Neutrino Scattering Physics with the SHiP Experiment

Antonia Di Crescenzo

INFN Naples
Italy

DIS 2015
Dallas, Texas
April 27 - May 1, 2015

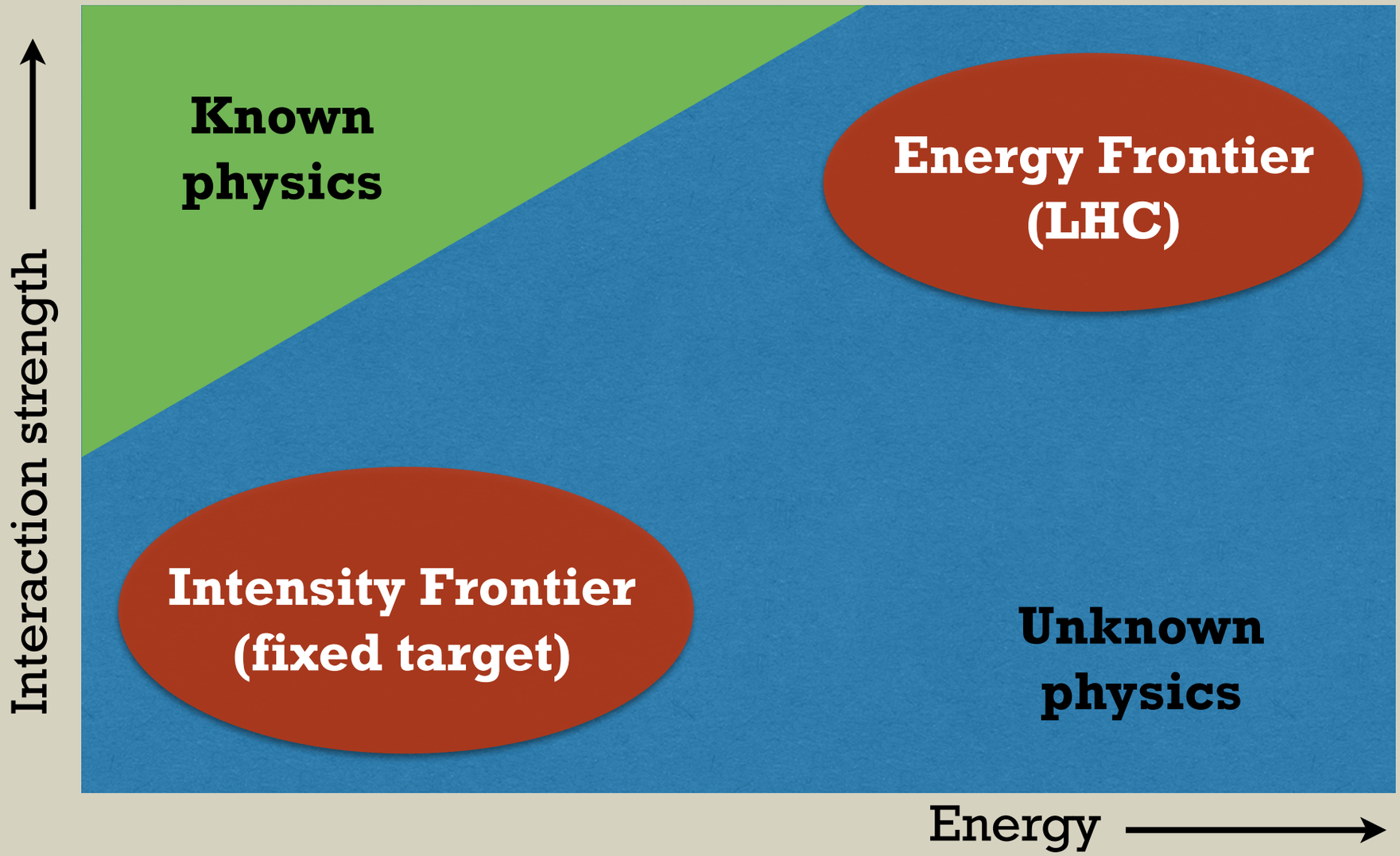
Introduction

- Standard Model provided consistent description of Nature's constituents and their interactions
- No significant deviation from SM found
- With a mass of the Higgs boson of 125 GeV, the Standard Model may be a self-consistent weakly coupled effective field theory up to very high scales (possibly up to the Planck scale) without adding new particles

- SM is not a complete theory: explanation of experimental observations "Beyond the Standard Model" still missing
  - **Neutrino masses and oscillations**
  - **Baryon asymmetry of the Universe (BAU)**
  - **Dark Matter**

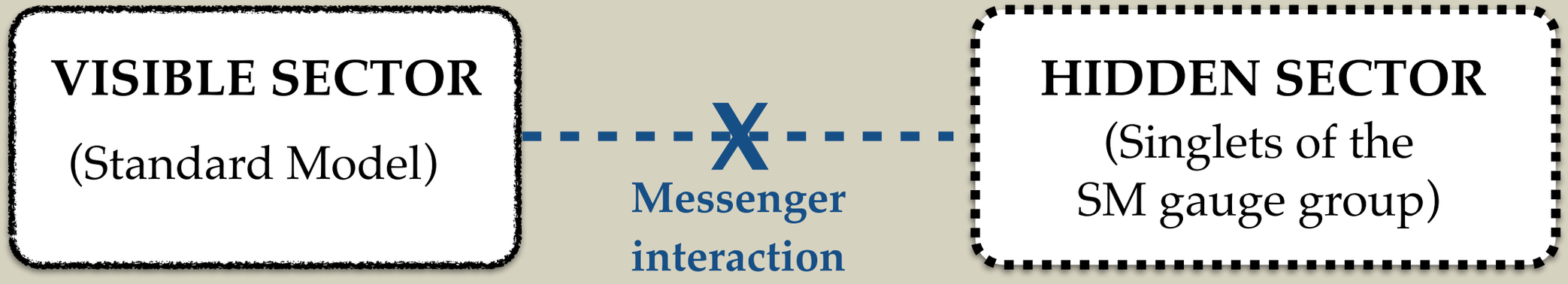
Introduction

- Unknown particles or interactions needed to explain these puzzles. Where to search for them?



Hidden Sector and Neutrinos

- Hidden Sector accessible to **intensity frontier** experiments via sufficiently light particles, coupled to the Standard Model sectors via renormalizable "**portals**"

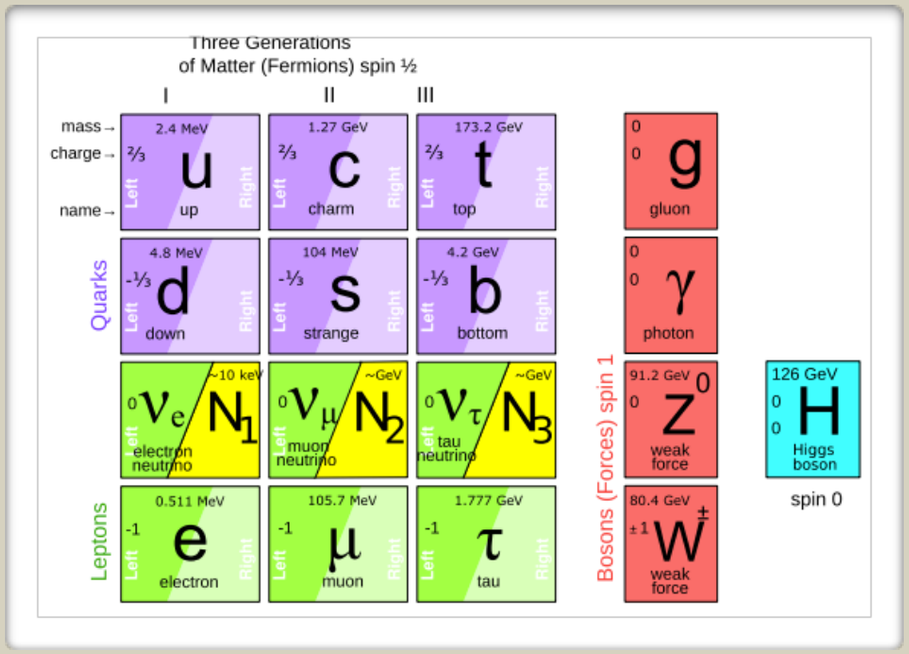


- **SHiP**: new fixed target facility at the intensity frontier to explore Hidden Sector
- Neutrino physics

- Large variety of models investigated: scalar portal, vector portal, neutrino portal, axion portal …

One Example: νMSM

- **νMSM**: **ν**-Minimal Standard Model
  3 additional Heavy Neutral Leptons: right-handed Majorana neutrinos

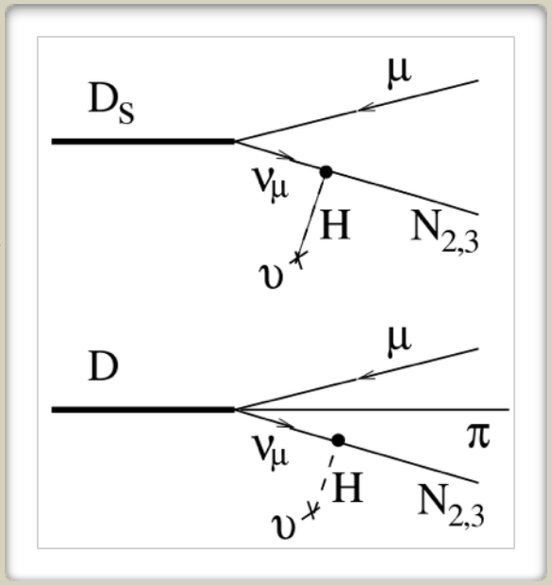


- N_1 : Dark Matter candidate
  - → Mass ~10 keV
- $N_{2,3}$: give mass to neutrinos via see-saw mechanism, produce baryon asymmetry
  - → Mass ~few GeV
  - → Lifetime>10 μs

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

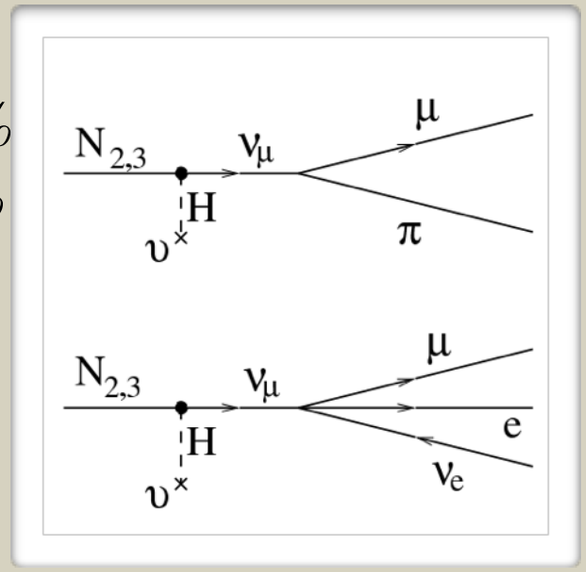
PRODUCTION

- Mixing with active neutrino
- Semi-leptonic decay



DECAY

- Br(N →μ / e π) ~ 0.1 - 50 %
- Br(N →μ / e ϱ) ~ 0.5 - 20%
- Br(N →νμe) ~ 1 - 10%



Proposal(s)

Physical

CERN-SPSC-2015-017/SPSC-P_350-ADD-1

arXiv:1504.04855 (hep-ph)

Prepared for submission to JHEP

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

Sergey Alekhin,[1,2] Wolfgang Altmannshofer,[3] Takehiko Asaka,[4] Brian Batell,[5] Fedor Bezrukov,[6,7] Kyrylo Bondarenko,[8] Alexey Boyarsky*,[8] Nathaniel Craig,[9] Ki-Young Choi,[10] Cristóbal Corral,[11] David Curtin,[12] Sacha Davidson,[13,14] André de Gouvêa,[15] Stefano Dell'Oro,[16] Patrick deNiverville,[17] P. S. Bhupal Dev,[18] Herbi Dreiner,[19] Marco Drewes,[20] Shintaro Eijima,[21] Rouven Essig,[22] Anthony Fradette,[17] Björn Garbrecht,[20] Belen Gavela,[23] Gian F. Giudice,[5] Dmitry Gorbunov,[24,25] Stefania Gori,[3] Christophe Grojean[§],[26,27] Mark D. Goodsell,[28,29] Alberto Guffanti,[30] Thomas Hambye,[31] Steen H. Hansen,[32] Juan Carlos Helo,[11] Pilar Hernandez,[33] Alejandro Ibarra,[20] Artem Ivashko,[8,34] Eder Izaguirre,[3] Joerg Jaeckel[§],[35] Yu Seon Jeong,[36] Felix Kahlhoefer,[27] Yonatan Kahn,[37] Andrey Katz,[5,38,39] Choong Sun Kim,[36] Sergey Kovalenko,[11] Gordan Krnjaic,[3] Valery E. Lyubovitskij,[40,41,42] Simone Marcocci,[16] Matthew Mccullough,[5] David McKeen,[43] Guenakh Mitselmakher ,[44] Sven-Olaf Moch,[45] Rabindra N. Mohapatra,[46] David E. Morrissey,[47] Maksym Ovchynnikov,[34] Emmanuel Paschos,[48] Apostolos Pilaftsis,[18] Maxim Pospelov[§],[3,17] Mary Hall Reno,[49] Andreas Ringwald,[27] Adam Ritz,[17] Leszek Roszkowski,[50] Valery Rubakov,[24] Oleg Ruchayskiy*,[21] Jessie Shelton,[51] Ingo Schienbein,[52] Daniel Schmeier,[19] Kai Schmidt-Hoberg,[27] Pedro Schwaller,[5] Goran Senjanovic,[53,54] Osamu Seto,[55] Mikhail [illegible]*,[§],[21] Brian Shuve,[3] Robert Shrock,[56] Lesya Shchutska[§],[44] [illegible] Spray,[58] Florian Staub,[5] Daniel Stolarski,[5] Matt Strassler [illegible] ano[§],[59,60] Anurag Tripathi,[59] Sean Tulin [illegible] r,[63] Kathryn M. Zurek[64,65]

85 theorists
200 pages

Technical

CERN-SPSC-2015-016/SPSC-P_350

arXiv:1504.04956 (hep-ph)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP
Search for Hidden Particles

CERN-SPSC-2015-016
SPSC-P-350
8 April 2015

Technical Proposal

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

The SHiP Collaboration[1]

234 authors
44 institutions
13 countries

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

REQUIREMENTS

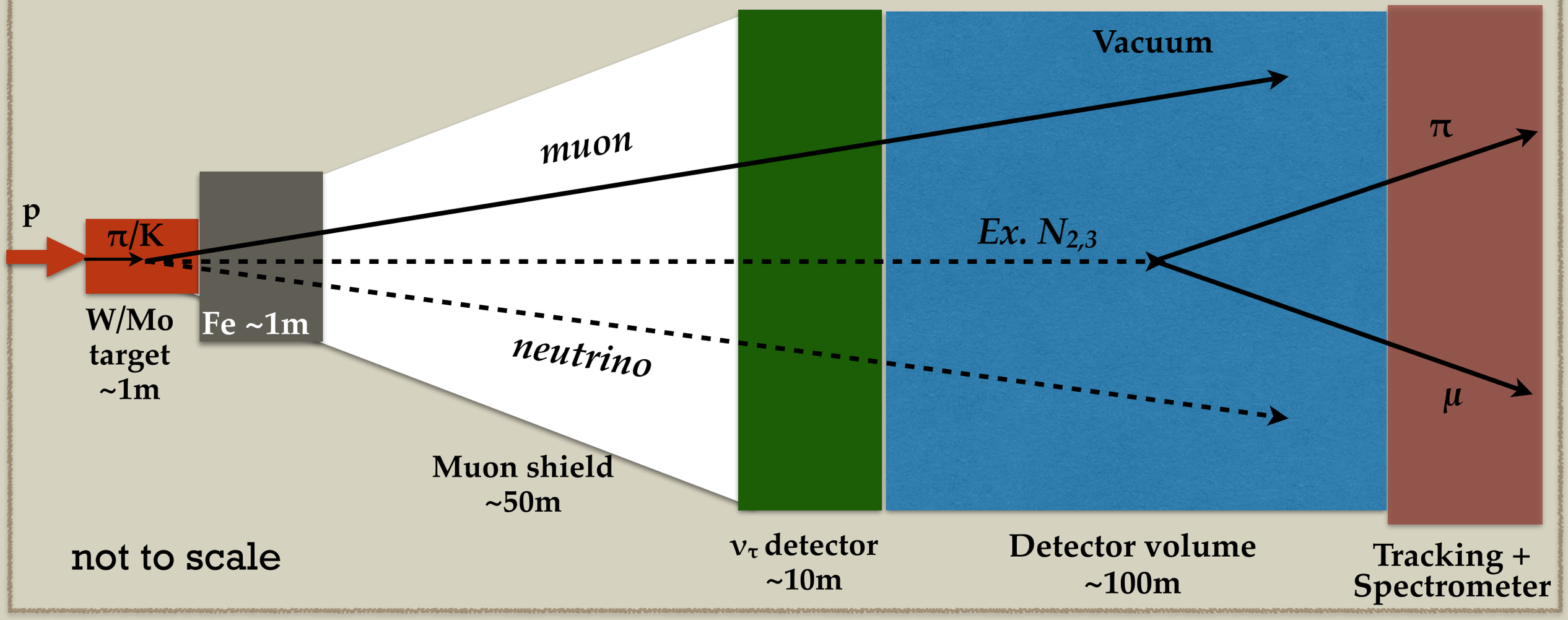
- Proposal: fixed target experiment at the CERN SPS
- SPS: 4×10^{13} protons per spill @ 400 GeV → 2×10^{20} pot in 5 years (same as CNGS)

1) BACKGROUND REDUCTION

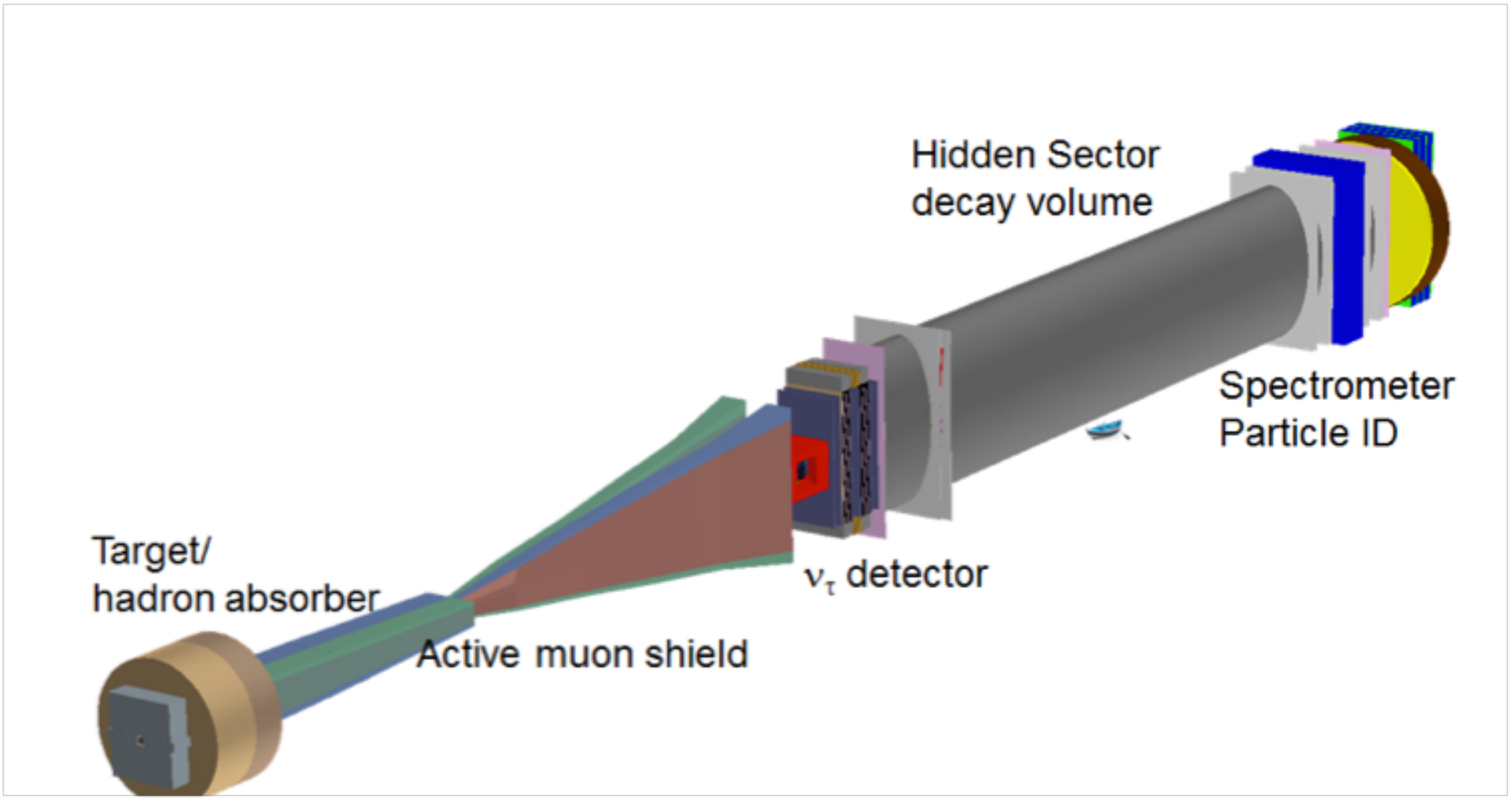
- Combinatorial background
- Neutrino flux
- Muon flux
- Neutrino interactions

1) SIGNAL ENHANCEMENT

- Geometrical acceptance
- Reconstruction of decays
- High sensitivity



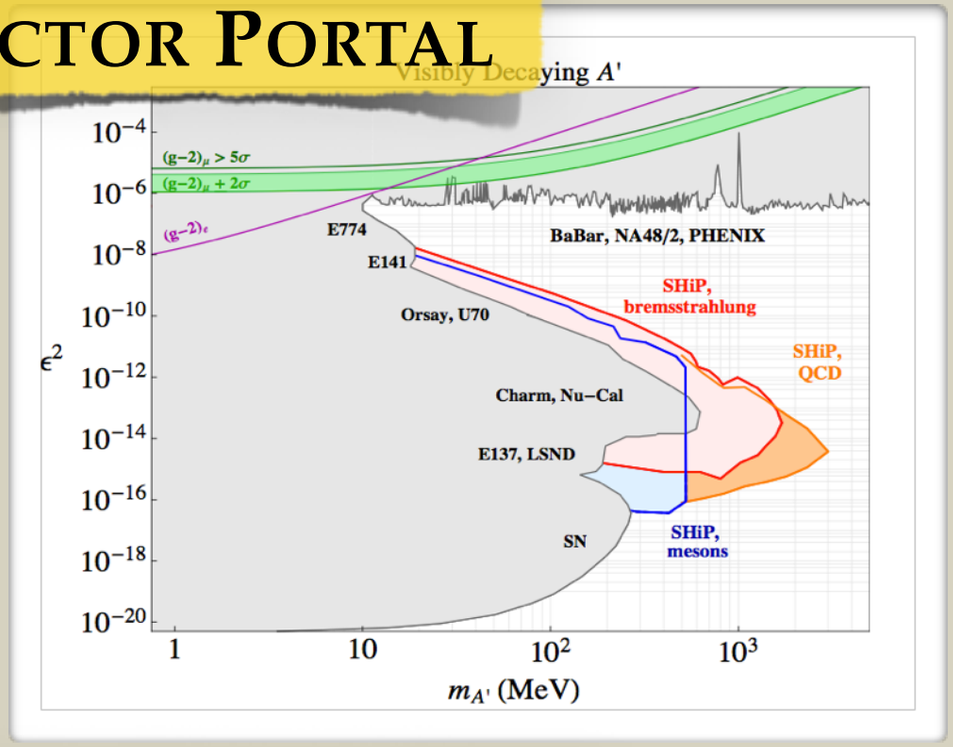
Detector Layout



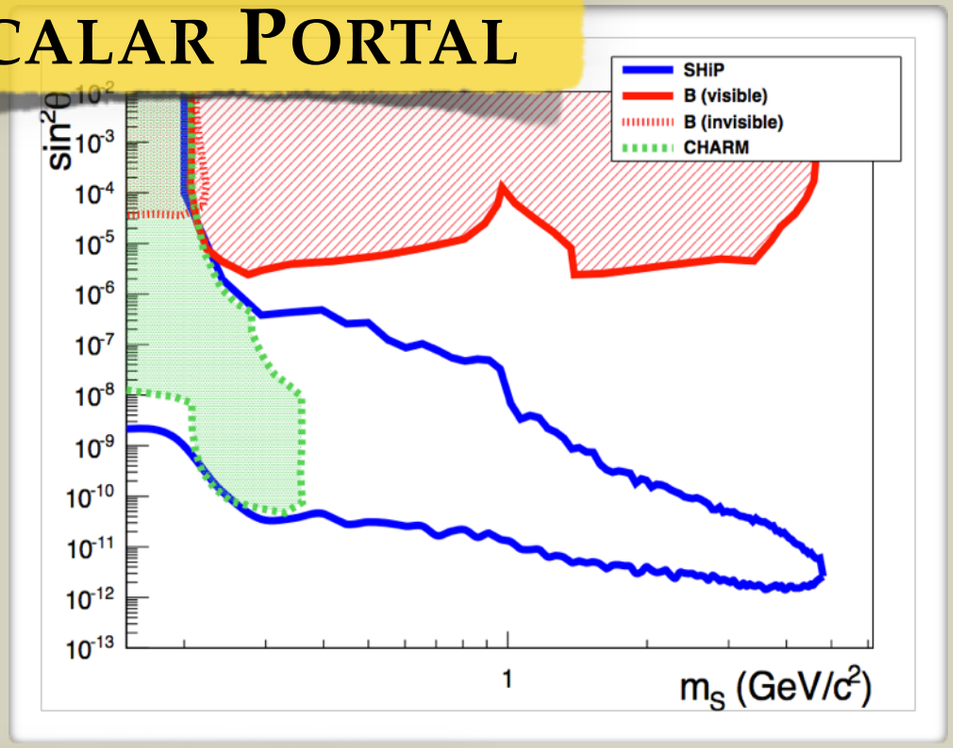
Sensitivities

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

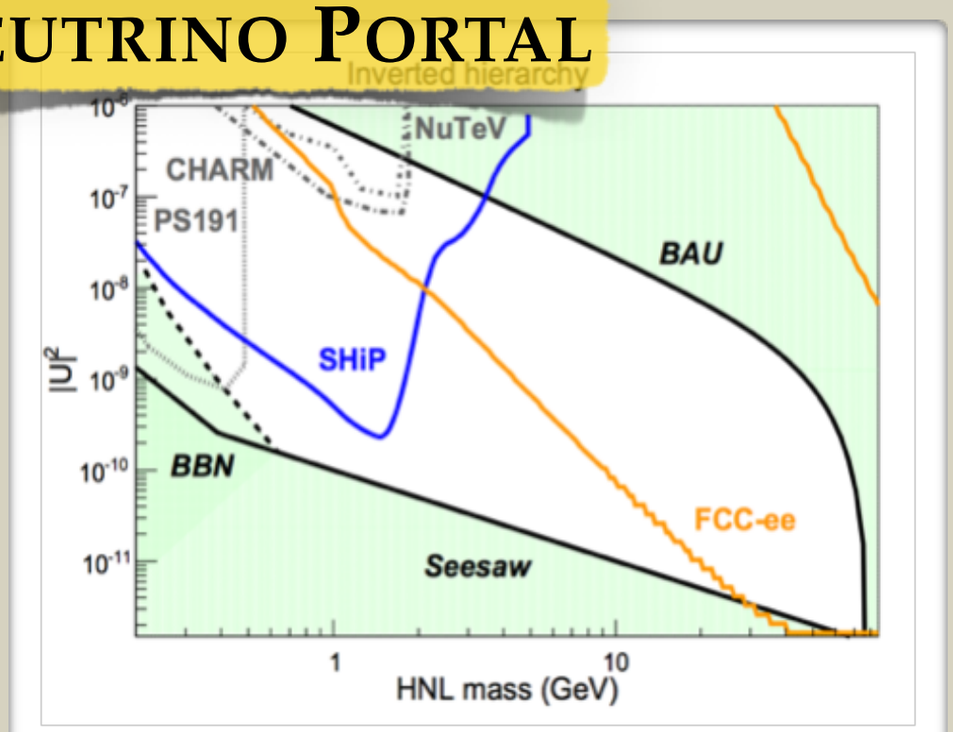
Vector Portal



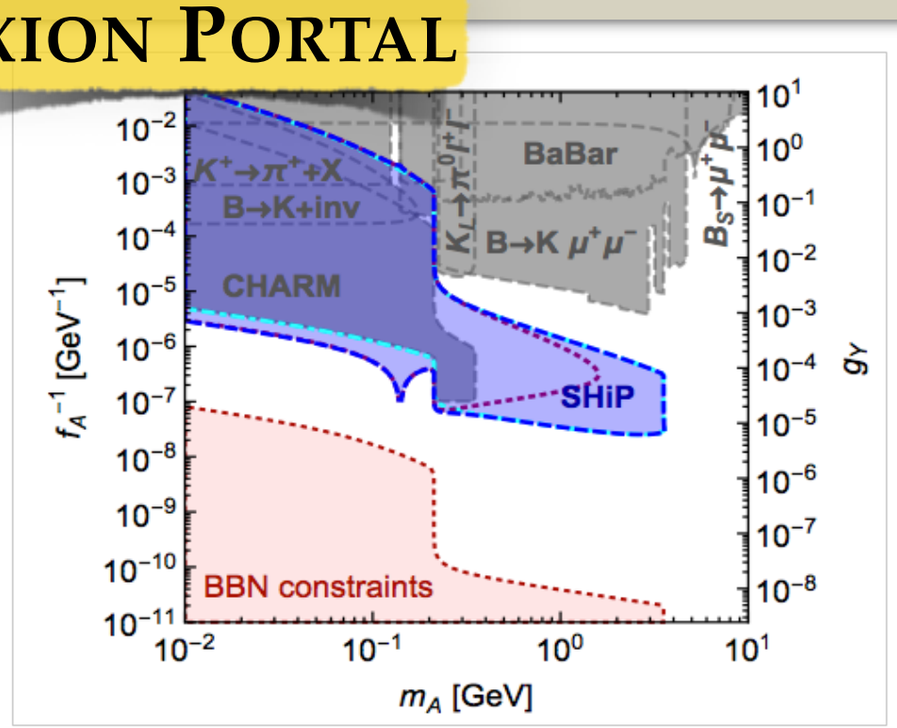
Scalar Portal



Neutrino Portal

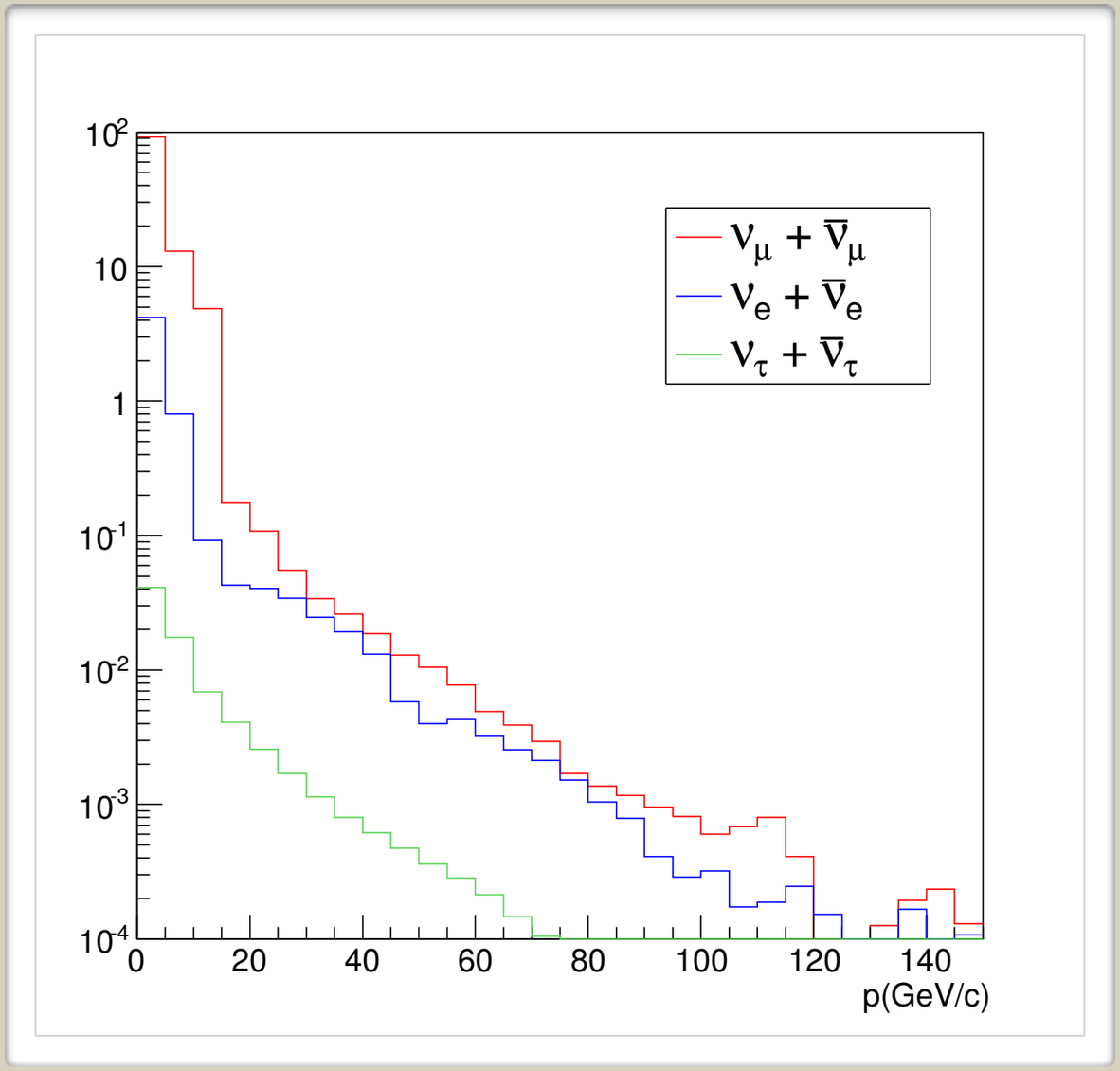


Axion Portal



Neutrino Physics @SHiP

- High neutrino flux expected
- Unique possibility of performing studies of ν_μ, ν_e, ν_τ



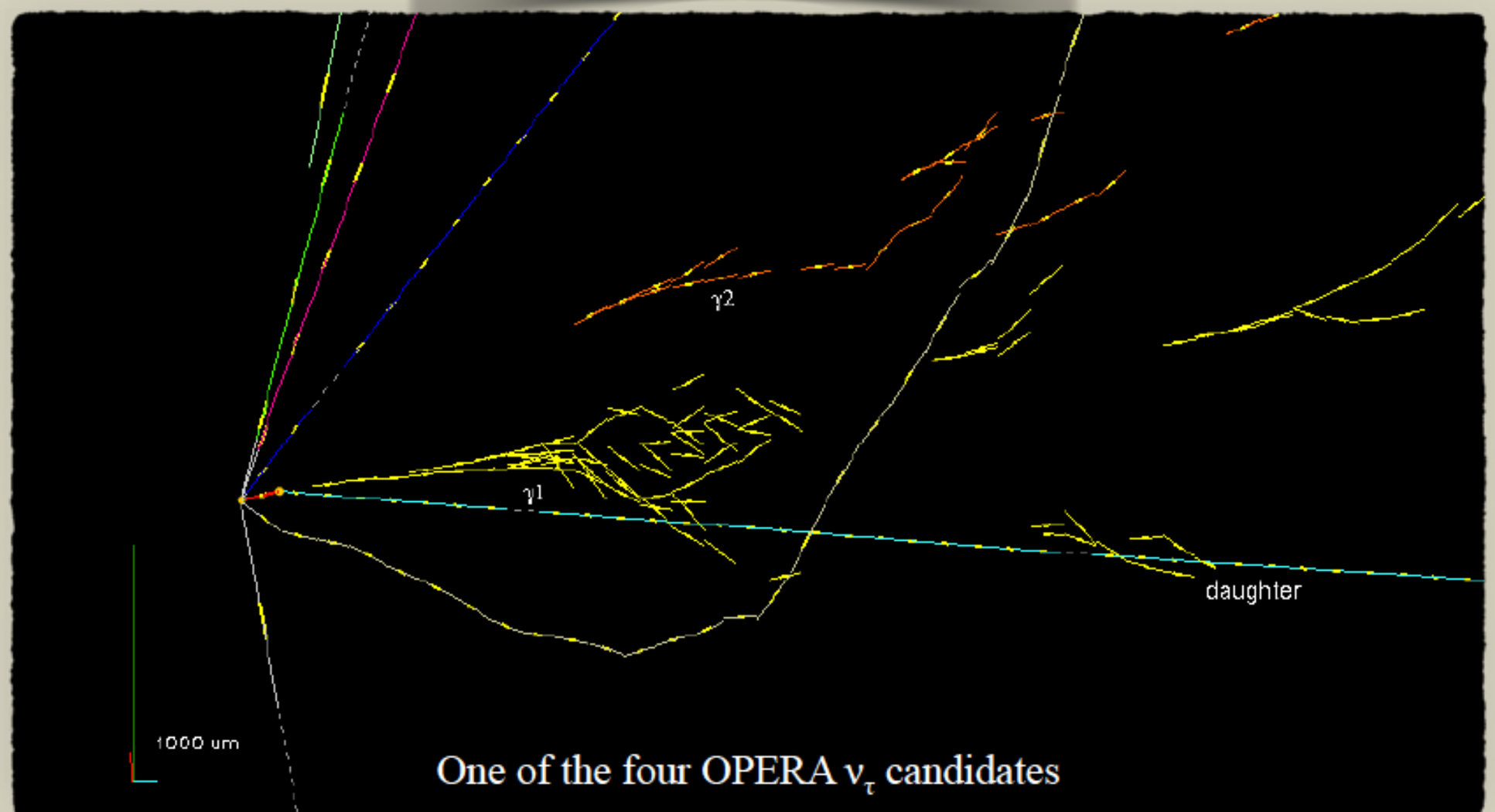
- Energy spectrum of different neutrino flavors @beam dump

Tau Neutrino Physics

- ν_τ: the less known particle in the Standard Model

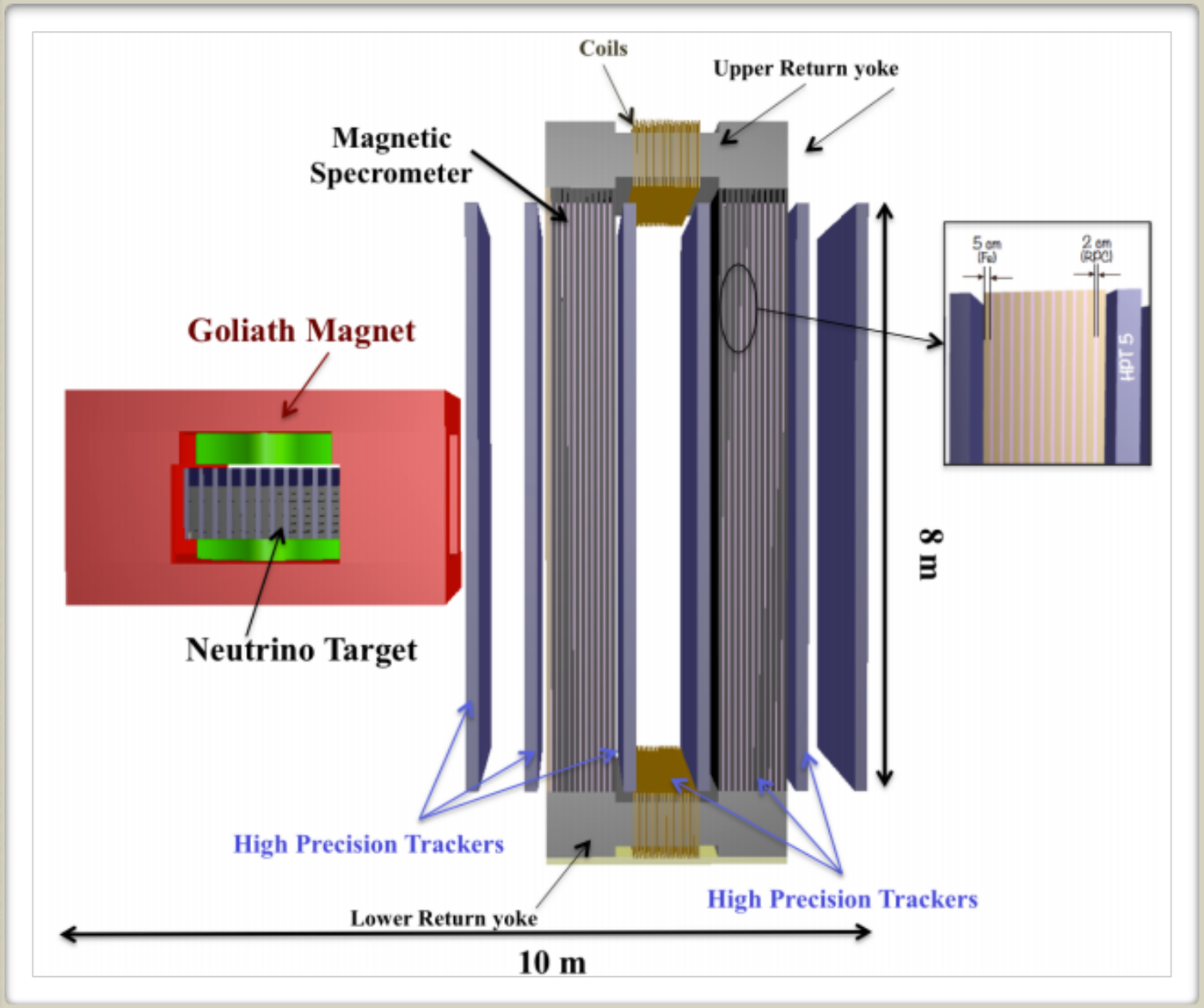
<u>**DONUT**</u>: 9 observed ν_τ candidate events (leptonic number not measured)
<u>**OPERA**</u>: first observation of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode

$\bar{\nu}_\tau$ not detected yet!



One of the four OPERA ν_τ candidates

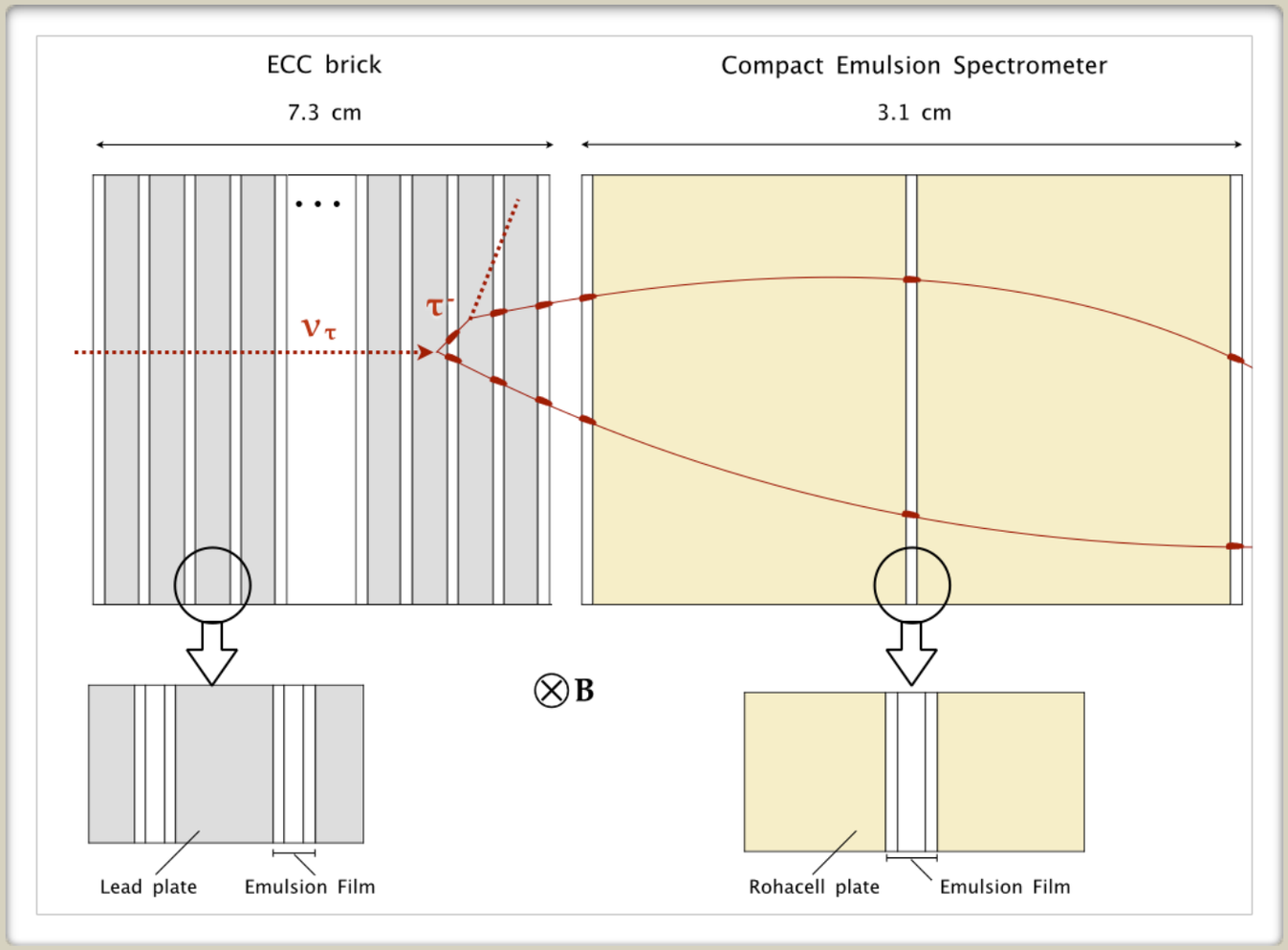
NEUTRINO DETECTOR



Requirements:

- High spatial resolution to observe the τ decay (~1 mm)
  - → *EMULSION FILMS*
- Electronic detectors to give "time" resolution to emulsions
  - → *TARGET TRACKER PLANES*
- Magnetized target to measure the charge of τ products
  - → *DIPOLAR MAGNET*
- Magnetic spectrometer to perform muon identification and measure its charge and momentum
  - → *MUON SPECTROMETER*

Neutrino Target



- 1155 ECC bricks to be replaced 10 times
- Total emulsion surface: 8700 m^2 (8% of OPERA emulsion production)
- Scanning with modern automated microscopes

Emulsion Cloud Chamber (ECC) BRICK

- Passive material (Lead) - 56 layers -
- High resolution tracker (Nuclear emulsions) - 57 films -
- 10 X_0

Performances

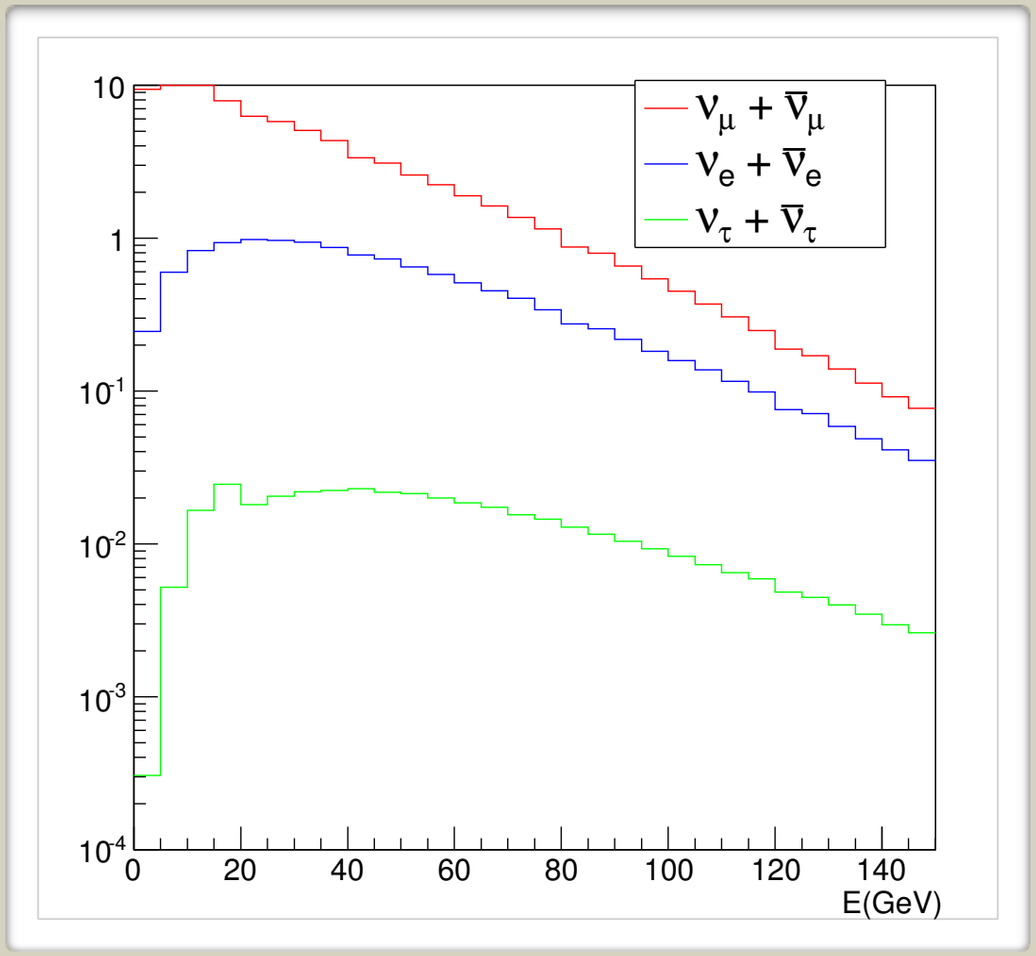
- Primary and secondary vertex definition with μm resolution
- Momentum measurement by Multiple Coulomb Scattering - largely exploited in the OPERA experiment -
- Electron identification: shower ID through calorimetric technique
- Sign of the electric charge can be determined with better than 3 sigma level up to 12 GeV

Neutrino Physics @SHiP

	<E> (GeV)	CC DIS interactions
N_{ν_μ}	29	1.7×10^6
N_{ν_e}	46	2.5×10^5
N_{ν_τ}	59	6.7×10^3
$N_{\overline{\nu}_\mu}$	28	6.7×10^5
$N_{\overline{\nu}_e}$	46	9.0×10^4
$N_{\overline{\nu}_\tau}$	58	3.4×10^3

- CC DIS neutrino interactions in 5 years run (2×10^{20} pot)

- Energy spectrum of different neutrino flavors interacting in the target



ν_τ Physics

- ν_τ and $\bar{\nu}_\tau$ produced in the leptonic decay of a D^-_s meson into τ^- and $\bar{\nu}_\tau$, and the subsequent decay of the τ^- into a ν_τ
- Number of ν_τ and $\bar{\nu}_\tau$ produced in the beam dump

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

- Main background source: charm production in ν_μ^{CC} ($\bar{\nu}_\mu^{CC}$) and ν_e^{CC} ($\bar{\nu}_e^{CC}$) interactions, when the primary lepton is not identified

SIGNAL EXPECTATION

BACKGROUND

R = S/B RATIO

- Geometrical, location and decay search efficiencies considered
- Expectations in 5 years run (2×10^{20}pot)

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

Structure Functions

- Deep-inelastic charged current neutrino cross section

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

<u>Structure functions</u>

- F_1
- F_2 → Same precision as other experiments
- F_3 → Opposite sign for ν and $\bar{\nu}$
- F_4
- F_5 → Dependent on the lepton mass. Suppressed in case of ν_μ interactions, becomes relevant for ν_τ interactions

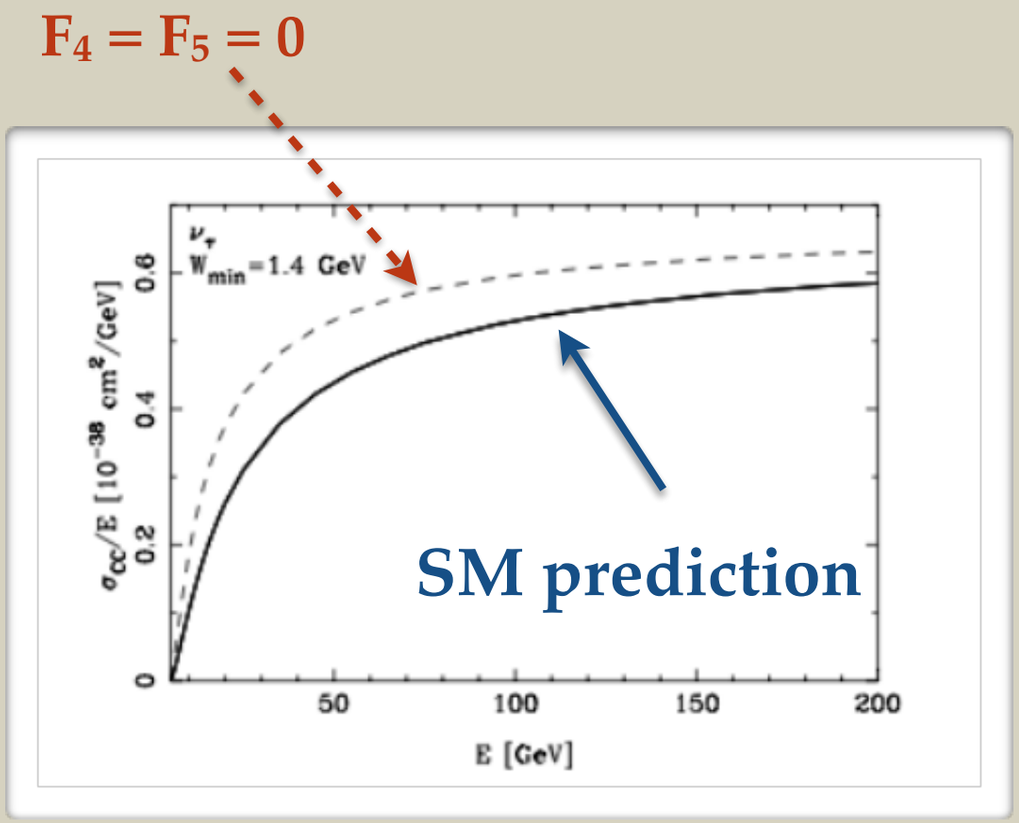
- Evaluation of F_3
- First evaluation of F_4 and F_5, not accessible with lighter neutrinos

- At LO $F_4=0$, $2xF_5=F_2$ (Albright-Jarlskog relations)
- At NLO $F_4 \sim 1\%$ of F_5

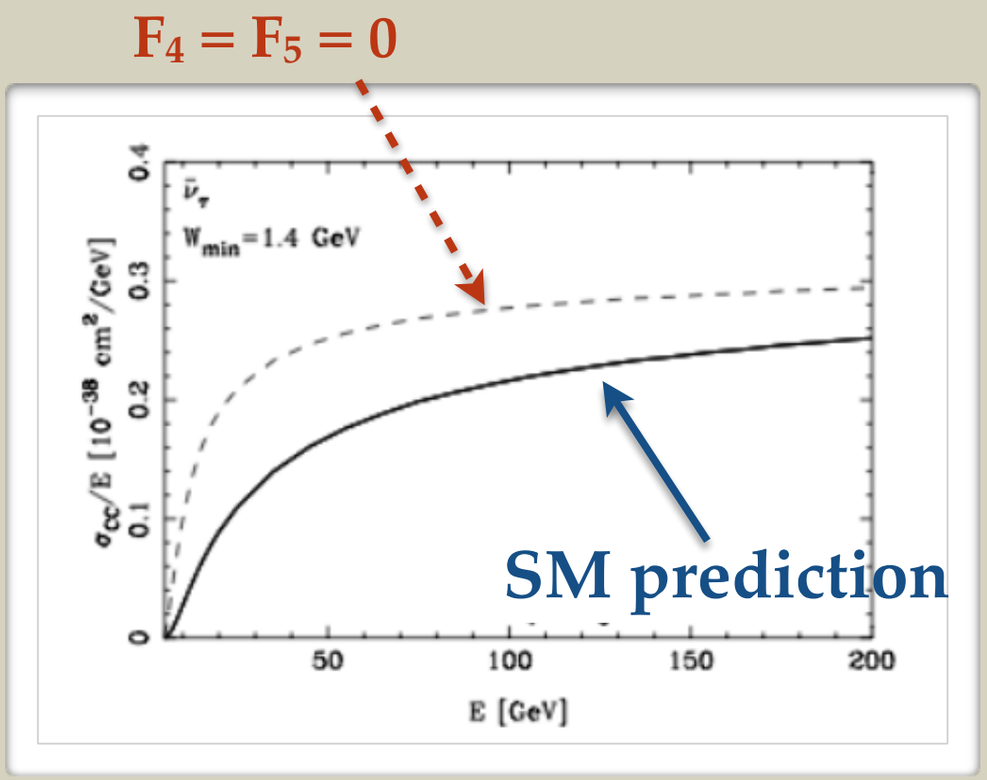
Sensitivity to F_4 and F_5

The SHiP experiment has the unique capability of being sensitive to F_4 and F_5

$F_4 = F_5 = 0$ hypothesis → increase of the ν_τ and $\bar{\nu}_\tau$ CC DIS cross sections
→ increase of the number of expected ν_τ and anti-ν_τ interactions

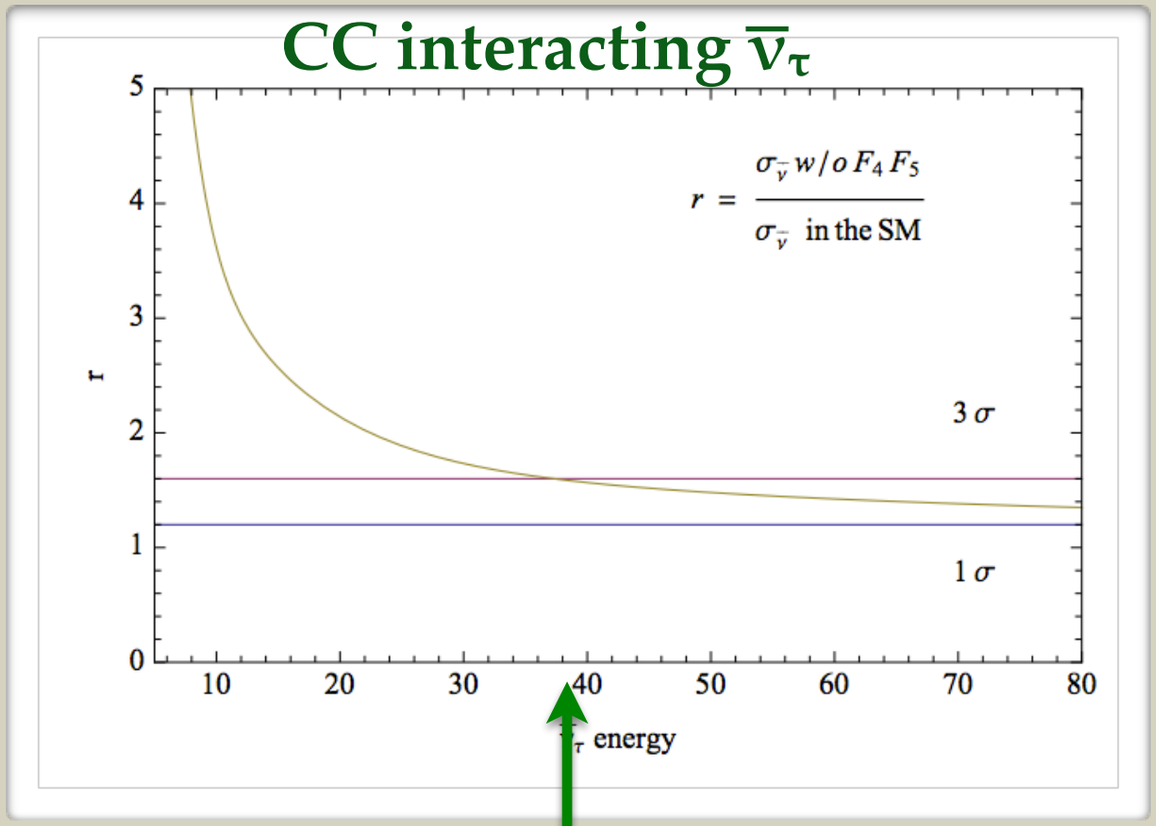


ν_τ CC DIS cross-section

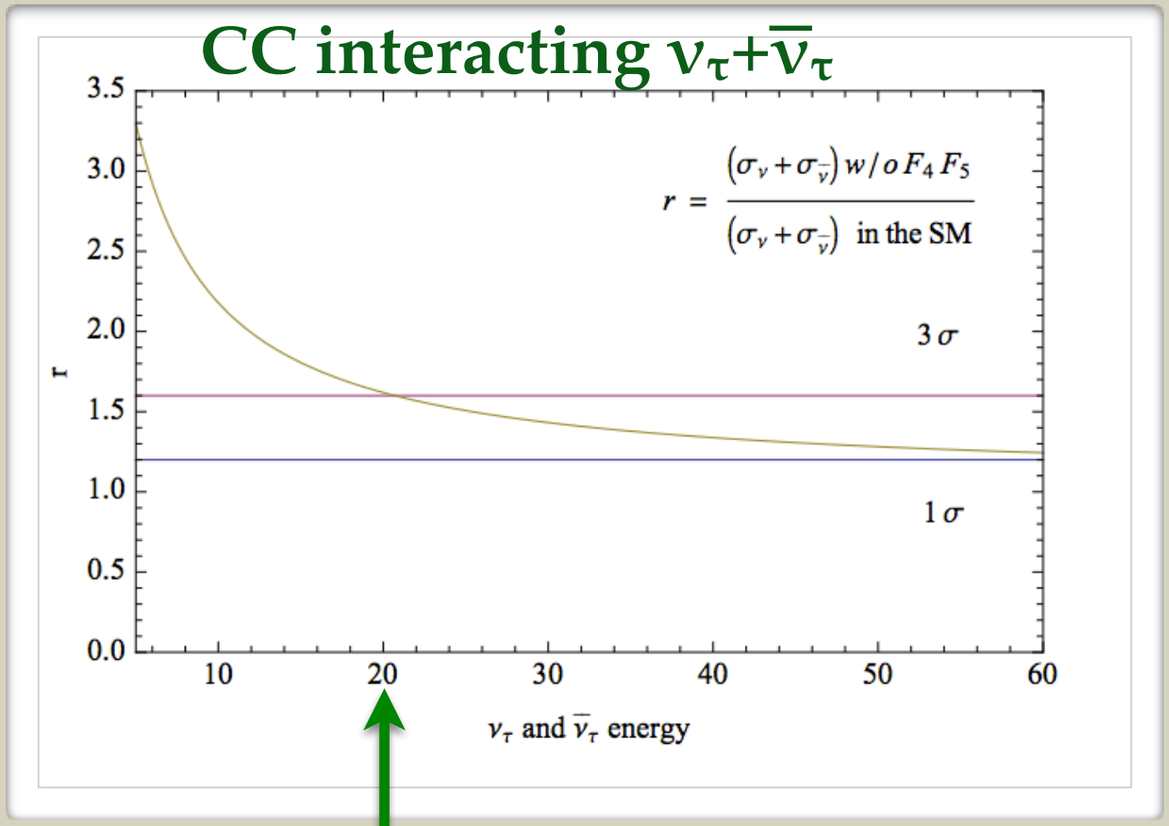


$\bar{\nu}_\tau$ CC DIS cross-section

Sensitivity to F_4 and F_5



r = ratio between the cross sections in the two hypotheses



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

(~300 events expected)

$E(\nu_\tau+\bar{\nu}_\tau) < 20$ GeV

(~420 events expected)

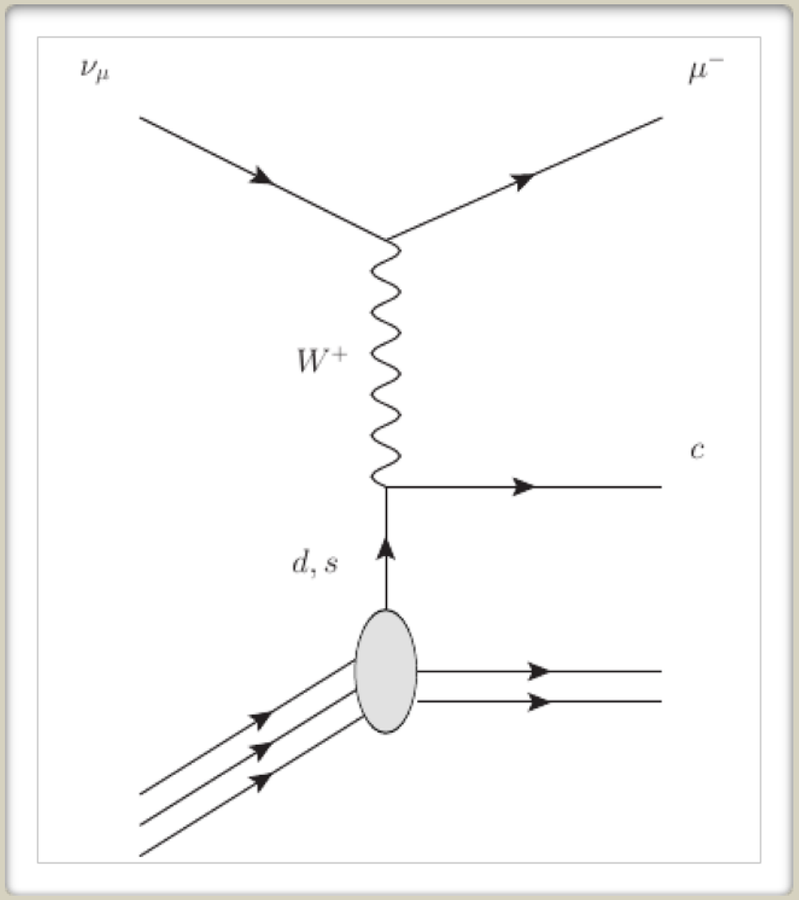
r>1.6

→ evidence for non-zero values of F_4 and F_5

Charm Physics @SHiP

- Large charm production in ν_μ^{CC} and ν_e^{CC} interactions

- Process sensitive to strange quark content of the nucleon



- Charm production with electronic detectors tagged by di-muon events (high energy cut to reduce background)
- Nuclear emulsion technique: charmed hadron identification through the observation of its decay
- Loose kinematical cuts → good sensitivity to the slow-rescaling threshold behavior and to the charm quark mass

Charm Physics @SHiP

- Fraction of neutrino-induced charm events:
- Convolution of CHORUS data with SHiP spectrum

ν_μ^{CC}

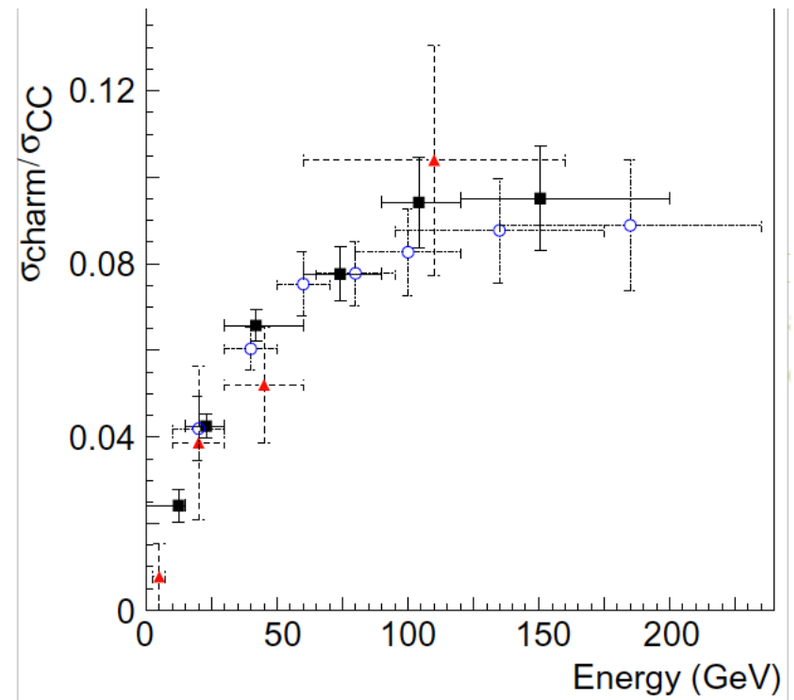
$$f(charm) = \frac{\int \Phi_{\nu_\mu} \sigma^{CC}_{\nu_\mu} \left(\frac{\sigma_{charm}}{\sigma^{CC}_{\nu_\mu}}\right) dE}{\int \Phi_{\nu_\mu} \sigma^{CC}_{\nu_\mu} dE}$$

ν_e^{CC}

$$f(charm) = \frac{\int \Phi_{\nu_e} \sigma^{CC}_{\nu_e} \left(\frac{\sigma_{charm}}{\sigma^{CC}_{\nu_e}}\right) dE}{\int \Phi_{\nu_e} \sigma^{CC}_{\nu_e} dE}$$

charm fractions	(%)
$\sigma_{charm}/\sigma_{\nu_\mu CC}$	4.1
$\sigma_{charm}/\sigma_{\bar{\nu}_\mu CC}$	4.1
$\sigma_{charm}/\sigma_{\nu_e CC}$	6.0
$\sigma_{charm}/\sigma_{\bar{\nu}_e CC}$	6.0

CHORUS, New J. Phys. 13 (2011) 093002



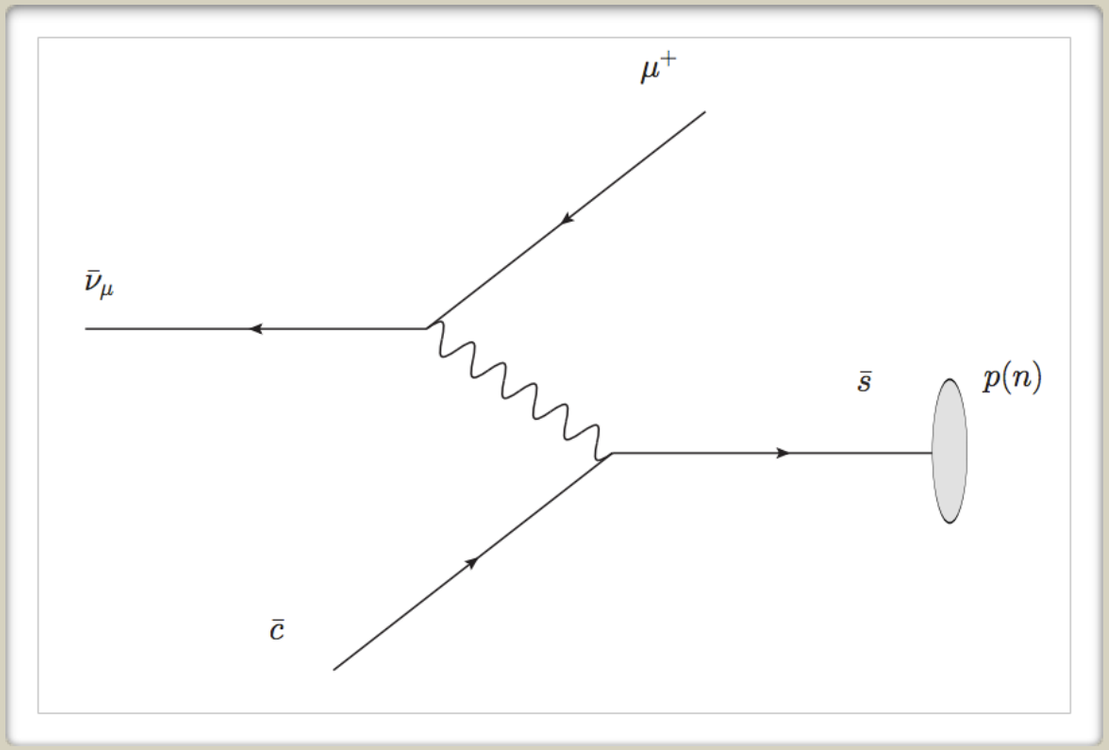
- Expected charm yield exceeds the statistics available in previous experiments by more than one order of magnitude

	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	$1.1 \cdot 10^5$

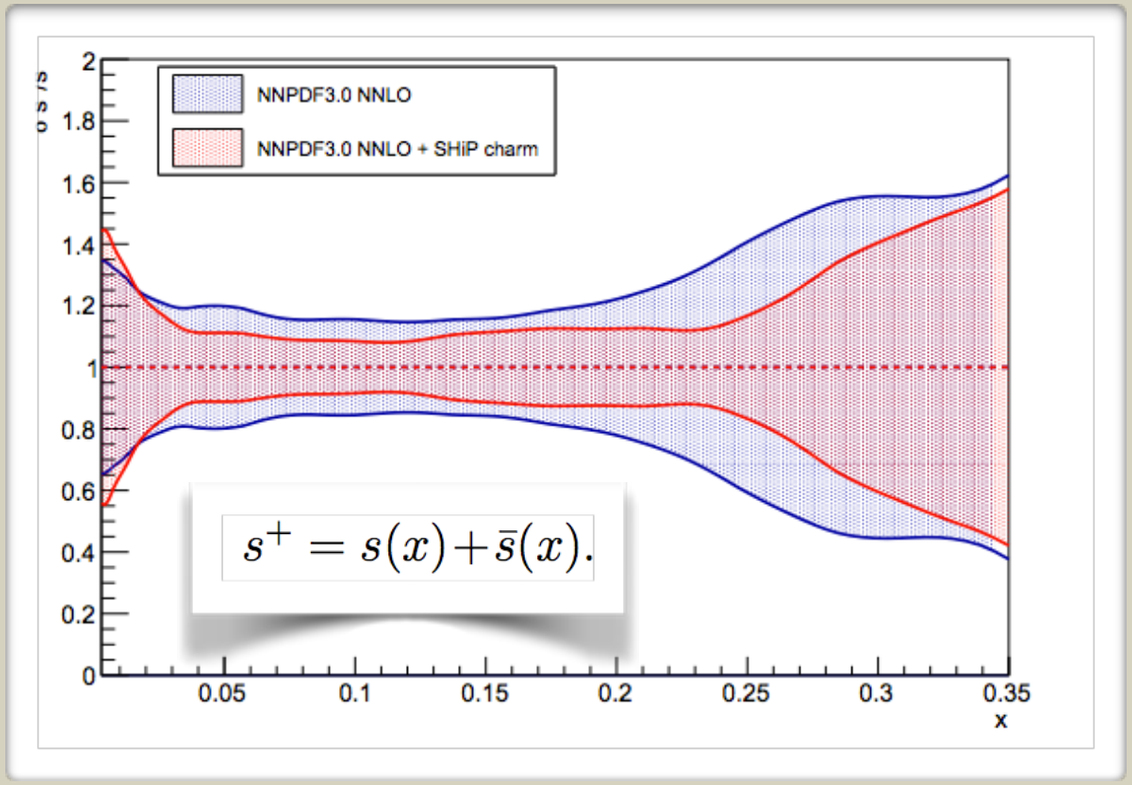
No charm candidate from ν_e and ν_τ interactions ever reported!

Strange Quark Nucleon Content

- Charmed hadron production in anti-neutrino interactions selects anti-strange quark in the nucleon



- Improvement achieved on s^+/s^- versus x
- Significant gain with SHIP data (factor 2) obtained in the x range between 0.03 and 0.35



Observed anti-ν in CHORUS ~32
in NuTeV ~1400

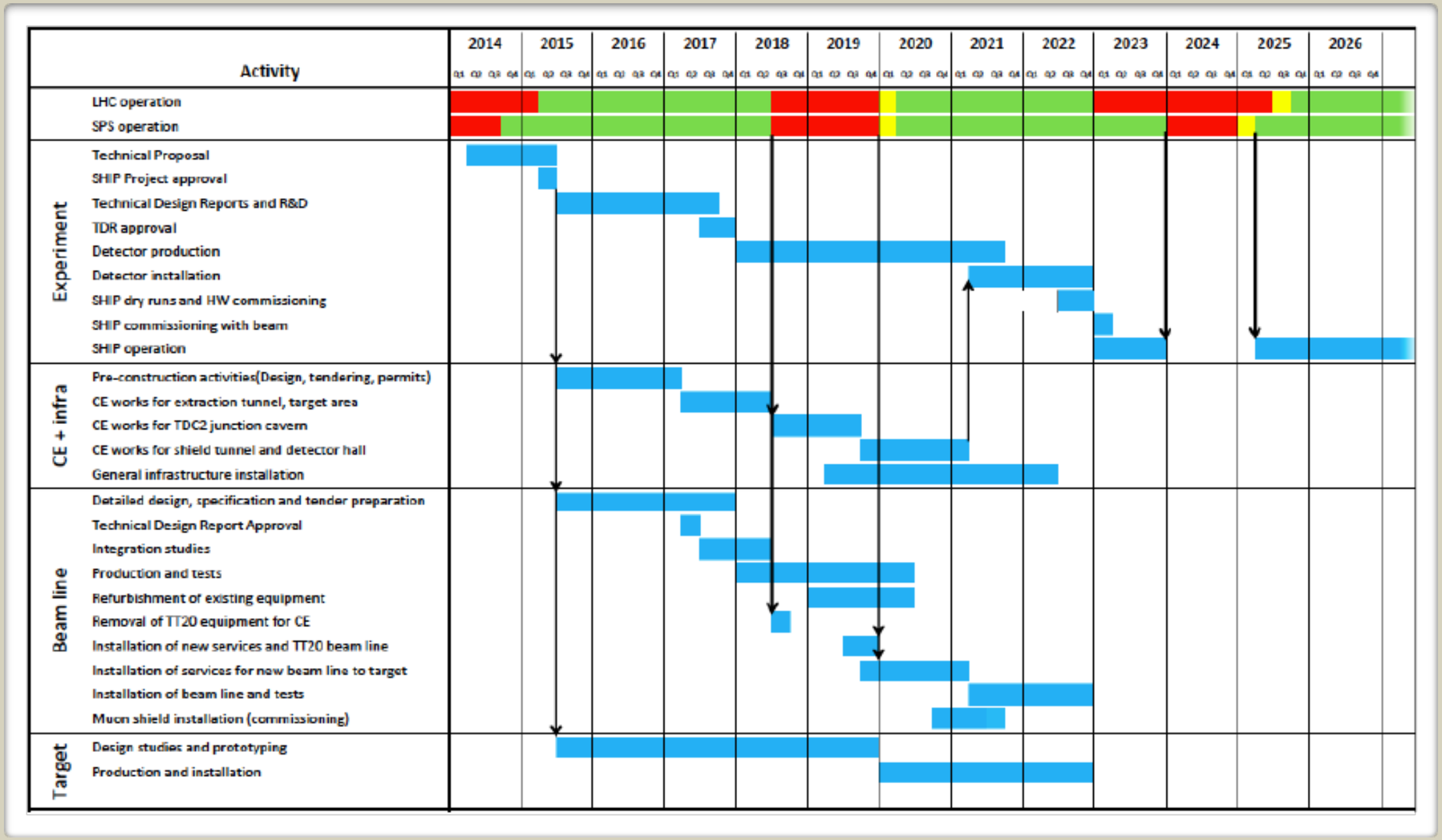
Conclusions

- Search for new physics beyond Standard Model: explore the intensity frontier

- Rich Standard Model physics program:
  - first observation of anti-ν_τ
  - ν_τ and anti-ν_τ cross section measurement
  - structure functions study
  - charm physics with neutrinos and anti-neutrinos
  - strange quark nucleon content

Back-up Slides

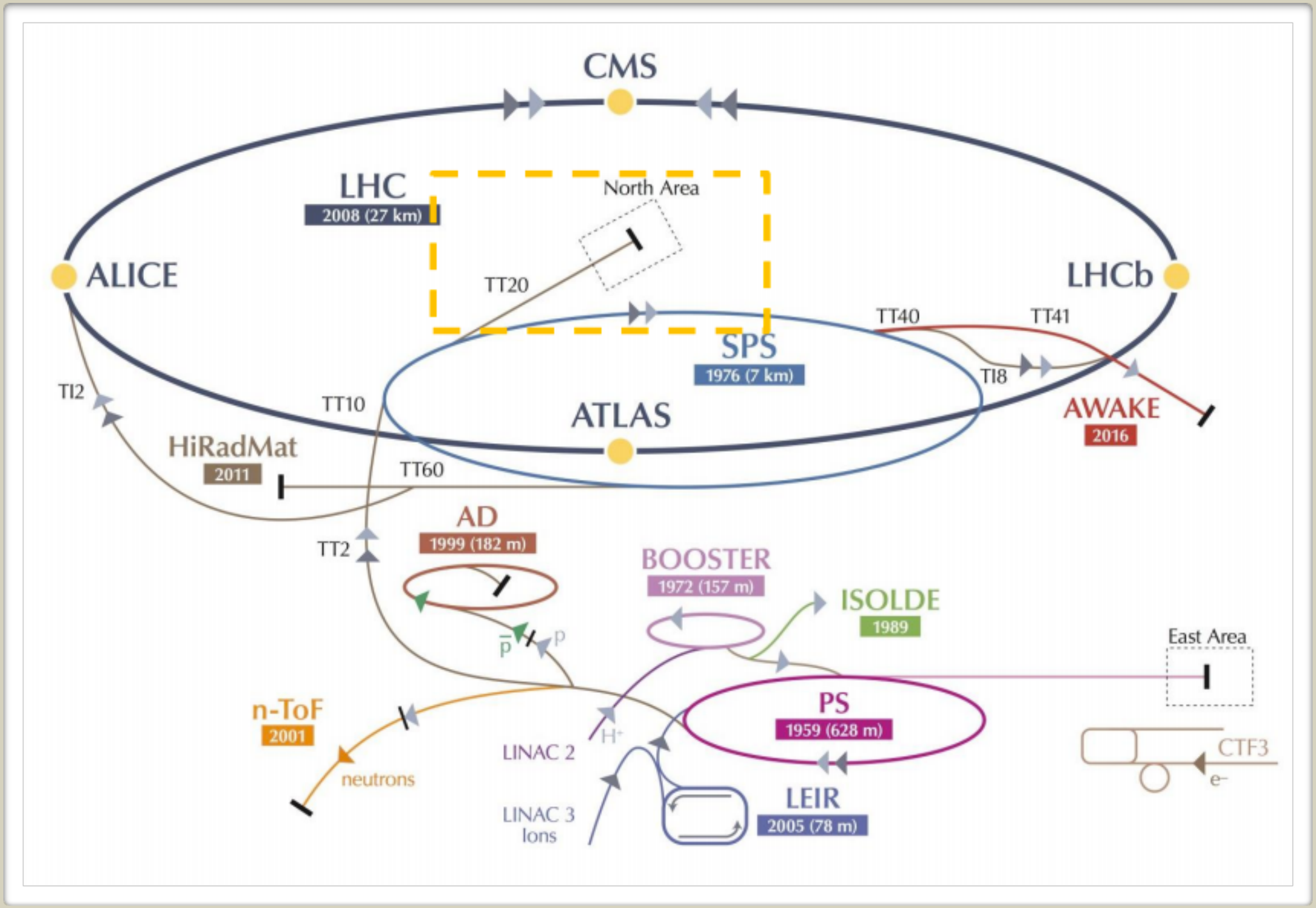
TIMESCALE



- **Form SHiP Collaboration** — **December 2014 ✔**
- **Technical Proposal** — **April 2015 ✔**
- Technical Design Report — 2018
- Construction and Installation — 2018-2022
- Commissioning — 2022
- Data taking and analysis — 2023-2027

SHiP Location

- Proposed location by CERN beams and support departments



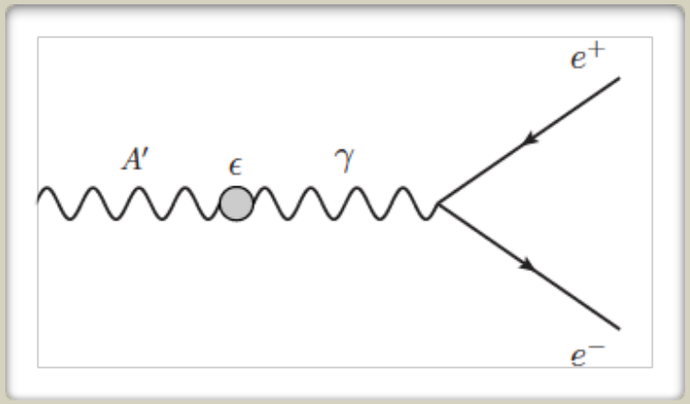
Cost Estimation

Table 6.2: Overall cost of the SHiP facility and the detectors.

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	11.1	
Hidden Sector detector	46.8	
Computing and online system	0.2	
Grand total		**194.5**

New Physics in the Hidden Sector

Standard Model portals



- **D=2 Vector Portal**
  Kinetic mixing with massive dark/secluded/para-photon **V**
  → Interaction with 'mirror world' constituting dark matter

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\rho & -\sin\rho \\ \sin\rho & \cos\rho \end{pmatrix} \begin{pmatrix} \phi_0' \\ S' \end{pmatrix}$$

- **D=2 Higgs Portal**
  Mass mixing with dark singlet scalar χ
  → Mass to Higgs boson and right-handed neutrino, and function as inflaton in accordance with Planck measurements
- **D=5/2 Neutrino Portal**
  Mixing with right-handed neutrino **N** (Heavy Neutral Lepton)
  → Neutrino oscillation, baryon asymmetry, dark matter
- **D=4 Axion Portal**
  Mixing with Axion Like Particles, pseudo-scalars pNGB, axial vectors
  → Solve strong CP problem, Inflaton
- And possibly higher dimensional operators portals and **SUper-SYmmetric portals** (light neutralino, light sgoldstino, …)
  → SUSY parameter space explored by LHC

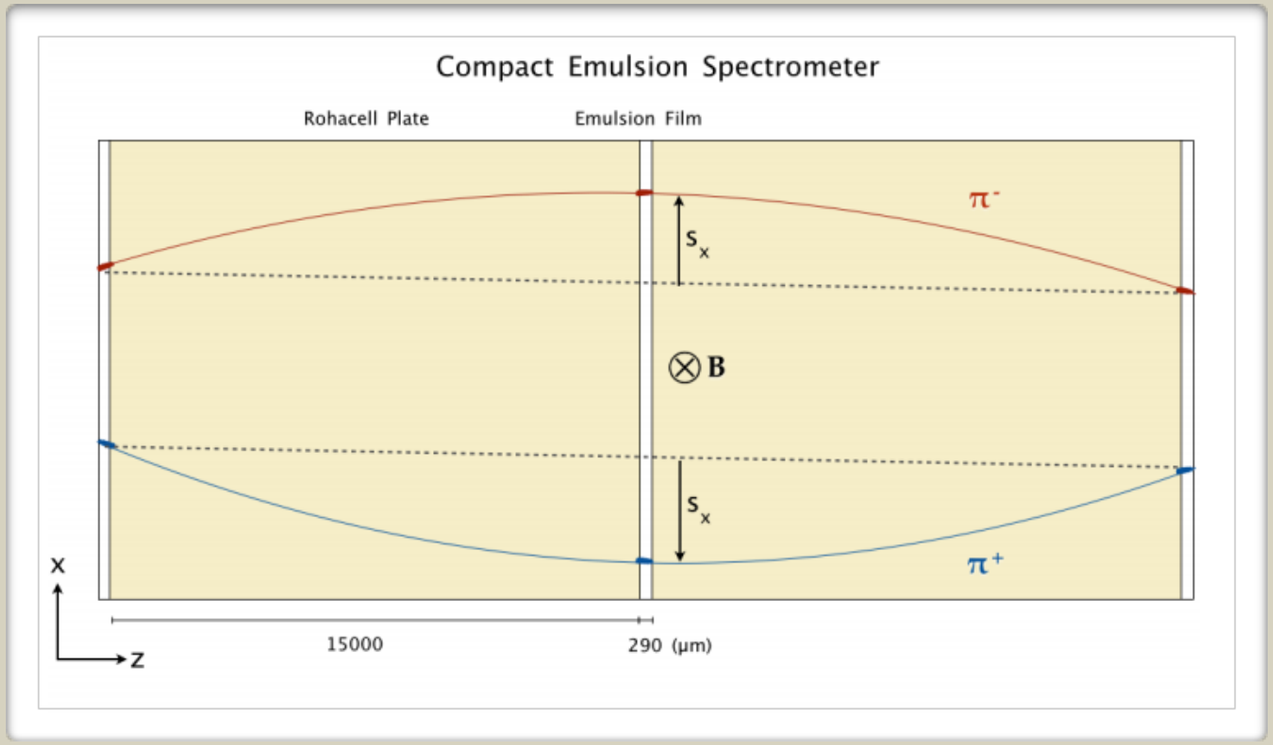
Neutrino Flavor Identification

REQUIREMENTS

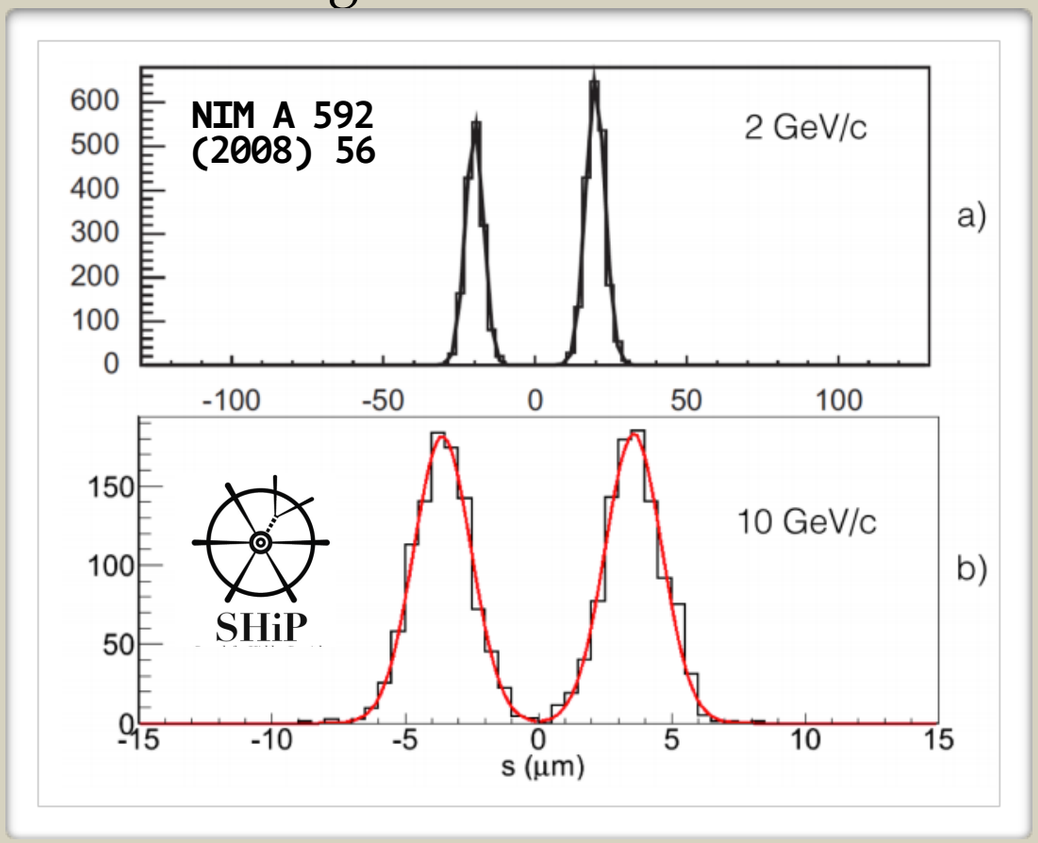
- Electric charge measurement of τ lepton decay products
- Key role for $\nu_\tau/\bar{\nu}_\tau$ separation in the $\tau \rightarrow h$ decay channel
- Momentum measurement

LAYOUT

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



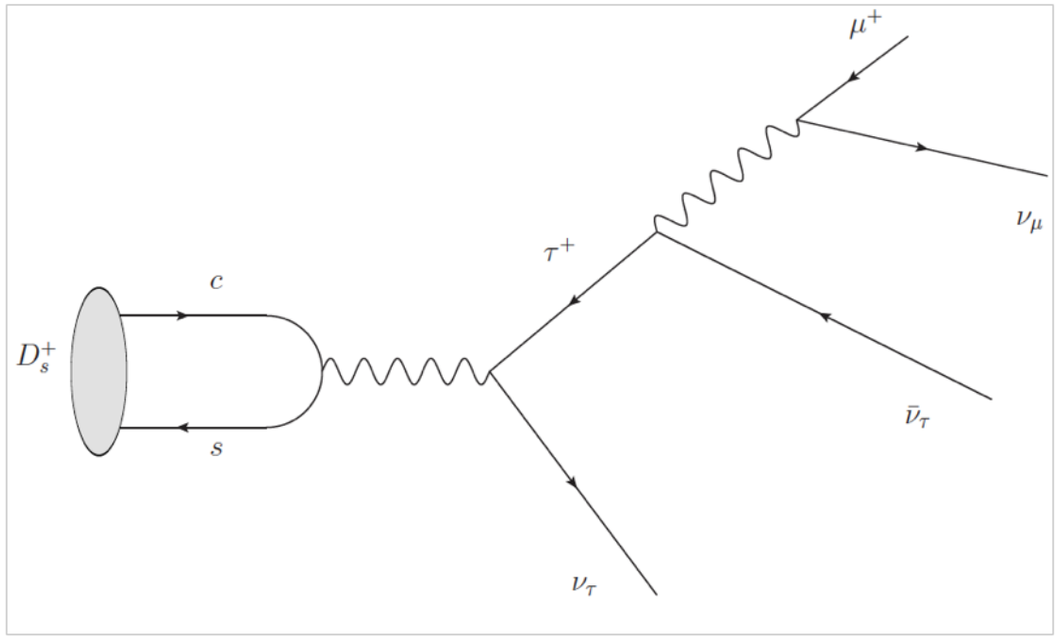
Charge measured from the curvature of the track with the **sagitta** method



PERFORMANCES

- Sign of the **electric charge** can be determined with better than 3 standard deviation level up to 12 GeV
- The **momentum** of the track can be estimated from the sagitta
- $Dp/p < 20\%$ up to 12 GeV/c

Neutrino Physics



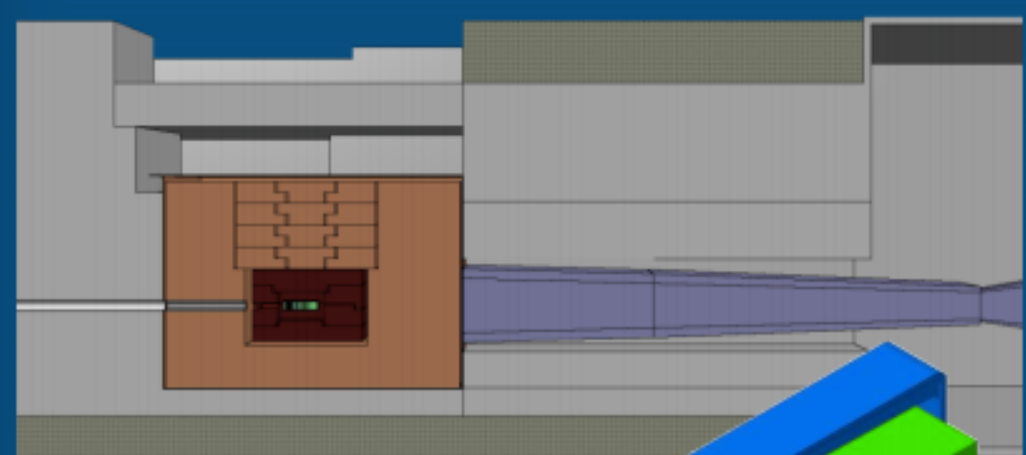
τ DECAY CHANNEL	BR (%)
τ →μ	17.7
τ →e	17.8
τ →h	49.5
τ →3h	15.0

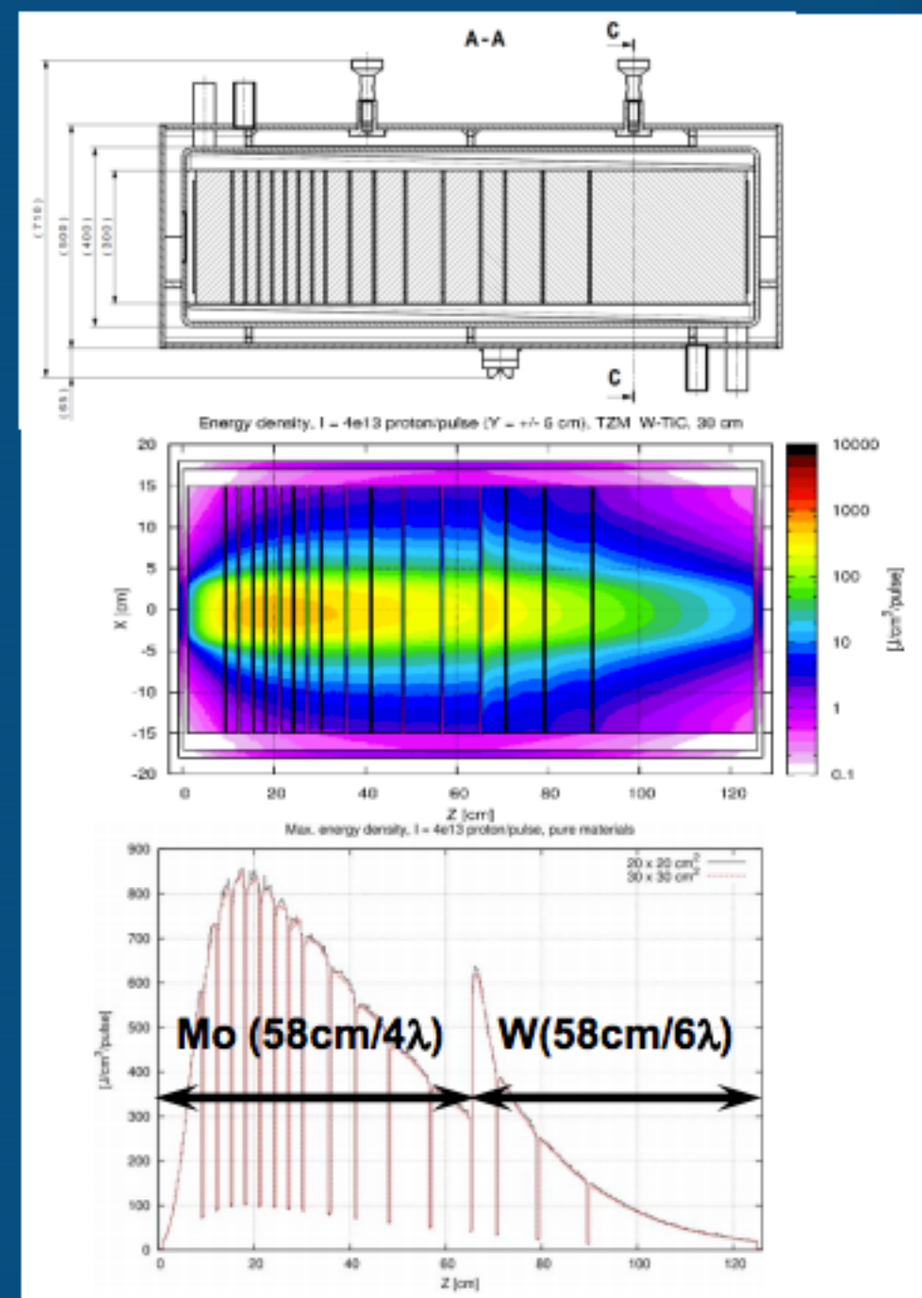
$$N_{\nu_\tau+\bar{\nu}_\tau} = N_p \frac{2\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \to \tau) 2 = 2.85 \times 10^{-5} N_p$$

Target Configuration

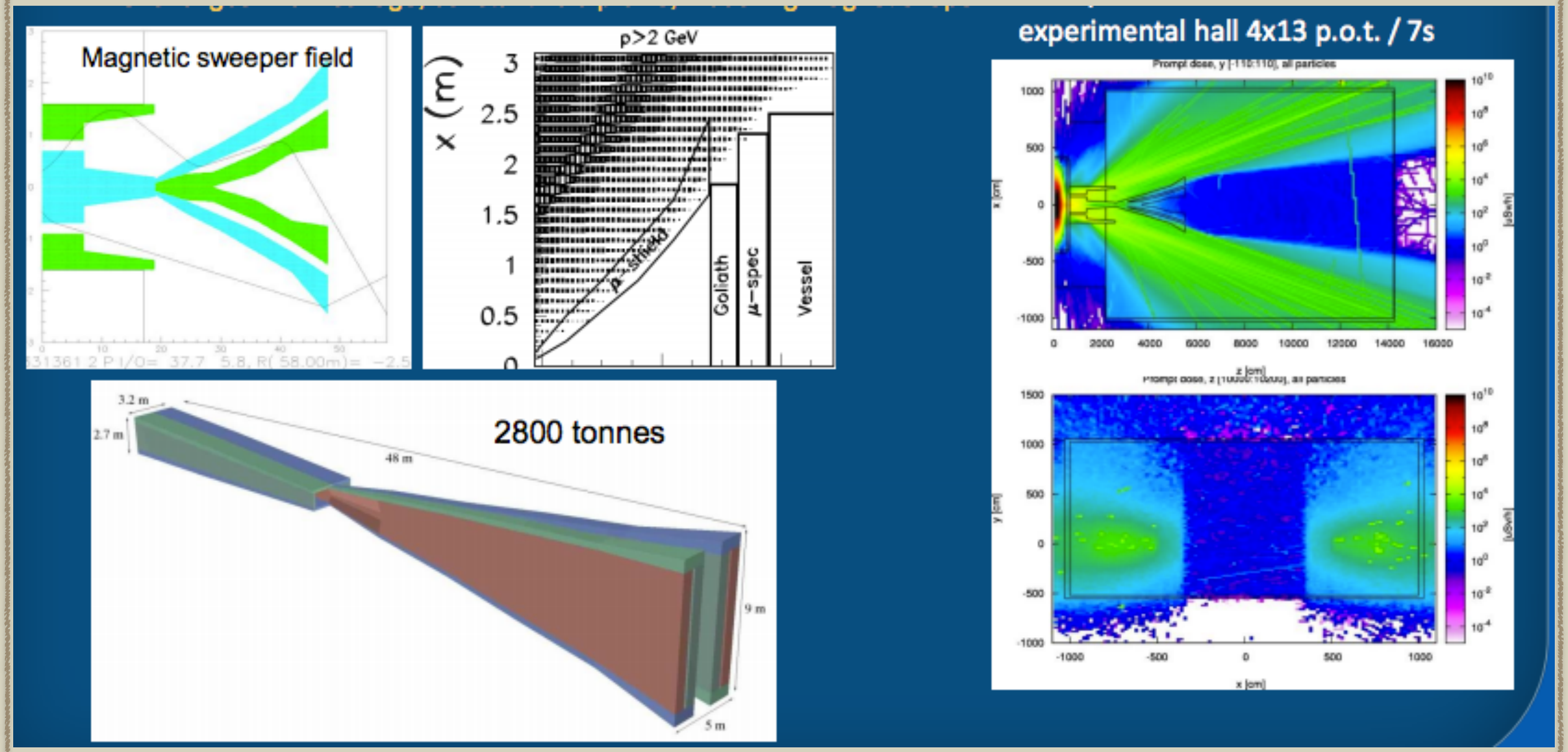
Design considerations with $4x10^{13}$ p / 7s → 400 kW

- High temperature
- Compressive stresses
- Atomic displacement
- Erosion/corrosion
- Material properties as a function of irradiation
- Remote handling (Initial dose rate of 50 Sv/h…)

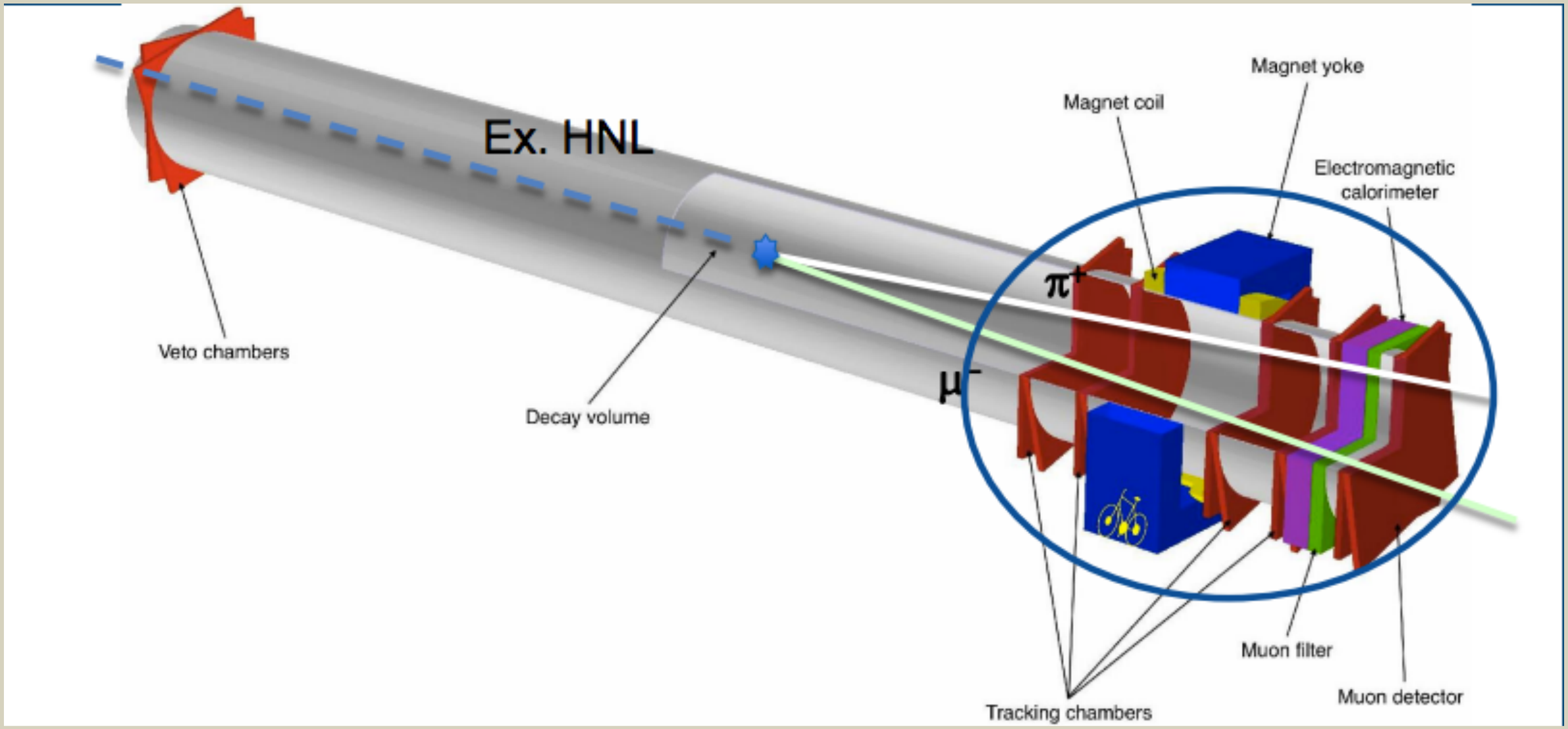




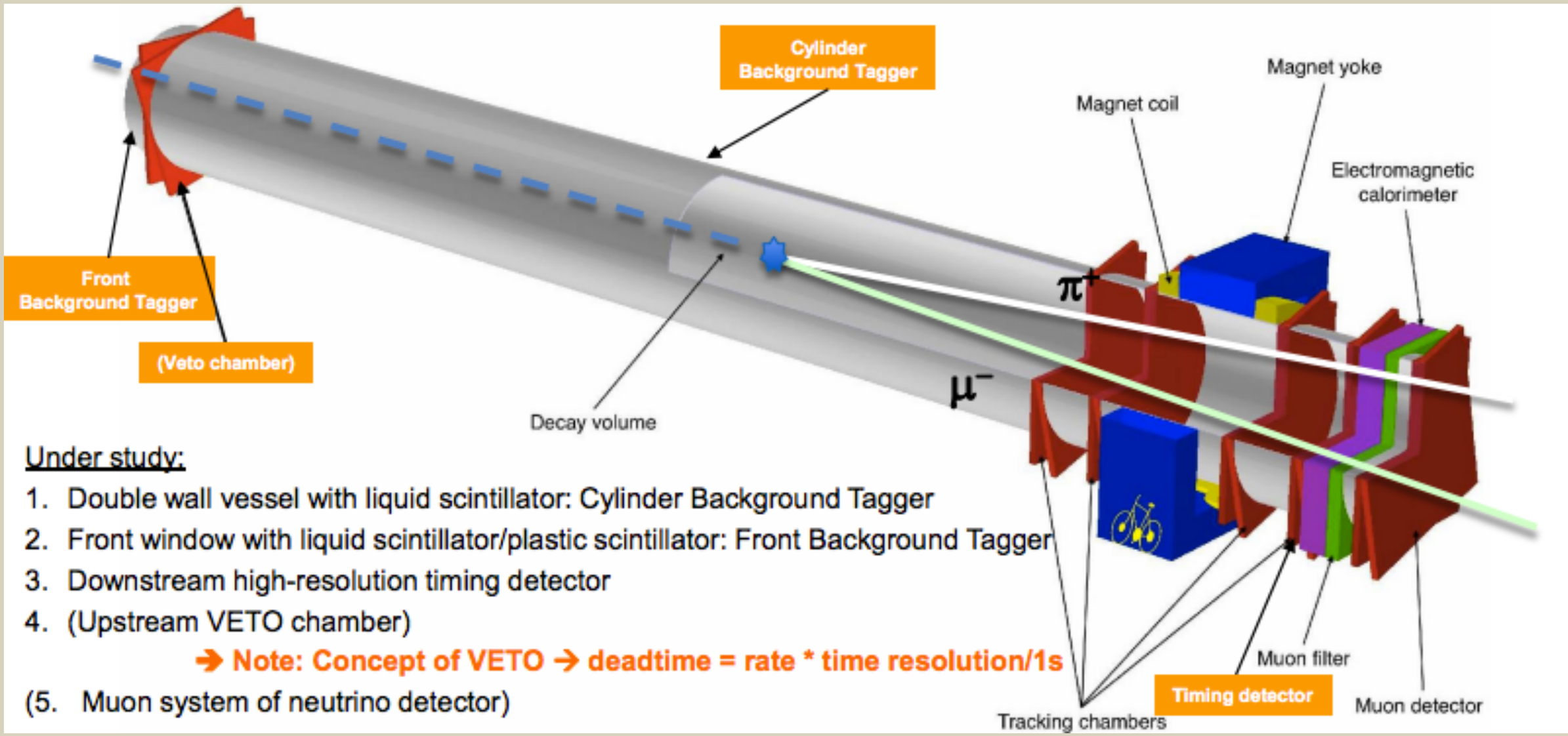
Muon Shield


Magnetic sweeper field
p>2 GeV
x (m)
3
2.5
2
1.5
1
0.5
0
p shield
Goliath
μ-spec
Vessel
experimental hall 4x13 p.o.t. / 7s
Prompt dose, y [-110:110], all particles
x [cm]
z [cm]
[μSv/h]
Prompt dose, z [10000:10000], all particles
y [cm]
x [cm]
2800 tonnes
3.2 m
2.7 m
48 m
9 m
5 m

Tracking System



Sistema Tracciante



Under study:

1. Double wall vessel with liquid scintillator: Cylinder Background Tagger
2. Front window with liquid scintillator/plastic scintillator: Front Background Tagger
3. Downstream high-resolution timing detector
4. (Upstream VETO chamber)

→ Note: Concept of VETO → deadtime = rate * time resolution/1s

(5. Muon system of neutrino detector)

Ricerca Diretta di Materia Oscura