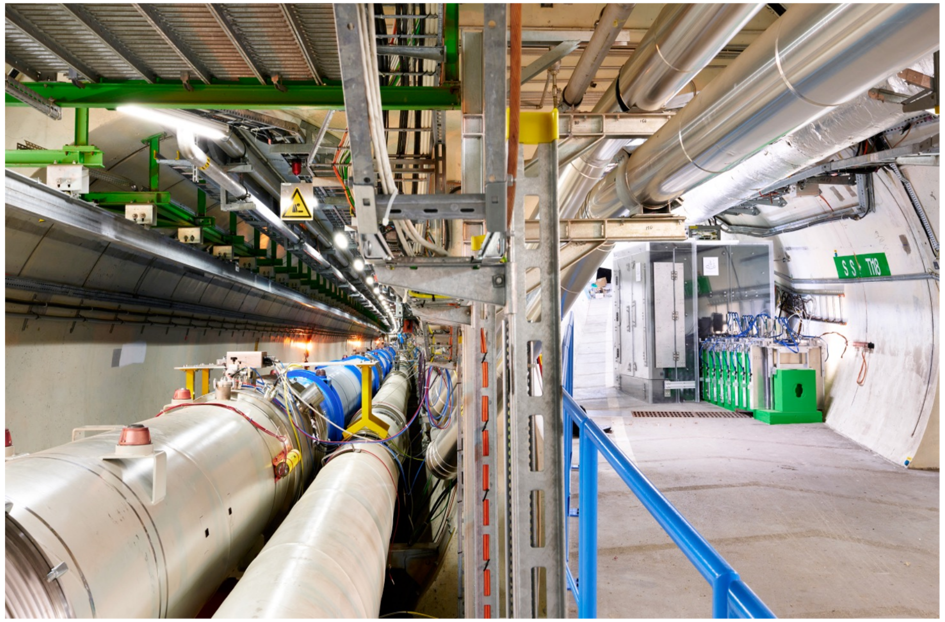
Neutrino experiments at CERN

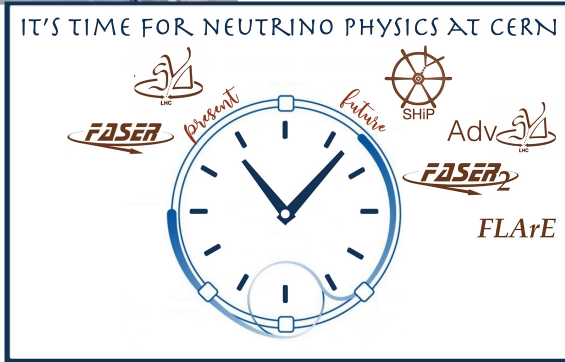
Giovanni De Lellis
University "Federico II" and INFN, Naples, Italy

with contributions from the FASER, SHiP and SND@LHC Collaborations



- *Neutrino experiments running at the LHC: FASER and SND@LHC*
- *Detectors and first results from the data taking*
- *Future plans: SHiP at the SPS and experiments at the HL-LHC*

XX International Workshop on Neutrino Telescopes, Venice, October 26th 2023

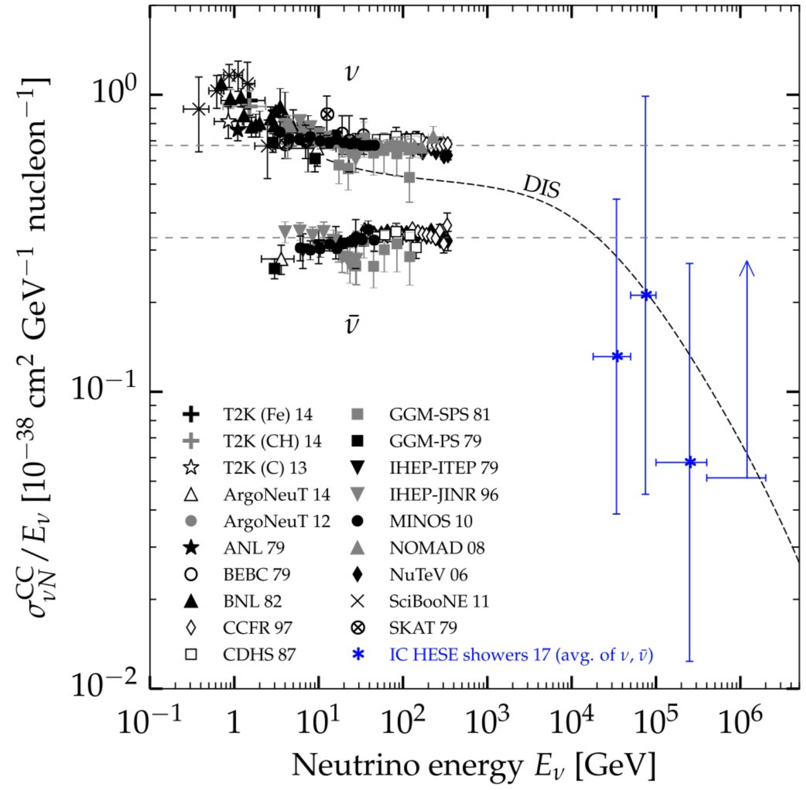


Neutrino physics at the LHC: motivation

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](http://arxiv.org/abs/1804.04413), 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
Check for updates
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

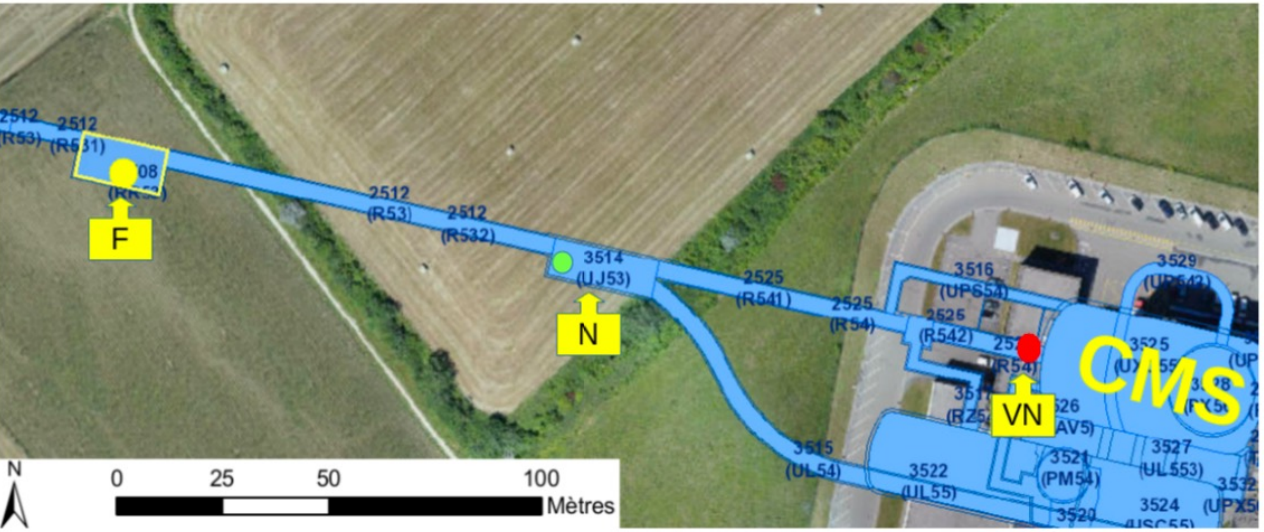
Investigating the background for a neutrino detector in different locations with a measurement campaign

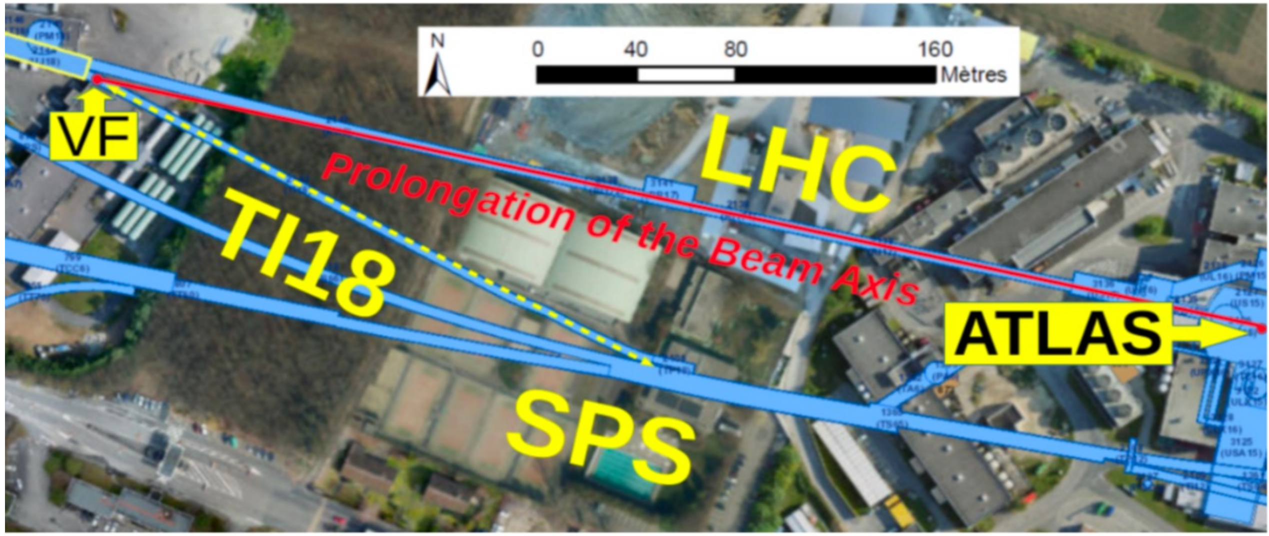
VN = Q1 in S45 at 25m

N = UJ53 and UJ57 at 90-120m

F = RR53 at 237m

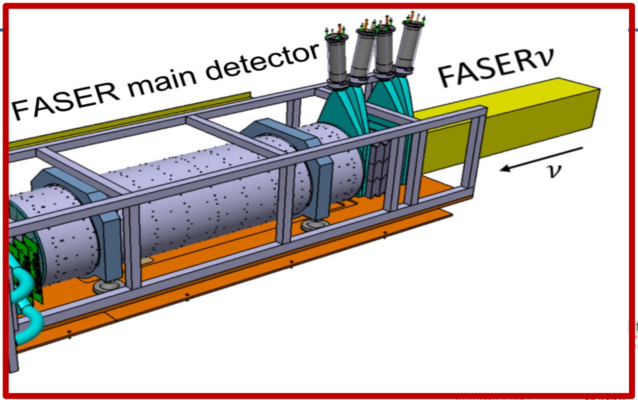
VF = TI18 at 480m (FASERν measurements)



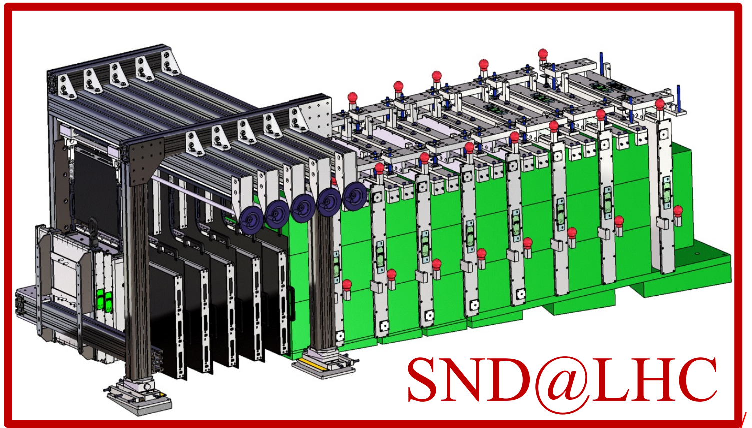


Journal of Physics G 46 (2019) 115008

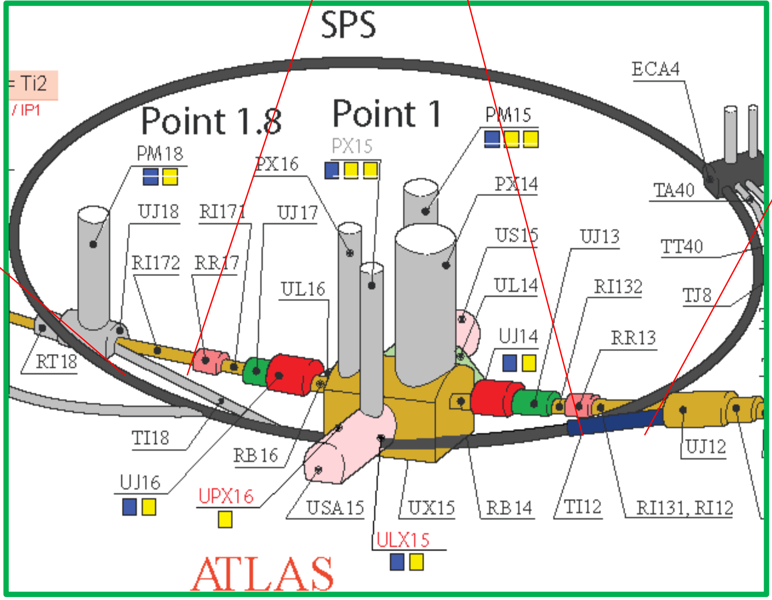
Locations

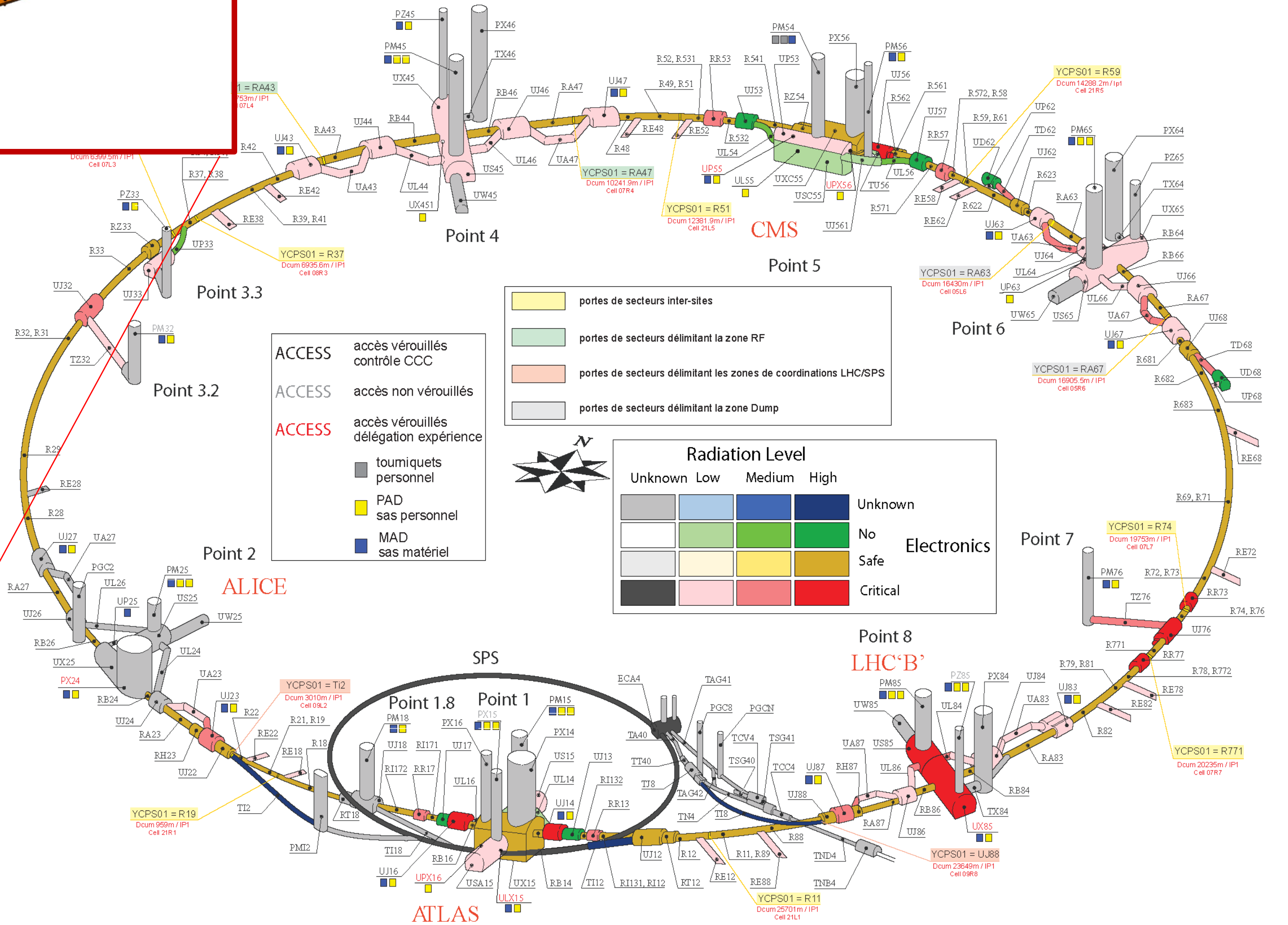


- 480 m away from the IP
- Charged particles deflected by LHC magnets
- Shielding from the IP provided by 100 m rock



Former transfer tunnels connecting SPS to LEP



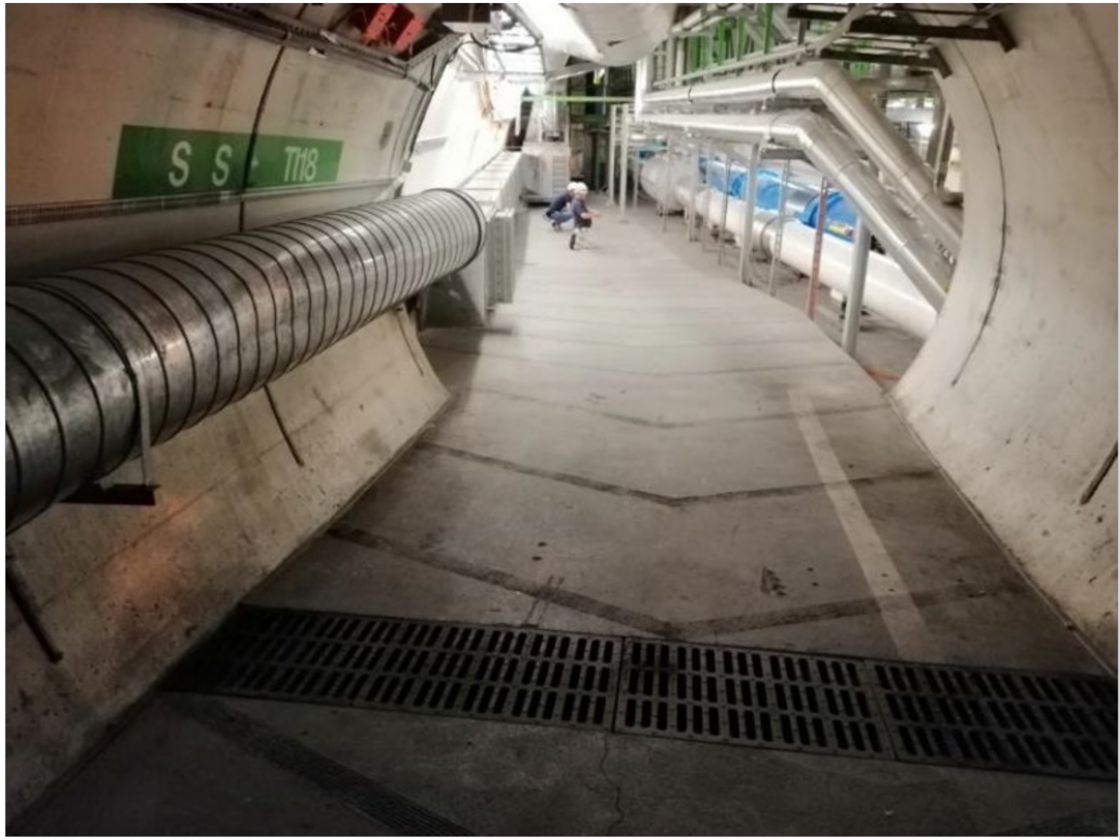


Injection tunnels used at LEP

SND LHC
Scattering and Neutrino Detector at the LHC

E.g. the TI18 tunnel in 2020

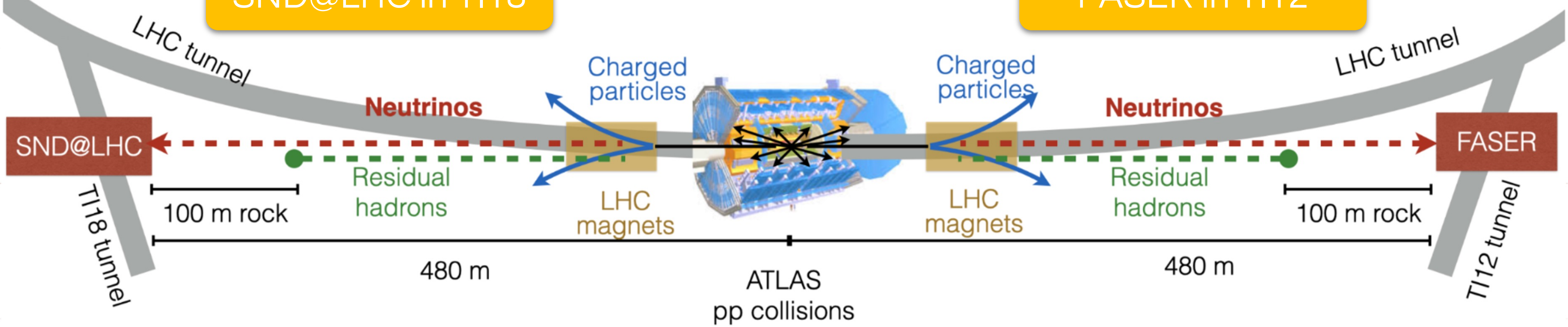
The LHC seen from the TI18 tunnel



Detectors ready for the run in March 2022

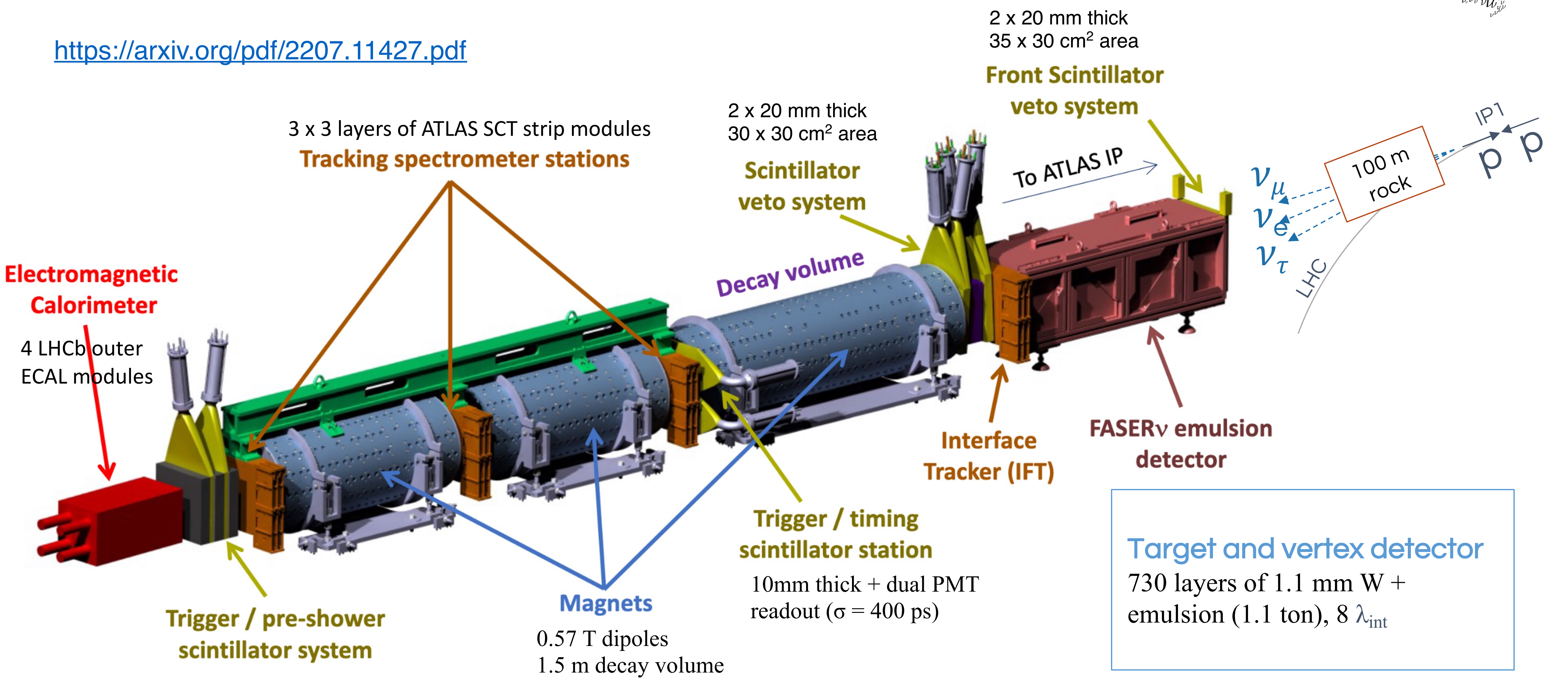
SND@LHC in TI18

FASER in TI12



ForwArd Search ExpeRiment

https://arxiv.org/pdf/2207.11427.pdf



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

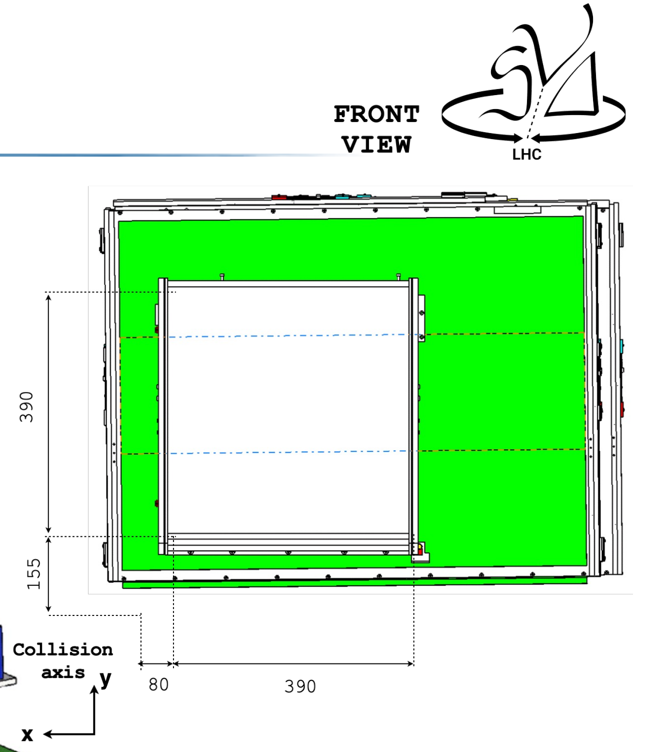
SND@LHC detector

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}

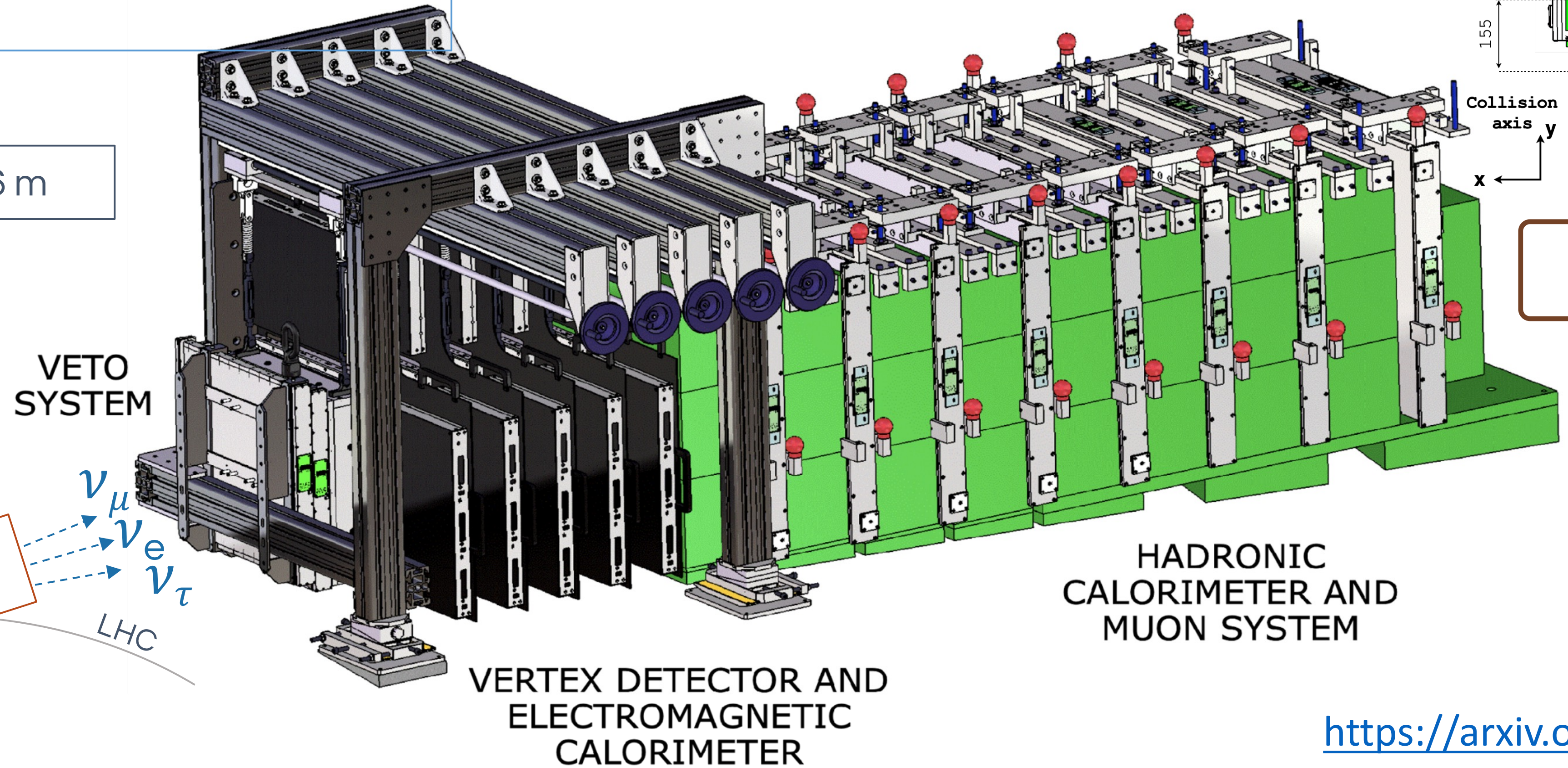
HCal and muon system
Eight 20 cm Fe blocks
+ scintillator planes.
Last 3 planes have finer
granularity to track muons.
9.5 λ_{int}

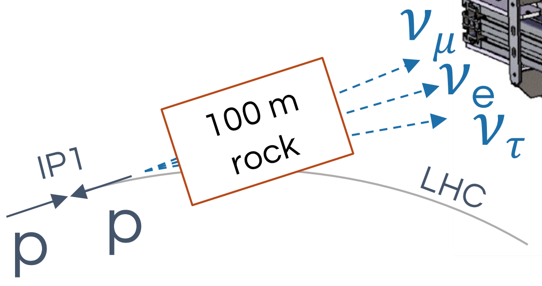
Length: 2.6 m



Off axis location

$7.2 < \eta < 8.4$



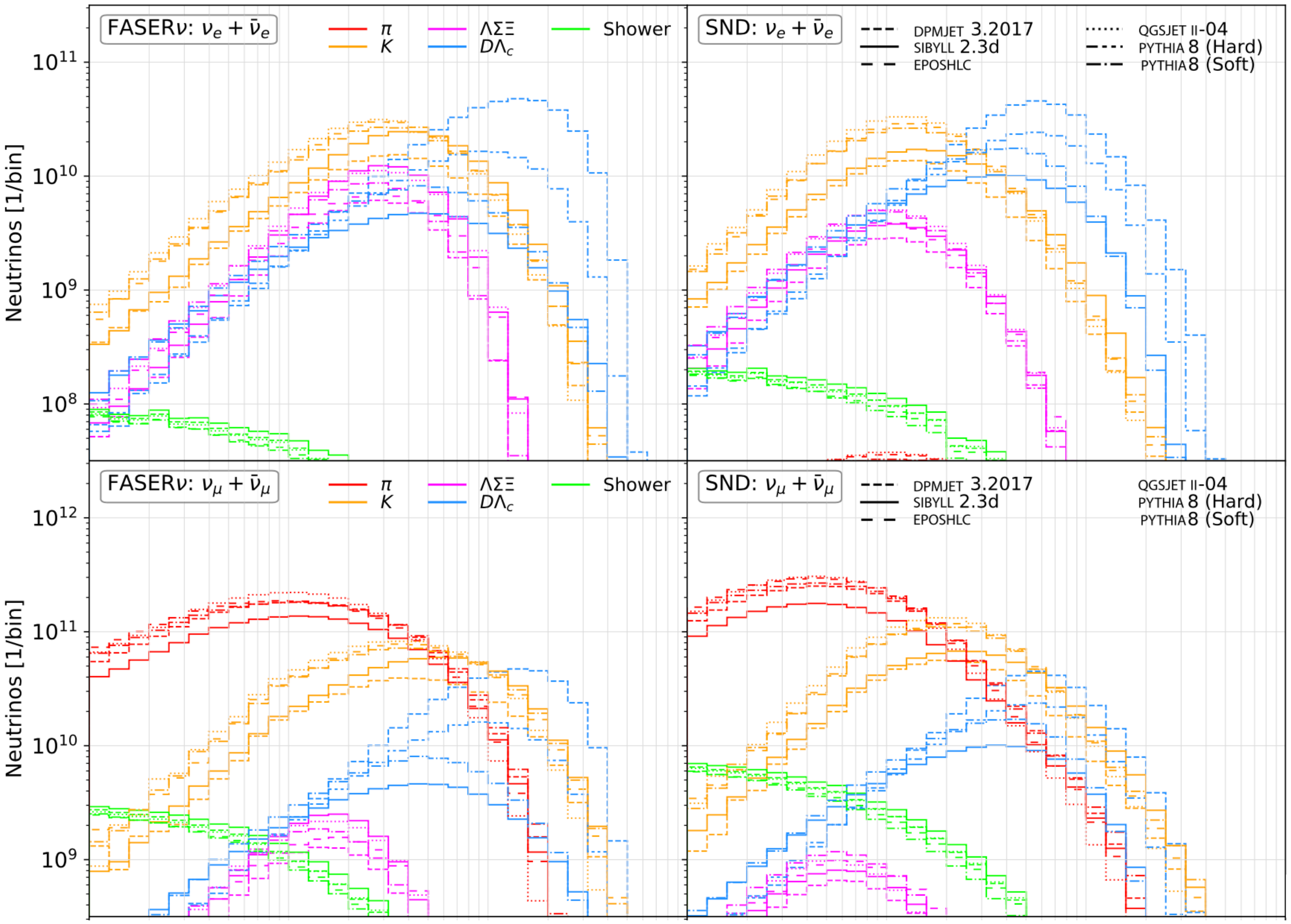


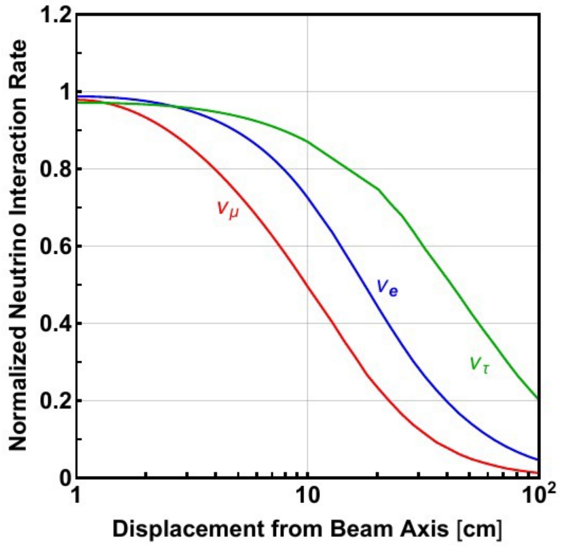
https://arxiv.org/pdf/2210.02784.pdf

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



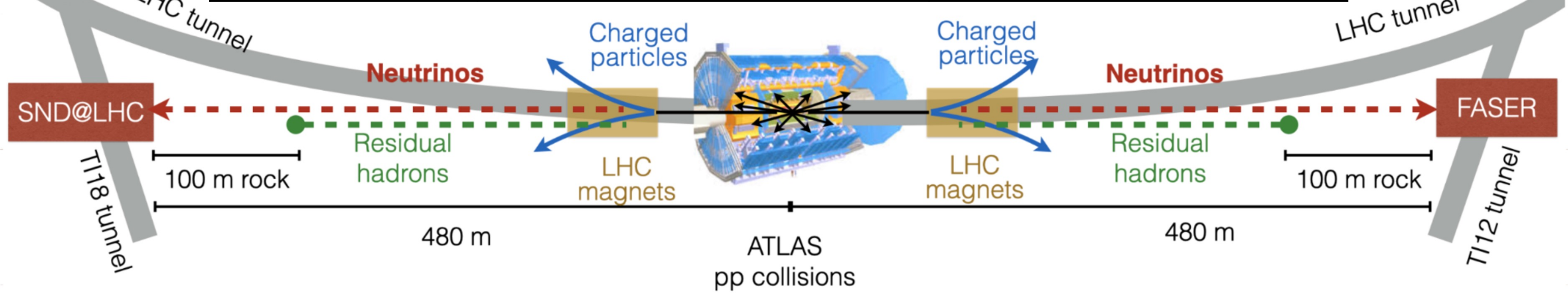


Courtesy of F. Kling, normalised to 250 fb^{-1}

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**

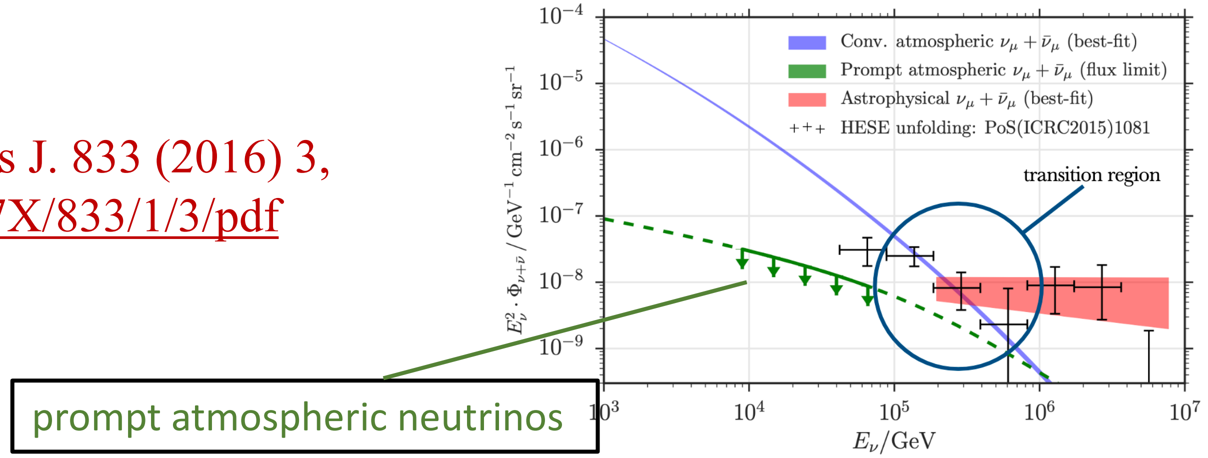


Physics goals

- Study neutrino interactions (cross-section, LFU, ..) in a new energy domain
- Systematic uncertainty on the cross-section measurement dominated by the uncertainty on the neutrino flux
- Studying the neutrino source, i.e. using neutrinos as probes, 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

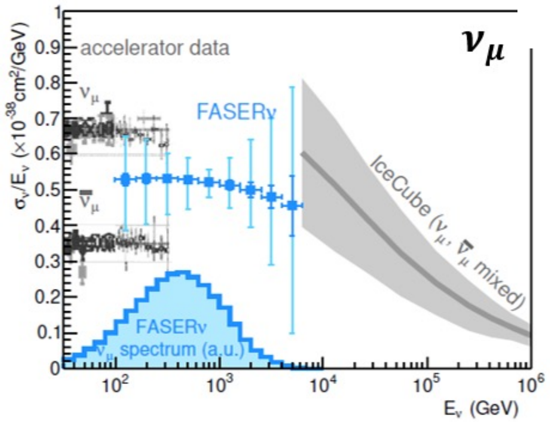
IceCube Collaboration, six years data, Astrophysics J. 833 (2016) 3, https://iopscience.iop.org/article/10.3847/0004-637X/833/1/3/pdf

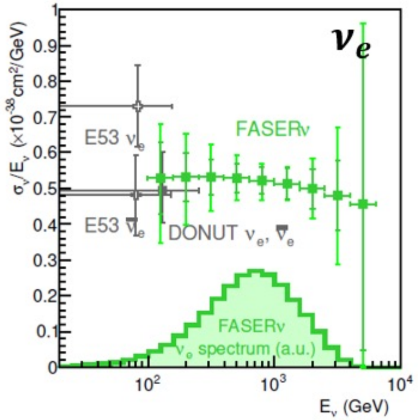
7+7 TeV *p*-*p* collisions correspond to 100 PeV proton interaction for a fixed target

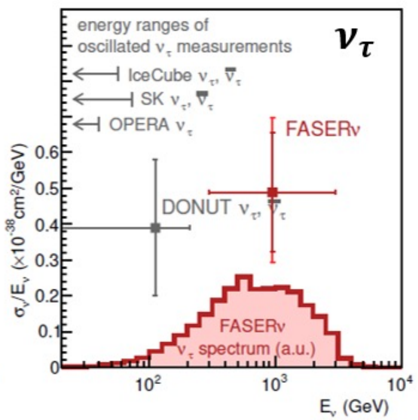


FASERν main physics goals

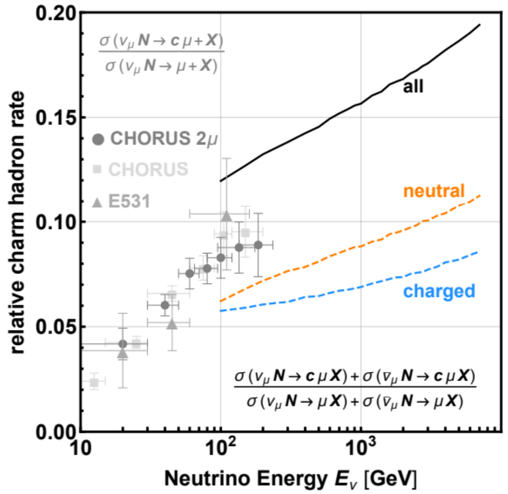
- Cross section measurements at the TeV scale
- ~2000 ν_e, 7000 ν_μ, 50 ν_τ CC interactions expected,
  Eur. Phys. J. C 80 (2020) 61
- NC measurements could constrain neutrino non-standard interactions, Phys. Rev. D 103, 056014 (2021)
- Neutrino CC interaction with charm production ($\nu s \rightarrow lc$)
  - Study the strange quark content
  - Relevant to predict the W production at the LHC



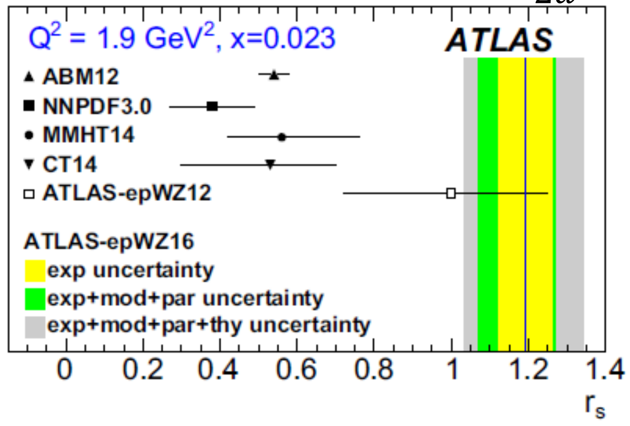




$\eta > 8.8$, ϑ<0.3 mrad



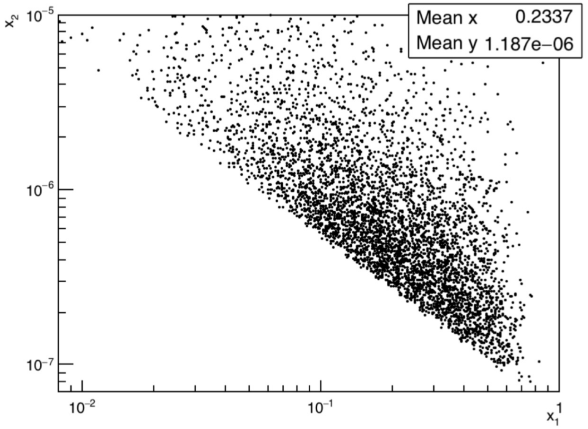
$$r_s = \frac{s + \bar{s}}{2\bar{d}}$$



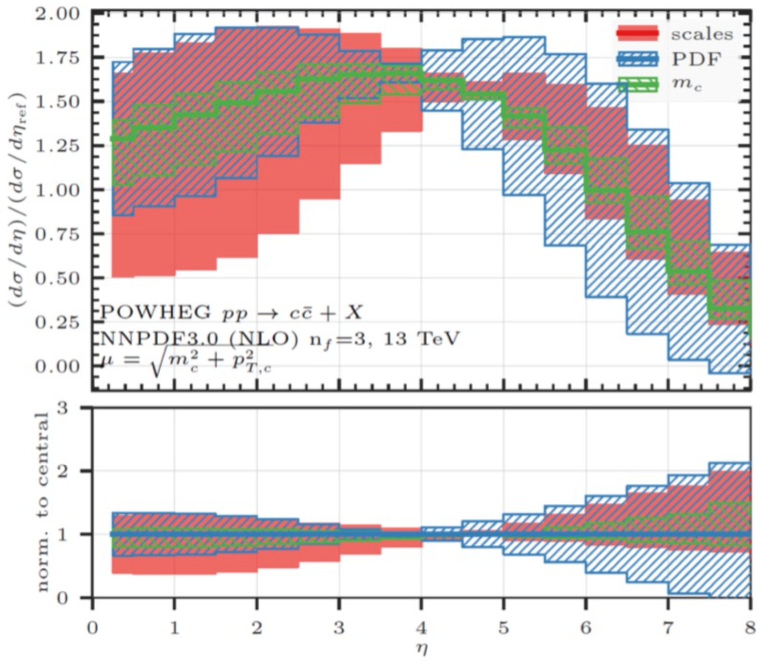
SND@LHC main physics goals

Measurement	Uncertainty Stat.	Uncertainty Sys.
$pp \to \nu_e X$ cross-section	5%	15%
Charmed hadron yield	5%	35%
ν_e/ν_τ ratio for LFU test	30%	22%
ν_e/ν_μ ratio for LFU test	10%	10%

$7.2 < \eta < 8.6$, $0.4 < \vartheta < 1.5$ mrad



Extraction of the gluon PDF in a *x*-region relevant for Future Circular Colliders



$$R = \frac{d\sigma/d\eta(13\,TeV)}{d\sigma/d\eta_{ref}(7\,TeV)} \qquad \eta_{ref} = [4, 4.5]$$

Expectations in 290 fb^{-1} (43/57 upward/downward crossing angle)

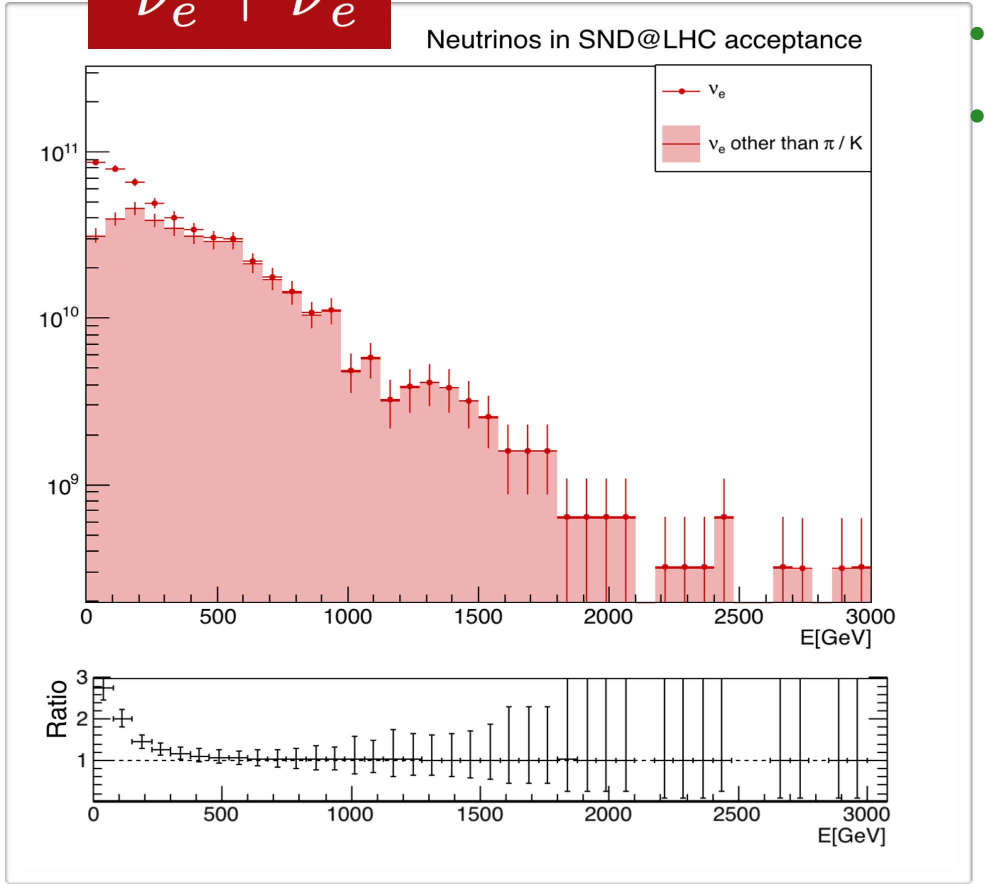
	CC neutrino interactions		NC neutrino interactions	
Flavour	⟨E⟩ [GeV]	Yield	⟨E⟩ [GeV]	Yield
ν_μ	450	1028	480	310
$\bar{\nu}_\mu$	480	419	480	157
ν_e	760	292	720	88
$\bar{\nu}_e$	680	158	720	58
ν_τ	740	23	740	8
$\bar{\nu}_\tau$	740	11	740	5
TOT		1930		625

~ 30 ν_τ CC interactions expected

Lepton flavour universality test in ν interactions

- The identification of 3 ν flavours offers a unique possibility to test LFU in ν interactions
  - ν_τs produced essentially only in D_s decays
  - ν_es produced in the decay of all charmed hadrons (D^0, D, D_s, Λ_c)
  - The ratio depends only on charm hadronisation fractions
  - Sensitive to ν-nucleon cross-section ratio

$\nu_e + \overline{\nu}_e$

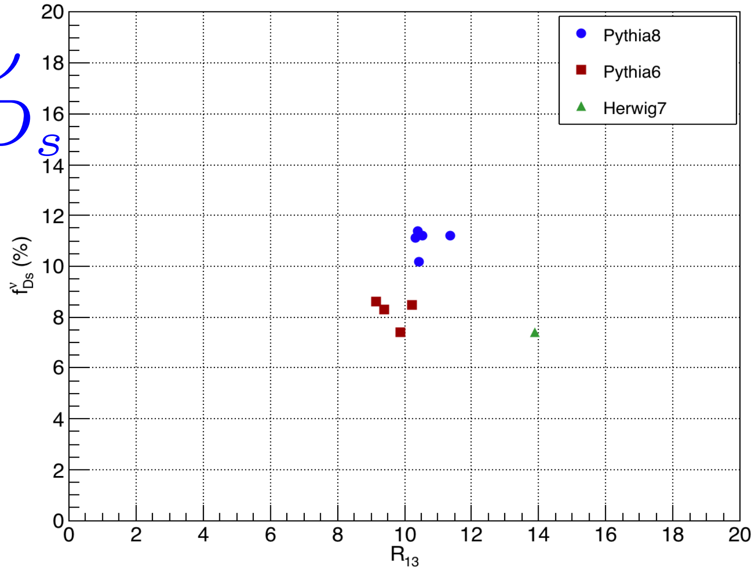


$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)},$$

$$R_{13} = \frac{\nu_e}{\nu_\tau}$$

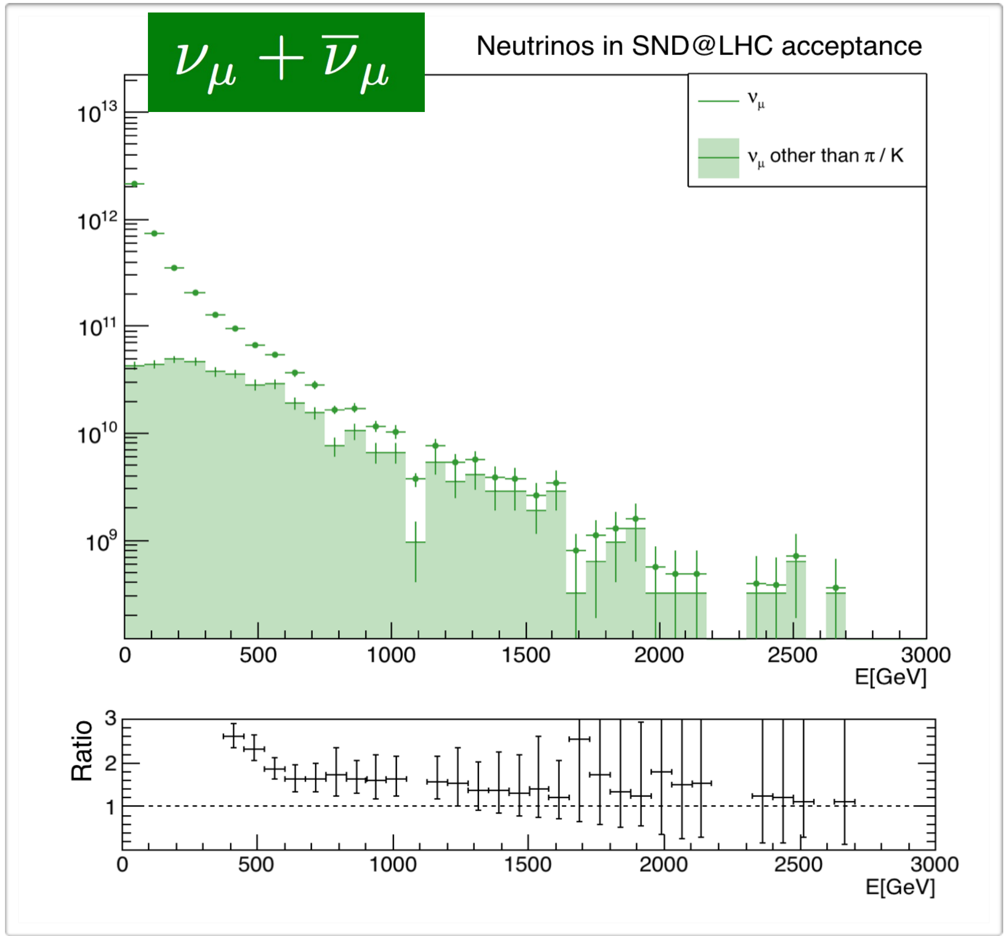
- Error on f_c evaluated as the discrepancy between Pythia8 and Herwig7 generators: **22%**
- **30%** error due to ν_τ statistics

$f^{\nu}_{D_s}$



Lepton flavour universality test in ν interactions

- ν_μ spectrum at low energies dominated by neutrinos produced in π/k decays
- For E>600 GeV the contamination of neutrinos from π/k keeps constant (~35%) with the energy



$$N(\nu_\mu + \overline{\nu}_\mu)[E > 600\,GeV] = 294 \quad \text{in 150 fb}^{-1}$$

$$N(\nu_e + \overline{\nu}_e)[E > 600\,GeV] = 191 \quad \text{in 150 fb}^{-1}$$

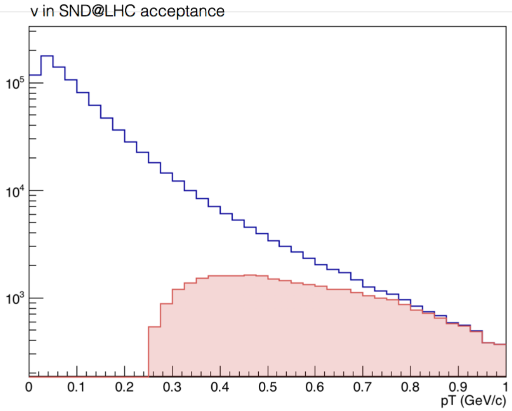
$$R_{12} = \frac{\nu_e}{\nu_\mu}$$

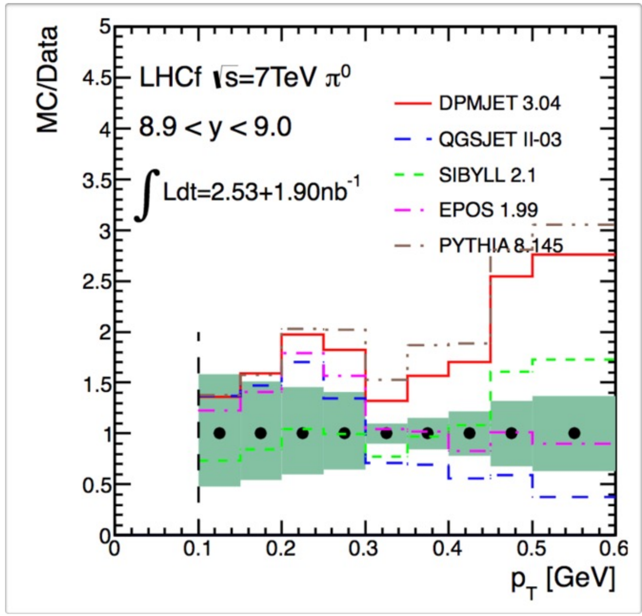
- ν_e/ν_μ as a LFU test in ν int for E>600 GeV
- No effect of uncertainties on f_c (and Br) since charmed hadrons decay almost equally in ν_μ and ν_e

$$R_{12} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\mu+\overline{\nu}_\mu}} = \frac{1}{1+\omega_{\pi/k}}.$$

contamination from π/k

- Statistcal error: **10%**
- Systematic uncertainty from the knowledge of π/k contamination: **10%**





Phys. Rev. D 86, 092001 (2012)

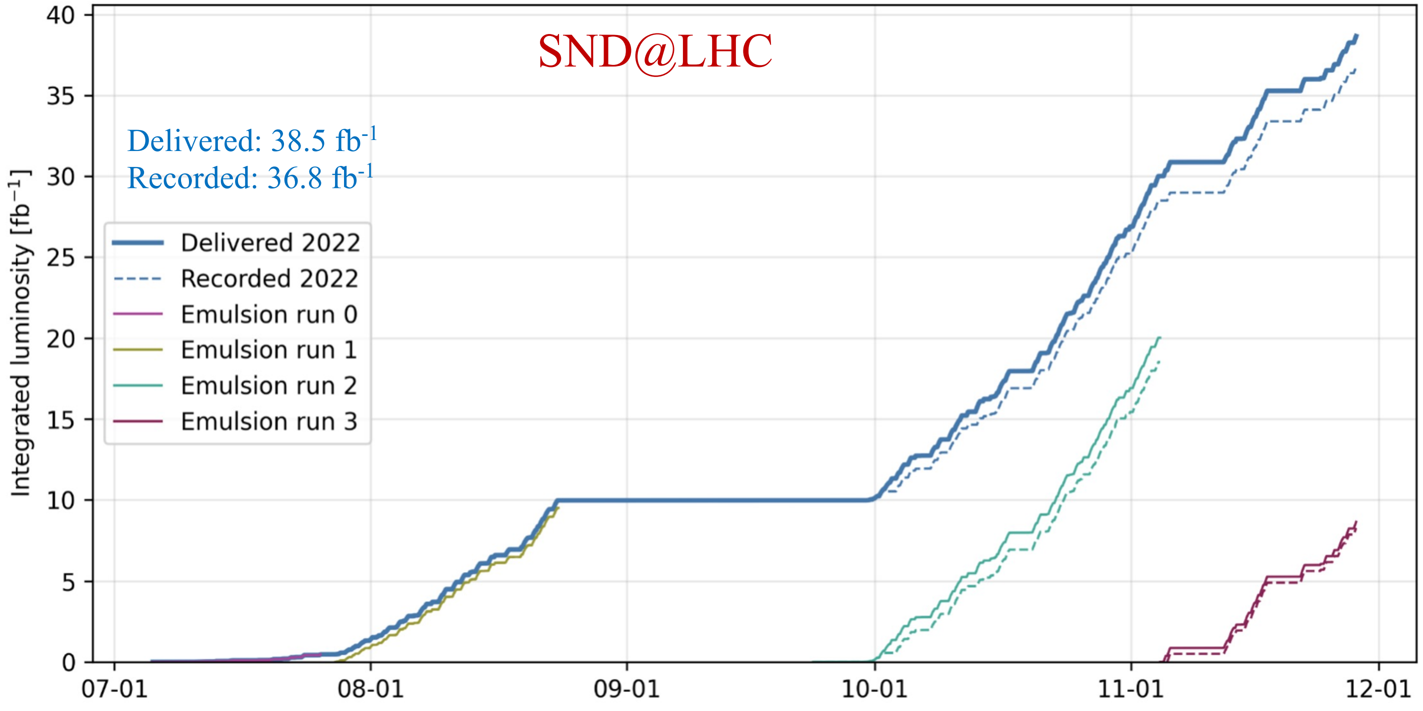
Observation of collider neutrinos

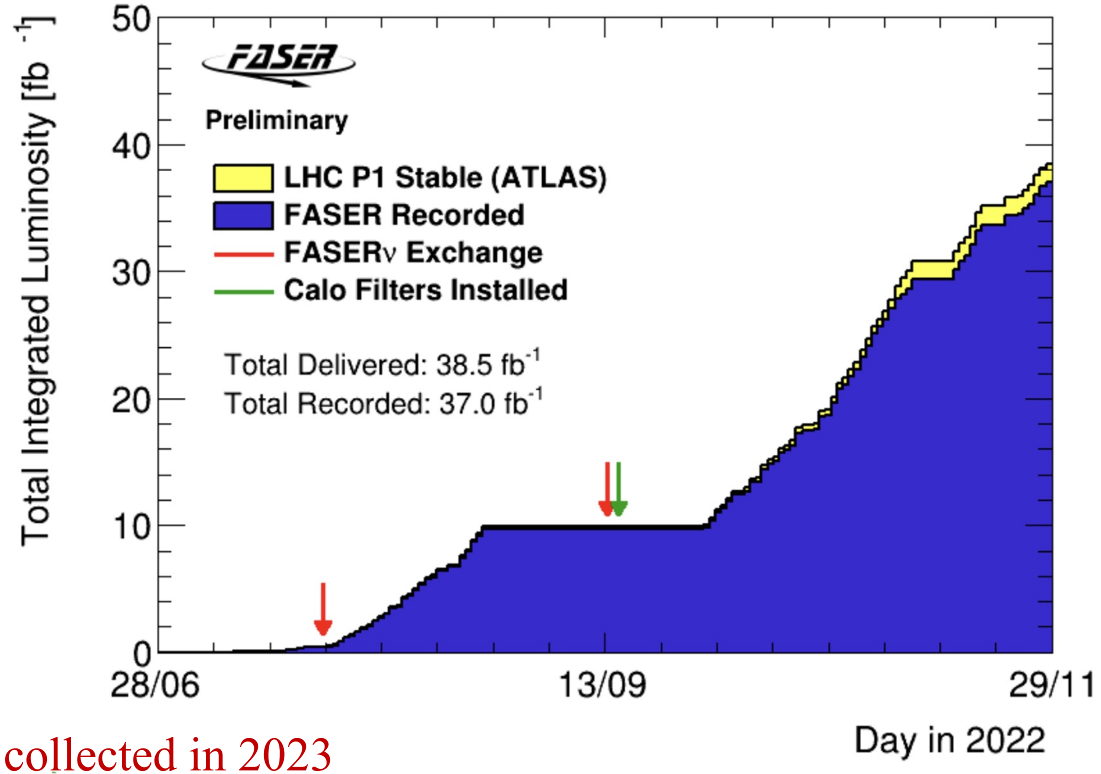
Analyses of SND@LHC and FASER electronic detector data collected in 2022

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.





Additional ~30 fb^{-1} collected in 2023

SND@LHC event selection

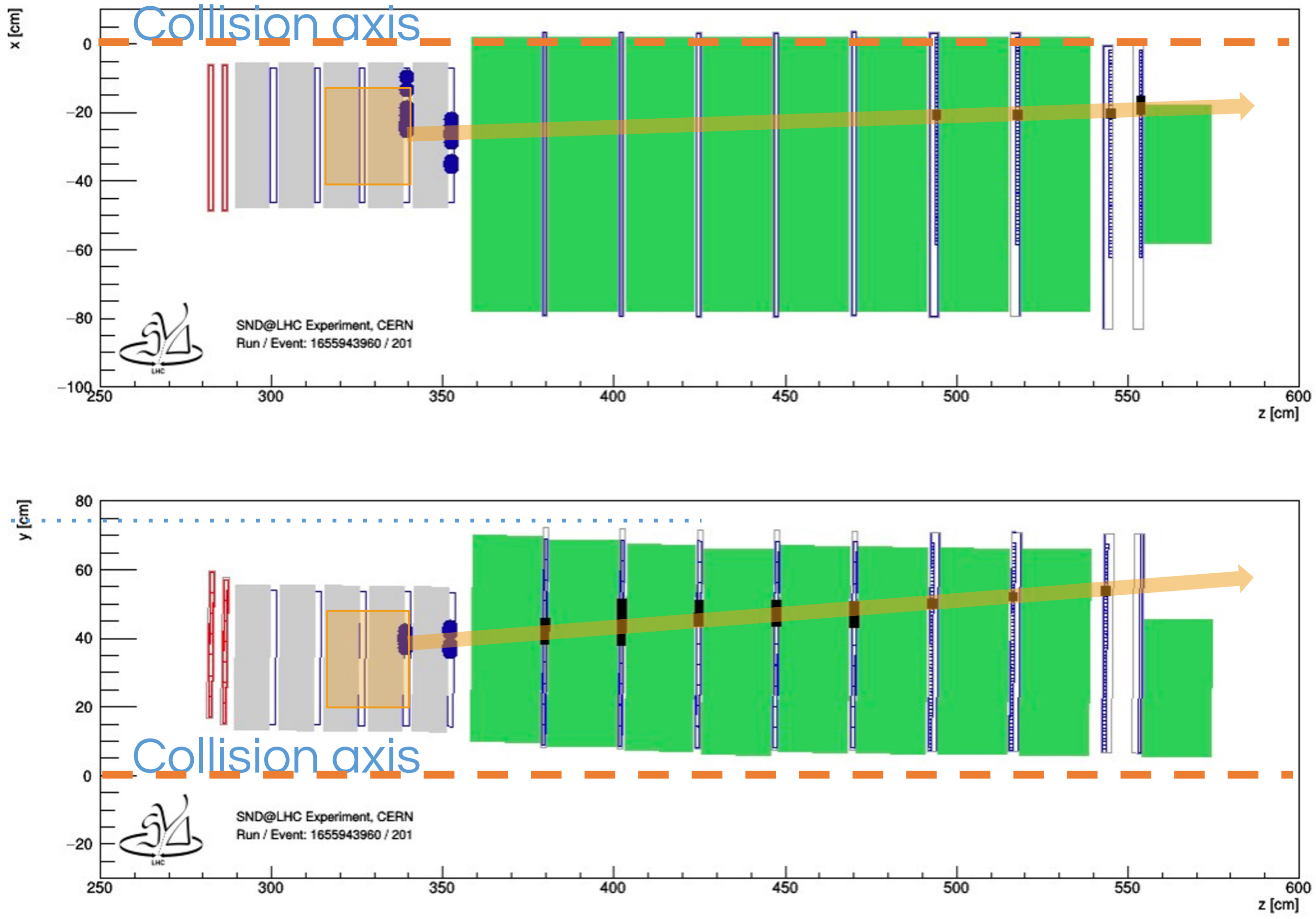
Fiducial volume

- Neutral vertex 3th or 4th wall.
- Reject side-entering backgrounds.
- Signal acceptance: 7.5%

Muon neutrino identification

- Large scintillating fibre detector activity.
- Large HCal activity.
- One muon track associated to the vertex.
- Signal selection efficiency: 36%

Number of ν_μCC events expected in 36.8 fb^{-1} after cuts: 4.2

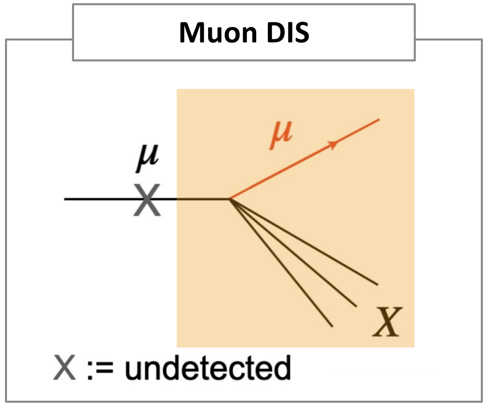


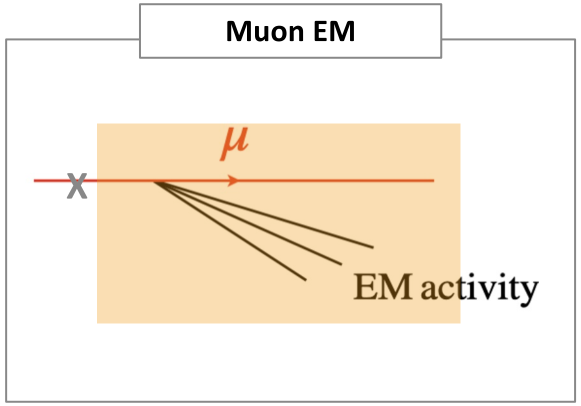
ν_μCC simulation

SND@LHC background

Entering muons

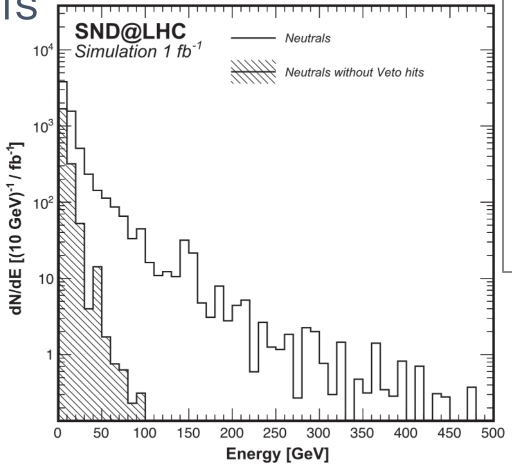
- Incoming μ track missed due to detector inefficiency.
- Shower induced by DIS or EM activity.
- Number of muons in acceptance: 5×10^8
  SNDLHC-NOTE-2023-001
- Veto rejection power: 5×10^{-12}
  - Two veto and two scintillating fibre planes.
- **Negligible** background with tight fiducial volume.

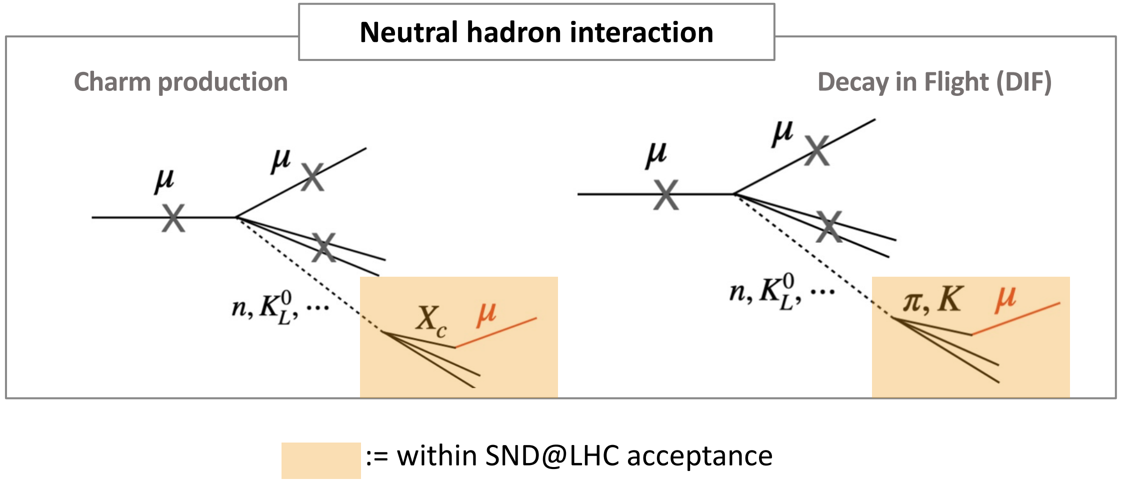




Neutral hadrons

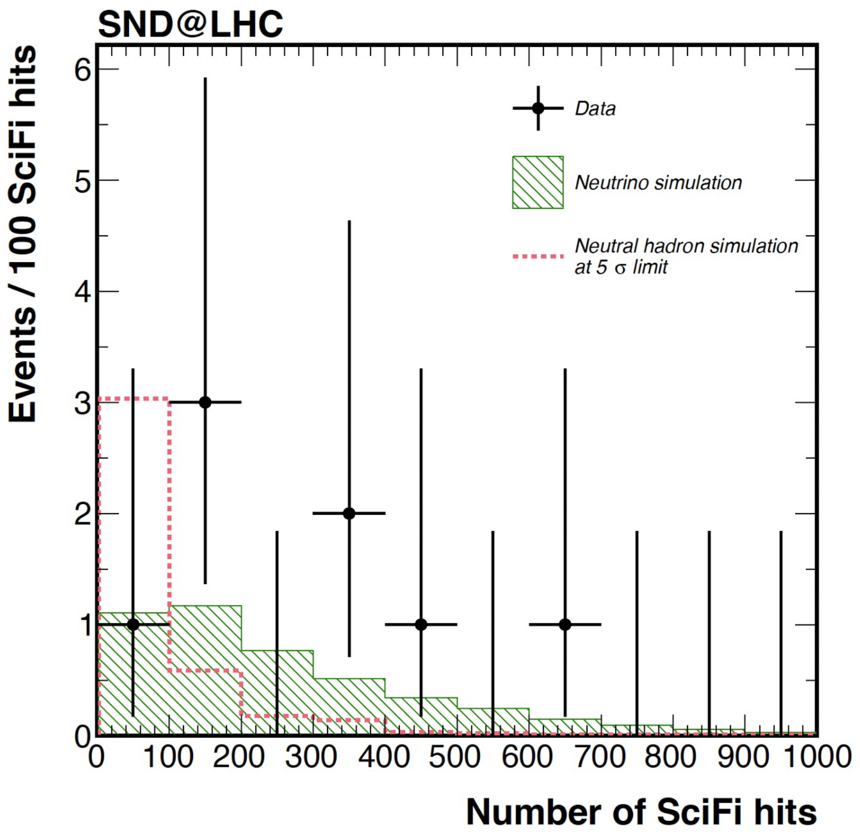
- Neutral hadrons produced in μ DIS upstream of detector.
- μ from π decay-in-flight or charm production.
- $(8.6 \pm 3.8) \times 10^{-2}$ background events



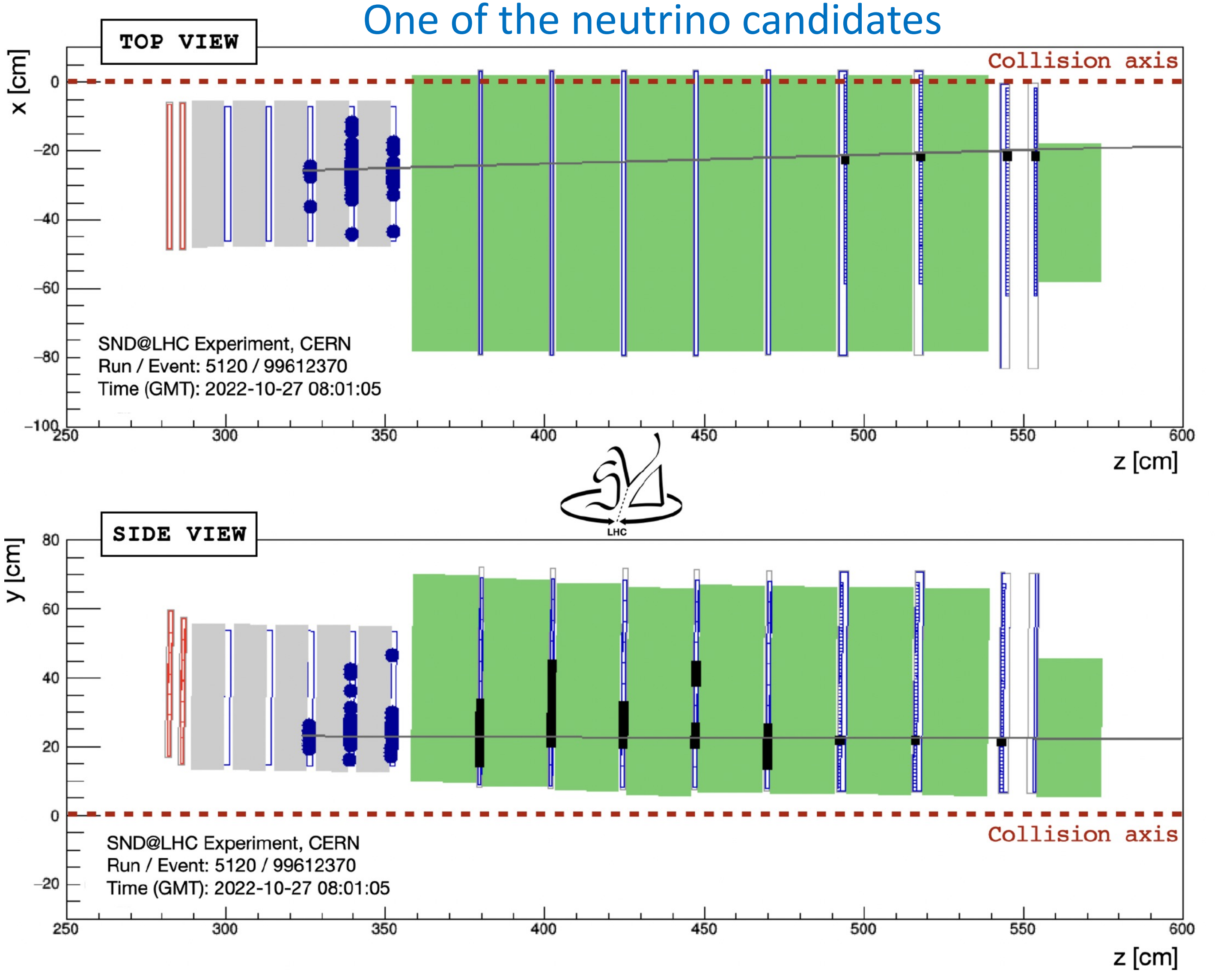


SND@LHC ν_μCC observation

Observed eight neutrino event candidates with a statistical significance of 6.8 σ



One of the neutrino candidates

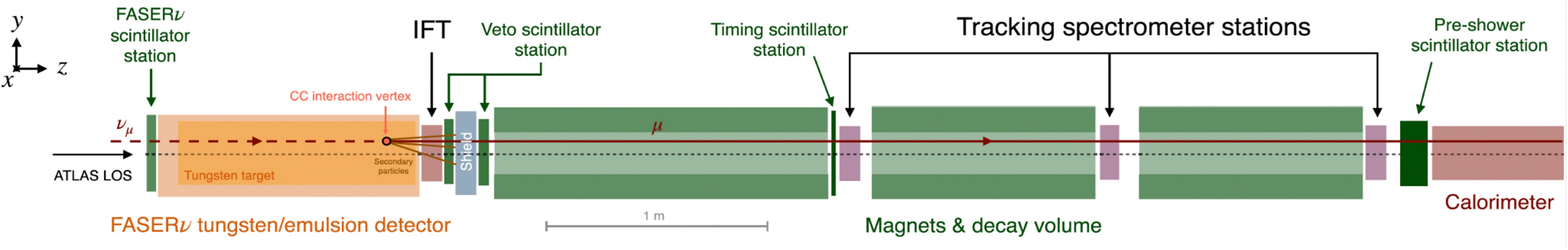


https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.031802

FASER event selection

- Event in time with collision and good data quality.
- No signal in the two front veto scintillators.
- Signals (> 40 pC) in all the scintillators downstream of FASERν.
- Exactly one good fiducial track:
  - p > 100 GeV/c
  - r < 95 mm in the IFT
  - r < 120 mm at the front veto

Number of ν_μCC events expected in 35.4 fb^{-1} after cuts: 151 ± 41



FASER background

Entering muons

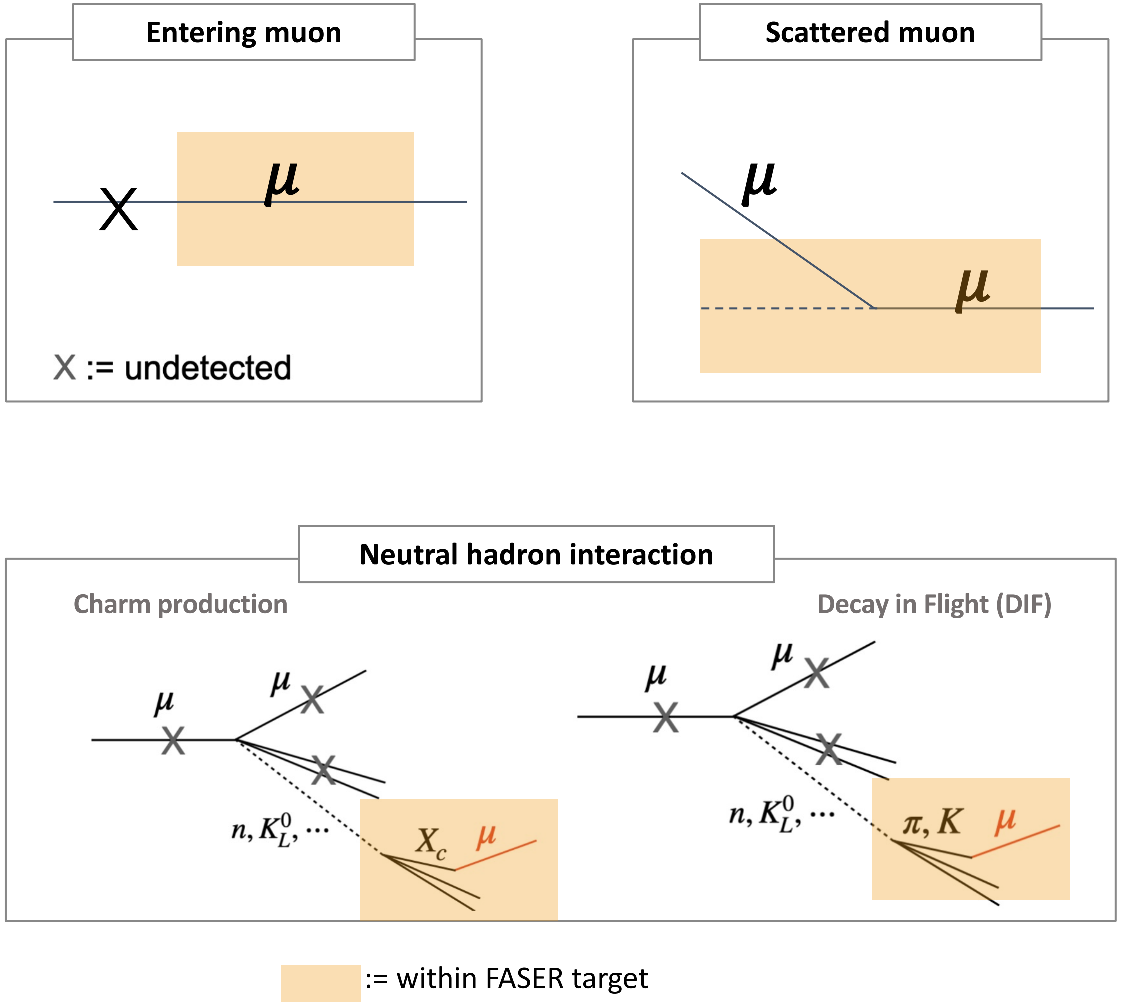
- Incoming muon track missed due to detector inefficiency.
- Expect (3.7 ± 2.5) x 10^{-7} events.
    - Estimated from events with only one scintillator plane firing.

Scattered muons

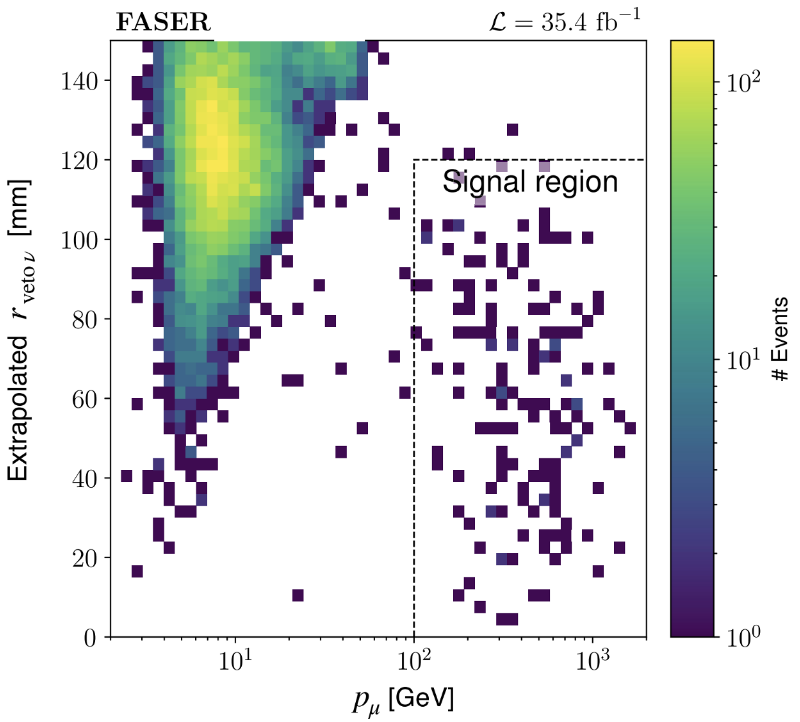
- Muon scattered in the target misses the veto planes.
- Expect **0.08 ± 1.83** events.
    - Estimated from control sample ($90 < r_{IFT} < 95$ mm)

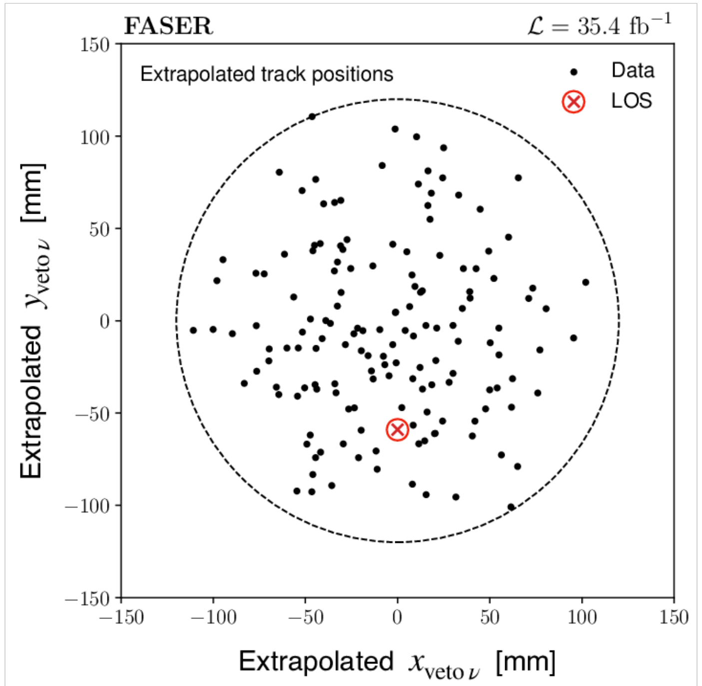
Neutral hadron interaction

- Neutral hadrons produced in muon DIS in materials upstream of the detector.
- Expect O(300) hadrons with E > 100 GeV.
    - Most are absorbed in the target.
- Expect **0.11 ± 0.06** events.

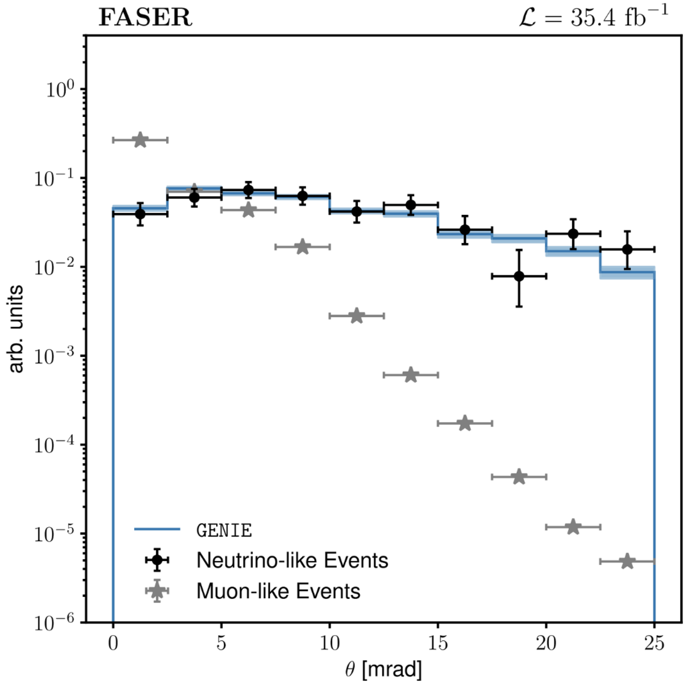


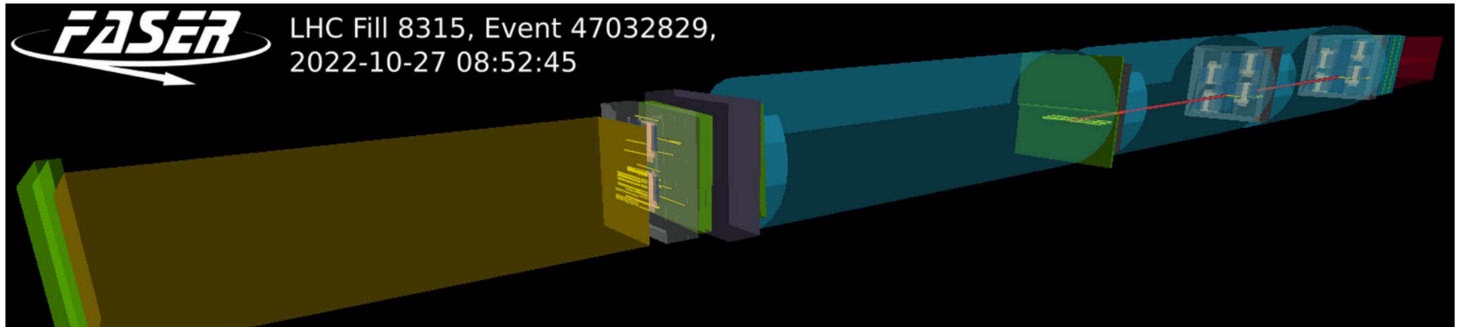
FASER ν_μCC observation





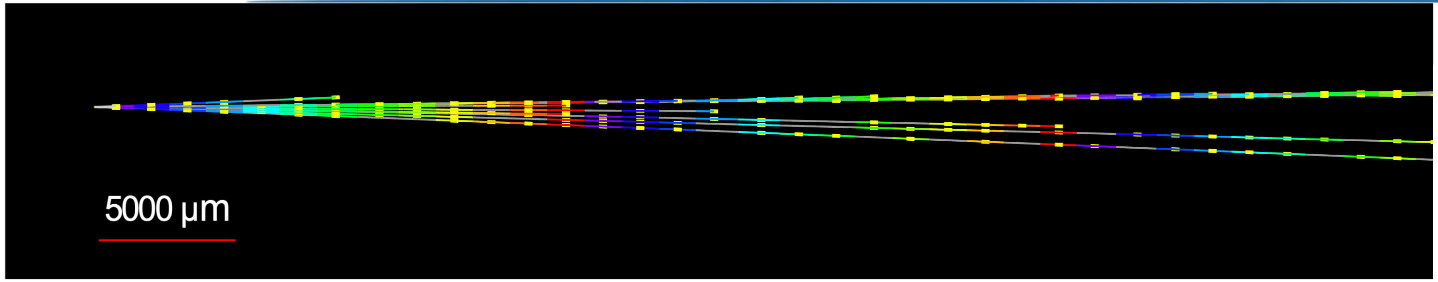
Observed 153 neutrino event candidates with a statistical significance of 16 σ

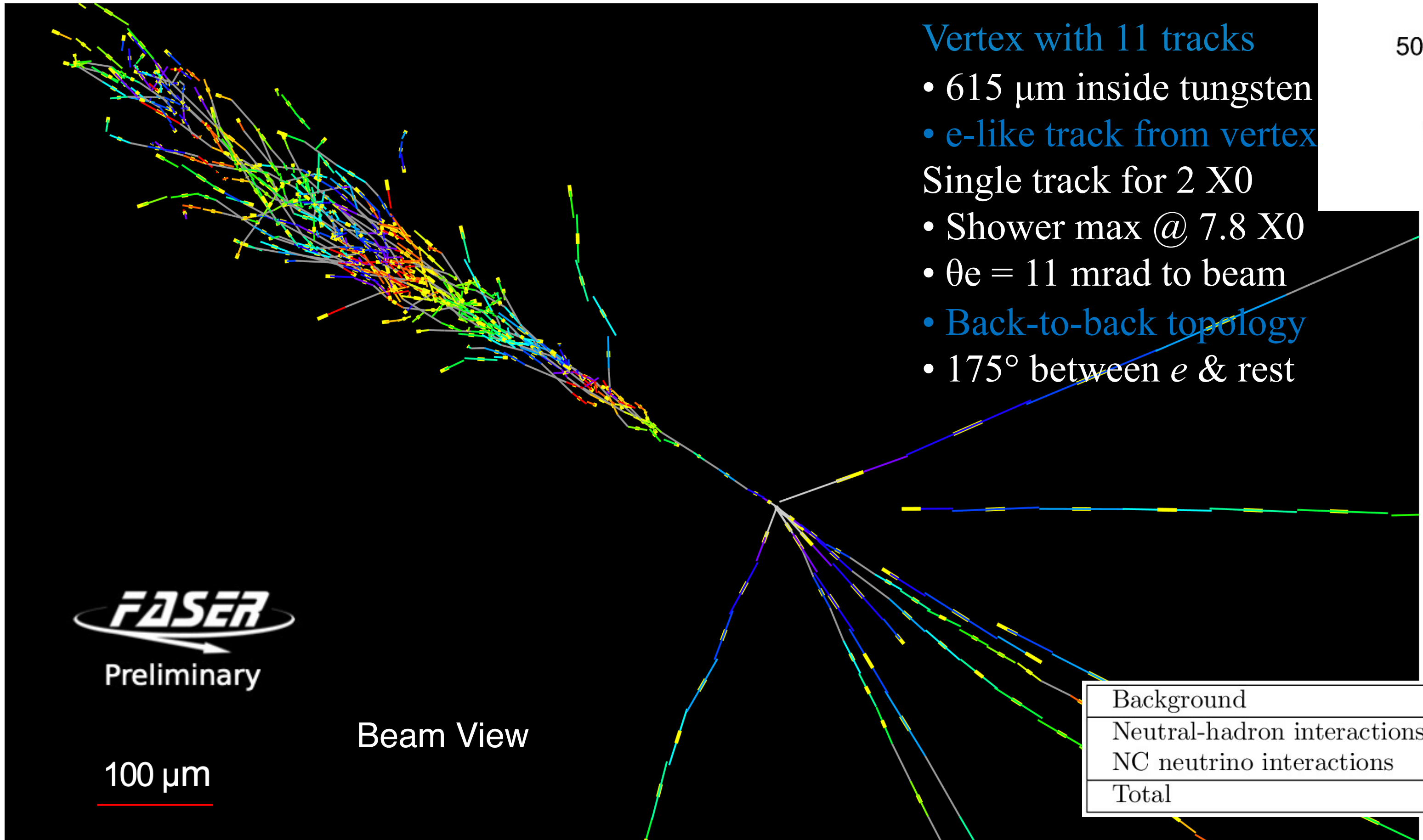




https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.131.031801

Preliminary observation of electron neutrinos in FASER

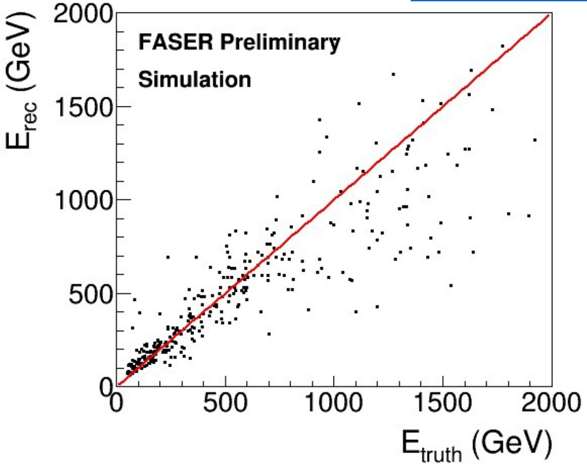


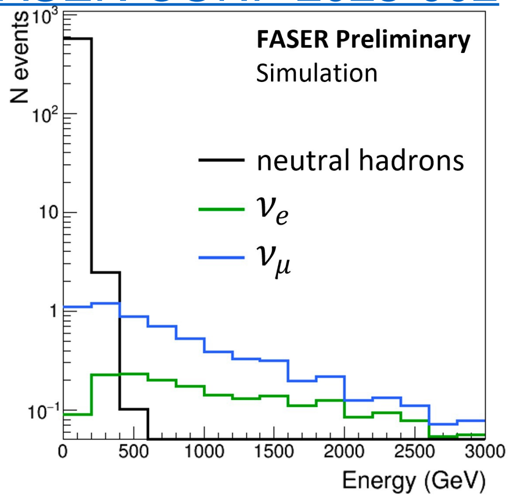


Vertex with 11 tracks
- 615 μm inside tungsten
- e-like track from vertex

Single track for 2 X0
- Shower max @ 7.8 X0
- θe = 11 mrad to beam
- Back-to-back topology
- 175° between *e* & rest

CERN-FASER-CONF-2023-002



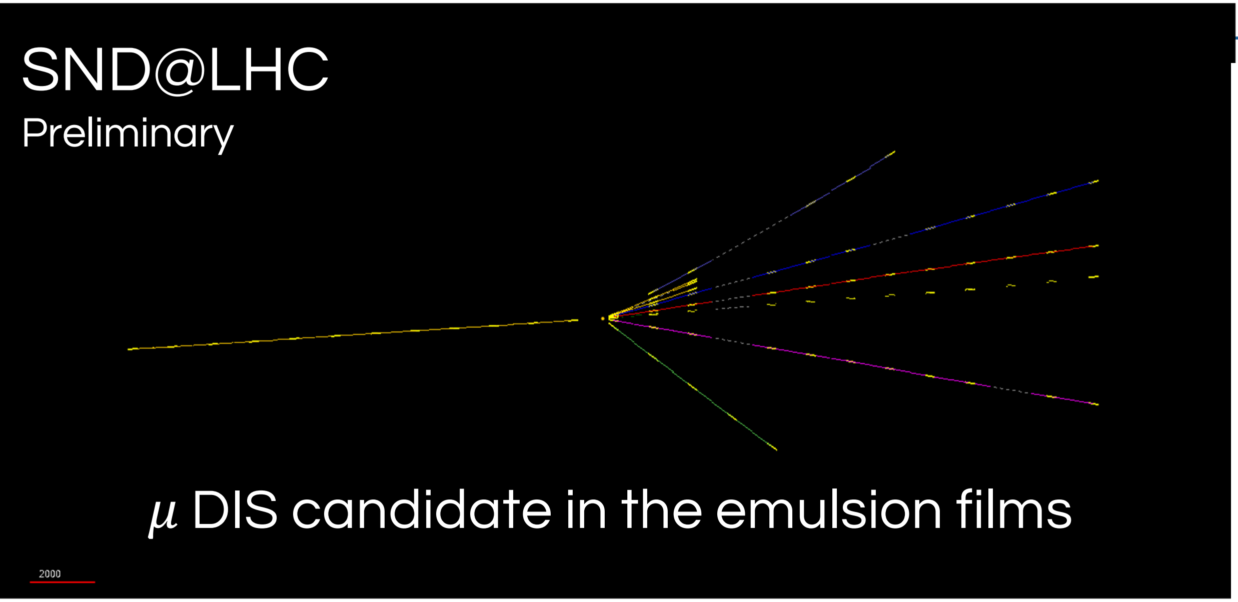


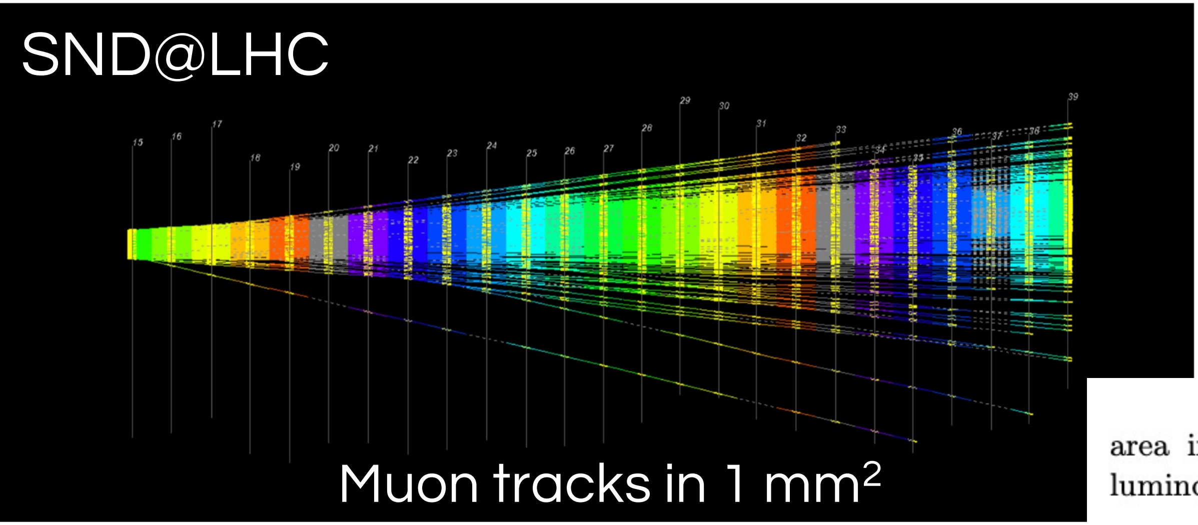
~25% resolution at 200 GeV

3 ν_e candidates observed (5sigma)
0.6÷5.2 ν_e CC expected

Background	ν_μ CC	ν_e CC
Neutral-hadron interactions	0.32 ± 0.15 (stat.) ± 0.16 (syst.)	0.002 ± 0.002 (stat.) ± 0.002 (syst.)
NC neutrino interactions	0.19 ± 0.15	-
Total	0.51 ± 0.27	0.002 ± 0.003

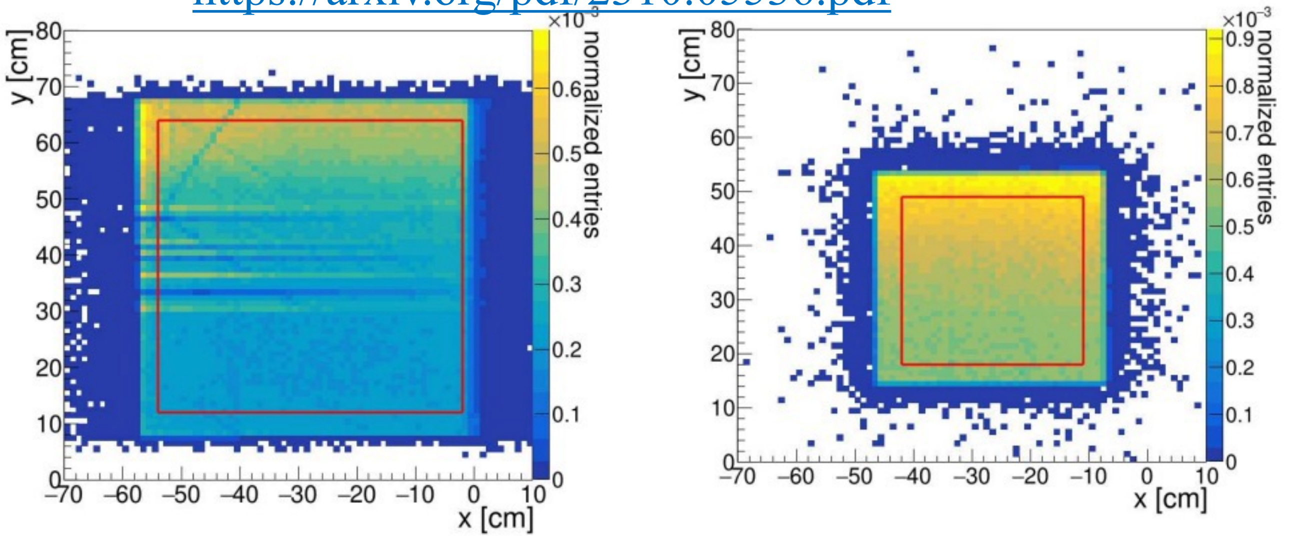
Muon flux measurement and emulsion analysis by SND@LHC





10^5 tracks/cm^2 in 10 fb^{-1} exposure

https://arxiv.org/pdf/2310.05536.pdf



SND@LHC measure muon flux in 3 different detector systems (emulsion, SciFi and Muon System).
Flux seen to increase with vertical distance from LOS.
FLUKA simulation estimate of flux ~20-25% lower than measurement.

The muon flux per integrated luminosity through an 18×18 cm^2 area in the emulsions is $\mathbf{1.5 \pm 0.1}$(stat) $\times$ $\mathbf{10^4}$ fb/cm^2. The measured muon flux per integrated luminosity through a 31×31 cm^2 central SciFi area is

$$\mathbf{2.06 \pm 0.01}(\text{stat}) \pm \mathbf{0.12}(\text{sys}) \times \mathbf{10^4}\ \text{fb/cm}^2,$$

while for the downstream muon system the flux is

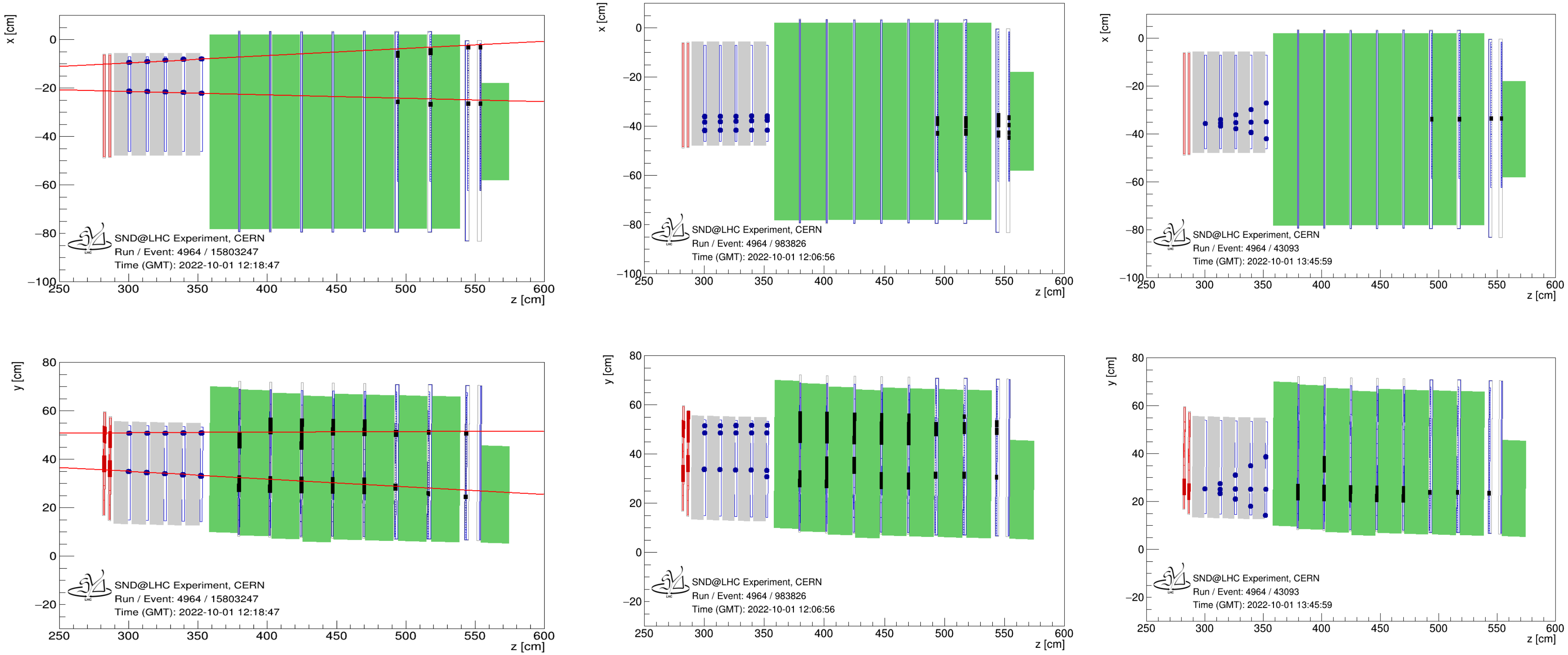
$$\mathbf{2.35 \pm 0.01}(\text{stat}) \pm \mathbf{0.10}(\text{sys}) \times \mathbf{10^4}\ \text{fb/cm}^2$$

for a 52×52 cm^2 central detector region.

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, $N_{collisions} = 25\times10^{12}$, $T = 26\times10^{3}s$, $N_{xings} = 0.72\times10^{12}$; Efficiency corrected average over this run: 300 tracks/s
- Single muon per bunch crossing: $\mu = 1.1\times10^{-5}$, Probability for k-track event from pile-up: $\frac{\mu^k e^{-\mu}}{k!}$
- Expected $N_{2\ track} = 43$, observed 224; Expected: $N_{3\ track} = 2\times10^{-4}$; Observed: 4

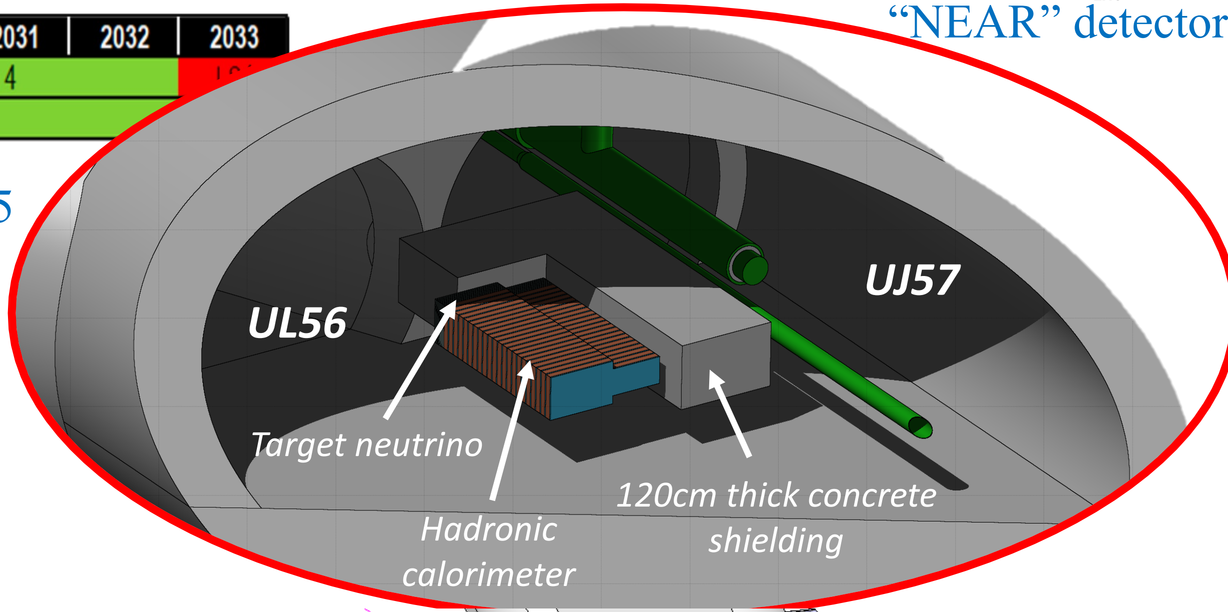
Additional rate due to trident process, muon pair production in rock, concrete, tungsten.



Future plans: Advanced SND@LHC in Run4

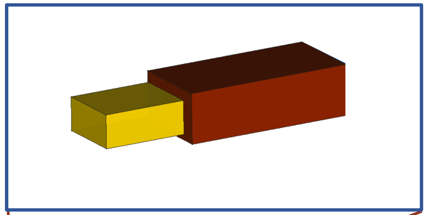
Accelerator schedule	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
LHC	Run 3				LS3			Run 4				LS…
SPS (North Area)												

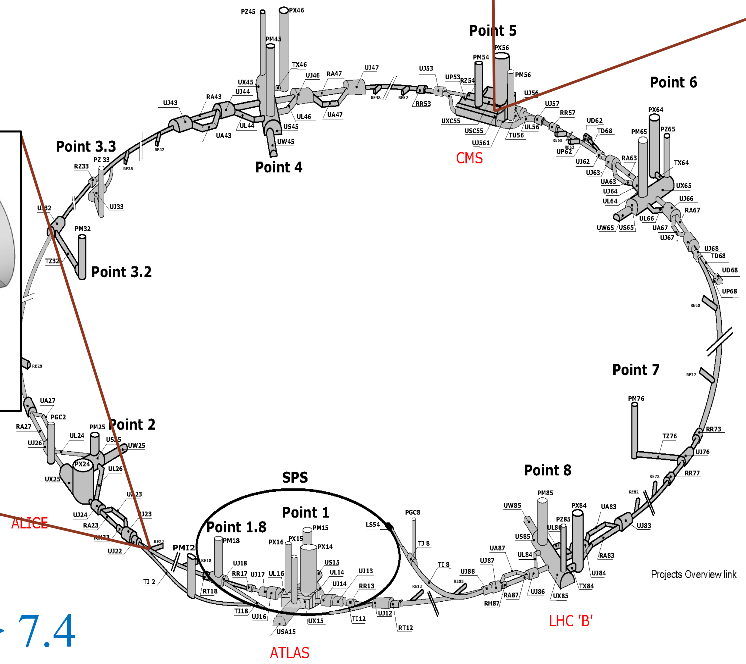
“NEAR” detector

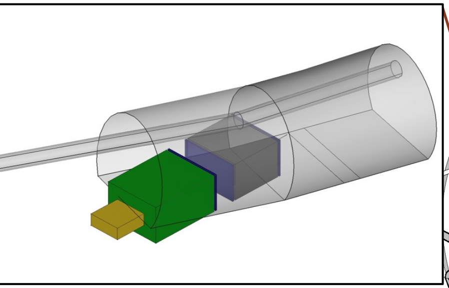


NEAR:
overlap with LHCb η (c/b measured)
Reduce systematics for the FAR
FAR:
Separate ν from ν-bar
LFU, $g\, g \rightarrow$ c cbar

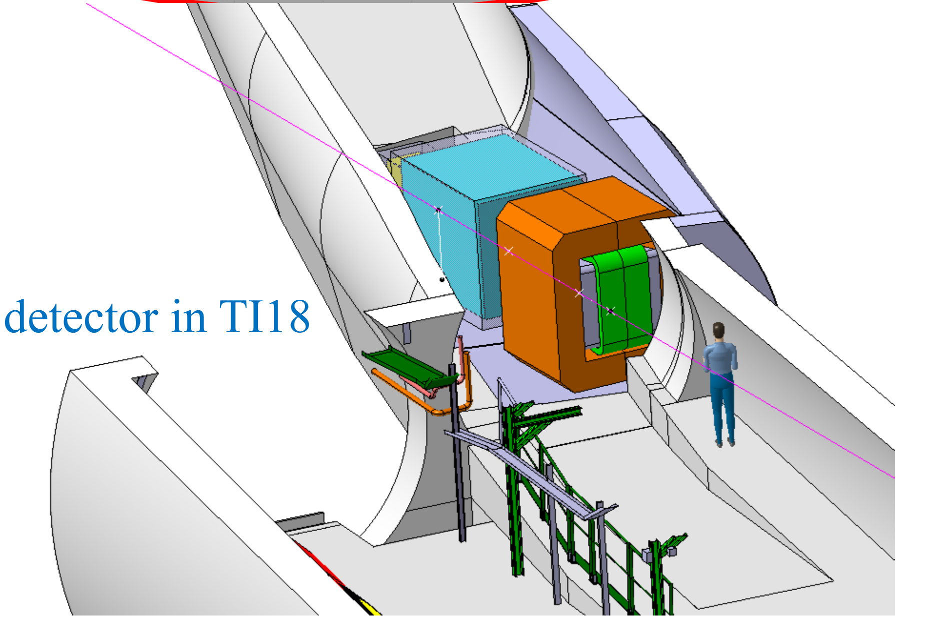
AdvSND-Near: $4 < \eta < 5$







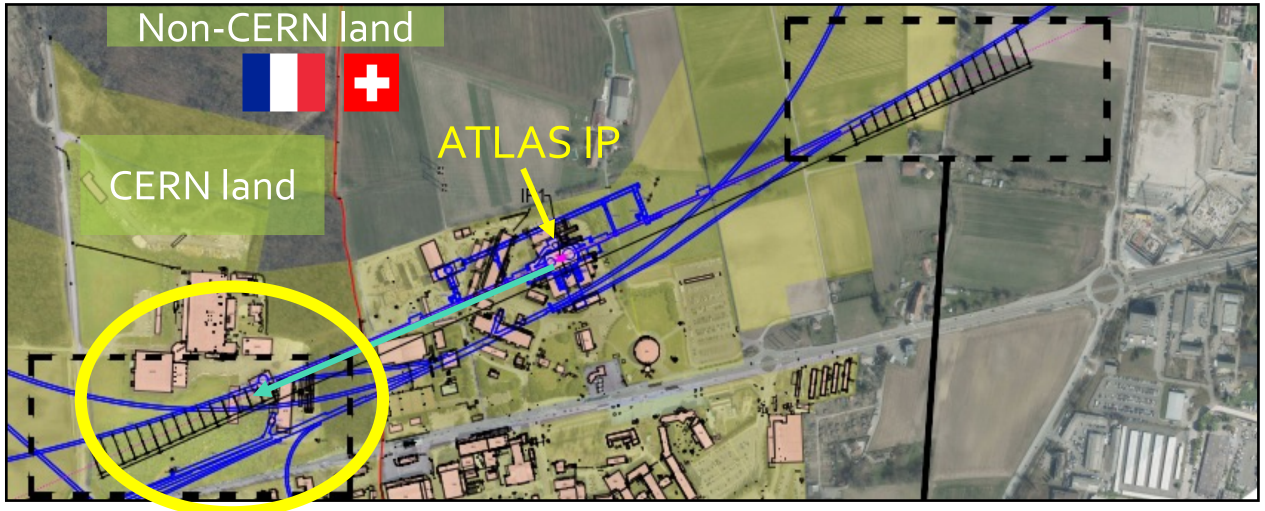
AdvSND-Far: $\eta > 7.4$



“FAR” detector in TI18

Beyond Run 4: Forward Physics Facility

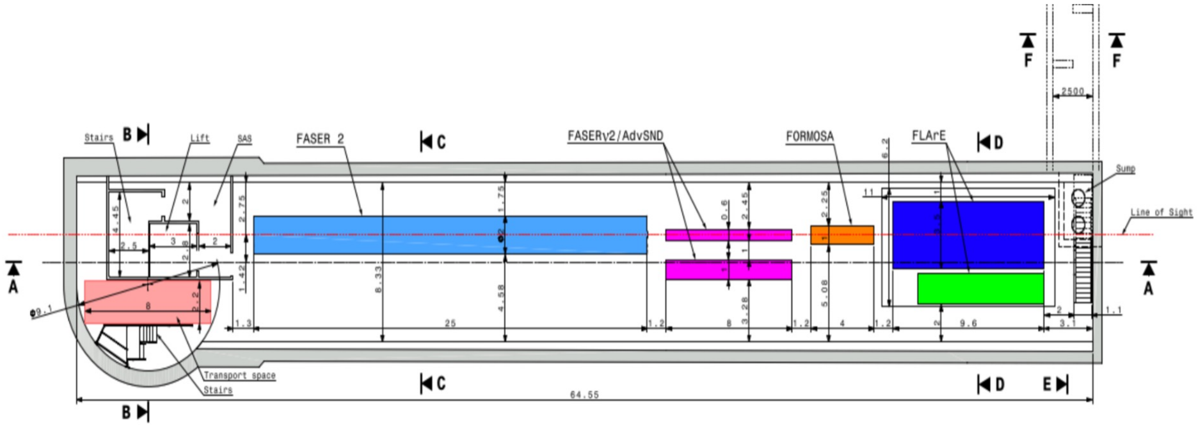
FASERν2 and AdvSND

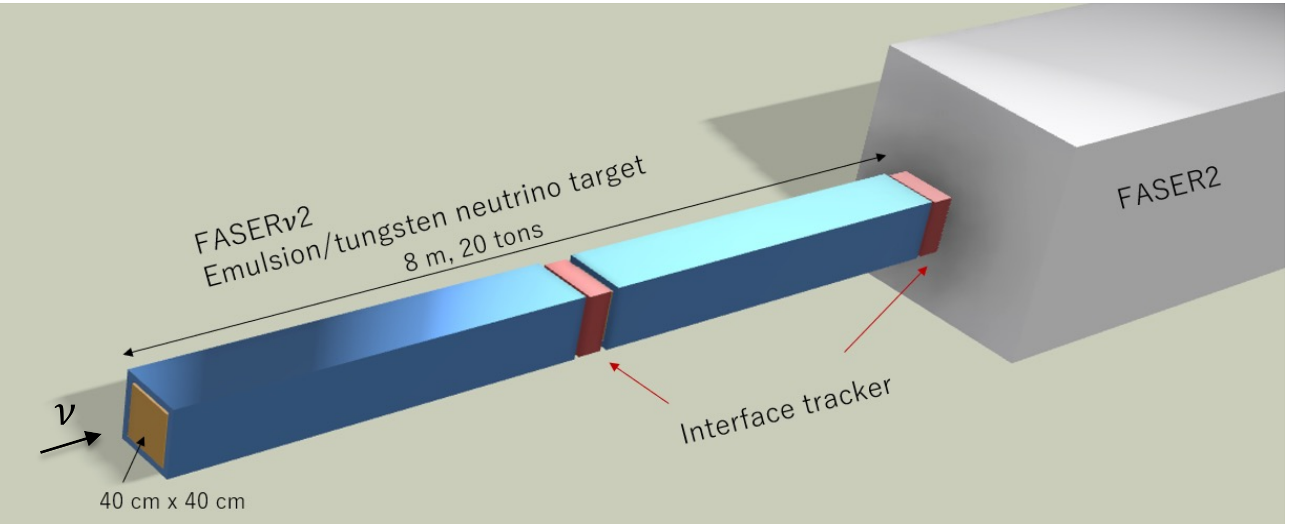


FPF White paper: *J. Phys. G: Nucl. Part. Phys. 50 (2023) 030501*

https://iopscience.iop.org/article/10.1088/1361-6471/ac865e/pdf

- FPF proposed to house a suite of experiments to for BSM physics searches, neutrino physics and QCD.
- FASERν2 designed to carry out precision ν_τ measurements and heavy flavour physics studies
  - ~2300 (SIBYLL) / ~20000 (DPMJET) ν_τ interactions are expected
- AdvSND with two off-axis forward detectors
  - SND1: $\eta \sim$ 8 Reduce systematic uncertainties
  - SND2: $\eta \sim$ 4.5 link to LHCb measurements & high-energy ν physics
- FLArE with an on-axis LArTPC with ~10 ton LAr mass
  - neutrino and light DM detector

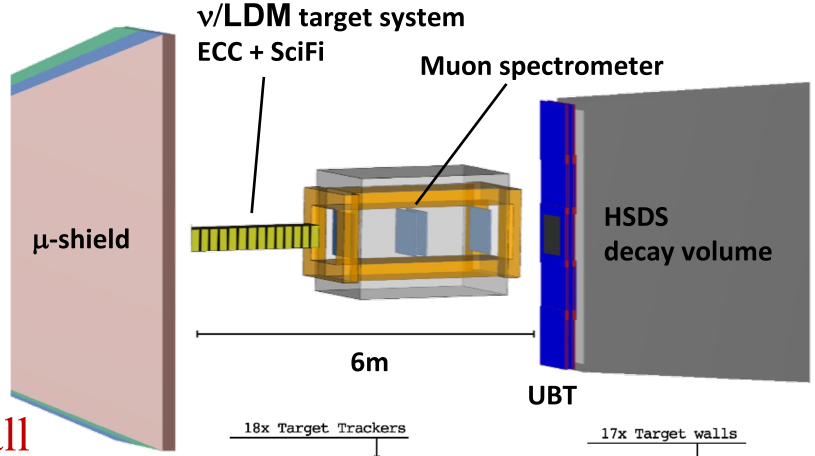


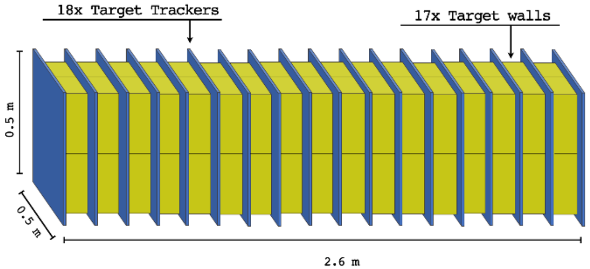


Future plans at the SPS: SHiP

Search for Feebly Interacting Particles and study νs

Accelerator schedule	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
LHC	Run 3				LS3			Run 4				LS4
SPS (North Area)												
BDF / SHiP	Study		Design and prototyping			Production / Construction / Installation				Operation		

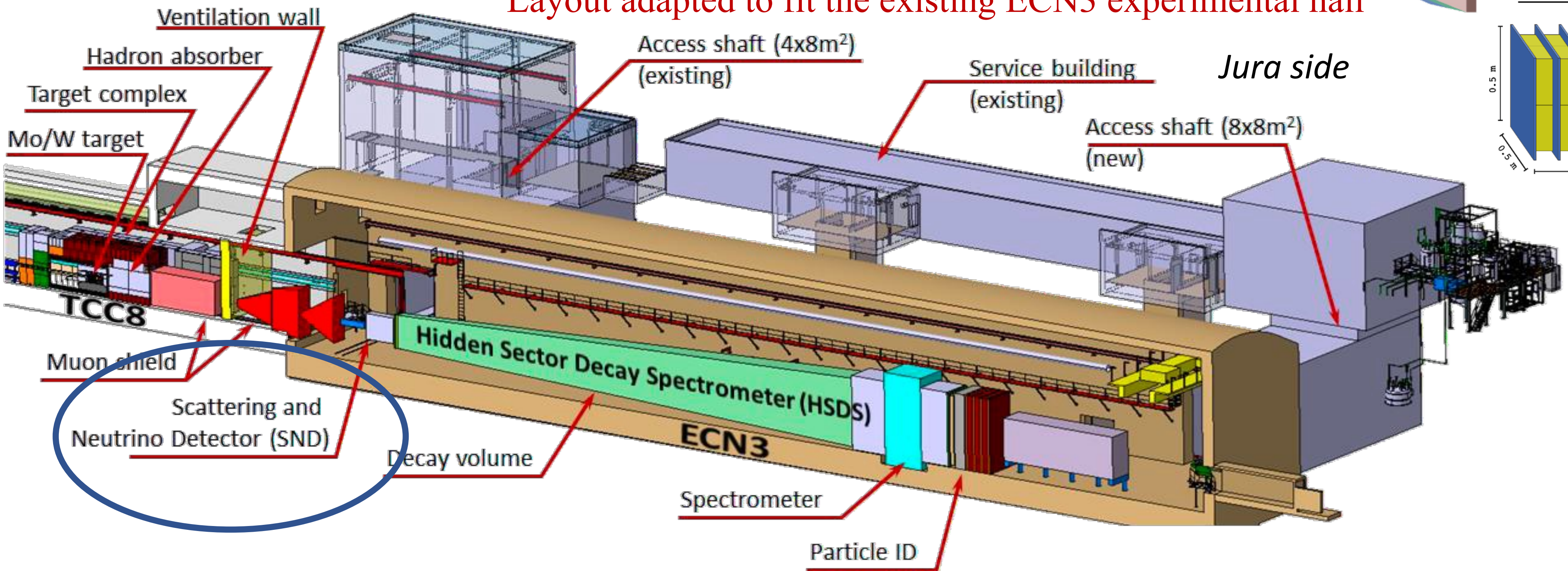




Beam Dump Facility

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

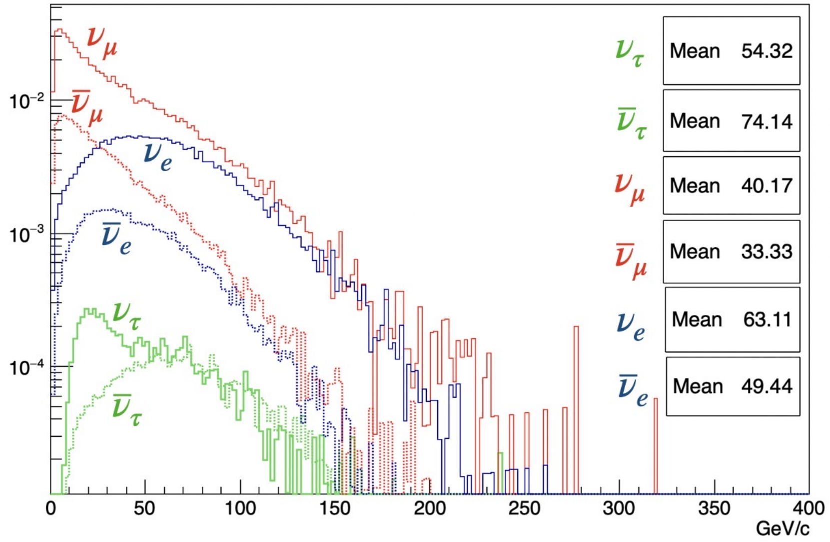
Layout adapted to fit the existing ECN3 experimental hall



Assume 6×10^{20} pot

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

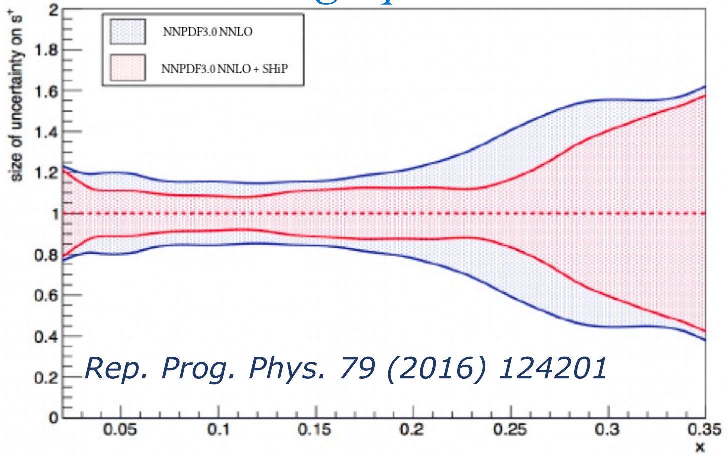
ν_τ cross-section, ν-induced charm, structure functions, …



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	

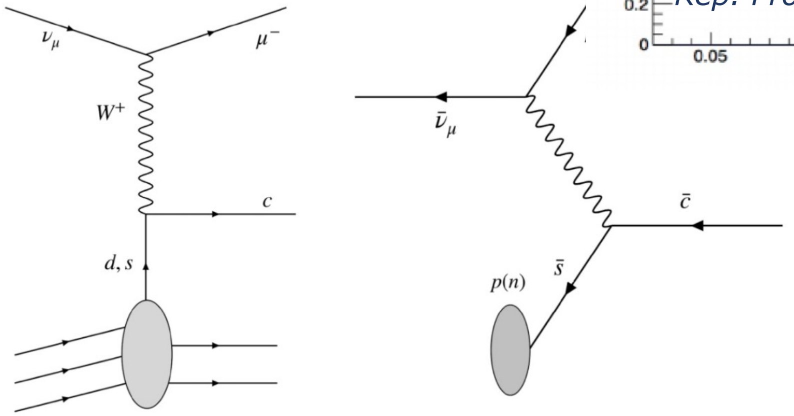
Complementary energy region to the LHC measurements

Strange quark distribution



Rep. Prog. Phys. 79 (2016) 124201

ν-induced charm



F4, F5 structure functions

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

At LO $F_4 = 0$, $2xF_5 = F_2$

At NLO $F_4 \sim 1\%$ at 10 GeV

	<E> (GeV)	CC DIS 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

New era of collider neutrinos started!

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

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

Stay tuned!