SHiP
Search for Hidden Particles

Neutrino physics with the SHiP experiment at CERN

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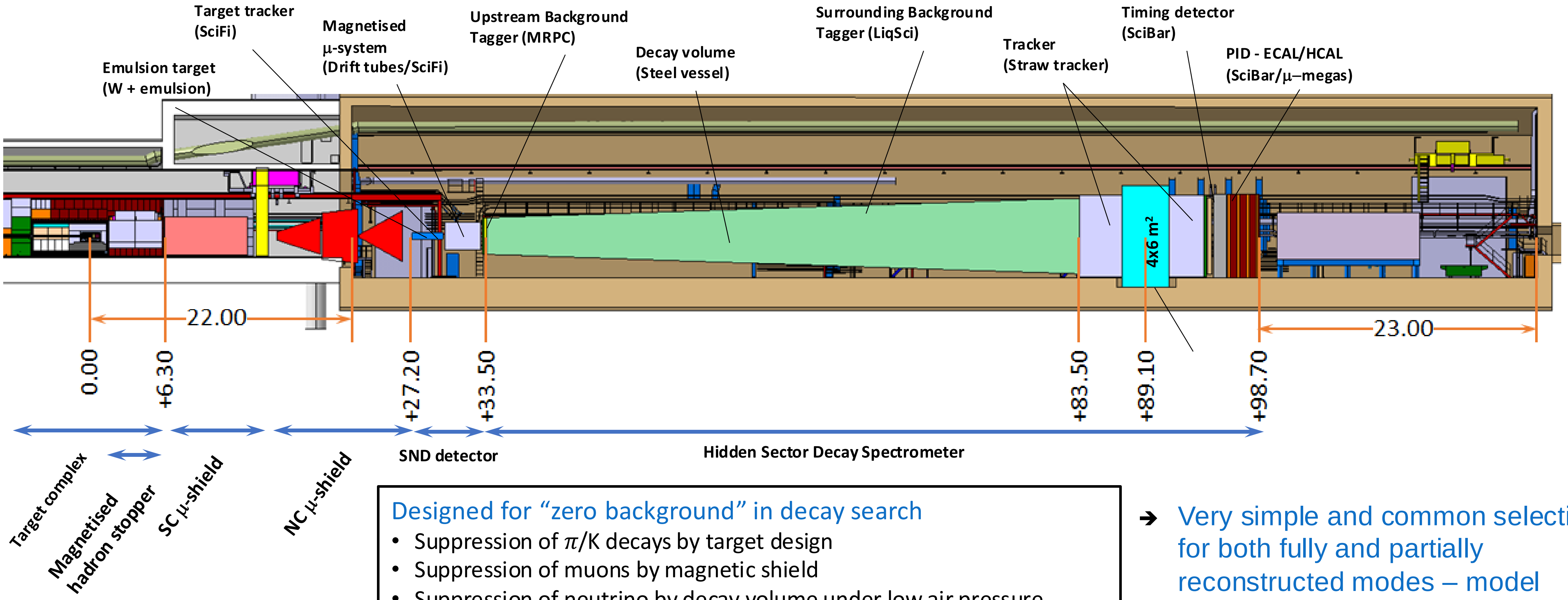
On behalf of the SHiP Collaboration

http://cds.cern.ch/record/2007512/files/SPSC-P-350.pdf Technical Proposal in 2015

EPJC (2022) 82:486

Overview of the SHiP detector for SM ν and HS particles



Designed for "zero background" in decay search

- Suppression of π/K decays by target design
- Suppression of muons by magnetic shield
- Suppression of neutrino by decay volume under low air pressure
- Background veto taggers
- Momentum and decay vertex information
- Impact parameter at target
- Coincidence timing

} by main tracker

- Invariant mass
- Particle identification

} Not currently used in background suppression

➔ Very simple and common selection for both fully and partially reconstructed modes – model independence

➔ Redundant selection- Possibility to measure background with data by relaxing suppression techniques

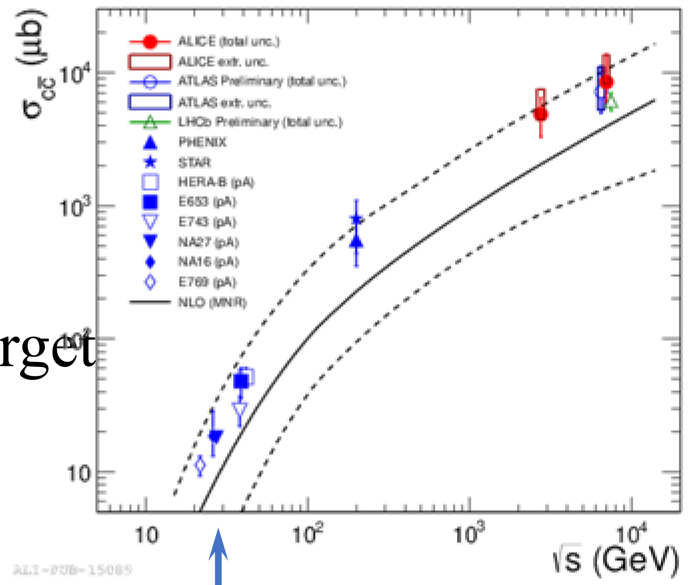
BDF/SHiP optimization of physics reach

- Target design for signal/background optimisation:
  - Very thick → use full beam and secondary interactions (12λ)
  - High-A&Z → maximise production cross-sections (Mo/W)
  - Short λ (high density) → stop π/kaons before decay

➔BDF luminosity with the optimised target and 4x10^{19} protons on target per year *currently available* in the SPS

➔ BDF@SPS $\mathcal{L}_{int}[year^{-1}]$ = >4 x 10^{45} cm^{-2} (cascade not incl.)

➔ HL-LHC $\mathcal{L}_{int}[year^{-1}]$ = 10^{42} cm^{-2}



BDF @ $\sqrt{s} = 27\ GeV$

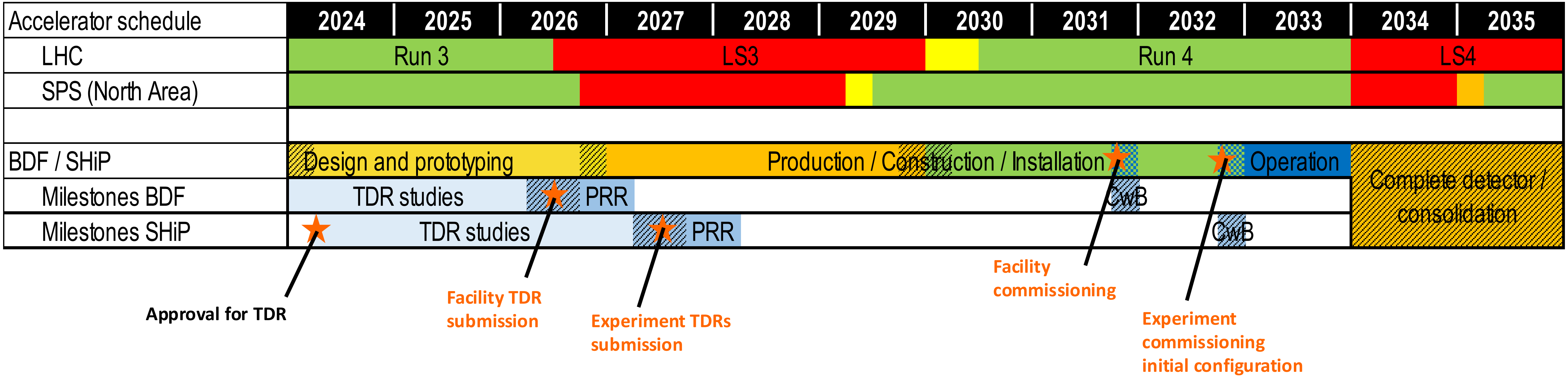
➔ BDF/SHiP ***annually*** access to yields towards detector acceptance:

- ~ 2×10^{17} charmed hadrons (>10 times the yield at HL-LHC)
- ~ 2 × 10^{12} beauty hadrons
- ~ 2×10^{15} tau leptons
- O(10^{20}) photons above 100 MeV
- Large number of neutrinos *detected* with 3t-W ν-target:
  3500 $\nu_\tau + \bar{\nu}_\tau$ *per year*, and 2×10^5 $\nu_e + \bar{\nu}_e$ / 7×10^5 $\nu_\mu + \bar{\nu}_\mu$ despite target design

σ(pp→ssbar X)/σ(pp→X) ~ 0.15
σ(pp→ccbar X)/σ(pp→X) ~ 2x10^{-3}
σ(pp→bbbar X)/σ(pp→X) ~ 1.6 x10^{-7}
Cascade effect, e.g. >2 for charm

- Plan to operate beam and facility with 4x10^{19} protons/year for 15 years

BDF/SHiP schedule



- ~3 years for detector Technical Design Reports
- Facility implementation starting in Long Shutdown 3 of CERN's accelerator complex
- Important to start data taking in 2032, ~2 year before Long Shutdown 4

➔ Complete detector at the latest in LS4 with initial configuration operating in 2032-2033

→ Objectives: commissioning facility/detector, performance, background measurements, physics in nominal conditions

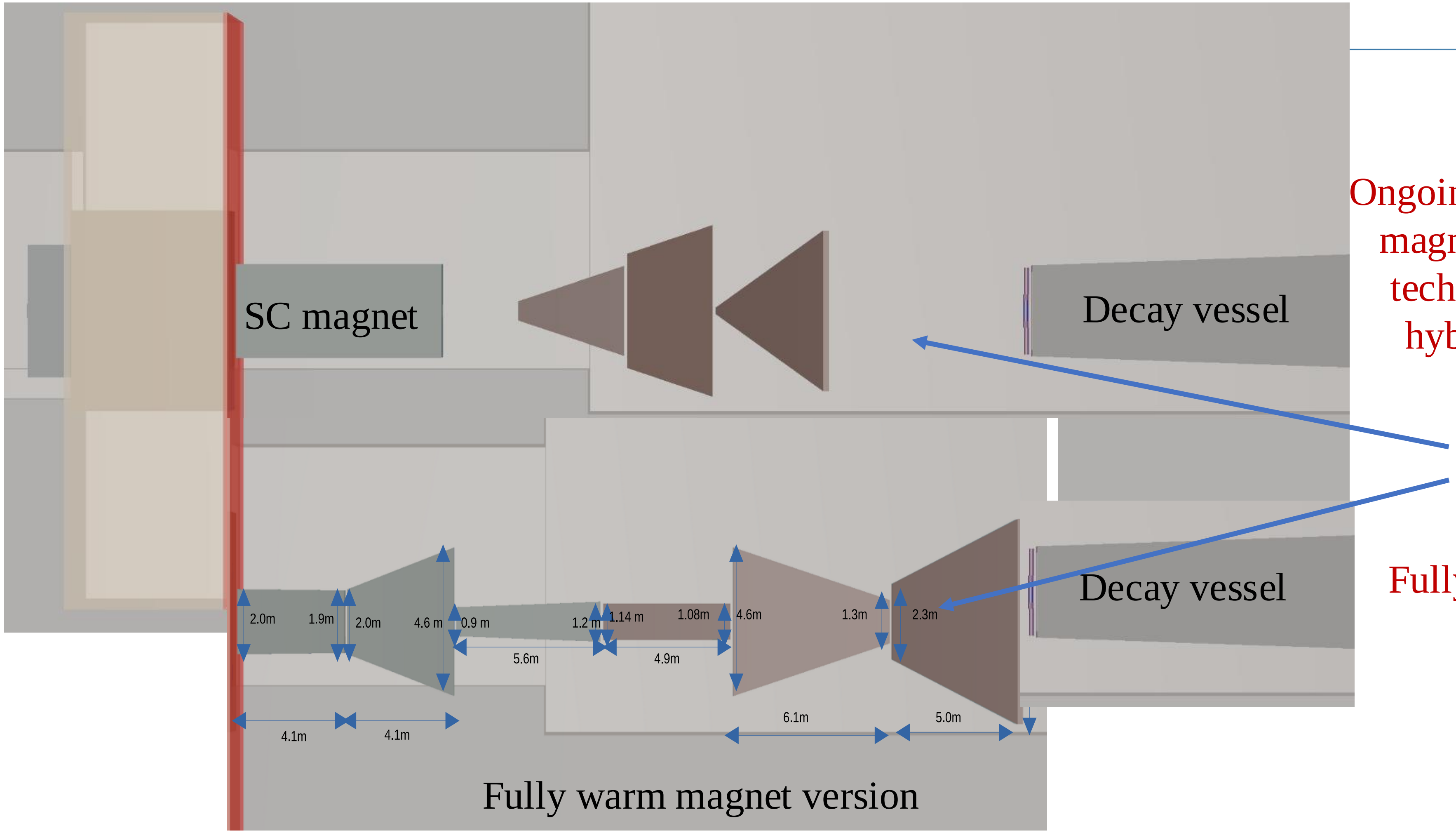
→ Critical systems in full scale and full physics capability

→ Prototypes may fill "holes" in 2032-2033

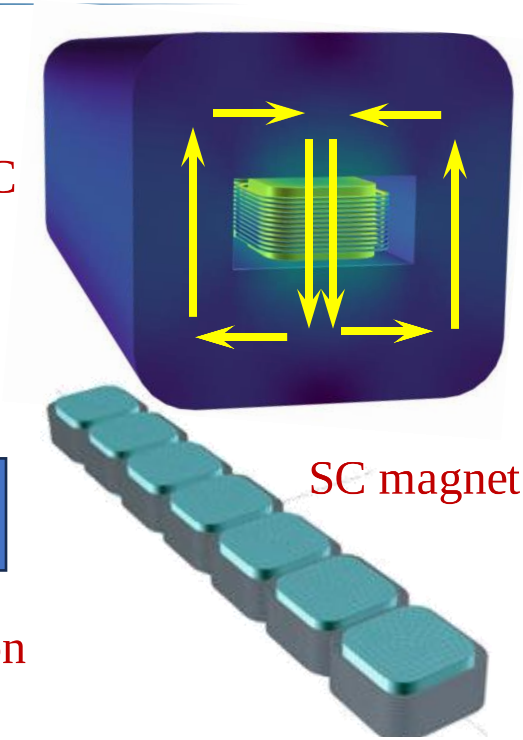
SPS decoupled from injector role in 2042, fully dedicated to proton/ion FT physics

➔ 15 years of physics exploration

SND detector embedded in the muon shield

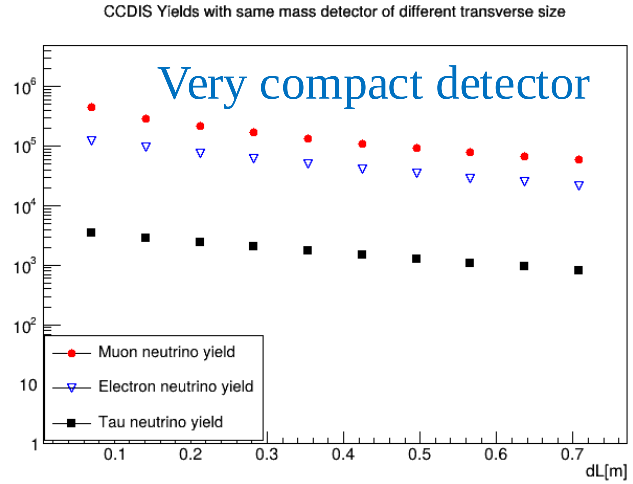


Ongoing R&D on SC magnet with HTS technology for a hybrid version



SND

Fully warm version



SND requires a muon spectrometer (magnet) → embed it within the magnetised iron of the muon shield

SND concept synergic with SND@LHC experiment → see C. Vilela's talk

http://arxiv.org/abs/1804.04413, First paper on feasibility of studying neutrinos at LHC, Apr 2018

Physics potential of an experiment using LHC neutrinos, in 2019

https://iopscience.iop.org/article/10.1088/1361-6471/ab3f7c/pdf

Existing site: TI-18 tunnel

- 480 from ATLAS IP1

Integrated luminosity so far (2022-2024): ~190 fb^{-1}

Off-axis: $7.2 < \eta < 8.4$

3 Scintillator planes as Veto system

Target, Vtx and Ecal

830 kg tungsten target.

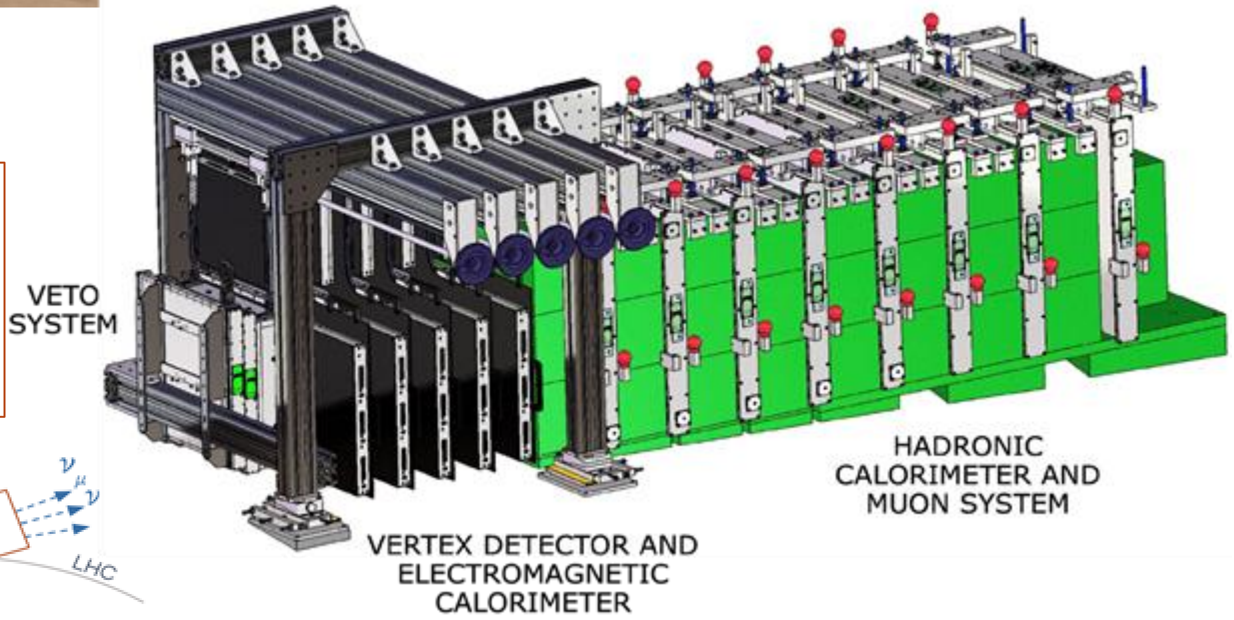
5 walls with 59 emulsion films

+ 5 SciFi stations. 84 X_0, 3 λ_{int}

HCal and μ ID system

Iron blocks + scintillator planes.

Finer granularity downstream to track muons. 9.5 λ_{int}



JINST 19 (2024) 05, P05067

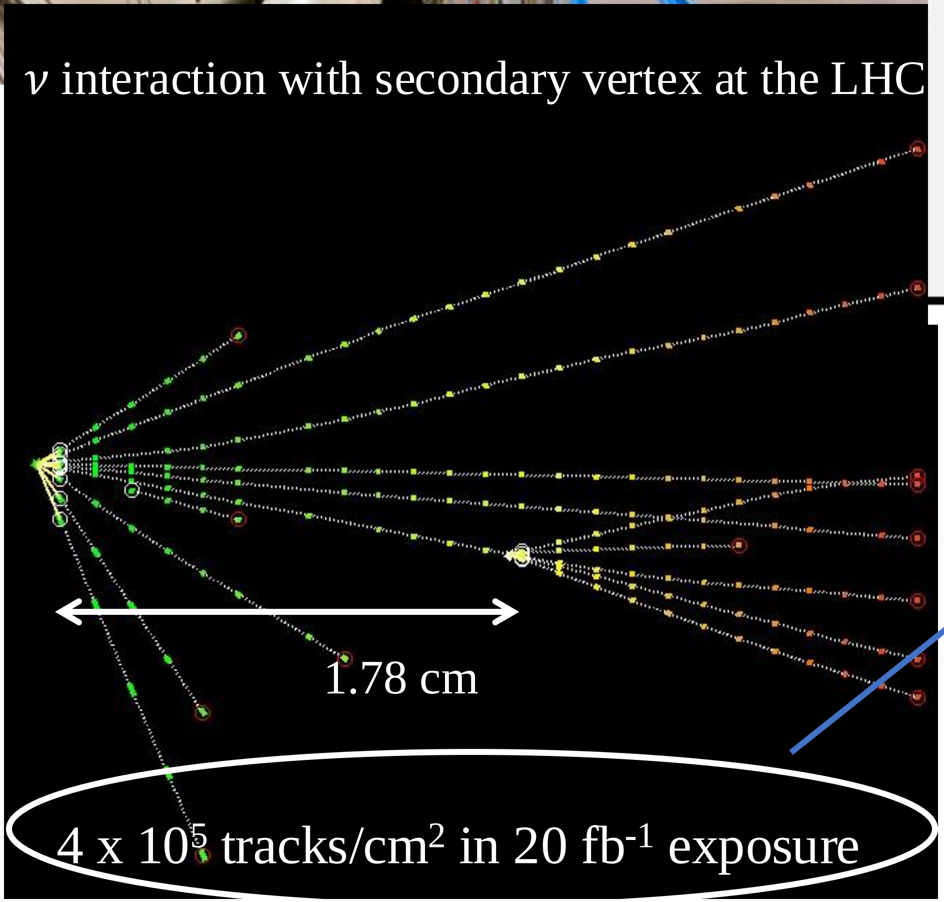
PHYSICAL REVIEW LETTERS **131**, 031802 (2023)

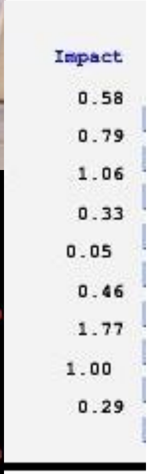
PRL

Editors' Suggestion

July 2023

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

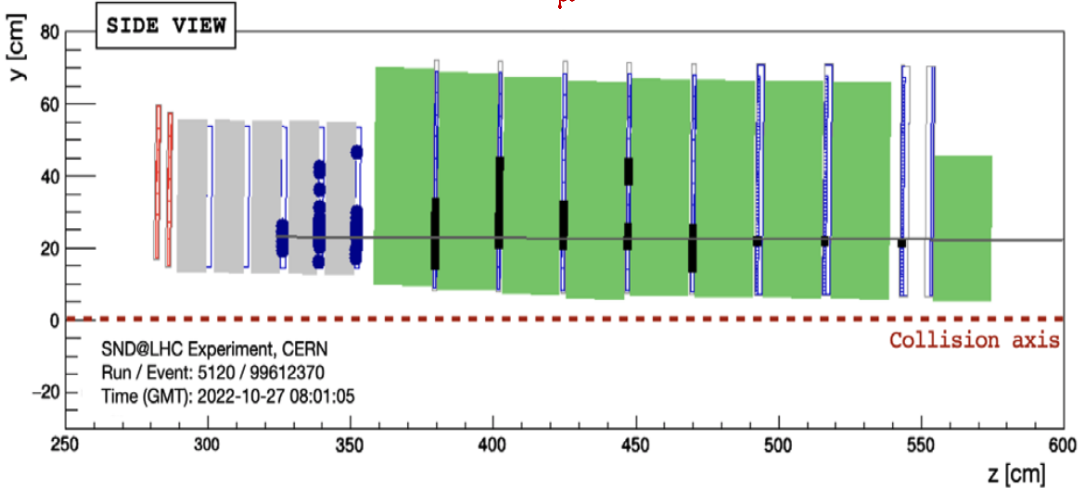




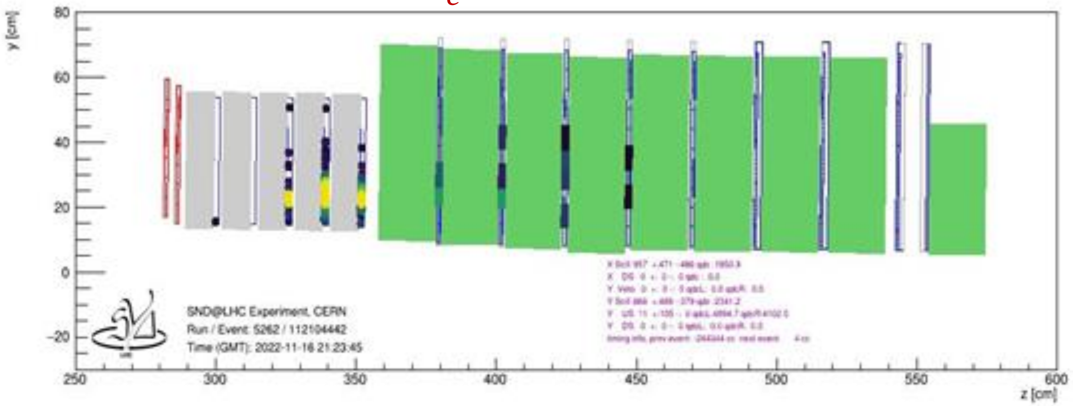
(μm)

Conditions similar to the expected SHiP environment!

One of the ν_μ candidates



ν_e-like candidate event



9 candidates

6.4 σ observation of $\nu_{0\mu}$

3.7 σ evidence for ν_e

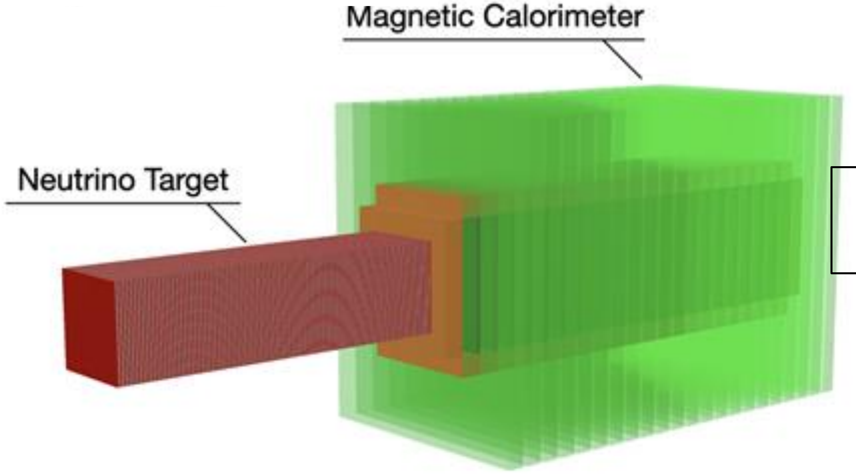
https://arxiv.org/abs/2411.18787

Observation of collider neutrinos without final state muons with the SND@LHC experiment

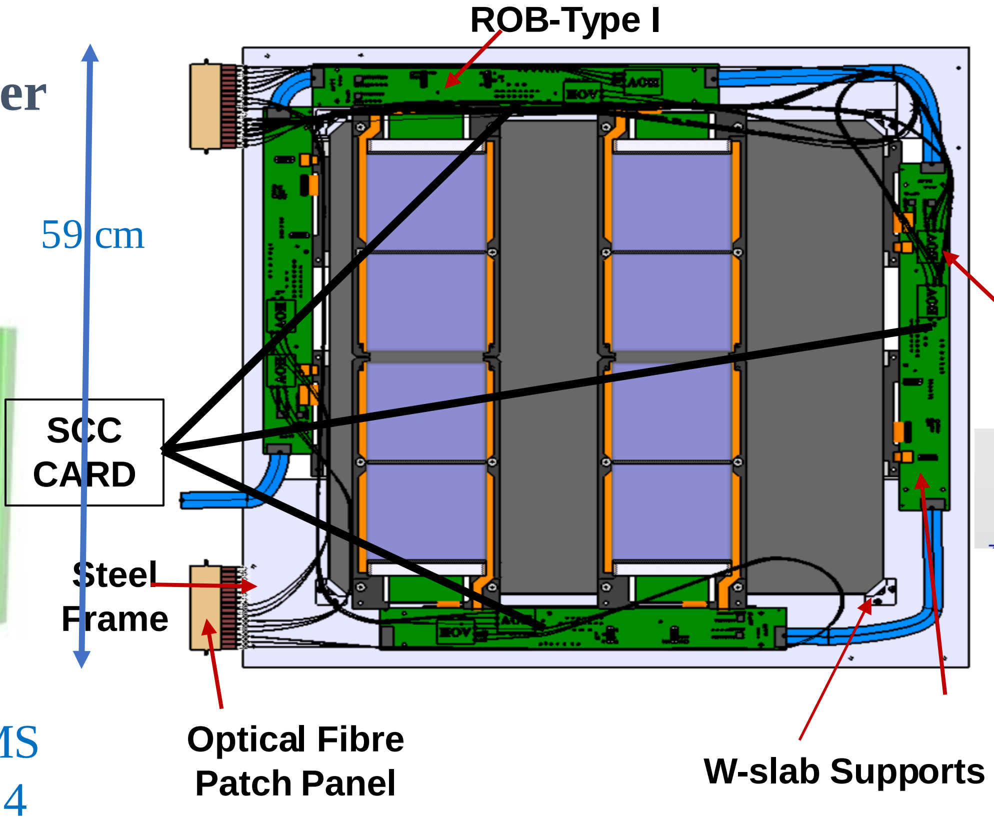
A first silicon prototype in synergy with the HL run of SND@LHC

- Silicon trackers as vertex detector
- Iron-core **muon spectrometer**
- Silicon-based **hadron calorimeter**

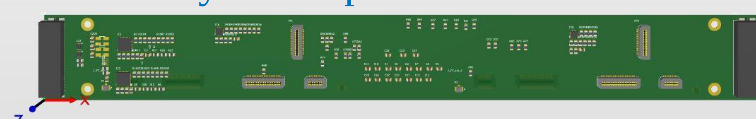
SND@LHC in HL

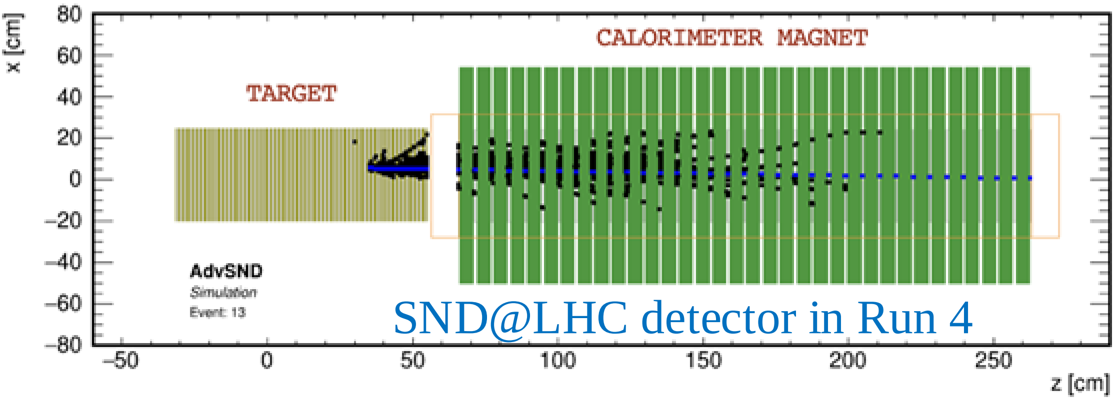


High-resolution silicon strips from CMS TOB used by the SND@LHC in Run 4



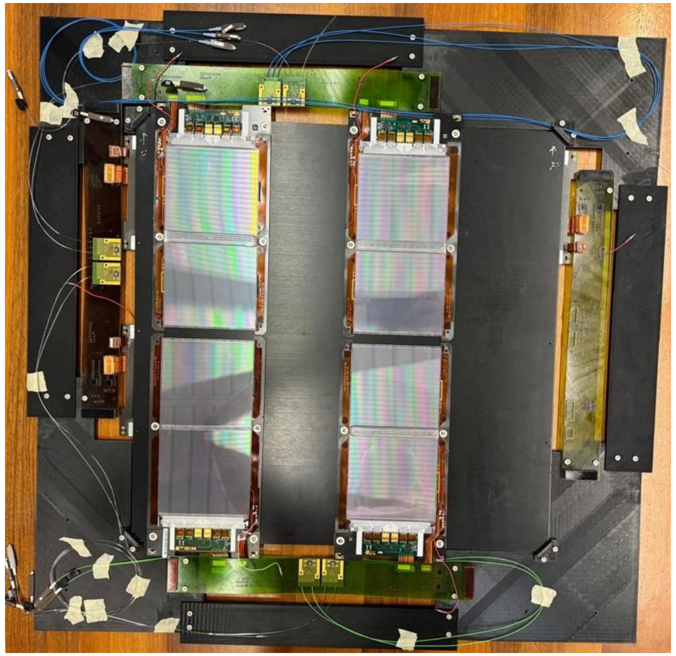
Newly developed ROB



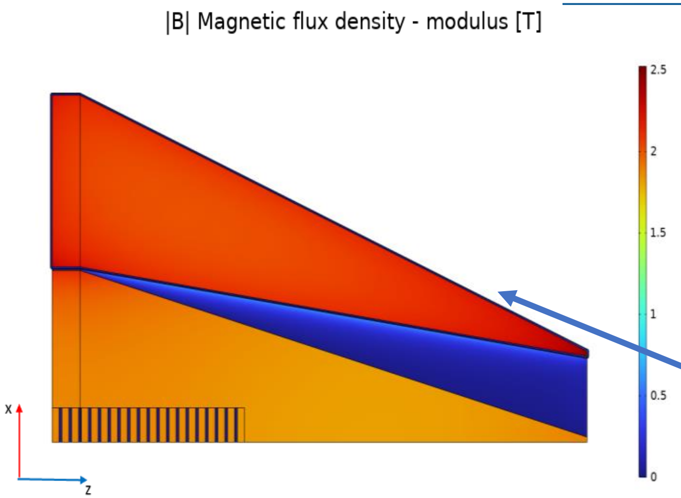


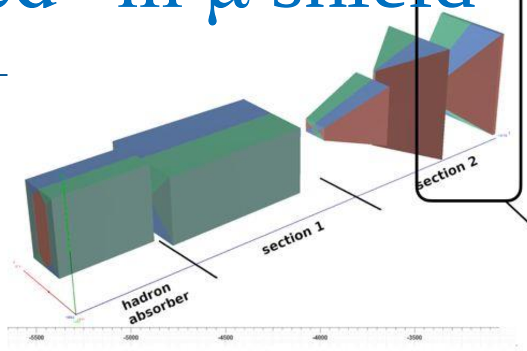
SND@LHC detector in Run 4

First full size
(40 x 40 cm^2)
Silicon module assembled



SND detector "embedded" in μ shield

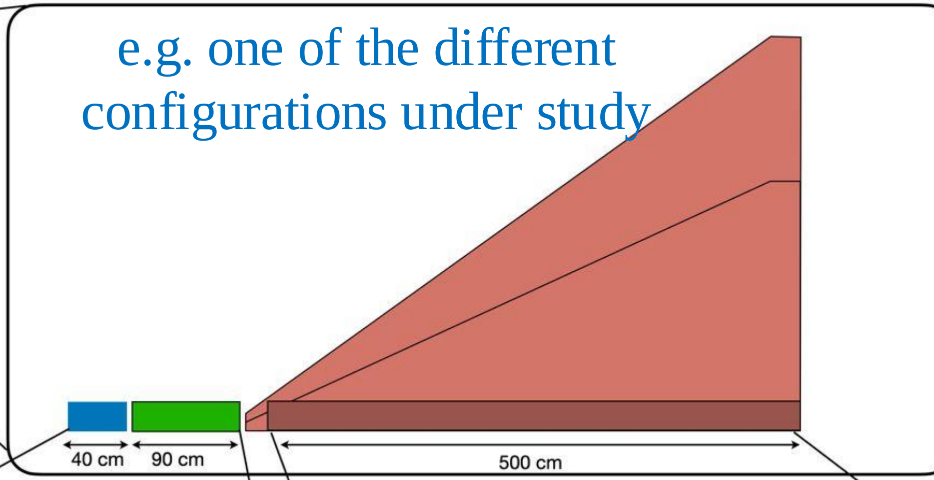




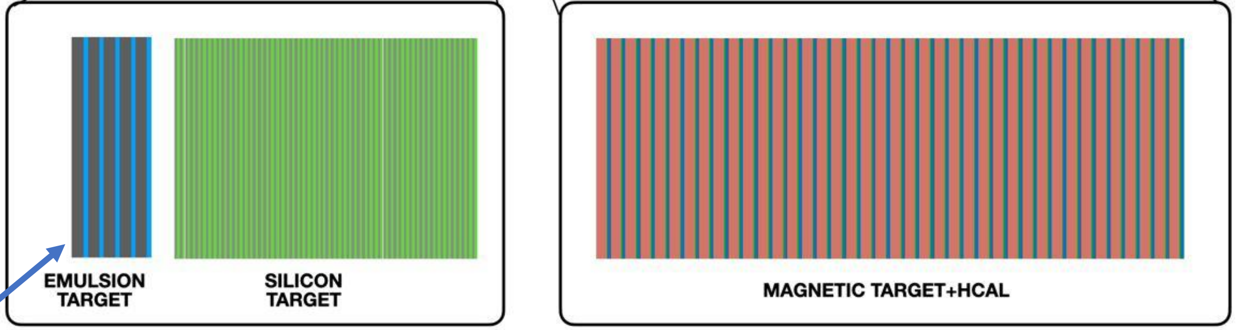
compliance with magnetic properties

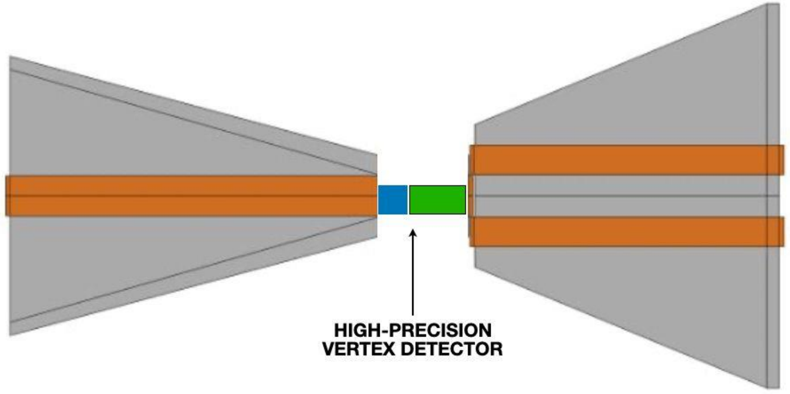
$N * I$ (magnetomotive force)	[kAturns]	53.6
$\langle B_y \rangle$ in the active region (iron leg)	[T]	1.678
$\left| \int_{z-length} B_y \, dl \right|$ (whole magnet)	[T*m]	6.371

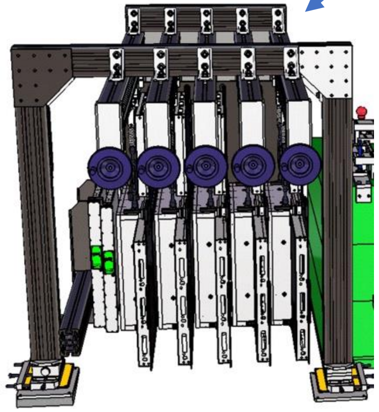
e.g. one of the different configurations under study

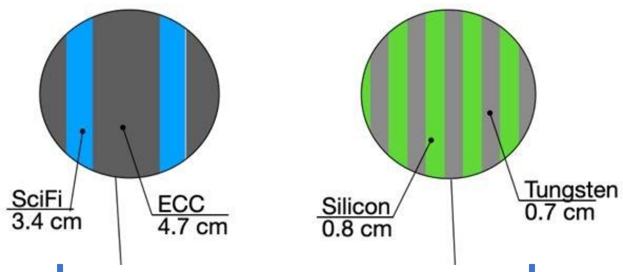


High-precision VTX detector





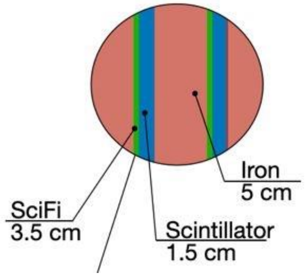




0.5t

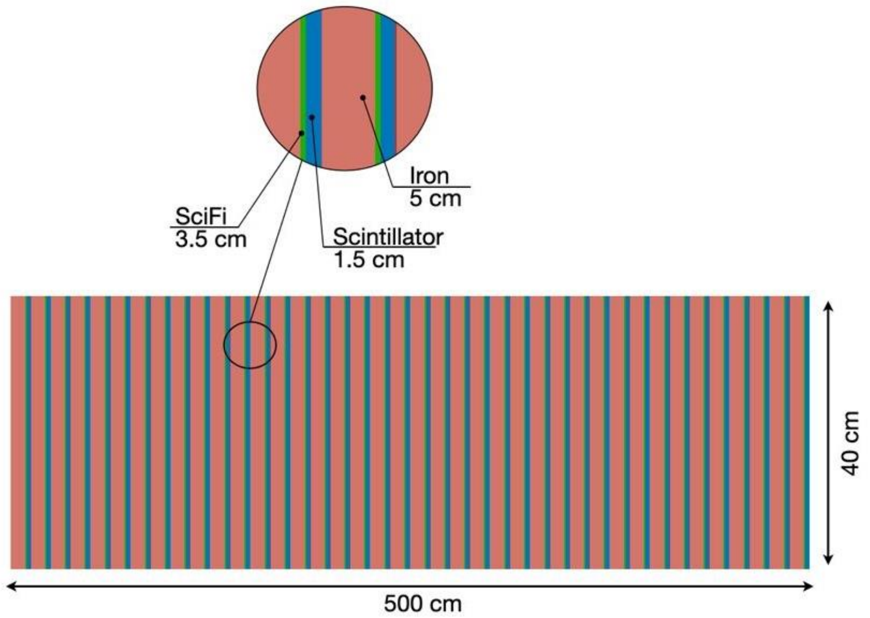
1.2t

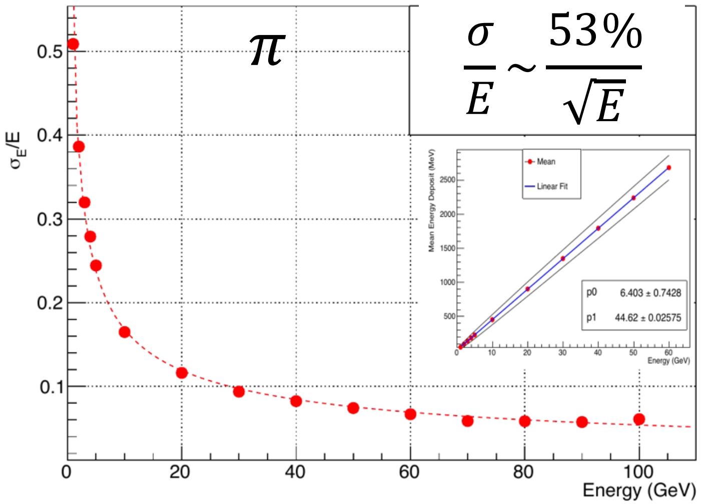
VTX detector & ECAL

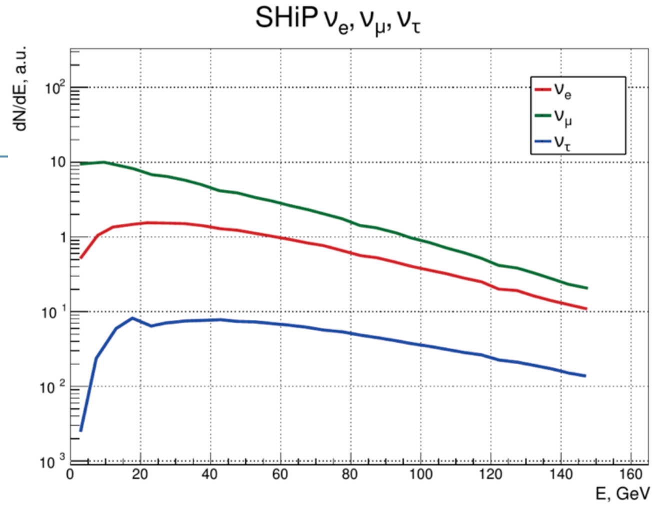


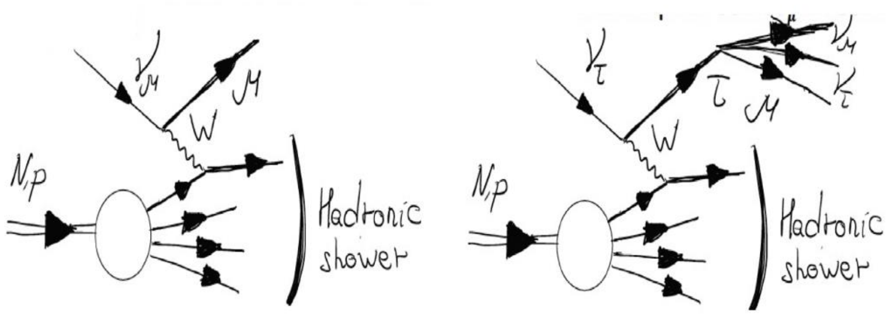
3.1t with 50 planes

Neutrino identification studies in the downstream part









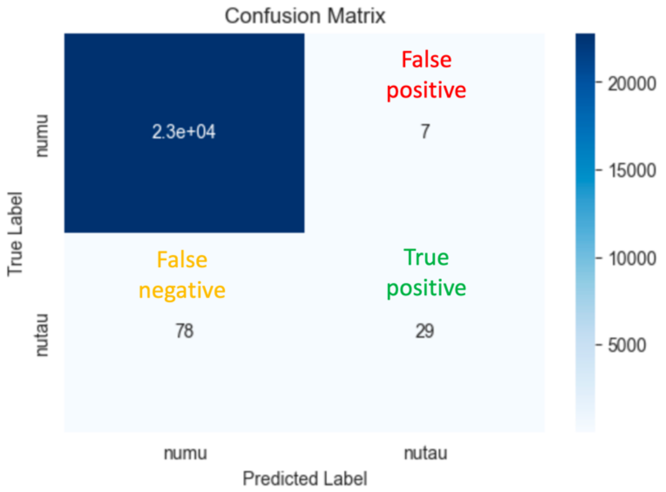
Magnetized HCAL (complementing the high-resolution VTX detector)

AND

A ν detector itself!

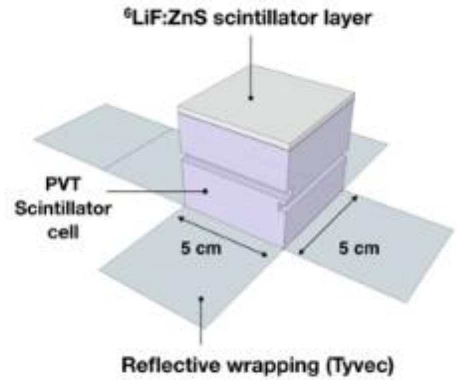
40 x 40 cm^2 cross-section

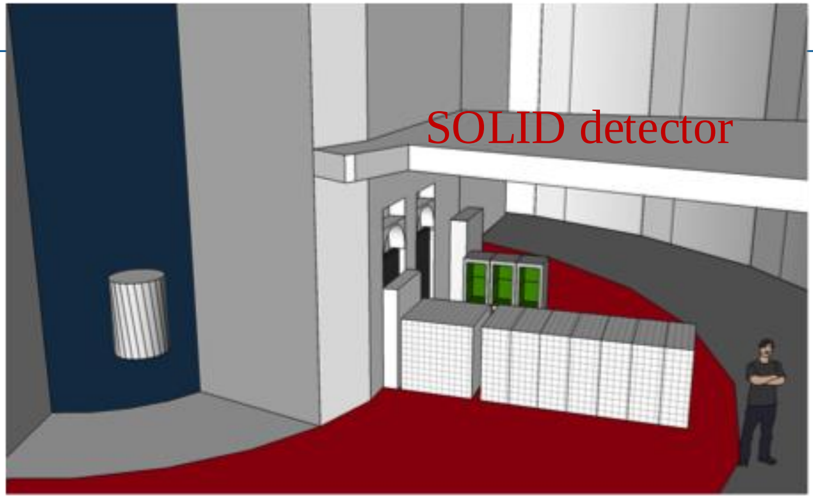
BDT results

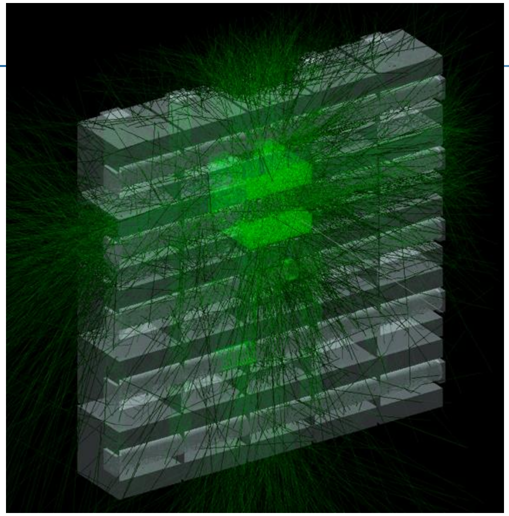


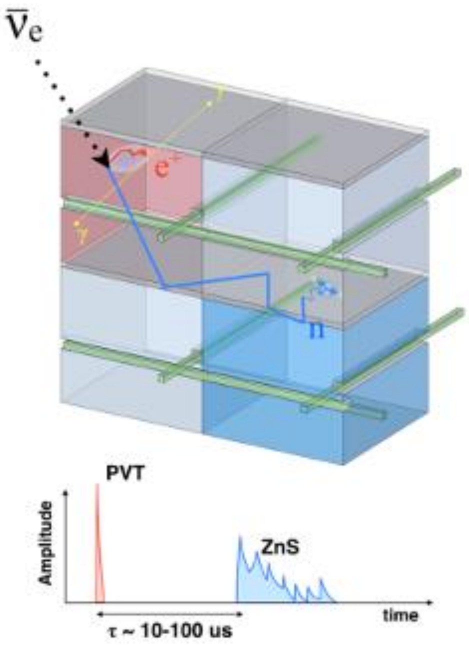
- main signature: missing P_T in CCDISν_τ (leptonic decay)
- $(S/B)_{\nu_\tau} \sim 4$

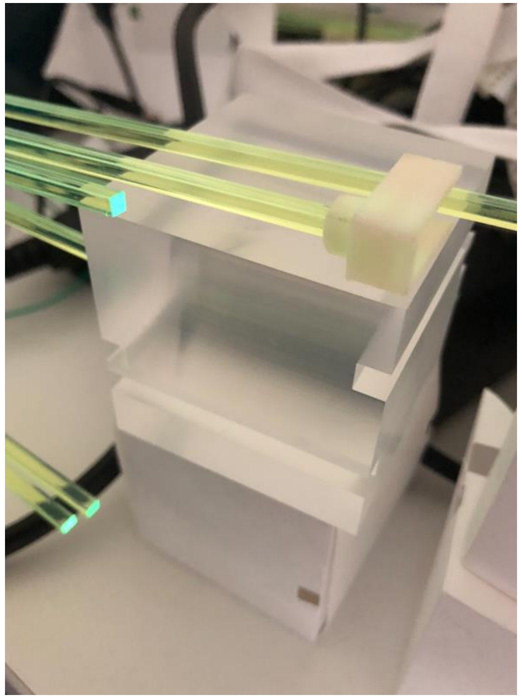
Extruded scintillator with fibre guides

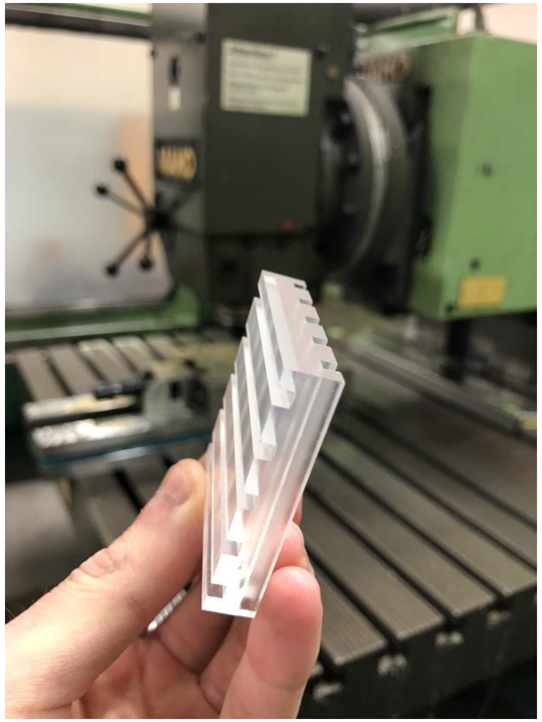








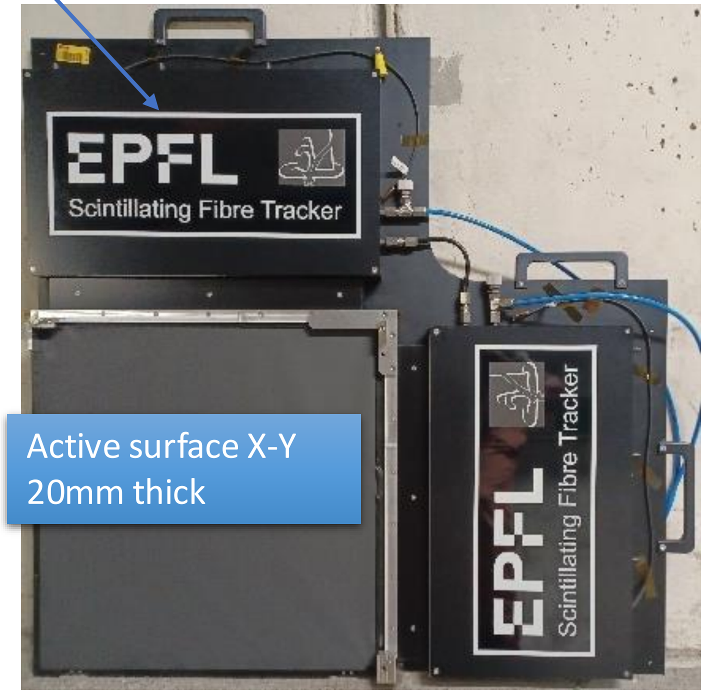


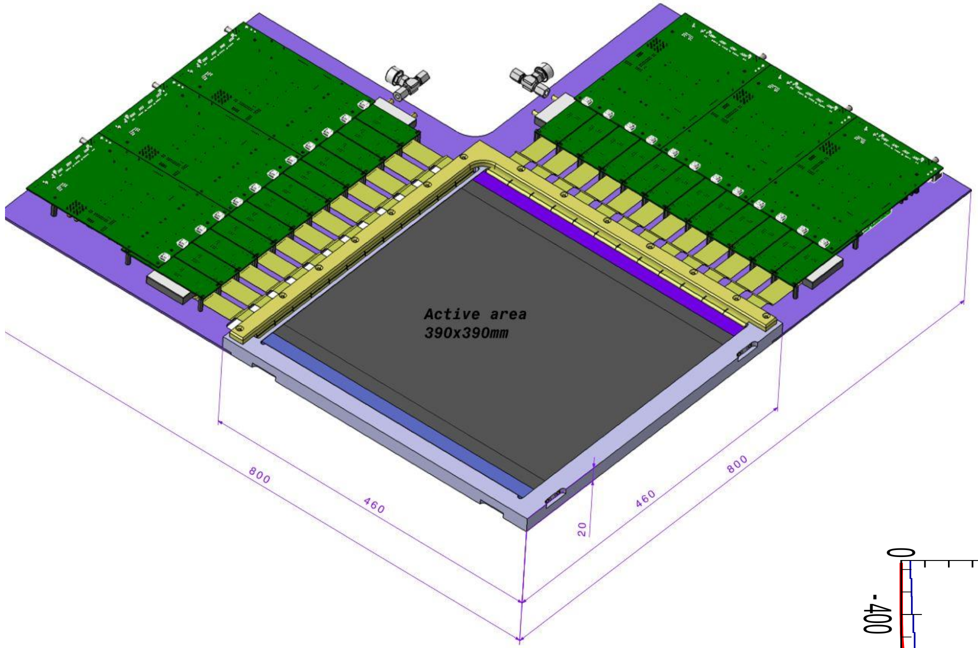


- Fibers every 1 cm
- Both horizontal and vertical
- Sensitivity to low energy (MeV scale)
- Expect ~ few % resolution at several GeV

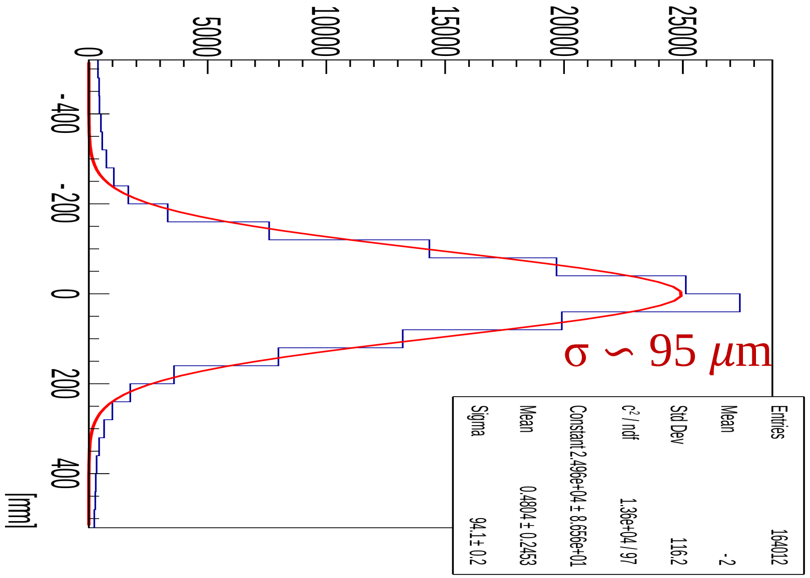
Will build a prototype and expose it to e/π beam to measure hadronic and e.m. energy resolution

SciFi technology already employed in SND@LHC





X-Y plane in SND@LHC
add X'Y' stereo angle to
suppress ghost

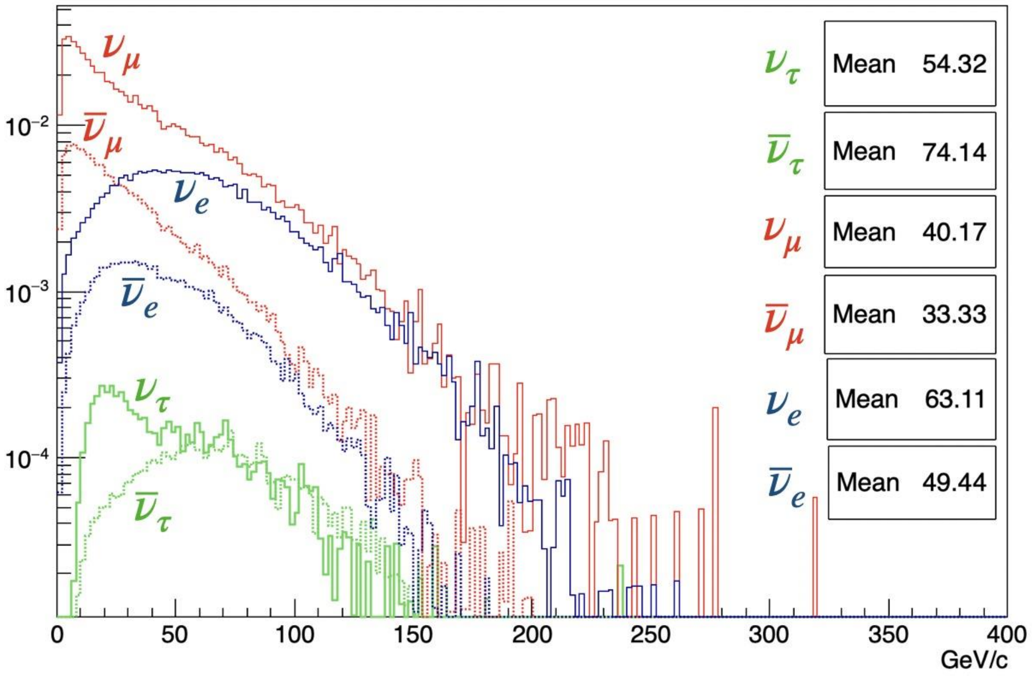


In SND@LHC
Active area 400mm x 400mm
Fibre layer orientation X-Y (orthogonal)
6-Layer fibre mats, 1.35mm thick
250µm fibres and 250µm channel pitch
Readout electronics developed at EPFL based on TOFPET2 ASIC

Neutrino interactions in the target

Normalised to 6×10^{20} pot, 3-ton detector

	<E> [GeV]	beam dump	<E> [GeV]	SND target acceptance	<E> [GeV]	CC DIS interactions
N_{ν_e}	6.3	4.1×10^{17}	30	1.3×10^{16}	63	2.8×10^{6}
N_{ν_μ}	2.6	5.4×10^{18}	8.4	1.5×10^{17}	40	8.0×10^{6}
N_{ν_τ}	9.0	2.6×10^{16}	22	1.0×10^{15}	54	8.8×10^{4}
$N_{\overline{\nu}_e}$	6.6	3.6×10^{17}	22	9.3×10^{15}	49	5.9×10^{5}
$N_{\overline{\nu}_\mu}$	2.8	3.4×10^{18}	6.8	1.2×10^{17}	33	1.8×10^{6}
$N_{\overline{\nu}_\tau}$	9.6	2.7×10^{16}	32	1.0×10^{15}	74	6.1×10^{4}



$\sigma_{\text{stat}} < 1\%$ for all neutrino flavours

Expected ν_τ including reconstruction efficiencies

Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	4×10^3	3×10^3
$\tau \to h$	27×10^3	
$\tau \to 3h$	11×10^3	
$\tau \to e$	8×10^3	
total	53×10^3	

Includes charge id in μ spectrometer ($\sigma_{\text{stat}} \sim 2\%$)

$D_s^+ \to \tau^+ \nu_\tau$

$\tau^+ \to$ anti-ν_τ X

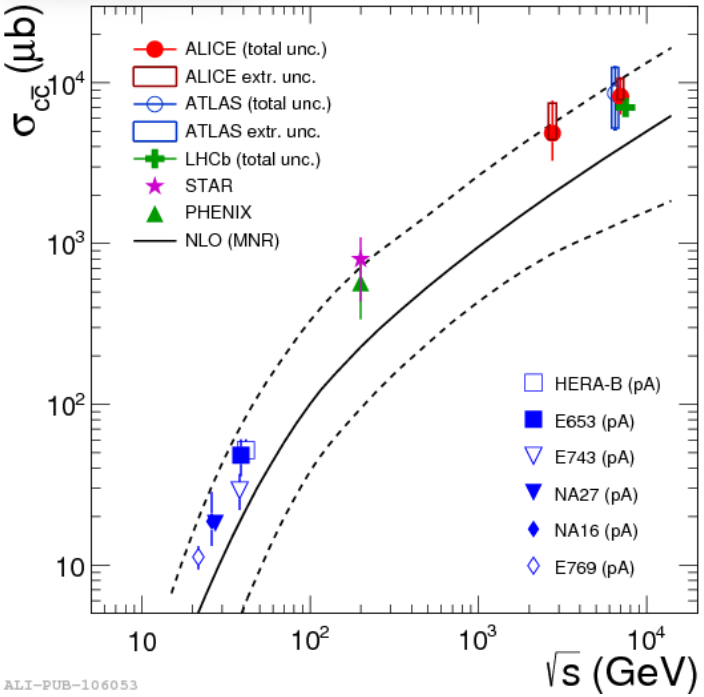
Charge asymmetry and decay chain explain why anti-ν_τs are more energetic

ν_τ cross-section measurement

When the τ charge is identified, expected statistical accuracy ~ 2%

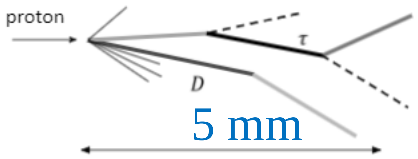
Charm production cross-section at 400 GeV: NA27 experiment (10%)

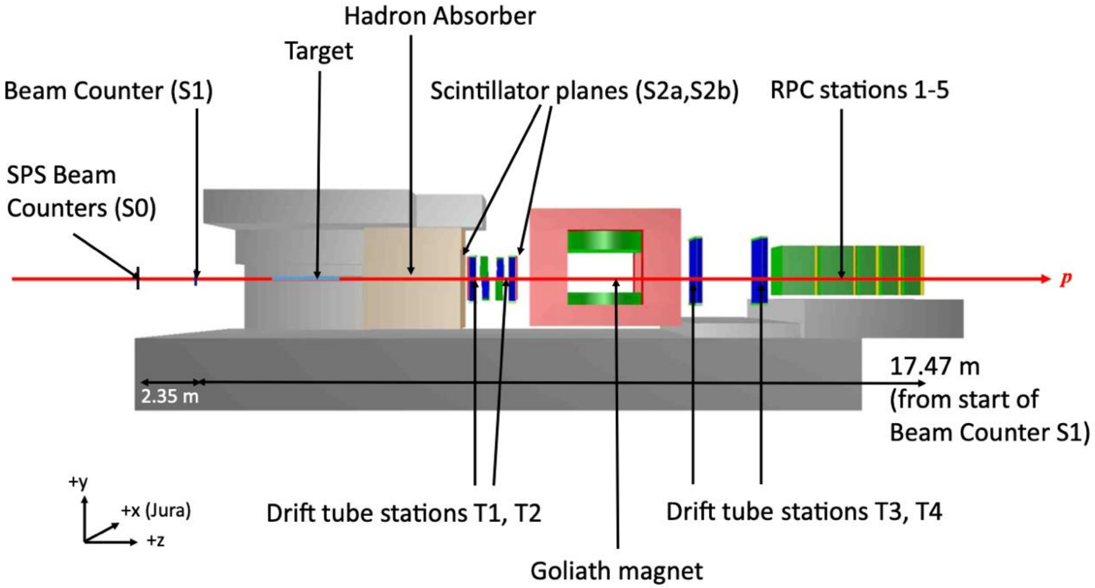
	exp NA27
$\sigma[\mu b]$	18.1 ± 1.7



Experiment	D^+/D^0	$D^0(\text{from } D^*)/D^0$	D_s^+/D^0
WA92: 350 GeV π^- on Cu	0.423 ± 0.012	0.280 ± 0.015	0.160 ± 0.037
WA92: 350 GeV π^- on W			0.183 ± 0.068

NA65 schematic





Setup of the muon flux measurement EPJ C80 (2020) 84

D_s uncertainty large, BR ($D_s \rightarrow \tau\, \nu_\tau$) = (5.32±0.11)% (2% small)

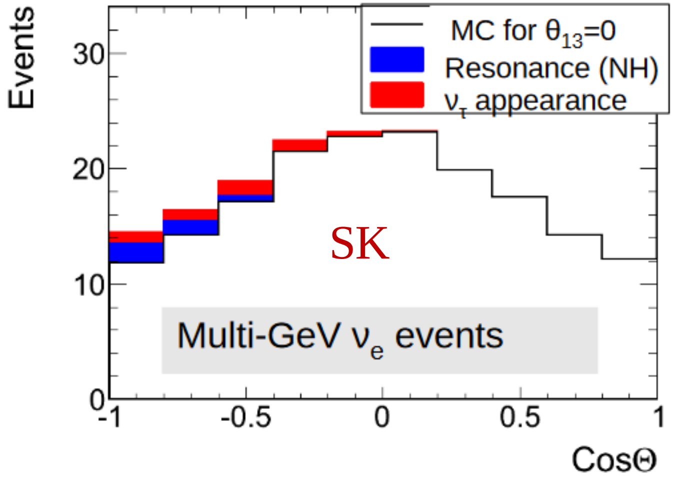
NA65 measuring p p → X D_s → τ in a thin target

NA65 expects 1000 events → potentially ~3%

Measure the $J/\psi \rightarrow \mu^+\mu^-$ $(5.961 \pm 0.033)\%$ in a thick/thin target at 400 GeV (and a few other energies)

Impact of ν_τ measurements on oscillation studies: SK/HK and IceCube

C. Bronner,
https://indico-sk.icrr.u-tokyo.ac.jp/event/5223/



M. Scott (Imperial College)

Mass ordering sensitivity from upward-going, multi-GeV electron-like samples

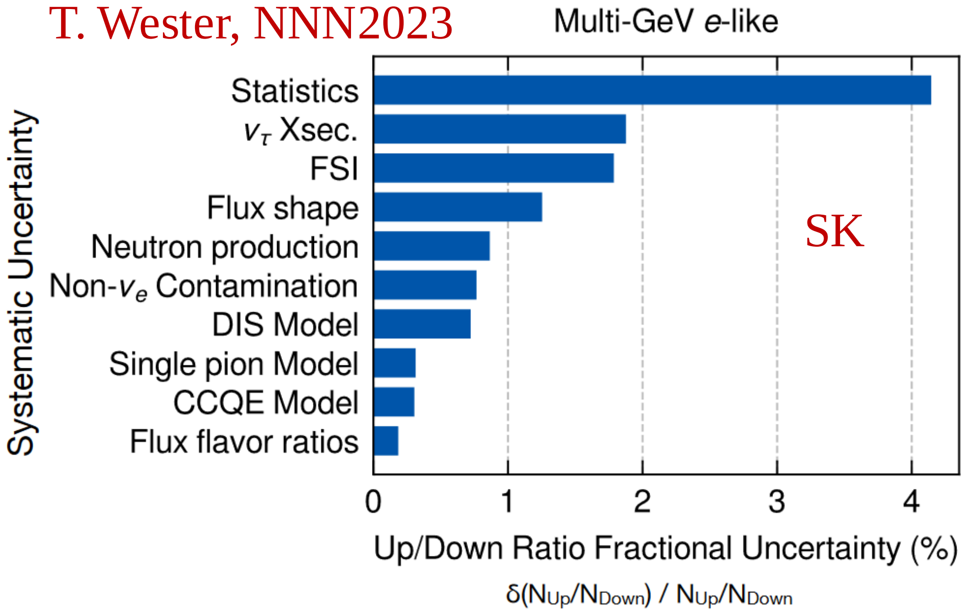
- ν_τ cross-section uncertainty dominant systematic
- Hyper-K will have stat error <2%

ICECUBE

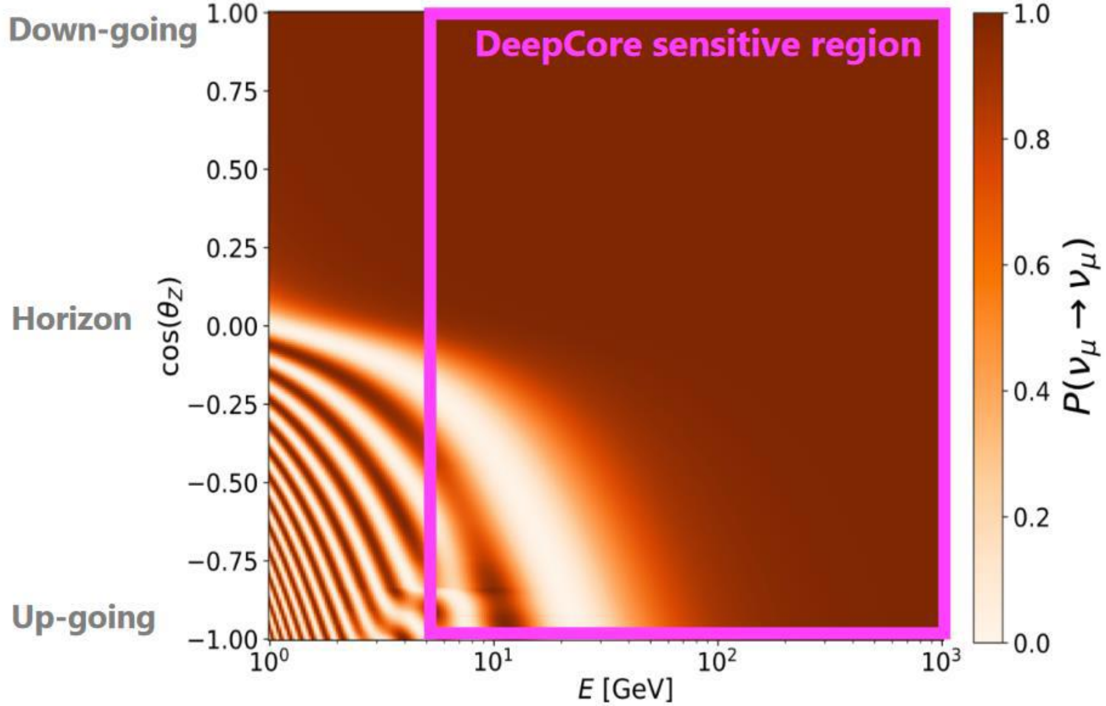
- Largest particle detector in existence (1Mt)
- Limited at low energy threshold ~ 10GeV
- Above threshold of τ production –can measure ν_τ appearance

IceCube-gen2 completed in 2032

T. Wester, NNN2023



T. Stuttard, NuFact 2019

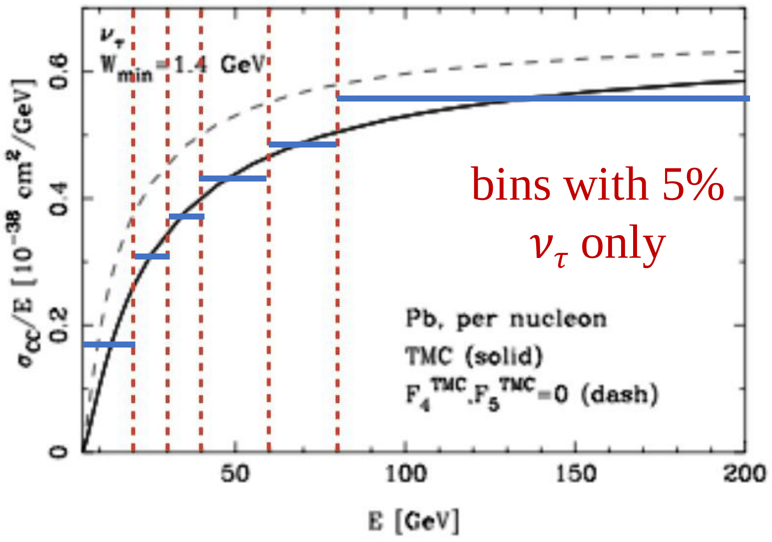


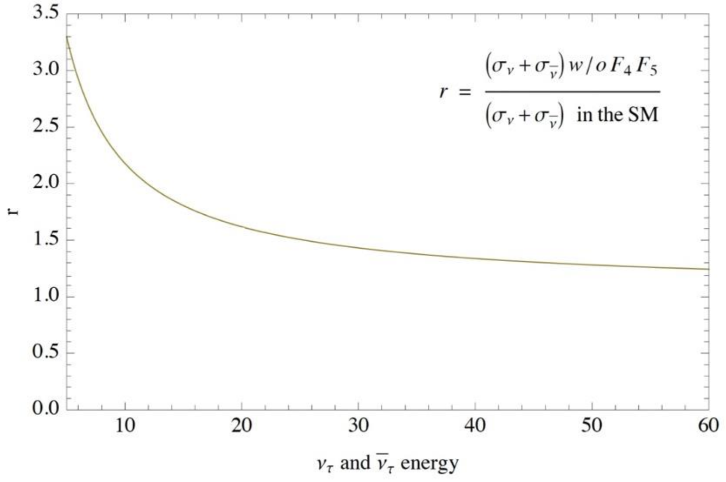
F4/F5 structure functions

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

C. Albright and C. Jarlskog, NP B84 (1975)

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





Rep. Prog. Phys. 79 (2016) 124201

About 3×10^4 detected events below 60 GeV

Evidence for F_5 can be assessed quickly

Measurement of F4/F5 ∽5% accuracy

→ differential measurement as a function of *x* and Q^2

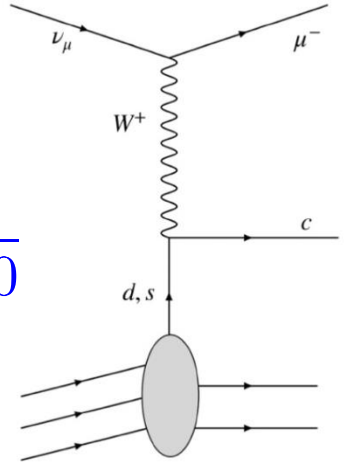
Charm physics with neutrinos

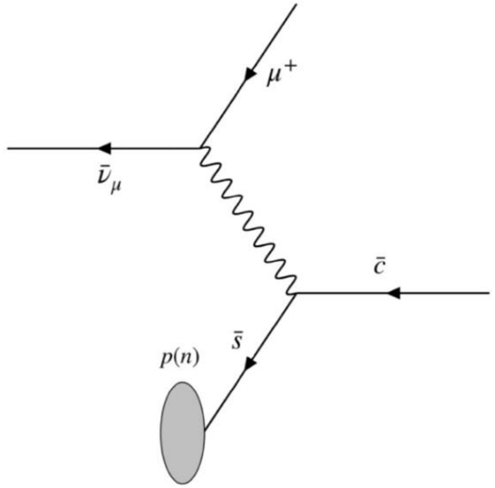
Physics Reports 399 (2004) 227–320

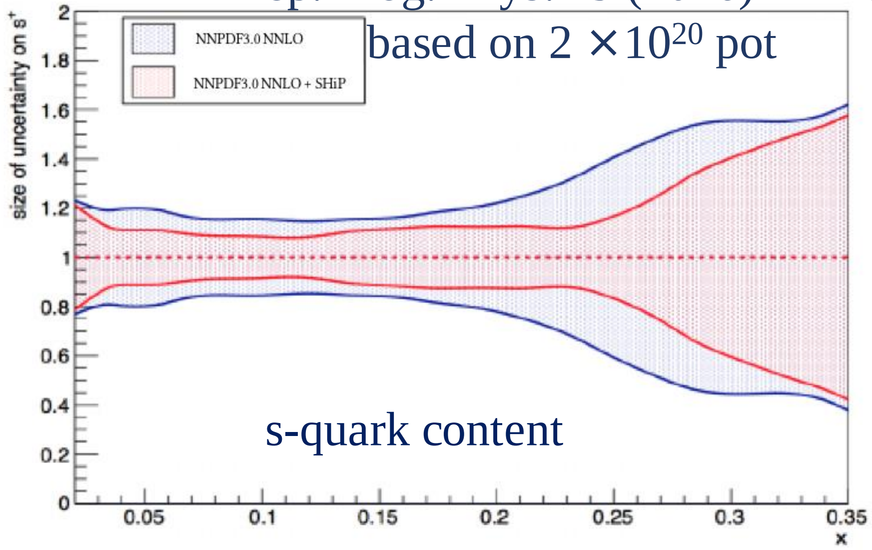
Rep. Prog. Phys. 79 (2016) 124201

based on 2×10^{20} pot

$$\left|\frac{V_{cd}}{V_{cs}}\right|^2 \simeq \frac{1}{20}$$







Charm production via anti-neutrinos dominated by s-bar quarks
Charm production via neutrinos shared ~50/50 between d (valence) and s (sea)

	<E> (GeV)	CC DIS with charm prod	Charm fractions (%)
N_{ν_μ}	57	3.5×10^5	4.4
N_{ν_e}	71	1.7×10^5	6.0
$N_{\bar{\nu}_\mu}$	50	0.7×10^5	3.8
$N_{\bar{\nu}_e}$	60	0.3×10^5	5.3
total		6.2×10^5	

V_{cd} Measurements by BESIII and CLEO

$$D^+ \to \mu^+\nu \text{ and } \tau^+\nu$$

$$|V_{cd}| = 0.2181 \pm 0.0049 \pm 0.0007$$

Earlier measurements by νs (CDHS, CCFR, CHARM II): subtraction of ratios of two-muon events in ν and anti-ν interactions, combined with B_μ

CHORUS: 2013 ν-induced charm events, limited by anti-ν being a contamination (32 events)

CHORUS

$$\mathcal{B}_\mu = 0.085 \pm 0.009 \pm 0.006$$

$$|V_{cd}| = 0.230 \pm 0.011$$

(PDG 2022 value from neutrinos)

SHiP can measure V_{cd} with <2% accuracy, comparable/better than other methods!

ν_e measurements

THIRD SERIES, VOLUME 41, NUMBER 9 Phys. Rev. D41, 2653 (1990) 1 MAY 1990

ν_μ-ν_e **universality in charged-current neutrino interactions**

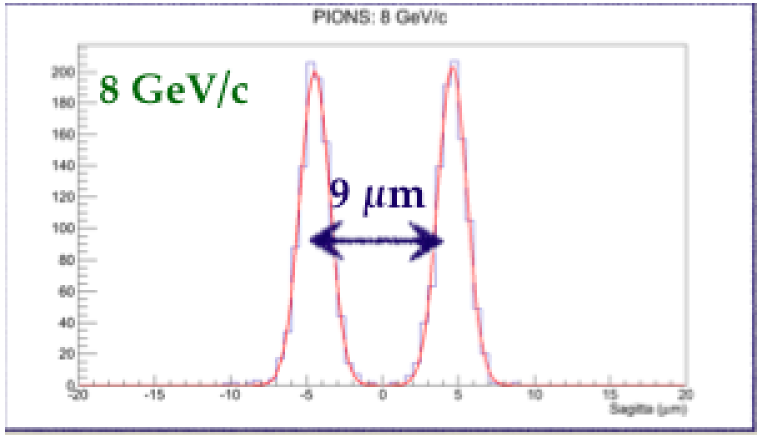
$$\frac{\sigma(\nu_e)}{\sigma(\nu_\mu)} = \frac{(\nu_e \text{ events observed})}{(\nu_\mu \text{ events observed})} \frac{\int E_{\nu_\mu}(\nu_\mu \text{ flux})dE}{\int E_{\nu_e}(\nu_e \text{ flux})dE} = 1.09 \pm 0.17 \,.$$

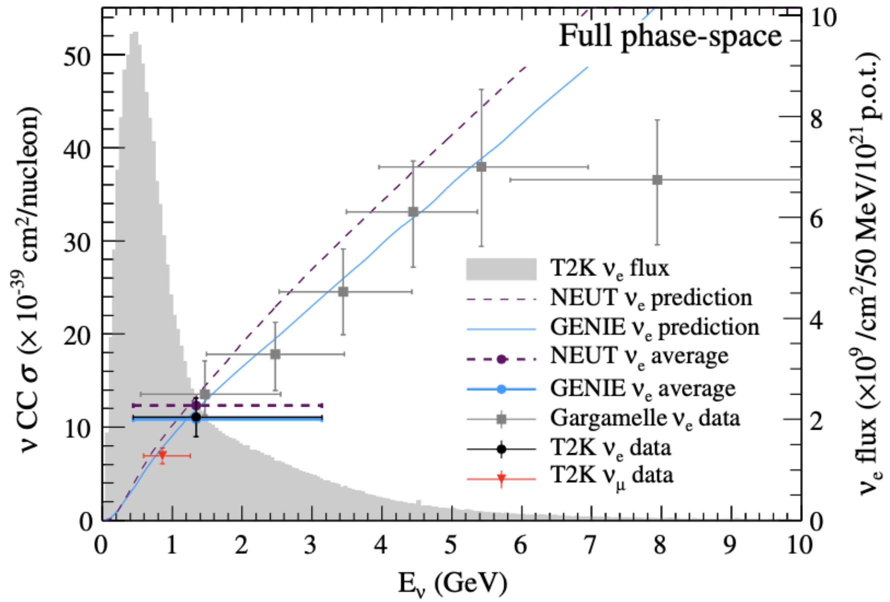
measurement in the same energy range (wide band beam, up to 200 GeV) at Fermilab (1990): 1403 ν_e + 179 anti-ν_e

The sample was 10 times larger than previously available measurements

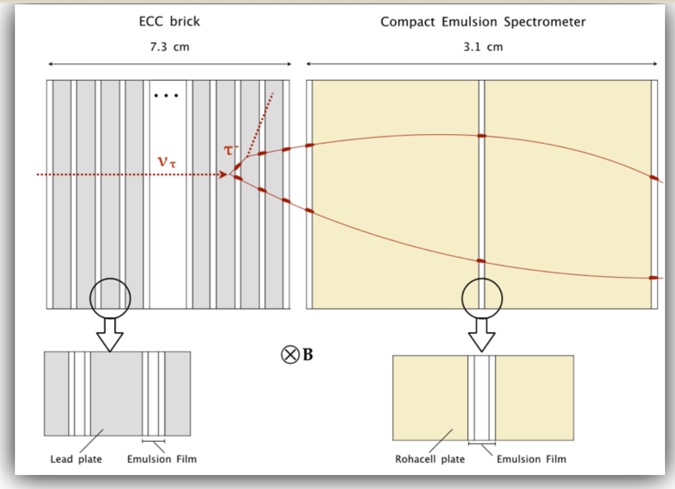
$$\frac{\sigma(\bar{\nu}_e)}{\sigma(\bar{\nu}_\mu)} = 1.46 \pm 0.34$$

Bubble chamber (Ne-H_2 mix) detector





Inclusive ν_e - C cross-section with T2K near detector in 2014 (<E> ~ 1.4 GeV)
Compared with Gargamelle



To separate ν_e /anti- ν_e dedicated run with an emulsion spectrometer (low mass) and a magnetised target

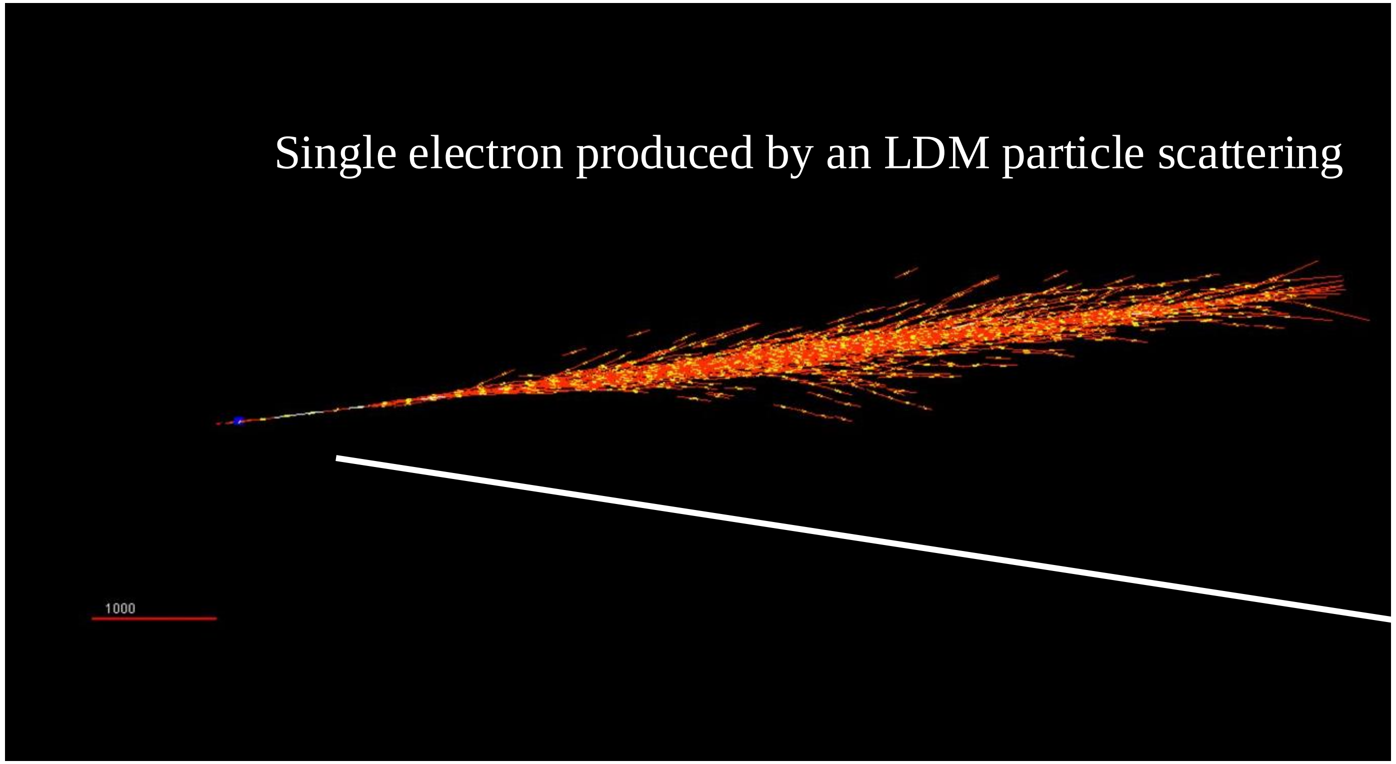
NIM A 592 (2008) 56-62

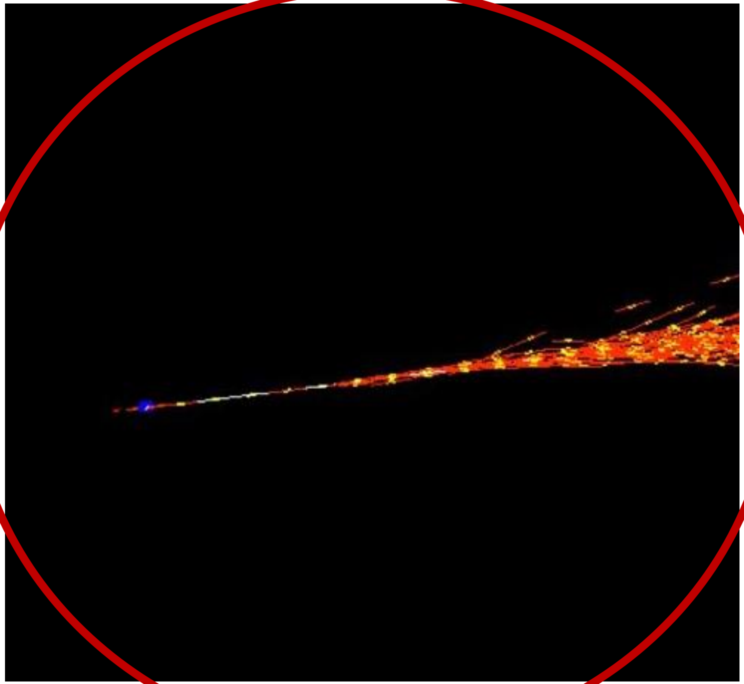
Also a LDM detector

In the background suppression against ν_e interactions, the most powerful handle is the isolation criterion: no extra-activity

	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	52	27	64	42	185
Quasi - elastic scattering	-	9			9
Resonant scattering	-	-			-
Deep inelastic scattering	-	-			-
Total	52	36	64	42	194

DIS cross-section ~ 2000 larger, made negligible by this cut

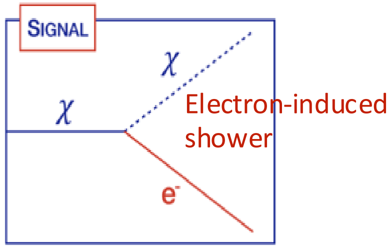


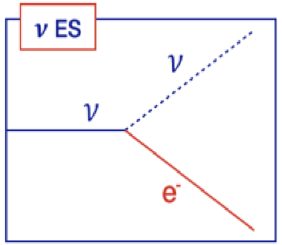


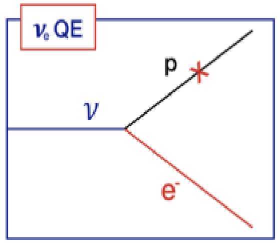
- A high-granularity vertex detector
- Tracking stations (for VTX) embedded in a high-density material (W) Optimise longitudinal segmentation
- Need to combine vertex reconstruction capabilities with electromagnetic energy reconstruction

SND: "Direct" light dark matter search

- *Direct search through scattering*, sensitivity to ϵ^4 instead of indirect searches ϵ^2 ($\not{E}$ technique)

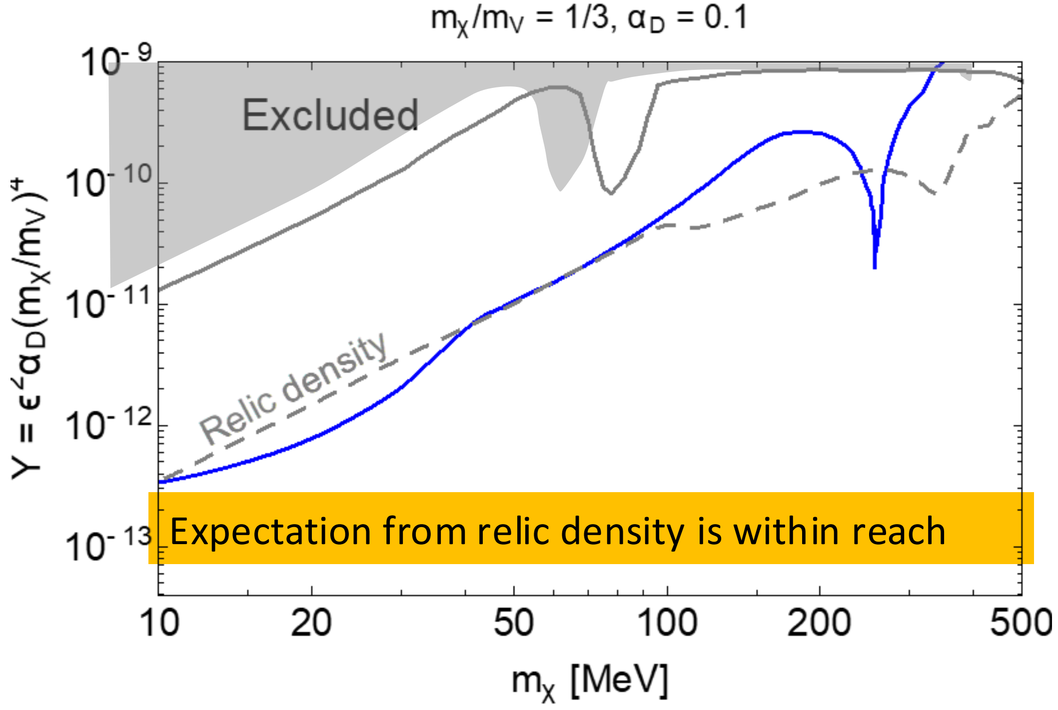






➔ Background is dominated by neutrino elastic and quasi-elastic scattering, for 6 ×10^{20} PoT

6 ×10^{20}	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	156	81	192	126	555
Quasi - elastic scattering	-	27			27
Resonant scattering	-	-			-
Deep inelastic scattering	-	-			-
Total	156	108	192	126	582



Reach ν physics program and most sensitive FIBs search at CERN

Stay tuned!