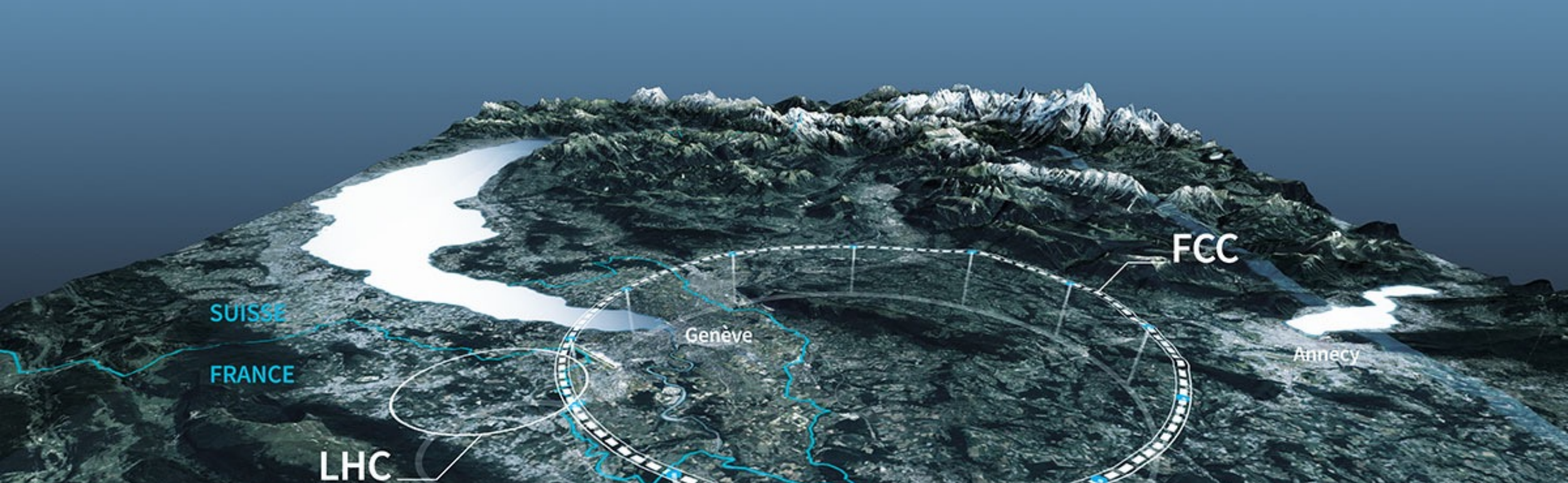

HNL searches with the FCC-hh

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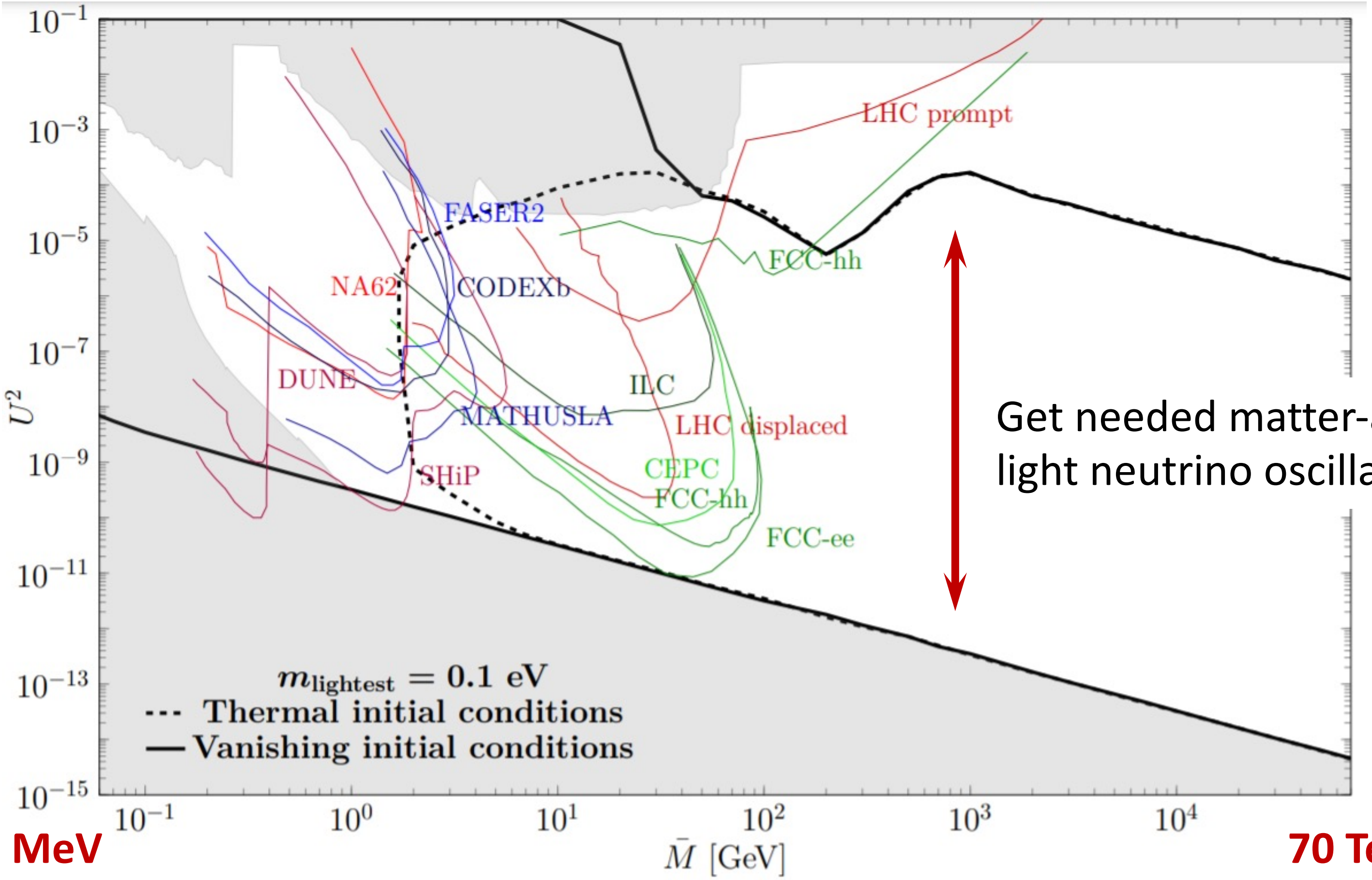
EPFL

European Research Council
Established by the European Commission

FCC Phenomenology Workshop
July 5, 2023

Viable HNL Parameter Space for Testable Leptogenesis

$$U^2 = \sum_\alpha U_\alpha^2$$



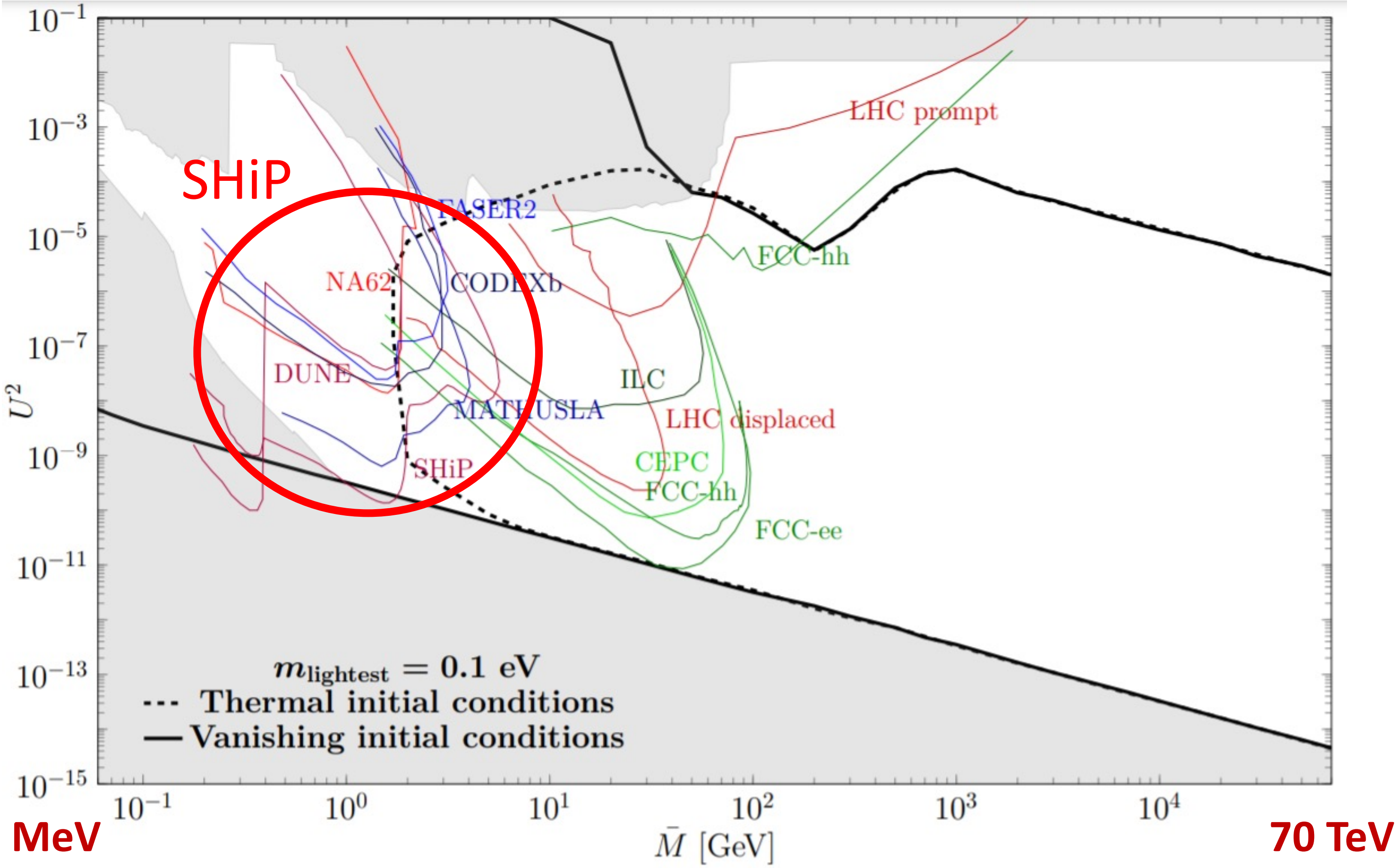
50 MeV **70 TeV**

Get needed matter-antimatter asymmetry + light neutrino oscillation data w/o fine-tuning

[Phys.Rev.Lett. 128 (2022) 051801](): Drewes, Georis and Klaric

SHiP: to be or not to be?

$$U^2 = \sum_\alpha U_\alpha^2$$

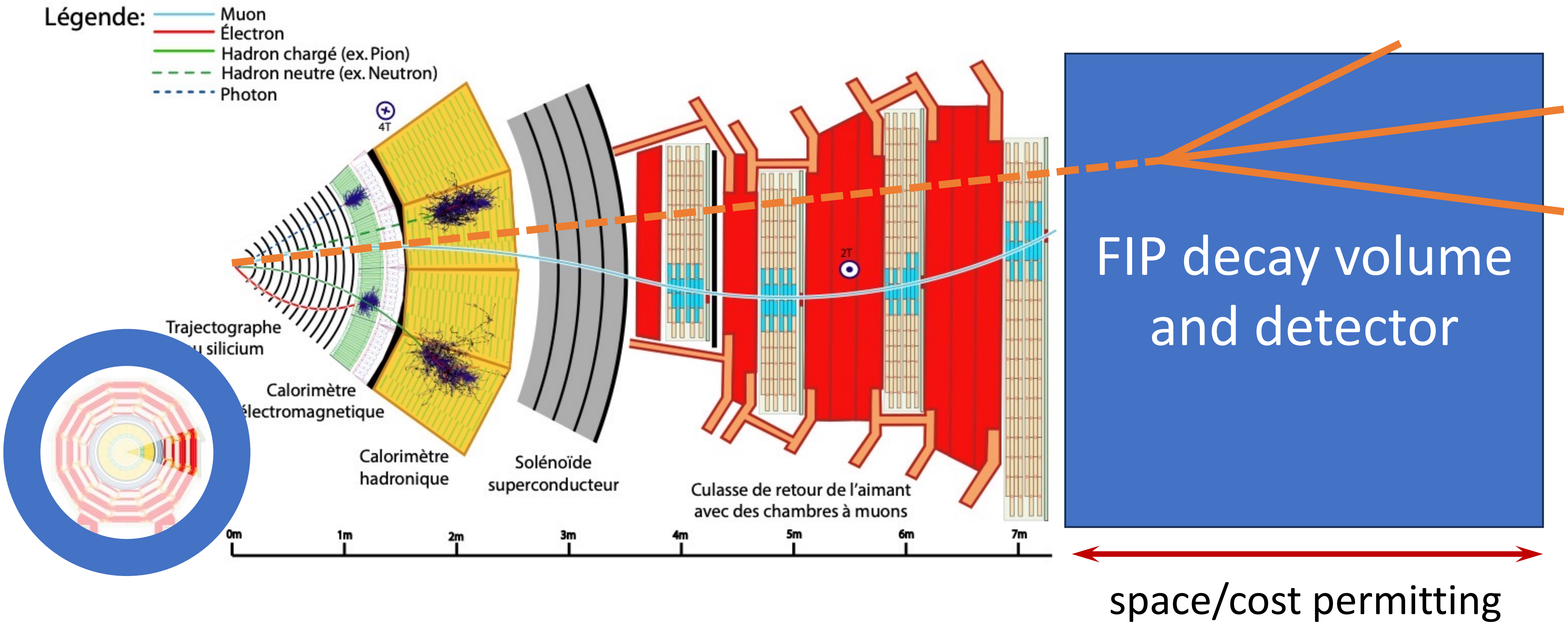


Even if there is FCC, SHiP is the only one closing fully allowed gap below 5 GeV (?)

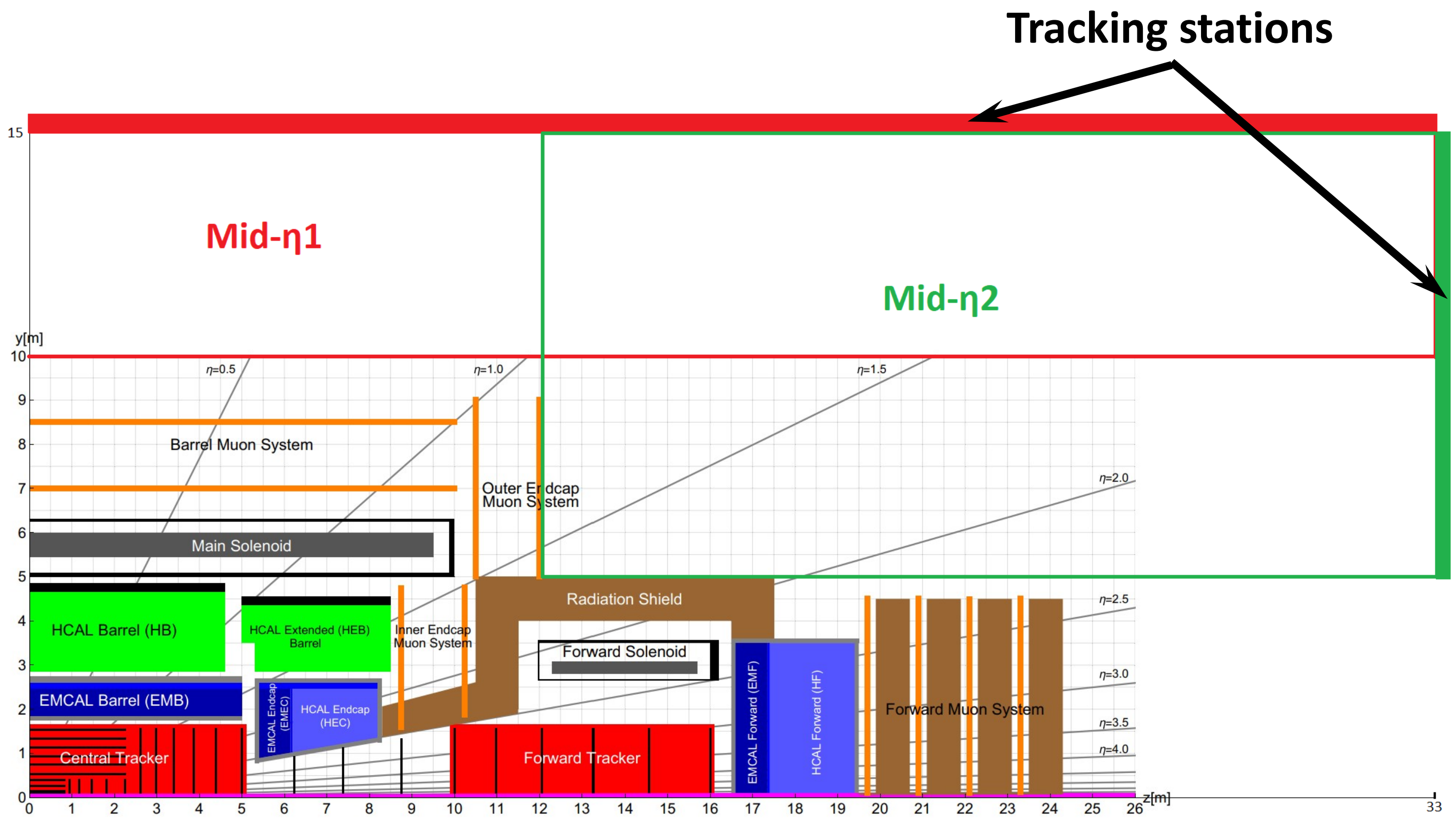
HNL production sources

- FCC-ee: Z-mediated production, no advantage to go to b decays
- FCC-hh:
  - ×30 b (1.5×10^{17}) and ×120 W compared to HL-LHC
  - plenty of time to think how to best exploit these sources
  - estimates:
    - use distributions and predictions from PYTHIA8 and FONLL for heavy flavor and W bosons production
    - take 100% signal efficiency in visible decay channels
    - compute only signal rate (no background estimate)

Brute force solution



FCC-hh "toy" design



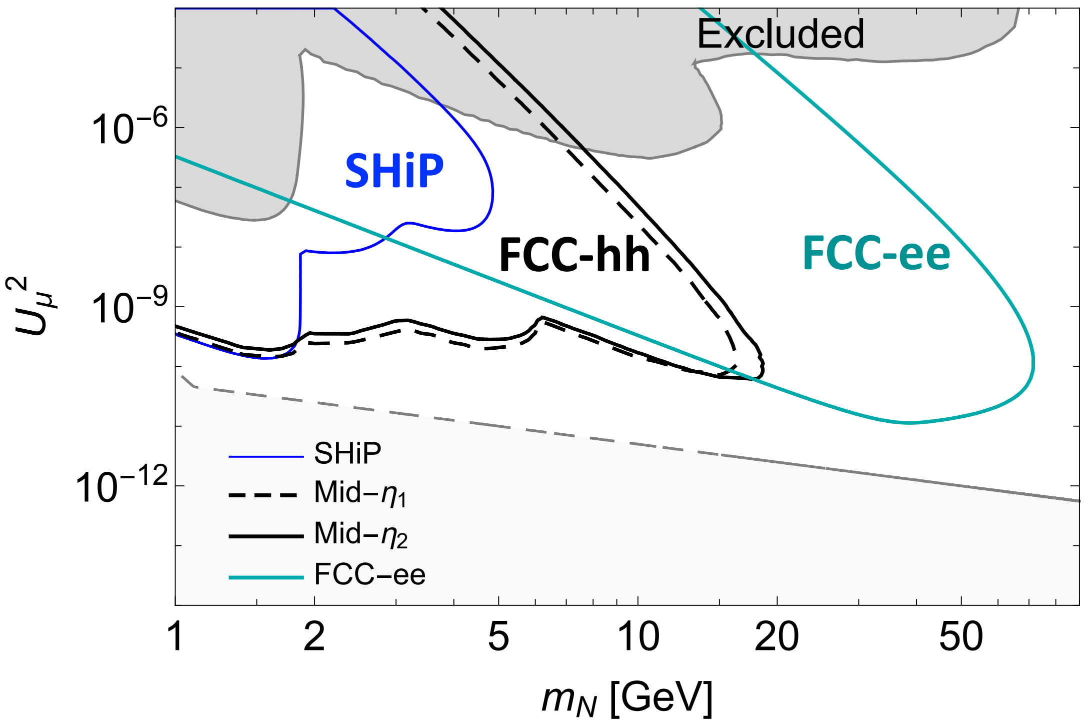
- Tracking stations composed of two layers of tracking detectors separated by 1 m, and providing spatial resolution of 1 mm

- **Mid-η1:**
  - over full detector length
  - $|z|<33$ m
  - 10 m < r < 15 m
  - $|\eta| < 1.5$
  - more expensive
- **Mid-η2:**
  - two disjoint pieces
  - 12 m < $|z|$ < 33 m
  - 5 m < r < 15 m
  - $1.5 < |\eta| < 2.6$
  - less expensive

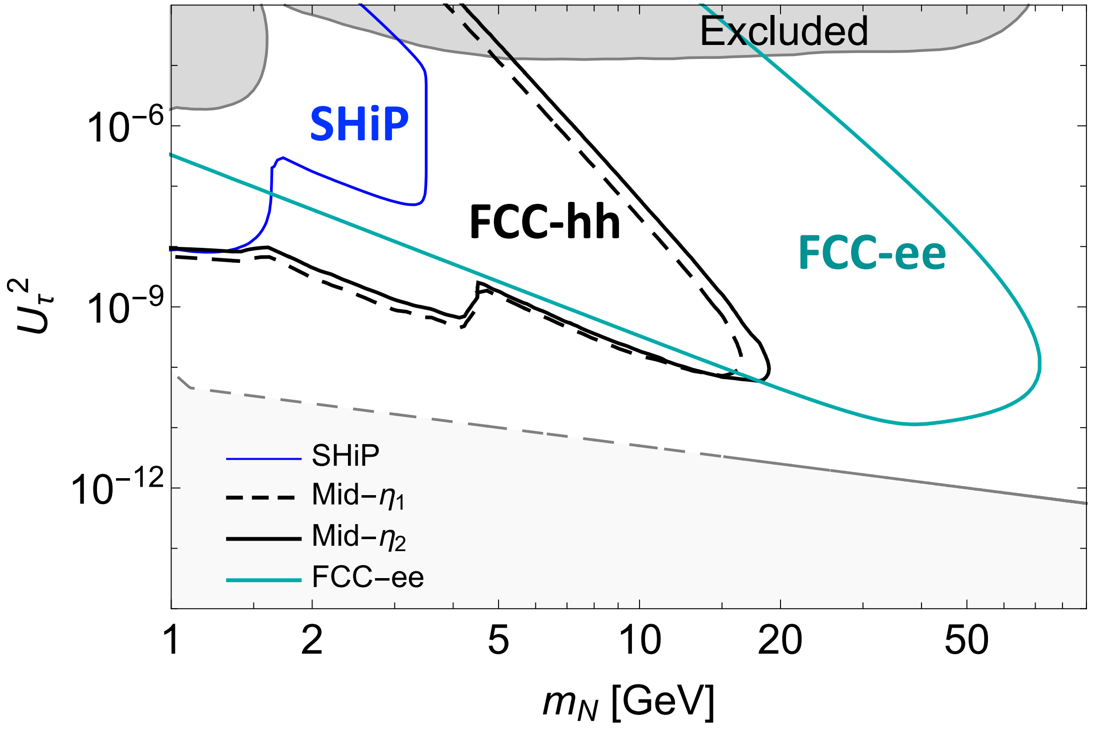
JHEP 01 (2023) 042

FCC-hh 3-event contours

μ (or e)-dominated scenario



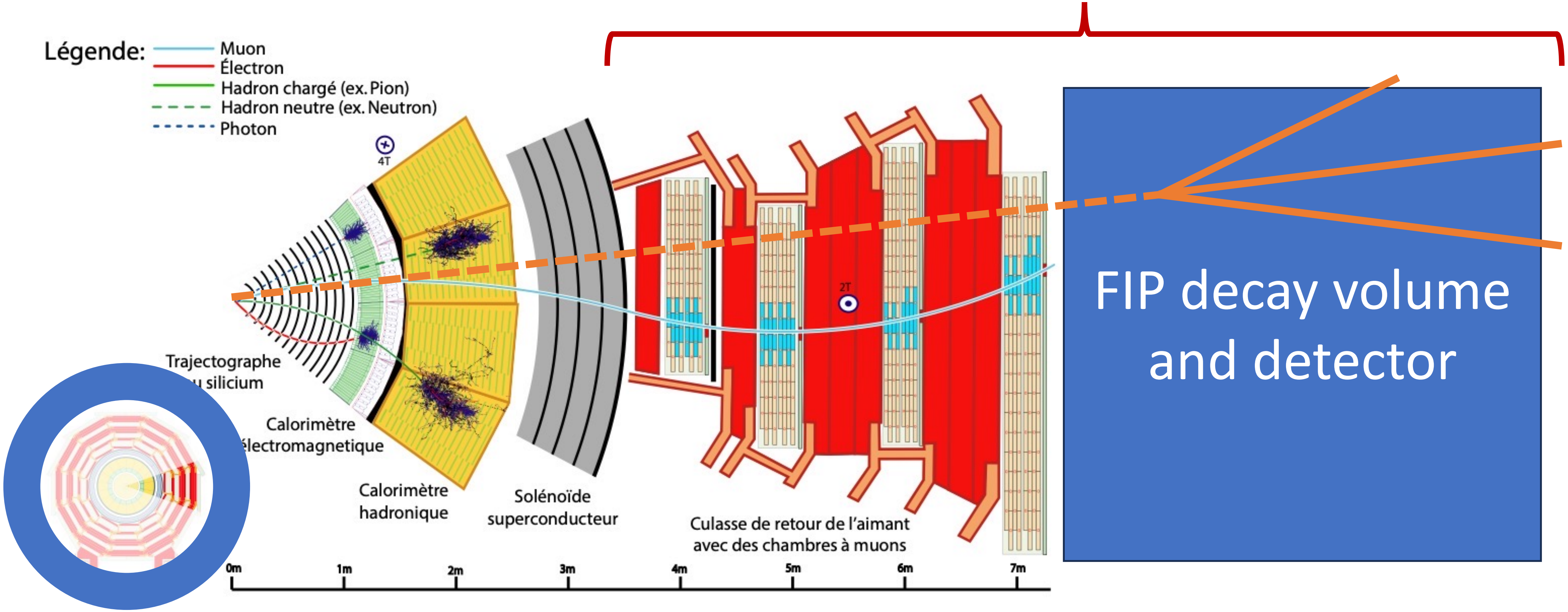
τ-dominated scenario



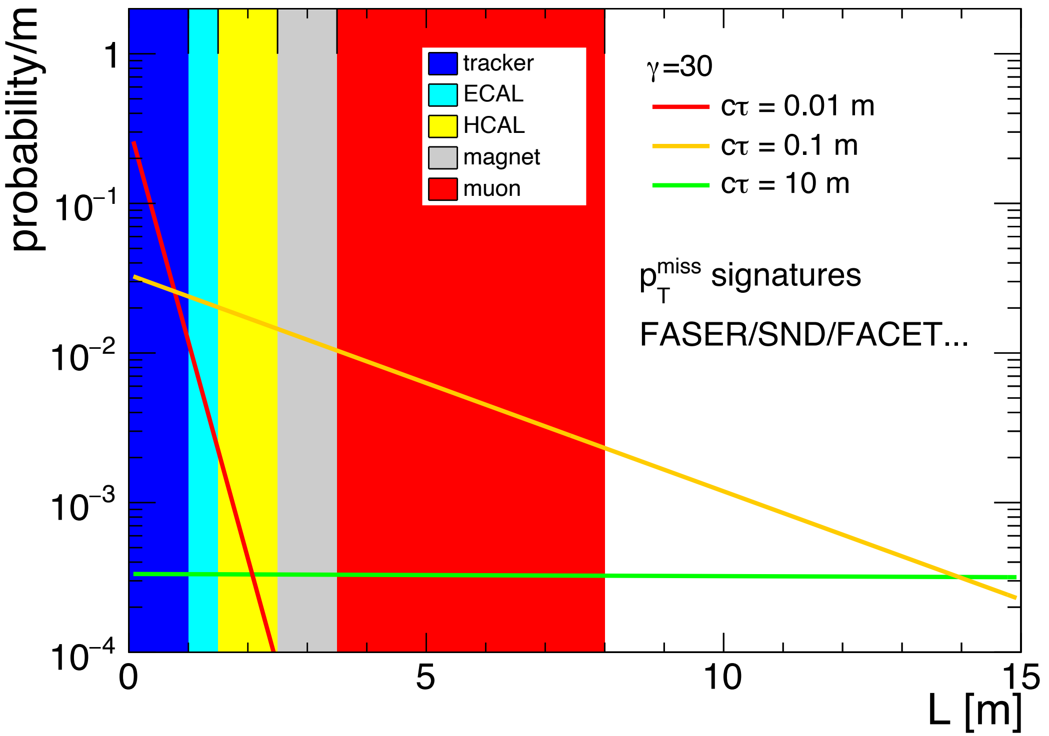
JHEP 01 (2023) 042

Less brute force?

Muon system design optimized for both muons and FIPs?

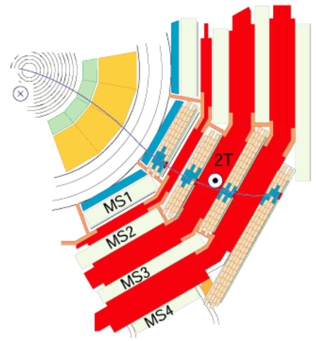


Now: subdetector usage for HNLs @ LHC



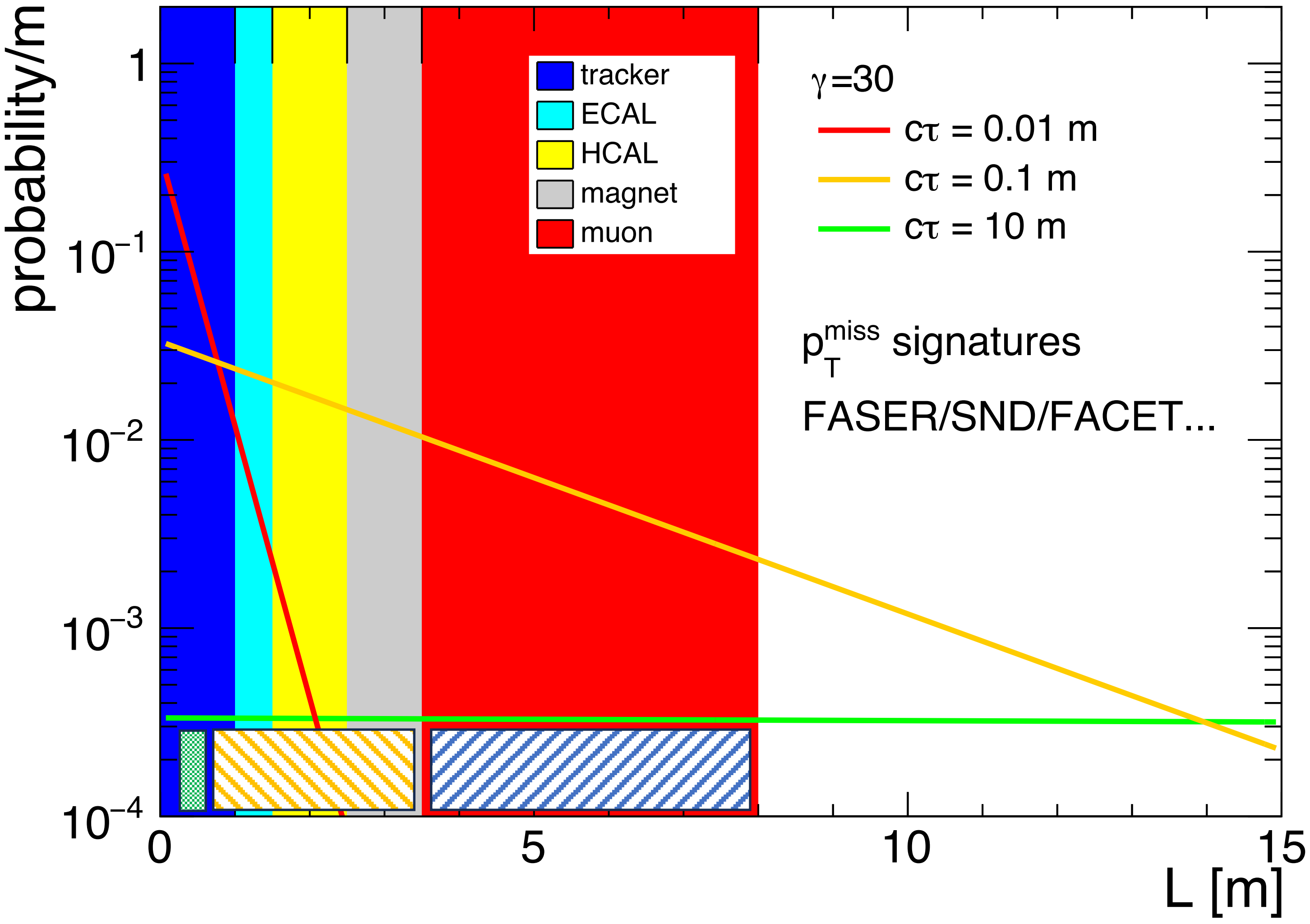
Tracker:
displaced vertices

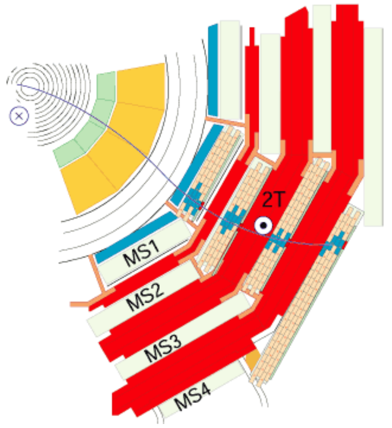
Muon system: huge decay volume
and little bkg after shielding



- Intermediate lifetime:
  - displaced vertices in tracker
- Large lifetime:
  - standalone muons in muon system (*decay volume*: all before MS)
  - showers in muon system (*decay volume*: entire MS)
  - missing momentum signatures (*decay volume*: everything outside the detector)
    - low HNL masses: not usable due to insufficient energy resolution
    - high HNL masses: not relevant due to prompt decays

Decay volume for HNLs @ LHC





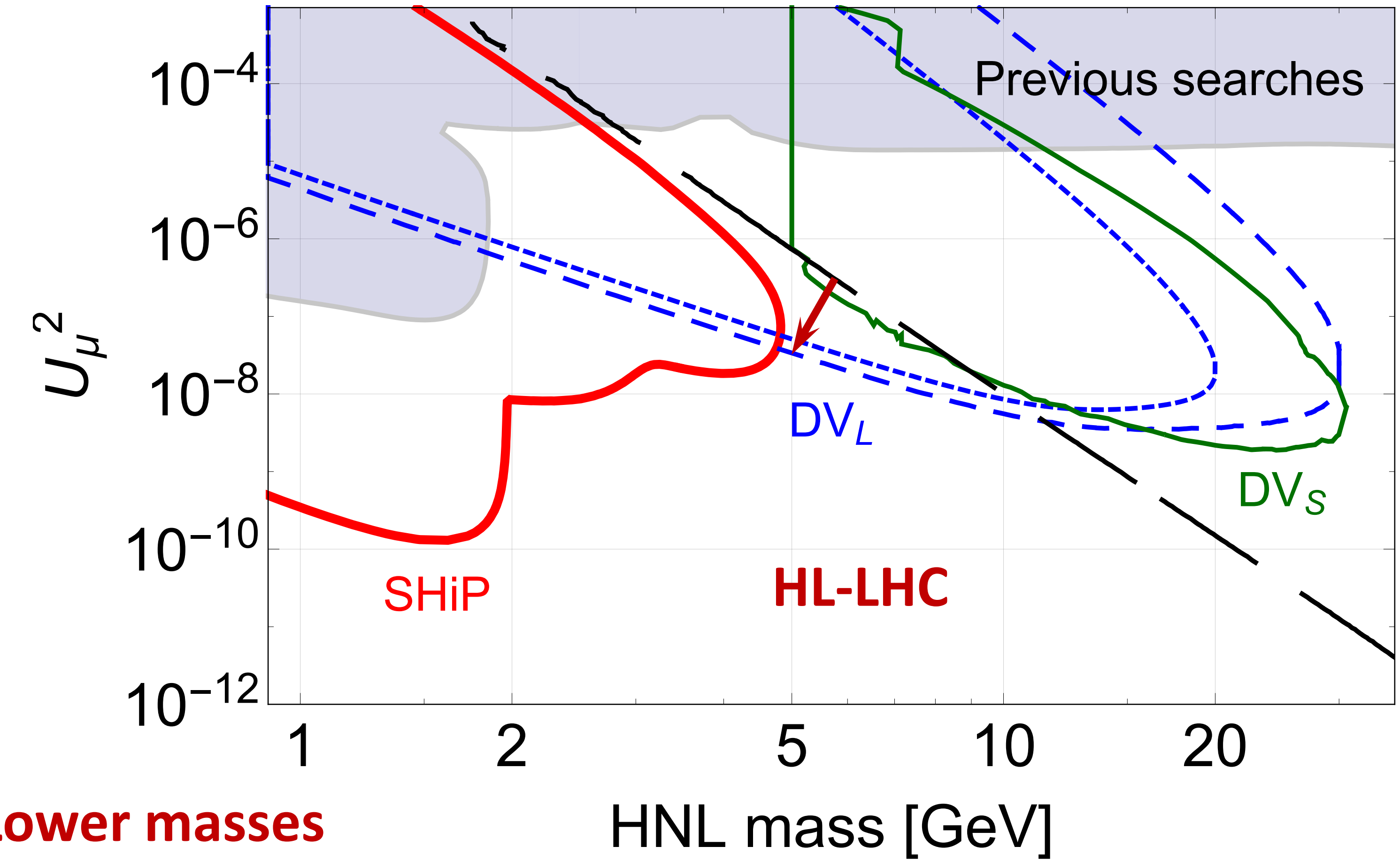
Decay volume of

- displaced vertices
- standalone muons
- muon detector showers

Displaced vertices in the tracker *vs* with standalone muons @ LHC

Sensitivity of
- displaced vertices (DV_S)
- standalone muons (DV_L)
- muon detector showers

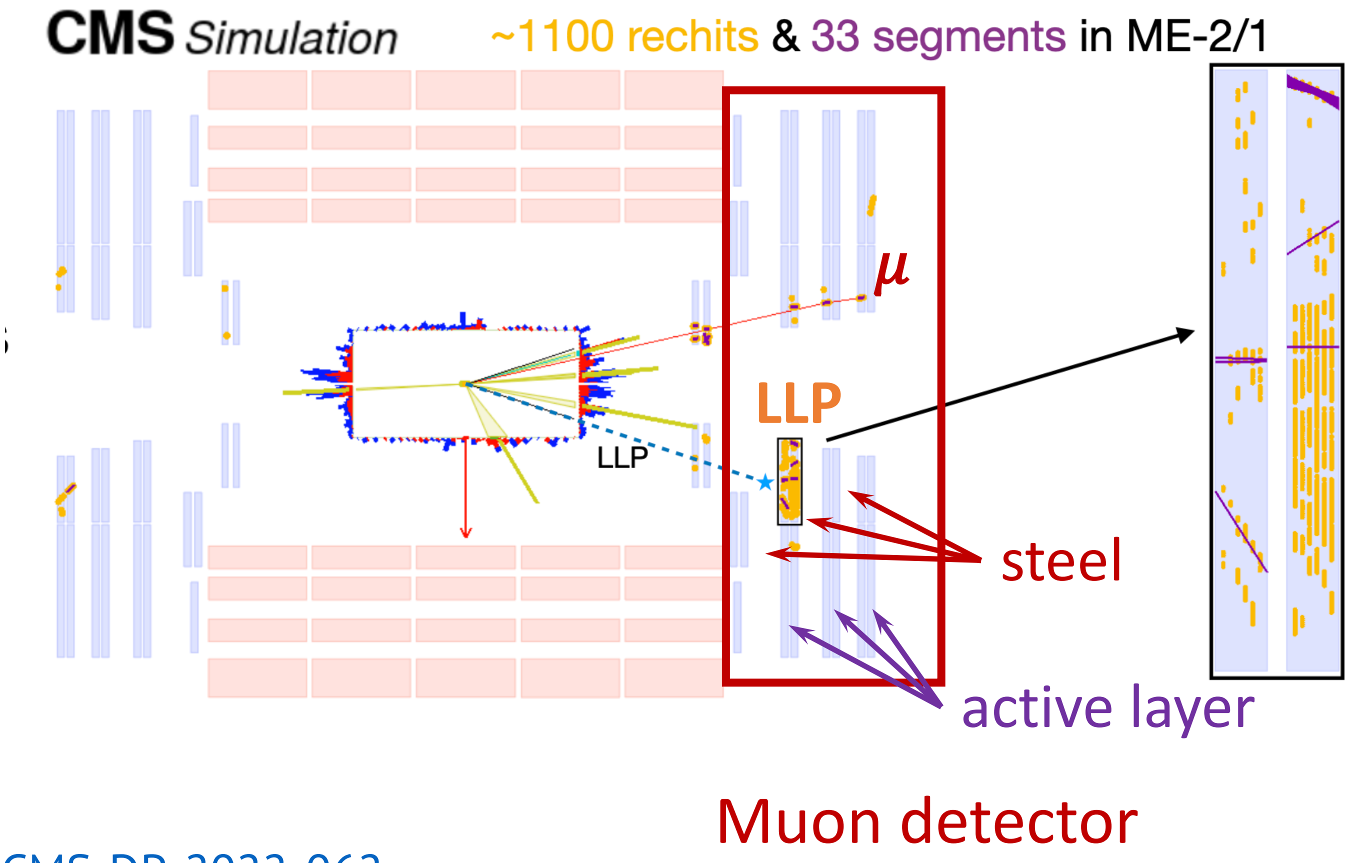
Lower masses
Lower couplings



Phys.Rev.D 100 (2019) 075015

Muon detector showers (MDS) @ CMS

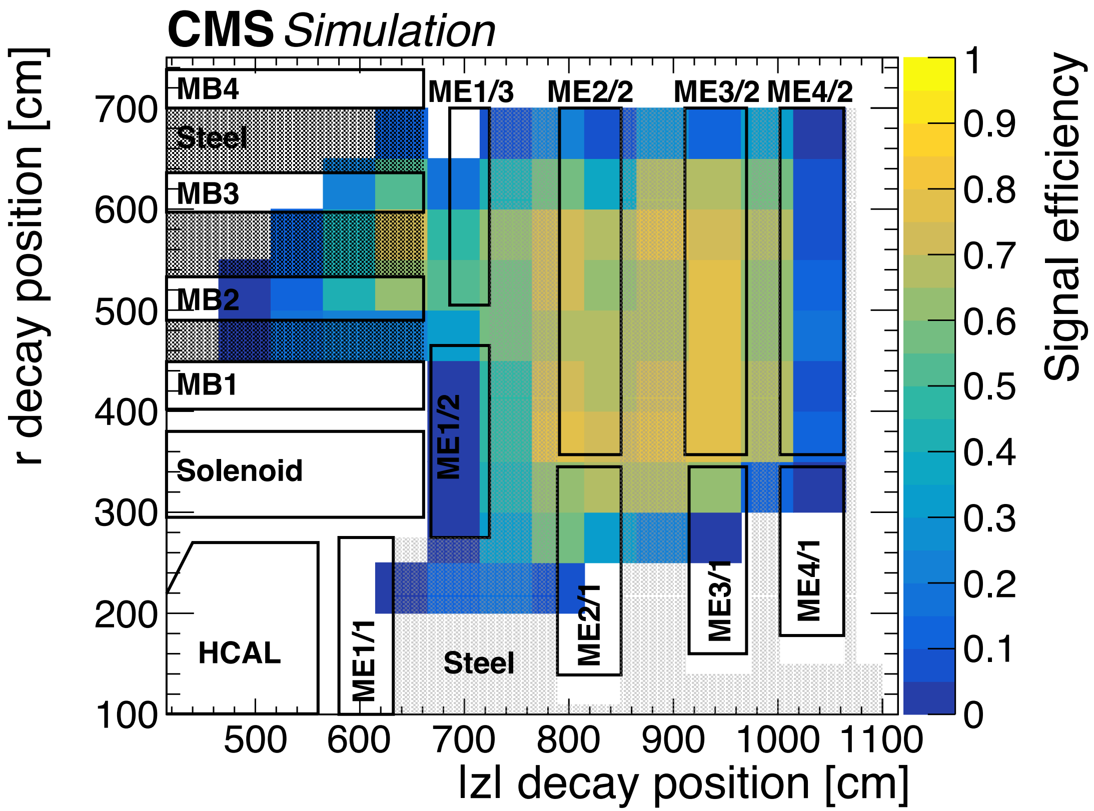
Example event display of a LLP signal event



- FIP traverses the detector and decays in the muon system
  - signal is proportional to the FIP energy rather than its mass
- muon detector acts as a sampling calorimeter
- low SM background as only muons typically survive there
- muons have much lower hit multiplicity than FIP-induced hadronic/EM shower – clear signature for a trigger

CMS-DP-2022-062

Muon detector showers (MDS): ATLAS/CMS

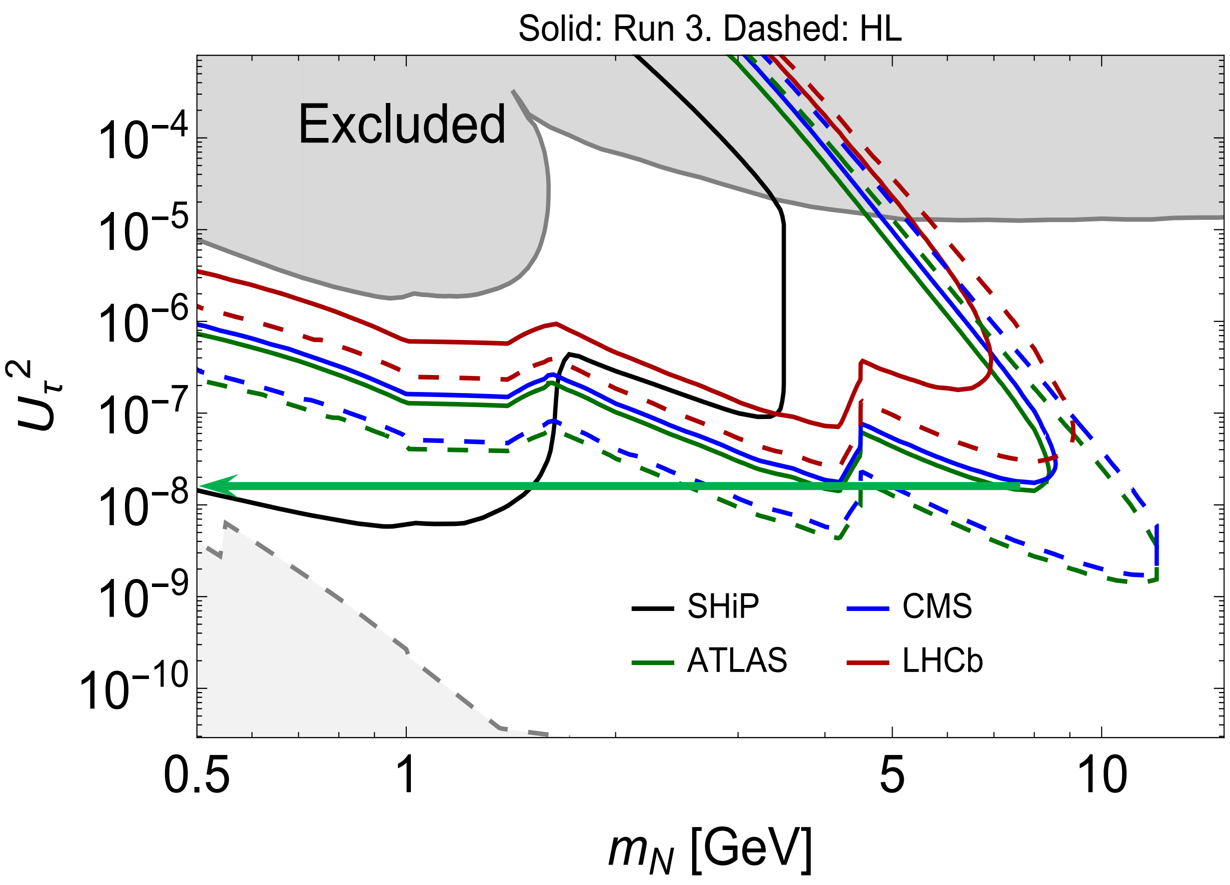


- signature sensitive to **all visible non-muonic decays (no final state suppression)**
- efficiency depends on the decay vertex and FIP energy:
  - if decay happens at the beginning of steel layer, the shower can be absorbed before reaching the sensitive layer
- → in future detectors, can optimize absorber thickness to be also sensitive to a typical spectrum of FIPs (e.g. at the FCC-ee/-hh)

Phys.Rev.Lett. 127 (2021) 261804

Phys.Rev.D 106 (2022) 032005

If triggering on MDS is accessible at (HL-)LHC

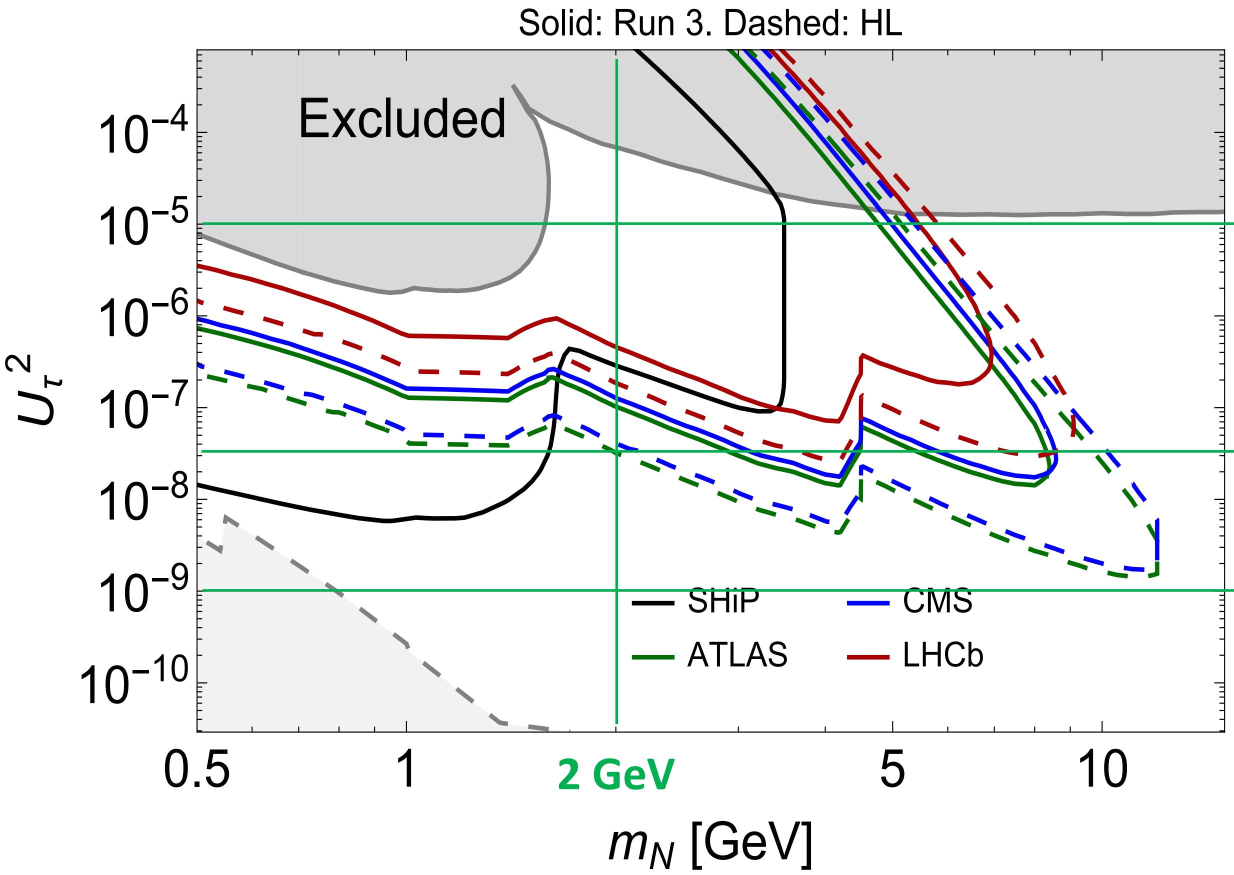


- Back-of-an-envelope estimate for HNLs in τ-dominant scenario:
  - HNLs produced in W, Z, B, D decays
  - coupling only to tau
  - visible decays within muon system (endcaps for CMS)
  - assume 70% detection eff-cy
- Sensitivity of 10^{-8} with Run 3 data!
- 2-3 orders of magnitude better than existing results

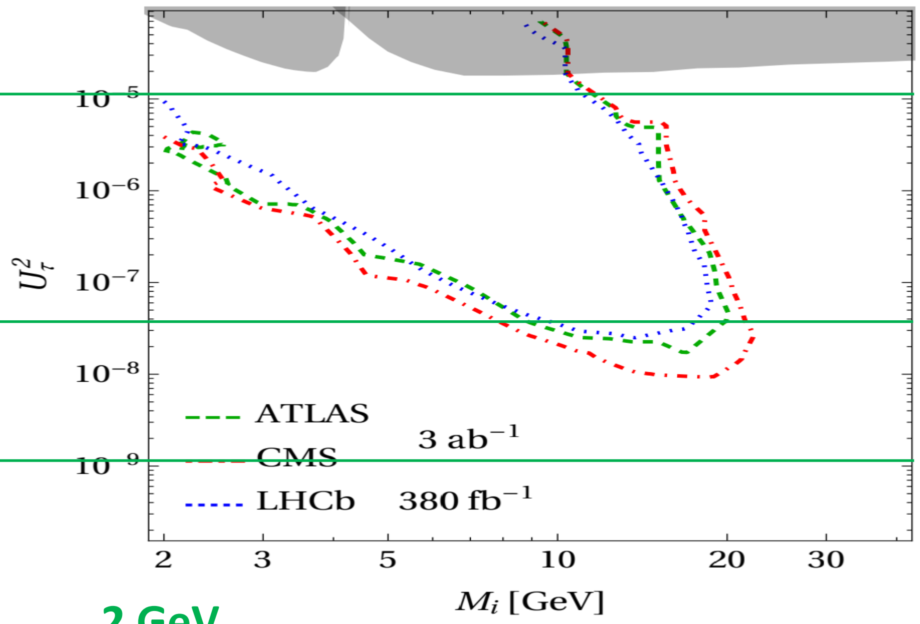
PoS LHCP2022 (2023) 094

If triggering on MDS is accessible at (HL-)LHC

At low masses $\times 10^{2\text{-}3}$ better than projections with more conventional techniques



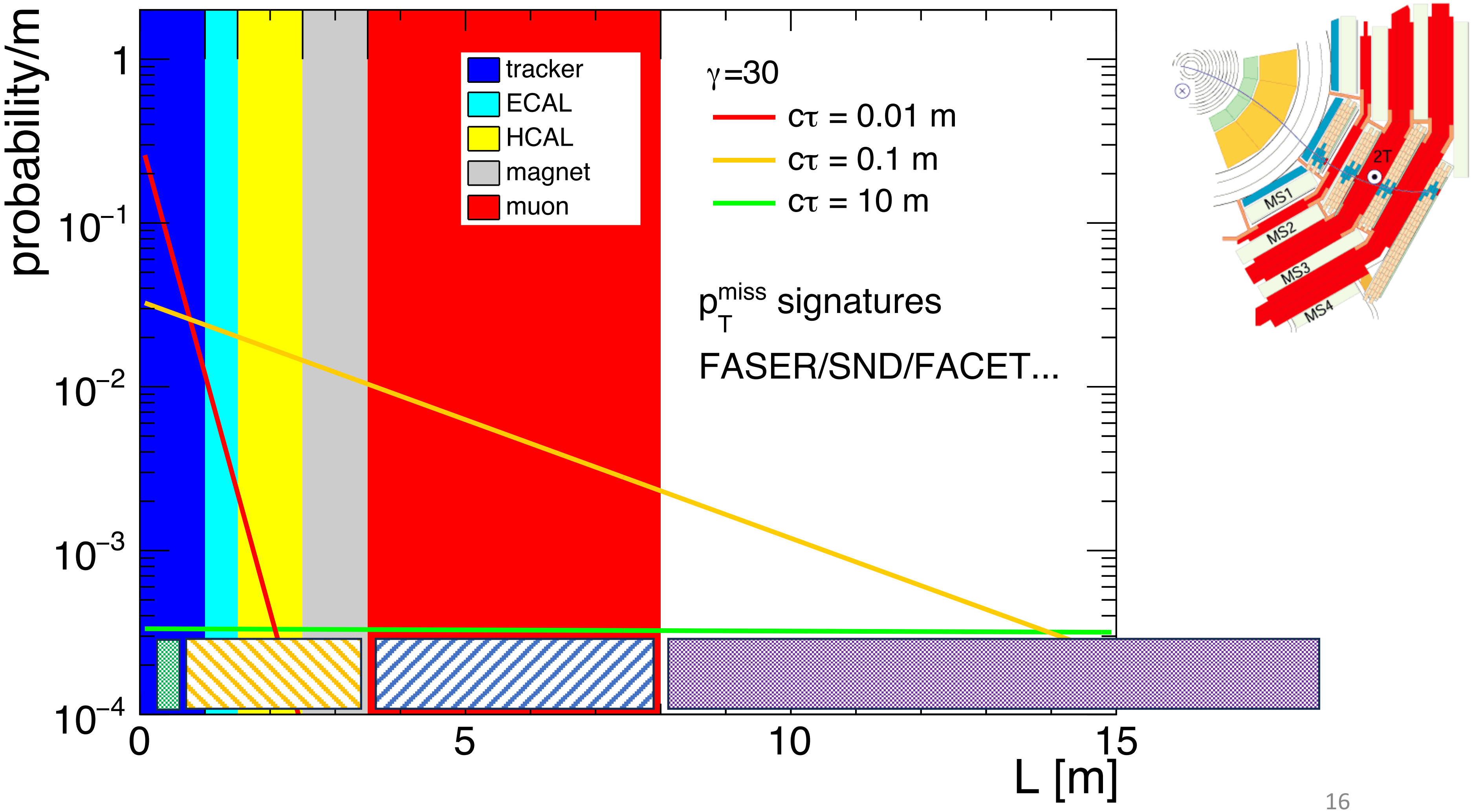
Displaced vertex search projection



2 GeV

[*PoS* LHCP2022 (2023) 094](#) [*Rept.Prog.Phys.* 85 (2022) 024201](#)

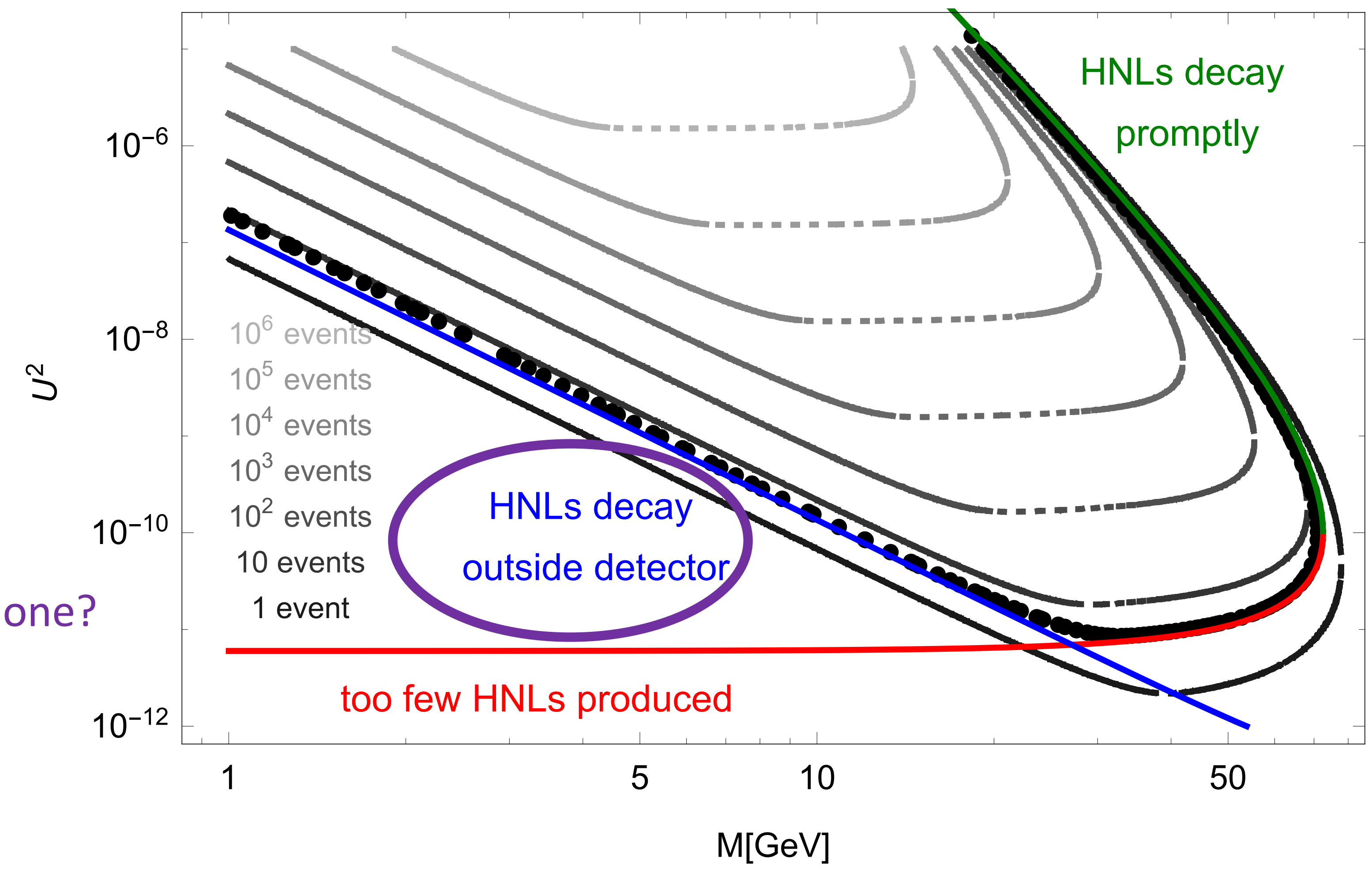
Another subdetector usage for HNLs @ LHC ?



Decay volume of

- displaced vertices
- standalone muons
- muon detector showers
- **missing particle?**

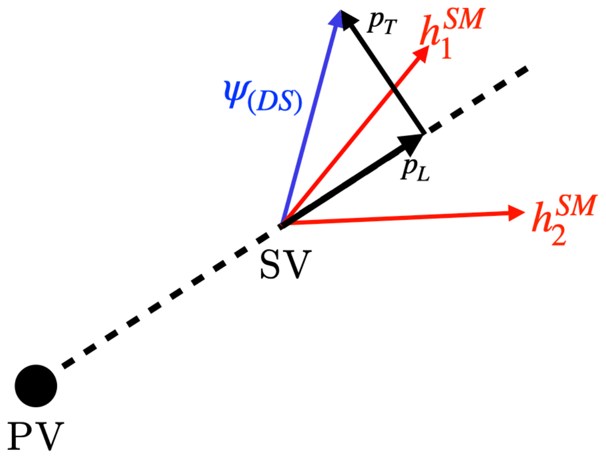
HNLs escaping detector



Can smth be done?

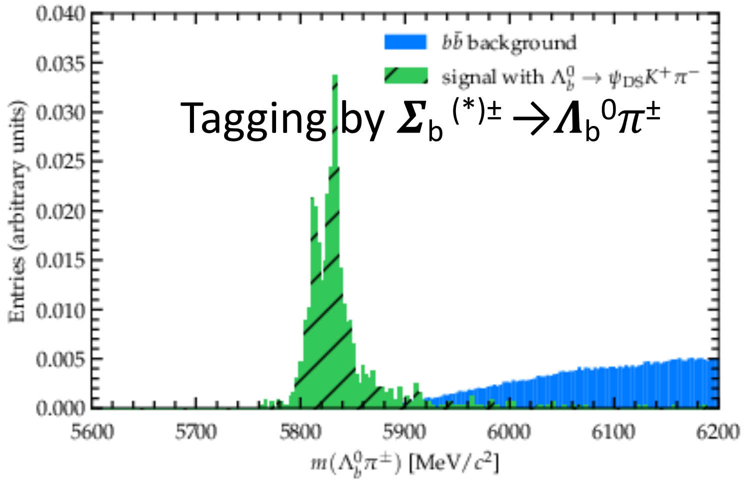
PoS ICHEP2022 (2022) 608

"Stable" low-mass particles: P_T^{miss} @ LHCb



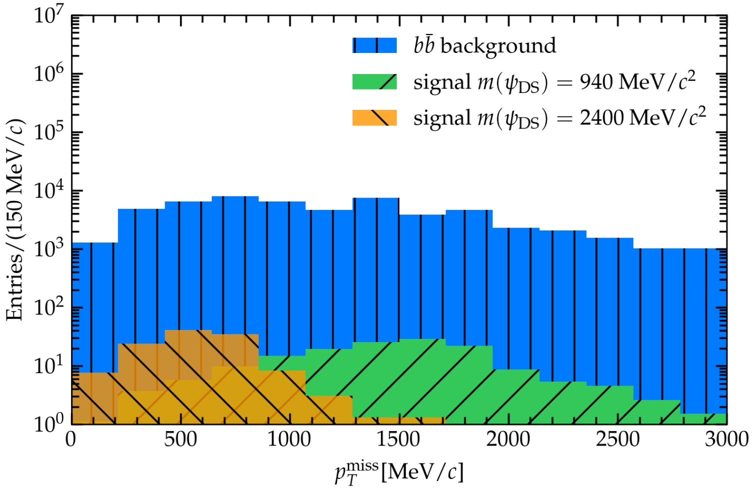
Proposal to use fully reconstructed decay vertices to infer missing particles:

- non-hermetic detector but excellent vertex resolution
- look for missing momentum in hadron decays!
- get access to much lower masses: 1-5 GeV

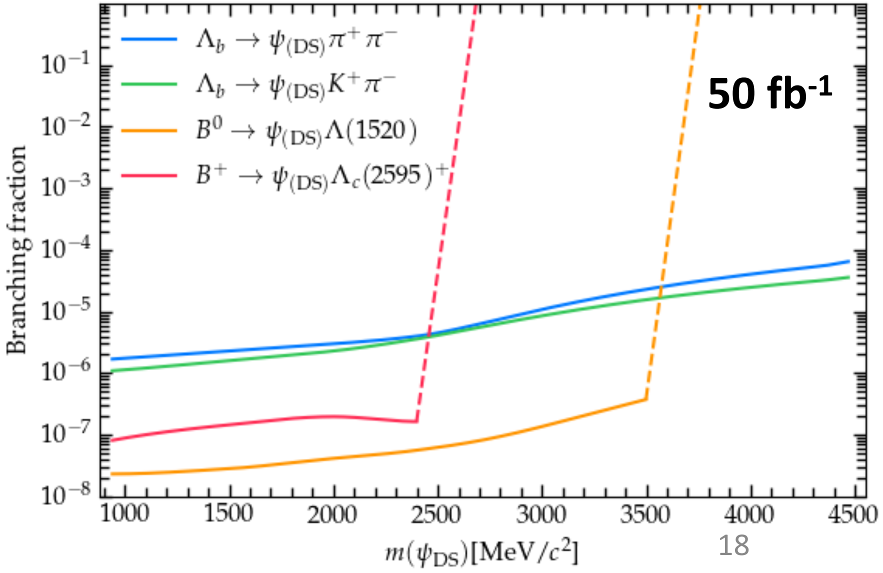


[Eur.Phys.J.C 81 (2021) 964]

p_T^{miss} in hadron decays

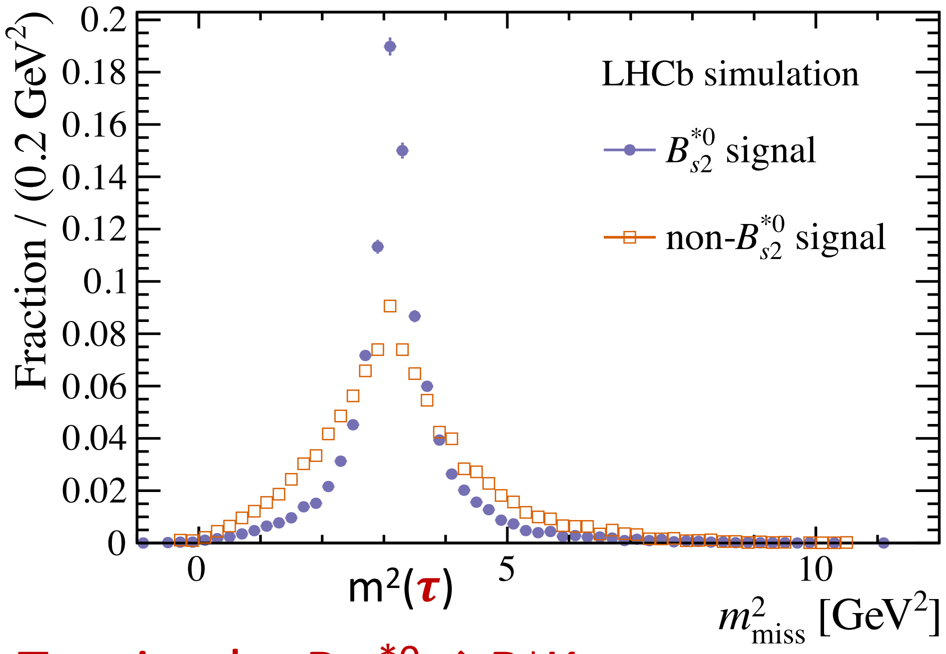


Systematic uncertainty is a challenge!



Science fiction idea: M_{miss} ?

Looking for $B^+ \to K^+ \mu^- \tau^+$



Tagging by $B_{s2}^{*0} \to B^+K^-$

- missing mass used in the LHCb search for LFV decays with **τ**:
  - B^+ momentum computed from its flight direction and known $m(B^+K^-)$
  - missing **τ** 4-momentum is computed as $P(B^+)-B(K^+\mu^-)$
- can be applied for HNLs at FCC?
  - fully inclusive for HNL decays
  - suppressed by B_{s2} cross section
  - can consider B→D→HNL chains
  - needs hadron identification…

JHEP 06 (2020) 129

Summary

- FCC-hh is a powerful source of neutrinos from b and W decays
- have quite some time to take into account the lessons from the LHC and optimize the FCC main detectors
- main strategy – shield as much as possible from the interaction point:
  - target a combined muon/FIP detector from the start (dimensions, absorber thickness)
  - envision a possibility for simple additional detectors on the walls or in the tunnel
  - sensitivity competes with SHiP and is complementary to FCC-ee
- strategy to consider: check options for hadron identification and precise secondary vertex measurement for missing mass signatures
  - sensitivity to be checked