Neutrino Physics with the SHiP experiment at CERN

SHiP
Search for Hidden Particles

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On behalf of the SHiP Collaboration

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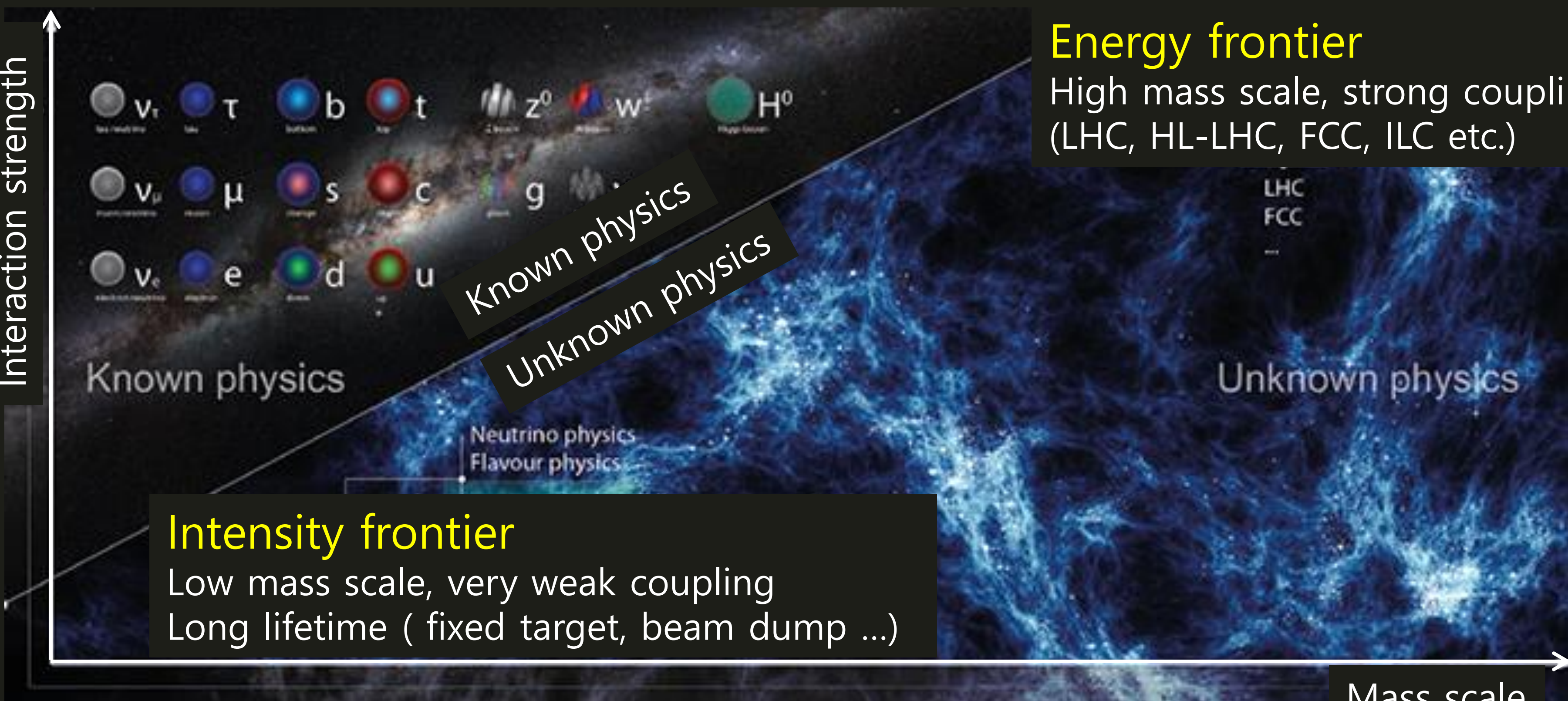
Mt. Biseul, photo provided by Daegu Metropolitan City

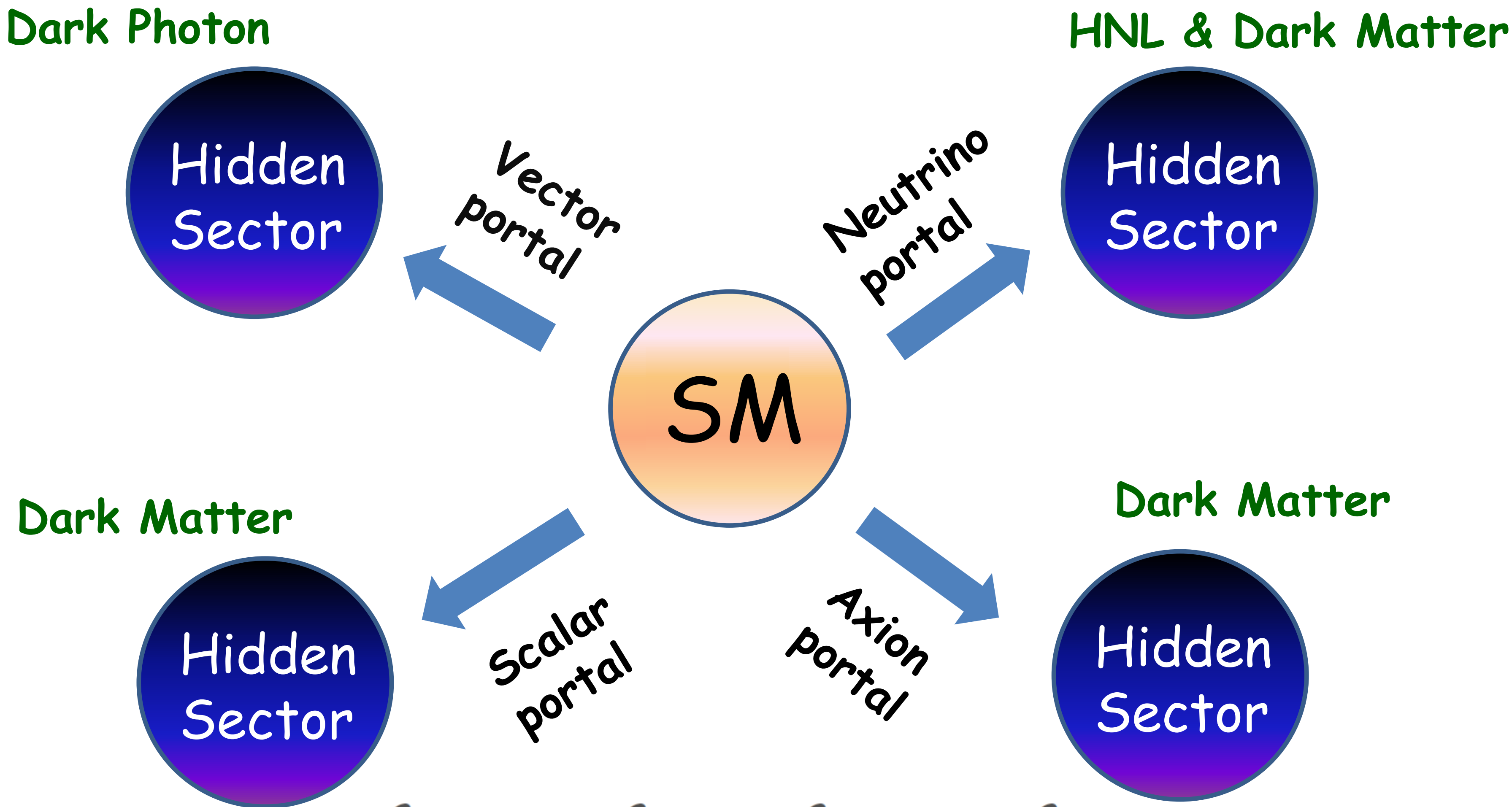
Where is new physics?

Why couldn't we detect them?
→ Too heavy or too weakly interacting



The intensity frontier aimed at exploring the Hidden sector region : Main target of PBC (Physics Beyond Colliders) activity at CERN → SHiP (Search for Hidden Particles)

Extensions of SM



$$\mathcal{L}_{\text{world}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{portal}} + \mathcal{L}_{\text{HS}}$$

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

Neutrino portal

νMSM

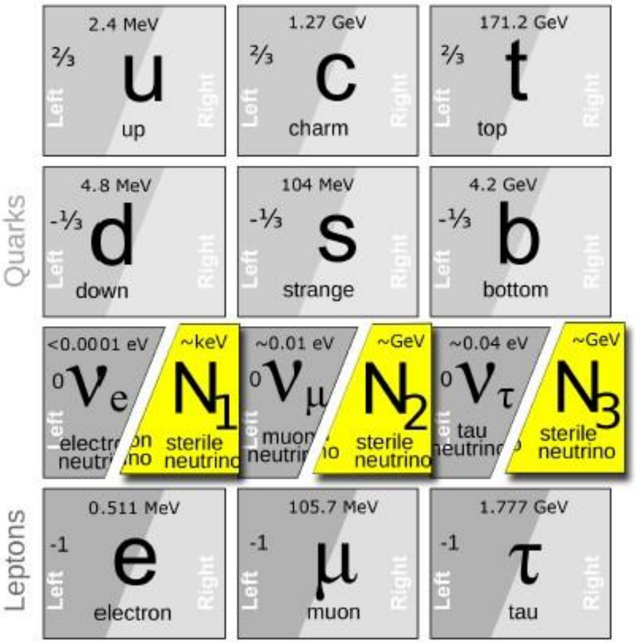
Extends SM by RH partners of neutrinos
T.Asaka, M.Shaposhnikov
PLB 620 (2005) 17

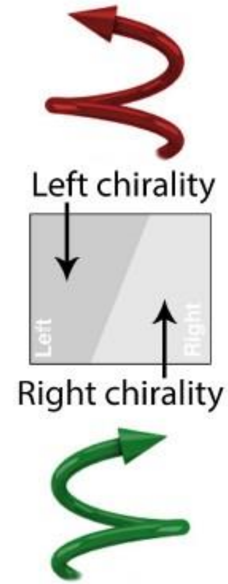
N_1 (~10 keV)

Dark matter candidate

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

Matter-Antimatter asymmetry
Neutrino mass (oscillation)





N = Heavy Neutral Lepton (HNL)

Heavy RH neutrinos

Experimental and Cosmological constraints on HNLs

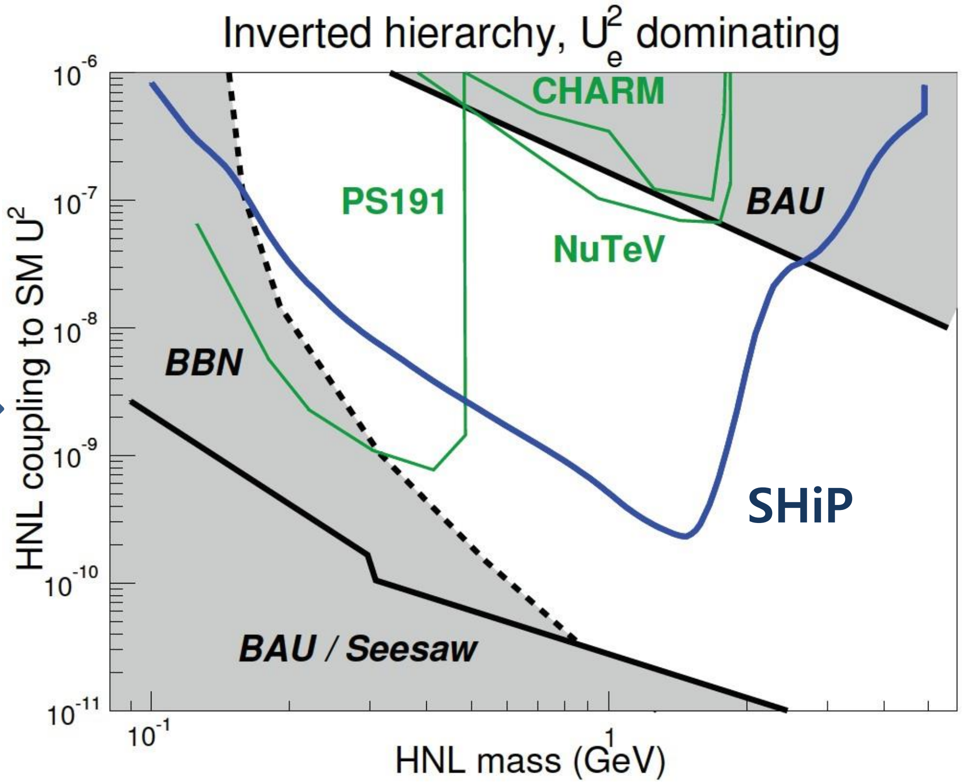
The cosmologically interesting region is at low couplings

Assuming $U^2 = 10^{-7}$
and $\tau_N = 1.8 \times 10^{-5}$ s
~12k fully reconstructed
$N_{2,3} \to \mu^- \pi^+$ events are expected
for M_N = 1 GeV.

~330 events for cosmologically favored region:
$U^2 = 10^{-8}$ & BR($N \to \mu\, \pi$)=20%

early estimations

#HNL will be increased if other decay products ($e\pi$, $\mu\rho$, $e\rho$ etc.) can be identified.



BAU, Seesaw and BBN constraints indicate that previous exp did not prove the interesting region of HNL masses above the Kaon mass.

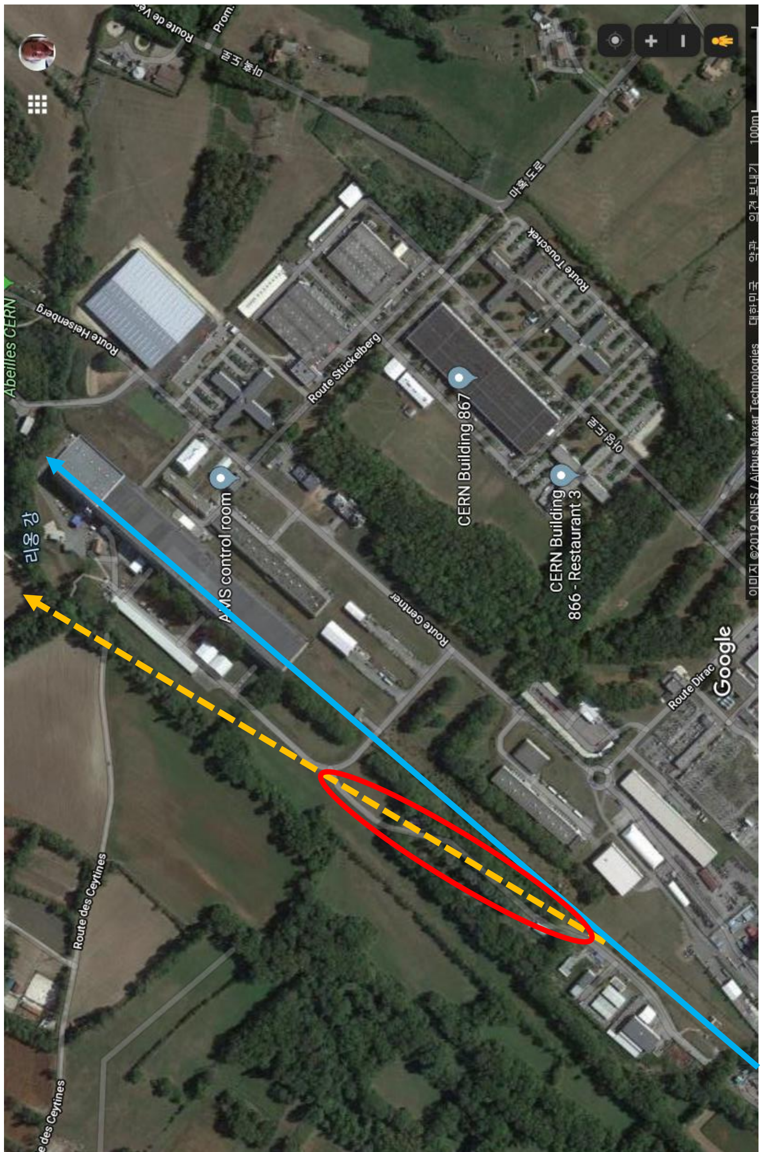
SHiP experiment

- Search for Hidden Particles -

A new experiment proposed at CERN
in order to search for ***Hidden particles***
which is feebly interacting long-lived particles
(LLPs) including ***Light dark matter (LDM)***
and to study ***Neutrino physics.***

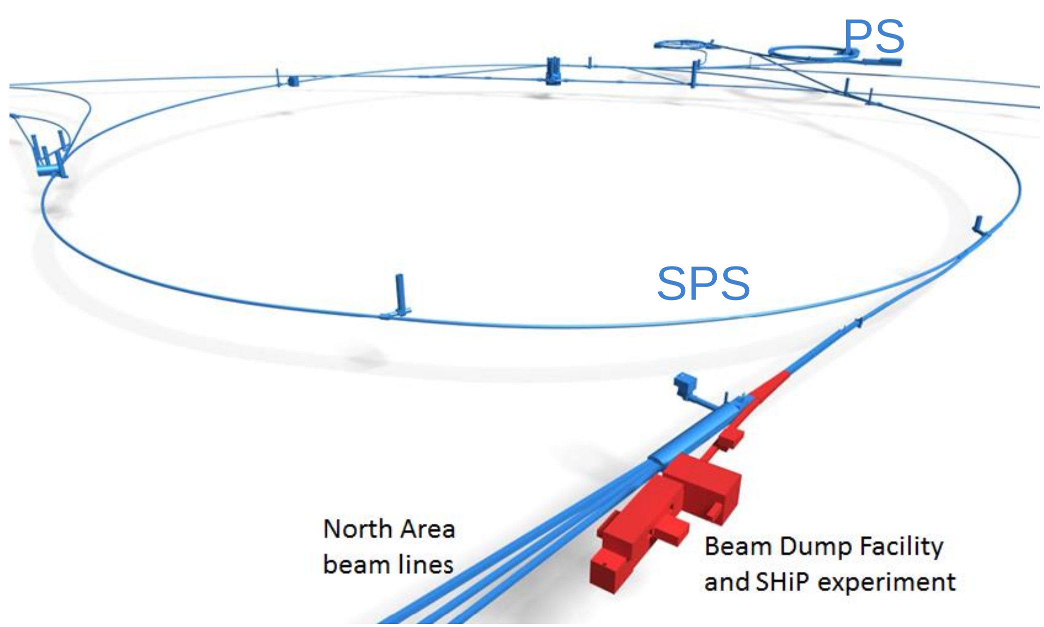
Using High-intensity
400 GeV proton beam
2 x 10^{20} pot, 5 years run

Fixed-target facility at the SPS



The SPS provides a unique high-intensity beam of 400 GeV protons: ideal setting for a CERN-based Beam Dump Facility (BDF).

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

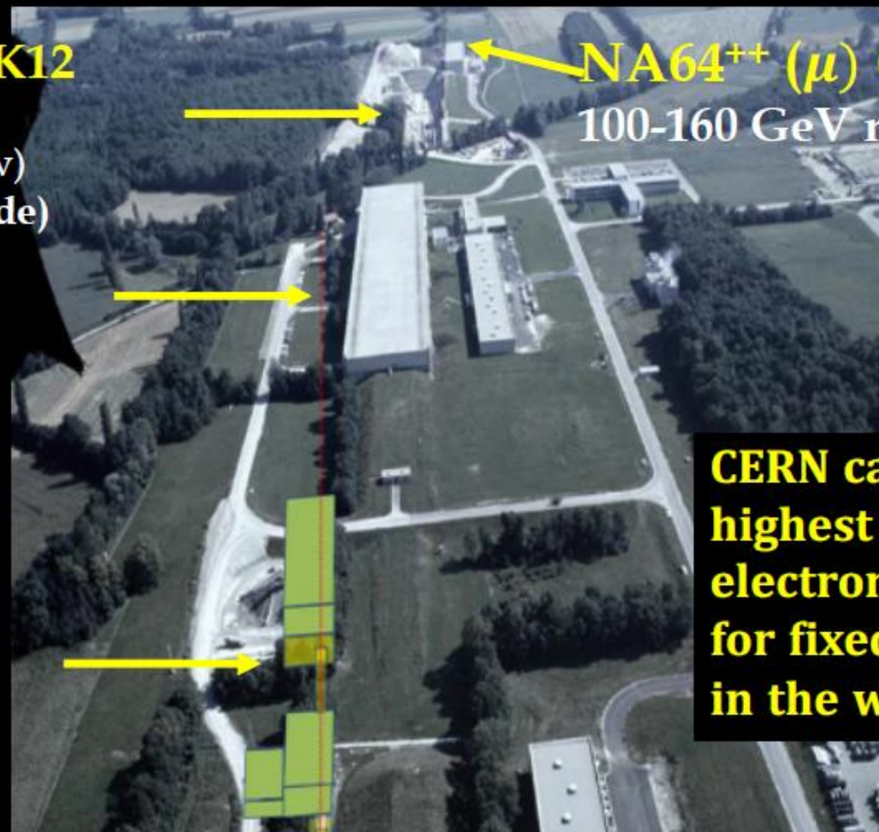


Hidden Sector proposals in CERN North Area

NA62^{++} , KLEVER @ K12
400 GeV p beam
up to 3×10^{18} pot/year (now)
up to 10^{19} pot/year (upgrade)

NA64^{++} (e) @ H4
(100 GeV e- beam
up to 5×10^{12} eot/year)

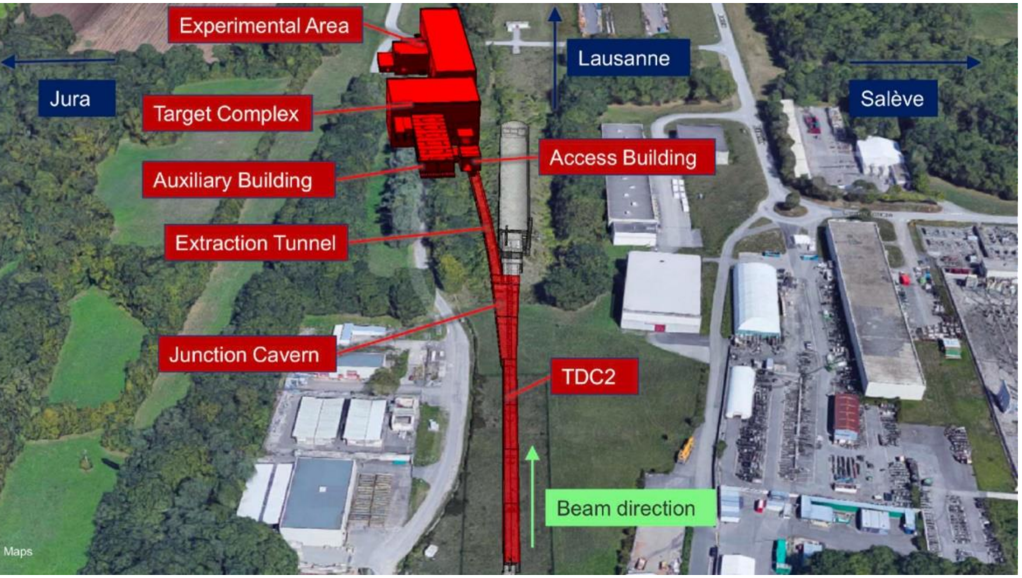
SHiP, TauFV @ BDF
400 GeV p
up to 4×10^{19} pot/year

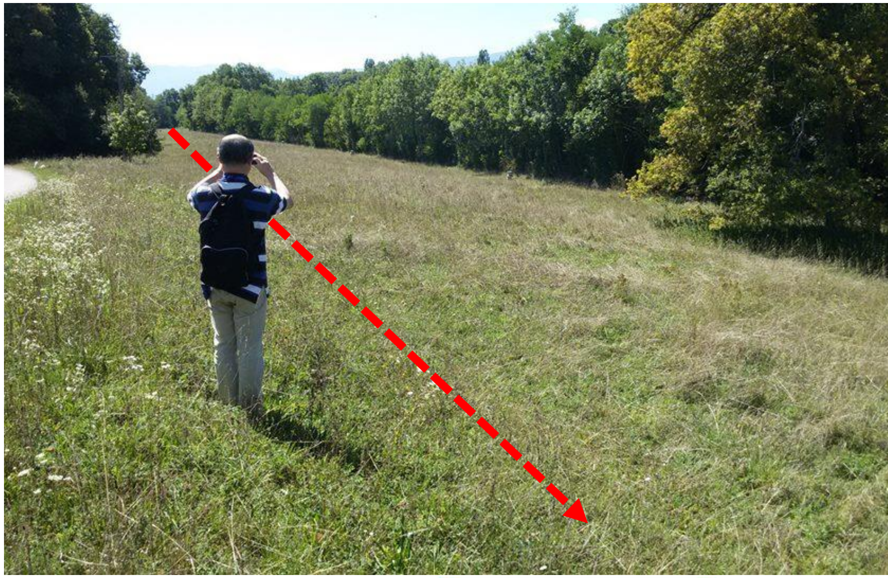


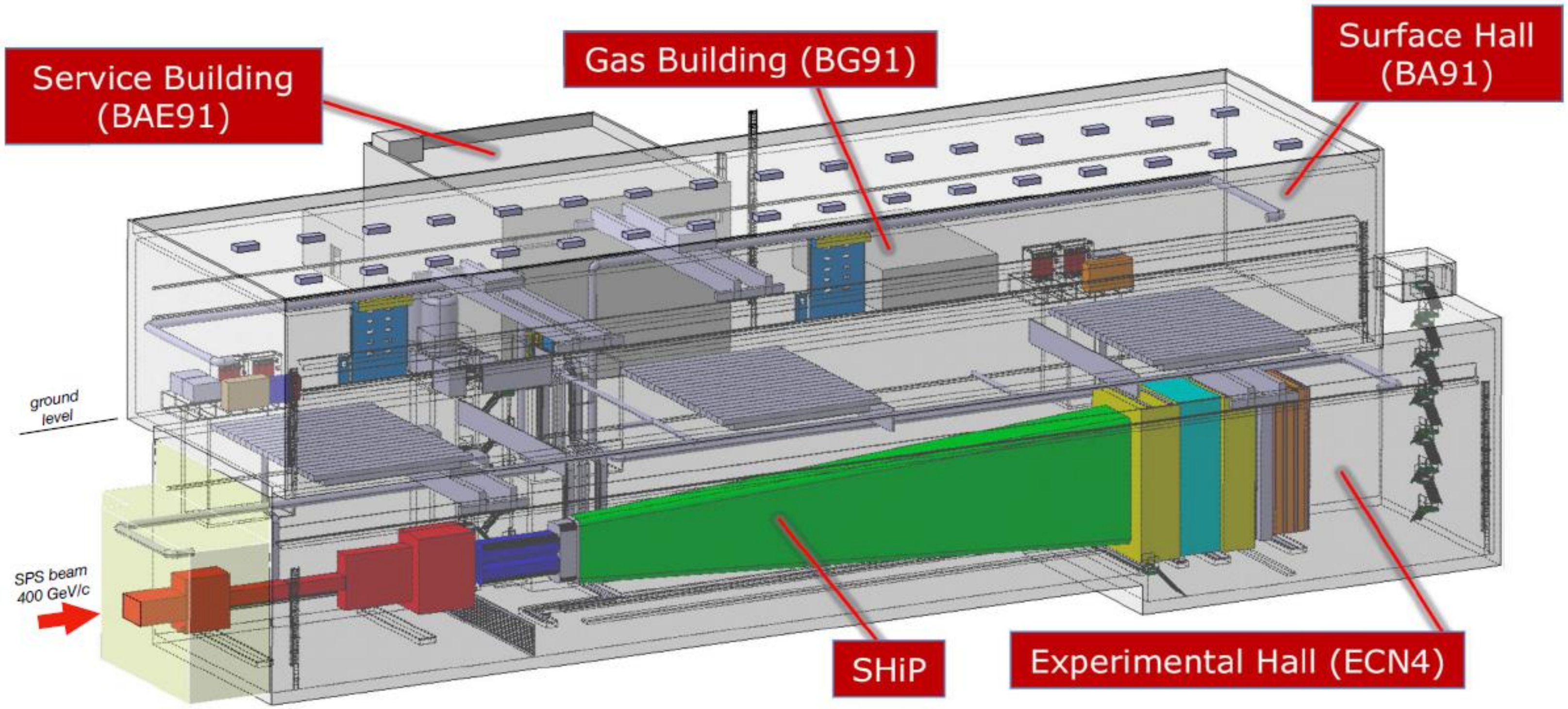
NA64^{++} (μ) @ M2
100-160 GeV **muons,** up to 10^{13} μ/year

CERN can provide the highest energy proton, electron and muon beams for fixed target experiments in the world.

The "Hidden Sector Campus" (HSC)

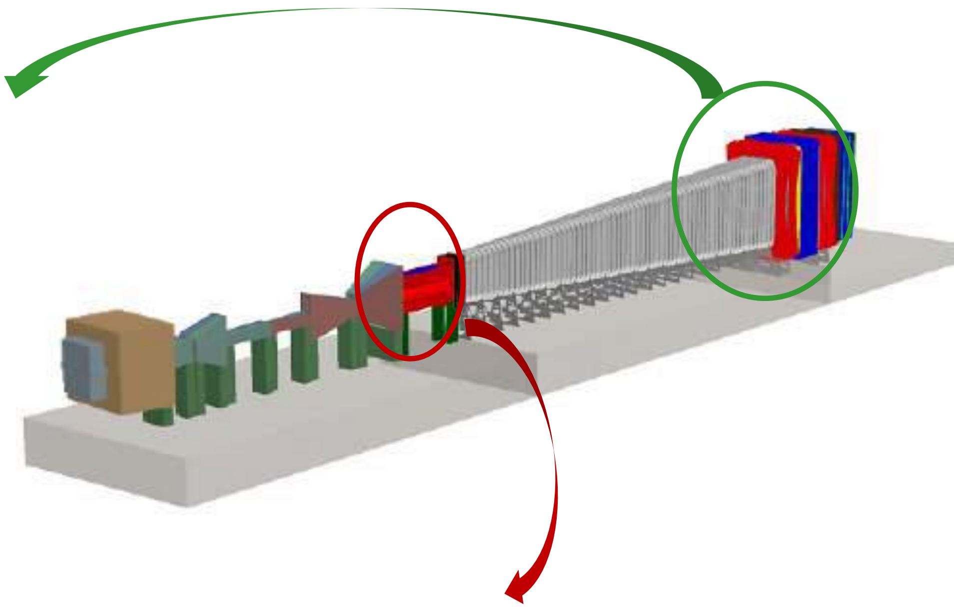

Experimental Area
Jura
Target Complex
Lausanne
Salève
Auxiliary Building
Access Building
Extraction Tunnel
Junction Cavern
TDC2
Beam direction
Maps




Service Building
(BAE91)
Gas Building (BG91)
Surface Hall
(BA91)
ground
level
SPS beam
400 GeV/c
SHiP
Experimental Hall (ECN4)

The SHiP detector

A discovery machine for **feebly coupled LLPs**, with a complementary detector for **Neutrino physics** and **LDM scattering**



HS Decay Spectrometor

ECAL, Muon detector
Straw trackers
Timing detector
Surround bg tagger

→ large geometrical acceptance :
long decay volume close to dump

Scattering and Neutrino Detector (SND)

Emulsion target (ECC+CES) - high spatial resolution tracker (sub-μm)
Target Tracker (TT) - charge & momentum measure with magnet
Muon filter (RPC) - muon identification

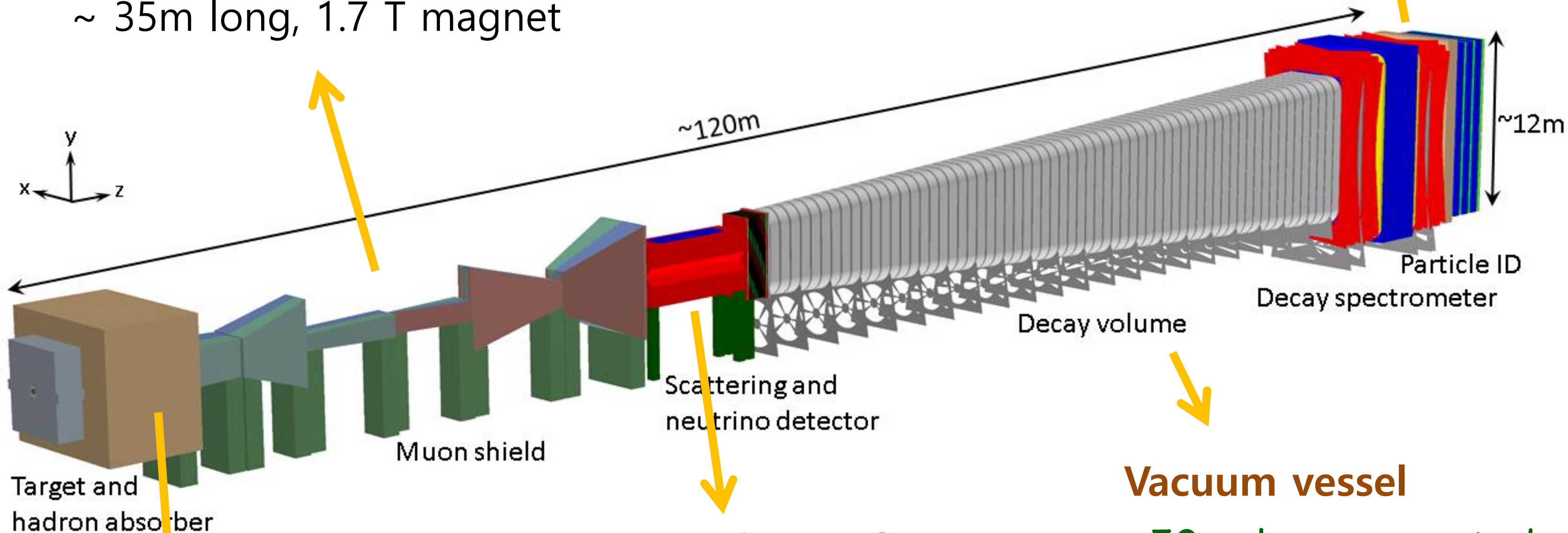
The SHiP detector

HS decay spectrometer

ECAL, Muon detector
PID, Energy & Timing

Active muon shield

deflect μ from 2ry meson decay
~ 35m long, 1.7 T magnet



Hadron absorber

eliminate 2ry mesons
(π, K) ~ 5m Fe

Scattering and Neutrino Detector

LDM & Tau neutrino

ECC + CES
(Nuclear emulsion)
TT, RPC

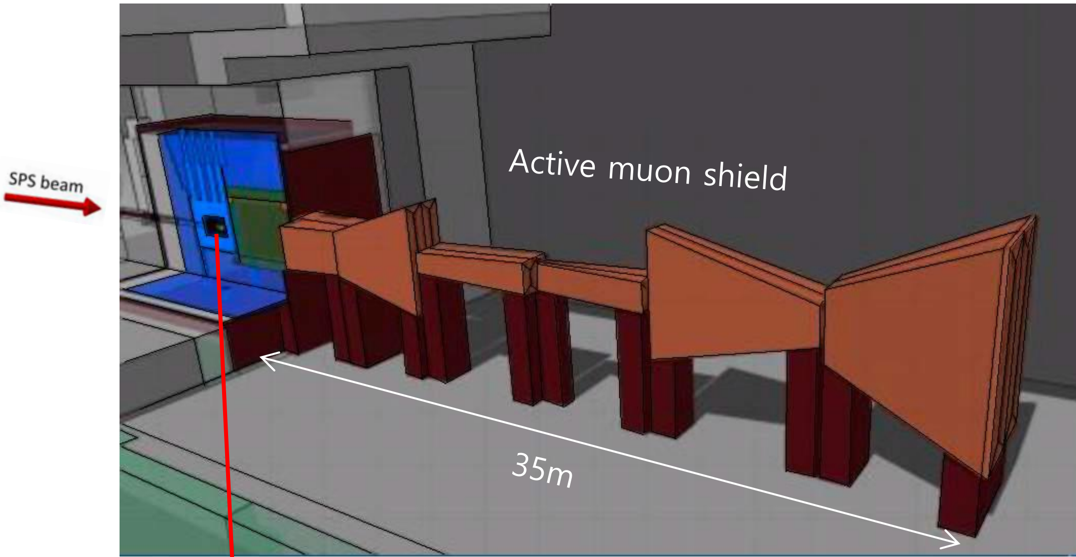
Vacuum vessel

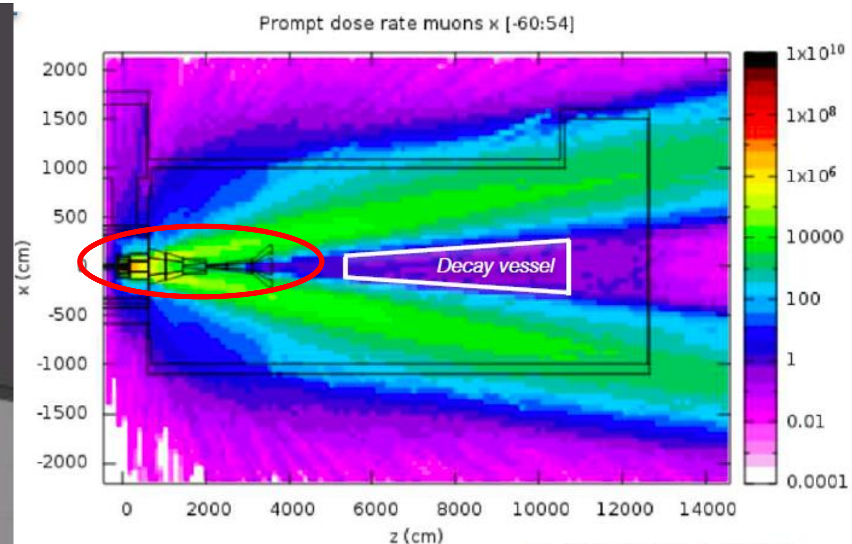
~50 m long evacuated decay vessel
surrounded by liquid scintillator veto system

Active muon shield

1400 tons magnet

μ rate reduced to ~ 25 kHz

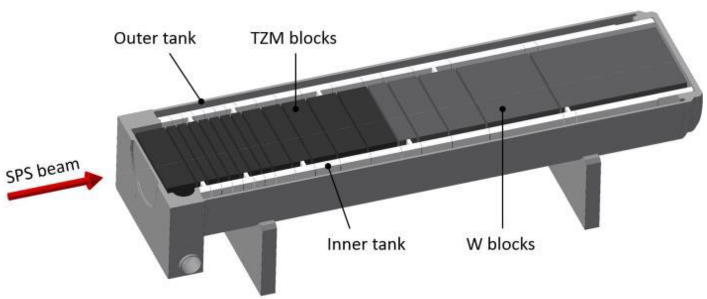




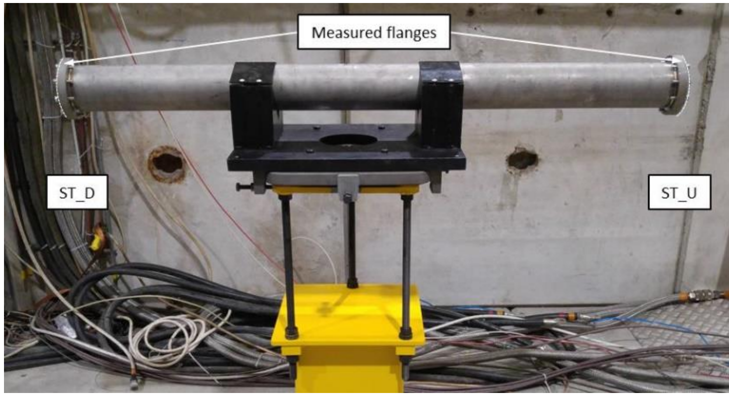
JINST 12 (2017) no.5, P05011

Top view

Target



Blocks of TZM (Titanium-Zirconium) doped Molibdenum alloy (10.22 g/cm^3) followed by blocks of pure Tungsten



SHiP replica target used for beam test at SPS H4 beamline in July 2018

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	$\pi^0\pi^0$

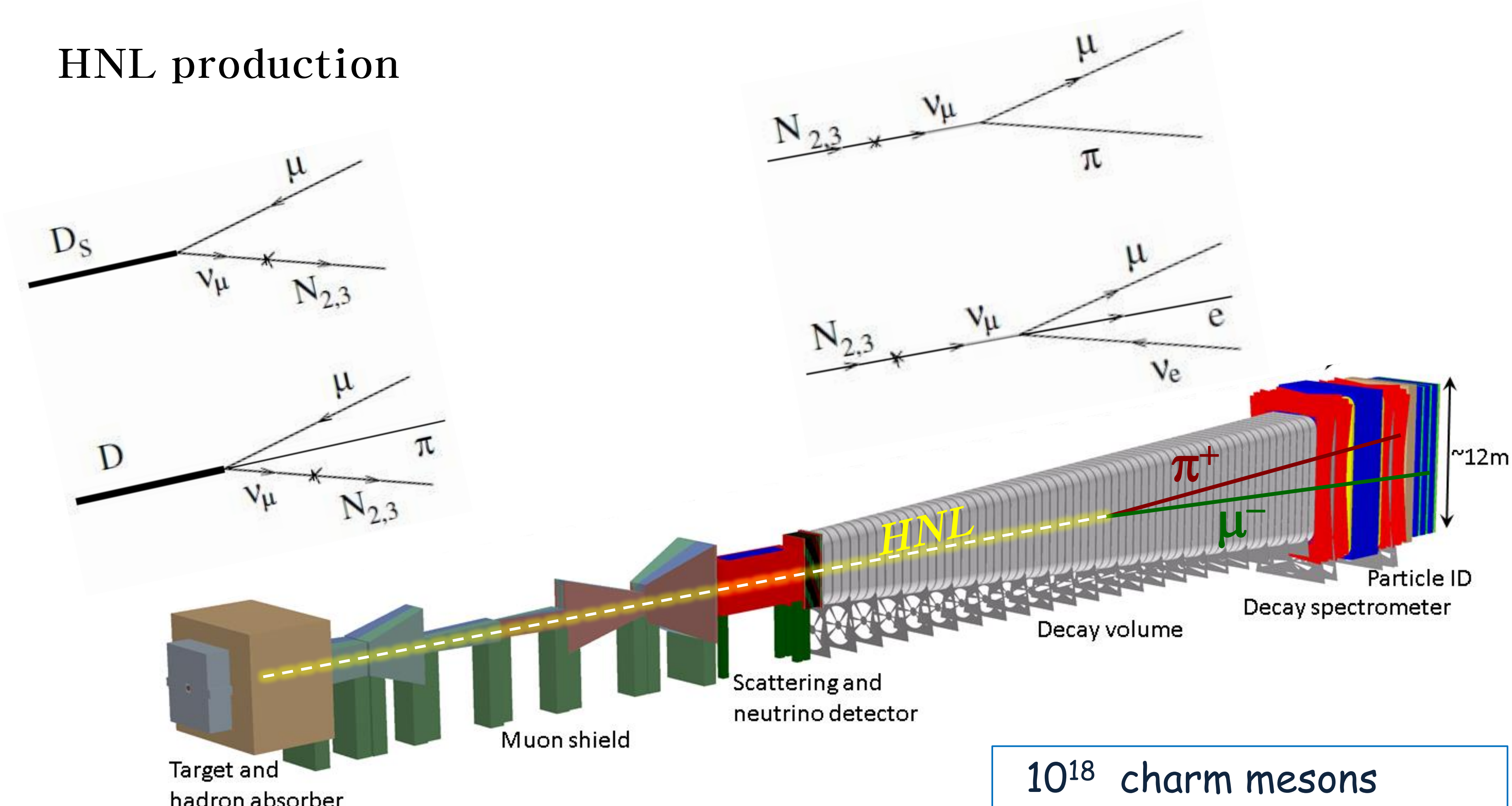
$$\ell = (e, \mu, \nu), \;\; \rho^\pm \to \pi^\pm \pi^0$$

Many Vee decay modes

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

HNL production

HNL decay

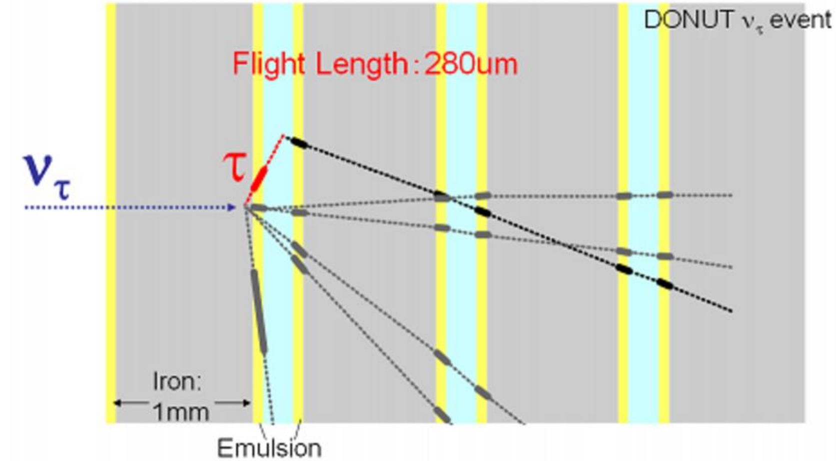


10^{18} charm mesons
10^{14} beauty mesons
10^{16} τ leptons
for 2×10^{20} pot (in 5 yrs)

Neutrino Physics with SHiP

- About **10,000 Tau neutrino & Anti-tau Neutrino CC events** can be observed in ECC target.
  - First observation of the **Anti-tau neutrino**
- **Tau neutrino physics**
  - Cross section, Magnetic moment measurements
  - First evaluation of F4 and F5 structure functions
  - Study of Strange quark content of nucleon
- **LDM search** in SND

Tau Neutrinos so far



DONuT **9 events**

First direct observation

Proton beam dump exp.

Cross section, mag mom

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

could not distinguish ν_τ and $\overline{\nu}_\tau$

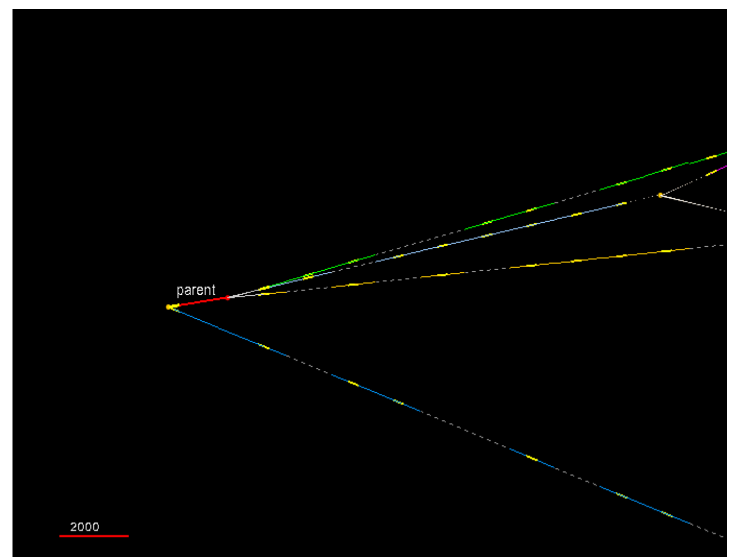
OPERA **10 events** from oscillation

Long-baseline CNGS beam

Discovery of ν_τ appearance

event by event basis (6.1σ)

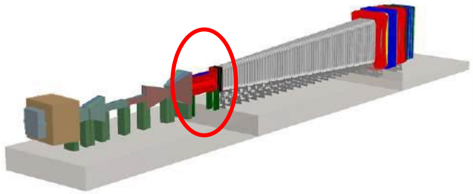
not statistical basis



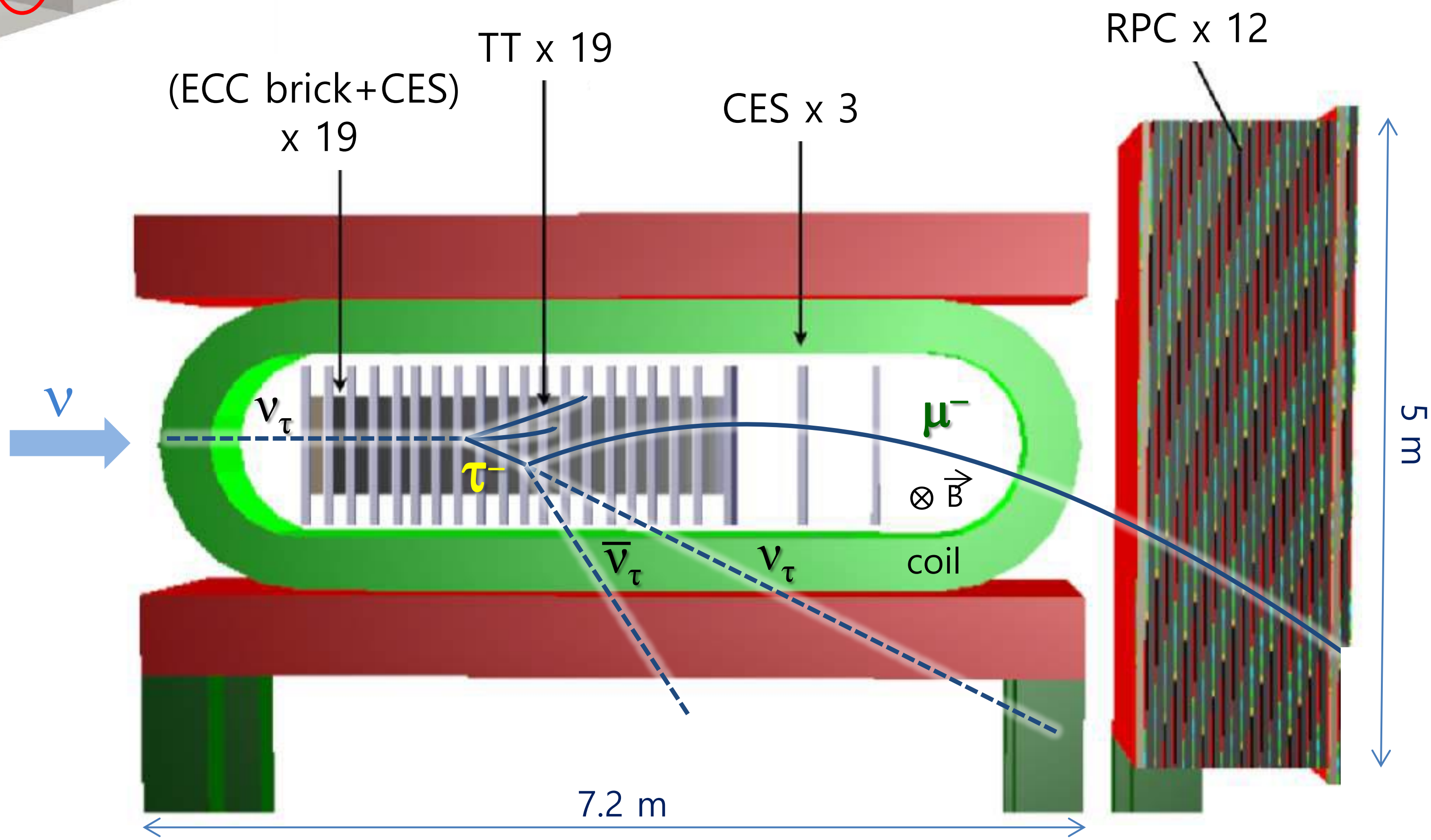
OPERA ν_τ event

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

→ Same technique will be used in SHiP

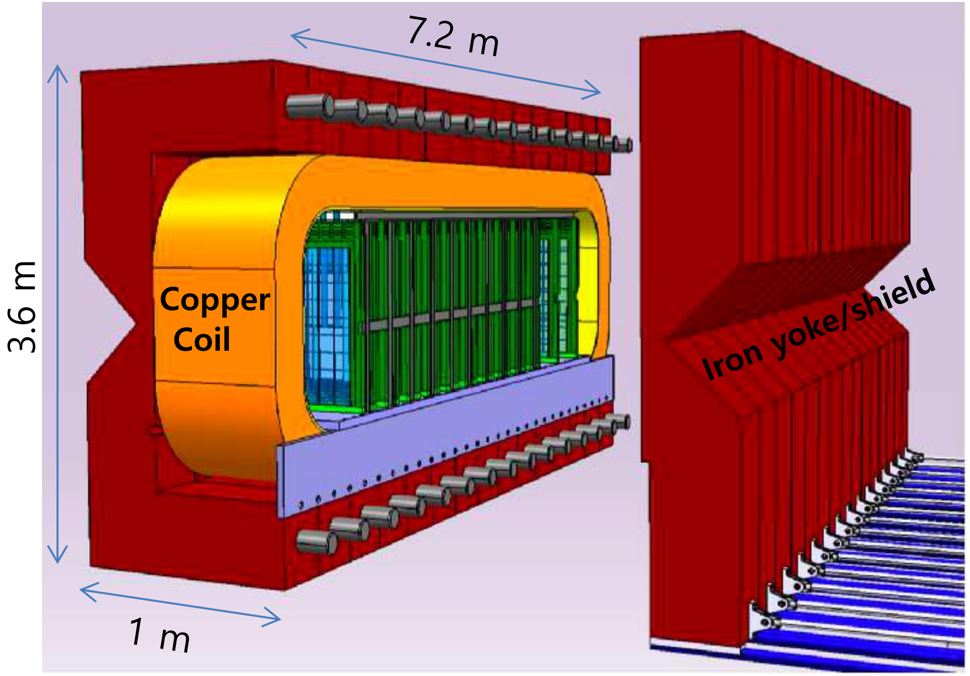


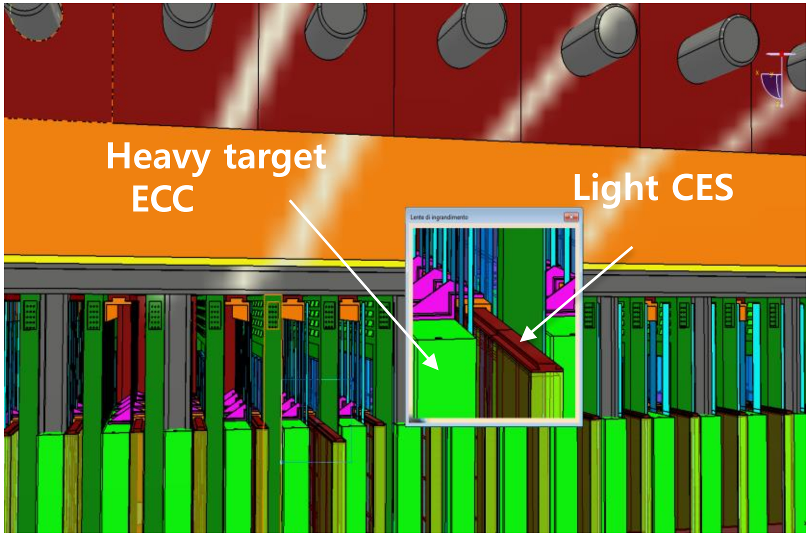
Scattering and Neutrino Detector

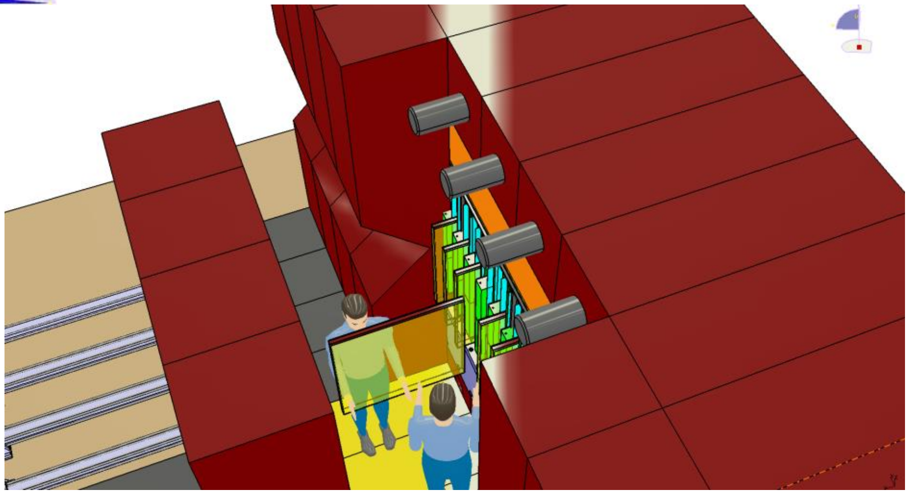


ECC (Emulsion Cloud Chamber) **:** High spatial resolution (~μm) to observe the τ decay
CES (Compact Emulsion Spectrometer) **:** measure muon charge & momentum
TT (Target tracker) **:** Electronic detector to predict ν interaction contained in ECC brick and provide the time stamp
Magnet : to measure the charge of τ products (1.25 T)
Muon filter (RPC) **:** Muon identification and tracking (area 2 x 5 m^2 x 12 planes)

Scattering and Neutrino Detector





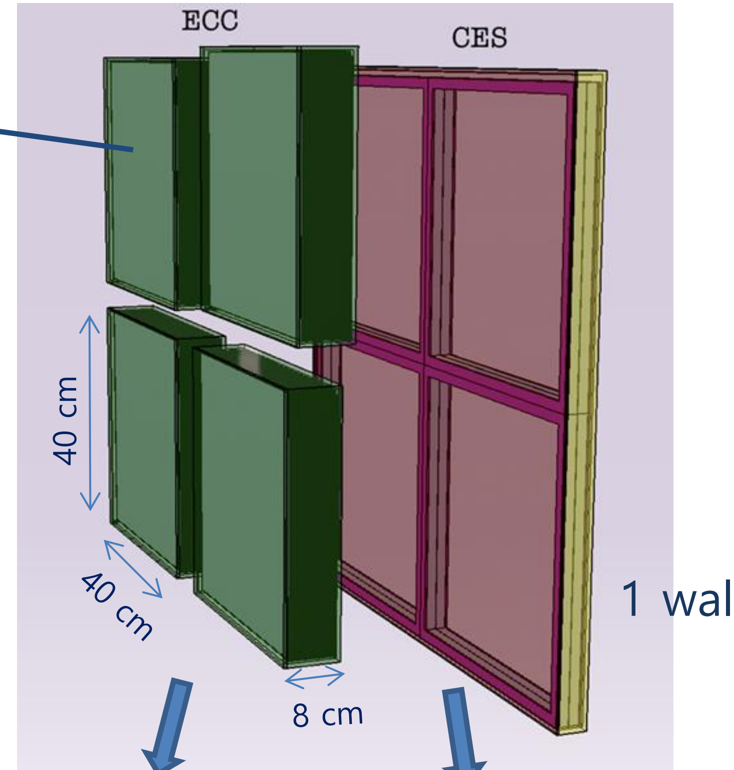


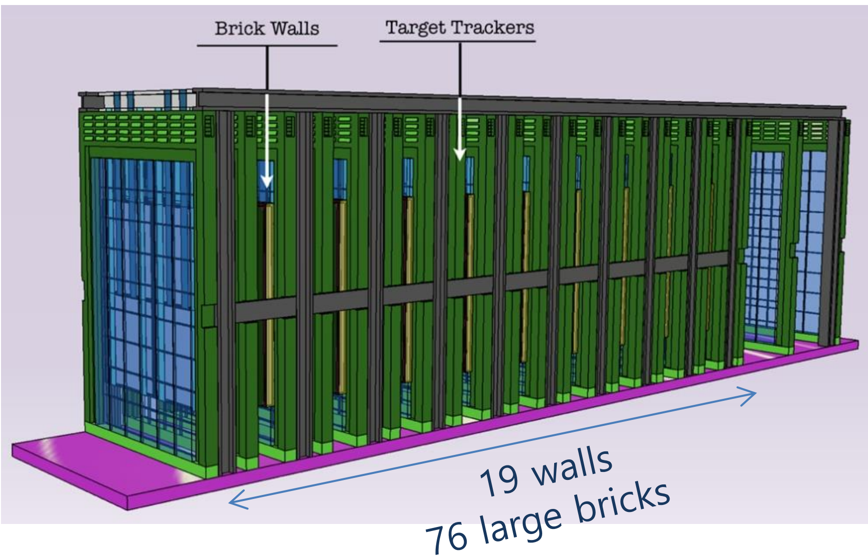
ECC brick

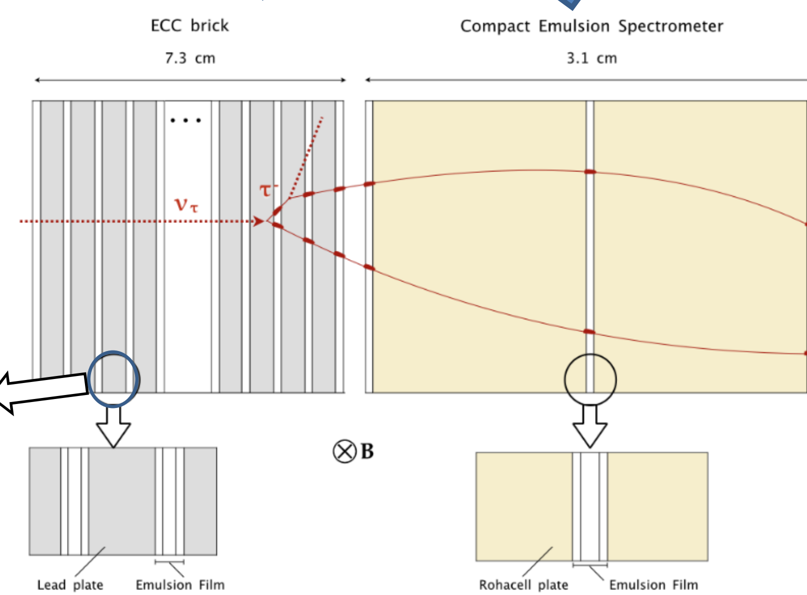
1 brick - 57 Emulsion film (40 x 40 cm^2) interleaved with 1 mm thick lead plates, ~100 kg

Total 19 walls

76 (=2x2x19) large bricks (~700 m^2), ~10 tons to be replaced 10 times (~7000 m^2 total)



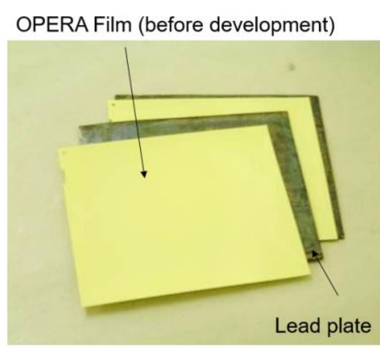




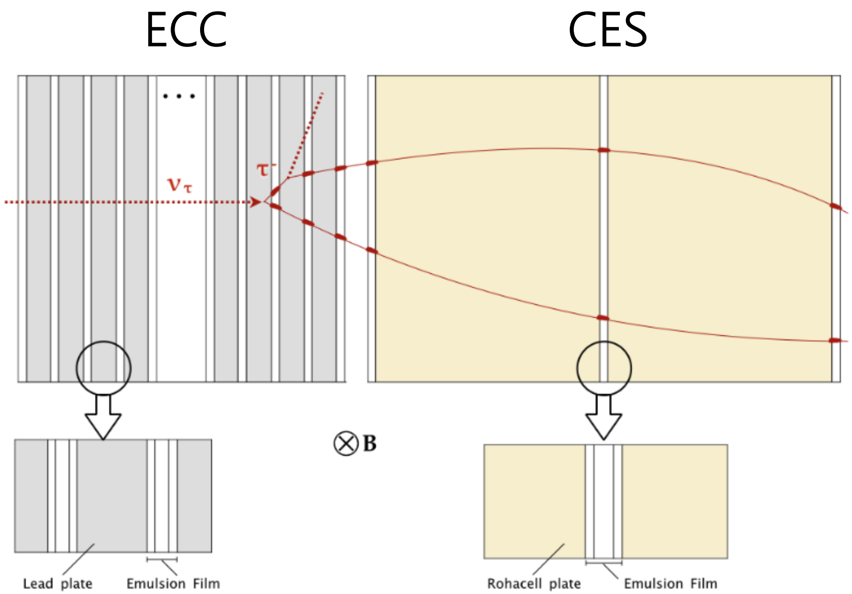
CES

made of 3 emulsion films interleaved by 2 layers of low density materials to be replaced every ~2 weeks

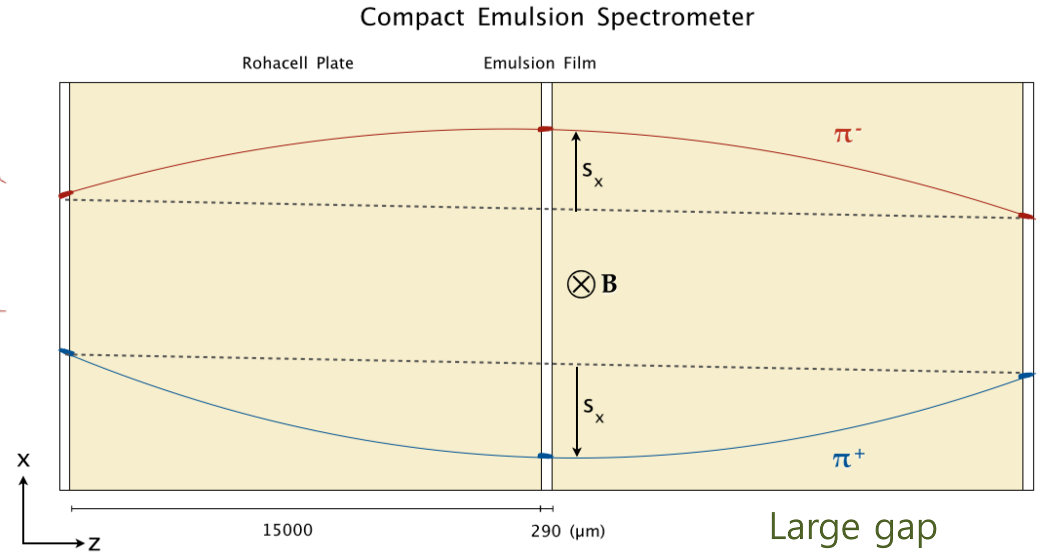
each CES ~ 10kg



Anti-tau Neutrino identification by CES



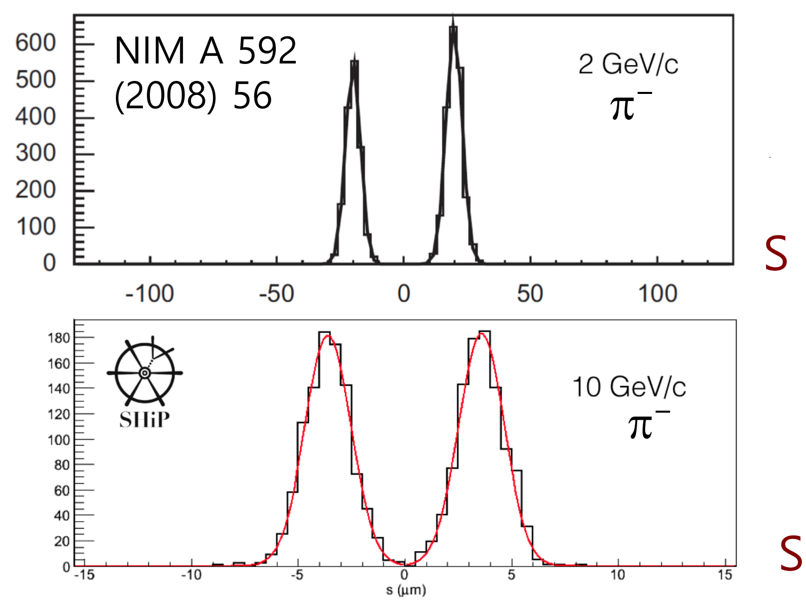
Measurement of Sagitta **S**



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

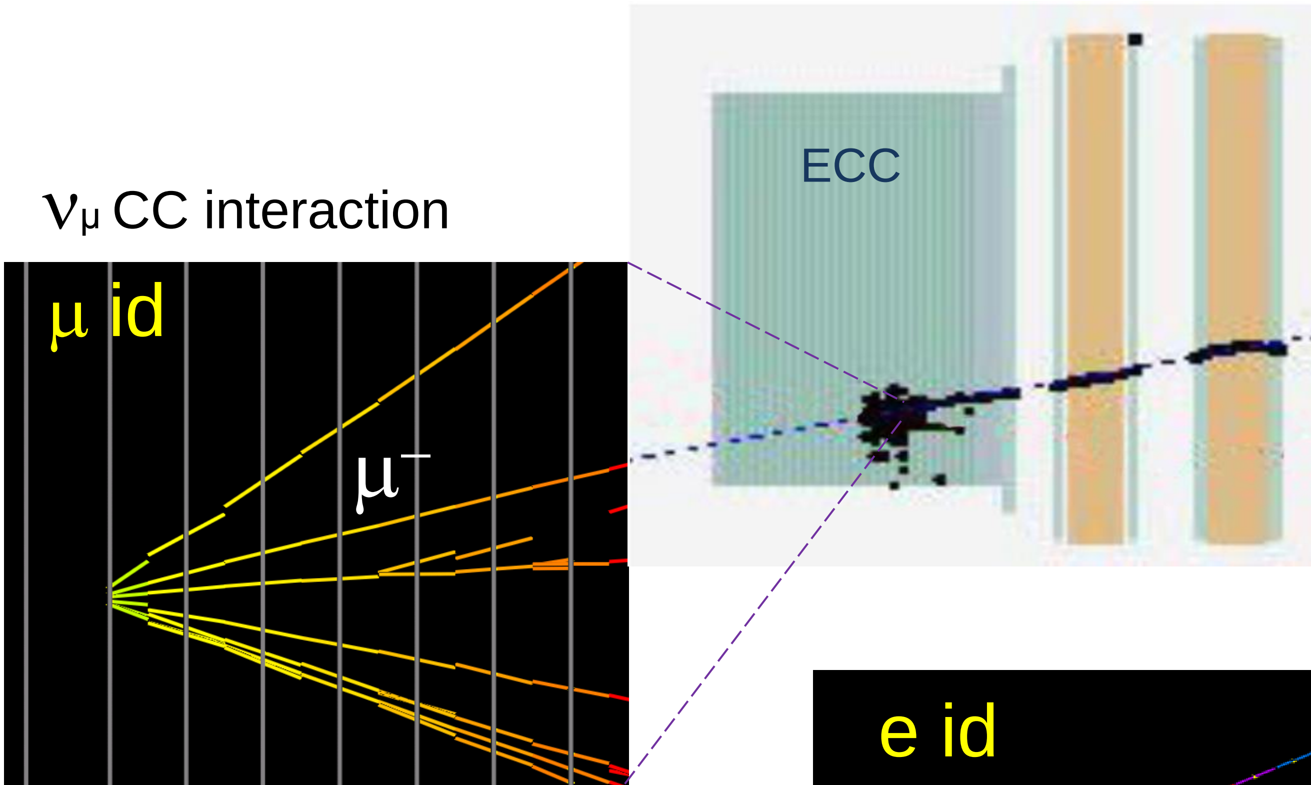
$$\overline{\nu}_\tau \rightarrow \tau^+ \rightarrow \mu^+$$

- Electric charge can be determined with better than 3σ level up to 12 GeV/c
- Momentum estimated from the sagitta Δp/p < 20% up to 12 GeV/c

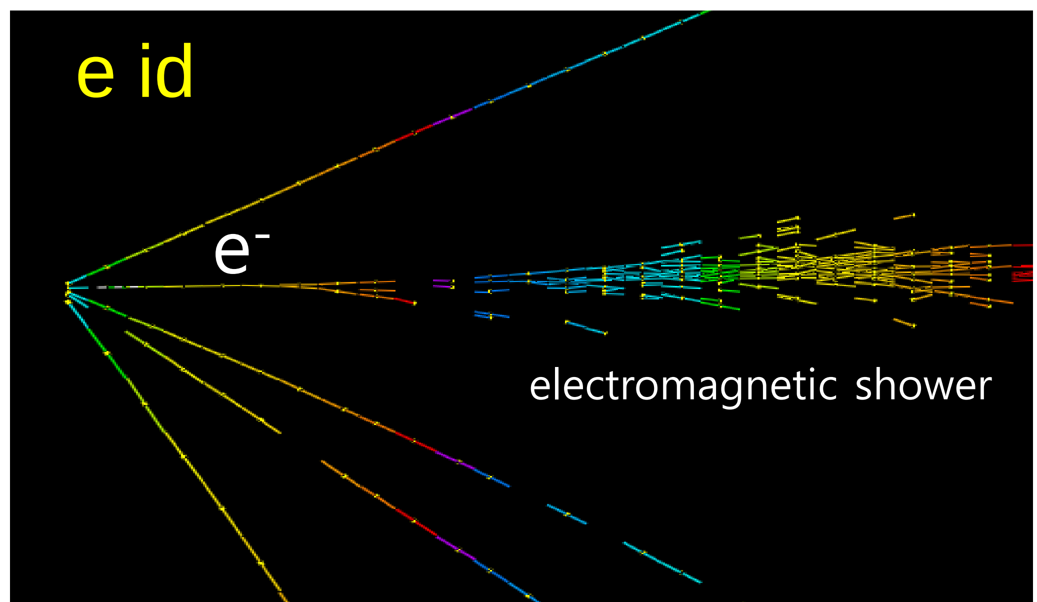


Identification of Neutrino flavors

ν_μ CC interaction



ν_e CC interaction



Emulsion film as high precision tracker

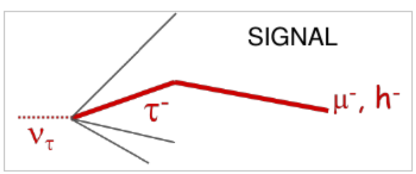
→ identification of ν_e , ν_μ , ν_τ is possible by distinguishing e , μ , τ particles

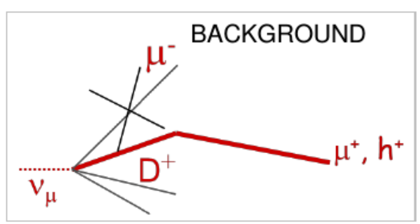
Tau Neutrino

Topological selecton
& Kinematical cuts

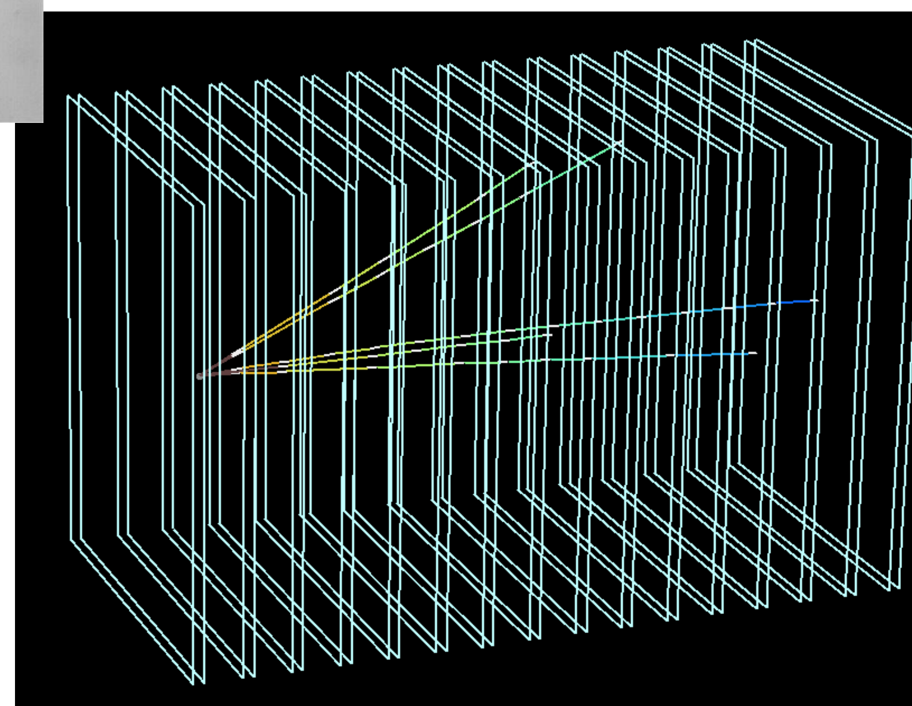
P_T , ϕ , θ_{kink} …

at interaction vtx
& decay vtx



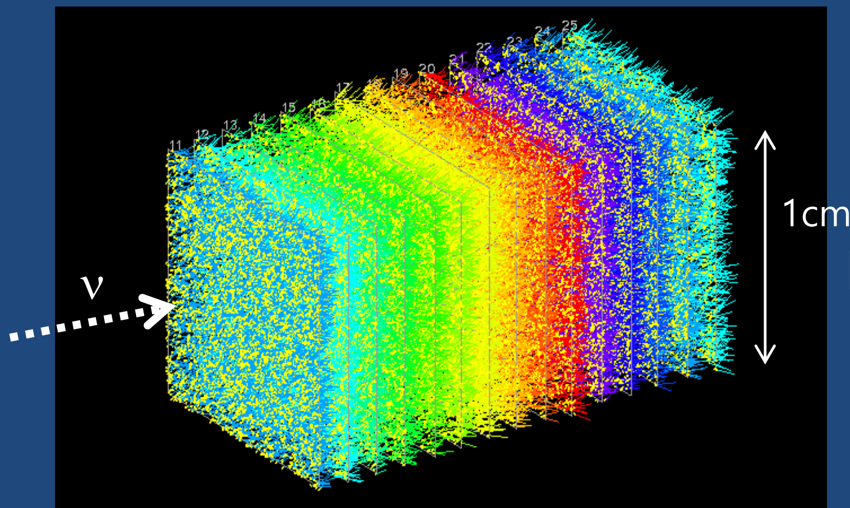


Charm &
Single-prong interaction
of 2ry hadrons (white kink)

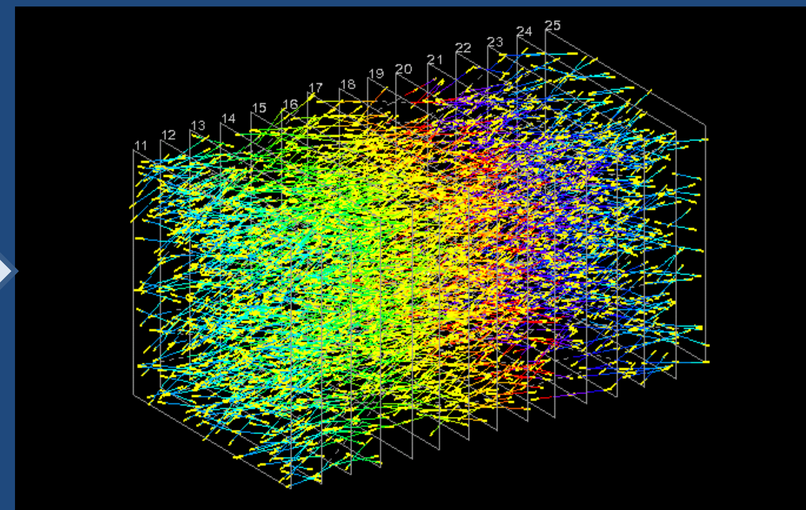


Track reconstruction in ECC brick

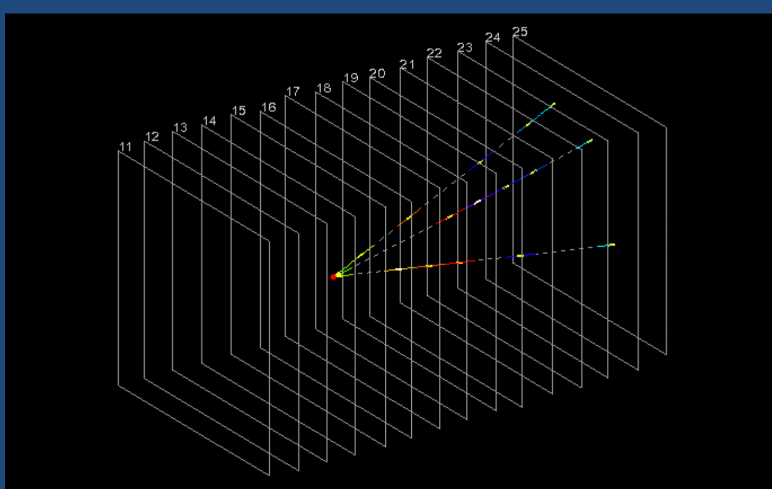
Scan 10 films around vertex plate
and reconstruct tracks



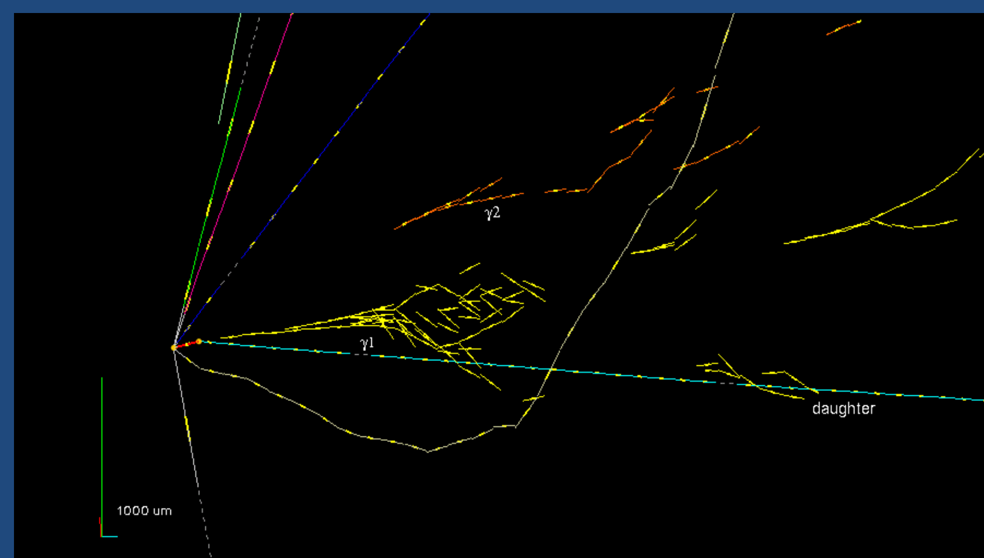
Reject passing-through tracks
& low energy tracks



Neutrino interaction vertex



Tau neutrino event (OPERA)



Infrastructure at CERN

Emulsion handling room

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

Emulsion development

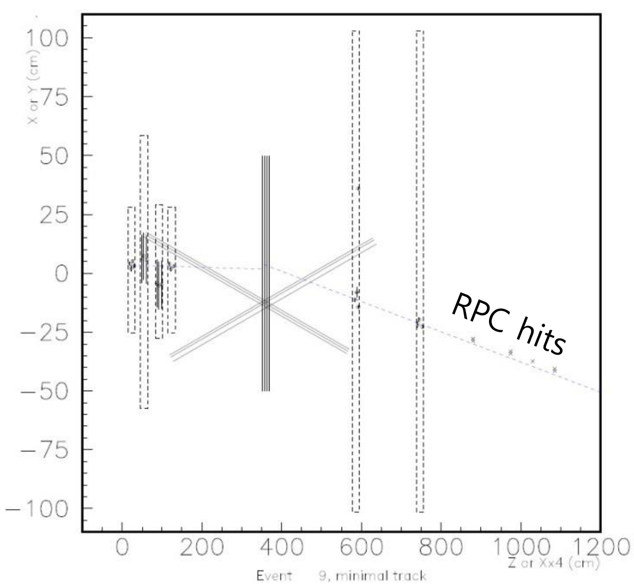
Flash box used in CHORUS

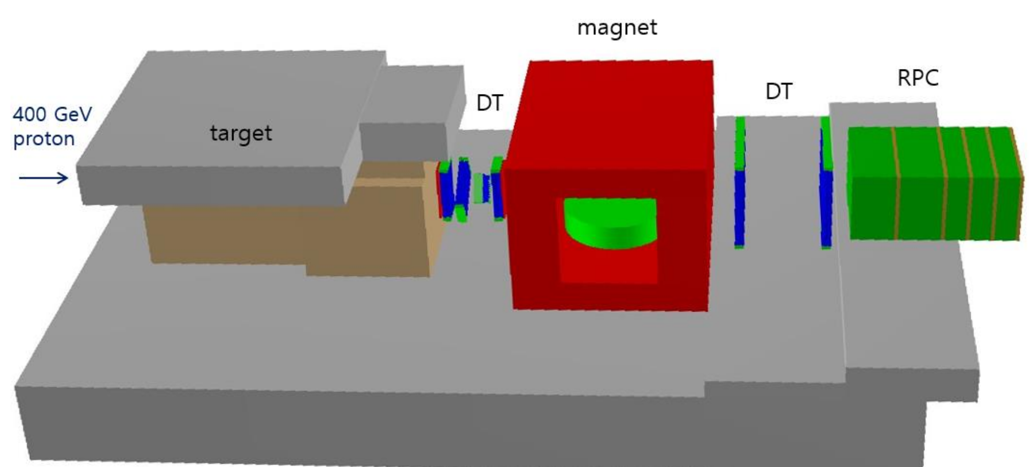
Brick Assembling machine

Dark room

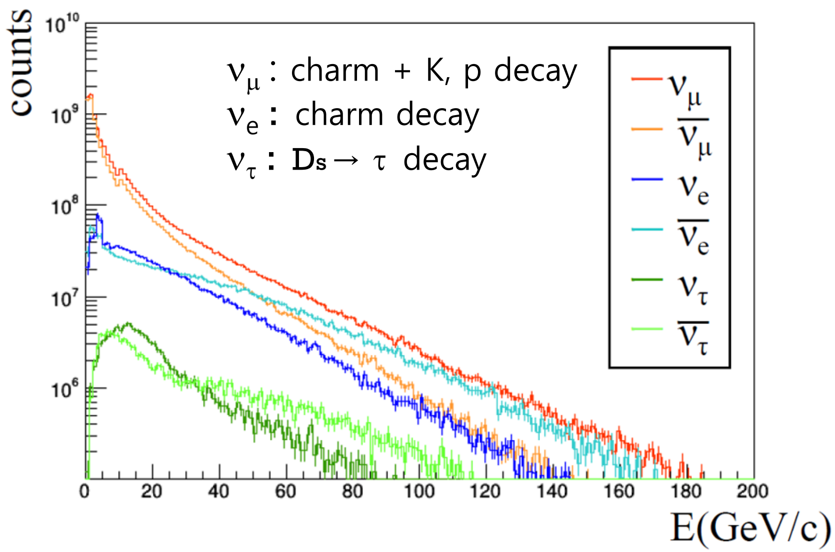
CES

SPS Test beam experiment (July 2018)
using Prototype RPC, DT, pixel detector …





Neutrino interactions



Expected yield of Neutrino CC DIS interactions in the **SND** (5 yrs)

	$\bar{E}$ [GeV]	CC DIS int.
ν_e	59	1.1×10^6
ν_μ	42	2.7×10^6
ν_τ	52	3.2×10^4
$\bar{\nu}_e$	46	2.6×10^5
$\bar{\nu}_\mu$	36	6.0×10^5
$\bar{\nu}_\tau$	70	2.1×10^4

~10,000 Tau & Anti-tau neutrino events
will be observed in ECC (except $\tau \rightarrow e$ channel)

decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	1200	1000
$\tau \to h$	4000	3000
$\tau \to 3h$	1000	700
total	6200	4700

Expected Neutrino CC DIS interactions with **Charm production**

	<E> (GeV)	CC DIS with charm prod
N_{ν_μ}	55	1.3×10^5
N_{ν_e}	66	6.0×10^4
$N_{\overline{\nu}_\mu}$	49	2.5×10^4
$N_{\overline{\nu}_e}$	57	1.3×10^4
total		2.3×10^5

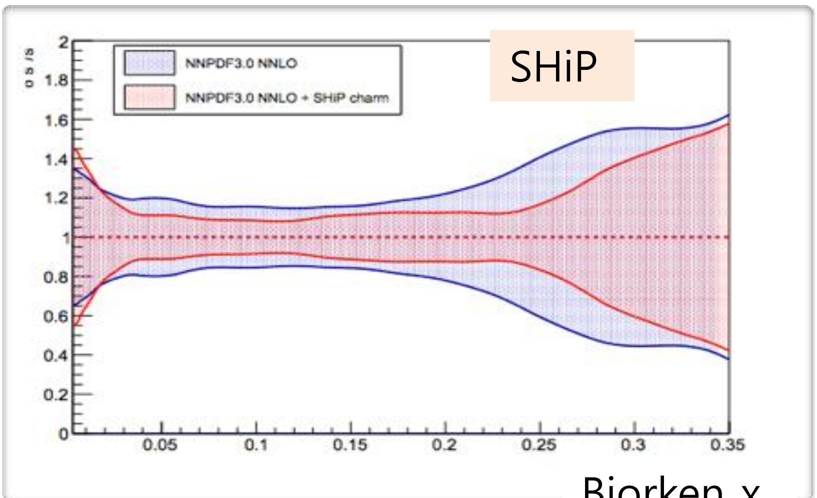
No charm candidates from electron neutrino was ever reported so far.

Strange quark content in nucleon

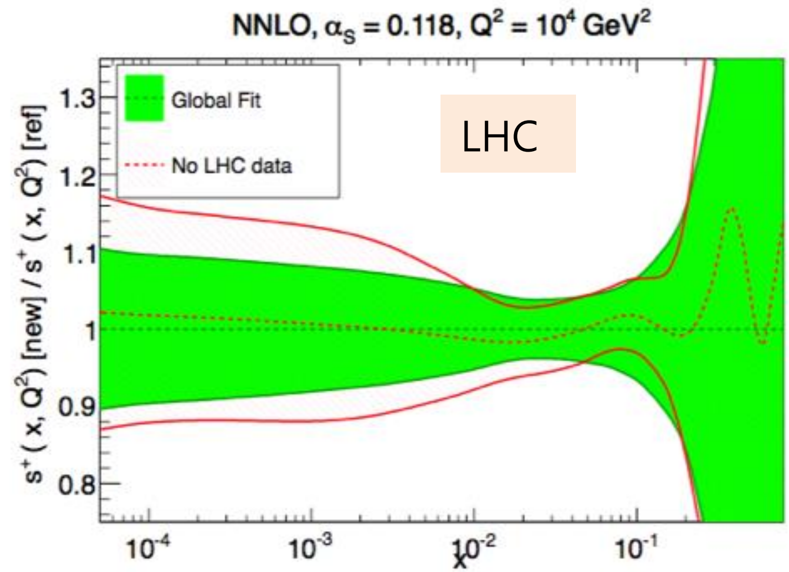
Significant reduction of uncertainty on s-quark distribution (factor two) in nucleon with SHiP data in the x range between 0.03 and 0.35.

Uncertainty band

$1+\Delta s^+/s^+$



Bjorken x



LHC and SHiP will probe the strangeness distribution in different ranges of x.

Neutrino induced Charm production is sensitive to s-quark content of nucleon.

Anti-charm production in Anti-neutrino CC interaction selects the anti s-quark content of nucleon.

Charm from anti-ν_μ
32 events in CHORUS
(2013 events from ν_μ)

Expected in SHiP ~ 25,000

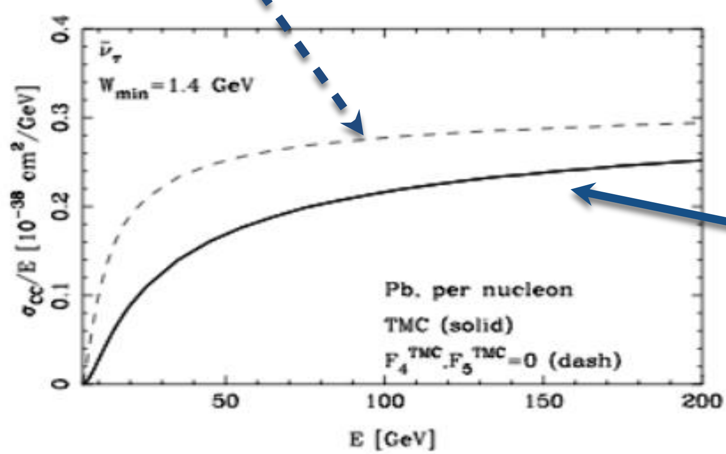
Structure functions F_4 , F_5

First evaluation of F_4 and F_5 only accessible by Tau neutrino

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

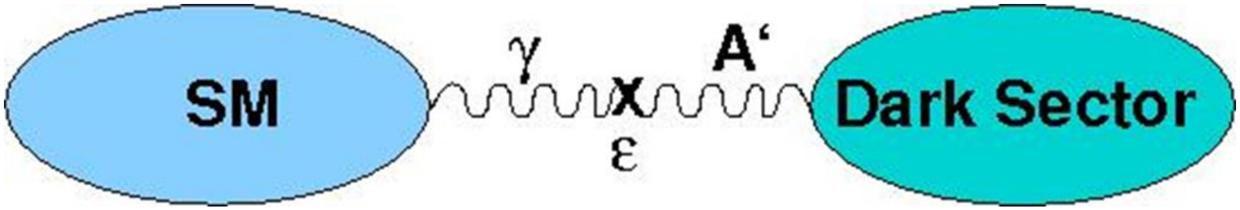
+ neutrino
- anti-neutrino

$F_4 = F_5 = 0$



ν_τ CC DIS cross-section predicted by SM

Vector portal



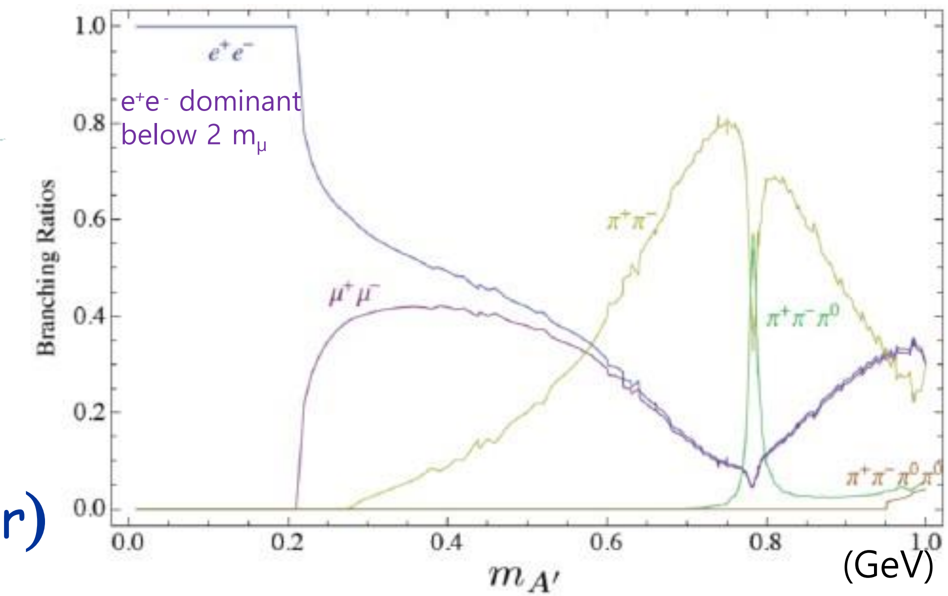
Dark photon can decay into pair of Light Dark matter.

Production of dark photon A'

- Meson decay π^0 (η, η', ω) → $\gamma A'$
- Proton bremsstrahlung $pp \to pp A'$
- QCD production $q + q \to A'$, $q + g \to q + A'$

Decay of dark photon

- $A' \to e^+ e^-$, $\mu^+ \mu^-$
- $A' \to$ hadrons
- $A' \to \chi \bar{\chi}$ (χ : Dark matter)



χ scatter on e or n, p → DM search

LDM (χ) can produce

via dark photon (A') decay

$$pp \rightarrow \pi^0 X$$

$$\pi^0 \rightarrow A' \gamma$$

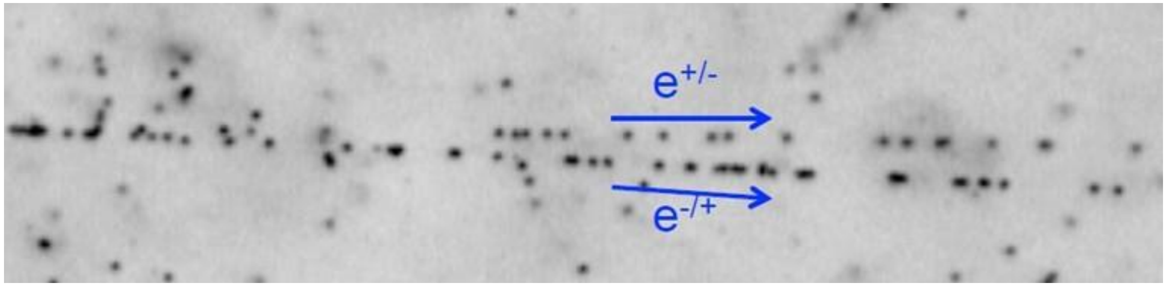
$$A' \rightarrow \chi \bar{\chi}$$

χ: LDM

Scatter on e

$$\chi e \rightarrow \chi e$$

Electron recoil
high energy



~ GeV electron sample in emulsion

Neutral Current DM-electron scattering is highly peaked in the forward direction. Cutting on very forward scattering can remove most other projected background.

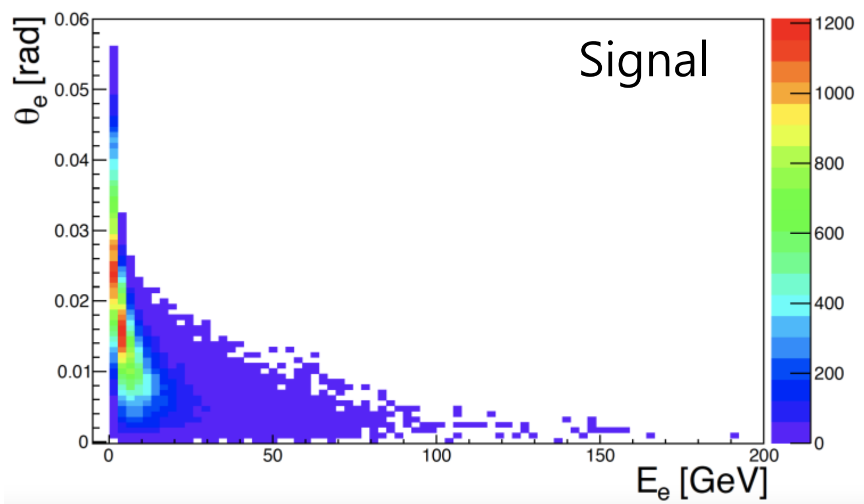
LDM search in emulsion

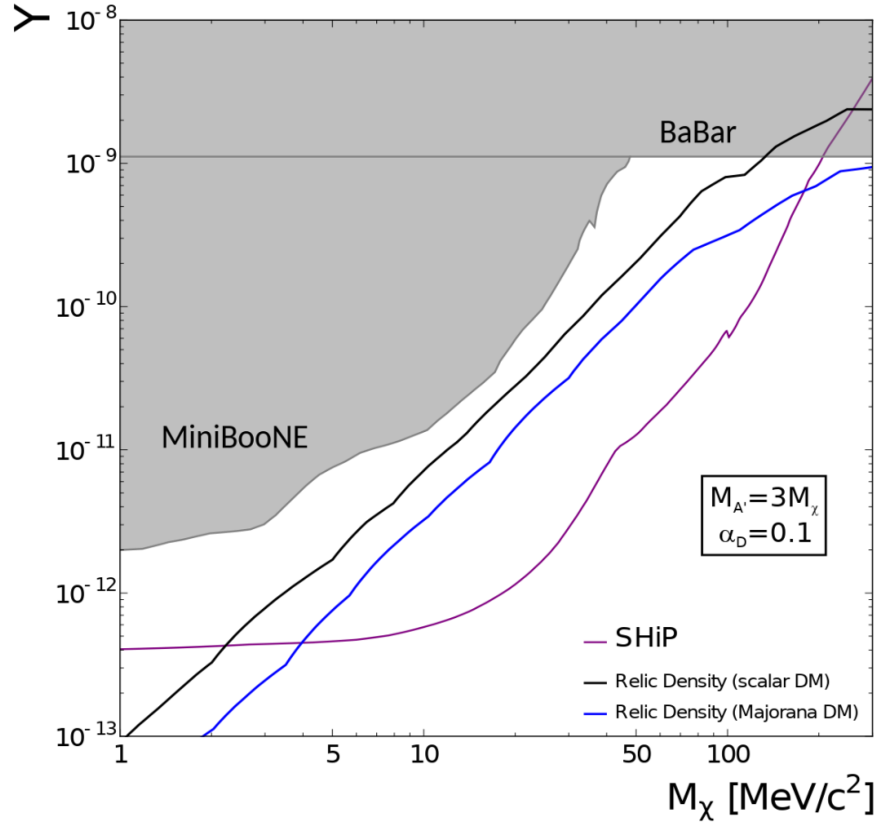
LDM χ produced in a dark photon decay interact with electron.

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

SIGNAL SELECTION

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



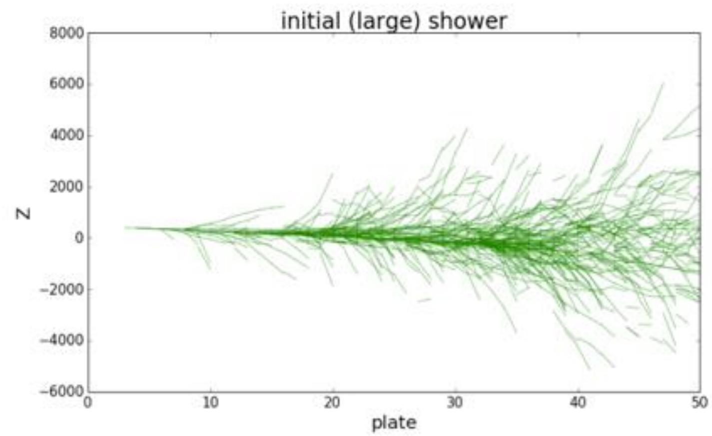


SHiP sensitivity to LDM produced in dark photon decays. The coupling is given as $Y = \varepsilon^2 \alpha'_D (m_\chi/m_{A'})^4$.

Number of background events in the LDM search after the selection for 2 x 10^{20} protons on target.

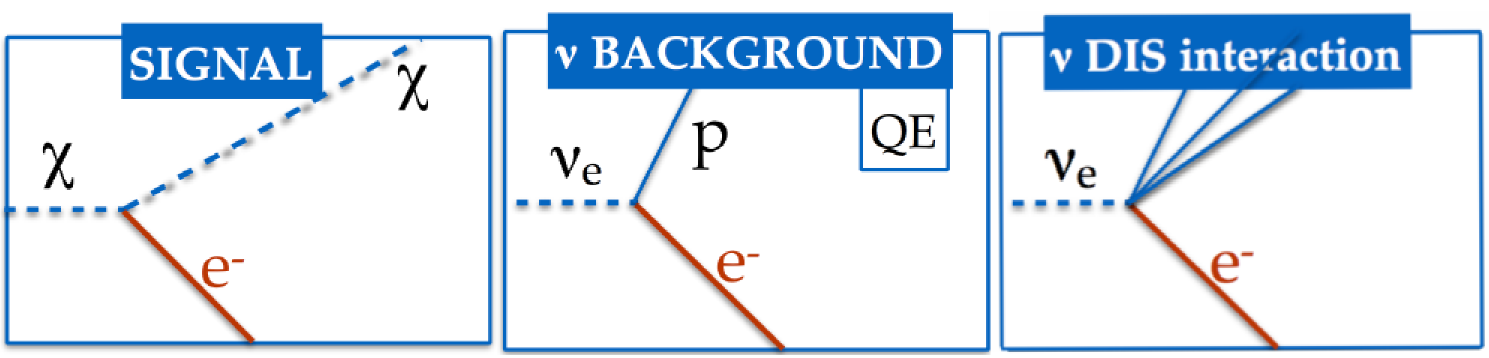
Background	ν_e	$\bar{\nu_e}$	ν_μ	$\bar{\nu_\mu}$	all
Elastic Scattering on e^-	81	45	56	35	217
Quasi-elastic Scattering	245	236	-	-	481
Resonant Scattering	8	77	-	-	85
Deep Inelastic Scattering	-	14	-	-	14
Total	334	372	56	35	797

Signal/bg discrimination currently being studied using Machine Learning



BG rejection

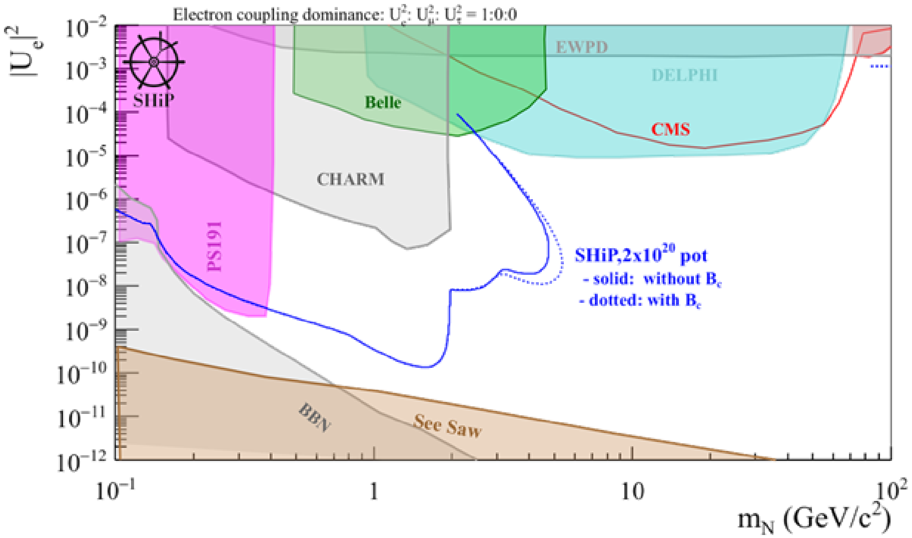
1) Energy–angle correlation
2) Presence of proton rejects Quasi-elastic scattering (QE)
3) Presence of hadron jets rejects Deep inelastic scattering (DIS)



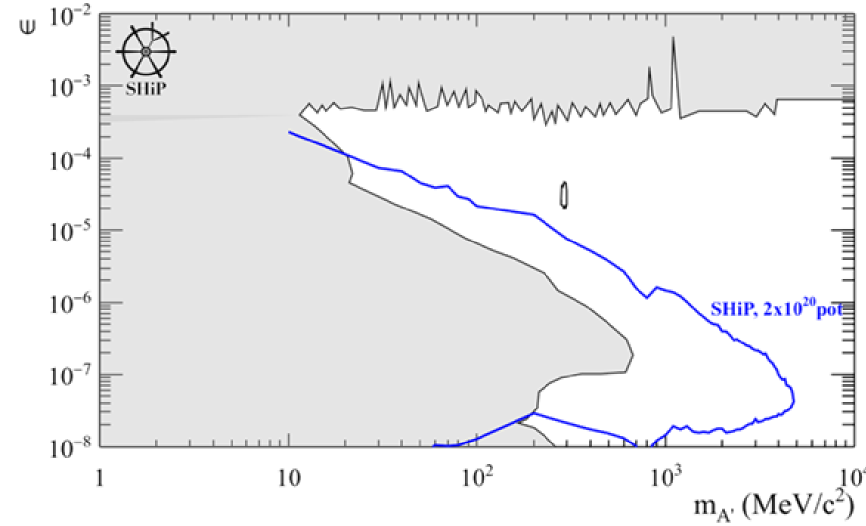
Sensitivities of the SHiP to HS particles

see K.Y. Lee's talk

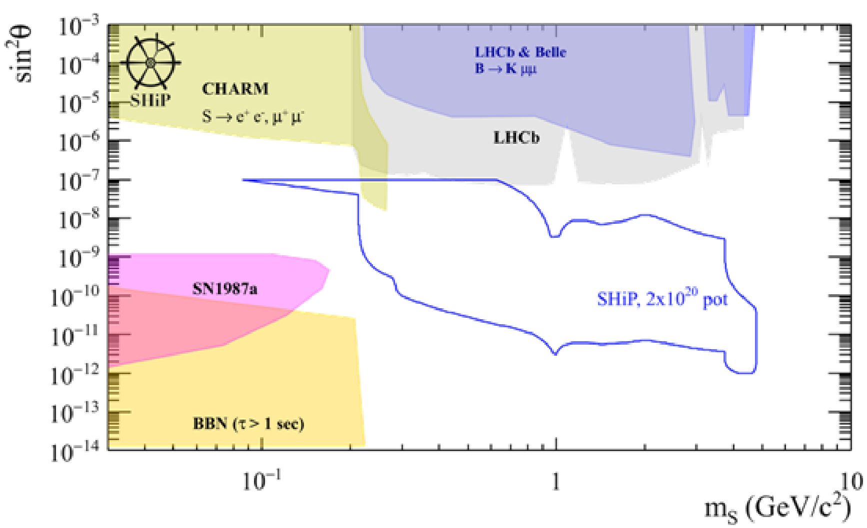
HNL



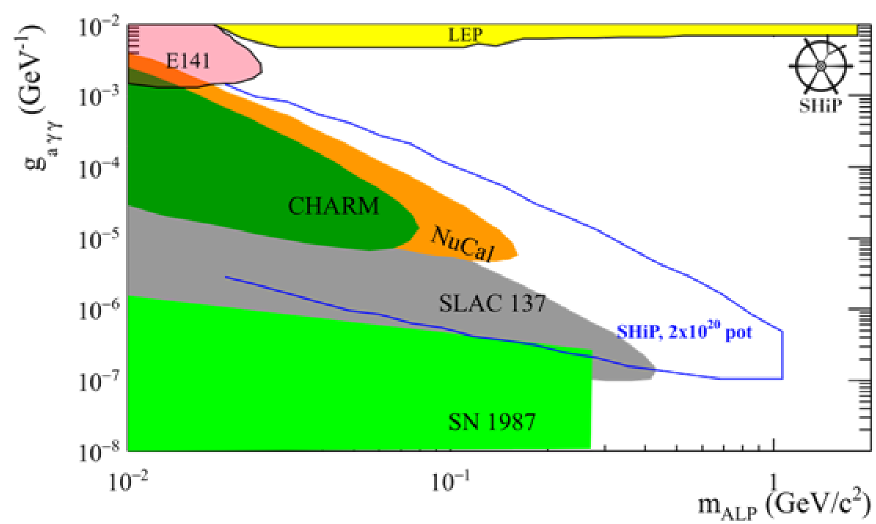
Dark photon



Dark scalars



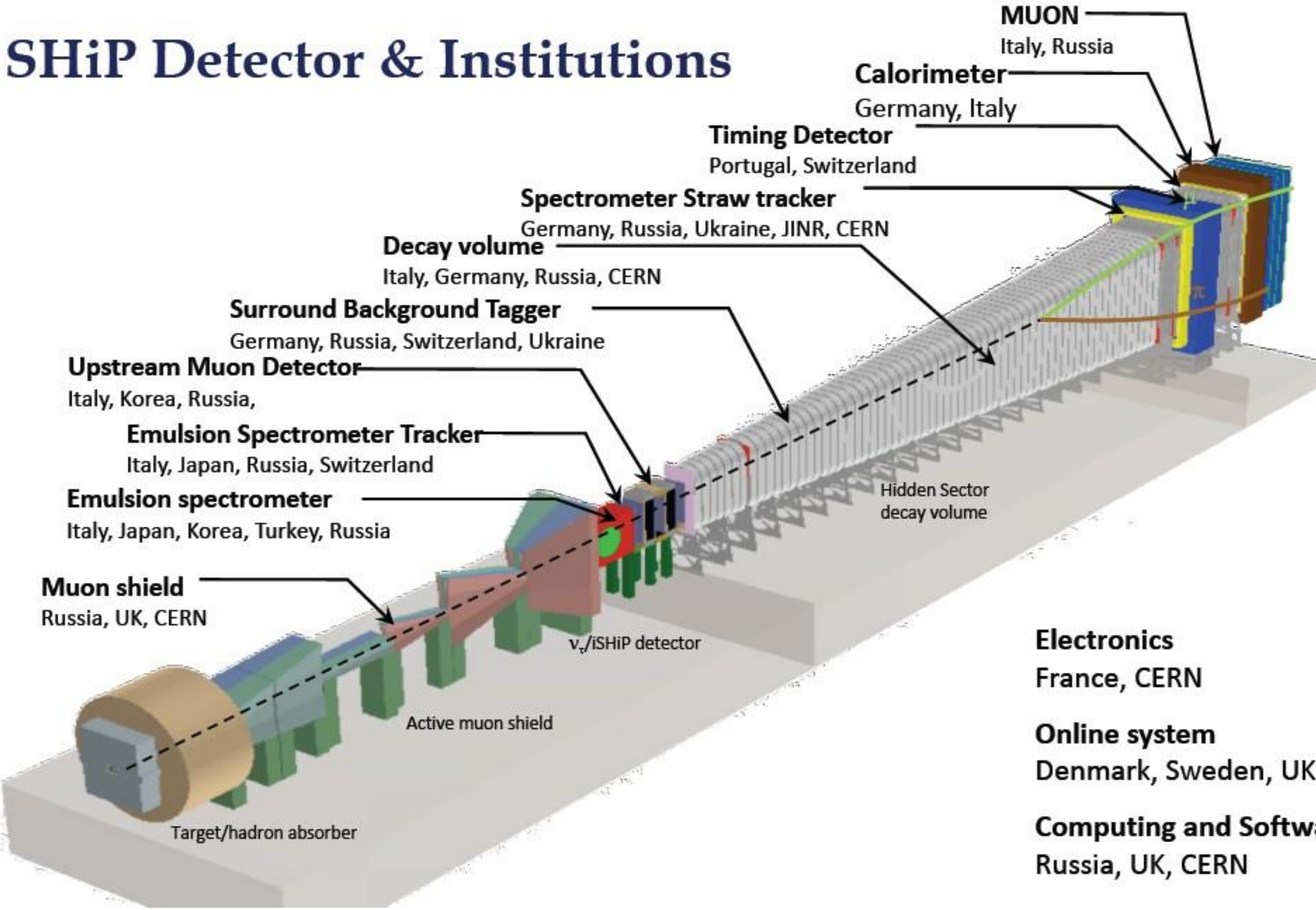
ALP



Member countries of the SHiP

54 institutes from 18 countries
295 members

SHiP Detector & Institutions

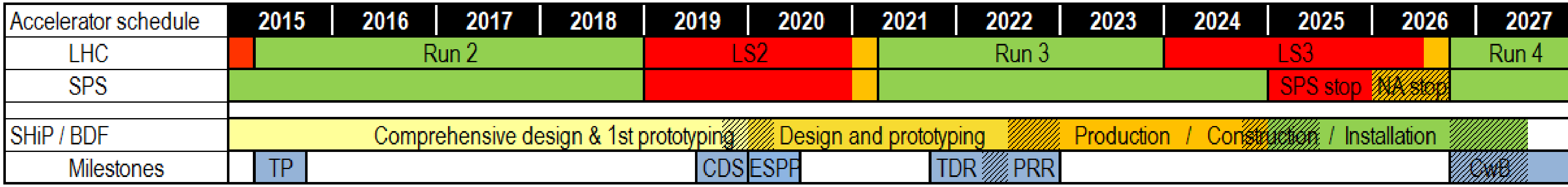


Electronics
France, CERN

Online system
Denmark, Sweden, UK, CERN

Computing and Software
Russia, UK, CERN

Project schedule

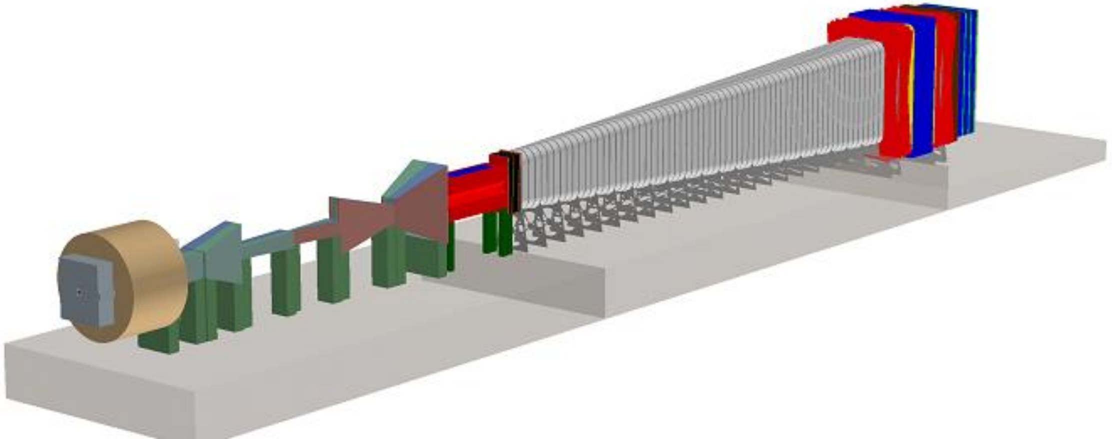


- Document submitted to **ESPP** on Dec. 2018 together with CERN Beam Dump Facility (BDF)
- **CDR** (Comprehensive Design Report) is in preparation for submission to SPSC in fall 2019
- Continue phase 2 module-level prototyping for **test beams**
  - at DESY (2019-2010), at CERN (2021)
- Detector engineering design and preparation of **TDR** after **Approval**

Summary

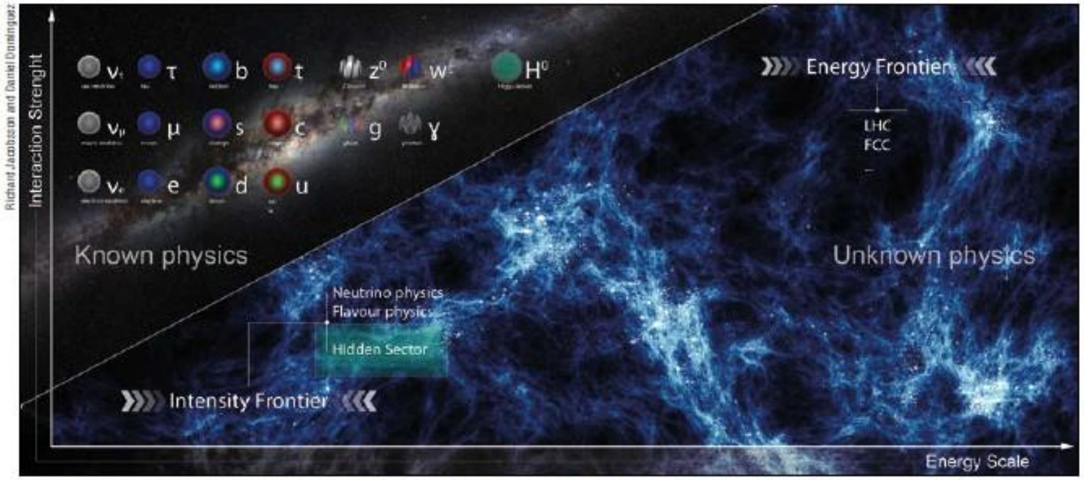
- The SHiP is a multi-purpose and very timely experiment for **Hidden particles, LDM** and **Tau neutrino physics**.
- About 10,000 ν_τ & Anti-ν_τ CC events can be observed with ECC target.
- First observation of the Anti-ν_τ
- ν_τ & Anti-ν_τ Cross-section and Mag moment measurements
- First evaluation of the F4 and F5 structure functions
- Study of Strange quark content of nucleon
- **LDM** search in the SND

…



Backup

CERN Courier
March 2016



SHiP is a new experiment at the intensity frontier aimed at exploring the hidden sector.

SPSC supported and recommended to make CDR.

SHiP sets a new course in intensity-frontier exploration

SHiP (Search for Hidden Particles) is a newly proposed experiment for CERN's Super Proton Synchrotron accelerator...

Why is the SHiP physics programme so timely and attractive?

A Golutvin, Imperial College London/CERN, and **R Jacobsson**, CERN, on behalf of SHiP.

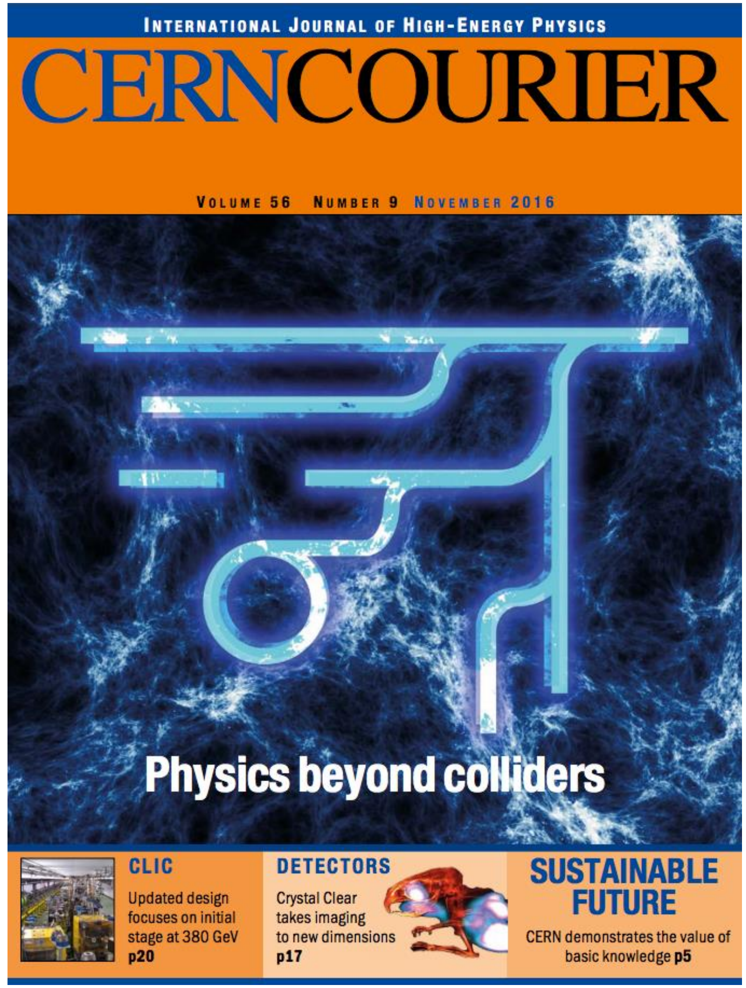
SHiP is an experiment aimed at exploring the domain of very weakly interacting particles and studying the properties of tau neutrinos. It is designed to be installed downstream of a new beam-dump facility at the Super Proton Synchrotron (SPS). The CERN SPS and PS experiments Committee (SPSC) has recently completed a review of the SHiP Technical and Physics Proposal, and it recommended that the SHiP collaboration proceed towards preparing a Comprehensive Design Report, which will provide input into the next update of the European Strategy for Particle Physics, in 2018/2019.

Why is the SHiP physics programme so timely and attractive? We have now observed all the particles of the Standard Model, however it is clear that it is not the ultimate theory. Some yet unknown particles or interactions are required to explain a number of ...

While these phenomena are well-established observationally, they give no indication about the energy scale of the new physics. The analysis of new LHC data collected at $\sqrt{s} = 13$ TeV will soon have directly probed the TeV scale for new particles with couplings at O(%) level. The experimental effort in flavour physics, and searches for charged lepton flavour violation and electric dipole moments, will continue the quest for specific flavour symmetries to complement direct exploration of the TeV scale.

However, it is possible that we have not observed some of the particles responsible for the BSM problems due to their extremely feeble interactions, rather than due to their heavy masses. Even in the scenarios in which BSM physics is related to high-mass scales, many models contain degrees of freedom with suppressed couplings that stay relevant at much lower energies.

Given the small couplings and mixings, and hence typically long lifetimes, these hidden particles have not been significantly ▷

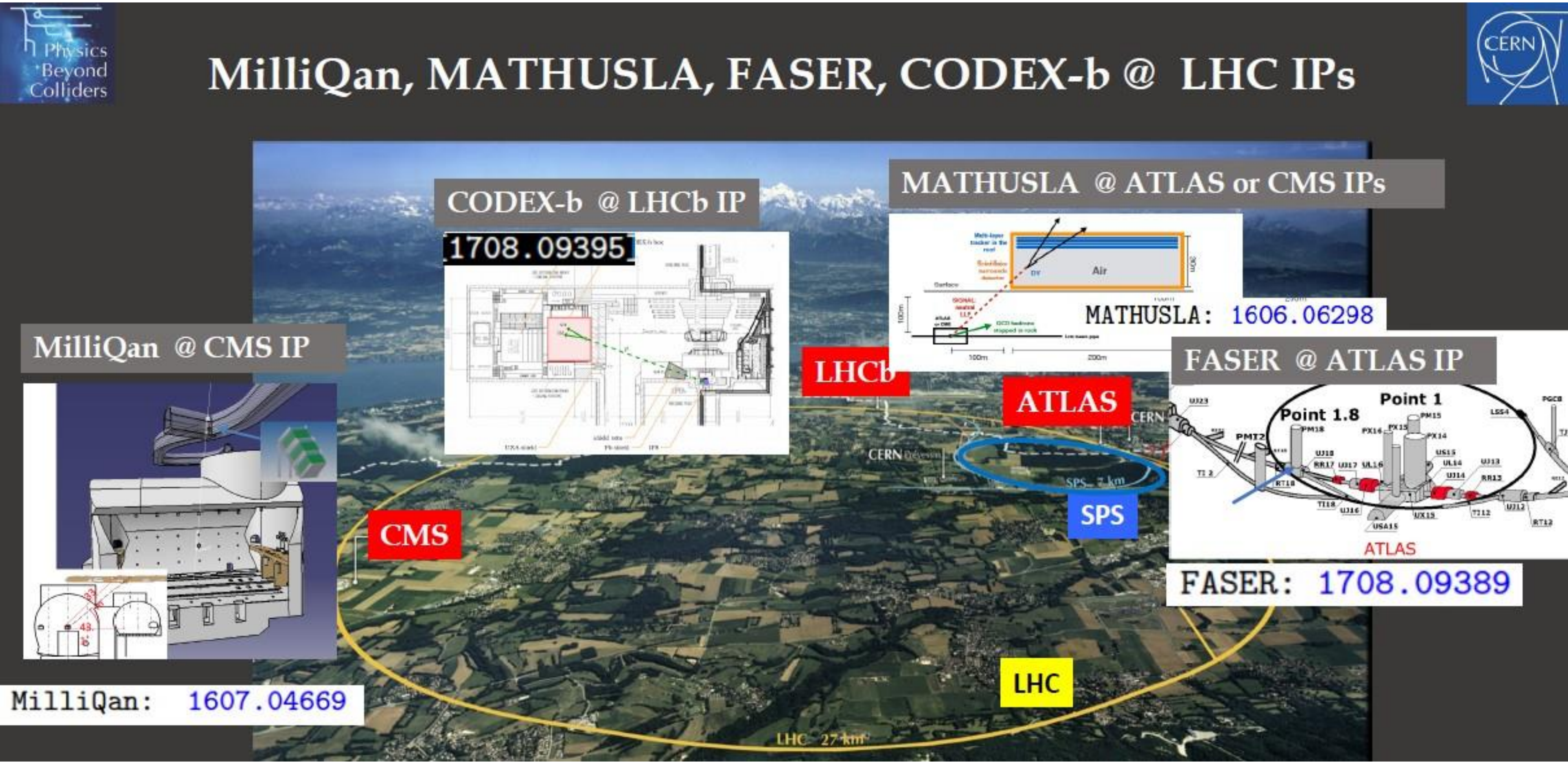


CERN launches Physics Beyond Colliders study group

CERN invites abstract applications for the workshop, which will investigat
CERN's accelerators can help solve questions of particle physics

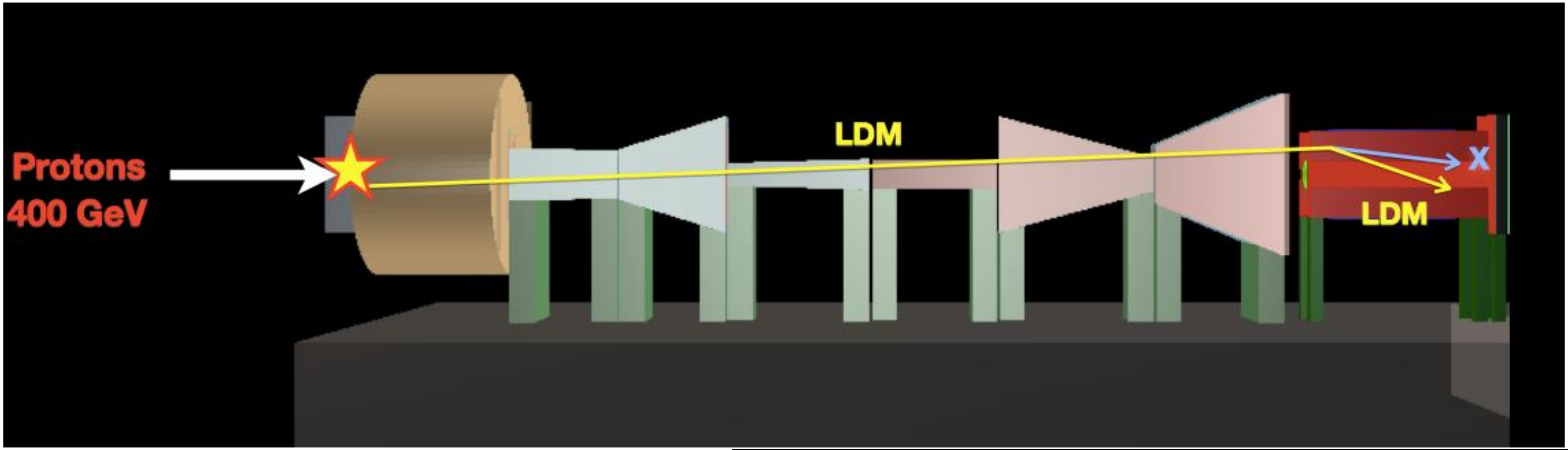
24 MAY, 2016

SHiP-like LLP projects at LHC



AL3X @ALICE: 1810.03636

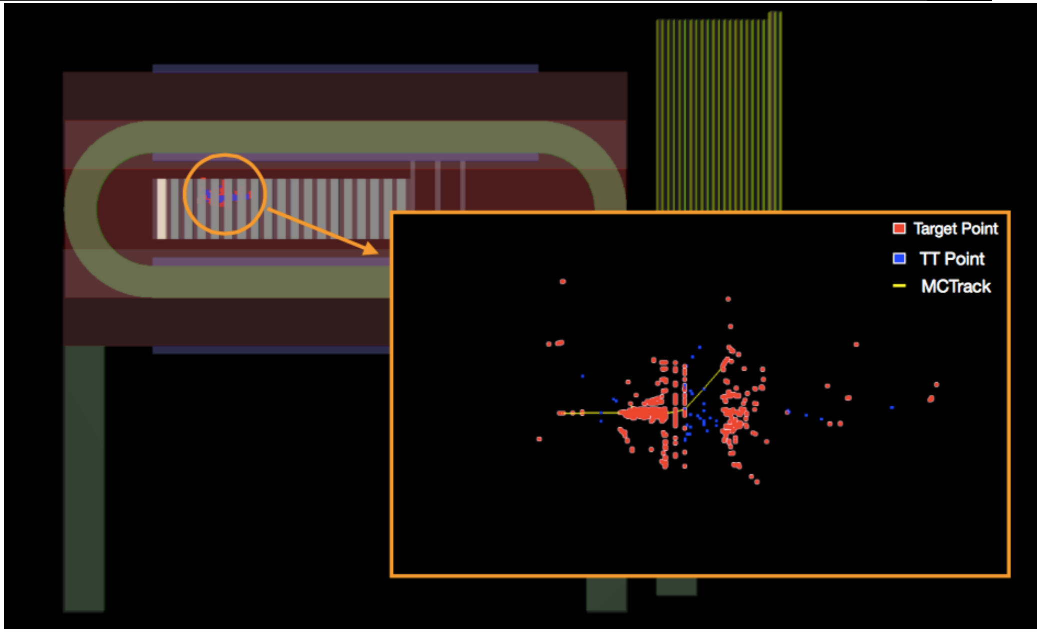
Light dark matter detection in Neutrino detector



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

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

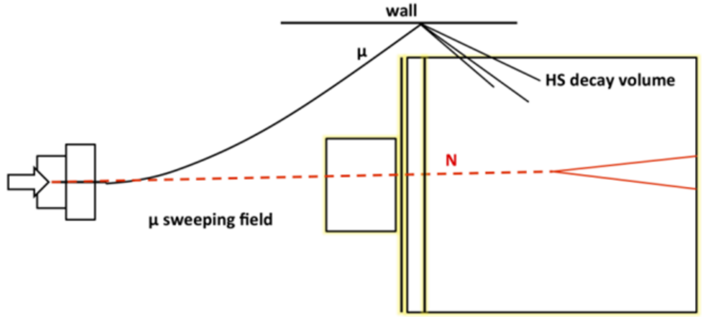
Electron recoil
Cascade shower in Emulsion



Top: Light Dark Matter simulation process in FairShip.
Bottom : Event display of a LDM scattering process simulated inside the Scattering Spectrometer.

HS background rejection

Muon induced background (inelastic interaction)



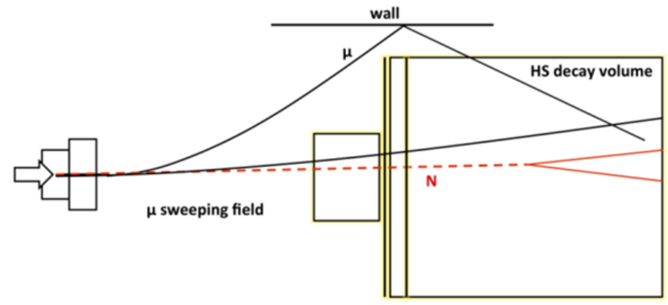
Deep inelastic

$6 \cdot 10^4$ μ/spill impinging on the decay volume
$2.1 \cdot 10^8$ inelastic interaction in 5 years
BG after cuts (full reco) = $2.7 \cdot 10^{-5}$
BG after cuts (partial reco) = $6 \cdot 10^{-4}$

Selection cut	Value
Track momentum	> 1 GeV/c
Distance of closest approach	< 1 cm
Vertex position	> 5 cm from vessel wall
Imp. Param. w.r.t. target (full reco)	< 10 cm
Imp. Param. w.r.t. target (partial reco)	< 250 cm

CERN-SPSC-2019-010

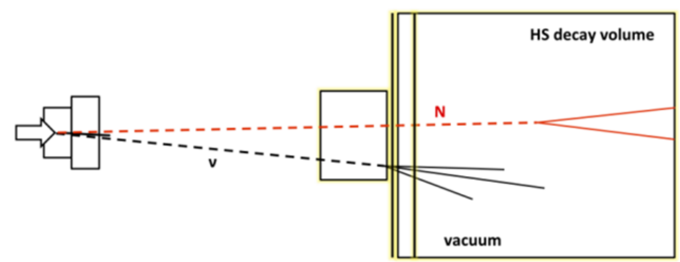
Muon combinatorial background (mimic vertex)



Muon combinatorial

$8.5 \cdot 10^{15}$ fake vertices without time info.
Reduced to $4.2 \cdot 10^{-2}$ with time info (TD)

Neutrino induced background (inelastic interaction)



Neutrino interactions

$2 \cdot 10^{18}$ **ν** from target in 5 years
$3.5 \cdot 10^7$ inelastic interaction in 5 years
BG after cuts (full reco) = 10^{-2}
BG after cuts (partial reco) < 0.1 (**γ** conversion cut)

Signal & Background channels for HS

SHiP Technical proposal, arXiv:1504.04956

Signature	Physics	Backgrounds	Cuts
$\pi^-\mu^+$,$K^-\mu^+$	HNL,NEU	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$	IP,TI,PID($\mu\pi$) P,IP,NT
$\pi^-\pi^0\mu^+$	HNL($\to \rho^-\mu^+$)	$K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$, $K_L^0 \to \pi^-\pi^+\pi^0$	P,IP,NT,TI, P,IP,NT,PID($\pi\mu$)
π^-e^+,K^-e^+	HNL, NEU	$K_L^0 \to \pi^-e^+\nu_e$	P,IP,NT
$\pi^-\pi^0e^+$	HNL($\to \rho^-e^+$)	$K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$	P,IP,NT,TI,PID(πe)
μ^-e^++p^{miss}	HNL,HP($\to \tau\tau$)	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$	P,NT, PID($\pi\mu, \pi e$)
$\mu^-\mu^+$+p^{miss}	HNL,HP($\to \tau\tau$)	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$	TI P,NT, PID($\pi\mu$)
$\mu^-\mu^+$	DP,PNGB,HP	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$	TI,IP P,NT, IP, PID($\pi\mu$)
$\mu^-\mu^+\gamma$	CS	$K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$	P,IP,NT, PID($\pi\mu$),TI,VP
e^-e^++p^{miss}	HNL,HP	$K_L^0 \to \pi^-e^+\nu_e$	P,NT, PID(πe)

e^-e^+	DP,PNGB,HP	$K_L^0 \to \pi^- e^+ \nu_e$	P,IP,NT, PID(πe)
$\pi^-\pi^+$	DP,PNGB,HP	$K_L^0 \to \pi^- \mu^+ \nu_\mu$, $K_L^0 \to \pi^- e^+ \nu_e$ $K_L^0 \to \pi^- \pi^+ \pi^0$, $K_L^0 \to \pi^- \pi^+$	P,NT, PID($\mu\pi$),IP PID($e\pi$),IP POA,IP
$\pi^-\pi^+ + p^{miss}$	DP,PNGB, HP($\to \tau\tau$), HSU,HNL($\to \rho^0\nu$)	$K_L^0 \to \pi^- \mu^+ \nu_\mu$, $K_L^0 \to \pi^- e^+ \nu_e$, $K_L^0 \to \pi^- \pi^+ \pi^0$, $K_L^0 \to \pi^- \pi^+$,$K_S^0 \to \pi^- \pi^+$,$\Lambda \to p\pi$	P,NT, PID($\mu\pi$), PID($e\pi$), POA
K^+K^-	DP,PNGB, HP	$K_L^0 \to \pi^- \mu^+ \nu_\mu$, $K_L^0 \to \pi^- e^+ \nu_e$ $K_L^0 \to \pi^- \pi^+ \pi^0$, $K_L^0 \to \pi^- \pi^+$,$K_S^0 \to \pi^- \pi^+$,$\Lambda \to p\pi$	P,NT, PID($\pi\mu, \pi e$),IP
$\pi^+\pi^-\pi^0$	DP,PNGB,HP, HNL($\eta\nu$)	$K_L^0 \to \pi^- \pi^+ \pi^0$	P,IP,NT
$\pi^+\pi^-\pi^0\pi^0$	DP,PNGB,HP	$K_L^0 \to \pi^- \pi^+ \pi^0 (+\pi^0)$	P,IP,NT,TI
$\pi^+\pi^-\pi^0\pi^0\pi^0$	PNGB($\to \pi\pi\eta$)	–	–
$\pi^+\pi^-\gamma\gamma$	PNGB($\to \pi\pi\eta$)	$K_L^0 \to \pi^- \pi^+ \pi^0$	P, IP, NT,M($\gamma\gamma$)

$\pi^+\pi^-\pi^+\pi^-$	DP,PNGB,HP	–	–
$\pi^+\pi^-\mu^+\mu^-$	HSU	–	–
$\pi^+\pi^-e^+e^-$	HSU	–	–
$\mu^+\mu^-\mu^+\mu^-$	HSU	–	–
$\mu^+\mu^-e^+e^-$	HSU	–	–

Table 5.3: Signal and background channels for the Hidden Sector detector. The last column lists the cuts which can be used to suppress the backgrounds. The abbreviations for the physics channels correspond to: HNL=Heavy Neutral Lepton, NEU=neutralino, DP=Dark Photon, PNGB= Pseudo-Nambu Goldston Boson, HP= Higgs Portal, CS=Chern-Simons, HSU= Hidden SUSY, RDM=random di-muons from the target, The abbreviations used for techniques to reject the backgrounds correspond to: IP=impact parameter at the target, CPV= charged particle veto, NT=neutrino interaction tagger, VP= photon veto (i.e. if there is a photon around), TI=timing cuts with timing detector, P=total momentum cuts of the daughters, POA=1 particle outside acceptance, PID($\mu\pi$)=probability that a μ is misidentified as π or kaon.

Selection criteria for Tau Neutrino event

At primary vertex

- there are no tracks compatible with that of a muon or an electron;
- the missing transverse momentum (P_T^{miss}) is smaller than 1 GeV/c;
- the angle Φ in the transverse plane between the τ candidate track and the hadronic shower direction is larger than $\pi/2$.

At decay vertex

- the kink angle θ_{kink} is larger than 20 mrad;
- the secondary vertex is within the two lead plates downstream of the primary vertex;
- the momentum of the charged secondary particles is larger than 2 GeV/c;
- the total transverse momentum (P_T) of the decay products is larger than 0.6 GeV/c if there are no photons emitted at the decay vertex, and 0.3 GeV/c otherwise.