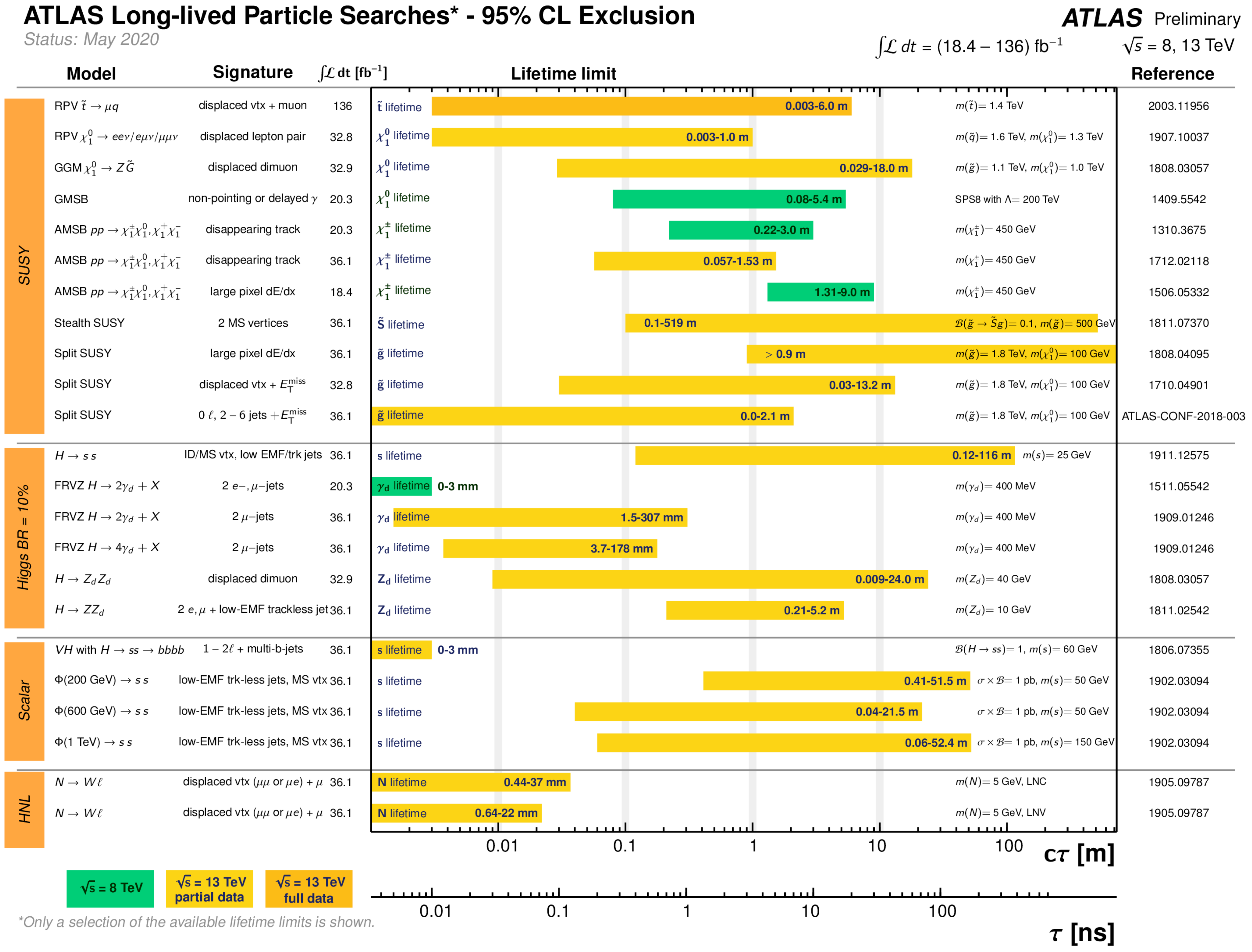
- Long-lived particle searches probe unconventional signatures
  - Displaced, disappearing, emerging, slow, stopped…
- This is a curse and a blessing
  - It makes them clearly different from other processes
    - Easy to spot! Background free!
  - It also could make them potentially invisible to current data-acquisition methods
    - Hard to spot! We may be throwing them away!



Long-lived particles
(Also slowed-down, out of time, stopped)

Are we working on this?

- Yes, since the start of the LHC, at LEP, and the Tevatron…
- They make up less than 10% of our exotic searches
- Starting to pick up a lot of interest
  - LHC Long-lived Particles Working Group (LHC LLP WG)
    - https://lpcc.web.cern.ch/lhc-llp-wg
  - LHC Long-lived particle community workshops
    - https://longlivedparticles.web.cern.ch/



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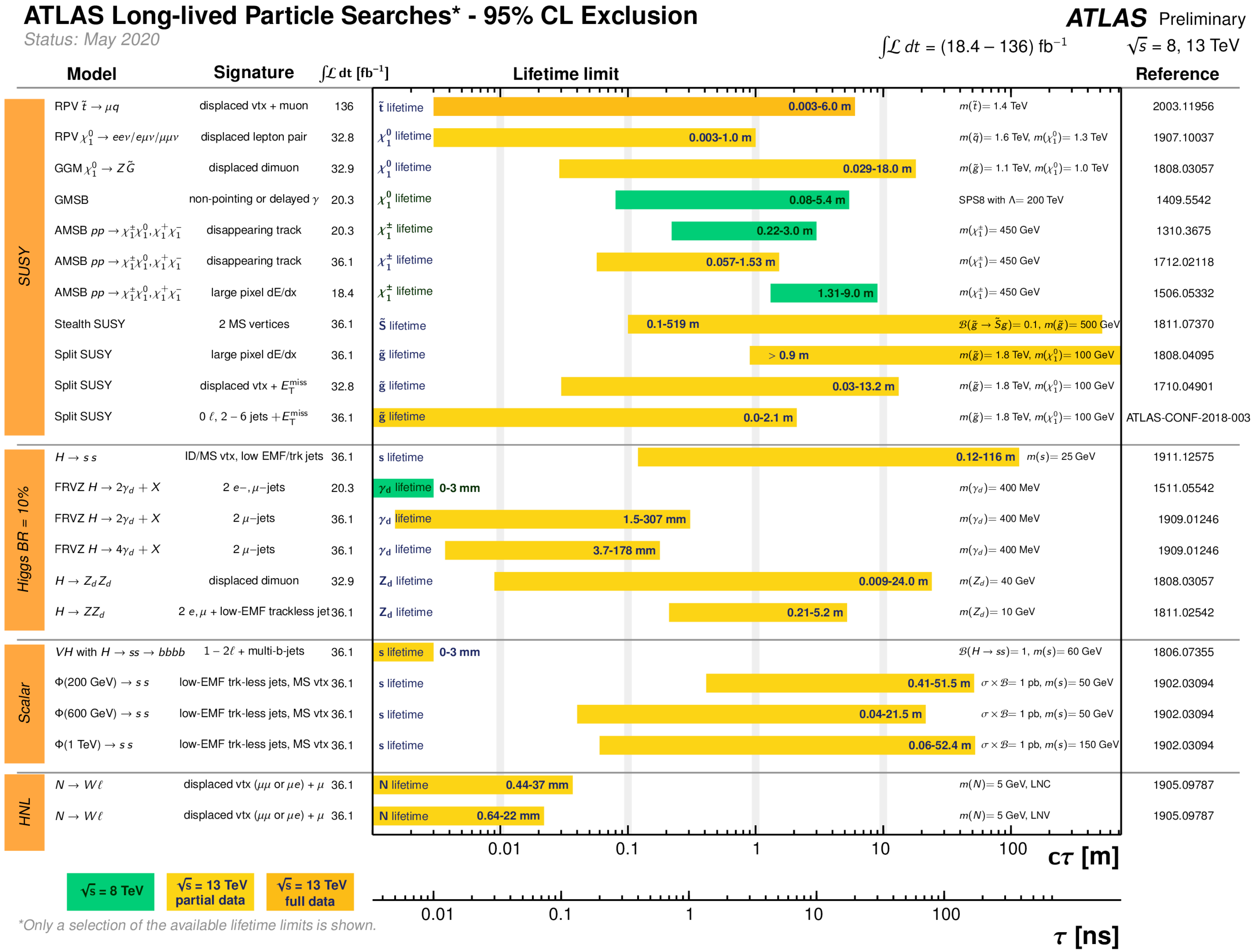


BUT IT IS HARD

Paradigm shift

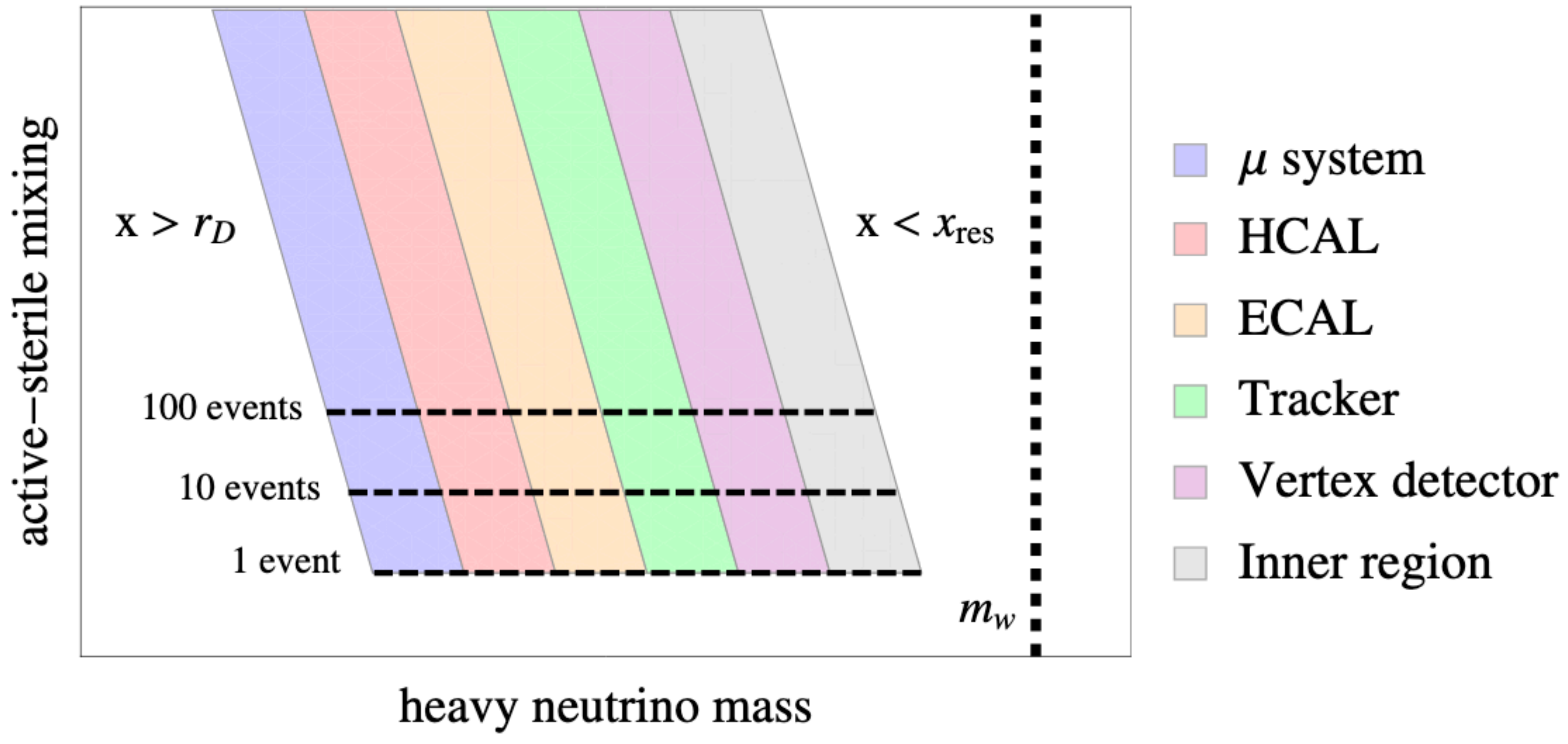
- Looking for this kind of signatures STILL represents a paradigm shift from the usual
- Implies exploiting the detectors in ways they were not designed for

Some of the **roadblocks**:

- Custom identification/reconstruction algorithms needed
  - Especially clear in the Tracker (less utilized subdetector for LLP so far)
- Very low background searches, but affected by instrumental effects
  - not well-modelled in the simulation
- Our “Trigger” may be biased against them (we may be throwing them away!)
  - Dedicated trigger paths

This won't be different at future colliders

arXiv:1604.02420



Sensitivity of different detector components to HNL as a function of the mixing parameter and mass

- At this point we have two ways to go:
  - Design the future detectors as usual and then try to make the best out of them for LLPs
    - which can be done but won't be easy as we know from the experience at the LHC -and before-
  - Design the future detectors with LLP in mind, prioritising for example displaced tracking and timing, and budgeting for unexpected signals
    - which can bring up not only a boost for these searches but also innovation

Just a precision tool?

We hope not!

I convene this group

- The added value of an e+e- Higgs factory for Beyond the Standard Model is the business of the FCC BSM Physics Performance group

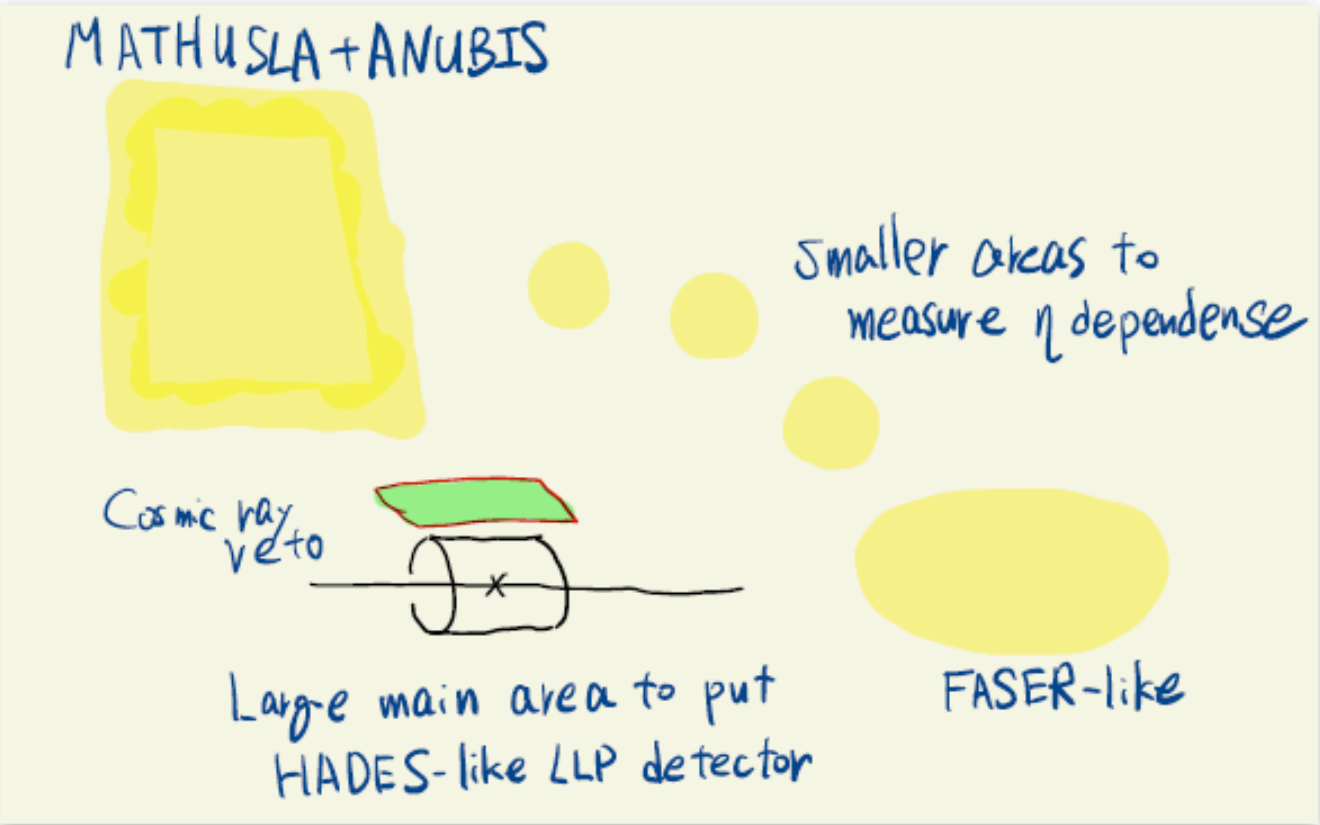
And also this one

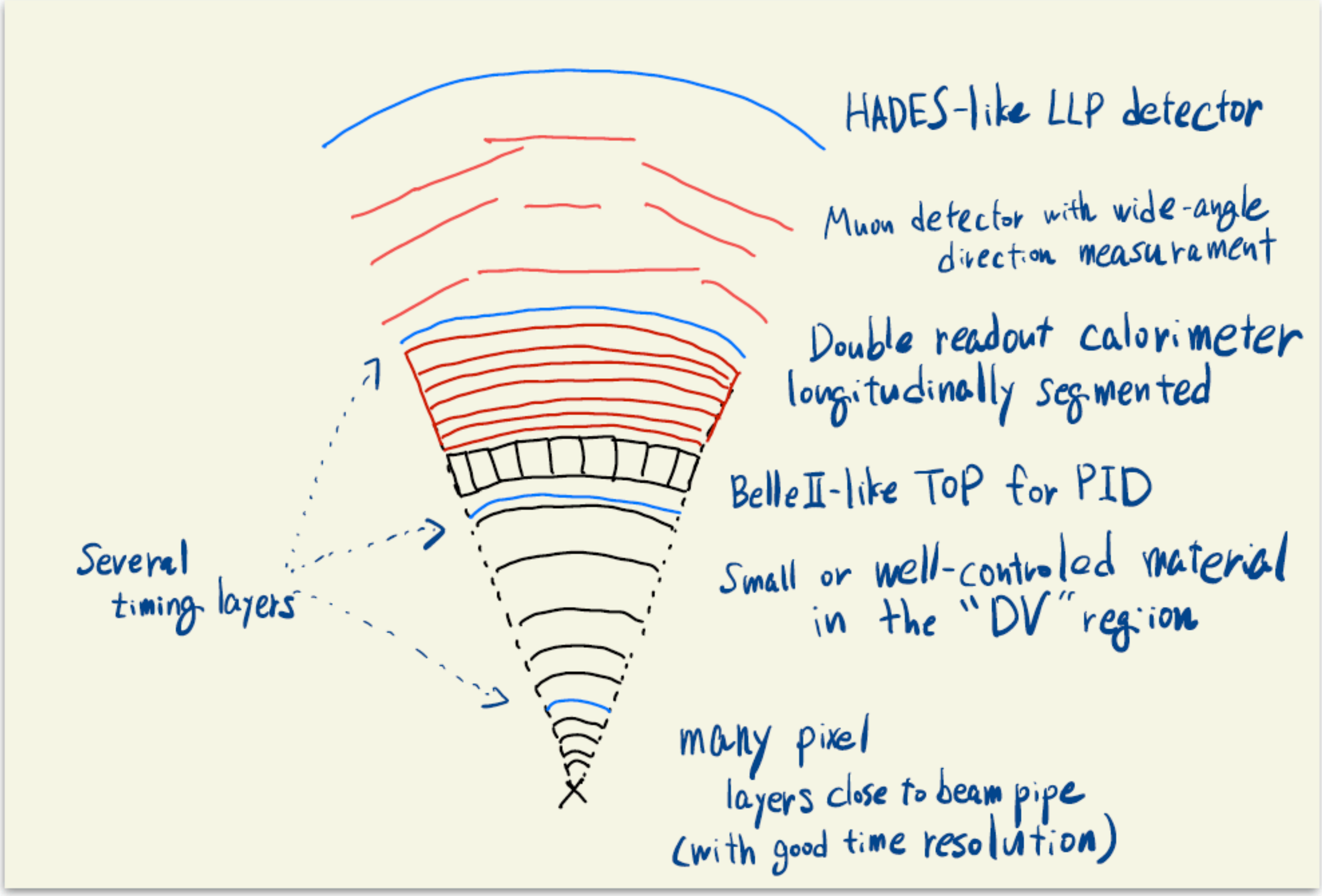
- And broadly for the ECFA Higgs Factory Study "Direct discovery potential" working group (WG1-SRCH)
  - Broad exploration of the new physics discovery potential of the future Higgs and top/EW factory, including the search for Feebly Interacting Particles also in connection with "Physics Beyond Colliders" activities.
- Work in both areas is starting to be officially coordinated now
  - Ramping up on top of previous work
    - European Strategy, Snowmass and other work!
    - LOI for Snowmass, arXiv:2106.15459
    - Multiple snowmass white papers in preparation
    - Multiple master theses

- **Simulation of long-lived Heavy Neutral Leptons and Axion-Like Particles at the FCC-ee** - Lovisa Ryagaard and Nils Eriksson, Uppsala University, January 2022
- **Towards Vertexing Studies of Heavy Neutral Leptons with the Future Circular Collider at CERN** - Rohini Sengupta, Uppsala University, June 2021.
- **Long-Lived Particles at the FCC-ee** - Rohini Sengupta, Uppsala University, January 2021.
- **Prospects of Sterile Neutrino Search with the FCC-ee** - Sissel Bay Nielsen, University of Copenhagen, December 2017.

Ryu Sawada

A dream LLP detector?

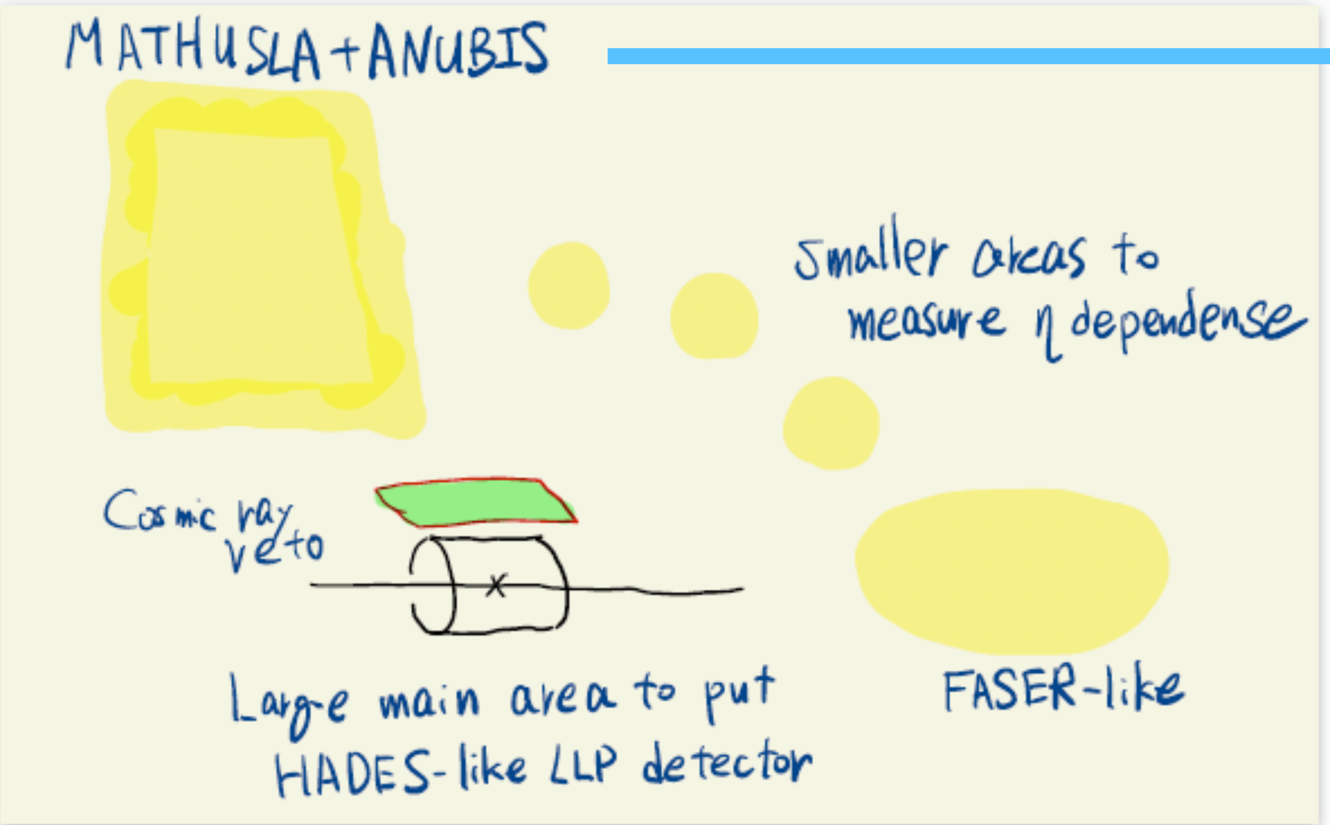


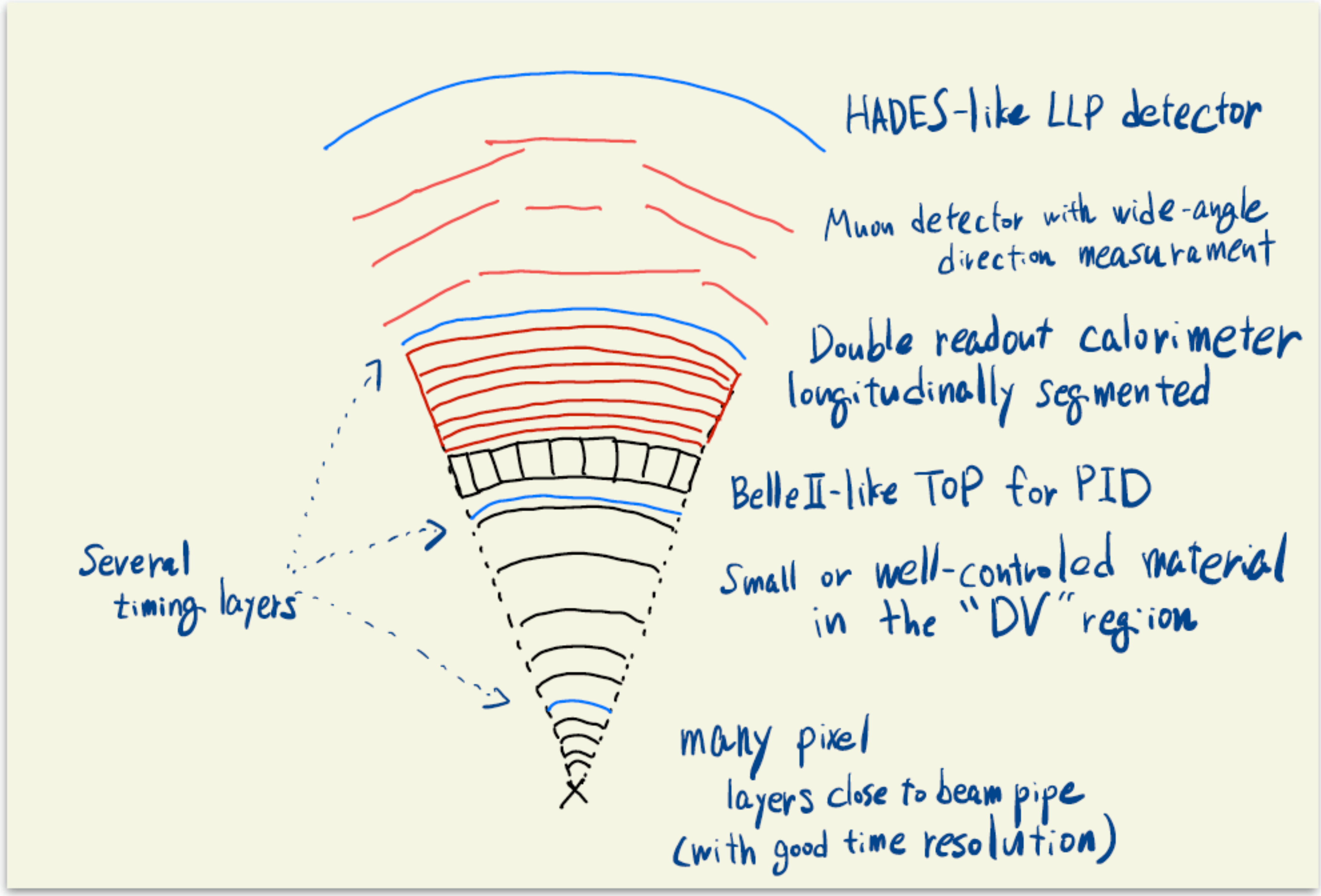


Can we incorporate LLP to the design of the future collider Experiments?

<u>Ryu Sawada</u>

A dream LLP detector?





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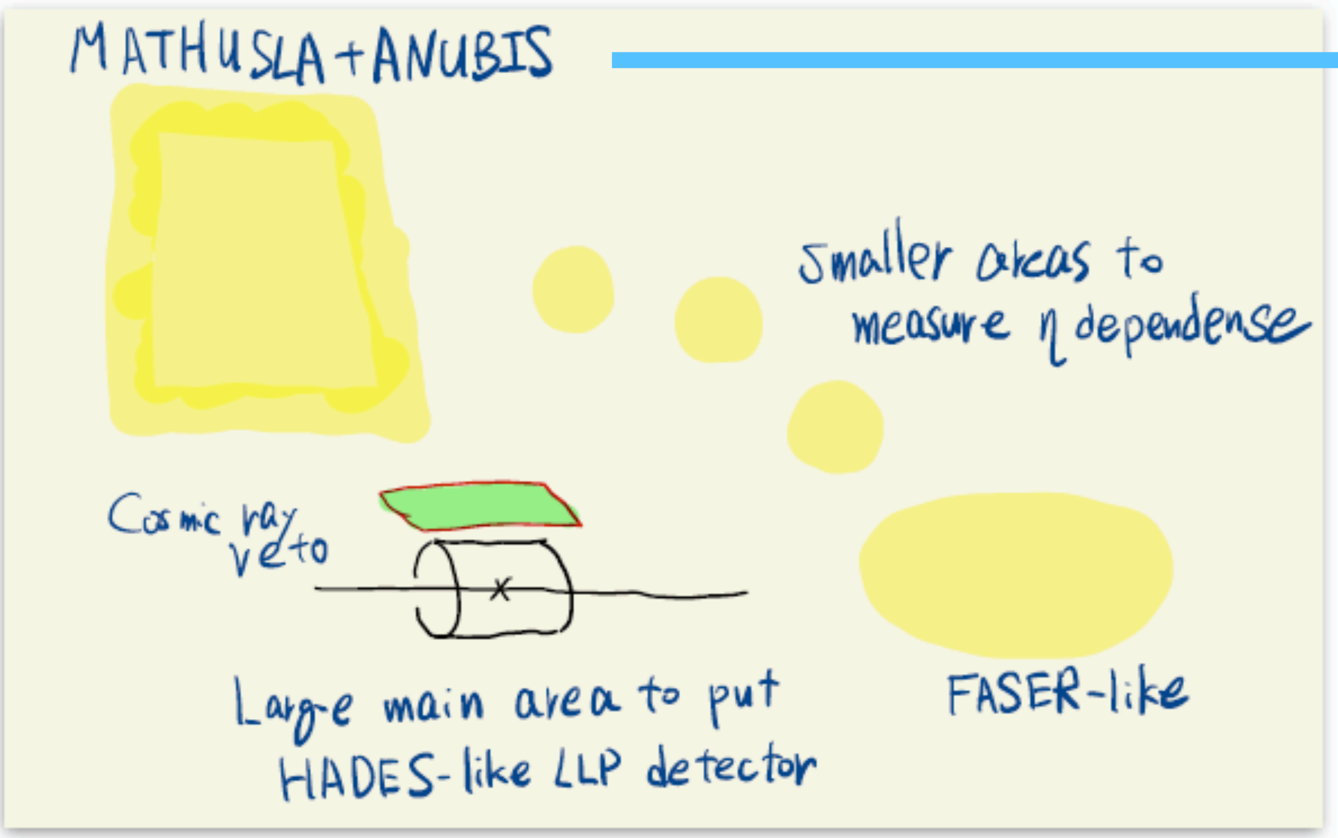
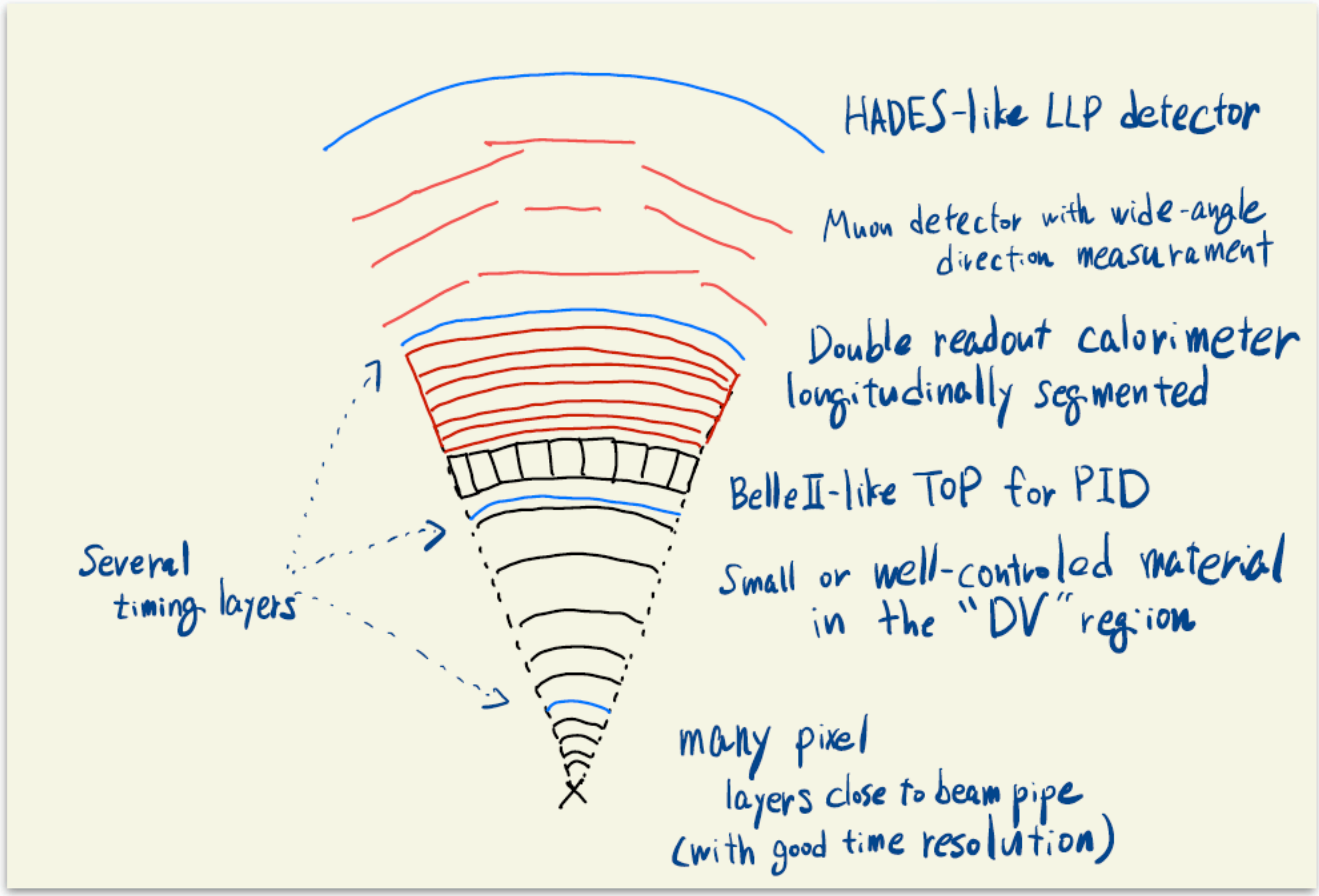
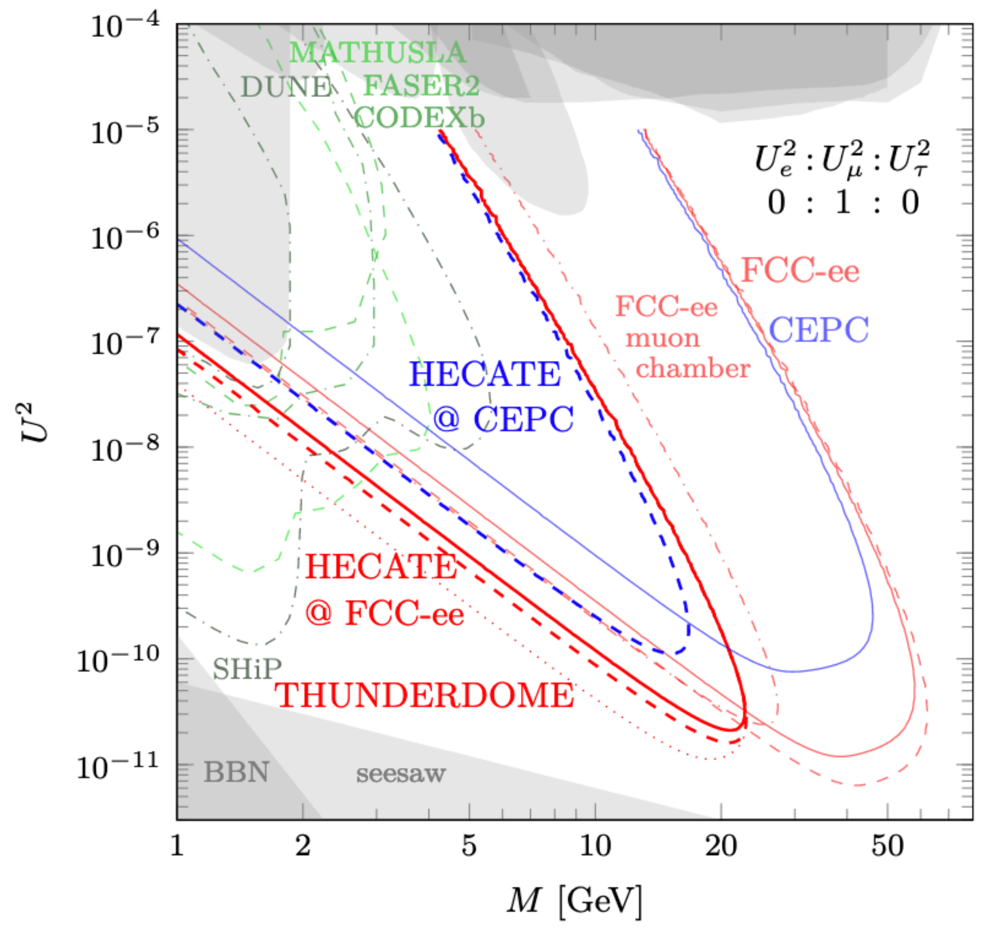
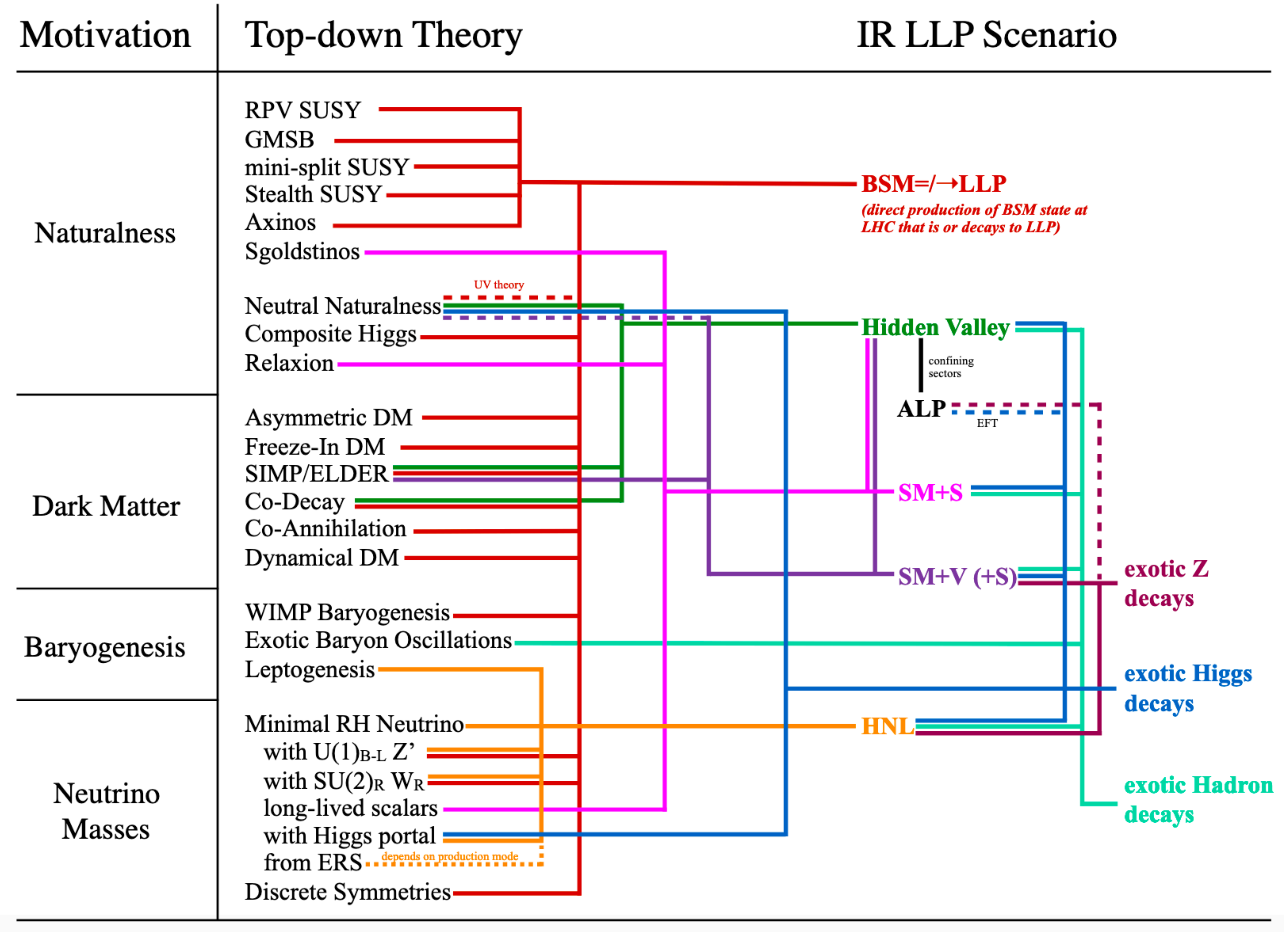






FCC-ee/CepC Mathusla-like concept
HECATE: arXiv:2011.01005

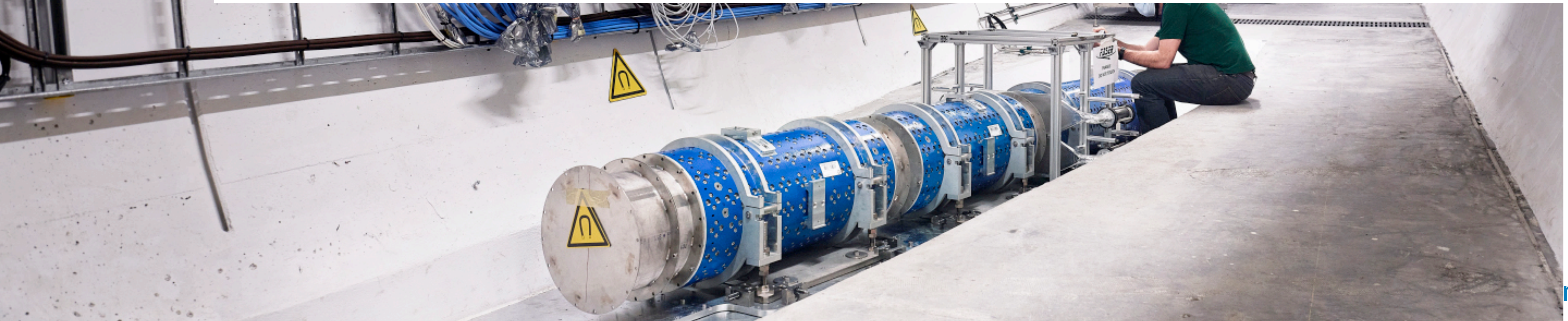
Can we incorporate LLP to the design of the future collider Experiments?

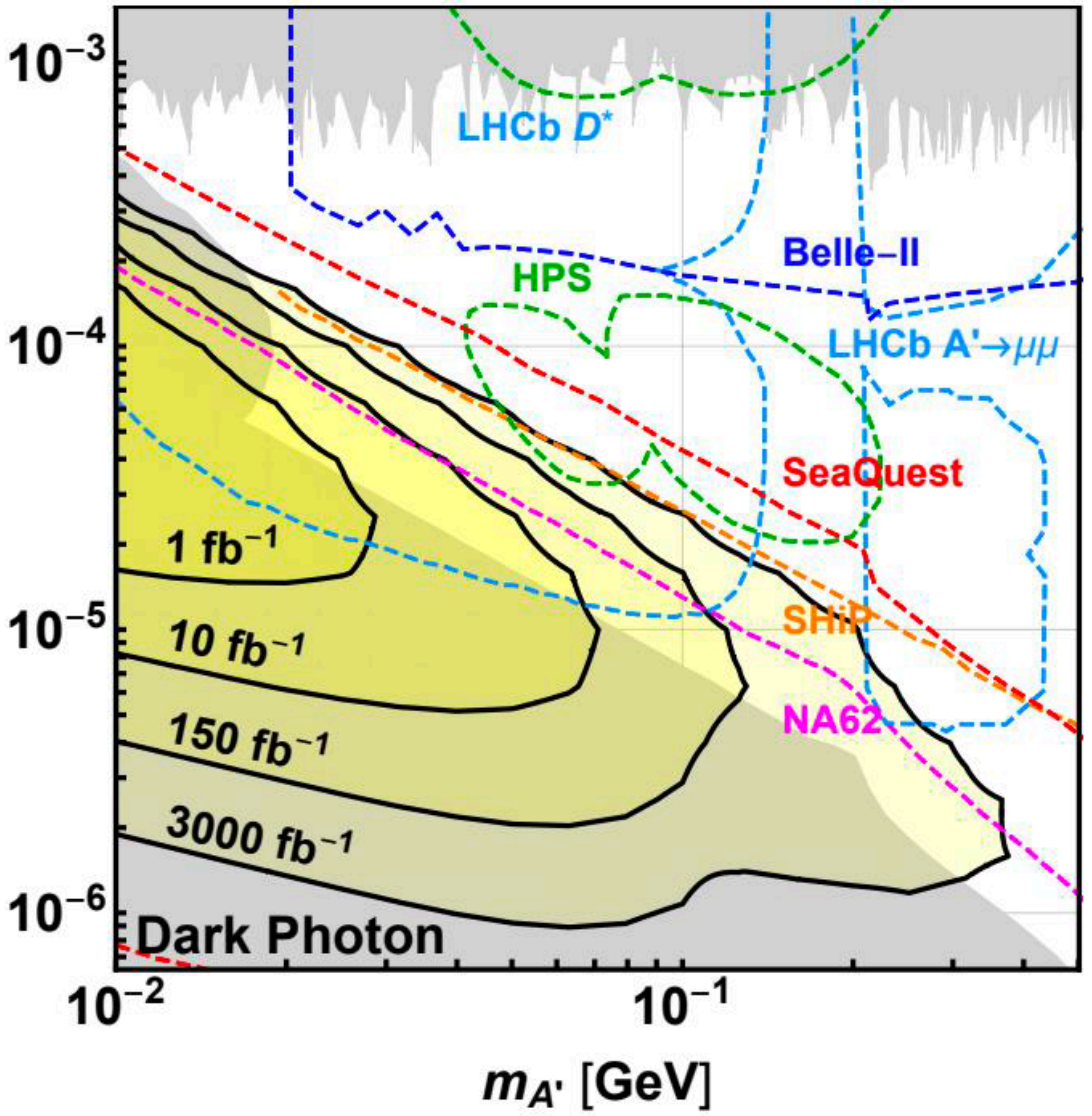


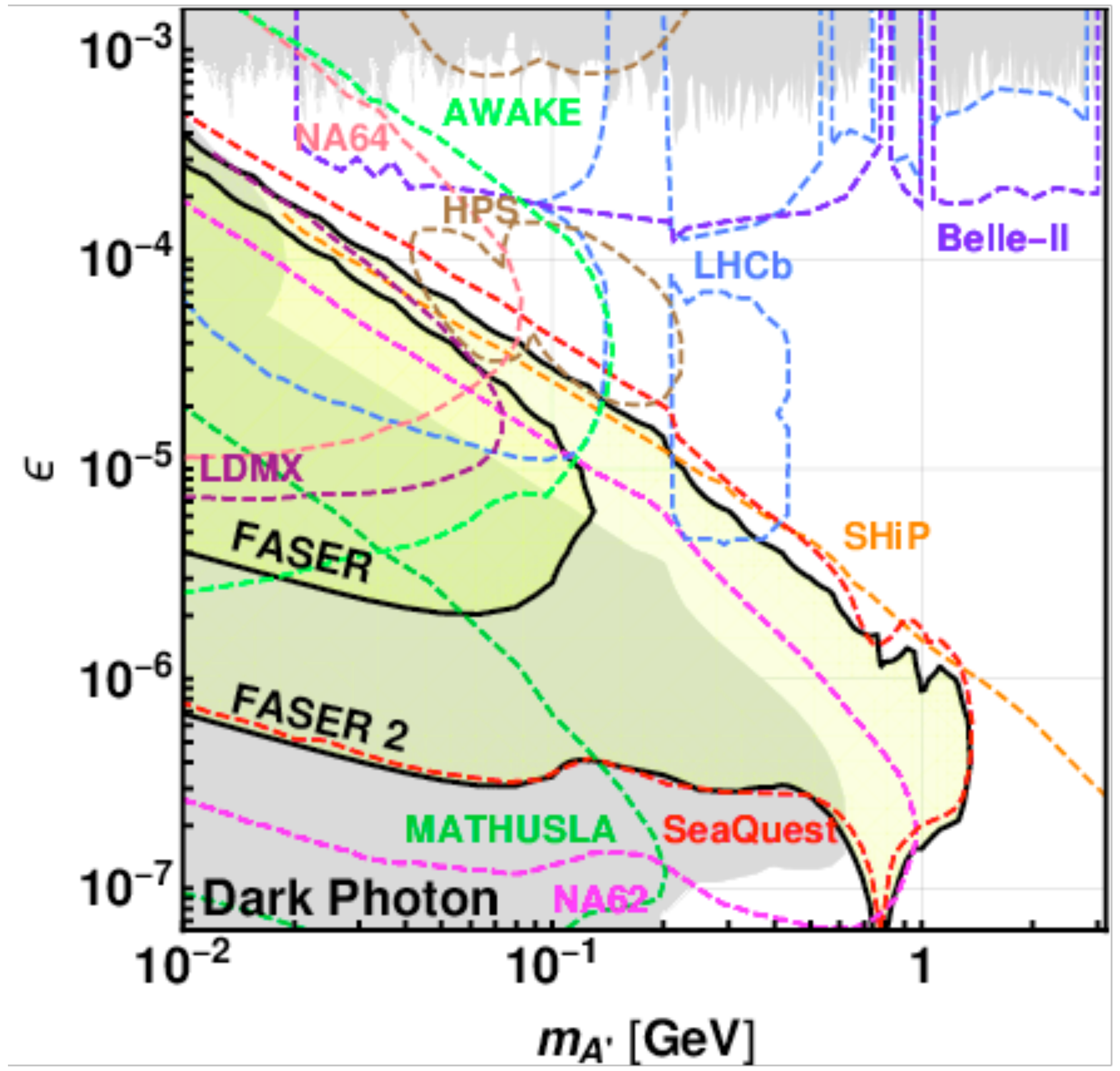
arXiv:1901.04040

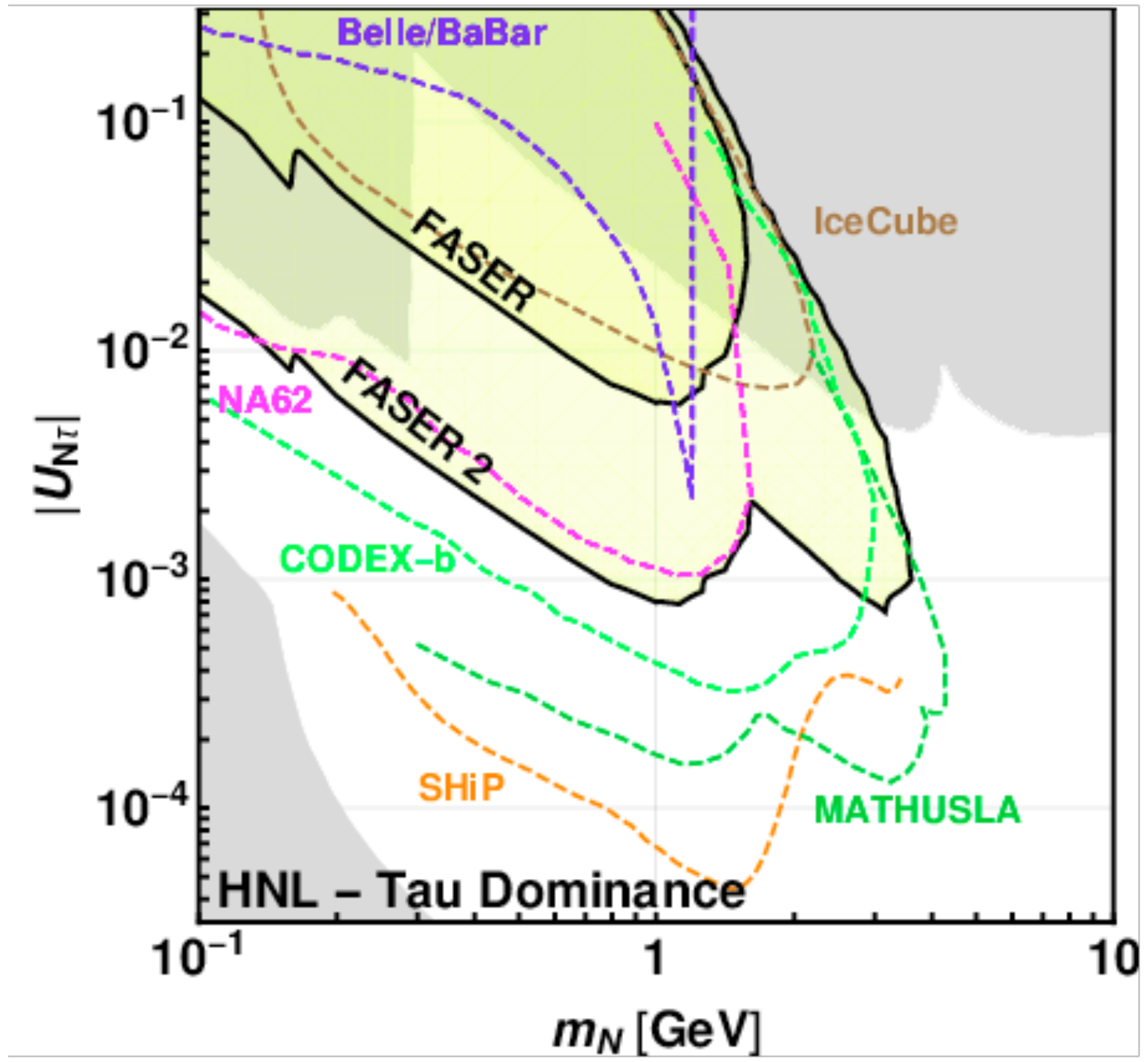
FASER

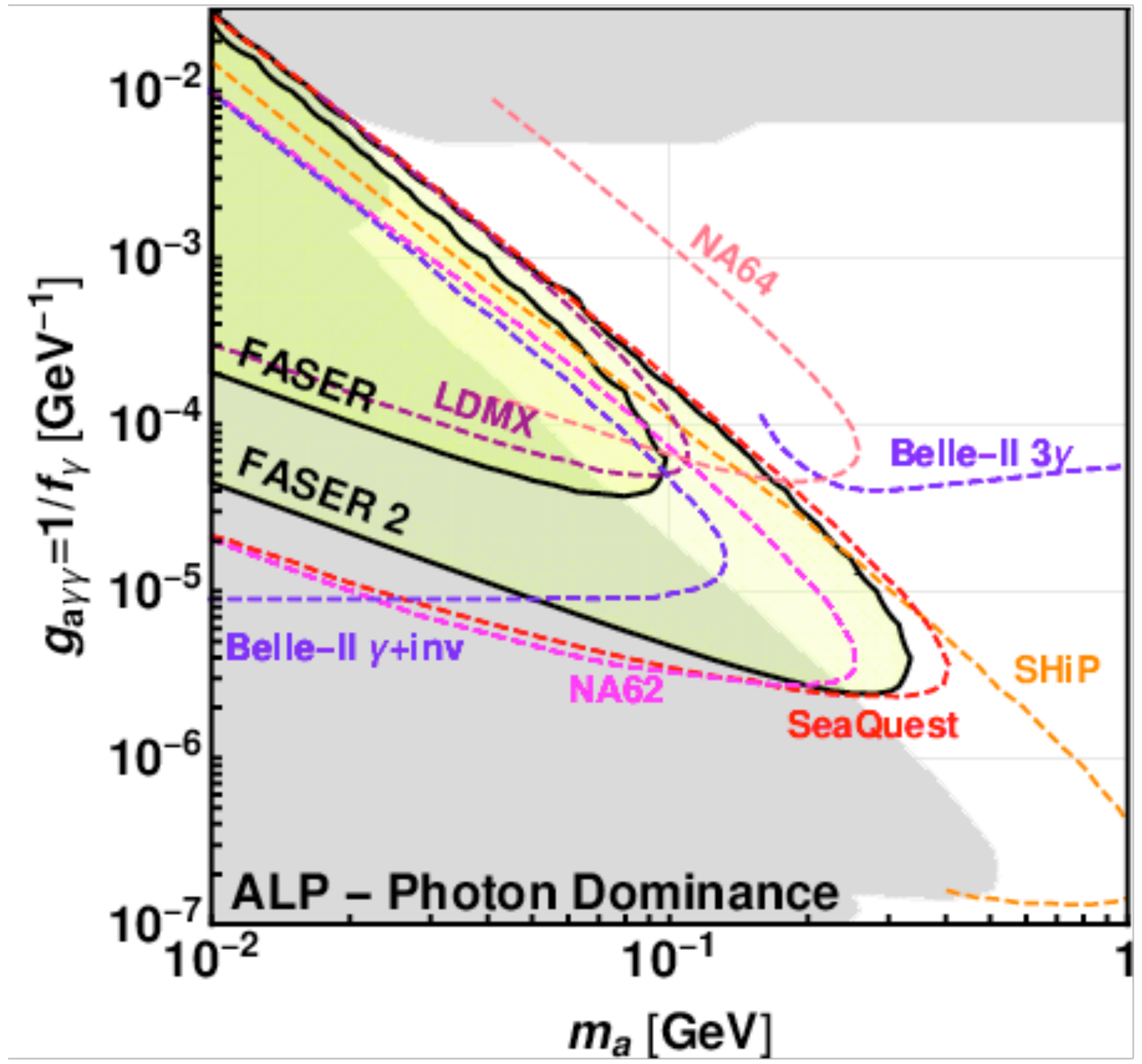
- ForwArd Search ExpeRiment, ~1 m^3 480 m downstream from the ATLAS interaction point (on-axis)
- https://faser.web.cern.ch/
- Approved in 2019, Installed during the Long Shutdown 2 - Taking data!
- Designed to detect LLPs produced at the ATLAS Interaction Point in the forward region
  - For highly collimated and extremely weakly coupled particles
  - decay products ~ TeV energies
- Sensitivity to dark photons, HNLs, ALPs …
  - pp → LLP + X,   LLP travels ~480 m,   LLP → charged tracks + X

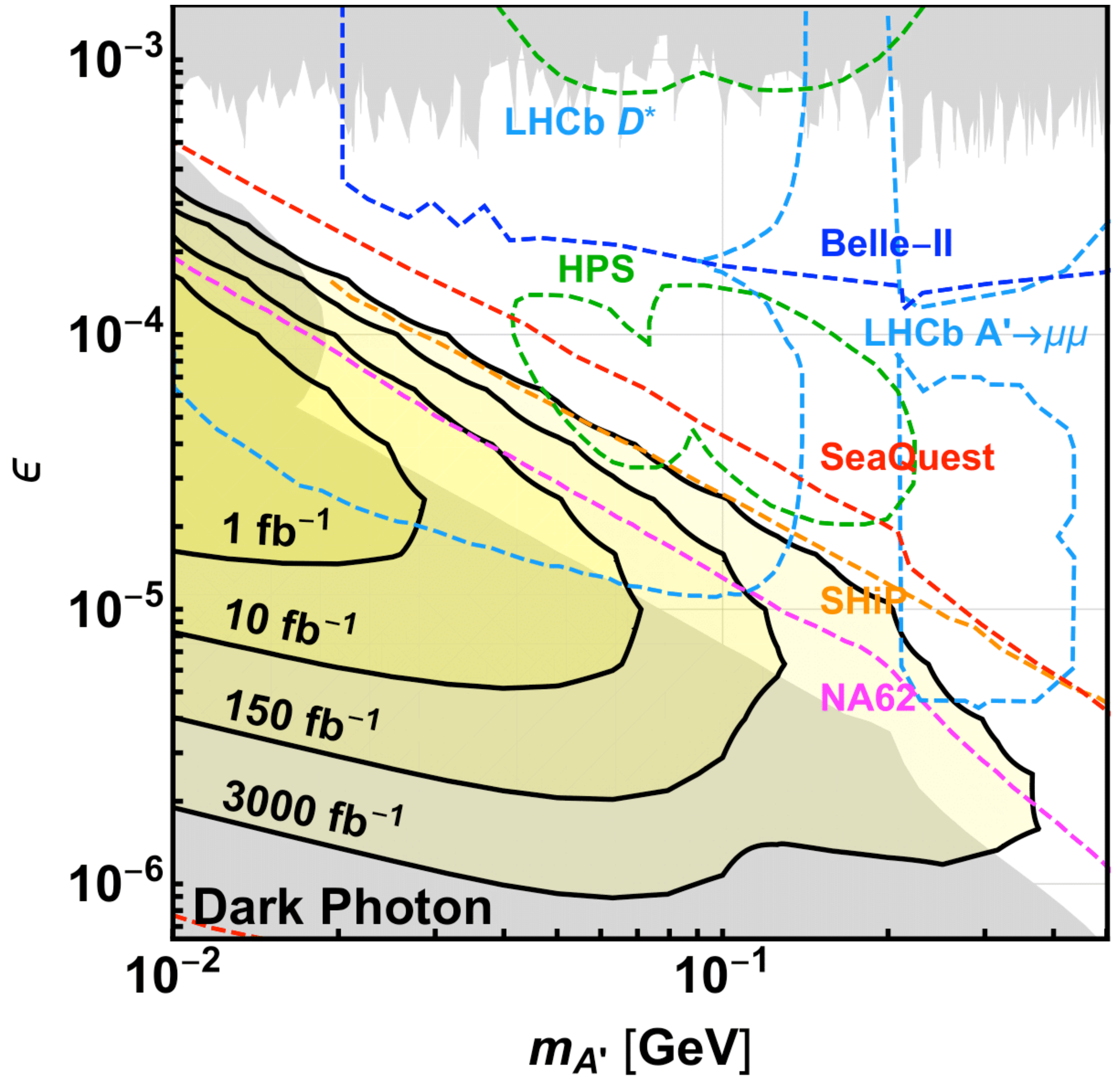






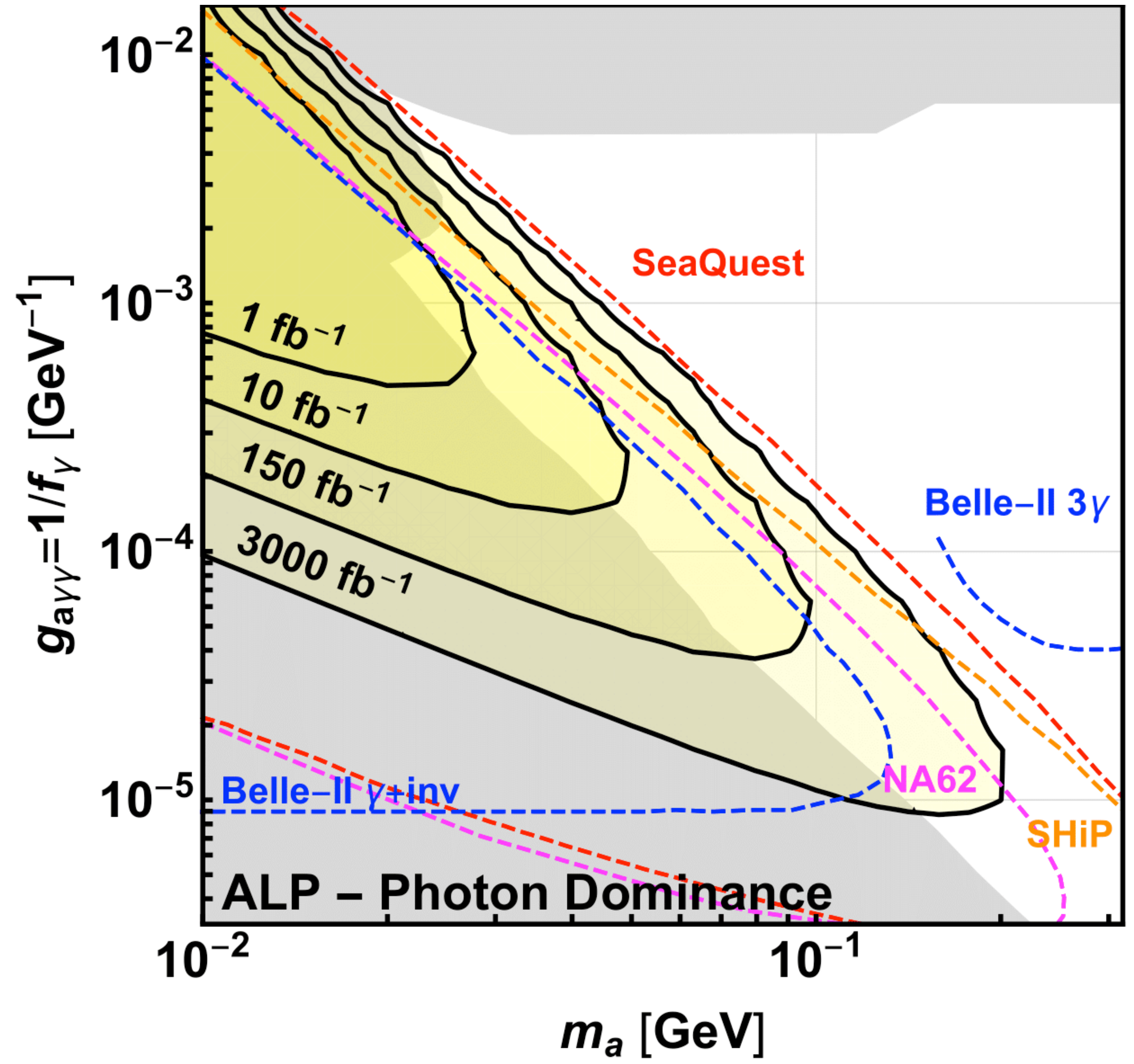






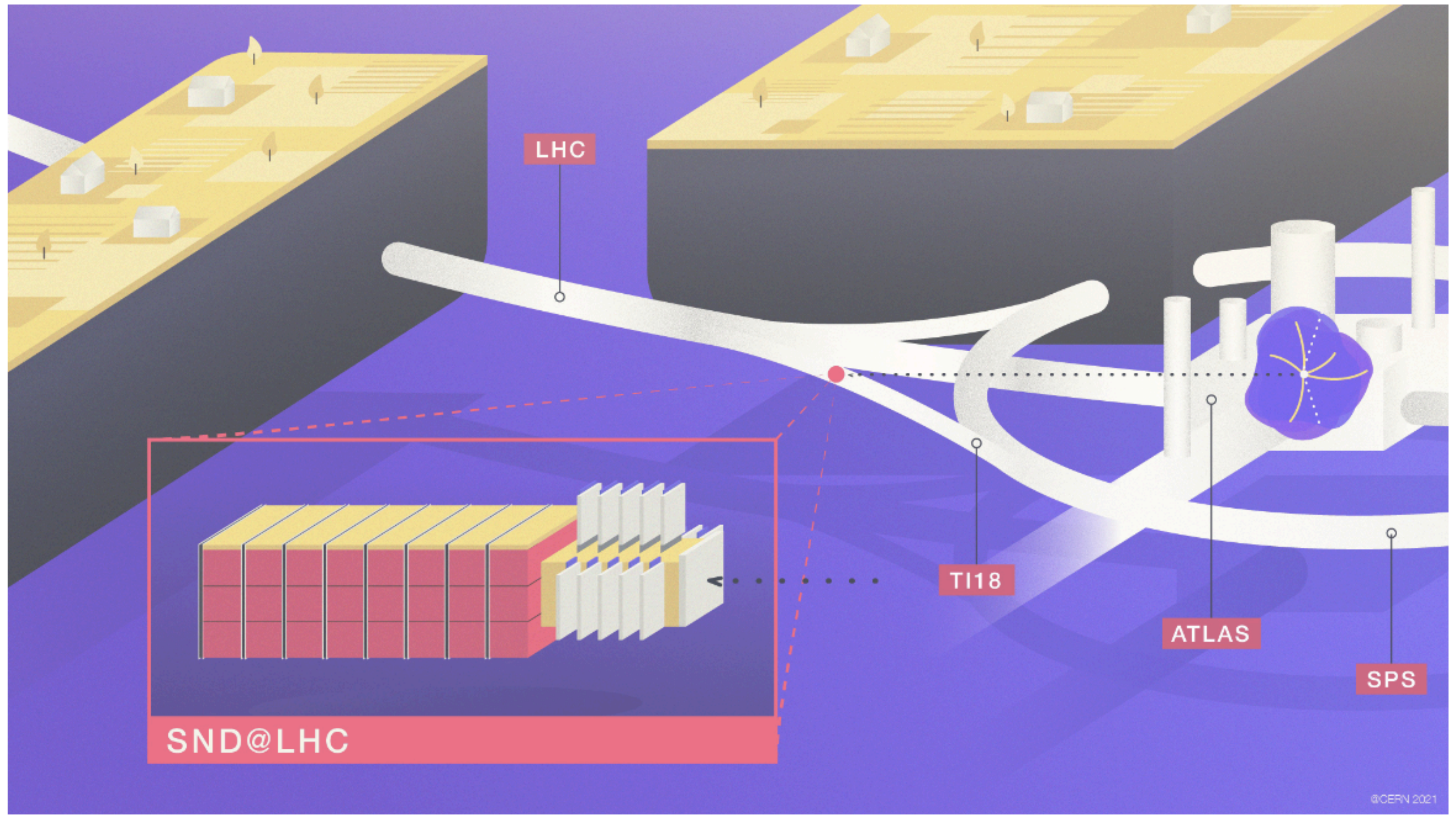
FASER:
radius R = 10 cm, length D = 1.5 m
luminosity L = 150 fb-1

FASER 2:
radius R = 1m, length D = 5 m
luminosity L = 3 ab-1

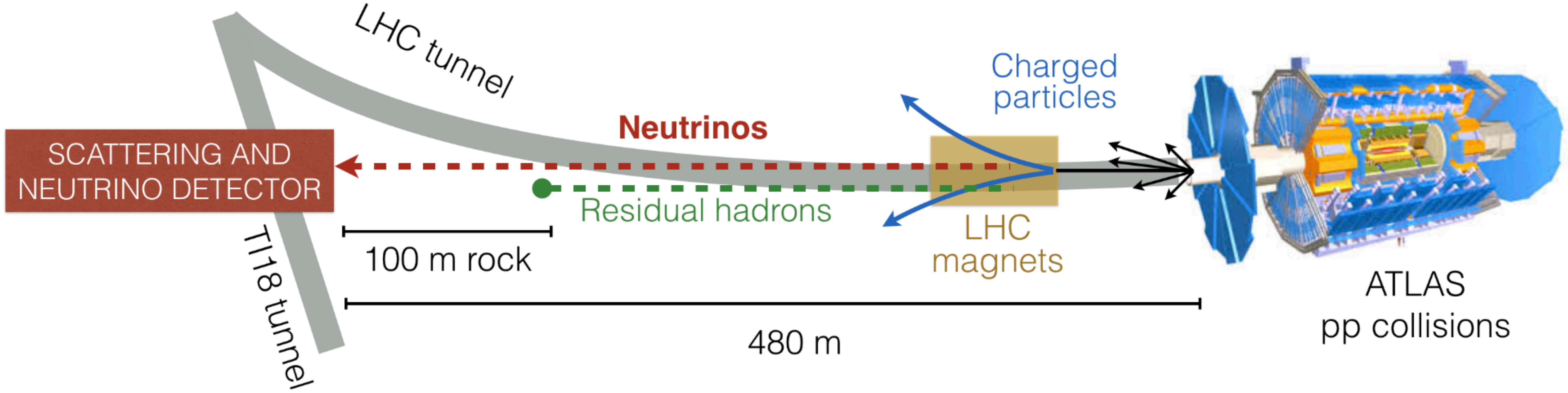


SND@LHC

- Neutrino experiment approved in 2021, installed, commissioned and taking data since the start of Run-3
- https://snd-lhc.web.cern.ch/
- 480 m from the ATLAS collision point (on the other side), 100 m of rock shielding
- Diverse neutrino physics program, can also probe LLPs in Hidden Sector models



LHC
Scattering and Neutrino Detector
at the LHC

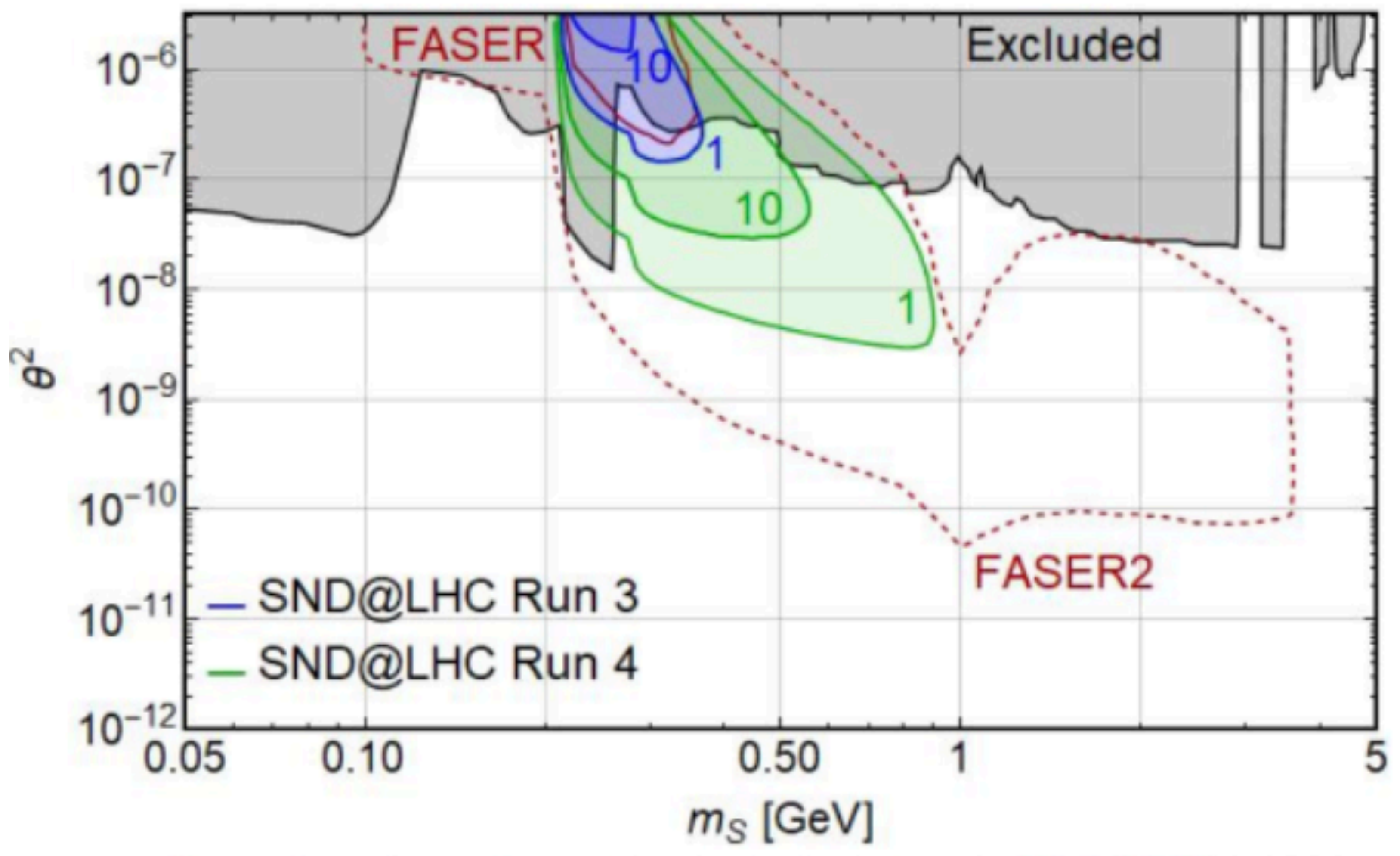


LHC

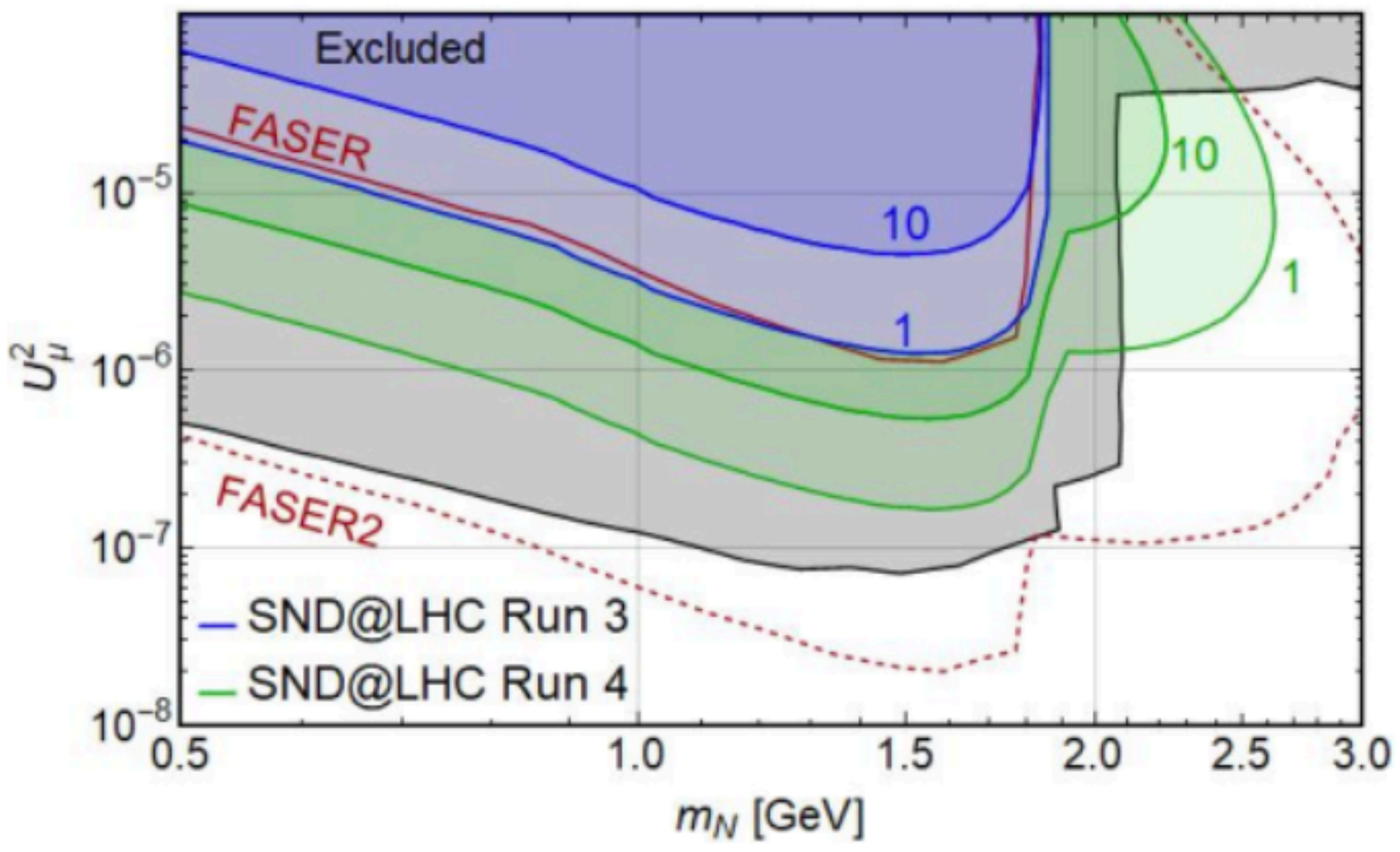
Scattering and Neutrino Detector
at the LHC

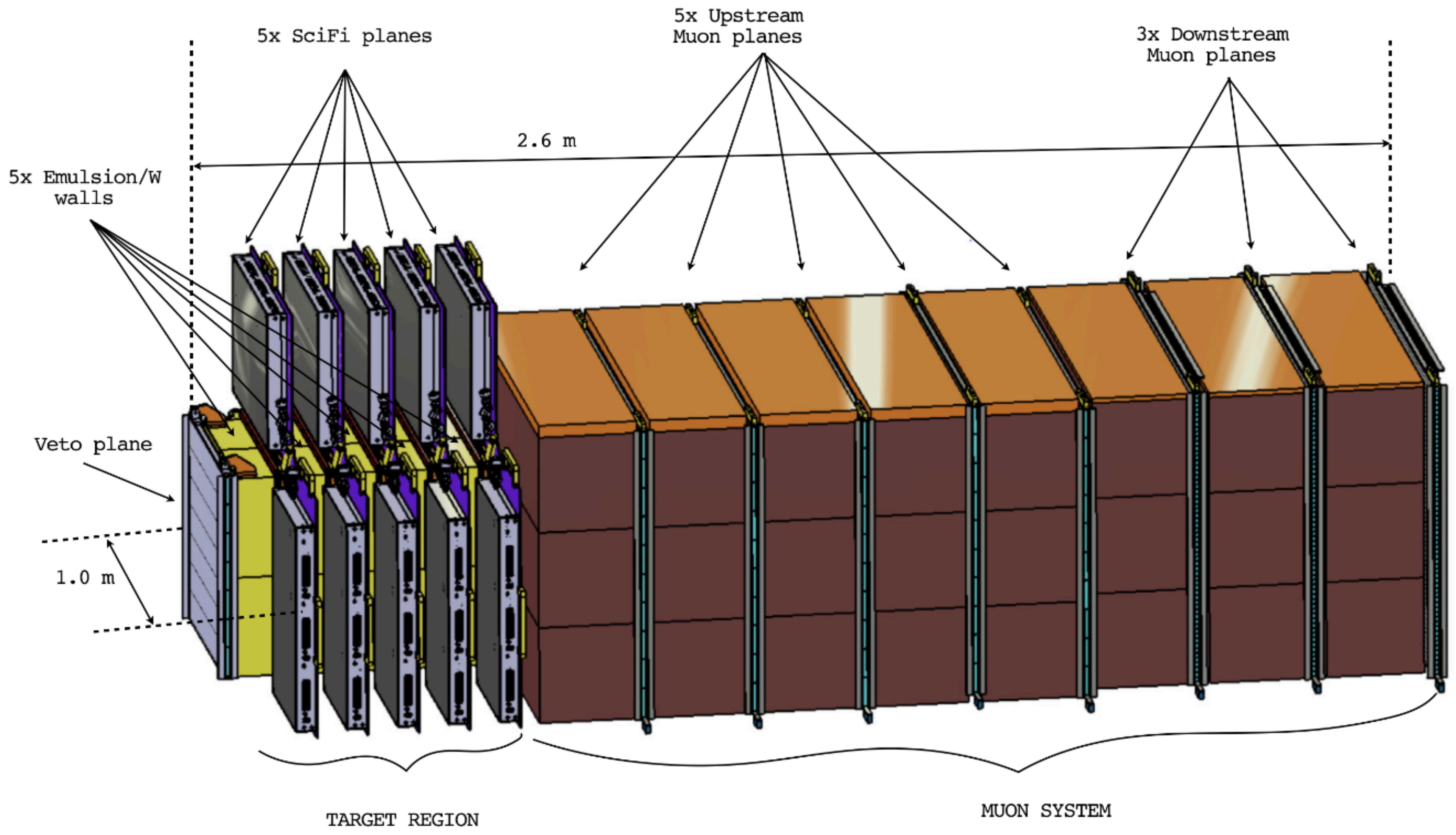
JHEP03(2022)006

Dark Scalar

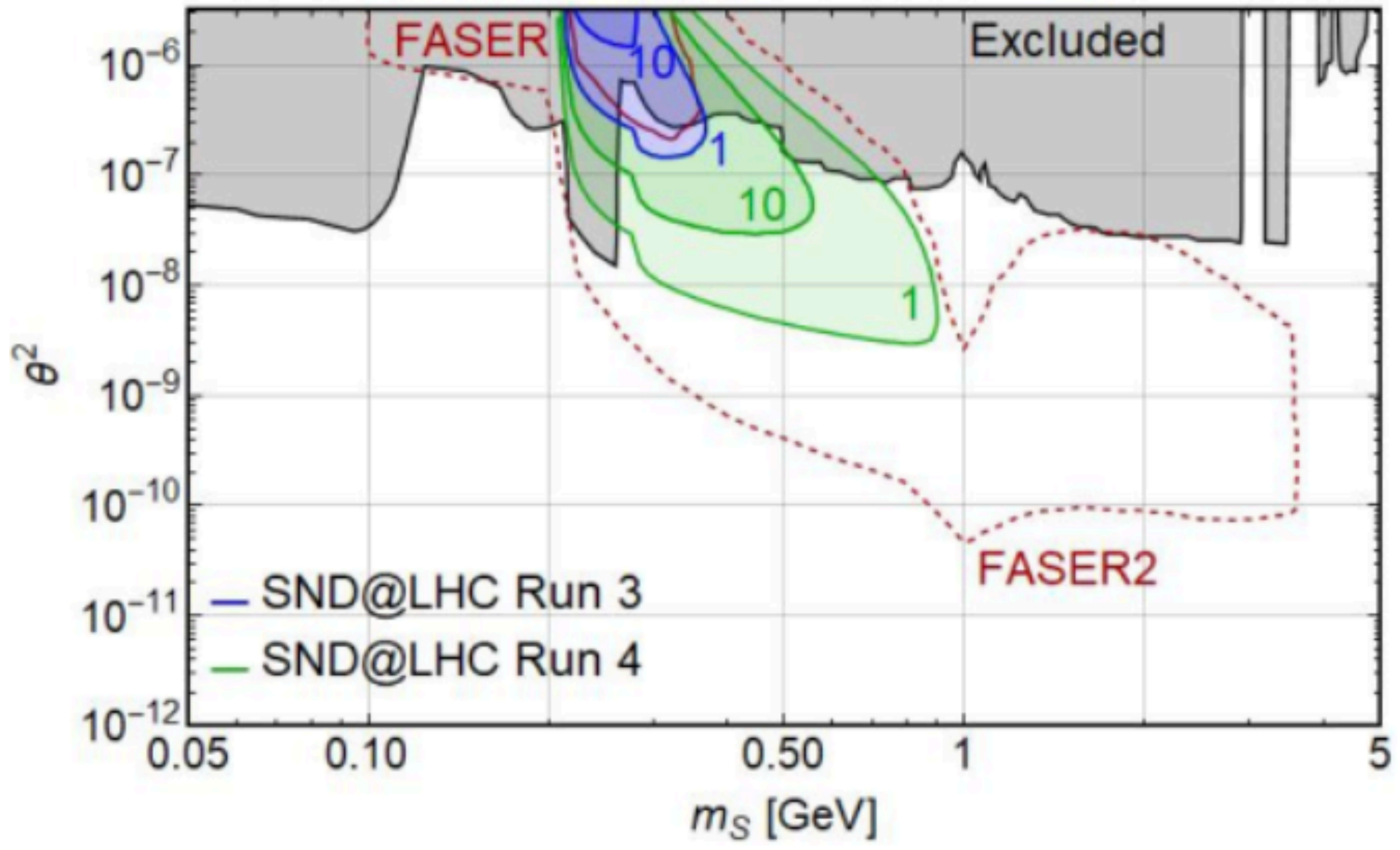


HNL



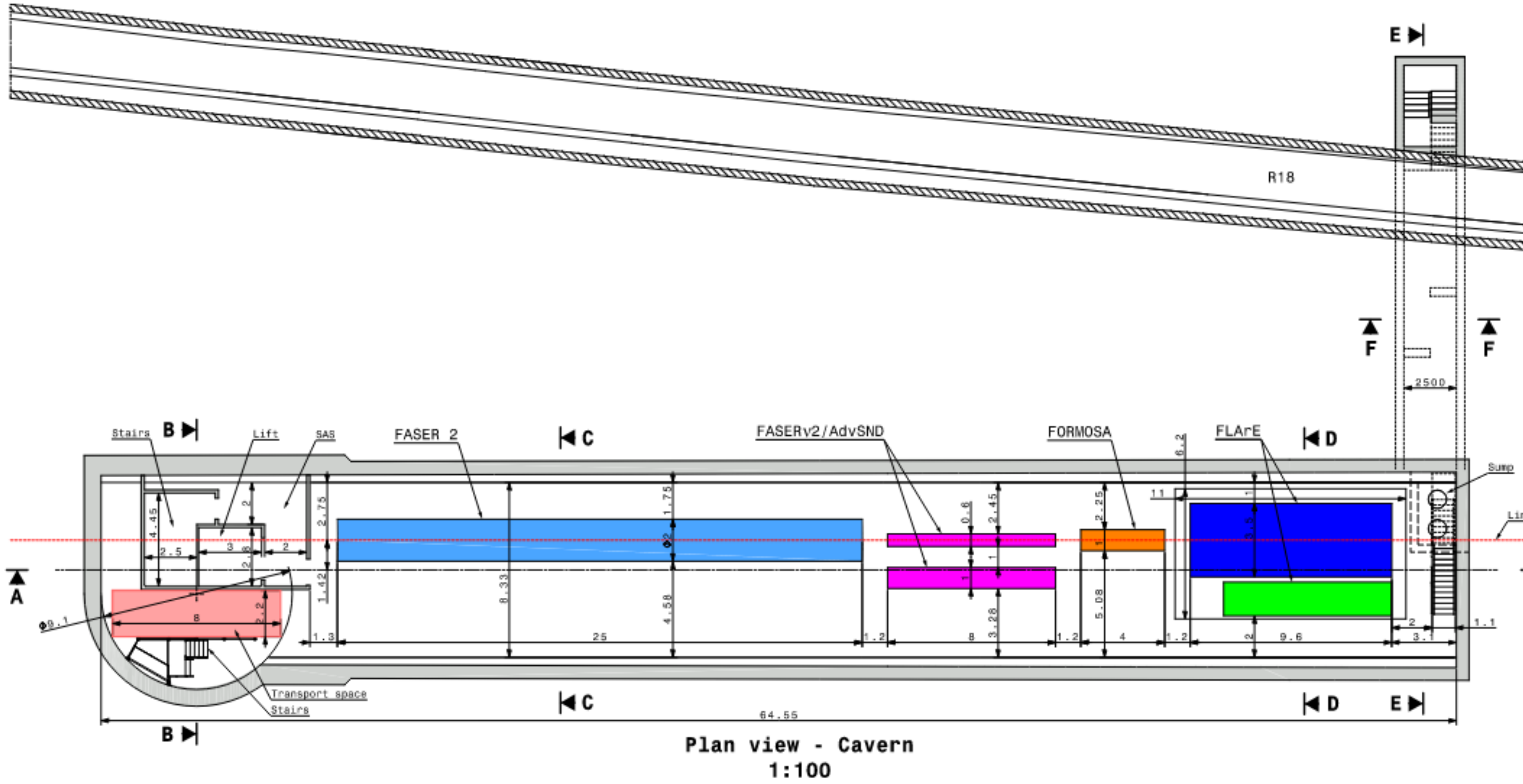


Dark Photon

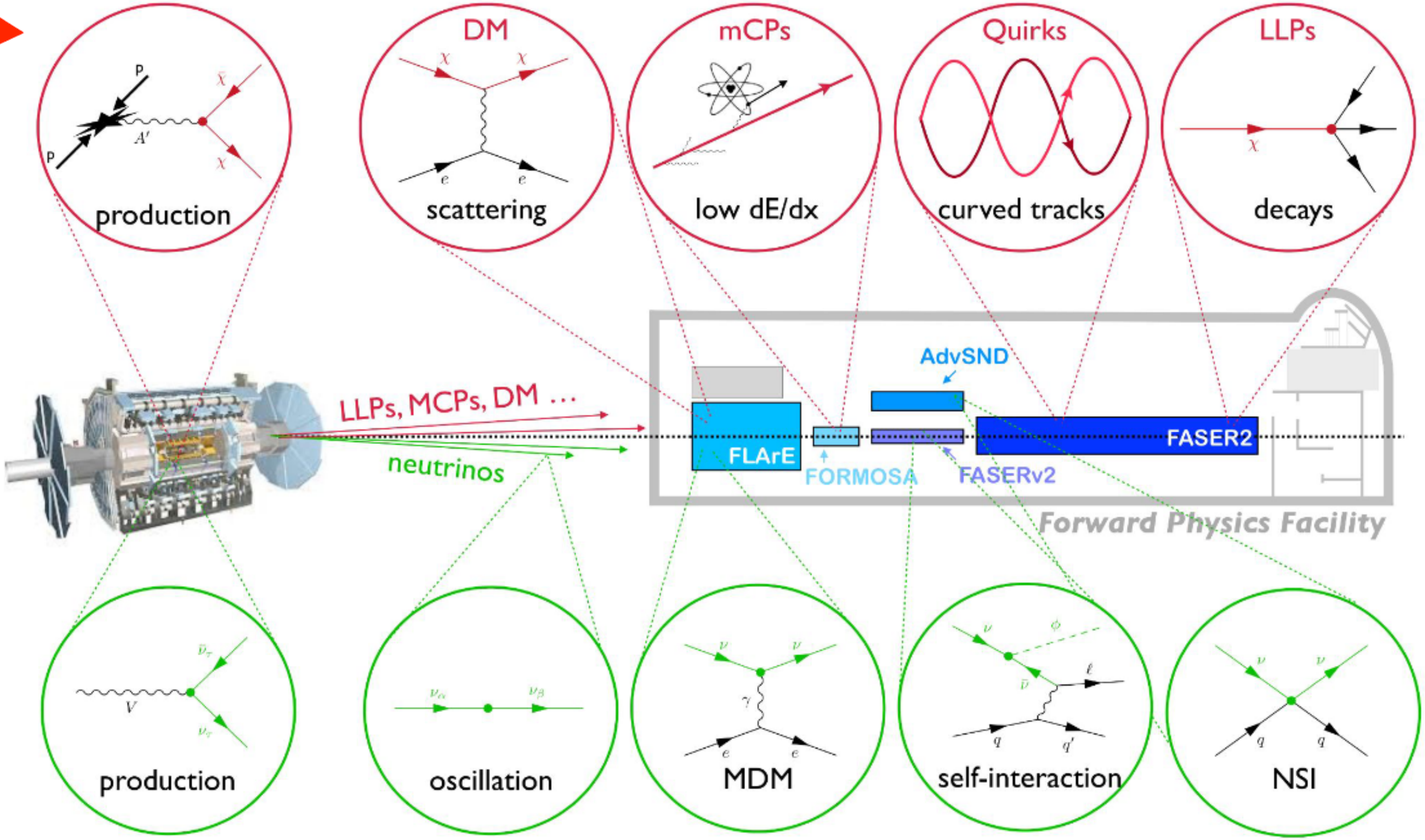


FPF

- FASER and SND@LHC: highly constrained by 1980's infrastructure that was never intended to support experiments
- Proposed dedicated Forward Physics Facility (FPF) for the HL-LHC

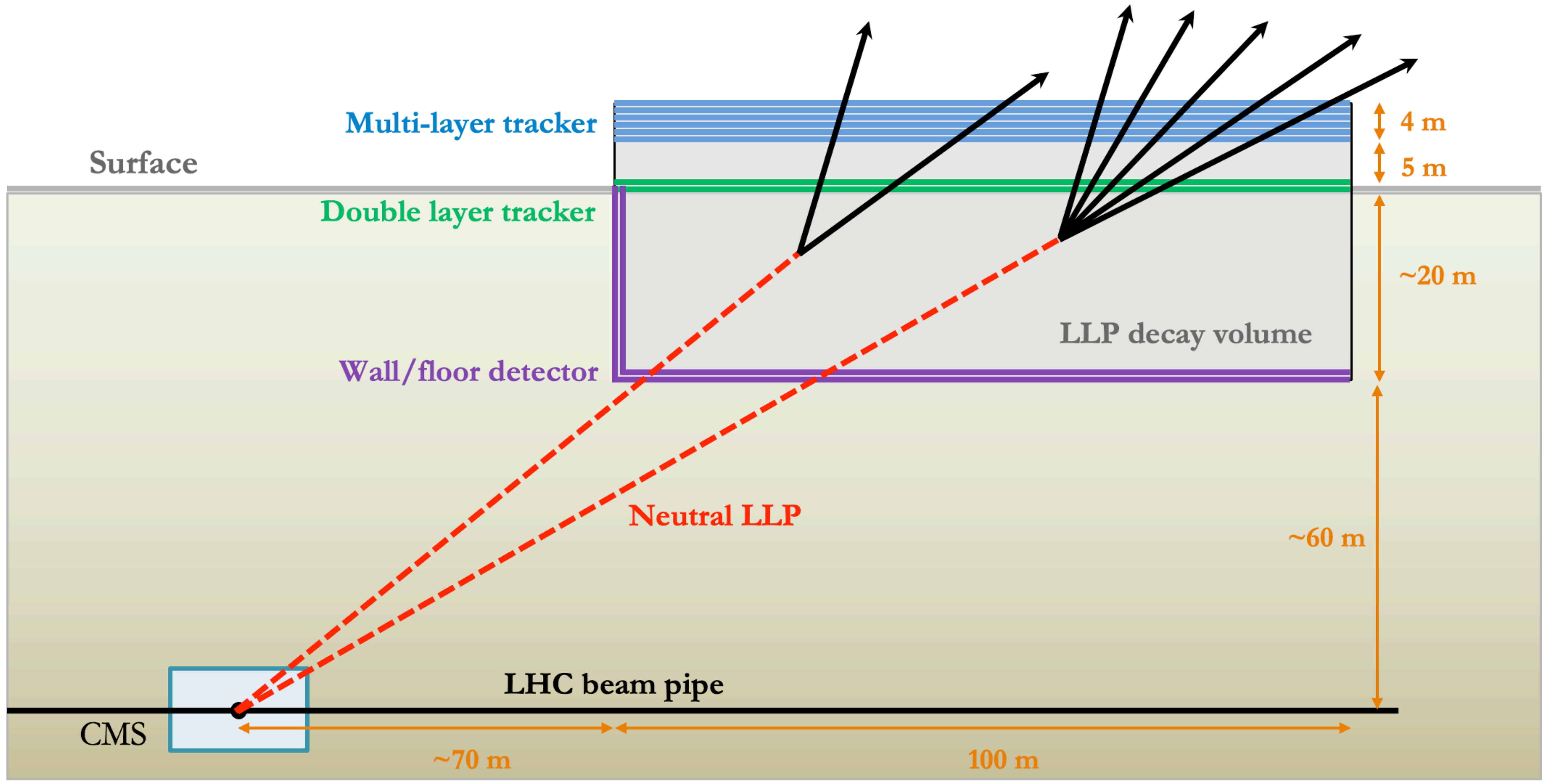


FPF Forward Physics Facility



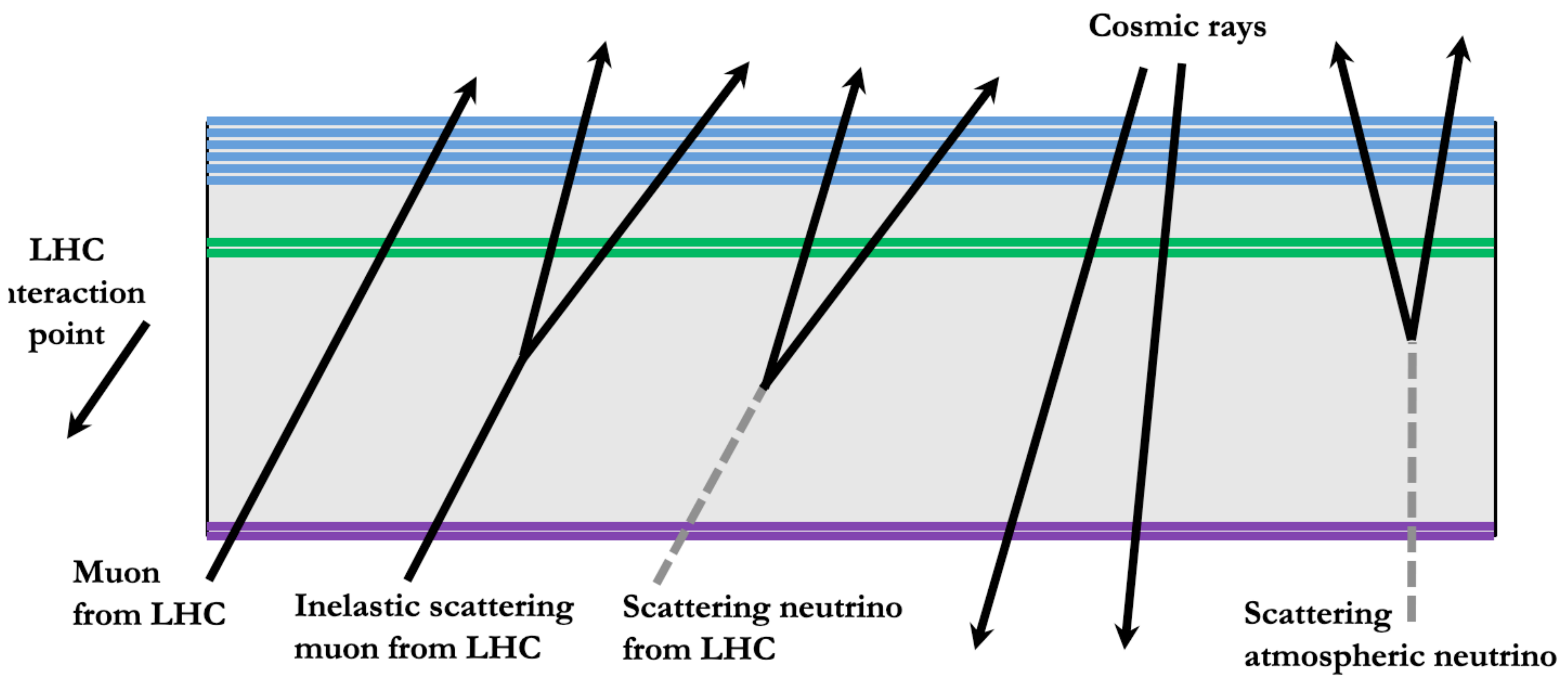
HL-LHC: Dedicated experiments

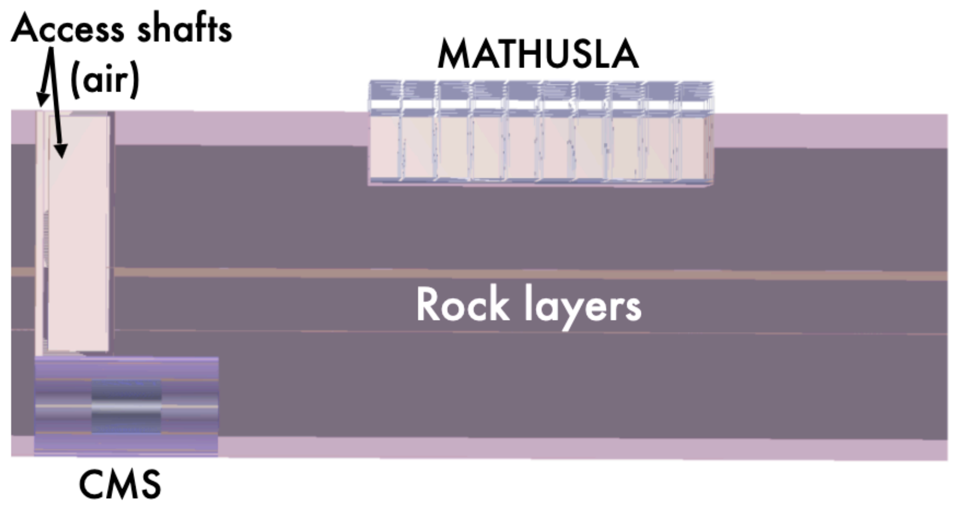
- MATHUSLA: (proposed) large-scale surface detector instrumenting ~$8\times10^5 m^3$ above ATLAS or CMS (off-axis) arXiv:2009.01693 website
  - Constructing a 64-channel, 4-layer prototype at University of Victoria
- CODEX-b: (proposed) ~$10^3 m^3$ detector in the LHCb cavern (off-axis) arXiv:2203.07316 git
  - Building of CODEX-β demonstrator unit ongoing.
- AL3X: (proposed) cylindrical~900 m^3 detector inside the L3 magnet and the time-projection chamber of the ALICE experiment (on-axis) arXiv:1810.03636
- ANUBIS: (proposed) 1×1 m^2 units on top of ATLAS/CMS (off-axis) arXiv:1909.13022 twiki
  - The proANUBIS prototype just been installed in the ATLAS experimental cavern
- FACET: (proposed) ~100m in front of CMS (on-axis). Large decay volume (50 m) arXiv:2201.00019



9 x 9 units, each with a 9 m x 9 m footprint, 30 m tall

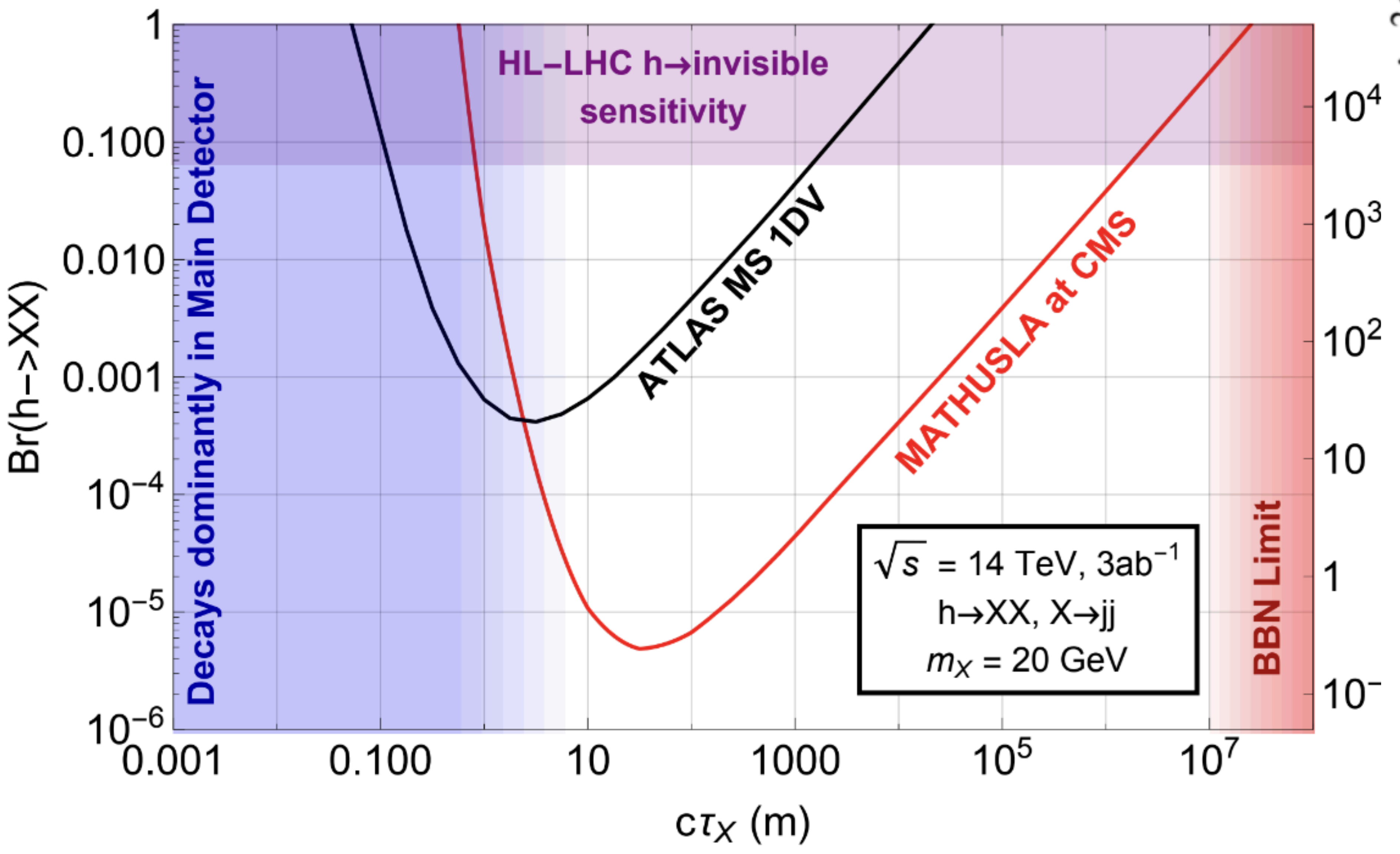
MATHUSLA (Massive Timing Hodoscope for Ultra Stable neutraL pArticles)

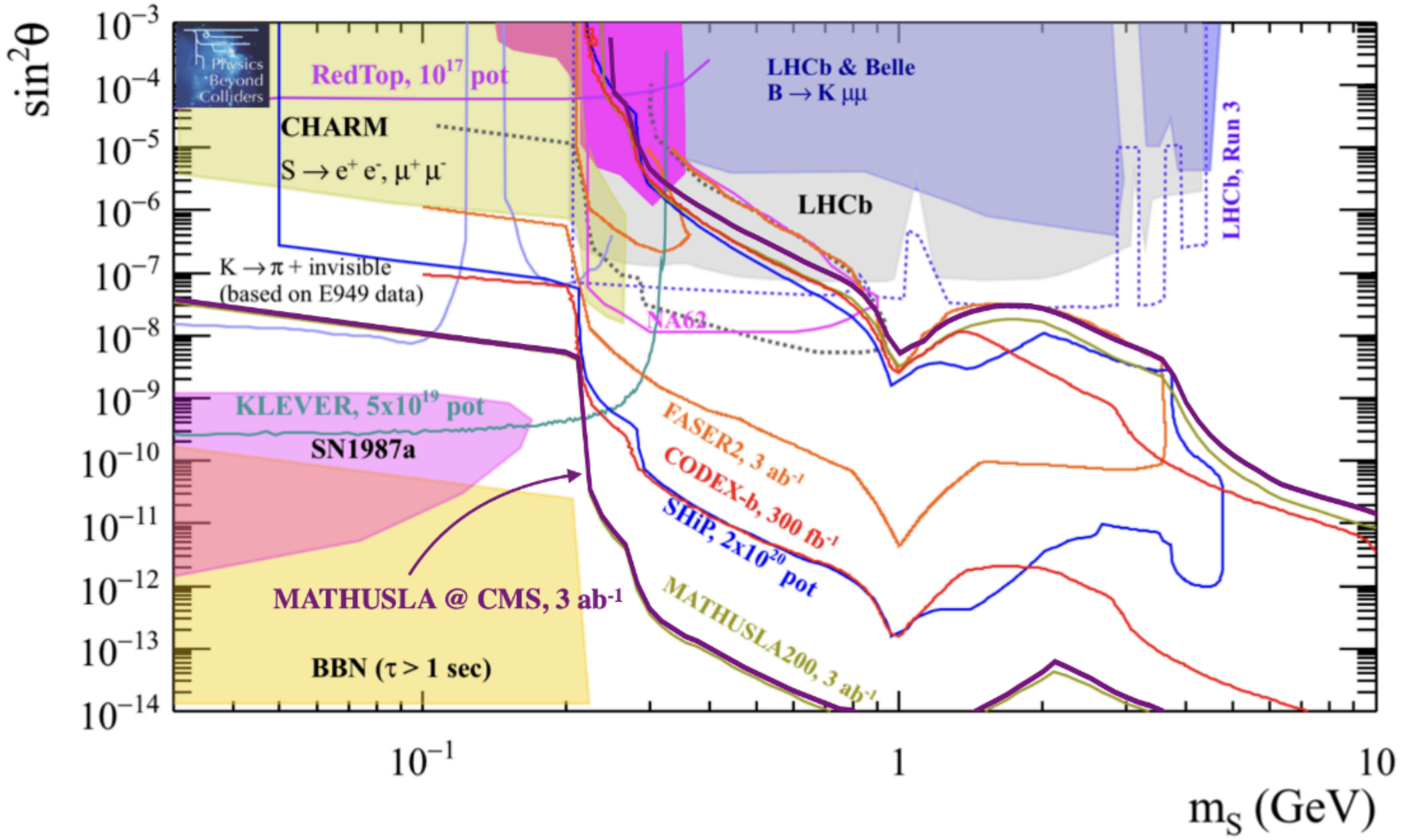




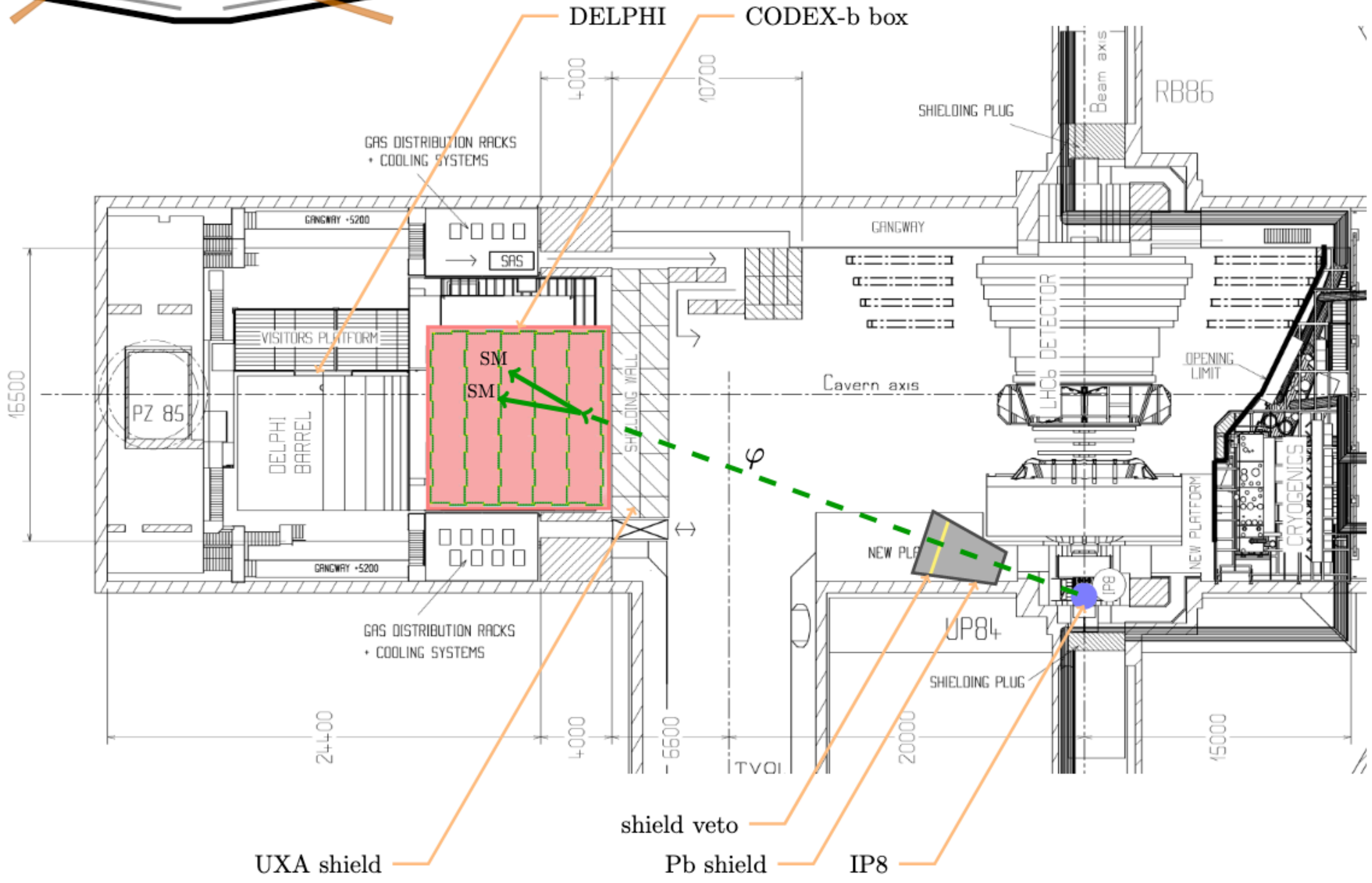
~1000x increased sensitivity compared ATLAS for Higgs neutral, hadronically-decaying LLPs

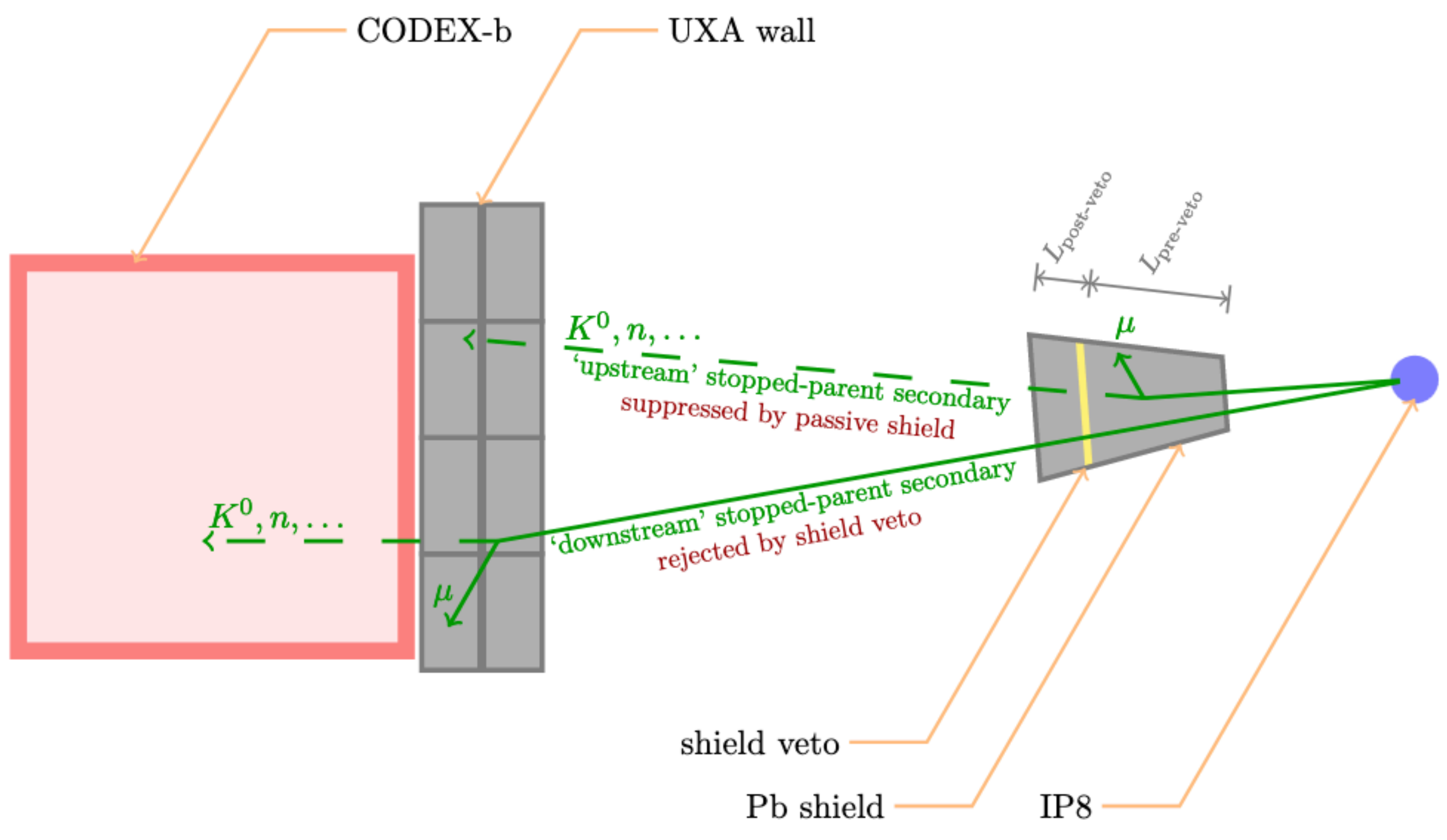
Sensitivity to small mixing angles for Singlet scalar s mixing with SM Higgs, BR(H → ss)

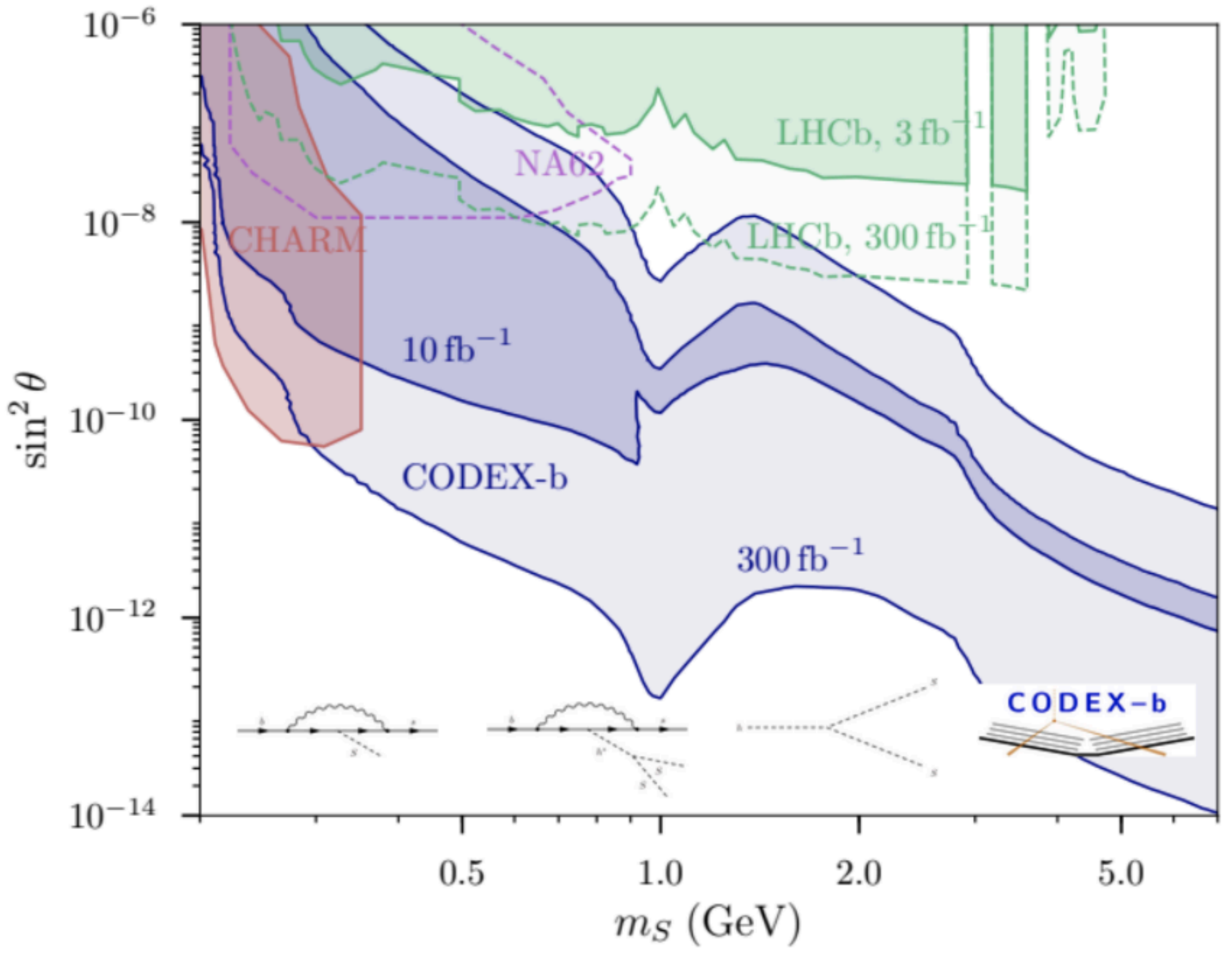




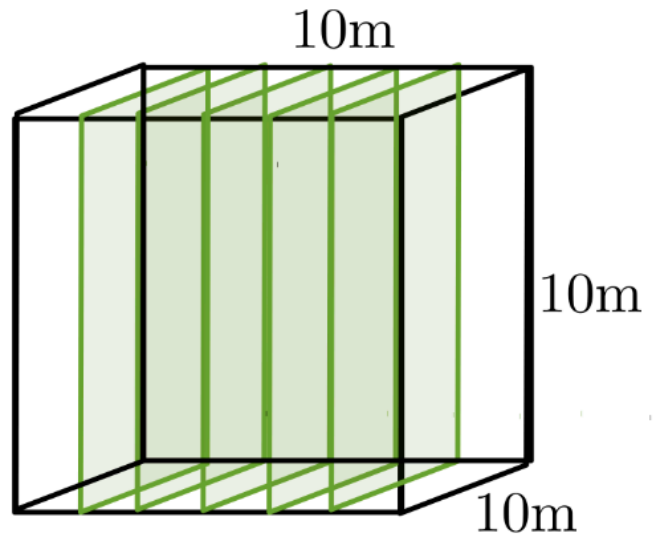
CODEX-b







$H^0 \to SS$, where S =Dark Scalar

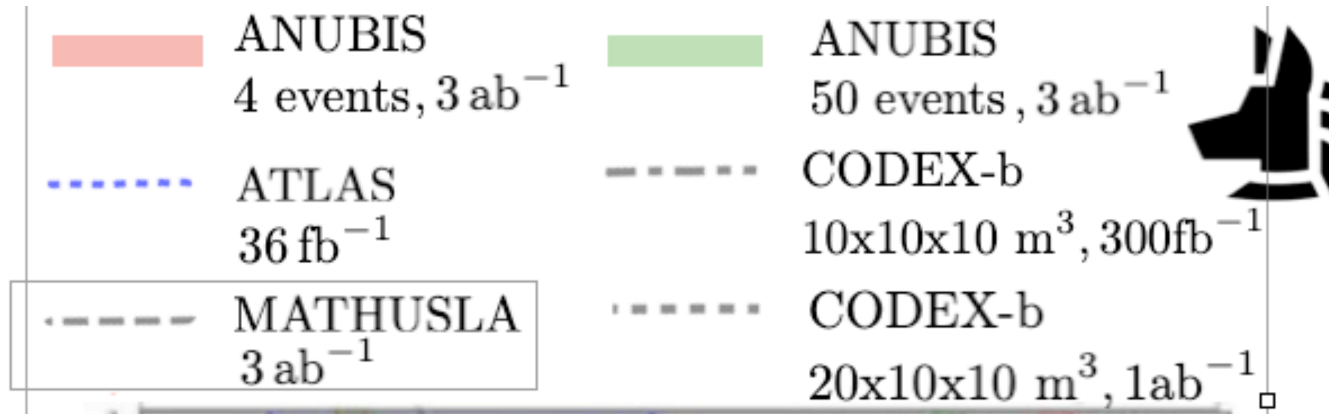


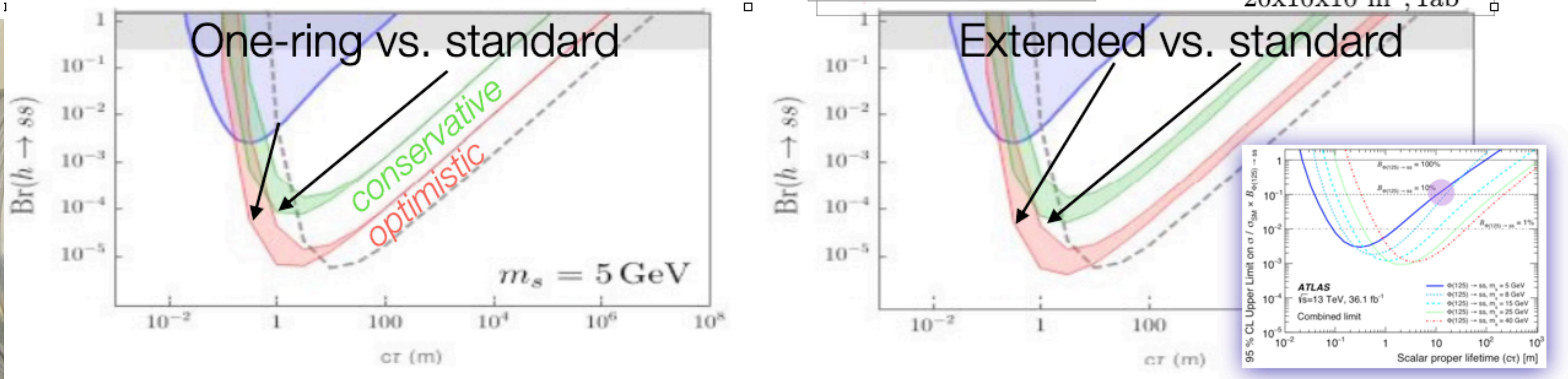
Complementary coverage of LLP parameter space.
Sensitivity to NP with heavy intermediates e.g. Higgs

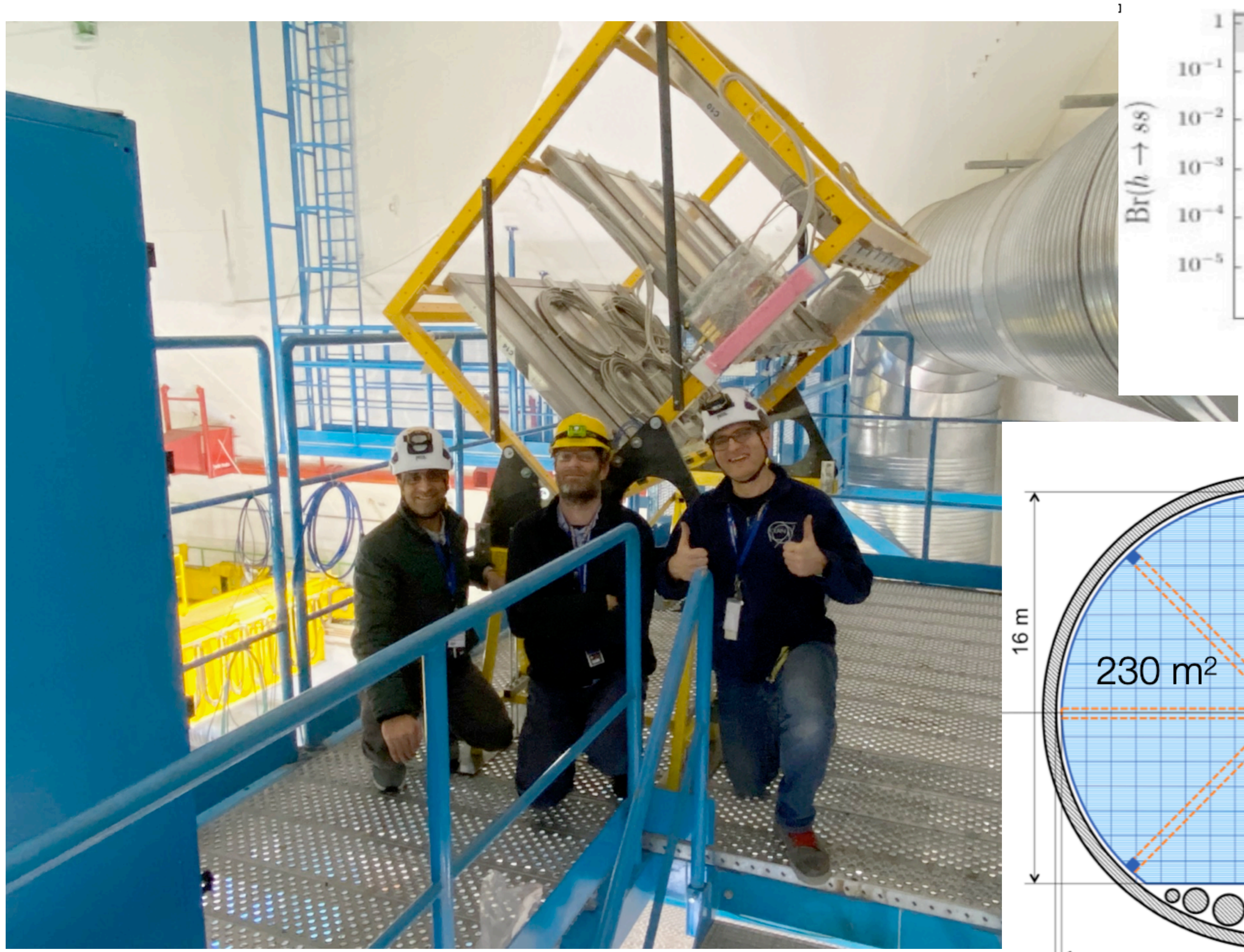
ANUBIS

ANUBIS: sensitivity

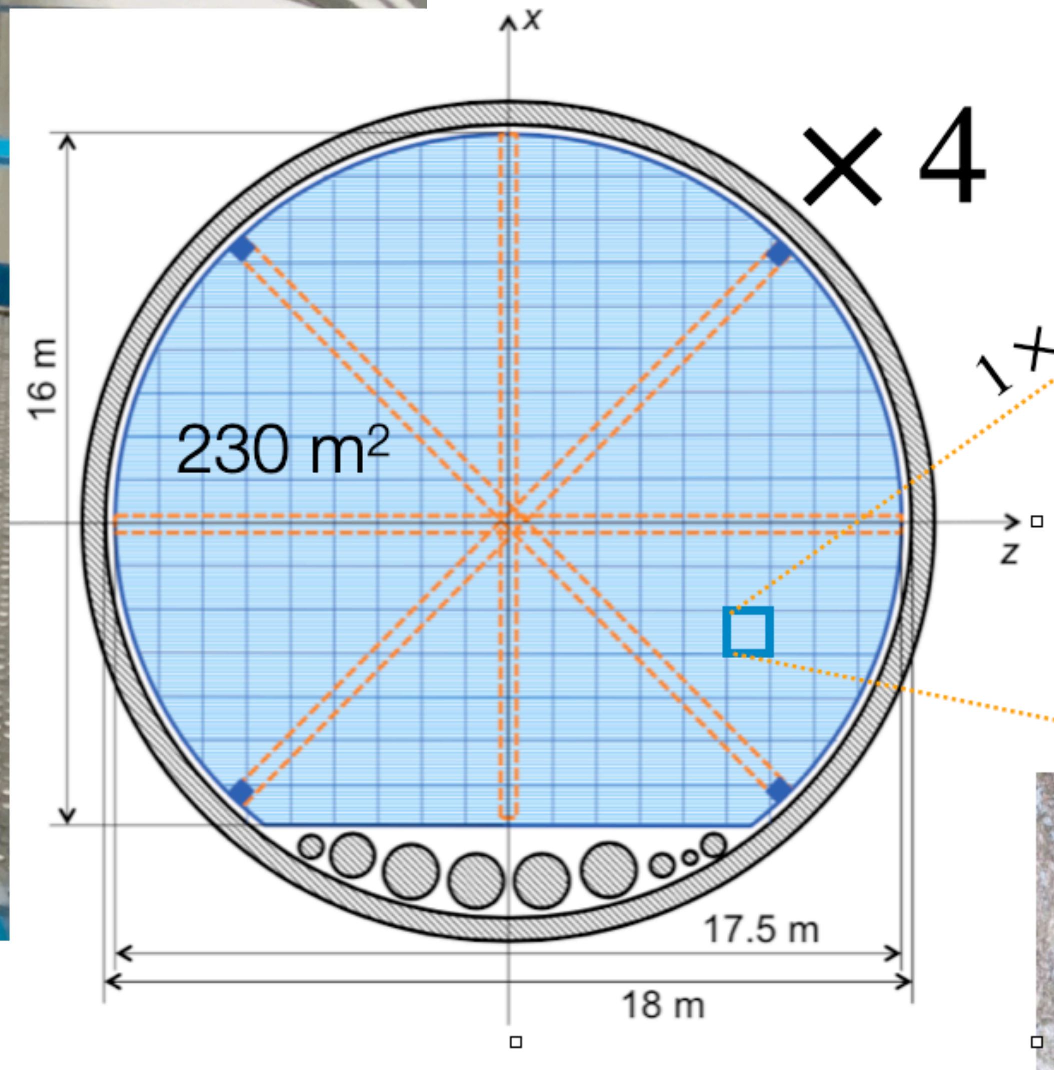
200 x 200 x 20 m³ decay volume →



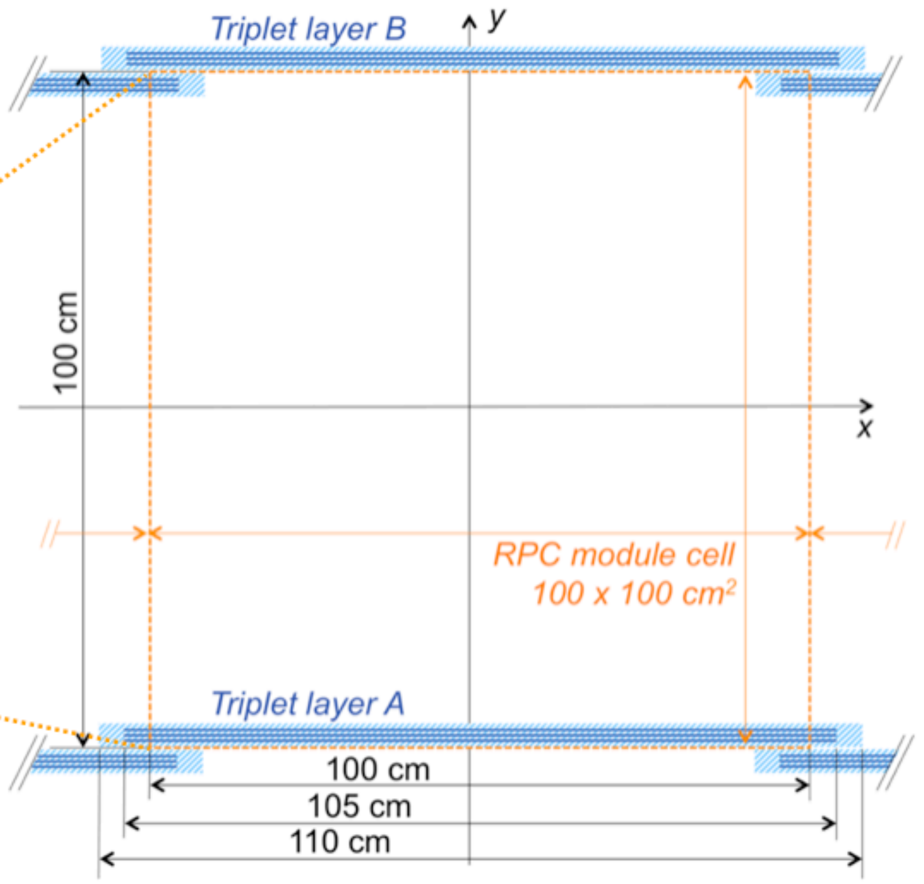




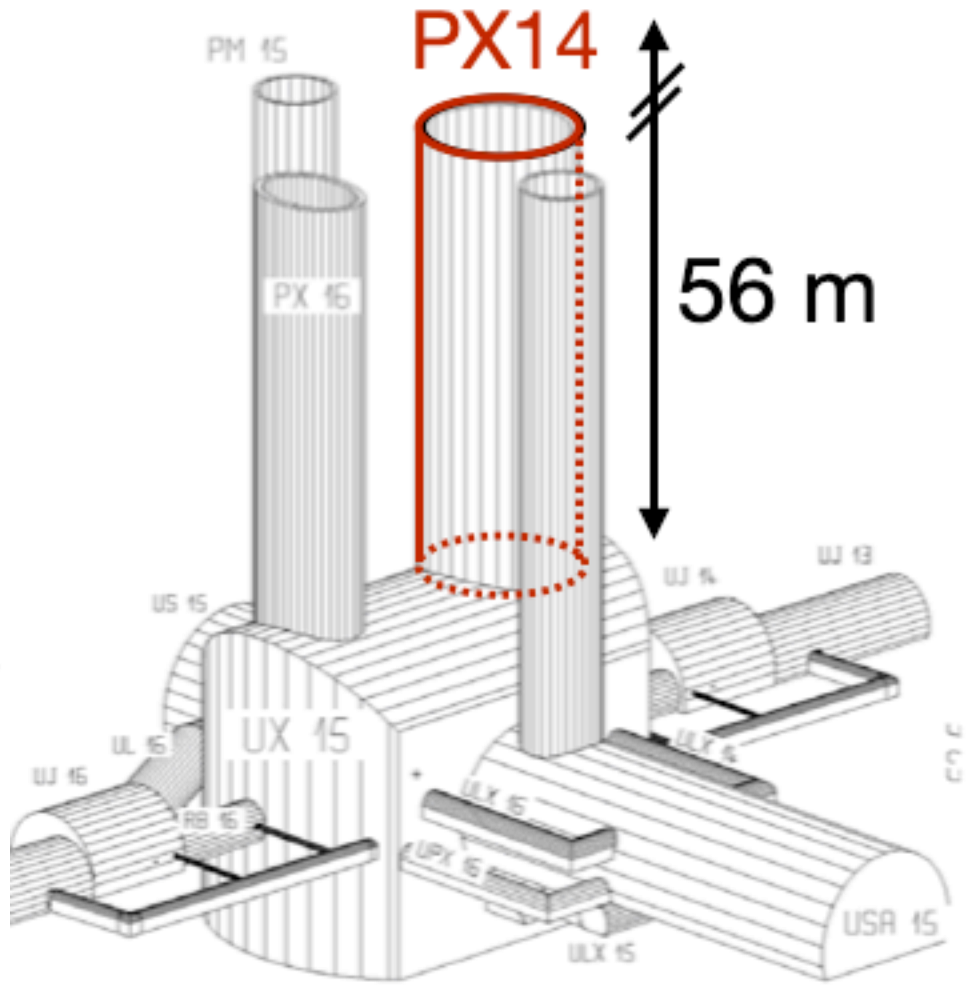
ANUBIS improves the LHC sensitivity by 2-3 orders of magnitude at large decay lengths > 10 m for electrically neutral LLPs with masses > 1 GeV for relatively low cost



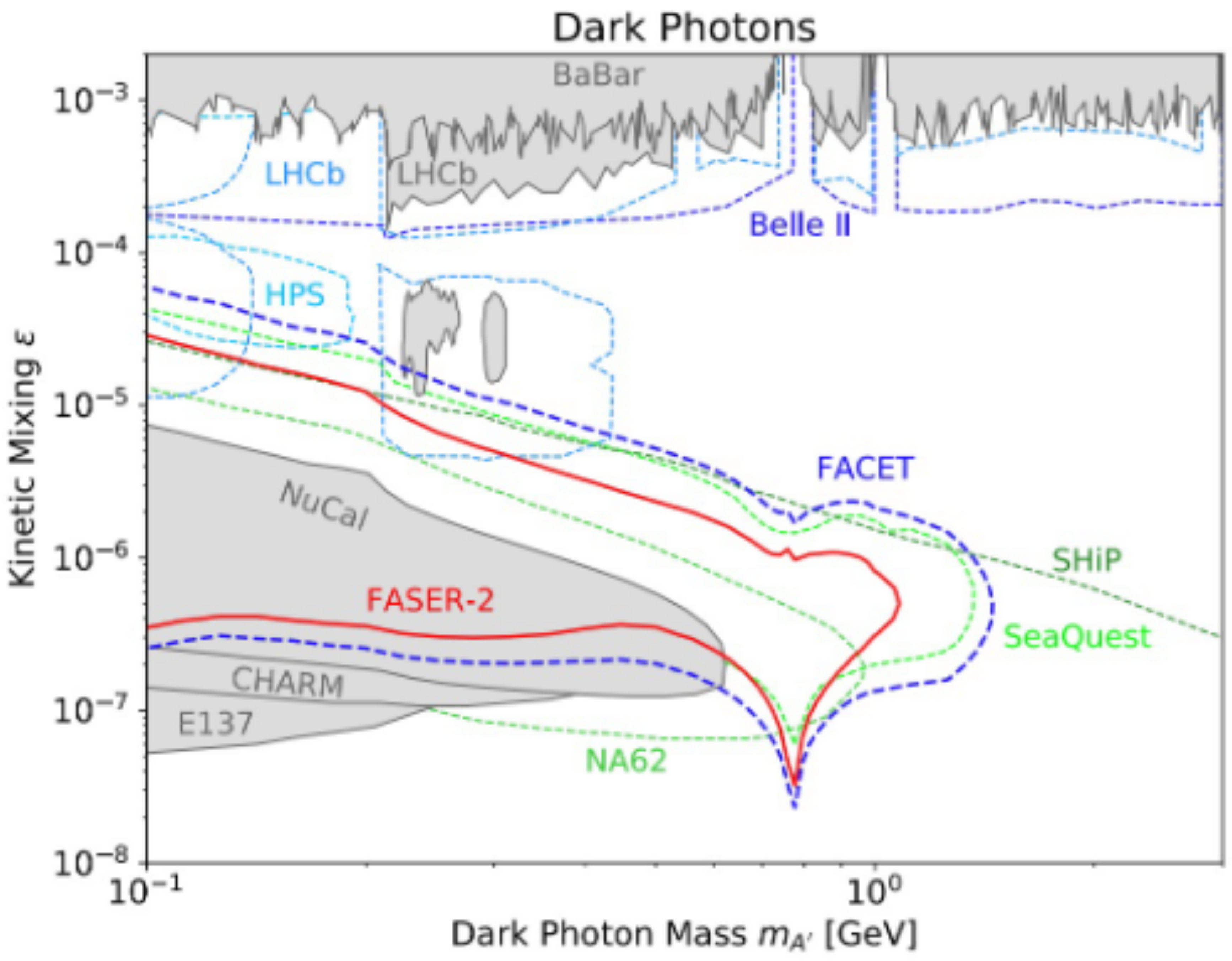
Tracking stations affixed with cams: extract tracking stations to surface quickly & easily in an emergency



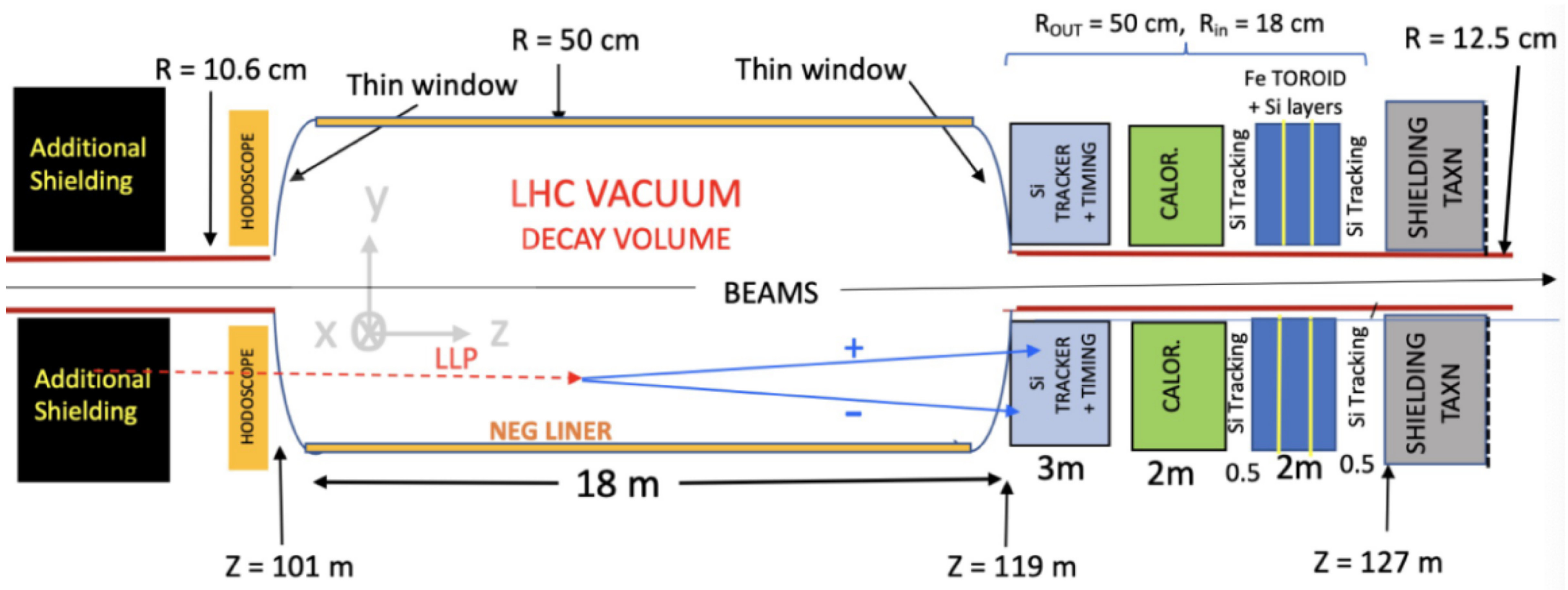
Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta\alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$



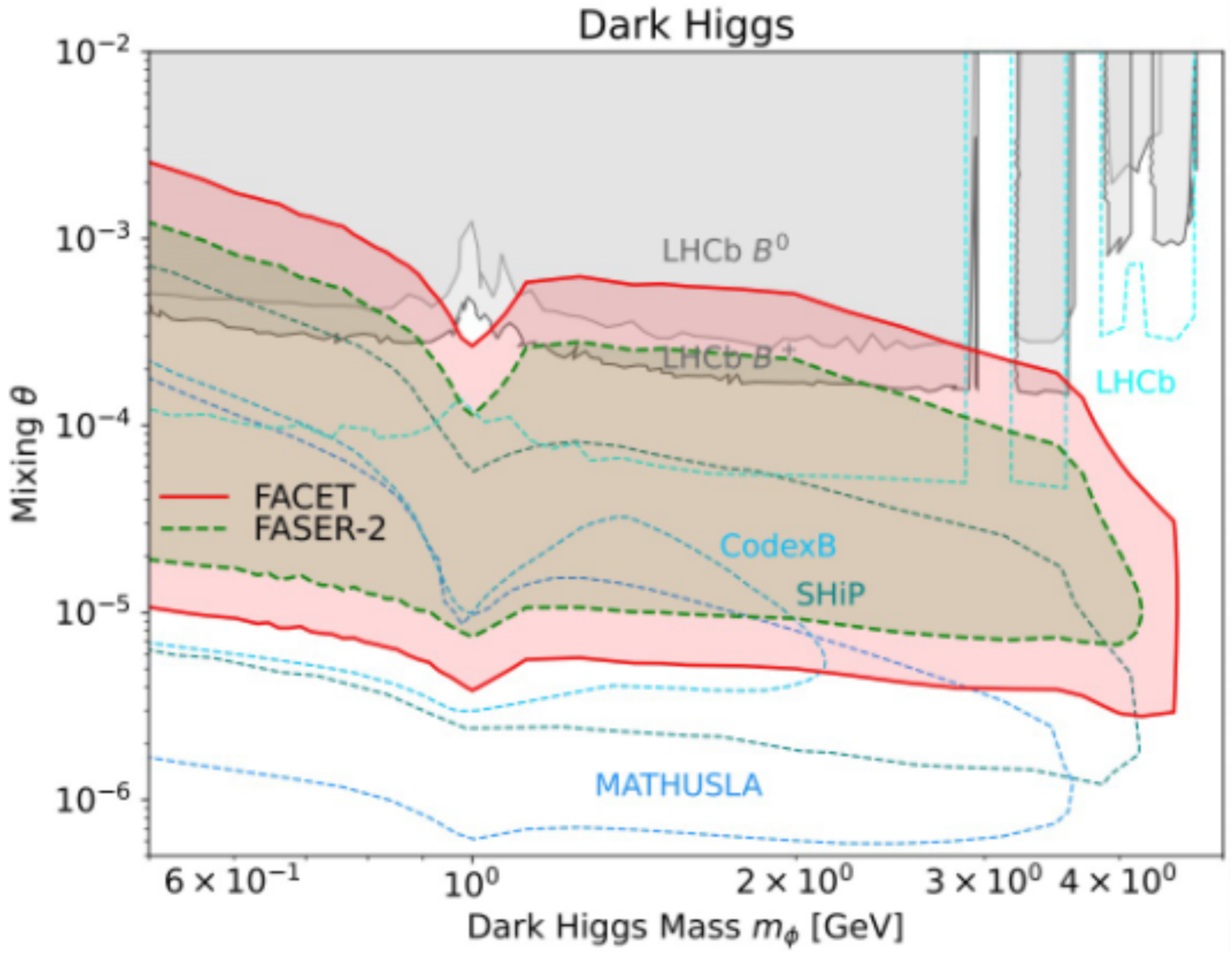
FACET



Dark Photons
BaBar
LHCb
LHCb
Belle II
HPS
FACET
SHiP
SeaQuest
NuCal
FASER-2
CHARM
E137
NA62
Kinetic Mixing ε
Dark Photon Mass $m_{A'}$ [GeV]



R = 10.6 cm
Thin window
R = 50 cm
Thin window
R_{OUT} = 50 cm, R_{in} = 18 cm
R = 12.5 cm
Additional Shielding
HODOSCOPE
LHC VACUUM
DECAY VOLUME
Fe TOROID + Si layers
Si TRACKER + TIMING
CALOR.
Si Tracking
SHIELDING TAXN
BEAMS
LLP
NEG LINER
18 m
3m
2m
0.5
Z = 101 m
Z = 119 m
Z = 127 m



Dark Higgs
LHCb B^0
LHCb B^+
LHCb
FACET
FASER-2
CodexB
SHiP
MATHUSLA
Mixing θ
Dark Higgs Mass m_ϕ [GeV]

More LLP experiments at the LHC

- Beam dump using the SPS proton beam line in the North area
  - NA62: (running) fixed-target experiment, kaon and beam-dump physics program with sensitivity to hidden sector (dark photon/Higgs, ALPs, HNLs..)
  - SHiP: (proposed) Intensity-frontier wide-spectrum (~GeV-scale) FIP search, zero-background reachable
  - SHADOWS: (proposed) competitive to CODEX-b and FASER2 for FIPs from charm/beauty
- Experiments for exotic electromagnetic charge:
  - MilliQan: (demonstrator taking data) searching for dark-sector millicharged particles with feeble coupling strength in the drainage gallery of CMS
  - MoEDAL-MAPP: (running) First LHC dedicated search experiment! looking for highly ionizing particles like magnetic monopoles at LHCb, upgrade with sensitivity to millicharged particles, SUSY LLP states, and even HNLs
  - FORMOSA: (proposed) millicharged particles in the 10 MeV to 100 GeV mass range using the FPF
- Many other experiments can also search for LLPs, e.g. Neutrino experiments, B-factories or dark matter experiments.

Kaon and beam dump modes, beam-dump mode sensitive to LLP signatures (HNL, dark photons/scalars, ALPs)

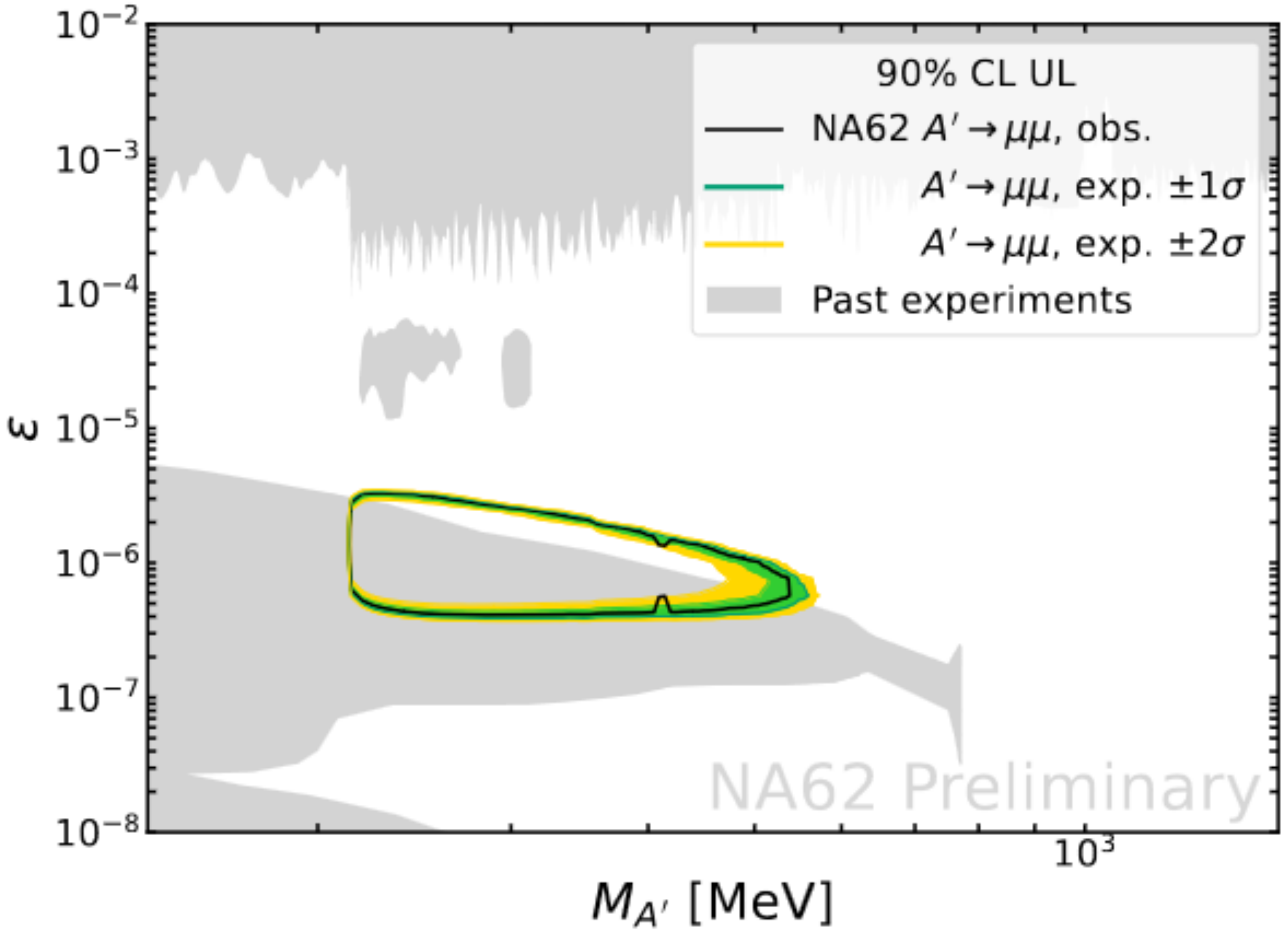
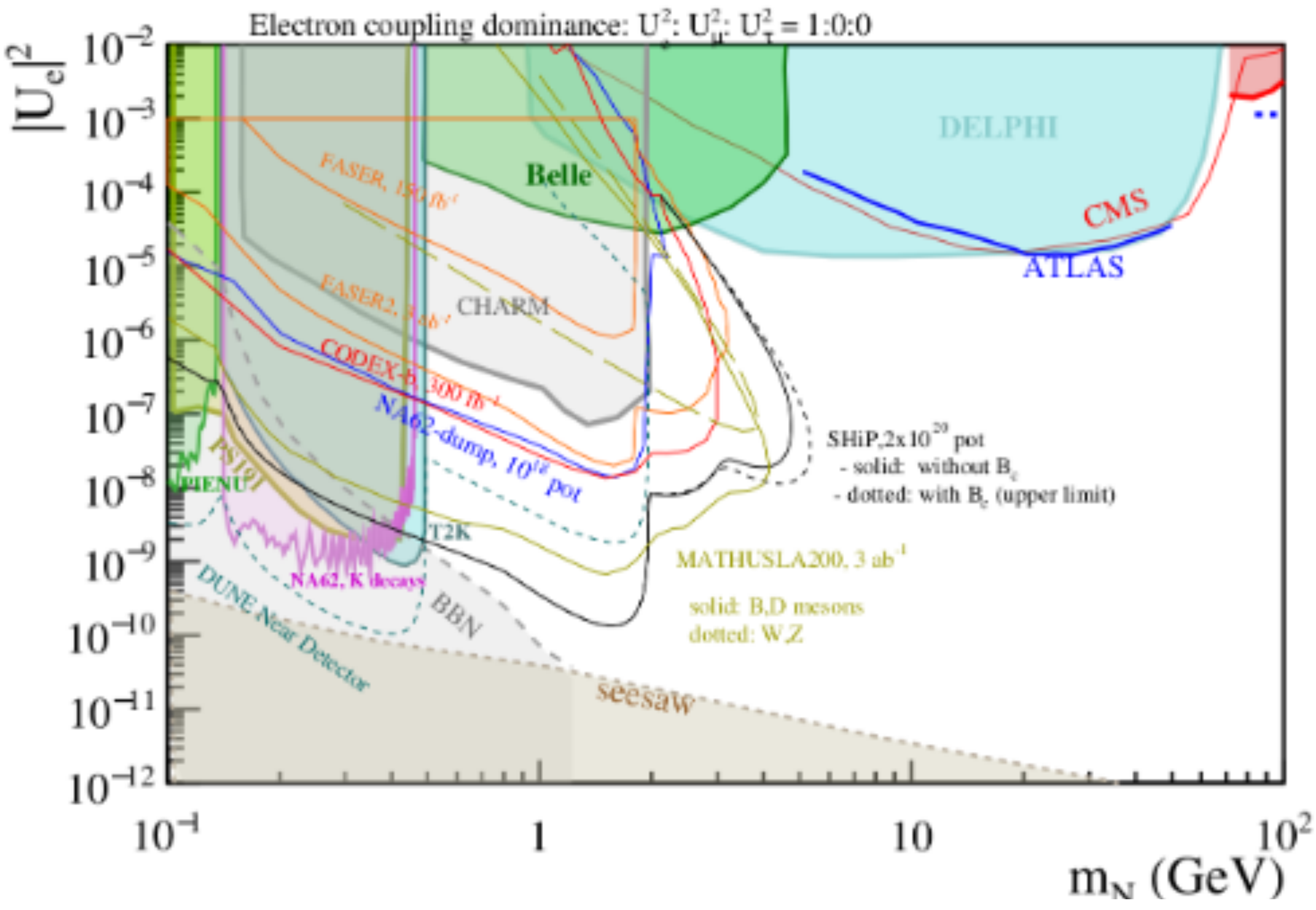
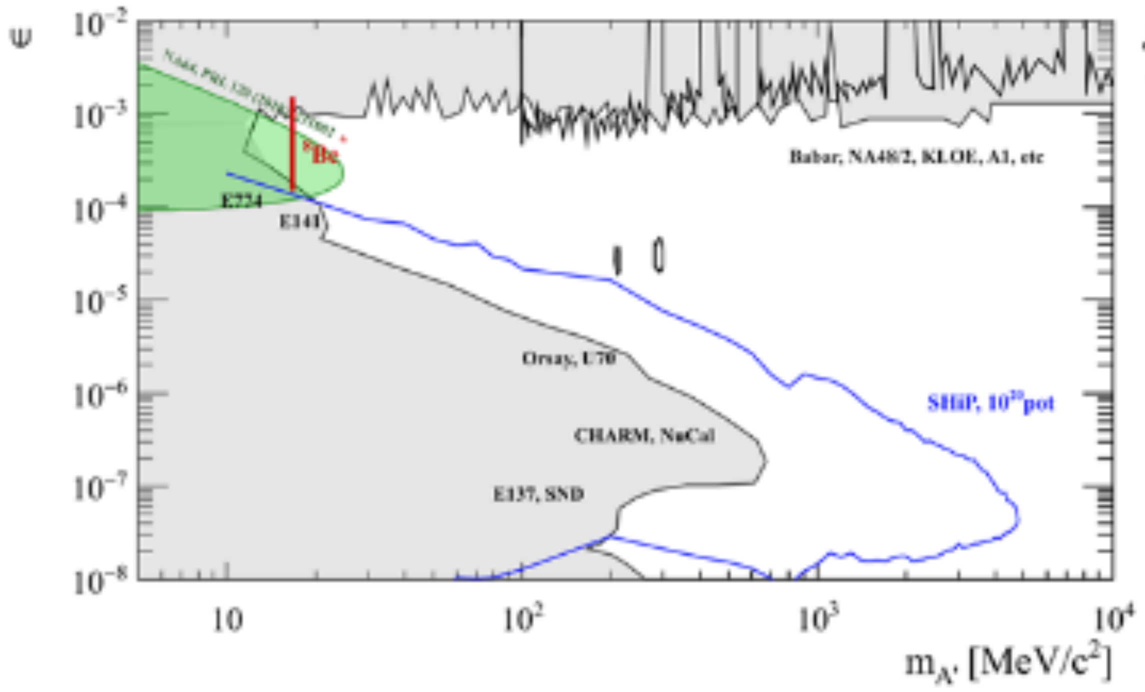


Figure: Final result with upper limit @90% CL.

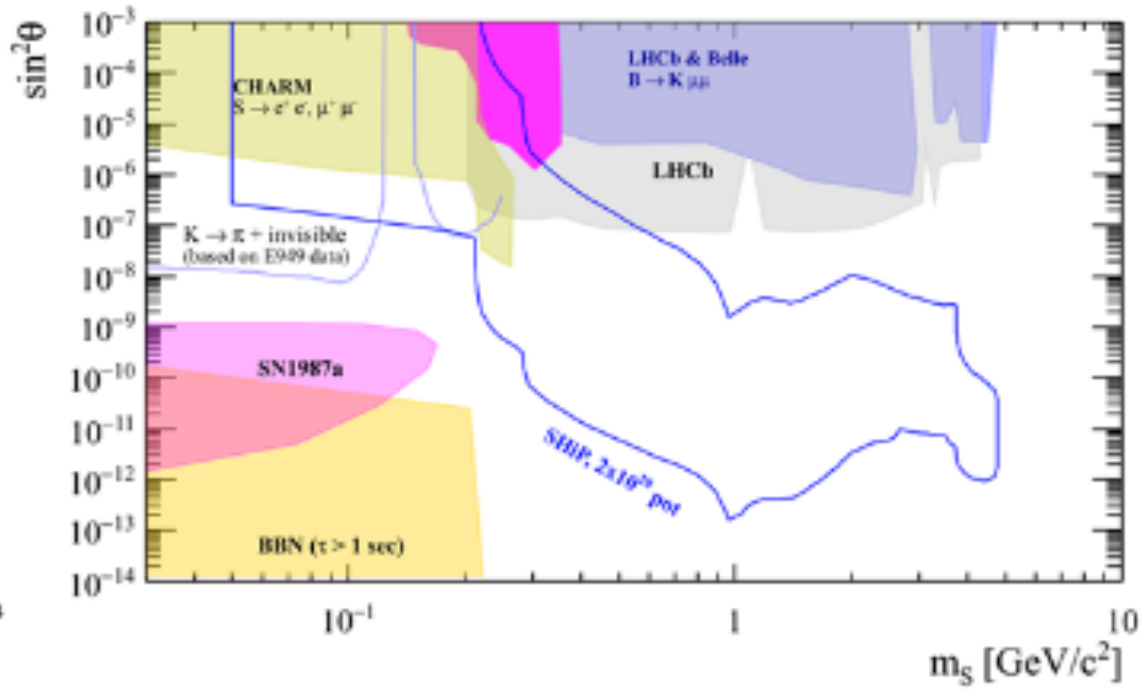


SHiP
Search for Hidden Particles

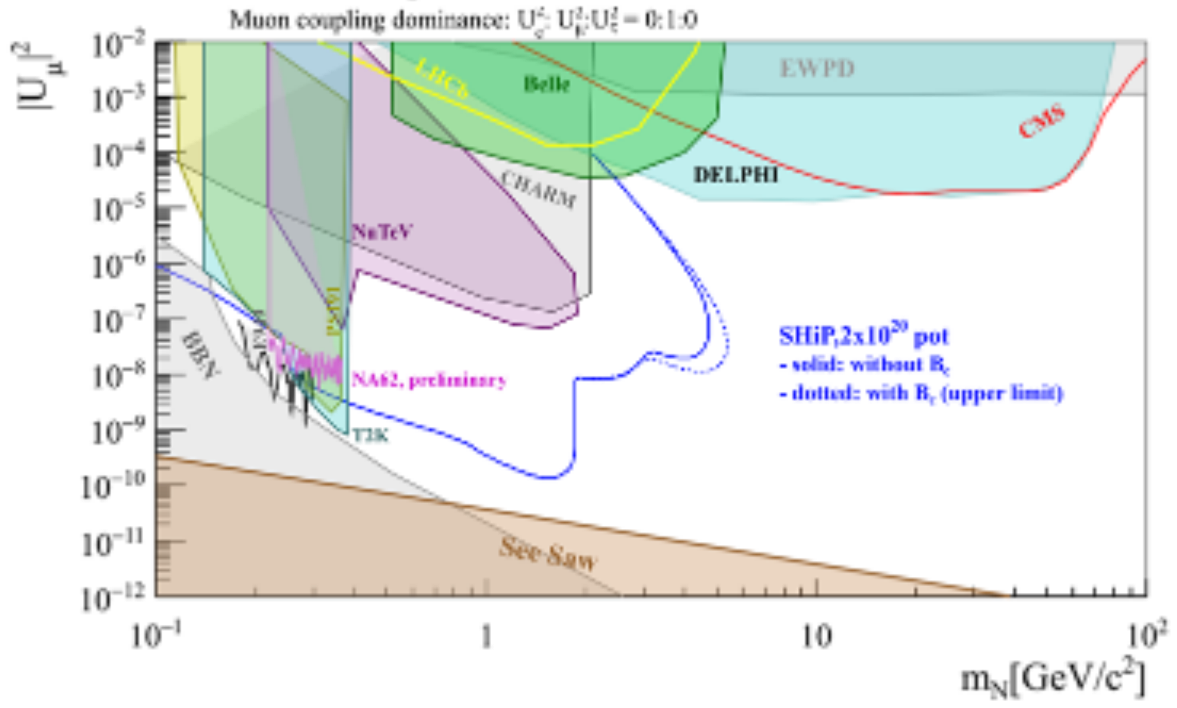
dark photons



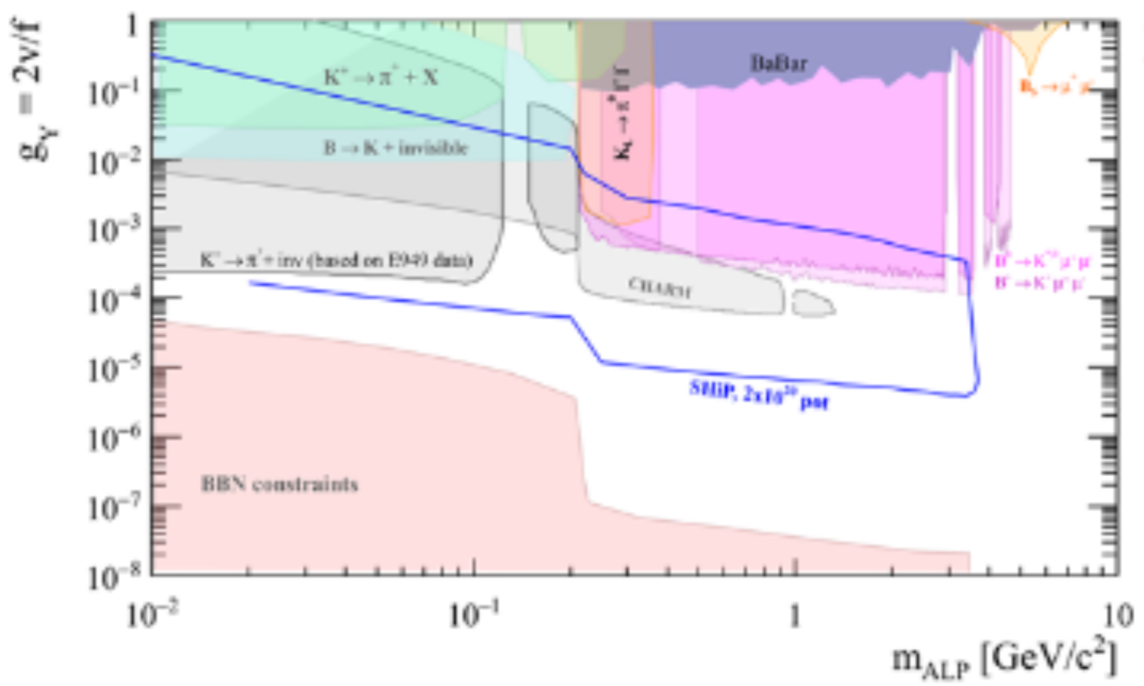
dark scalars



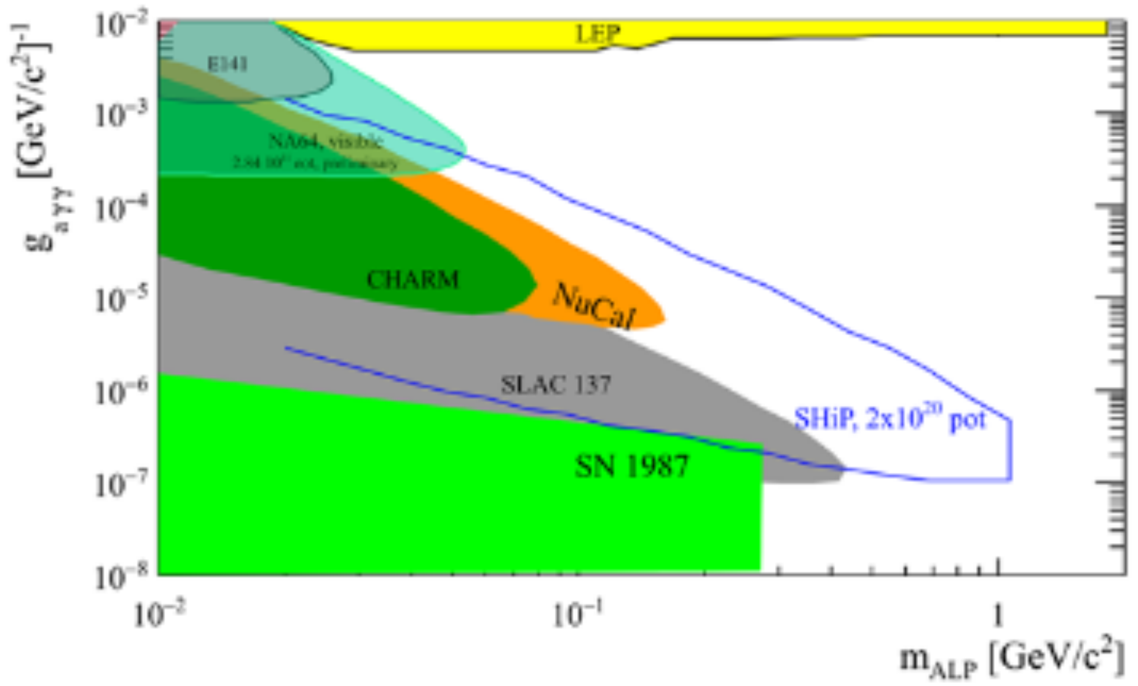
heavy neutral leptons



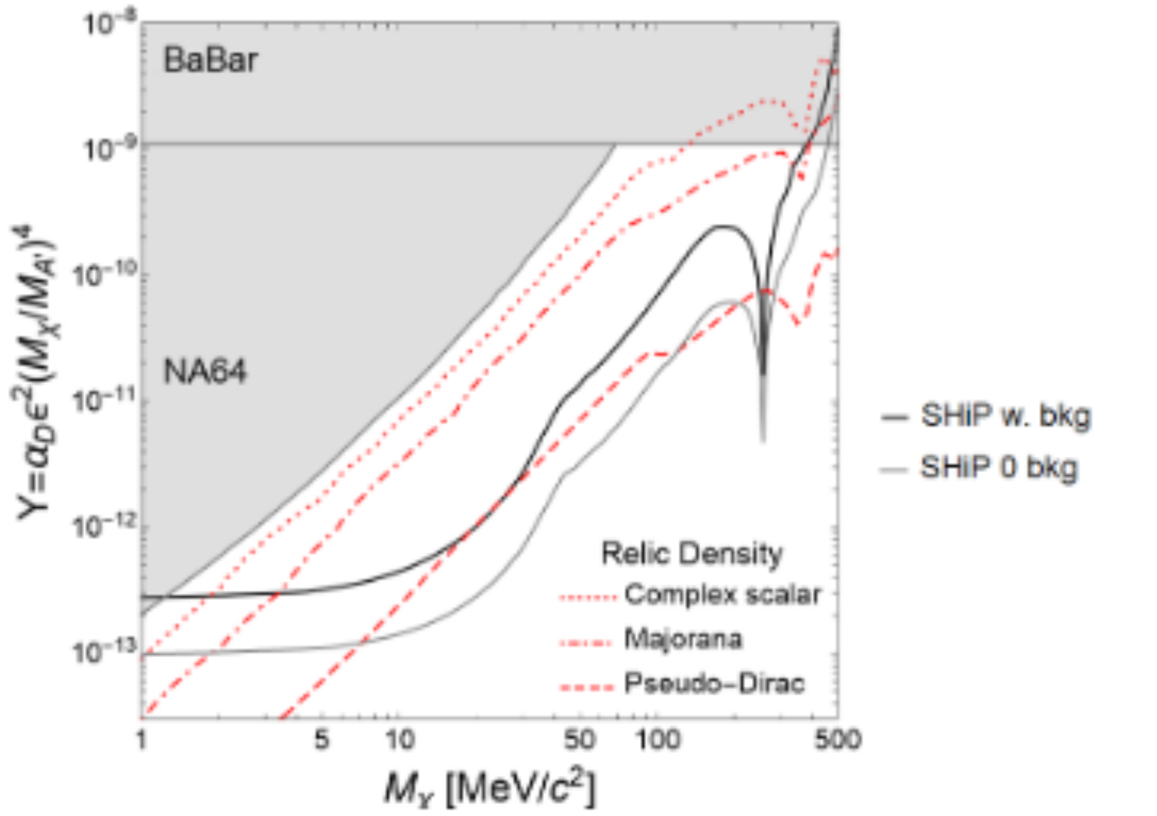
ALPs coupled to fermions

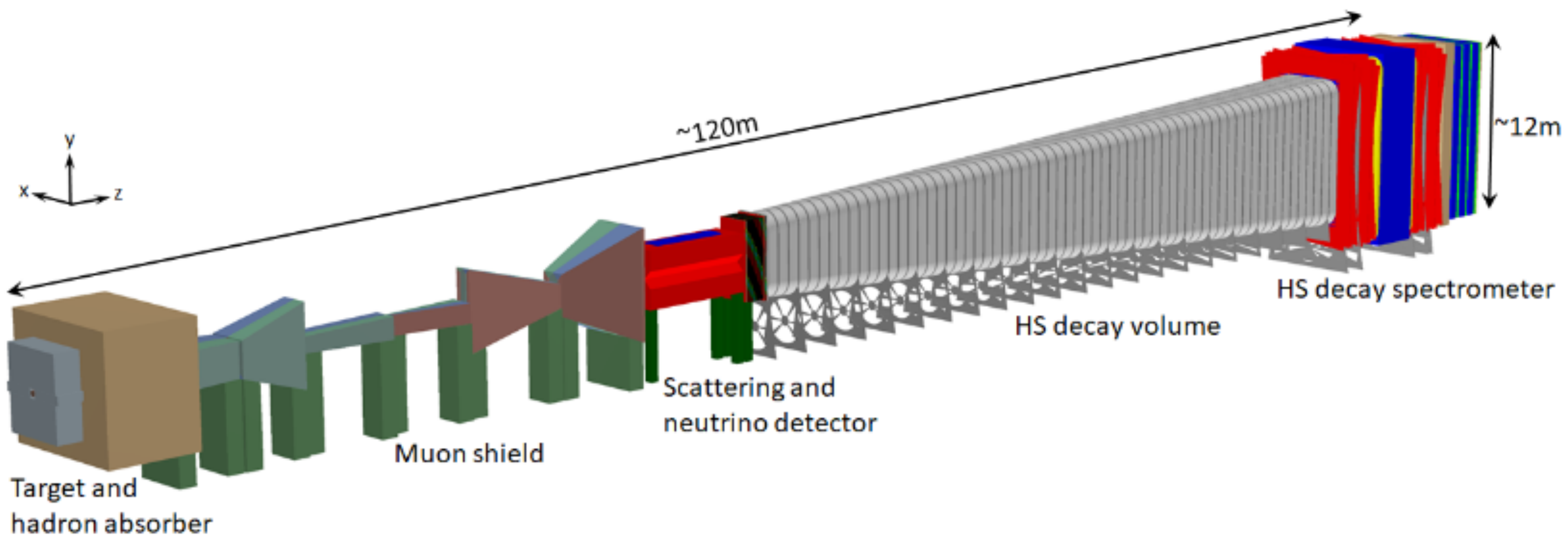


… and to photons



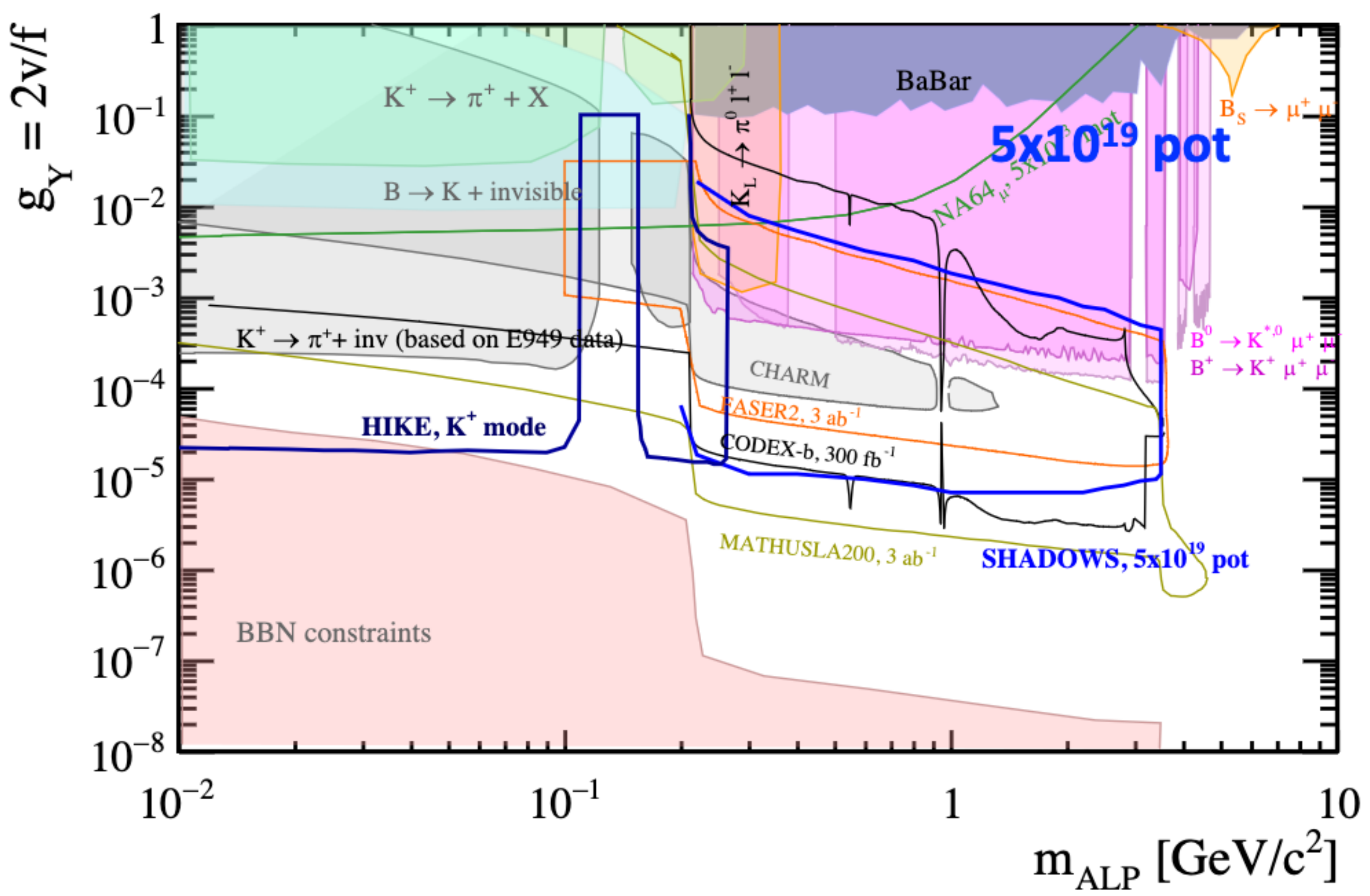
light dark matter jhep04

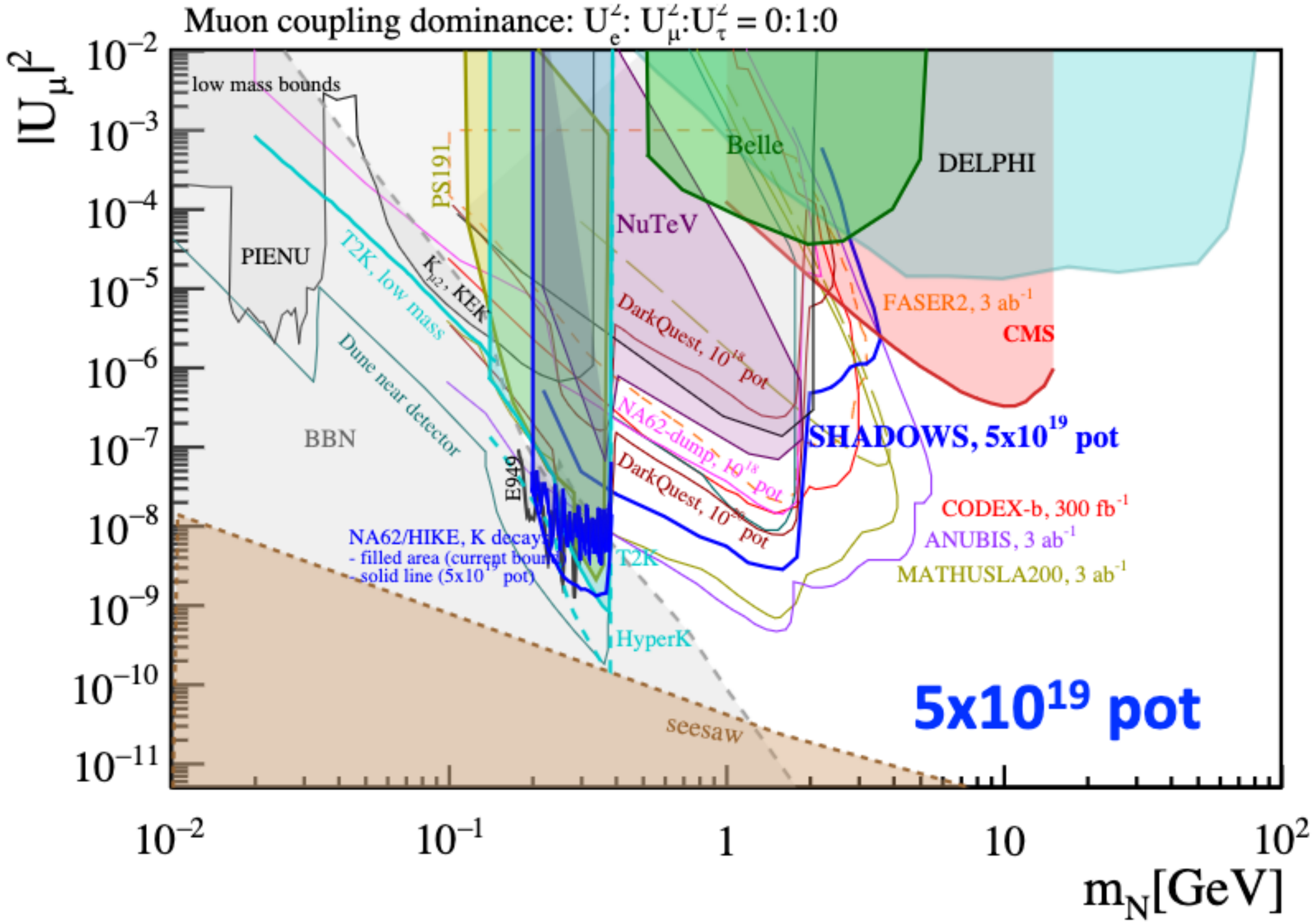




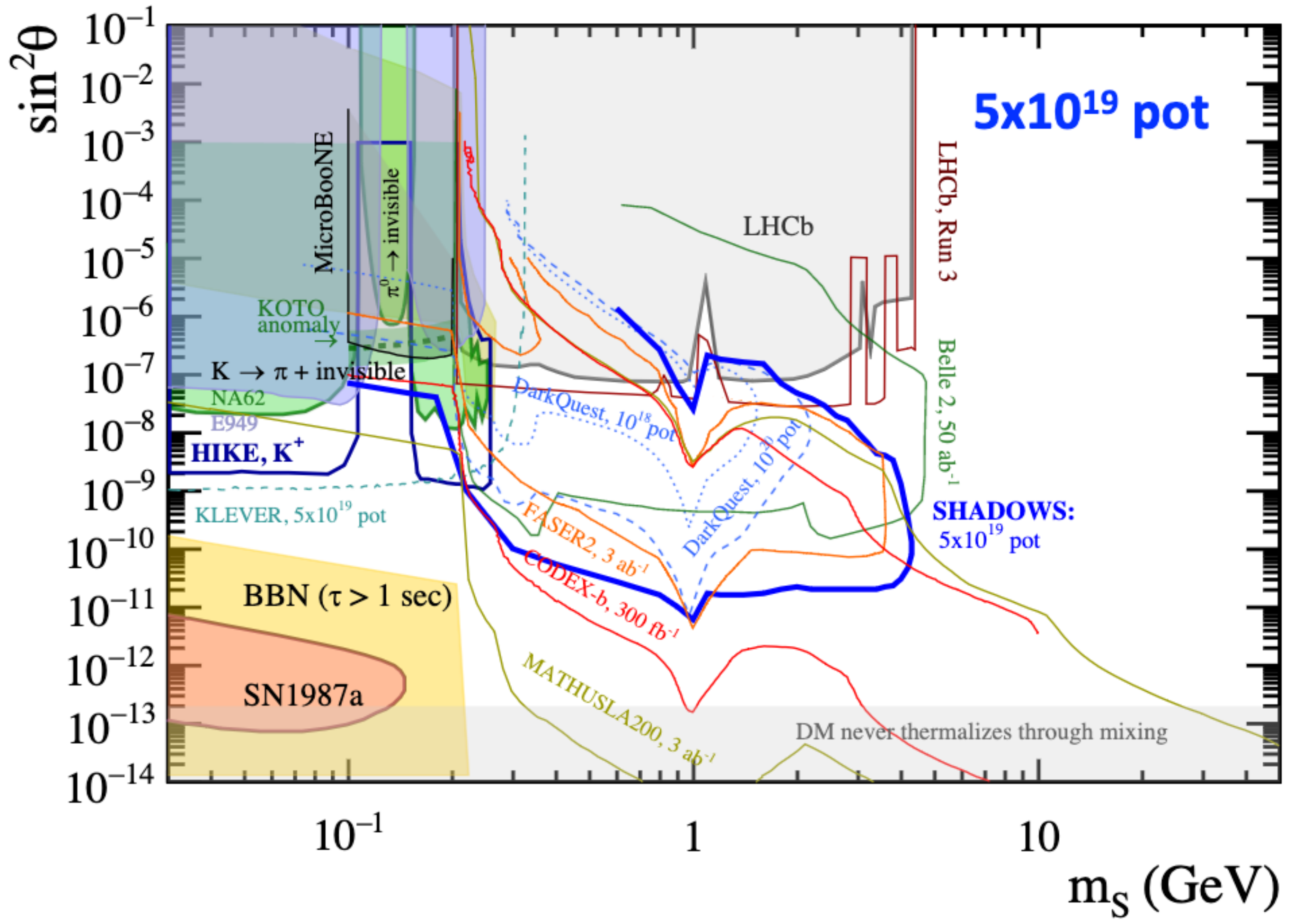
SHADOWS

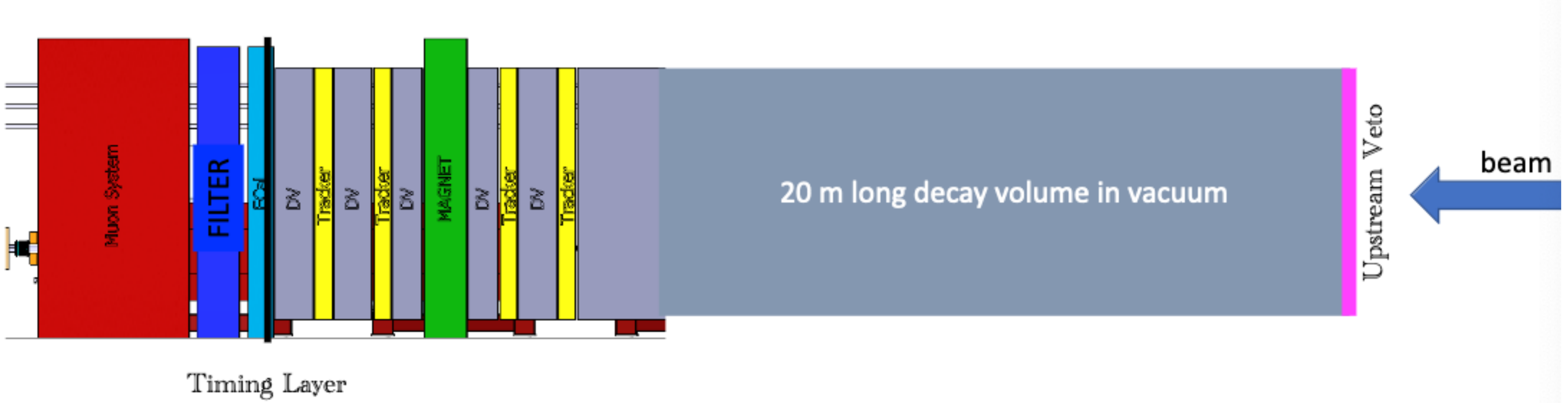
ALPs with fermion couplings (BC10)





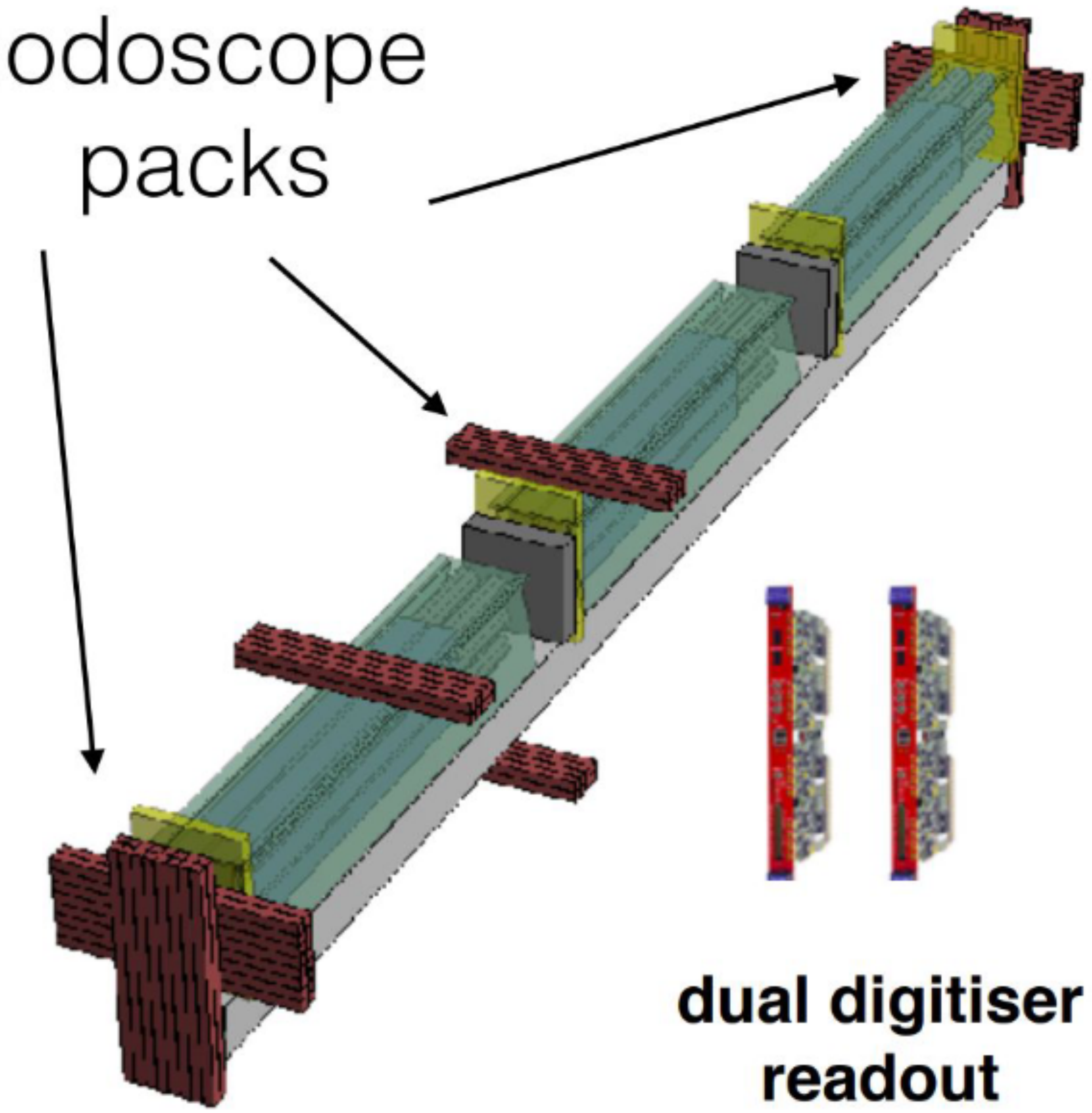
Light Dark Scalar mixing with the Higgs (BC4)





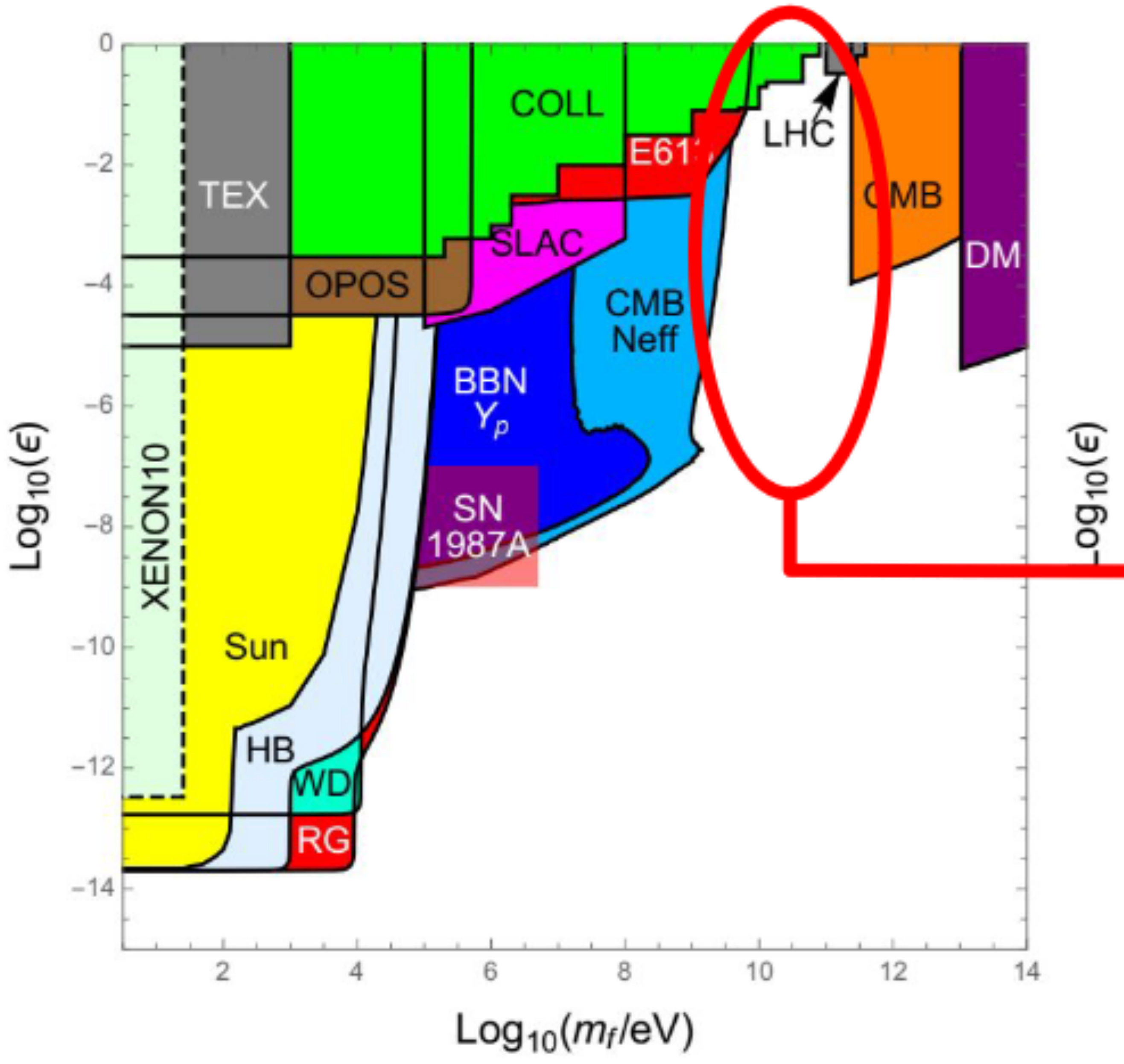
THE MILLIQAN EXPERIMENT

hodoscope packs

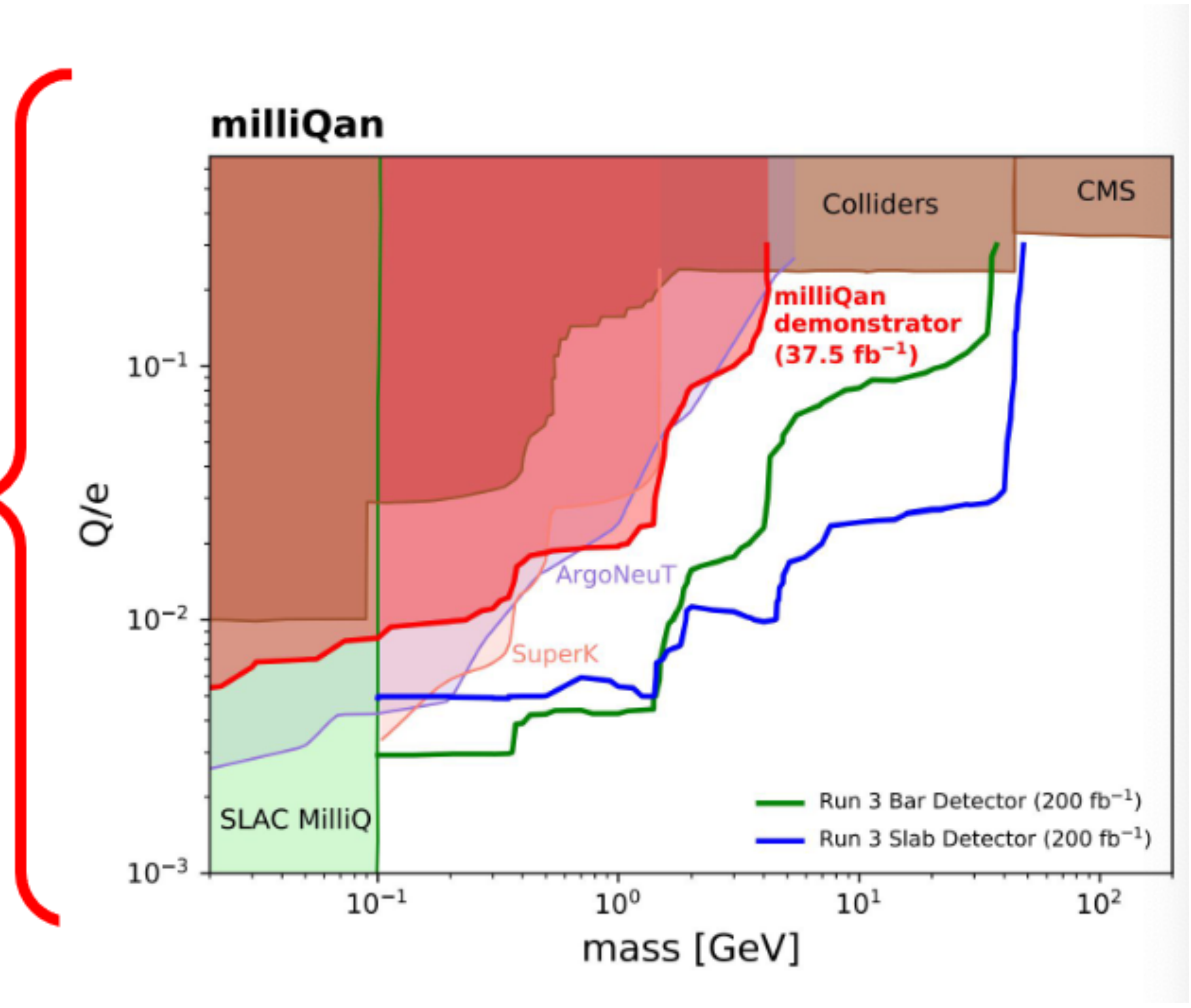


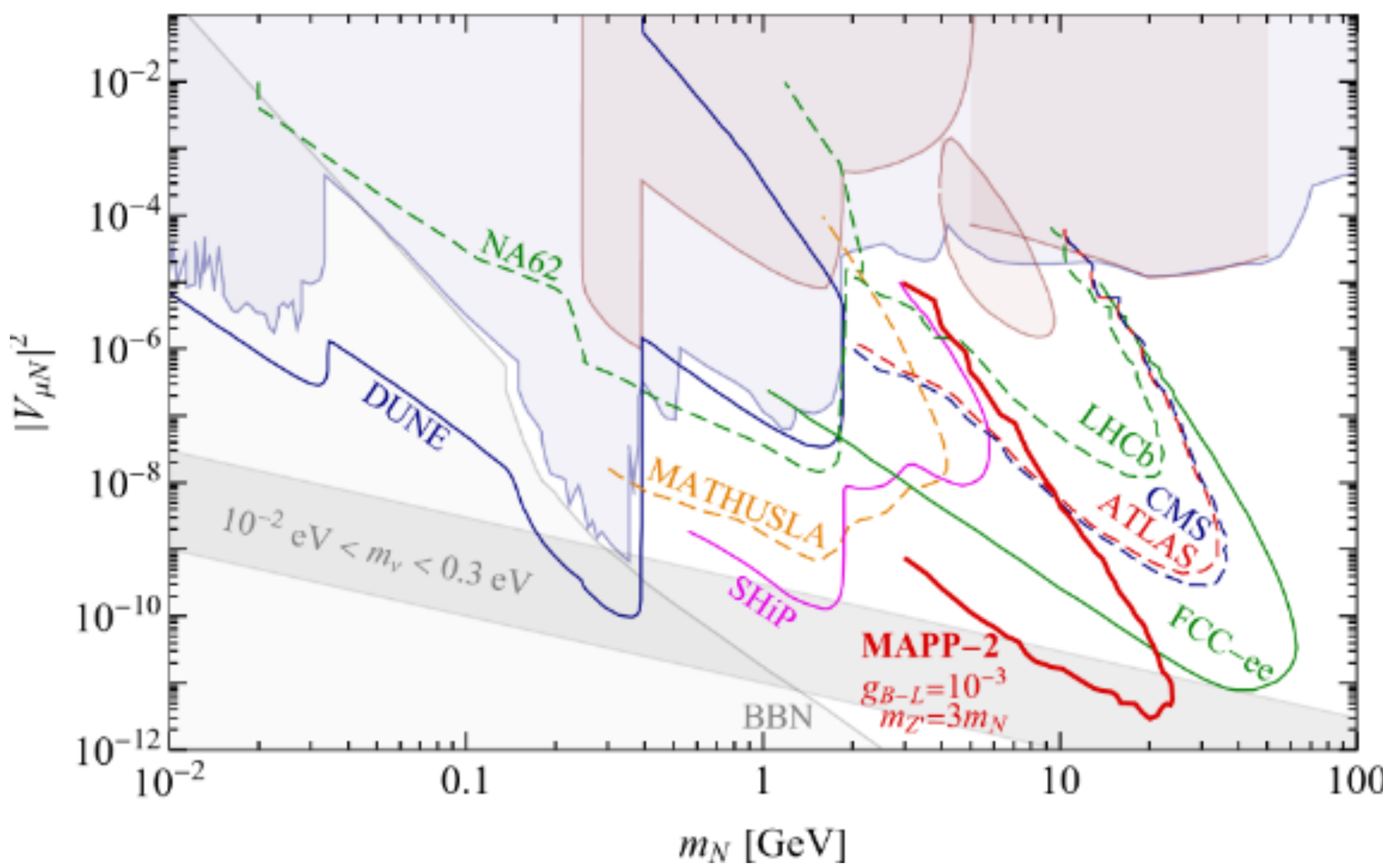
dual digitiser readout

CAEN V1743 digitizer:
16 chan, 1.6 GS/s,
640 ns window

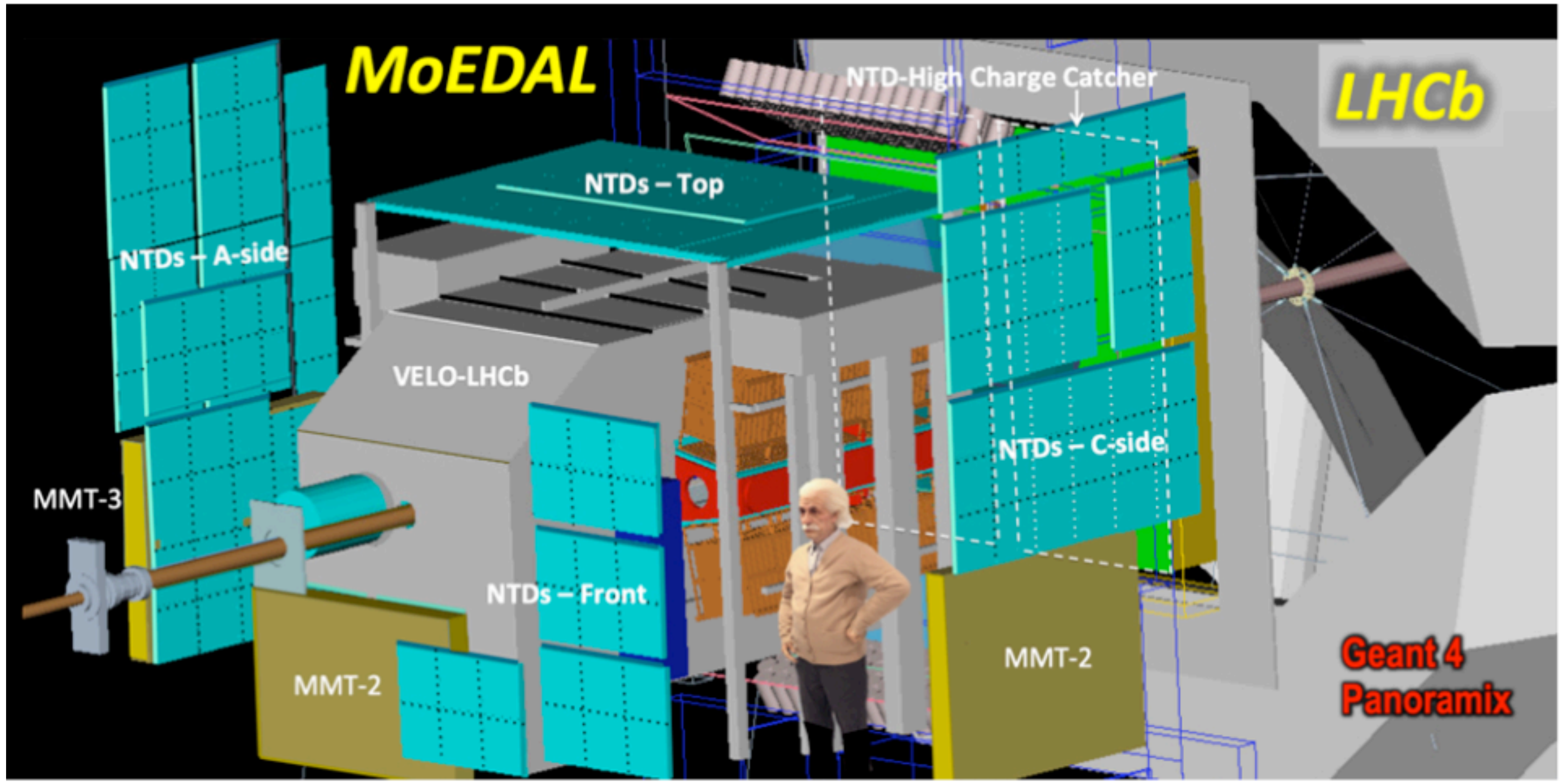


10.1103/PhysRevD.102.032002

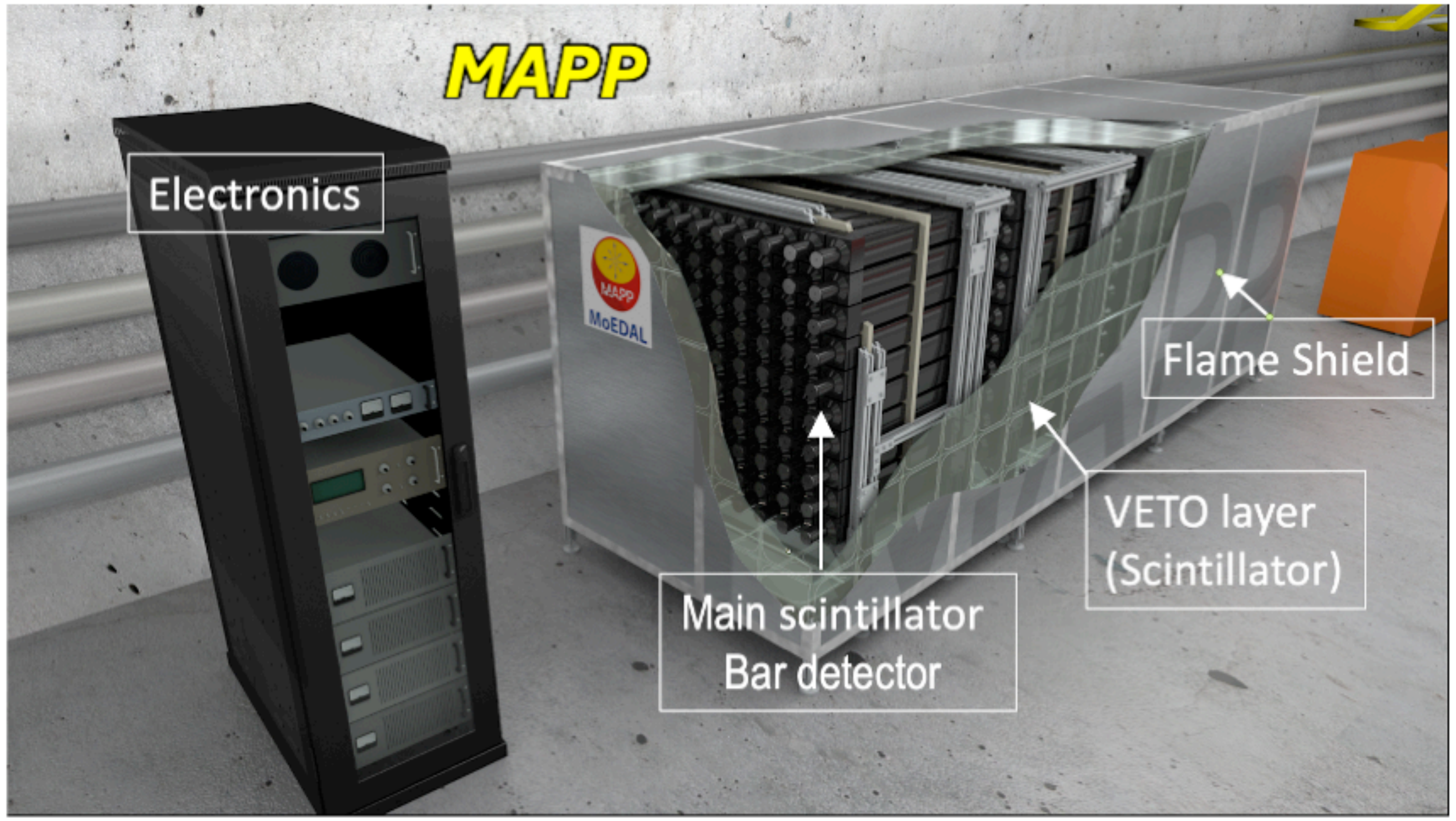




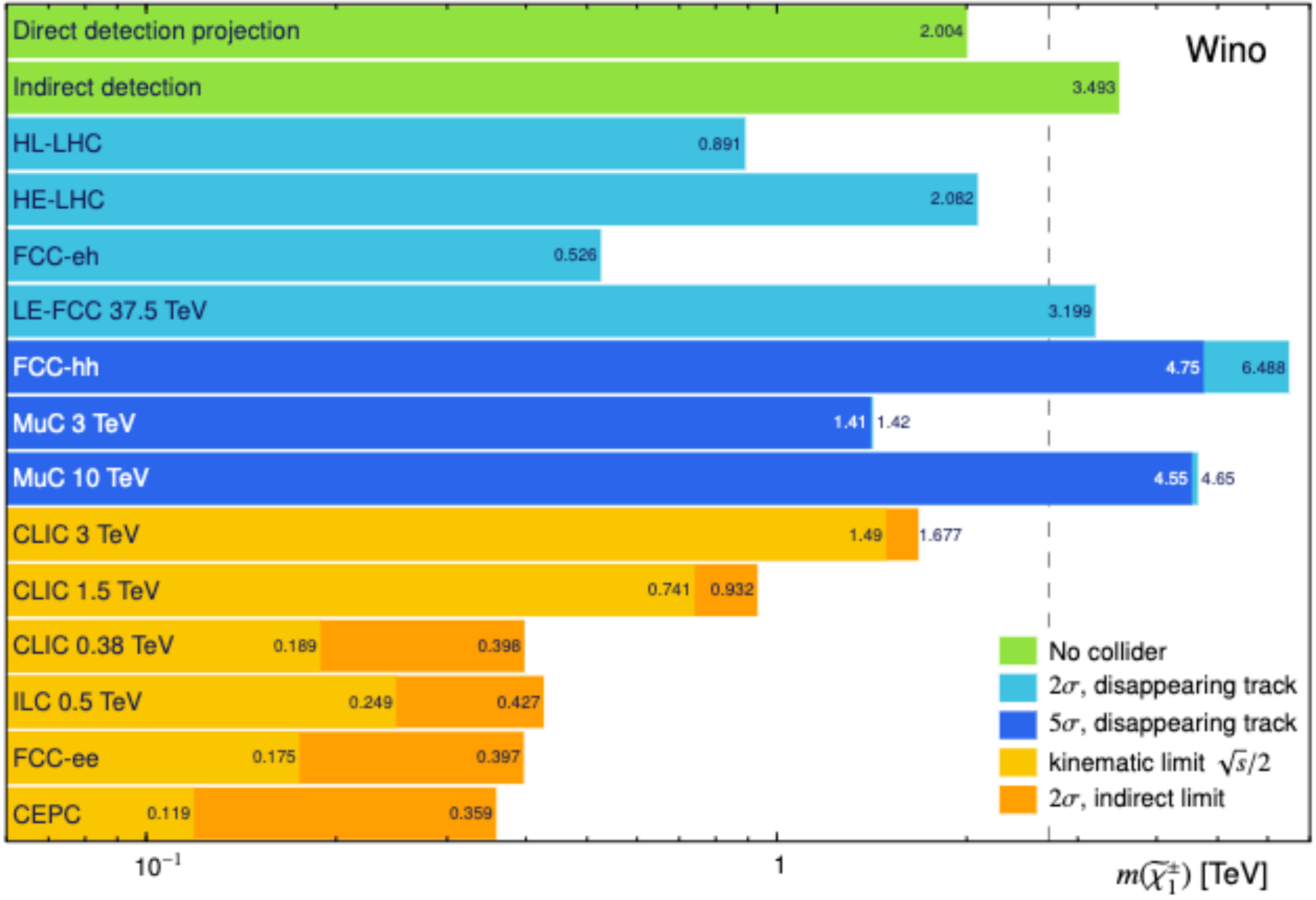
$|V_{\mu N}|^2$
m_N [GeV]
NA62
DUNE
MATHUSLA
SHiP
LHCb
CMS
ATLAS
FCC-ee
MAPP–2
$g_{B-L}=10^{-3}$
$m_{Z'}=3m_N$
BBN
10^{-2} eV $< m_\nu <$ 0.3 eV

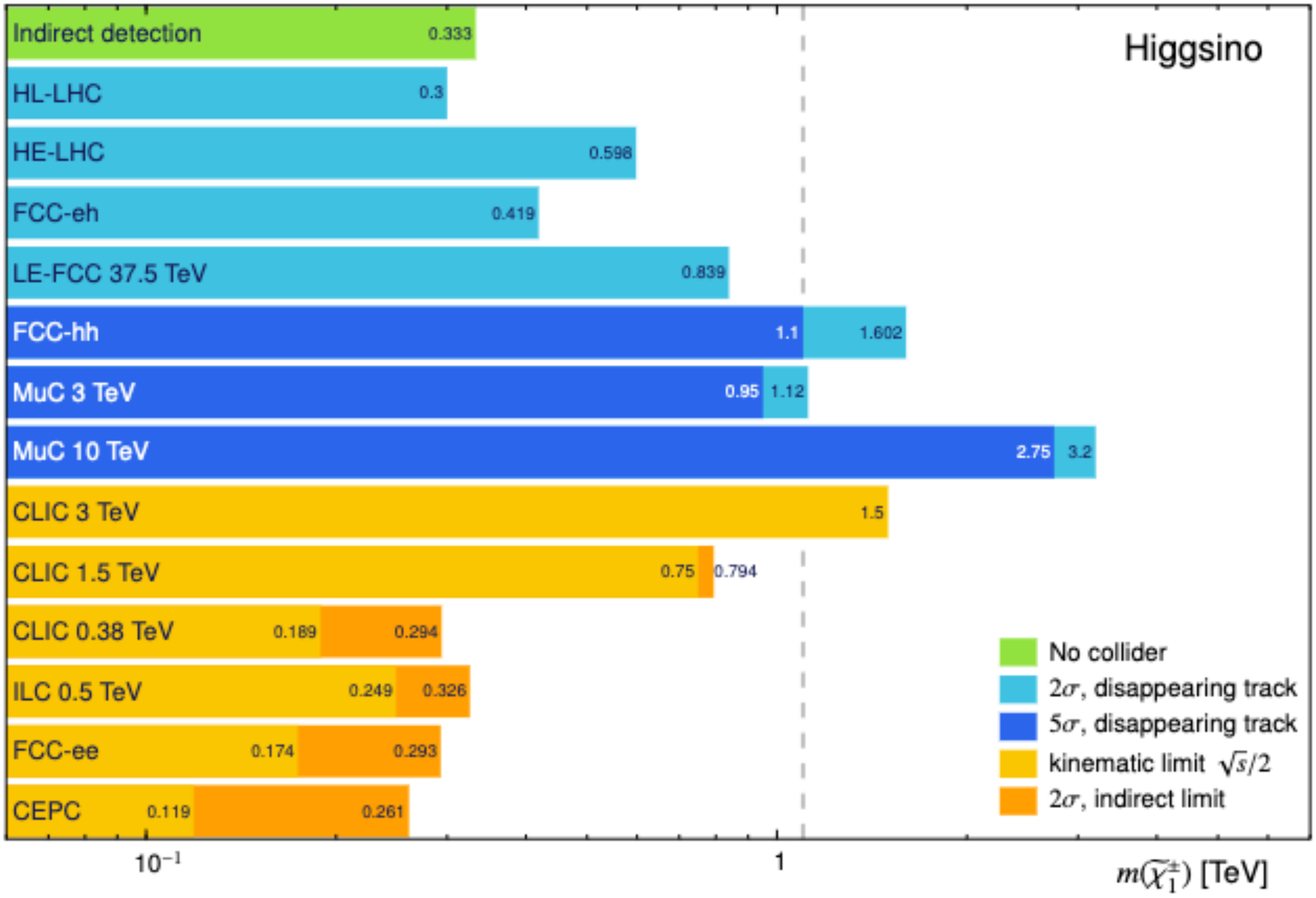


MoEDAL
LHCb
NTD-High Charge Catcher
NTDs – Top
NTDs – A-side
VELO-LHCb
NTDs – C-side
MMT-3
NTDs – Front
MMT-2
MMT-2
Geant 4
Panoramix



MAPP
Electronics
Flame Shield
VETO layer
(Scintillator)
Main scintillator
Bar detector

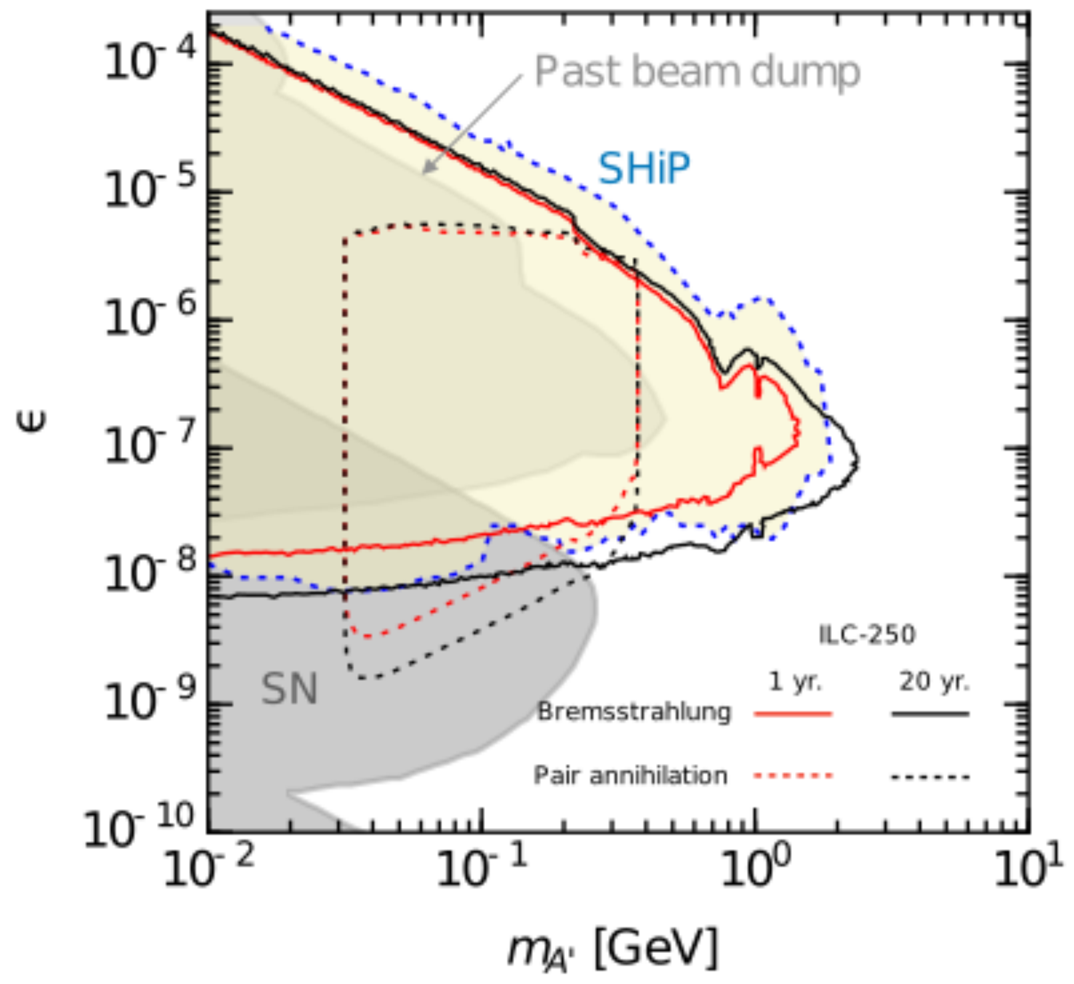

Wino
Direct detection projection
2.004
Indirect detection
3.493
HL-LHC
0.891
HE-LHC
2.082
FCC-eh
0.526
LE-FCC 37.5 TeV
3.199
FCC-hh
4.75
6.488
MuC 3 TeV
1.41
1.42
MuC 10 TeV
4.55
4.65
CLIC 3 TeV
1.49
1.677
CLIC 1.5 TeV
0.741
0.932
CLIC 0.38 TeV
0.189
0.398
ILC 0.5 TeV
0.249
0.427
FCC-ee
0.175
0.397
CEPC
0.119
0.359
No collider
2σ, disappearing track
5σ, disappearing track
kinematic limit $\sqrt{s}/2$
2σ, indirect limit
10^{-1}
1
$m(\tilde{\chi}_1^{\pm})$ [TeV]


Higgsino
Indirect detection
0.333
HL-LHC
0.3
HE-LHC
0.598
FCC-eh
0.419
LE-FCC 37.5 TeV
0.839
FCC-hh
1.1
1.602
MuC 3 TeV
0.95
1.12
MuC 10 TeV
2.75
3.2
CLIC 3 TeV
1.5
CLIC 1.5 TeV
0.75
0.794
CLIC 0.38 TeV
0.189
0.294
ILC 0.5 TeV
0.249
0.326
FCC-ee
0.174
0.293
CEPC
0.119
0.261
No collider
2σ, disappearing track
5σ, disappearing track
kinematic limit $\sqrt{s}/2$
2σ, indirect limit
10^{-1}
1
$m(\tilde{\chi}_1^{\pm})$ [TeV]

Beam dump experiments at linear colliders

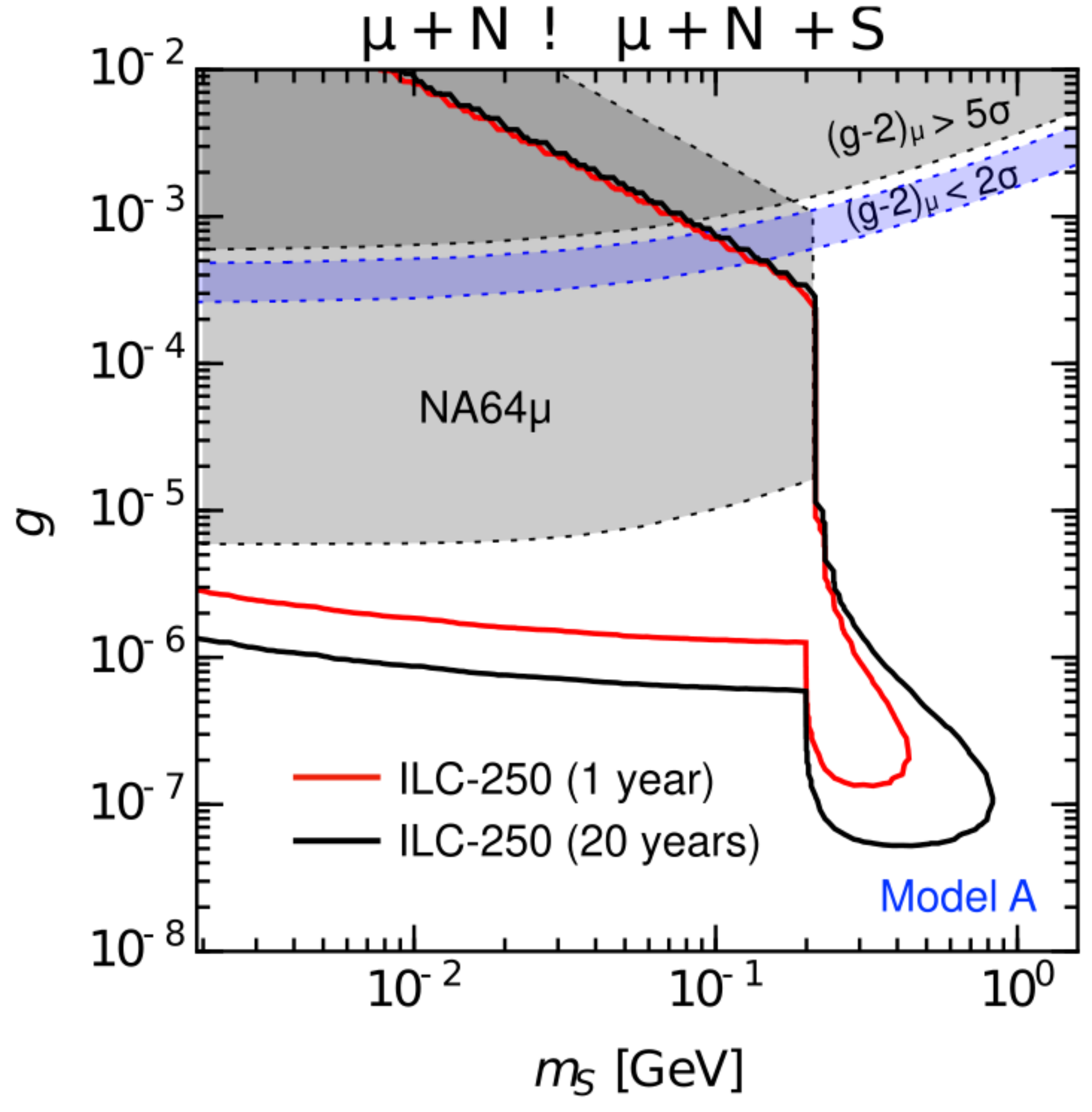
arxiv:2105.13768

- At linear colliders extreme intensities expected at electron and positron beam dumps open unique options for fixed-target experiments focused on rare processes.
- ALPs, new scalars or dark photons

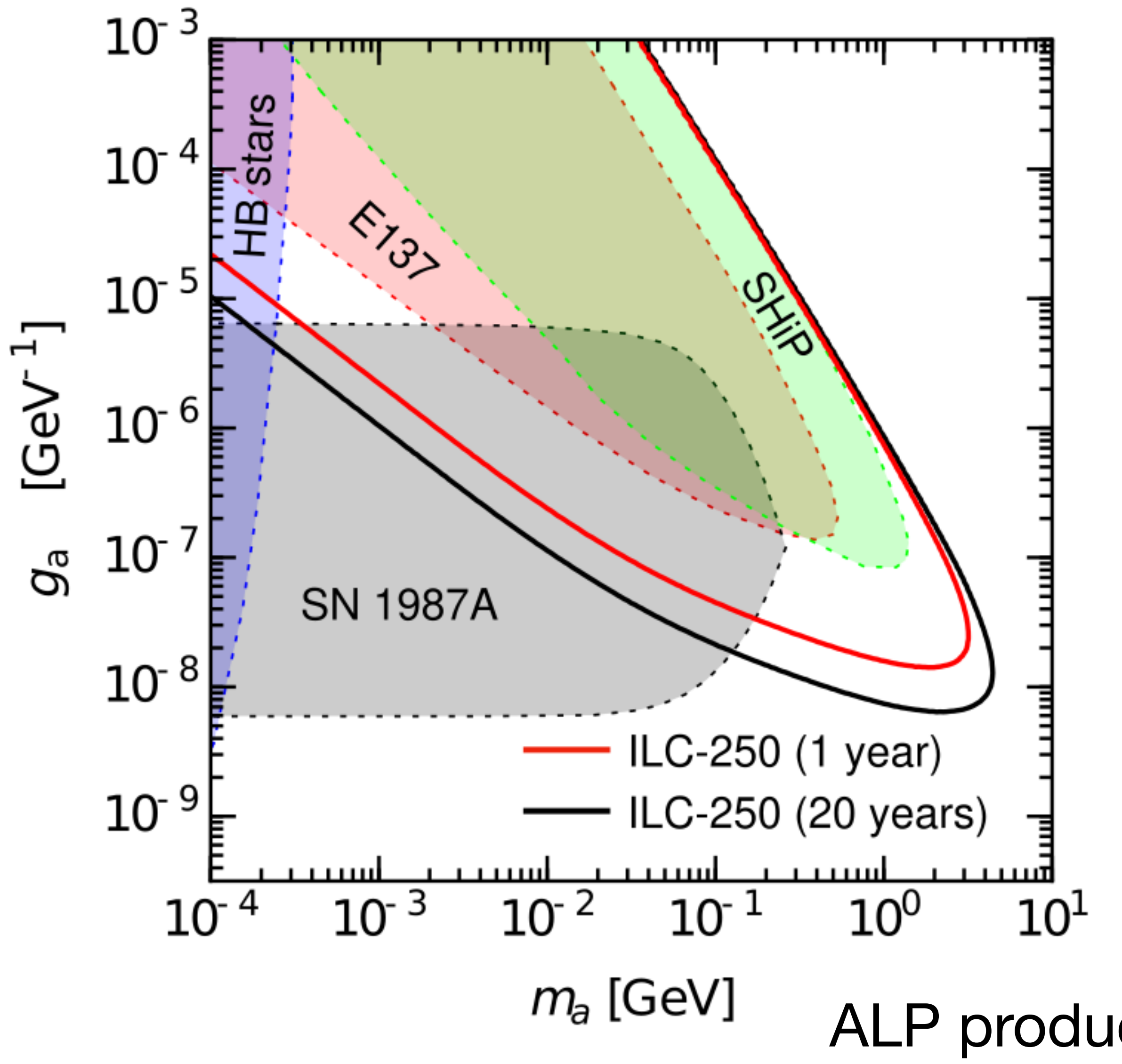


Dark Photon decays:
← invisible and visible ↑

arxiv:2009.13790

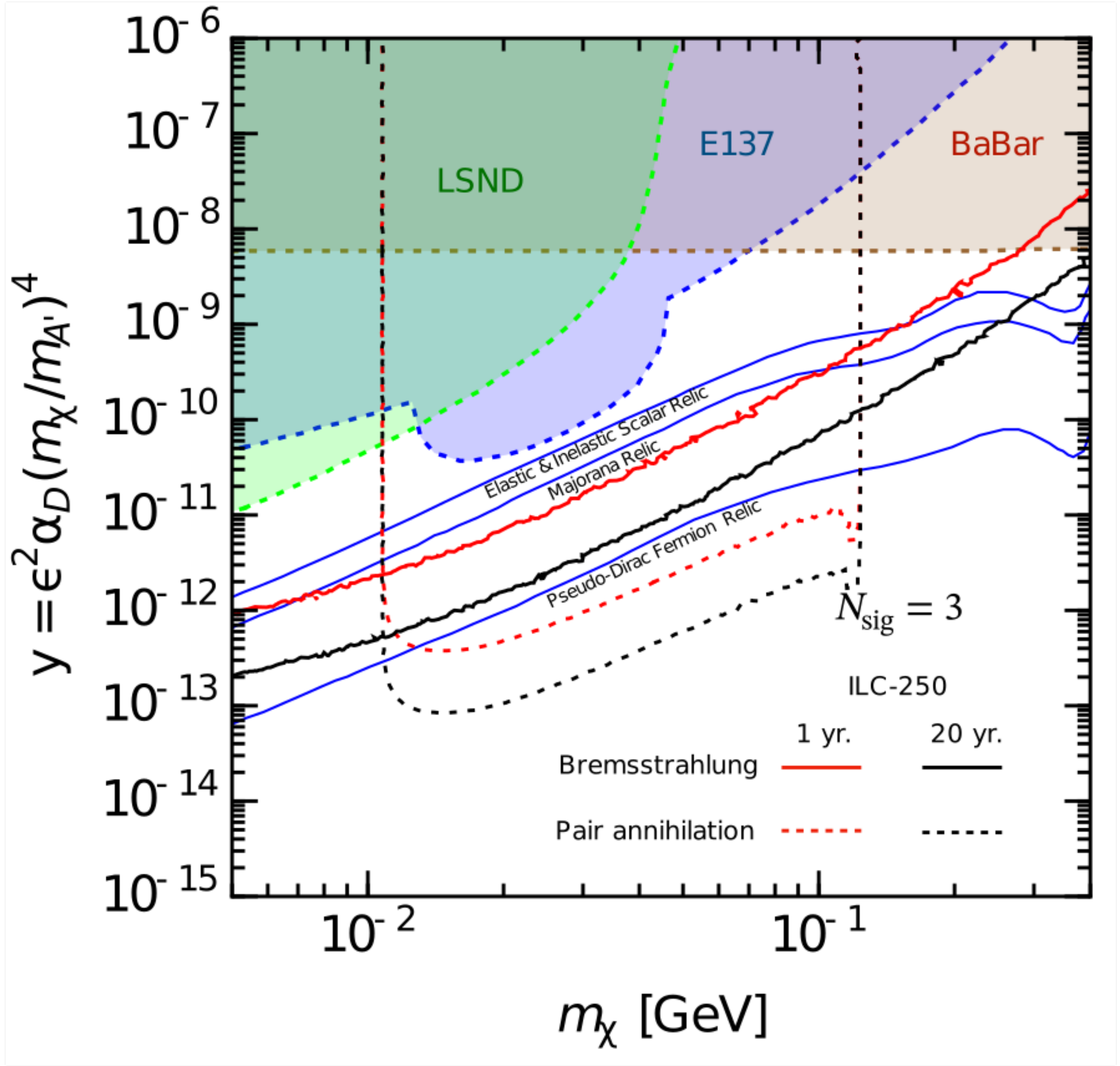


New scalars



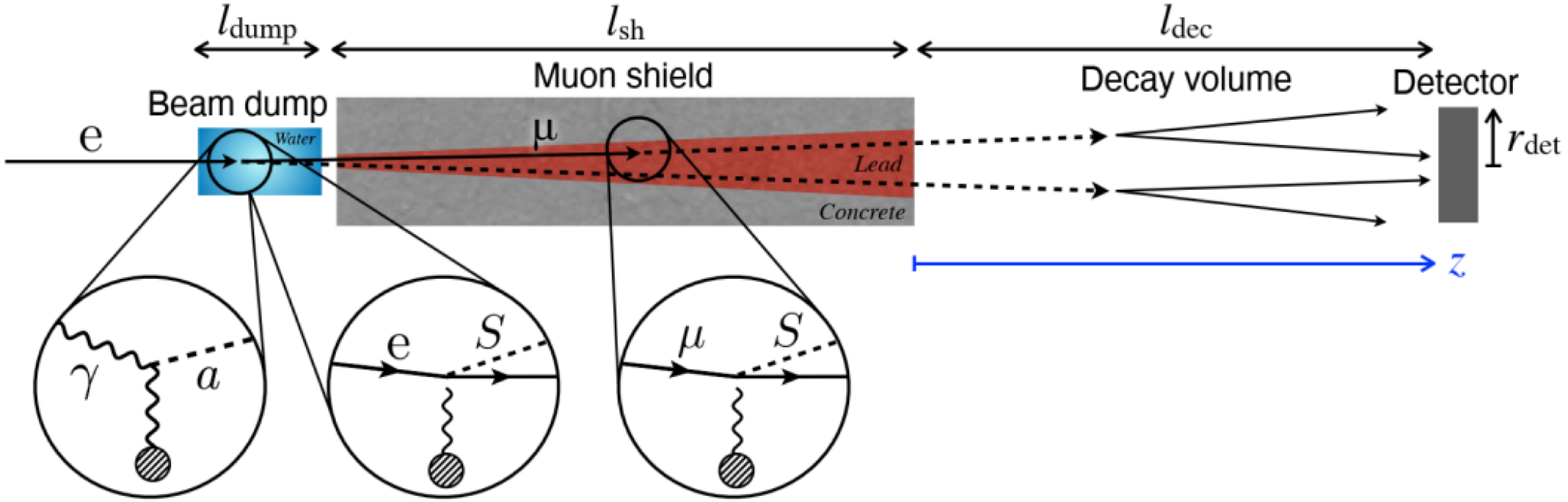
ALP production

D.Ueda @ ILCX2021



Beam dump experiments at linear colliders

- General scheme of an experiment searching for axion-like particles, new scalars or dark photons

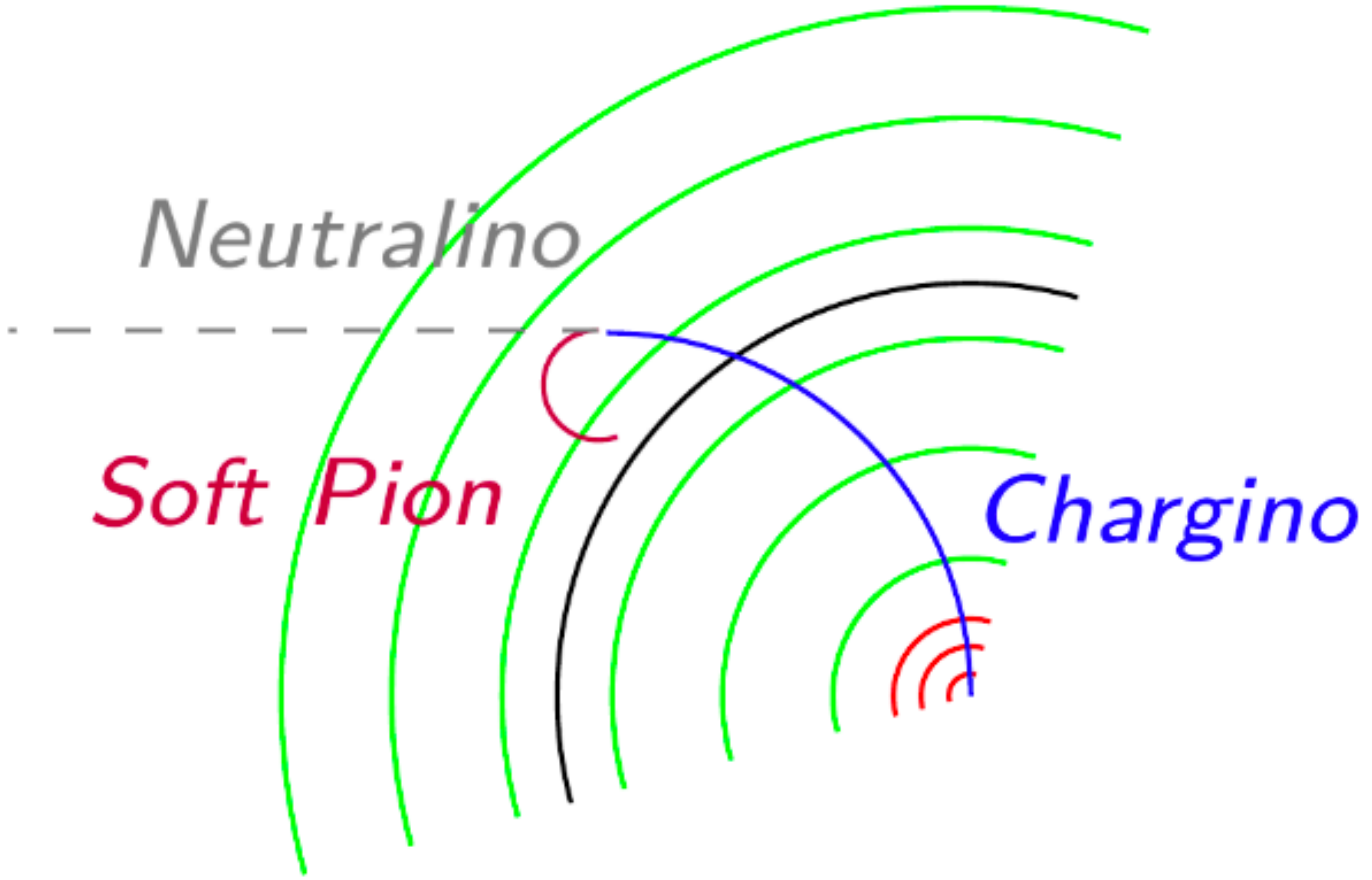


- One can look for visible products of LLPs decays (like a →γγ, S→ℓℓ) or for secondary interactions of invisible decay products in dedicated far detector (like in direct DM detection experiments; approach used in SLAC Beam Dump Experiment E137: arXiv:1406.2698)

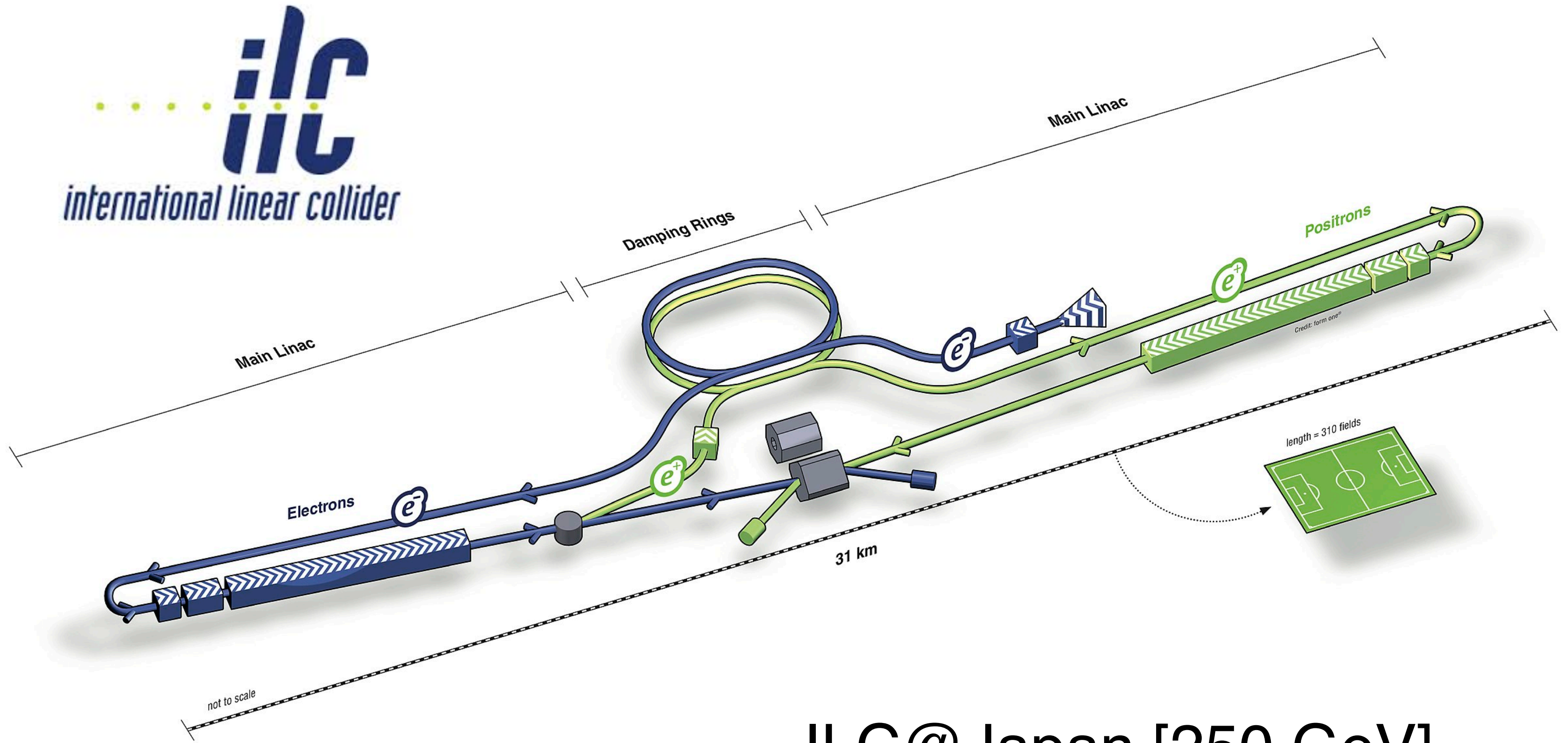
Ryu Sawada

Linear e+e- Colliders

- CLIC: (https://agenda.linearcollider.org/event/8217/contributions/44770/)
  - Hidden valley searches in Higgs boson decays with displaced vertices (https://cds.cern.ch/record/2625054)
  - Degenerate Higgsino Dark Matter → chargino pair production (disappearing tracks) (arXiv:1812.02093, arXiv:1812.06018)

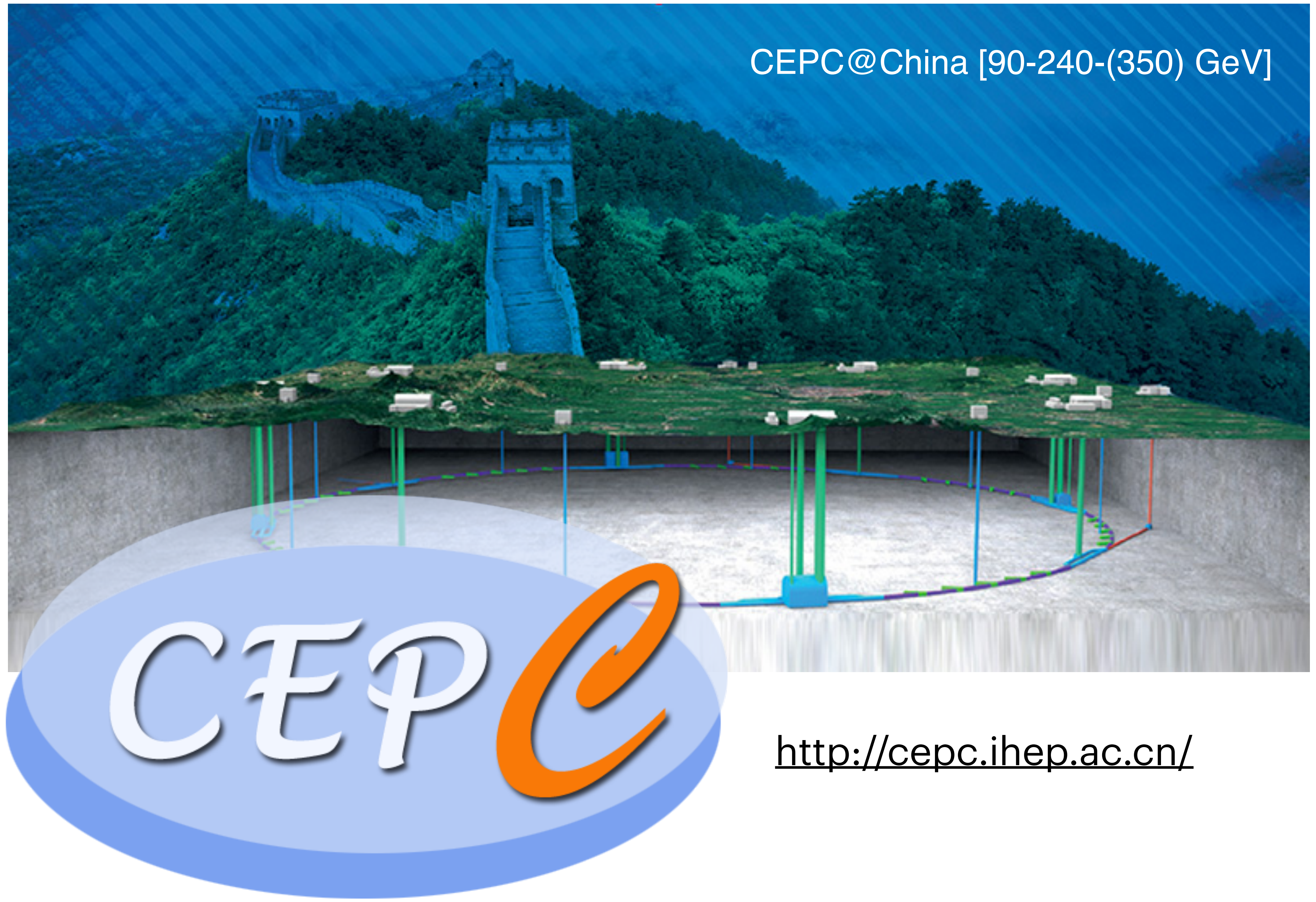


https://clic.cern/



ILC@Japan [250 GeV]

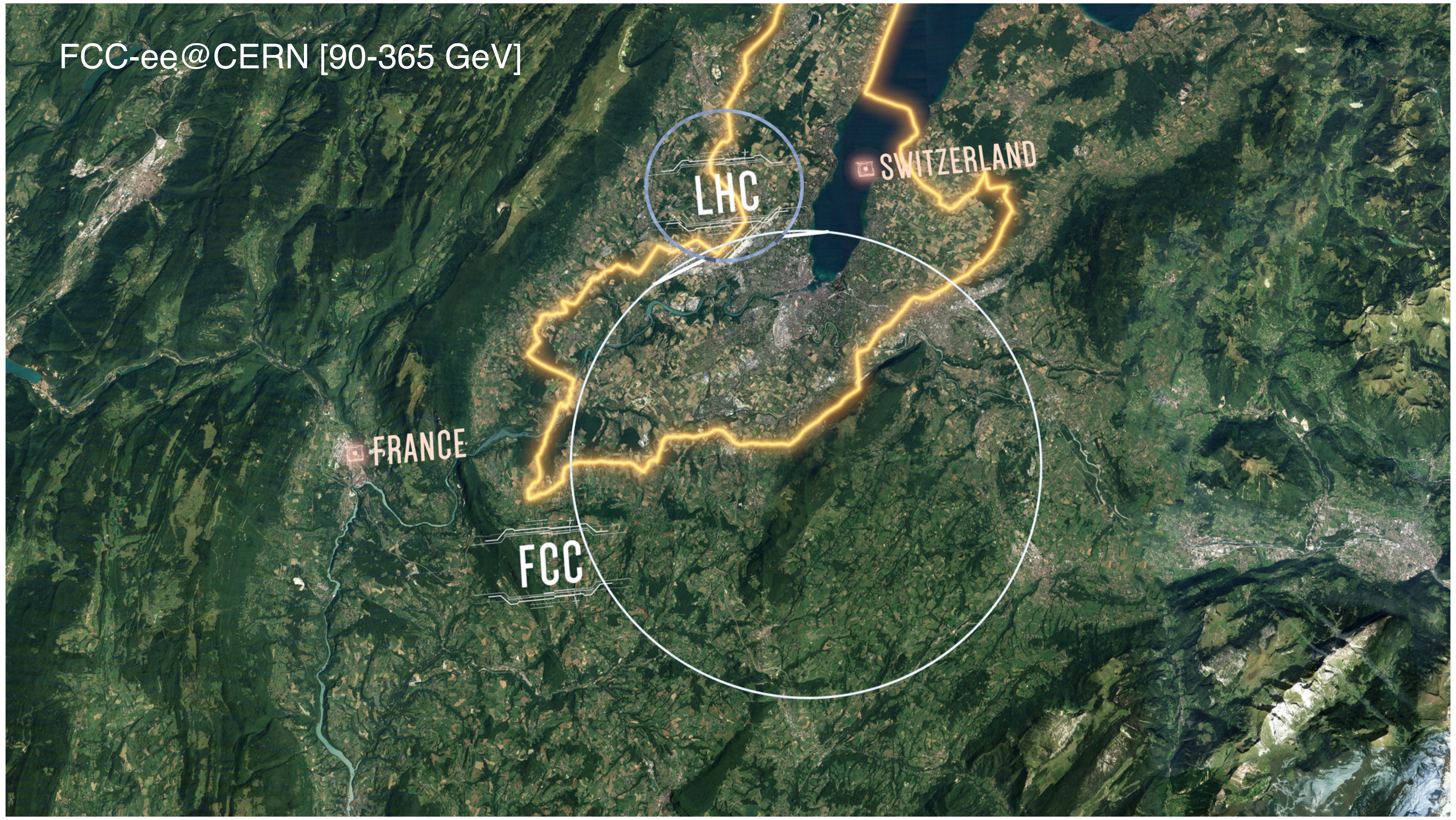
Circular e$^+$e$^-$ Colliders

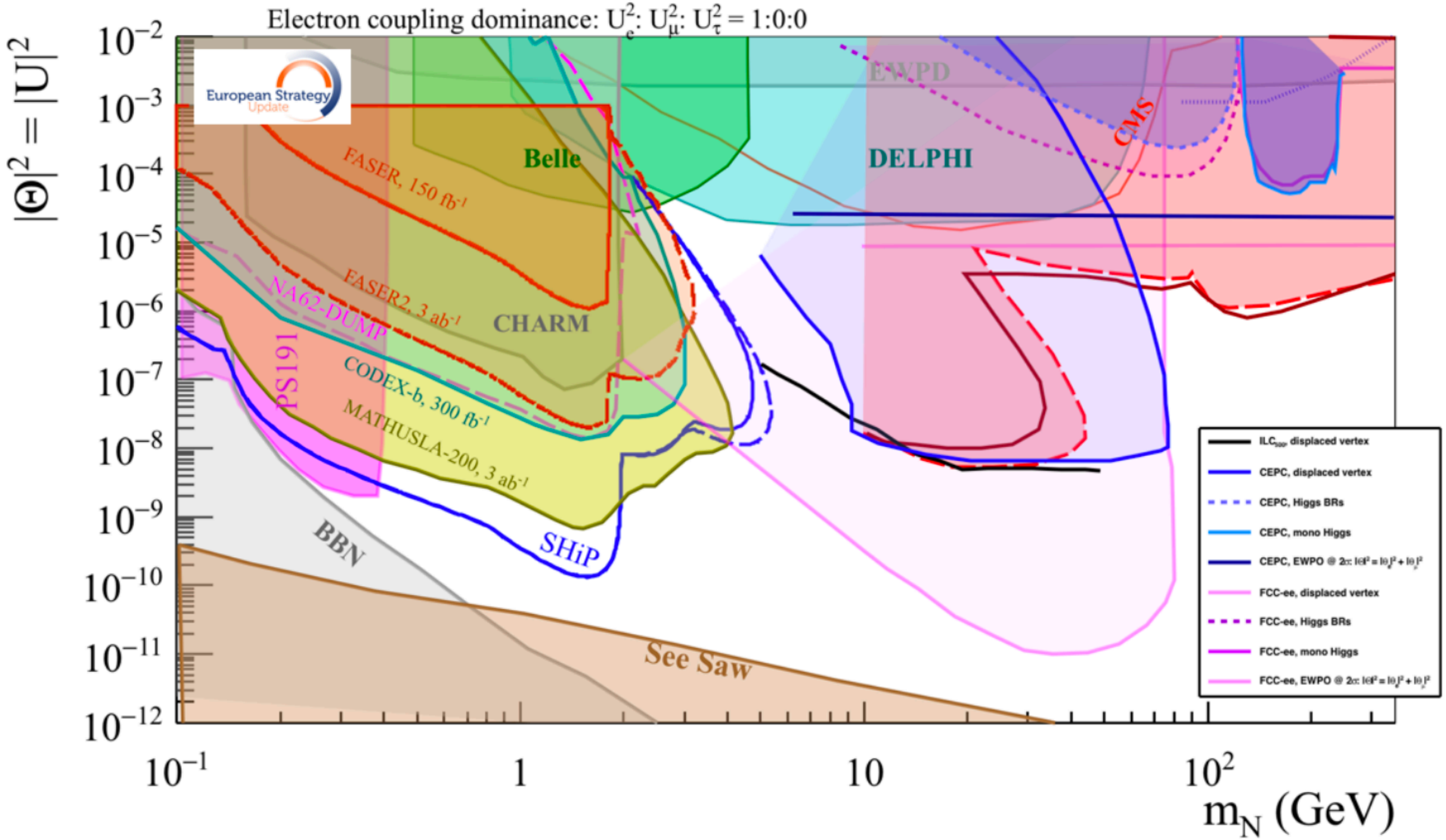


http://cepc.ihep.ac.cn/

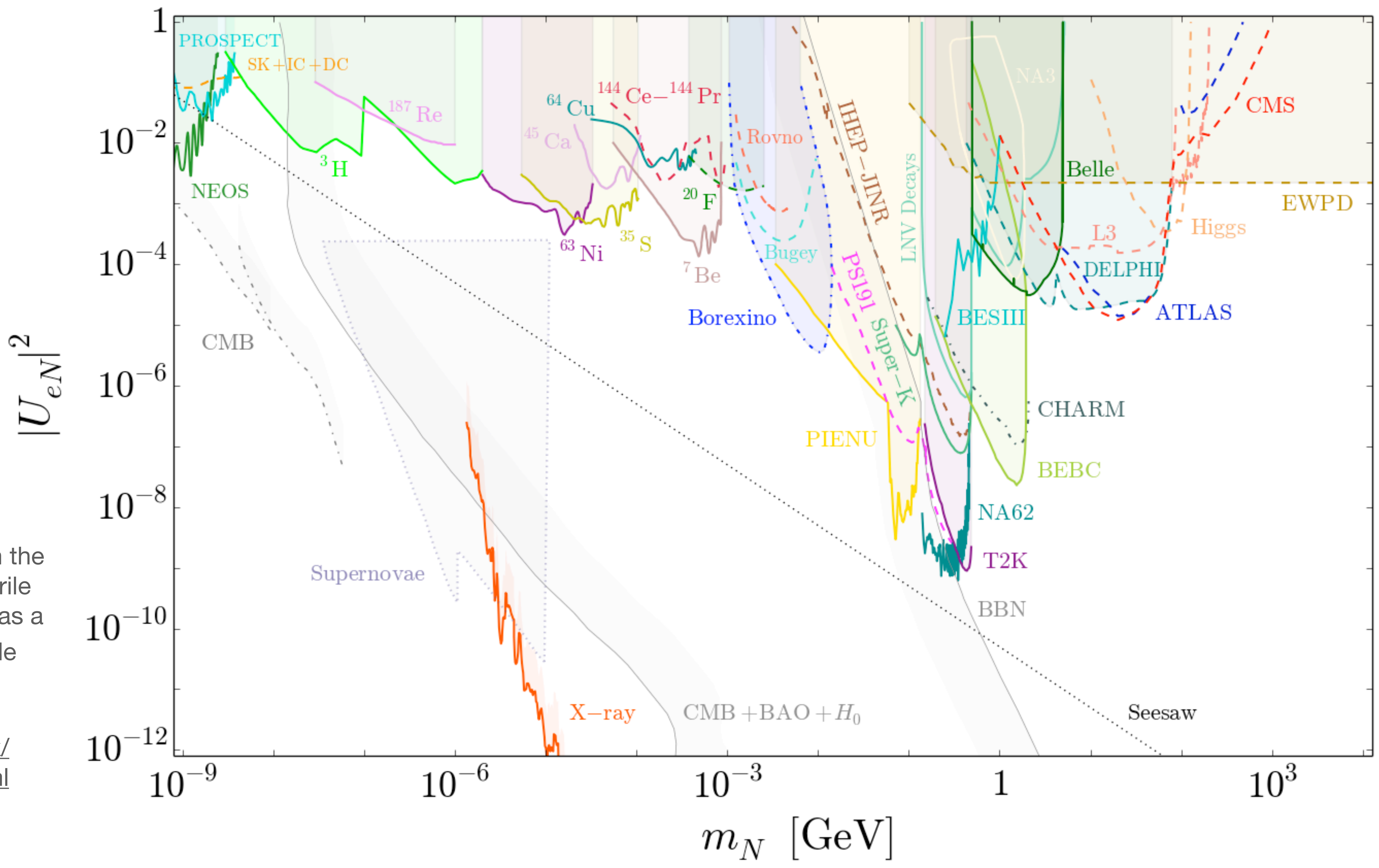
FUTURE CIRCULAR COLLIDER

https://fcc-ee.web.cern.ch/





90% CL exclusion limits for a HNL mixed with the electron neutrino, from the Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020 (https://cds.cern.ch/record/2691414/)



Current constraints on the electron neutrino-sterile neutrino mixing $|U_{eN}|^2$ as a function of the sterile neutrino mass m_N

https://www.hep.ucl.ac.uk/~pbolton/plots.html

Future constraints on the electron neutrino-sterile neutrino mixing $|U_{eN}|^2$ as a function of the sterile neutrino mass m_N
https://www.hep.ucl.ac.uk/~pbolton/plots.html