SHiP
Search for Hidden Particles

THE SHiP EXPERIMENT AT CERN

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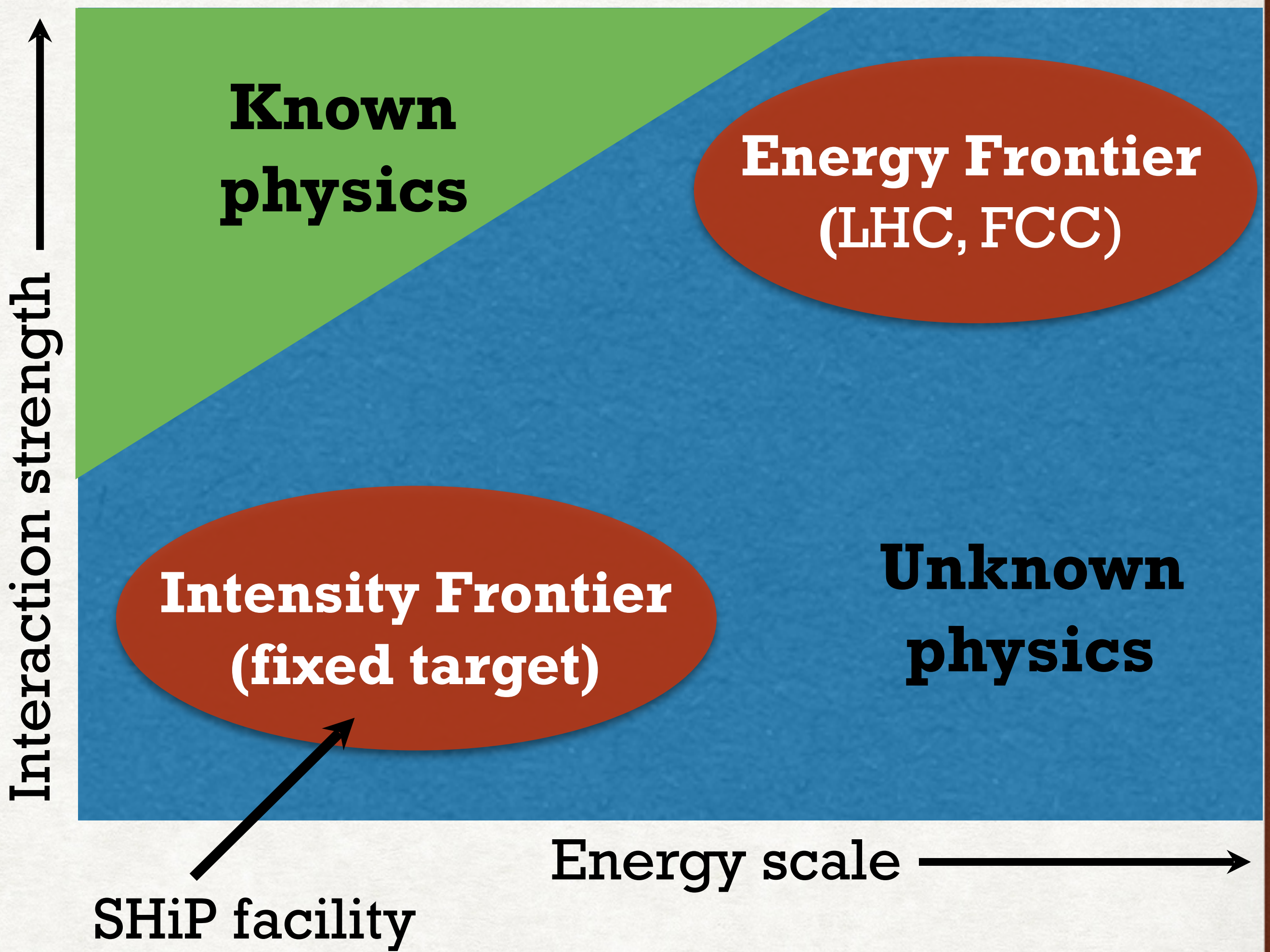
MOTIVATION

- The **Standard Model** provides an explanation for many subatomic processes
- Although very successful, it fails to explain many observed phenomena
  - **Dark Matter**
  - **Neutrino Oscillation and masses**
  - **Matter/antimatter asymmetry in the Universe**
- A **Hidden Sector (HS)** of weakly-interacting BSM particles as an explanation



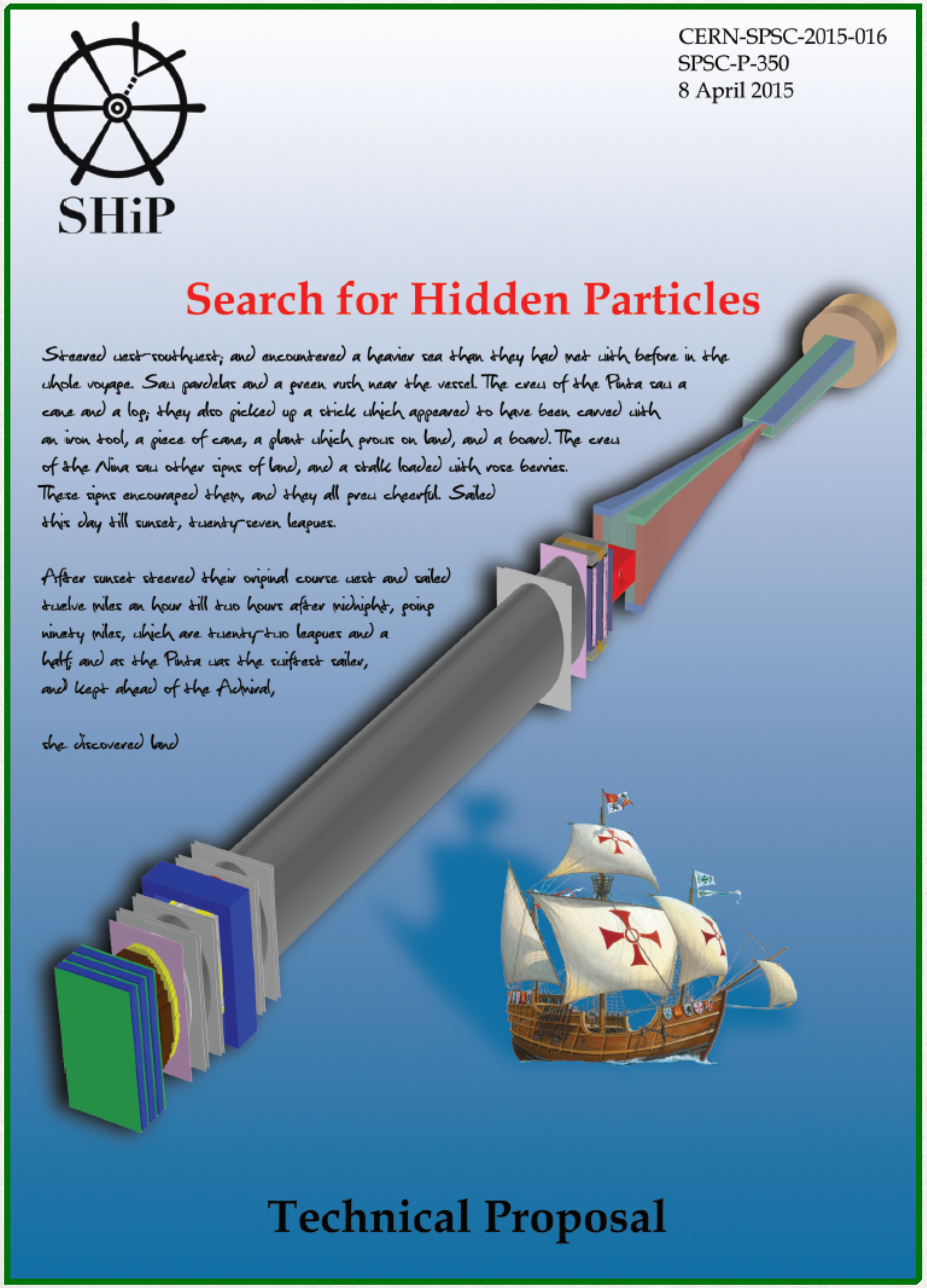
Energy Frontier:
Heavy particles → high energy collisions needed

Intensity Frontier:
Very weakly interacting particles → high intensity beam needed

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

Several **portals** to the HS: scalar portal, neutrino portal, vector portal, SUSY…

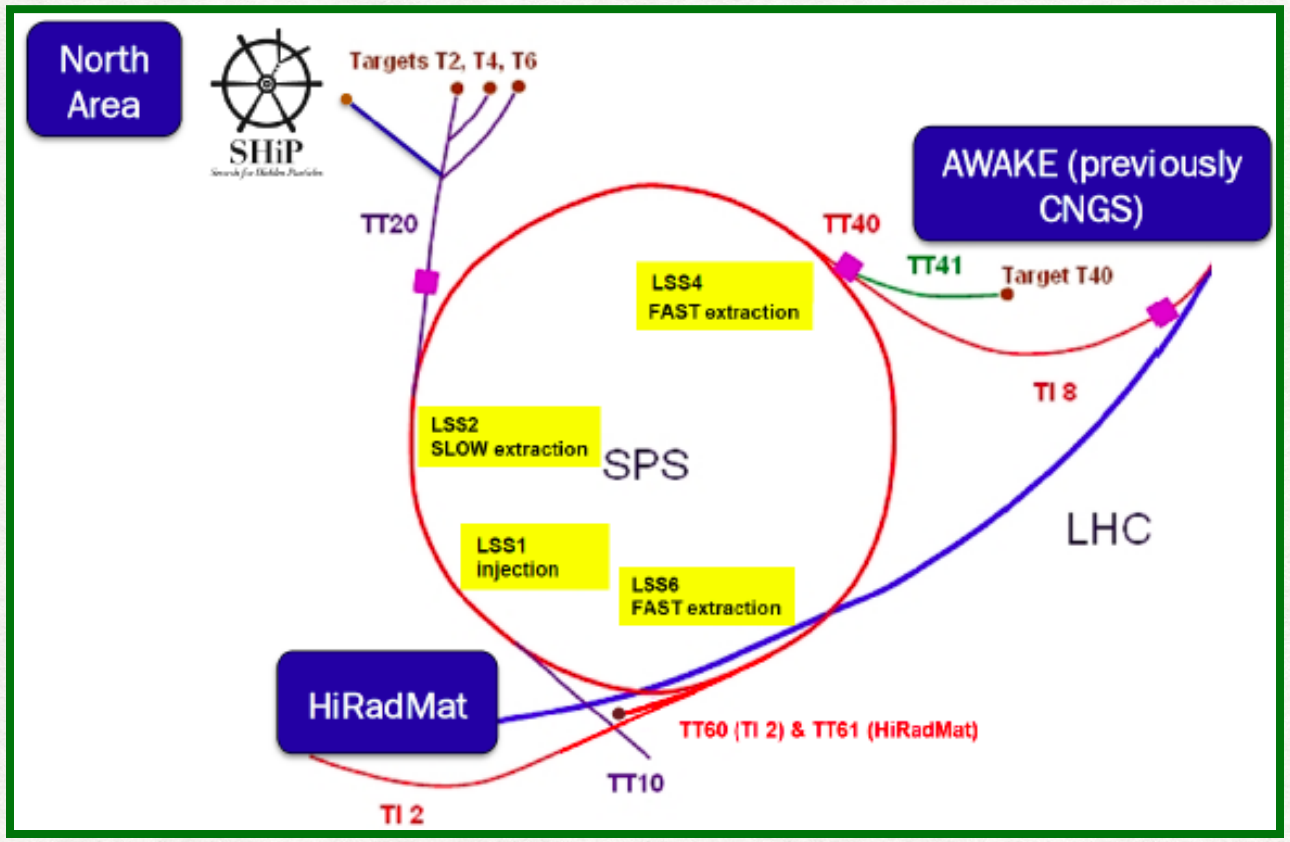
THE SHiP PROJECT

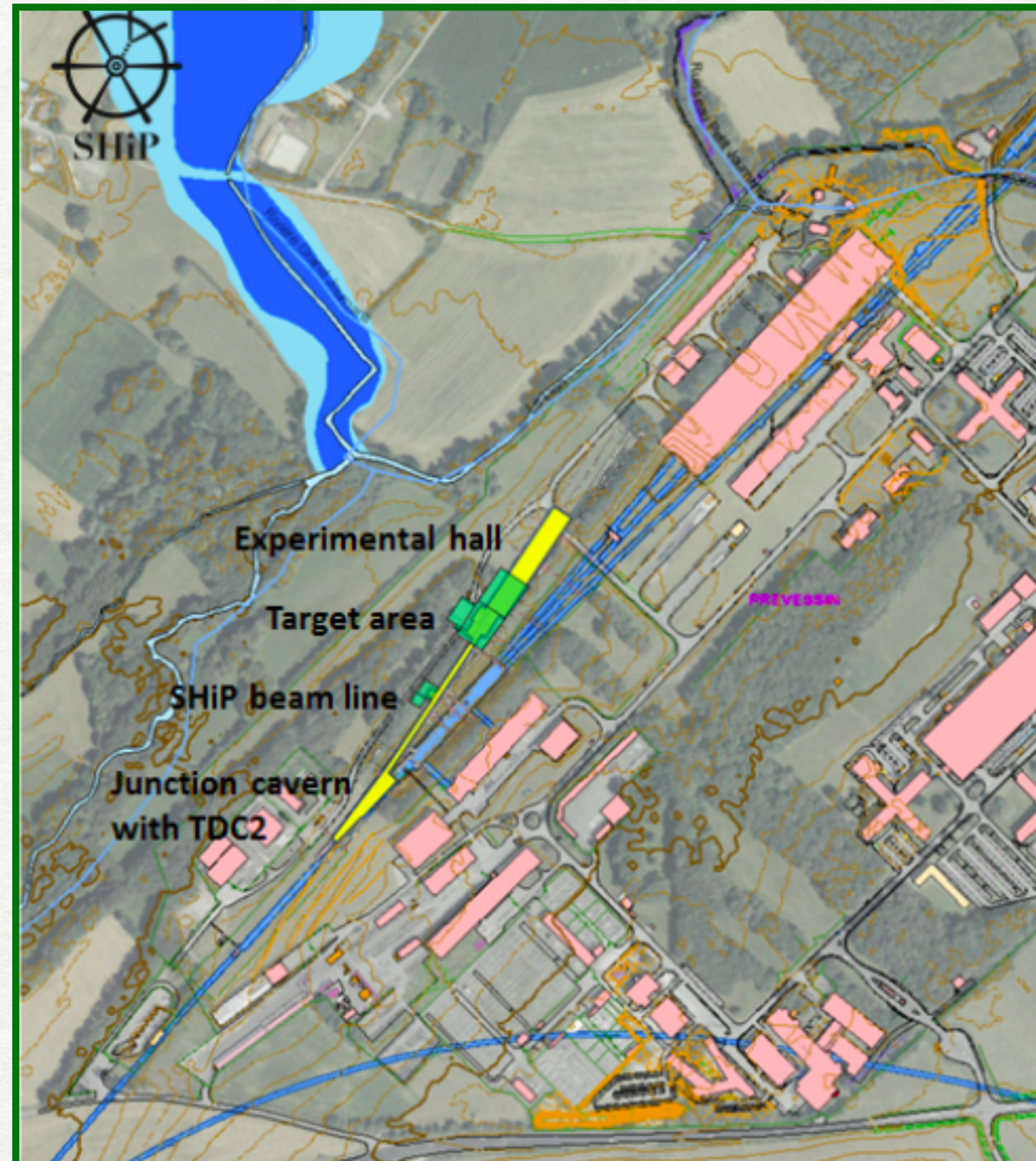


- **SHiP** (Search for Hidden Particles) in a proposed fixed target experiment at CERN SPS
- Collaboration of 250 members from 49 institutes, 17 countries
- Technical Proposal *arXiv:1504.04956 (2015)*
- Physics case signed by 80 theorists *Rep. Prog. Phys. 79 (2016)* *arXiv:1504.04855*
- Positive SPSC recommendation
- Comprehensive Design Study by 2019 → decision about approval in 2020
- Important actor in the CERN Physics Beyond Colliders study group

THE SHiP FACILITY

- Fixed target experiment at the **CERN SPS**
- Beam: **400 GeV protons** ($4x10^{13}$ protons per spill)
  - → $2x10^{20}$ pot in 5 years

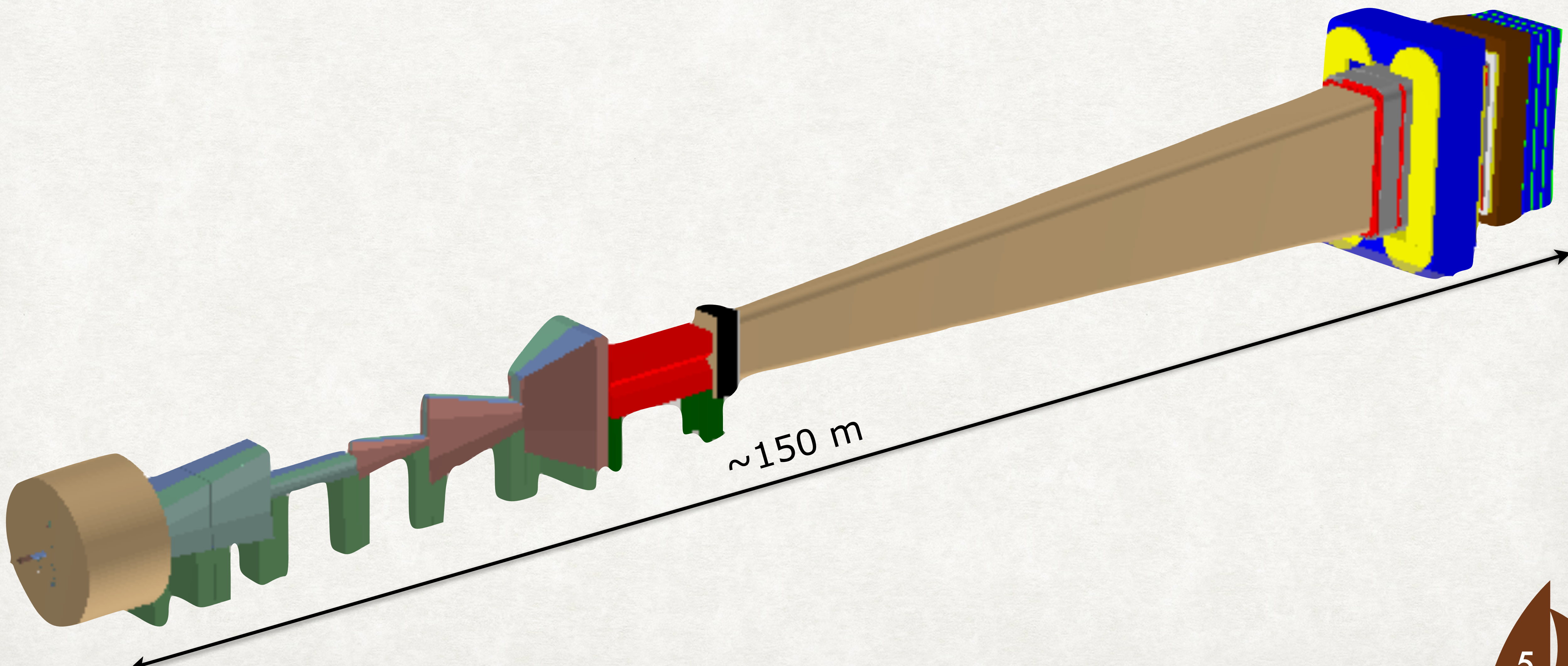




Location: Prevessin North Area site

Sharing of the TT20 transfer line and slow extraction mode with the fixed target programs

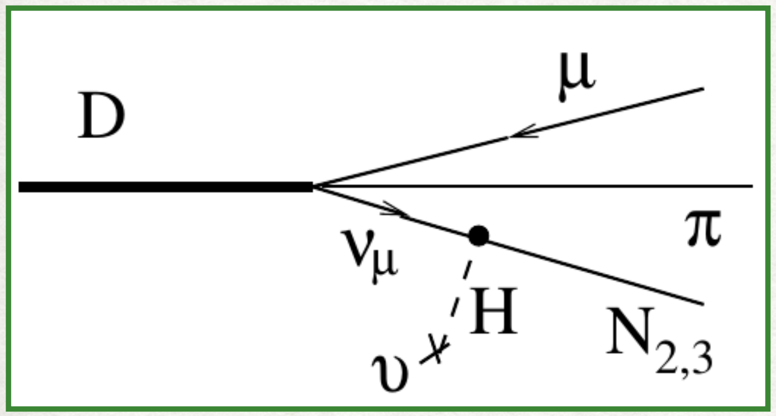
THE SHiP DETECTOR

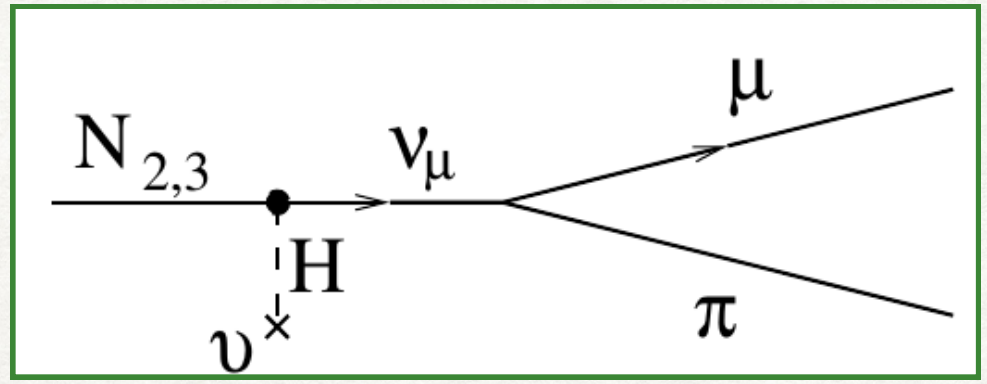


THE SHiP DETECTOR

- Designed for **large acceptance** and **zero background**
- 400 GeV protons on ~1 m long TZM, W target

Example of Hidden Sector search: Right-handed Neutrinos in the νMSM





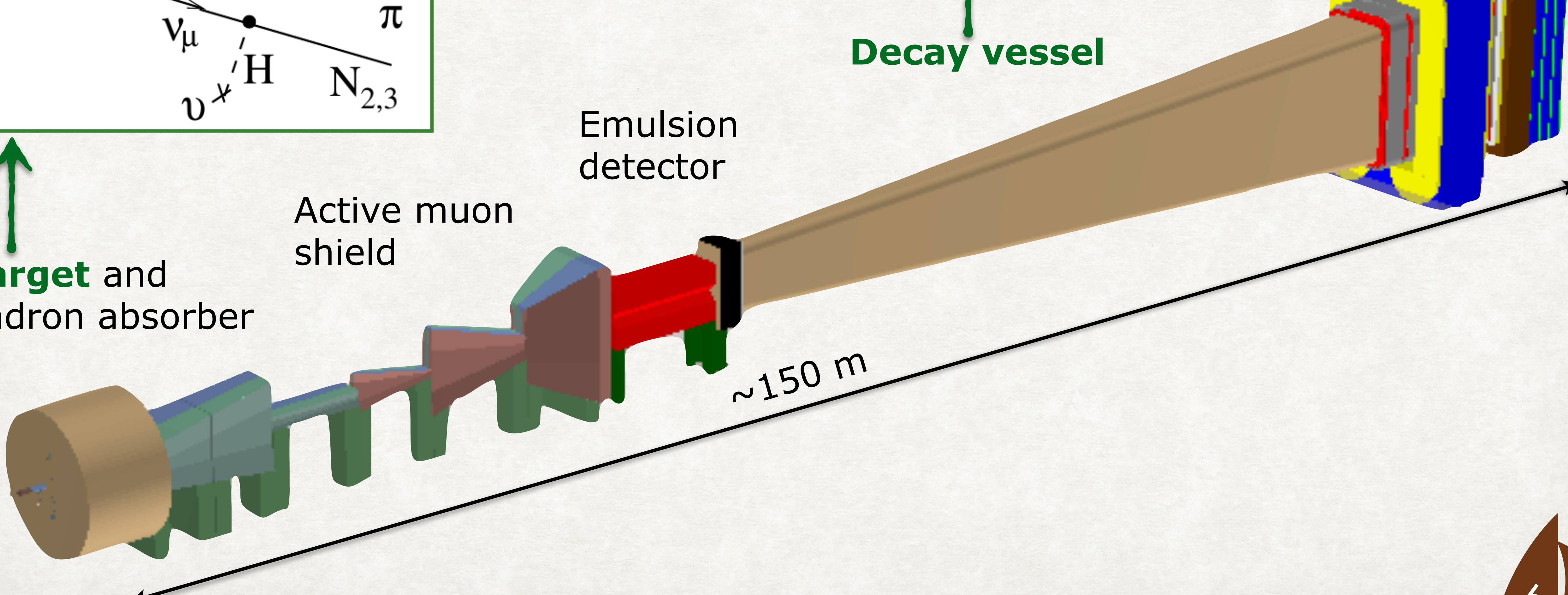
Tracker
spectrometer
Particle ID

Decay vessel

Emulsion
detector

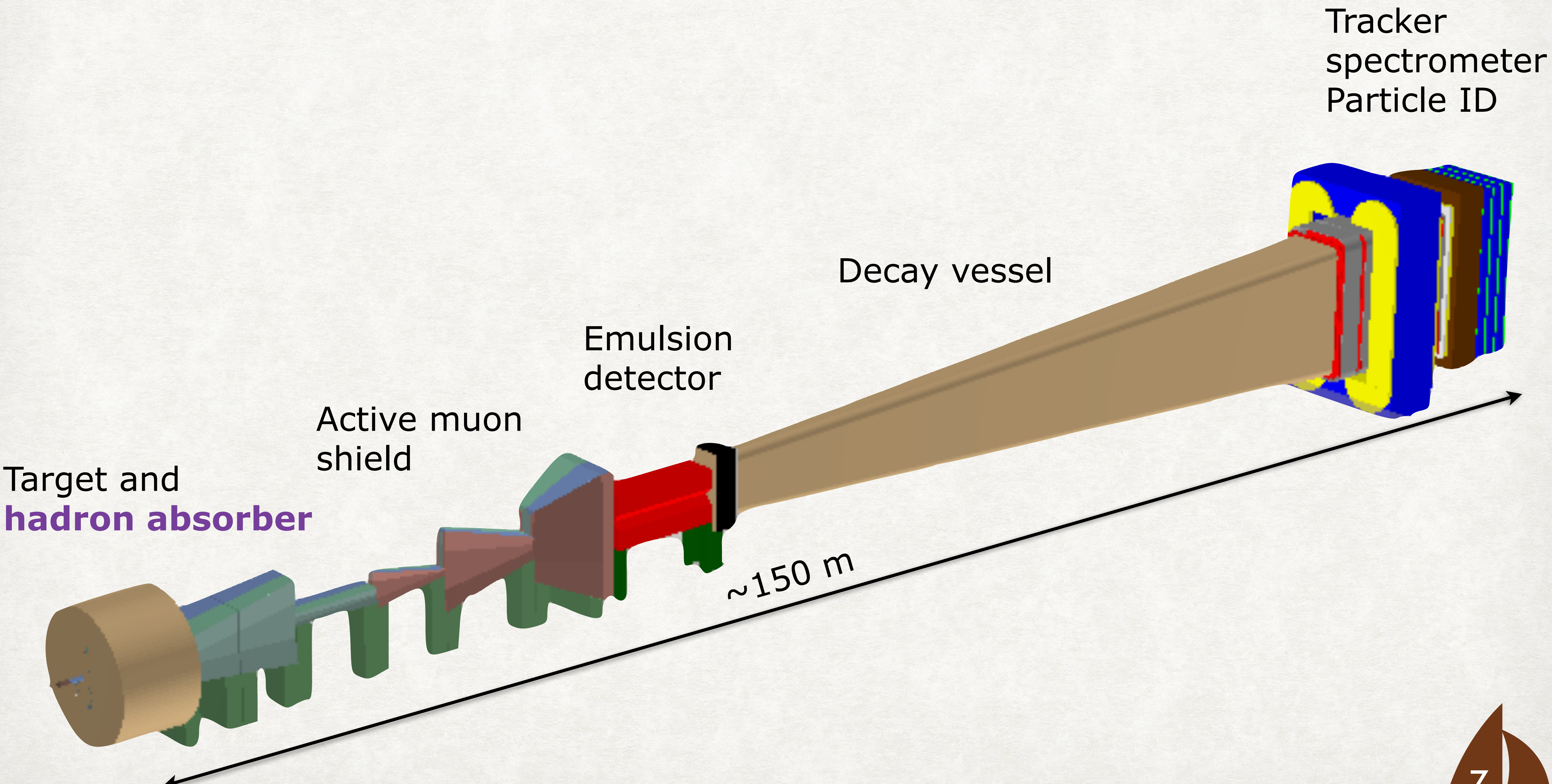
Active muon
shield

Target and
hadron absorber



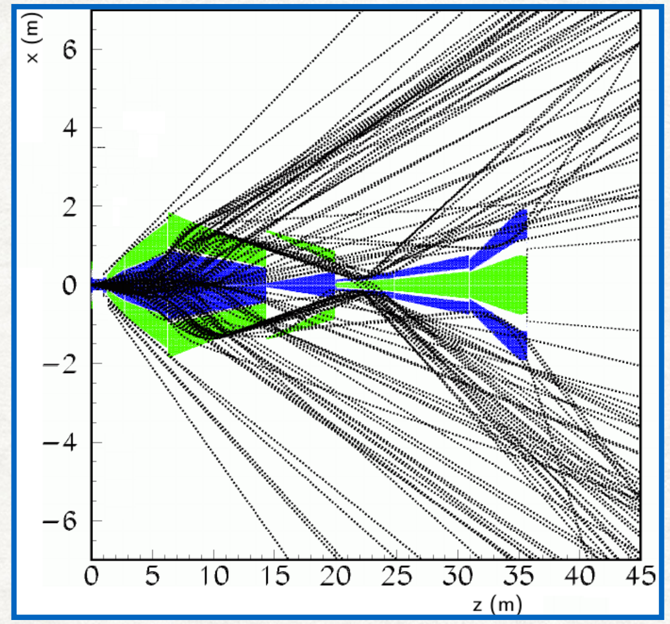
THE SHiP DETECTOR

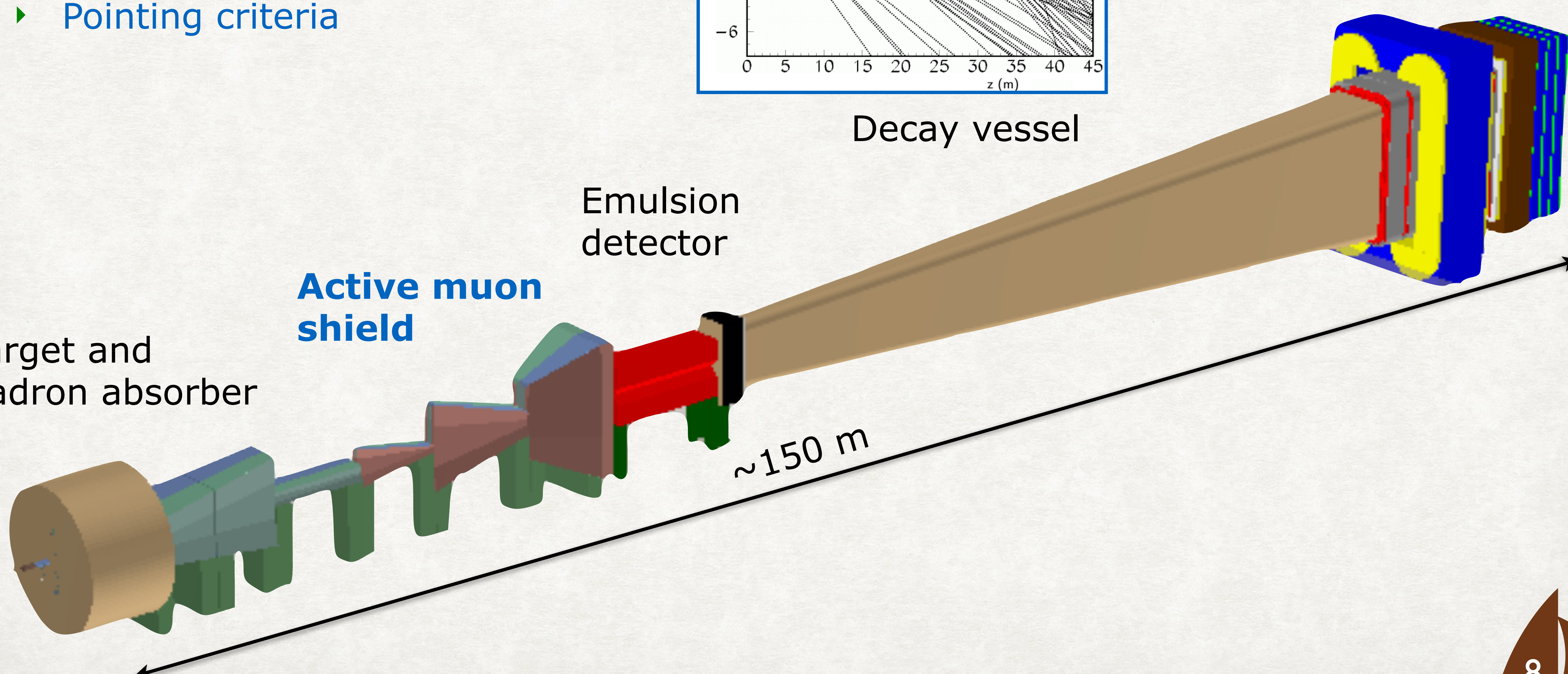
- Designed for **large acceptance** and **zero background**
- Reduction of neutrino background
    - Stop pion and kaons before decay
    - Evacuate the vessel



THE SHiP DETECTOR

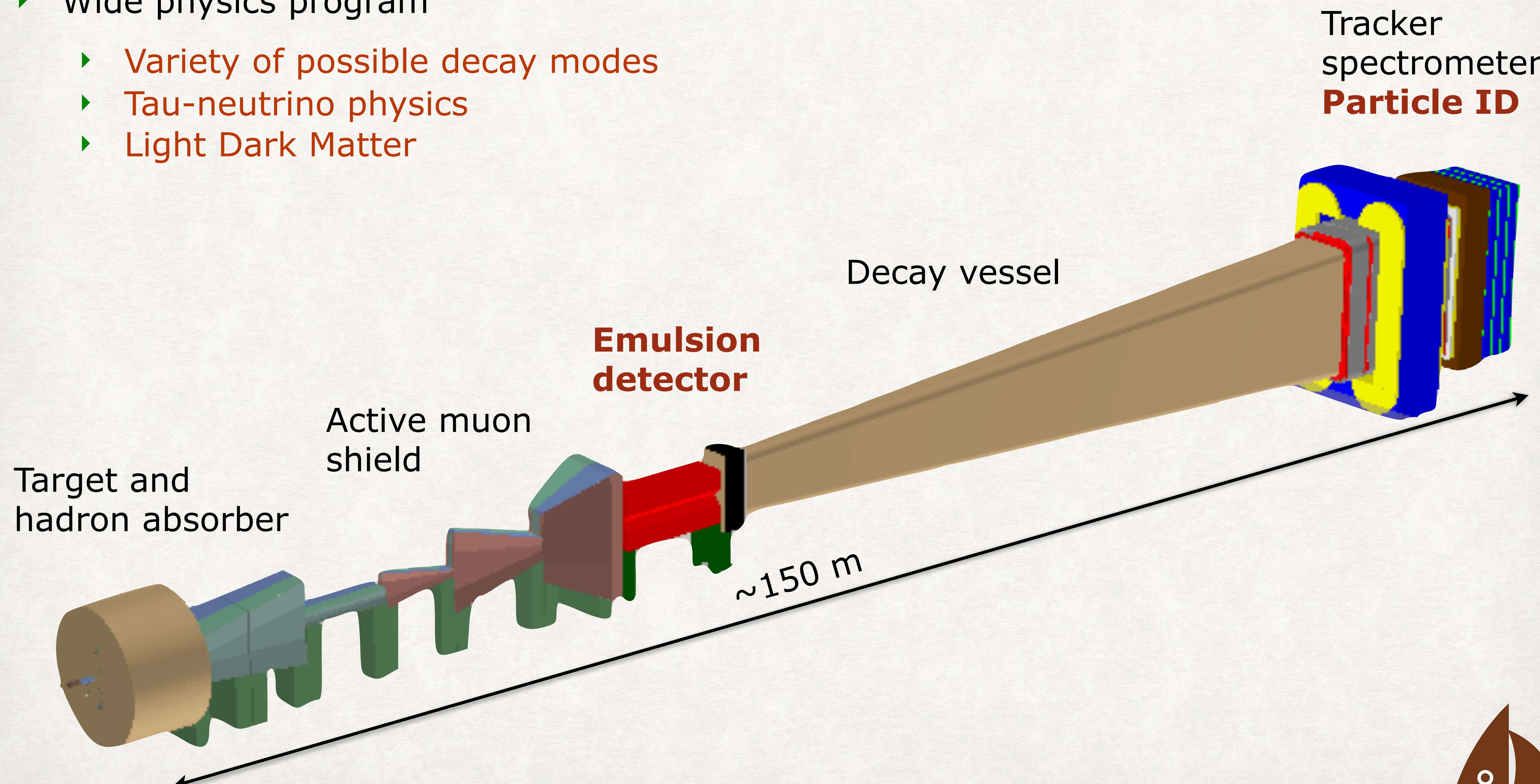
- Designed for **large acceptance** and **zero background**
- Reduction of neutrino background
- Reduction of muon background
  - Magnetic deflection in the shield
  - Particle ID
  - Surround veto taggers
  - Timing detector
  - Pointing criteria





THE SHiP DETECTOR

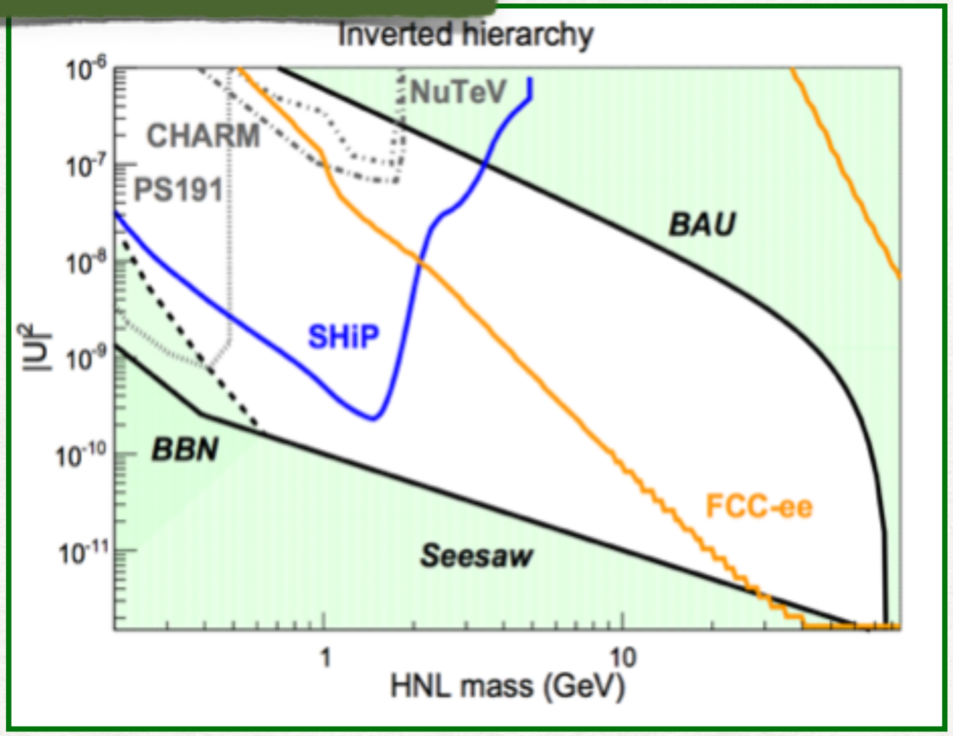
- Designed for **large acceptance** and **zero background**
- Reduction of neutrino background
- Reduction of muon background
- Wide physics program
  - Variety of possible decay modes
  - Tau-neutrino physics
  - Light Dark Matter



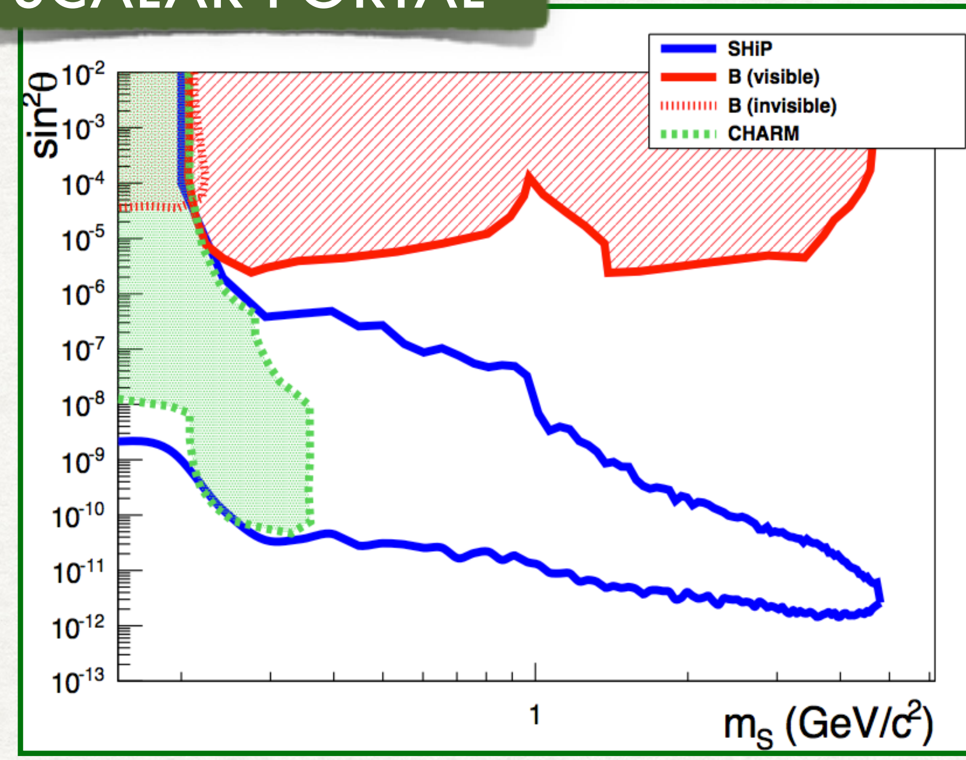
SENSITIVITIES

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

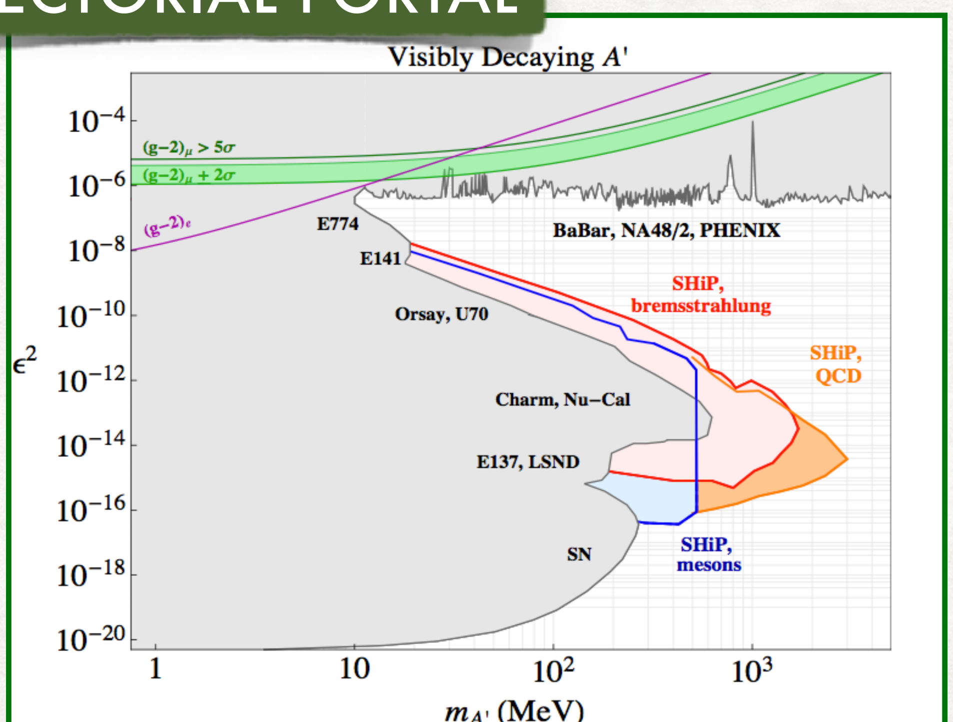
NEUTRINO PORTAL



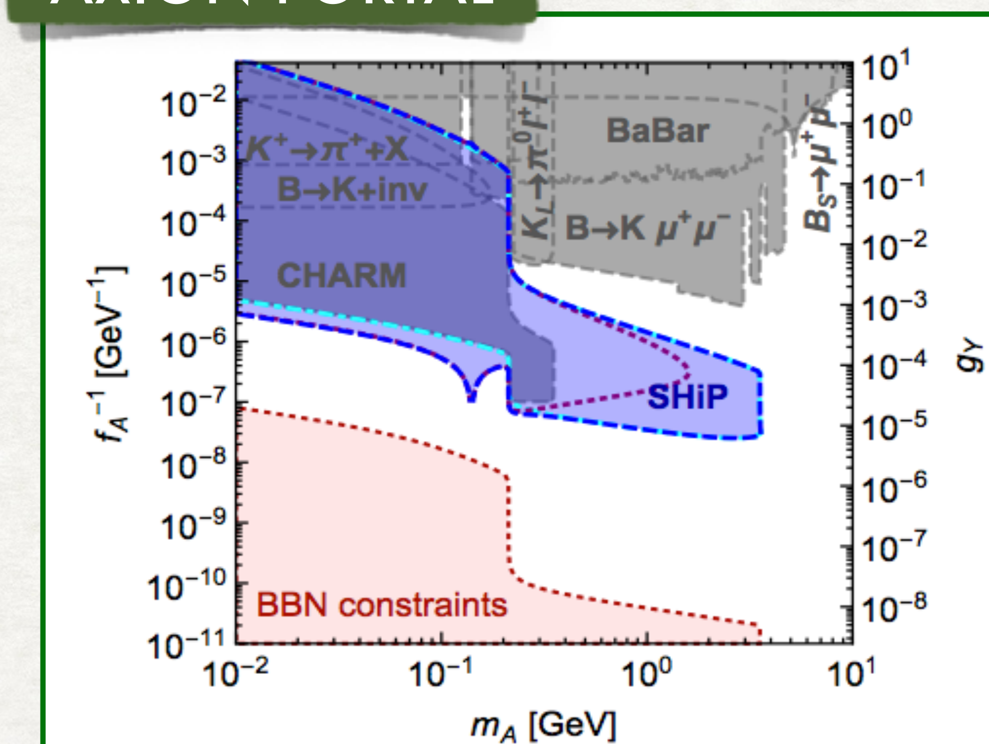
SCALAR PORTAL



VECTORIAL PORTAL

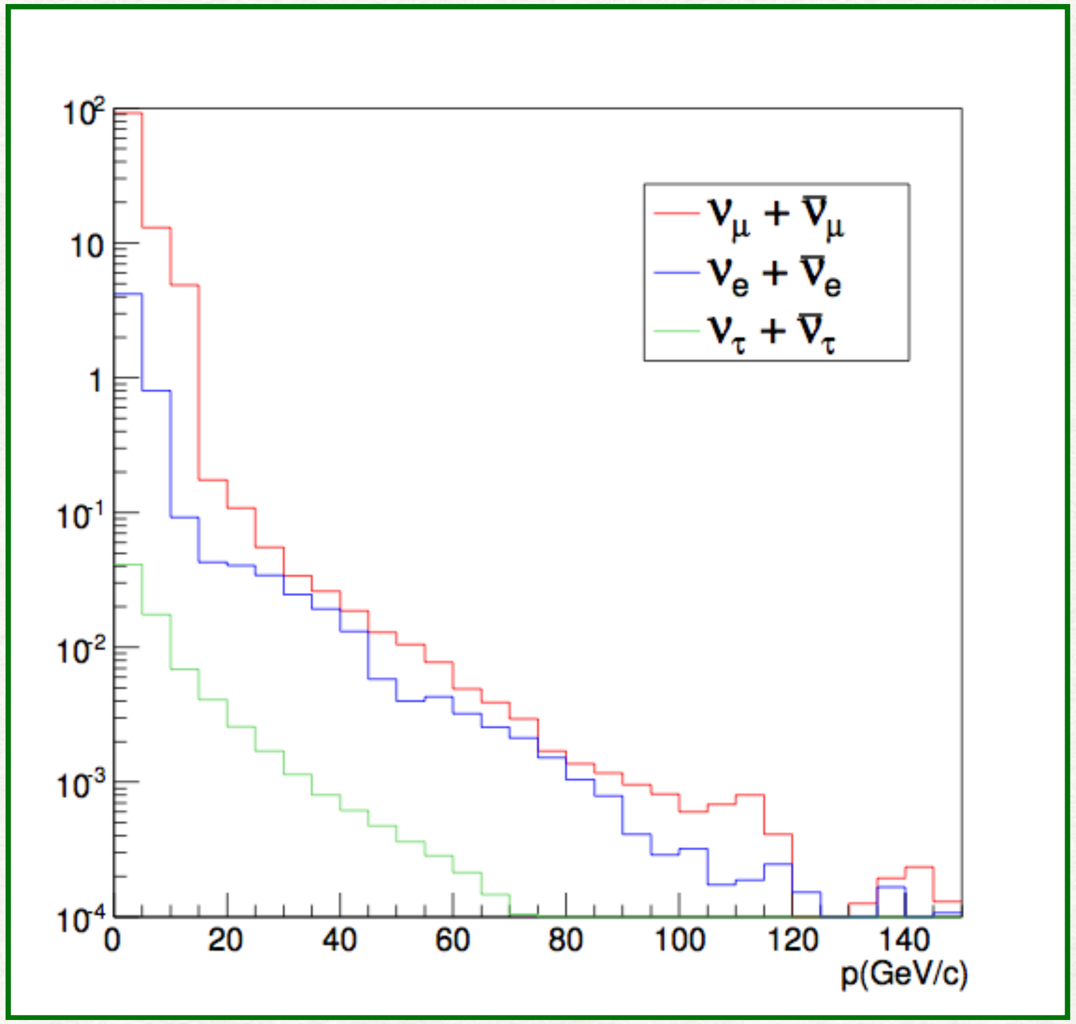


AXION PORTAL



NEUTRINO PHYSICS @SHiP

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



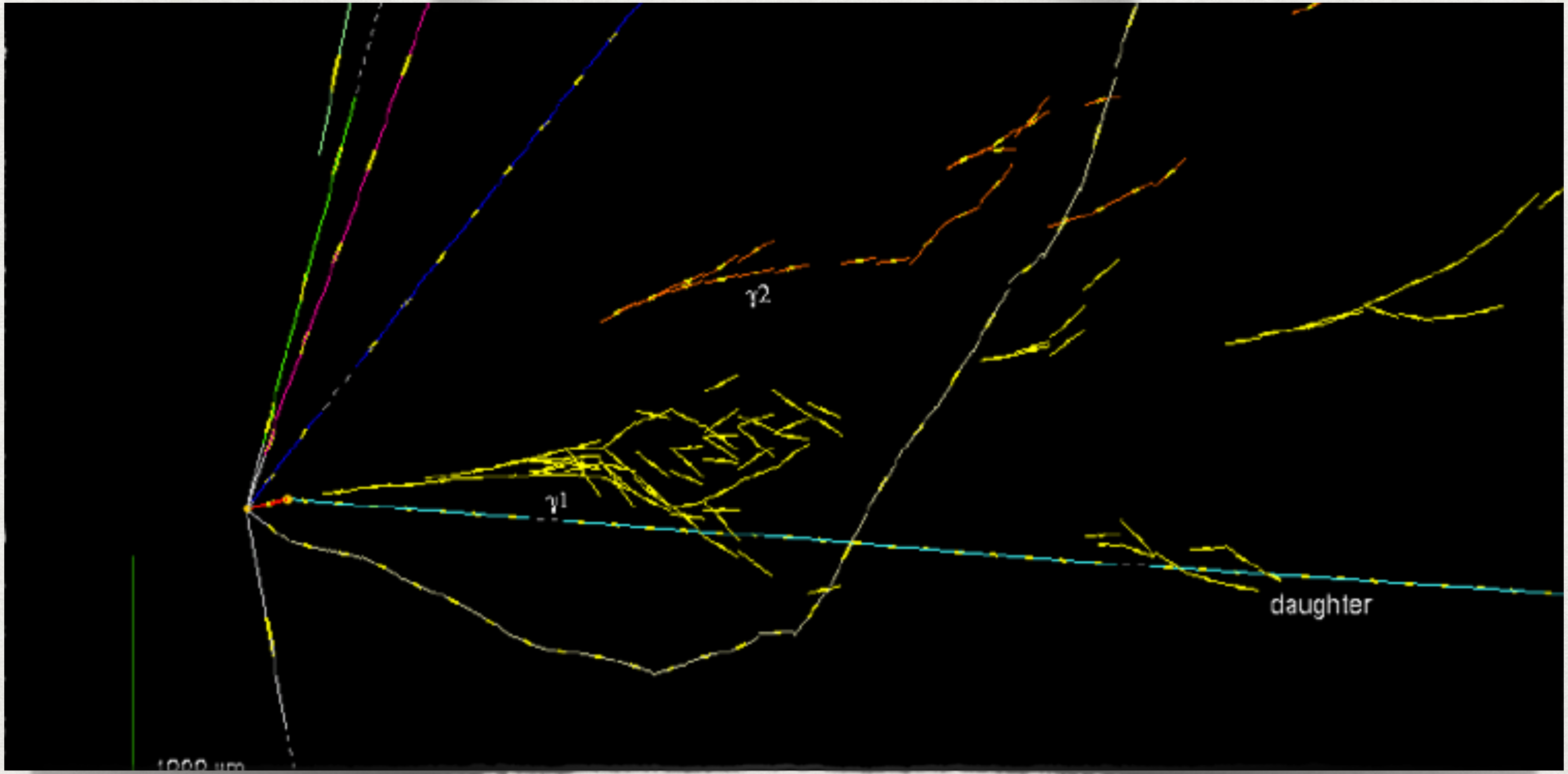
- Energy spectrum of different neutrino flavors @beam dump

TAU NEUTRINO PHYSICS

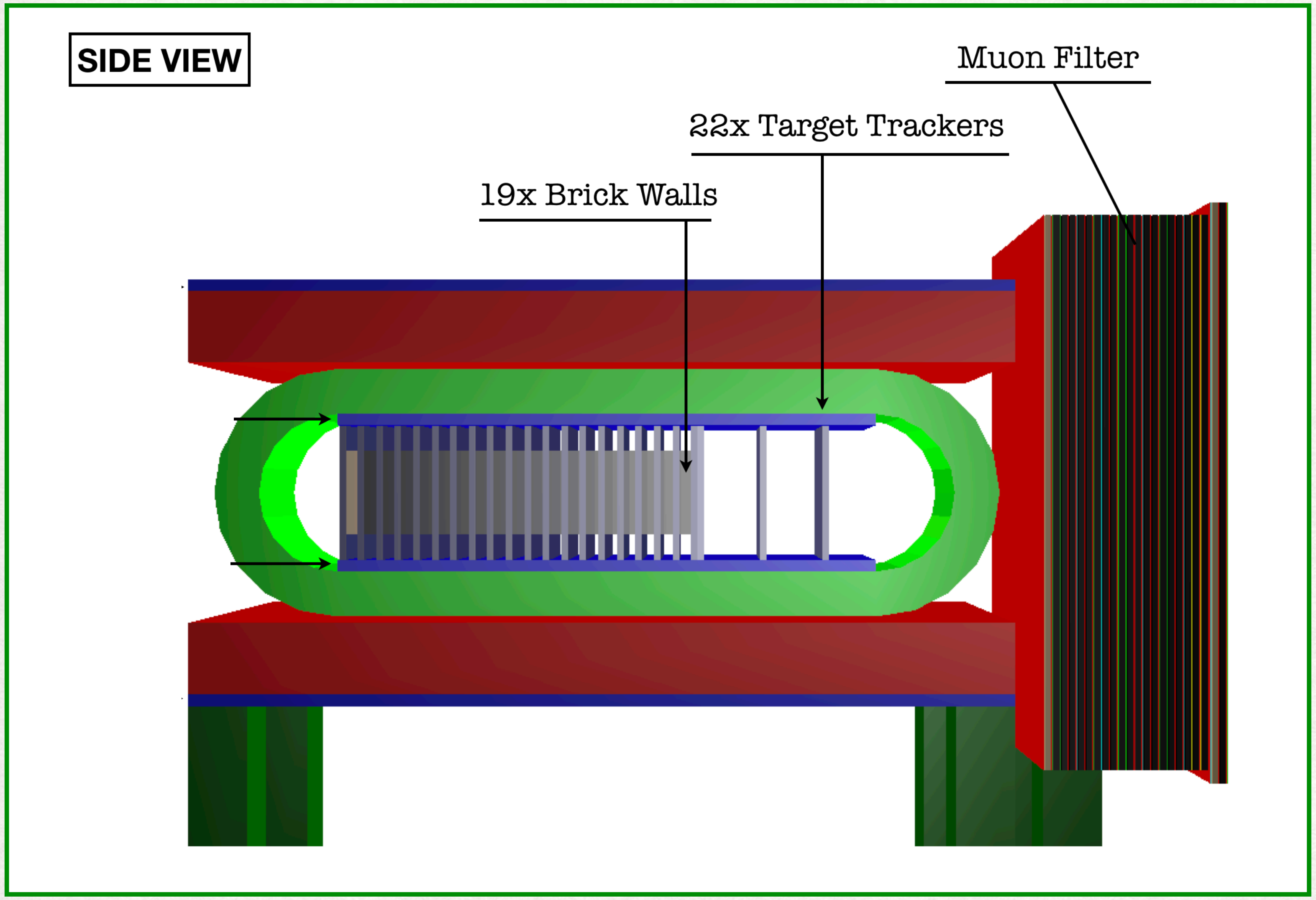
- High neutrino flux expected
- ν_τ: the less known particle in the Standard Model

DONUT: 9 observed ν_τ candidate events (leptonic number not measured)
OPERA: discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode

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



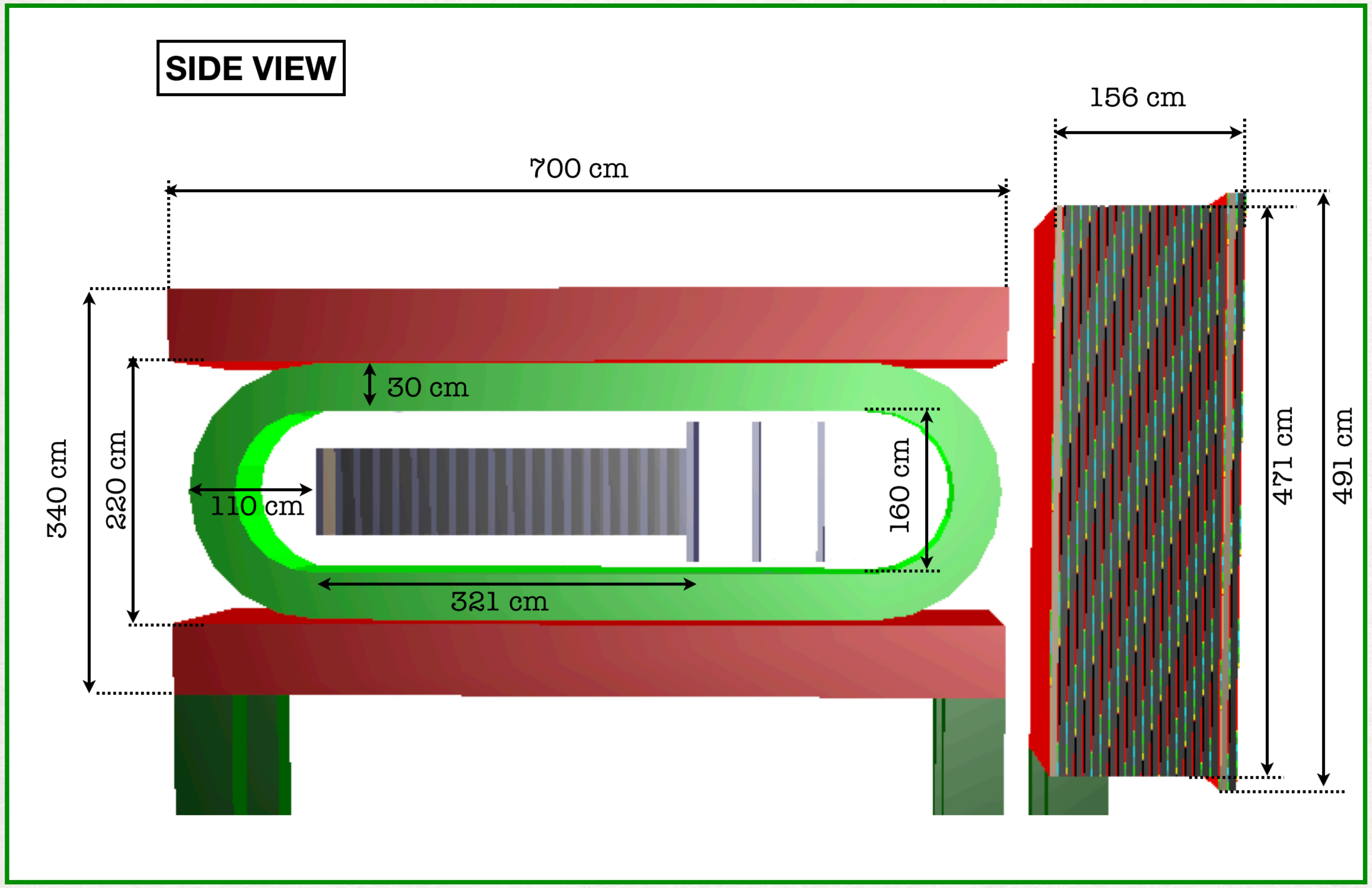
NEUTRINO DETECTOR

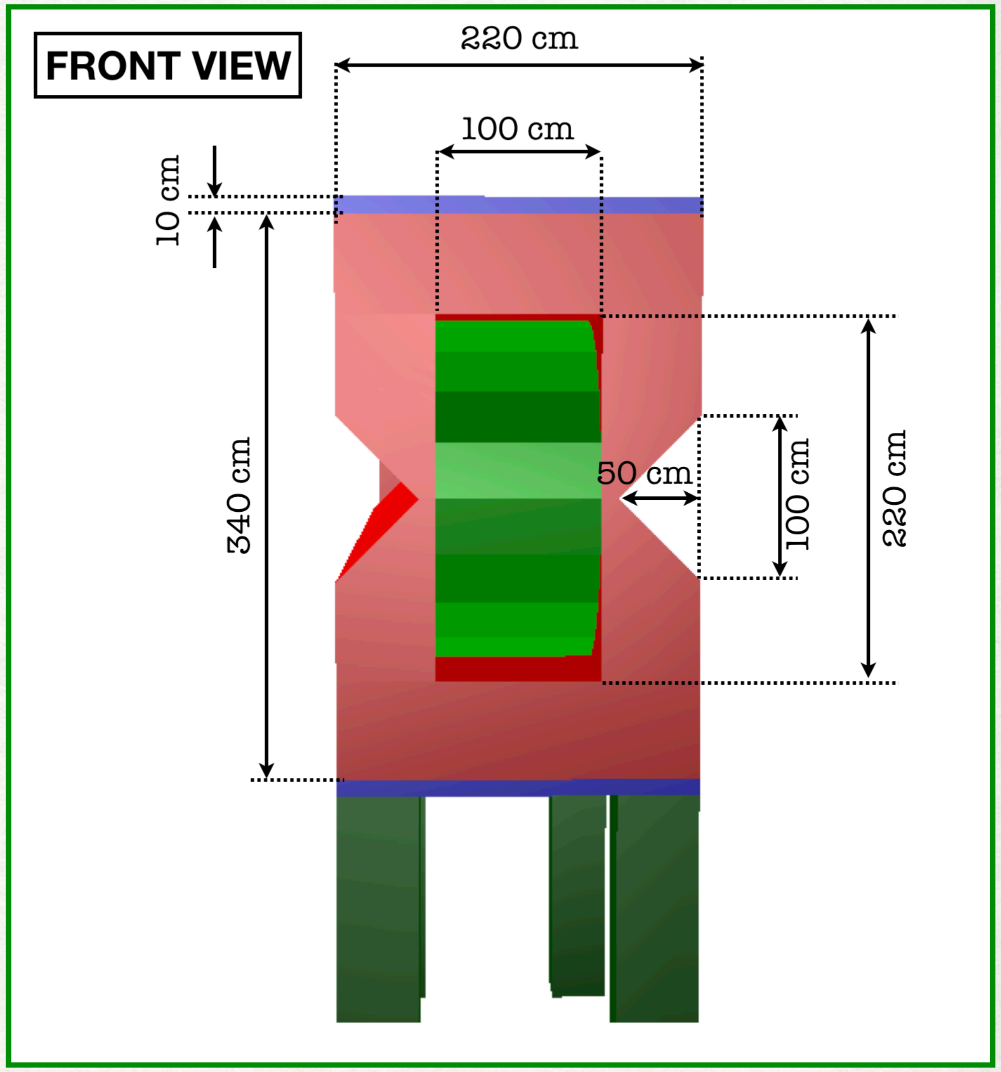


REQUIREMENTS

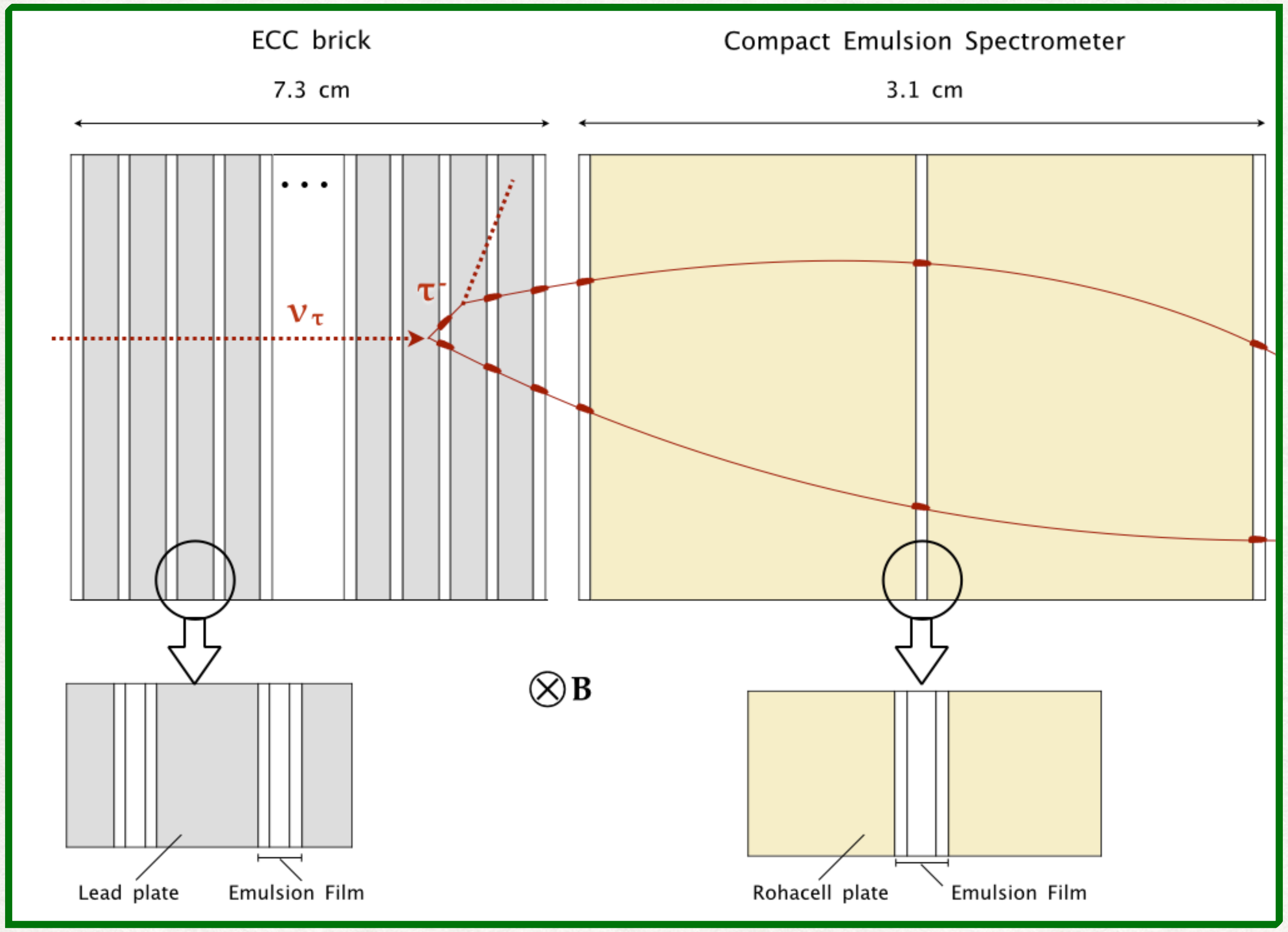
- High spatial resolution to observe the τ decay (~1 mm)
  → ***EMULSION FILMS***
- Electronic detectors to give "time" resolution to emulsions
  → ***TARGET TRACKER PLANES***
- Magnetized target to measure the charge of τ products
  → ***MAGNET***
- Magnetic spectrometer to measure muon momentum
  →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

NEUTRINO DETECTOR





NEUTRINO TARGET



Emulsion Cloud Chamber (ECC) BRICK

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

PERFORMANCES

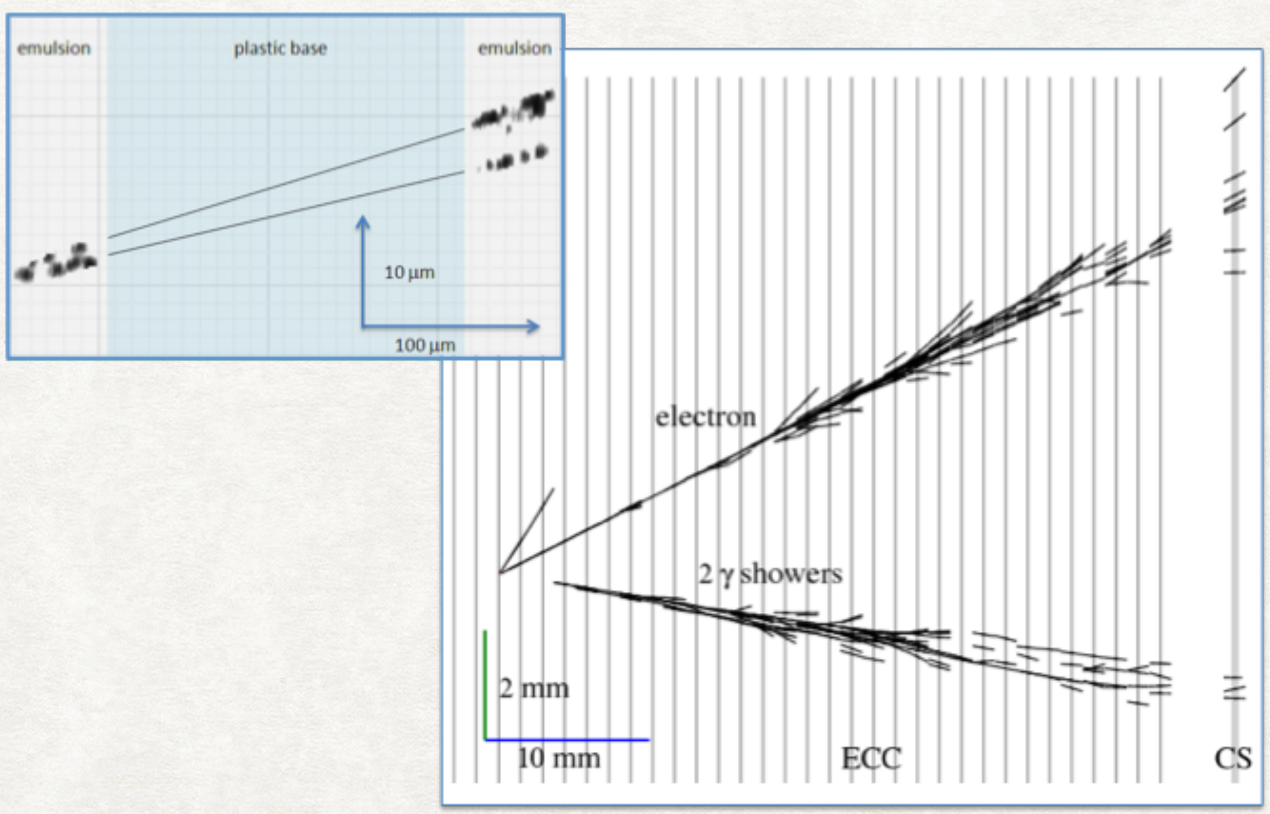
- Primary and secondary vertex definition with μm resolution
- Momentum measurement by Multiple Coulomb Scattering
  - largely exploited in the OPERA experiment -
- Electron identification: shower ID through calorimetric technique

LEPTON FLAVOR IDENTIFICATION

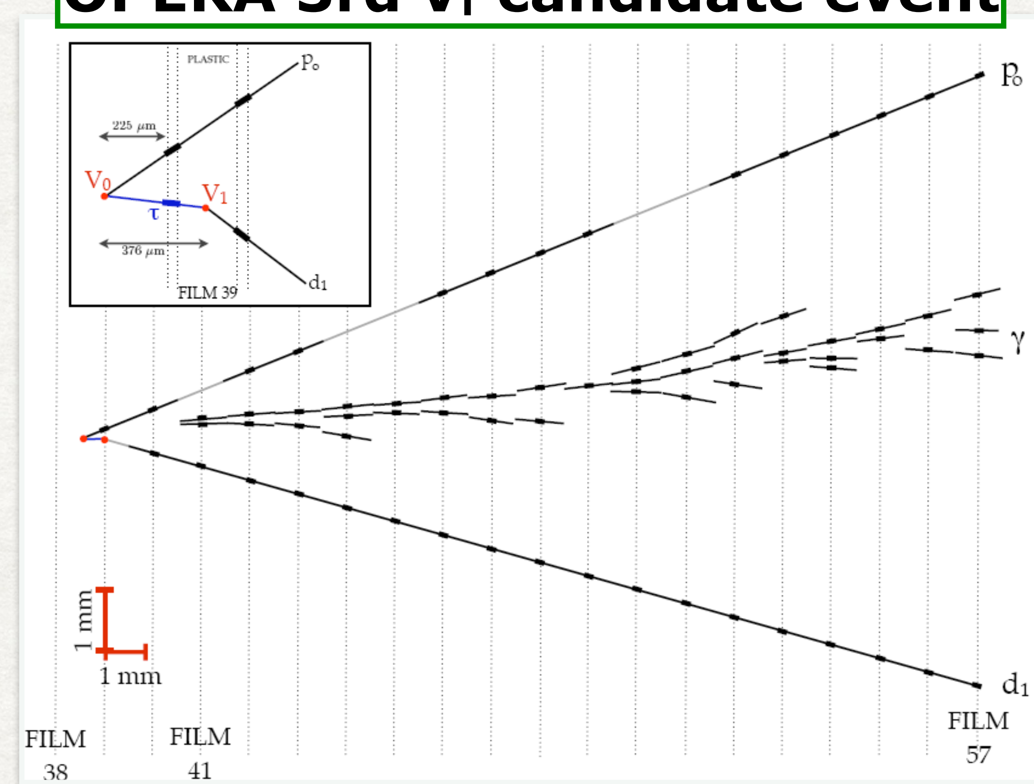
Emulsion Cloud Chamber technique

Lead plates (high density material for the interaction) interleaved with **emulsion films** (tracking devices with **µm resolution**)

- ***ν_μ identification*:** muon reconstruction in the magnetic spectrometer
- ***ν_e identification:*** electron shower identification in the brick
- ***ν_τ identification:*** disentanglement of τ production and decay vertices



OPERA 3rd ν_τ candidate event



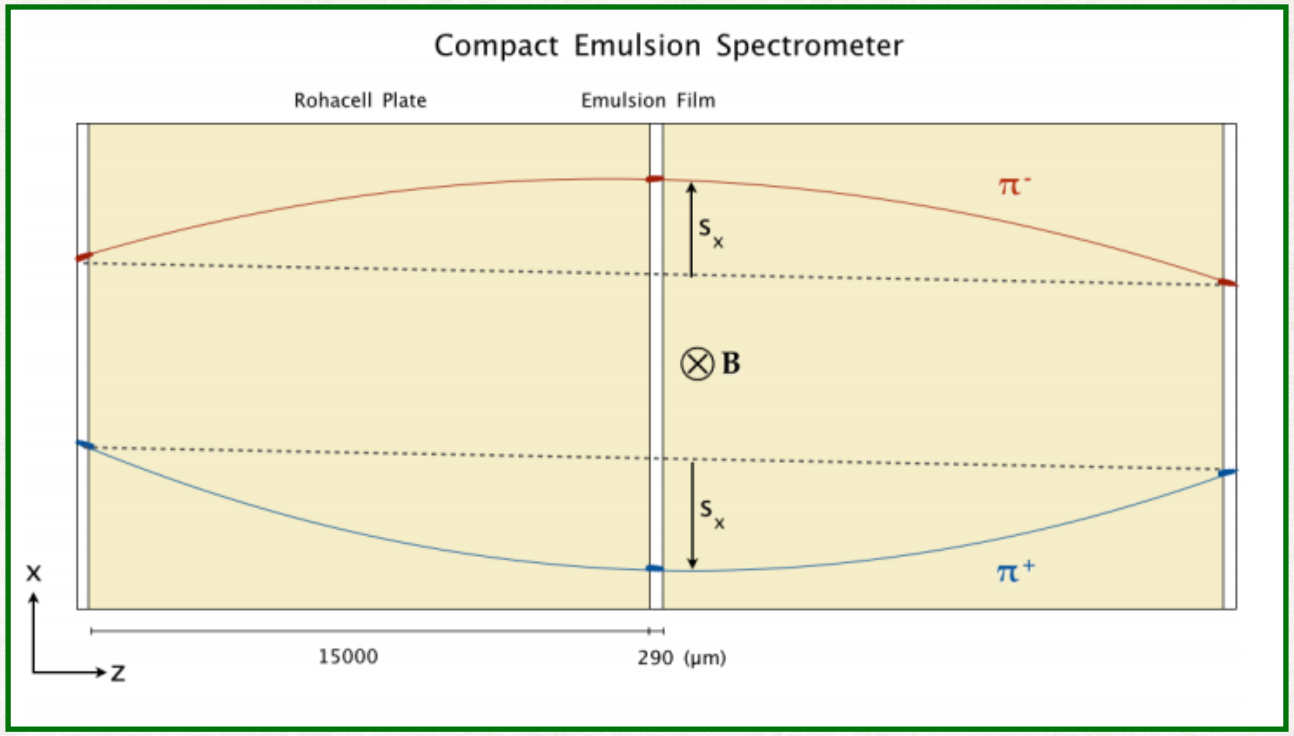
ν_τ/ANTI-ν_τ SEPARATION

REQUIREMENTS

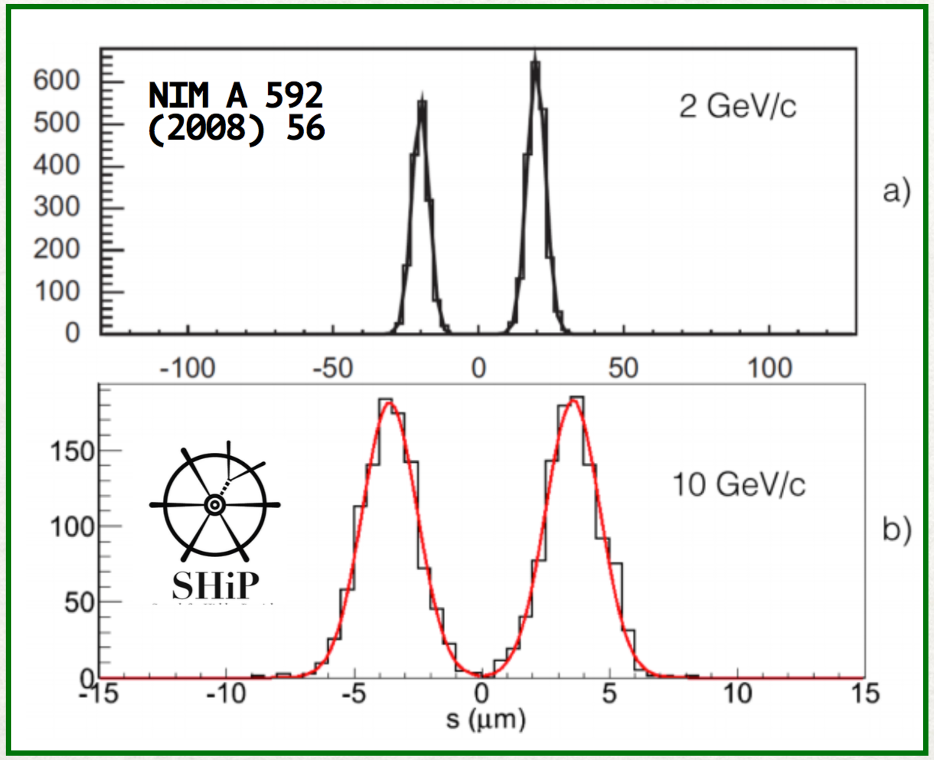
- Electric charge measurement of τ lepton decay products
- Key role for $\nu_\tau/\bar{\nu}_\tau$ separation in the $\tau \rightarrow h$ decay channel
- Momentum measurement

LAYOUT

- 3 OPERA-like emulsion films
- 2 Air gaps
- 1.2 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
- $\Delta p/p < 20\%$ up to 12 GeV/c

ν_τ PHYSICS

- ν_τ and anti-ν_τ produced in the leptonic decay of a D^-_s meson into τ^- and anti-ν_τ, and the subsequent decay of the τ^- into a ν_τ
- Number of ν_τ and anti-ν_τ produced in the beam dump

$$N_{\nu_\tau+\bar{\nu}_\tau} = 4N_p\frac{\sigma_{c\bar{c}}}{\sigma_{pN}}f_{D_s}Br(D_s\to\tau) = 3.26\times10^{-5}N_p = 6.5\times10^{15}$$

- Main background source: charm production in ν_μ^{CC} (anti-ν_μ^{CC}) and ν_e^{CC} (anti-ν_e^{CC}) interactions, when the primary lepton is not identified

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

SIGNAL EXPECTATION

BACKGROUND

R = S/B RATIO

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

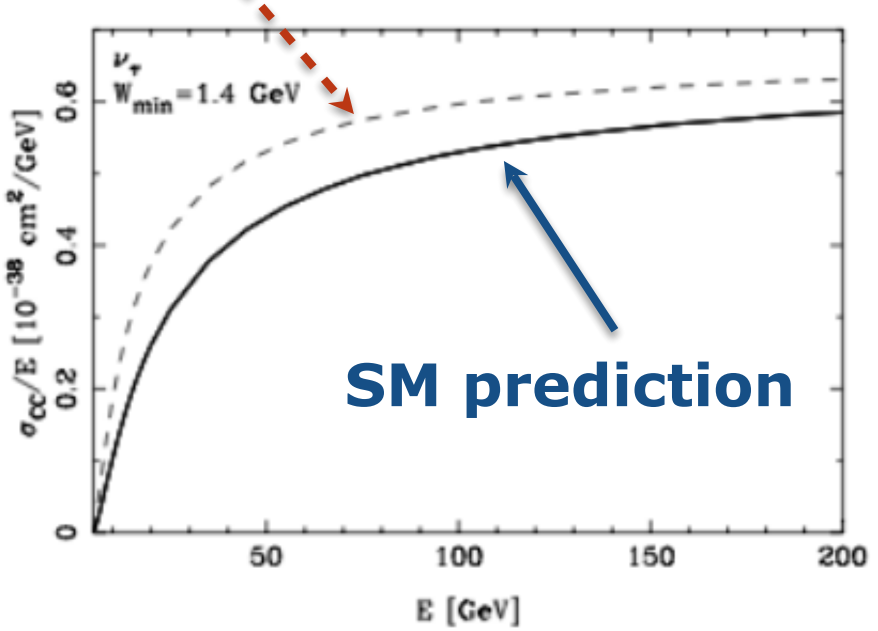
STRUCTURE FUNCTIONS

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

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

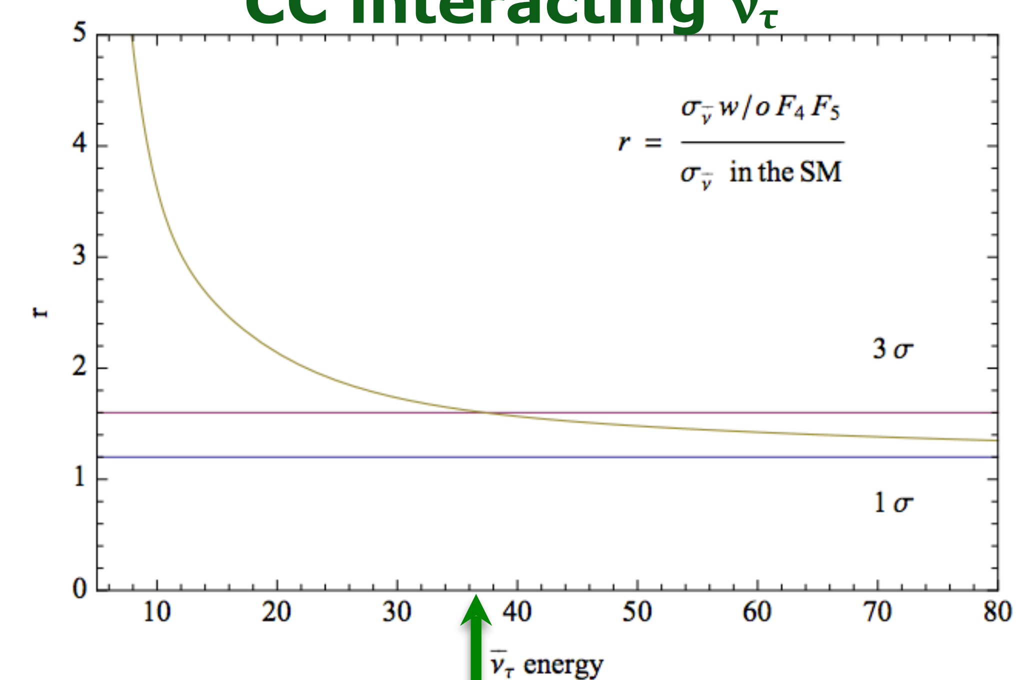
r = ratio between the cross sections in the two hypotheses

$F_4 = F_5 = 0$



ν_τ CC DIS cross-section

CC interacting ν_τ

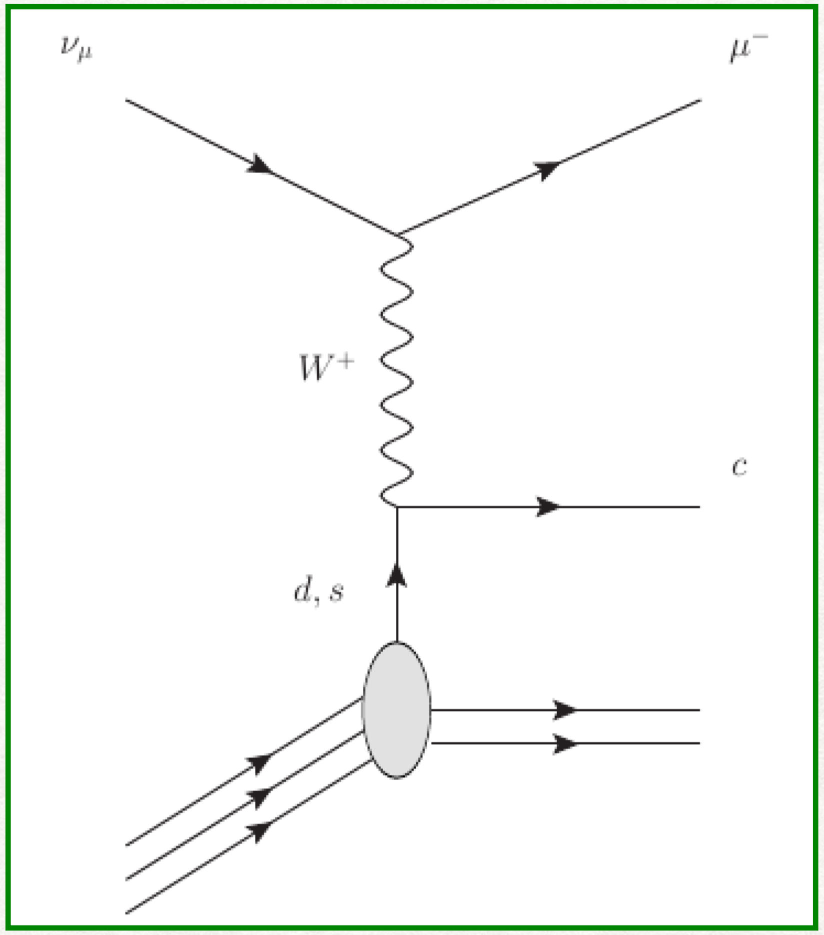


$E(\nu_\tau) < 38$ GeV

(~300 events expected)

CHARM PHYSICS @SHiP

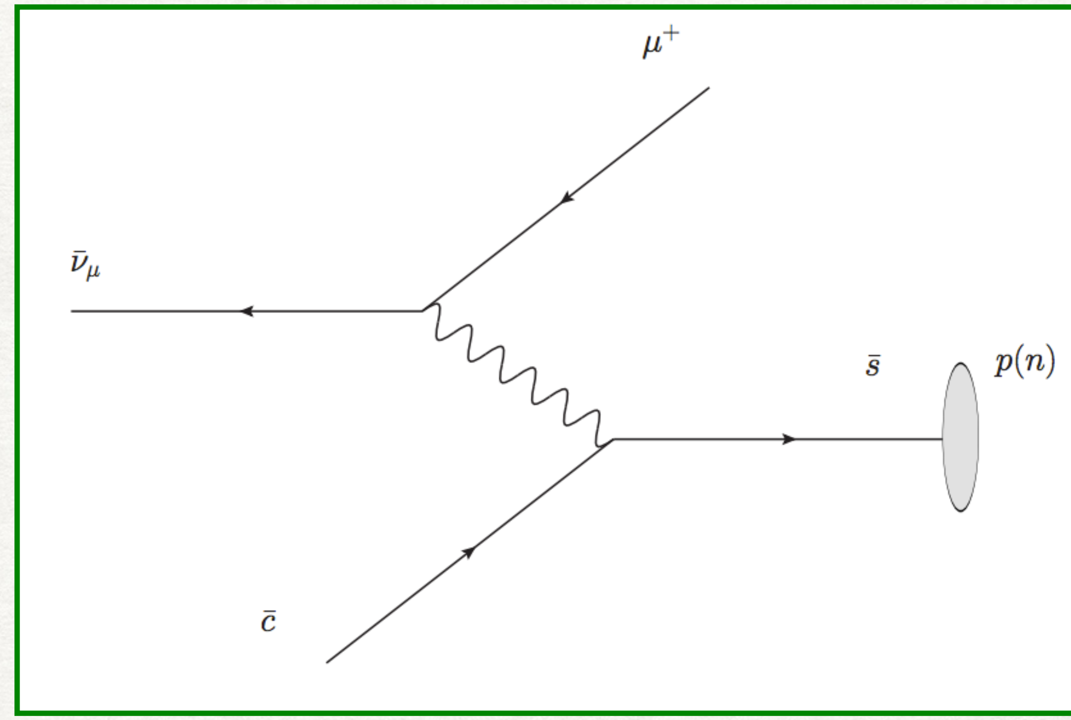
- Large **charm production** in ν_μCC and ν_eCC interactions
- Process sensitive to **strange quark** content of the nucleon



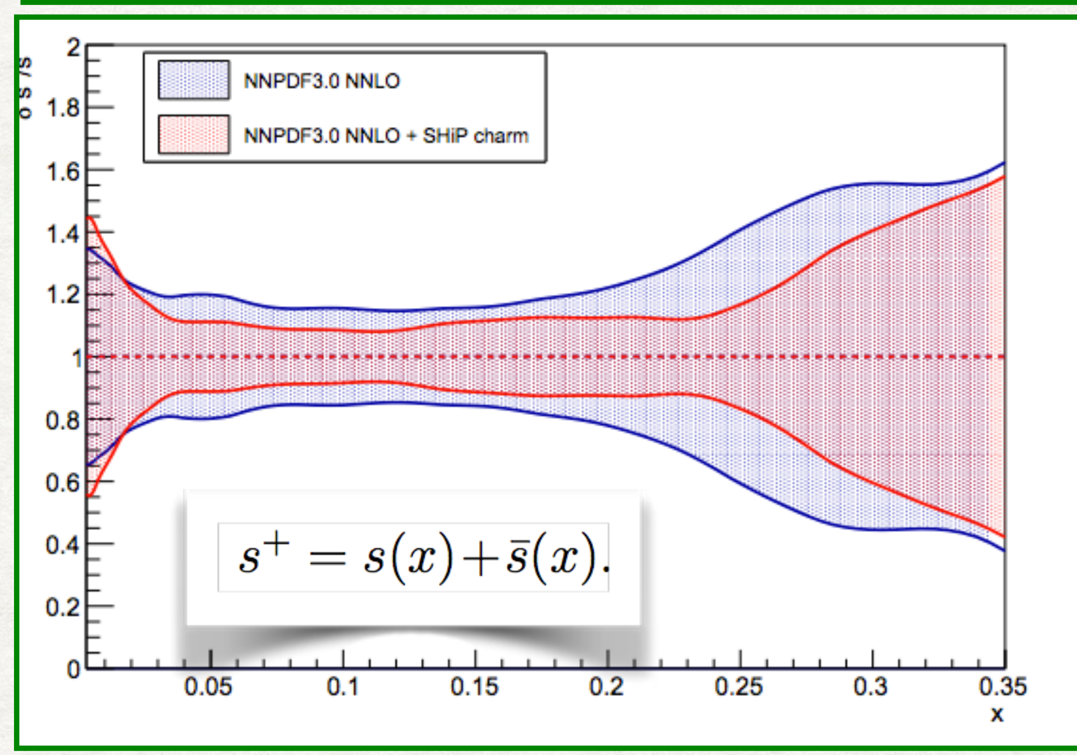
- Charm production with electronic detectors tagged by di-muon events (high energy cut to reduce background)
- **Nuclear emulsion** technique: charmed hadron identification through the observation of its decay
- Loose kinematical cuts ➙ good sensitivity to the **slow-rescaling** threshold behavior and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

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

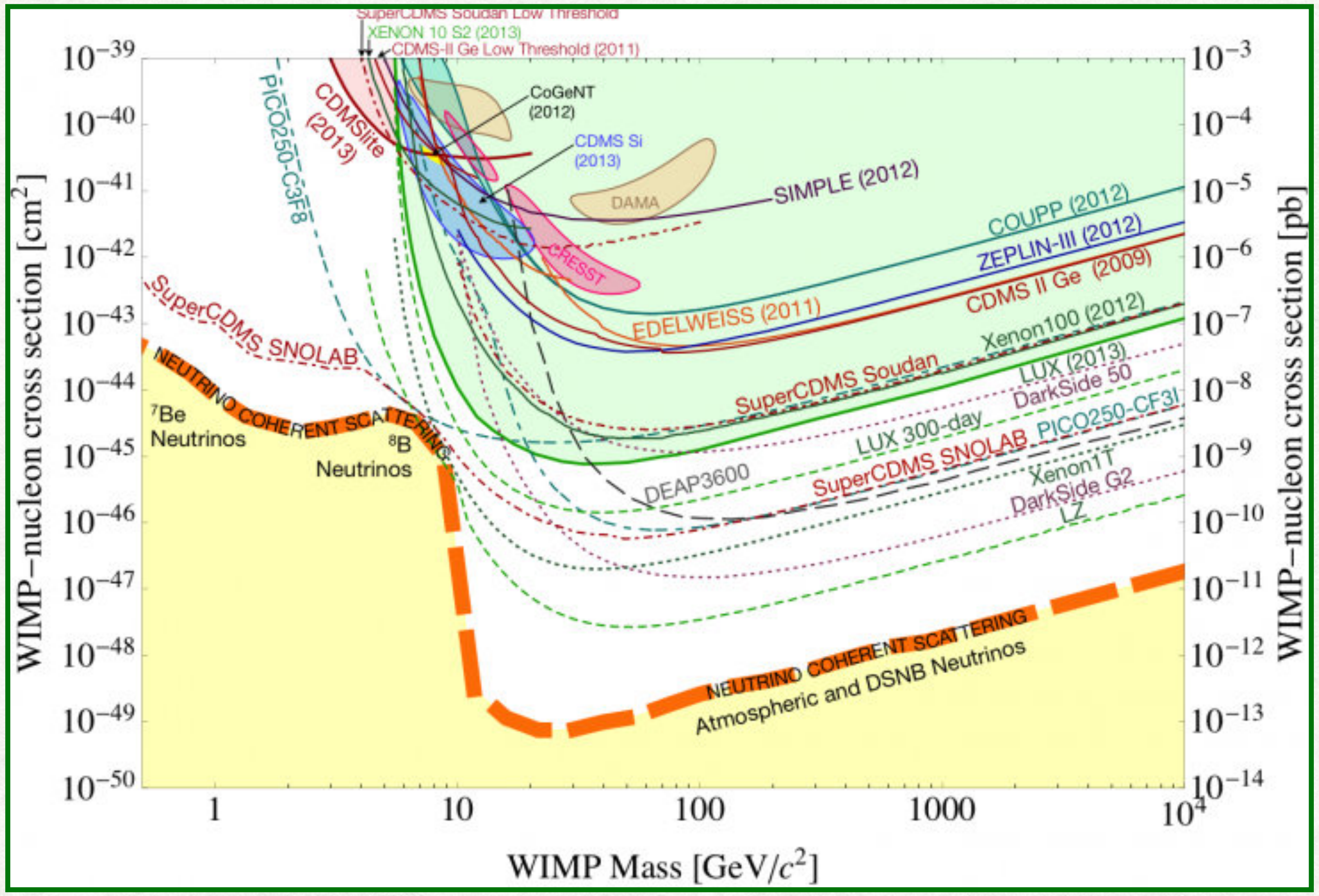


Observed anti-ν in CHORUS ~32
in NuTeV ~1400
Expected in SHIP ~ 27 000

LIGHT DARK MATTER SEARCH

- The prediction for the mass scale of Dark Matter spans from 10^{-22} to 10^{20} GeV
- WIMP Dark Matter is a popular theoretical model (“WIMP miracle”)
- Extensive experimental search for WIMP with masses 10 GeV/c^2 -1 TeV/c^2

- **Sensitivity very limited for masses below a few GeV**



- **Essential to explore sub-GeV mass range for Dark Matter**

LIGHT DARK MATTER PROSPECTS@SHiP

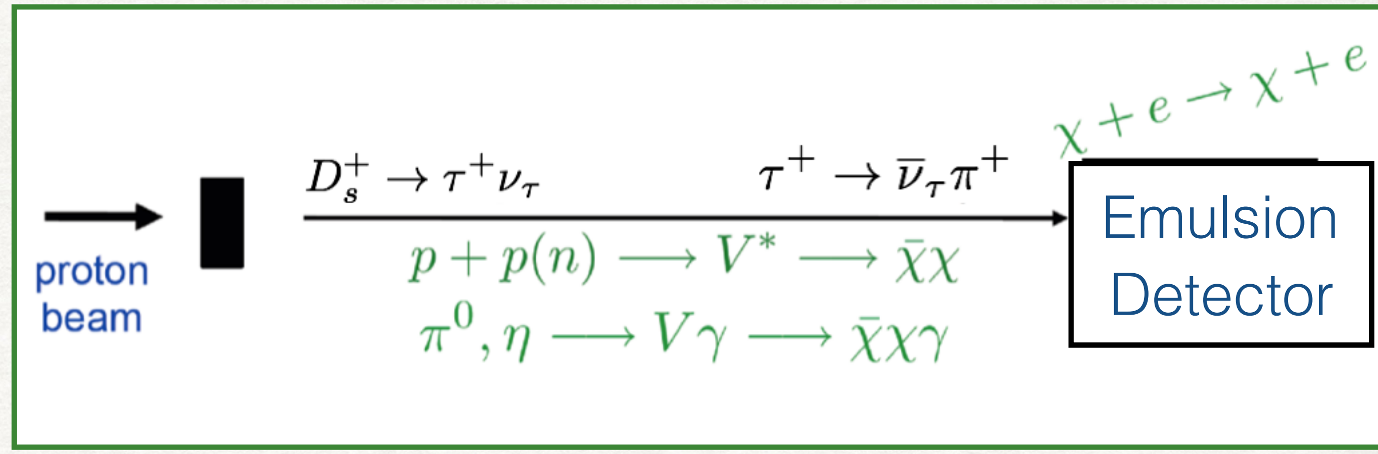
LDM PRODUCTION

- Generated in the beam-dump, e.g. via light dark photon mediators (***V***)
- Main production modes

1) direct production

2) decay in flight

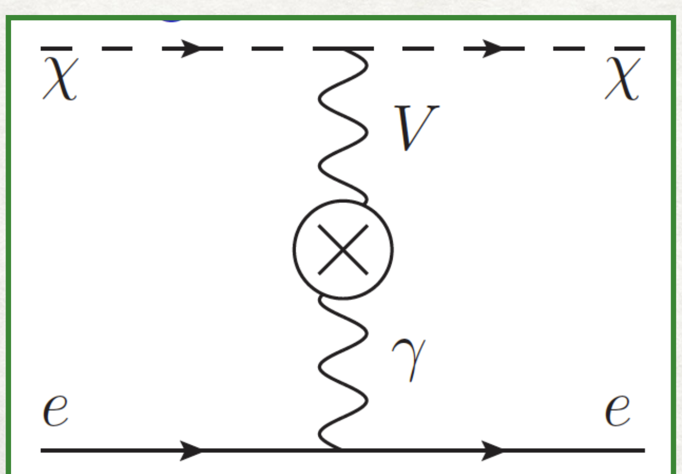
3) resonant vector meson mixing

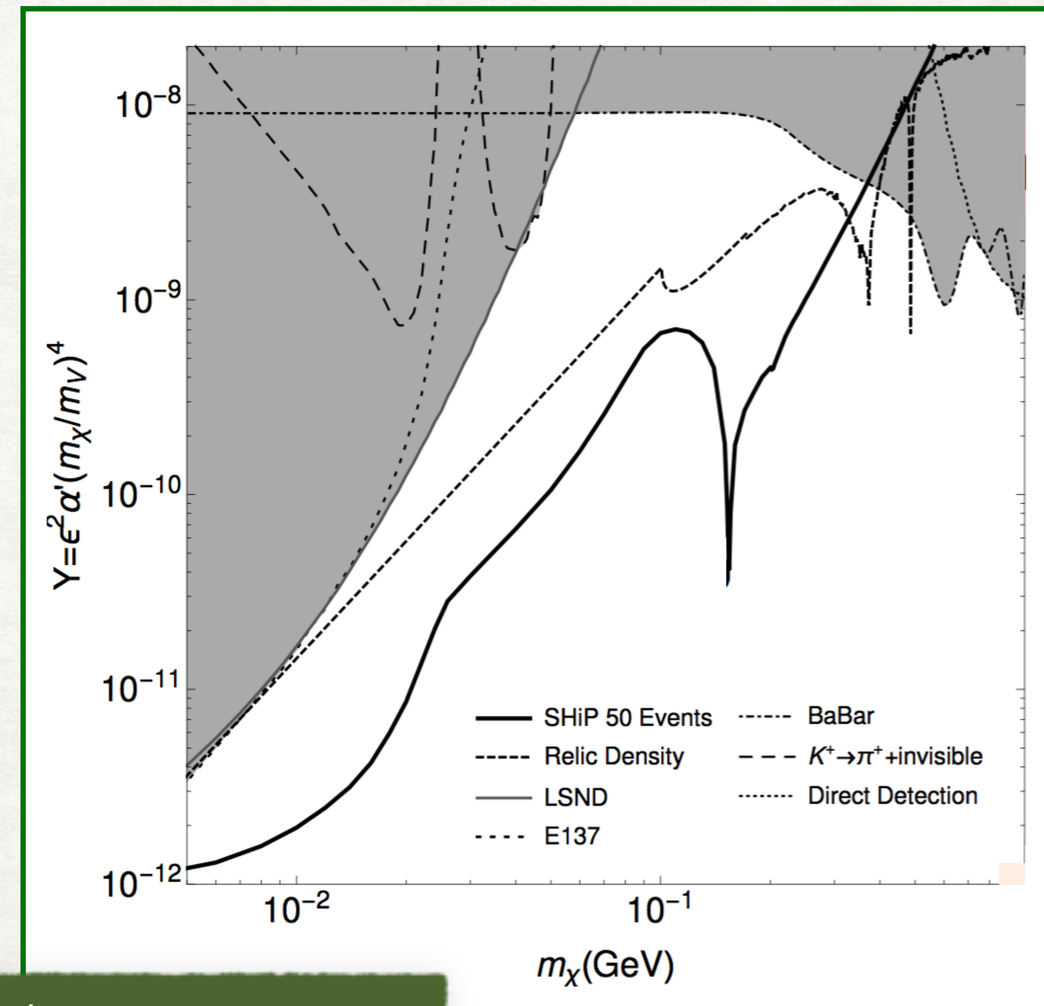


LDM DETECTION

- LDM elastic scattering on atomic electrons of the target
- High energy beam dump:

  → LDM-electron scattering is highly peaked in the forward direction

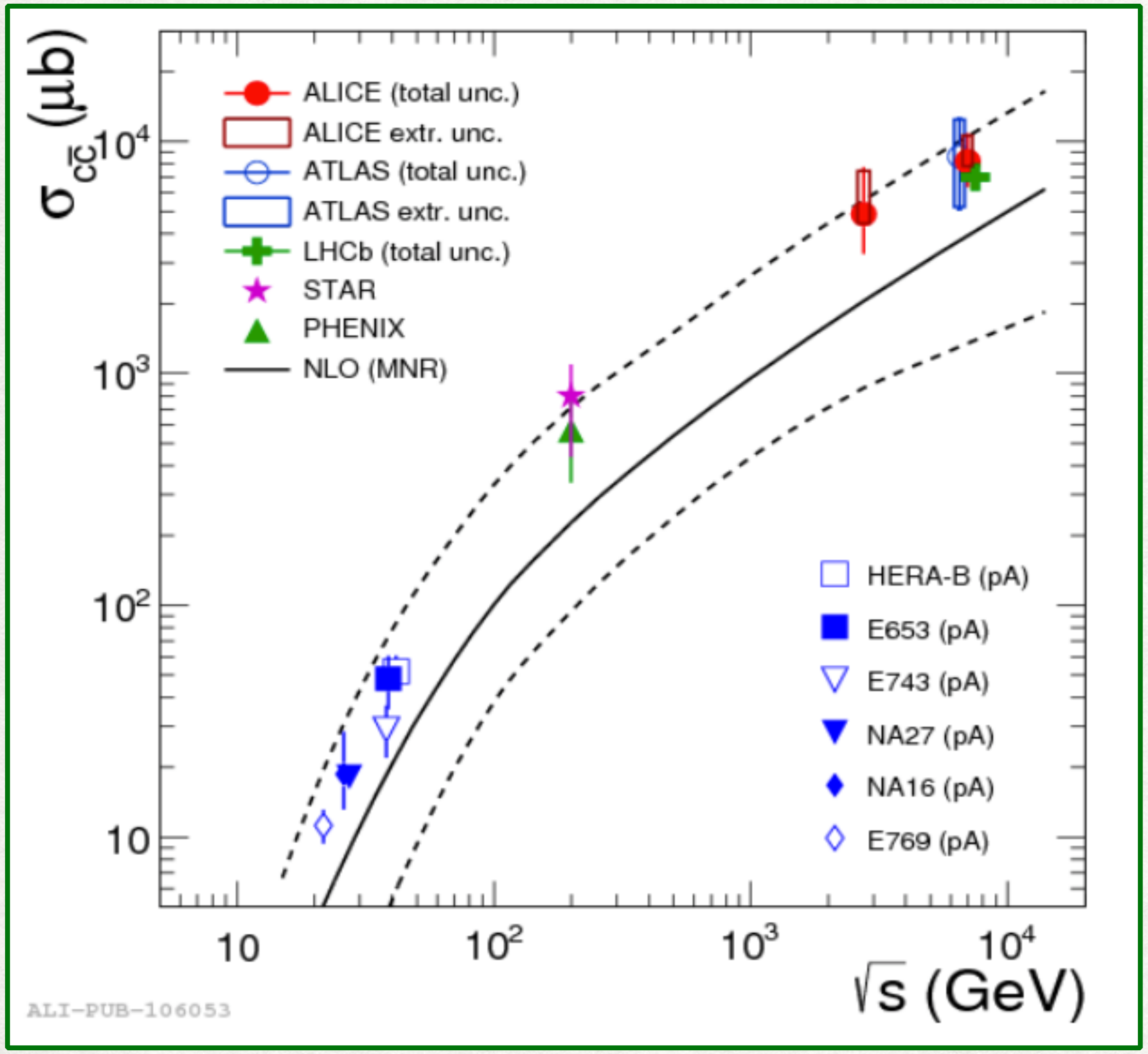




$m_V/m_X = 5$

SHiP-CHARM PROJECT: Motivation

- Charm production in **proton interactions** and in **hadron cascades** in the SHiP target important for Hidden Sector searches normalization and ν_τ cross-section measurement



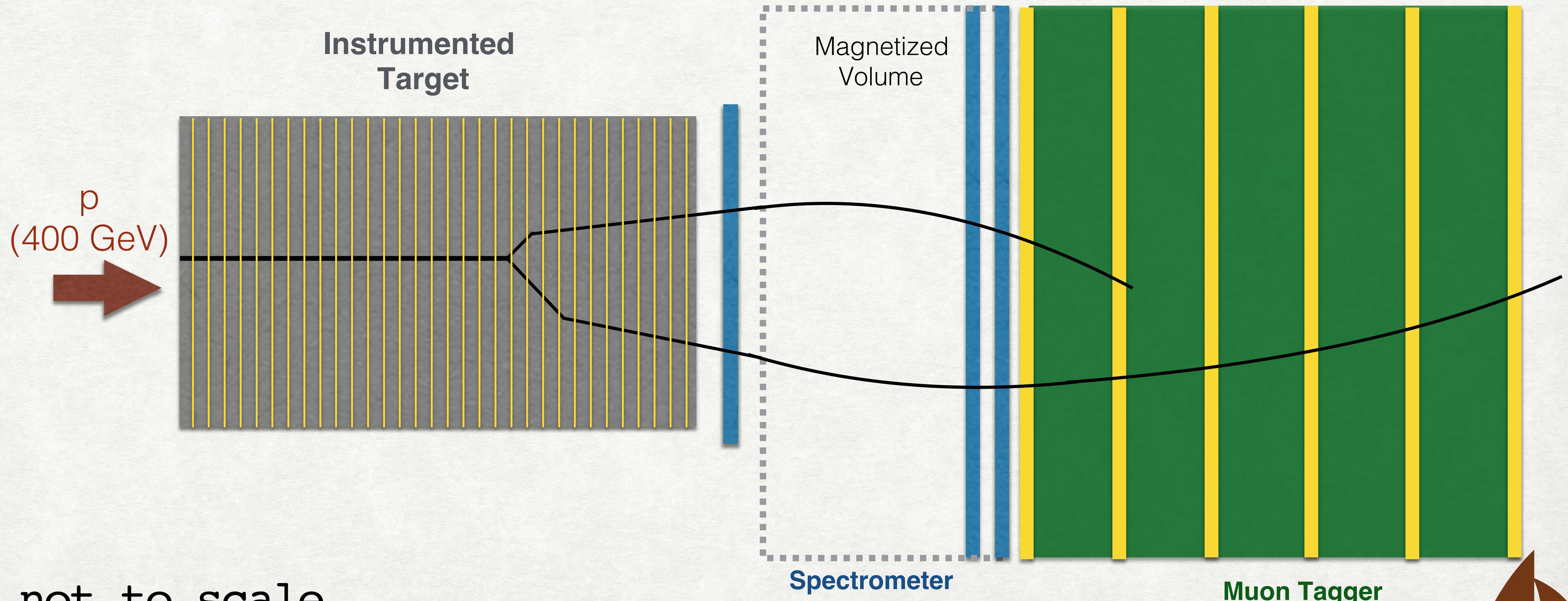
- Inclusive double-charm cross-section measured in NA27 using thin target

	exp NA27
$\sigma[\mu b]$	18.1 ± 1.7

- Missing information: charm production in **hadron cascades**
- Charm yield from cascade expected 2.3 times larger than prompt contribution

SHiP-CHARM PROJECT: Conceptual design

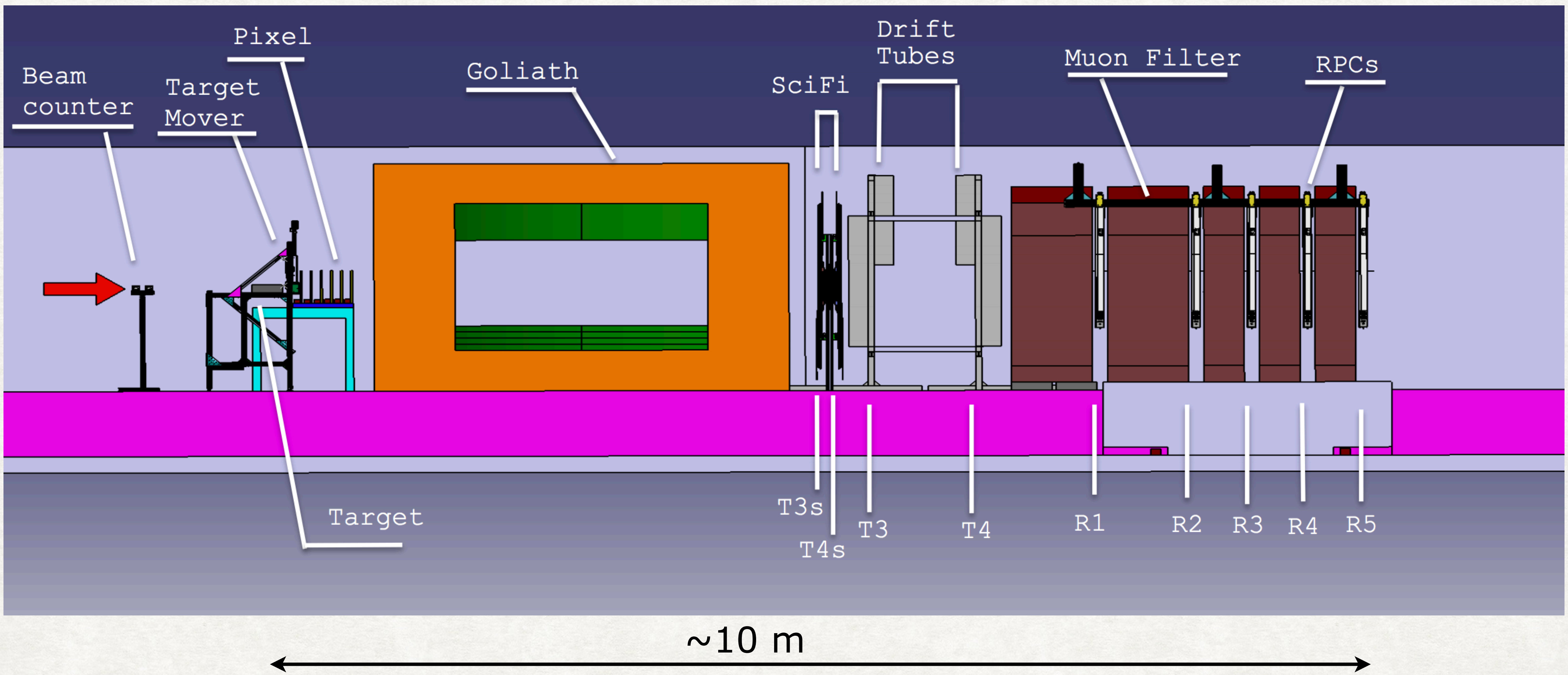
- **Double-differential** cross-section measurement ***($d^2\sigma/dEd\theta$)***
- Proton collisions in Mo/W target instrumented with **nuclear emulsions**
- **Nuclear emulsions** as tracking detector
  - identification of hadronic and leptonic charm decay modes
  - volume of sensitive layers << target volume
- Charm daughters charge and momentum by a dedicated **Spectrometer** based on silicon pixel detectors, Scintillator fibers and drift tubes
- Muon identification with a **Muon Tagger** based on RPC



not to scale

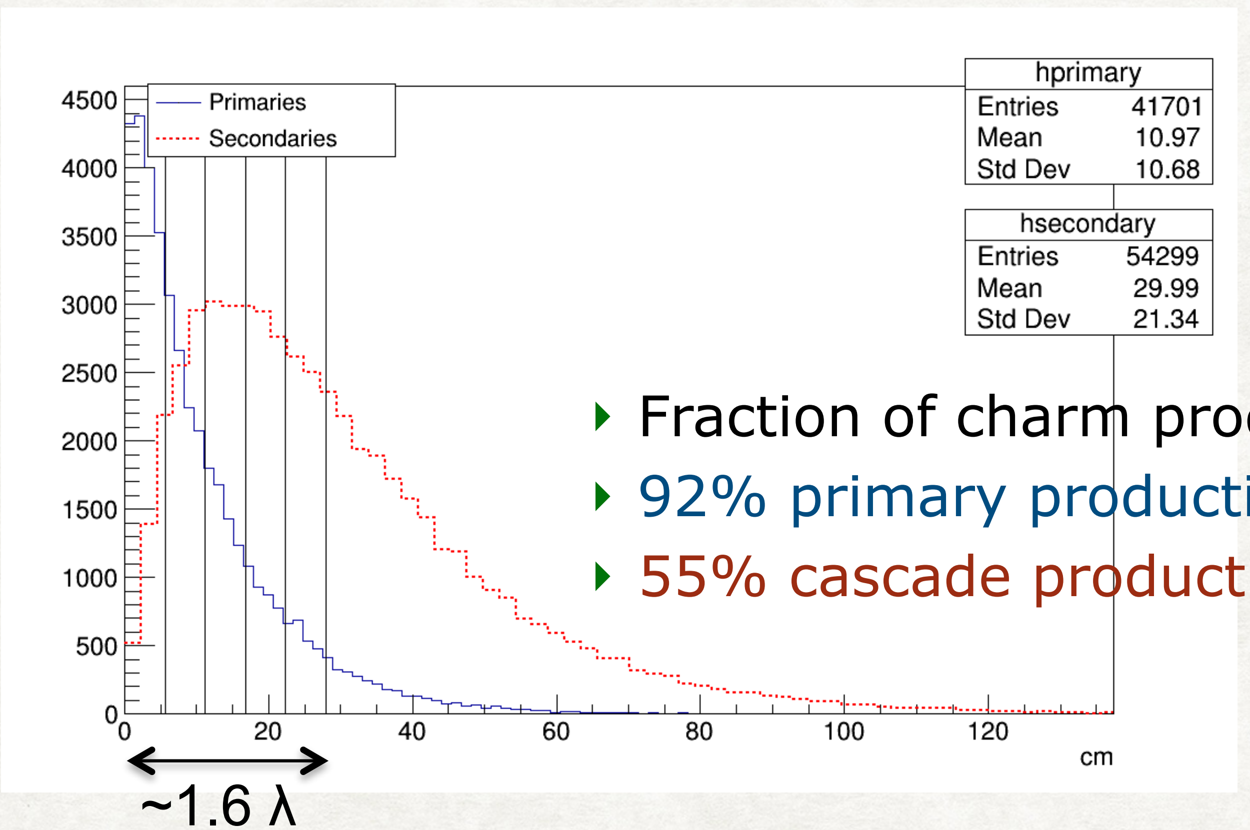
MEASUREMENT IN 2018

- **Lead target**, 12×10 cm² Pb blocks (few cm) interleaved with emulsion to identify charm topology
- **Spectrometer** to measure momentum and charge of the charm daughters
- **Muon tagger** to identify muons

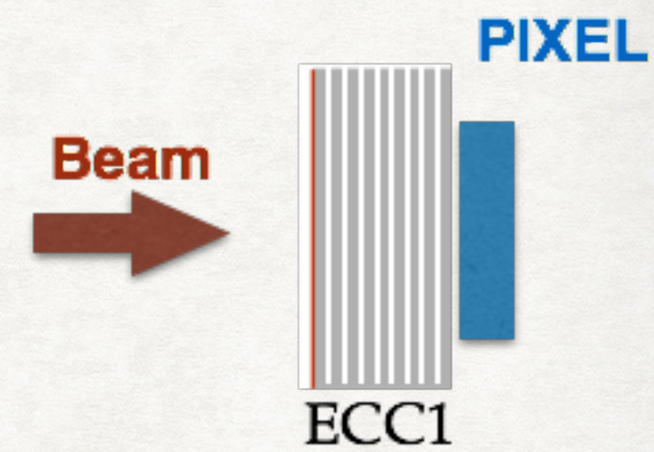


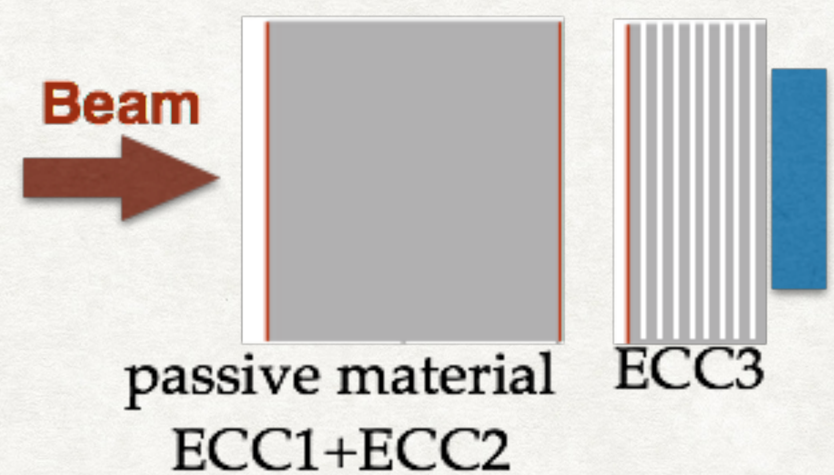
EXPOSURE CONFIGURATION

- Target material: lead
- Instrumentation of ~1.6 λ to study charm production in primary interactions and hadron cascades



- Fraction of charm produced in ~1.6 λ
- 92% primary production
- 55% cascade production

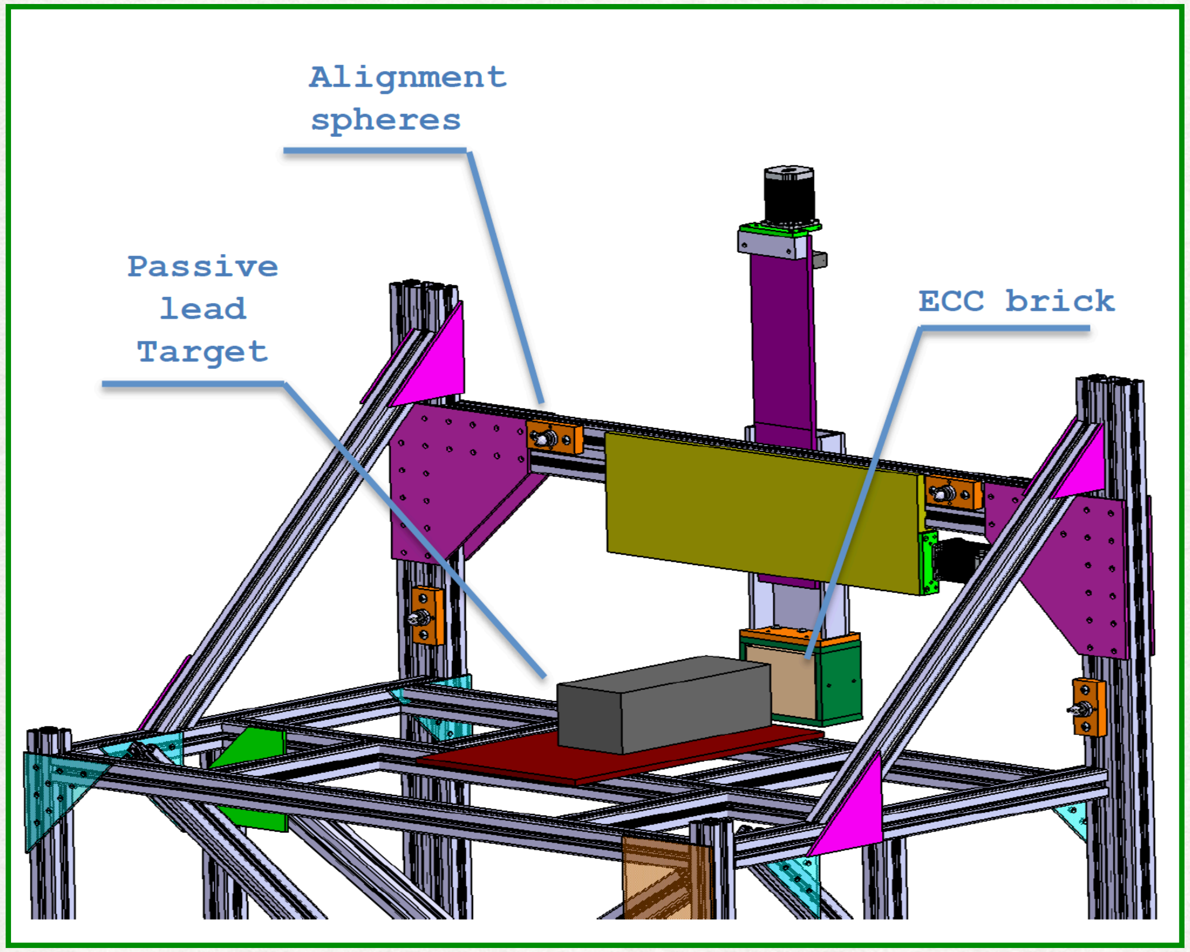




- Instrumentation of ~1.6 λ allows the study of a large fraction of charmed hadrons
- Five Emulsion Cloud Chambers (ECC)
- ECC is the most downstream target part to let charm daughters reach the spectrometer
- Target modules retained upstream of the ECC

ECC TARGET

- Target mover to have protons uniformly distributed on the emulsion films
- Design: shift along y axis during the spill
  - Shift along x axis in the inter-spill



2018 EXPOSURE PLAN

- Maximum track density in emulsion films: 10^3/ mm^2
- Emulsion surface available in July 2018: 10 m^2
- ~20 ECC bricks exposed to proton beam with maximum intensity 10^4 pot/spill
- Fully reconstructed charm-pairs: ~150

Full data taking after LS2: ~1000 fully reconstructed charm pairs

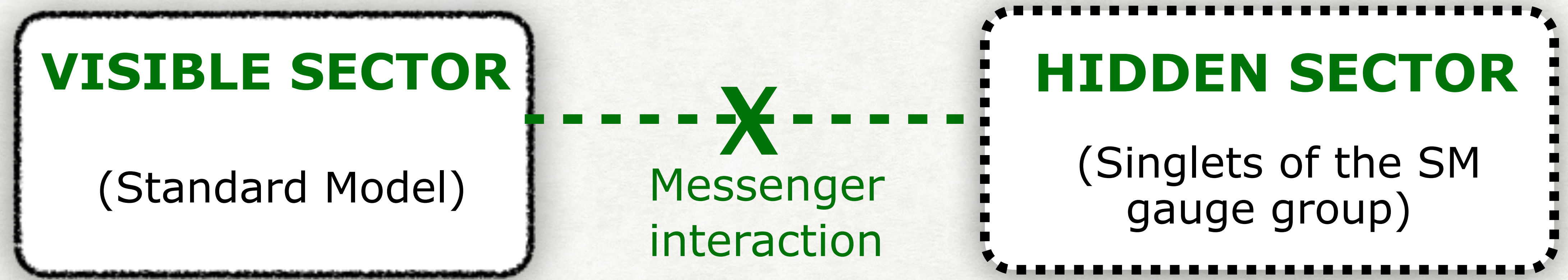
CONCLUSIONS

- **SHiP** is a fixed target experiment proposal al CERN SPS at the intensity frontier
- High energy **beam dump**: large variety of Hidden Sector portals explored
- Wide physics program with the Neutrino/Light Dark Matter Detector
- SHiP-charm measurement in **July 2018**

BACKUP SLIDES

HIDDEN SECTOR AND NEUTRINOS

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



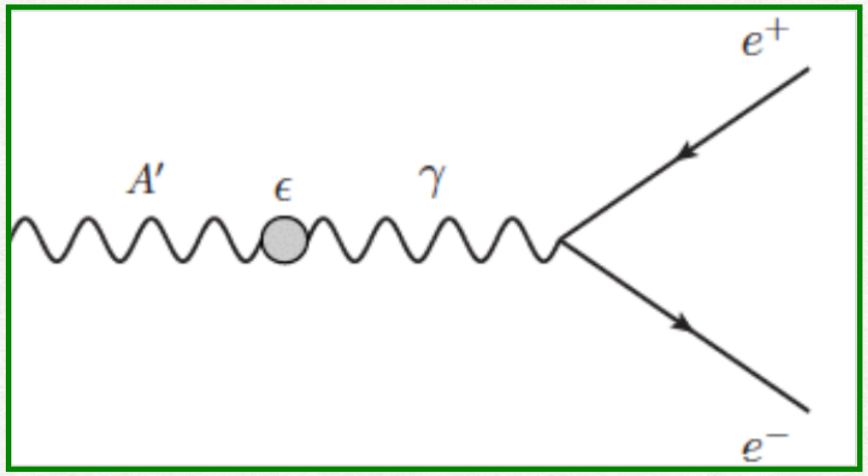
- **SHiP**: new fixed target facility at the intensity frontier to explore Hidden Sector
- Neutrino physics
- Light Dark Matter search

> - Several **portals** to the HS: scalar portal, neutrino portal, vector portal, SUSY…
> - All of these can be probed at the **intensity frontier** with **SHiP**!

STANDARD MODEL PORTALS

VECTOR PORTAL

- Kinetic mixing with the **dark photon**
- Possible dark matter candidate



Production of the dark photon at CERN SPS

- proton bremsstrahlung
- decay of pseudo-scalar mesons
- limits on mean life from BBN $\tau_{\gamma} < 0.1$s

Dark photons decay

- e^+e^-, $\mu^+\mu^-$, $q\bar{q}$
- light dark matter $\chi\bar{\chi}$

HIGGS PORTAL

- **Scalar singlet**
- Mixing with the SM Higgs

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\rho & -\sin\rho \\ \sin\rho & \cos\rho \end{pmatrix} \begin{pmatrix} \phi'_0 \\ S' \end{pmatrix}$$

Main production mechanism

- Rare decay of B mediated by light scalar φ

Decay channels

- e^+e^-, $\mu^+\mu^-$

STANDARD MODEL PORTALS

AXION PORTAL

- **Pseudo-scalar** particles (pNGB, Axions, ALPs)
- Produced by symmetry breaking at high mass scale *F*
- Interaction proportional to *1/F*
- Mixing with SM particles proportional to m_X/F

Production mechanism

- Mixing with π^0

Decay channels

- e^+e^-, $\mu^+\mu^-$, $q\bar{q}$, $\gamma\gamma$

NEUTRINO PORTAL

- Mixing with **right-handed** neutrino *(details in the following slides)*

SUSY PORTAL

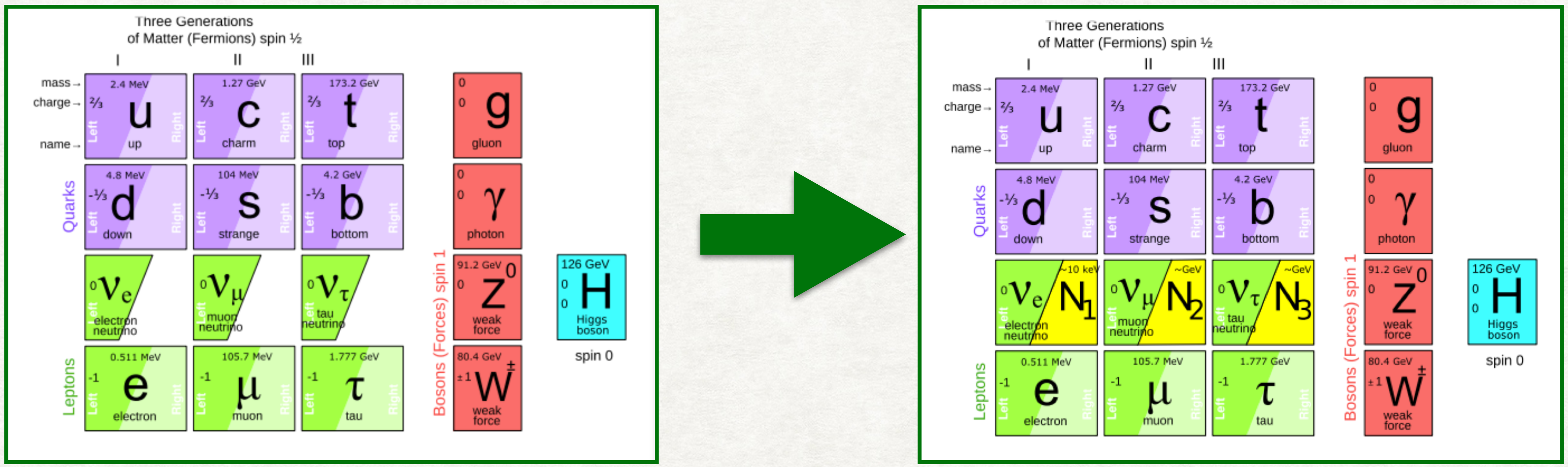
… and possibly higher dimensional operators portals and **Super-Symmetric** portals

(light neutralino, light sgoldstino, …)

NEUTRINO PORTAL

- **νMSM**: **ν-**Minimal Standard Model

3 additional Heavy Neutral Leptons: right-handed Majorana neutrinos



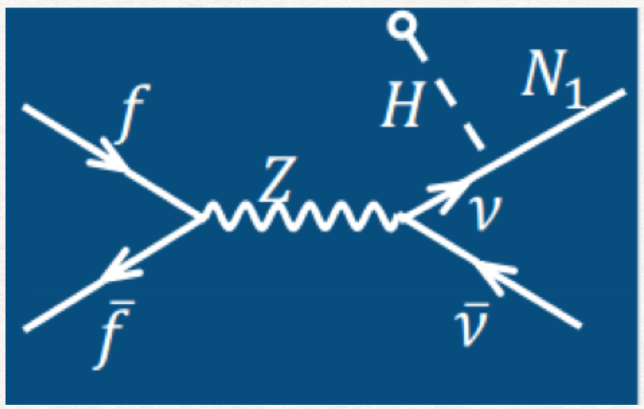
- **N₁** : Dark Matter candidate
- **N₂,₃** : give mass to neutrinos via see-saw mechanism, produce baryon asymmetry

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

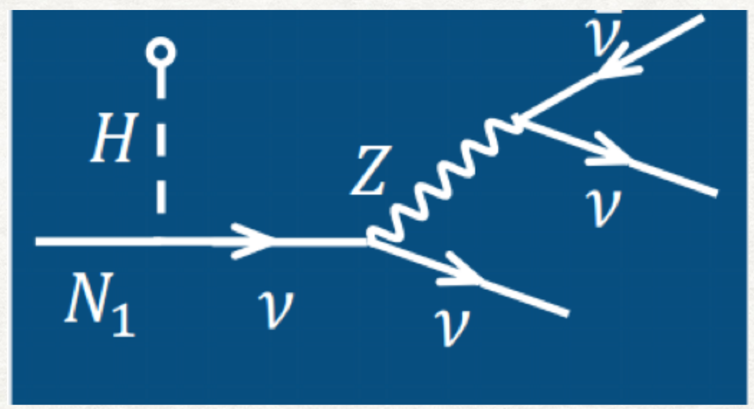
N_1: DARK MATTER CANDIDATE

- Weak coupling with other leptons
- Mass(N_1) ~ 10 KeV
- Enough stable to be a dark matter candidate

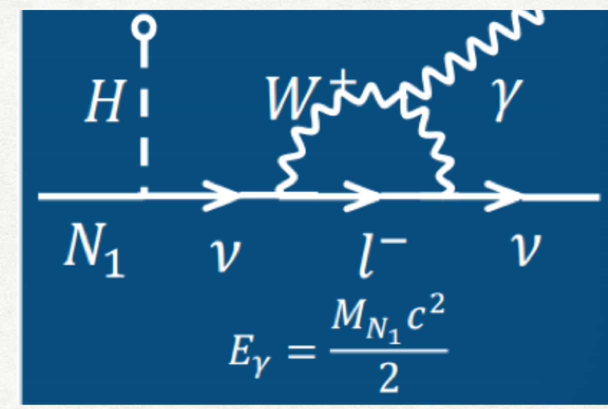
mixing ν-N

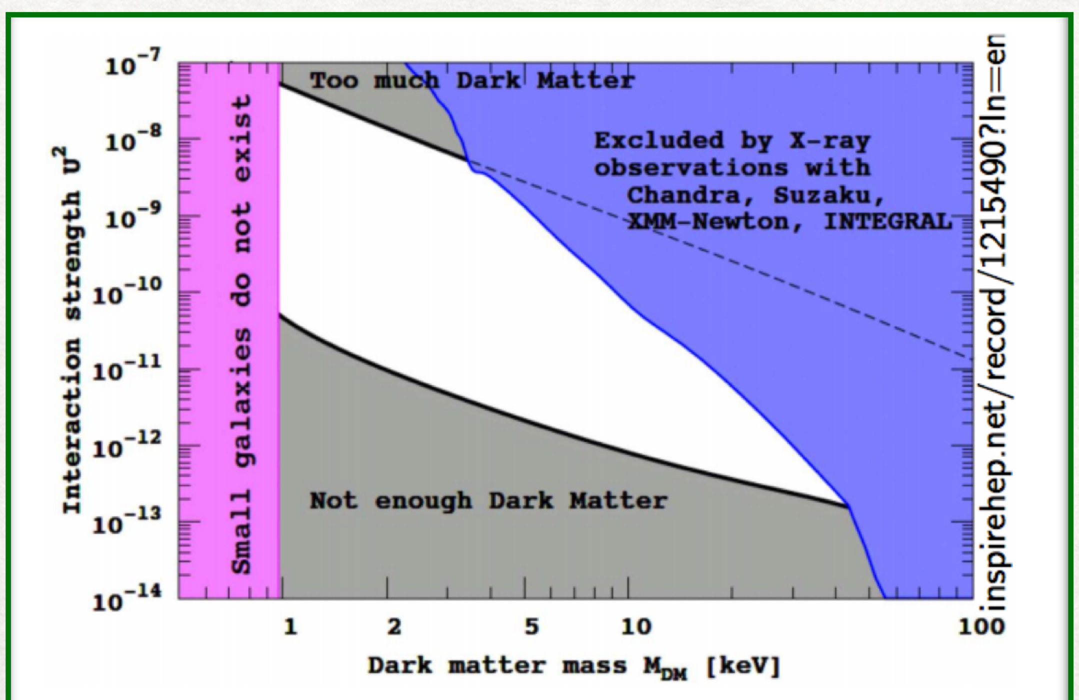


dominant process



subdominant radiative decay





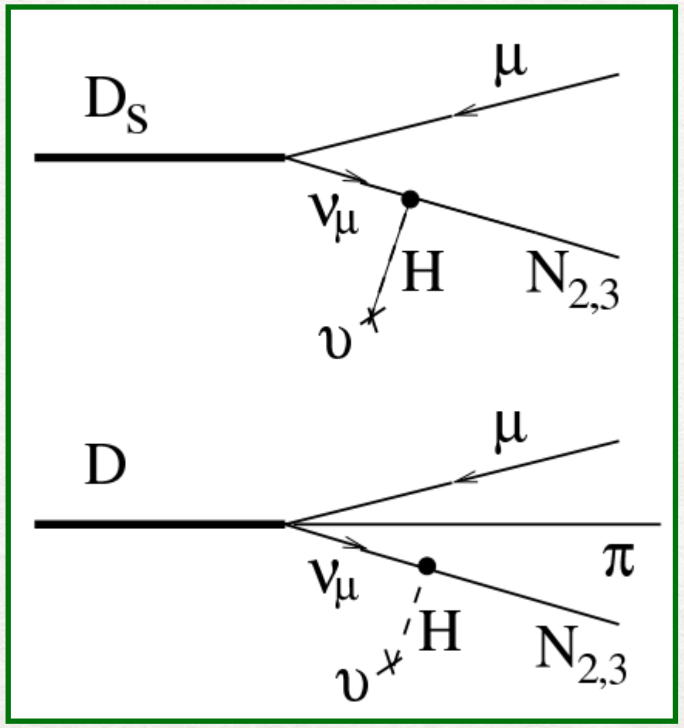
- **GALACTIC HINTS**
- *Astr. Phys. J. 789 (2014) 13, Phys. Rev. Lett. 113 (2014) 251301*
- Not identified line in the X-ray spectrum of Andromeda and Perseus galaxies ($E\gamma$=3.5 keV)

$N_{2,3}$: PRODUCTION AND DECAY

- Mass(N_2) ~ Mass(N_3) ~ few GeV
- Weak mixing with active neutrino
  - → very long lifetimes wrt SM particles >10 μs
  - → flight length ~km

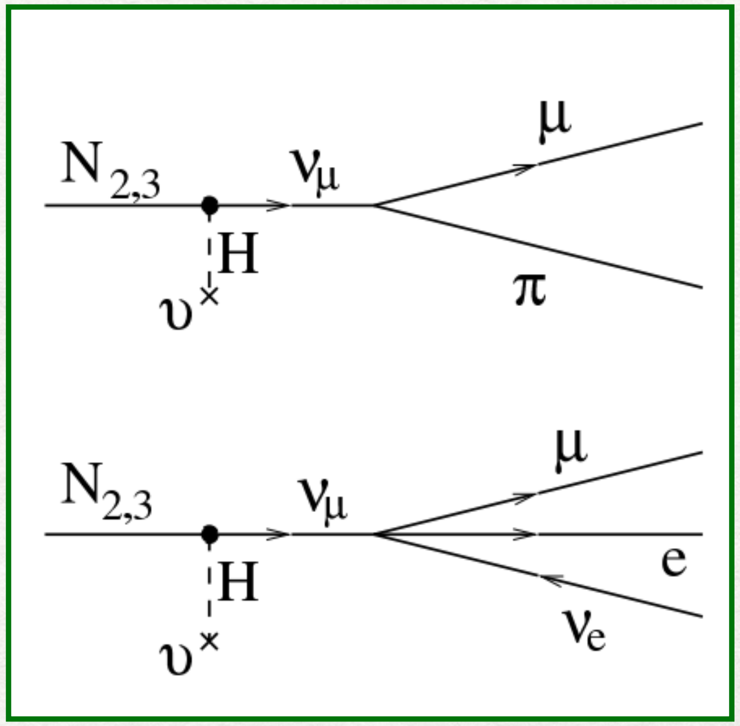
PRODUCTION

- Mixing with active neutrino
- Semi-leptonic decay



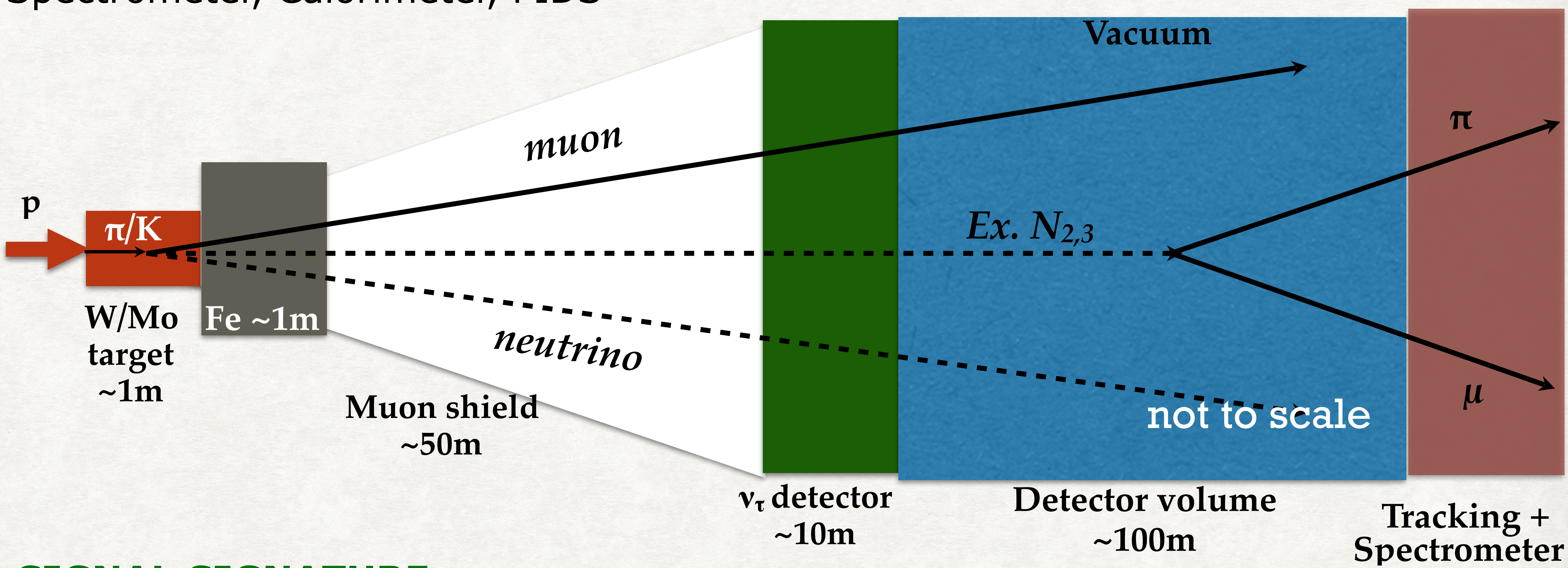
DECAY

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



REQUIREMENTS

- High intensity beam dump experiment ⇒ K, D, B mesons
- Long-lived, weakly interacting particles require:
  - large decay volume
  - shielded from SM particles
- Spectrometer, Calorimeter, PIDS



SIGNAL SIGNATURE

- charged tracks forming an isolated vertex inside the fiducial volume acceptance
- Candidate momentum pointing back to the target
- “silent” VETO detectors