CERN Neutrino Platform and Neutrinos @ CERN/Europe

Albert De Roeck
CERN, Geneva, Switzerland

CHIPP Strategy Update Workshop 2025
4–5 Feb 2025
ExWi
Europe/Zurich timezone

Contents

- Present and future planned/possible activities at the CERN Neutrino Platform in global & European neutrino program context
- Neutrino experimental program @ CERN
  - at the LHC and CERN-SPS
- Other accelerator based neutrino experimental potential options in Europe

Workshop on Neutrinos@CERN

23–24 Jan 2025
CERN
Europe/Zurich timezone

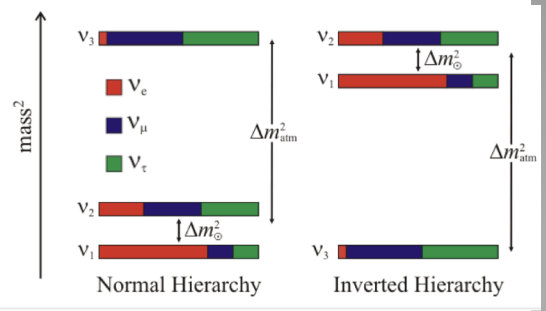
Most information from this workshop (300 participants)
https://indico.cern.ch/event/1460367/

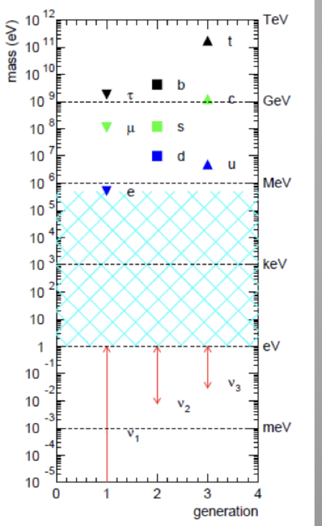
Neutrinos

Since '98 we know neutrinos have mass

- What are the absolute neutrino masses and what is the mass ordering?
- Is there CP violation in neutrino sector? (matter-antimatter asymmetry)
- Are there > 3 neutrinos? Sterile neutrinos?
- BSM effects in neutrino interactions?

- Cosmological/Supernova neutrinos?
- Is the neutrino its own anti-particle? (THEIA?)





=> Will discuss here opportunities related to experiments with accelerator generated neutrinos

Accelerator Neutrino Experiments

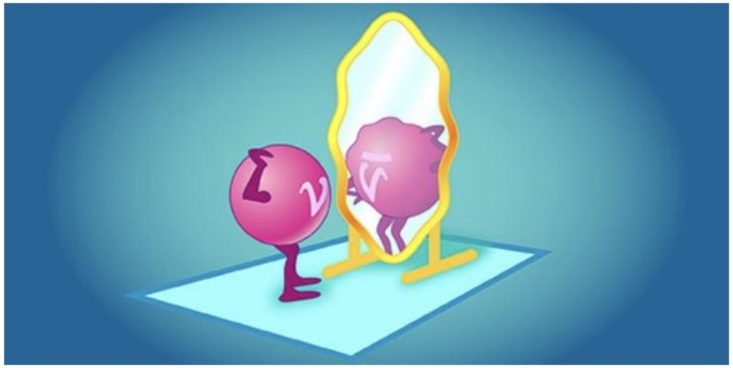
A new era for neutrino oscillations

Neutrino oscillations entered **the precision era :**

- huge statistics from neutrino **atmospherics** experiments

- neutrino from **reactors** become a benchmark to study nuclear physics

- **long-baseline experiments** enable the unique possibility to compare oscillation in controlled beams of neutrinos and antineutrinos separately

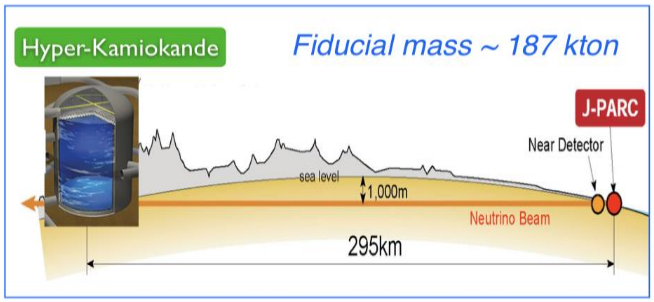


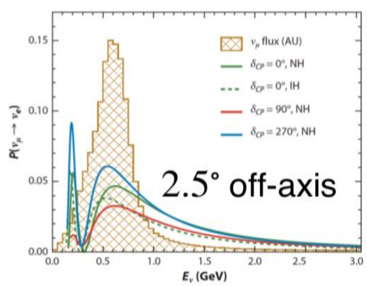
Next generation long baseline experiments will collect much larger statistics than present experiments, namely several 10Ks of events..

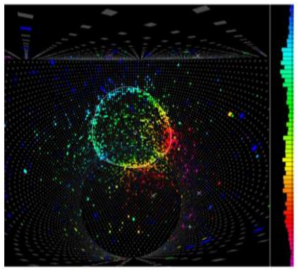
Next Major LBL Neutrino Experiments

Long-baseline experiments: T2HK and DUNE

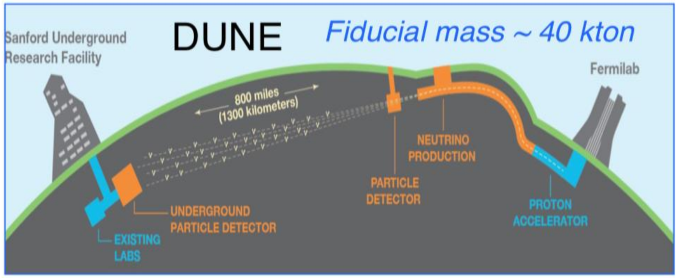
- Towards the measurement of the CP violating phase and Mass Hierarchy
  - Search for different $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities

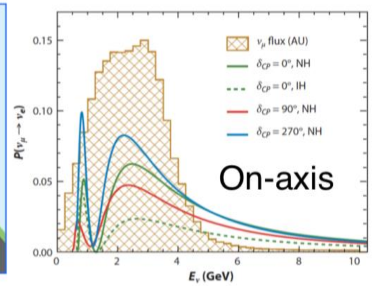


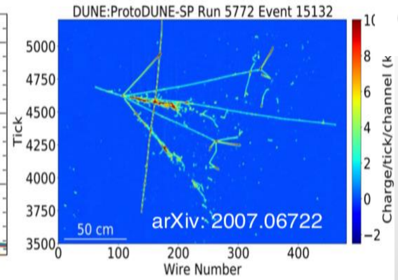




Annu. Rev. Nucl. Part. Sci. 2016. 66:47–71







Note:
These near and far detectors are "observatories"

Broad physics program:

- Solar ν's
- Supernova burst and diffuse background ν's
- Search for proton decay
- Dark matter search …

Both Collaborations have a large European participation (40/50%)

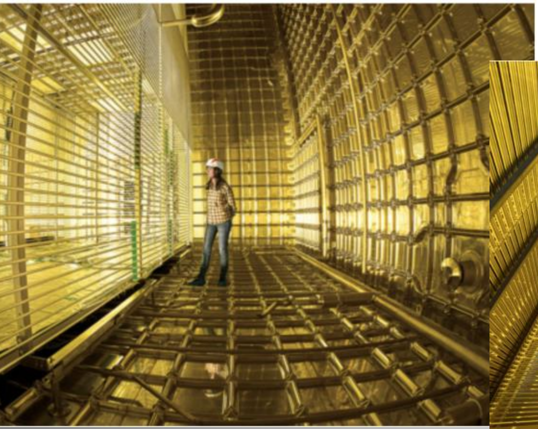
Expected Start-up: T2HK: End of 2027

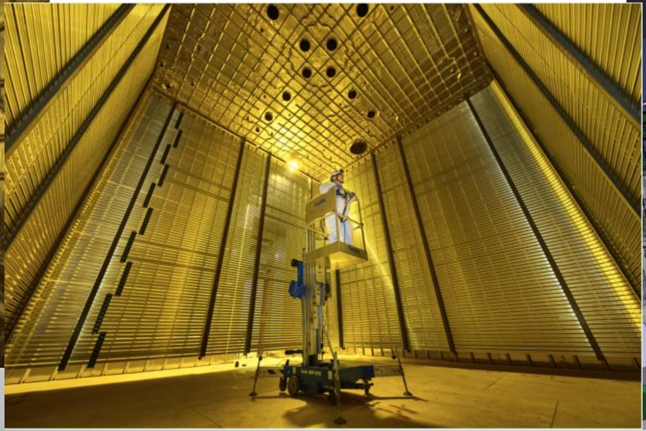
DUNE End of 2029 (in 2031 with beam)

The Neutrino Platform @CERN

Support for neutrino experiments on accelerators

- Recommended by the ESPP strategy in 2013
- It includes the provision of a facility at CERN to allow the global community of neutrino experts to develop and prototype the next generation of neutrino detectors, and especially to act as a hub for European contributions & participation..
- 2015-now: ProtoDUNES for DUNE, BabyMind & ND280 activities for T2K, ICARUS & SND (SBN@FNAL) & ENUBET support…
- “Bringing neutrinos back @ CERN since 2001”…

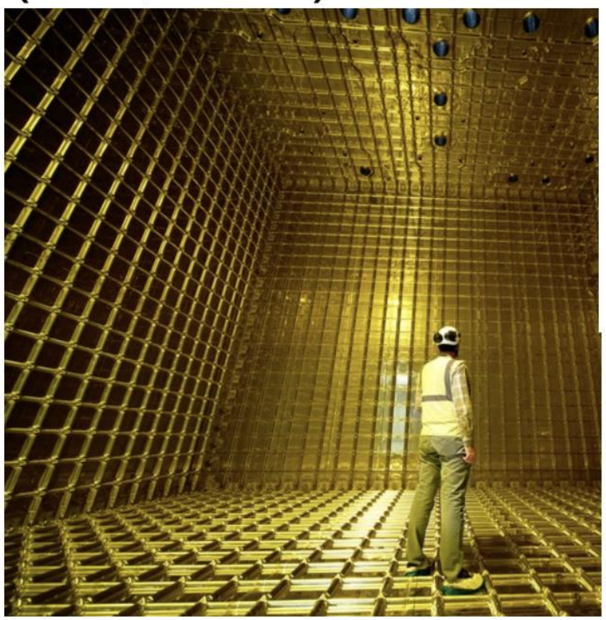




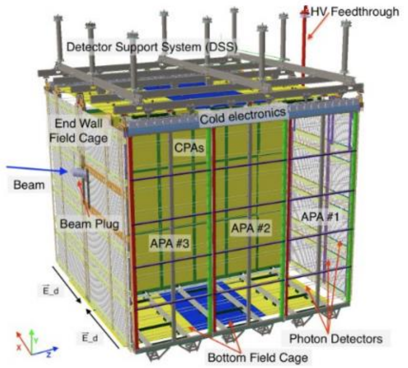
ProtoDUNEs

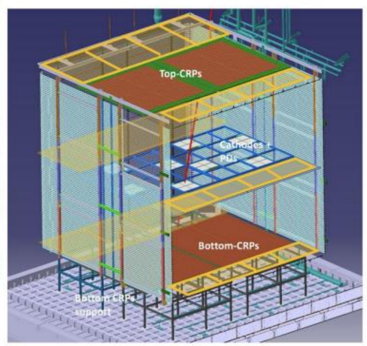
The ProtoDUNEs are 4% size prototypes for the Far Detectors (FD) of DUNE
The PDs are the largest projects on the Neutrino Platform so far.

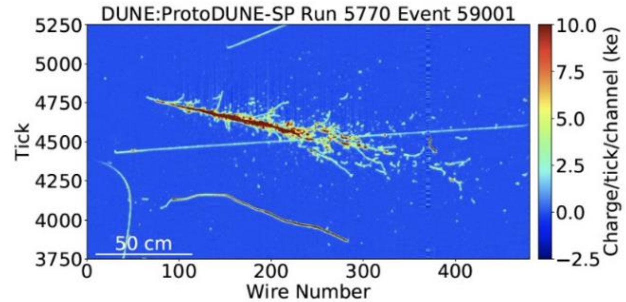
ProtoDUNE LAr modules
(>700t, >200m³)



Horizontal and vertical drift







Xe-doping in PDSP
with dedicated sensors

ARIADNE : TPC
optical readout
(tested in the cold-box)

- Past: horizontal drift prototype results in 2018. Vertical drift is a new concept
- Now: tests with final (?) configurations of HD and VD for FD1 and FD2
- Future: new technologies on the NP for future decisions on FD3 and FD4

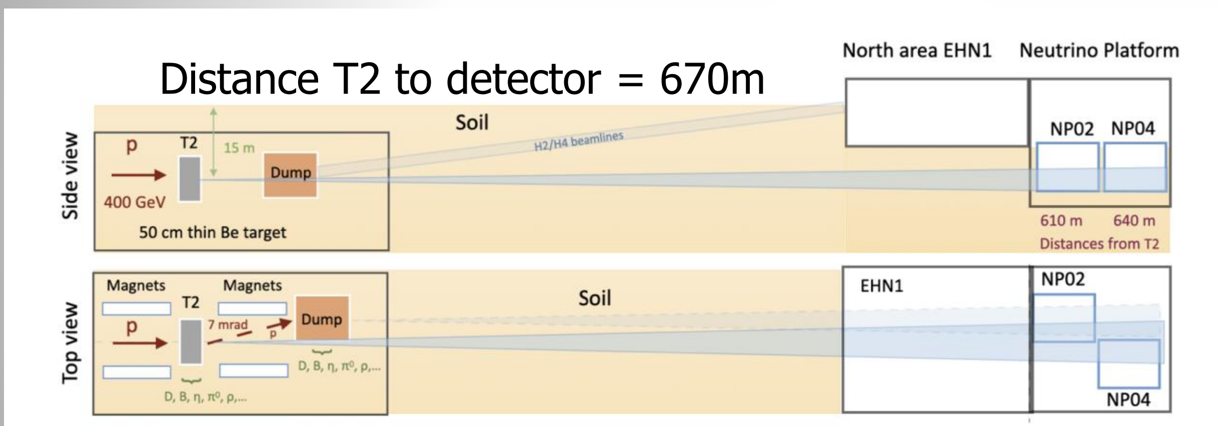
New: ProtoDUNEs for BSM Searches?

arXiv:2304.06765

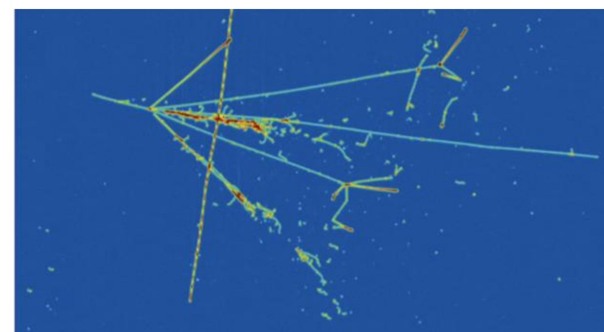
New Physics searches using ProtoDUNE and the CERN SPS accelerator

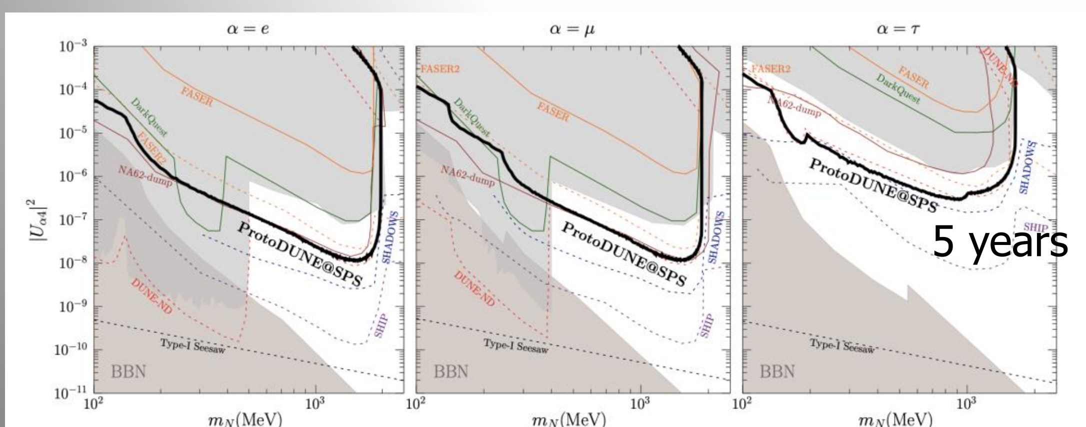
Pilar Coloma,[1,*] Jacobo López-Pavón,[2,†] Laura Molina-Bueno,[2,‡] and Salvador Urrea[2,§]

Use the ProtoDUNE detectors (700t LArTPCs) to hunt for weakly interaction LLPs or light dark matter scattering? The 'beam' comes for free!!



First "neutrino" in NP04



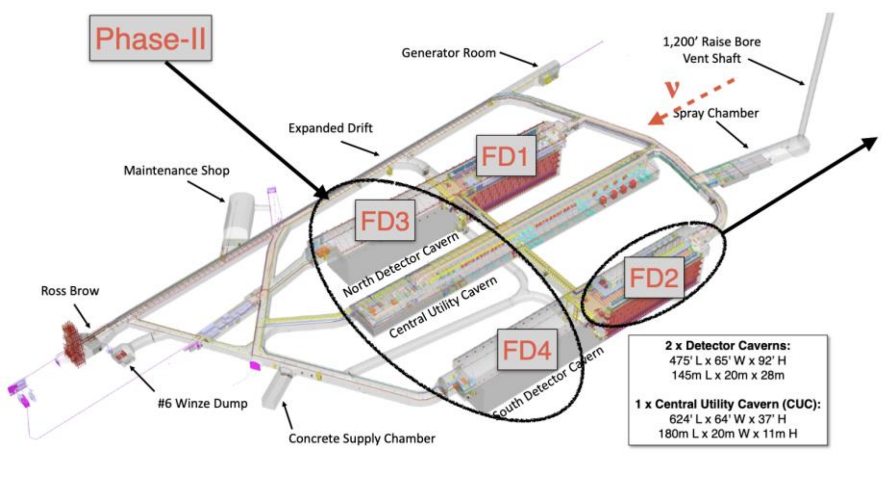


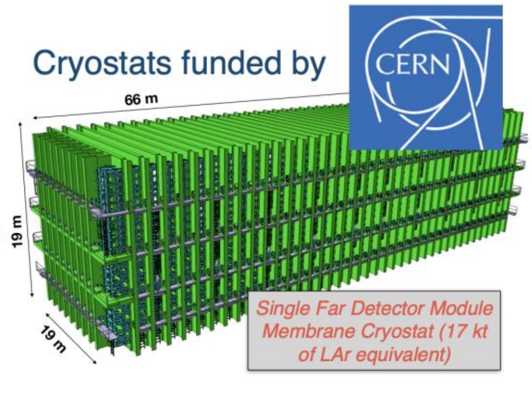
HNL Sensitivity:
Competitive for masses above the Kaon threshold

Experimental feasibility study made during 2024
Demonstrator run in '25 & '26?

CERN & DUNE Far Detector

Two first cryostats are funded by CERN

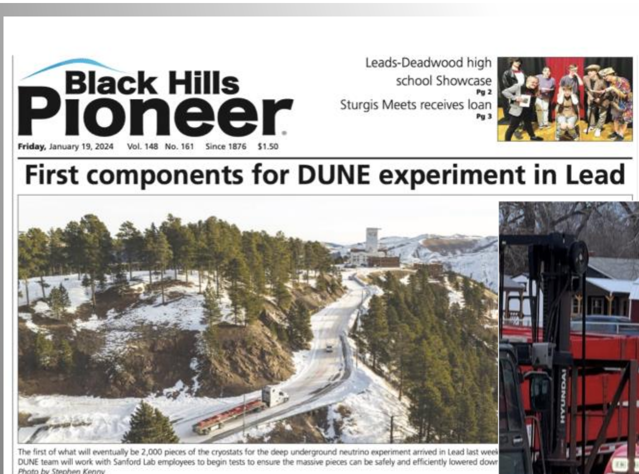




Phase-I: two 17Kt modules

Phase-II: two more modules

- **FD1**: Horizontal Drift (HD)
- **FD2**: Vertical Drift (VD)
- **FD3**: Improved VD-LArTPC
- **FD4:** Module of opportunity


Black Hills Pioneer

Leads-Deadwood high school Showcase Pg 2

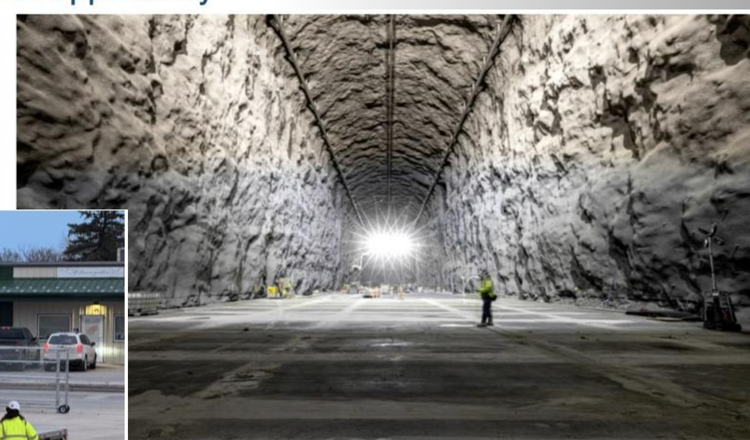
Sturgis Meets receives loan Pg 3

Friday, January 19, 2024 Vol. 148 No. 161 Since 1876 $1.50

First components for DUNE experiment in Lead

The first of what will eventually be 2,000 pieces of the cryostats for the deep underground neutrino experiment arrived in Lead last week. DUNE team will work with Sanford Lab employees to begin tests to ensure the massive pieces can be safely and efficiently lowered down

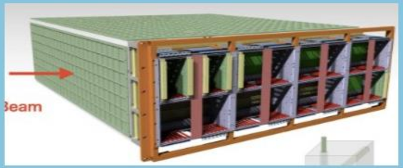
Photo by Stephen Kenny

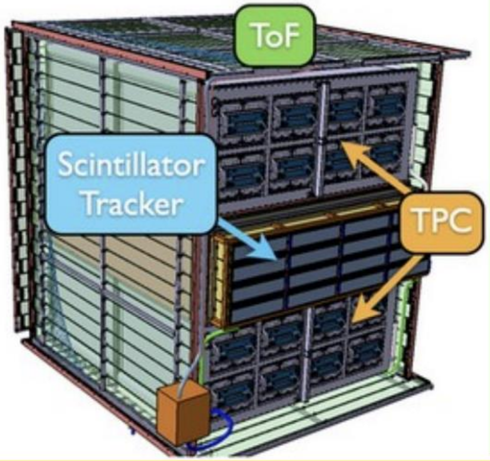


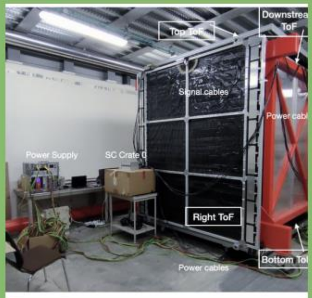
T2K Related Activities

- CERN is a member of T2K and contributed to the ND280 near detector.
- Much of the assembly and testing of the new ND280 components from Europe was done @ CERN, before shipping to Tokai.


SFGD prototype test beam & mechanical tests of the box

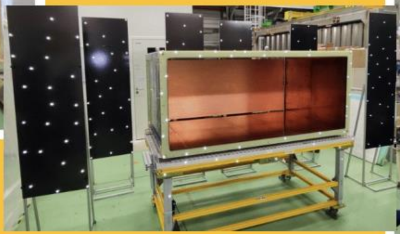
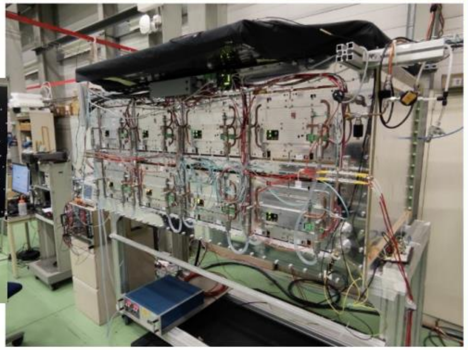







ToF prototype test beam, full assembly and test of final detector



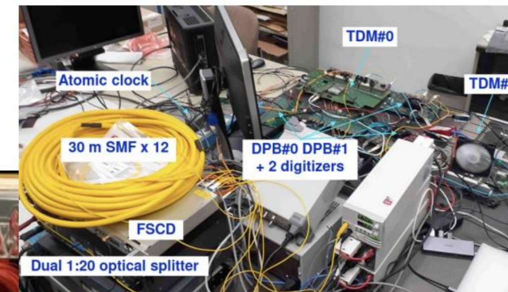
2 TPCs : multiple test-beam prototypes, Micromegas production and characterization, metrology, full assembly and test of final detector

….Repeat this for ND280++?

T2HK @ CERN

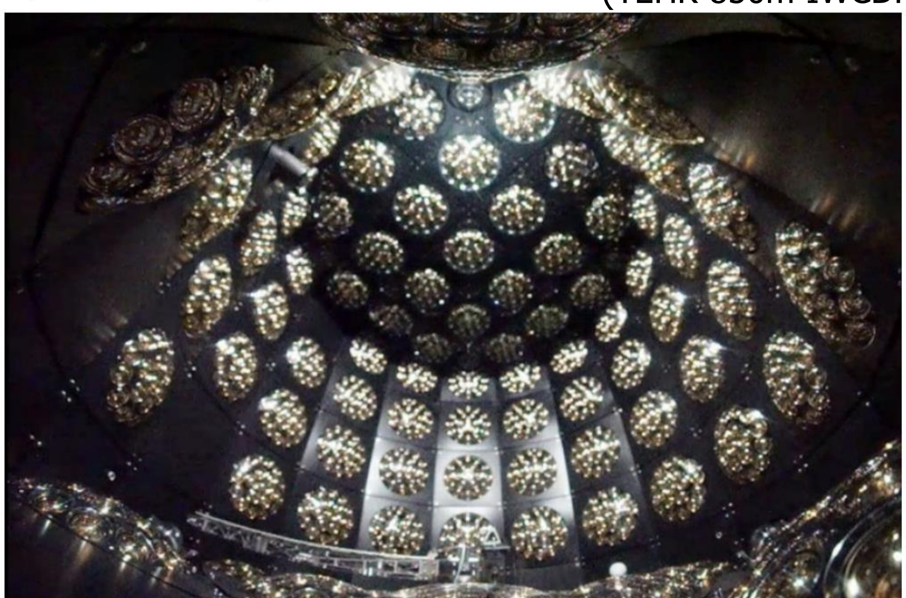
- T2HK is a CERN recognized experiment.
- Electronics assembly & underwater tests set-up on the NP @ CERN
- Water Cherenkov test experiment in the East Hall @ CERN

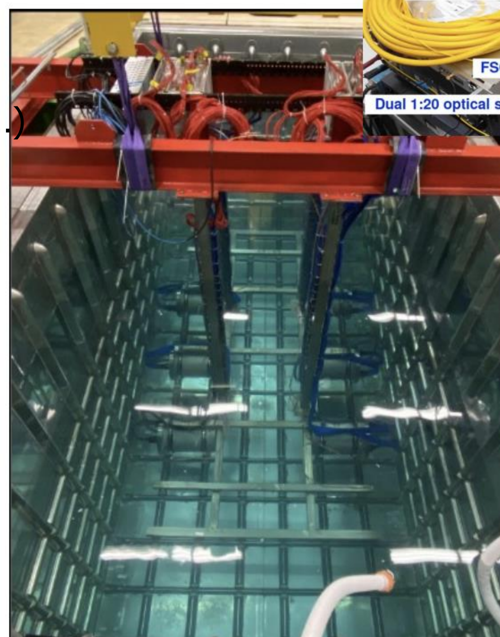
HyperKamiokande multi-PMTs and electronics

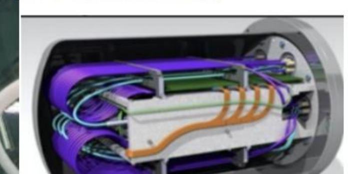


Water Cherencov Test Experiment
(4m d x 4m h) on test beam

(T2HK 850m IWCD...)







HK electronics (900 boxes, ~4500 cards) : integration, calibration, assembly and test underpressure and underwater

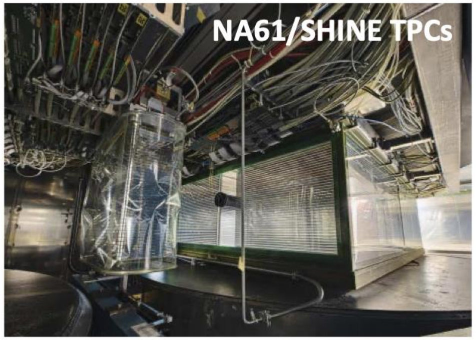
Auxiliary Experiments @ CERN

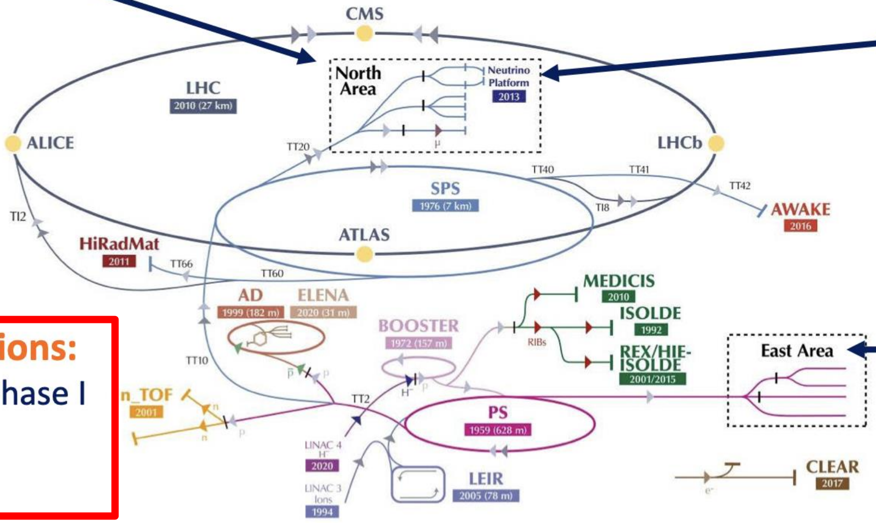
FUTURE CONTRIBUTIONS TO EXTERNAL NEUTRINO PROJECTS

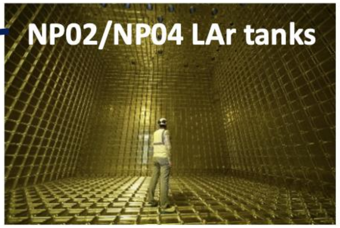
Neutrino beam control:
All beams: NA61/SHINE hadroproduction cross-sections and hadron production measurements with FNAL/JPARC neutrino beam replica targets
→ *to be continued, additional low-E beam foreseen*

Neutrino detector technology and response:

- T2K: NP07 near detector → *completed*
- DUNE: NP02 and NP04 far detector prototypes
  → *new technologies (DUNE Phase II) + physics*
- HK: NP08 for electronics
  WCTE detector prototype
  → *data taking to be completed < LS3*







Neutrino interaction cross-sections:
NuSTORM@CERN studied by PBC Phase I
→ *SBN@CERN(ENUBET+NuTag) studied by PBC Phase II*

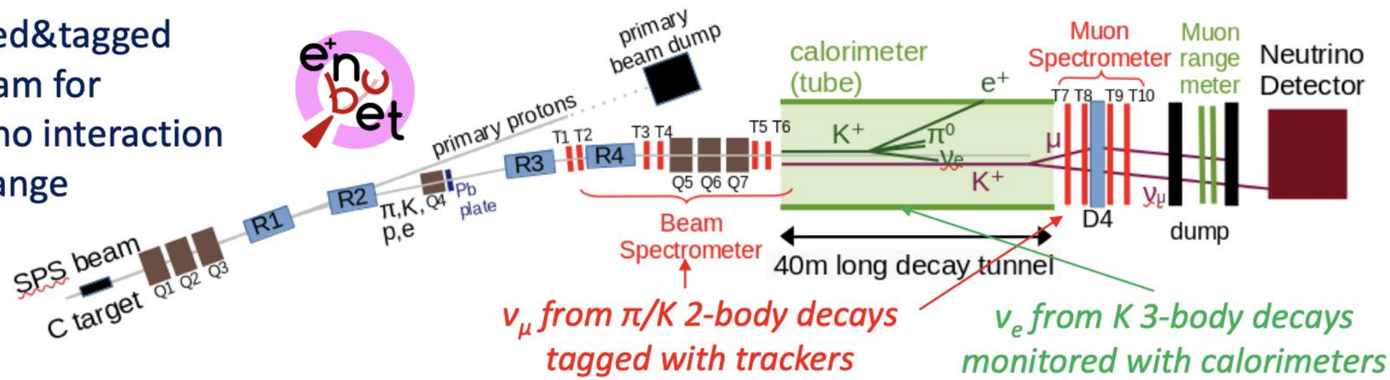
Auxiliary Experiments @ CERN

Next LBL experiments wil have > O(10K) events -> large statistics
Important to keep the systematics uncertainty O(1%) -> Proposal:

SBN@CERN: a new facility under study for DUNE/HK

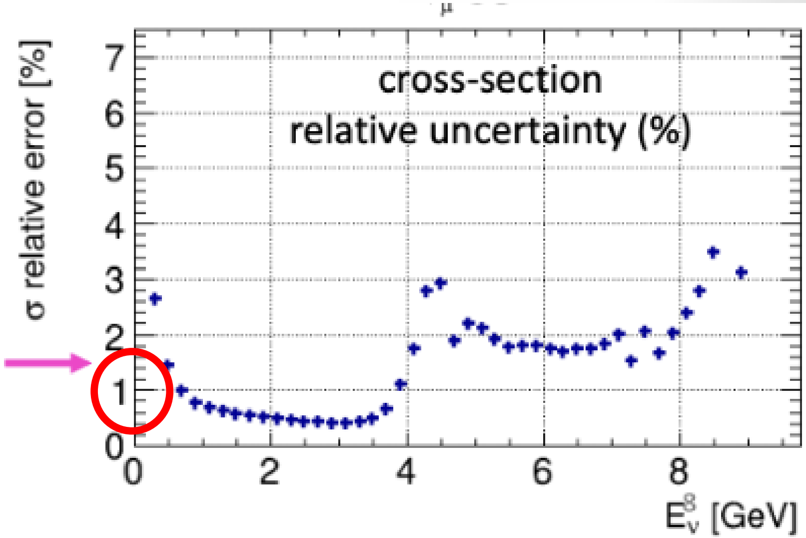
Medium-intensity monitored&tagged Short Baseline neutrino beam for %-level precision on neutrino interaction cross-sections in the GeV range

Innovative slow extraction and focusing



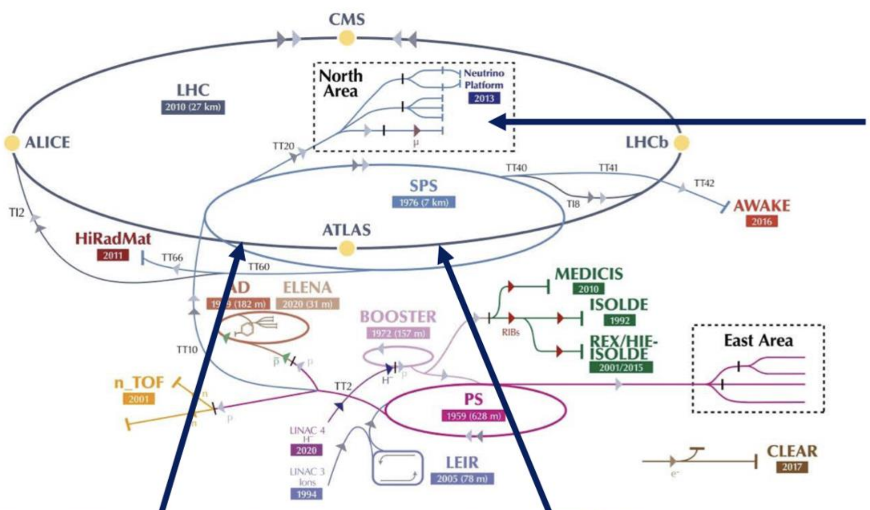
A dedicated neutrino experiment and beamline at the SPS ?…

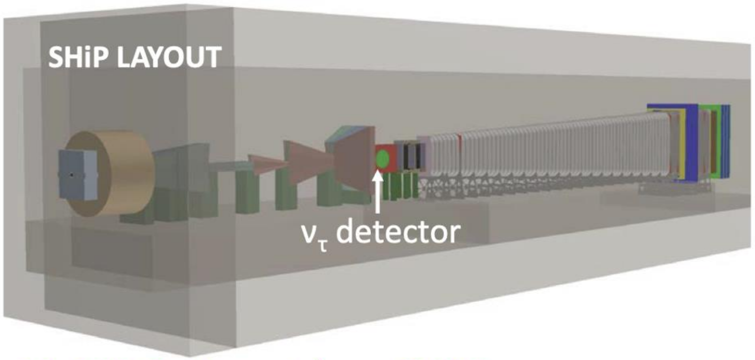
Expect a strong reduction of a dominant systematics of DUNE/HK



CERN Neutrino Experiments

Neutrino physics experiments are back at CERN since 2022!!





10-100 GeV neutrinos @SPS

- DsTau τ-neutrino production cross-section
  → *data taking completed, final results to come*
- SHiP high-statistics τ-neutrino measurements
  → *final design and construction to come*

TeV neutrinos @LHC:

- FASERν → *upgrades foreseen for run 4 at present location*
- SND@LHC → *upgrades foreseen for HL-LHC at present location*

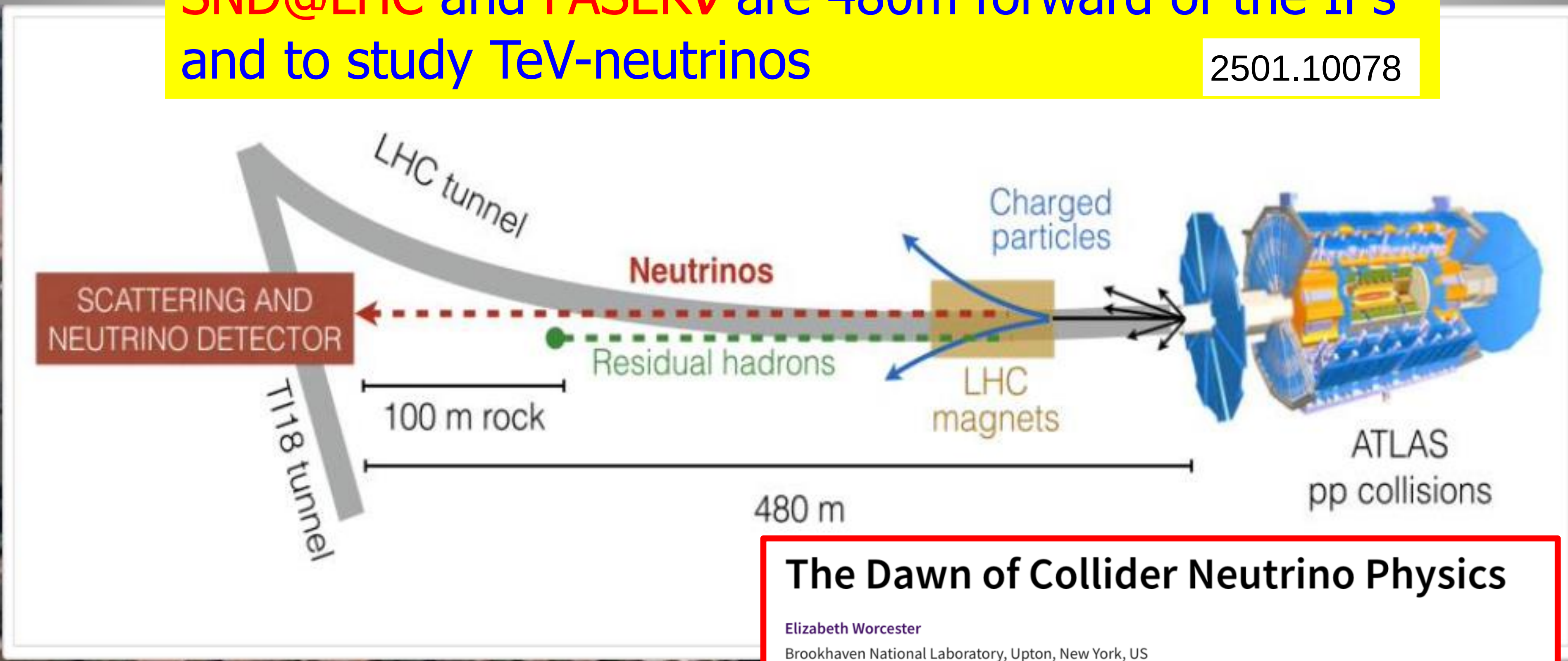
→ *Forward Physics Facility studied by PBC Phase II*

- NA65/DsTau experiment took their anticpated data sample in 2022-2023
- SND@LHC and FASER(ν) started in 2022. Will also take data in run 4
- SHiP approved as ν and feebly interacting particle search exp. at the SPS

Measuring Neutrino Interactions @ LHC

SND@LHC and FASERν are 480m forward of the IPs and to study TeV-neutrinos

2501.10078



The Dawn of Collider Neutrino Physics

Elizabeth Worcester

Brookhaven National Laboratory, Upton, New York, US

July 19, 2023 • *Physics* 16, 113

The first observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.

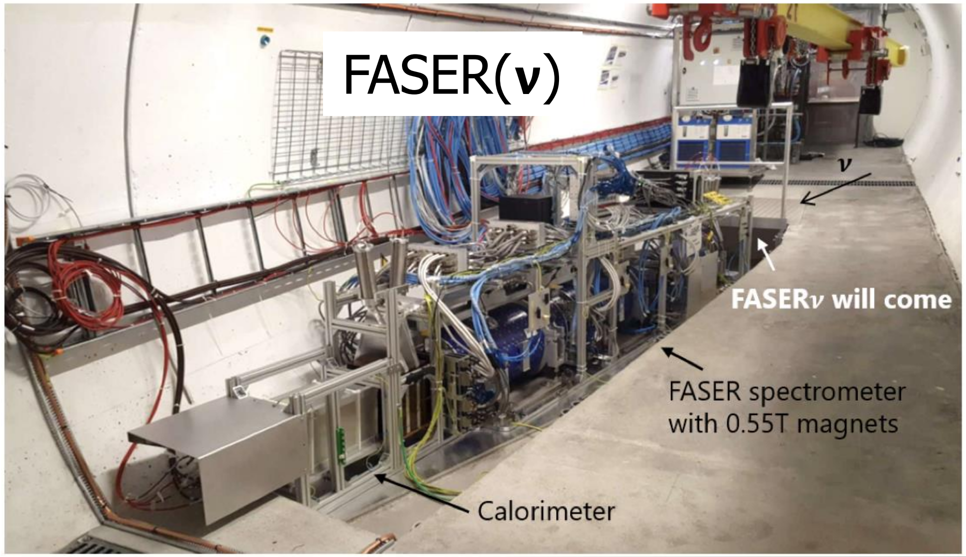
FASER was approved in 2019. FASERν (extension with emulsion) in 2020.
SND@LHC was proposed in 2020 and approved in 2021.
Both experiments take now data since the start of the Run 3 at the LHC.

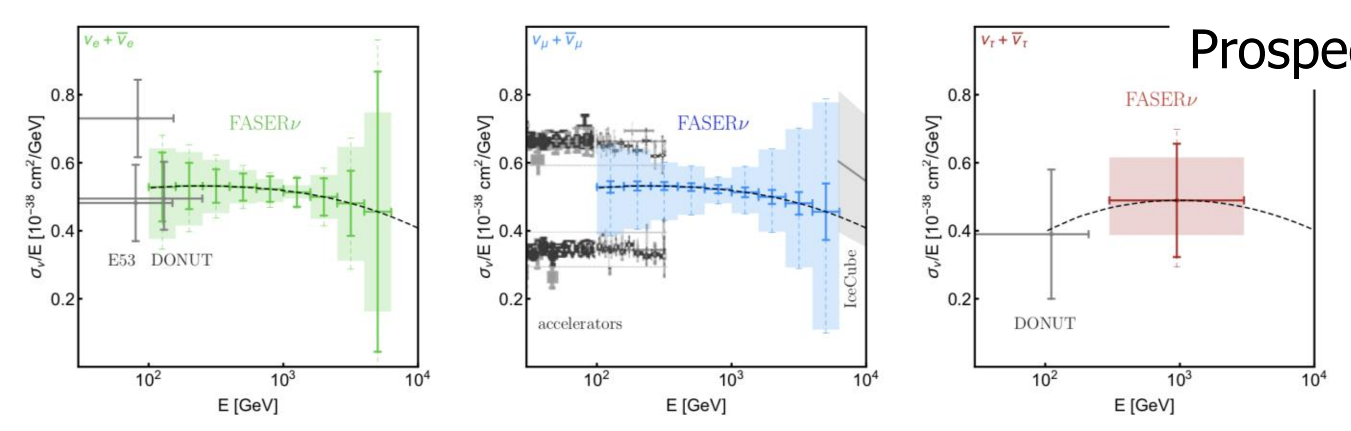
Neutrinos @ the LHC: SND@LHC & FASERν

SND@LHC/FASERν are 480m forward and can study TeV-neutrinos with emulsion and tracking+muon/calo detectors

SND= Scattering and Neutrino Detector

FASER= ForwArd Search ExpeRiment



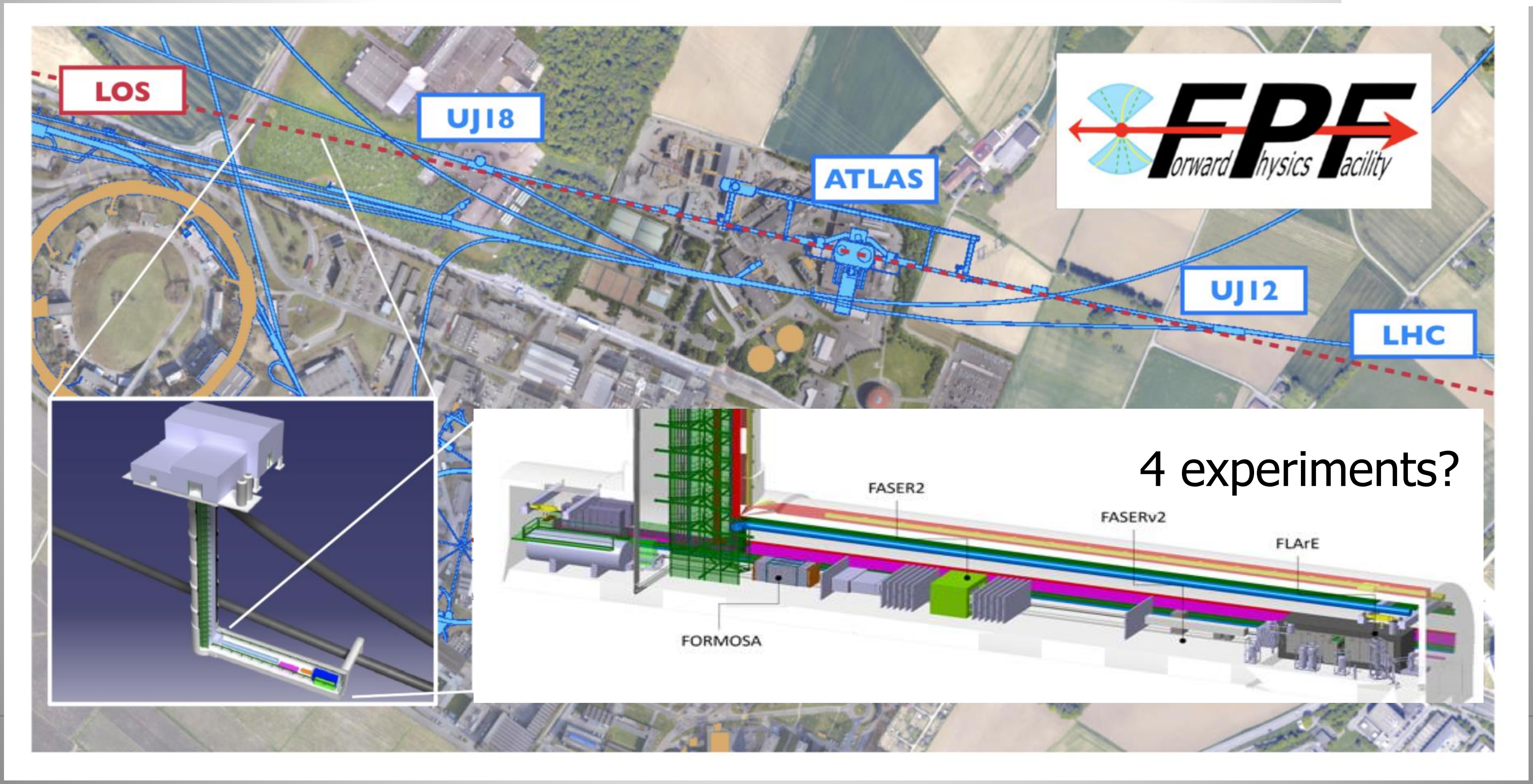


Prospects for Run 3

The Forward Physics Facility

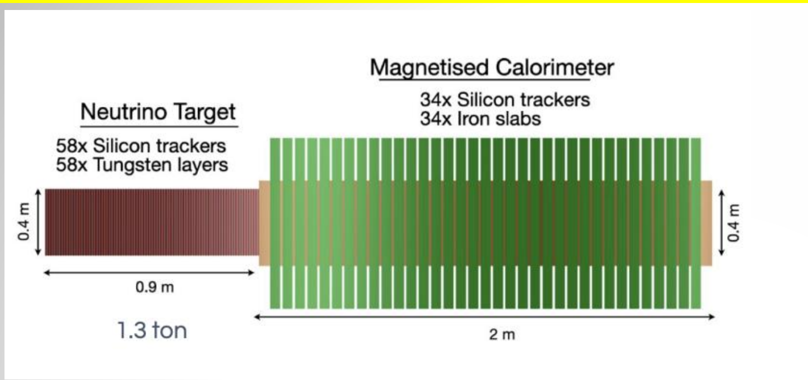
Origin: Letter of intent contributed to the Snowmass21 process.
Based on the FASER experience and studies: propose to have a Forward Physics Facility (FPF) experimental hall with room to include large forward detectors for new physics searches (and QCD): FASER2, others

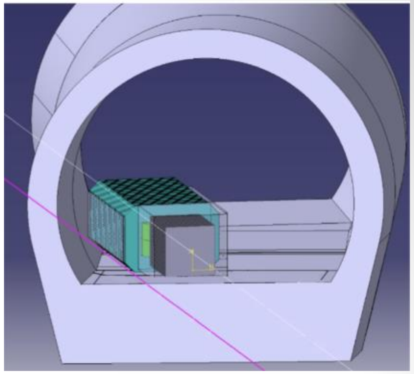
2203.05090



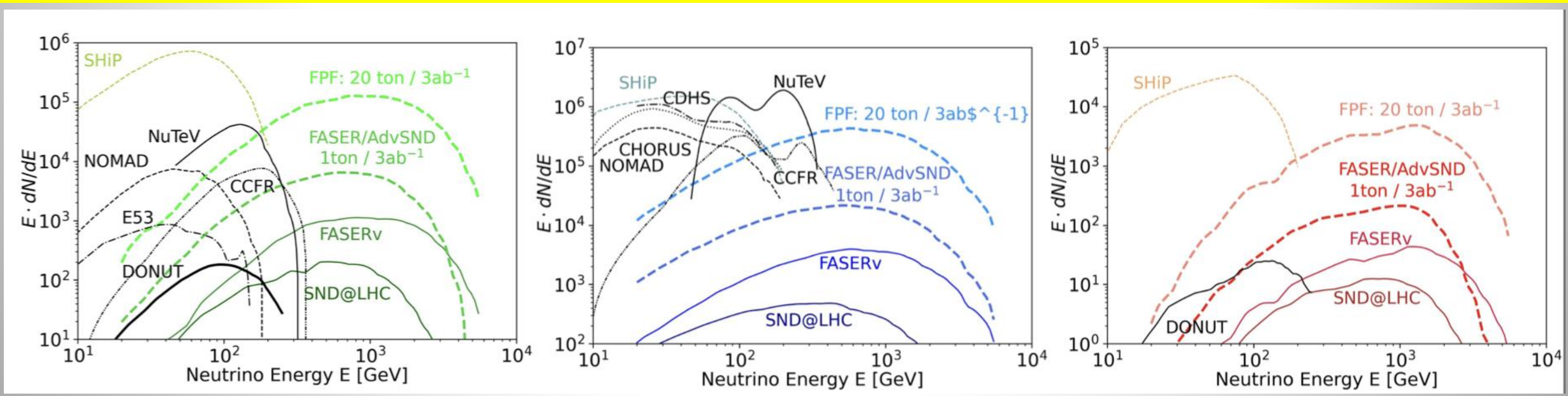
Future Neutrinos @ the LHC

SND@LHC will upgrade the detector in the tunnel for Run 4 and beyond





Neutrino rates in FASER and SND@LHC during the high luminosity LHC



Current LHC experiments will detect thousands of neutrinos
The FPF experiments will detect millions of neutrinos.

Future Neutrinos @ the LHC

Physics with LHC neutrinos

Neutrino interactions

- Measure ν **interactions** in unexplored ~TeV energy range.
- Large yield of ν_τ will more than double existing data.
    - About 20 events observed by DONuT and OPERA.
- First observation of $\bar{\nu}_\tau$.

QCD

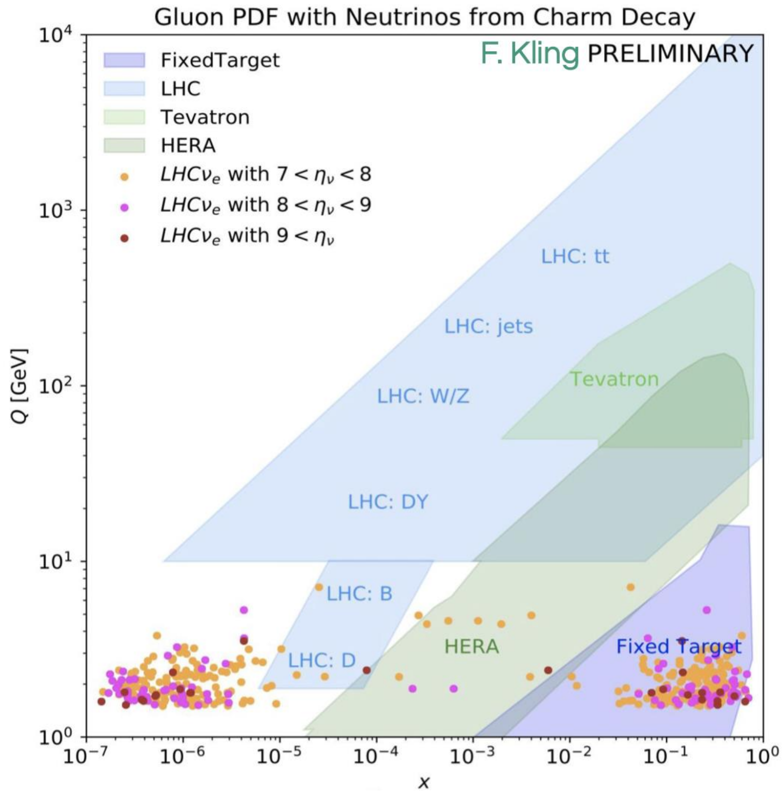
- Decays of **charm** hadrons contribute significantly to the neutrino flux.
  ⇒ Measure **forward charm production** with neutrinos.
  ⇒ Constrain **gluon PDF** at very **small x**.

Flavour

- Detection of all **three types of neutrinos** allows for tests of **lepton flavour universality**.

Beyond the Standard Model

- Search for **new**, feebly interacting, **particles decaying** within the detector or **scattering** off the target.



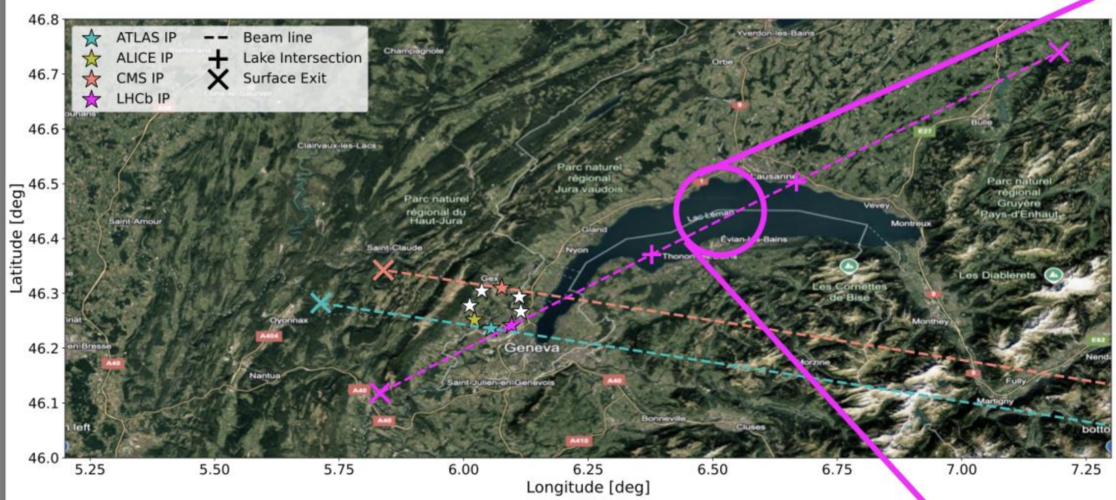
The forwards measurements will have implications for astroparticle physics/cosmic rays, FCC-pp cross sections…

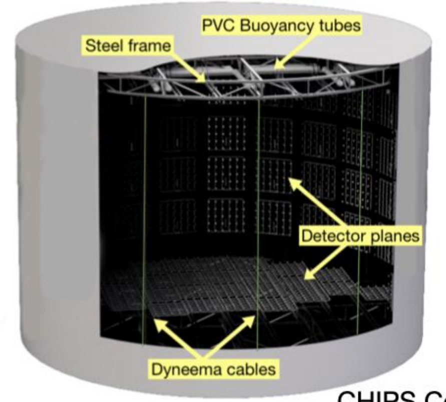
Neutrinos @ CERN: Lake Geneva

Recently: Instead of digging a new underground area, let the LHC neutrinos surface!….And catch them with a detector, e.g. in Lake Geneva…

2501.08278
2501.06142

UNDINE: UNDerwater Integrated Neutrino Experiment





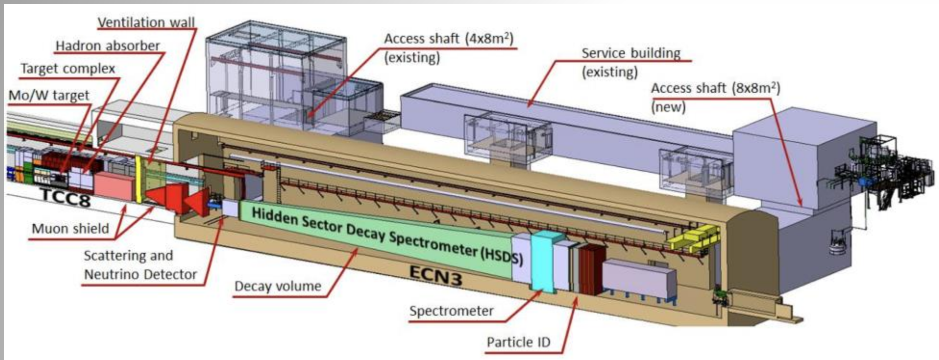
CHIPS Collab. 2024

- A suite of CHIPS-style water Cherenkov detectors deployed in a modular fashion
- Benchmark lake detector: 5 CHIPS modules (~30 kT)

Event samples with O(10^6) interactions possible

SHIP: A Future Experiment at the SPS

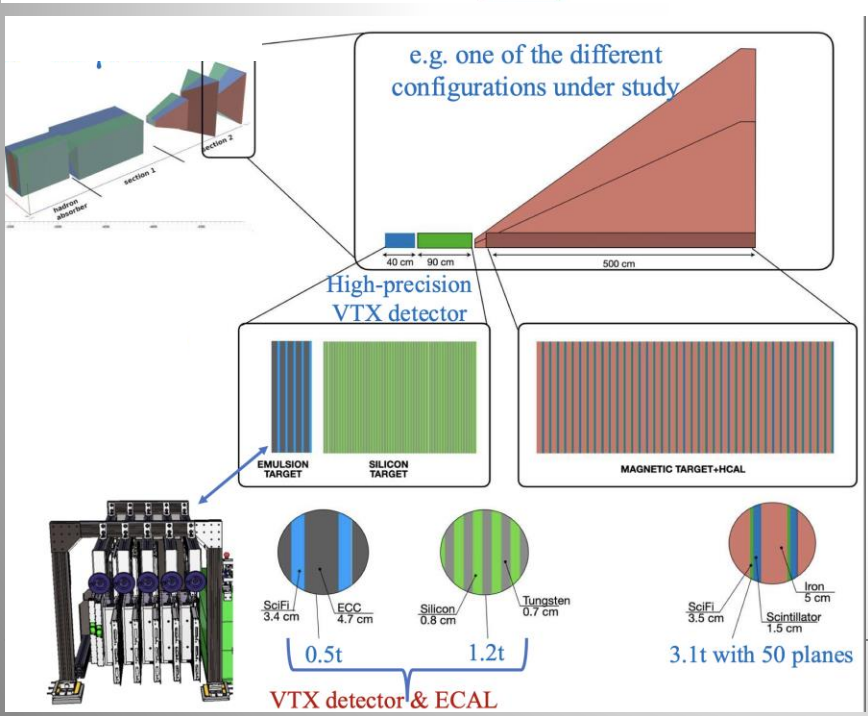
SHiP is an experiment for the new beam dump facility for the CERN North Hall. SHiP foreseen to take data as of ~2032/33 for 15 years



SHiP: Search for Hidden Particles

SHIP includes a neutrino detector

Planned: 4×10^{19} POT/year



The SHiP Scattering and Neutrino Detector SND has a similar structure as SND@LHC

Physics Targets: tau neutrino physics, charm physics, measure F_4 and F_5 structure functions…

O(10^6/10^7/10^5) $\nu_e/\nu_\mu/\nu_\tau$ interactions

Future Opportunities in Europe

- DUNE technology developments e.g. optical or pixel readout LAr & near detector for phase II, water based liquid scintilator…
- Physics searches with the ProtoDUNEs during run 4?
- T2HK: near detector ND280++ & Water Cherenkov Detector studies
- NA61: low energy run/more targets proposed
- SBN@CERN: New GeV tagged neutrino exp.? (…maybe aim to KM3NET?)
- TeV Neutrinos at the LHC: Upgrades, the FPF(?), surface TeV neutrinos
- Neutrinos in SHiP at the SPS
- …. More new ideas?

CERN → KM3NeT

SUMMARY

The CERN Neutrino Platform is playing an important role for the international/european neutrino community… and should continue to do so!

- Suggestion was made for a formal "neutrino center @ CERN" for better experiment/theory interaction.
- Support from the community during the ESPPU for the NP will be essential for longer term continuity!
- Other further future opportunities not discussed here.
  - nuSTORM, part of a muon collider demonstrator?
  - Neutrino beams from the European Spalation Source?
- …

Neutrino Physics is a very vibrant field &
Neutrinos are back @ CERN!

BACKUP

FPF Projects

CERN NP experiments / projects

8 Experiments approved by the SPS Committee and by the Research Board:

- **NP01**: ICARUS for the US/FNAL SBN (completed 2017), SBND

LAr TPC developments for LBNF/DUNE

- **NP02**: demonstrator/engineering prototype initially for a double phase TPC - now Vertical Drift (ongoing)
- **NP03**: PLAFOND, a generic detector R&D framework for accelerator-based neutrino experiments (ongoing)
- **NP04**: ProtoDUNE for single phase (Horizontal Drift) engineering prototype (ongoing)
- **NP05**: Baby Mind, a muon spectrometer for the WAGASCI experiment at T2K (delivered 2017)
- **NP06**: Enhanced Neutrino Beam via kaon tagging (ENUBET)
- **NP07**: Contributions to the T2K Near Detector
- **NP08**: Procurement, assembly and testing of electronics components for the Hyper-K experiment

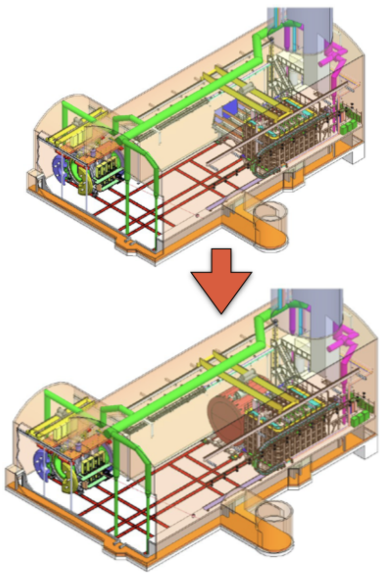
LBNF/DUNE: FD1,2 cryostats; Cryo; Compliance Office; HV; TDAQ; Andes; Electronics.

Darkside-20k cryostat (DM experiment at INFN LNGS)

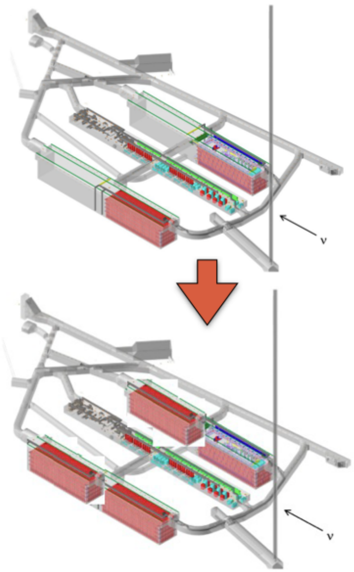
DUNE Phase I & II

DUNE to built in two phases

Near Detector (ND)



Far Detector (FD)



Phase I
- **FD:** 2 x 17 kt LArTPC modules
- **ND:** ND-LAr+TMS (with PRISM) + SAND
- **Beam:** 1.2 MW beam line (PIP-II)

Phase II
- **FD:** 2 additional modules (total: 4 x 17 kt LAr-equivalent)
- **MCND:** ND-LAr+ND-GAr (with PRISM) + SAND
- **Beam:** > 2 MW beam line (ACE Upgrades)

The LBNF facilities at the near and far sites support Phase II beam and detectors from the start (part of Phase-I scope) — ***simplifying Phase-II implementation***

LArTPC: *Liquid Argon Time Projection Chamber*
ND-LAr: *Liquid argon-based ND*
TMS: *Temporary Muon Spectrometer*
SAND: *System for on-axis ND*
MCND: *More Capable ND*
ND-GAr: *Gaseous argon-based ND*
PRISM: *movable ND capability for off-axis beam measurements*
PIP-II: *Proton Improvement Plan-II*
ACE: *Accelerator Complex Evolution at Fermilab*

Parameter	Phase I	Phase II	Impact
FD mass	2 FD modules (20 kt fiducial)	4 FD modules (40 kt fiducial LAr equivalent)	FD statistics
Beam power	1.2 MW	Up to 2.3 MW	FD statistics
ND configuration	ND-LAr+TMS, SAND	ND-LAr, ND-GAr, SAND	Systematics

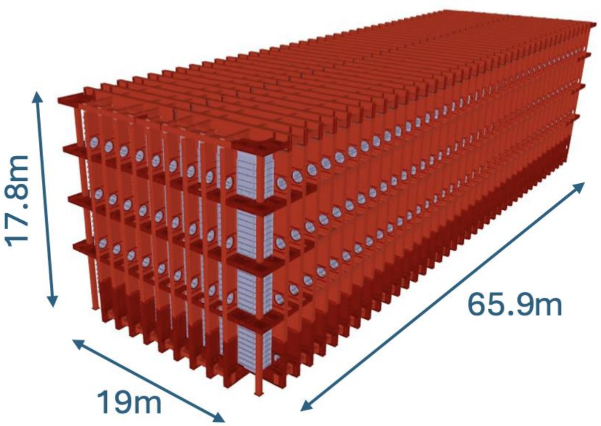
***Non-argon options currently under consideration for Phase-II near and far detectors not listed**

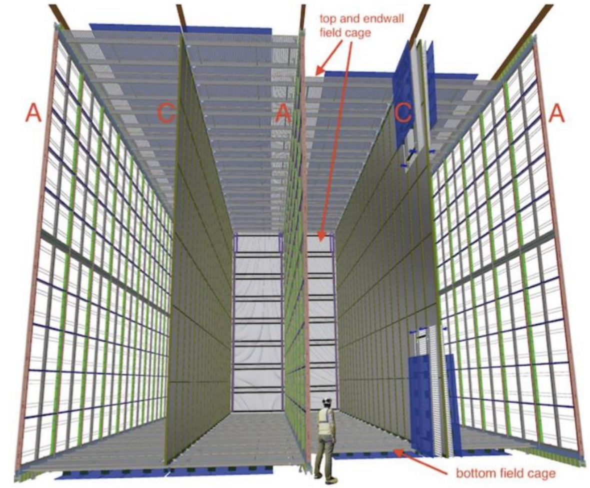
ProtoDUNEs

One detector principle, two realizations: HD, DV

First 2 modules, each one holds 17 kt Argon total :

- Horizontal (charge) Drift
- Vertical (charge) Drift

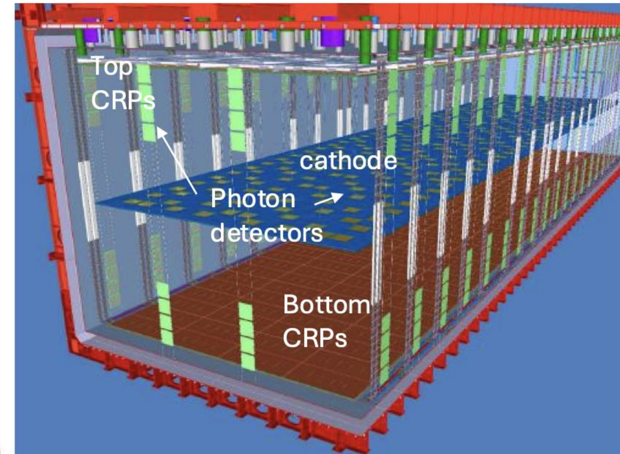




HD

Anode Plane Assemblies : wire chamber technology

Drift length 350 cm -> ~ 180 KV
9800 m^3 = 13.2 ktons active LAr



VD

Charge Readout Planes : perforated PCB technology

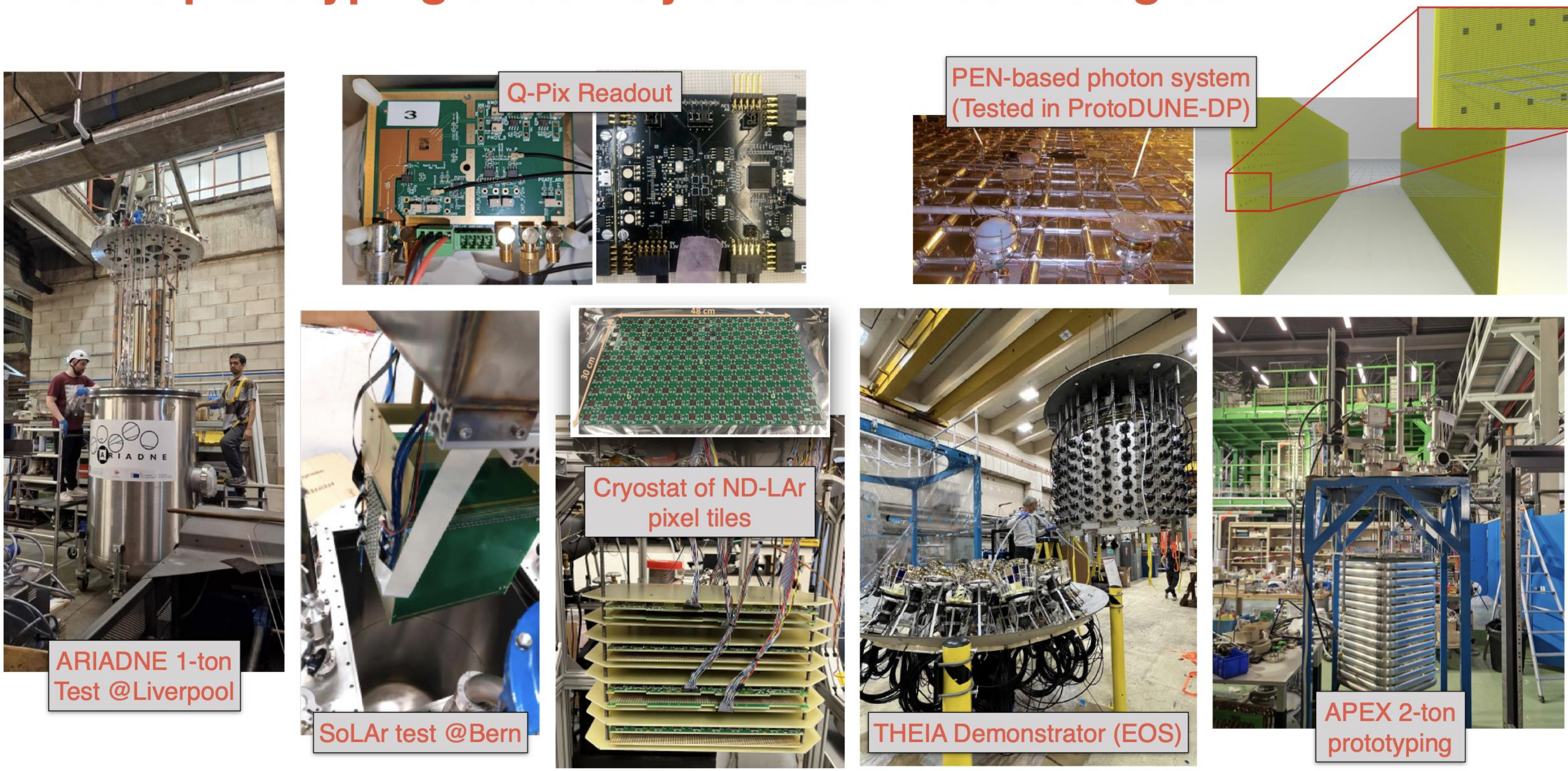
Drift length ~ 640 cm -> ~ 300 KV
10180 m^3 = 14.2 ktons active LAr

Photon detectors on the cathode at 300 KV

Construction and operation of 4% size prototypes of the large forward detectors fo DUNE. CERN also committed to build two FD cryostats

DUNE Detetor Technology Studies

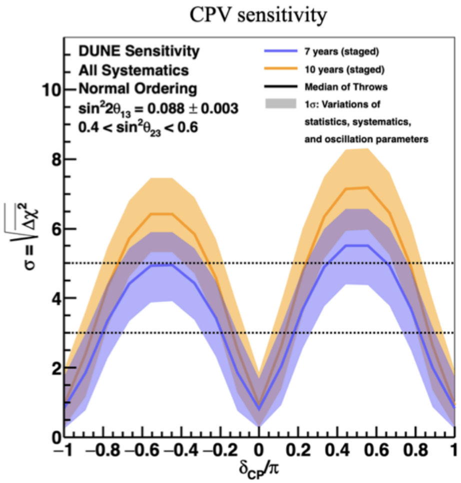
Active prototyping underway across all technologies



Oscillation Physics with DUNE

DUNE (Phase I+II) will enable

- *high precision measurements of all 4 parameters governing long-baseline oscillations (Δm^2_{32}, θ_{13}, θ_{23}, and δ_{CP})*
- *Establish CP violation at high significance over a broad range of possible values of δ_{CP}, and test the 3-flavour paradigm as a way to search for and constrain νBSM*

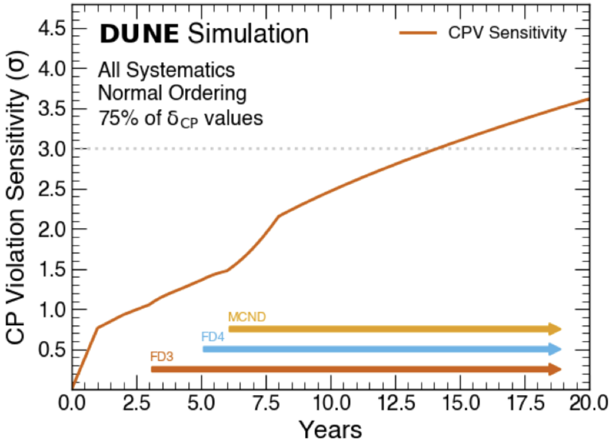


Impact of Phase II:

- Far Detectors 3/4 will increase fiducial mass by a factor of two.
- ACE-MIRT increases beam intensity right away, and throughout the DUNE programme.

Both will enable much faster resolution to mass ordering and much faster significance to maximal CPV

- MCND provides important systematic constraints to match the ~1% precision goal.

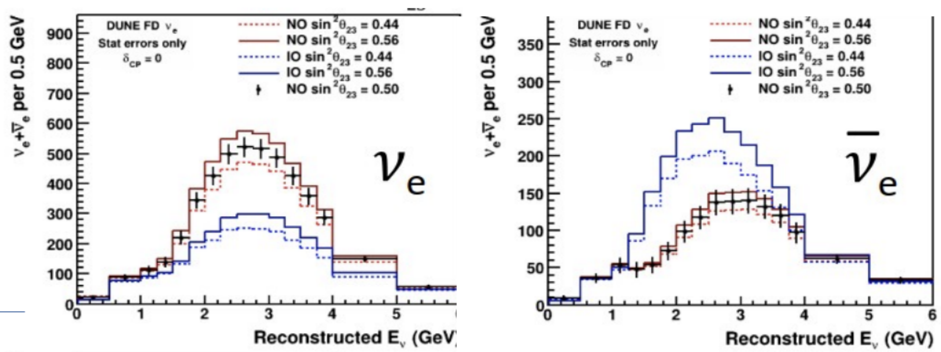


Oscillation Parameter Measurements

Neutrino oscillations (at LBL)

	Today	Future
θ_{12}, Δm^2_{12}	Few %	<1% (JUNO)
θ_{13}	~1 %	~1 %
$\lvert\Delta m^2_{32}\rvert$	~few - 1 %	~0.5 %
θ_{23}	~few %	<1 %
CPV (δ_{CP})	90 % CL	5σ (~5^o-20^o)
MO	1.2σ	5σ (atm&LBL&JUNO)

(Indirect sensitivity from combination of Δm^2_{ee} measured at reactors and $\Delta m^2_{\mu\mu}$ from LBL and JUNO)



Direct sensitivity at LBL with **rate of ν_e/$\bar{\nu}_e$** **(shape of** ν_e help breaking degeneracies)

'Charge' selected flux of

$\nu_\mu \rightarrow \nu_\mu$ ν_e

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ $\bar{\nu}_e$

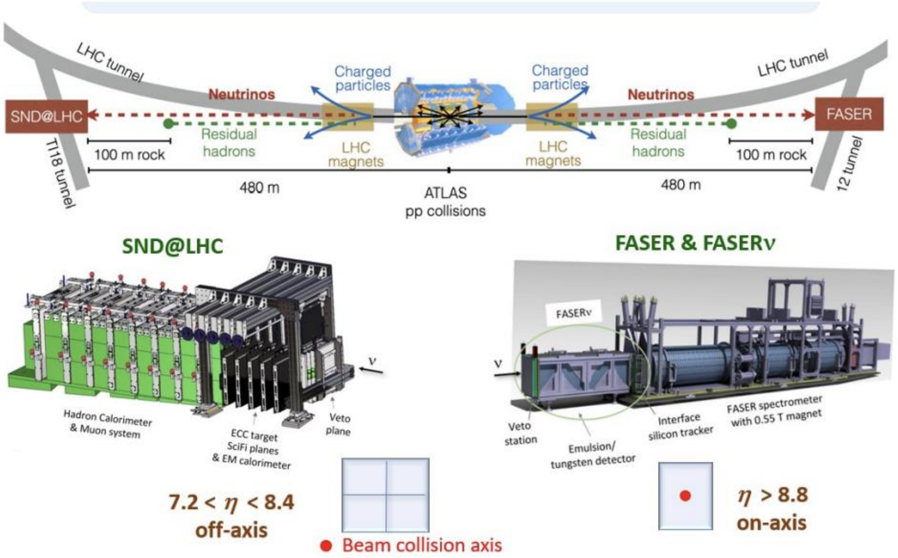
oscilllated samples at LBL far detectors

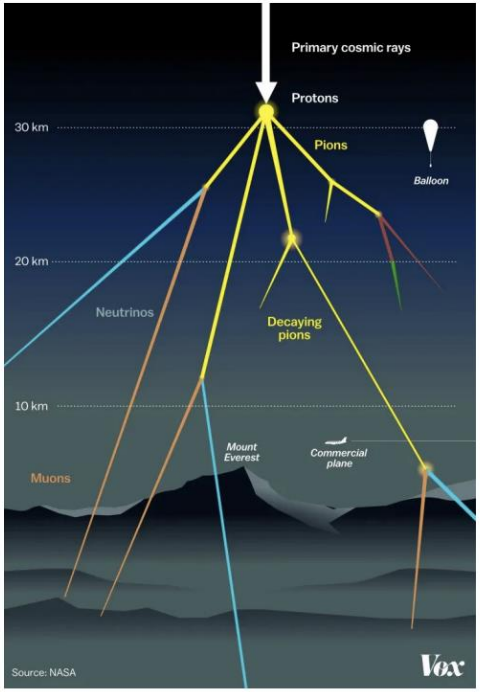
FPF & Cosmic Rays

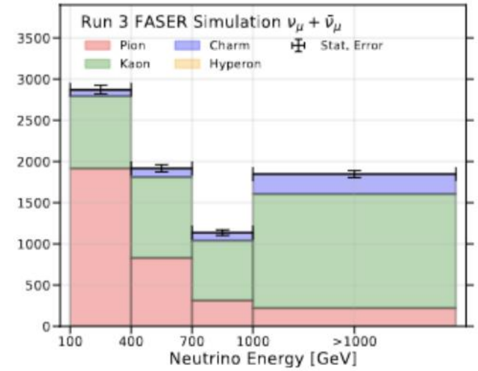
Atm flux modeling : fwd detectors at LHC

Need good control of very forward and high energy hadron production to model properly the atmospheric flux (eg, muon puzzle)

Can be measured at a new regime in LHC forward regions : FASER and SND





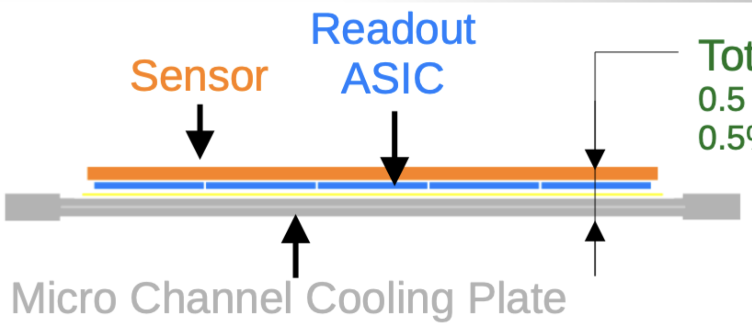


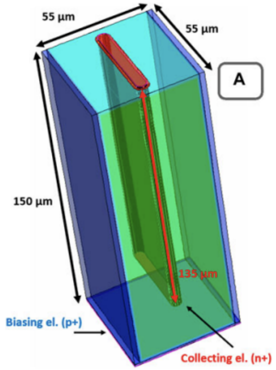
Neutrino Beam Tagging

Pixel detector made of

- sensor (time reso, radiation)
- ASIC (time reso, hit rate, radiat
- Cooling (>1.5W/cm²) system

with the lowest material budget





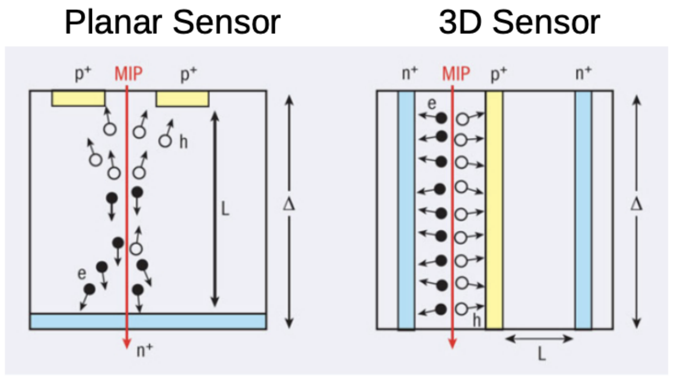
NA62: planar n-in-p sensor (200µm) readout with TDCPix ASIC (130nm CMOS)

► 130 ps per hit ► 2 MHz/mm² ► $4.5 \cdot 10^{14}$ n_{eq}/cm^2 ► 0.5%X_0

New technology being developed

- 3D trench sensors:
  ► **10ps hit time resolution** after large irradiation: **>10^{16} neq/cm² *** (IGNITE/TIMESPOT)
- Readout ASIC is being developed using **28nm CMOS** (IGNITE, PICOPIX)

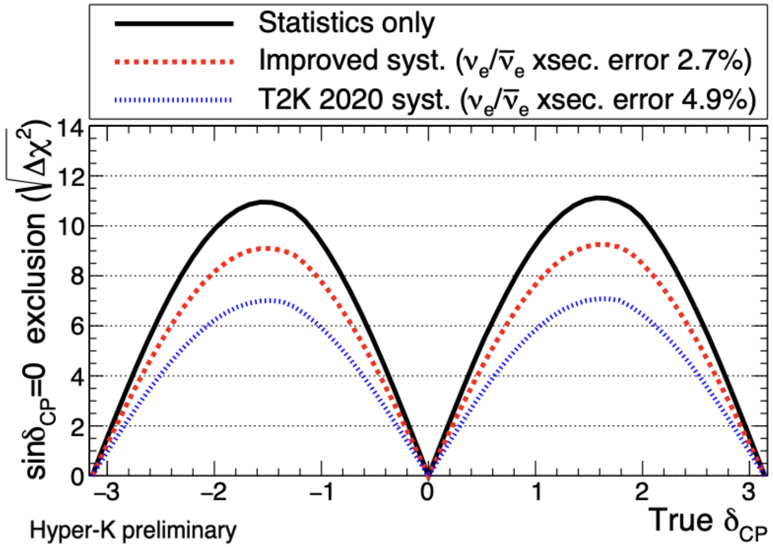
* Borgato et al. Frontiers in Physics, 2023, 11



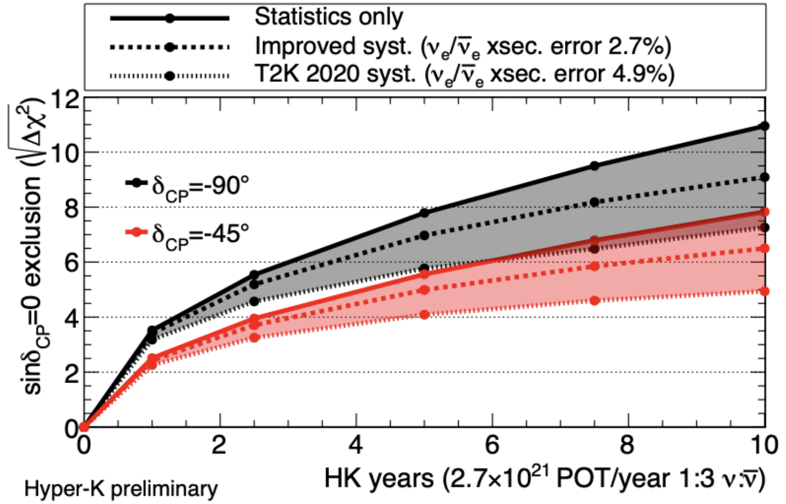
T2HK Measurements

Long-baseline ν oscillations

- Sensitive to the CP violation phase by measuring $P(\nu_\mu \to \nu_e)$ vs $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
- With known MO → 5σ sensitivity for 62% of true δCP values in 10 years
- If NO and $\delta_{CP}=-\pi/2$ → exclude CP conservation in 3-5 years depending on systematics



* True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 $\nu:\bar{\nu}$)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3} eV^2/c^4$



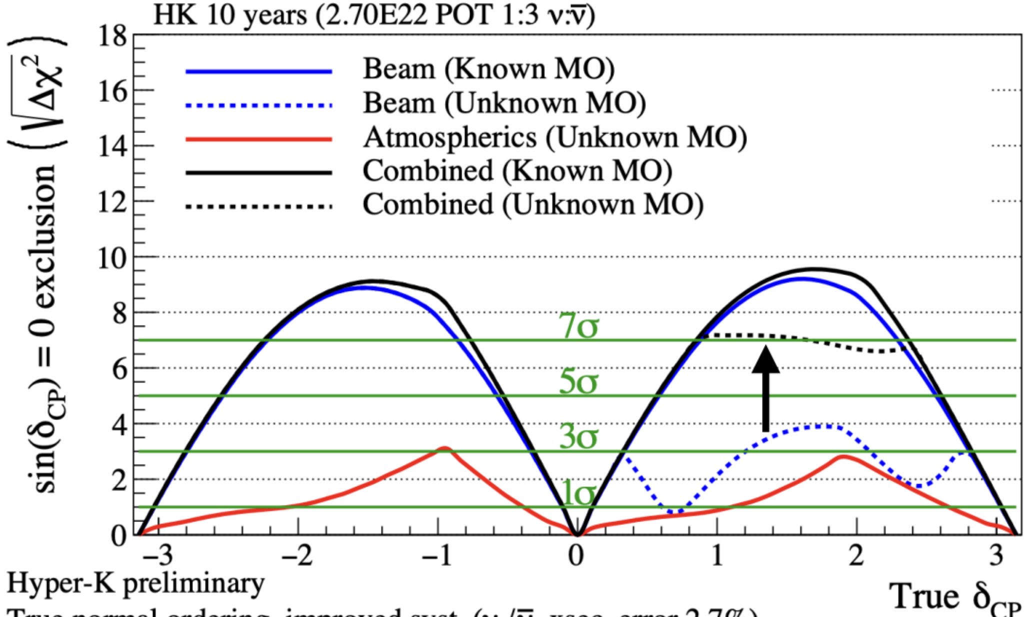
- Resolution to δ_{CP}= 20° if $\delta_{CP}=-\pi/2$, and 6° if $\delta_{CP}=0$
- With known MO:
  - ✓Precise measurements of Δm^2_{32} (0.35% error) and $\sin^2\theta_{23}$ (2.47% error)
  - ✓Can determine octant if true $\sin^2\theta_{23} < 0.45$ or true $\sin^2\theta_{23}>0.57$

T2HK Measurements

Oscillations w/ accelerator and atmospheric ν

- Atmospheric ν's allow to solve the degeneracy between δ_{CP}, MO and octant
- Ability to reject the CP conserving hypothesis independently from the true MO

True Normal Ordering



Hyper-K preliminary
True normal ordering, improved syst. ($\nu_e/\bar{\nu}_e$ xsec. error 2.7%)
$\sin^2(\theta_{13})=0.0218$ $\sin^2(\theta_{23})=0.528$ $|\Delta m^2_{32}|= 2.509 \times 10^{-3}$ eV^2/c^4

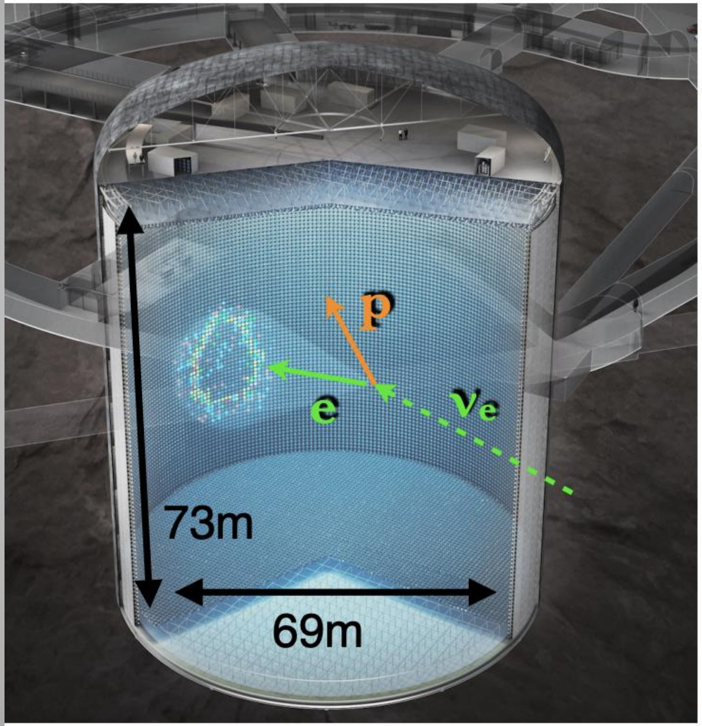
	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ	→ 3.8 σ
	0.60	4.9 σ	→ 6.2 σ
θ_{23} octant	0.45	2.2 σ	→ 6.2 σ
	0.55	1.6 σ	→ 3.6 σ

10 years with 1.3MW, normal mass ordering is assumed

4-6σ determination of MO and octant on the value of $\sin^2\theta_{23}$ after 10 years of data taking

T2HK

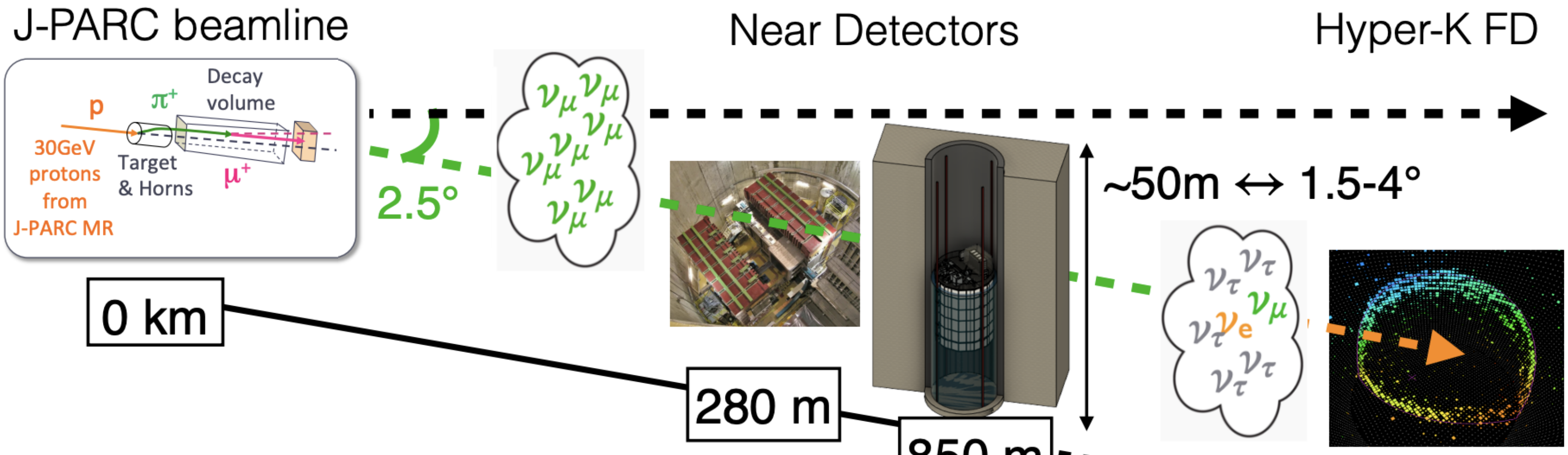
The water-Cherenkov Far Detector



- Building the largest ever human-made cavern
- 188.4 kton fiducial volume (~8.4 x Super-K)

T2HK

Long-baseline ν oscillations



It builds on the experience of T2K

$\nu_\mu \to \nu_\mu \quad \nu_\mu \to \nu_e$

$\bar{\nu}_\mu \to \bar{\nu}_\mu \quad \bar{\nu}_\mu \to \bar{\nu}_e$

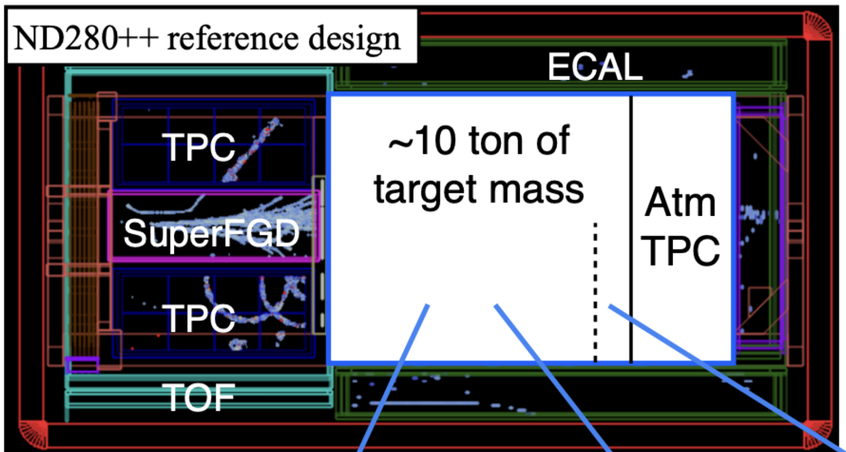
- Upgraded beamline → x2.5 higher from 0.5 (as of 2019) to 1.3 MW
- ND280 as magnetised near detector (plans to be taken over by Hyper-K)
- A new Intermediate Water Cherenkov Detector (IWCD)
- Water Cherenkov far detector: 188.4 kton fiducial volume (~8.4 x Super-K)

→ **Measure the CP violating phase from** $P(\nu_\mu \to \nu_e)$ **vs** $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

ND280++

ND280++ for the Hyper-K high-statistic phase

A possible final upgrade of ND280 for the high-statistics phase (after 2030)
→ improve sensitivity to non-maximal CP violation and atmospheric parameters

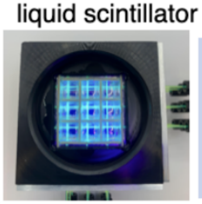


Developing the conceptual design of a new high-performance tracker:
large mass for $\sigma_{\nu_e/\bar{\nu}_e}$, ν-water,
low-energy protons, neutron energy

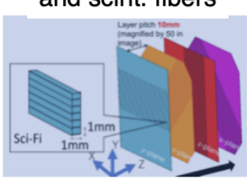
- ✓Replace old tracker (2010)
- ✓Several ongoing R&D:
  water, scintillator, atm/high-p TPC

Water-based tracker

3D water-based liquid scintillator

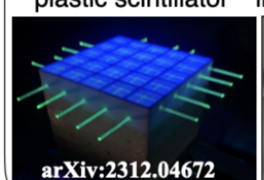


Inactive target and scint. fibers



Massive SuperFGD

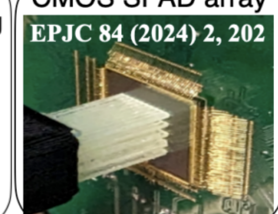
3D printing of plastic scintillator



Optimised inject. molding

XY SciFi target

CMOS SPAD array



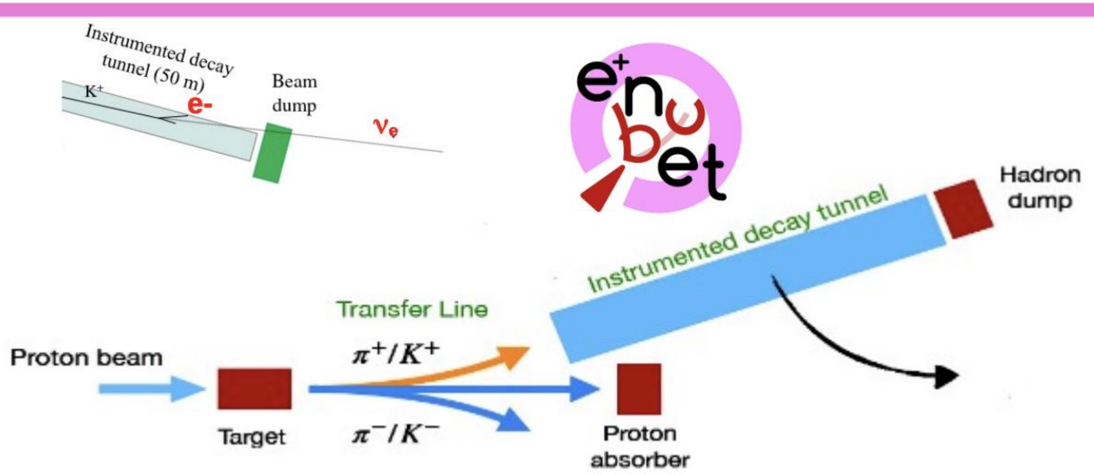
Many of us are involved in CERN DRD 1&4, 3DET R&D collaboration (hosted by CERN)

ND280++ is a great opportunity for new institutes to join a starting project

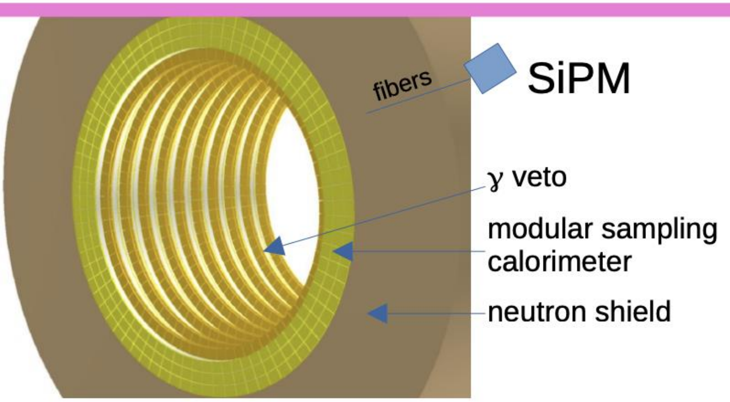
ENUBET: Monitored Beam

Monitored beam : R&D @ CERN

Measure the leptons in the decay tunnel ⇨ Need slow extraction (for a reasonable rate) → transfer line (instead of pulsed horns) + fast detectors (and radiation hard)



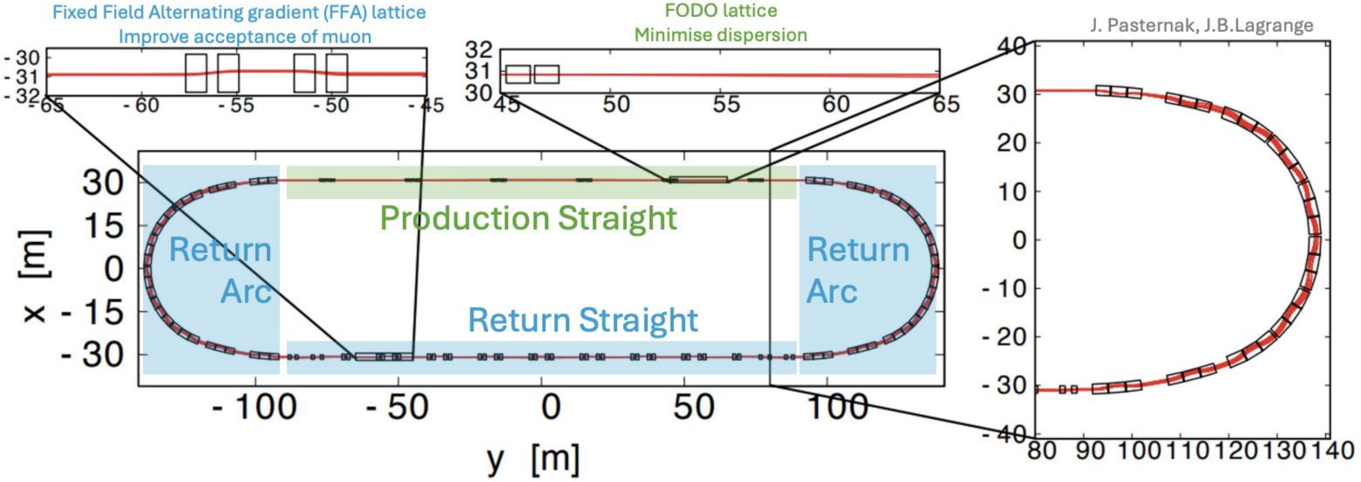
Preliminary studies : propagating hadro-production uncertainties to lepton observables → ν_μ and ν_e rate from 5 % to 1 %



Prototype succesfully tested on CERN T9 beamline

nuSTORM

ν from STORed Muons (nuSTORM)

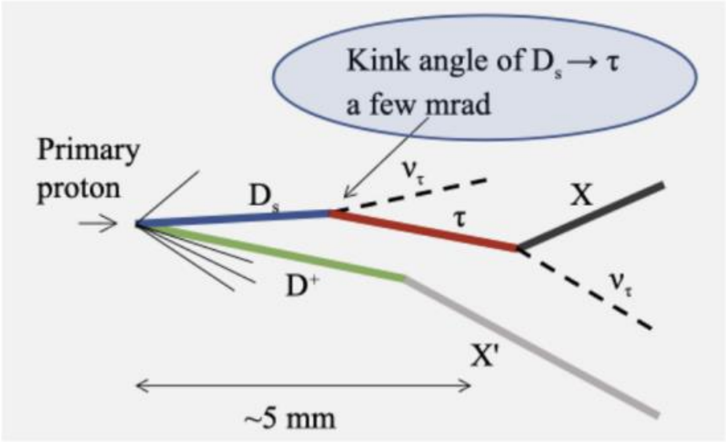


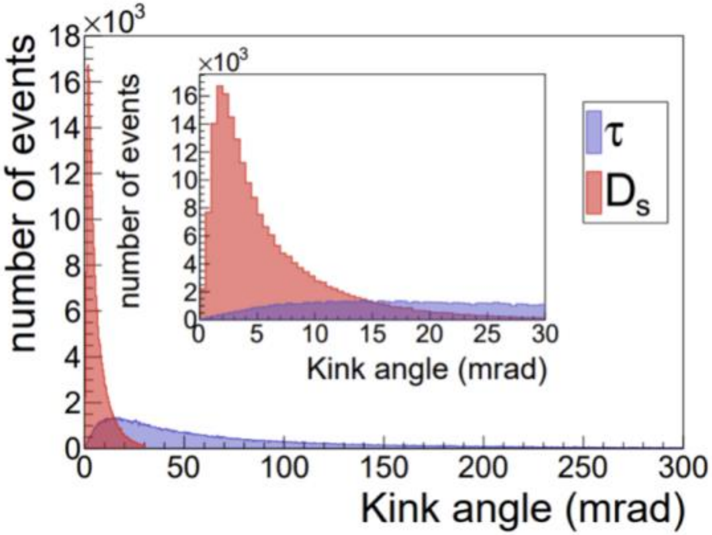
- **1st ν beam facility based on a stored muon beam**
- **Highest ever stored-muon beam power**
- ν flux deduced by μ beam monitoring

- Production Straight (example w/ π^+ injection)
  - ν_μ flux from $\pi^+ \rightarrow \mu^+\nu_\mu$ ("pion flash")
  - $\nu_e + \bar{\nu}_\mu$ flux from $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$
  - Maximise μ capture efficiency
- Arcs and Return Straight
  - μ momentum tunable between 1 and 6 GeV/c, spread ±16%

NA65

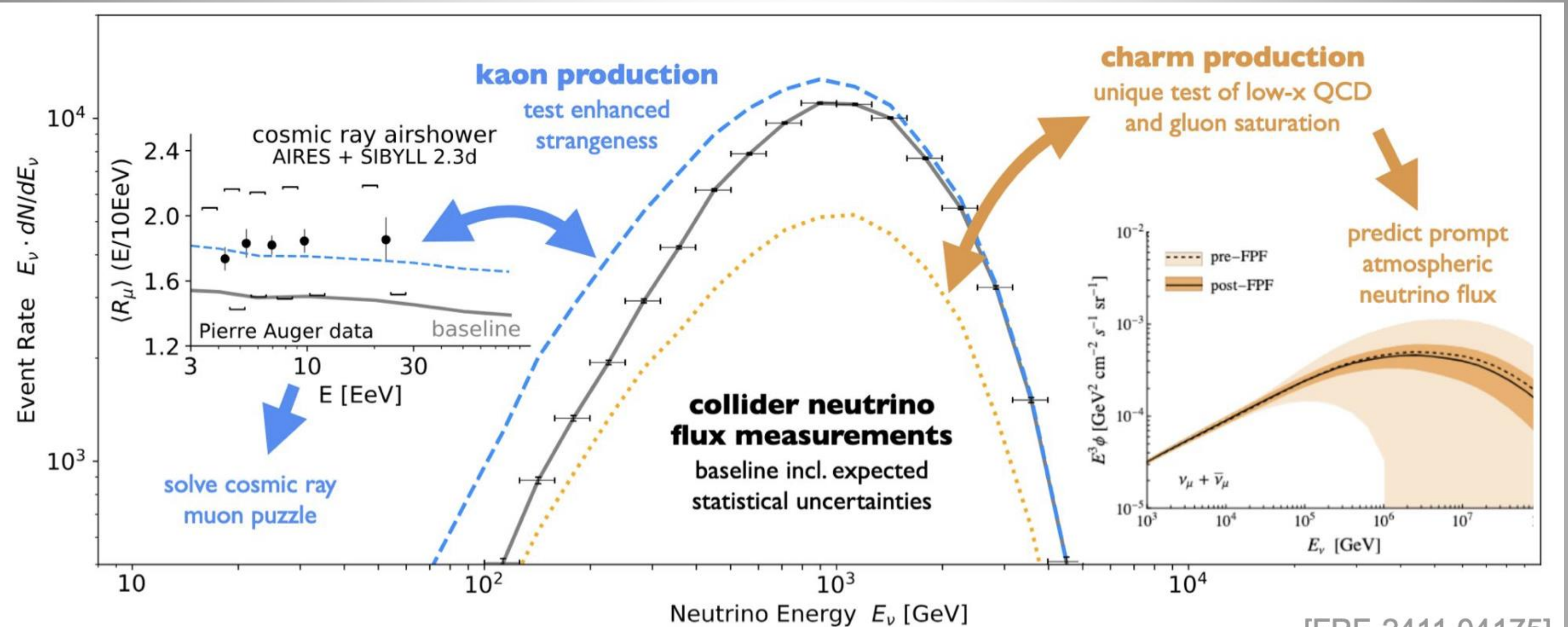
- The main source of tau neutrinos is decay of D_s mesons to tau neutrino and tau lepton.
- Detect double kink topology of $D_s \to \nu_\tau \tau \to X$ & partner charm decay topology within a few mm.
- Technical challenge to a few mrad kink angle of $D_s \to \nu_\tau \tau$ decays.





- Observing the decay topology of D_s into τ requires sub-micron spatial resolution and sub-mrad three-dimensional angular resolution.

FPF Physics



[FPF 2411.04175]

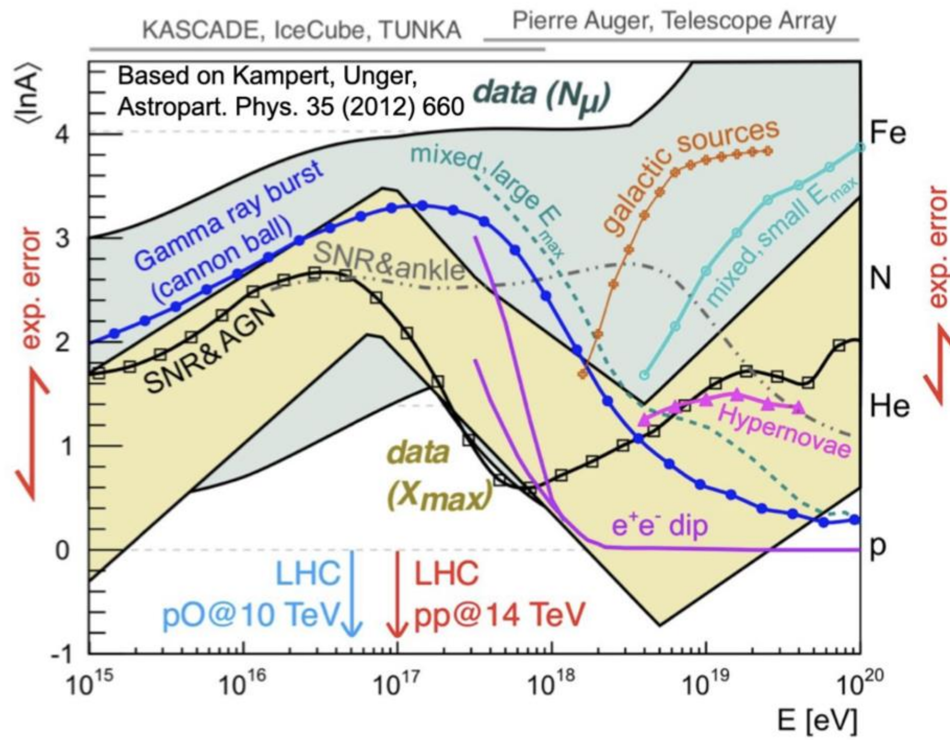
cosmic ray muon puzzle: observed 8σ excess of muons compared to predictions from hadronic interaction models

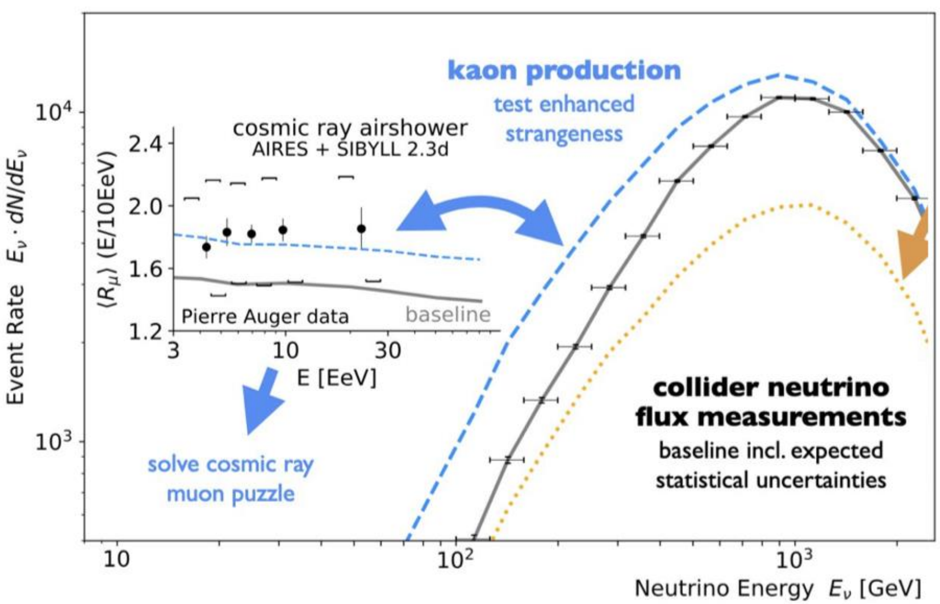
forward charm production at the LHC constraints on **prompt atmospheric neutrino flux** at IceCube

FPF Physics

cosmic ray muon puzzle: observed 8σ excess of muons compared to predictions from hadronic interaction models

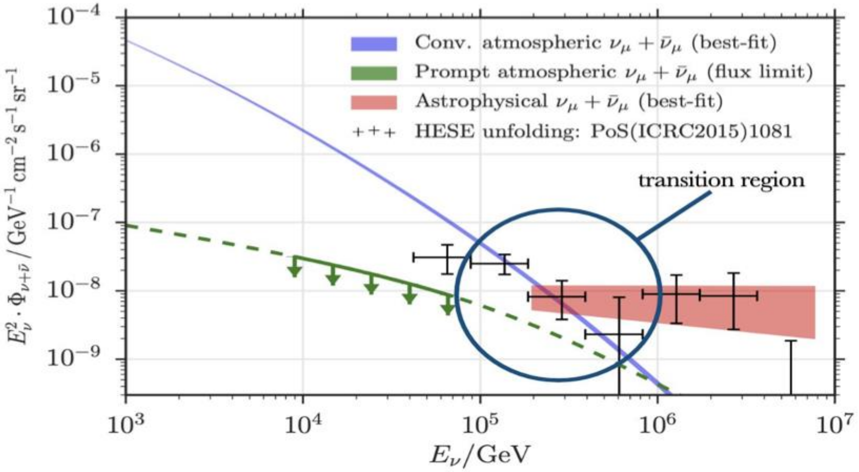
prevents extracting flux composition and origin of cosmic rays





strangeness enhancement: solves puzzle and can lead to large differences at LHC

FPF Physics

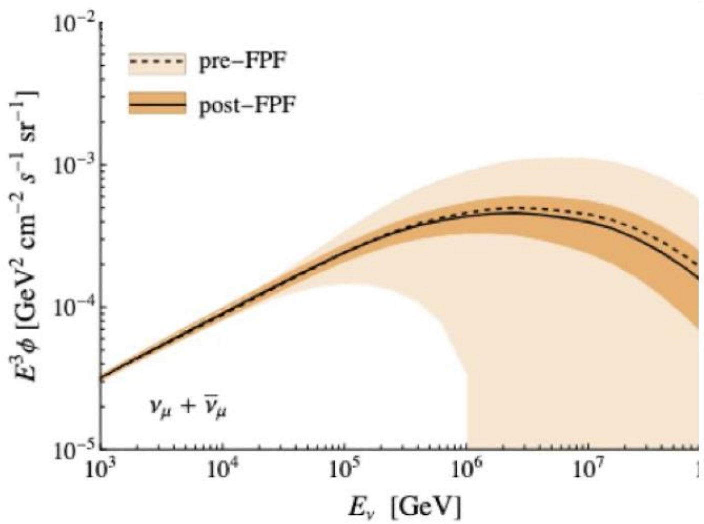


forward charm production at the LHC

↓

constraints on prompt atmospheric neutrino flux at IceCube

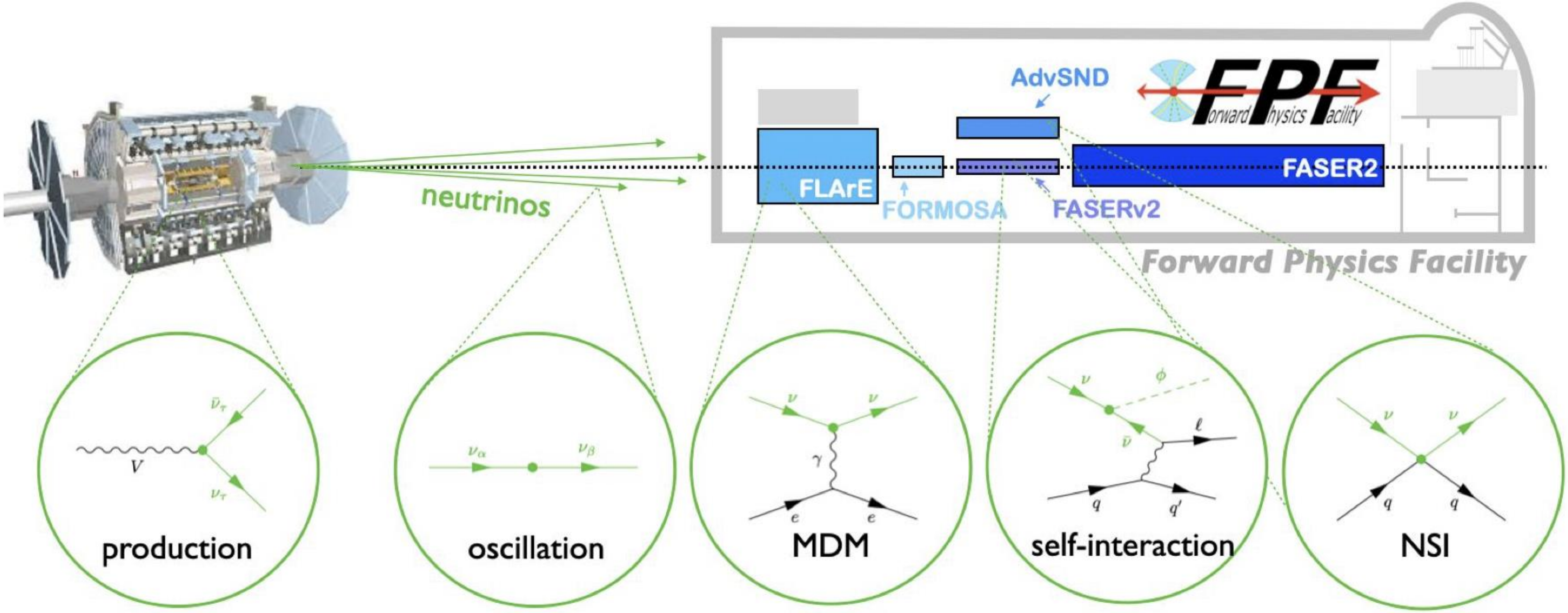
(currently very poorly constrained/understood)



FPF data will improve flux predictions!

[Reno, Jeong, FPF 2411.04175]

FPF Physics



[FK, 2005.03594]

[FASER, 1908.02310]

[Abraham, Abari, FK, Tsai, 2301.10254]

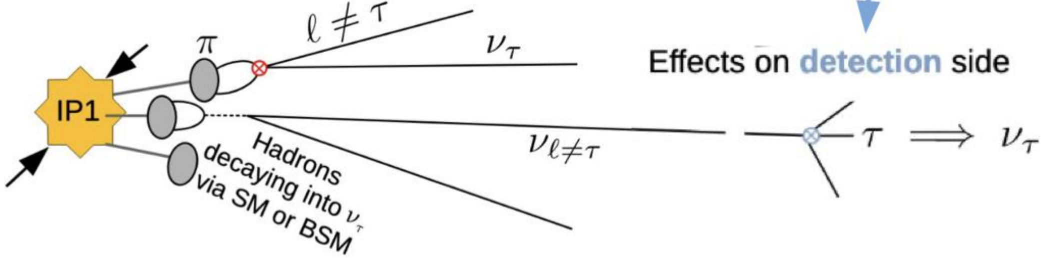
[Kelly, FK, Tuckler, Zhang, 2111.05868]

[Abraham, Ismail, FK, 2012.10500]

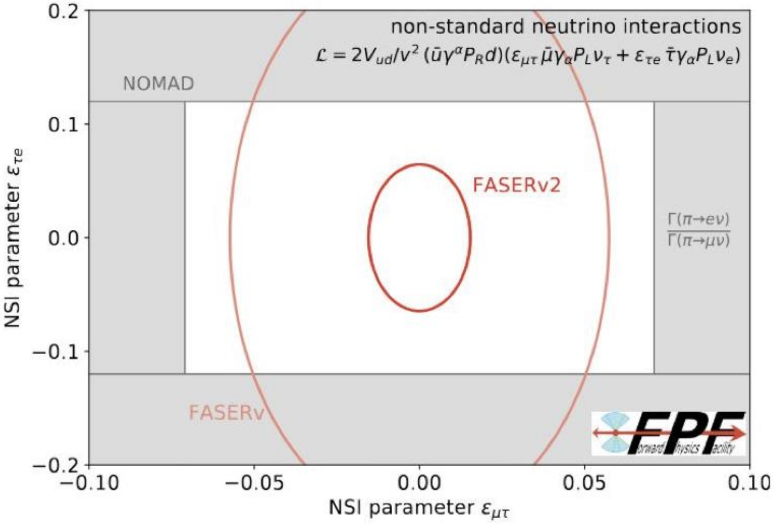
FPF Physics

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{2V_{ud}}{v^2} \times (\bar{u}\gamma^\kappa P_R d) \times \left[\epsilon_R^{\mu\tau}(\bar{\ell}_\mu \gamma_\kappa P_L \nu_\tau) + \epsilon_R^{\tau e}(\bar{\ell}_\tau \gamma_\kappa P_L \nu_e)\right]$$

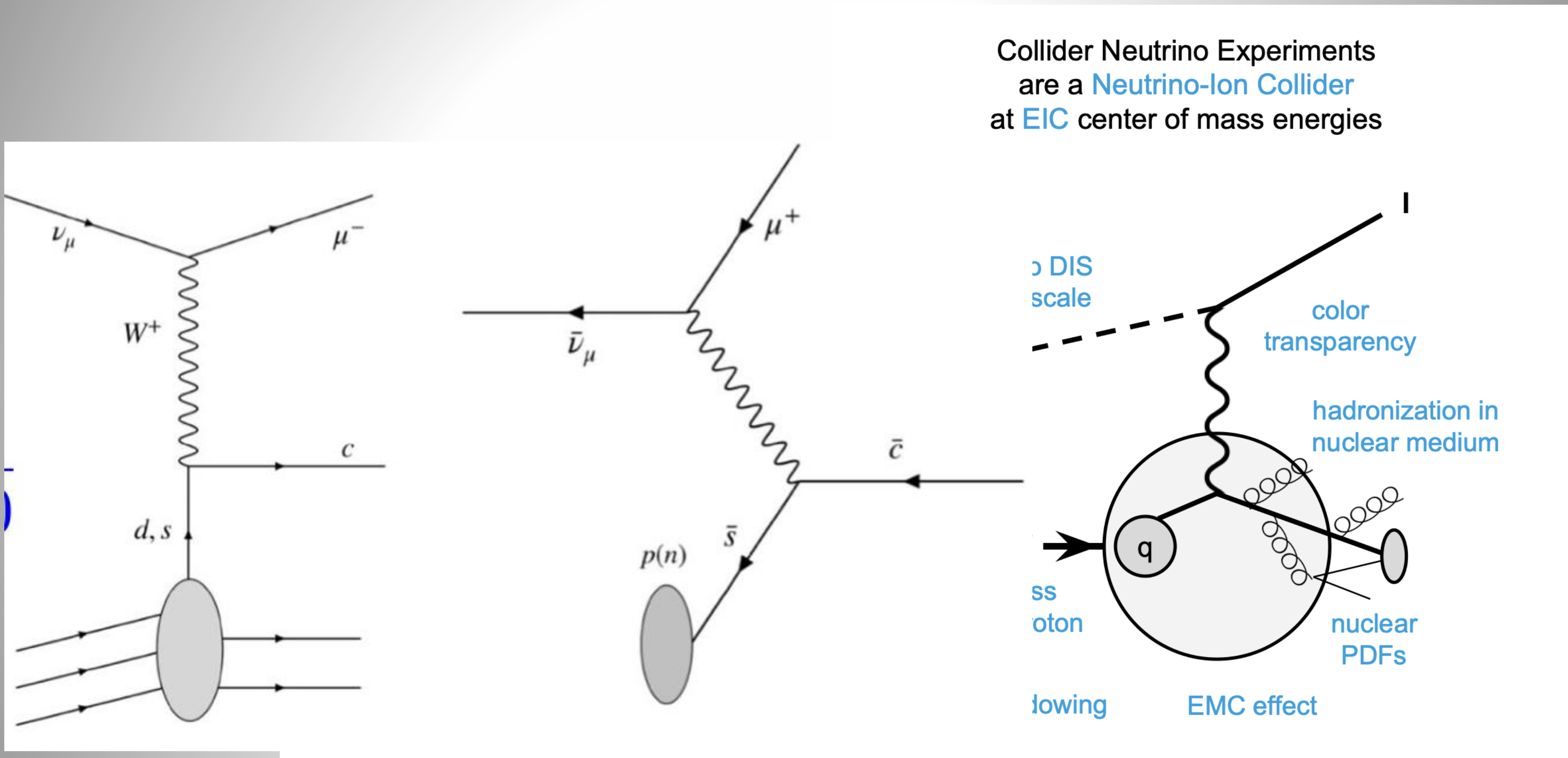
Non Standard Interactions associated can modify tau neutrino flux
[Falkowski et al, 2105.12136]



Can be probed at FPF!
[FK, Mäkelä, Trojanowski, 2309.10417]

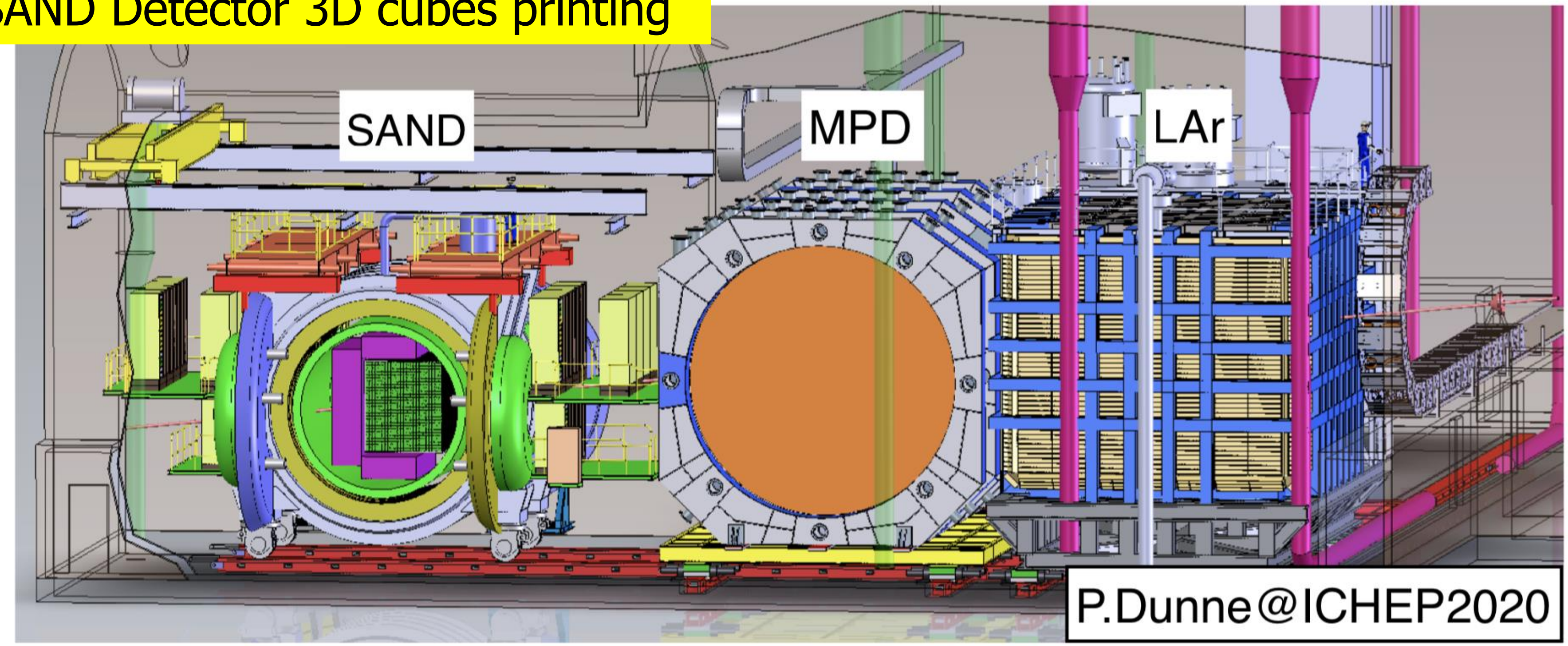


FPF Physics


Collider Neutrino Experiments
are a Neutrino-Ion Collider
at EIC center of mass energies
ν_μ
μ^-
W^+
c
d, s
μ^+
$\bar{\nu}_\mu$
$\bar{c}$
$\bar{s}$
$p(n)$
DIS
scale
color
transparency
hadronization in
nuclear medium
q
nuclear
PDFs
EMC effect

The DUNE Near Detector

SAND Detector 3D cubes printing

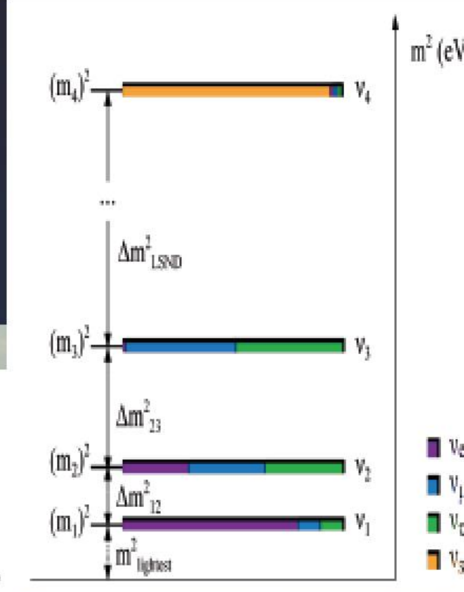


- Three main near detector complexes:
  - System for on-Axis Neutrino Detection (SAND)
  - HpTPC+ECAL (ND-GAR)
  - Liquid Argon (ND-LAr)
- Complementarity necessary to achieve:
  - Detection of ν interactions in argon nucleus, Low-momentum threshold for protons, Neutron detection, Beam monitor, ν flux estimation

Detector	Target (Fid. mass t)	# ν_μ CC ($X10^6$)
LAr	Ar (50)	80
HPgTPC	Ar (1)	1.5
SAND	CH (8)	12

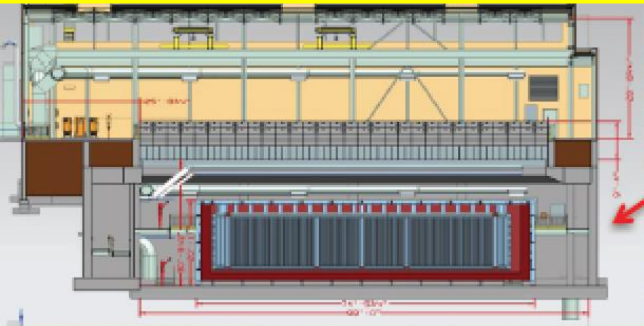
SBL @ FNAL

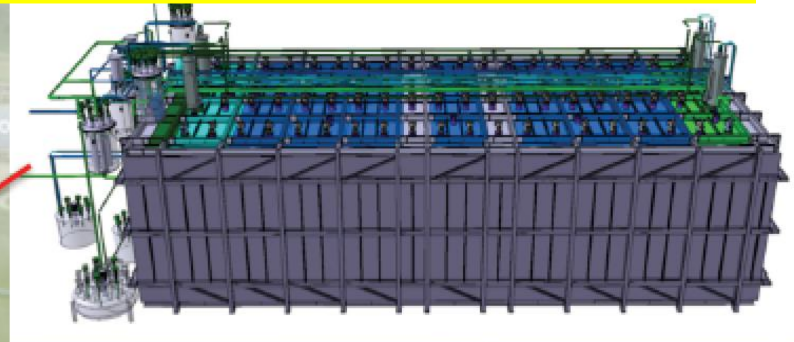
A Multi-detector program will address the unexplained anomalies which together could be hinting at new physics (steriles?)

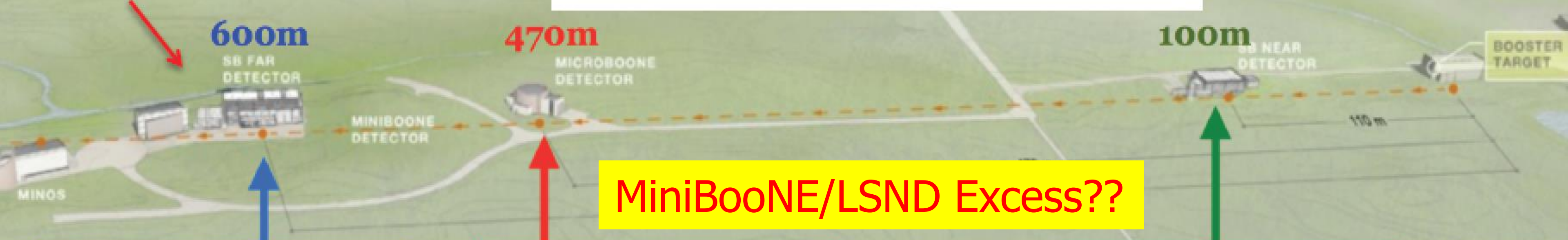


Installation has been delayed till end 2018

Filling and commissioning to starting 2019. Data 2nd part of 2019







MiniBooNE/LSND Excess??

ICARUS T600
476t Active Mass

MicroBooNE
89t Active Mass

SBND
112t Active Mass