Neutrino Physics with the SHiP experiment at CERN

SHiP
Search for Hidden Particles

On behalf of the SHiP Collaboration
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ICHEP2018 SEOUL
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SHiP experiment

- Search for Hidden Particles -

A new experiment proposed at CERN
in order to search for ***Hidden particles***
with mass from sub-GeV up to *O* (10)
GeV with super-weak coupling down to 10^{-10},
and to study ***Tau neutrino physics***.

Using High-intensity
400 GeV proton beam
2 x 10^{20} pot, 5 years run

Physics Motivation

Higgs discovery

SM very successful but incomplete …

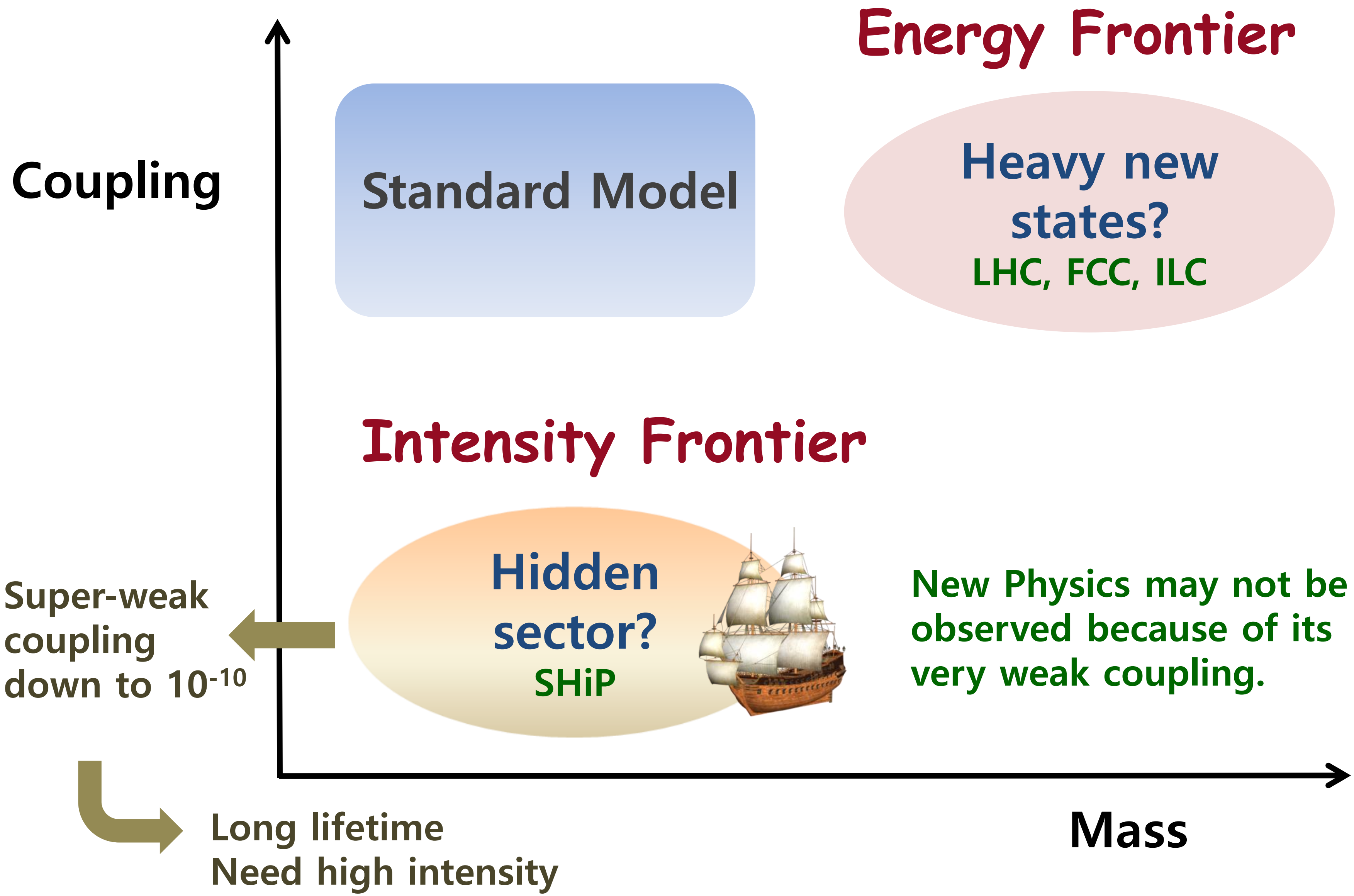
- Baryon asymm
- Dark matter
- Neutrino mass
- Inflation …

Beyond SM

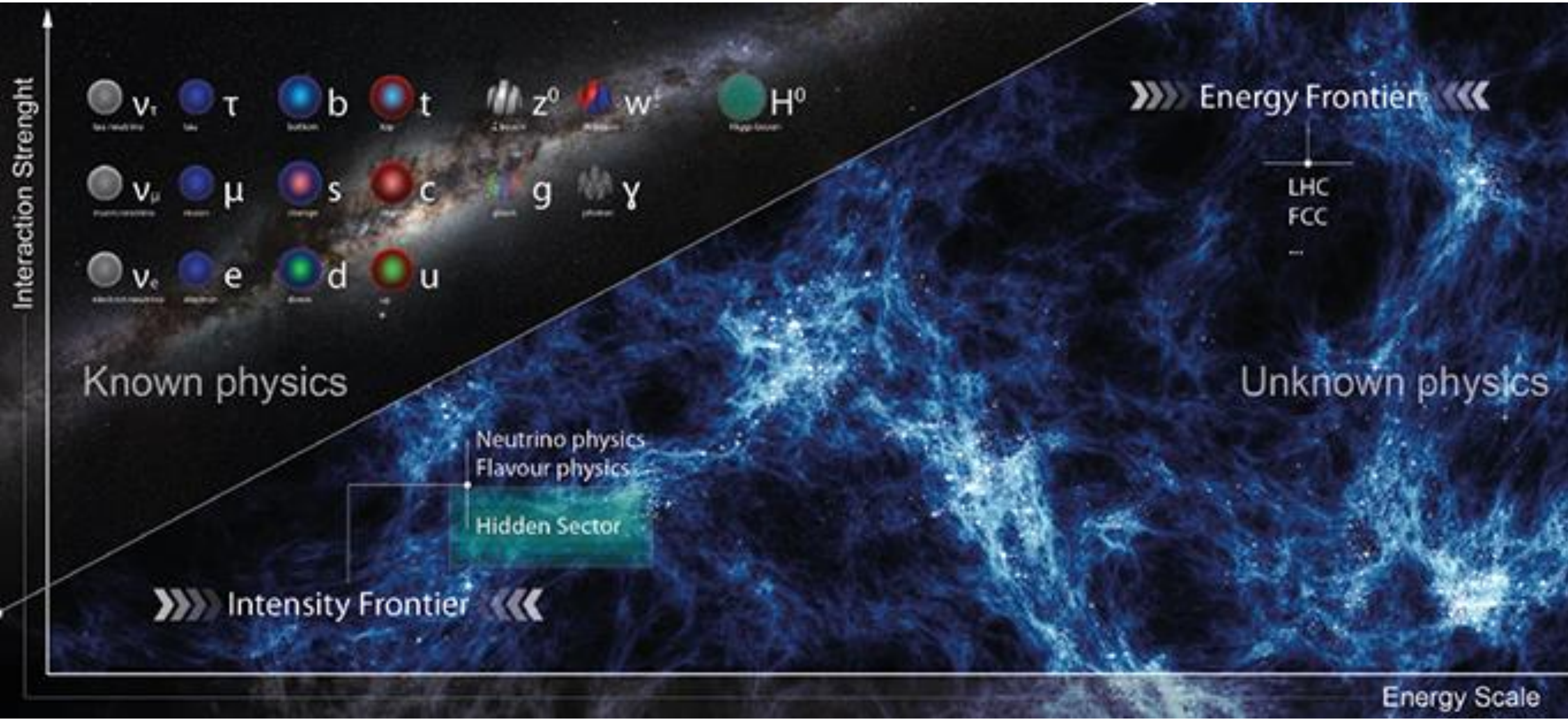
so far Neutrino osc. only

Search for New Physics

Where is the New Physics ?

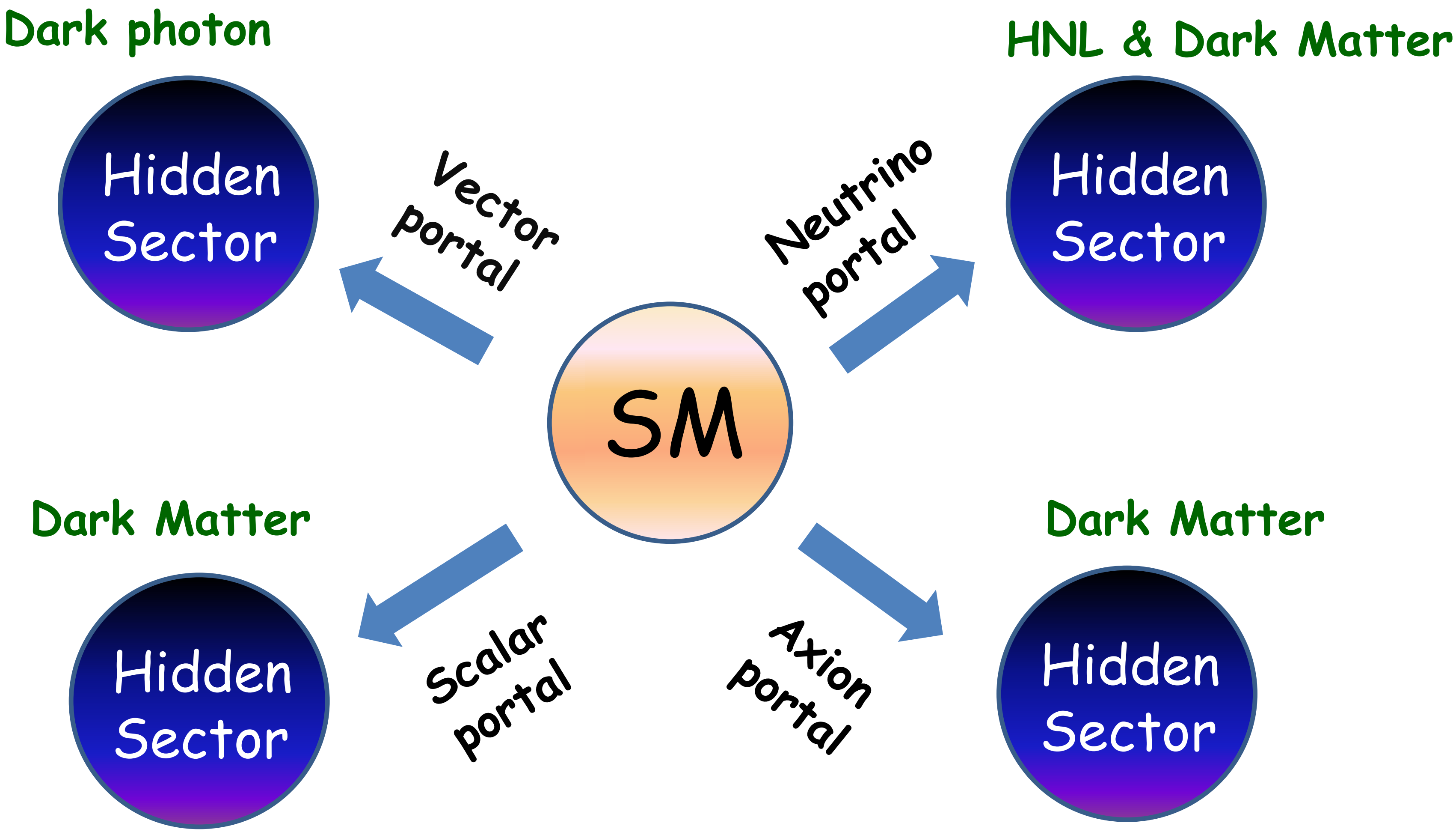


Explore the unexplored region



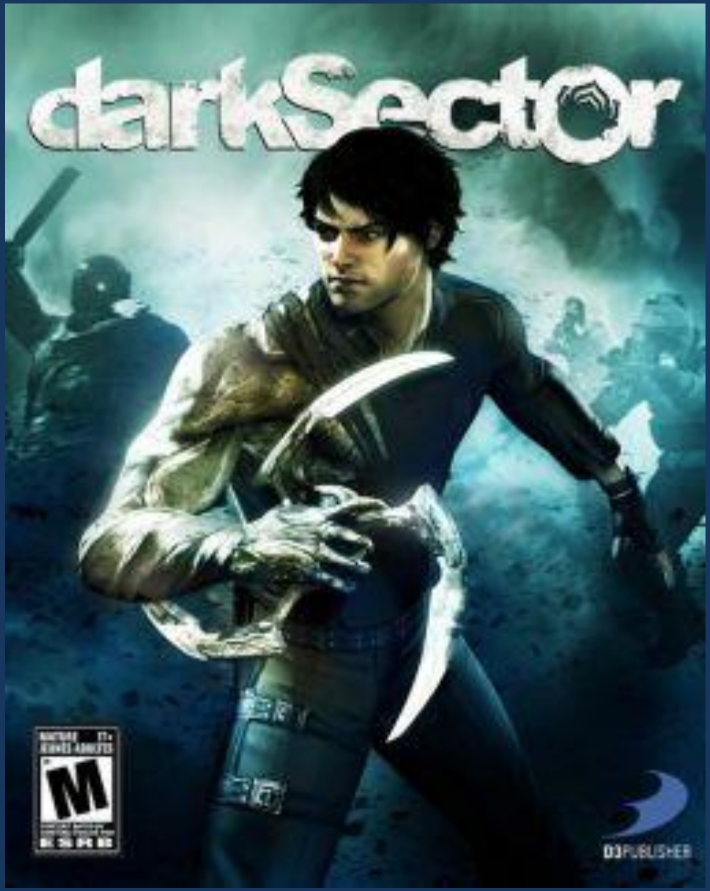
The SHiP is a new experiment at the intensity frontier aimed at exploring the Hidden sector region.

Extensions of SM



Many hidden sector models often include **low mass particles around GeV scale** (**Light dark matter candidates**).

Search for Dark Sector



PC Game

Neutrino portal

νMSM

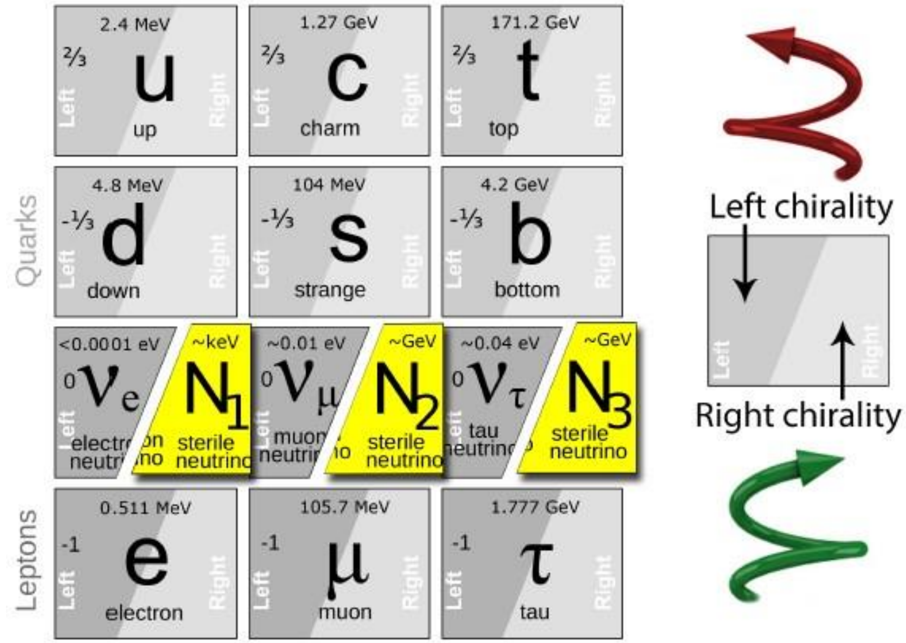
Extends SM by RH partners of neutrinos
T.Asaka, M.Shaposhnikov
PLB 620 (2005) 17

N_1 (~10 keV)

Dark matter candidate

$N_{2,3}$ (100 MeV~GeV)

Matter-Antimatter asymmetry
Neutrino mass (oscillation)



N = Heavy Neutral Lepton (HNL)

Majorana partners of active neutrinos
Sterile RH neutrinos

$HNL_{2,3}$ Production

2×10^{20} pot
(10^{18} D, 10^{14} B, 10^{16} τ)

$D_S \rightarrow \mu N_{2,3}$

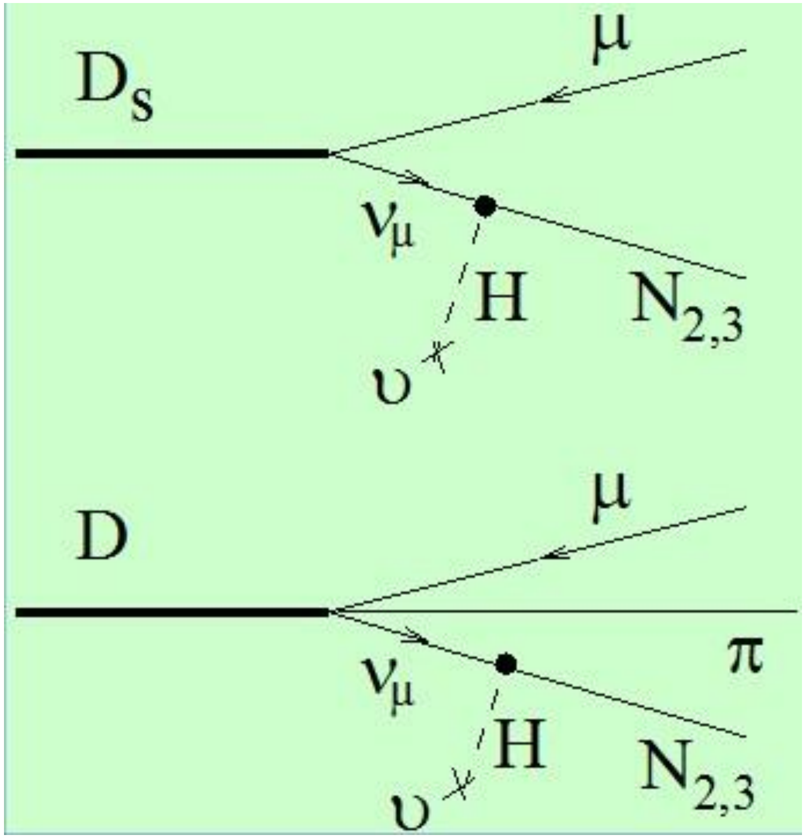
$D \rightarrow \pi \mu N_{2,3}$

Decays of **Charm & Beauty**

Particles (above Kaon mass)

Super-week coupling

→ **long lifetime**



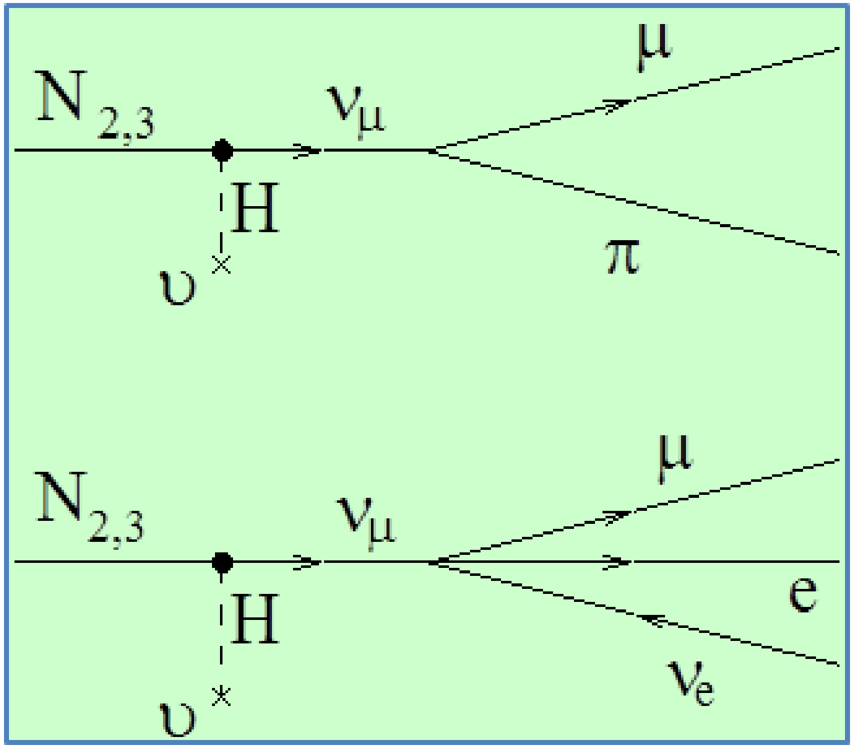
HNL mix with active ν

$HNL_{2,3}$ Decay

$N \rightarrow \mu^- \pi^+$
$\rightarrow e^- \pi^+$
} 0.1~50%

$N \rightarrow \mu^- \rho^+$
$\rightarrow e^- \rho^+$
} 0.5~20%

$N \rightarrow \nu \mu e$ 1~10%

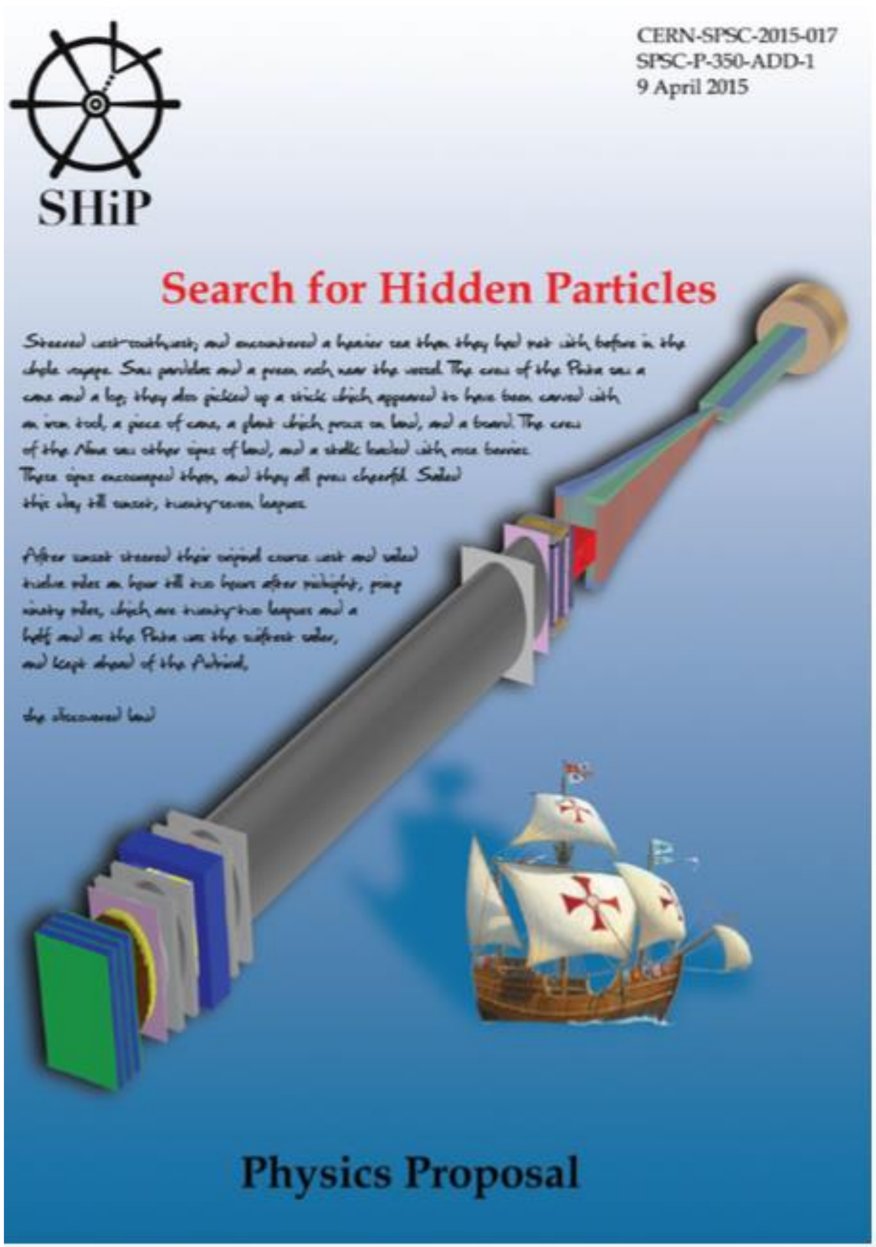


Branching ratio depends on Mixing

Typical lifetime > 10 μs for $m(N_{2,3})$ ~1 GeV

Decay distance (FL) ~ O(km)

Apr 2015



Technical proposal

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

Physics proposal

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

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Main objectives

Hidden particles

Heavy Neutral Leptons (HNL)
Dark photons
Hidden Scalar
Axion Like Particles (ALP)
Low energy SUSY particles etc.

See Iaroslava Bezshyiko's talk

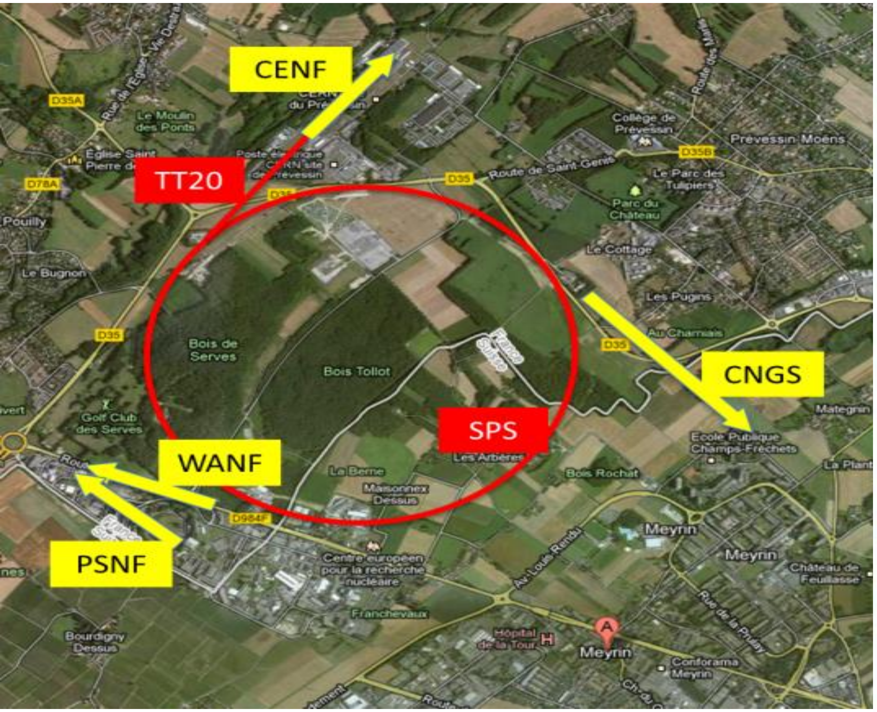
Tau neutrinos

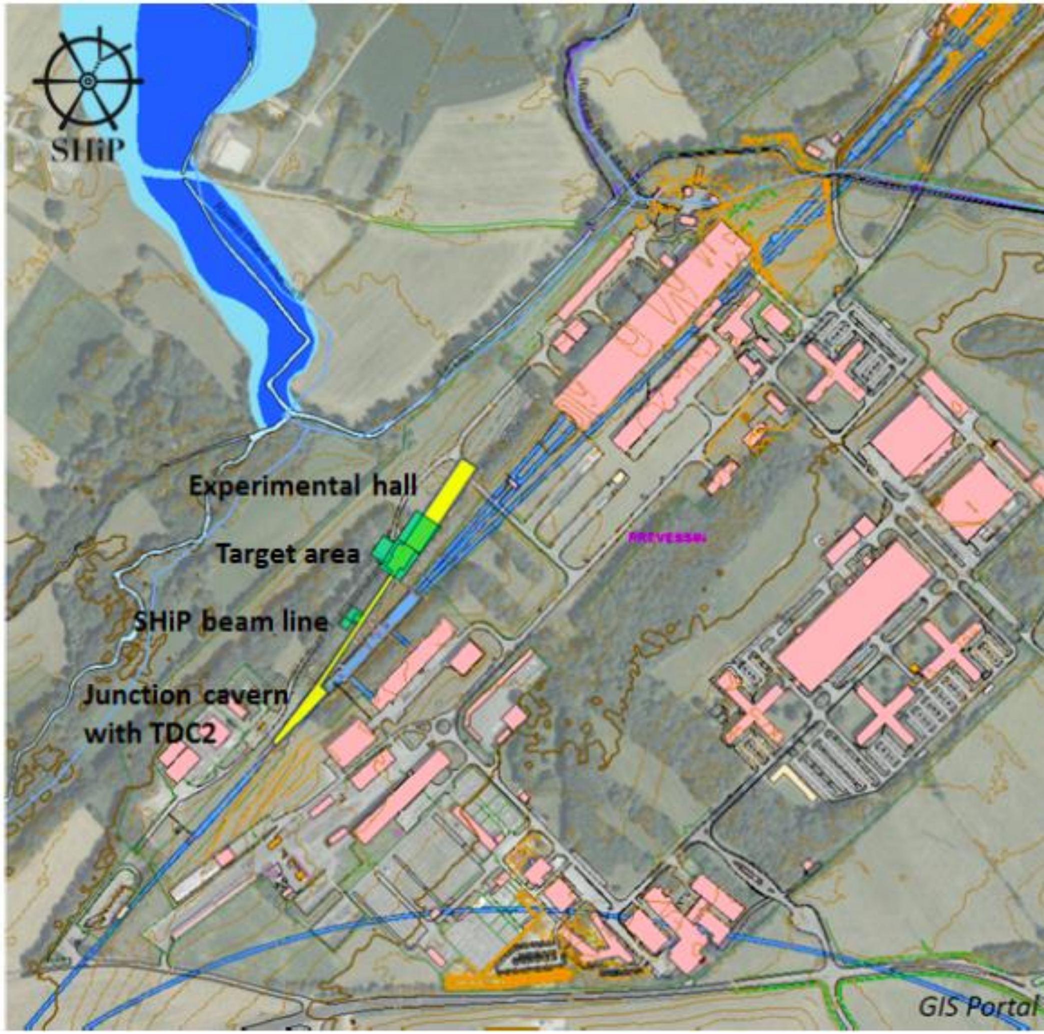
Expect ~10,000 ν_τ interactions
in ~7 tons Emulsion target

ν_τ *and* Anti-ν_τ *physics (Cross-section …)*

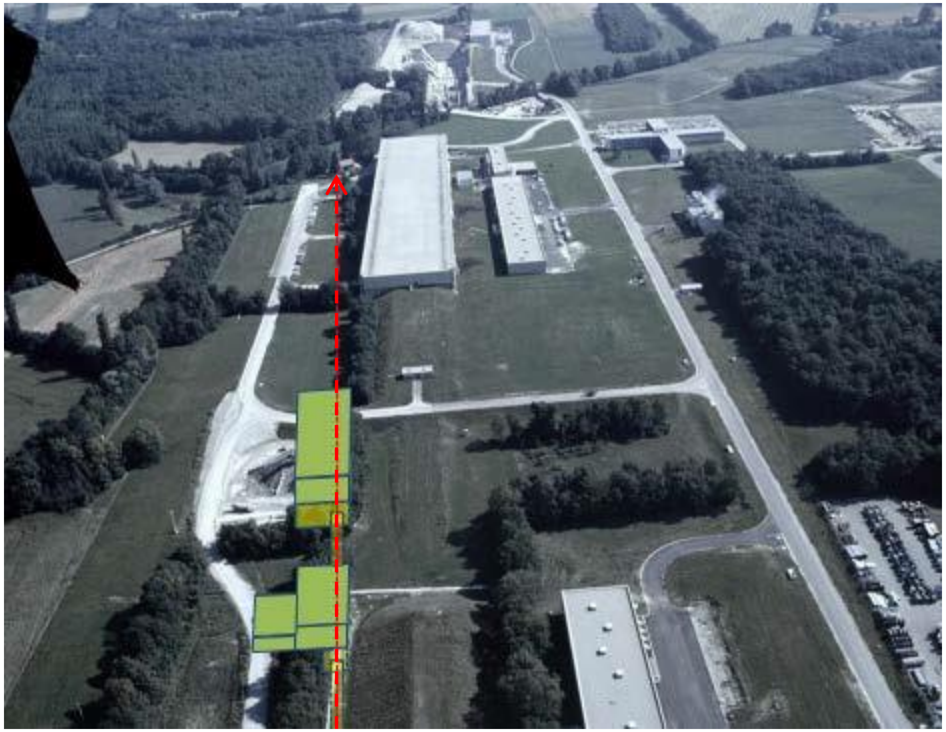
Fixed-target facility at the SPS

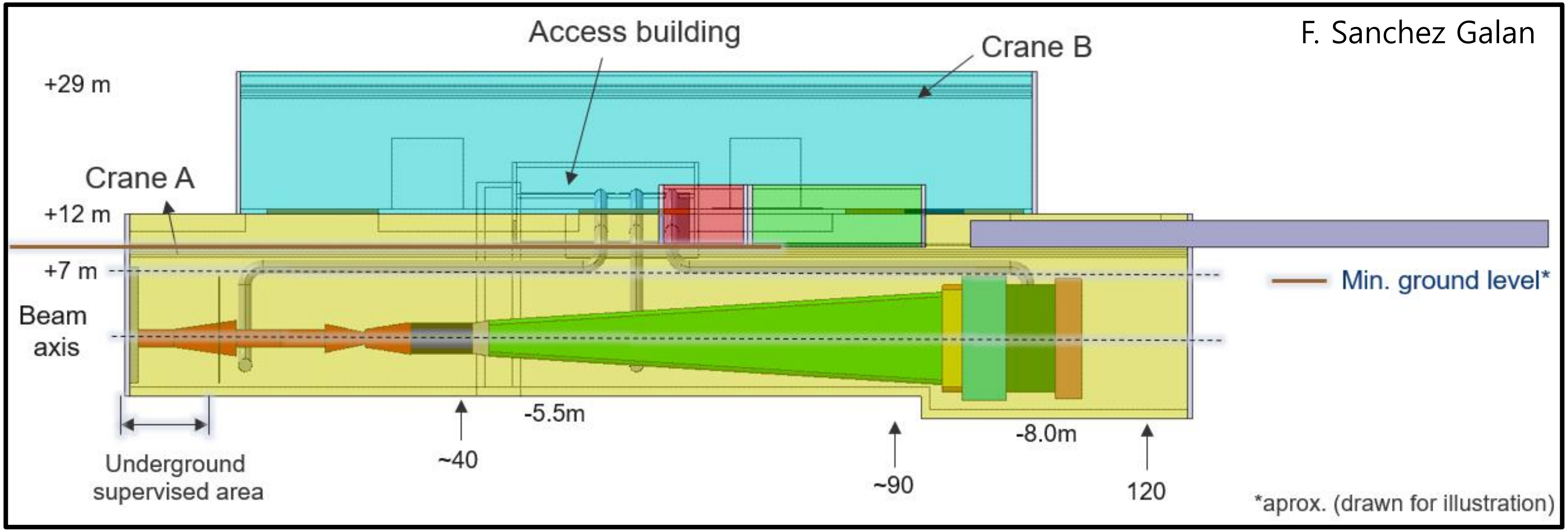
High-intensity proton beam: 2 x10^{20} pot, 5 years run





The SHiP facility is located on the North Area (Prévessin site), *and shares the TT20 transfer line.*



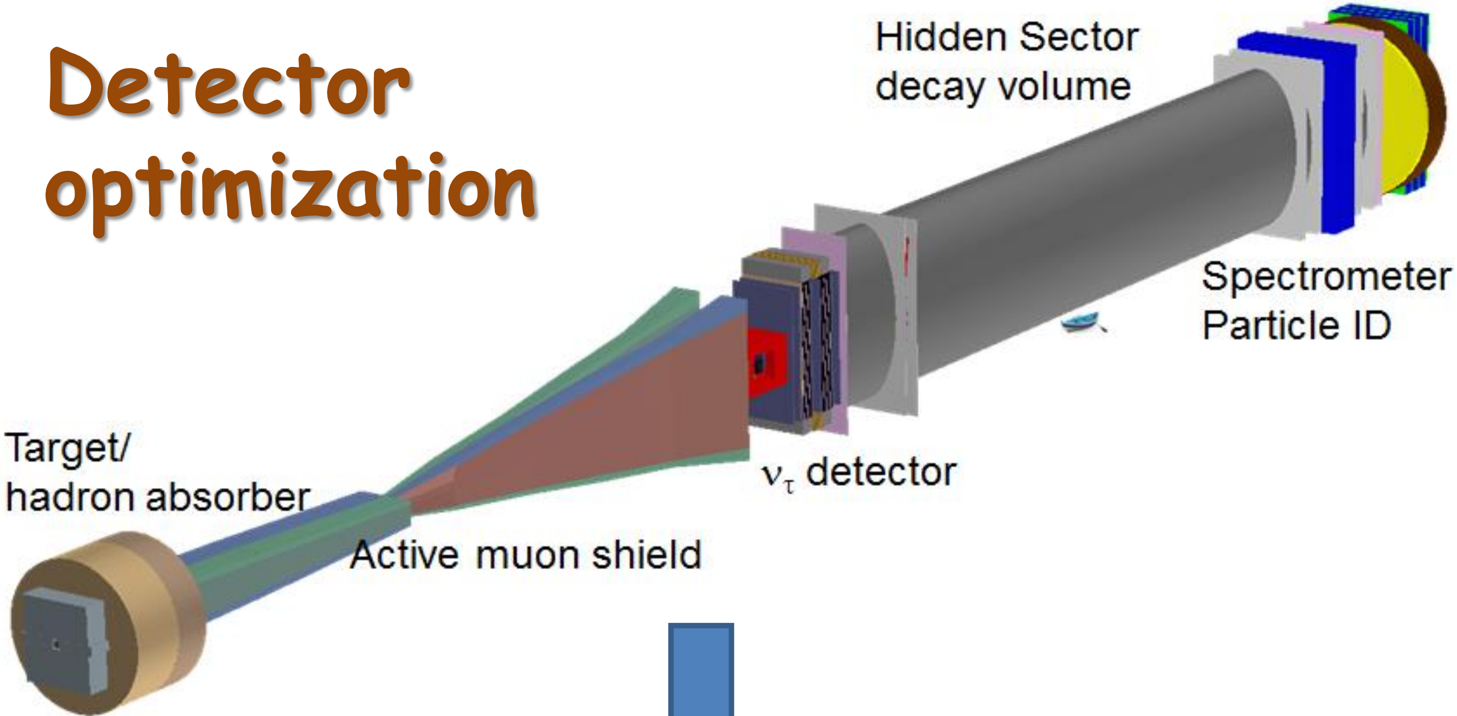


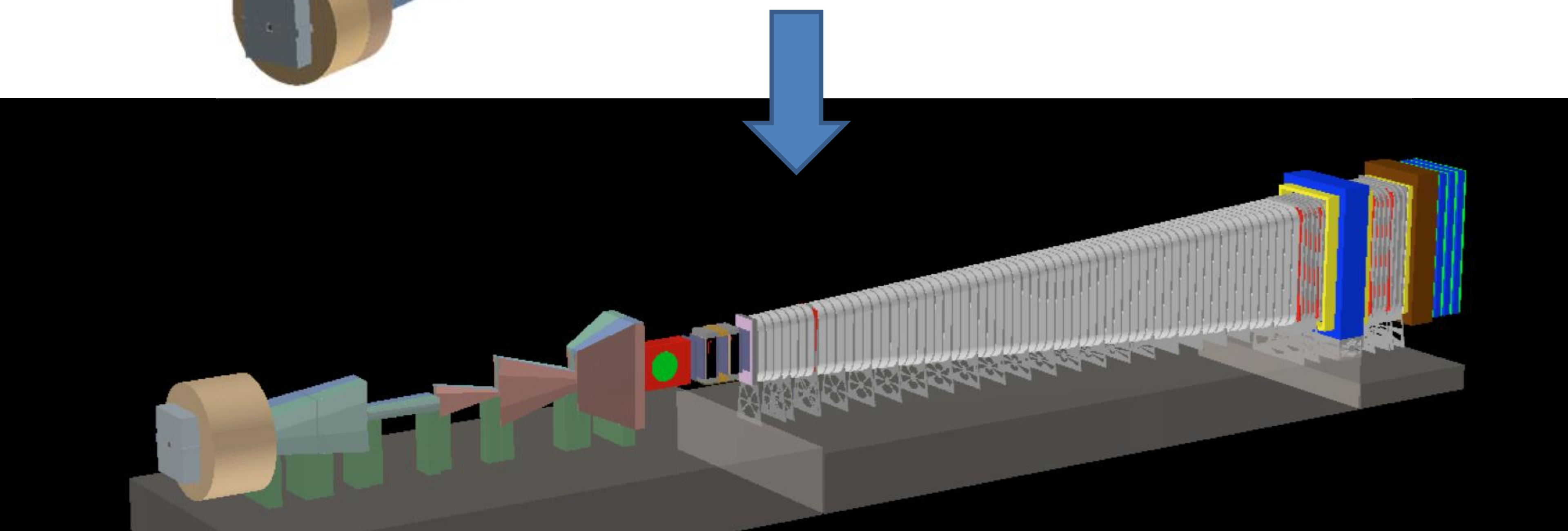
F. Sanchez Galan
Access building
Crane B
+29 m
Crane A
+12 m
+7 m
Min. ground level*
Beam
axis
-5.5m
-8.0m
Underground
supervised area
~40
~90
120
*aprox. (drawn for illustration)

SHiP detectors

- **Hidden particle detector**
  - **Long evacuated decay vessel**
  - Straw trackers with magnet
  - Calorimeters and Muon detector
- **Tau neutrino detector**
  - **Emulsion target (ECC)**
  - Target trackers (TT) in Magnetic field
  - Muon spectrometer

Detector optimization





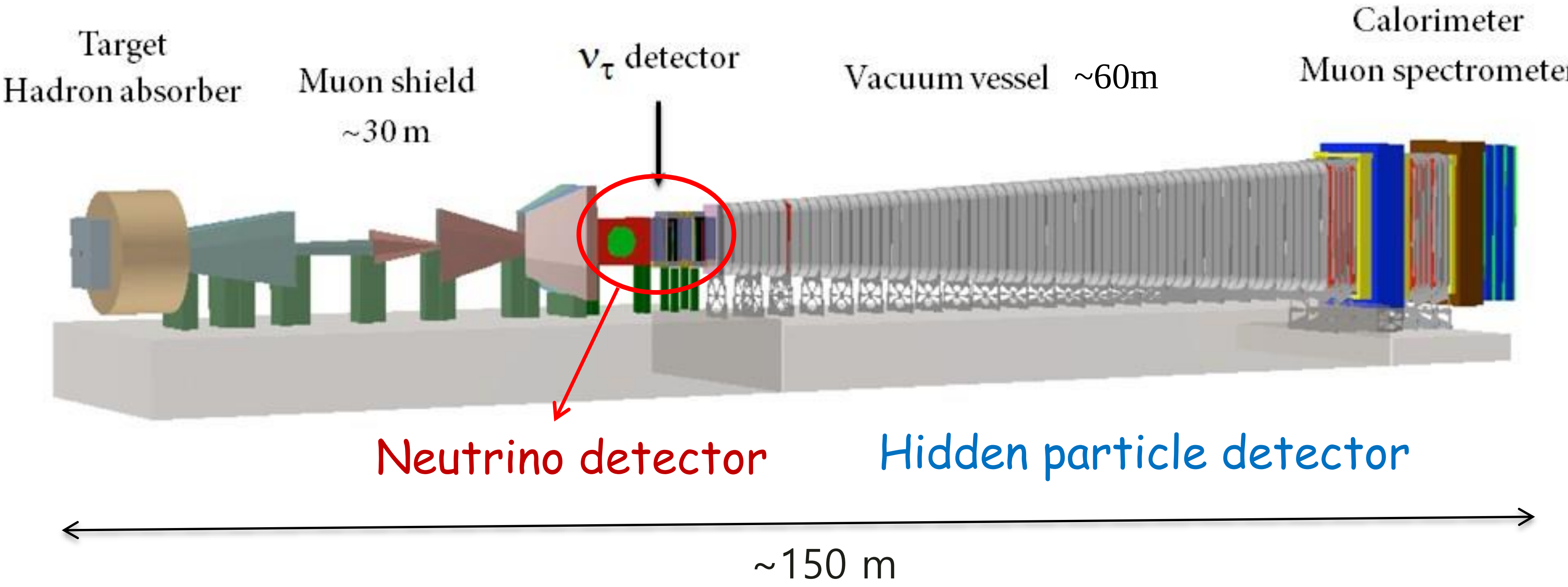
Decay vessel now pyramidal frustum shaped

Type of Muon shield modified

SHiP Detector

Active muon shield
deflect muons from 2ry meson decay
~ 35m long, 1.7 T magnet

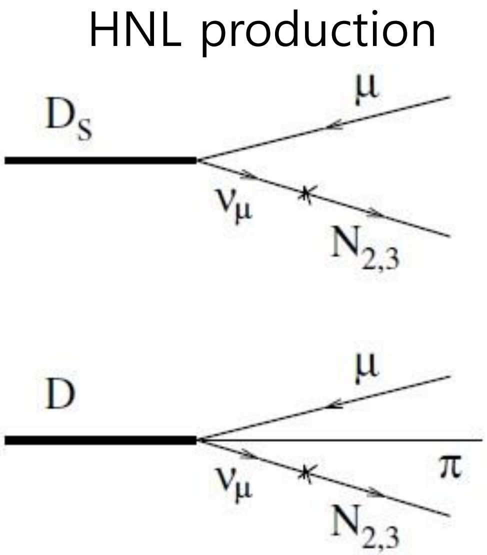
PID
Energy measure

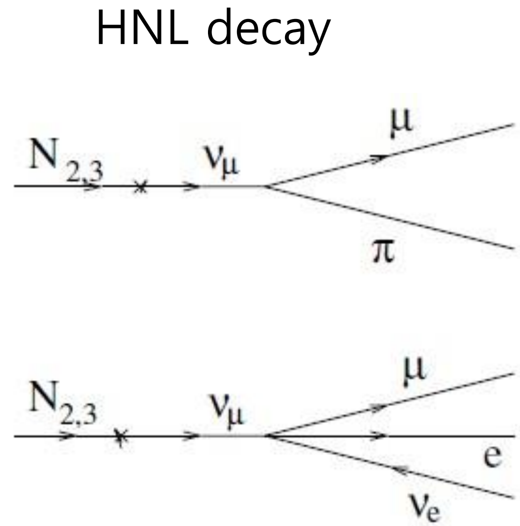


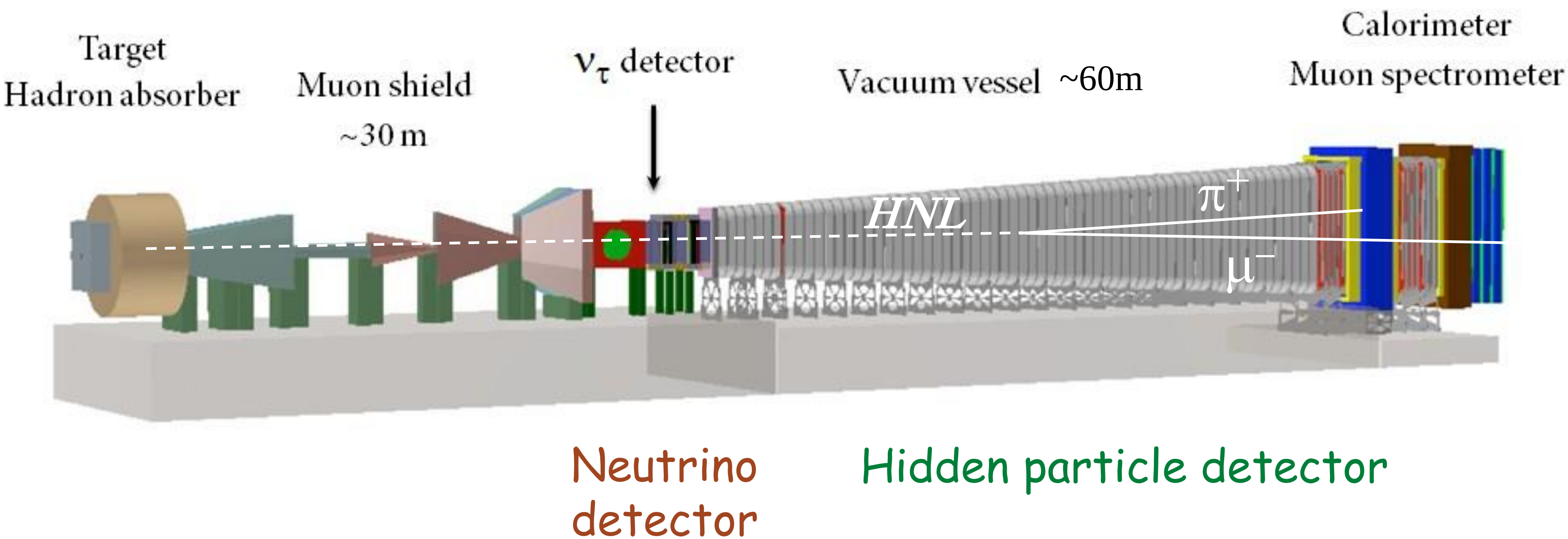
Hadron absorber
eliminate
2ry mesons
~ 5m Fe

Nuclear Emulsion
Tau-neutrino physics
LDM search

Vacuum decay vessel
~60 m long evacuated decay vessel surrounded by liquid scintillator veto system


HNL production
D_S
μ
ν_μ
N_2,3
D
μ
π
ν_μ
N_2,3


HNL decay
N_2,3
ν_μ
μ
π
N_2,3
ν_μ
μ
e
ν_e

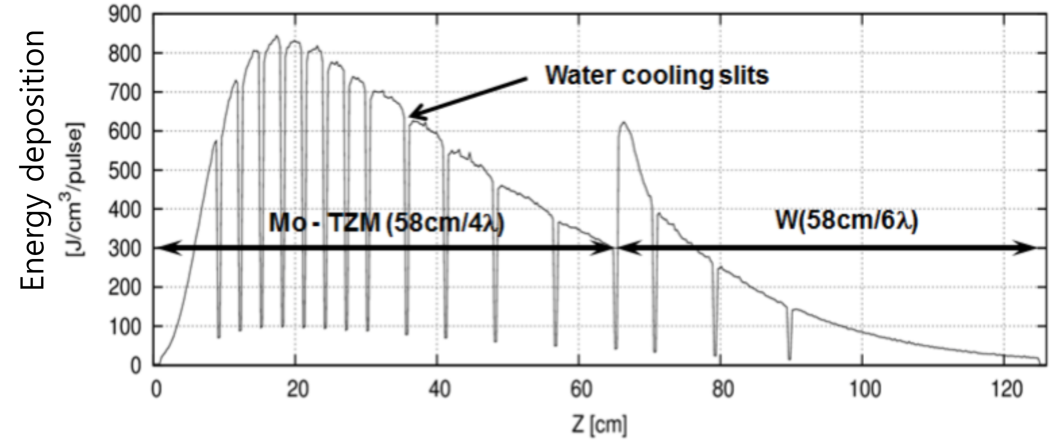

Target
Hadron absorber
Muon shield
~30 m
ν_τ detector
Vacuum vessel ~60m
Calorimeter
Muon spectrometer
HNL
π+
μ−
Neutrino
detector
Hidden particle detector

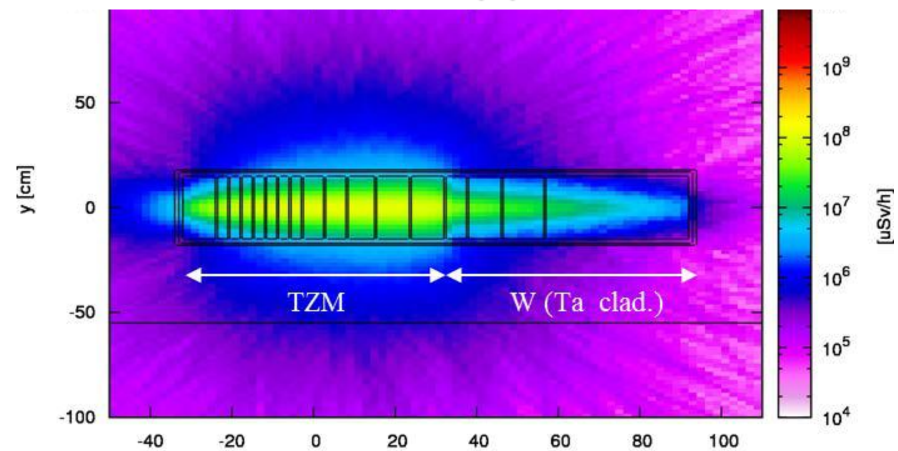
Beam dump target

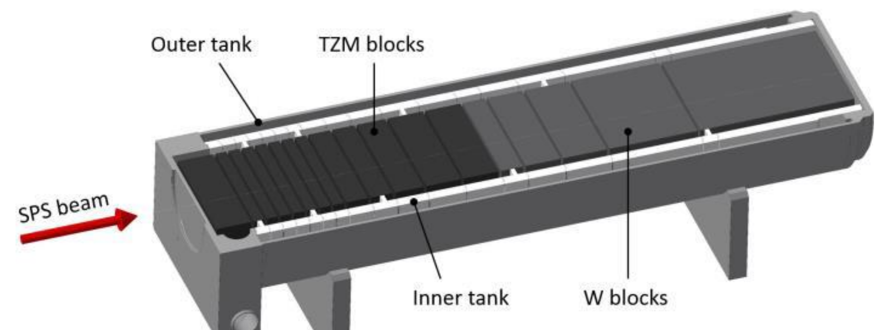
- Titanium/Zirconium/Molibdenum followed by layers of pure W
- Each layer is cooled by water alternative cooling with He under study

High A/Z target
→ maximize D, B production and to stop π, K before decay into μ ν

TZM 58 cm-thick + Tungsten 58 cm-thick





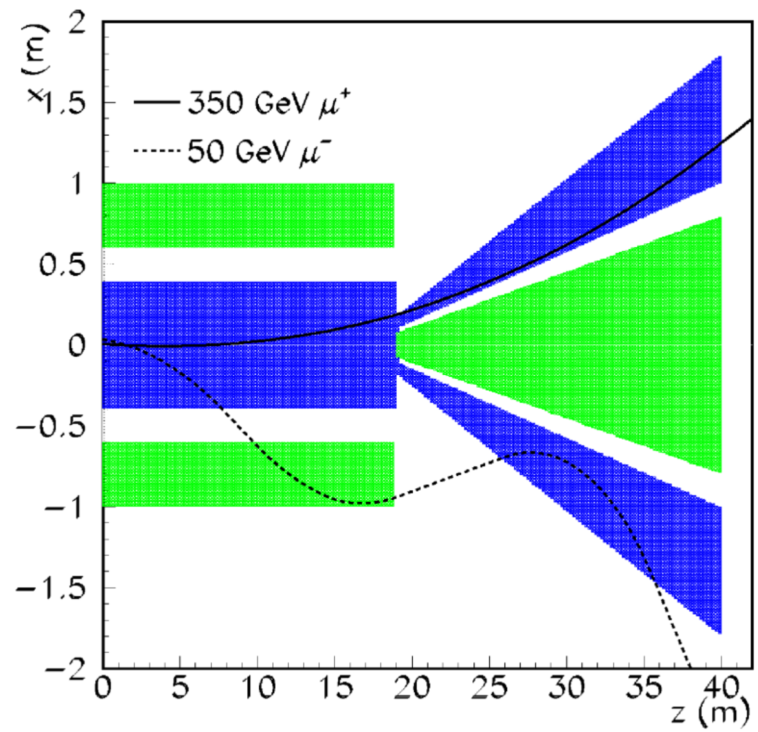


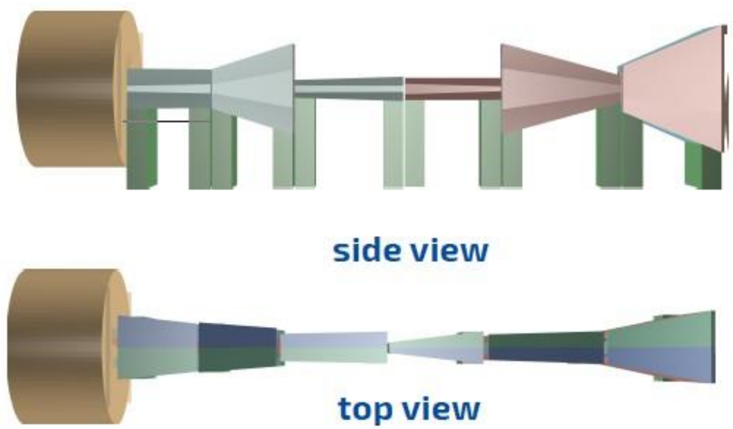
13 TZM+5 W blocks

Active muon shield

Large muon flux

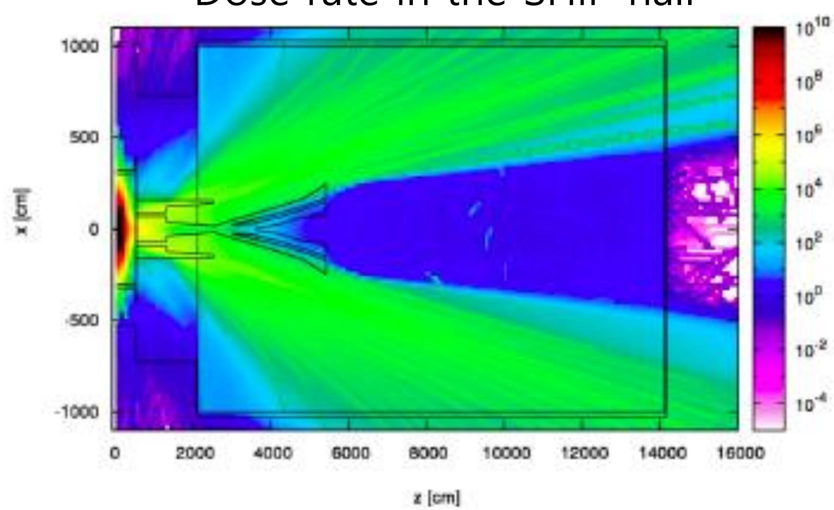
- Deal with 10^{11} muons/spill from π, K, ρ, ω and charm mesons
- Series of magnets to deflect out off acceptance
- Large p range → complicates geometry





SHiP Coll., JINST 12 (2017) P05011

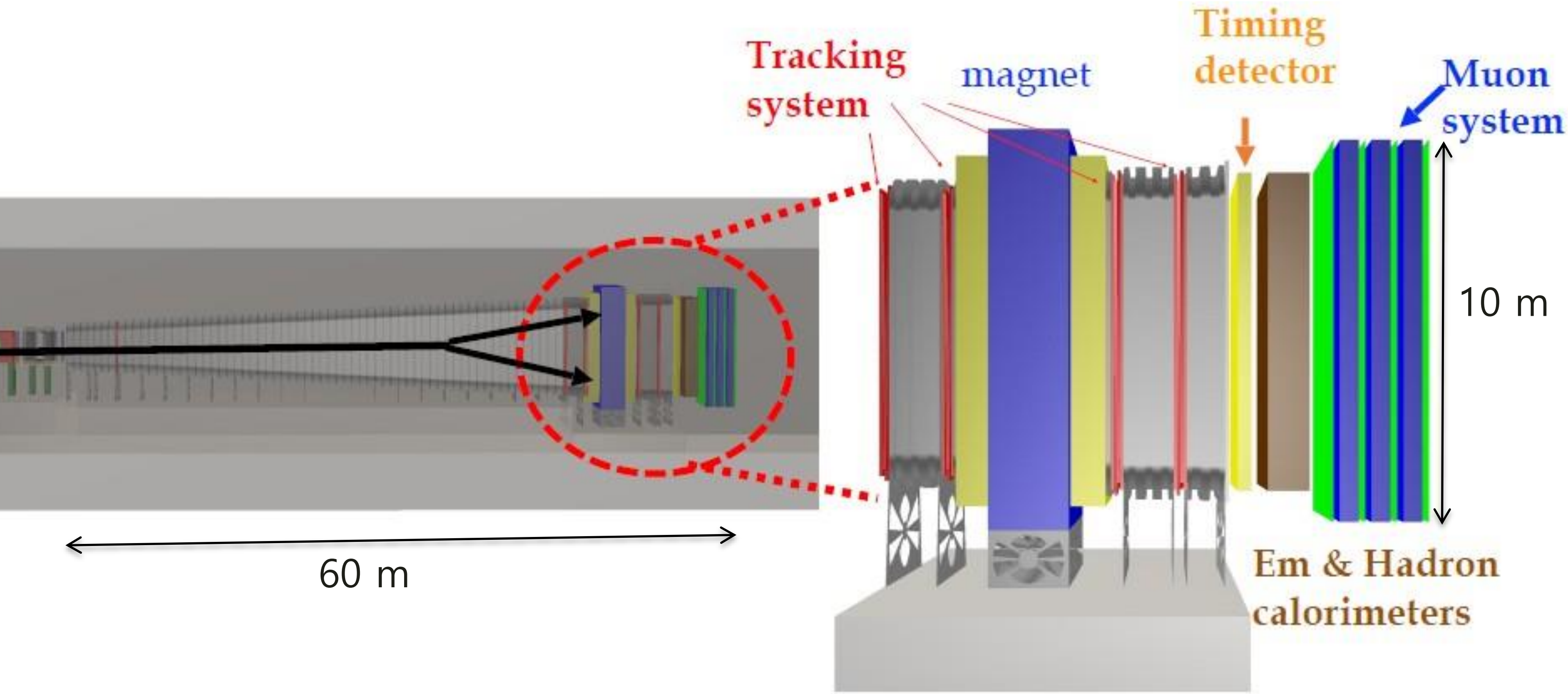
Dose rate in the SHiP hall



Recent optimization

- reduced length from 50 to 35 m
- reduced total weight from 1.7 to 1.3 kt
- B = 1.7 T

Hidden Sector detector



Challenges

- *Large vacuum vessel*
- *5 m long straw tubes*
- *100 ps timing resolution*

Many Trackers

Vertex reconstruction

Timing detector

ECAL, HCAL
Muon detector

PID
Charge
Momentum

Decay of Hidden Particles

$\mu^-\pi^+$

Models tested	Final states
Neutrino portal, SUSY neutralino	$\ell^\pm\pi^\mp, \ell^\pm K^\mp, \ell^\pm\rho^\mp$
Vector, scalar, axion portals, SUSY sgoldstino	$e^+e^-, \mu^+\mu^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-, K^+K^-$
Neutrino portal ,SUSY neutralino, axino	$\ell^+\ell^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

$\ell = (e, \mu, \nu), \ \rho^\pm \to \pi^\pm\pi^0$

Many Vee decay modes

→ ***Particle ID and Full reconstruction** are essential to minimize model dependence.*

See Iaroslava Bezshyiko's talk

HNL sensitivity

Cosmologically interesting region at low couplings

- **$m_{HNL} < m_b$**

  SHiP will have much better sensitivity than LHCb or Belle2

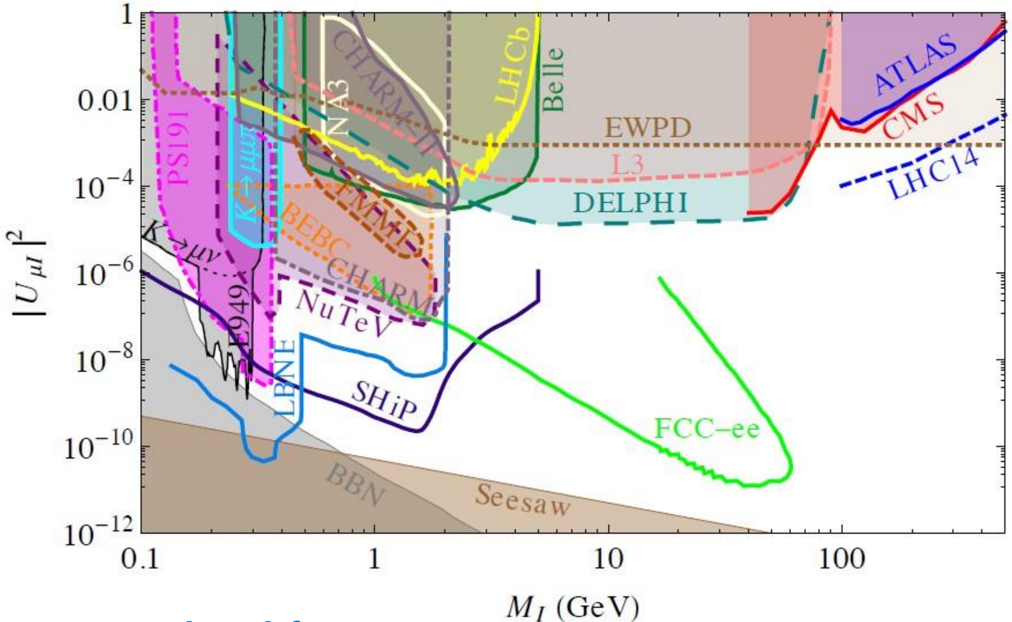
- **$m_b < m_{HNL} < m_Z$**

  FCC-ee, improvements expected from ATLAS/CMS

- **$m_{HNL} > m_Z$**

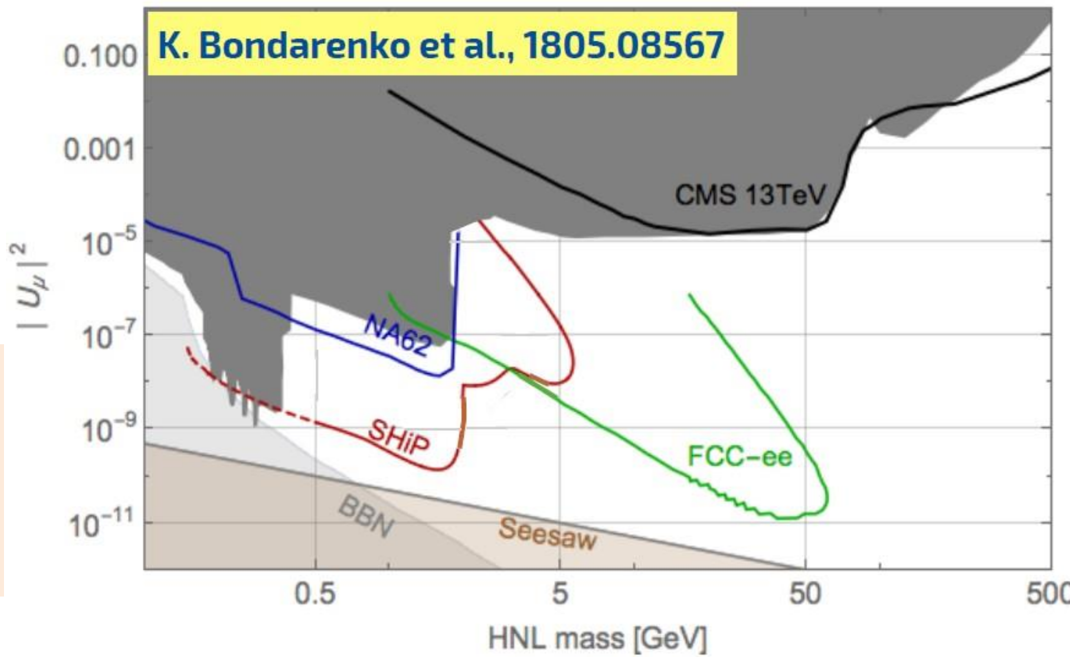
  targeted by ATLAS/CMS at HL-LHC

At **m_{HNL} = 1 GeV** and **U^2 = 10^{-8}** (50 x lower than present limit), SHiP will see more than **1,000** fully reconstructed events.



Updated from

K. Bondarenko et al., 1805.08567



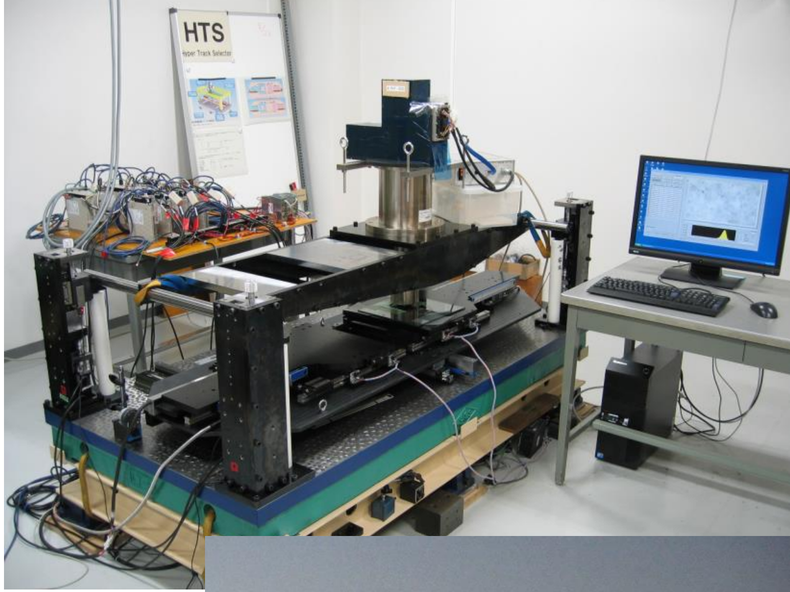
Neutrino Physics with SHiP

- ν_τ least known SM particle
- Anti-ν_τ not yet observed
- ~ 10,000 ν_τ events with 7 tons detector
- First direct observation of Anti-ν_τ
- Cross sections & Mag moments of ν_τ & Anti-ν_τ
- Charm physics with ν_τ & Anti-ν_τ
- F_4, F_5 evaluation from ν_τ & Anti-ν_τ events etc…

→ Using Nuclear Emulsion Technique

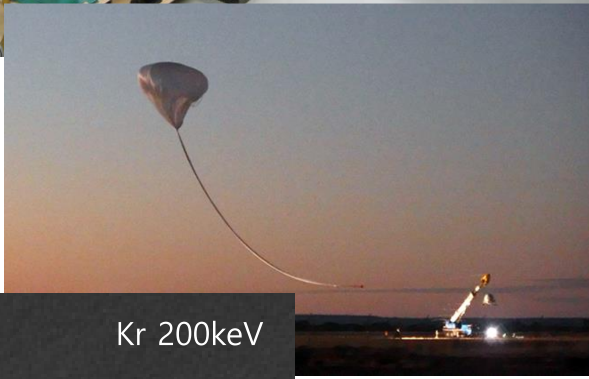
Nuclear Emulsion

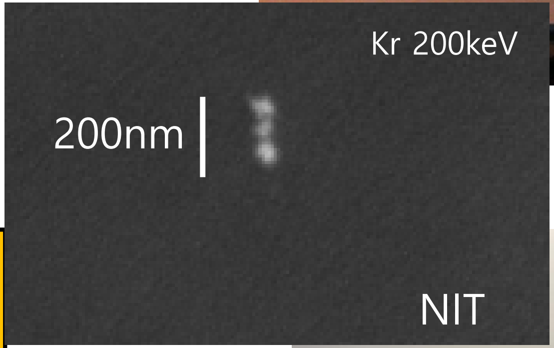
Old type of detector but still very effective tool thanks to development of High speed Auto-scanning system and new analysis method (mainly by Nagoya group)



- Spatial resolution → sub micron
- PID → electron, pion, tau …
- Momemtum measurement → using MCS

Tracker, Calorimeter
Target (C, N, O,Ag, Br)
3D visual detector





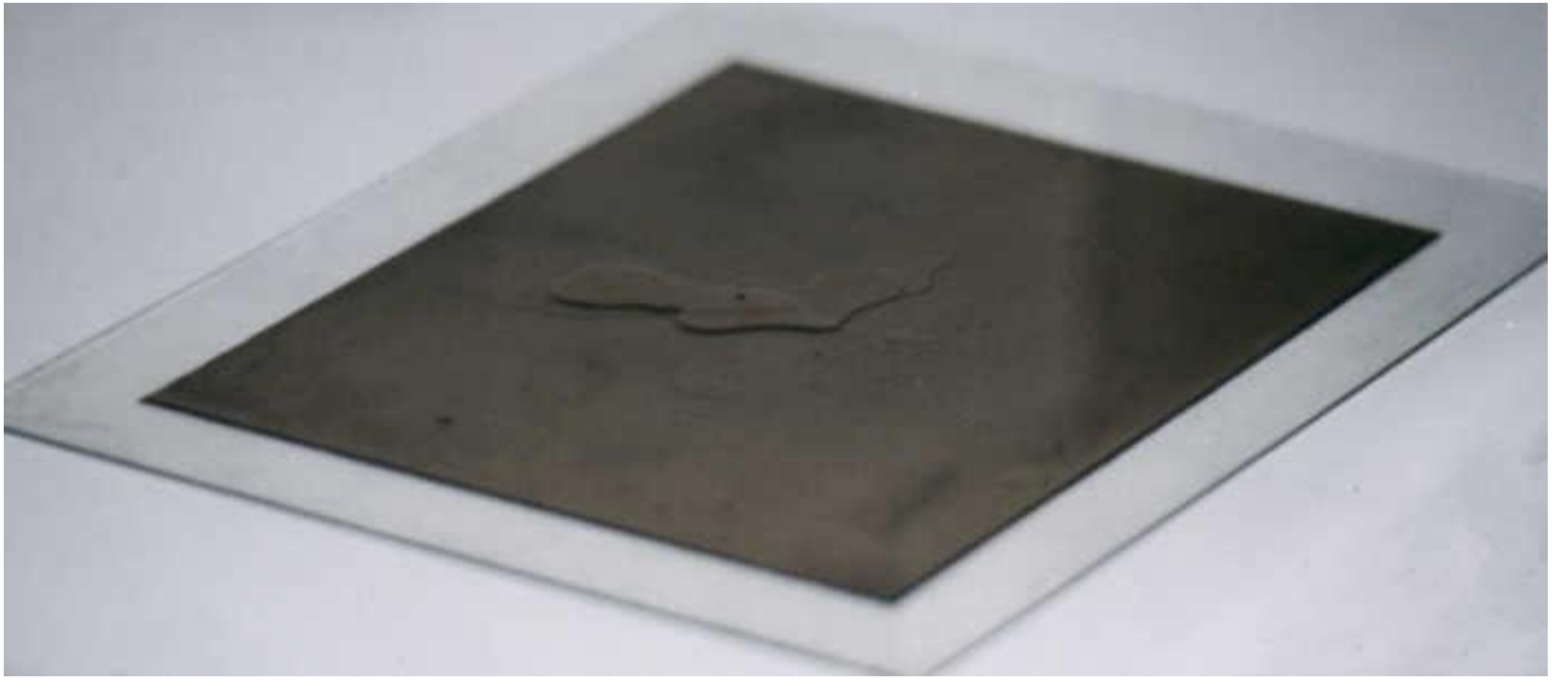
✔ Application to various fields

Neutrino exp, WIMP search,

S=-2 nuclei, Gamma ray telescope,

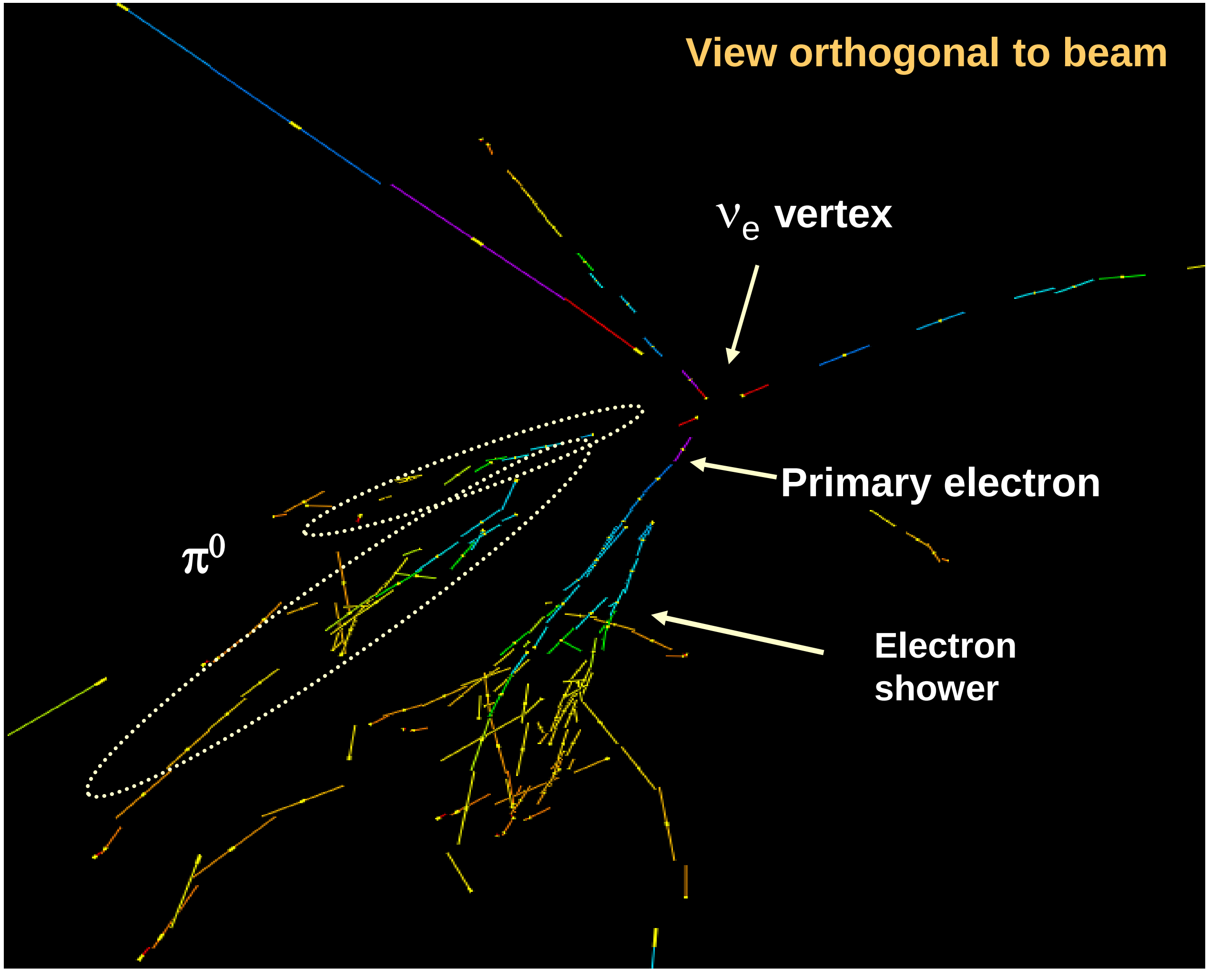
Anti-matter, Muon radiography …

Emulsion Plate



CHORUS exp

71 cm x 36 cm (CHORUS)
50 cm x 50 cm (DONuT)
10 cm x 12.5 cm (OPERA)

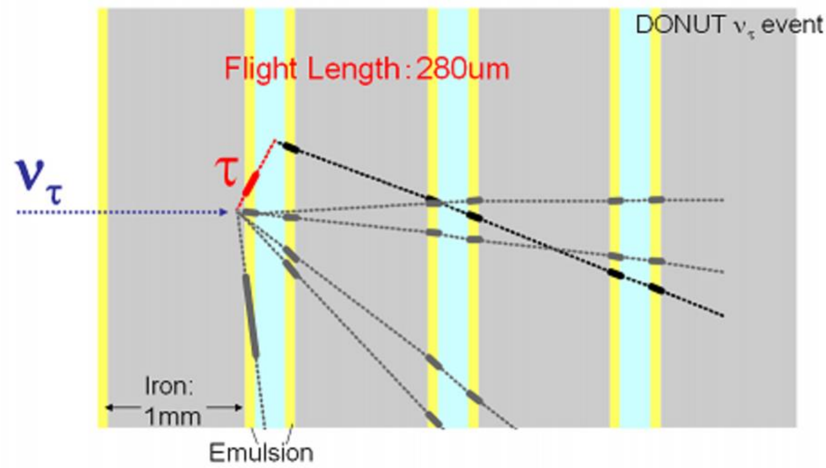


ν_e CC event in Emulsion

PID in emulsion → electron, π^0

Tau etc.

Tau Neutrinos so far



DONuT **9 events**

First direct observation
Proton beam dump exp.
Cross section, mag mom

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

can not distinguish ν_τ and $\bar{\nu}_\tau$

OPERA **10 events** (from oscillation)

Discovery of Nu tau appearance
(5.1σ, 2015) (final 6.1σ, 2018)

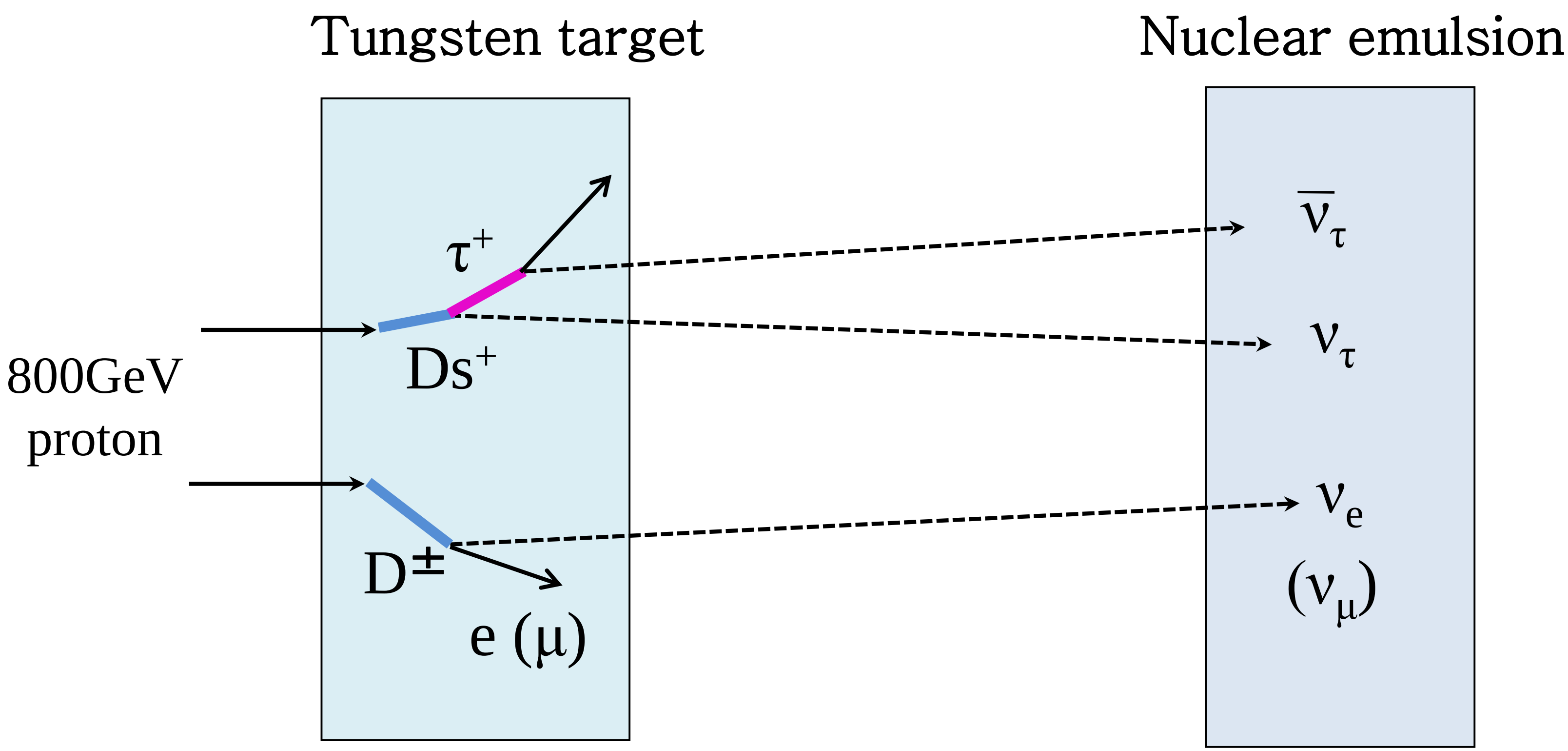
identified $\mu^- \rightarrow \tau^- \rightarrow \nu_\tau$ (not $\bar{\nu}_\tau$)

Using Emulsion-Counter hybrid system &
High speed auto-scanning system

→ Same technique will be used in SHiP

DONuT (Direct Observation of Nu Tau)

Proton beam dump exp at Fermilab → same method with SHiP



ν_τ CC events : 9

ν_μ CC events : 225

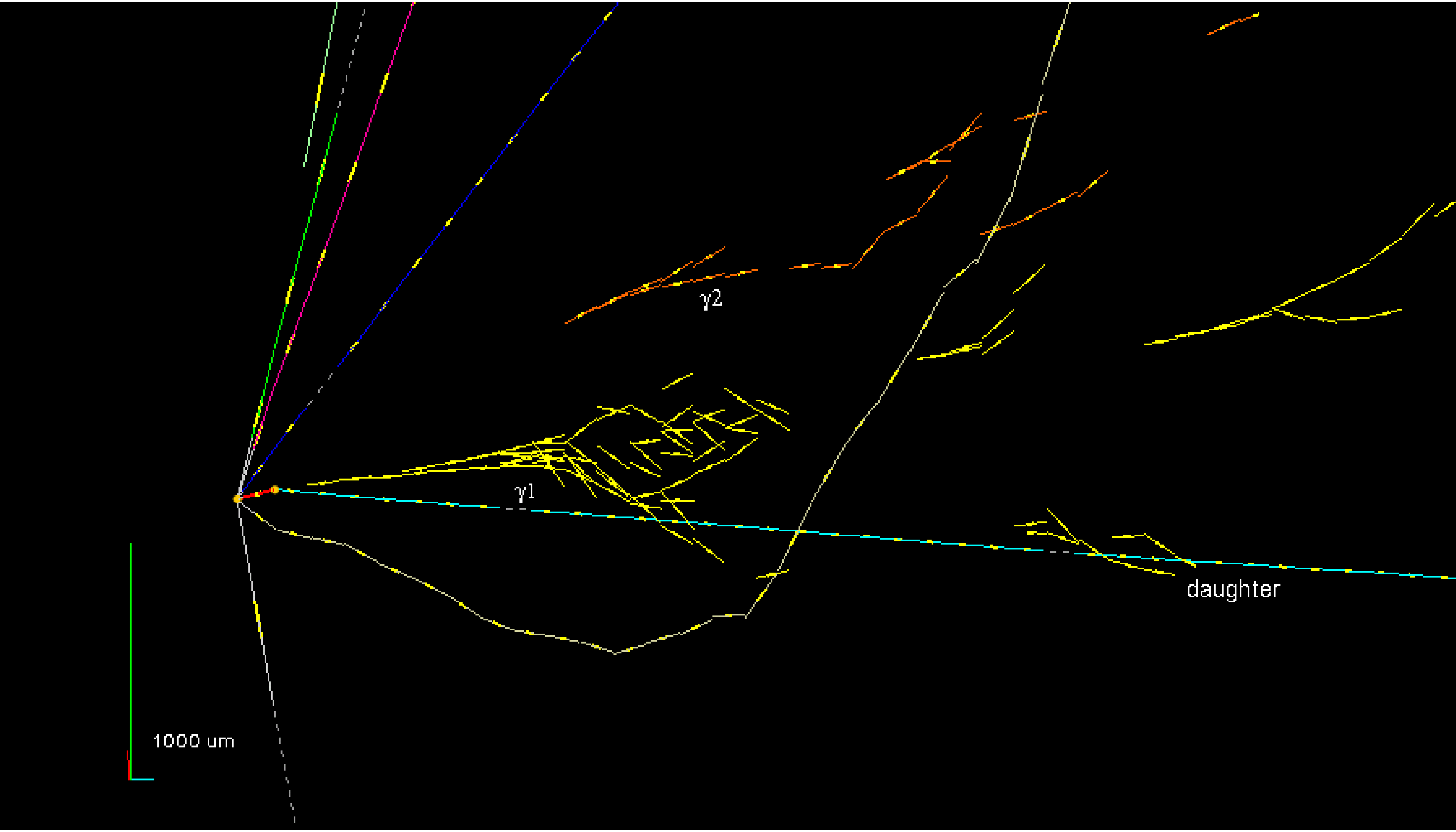
ν_e CC events : 82

OPERA **1st ν_τ event (May 2010)**

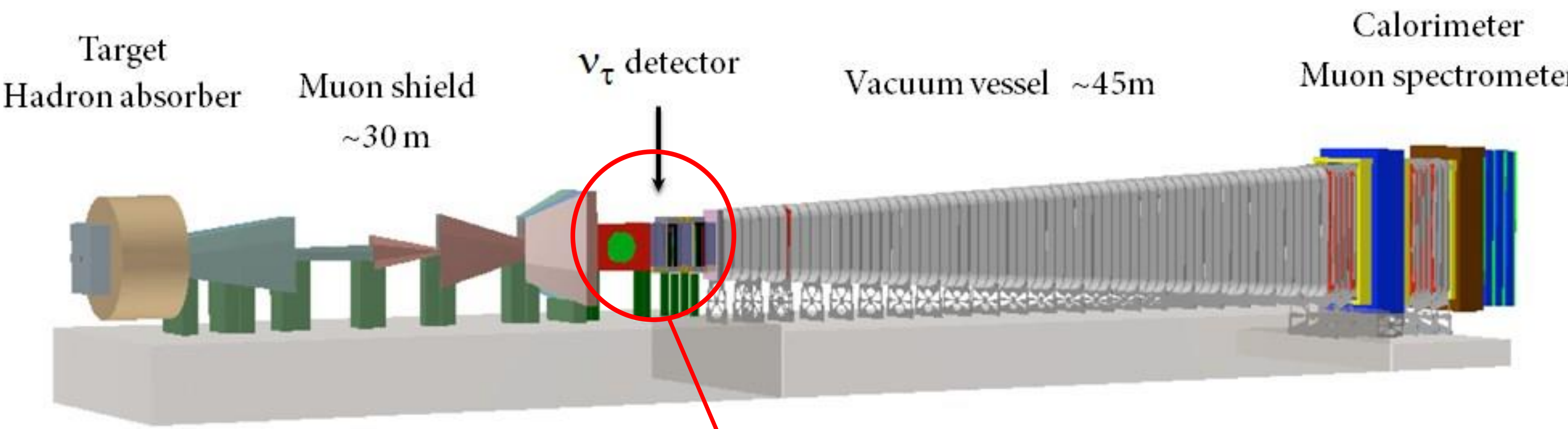
$\tau \rightarrow$ 1h (hadronic kink event)

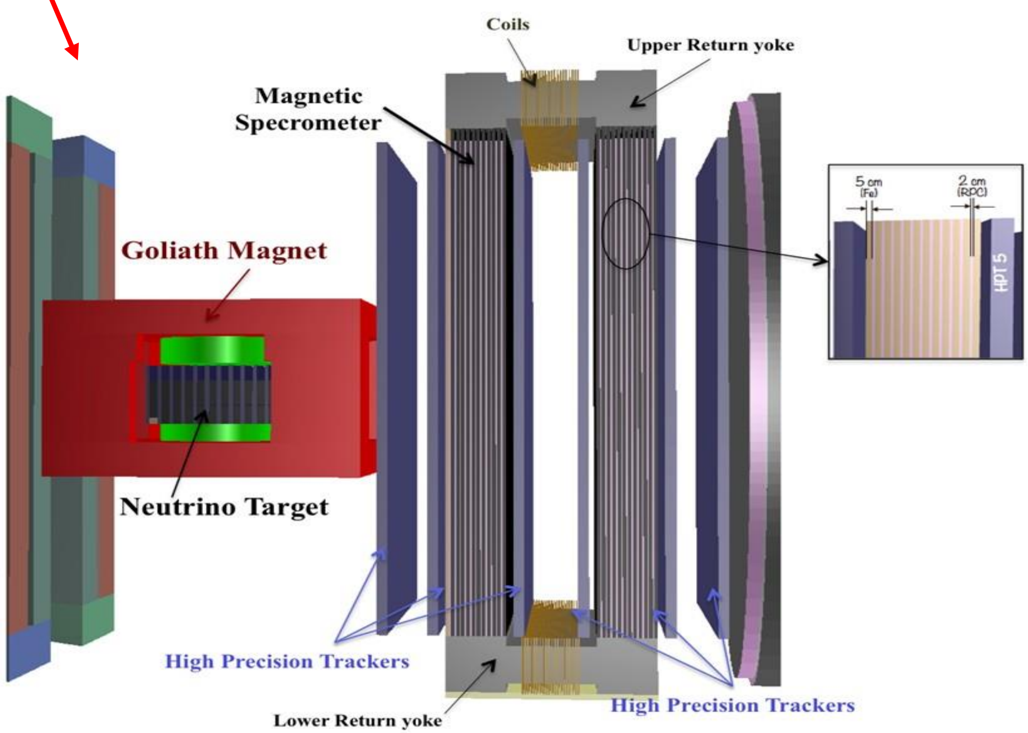
($\tau^- \rightarrow \rho^- \nu_\tau$, $\rho^- \rightarrow \pi^0 \pi^-$, $\pi^0 \rightarrow 2\gamma$)

kink angle (mrad)	41 ± 2
τ fight length (μm)	1335 ± 35
Φ (degrees)	173±2

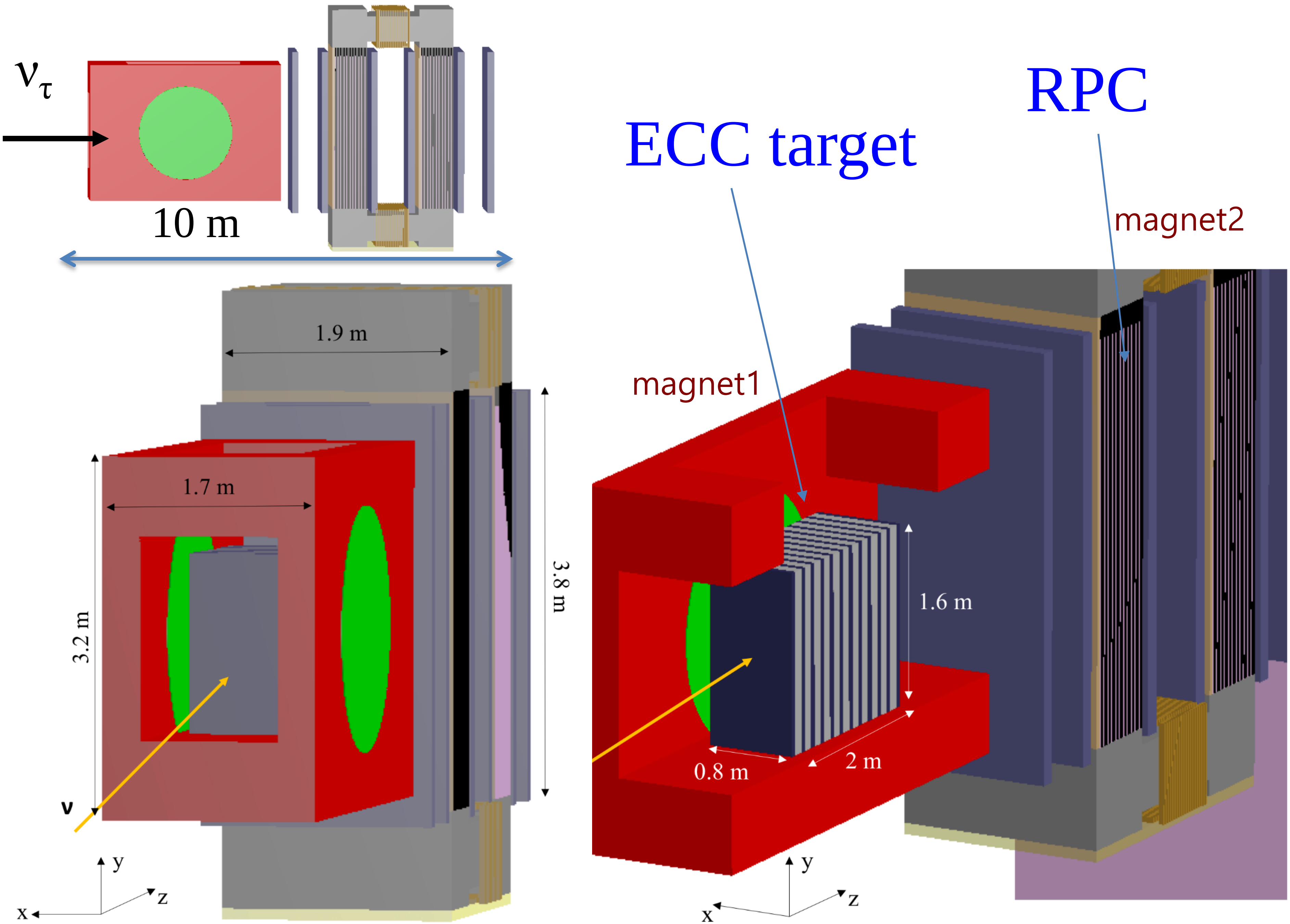


SHiP Neutrino detector





Two magnet type

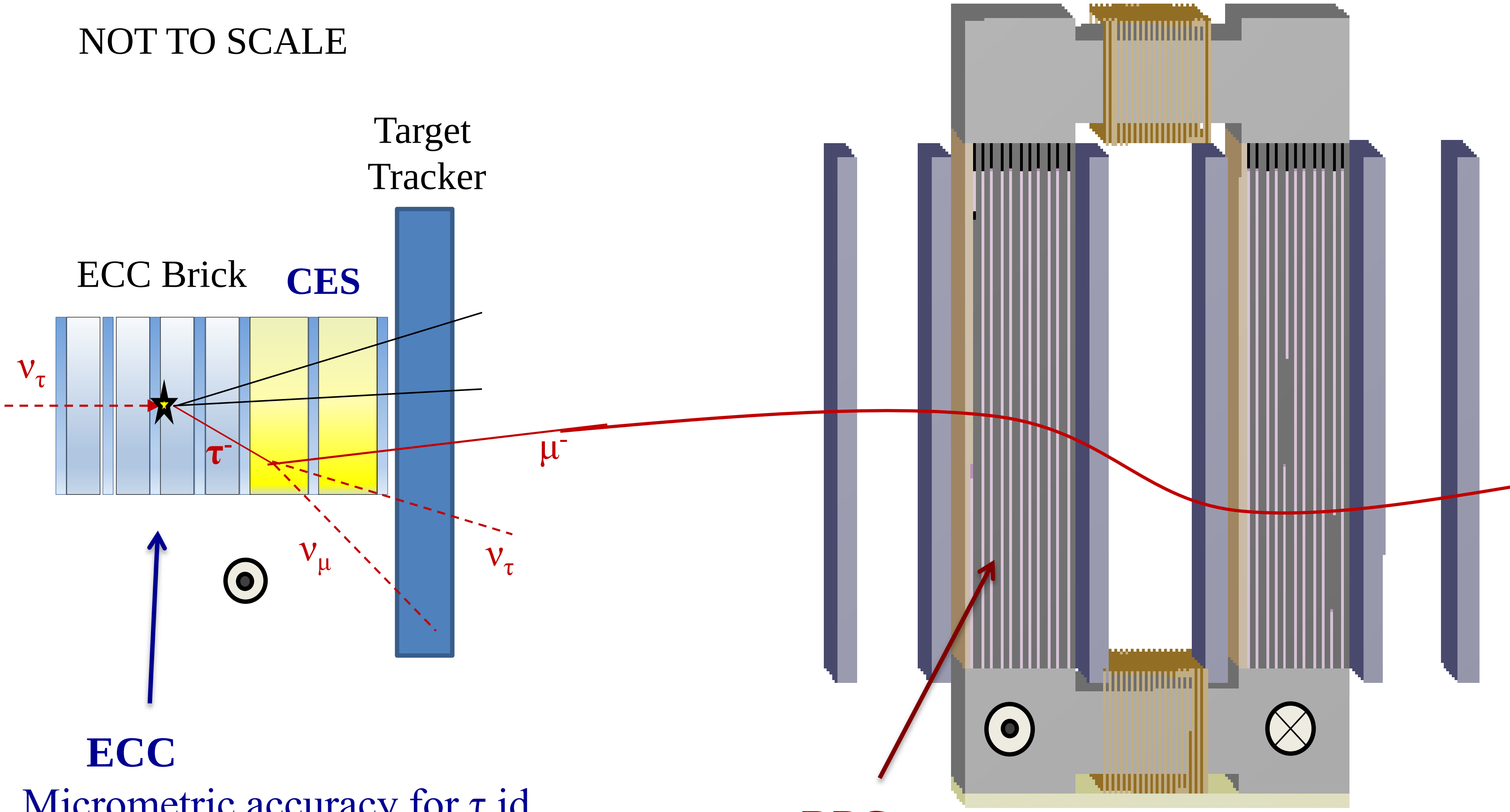


ν_τ
10 m
ECC target
RPC
magnet2
magnet1
1.9 m
1.7 m
3.2 m
3.8 m
1.6 m
0.8 m
2 m
ν
y
z
x
y
z
x

Typical Tau Neutrino event

Giovanni De Lellis

NOT TO SCALE



ECC

Micrometric accuracy for τ id

Momentum and Charge measurement

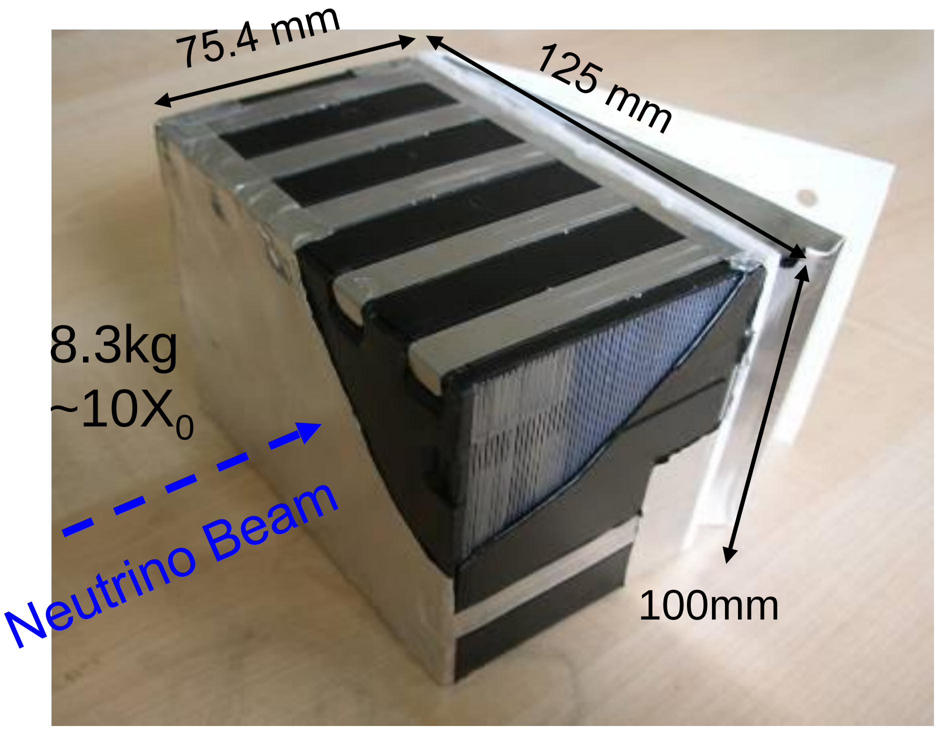
for τ^+/τ^- separation

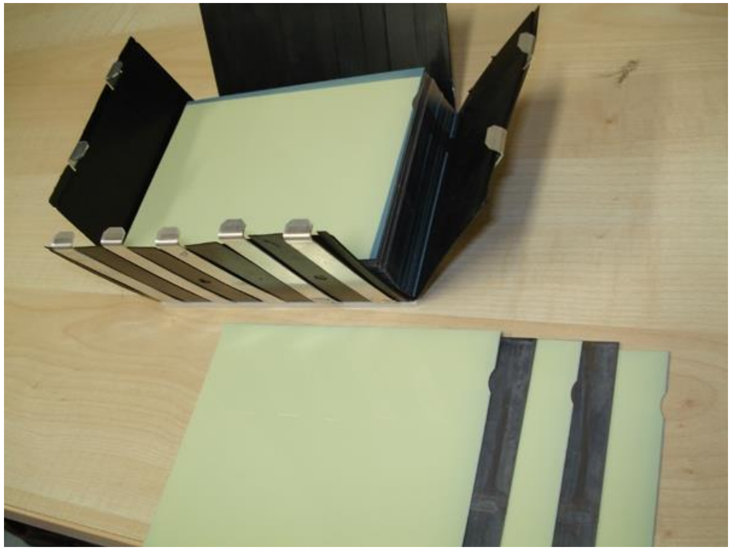
RPC

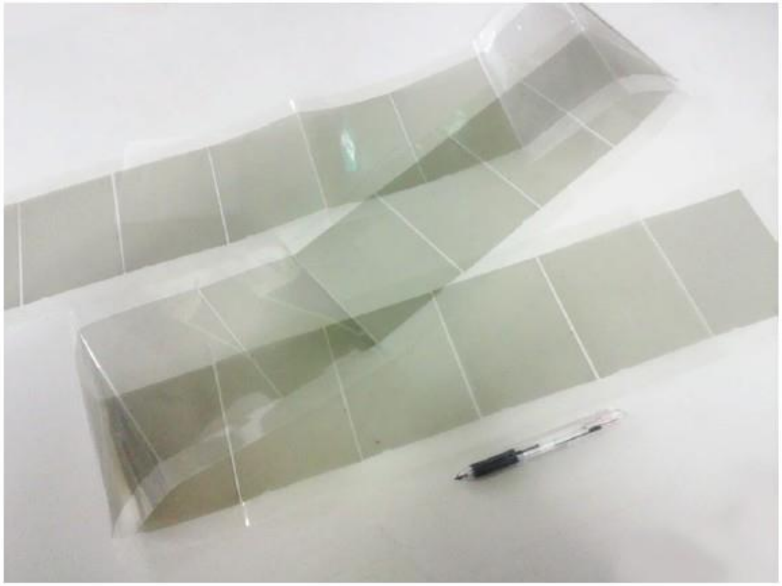
Muon identification

Momentum and Charge measurement

ECC (Emulsion Cloud Chamber) Brick Structure







OPERA Film after development

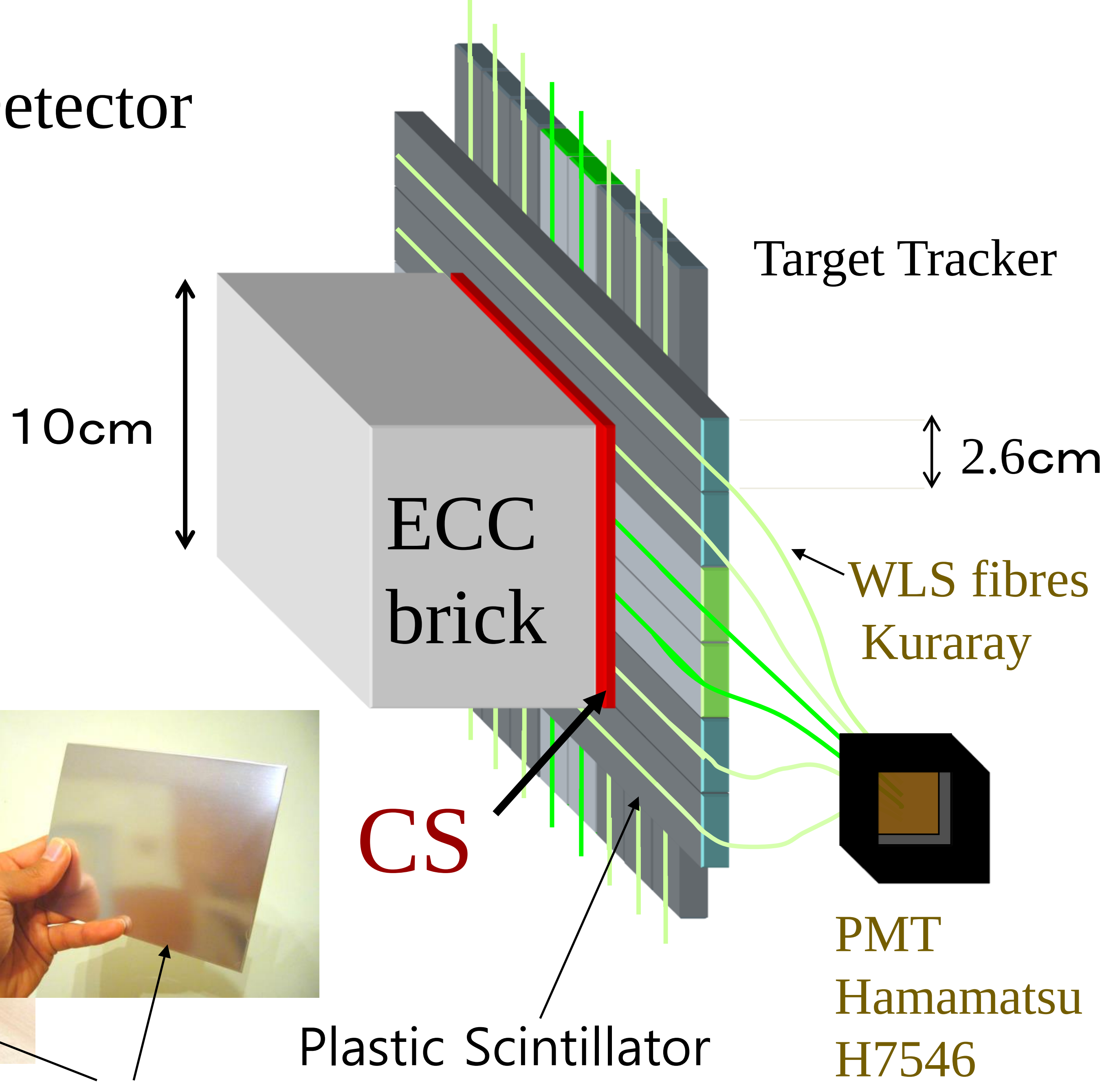
ECC Brick

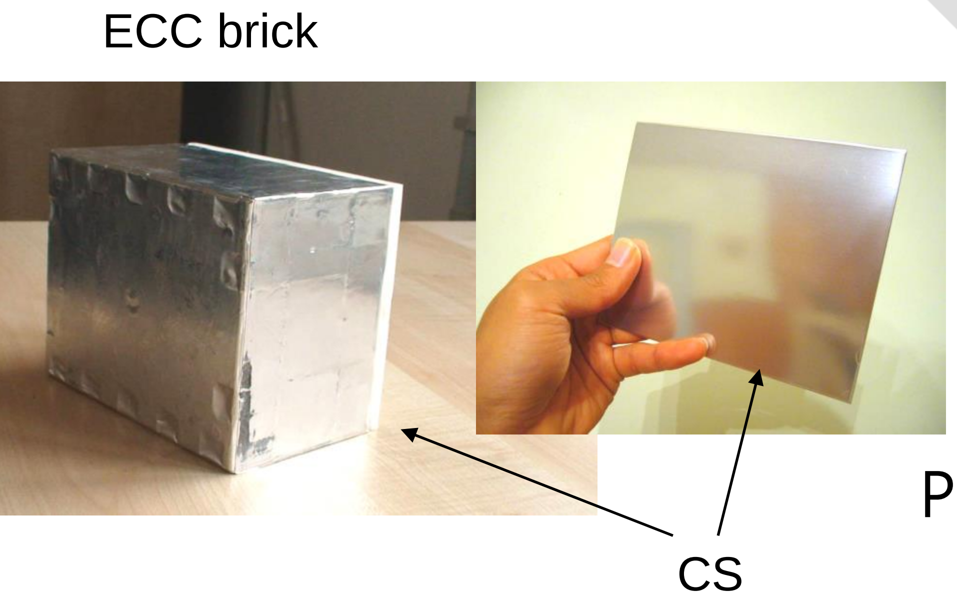
57 Lead plates and
58 Nuclear emulsion films

CES (Compact Emulsion Spectrometer)

Air gaps and Nuclear Emulsions
Electric charge measurement of τ lepton
ν_τ/anti-ν_τ separation

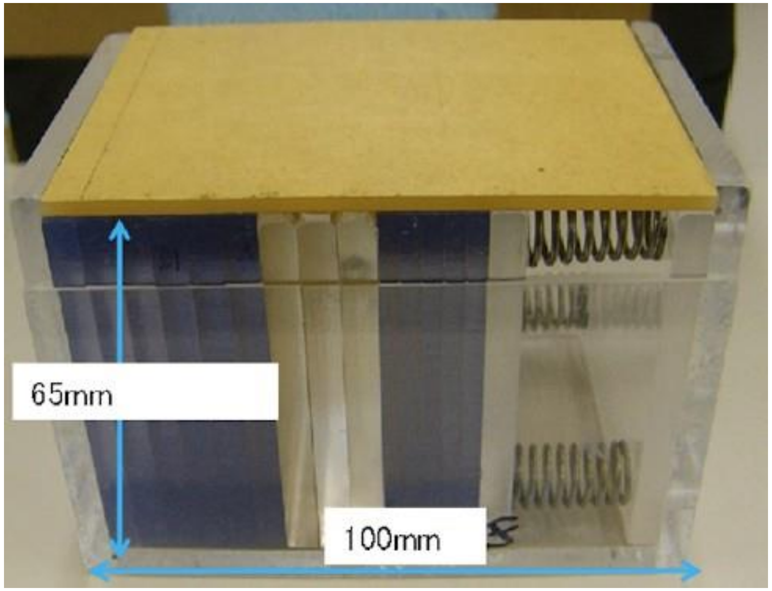
Basic unit of Detector (OPERA type)

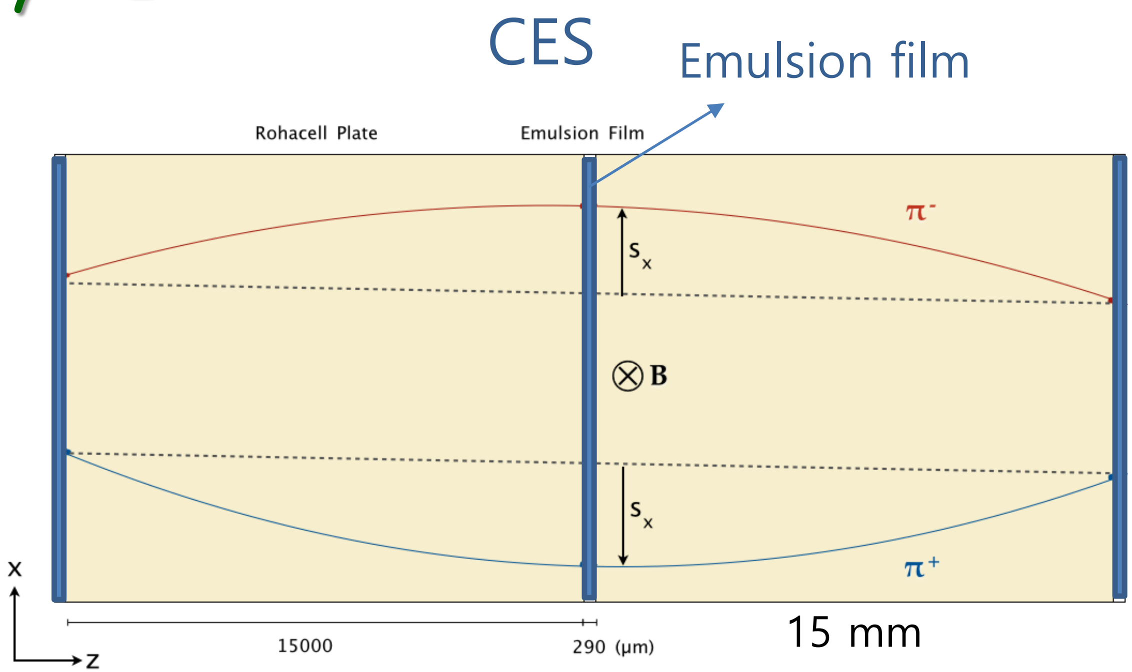




Anti-Tau Neutrino by CES

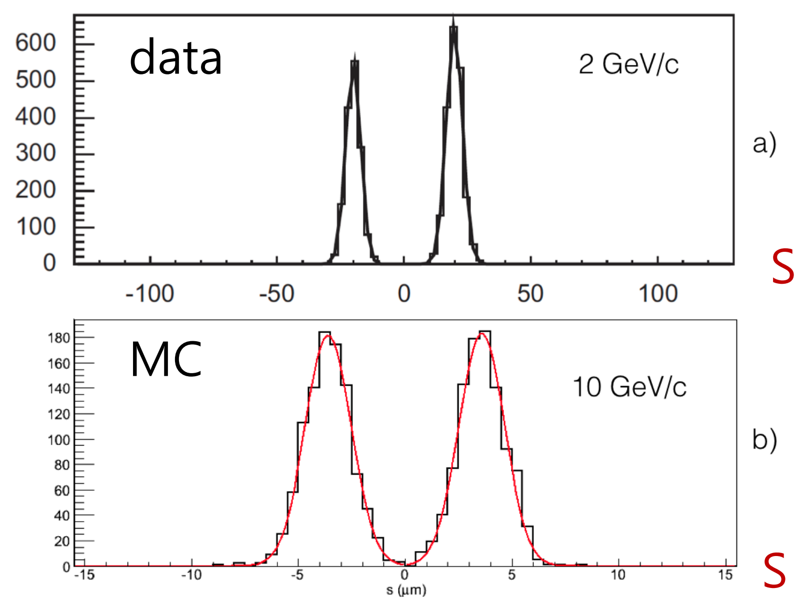
Measurement of Sagitta





$$\nu_\tau \rightarrow \tau^- \rightarrow \mu^-$$

$$\overline{\nu}_\tau \rightarrow \tau^+ \rightarrow \mu^+$$



- Electric charge can be determined with better than 3σ level up to 10 GeV/c
- Momentum estimated from the Sagitta $\Delta p/p < 20\%$ up to 12 GeV/c

Expected Number of Tau Neutrinos

2x10[20]pot

- 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**

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

In Neutrino detector

decay channel	ν_τ	
	$N^{\exp}$	N^{bg}
$\tau^- \to \mu^-$	570	30
$\tau^- \to h^-$	990	80
$\tau^- \to h^- h^+ h^-$	210	30
Total	1770	140

decay channel	$\bar{\nu}_\tau$	
	$N^{\exp}$	N^{bg}
$\tau^+ \to \mu^+$	290	140
$\tau^+ \to h^+$	500	380
$\tau^+ \to h^- h^+ h^+$	110	140
Total	900	660

decay channel	ν_τ , $\bar{\nu}_\tau$	
	$N^{\exp}$	N^{bg}
$\tau \to e$	850	160

Since the charge of the electron is not measurable, only an inclusive measurement of tau neutrinos and anti-tau neutrinos is possible in the tau→ e decay channel.

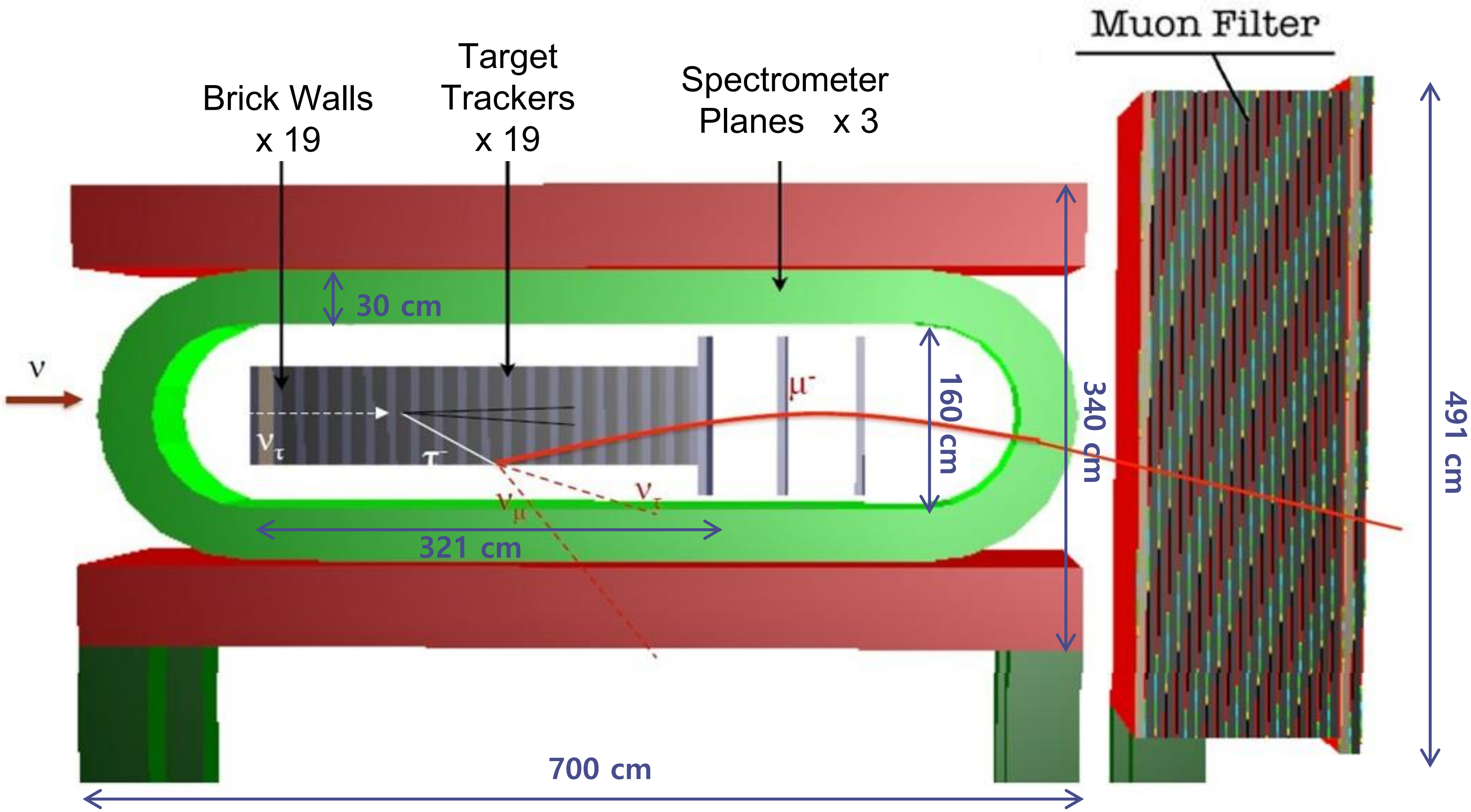
After geometrical, location and decay search efficiencies consideration

Total expected number of Tau neutrinos and Anti-tau neutrinos

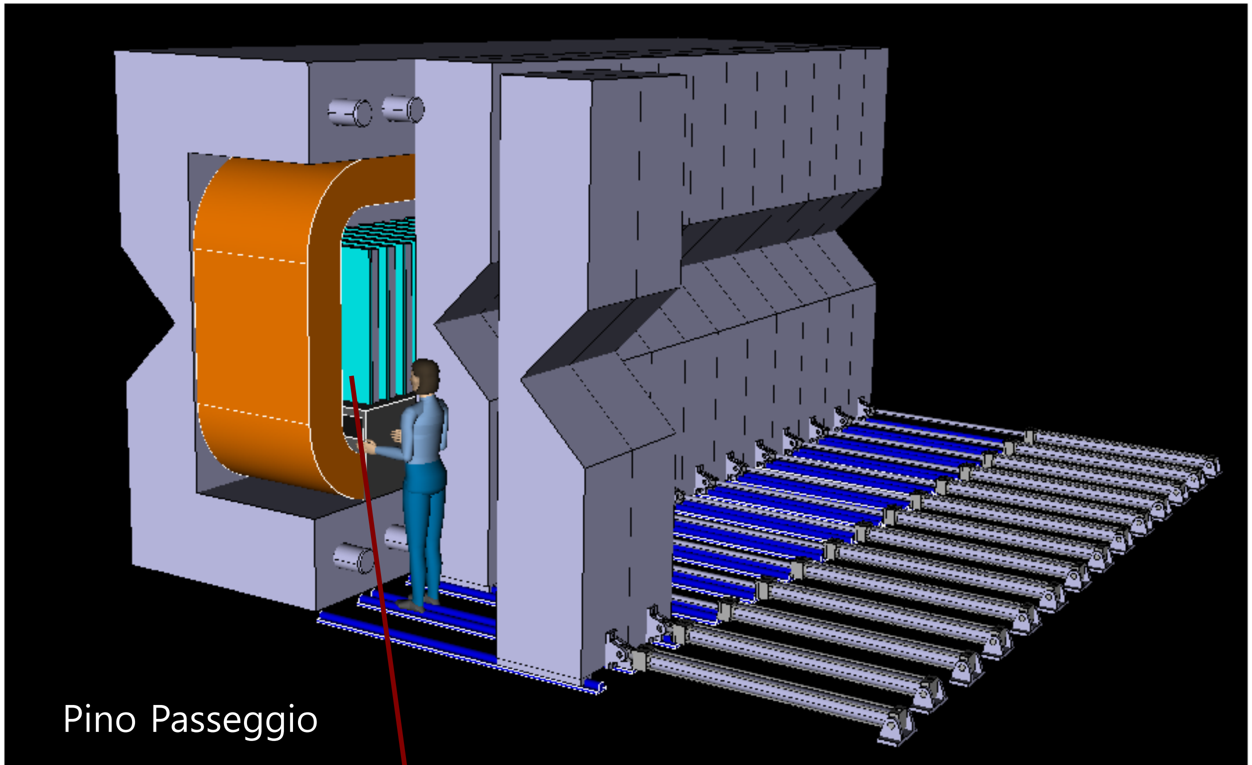
→ 3520 events with 960 bg events in 5 yrs run

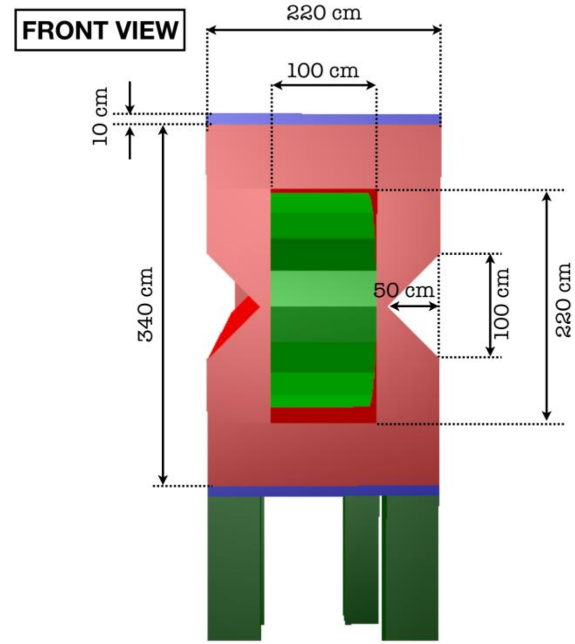
One magnet option

A. Di Crescenzo

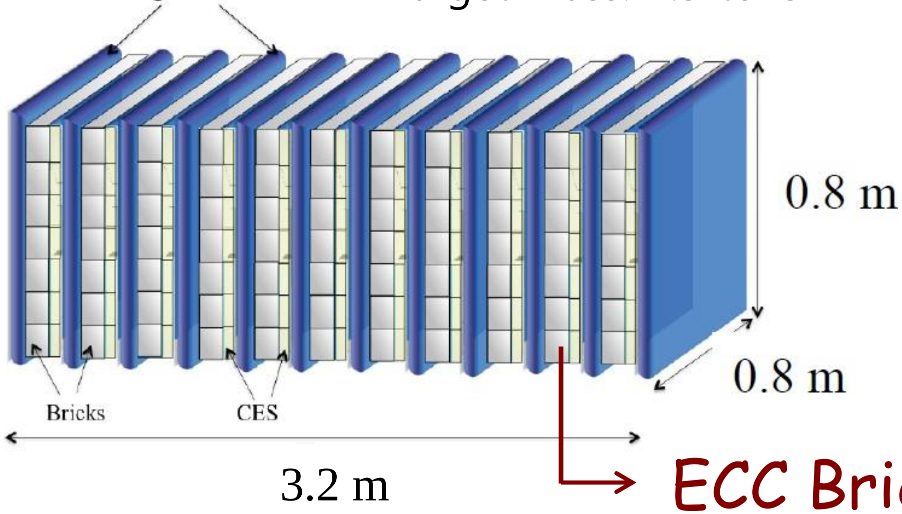


Emulsion films : High spatial resolution to observe the τ decay (~1 mm)
Target tracker (TT) : Electronic detector to predict ECC brick contained ν interaction and provide the time stamp
Magnet : magnetized target to measure the charge of τ products
Spectrometer (CES) : Compact Emulsion Spectrometer to measure muon momentum & charge
Muon filter (RPC) : Muon identification

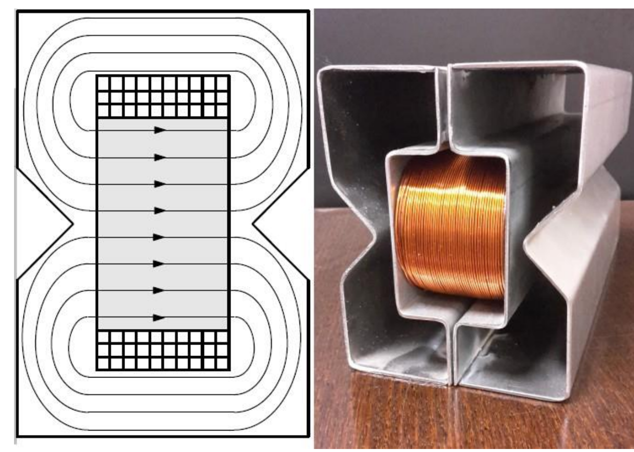




Target mass: 7.3 tons

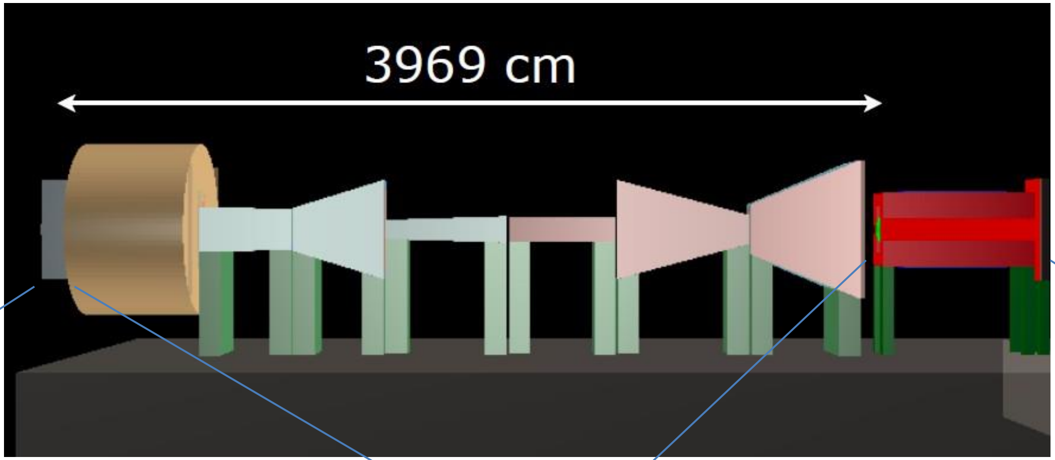


ECC Brick



B_{min}=1.2 T

ν_τ fluxes



One magnet option

BEAM DUMP		
	<E> (GeV)	Yield
ν_e	4.1	2.8×10^{17}
ν_μ	1.5	4.2×10^{18}
ν_τ	7.4	1.4×10^{16}
ν_e-bar	4.7	2.3×10^{17}
ν_μ-bar	1.6	2.7×10^{18}
ν_τ-bar	8.1	1.4×10^{16}

INTERACTING CC-DIS		
	<E> (GeV)	Yield
ν_e	59	1.1×10^{6}
ν_μ	42	2.7×10^{6}
ν_τ	52	3.2×10^{4}
ν_e-bar	46	2.6×10^{5}
ν_μ-bar	36	6.0×10^{5}
ν_τ-bar	70	2.1×10^{4}

Antonia Di Crescenzo

Neutrino Signal Yield

One magnet option
5 years run 2×10^{20} p.o.t.

$$N^{exp}_{\nu_\tau(\overline{\nu}_\tau)}(\tau \to i) = N_{\nu_\tau(\overline{\nu}_\tau)} Br(\tau \to i)\epsilon^{\tau \to i}_{tot}$$

PRELIMINARY

ν_τ SIGNAL EVENTS	
	Yield
$\tau \to \mu$	1200
$\tau \to h$	4000
$\tau \to 3h$	1000
TOTAL	**6200**

anti-ν_τ SIGNAL EVENTS	
	Yield
$\tau \to \mu$	1000
$\tau \to h$	3000
$\tau \to 3h$	700
TOTAL	**4700**

No kinematical selection applied
- Background from charm and hadronic re-interactions to be evaluated
- Signal/background rejection to be optimized

Structure Function F4, F5

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

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

$$\pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\Bigg),$$

Neutrino ($+$), Anti neutrino ($-$)

The DIS Charged Current Tau neutrino (Anti-Tau neutrino) differential **cross-section** is given by **5 structure function**. The contribution to the cross-section of **F4** and **F5** is negligible in Muon and Electron neutrino interactions due to light charged lepton mass. (Albright & Jarlskog)

On the contrary, Tau neutrino (Anti-Tau neutrino) scattering can contribute to **F4** and **F5** due to non-negligible Tau lepton mass.

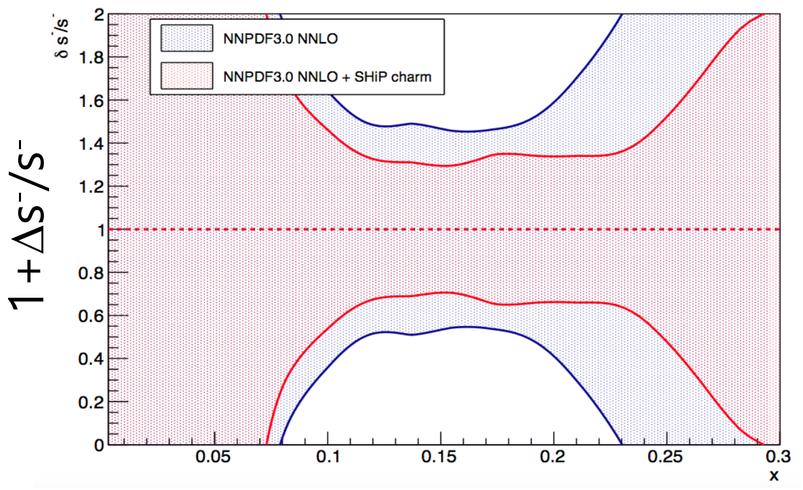
For Tau neutrino, the effect of **F4** and **F5** is **30%** at E=20 GeV and **7%** at 200GeV.
For Anti-Tau neutrino, the effects are **53%** and **14%** at the corresponding energy.

(Y.S.Jeong)

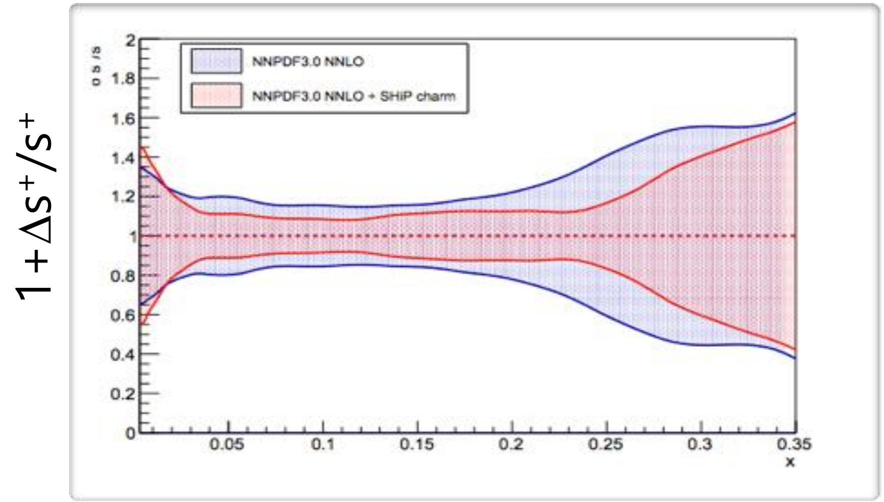
Strange quark content in nucleon

Charm production in Neutrino scattering is extremely sensitive to s-quark content of nucleon, especially with Anti-neutrino where anti-s quark is dominant.

Significant improvement (factor two) of **the uncertainty on s-quark distribution in nucleon** with SHIP data in the *x* range between 0.03 and 0.35



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

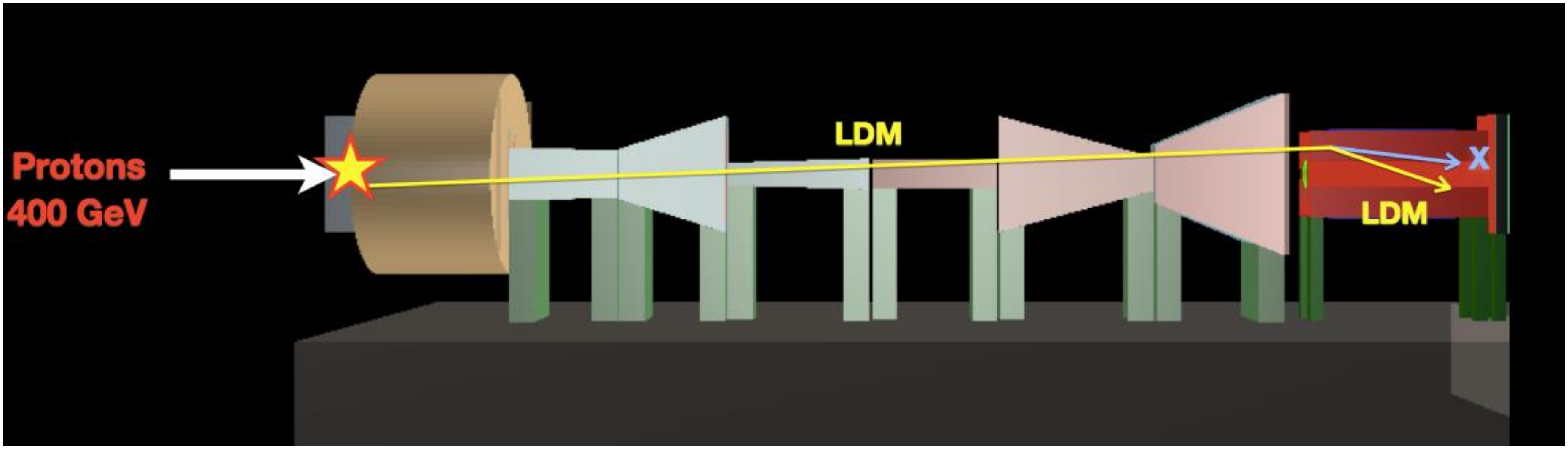


$$s^{+} = s(x) + \overline{s}(x)$$

Improvement of the accuracy on S^- and S^+

Charm yield in ν int. @ SHiP is >10 the sample from previous experiments (~10^5 expected events)

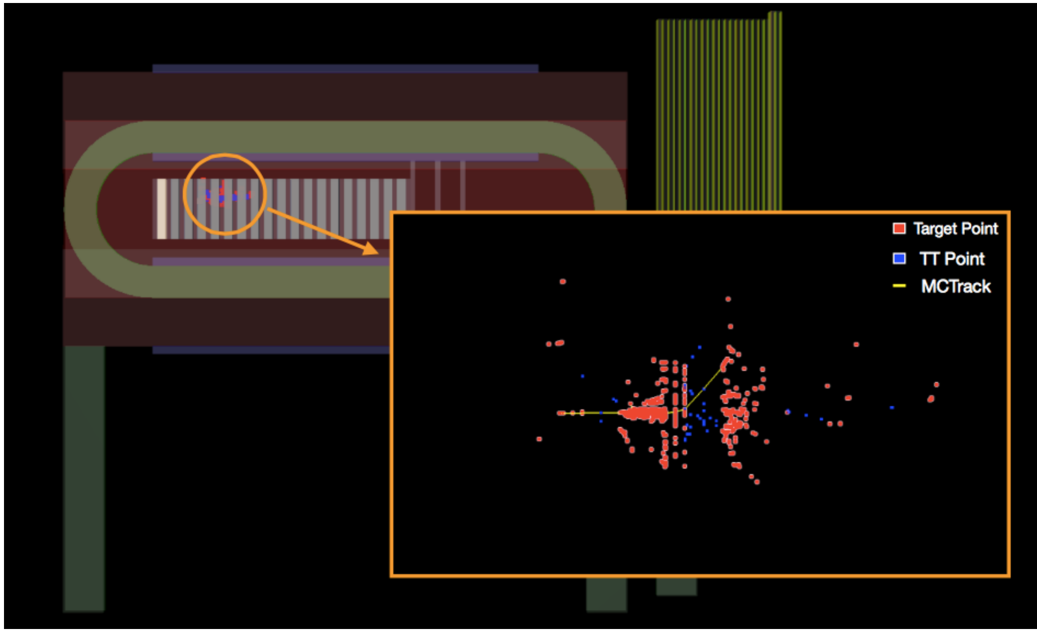
Light dark matter detection in Neutrino detector

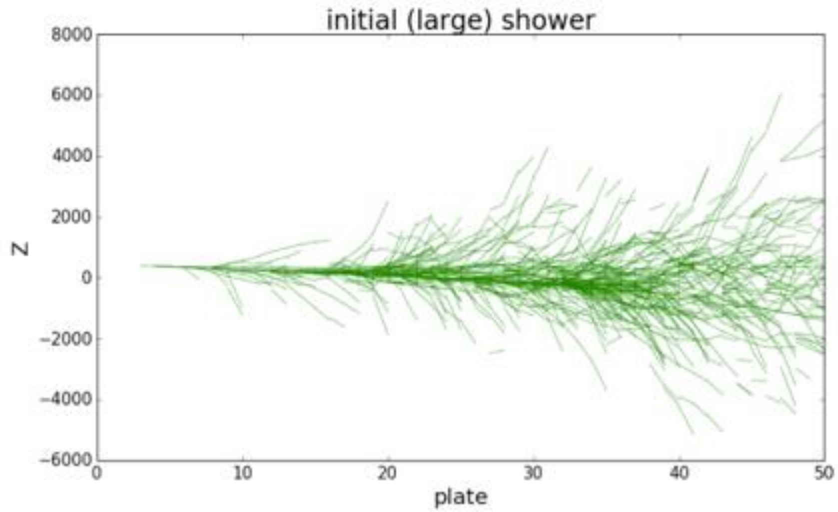


$A' \rightarrow \chi\,\bar{\chi}$

$\chi\, e^- \rightarrow \chi\, e^-$

Electron recoil
Cascade shower in Emulsion





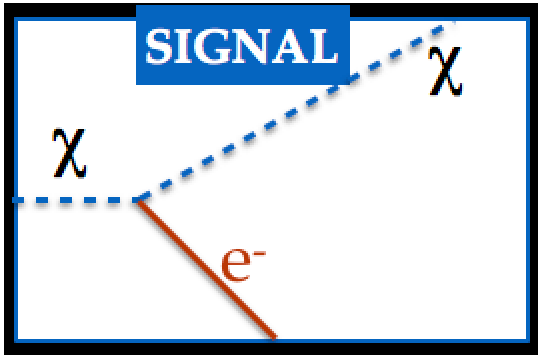
Development of new software tools based on Machine learning techniques to improve electron identification and energy measurement in ECC

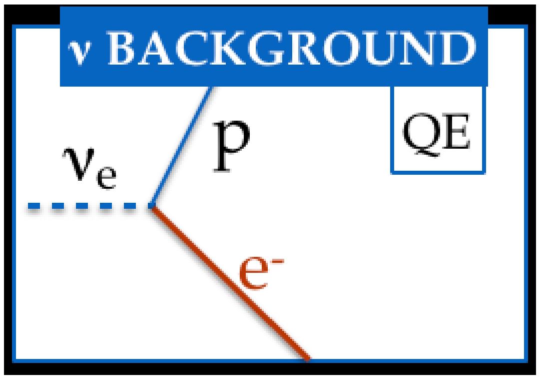
also for signal/background discrimination
→Dominant background in DM search comes from **neutrino interactions**

	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Quasi-elastic scattering	105	73			178
Elastic scattering on e^-	16	2	20	18	56
Resonant scattering	13	27			40
Deep inelastic scattering	3	7			10
Total	137	109	20	18	284

Number of background events to the dark matter search after cuts, from neutrino interactions with 2×10^{20} pot.

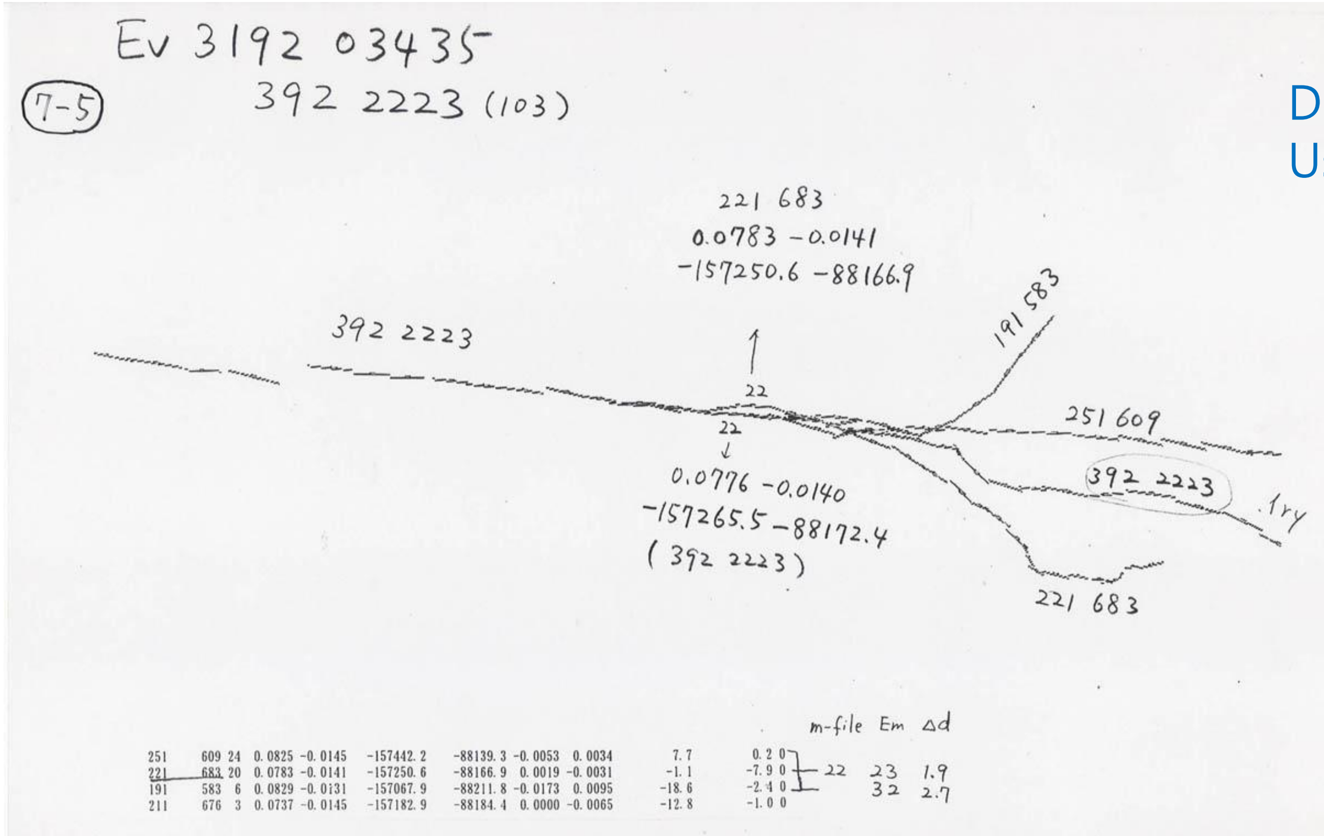
SHiP TP

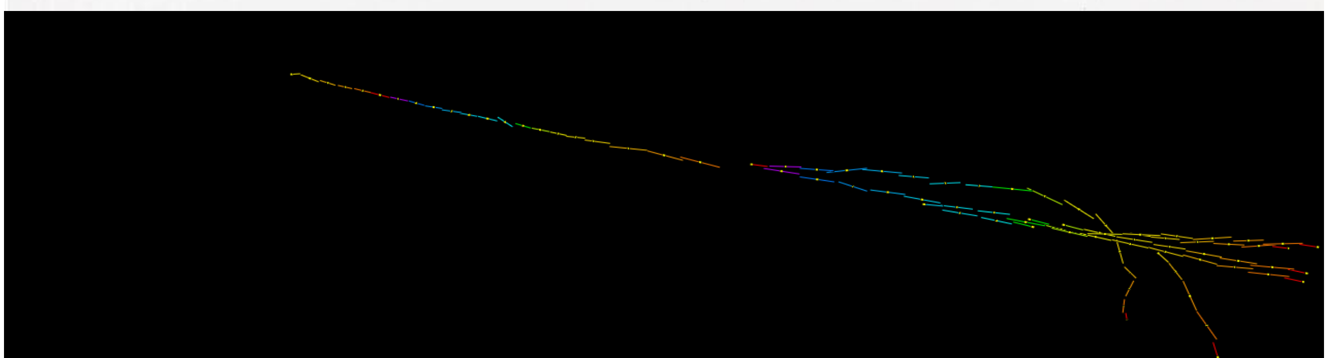




Example of ~GeV electron from ν_e CC events in emulsion

DONuT exp
Using Net-Scan





Net-Scan (alignment, tracking, reconstruction)

LDM search in emulsion

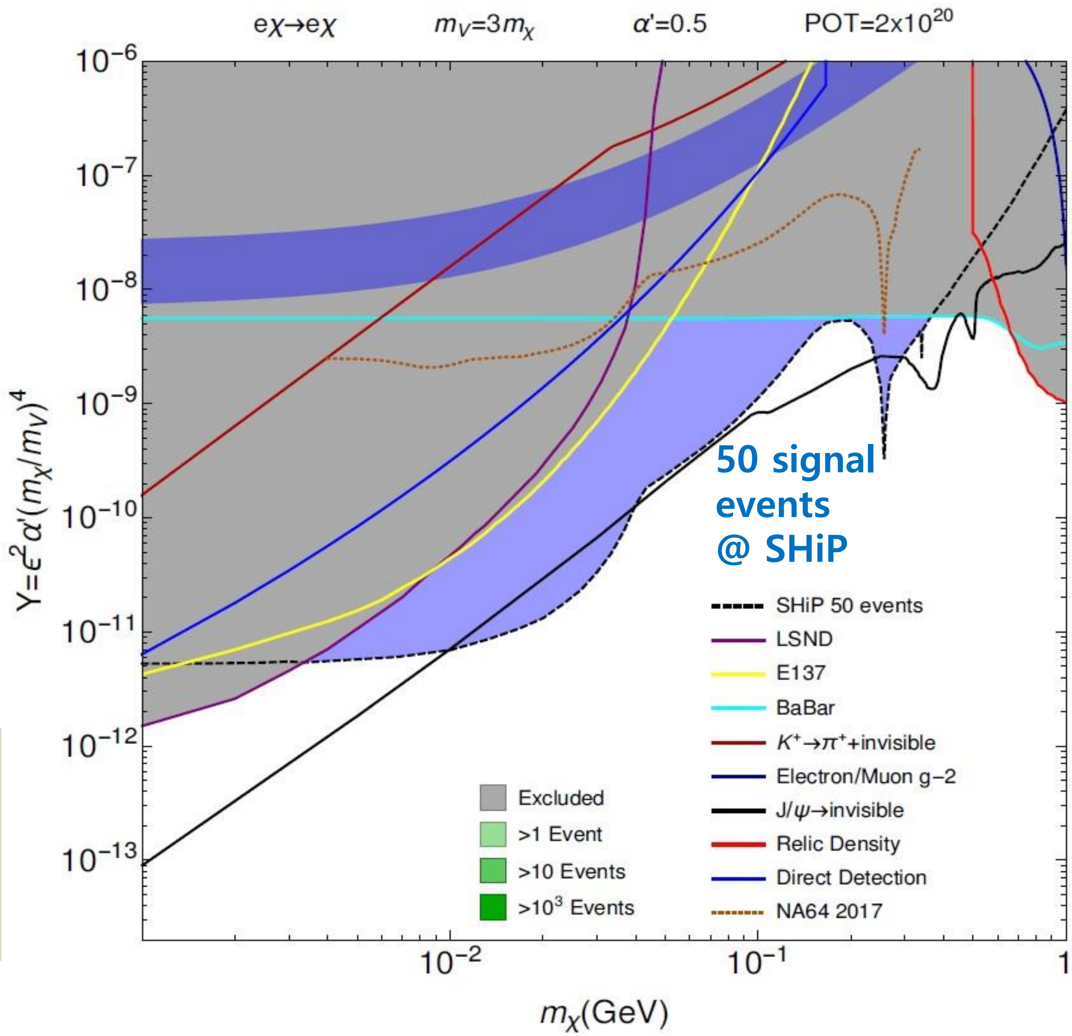
LDM χ produced by a dark photon decay → interact with electron in Neutrino detector

$$\chi\, e^- \rightarrow \chi\, e^-$$

SIGNAL SELECTION

$$\begin{cases} 0.01 < \theta < 0.02 \\ E < 20 \text{ GeV} \end{cases}$$

Electron ID and its Energy measurements are very crucial …



Patrick deNiverville

Test experiments in July 2018 at CERN (2018. 7. 4 - 8. 1)

SHiP
Search for Hidden Particles

SPSC-EOI-016

June 2, 2017

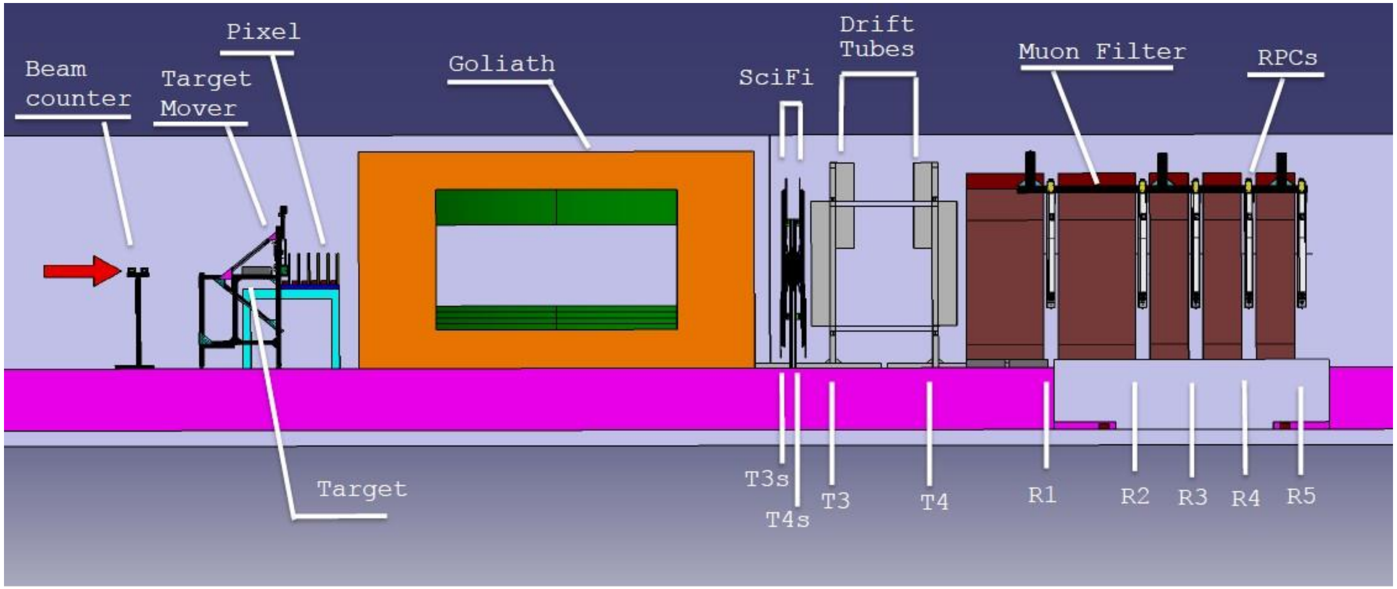
μ-flux measurements for SHiP at H4

SPSC-EOI-017

Measurement of associated charm production induced by 400 GeV/c protons

The SHiP Collaboration

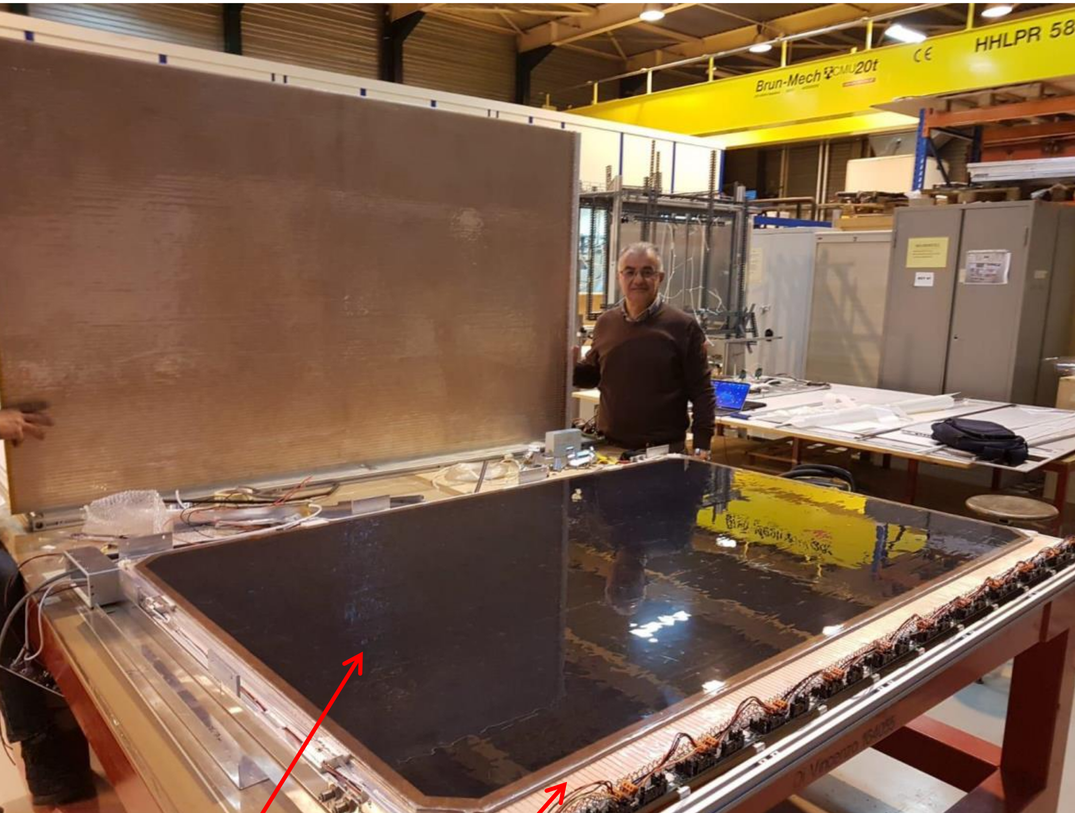
Charm cross-section measurement



ECC target 12×10 cm^2 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

July 2108 : ~150 fully reconstructed charm-pairs
Data taking after LS2 (2021) : >1000 fully reconstructed charmed pairs

RPC for the Test experiment



Gaps and Strip panels
fabricated by KODEL, Korea Univ

assembled at CERN

Infrastructure at CERN

Emulsion handling room

Laboratory used for past emulsion experiments (CHORUS, OPERA preparatory phase)

Emulsion development

Flash box used in CHORUS

Brick Assembling machine

Dark room

CES

Member countries of the SHiP

57 institutes from 18 countries
~250 members

Project schedule

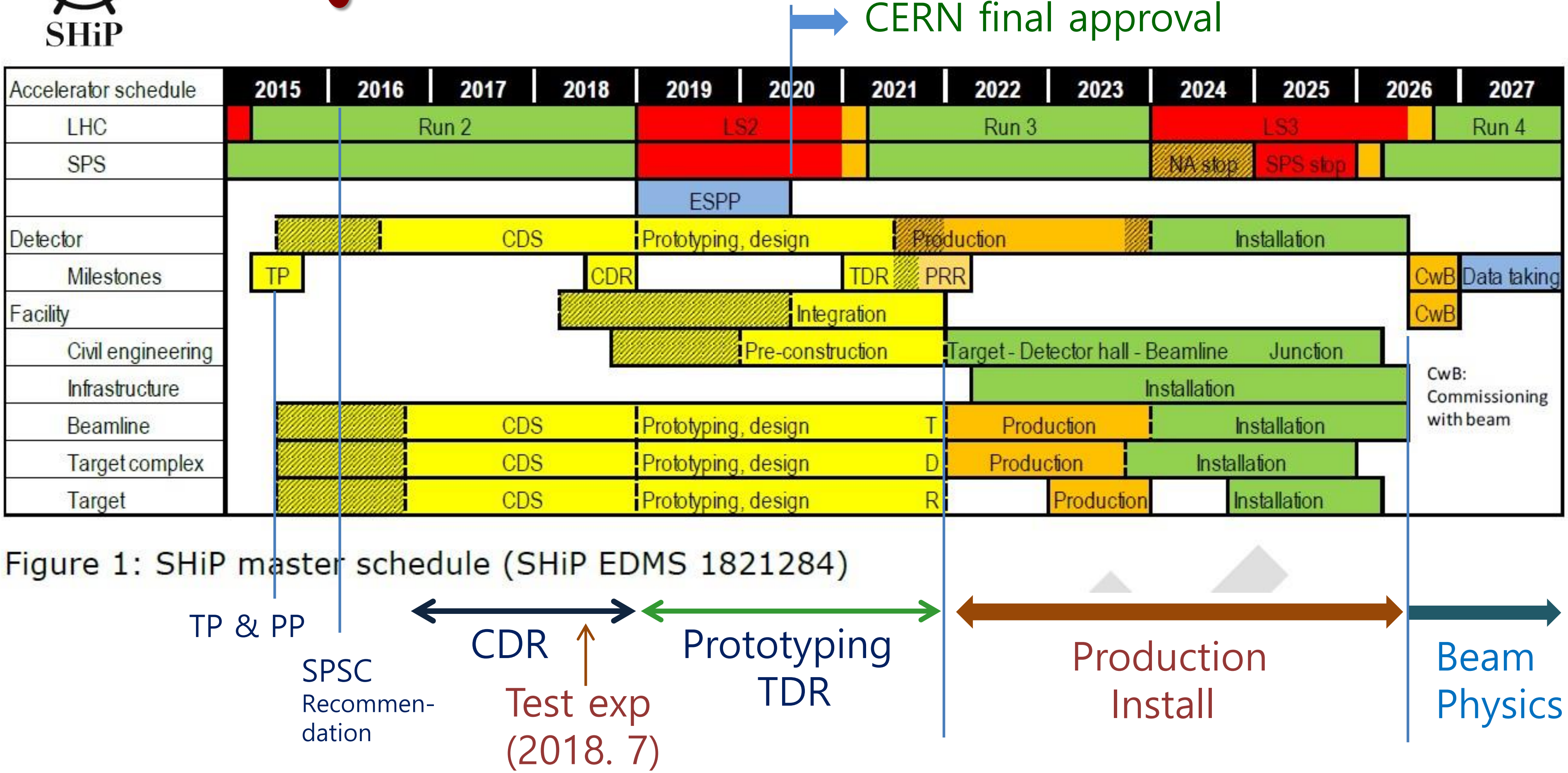


Figure 1: SHiP master schedule (SHiP EDMS 1821284)

- Currently produce **CDS** (Comprehensive Design Study) by end 2018 for next update of the **ESPP** (European Strategy for Particle Physics)
- Four years for detector construction, plus two years for installation
- **Data taking 2026~**

Summary

- The SHiP is a multi-purpose and very timely experiment for **Hidden particles** and **Tau neutrino**.
- ~10,000 Tau Neutrino and Anti-tau neutrino CC events are expected (more than 10,000 events with target mass of ~10 tons).
- First observation of the Anti-ν_τ
- ν_τ/Anti-ν_τ Cross-section and Mag moment measurements
- First evaluation of the F4 and F5 structure functions
- Study of Strange quark content of nucleon
- LDM search in Neutrino detector
- And others …

dSHiP : Hidden Sector search through decay to SM
νSHiP : Neutrino physics
iSHiP : Hidden Sector search through interaction with SM matter
τSHIP : LFV τ search

Thank you for your attention !

Backup

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

Np is the number of interacting protons (all incoming ones)

σ cc¯ = 18.1 ± 1.7 μbarn the associated charm production per nucleon
σ pN = 10.7 mbarn the hadronic cross-section per nucleon in a Mo target
The inelastic cross section pA shows the $A^{0.71}$ dependence

f Ds = $(8.8 \pm 0.6^{+0.5}_{-0.9})\%$ is the fraction of Ds mesons produced
Br(Ds→tau) = (5.54 ± 0.24)% is the Ds branching ratio into tau

Factor 4 accounts for the charm pair production and for the two Tau neutrinos produced per Ds decay.

The SHiP facility is therefore a factory with **6.5 × 10^{15}** Tau neutrinos produced, equally divided in neutrinos and anti-neutrinos.

Given the neutrino target mass of about 10 tons, one expects more than **10,000 interactions** of tau neutrinos and anti-neutrinos.