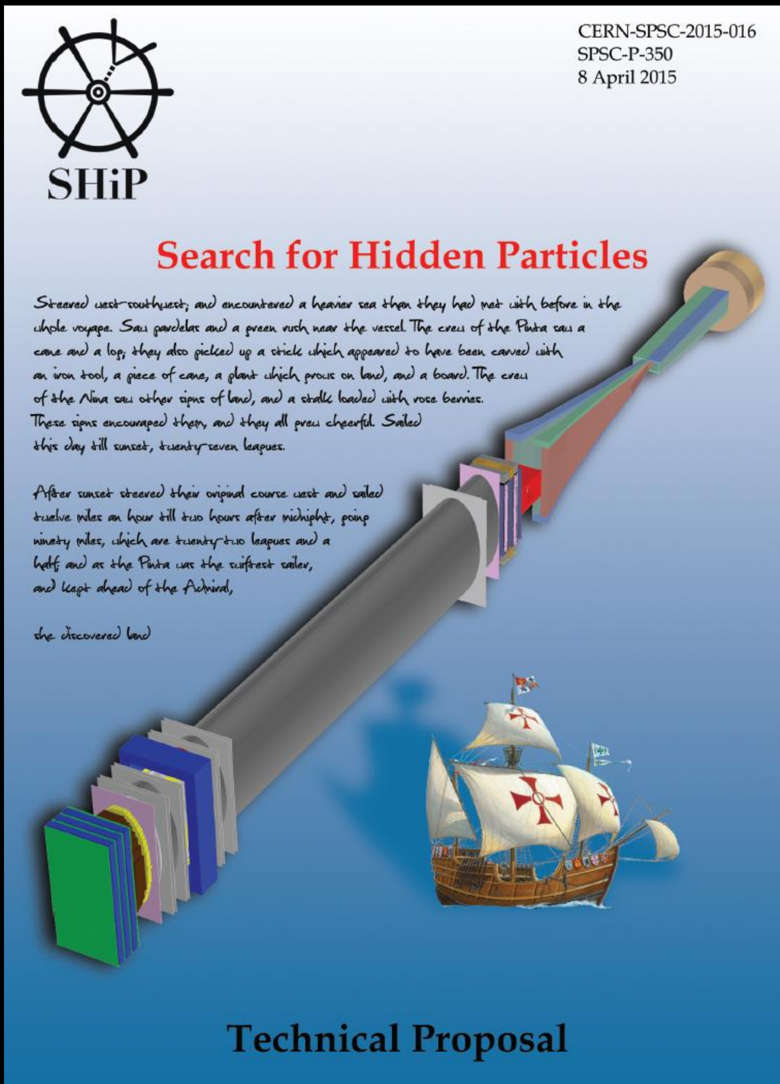
SHiP : a new facility with a dedicated detector for studying tau neutrino properties

M. Komatsu (Nagoya Univ. JAPAN) on behalf of the SHiP collaboration

SHiP
Search for Hidden Particles

The 14th International Workshop on Tau Lepton Physics (Tau2016)
IHEP, Beijing, 18-23 September 2016

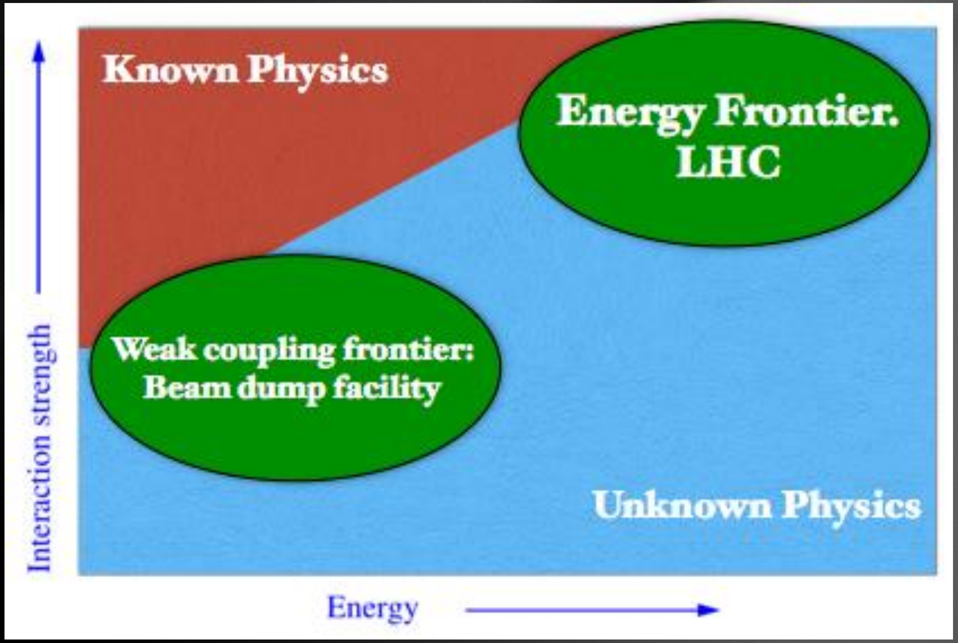
The SHiP experiment



- Proposal for a new beam dump facility at the CERN SPS
  - Hidden sector detector
  - Tau neutrino detector
- 235 authors from 45 institutes and 15 countries + CERN
  - Technical Proposal is submitted in April 2015 (arxiv.org/abs/1504.04956)
  - Physics Proposal signed by 85 theorists (arxiv.org/abs/1504.0855)
- SPSC positive recommendation in January 2016

Primary motivation

- Look for Beyond Standard Model in :
  - High Energy Frontier : LHC
  - Intensity Frontier : SHiP
- Look for long lived neutral (hidden) particle from beam dump
- ν_τ beam source
  - $D_s \rightarrow \tau\ \nu_\tau$



SHiP (Search for Hidden Particles) Physics objectives

- Explore hidden portals of the SM using > 2 × 10^{20} p.o.t. (>10^{17} D, >10^{15} τ)
  - Heavy neutral lepton in various states
  - Dark photon
  - SUSY neutralino ….
  - See more detail on http://ship.web.cern.ch/
- Neutrino interactions (expect ~3500 ν_τ interactions identified in 9.6 tons emulsion target)
  - ν_τ and anti- ν_τ physics, cross-section
  - Physics in ν_τ scattering, structure function, magnetic moment.
  - Charm physics in neutrino and anti-neutrino interactions

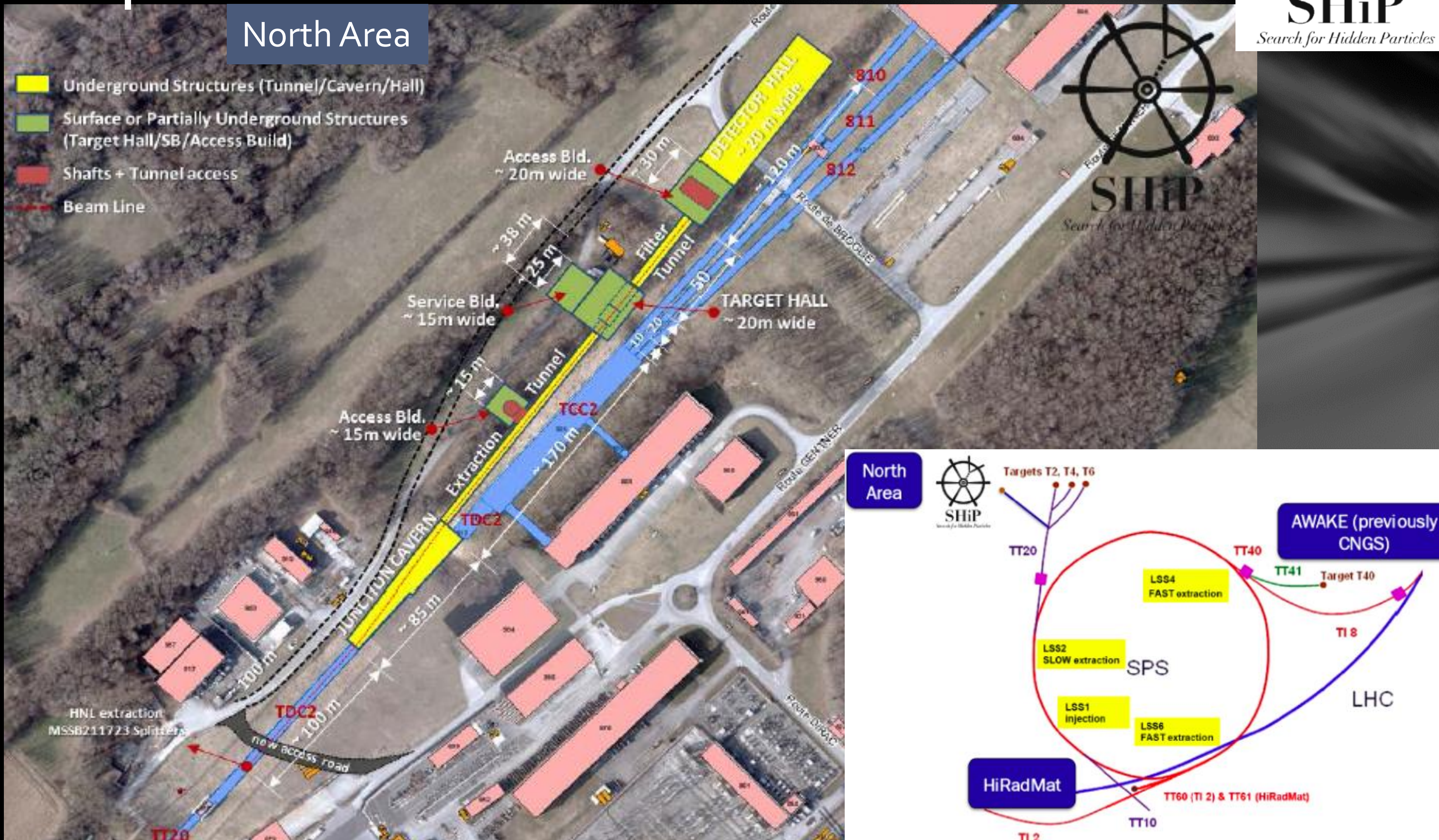
Physics programs

Full physics program

Tau neutrino (Main in this talk)

- We started look for tau neutrino since 1994 in CERN WA95 CHORUS (SBL $\nu_\mu \rightarrow \nu_\tau$ oscillation).
- Fermilab E872 DONUT (1997)
  - First observation : Phys. Lett. B504 (2001) 218-224
  - Cross-section : Phys. Rev. D78 (2008) 052002
    - 9(7.5) tau neutrino candidate events
    - $\sigma^{const}(\nu_\tau)=(0.39\pm0.13\pm0.13)\times10^{-38}$ cm^2 GeV^{-1}
- CERN CNGS1 OPERA (2008-2012) LBL $\nu_\mu \rightarrow \nu_\tau$
  - 5 tau neutrino, 5.1σ : Phys. Rev. Lett. 115 (2015) 121802
- Only 14 tau neutrino events ever observed.

Experiment site

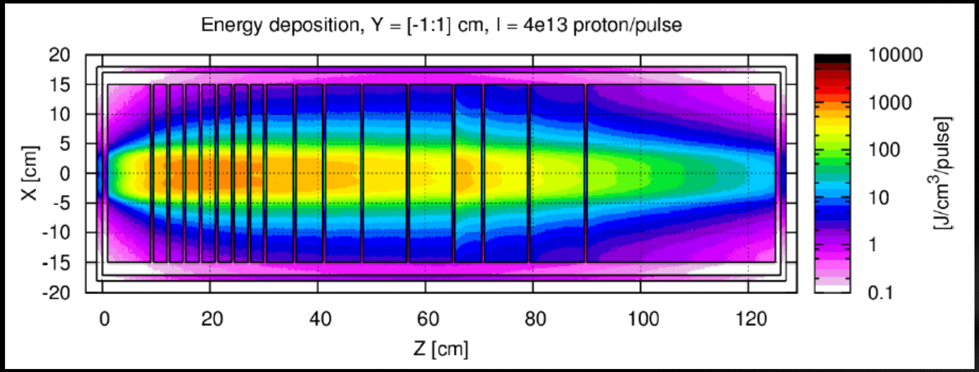


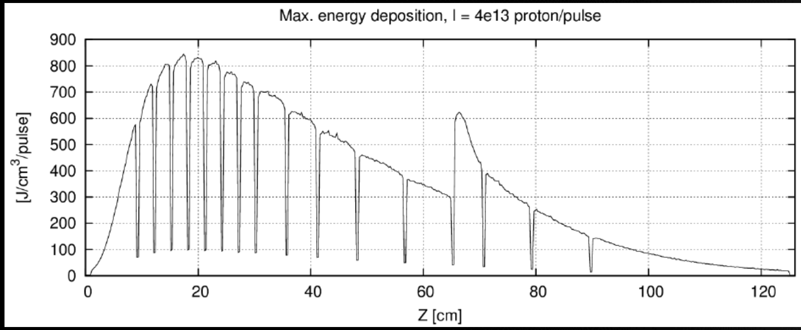
North area

Beam parameters for SHiP

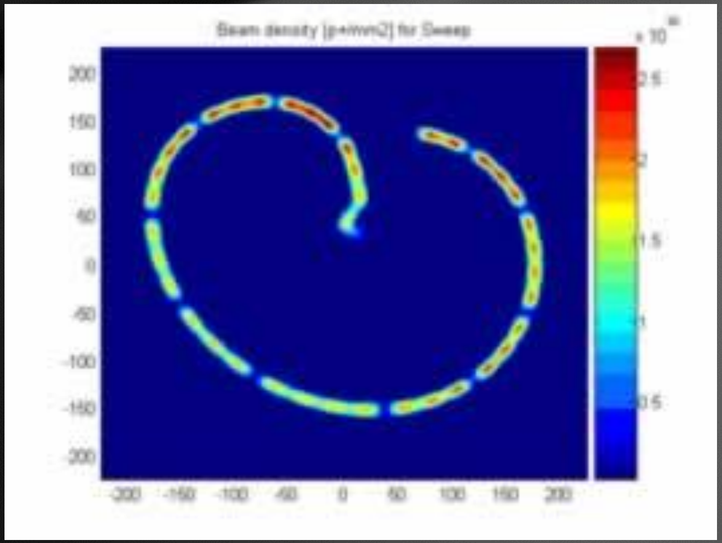
- Proton beam
  - Momentum : 400GeV/c
  - Beam intensity : 4-5 x 10^{13} /cycle
  - Cycle length : 7.2 s
  - Spill duration : 1 s (slow spill)
  - Average power : 400kW (during spill ~3MW)
  - Expected spot size (H/V) : 6mm/6mm
- 4×10^{19} pot / year → 2×10^{20} pot for 5 years
  - Very same with CNGS performance
    - Plan was 2.25×10^{20} but 1.8×10^{20} was delivered.

Beam dump target





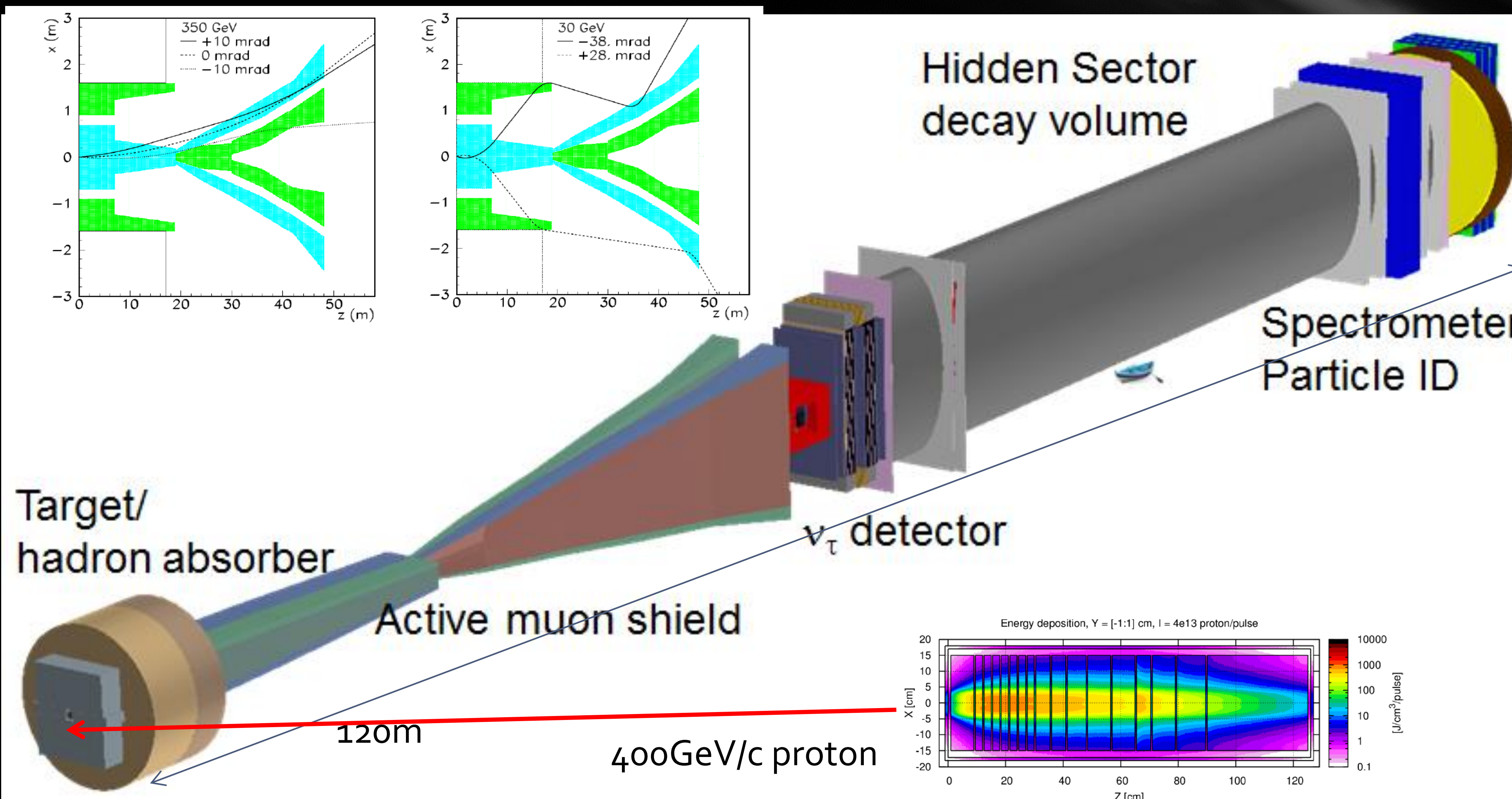
- Segmented Mo and W target actively cooled with water.
- Beam on target
  - Sweep is necessary like LHC



- In case of no sweep, the target would not melt but will fail by pressure.
- 1.2 DPA (displacement per atom) with 2×10^{20} pot

SHiP (Search for Hidden Particles) Beam dump experiment like DONUT

Reconstruction of the HNL decays in the final states: $\mu^- \pi^+$, $\mu^- \rho^+$ & $e^- \pi^+$

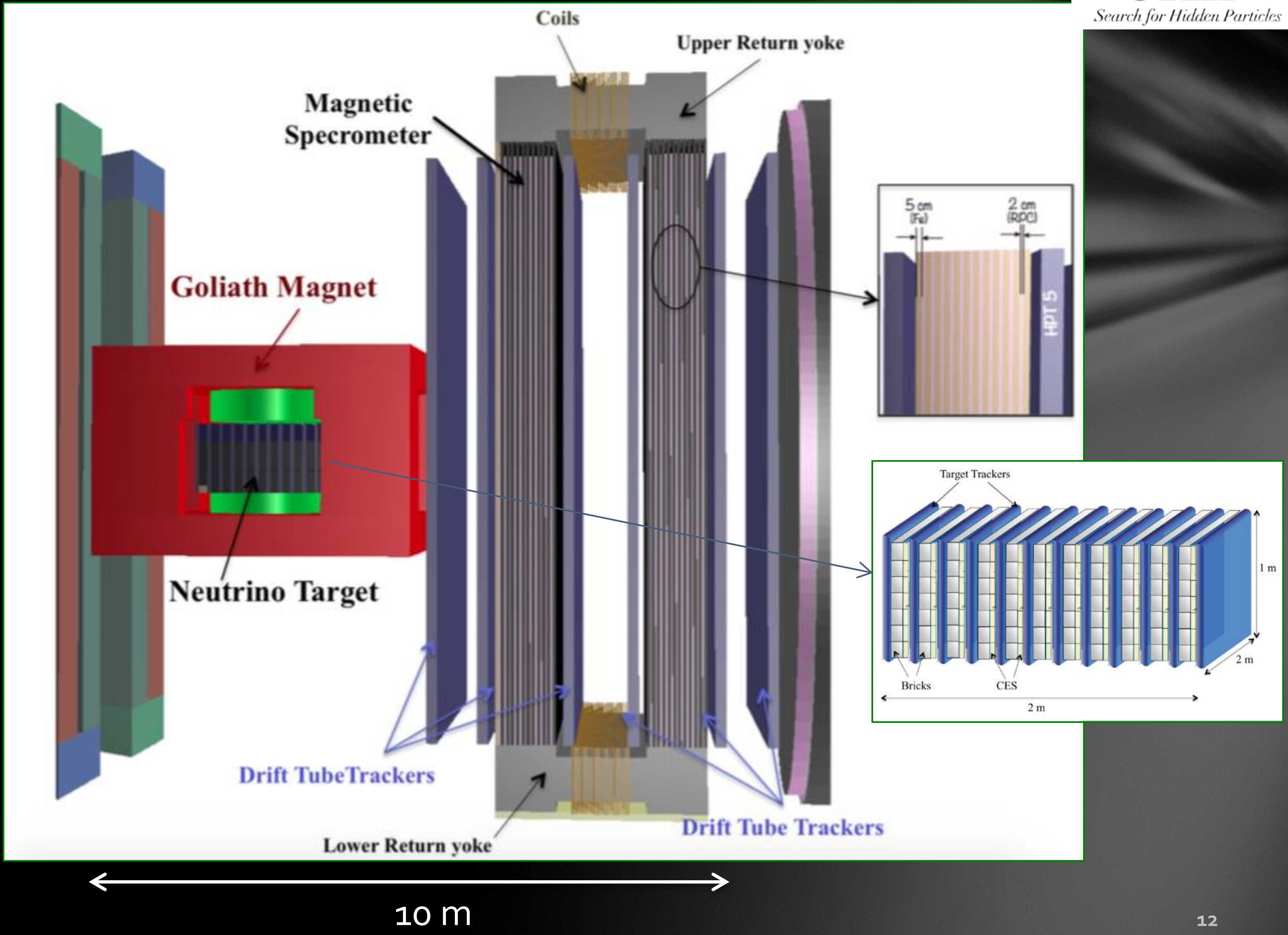


Comparison with DONUT

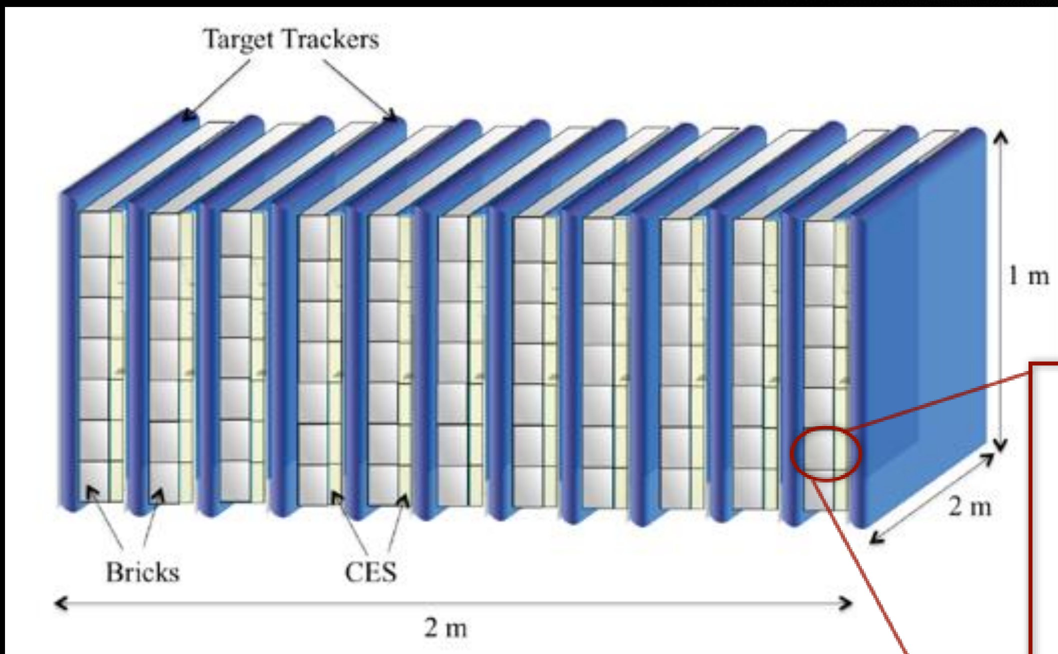
- Charm production by 400GeV, detector acceptance at 60m and tau neutrino cross-section
  - DONUT/SHiP → 1/(0.36 x 0.2 x 0.52) ~ 27
- Proton on target for SHiP and DONUT
  - SHiP/DONUT → $2x10^{20}$ / $3.6x10^{17}$ ~ 560
- Target mass
  - SHiP/DONUT → 9600kg/260kg ~ 37
- Overall advantage against DONUT → 560*37/27 ~ 770

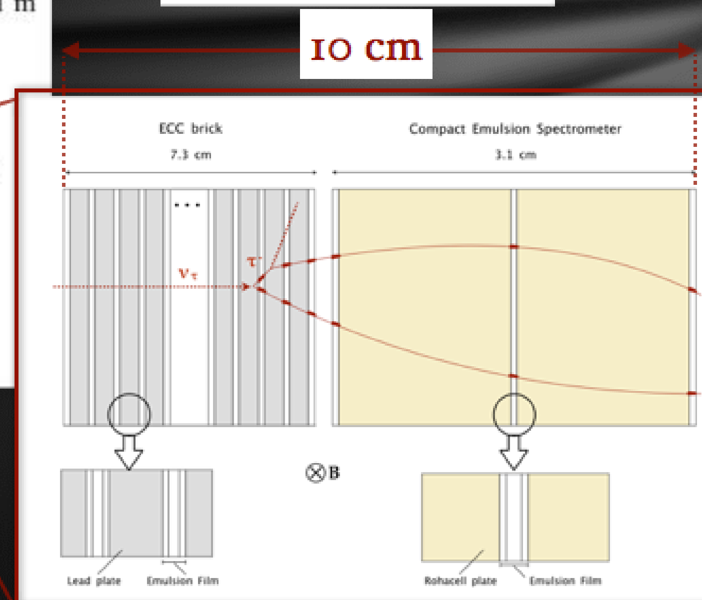
- Assuming OPERA like brick (8.3kg) → 1155 bricks
  - 1155/150 000 = 0.8% of OPERA experiment

SHiP neutrino detector



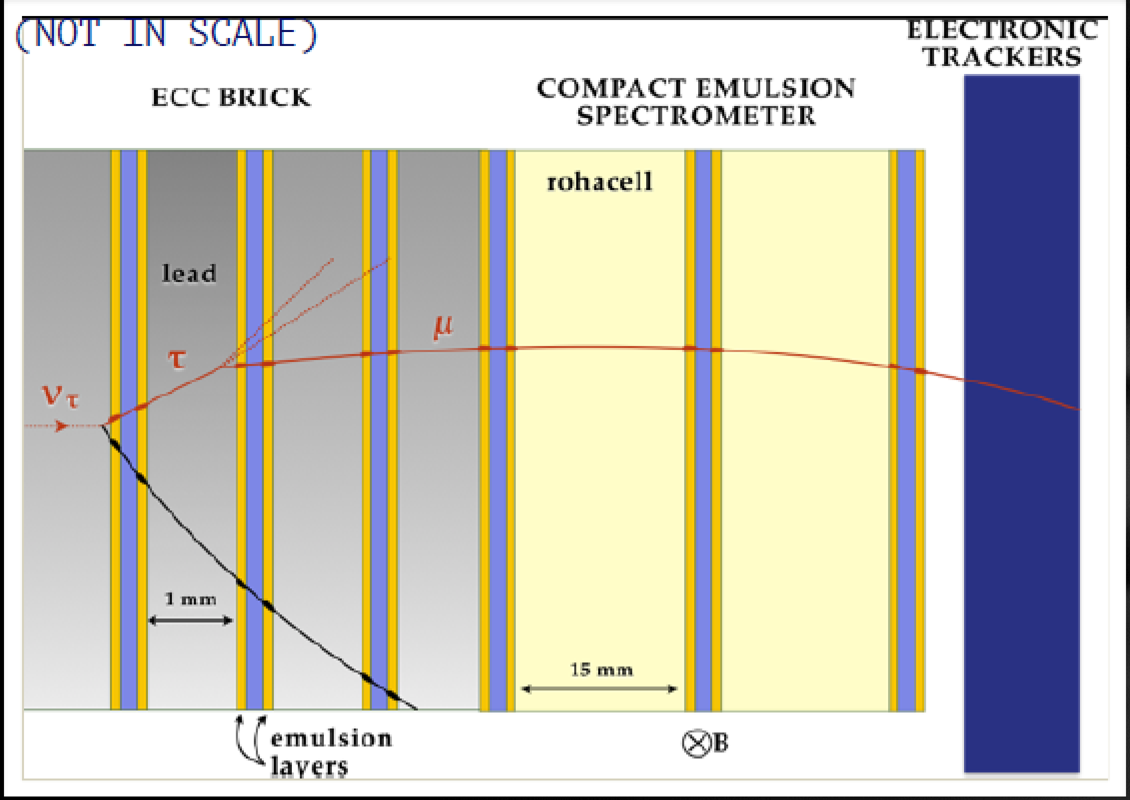
The neutrino target





- Emulsion Cloud Chamber (ECC) technology used in OPERA and DONUT
- Lead plates (high density material for the interaction) interleaved with emulsion films (tracking devices with µm resolution)

Detector design with CES



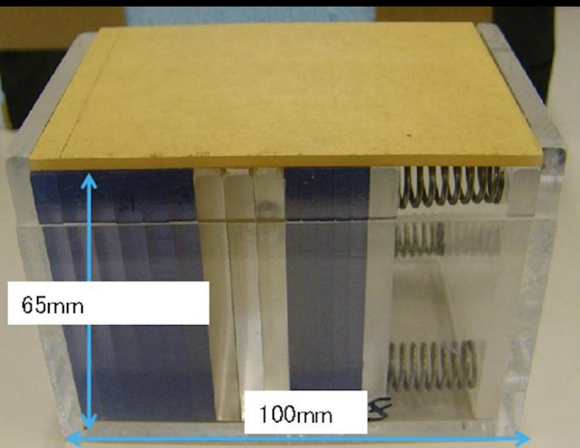
Target region: 11 mini-walls
One wall contains 15x7 bricks
Mass ~ 8.3kg x 15x7 x 11 ~ 9.6 ton

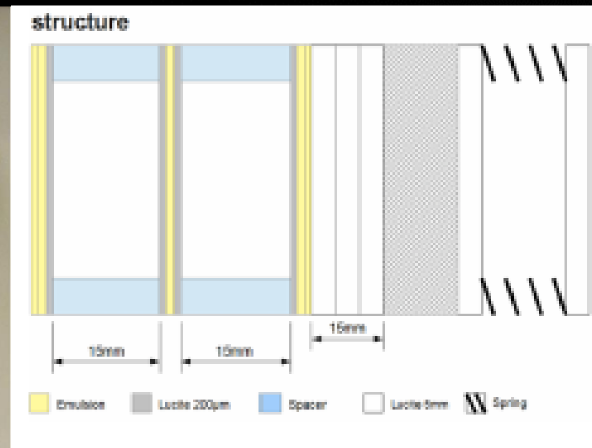
Charge determination not only for muonic channel.

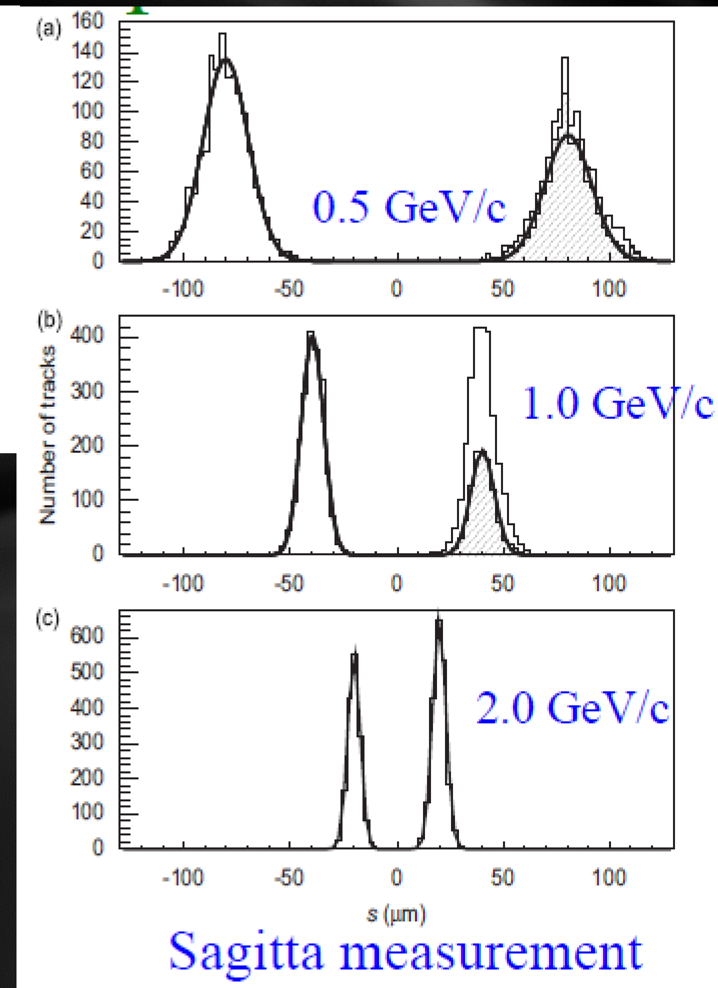
MC simulation of CES provide 53% charge determination for hadrons

Statistical gain due to the CES $\frac{\sum_{i=1}^{N} br_i \varepsilon_i}{br_\mu \varepsilon_\mu} \simeq \frac{18 \cdot 0.95 + 50 \cdot 0.53 + 15 \cdot 0.53^2}{18 \cdot 0.9} \simeq 3$

Compact Emulsion Spectrometer





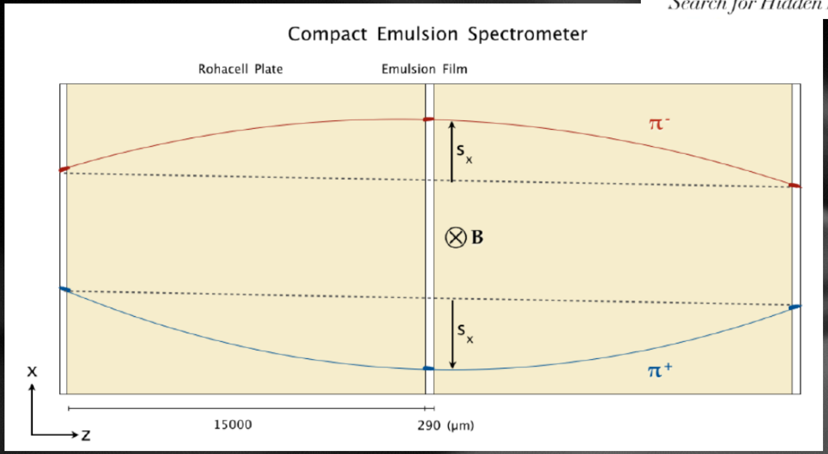


Three emulsion films interleaved with 1.5cm air gap in magnetic field (~1T), 3cm thick compact spectrometer.

H. Shibuya et al, NIM A592 (2008) 56

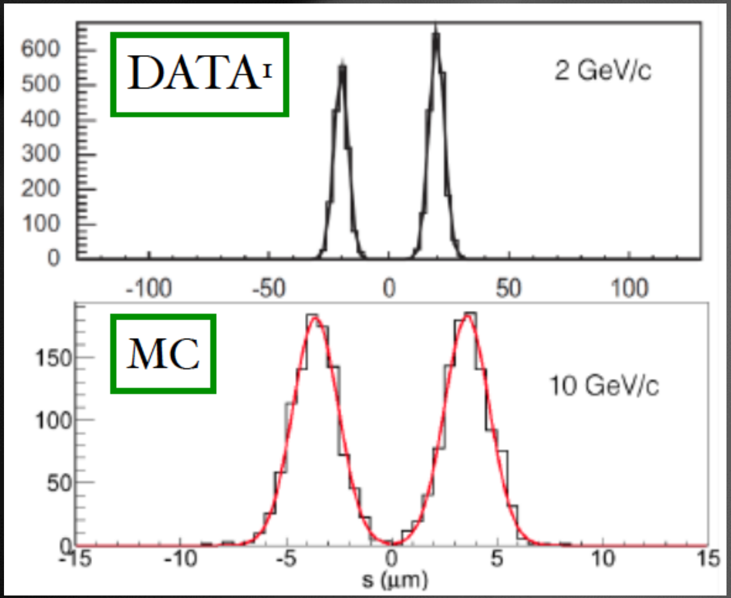
Separation ν_τ /anti-ν_τ

- three emulsion films interleaved with two, 15-mm thick, Rohacell layers
- 90% efficiency for hadronic τ daughters reaching the end of ECC brick in a 1 T field
- sagitta method used to discriminate between positive and negative charge



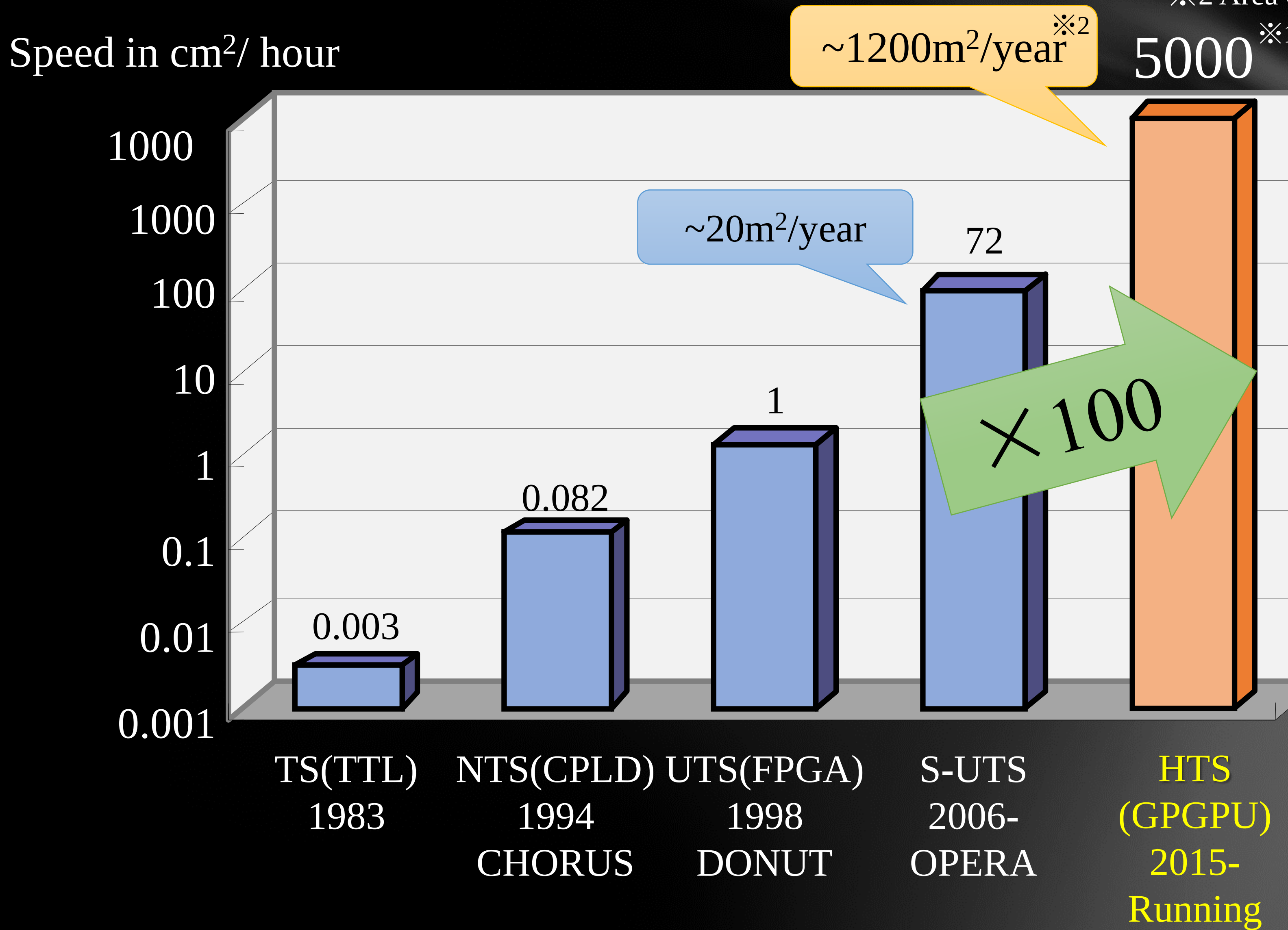
Performance

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

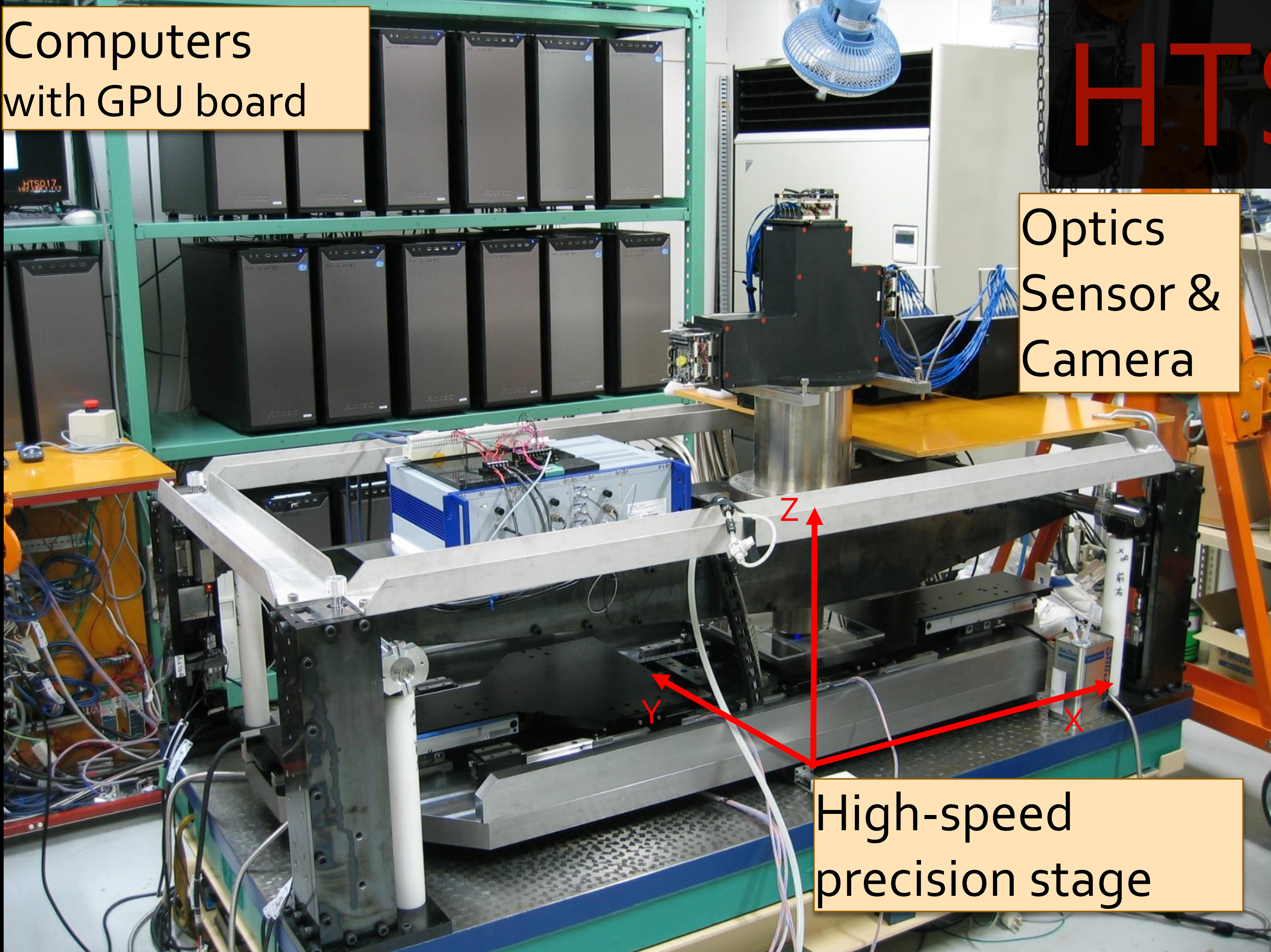


Evolution of the Scanning Speed

※1 Area of each layer
※2 Area of the films



HTS


Computers
with GPU board
Optics
Sensor &
Camera
Z
Y
X
High-speed
precision stage

Objective lens

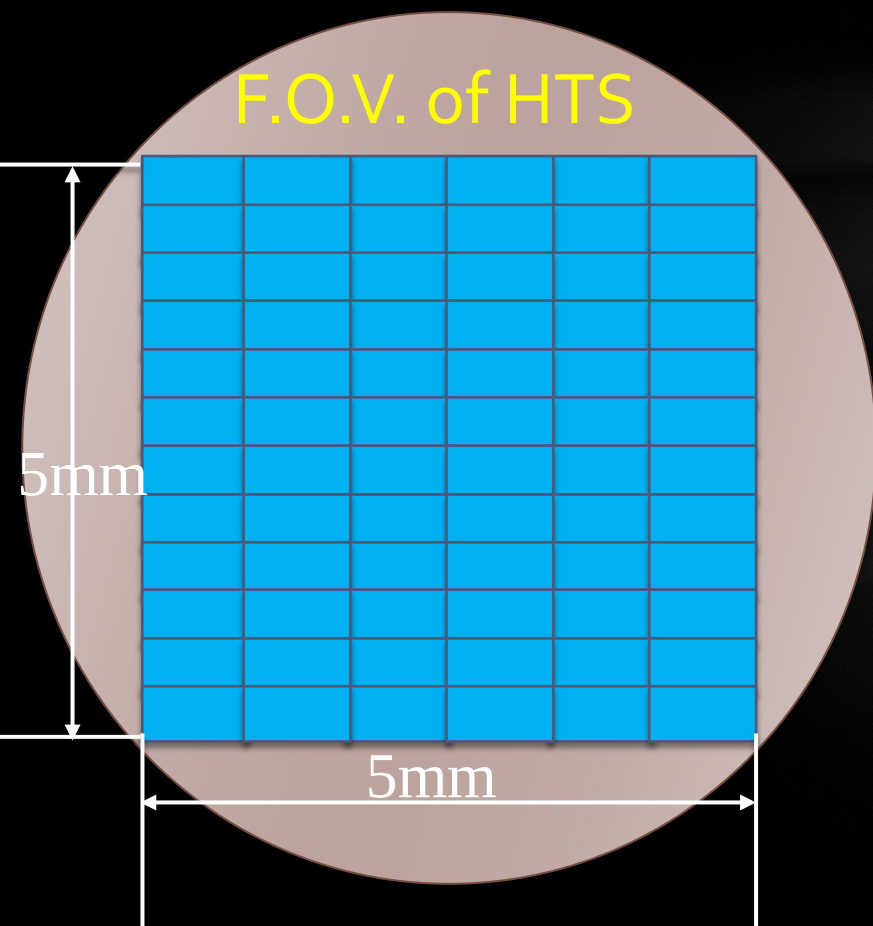
Resolution : ~420nm
N.A. : 0.65
Light source : G-line (436nm)
Magnification : ×12.2
F.O.V : 5.1 (H)×5.1 (V)mm

#of image plane 6
(by Beam splitter)

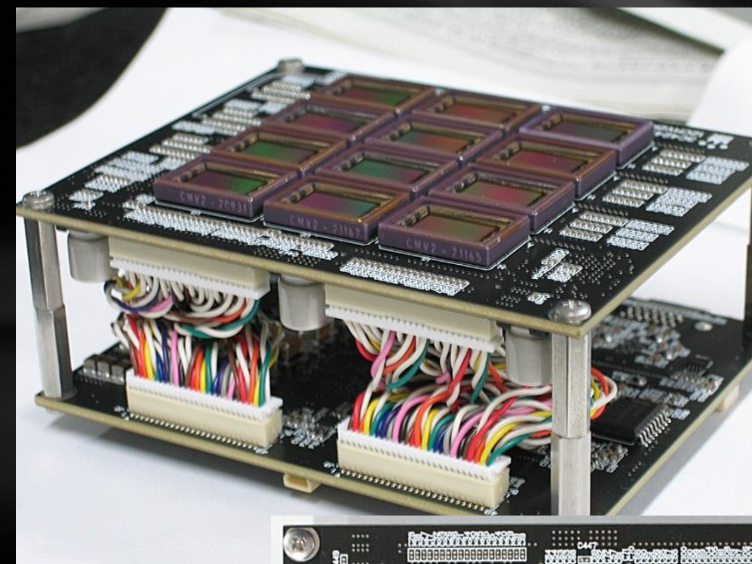
Weight : 90kg
Total length : 844mm

Speed and Coverage of Mosaic Imager

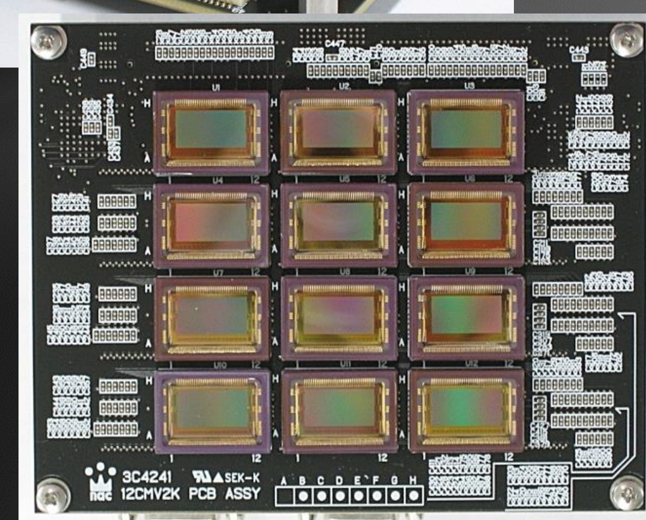
Divide FOV into 72 parts.
Need the sensor of 2M pixel and 340fps.



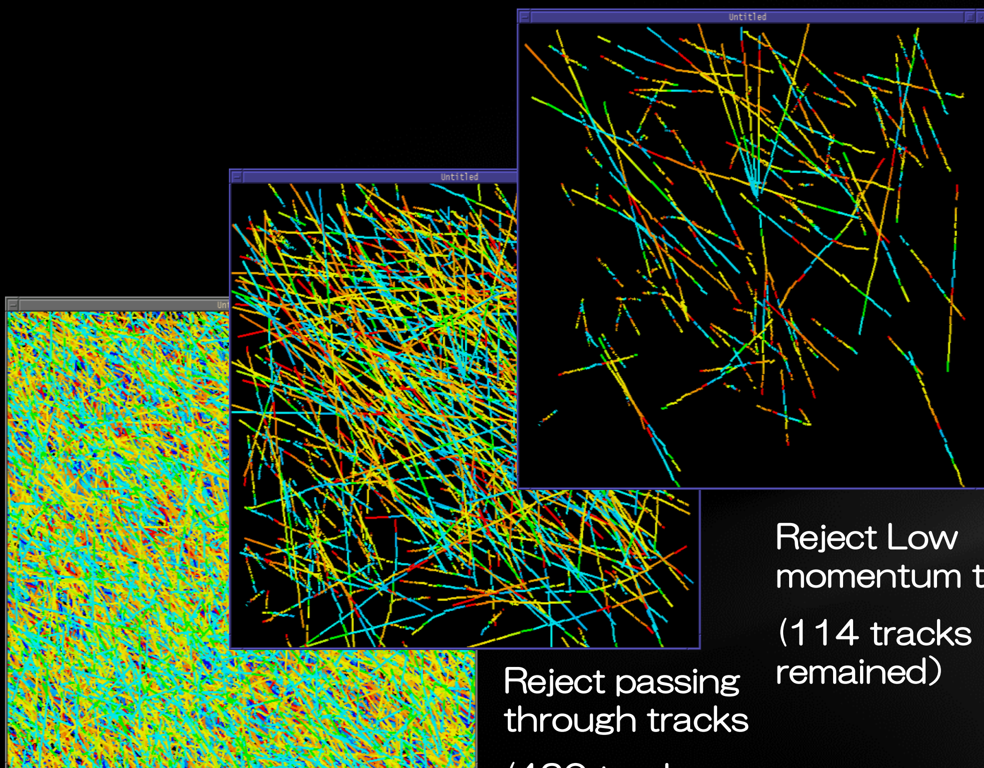
Specially ordered Mosaic Imager



×6



Data taking and offline reconstruction



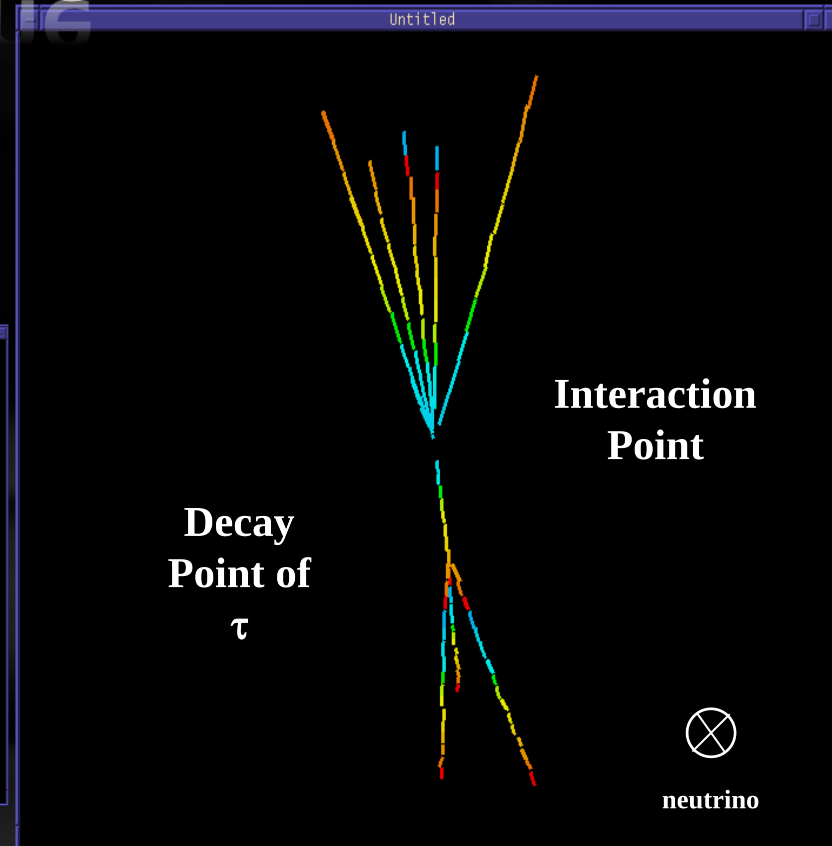
All tracks in the Scanning region（4179 tracks）

Reject passing through tracks

(420 tracks remained)

Reject Low momentum tracks

(114 tracks remained)



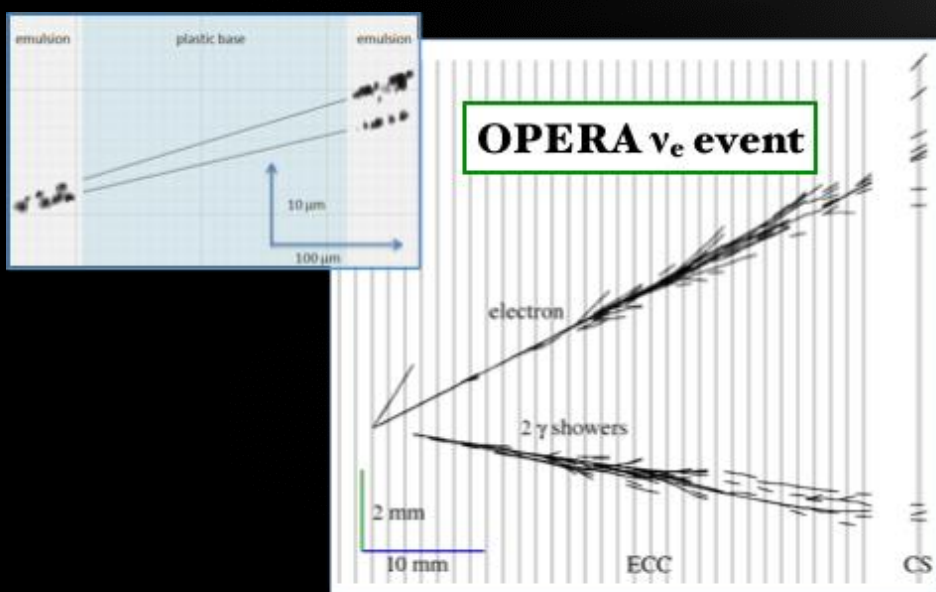
Vertex detection :

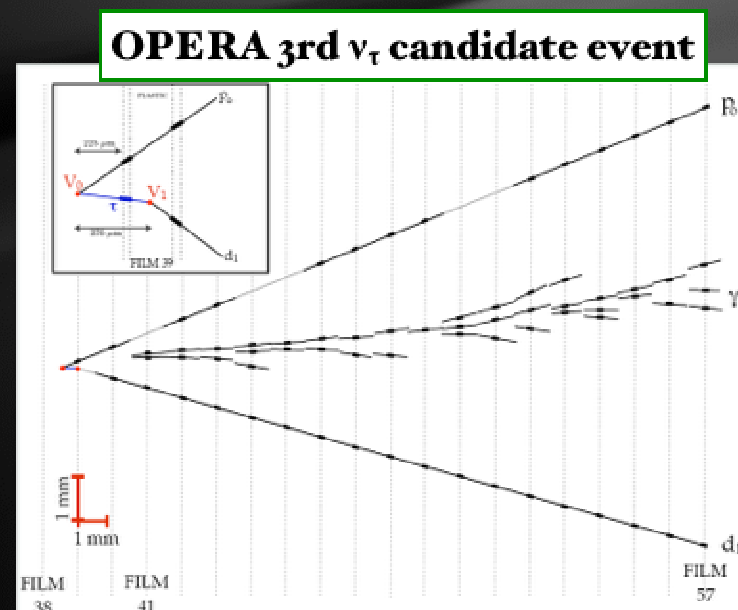
Neutrino interaction and decay of short lived particles

Detection of ν_τ^{CC} in DONUT

Neutrino Flavor Identification

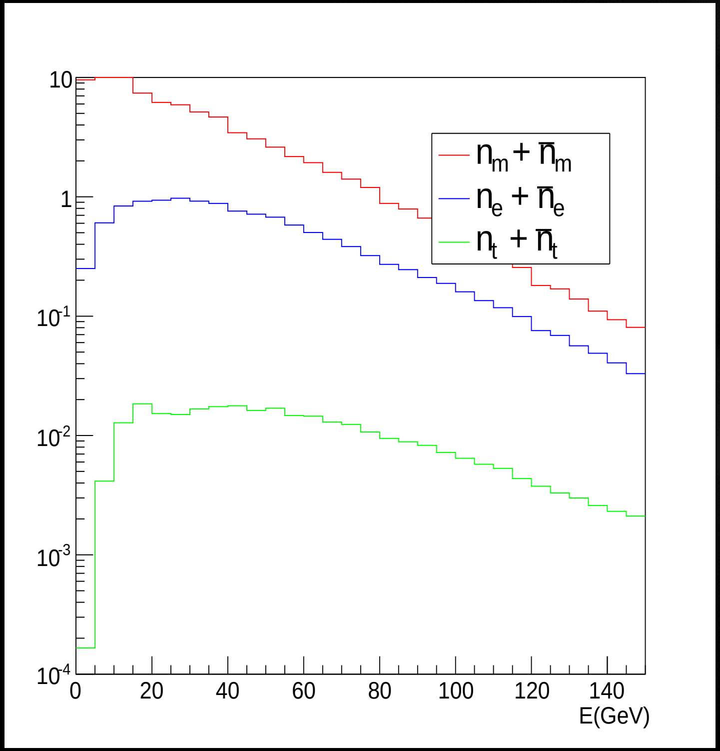
- ν_μ : muon reconstruction in the magnetic spectrometer
- ν_e : EM shower detection in ECC
- ν_τ : tau decay topological detection and kinematics
  - Also charge determination by CES





Neutrino interaction

- Rich tau neutrino content
  - 0.45% relative to muon neutrino
  - 3.0% relative to electron neutrino



	Φ	<E> (GeV)
ν_μ	1.7x10^6	29
ν_e	2.5x10^5	46
ν_τ	7.6x10^3	59
Anti-ν_μ	6.7x10^5	28
Anti-ν_e	9.0x10^4	46
Anti-ν_τ	3.9x10^3	58

Rates for five years of nominal operation with 2 x 10^{20} protons on target

Signal and background

SIGNAL EXPECTATION

BACKGROUND

R=S/B RATIO

decay channel	ν_τ			$\overline{\nu}_\tau$		
	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

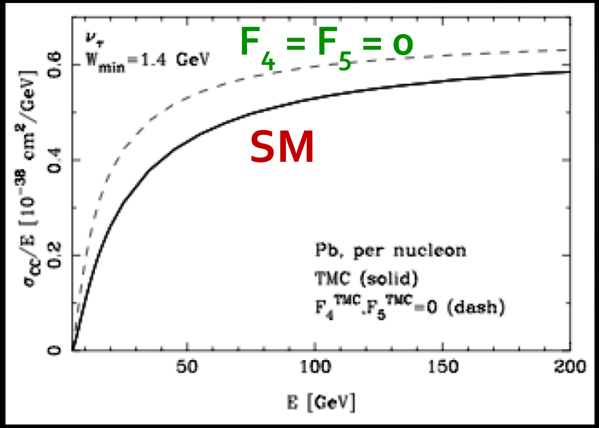
Main background source: charm production in ν_μ^{CC} (anti-ν_μ^{CC}) and ν_e^{CC} (anti-ν_e^{CC}) interactions, when the primary lepton is not identified

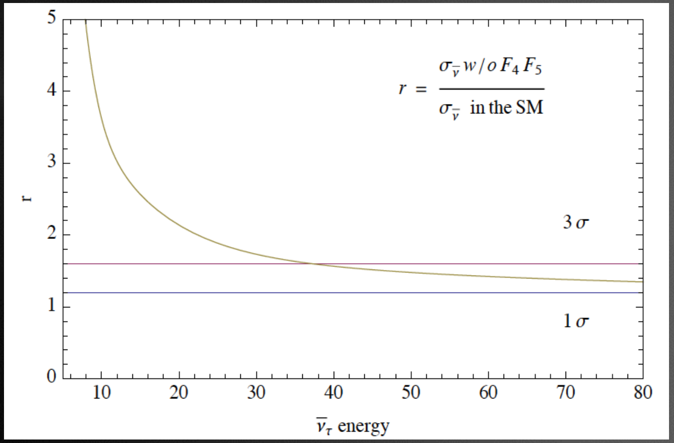
Physics with tau neutrino DIS

- Structure function only accessible by tau neutrino

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

- Dependent on the lepton mass



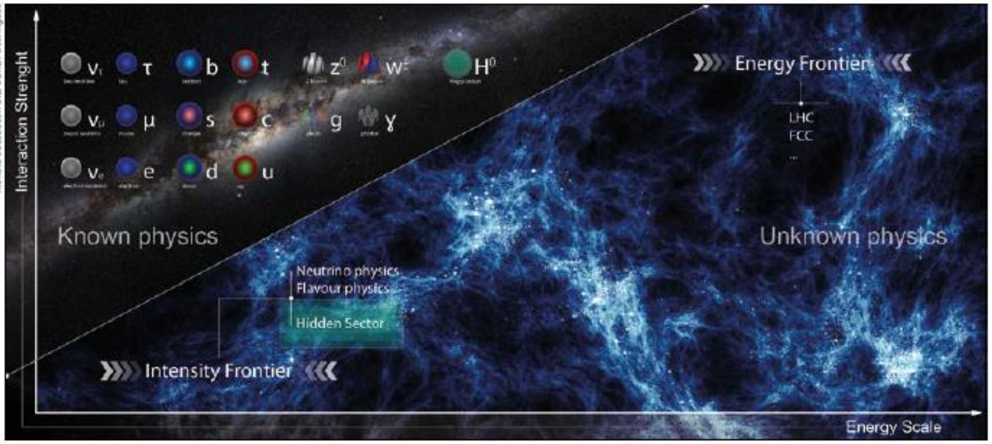


Summary and prospect

- Unique opportunity to study tau neutrino physics
  - We have only 9 (DONUT)+5 (OPERA) tau neutrino CC interactions. Study with 3500 tau neutrino interaction can be done in SHiP.
  - Unique chance to study tau and anti tau neutrino cross-section and anti neutrino charm production.
    - More than one order of magnitude.
- Technical Proposal is submitted (April 2015)
  - Physics run from 2026 .
  - Detector design is also under way, CDR in 2018.
- SPSC gave positive statement. Proceed to Comprehensive Design Report (CDR) in 2016-2018.
- "Physics Beyond Colliders" kickoff workshop just took place at CERN on 6-7 September.

SHiP is in CERN Courier : March 2016

New physics



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

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. Its challenging goals include the direct search for hidden non-Standard Model particles.

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 observed phenomena in particle physics, astrophysics and cosmology, the so-called beyond-the-Standard Model (BSM) problems, such as dark matter, neutrino masses and oscillations, baryon asymmetry, and the expansion of the universe.

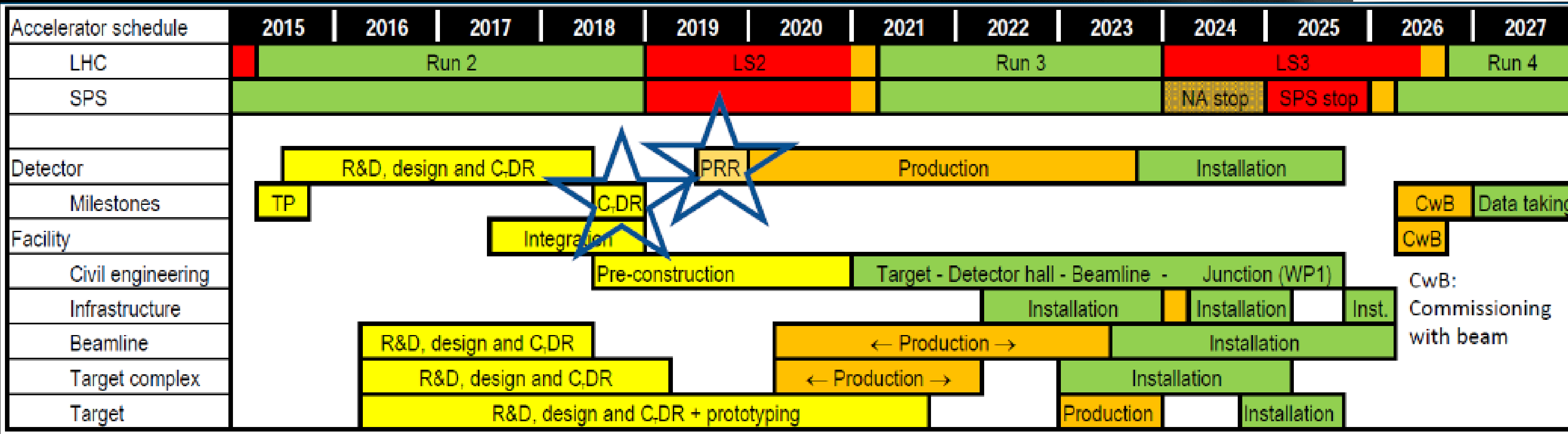
While these phenomena are well-established observationally, they give no indication about the energy scale of the new physics. The analysis of new LHC data collected at $\sqrt{}=13$ TeV will soon have directly probed the TeV scale for new particles with couplings at O(%) level. The experimental effort 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 ▷

Backup

Planning schedule of the SHiP



Form SHiP collaboration → 2014 Done

Technical Proposal → April 2015 Done

Comprehensive Design Report → 2016 – 2018

Production Readiness Review → End of 2019

Construction / production → 2021-

Data taking of $2x10^{20}$pot → 2026-

Estimated cost

Detector breakdown

Item		Cost (MCHF)
Tau neutrino detector		**11.6**
Active neutrino target	6.8	
Fibre tracker	2.5	
Muon magnetic spectrometer	2.3	
Hidden Sector detector		**46.8**
HS vacuum vessel	11.7	
Surround background tagger	2.1	
Upstream veto tagger	0.1	
Straw veto tagger	0.8	
Spectrometer straw tracker	6.4	
Spectrometer magnet	5.3	
Spectrometer timing detector	0.5	
Electromagnetic calorimeter	10.2	
Hadronic calorimeter	4.8	
Muon detector	2.5	
Muon iron filter	2.3	
Computing and online system		**0.2**
Total detectors		**58.7**

Overall cost of SHiP facility

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

Impact on ν_τ YIELD

$$N_{\nu_\tau+\bar{\nu}_\tau} = 4N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \to \tau) = 2.85 \times 10^{-5} N_p = 5.7 \times 10^{15}$$

$$\sigma_{c\bar{c}} = 18.1 \pm 1.7\ \mu\text{barn}$$

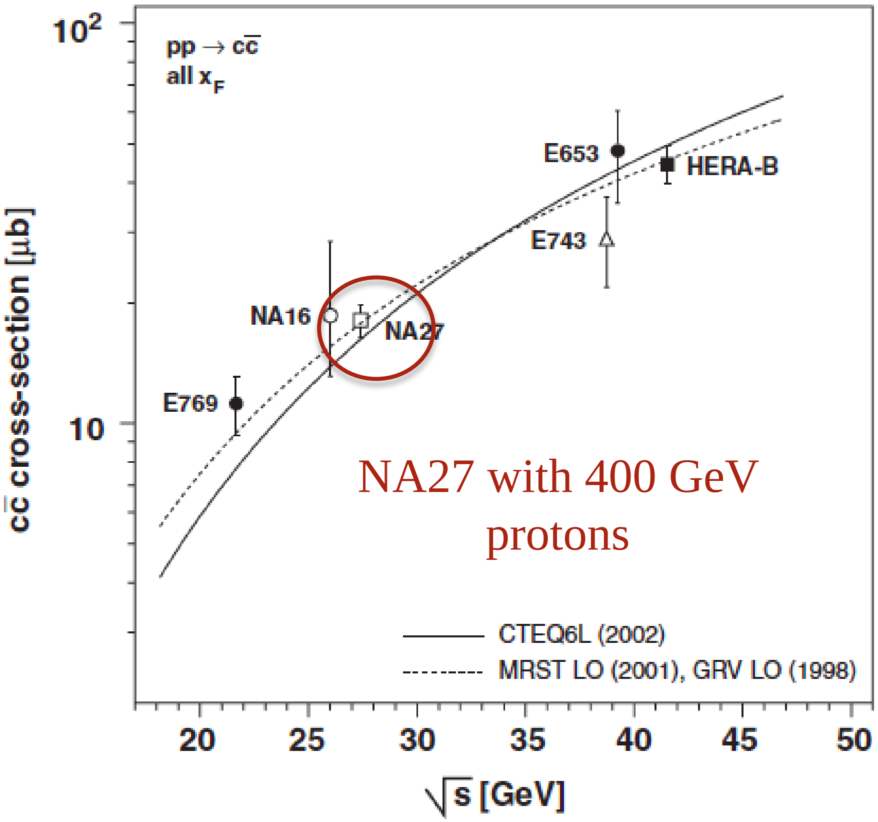
Physics Reports 433 (2006) 127

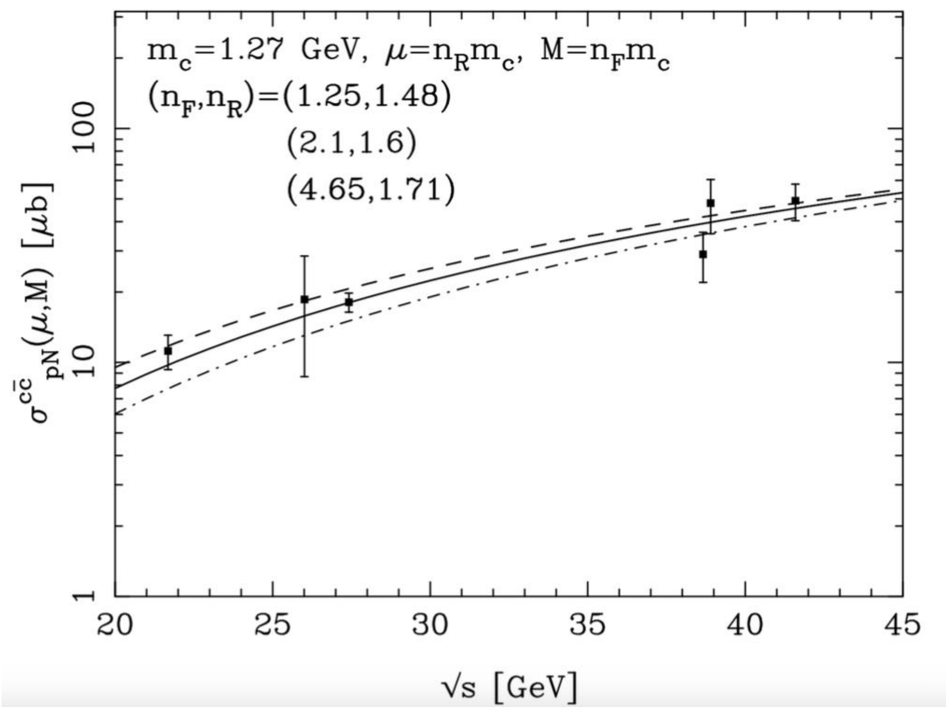
$$\sigma_{c\bar{c}} \propto A$$
$$\sigma_{pN} \propto A^{0.71}$$

$$Br(D_s \to \tau) = (5.54 \pm 0.24)\%$$ *PDG 2014*

$$f_{D_s} = (7.7 \pm 0.6^{+0.5}_{-0.4})\%$$ *JHEP 1309 (2013) 058*

Charm production vs energy





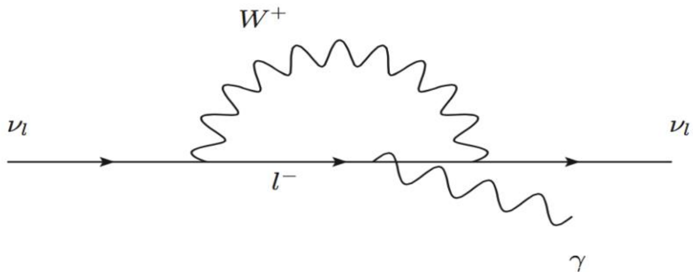
Cacciari, Greco, Nason JHEP 9805 (1998) 007
Cacciari, Frixione, Nason JHEP 0103 (2001) 006

arXiv: 1504.04855 SHiP Physics Proposal

TAU NEUTRINO MAGNETIC MOMENT

A massive neutrino may interact e.m.

→ magnetic moment proportional to its mass



$$\mu_\nu = \frac{3\,e\,G_F\,m_\nu}{8\,\pi^2\,\sqrt{2}} \simeq (3.2\times 10^{-19})\left(\frac{m_\nu}{1\,\mathrm{eV}}\right)\mu_B$$

Current limits
$$\begin{cases} (\nu_e) & \mu_\nu < 2.9\cdot 10^{-11}\mu_B \\ (\nu_\mu) & \mu_\nu < 6.9\cdot 10^{-10}\mu_B \end{cases}$$

$$\left.\frac{\sigma_{(\nu e,\bar\nu e)}}{dT}\right|_{\mu_\nu} = \frac{\pi\alpha_{em}^2\mu_\nu^2}{m_e^2}\left(\frac{1}{T}-\frac{1}{E_\nu}\right)$$

No interference as it involves a spin flip of the neutrino

$$\theta_{\nu-e}^2 < 2m_e/E_e$$

IN SHiP

SIGNAL SELECTION

$$\begin{cases} \theta_{\nu-e} < 30\,mrad \\ \mathrm{E}_e > 1\ \mathrm{GeV} \end{cases}$$

$$n_{evt} = \frac{\mu_\nu^2}{\mu_B^2}\int \Phi_{\nu_\tau}\sigma^\mu N_{nucl}\,dE = 4.3\times 10^{15}\,\frac{\mu_\nu^2}{\mu_B^2}$$

BACKGROUND PROCESSES

$$\begin{array}{rcll} \nu_x + e^- & \rightarrow & \nu_x + e^- & \mathrm{NC} \\ \nu_e(\bar\nu_e) + e^- & \rightarrow & e^- + \nu_e(\bar\nu_e) & \mathrm{CC} \\ \nu_e + n & \rightarrow & e^- + p & \mathrm{QE} \\ \bar\nu_e + p & \rightarrow & e^+ + n & \mathrm{QE} \\ \nu_e(\bar\nu_e) + N & \rightarrow & e^-(e^+) + X & \mathrm{DIS} \end{array}$$

NC + CC: 390

QE + QE: 2440

DIS: 730

Assuming 5% systematics from DIS measurements

SHiP can explore a region down to

$$\mu_\nu = 1.5\times 10^{-7}\mu_B$$

CHARM PHYSICS @SHiP

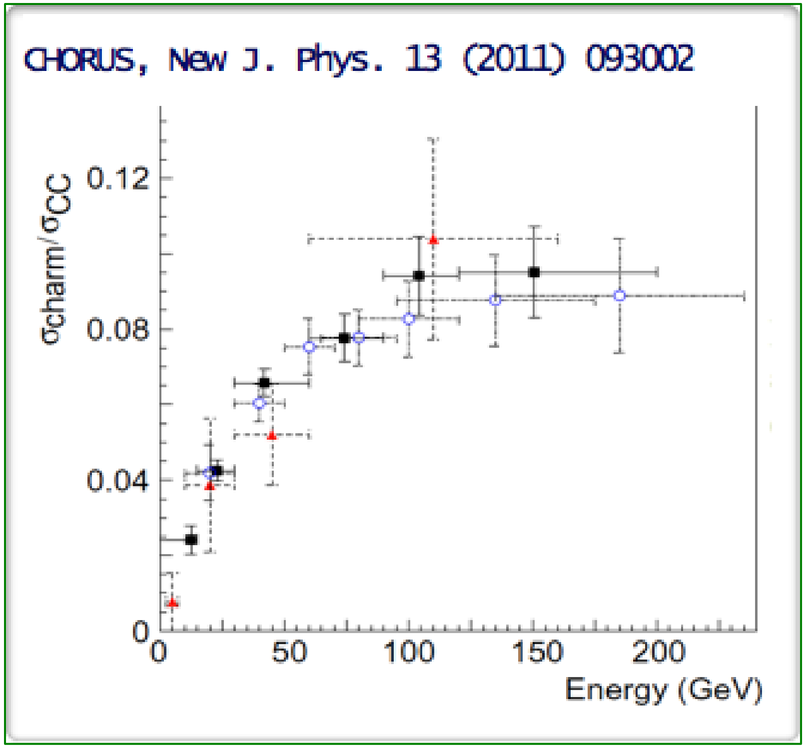
- Fraction of neutrino-induced charm events
- Convolution of CHORUS data with SHiP spectrum

ν_μ^{CC}

$$f(charm) = \frac{\int \Phi_{\nu_\mu} \sigma^{CC}_{\nu_\mu} \left(\frac{\sigma_{charm}}{\sigma^{CC}_{\nu_\mu}} \right) dE}{\int \Phi_{\nu_\mu} \sigma^{CC}_{\nu_\mu} dE} \approx 4\%$$

ν_e^{CC}

$$f(charm) = \frac{\int \Phi_{\nu_e} \sigma^{CC}_{\nu_e} \left(\frac{\sigma_{charm}}{\sigma^{CC}_{\nu_e}} \right) dE}{\int \Phi_{\nu_e} \sigma^{CC}_{\nu_e} dE} \approx 6\%$$



Expected charm 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	$1.1 \cdot 10^5$

In NuTeV ~5100 ν_μ
~ 1460 anti-ν_μ
In CHORUS ~2000 ν_μ
32 anti-ν_μ

No charm candidate from ν_e and ν_τ interactions ever reported!