Neutrinos and hidden particle searches at CERN

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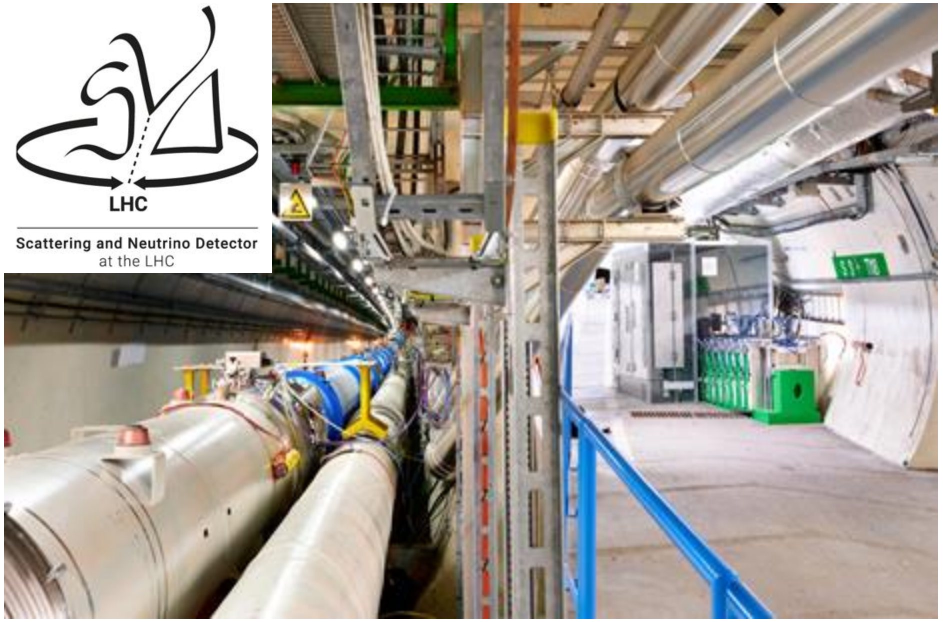
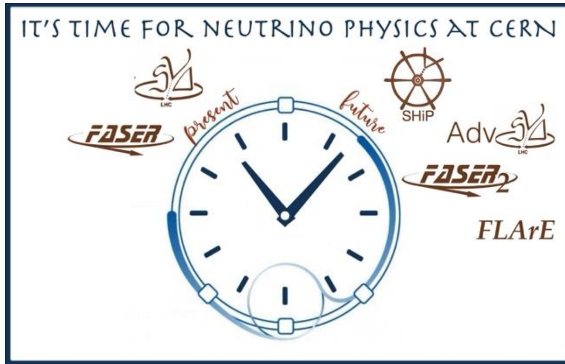


- *Neutrino experiments running at the LHC: FASER and SND@LHC*
- *First results from the data taking*
- *The Beam Dump Facility and the SHiP experiment at the SPS*



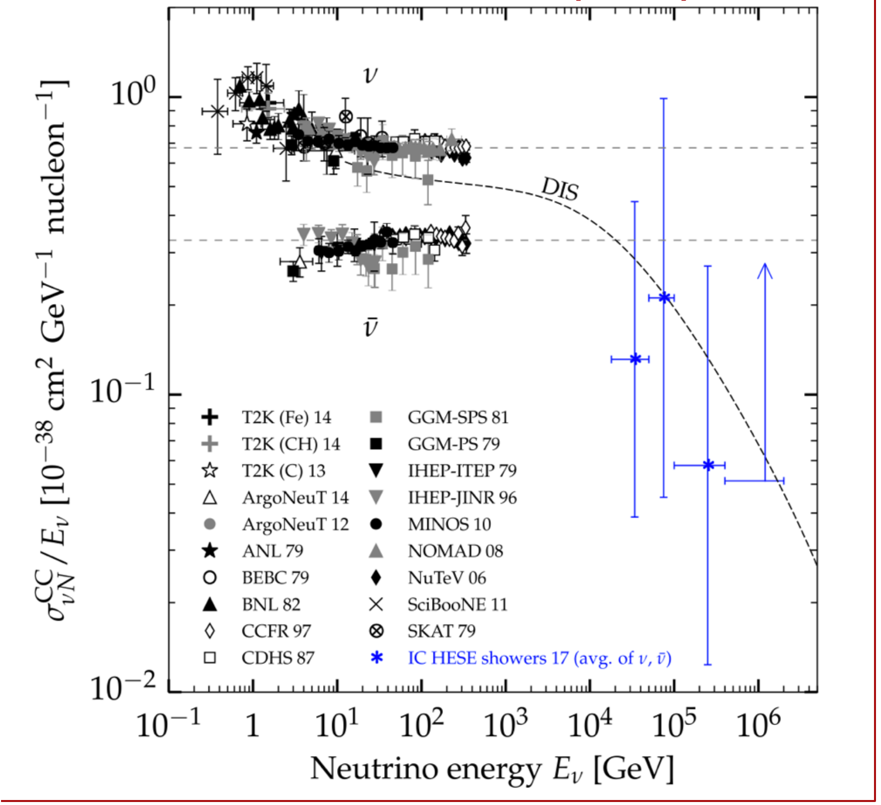
Neutrino Oscillation Workshop, Otranto, September 5th 2024

Neutrino physics at the LHC: motivation

SND@LHC
Scattering and Neutrino Detector at the LHC

- A. De Rujula and R. Ruckl, Neutrino and muon physics in the collider mode of future accelerators, CERN-TH-3892/84
- Klaus Winter, 1990, observing tau neutrinos at the LHC
- F. Vannucci, 1993, neutrino physics at the LHC
- http://arxiv.org/abs/1804.04413 April 12th 2018, First paper on feasibility of studying neutrinos at LHC

PRL 122 (2019) 041101



OPEN ACCESS

IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **46** (2019) 115008 (19pp) https://doi.org/10.1088/1361-6471/ab3f7c

Physics potential of an experiment using LHC neutrinos

N Beni[1], M Brucoli[2], S Buontempo[5], V Cafaro[4], G M Dallavalle[4,8], S Danzeca[2], G De Lellis[2,3,5], A Di Crescenzo[3,5], V Giordano[4], C Guandalini[4], D Lazic[6], S Lo Meo[7], F L Navarria[4] and Z Szillasi[1,2]

Eur. Phys. J. C (2020) 80:61
https://doi.org/10.1140/epjc/s10052-020-7631-5

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Experimental Physics

Detecting and studying high-energy collider neutrinos with FASER at the LHC

FASER Collaboration

CERN is unique in providing energetic **ν** (from LHC) and measure pp → **ν**X in an unexplored domain

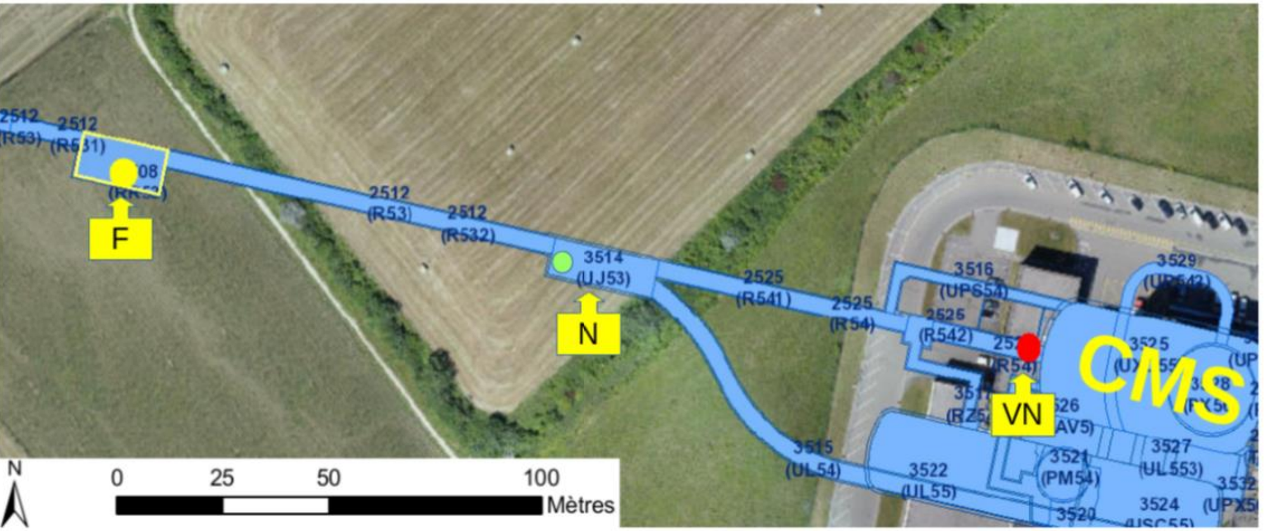
Investigating the background for a neutrino detector in different locations with a measurement campaign

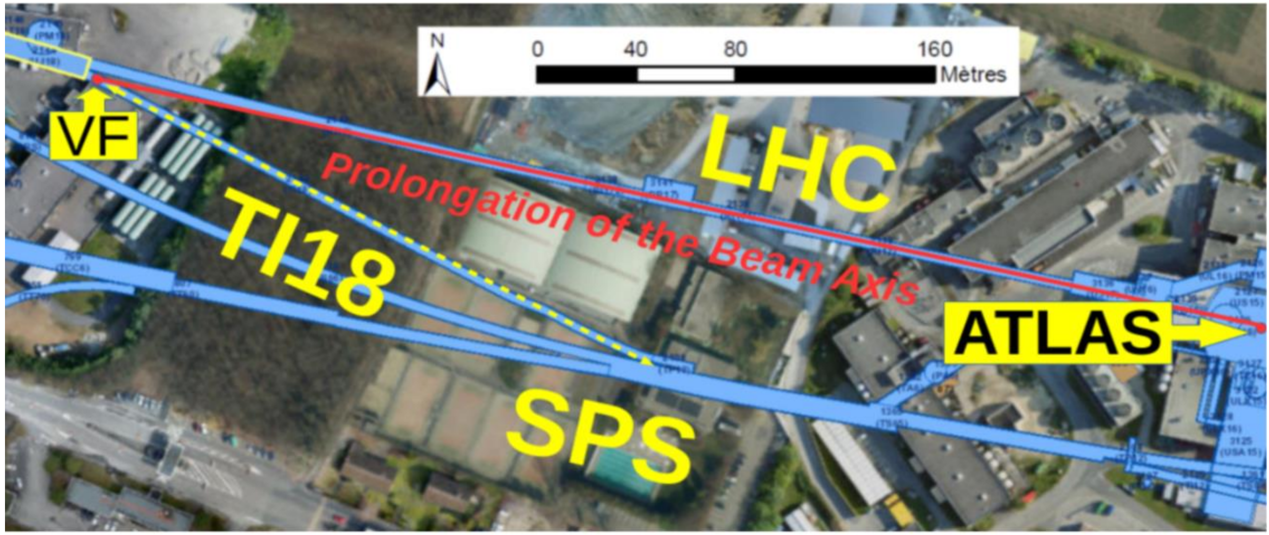
VN = Q1 in S45 at 25m

N = UJ53 and UJ57 at 90-120m

F = RR53 at 237m

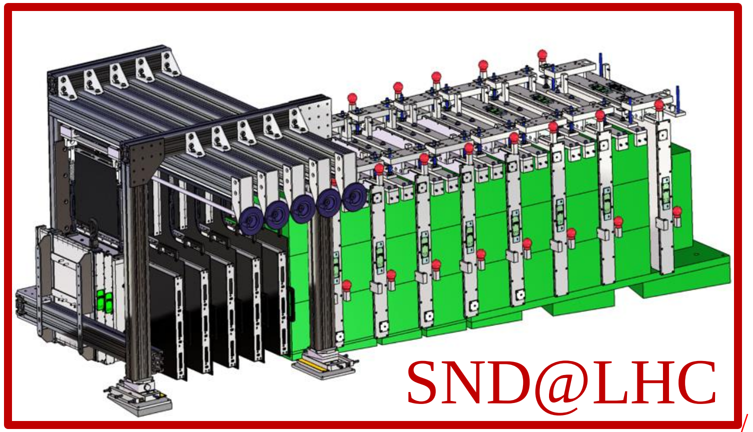
VF = TI18 at 480m (FASERν measurements)

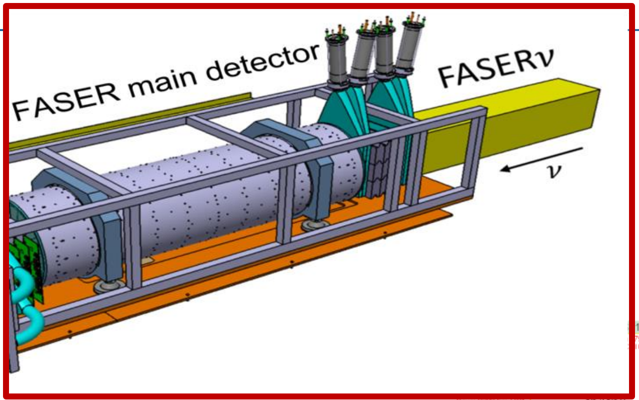




Journal of Physics G 46 (2019) 115008

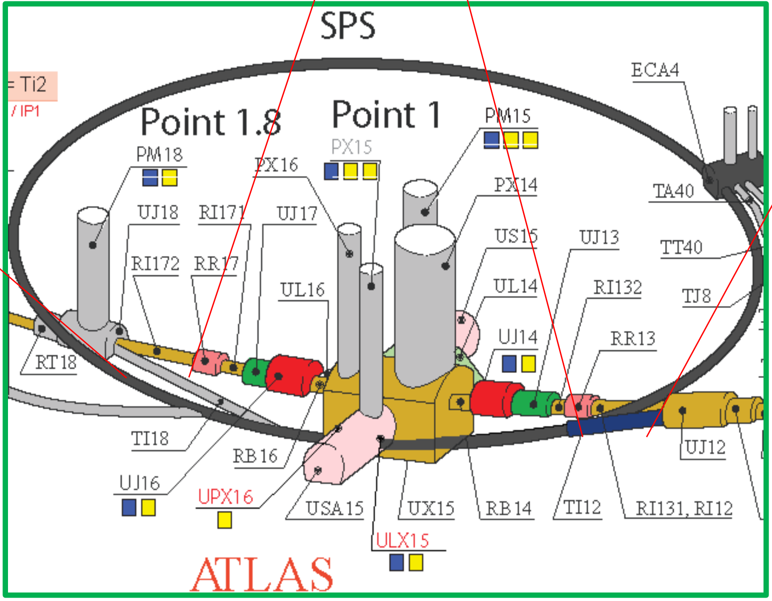
Locations

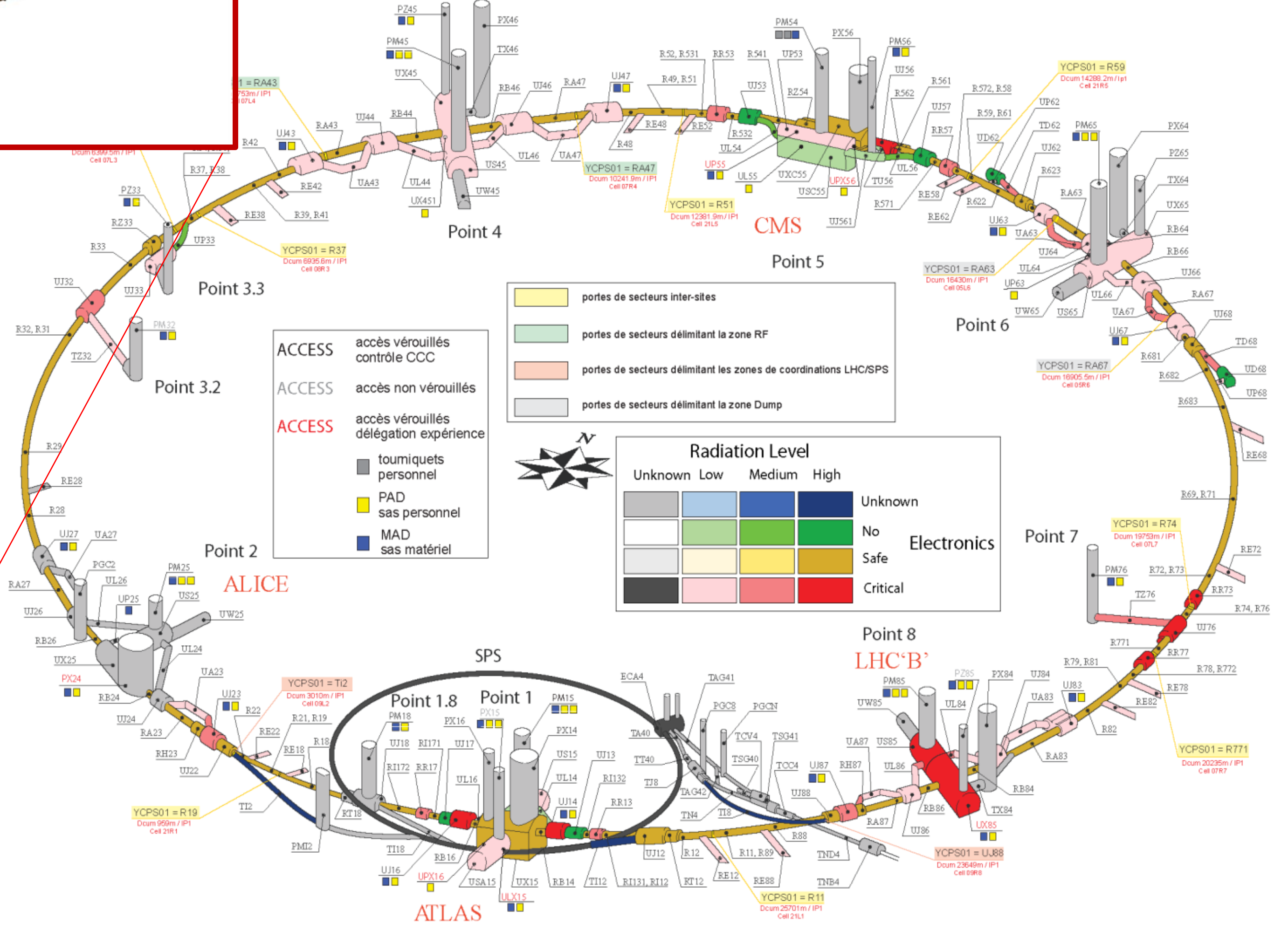




- 480 m away from the IP
- Charged particles deflected by LHC magnets
- Shielding from the IP provided by 100 m rock

Former transfer tunnels connecting SPS to LEP





Injection tunnels used at LEP

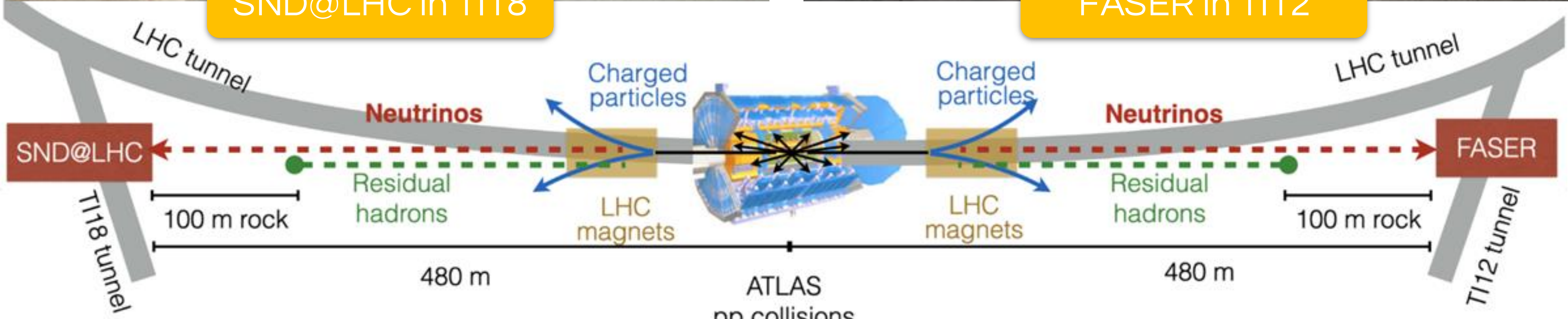
E.g. the TI18 tunnel in 2020

The LHC seen from the TI18 tunnel

Detectors ready for the run in March 2022

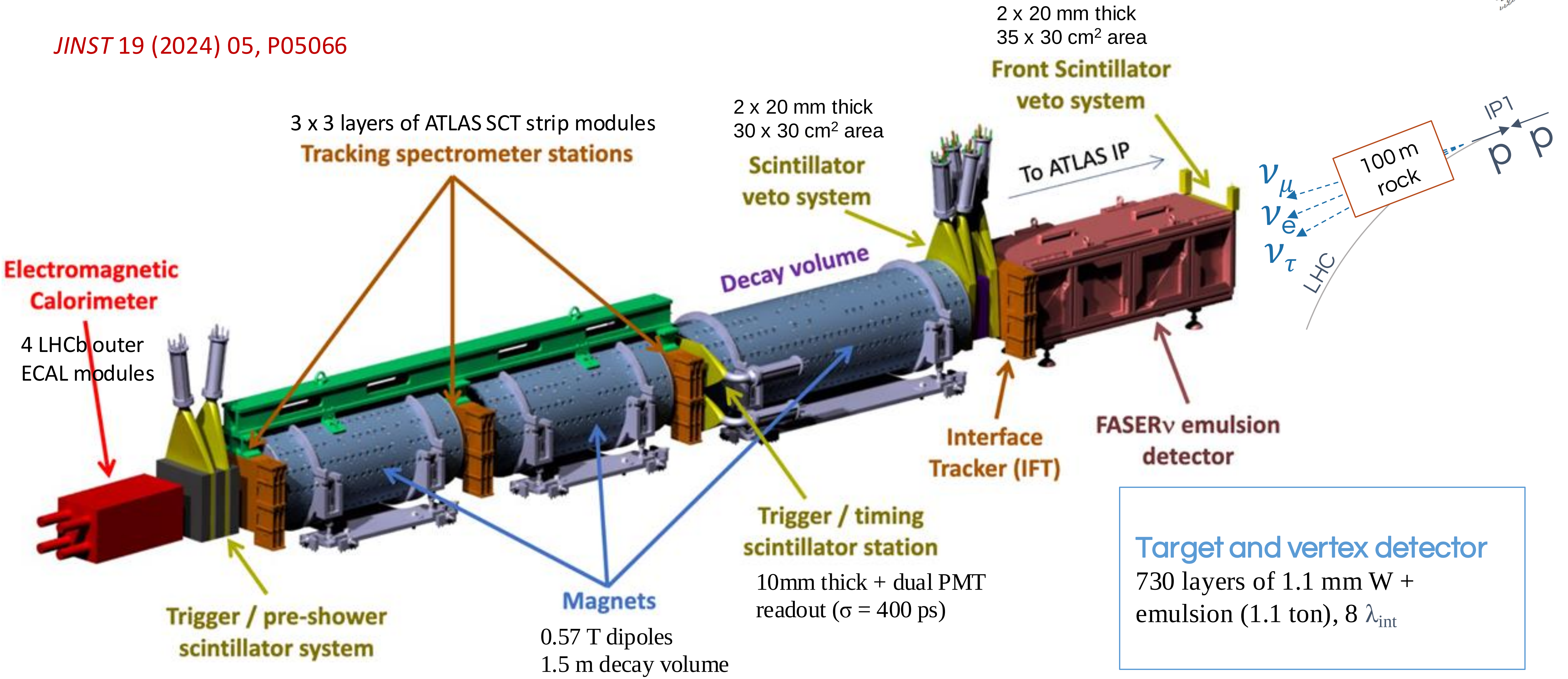
SND@LHC in TI18

FASER in TI12



ForwArd Search ExpeRiment

JINST 19 (2024) 05, P05066



Target and vertex detector

730 layers of 1.1 mm W + emulsion (1.1 ton), 8 λ_{int}

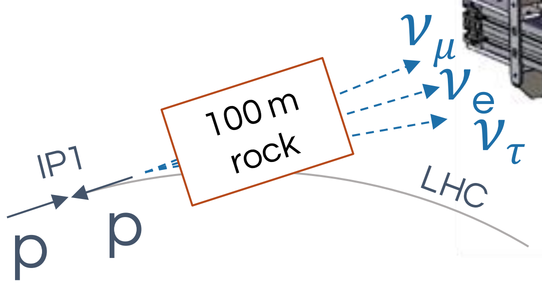
SND@LHC detector

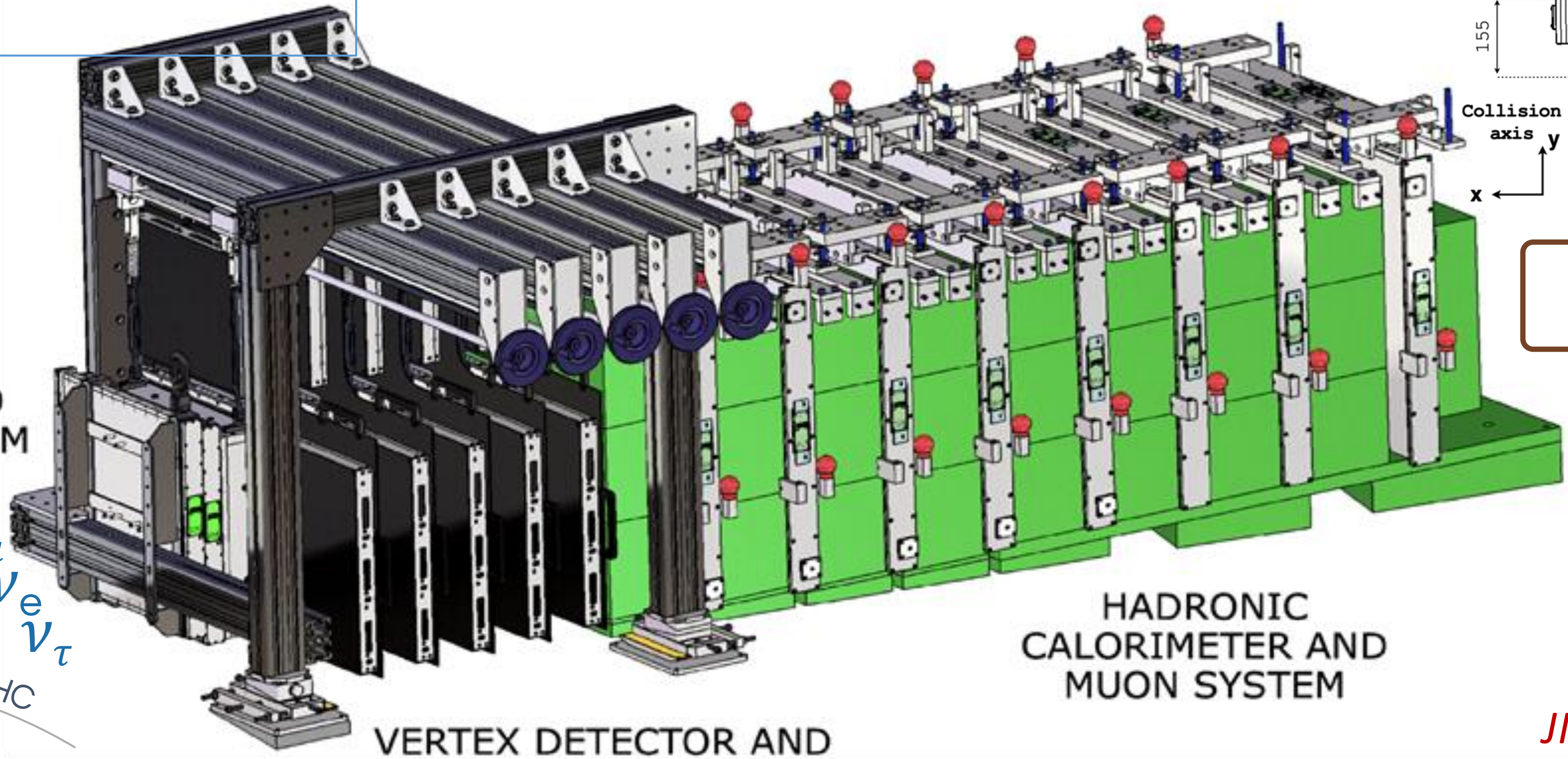
Veto system
Two 1 cm thick scintillator planes.

Target, vertex detector and ECal
830 kg tungsten target.
Five walls x 59 emulsion layers
+ five scintillating fibre stations.
84 X_0, 3 λ_{int}

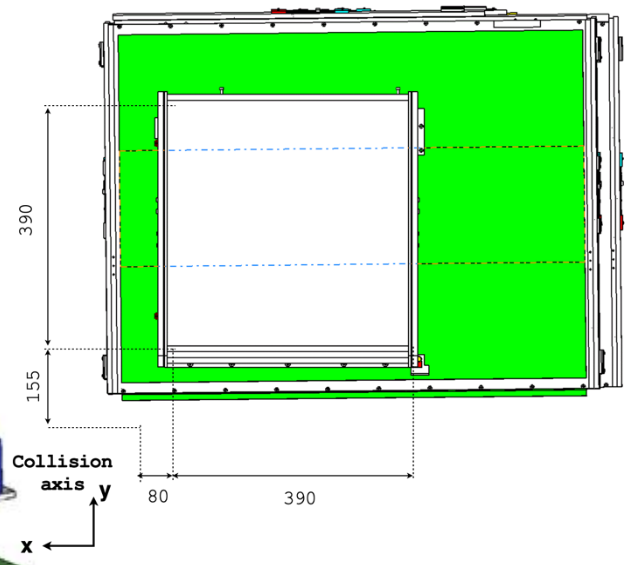
HCal and muon system
Eight 20 cm Fe blocks
+ scintillator planes.
Last 3 planes have finer
granularity to track muons.
9.5 λ_{int}

Length: 2.6 m





FRONT VIEW



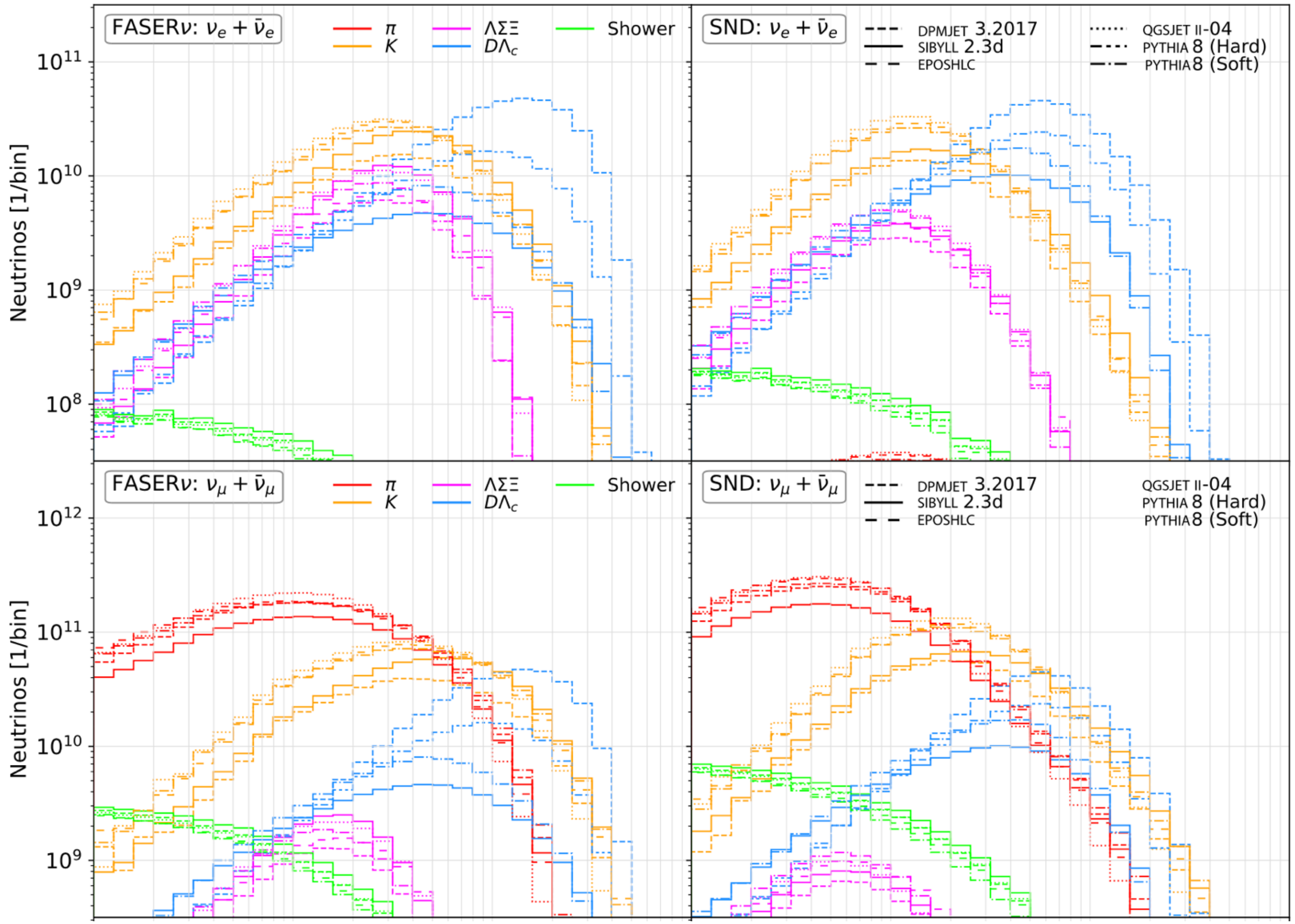
Off axis location

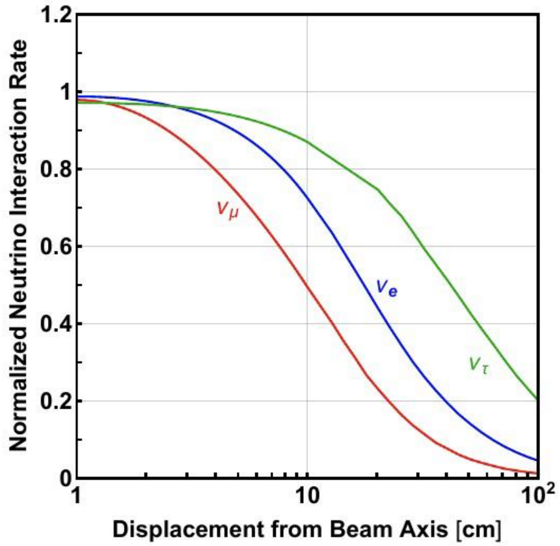
$7.2 < \eta < 8.4$

JINST 19 (2024) 05, P05067

Comparison of the neutrino fluxes and sources

Felix Kling, Laurence J. Nevay, Phys. Rev. D 104 (2021) 11, 113008
https://arxiv.org/pdf/2105.08270.pdf



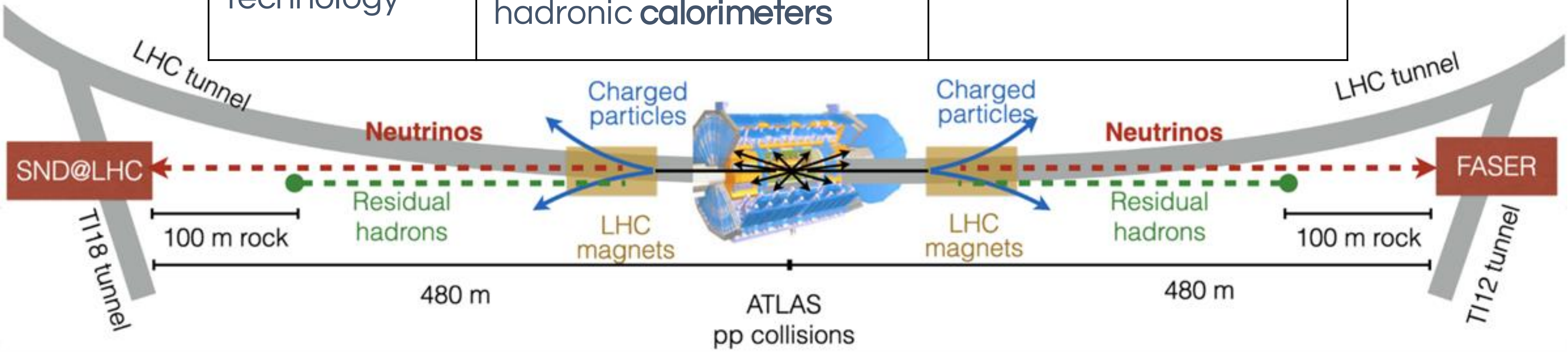


Courtesy of F. Kling, normalised to 250 fb^{-1}

Generators	FASERν			SND@LHC		
heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	1501	7971	24.5	223	1316	12.6
DPMJET	5761	11813	161	658	1723	31
Pythia8 (Hard)	2521	9841	57	445	1871	19.2
Pythia8 (Soft)	1616	8918	26.8	308	1691	12
Combination (all)	2850^{+2910}_{-1348}	9636^{+2176}_{-1663}	67.5^{+94}_{-43}	408^{+248}_{-185}	1651^{+220}_{-333}	$18.8^{+12}_{-6.6}$

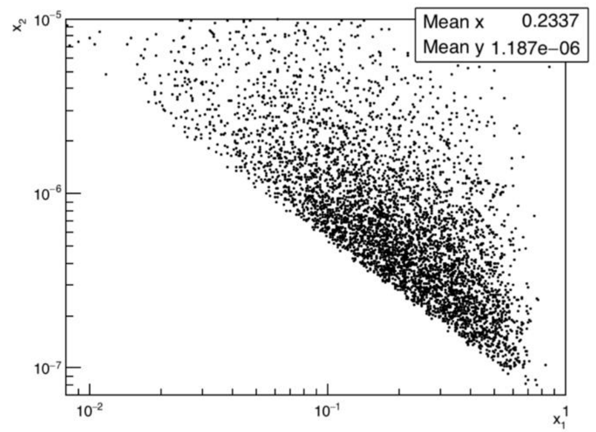
Two complementary LHC ν experiments

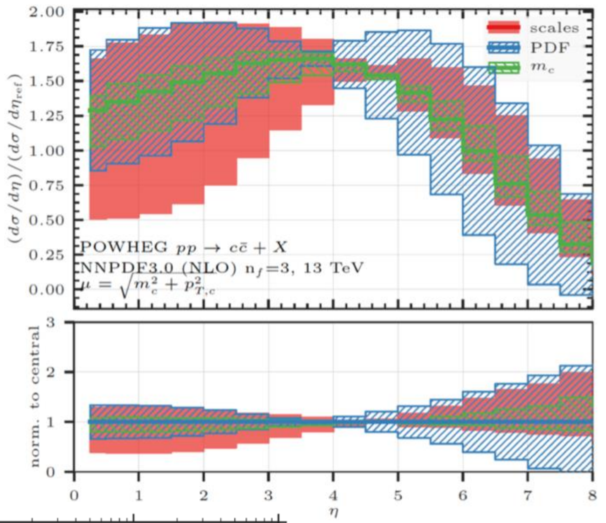
	SND@LHC	FASER
Location	**Off-axis:** $7.2 < \eta < 8.4$ Enhances **charm** parentage	**On-axis:** $\eta > 9.2$ Enhances **statistics**
Target	**800 kg** of tungsten	**1100 kg** of tungsten
Detector technology	**Emulsion vertex detector,** electromagnetic and hadronic **calorimeters**	**Emulsion vertex detector** and **spectrometer**



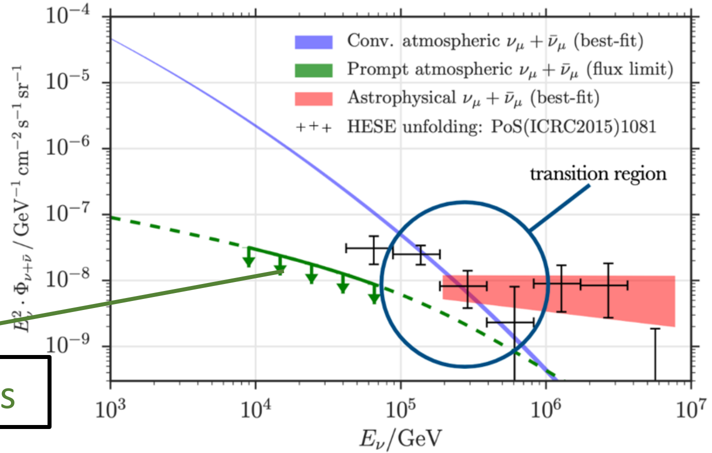
Physics goals

- Study neutrino interactions (cross-section, LFU, ..) in a new energy domain
- Lepton flavour universality tests with ν interactions with $R_{e\mu}$ and $R_{e\tau}$
- Use νs as probes of their parent, e.g. in some angular region ν_e production dominated by charm decays → measuring charm production in pp collisions in the forward region
- Manyfold interest for the charm measurement in pp collision at high η
- Prediction of very high-energy neutrinos produced in cosmic-ray interactions → experiments also acting as a bridge between accelerator and astroparticle physics





IceCube Collaboration, six years data, Astrophysics J. 833 (2016) 3, https://iopscience.iop.org/article/10.3847/0004-637X/833/1/3/pdf



7+7 TeV *p*-*p* collisions correspond to 100 PeV proton interaction for a fixed target

prompt atmospheric neutrinos

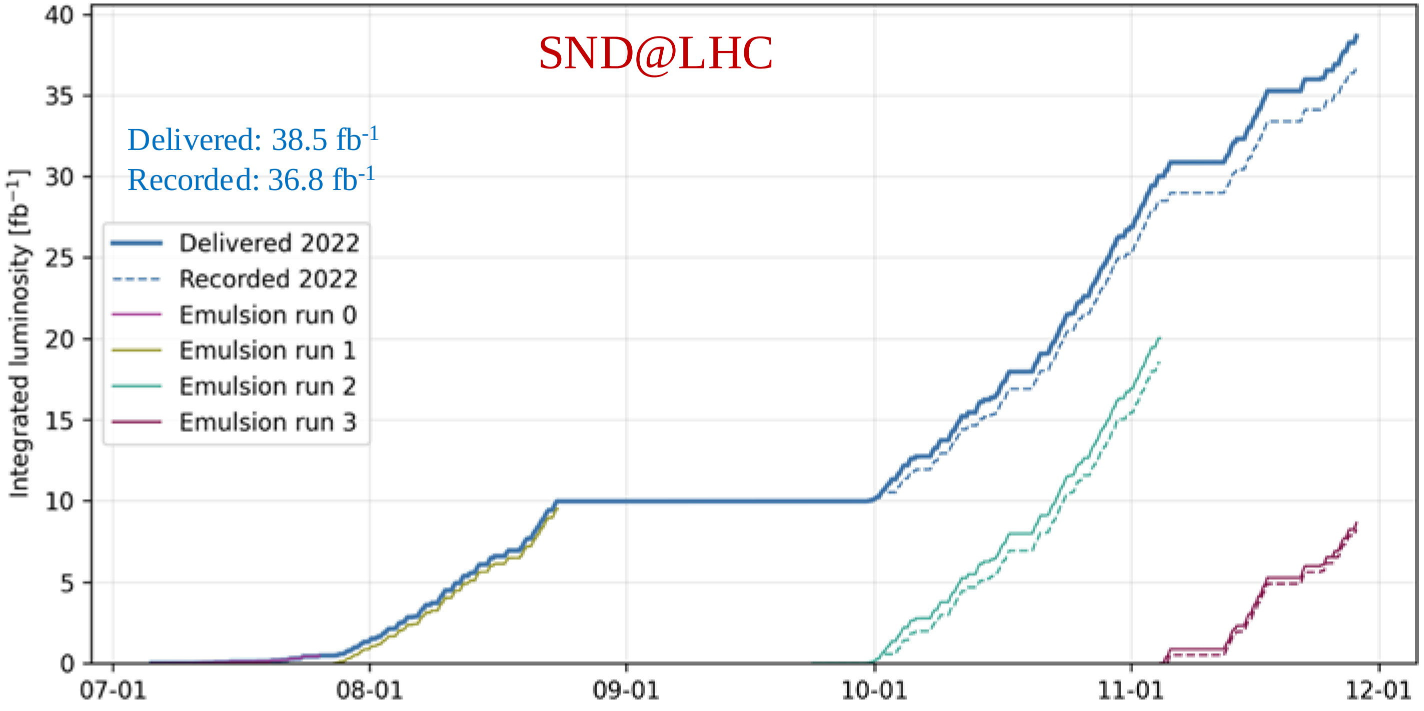
Observation of collider neutrinos with 2022 data

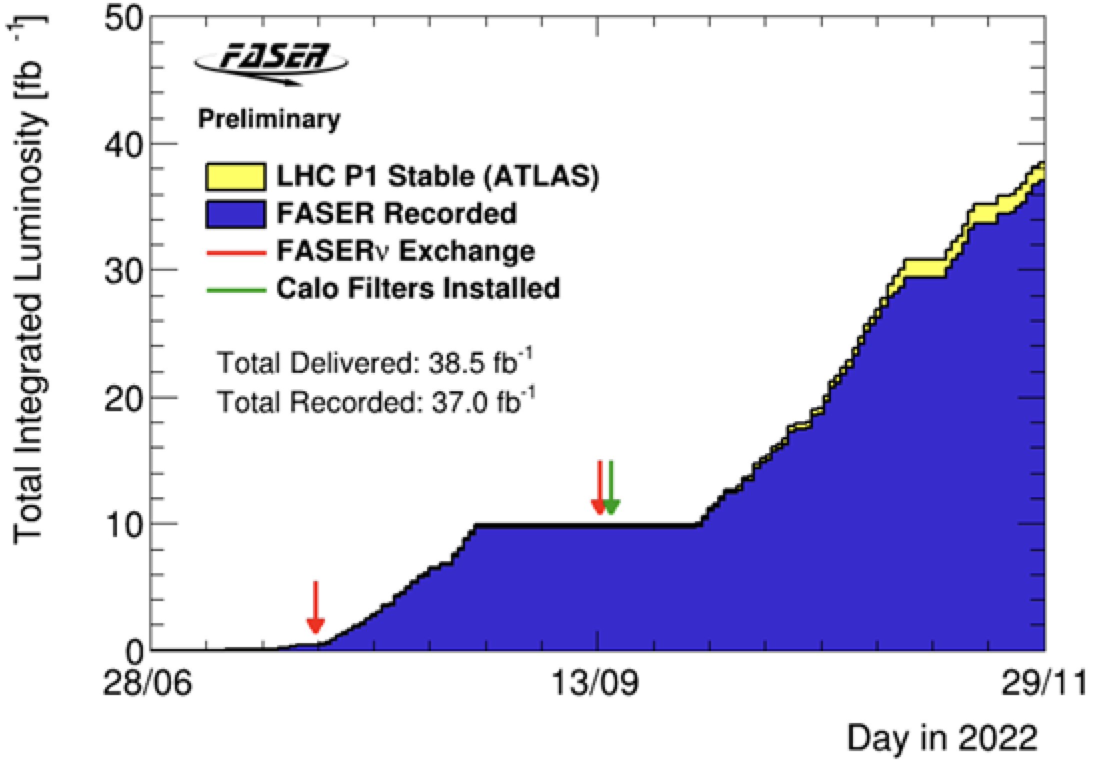
Analyses of SND@LHC and FASER electronic detector data

FASER: PRL 131 (2023) 031801

SND@LHC: PRL 131 (2023) 031802

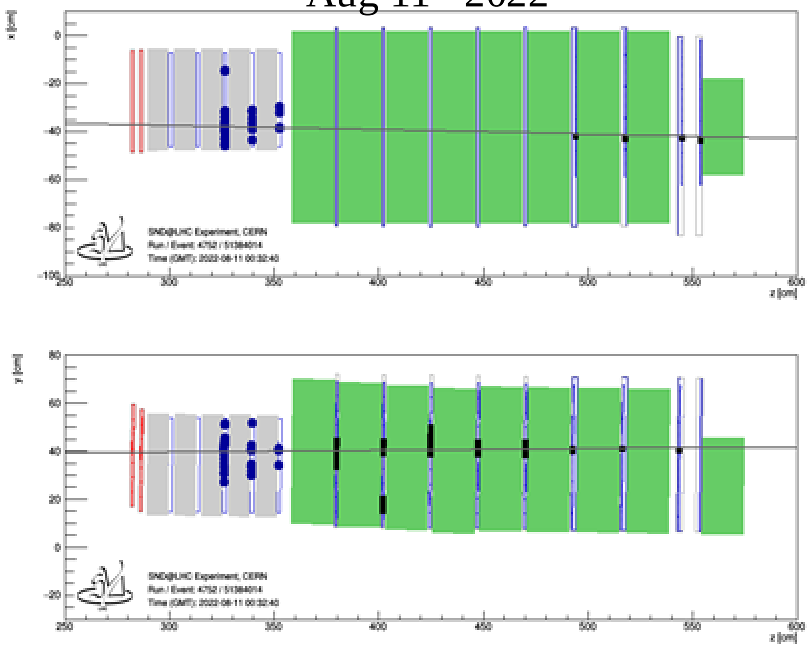
- Both experiments operating since the start of LHC Run 3
- Successful data-taking campaigns in 2022: electronic detectors uptime of ~95%
- Three emulsion detector exchanges in SND@LHC and two in FASER.





Observation of collider muon neutrinos with 2022 data

Aug 11th 2022



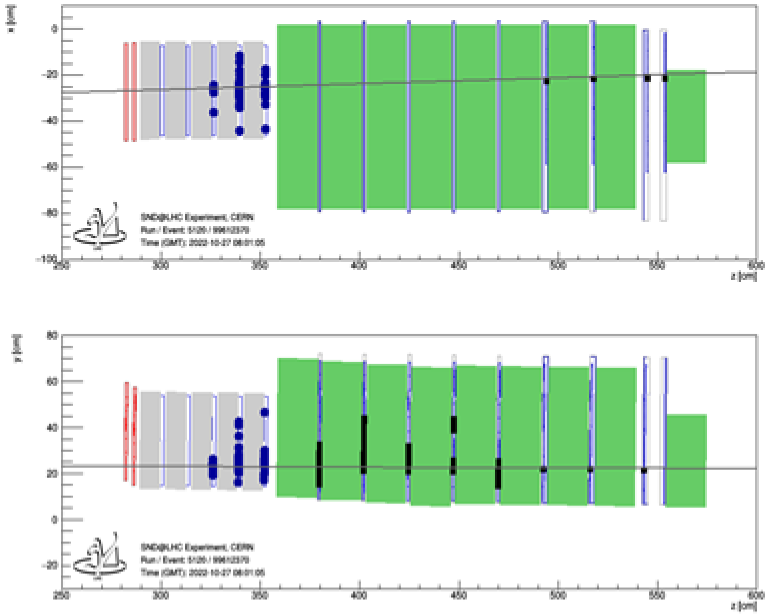
Editors' Suggestion

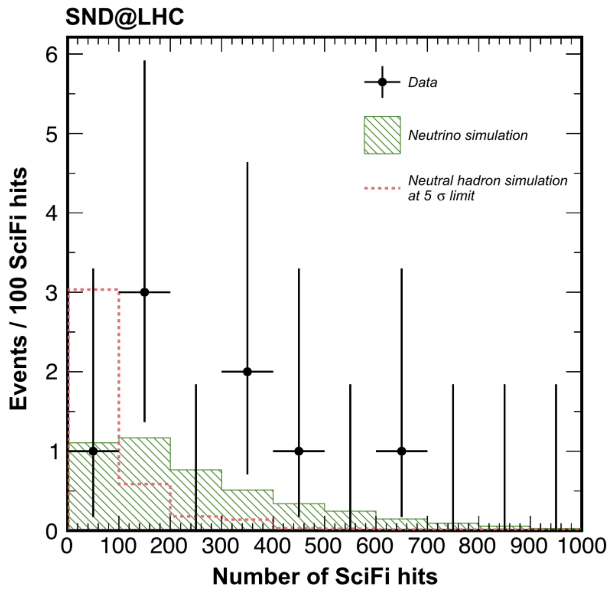
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

R. Albanese *et al.* (SND@LHC Collaboration)

Phys. Rev. Lett. **131**, 031802 (2023) – Published 19 July 2023

Oct 27th 2022





Distribution of SciFi hits for ν_μ candidates with the MC expectation for ν events and background (augmented to the 5-sigma level)

8 observed events and an expected background

$$(8.6 \pm 3.8) \times 10^{-2}$$

Background only hypothesis probability:

$$P = 7.15 \times 10^{-12}$$

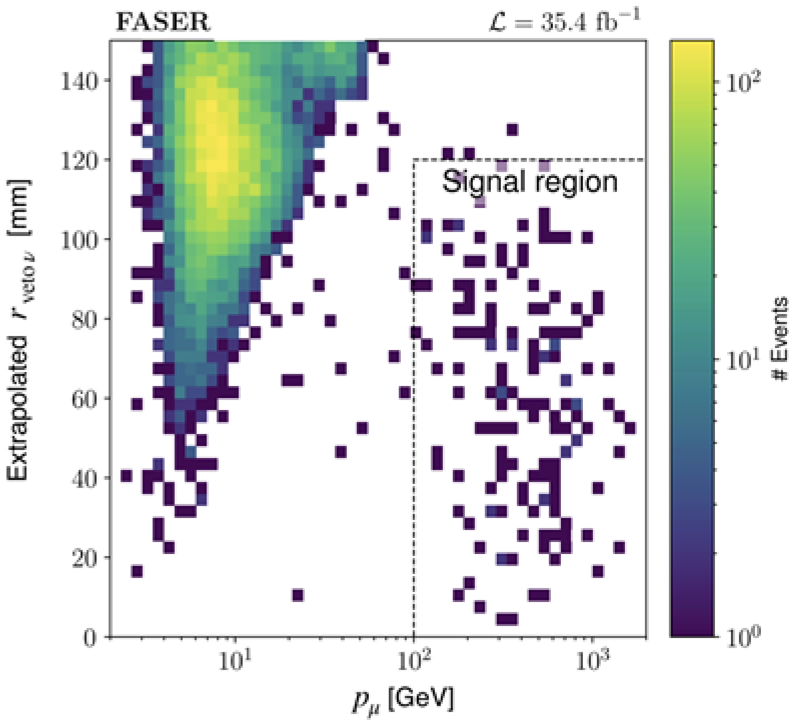
6.8 σ observation

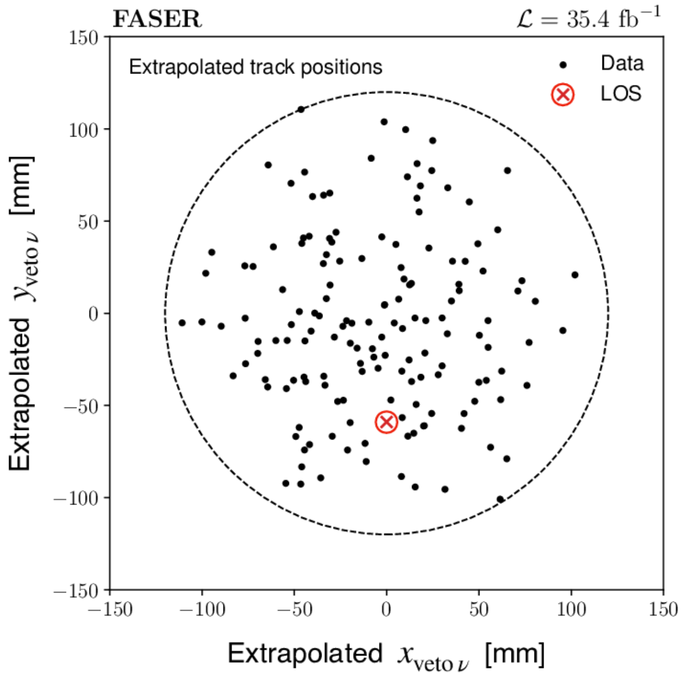
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.031802

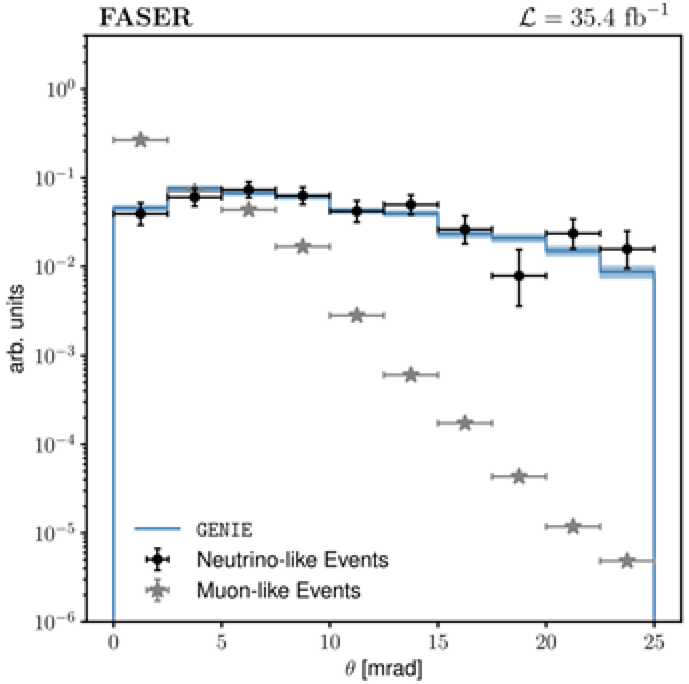
FASER ν_μCC observation with 2022 data

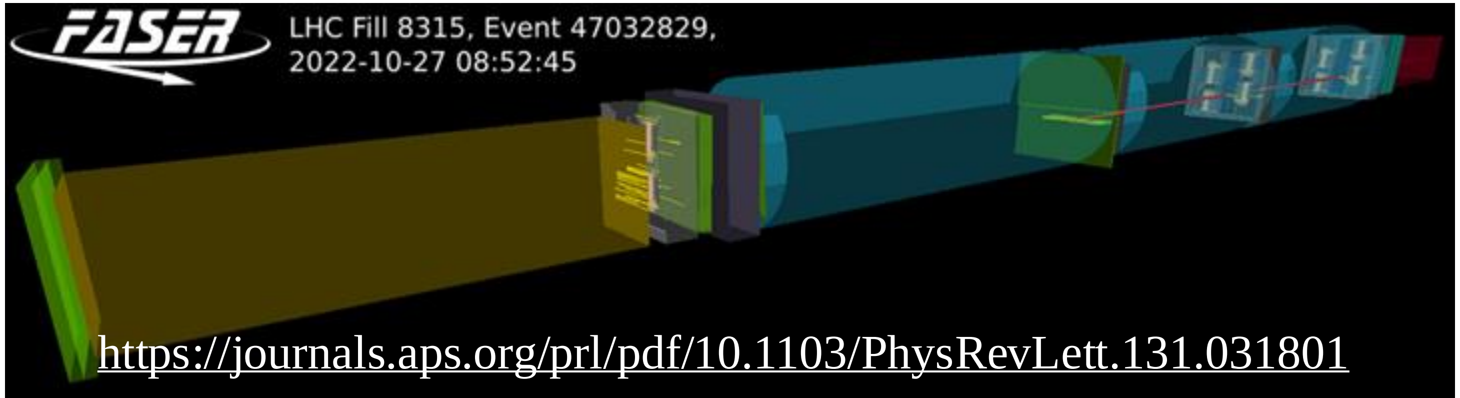
- p > 100 GeV/c
- r < 95 mm in the IFT
- r < 120 mm at the front veto

Observed 153 neutrino event candidates with a statistical significance of 16 σ









https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.131.031801

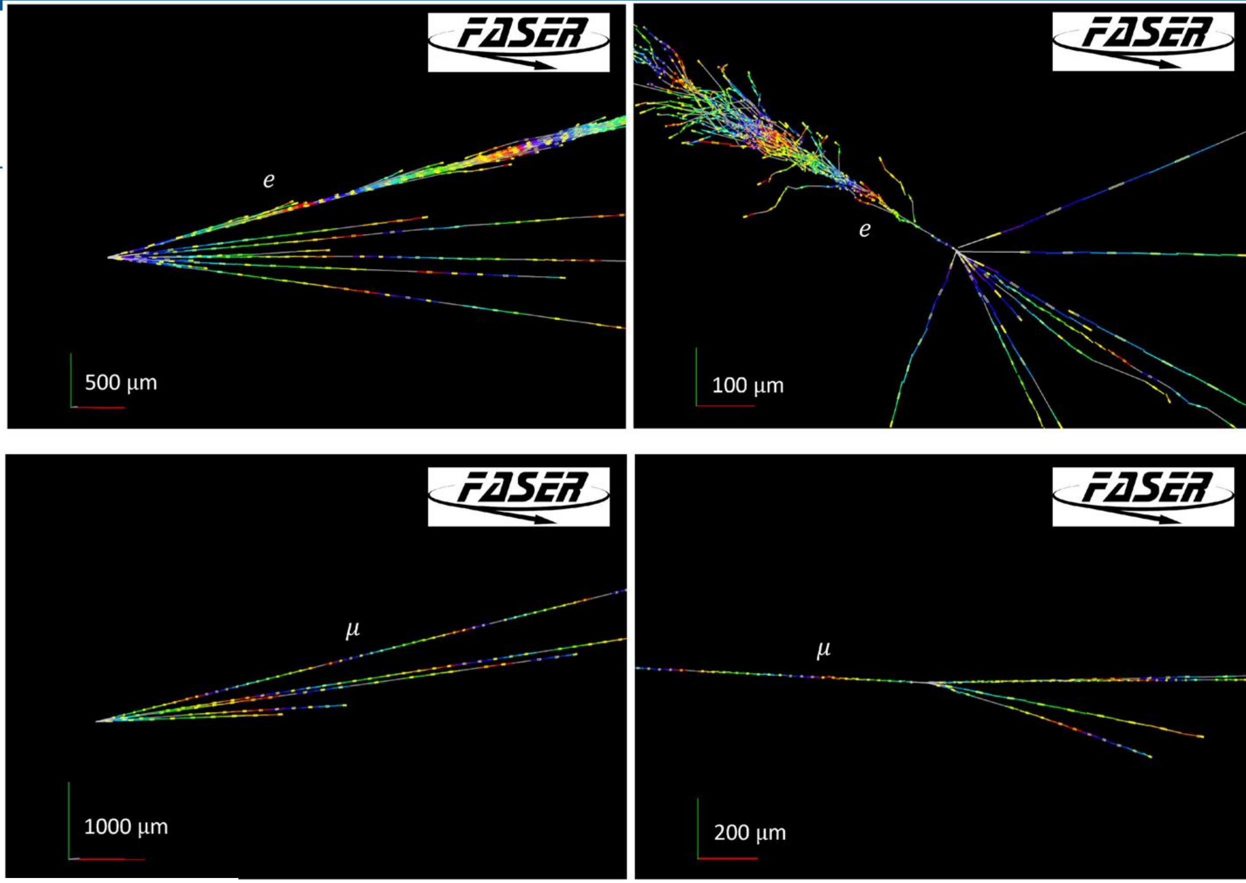
ν_e observation in FASER

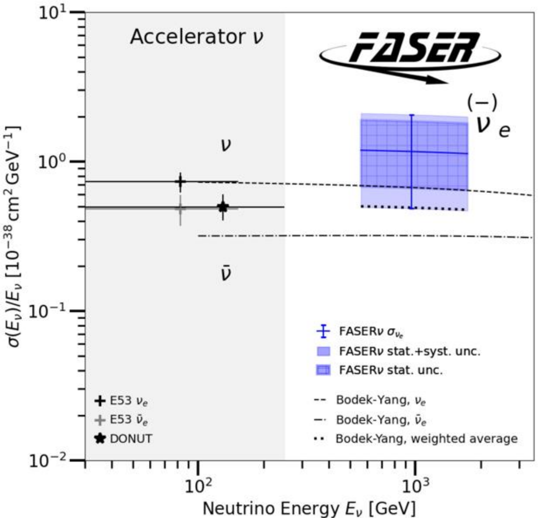
Target mass of 128.6 kg exposed in 2022 to 9.5 fb-1
of pp collisions at 13.6 TeV CoM energy

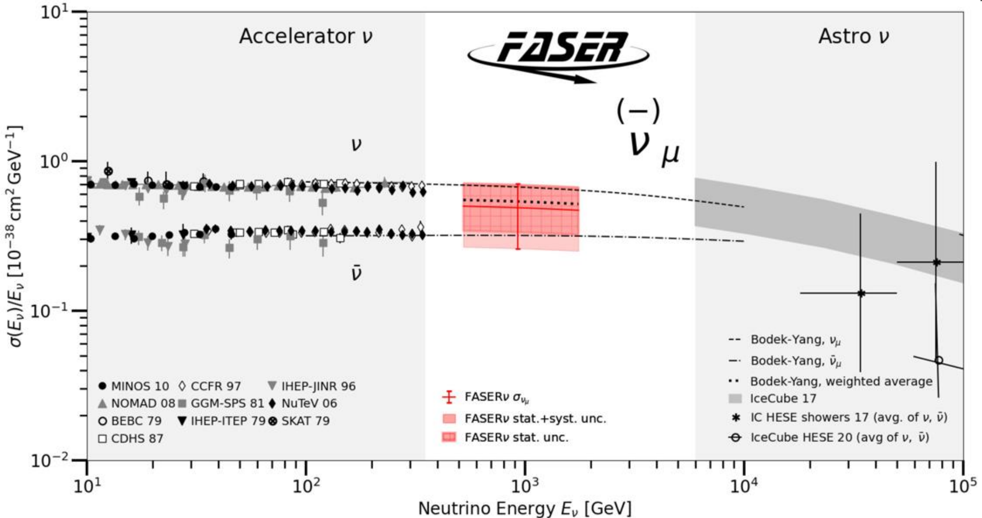
4 ν_e and 8 ν_μ candidates observed

The total background estimates are $0.025^{+0.015}_{-0.010}$ and $0.22^{+0.09}_{-0.07}$ for the ν_e and ν_μ selections, respectively.

PRL 133, 021802 (2024)





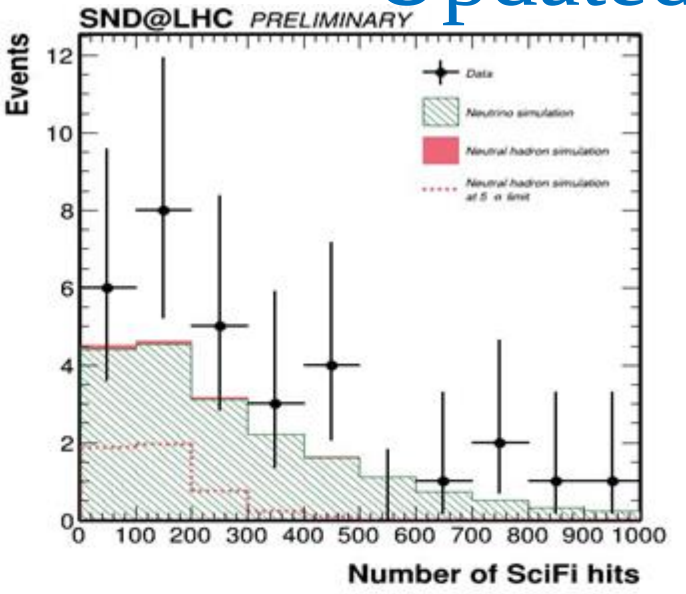


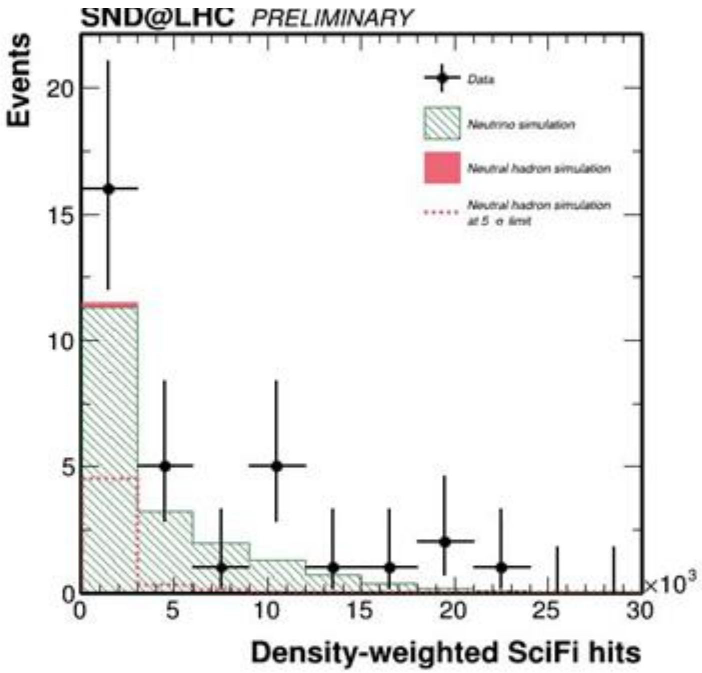
Updated ν_μ results (2022-2023) by SND@LHC

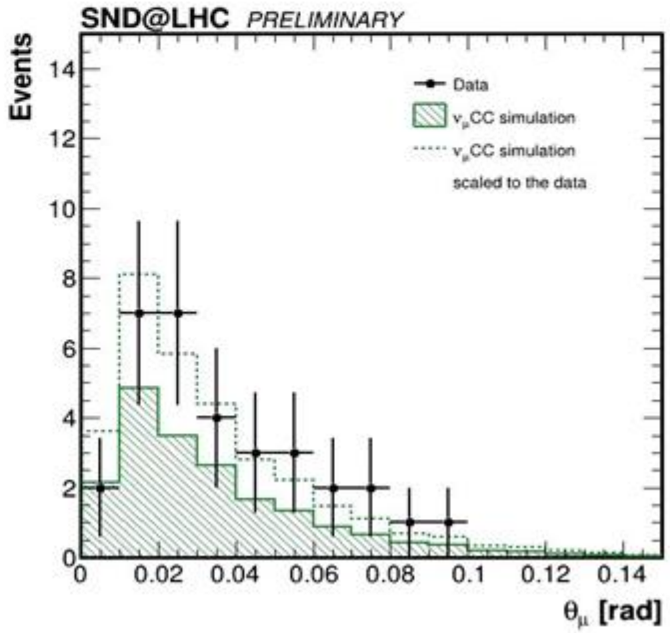
Events expected in 68.6 fb^{-1}

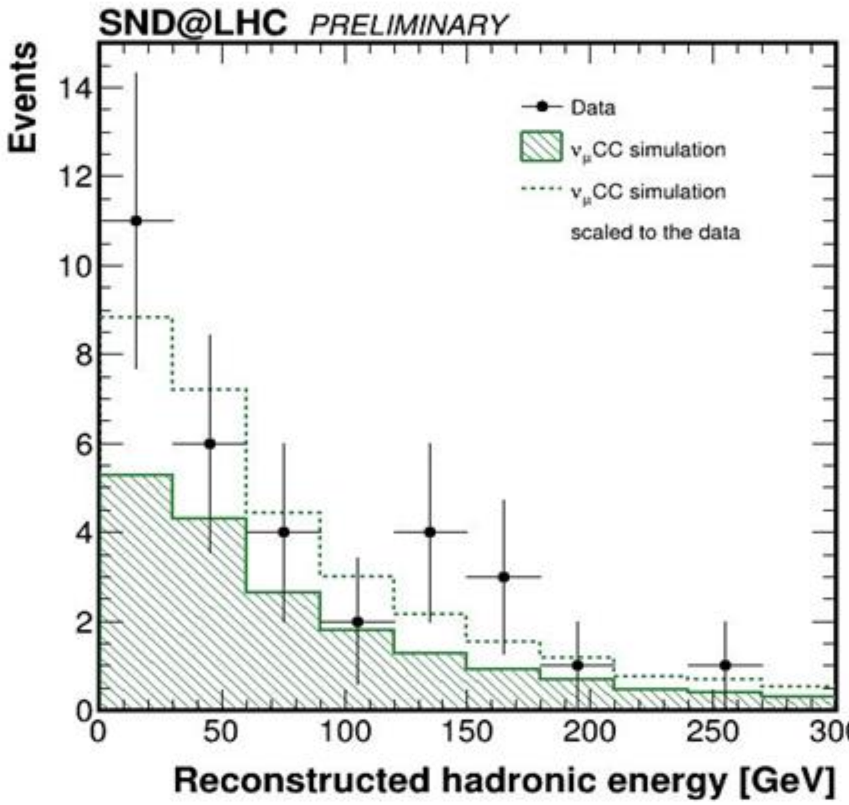
- Signal: 19.1± 4.1
- Neutral hadrons: 0.25 ± 0.06

32 events observed









Observation of 0μ ν events by SND@LHC

Neutral hadron background

- Define background-dominated control region to normalise the simulation
- Events **expected in signal region**: **0.01**

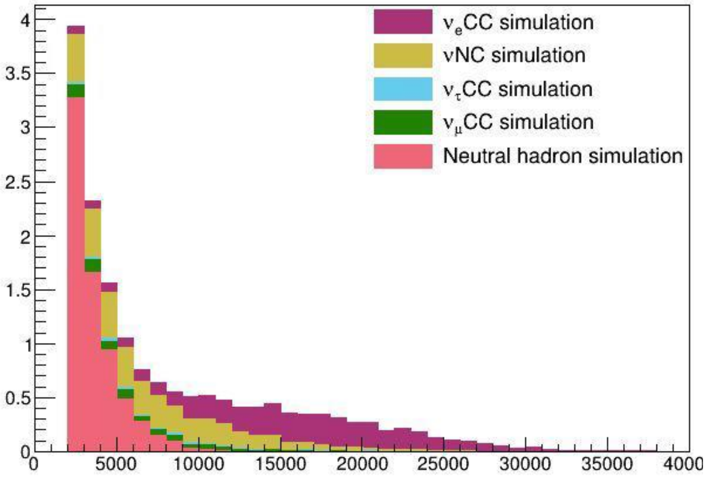
Neutrino background

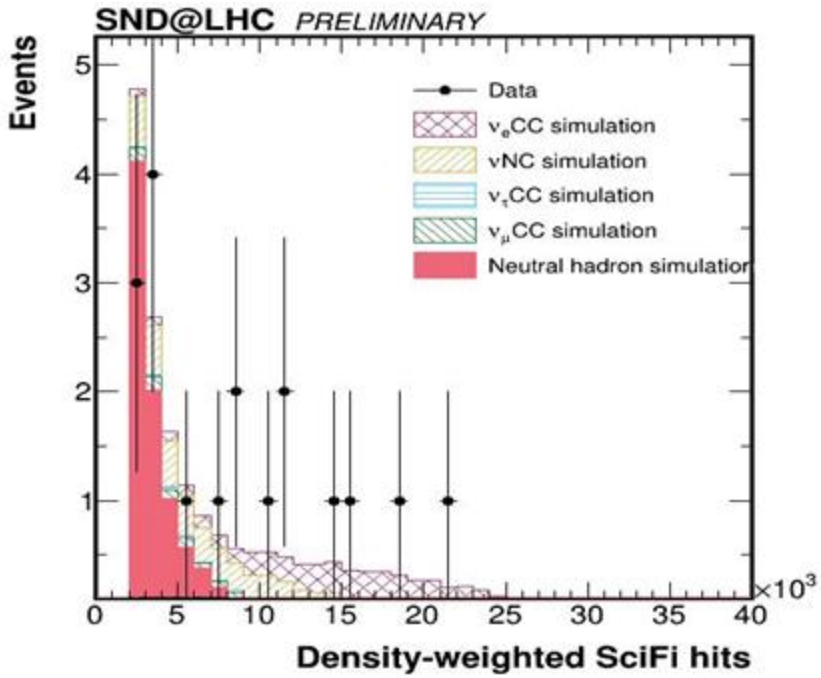
- Muon neutrino CC interactions are the dominant background, with **0.12** expected events.
- Tau neutrino CC interactions expected: **0.002**

0μ observation significance

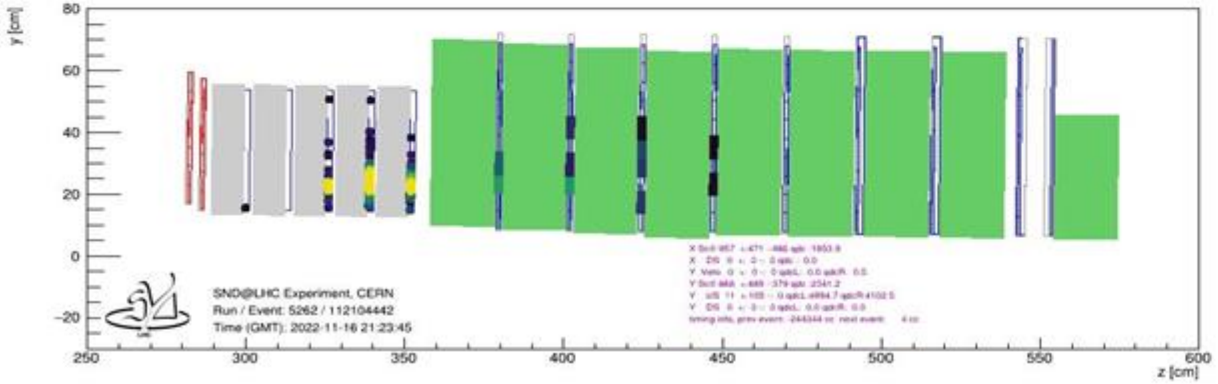
- **Expected background: 0.13 ± 0.07 events**
- **Expected signal: 4.7 events**

Number of events observed: 6
Observation significance 5.8 σ





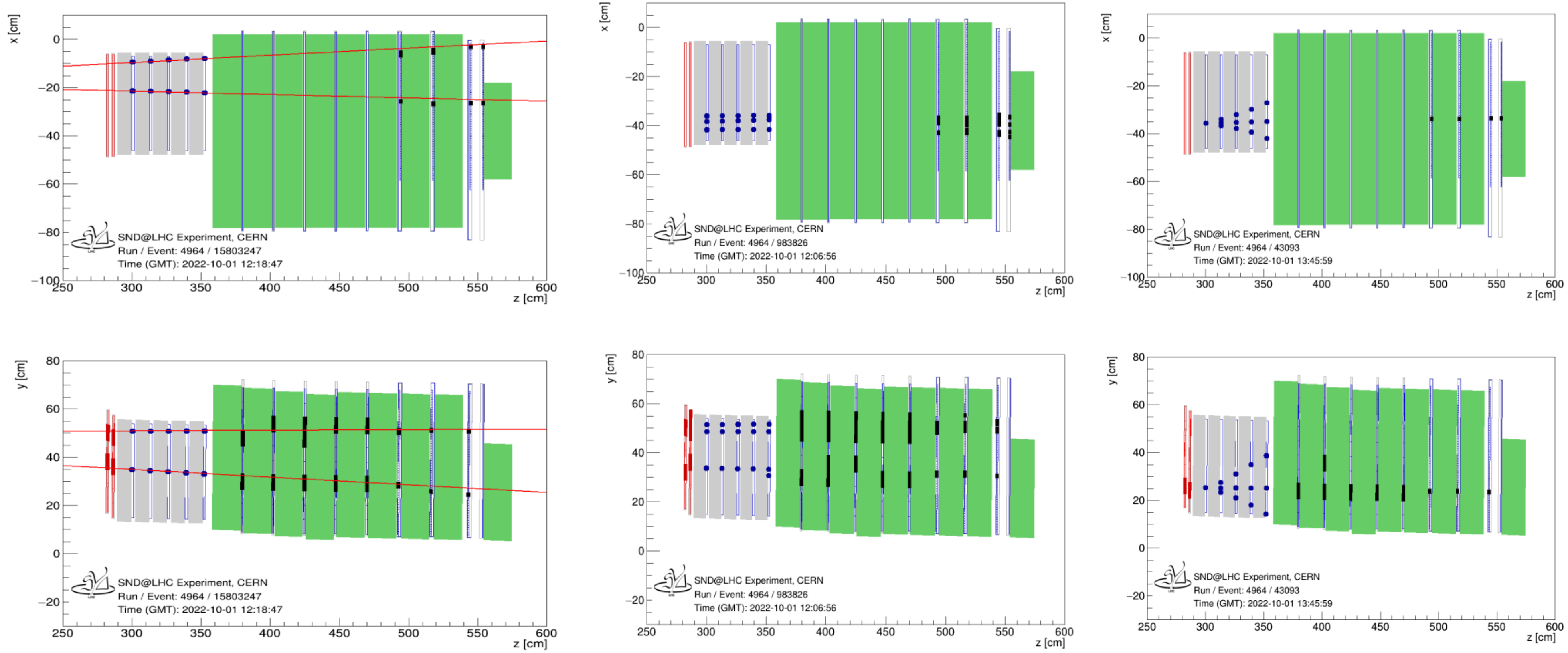
ν_e-like candidate in SND



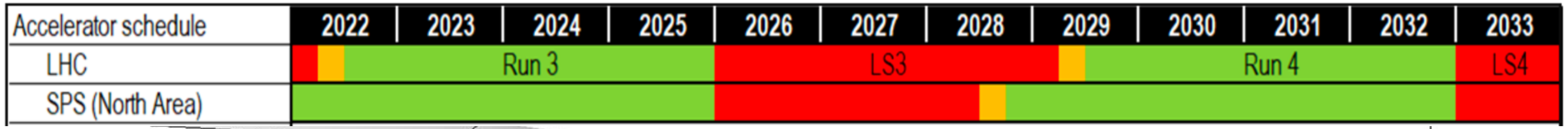
Multi-μ events in SND@LHC: resonances and tridents

- Run 4964: $\int Ldt = 0.31 fb^{-1}$, $\sigma_{inelastic} = 80\, mb$, 2448 bunch crossings of 3564, $N_{collisions} = 25 \times 10^{12}$, $T = 26 \times 10^{3} s$, $N_{xings} = 0.72 \times 10^{12}$; Efficiency corrected average over this run: 300 tracks/s
- Single muon per bunch crossing: $\mu = 1.1 \times 10^{-5}$, Probability for k-track event from pile-up: $\frac{\mu^k e^{-\mu}}{k!}$
- Expected $N_{2\ track} = 43$, observed 224; Expected: $N_{3\ track} = 2 \times 10^{-4}$; Observed: 4

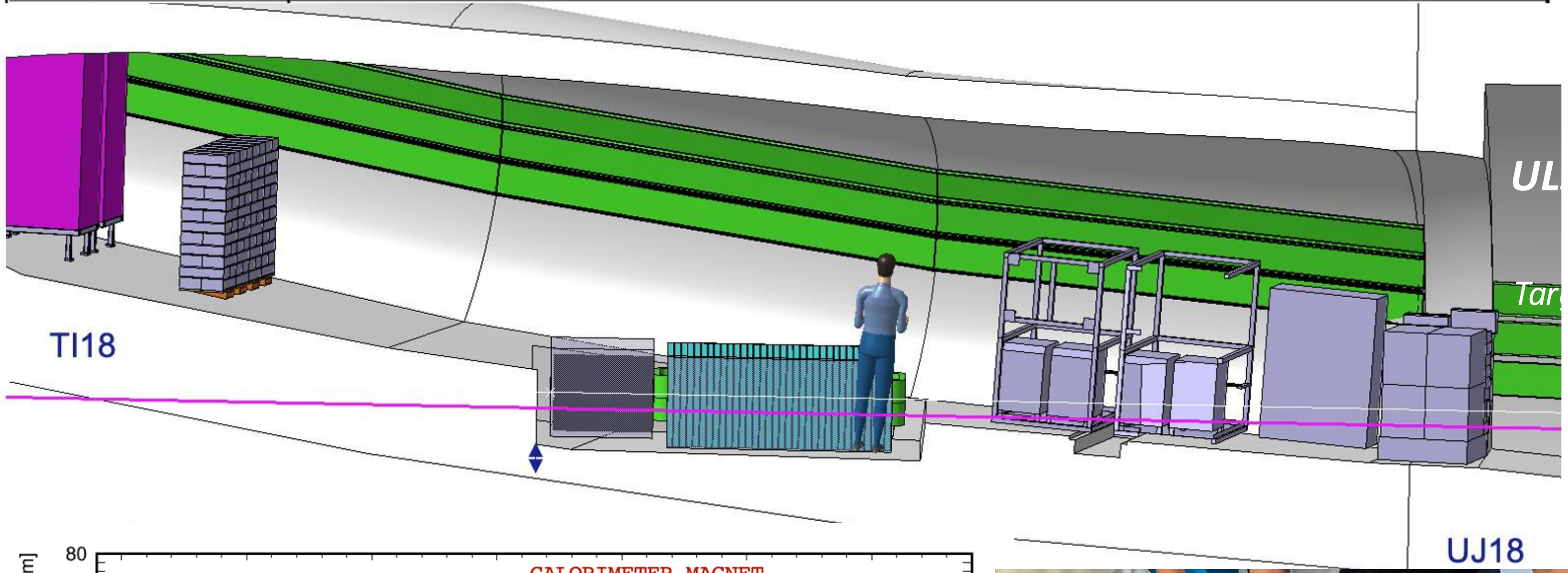
Additional rate due to trident process, muon pair production in rock, concrete, tungsten.

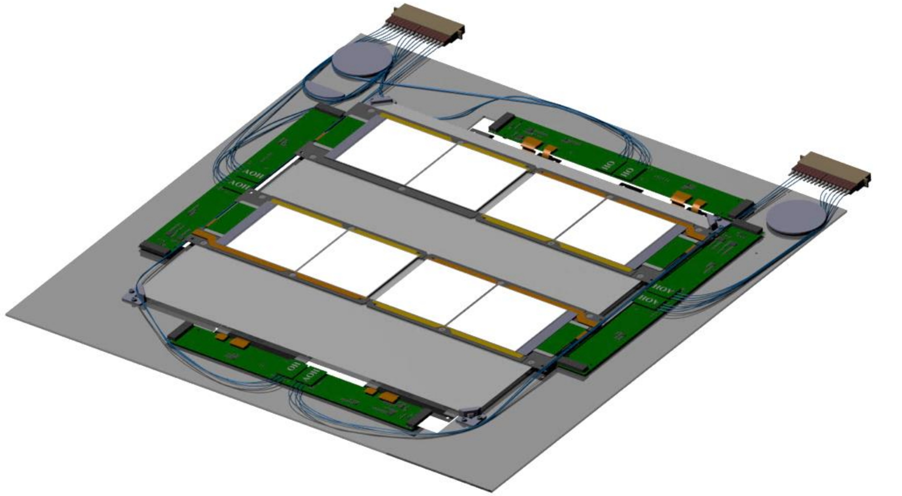


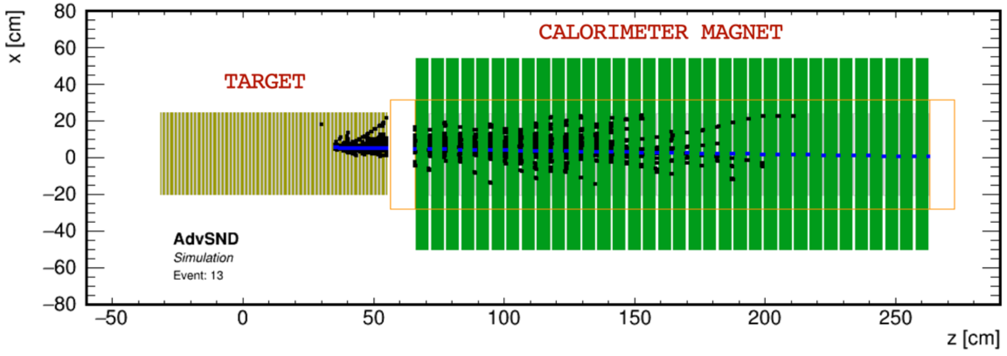
Near future plans: upgraded SND@LHC for Run4

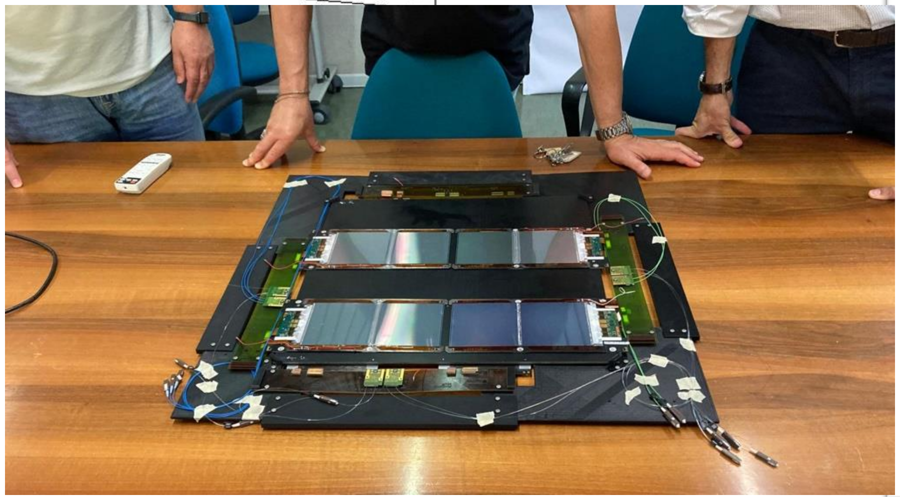


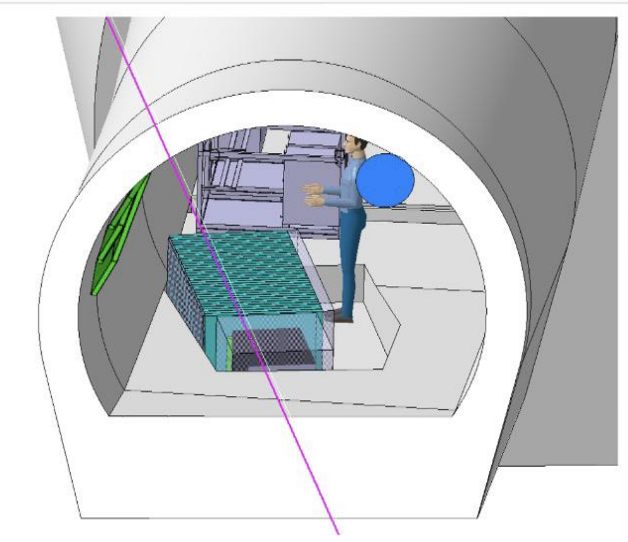
Both neutrino target/vertex and HCAL based on silicon strip technology



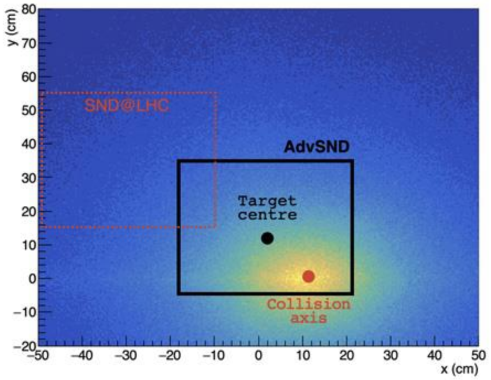




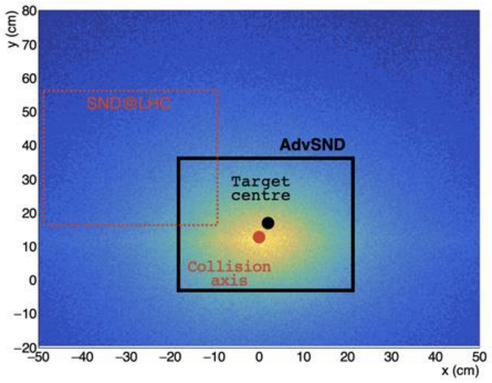




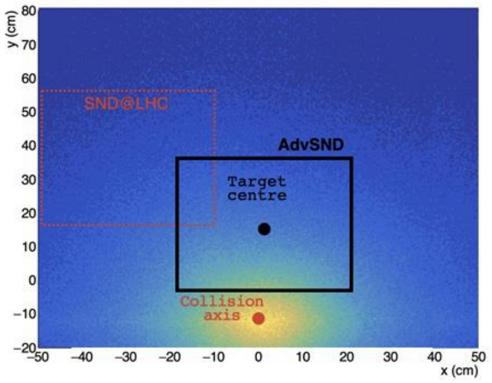
Expected ν yield for SND@LHC in the HL-LHC



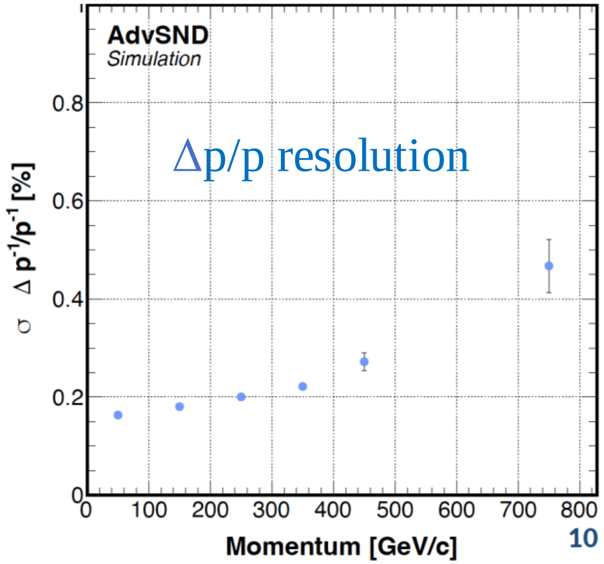
HORIZONTAL
+250 μrad



VERTICAL
+250 μrad



VERTICAL
-250 μrad



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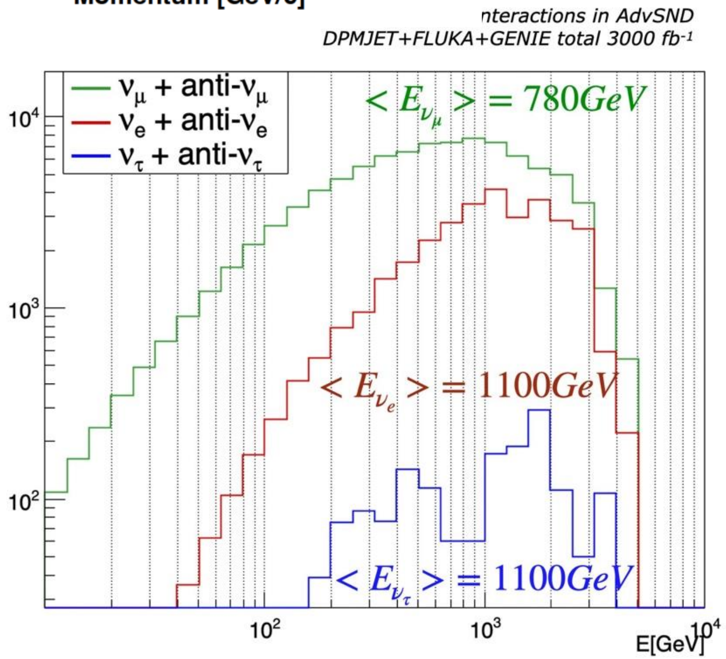
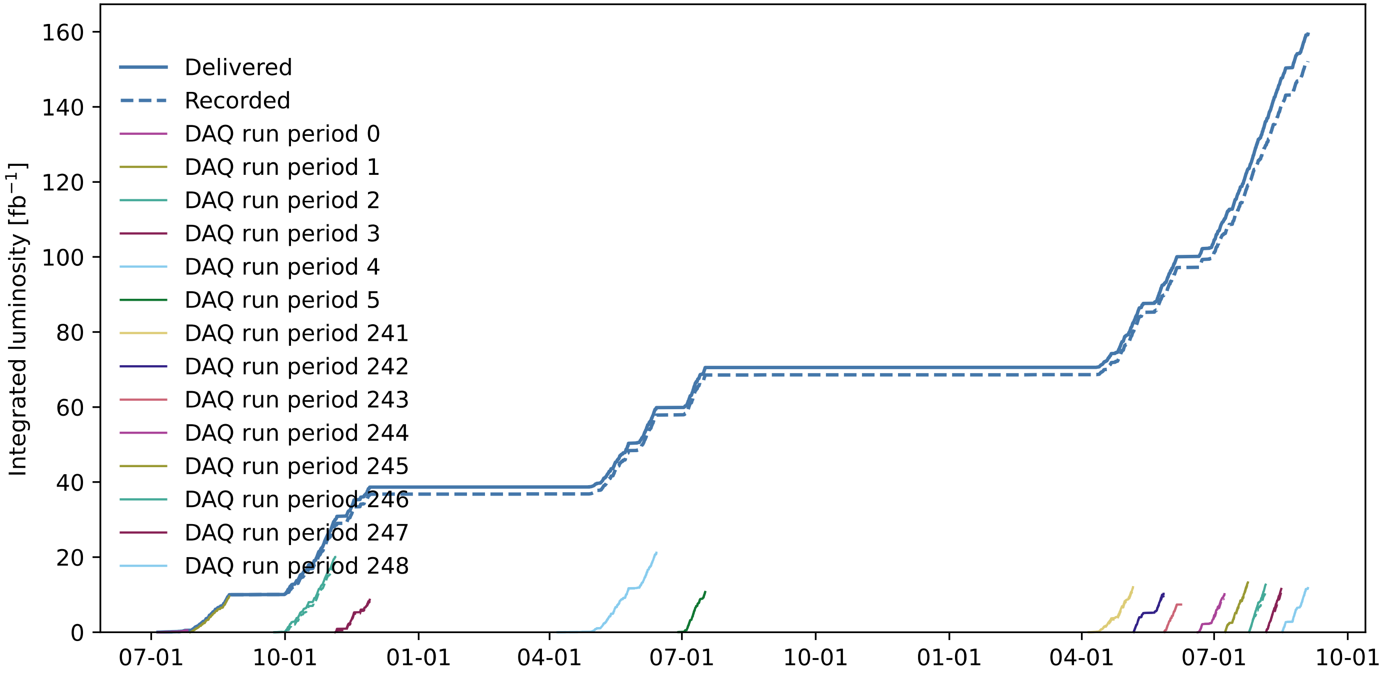
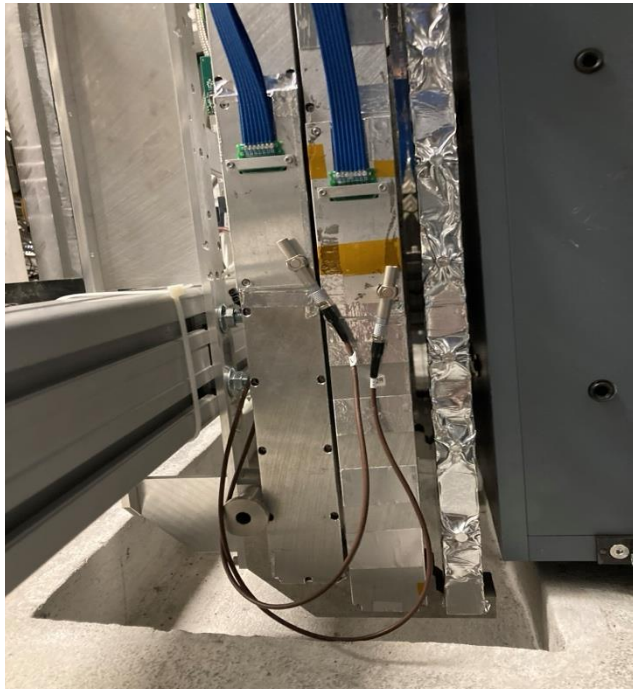


Flavour	ν in acceptance		CC DIS		NC DIS	
	All	not from π/K	All	not from π/K	All	not from π/K
ν_μ	7.9×10^{13}	7.6×10^{12}	6.8×10^{4}	1.8×10^{4}	2.1×10^{4}	5.4×10^{3}
$\bar{\nu}_\mu$	6.5×10^{13}	8.9×10^{12}	2.5×10^{4}	9.8×10^{3}	9.1×10^{3}	3.6×10^{3}
ν_e	1.1×10^{13}	7.7×10^{12}	2.2×10^{4}	1.9×10^{4}	6.6×10^{3}	5.7×10^{3}
$\bar{\nu}_e$	1.1×10^{13}	8.1×10^{12}	1.0×10^{4}	9.0×10^{3}	3.8×10^{3}	3.3×10^{3}
ν_τ	6.4×10^{11}	6.4×10^{11}	1.0×10^{3}	1.0×10^{3}	3.4×10^{2}	3.4×10^{2}
$\bar{\nu}_\tau$	8.6×10^{11}	8.6×10^{11}	5.7×10^{2}	5.7×10^{2}	2.3×10^{2}	2.3×10^{2}
Tot	1.7×10^{14}	3.4×10^{13}	1.3×10^{5}	5.7×10^{4}	4.1×10^{4}	1.8×10^{4}

(Much) more data coming…

Integrated luminosity above 150 fb-1!





Upgraded veto system at the end of 2023

Current analyses based on 10÷20 fb-1, large statistical improvement thanks to the good LHC run in 2024 and to the upgrade of the detector (increase the acceptance by a factor of 2)

The SHiP (Search for Hidden Sector) experiment at CERN

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

EPJC (2022) 82:486

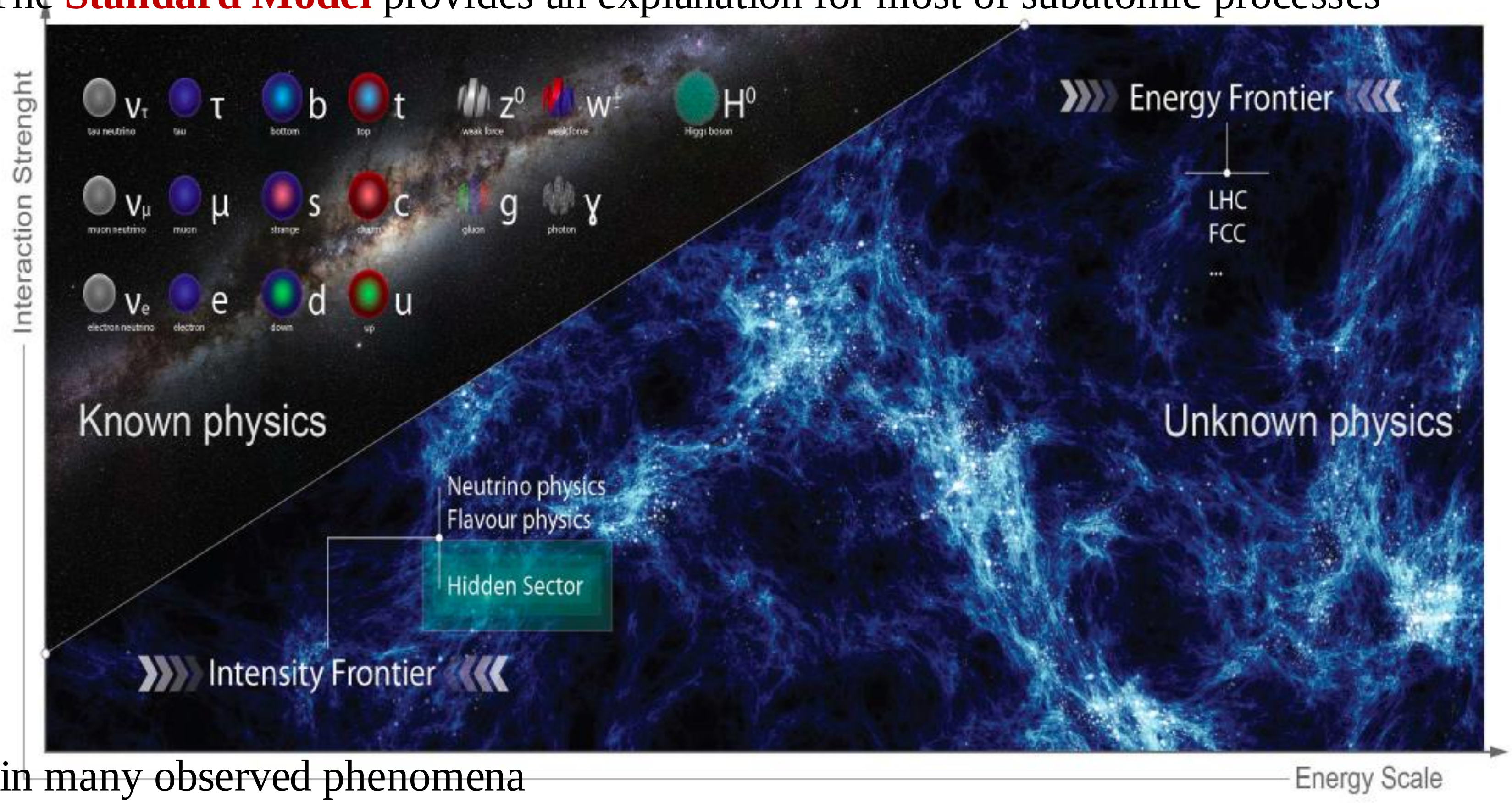
Experiment approved by the Research Board in March 2024

Collaboration of 38 Institutes from 15 Countries and CERN

Collaboration meeting in April 2024

Motivation

- The **Standard Model** provides an explanation for most of subatomic processes



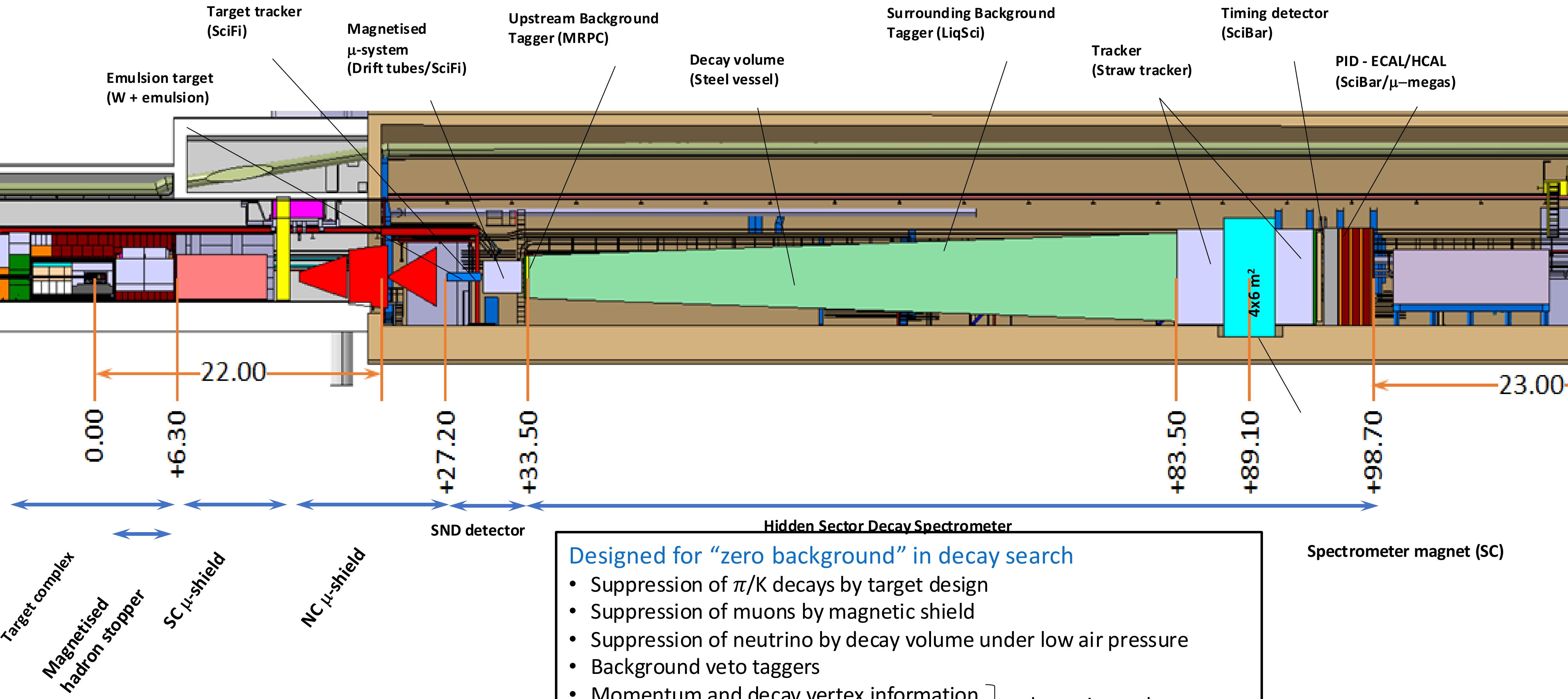
- It fails to explain many observed phenomena
  - **Dark Matter**
  - **Neutrino Oscillation and masses**
  - **Matter/antimatter asymmetry in the Universe**

- A **Hidden Sector (HS)** of weakly-interacting BSM particles as an explanation

Energy Frontier:
Heavy particles → high energy collisions

Intensity Frontier:
Very weakly interacting particles → high intensity beam

SHiP detector in more detail



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 } by main tracker
- Impact parameter at target } by main tracker
- Coincidence timing

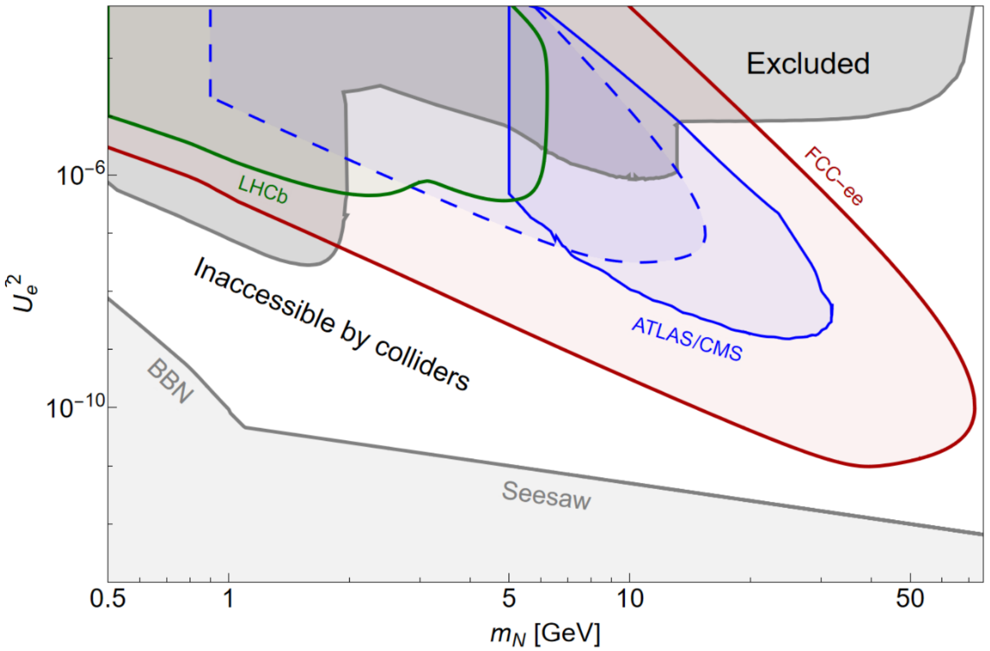
- Invariant mass } Not currently used in background suppression
- Particle identification } Not currently used in background suppression

SHiP strategy

- Initiative to identify
  - Full exploitation of unique physics potential of SPS available since CNGS (*Rep. Prog. Phys.* **79** (2016)124201)
  - Rich and relevant physics programme with the injectors at CERN going beyond LHC, bridging gap to next collider

➔ SPS suitability to explore *Light Dark Matter and associated mediators, and ν mass generation* – FIPs generically

E.g. Heavy Neutral Leptons



➔ Region that can *only* be explored by optimised beam-dump experiment

➔ Production modes in limited forward cone – large lifetime acceptance

➔ SPS energy and intensity provide huge production of charm, beauty and electromagnetic processes

➔ Unique *direct discovery potential in the world in the heavy flavour region,* capable of reaching "physical floor/background floor"

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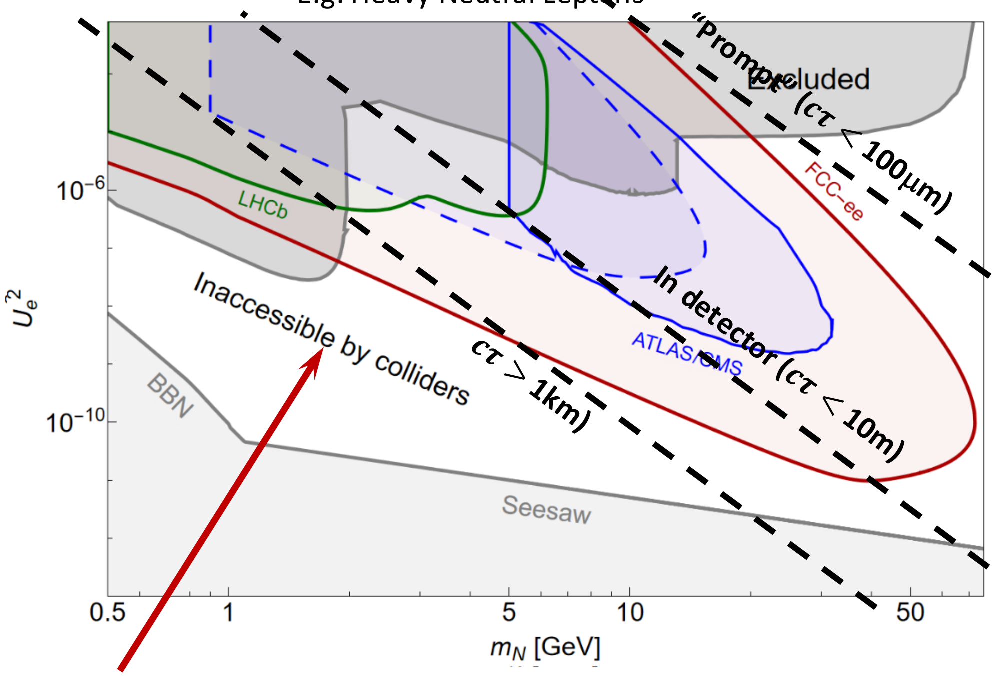

Similar behaviour $\tau_{FIP} \propto \frac{1}{\epsilon_{FIP}^{x} m_{FIP}^{y}}$

for all types of FIPs

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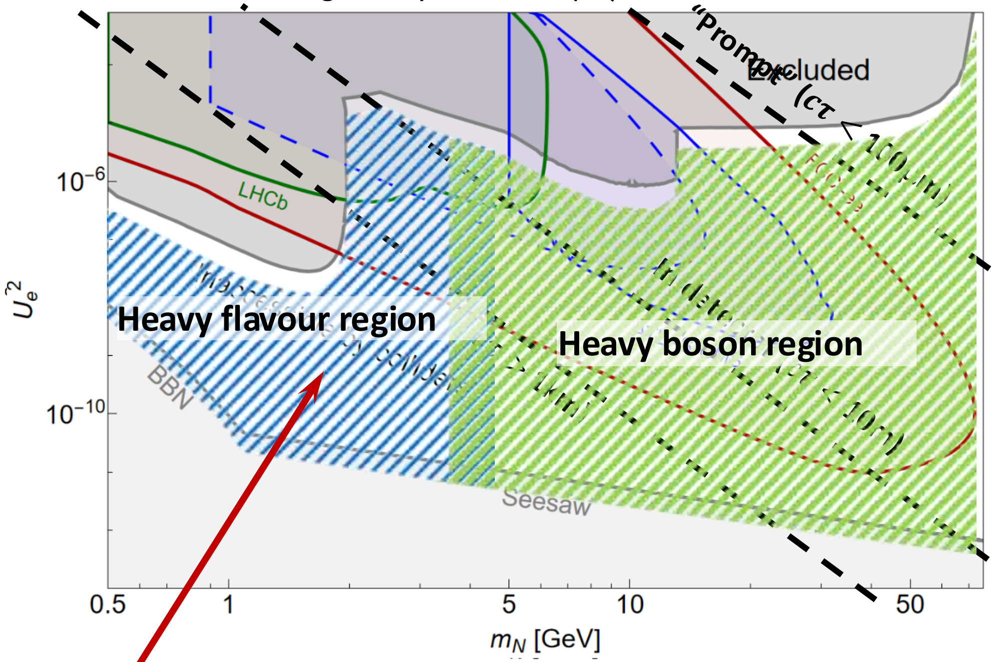

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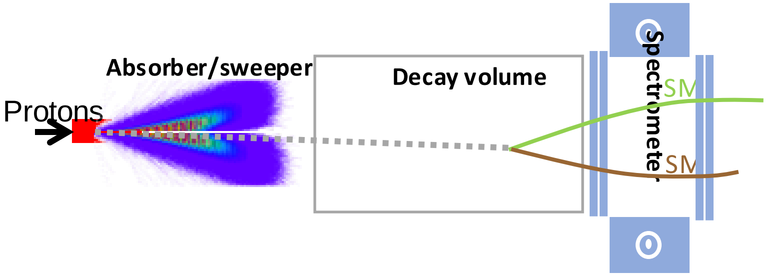
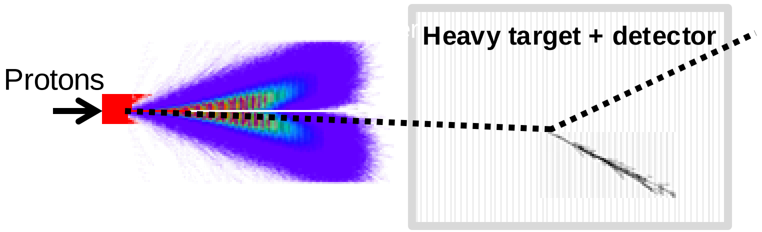
BDF/SHiP experimental techniques

➔ Explore Light Dark Matter, and associated mediators - generically domain of FIPs - and ν mass generation through:

Decay signatures



Scattering signatures



Also suitable for neutrino interaction physics with all flavours

- Acceptance optimisation of both techniques described in arXiv:2304.02511, *EPJC* 83 (2023) 12

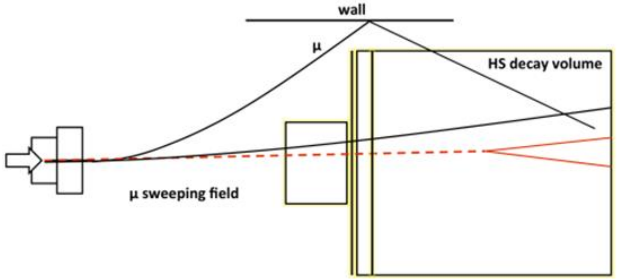
- Exhaustive search by aiming at model-independent detector setup
  - Full reconstruction and identification of both fully and partially reconstructible modes
    - ➔ Sensitivity to partially reconstructed modes also proxy for the unknown
  - In case of discovery ➔ precise measurements to discriminate between models / test compatibility with hypothetical signal

➔ FIP decay signature search in background-free environment and LDM scattering
➔ Rich neutrino interaction physics with access to tau neutrino

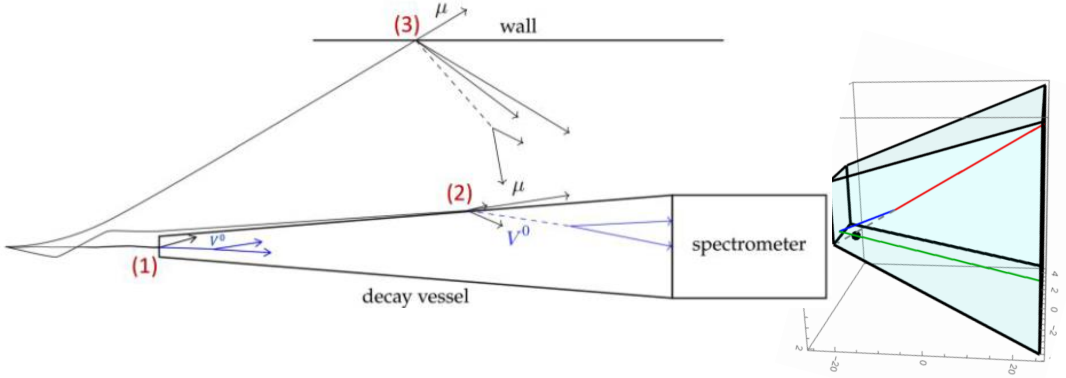
HSDS: FIP decay search background evaluation

Three categories of background from residual muons and neutrinos

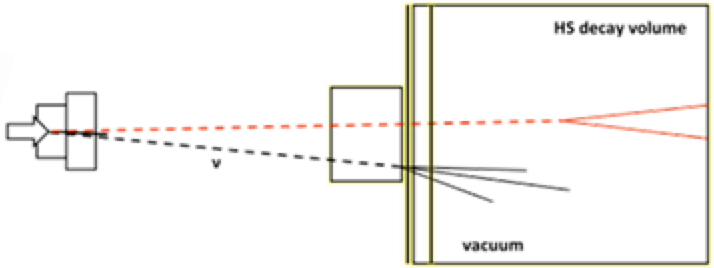
Muon combinatorial



Muon DIS



Neutrino DIS



- Backgrounds from μ and ν DIS dominated by random combinations of secondaries, not by V^0s

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

➔Possibility to measure background with data, relaxing veto and selection cuts, muon shield, decay volume

Selection

Criterion	Requirement
Track momentum (and track quality)	$> 1.0\,\mathrm{GeV}/c$
Vertex quality (distance of closest approach)	$< 1\,\mathrm{cm}$
Track pair vertex position in decay volume	$> 5\,\mathrm{cm}$ from inner wall
	$> 100\,\mathrm{cm}$ from entrance (partially)
Impact parameter w.r.t. target (fully reconstructed)	$< 10\,\mathrm{cm}$
Impact parameter w.r.t. target (partially reconstructed)	$< 250\,\mathrm{cm}$

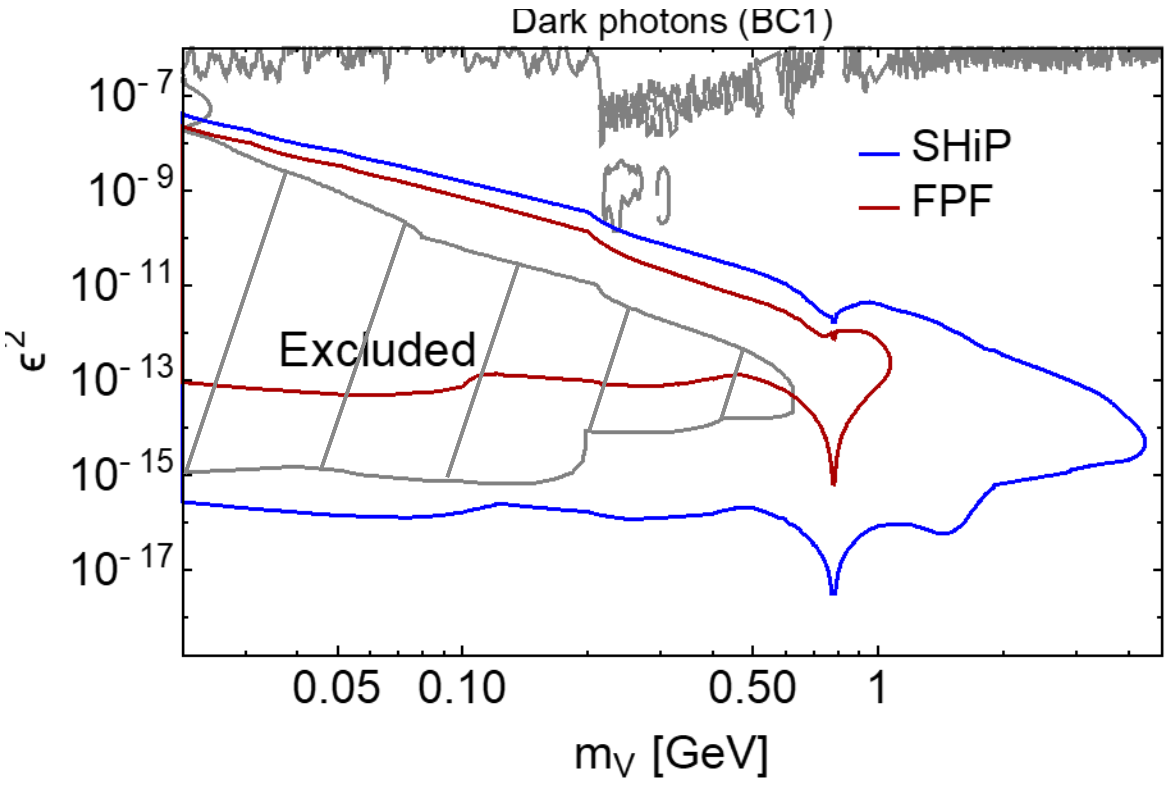
+ Time coincidence **+ UBT/SBT**

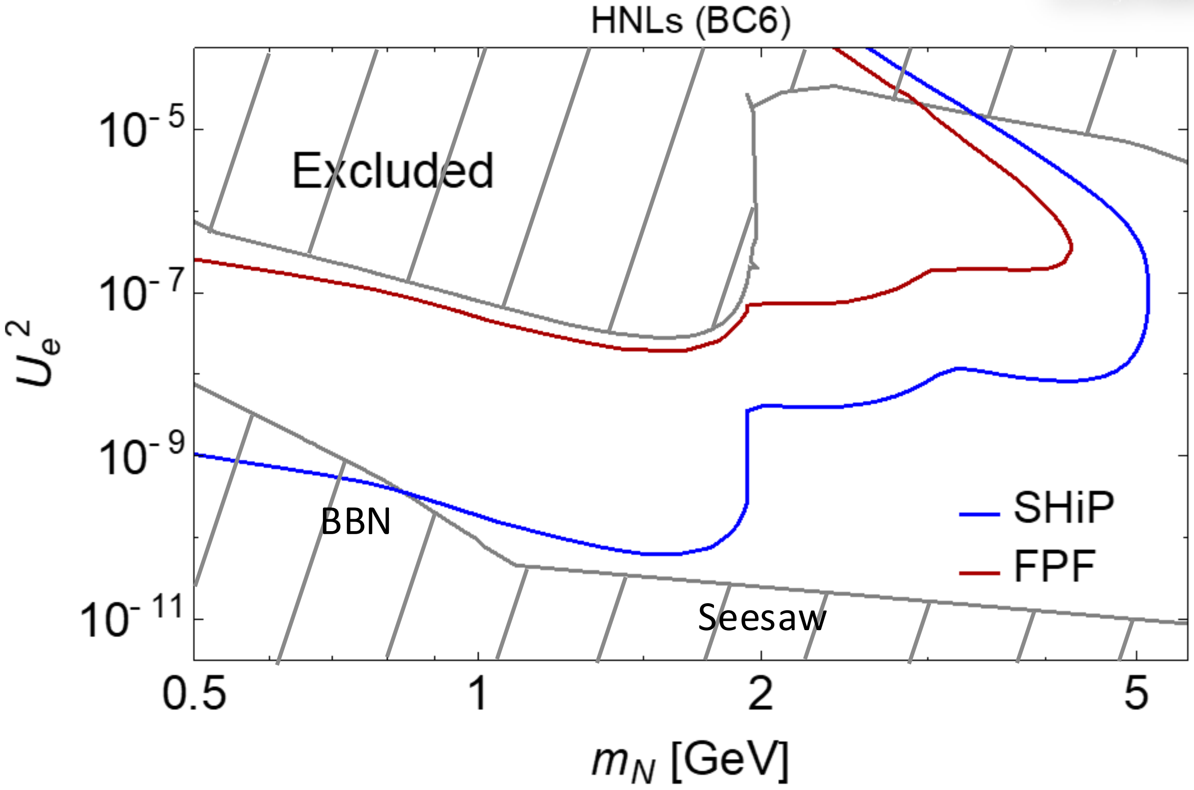
Expected background is <1 event for 6×10^{20} pot (15 years of operation)

Background source	Expected events
Neutrino DIS	< 0.1 (fully)/< 0.3(partially)
Muon DIS (factorisation)*	$< 5\times10^{-3}$ (fully) / < 0.2(partially)
Muon combinatorial	$(1.3\pm2.1)\times10^{-4}$

HSDS: FIP decay search performance

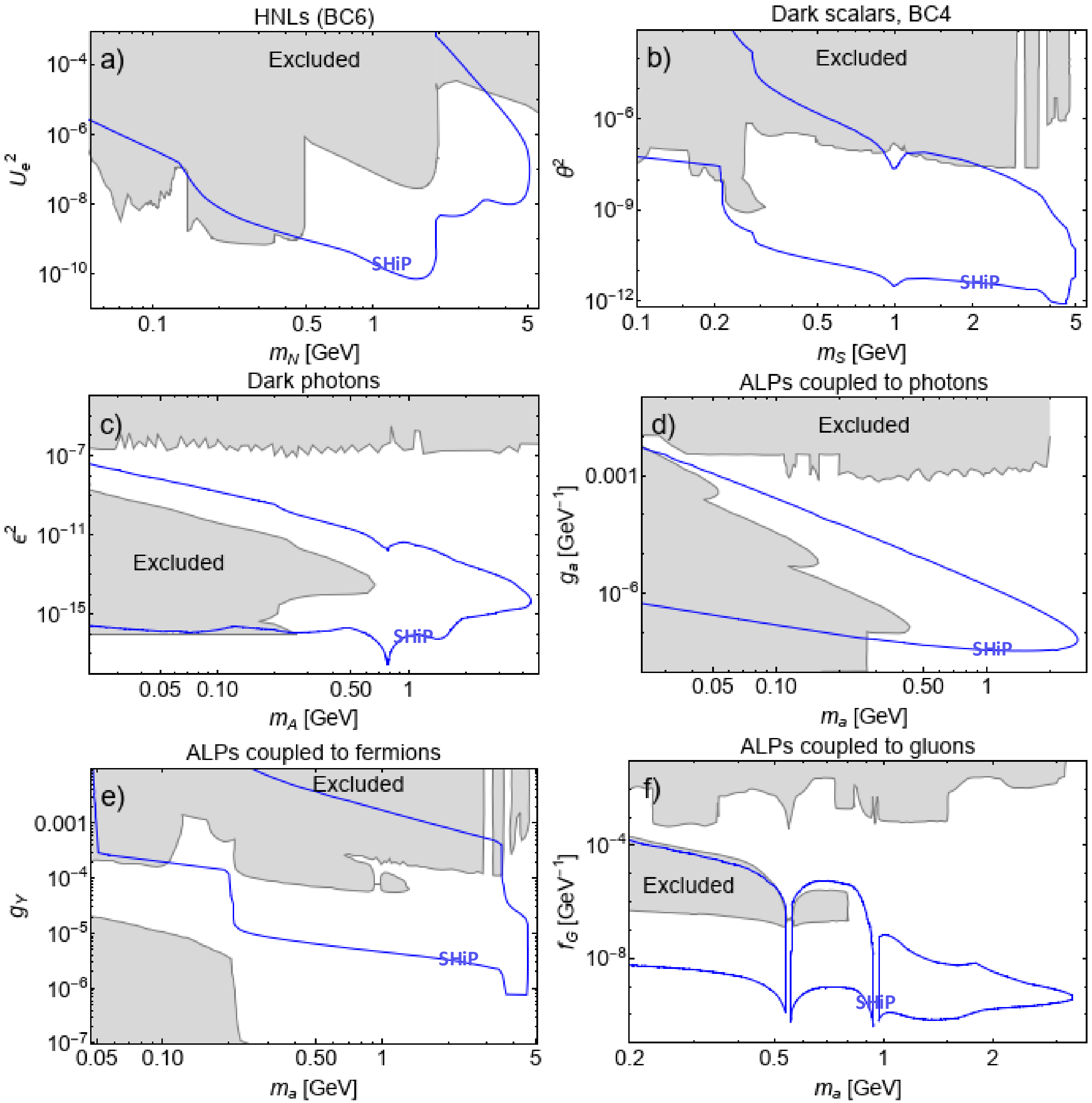
➔ SHiP sensitivity is not limited by backgrounds in 6 x 10^{20} PoT

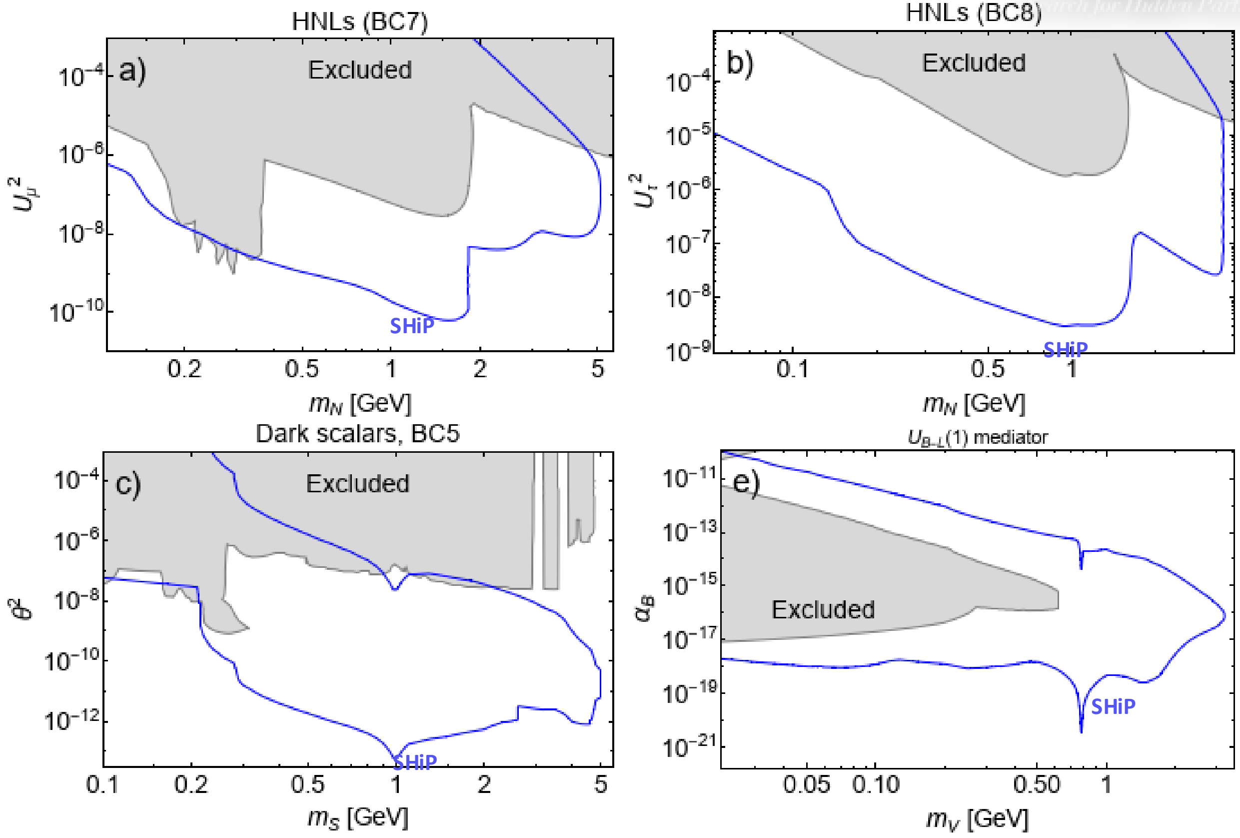




SHiP sensitivities to FIPs are orders of magnitude better than other projects

HSDS: FIP decay search performance, all benchmarks





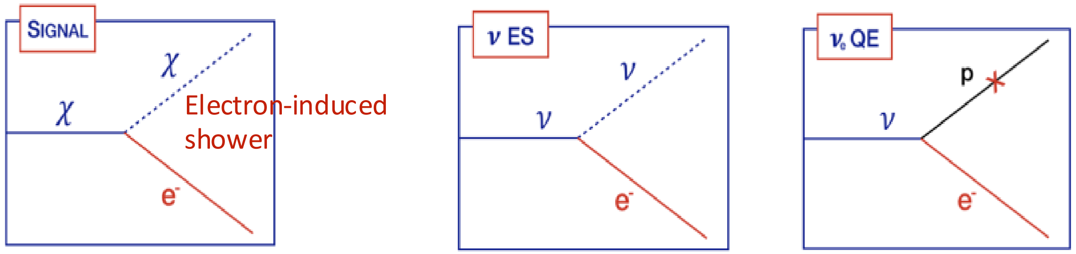
+ also SUSY-related benchmarks

Exploration of (2-5 ⊗ 1-2) orders of magnitude (coupling^2 ⊗ mass) beyond current experiments in all benchmark models

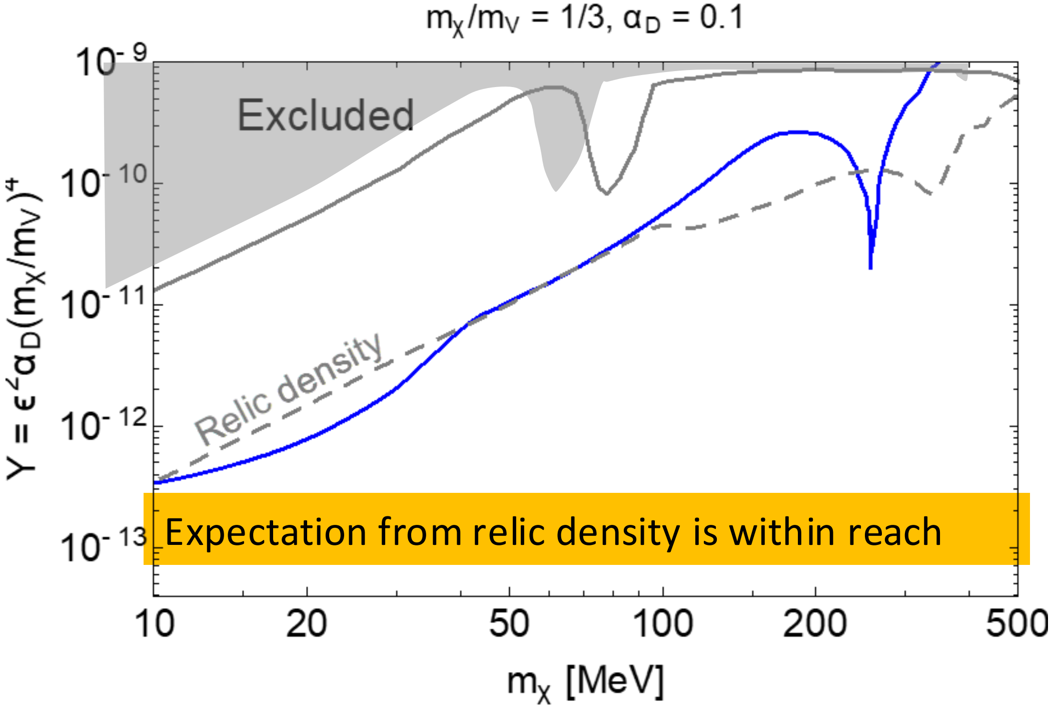
SND: "Direct" light dark matter search

- *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 $\times 10^{20}$ PoT

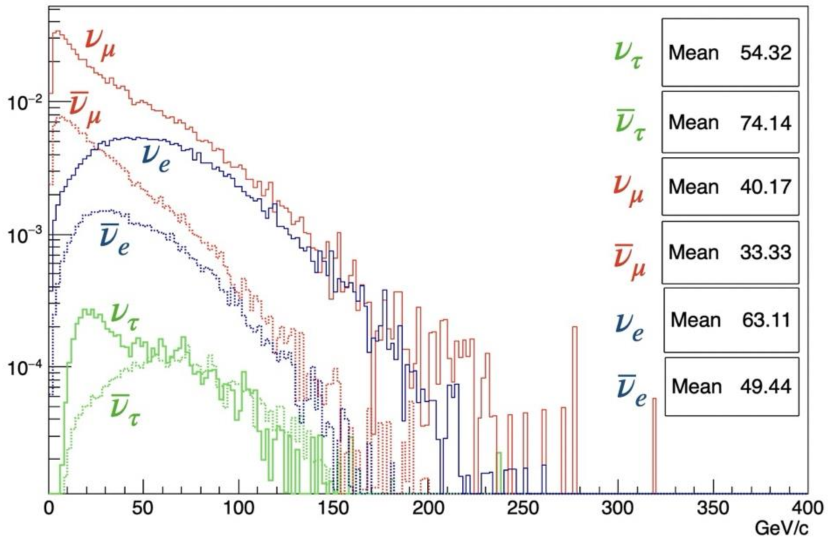


6×10^{20}	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	156	81	192	126	555
Quasi - elastic scattering	-	27			27
Resonant scattering	-	-			-
Deep inelastic scattering	-	-			-
Total	156	108	192	126	582



ν_τ cross-section, ν-induced charm, structure functions, …

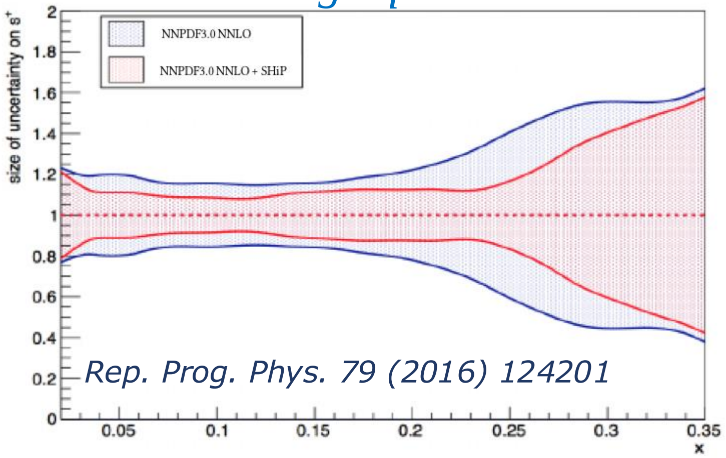
Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	4×10^3	3×10^3
$\tau \to h$	27×10^3	
$\tau \to 3h$	11×10^3	
$\tau \to e$	8×10^3	
total	53×10^3	



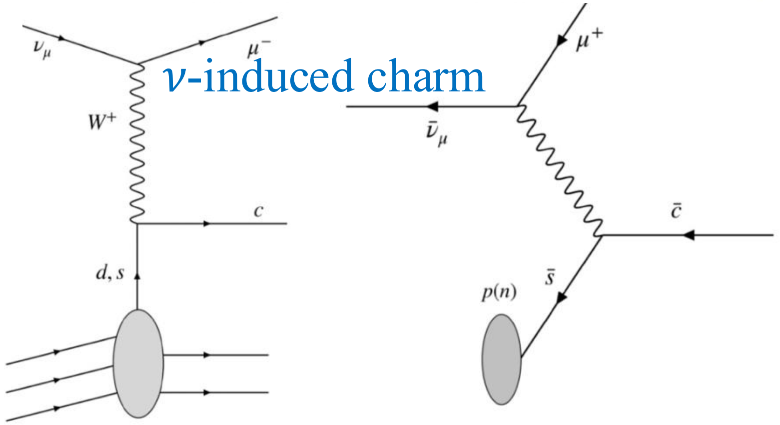
Complementary energy region to the LHC measurements

	<E> [GeV]	CC DIS interactions
N_{ν_e}	63	2.8×10^6
N_{ν_μ}	40	8.0×10^6
N_{ν_τ}	54	8.8×10^4
$N_{\overline{\nu}_e}$	49	5.9×10^5
$N_{\overline{\nu}_\mu}$	33	1.8×10^6
$N_{\overline{\nu}_\tau}$	74	6.1×10^4

Strange quark distribution



ν-induced charm



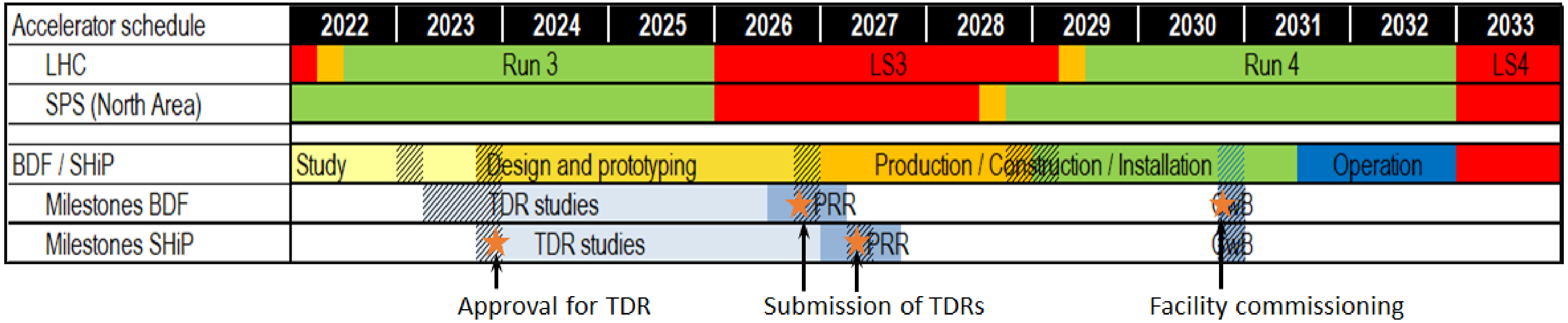
	(GeV)	with charm prod
N_{ν_μ}	57	3.5×10^5
N_{ν_e}	71	1.7×10^5
$N_{\overline{\nu}_\mu}$	50	0.7×10^5
$N_{\overline{\nu}_e}$	60	0.3×10^5
total		6.2×10^5

F4, F5 structure functions

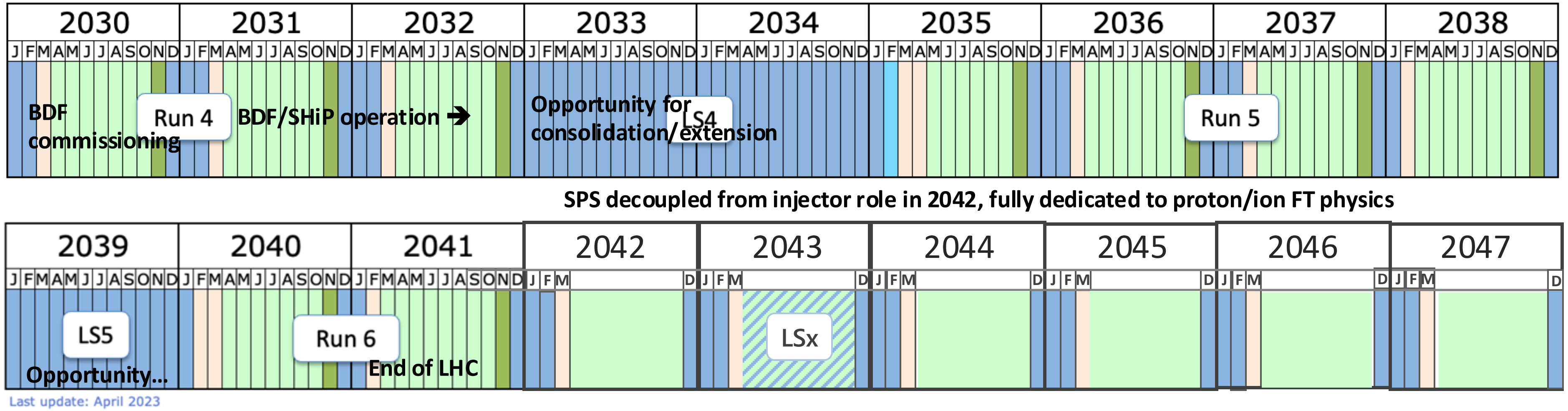
$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg(\Big(y^2 x + \frac{m_\tau^2 y}{2E_\nu M}\Big)F_1 + \left[\Big(1-\frac{m_\tau^2}{4E_\nu^2}\Big) - \Big(1+\frac{Mx}{2E_\nu}\Big)\right]F_2 \pm \left[xy\Big(1-\frac{y}{2}\Big) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3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

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

BDF/SHiP schedule: 15 years of data taking!



- ~3 years for detector TDRs
- Construction / installation of facility and detector is decoupled from NA operation
- Availability of test beams challenging
- Important to start data taking >1 year before LS4
- Several upgrades/extensions of the BDF/SHiP in consideration over the operational life



Reach ν physics program and most sensitive FIBs search at CERN

https://home.cern/news/news/physics/new-lhc-experiments-enter-uncharted-territory

CERNCOURIER | Reporting on international high-energy physics

Physics ▾ | Technology ▾ | Community ▾ | In focus | Magazine

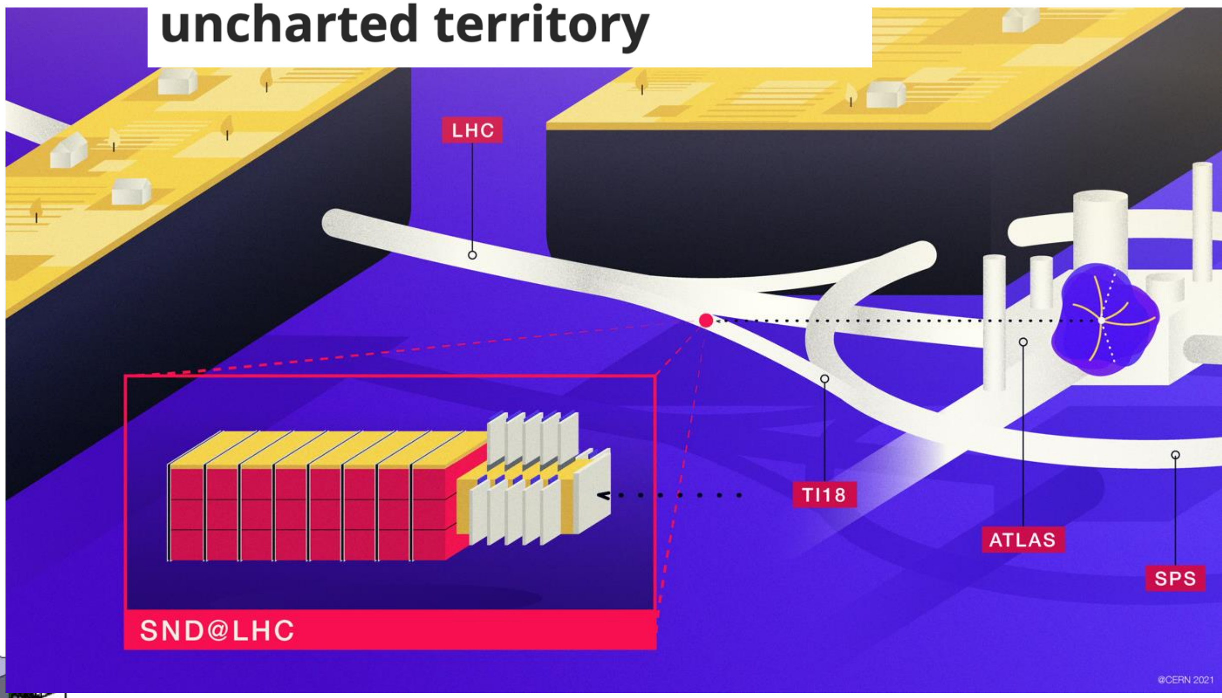
NEUTRINOS | NEWS

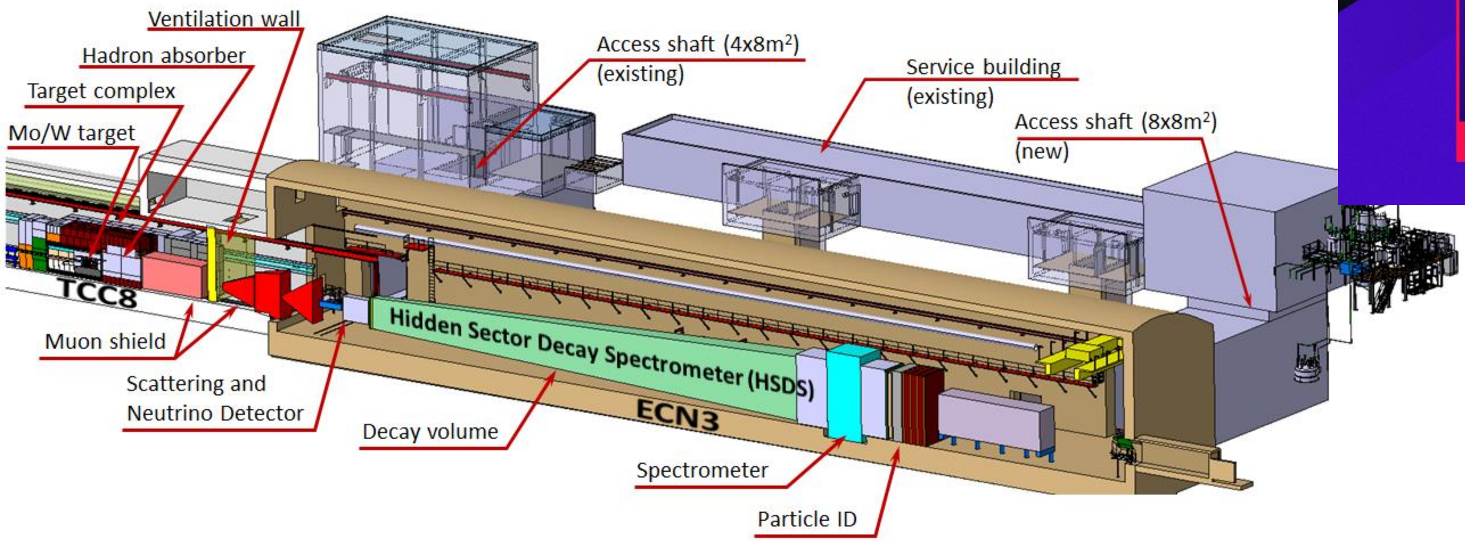
Collider neutrinos on the horizon

2 June 2021

https://cerncourier.com/a/collider-neutrinos-on-the-horizon/

New LHC experiments enter uncharted territory





Stay tuned!