SHiP: Search for Hidden Particles

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On behalf of the SHiP Collaboration

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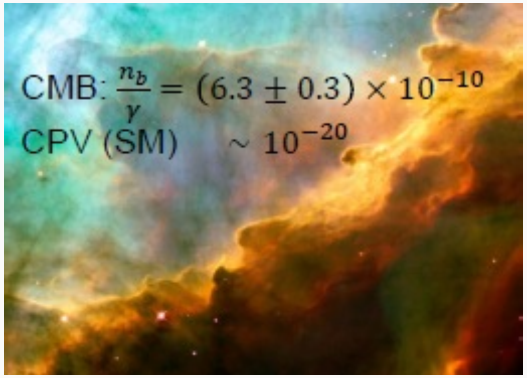
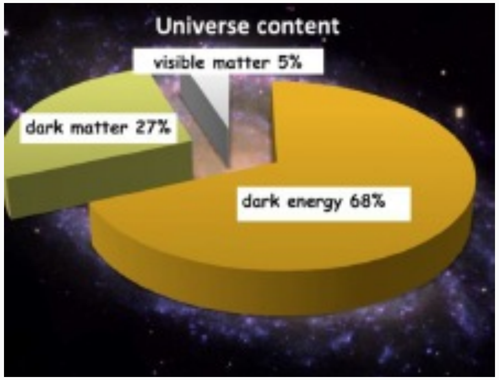
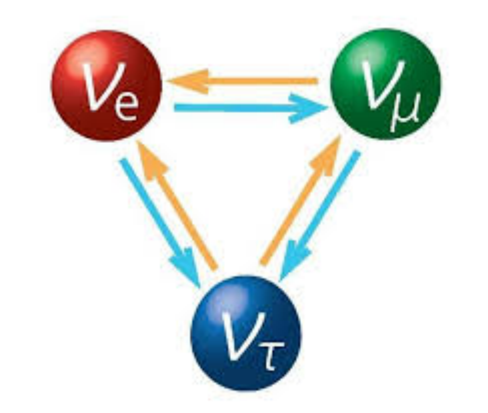
XIIth Rencontres du Vietnam, July 10-16, 2016, ICISE, Quy Nhon, Vietnam

Physics Motivation

- Standard Model provided consistent description of Nature's constituents and their interactions.
  - No significant deviation from SM.
- But the Standard Model can not explain
  - Neutrino masses and oscillations
  - Dark matter
  - Baryon asymmetry
  - Cosmological inflation

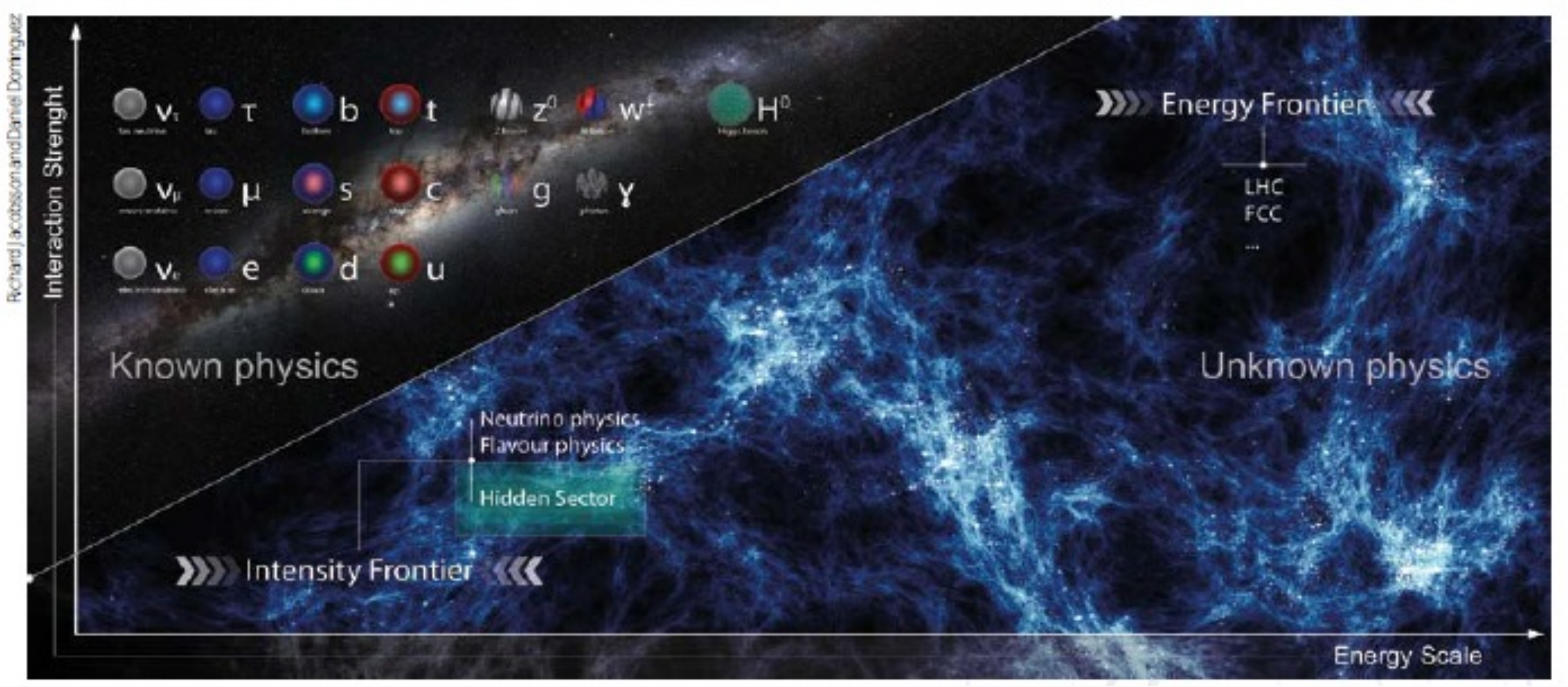






Physics Motivation

- There are compelling experimental and theoretical reasons to extend the theory.
- The SHiP facility will provide a unique experimental platform for physics at the Intensity Frontier.



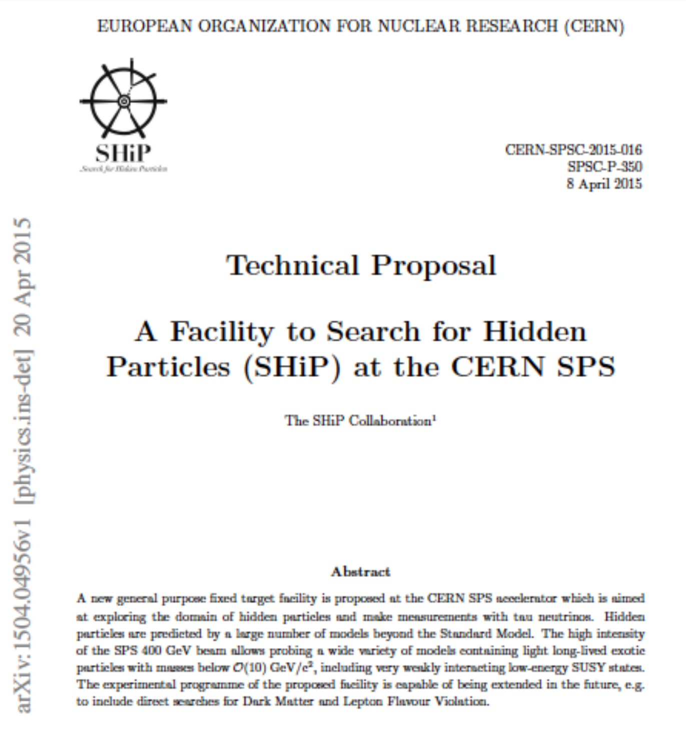
SHiP: masses below O(10) GeV

SHiP: Search for Hidden Particles

- SHiP is a new proposed fixed-target experiment at the CERN SPS accelerator to search for hidden, very weakly interacting new particles.
- At the same time, also ideal for ν_τ physics.

Collaboration

- 46 institutes from 16 Countries, plus CERN


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP

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

arXiv:1504.04956v1 [physics.ins-det] 20 Apr 2015

Technical Proposal

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

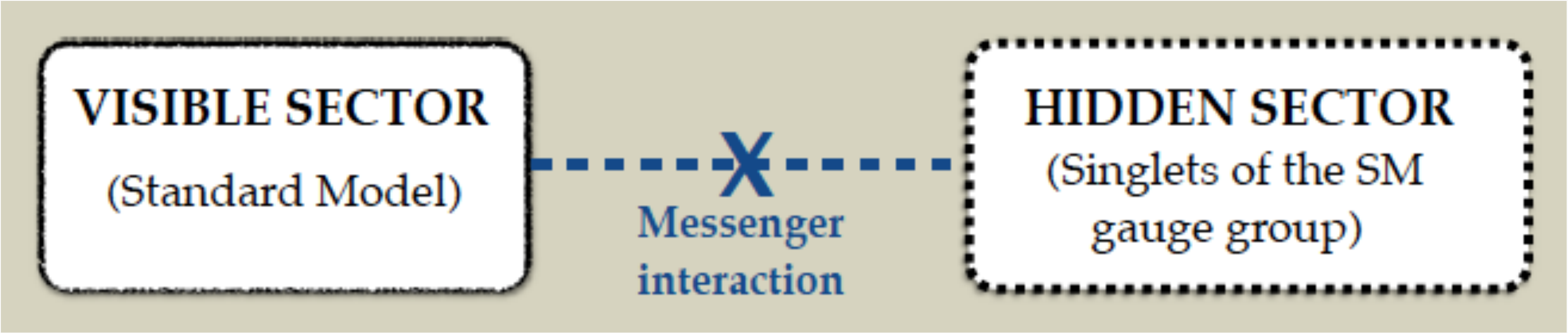
The SHiP Collaboration[1]

Abstract

A new general purpose fixed target facility is proposed at the CERN SPS accelerator which is aimed at exploring the domain of hidden particles and make measurements with tau neutrinos. Hidden particles are predicted by a large number of models beyond the Standard Model. The high intensity of the SPS 400 GeV beam allows probing a wide variety of models containing light long-lived exotic particles with masses below $\mathcal{O}(10)$ GeV/c^2, including very weakly interacting low-energy SUSY states. The experimental programme of the proposed facility is capable of being extended in the future, e.g. to include direct searches for Dark Matter and Lepton Flavour Violation.

Physics Goals

- Rather than being heavy, could new particles be light but very weakly interacting?
- Portals : possible interactions between new physics (hidden sector) and the SM particles.



i) Neutrino portal ii)Scalar portal iii) Vector portal iv)Axion portal

- Large number of models investigated.
- Tau Neutrino Physics.

Physics Goals

- Production through hadron decays (π, K, D, B, proton bremsstrahlung, …)

Models tested	Final states
Neutrino portal, SUSY neutralino	$l\pi$, lK, $l\rho$ ($l=e,\mu,\nu$) ($\rho^+ \rightarrow \pi^+\pi^0$)
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	$l^+ l^- \nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\ \pi^0$

- Production and decay rates are strongly suppressed relative to SM.
  - Production branching ratios $O(10^{-10})$.
  - Long-lived objects.
  - Travel unperturbed through ordinary matter.

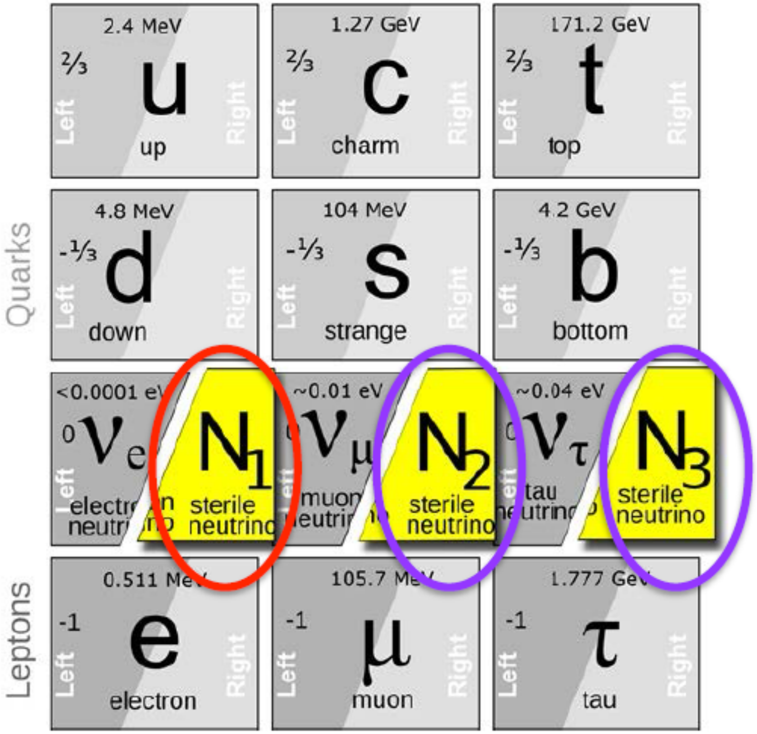
Physics Program

A facility to search for hidden particles (SHiP) at the SPS: the physics case

85 theorists
arXiv: 1504.0855

Contents

Neutrino Portal



The neutrino Minimal Standard Model (υMSM) aims to explain.

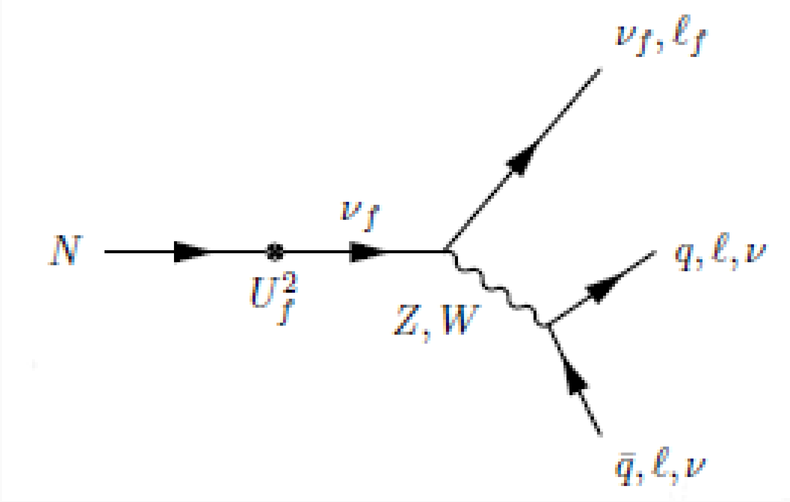
T. Asaka, M. Shaposhnikov PLB620 (2005), 17.

➢Matter anti-matter asymmetry in the Universe, neutrino masses and oscillations, non-baryonic dark matter.

➢Adds three right-handed, Majorana, Heavy Neutral Leptons (HNL), N1, N2 and N3.

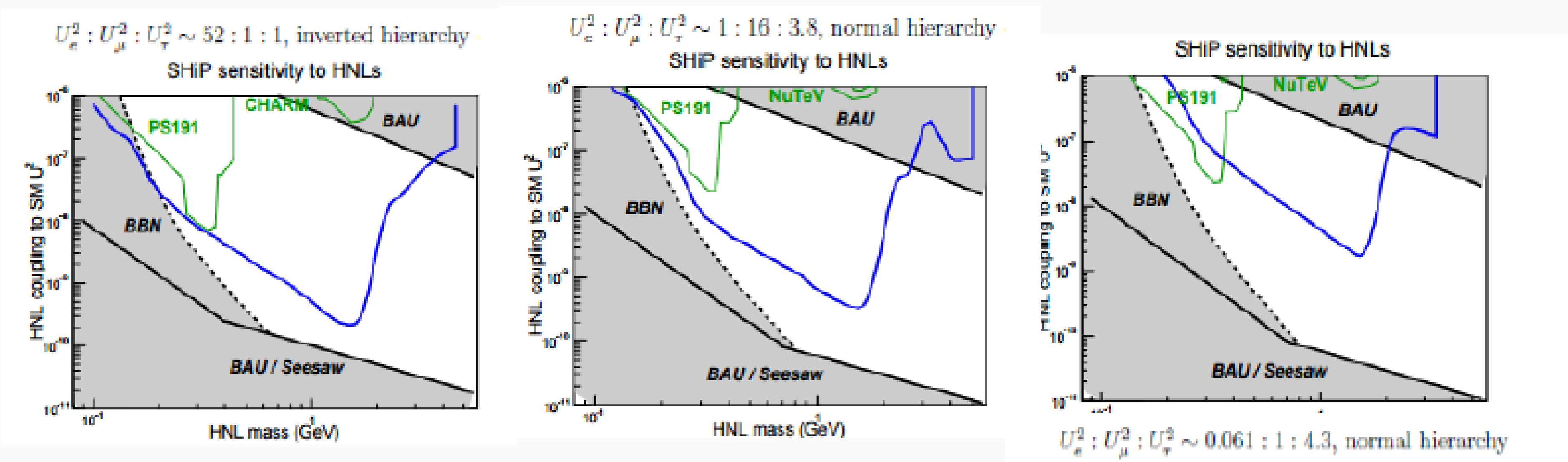
- N1 is a dark matter candidate (m≈ O(1) keV).
- N2, N3 give masses to neutrinos and produce baryon asymmetry of the Universe

  m≈ O(100 MeV-GeV)

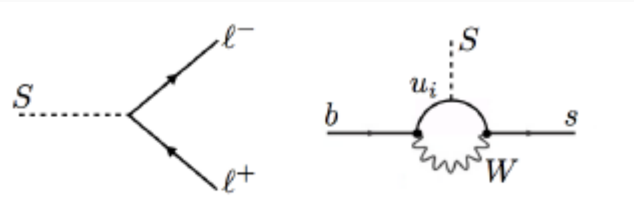


HNL Sensitivity

- Production in charm and beauty meson decays
- Decay into *hl* and *llν*
- νMSM parameter space almost totaly explored for $m_N \leq 2$ GeV



The Scalar and Vector Portals



- ➢S production: from B, D and K decays
- ➢S decays : $S \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-$

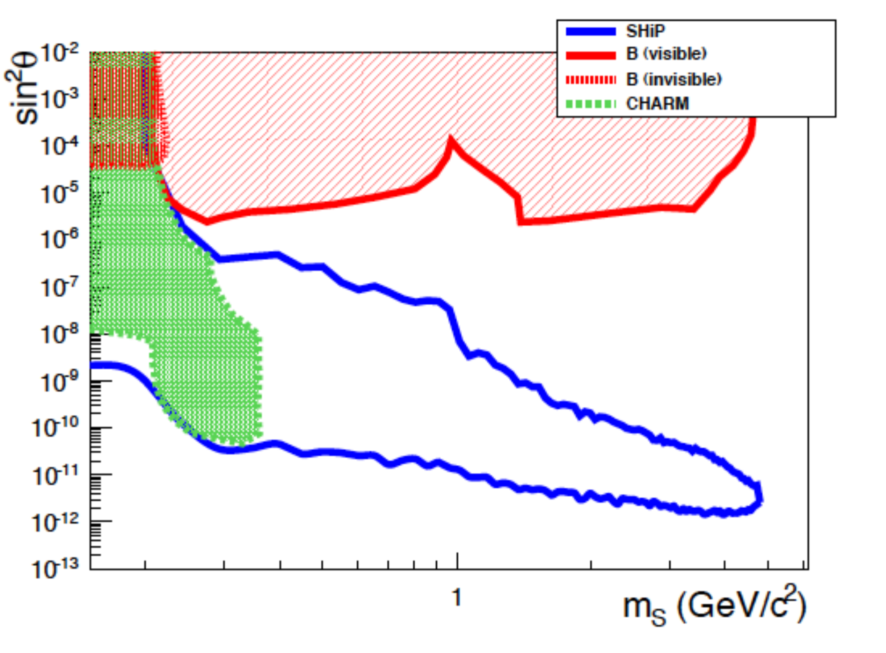
Vector portal : dark photon (A') model

Production:

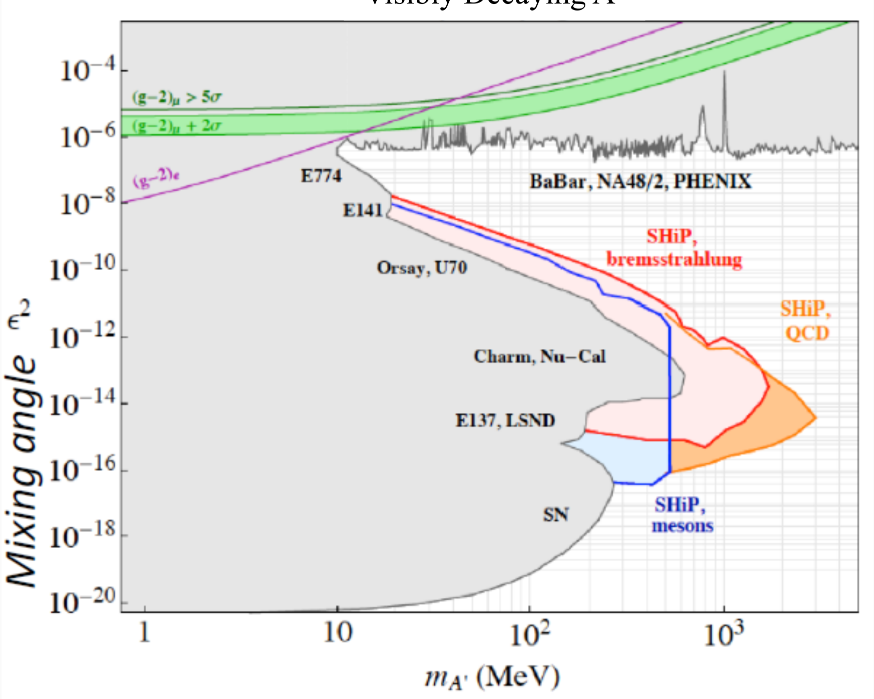
1)Meson decays

2)Bremsstrahlung (pp→ppV)

3)QCD (q+q →V ; q+g →q+V)



Visibly Decaying A'



Experimental Requirements

- **Long-lived neutral particles are predicted in many Beyond Standard Models (BSM)**

- High intensity beam dump experiment ⇒K, D, B mesons.
- The detector is close as possible to target.
- Decay vessel: "vacuum" to avoid ν-interaction.
- Magnetic spectrometer to reconstruct HNL mass.

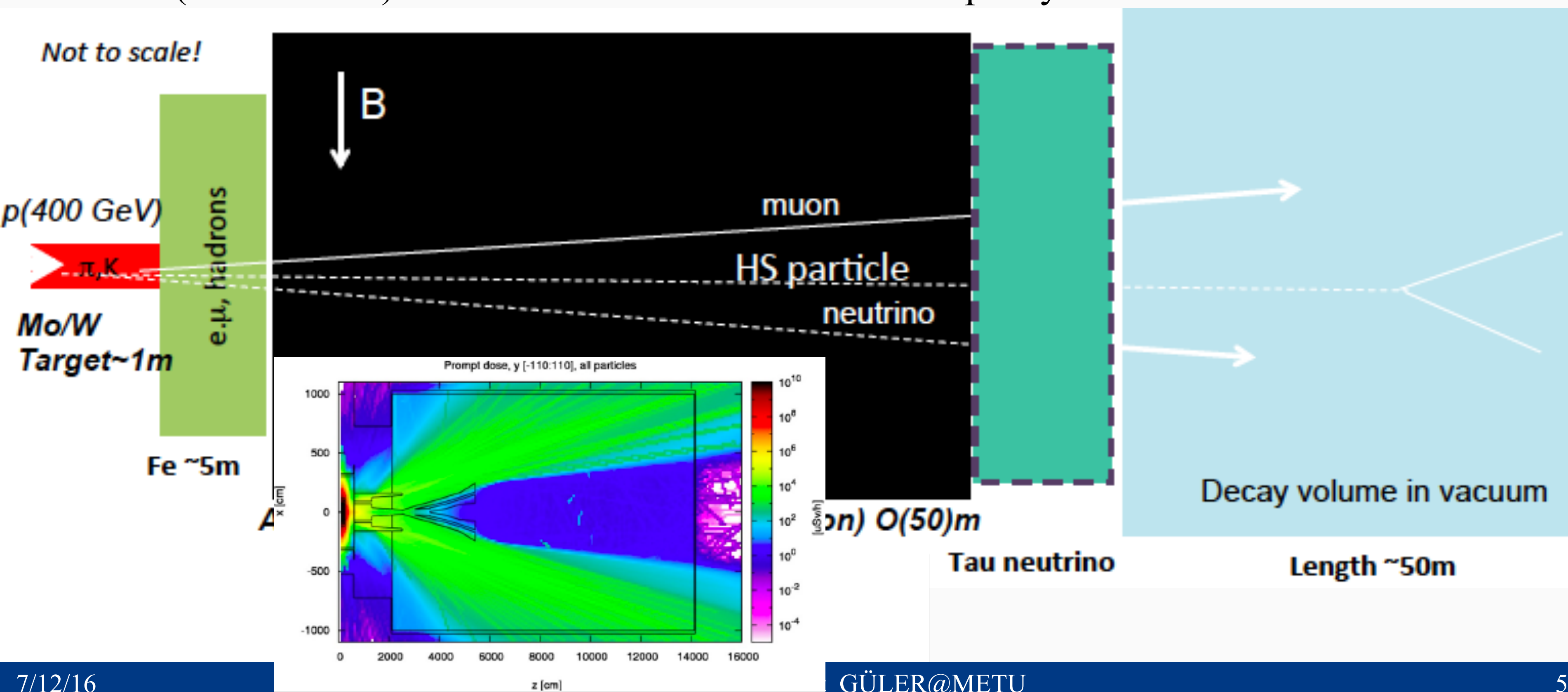
Signal signature:

- Charged tracks forming an isolated vertex inside the fiducial volume.
- Candidate momentum pointing back to the target.

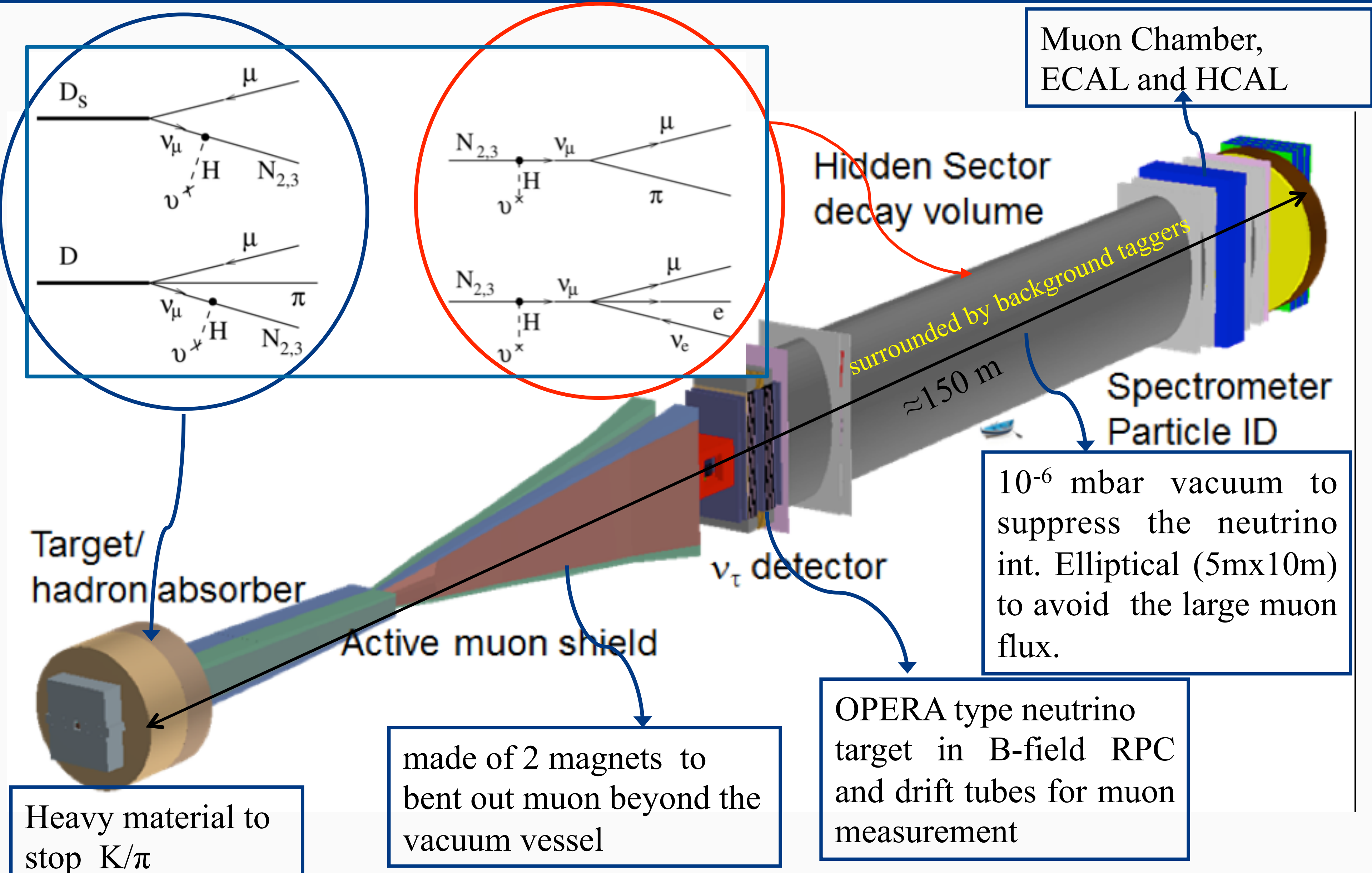
SHiP beam-line

- ➢ Essential part in order to reduce beam induced background

- Heavy target to maximize Heavy Flavour production (large A) and minimize neutrinos from $\pi/K \rightarrow \mu\nu$ decays (short λ_{int})
- Hadron absorber
- Effective muon shield (without shield: muon rate ~10^{10} per spill)
- Slow (and uniform) beam extraction ~1s to reduce occupancy in the detector.



The SHiP Detector



Muon Chamber, ECAL and HCAL

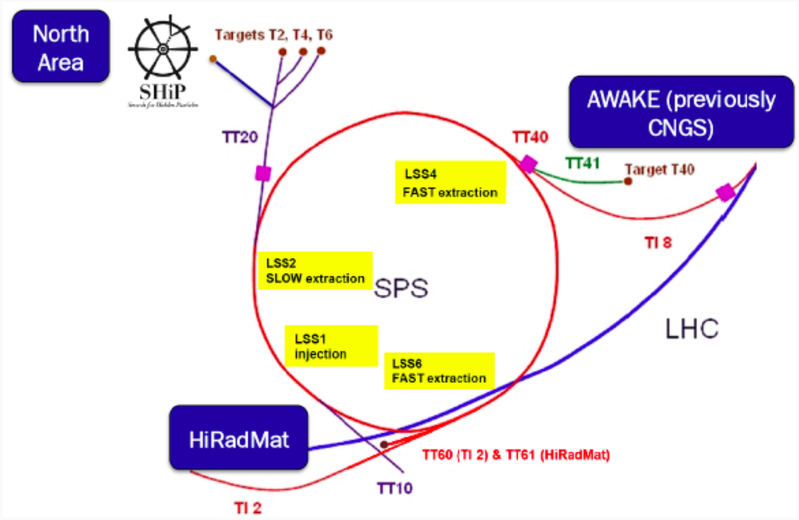
10^{-6} mbar vacuum to suppress the neutrino int. Elliptical (5mx10m) to avoid the large muon flux.

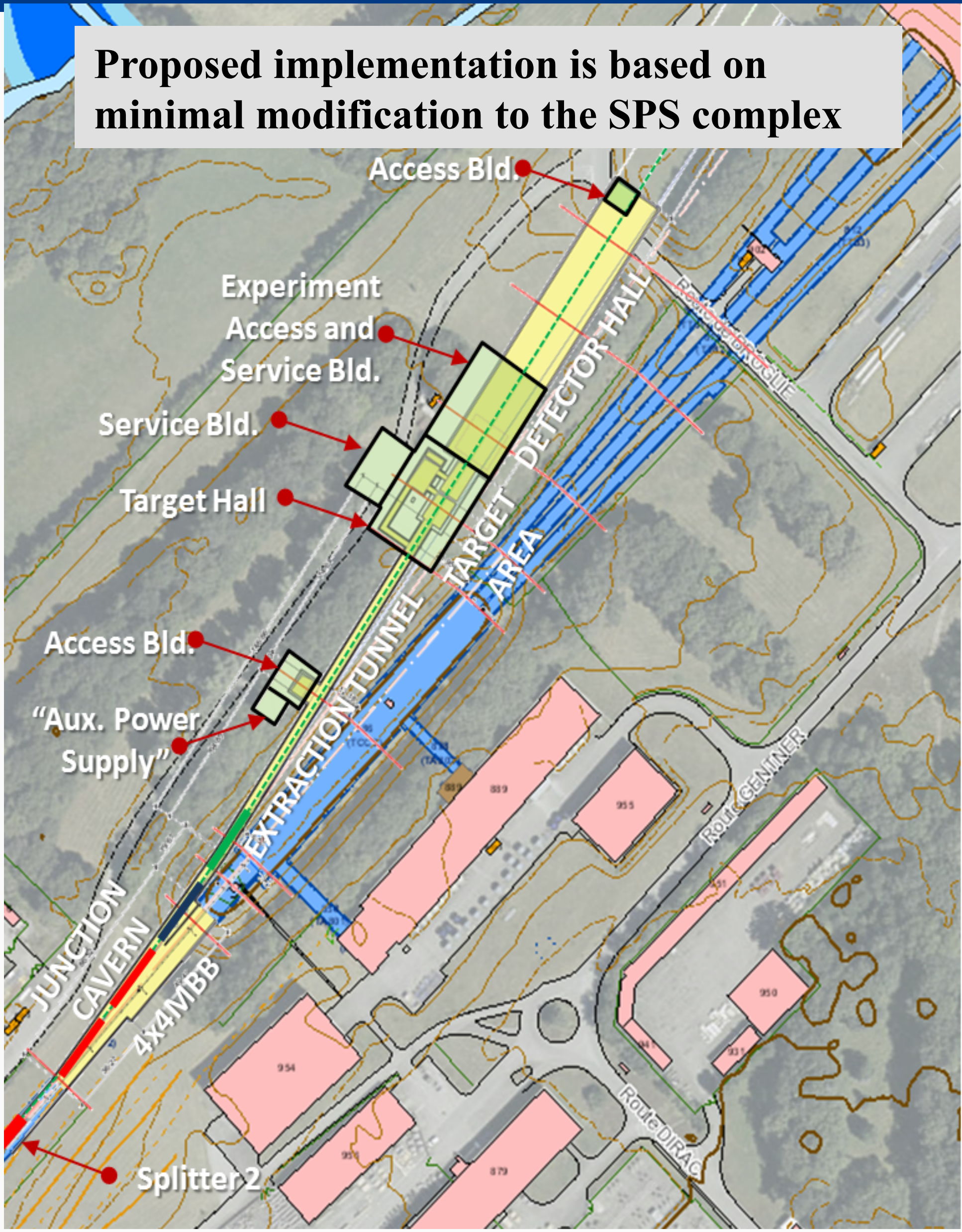
OPERA type neutrino target in B-field RPC and drift tubes for muon measurement

made of 2 magnets to bent out muon beyond the vacuum vessel

Heavy material to stop K/π

SHiP: a fixed-target facility at the SPS

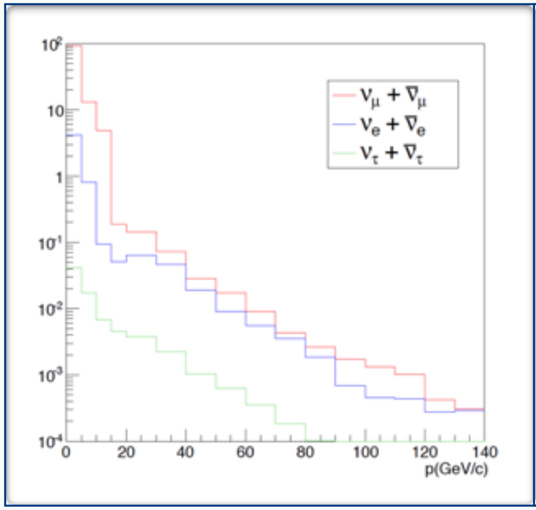


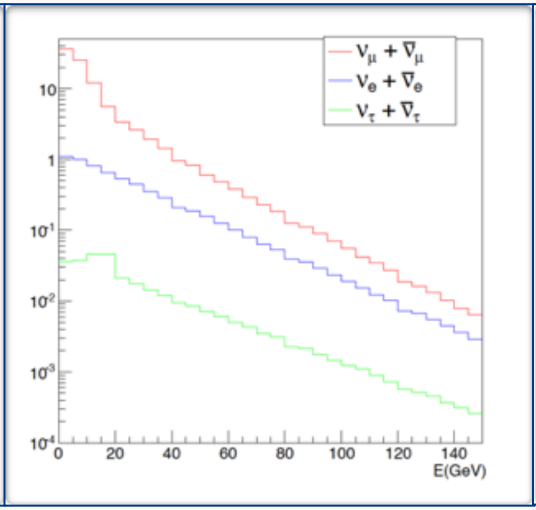


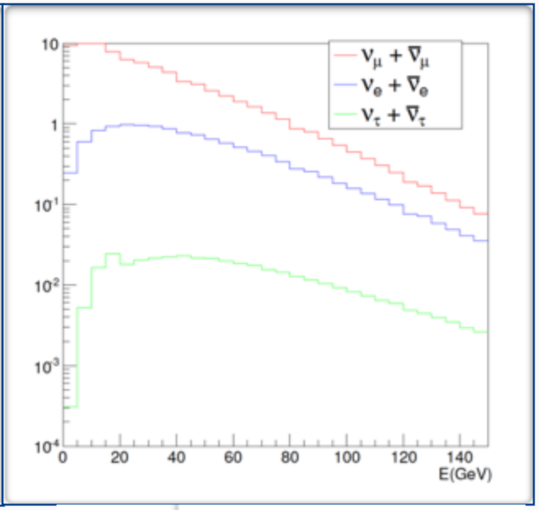
- The SHiP facility is located on the North Area, and shares the TT20 transfer line and slow extraction mode.
  - 400 GeV protons from SPS
  - $4x10^{19}$ pot/year (~200 days of running)
  - Spill = $4x10^{13}$ pot per cycle of 7.2 s with slow beam extraction (1s)

SHiP Neutrino Program

- SHiP setup ideally suited to study neutrino and anti-neutrino physics for all three active flavours.
- High charmed hadrons production rates ⇒ high neutrino fluxes from their decays, including remnant pion and kaon decays.







	<E> (GeV)	Beam dump
N_{ν_μ}	1.4	4.4×10^{18}
N_{ν_e}	3	2.1×10^{17}
N_{ν_τ}	9	2.8×10^{15}
$N_{\bar{\nu}_\mu}$	1.5	2.8×10^{18}
$N_{\bar{\nu}_e}$	4	1.6×10^{17}
$N_{\bar{\nu}_\tau}$	8	2.8×10^{15}

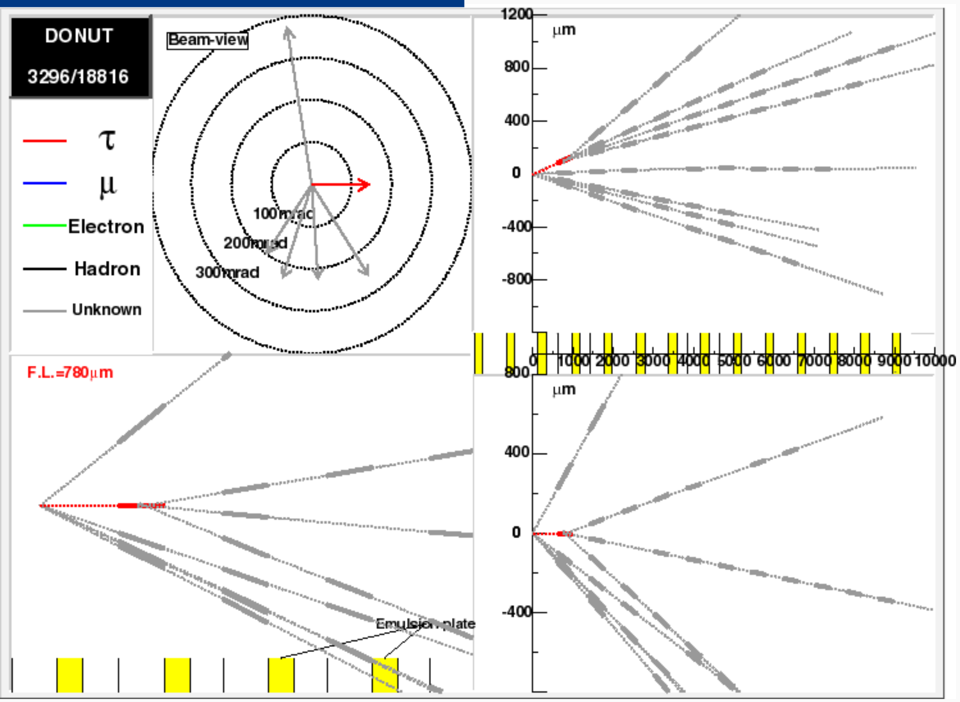
	<E> (GeV)	Neutrino target
N_{ν_μ}	8	5.2×10^{16}
N_{ν_e}	28	3.6×10^{15}
N_{ν_τ}	28	1.4×10^{14}
$N_{\bar{\nu}_\mu}$	8	4.0×10^{16}
$N_{\bar{\nu}_e}$	27	2.7×10^{15}
$N_{\bar{\nu}_\tau}$	26	1.4×10^{14}

	<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}
$N_{\bar{\nu}_\mu}$	28	6.7×10^{5}
$N_{\bar{\nu}_e}$	46	9.0×10^{4}
$N_{\bar{\nu}_\tau}$	58	3.4×10^{3}

Tau Neutrino Physics

- Less known particle in the Standard Model
  - First observation by DONUT at Fermilab in 2001 *Phys. Lett. B504 (2001) 218-224.*

DONUT ν_τ Candidate



- 9 events (with an estimated background of 1.5) reported in 2008 with looser cuts.

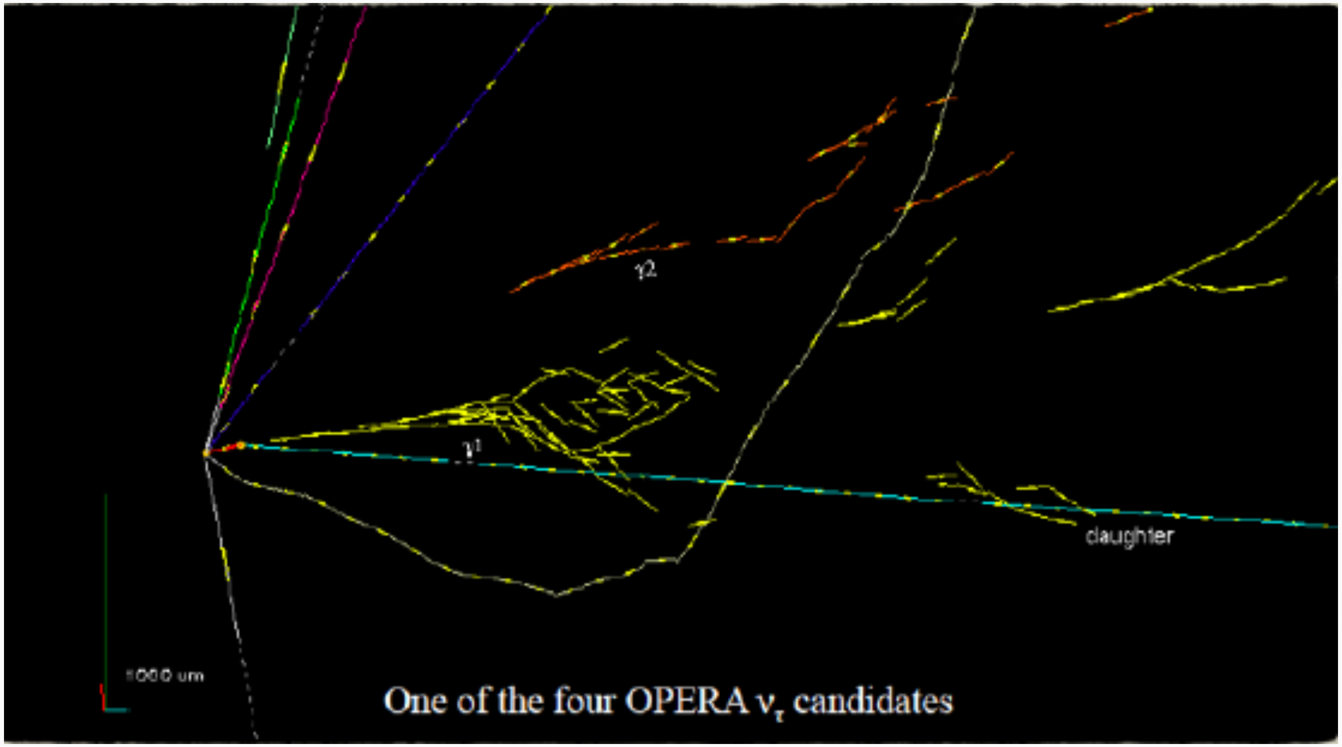
$$\sigma(\nu_\tau) = \sigma^{const}\, EK(E)$$

$$\sigma^{const}\,(\nu_\tau) = (0.39\pm0.13\pm0.13)\times10^{-38}\ \text{cm}^2\ \text{GeV}^{-1}$$

(K(E) describes the kinematical suppression due to the tau mass)

Tau Neutrino Physics

- 5 ν_τ candidates reported by OPERA for the discovery (5.1σ result) of ν_τ appearance in the CNGS neutrino beam PRL 115 (2015) 12.



One of the four OPERA ν_τ candidates

- Tau anti-neutrino never observed.

Signal/Background Yield

- Number of υ_τ and anti-υ_τ produced in the beam dump.

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

- Main background in υ_τ and anti-υ_τ searches is the charm production in υ_μCC (anti-υ_μCC) and υ_eCC (anti-υ_eCC) interactions, when the primary lepton is not identified.

SIGNAL EXPECTATION

BACKGROUND

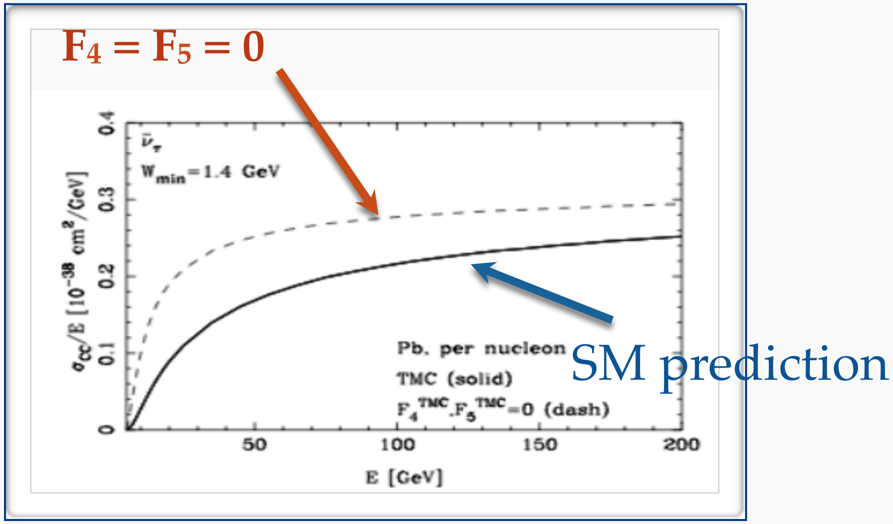
R=S/B RATIO

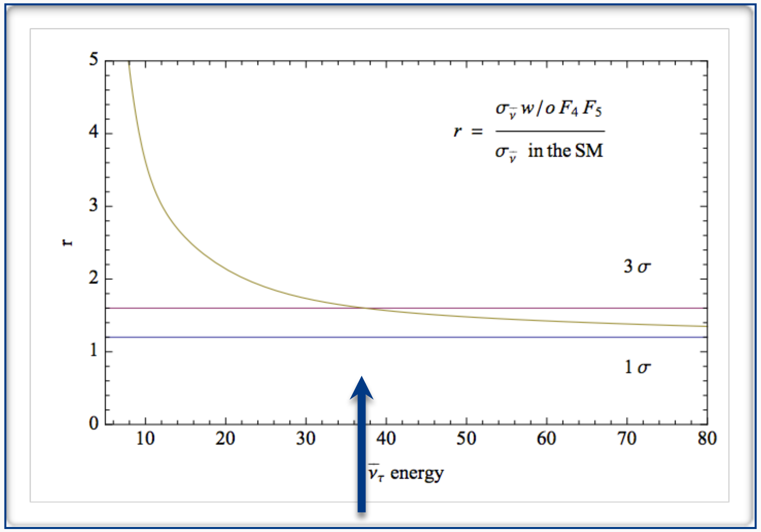
decay channel	ν_τ			$\overline{\nu}_\tau$		
	N^{exp}	N^{bg}	R	N^{exp}	N^{bg}	R
$\tau \to \mu$	570	30	19	290	140	2
$\tau \to h$	990	80	12	500	380	1.3
$\tau \to 3h$	210	30	7	110	140	0.8
total	1770	140	13	900	660	1.4

F_4 and F_5 Structure Functions

- Through ν_τ and anti-ν_τ identification: unique capability of being sensitive to F4 and F5

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





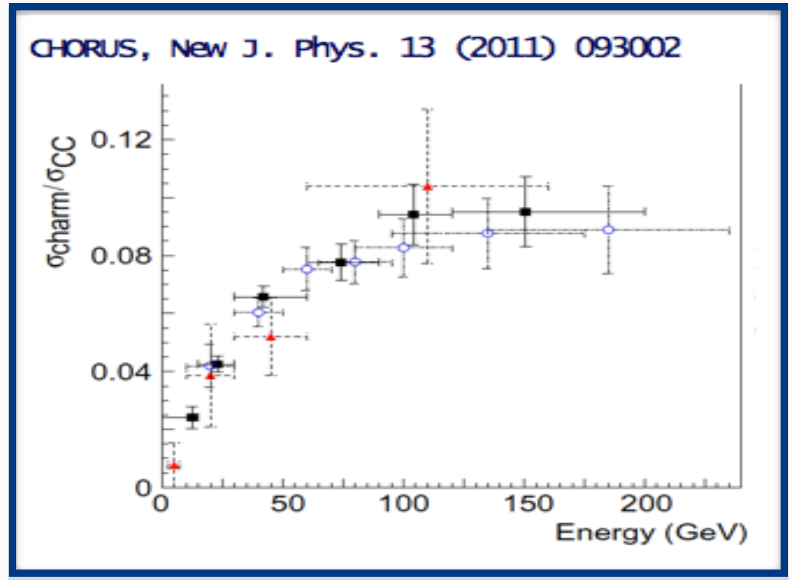
- At LO F_4= 0, $2xF_5$=F_2
- At NLO F_4 ~ 1% at 10 GeV

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

r>1.6 evidence for non-zero values of F_4 and F_5

Charm Physics

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



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

	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	$1.1 \cdot 10^5$

ν_μCC

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

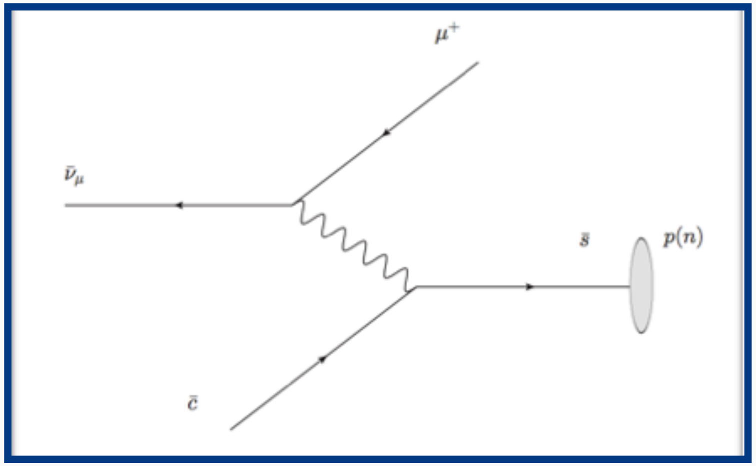
ν_eCC

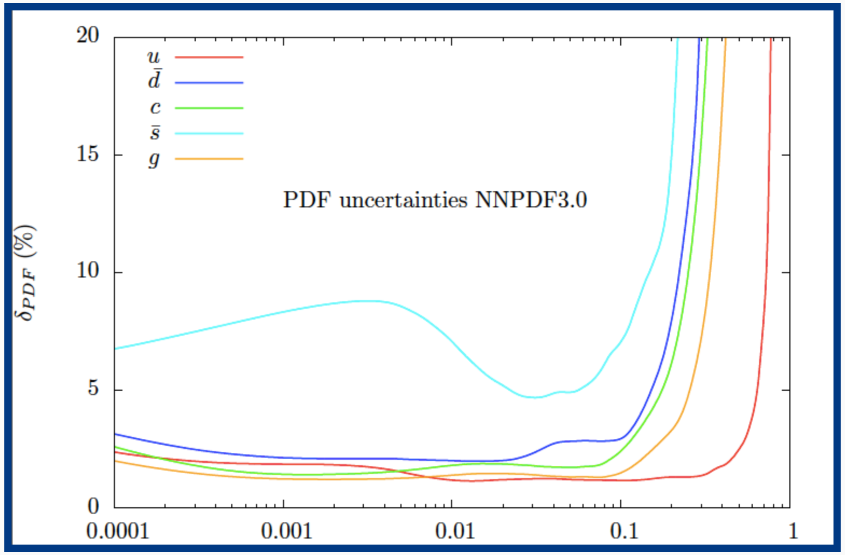
$$f(charm) = \frac{\int \Phi_{\nu_e} \sigma^{CC}_{\nu_e} \left(\frac{\sigma_{charm}}{\sigma^{CC}_{\nu_e}}\right) dE}{\int \Phi_{\nu_e} \sigma^{CC}_{\nu_e} dE} \approx 6\%$$

No charm candidate from ν_e and ν_τ interactions ever reported!

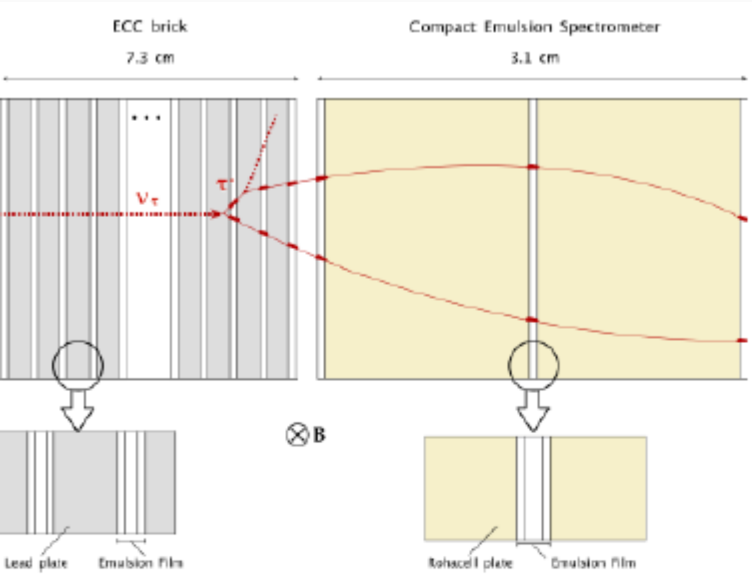
Strange Quark Content

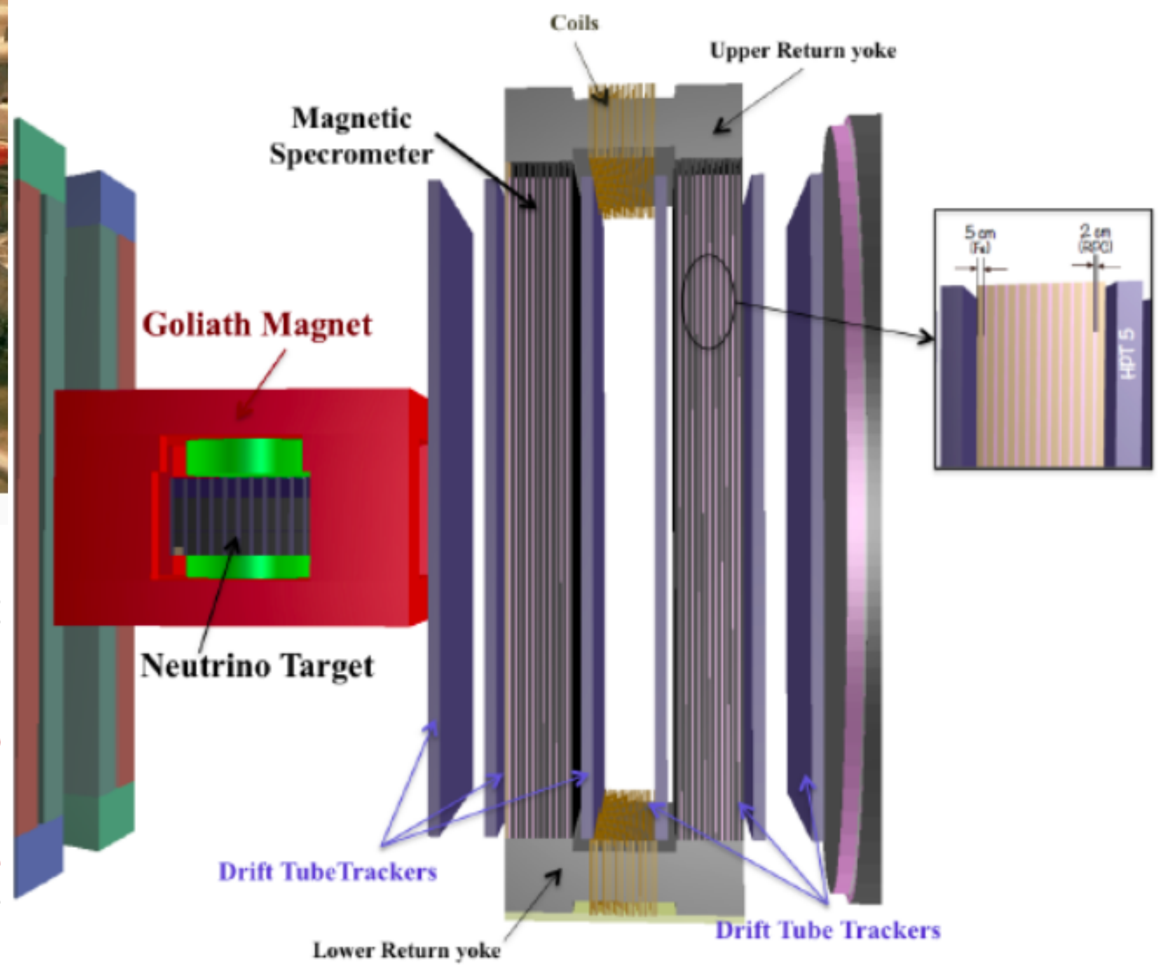
- ➢Charmed hadron production in anti-neutrino interactions selects anti-strange quark in the nucleon.
- ➢Strangeness important for precision SM tests and for BSM searches.
- ➢W boson production at 14 TeV: 80% via *ud* and 20% via *cs*.



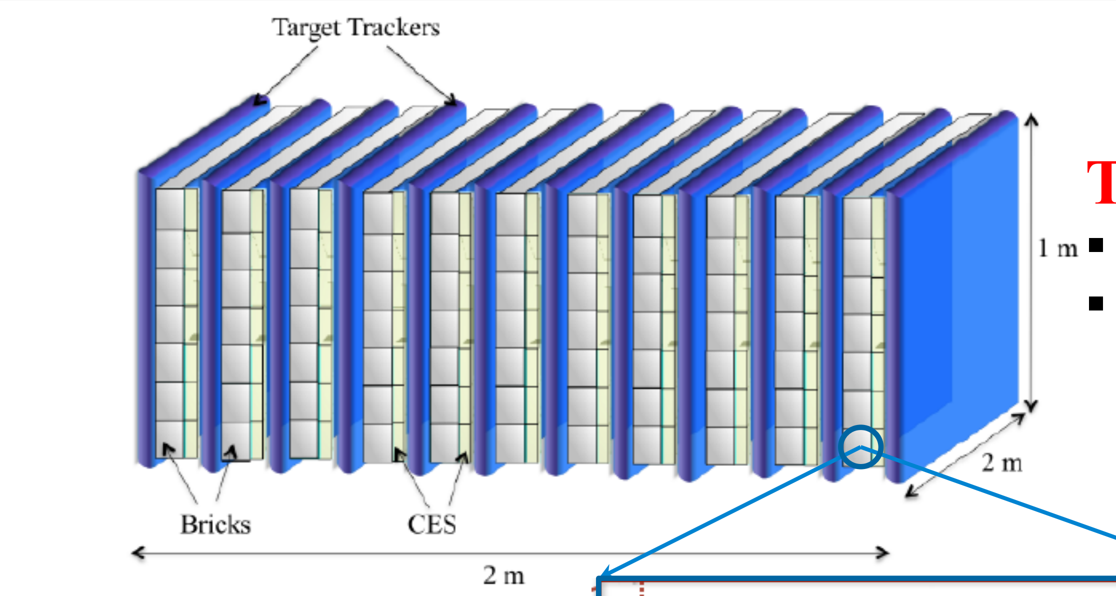


SHiP Neutrino Detector



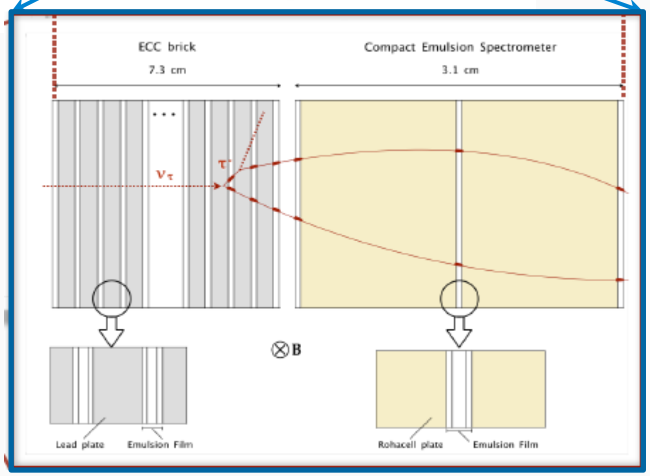


The Neutrino Target



Target Trackers

- Provide time stamp
- Link track information in emulsion to signal in TT.



Emulsion Cloud Chamber (ECC)

- Nuclear emulsion provides high spatial resolution for tau/charm detection
- Passive material(Lead)10X_0

Diopolar Magnet

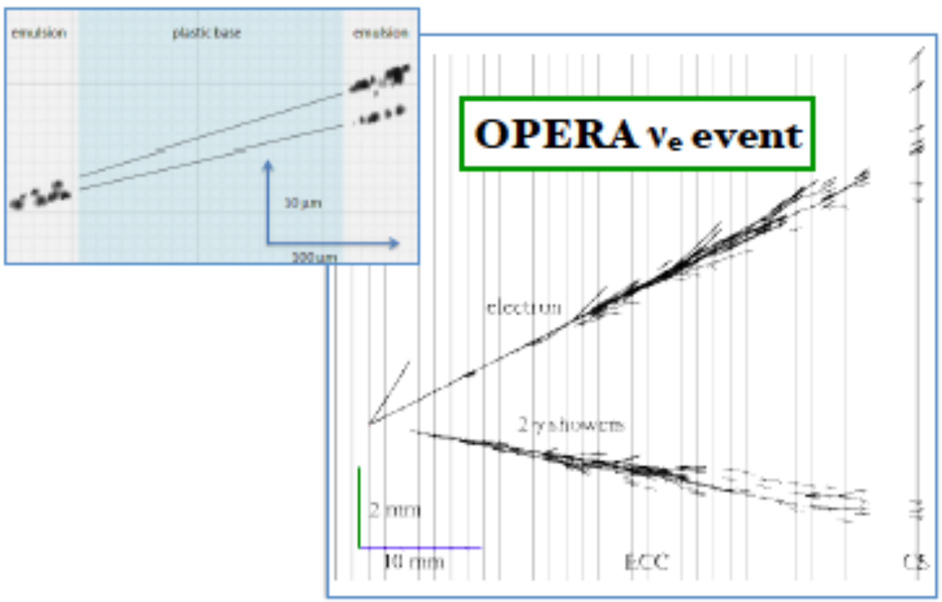
- To measure the charge of the decay products .

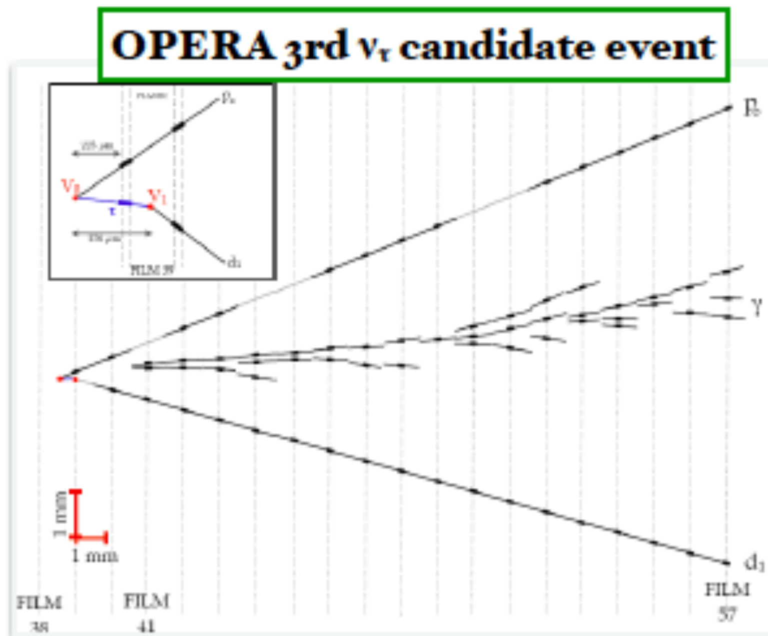
Muon Spectrometer

- Perform the muon identification and measure its charge and momentum.

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



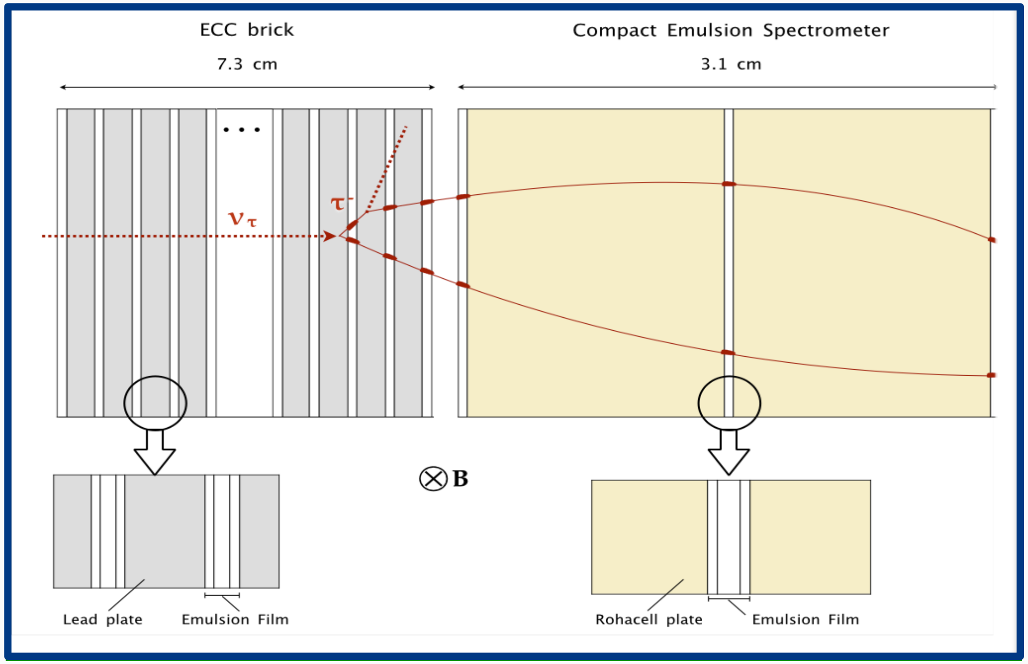


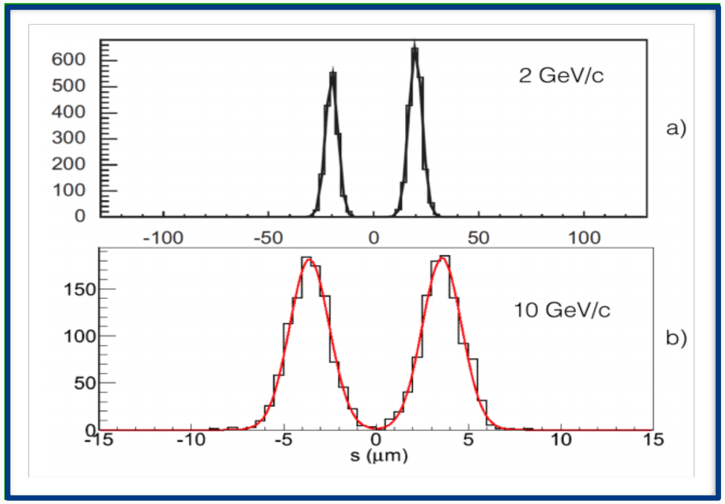
Tau/anti-tau Separation

TASK

- Electric charge and momentum measurement of τ lepton decay products
- Key role for the τ→h decay channel

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

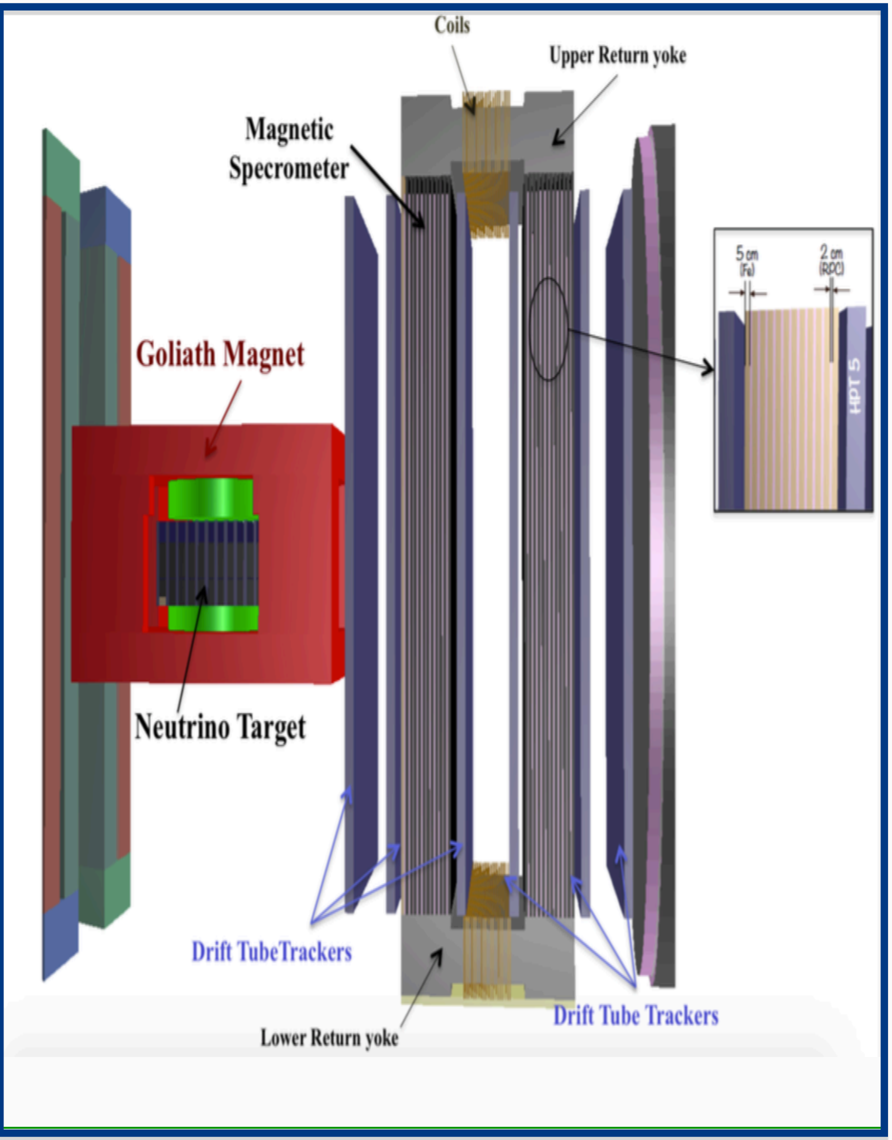




PERFORMANCES

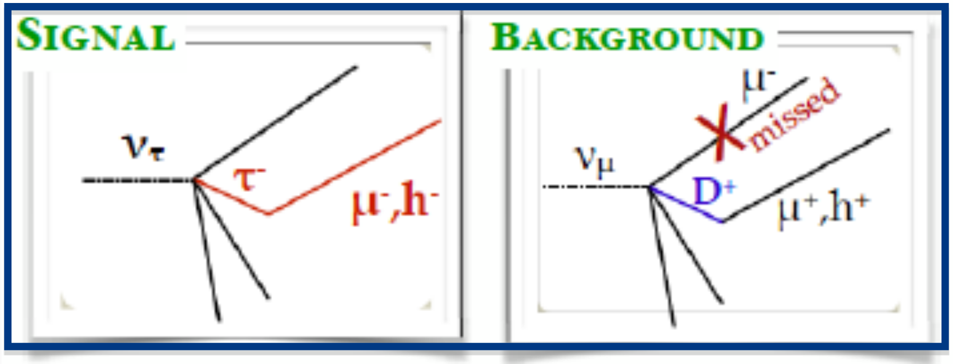
- Electric charge determined up to 10 GeV/c.
- Momentum estimated from the sagitta.
- $\Delta p/p < 20\%$ up to 12 GeV/c

Muon Identification



Muon come from

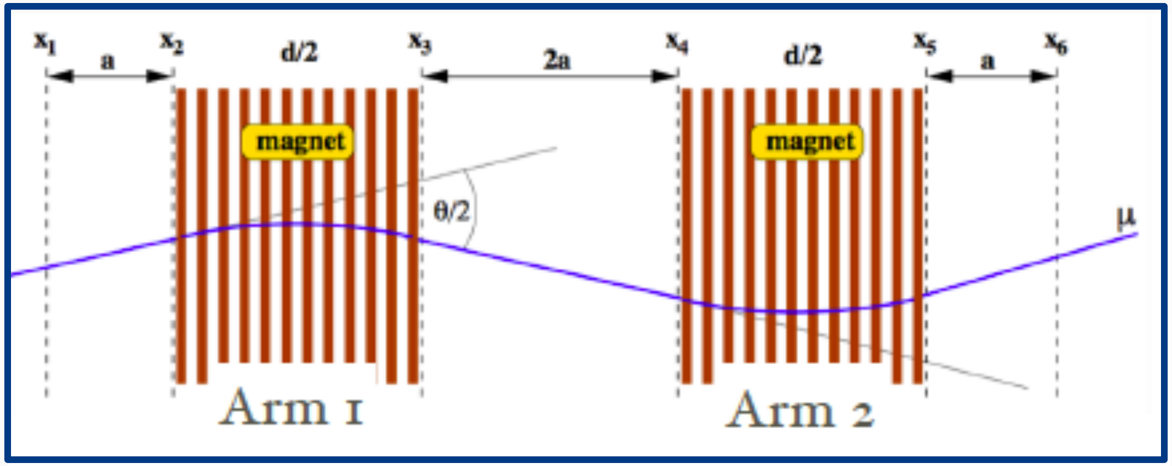
- $\tau \rightarrow \mu$ decays
- ν_μ CC interactions
- μ identification at primary vertex for background rejection

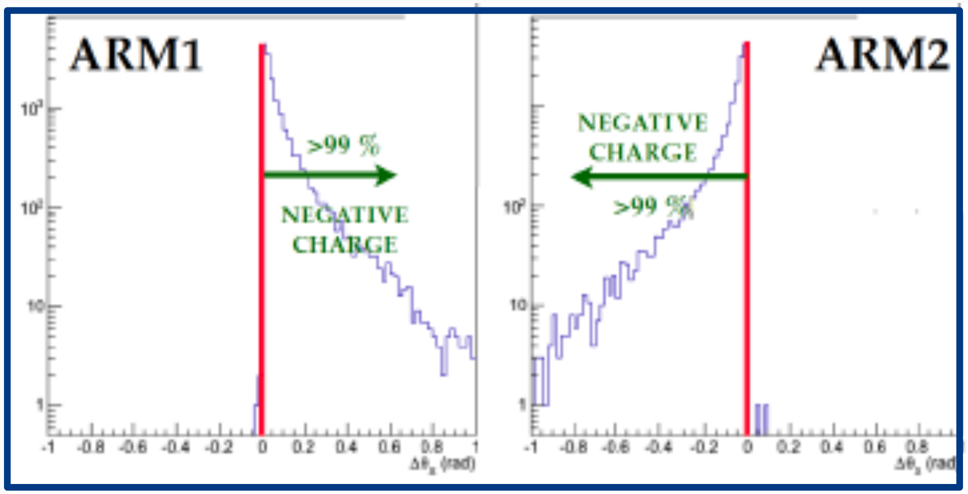


12 iron layers
11 RPC layers
6 Drift Tube Trackers Planes

Muon Charge and Momentum Measurement

➢Opposite magnetization in the two arms two opposite curvatures.





$$\frac{\Delta p}{p} \approx \frac{\Delta\theta}{\theta} = \frac{1}{eBd}\sqrt{6\left(\frac{\varepsilon p}{a}\right)^2 + \frac{d}{X_0}\left(\frac{14\,\mathrm{MeV}}{c}\right)^2}$$

- Momentum resolution is better than 25 %.

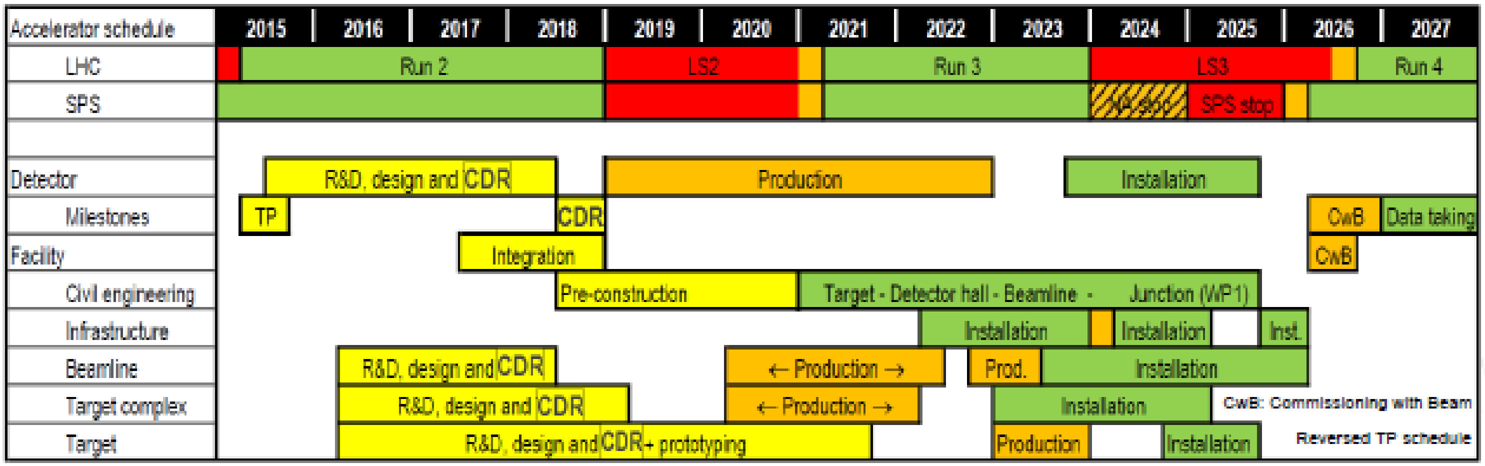
- Charge measurement efficiency is 94 %.

Summary

- SHiP experiment at CERN is proposed to search for New Physics in the largely unexplored domain of new, very weakly interacting particles with mass O(10) GeV.
- SHiP will perform a complement searches for new searches at energy frontier at CERN.
- Also unique detector for neutrino physics/charm physics.

Summary

- **Technical and Physics - proposals** prepared in 2014-2015
  - feasibility studies, facility design, engineering, test beams, sensitivities.
- **Green lights** from the SPSC, recommendation to produce CDR(Comprehensive Design Report) for European HEP strategy 2019.

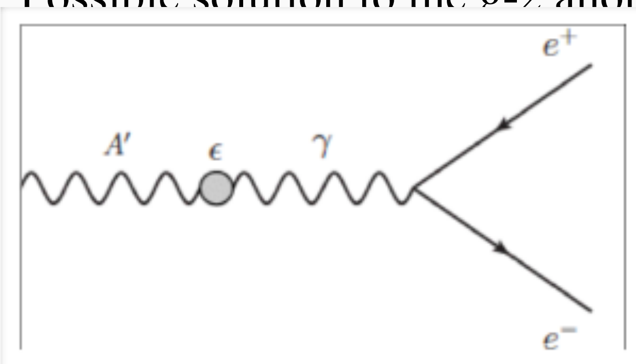


Back up Slides

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 photon at the SPS

- proton bremsstrahlung
- decay of pseudo-scalar mesons
- limits on mean life from BBN τ_γ <0.1s

Dark photons decay

e^+e^-, $\mu^+\mu^-$,qqbar

light dark matter χχbar

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

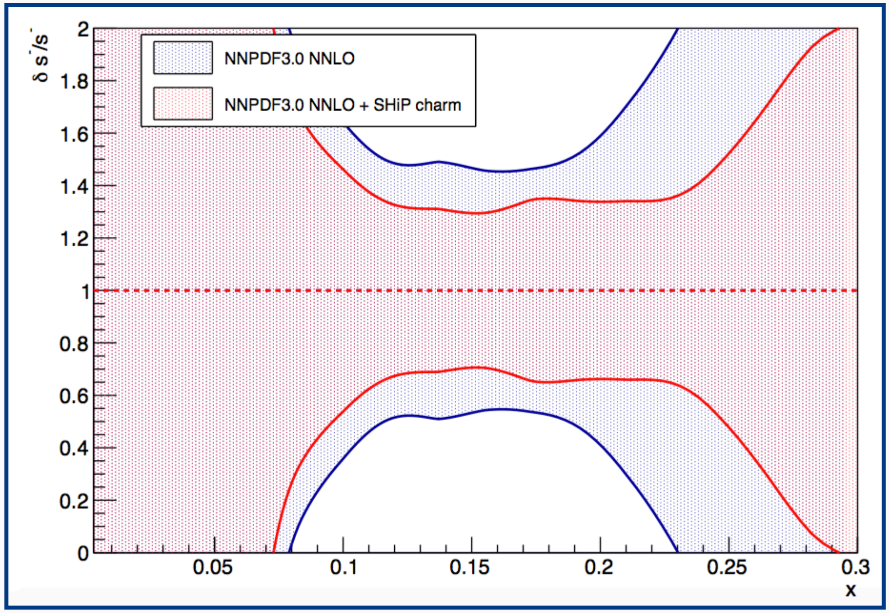
- e^+e^-, $\mu^+\mu^-$, qq-, $\gamma\gamma$

SUSY PORTAL

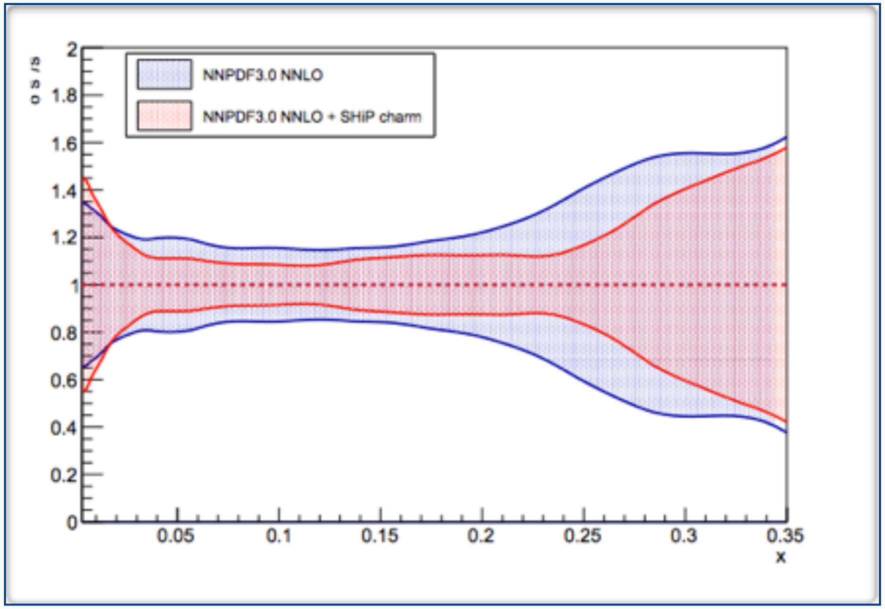
and possibly higher dimensional operators portals and Super-Symmetric portals (light neutralino, light sgoldstino, …)

Strange Quark Content

- Improvement achieved on s^+/s^- versus x
- Significant improvement (factor two) with SHIP data



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

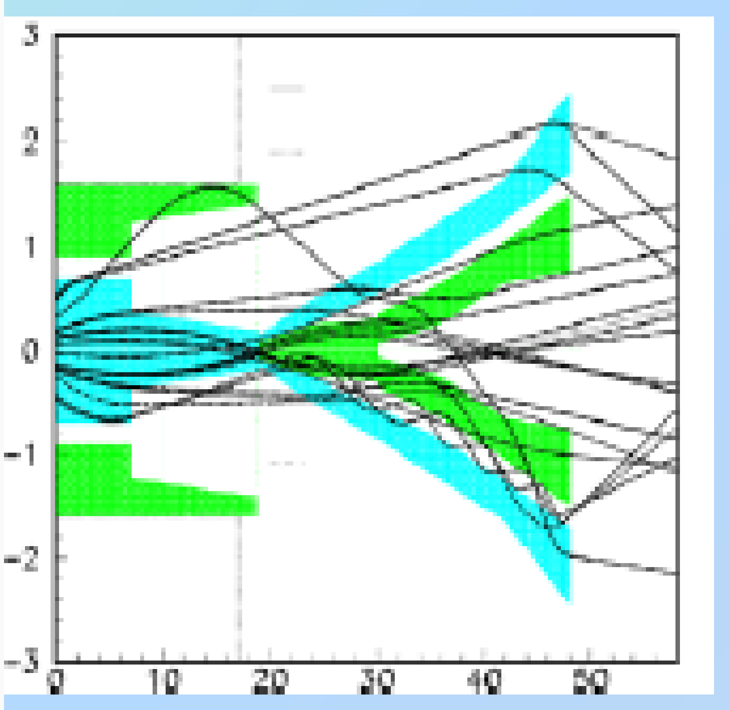


$$s^+ = s(x) + \bar{s}(x)$$

Added to NNPDF3.0 NNLO fit, Nucl. Phys. B849 (2011) 112–143, at $Q^2 = 2$ GeV^2

Background Sources

- ➢ Muon Flux
  - – Active muon shield



- ➢ Combinatorial
  - – Slow beam extractions
- ➢ ν interactions inside the vessel
  - – 10^{-6} bar pressure decay vessel
- ➢ After selections : O(0.1)≤ bkg/ 5 years

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**