SHiP: a new facility for searching for long-lived neutral particles and studying the tau neutrino properties

Search for Hidden Particles

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on behalf of the SHiP collaboration

SHiP
Search for Hidden Particles

CERN

27th Rencontres de Blois, June 3rd 2015

Energy versus Intensity Frontiers

- **Experimental facts** of *Beyond Standard Model (BSM)* physics (neutrino masses, excess of matter over antimatter in the universe,…)

- **Theory motivations** for BSM physics (hierarchy problem, mass pattern,…)

Long-lived neutral (hidden) particles
are predicted in many BSM models.
We can look for them at:

Energy frontier :

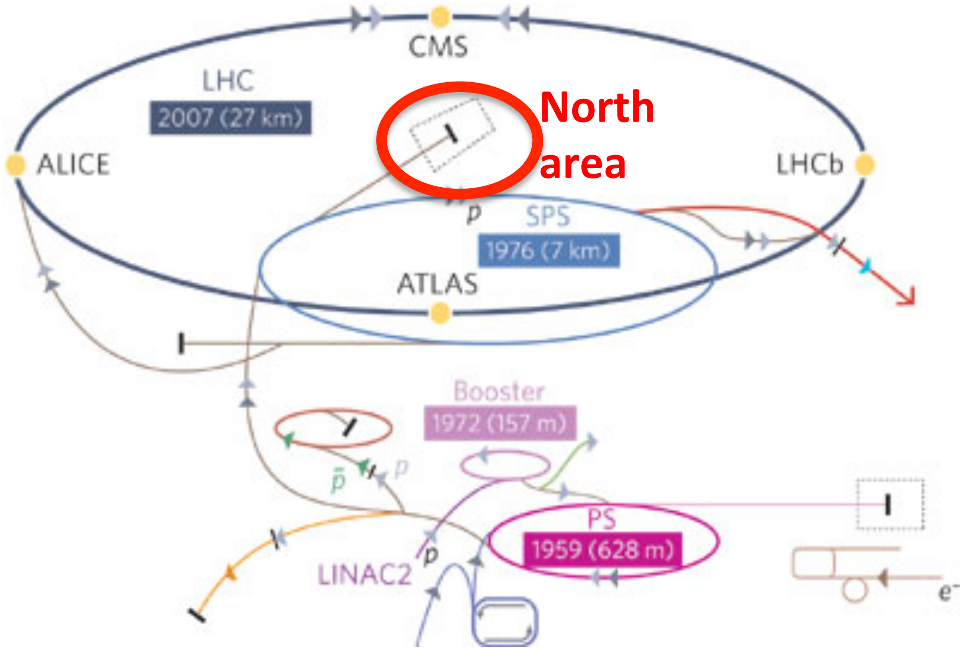
Heavy particles
→ look into **higher energy** events

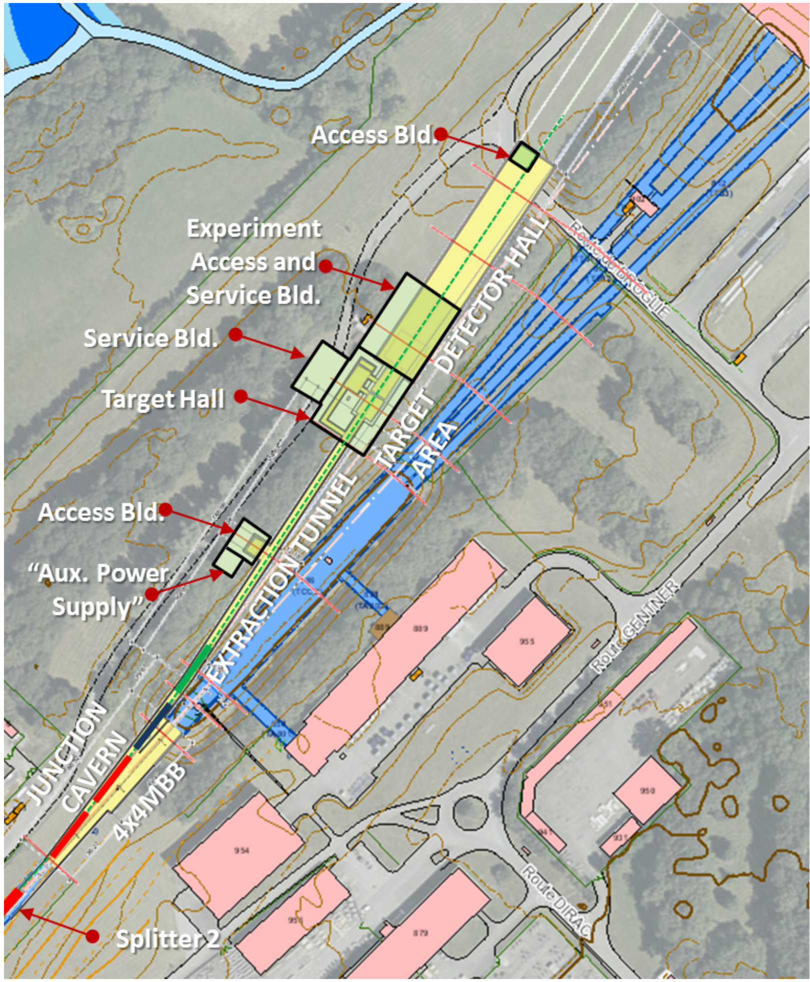
Intensity frontier :

Light particles
→ search for **rare** events associated with them

SHiP : masses below O(10) GeV

Proposal for a new facility at the SPS





- **400 GeV protons** from SPS, E_{CM}=27 GeV

Spill = 4×10^{13} protons on target per **cycle** of 7.2s with **slow beam extraction** (1s)

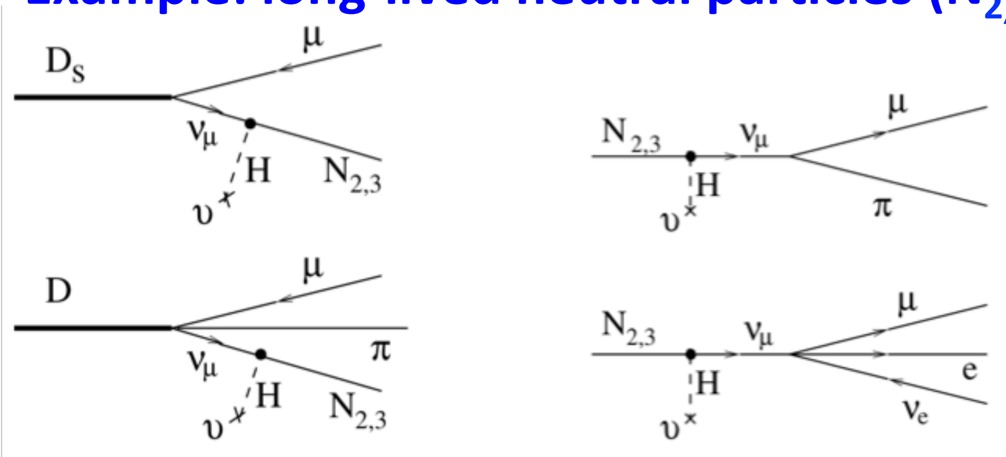
reduces **detector occupancy**, hence combinatorial background

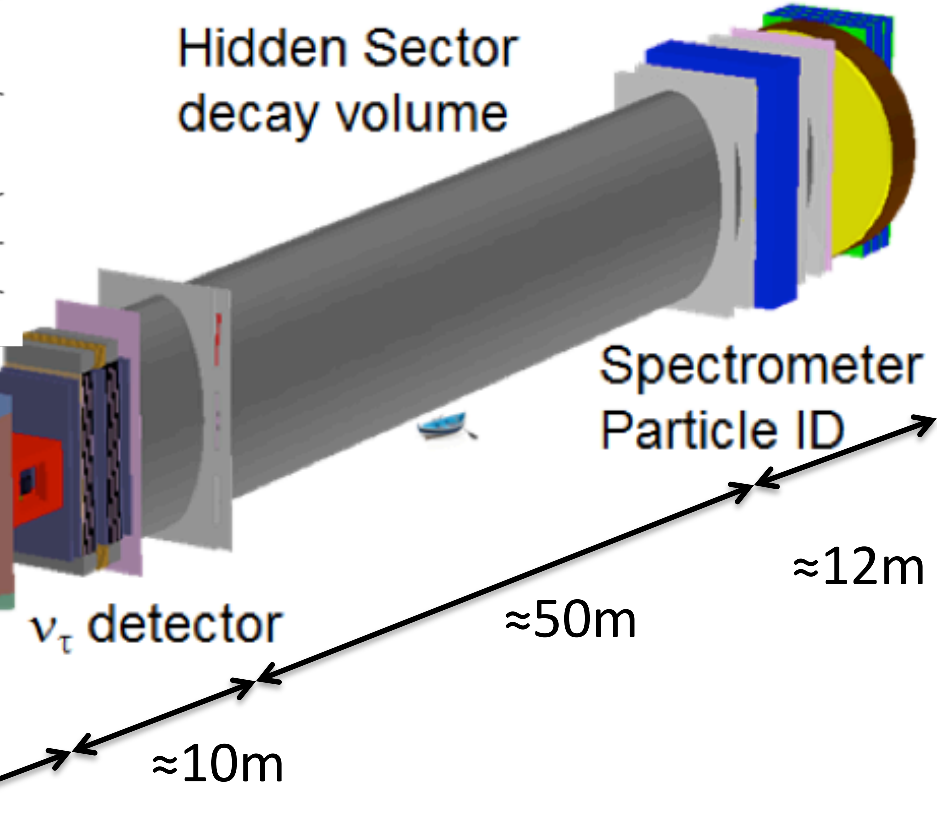
reduces **heat load of the target**

- **4×10^{19}** protons on target per year (~200 days of running)

The SHiP experiment

Example: long-lived neutral particles ($N_{2,3}$)

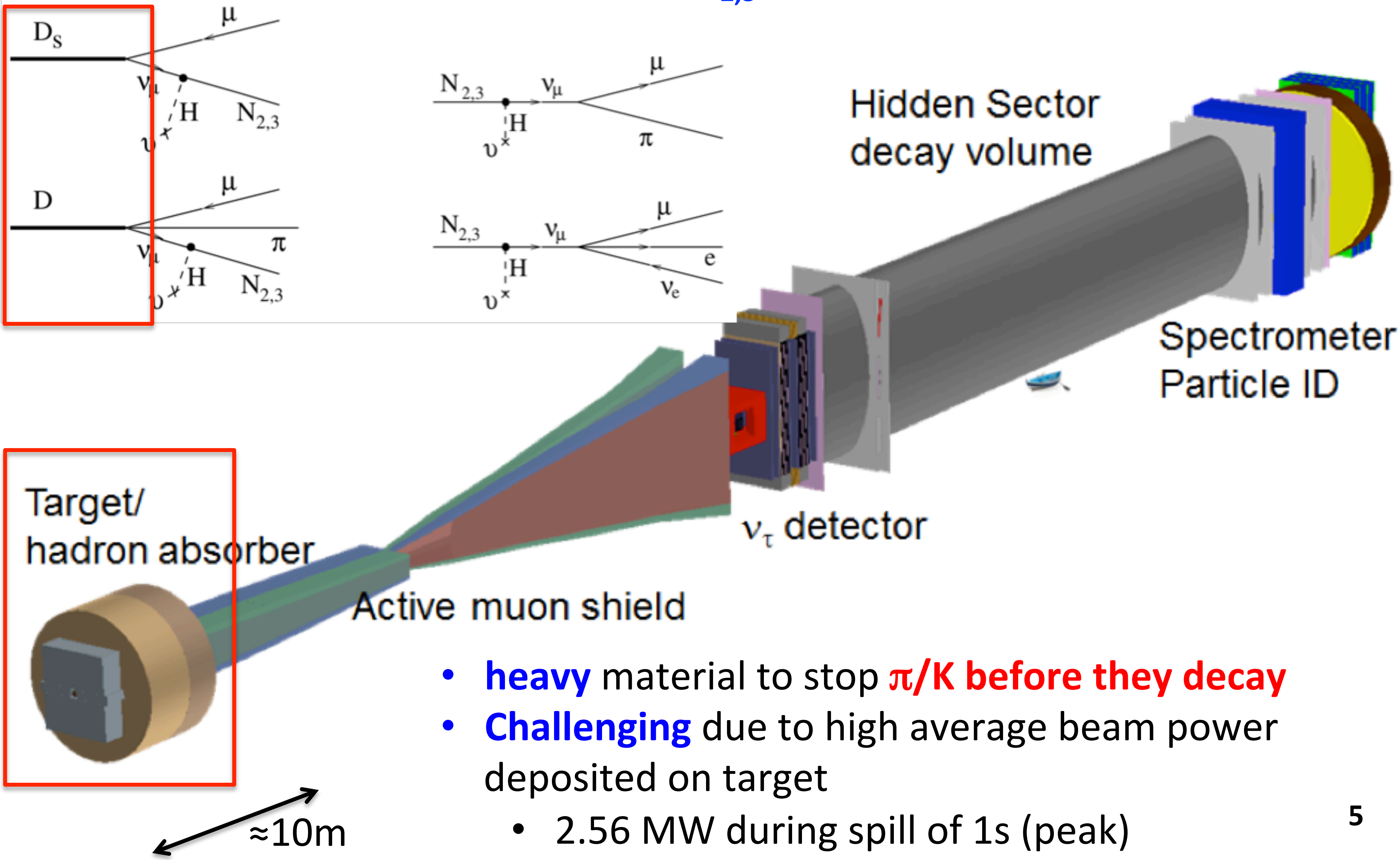




Designed as a **very low background** experiment → need for lots of **background veto systems**

The Target

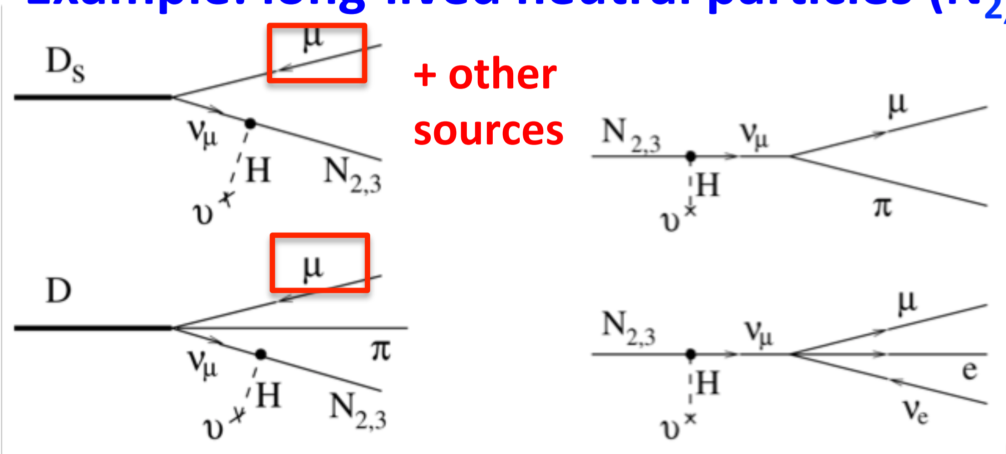
Example: long-lived neutral particles ($N_{2,3}$)

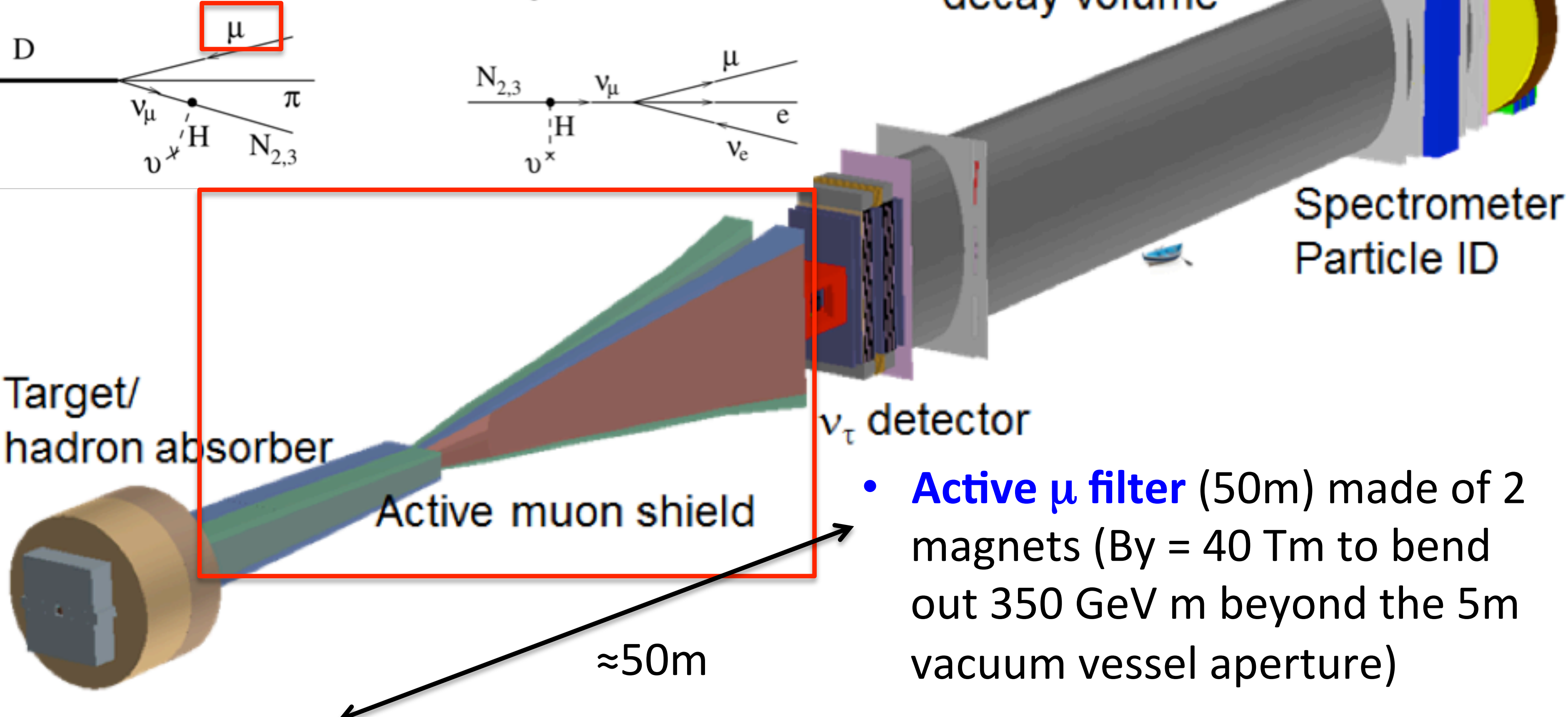


- **heavy** material to stop **π/K before they decay**
- **Challenging** due to high average beam power deposited on target
  - 2.56 MW during spill of 1s (peak)

The Muon filter

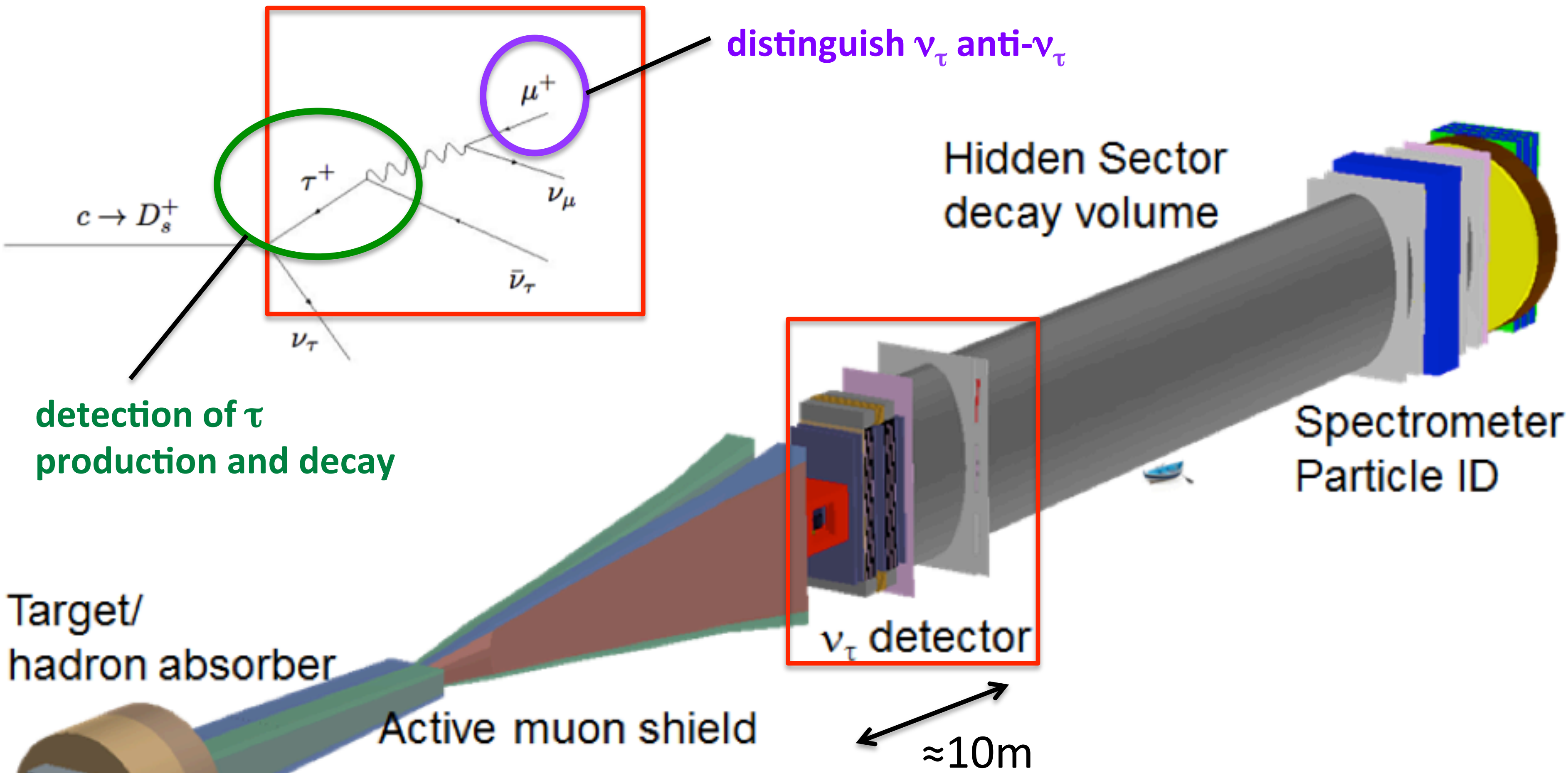
Example: long-lived neutral particles ($N_{2,3}$)





- **Active μ filter** (50m) made of 2 magnets (By = 40 Tm to bend out 350 GeV m beyond the 5m vacuum vessel aperture)
- **Reduce the μ flux** to <100k μ/spill

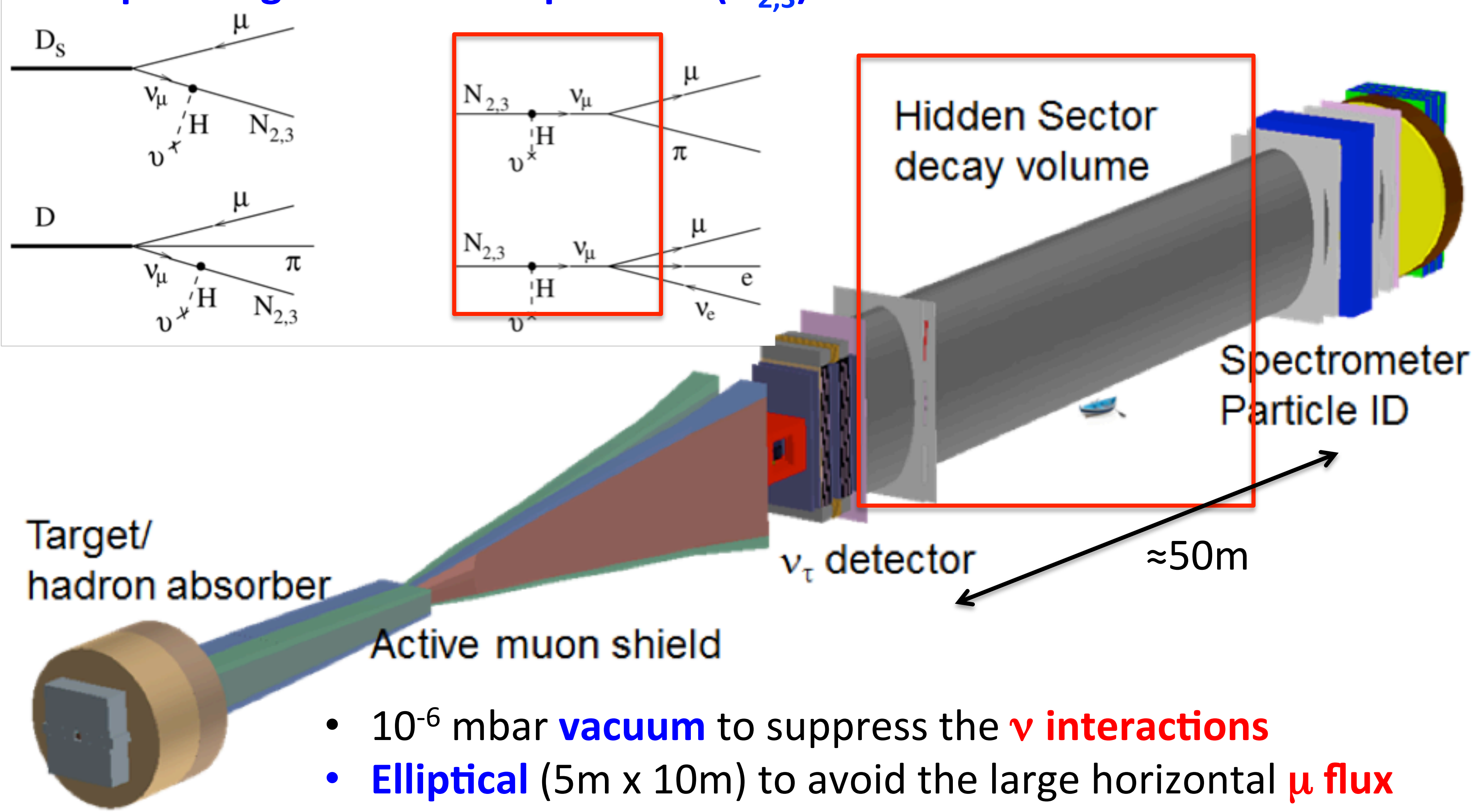
The ν_τ detector



- **OPERA-type** ν target in B-field
  - μ flux : 10^3 μ/mm^2 in 6 months
- RPC and drift tubes for μ measurements

The vacuum vessel

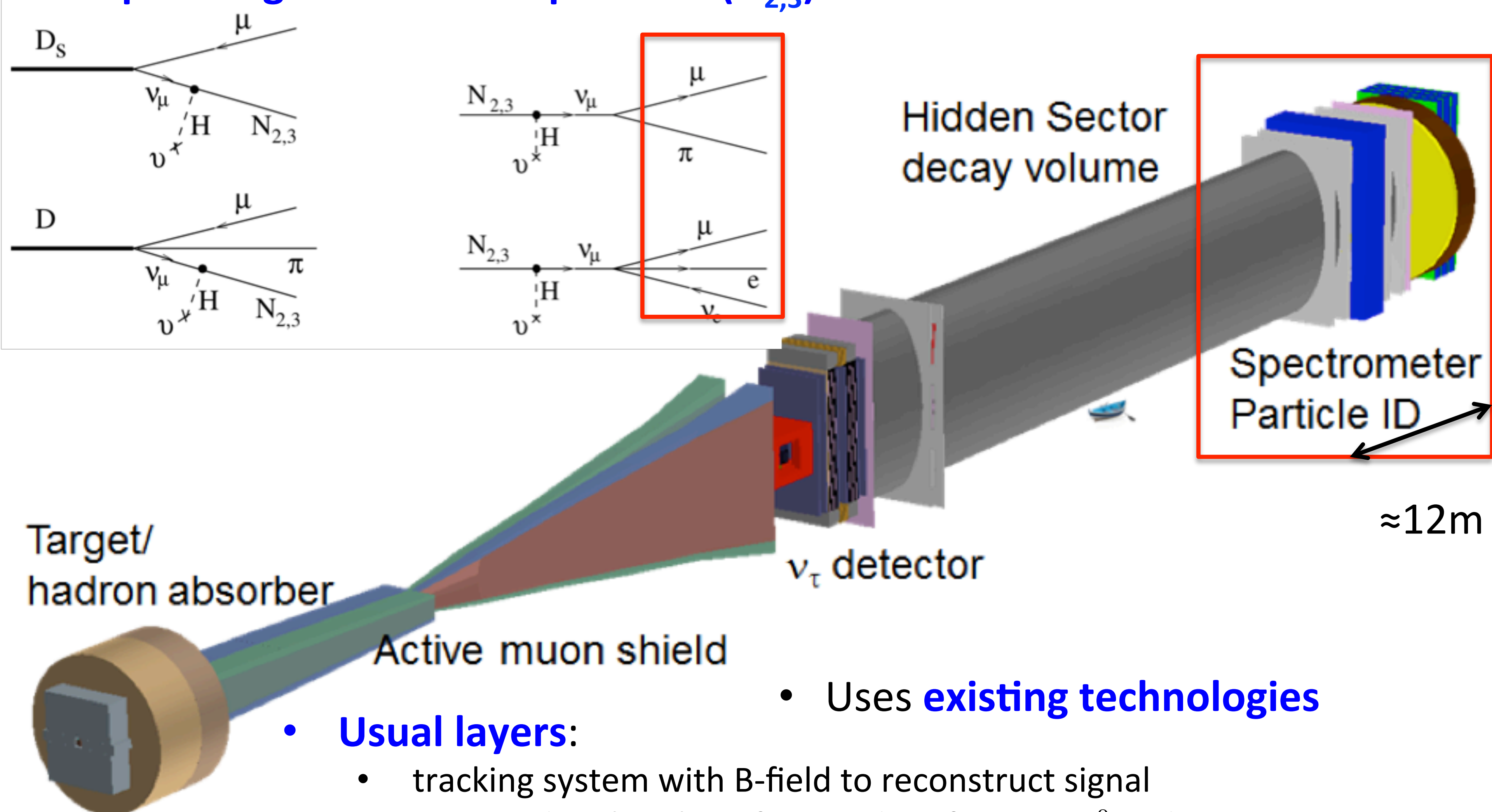
Example: long-lived neutral particles ($N_{2,3}$)



- 10^{-6} mbar **vacuum** to suppress the **ν interactions**
- **Elliptical** (5m x 10m) to avoid the large horizontal **μ flux**
- Double-wall structure, space filled with **liquid scintillator** to tag background entering **from the sides**

The spectrometer

Example: long-lived neutral particles ($N_{2,3}$)



- Uses **existing technologies**

- **Usual layers**:
  - tracking system with B-field to reconstruct signal
  - ECAL and μ-chambers for e/γ identification, π^0 and η reconstruction
  - HCAL for π/μ separation

Physics cases

- Before LHC Run1, the idea of **naturalness** was very popular: the *new physics scale must be close to the Higgs scale → possible scenarios*

LHC Run2 is sensitive to it **OR** **Intensity frontier facilities (SHiP)** are sensitive to it (scale of NP not always ≈ mass of new particles!) **OR** **No new** physics scale

SHiP can test this (example given later)

Portals = possible interactions between new physics (hidden sector) and the SM particles

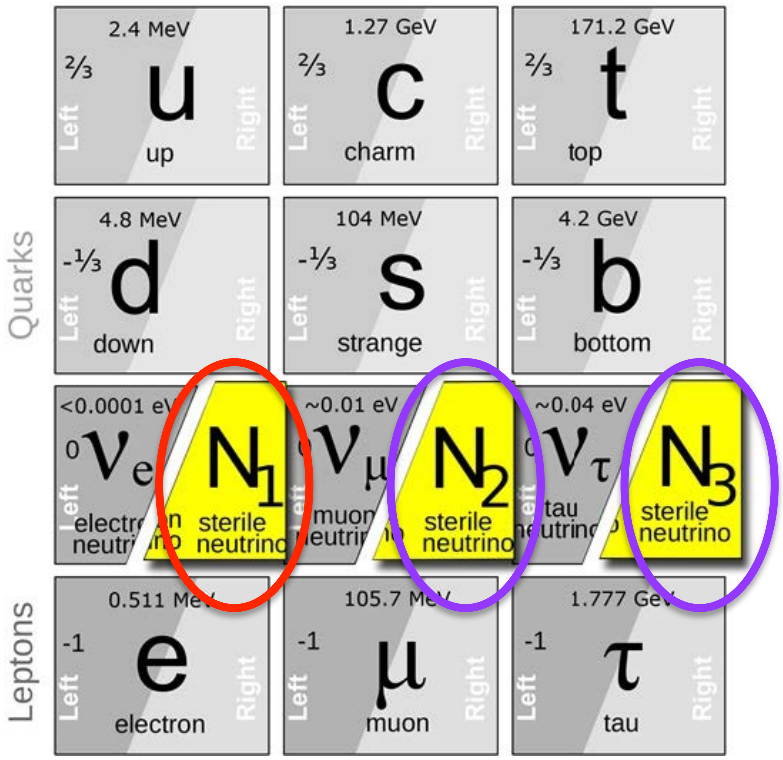
Vector portal **Scalar portal** **Neutrino portal** **Axion portal**

Beyond portals : **SUSY**

Models tested	Final states
Neutrino portal, SUSY neutralino	$l\pi$, lK, $l\rho$ ($l=e,\mu,\nu$) ($\rho^+ \rightarrow \pi^+\pi^0$)
Vector, scalar, axion portals, SUSY sgoldstino	e^+e^-, $\mu^+\mu^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-$, K^+K^-
Neutrino portal, SUSY neutralino, axino	$l^+ l^- \nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\ \pi^0$

The Neutrino portal

- Example of one BSM theory with no new physics between Fermi and Planck scales: the **νMSM** T. Asaka, M. Shaposhnikov, PL B620 (2005) 17



$N_{1,2,3}$ = heavy neutral lepton (HNL), heavy (RH) neutrinos, sterile neutrinos,…

N1 is a dark matter candidate (m≈O(1) keV)

- Compatible with XMM-Newton emission line at E≈3.6 keV

Astrophys.J.789, 13(2014), Phys.Rev.Lett. 113,25301

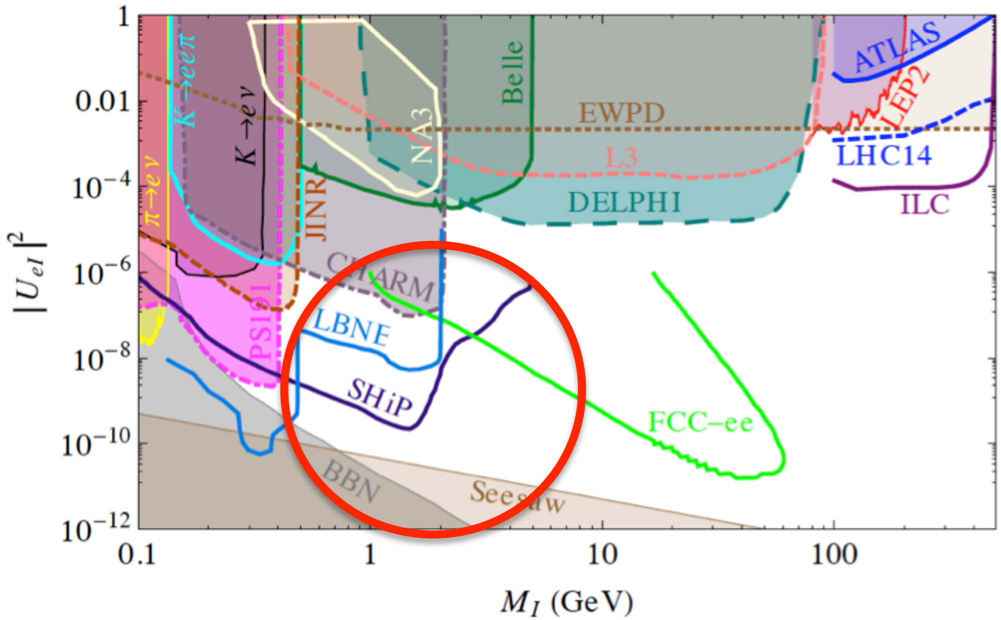
N2,N3 give masses to neutrinos and produce baryon asymmetry of the Universe (m≈O(100) MeV – GeV)

The Higgs gives masses to quarks, leptons, Z and W, and it inflates the Universe

The Neutrino portal

- The SHiP limit are set **on $N_{2,3}$** (N_1 is the dark matter candidate)

Coupling of the HNL to the SM particles →



- The region **above the kaon mass** is not yet well covered and **SHiP has the best sensitivity reach**

$M_K \approx 0.5$ | $M_D \approx 2$ | $M_Z \approx 91$ | M_N [GeV]

Impressive limits from **PS-191**

D and B decays

LHCb, BELLE

SHiP has the **best** sensitivity reach

$Z \to N\nu \to (\ell + 2\text{jets})\nu$

L3, DELPHI

Best explored at **FCC e^+e^-** mode

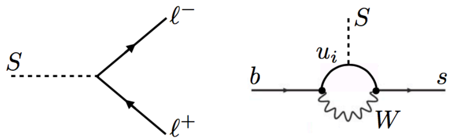
$pp \to W^* \to N\ell^\pm \to \ell^\pm \ell^\pm jj$

ATLAS/CMS

ATLAS/CMS in **HL-LHC**

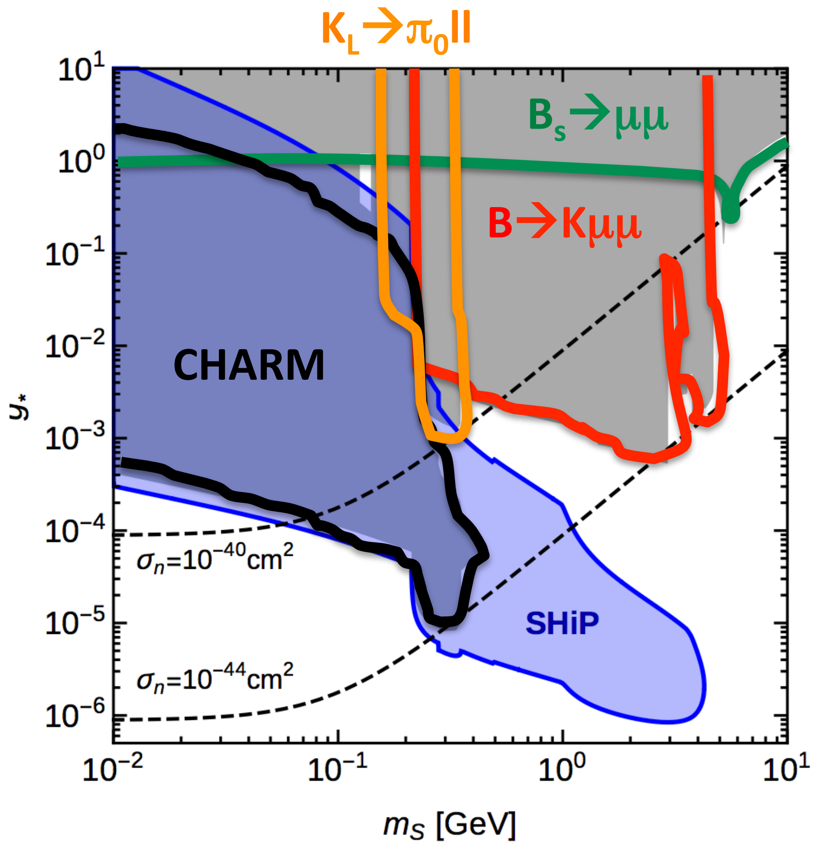
The Scalar and Vector portals

Scalar portal :



S production : from B, D and K decays

S decays : S→ee,μμ,ππ,KK

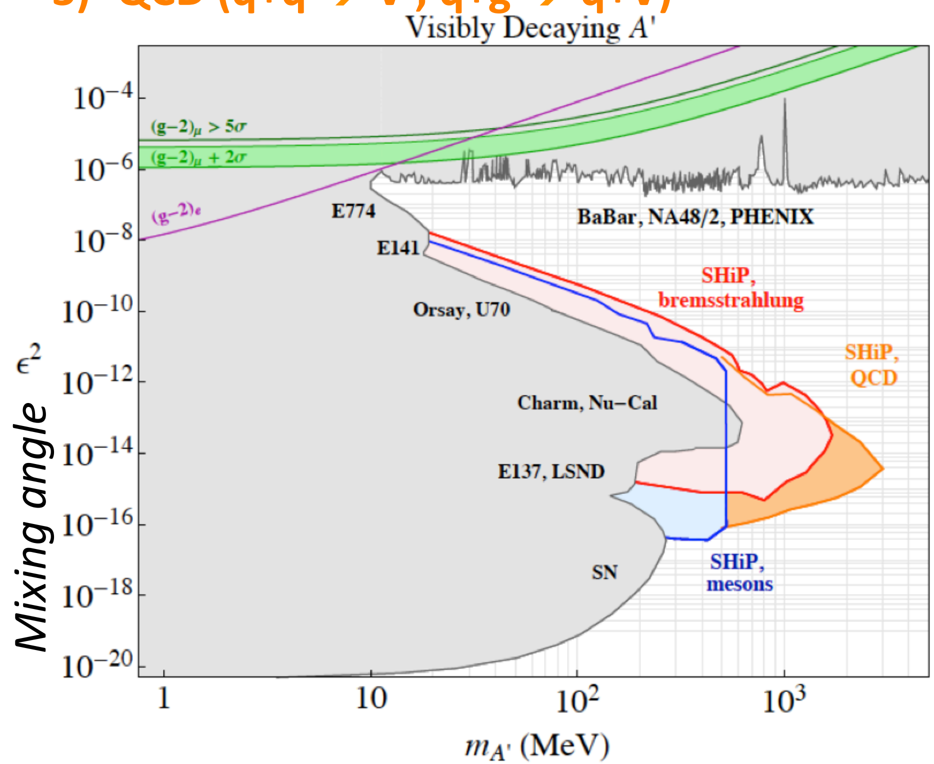


SHiP will give insights for **masses < 10 GeV** and small couplings

Vector portal : dark photon (A') model

Production :

1) **Meson decays**
2) **Bremsstrahlung (pp→ppV)**
3) **QCD (q+q → V ; q+g → q+V)**



SHiP will give insights for **masses > 200 MeV,** up to **3 GeV**.

ν_τ physics at SHiP

- **ν_τ observations**
  - DONUT (Tevatron) : 9 events (from charm) with 1.5 backgrounds
    - Not possible to distinguish the charge of the τ
  - OPERA (Gran Sasso) : 4 events with 0 bakground
    - from $\nu_\mu \rightarrow \nu_\tau$ oscillations, only τ^- leptons

  → SHiP would increase **by three orders of magnitude** the current ν_τ sample, allowing for cross section measurements at **inclusive** and **differential** levels

- The anti-ν_τ has never been observed
  - SHiP could **observe the anti-ν_τ** by detecting the τ^+ lepton produced

- Structure functions **F4 and F5** in ν_τ and anti-ν_τ charged current cross sections can be measured (deep inelastic scattering)
  - At incident energy E=20 GeV, these terms account for 30% of the cross section

Timescale

Operation :

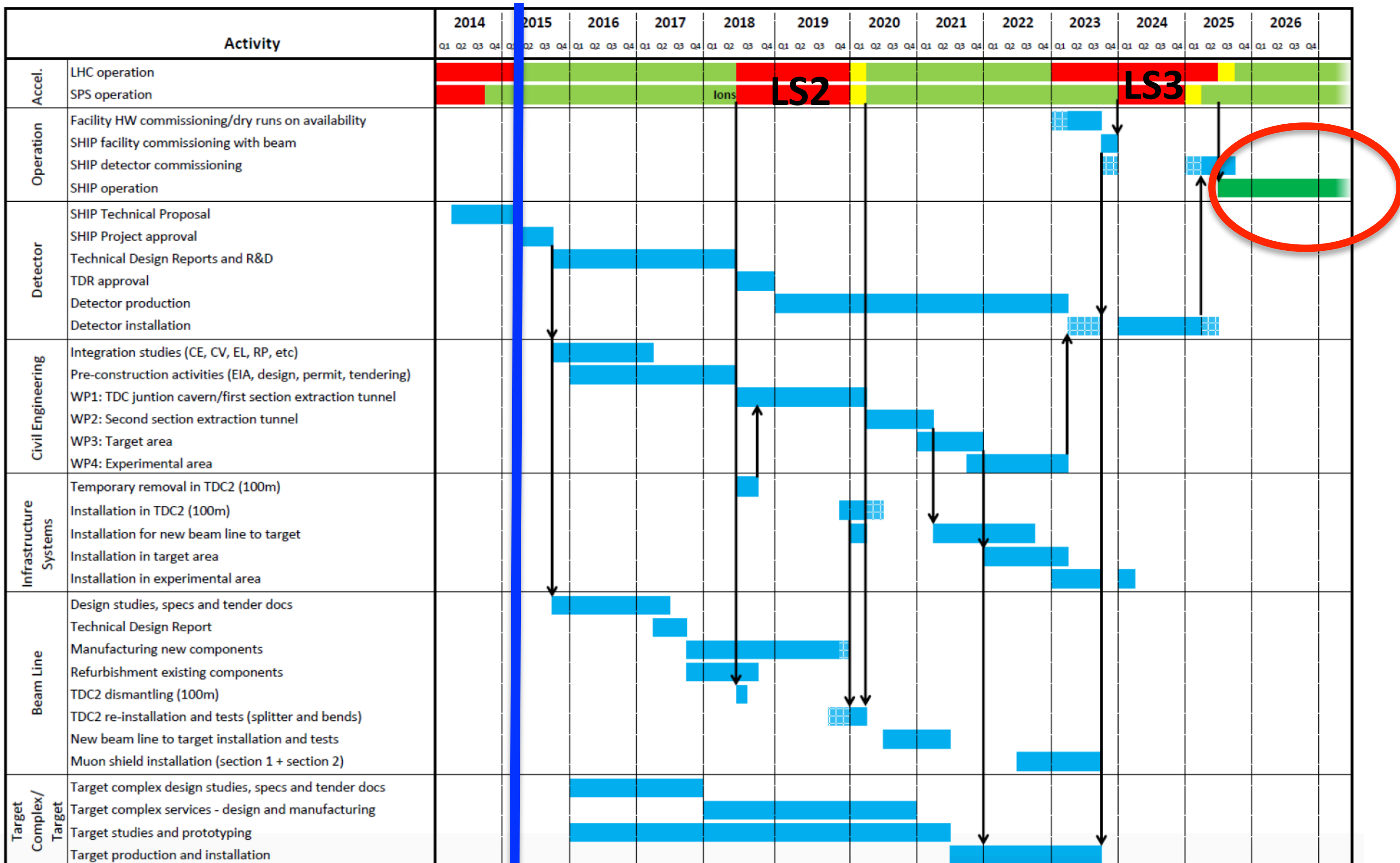
Detector :

Civil Engineering :

Infrastructure system :

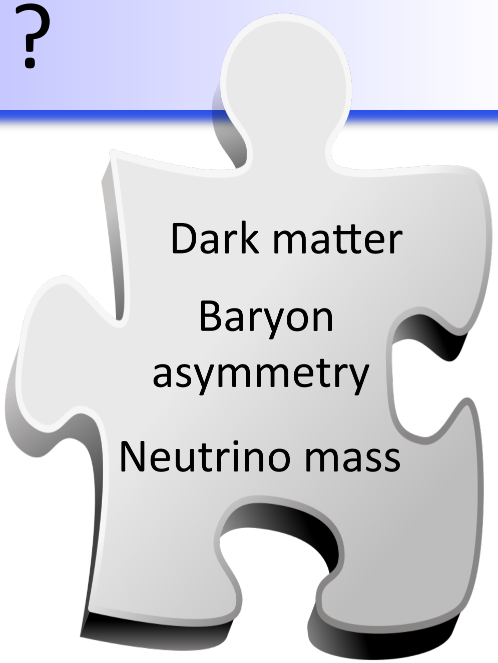
Beam line :

Target :



- CERN decision on the strategy with SHiP **within a year**
  - Weeks of **test beam** planned on SPS and PS this year to test detector technologies
- **10 years** from submission of Technical Proposal to data taking
- 5 years of data taking (**from 2025**) of **2×10^{20} protons on target**

Why signing up for SHiP ?



- could explore **with unprecedented sensitivity** phase spaces of "Beyond the Standard Model" physics that are of greatest interest in light of the LHC and astrophysical results, for example **heavy neutral leptons with masses below O(10) GeV**

- could provide important results **in the ν_τ sector**

- is rather **low-cost**

uses **existing** detector technologies

recycles material (Goliath magnet)

- takes the **lifetime** of a Swiss passport to become real !

45 institutes in SHiP

> 80 theorists

The crew members

The SHiP Collaboration

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A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case

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arXiv:1504.04956v1 [physics.ins-det]

arXiv:1504.04855v1 [hep-ph]

Physics case is >200 pages long !

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Back-Up Slides

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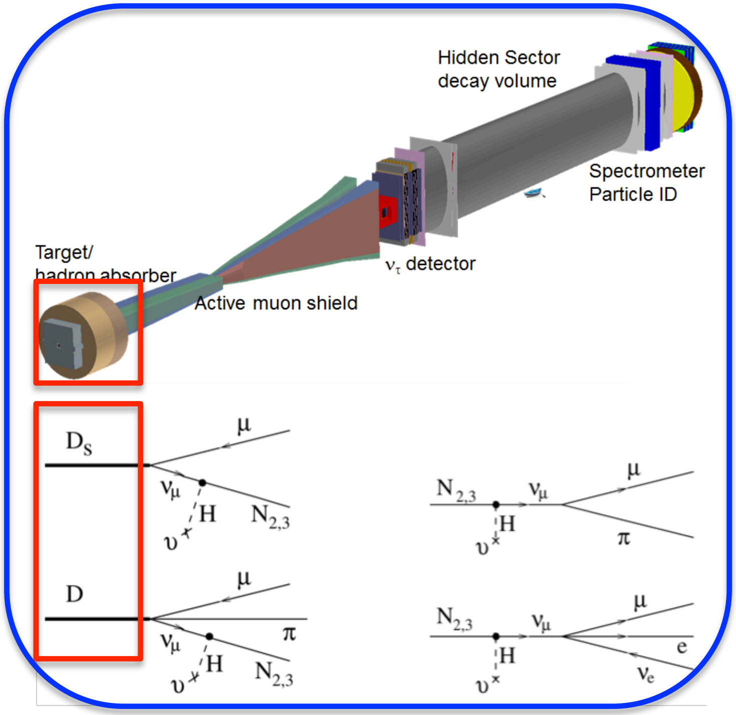
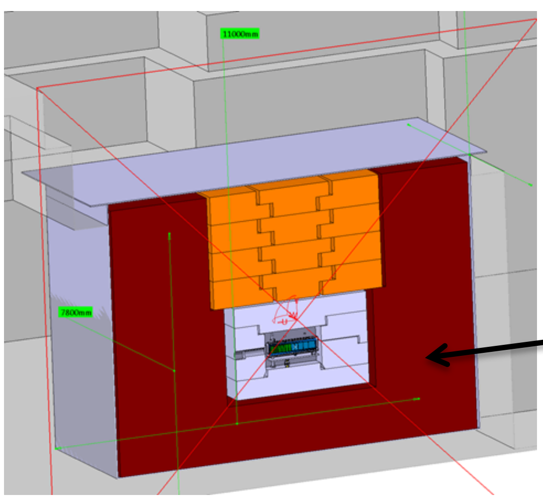
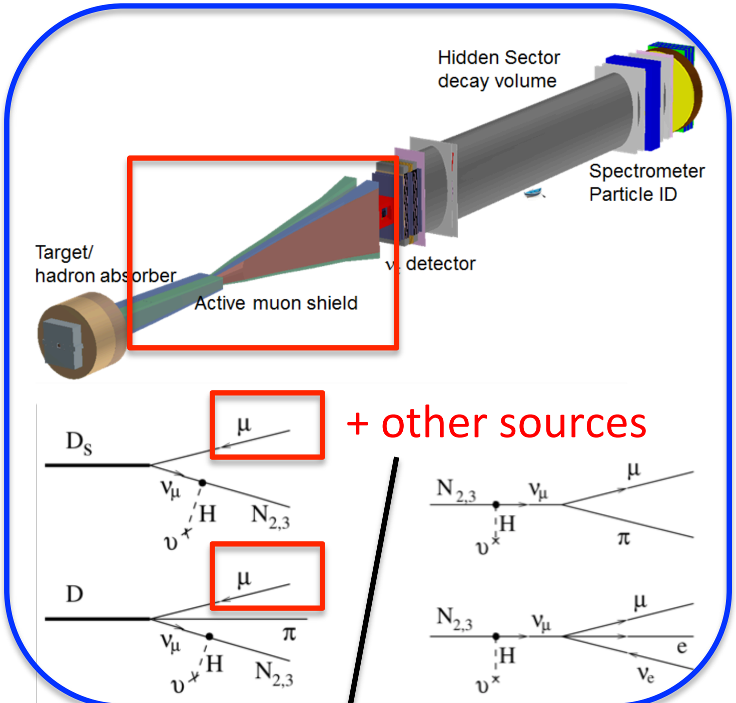
The target





- **Challenging** due to high average beam power deposited on the target
  - 2.56 MW during spill of 1s (peak)
  - ~350 kW averaged over 7s cycle
- **Hybrid** target, water cooled
  - 58cm of titanium-zirconium doped molybdenum
  - 58cm of pure tungsten, water cooled
  - **heavy** to **stop π/K before they decay**
- ~1.2m-long, 30x30cm^2 to **maximize shower containment**
- Embedded in **cast iron bunker** (440m^3)

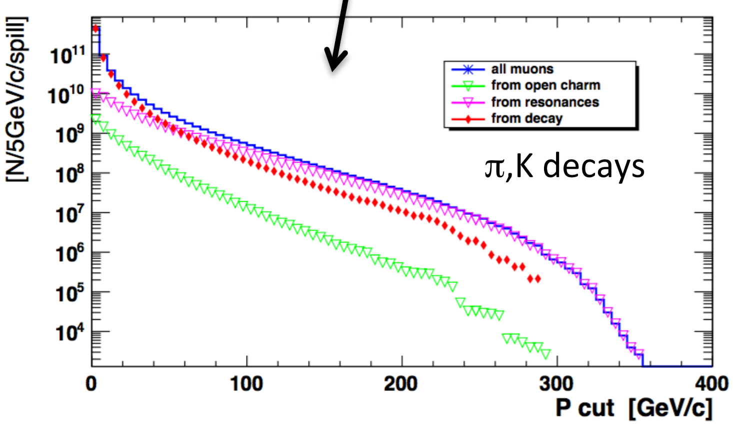
The muon filter

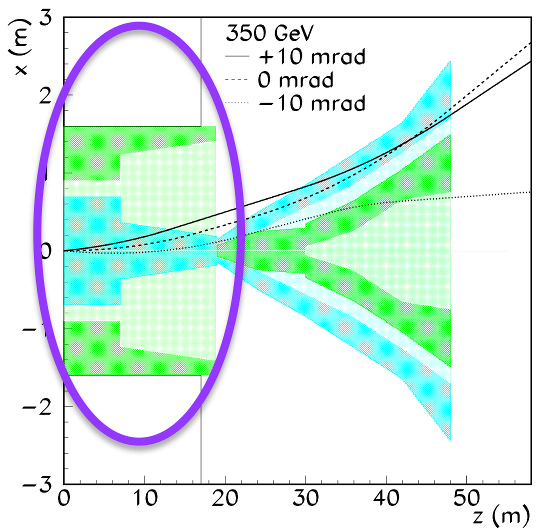


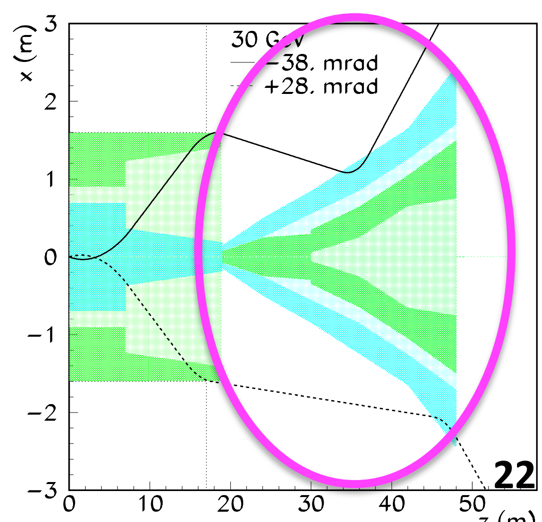
- **Reduce the μ flux** to <100k μ/spill (also to reduce **occupancy** in the ν_τ detector)
- **Active** μ filter (50m) made of **2 magnets** (B_y = 40 Tm to bend out 350 GeV μ beyond the 5 m vacuum vessel aperture)

1st part to separate μ^+/μ^- :

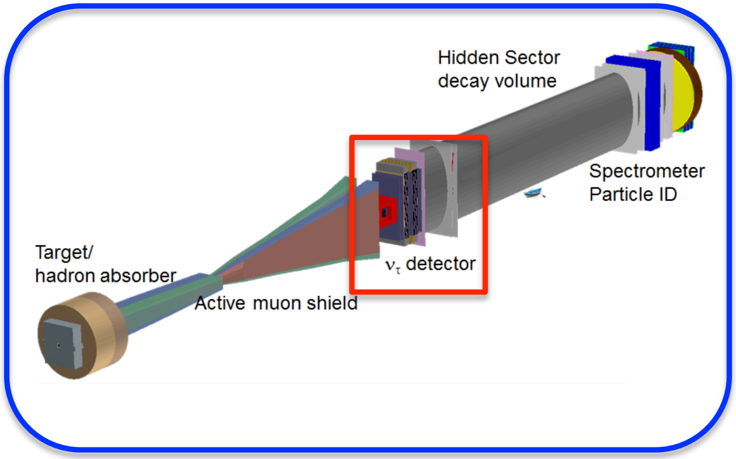
2nd part to remove the μ bent back by the return field :



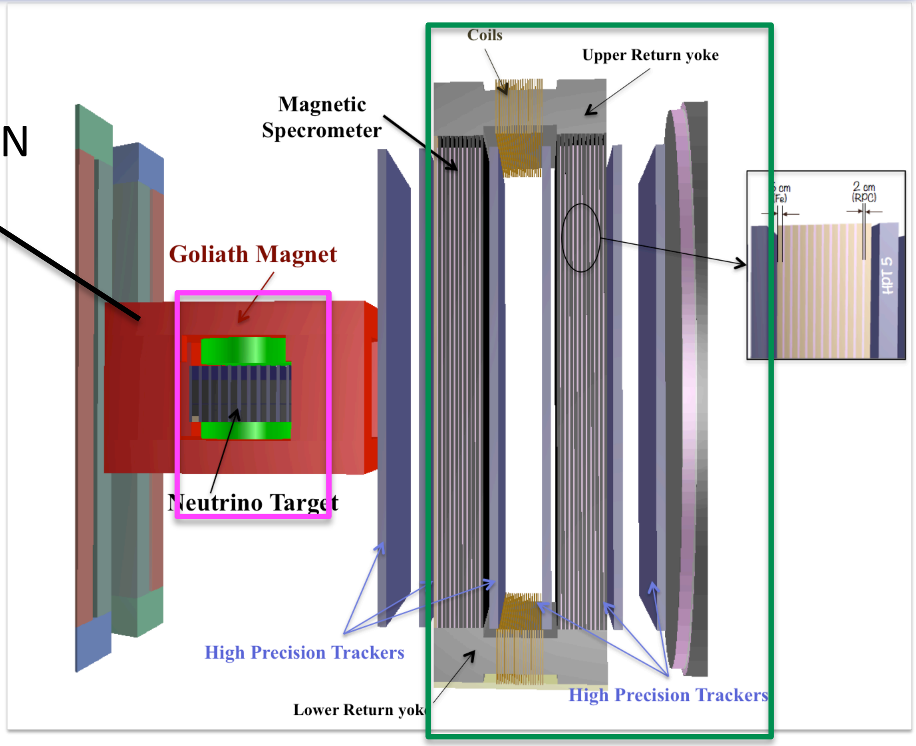




The ν_τ detector



from CERN H4 beam line



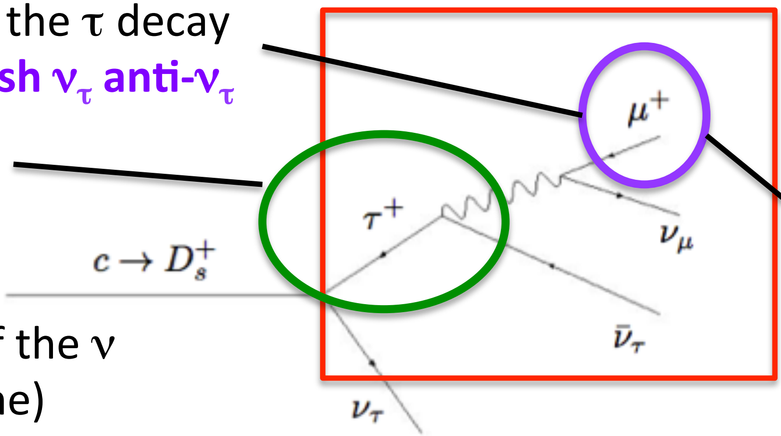
OPERA-type modules in B-field

- lead and emulsion cloud chambers
- 1x1m, close to the beam line
- μ flux : 10^3 μ/mm^2 in 6 months

look at the **charge** of the τ decay products to **distinguish ν_τ anti-ν_τ**

detection of τ production and decay to identify a ν interaction:

(contained within a brick of the ν target due to short τ lifetime)



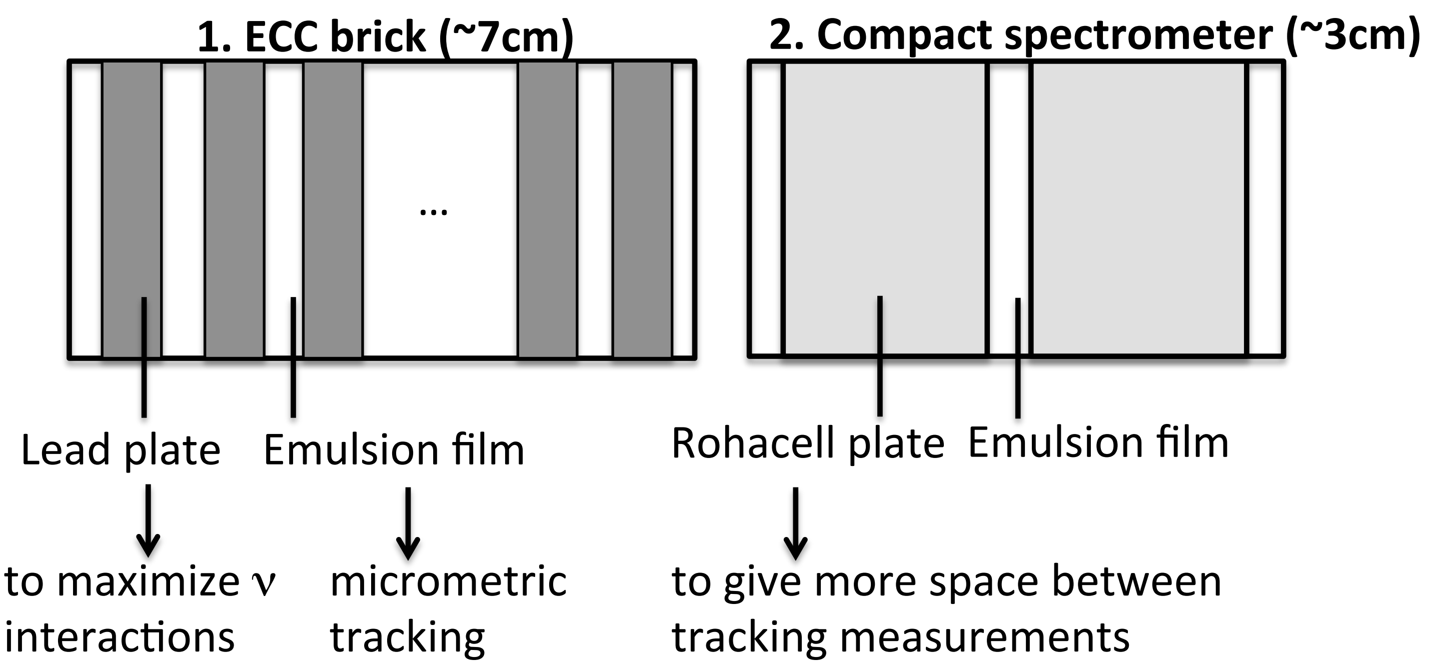
RPC and drift tubes :

Identify μ coming from τ decays; μ momentum measurement

The ν_τ detector : target

OPERA-type modules (emulsion cloud chambers (ECC))

- A unitary cell of the neutrino detector has two parts :

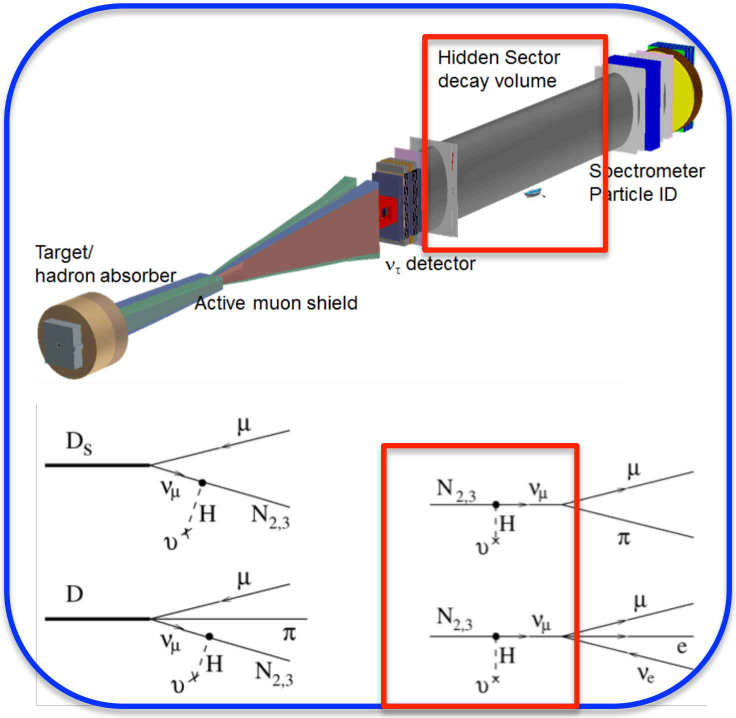


ν interaction : identified through **detection of τ production and decay** (contained within a brick due to short τ lifetime)

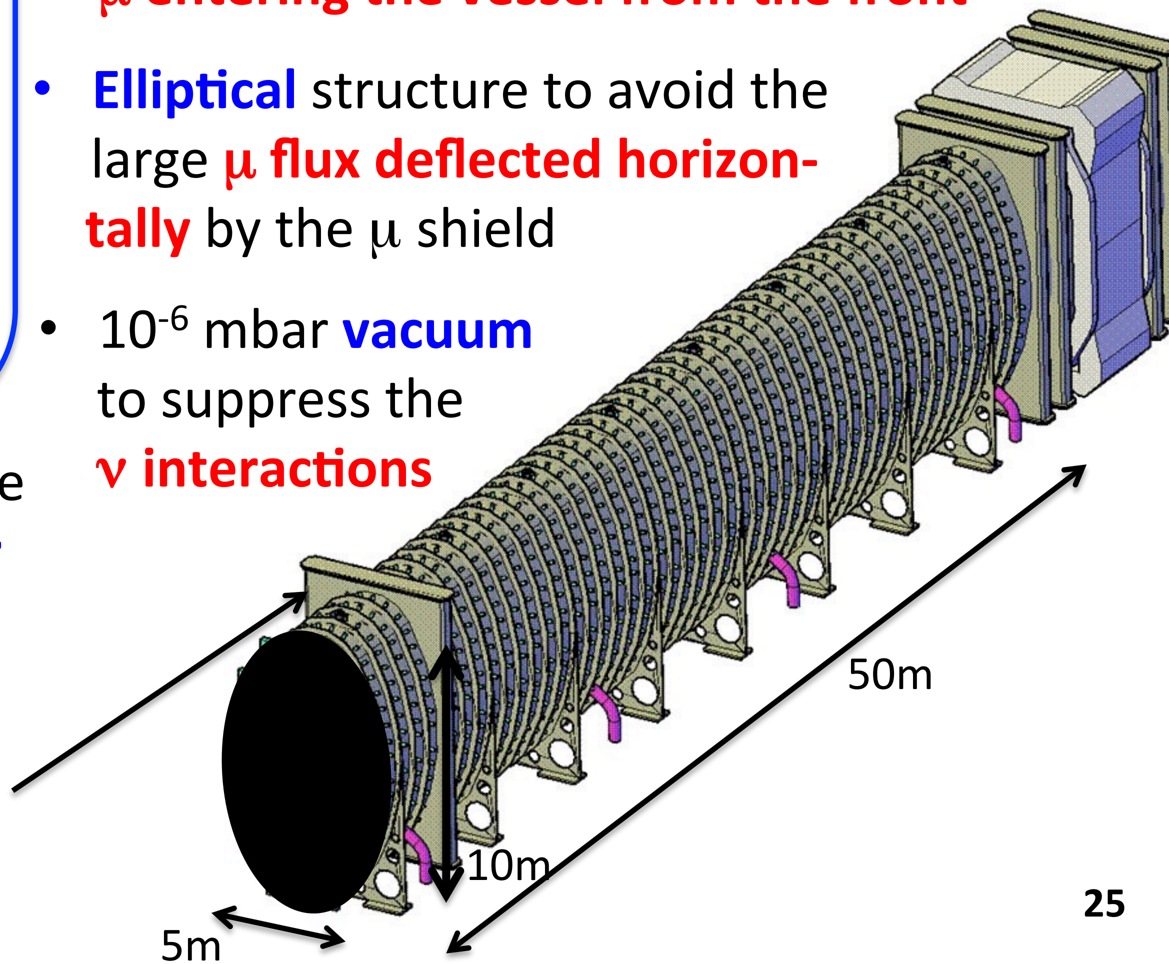
distinguish ν_τ anti-ν_τ : look at the **charge of the τ decay** products

- hundreds of target units assembled together to achieve the ton scale for a very high resolution device

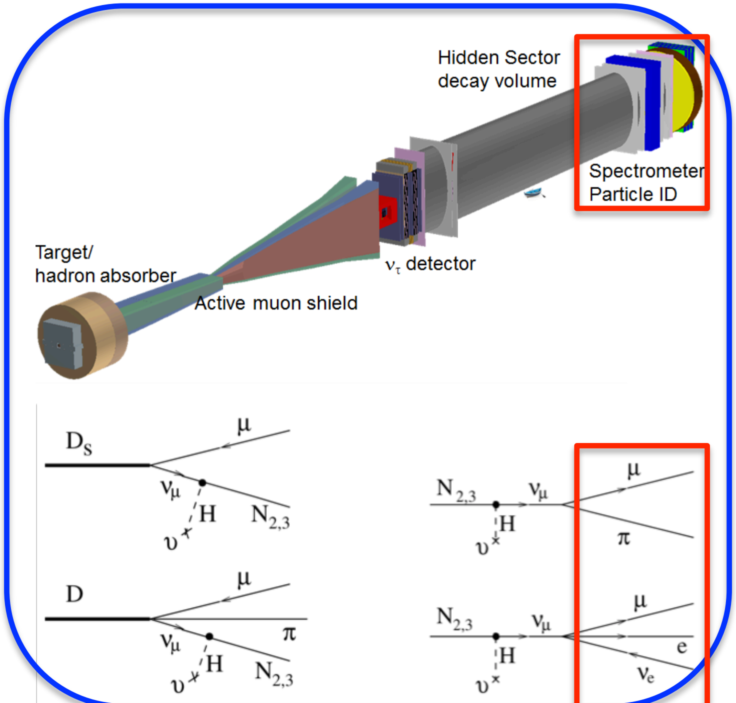
The vacuum vessel

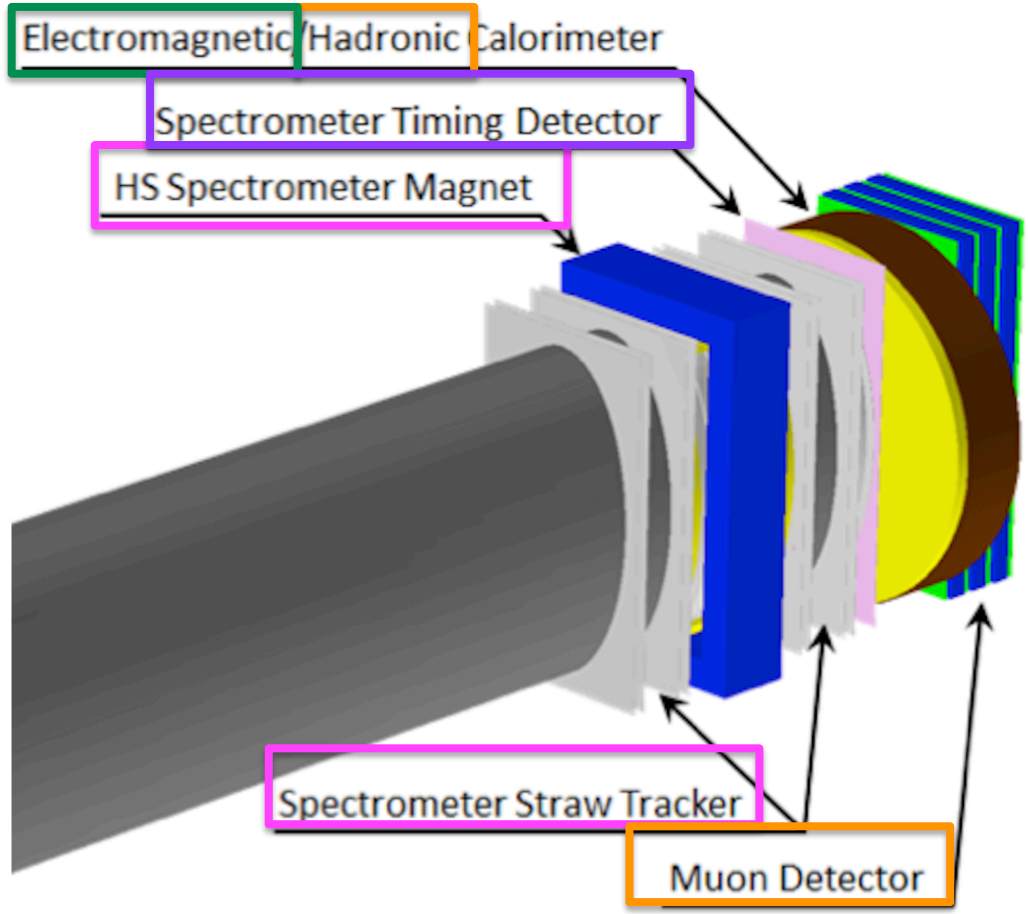


- **Veto tagger** just after ν_τ detector to tag indirectly **neutral K** produced by ν and μ interactions in the passive material and **μ entering the vessel from the front**
- **Elliptical** structure to avoid the large **μ flux deflected horizontally** by the μ shield
- 10^{-6} mbar **vacuum** to suppress the **ν interactions**
- Double-wall structure, space filled with **liquid scintillator** to tag background entering **from the sides**
- tracking detector to reject residual charged bkg **in the forward region (K_s^0,..)**



The spectrometer





Signal reconstruction and background rejection: warm magnet (LHCb) with 0.65Tm bending power; tracker (NA62) with horizontal straws and stereo angle

Veto anti-coincidence from combinatorial : timing detector (50ps resolution)

e/γ identification, π^0 and η reconstruction: ECAL (Shashlik (sampling scintillator-lead structure read out by plastic WLS fibres), LHCb)

π/μ separation : hadronic calorimeter (similar technology as ECAL), muon detector (WLS fiber bars, MINOS)

Vector Portal

- Existence of new vector states associated with new U(1) gauge groups : SU(3) x SU(2) x $[U(1)]^n$
- LHC : strong limits provided that the coupling to the SM is large
- Light vector states (GeV) with small couplings to SM not well constrained
- Motivation: could provide solution to m g-2 discrepancy, explain the strong emission of 511 keV photons from the galactic bulge, also explain the observation of the rise in the positron flux as a function of energy.

ALPS at SHiP

- Motivations for **axions** :
  - Particle that can solve the **strong CP problem of QCD**
- Large spontaneous symmetry breaking scale f_A
  - → small couplings
  - → small mass m_A proportional to $1/f_A$
- Wide range of (pseudo-)scalar particles with similar features to axions but different masses (called **axion-like particles** or **ALPS**)
  - needed in **string theory**
  - can **mediate to DM**

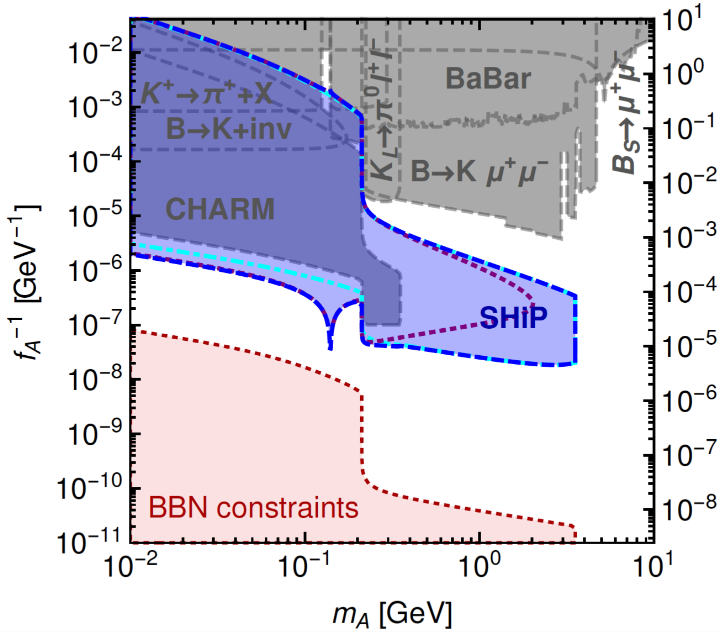
Particularly interesting decays : γγ, μμ

Coupling to fermions :

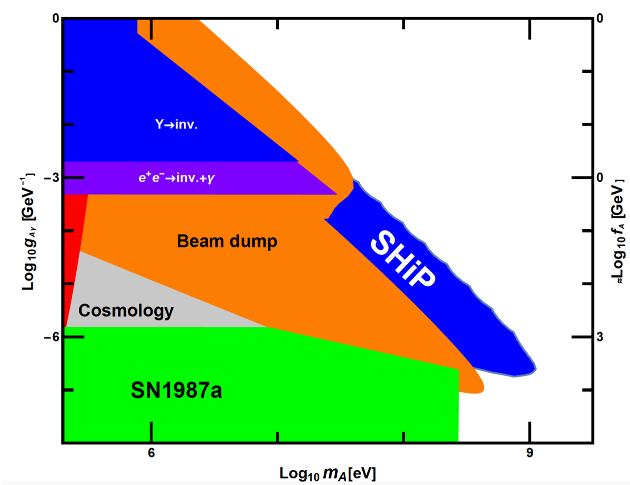
Direct ALP production from ALP-pion mixing

Indirect ALP production from B decays

combination



Coupling to photons/ gauge bosons :



SUSY at SHiP : s-goldstinos (1)

- SUSY breaking may be accompanied **by s-goldstinos (pseudo-scalar P,scalar S)** with couplings ~1/(SUSY breaking scale) → could have escaped detection !

- S-goldstinos are R-even, hence they may be **directly produced**. The production is dominated by gluon fusion.

- They can also be **indirectly produced** through meson decays

$$pp \to S(\text{gluon fusion}),\ \text{S} \xrightarrow{\text{long lived}} \ell^+\ell^-, \pi^+\pi^-, \pi^0\pi^0$$

$$pp \to D + X \to S + X',\ S \xrightarrow{\text{long lived}} \ell^+\ell^-, \pi^+\pi^-, \pi^0\pi^0$$

SUSY at SHiP : neutralinos (2)

- **R-parity violating light neutralinos**
  - Stable neutralinos LSPs excluded in mass range [0.7eV,24GeV], as it would give too much dark matter → mass range still allowed if neutralino decays (R-parity violation)

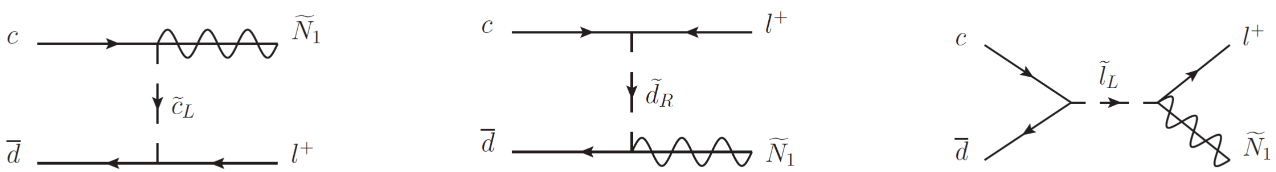
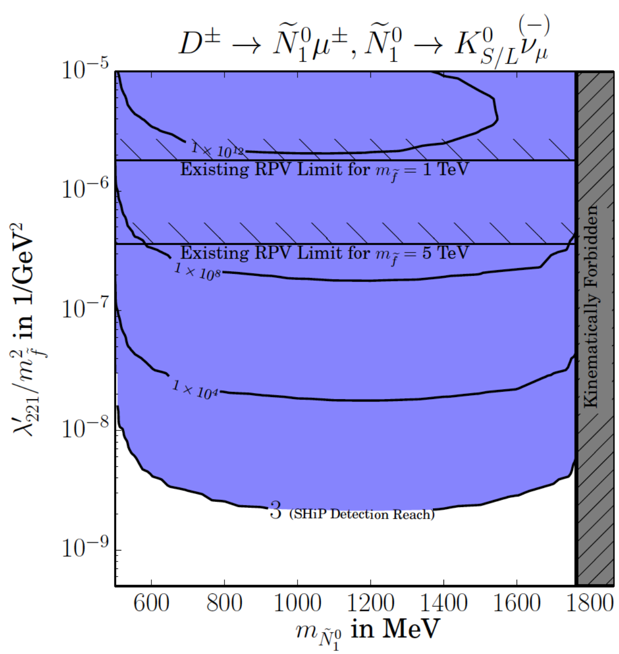


Figure 6.1: Relevant Feynman Diagrams for $D^+ \to \widetilde{N}_1^0 + \ell^+$.

Neutralino decays :

1) K^+l^-
2) $K_{S/L}\,\nu$



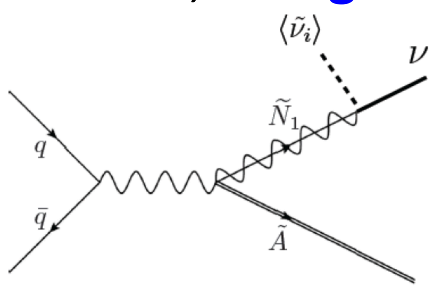
SHiP can probe sfermions in the region of **a few 10s of TeV**.

SUSY at SHiP : axinos (3)

- In a supersymmetric version of axion models, the axion A has as fermionic partner the **axino**.

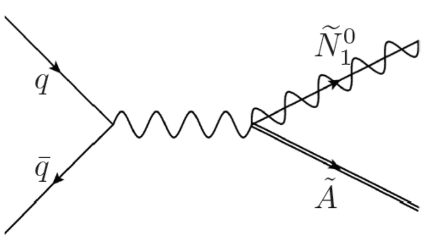
- The most direct constraints typically arise from the search for the axion itself. But if the axino is **light**, then it is interesting to **search for it directly**.

- If **R-parity is broken**, a **single axino** is produced together with a neutrino:



The axion LSP can decay to γ and ν dominantly. In models with DSFZ-type interaction, they **can decay into llν** with a similar decay rate.

- If **R-parity is conserved**: pair production of SUSY particles



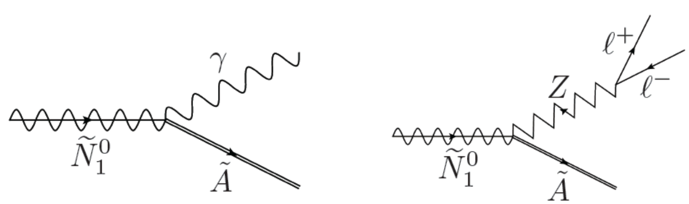


Figure 6.8: Neutralino to axino decay channels.

Mono-γ or two-lepton **final state**

F4,F5

charged current events. With the usual DIS variables: $x \equiv Q^2/2\,p\cdot q$ and $y \equiv p\cdot q/p\cdot k$, where the momentum assignments are:

$$\nu_\tau/\bar{\nu}_\tau(k) + N \quad\rightarrow\quad \tau^-/\tau^+(k') + X \tag{7.1.2}$$

$$q^2 \equiv (k-k')^2 = -Q^2, \tag{7.1.3}$$

the tau neutrino and anti-neutrino charged current cross sections in terms of the structure functions $F_1, ..., F_5$ are [944]:

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2 x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})y\right] F_2$$
$$\pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right] F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\Bigg),$$

where $+F_3$ applies to neutrino scattering and $-F_3$ to antineutrinos. M and m_τ are the nucleon and τ lepton masses respectively, E_ν is the initial neutrino energy and G_F is the Fermi constant. As we will see, at the lower ν_τ energies the SHiP experiment offers the first opportunity to measure the structure functions F_4 and F_5. At the Born level, neglecting target mass corrections, the Albright-Jarlskog relations apply [944]

$$F_4 = 0\,, \tag{7.1.4}$$

$$F_5 = \frac{F_2}{2x}\,. \tag{7.1.5}$$

The QCD predictions for the DIS structure functions F_4 and F_5 are known up to NLO accuracy [945], including full dependence on heavy-quark masses, though. The detailed relationships between the five structure functions, including NLO QCD together with target mass and charm quark mass corrections, are discussed, for example, in Refs. [945–948].

Backgrounds

- Discriminate residual background: with/out misidentification, $X = X^{\pm},\ X^0,\ \not{X}$
  - Inelastic scattering: ν or $\mu + N \ \rightarrow X + K_L \rightarrow \pi\mu\nu,\ \pi e\nu,\ \pi^+\pi^-,\ \ \pi^+\pi^-\pi^0$

    $\rightarrow X + K_S \rightarrow \pi^0\pi^0,\ \pi^+\pi^-$

    $\rightarrow X + n \rightarrow pe^-\bar{\nu}_e \qquad \rightarrow X + \Lambda \rightarrow p\pi^-$

    $n + N \ \rightarrow X + \ K_L\ \ldots..$
  - Muon combinatorial

→ Tracking + particle identification !