University of Zurich[UZH]

Heavy Neutrinos below the EW scale

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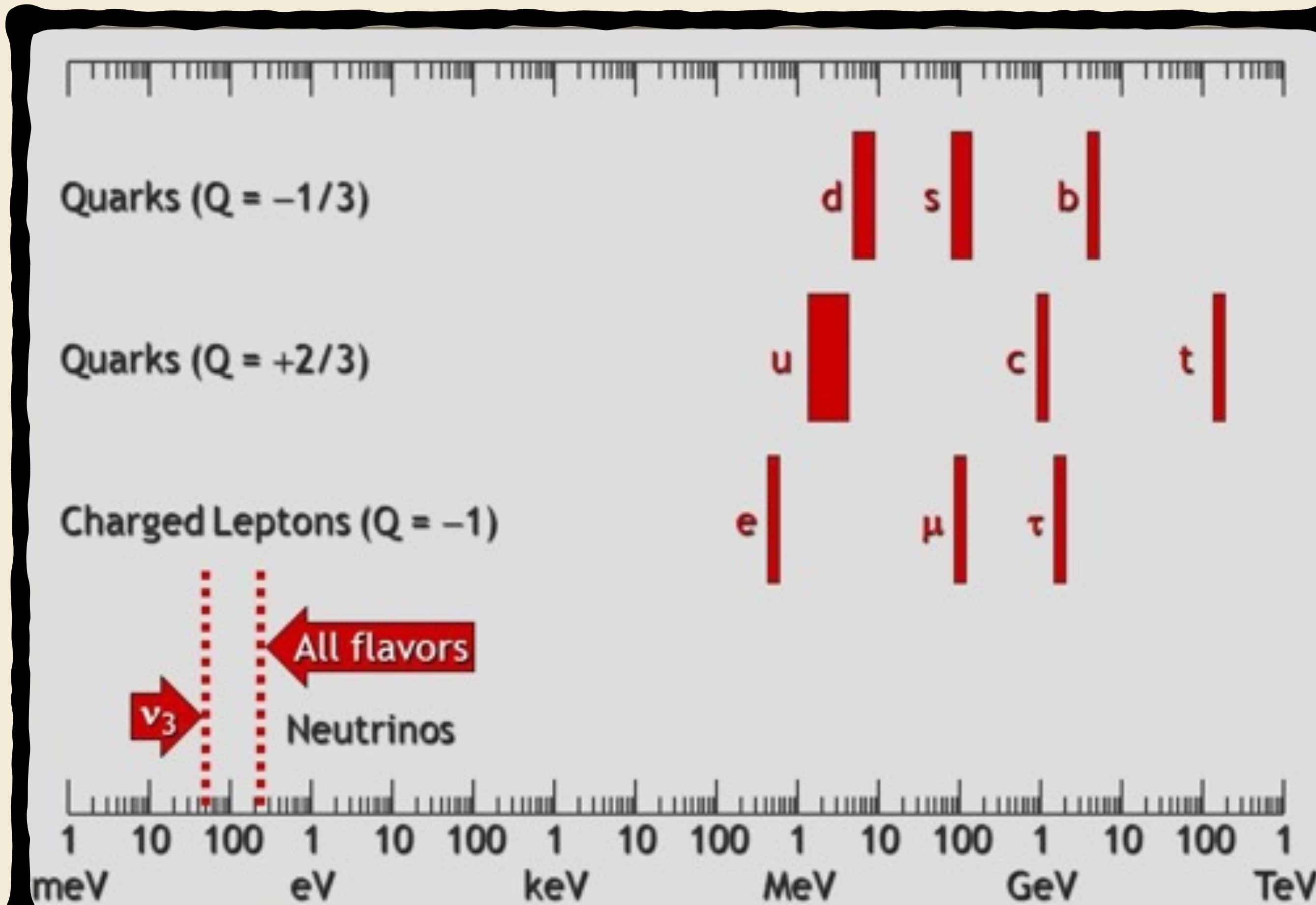
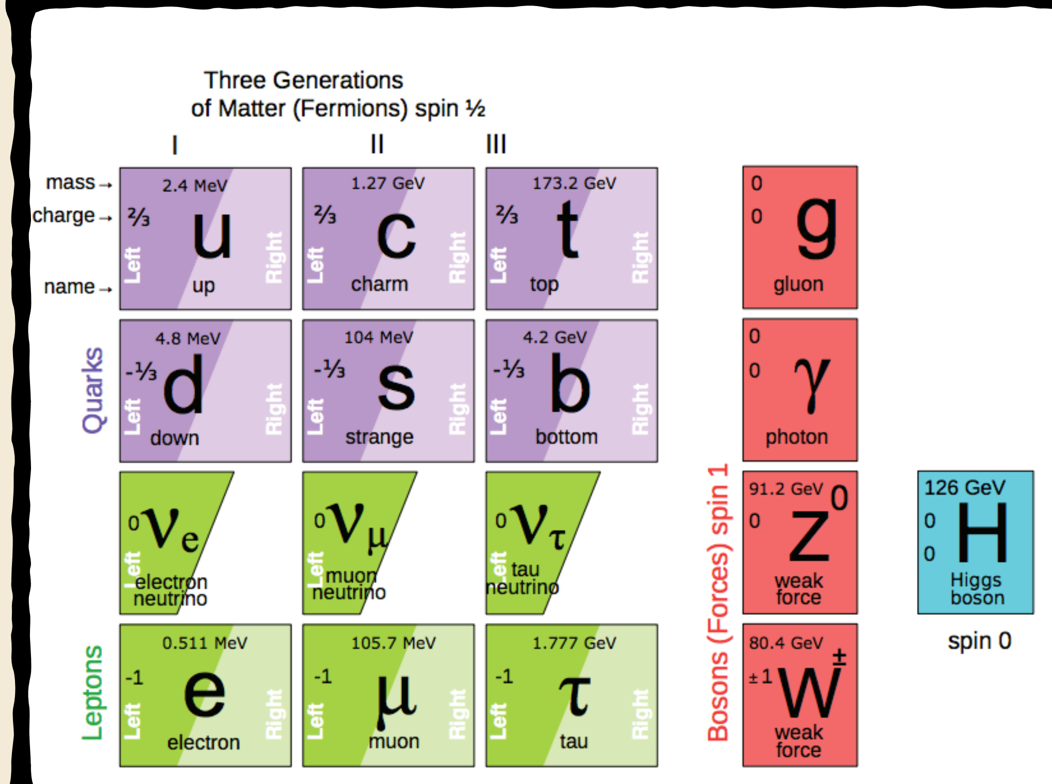
CBPF - Rio de Janeiro
Brazil

Standard Model neutrinos

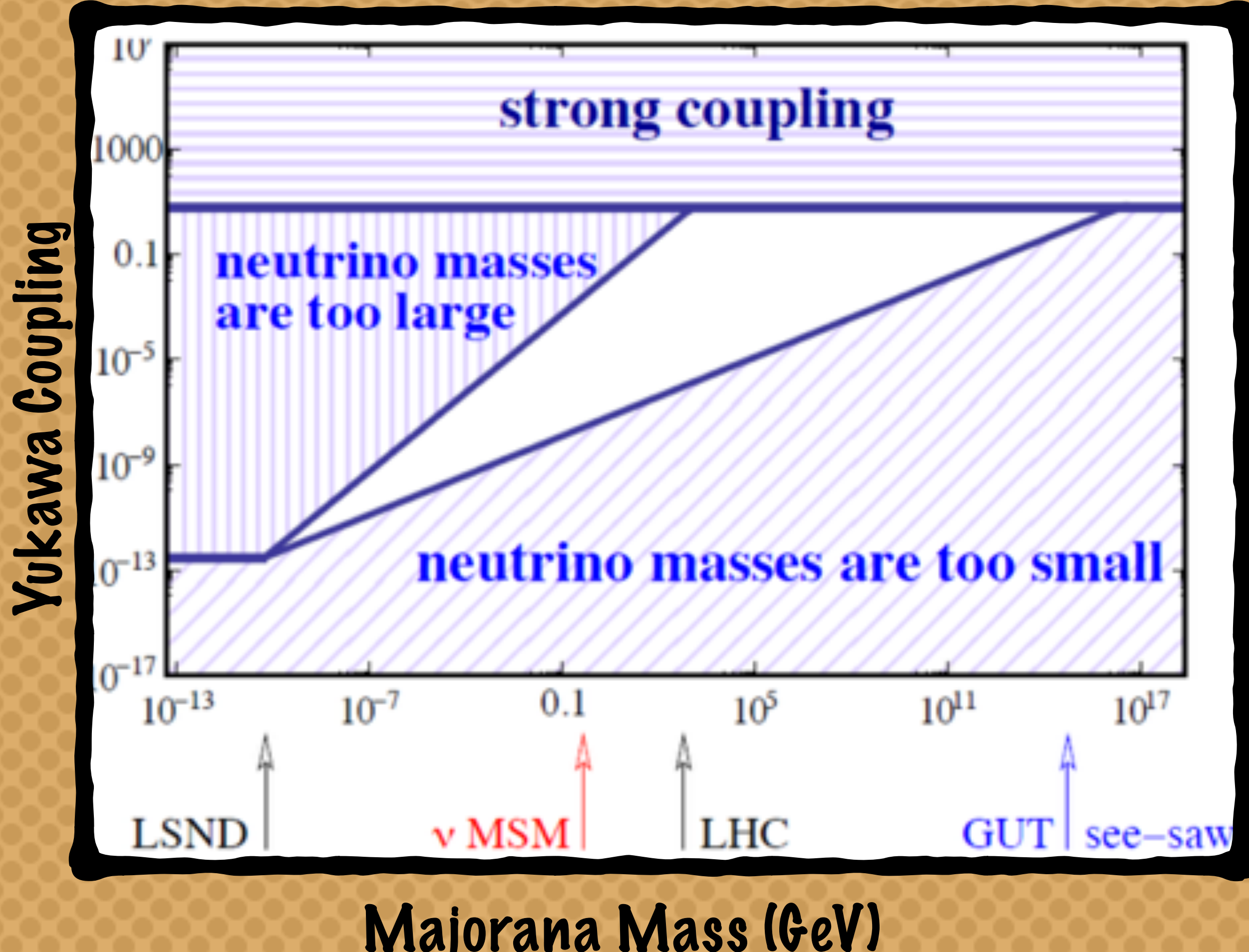




- In the SM only left-handed neutrinos are present, but neutrinos have a small but non-vanishing mass
- The mass of neutrinos is much smaller than the other fermions of the SM

Sterile Neutrinos Masses

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

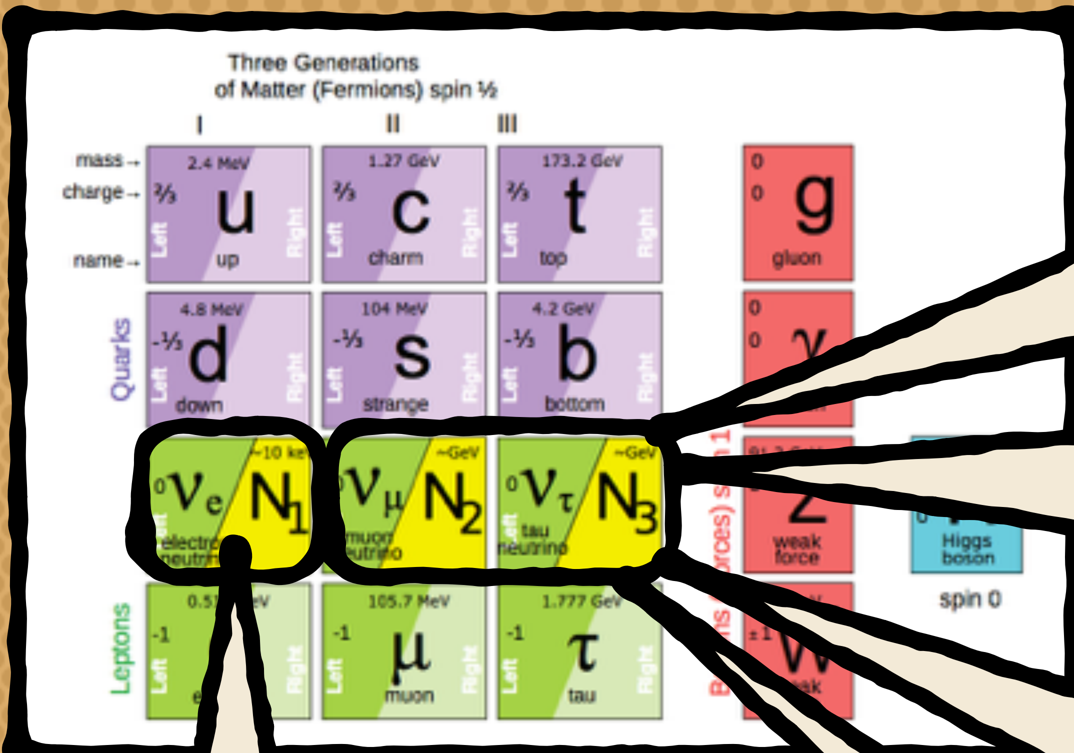


- Assuming $m_\nu = 0.1\text{eV}$
- if $Y \sim 1$ implies $M \sim 10^{14}\text{GeV}$
- if $M_N \sim 1\text{GeV}$ implies $Y_\nu \sim 10^{-7}$

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

The νMSM



The other two neutrinos are almost degenerate in mass

They are responsible for neutrino oscillations

They generate BAU via leptogenesis

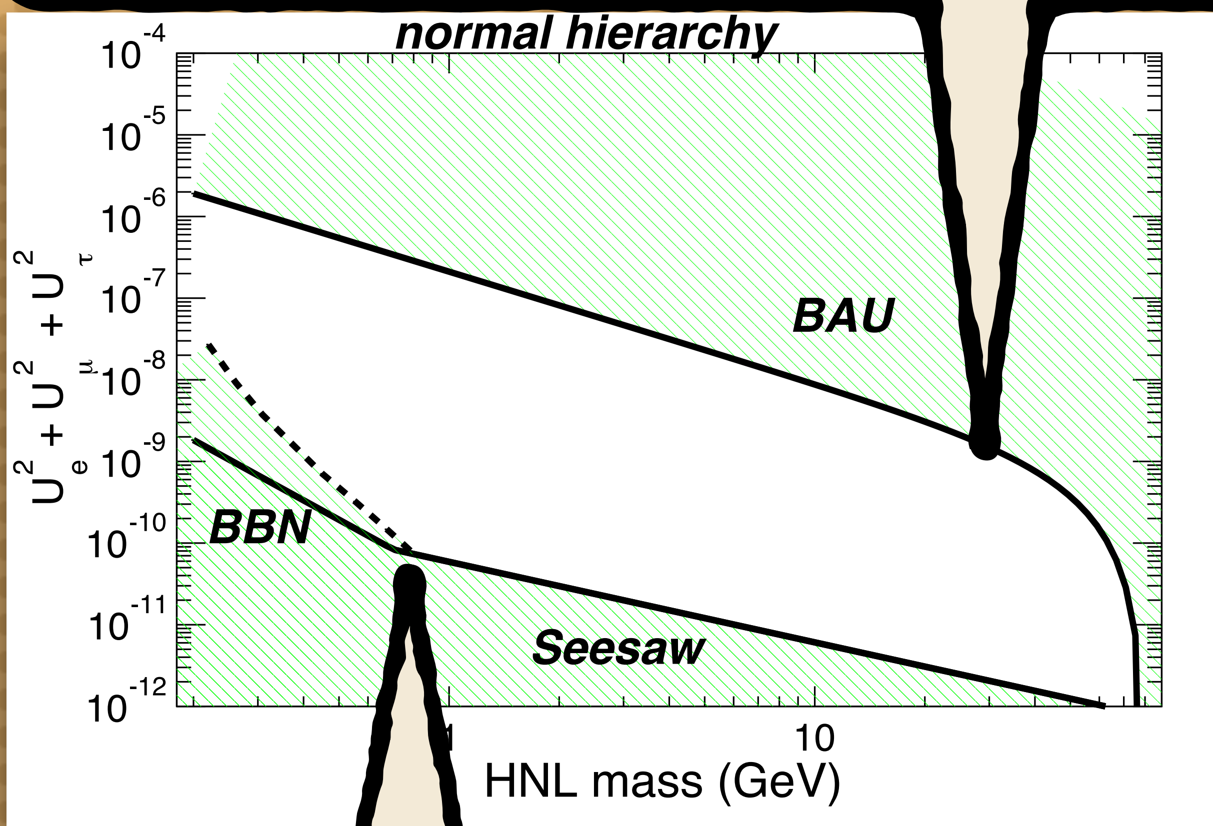
They are responsible of smallness of active neutrino masses via the seesaw mechanism

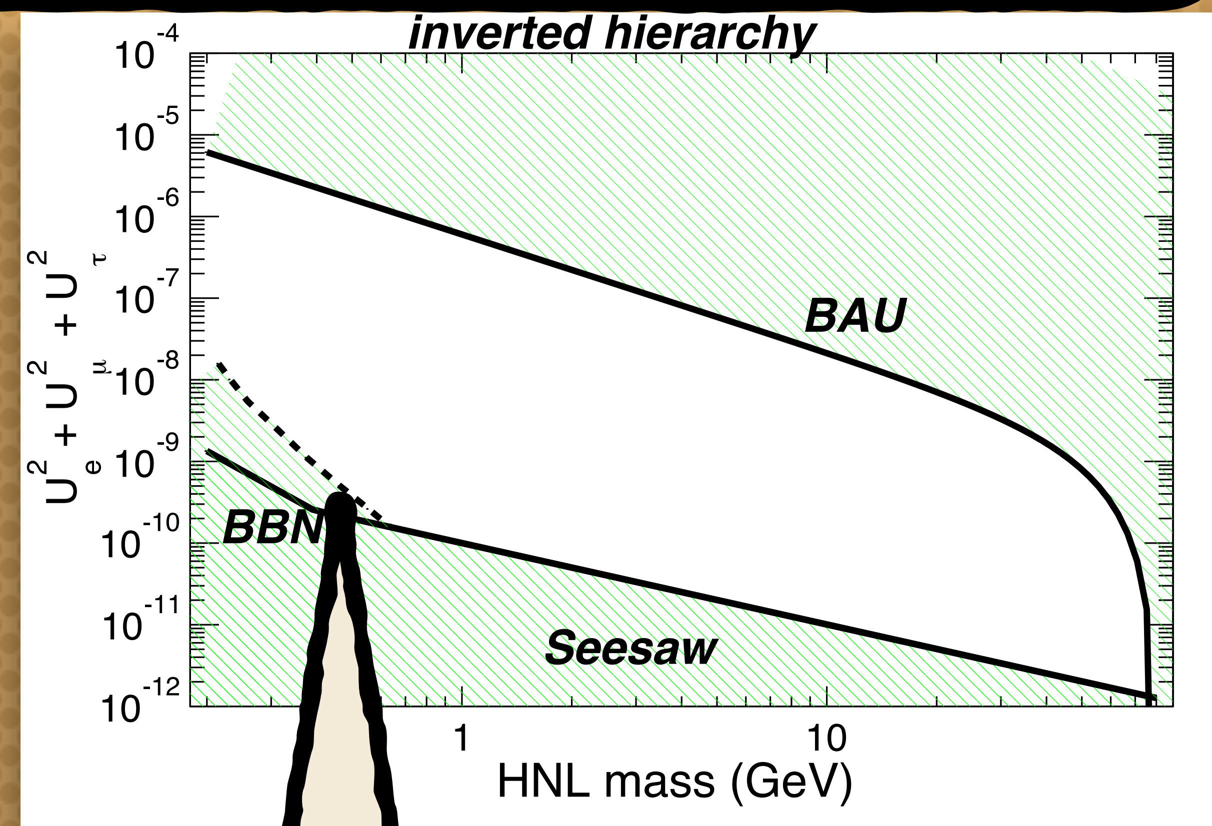
The lightest sterile neutrino, in the KeV region is a warm Dark Matter candidate

Shaposhnikov et al. arXiv:0503065 (and references therein)

Constraints on $N_{2,3}$

- U^2 too large implies that $N_{2,3}$ are in thermal equilibrium during the relevant period of the Universe expansion
- $M_N > M_W$ the rate is enhanced due to N—>Wl leading to stronger constraints on U^2



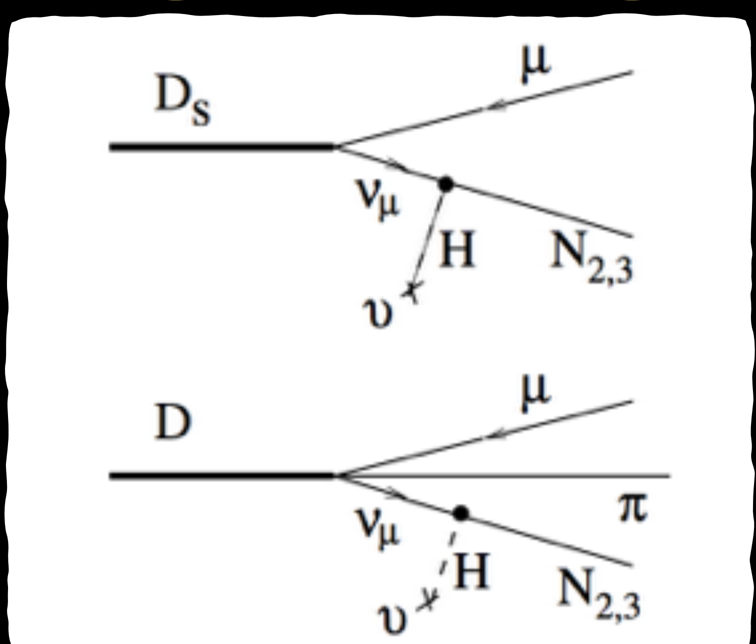


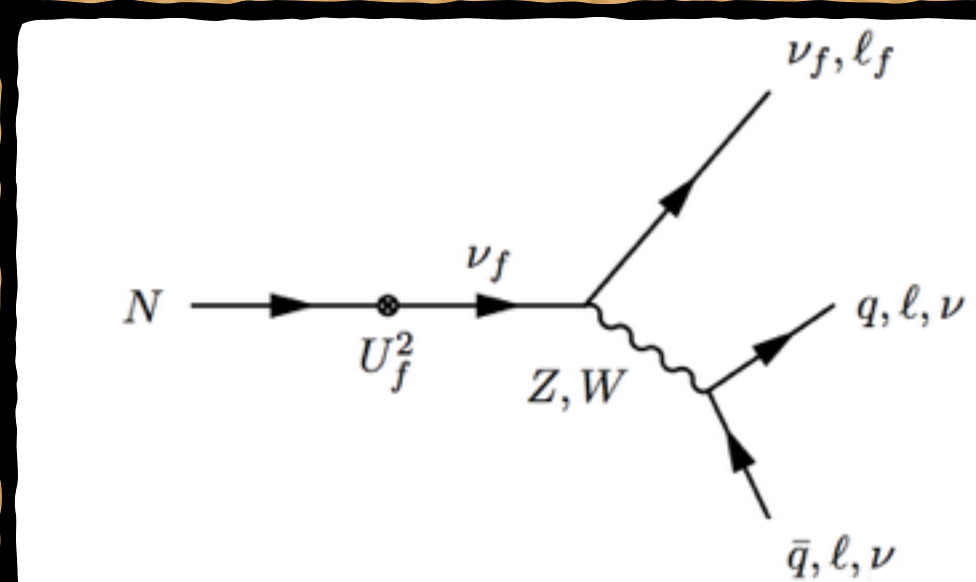
Below the seesaw line $N_{2,3}$ cannot explain the neutrino mass differences observed in experiments

If the lifetime of $N_{2,3}$ is smaller than 0.1 sec they cannot affect the BBN

Sterile neutrino production at low masses

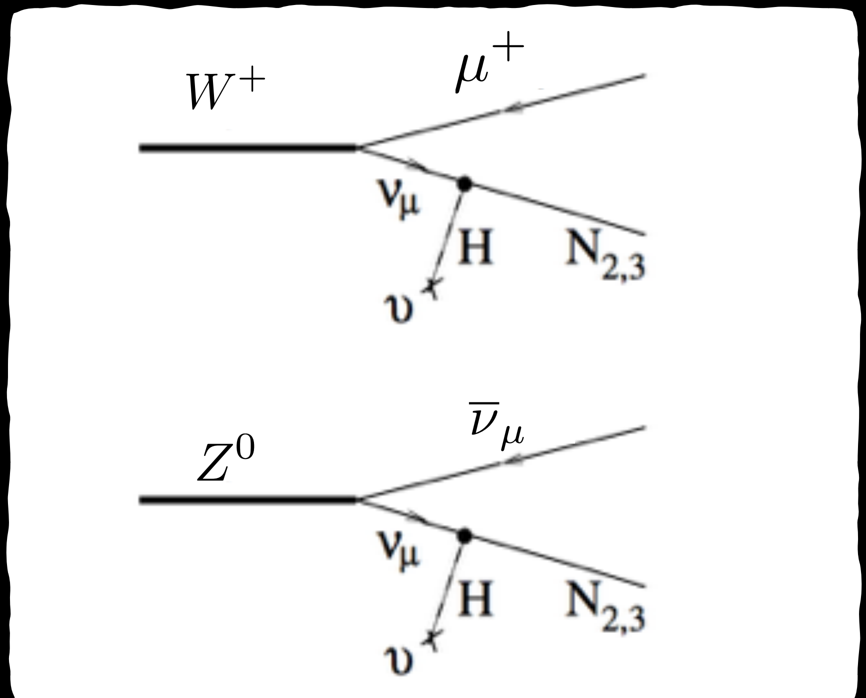
- The production of sterile neutrinos happens via mixing of sterile neutrinos with active neutrinos, i.e. it is suppressed by a factor U^2
- If the mass is small enough they can be produced in semileptonic meson decays (pions, kaons, D-mesons, B-mesons)
- The decay of sterile neutrinos also happens via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

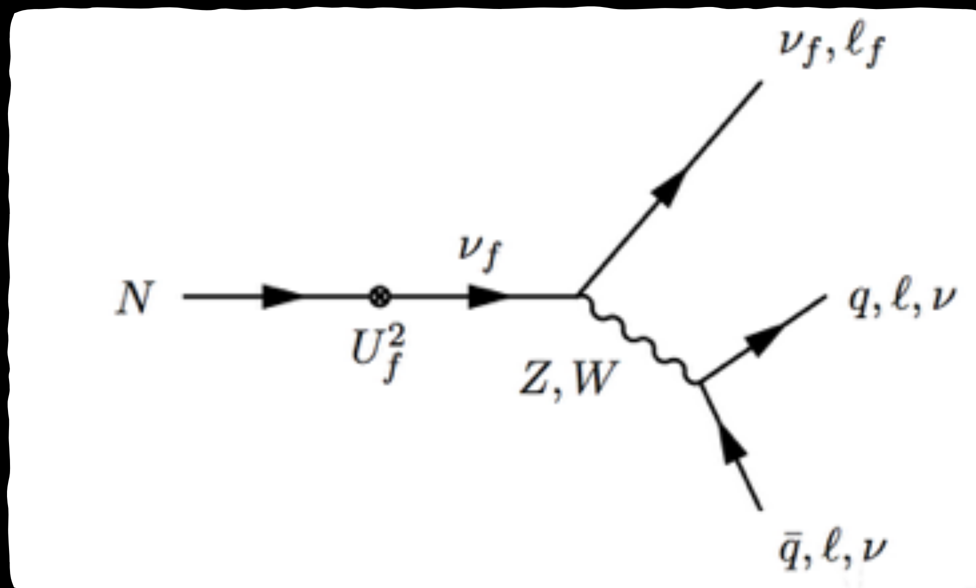




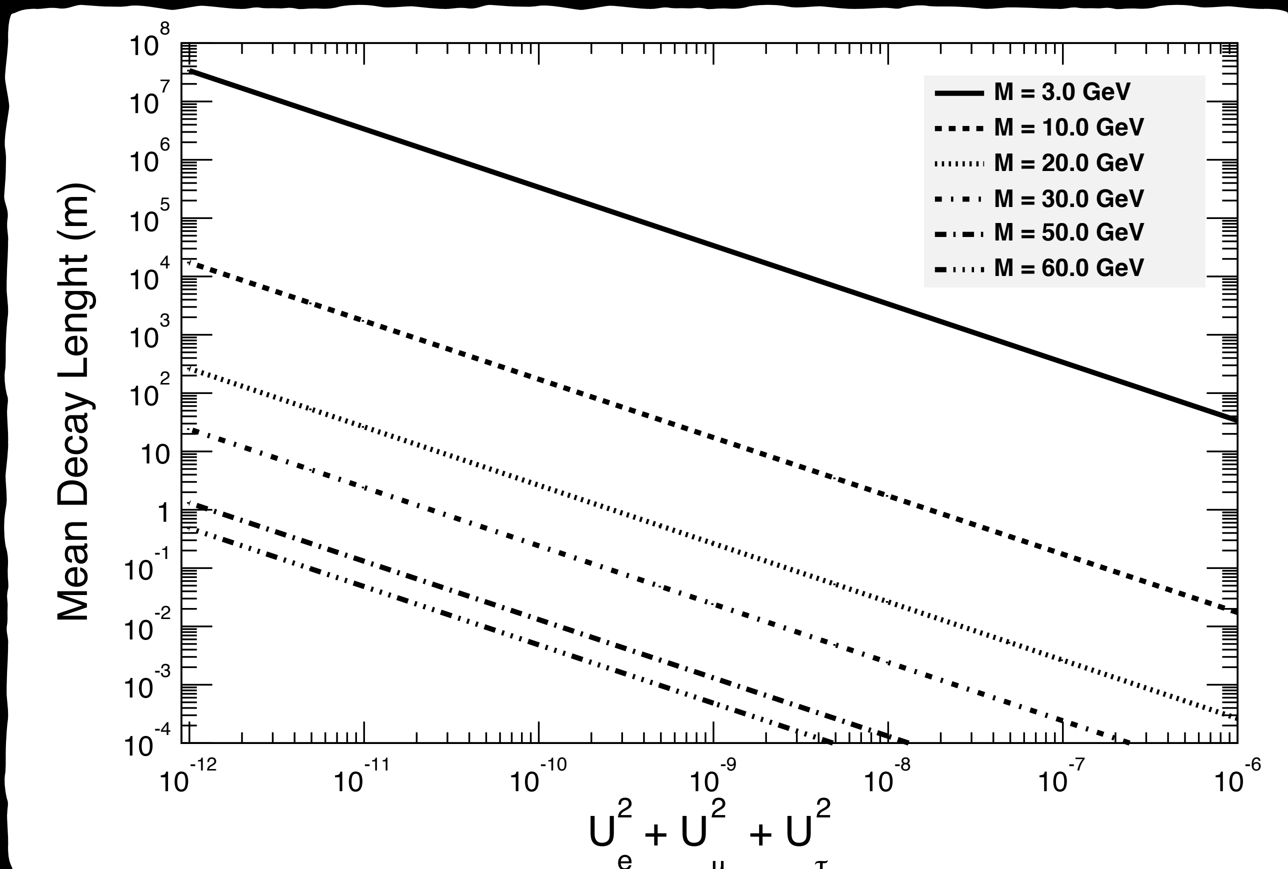
Sterile neutrino production at high mass

- 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 $N \to \text{jet jet } \ell$, $N \to \ell\ell^{(\prime)}\nu$, $N \to \text{jet jet } \nu$





Lifetime of seesaw sterile neutrinos



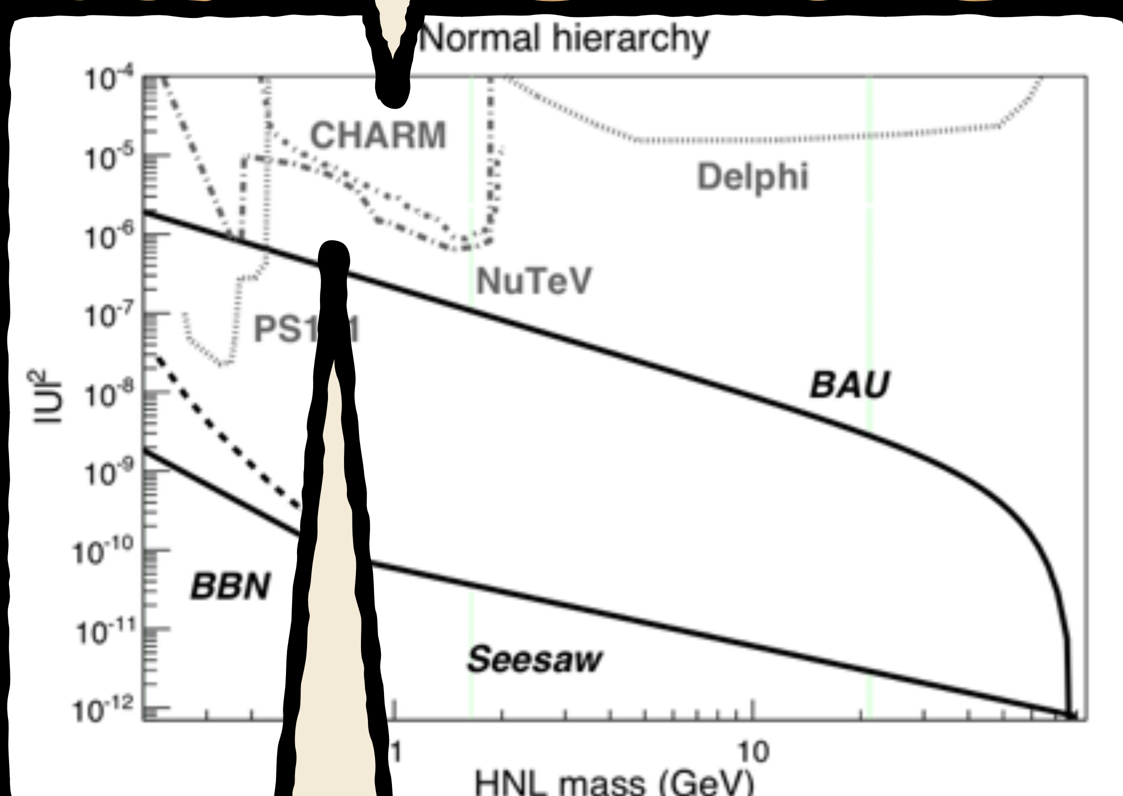
$$\Gamma_N = \frac{G_F^2 M_N^5 U^2}{192\pi^3}\mathcal{N}$$

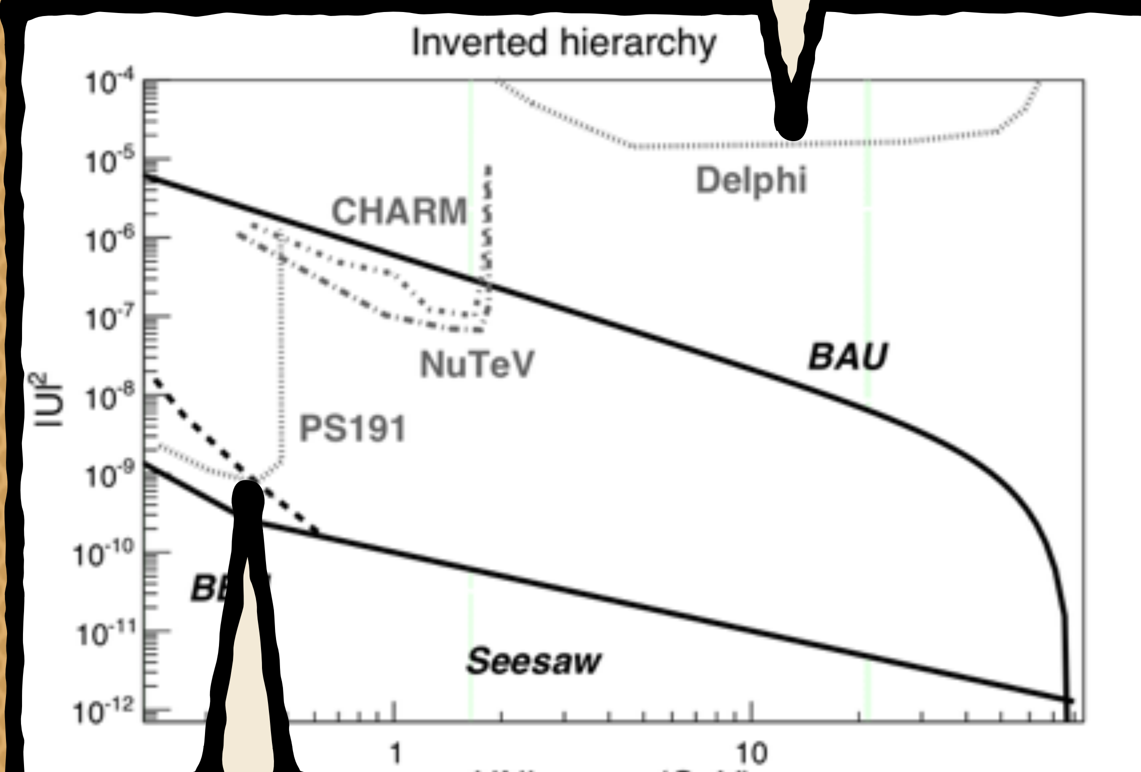
- The lifetime is very different for different values of U^2 and M
- In general different backgrounds and experimental signatures for different values of U^2 and M

Present experimental constraints

CHARM (Phys. Lett. B 166, 473 (1986)):
- p at 400 GeV, detector about 500m from target, 10^{18} pot
- Search for HNLs coming from D-meson decays

DELPHI (Z. Phys. C 74, 57 (1997)):
- Limit using Z^0 decaying
- Number of Z^0 ~10^7

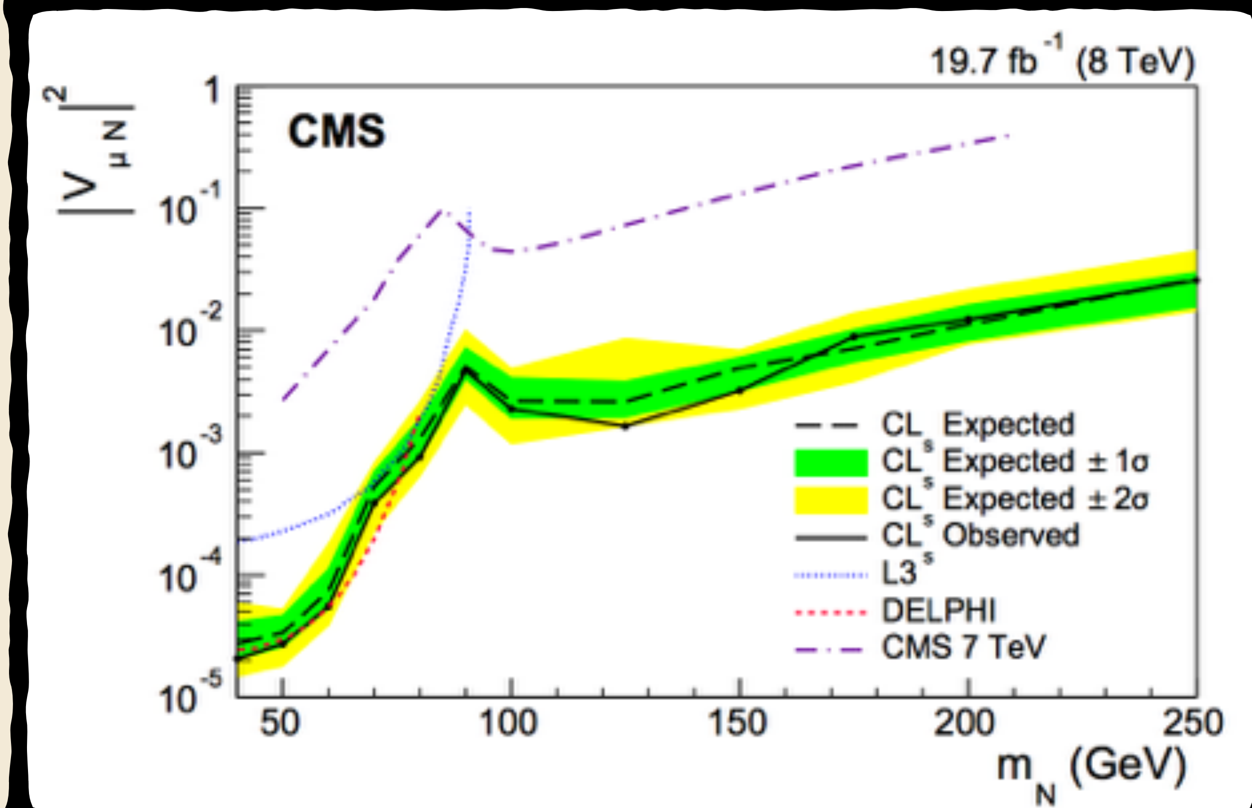




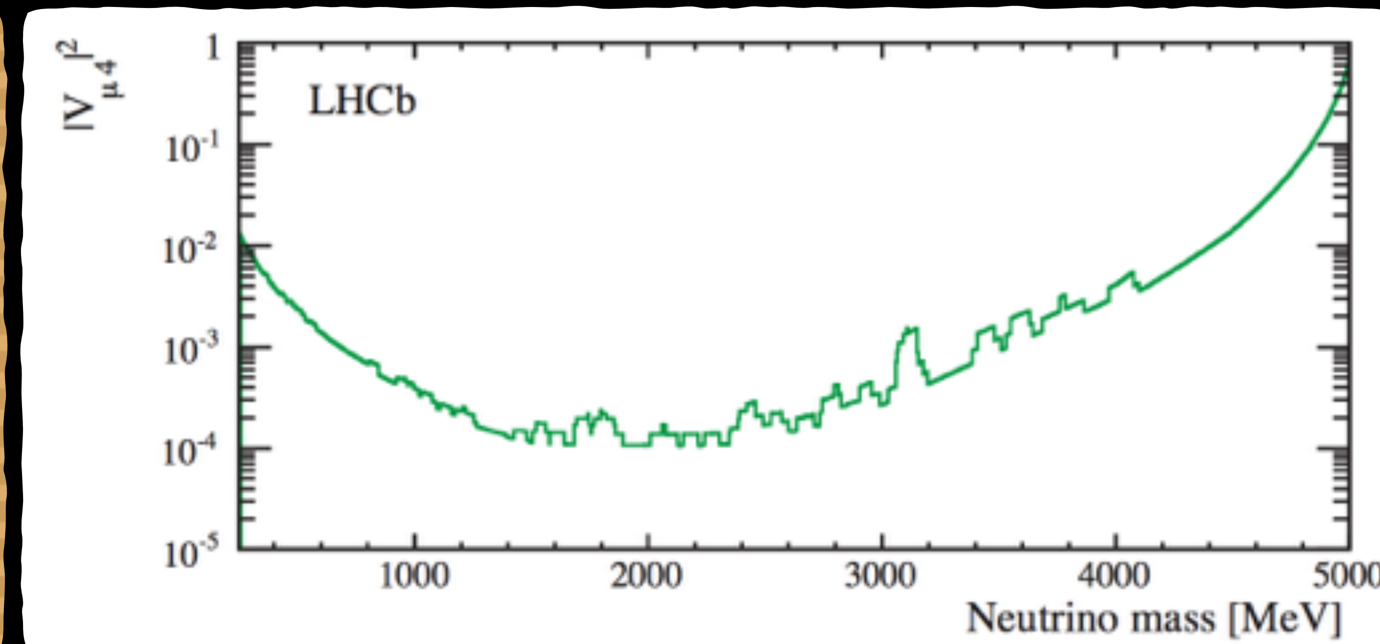
nuTeV (Phys. Rev. Lett. 83 (1999) 4943):
- p at 800GeV on target, ~1.5Km from target
- 2.5×10^{18} pot
- HNLs coming from kaon and D-mesons

PS191 (Phys. Lett. B 166 (1986) 479
Phys. Lett. B 203 (1988) 332):
- p energy 19GeV, 128 m from target
- 0.9×10^{19} pot
- HNLs coming from Kaon decays

LHC limits



CMS Phys. Lett. B 748 (2015) 14



LHCb Phys. Rev. Lett. 112, 131802 (2014)

- Searches for same sign/displaced dimuon vertexes
- LEP still best limit at collider

How to improve in the low mass

- Increase the number of POT
- Go as close as possible to the target
- Have a decay volume as large as possible
- Have as low background as possible

The SHiP Experiment

arXiv:1504.04855

Physics Proposal
signed by about 80 theorists

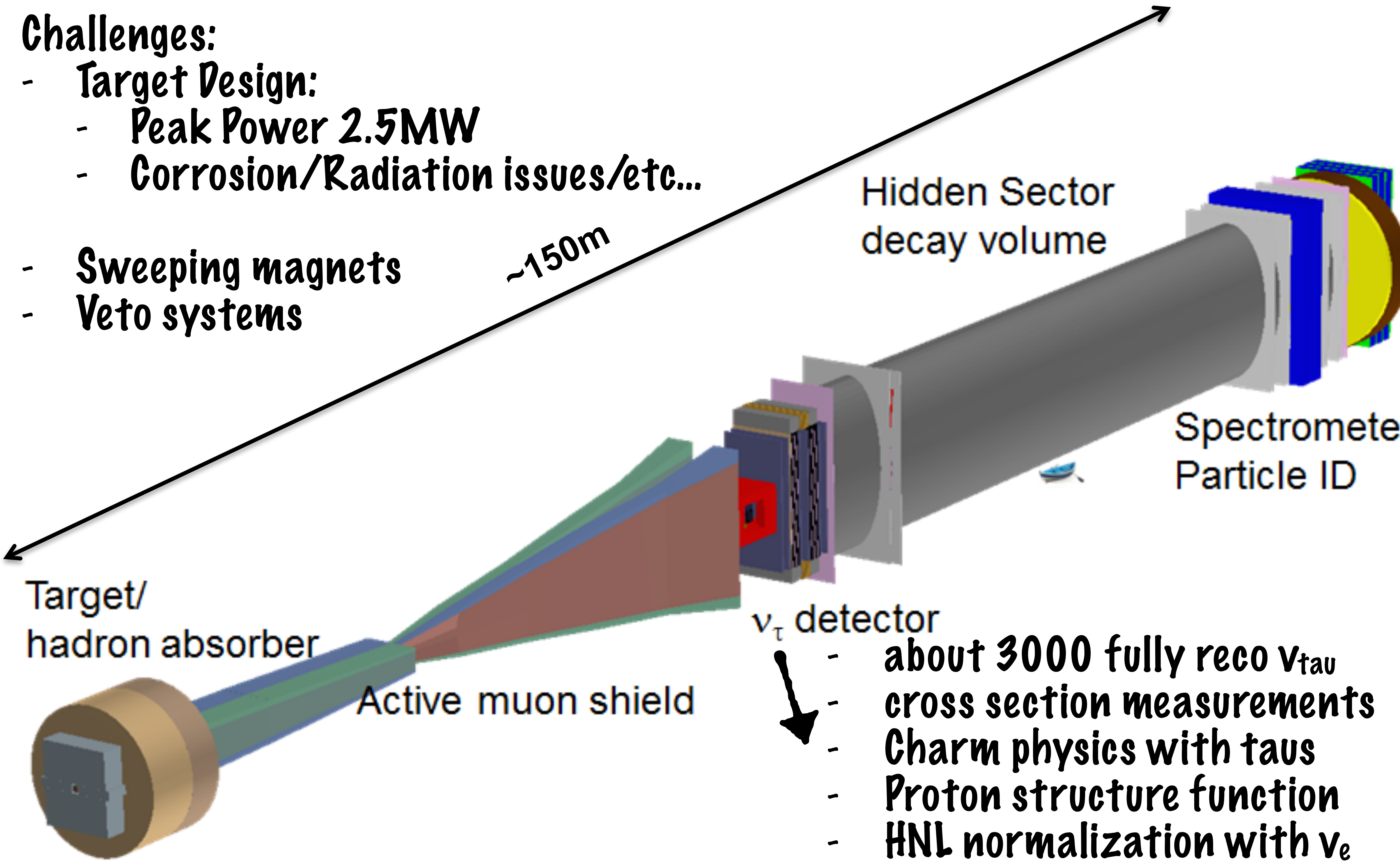
arXiv:1504.04956

Technical Proposal
about 200 experimentalists
45 institutes from 16 countries

The SHiP Experiment

Challenges:
- Target Design:
  - Peak Power 2.5MW
  - Corrosion/Radiation issues/etc...

- Sweeping magnets
- Veto systems



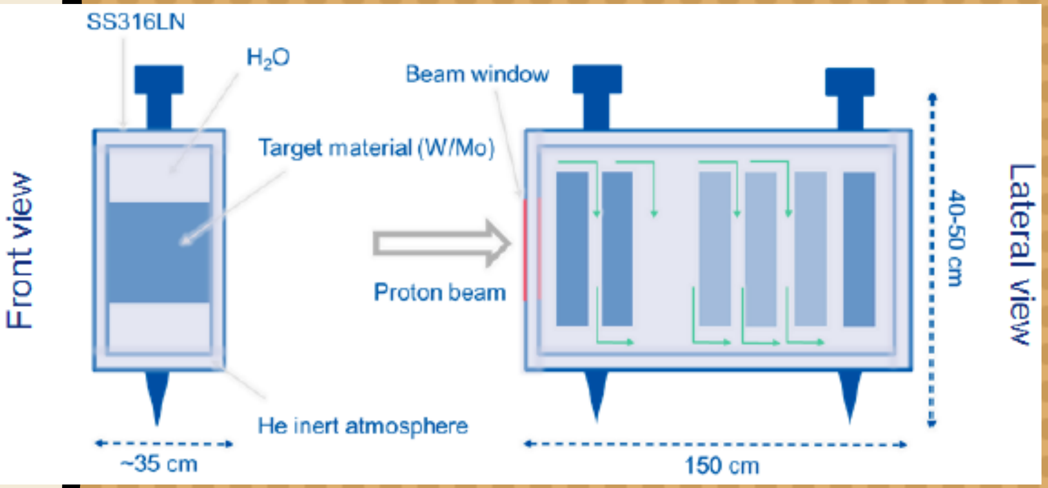
- about 3000 fully reco ν_{tau}
- cross section measurements
- Charm physics with taus
- Proton structure function
- HNL normalization with ν_e

Target and Muon filter

Design consideration

- *High temperature*
- *Compressive stresses*
- *Erosion/corrosion*
- *Material properties as a function of irradiation*
- *Remote handling*

Peak Power during spill of 2.5MW

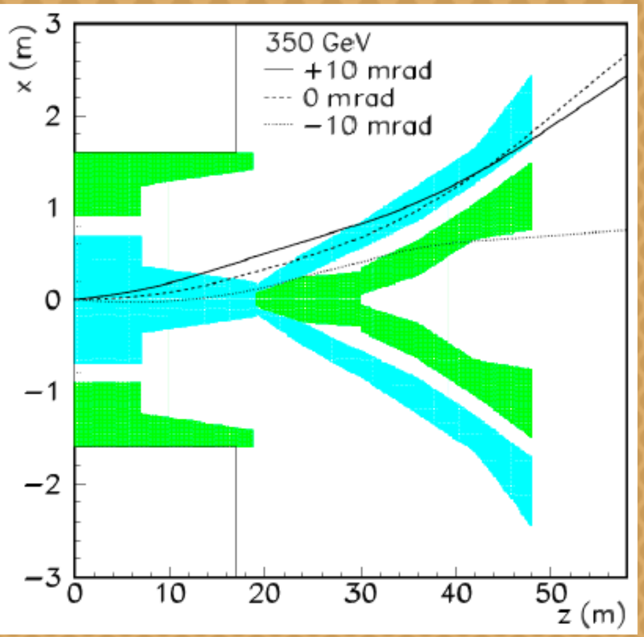


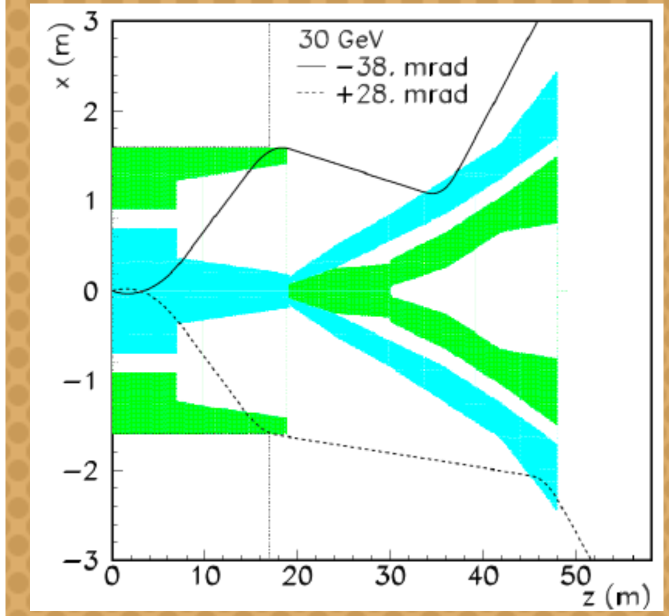
Without muon filter $5x10^9$ muon/spill (1 spill is $5x10^{13}$ POT)

Realistic design of sweeper magnets in progress

Challenges:
flux leakage, constant field profile, modeling magnet shape< 7k muons / spill (E_μ > 3 GeV), (well below the emulsion saturation limit)

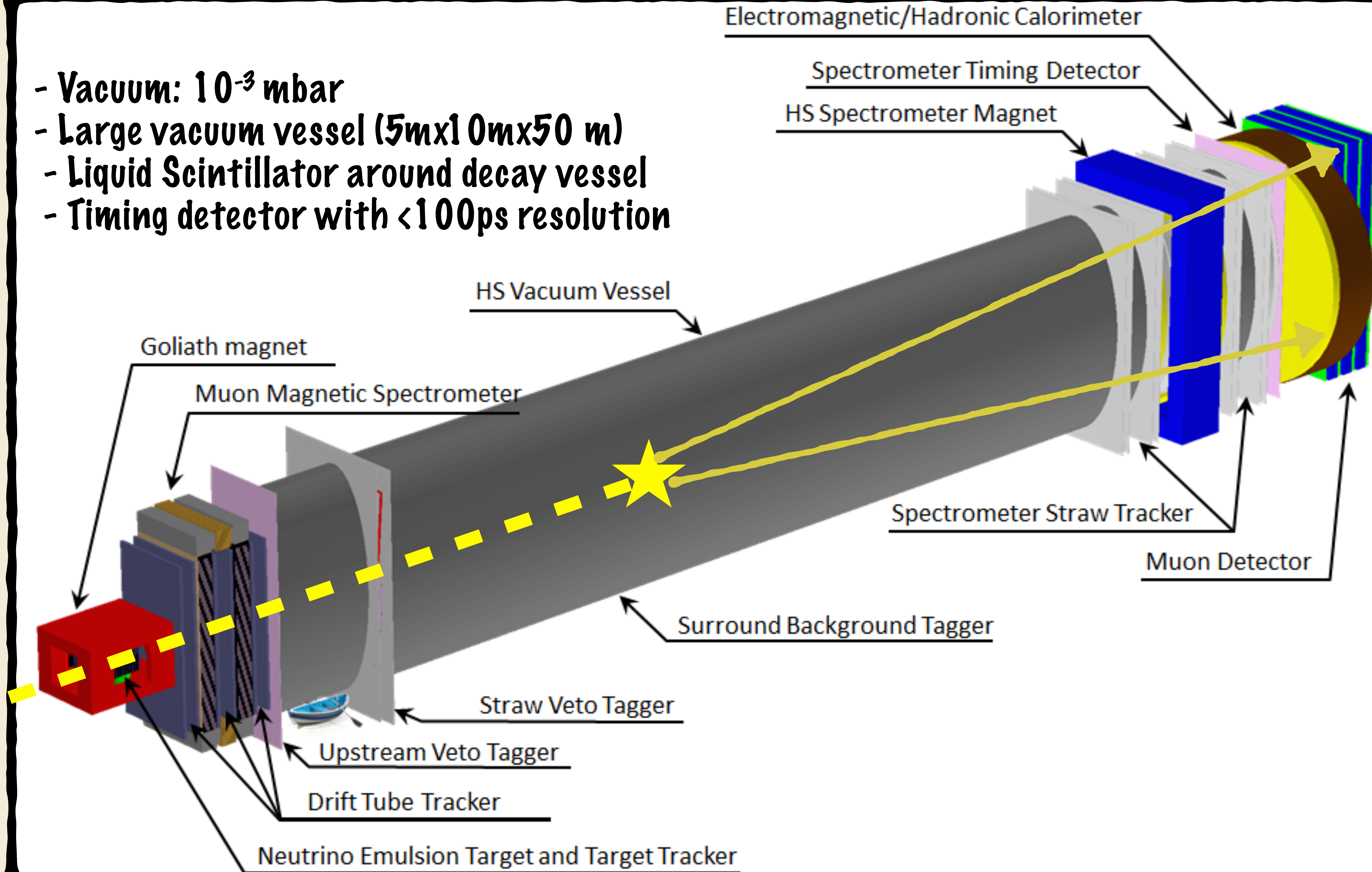
Negligible flux in terms of detector occupancy





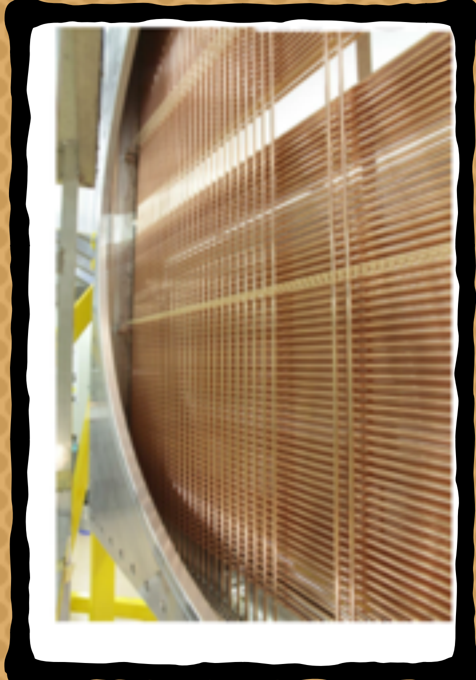
HS Detector

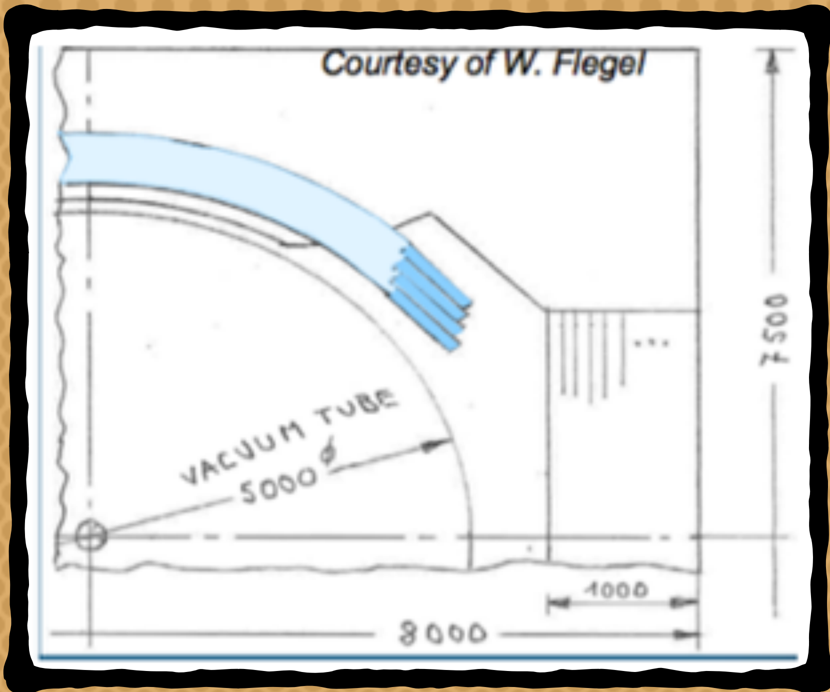
- Vacuum: 10^{-3} mbar
- Large vacuum vessel (5mx10mx50 m)
- Liquid Scintillator around decay vessel
- Timing detector with <100ps resolution

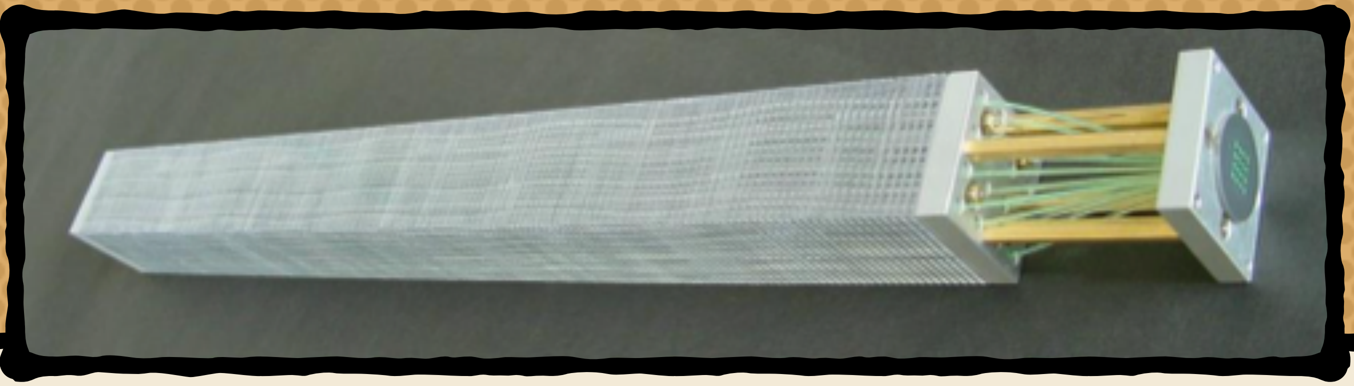


Magnet

- Straw tubes similar to NA62 with 120um spatial resolution and 0.5% X_0/X
- LHCb-like magnet
- Shashlik calorimeter
- Muon station consisting by plastic scintillators interval by iron







Veto Systems

Several Veto systems

- Surrounding Background Tagger: Liquid scintillator (LS) readout by WLS optical modules (WOM) and PMTs

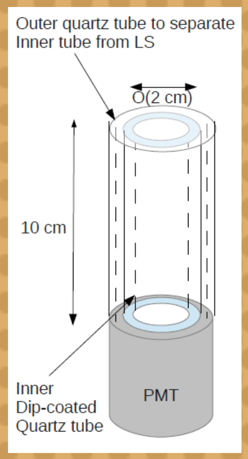
- Timing Detector: Plastic Scintillators read out by SiPMTs/ Multigap RPC

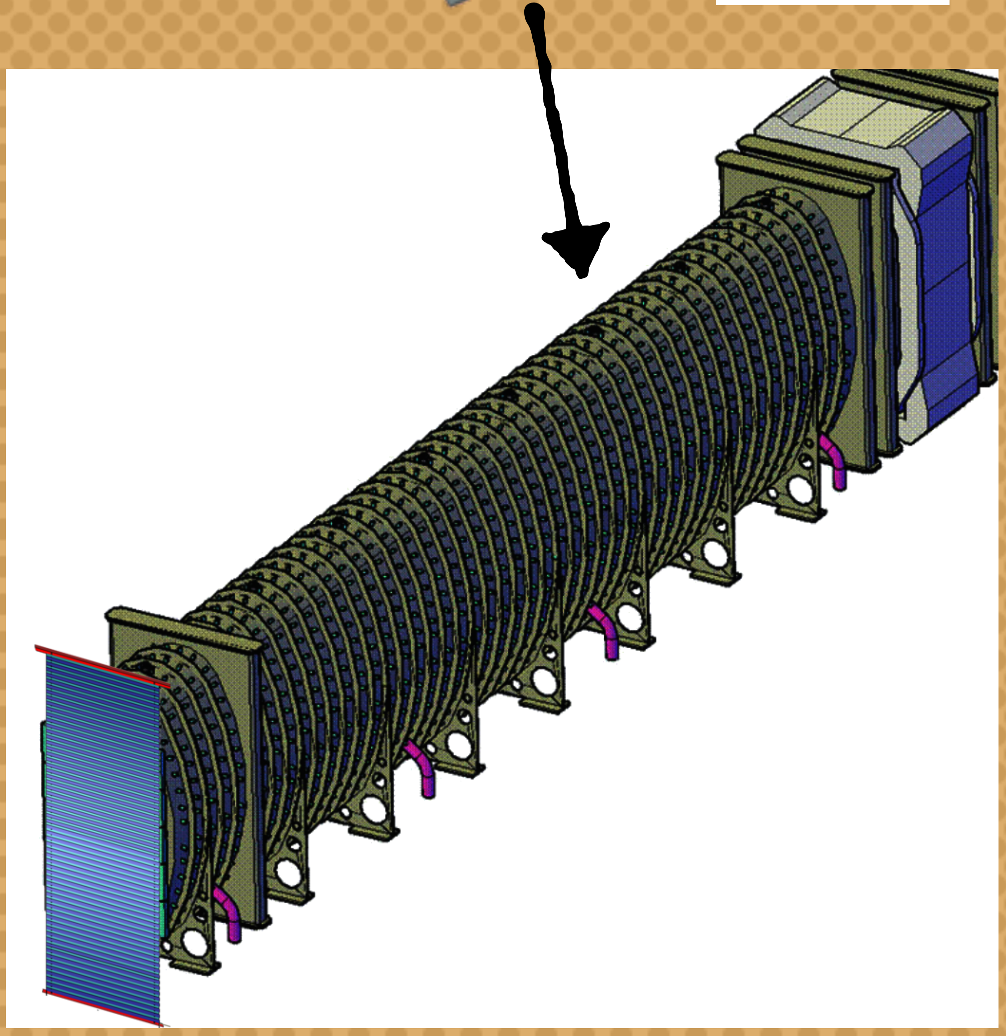
- Upstream Veto Tagger: Plastic Scintillators read out by PMTs

- Straw Veto Tagger: Straw tube station after 5m from the entrance

-

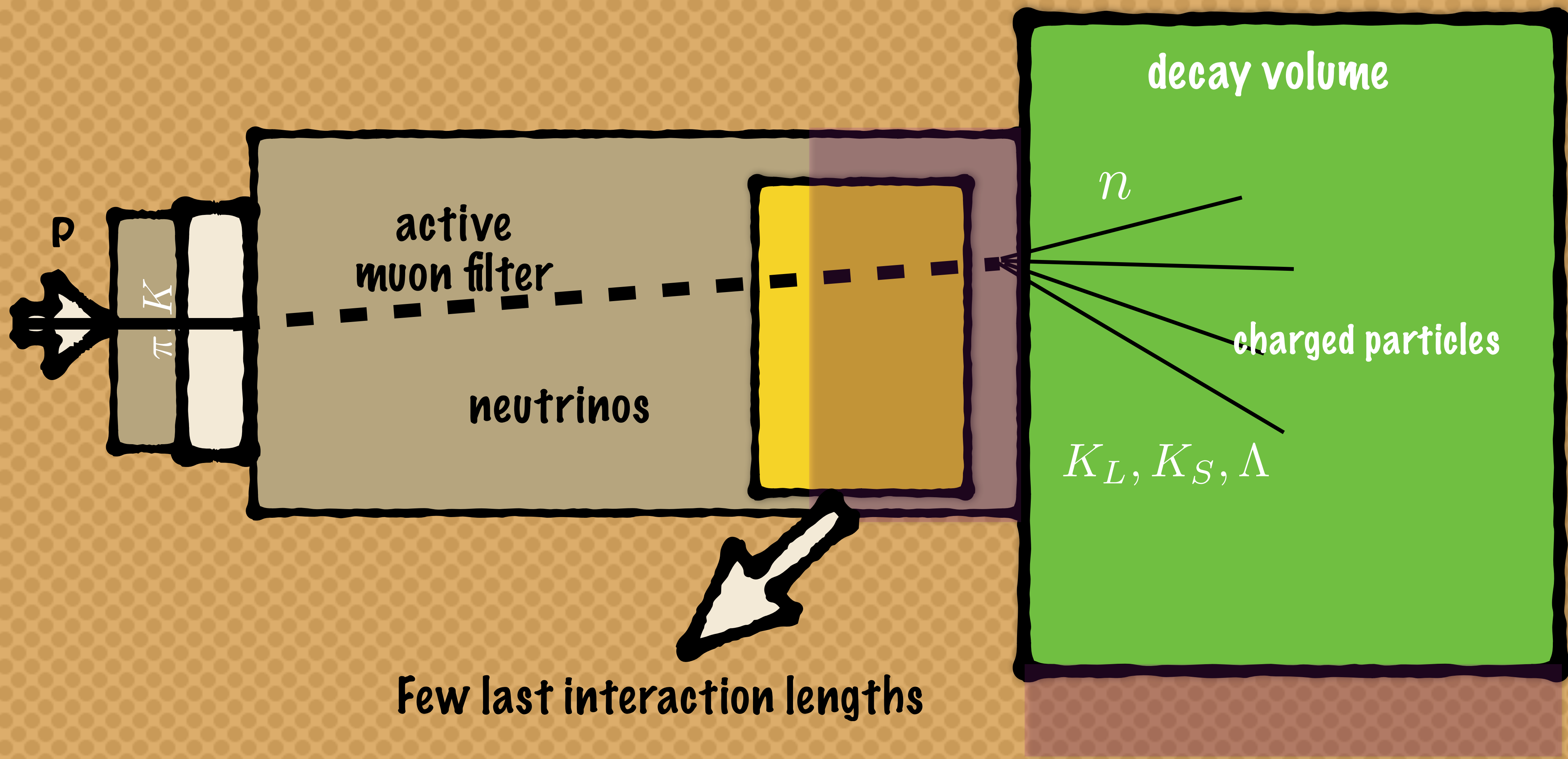
LS cell with WOM



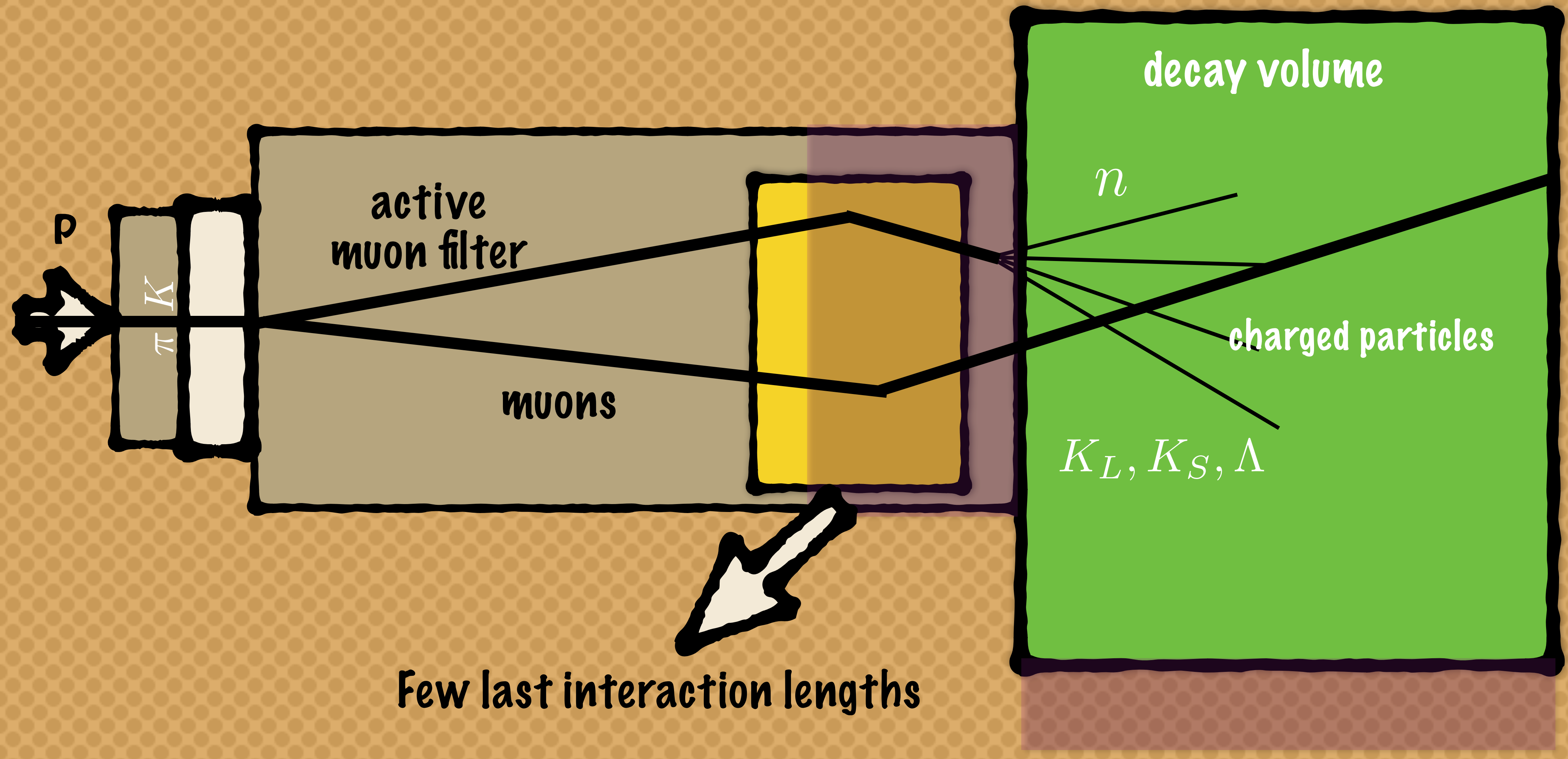


Background Studies

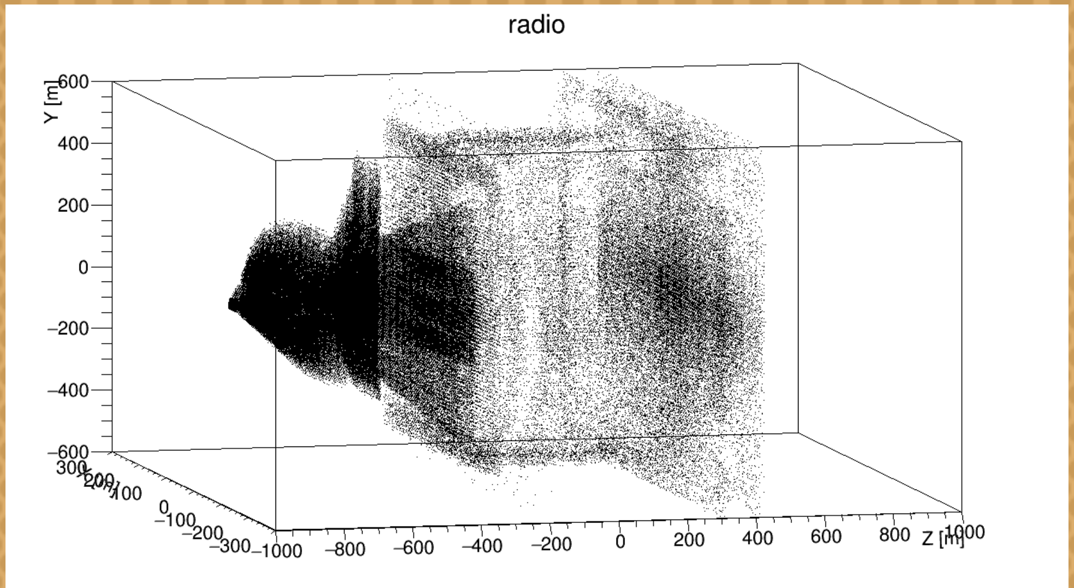
Neutrino background



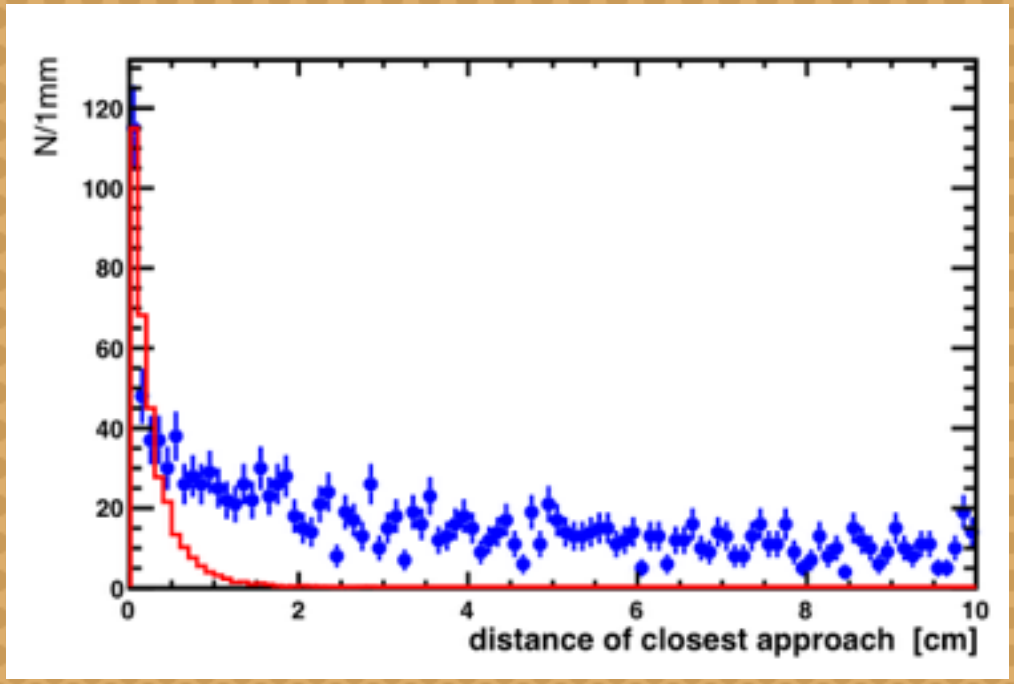
Muon induced background

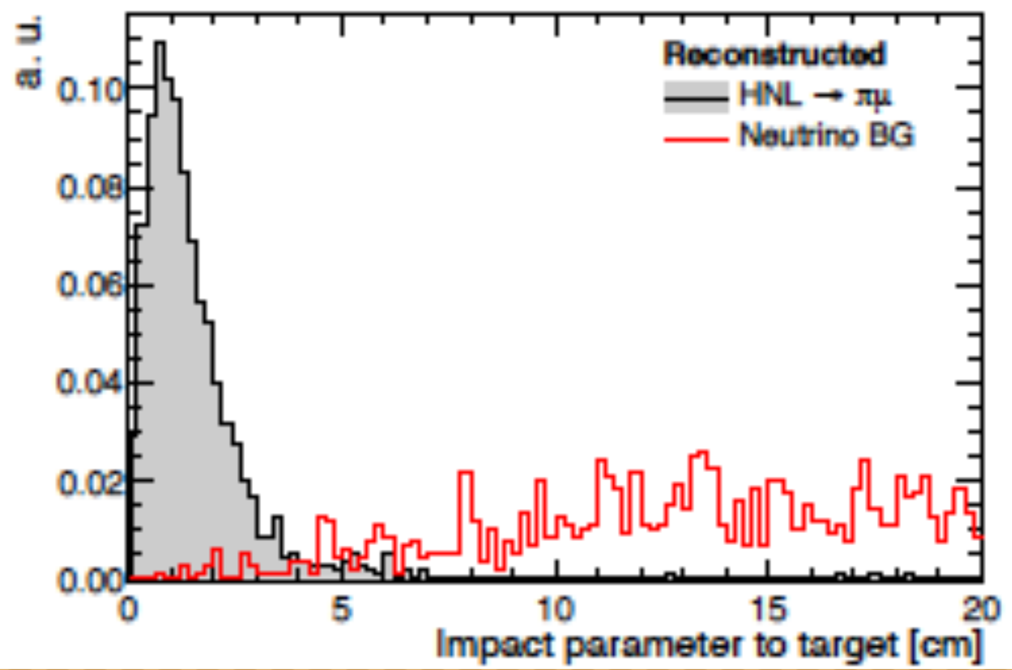


Background rejection



- Veto systems
- isolated good quality vertex
- Timing
- IP to the target
- According to MC studies possible to reduce the bkg to <0.1 event in 5 years

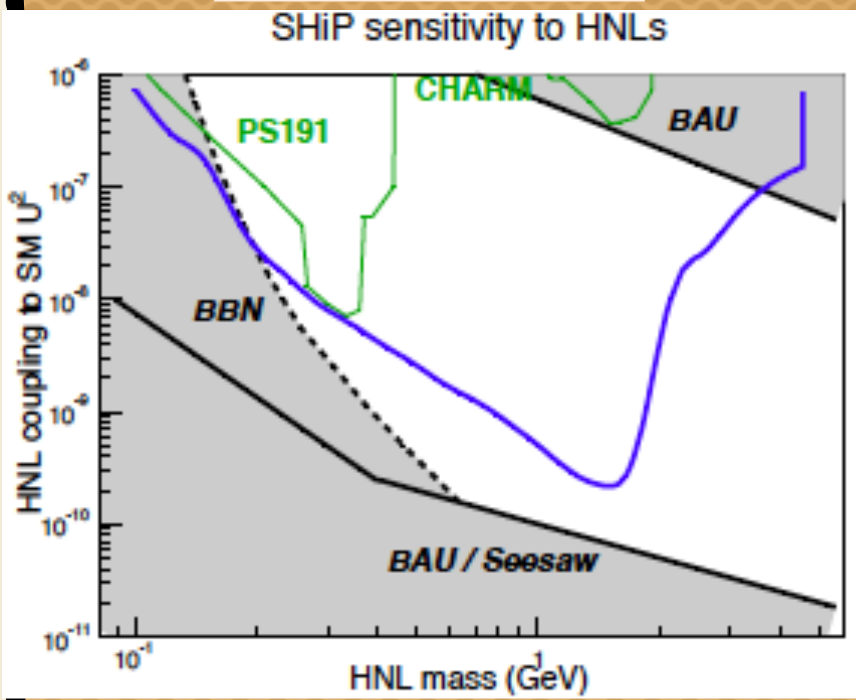




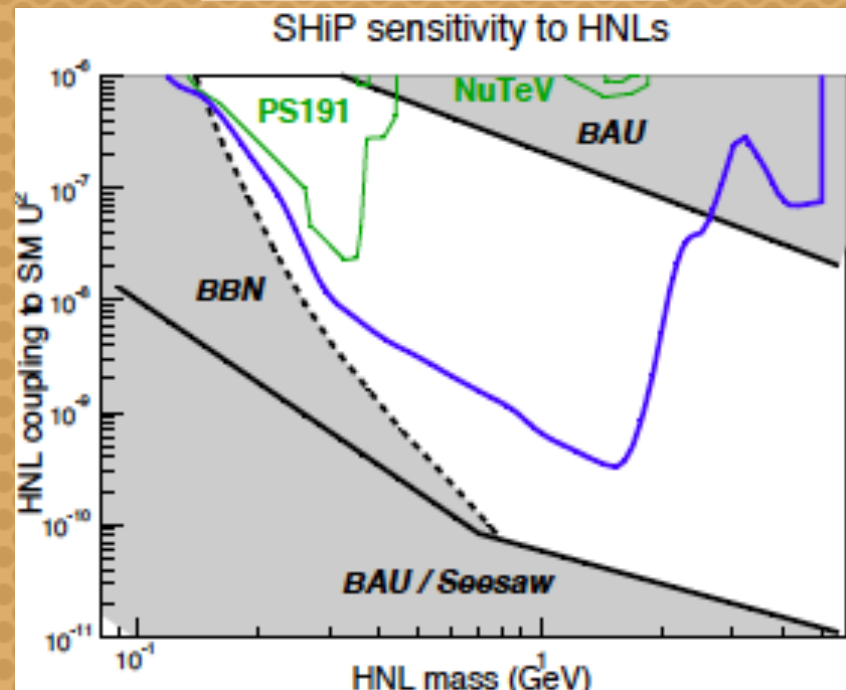
Sensitivity

Sensitivity Sterile Neutrinos

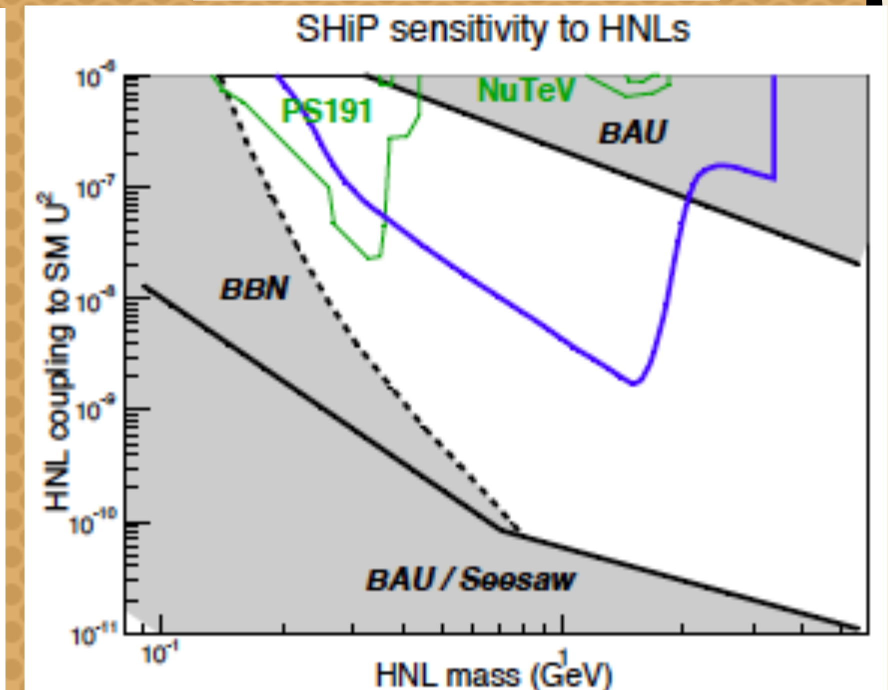
$U^2_e : U^2_\mu : U^2_\tau \sim 52:1:1$
Inverted hierarchy



$U^2_e : U^2_\mu : U^2_\tau \sim 1:16:3.8$
Normal hierarchy



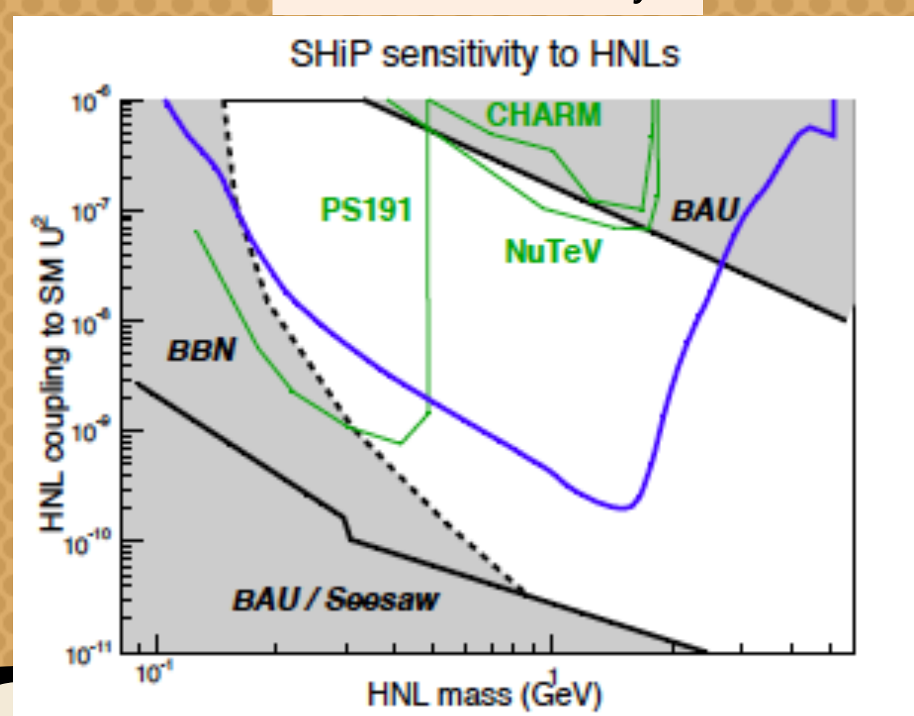
$U^2_e : U^2_\mu : U^2_\tau \sim 0.061:1:4.3$
Normal hierarchy



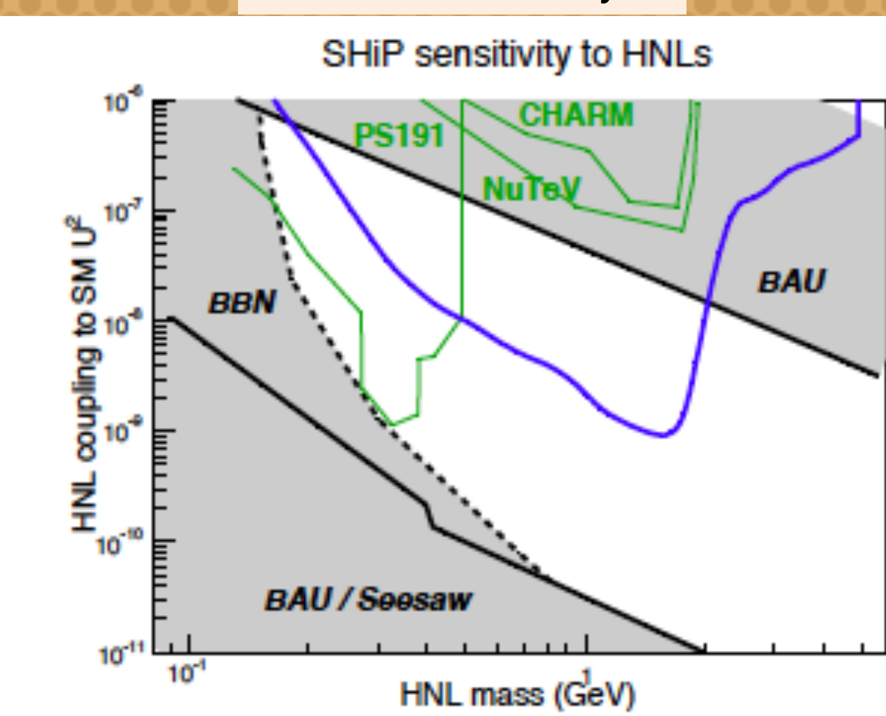
With a coupling of $U^2 = 10^{-8}$
and M=1GeV
We expect about 1000 events

Scenarios for which baryogenesis was numerically proven

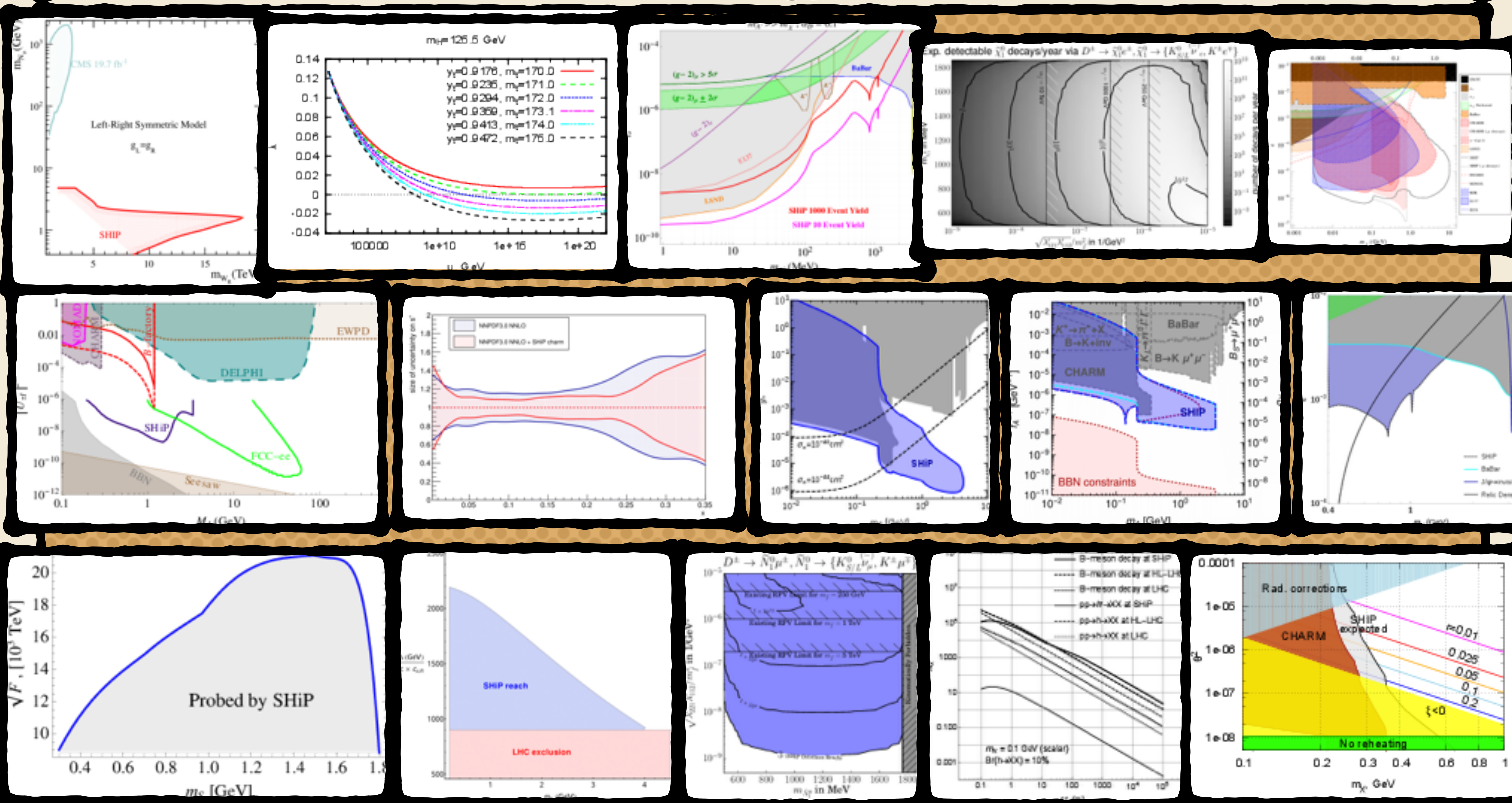
$U^2_e : U^2_\mu : U^2_\tau \sim 48:1:1$
Inverted hierarchy



$U^2_e : U^2_\mu : U^2_\tau \sim 1:11:11$
Normal hierarchy



Below just a few sensitivity plots from the SHiP Physics Paper



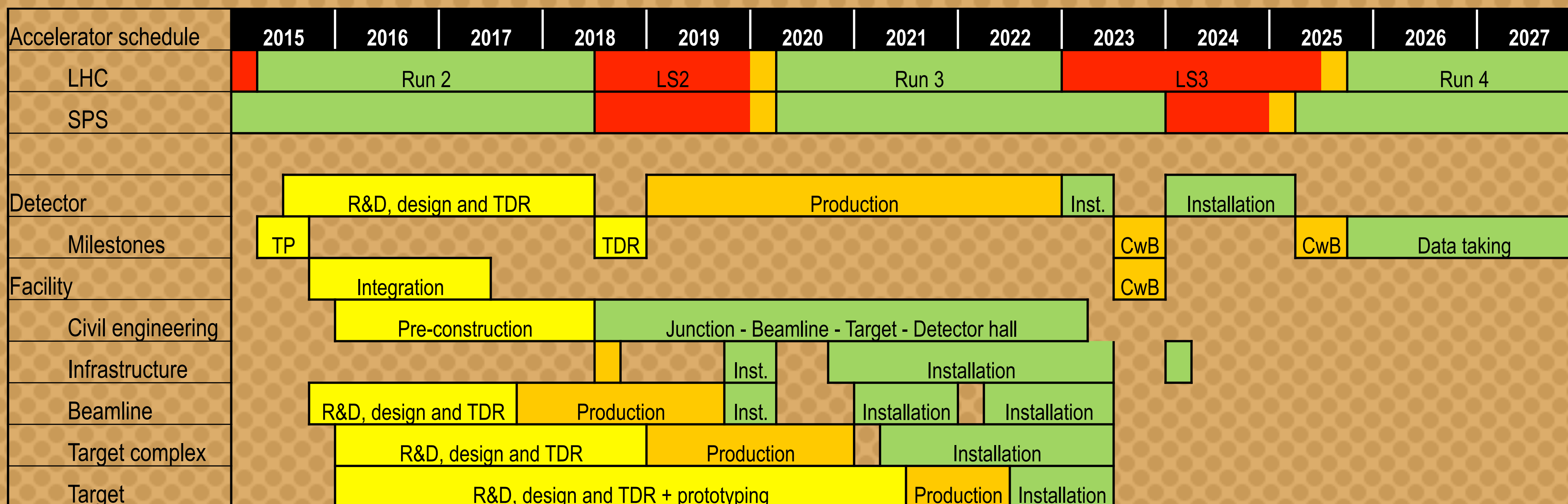
... and much much more

Where and When?

North Area

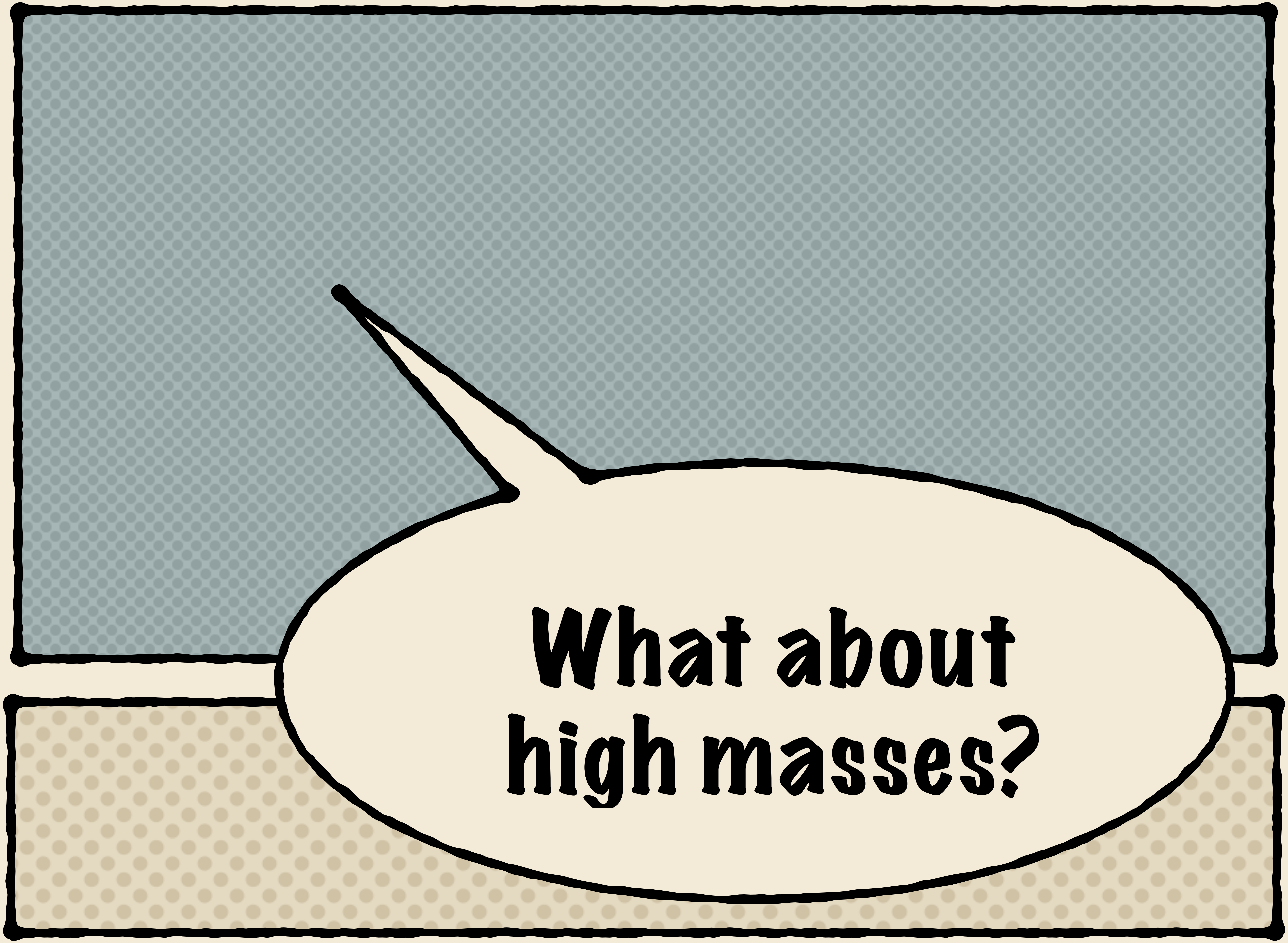
Underground Structures (Tunnel/Cavern/Hall)
Surface or Partially Underground Structures (Target Hall/SB/Access Building)
Shafts + Tunnel access
Access Area + Car Park
New SHIP Beamline
Future SHIP Extension Area
DETECTOR HALL ~ 20 m wide
810
811
812
~ 120 m
Access Bld. ~ 20m wide
40 m
38 m
25 m
Filter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

Time Schedule

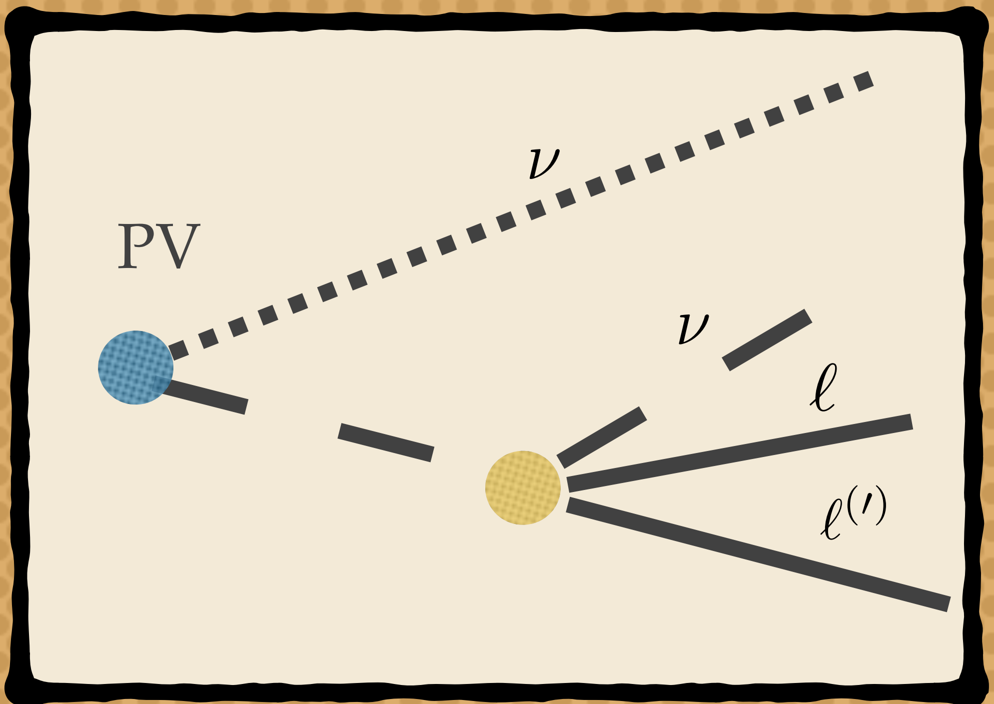


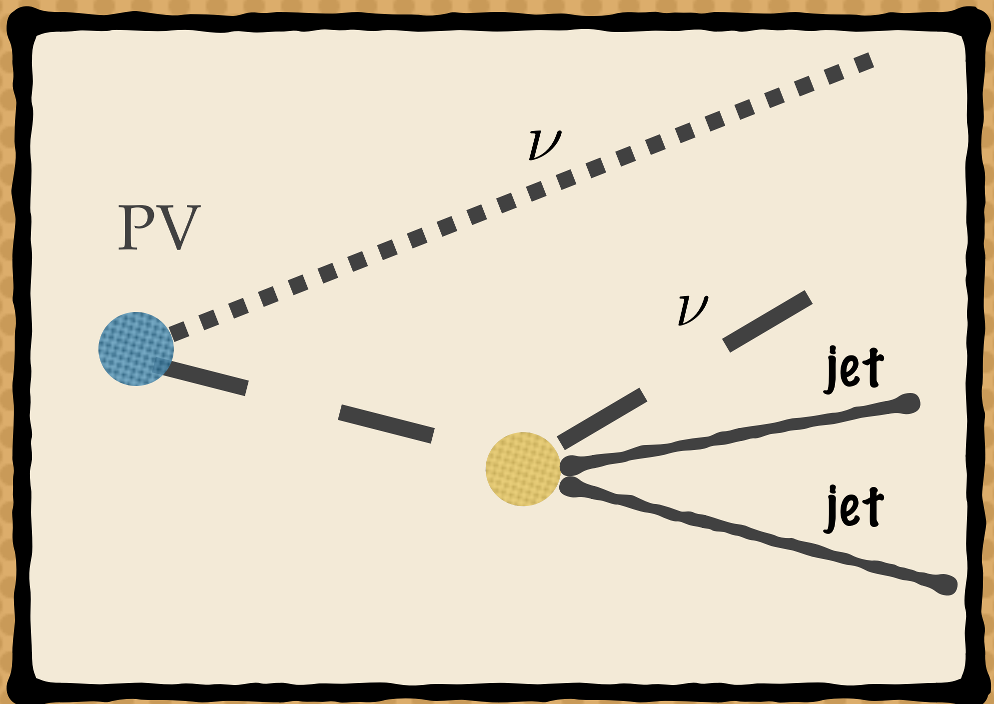
10 years from TP to data taking

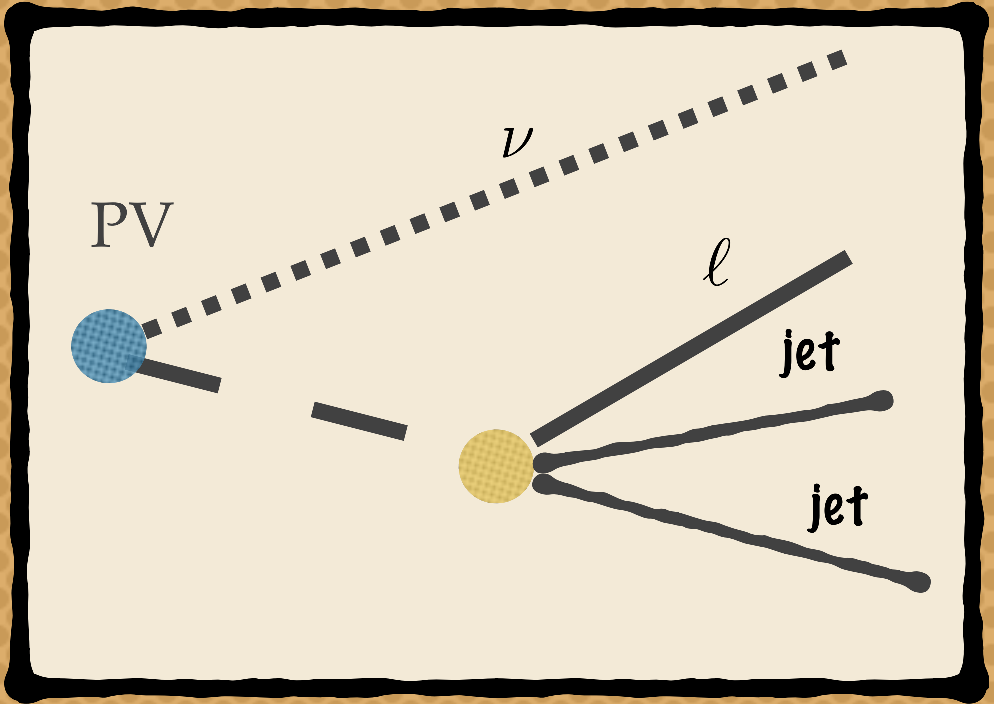
- ✓ *Schedule optimized for almost no interference with operation of North Area*
  - ➔ *Preparation of facility in four clear and separate work packages (junction cavern, beam line, target complex, and detector hall)*
  - ➔ *Maximum use of LS2 for junction cavern and first short section of SHiP beam line*
- ✓ *All TDRs by end of 2018*
- ✓ *Commissioning run at the end of 2023 for beam line, target, muon shield and background*
- ✓ *Four years for detector construction, plus two years for installation*
- ✓ *Updated schedule with new accelerator schedule (Run 2 up to end 2018, 2 years LS2) relaxes current schedule*
  - ➔ ***Data taking 2026***


What about high masses?

Signatures at Colliders

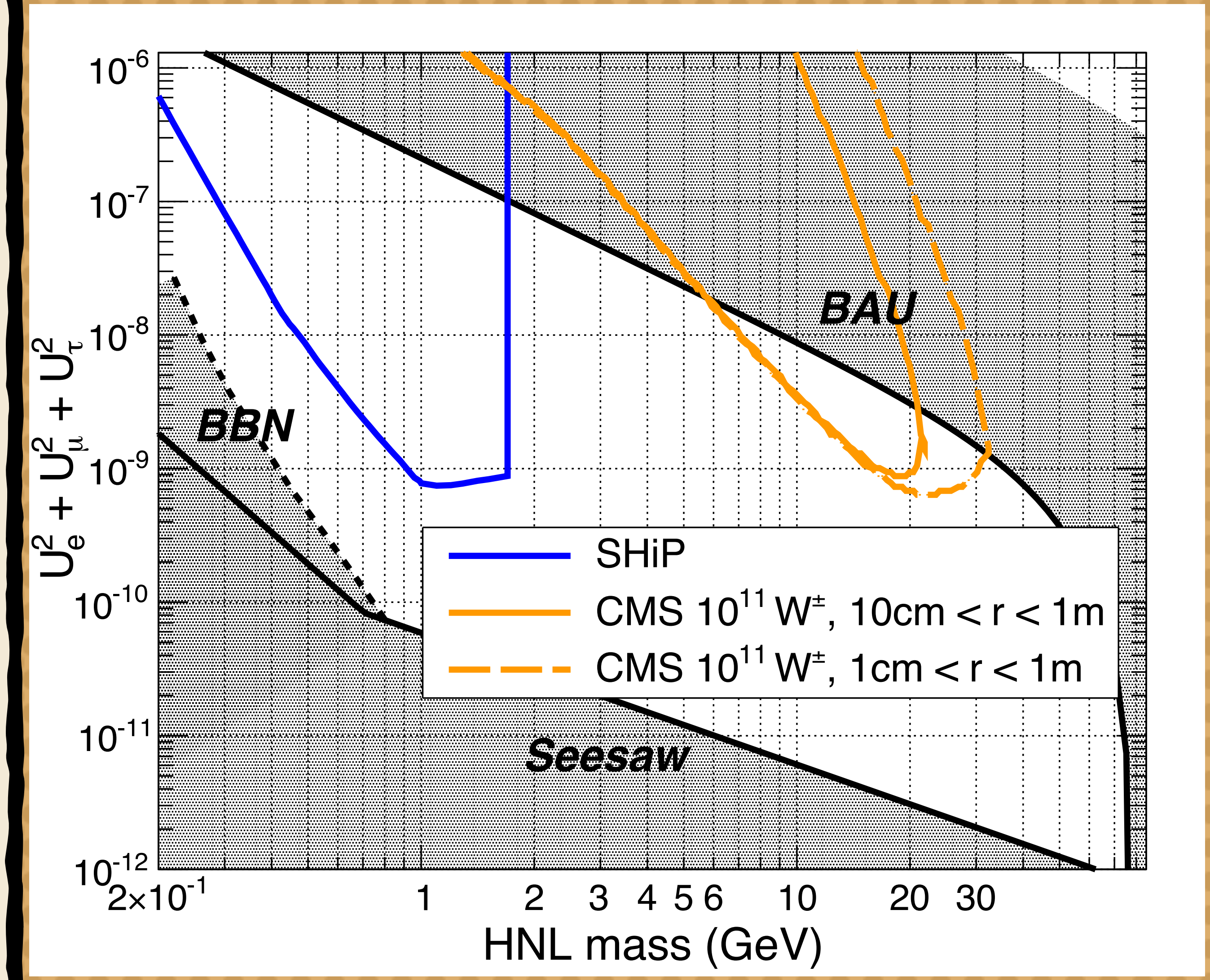






The main signature are displaced vertexes, depending on the coupling and the mass of sterile neutrinos from 1um to 1m

CMS/ATLAS toy study

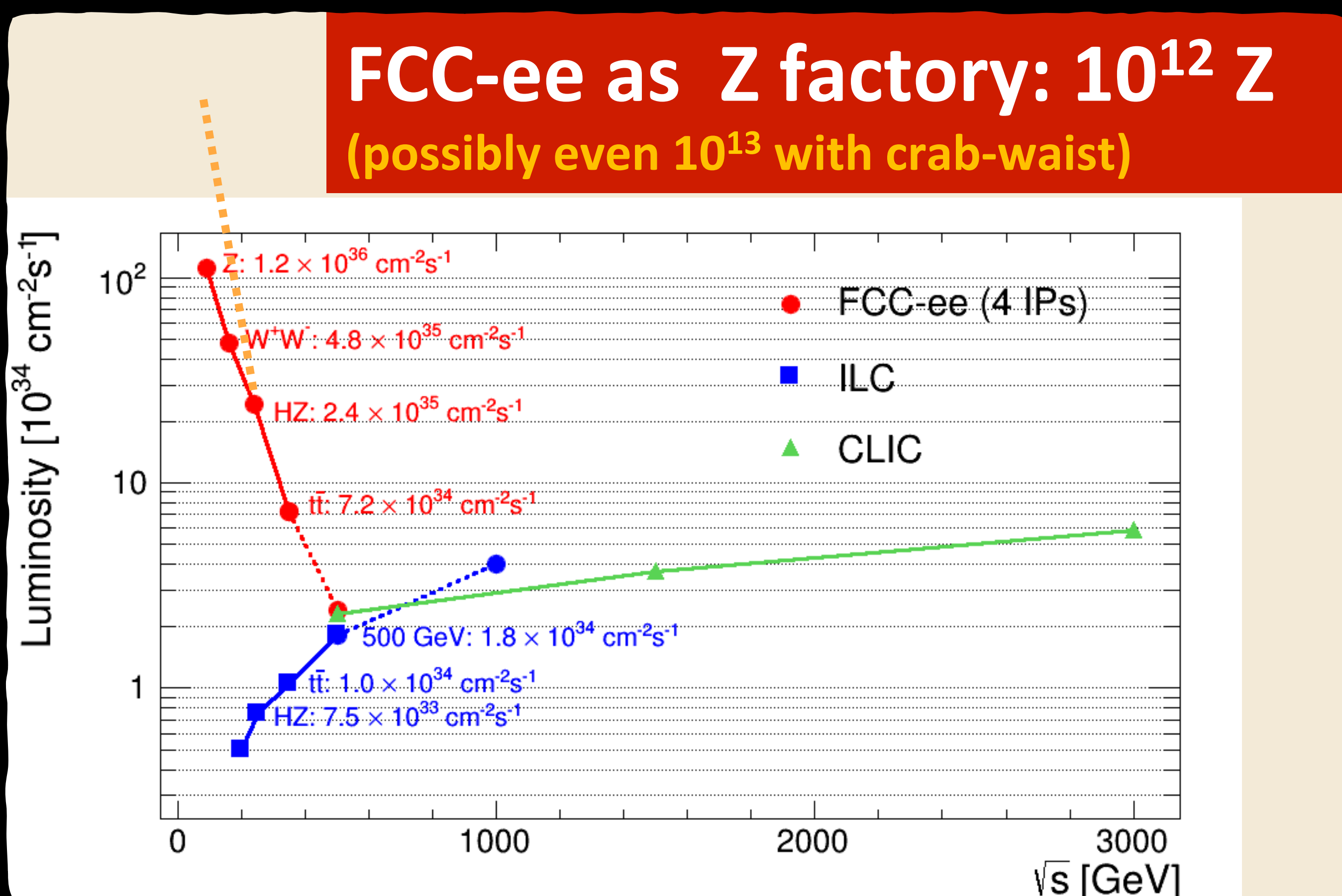


A. Blondel, E. Graverini, N.S. and M. Shaposhnikov

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

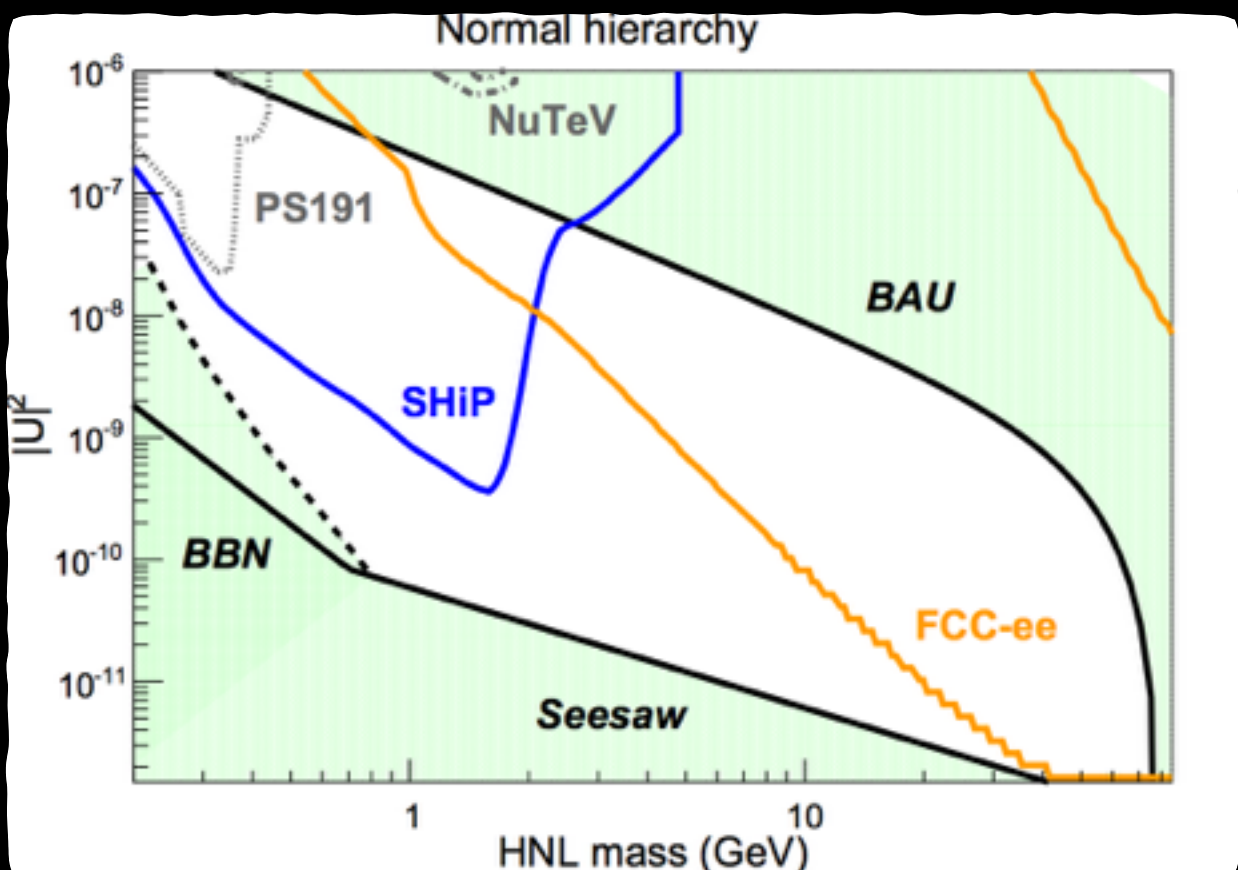
One should remember that the BAU limit is less constraint by several orders of magnitudes if we consider three sterile neutrinos participating to the seesaw

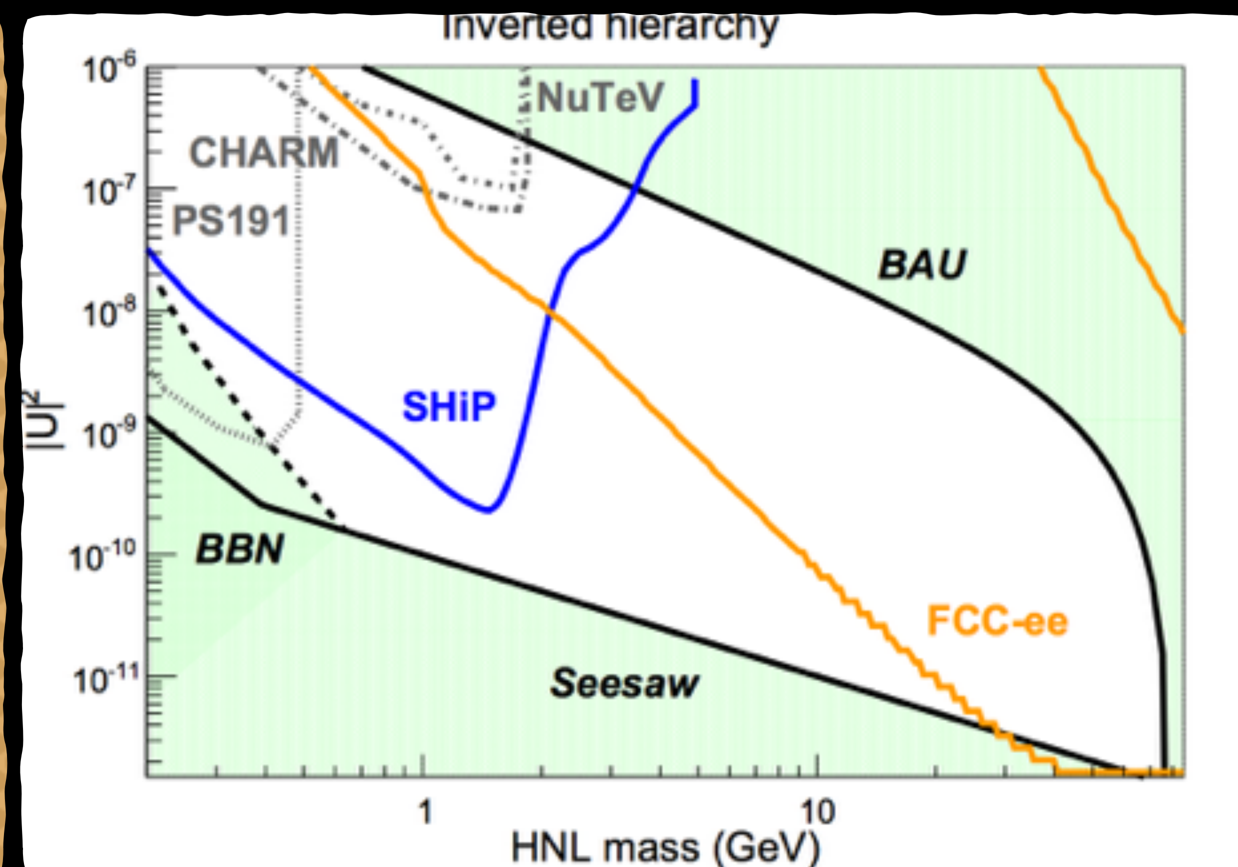
Future Z factories



- Proposal for Z, W, H and t factory at high luminosity
- CERN is launching a 5 years international design study of high luminosity e+e- collider (FCCee) and 100TeV pp collider (FCChh)
- IHEP in China is studying a 70Km ring with

FCCee sensitivity to sterile neutrinos

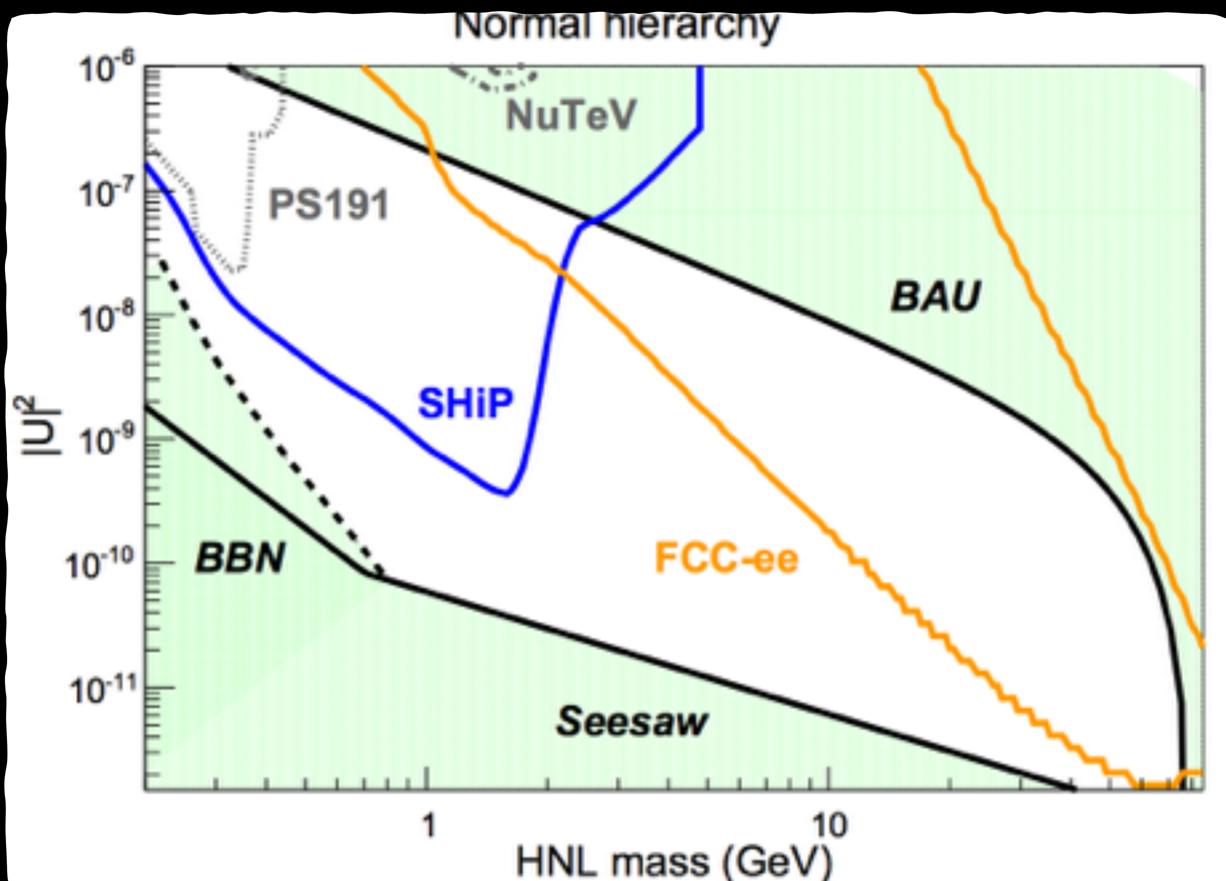


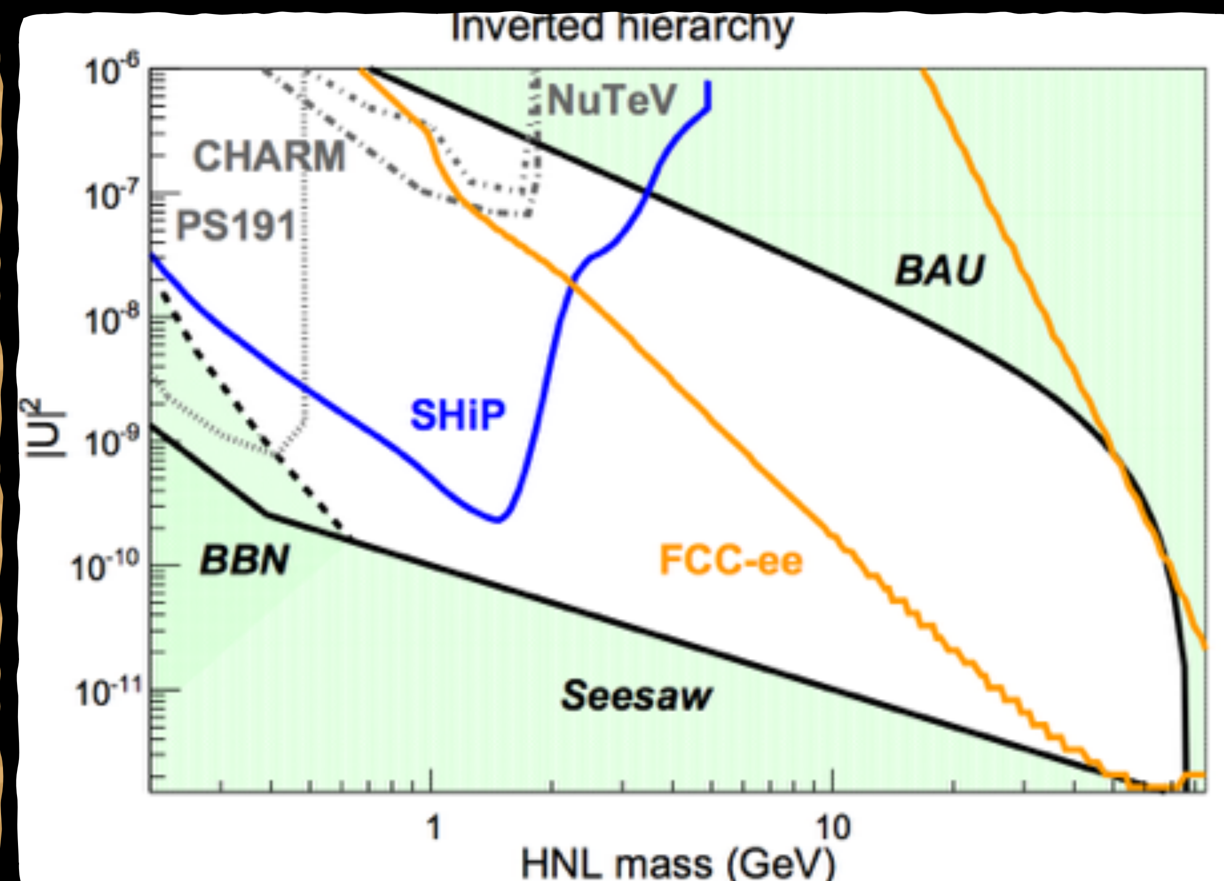


- This is the sensitivity assuming zero background for displaced vertexes between 1um and 5m and 10^{13} Z^0
- No reconstruction efficiency is included

A. Blondel, E. Graverini, N.S. and M. Shaposhnikov (arXiv:1411.5230v2)

FCCee sensitivity to sterile neutrinos





- This is the sensitivity assuming zero background for displaced vertexes between 10cm and 1m and 10^{13} Z^0
- No reconstruction efficiency is included
- The low contour depends on the maximum size and on the number of Z^0
- The high contour depends on the minimum flight distance cut

A. Blondel, E. Graverini, N.S. and M. Shaposhnikov (arXiv:1411.5230v2)

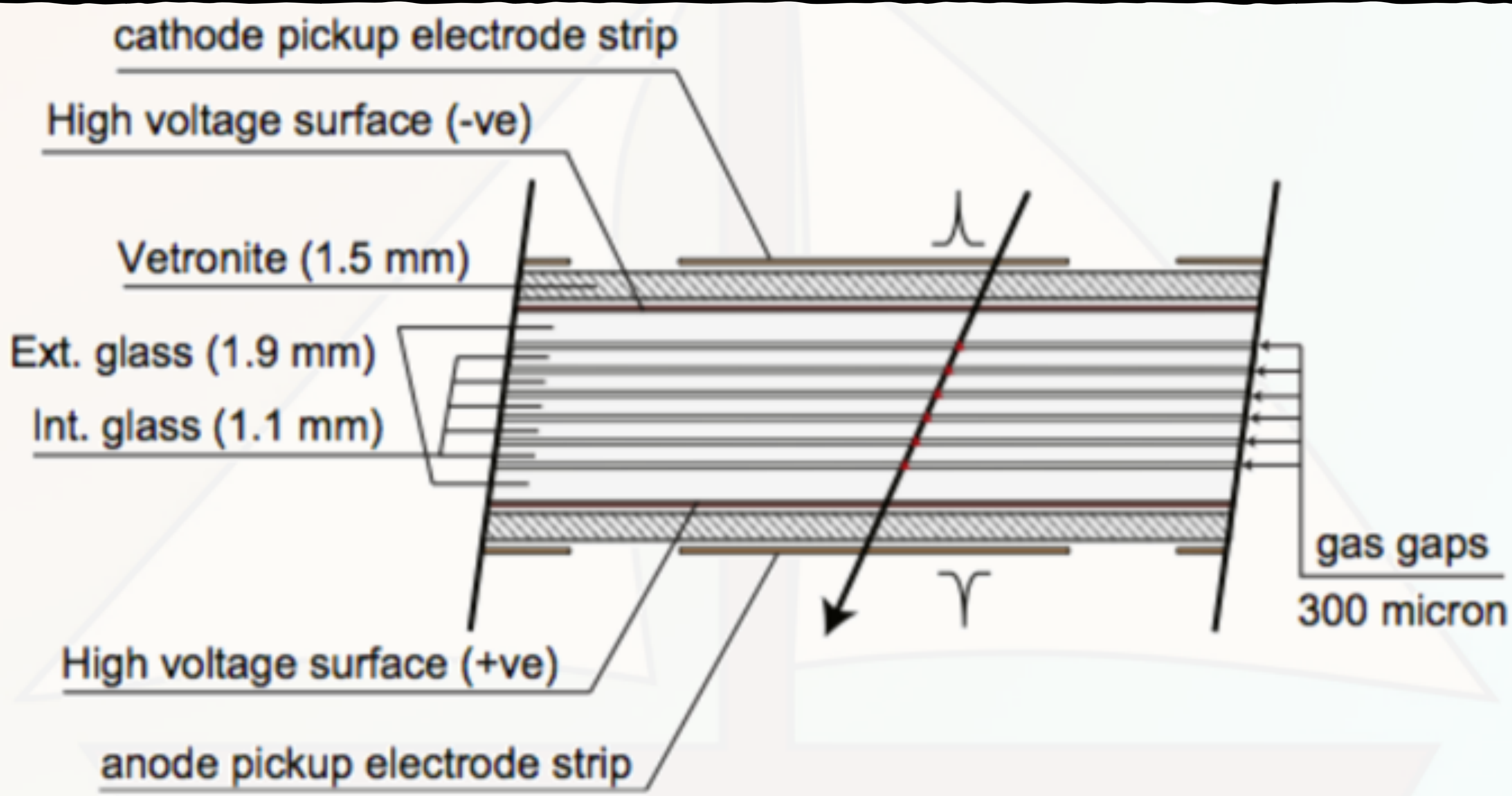
Conclusions

- Strong theoretical motivation to search for sterile neutrinos below the EW scale
- We are just entering the most interesting region of couplings
- Best limits NuTeV/CHARM/PS191 at low masses and DELPHI at high masses… LHC experiment are catching up
- SHiP experiment could scan the most interesting coupling below the B-mass
- Z^0 factories (FCCee) can scan the interesting region at high masses

Thanks for the attention

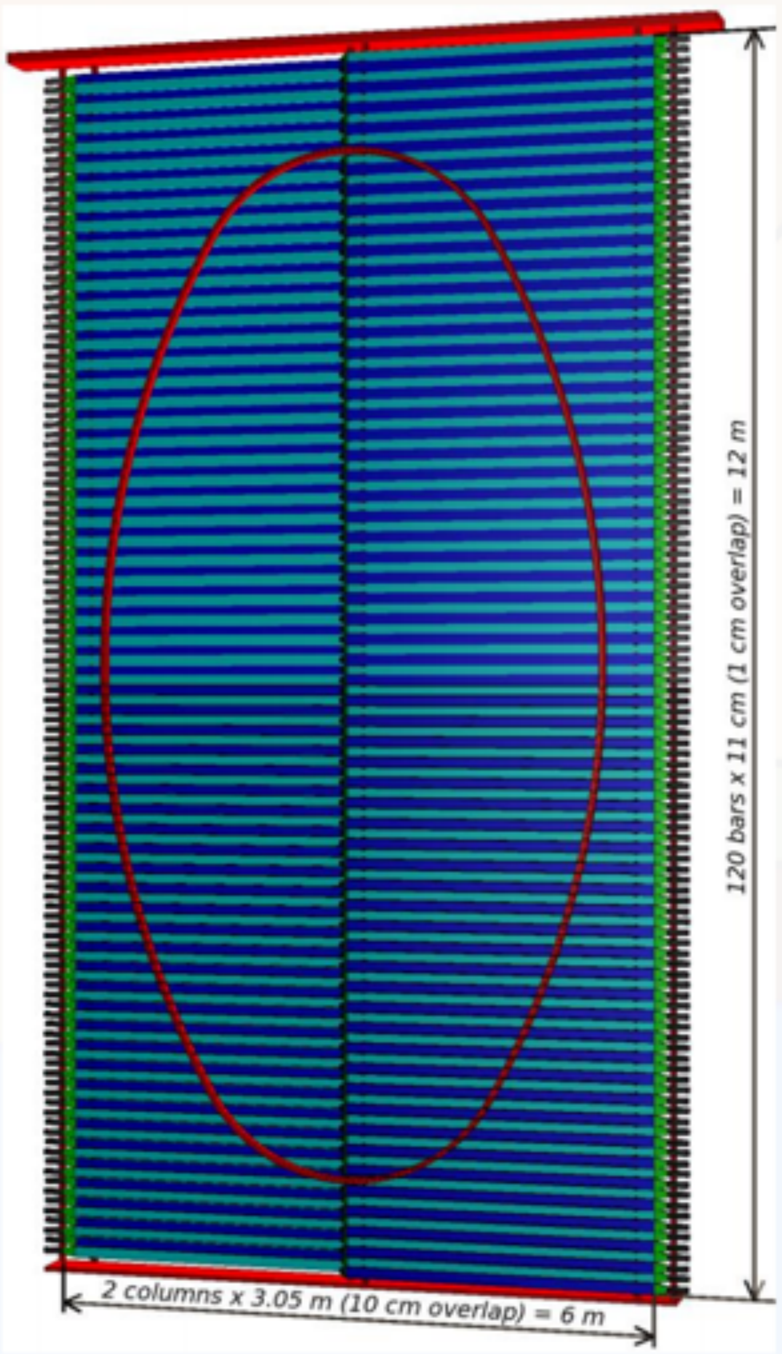
Backup slides

Timing detector: MRPC option



61 chambers x 120 cm strips, 3 cm pitch
Based on the EEE project
50 ps resolution achievable

Timing detector: Scintillating bars



Challenges:

- large area
- required resolution < 100 ps

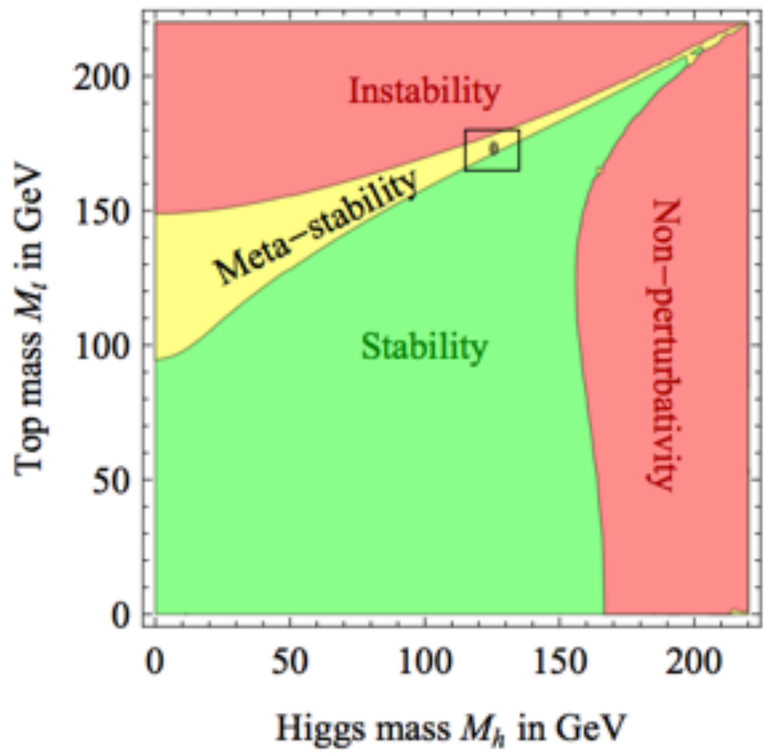
NA61/SHINE ToF:

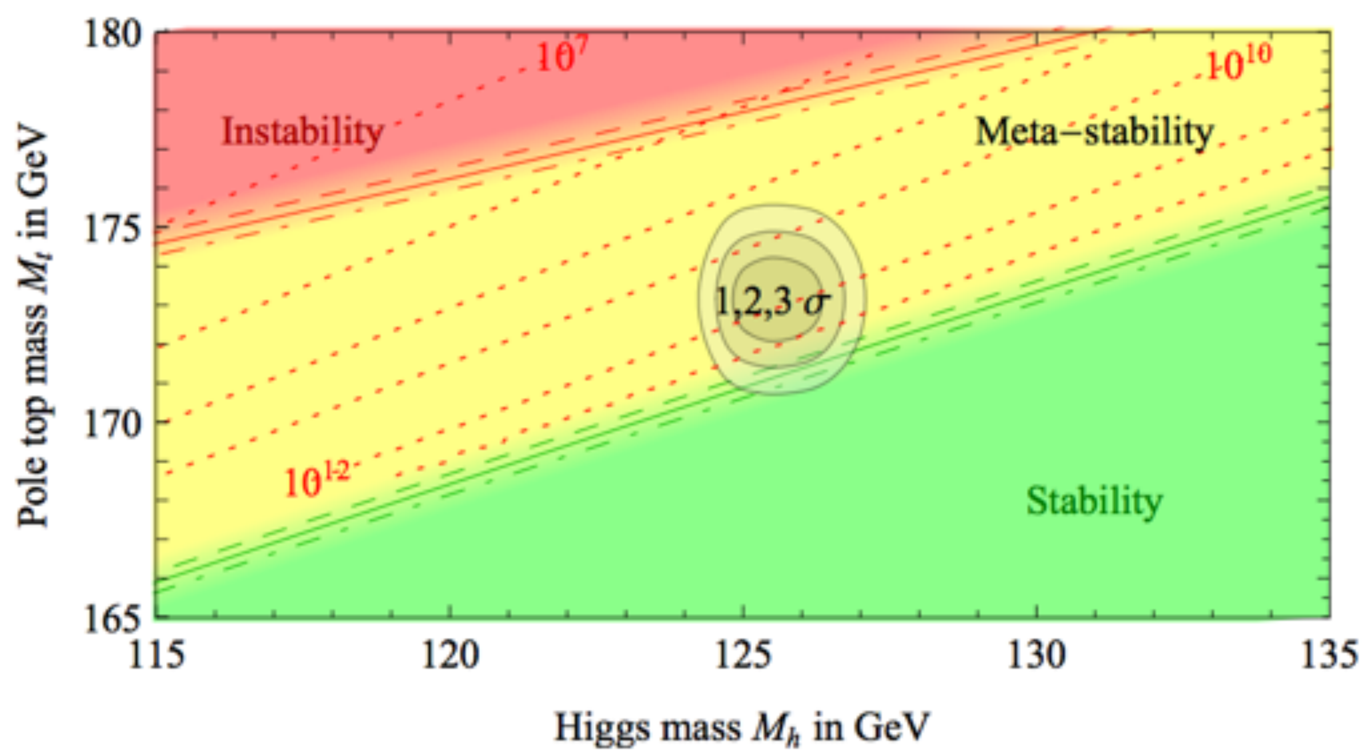
- 100 ps resolution
- size of scint. counter 120 x 10 x 2.5 cm^3
- total active area 1.2 x 7.2 m^2

Energy loss in plastic: dE/dx min = 2 MeV/cm,
light yield: 10000 photons/MeV ⇒
for 2.5 cm bar: $N\gamma$= 2.5 x 2 x 10k = 50 k

For long bars, mainly photons with total internal reflection ($\theta > 39^o$) are detected

Shaposhnikov's Minimal Hypothesis





Degrassi, Di Vita, Elias-Miró, Espinosa, Giudice, Isidori, Strumia (2012)

Bezrukov, Kalmykov, Kniehl, Shaposhnikov (2012)

- The Landau pole for SM is above the Planck scale
- The SM vacuum is either stable of meta-stable
- The naturalness paradigm that would predict NP at the Electroweak scale is challenged

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

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

Kinetic term

Majorana mass term

Yukawa coupling

Seesaw Mechanism

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

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

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

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

Eigenvalues

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

Assuming $M_N >> M_D$

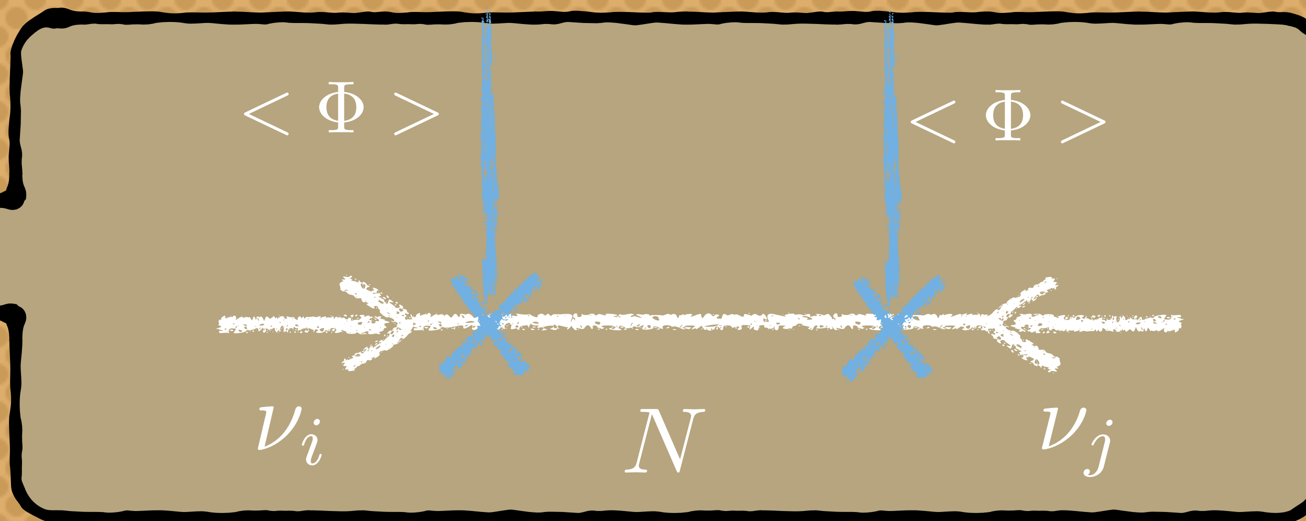
$$\lambda_- \sim \frac{M_D^2}{M_N}$$

$$\lambda_+ \sim M_N$$

Neutrino Oscillations

Neutrino oscillations is also explained via the Yukawa coupling of sterile and active neutrinos

$$Y_{I\ell} L_\ell \overline{\Phi} N_I$$



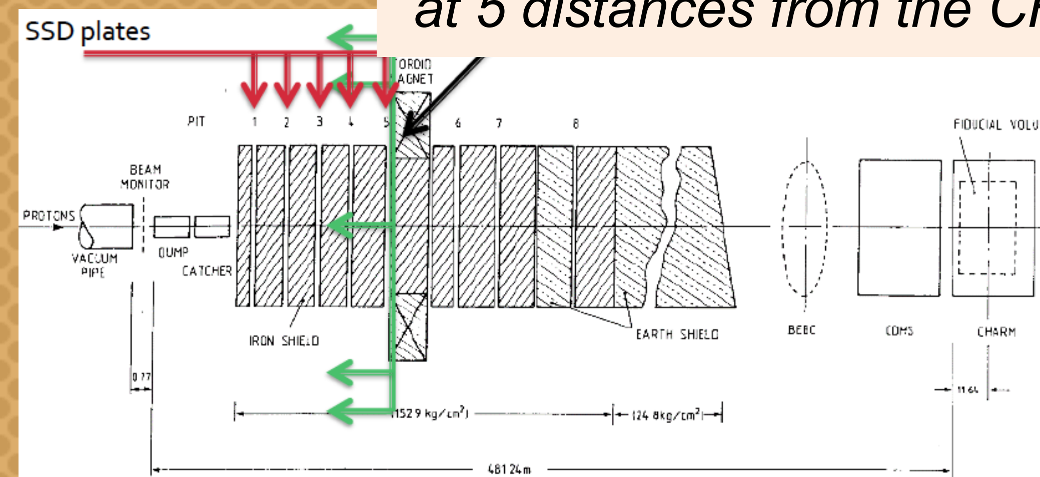
Active neutrinos mix with sterile neutrinos with a mixing angle

$$U_{I\ell} \sim \frac{M_D^\ell}{M_N^I} = \frac{Y_{I\ell} v}{M_N^I}$$

This is why people can search for sterile neutrinos, i.e. they can interact with SM particles by mixing with active neutrinos (neutrino portal)

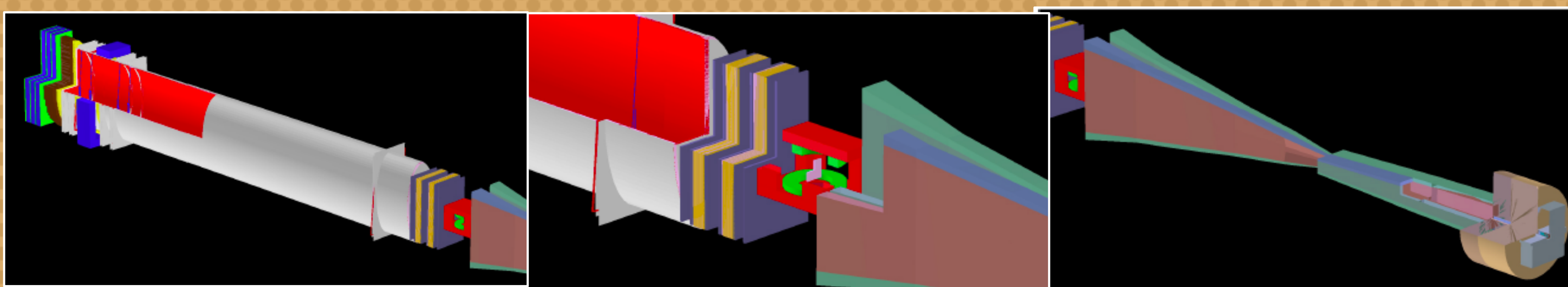
Simulation

Compare data with simulation
at 5 distances from the CHARM target



FairSHiP simulation:

- Pythia 6/8
- Geant 4
- Genie



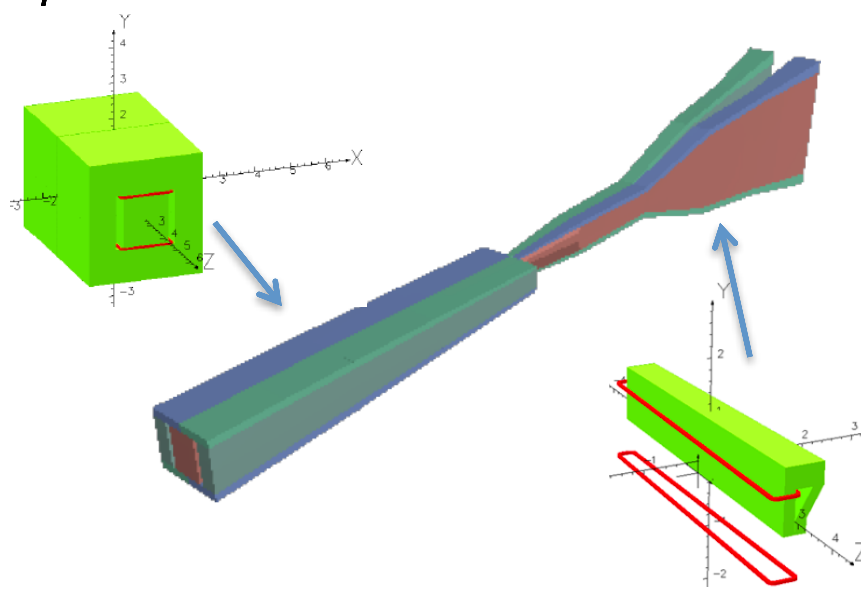
Simulation of the Muon shield
- performance validated with CHARM data
- very good agreement

Type of simulation:	EMV QGSP	EMV FTFP	EMX QGSP	EMX FTFP	CHARM data
Pit 1	8419	9225	8583	9226	8200
Pit 2	624	630	697	645	655
Pit 3	147	168	208	165	137
Pit 4	36	55	37	45	33.1
Pit 5	14	8	4	9	6.1

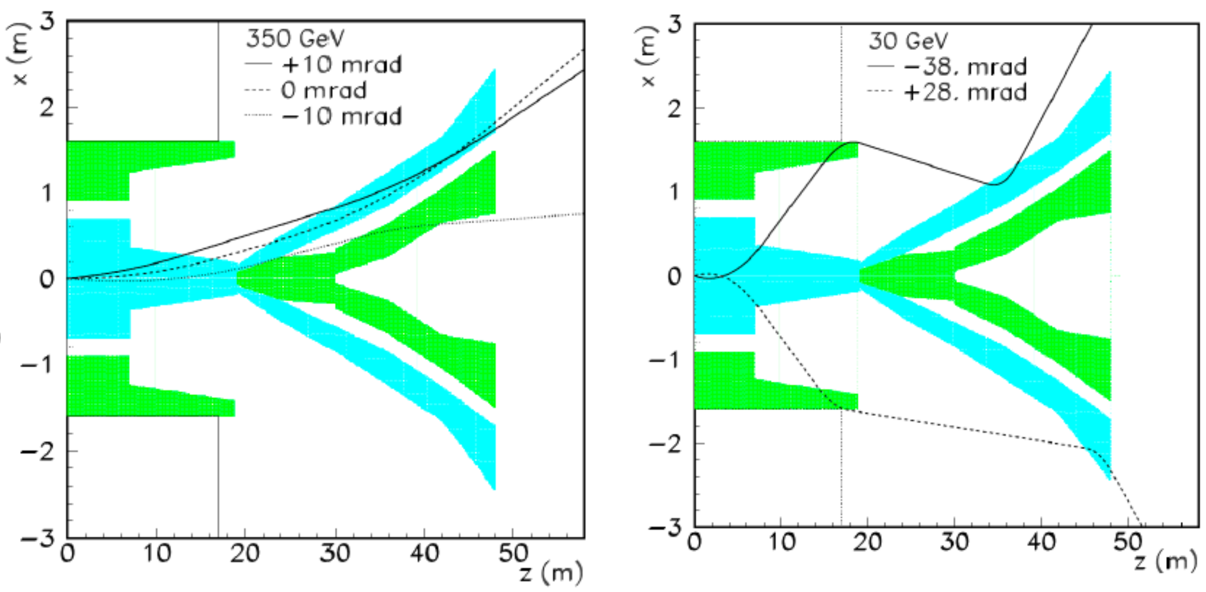
Muon Filter

SHiP muon shield

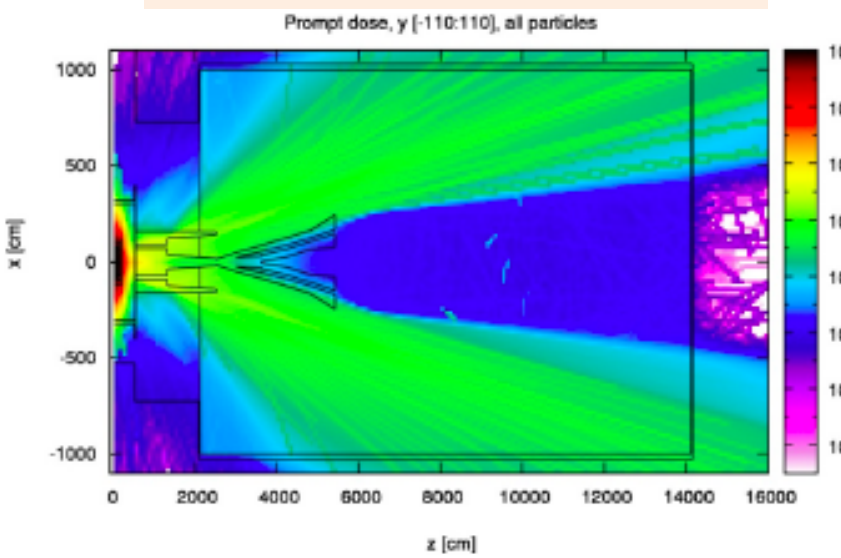
- ✓ Muon flux limit driven by emulsion based neutrino detector and HS background
- ✓ Active muon shield based entirely on magnet sweeper with a total field integral B_y = 86.4 Tm
  Realistic design of sweeper magnets in progress
  Challenges: flux leakage, constant field profile, modeling magnet shape
- ✓ < 7k muons / spill (E_μ > 3 GeV), well below the emulsion saturation limit
- ✓ Negligible flux in terms of detector occupancy



Magnetic sweeper field



Dose rate in the SHiP hall

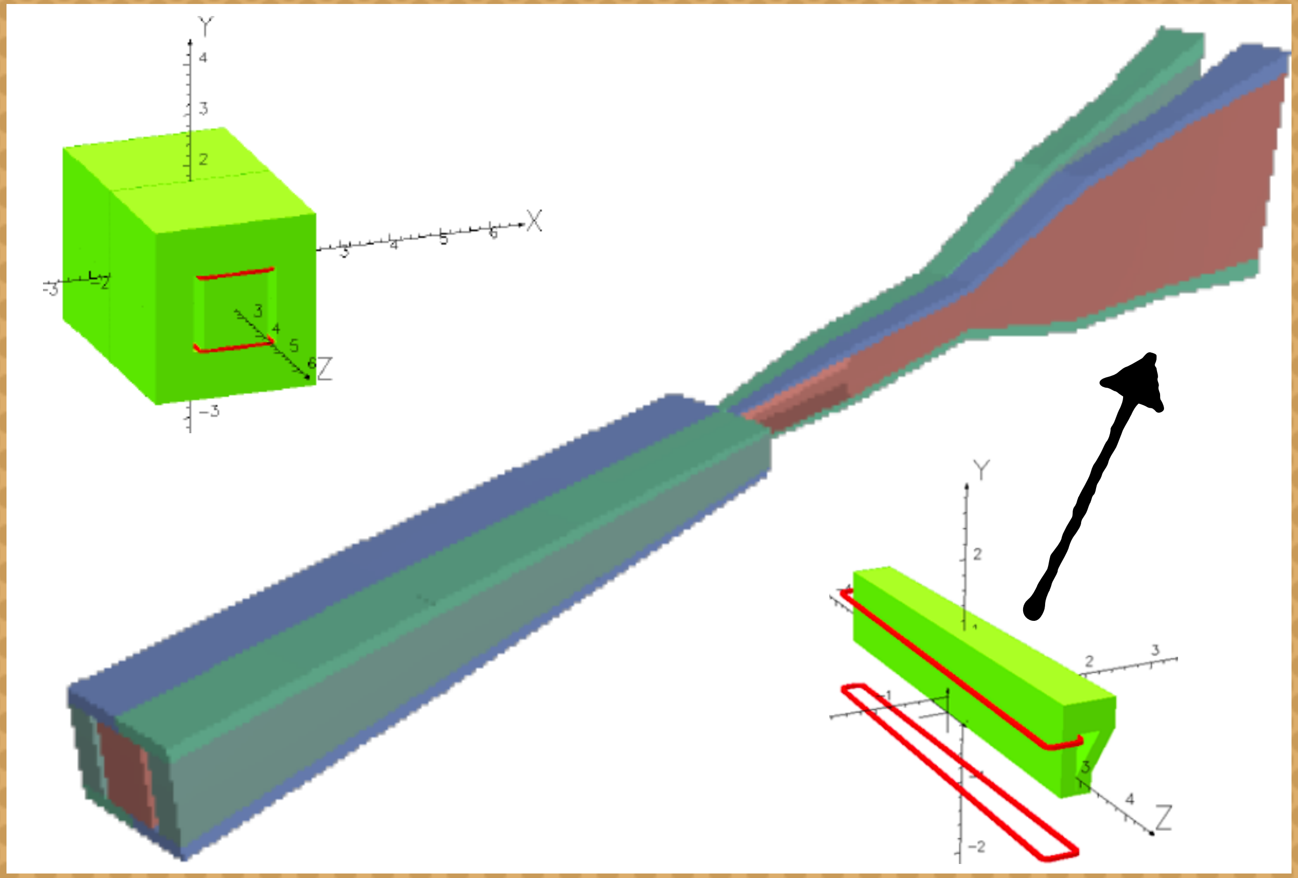


Sweeping magnet

Realistic design of sweeper magnets in progress

Challenges:
flux leakage, constant field profile, modeling magnet shape< 7k muons / spill (E_μ > 3 GeV), well below the emulsion saturation limit

Negligible flux in terms of detector occupancy

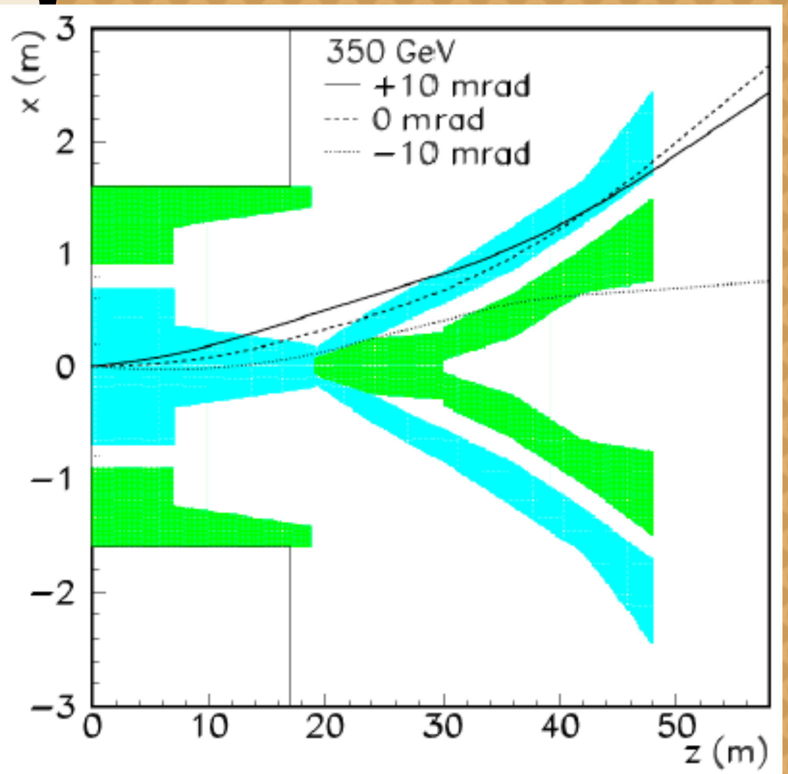


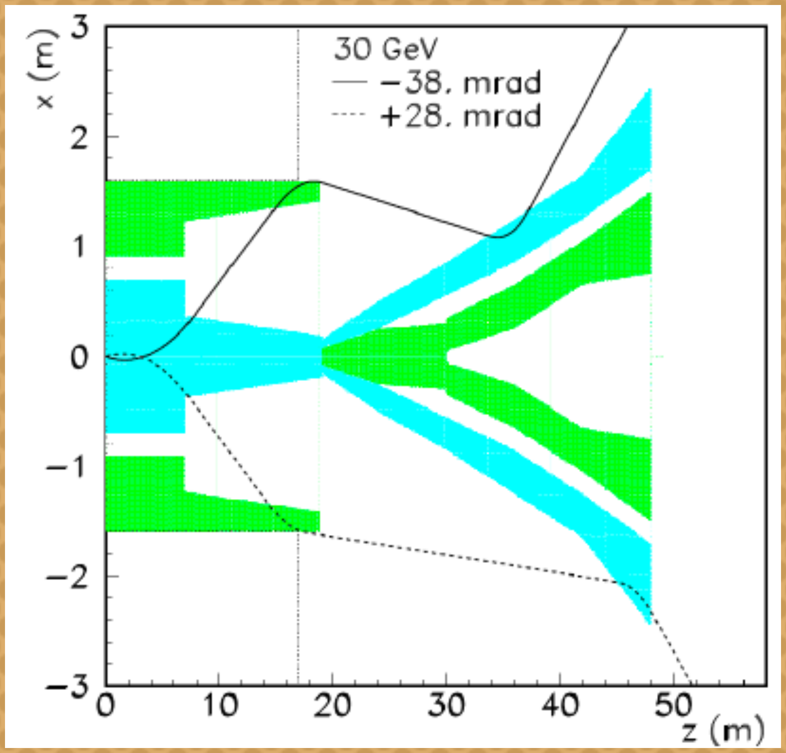
Sweeping magnet

Muon Flux Limit:
- Background for the HS searches
- Ageing of emulsion for neutrino detector

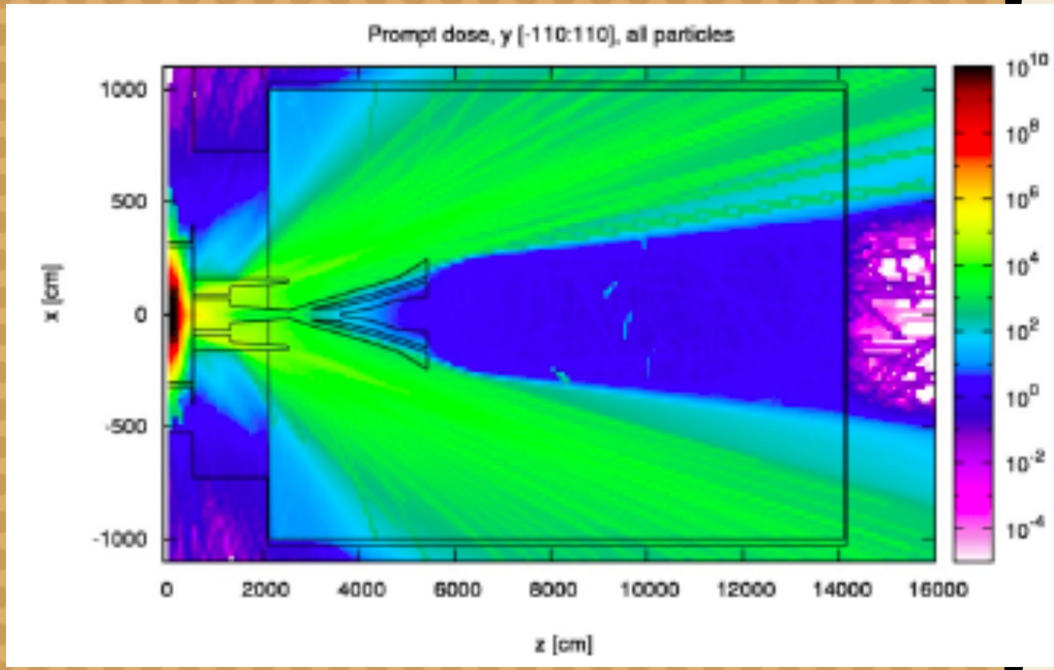
Active muon shield based entirely on magnet sweeperwith a total field integral B_y = 86.4 Tm

Magnetic sweeper field



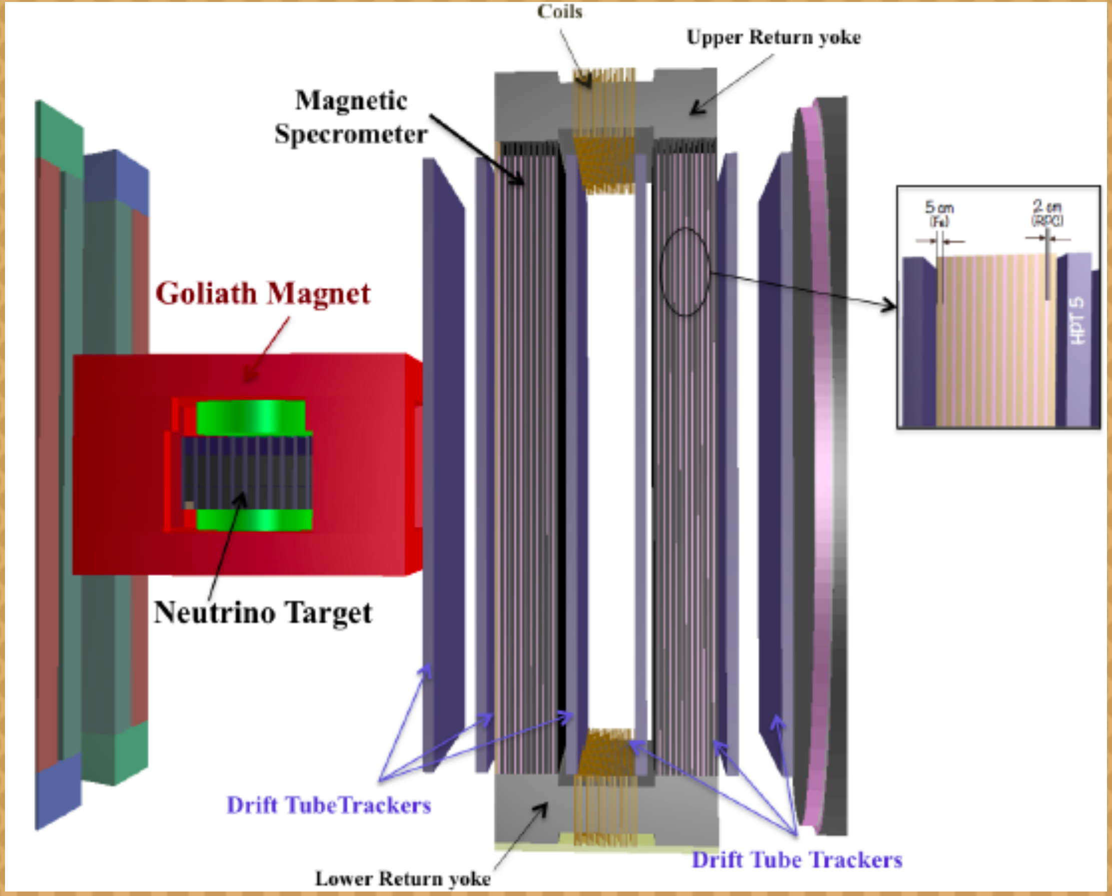


Dose rate in the SHiP hall

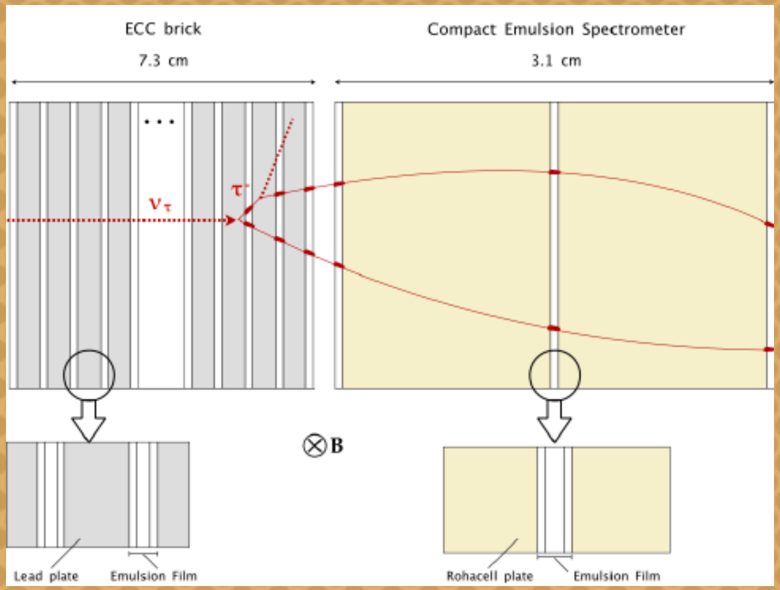


Neutrino Detector

neutrino tau detector very similar to OPERA



Emulsion Cloud Chamber
Is a key element of ν_τ detection



decay channel	ν_τ N^{exp}	ν_τ N^{bg}	ν_τ R	$\overline{\nu}_\tau$ N^{exp}	$\overline{\nu}_\tau$ N^{bg}	$\overline{\nu}_\tau$ R
$\tau \to \mu$	570	30	19	290	140	2
$\tau \to h$	990	80	12	500	380	1.3
$\tau \to 3h$	210	30	7	110	140	0.8
Total	1770	140	13	900	660	1.4

- tau neutrino cross section measurements
- Charm physics with taus
- Proton structure function
- Large electron neutrino flux to measure Charm production

Timing Veto Detector

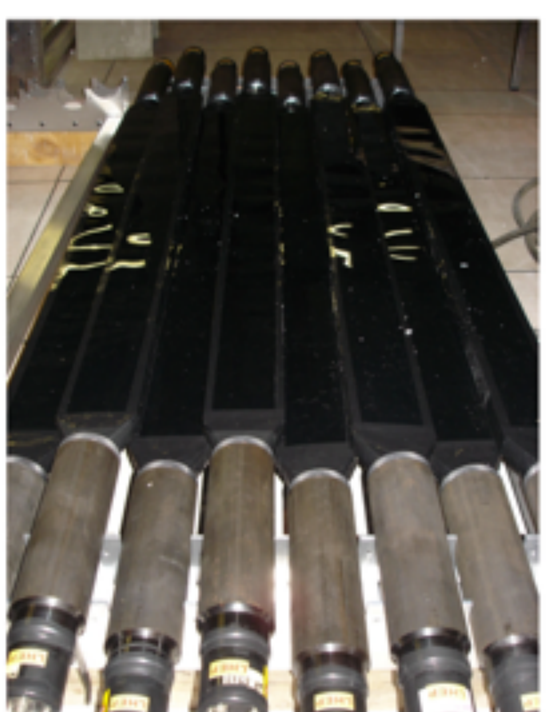
UZH and UniGe involved in the project

Challenges:
- Large area
- Required time resolution <100ps

SAINT-GOBAIN CRYSTALS	ELJEN	Light output	Wavelength	Decay const	Att. length
BC-404	EJ-204	68 %	408 nm	1.8 ns	1.6 m
BC-408	EJ-200	64 %	425 nm	2.1 ns	~4 m

NA61/SHINE, bars with PMTs

UniGe 2006

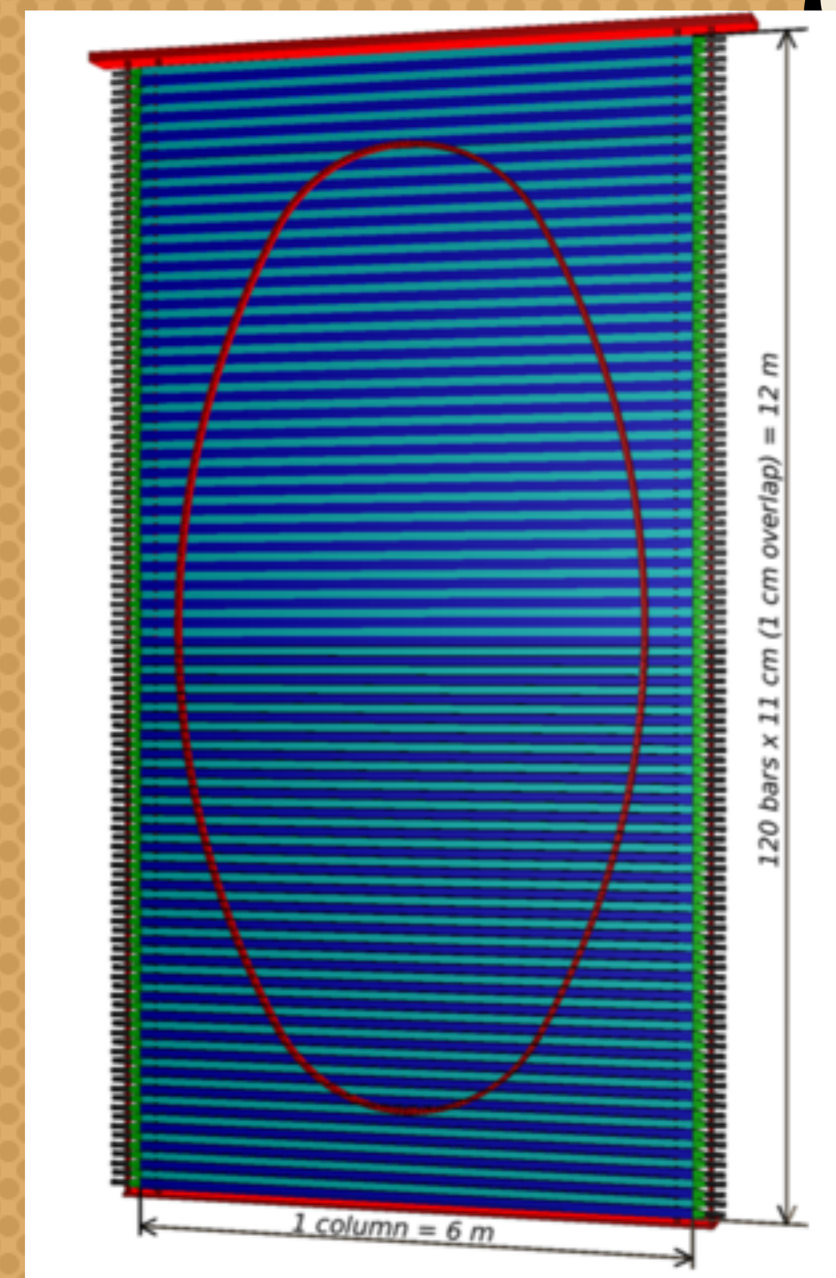


Energy loss in plastic: dE/dx_{min} = 2 MeV/cm, light yield: 10000 photons/MeV ⇒

for 2.5 cm bar: N_γ= 2.5 x 2 x 10k = 50 k

For long bar mainly those γ which have total internal reflection (θ >39°) are detected

NA61/SHINE ToF
- 100ps resolution in NA61/Shine ToF
- Size of scintillator counter 120x10x2.5 cm³
- Total active area 1.2x7.2 m²



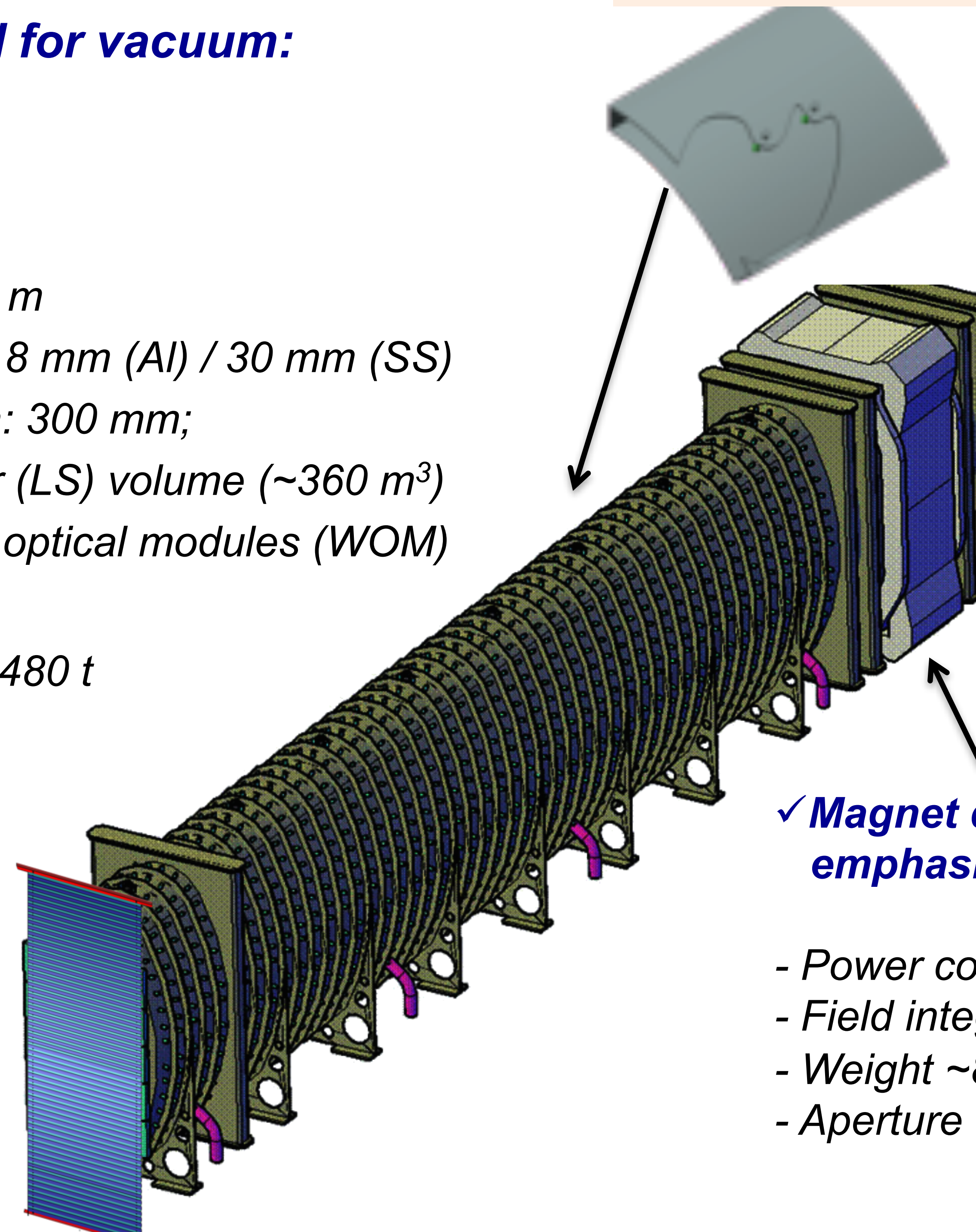
Muon Filter

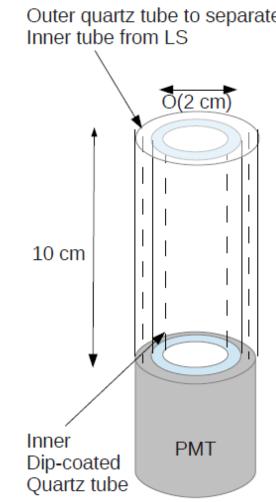
Decay volume and spectrometer magnet

- ✓ ***Estimated need for vacuum:***
  ~ 10^{-3} mbar

- ✓ ***Vacuum vessel***
  - *10 m x 5 m x 60 m*
  - *Walls thickness: 8 mm (Al) / 30 mm (SS)*
  - *Walls separation: 300 mm;*
  - *Liquid scintillator (LS) volume (~360 m^3) readout by WLS optical modules (WOM) and PMTs*
  - *Vessel weight ~ 480 t*

LS cell with WOMs



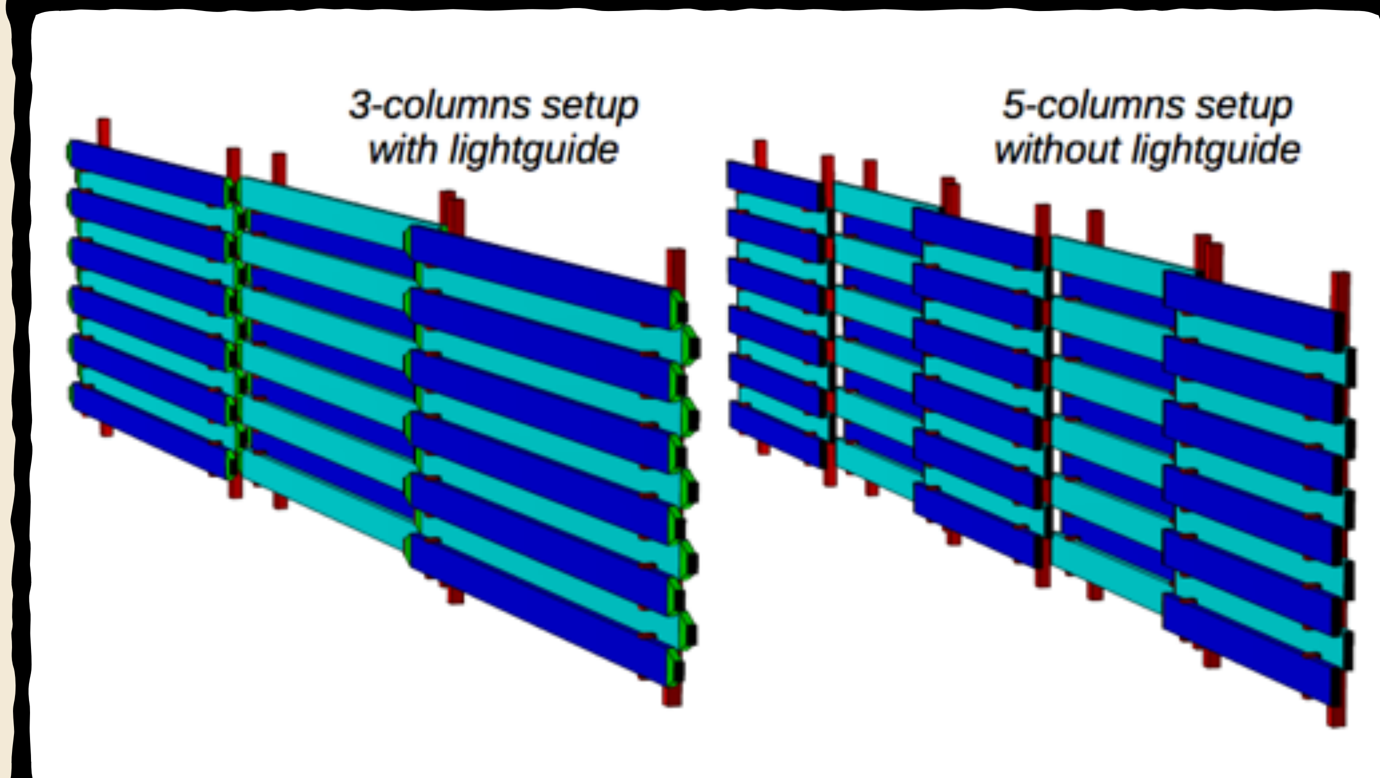


- ✓***Magnet designed with an emphasis on low power***
  - *Power consumption < 1 MW*
  - *Field integral: 0.65Tm over 5m*
  - *Weight ~800 t*
  - *Aperture ~50 m^2*

Timing Veto Detector

Various design under study

- 6m long bars read by PMTs
- Replace PMTs by SiPM
- Different possible designs



Strong Point of SiPM:

- Possible multi column setup
- No problem with the magnetic field
- No shadow for the CALO

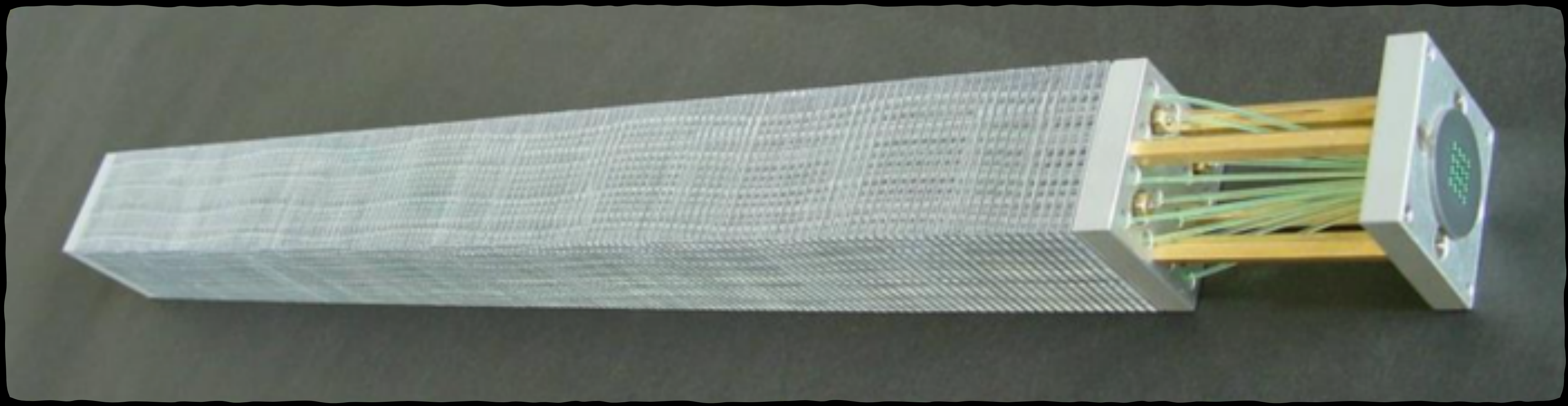
Challenges:

- Dark rate, typical value (Hamamatsu, C-series of sensL) is 100 kHz/mm2= 10 MHz/cm2

- Investigate whether we have enough photons to have sufficient time resolution

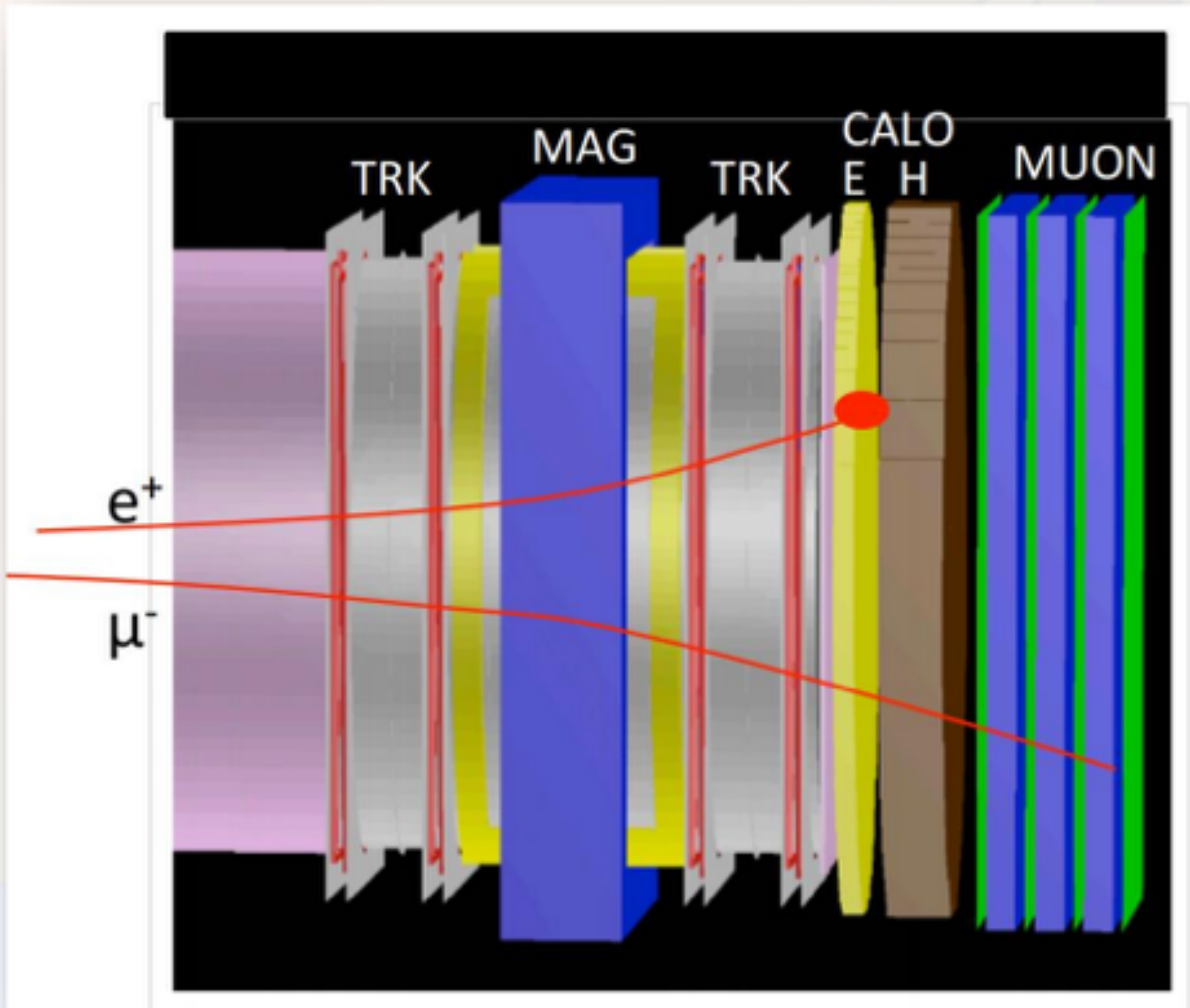
Calorimeter

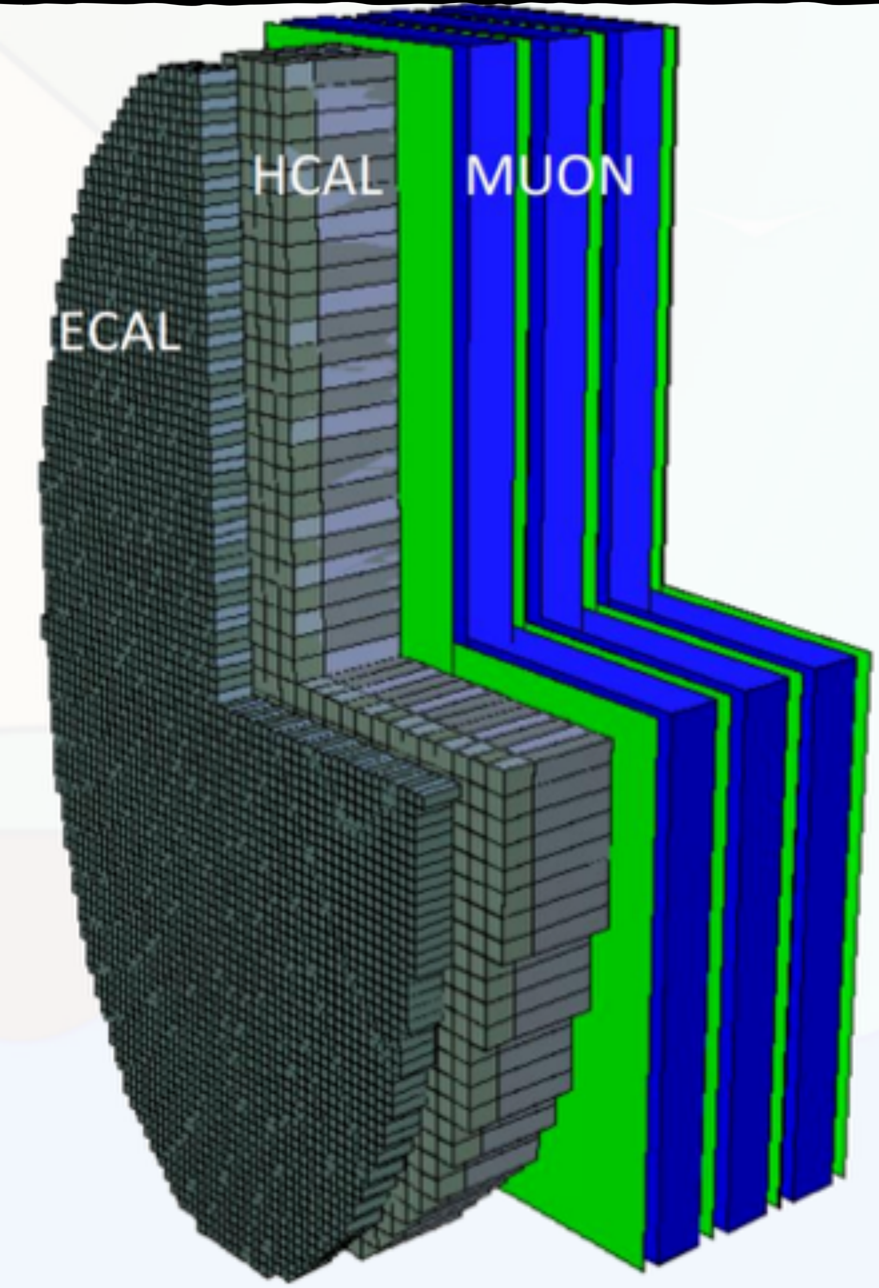
Based on spiral-fibre Shashlik module



Dimensions	38.2x38.2 mm^2
Radiation length	17.5mm
Moliere radius	36mm
Radiation thickness	22.5 X0
Scintillator/lead thickness	1.5mm/0.8mm
Energy resolution	$6.5\%/\sqrt{E} \oplus 1\%$

Calorimeter



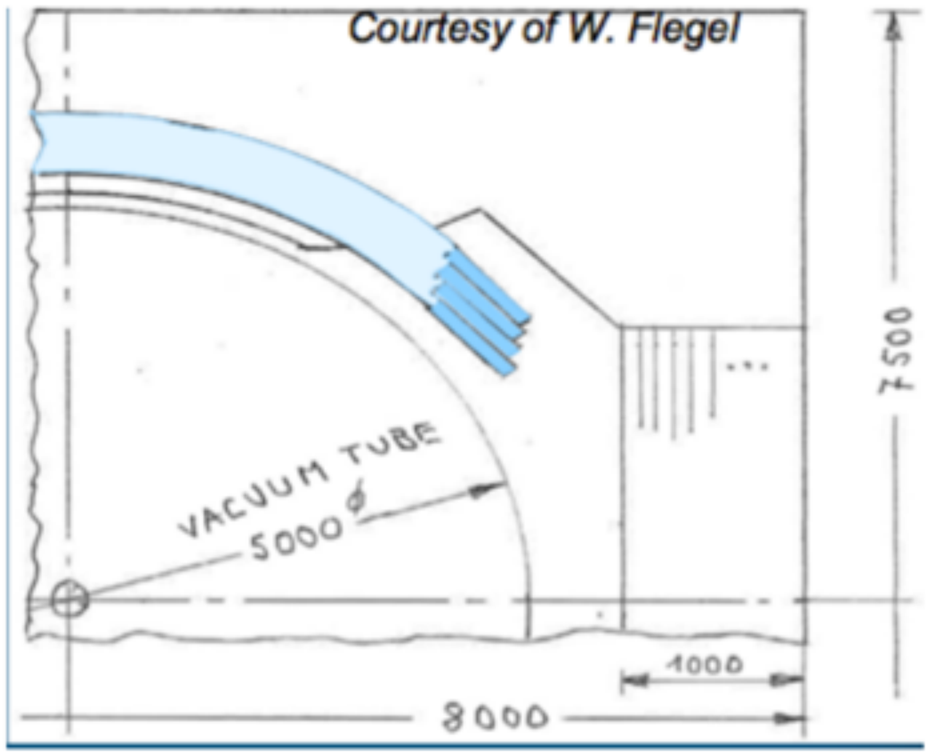


Magnet

- Dipole magnet similar to LHCb magnet, but with 40% less iron and three times less power

- LHCb: 4Tm and aperture of $16m^2$

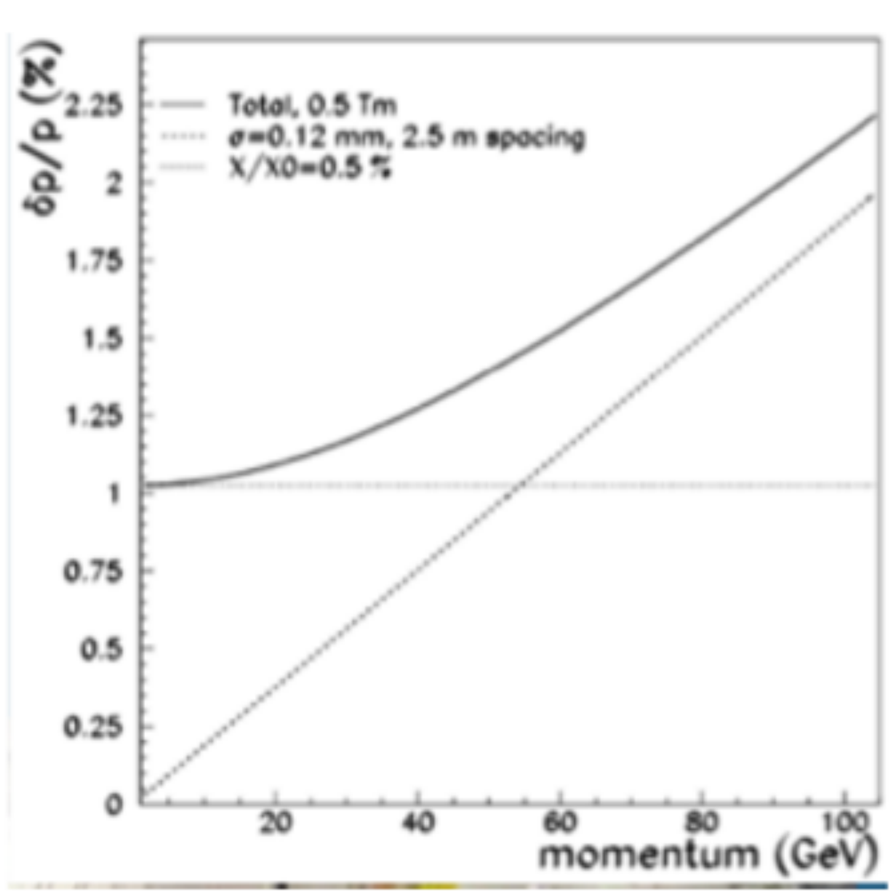
- This design:
  - aperture 20 m^2
  - Peak B-field 0.2T
  - Field integral 0.5Tm over 5m



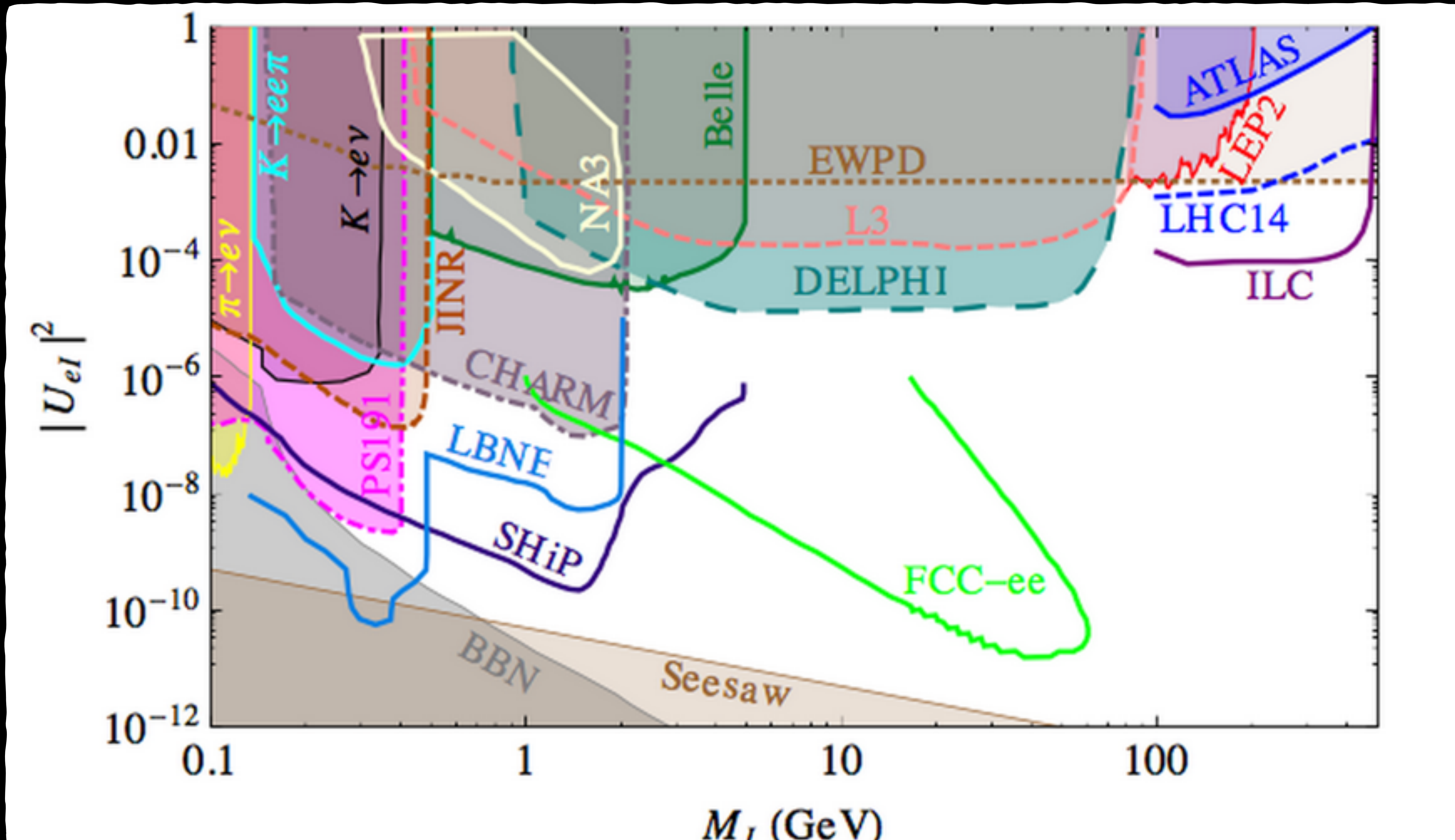
Tracker

Straw tubes similar to NA62 with 120um spatial resolution and 0.5% X_0/X

Main difference with Na62: 5m length, vacuum 10^{-2}mbar,



Sterile Neutrinos



Comparison with double beta