(Direct) Searches for sterile neutrinos below the electroweak scale

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GdR Neutrino
CPPM - Marseille
26th-27th November 2014

Sterile Neutrinos

Fermions get mass via the Yukawa couplings

$$-\mathcal{L}_{\text{Yukawa}} = Y^d_{ij}\overline{Q_{Li}}\phi D_{Rj} + Y^u_{ij}\overline{Q_{Li}}\tilde{\phi}U_{Rj} + Y^\ell_{ij}\overline{L_{Li}}\phi E_{Rj} + \text{h.c.}$$

If we want the same coupling for neutrinos, we need right-handed (sterile) neutrinos… the most generic lagrangian is

$$\mathcal{L}_N = i\overline{N}_i\partial_\mu\gamma^\mu N_i - \frac{1}{2}M_{ij}\overline{N^c}_i N_j - Y^\nu_{ij}\overline{L_{Li}}\tilde{\phi}N_j$$

Yukawa coupling

Kinetic term

Majorana mass term

Seesaw

$$-\mathcal{L}_{M_\nu} = M_{Dij}\overline{\nu_{Li}}N_j + \frac{1}{2}M_{Nij}\overline{N_i^c}N_j + h.c.$$

$$\mathcal{V} = (\nu_{Li}, N_j)$$

$$-\mathcal{L}_{M_\mathcal{V}} = \frac{1}{2}\overline{\mathcal{V}}M_\mathcal{V}\mathcal{V} + h.c.$$

$$M_\nu = \begin{pmatrix} 0 & M_D \\ {M_D}^T & M_N \end{pmatrix}$$

Eigenvalues

$$\lambda_\pm = \frac{M_N \pm \sqrt{M_N^2 + 4M_D^2}}{2}$$

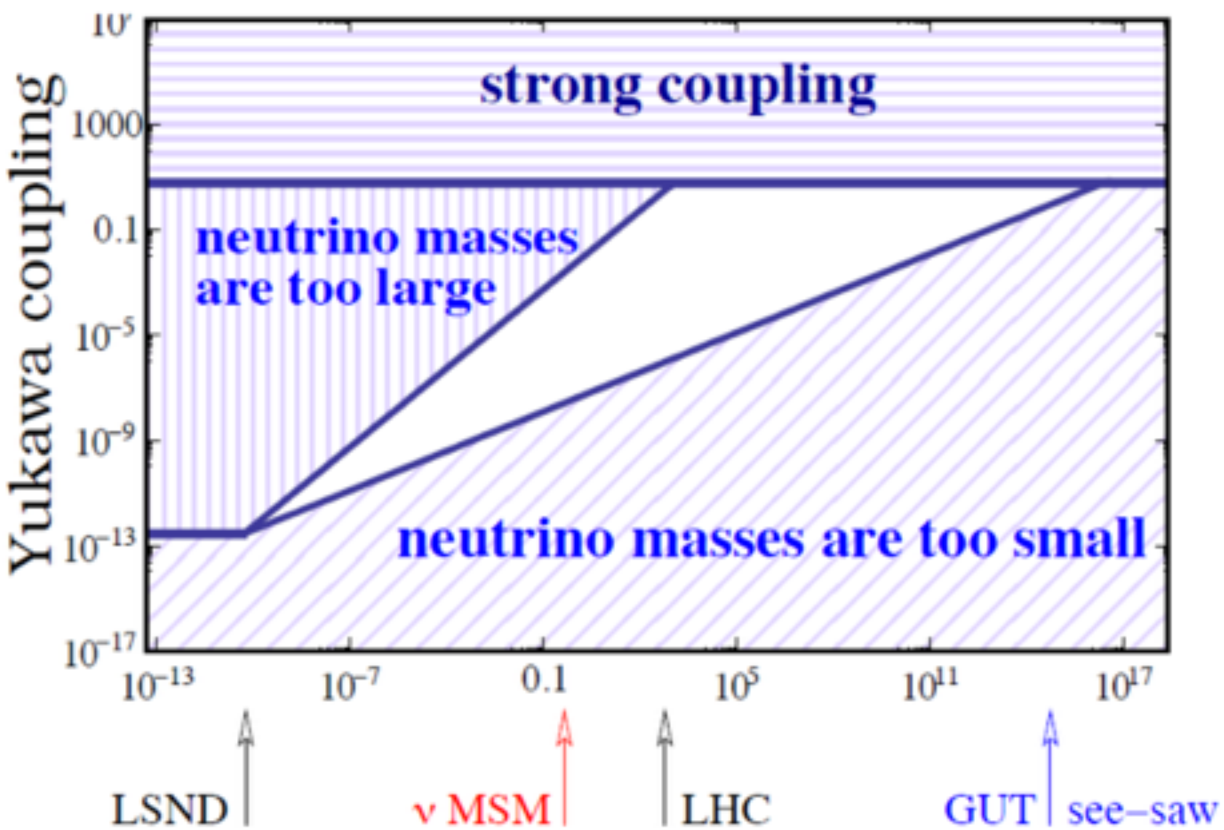
Assuming $M_N \gg M_D$

$$\lambda_- \sim \frac{M_D^2}{M_N}$$

$$\lambda_+ \sim M_N$$

Sterile Neutrinos Masses

Seesaw formula $m_D \sim Y_{I\alpha} < \phi >$ and $m_\nu = \frac{m_D^2}{M}$



Majorana Mass (GeV)

- Assuming $m_\nu = 0.1\text{eV}$
- if $Y \sim 1$ implies $M \sim 10^{14}\text{GeV}$
- if $M_N \sim 1\text{GeV}$ implies $Y_\nu \sim 10^{-7}$

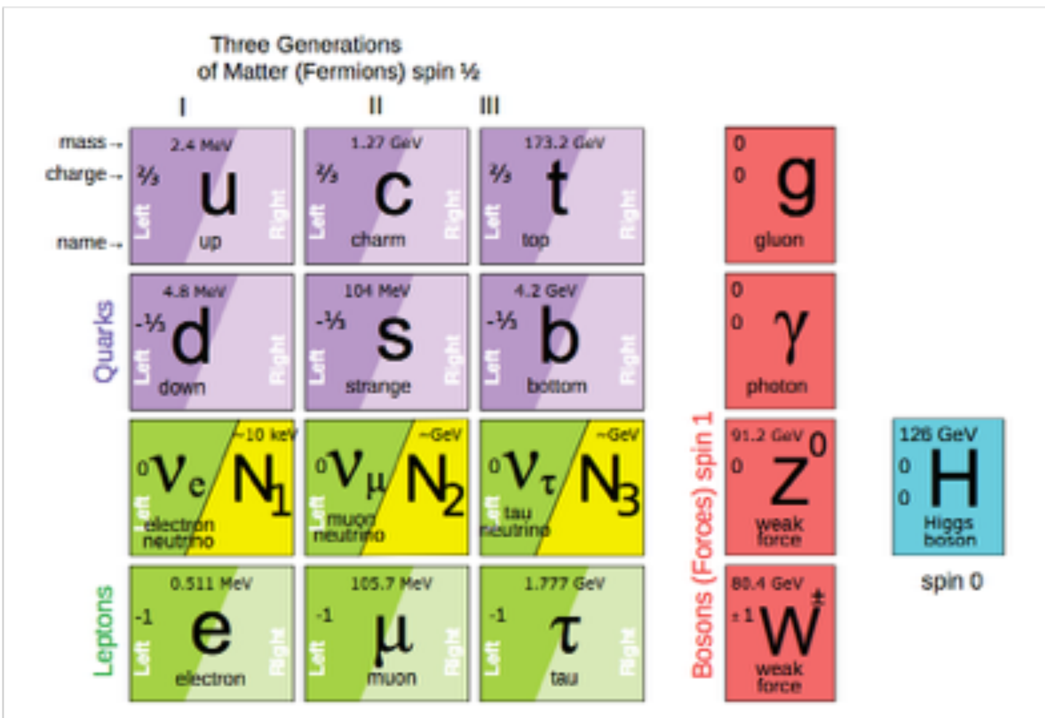
remember $Y_{top} \sim 1.$ and $Y_e \sim 10^{-6}$

- From the seesaw point of view the mass of sterile neutrinos can be basically anything
- If we want to explain the smallness of neutrino masses (in a natural way) the mass of sterile neutrinos should be at least at the GeV scale

Sterile neutrino in cosmology

- There is in principle no constraint on the number of sterile neutrinos
- We need at least two sterile neutrinos to justify two mass differences, solar and atmospheric
- Role of sterile neutrinos in cosmology (talk by M. Frigerio):
    - A light sterile neutrino with mass around the KeV can be candidate for warm Dark Matter
    - Two or more sterile neutrinos can be responsible for BAU via leptogenesis

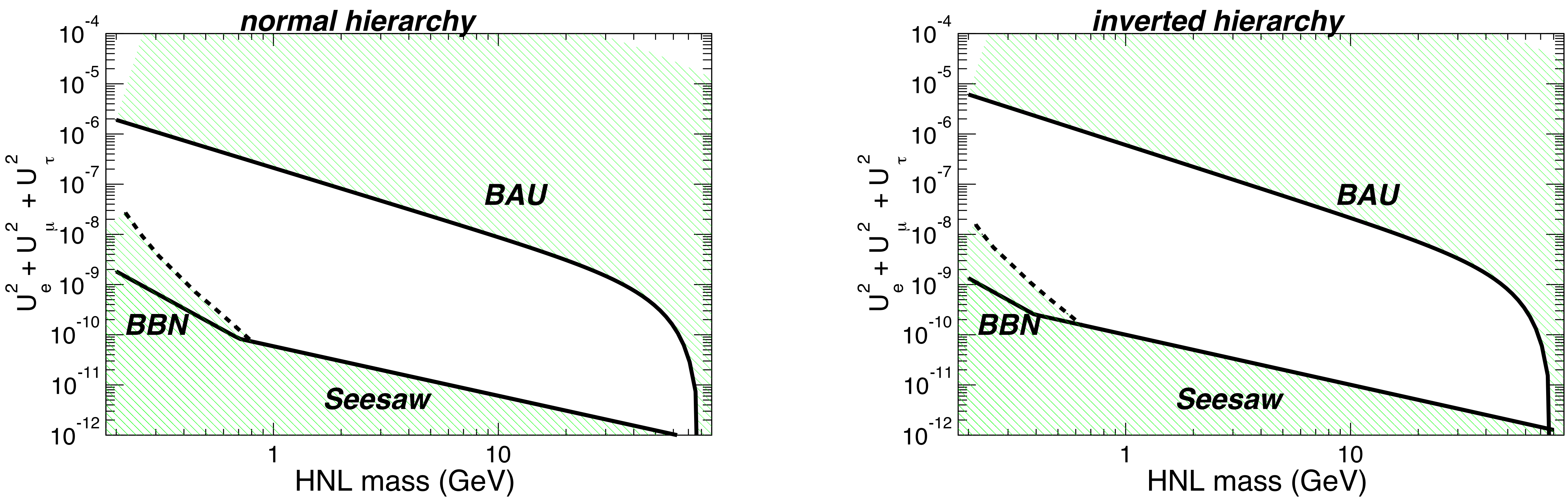
The nuMSM



T.Asaka, M.Shaposhnikov PL B620 (2005) 17
M.Shaposhnikov Nucl. Phys. B763 (2007) 49

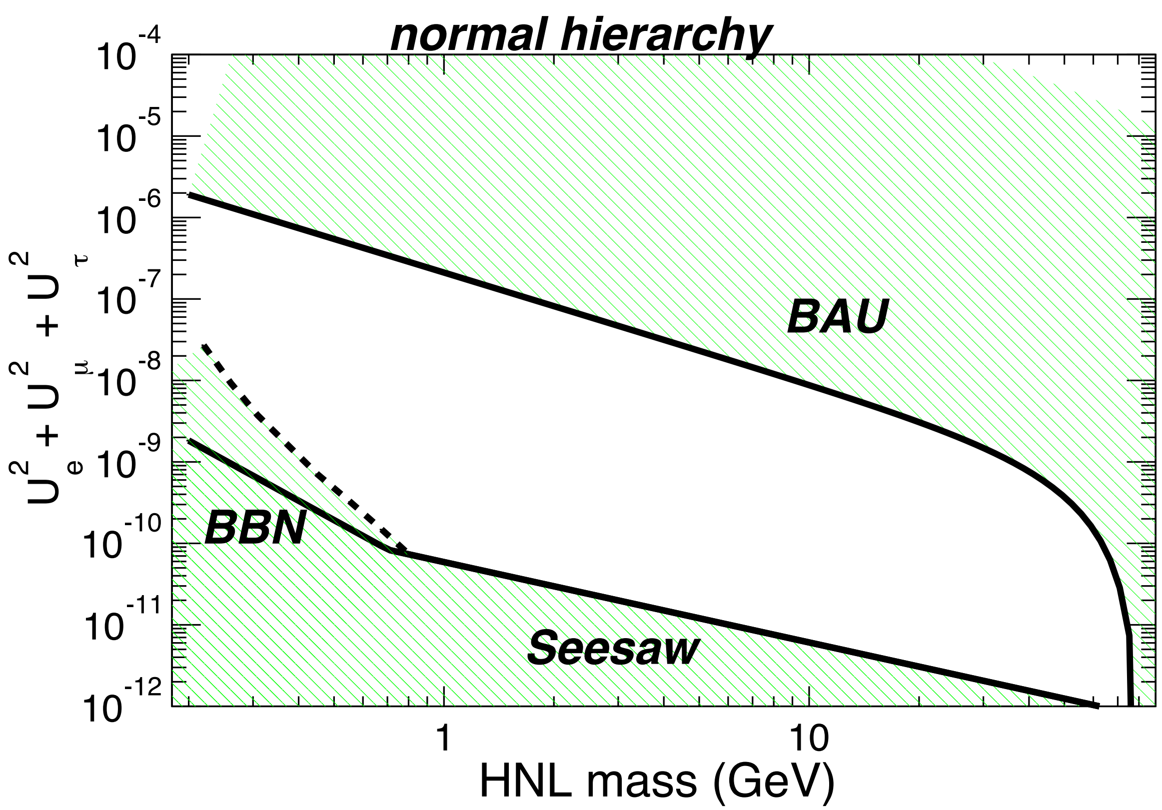
- The lightest sterile neutrino in the KeV region, has a lifetime longer than the age of the Universe and is warm Dark Matter
- Only the two heavier contribute to the seesaw and also generate BAU
- Shaposhnikov proposed that with no mass scale associated to the Planck scale and other problems solved at low energy you do not need other NP (debated in the theory community)

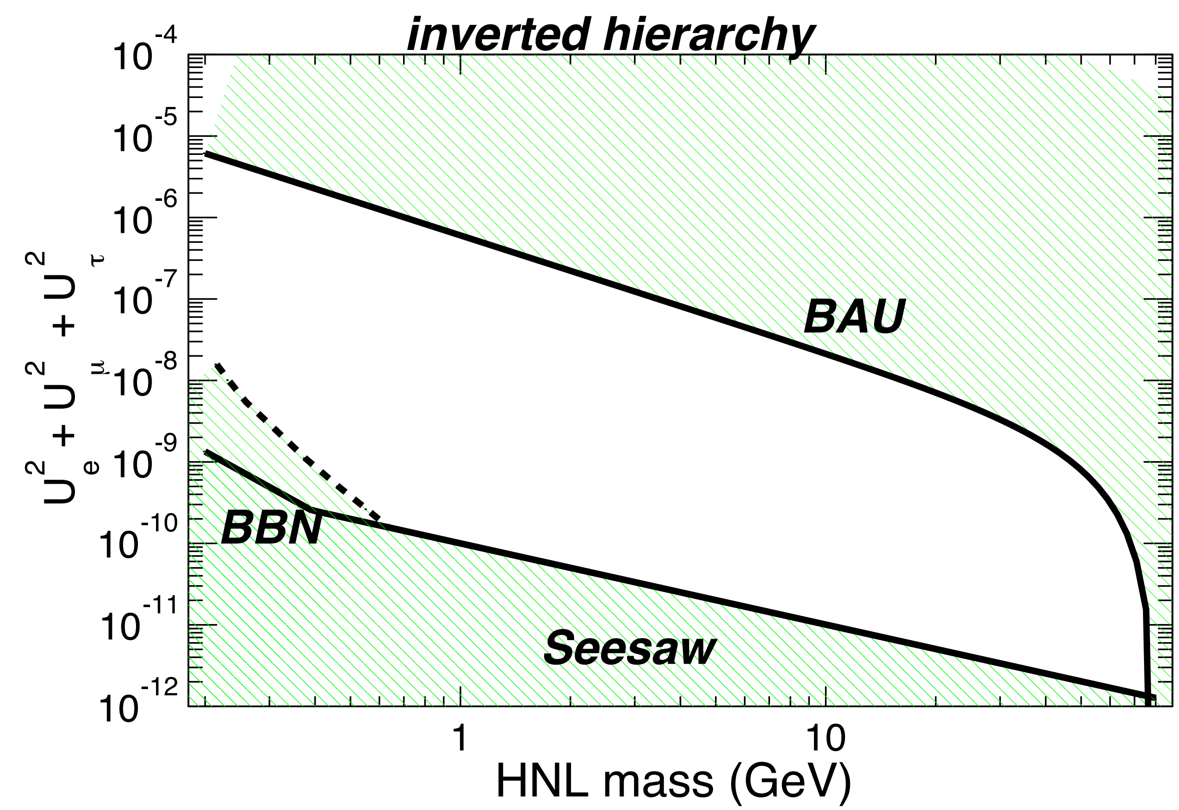
Constraints on the nuMSM



- Seesaw: The bottom region derive on the finite mass of active neutrino, not all sterile neutrinos can be below this line

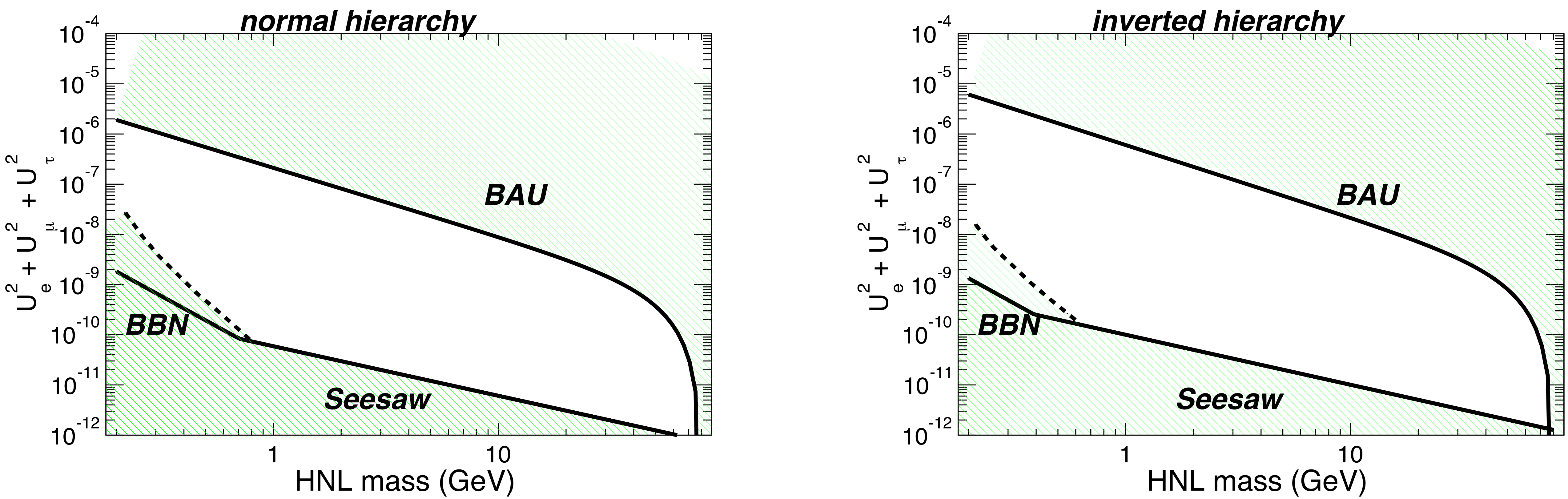
Constraints on the nuMSM





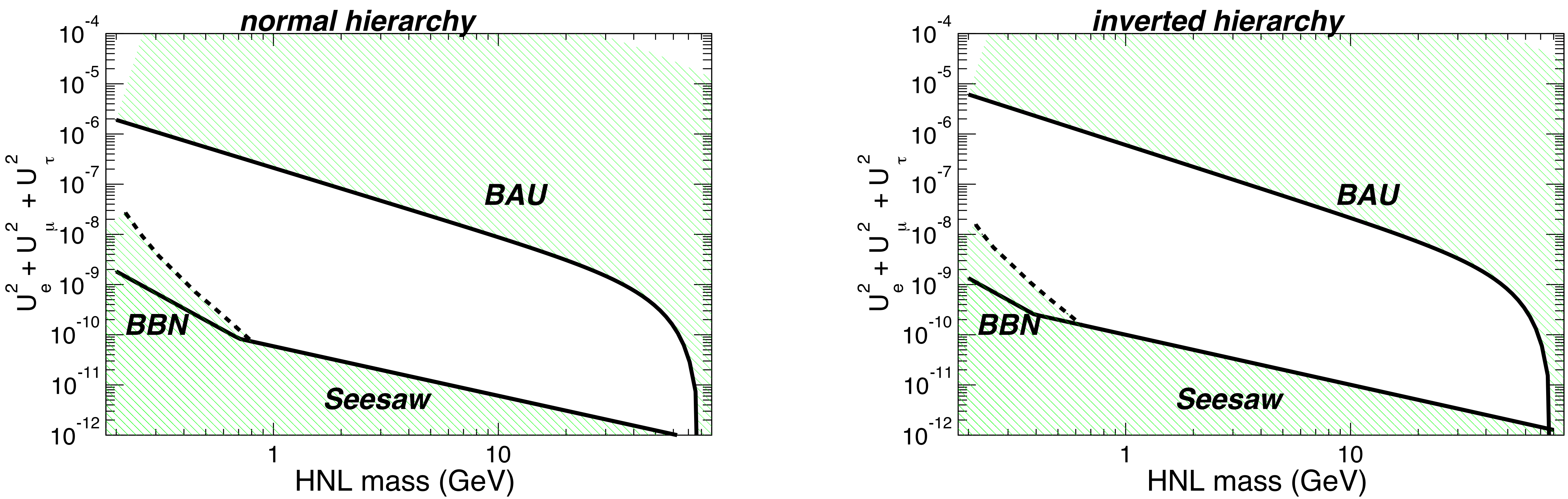
- BBN: Constraint derived asking that the sterile neutrinos decay before the Big Bang Nucleosynthesis

Constraints on the nuMSM



- BAU: If the coupling with neutrinos is too strong they would be in thermal equilibrium and the BAU would be washed out
- If you have three sterile neutrino participating to the seesaw than the BAU constraint are around $U^2 < 10^{-3}$ (Canetti et al. arxiv:1404.7114)

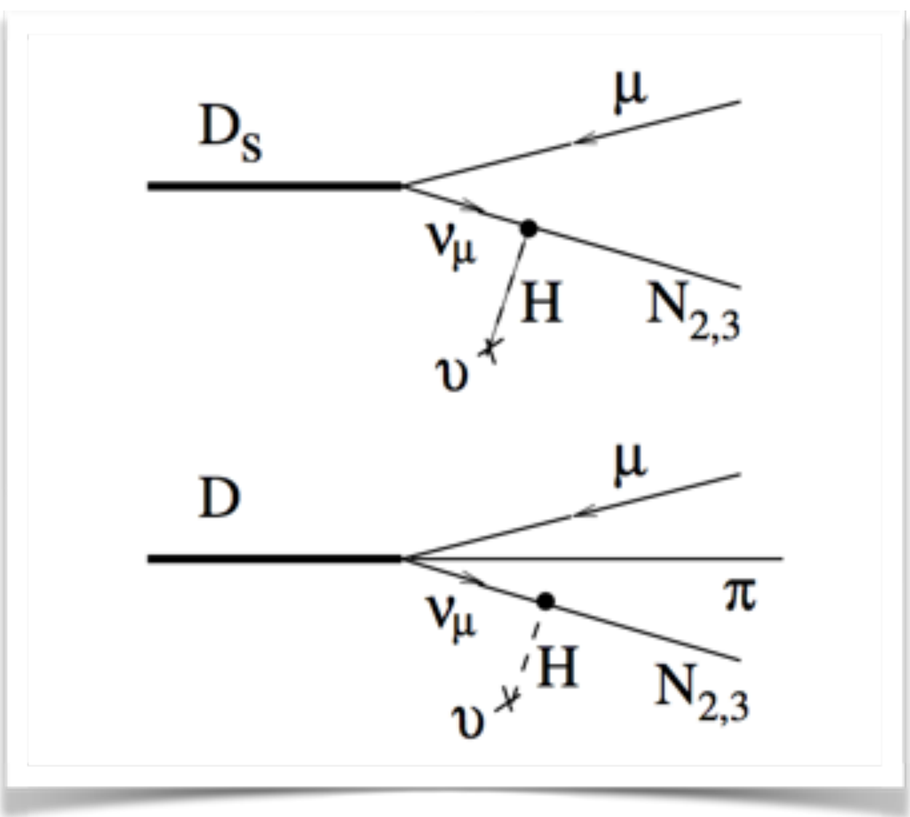
Constraints on the nuMSM

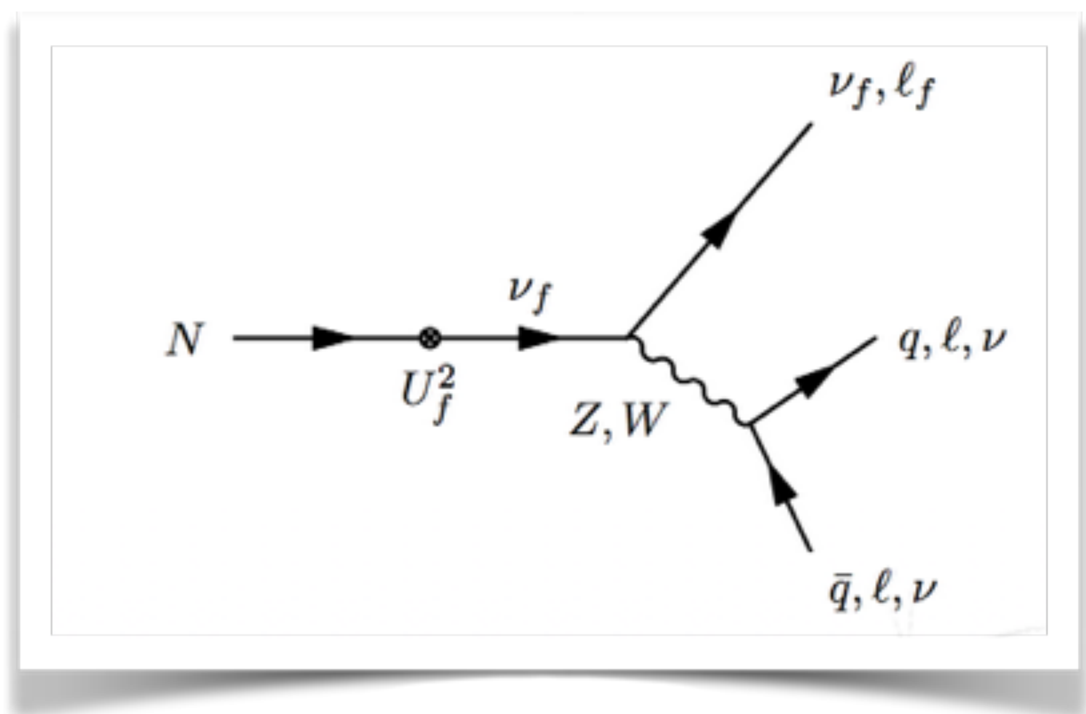


- There is another region that opens up at high energies (above EW scale) which is not part of this talk

Production and decays

- The production of sterile neutrinos happens via mixing of sterile neutrinos with active neutrinos, i.e. it is suppressed by a factor U^2
- If the mass is small enough they can be produced in semileptonic meson decays (pions, kaons, D-mesons, B-mesons)
- The decay of sterile neutrinos also happens via mixing with active neutrinos, decay channels $N \to h\ell$, $N \to \ell\ell^{(\prime)}\nu$, $N \to h^0\nu$

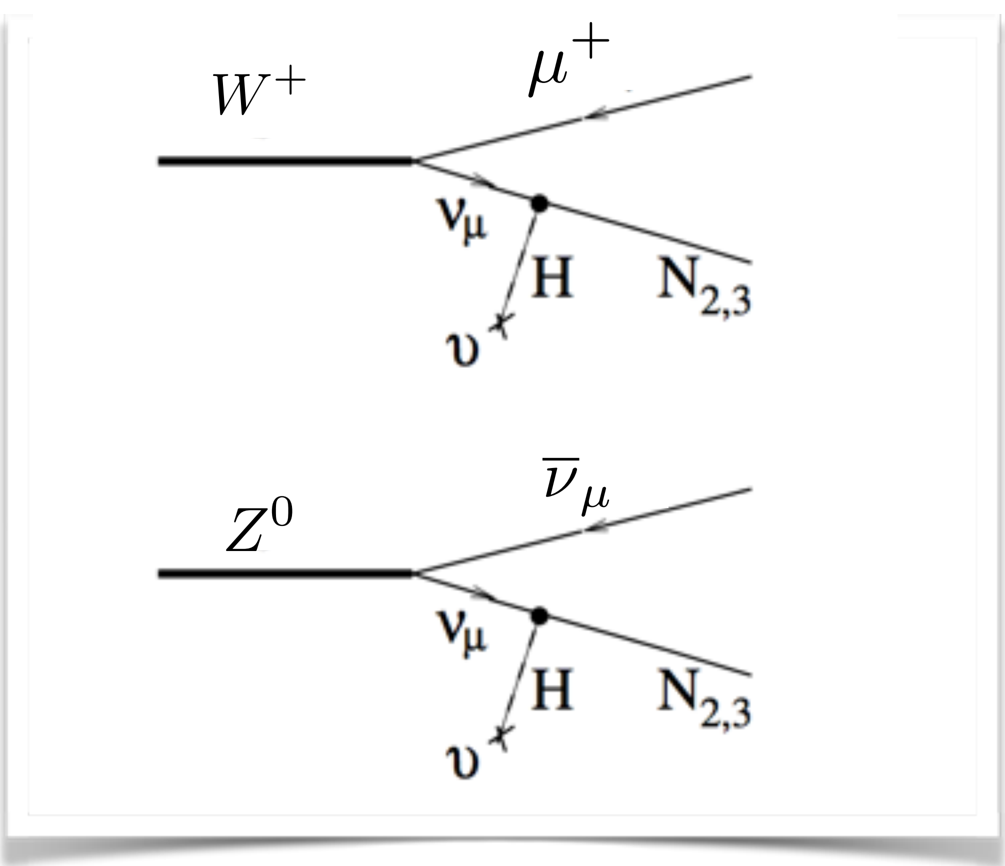


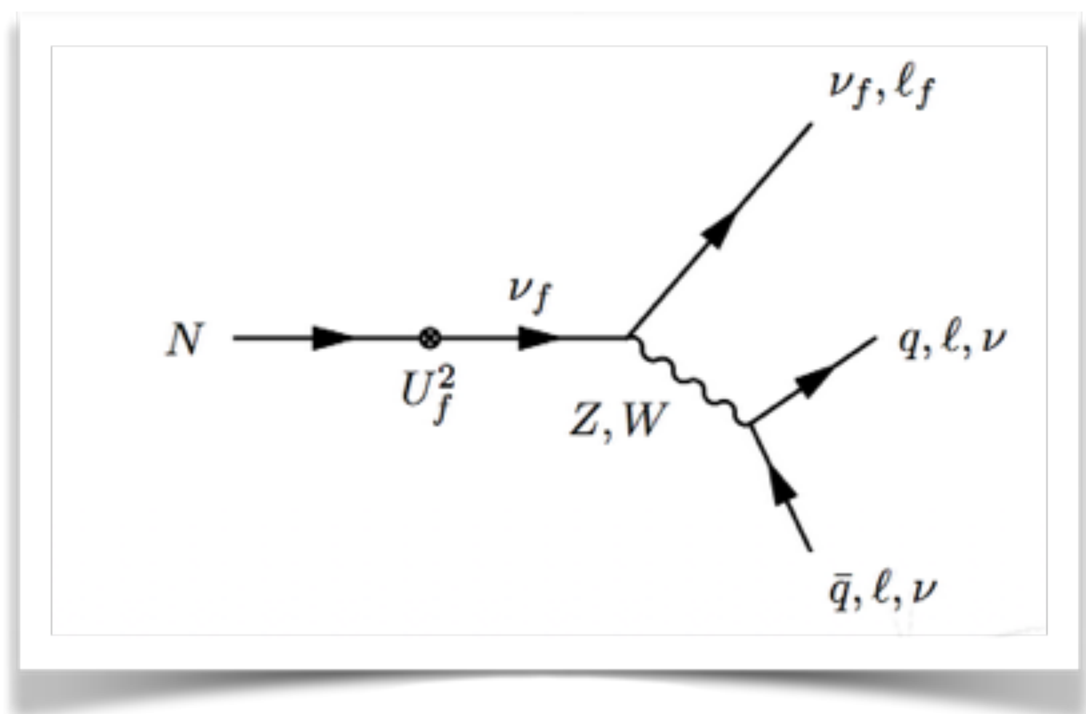


Production and decays

- For high masses of sterile neutrinos they can be produced by decays of Z and W involving neutrinos with one neutrino mixing with the sterile neutrino

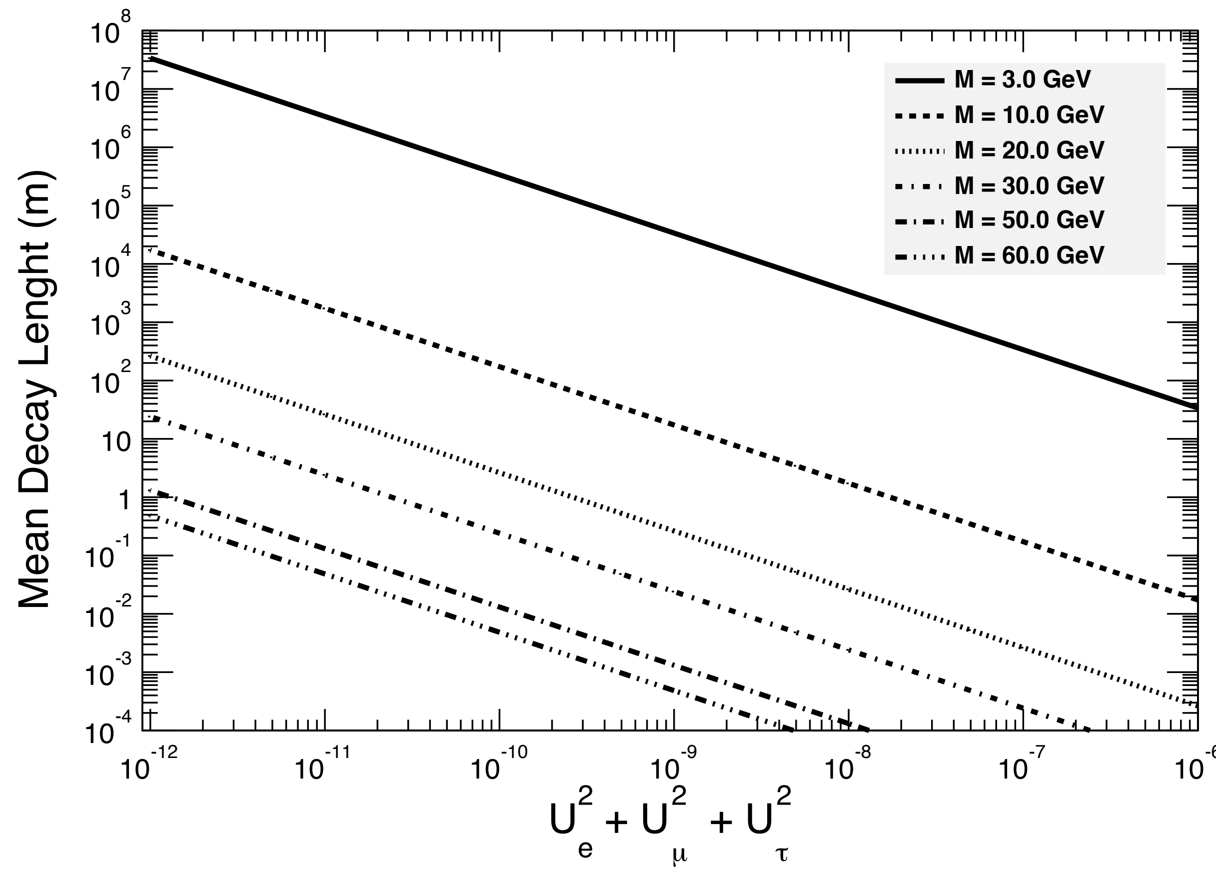
- At high masses of N (>> Lambda_{QCD}) the two quarks do not hadronize together and you have the channels $N \to$ jet jet ℓ, $N \to \ell\ell^{(\prime)}\nu$, $N \to$ jet jet ν





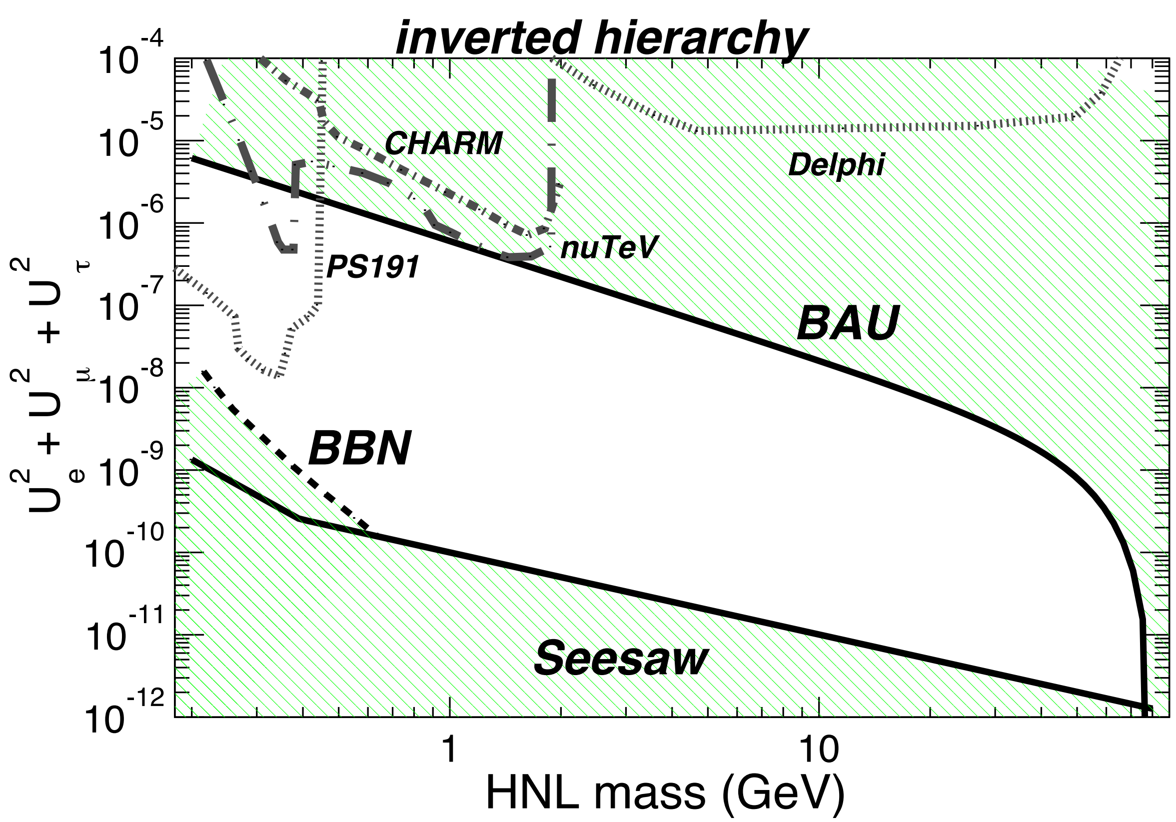
Lifetime

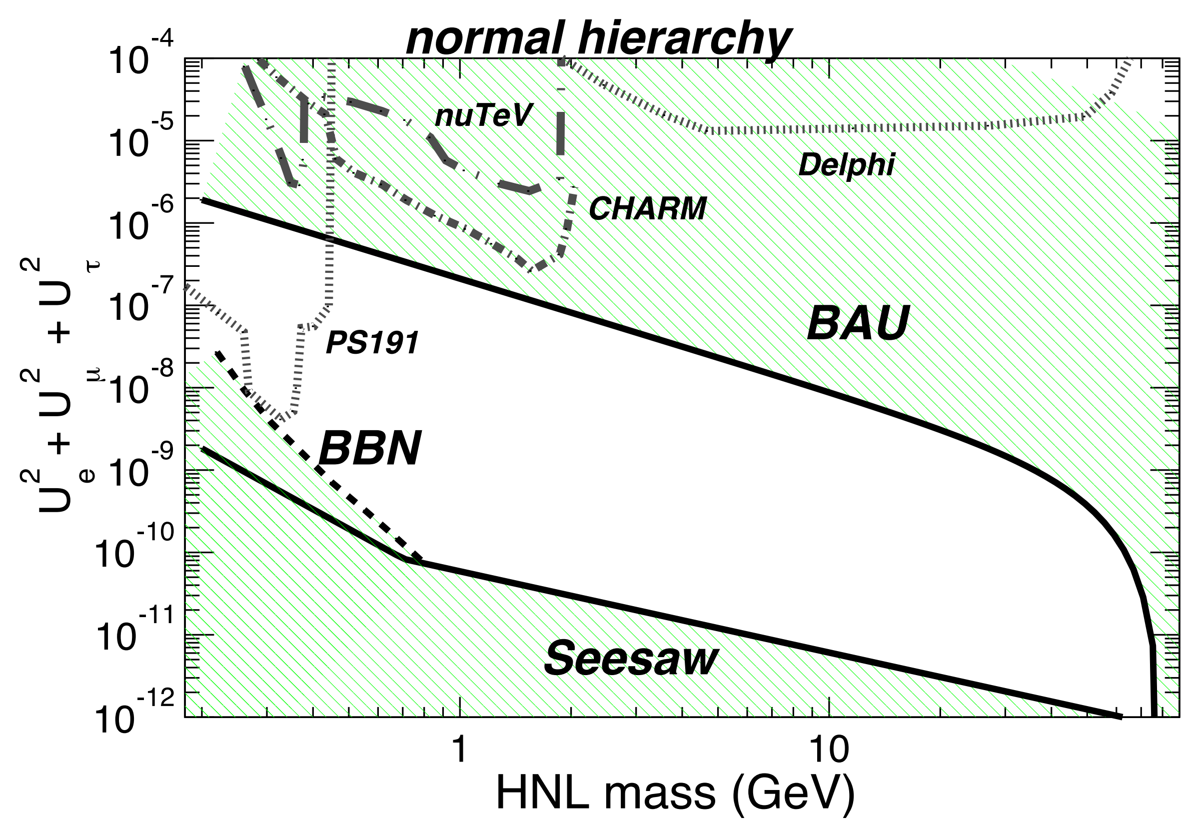
- Lifetime very different for different values of U^2 and M
- Different backgrounds in the different regions of the U^2,M plane
- Likely very different analyses for long and short lifetimes and for low and high masses



The decay width goes has a strong dependence on the mass $\Gamma_N = \frac{G_F^2 M_N^5 U^2}{192\pi^3} \times \mathcal{N}$ where $\mathcal{N}$ is the number of decay channels

Experimental constraints

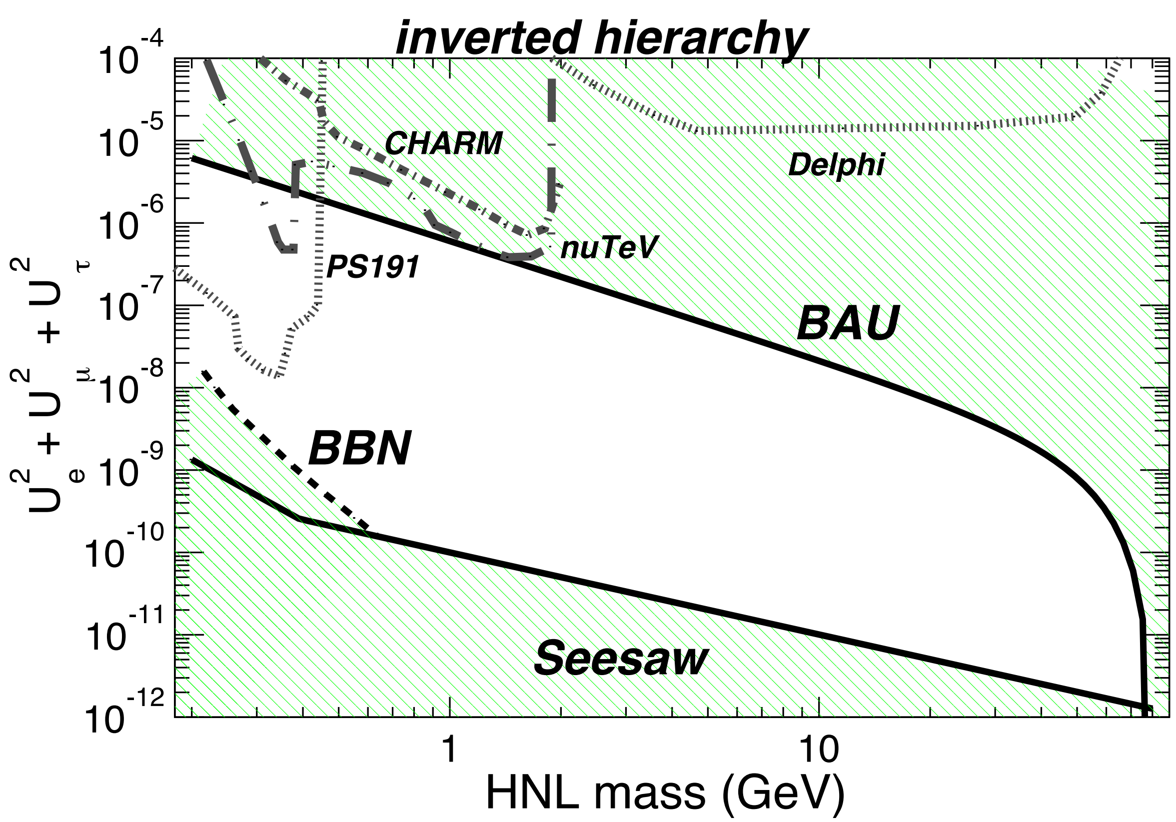


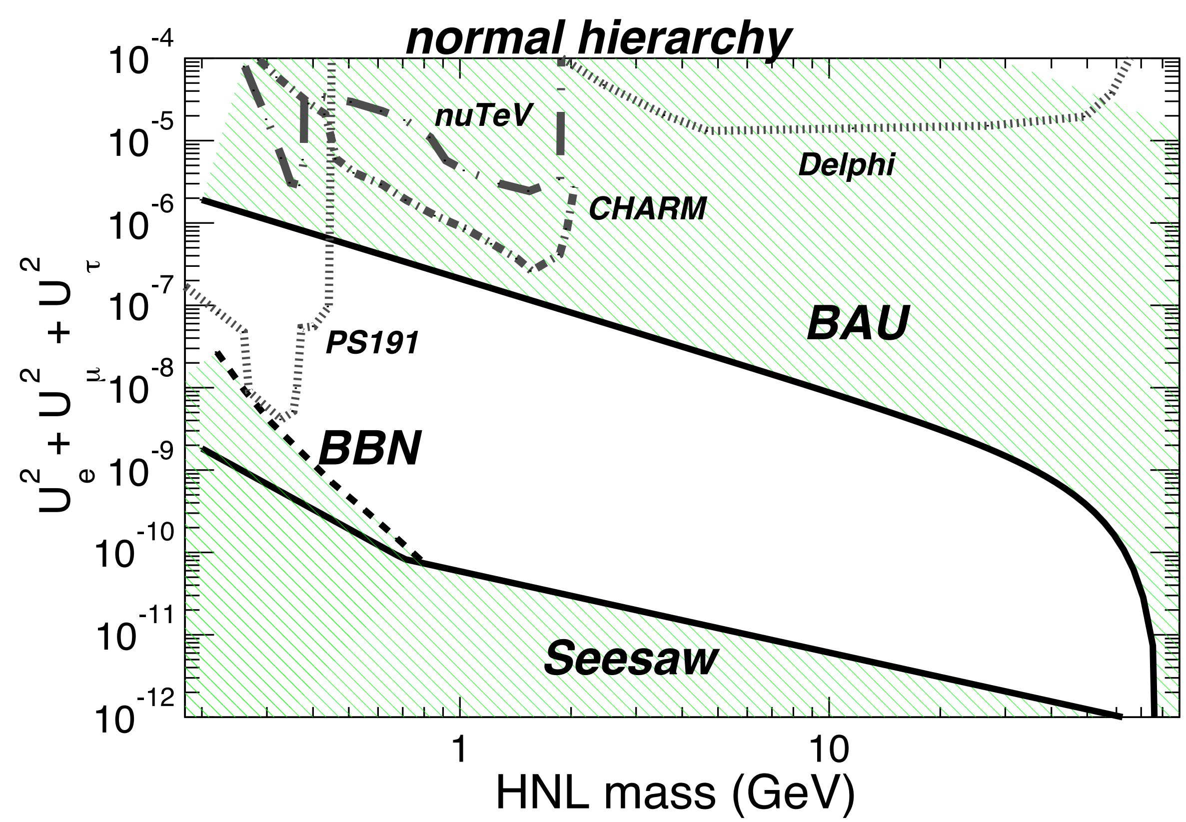


PS191 (Phys. Lett. B 166 (1986) 479; Phys. Lett. B 203 (1988) 332):

- Fixed target experiment at PS of CERN
- p energy 19GeV, 128 m from target, ~0.9×10^{19} pot
- Search for sterile neutrinos coming from Kaon decays

Experimental constraints

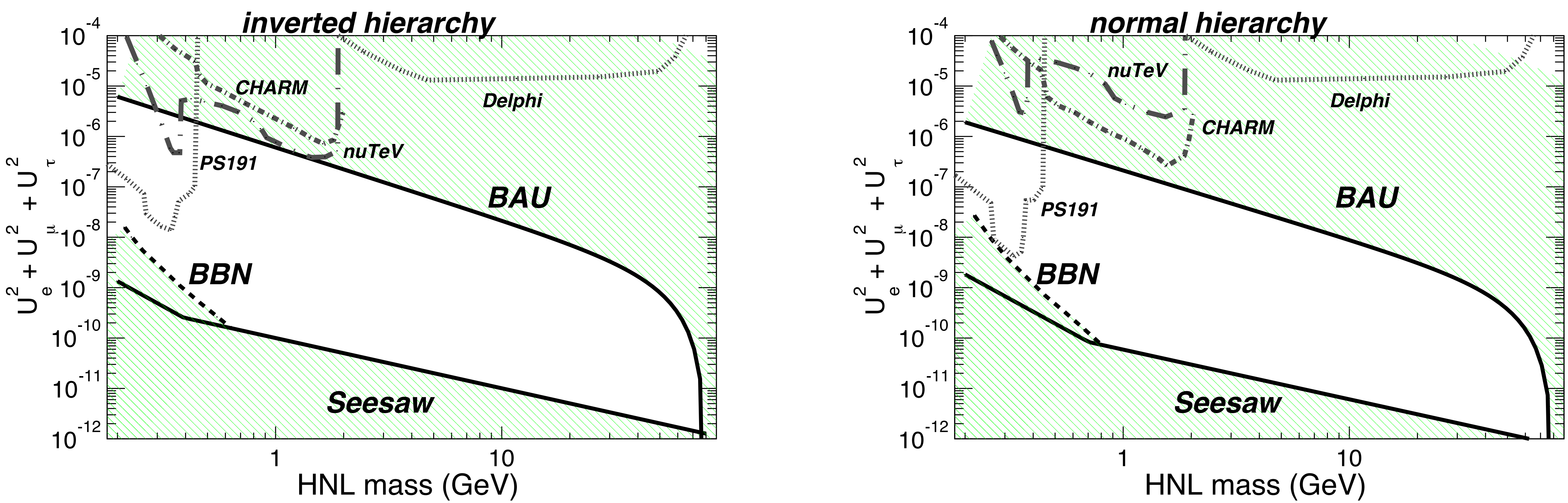




CHARM (Phys. Lett. B 166, 473 (1986)):

- Fixed target experiment at CERN
- p at 400 GeV, detector about 500m from target, ~10^{18} pot
- Search for HNLs coming from D-meson decays

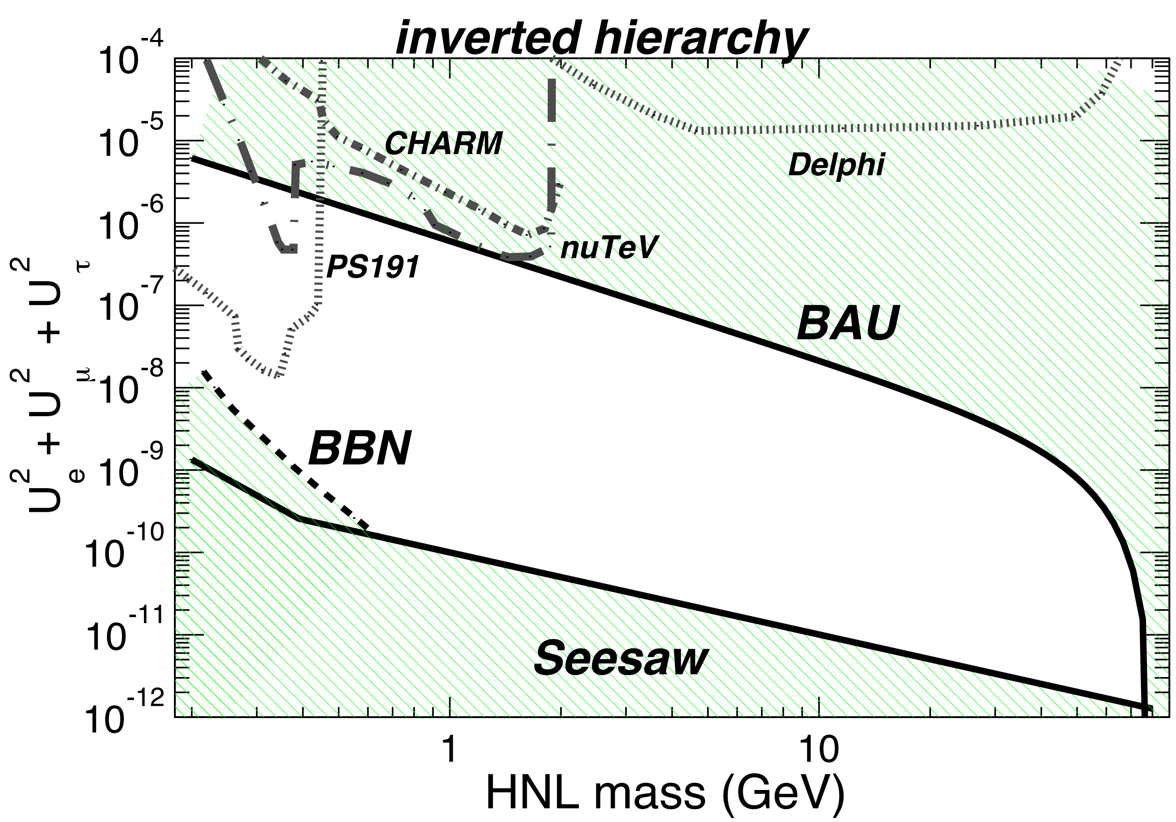
Experimental constraints

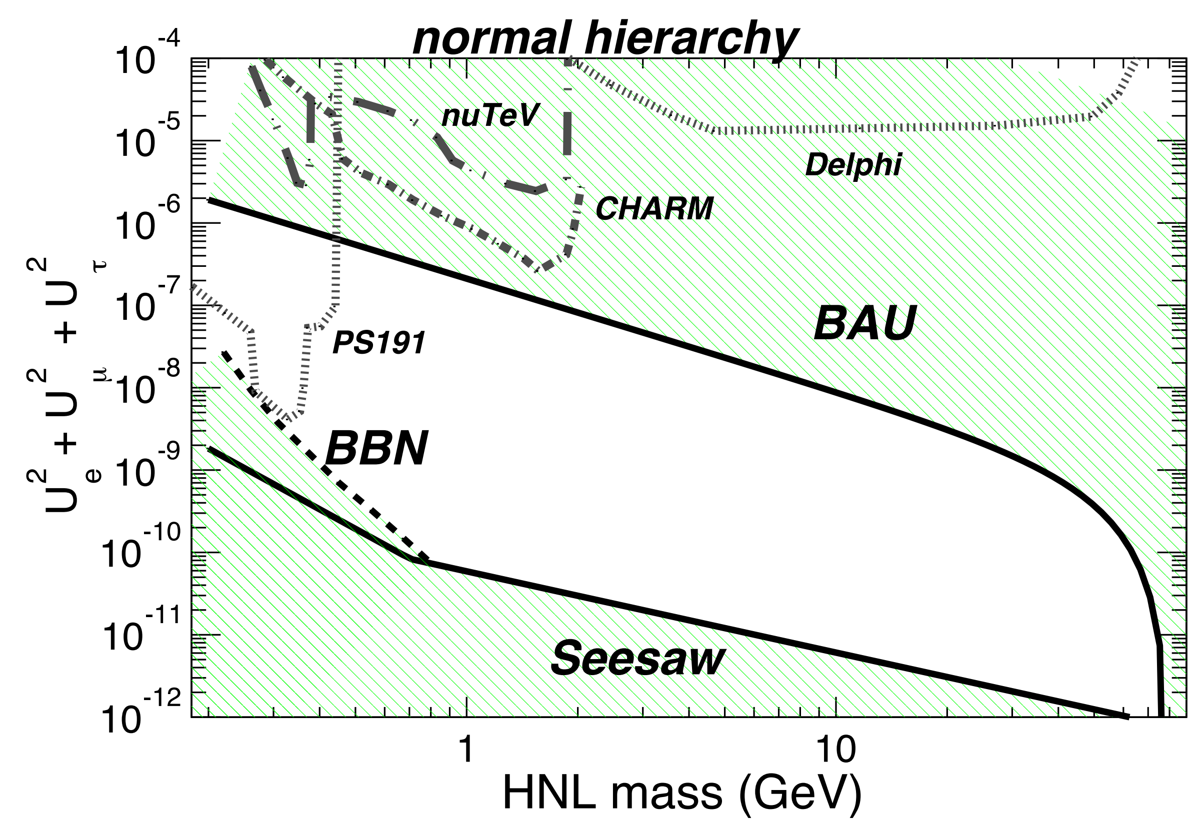


nuTeV (Phys. Rev. Lett. 83 (1999) 4943):

- Tevatron fixed target
- p at 800GeV on target, ~1.5Km from target, ~2.5x10^{18} pot
- Search for HNLs in kaon and D-mesons

Experimental constraints



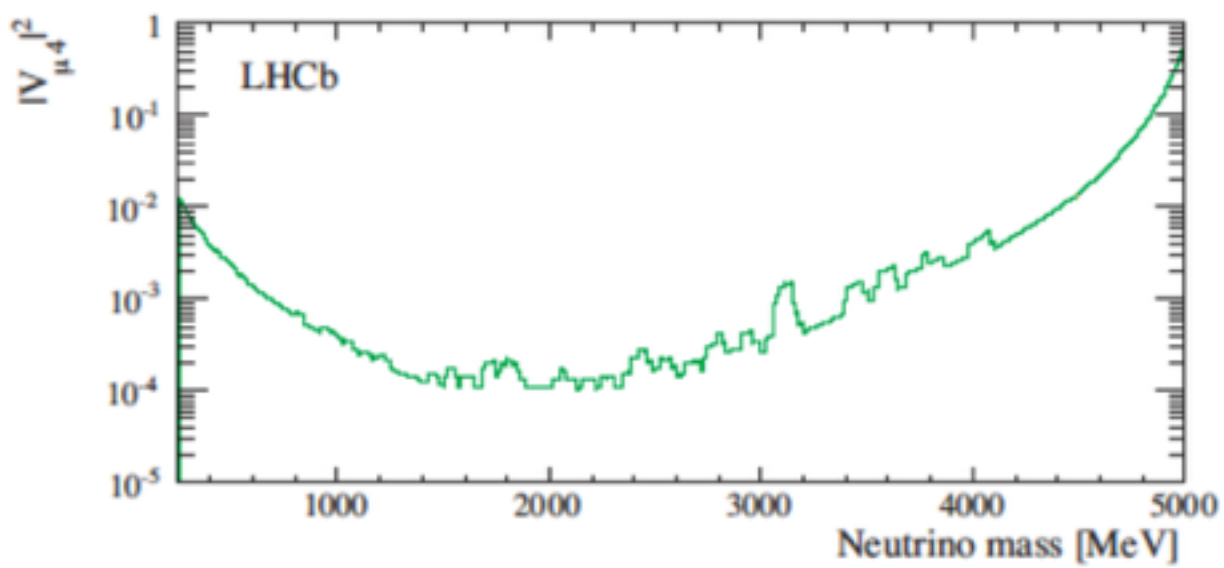


DELPHI (Z. Phys. C 74, 57 (1997)):

- Limit using Z^0 decaying into two neutrinos, one of them mixing with sterile neutrinos
- Number of Z^0 ~10^7

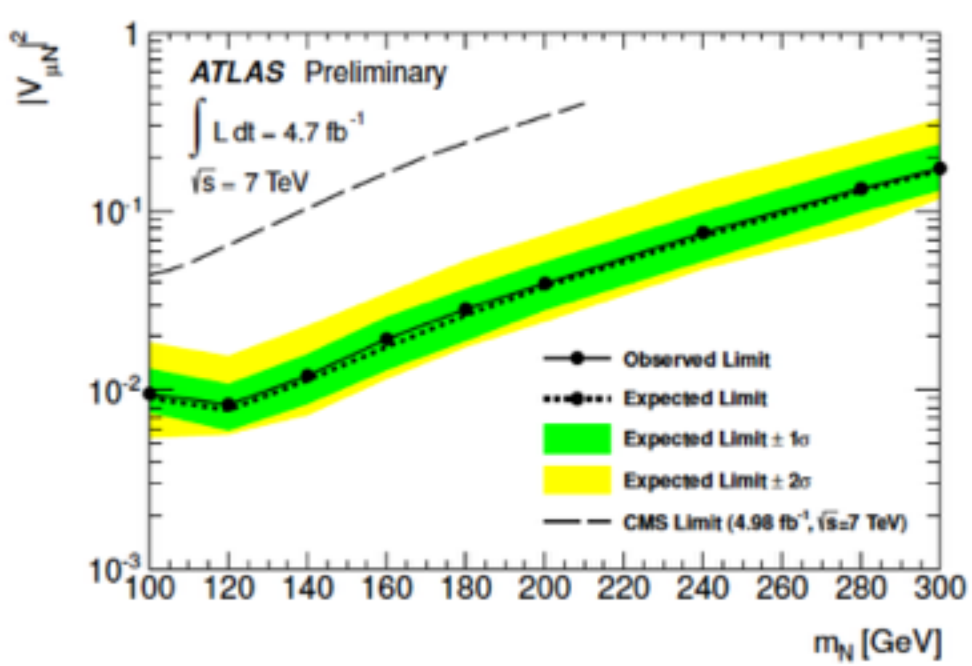
Other searches

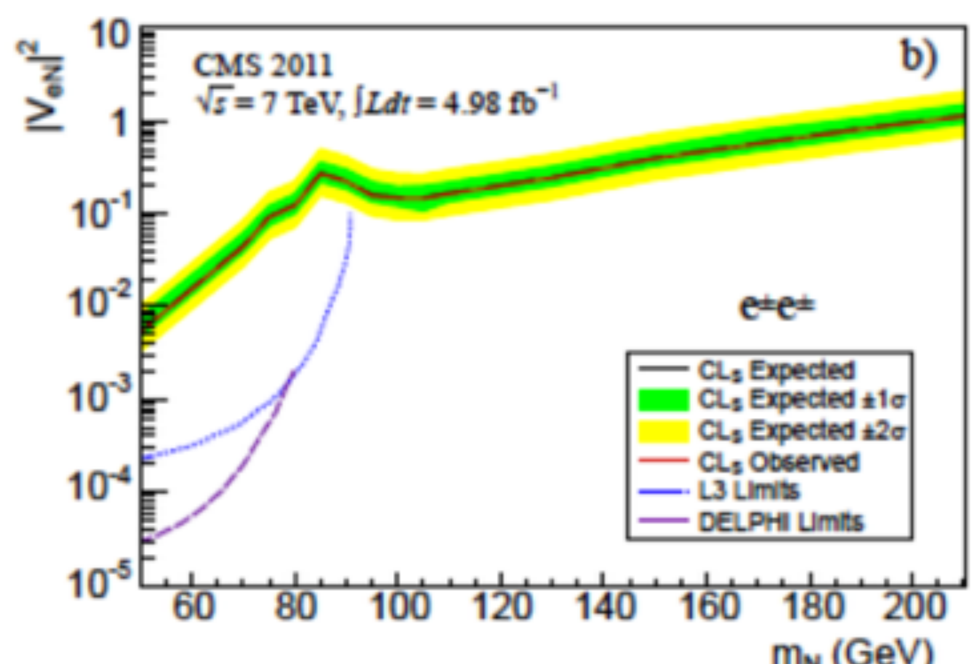
- Searches at B-factories and LHCb



Phys.Rev. D85 (2012) 071103

- Searches at ATLAS/CMS of displaced vertexes (two displaced vertexes) and also for masses larger than the mass of the Z



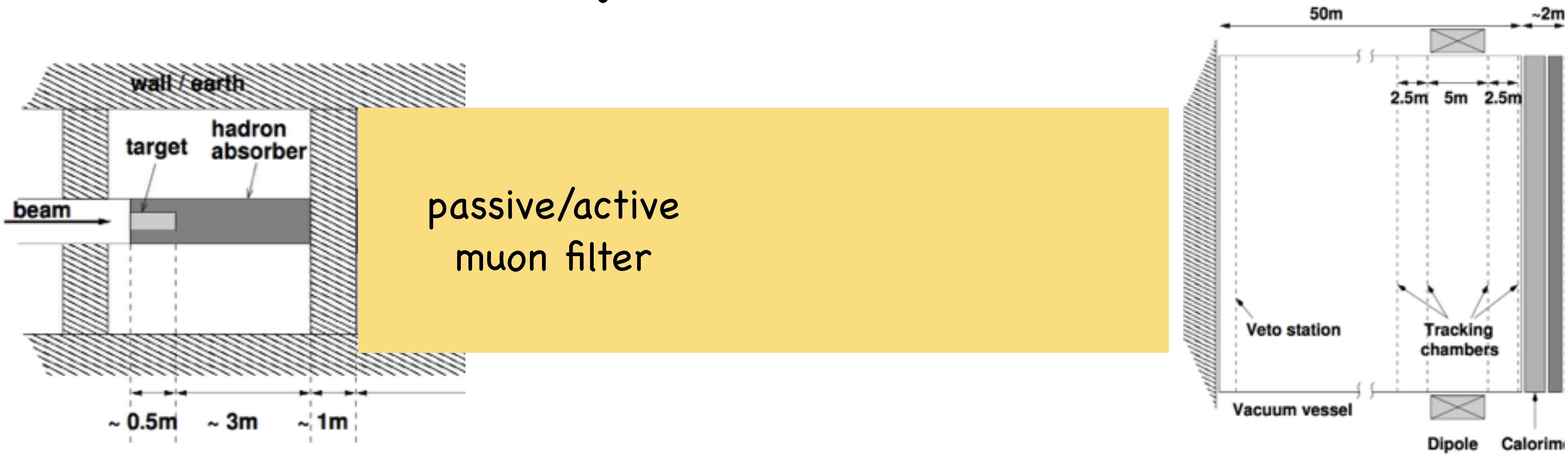


SHiP experiment

- Increase the number of pot
- Go as close as possible to the target
- Decay volume as large as possible
- As low background as possible

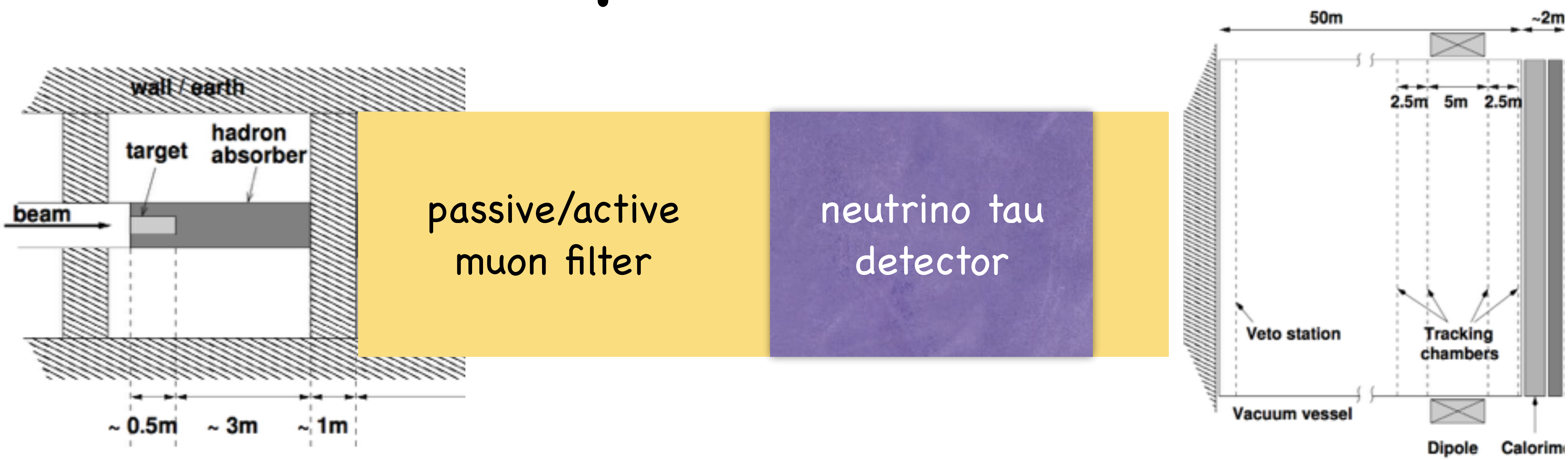
EoI arXiv:1310.1762
www.cern.ch/ship

Concept of the experiment



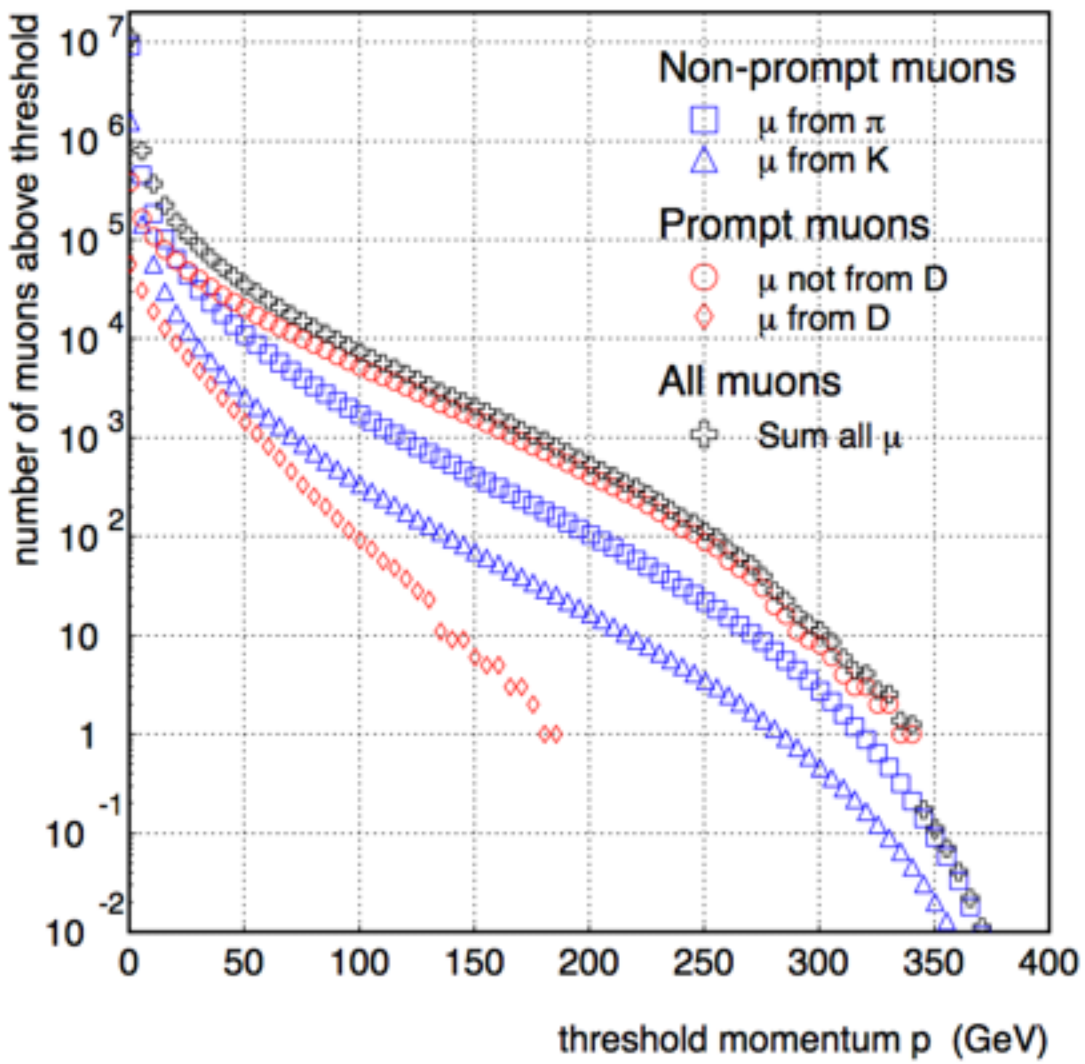
- p on heavy target (W) $2x10^{20}$ pot at 400GeV energy
- Slow beam extraction (1s) to minimise the background
- Heavy target to stop pion and kaons before they decay into neutrinos
- Long muon shield to range out muons

Concept of the experiment



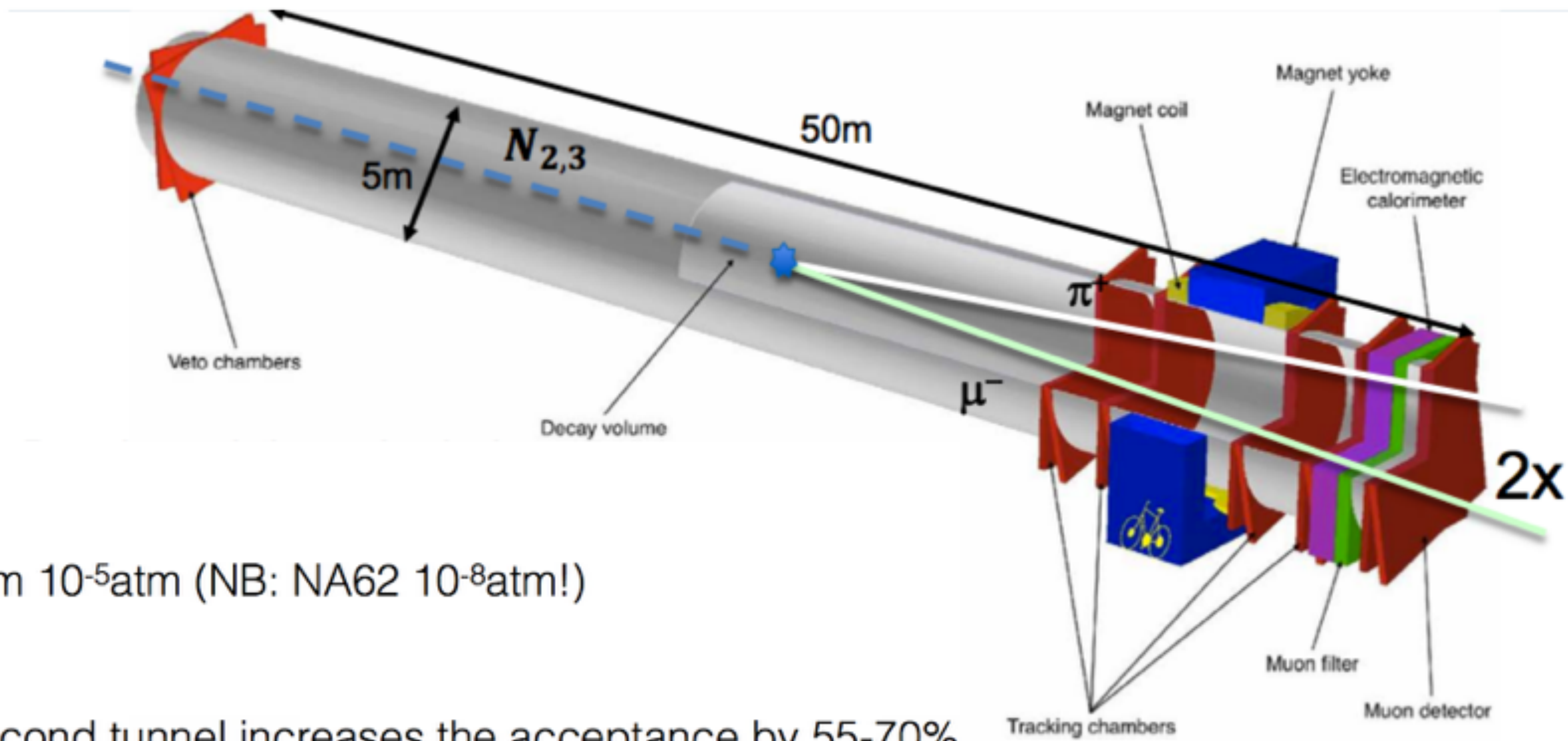
- Same optimisation also maximise the flux of tau neutrinos, since they come from D_s leptonic decays
- We also foresee a tau neutrino detector immediately before the sterile neutrino decay volume

Muon background



- Muons coming mainly from eta(') and omega
- We are studying two solutions: passive and <u>active filter</u>
- Active filter with sweeping magnets preferred (under design)
- Enormous flux of about 10^{11} muons/spill(5×10^{13} pot)

Evacuated Decay Volume



Vacuum 10^{-5}atm (NB: NA62 10^{-8}atm!)

The second tunnel increases the acceptance by 55-70%

<u>Vacuum level chosen to have the background coming from neutrino scattering in the air to a negligible level</u>

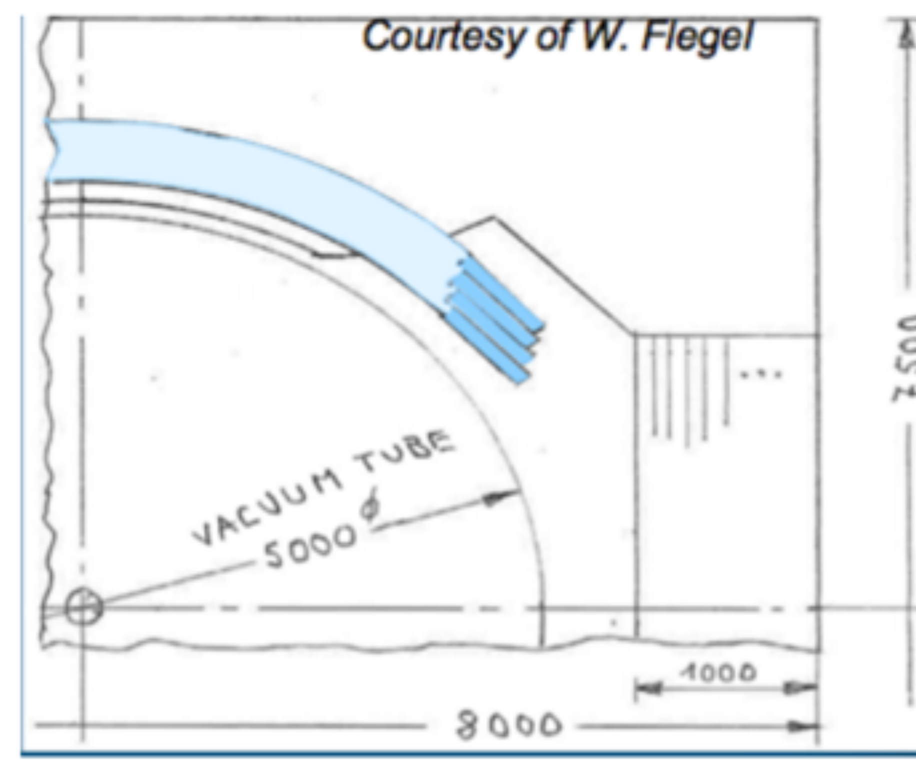
Magnet

A dipole magnet very similar to the LHCb one but with 40% less iron and three times less power

LHCb: 4Tm and aperture ~ 16 m^2

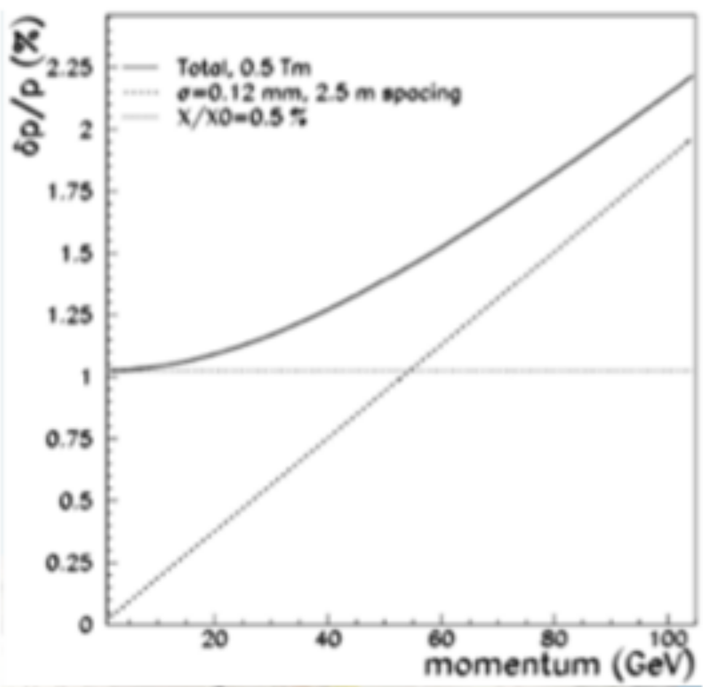
This design:

- aperture 20 m^2
- Two coils Al-99.7
- peak B field ~ 0.2 T
- field integral ~ 0.5 Tm su 5 m



Tracker

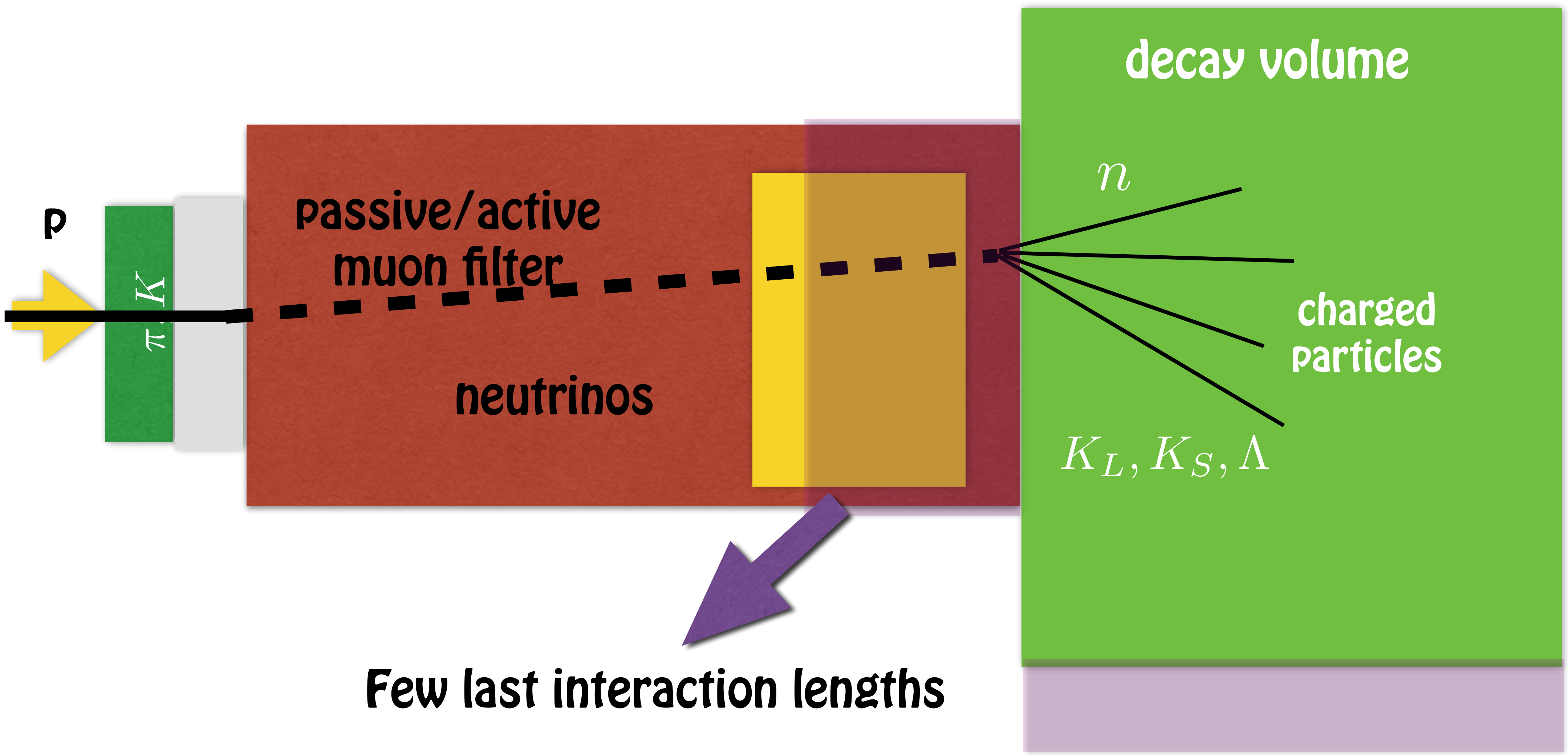
Straw tubes similar to NA62 with 120 μm space resolution, 0.5% X_0/X.



Main difference to NA62:

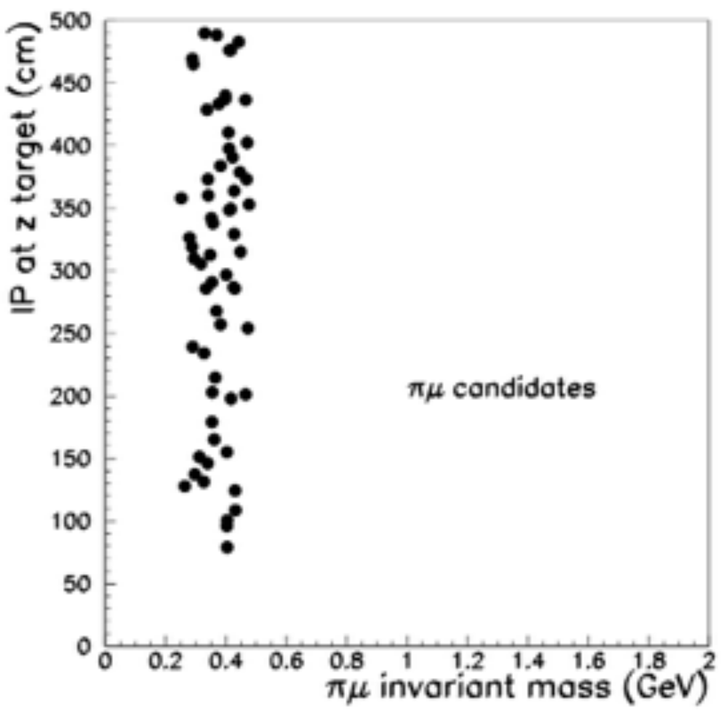
A. 5m lenght
B. vacuum 10^{-2} mbar
C. 2kHz/straw of 1cm diam

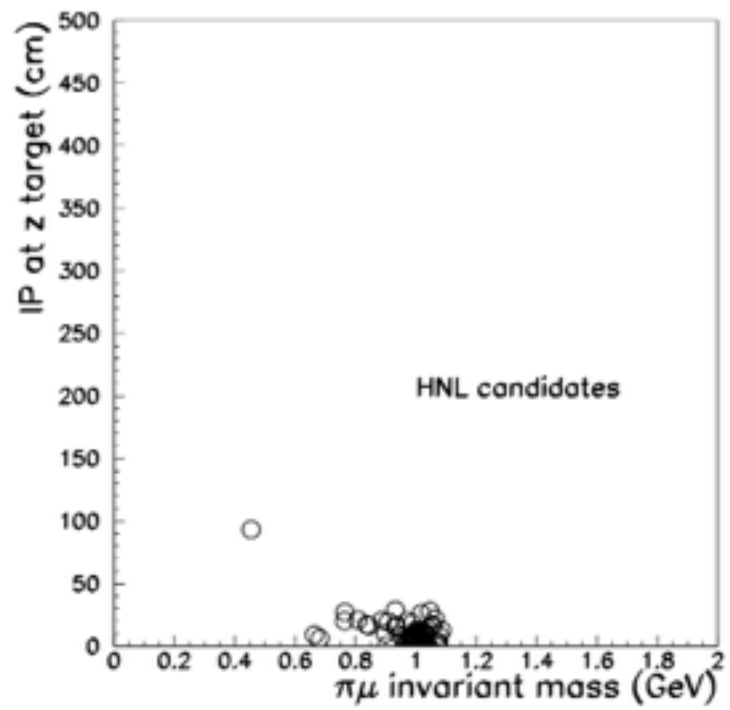
Background



- Strangeness from neutrino interactions in the material (especially K_L)
- Kinematic difference with the signal (especially at high masses)

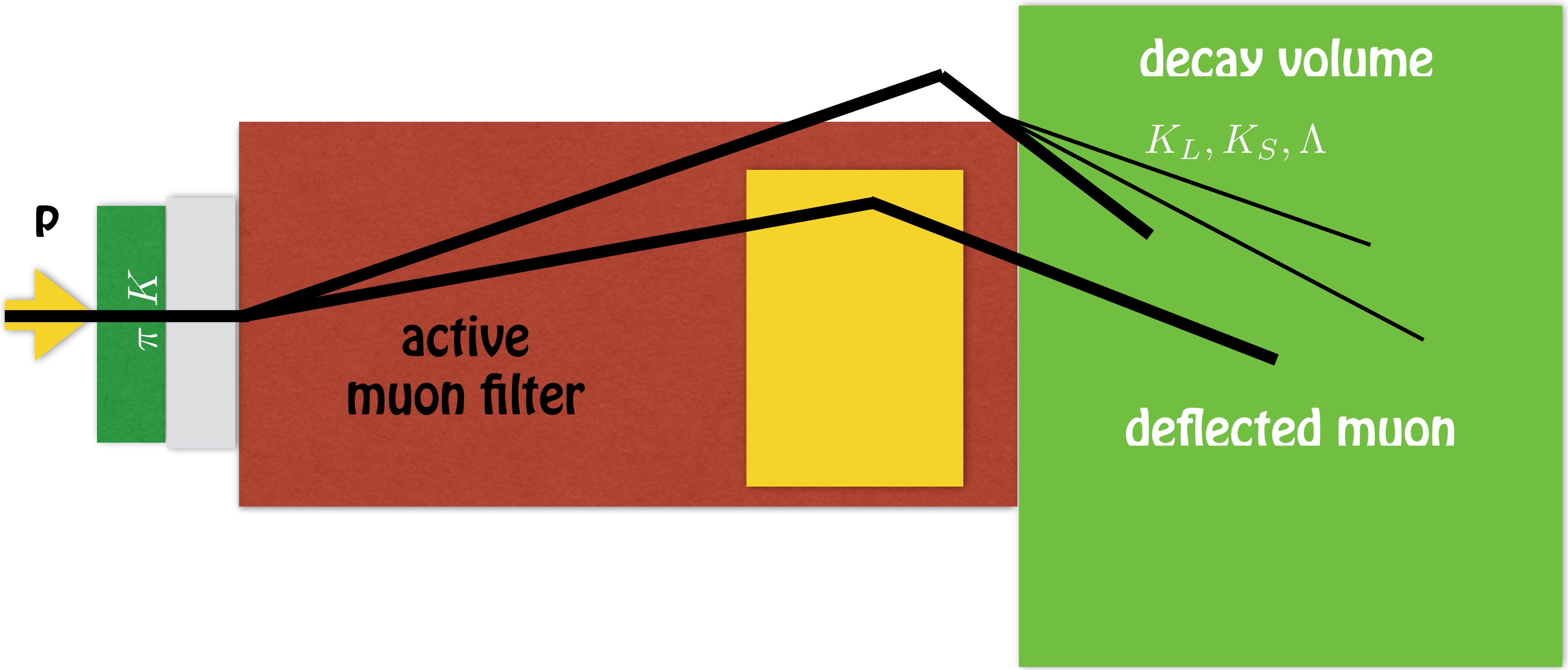
Background





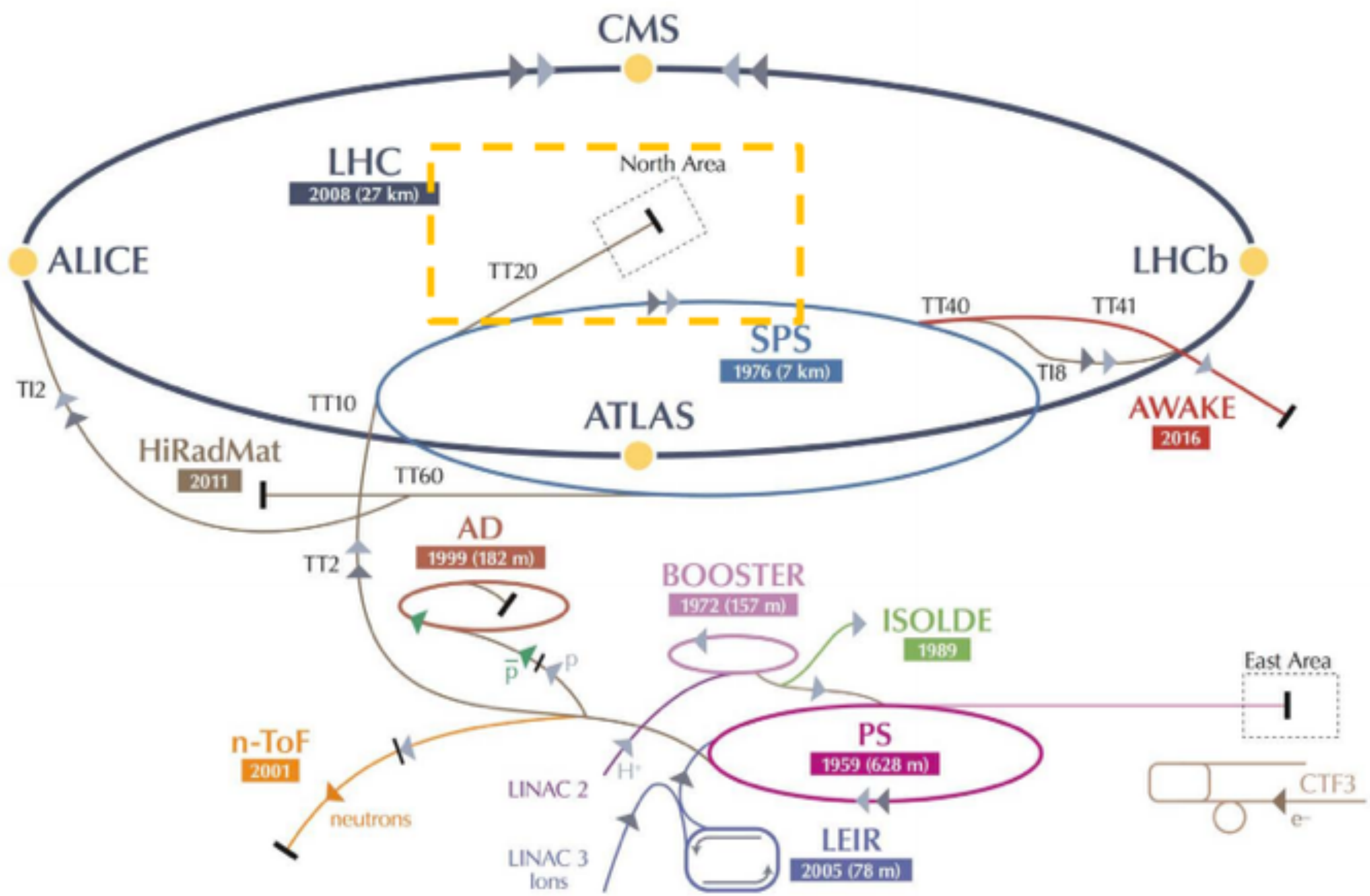
- Pointing and invariant mass for HNLs and K_L—> pi mu nu
- Clearly less of a problem for fully reconstructed signal decays (N—>pi mu)
- Plan to equipe the last few interaction length with specific veto detectors

Background



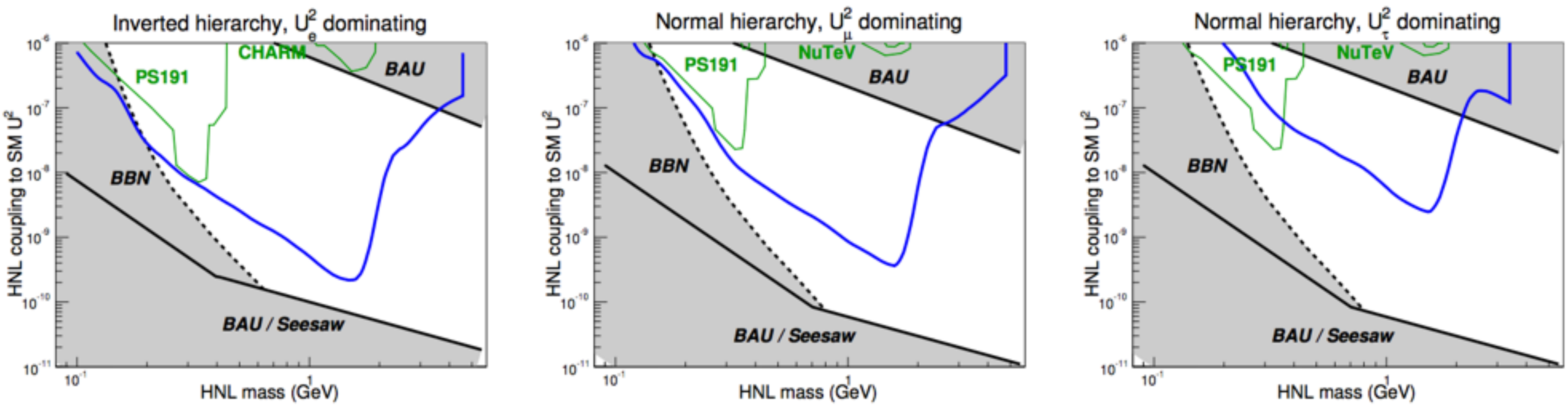
- Careful design of the sweeping magnets
- Kinematic rejections of K_L
- Veto with very good time resolution (at least ns)

CERN accelerator complex




Underground Structures (Tunnel/Cavern/Hall)
Surface or Partially Underground Structures (Target Hall/SB/Access Building)
Shafts + Tunnel access
Access Area + Car Park
New SHIP Beamline
Future SHIP Extension Area
DETECTOR HALL ~ 20 m wide
810
811
812
Access Bld. ~ 20m wide
~ 40 m
~ 120 m
~ 38 m
~ 25 m
Service Bld. ~ 15m wide
Filter Tunnel
50
TARGET HALL ~ 20m wide
Bypass tunnel
10 - 20
~ 140 m
Technical Gallery
Existing Technical Gallery GT801
Access Bld. ~ 15m wide
~ 15 m
Tunnel
TCC2
"Aux. Power Supply"
Extraction
~ 170 m
TDC2
JUNCTION CAVERN
~ 85 m
Splitter 2
TDC2
~ 100 m
SHIP extraction MSSB2117 Splitters
new access road
SHIP AREA on the French CERN Site in Prévessin

SHiP Expectation for sterile neutrinos



- Expected sensitivity of the SHiP experiment in three different scenarios
- Sterile neutrinos from D and B mesons
- In all cases we expect to improve previous results by 3-4 orders of magnitudes

Other SHiP physics case

SHiP is in general sensitive to relatively light very weakly coupled long lived particles (e.g. models with Hidden sectors):

- Light scalars mixing with the Higgs
- Axion-like particles
- Dark photons
- Light Susy (light R-parity violating neutralino, light sgoldstino, hidden susy)

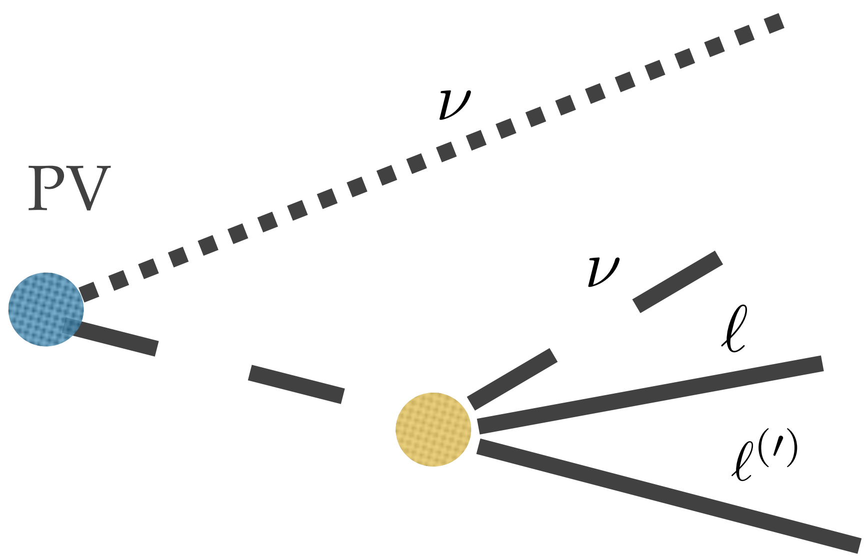
- …

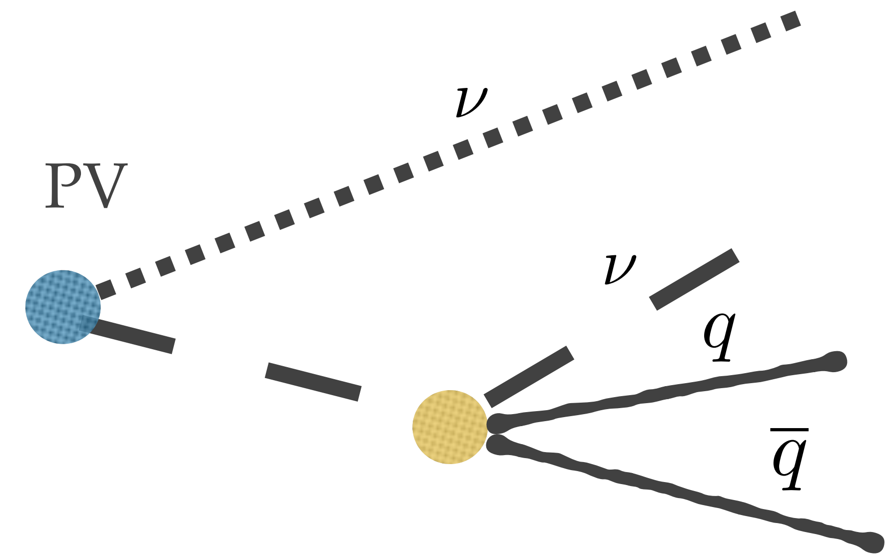
<u>In addition tau neutrino detector before the decay volume, expected about 3000-4000 reconstructed tau neutrinos:</u>

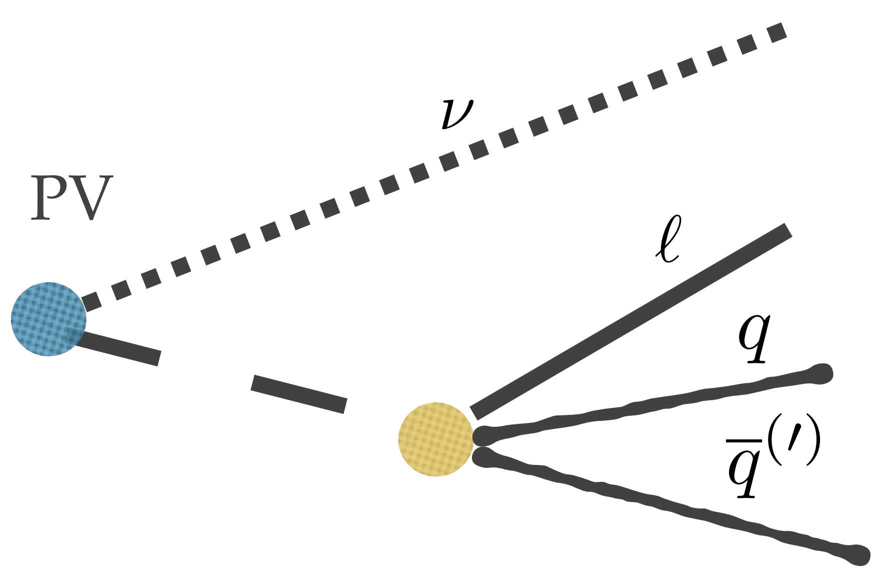
  - Charm cross section production with tau neutrinos
  - Discover the tau antineutrino
  - …

What about sterile neutrinos with larger masses?

Signature at colliders

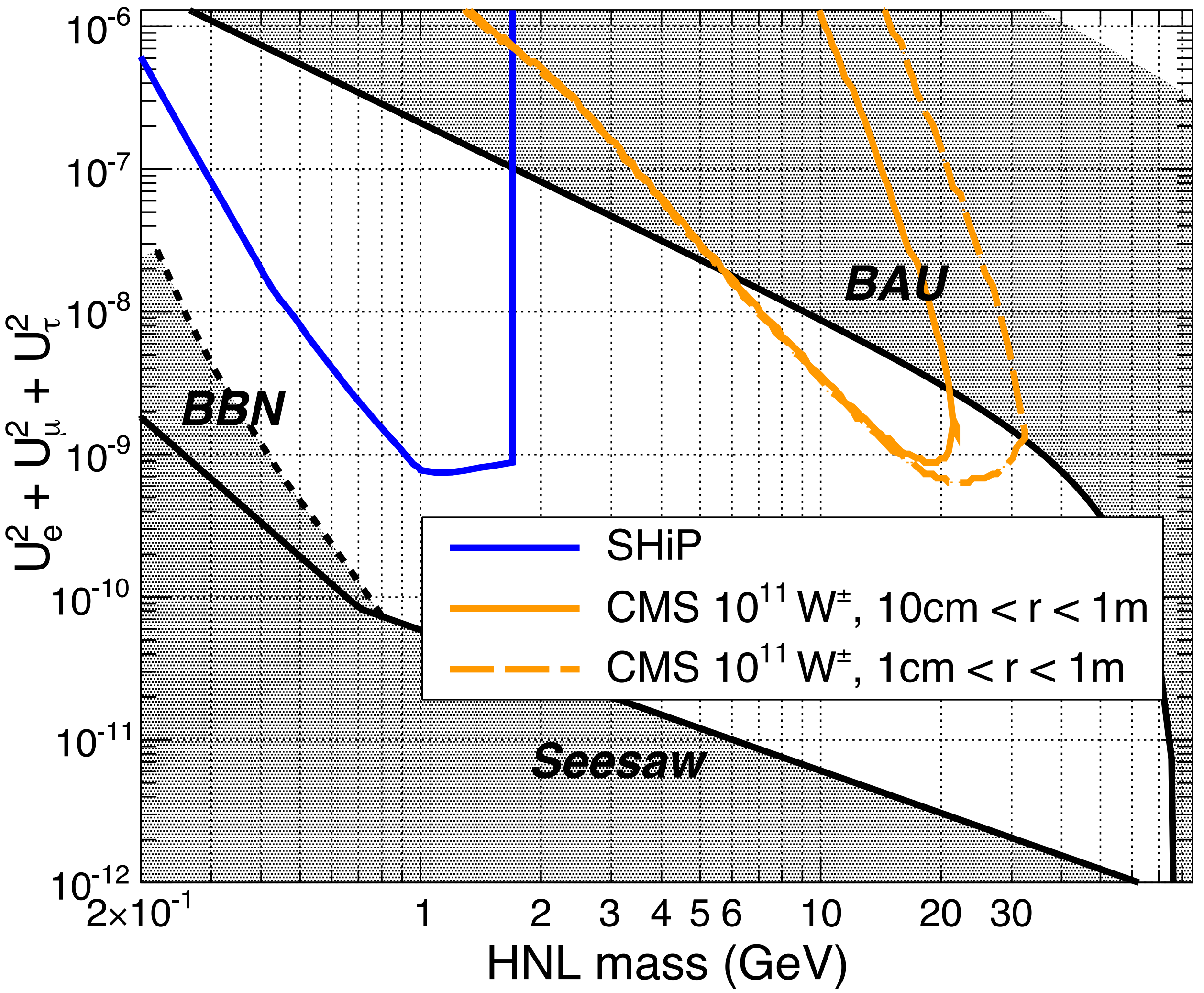






The main signature are very displaced vertexes

CMS/ATLAS toy study

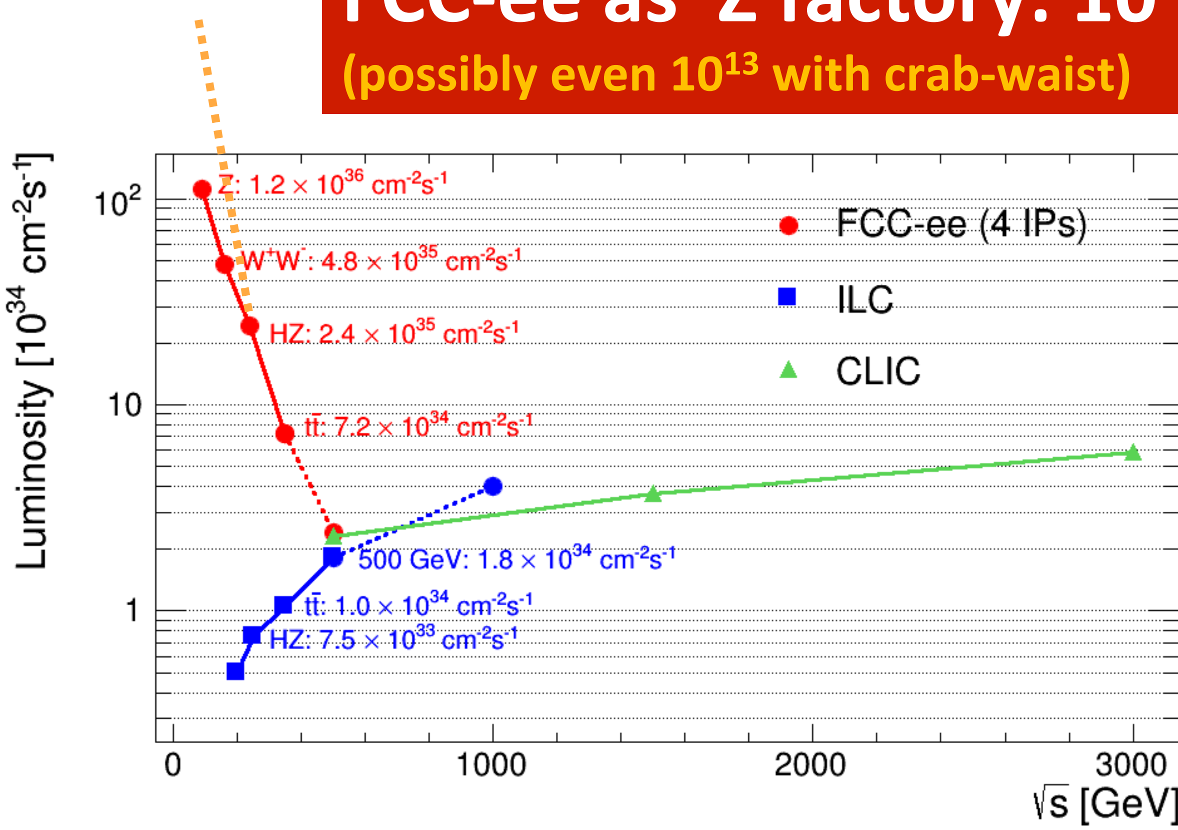


- Considering the full 3000 fb^{-1}
- Sterile neutrinos coming from Ws
- Assuming to go to ~0 background with flight distance cuts

One should remember that the BAU limit is less constraint by several orders of magnitudes if we consider three sterile neutrinos participating to the seesaw

Future Z factories

FCC-ee as Z factory: 10^{12} Z
(possibly even 10^{13} with crab-waist)

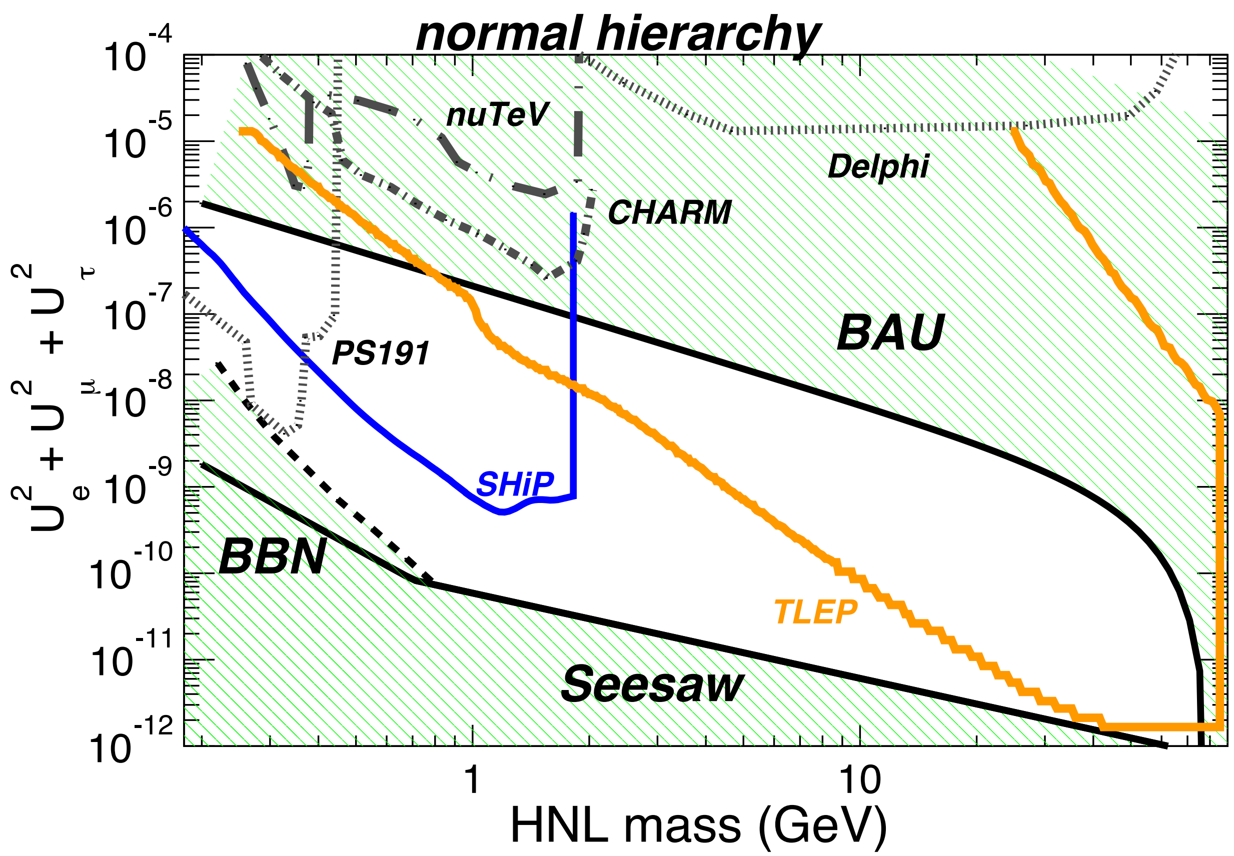


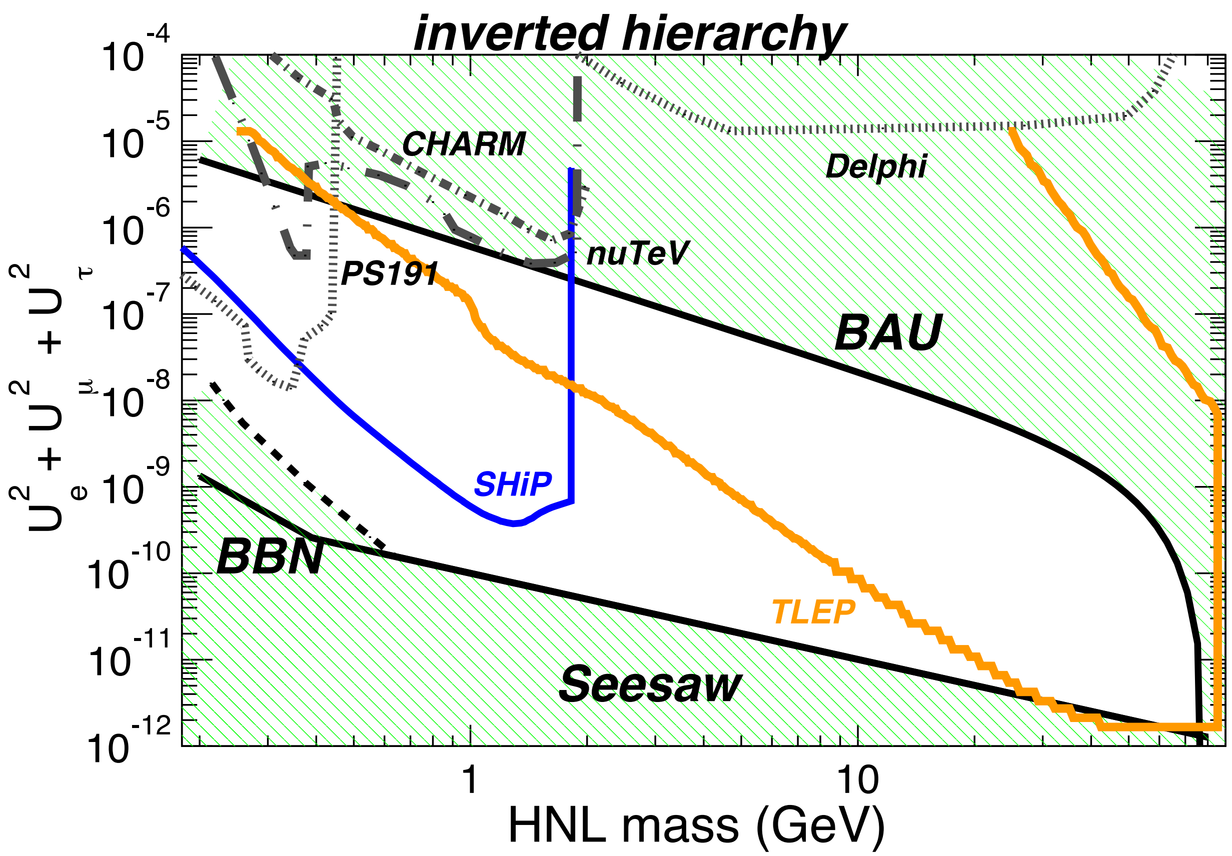
30 years later and with experience gained on LEP, LEP2 and the B factories we can propose a Z,W,H,t factory of many times the luminosity of LEP, ILC, CLIC

CERN is launching a 5 years international design study of Circular Colliders
100 TeV pp collider (FCC-hh) and high luminosity e+e- collider (FCC-ee)

IHEP in China is studying CEPC a 50-70 km ring with e+e- Higgs factory followed by HE pp.

FCCee sensitivity



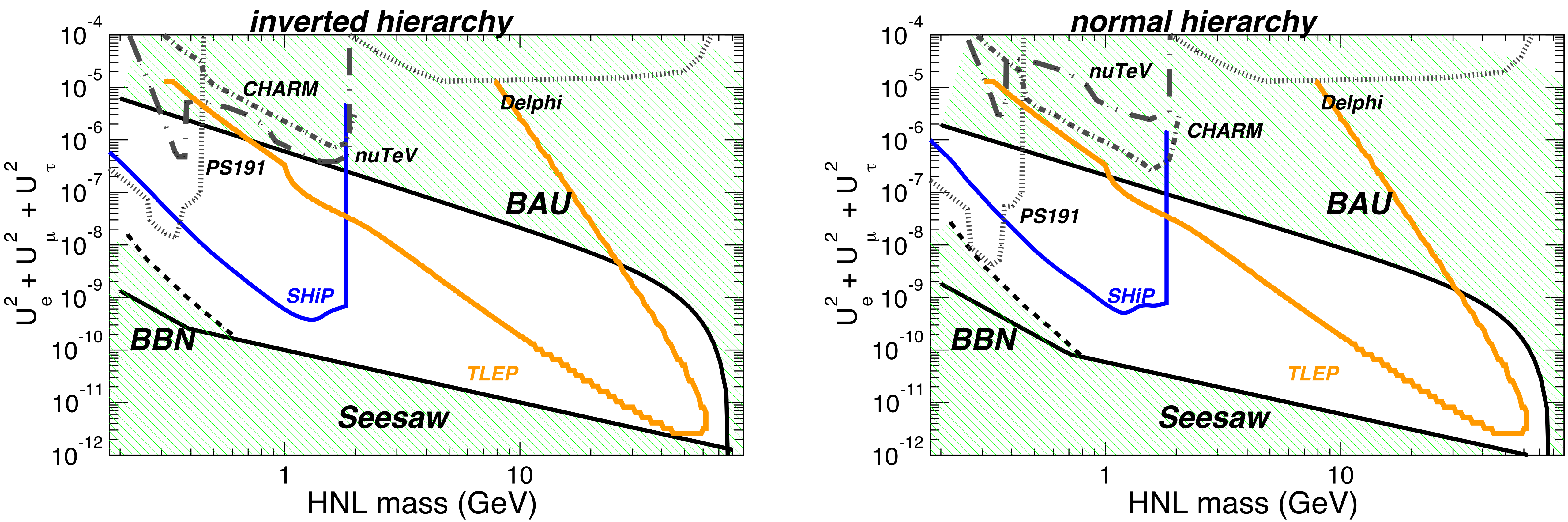


This should be considered the maximum sensitivity managing to go to zero background in the region 100um and 5m with 10^{13} Z^0

A. Blondel, E. Graverini, N.S. and M. Shaposhnikov arxiv:1411.5230

FCCee sensitivity

Assuming zero background in the region 10cm and 5m with 10^{13} Z^0



- The lower line depends on the decay volume and the number of Z^0
- The higher line depends on the minimum distance from PV and the number of Z^0

A. Blondel, E. Graverini, N.S. and M. Shaposhnikov arxiv:1411.5230

Conclusions

- Right-handed (i.e. sterile) neutrinos are a natural way of explaining neutrinos via the seesaw mechanism

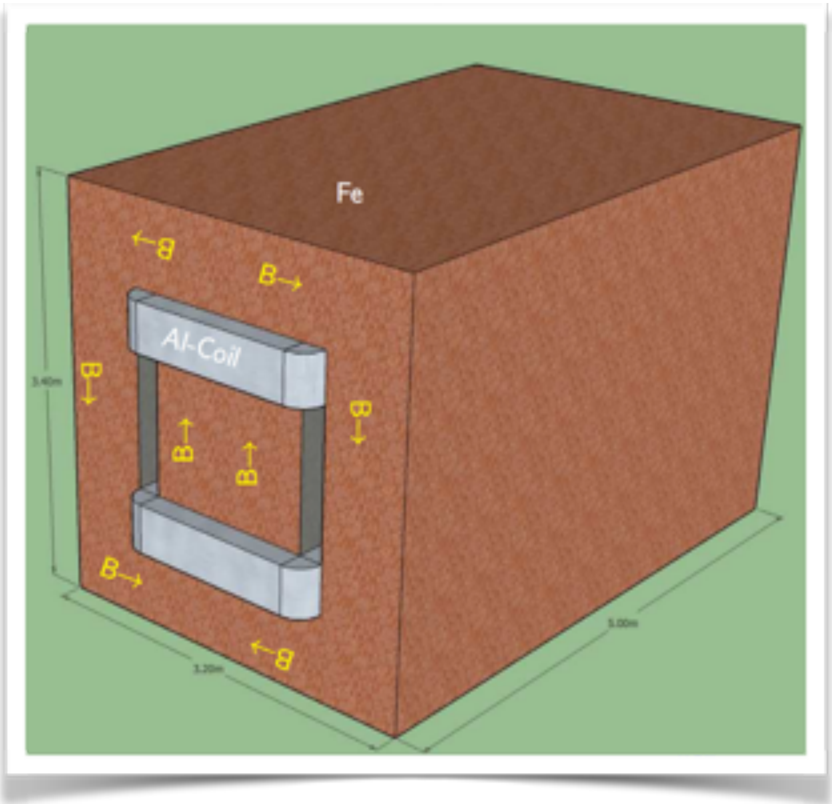
- Strong physics case for sterile neutrinos below the EW scale

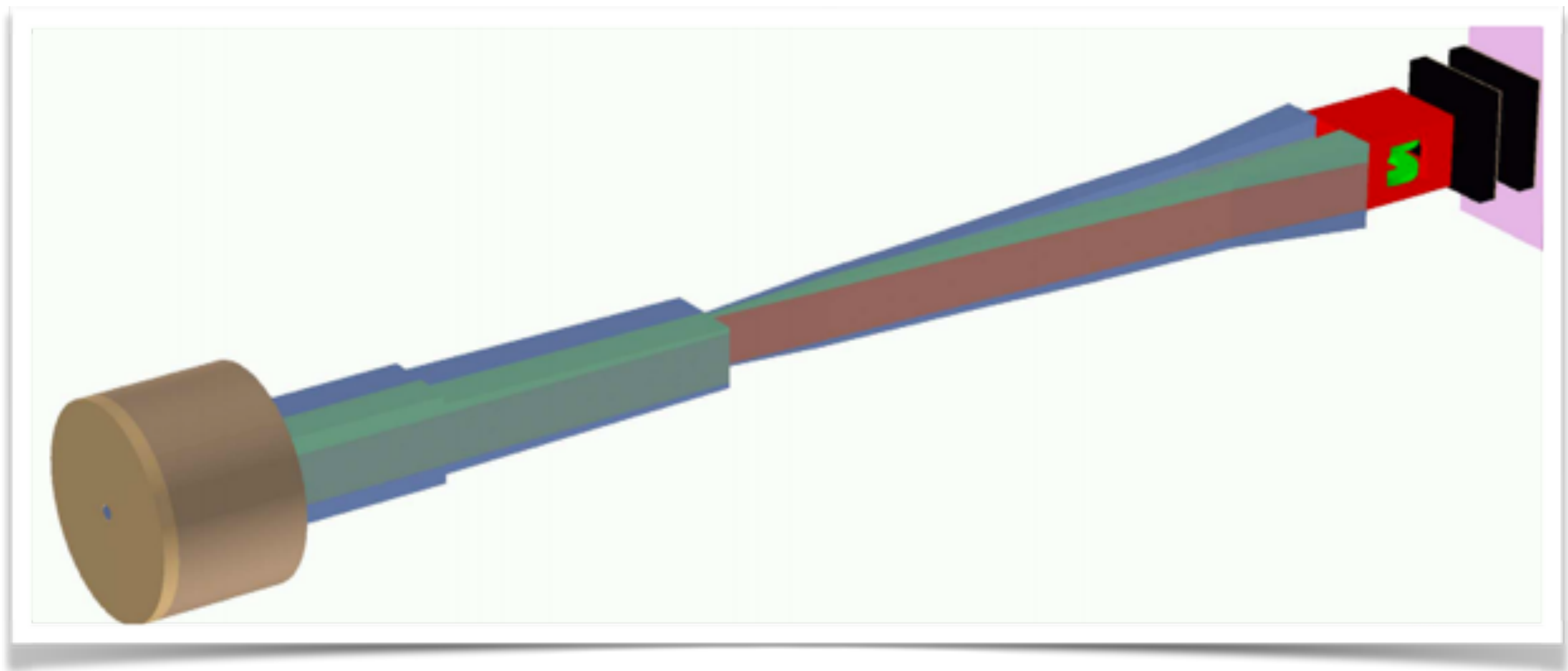
- They could play a crucial role in cosmology, i.e. explaining Dark Matter and/or baryon-antibaryon asymmetry

- Direct searches have been performed for several decades, but in the next decades we will have the chance to touch the bottom of U^2 with a range of experiments:
    - Beam dump for D- and B-meson produce with masses below few GeV (e.g. SHiP)
    - W and Z factories for higher masses (e.g. ATLAS/CMS, IHEP and FCCee)

Backup

Magnets

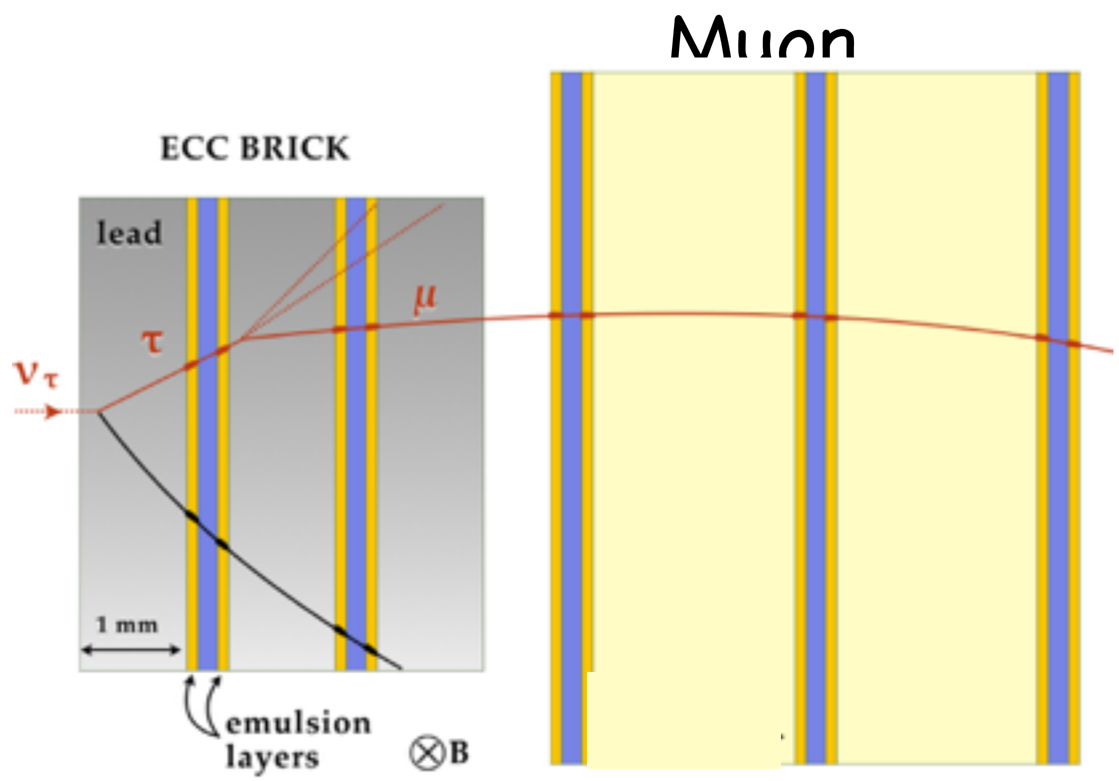


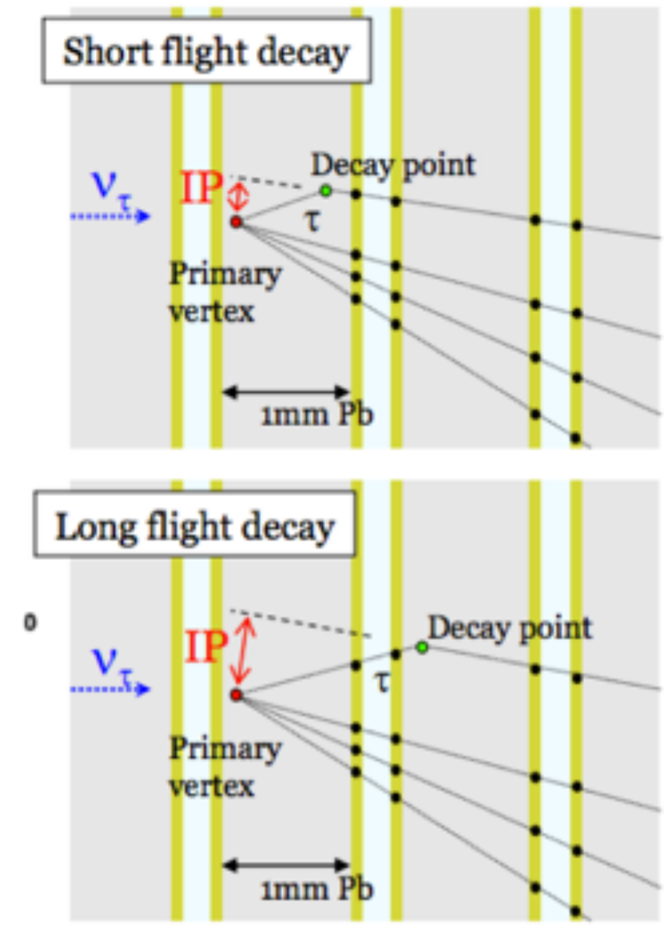


Tau neutrino physics

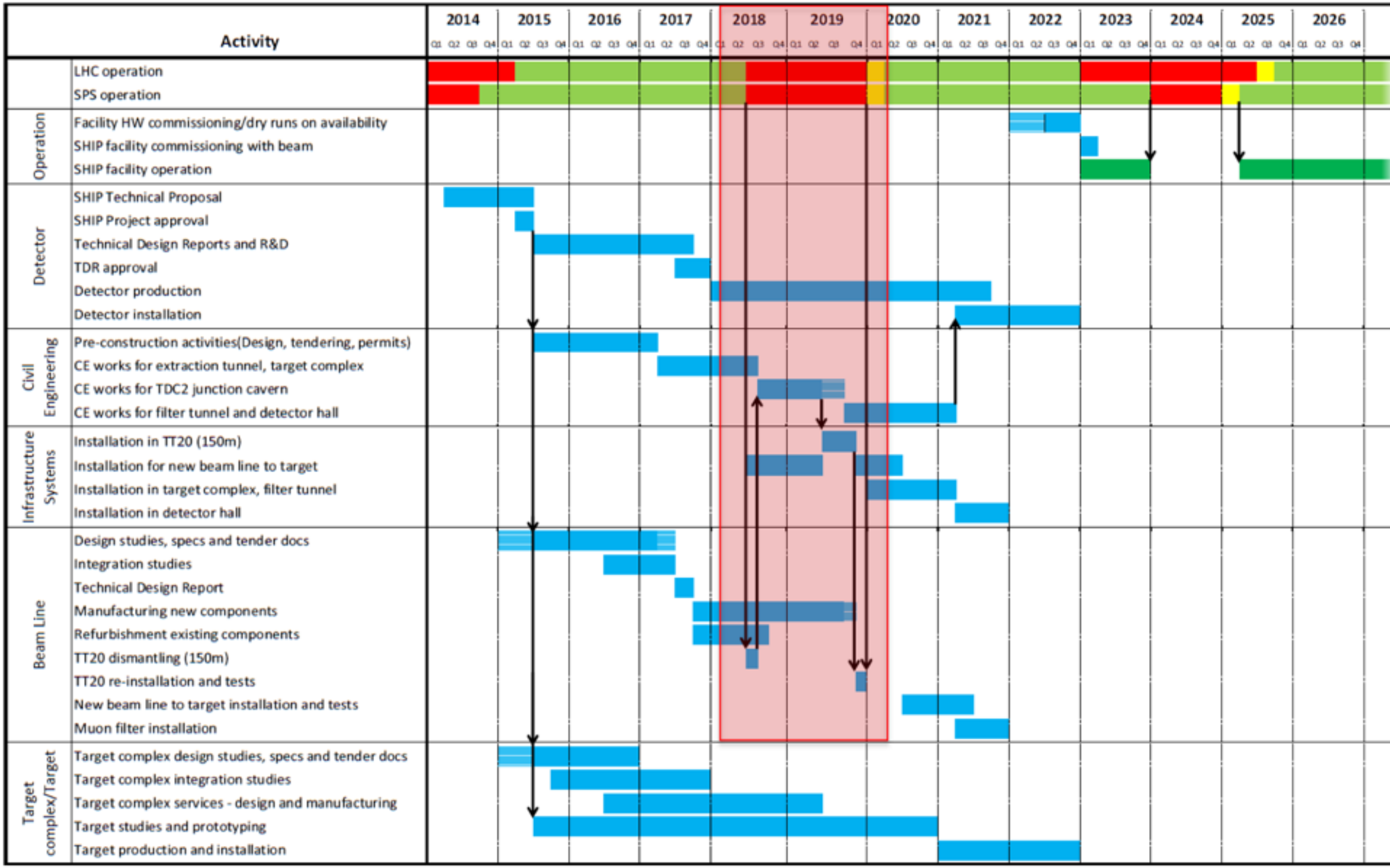
- So far 4 ν_τ events observed by OPERA and 9 by DONUT
- We expect between 3000-4000 reconstructed ν_τ per 2×10^{20} POT
- Physics goals:
  - First observation of $\overline{\nu}_\tau$, which has never been observed
  - τ_ν and $\overline{\nu}_\tau$ cross section measurements
  - Charm physics with τ_ν and $\overline{\nu}_\tau$
  - ν_e cross section at high energy to measure charm hadron production (possible normalization for HNLs)

Tau neutrino detector





- ν_τ target: Opera-like bricks, laminated lead and nuclear emulsions (for micrometric resolution)
- 750 Opera-like bricks, to be replaced 10 times
- Muon spectrometer to measure charge and momentum and give time stamp


Activity
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
Q1 Q2 Q3 Q4
LHC operation
SPS operation
Operation
Facility HW commissioning/dry runs on availability
SHIP facility commissioning with beam
SHIP facility operation
Detector
SHIP Technical Proposal
SHIP Project approval
Technical Design Reports and R&D
TDR approval
Detector production
Detector installation
Civil Engineering
Pre-construction activities(Design, tendering, permits)
CE works for extraction tunnel, target complex
CE works for TDC2 junction cavern
CE works for filter tunnel and detector hall
Infrastructure Systems
Installation in TT20 (150m)
Installation for new beam line to target
Installation in target complex, filter tunnel
Installation in detector hall
Beam Line
Design studies, specs and tender docs
Integration studies
Technical Design Report
Manufacturing new components
Refurbishment existing components
TT20 dismantling (150m)
TT20 re-installation and tests
New beam line to target installation and tests
Muon filter installation
Target complex/Target
Target complex design studies, specs and tender docs
Target complex integration studies
Target complex services - design and manufacturing
Target studies and prototyping
Target production and installation

Working hypotheses

- Detector located ~60m from the proton target
- Charm production cross-sections in p-W affected by large uncertainties
- Compare with DONUT to extrapolate the expected numbers
- Energy dependence of σ_{cc} and ν_τ cross-section, acceptance: production ~ 0.36, detector acceptance ~ 0.2, energy dependence of the ν_τ cross-section ~0.52 → DONUT/SHIP ~ 26
- 2×10^{20} pot for SHIP compared to 3.6×10^{17} DONUT → ~ 550 in favour of SHIP
- Overall rate SHIP/DONUT ~ 20
- DONUT observed 9 events with a background of 1.5 → 7.5±3 (40% error)
- 150 events expected with the same mass (260 kg)
- Measurement of ν_τ and anti-ν_τ cross-section, including the study of structure functions sets the scale for the mass: ~ 6 tons for ~ 3400 ν_τ interactions
- Assume OPERA-like bricks (8.3 kg) and wall target structure: ~ 750 bricks

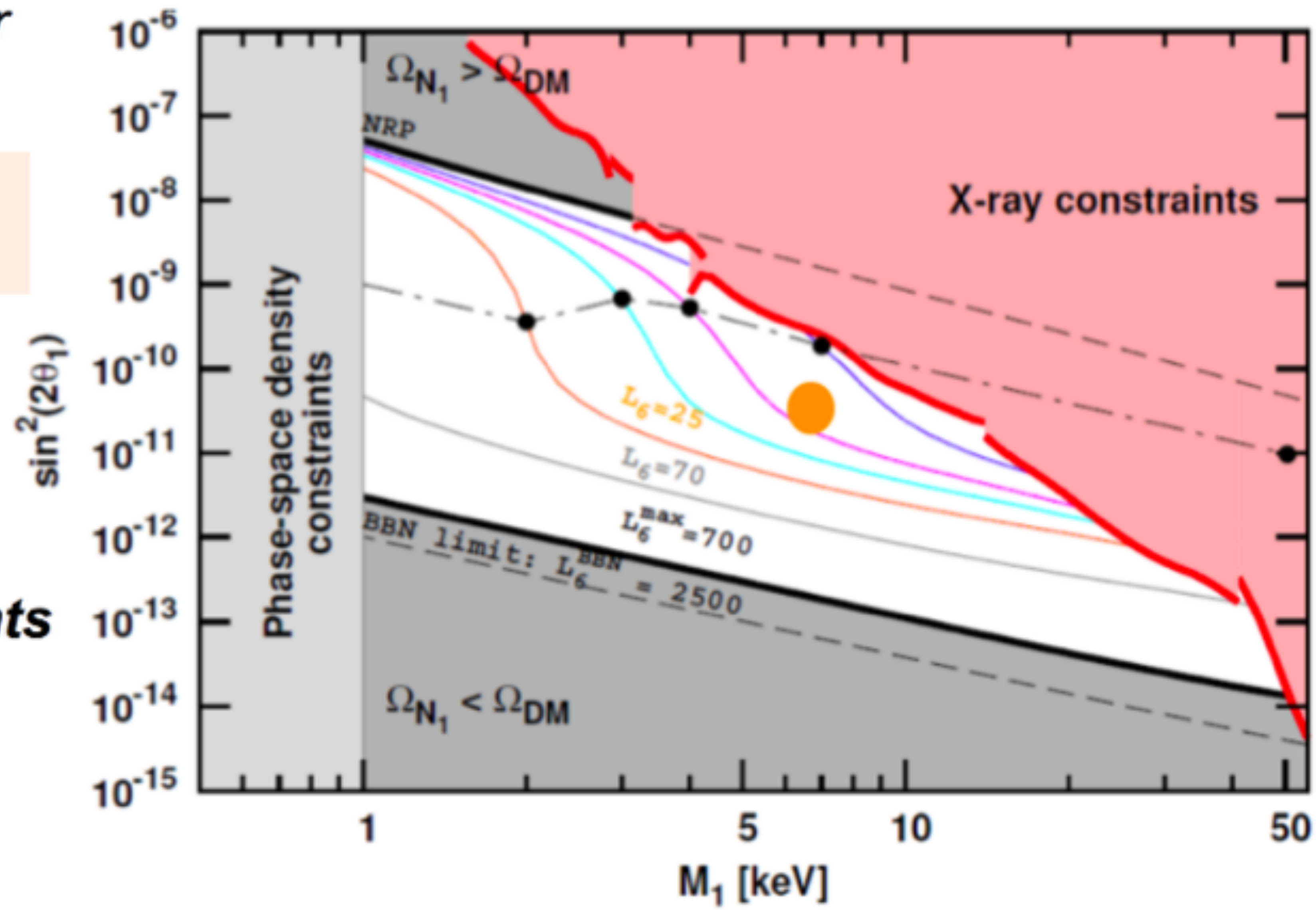
Sterile neutrino DM search

- ✓ *There are also recent papers on non-detection of dark matter sterile neutrino candidates:*

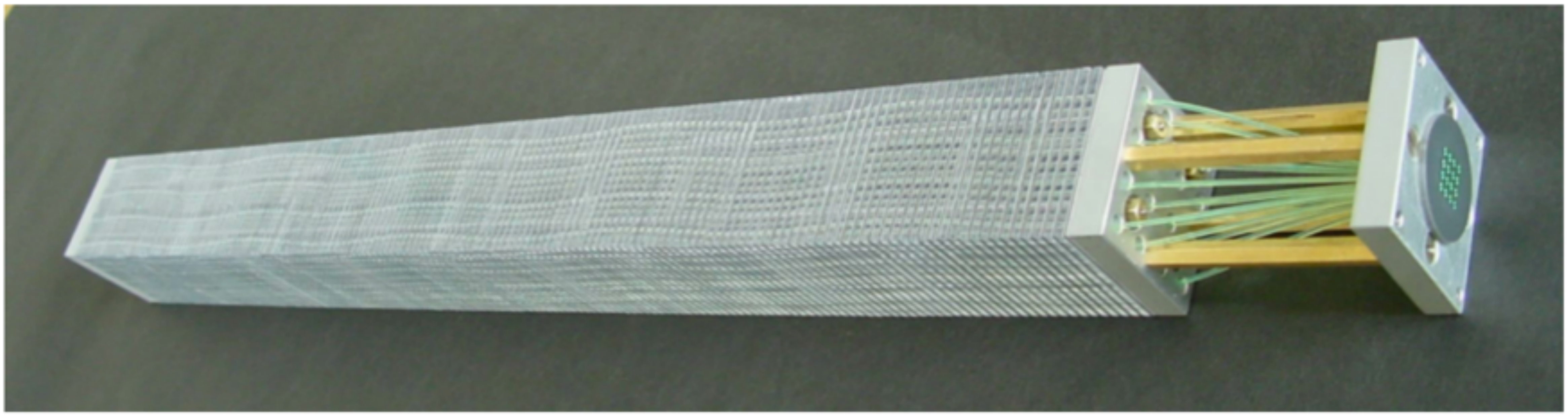
  M.E.Anderson et. al. (1408.4115)
  D.Malyshev et.al. (1408.3531)

- ✓ *Ongoing discussions on reliability of the signal …*

- ✓ ***Accuracy of the measurements limited by systematics***



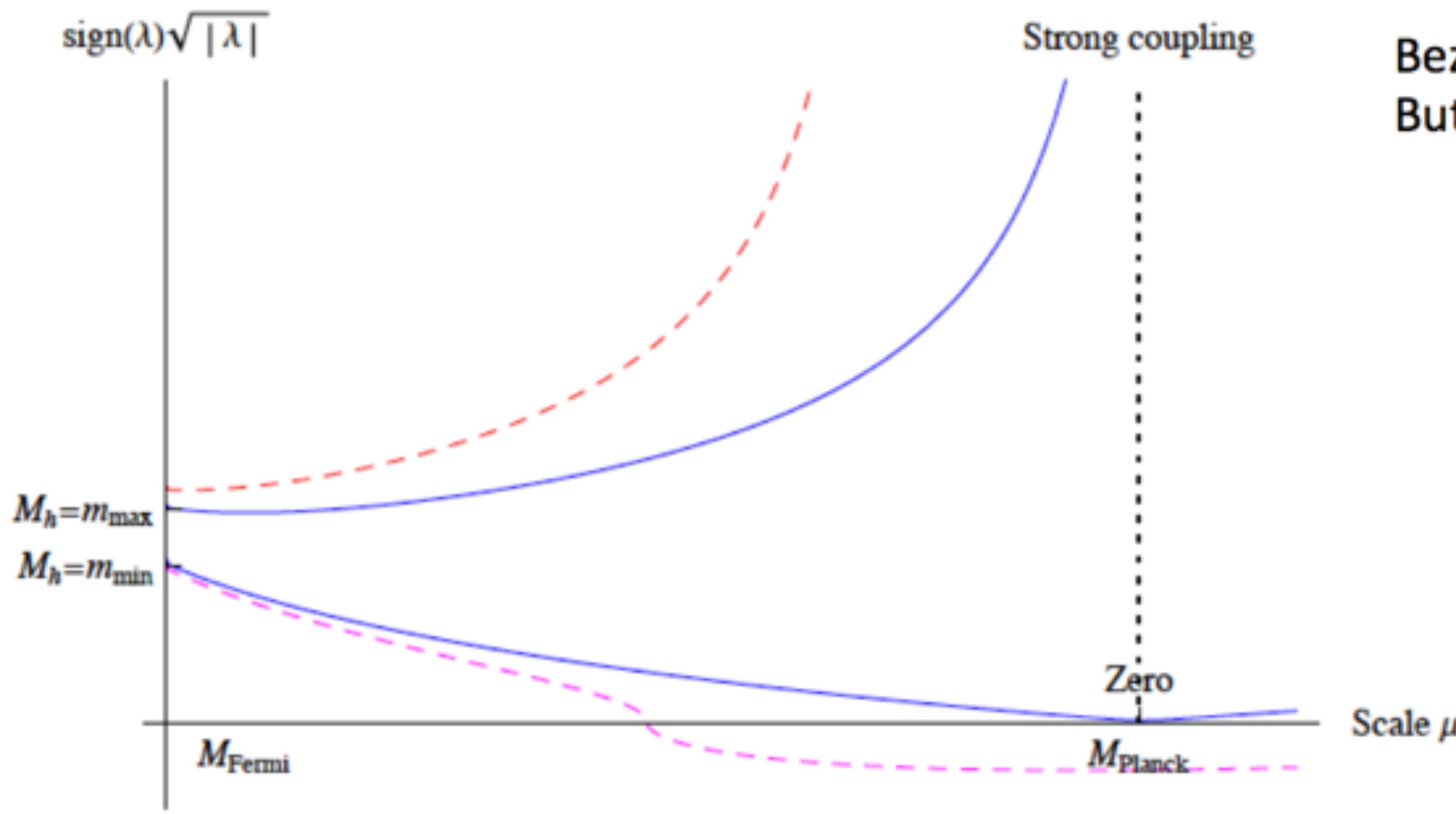
Possible Calorimeter



The spiral Shashlik ECAL

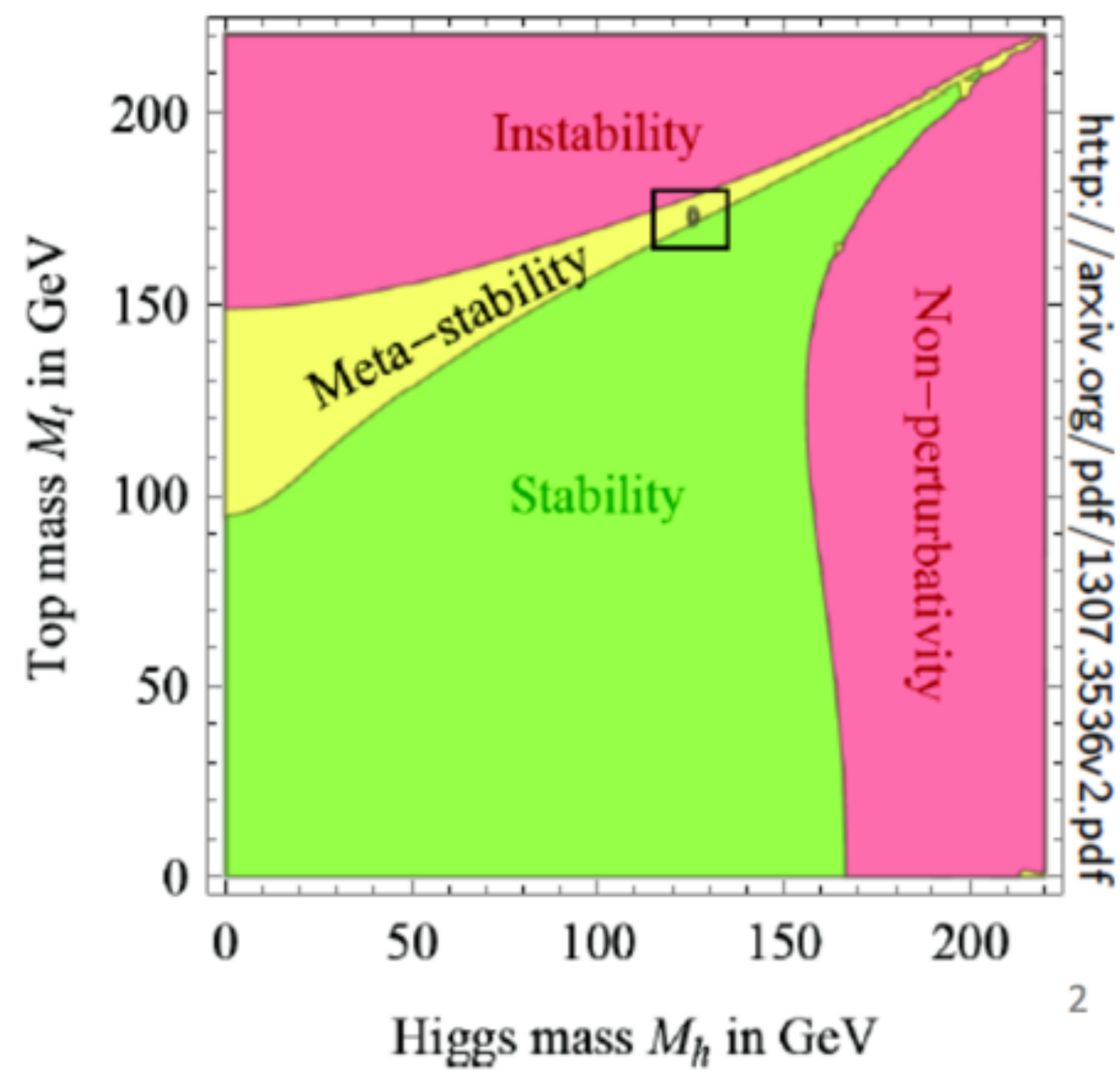
Uniformity few %, time resolution σ~1ns and
$\sigma(E)/E=6.5\%/\sqrt{E}\oplus1\%$

✓ ***Discovery of the 126 GeV Higgs boson → Triumph of the Standard Model***
The SM may work successfully up to the Planck scale !



Bezrukov et al. [1205.2893], Degrassi et al.[1205.6947]
Buttazzo et al. [1307.3536]

Hard to believe that this is a pure coincidence



SM is not complete

Shortcomings of the SM:

- ***Neutrino masses & oscillations***
- *Excess of matter over antimatter in the Universe*
- *The nature of Dark Matter*