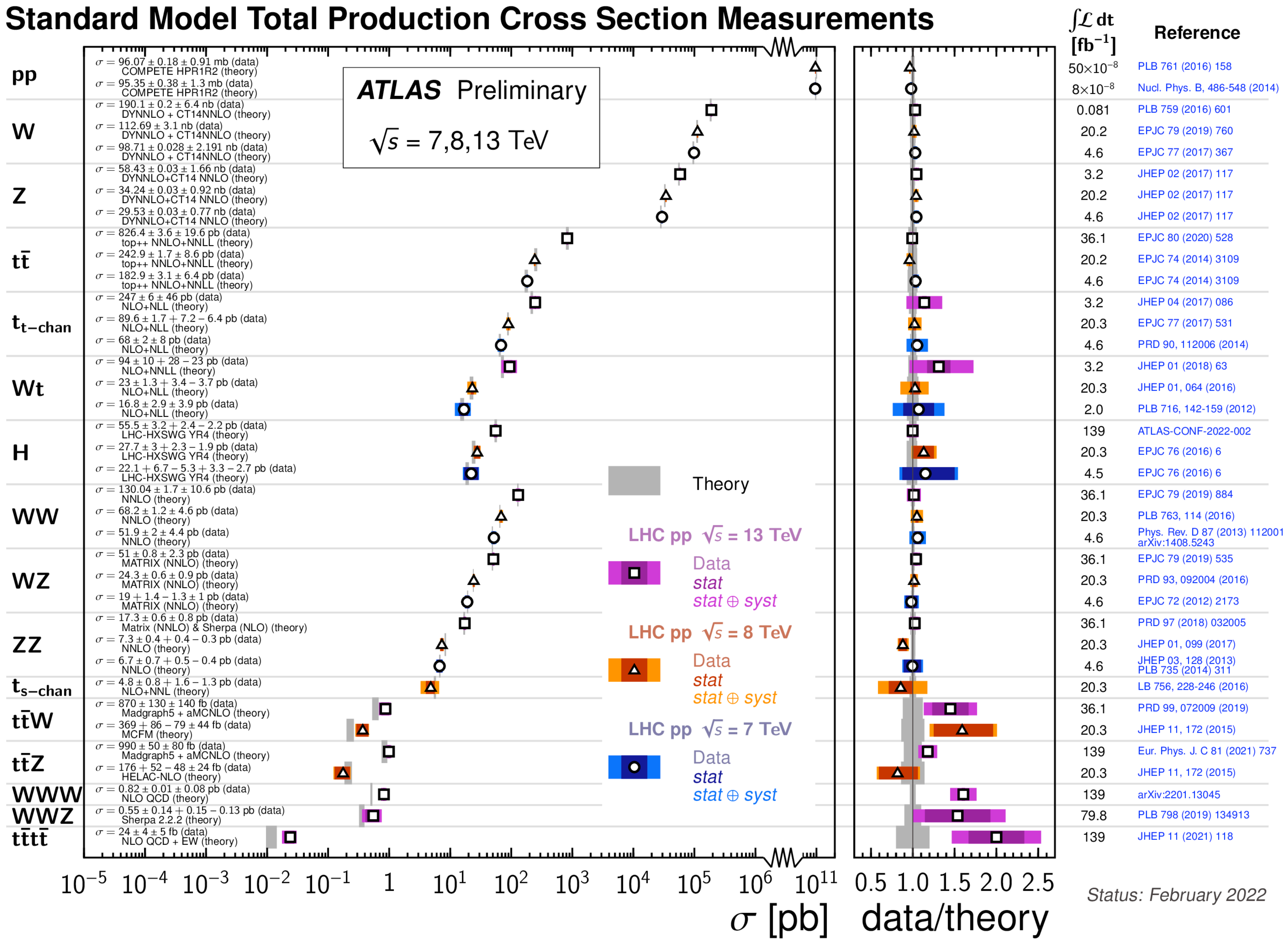
Future colliders: Physics motivation for future colliders

CHIPP/CHART Workshop on Sustainability in Particle Physics

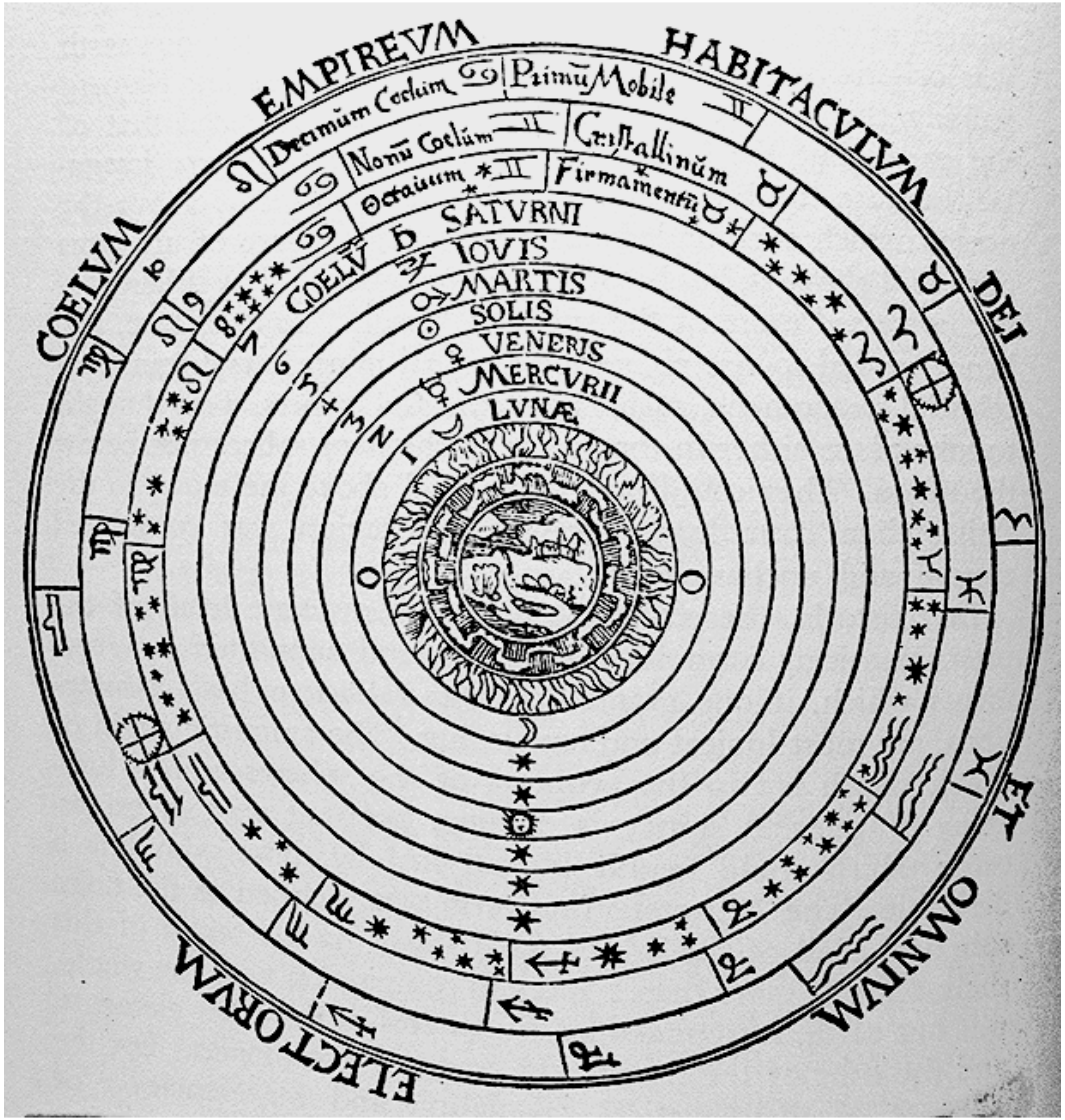
Rebeca Gonzalez Suarez - Uppsala University

The situation

- After decades, we have a model that works, is robust, thoroughly tested, and provides very precise predictions
- It works great



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



Aristotelian Ptolemaic system was remarkably plausible and powerful as a scientific theory but it was known that it had some “imperfections”

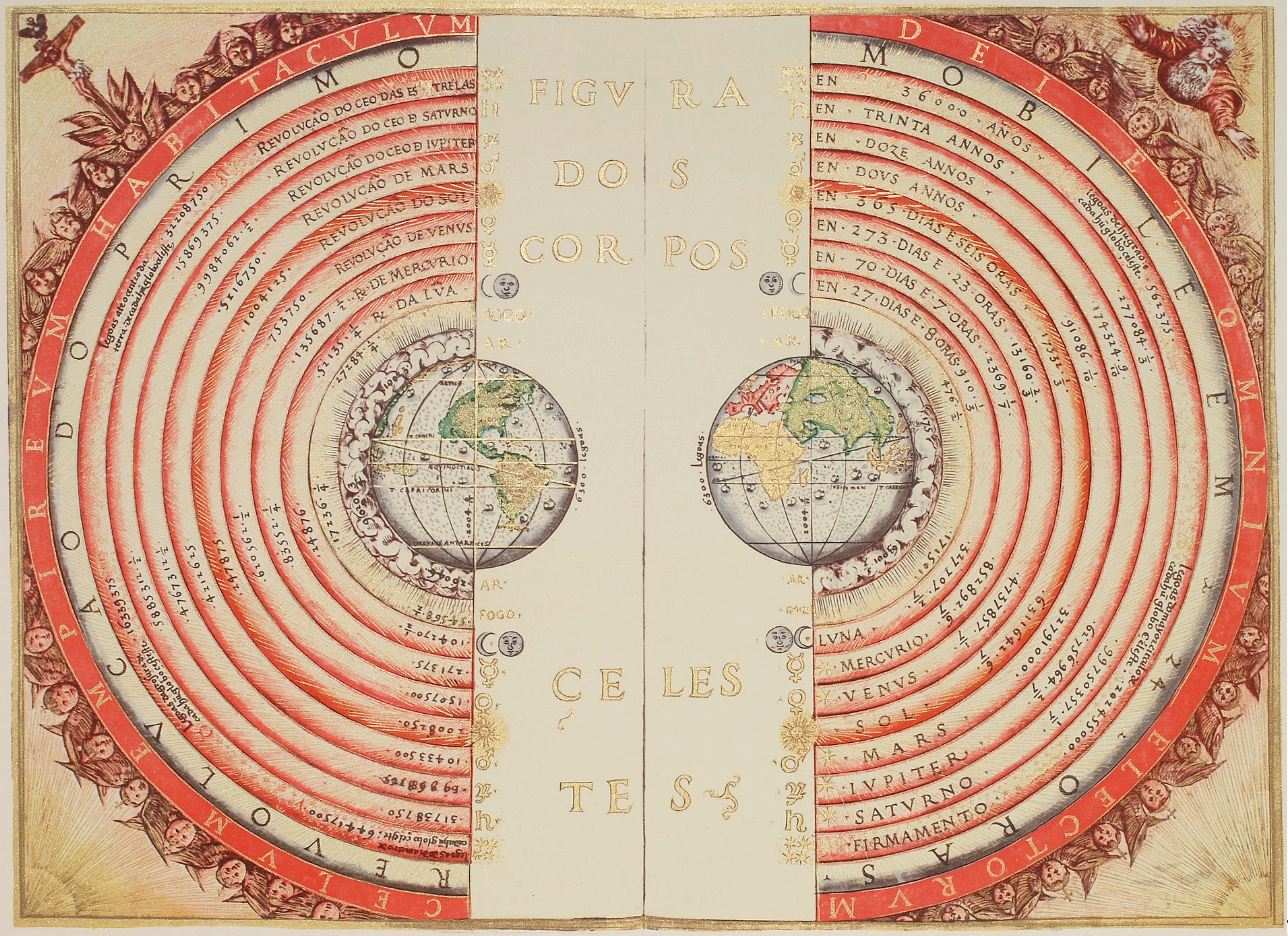
Our model

Also has some "small imperfections"

- Neutrinos have nonzero masses
- The masses of the other particles are weird
- It cannot describe a couple of important effects
  - Dark matter, dark energy, gravitation
- It has some 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)



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

Let's not take that long this time!

What do we have at hand

- 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 (previous talk by Daniel Schulte)
- 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

FUTURE CIRCULAR COLLIDER

FCC

The Swiss knife of future colliders

- A Swiss product
- Does everything you need, pretty well
- It is based on existing technology from decades ago, optimized for today's needs
- **It may be expensive, but it is going to last a lifetime**
  - **You are buying quality**
- It can keep you alive in the field! (Or the field alive!)

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

Let’s then look at the physics

Strength

In physics potential

Introductory Remarks - F. Gianotti

	$\sqrt{s}$	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

	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

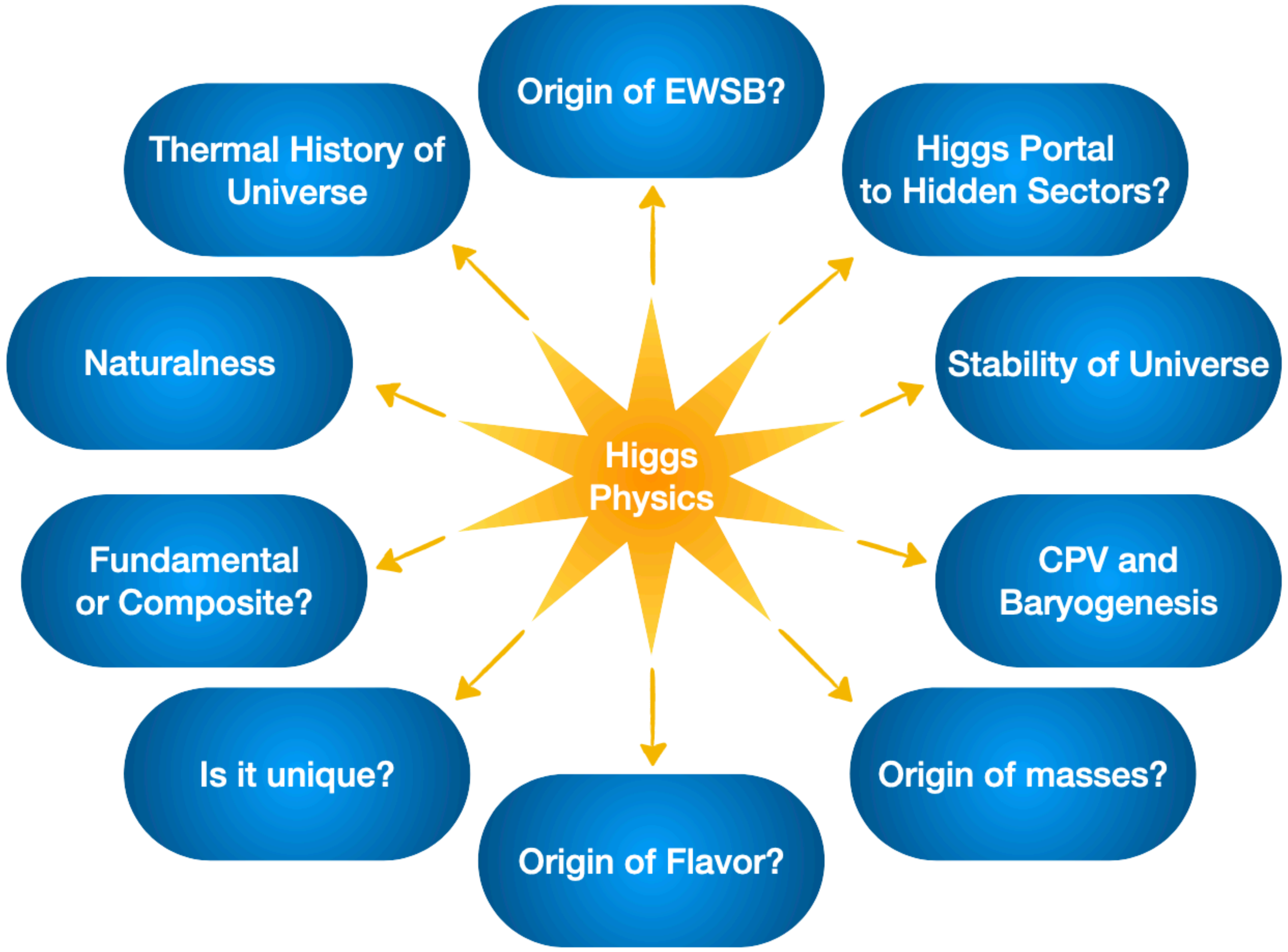
Detector requirements from physics - M. Selvaggi

- **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
- **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

HET factory physics

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

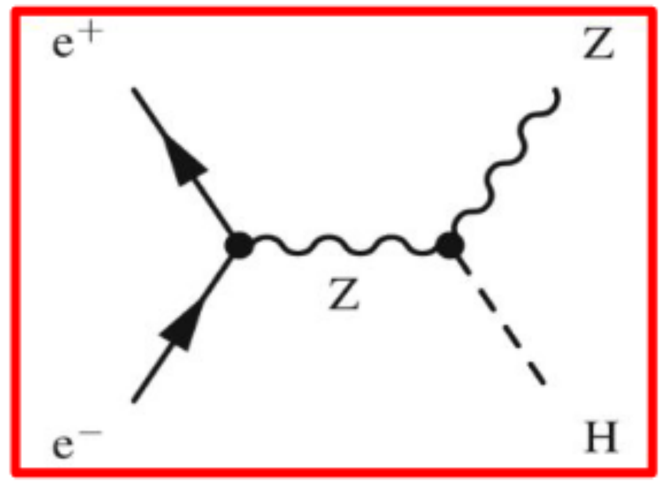


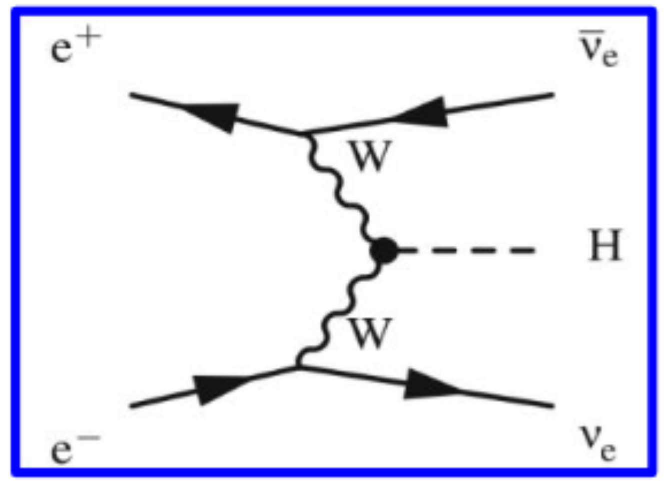
arXiv:2209.07510

Giant step forward in precision

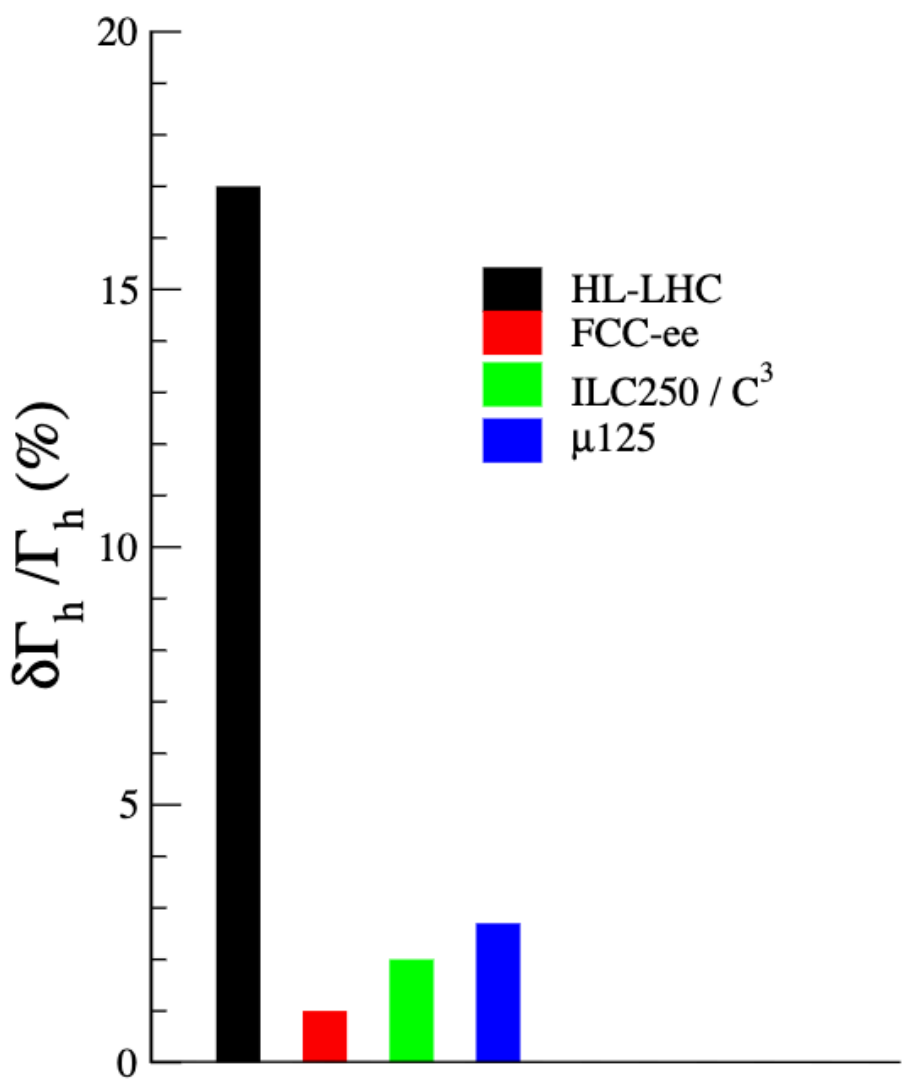
Wednesday session in the FCC week 2023

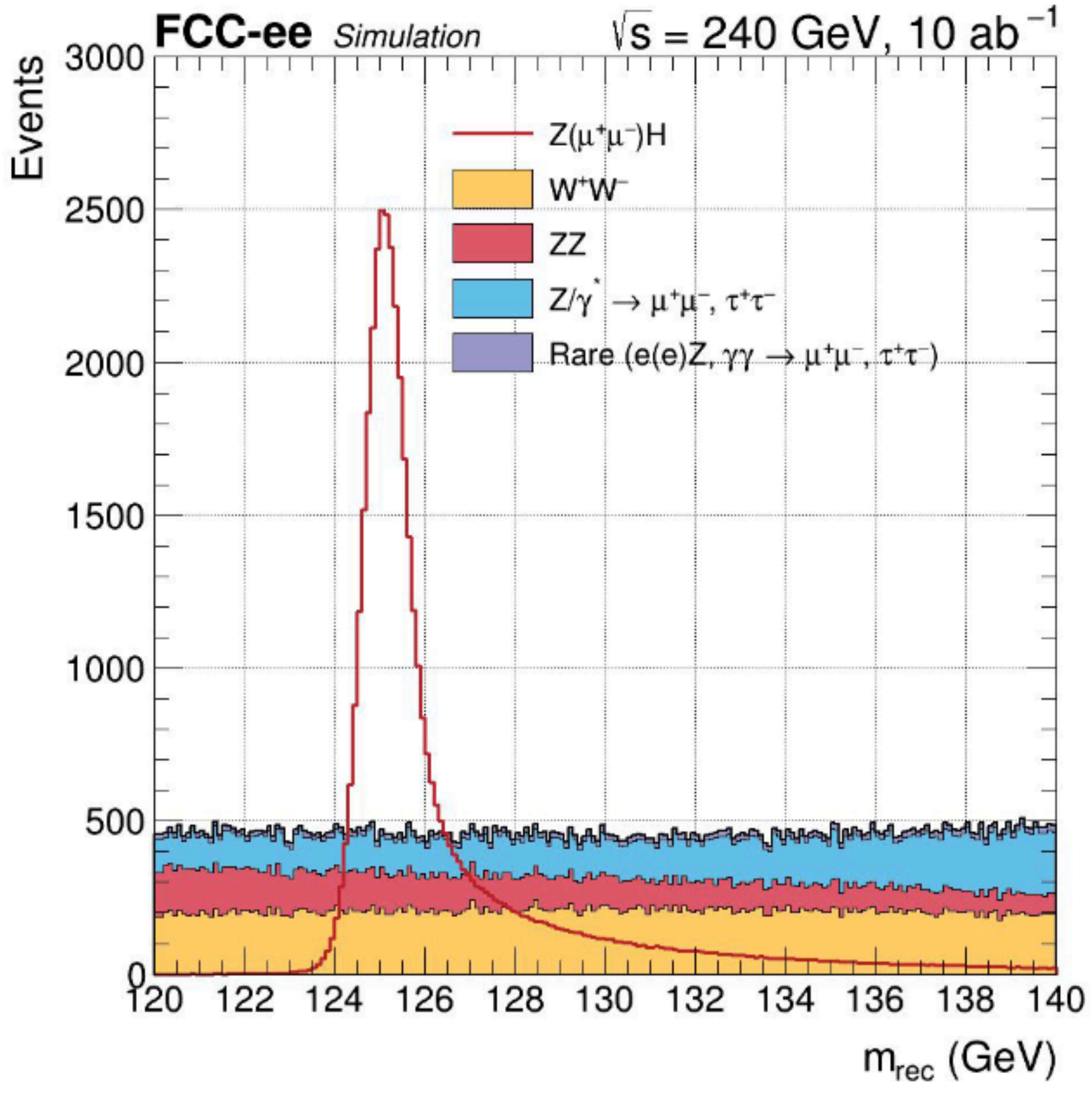
- x10 precision
- Recoil mass method for ZH production
  - Measurement of σ_{ZH} ⇒ Absolute measurement of HZZ interaction
  - Precise Higgs mass O(MeV) and width determination <1%





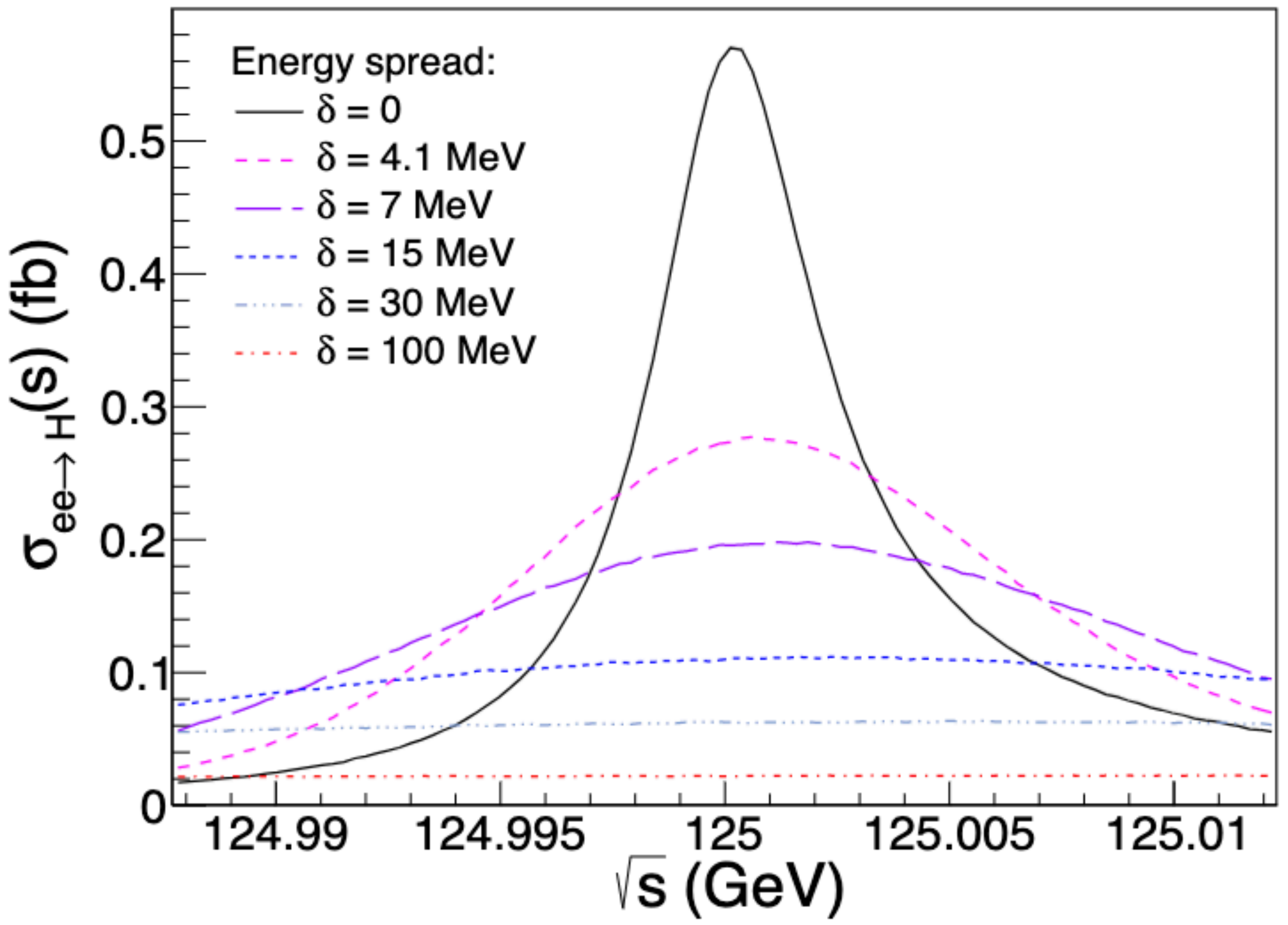
Total Higgs production @ FCC-ee (baseline – 4 IP)		
Threshold	ZH production	VBF production
240 GeV / 10 ab^{-1}	2 M	50 k
365 GeV / 3 ab^{-1}	0.4 M	0.1 M

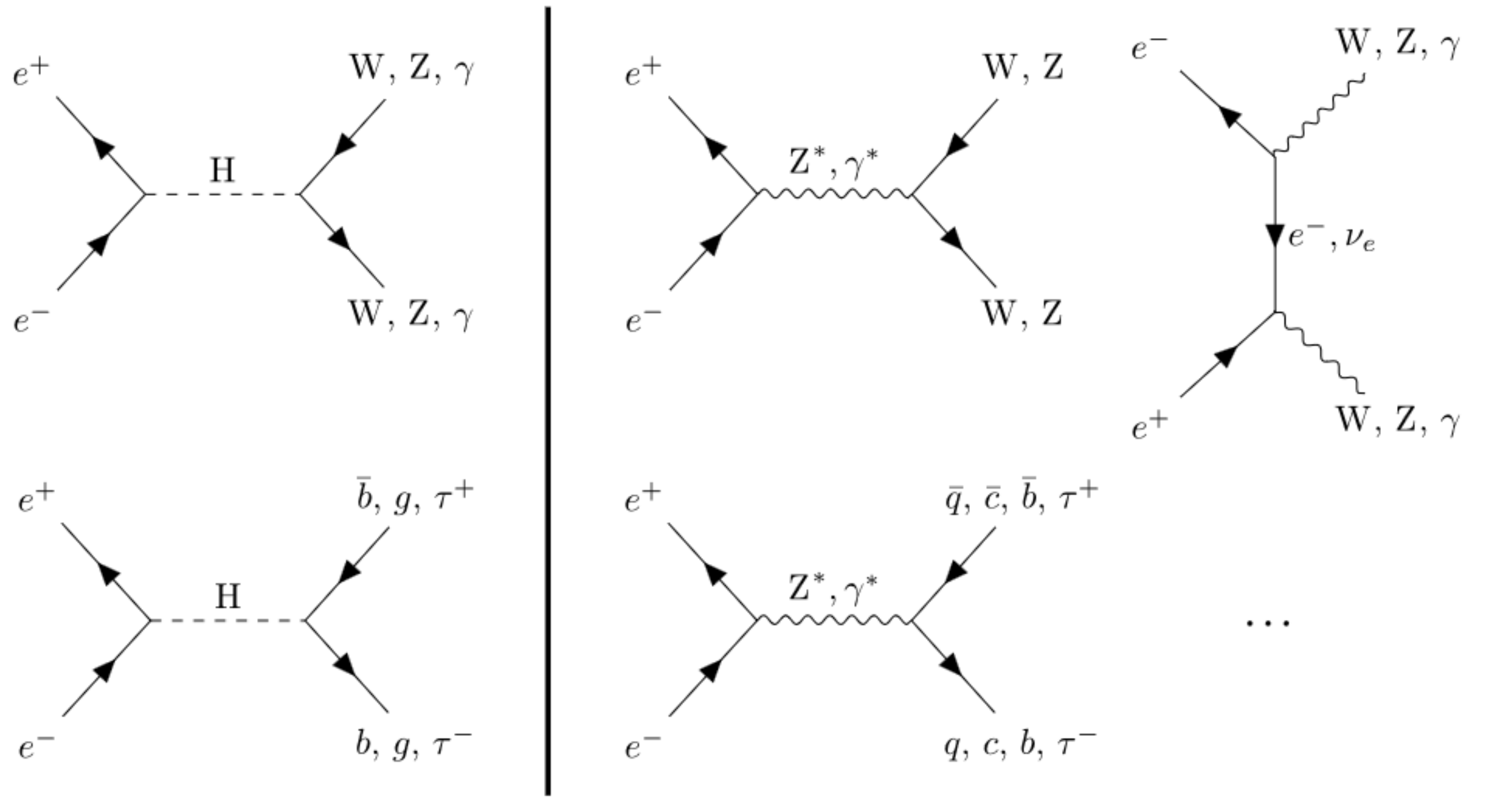


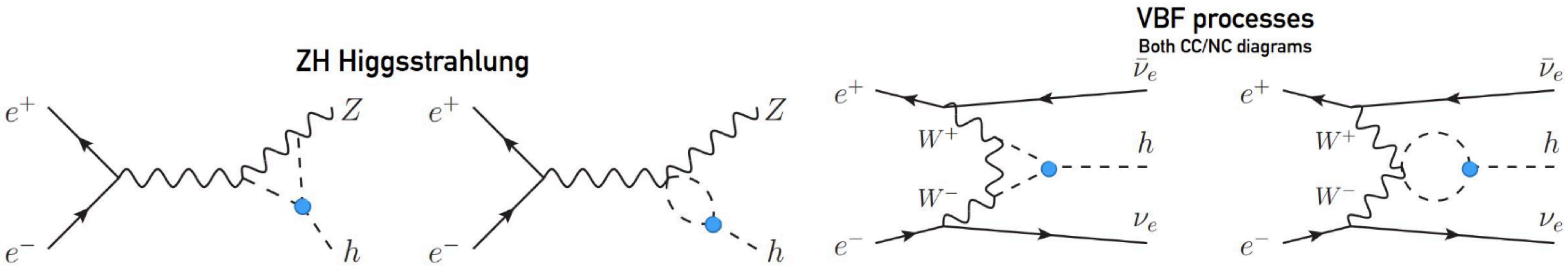


Per-mil level in couplings

- 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 $\sqrt{s}$ = 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

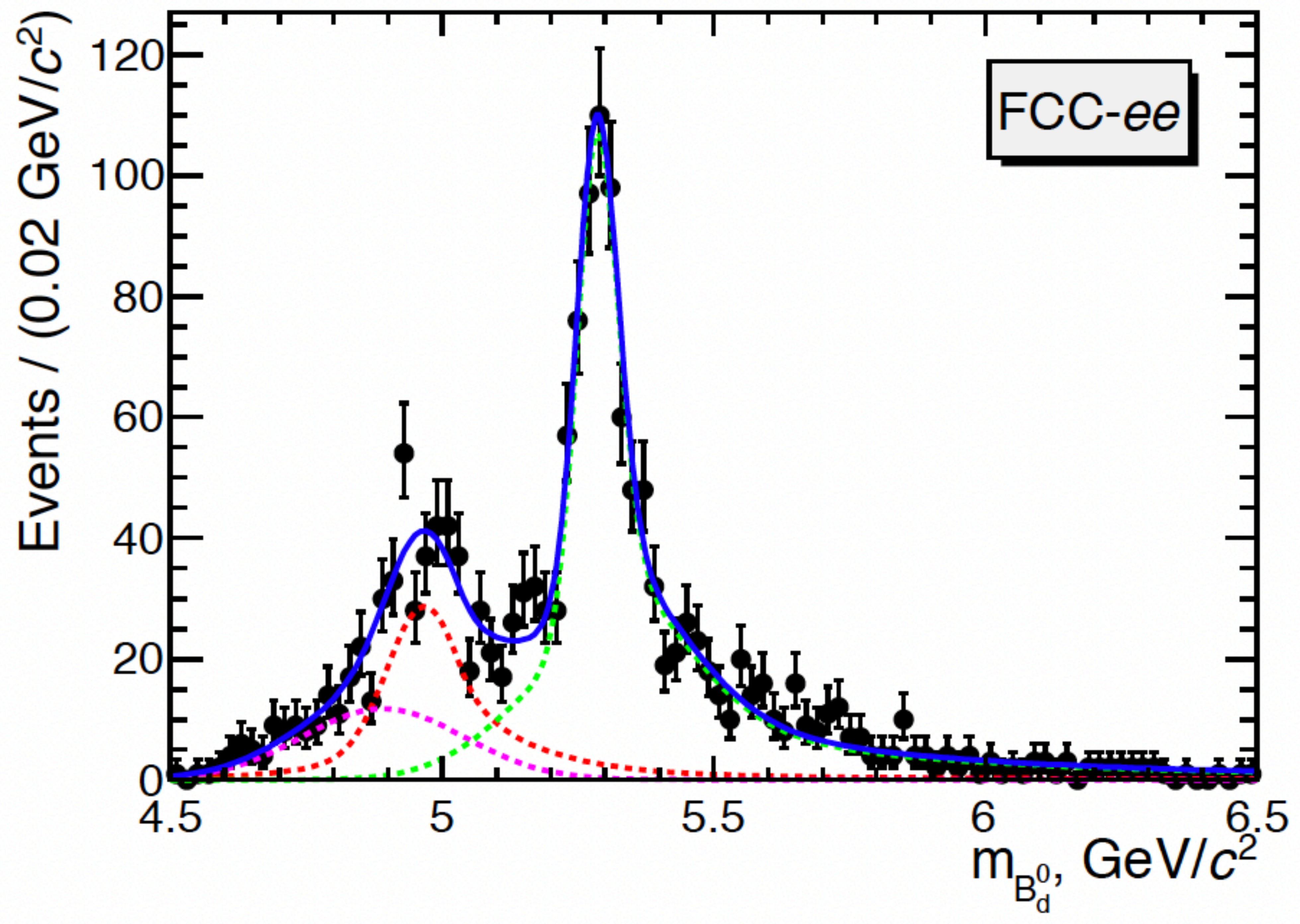
Precision electroweak - Christoph Paus

- $O(10^5)$ 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
σ^0_{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
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	$231,480 \pm 160$	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 $A_{FB}^{\text{pol},\tau}$; 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



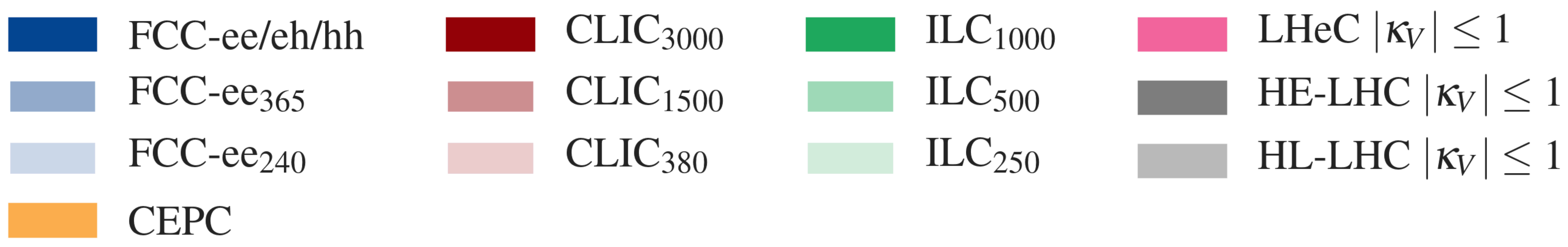
Flavour physics - Jernej F. Kamenik

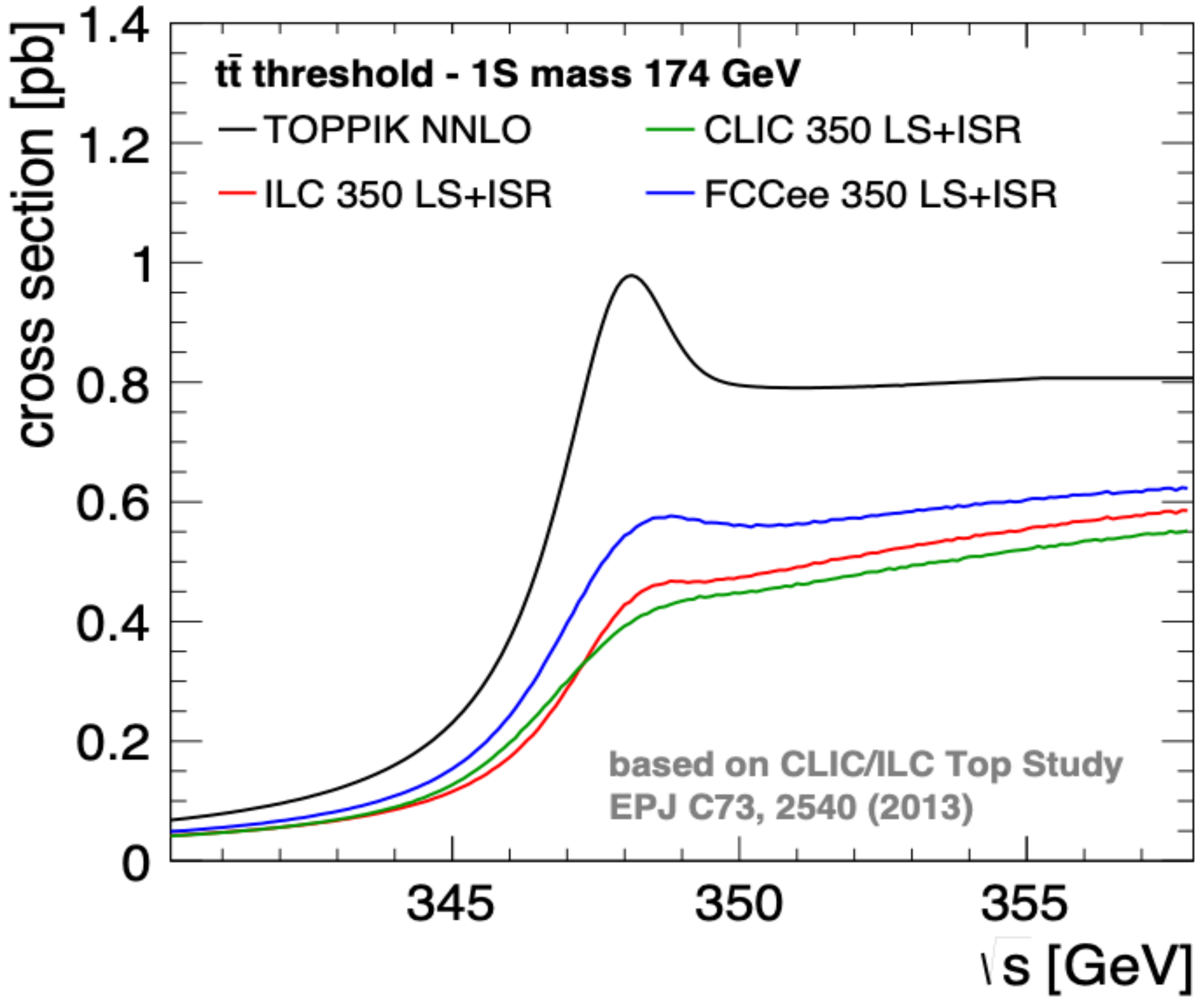
Wednesday session in the FCC week 2023

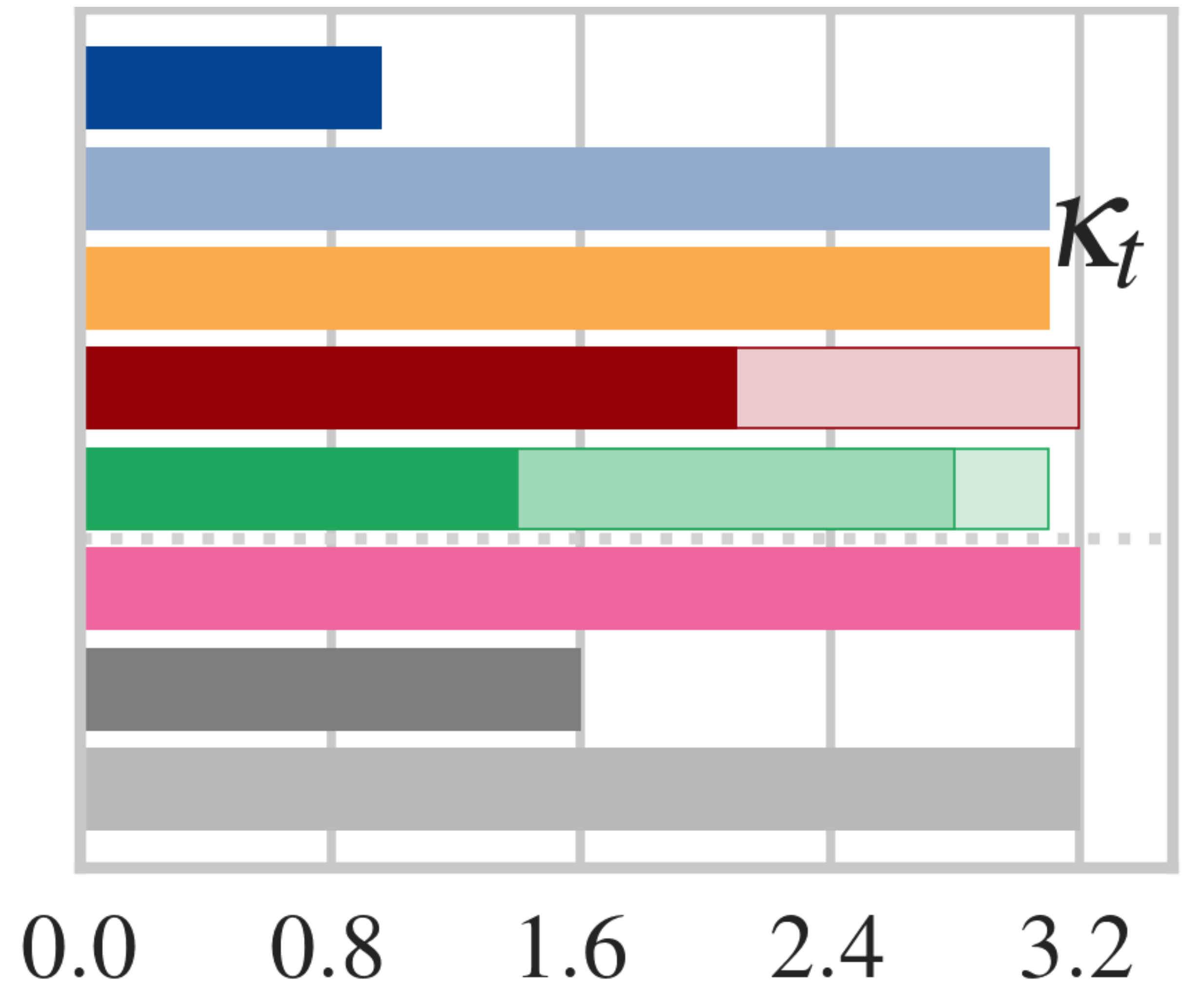
Top

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





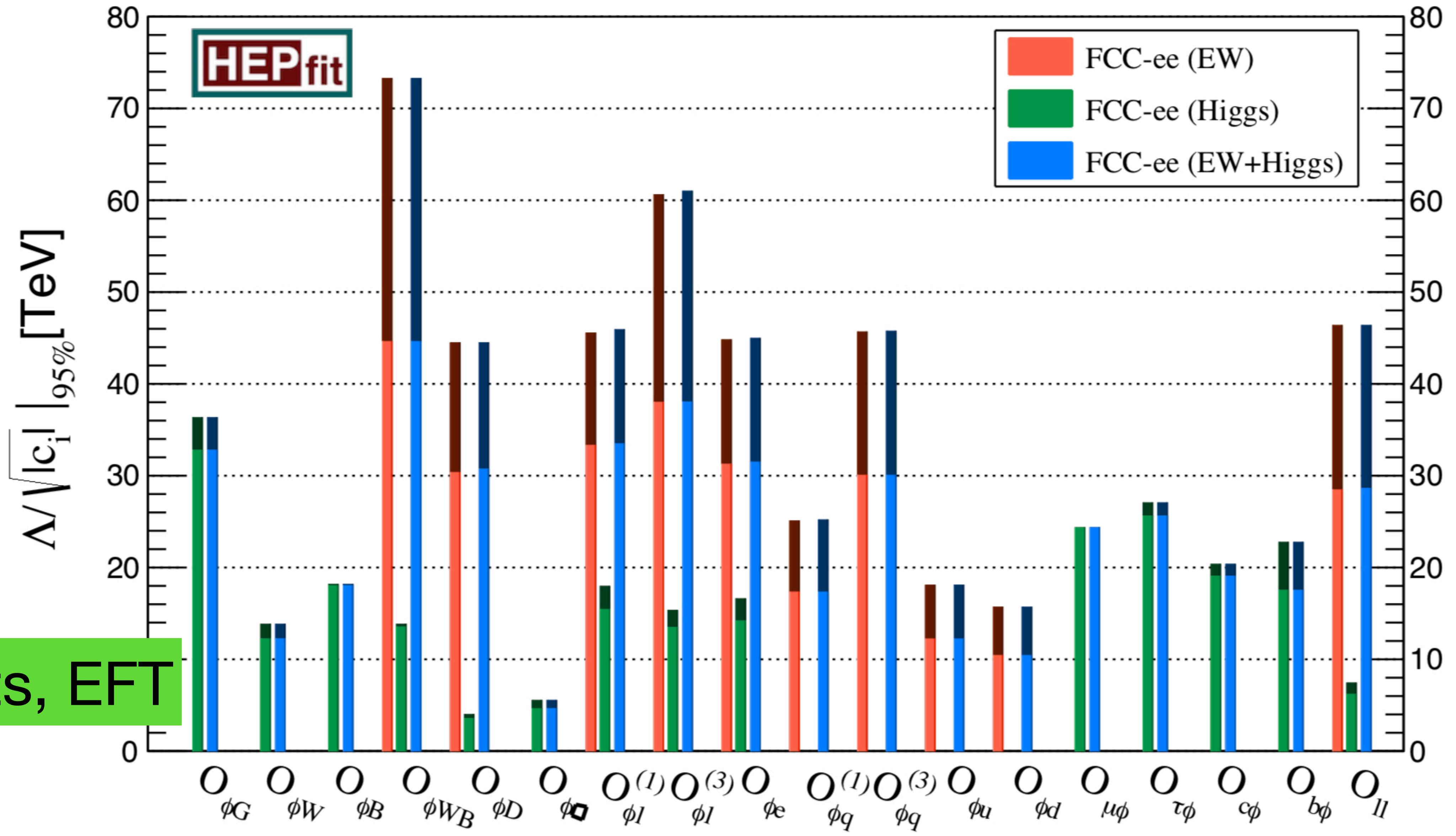


But enough about precision

Direct searches for new physics

- Direct search at high scales will be the business of FCC-hh
  - 6x HL-LHC mass reach
- But FCC-ee also offers potential for direct searches of new, feebly interacting particles that could manifest **long-lived signatures** Signature-driven!
  - closely linked to central questions of the field:
    - dark matter, neutrino masses, BAU
    - ALPs, exotic Higgs decays, Heavy Neutral Leptons
    - Complementary prompt searches also considered

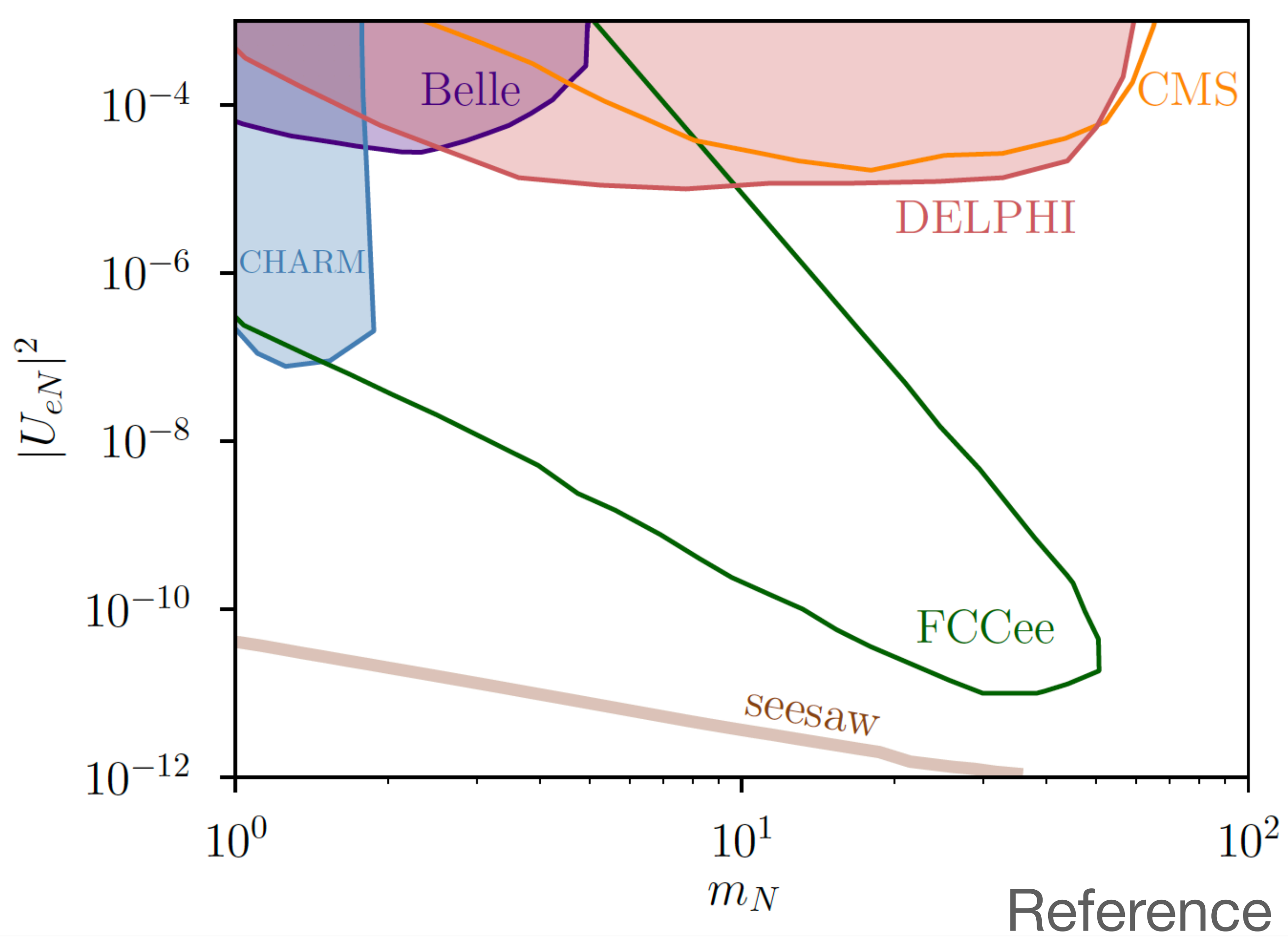
Indirect → all measurements, EFT



Heavy Neutral Leptons

Flagship search for new physics

- Many of the current HNL limits cover large neutrino mixing angles. For small values of the mixing angle, the decay length of the HNL can be significant → LLP signature (displaced vertex search)
- The FCC-ee will offer an unbeatable reach for HNL at the Z-Pole



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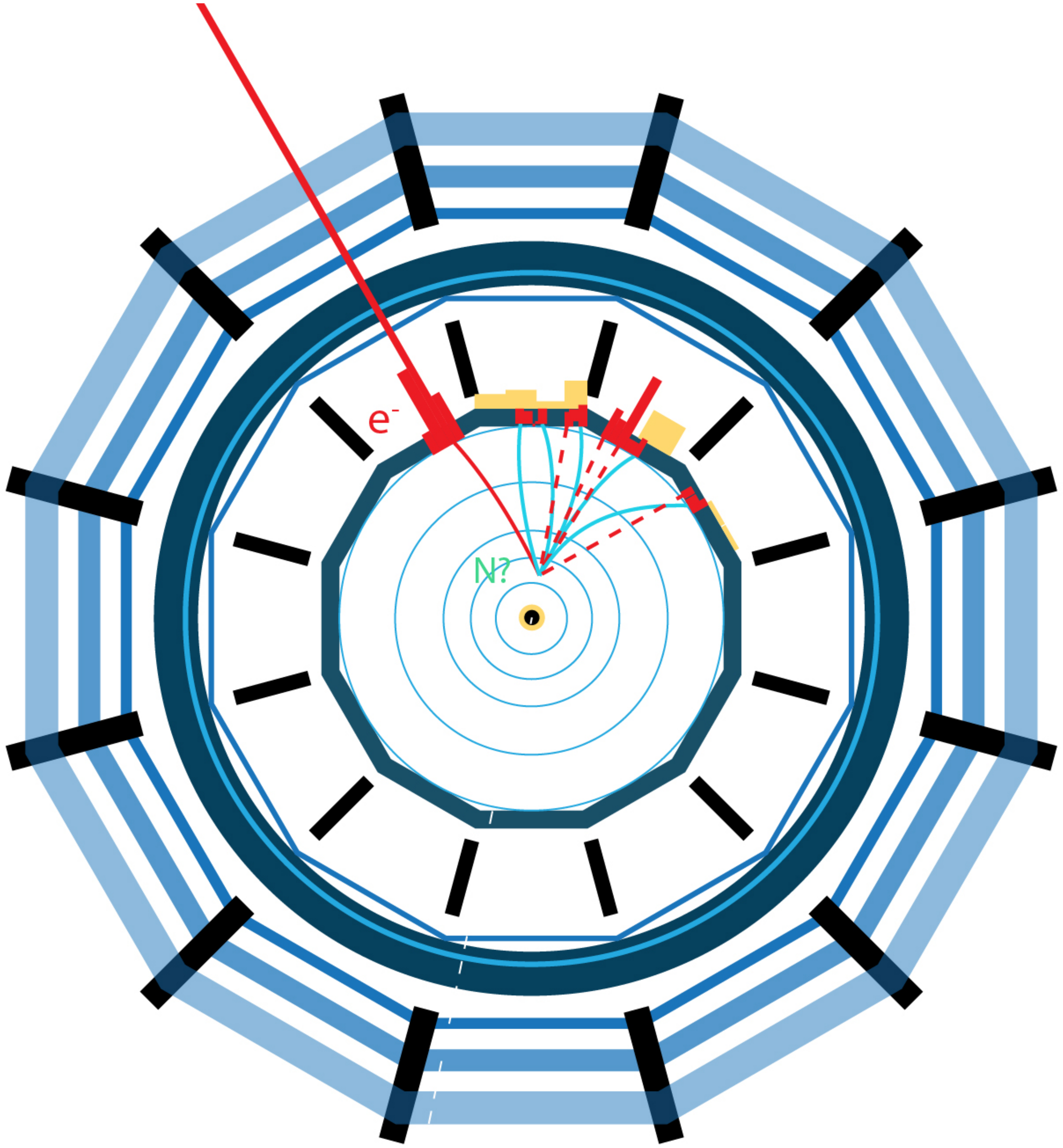
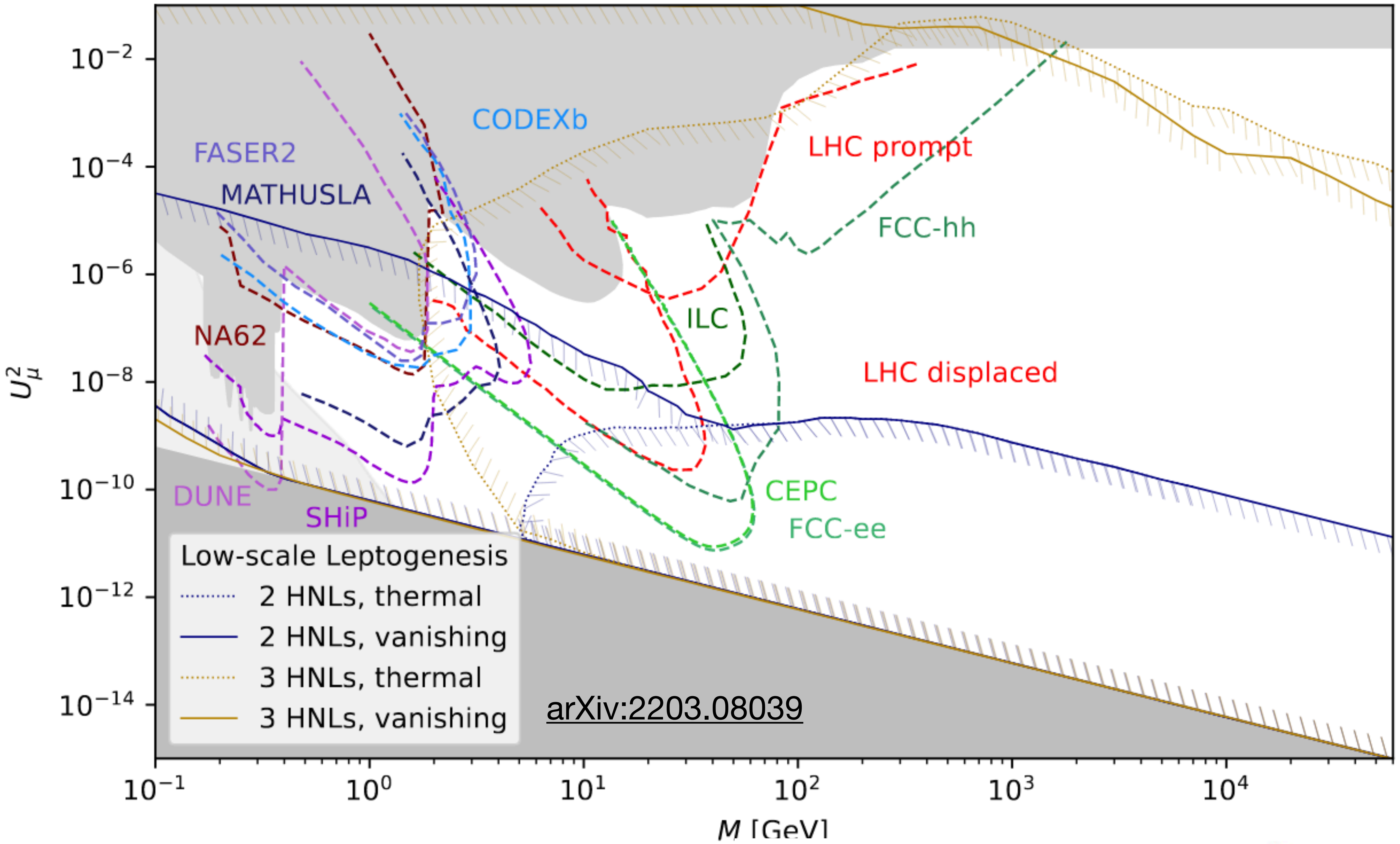
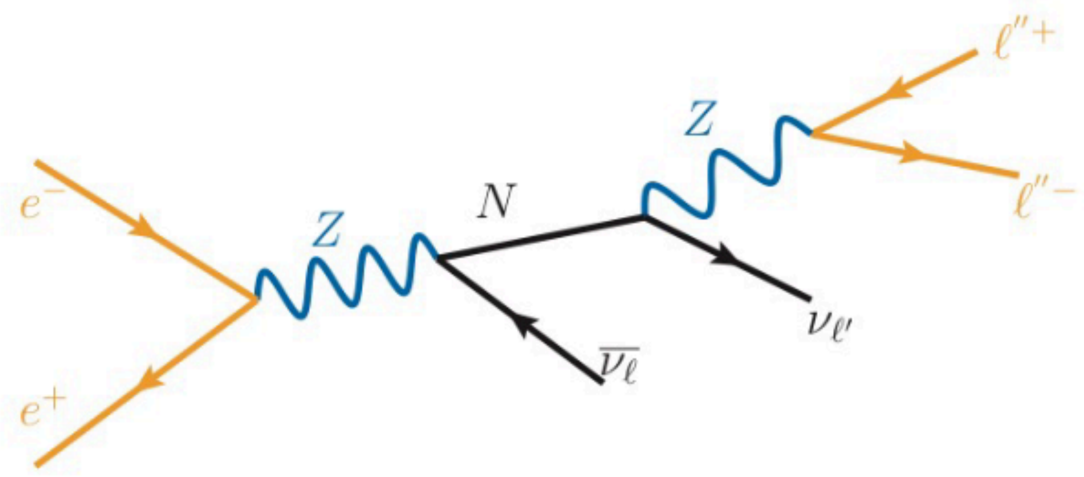


Experimental sensitivity studies

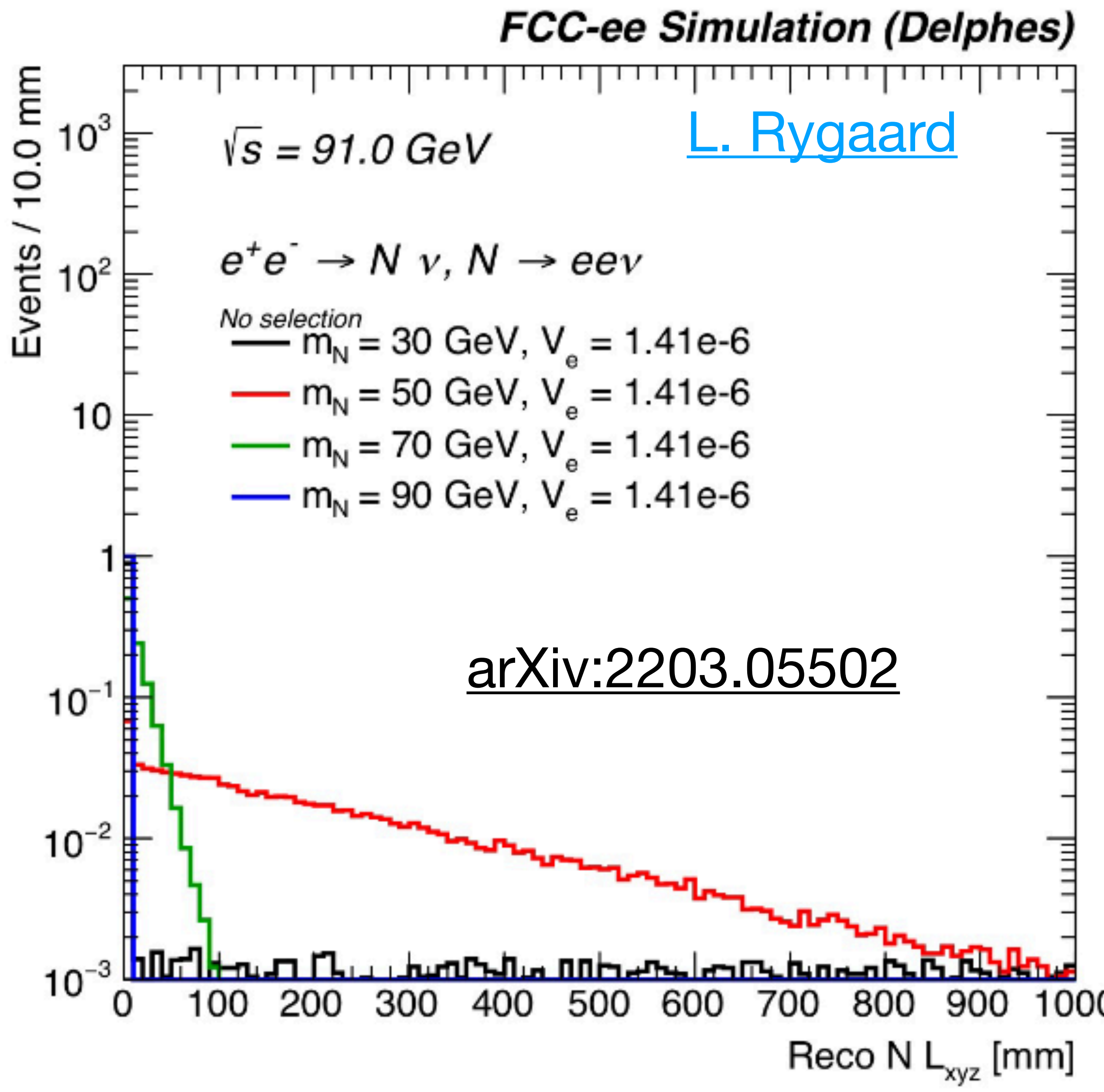


- Work in progress towards a complete sensitivity analysis implemented in FCC software
- First steps in eev final state (other final states to be added)
- Majorana/Dirac nature also studied (T. Sharma)

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



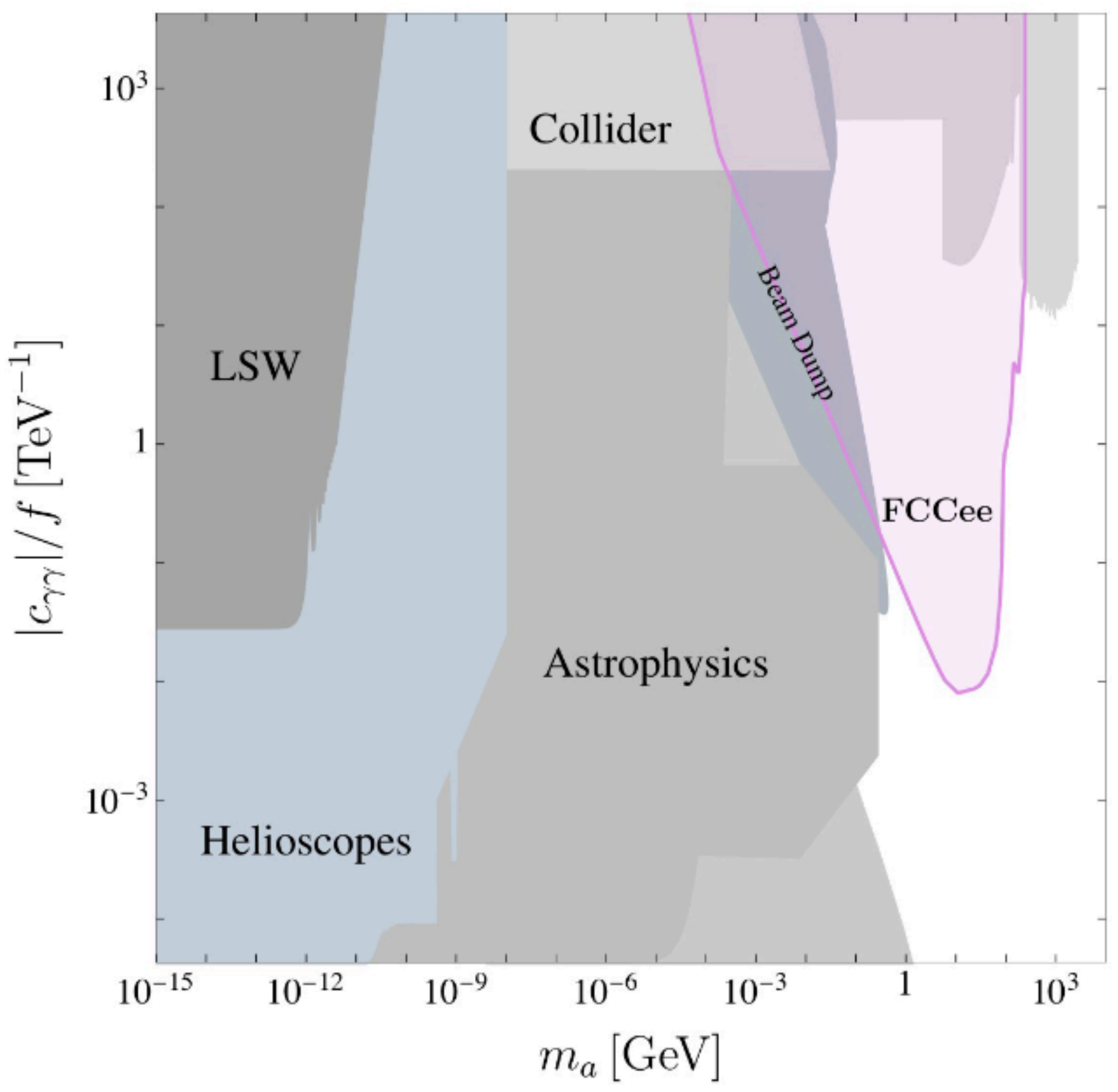
Reconstruction-level three-dimensional decay length of the N

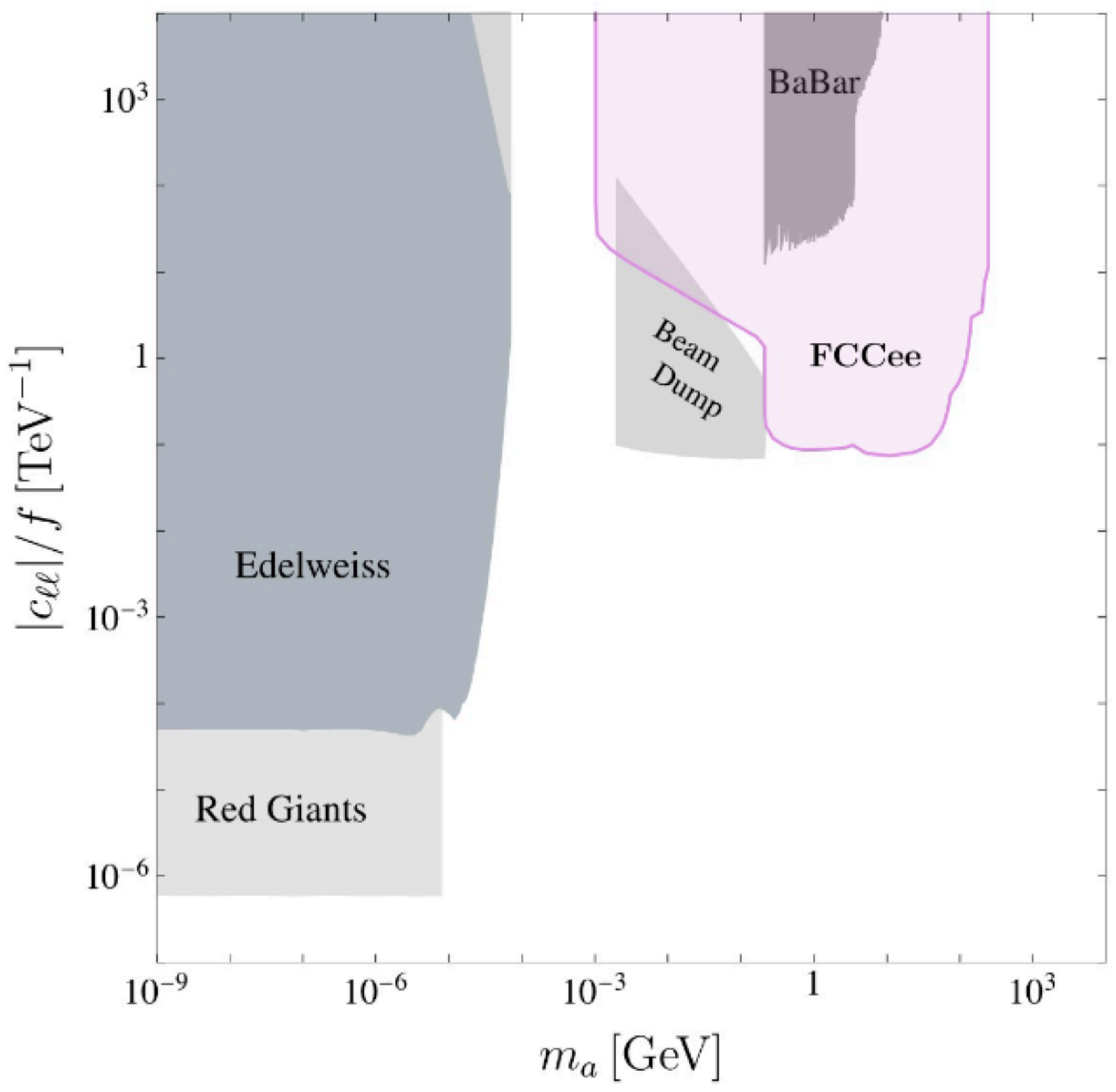


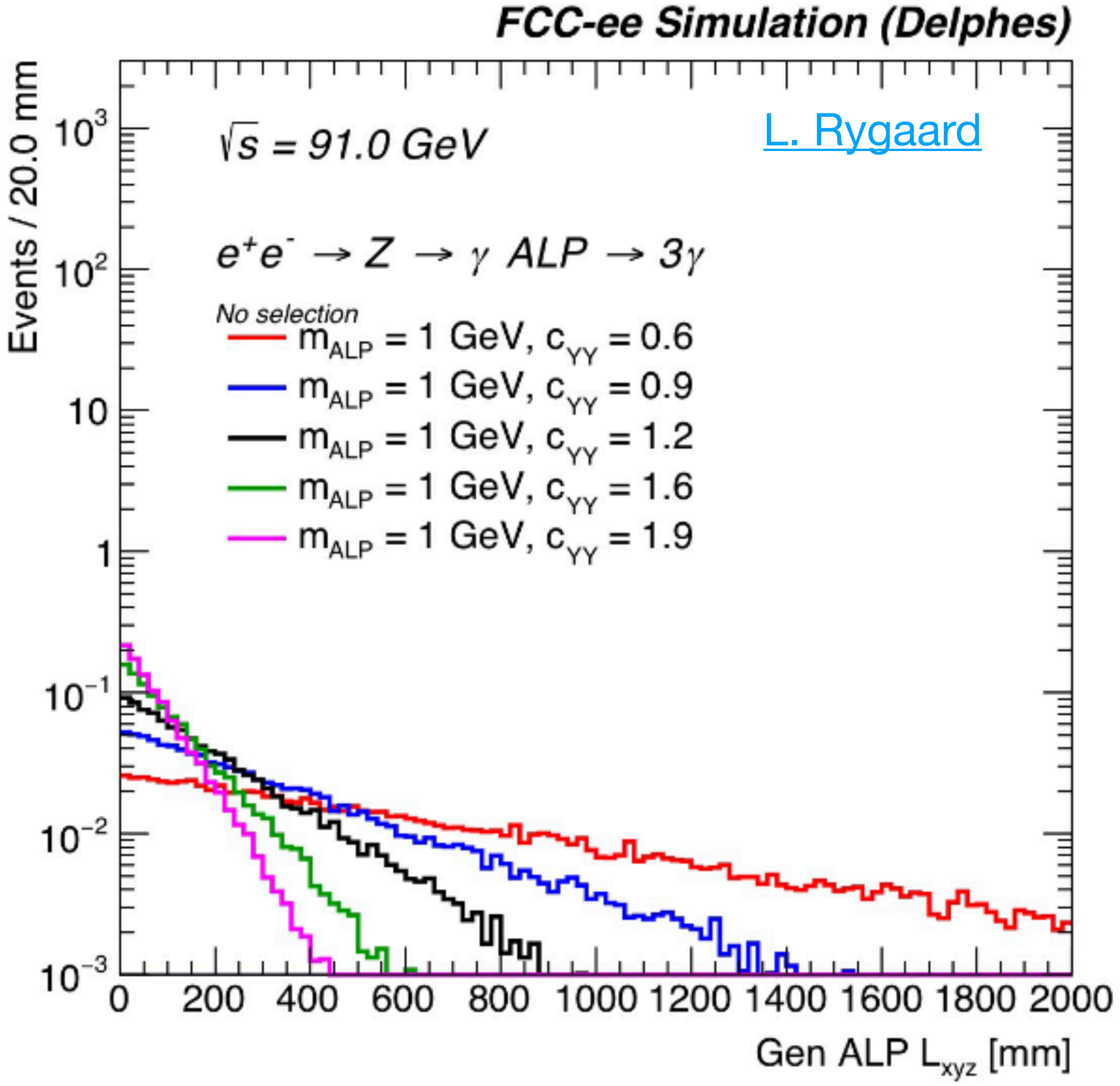
Axion-like particles

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

Exotic Higgs boson decays

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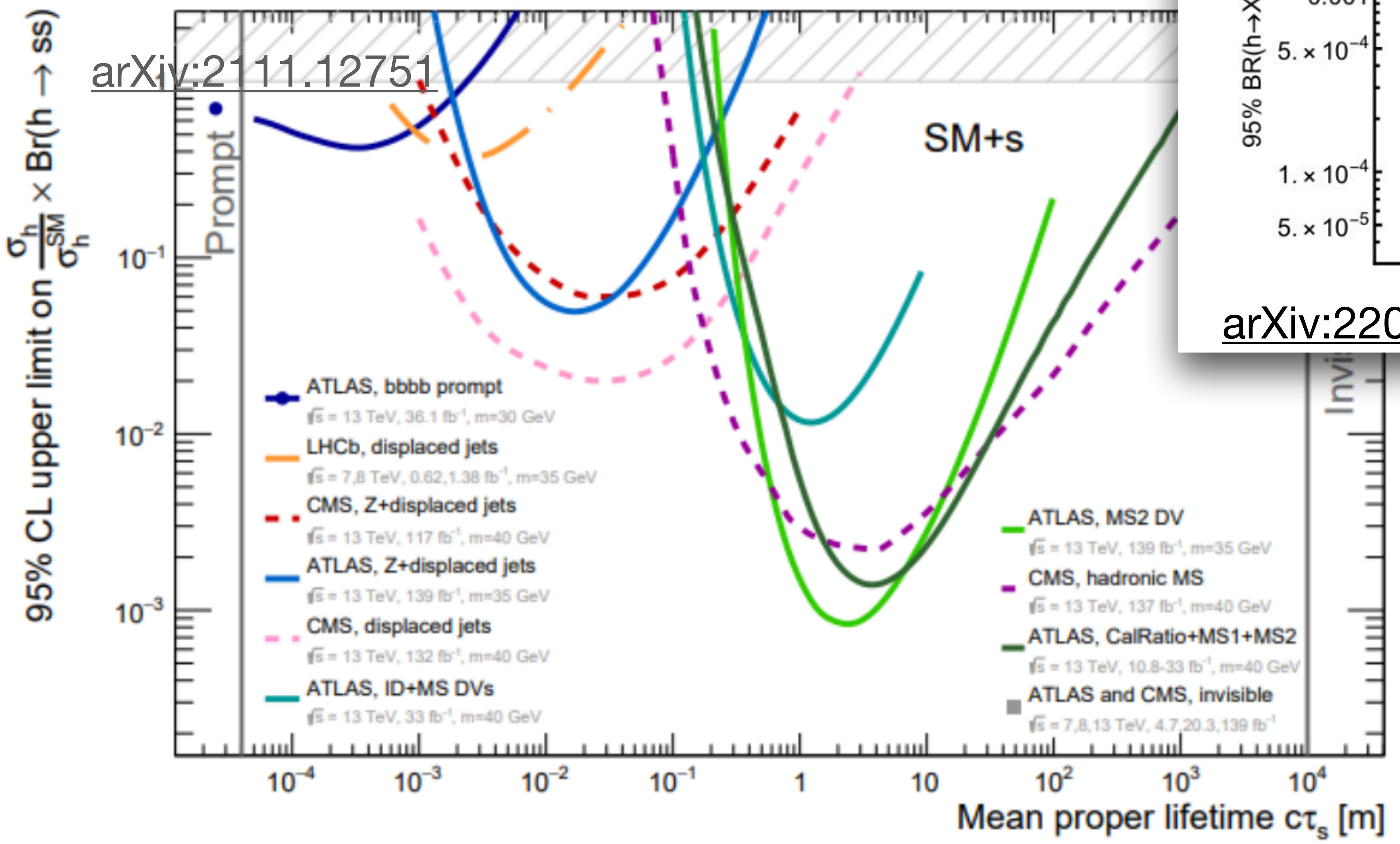
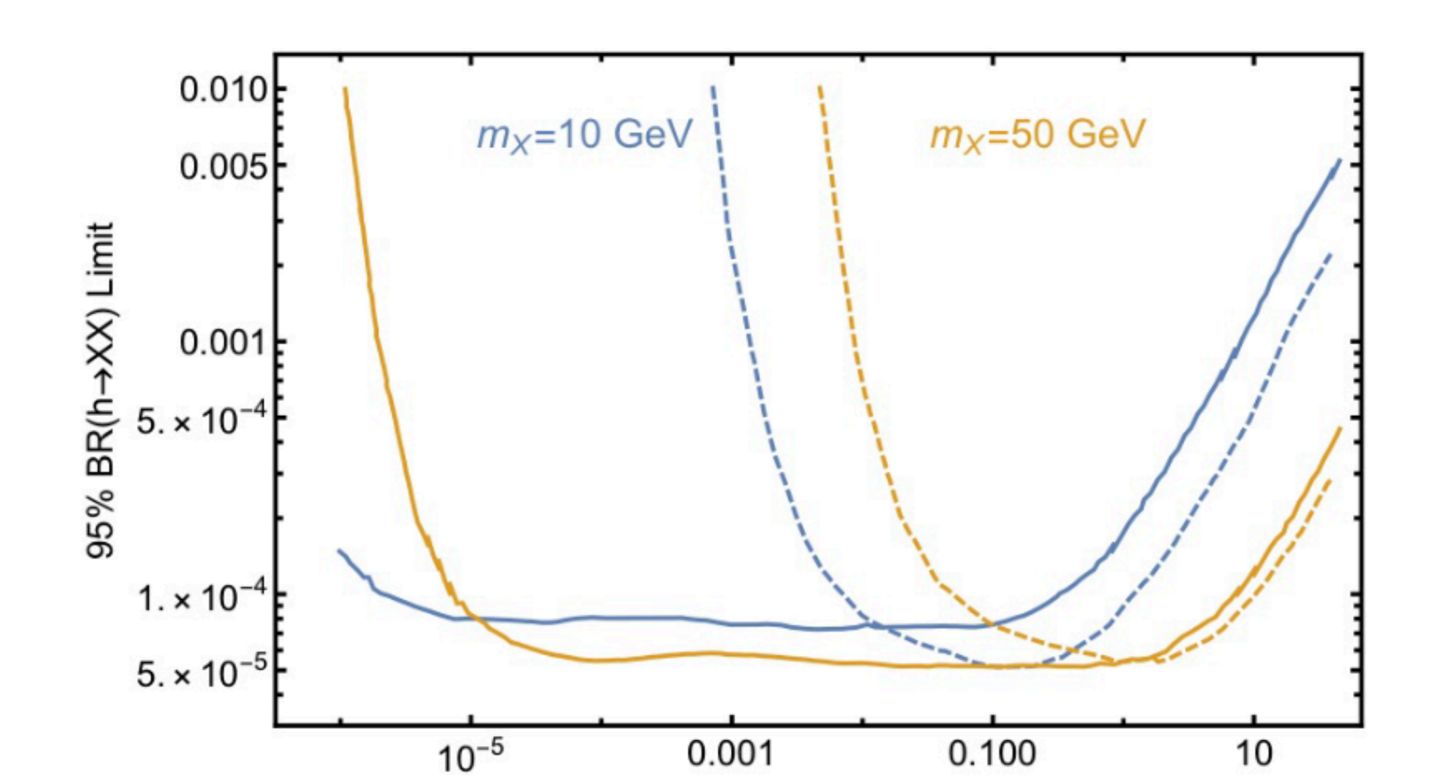
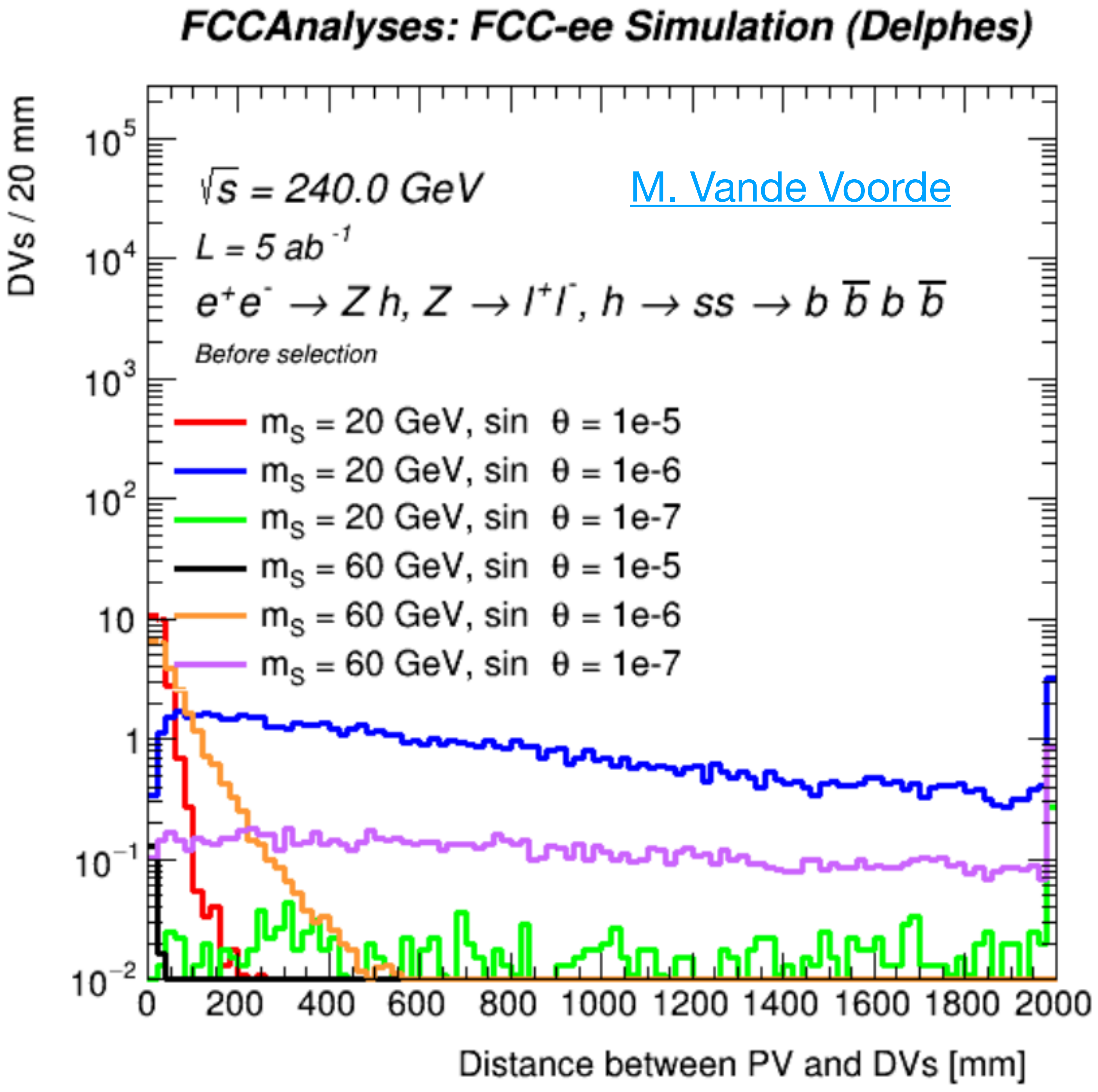
- Exotic Higgs decays to long-lived particles (LLPs) are possible and present in many models:
  - SM extensions with scalars/fermions/ vectors, MSSM, NMSSM, Hidden Valleys, Twin Higgs (arXiv:1312.4992, arXiv:1812.05588, arXiv:1712.07135)

arXiv:2111.12751



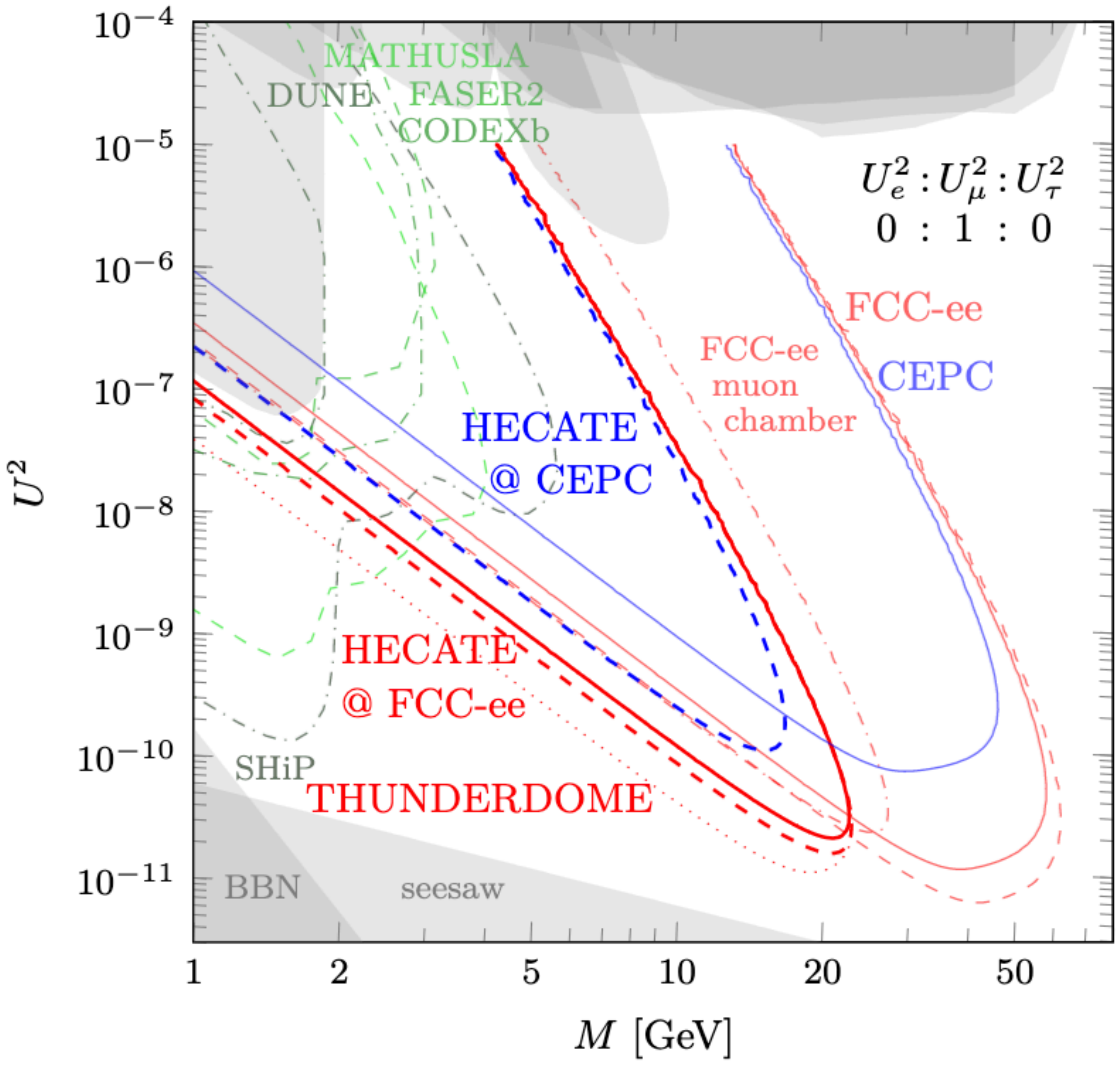


arXiv:2203.05502



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

Extra detectors!

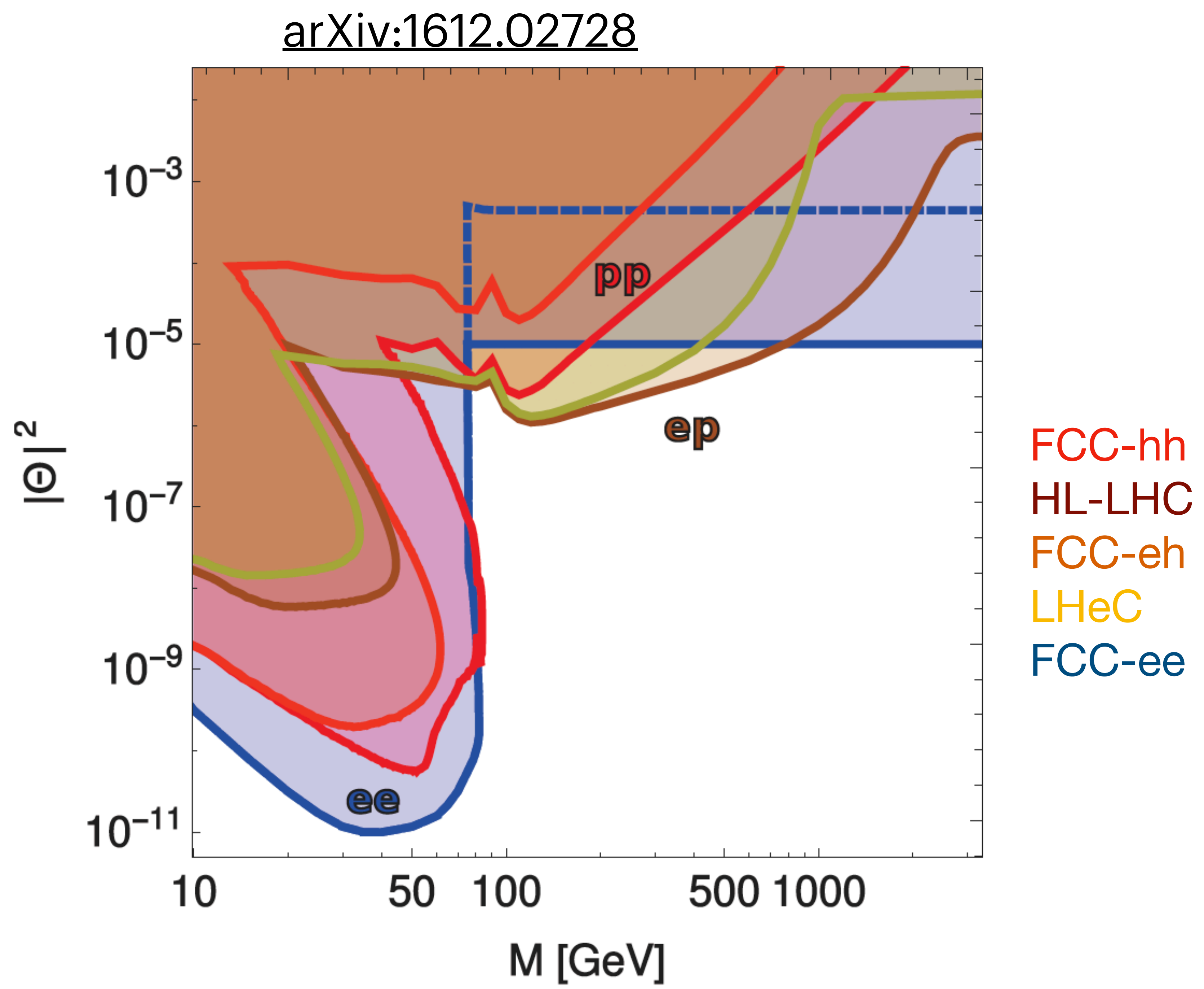


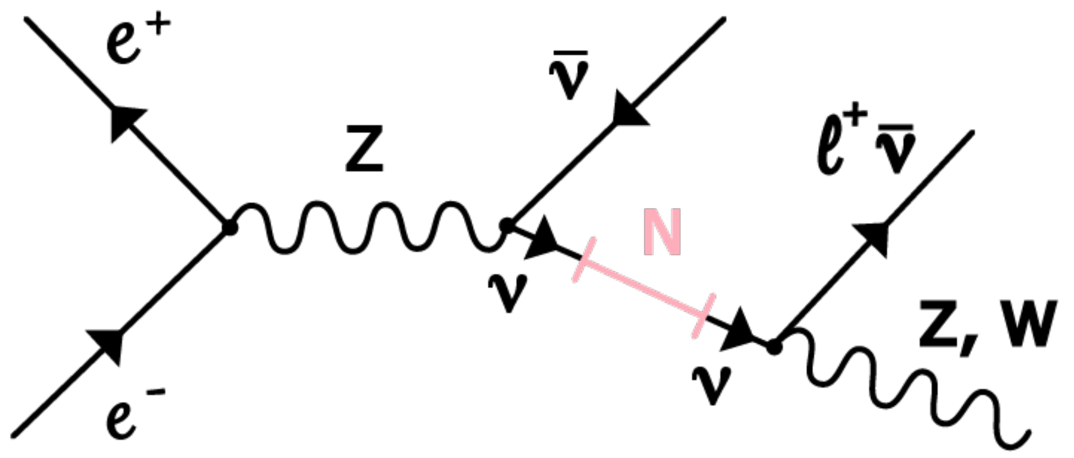
- Following the plans for different additional LLP experiments at the HL-LHC it is possible to also envision similar concepts at other future colliders
- The civil engineering of the FCC-ee will have much bigger detector caverns than needed for a lepton collider (to use them further for a future hadron collider)
- We could install extra instrumentation at the cavern walls to search for new long lived particles
- **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

Complementarity

Across stages

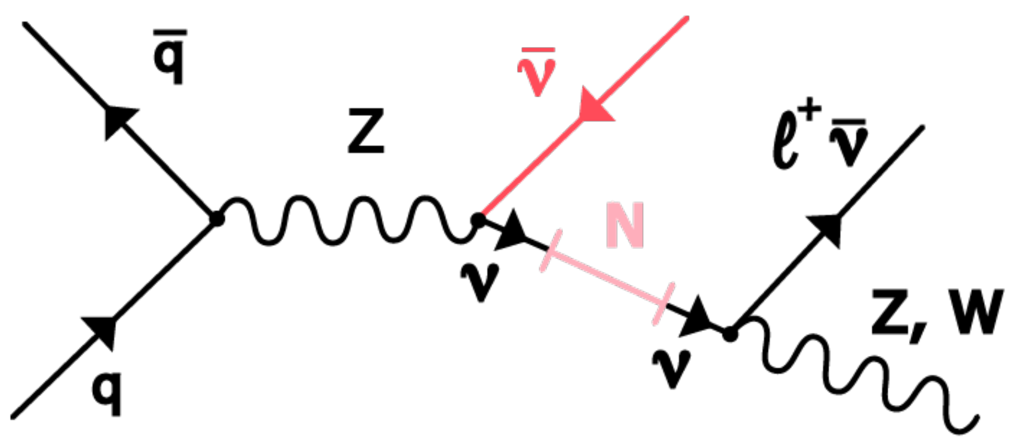


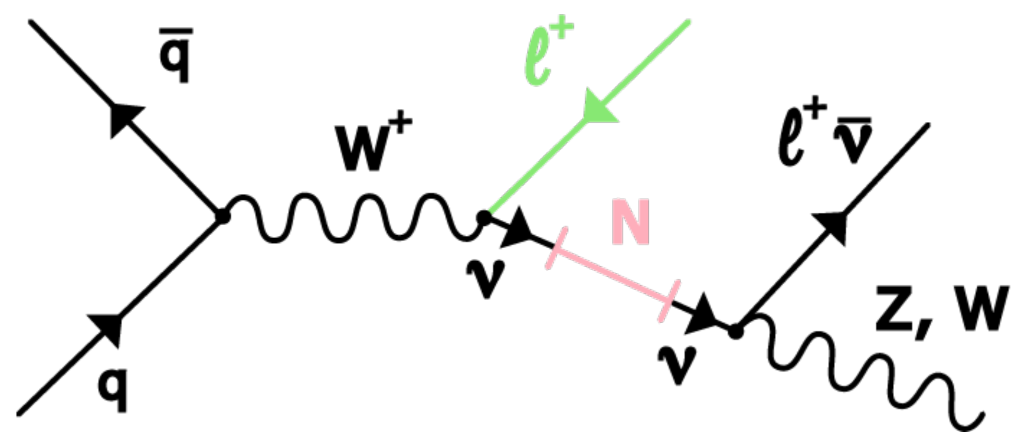


FCC-ee
Indirect constrains from precision SM measurements
Direct search: single HNL production in Z decays
Sensitive to 10^{-11} for M below the W mass

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 multiple new physics searches

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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

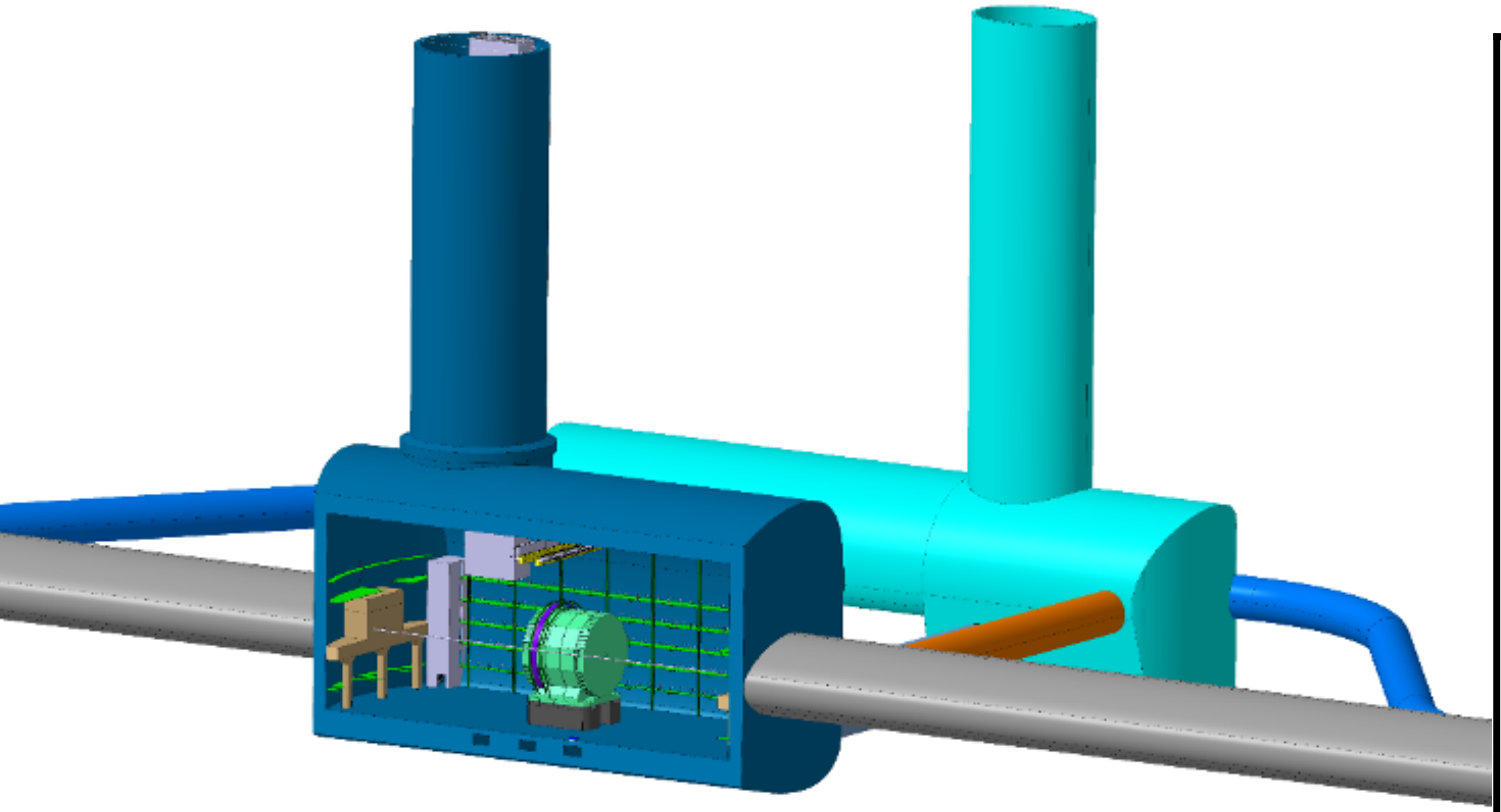
Time to do the work to

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

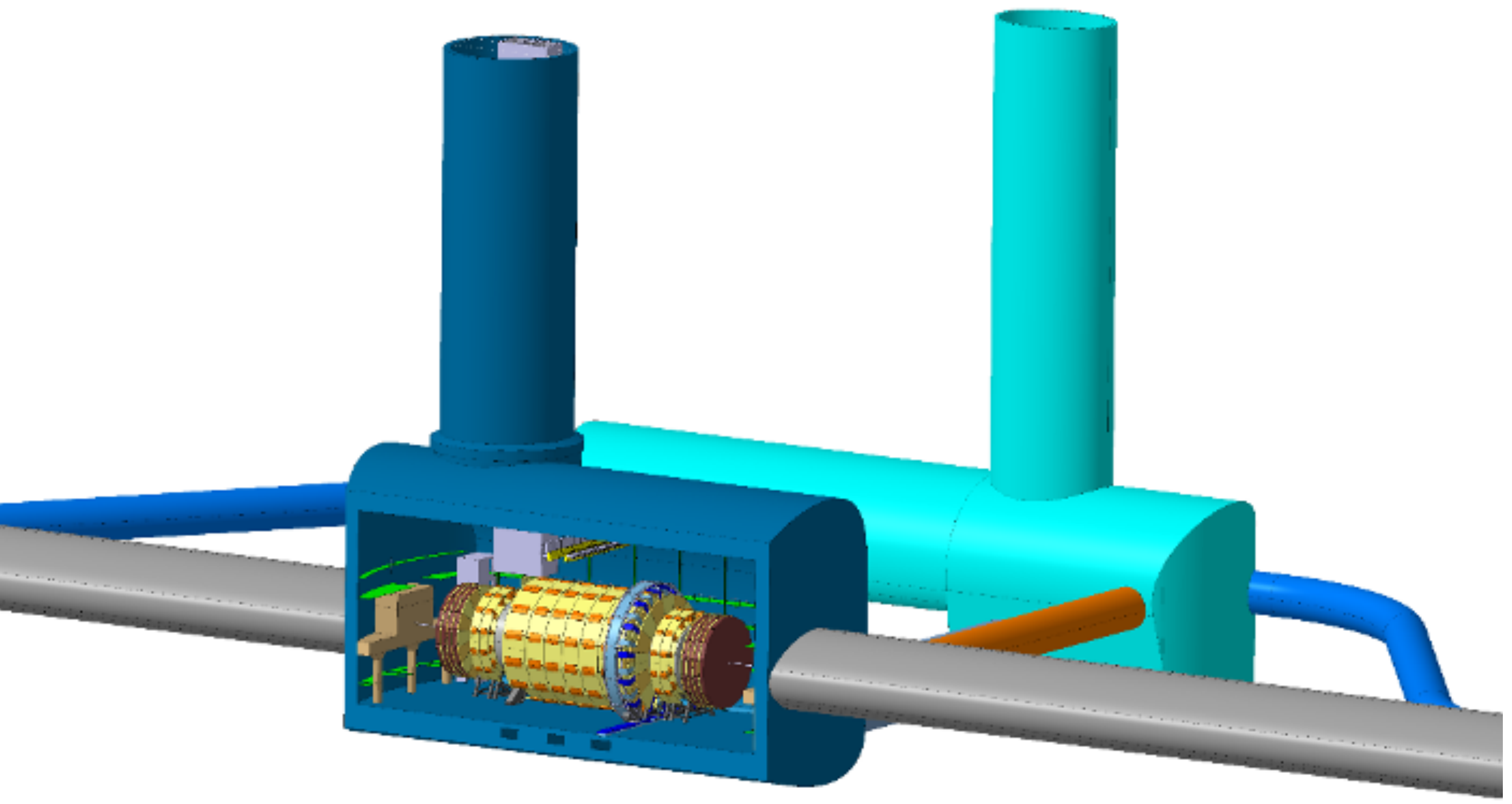
Maximize not only physics but the value returned to society (included but not limited to training, technology and knowledge transfer)

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

Detector concepts

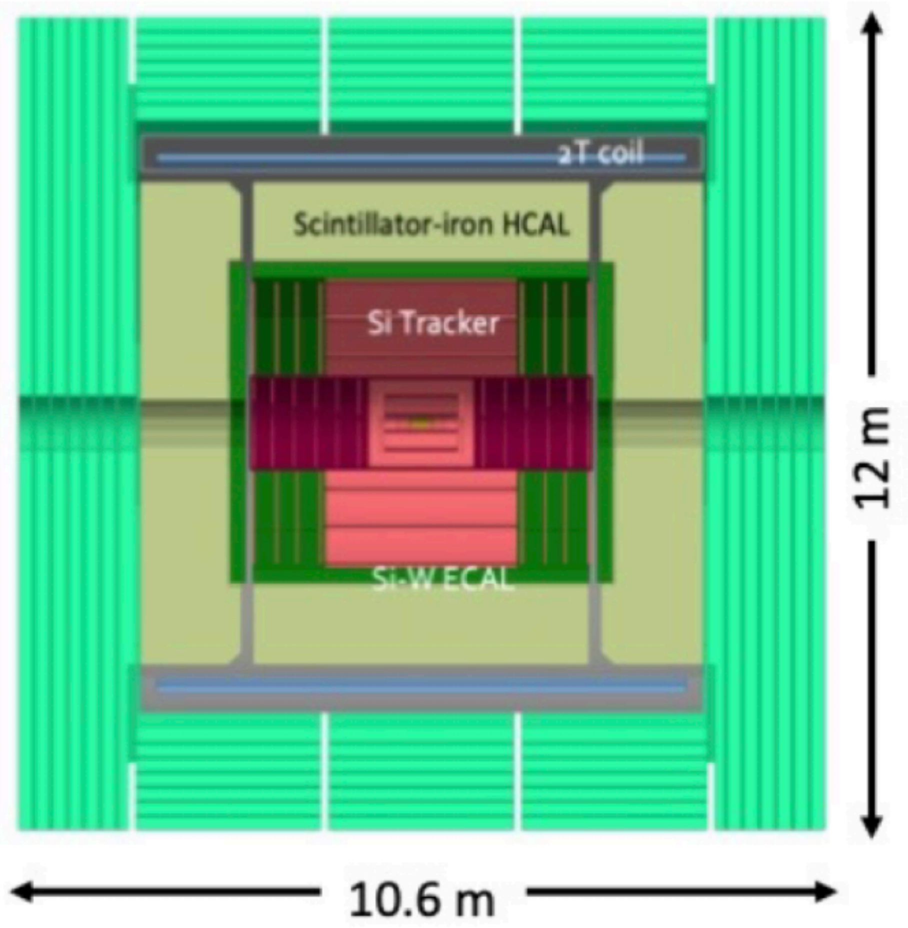


FCC-ee



FCC-hh

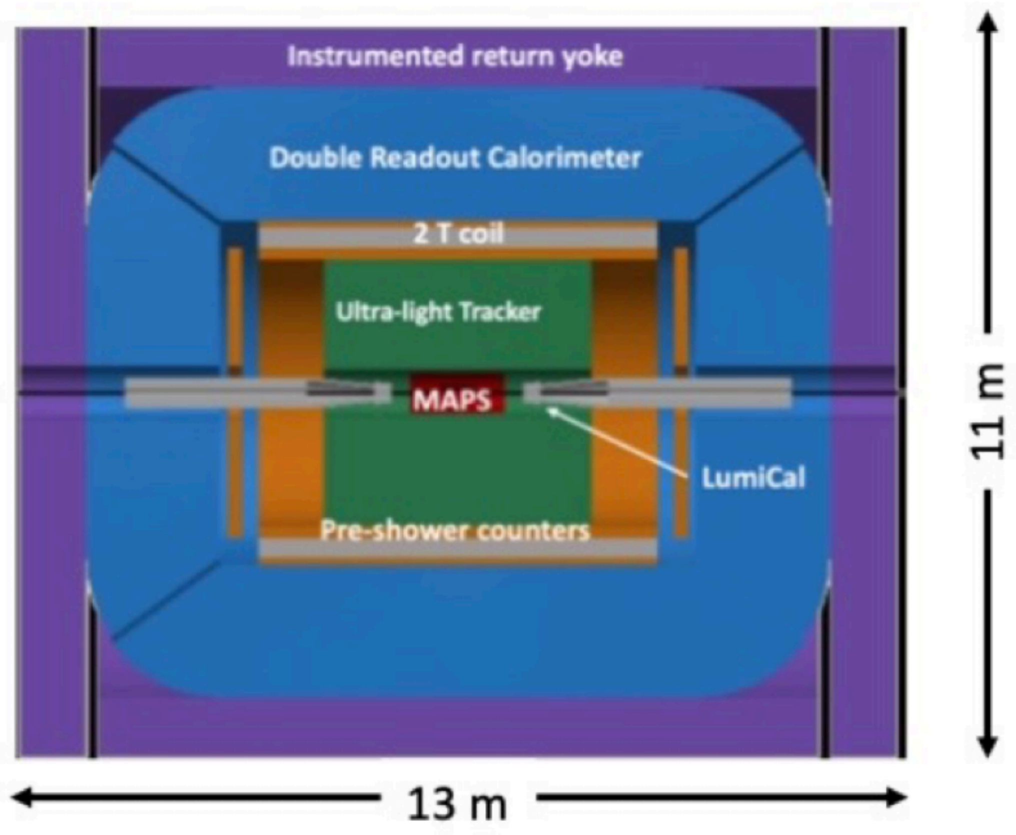
CLD



Based on CLIC detector design, arXiv:1911.12230

Full silicon vertex detector and tracker
3D-imaging highly-granular calorimeter system
Coil outside calorimeter system

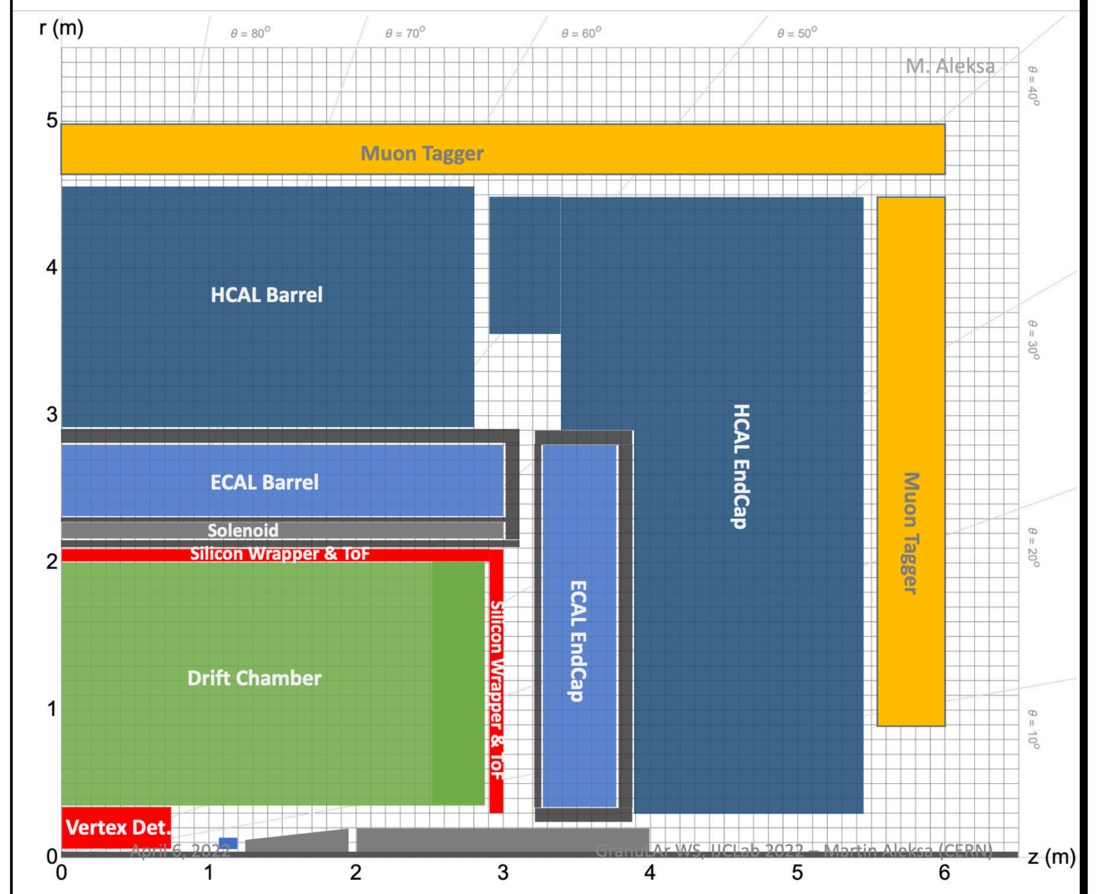
IDEA



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

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FCC-ee Physics Programme