On behalf of the SHiP collaboration

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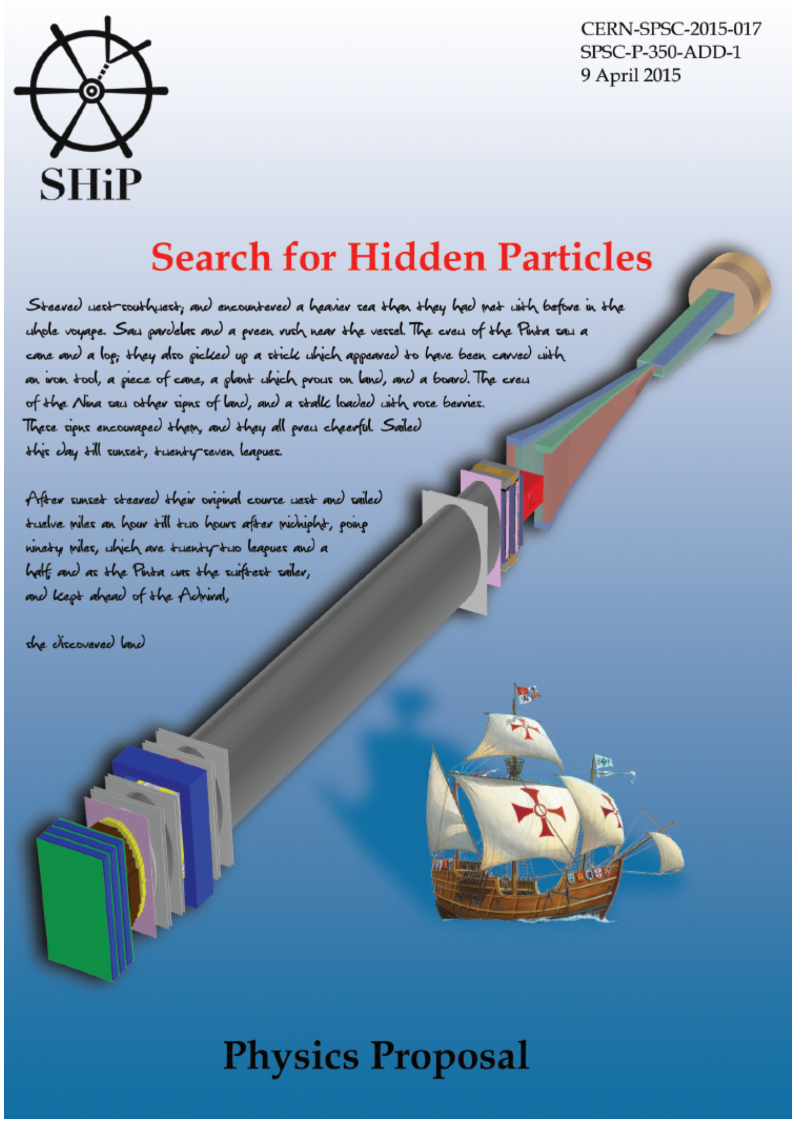


SHiP

CERN-SPSC-2015-017
SPSC-P-350-ADD-1
9 April 2015

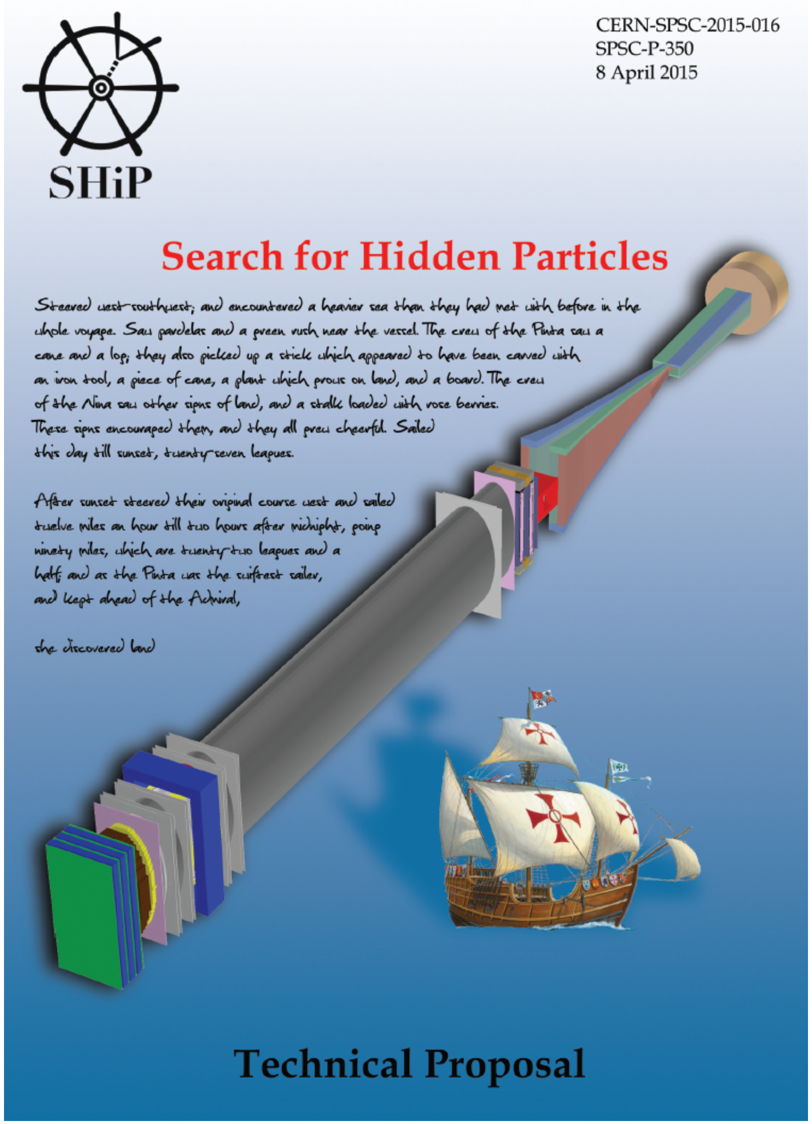
Search for Hidden Particles

Steered west-southwest, and encountered a heavier sea than they had met with before in the whole voyage. Saw pardelas and a green rush near the vessel. The crew of the Pinta saw a cane and a log; they also picked up a stick which appeared to have been carved with an iron tool, a piece of cane, a plant which grows on land, and a board. The crew of the Nina saw other signs of land, and a stalk loaded with rose berries. These signs encouraged them, and they all grew cheerful. Sailed this day till sunset, twenty-seven leagues.

After sunset steered their original course west and sailed twelve miles an hour till two hours after midnight, going ninety miles, which are twenty-two leagues and a half; and as the Pinta was the swiftest sailer, and kept ahead of the Admiral,

she discovered land

Physics Proposal



SHiP

CERN-SPSC-2015-016
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Search for Hidden Particles

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Technical Proposal

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

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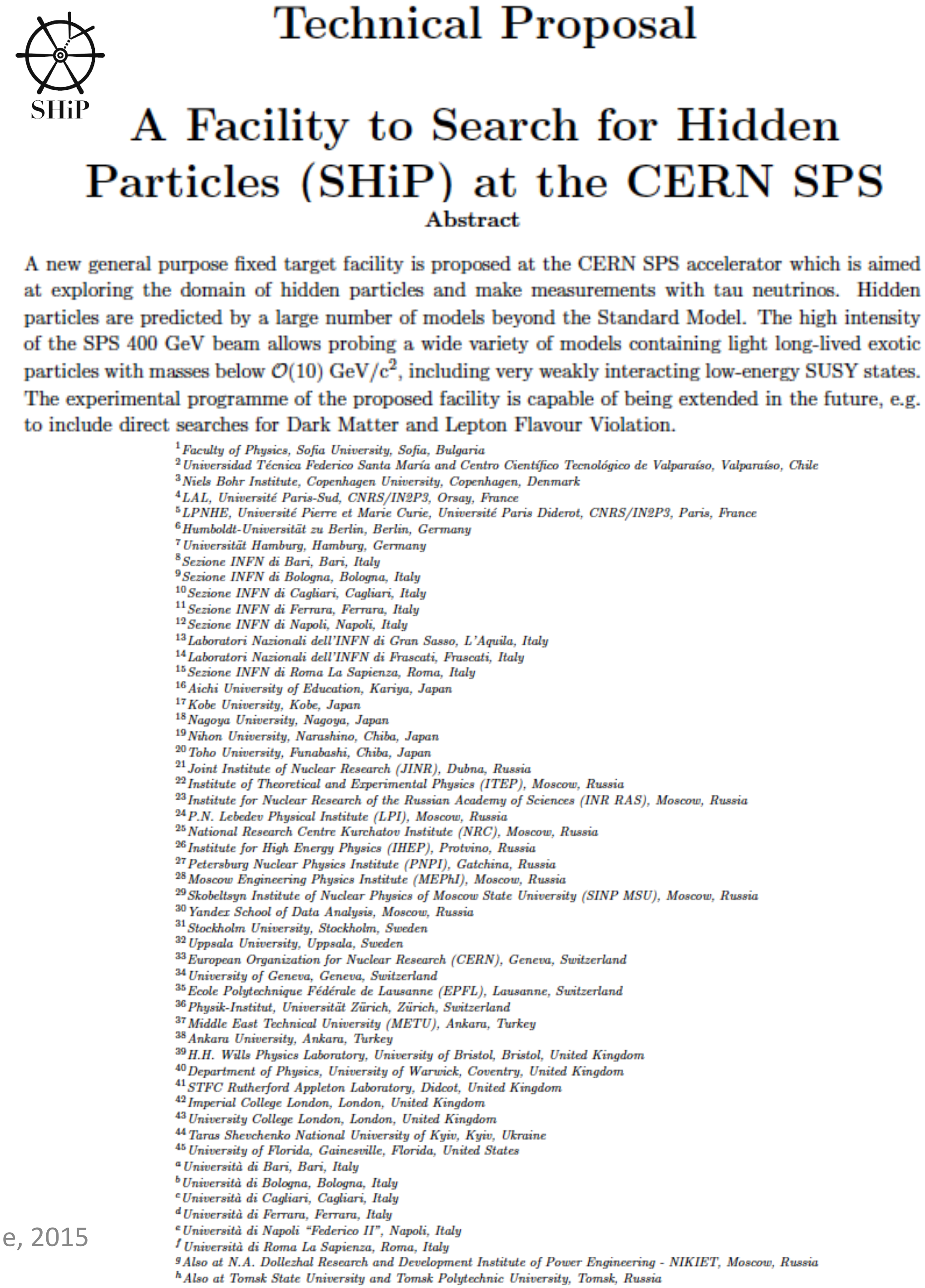
Abstract: This paper describes the physics case for a new fixed target facility at CERN SPS. The SHiP (*Search for Hidden Particles*) experiment is intended to hunt for new physics in the largely unexplored domain of very weakly interacting particles with masses below the Fermi scale, inaccessible to the LHC experiments, and to study tau neutrino physics. The same proton beam setup can be used later to look for decays of tau-leptons with lepton flavour number non-conservation, $\tau \to 3\mu$ and to search for weakly-interacting sub-GeV dark matter candidates. We discuss the evidence for physics beyond the Standard Model and describe interactions between new particles and four different *portals* — scalars, vectors, fermions or axion-like particles. We discuss motivations for different models, manifesting themselves via these interactions, and how they can be probed with the SHiP experiment and present several case studies. The prospects to search for relatively light SUSY and composite particles at SHiP are also discussed. We demonstrate that the SHiP experiment has a unique potential to discover new physics and can directly probe a number of solutions of beyond the Standard Model puzzles, such as neutrino masses, baryon asymmetry of the Universe, dark matter, and inflation.

⋆Editor of the paper

§Convener of the Chapter



Technical Proposal

SHiP

A Facility to Search for Hidden Particles (SHiP) at the CERN SPS

Abstract

A new general purpose fixed target facility is proposed at the CERN SPS accelerator which is aimed at exploring the domain of hidden particles and make measurements with tau neutrinos. Hidden particles are predicted by a large number of models beyond the Standard Model. The high intensity of the SPS 400 GeV beam allows probing a wide variety of models containing light long-lived exotic particles with masses below $\mathcal{O}(10)$ GeV/c^2, including very weakly interacting low-energy SUSY states. The experimental programme of the proposed facility is capable of being extended in the future, e.g. to include direct searches for Dark Matter and Lepton Flavour Violation.

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In-spite of the fact that after the discovery of the Higgs boson at the LHC the Standard Model is complete and can be a consistent effective quantum field theory up the the Planck energies $\sim \mathbf{10^{19}}$ GeV it suffers from a number of experimental and theoretical problems.

Experiment:

- Neutrino masses and oscillations, absent in the SM
- Dark matter, absent in the SM
- Baryogenesis, absent in the SM
- Different anomalies: muon magnetic moment, LSND,...

Theory:

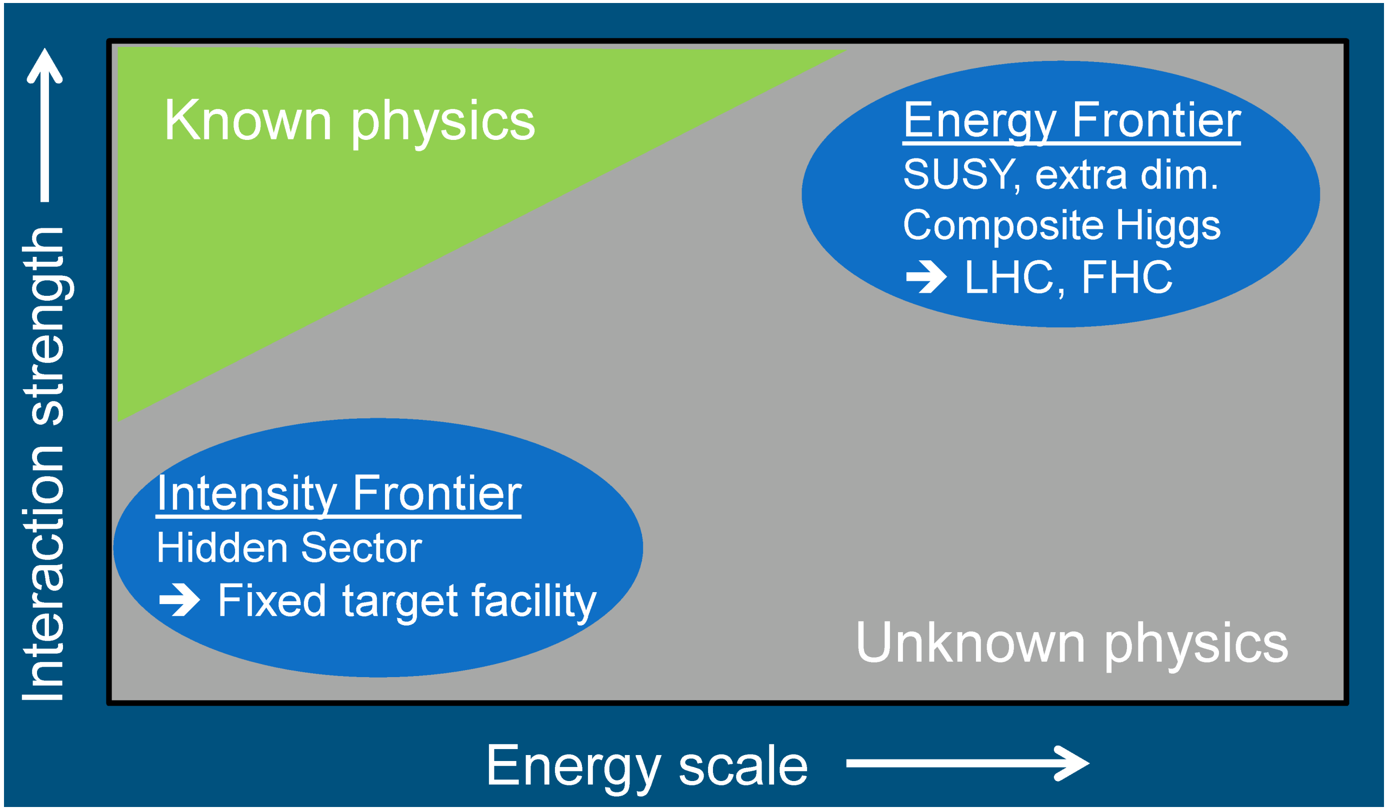
- Most importantly : hierarchy problem - “Why the Fermi scale is so much smaller than the Planck scale?"
- Probably, related problem: “Why the cosmological constant is so tiny?”
- Strong CP, flavour, ...

Can we get with certainty the energy scale of new physics from experiment or theory?

Not really!

- Neutrino masses and oscillations:
  - the masses of right-handed see-saw neutrinos can vary from $\mathbf{1}$ eV to $\mathbf{10^{15}}$ GeV
- Dark matter, absent in the SM:
  - the masses of DM particles can be as small as $\mathbf{10^{-22}}$ eV (super-light scalar fields) or as large as $\mathbf{10^{20}}$ GeV (wimpzillas, Q-balls)
- Baryogenesis, absent in the SM:
  - the masses of new particles, responsible for baryogenesis (e.g. right-handed neutrinos), can be as small as $\mathbf{10}$ MeV or as large as $\mathbf{10^{15}}$ GeV
- Higgs mass hierarchy
  - BSM models related to SUSY, composite Higgs, large extra dimensions require the presence of new physics right above the Fermi scale , whereas the BSM models based on scale invariance (quantum or classical) may require the absence of new physics between the Fermi and Planck scales

Where is new physics?



Known physics

Energy Frontier

SUSY, extra dim.

Composite Higgs

➔ LHC, FHC

Intensity Frontier

Hidden Sector

➔ Fixed target facility

Unknown physics

Interaction strength →

Energy scale →

Systematic approach to Hidden Sector Particles

If new hidden particles are light, they must be singlets with respect to the gauge group of the SM. So, they may couple to different singlet composite operators (portals) of the SM

- dim 2: Hypercharge U(1) field, $B_{\mu\nu}$: vector portal. New particle - dark photon; renormalisable coupling - kinetic mixing

$$\epsilon B_{\mu\nu} F'^{\mu\nu}$$

- dim 2: Higgs field, $H^\dagger H$: Higgs portal. New particle - “dark” scalar; renormalisable couplings

$$(\alpha_1 S + \alpha S^2) H^\dagger H$$

- dim $2\frac{1}{2}$: Higgs-lepton, $H^T L$: neutrino portal. New particles - Heavy Neutral Leptons, HNL; renormalizable couplings

$$Y H^T \bar{N} L$$

- dim 4: New particles - ALPs (axion like particles), pseudo-scalars: axion portal. Non-renormalizable couplings,

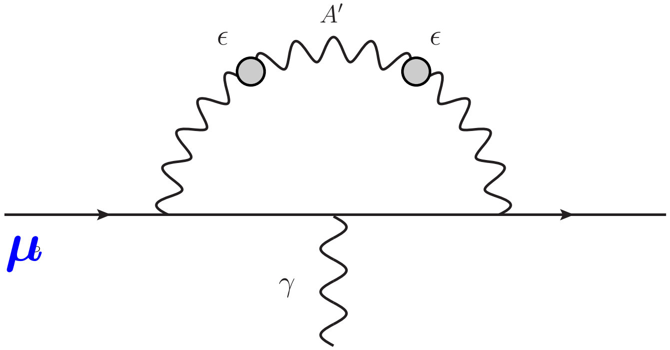
$$\frac{a}{f_A} G_{\mu\nu}\tilde{G}^{\mu\nu}, \quad \frac{a}{f_A}\partial_\mu J^\mu, \quad etc$$

  J_μ - some SM current

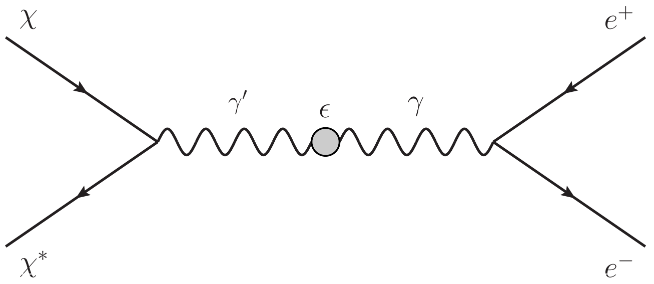
- ...

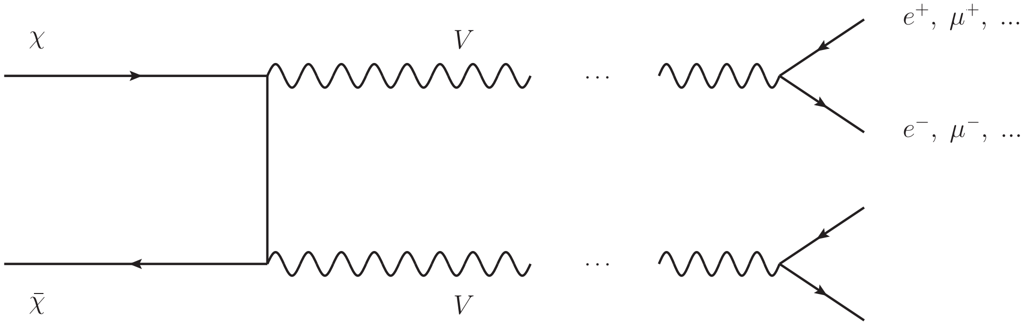
New vector particles: motivations

- Structure of the SM gauge group SU(3)×SU(2)×U(1) may descend from a larger (e.g. GUT) group, and low energy theory symmetric under SU(3)×SU(2)×[U(1)]^n is possible. Examples: gauging of the $B - L$ “accidental” global symmetry of the SM; messenger between left and right mirror particles (spontaneous parity breaking)
- Possible solution of muon $g - 2$ discrepancy



- Mediator of interaction with Dark matter
  - Light dark matter with M as small as few MeV: increase of annihilation cross-section of DM particles. Used for DM explanations of the positron excess;





  - Self-interacting dark matter: core-cusp problem in dwarf galaxies, too-big-to-fail problem (excess of massive sub-halos in N-body simulations of Milky Way type galaxies)

Vector portal: phenomenology

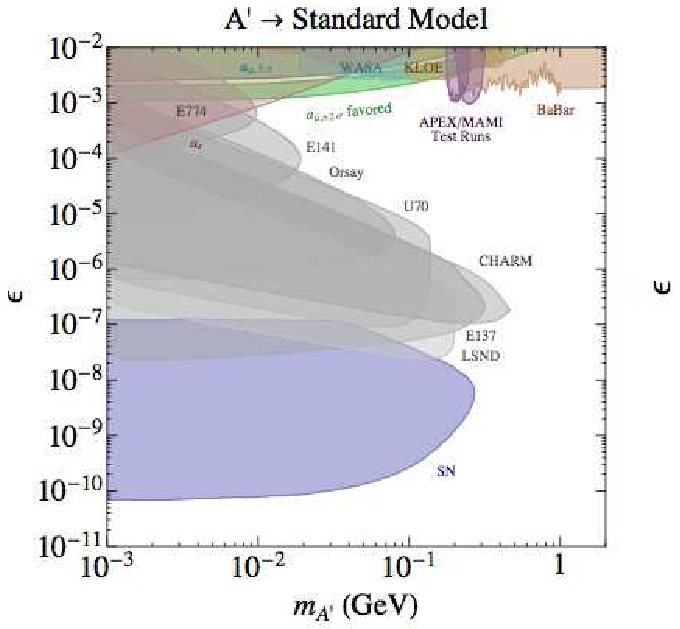
Production

- Meson decays, such as $\eta,\ \rho,\ \pi, \ldots \to \gamma A'$; Bremsstrahlung processes $pp \to ppA'$; Direct QCD production $q\,\bar{q} \to A',\ q\,g \to A'\,q$

Decays

- $A' \to l^+l^-,\quad A' \to \text{hadrons},\quad A' \to \chi\bar{\chi}$

Example of constraints



New scalars: motivations

- LHC: fundamental scalar boson exists in nature. There are many quarks, leptons, vector bosons. Why the Higgs boson should be unique? In fact, all BSM models contain extra scalars.
- Hierarchy problem (mirror world with twin Higgs, neutral naturalness)
- Inflation is most probably driven by a scalar field
- Candidate for dark matter
- Electroweak baryogenesis (new scalar can make the EW phase transition of the first order, resulting in thermal non-equilibrium)
- pseudo-Nambu-Goldstone bosons (PNGB) of a spontaneously broken symmetry
- neutrino masses
- flavour problem
- SUSY and extended SUSY, R-parity violation
- Hidden Valley scenario: low mass hidden sector coupled to the SM through mediators of different nature

Scalar portal: phenomenology

Typical Lagrangian:

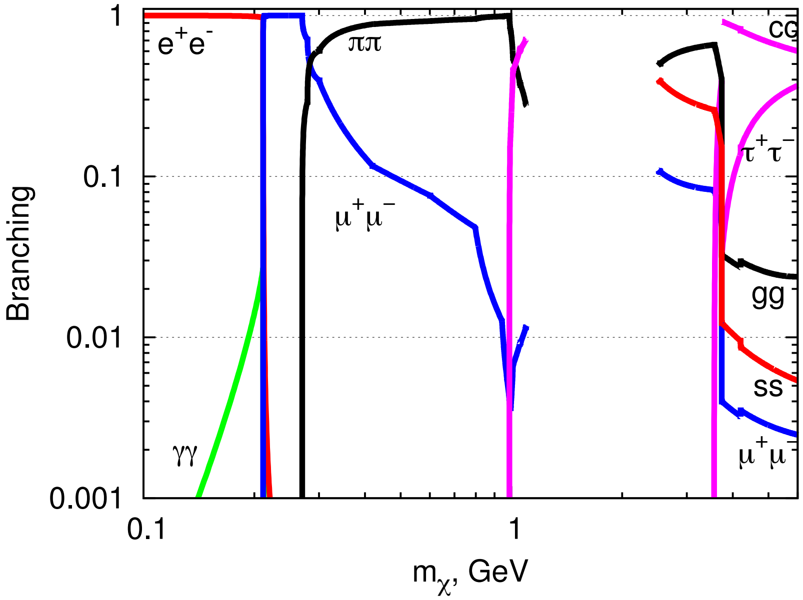
$$(\alpha_1 S + \alpha S^2) H^\dagger H + L_{SM} + L_{hidden}$$

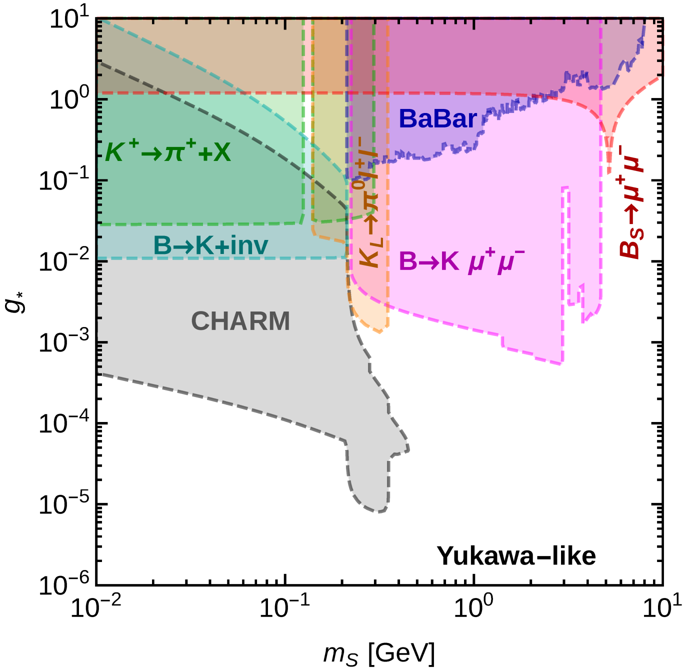
Production

- Direct production $p + \mathrm{target} \rightarrow S + \ldots$
- Production via intermediate (hadronic) state $p + \mathrm{target} \rightarrow \mathrm{mesons} + \ldots$, and then $\mathrm{hadron} \rightarrow S + \ldots$.

Decays

- Subsequent decay of S to SM particles





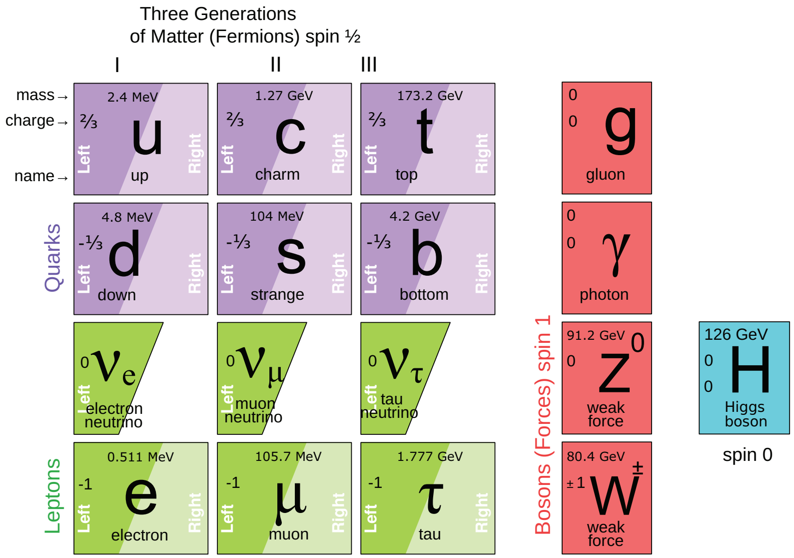
Through mixing with Higgs

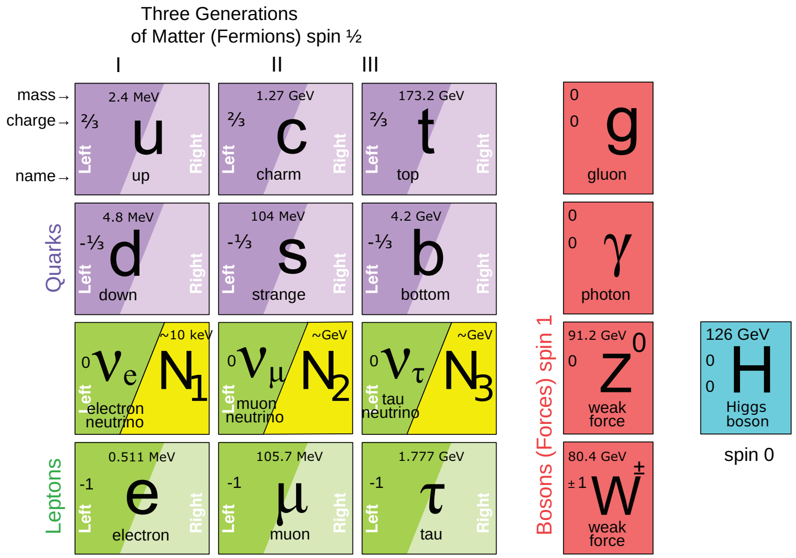
Example of constraints,

$$g_* = \alpha_1 V / m_h^2$$

New neutral leptons: motivations

- Origin of active neutrino masses via see-saw
- Left-right symmetry
- Dark matter candidate
- Baryon asymmetry of the Universe
- Natural completion of the Standard Model in neutrino sector



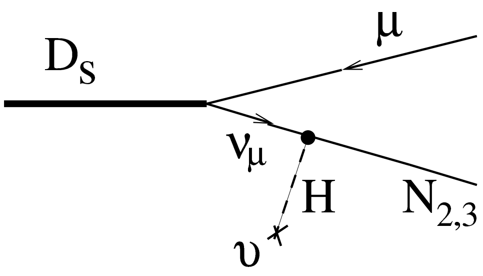


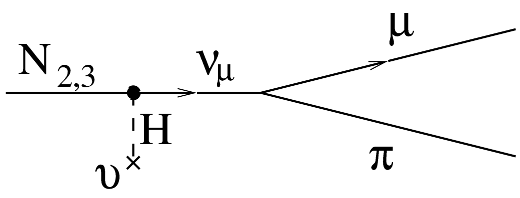
Neutrino portal: phenomenology

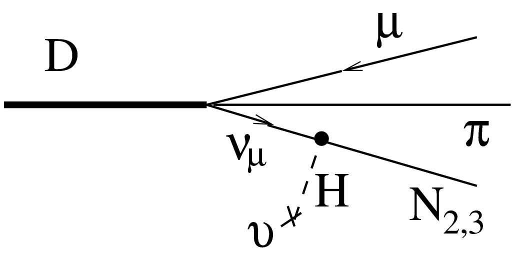
- Production via intermediate (hadronic) state

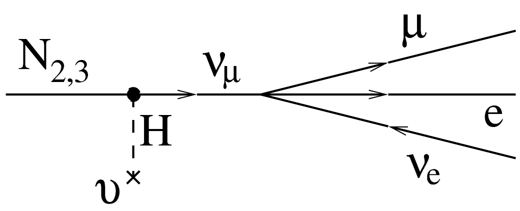
  $p + \mathbf{target} \to \mathbf{mesons} + \ldots$, and then $\mathbf{hadron} \to N + \ldots$.

- Subsequent decay of N to SM particles

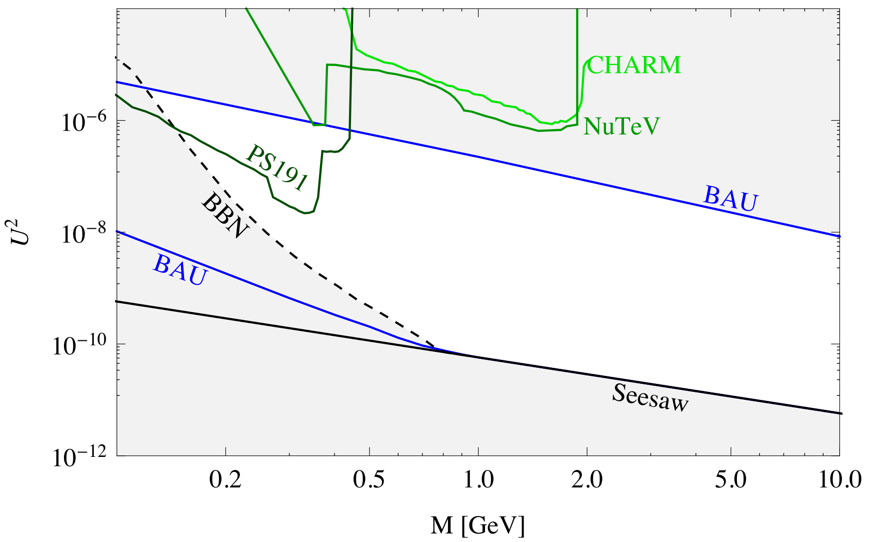


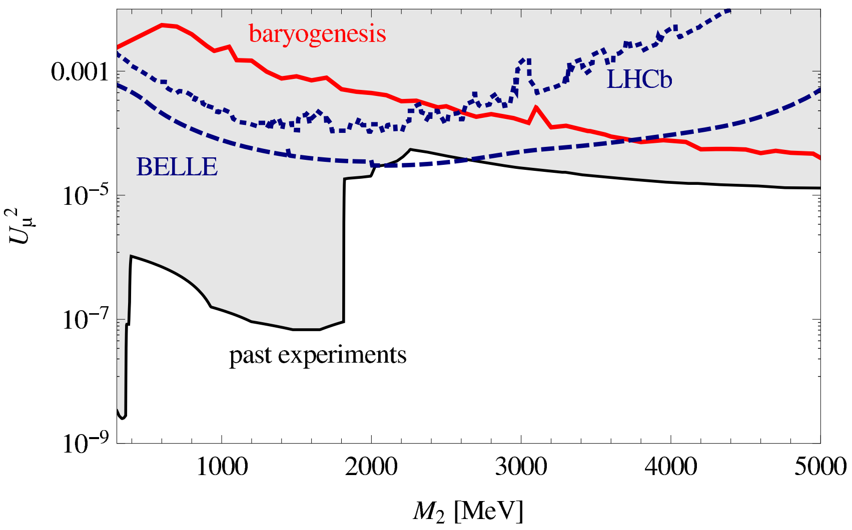






Neutrino portal: cosmological and experimental constraints





Constraints on mixing angle U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches.

Left panel - normal hierarchy, 2HNL+1 DM HNL; right panel - 3 HNL .

Axion-like particles and PNGB: motivations

Well known example: axion to solve strong CP-problem (different mass region, cannot be searched at SHiP)

- String theory compactifications: axiverse with ALPs with masses taking values distributed across every scale of energy
- Pseudoscalars in extended Higgs sectors (e.g. NMSSM)
- Large extra dimensions with relatively small fundamental Planck scale
- PNGBs of spontaneously broken global flavour symmetries : familons
- Dark matter - mediation of interactions between SM and DM particles

Typical interaction:

$$\frac{a}{f_A} G_{\mu\nu} \tilde{G}^{\mu\nu}, \quad \frac{\partial_\mu a}{f_A} \bar{\psi} \gamma_\mu \gamma_5 \psi, \quad etc$$

Axion portal: phenomenology

Production

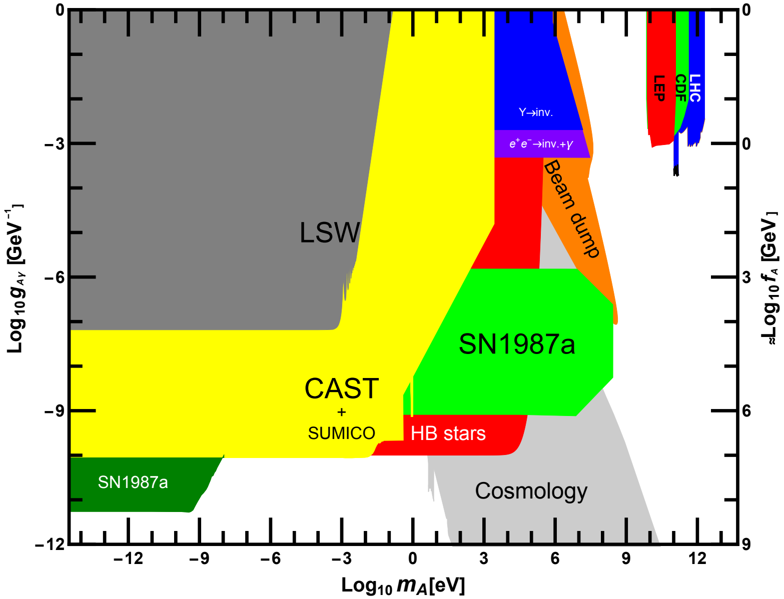
- Drell-Yan production of photon $q\bar{q} \to \gamma^*$, followed by Primakoff production of ALPs $\gamma^* \to a\gamma$
- meson decays, e.g. $B \to Ka$

Decays

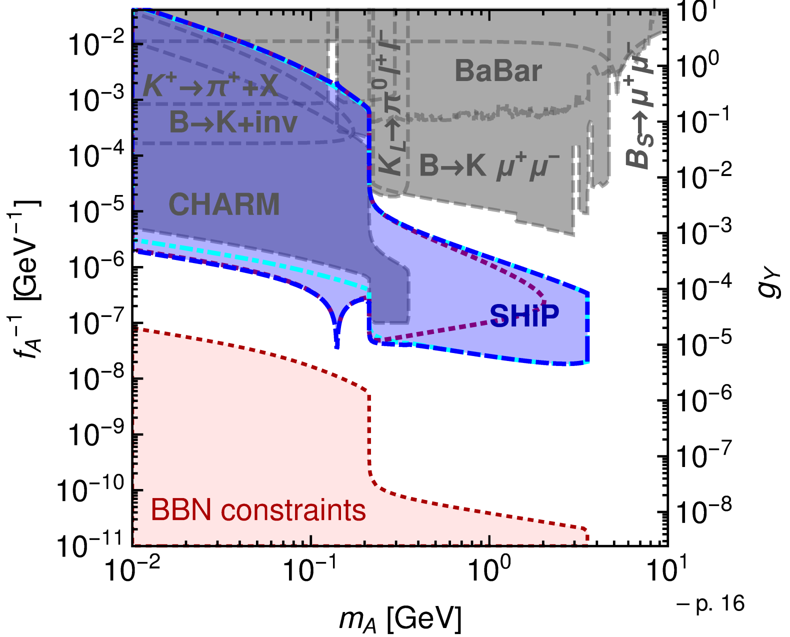
- $a \to \gamma\gamma, \;\; a \to l^+ l^-$, etc

Example of constraints

Coupling to 2 photons, $g_{A\gamma} \propto 1/f_A$



Coupling to all fermions



Light SUSY particles: motivations

SUSY: general framework for addressing hierarchy problem and Grand Unification. The prejudice that SUSY particles are heavy comes from the minimal models such as MSSM or CMSSM

- Unstable neutralino in models with R-parity breaking (then DM candidates - axino or axion)
- Scalar and pseudoscalar sgoldstinos coming from SUSY breaking (e.g. no-scale SUGRA)
- Pseudo Dirac gauginos χ_1, χ_2: dark matter candidate χ_1
- SUSY partners of axion: axino and saxion
- SUSY partners of dark photons: hidden photinos $\tilde{\gamma}, \tilde{\gamma}', \ldots$ (string theory compactifications)

Light SUSY particles: phenomenology

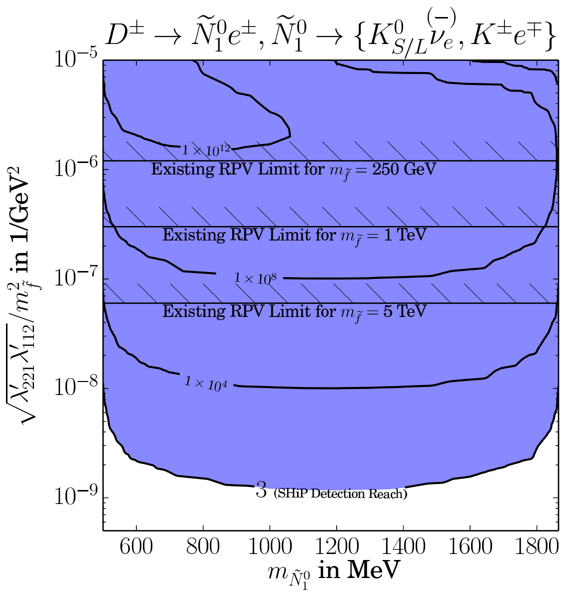
- Neutralino: similarity with HNL
- Sgoldstino: similarity with ALPs
- Pseudo Dirac gauginos: $pp \to \chi_2 + \chi_{1,2}, \quad \chi_2 \to \chi_1 + l^+ l^-$
- Photinos: $B \to K\tilde{\gamma}\tilde{\gamma}, \quad \tilde{\gamma} \to \tilde{\gamma}' + l^+ l^-$
- Saxions: similarity with ALPs
- Axinos: similarity with neutralino

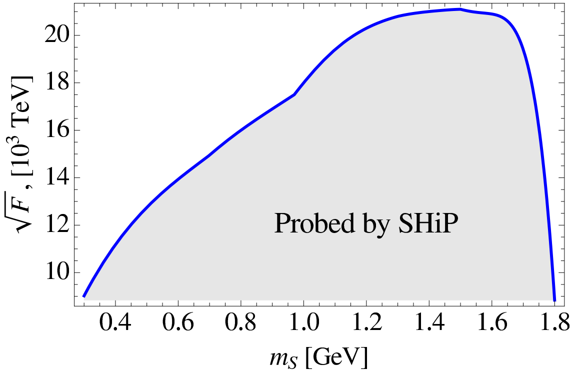
Examples of constraints

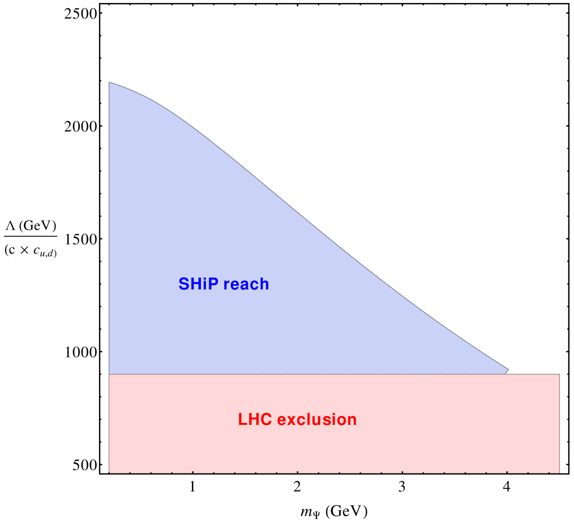
SUSY breaking scale

as a function of

sgoldstino mass







RPV neutralinos

λ- amplitude of RPV

Pseudo-Dirac fermion

$1/\Lambda^2$ - interaction

with SM fields

Summary

Two distinct possibilities exist:

- There is BSM physics with a new energy scale (SUSY , GUT, extra dimensions, new strong dynamics, etc) but *there are also light particles in the spectrum*
  Examples: dark photon, light scalars, pseudo-Goldstone bosons of high energy symmetries, RPV neutralino, sgoldstino, . . .
- Standard Model plus some light particles is valid up to very high energies. *No new physics between Fermi and Planck scale*
  Example: heavy neutral leptons

SHiP at CERN offers a possibility to discover these new particles

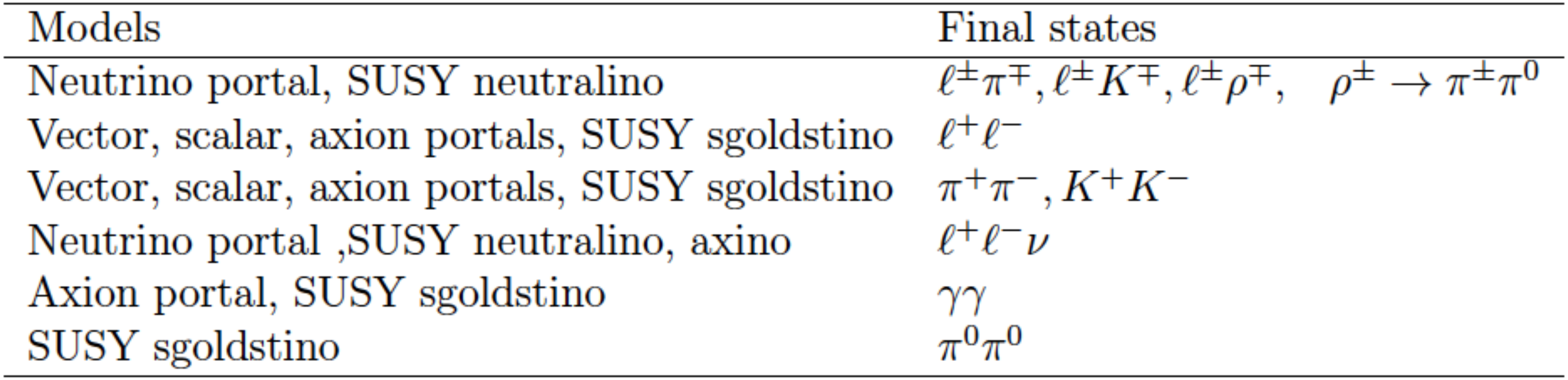
Tau neutrino physics and precision measurements

- τ-neutrino charged current cross section ($\sim few \times 10^3$ events) (present situation: 9 events in DONUT and 5 events in OPERA).
- Discovery of $\bar{\nu}_\tau$
- Determination of $\nu_\tau, \;\; \bar{\nu}_\tau$ DIS structure functions F_4 and F_5.
- Update of DIS of muon (~ 2 Mio events) and electron neutrinos (~ 1 Mio events)
- α_s measurement via Gross-Llewellin Smith sum rule
- EW parameters $\sin^2\theta_W$
- Charmed pentaquark searches
- Tau neutrino magnetic moment (cross section of elastic scattering on electron)
- Lepton flavour violation, $\tau \to 3\mu$ (current limit 2×10^{-8}, improvement to $\simeq 10^{-10}$)

Common experimental features of Hidden Sector (HS)

- ✓ *Production through hadron decays (π, K, D, B, proton bremsstrahlung, …)*

- ✓ *Decays:*



Models	Final states
Neutrino portal, SUSY neutralino	$\ell^{\pm}\pi^{\mp}, \ell^{\pm}K^{\mp}, \ell^{\pm}\rho^{\mp}, \quad \rho^{\pm} \to \pi^{\pm}\pi^{0}$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^{+}\ell^{-}$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^{+}\pi^{-}, K^{+}K^{-}$
Neutrino portal ,SUSY neutralino, axino	$\ell^{+}\ell^{-}\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^{0}\pi^{0}$

- ✓ *Full reconstruction and PID are essential to minimize model dependence*

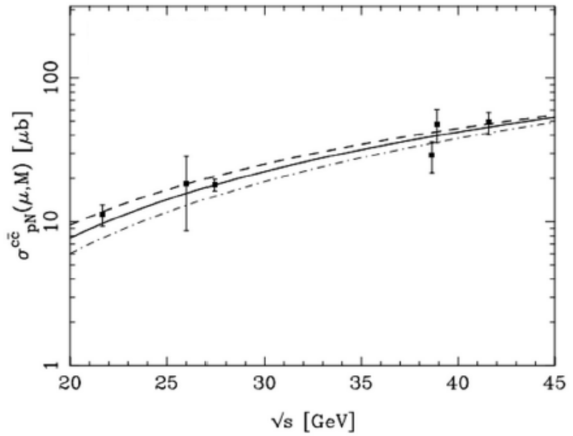
- ✓ *Production and decay rates are strongly suppressed relative to SM*
  - *Production branching ratios O(10^{-10})*
  - *Long-lived objects*
  - *Travel unperturbed through ordinary matter*

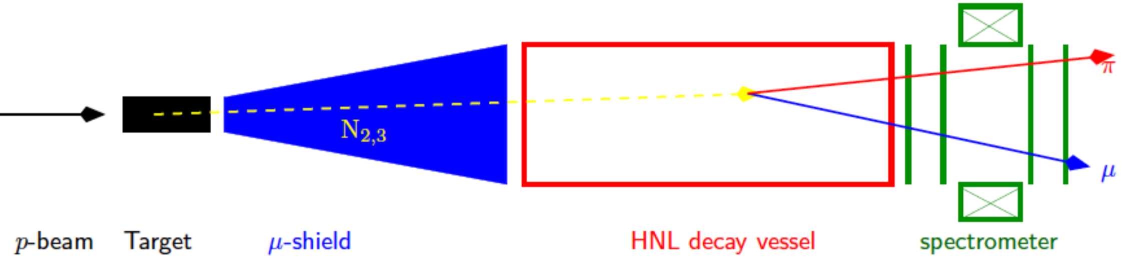
- ✓ ***Challenge is background suppression → requires O(0.01) carefully estimated***

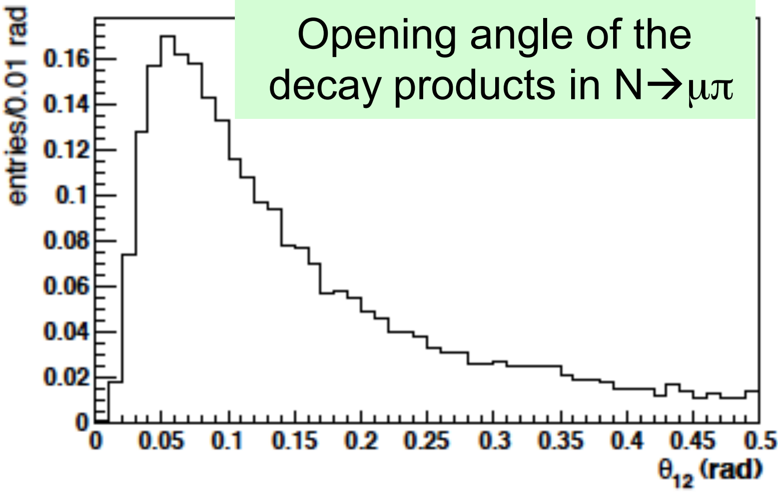
- ✓ ***Physics with ν_τ produced in D_s decays share many of these features***

General experimental requirements

- ✓ *Search for HS particles in Heavy Flavour decays*
- ✓ *HS produced in charm and beauty decays have significant P_T*





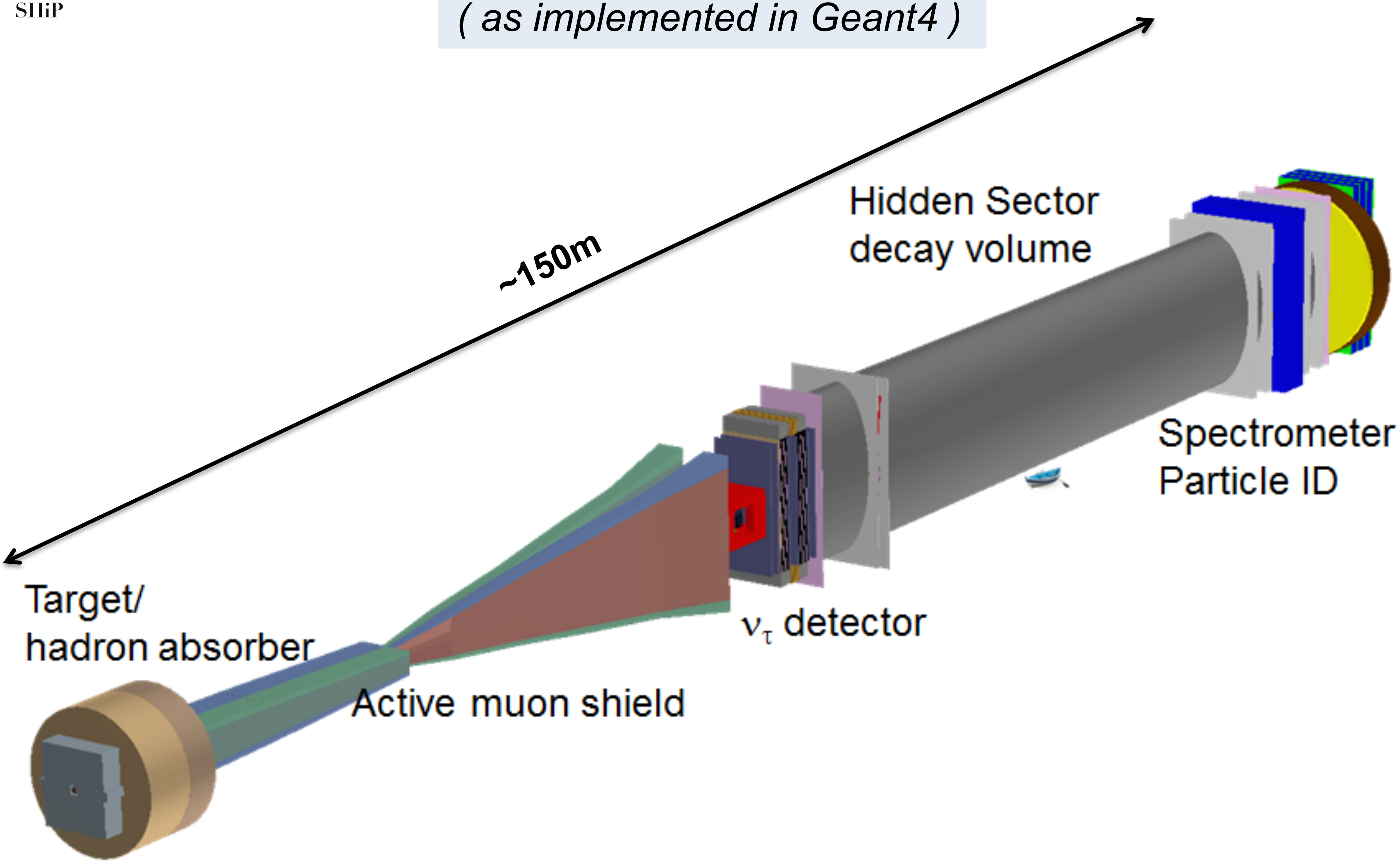


Opening angle of the decay products in N→$\mu\pi$

- ✓ *Detector must be placed close to the target to maximize geometrical acceptance*
- ✓ *Effective (and "short") muon shield is essential to reduce muon-induced backgrounds*

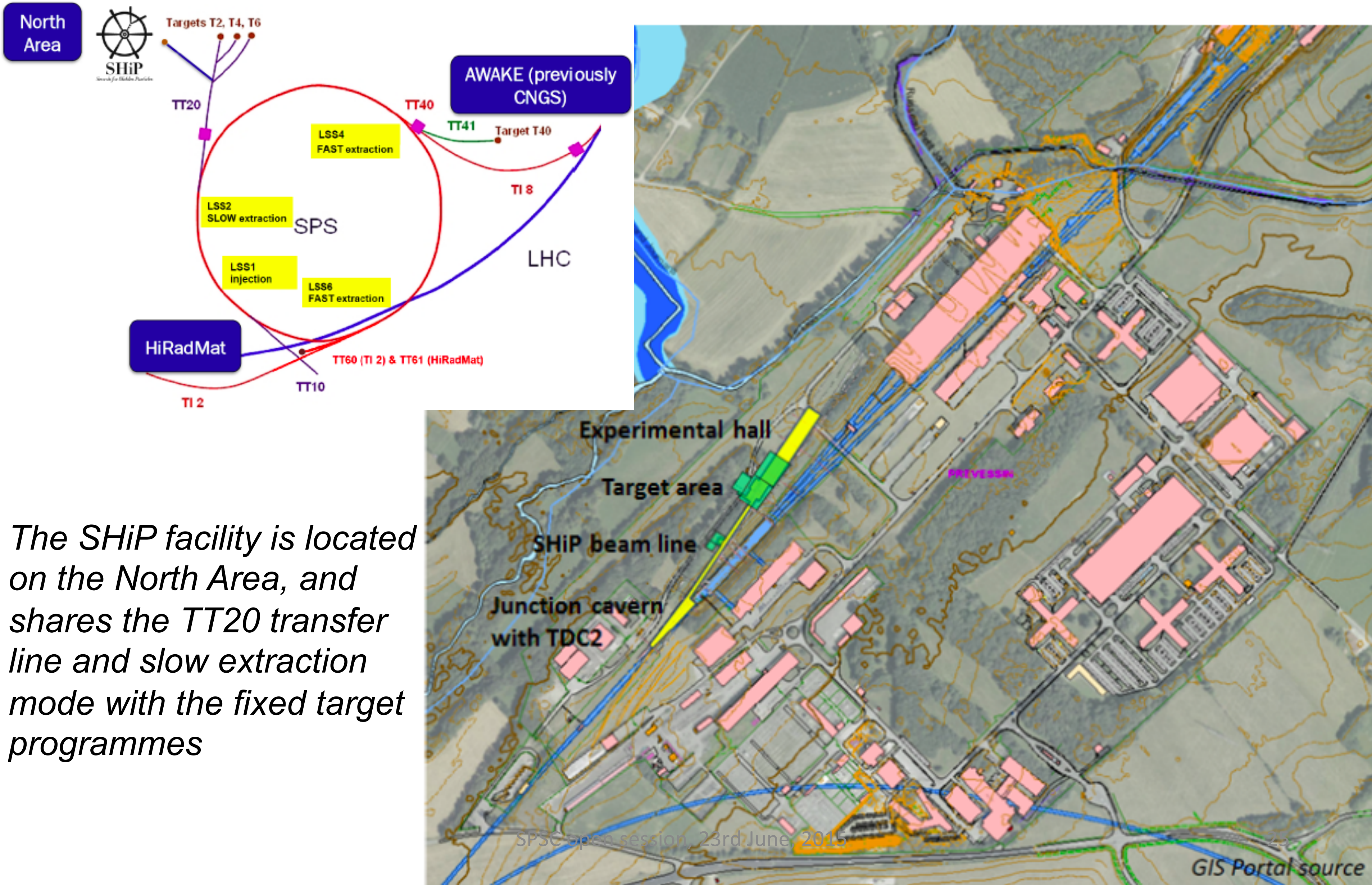
The SHiP experiment

(as implemented in Geant4)



The Fixed-target facility at the SPS (Prevessin North Area site)

Proposed implementation is based on minimal modification to the SPS complex



GIS Portal source

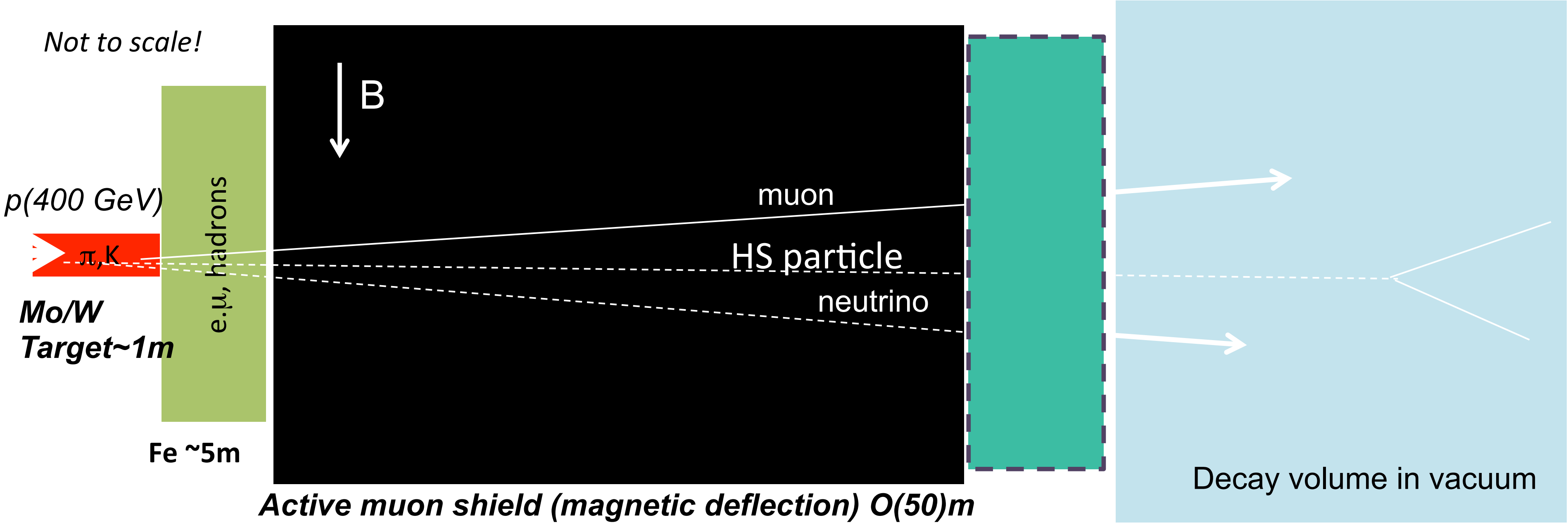
The SHiP facility is located on the North Area, and shares the TT20 transfer line and slow extraction mode with the fixed target programmes

SHiP beam-line

(incompatible with conventional neutrino facility)

Initial reduction of beam induced backgrounds

- *Heavy target to minimize neutrinos from $\pi/K \rightarrow \mu\nu$ decays*
- *Hadron absorber*
- *Effective muon shield (without shield: muon rate ~10^{10} per spill of 5×10^{13} pot)*
- *Slow (and uniform) beam extraction ~1s to reduce occupancy in the detector*



Multidimensional optimization: *beam energy, beam intensity, background conditions and detector acceptance*

SHiP target

Main requirements:

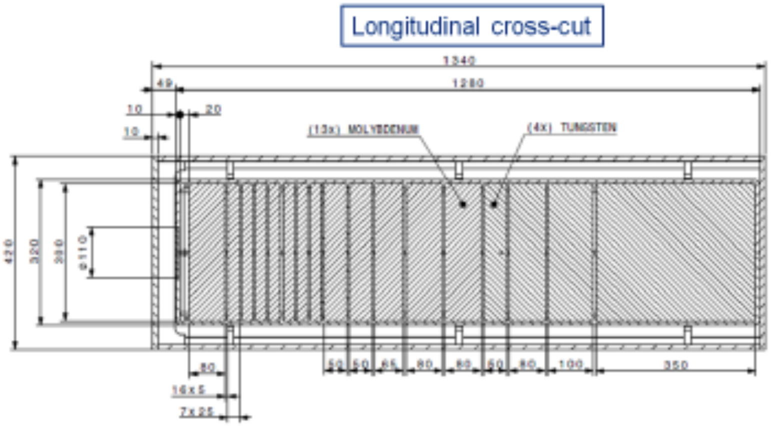
- *Maximize Heavy Flavour production → use material with high A*
- *Minimize production of neutrinos from π decays → shortest possible λ_{int}*

Peak power per spill ~2.56 MW

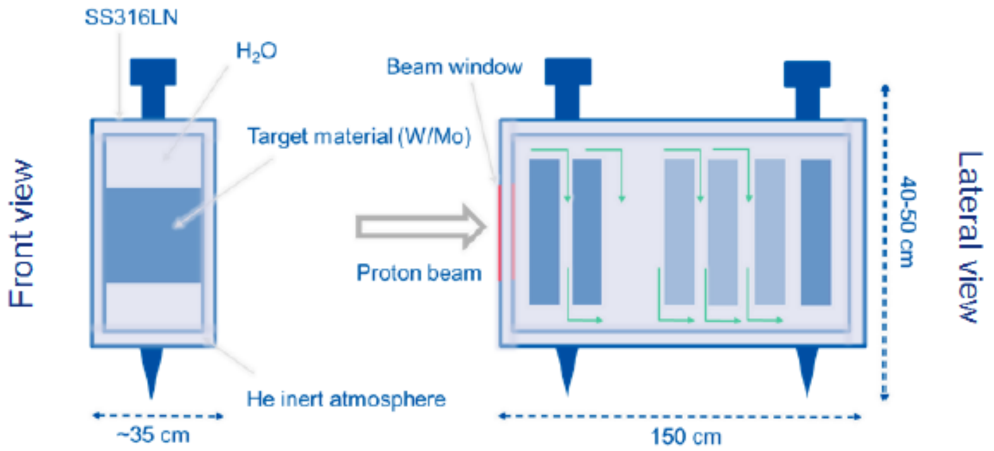
Design consideration

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

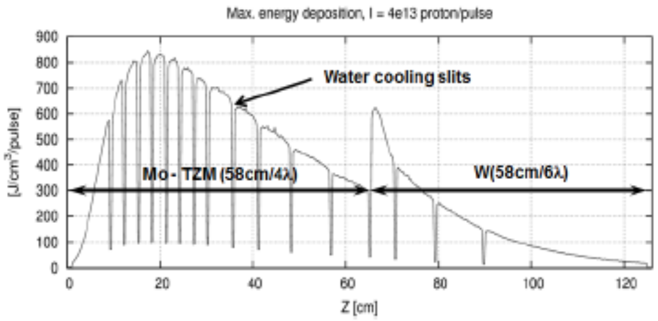
Longitudinally segmented hybrid target: Mo(58cm)/W(58cm)



SHiP Target Assembly



Pressurized water cooling of 15-20 bar

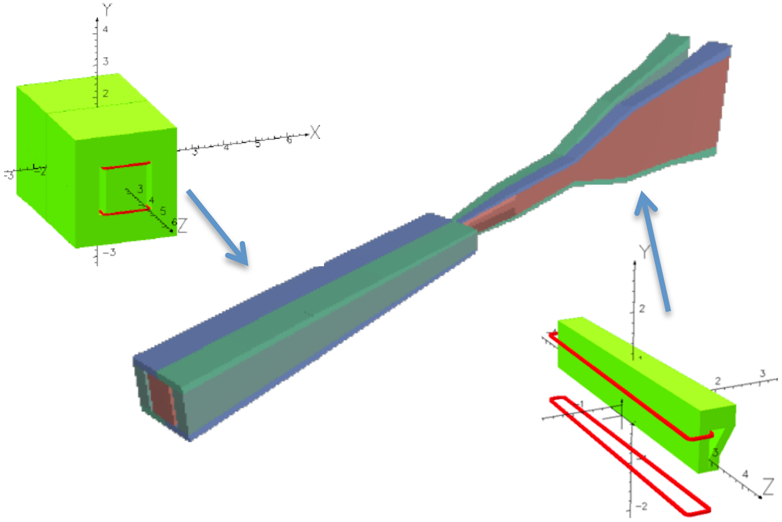


SHiP muon shield

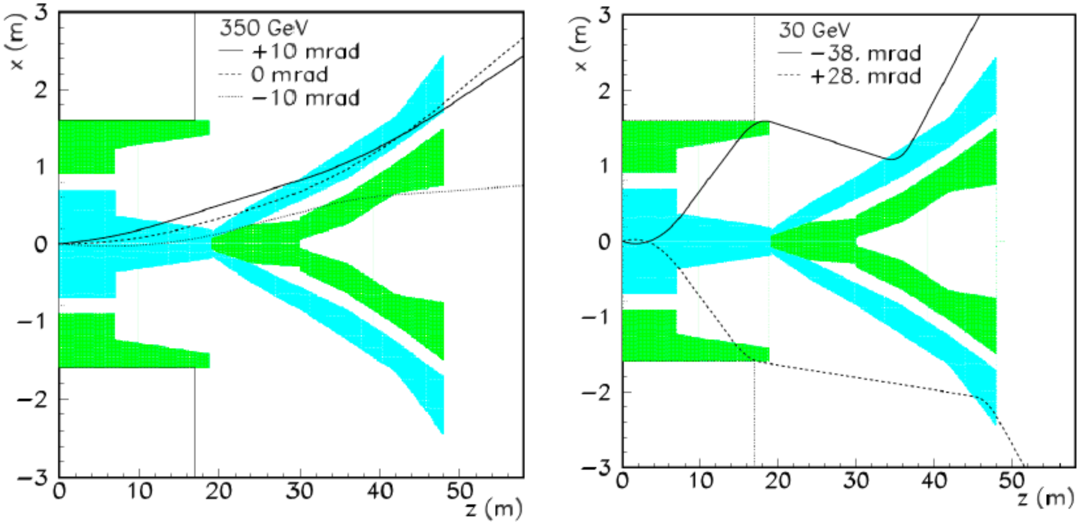
- ✓ *Muon flux limit driven by emulsion based neutrino detector and HS background*
- ✓ *Active muon shield based entirely on magnet sweeper with a total field integral B_y = 86.4 Tm*

  Realistic design of sweeper magnets in progress

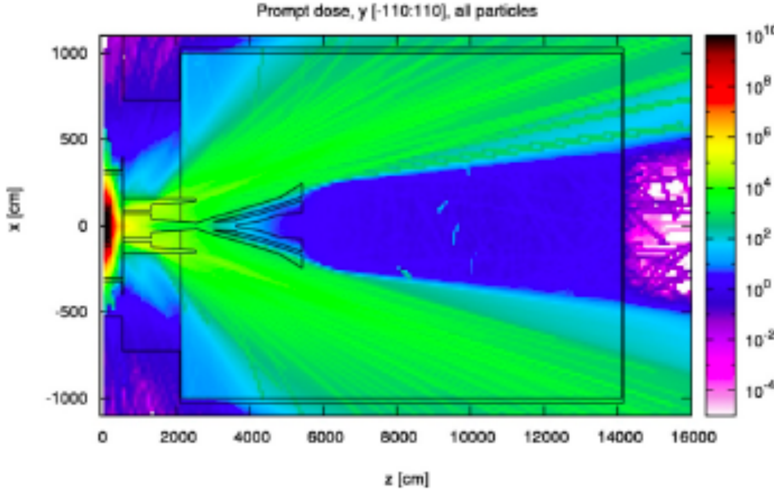
  Challenges: flux leakage, constant field profile, modeling magnet shape
- ✓ *< 7k muons / spill (E_μ > 3 GeV), well below the emulsion saturation limit*
- ✓ *Negligible flux in terms of detector occupancy*



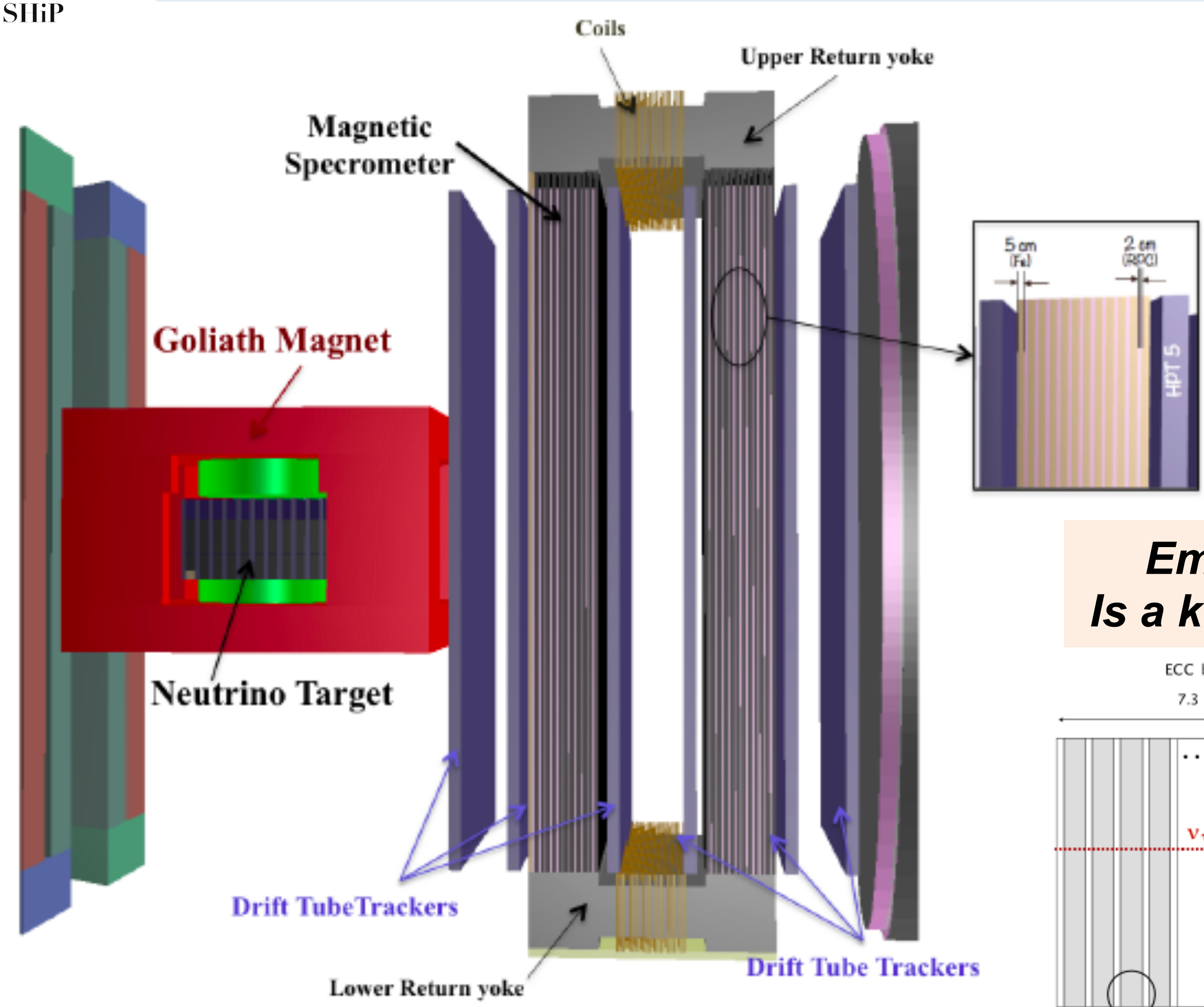
Magnetic sweeper field



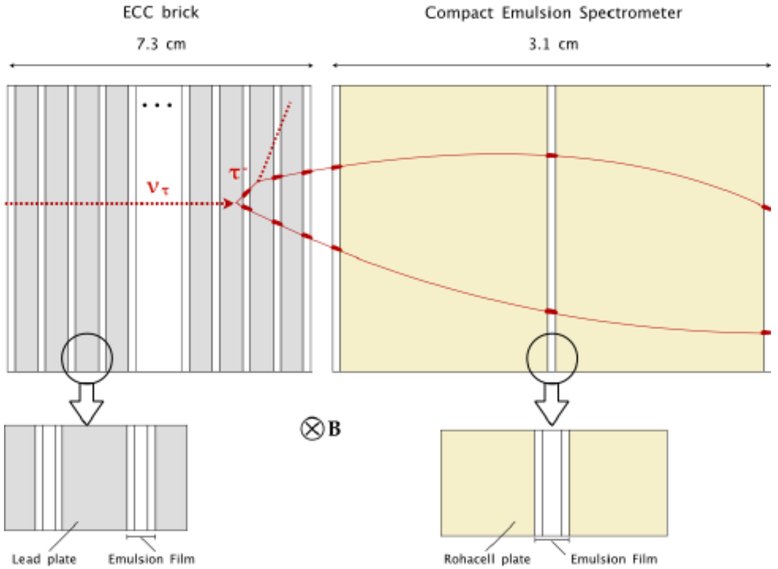
Dose rate in the SHiP hall



ν_τ detector follows the concept of OPERA



Emulsion Cloud Chamber
Is a key element of ν_τ detection



HS detector concept
(based on existing technologies)

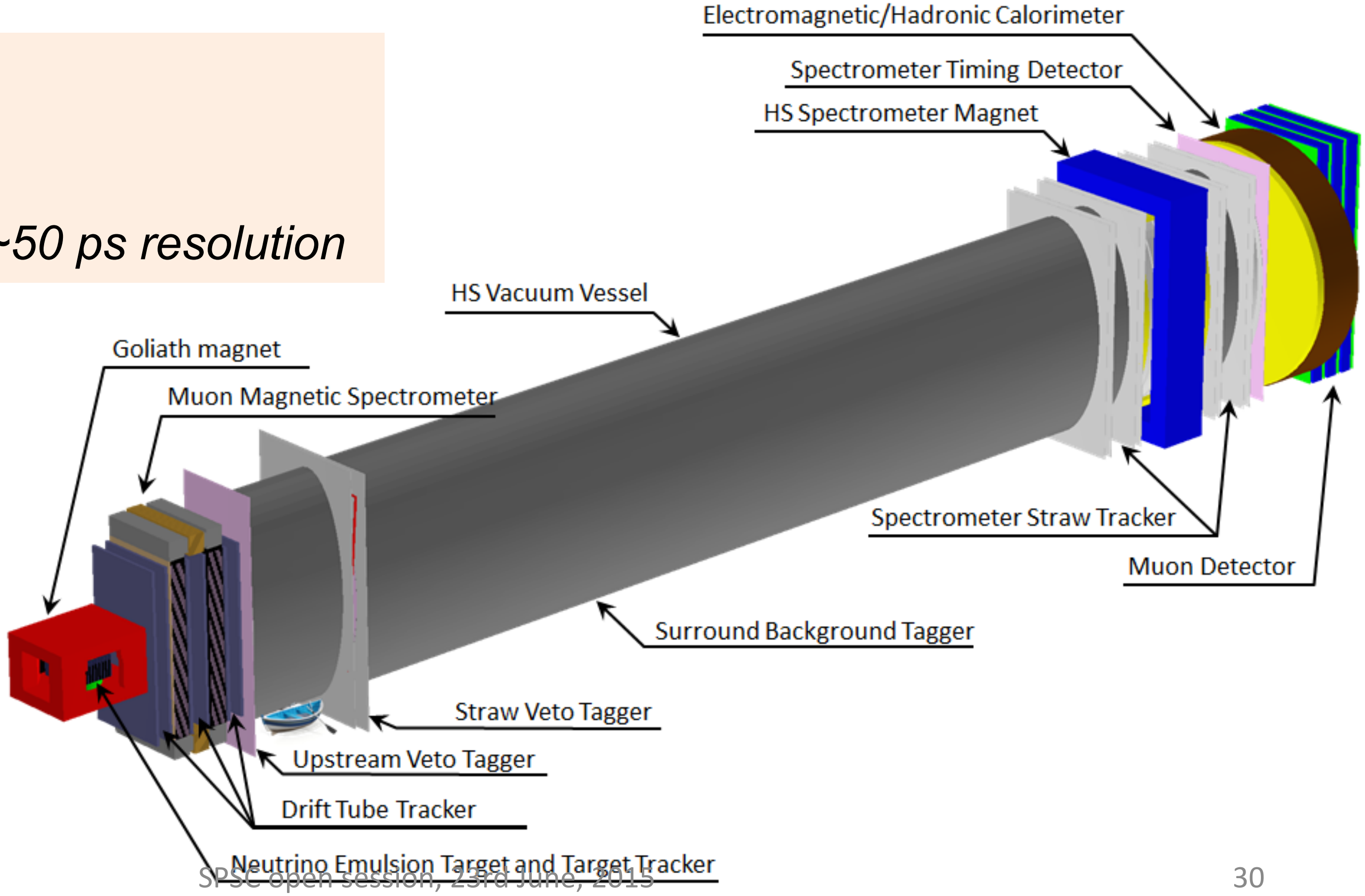
✓ *Reconstruction of HS decays in all possible final states*

Long decay volume protected by various Veto Taggers, Magnetic Spectrometer followed by the Timing Detector, and Calorimeters and Muon systems.

All heavy infrastructure is at distance to reduce neutrino / muon interactions in proximity of the detector

Challenges:

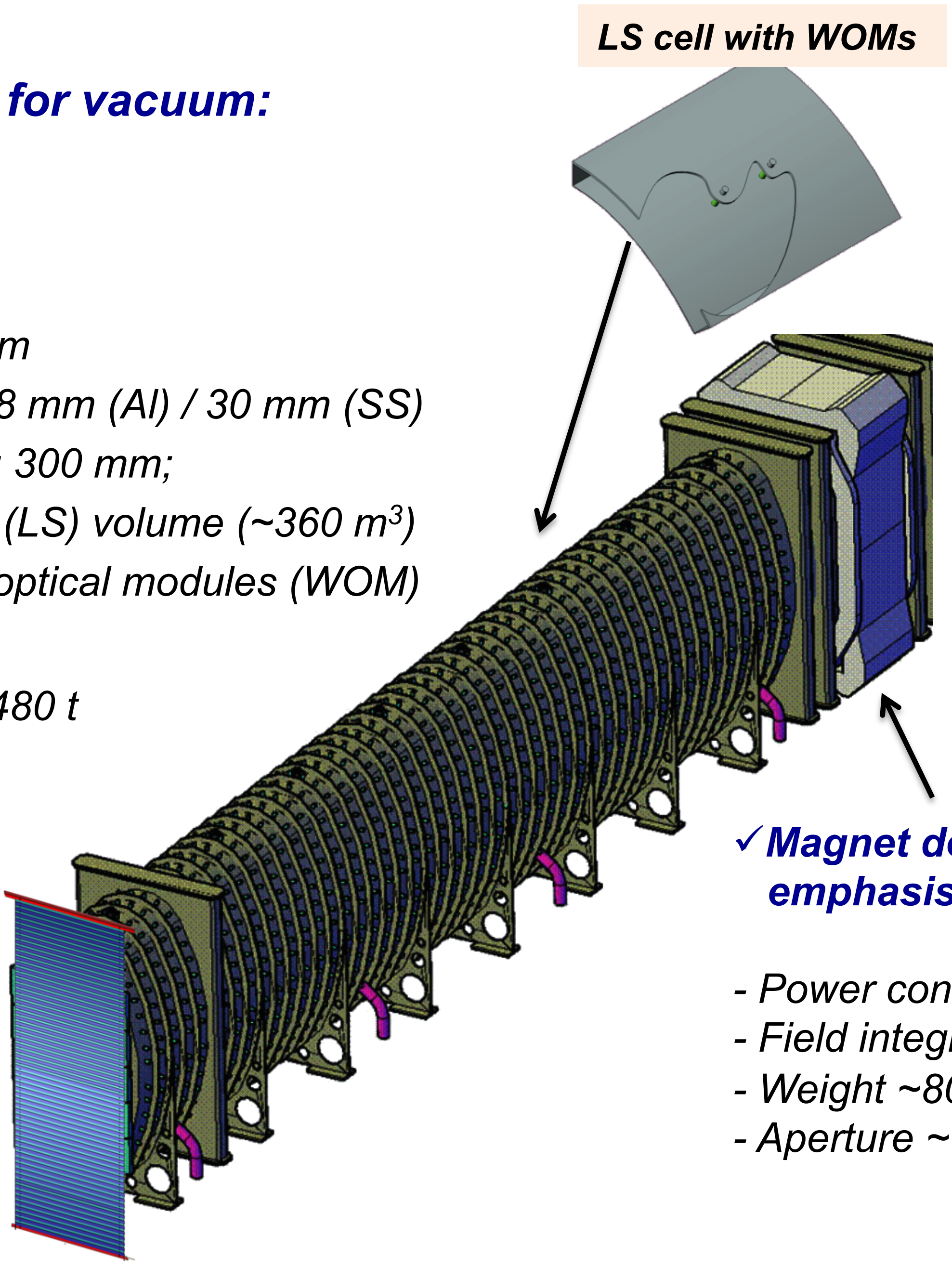
- *Large vacuum vessel*
- *5 m long straw tubes*
- *Timing detector with ~50 ps resolution*



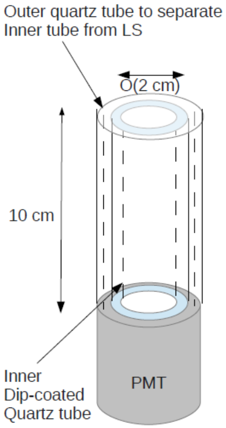
Decay volume and spectrometer magnet

- ✓ ***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



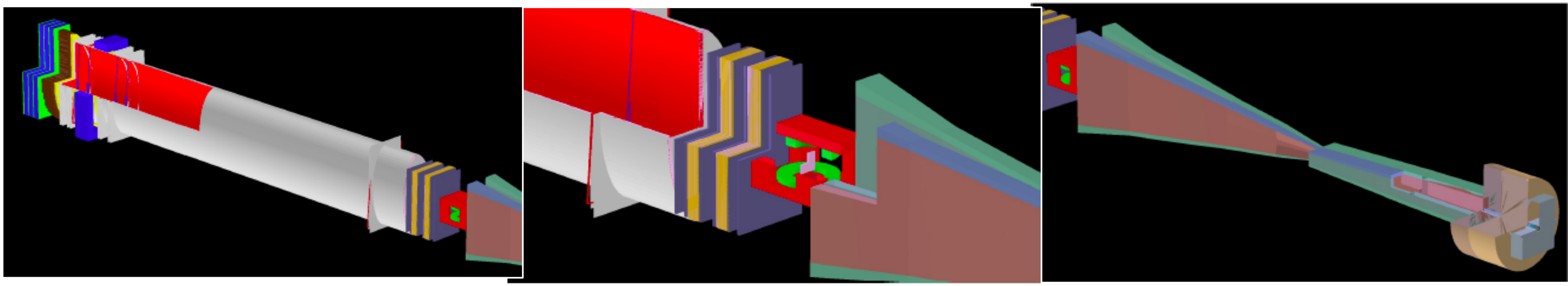
- ✓ ***Magnet designed with an emphasis on low power***

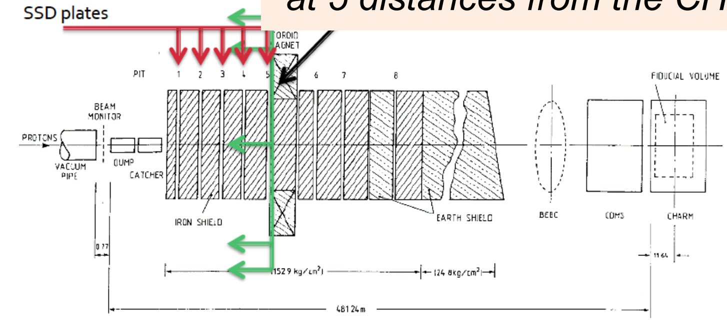
  - *Power consumption < 1 MW*
  - *Field integral: 0.65Tm over 5m*
  - *Weight ~800 t*
  - *Aperture ~50 m^2*

MC simulation: FairShip

(based on FairRoot)

- ✓ **Physics signals and backgrounds simulated using PYTHIA 6/8 and GENIE**
- ✓ **GEANT4 to follow particles through the detector**





Compare data with simulation
at 5 distances from the CHARM target

- ✓ Simulation of the Muon shield performance validated with data from the CHARM beam-dump experiment → **very good agreement**

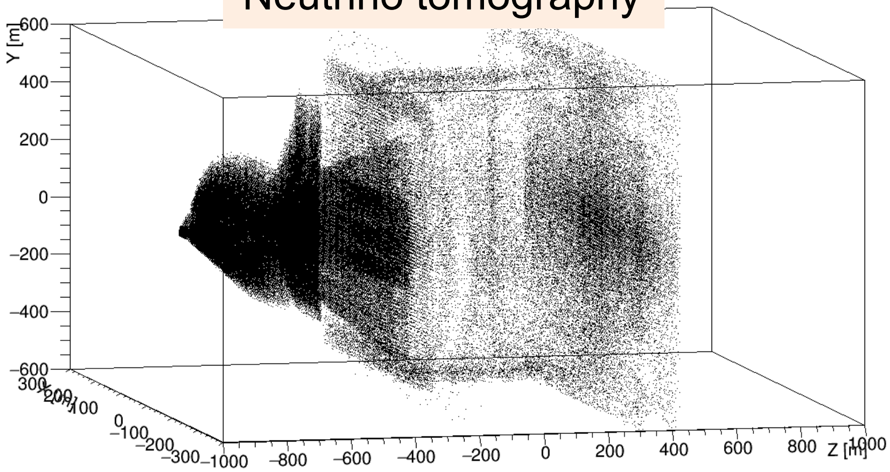
Type of simulation:	EMV		EMX		CHARM
	QGSP	FTFP	QGSP	FTFP	data
Pit 1	8419	9225	8583	9226	8200
Pit 2	624	630	697	645	655
Pit 3	147	168	208	165	137
Pit 4	36	55	37	45	33.1
Pit 5	14	8	4	9	6.1

Backgrounds (1)

Main sources of background

✓ ***Neutrino DIS interactions with material in the vicinity of the HS decay volume*** *(interactions of ν with air in the decay volume are negligible at 10^{-3} mbar)*

Neutrino tomography

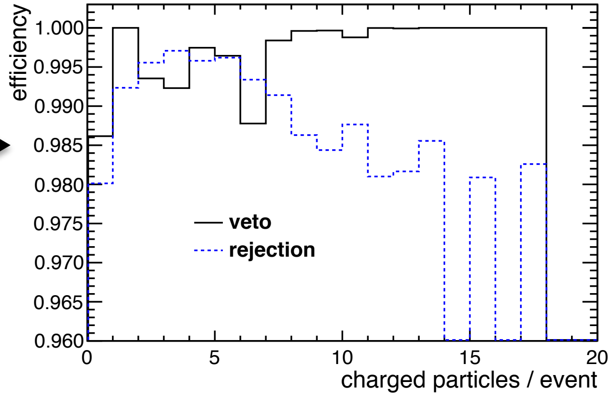


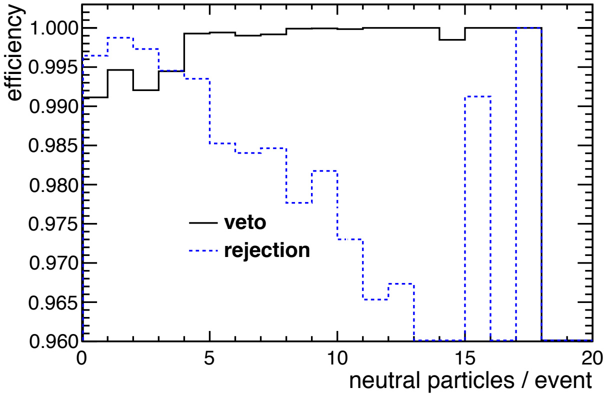
Origin of neutrino interactions

- *Walls of the decay volume (>80%)*
- *Tau neutrino detector*
- *HS tracking system*

Combination of veto and selection cuts reduces the ν-induced background to zero

Veto efficiency increases with event multiplicity →





Backgrounds (2)

✓ **Muon combinatorial background**

Simulation predicts O(10^{12}) muon pairs in the decay volume in 5 years of data taking

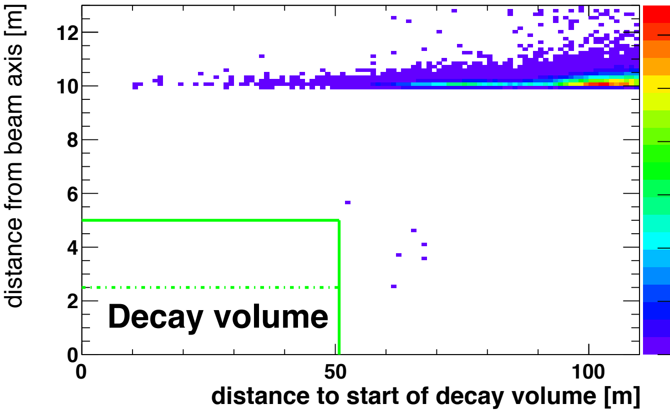
Suppressed by:

- *Basic kinematic and topological cuts ~10^4*
- *Timing veto detectors ~10^7*
- *Upstream veto and surrounding veto taggers ~10^4*

Cut	Value
Track P	> 1.5 GeV/c
Track χ^2/ndof	< 25
dimuon DOCA	< 1 cm
dimuon vertex	fiducial
dimuon mass	> 0.2 GeV/c^2
IP w.r.t target	< 2.5 m
Efficiency	10^{-4}

✓ **Muon DIS interactions**

- *V^0s produced in the walls of the cavern*
- *DIS close to the entry of the decay volume* →
  - → *smaller than neutrino induced background*



✓ **Cosmics**

✓ **Background summary: no evidence for any irreducible background**

Studies with larger simulated samples of backgrounds are ongoing

Signal yield

The same procedure applied to all physics signals, outlined here for HNLs:

$$n(HNL) = N(\text{p.o.t}) \times \chi(pp \to HNL) \times \mathcal{P}_{\text{vtx}} \times \mathcal{A}_{\text{tot}}(HNL \to \text{visible})$$

- ✓ *$N(p.o.t.) = 2\times10^{20}$*
- ✓ $$\chi(pp \to HNL) = 2 \times [\chi(pp \to c\bar{c}) \times \mathcal{BR}(c \to HNL) + \chi(pp \to b\bar{b}) \times \mathcal{BR}(b \to HNL)] \times U^2$$
  - *$\chi(pp \to cc) = 1.7\times10^{-3}$, $\chi(pp \to bb) = 1.6\times10^{-7}$ are production fractions for 400 GeV proton colliding on a Mo target*
  - *$U^2 = U^2_e + U^2_\mu + U^2_\tau$ (ratio between different LF is model dependent)*
- ✓ *$\mathcal{P}_{vtx}$ - probability that HNL (of a given mass and couplings) decays in the SHiP fiducial volume*
- ✓ *$\mathcal{A}_{tot}$ (HNL→visible) – detector acceptance for all HNL final states, HNL → 3ν, $\pi^0\nu$, π^+l^-, $\rho^0\nu$, ρ^+l^-, $l^+l^-\nu$*

$$\mathcal{A}_{\text{tot}}(HNL \to \text{visible}) = \sum_{i=\text{visible channel}} \mathcal{BR}(HNL \to i) \times \mathcal{A}(i)$$

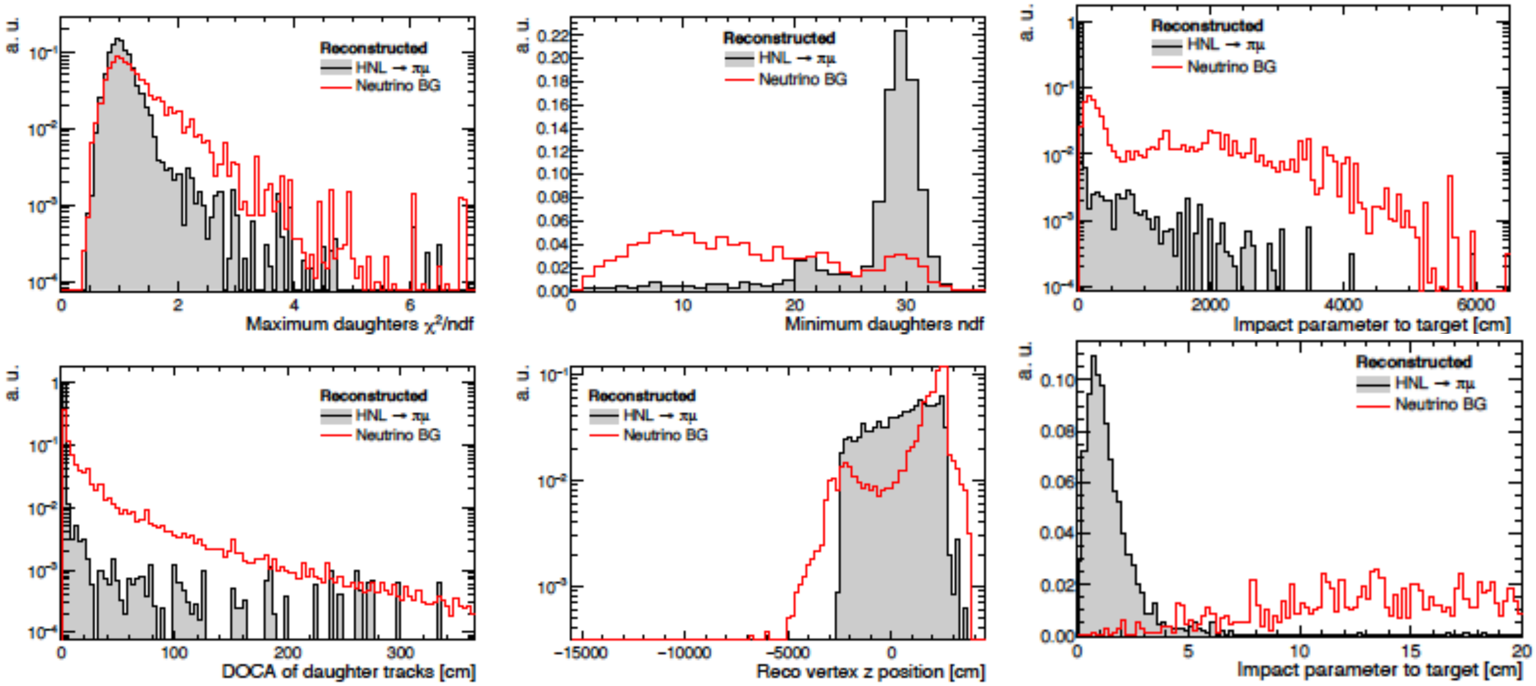
Reconstruction and selection efficiencies

Typical $\mathcal{P}_{vtx}$ × $\mathcal{A}$ × Selection ~ 10^{-6}

Example is shown for
HNL → $\mu\pi$, M(HNL) = 1 GeV

For M(HNL) = 1 GeV with $U^2 = 10^{-8}$
and BR (HNL → $\mu\pi$) =20%,
expect ~330 signal events

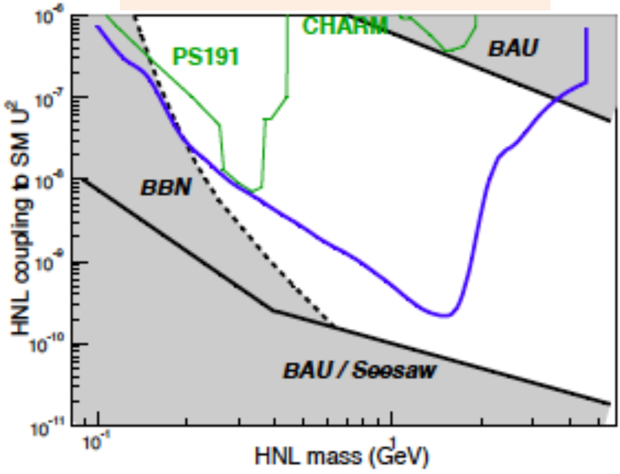
Selection	Acceptance	Efficiency (%)
Event not vetoed	4.87×10^{-6}	75.8
χ^2 / n.d.f. < 5 for both tracks	4.87×10^{-6}	100
n.d.f. > 25 for both tracks	4.37×10^{-6}	89.7
Vertex in fiducial volume	4.34×10^{-6}	99.3
Tracks in fiducial volume	4.34×10^{-6}	100
Energy in ECAL > 150 MeV	4.34×10^{-6}	100
1 muon in 1st muon station	4.30×10^{-6}	99.1
1 muon in 2nd muon station	4.22×10^{-6}	98.2
DOCA < 30 cm	4.22×10^{-6}	100
IP < 2.5 m	4.22×10^{-6}	100



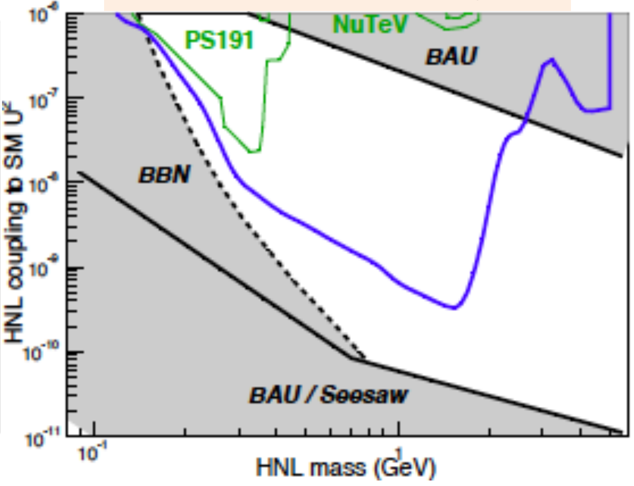
Sensitivity to HNLs for representative scenarios

(moving down to ultimate see-saw limit)

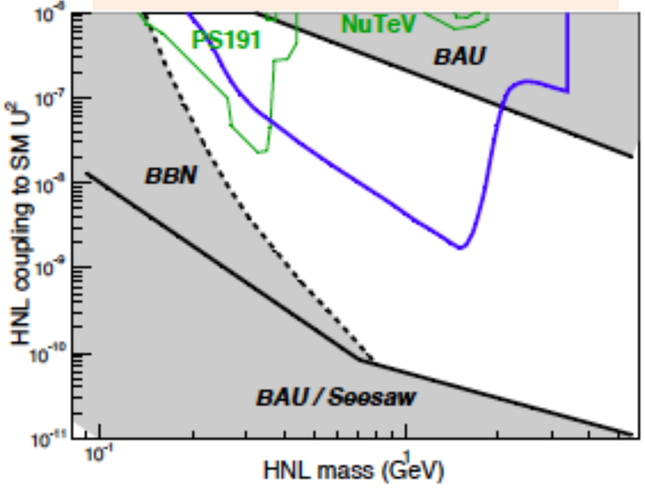
$U^2_e : U^2_\mu : U^2_\tau \sim 52:1:1$
Inverted hierarchy



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

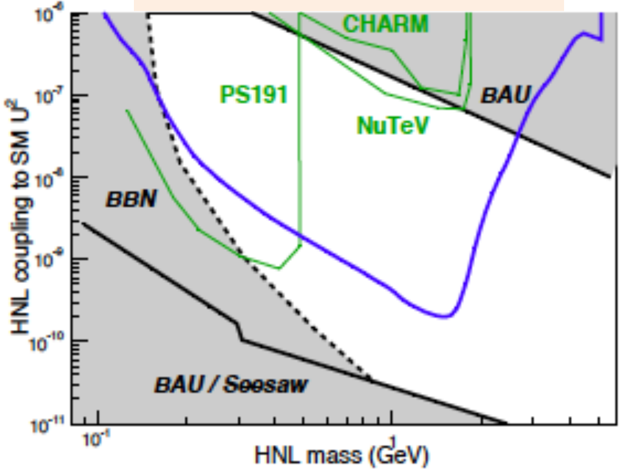


$U^2_e : U^2_\mu : U^2_\tau \sim 0.061:1:4.3$
Normal hierarchy

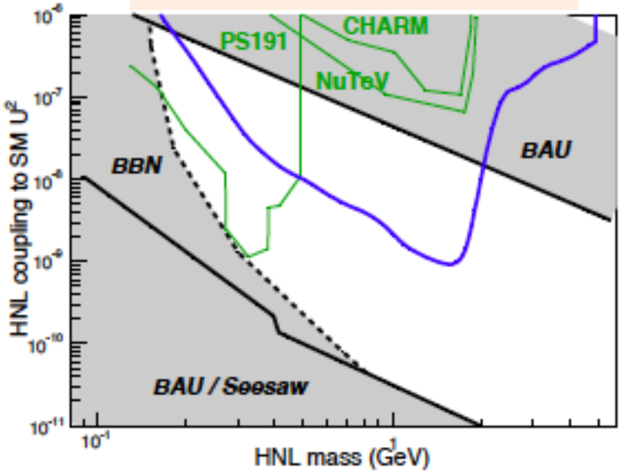


Scenarios for which baryogenesis was numerically proven

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



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



Sensitivity to dark photons

✓ ***Production:***

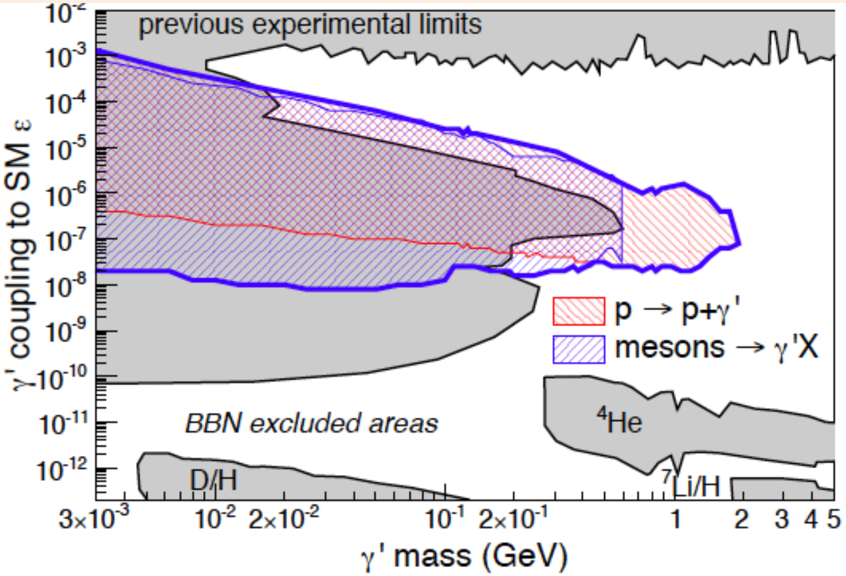
- *mainly decays of $\pi^0 \rightarrow \gamma'\gamma$, $\eta \rightarrow \gamma'\gamma$, $\omega \rightarrow \gamma'\pi^0$ and $\eta' \rightarrow \gamma'\gamma$*
- *a la proton bremsstrahlung (above Λ_{QCD} one should consider parton bremsstrahlung, currently is approximated by the form factor)*

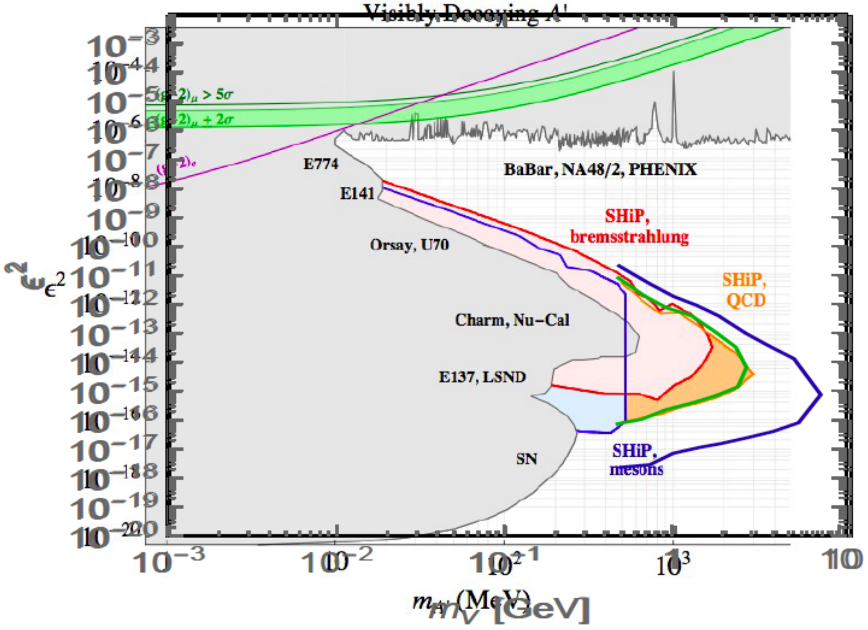
✓ ***Decay***

into a pair of SM particles by mixing again with the SM photon

With new QCD calculations (still in progress) actual sensitivity extends to higher masses O(10 GeV)

SHiP sensitivity (only p-bremsstarhlung)





Sensitivity to hidden scalars

(mixing with the SM Higgs with $\sin^2\Theta$)

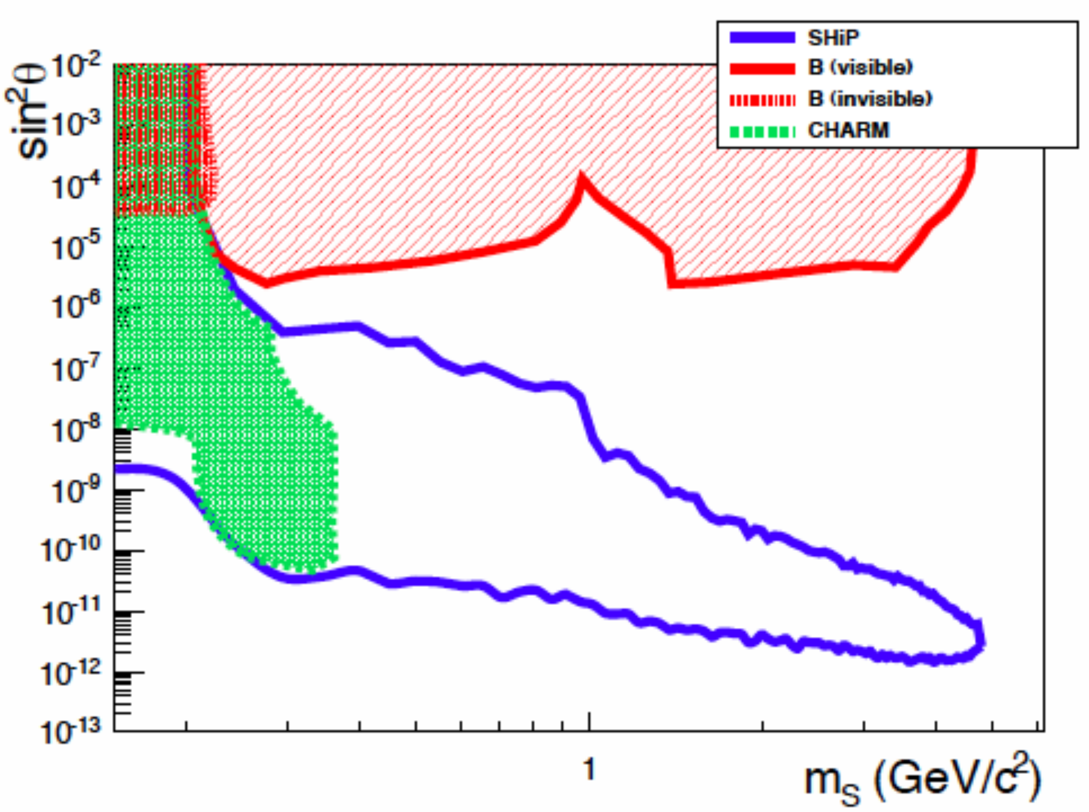
✓ ***Production:***

- mostly penguin-type decays of B and K decays
(D decays are strongly suppressed by CKM)

✓ ***Decay***

into $\underline{e^+e^-, \mu^+\mu^-, \pi^+\pi^+, KK}$, $\eta\eta$, $\tau\tau$, DD, …

SHiP sensitivity



SHiP probes unique range of couplings and masses, thus complementing existing limits from CHARM and B-factories

Neutrino detection

✓ ***Unique capability of detecting all three neutrino flavours***

- $\nu_\tau / \bar{\nu}_\tau$ → *ν interaction and τ decay vertices in emulsion target*
- ν_e → *electrons producing em shower in emulsion target*
- ν_μ → *muons identified by TT, DTT and the muon spectrometer of the tau neutrino detector*

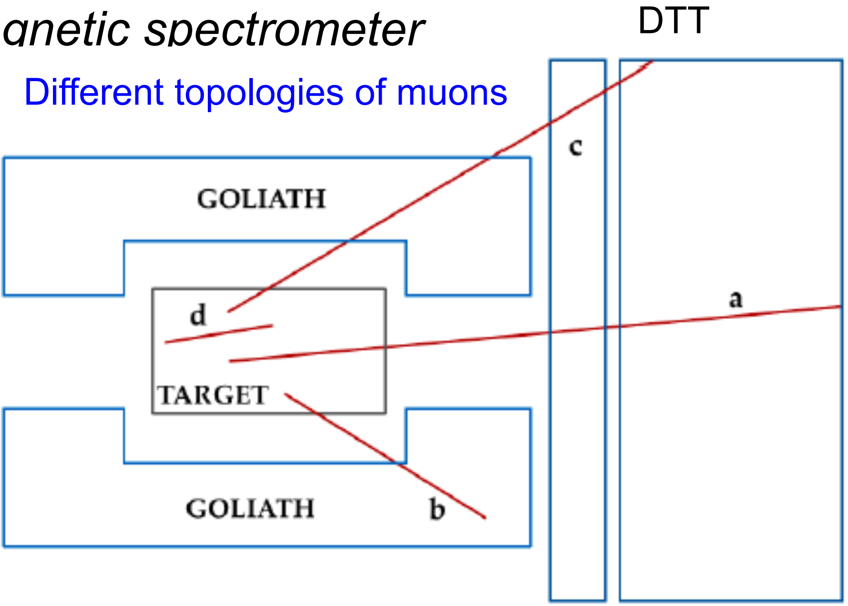
	ε_{tot} (%)
$\tau \to \mu X$	60
$\tau \to hX$	62
$\tau \to 3hX$	63
$\tau \to eX$	56

✓ ***Separation between tau and anti tau-neutrinos by the charge measurement***

- *charge of hadrons is measured by CES*
- *charge of muons is measured by CES and magnetic spectrometer*

	$\tau \to hX$	$\tau \to 3hX$	$\tau \to \mu X$
Correct charge	70%	49%	94%
Wrong charge	0.5%	1.0%	1.5%

Different topologies of muons

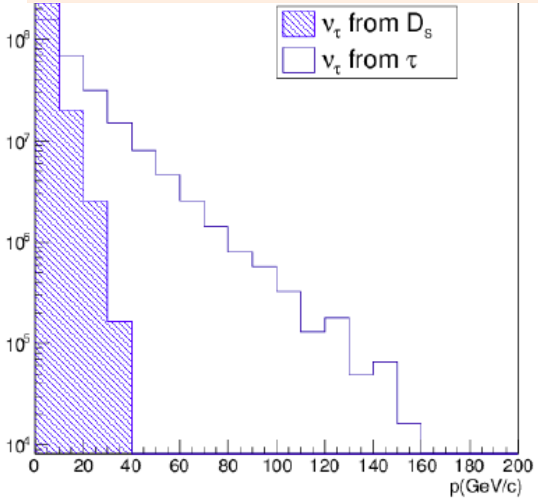


Signal and background yields

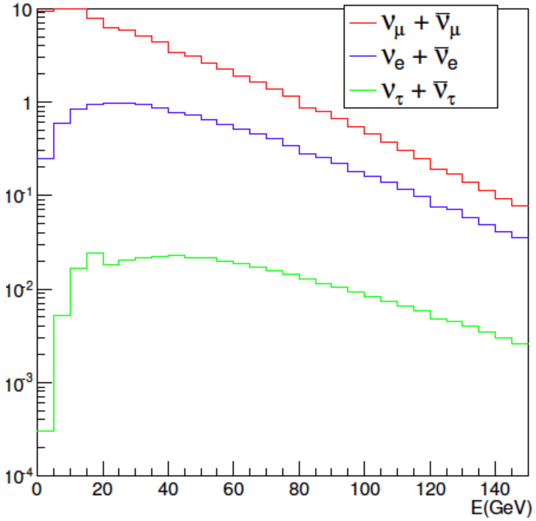
- ✓ ***Copious production in $D_s \rightarrow \tau\bar{\nu}_\tau$:***

$$N_{\nu_\tau+\bar{\nu}_\tau} = 4N_p\frac{\sigma_{c\bar{c}}}{\sigma_{pN}}f_{D_s}Br(D_s\rightarrow\tau) = 2.85\cdot10^{-5}N_p$$

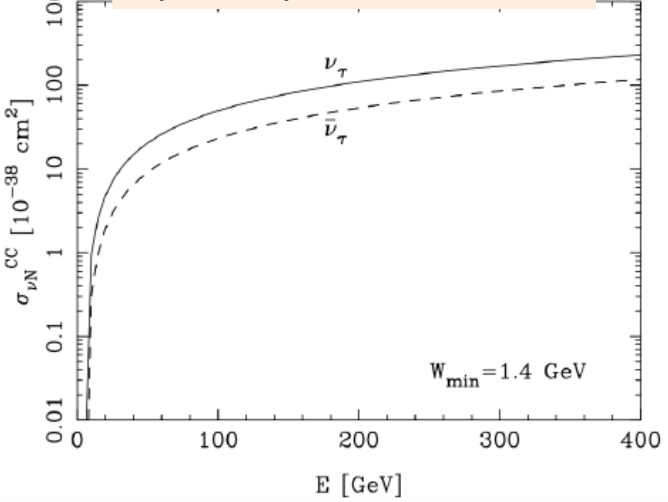
ν_τ produced in D_s is softer



ν spectra in the detector



ν_τ and $\bar{\nu}_\tau$ cross sections



- ✓ *Main backgrounds in two vertex signal topology are hadron re-interactions and decays of charmed particles*

- ✓ ***Expected number of signal and background events for different detection channels***
  (lepton number can not be determined in $\tau \rightarrow eX$)

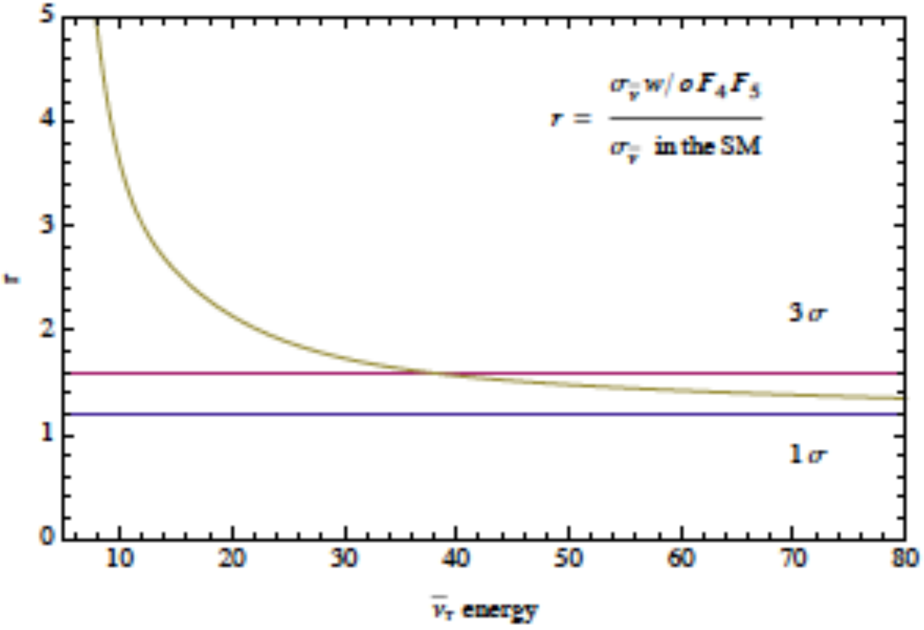
decay channel	ν_τ N^{exp}	ν_τ N^{bg}	ν_τ R	$\bar{\nu}_\tau$ N^{exp}	$\bar{\nu}_\tau$ N^{bg}	$\bar{\nu}_\tau$ R
$\tau\rightarrow\mu$	570	30	19	290	140	2
$\tau\rightarrow h$	990	80	12	500	380	1.3
$\tau\rightarrow 3h$	210	30	7	110	140	0.8
Total	1770	140	13	900	660	1.4

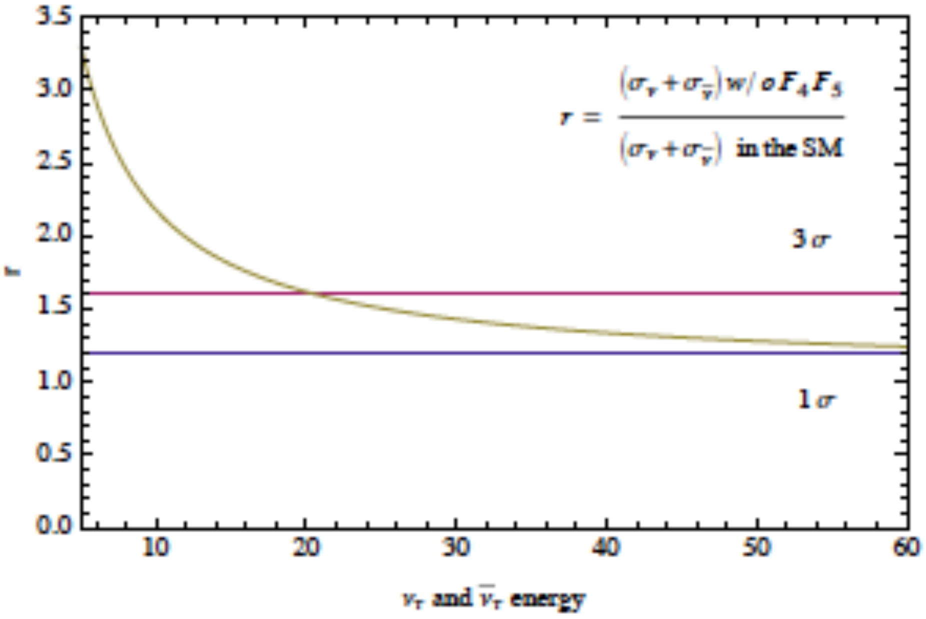
Structure functions F_4 and F_5

F_4 and F_5 , neglected in muon neutrino interactions, give significant contribution to the tau neutrino cross-section:

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

SHiP will provide 3σ evidence for non-zero F_5 (F_4 is ~1% of F_5) for neutrino energies below 20 GeV



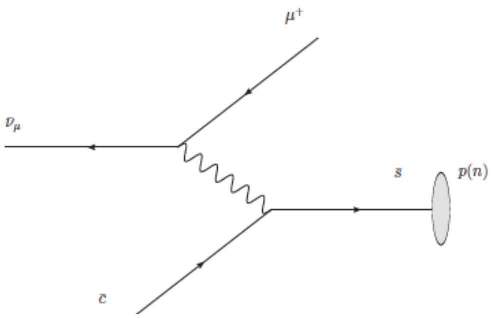


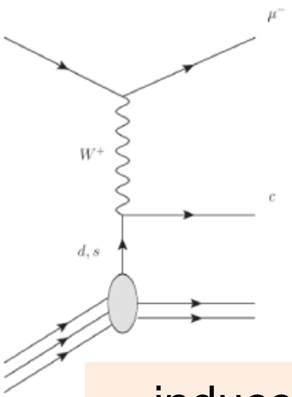
Neutrino induced charm production

In emulsion charm decays can be reconstructed in many channels without kinematical constraints

	Expected events
ν_μ	$6.8 \cdot 10^4$
ν_e	$1.5 \cdot 10^4$
$\bar{\nu}_\mu$	$2.7 \cdot 10^4$
$\bar{\nu}_e$	$5.4 \cdot 10^3$
Total	$1.1 \cdot 10^5$

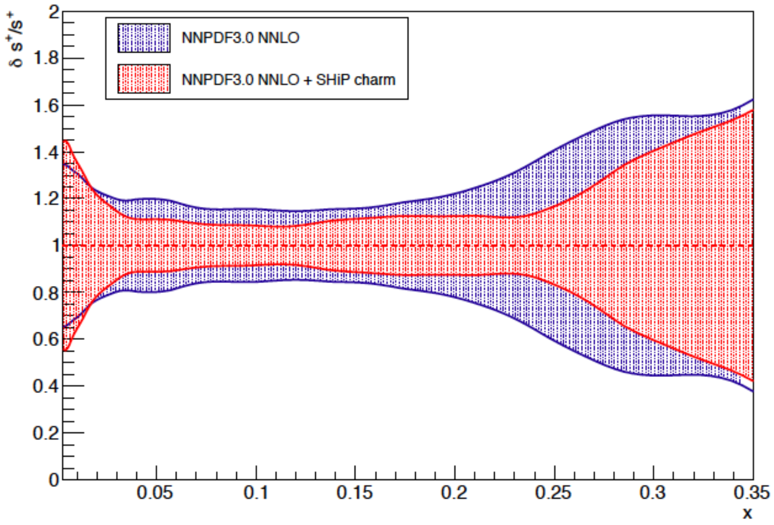
$\bar{\nu}$–induced

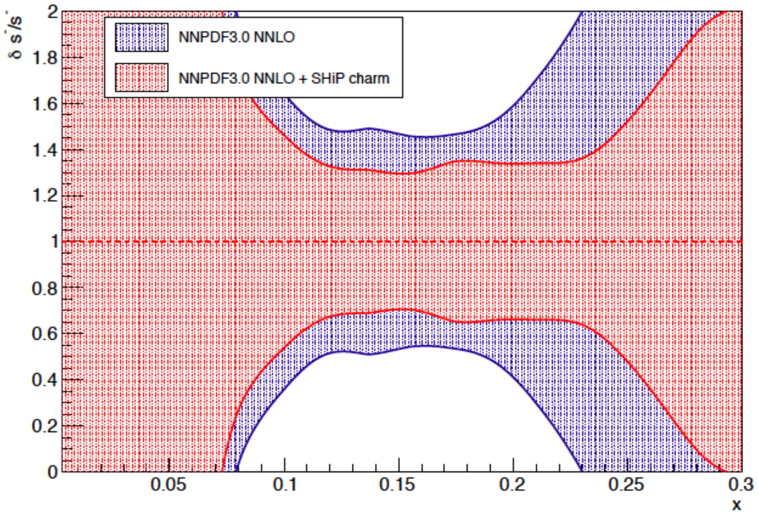




ν–induced

Charmed hadron production in anti-neutrino interaction selects Cabibbo favoured anti-strange quark in the nucleon → useful for constraining $s^+=s(x)+\bar{s}(x)$ and $s^-=s(x)-\bar{s}(x)$





Project organization: cost and resources

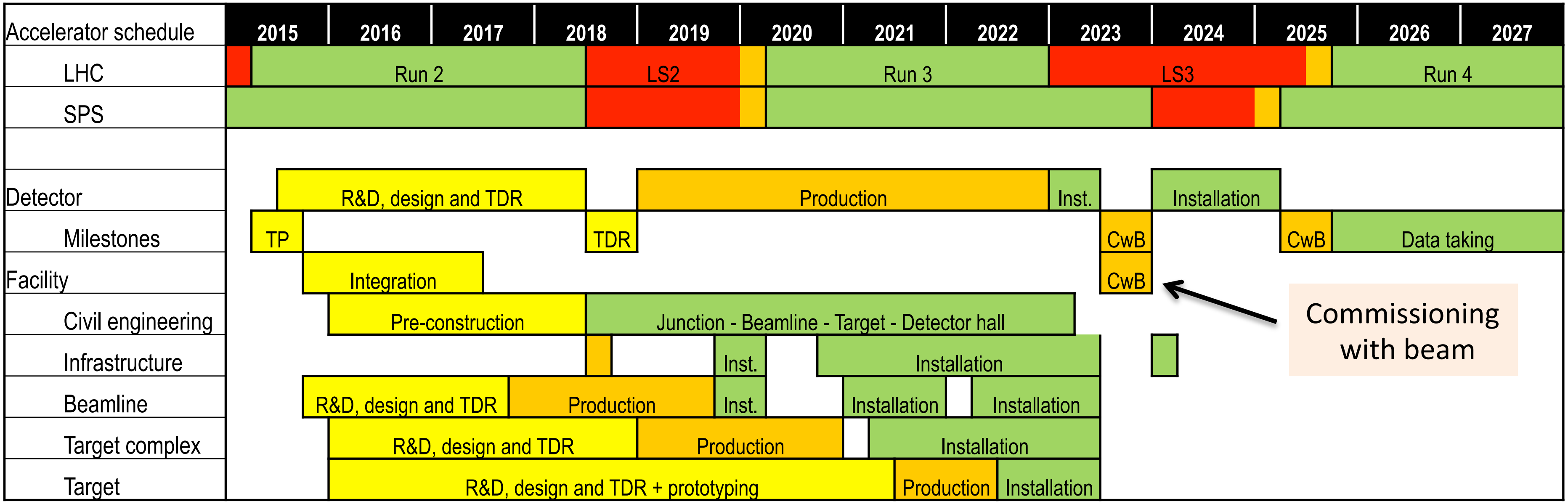
SHiP Collaboration at the time of TP:

- *243 members from 45 institutes in 14 countries*
- *Admission of several additional institutes pending*

Current commitments for preparation of TP and TDR

Component	**Countries**	**Institutes**
Beamline and target	CERN	CERN
Infrastructure	CERN	CERN
Muon shield	UK	RAL, Imperial College, Warwick
HS vacuum vessel	Russia	NRC KI
Straw tracker	Russia, CERN	JINR, MEPhI, PNPI, CERN
HS spectrometer magnet		
ECAL	France, Italy, Russia	ITEP, Orsay, IHEP, INFN-Bologna
HCAL	Italy, Russia, Sweden	ITEP, IHEP, INFN-Bologna, Stockholm
Muon	Italy, Russia	INFN-Bologna, INFN-Cagliari, INFN-Lab. Naz. Frascati, INFN-Ferrara, INR RAS, MEPhi
Surrouding background tagger	Germany, Russia	Berlin, LPNHE, MEPhI
Timing detector and upstream veto	France, Italy, Russia, Switzerland	Zurich, Geneva, INFN-Cagliari, Orsay, LPNHE
Tau neutrino emulsion target	Italy, Japan, Russia, Turkey	INFN-Naples, INFN-Bari, INFN-Lab. Naz. Gran Sasso, Nagoya, Nihon, Aichi, Kobe, Moscow SU, Lebedev, Toho, Middle East Technical University, Ankara
Tau neutrino tracker (GEM)	Italy, Russia	NRC KI, INFN-Lab. Naz. Frascati
Tau neutrino detector magnet	Italy	INFN-Lab. Naz. Frascati, INFN-Bari, INFN-Naples, INFN-Roma
Tau neutrino tracking (RPC)	Italy	INFN-Lab. Naz. Frascati, INFN-Bari, INFN-Lab. Naz. Gran Sasso, INFN-Naples, INFN-Roma
Tau neutrino tracker (drift tubes)	Germany	Hamburg
Online computing	Denmark, Russia, Sweden, UK, CERN	Niels Bohr, Uppsala, UCL, YSDA, LPHNE, CERN
Offline computing	Russia, CERN	YSDA, CERN
MC simulation	Bulgaria, Chile, Germany, Italy, Russia, Switzerland, Turkey, UK, Ukraine, USA, CERN	Sofia, INFN-Cagliari, INFN-Lab. Naz. Frascati, INFN-Napoli, Zurich, Geneva and EPFL Lausanne, Valparaiso, Berlin, PNPI, NRC KI, SINP MSU, MEPhI, Middle East Technical University, Ankara, Bristol, YSDA, Imperial College, Florida, Kyiv, CERN

Project schedule

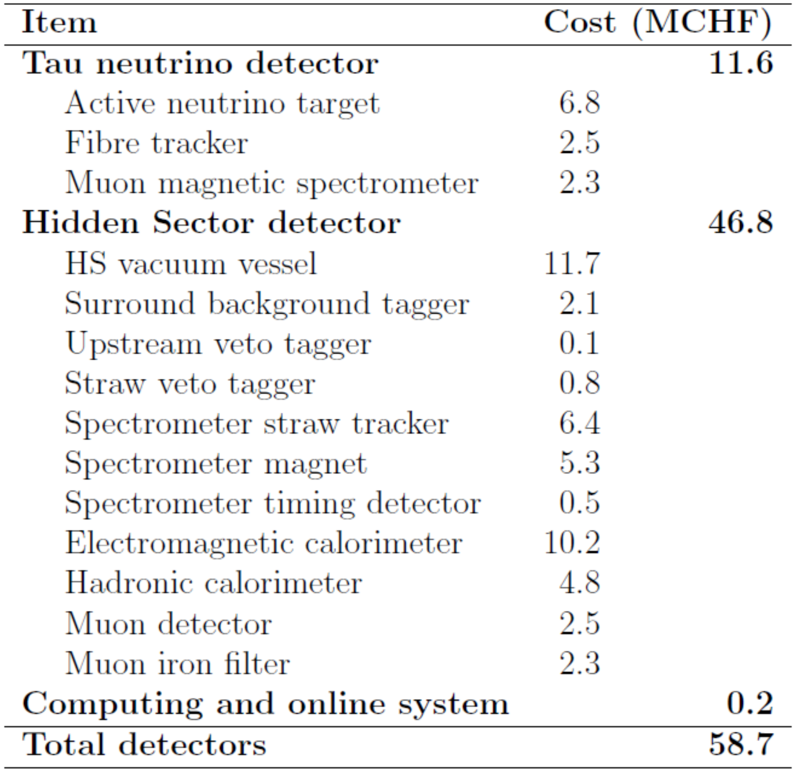


10 years from TP to data taking

- ✓ *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***

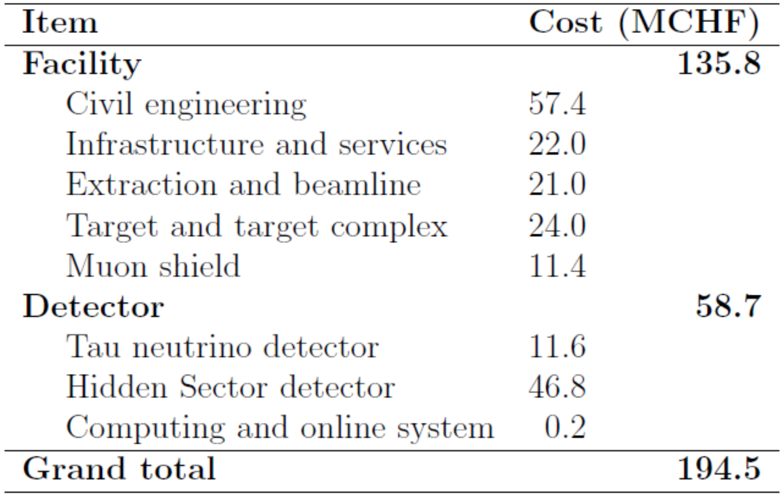
Project organization: Cost and resources

Detector breakdown



Item	Cost (MCHF)	
Tau neutrino detector		**11.6**
Active neutrino target	6.8	
Fibre tracker	2.5	
Muon magnetic spectrometer	2.3	
Hidden Sector detector		**46.8**
HS vacuum vessel	11.7	
Surround background tagger	2.1	
Upstream veto tagger	0.1	
Straw veto tagger	0.8	
Spectrometer straw tracker	6.4	
Spectrometer magnet	5.3	
Spectrometer timing detector	0.5	
Electromagnetic calorimeter	10.2	
Hadronic calorimeter	4.8	
Muon detector	2.5	
Muon iron filter	2.3	
Computing and online system		**0.2**
Total detectors		**58.7**

Overall cost of SHiP facility

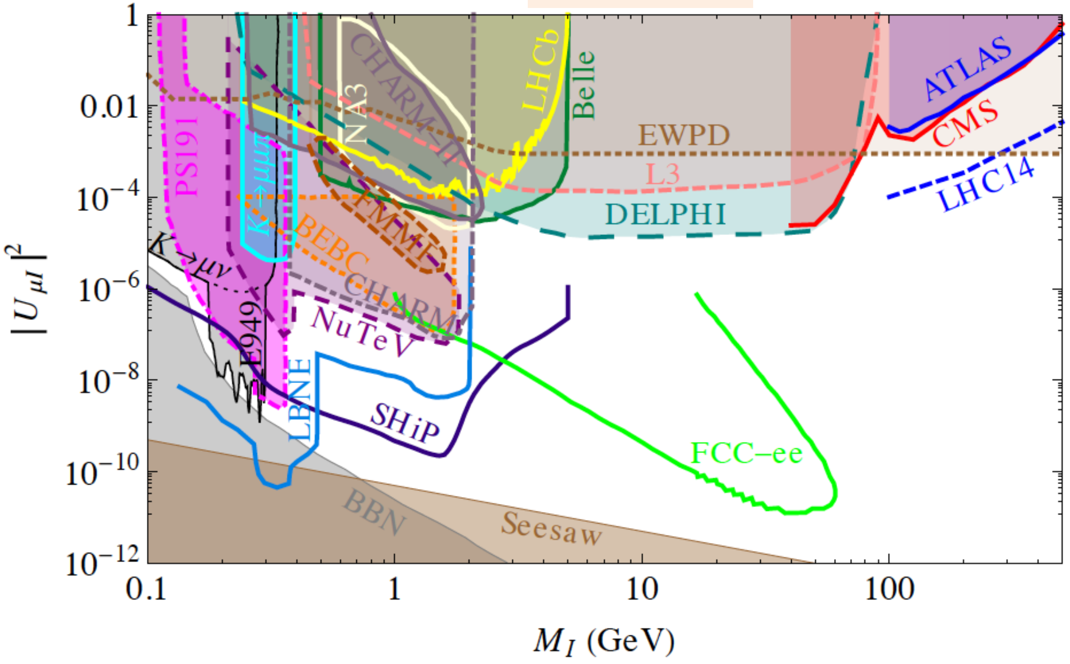


Item	Cost (MCHF)	
Facility		**135.8**
Civil engineering	57.4	
Infrastructure and services	22.0	
Extraction and beamline	21.0	
Target and target complex	24.0	
Muon shield	11.4	
Detector		**58.7**
Tau neutrino detector	11.6	
Hidden Sector detector	46.8	
Computing and online system	0.2	
Grand total		**194.5**

- ✓ *CERN manpower for preparation of entire facility and installation: 103 FTEs*
  - Fellows (6.3 MCHF) included in cost
- ✓ *CERN resource requirements for TDR phase (3years) excluding integration and CE : ~3.2 MCHF and 12.5 FTEs*
- ✓ *CE preparatory cost (integration, design, EIA, permit, tendering, 2.5 years)*
  → 2.5 MCHF and 12.5 FTEs

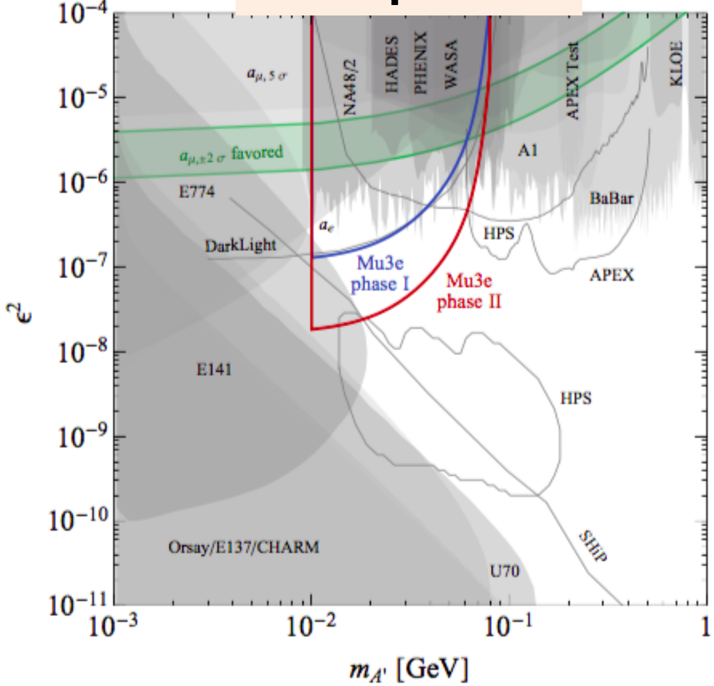
Hidden Sector experimental constraints in future

HNL



- ✓ *$M_{HNL} < M_b$*
LHCb, BelleII
SHiP will have much better sensitivity
- ✓ *$M_b < M_{HNL} < M_Z$ FCC in ee mode*
- ✓ *$M_{HNL} > M_Z$ Prerogative of ATLAS/CMS @ HL LHC*

Dark photon



- ✓ *SHiP will have unique sensitivity for “heavy” dark photons*
- ✓ *HPS is expected to cover new range of ε^2 in a couple of years*

SHiP at CERN @ 400 GeV vs XXX at Fermilab @ 120 GeV

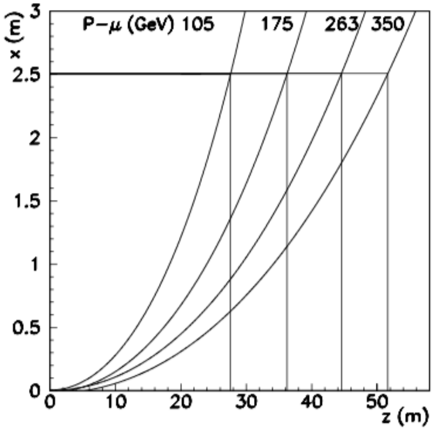
Assume:

- *Hypothetical detector XXX has similar size to the SHiP detector*
- *Slow beam extraction (*)*
- *The target with the same material (*)*
- *Full background suppression*
- ***Dedicated to XXX operation (in conflict with neutrino programme)***

(*) – technical feasibility to be demonstrated for XXX

	SHiP	**XXX** **40 m long and at 37 m from the target**
N_{pot} / year delivered at ~1s extraction	4×10^{19}	$\sim5.3\times10^{20}$
$\sigma_{cc}(E_{beam})$, au	1	1/7
Detector acceptance (E), au	1	0.6

Trajectory of m in Fe(1.8T)



- ✓ ***Similar performance for HS produced in charm decays***
  Sensitivity for HS produced in B decay is severely compromised, σ_{bb} (120/400) = 625
- ✓ ***Really poor prospects for tau neutrino physics at 120 GeV beam energy***

Summary

- ✓ *SHiP is proposed to search for New Physics in the largely unexplored domain of new, very weakly interacting particles with masses O(10) GeV*
- ✓ *Also unique opportunity for ν_τ physics*
- ✓ *Sensitivity improves previous experiments by O(10000) for Hidden Sector and by O(200) for ν_τ physics*
- ✓ ***The technical feasibility of the SHiP facility has been demonstrated by the CERN Task Force. Great thanks !***
- ✓ ***The impact of the discovery of a new light hidden particle is hard to overestimate !***
- ✓ ***SHiP will greatly complement searches for New Physics at energy frontier at CERN***