The SHiP Experiment at CERN

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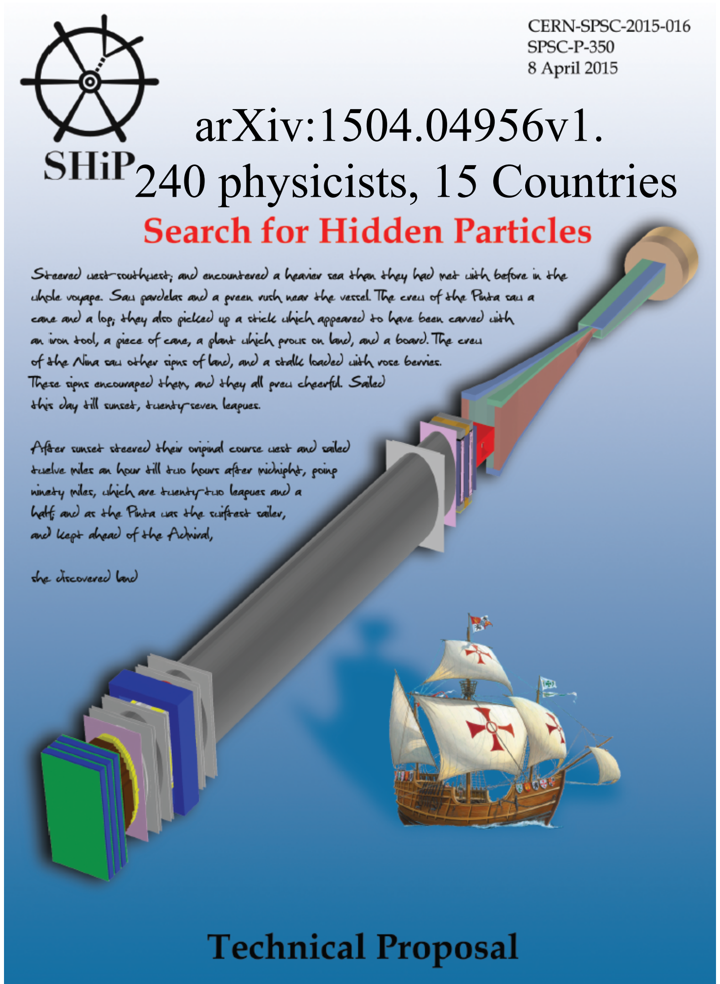
On behalf of the SHiP Collaboration

SHiP

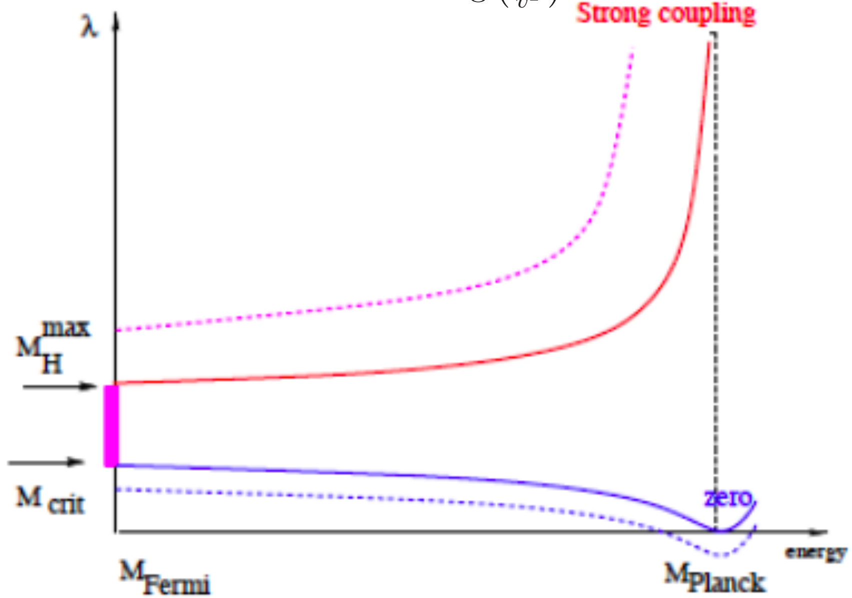


SM may well be a consistent effective theory all the way up to the Plank scale

- ✓ *M_H < 175 GeV → SM is a weakly coupled theory up to the Plank energies!*
- ✓ *M_H > 111 GeV → EW vacuum is stable or metastable with a lifetime greatly exceeding the age of our Universe (Espinosa et al)*

S. Heinemeyer, Higgs Physics, arXiv:1405.3781

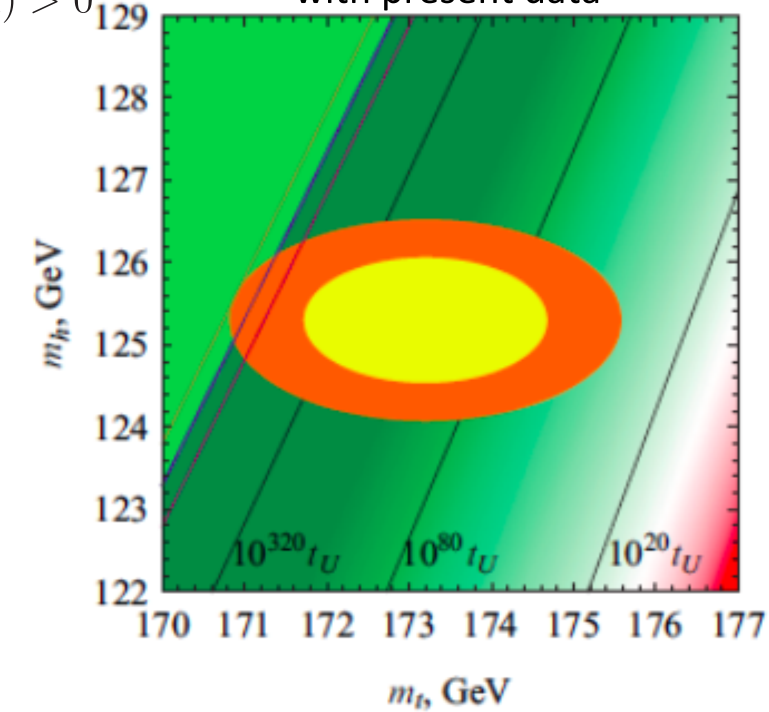
$$\lambda(\Lambda) < \infty \quad \Rightarrow \quad M_H^2 \le \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}$$



$1{,}22 \times 10^{19}$ GeV

$$\lambda(\Lambda) > 0$$

Stable vacuum fully consistent with present data



G. Degrassi et al.,Higgs mass and vacuum stability in the SM at NNLO, JHEP 1208 (2012) 098

- ✓ *No sign of New Physics seen*

Nevertheless, many open questions in particle physics!

Among the most relevant ones:

Why is the Higgs boson so light (so-called "naturalness" or "hierarchy" problem) ?

What is the origin of the matter-antimatter asymmetry in the Universe ?

Why 3 fermion families ? Why do neutral leptons, charged leptons and quarks behave differently ?

What is the origin of neutrino masses and oscillations ?

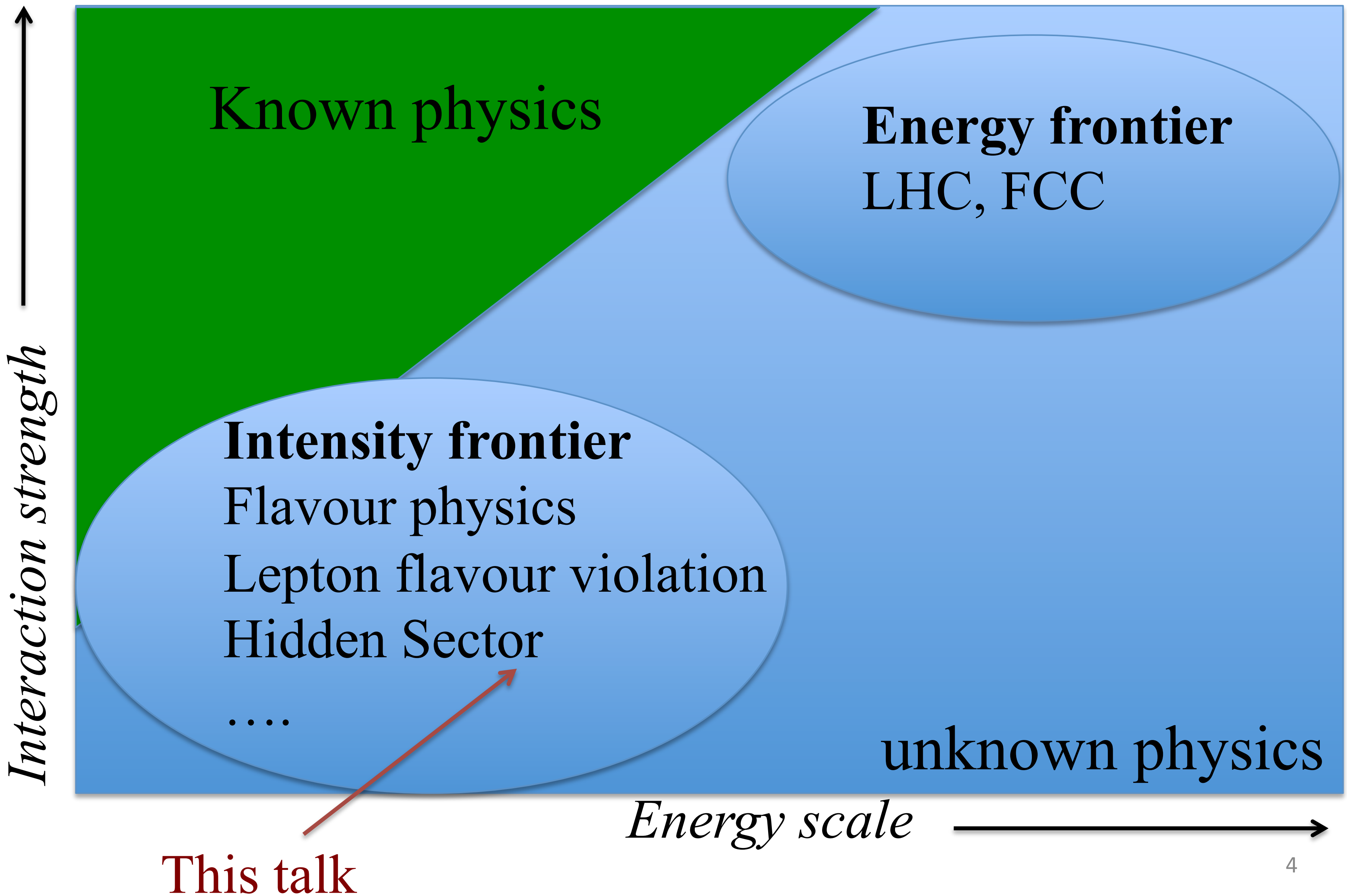
What is the composition of dark matter (~25% of the Universe) ?

However: there is NO direct evidence for new particles (yet…) from the LHC or other facilities

Where is the New Physics ?

i.e. at what E scale(s) will we find the answers to these questions ?

High Intensity Frontier



Light Hidden particles → singlets with respect to the SM gauge group
→ couple to different singlet composite operators (**Portals**) of the SM

Renormalizable

$$LHN$$ Neutrino portal

$$(\mu S + \lambda S^2) H^\dagger H$$ Higgs Portal

$$-\frac{\kappa}{2} B_{\mu\nu} V^{\mu\nu}$$ Vector Portal

Higher dimension operators

$$\frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$ Axion Portal

$$\frac{1}{\Lambda^2} \bar{\chi}\chi\bar{q}q + \ldots,$$

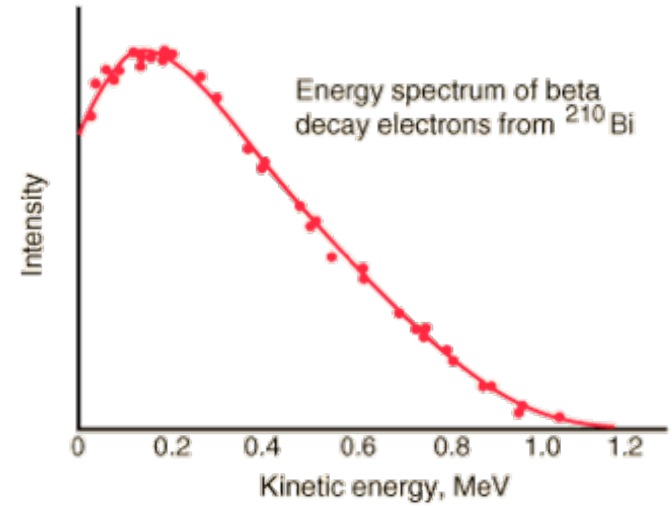
Dark Matter

Light mediator

$$g_\chi \phi \bar{\chi}\chi + g_q \phi \bar{q} q + \ldots$$

History lesson - 1930s:

- Back then, the "Standard Model" was photon, electron, nucleons
- Beta decay: $n \to p + e^-$



Continuous spectrum!

- Pauli proposes a radical solution - the neutrino!

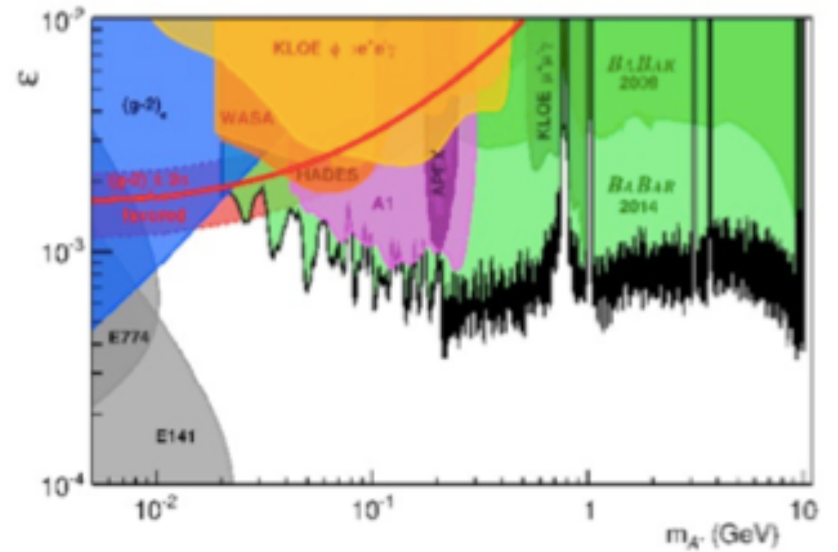
$$n \to p + e^- + \bar{\nu}$$

- Great example of a hidden sector!
  - neutrino is electrically neutral (QED gauge singlet)
  - very weakly interacting and light
  - interacts with "Standard Model" through "portal" - $(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu)$

Search for dark photons

- Assuming no lighter hidden particles, γ' decay into SM particles through a virtual photon:

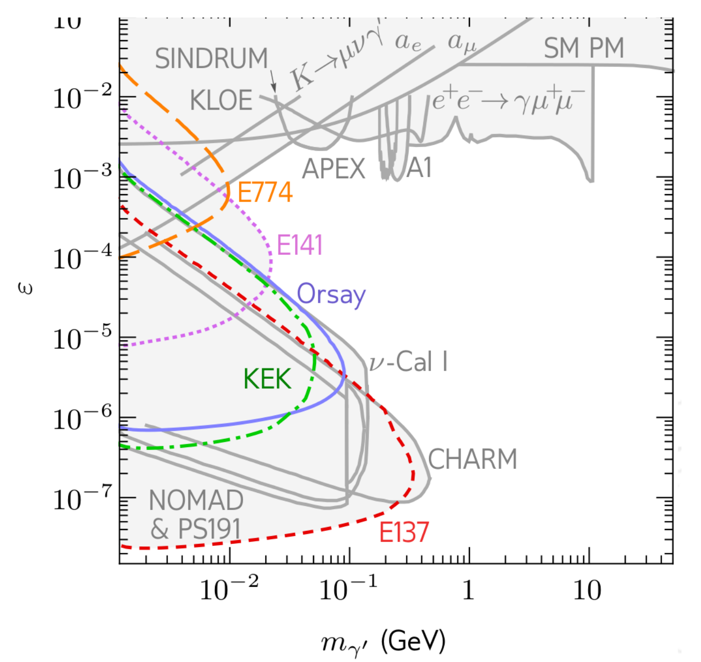
$$\gamma' \to e^+e^-, \quad \mu^+\mu^-, \quad q\bar{q}, \ldots$$



- decay length $c\tau \sim \varepsilon^{-2} m_{\gamma'}^{-1}$
- cosmological constraints (nucleo-synthesis): $\tau < 0.1$ s $\Rightarrow \varepsilon^2 m_{\gamma'} > 10^{-21}$ GeV

γ' production

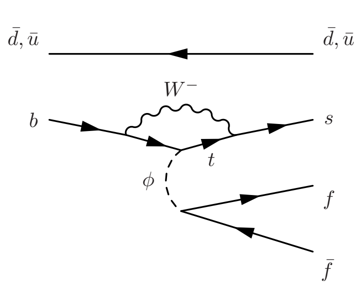
- proton bremsstrahlung:
  - initial-state radiation from the incoming proton, followed by a hard proton-nucleus interaction



- secondary particles decay:

Mass interval (GeV)	Process	$n_{\gamma'}/p.o.t$
$m_{\gamma'} < 0.135$	$\pi^0 \to \gamma\gamma'$	$\varepsilon^2 \times 5.41$
$0.135 < m_{\gamma'} < 0.548$	$\eta \to \gamma\gamma'$	$\varepsilon^2 \times 0.23$
$0.548 < m_{\gamma'} < 0.648$	$\omega \to \pi^0\gamma'$	$\varepsilon^2 \times 0.07$
$0.648 < m_{\gamma'} < 0.958$	$\eta' \to \gamma\gamma'$	$\varepsilon^2 \times 10^{-3}$

Higgs (scalar) portal: production and decay modes

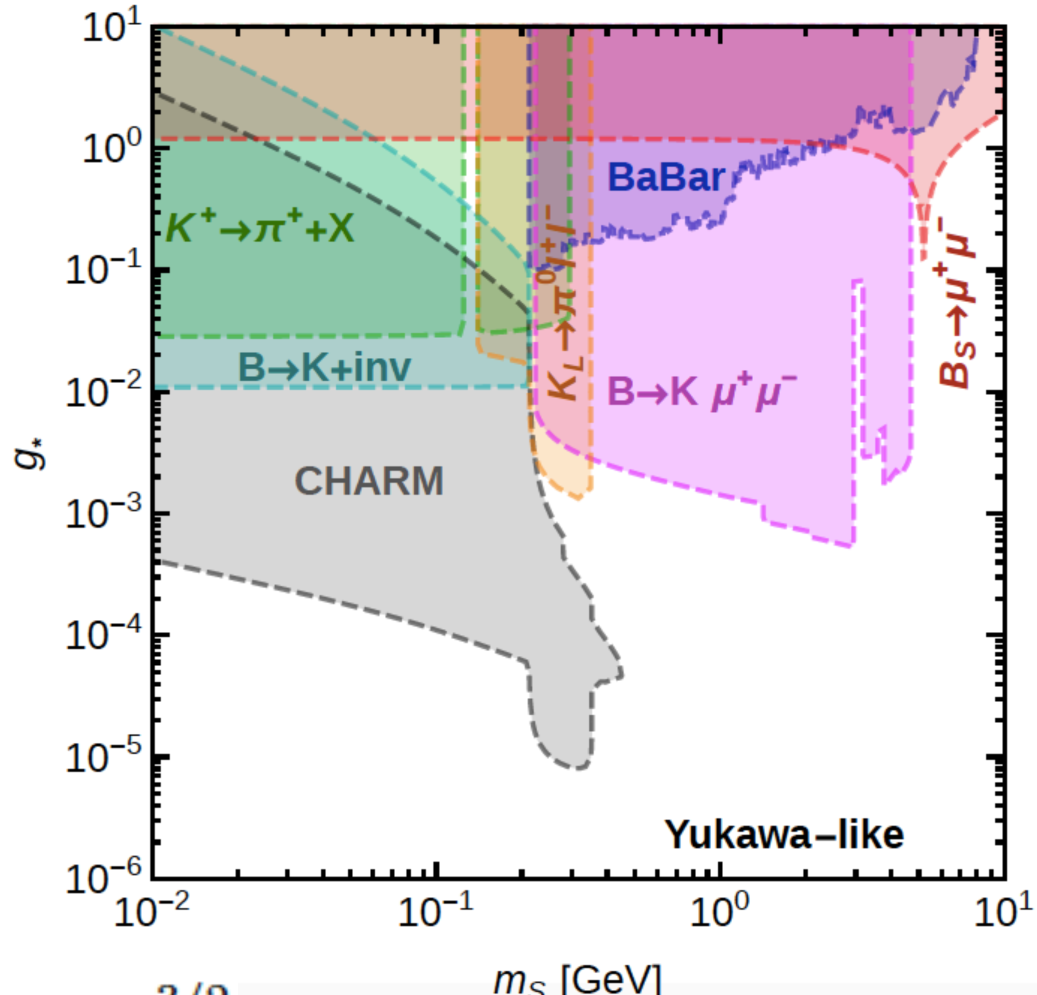


$$\Gamma(D \to \pi\phi) \sim (m_b^2 |V_{cb}^* V_{ub}|)^2 \propto m_b^4 \lambda^5$$

$$\Gamma(B \to K\phi) \sim (m_t^2 |V_{ts}^* V_{tb}|)^2 \propto m_t^4 \lambda^2$$

B decays favoured compared to D

Rare B meson decays mediated by a light scalar ϕ



$$\Gamma(S \to \ell\bar{\ell}) = \frac{g_\star^2\, m_\ell^2 m_S}{8\pi v^2}\left(1 - \frac{4m_\ell^2}{m_S^2}\right)^{3/2}$$

Motivation for Heavy Neutral Leptons

See-saw mechanism for neutrino masses

Most general renormalisable Lagrangian of SM particles (+3 singlets wrt SM gauge group):

$$L_{singlet} = i\bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\alpha} \bar{N}_I^c \tilde{H} L_\alpha - M_I \bar{N}_I^c N_I + h.c.$$

Yukawa term: mixing of N_I with active neutrinos to explain oscillations

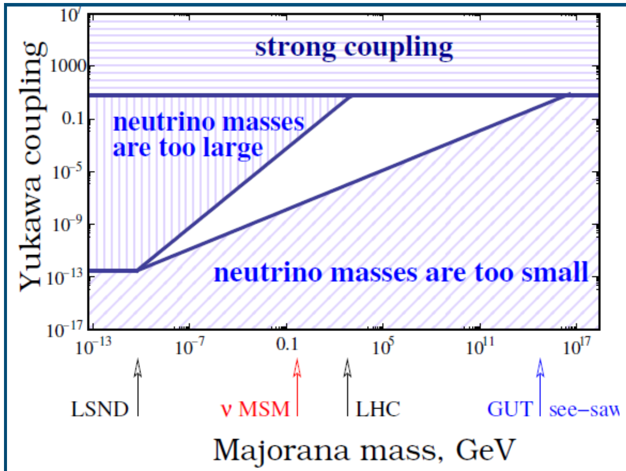
Majorana term which carries no gauge charge

$$v \sim 246 \text{ GeV}$$

The scale of the active neutrino mass is given by the see-saw formula: $m_\nu \sim \frac{m_D^2}{M}$

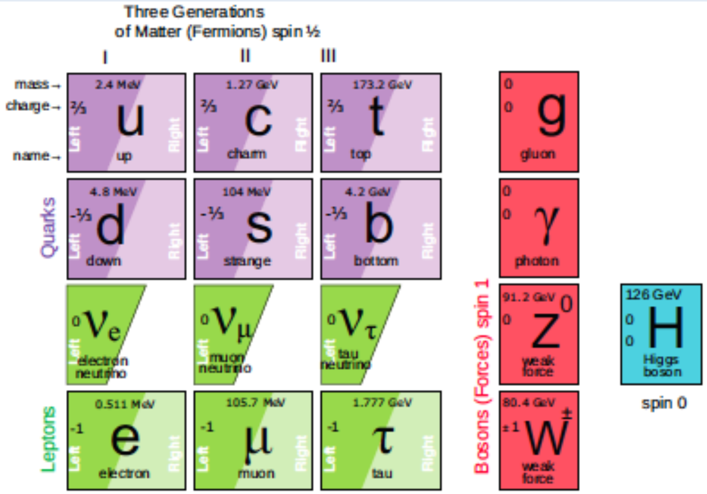
where $m_D \sim Y_{I\alpha} v$ *- typical value of the Dirac mass term*

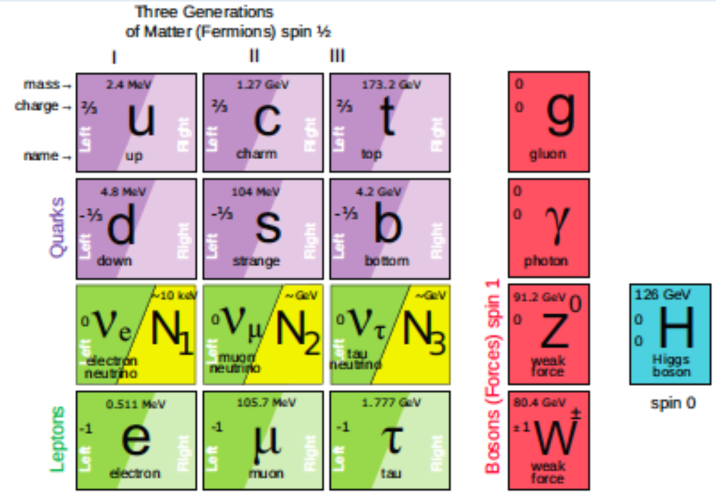
Four "popular" N mass ranges



	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

The νMSM model: leptogenesis and dark matter





N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter

Role of $N_2,\ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

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

global lepton-number symmetry broken at the level of O(10^{-4}) leads to the required pattern of sterile neutrino masses consistent with neutrino oscillations data

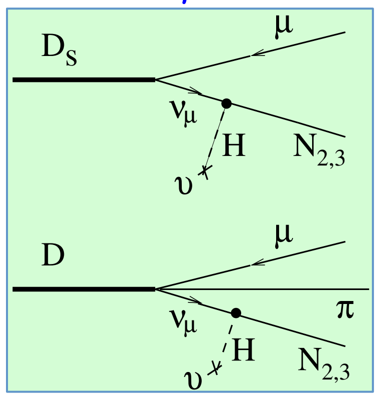
Masses and couplings of HNLs

- ***M(N_2) ≈ M(N_3) ~ a few GeV→ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)***

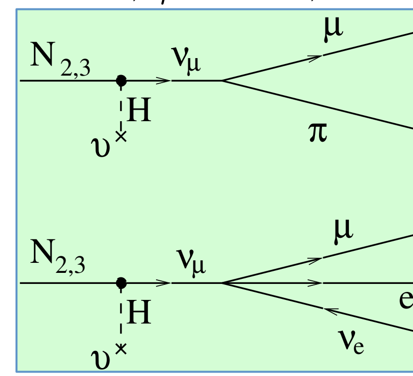
Very weak $N_{2,3}$-to-ν mixing (~ U^2) → $N_{2,3}$ are much longer-lived than SM particles

- Produced in semi-leptonic decays, $\mathrm{K} \to \mu\nu,\ \mathrm{D} \to \mu\pi\nu,\ \mathrm{B} \to \mathrm{D}\mu\nu$
- $\propto \sigma_D \times U^2$
- $U_2^2 = U_{2,\nu_e}^2 + U_{2,\nu_\mu}^2 + U_{2,\nu_\tau}^2$

Example:
$N_{2,3}$ production in charm



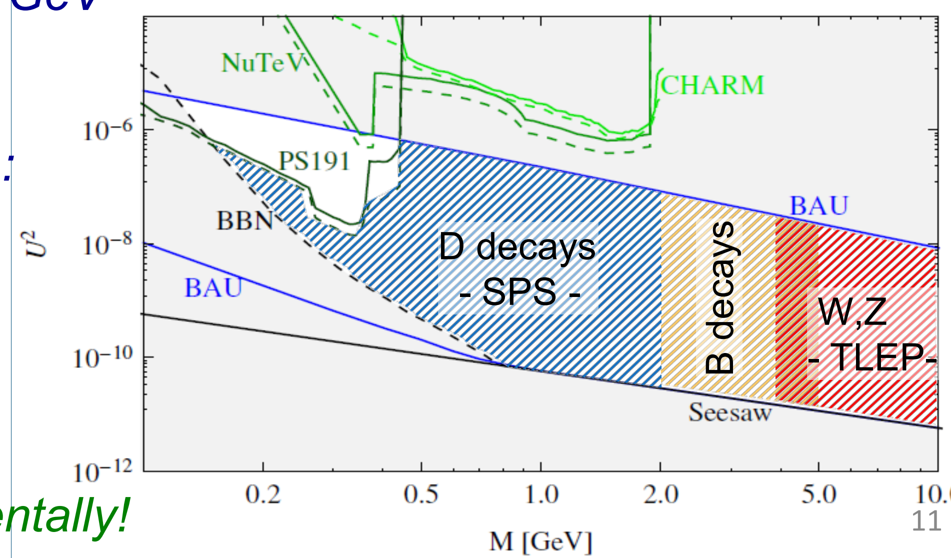
and subsequent decays



- *Typical lifetimes > 10 μs for M($N_{2,3}$) ~ 1 GeV*
  Decay distance O(km)

- *Typical BRs (depend on flavour mixing):*

  Br(N → μ/e π) ~ 0.1 – 50%
  Br(N → $\mu^-/e^-\ \rho^+$) ~ 0.5 – 20%
  Br(N → νμe) ~ 1 – 10%



Domain only marginally explored, experimentally!

Common experimental features of Hidden Sector (HS)

SHiP

- ✓ *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*

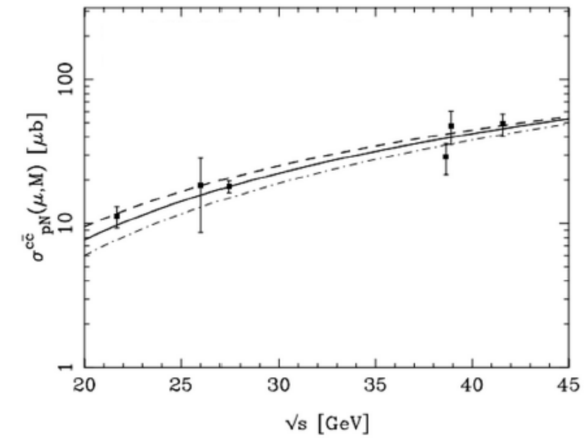
- ✓ *Production and decay rates are strongly suppressed when compared to SM*
  - *Production branching ratios O(10^{-10})*
  - *Long-lived objects*
  - *Travel unperturbed through ordinary matter*

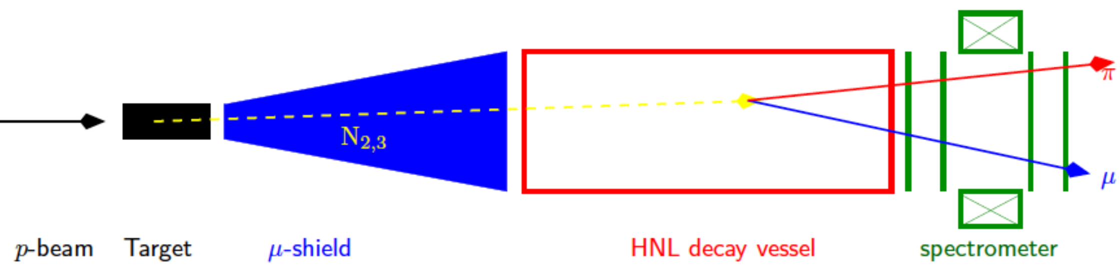
- ✓ ***Challenge is background suppression → requires O(0.01) carefully estimated***

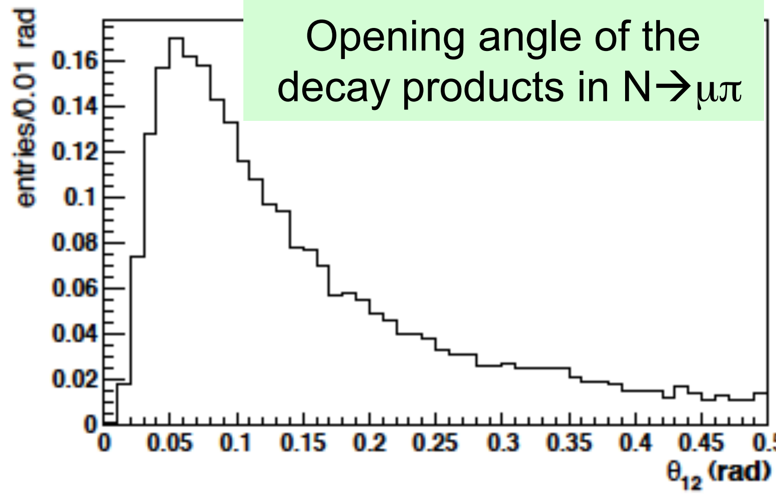
- ✓ ***Physics with ν_τ produced in D_s decays share many of these features***

General experimental requirements

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





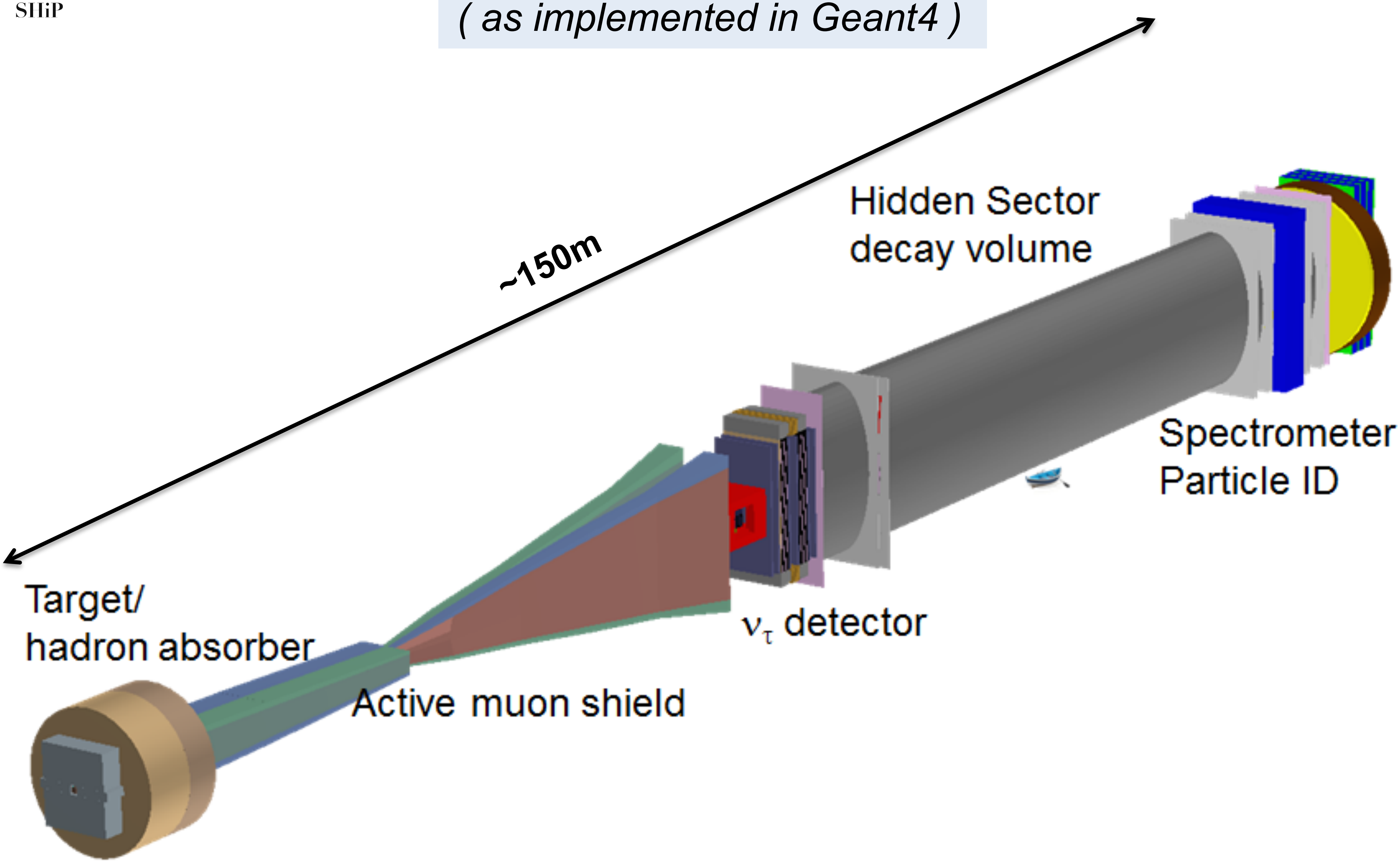


Opening angle of the decay products in N→$\mu\pi$

- ✓ *Detector must be placed close to the target to maximize geometrical acceptance*
- ✓ *Effective (and "short") muon shield is essential to reduce muon-induced backgrounds*
- ✓ *With 2 x 10^{20} 400 GeV pot, ~ 2 x 10^{17} charm produced*

The SHiP experiment

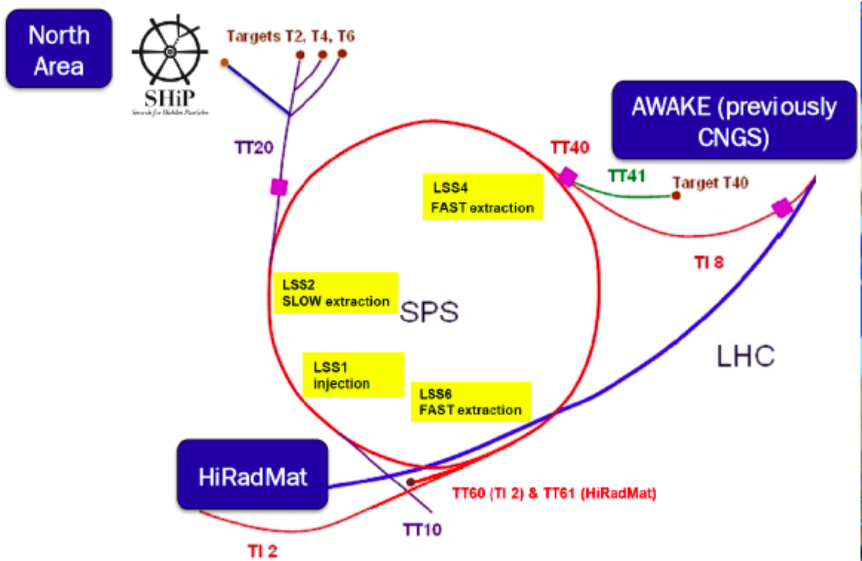
(as implemented in Geant4)

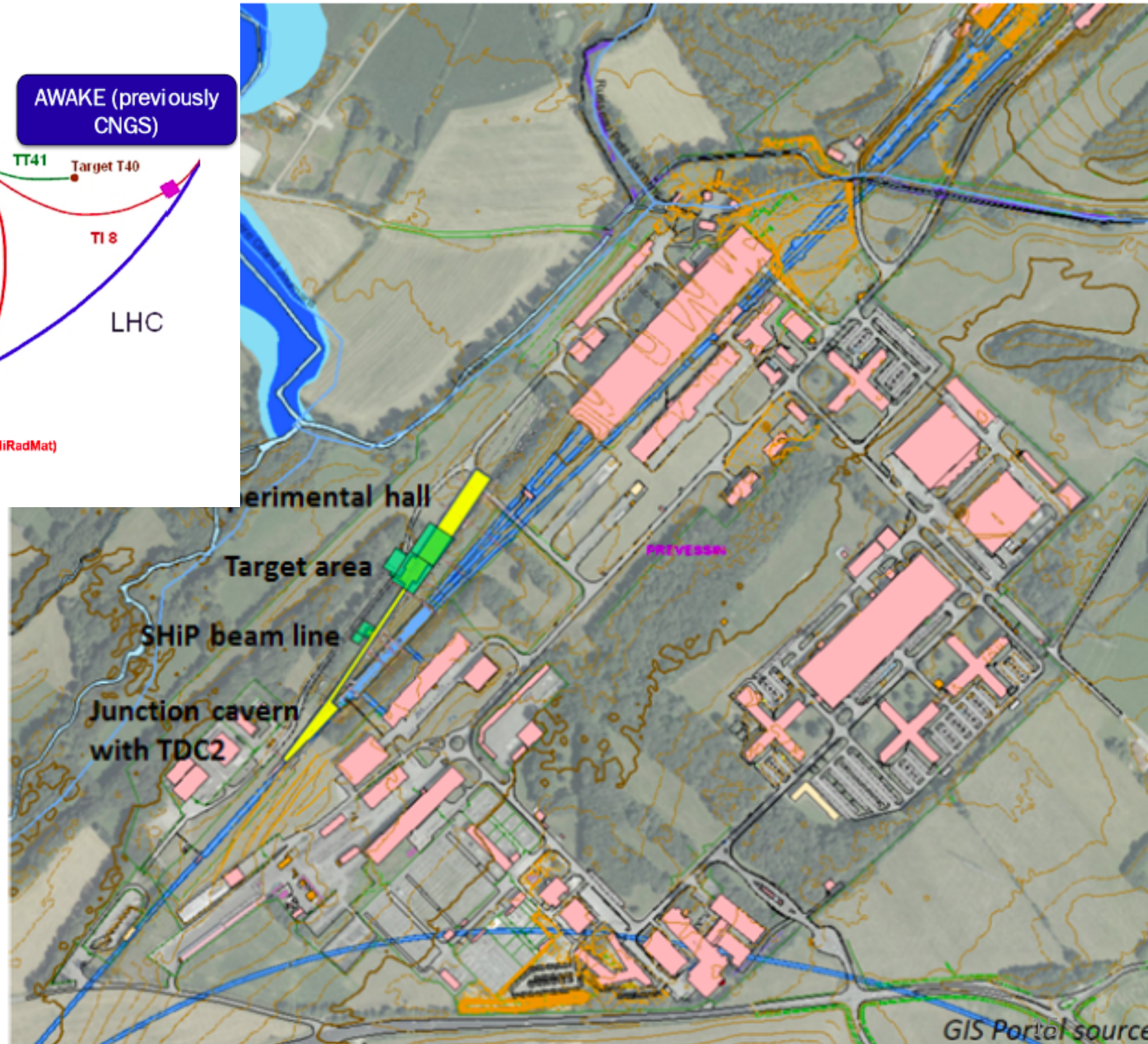


The Fixed-target facility at the SPS: Prevessin North Area site

Proposed implementation based on minimal modification of the SPS complex

High-intensity proton beam: 4 10^{13} ppp, 4 10^{19} pot/yr, 5 years run (as for CNGS)

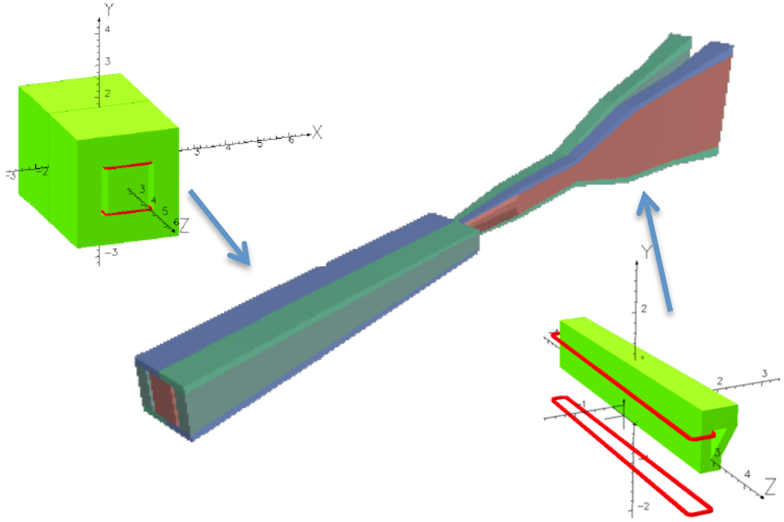




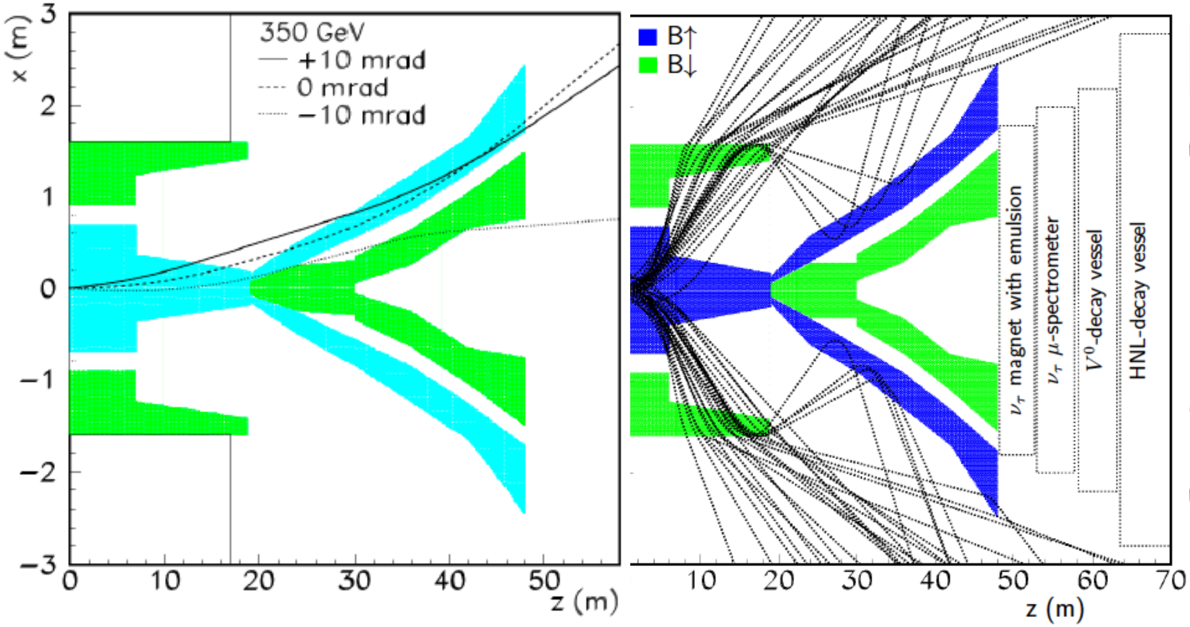
The SHiP facility is located on the North Area, and shares the TT20 transfer line and slow extraction mode with the fixed target programmes

SHiP muon shield

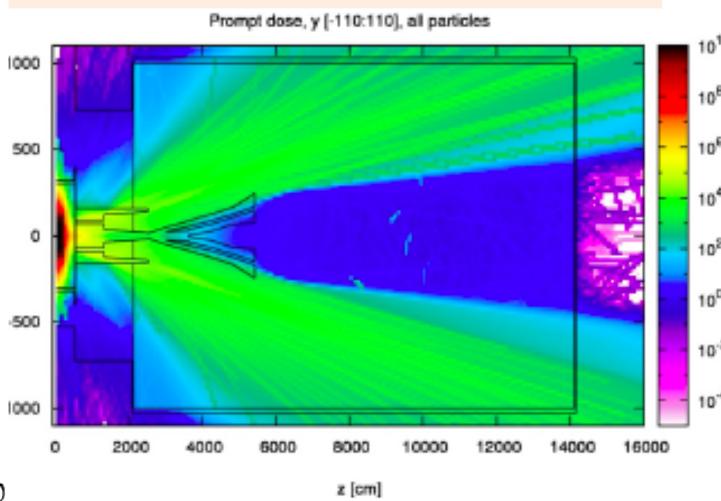
- ✓ *Muon flux limit driven by HS background and emulsion-based neutrino detector*
- ✓ *Active muon shield based entirely on magnet sweeper with a total field integral B_y = 86.4 Tm*
  Realistic design of sweeper magnets in progress
  Challenges: flux leakage, constant field profile, modeling magnet shape
- ✓ *< 7k muons / spill (E_μ > 3 GeV), from 10^{10}*
- ✓ *Negligible flux in terms of detector occupancy*



Magnetic sweeper field

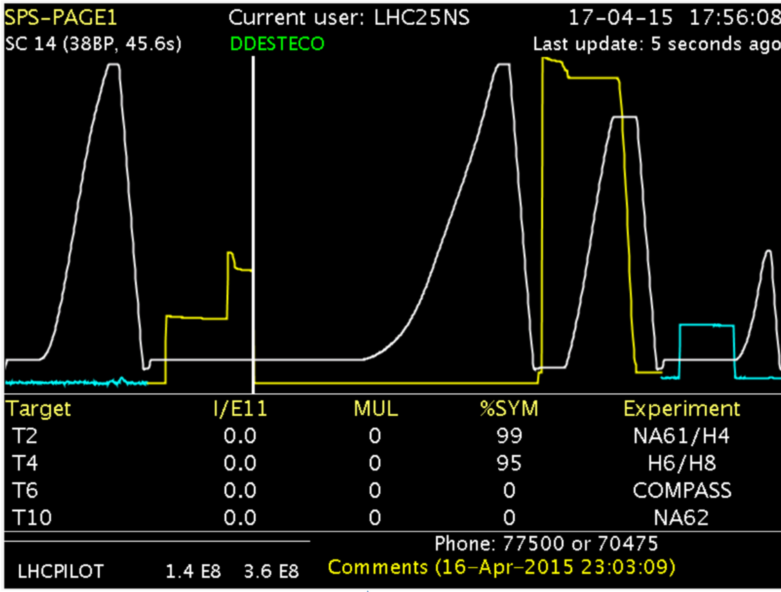


Dose rate (μSv/h) in the SHiP hall



R&D at CERN for extraction and beam lines

- Deployment of the new SHiP cycle
- Extraction loss characterisation and optimisation
  - Reduce p density on septum wires
  - Probe SPS aperture limits during slow extraction
- Development of new TT20 optics
  - Change beam at splitter on cycle-to cycle basis
- Characterisation of spill structure
- R&D and development of laminated splitter and dilution (sweep) magnets



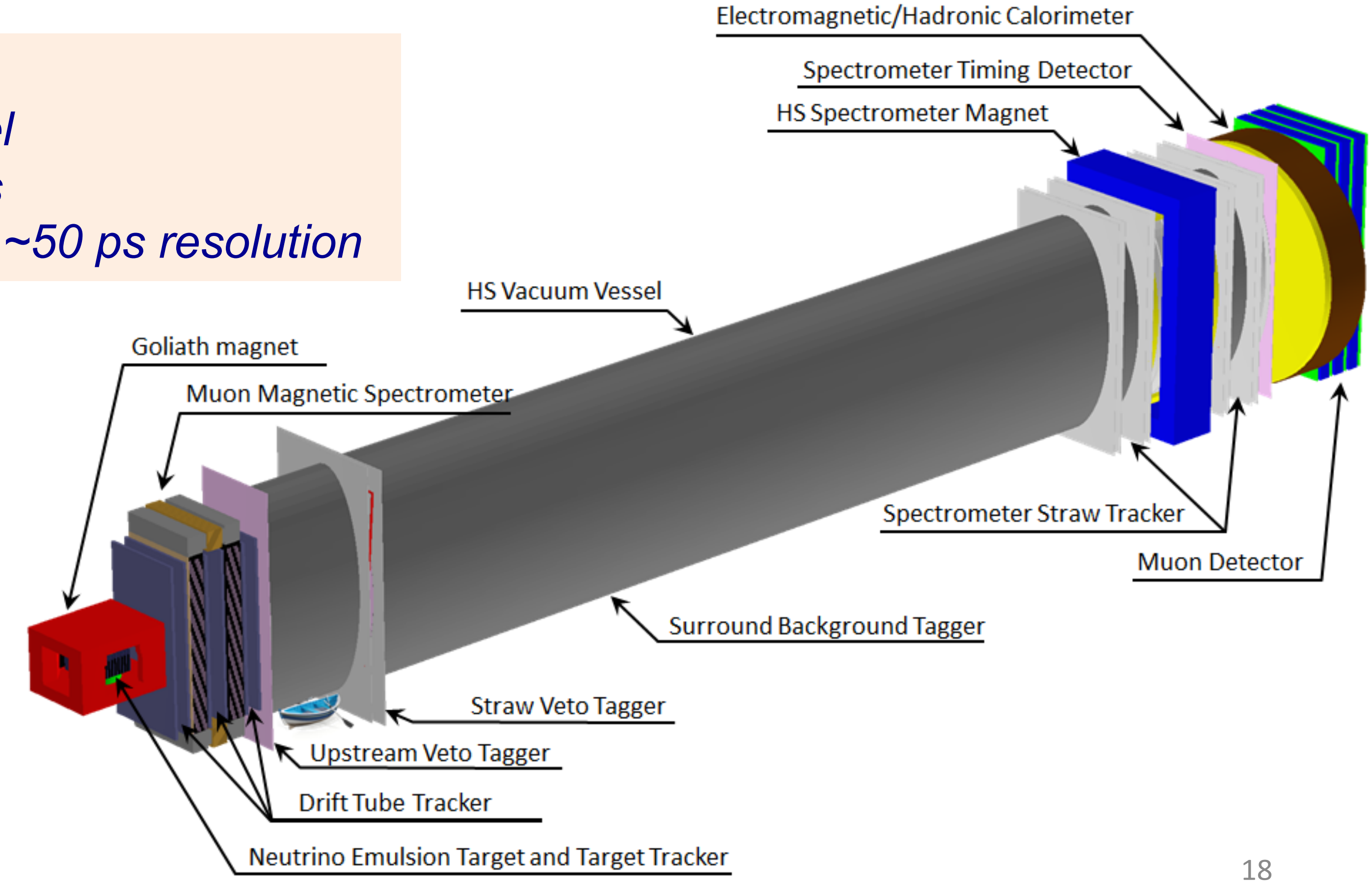
Successful test in April 2015

Hidden Sector 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*



HS decay volume and spectrometer magnet

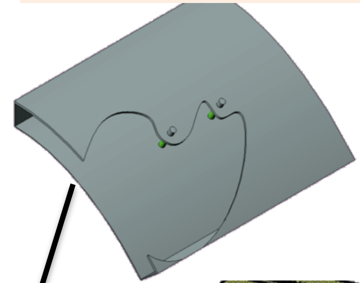
SHiP

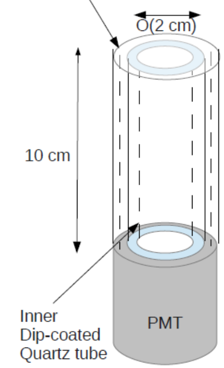
✓ ***Estimated need for vacuum:***
~ 10^{-3} mbar (<1 ν interaction)

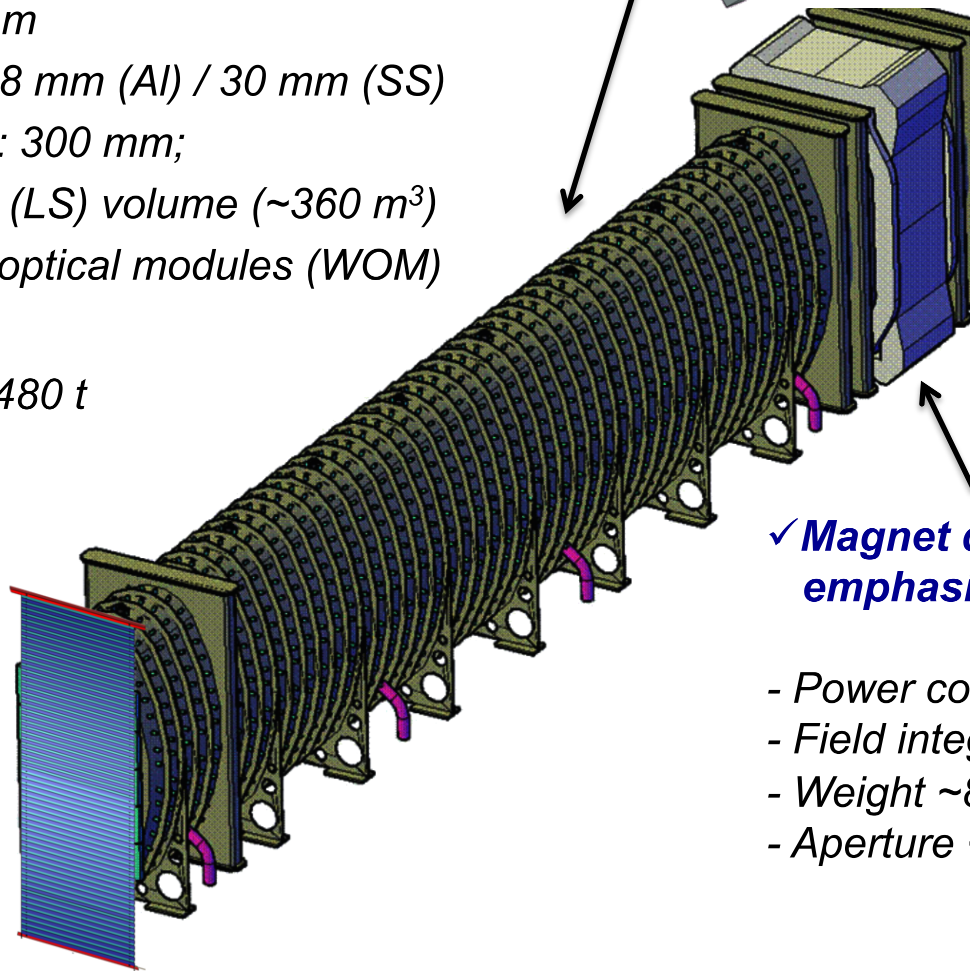
✓ ***Vacuum vessel***

- *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*

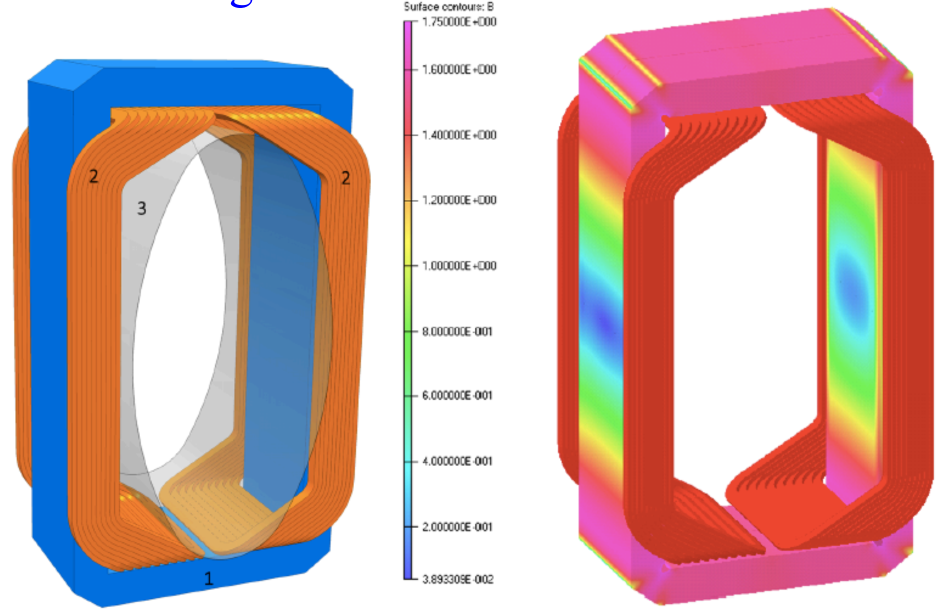
Momentum resolution of the HS (straw tubes) tracker

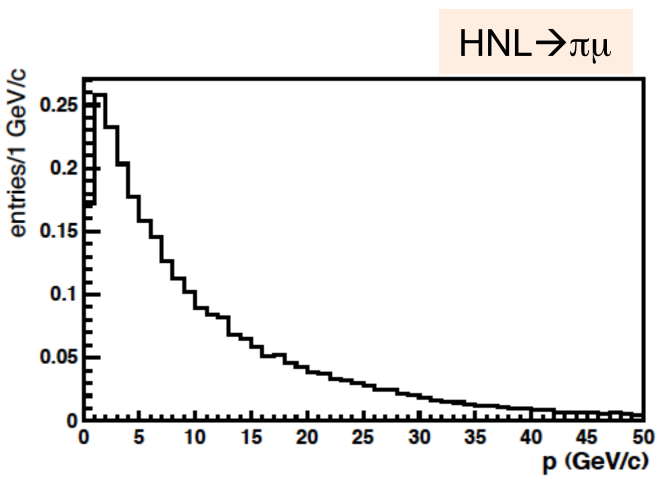
- material budget per station 0.5% X_0
- position resolution 120 μm per straw, 8 hits per station on average

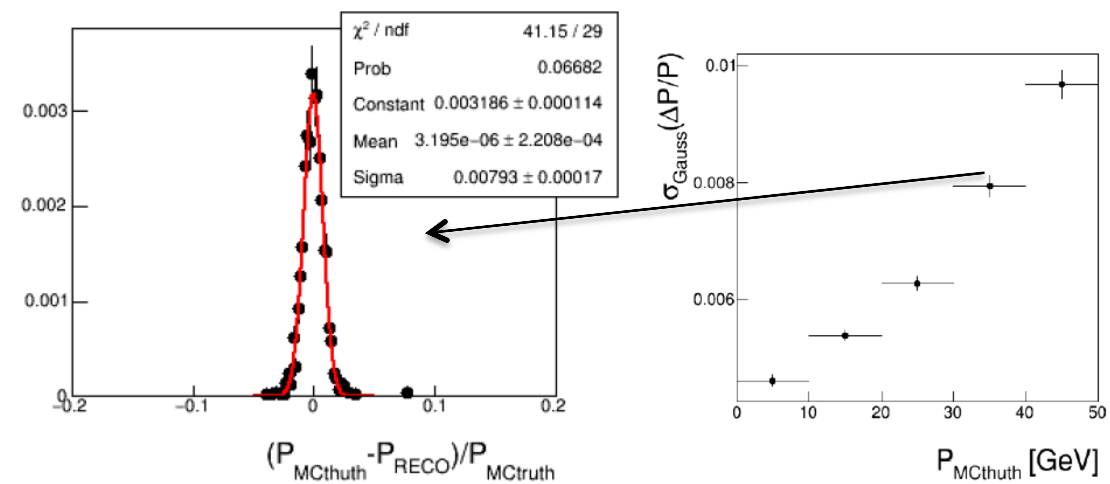
$$\left(\frac{\sigma_p}{p}\right)^2 \approx [0.49\%]^2 + [0.022\%/(\mathrm{GeV}/c)]^2 \cdot p^2$$

Momentum resolution is dominated by multiple scattering below 22 GeV/c
(For HNL → $\pi\mu$, 75% of both decay products have P < 20 GeV/c)

Magnet with vacuum vessel





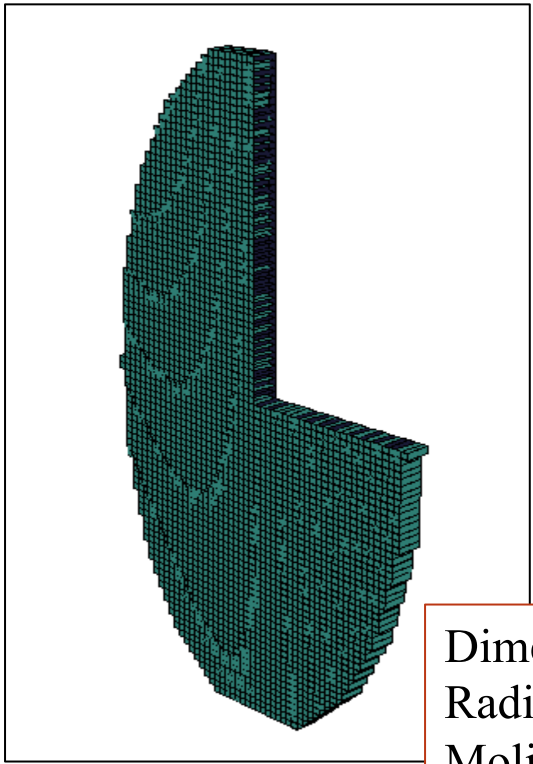


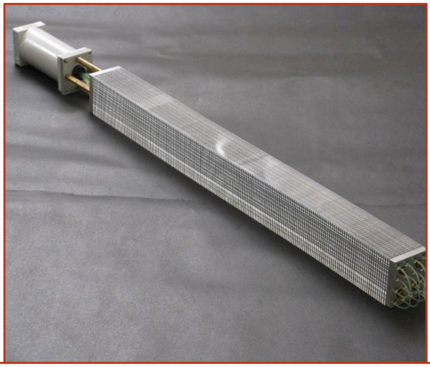
***Vertex resolution** (also driven by multiple scattering and ΔP/P):*
σ_{xy} ~ O(mm), σ_z ~ O(cm)

Calorimeters

ECAL

- Almost elliptical shape (5 m x 10 m)
- 2876 Shashlik modules
- 2x2 cells/modules, width=6 cm
- 11504 independent readout channels

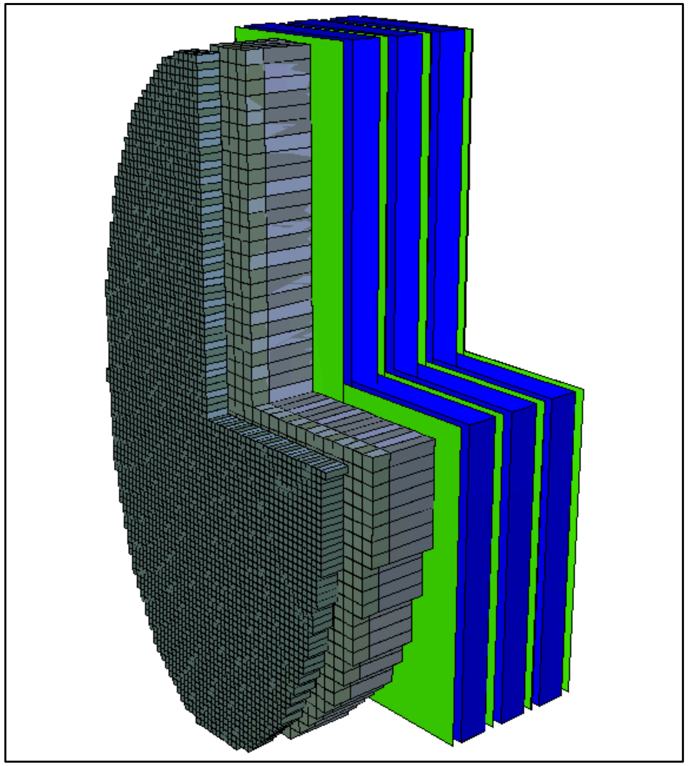




Dimensions	60x60 mm^2
Radiation length	17 mm
Moliere radius	36 mm
Radiation thickness	25 X_0
Scintillator thickness	1.5 mm
Lead thickness	0.8 mm
Energy resolution	1%

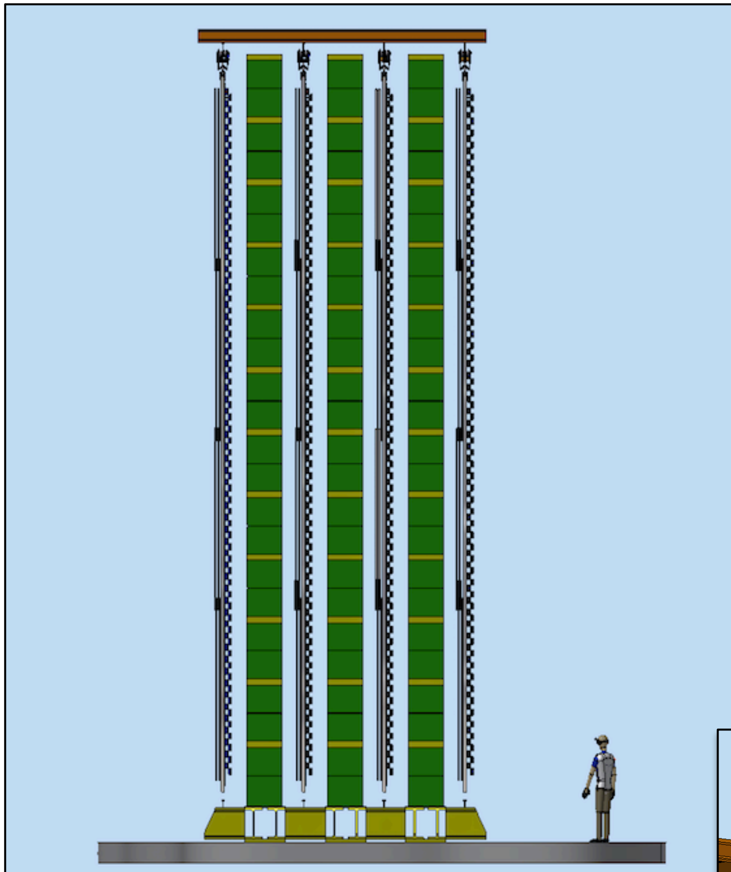
HCAL

- Matched with ECAL acceptance
- 2 stations
- 5 m x 10 m
- 1512 modules
- 24x24 cm^2 dimensions
- Stratigraphy: N x (1.5 cm steel+0.5 cm scint)
- 1512 independent readout channels



Muon System

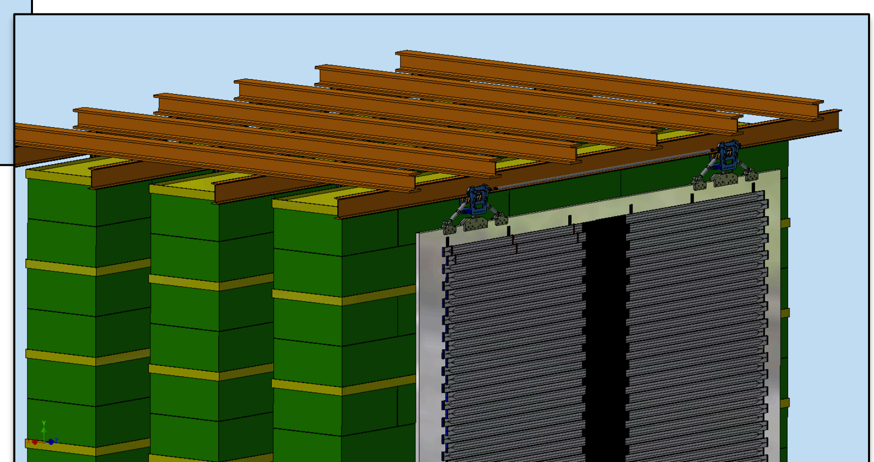
Based on scintillating bars, with WLS fibers and SiPM readout



Requirements:

- High-efficiency identification of muons in the final state
- Separation between muons and hadrons/electrons
- Complement timing detector to reject combinatorial muon background

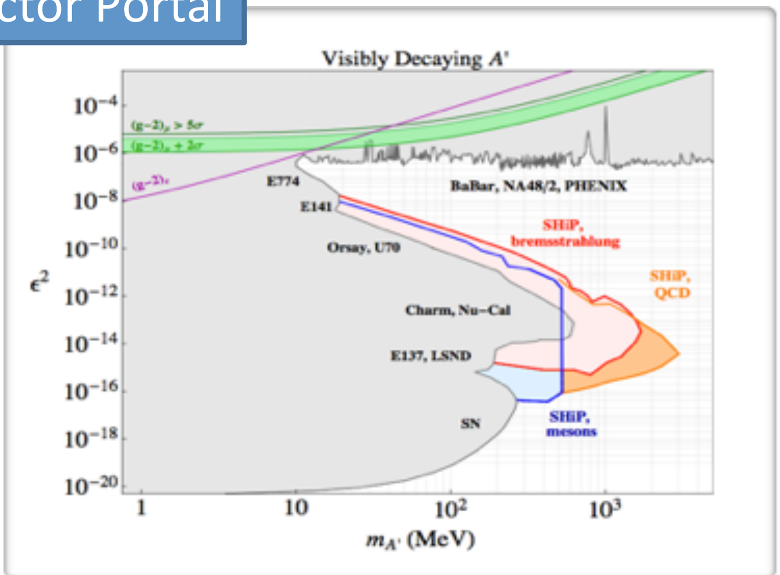
Technical Proposal (preliminary design)
- 4 active stations
- transverse dimensions: 1200x600 cm^2
- x,y view
- 3380 bars, 5x300x2 cm^3/each
- 7760 FEE channels
- 1000 tons of iron filters



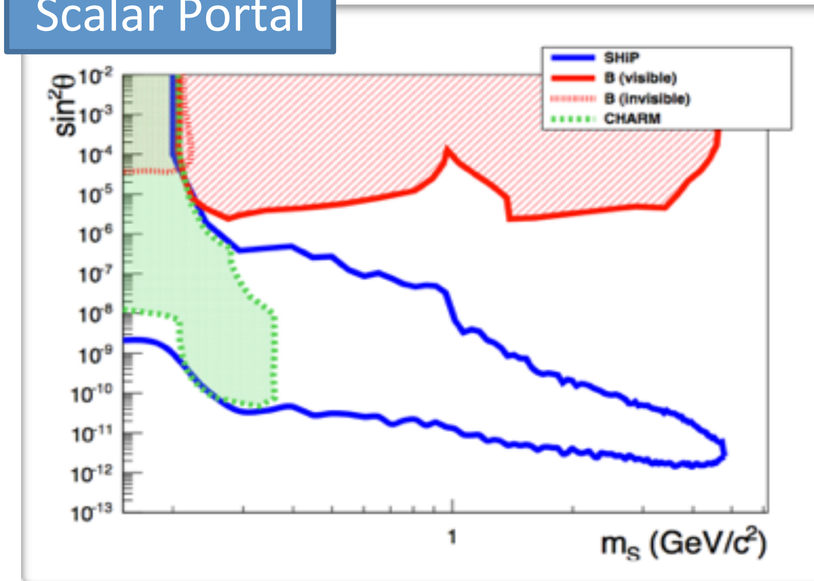
SHiP sensitivity to Hidden Sector

Based on 2x10^{20} pot @400 GeV in 5 years

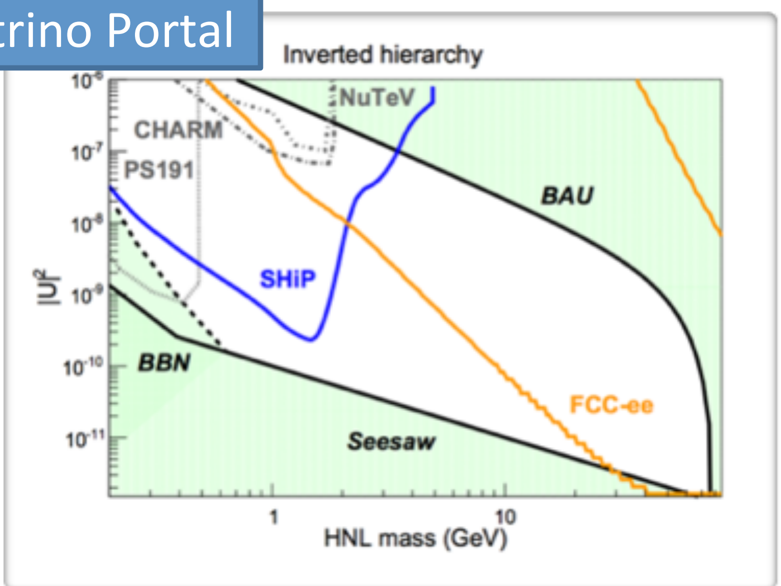
Vector Portal



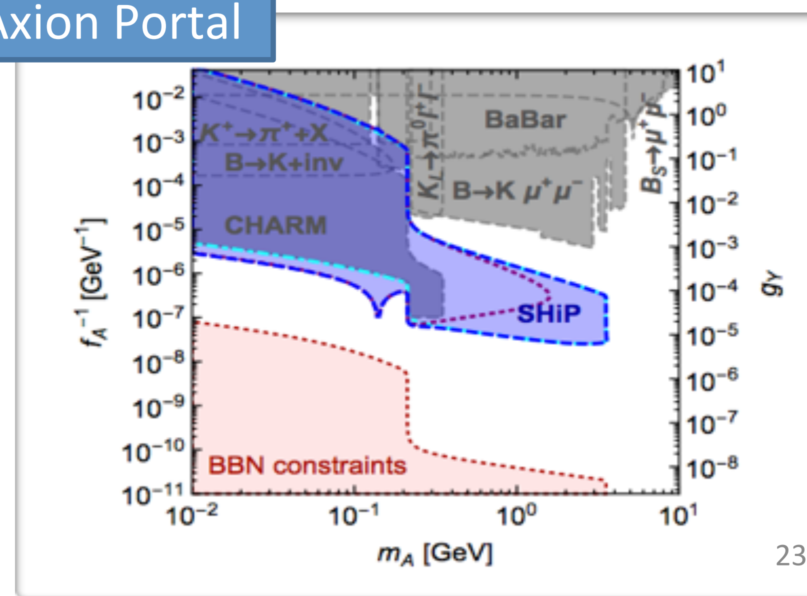
Scalar Portal



Neutrino Portal



Axion Portal



ν_τ Studies

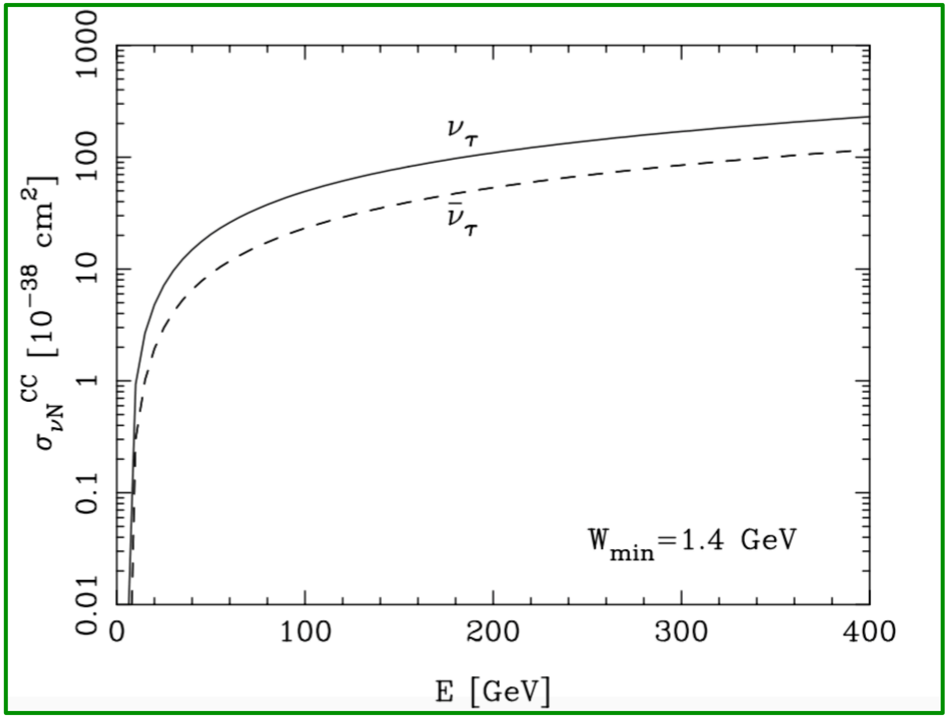
- Less known particle in the Standard Model
- First observation by DONUT at Fermilab in 2001 with 4 detected candidates, *Phys. Lett. B504 (2001) 218-224*
- 9 events (with an estimated background of 1.5) reported in 2008 with looser cuts

$$\sigma^{const}(\nu_\tau) = (0.39 \pm 0.13 \pm 0.13) \times 10^{-38}\ \mathrm{cm}^2\ \mathrm{GeV}^{-1}$$

- 5 ν_τ candidates reported by OPERA for the discovery (5.1σ result) of ν_τ appearance in the CNGS neutrino beam PRL 115 (2015) 121802
- Tau anti-neutrino never observed

$$N_{\nu_\tau + \bar{\nu}_\tau} = 4 N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \to \tau) = 2.85 \times 10^{-5} N_p = 5.7 \times 10^{15}$$

ν_τ Interactions In The Target



M. H. Reno, Phys. Rev. D74 (2006) 033001

Uncertainty ($\lesssim$10%) from:

- Scale choices
- Pdf
- Target mass correction

Expected number of interactions*

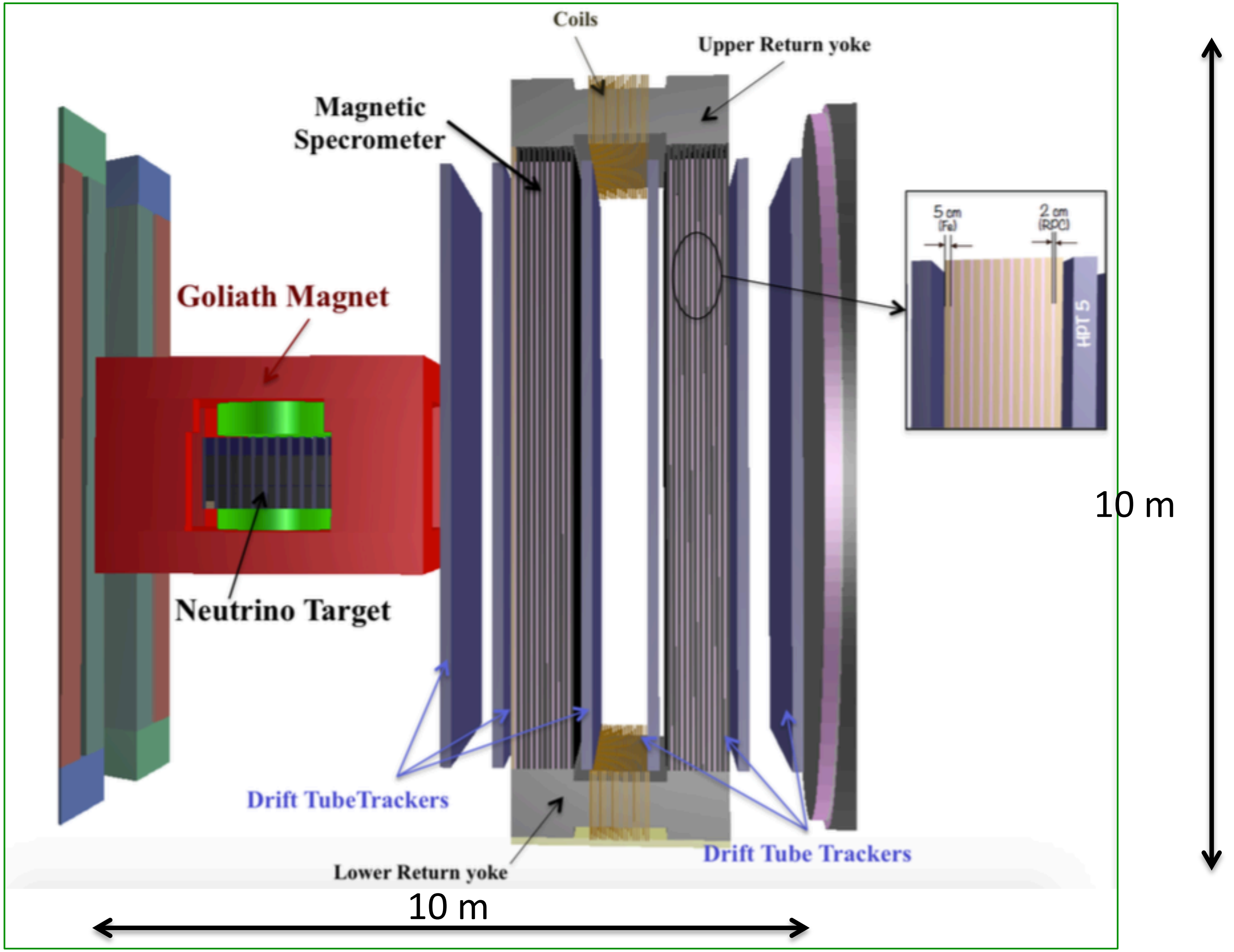
*in 5 years run (2x10[20] pot)
target mass ~ 9.6 ton (Pb)

$$N_{\nu_\tau} \simeq 6.7 \times 10^3$$

$$N_{\overline{\nu}_\tau} \simeq 3.4 \times 10^3$$

20% uncertainty mainly from scale variations in ccbar differential cross-section

THE NEUTRINO DETECTOR



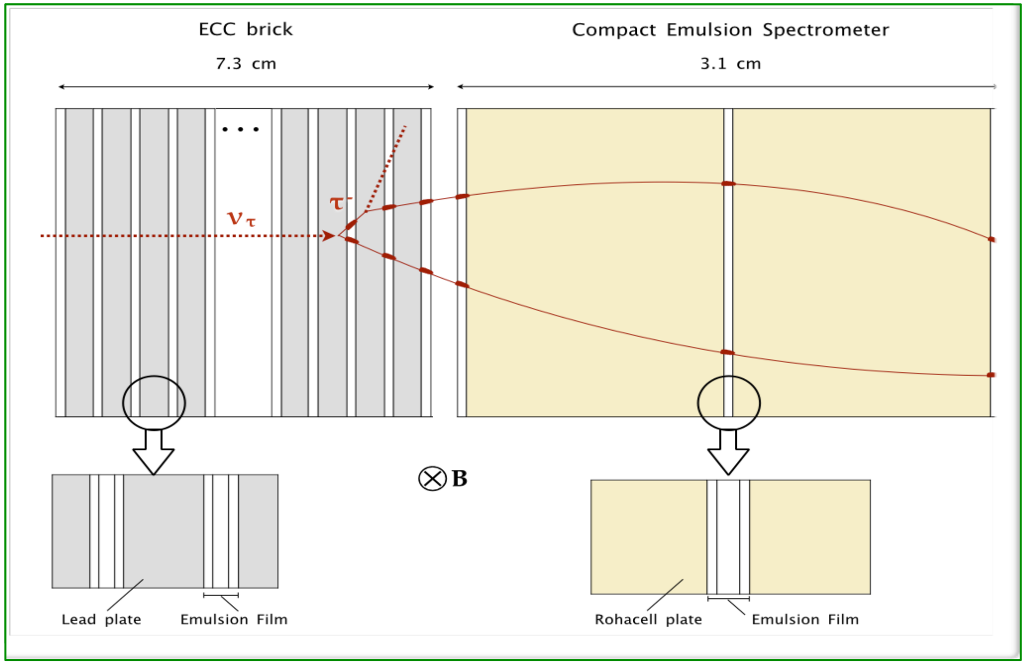
ν_τ/ANTI-ν_τ SEPARATION IN THE TARGET

THE COMPACT EMULSION SPECTROMETER

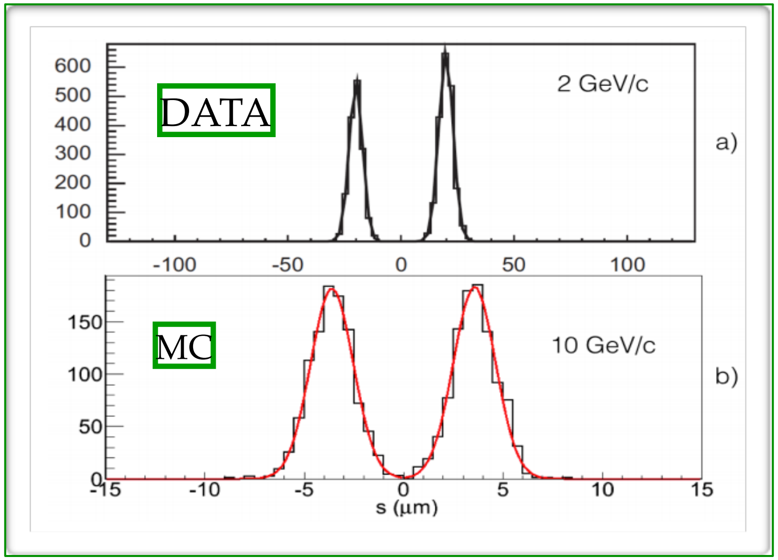
TASK

- Charge and momentum measurement of τ decay products
- Key role for the τ→h decay channel

- 3 OPERA-like emulsion films
- 2 Rohacell spacers (low density material)
- 1 Tesla magnetic field



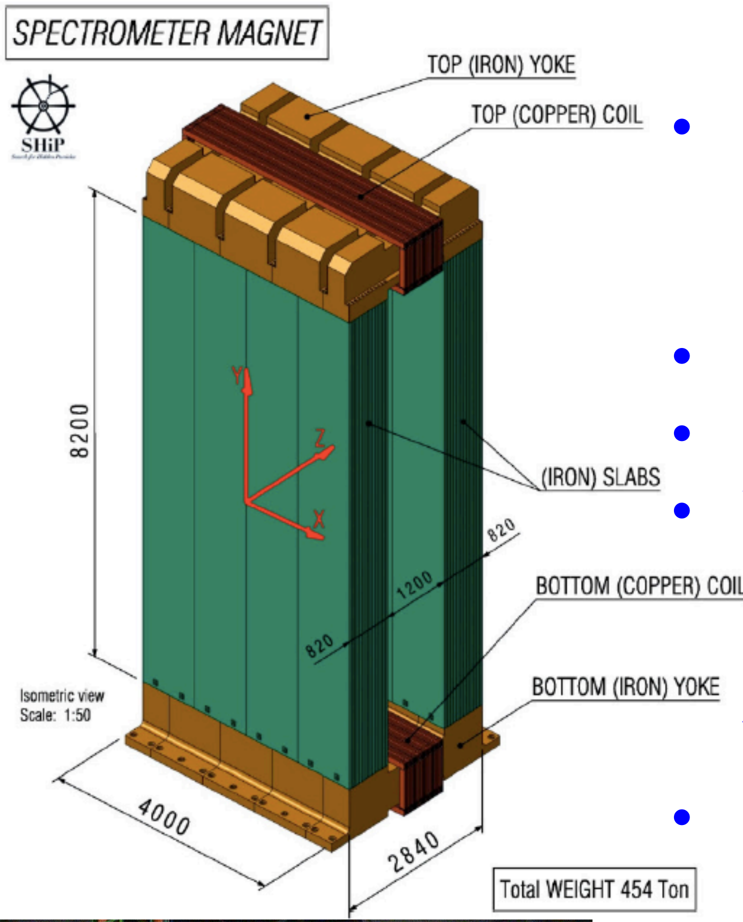
Not to scale



PERFORMANCES

- **Electric charge** determined up to 12 GeV
- **Momentum** estimated from the sagitta
- $\Delta p/p < 20\%$ up to 12 GeV/c

RPC's in SHiP



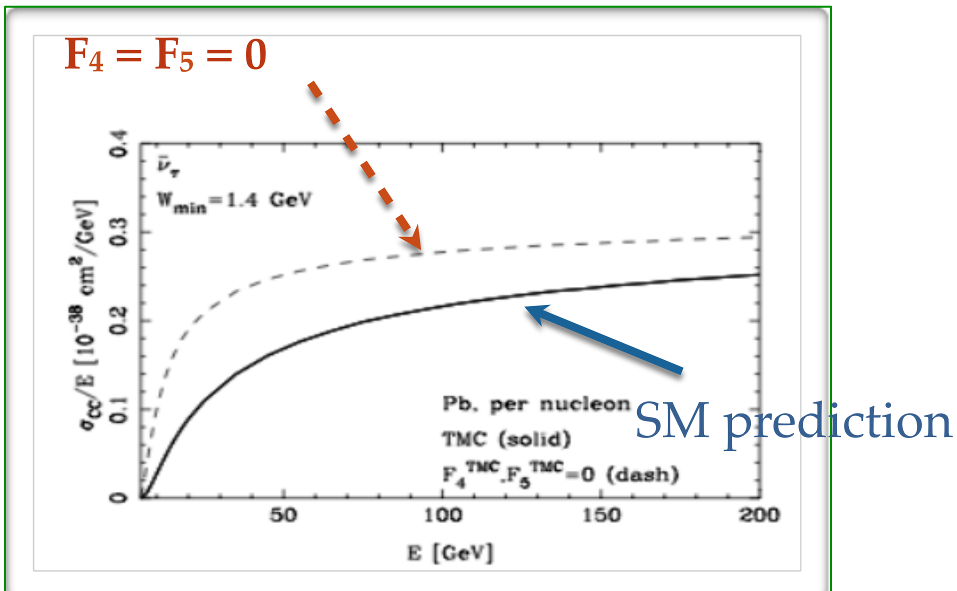

RPC assembly in the OPERA magnet

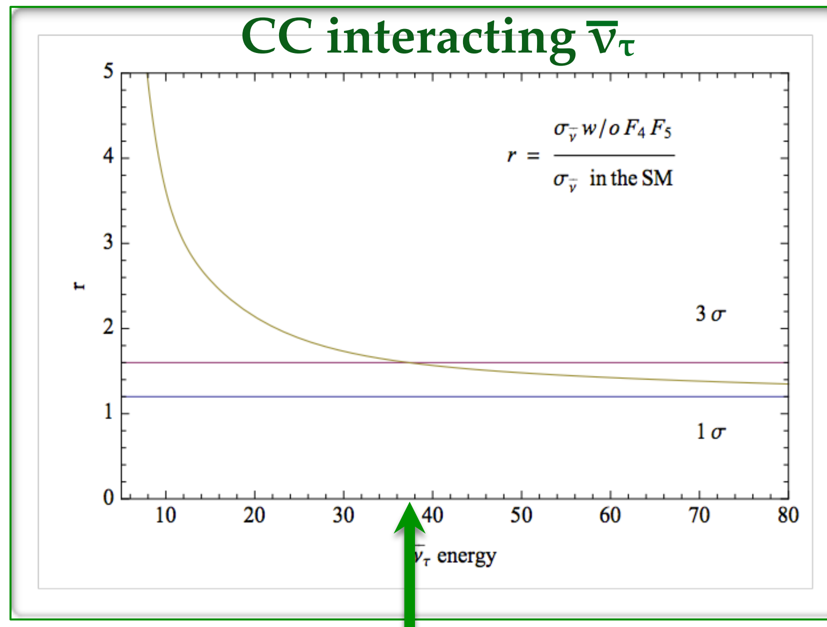
- Requirements:
  - Provide a coarse (1 cm) tracking inside the magnetised volume
- Re-use the OPERA spectrometer magnet
- RPC technology also in SHiP
- Use the same chambers: challenge from the higher (muons at ~5kHz/m^2) rate, resistivity range, $5 \times 10^{11} \div 10^{13}$ Ωcm → being tested
- Current magnet size constraining the RPC chambers → new chambers to be produced → likely all
- RPC's might be advantageous due to the neutron and gamma rate in the experimental hall
- Streamer or avalanche mode to be studied

F_4 AND F_5 STRUCTURE FUNCTIONS

First evaluation of F_4 and F_5, not accessible with other neutrinos

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



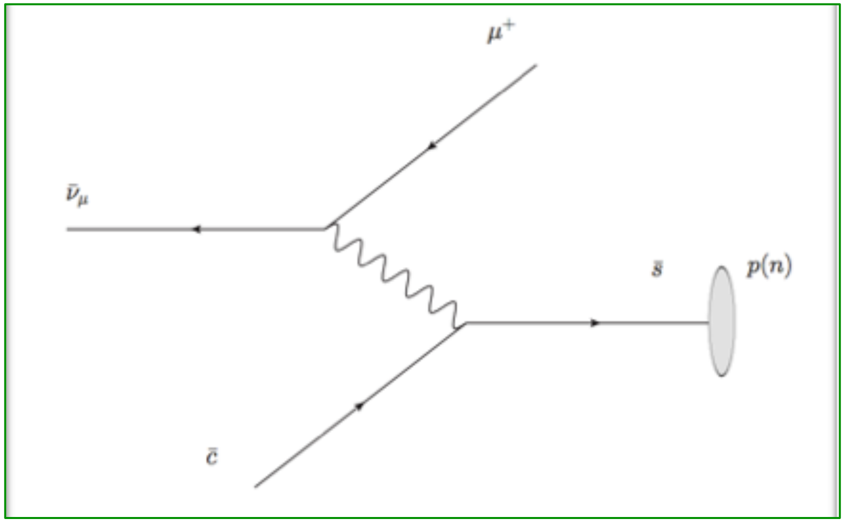


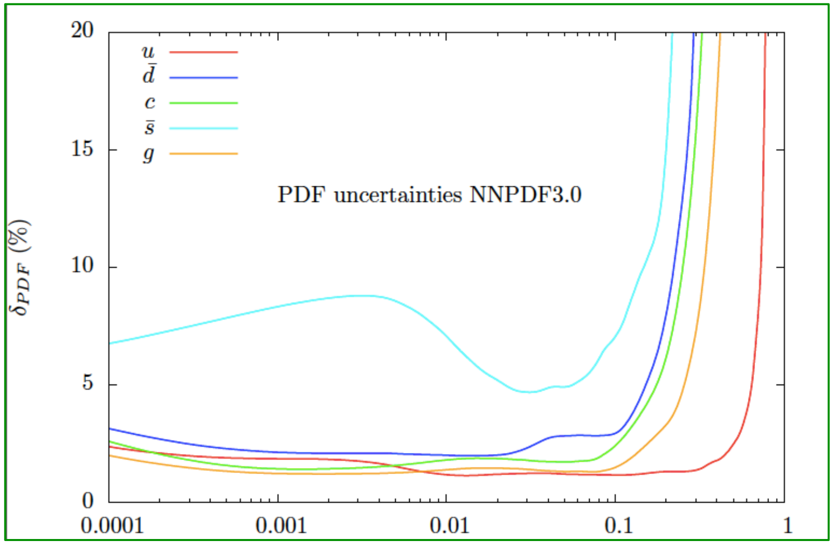
E($\bar\nu_\tau$) < 38 GeV

- At LO $F_4 = 0$, $2xF_5 = F_2$
- At NLO $F_4 \sim 1\%$ at 10 GeV

STRANGE QUARK NUCLEON CONTENT

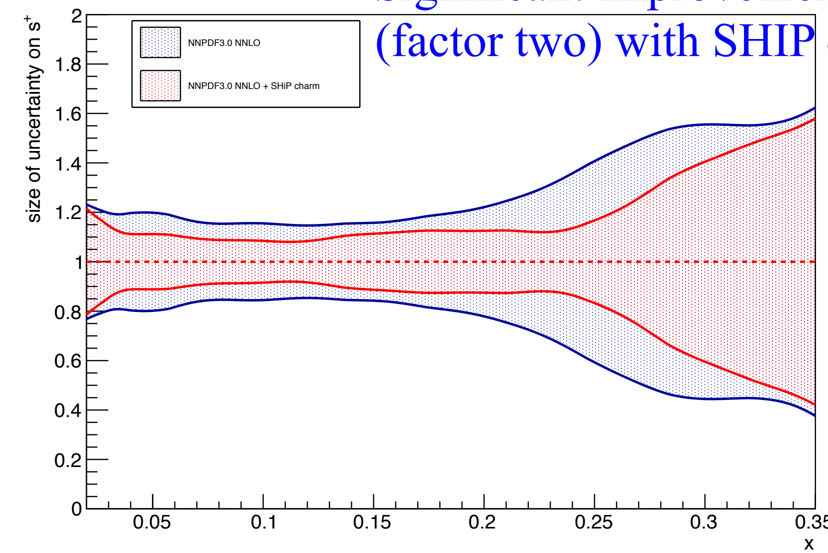
- Charmed hadron production in anti-neutrino interactions selects anti-strange quark in the nucleon
- Strangeness important for precision SM tests and for BSM searches
- W boson production at 14 TeV: 80% via $u\bar{d}$ and 20% via $c\bar{s}$





Phys. Rev. D91 (2015) 113005

Fractional uncertainty of the individual parton densities $f(x;m^2_W)$ of NNPDF3.0



- Significant improvement (factor two) with SHIP data

$$s^+ = s(x) + \overline{s}(x)$$

Added to NNPDF3.0 NNLO fit, Nucl. Phys. B849 (2011) 112–143, at $Q^2 = 2$ GeV^2

Dark Matter Search with the neutrino detector

χ produced by a dark photon decay

$$\chi e^- \to \chi e^-$$

P. deNiverville, D. McKeen, and A. Ritz, Phys.Rev. D86 (2012) 035022

$\alpha' =$ dark photon coupling with χ

SIGNAL SELECTION

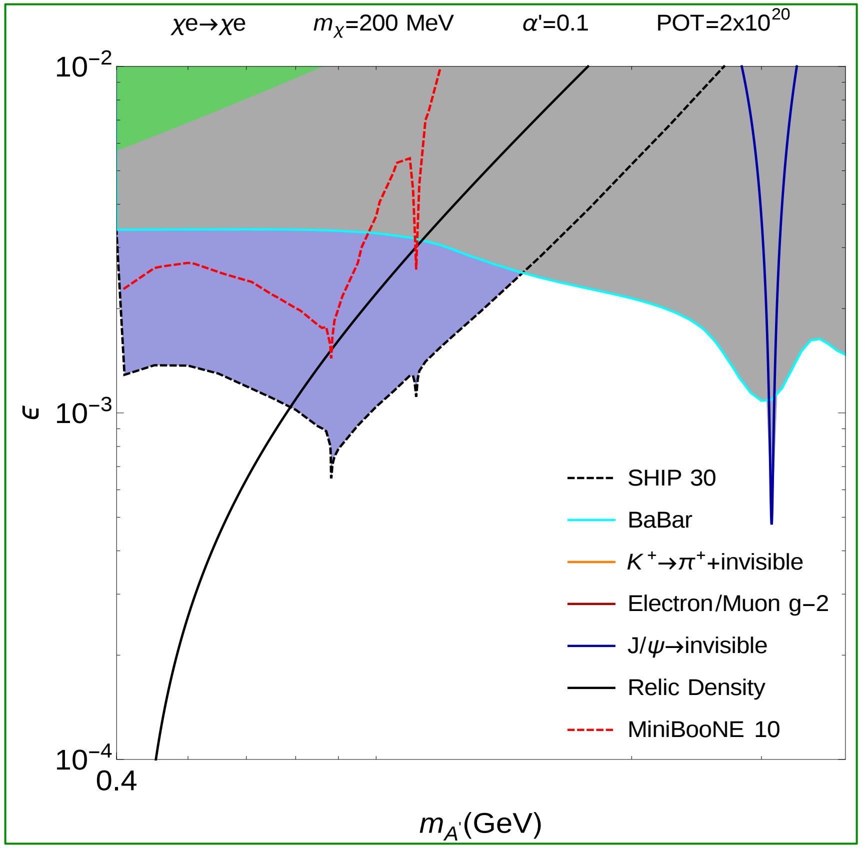
$$\begin{cases} 0.01 < \theta < 0.02 \\ E < 20 \text{ GeV} \end{cases}$$

BACKGROUND PROCESSES

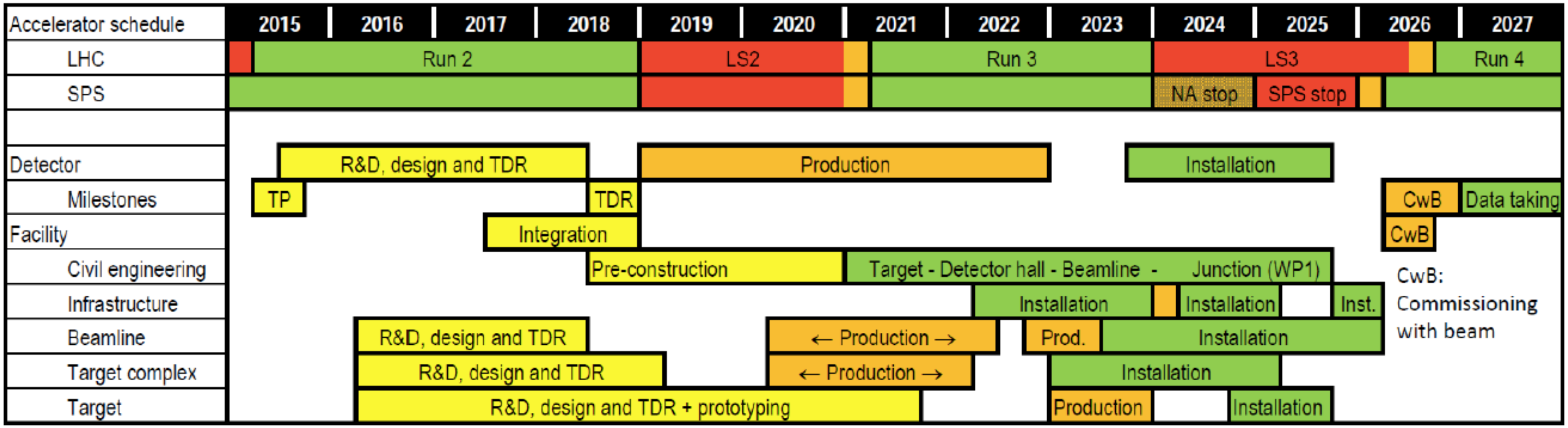
	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	16	2	20	18	56
Quasi - elastic scattering	105	73			178
Resonant scattering	13	27			40
Deep inelastic scattering	3	7			10
Total	137	109	20	18	284

$\epsilon =$ dark photon coupling with e.m. current

$m_A =$ dark photon mass



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 (target complex, detector hall, beam line and junction cavern)*
- ✓ *All TDRs by the end of 2018*
- ✓ *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***

Summary

- ✓ *SHIP proposed to search for New Physics in the largely unexplored domain of new, very weakly interacting particles with masses O(10) GeV*

- ✓ *Unique opportunity for ν_τ physics*

- ✓ *Sensitivity improves past experiments by O(10000) for Hidden Sector and by O(200) for ν_τ physics*

- ✓ *The SHiP proposal submitted in April 2015 and evaluated by the SPS Committee at CERN*

- ✓ *SHiP could therefore constitute a key part of the CERN Fixed Target programme in the HL-LHC era. SPSC **recommends** that the SHiP proponents proceed with the preparation of a Comprehensive Design Report (CDR), and that this preparation be made in close contact with the planned Fixed Target working group.*

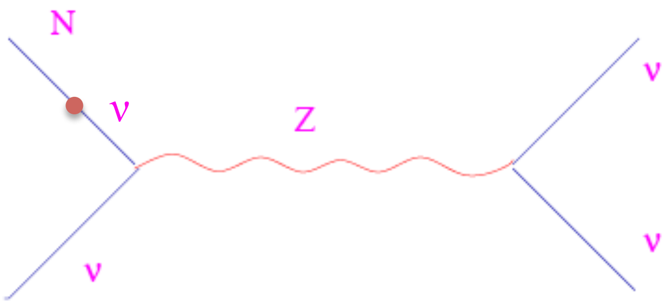
- ✓ ***SHiP will greatly complement searches for New Physics at energy frontier at CERN***

Back-up slides

Dark Matter candidate HNL N_1

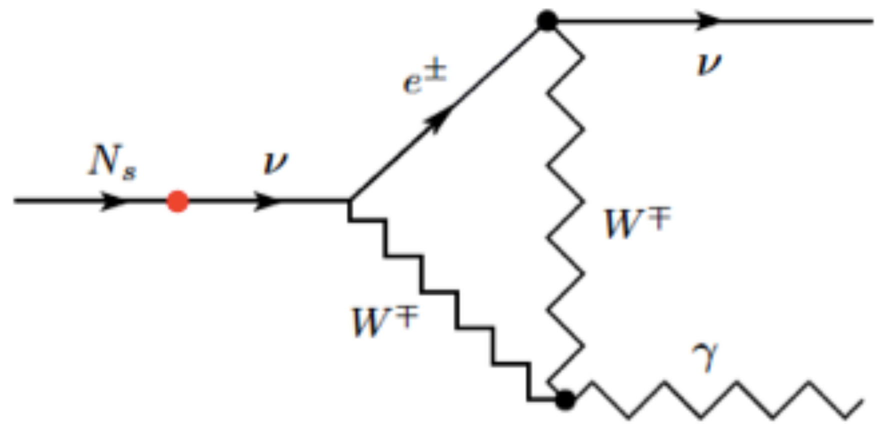
- ***N_1 can be sufficiently stable to be a DM candidate, $M(N_1)$~10keV***

Yukawa couplings are small $\rightarrow$ N can be very stable.



Main decay mode: $N \rightarrow 3\nu$.

Subdominant radiative decay channel: $N \rightarrow \nu\gamma$.



Photon energy:

$$E_\gamma = \frac{M}{2}$$

Radiative decay width:

$$\Gamma_{\rm rad} = \frac{9\,\alpha_{\rm EM}\,G_F^2}{256 \cdot 4\pi^4}\,\sin^2(2\theta)\,M_N^5$$

Interaction strength

New line in photon galaxy spectrum at 3.5 keV?
To be checked with higher accuracy

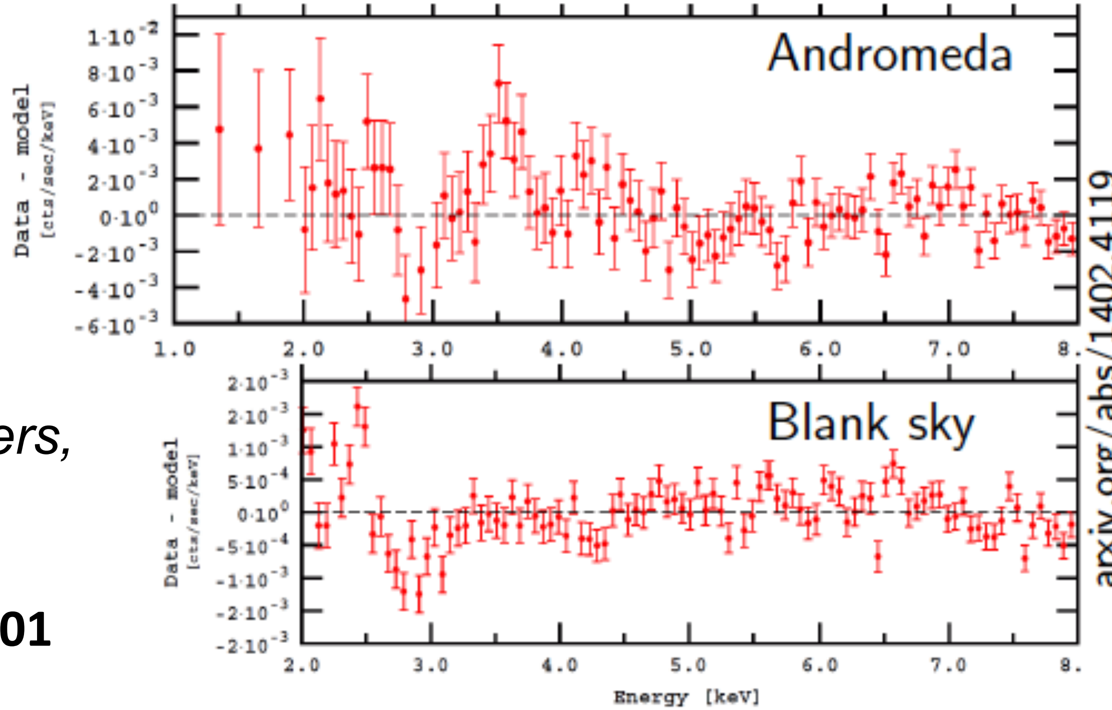
New line in photon galaxy spectrum ???

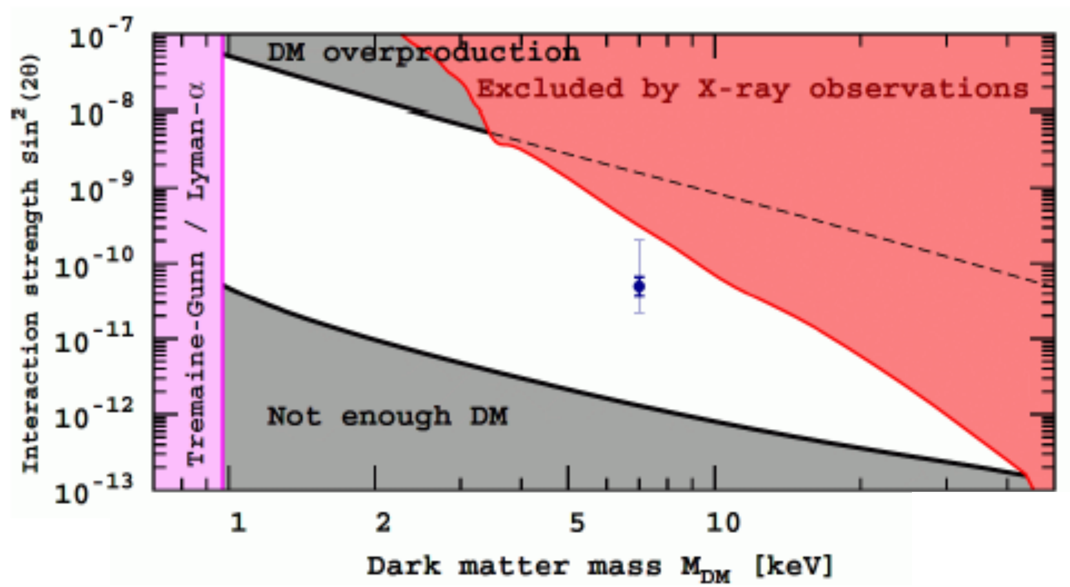
Two recent publications in

- **Astrophys. J. 789 (2014) 13**
Detection of an unidentified emission line in the stacked X-ray spectrum of Galaxy Clusters, E_γ ~ 3.56 keV

- **Phys.Rev.Lett. 113 (2014) 251301**
An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster, E_γ ~ 3.5 keV

Will soon be checked by Astro-H with higher energy resolution





Axion portal, e.g. PNGB

- PRD 82, 113008 (2010), Discovering new light states at neutrino experiments
- Approximate symmetry broken at a high mass scale F gives rise to light pseudoscalars, pseudo-Nambu-Goldstone bosons (or "axions") with couplings of order m_X/F to SM particle X
- Production from mixing with π^0
- For m_a<400MeV, total width ~ $\Gamma ee + \Gamma \mu\mu$

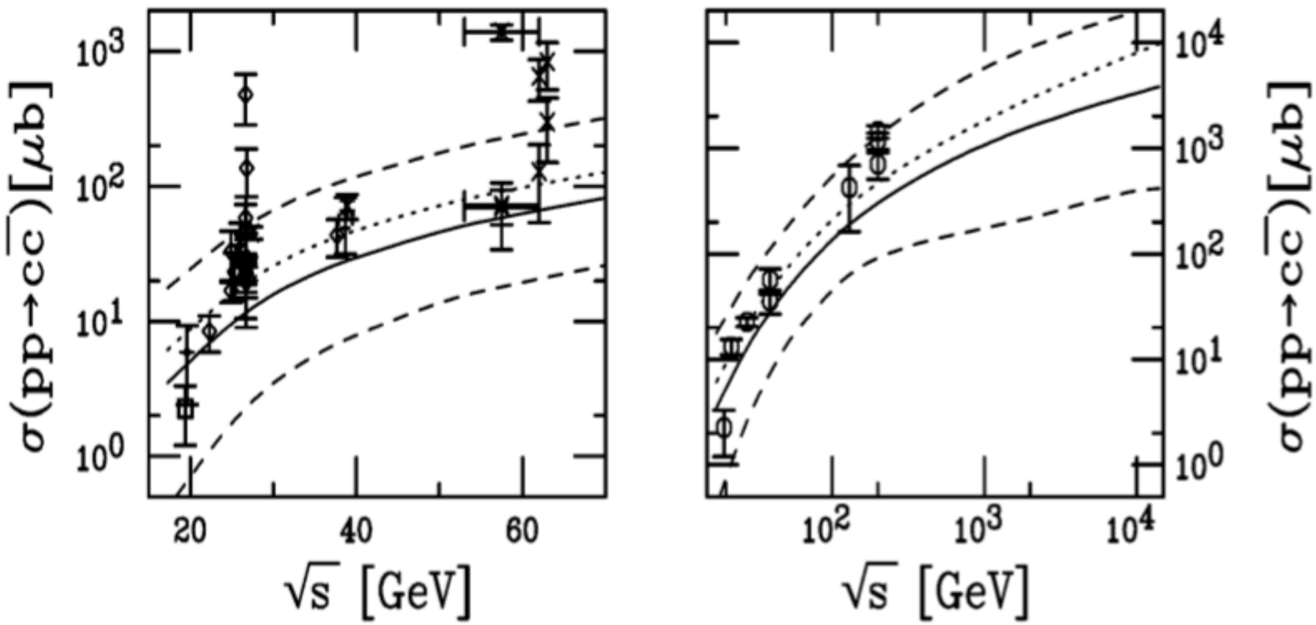
$$N_a = \left(\frac{F_\pi}{F}\right)^2 n_{\pi^0} N_p \epsilon_{\rm geo}.$$

$$\Gamma_\ell = \frac{m_a}{8\pi}\left(\frac{m_\ell}{F}\right)^2 \sqrt{1 - (4m_\ell^2/m_a^2)},$$

	$E_{\rm beam}$ (GeV)	N_p	X_t (m)	X_d (m)	$n_{\pi^0}\epsilon_{\rm geo}$	$\bar{E}_a$ (GeV)
CHARM [2]	400	2.4×10^{18}	480	515	0.12	25
LSND [71,74,75]	0.8	$\sim 10^{23}$	29.7	38	see text	0.3
MINOS/MINERvA [76,77]	120	3.8×10^{20}	1050	1087	0.0006	20
MiniBooNE [78]	8.9	10^{21}	541	553	0.002	2.7

Sensitivity for $N_{2,3} \propto U^4$

- PS-191: with K decays → limited to 500 MeV (PLB 203 (1988) 332)
- Goal: Extend mass range to ~ 2 GeV by using charmed hadron decays
- B-decays: 20÷100 smaller σ, and B → Dμν, i.e. limited to ~ 3 GeV still



arxiv.org/pdf/0709.2531v1

Where to produce charmed hadrons?

LHC ($\sqrt{s} = 14$ TeV): with 1 ab^{-1} ($\sim$ 3-4 years): $\sim 2 \times 10^{16}$ in 4π

SPS (400 GeV p-on-target (pot) $\sqrt{s} = 27$ GeV): with 2×10^{20} pot ($\sim$ 3-4 years): $\sim 2 \times 10^{17}$

The acceptance of a beam dump facility is much larger for long lived particles