



THE SHiP PROJECT

SEARCH FOR HIDDEN PARTICLES

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On behalf of SHiP Collaboration

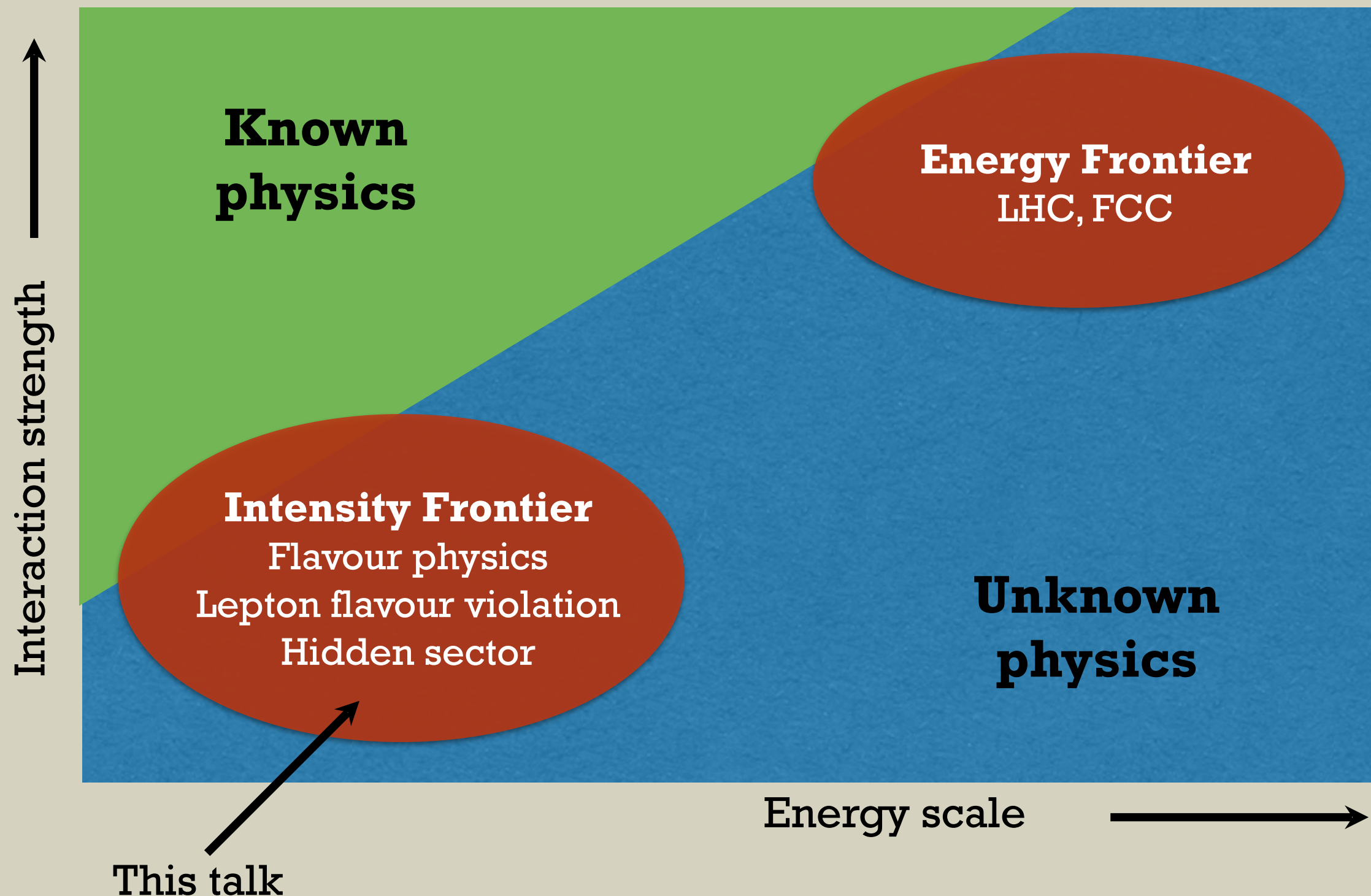
INTRODUCTION

- ▶ **Standard Model** provides consistent description of Nature's constituents and their interactions
- ▶ **No significant deviation** from SM observed so far
- ▶ 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

nevertheless ...

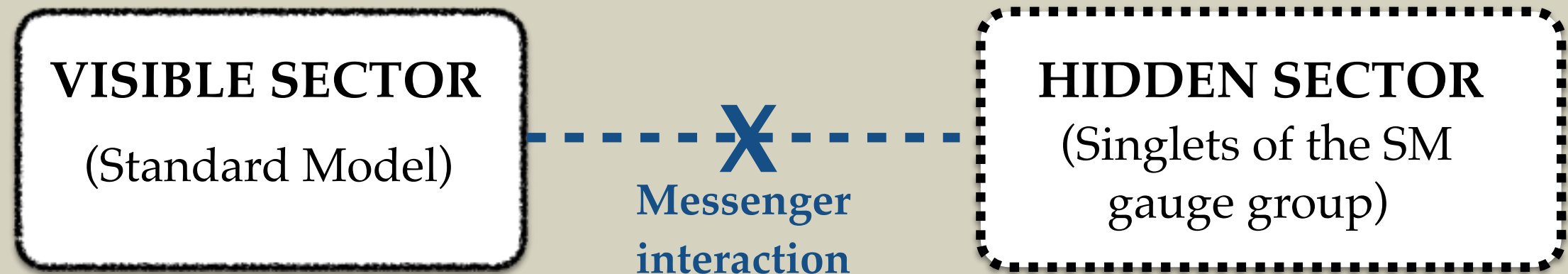
- ▶ SM is not a complete theory: explanation of experimental observations “**Beyond the Standard Model**” still missing
 - ▶ Neutrino masses and oscillations
 - ▶ Baryon asymmetry of the Universe (BAU)
 - ▶ Dark Matter

HIGH INTENSITY FRONTIER



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

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

PROPOSAL(S)

PHYSICS

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

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85 theorists
200 pages

TECHNICAL

CERN-SPSC-2015-016/SPSC-P_350
arXiv:1504.04956 (hep-ph)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)



234 authors
44 institutions
13 countries

Technical Proposal

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

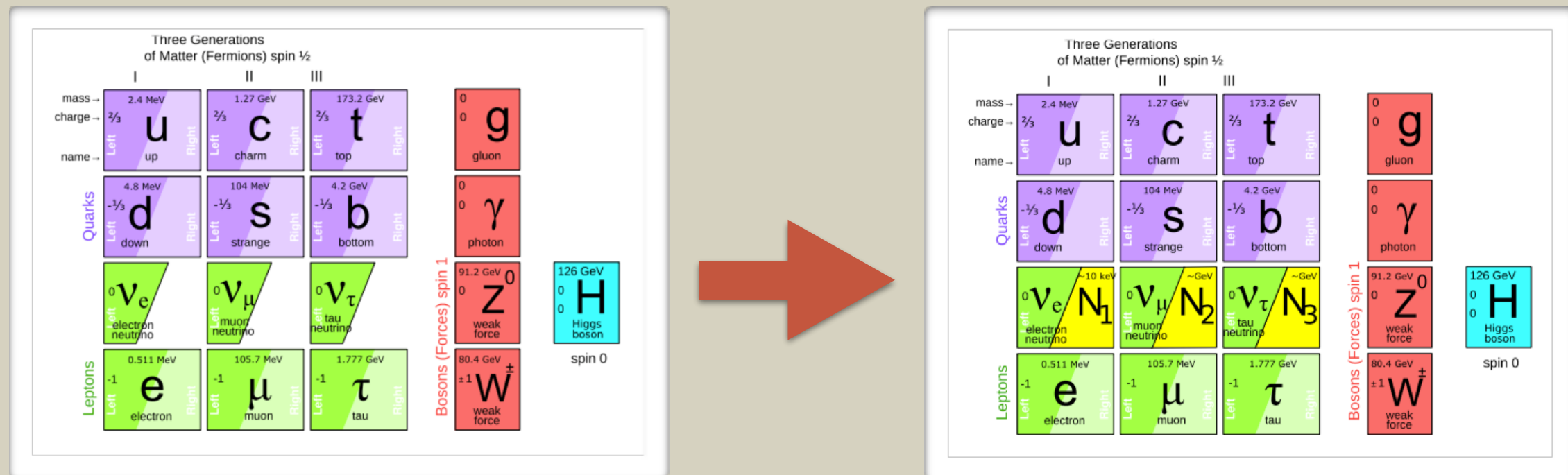
The SHiP Collaboration¹

- ▶ April 2015 **Proposals** submitted to **SPSC**
- ▶ January 2016 Positive recommendation by SPSC
- ▶ March 2016 **Physics Beyond Colliders**: working group set-up at CERN
SHiP preparatory phase within the working group

Comprehensive Design Report expected for **European HEP strategy 2019**

NEUTRINO PORTAL

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



- **N_1** : Dark Matter candidate
- **$N_{2,3}$** : give mass to neutrinos via see-saw mechanism, produce baryon asymmetry

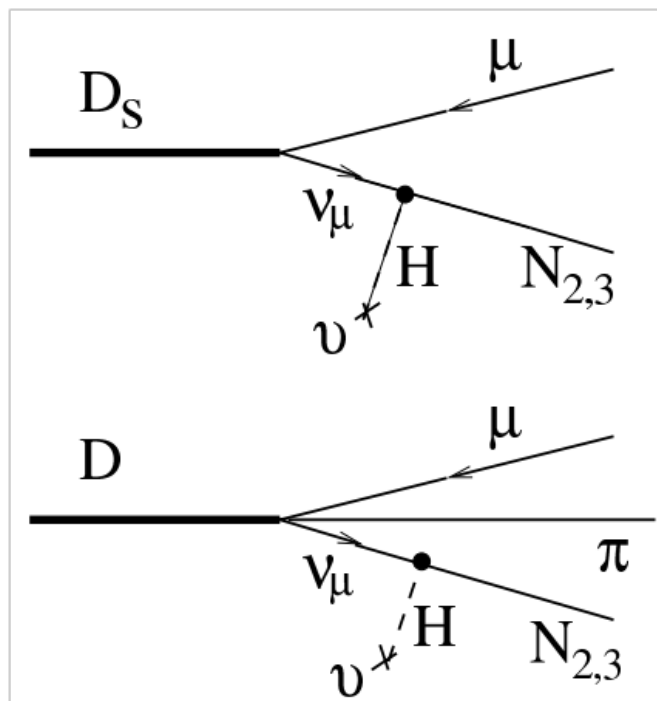
T.Asaka, M.Shaposhnikov PL B620 (2005) 17
M.Shaposhnikov Nucl. Phys. B763 (2007) 49

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

- ▶ $\text{Mass}(N_2) \sim \text{Mass}(N_3) \sim \text{few GeV}$
- ▶ Weak mixing with active neutrino
 - very long lifetimes wrt SM particles $> 10 \mu\text{s}$
 - flight length $\sim \text{km}$

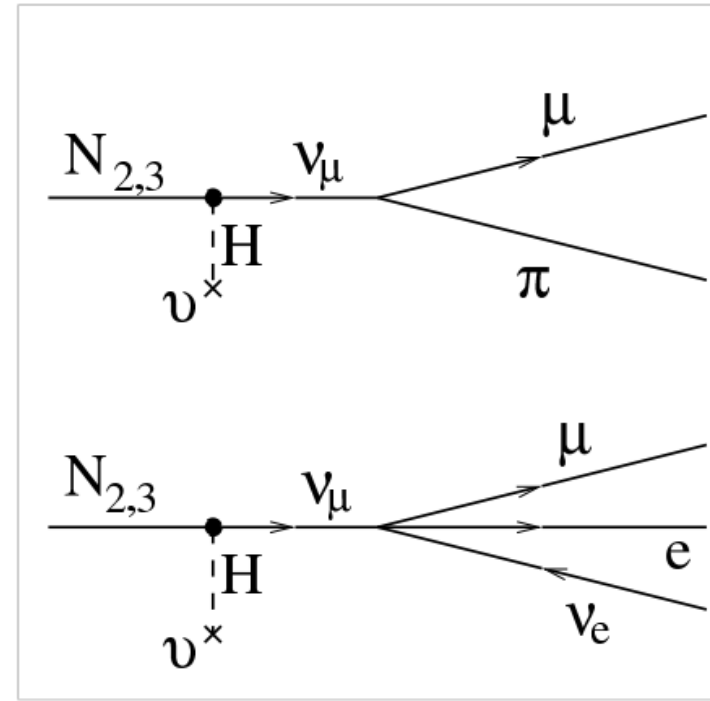
PRODUCTION

- ▶ Mixing with active neutrino
- ▶ Semi-leptonic decay



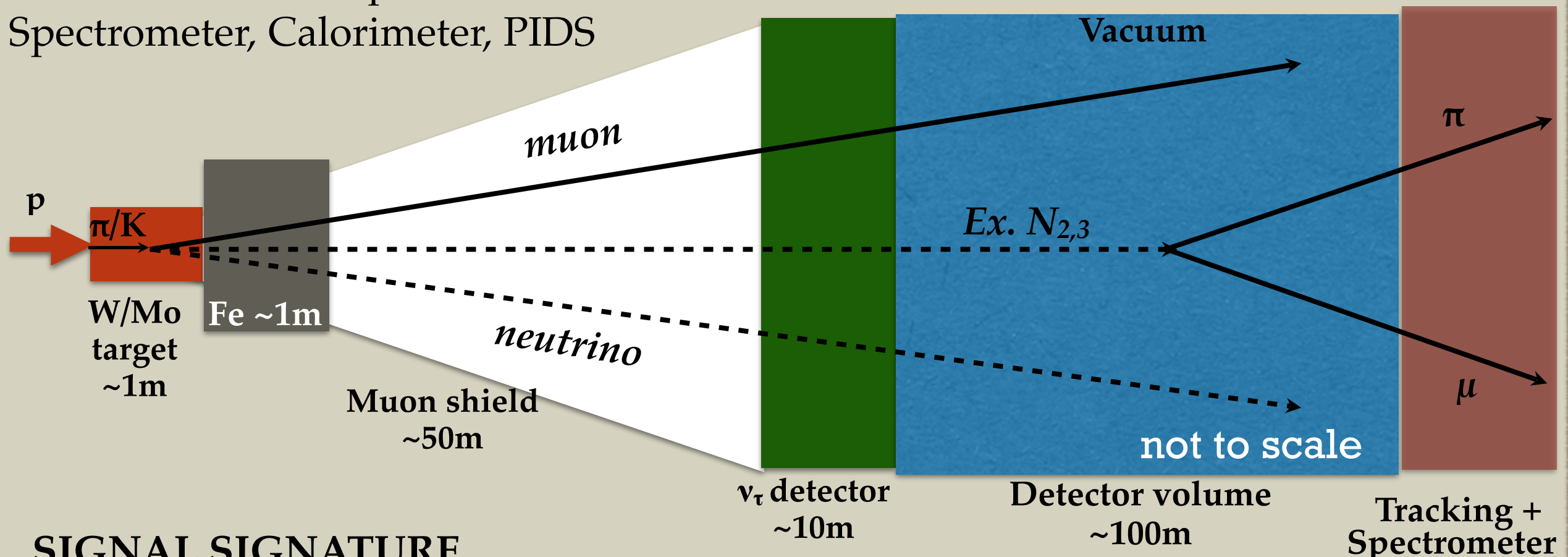
DECAY

- ▶ $\text{Br}(N \rightarrow \mu / e \pi) \sim 0.1 - 50 \%$
- ▶ $\text{Br}(N \rightarrow \mu / e \rho) \sim 0.5 - 20\%$
- ▶ $\text{Br}(N \rightarrow \nu \mu e) \sim 1 - 10\%$



REQUIREMENTS

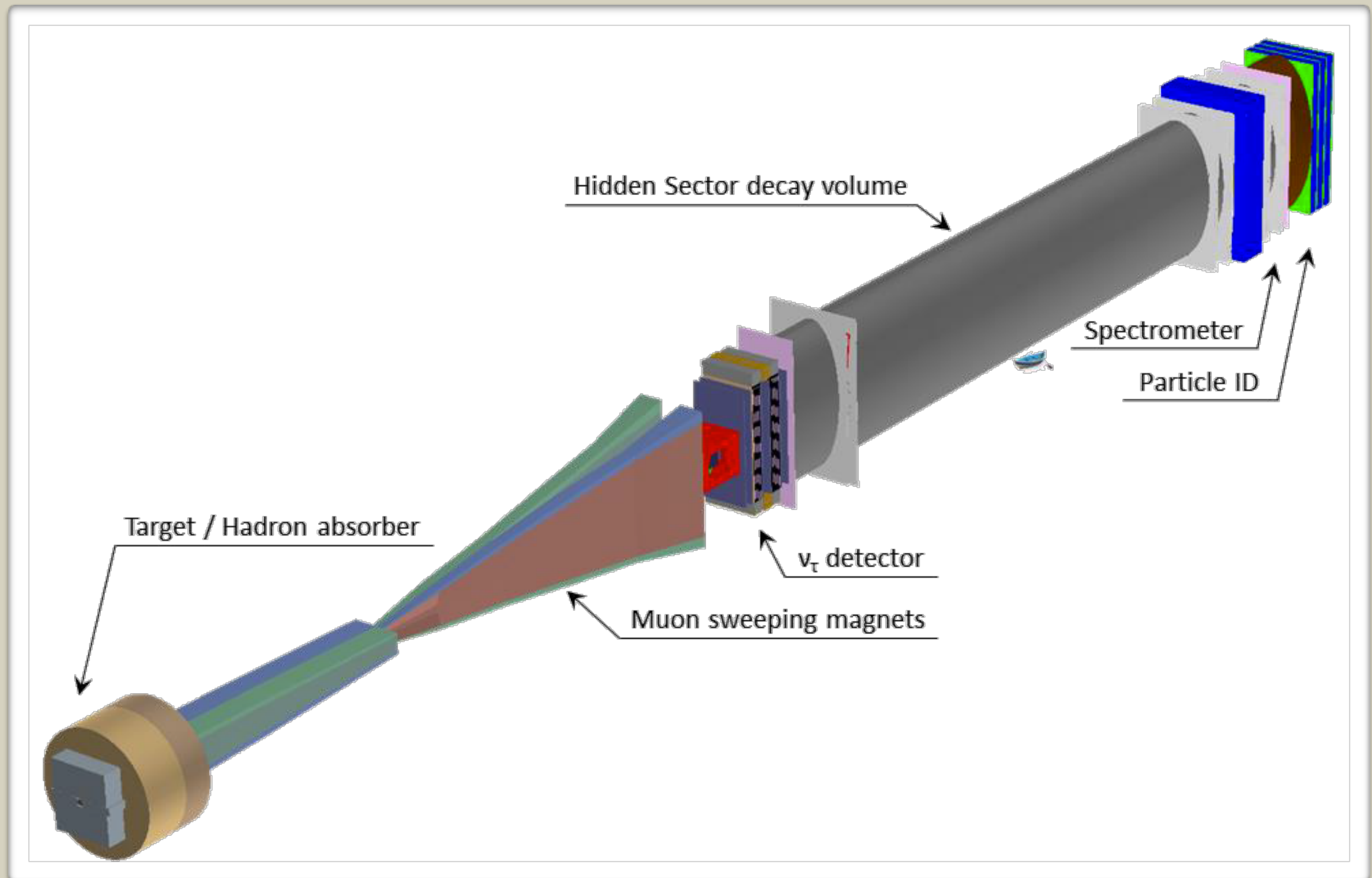
- ▶ High intensity beam dump experiment \Rightarrow K, D, B mesons
- ▶ Long-lived, weakly interacting particles require:
 - large decay volume
 - shielded from SM particles
- ▶ Spectrometer, Calorimeter, PIDS



SIGNAL SIGNATURE

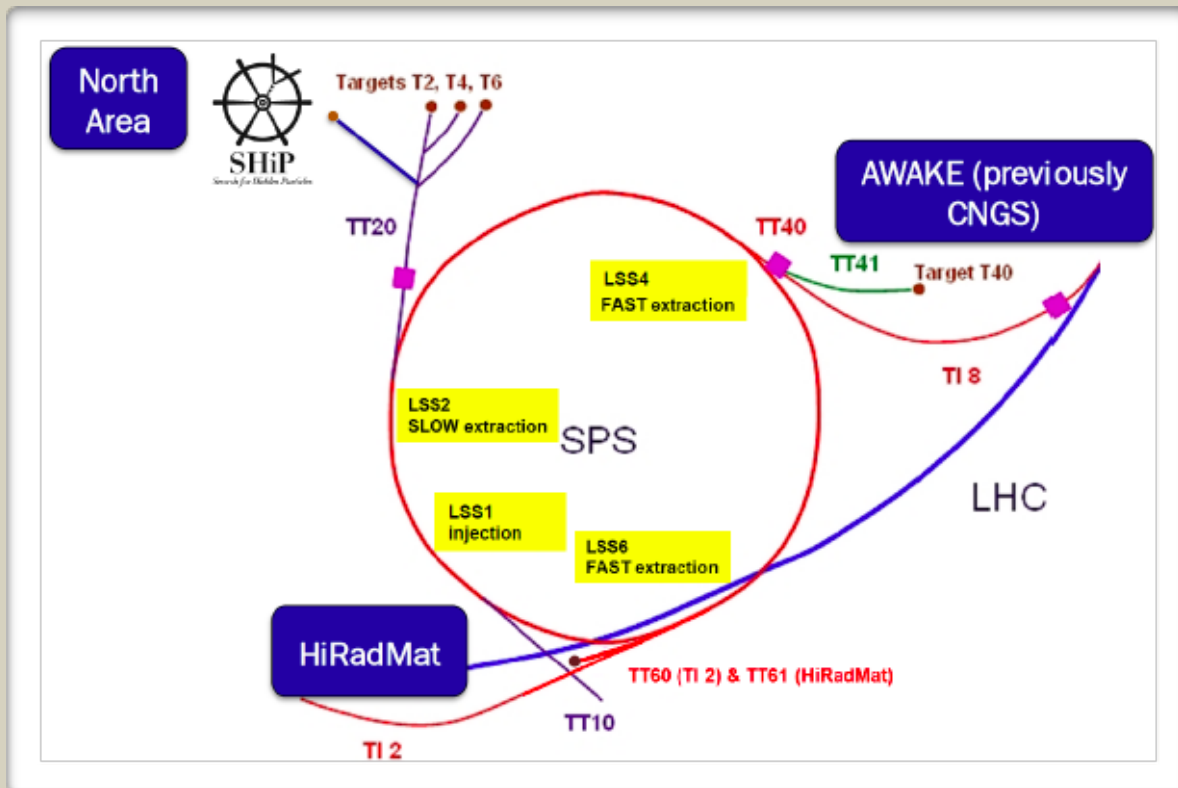
- ▶ charged tracks forming an isolated vertex inside the fiducial volume acceptance
- ▶ Candidate momentum pointing back to the target
- ▶ "silent" VETO detectors

DETECTOR LAYOUT



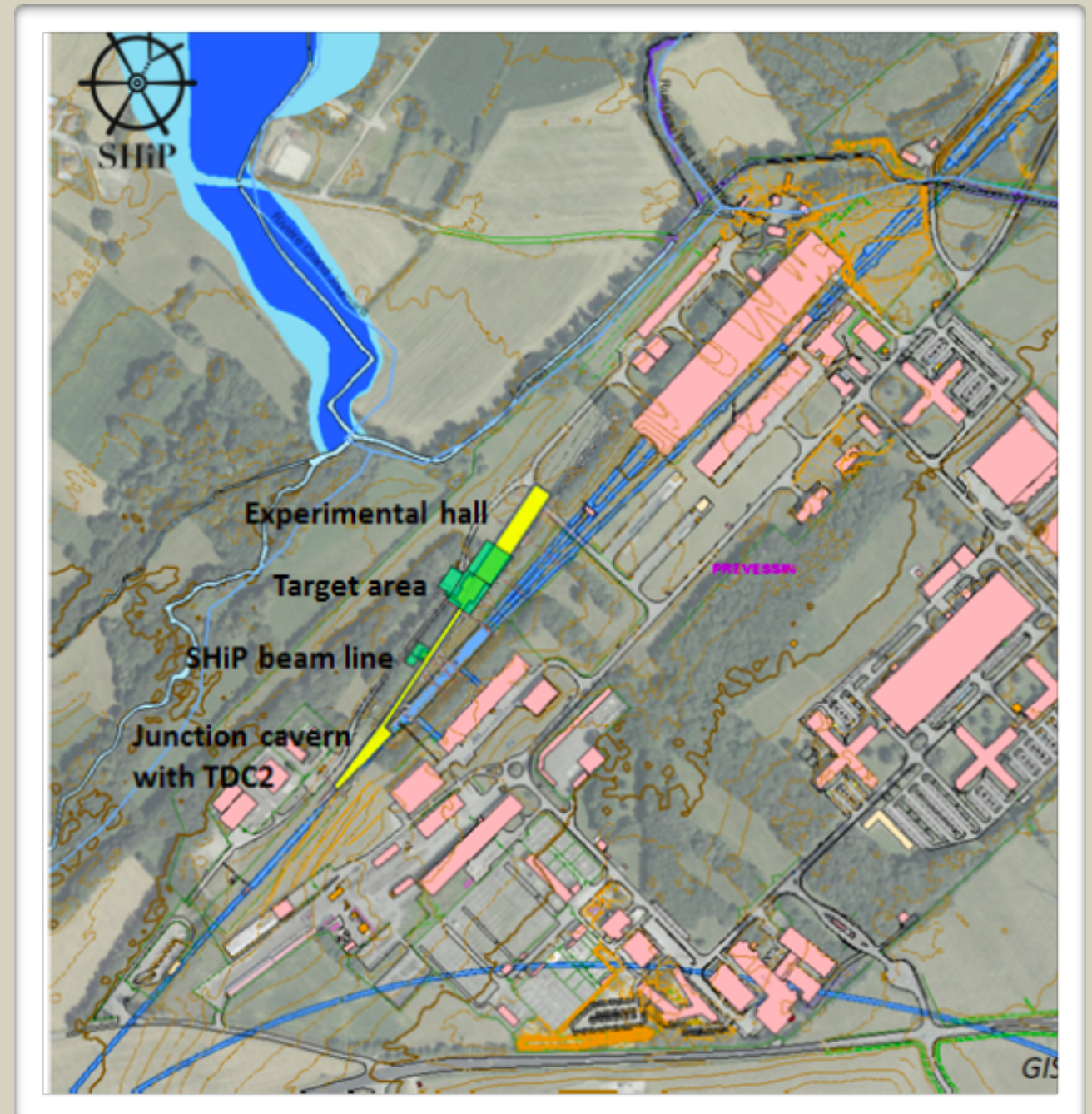
THE FIXED-TARGET FACILITY AT SPS

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



Location: Preveessin North Area site

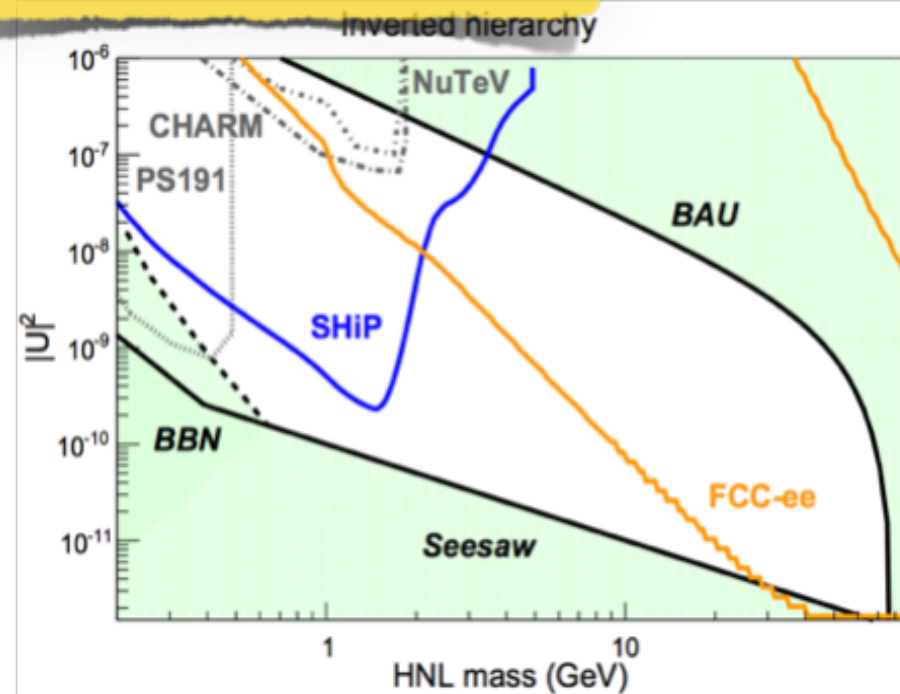
Sharing of the TT20 transfer line and slow extraction mode with the fixed target programs



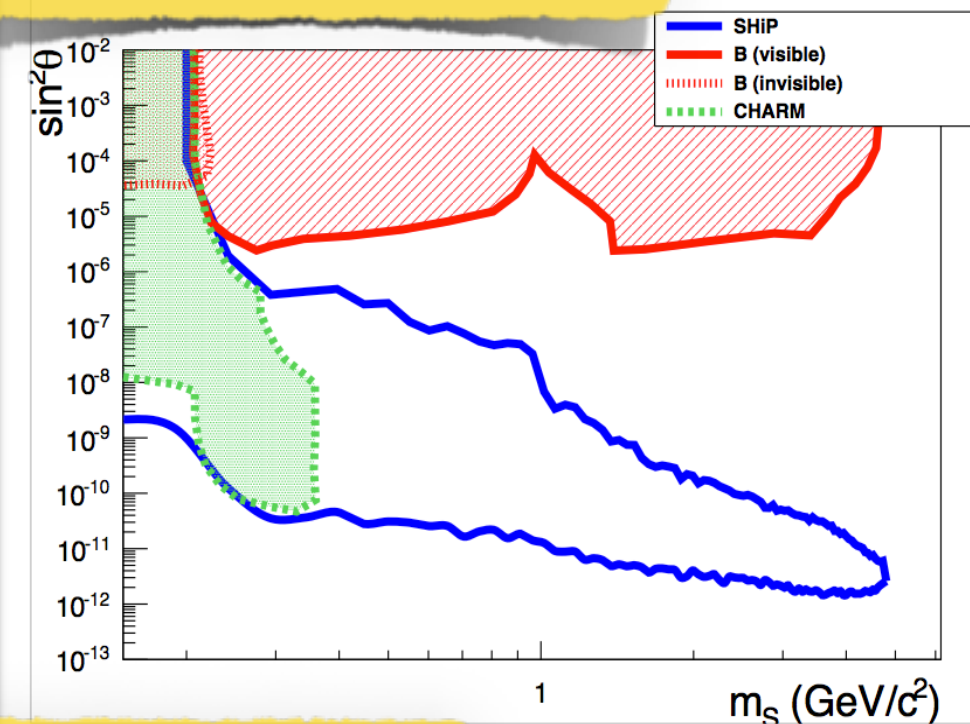
SENSITIVITIES

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

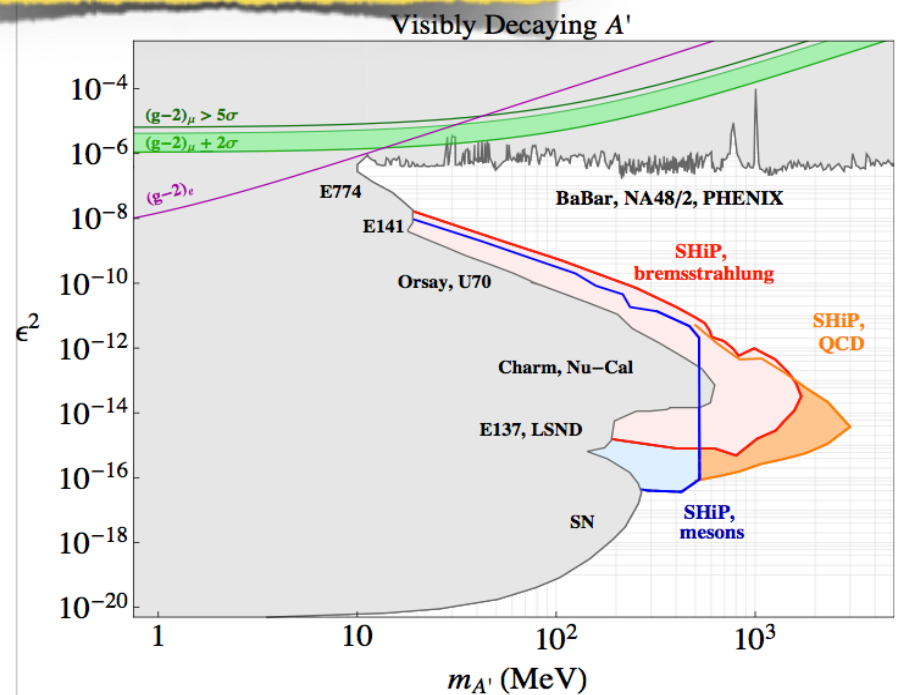
NEUTRINO PORTAL



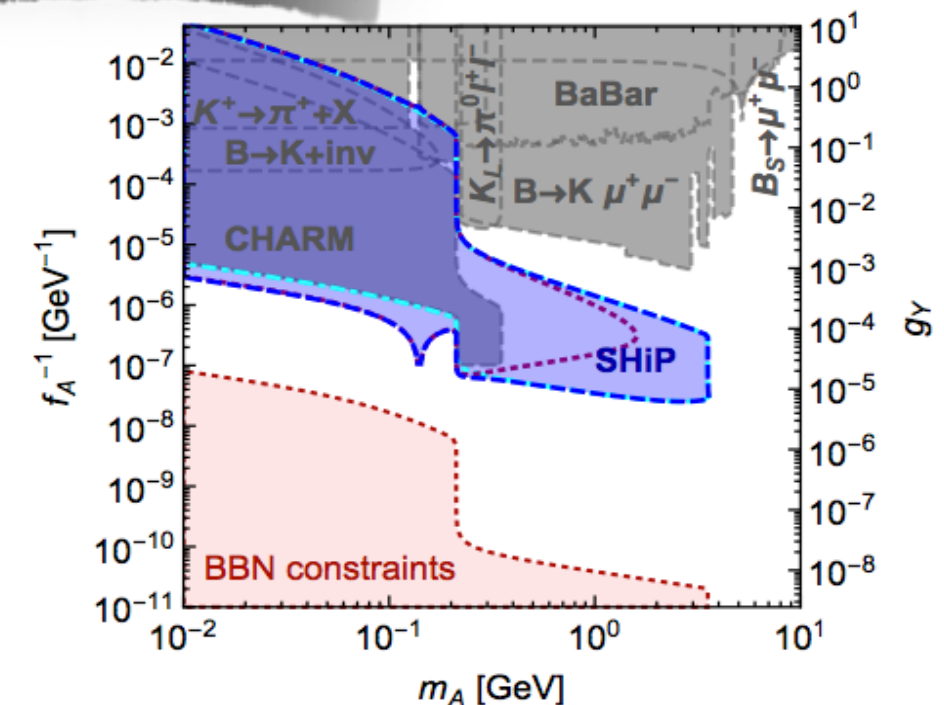
SCALAR PORTAL



VECTOR PORTAL

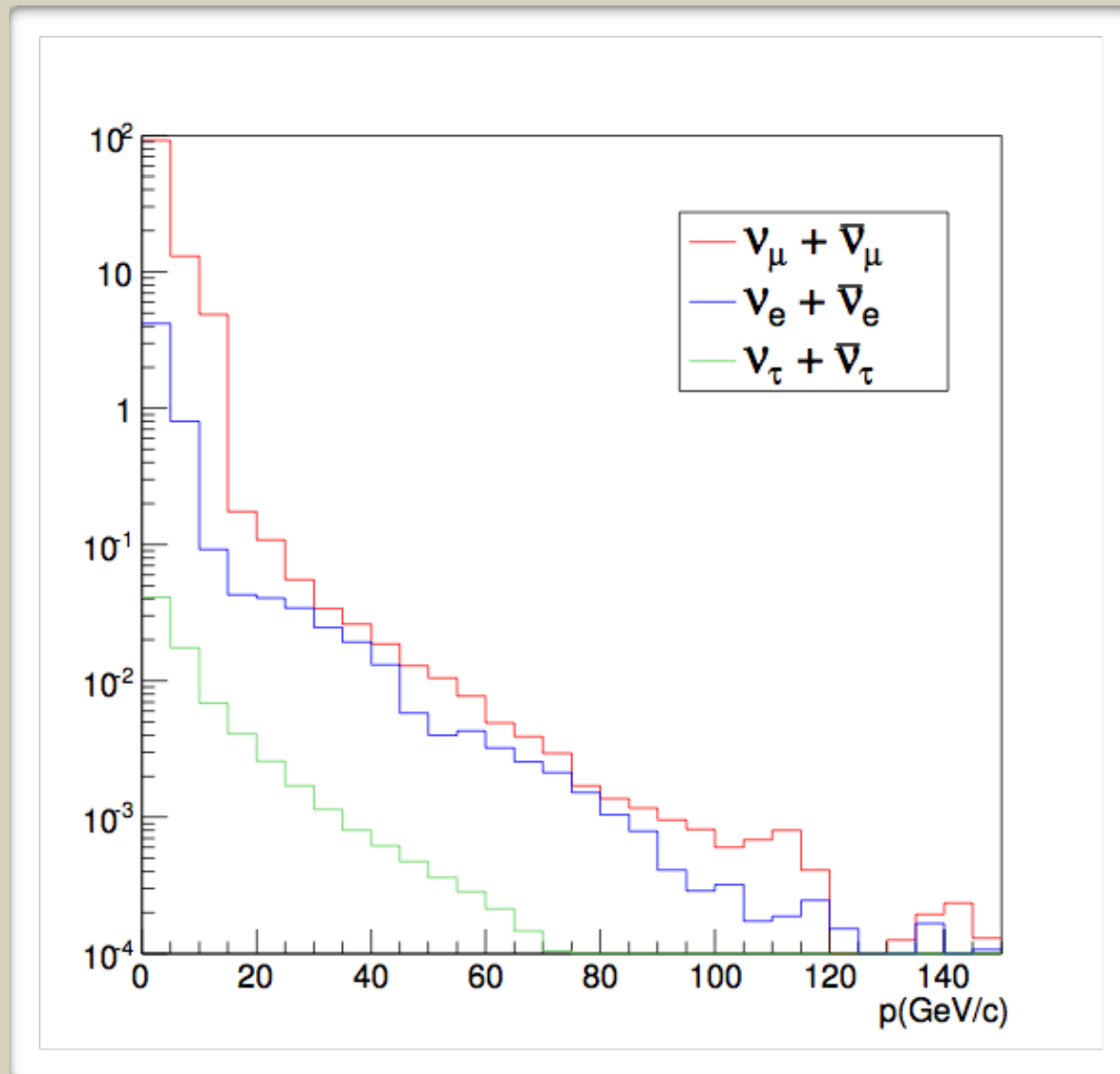


AXION PORTAL



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

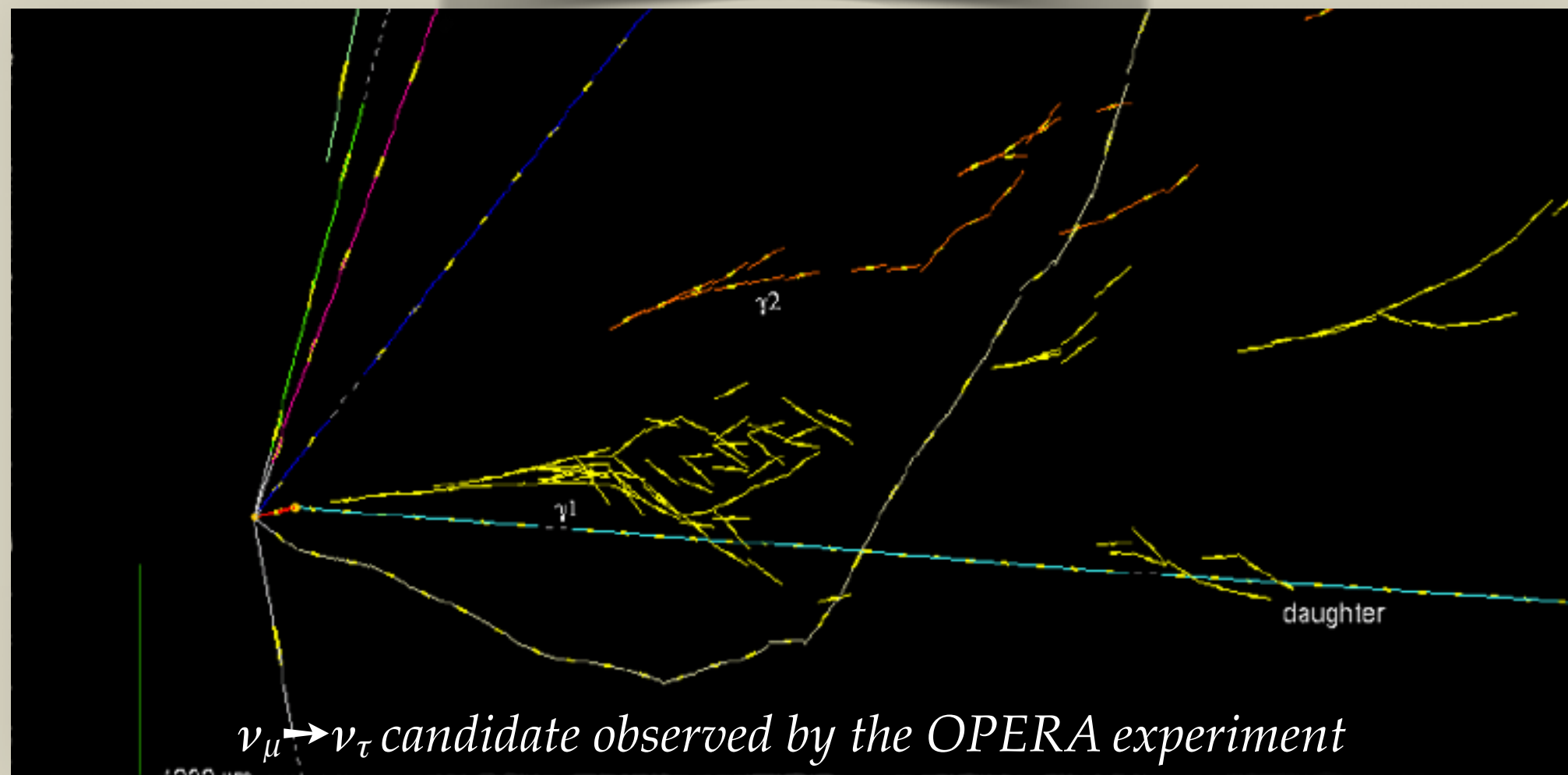
TAU NEUTRINO PHYSICS

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

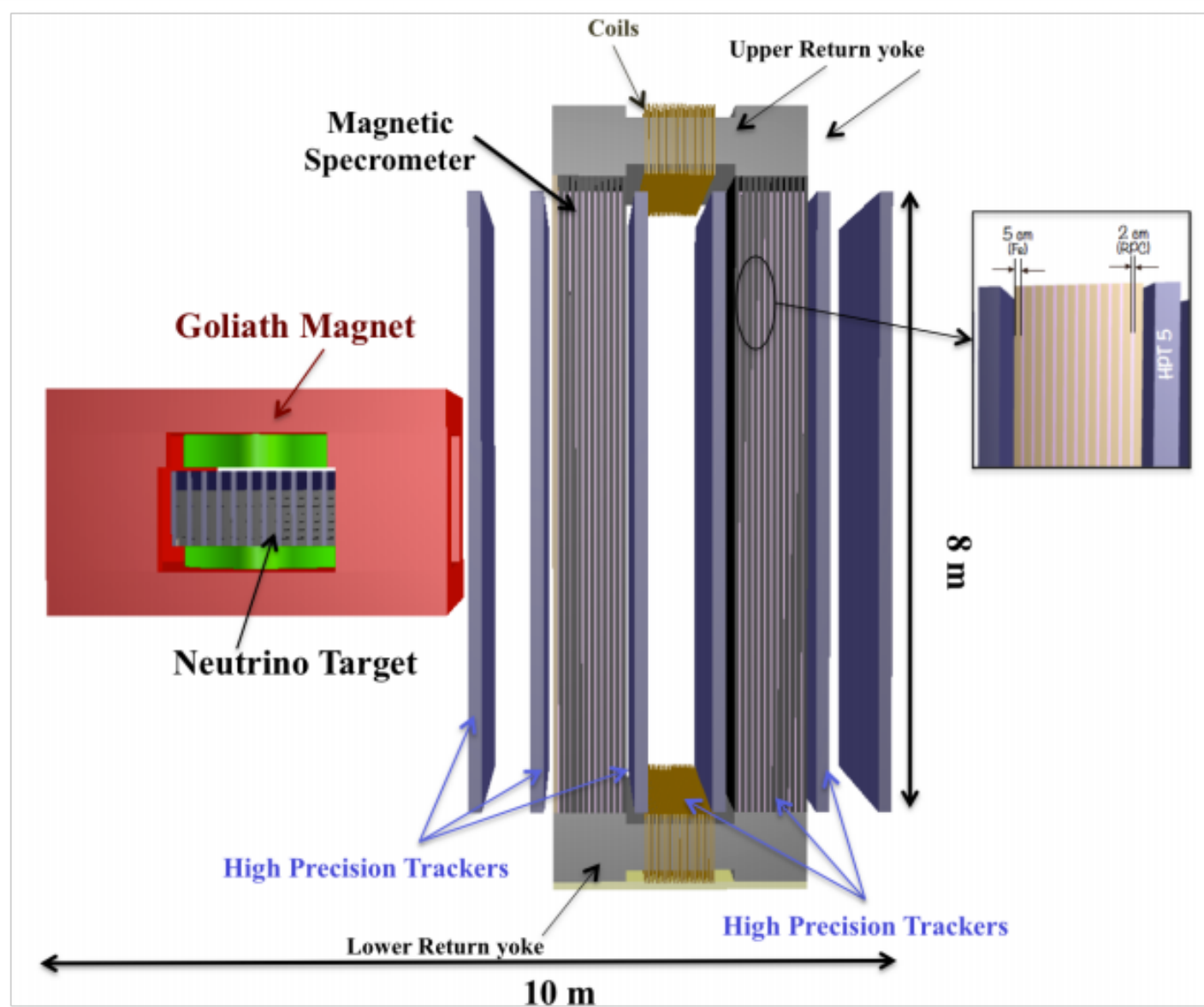
DONUT: 9 observed ν_τ candidate events (leptonic number not measured)

OPERA: discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode

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



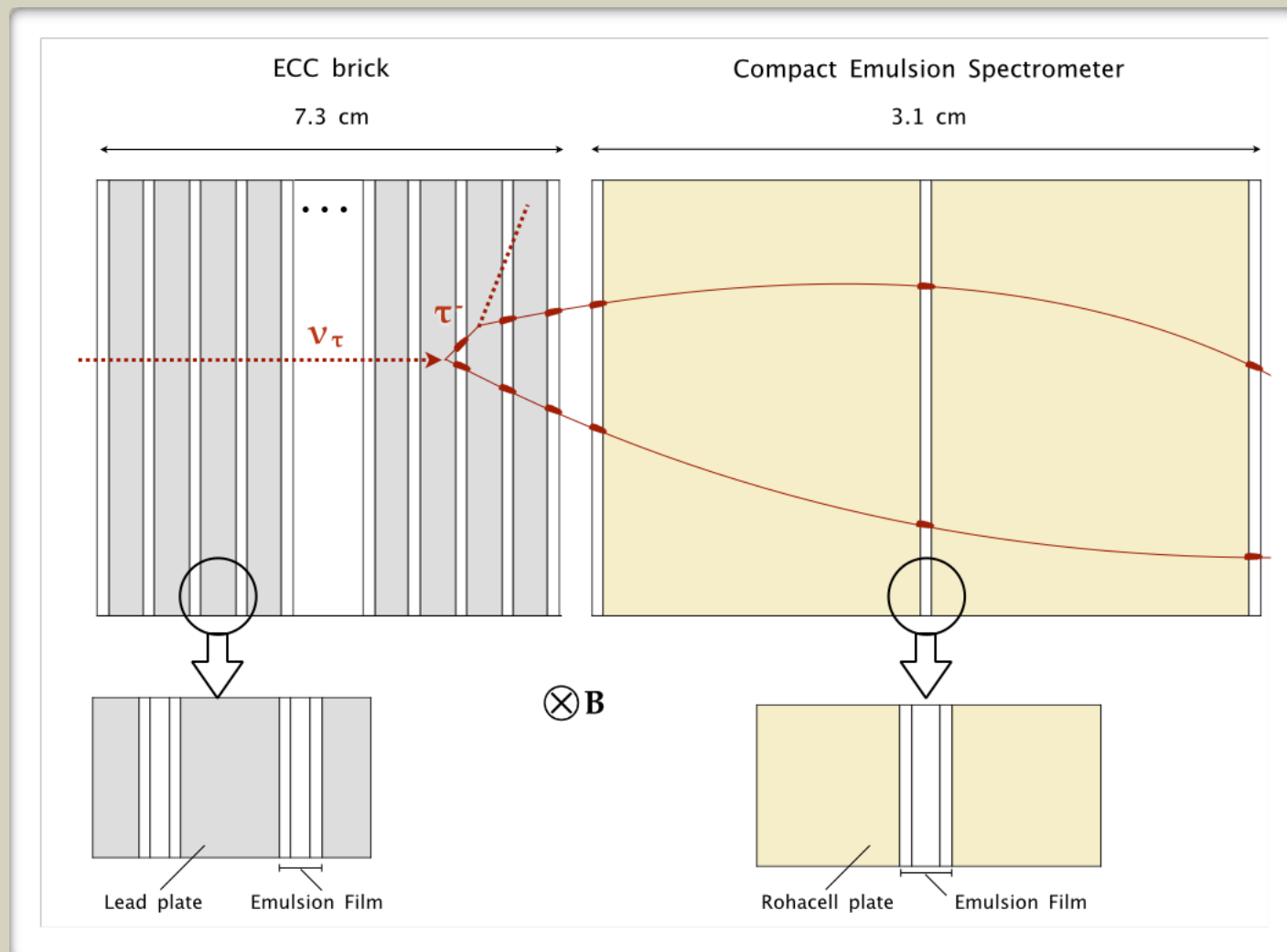
NEUTRINO DETECTOR



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
 - **DIPOLAR MAGNET**
- ▶ Magnetic spectrometer to perform muon identification and measure its charge and momentum
 - **MUON SPECTROMETER**

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

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

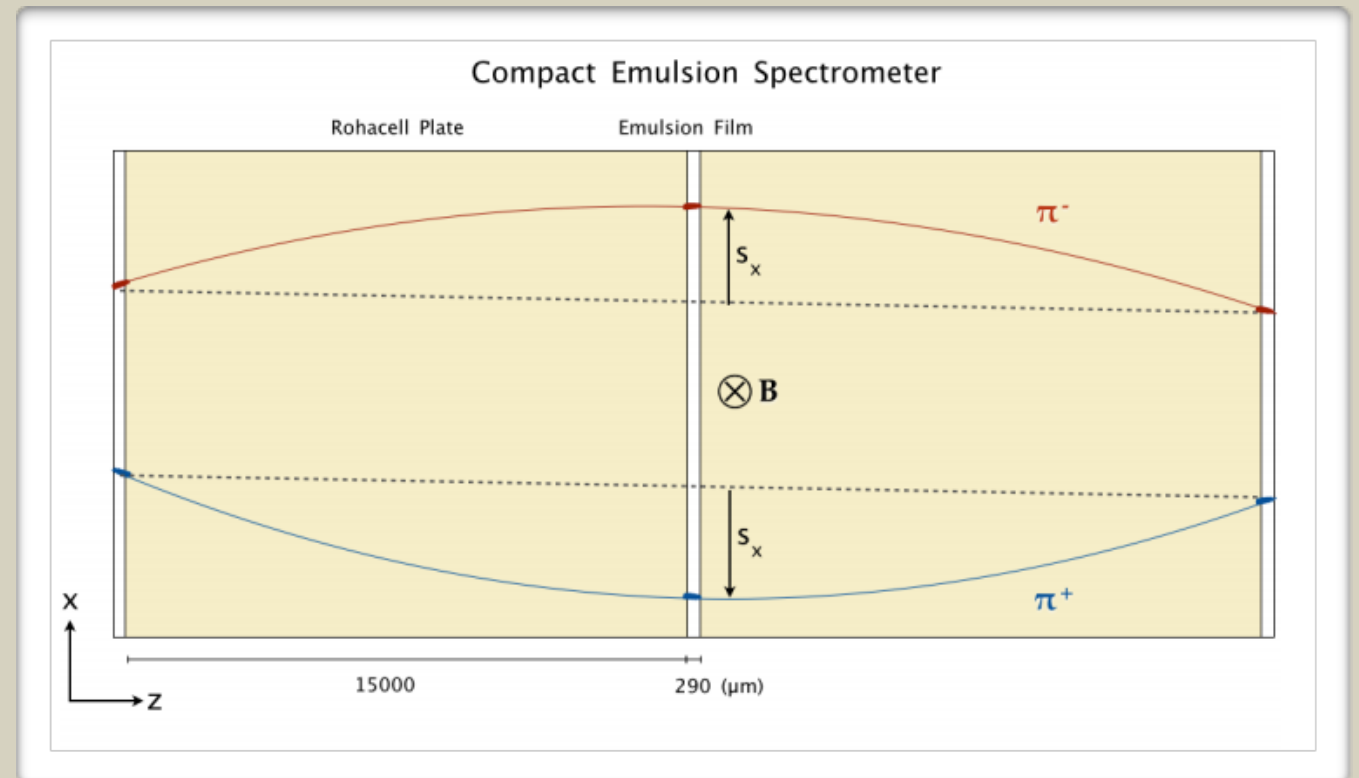
ν_τ / ANTI- ν_τ SEPARATION

REQUIREMENTS

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

LAYOUT

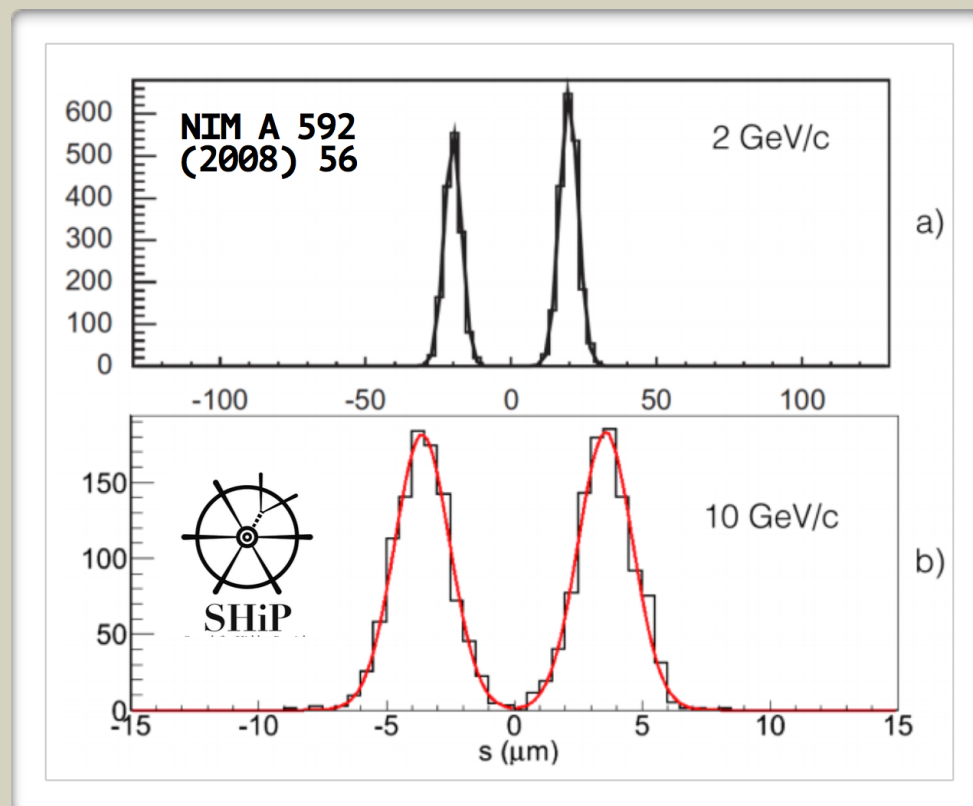
- ▶ 3 OPERA-like emulsion films
- ▶ 2 Rohacell spacers (low density material)
- ▶ 1 Tesla magnetic field



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
- ▶ $\Delta p / p < 20\%$ up to 12 GeV / c



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

$$N_{\nu_\tau + \bar{\nu}_\tau} = 4N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \rightarrow \tau) = 3.26 \times 10^{-5} N_p = 6.5 \times 10^{15}$$

- ▶ 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)

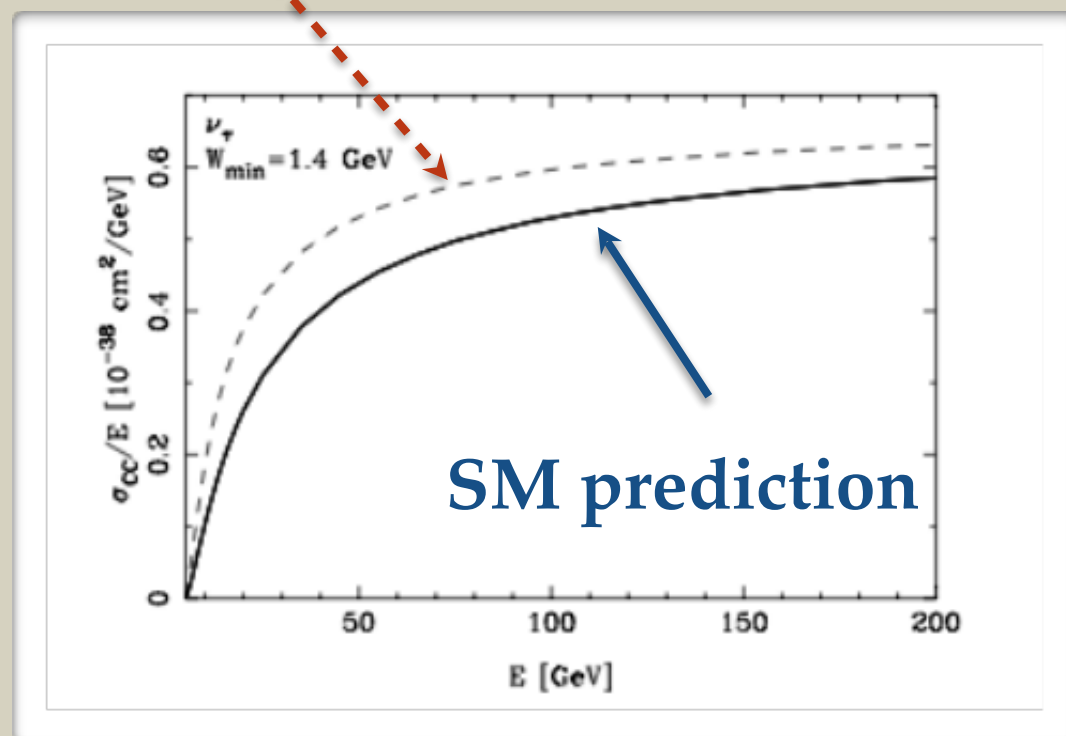
decay channel	ν_τ			$\bar{\nu}_\tau$		
	N^{exp}	N^{bg}	R	N^{exp}	N^{bg}	R
$\tau \rightarrow \mu$	570	30	19	290	140	2
$\tau \rightarrow h$	990	80	12	500	380	1.3
$\tau \rightarrow 3h$	210	30	7	110	140	0.8
total	1770	140	13	900	660	1.4

STRUCTURE FUNCTIONS

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

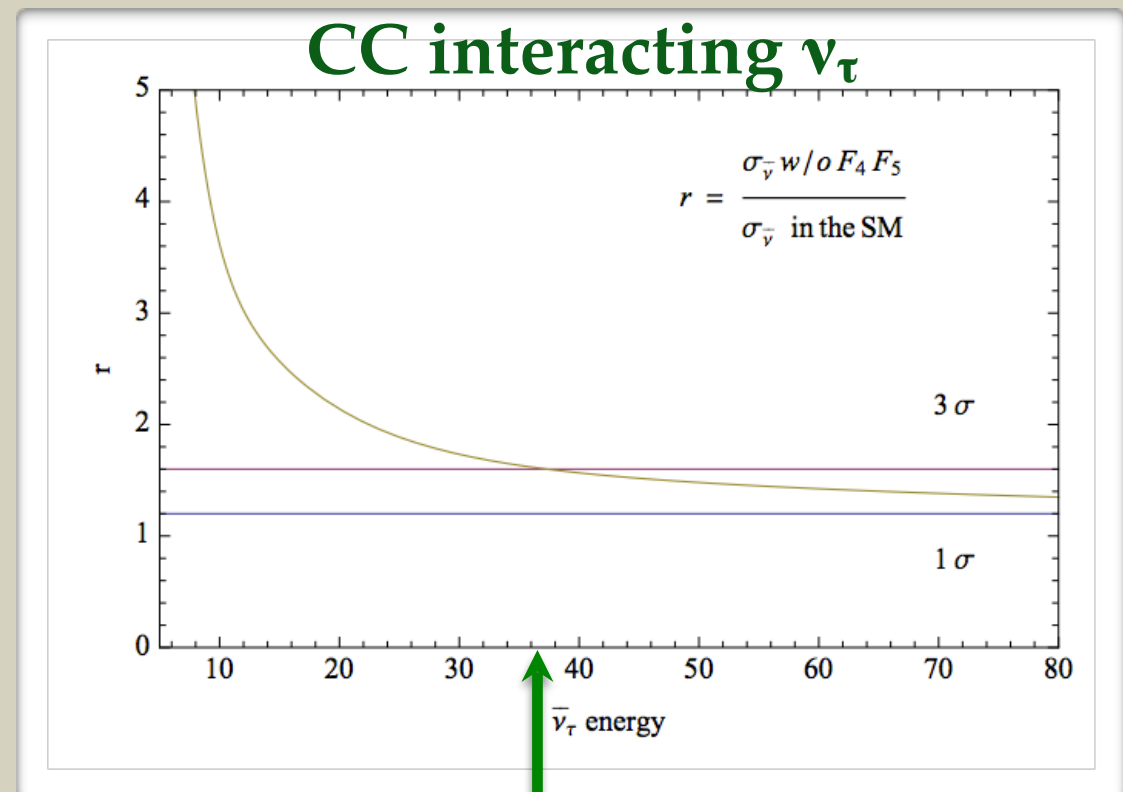
$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1 + Q^2/M_W^2)^2} \left((y^2x + \frac{m_\tau^2 y}{2E_\nu M}) F_1 + \left[(1 - \frac{m_\tau^2}{4E_\nu^2}) - (1 + \frac{Mx}{2E_\nu}) \right] F_2 \right. \\ \left. \pm \left[xy(1 - \frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M} \right] F_3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

$F_4 = F_5 = 0$



ν_τ CC DIS cross-section

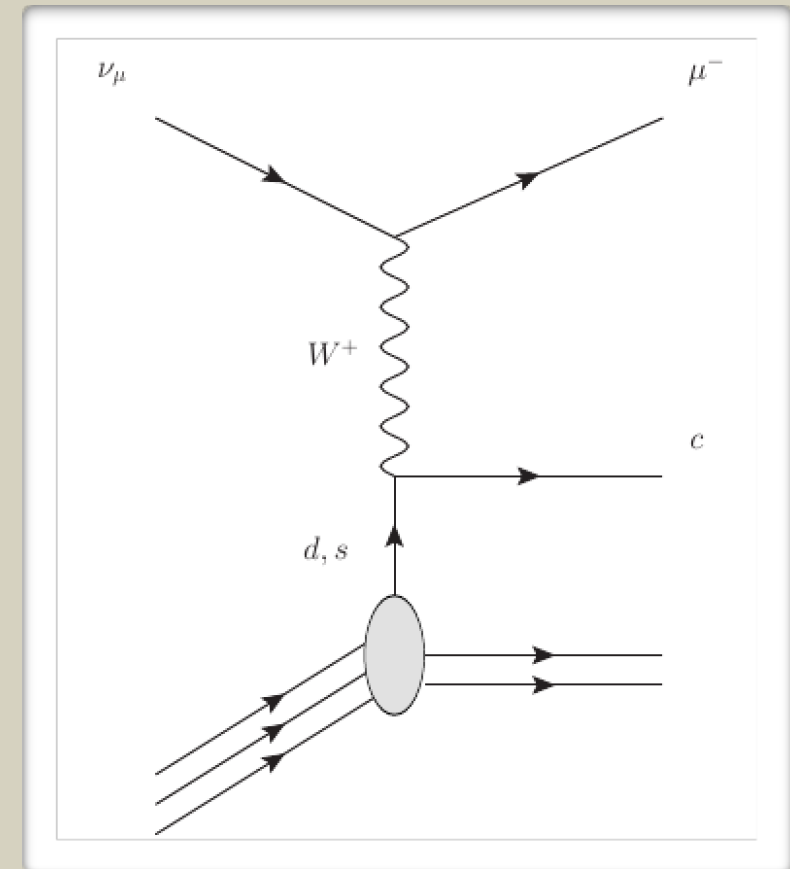
r = ratio between the cross sections in the two hypotheses



$E(\nu_\tau) < 38 \text{ GeV}$
(~300 events expected)

CHARM PHYSICS @SHiP

- ▶ Large **charm production** in ν_μ^{CC} and ν_e^{CC} interactions
- ▶ Process sensitive to **strange quark** content of the nucleon

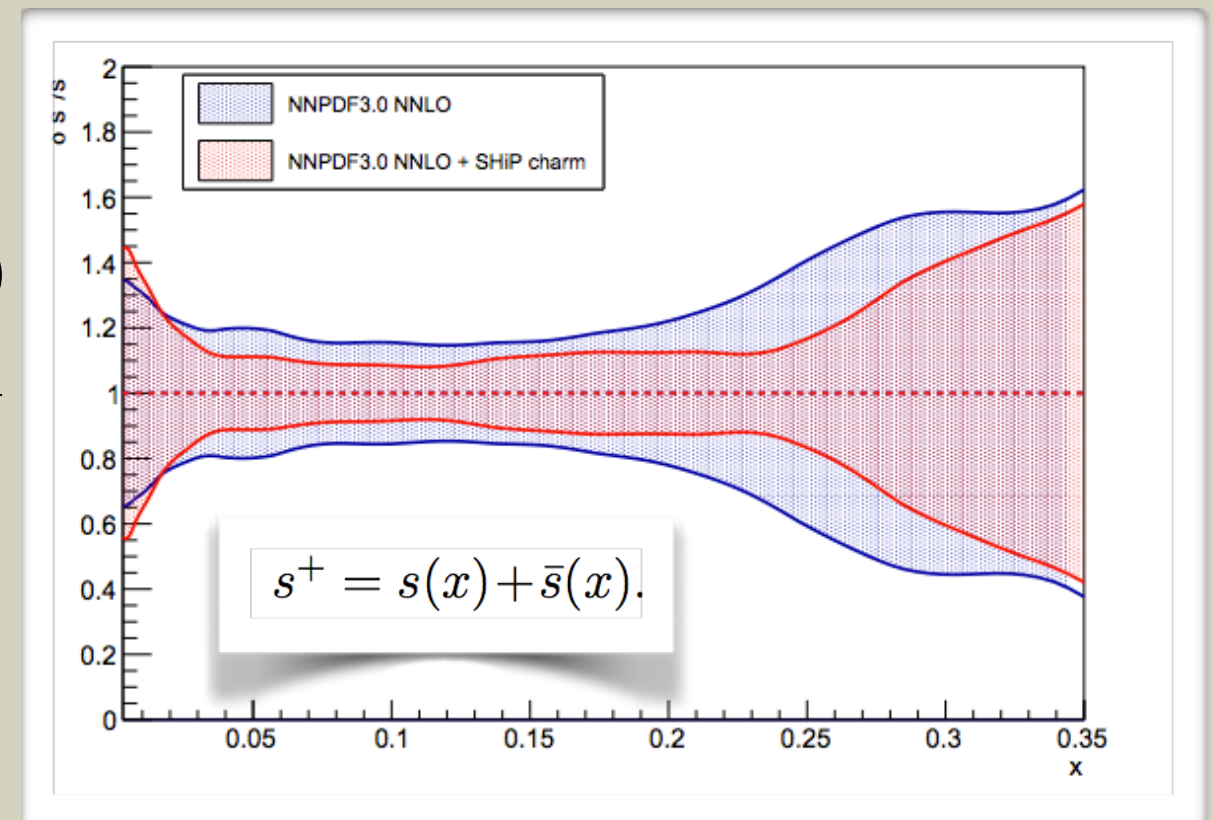
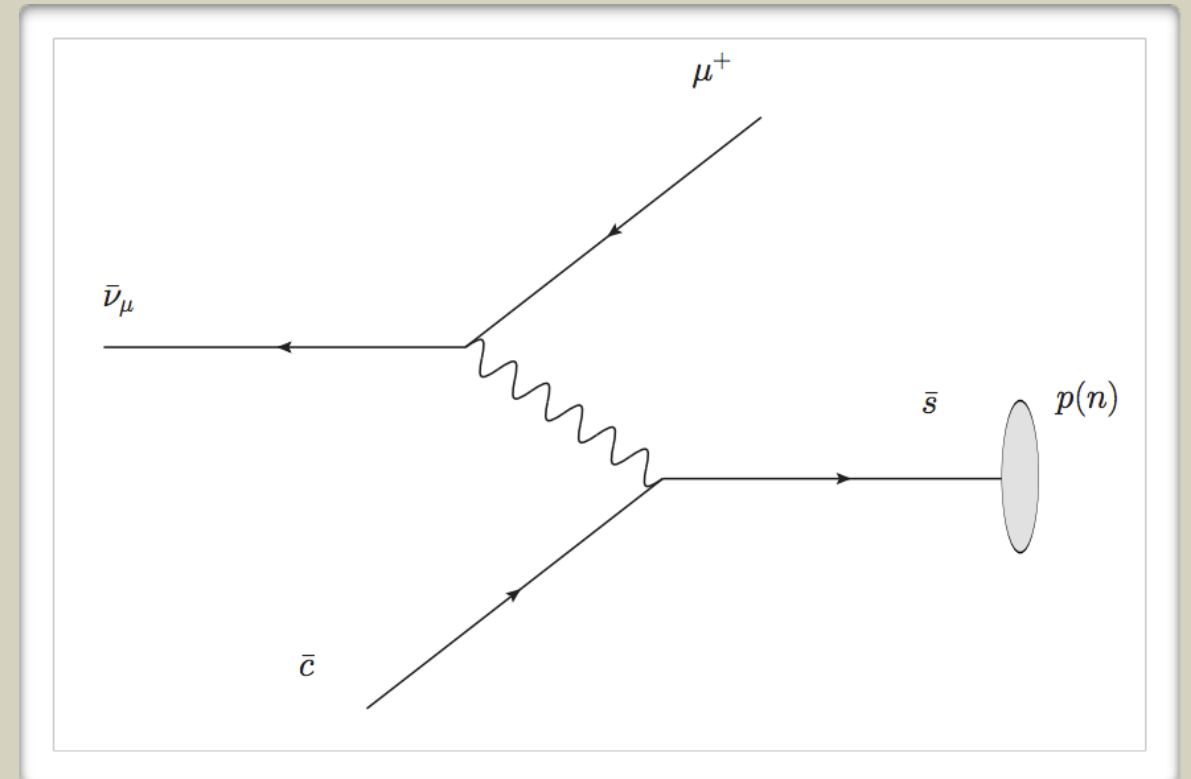


- ▶ Charm production with electronic detectors tagged by di-muon events (high energy cut to reduce background)
- ▶ **Nuclear emulsion** technique: charmed hadron identification through the observation of its decay
- ▶ Loose kinematical cuts → good sensitivity to the **slow-rescaling** threshold behavior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

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*

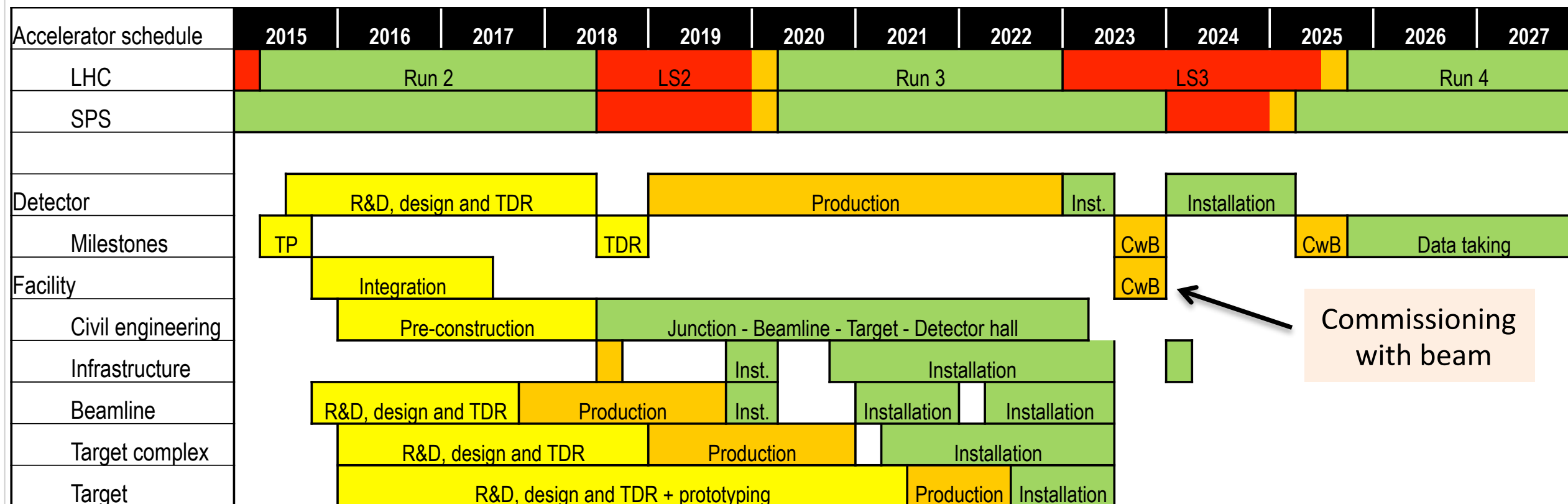


CONCLUSIONS

- ▶ Search for new physics Beyond Standard Model: explore the intensity frontier
- ▶ Rich Standard Model physics program: first observation of anti- ν_τ , ν_τ cross section studies and more
- ▶ Technical and Physics proposal submitted to the SPSC in **April 2015**
- ▶ Positive recommendation from the SPSC in **January 2016**
- ▶ Comprehensive Design Report expected for **European HEP strategy 2019**

BACK-UP SLIDES

PROJECT SCHEDULE



- ▶ **Form SHiP Collaboration**
- ▶ **Technical Proposal**
- ▶ Comprehensive Design Report
- ▶ Construction and Installation
- ▶ Commissioning
- ▶ Data taking and analysis

December 2014 ✓
April 2015 ✓
 2018
 2018-2023
 2023
 2026

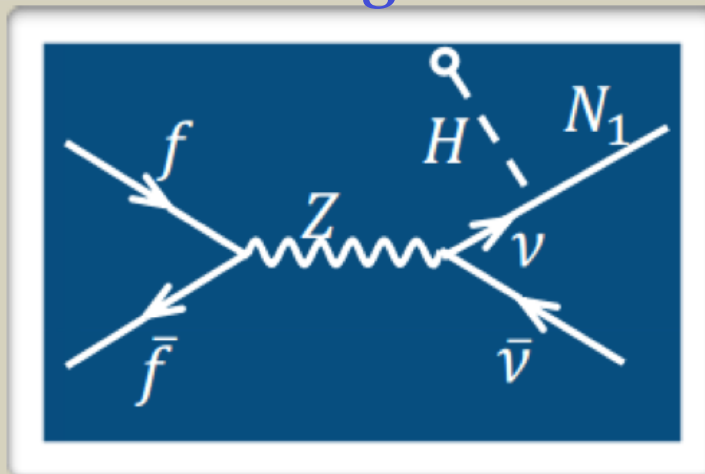
COSTS

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

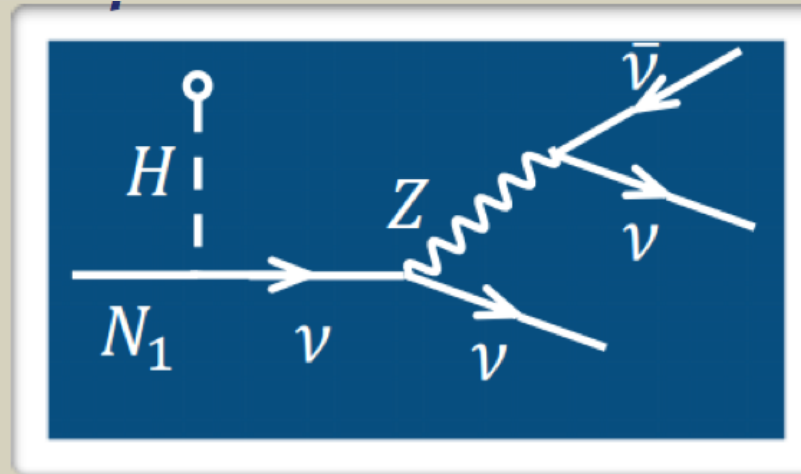
N_1 : DARK MATTER CANDIDATE

- ▶ Weak coupling with other leptons
- ▶ $\text{Mass}(N_1) \sim 10 \text{ KeV}$
- ▶ Enough stable to be a dark matter candidate

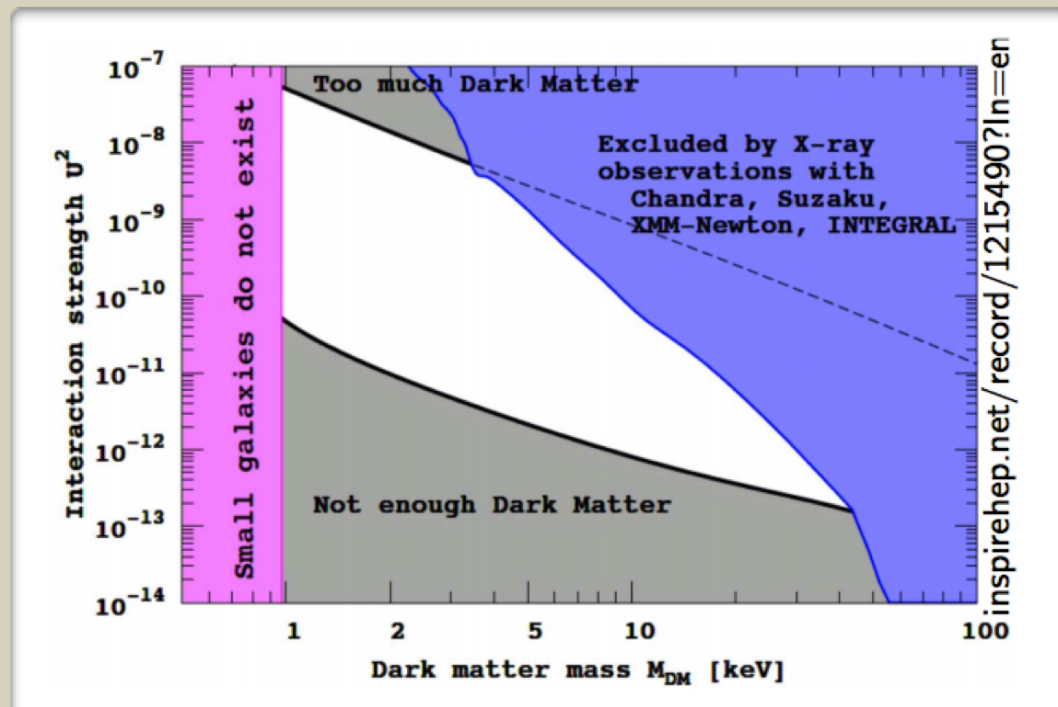
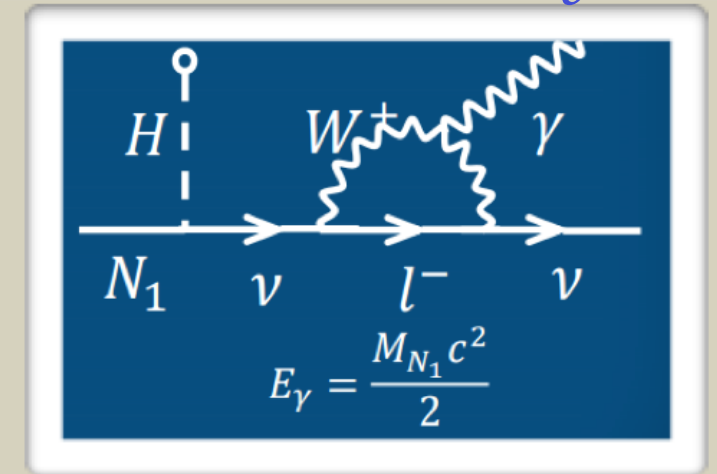
mixing ν - N



dominant process



*subdominant
radiative decay*

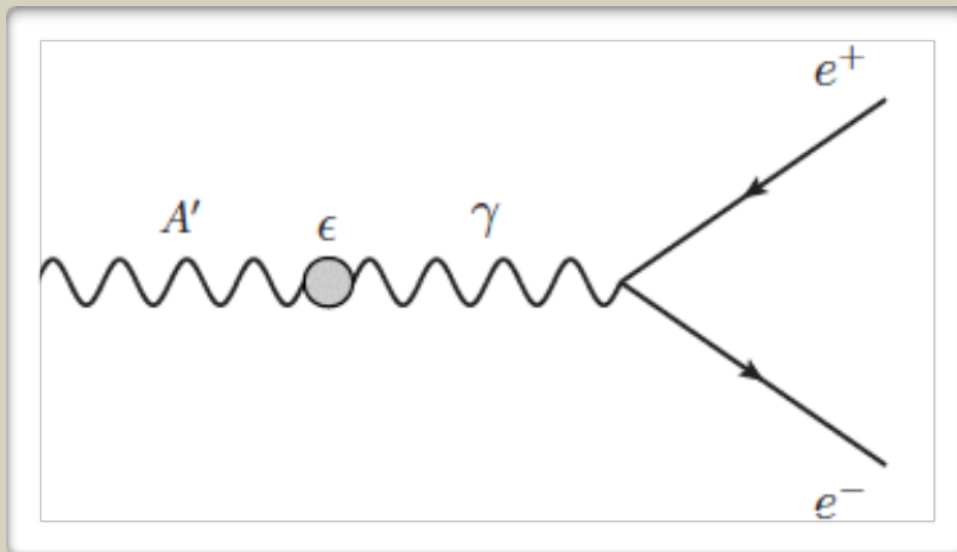


- ▶ **GALACTIC HINTS**
- ▶ *Astr. Phys. J.* 789 (2014) 13,
Phys. Rev. Lett. 113 (2014) 251301
- ▶ Not identified line in the X-ray spectrum of Andromeda and Perseus galaxies ($E_\gamma = 3.5 \text{ keV}$)

STANDARD MODEL PORTALS

VECTOR PORTAL

- ▶ Kinetic mixing with the **dark photon**
- ▶ Possible dark matter candidate
- ▶ Possible solution to the $g-2$ anomaly



Production of the dark photon at the SPS

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

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*)

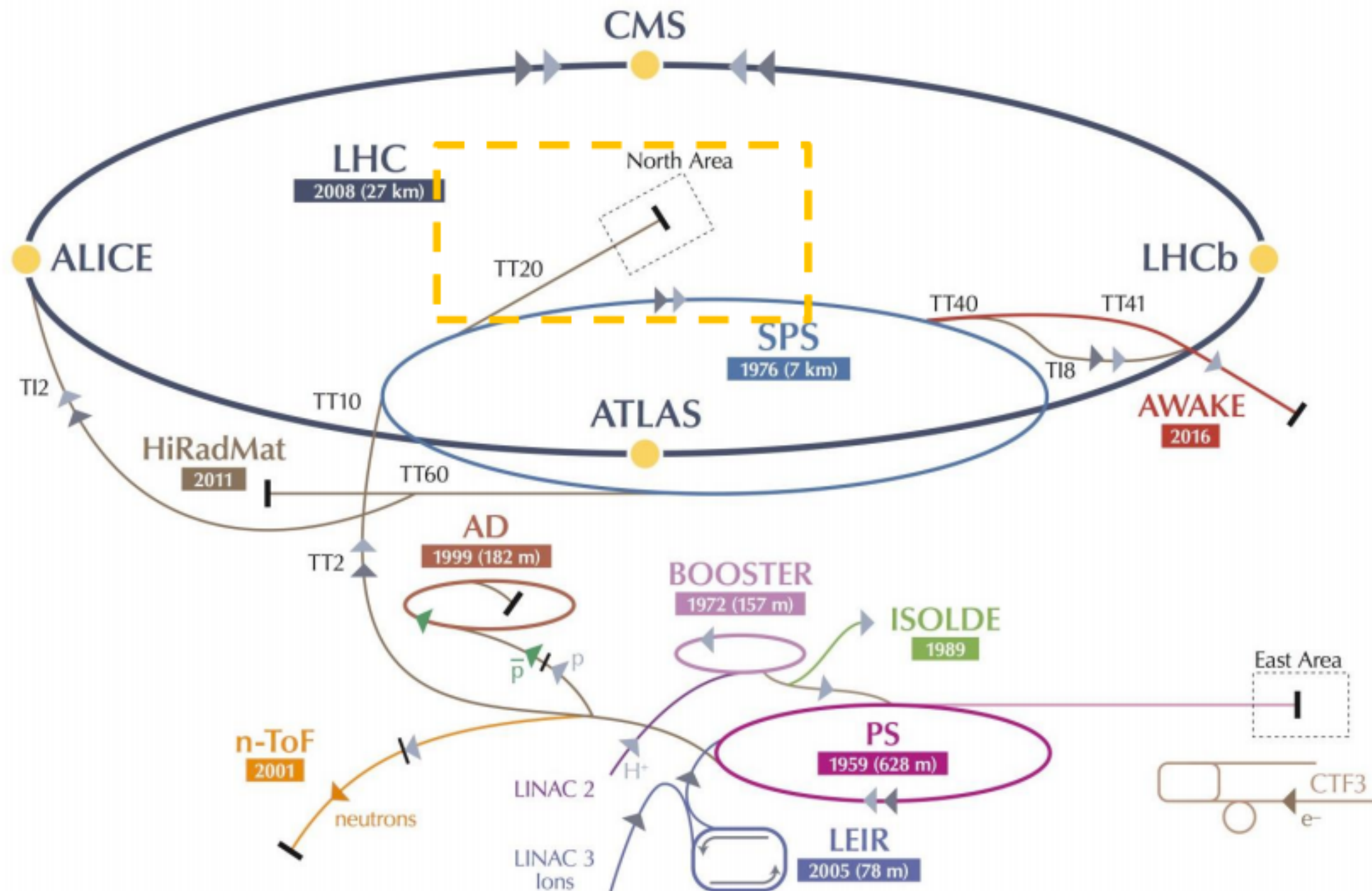
SUSY PORTAL

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

(light neutralino, light sgoldstino, ...)

SHIP LOCATION

- Proposed location by CERN beams and support departments

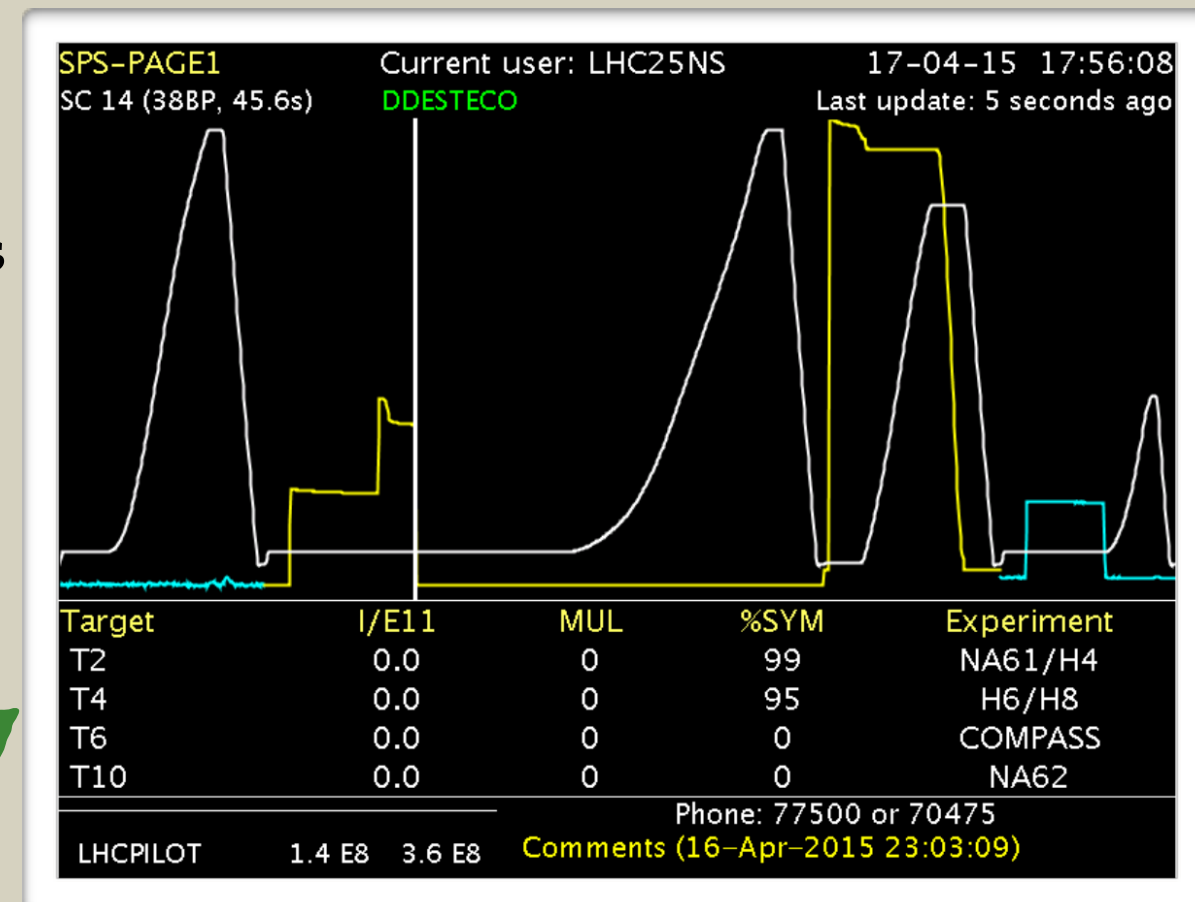


R&D AT CERN FOR PROTON

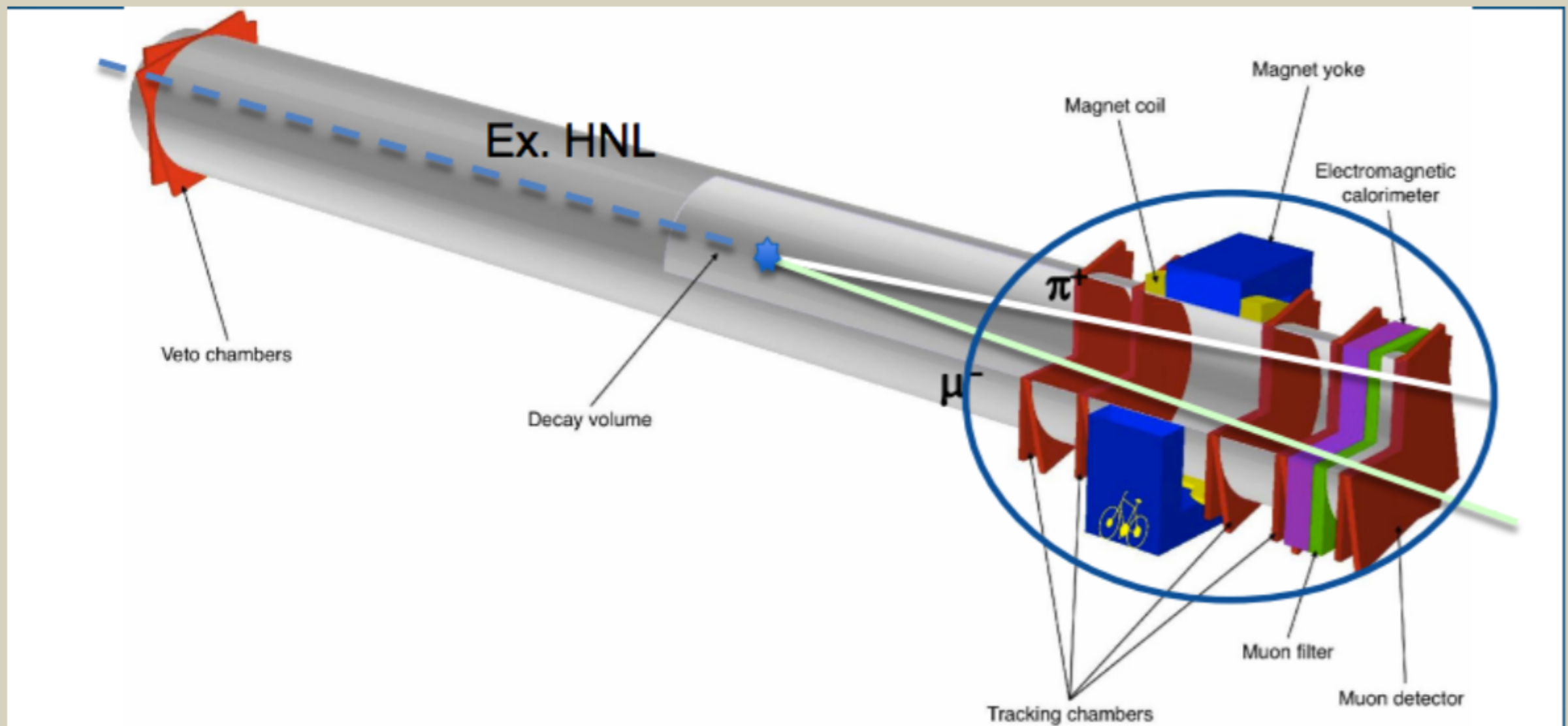
EXTRACTION

- ▶ 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

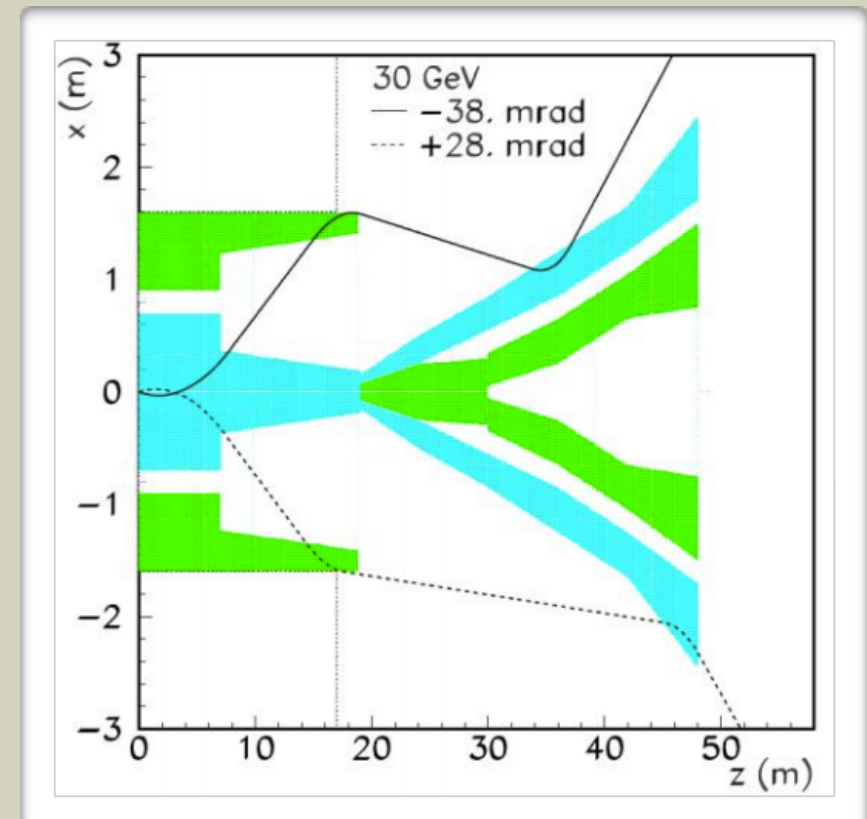
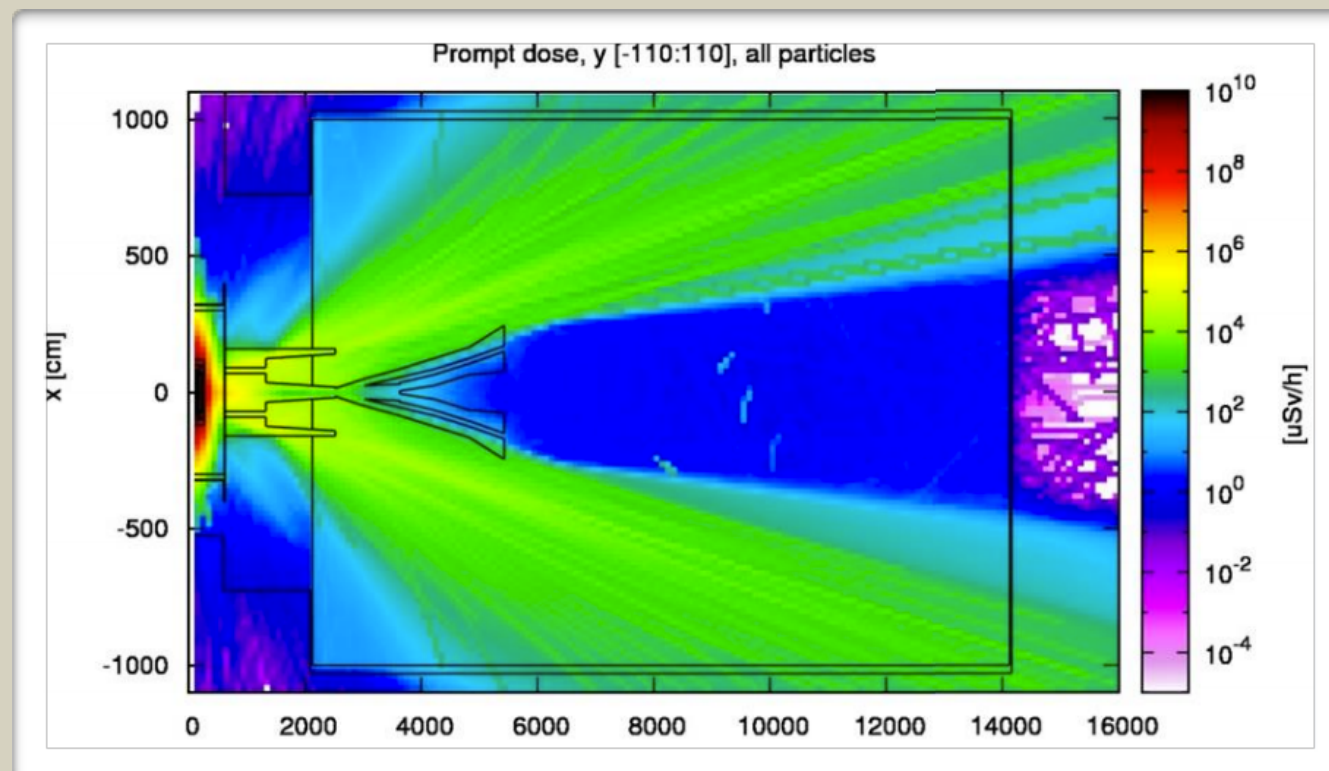
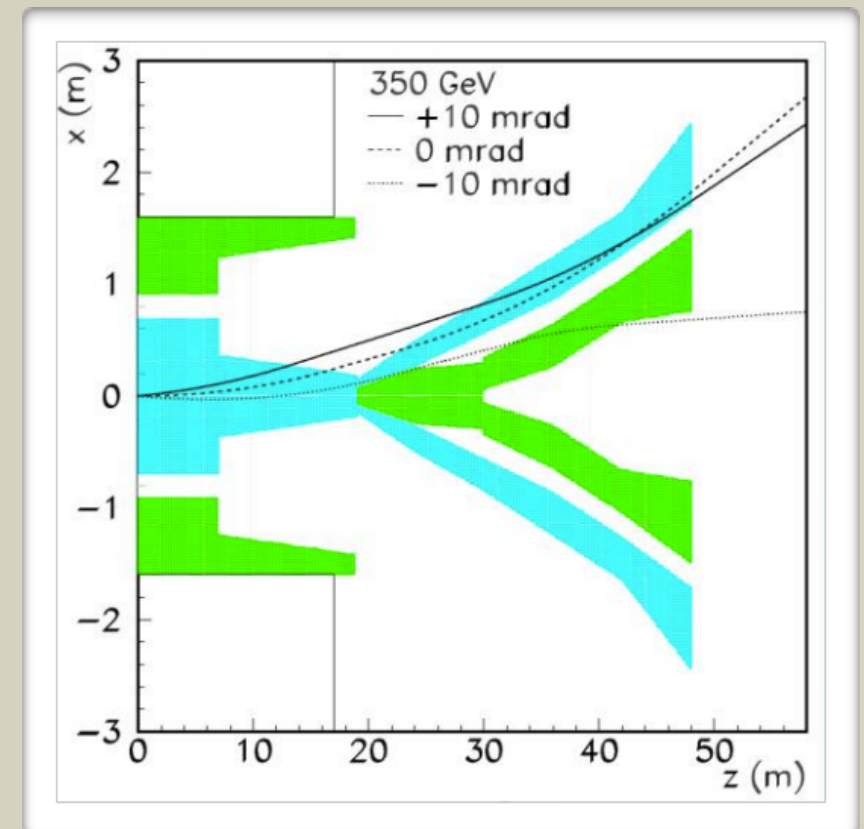


Successful test in April 2015



ACTIVE MUON SHIELD

- ▶ Muon flux driven by the HS background and emulsion-based neutrino detector
- ▶ Active muon shield based entirely on **magnet sweeper** with a total field integral $B = 86.4 \text{ Tm}$
- ▶ Realistic **design** of sweeper magnets in progress
- ▶ **Challenges**: flux leakage, constant field profile, modeling magnet shape
- ▶ Rate reduction: from 10^{10} to 10^4 muons/spill
- ▶ **Negligible flux** in terms of detector occupancy



HIDDEN SECTOR DETECTOR CONCEPT

Aim: Reconstruction of HS decays in all possible final states

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

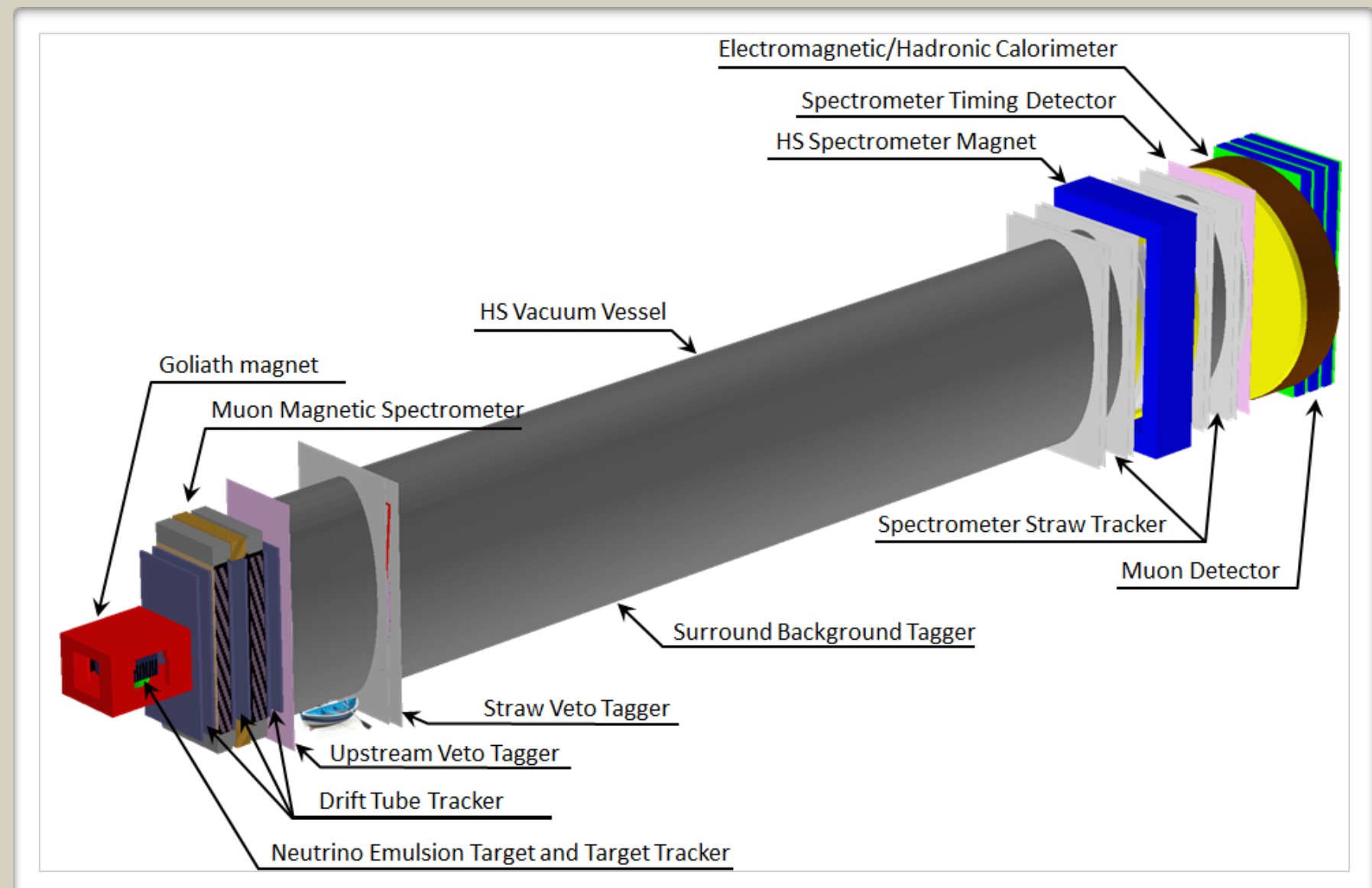
$$\sigma_p / p \sim 0.5\% \oplus 0.02\% \times p$$

$$\sigma E / E \sim 6\% / \sqrt{E}$$

$$\sigma t \sim 100\text{ps}$$

Challenges

- ▶ Large vacuum vessel
- ▶ 5 m long straw tubes
- ▶ High resolution timing detector



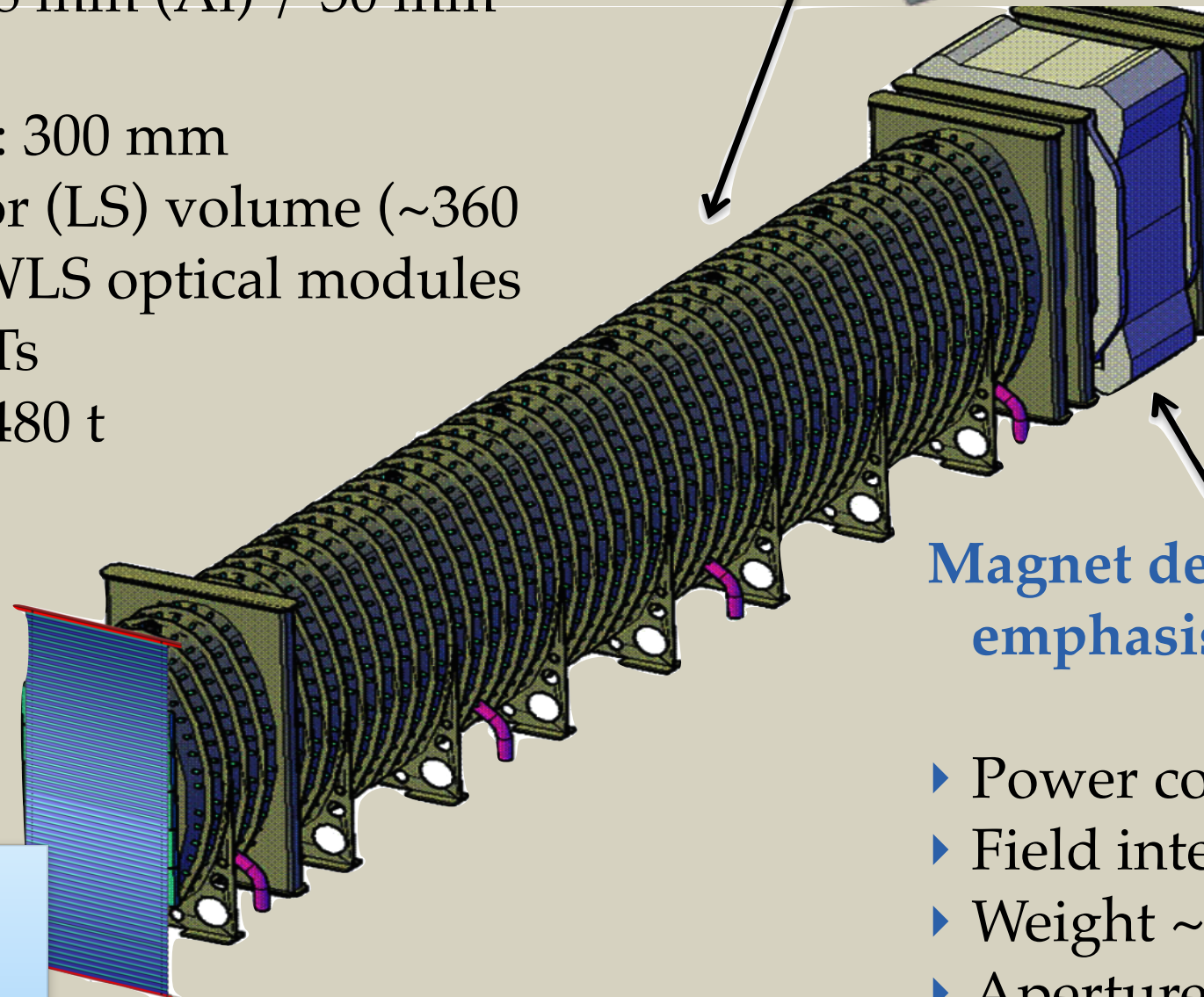
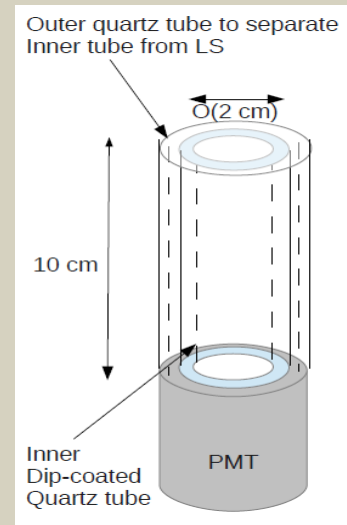
DECAY VOLUME AND SPECTROMETER

Estimated need for vacuum: $\sim 10^{-3}$ mbar

Vacuum Vessel

- ▶ 10 m x 5 m x 60 m
- ▶ Walls thickness: 8 mm (Al) / 30 mm (SS)
- ▶ Walls separation: 300 mm
- ▶ Liquid scintillator (LS) volume (~ 360 m³) 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 m²

viene da richiesta di <1 interazioni di neutrino, può non essere necessario stiamo studiando

TIMING DETECTOR

Challenges:

- ▶ Large area
- ▶ Required resolution < 100 ps
- ▶ Spatial resolution under study

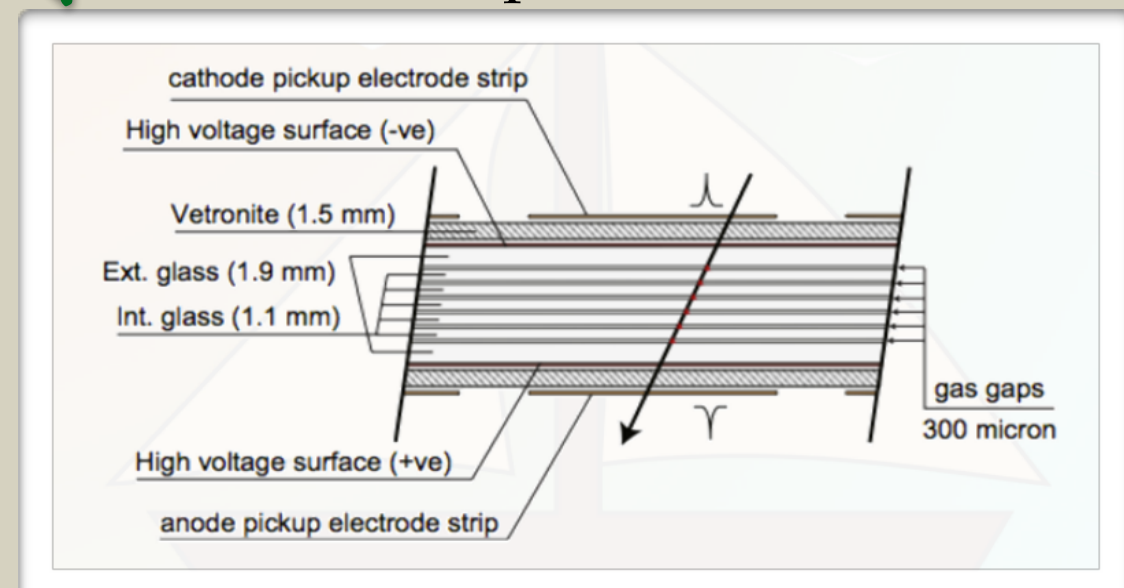
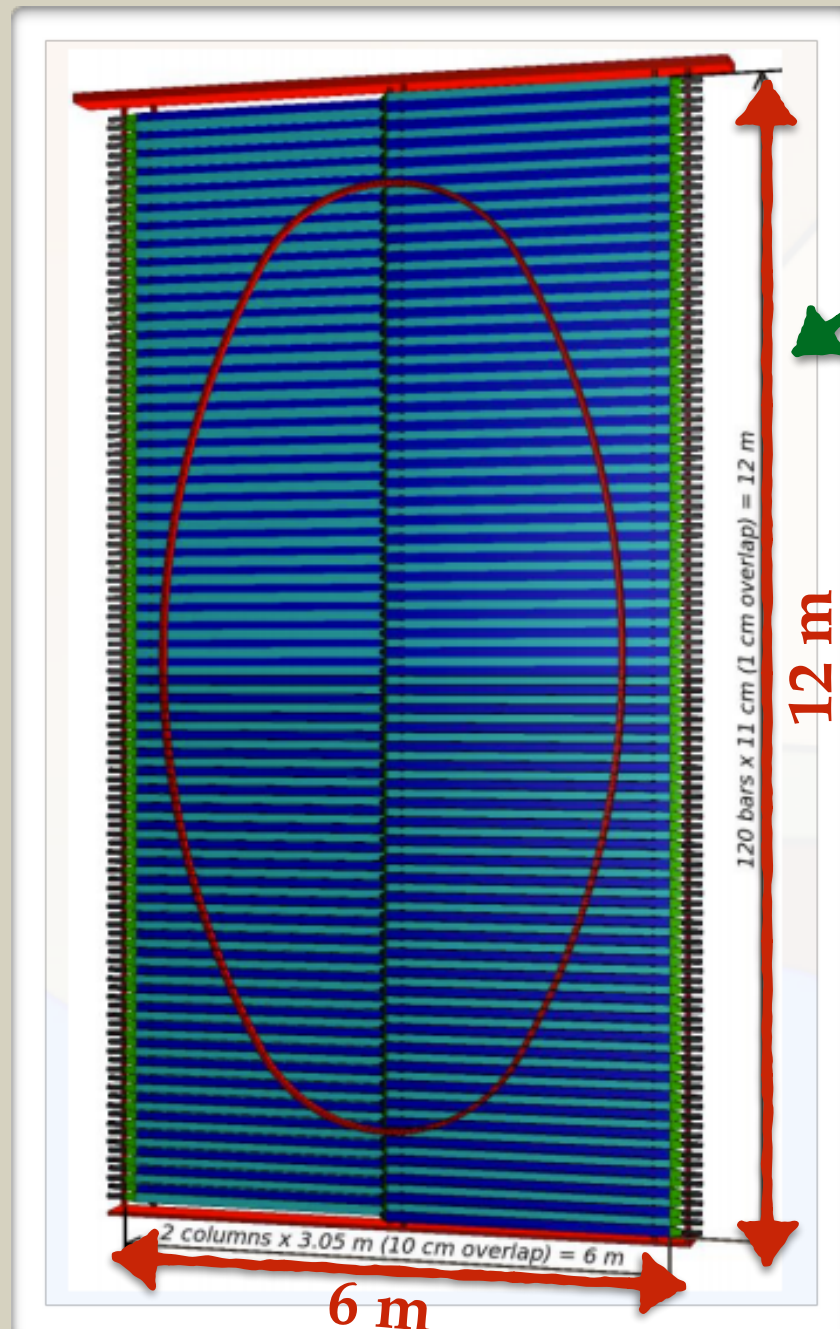
Two options considered:

Scintillator bars (NA61/SHINE, COMPASS)

NA61 / SHINE ToF
100 ps resolution
Long scintillator bars

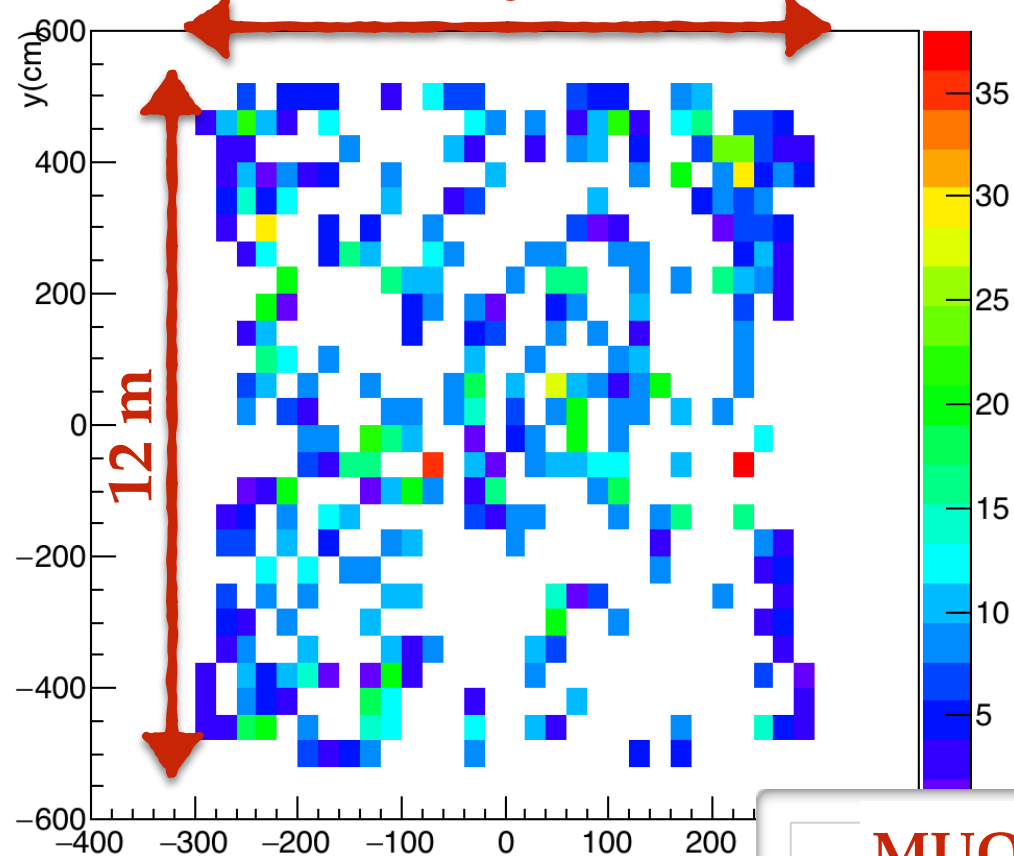
Multi-gap resistive plate chambers (MRPC)

61 chambers x 120 cm strips, 3 cm pitch
Used in ALICE TOF and EEE project
50 ps resolution achievable



TIMING DETECTOR

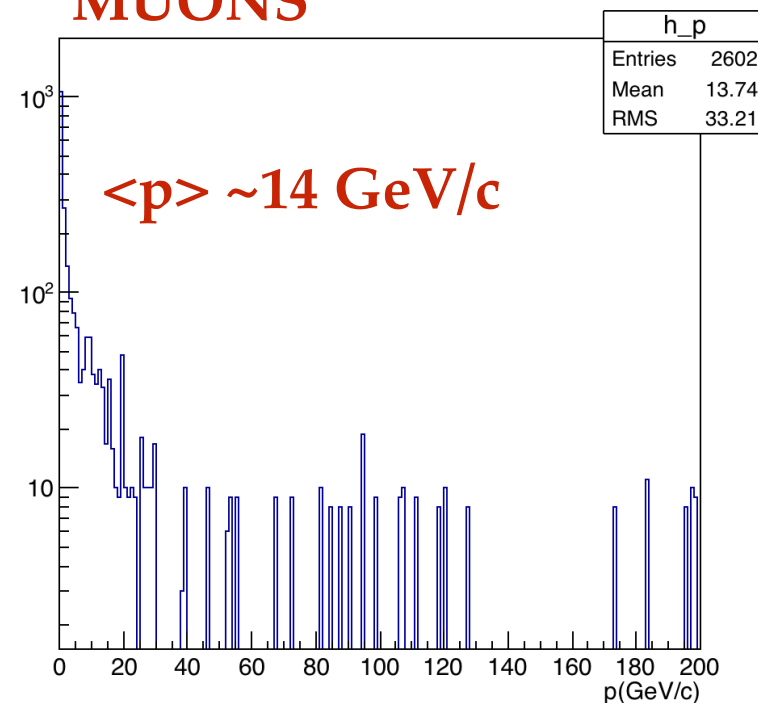
MUONS ONLY 6 m



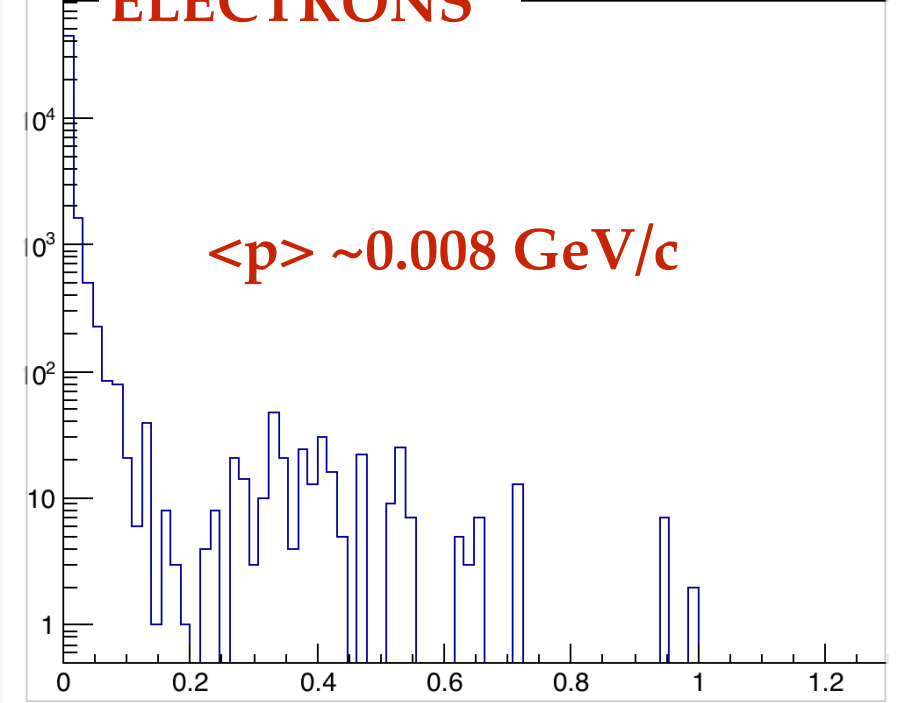
Expected background rates/spill

Muons 3 kHz/m^2
Electrons 50 kHz/m^2

MUONS



ELECTRONS



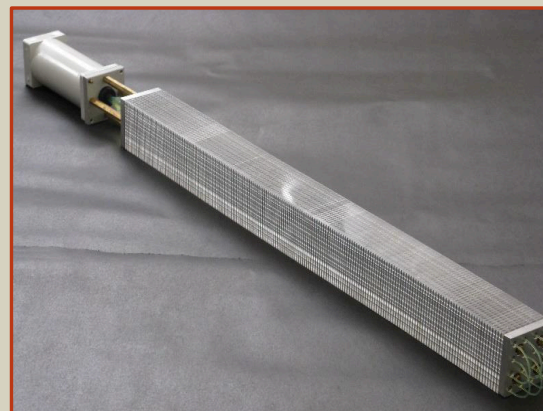
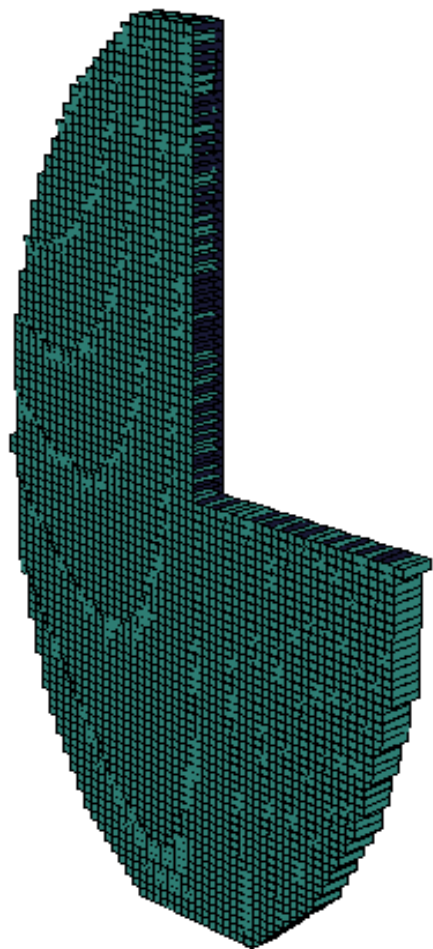
CALORIMETERS

ECAL

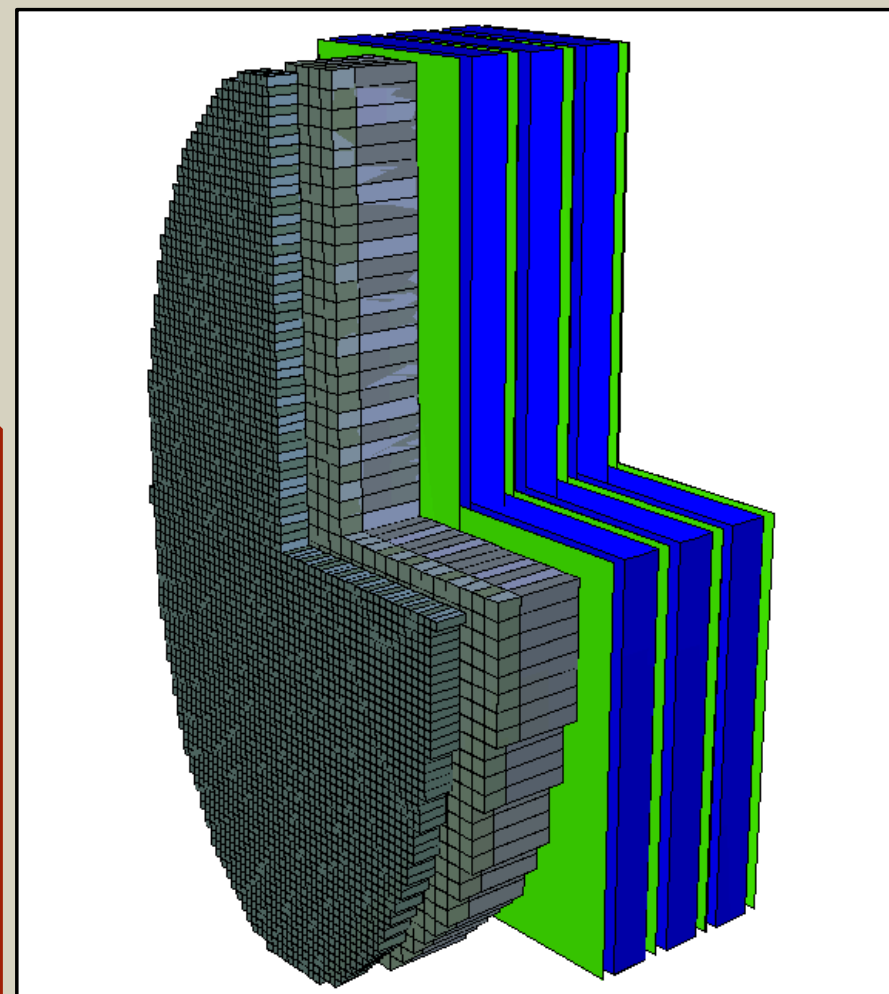
- ▶ Almost elliptical shape (5 m x 10 m)
- ▶ 2876 Shashlik modules
- ▶ 2x2 cells/modules, width=6 cm
- ▶ 11504 independent readout channels

HCAL

- ▶ Matched with ECAL acceptance
- ▶ 2 stations
- ▶ 5 m x 10 m
- ▶ 1512 modules
- ▶ 24x24 cm² dimensions
- ▶ Stratigraphy: N x (1.5 cm steel+0.5 cm scint)
- ▶ 1512 independent readout channels

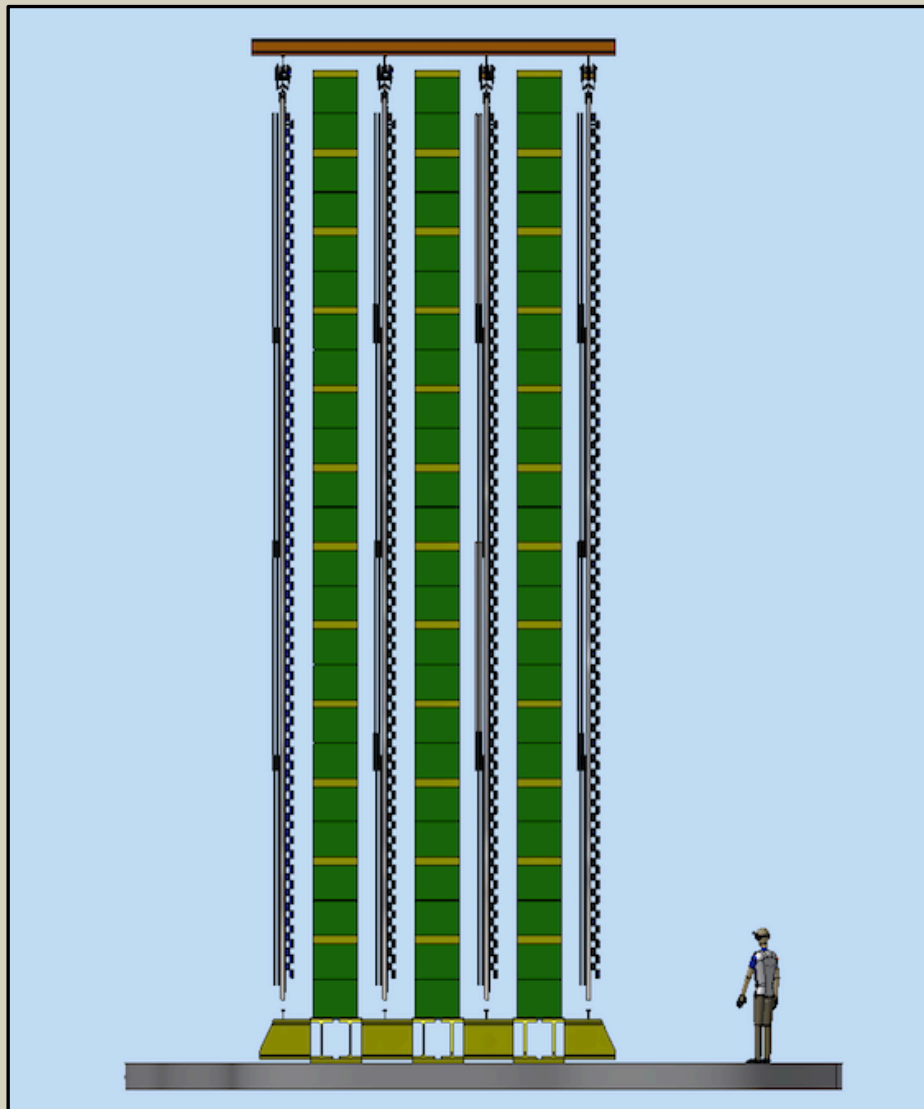


Dimensions	60x60 mm ²
Radiation length	17 mm
Moliere radius	36 mm
Radiation thickness	25 X ₀
Scintillator thickness	1.5 mm
Lead thickness	0.8 mm
Energy resolution	1%



MUON SYSTEM

Based on scintillating bars, with WLS fibers and SiPM readout

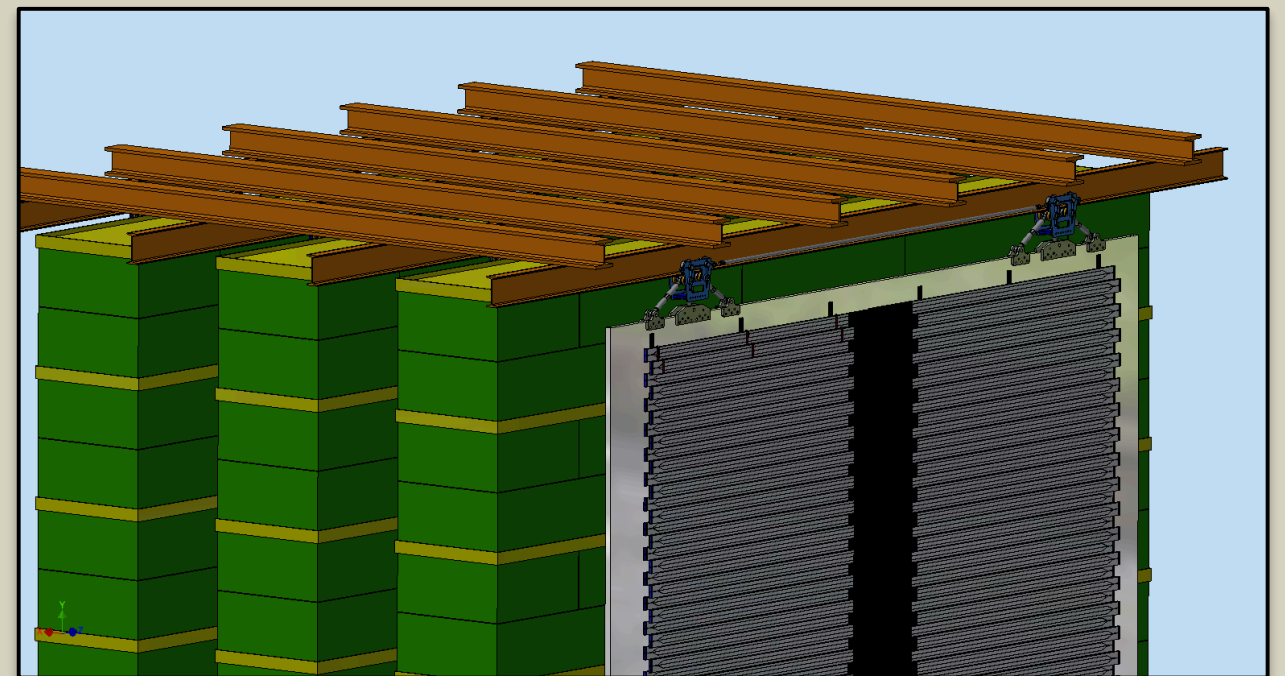


Technical Proposal (preliminary design)

- 4 active stations
- transverse dimensions: 1200x600 cm²
- x,y view
- 3380 bars, 5x300x2 cm³/each
- 7760 FEE channels
- 1000 tons of iron filters

Requirements:

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

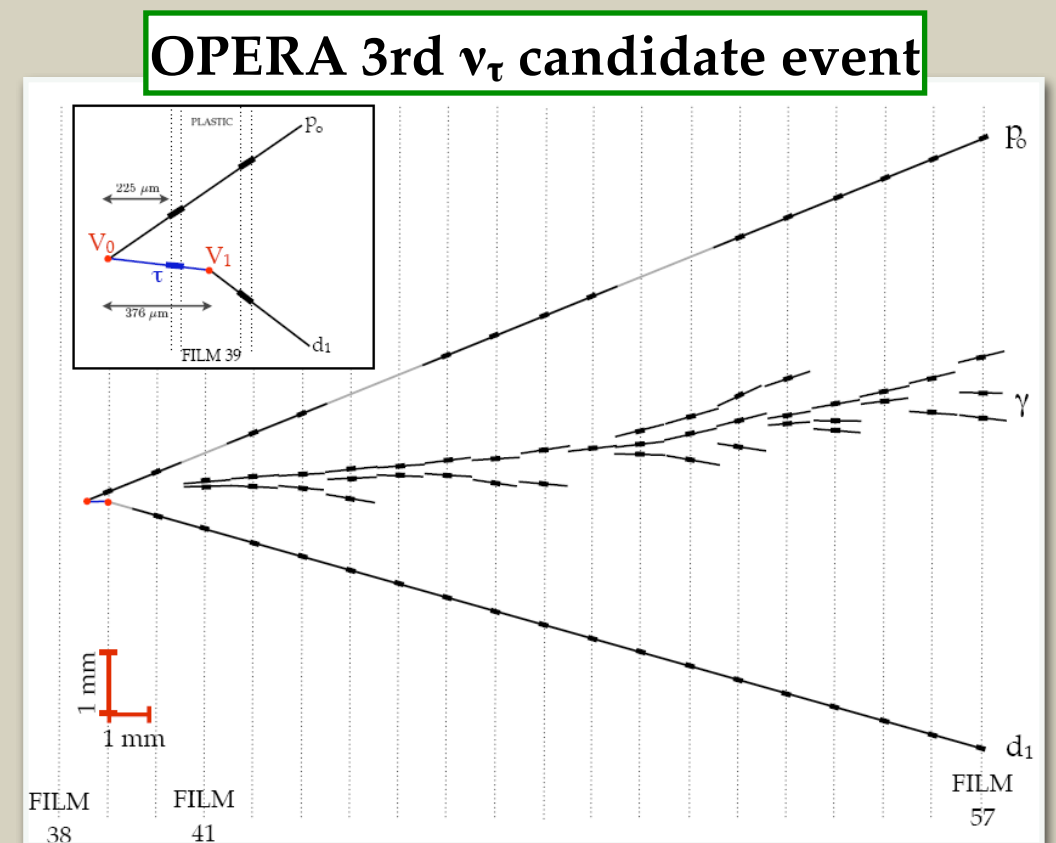
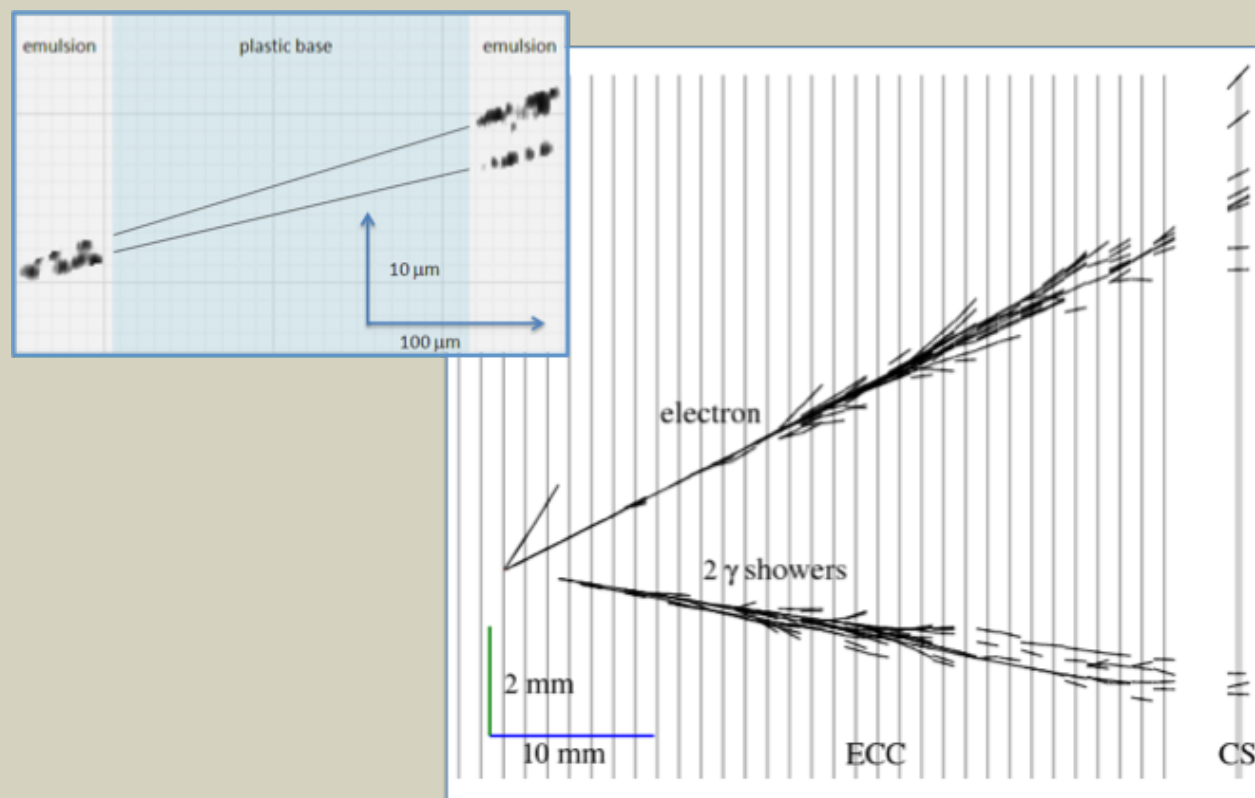


LEPTON FLAVOUR IDENTIFICATION

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



EVENT TIME STAMP

Target tracker (TT)

FEATURES:

- ▶ Provide Time stamp
- ▶ Link track information in emulsions to signal in TT
- ▶ Link muon track information in ν target to μ magnetic spectrometer

REQUIREMENTS IN 1T FIELD:

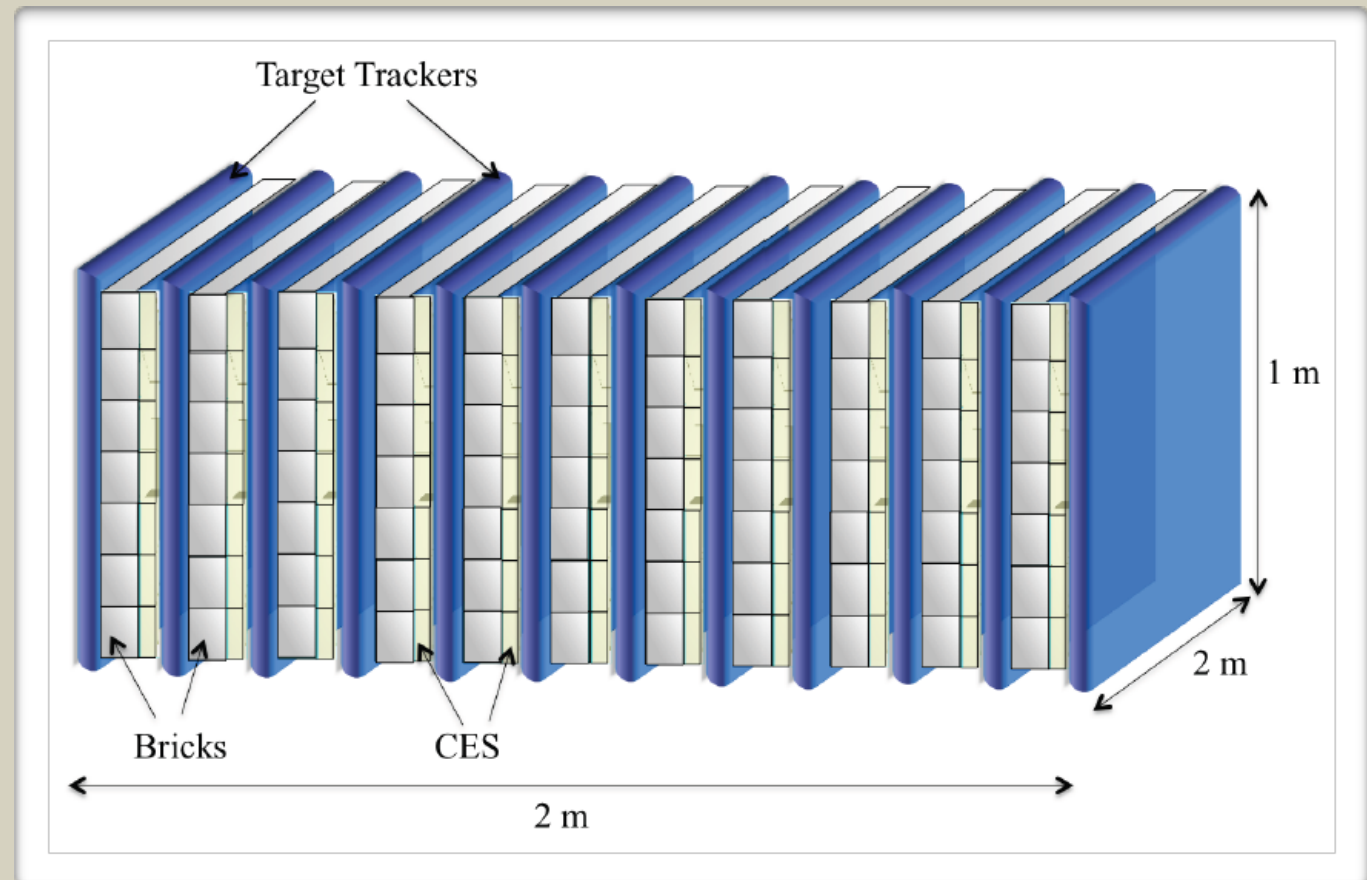
- ▶ 100 μm position resolution on both coordinates
- ▶ high efficiency ($>99\%$) for angles up to 1 rad

POSSIBLE OPTIONS:

- ▶ Scintillating fibre trackers
- ▶ Micro-pattern gas detectors (GEM, Micromegas)

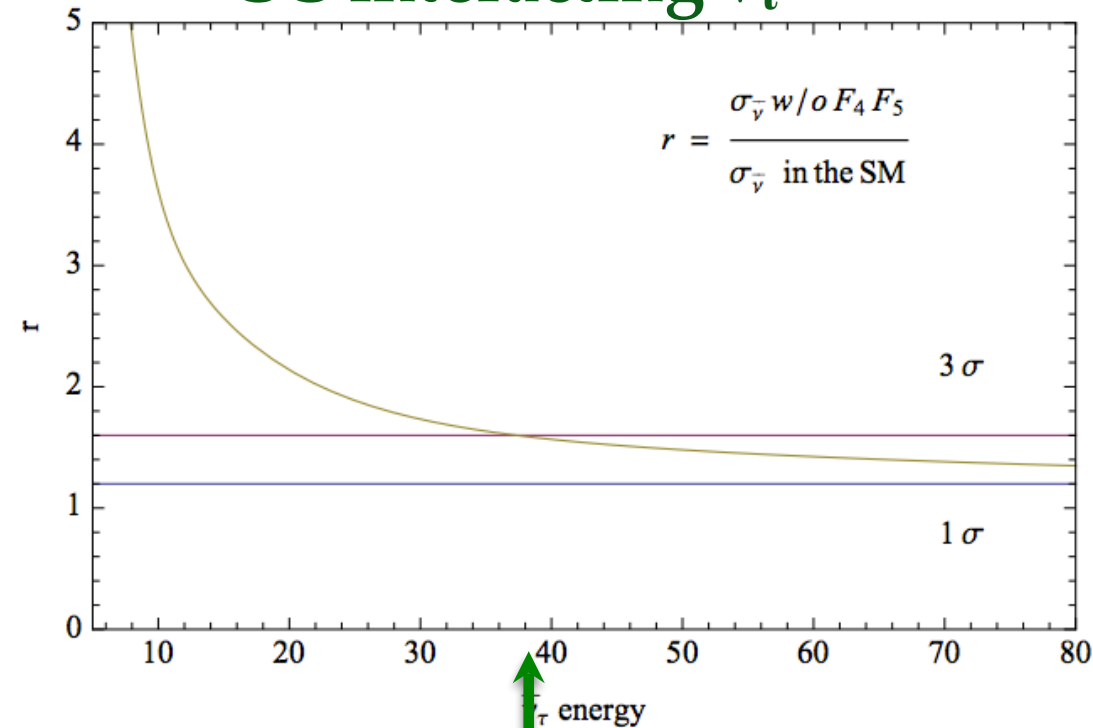
DETECTOR LAYOUT:

- ▶ 12 target planes interleaving the 11 brick walls at a few mm distance
- ▶ Transverse size of about $2 \times 1 \text{ m}^2$



SENSITIVITY TO F_4 AND F_5

CC interacting $\bar{\nu}_\tau$



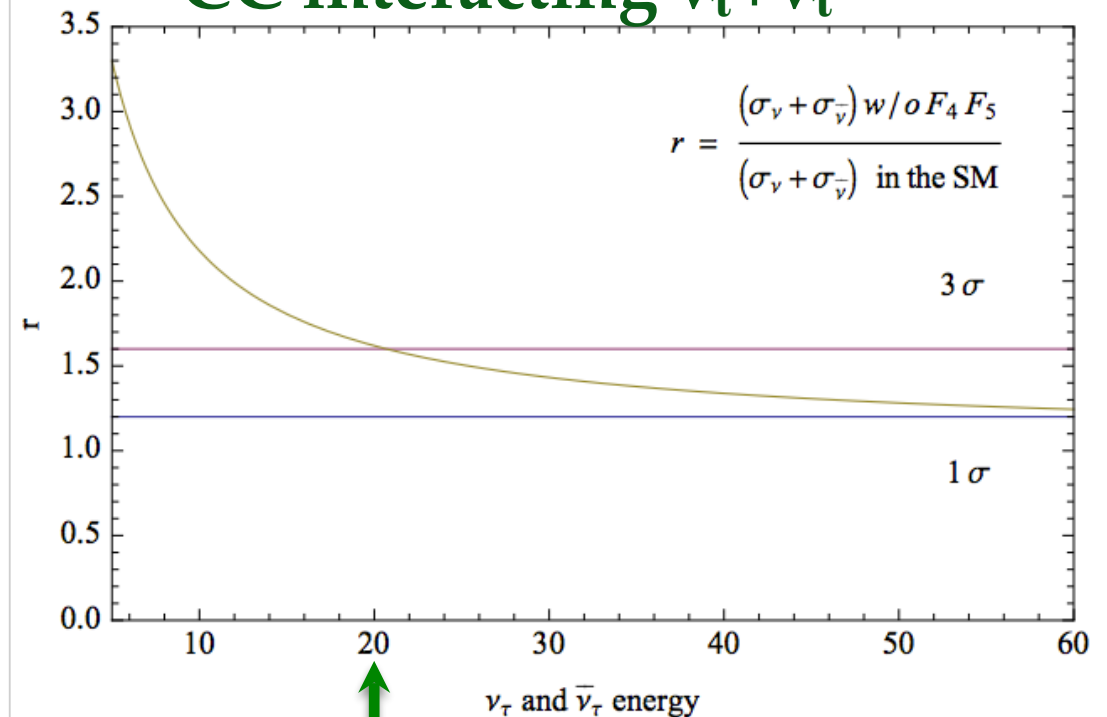
$E(\bar{\nu}_\tau) < 38 \text{ GeV}$
(~300 events expected)

$$r > 1.6$$

→ evidence for non-zero values of F_4 and F_5

r = ratio between the cross sections in the two hypotheses

CC interacting $\nu_\tau + \bar{\nu}_\tau$



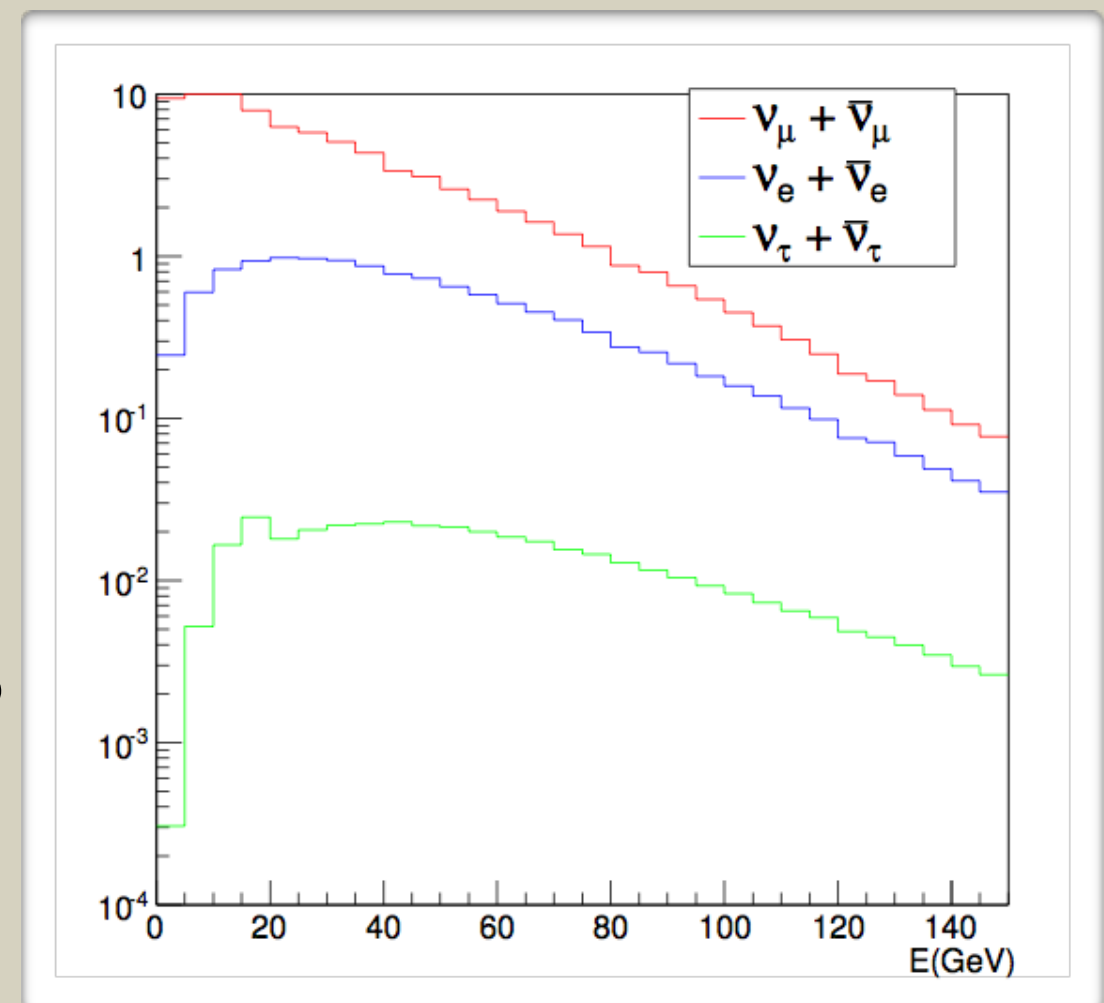
$E(\nu_\tau + \bar{\nu}_\tau) < 20 \text{ GeV}$
(~420 events expected)

NEUTRINO PHYSICS @SHiP

	$\langle E \rangle$ (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
$N_{\bar{\nu}_\mu}$	28	6.7×10^5
$N_{\bar{\nu}_e}$	46	9.0×10^4
$N_{\bar{\nu}_\tau}$	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



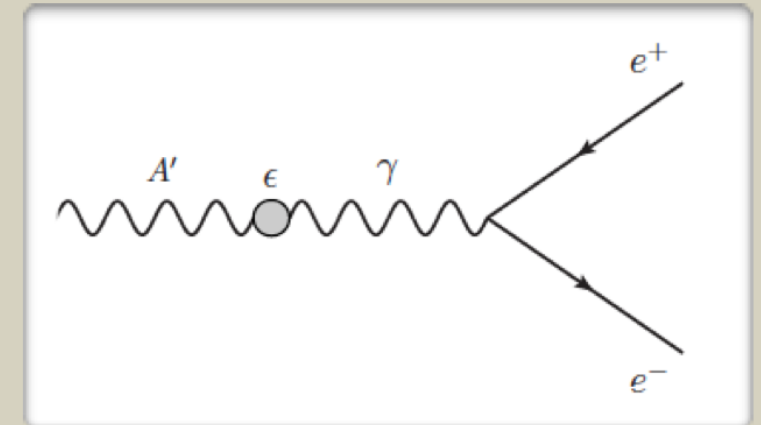
NEW PHYSICS IN THE HIDDEN SECTOR

Standard Model portals

► **D=2 Vector Portal**

Kinetic mixing with massive dark / secluded / para-photon V

→ Interaction with 'mirror world' constituting dark matter



► **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

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

► **D=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