SHiP Physics Program

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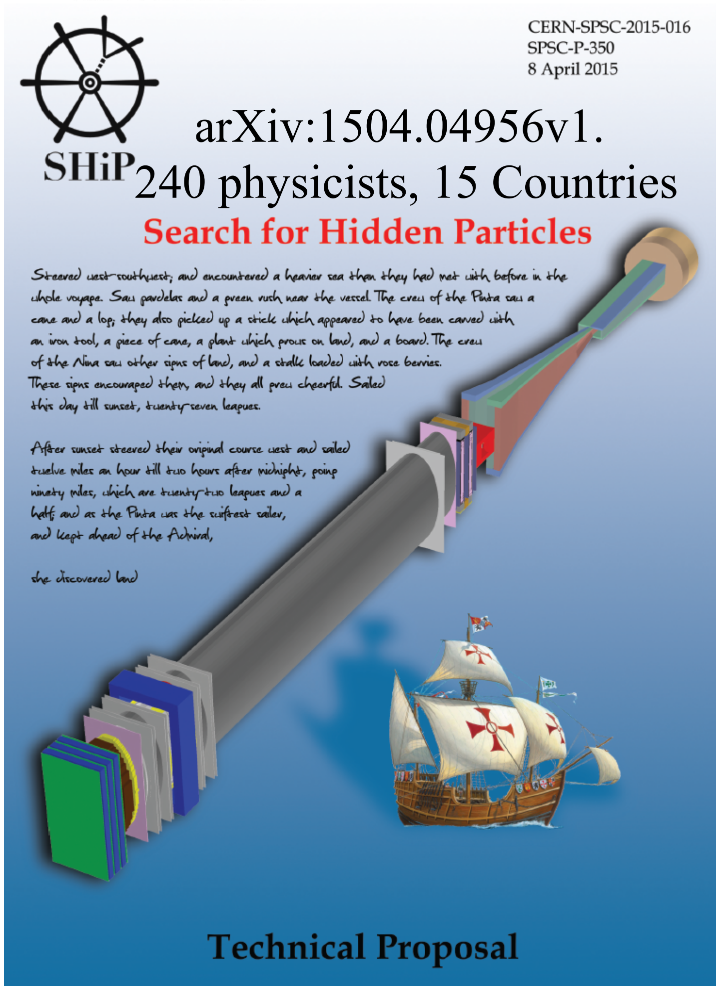
On behalf of the SHiP Collaboration

arXiv:1504.04956v1.

240 physicists, 15 Countries



arXiv:1504.04855v1.

Rept. Prog. Phys. 79 (2016) no. 12

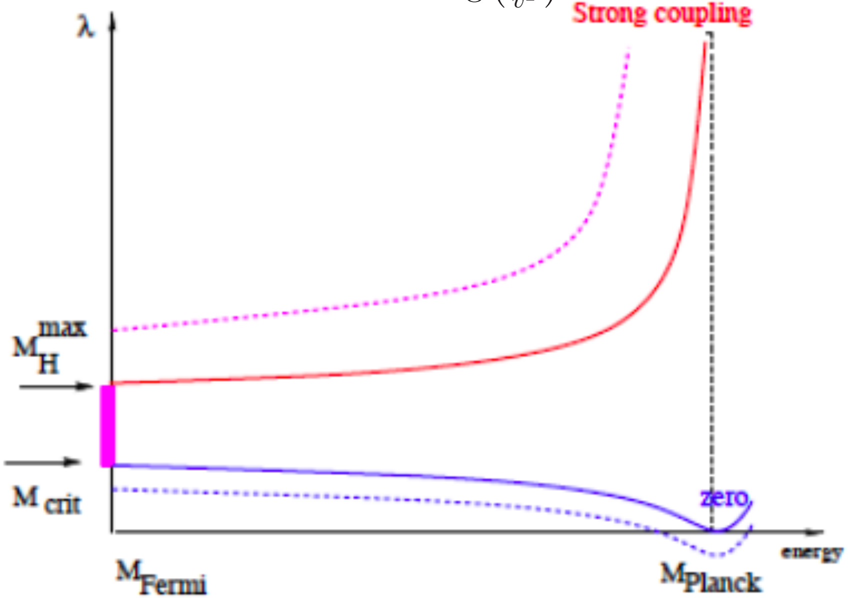
85 theorists

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

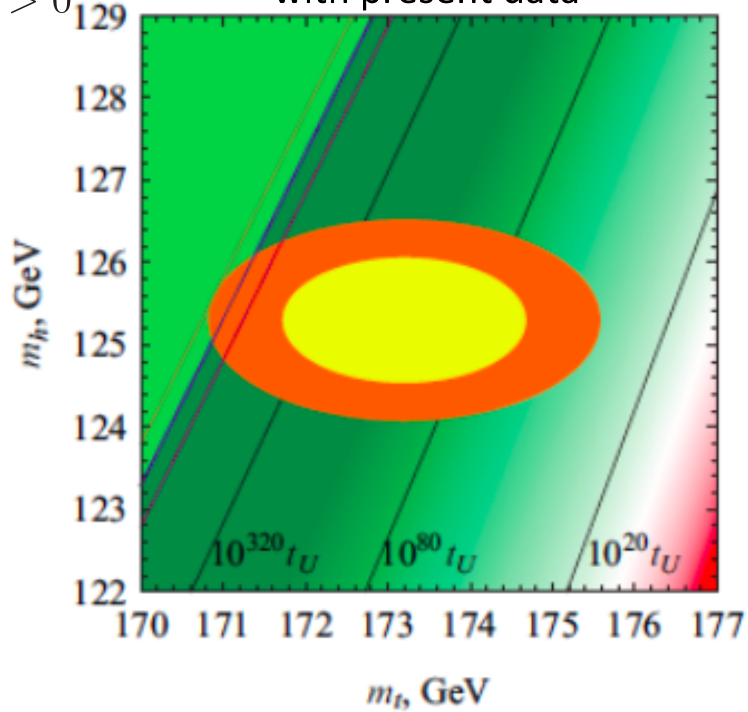
$$\lambda(\Lambda) < \infty \quad \Rightarrow \quad M_H^2 \leq \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}$$



1,22 × 10^{19} GeV

Stable vacuum fully consistent with present data

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



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 ?

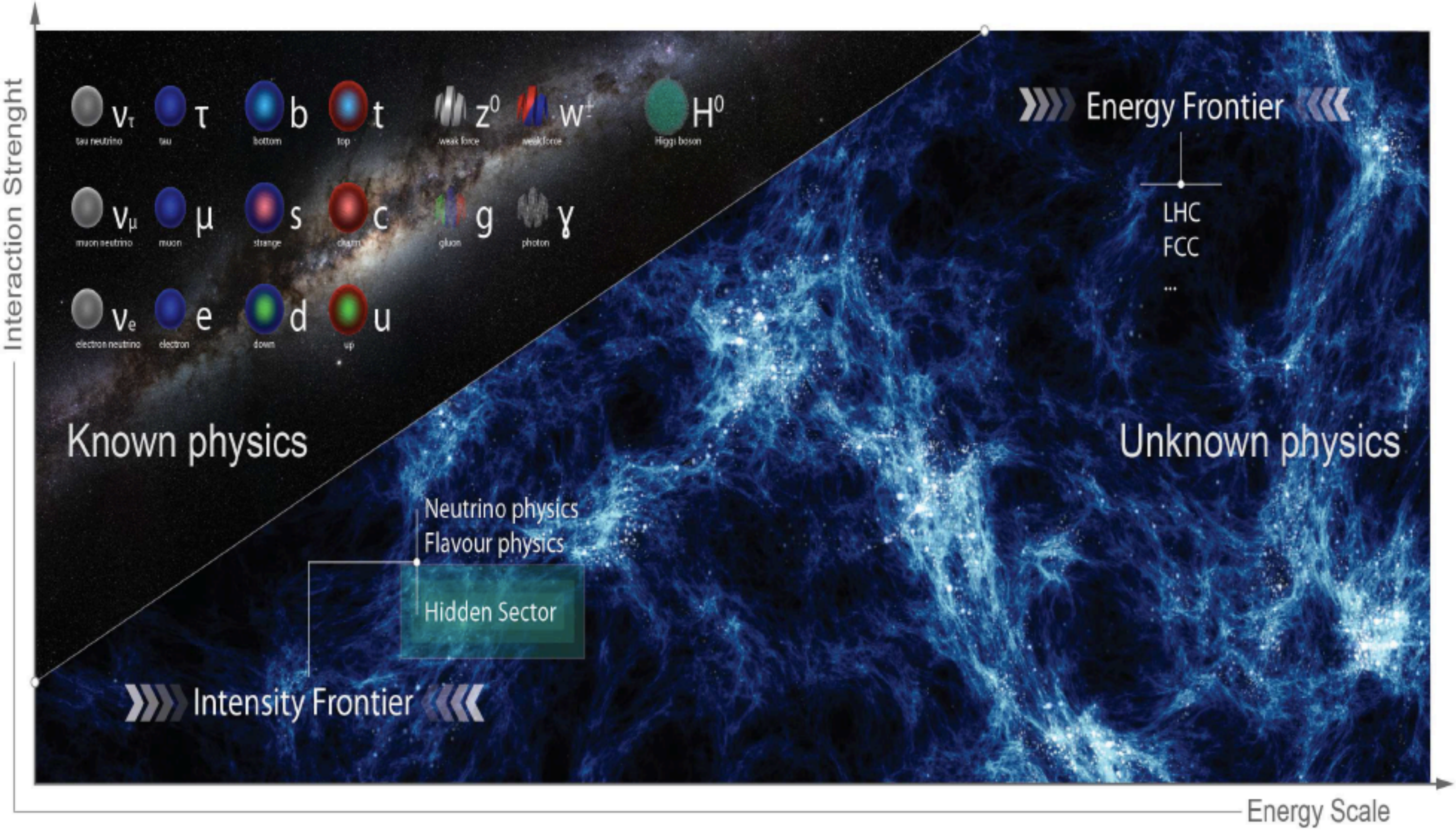
What is the composition of dark matter (~25% of the Universe) ?

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



Search for Hidden Sector (HS)

or very weakly interacting NP

$$L = L_{SM} + L_{mediator} + L_{HS}$$

Visible Sector

Mediators or portals to the HS: vector, scalar, axial, neutrino

Hidden Sector

Naturally accommodates Dark Matter (may have rich structure)

✓ *HS production and decay rates are strongly suppressed relative to SM*
- *Production fractions $O(10^{-10})$*
- *Long-lived objects*
- *Interact very weakly with matter*

Models	*Final states*
HNL, SUSY neutralino	$l^+\pi^-$, l^+K^-, $l^+\rho^-$ $\rho^+\rightarrow\pi^+\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	l^+l^-
HNL, SUSY neutralino, axino	$l^+l^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

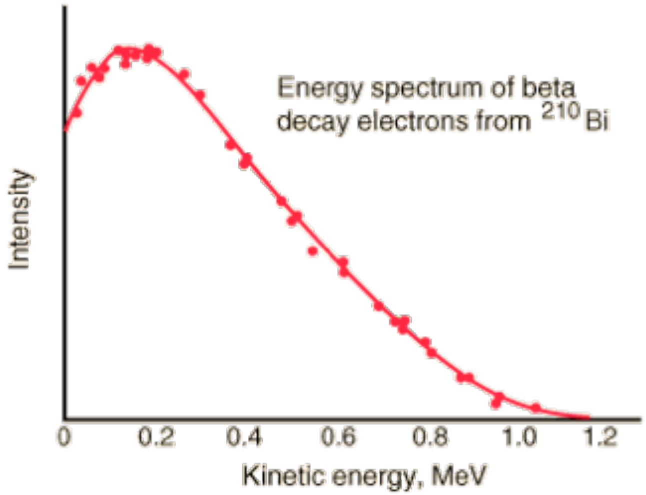
Full reconstruction and PID are essential to minimize model dependence

Experimental challenge is background suppression

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!

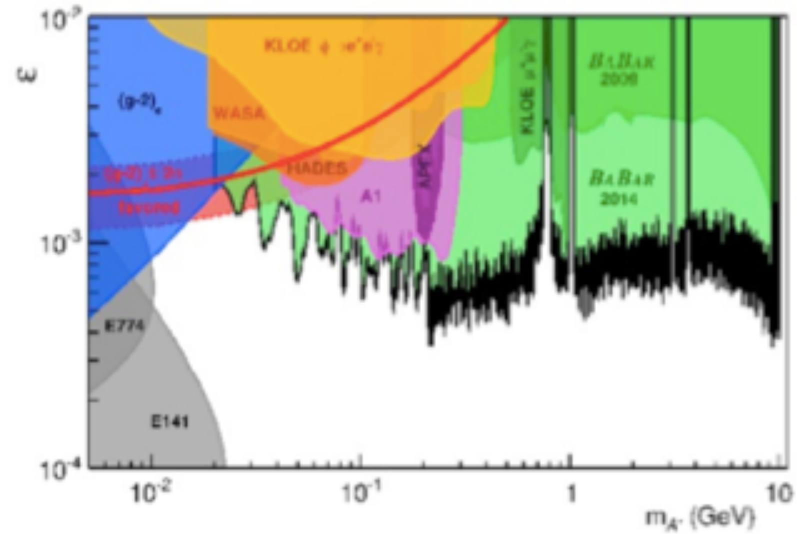
$$n \to p + e^- + \bar{\nu}$$

- **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:

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



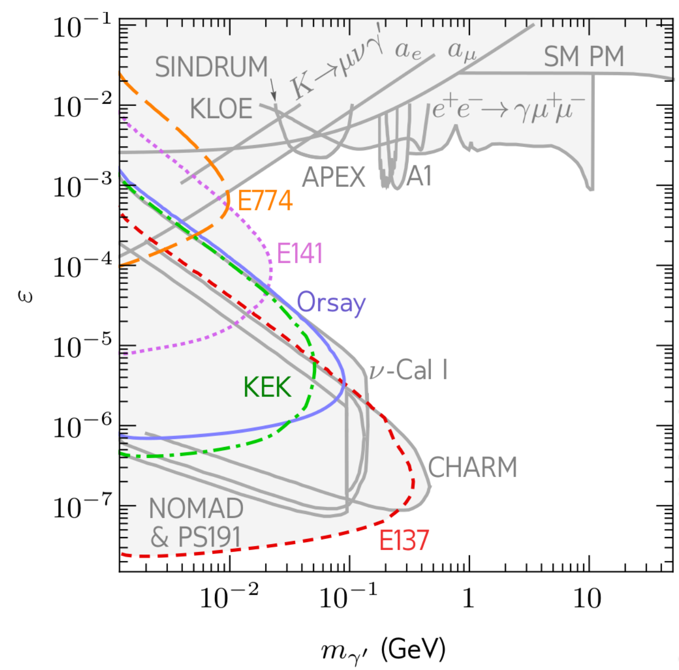
- decay length $c\tau \sim \varepsilon^{-2} m_{\gamma'}^{-1}$
- cosmological constraints (nucleo-synthesis): $\tau < 0.1$ s $\Rightarrow \varepsilon^2 m_{\gamma'} > 10^{-21}$ GeV

γ' production

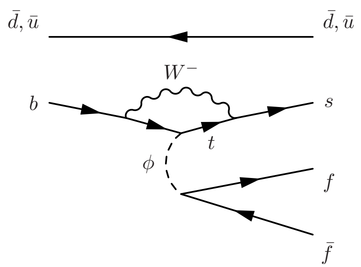
- proton bremsstrahlung:
  - initial-state radiation from the incoming proton, followed by a hard proton-nucleus interaction

- secondary particles decay:

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



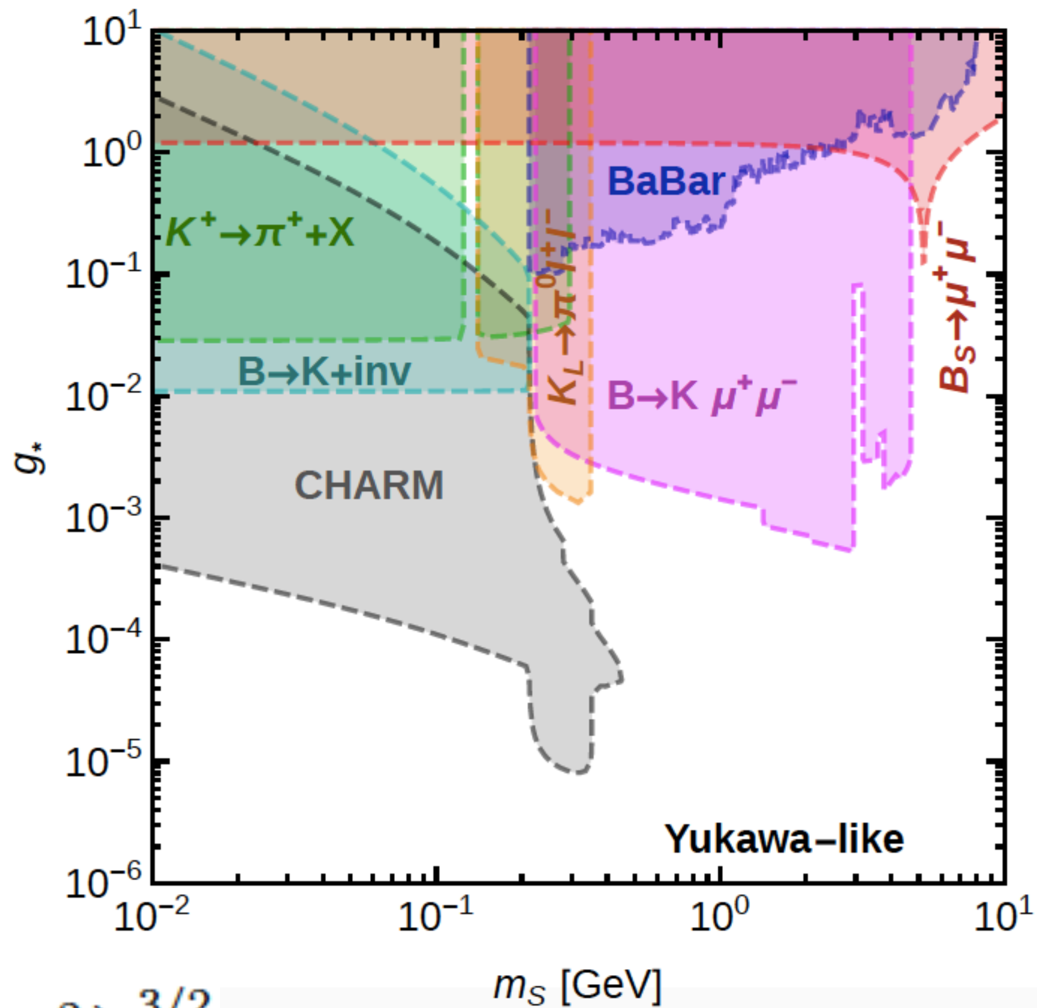
Higgs (scalar) portal: production and decay modes



Rare B meson decays mediated by a light scalar ϕ

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

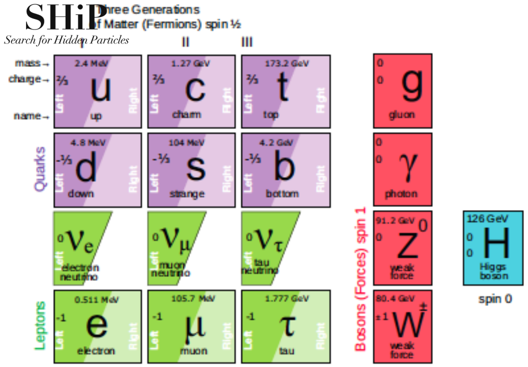
$$\Gamma(B \to K\phi) \sim (m_t^2 |V_{ts}^* V_{tb}|)^2 \propto m_t^4 \lambda^2$$

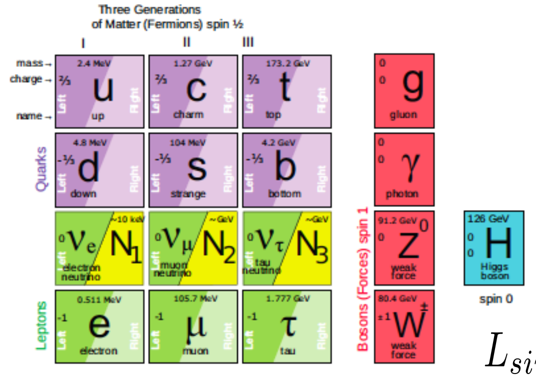


B decays favoured compared to D

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

Neutrino masses & BAU *can be solved with Heavy Neutral Leptons (HNL)*





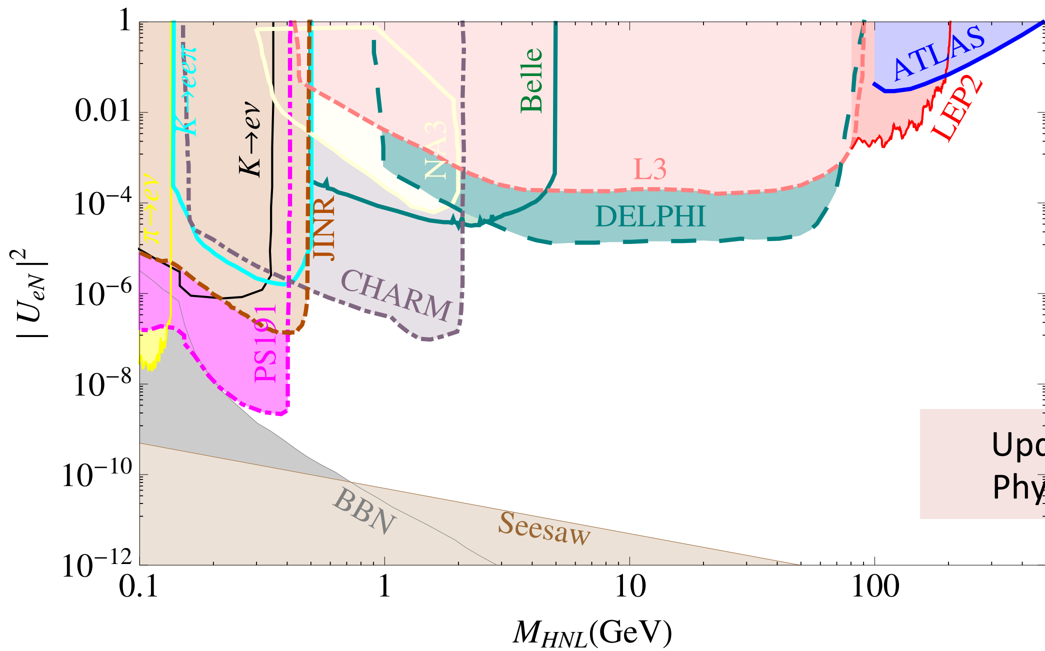
νMSM: T.Asaka, M.Shaposhnikov
PL B620 (2005) 17

N_1 (O(keV) mass) → Dark Matter

$N_{2,3}$ (O(GeV mass) → Neutrino masses and BAU

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

Existing constraints



Updated SHiP
Physics Paper

Previous experiments did not probe cosmologically interesting region for HNL masses above the kaon mass

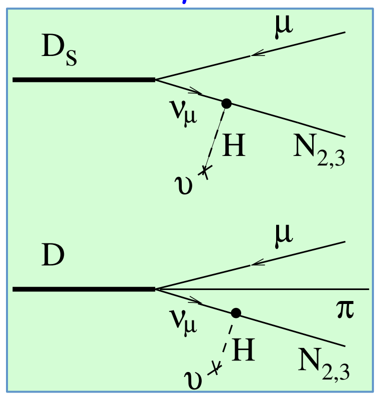
Masses and couplings of HNLs

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

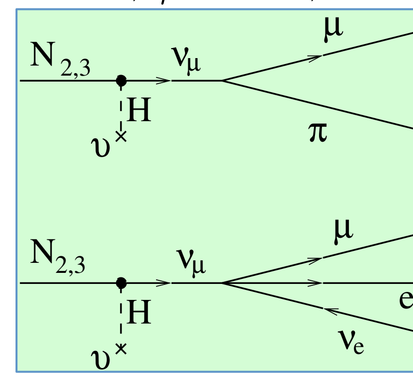
Very weak $N_{2,3}$-to-ν mixing (~ U^2) → $N_{2,3}$ are much longer-lived than SM particles

- 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



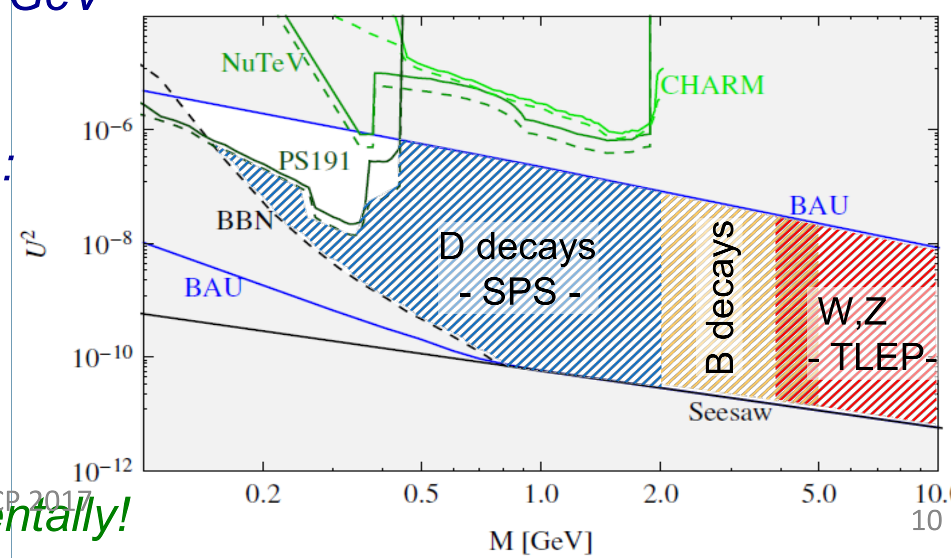
and subsequent decays



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

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

  $Br(N \to \mu/e\ \pi)$ ~ 0.1 – 50%
  $Br(N \to \mu^-/e^-\ \rho^+)$ ~ 0.5 – 20%
  $Br(N \to \nu\mu e)$ ~ 1 – 10%

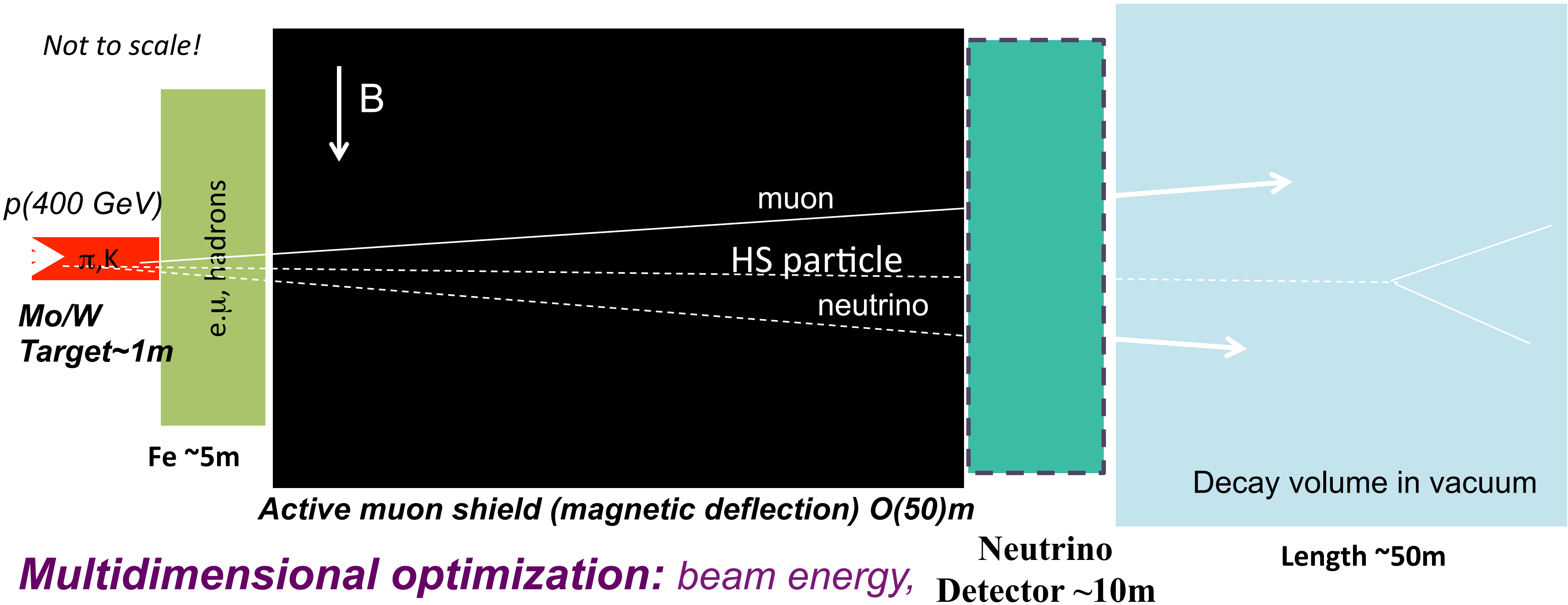


Domain only marginally explored, experimentally!

General experimental requirements

Initial reduction of beam induced backgrounds

- *Heavy target to maximize Heavy Flavour production (large A) and minimize production of neutrinos in $\pi/K \rightarrow \mu\nu$ decays (short λ_{int})*
- *Hadron absorber*
- *Effective muon shield (without shield: muon rate ~10^{10} per spill of 4×10^{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*

The SHiP experiment at SPS

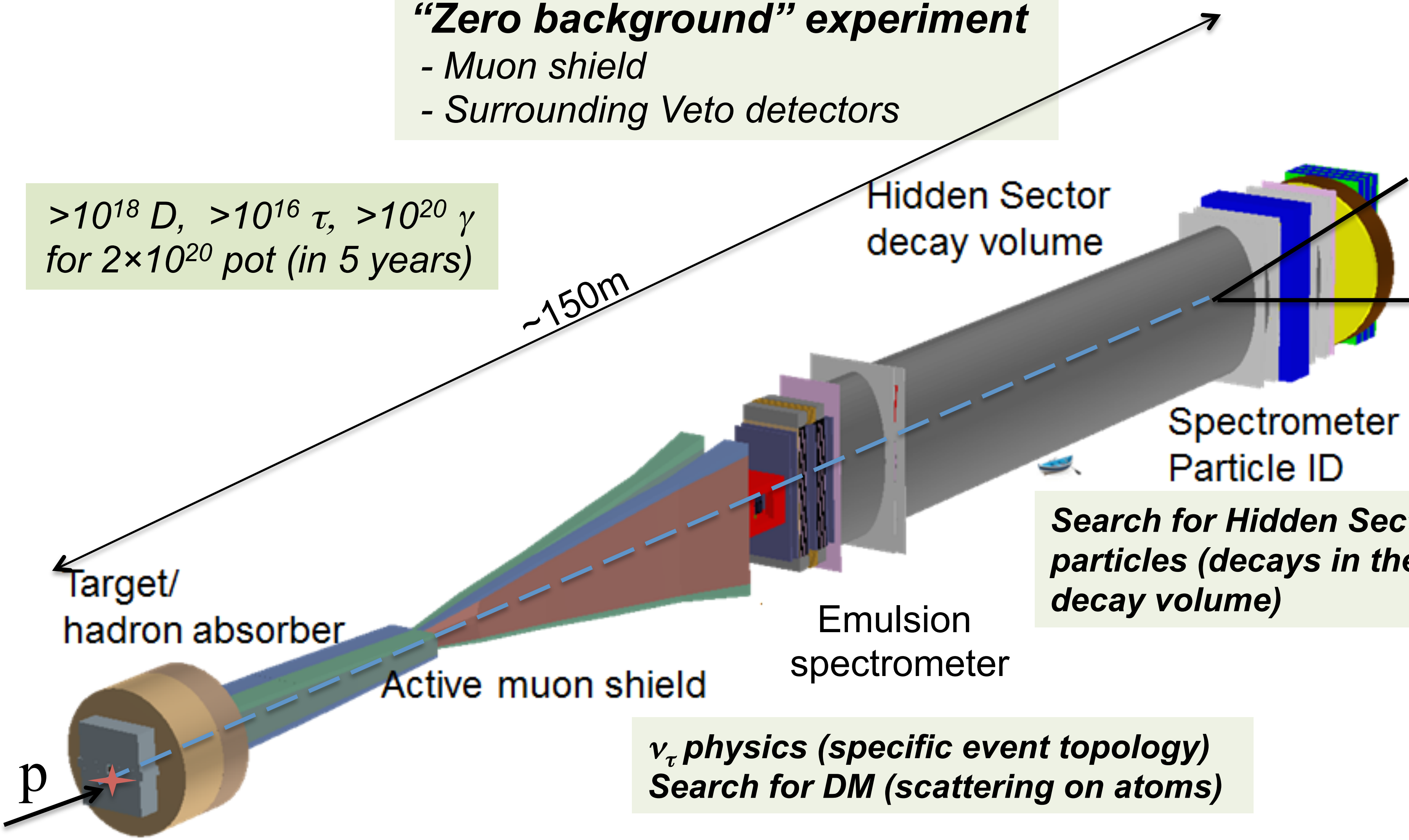
(as implemented in Geant4 for TP)

SHiP Technical Proposal: 1504.04956

"Zero background" experiment

- *Muon shield*
- *Surrounding Veto detectors*

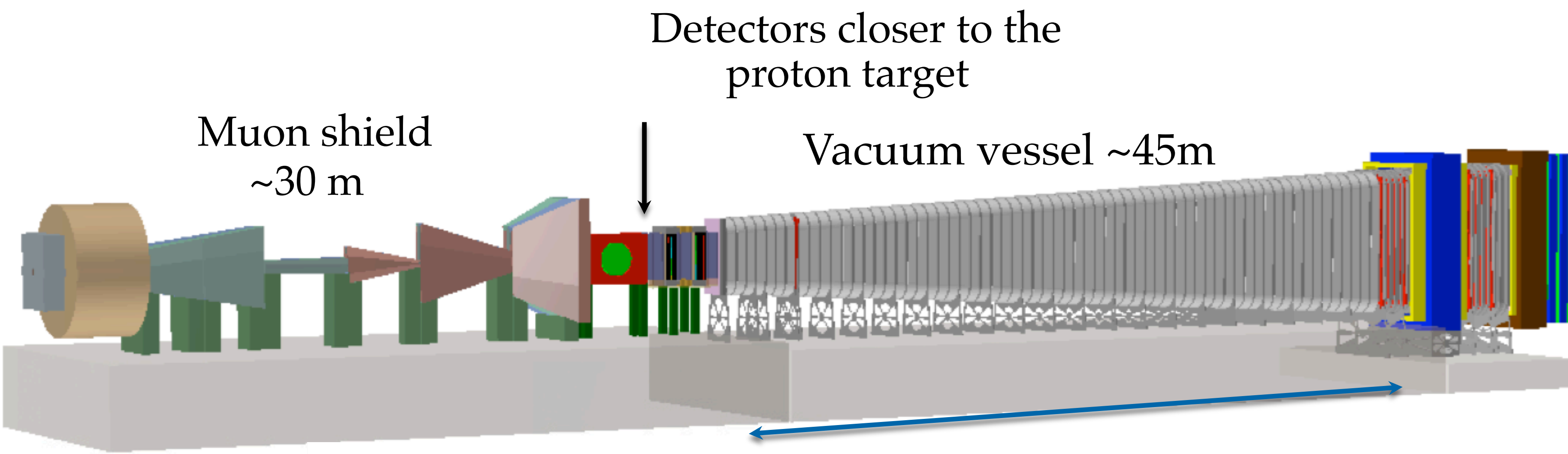
$>10^{18}$ D, $>10^{16}$ τ, $>10^{20}$ γ for 2×10^{20} pot (in 5 years)

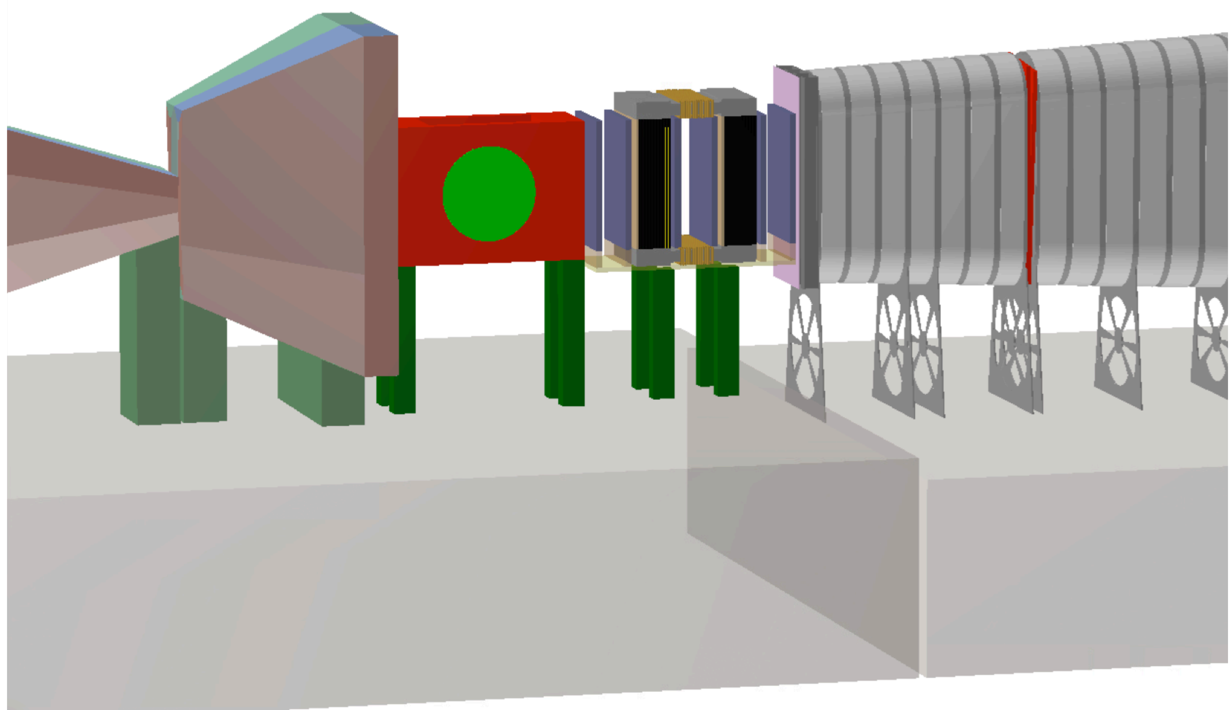


Search for Hidden Sector particles (decays in the decay volume)

ν_τ physics (specific event topology)
Search for DM (scattering on atoms)

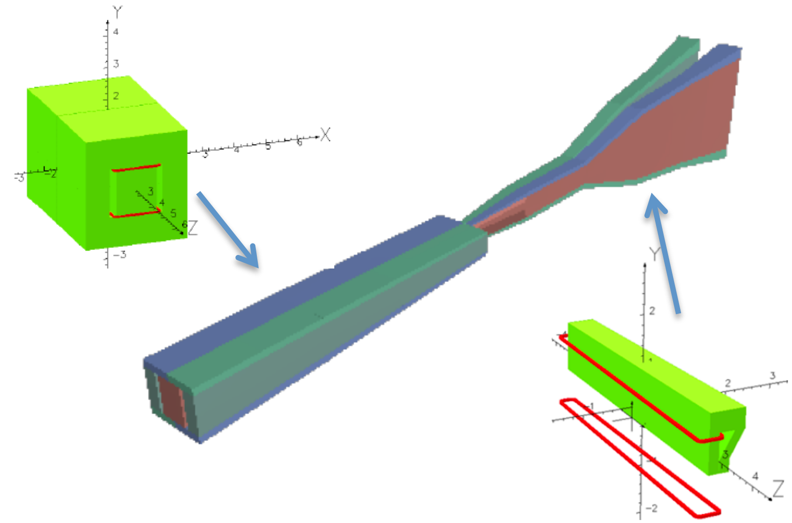
Detector Optimization: conical shape



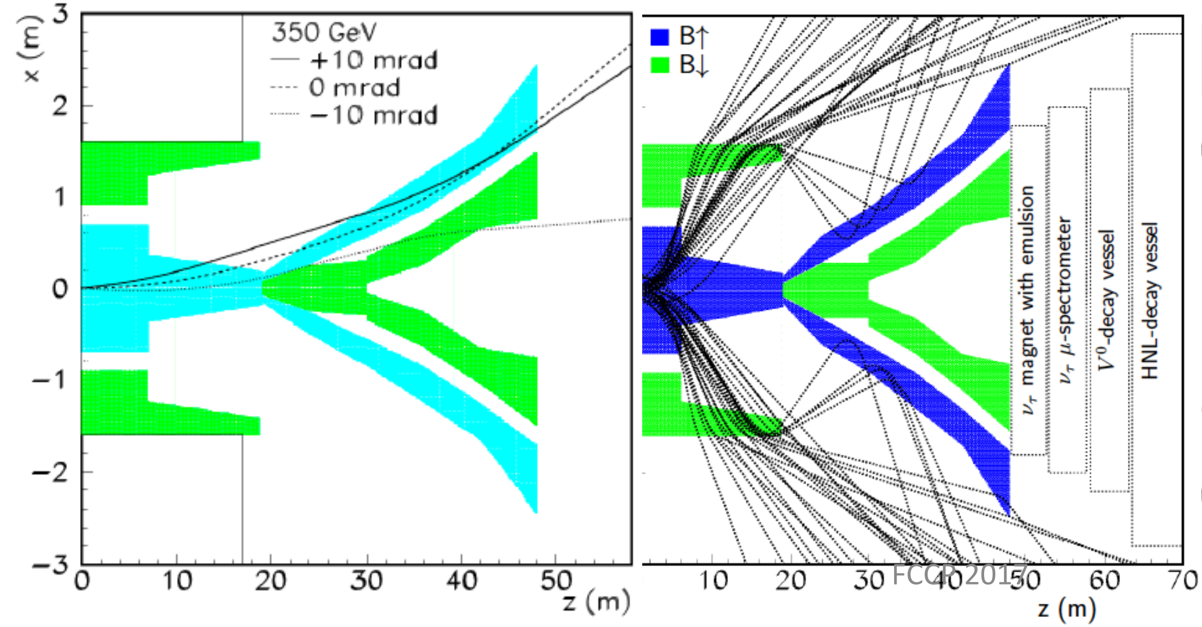


SHiP muon shield, JINST 12 (2017) P05011

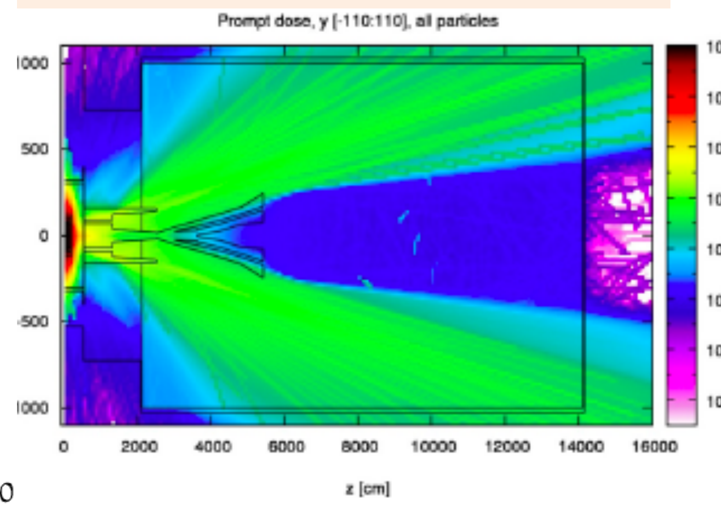
- ✓ *Muon flux limit driven by HS background and emulsion-based neutrino detector*
- ✓ *Active muon shield based entirely on magnet sweeper with a total field integral B_y = 86.4 Tm*
  Realistic design of sweeper magnets in progress
  Challenges: flux leakage, constant field profile, modeling magnet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



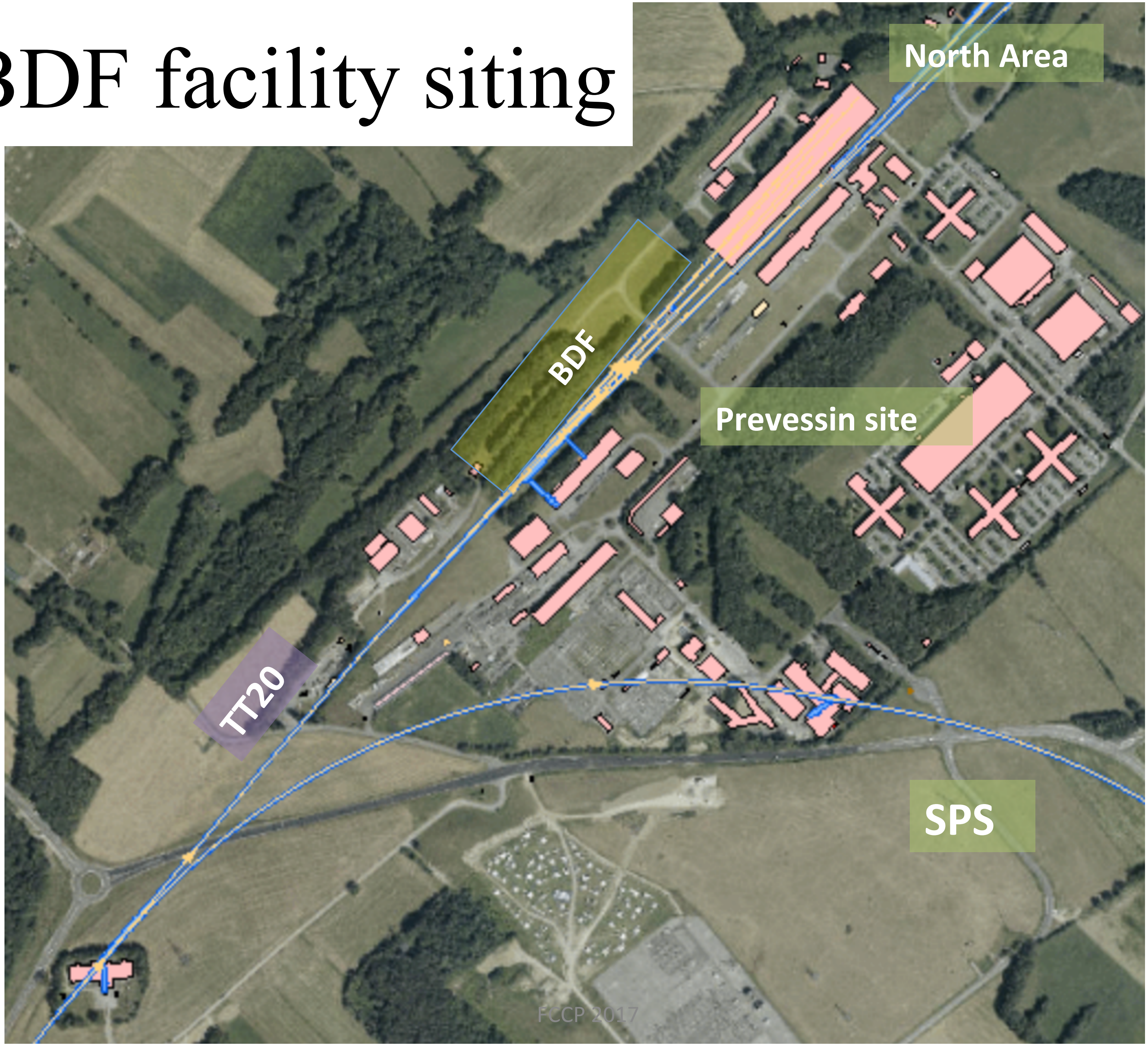
Magnetic sweeper field



Dose rate (μSv/h) in the SHiP hall

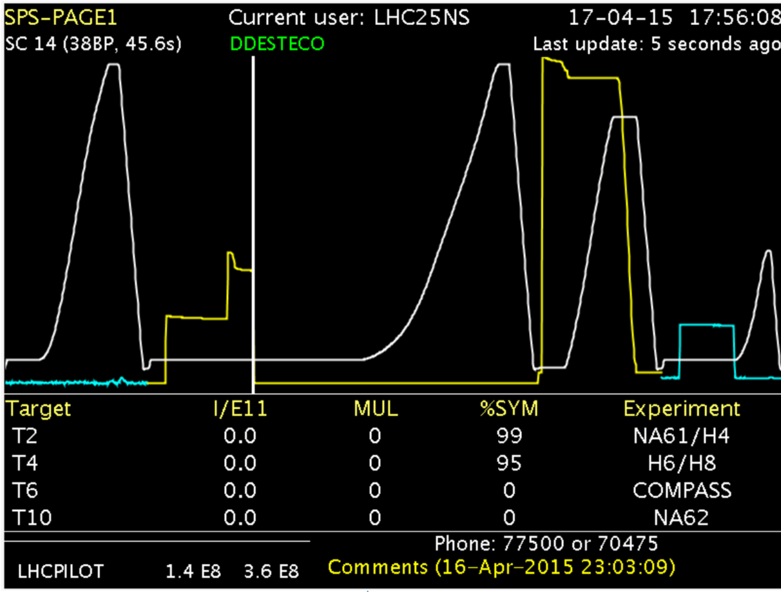


BDF facility siting



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 2015

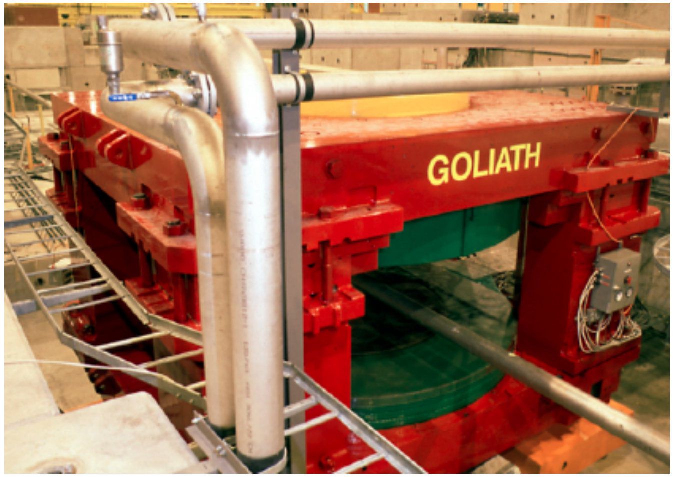
ν_τ Studies

- Less known particle in the Standard Model
- First observation by DONUT at Fermilab 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

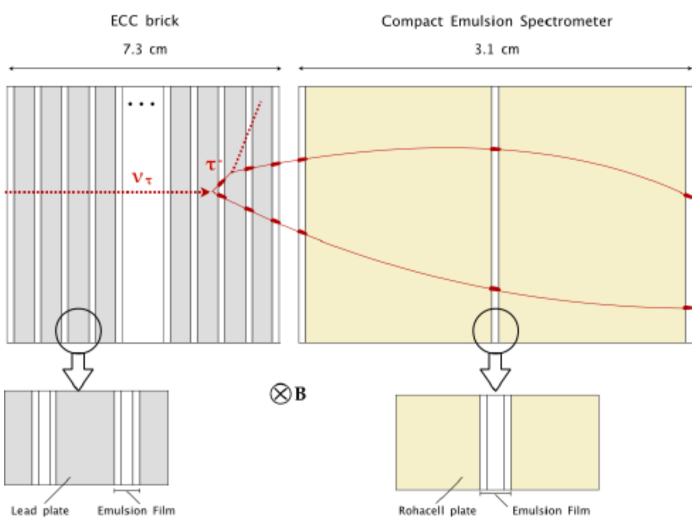
$$\sigma^{const}(\nu_\tau) = (0.39 \pm 0.13 \pm 0.13) \times 10^{-38}\ cm^2\ GeV^{-1}$$

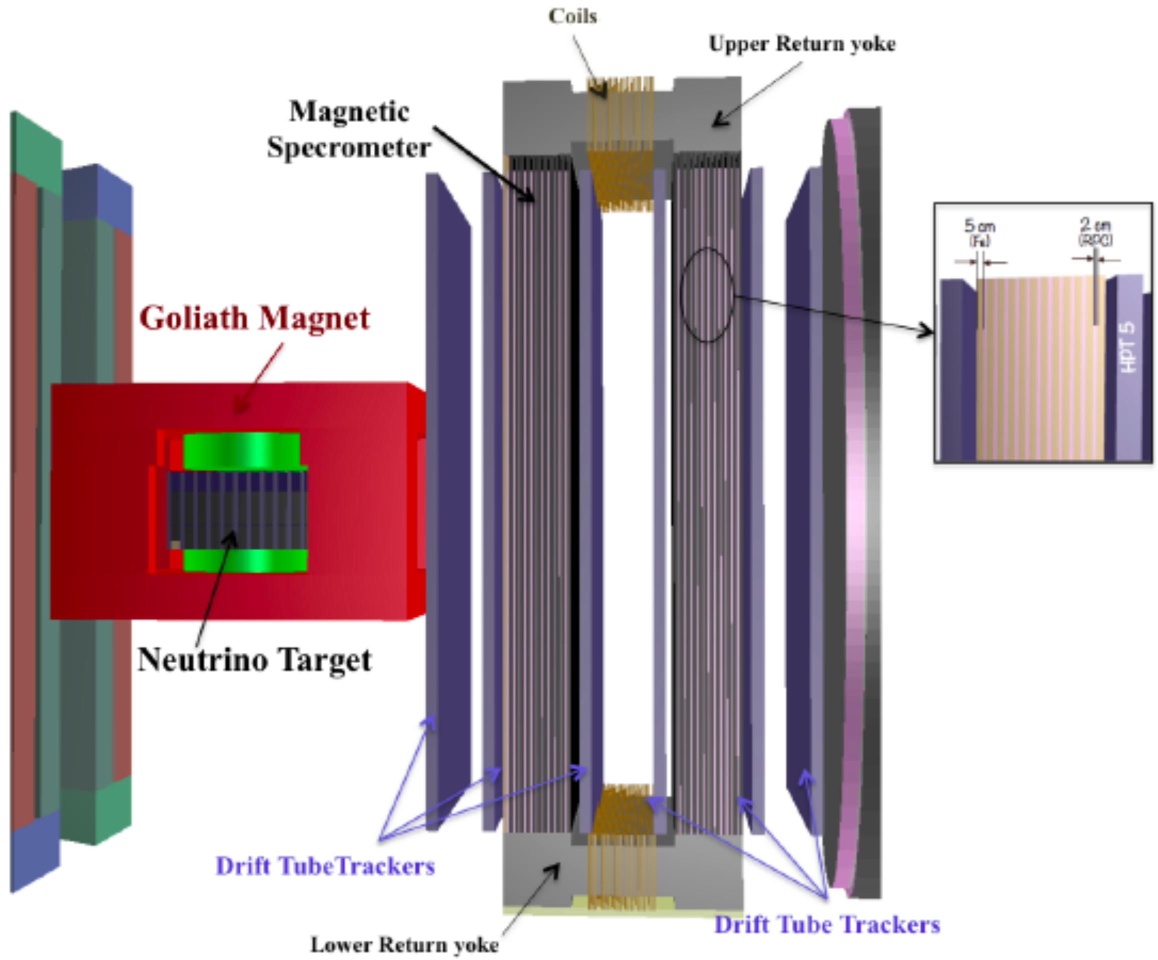
- 5 ν_τ candidates reported by OPERA for the discovery (5.1σ result) of ν_τ appearance in the CNGS neutrino beam PRL 115 (2015) 121802
- Tau anti-neutrino never observed

ν_τ detector follows the OPERA concept



Emulsion Cloud Chamber is the key element of ν_τ detection

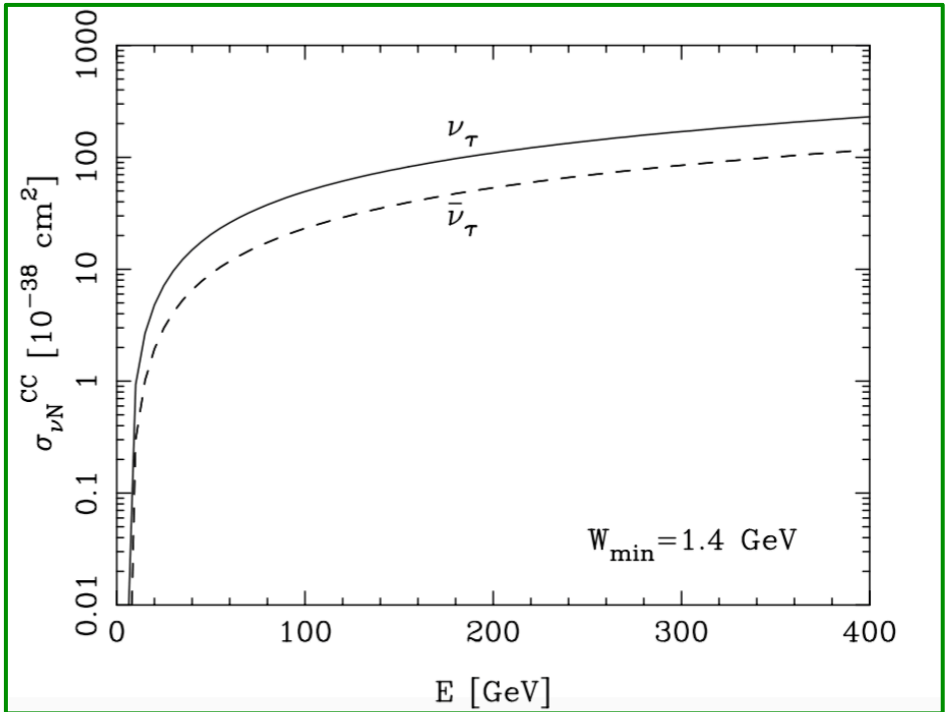




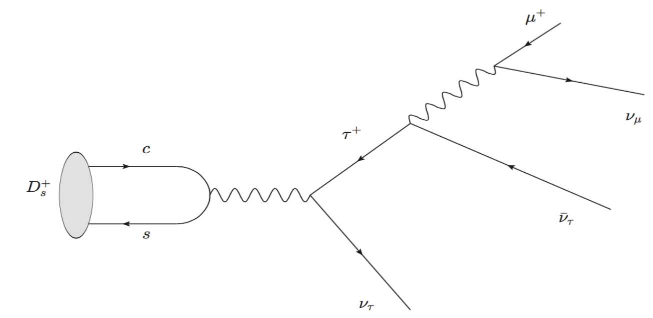
OPERA: 1 event in 1 brick
SHIP: ~230 events/brick

ν_τ Interactions In The Target

$$N_{\nu_\tau+\bar{\nu}_\tau} = 4N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \to \tau) = 2.85 \times 10^{-5} N_p = 6.6 \times 10^{15}$$



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



Expected number of interactions*

*in 5 years run (2x10^{20} pot)

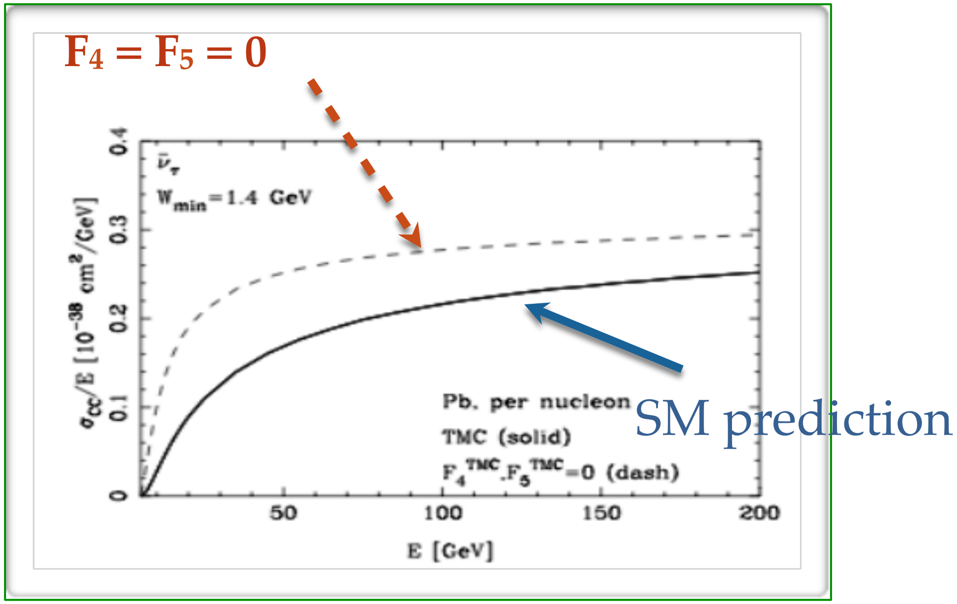
	CC DIS
$N_{\nu_\mu} + N_{\overline{\nu}_\mu}$	2.4×10^6
$N_{\nu_e} + N_{\overline{\nu}_e}$	3.4×10^5
$N_{\nu_\tau} + N_{\overline{\nu}_\tau}$	1.1×10^4

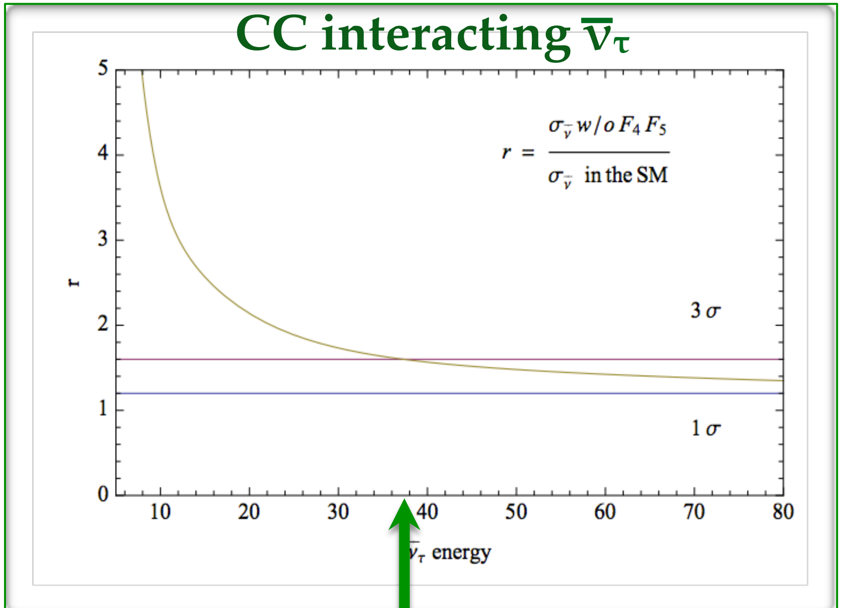
Large enhancement in a thick target
due to hadron cascade effect

F_4 and F_5 Structure Functions

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

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



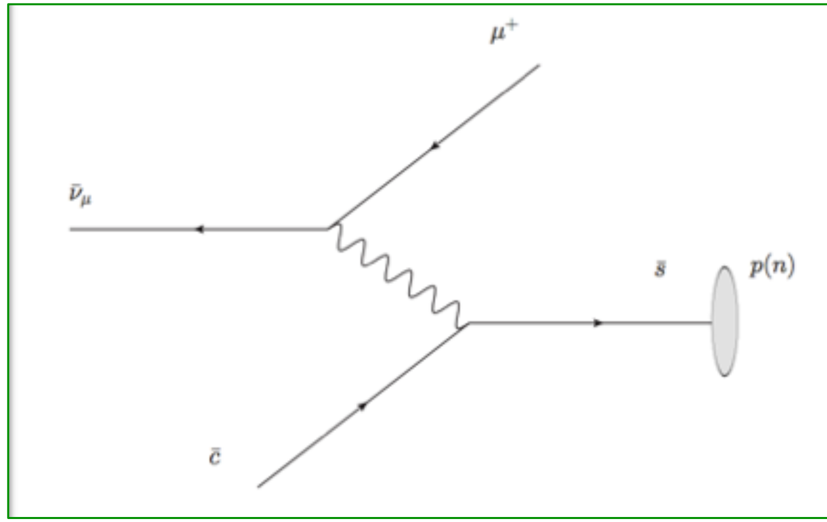


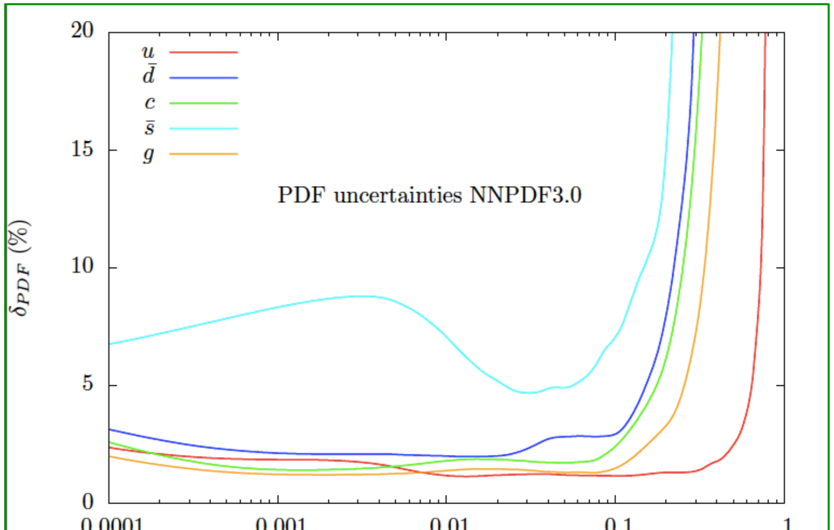
E($\overline{\nu}_\tau$) < 38 GeV

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

STRANGE QUARK NUCLEON CONTENT

- D production in anti-neutrino interactions selects anti-strange quark in the nucleon
- *Charm yield in ν int. (~10^5events) is >10x the sample from past experiments*
- Strangeness important for precision SM tests and for BSM searches
- W boson production at 14 TeV: 80% via $u\bar{d}$ and 20% via $c\bar{s}$

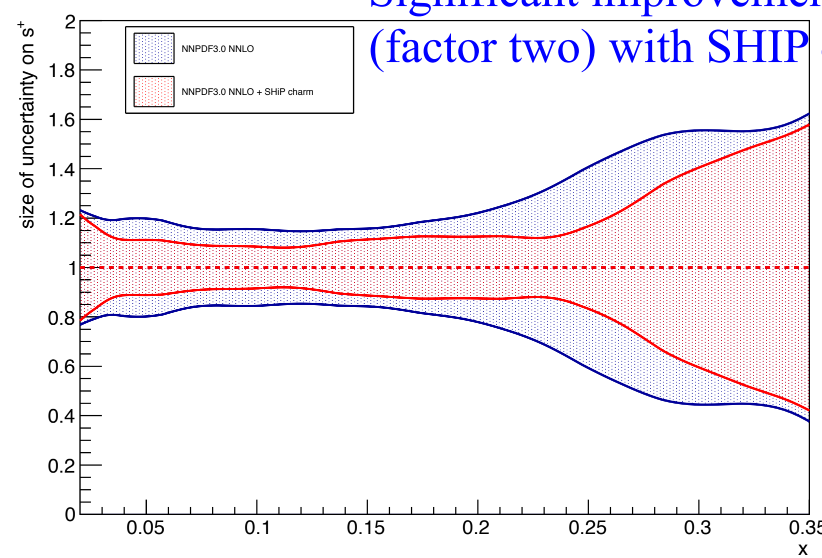




Phys. Rev. D91 (2015) 113005

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

- Significant improvement (factor two) with SHIP data



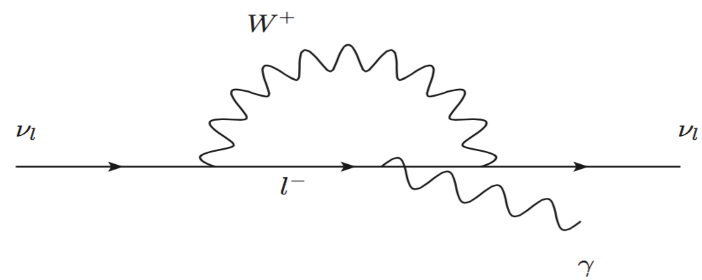
$$s^+ = s(x) + \overline{s}(x)$$

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

TAU NEUTRINO MAGNETIC MOMENT

A massive neutrino may interact e.m.

→ magnetic moment proportional to its mass



$$\mu_\nu = \frac{3\,e\,G_F\,m_\nu}{8\,\pi^2\,\sqrt{2}} \simeq (3.2 \times 10^{-19}) \left(\frac{m_\nu}{1\,\text{eV}}\right) \mu_B$$

$$\left.\frac{\sigma_{(\nu e, \bar{\nu} e)}}{dT}\right|_{\mu_\nu} = \frac{\pi \alpha_{em}^2 \mu_\nu^2}{m_e^2} \left(\frac{1}{T} - \frac{1}{E_\nu}\right)$$

No interference as it involves a spin flip of the neutrino

Current limits
- (ν_e) $\mu_\nu < 2.9 \cdot 10^{-11} \mu_B$
- (ν_μ) $\mu_\nu < 6.9 \cdot 10^{-10} \mu_B$

$$\theta_{\nu-e}^2 < 2m_e/E_e$$

IN SHiP

SIGNAL SELECTION
- $\theta_{\nu-e} < 30\,mrad$
- $E_e > 1$ GeV

$$n_{evt} = \frac{\mu_\nu^2}{\mu_B^2} \int \Phi_{\nu_\tau} \sigma^\mu N_{nucl} dE = 4.3 \times 10^{15} \frac{\mu_\nu^2}{\mu_B^2}$$

BACKGROUND PROCESSES

$\nu_x(\bar{\nu}_x) + e^- \to \nu_x(\bar{\nu}_x) + e^-$	NC	750 (NC + CC)
$\nu_e + e^- \to e^- + \nu_e$	CC	
$\nu_e + n \to e^- + p$	QE	11700 (QE + QE)
$\bar{\nu}_e + p \to n + e^+$	QE	
$\nu_e(\bar{\nu}_e) + N \to e^-(e^+) + X$	DIS	1700

Assuming 5% systematics from DIS measurements

SHiP can explore a region down to

$$\mu_\nu = 1.3 \times 10^{-7} \mu_B$$

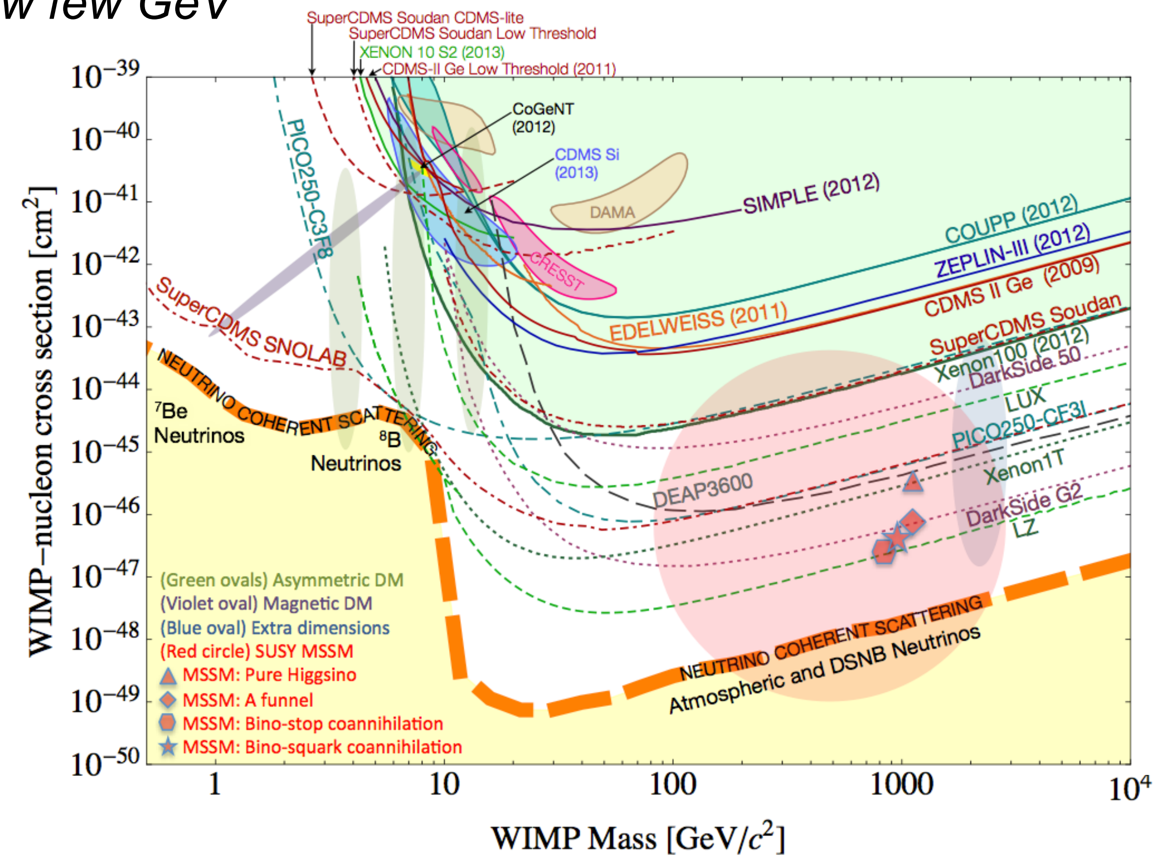
Light Dark Matter (LDM)

The prediction for the mass scale of DM spans from 10^{-22} eV to 10^{20} GeV

- ✓ *WIMP DM is a popular theoretical paradigm ("WIMP miracle")*
- ✓ *Extensive exp. search for WIMPs with masses 10 GeV – 1 TeV*
  Sensitivity is very limited below few GeV

Large classes of theor. models can make the observed relic density with sub-GeV DM:

- *Hidden-sector models*
- *Supersymmetry*
- *Strongly Interacting DM (SIMP)*
- *Extra dimensions*



Essential to explore the sub-GeV mass range for DM

LDM prospects @ SHiP

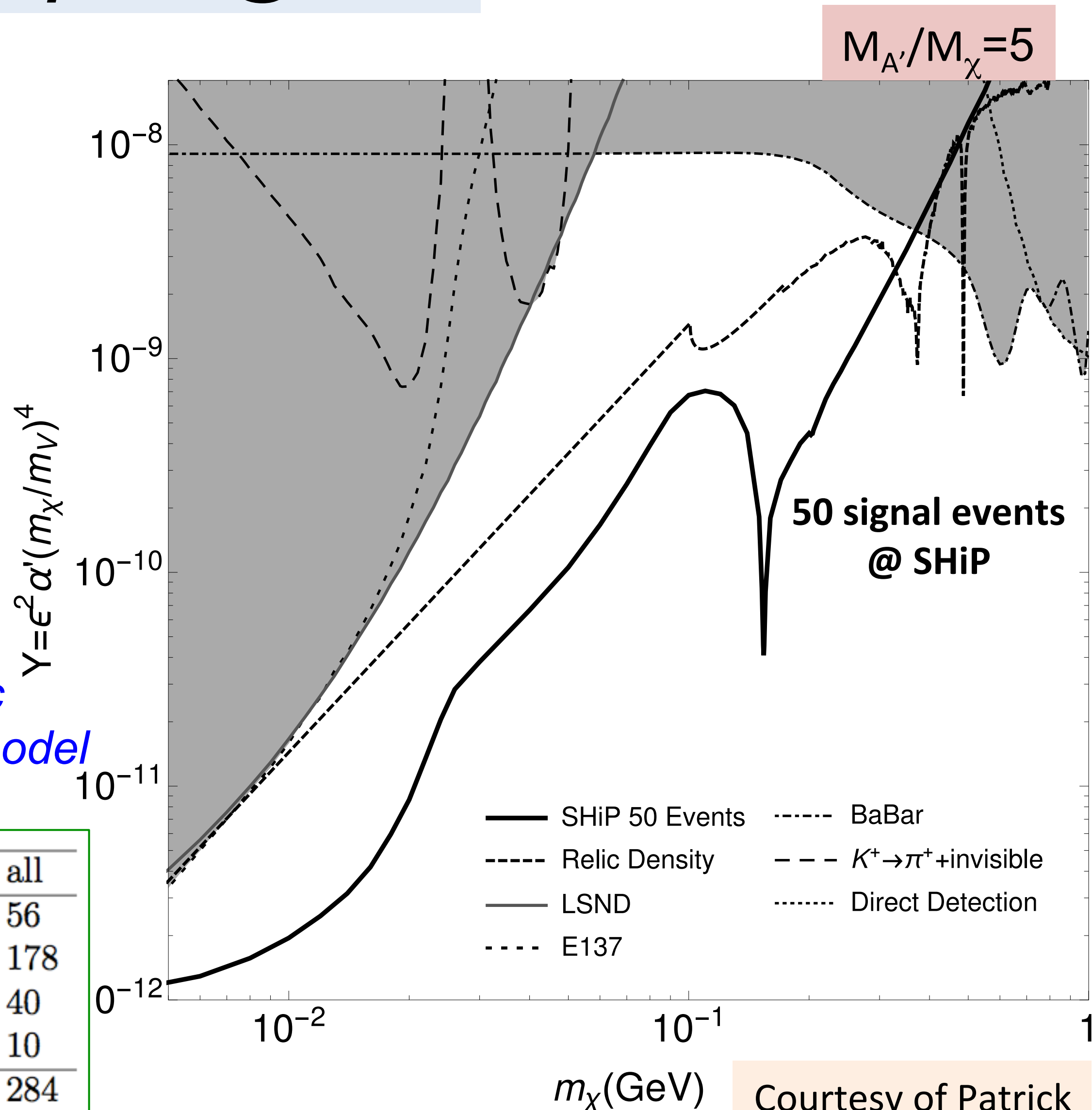
LDM (χ) can be generated in a beam-dump, *for example in* ***decays of HS mediators****,*
e.g. dark photons A' → χχ

>10^{20} photons expected in SHiP can be used as ***a LDM beam***

Detect LDM via its scattering on atoms of emulsion spectrometer

SHiP would probe even beyond relic density in minimal hidden-photon model

	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



Courtesy of Patrick deNiverville

Requires dedicated study/beam test

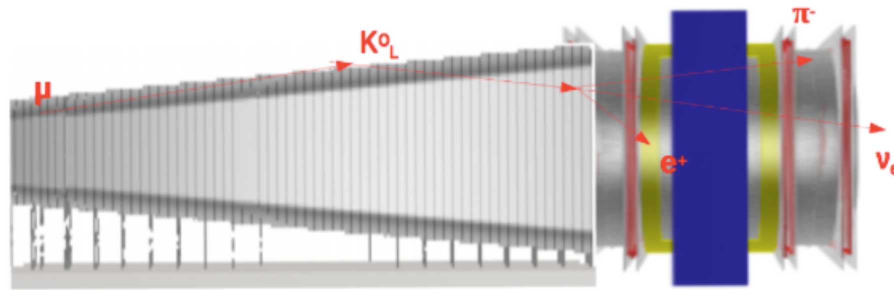
Hidden Sector detector concept

✓ 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

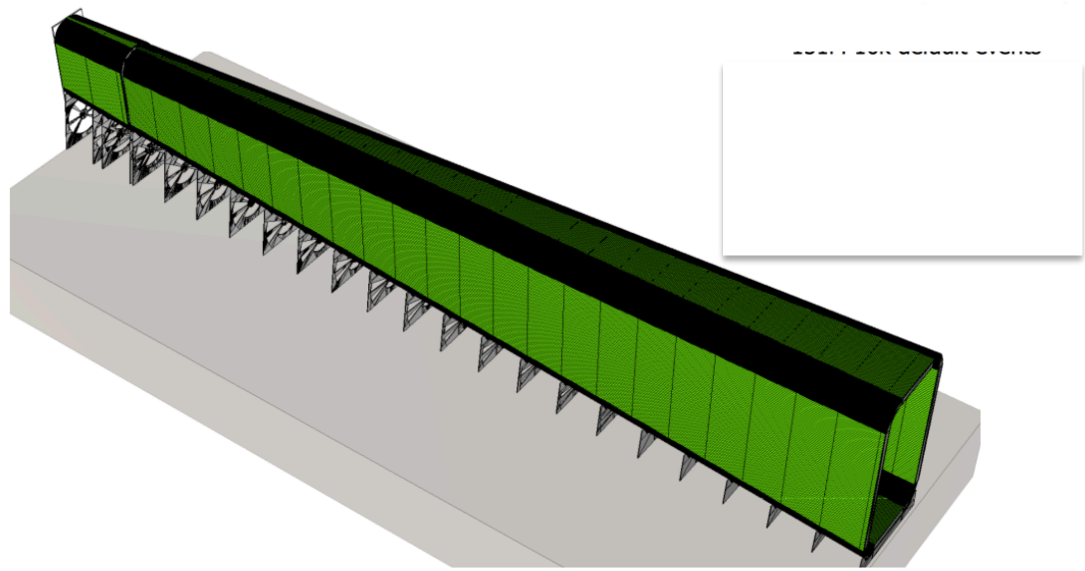
✓**Estimated need for vacuum:**
~ 10^{-3}

Challenges:
- Large vacuum vessel
- 5 m long straw tubes
- Timing detector with ~50-100 ps resolution



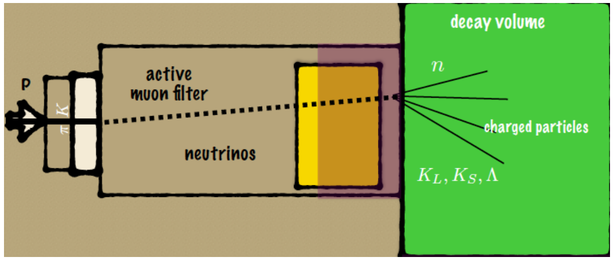
✓**Magnet designed with an emphasis on low power**

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



HS Backgrounds (1)

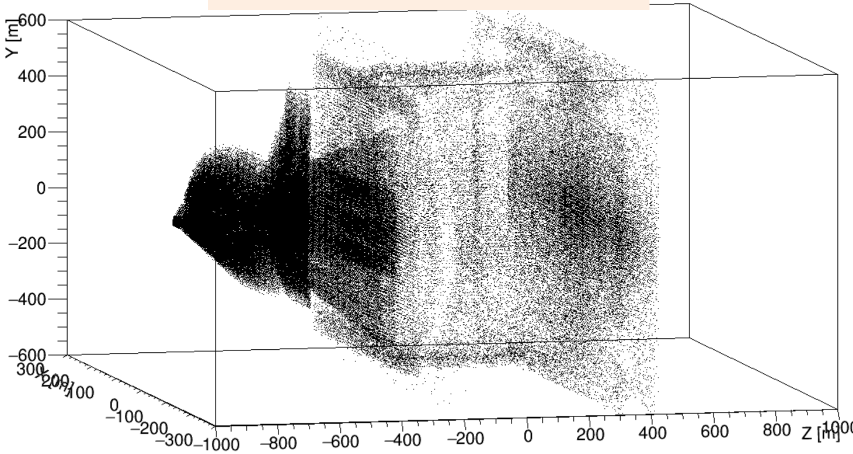
Main sources of background



- ✓ ***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)

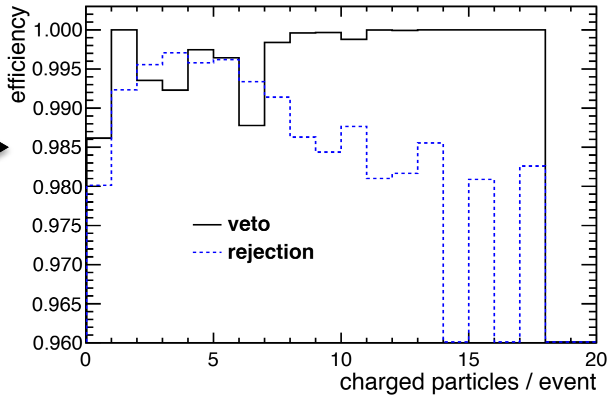
Origin of neutrino interactions
- *Walls of the decay volume (>80%)*
- *Tau neutrino detector*
- *HS tracking system*

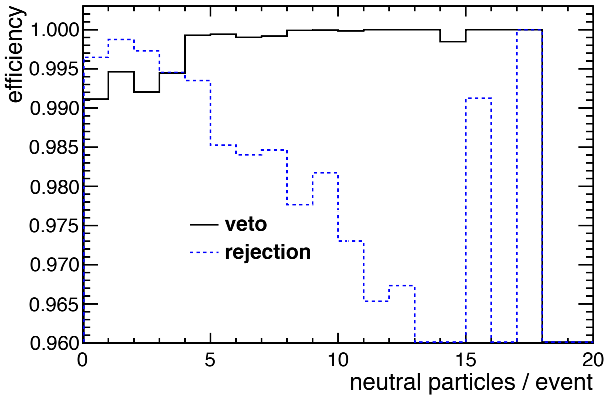
Neutrino tomography



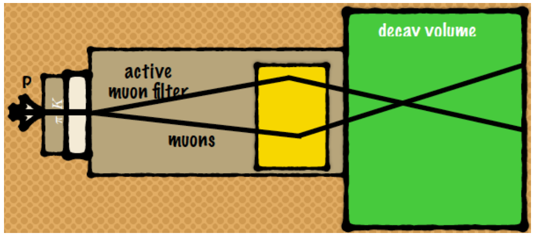
Combination of veto and selection cuts reduces the ν-induced background to zero

Veto efficiency increases with event multiplicity →





HS Backgrounds (2)



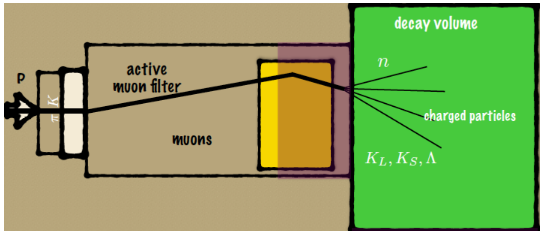
✓ ***Muon combinatorial background***

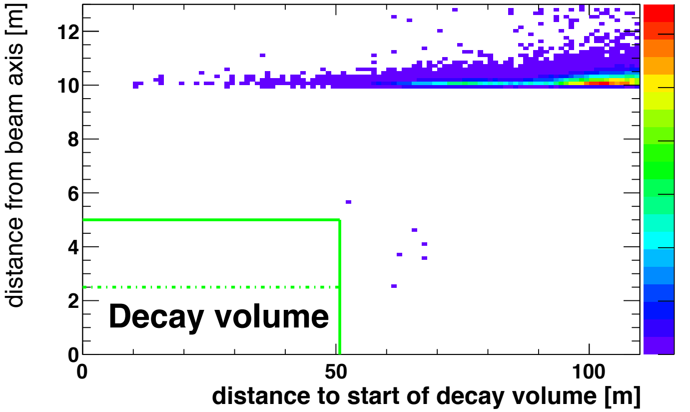
Simulation predicts O(10^{12}) muon pairs in the decay volume in 5 years of data taking

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

✓ ***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





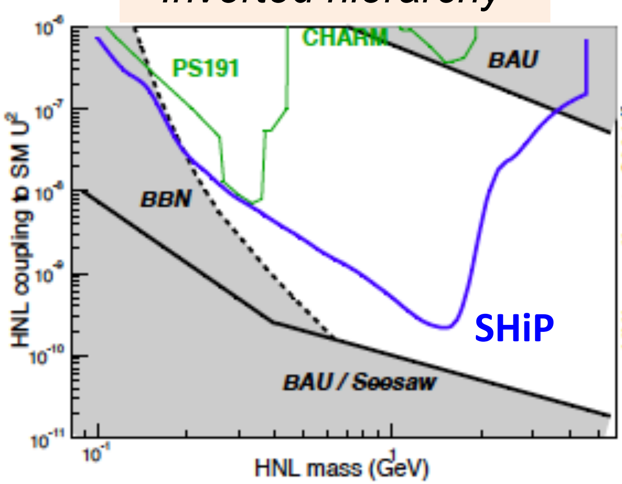
✓ ***Cosmic rays***

Background summary: no evidence for any irreducible background

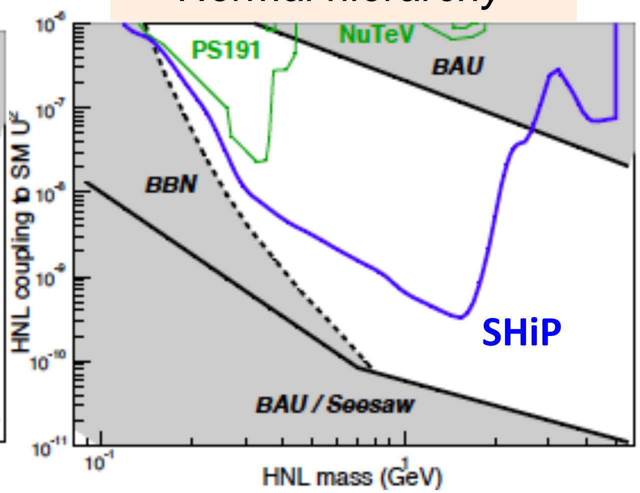
HNL prospects @ SHiP

BAU constraint is model-dependent (shown below for νMSM)

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



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

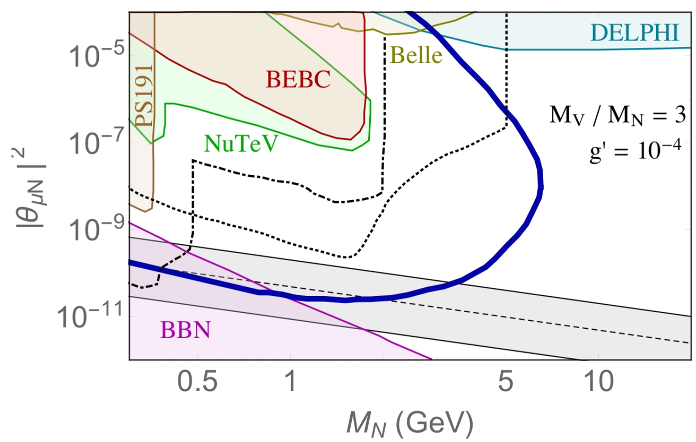


Further studies:

Drewes et al. (2016)
Hernandez et al. (2016)
Hernández (2015)
Drewes & Garbrecht (2012)
Abada et al. (2015)

Enhanced HNL production
(B-L gauge symmetry)

Batell, Pospelov, Shuve 1604.06099

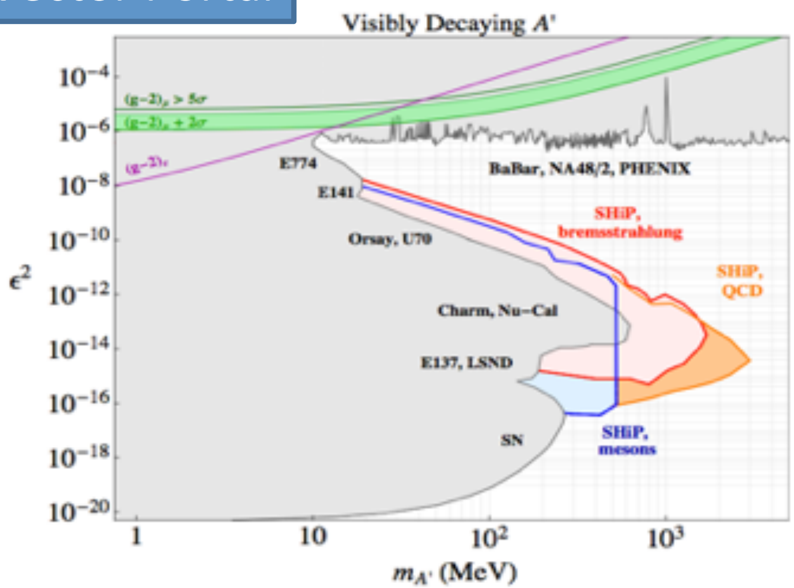


SHiP sensitivity covers large area of parameter space below the B mass
Moving down towards the ultimate see-saw limit

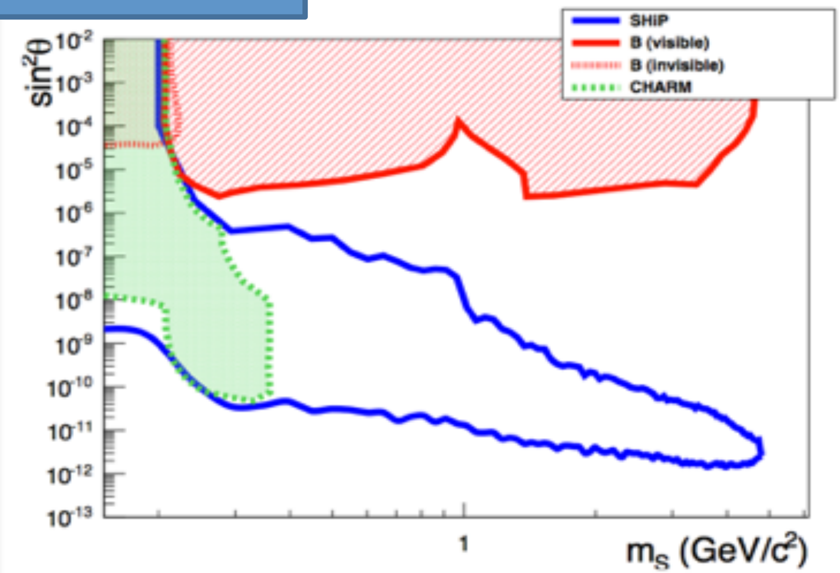
SHiP sensitivity to Hidden Sector

Based on 2×10^{20} pot @400 GeV in 5 years

Vector Portal

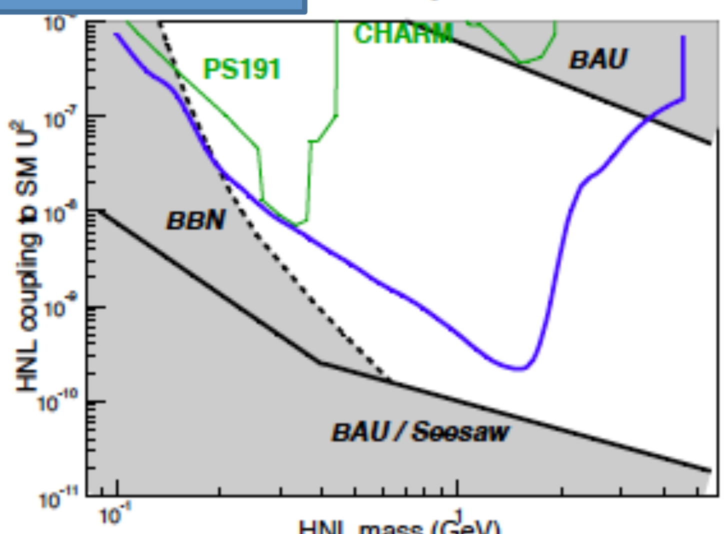


Scalar Portal

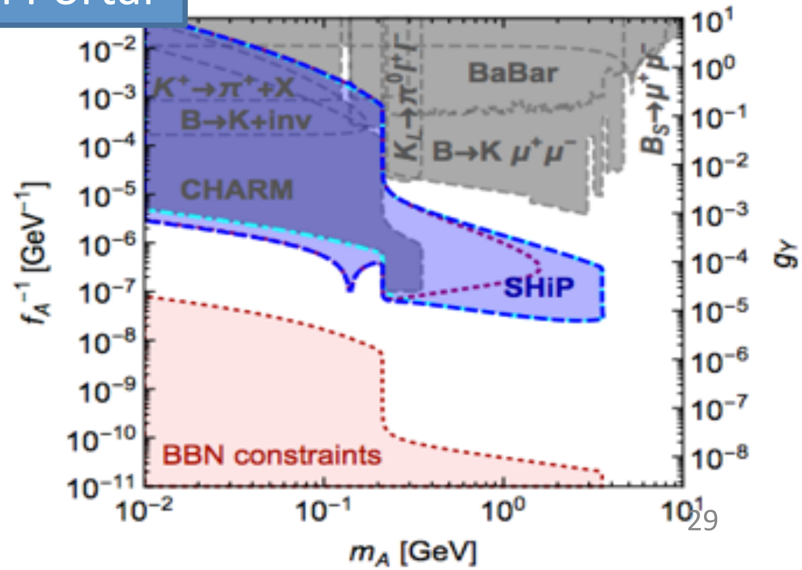


Neutrino Portal

sensitivity to HNLs

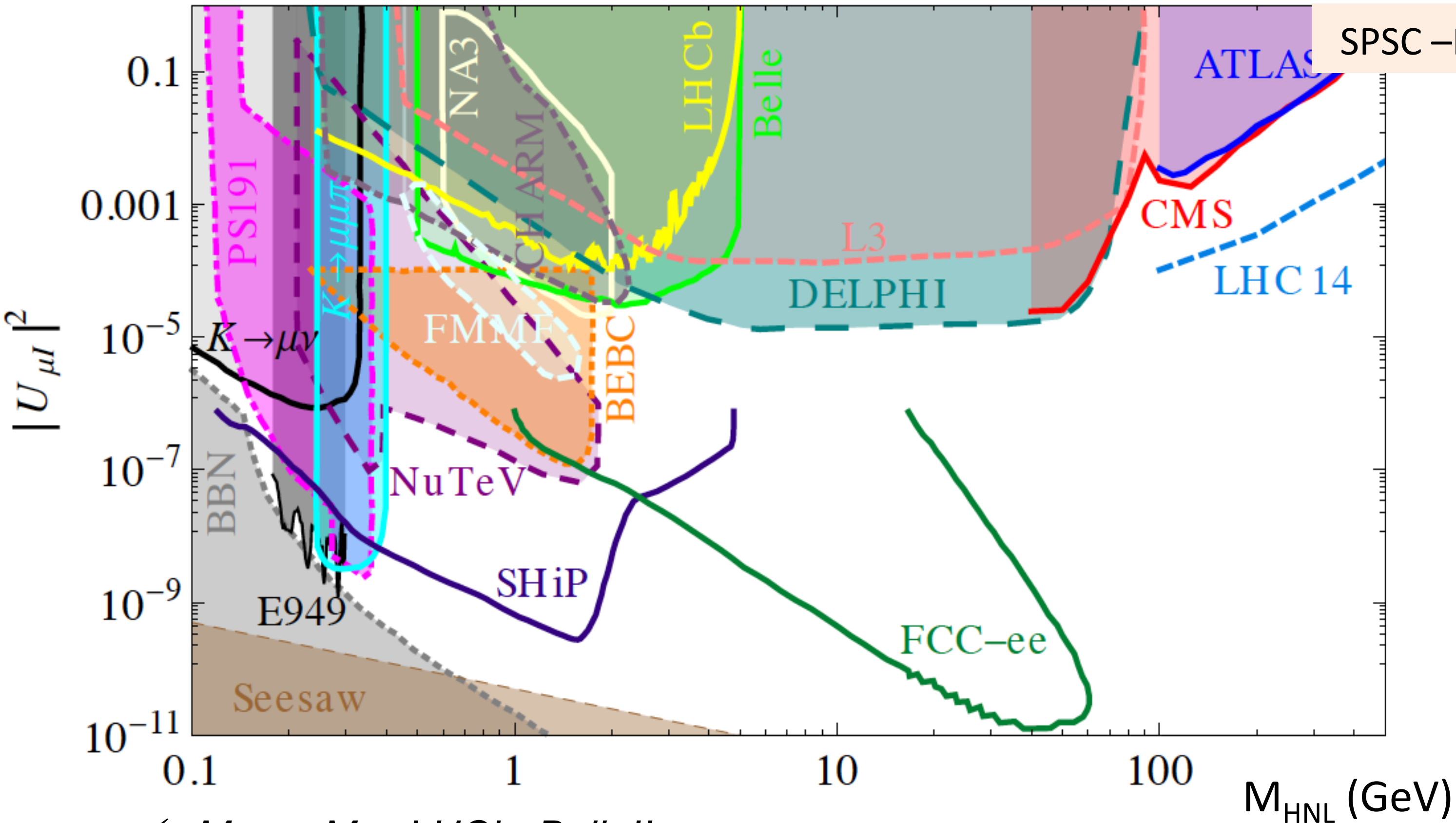


Axion Portal



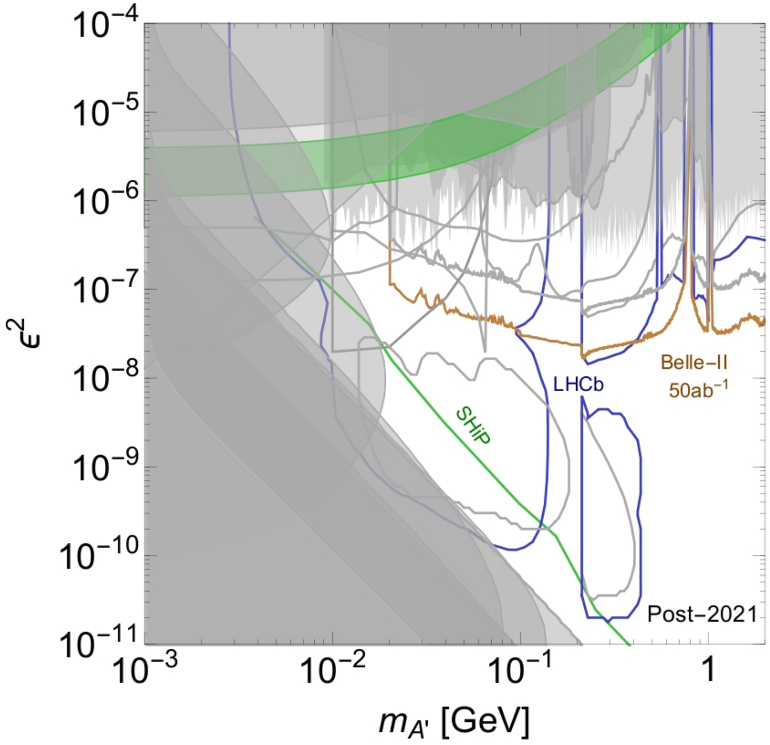
Comparison with future facilities

SPSC –P350-ADD-2



- ✓ $M_{HNL} < M_b$ *LHCb, BelleII*
  SHiP will have much better sensitivity
- ✓ $M_b < M_{HNL} < M_Z$ ***FCC in e^+e^- mode*** *(improvements are also expected from ATLAS / CMS)*
- ✓ $M_{HNL} > M_Z$ ***Prerogative of ATLAS/CMS @ HL LHC***

Also the best prospects for HS particles produced in heavy flavour decays (e.g. hidden scalars) and ν_τ physics

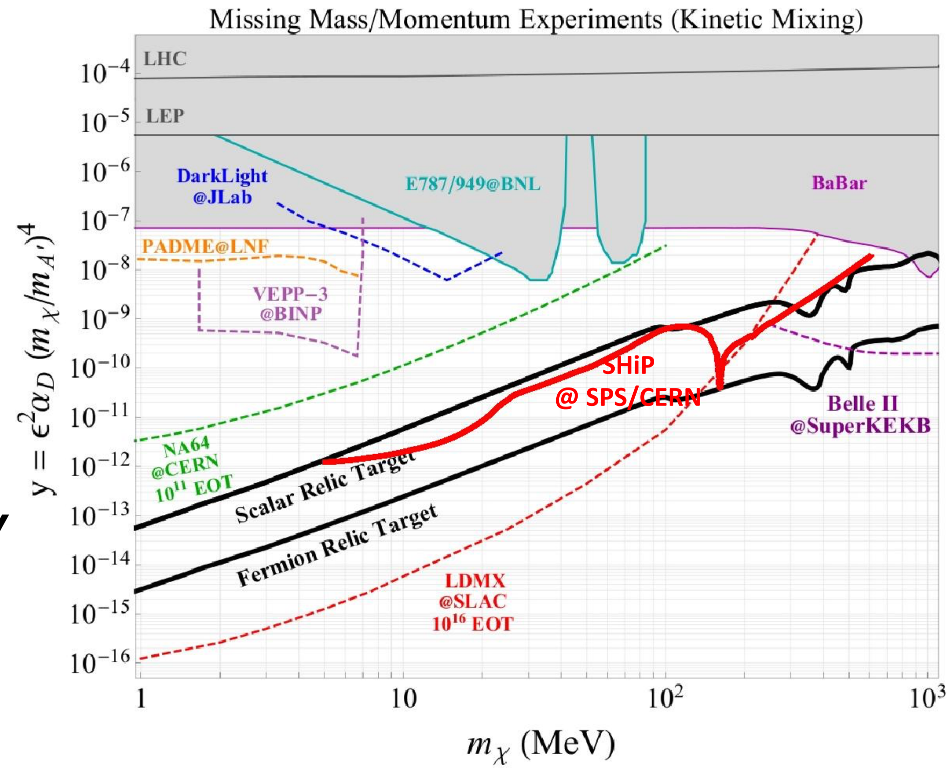


Comparison with future facilities

Dark photons:

SHiP is unique up to O(10GeV) and $\varepsilon^2 < 10^{-11}$

$M_{A'}/M_\chi=3$



Light Dark Matter

Direct Detection exp.

- ***SHiP has unique potential for M_χ <1GeV***
- *BDX in Jlab may have a competitive sensitivity for M_χ <10 MeV with 10^{22}eot.*

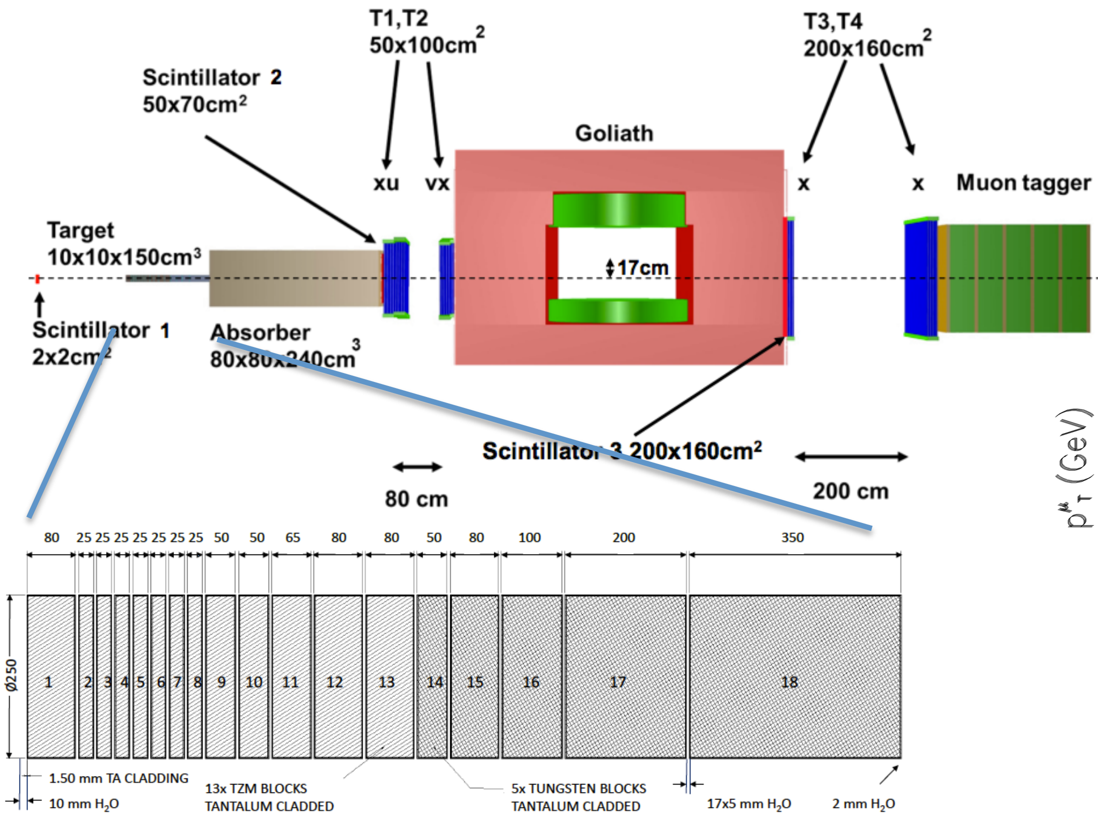
Missing mass / momentum exp.

- *Belle II – comparable to SHiP for M_χ>0.5 GeV with 50 ab^{-1} provided that low energy mono-photon is implemented*
- *LDMX (under discussion at SLAC) has the best prospects for M_χ< 100 MeV with 3×10^{21} eot. Time scale is unclear.*

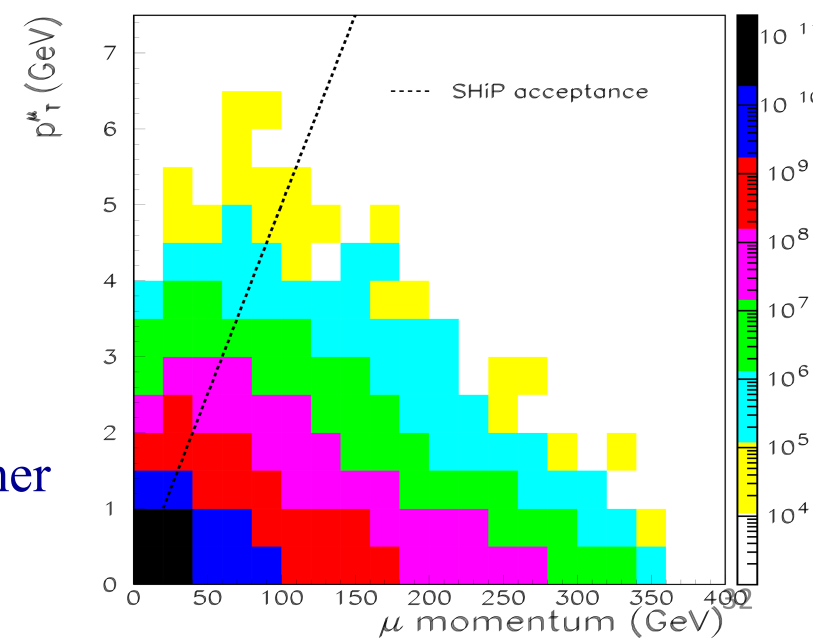
Dark sectors 2016: 1608.08632

Active test beam programme

- ✓ ***Construct and test prototypes of various sub-detectors***
- ✓ ***Measurement of muon flux expected at SHiP***
  Replica of the SHiP target followed by a muon spectrometer in 2018



- ✓ ***SHIP target****, 10×10 cm² Mo/W replica*
- ✓ ***Spectrometer*** *to measure momentum and charge of the muons*
- ✓ ***Muon tagger*** *to identify muons*



10^{11} pot → 100 events in the dangerous corner

Validate simulation

EoI-016 submitted to the SPSC

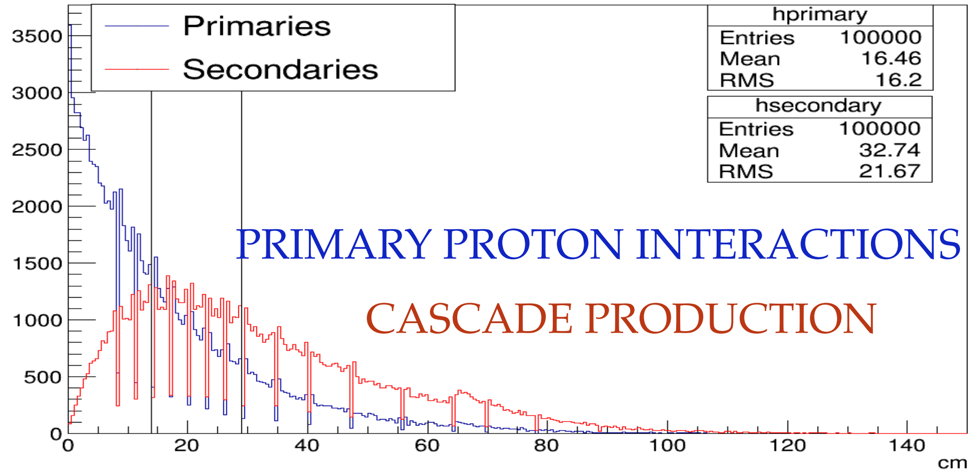
Active test beam programme

✓ ***Measurement of inclusive $d^2\sigma / dEd\theta$ charm cross section in SHiP-like target*** *(to validate cascade production in the target) in 2018*

✓ ***SHIP target****, 10×10 cm^2 Mo/W blocks (few mm)interleaved with emulsion to identify charm topology*

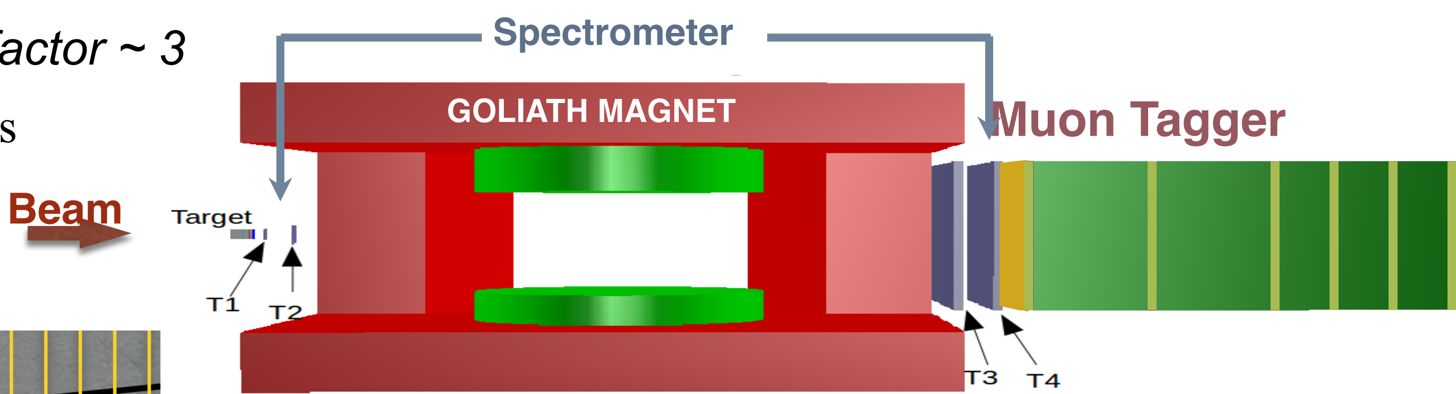
✓ ***Spectrometer*** *to measure momentum and charge of the charm daughters*

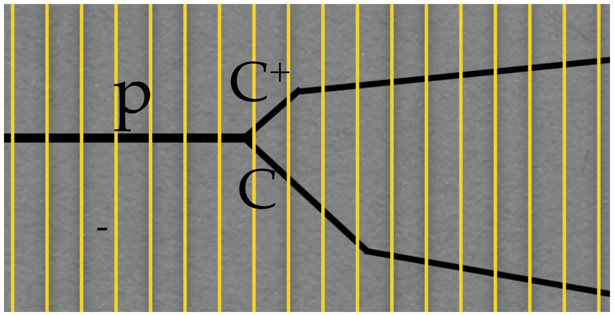
✓ ***Muon tagger*** *to identify muons*



Cascade effect → factor ~ 3

400 GeV protons

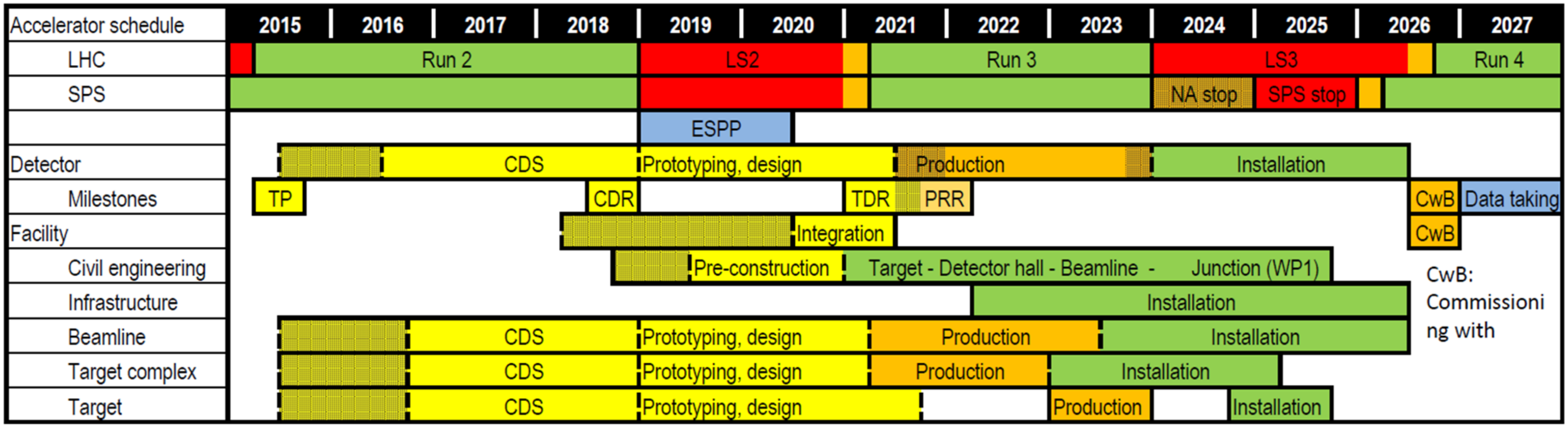




5 x 10^7 pot → ~ 10000 charmed hadron pairs

EoI-016 submitted to the SPSC

Project schedule and next steps



- ✓ *Schedule optimized to avoid interference with operation of North Area*
  - ➔ *Four separate work packages (junction cavern, beam line, target complex and detector hall)*
  - ➔ *Use LS3 for junction cavern and first short section of SHiP beam line*
- ✓ *Positive recommendation by the SPSC in January 2016 to prepare a Comprehensive Design Study 2016-2018*
- ✓ *Positive feedback by the Research Board in March 2016*
- ✓ *CERN DG launched the "Physics Beyond Colliders" Working Group:*

kick-off meeting in September 2016, next annual meeting November 21st 2017

- ✓ *Outcome of the WG at the European HEP strategy in 2020*
- ✓ *Construction/production 2021-*
  - ➔ ***Data taking 2026***