THE SHiP PROJECT

SEARCH FOR HIDDEN PARTICLES

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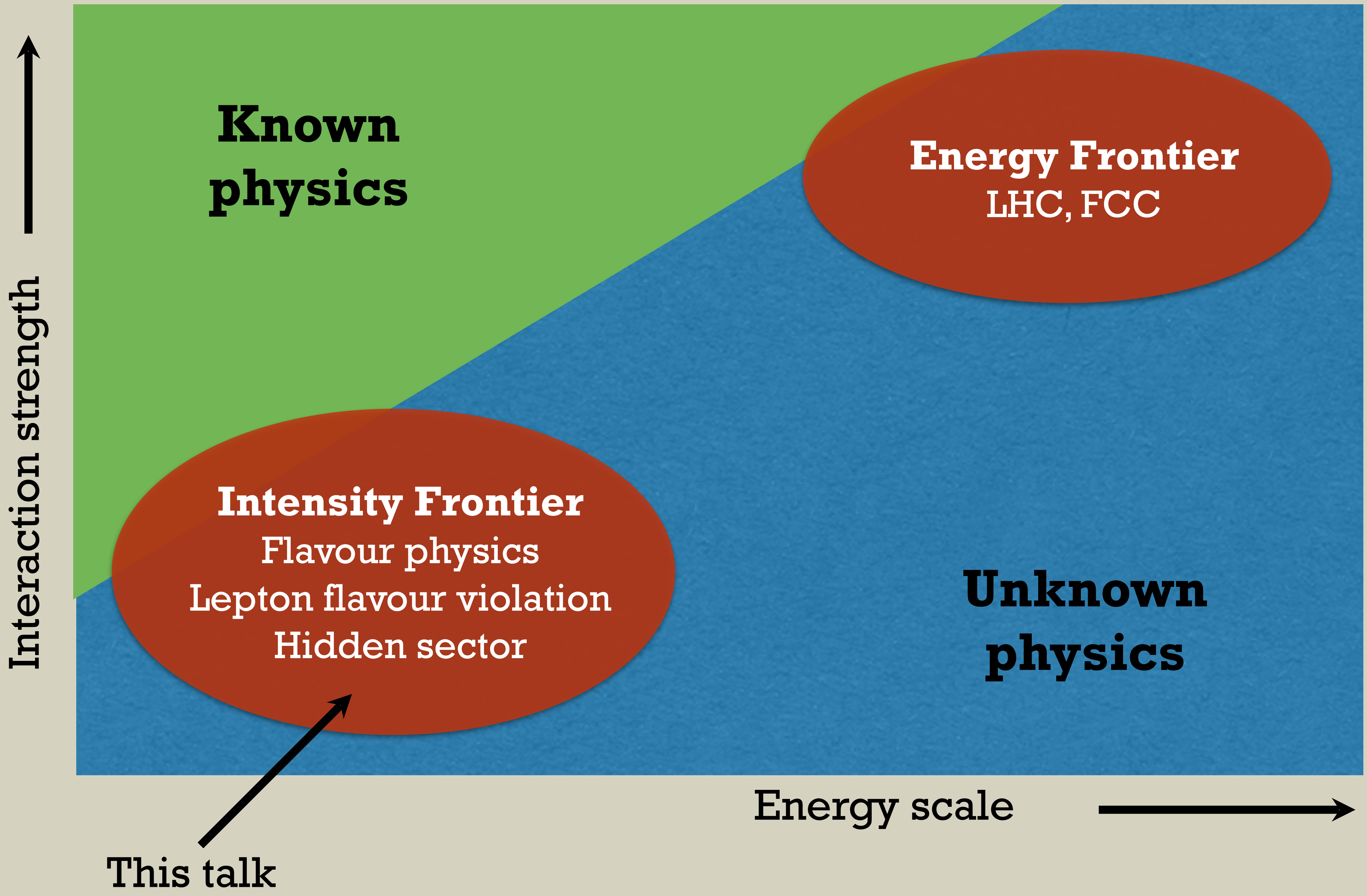
INTRODUCTION

- 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

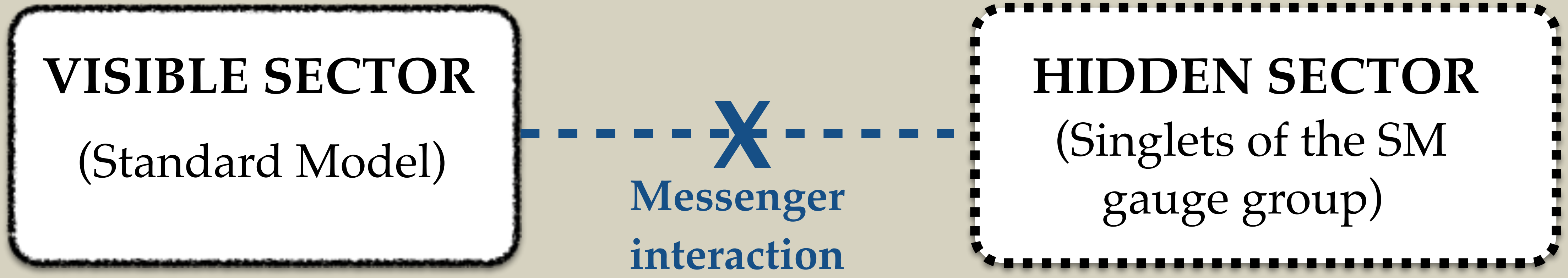
- SM is not a complete theory: explanation of experimental observations "Beyond the Standard Model" still missing
  - **Neutrino masses and oscillations**
  - **Baryon asymmetry of the Universe (BAU)**
  - **Dark Matter**

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**”



VISIBLE SECTOR

(Standard Model)

Messenger interaction

HIDDEN SECTOR

(Singlets of the SM gauge group)

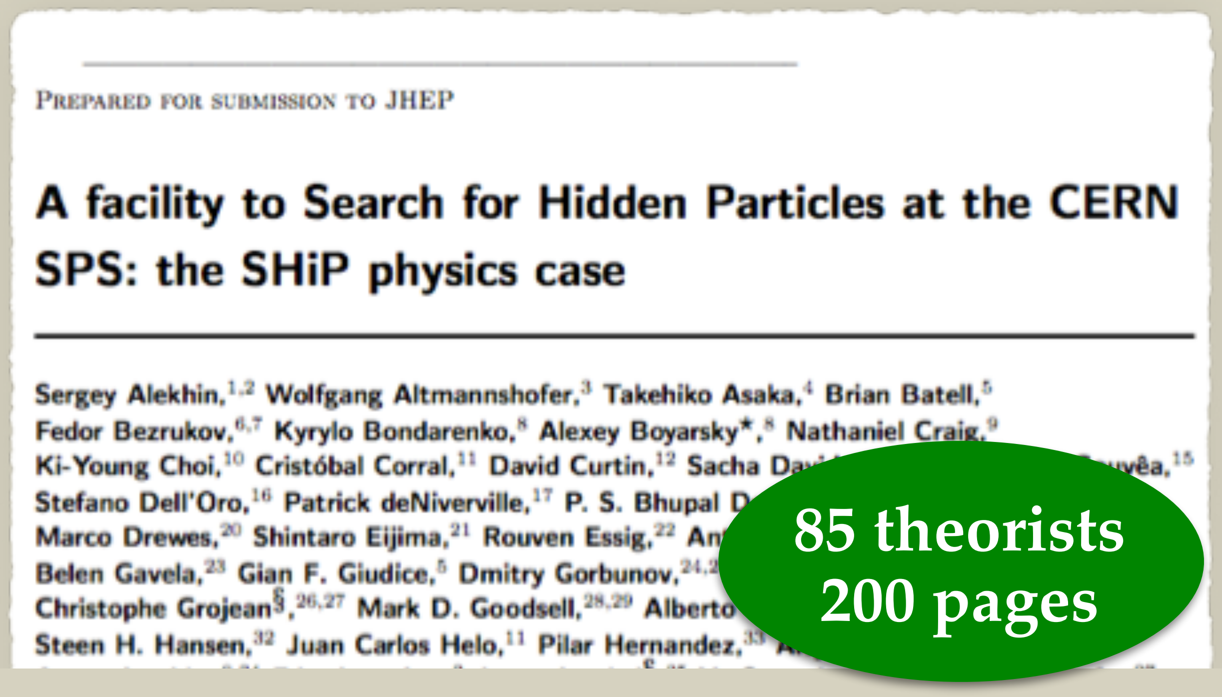
- **SHiP**: new fixed target facility at the intensity frontier to explore Hidden Sector
- Neutrino physics

- Large variety of particles searched for and of theoretical models tested: scalar portal, vector portal, neutrino portal, axion portal …

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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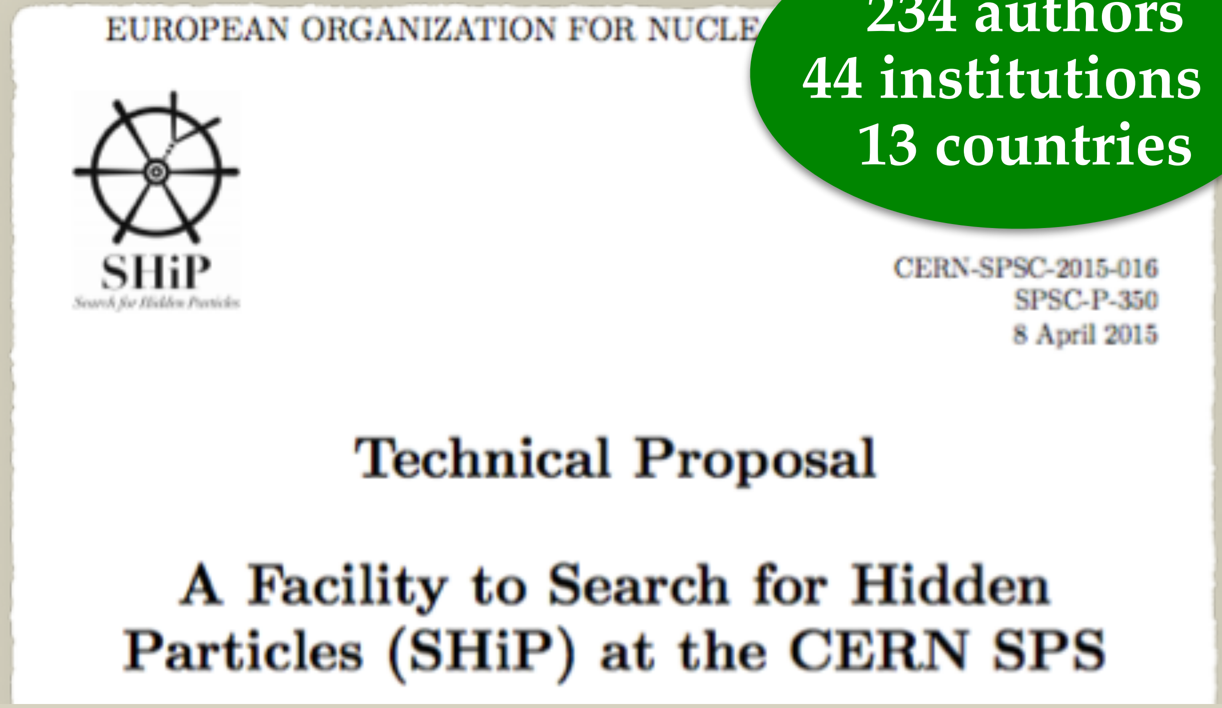
Steen H. Hansen,[32] Juan Carlos Helo,[11] Pilar Hernandez,[33]

85 theorists
200 pages

TECHNICAL

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

234 authors
44 institutions
13 countries



EUROPEAN ORGANIZATION FOR NUCLE

SHiP
Search for Hidden Particles

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

Technical Proposal

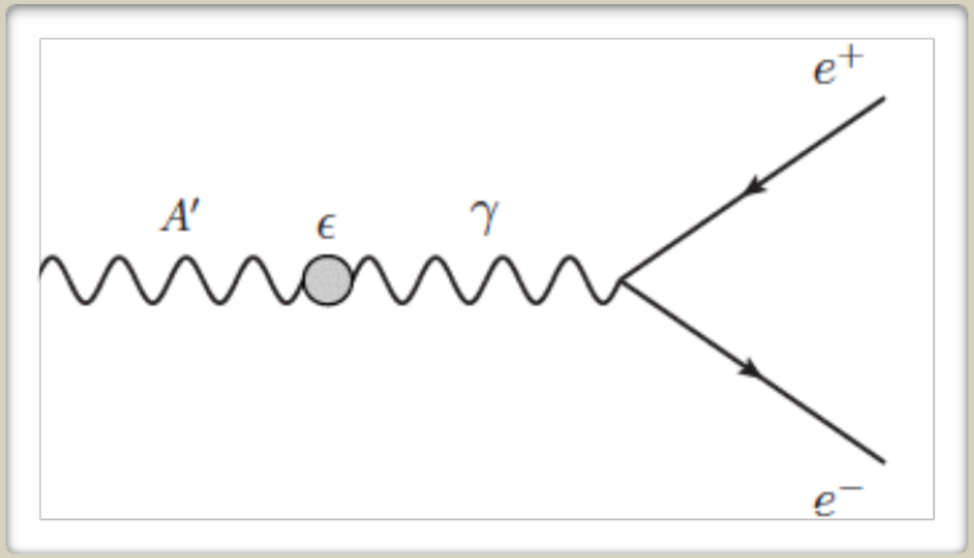
A Facility to Search for Hidden Particles (SHiP) at the CERN SPS

Proposals submitted to SPSC	April 2015
Referee's comments to TP	May 2015
Addendum to TP submitted	October 2015
Referee's comments to PP	September 2015
Addendum to PP submitted	December 2015

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 $\tau_\gamma < 0.1$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

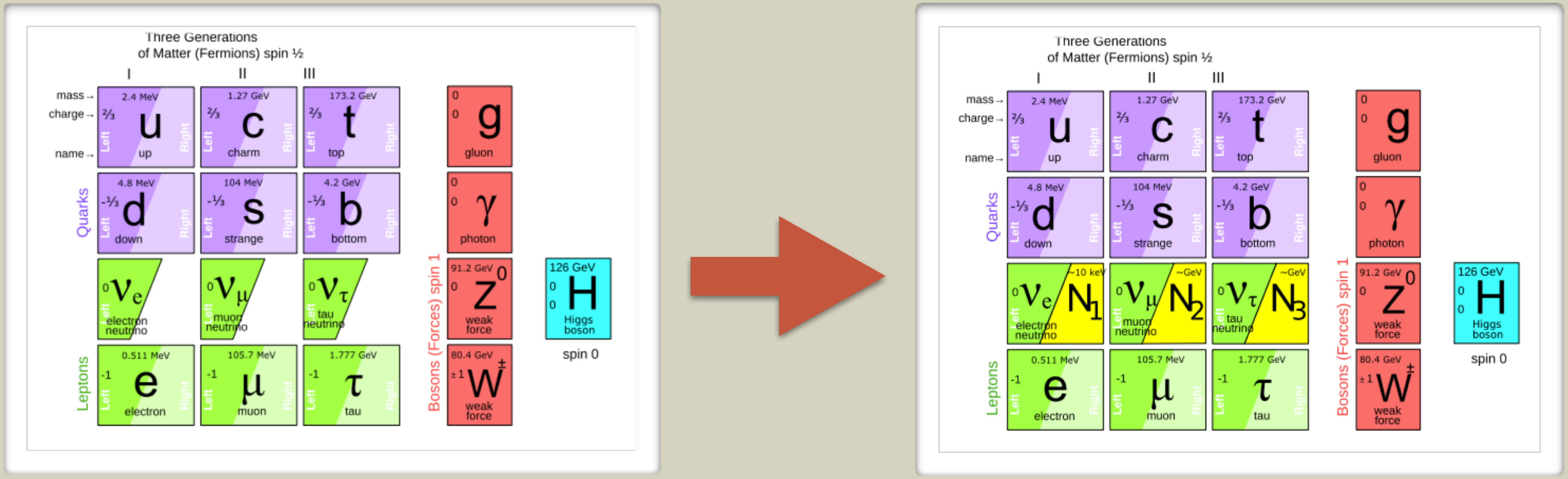
… and possibly higher dimensional operators portals and **Super-Symmetric** portals

(light neutralino, light sgoldstino, …)

NEUTRINO PORTAL

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

3 additional Heavy Neutral Leptons: right-handed Majorana neutrinos



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

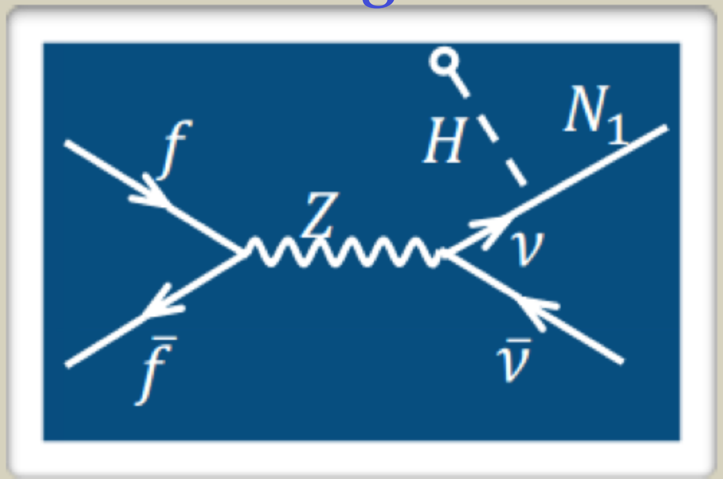
T.Asaka, M.Shaposhnikov PL B620 (2005) 17

M.Shaposhnikov Nucl. Phys. B763 (2007) 49

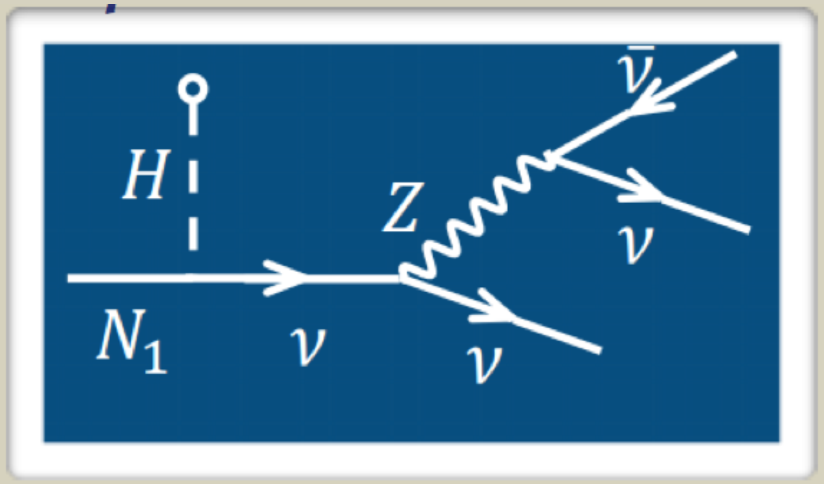
N_1: DARK MATTER CANDIDATE

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

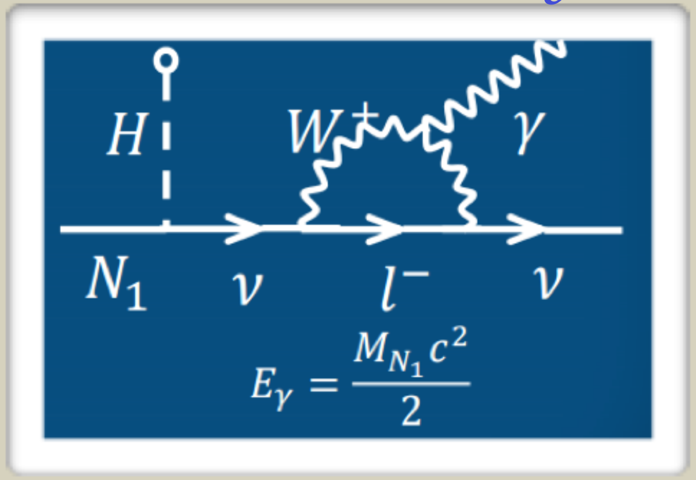
mixing ν-N

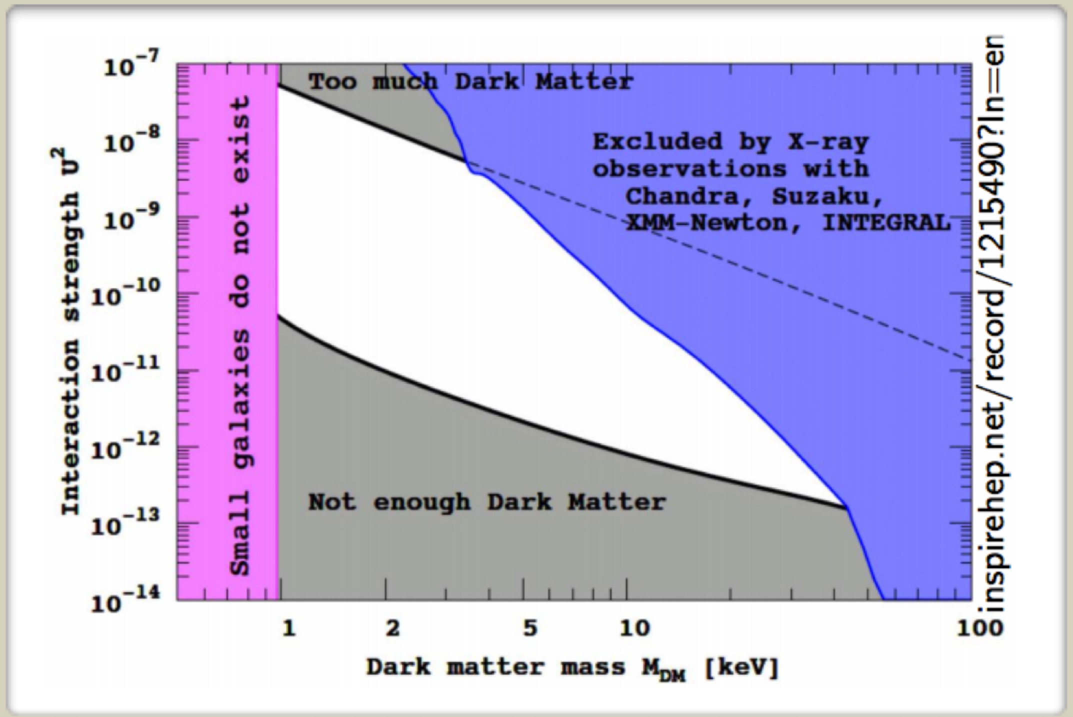


dominant process



subdominant radiative decay





inspirehep.net/record/1215490?ln=en

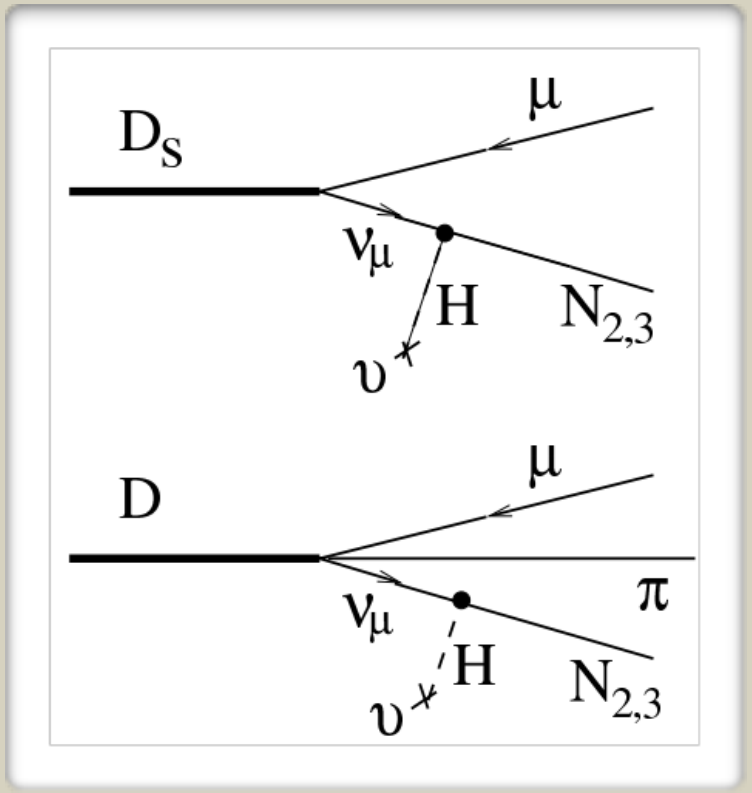
- **GALACTIC HINTS**
- *Astr. Phys. J. 789 (2014) 13, Phys. Rev. Lett. 113 (2014) 251301*
- Not identified line in the X-ray spectrum of Andromeda and Perseus galaxies (E_γ=3.5 keV)

$N_{2,3}$: 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

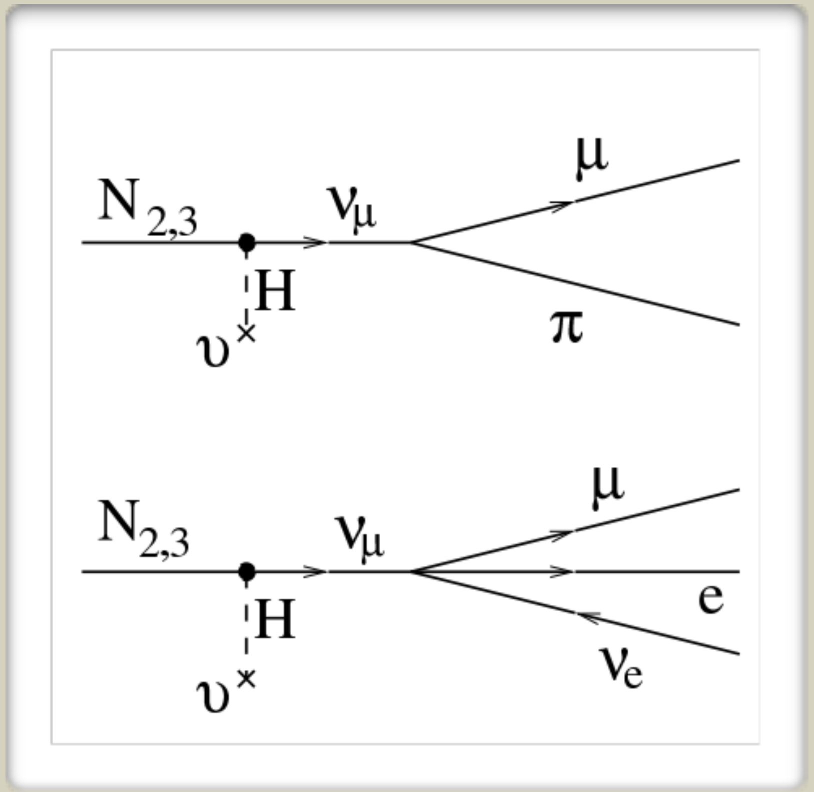
PRODUCTION

- 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

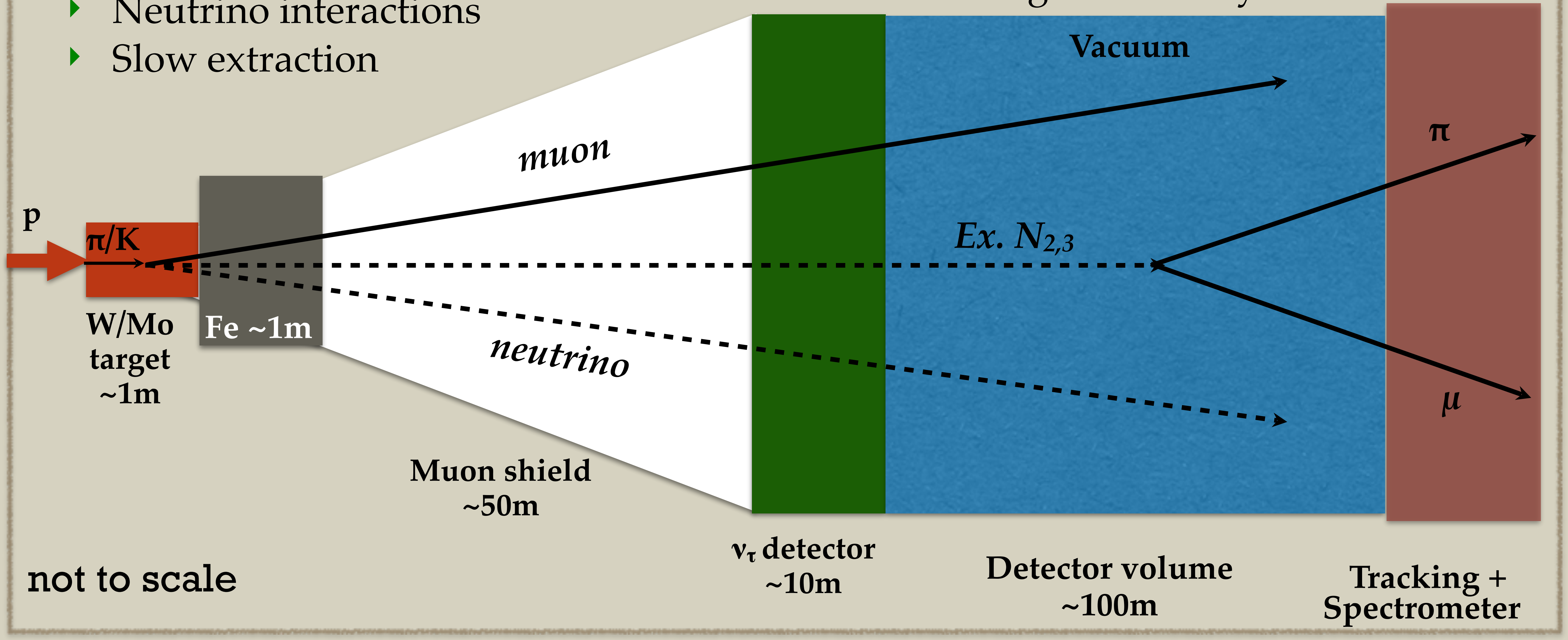
- Proposal: fixed target experiment at the CERN SPS
- SPS: 4x10^{13} protons per spill @ 400 GeV ➙ 2x10^{20} pot in 5 years (same as CNGS)

1) BACKGROUND REDUCTION

- Combinatorial background
- Neutrino flux
- Muon flux
- Neutrino interactions
- Slow extraction

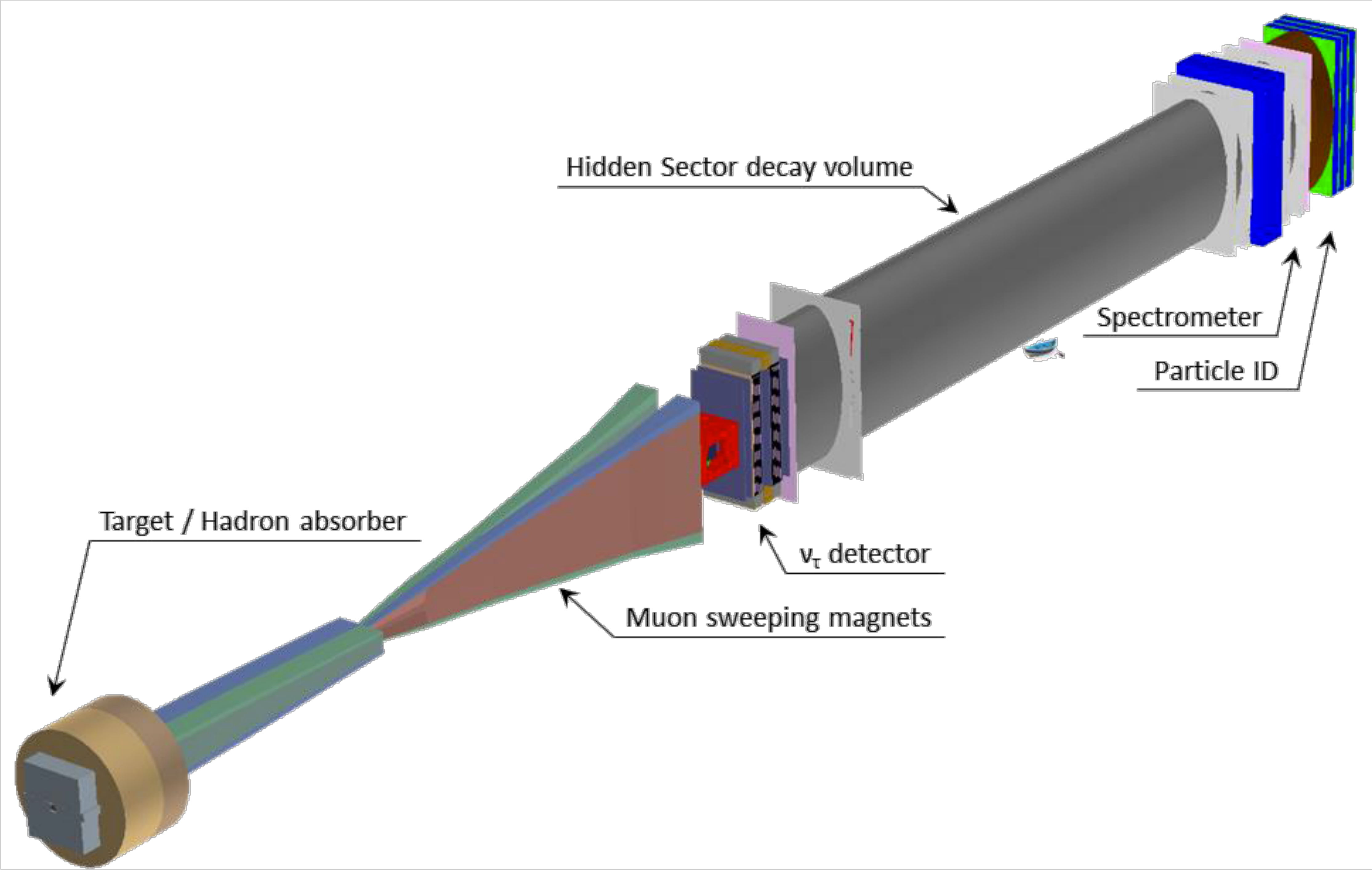
1) SIGNAL ENHANCEMENT

- Geometrical acceptance
- Reconstruction of decays
- High sensitivity



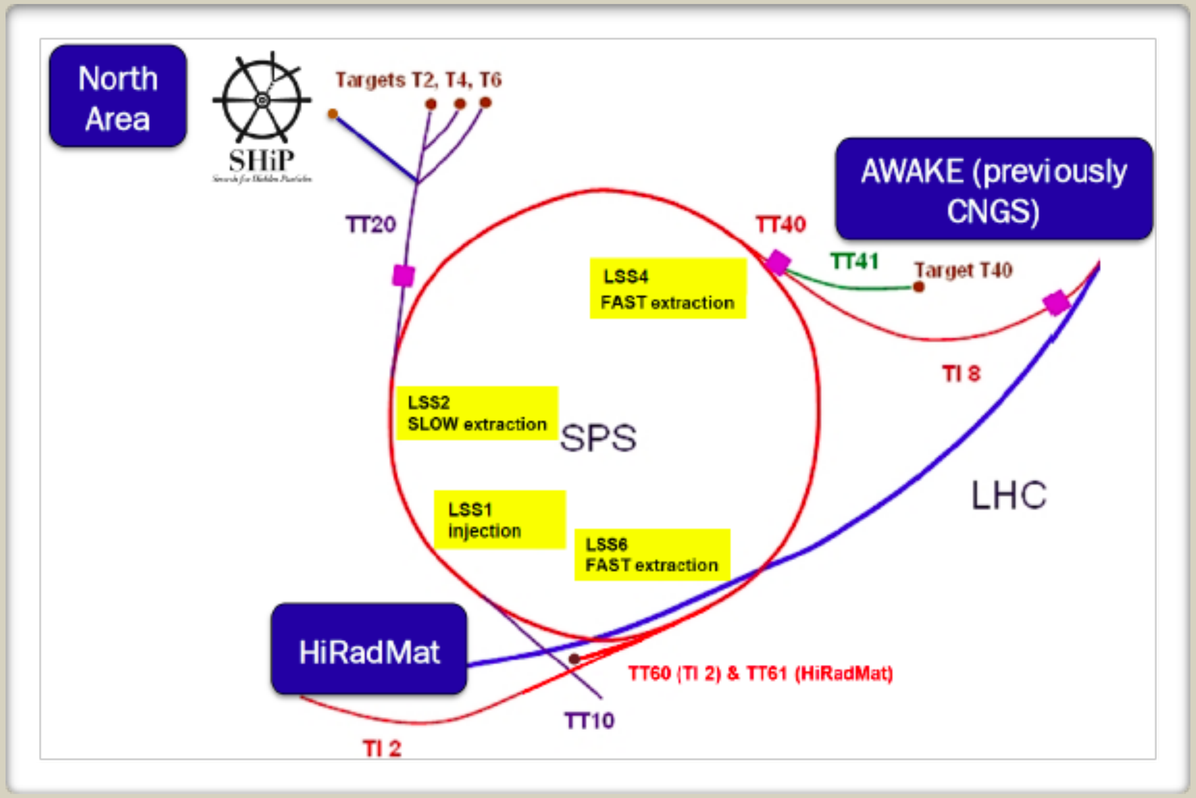
not to scale

DETECTOR LAYOUT



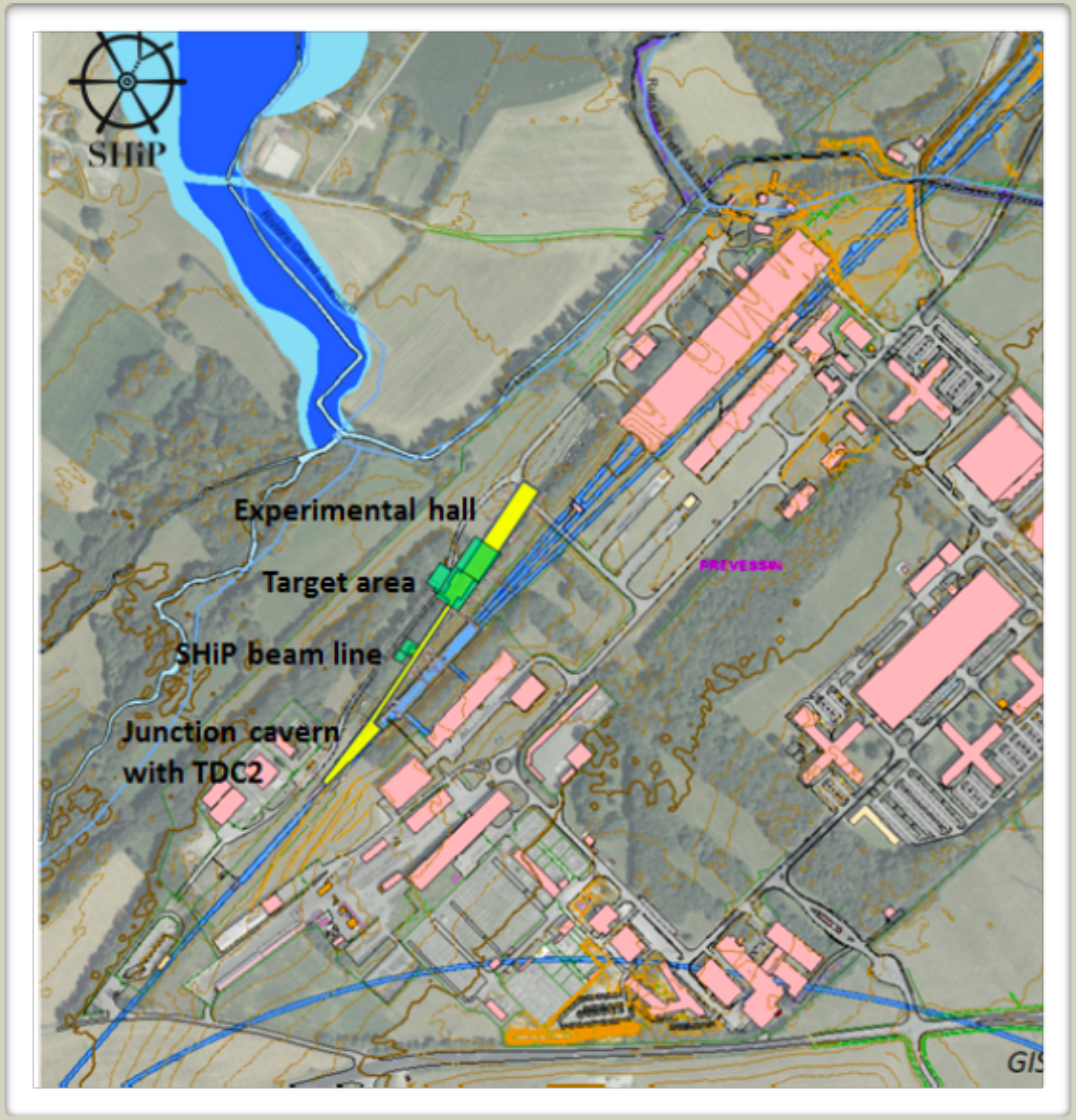
THE FIXED-TARGET FACILITY AT SPS

High-intensity proton beam: 4x10^{19} pot/yr, 5 years run



Location: Prevessin North Area site

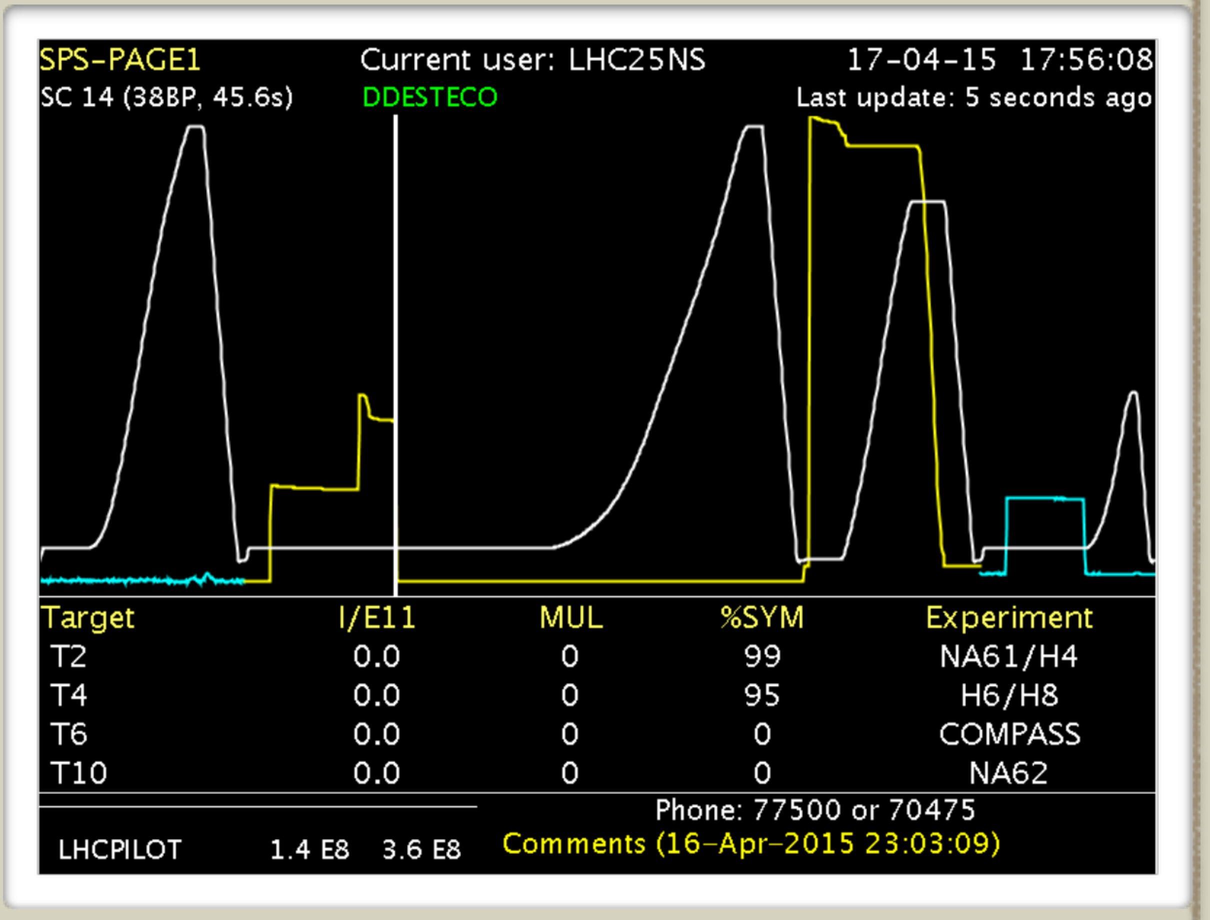
Sharing of the TT20 transfer line and slow extraction mode with the fixed target programmes



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



SPS-PAGE1 Current user: LHC25NS 17-04-15 17:56:08

SC 14 (38BP, 45.6s) DDESTECO Last update: 5 seconds ago

Target	I/E11	MUL	%SYM	Experiment
T2	0.0	0	99	NA61/H4
T4	0.0	0	95	H6/H8
T6	0.0	0	0	COMPASS
T10	0.0	0	0	NA62

Phone: 77500 or 70475

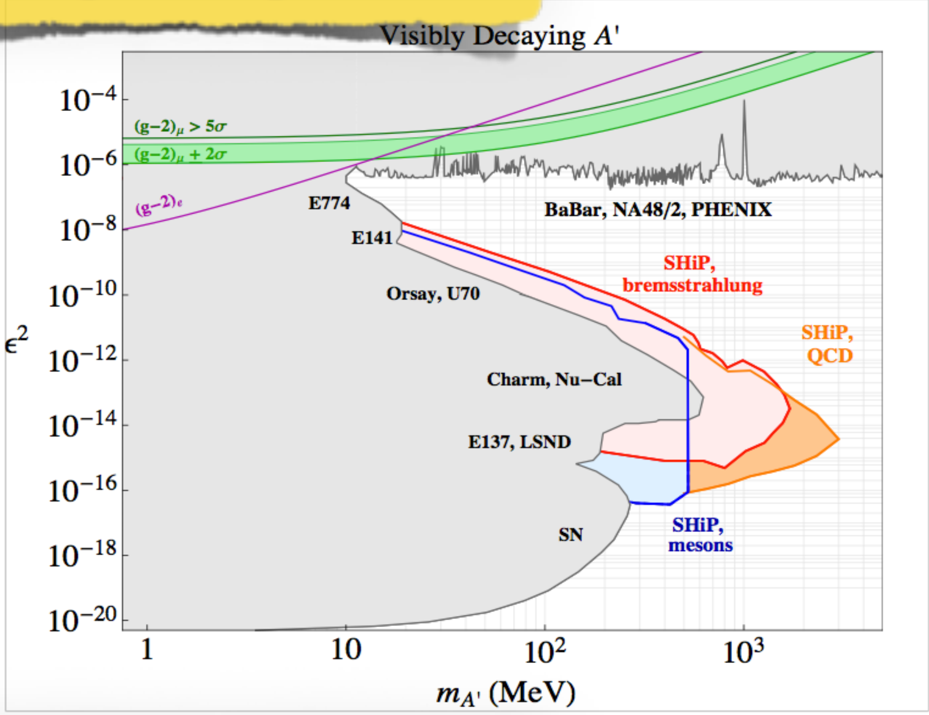
LHCPILOT 1.4 E8 3.6 E8 Comments (16-Apr-2015 23:03:09)

Successful test in April 2015

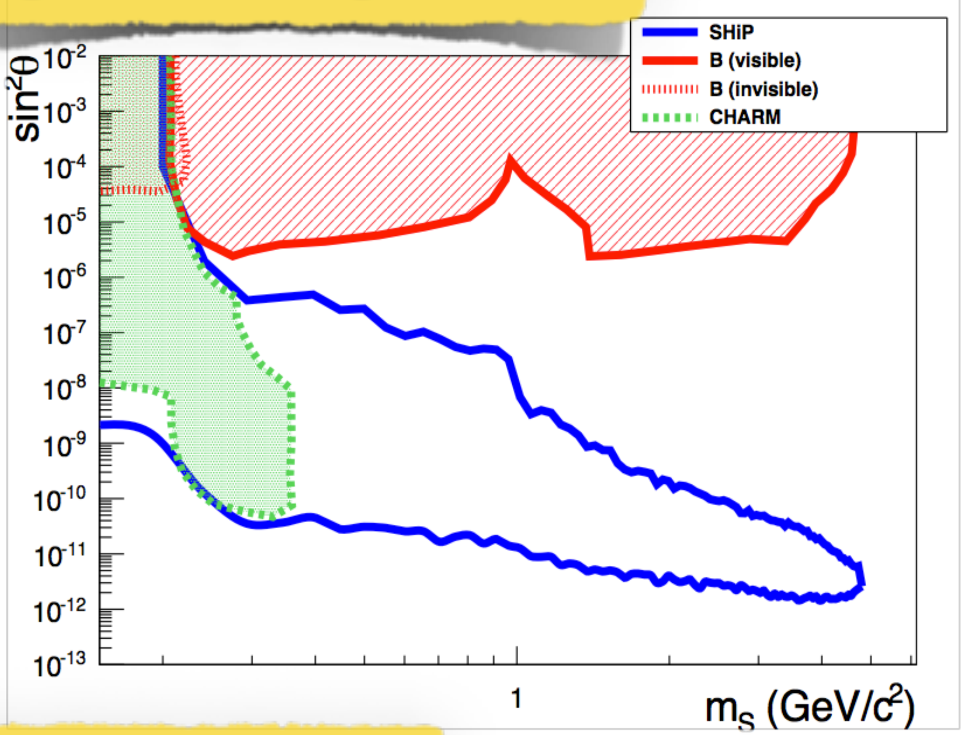
SENSITIVITIES

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

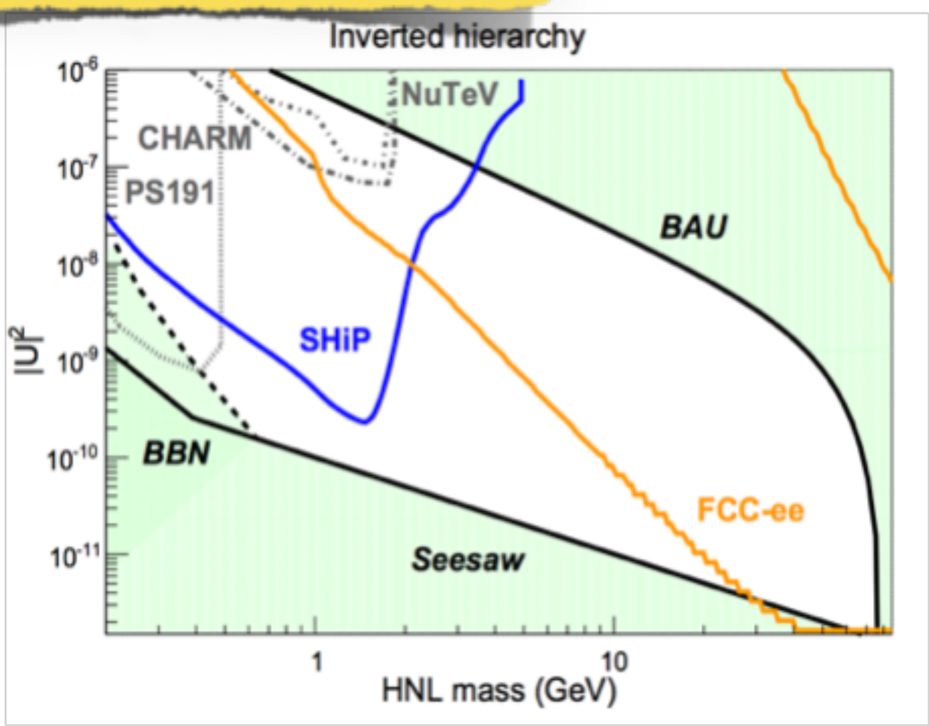
VECTOR PORTAL



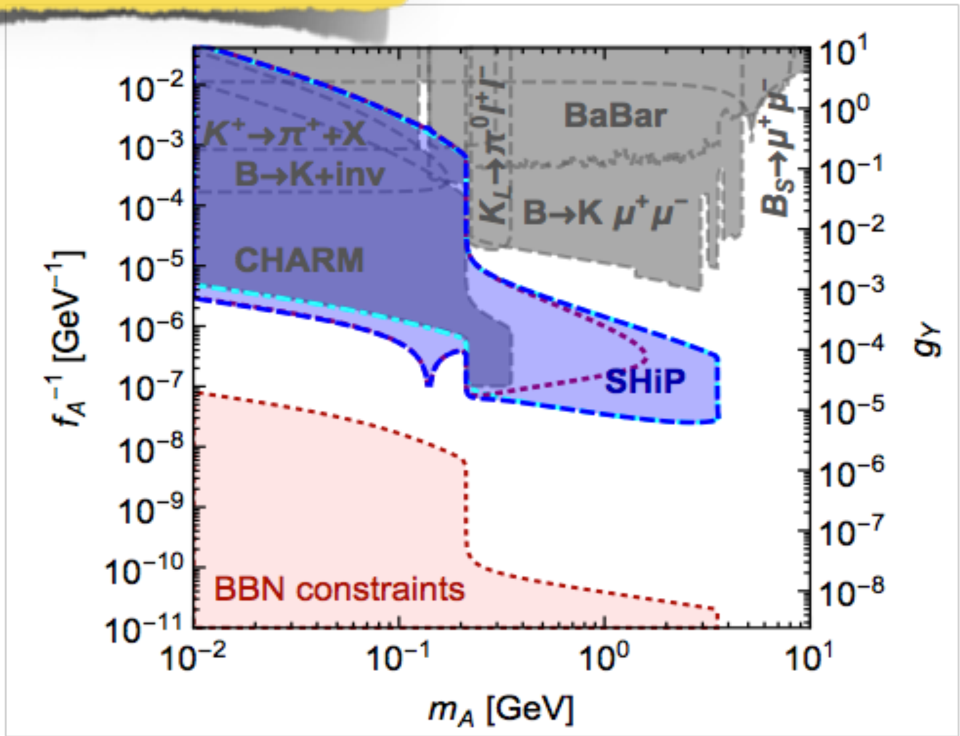
SCALAR PORTAL



NEUTRINO PORTAL

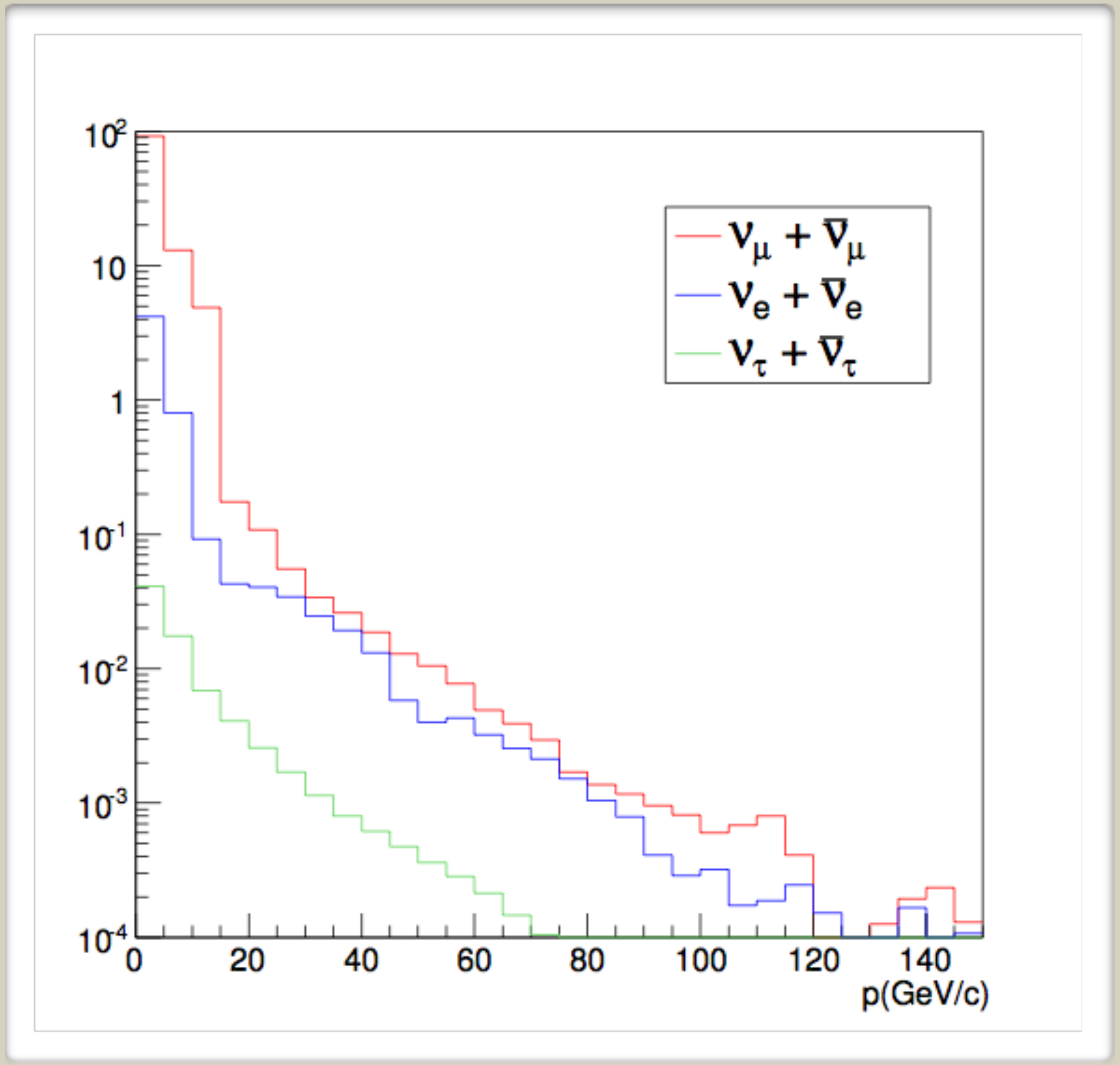


AXION PORTAL



NEUTRINO PHYSICS @SHIP

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



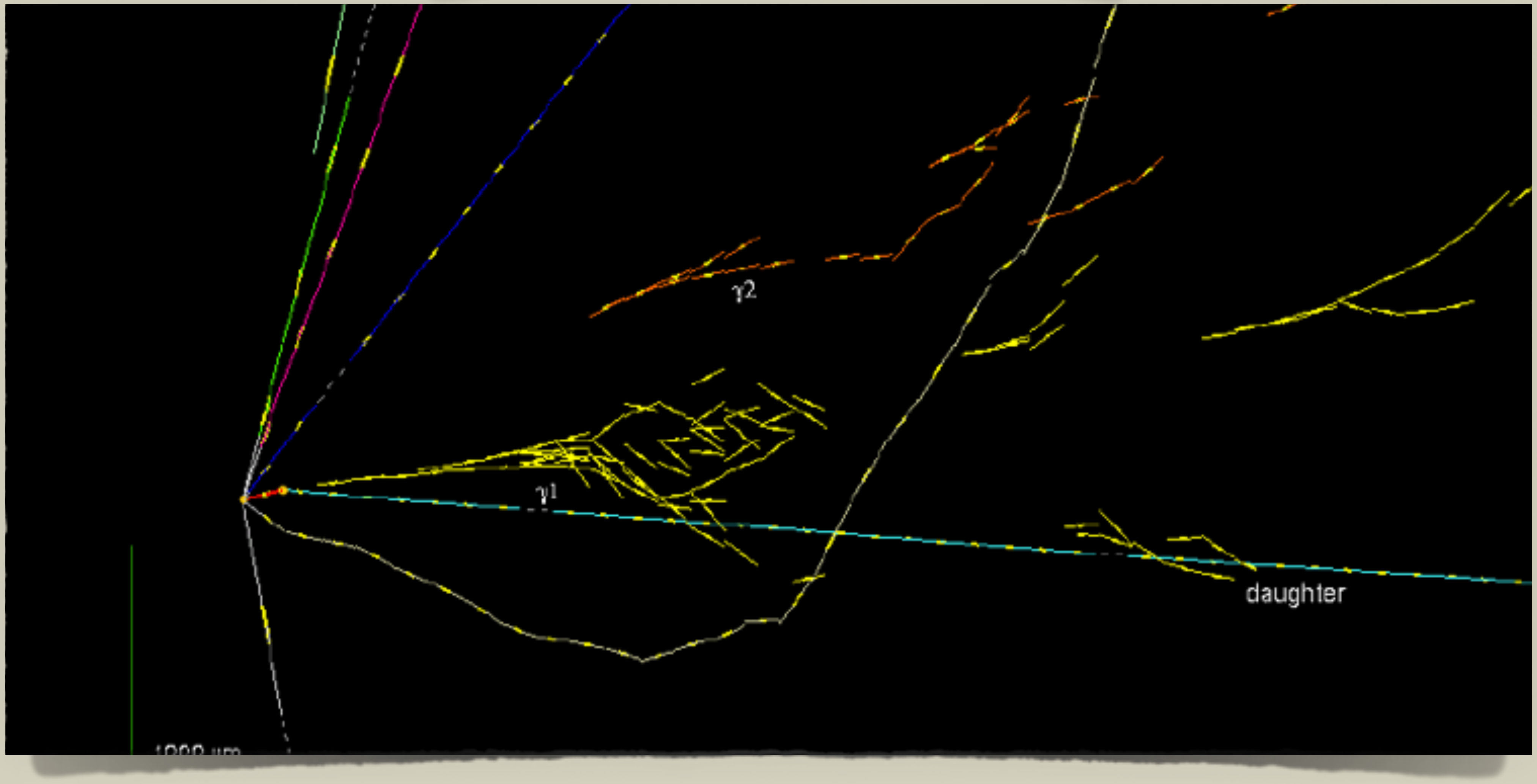
- Energy spectrum of different neutrino flavors @beam dump

TAU NEUTRINO PHYSICS

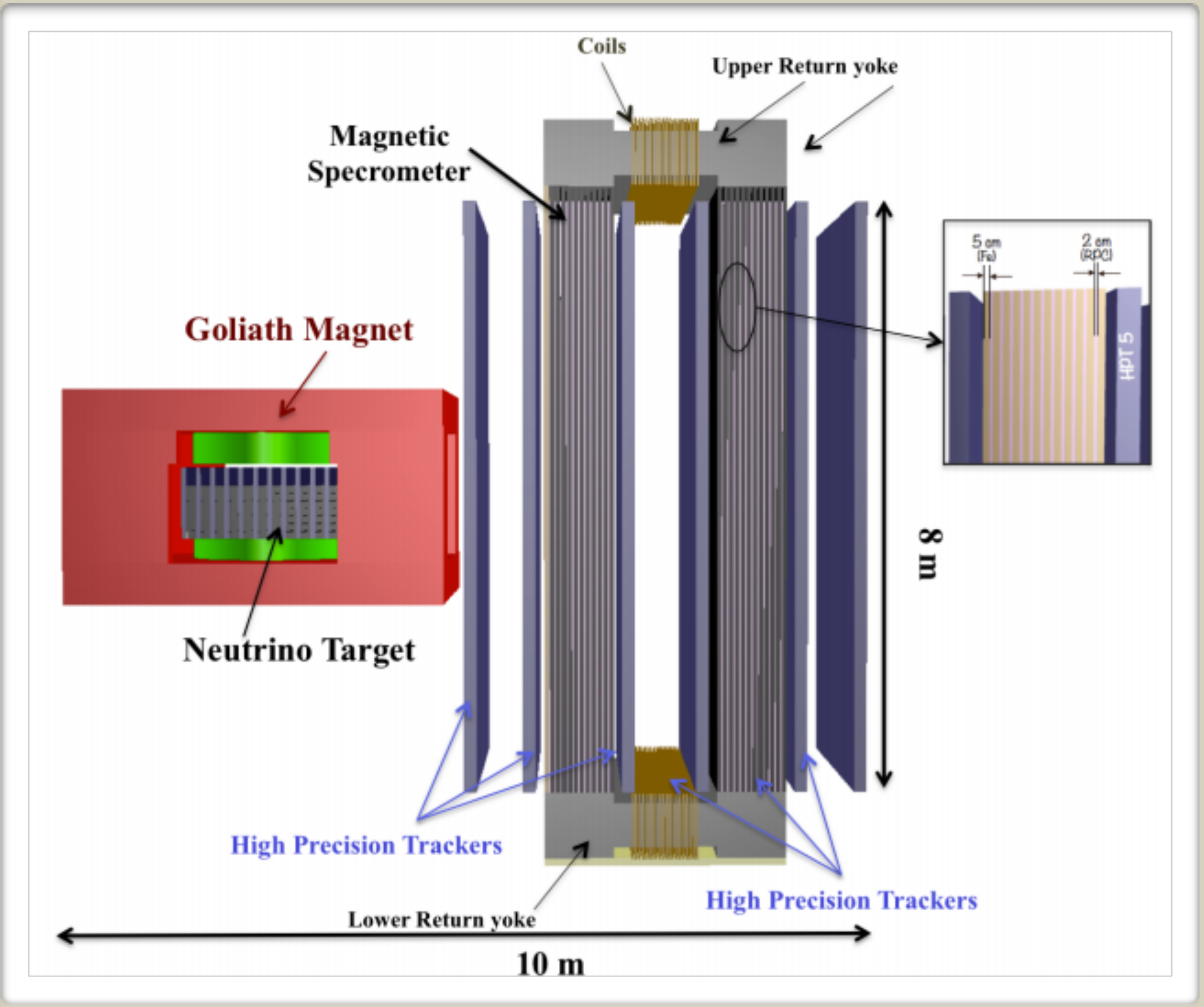
- $\boldsymbol{\nu_\tau}$: the less known particle in the Standard Model

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

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



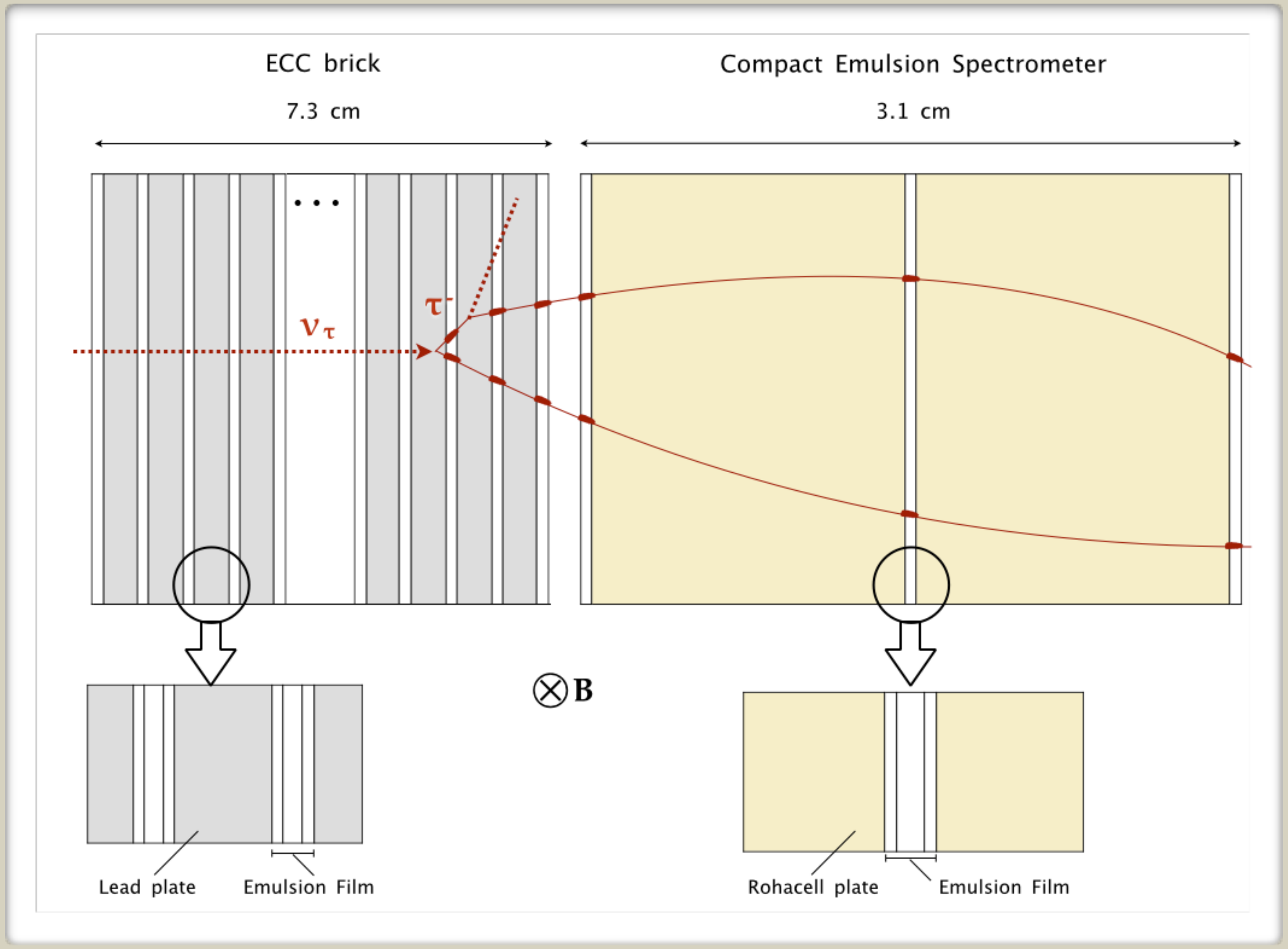
NEUTRINO DETECTOR



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



- 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

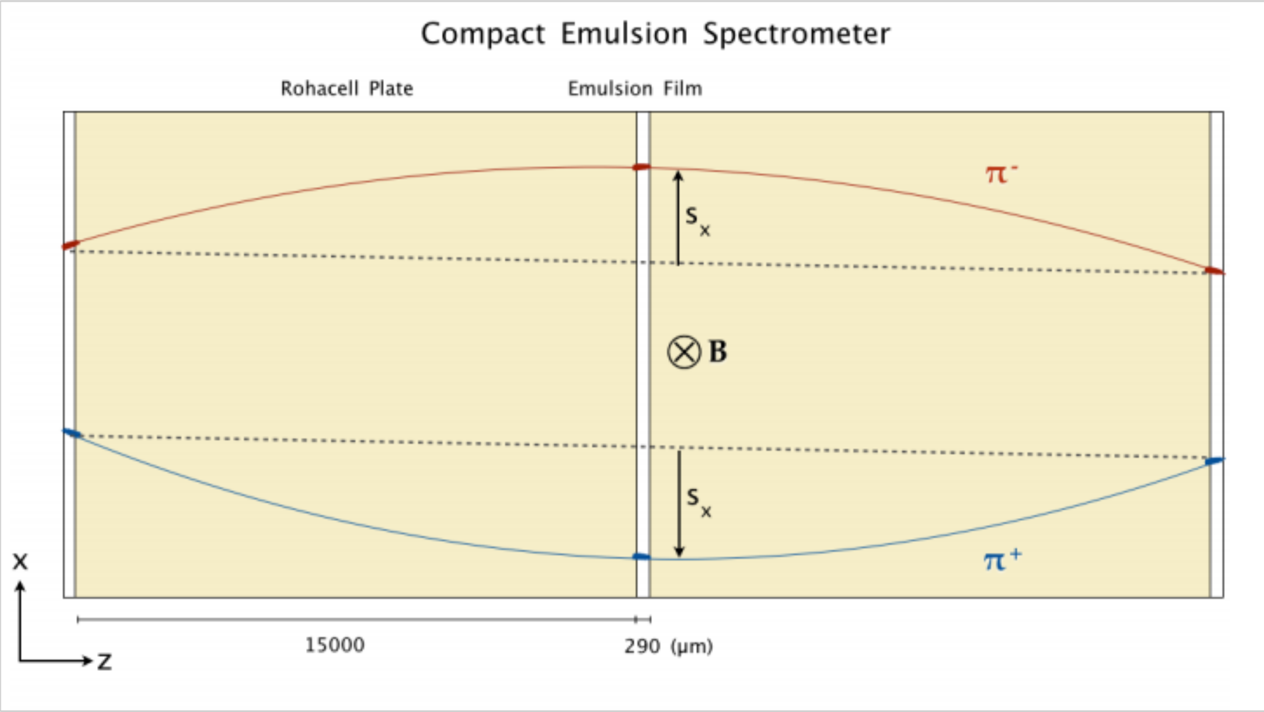
ν_τ /ANTI-ν_τ SEPARATION

REQUIREMENTS

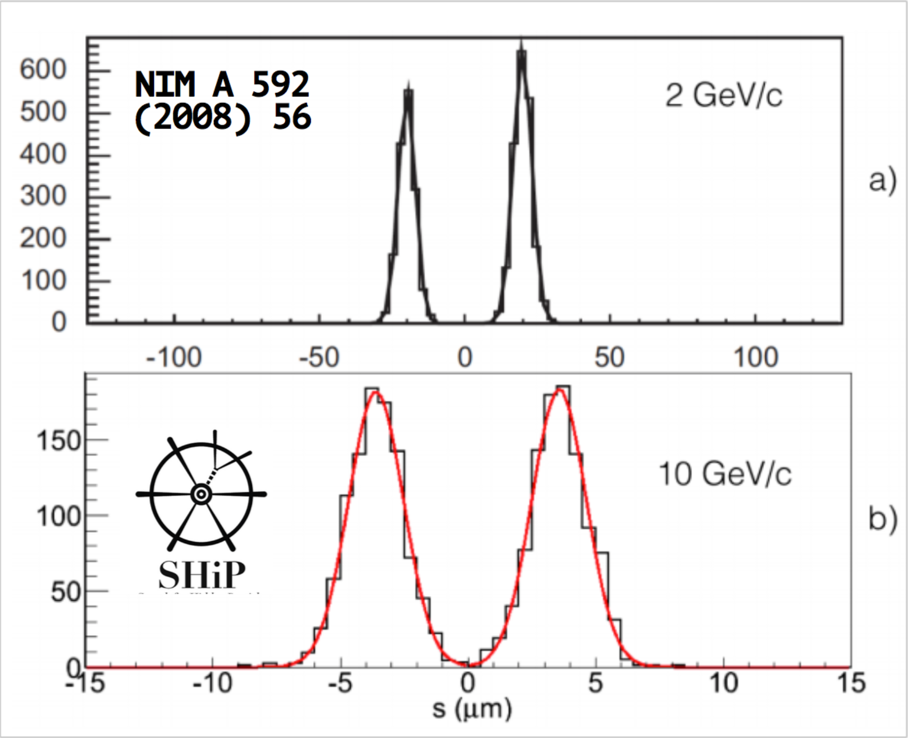
- Electric charge measurement of τ lepton decay products
- Key role for ν_τ/ν_τ separation in the τ→h decay channel
- Momentum measurement

LAYOUT

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



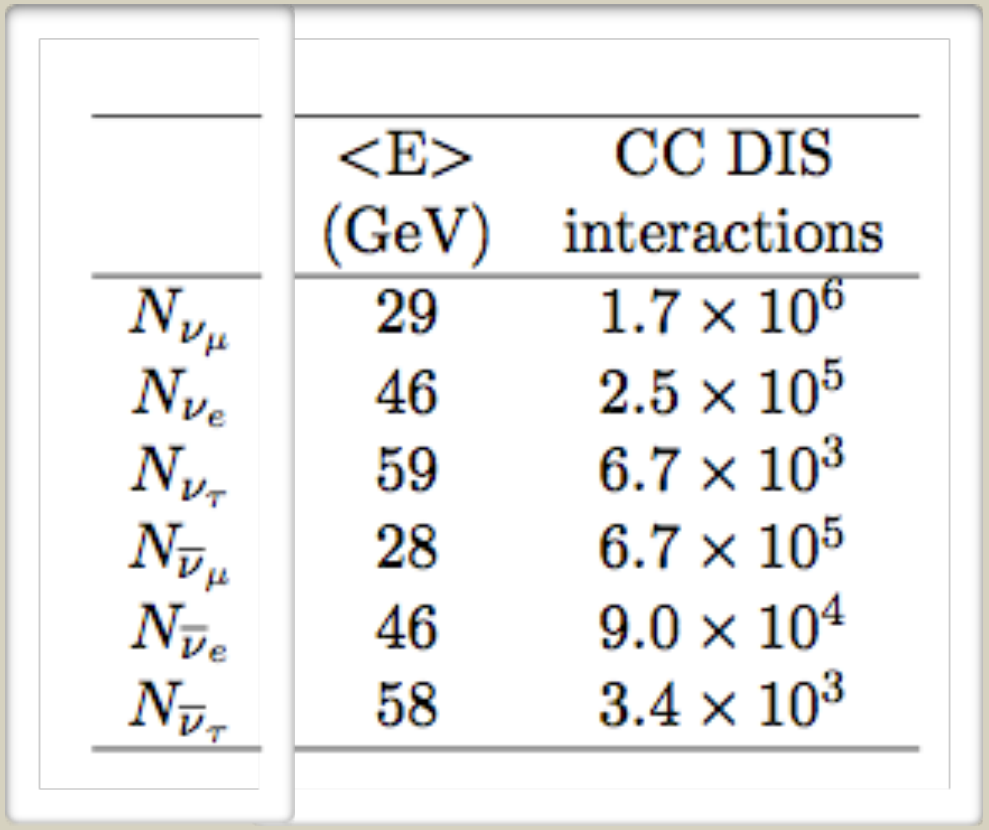
Charge measured from the curvature of the track with the **sagitta** method



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

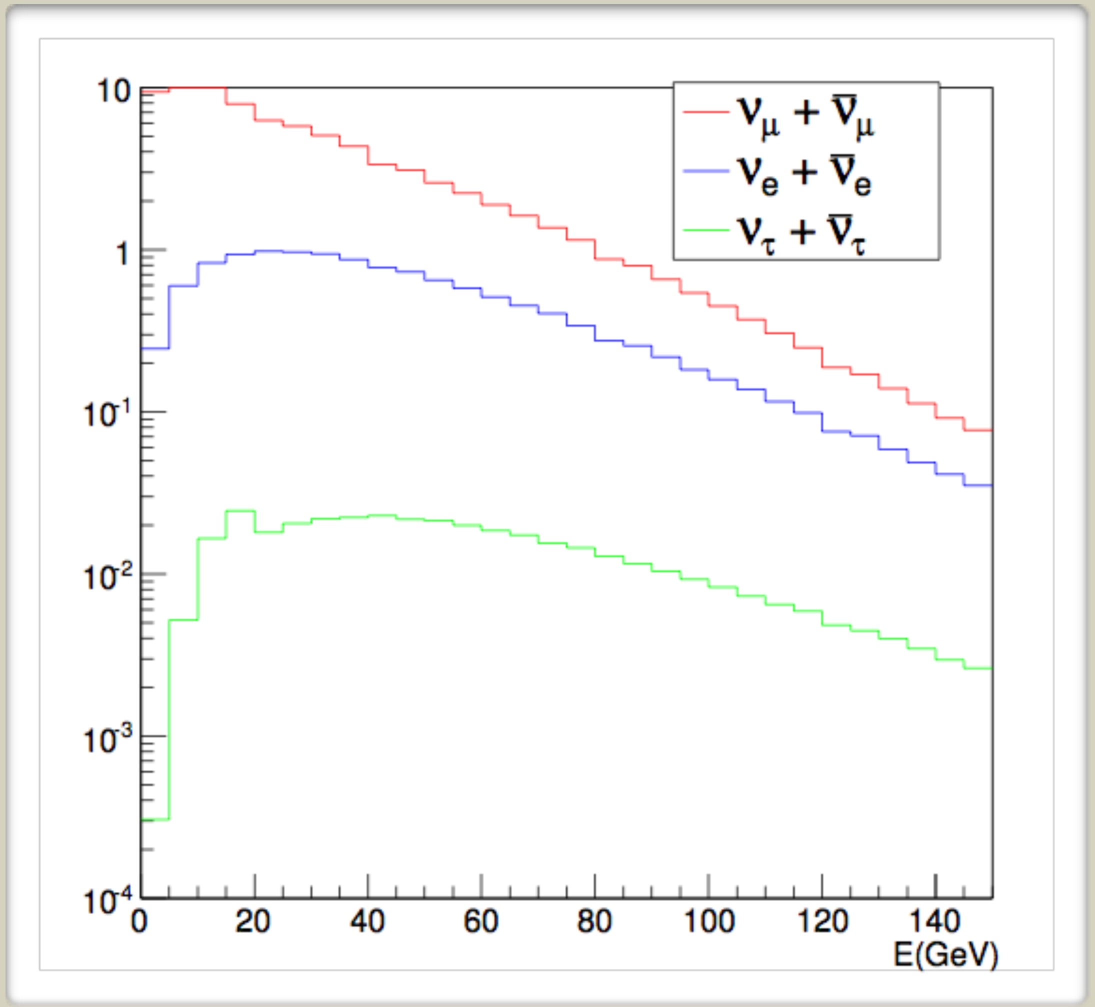
Neutrino Physics @SHiP



	<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 (2x10^{20} pot)

- Energy spectrum of different neutrino flavors interacting in the target



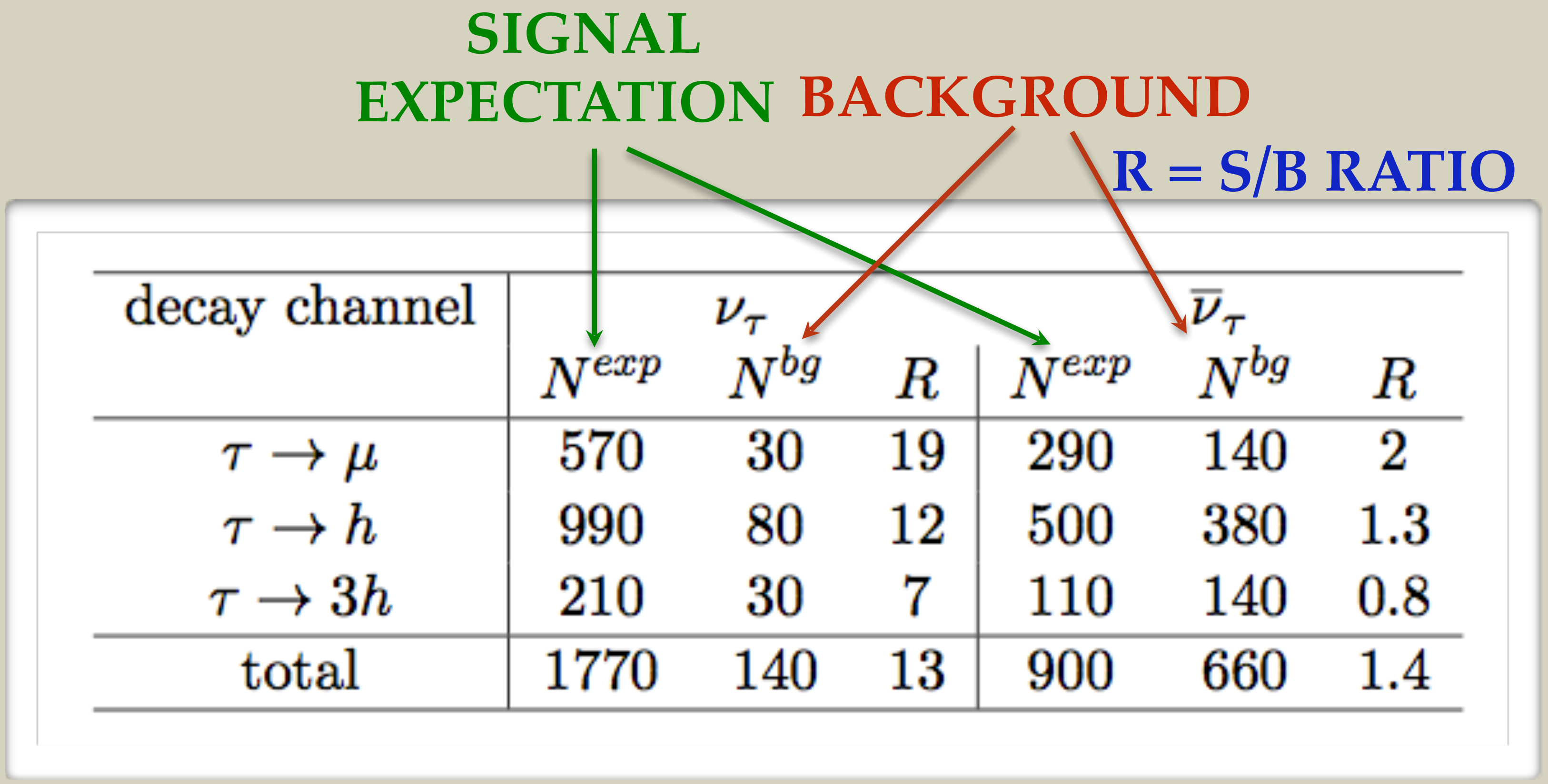
ν_τ PHYSICS

- 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

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



SIGNAL EXPECTATION

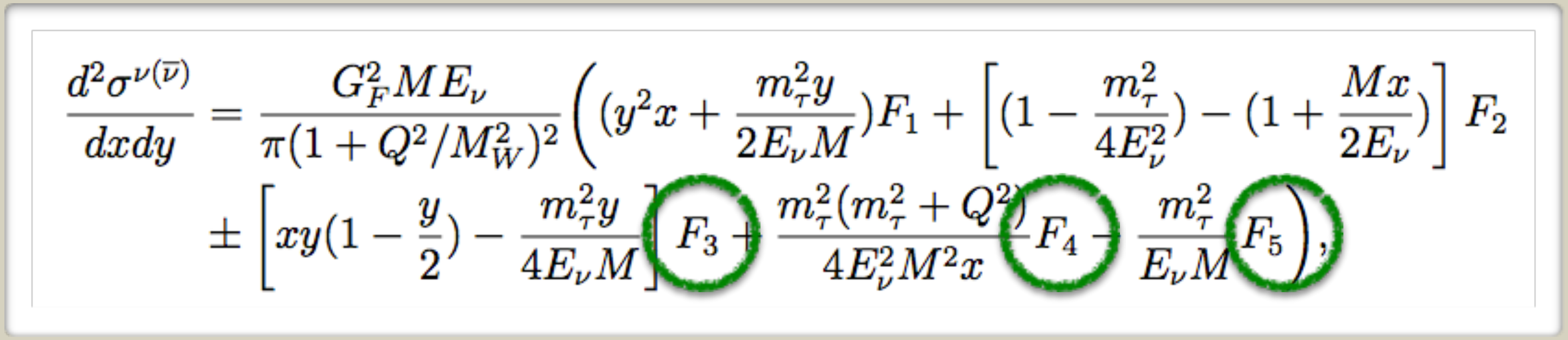
BACKGROUND

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

High rates of Deep Inelastic Scattering interactions from ***all three neutrino flavours*** on target nucleons expected



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

Structure functions

- F_3 → Opposite sign for ν and ν̄
- F_4
- F_5

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 ~ 1%

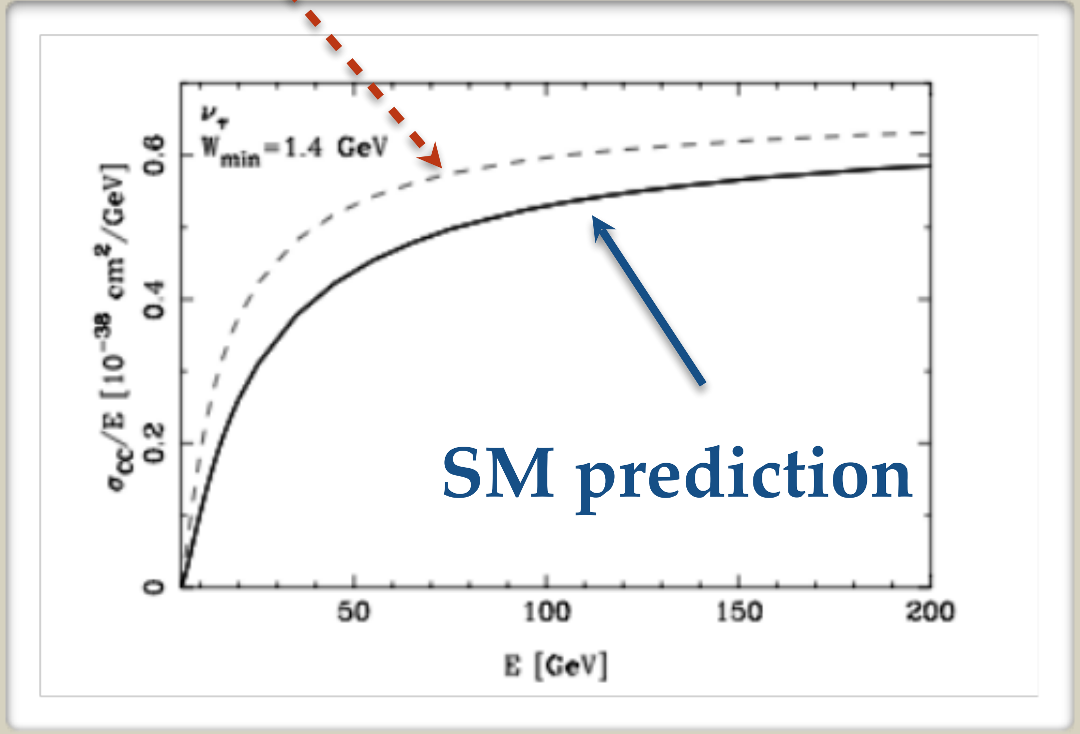
SENSITIVITY TO F_4 AND F_5

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 ν_τ CC DIS cross sections

➝ increase of the number of expected ν_τ and anti-ν_τ interactions

$F_4 = F_5 = 0$

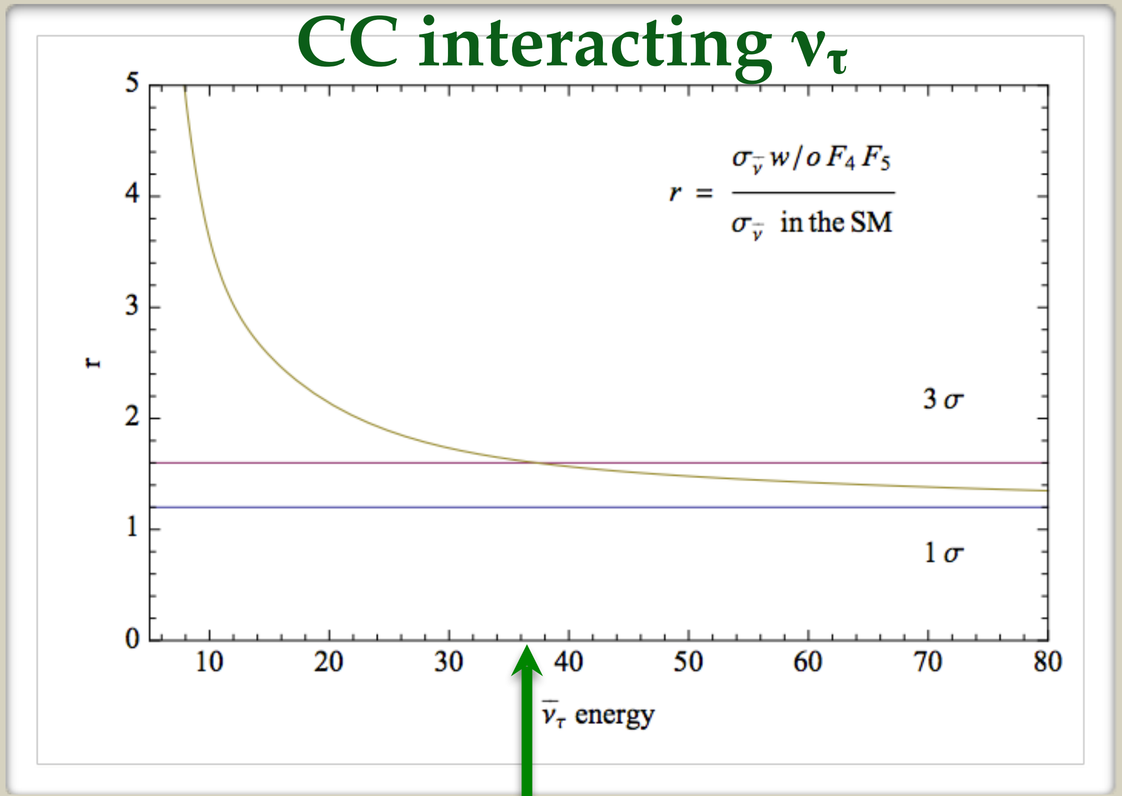


SM prediction

ν_τ CC DIS cross-section

r = ratio between the cross sections in the two hypotheses

CC interacting ν_τ



r>1.6

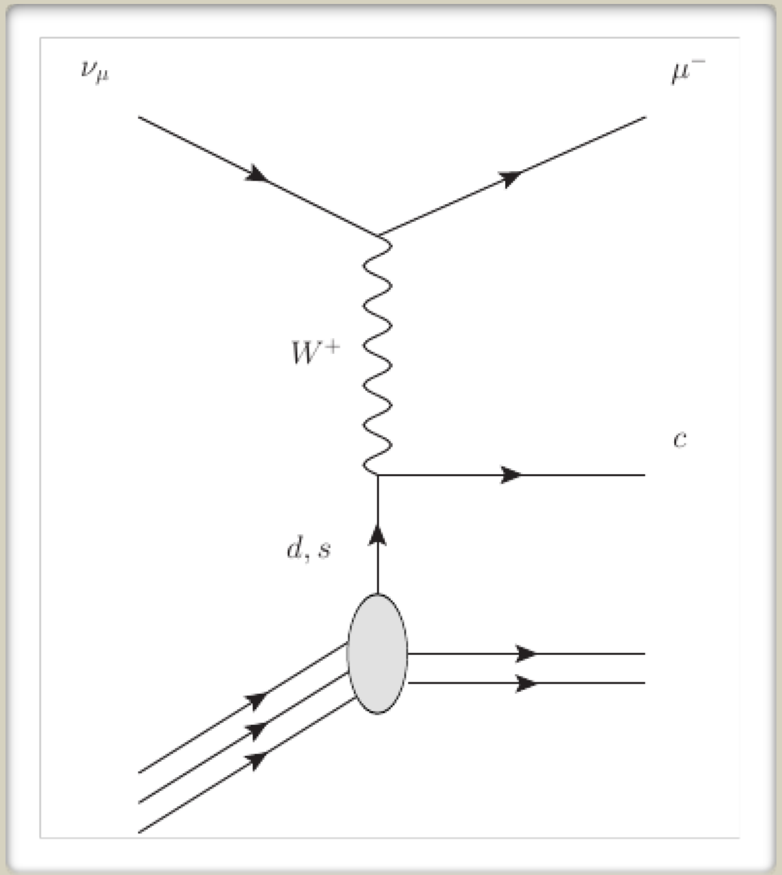
➝ evidence for non-zero values of F_4 and F_5

$E(\nu_\tau) < 38$ 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

CHARM PHYSICS @SHIP

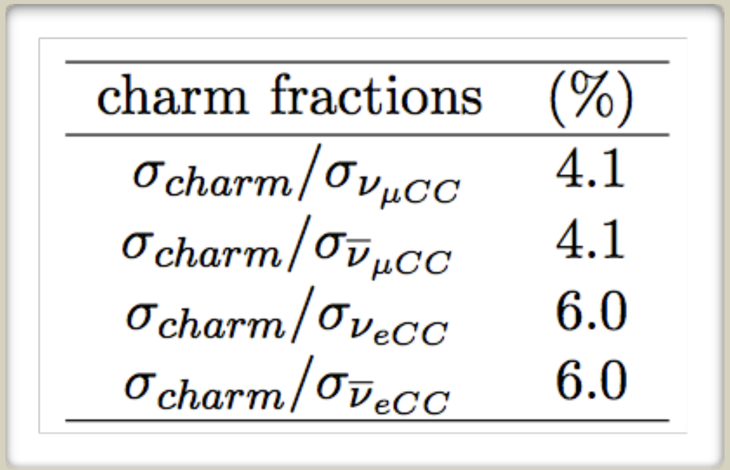
- Fraction of neutrino-induced charm events:
- Convolution of CHORUS data with SHiP spectrum

ν_μ CC

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

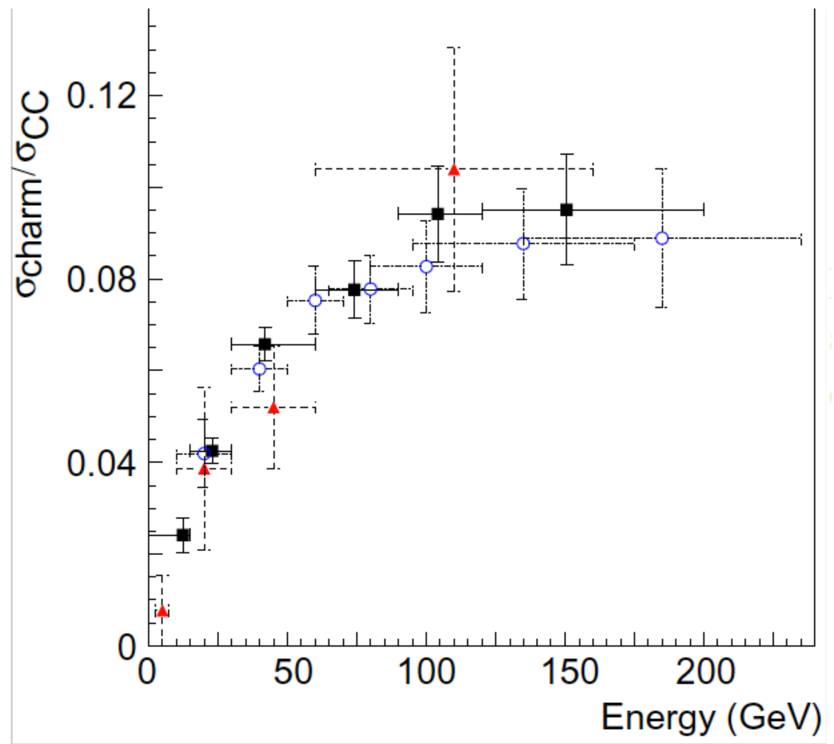
ν_e CC

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

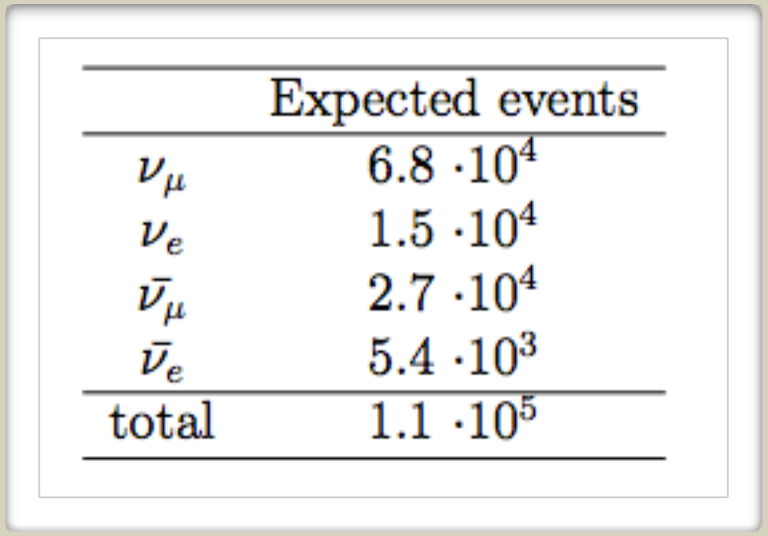


charm fractions	(%)
$\sigma_{charm}/\sigma_{\nu_\mu CC}$	4.1
$\sigma_{charm}/\sigma_{\overline{\nu}_\mu CC}$	4.1
$\sigma_{charm}/\sigma_{\nu_e CC}$	6.0
$\sigma_{charm}/\sigma_{\overline{\nu}_e CC}$	6.0

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



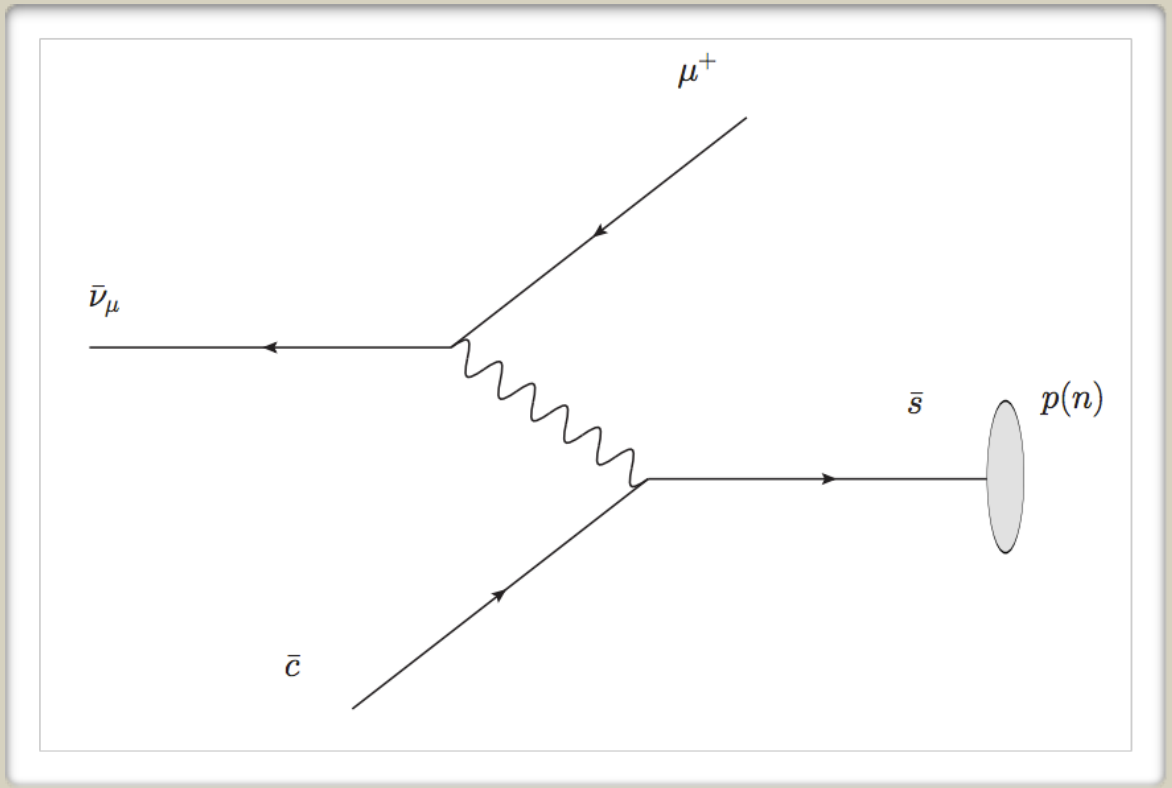
- Expected charm yield exceeds the statistics available in previous experiments by more than one order of magnitude



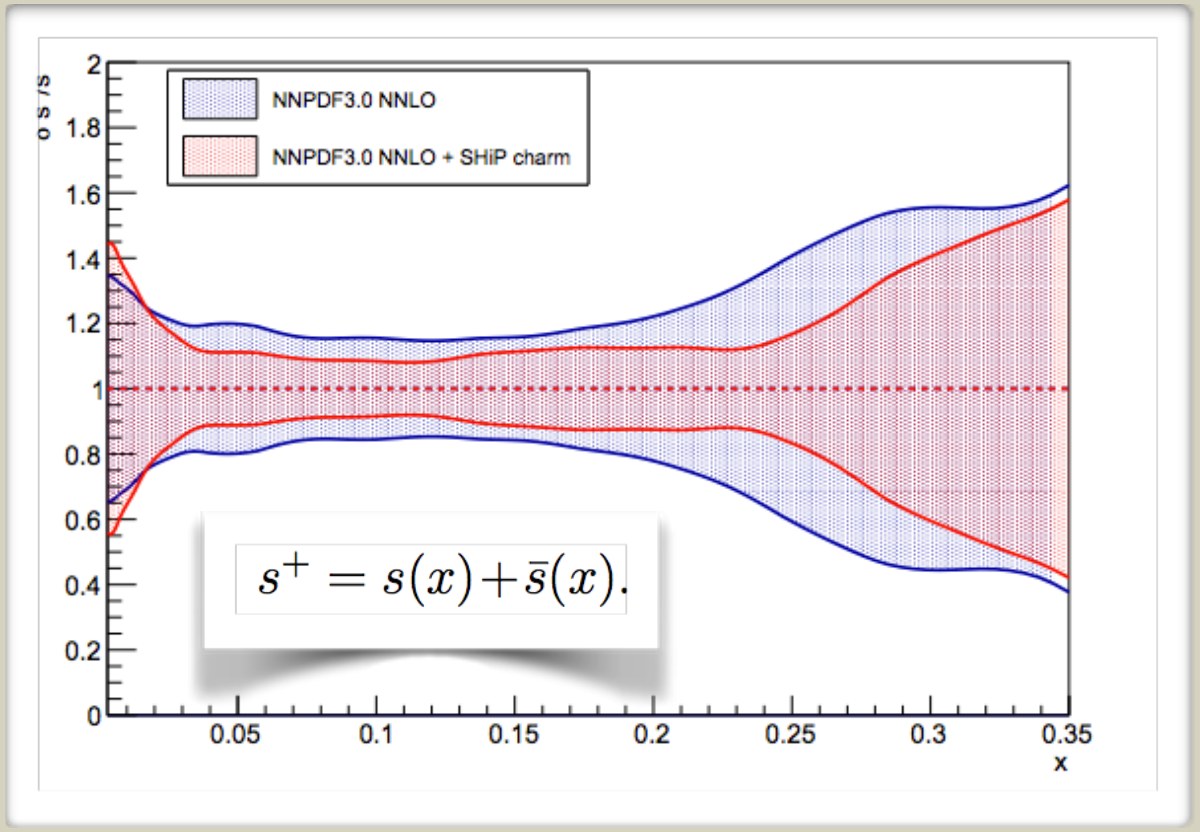
	Expected events
ν_μ	$6.8 \cdot 10^4$
ν_e	$1.5 \cdot 10^4$
$\bar{\nu}_\mu$	$2.7 \cdot 10^4$
$\bar{\nu}_e$	$5.4 \cdot 10^3$
total	$1.1 \cdot 10^5$

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
Expected in SHIP ~ 27 000

TEST BEAM ACTIVITIES

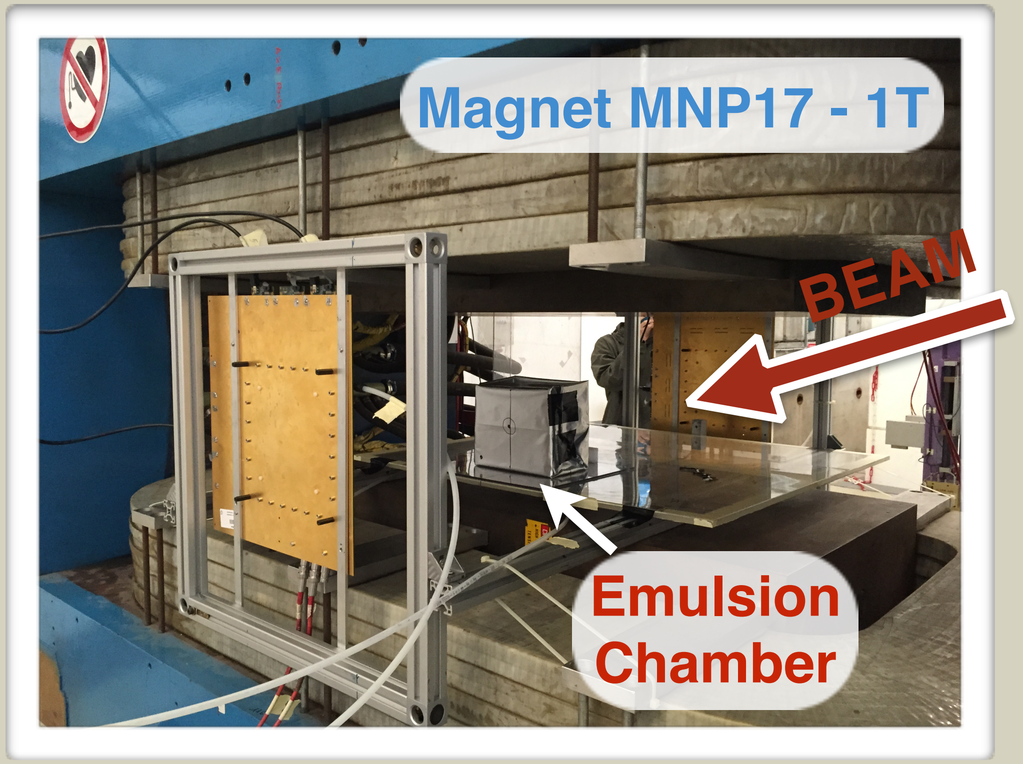
- First SHiP test beam @CERN with nuclear emulsions performed in September/October 2015
- Aims:

  1) Tracking in ECC with high density in magnetic field

  2) Measurement of particles charge and momentum with the Compact Emulsion Spectrometer

  3) Matching between emulsions and Micromegas

  4) Matching between emulsions and GEM



- Facilities:
  - Emulsion laboratory & dark room @CERN
  - T9 beam line (PS - East Area), MNP-17 magnet
  - SPS - North Area, Goliath Magnet

- Groups involved: **Napoli-Emulsion** group, **RD51** groups for both Micromegas and GEM, Nagoya Group

THE NAPOLI GROUP

- A. Alexandrov
- A. Buonaura
- S. Buontempo
- L. Consiglio
- G. De Lellis
- A. Di Crescenzo
- G. Galati
- M. Iacovacci
- A. Lauria
- L. Lista
- M. C. Montesi
- V. Tioukov
- P. Strolin

CONCLUSIONS

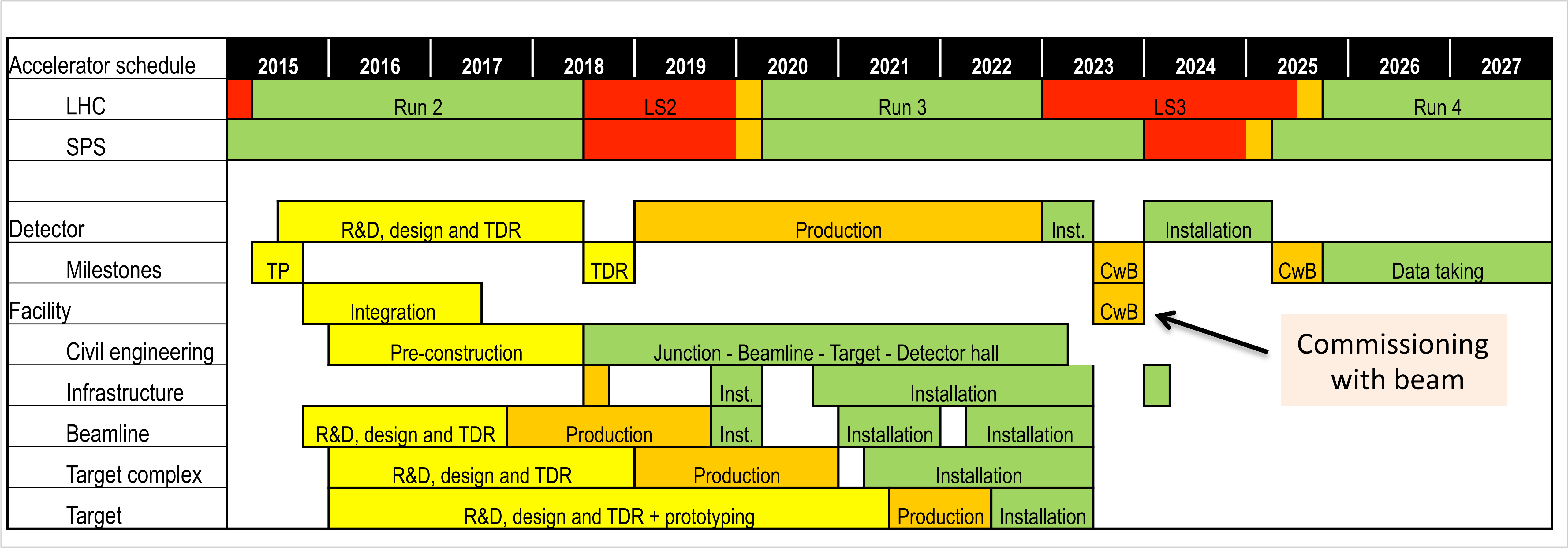
- Search for new physics beyond Standard Model: explore the intensity frontier

- Rich Standard Model physics program: first observation of anti-ν_τ ,ν_τ cross section studies and more

- First official outcome of the SPSC review expected in January 2016

BACK-UP SLIDES

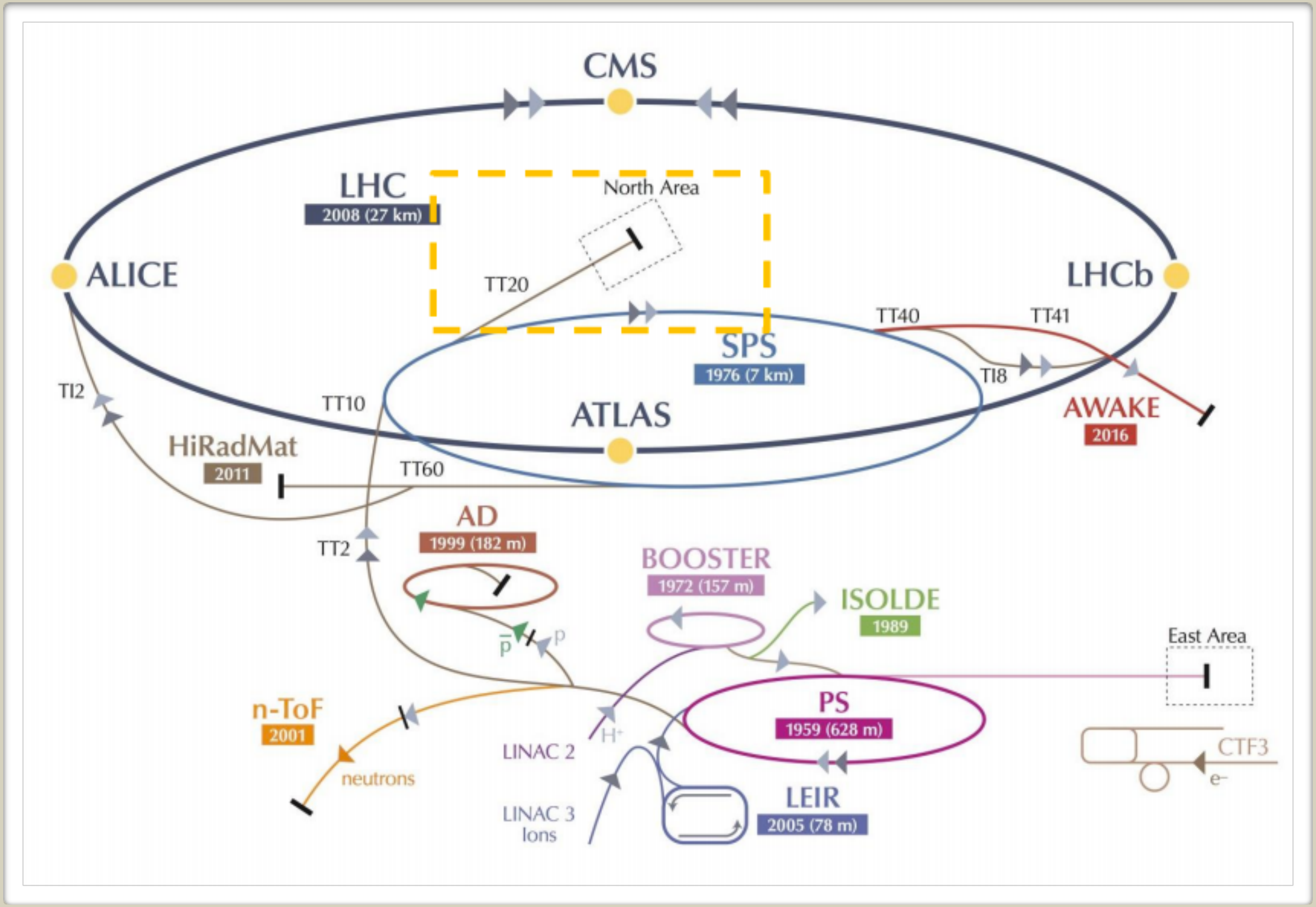
PROJECT SCHEDULE

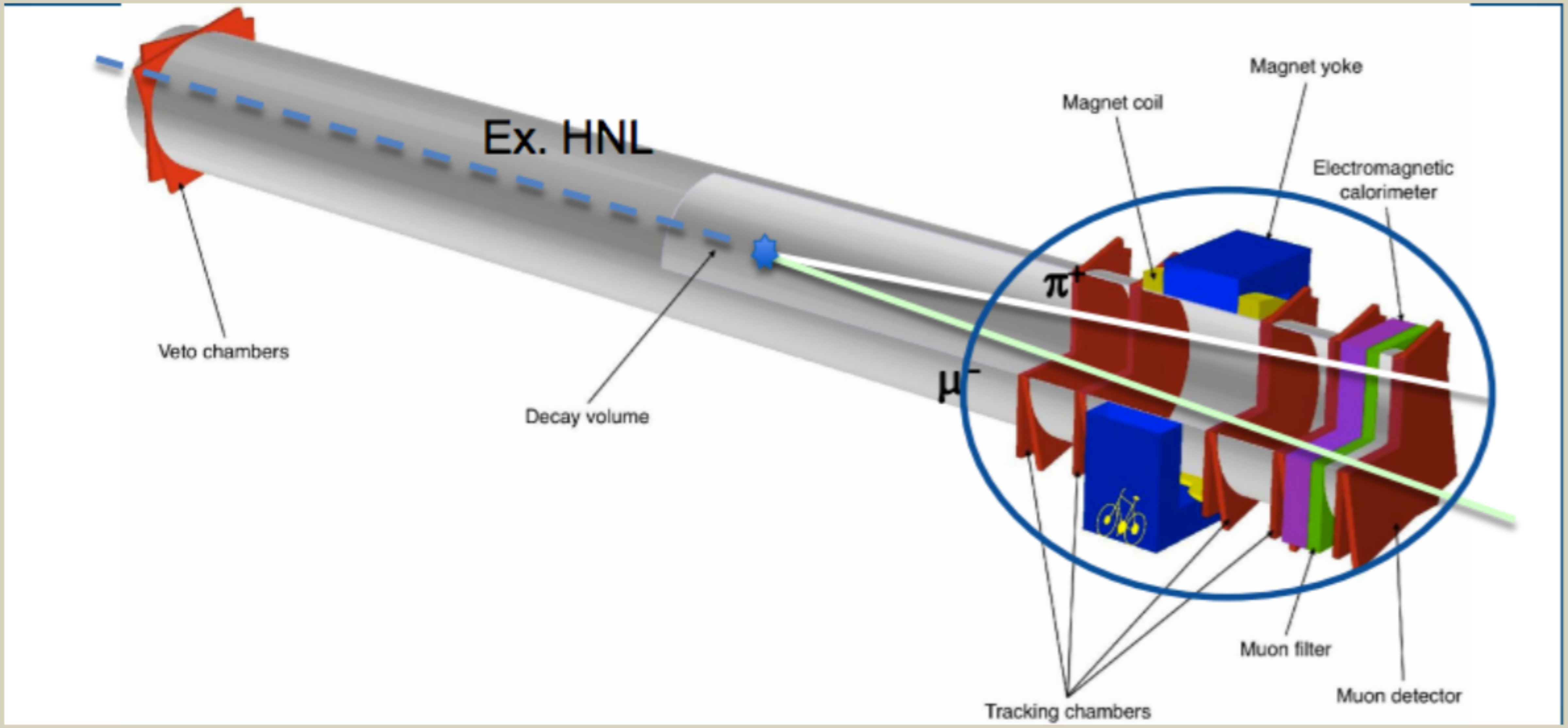


Form SHiP Collaboration	**December 2014 ✔**
Technical Proposal	**April 2015 ✔**
Technical Design Report	2018
Construction and Installation	2018-2023
Commissioning	2023
Data taking and analysis	2026

SHIP LOCATION

- Proposed location by CERN beams and support departments

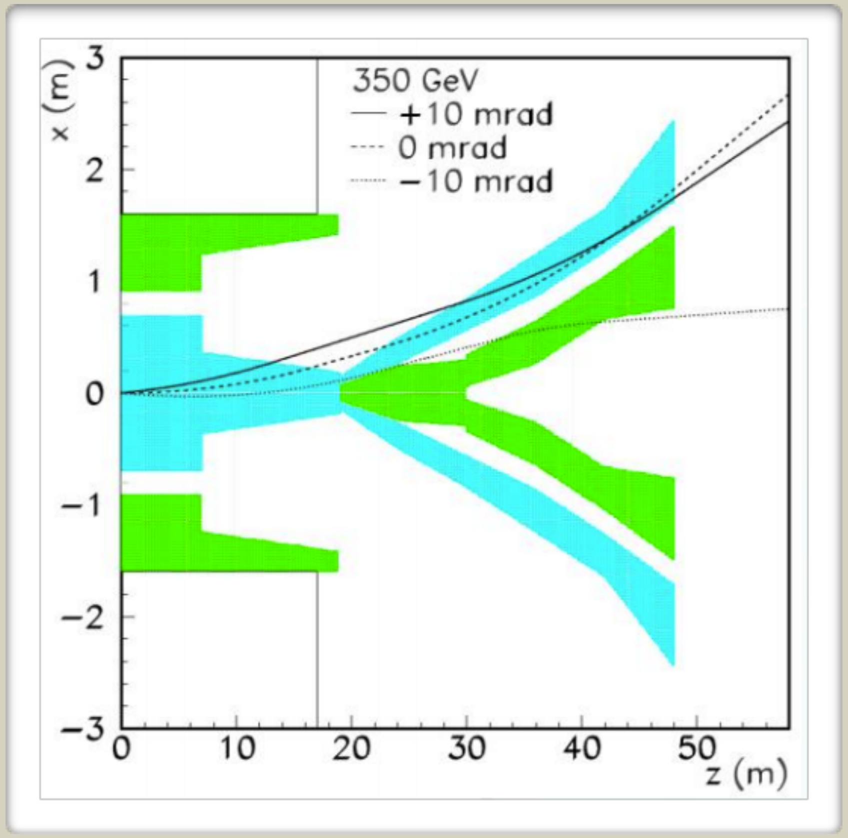


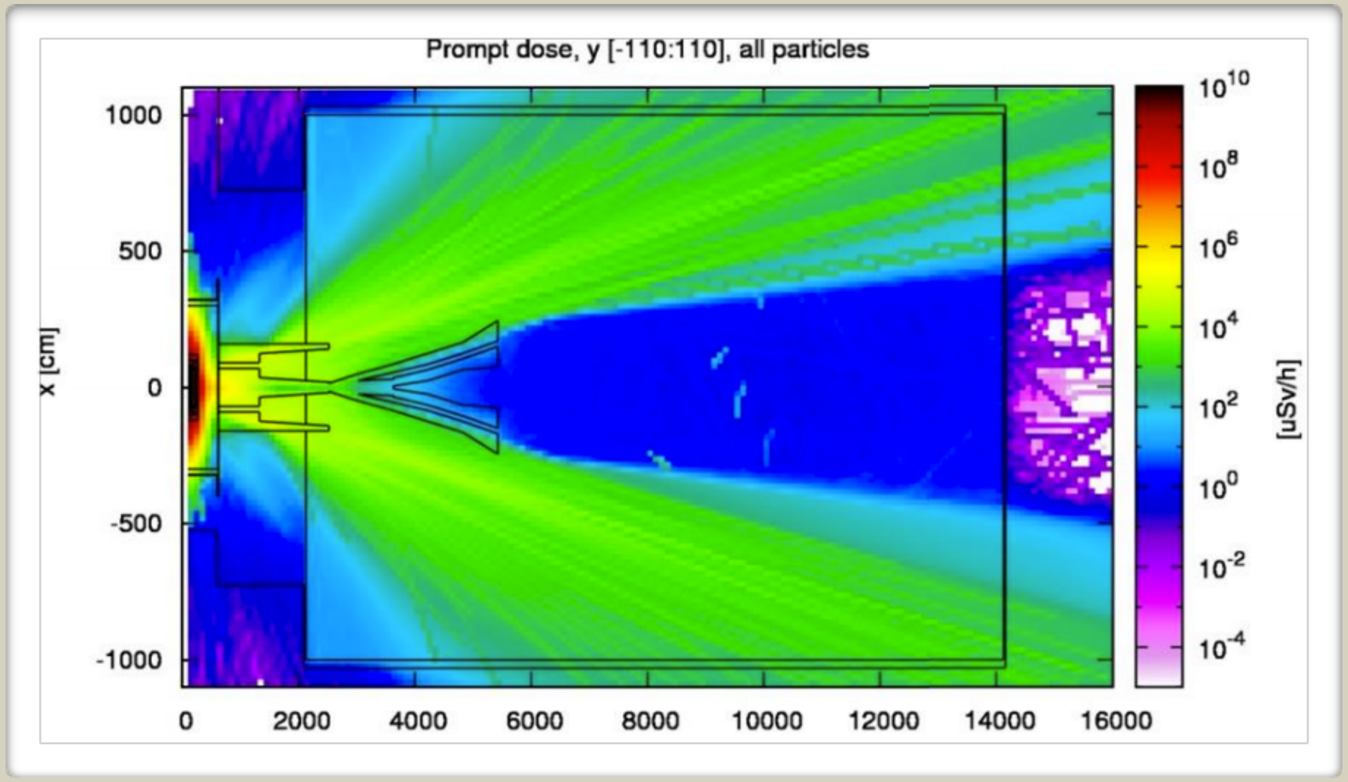

Ex. HNL
Veto chambers
Decay volume
Magnet coil
Magnet yoke
Electromagnetic calorimeter
π^+
μ^-
Muon filter
Muon detector
Tracking chambers

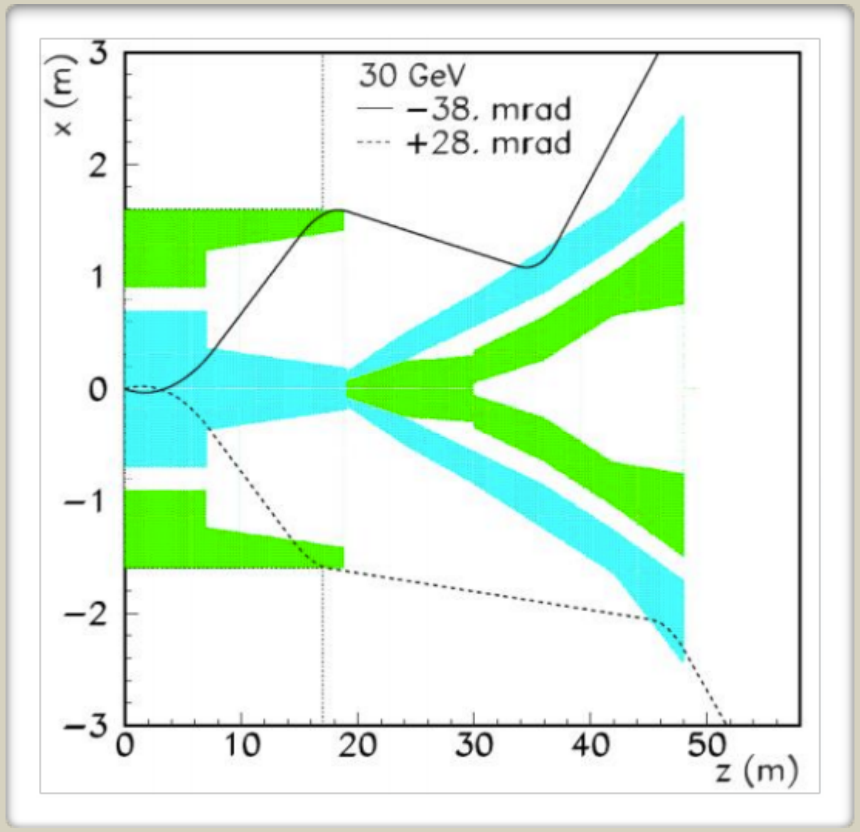
ACTIVE MUON SHIELD

- 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 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

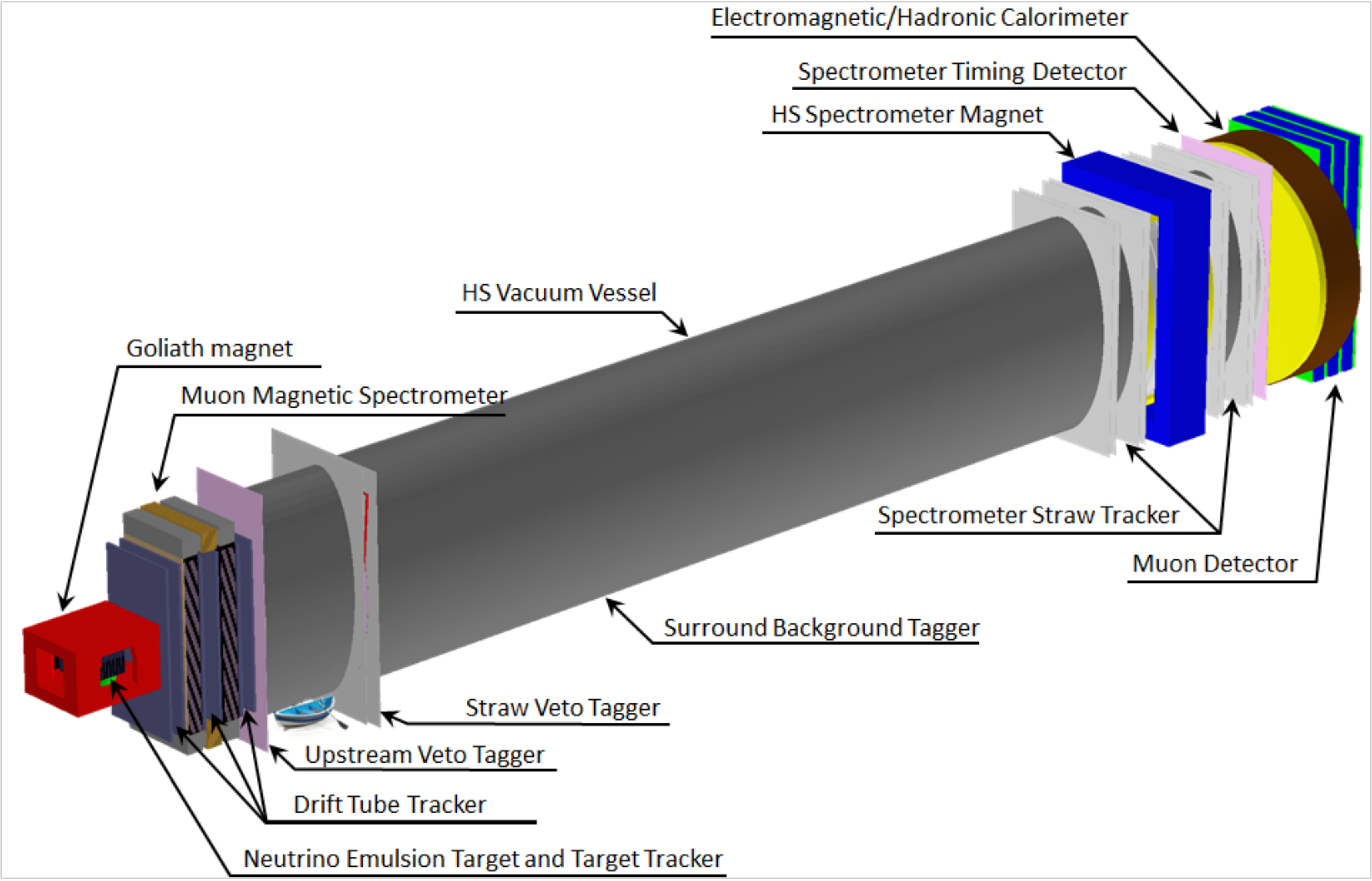
Aim: Reconstruction of HS decays in all possible final states

- 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



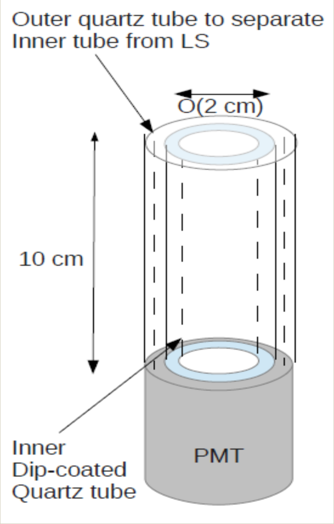
DECAY VOLUME AND SPECTROMETER

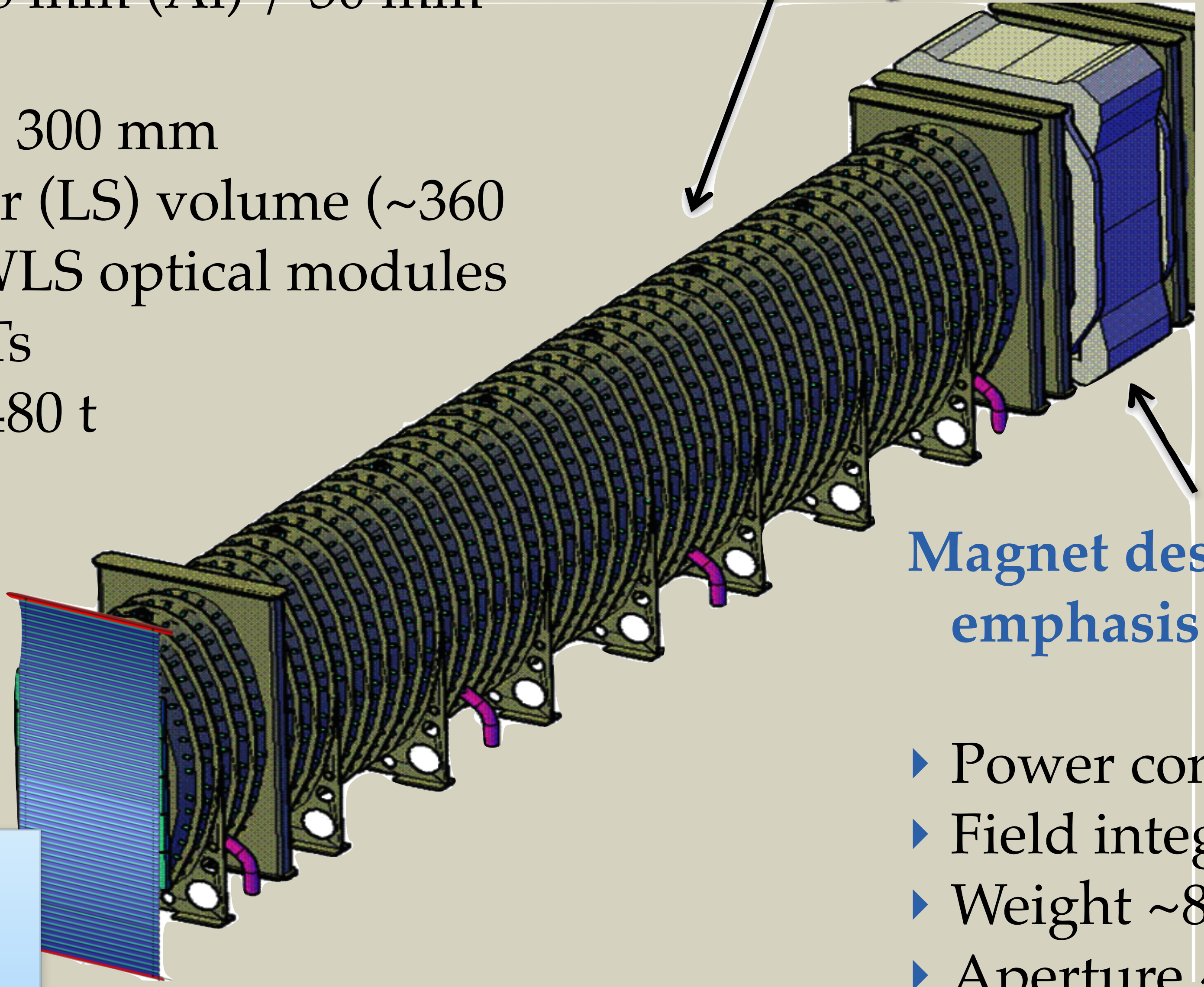
Estimated need for vacuum: ~10^{-3} mbar

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 m^3) readout by WLS optical modules (WOM) and PMTs
- Vessel weight ~ 480 t

LS cell with WOMs





Magnet designed with an emphasis on low power

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

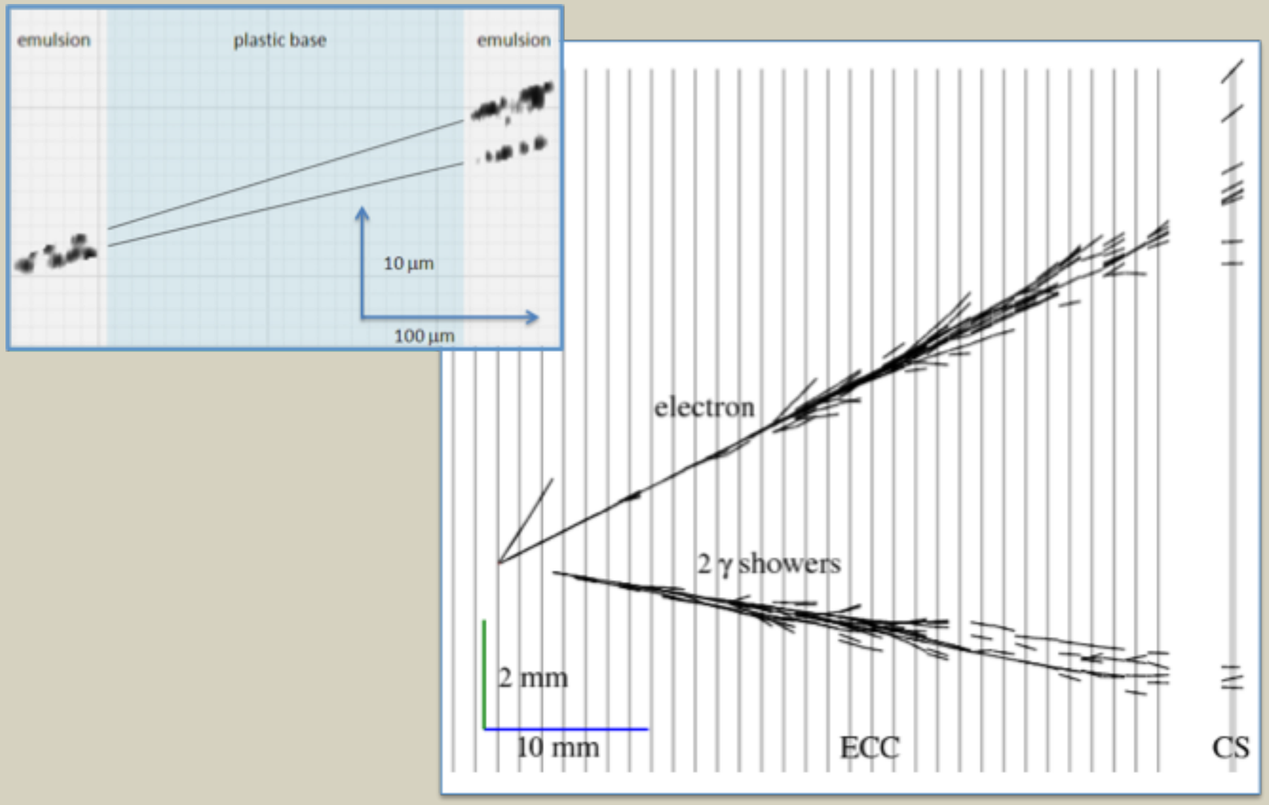
viene da richiesta di <1 interazioni di neutrino, può non essere necessario stiamo studiando

LEPTON FLAVOUR IDENTIFICATION

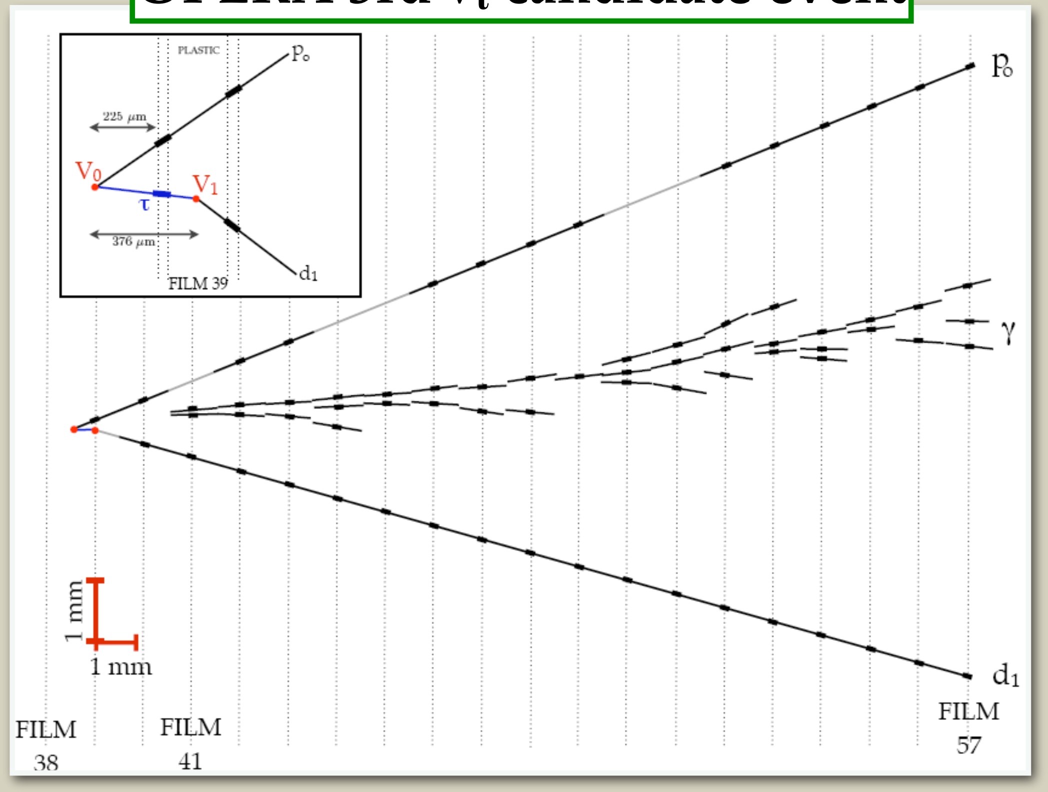
Emulsion Cloud Chamber technique

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

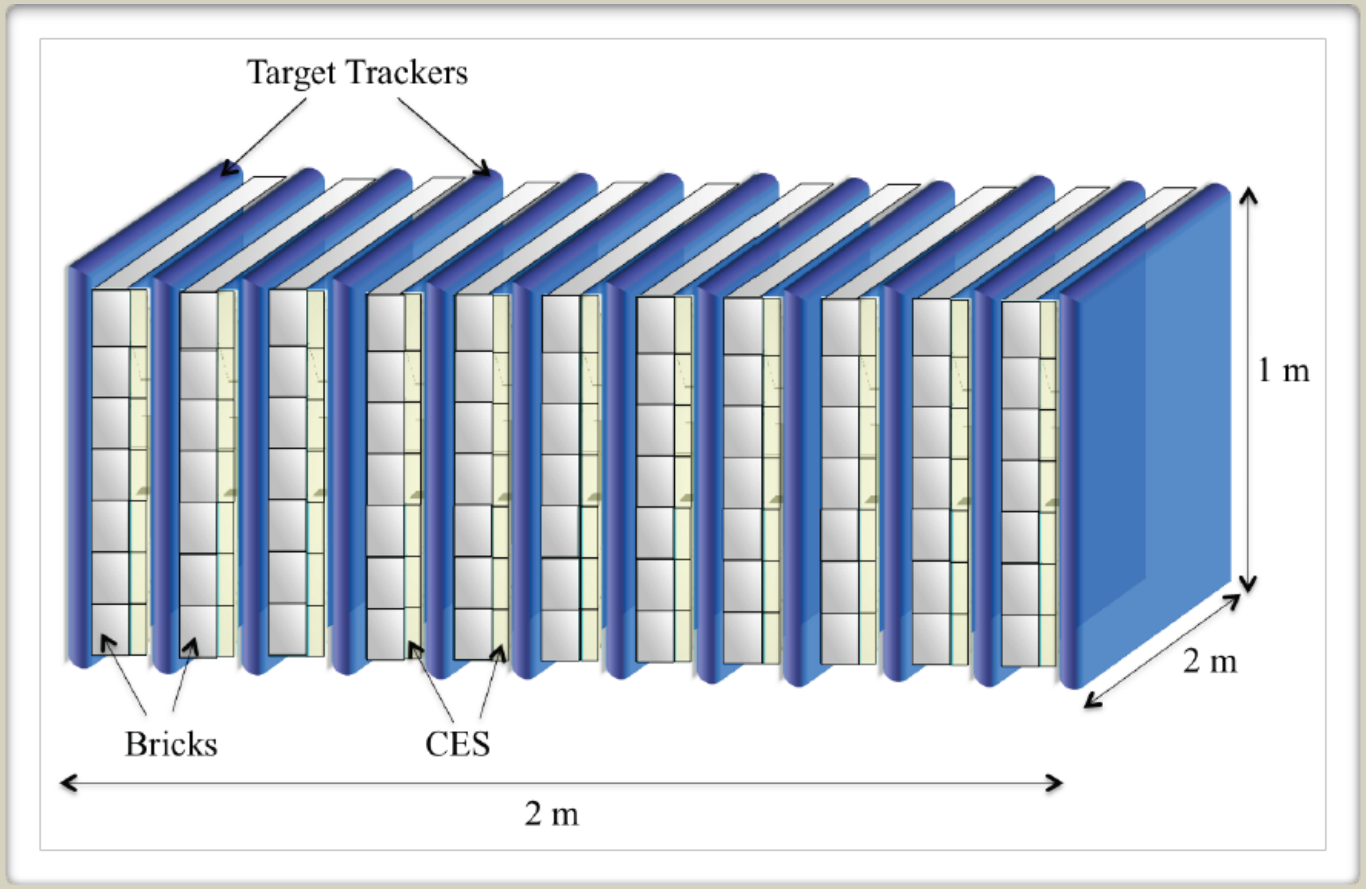


OPERA 3rd ν_τ candidate event



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

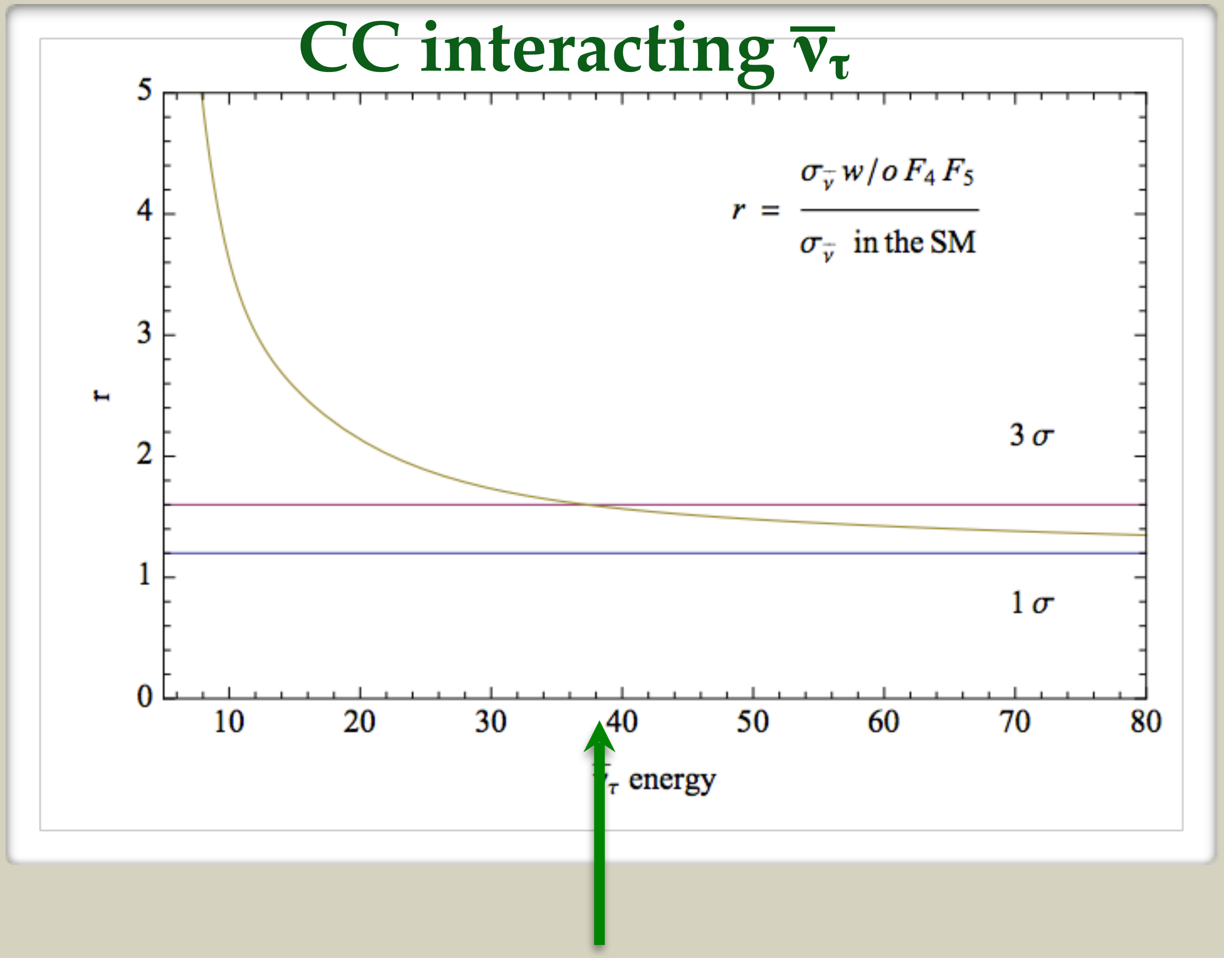
POSSIBLE OPTIONS:

- 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 x 1 m^2

SENSITIVITY TO F_4 AND F_5


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

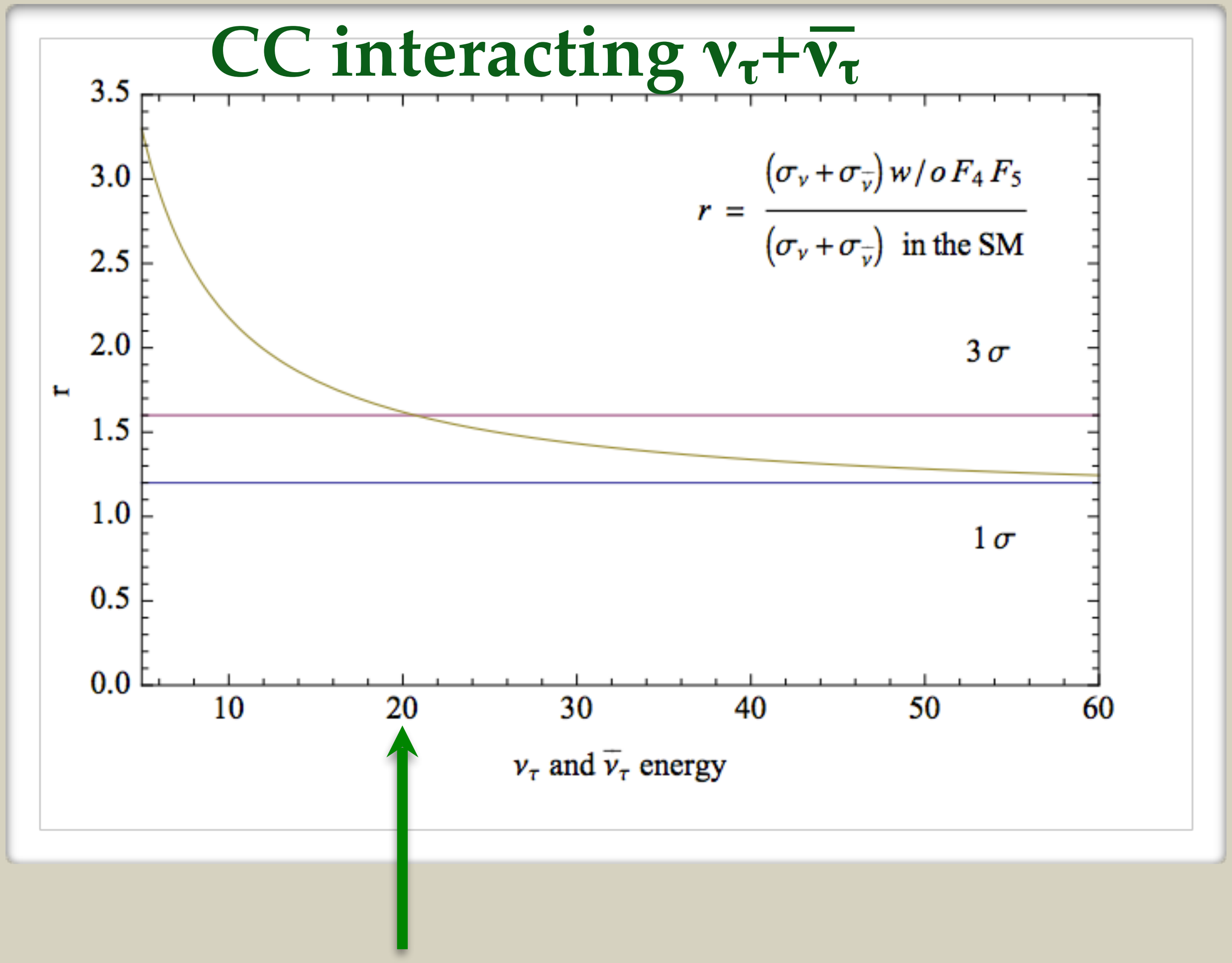
$E(\overline{\nu}_\tau) < 38$ GeV

(~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 $\nu_\tau + \overline{\nu}_\tau$

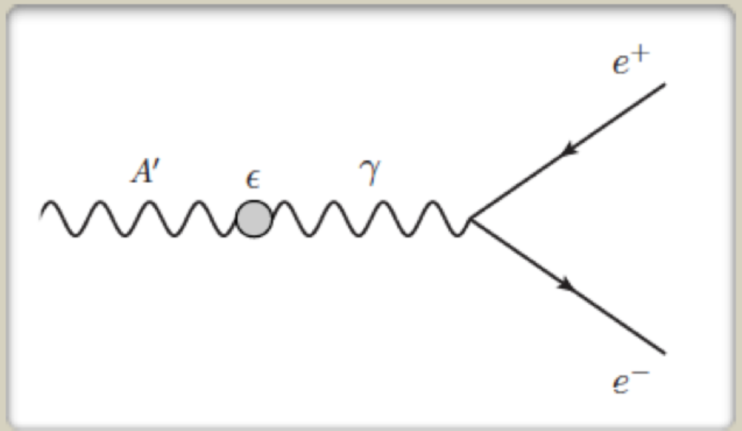
$E(\nu_\tau + \overline{\nu}_\tau) < 20$ GeV

(~420 events expected)

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

TEST BEAM ACTIVITIES