THE SHIP EXPERIMENT AND ITS DETECTOR FOR NEUTRINO PHYSICS

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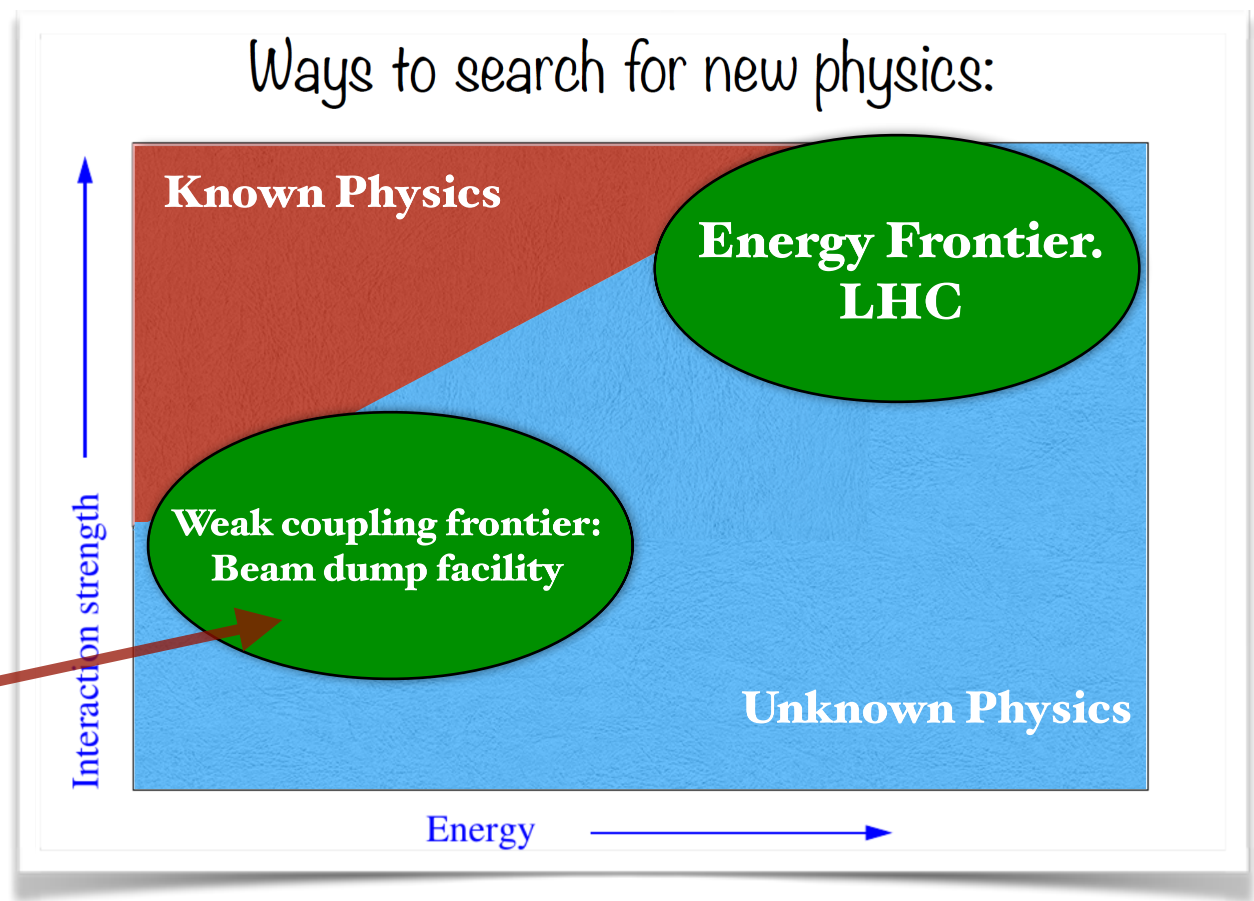
STATE OF THE ART

- Current model for the description of the particle physics world: **Standard Model (SM)**
  - Effective field theory
  - Self-consistent
  - Weakly coupled up to 10^{10} GeV
  - Validated by:
    - Discovery of the Higgs boson with 126 GeV mass
    - No signicant deviation from Charged Flavour Physics.
- No new particles observed up to the TeV scale

SHiP experiment

- Three **open questions**:
  - Neutrino masses
  - Baryon Asymmetry in the Universe (BAU)
  - Presence of Non-baryonic Dark Matter



SHiP
(SEARCH FOR HIDDEN PARTICLES)

- General purpose fixed target facility at CERN
  - 400 GeV proton spills (4×10^{13} p.o.t.) from a dedicated beam line at the SPS accelerator

Primary physics goals

- Explore **Hidden portals and extension of the SM** incorporating *long-lived and very weakly interacting particles*
  - Sterile neutrinos (Heavy Neutral Leptons)
  - Dark photons
  - Paraphoton
  - SUSY: Sgoldstino, Light neutralino
- Study **ν_τ and anti-ν_τ interactions**
  - Perform cross section measurements
  - Estimate structure functions (F_4 and F_5) from charged current neutrino nucleon deep-inelastic scattering
- Study **nucleon strangeness content** with charm production from neutrino scattering

http://arxiv.org/abs/1504.04855

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

85 theorists
200 pages

Contents

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP
Search for Hidden Particles

http://arxiv.org/abs/1504.04956

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

Technical Proposal

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

The SHiP Collaboration[1]

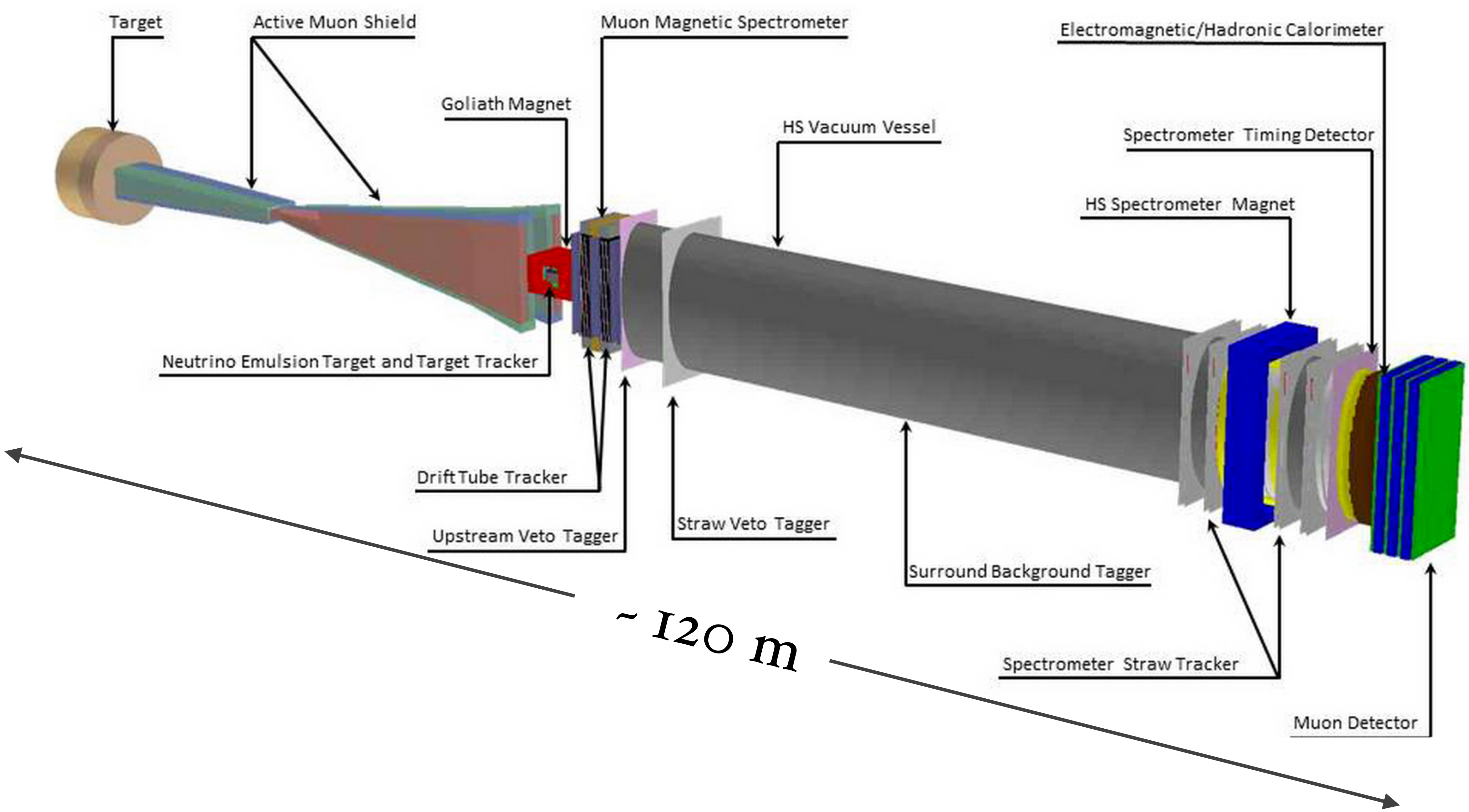
234 authors
45 institutions
14 countries

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.

A DETECTOR TO REVEAL THE HIDDEN SECTOR

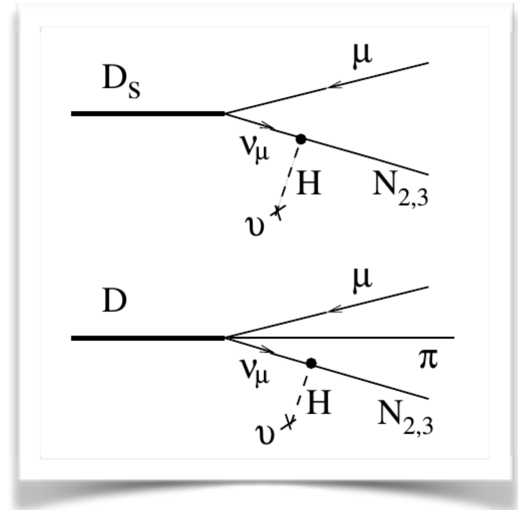
SHIP APPARATUS



EXPERIMENTAL REQUIREMENTS

Hidden particles accessible through the decays of charmed and beauty hadrons above the kaon mass

- **Maximize neutrinos from charmed hadrons**
- **Minimize neutrinos from π and K**



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

- Hybrid target: blocks of titanium-zirconium doped molybdenum (TZM) followed by blocks of pure tungsten
  - materials with the shortest possible interaction length
  - ~ 1.3 m long to contain the hadron shower
- Hadron Stopper: 5m of Fe
  - absorb secondary hadrons
  - absorb residual non-interacting protons emerging from the target

EXPERIMENTAL REQUIREMENTS

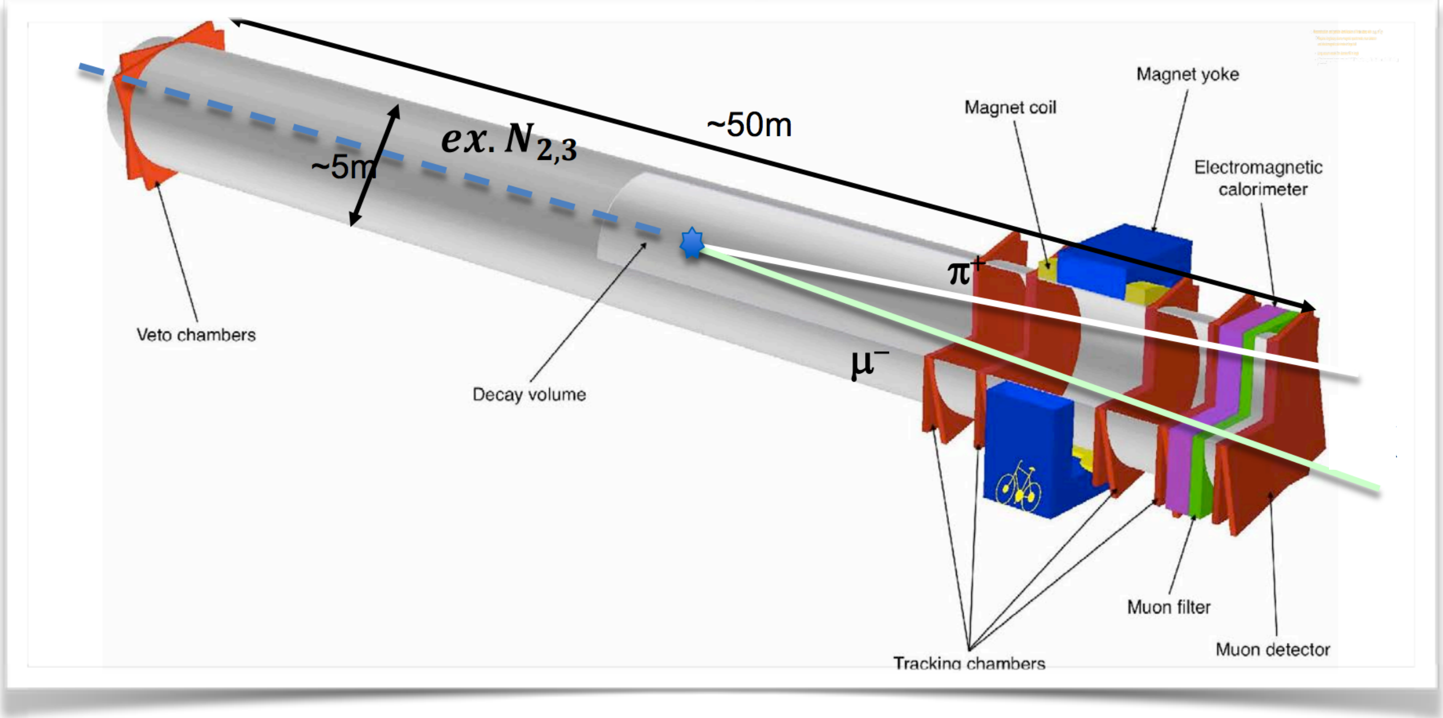
Hidden particles produced in charm decays have significant transverse momentum:

→ Detector must be placed close to the target to maximize geometrical acceptance

Hidden particles can decay in SM particles:

	BR (%)
$N \rightarrow \mu/e\ \pi$	0.1 – 50%
$N \rightarrow \mu^-/e^-\ \rho^+$	0.5 – 20%
$N \rightarrow \nu\mu e$	1 - 10 %

Typical lifetimes > 10 μs
⇒ Decay distance O(km)



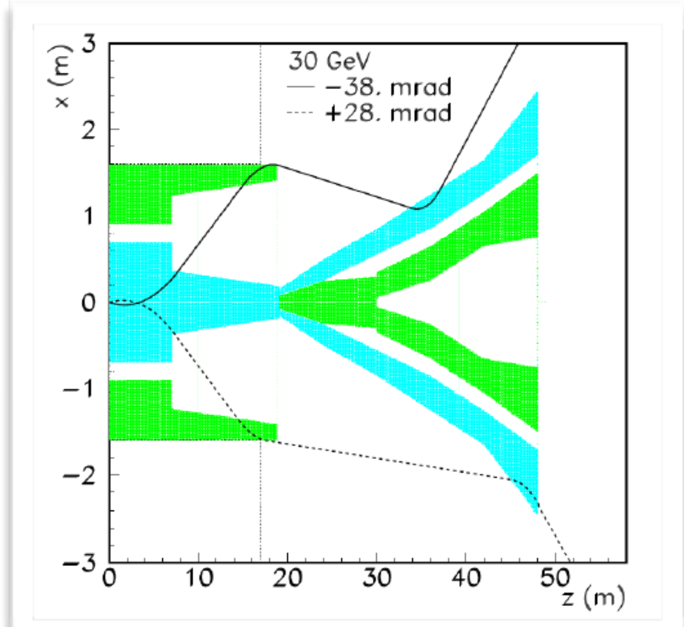
→ Long decay volume O(5) m diameter, O(50) m length

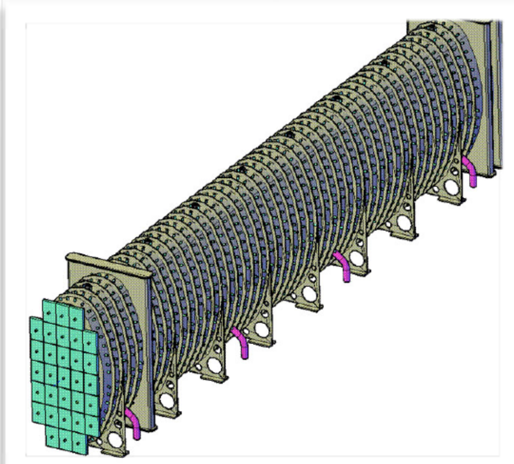
→ Magnetic spectrometer, muon detector, hadronic and electromagnetic calorimeter

EXPERIMENTAL REQUIREMENTS

Main Background sources

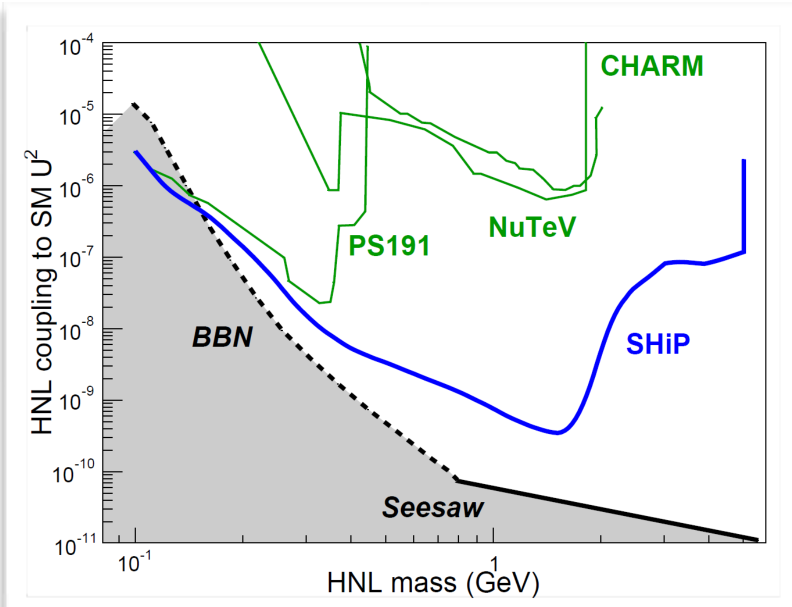
- Muon Flux →
  - 48 m long active muon shield
  - veto system around the decay vessel
- Combinatorial →
  - Proton spills prepared with slow beam extractions (~1s)
  - Uniform extractions
- Neutrino interactions inside the vessel →
  - Low pressure decay vessel
- Neutrino interactions in the vessel proximity →
  - Light taggers located upstream and at the beginning of the HS fiducial volume



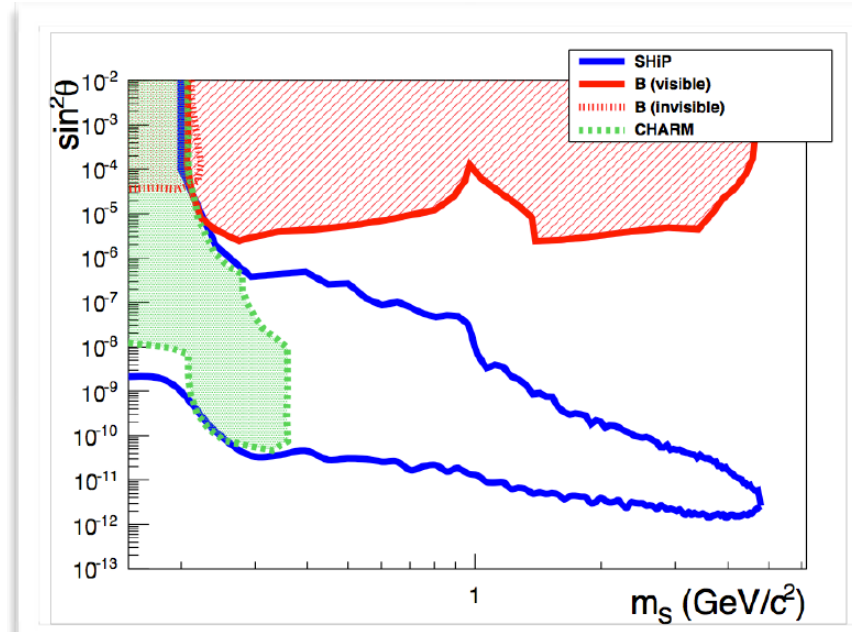


SENSITIVITIES

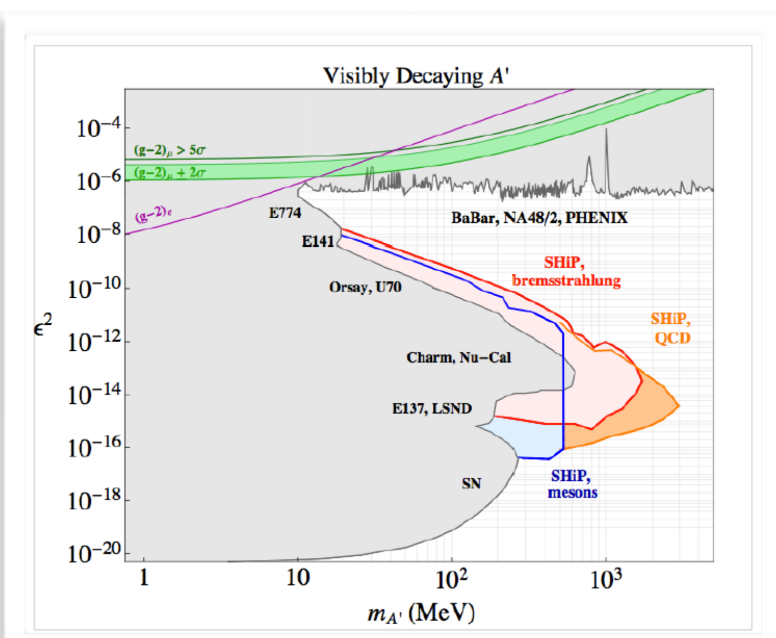
Neutrino Portal (HNL)



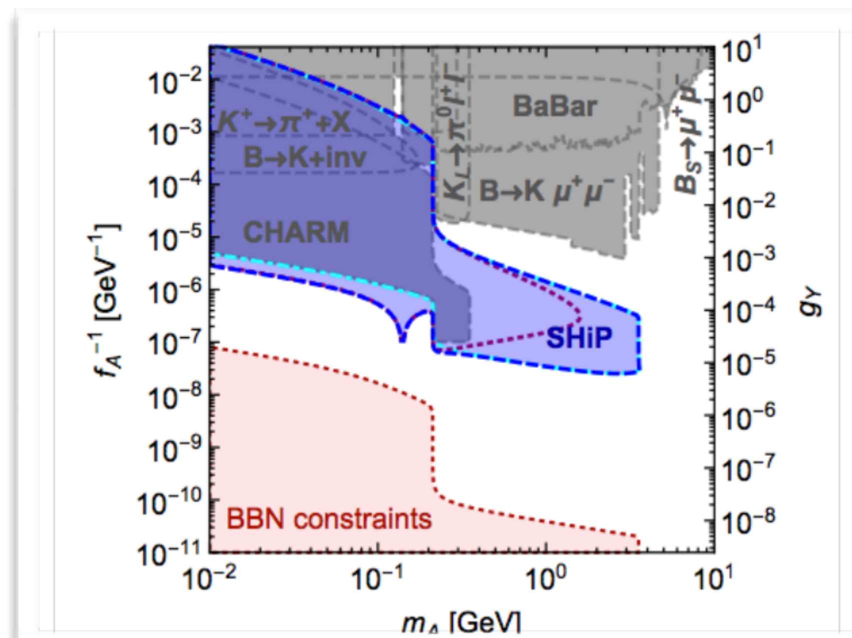
Scalar Portal



Vector Portal



Axion Portal

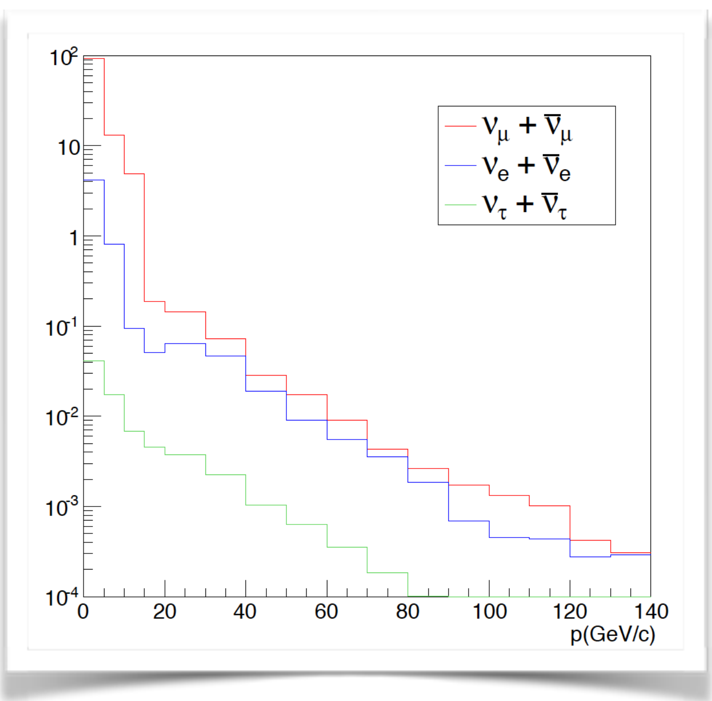


NEUTRINO DETECTOR FOR A NEUTRINO PHYSICS PROGRAM

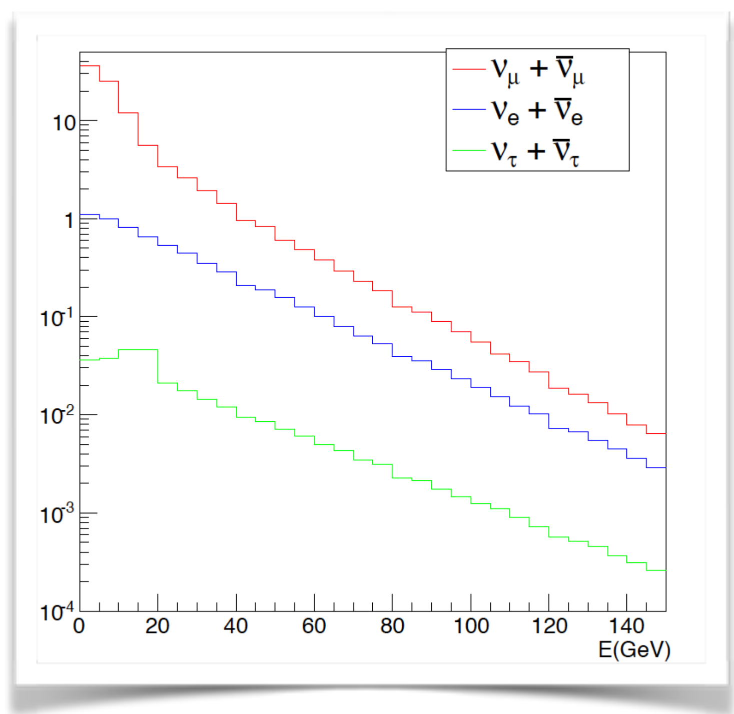
NEUTRINO FLUXES

SHiP experimental setup ideally suited to perform studies on neutrino and anti-neutrino physics.
High charmed hadrons decay rates ⇒ high ordinary neutrino fluxes

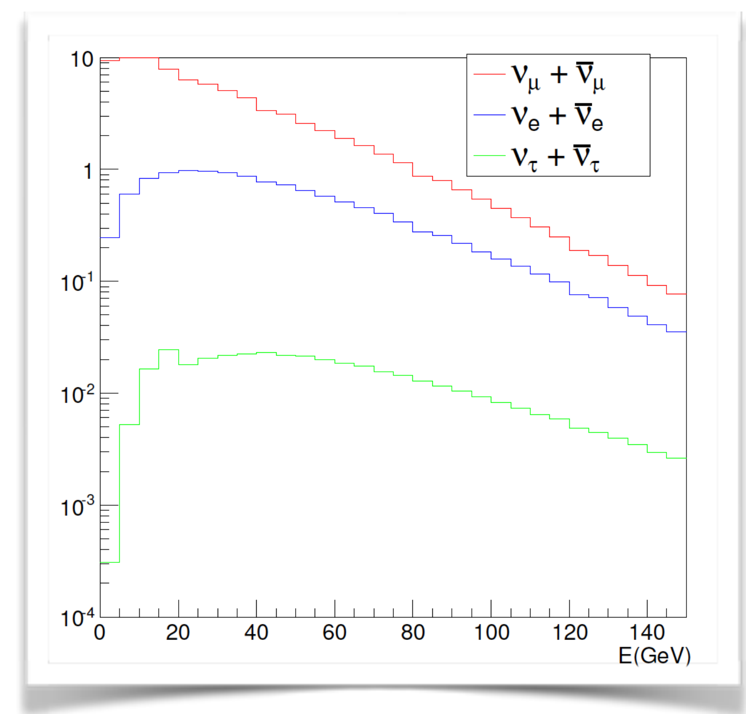
ν energy spectra @ beam dump



@ neutrino detector



CC interacting ν



Total number of neutrinos is normalized to 100

ν_τ PHYSICS

Number of expected ν_τ and anti-ν_τ arriving on the neutrino detector in 5 yrs of data taking:

$$N(\nu_\tau + \bar{\nu}_\tau) = N_p \times 4 \times \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} \times f_{D_s} \times BR(D_s \to \tau) \times \epsilon_{geom} \sim 3 \times 10^{14}$$

- $N_p = 2 \times 10^{20}$
- $\sigma^{CCbar} = 18\ \mu barn$
- $\sigma_{pN} = 10.7\ mbarn$
- $f_{Ds} = 0.077$
- $BR(Ds \to \tau) = 0.055$
- $\varepsilon_{geom} = 0.053\ (\nu_\tau)$

- **~7000** expected ν_τ and **~3500** anti-ν_τ interactions in the target
  - First observation of anti-ν_τ
  - Sufficient statistics to perform ν_τ and anti-ν_τ cross section measurement.

τ Decay Channels	BR (%)
$\tau \to \mu$	17.7
$\tau \to e$	17.8
$\tau \to h$	48.5
$\tau \to 3h$	15.0

PHYSICS WITH DIS

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

→ Perform structure functions estimation

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

Estimation through ν/anti-ν data subtraction

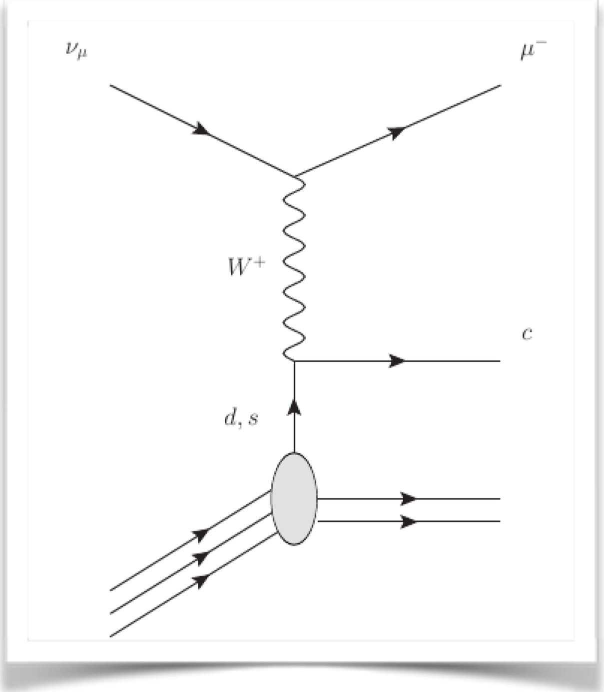
Dependent on the lepton mass.
Relevant only for ν_τ interactions

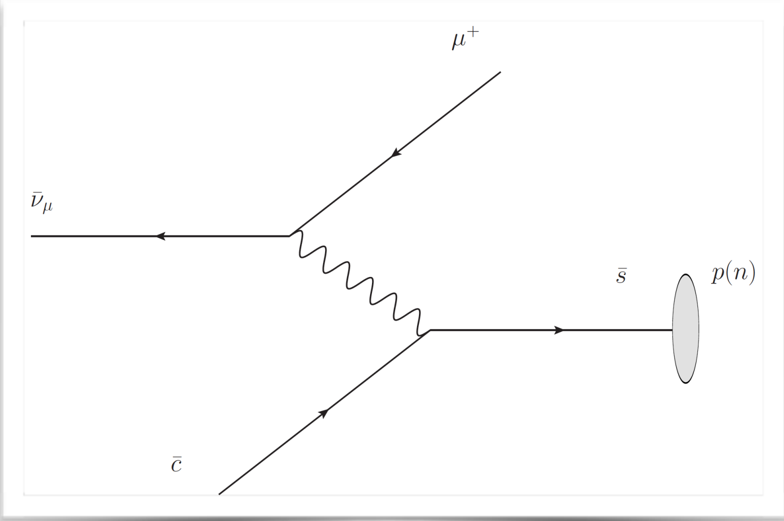
From ν_τ and anti-ν_τ CC interactions:

→
- Estimation of F_3
- First evaluation of F_4 and F_5 not accessible with lighter neutrinos

PHYSICS WITH DIS

- **Charm production with ν and anti-ν scattering**
  - Charmed hadrons produced at a level of a few % in ν_μ and ν_e CC interactions
  - s-quark content of the nucleon: anti-ν are a good probe in interactions where a charmed hadron is produced





- **ν_e physics**
  - Study of ν_e cross section at high energies
  - Possibility to normalize the charm production at the beam dump

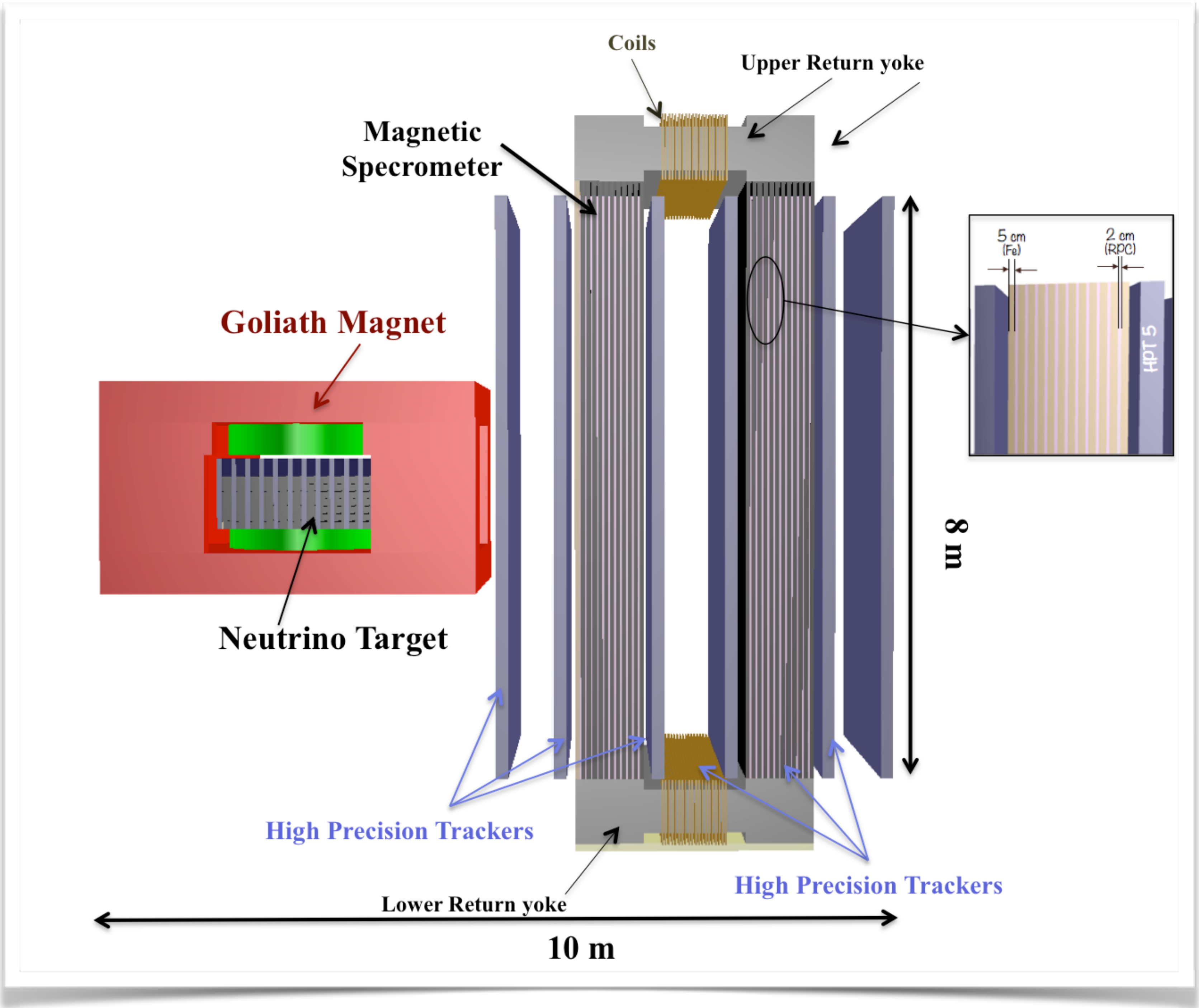
EXPERIMENTAL REQUIREMENTS

Dimensions must be adapted to the region cleared by the muon active shield →	Compact
Target must be optimized to induce the maximum number of ν_τ interactions →	High density
Disentangle τ production and decay vertices →	Micron position resolution
Distinguish neutrinos from anti-neutrinos →	Magnetised target
Muon identification, charge and momentum measurement to discriminate signal/background processes →	Muon Magnetic spectrometer

Taking advantage of the OPERA experience

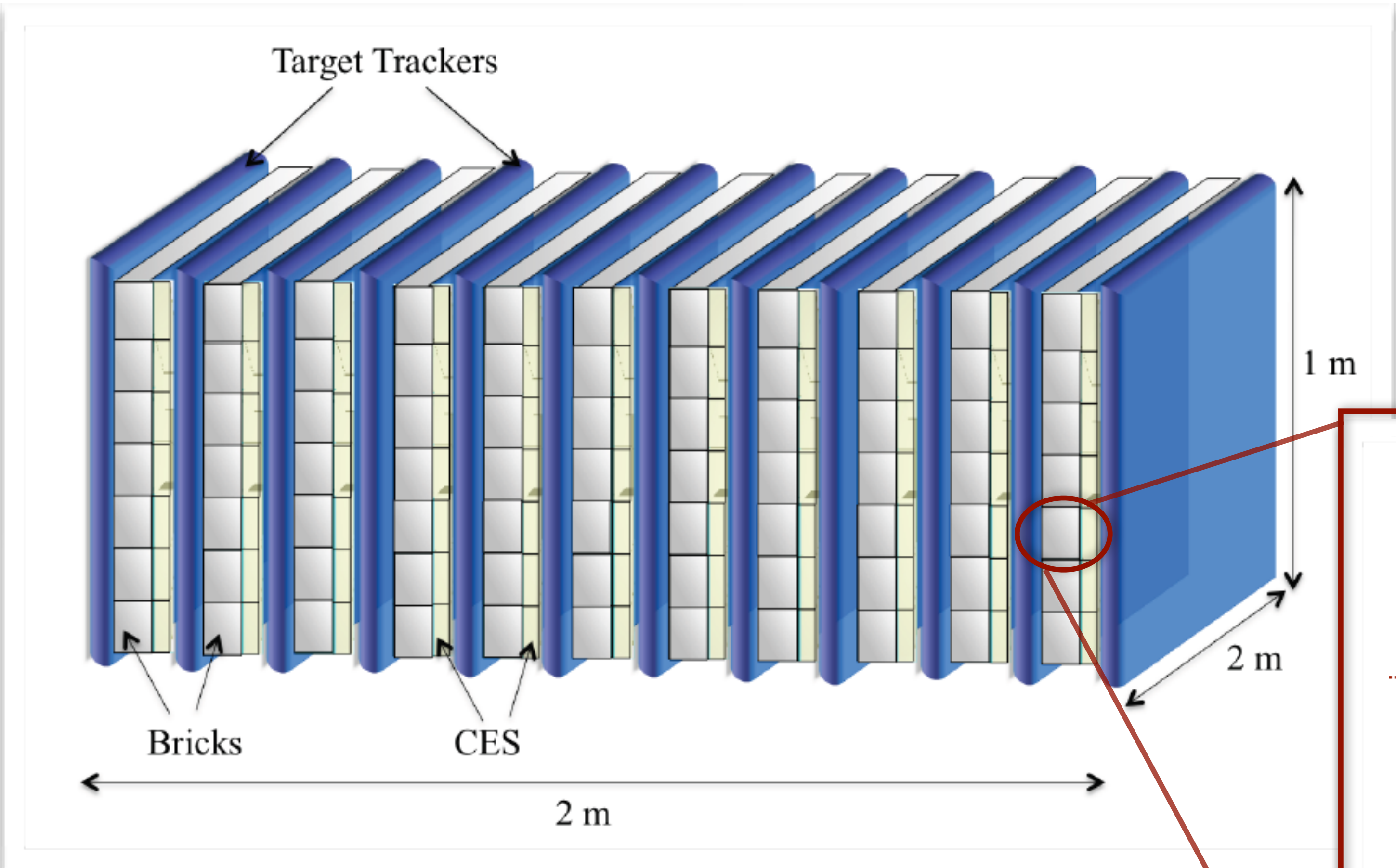
Identify all 3 neutrino flavour →	Emulsion Cloud Chamber technique

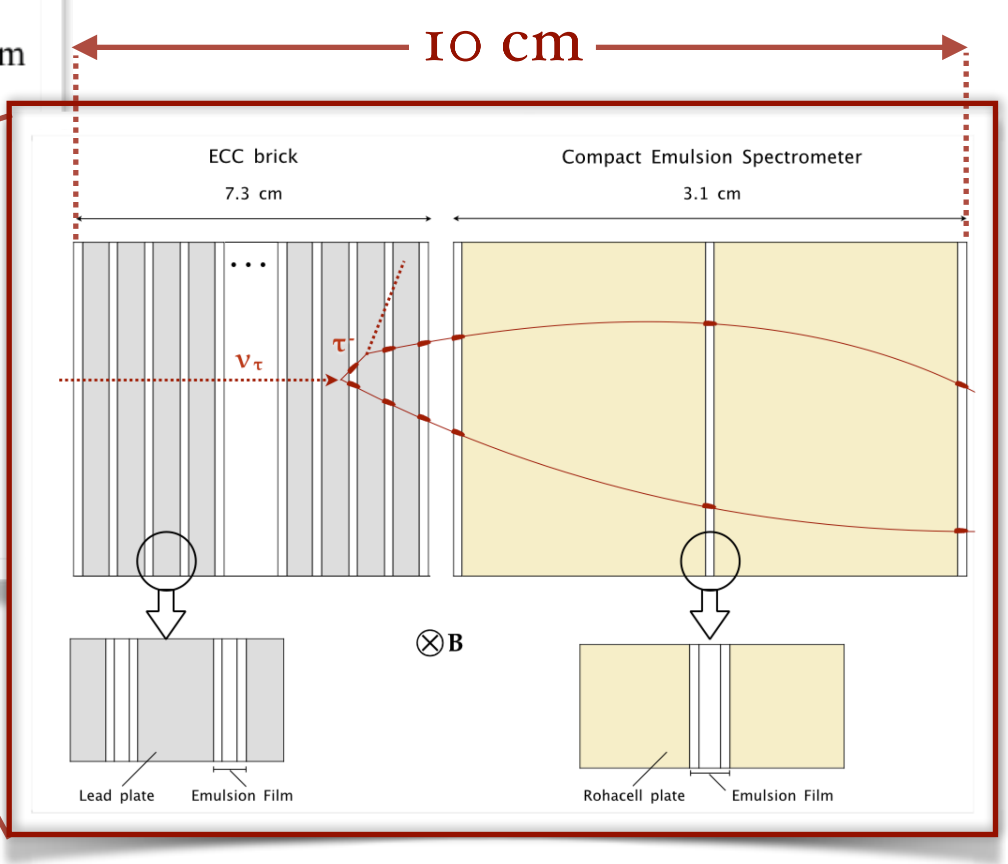
TAU NEUTRINO DETECTOR



THE NEUTRINO TARGET

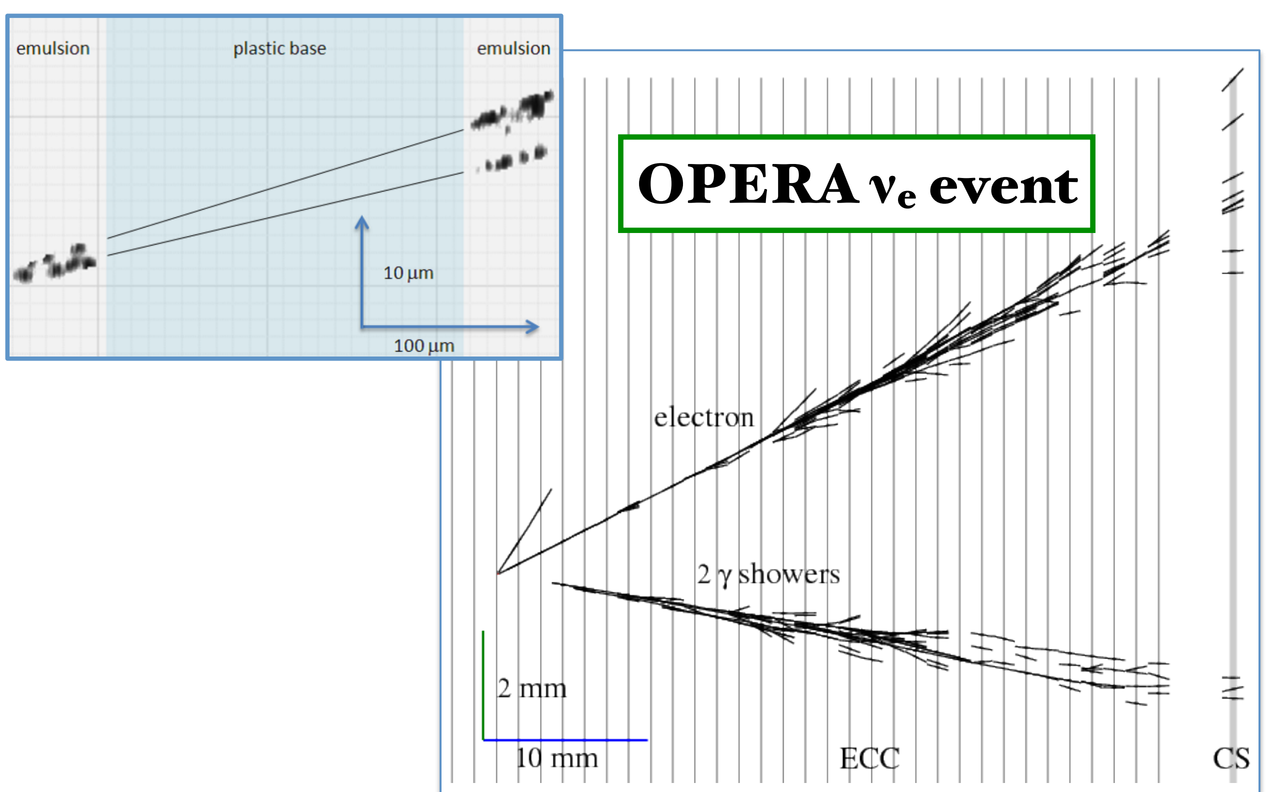
ν target + vertex detector

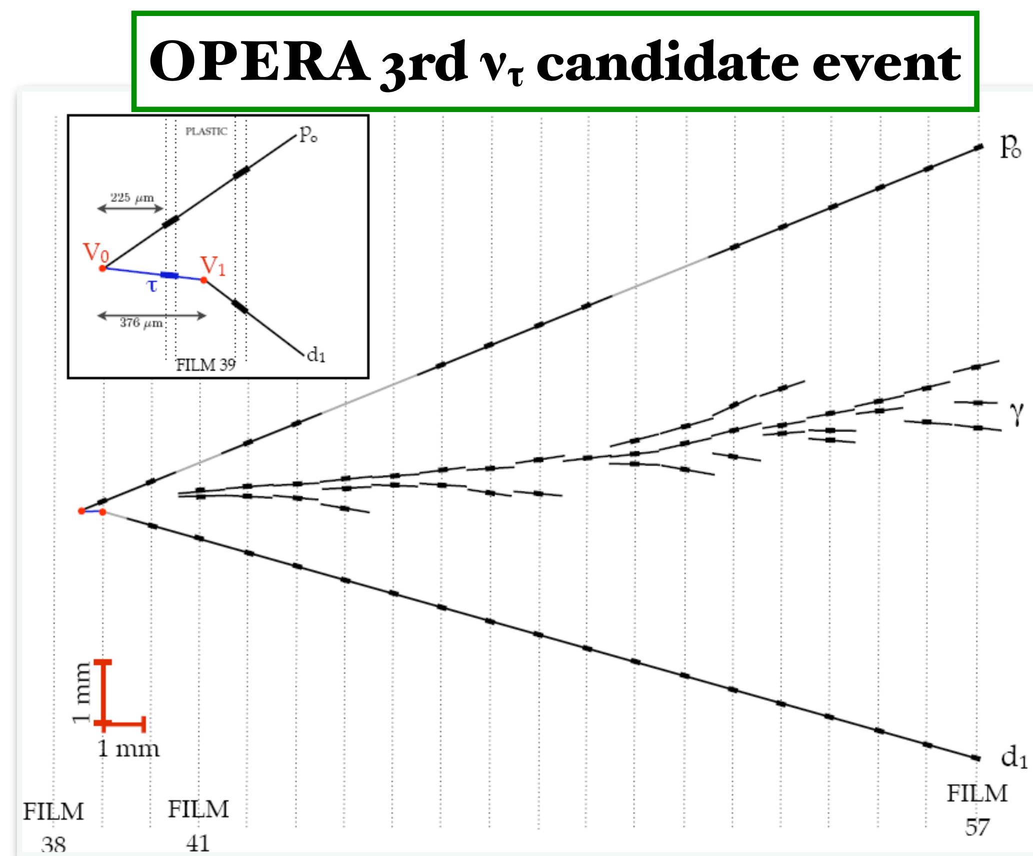




LEPTON FLAVOUR IDENTIFICATION WITH ECC

- **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

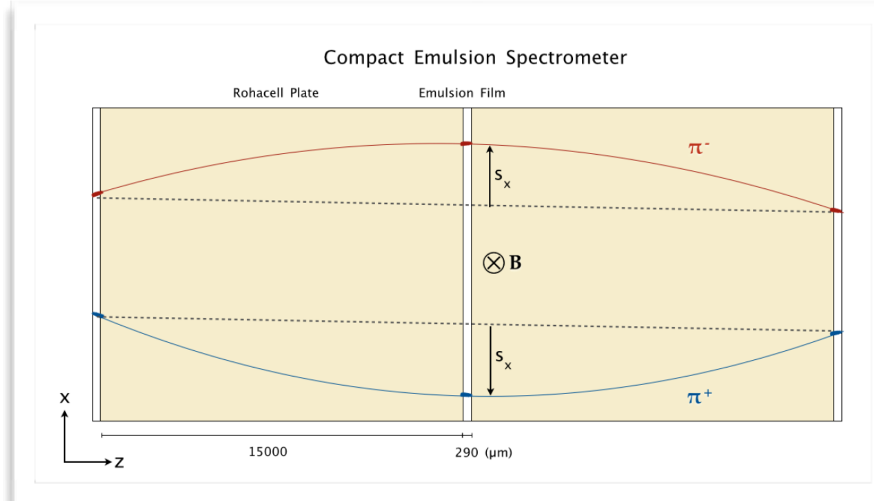


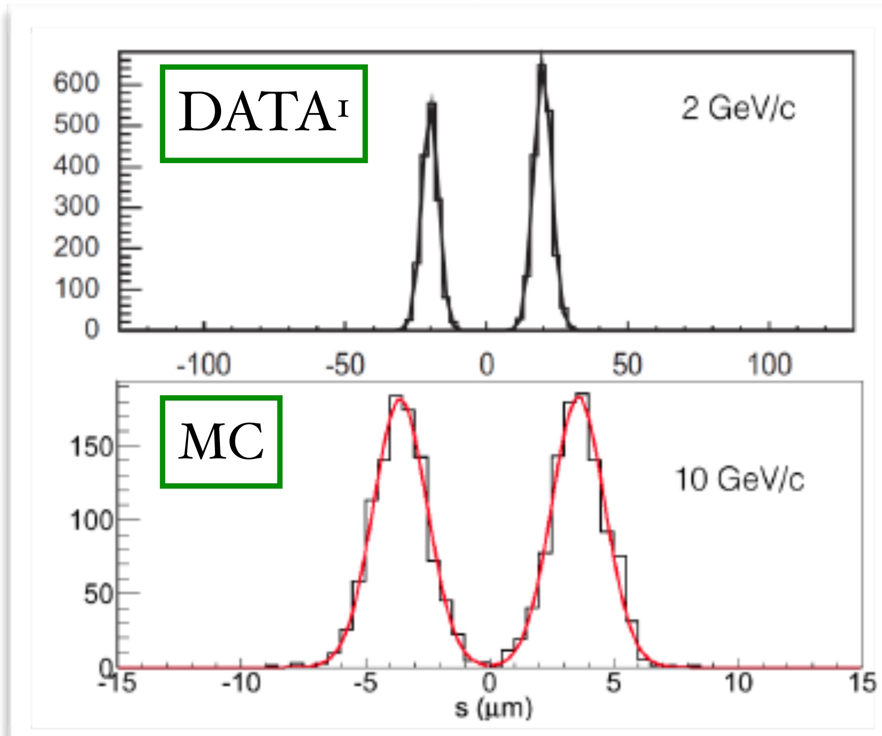


SEPARATION ν_τ /ANTI-ν_τ

Compact Emulsion Spectrometer (CES)

- three emulsion films interleaved with two, 15-mm thick, Rohacell layers
- capable of measuring the hadron track curvature
  - 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
  - electric charge can be determined with better than 3 σ level up to 10 GeV/c





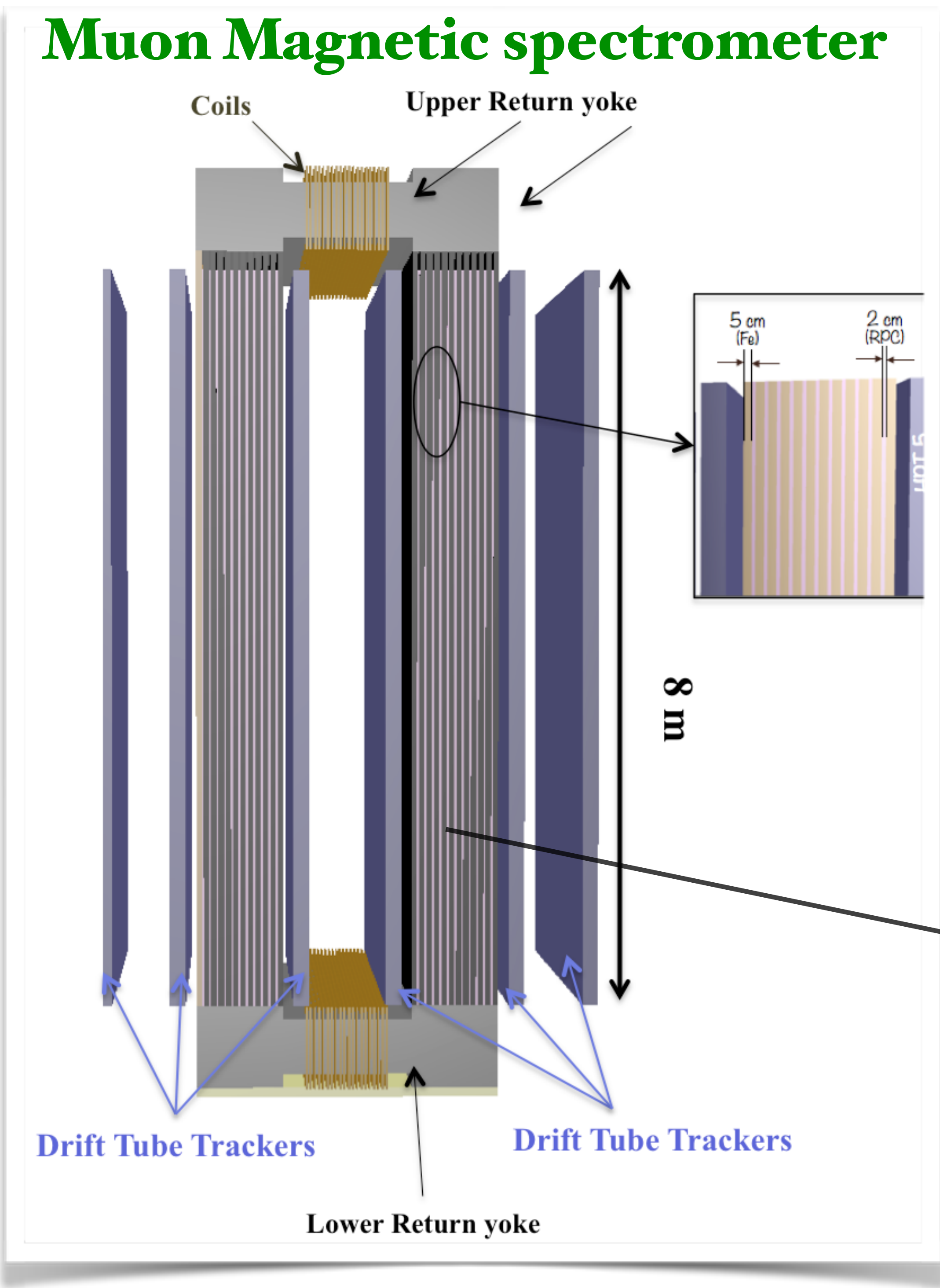
[1] NIM A 592 (2008) 56–62

EVENT TIME STAMP

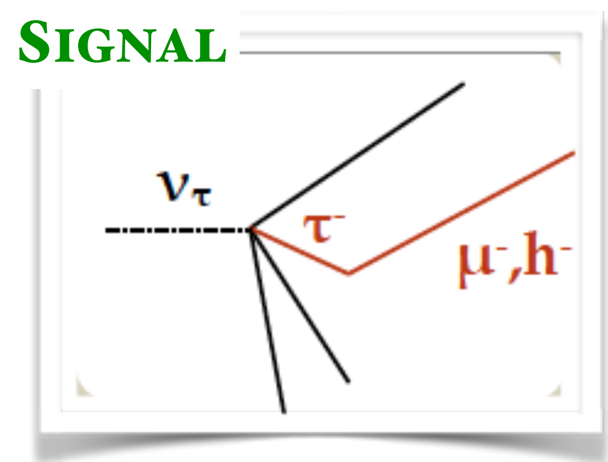
Target tracker (TT)

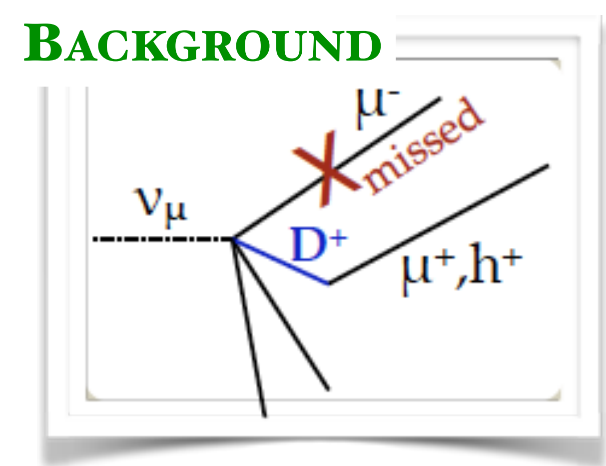
- **FEATURES:**
  - Provide Time stamp
  - Link track information in emulsions to signal in TT
  - Link muon track information in ν target to μ magnetic spectrometer
- **REQUIREMENTS IN 1T FIELD:**
  - 100 μm position resolution on both coordinates
  - high efficiency (>99%) for angles up to 1 rad
- **POSSIBLE OPTIONS:**
  - Scintillating fibre trackers
  - Micro-pattern gas detectors (GEM, Micromegas)
- **DETECTOR LAYOUT:**
  - 12 target planes interleaving the 11 brick walls at a few mm distance
    - 1st plane used as veto
  - Transverse size of about 2 x 1 m^2

μ IDENTIFICATION



- μ come from:
  - τ -> μ decays
  - ν_μ CC interactions
    - μ identification at 1ry vertex for bkg rejection



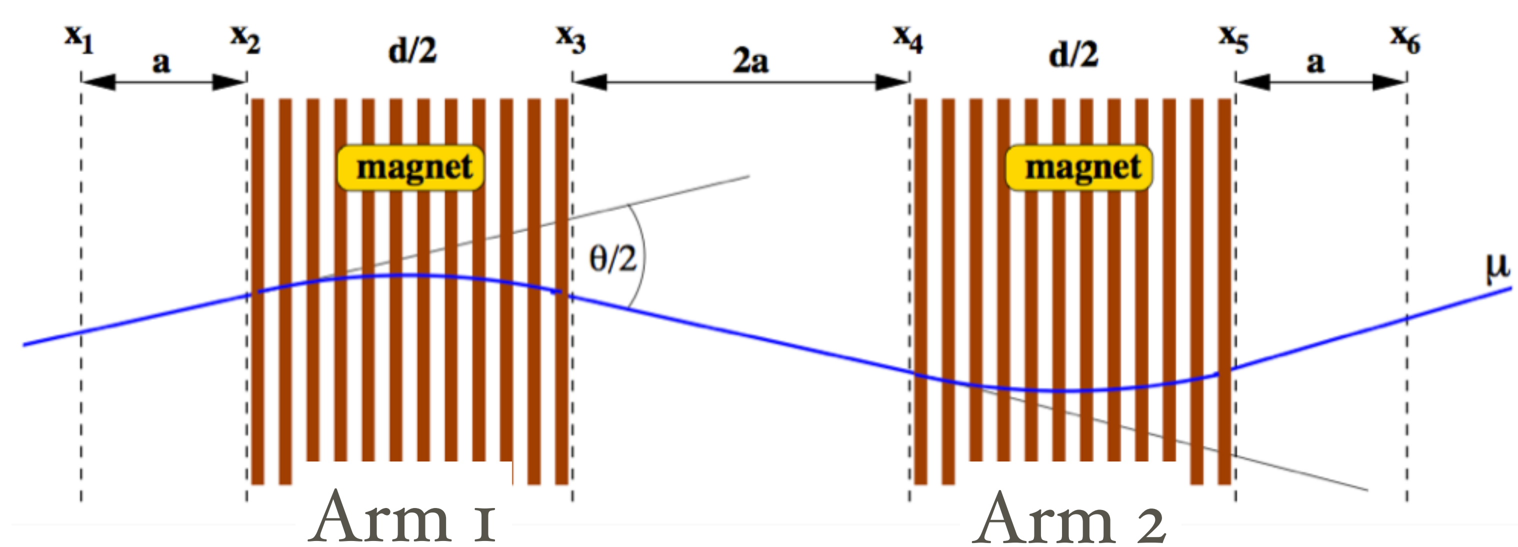


- 12 iron layers (5cm each) } Per arm
- 11 RPC layers (2cm each) } Per arm
- 6 Drift Tube Tracker Planes

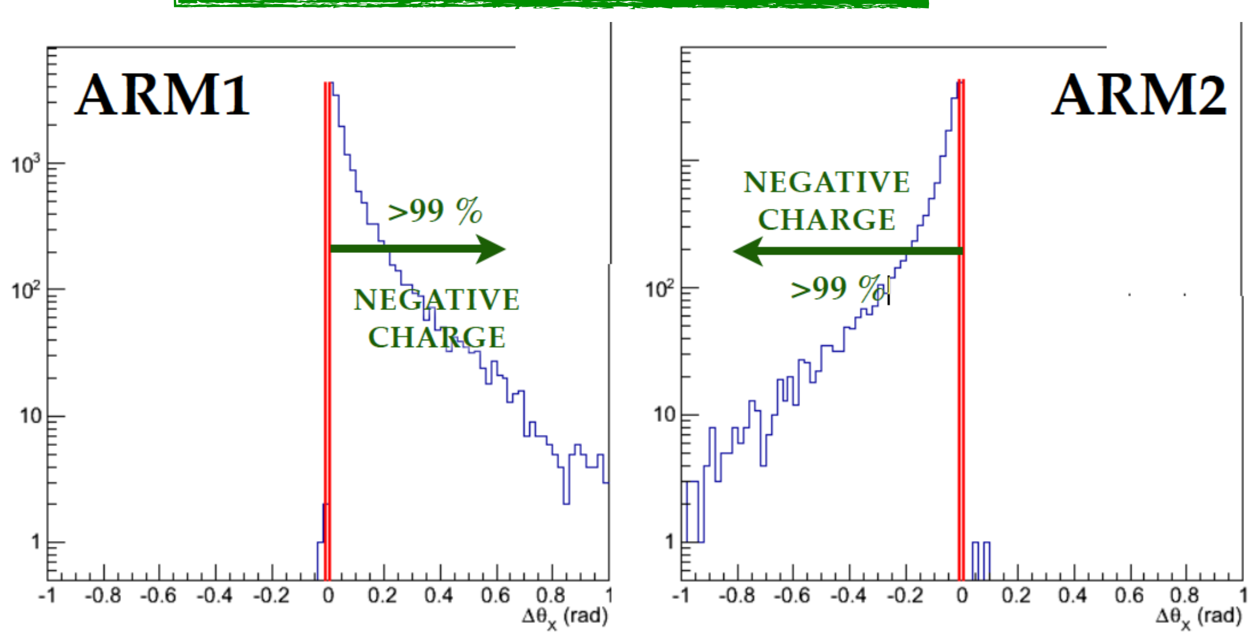
μ CHARGE AND MOMENTUM MEASUREMENT

Opposite magnetization in the two arms

Two opposite curvatures



Charge measurement



Charge measurement efficiency ~ 94%

Momentum measurement

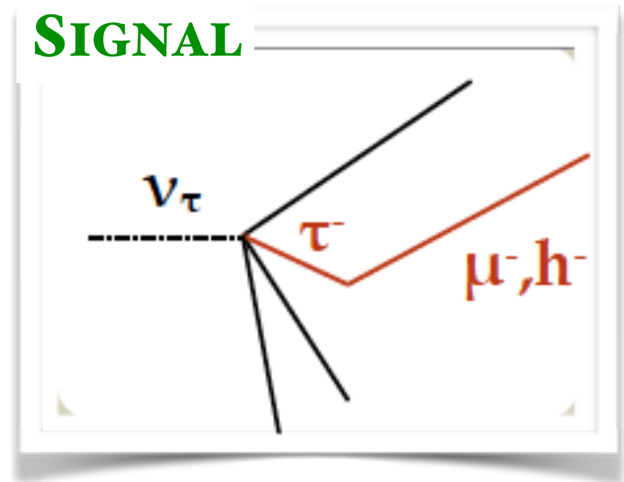
$$\frac{\Delta p}{p} \approx \frac{\Delta\theta}{\theta} = \frac{1}{eBd}\sqrt{6\left(\frac{\varepsilon p}{a}\right)^2 + \frac{d}{X_0}\left(\frac{14\,\mathrm{MeV}}{c}\right)^2}$$

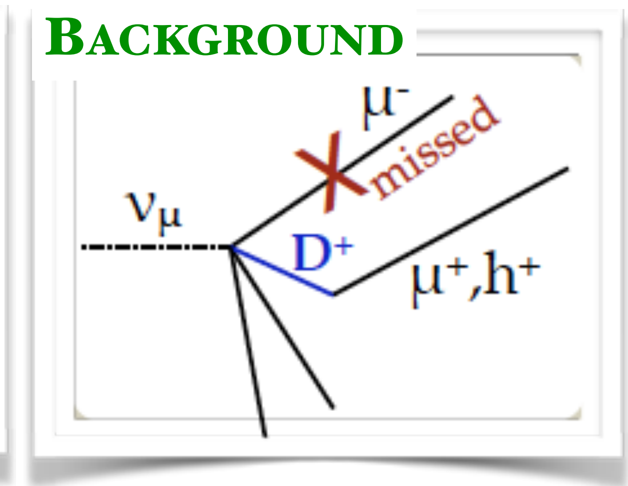
Momentum resolution better than 25%

MC simulation: muons from ν_μ CC interactions

SIGNAL AND BACKGROUND EXPECTATION YIELD

Main background in ν_τ and anti-ν_τ searches is the charm production in ν_μCC (anti-ν_μ CC) and ν_e CC (anti-ν_e CC) interactions, when the primary lepton is not identified





τ→e channel is not included because the lepton number cannot be determined

Efficiencies included

SIGNAL — BACKGROUND — R = S/B RATIO

decay channel	ν_τ N^{exp}	ν_τ N^{bg}	ν_τ R	$\overline{\nu}_\tau$ N^{exp}	$\overline{\nu}_\tau$ N^{bg}	$\overline{\nu}_\tau$ 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

Cut based analysis (to be improved with likelihood analysis)

SENSITIVITY TO F4 AND F5

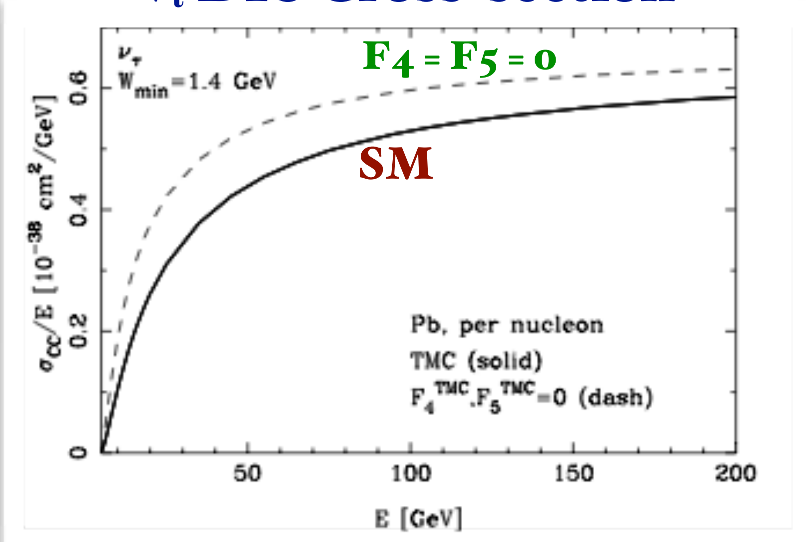
Through ν_τ and anti-ν_τ identification: unique capability of being sensitive to F4 and F5

$F_4 = F_5 = 0$ hypothesis

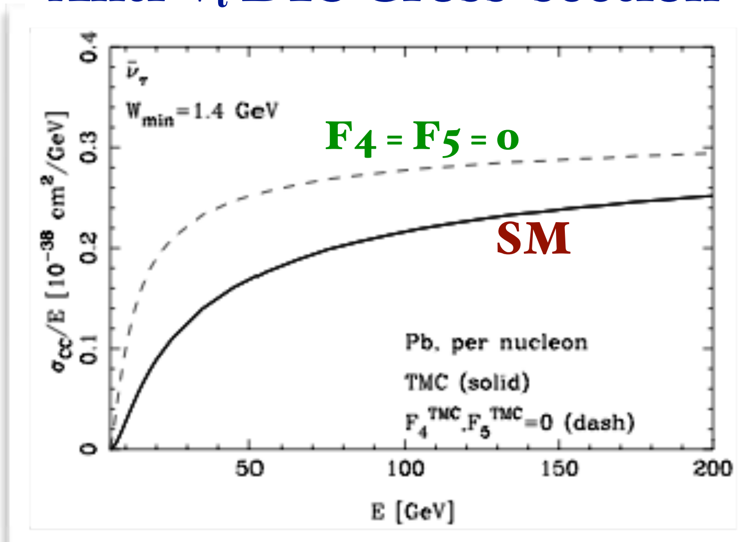
Increases ν_τ and anti-ν_τ cross-sections

Differences larger for lower ν energies

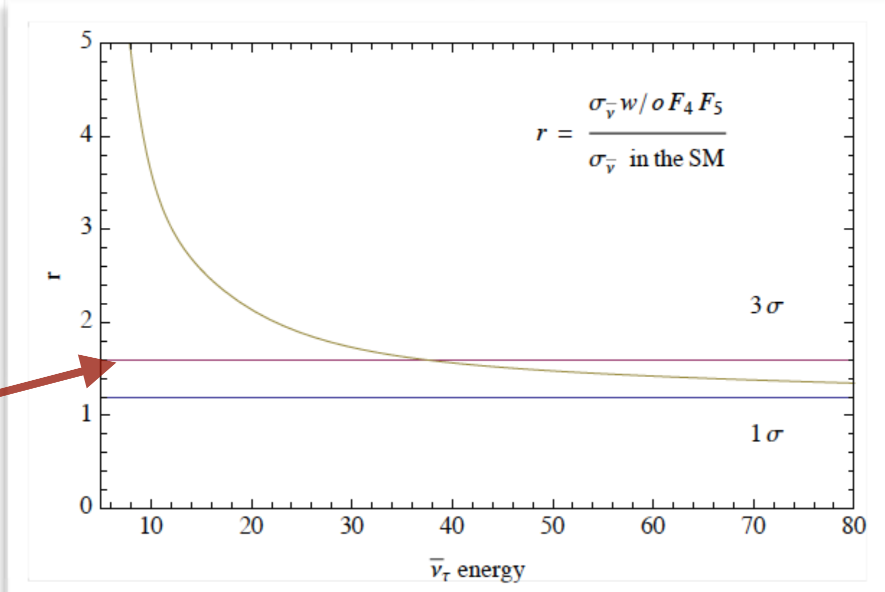
ν_τ DIS Cross-section



Anti-ν_τ DIS Cross-section



r = ratio between the cross section in the two hypotheses



E(anti-ν_τ) < 38 GeV (~300 evts)

E(ν_τ + anti-ν_τ) < 20 GeV (~420 evts)

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

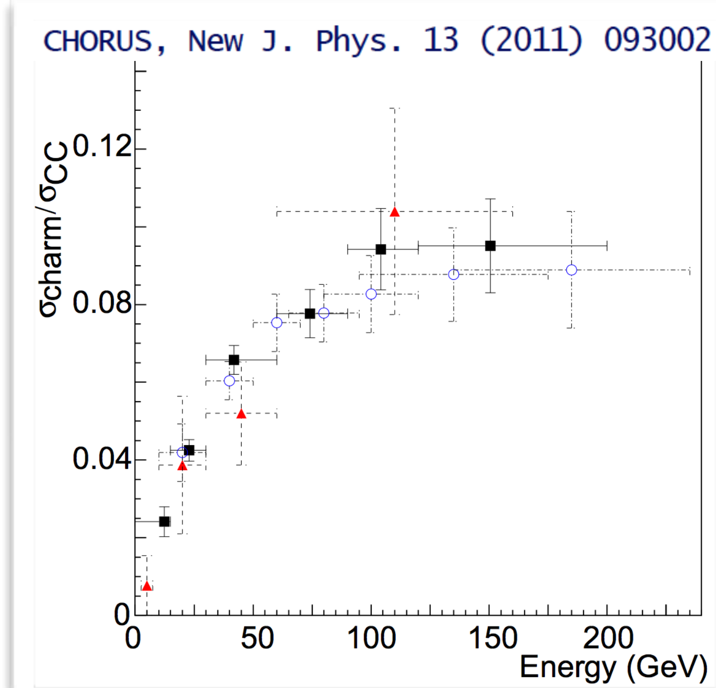
SENSITIVITY TO S-QUARK

- Charmed hadrons identified through the observation of their decay.
- Expected ν-induced charm yield in 5 years run:

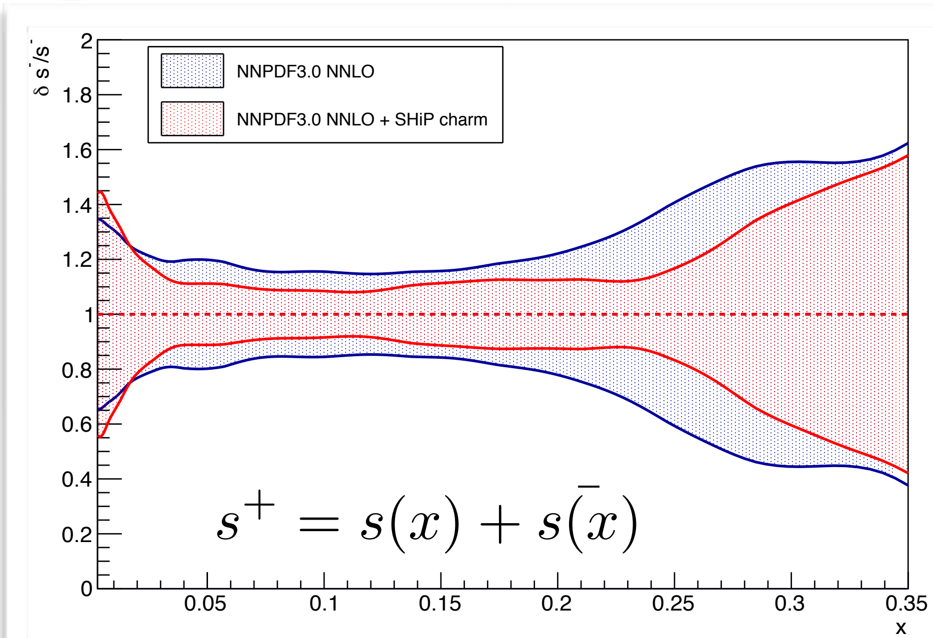
$$f(charm) = \frac{\int \Phi_{\nu_\mu} \sigma^{CC}_{\nu_\mu} \left(\frac{\sigma_{charm}}{\sigma^{CC}_{\nu_\mu}}\right) dE}{\int \Phi_{\nu_\mu} \sigma^{CC}_{\nu_\mu} dE} \approx 4\%$$

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

	Expected 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	$1.1 \cdot 10^5$



- Charmed hadron production in antineutrino interactions selects anti-strange quark in the nucleon
  - Improvement achieved on s+/s- versus x
  - Significant gain with SHiP data obtained in the x range between 0.03 and 0.35

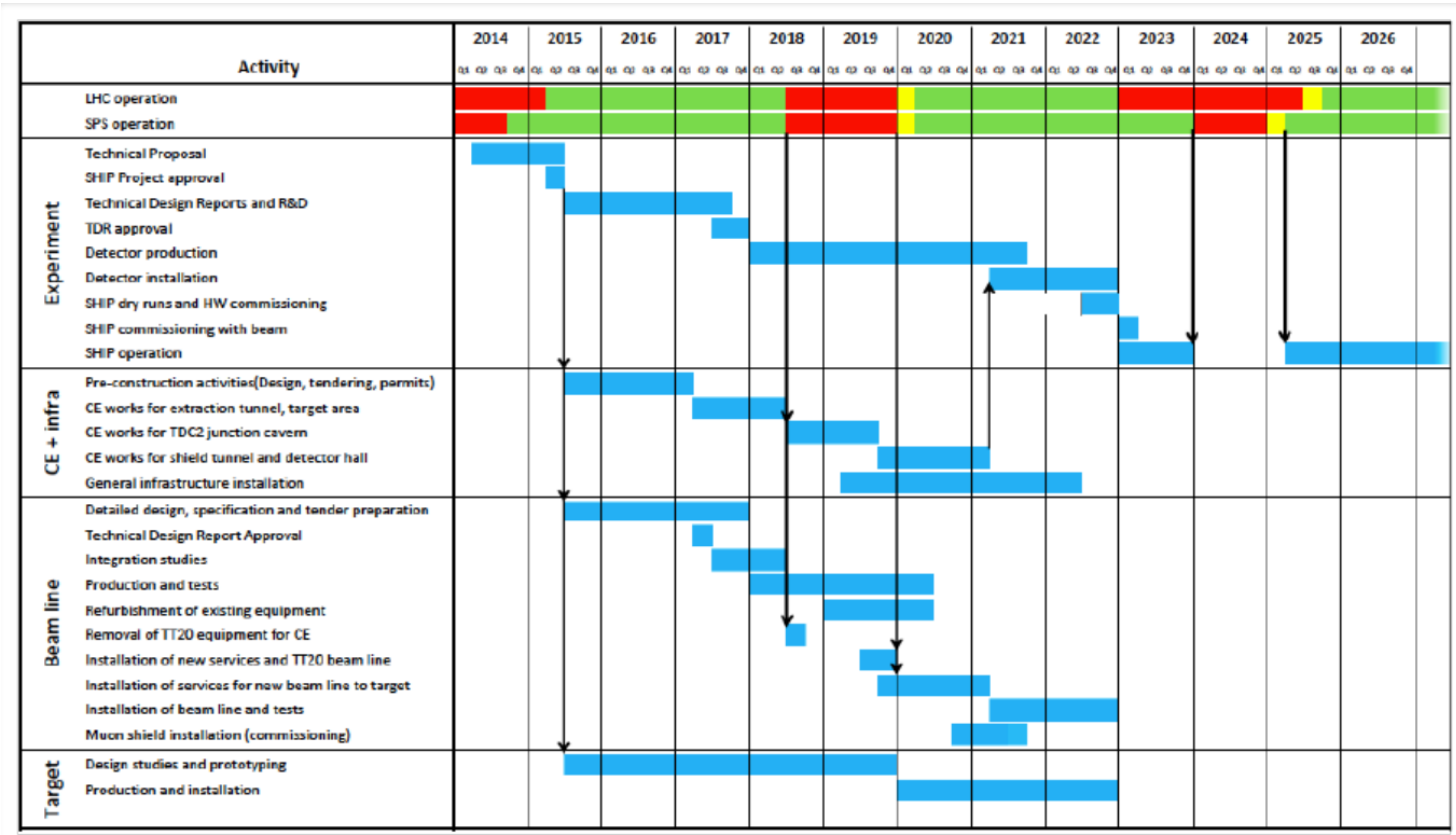


CONCLUSIONS

- The SHiP experiment is complementary to LHC physics program exploring the intensity frontier
  - Long-lived and very weakly interacting particles are searched for
    - Sterile neutrinos (Heavy Neutral Leptons)
    - Dark photons
    - Paraphoton
    - SUSY: Sgoldstino, Light neutralino
- Technical and Physics proposal have been submitted to the SPSC in April 2015
- Compact neutrino detector to perform SM physics studies @SHiP
  - Study ν_τ *and anti-*ν_τ *interactions*
    - Perform cross section measurements
    - Estimate structure functions (F_4 and F_5) from charged current neutrino nucleon deep-inelastic scattering
  - Study *physics of* ν*-induced charm events*

BACKUP SLIDES

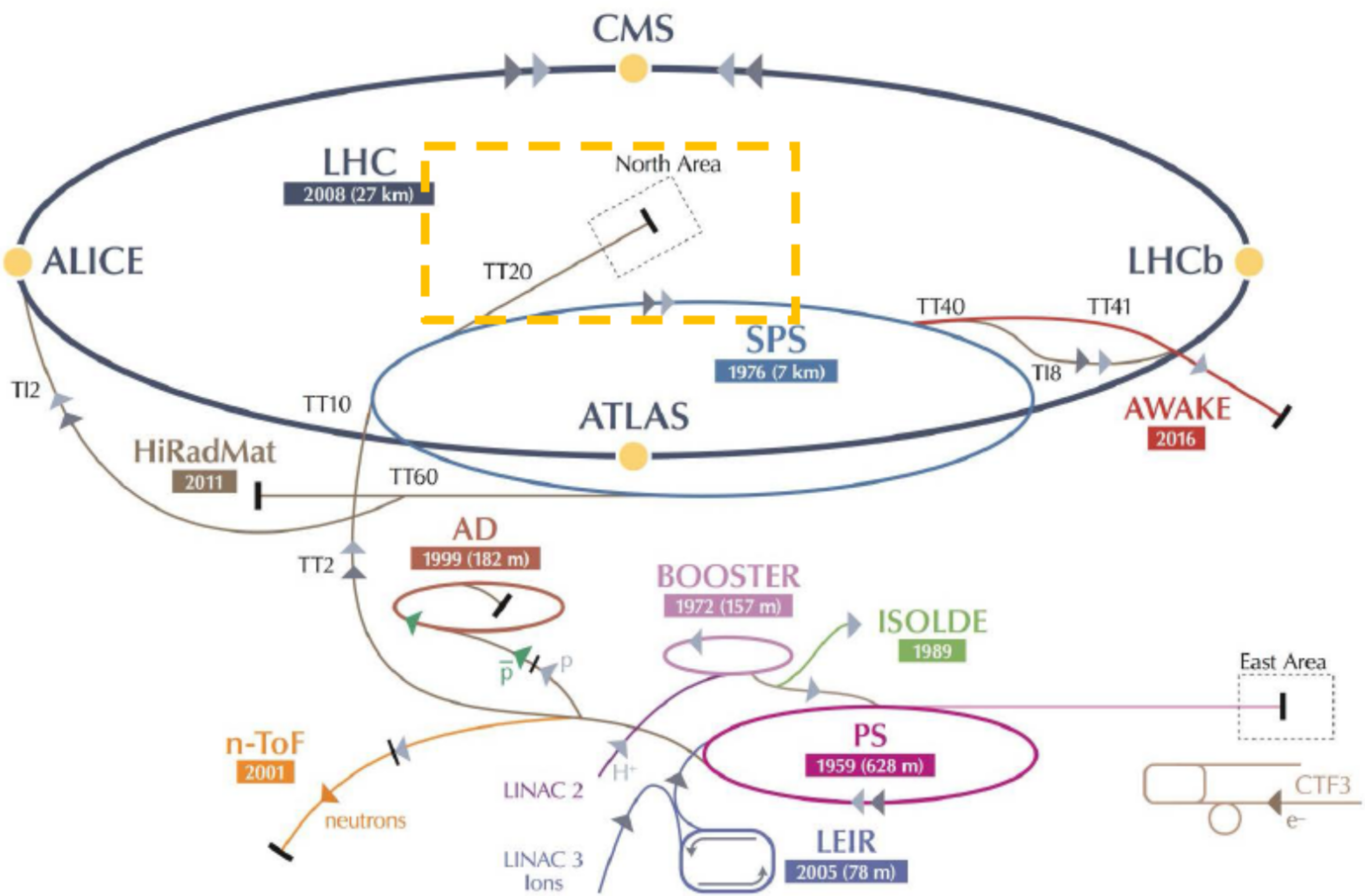
TIME SCALE



Form SHiP Collaboration	December 2014 ✓
Technical Proposal submission	April 2015 ✓
Technical Design Report submission	2018
Building and installation	2018-2022
Commision	2022
Data taking and analysis	2023-2027

CERN Accelerator complex

proposed location by CERN beams and support department



HIDDEN PORTALS

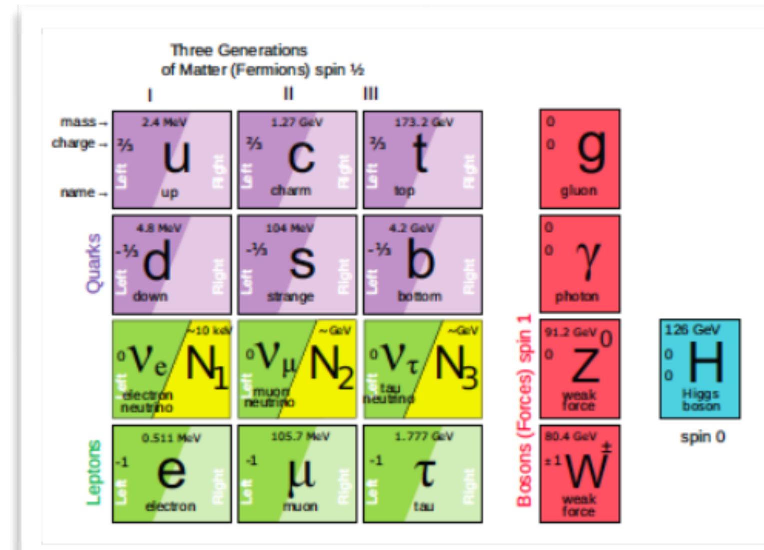
- The Hidden Sector can be accessed in weak coupling frontier experiments through light particles coupled to the SM through renormalized portals.

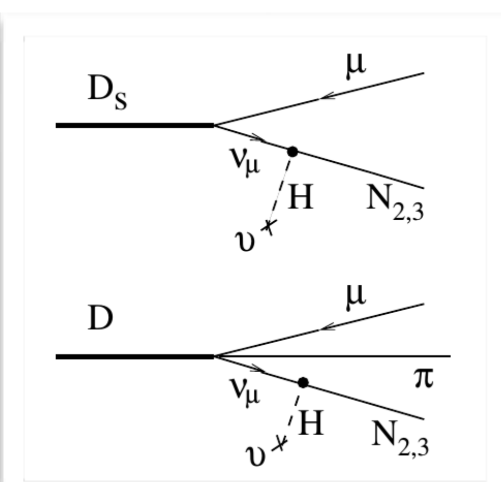
- Vector portal (dark, hidden, para-photons)
  - Connection between MS and DM
  - Solution to g-2 muon anomaly
- Scalar portal
  - Mixing with standard model Higgs
- Neutrino portal
  - Mixing with RH neutrinos (HNL)
  - Explain neutrino oscillations, Dark Matter, Baryon Asymmetry

THE NEUTRINO MINIMAL STANDARD MODEL

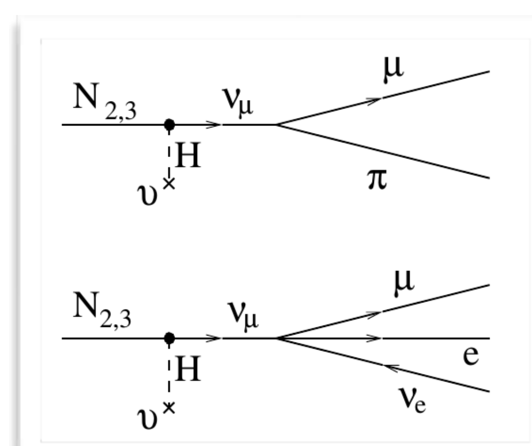
[1] T.Asaka, M.Shaposhnikov PL B620 (2005) 17

- Minimal extension (nor new physical principles nor new energy scales required) of the SM fermion sector by three RH (Majorana) Heavy Neutral Leptons (**HNL**): N_1, N_2, N_3.
- HNL Main Features:
  - Lightest singlet N_1 (mass in KeV region): good dark matter candidate.
  - N_2, N_3 (mass in 100 MeV - GeV region):
    - "give" masses to neutrinos;
    - explain baryon asymmetry;





Can be produced in the decay of charm hadrons



Can decay in SM particles

HP BACKGROUND

Expected number of background events from MC simulation for 5 years of data taking.

ratio between the equivalent MC statistics and the total expected number of events

Background source	Statistical factor	Expected background
ν ($p > 10.0$GeV)	35.	≤ 0.07
ν (4.0GeV$< p <$ 10.0GeV)	~ 1	0 (MC)
ν (2.0GeV$< p <$ 4.0GeV)	0.07	0 (MC)
μ DIS HS	~ 1	0 (MC)
μ DIS wall	0.001	0 (MC)
μ Combinatorial	10^4	< 0.1
μ Cosmics ($p <$ 100GeV)	0.2	0 (MC)
μ Cosmics ($p >$ 100GeV)	800.	< 0.1
μ Cosmics DIS ($p >$ 100GeV)	10^3	< 0.1
μ Cosmics DIS (10GeV$< p <$ 100GeV)	~ 1	0 (MC)

0 bkg events observed in the MC

- no evidence of significant impact of any of these backgrounds on the experiment
- any evidence for any source of irreducible background

Assumed a level of background of 0.1 events for the entire run of the experiment → 3σ evidence if 2 events of HNL are observed

NEUTRINO FLUXES

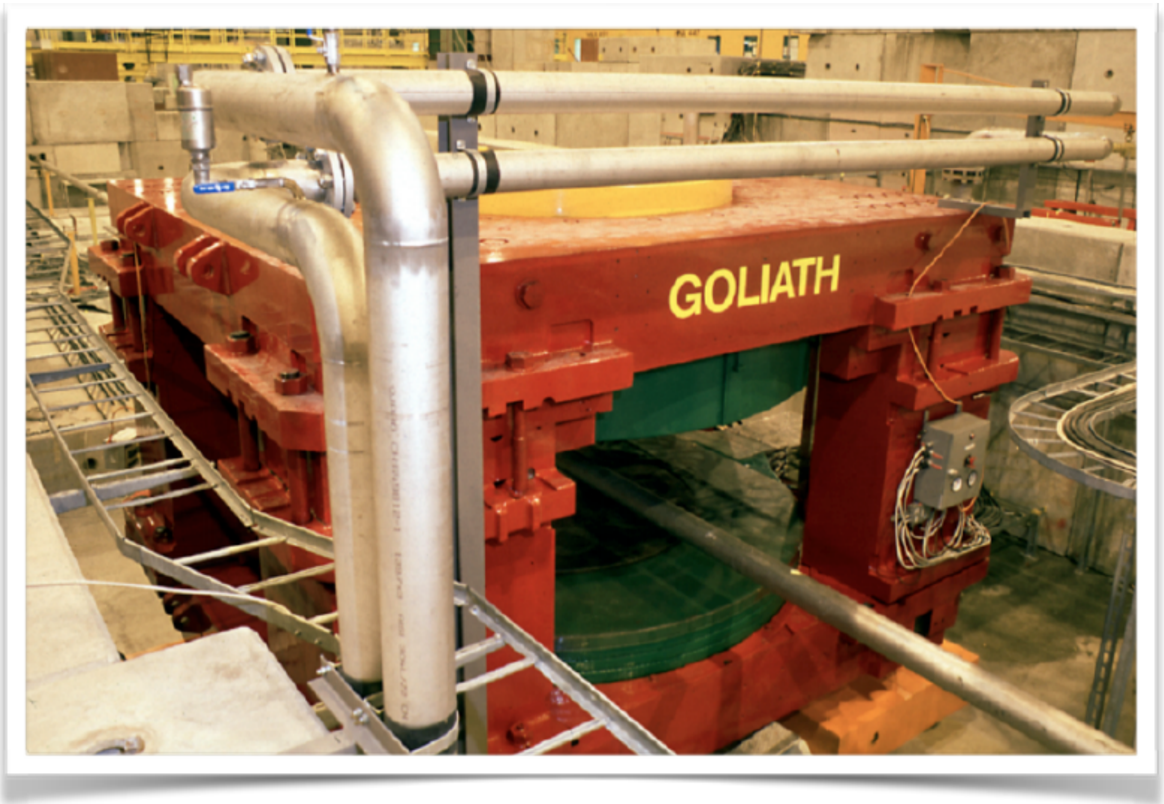
SHiP experimental setup ideally suited to perform studies on neutrino and anti-neutrino physics.
High charmed hadrons decay rates ⇒ high ordinary neutrino fluxes

	<E> (GeV)	Beam dump	<E> (GeV)	Neutrino target	<E> (GeV)	CC DIS interactions
N_{ν_e}	3	$2.1 \cdot 10^{17}$	28	$3.6 \cdot 10^{15}$	46	$2.5 \cdot 10^{5}$
N_{ν_μ}	1.4	$4.4 \cdot 10^{18}$	8	$5.2 \cdot 10^{16}$	29	$1.7 \cdot 10^{6}$
N_{ν_τ}	9	$2.8 \cdot 10^{15}$	28	$1.4 \cdot 10^{14}$	59	$6.7 \cdot 10^{3}$
$N_{\overline{\nu}_e}$	4	$1.6 \cdot 10^{17}$	27	$2.7 \cdot 10^{15}$	46	$9.0 \cdot 10^{4}$
$N_{\overline{\nu}_\mu}$	1.5	$2.8 \cdot 10^{18}$	8	$4.0 \cdot 10^{16}$	28	$6.7 \cdot 10^{5}$
$N_{\overline{\nu}_\tau}$	8	$2.8 \cdot 10^{15}$	26	$1.4 \cdot 10^{14}$	58	$3.4 \cdot 10^{3}$

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

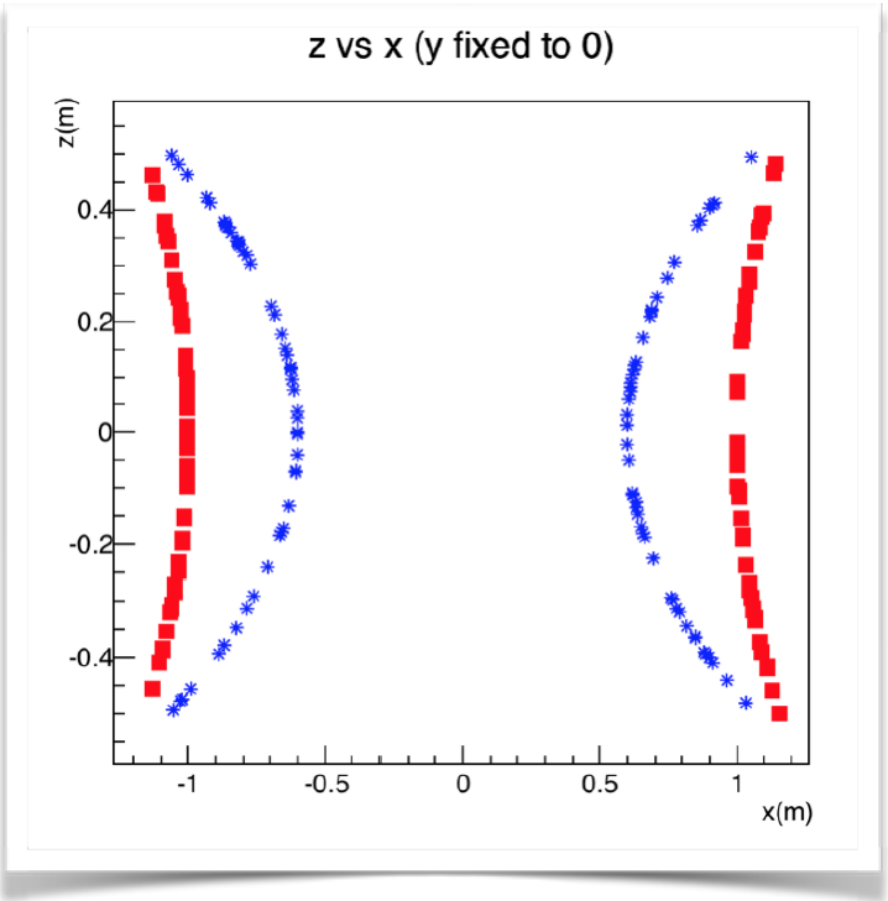
TARGET MAGNETIZATION

GOLIATH MAGNET
CERN H4 beam line inside 2389 PPE 134 zone



- 1 Tesla vertical magnetic field
- few m^3 volume with constant magnetization

Magnetic field behavior in the target region

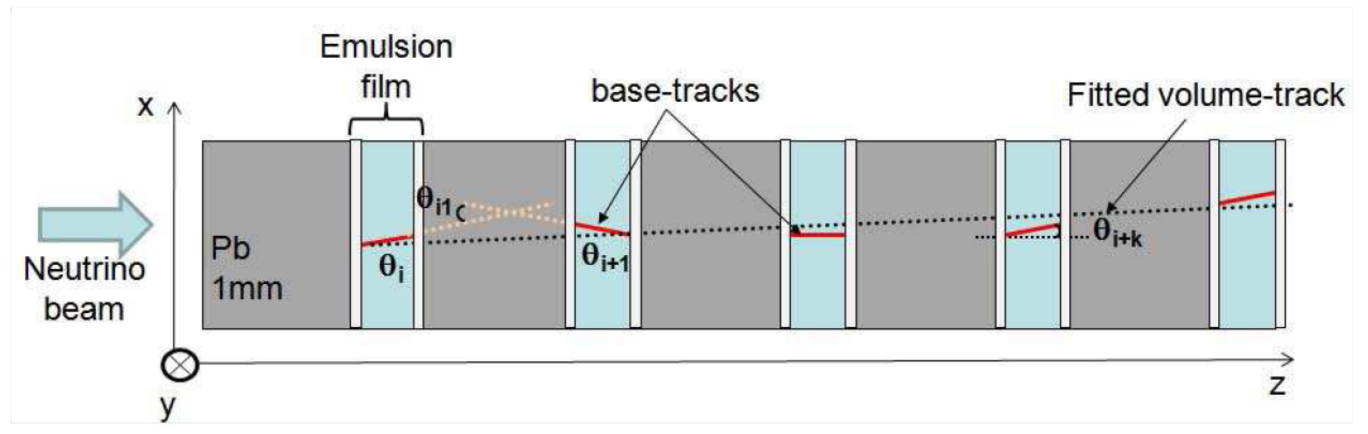


Within the blu curves B ≈ 1.5 T
Within the red curves B >=1 T

MEASURING MOMENTUM WITH ECC

- Total length of a brick ~ 10 X_0 (X_0 = 5.6 mm).
- Scattering is dominated by the lead
- Momentum measurement by MCS can be carried out in 2 ways:
  - track position (coordinate method)
  - track angle (angular method)

} Deviation of the trajectory from a straight line



$$\theta_0 = \frac{13.6}{(pc\beta)} \times \sqrt{\frac{x}{X_0}} \times \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

Momenta up to 8 GeV/c can be measured with a resolution better than 30%

ELECTRON/PION IDENTIFICATION

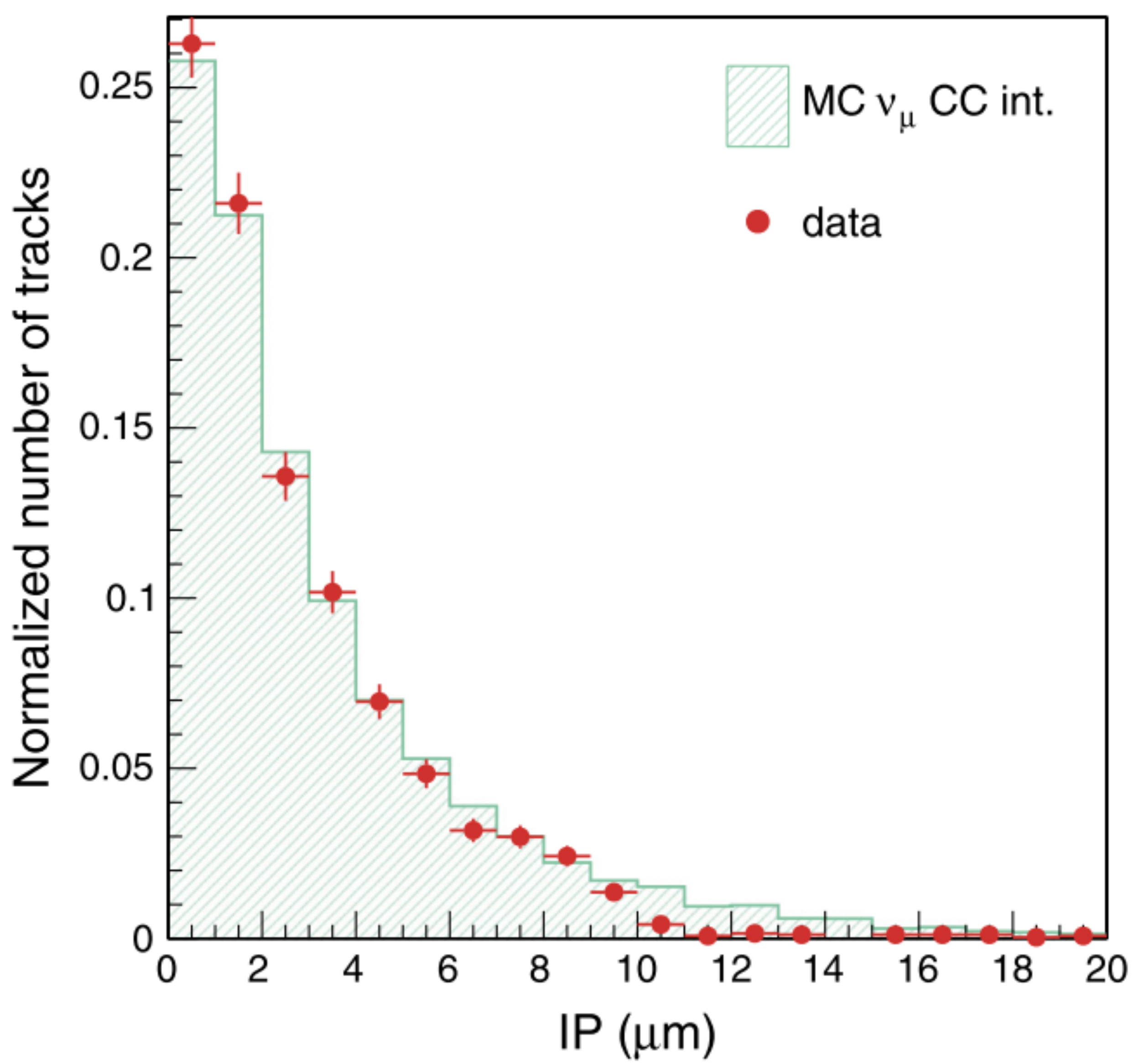
- The high granularity of the emulsions allows excellent e.m. shower identification.
- The separation of electrons and pions obtained by exploiting different behavior in passing through and interacting in an ECC.
- 2 complementary approaches:
  - study total number of tracks and different longitudinal and transverse profiles
  - study of Multiple Coulomb Scattering longitudinal profiles
    - going through a material, the energy remains almost constant for pions whilst strongly decreases for electrons

π CONTAMINATION

e⁻ EFFICIENCY

E (GeV)	$\varepsilon_{e\to e}$ %	$\eta_{\pi\to e}$ %
	Data	
0.5	—	—
1	—	—
2	—	0.5±0.1
3	80±18	—
4	—	0.3±0.1
5	—	—
6	94.7±0.9	0.2±0.1
8	—	—

RESOLUTION ON THE I.P.



Impact parameter distribution after the vertex film analysis of located ν_μ CC interactions compared to MC expectations.

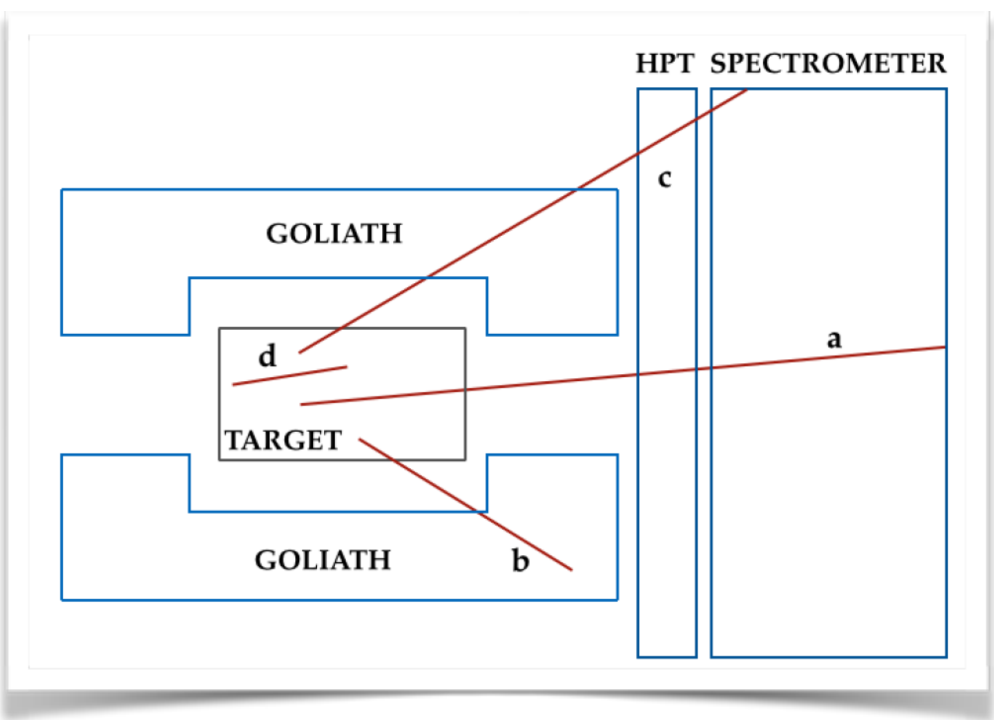
Average value of about 3 μm

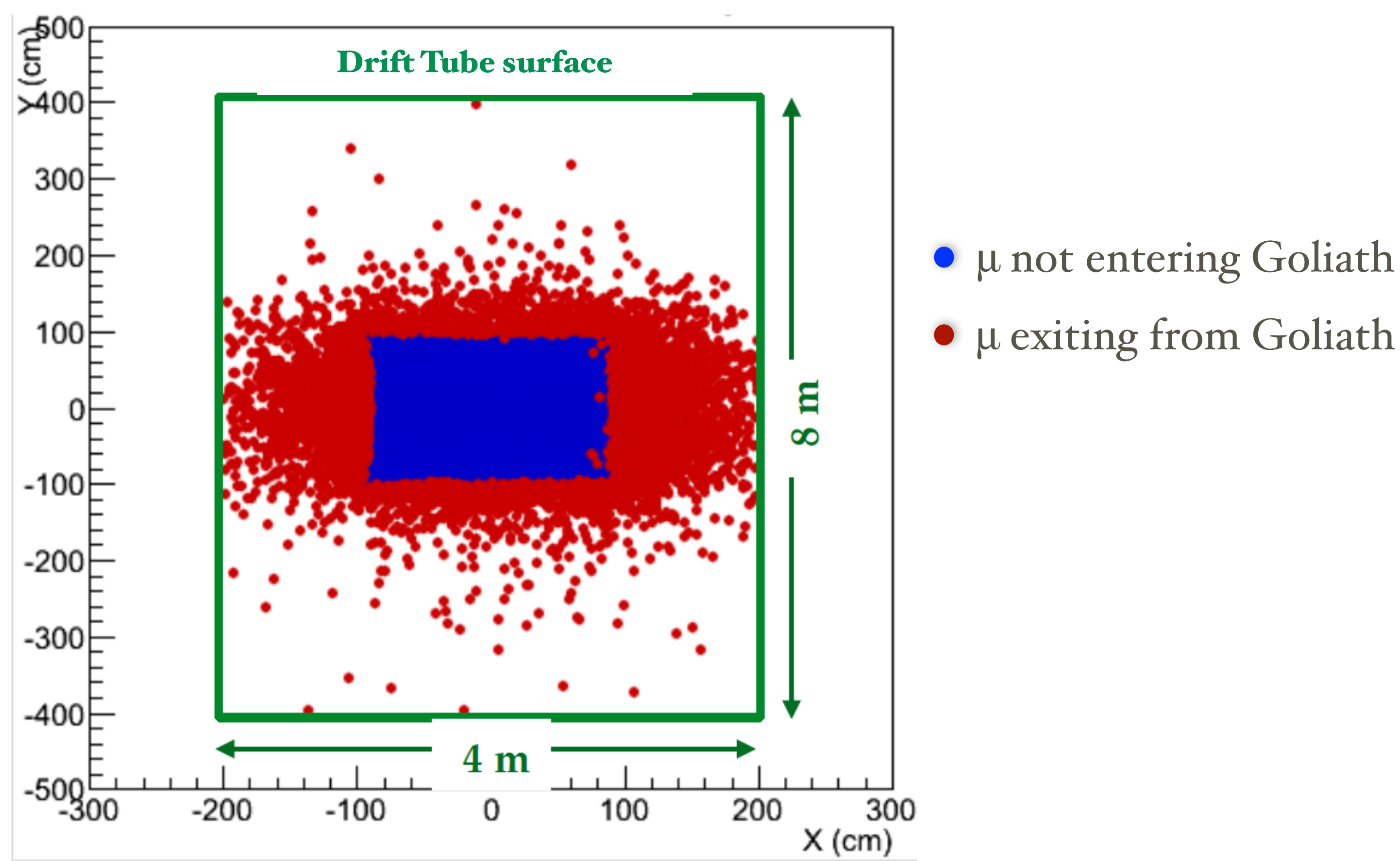
μ IDENTIFICATION

Muons produced in ν_μ CC interactions with ***charm production*** in the target:

- **~ 70%** reach the Spectrometer without entering the Goliath Magnet **(A)**
- **~ 2%** absorbed in the Goliath Iron **(B)**
- **~ 4%** exit the Goliath and reach the first HPT plane **(C)**
- **~ 5%** stop in the neutrino target or exit laterally **(D)**

➡ Drift Tube detectors can partially recover muons crossing the Goliath Iron





DETECTOR PERFORMANCES

μ identification

Requirements:

1. track crossing 3 RPC layers in the ARM1 of the Magnetic Spectrometer
2. track crossing the Goliath Iron and reaching at least the first HPT plane

The usage of the HPT plane for the muon identification in case 2. increases the muon identification efficiency of about 2%

Muon identification efficiency of about 90% for both charm events (and for the muonic decay channel of the τ lepton

Charge measurements

- Charge of the hadrons is measured by the Compact Emulsion Spectrometer (CES)
- Charge of the muons by the magnetic spectrometer and the CES

$\epsilon^{h}_{charge} = 70\%$ $\epsilon^{\mu}_{charge} = 94\%$ $\epsilon^{3h}_{charge} = 49\%$ Correct assignment efficiencies

$\omega^{h}_{charge} = 0.5\%$ $\omega^{\mu}_{charge} = 1.5\%$ $\omega^{3h}_{charge} = 1.0\%$ Charge Misidentification probabilities

COSTS

Table 6.2: Overall cost of the SHiP facility and the detectors.

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	11.1	
Hidden Sector detector	46.8	
Computing and online system	0.2	
Grand total		**194.5**