Neutrinos at CERN

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- Introduction: TeV neutrinos at CERN from the LHC
- Dedicated experiments since 2022: FASER(ν) and SND@LHC
  - Results on neutrino detection/scattering
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  - Upgrades – short and longer term plans
- The Forward Physics Facility proposal/ Neutrinos in lake Geneva..
- More ongoing/planned neutrino-related activities @CERN
- Summary and outlook

Workshop on Neutrinos@CERN

23–24 Jan 2025
CERN
Europe/Zurich timezone

https://indico.cern.ch/event/1460367/

Neutrinos at the Large Hadron Collider

- Initial studies on **neutrino detection at the LHC** date back to the 80s.
  CERN-1984-010-V-2.571; Nucl. Phys. B405, 80; LPNHE-93-03
  - Back then, seen as an opportunity to discover the ν_τ.

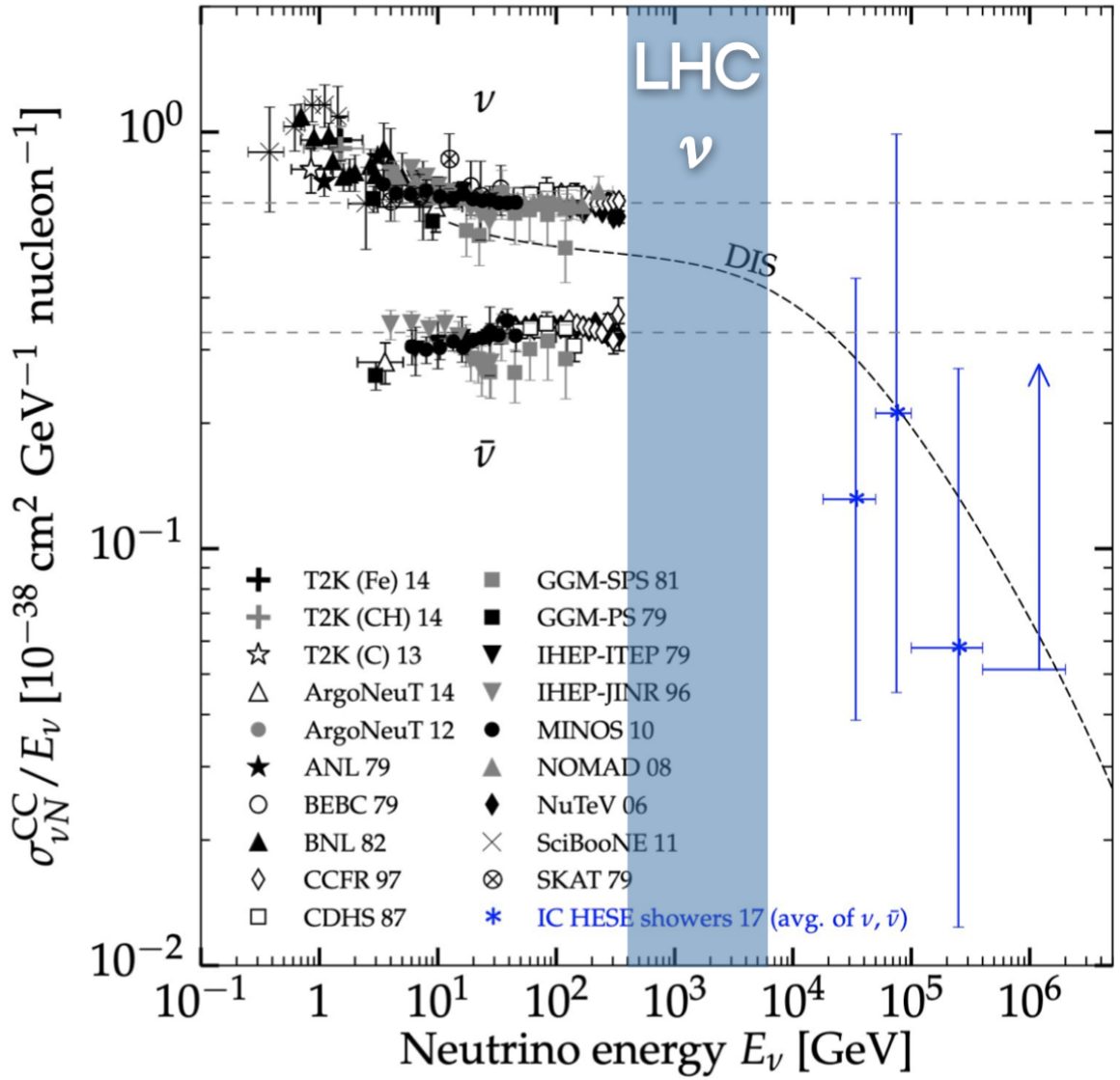
- **Large flux** of neutrinos in the forward region.
- Very **high neutrino energy** ($\sigma_\nu \propto E_\nu$).

⇒ A small-scale LHC experiment can observe neutrinos of all **three types**.

  - Highest energy human-made neutrinos!

- Two neutrino experiments in operation at the ATLAS interaction point since June 2022:
  SND@LHC and FASERν

PRL 122 041101 (2019)



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 $\overline{\nu}_\tau$.

QCD

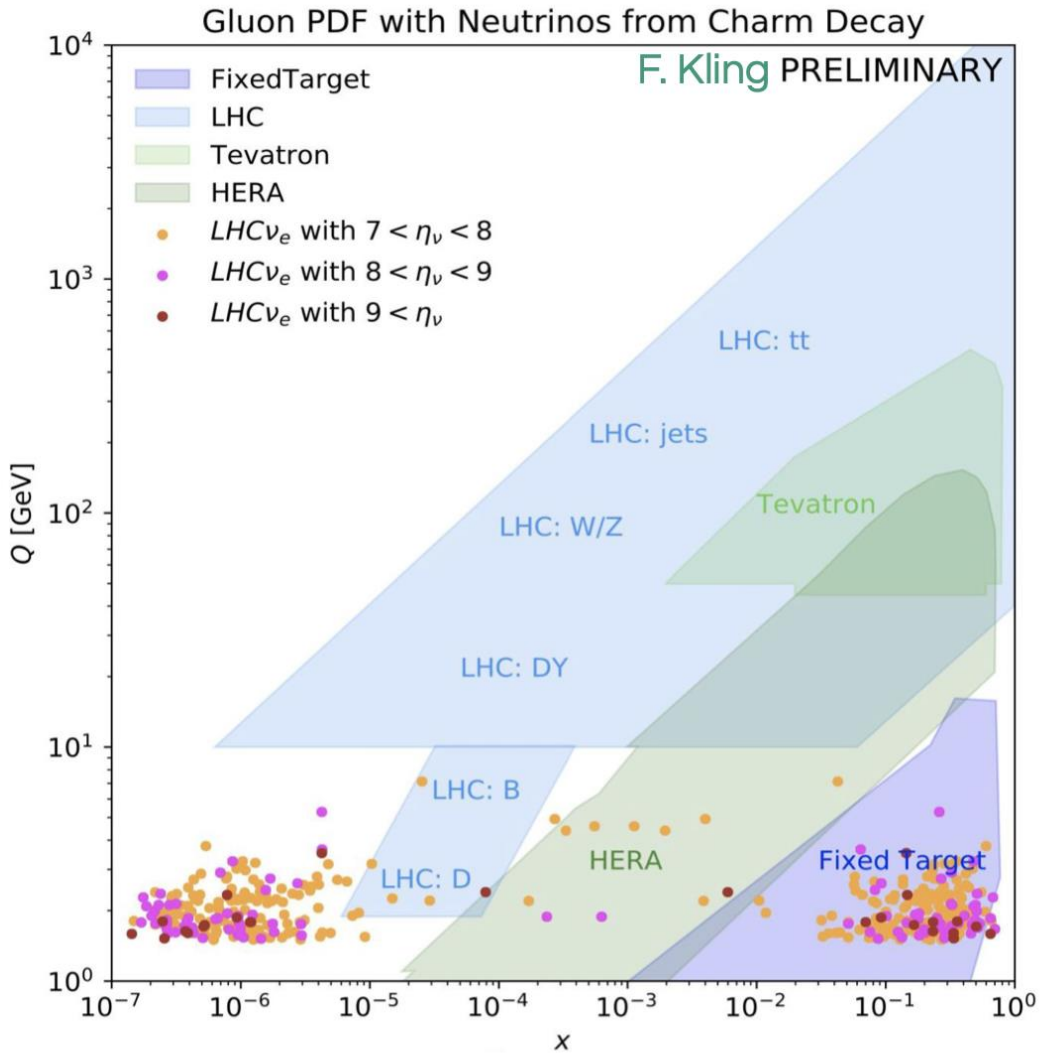
- Decays of **charm** hadrons contribute significantly to the neutrino flux.
  ⇒ Measure **forward charm production** with neutrinos.
  ⇒ Constrain **gluon PDF** at very **small x**.

Flavour

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

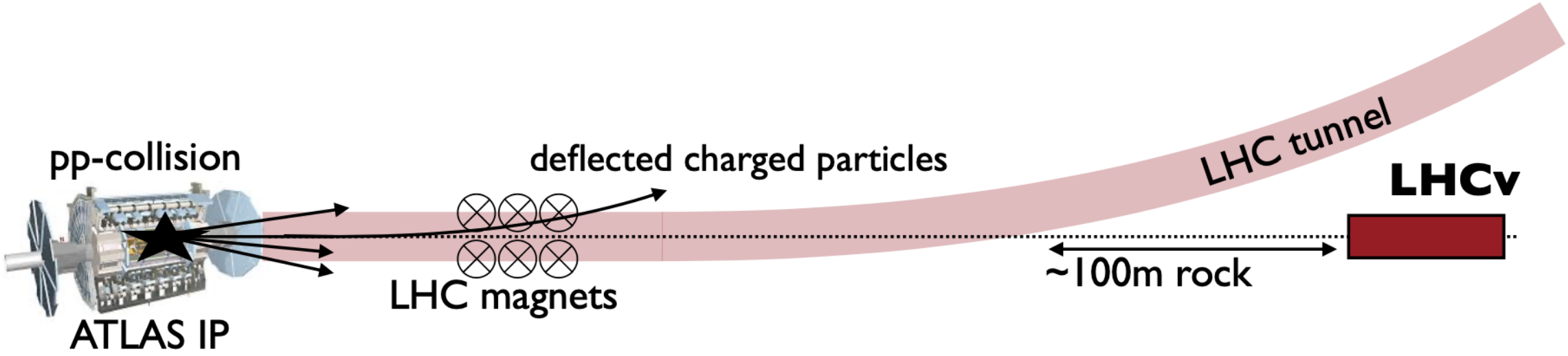
Beyond the Standard Model

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



The results will have implications for astroparticle physics, FCC-pp cross sections…

Neutrino Detection at the LHC



neutrino production

neutrino propagation

neutrino interactions

Forward Particle Production

LHC as Short Baseline Neutrino Experiment

TeV-energy Neutrino Interaction

~few times 10^{17} pions, 10^{16} η mesons, 10^{15} D mesons ... per year.

High intensity neutrino 'beam'
High energy neutrinos

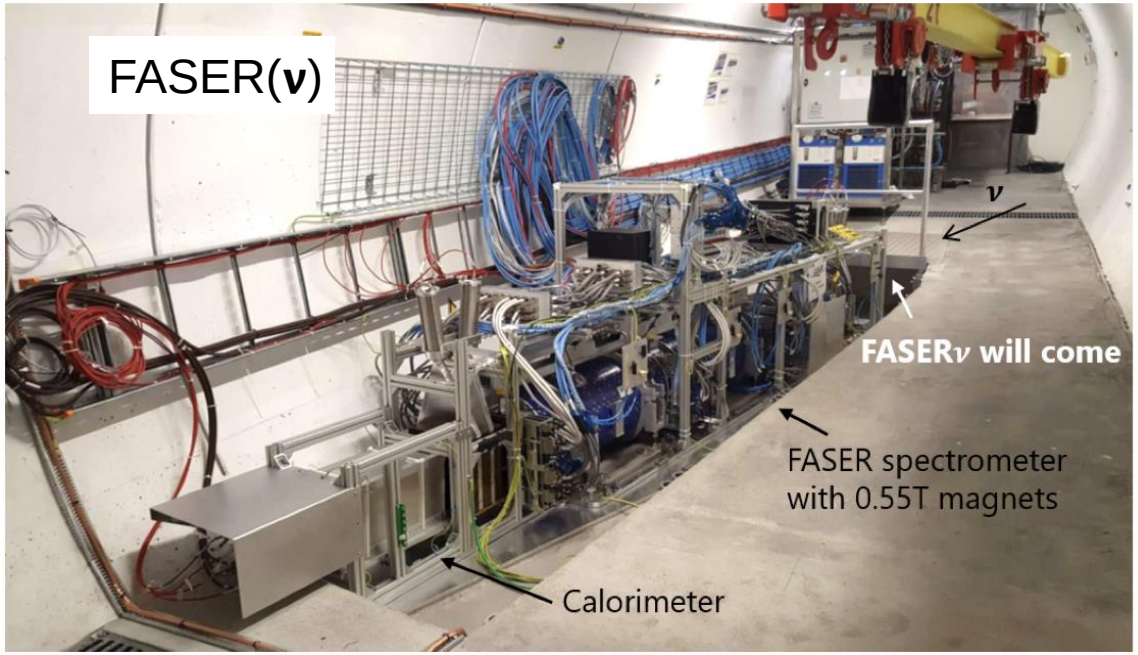
Neutrino Detectors at the LHC

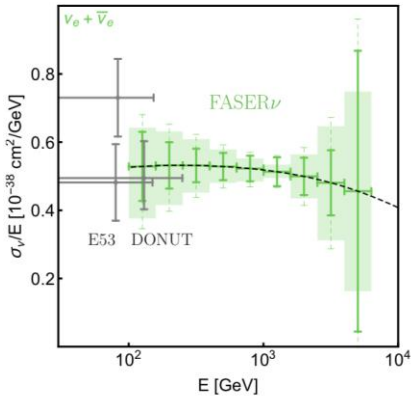
SND@LHC: approved March ‘21

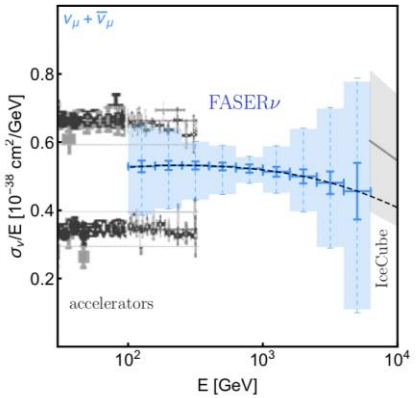
SND= Scattering and Neutrino Detector

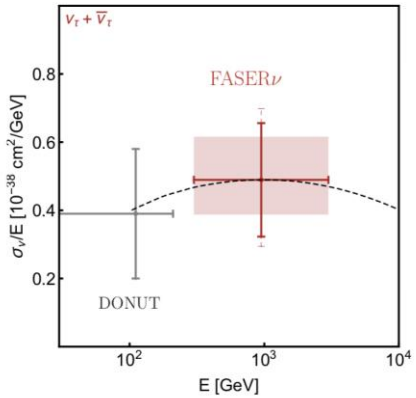
FASER(ν): approved March ‘19

FASER= ForwArd Search ExpeRiment









Run 3:
expect a few to 10K muon-**ν** events

The Dawn of Collider Neutrino Physics

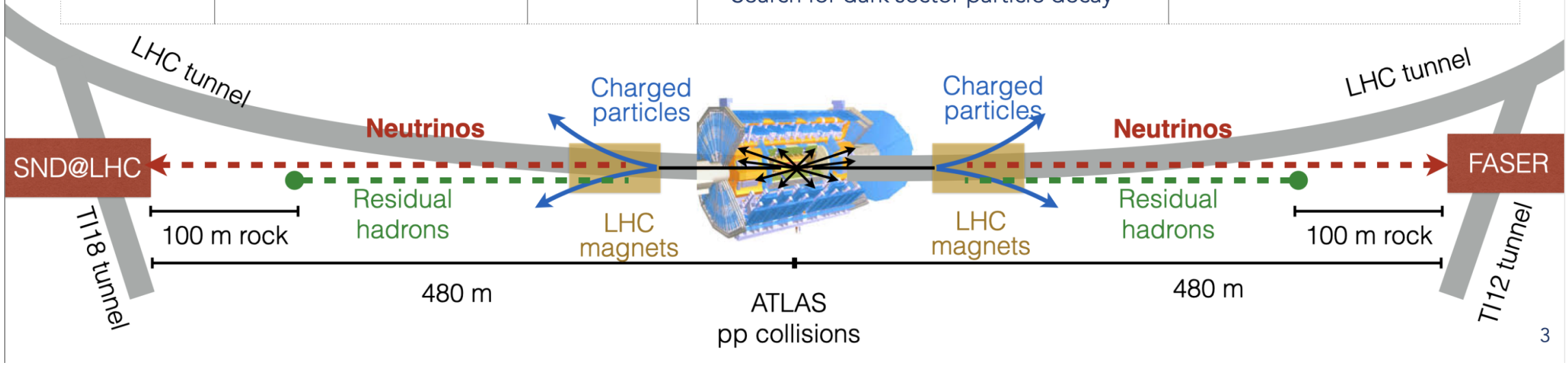
Elizabeth Worcester
Brookhaven National Laboratory, Upton, New York, US

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.

Neutrino Detectors at the LHC

	Acceptance	Target	Physics	Detector
SND@LHC	Off-Axis: $7.2 < \eta < 8.4$ 	800 kg of tungsten	• Detect & identify all neutrino flavours • Probe QCD with neutrinos from charm • Search for dark sector particle scattering	• Emulsion vertex detector • ECAL & HCAL
FASER	On-Axis: $\eta > 8.8$ 	1100 kg of tungsten	• Detect & identify all neutrino flavours • High energy & statistics for neutrinos • Probe QCD with neutrinos from charm • Search for dark sector particle decay	• Emulsion vertex detector • Spectrometer & ECAL



Experiment	Quantity	ν_e	ν_μ	ν_τ
FASER	N_{int}	2331^{+1227}_{-544}	12014^{+1145}_{-1636}	46^{+77}_{-21}
	average energy	785 GeV	716 GeV	849 GeV
SND@LHC	N_{int}	307^{+307}_{-116}	1694^{+297}_{-549}	15^{+26}_{-7}
	average energy	442 GeV	357 GeV	596 GeV

Prospects for Run 3
EPOS-LHC-POWHEG

2501.10078

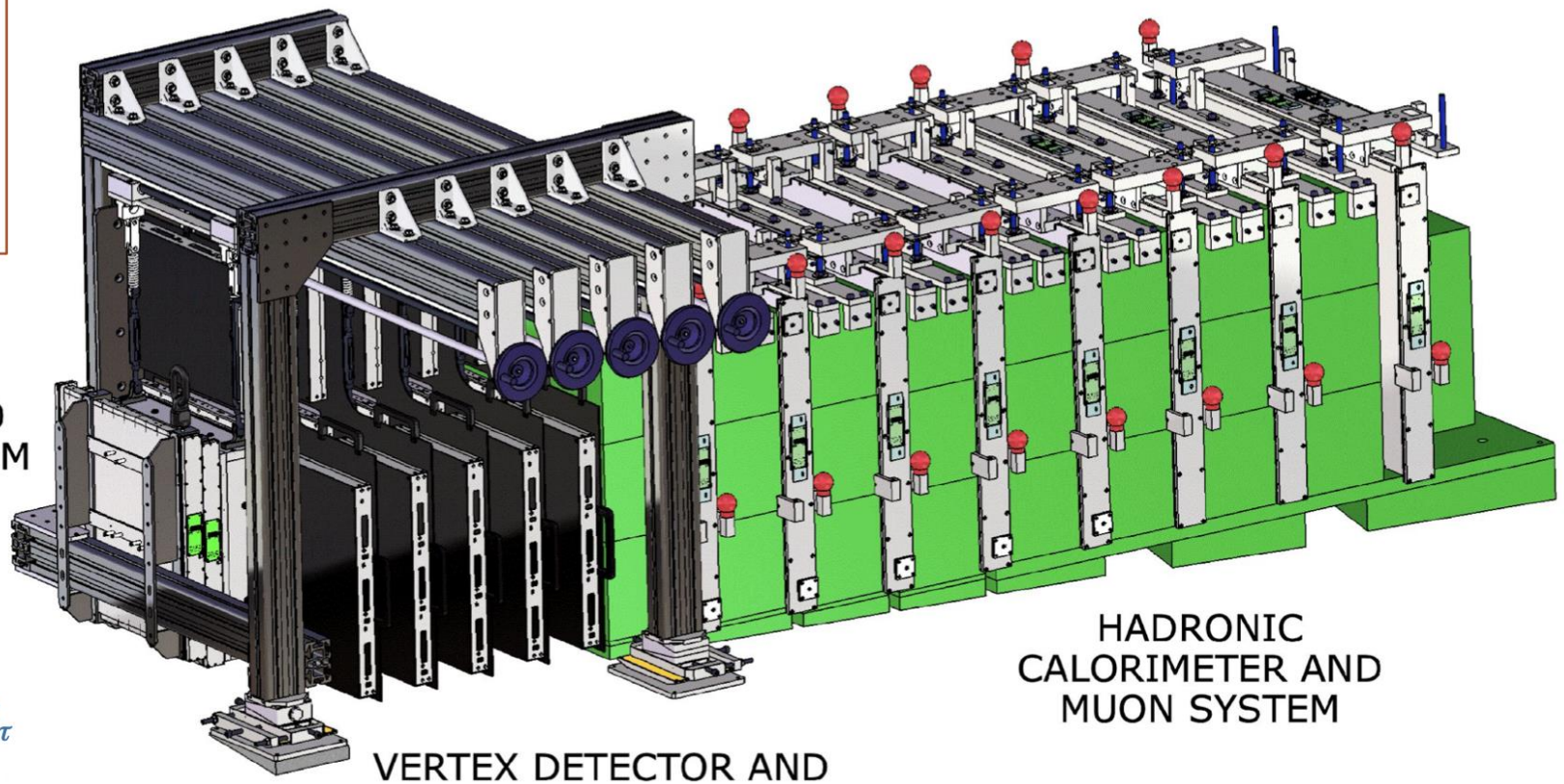
Scattering and Neutrino Detector @ the LHC

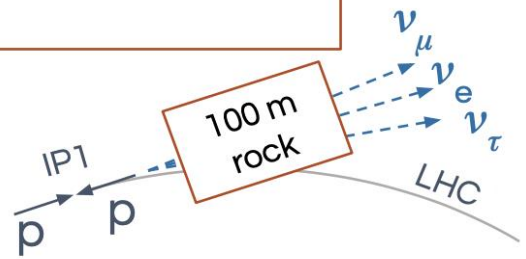
Veto system
Two 1 cm thick scintillator planes.

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}

Cross-sectional area: 40 x 40 cm^2
Length: 2.6 m
Off-axis: $7.2 < \eta < 8.4$





arXiv:2210.02784

The FASER(ν) Detector

Decay Volume & Tracking Spectrometer

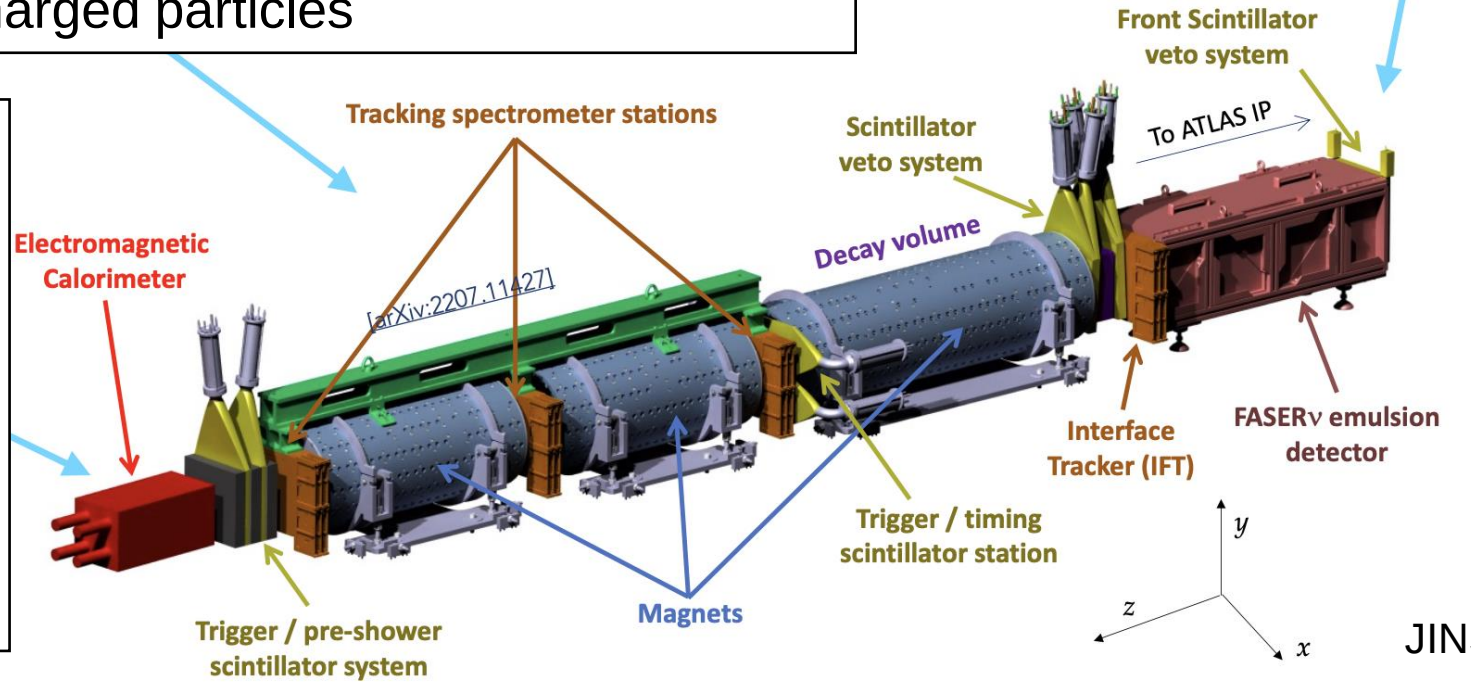
- Dipole magnets separate collimated opposiite charged particles and measure the charge and momentum of the μ from ν interactions
- Silicon strip trackers to measure position, charge & momentum of the charged particles

Faser ν Emulsion Detector

- Emulsion cloud chambers with tungsten for ν identification via precise vertexing
- IFT tracking station for matching of emulsion tracks with electronic detector information

ECAL

- Plastic scintillator interleaved with lead
- Measures the total electromagnetic energy



Scintillators

- Scintillator counters for veto, trigger and timing

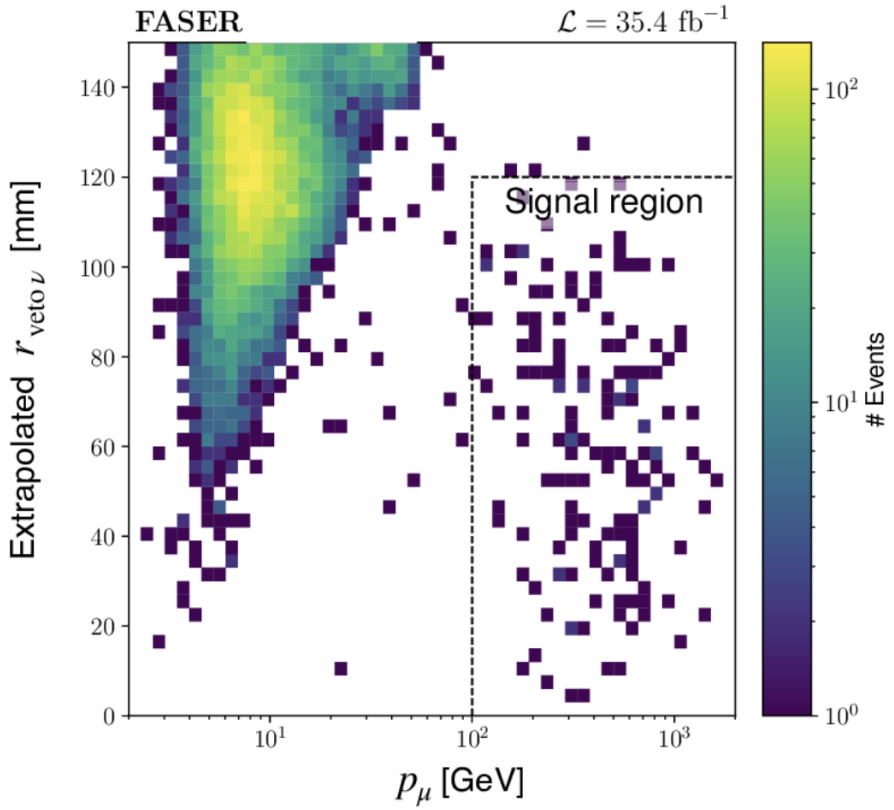
JINST 19 P05066 (2024)

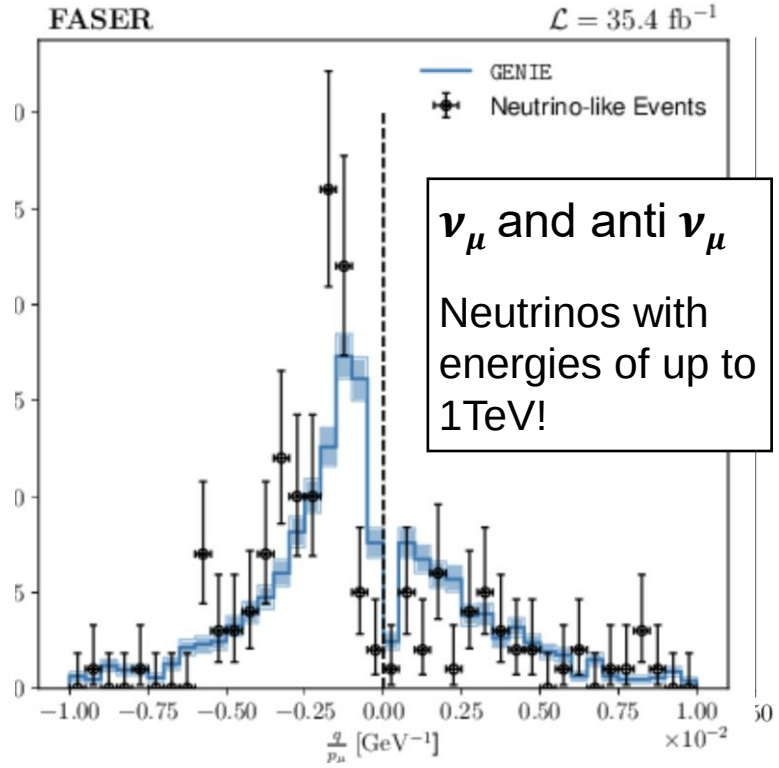
First Direct Observation of Collider Neutrinos

- Using of the electronic detector of FASER only & 35.4 fb^{-1}
- Select events with muons produced in the neutrino target
- Veto incoming charged particles. 2022 data

$$n_\nu = 153^{+12}_{-13}(\text{stat})\,^{+2}_{-2}(\text{bkg}) = 153^{+12}_{-13}(\text{tot})$$

16σ significance





ν_μ and anti ν_μ

Neutrinos with energies of up to 1TeV!

- q: assigned track charge

PHYSICAL REVIEW LETTERS 131, 031801 (2023)

Editors' Suggestion | Featured in Physics

First Direct Observation of Collider Neutrinos with FASER at the LHC

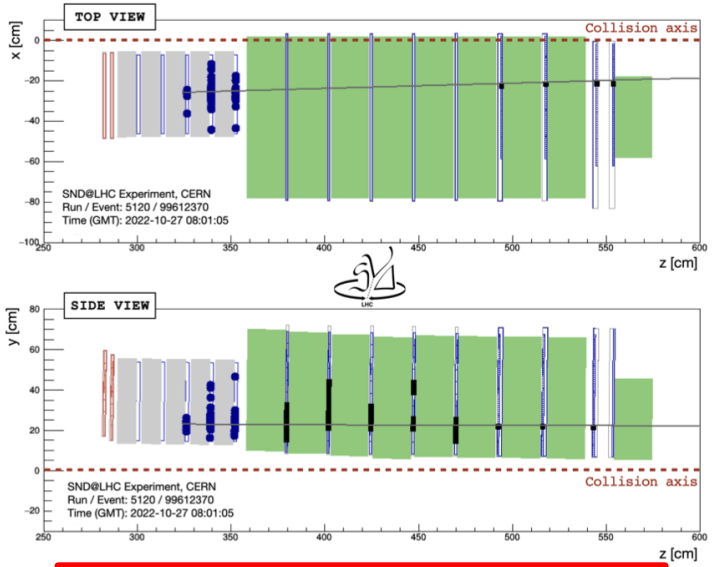
Editors' Suggestion

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

SND@LHC with 36.8 fb^{-1}



- 8 events observed events
- 8.6×10^{-2} background
  $\rightarrow$ 6.8 σ significance

SND@LHC Updated Muon Neutrino Results

New this year

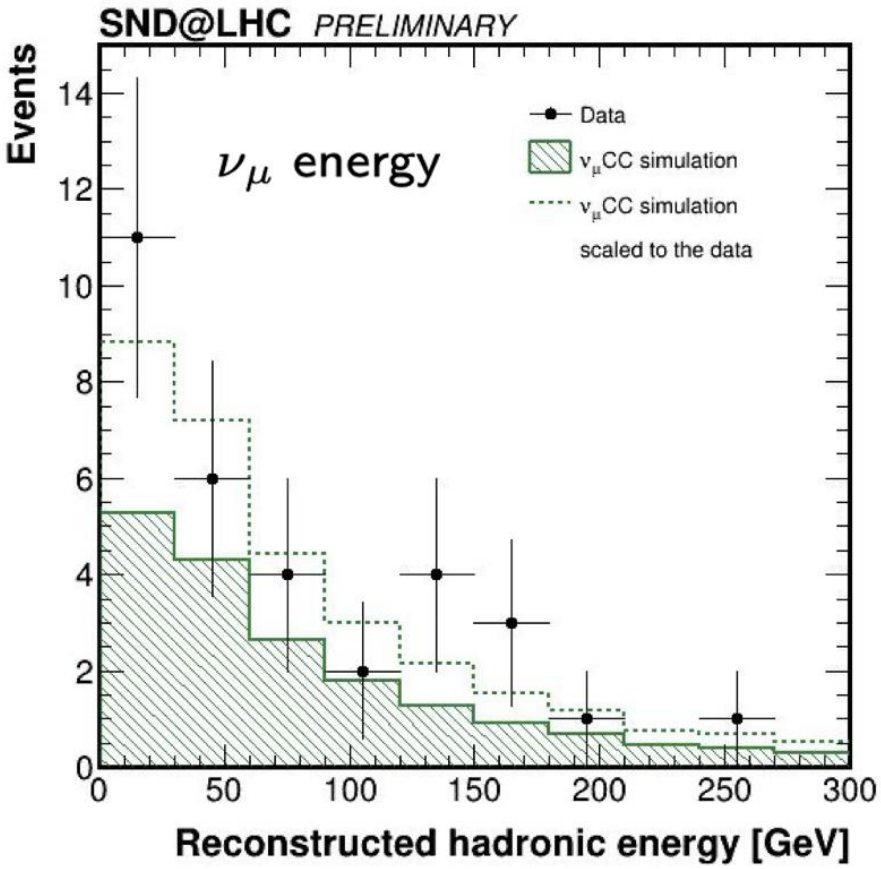
Updated analysis with 2023 data and extended fiducial volume.

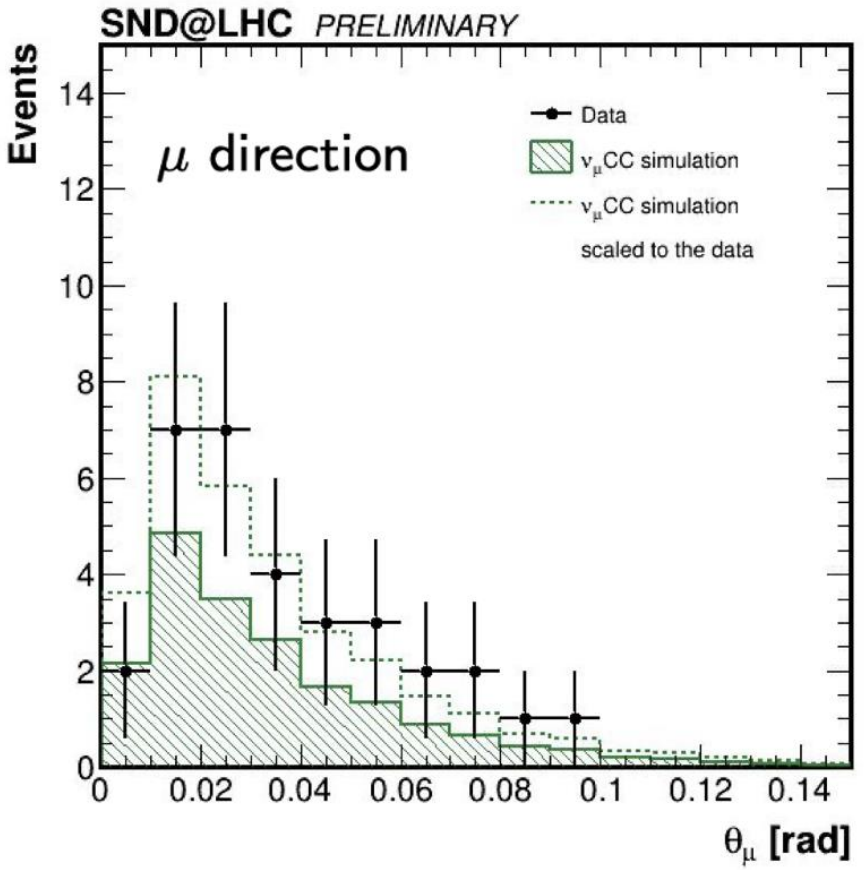
Number of events expected in 68.6 fb^{-1}

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

2022+2023 data

Moriond QCD '24





Kinematics of muon neutrino candidates in agreement with signal prediction

Number of events observed: 32

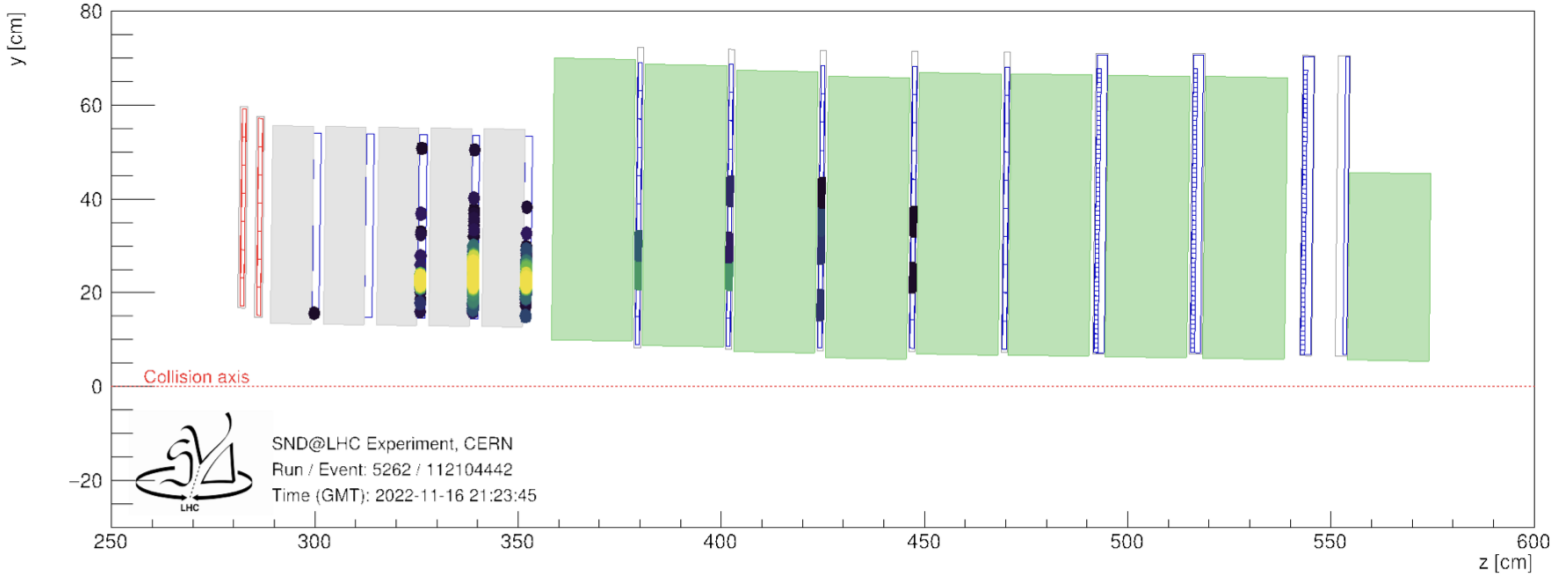
12σ significance

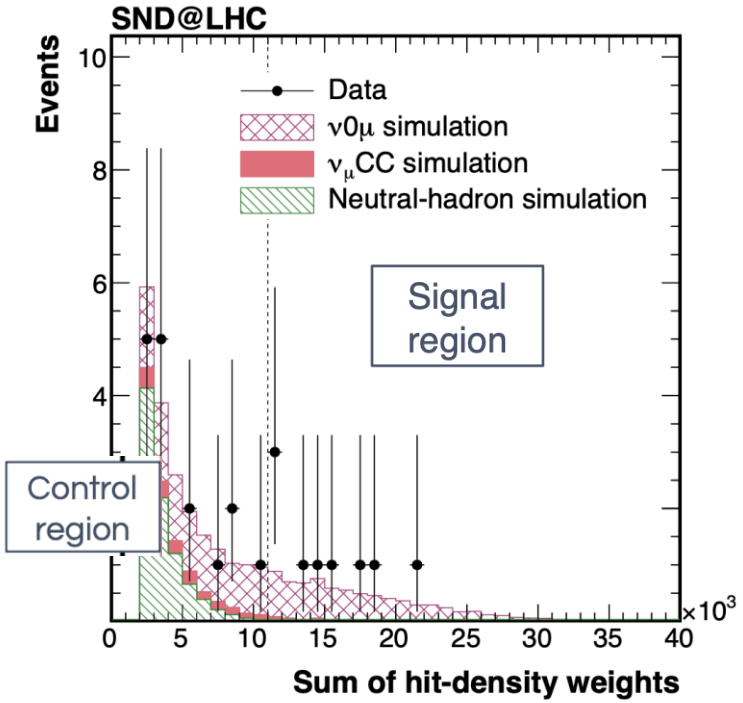
Observation of 0μ Events in SND@LHC

ν_e CC and ν_τ CC (0μ) + Neutral Current events

- Data sample of 68.6 fb^{-1}, select neutrino candidate vertices with no outgoing muon but significant EM and HAD activity (→ large "sum of hit-density weights")
- Background in signal region: 0.3 ν_μ CC events, 0.01 neutral hadrons events
- 9 events $\nu 0\mu$ observed (7.2 expected) -> significance = 6.4σ
- Signal region is dominantly ν_e CC events -> significance = 3.7σ for ν_e CC

2411.18787



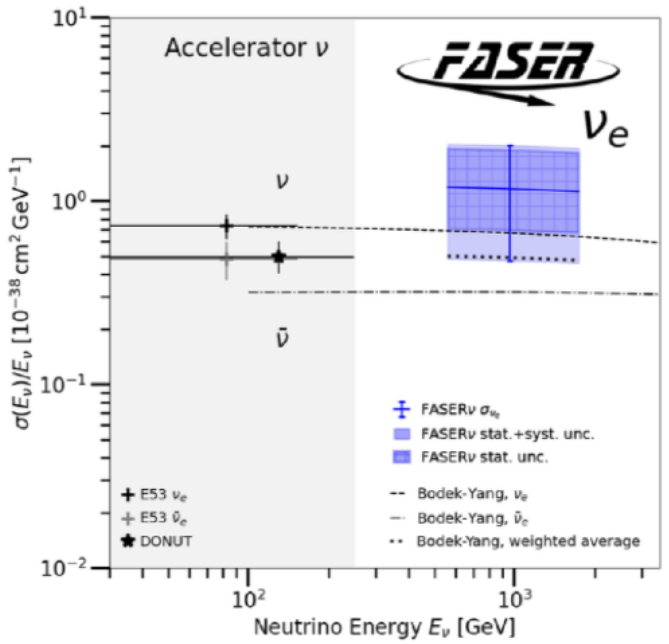


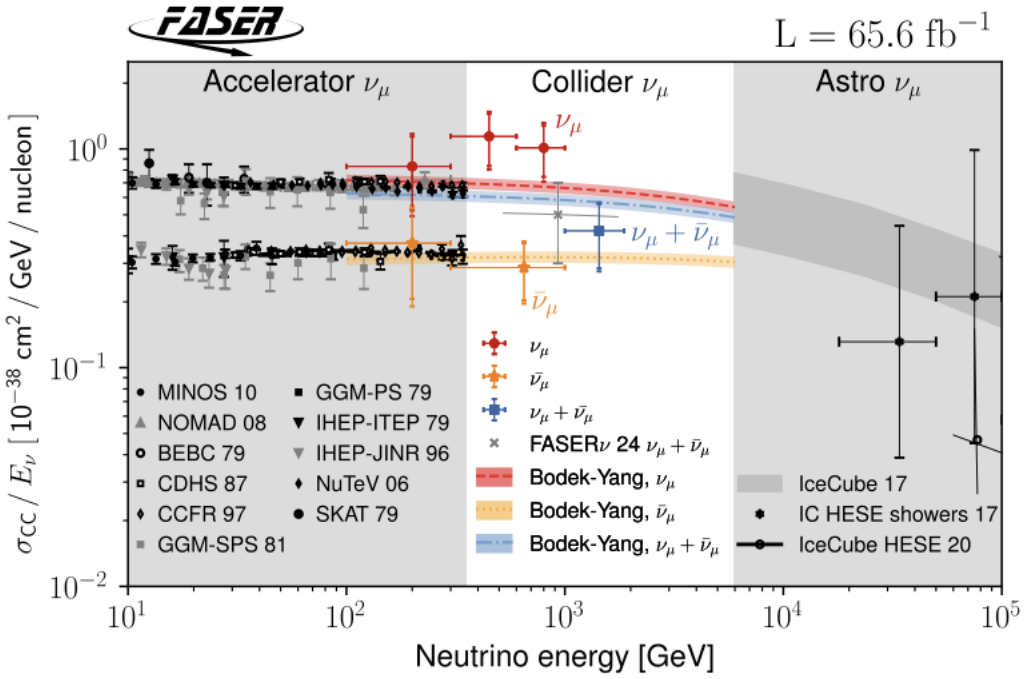
Measurement of ν_e and ν_μ Interaction Cross Sections

- Electron neutrinos: with the emulsion detector using a small fraction of the 2022 data
- Vertices reconstructed in emulsion films. Electron energy from shower multiplicity.
- Electron neutrinos observed 4(5.2 σ)

- Muon neutrinos: with the electronic detectors using 2022 and 2023 data sample
- 338 Muon neutrino events are identified. Muon momentume measured with the FASER spectrometer, and first differential cross sections are measured.

Analysed target mass of 128.6 kg

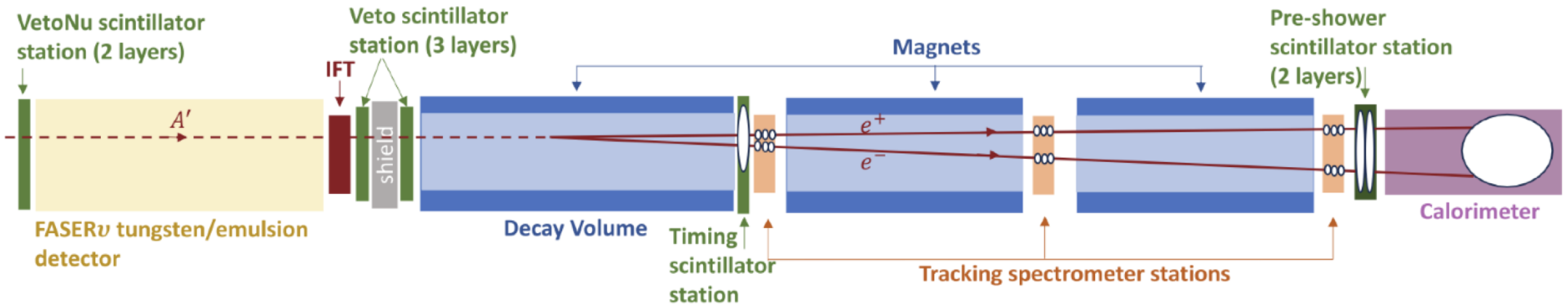




2403.12520

2412.03186

BSM Searches with FASER: Dark Photons

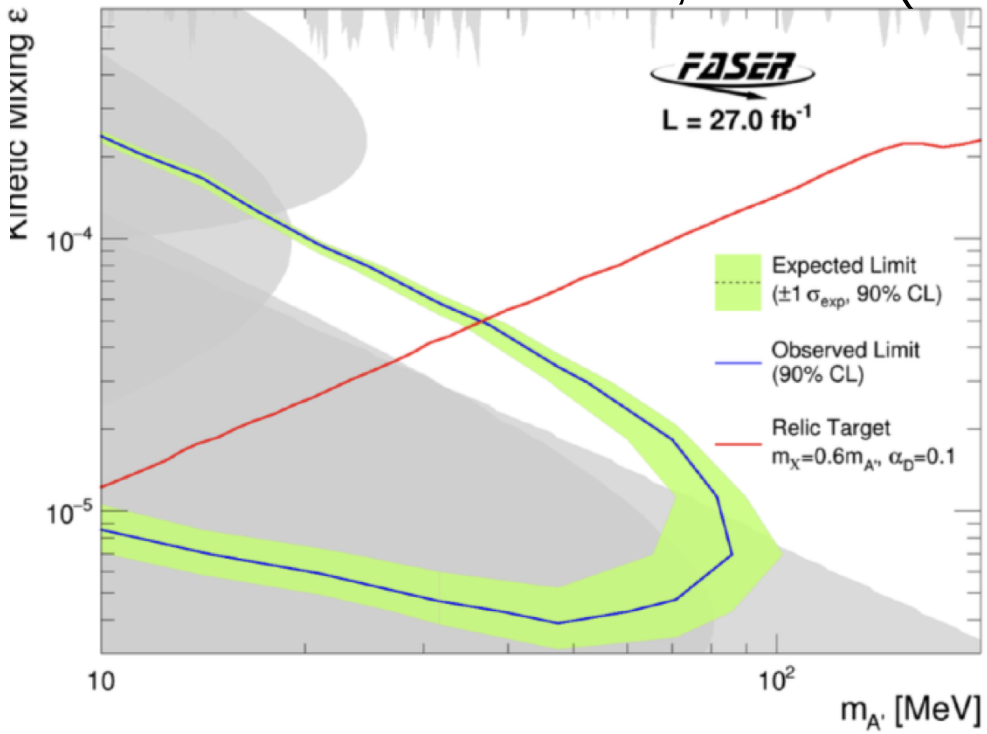


PLB 848, 138378 (2024)

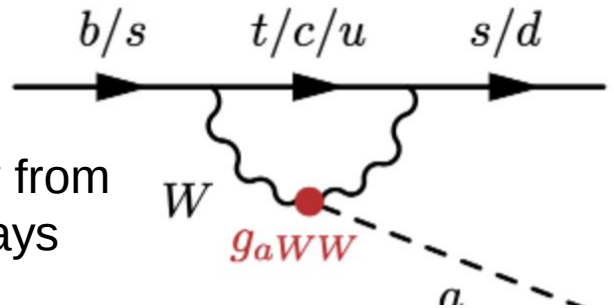
- Dark Photons: U(1) gauge group
  Signature: decay into e+e- pair in decay volume

- Selection
  - 2 opposite-sign tracks & 500 GeV in calorimeter
  - No signal in veto counters
  - Signal in downstream scintillators

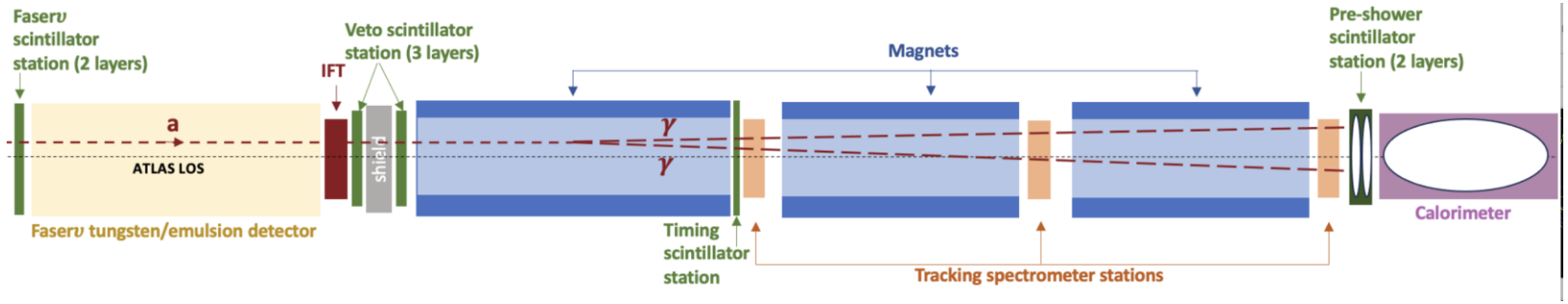
0 events observed / expected



BSM Searches with FASER: ALPs



Mainly from
B decays

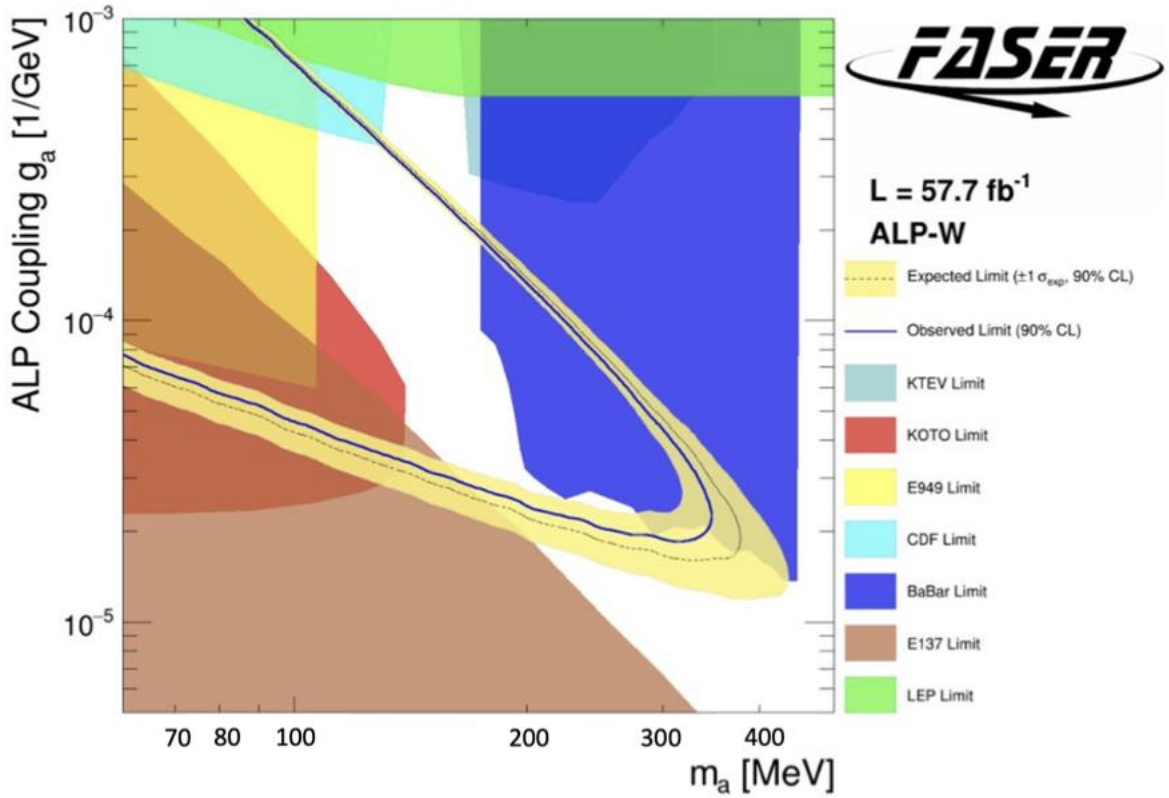


- Currently sensitive to axion-like particles (ALPs) coupling to $SU(2)_L$ gauge bosons

- Signature:
  - decay a-> $\gamma\gamma$ with >1 TeV in calorimeter
  - No signal in veto counters
  - In time with LHC collision
  - Background dominated by neutrinos interacting in the detector material!

1 event observed / 0.4 +/- 0.4 expected

2410.10363



SND@LHC Upgrade Proposal for HL-LHC (~2030)

CERN-LHCC-2025-004

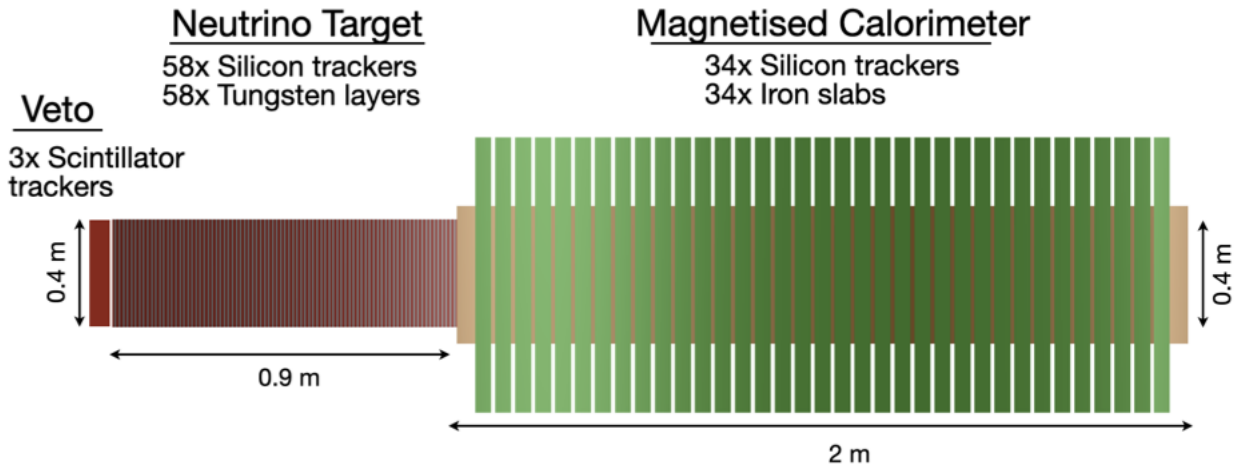
- Electronic vertex detector
  Silicon tracker option being studied
- Improved hadron calorimeter and timing detectors with a magnetized muon spectrometer
- Better acceptance …

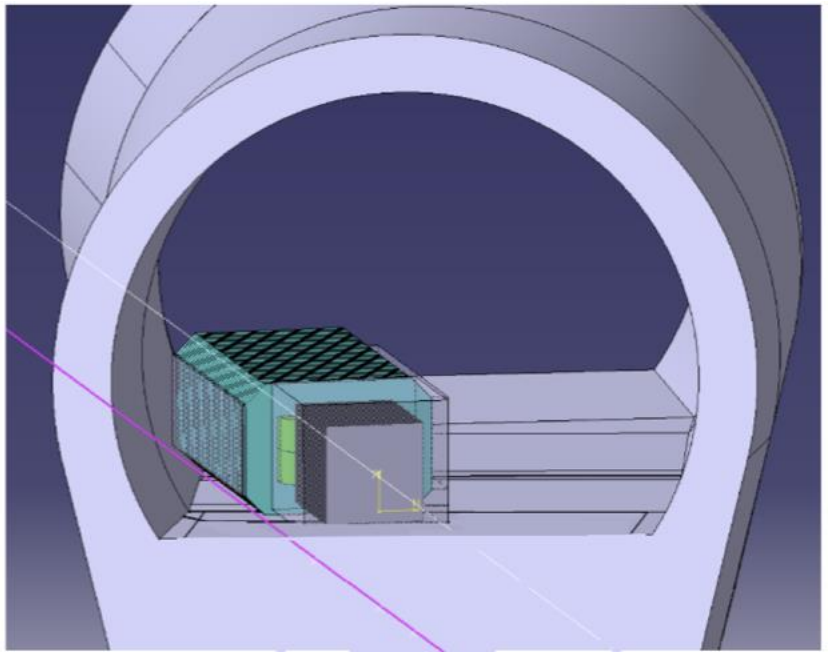
Expected number of CC neutrino interactions for 3000 ab^{-1}

$2.10^4\ \nu_\mu$

$3.10^3\ \nu_e$

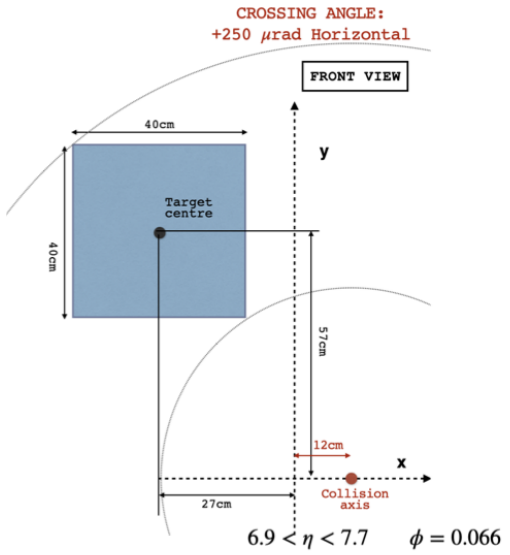
$3.10^2\ \nu_\tau$



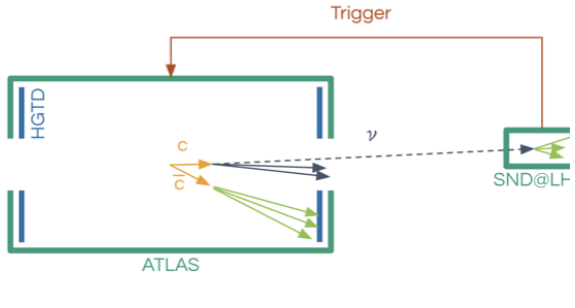


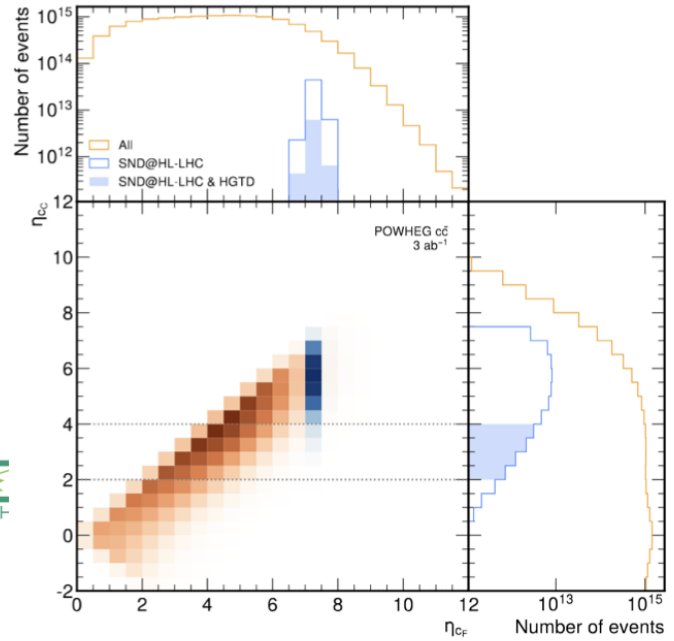
SND@LHC Upgrade Proposal for HL-LHC (~2030)

- **Larger statistics**
  - 13 times more statistics wrt Run3
- **Magnetic field for antineutrino interactions:**
  - allow separate identification of neutrino and anti-neutrino interactions for both muon and tau neutrinos
  - first experimental direct observation and the study of tau anti-neutrinos up to 1TeV
- **Prospects for charm-tagged neutrinos**
  - sizeable fraction of the interacting neutrinos originate from open **charm** decays
  - In around 10% of these events, the associated charm quark is emitted within the acceptance of ATLAS
  - A **charm-tagged neutrino sample** would allow for clean flavour ratio measurements.



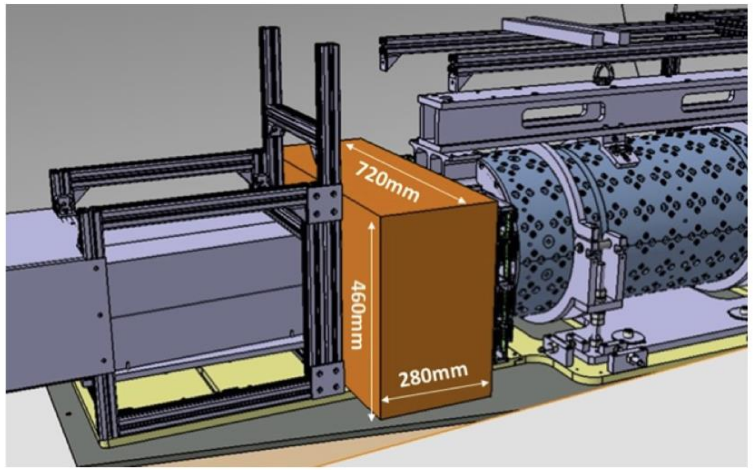
Flavour	CC DIS Interactions (3k fb^{-1}, 1.3 ton) total (DPMJET)	cc-bar (DPMJET)
$\nu_\mu + \bar{\nu}_\mu$	1.5x10^4	2.4x10^3
$\nu_e + \bar{\nu}_e$	3.4x10^3	2.7x10^3
$\nu_\tau + \bar{\nu}_\tau$	2.8x10^2	2.8x10^2
Total	**1.9x10^4**	**5.4x10^3**

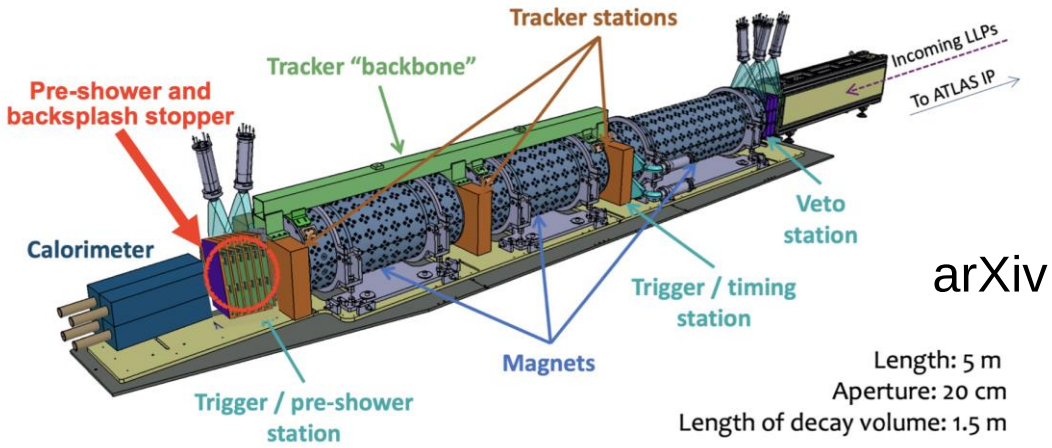




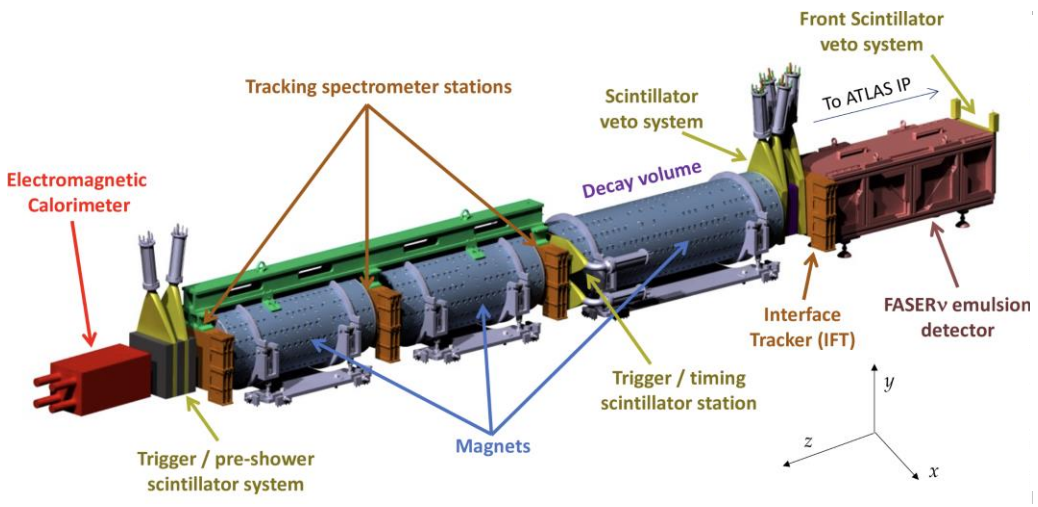
FASER Upgrade for Run-3 and Run-4

- A new W-Si Precision Preshower has been added to FASER for the run starting in 2025. This will be especially usefull background reduction for ALP searches (LHCC-2022-006)





arXiv:2503.19775



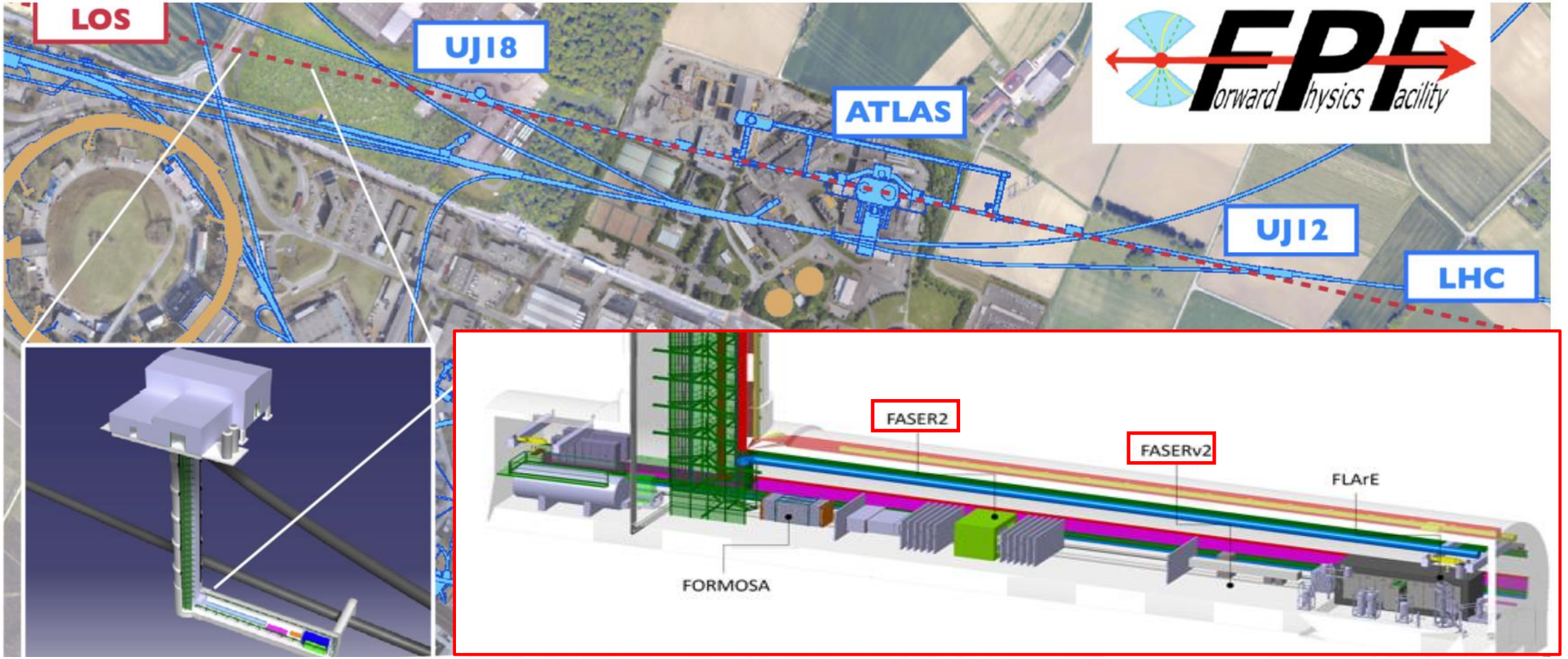
- FASER is approved for Run-4
  Expected luminosity: 680 fb^{-1}

- The target will not have emulsion film for Run-4-> too frequent target echange
- Other options: scintillator+ tungsten tracking calorimeter (+ silicon detectors)…

Proposal: The Forward Physics Facility

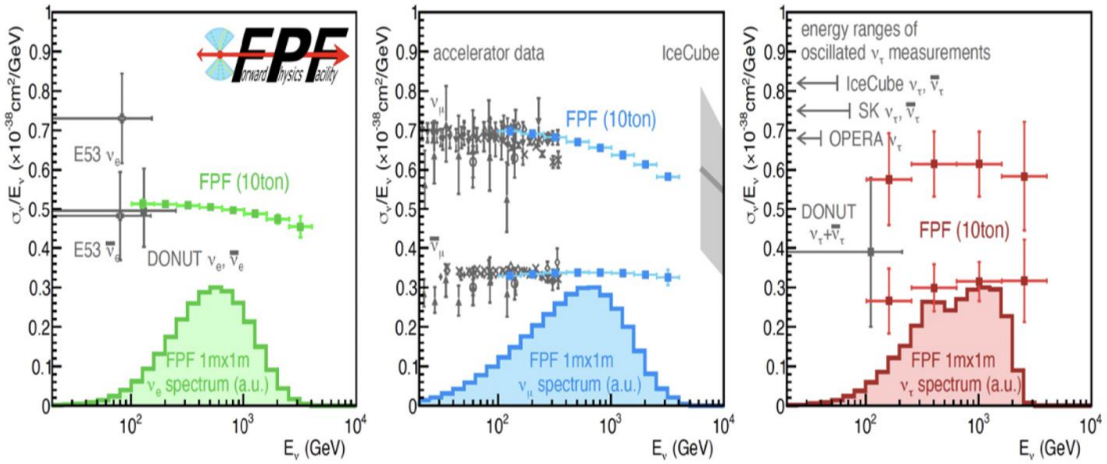
2203.05090
2411.04175

A proposed new CERN facility to achieve the full potential of **LHC far-forward physics**



- A new underground area with a complementary suite offorward experiments operating concurrently with the HL-LHC. Positive outcome of geological drilling studies so far.

Neutrinos at the Forward Physics Facility



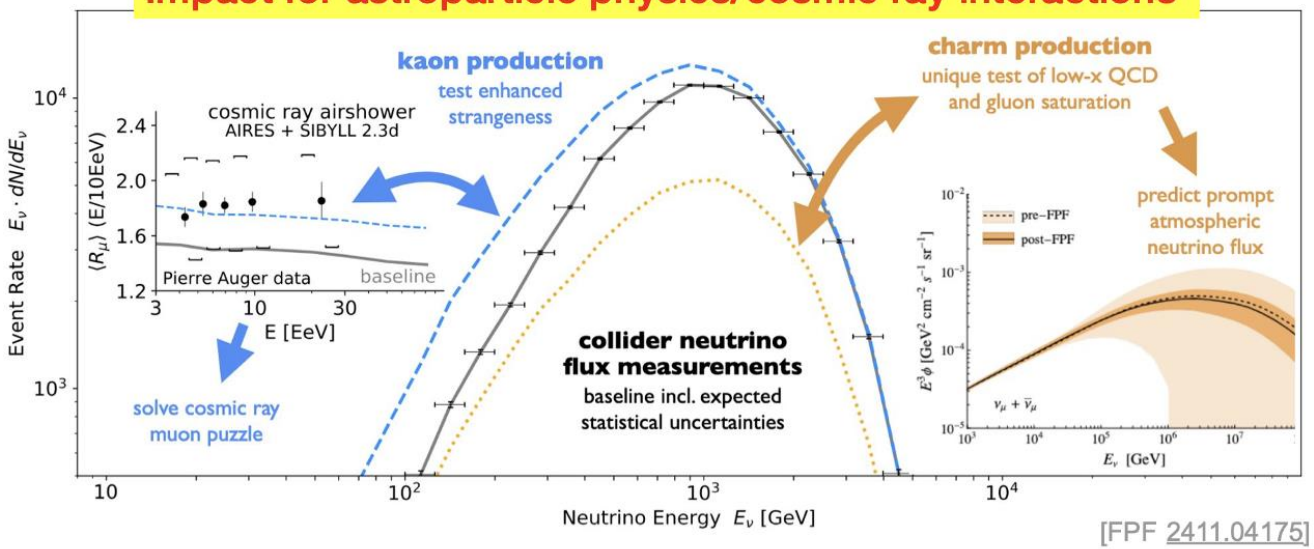
J.Phys.G 50 (2023) 3, 030501

Assuming a 10 ton detector with η > 6.9 for 3000 fb^{-1} of data

- FPF experiments FLArE, FASERν2, will see 10^5 ν_e, 10^6 ν_μ, 10^4 ν_τ interactions at ~TeV energies.

- Implications for
  - neutrino properties
  - QCD (x~$10^{-7}-0.1$, DIS)
  - astroparticle physics

Impact for astroparticle physics/cosmic ray interactions



[FPF 2411.04175]

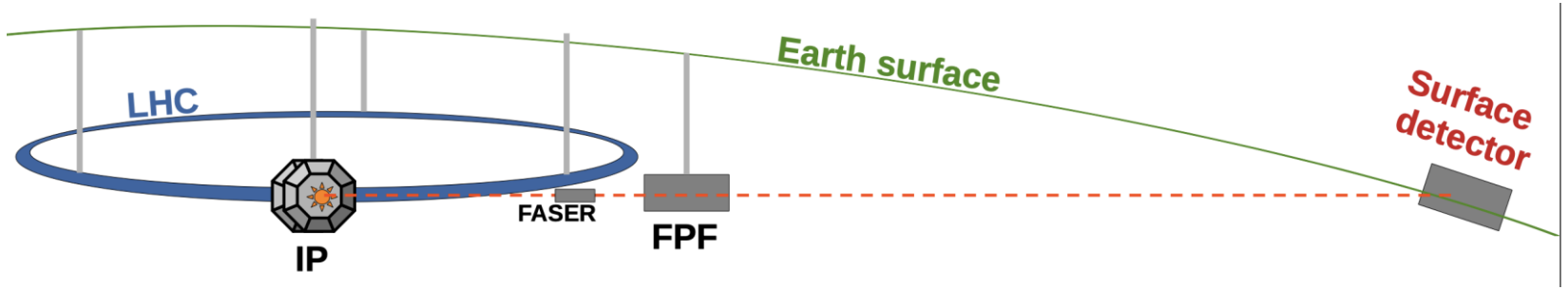
cosmic ray muon puzzle: observed 8σ excess of muons compared to predictions from hadronic interaction models

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

More Neutrino Experiments@LHC?

Instead of digging a new underground area.. Let the LHC neutrinos surface!

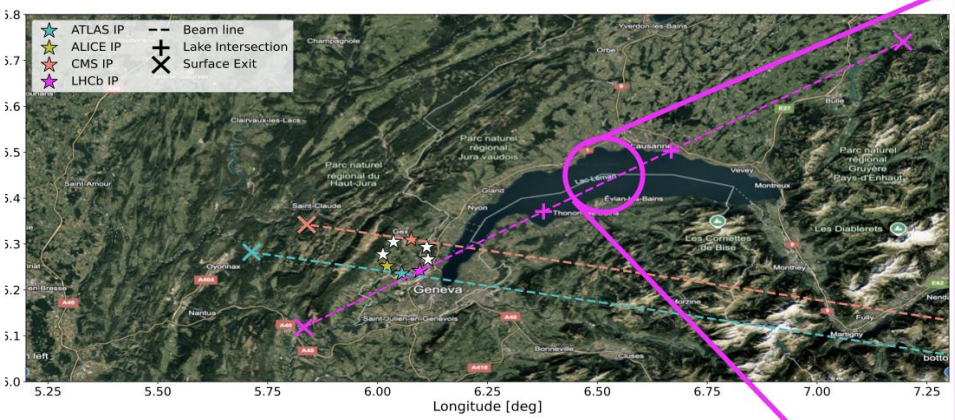
….And catch them with a kiloton detector, eg in Lake Geneva… (or Jura mountains)

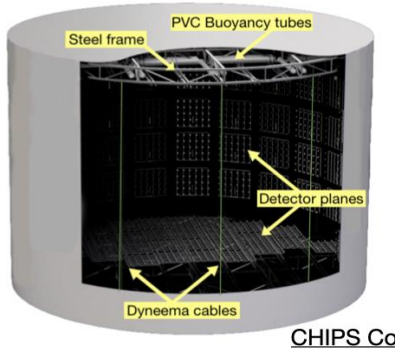


2501.08278
2501.06142

Collect more than 1M neutrino interaction events with 3000 fb^{-1}

UNDINE: UNDerwater Integrated Neutrino Experiment





CHIPS Collab. 2024

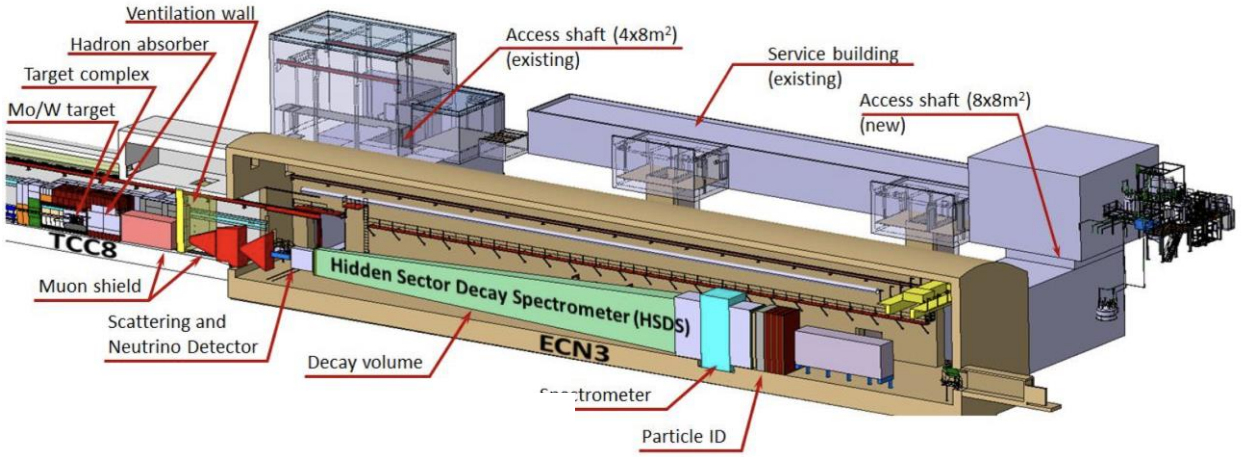
- A suite of CHIPS-style water Cherenkov detectors deployed in a modular fashion
- Benchmark lake detector: 5 CHIPS modules (~30 kT)

E.g. UNDINE: a detector proposal based on the CHIPs water Cherenkov technology

What exactly can we measure, apart from cross sections?

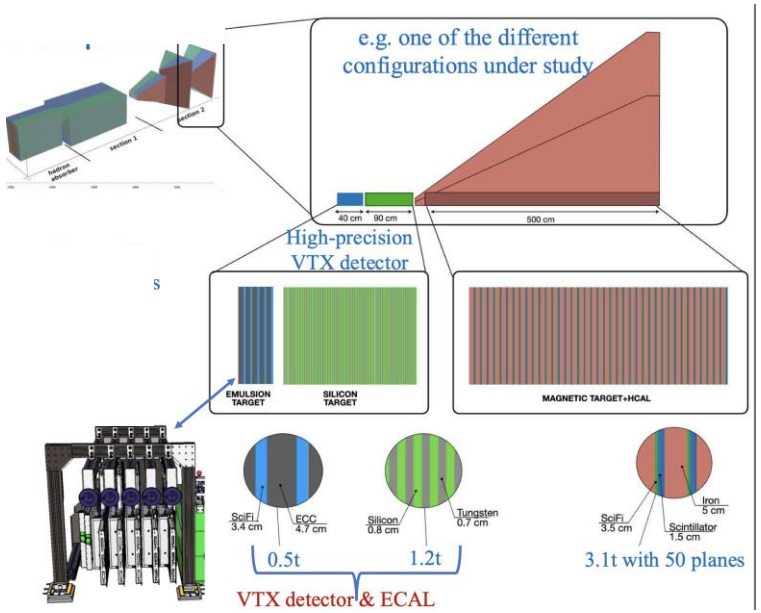
SHiP a Future (Neutrino)Experiment @ CERN

SHiP for the new CERN beam dump facility, foreseen to take data ~2032/33 for 15 years



SHiP: Search for Hidden Particles
Fixed target collisions with 400 GeV/c proton beam
SHiP includes a neutrino detector: SND

Planned: 4×10^{19} POT/year



The SHiP Scattering and NeutrinoDetector SND based on a similar concept as SND@LHC

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

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

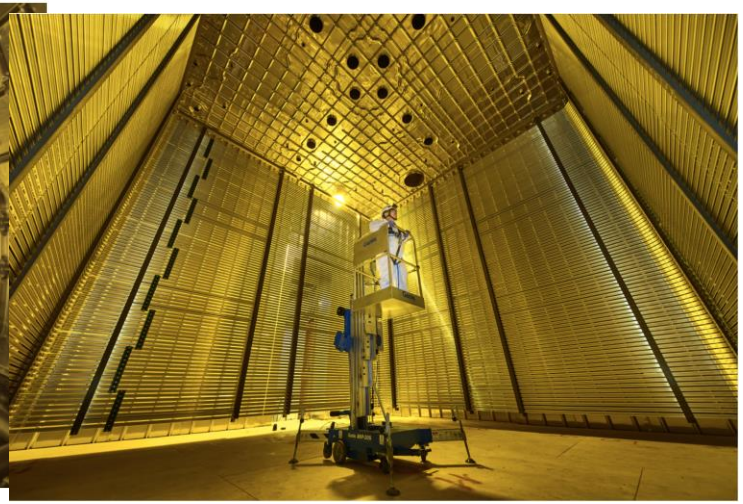
The Neutrino Platform @ CERN

Support for neutrino experiments at accelerators (ESPPU 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 technology hub for European contributions & participation..

- 2015-now: ProtoDUNES for DUNE, BabyMind & ND280 activities for T2K, ICARUS & SND (SBN@FNAL) & ENUBET support…

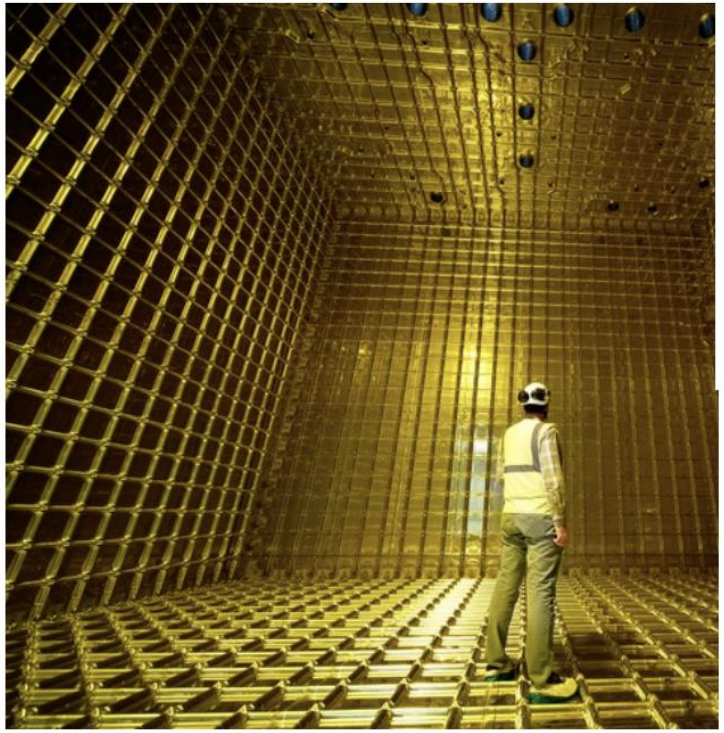
- "Bringing neutrinos back @ CERN since 2001"…



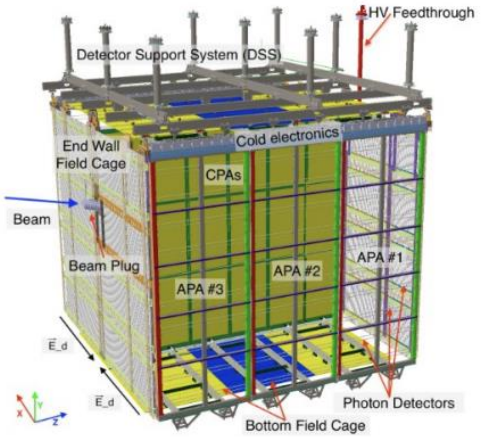
Protodunes at the Neutrino Platform

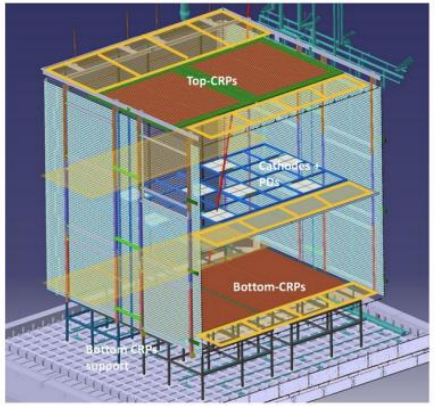
The ProtoDUNEs are 4% size prototypes for the Far Detectors (FD) of DUNE

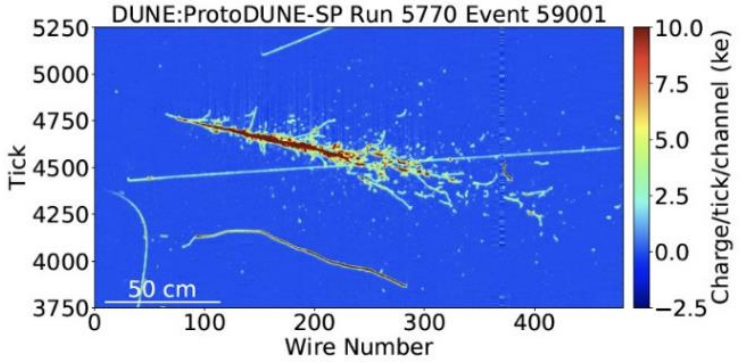
ProtoDUNE LAr modules
(>700t, >200m³)



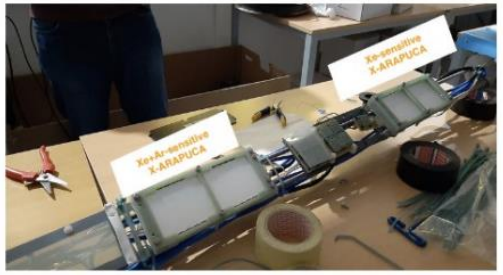
Horizontal and vertical drift







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 Physics

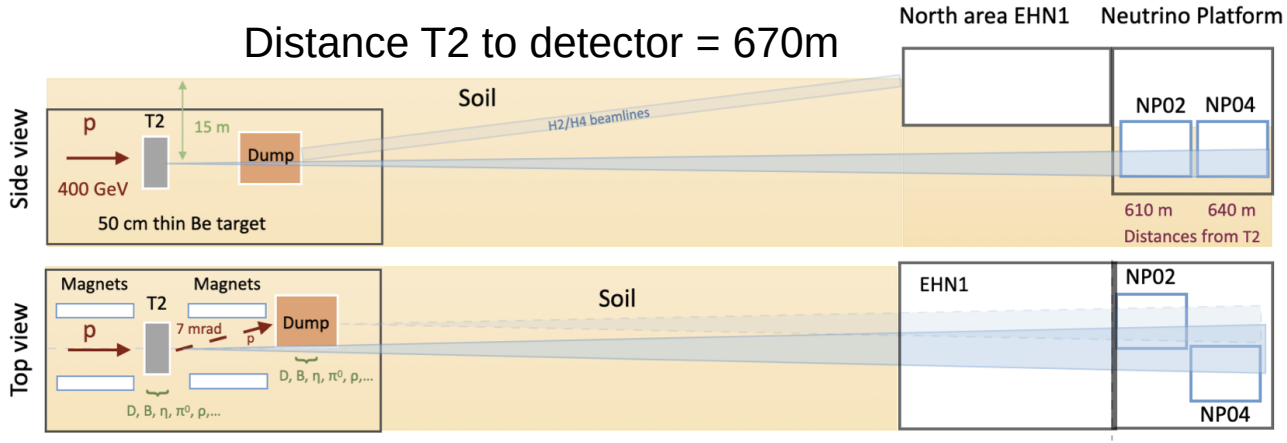
arXiv:2304.06765

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,§]

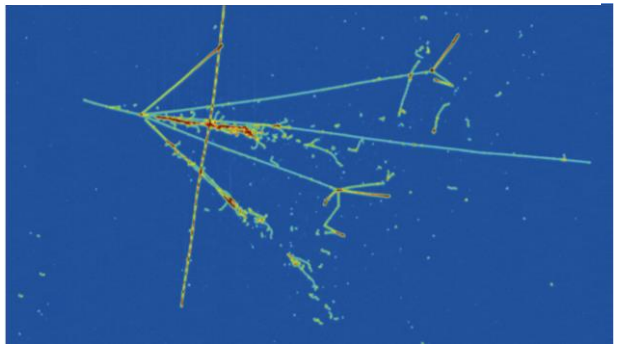
Use the ProtoDUNE detectors (700t LArTPCs) to hunt for weakly interaction LLPs or light dark matter scattering? The 'beam' comes for free!!

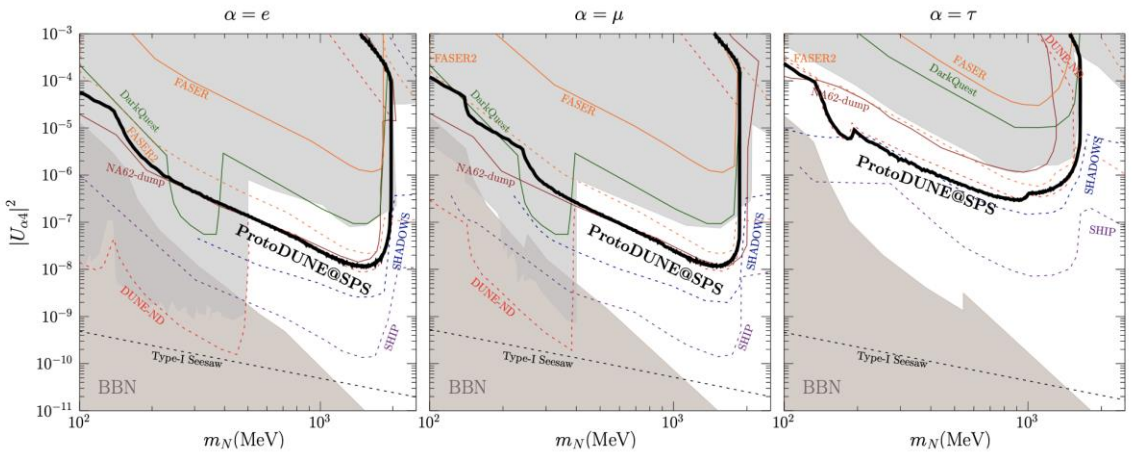
Distance T2 to detector = 670m



The T2 target in the North Hall "acts" like a beam dump for the 400 GeV SPS beam, and can deliver 3.5×10^{18} POTs/year

First "neutrino" in NP04





5 years

HNL Sensitivity:
Competitive for masses above the kaon threshold

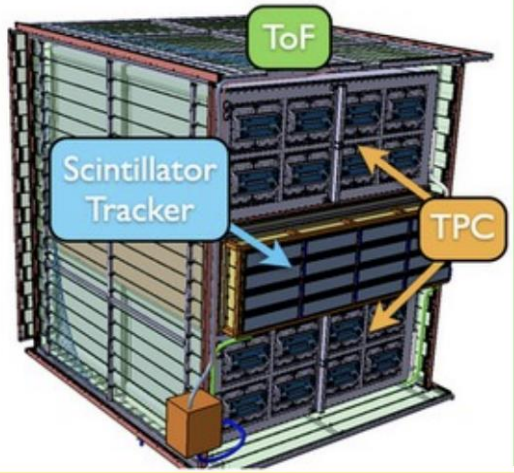
Experimental feasibility study made during 2024
Demonstrator runs in '25 & '26?

T2K Related activities

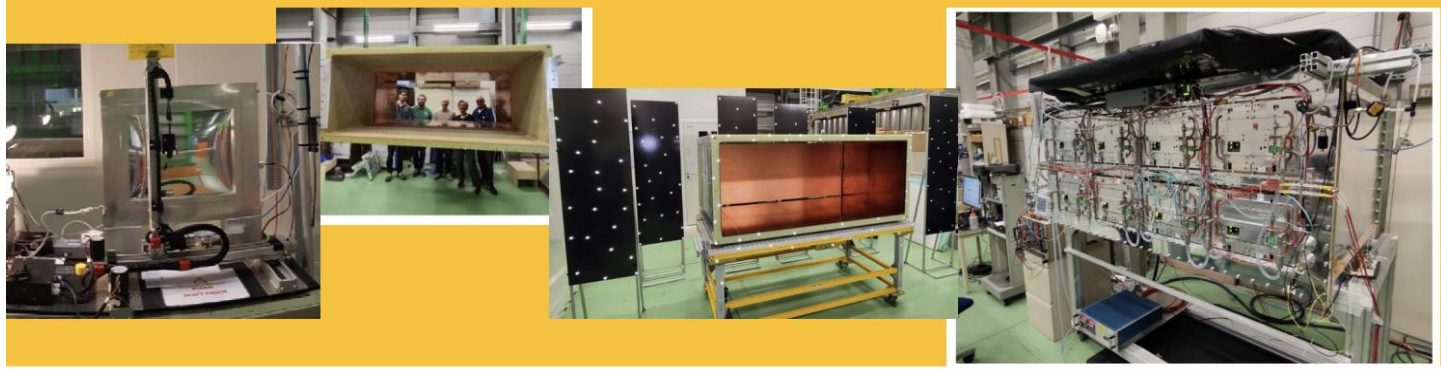
- CERN is a member of T2K and contributed to the ND280 near detector.
- Much of the assembly and testing of the new ND280 components from Europe was done @ CERN, before shipping to Tokai.

....Repeat this for ND280++ for T2HK?

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

....as well as

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

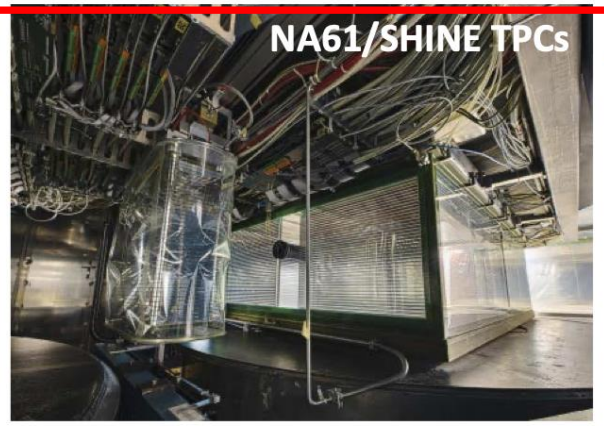
Auxiliary Experiments @ CERN

FUTURE CONTRIBUTIONS TO EXTERNAL NEUTRINO PROJECTS

Neutrino beam control:

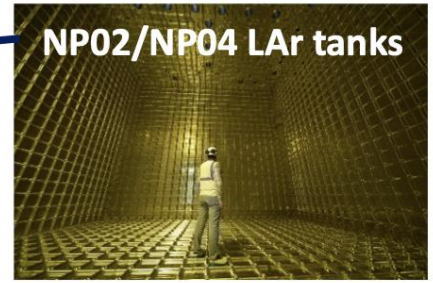
All beams: NA61/SHINE hadroproduction cross-sections and hadron production measurements with FNAL/JPARC neutrino beam replica targets

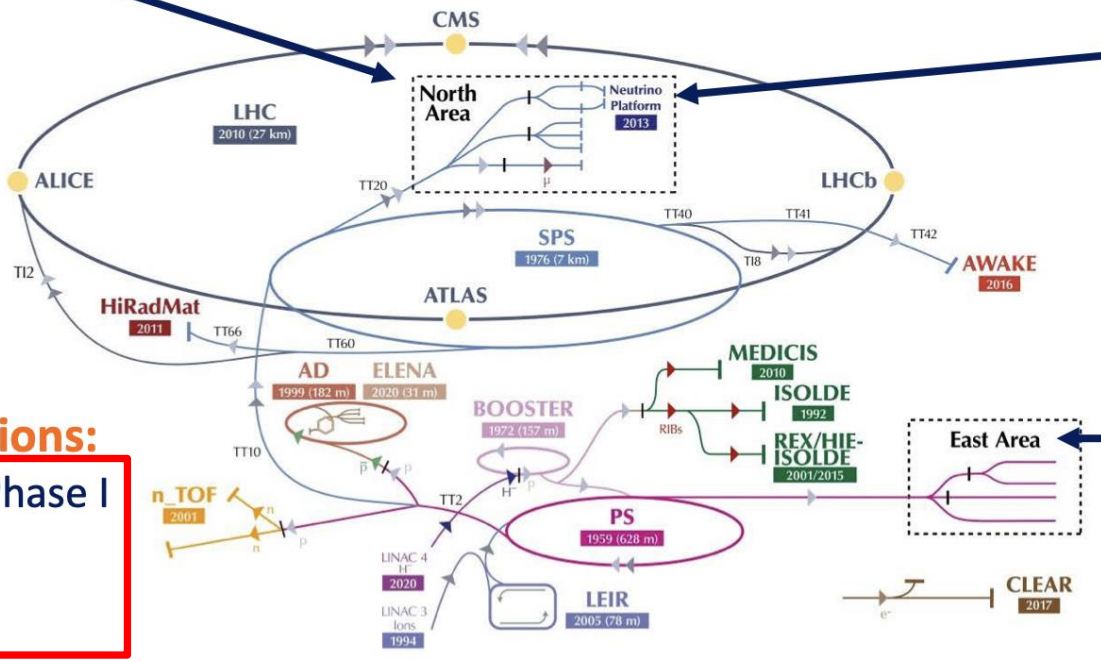
→ *to be continued, additional low-E beam foreseen*



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*



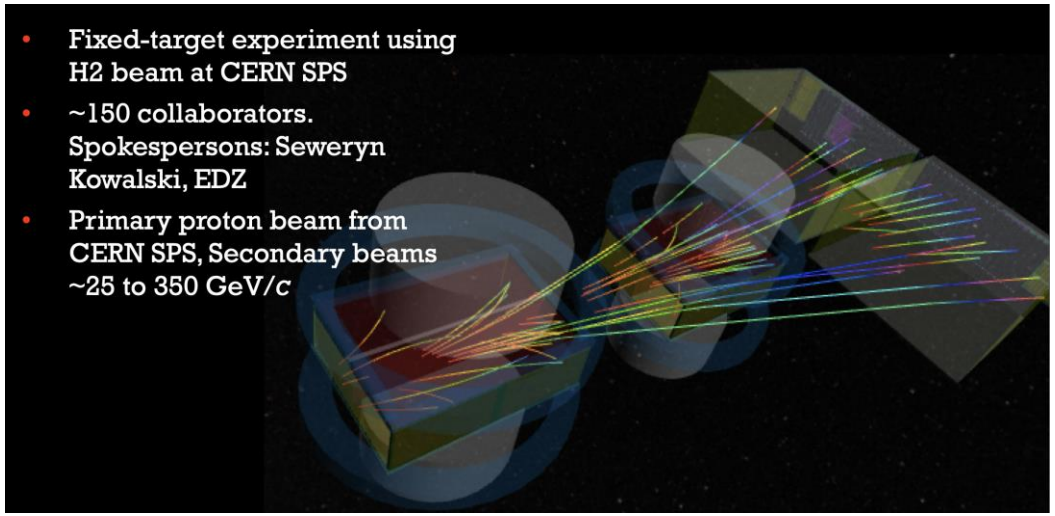


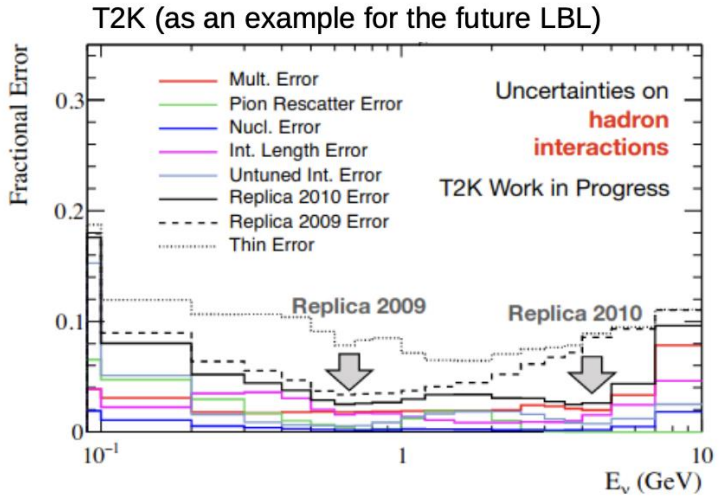
Neutrino interaction cross-sections:

NuSTORM@CERN studied by PBC Phase I

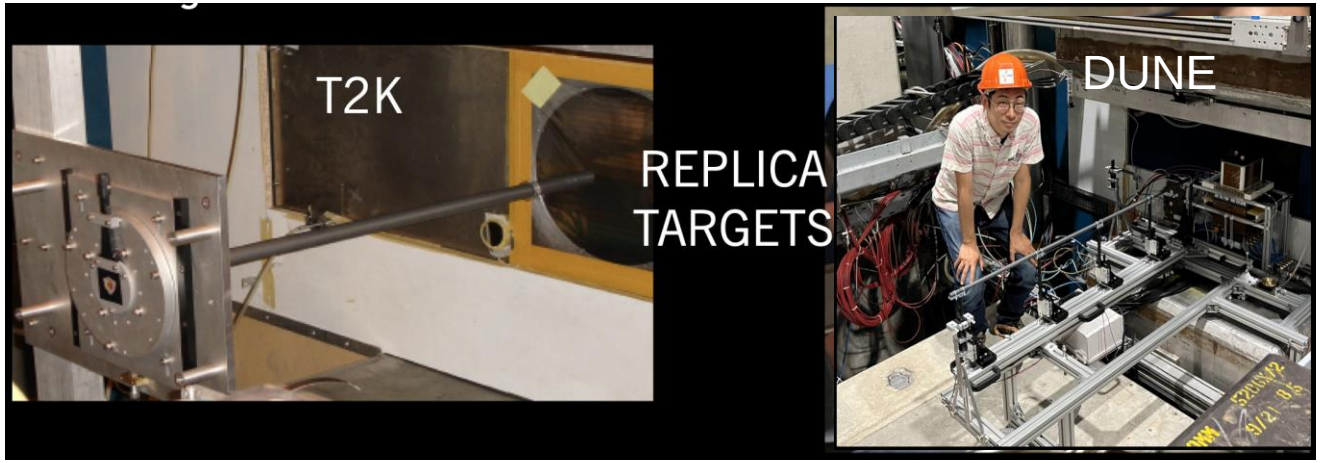
→ *SBN@CERN(ENUBET+NuTag) studied by PBC Phase II*

NA61/SHINE





Hadronic interaction studies with a large acceptance spectrometer



High statistics samples collected in ’23 -> ‘25

Particle identification with de/dx and TOF

Plan after LS3 shutdown ->
Lower energies? New beam/Targets?

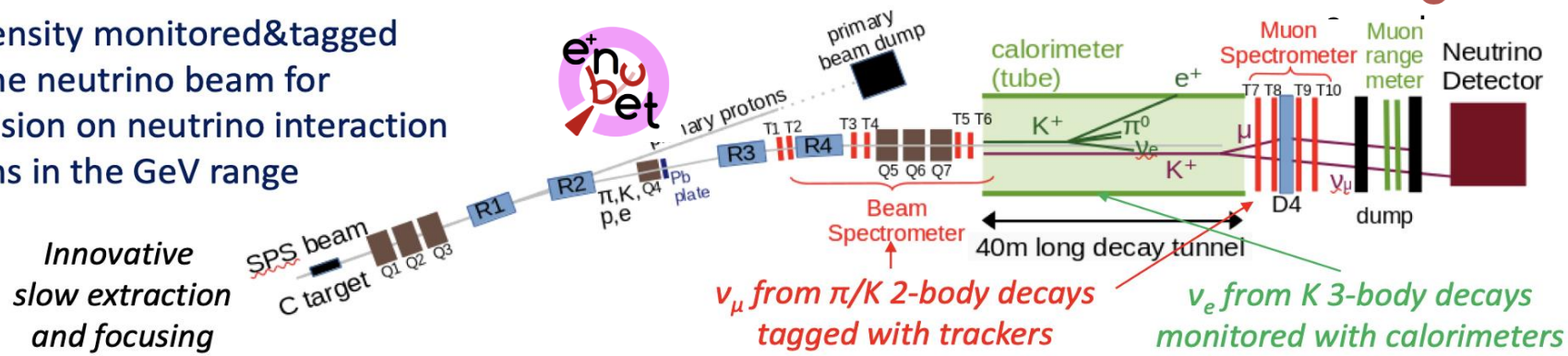
- **A program of precise measurements with 3-20 GeV/c beams could make major improvements in flux (factor of >2)**

A New Experimental Proposal: NuScope

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

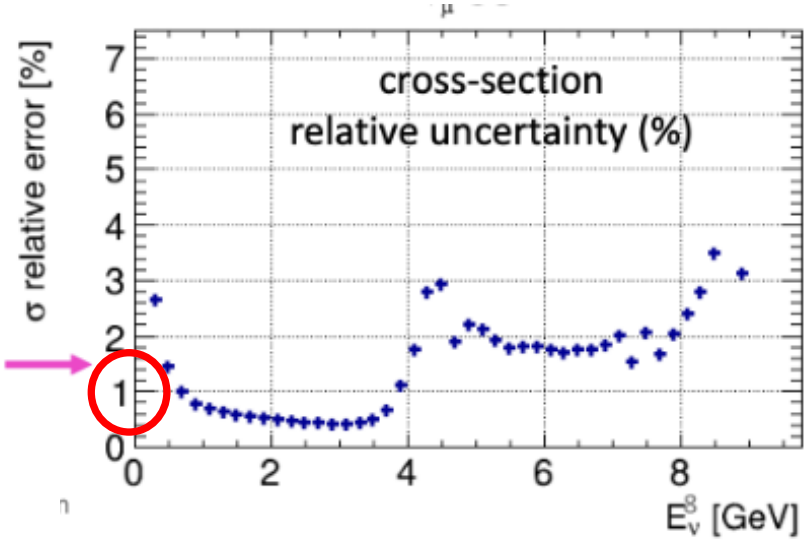
SBN@CERN: a new facility under study for DUNE/HK

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



A dedicated neutrino beamline and experiment at the SPS ?…

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



First collaboration meeting @ CERN on October 13-15 2025

https://indico.cern.ch/event/1548855/

Conclusions and Outlook

The Dawn of Collider Neutrino Physics has arrived!

- Two dedicated experiments are taking data since 2022: FASER(ν) and SND@LHC
- 2023: both experiments observed (muon) neutrinos for the first time at a collider with the electronic detectors
- Now: observation of other flavours, and first cross section measurements.
- FASER presented first results for searches for BSM particles: dark photons and axions
- Upgrades are planned for next both experiments, for run4-run5 at the LHC, subject to approval for SND@LHC. Samples of 10^5 – 10^6 neutrinos events should be collected

- A facility is being studied for the neutrino –and other physics- at the LHC: the Forward Physics Facility FPF. Or maybe use the neutrinos that exit close to the surface?

- In addition: The CERN neutrino platform as a central point for neutrino experiment development; The SHiP experiment planned for data taking in early 2030's; auxiliary experiments such as NA61; A new experiment with tagged neutrino beam (NuScope?)…

Backup

FASER

SND@LHC

POSTERS:

Recent FASER Results and Development of Neutrino Energy Reconstruction for the FASERnu Detector - Jeremy Atkinson #270

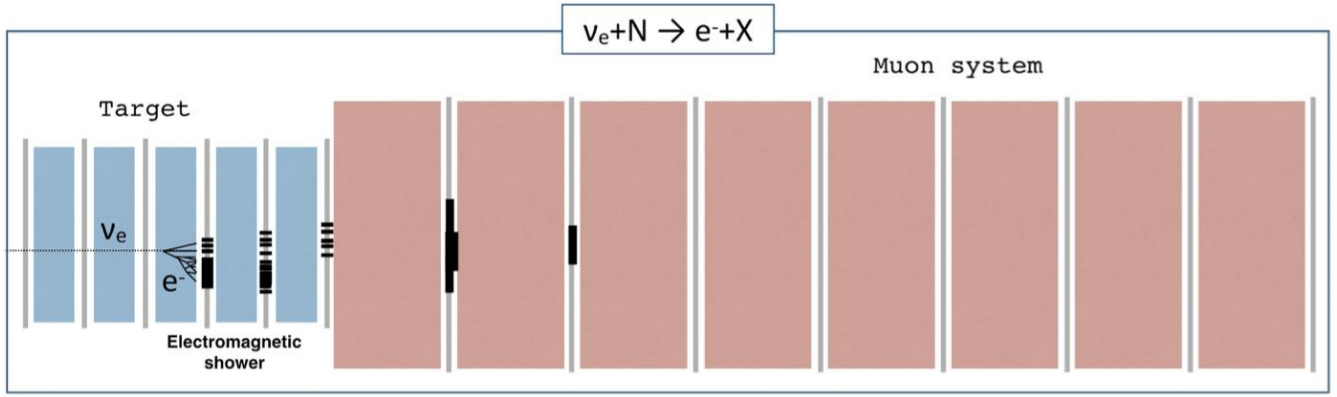
The muon measurements at the FASER experiment - Ken Ohashi #136

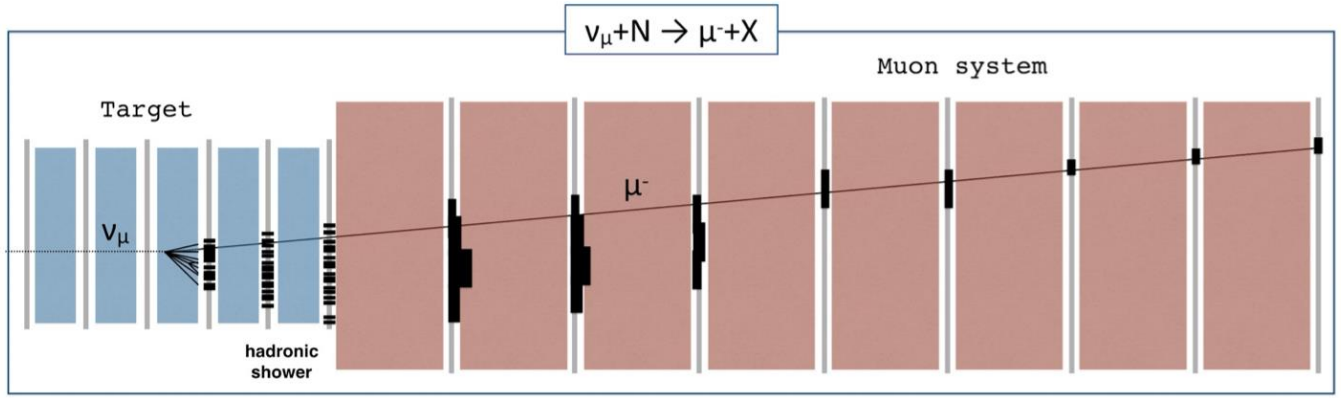
Momentum measurement in the FASERv detector in the LHC-FASER experiment - Haruhi Fujimori #387

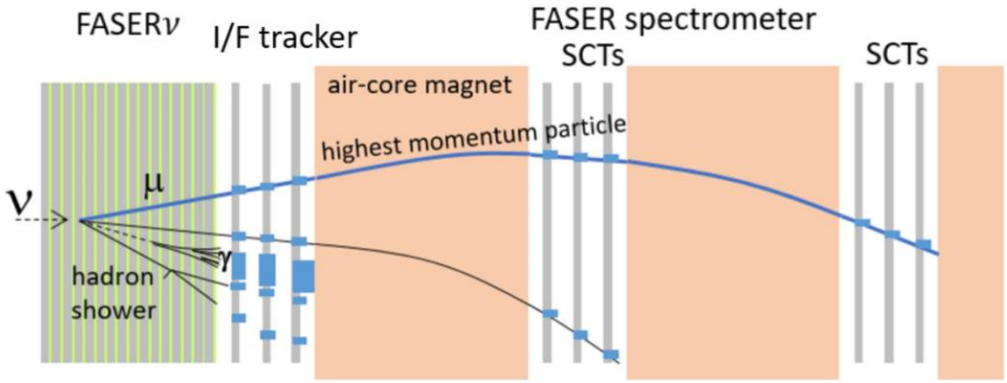
Neutrino Event Reconstruction Strategies

SND@LHC

- Use **scintillating fibre** hit pattern to **match** electronic detector events to emulsion detector vertices.
- Measure **showers** with **ECal** and **HCal**.
- Tag muon tracks with the **muon system**.







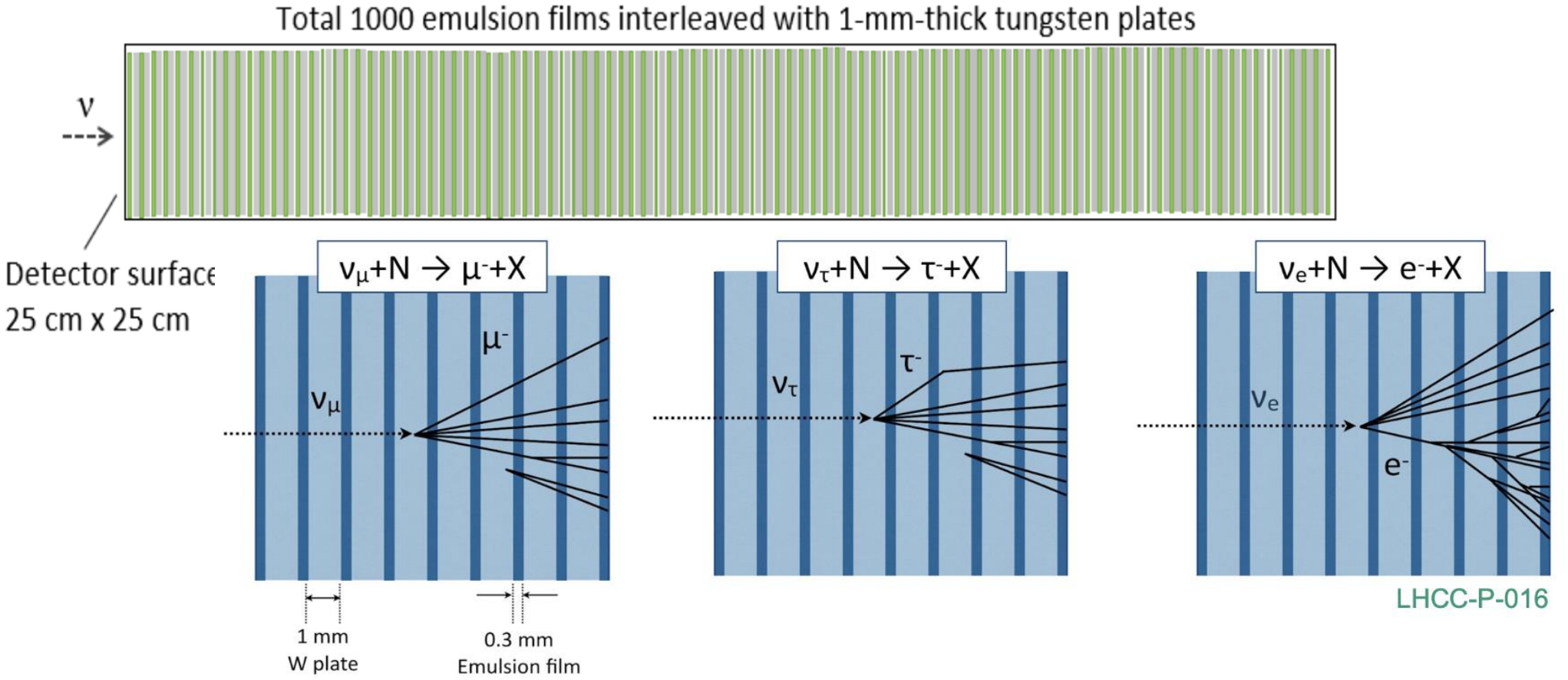
FASER

- Use **interface tracker** to **match** electronic detector events to emulsion detector vertices.
- Measure **track momenta** with **spectrometer**.
- **Muon tagging** based on absence of hadronic interactions in the tungsten and track momentum.

Initial analyses of both experiments used only the electronic detector data

Identification of the Neutrino Flavor

- Both FASER and SND@LHC use a tungsten/emulsion film target for the neutrino interactions -> Emulsion Cloud Chamber (ECC) technique a la OPERA
- An instrumented target is key to flavour tagging!
- In Run3 the target needs to be exchanged a few times per year … (2022/2023)

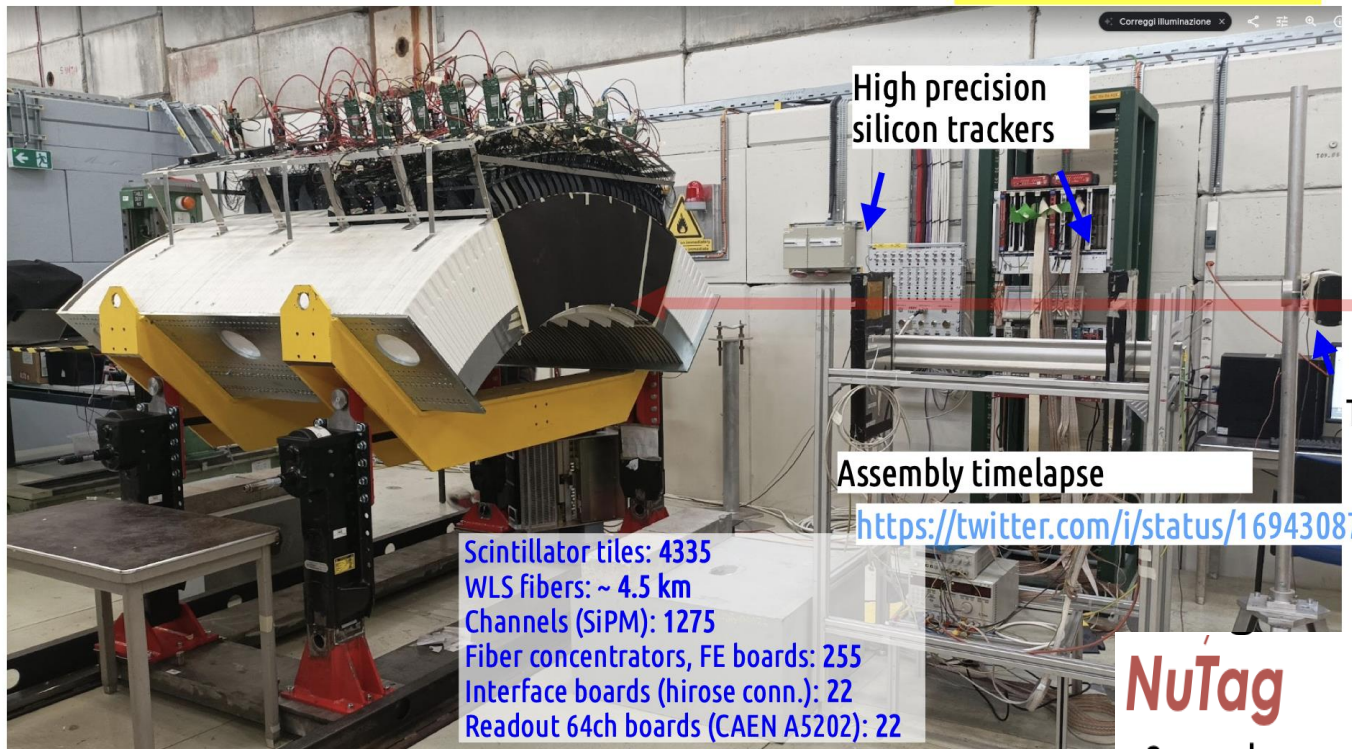


A New Experimental Proposal: NuScope

Eur. Phys. J. C 83 (2023) 10, 964

The calorimeter demonstrator

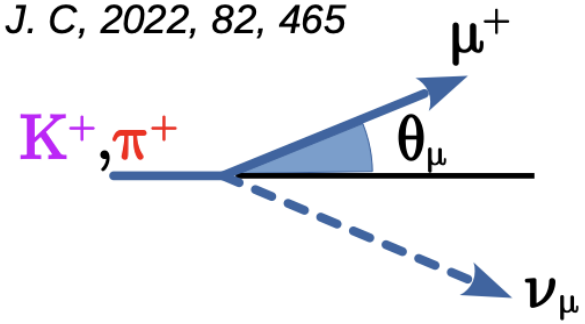
10/22 + 08/23 + 08/24 @ CERN-PS-T9

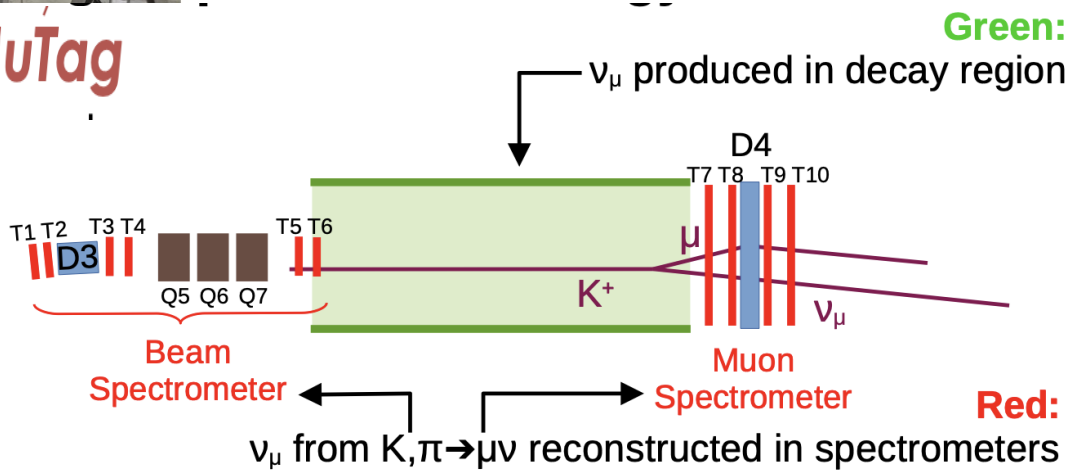


Neutrino beam monitoring and tagging

NuTag

More in *Eur. Phys. J. C, 2022, 82, 465*



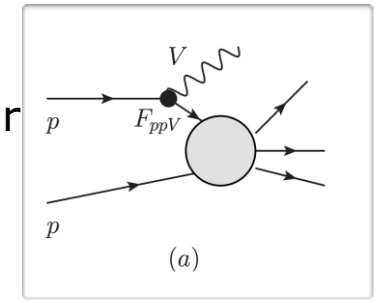


More BSM Searches Channels to Come…

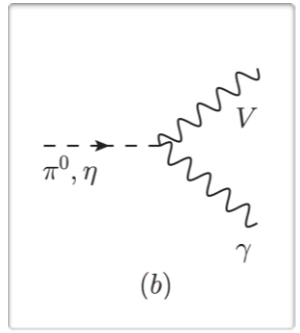
- Eg. SND@LHC sensitivity for light dark matter

Production: consider a scalar χ particle coupled to the Standar Model via a leptophobic portal,

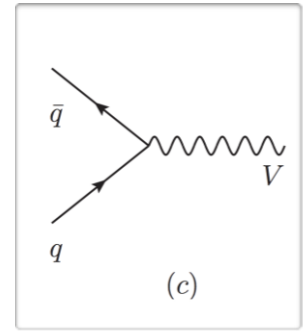
$$\mathcal{L}_{\text{leptophob}} = -g_B V^\mu J^B_\mu + g_B V^\mu (\partial_\mu \chi^\dagger \chi + \chi^\dagger \partial_\mu \chi),$$



Proton bremsstrahlung

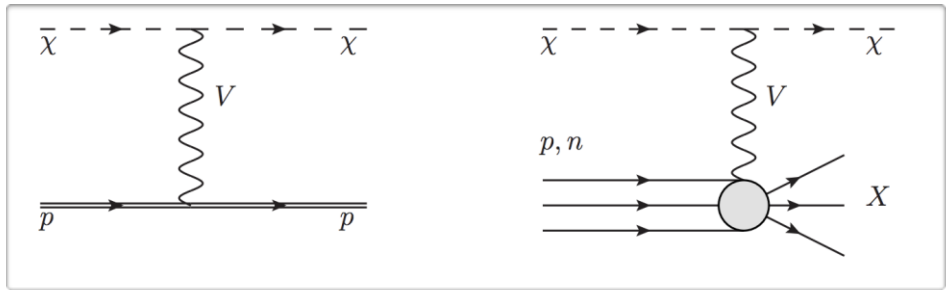


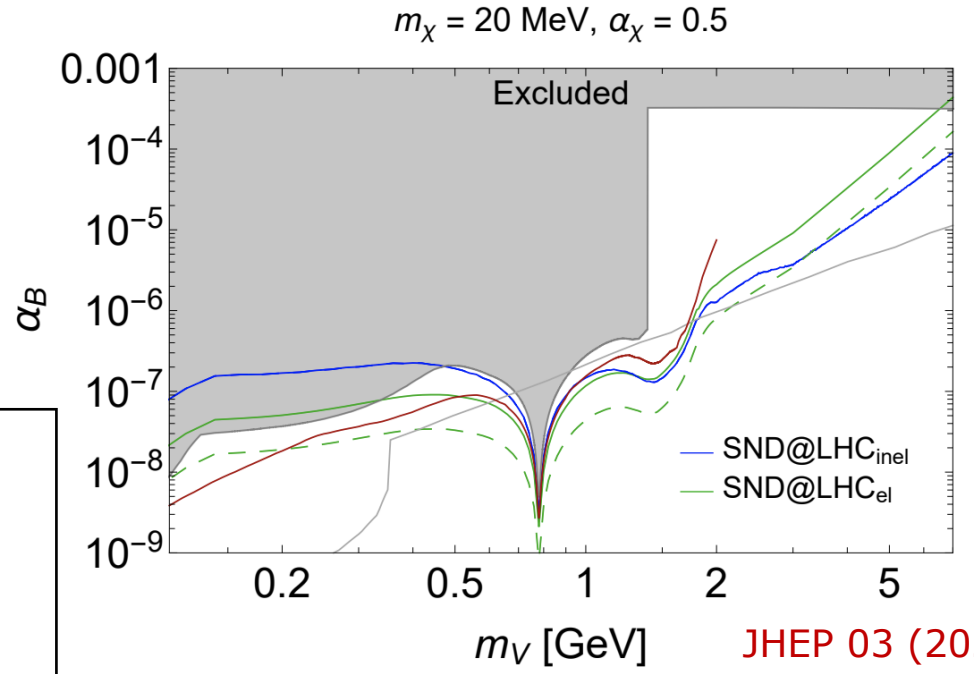
Meson decay



Drell-Yan process

Detection: χ elastic/inelastic scattering off nucleons of the target





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- More channels to explore by SND@LHC and FASER Higgs-like scalars, Heavy Neutral Leptons, final state radiation effects, Quirks, LFV with tau excess, exotic interactions…

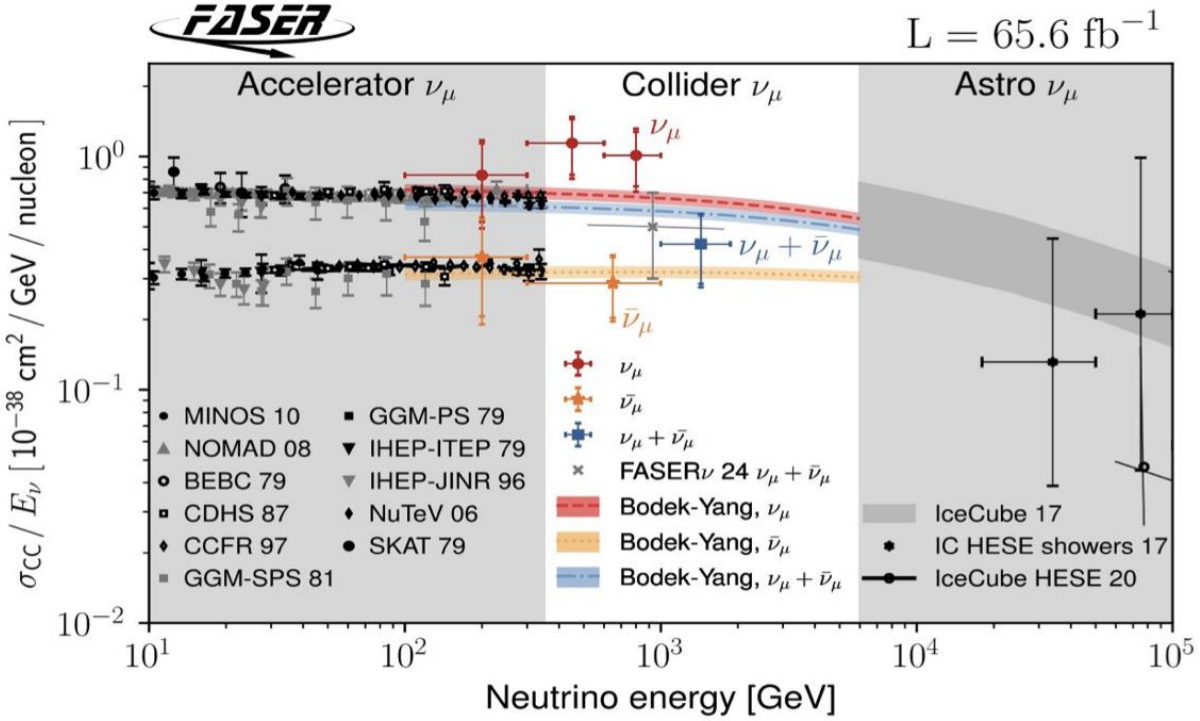
Study of collider ν_μ neutrinos: FASER electronic detector

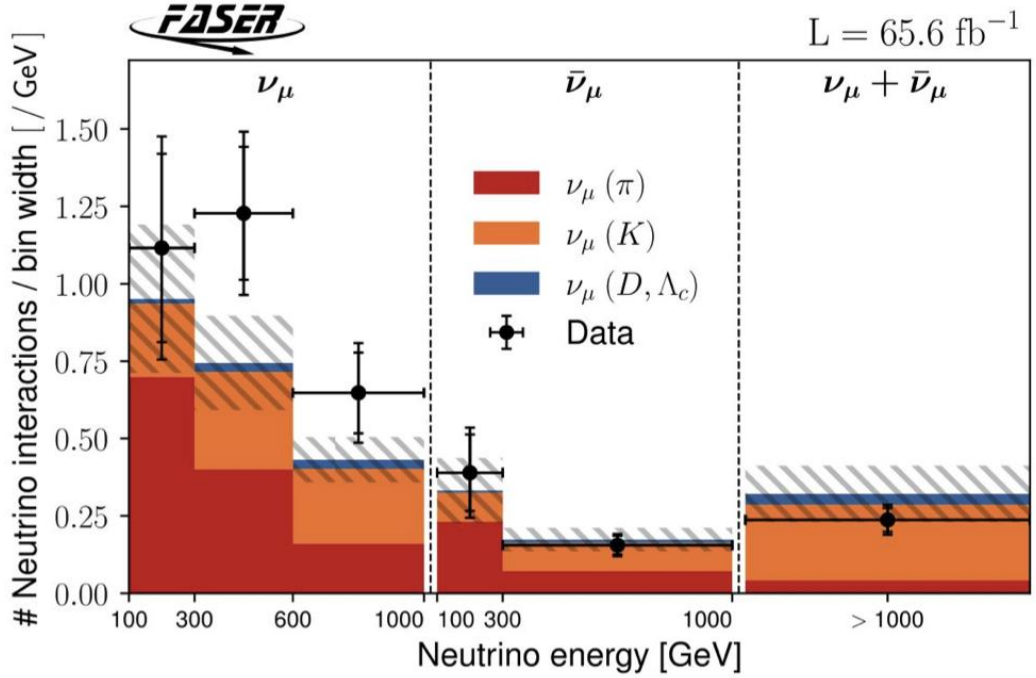
Phys. Rev. Lett. 134, 211801

Unfolded muon momentum into six neutrino energy bins:

New since LLP 2024!

$$n_{\nu,\mathrm{obs}} = 338.1 \pm 19.0\,(\mathrm{stat.}) \pm 8.8\,(\mathrm{sys.})$$





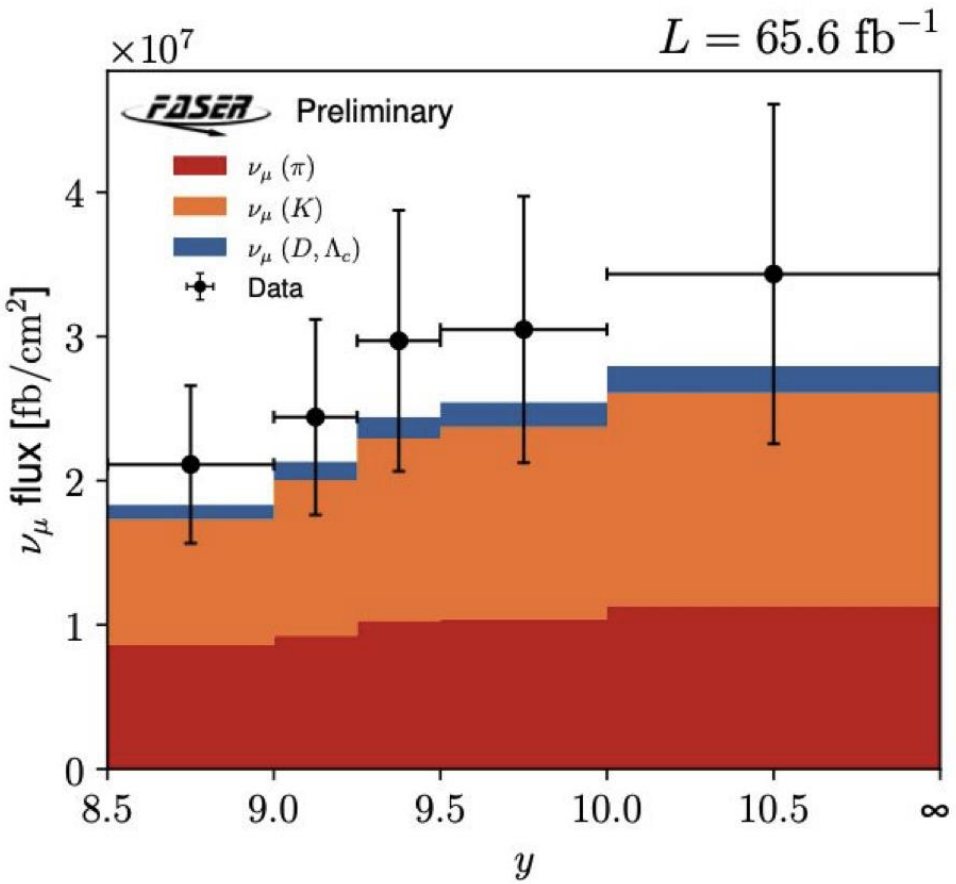
First differential neutrino interaction measurement in the TeV energy range

study of collider ν_μ neutrinos: FASER electronic detector

CERN-FASER-CONF-2025-001

Measurements: ν_μ flux as a function of the rapidity y

New since LLP 2024!

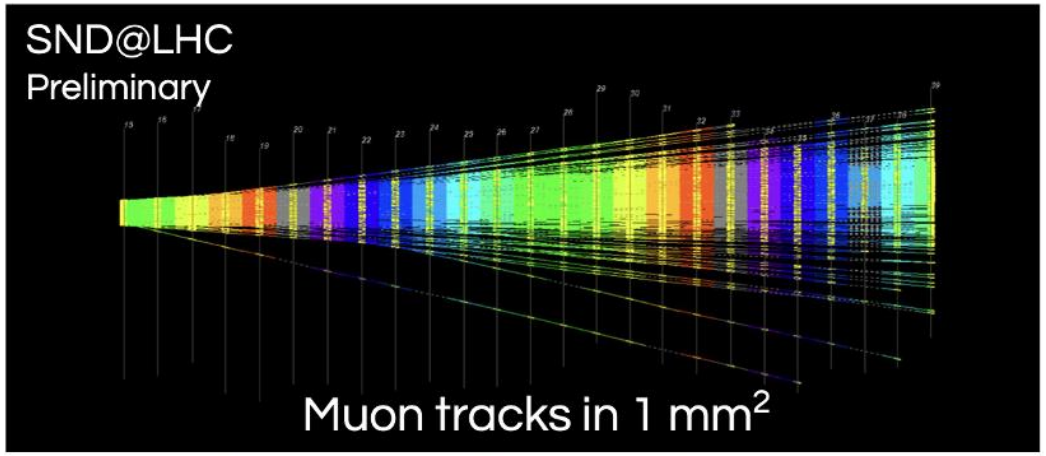


Rapidity bin	[8.5, 9.0]	[9.0, 9.25]	[9.25, 9.5]	[9.5, 10]	[10, ∞)
Uncertainty Sources					
MC Stat. unc.	1.5	1.2	1.0	1.1	1.0
`Geant4` + `GENIE` unc.	1.3	4.3	3.5	3.6	1.8
Neutrino Flux Modeling unc.	38.3	29.4	19.5	23.0	22.4
LOS unc.	29.9	3.5	0.2	9.0	12.7
Mass	3.3	2.3	1.6	1.9	1.5
Luminosity	6.9	4.8	3.4	4.0	3.2
Total	49.2	30.4	20.2	25.4	26.0

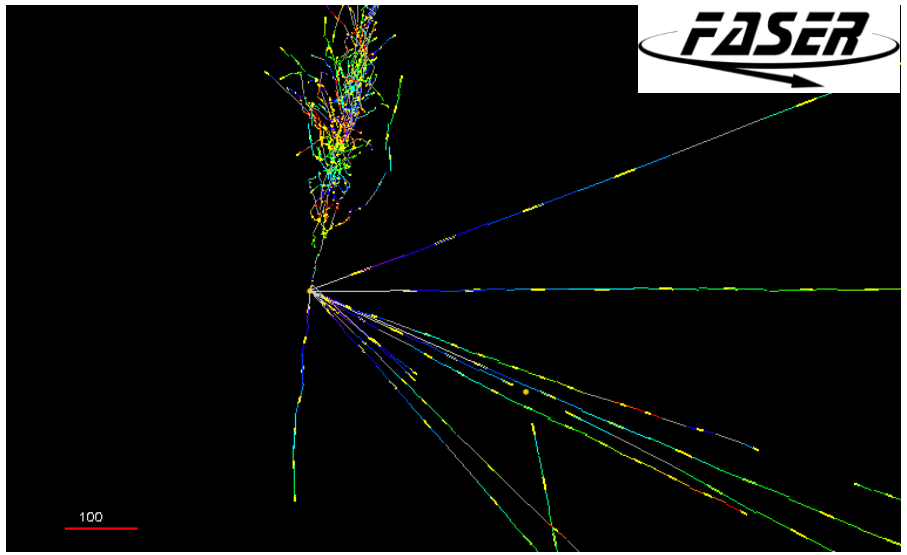
Neutrino flux modeling is the dominant source of uncertainty

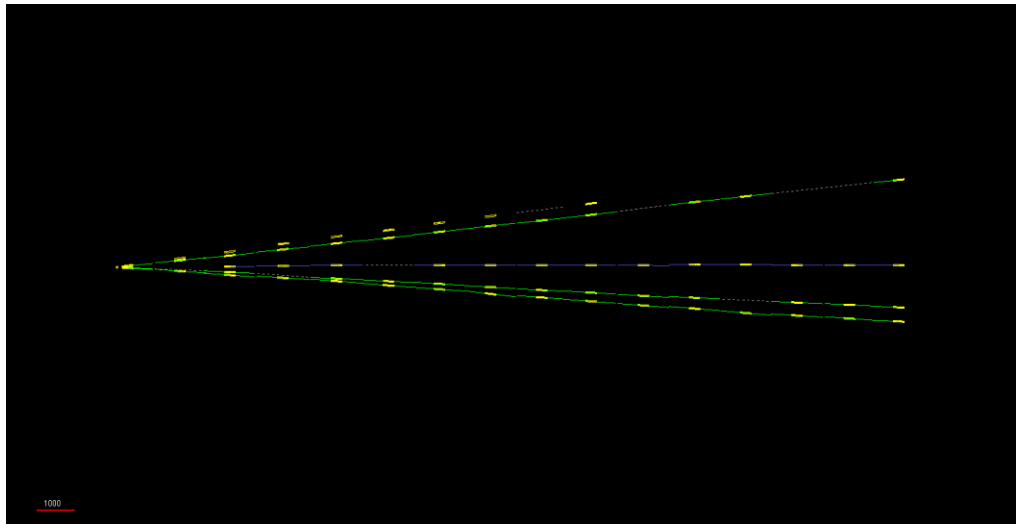
Emulsion Detector Data Analysis

- Significant parts from 2022 data have been already scanned. 2023 data to start
- Examples of vertices found based on predictions from electron detectors
- FASER released a first analysis based on the emulsion data
- Performance affected by muon background…



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



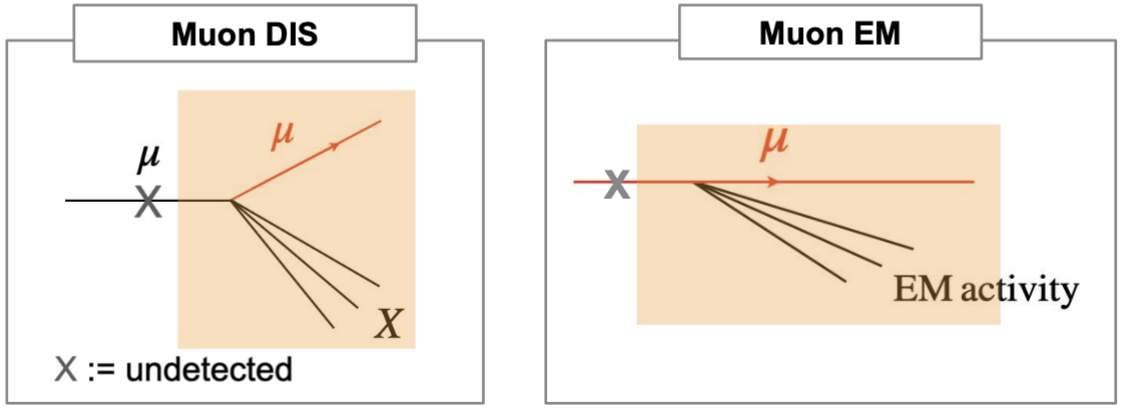


- Concern: Due to change in machine optics the muon background is 2x larger in 2024!

SND@LHC backgrounds

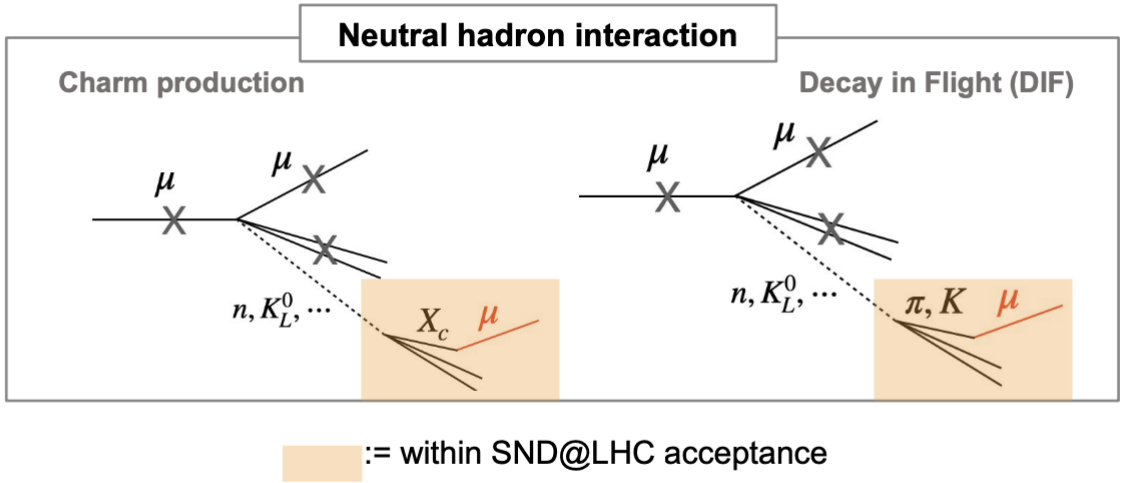
Entering muons

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



Neutral hadrons

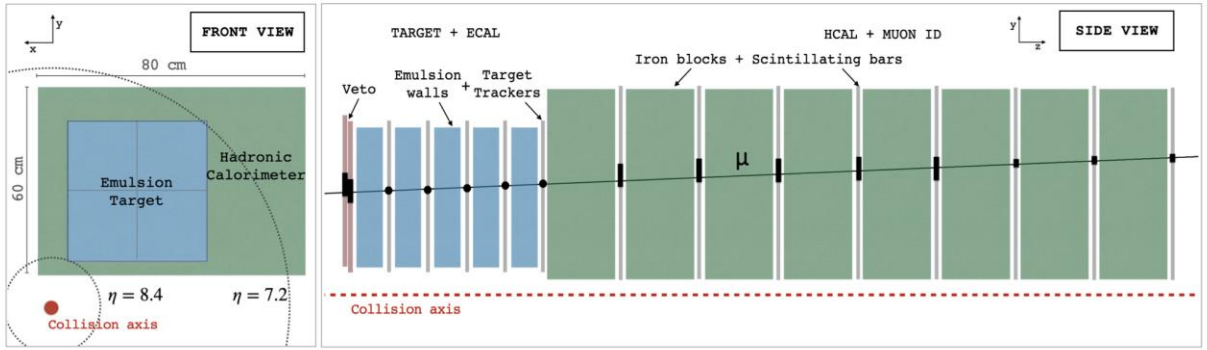
- Neutral hadrons are produced in muon DIS in materials upstream of the detector.
- Muon from pion decay-in-flight or charm production.
- Expect a total of **(8.6 ± 3.8) x 10^{-2}** background events due to neutral hadrons.



SND@LHC backgrounds

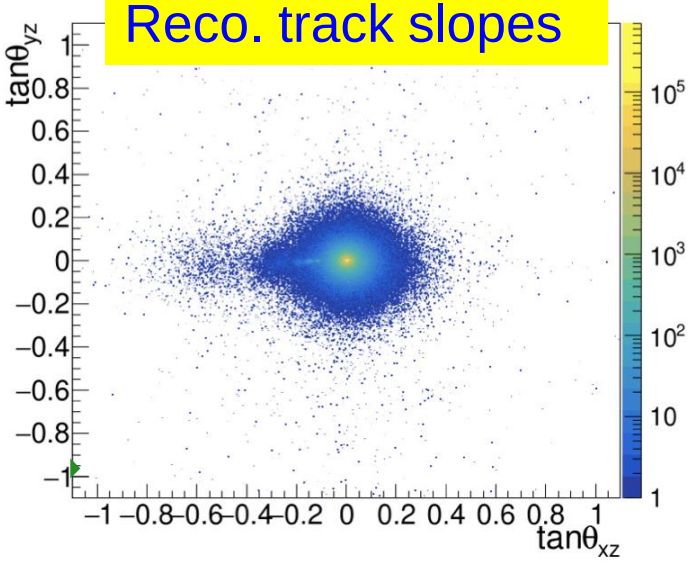
CERN-EP-2023-222

- The majority of the background from muons from pp interactions
  - Muon flux measurements in situ during physics runs
  - Compare with the Monte Carlo (FLUKA) predictions

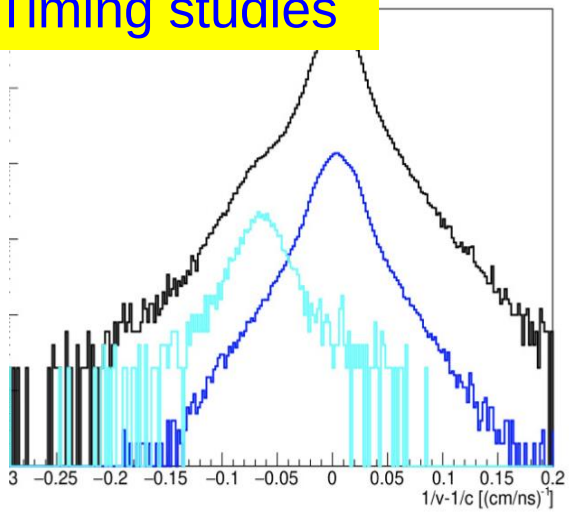


system	muon flux $[10^4$ fb/cm$^2]$ *same fiducial area*
SciFi	$2.06 \pm 0.01(\text{stat.}) \pm 0.12(\text{sys.})$
DS	$2.02 \pm 0.01(\text{stat.}) \pm 0.08(\text{sys.})$

Reco. track slopes



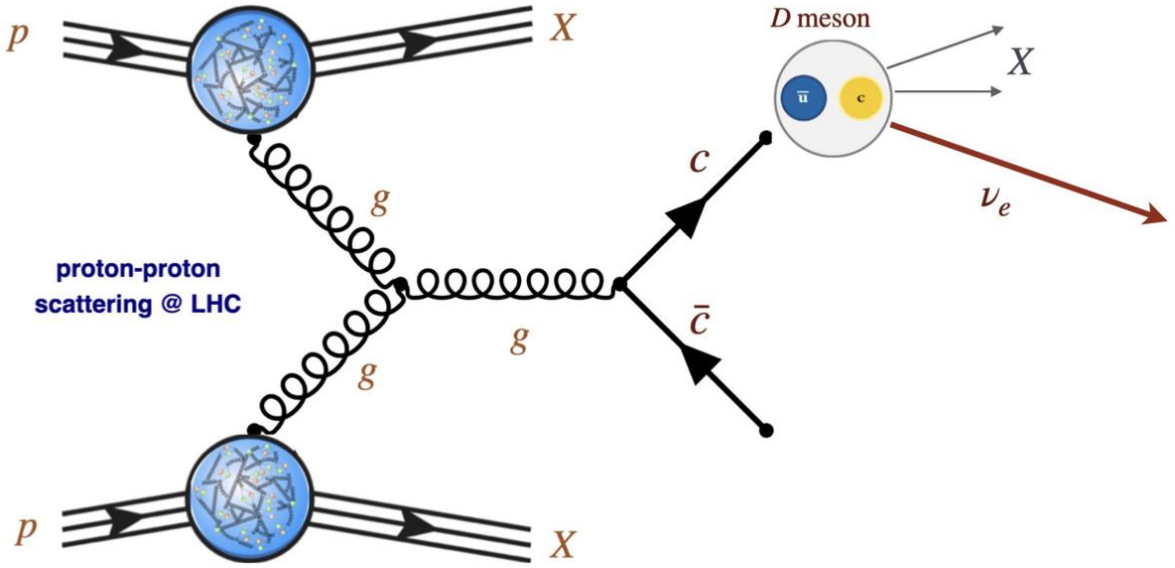
Timing studies



system	sample	muon flux $[10^4$ fb/cm$^2]$	$1-\frac{\text{sim}}{\text{data}}$ [%]
on the level of eff. corrected data and generator MC flux			
SciFi	data	$2.06 \pm 0.01(\text{stat.}) \pm 0.12(\text{sys.})$	22 ± 9
	sim	$1.60 \pm 0.05(\text{stat.}) \pm 0.19(\text{sys.})$	
DS	data	$2.35 \pm 0.01(\text{stat.}) \pm 0.10(\text{sys.})$	24 ± 9
	sim	$1.79 \pm 0.03(\text{stat.}) \pm 0.15(\text{sys.})$	

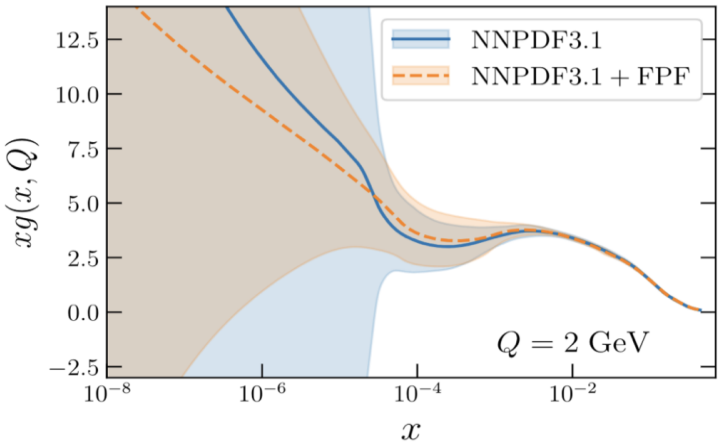
Data-MC difference ~ 25%

Neutrinos as a probe for charm production

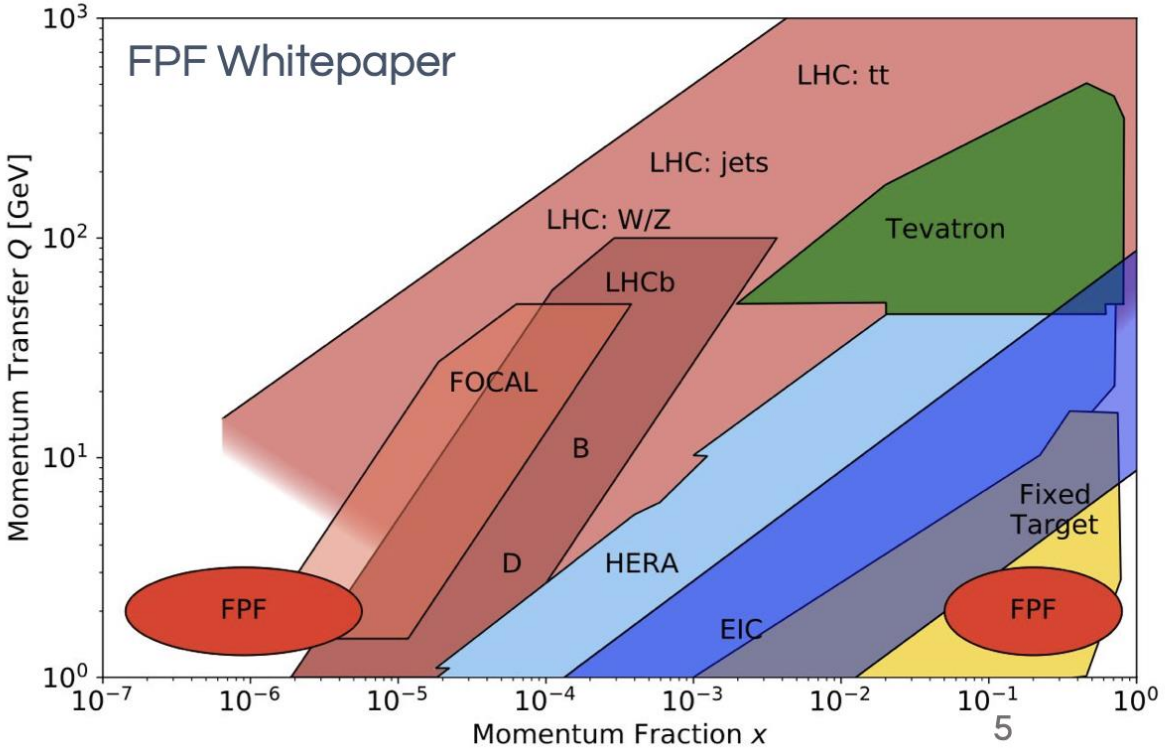


- Dominant partonic process: **gluon-gluon** scattering.
- SND@LHC will constrain the gluon PDF in the **very small x** region.
  - Only LHC neutrinos have sensitivity in this region.
- Relevant for **FCC-pp, ultra-high energy neutrinos** and **cosmic rays.**

Electron neutrinos, 2% uncertainty in inclusive event rates

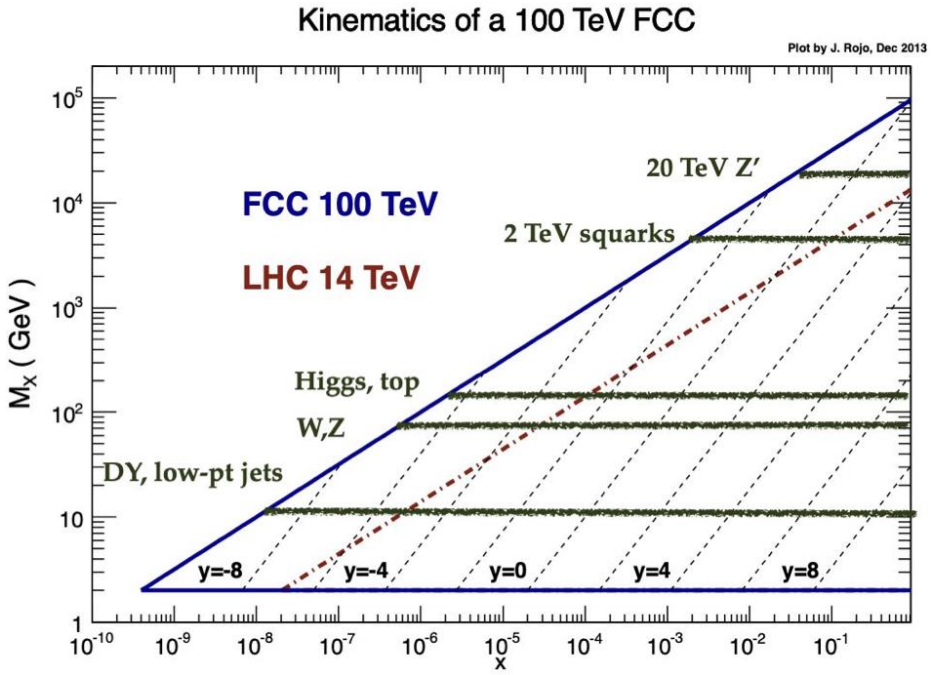


$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$



Implications for FCC-pp

- Much of the ***FCC-pp*** physics will be produced at very ***small x***.
  - Even electroweak and Higgs measurements will be sensitive to ***small-x QCD***.
- Current estimates show a ***large reduction*** in FCC-pp ***cross sections*** with ***constraints*** from the ***HL-LHC neutrino*** data.



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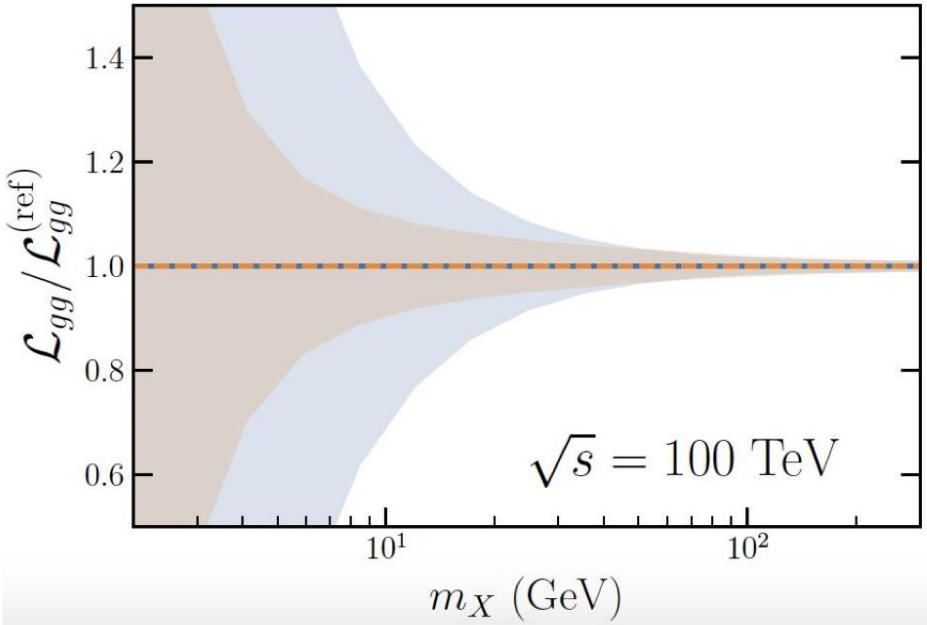
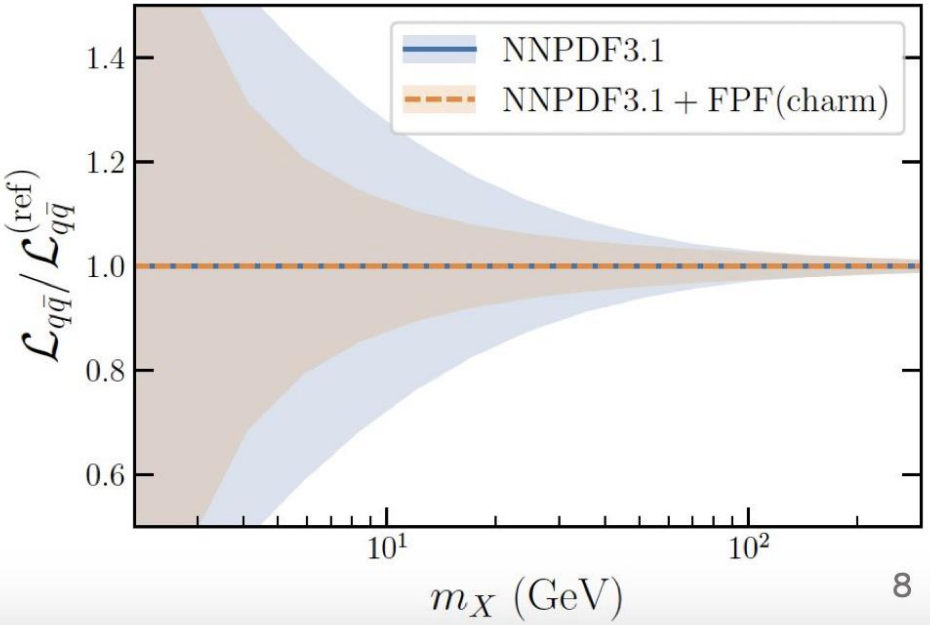
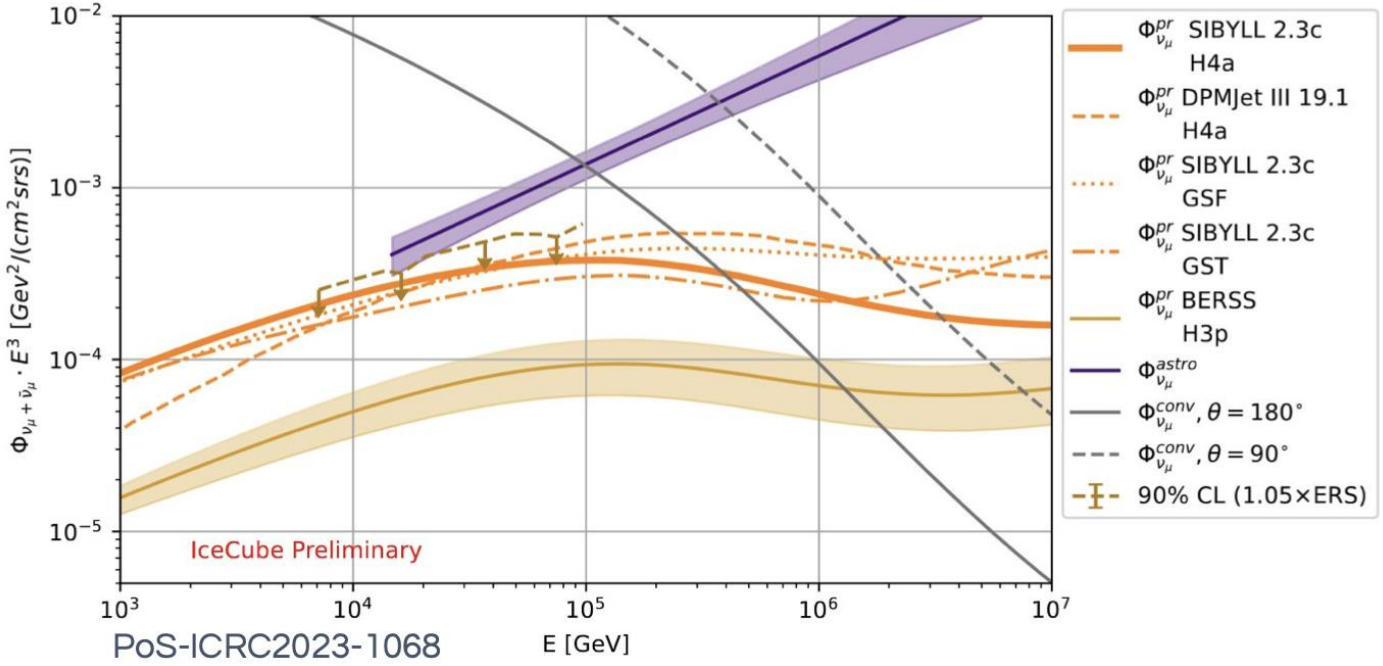




Implications for astroparticle physics

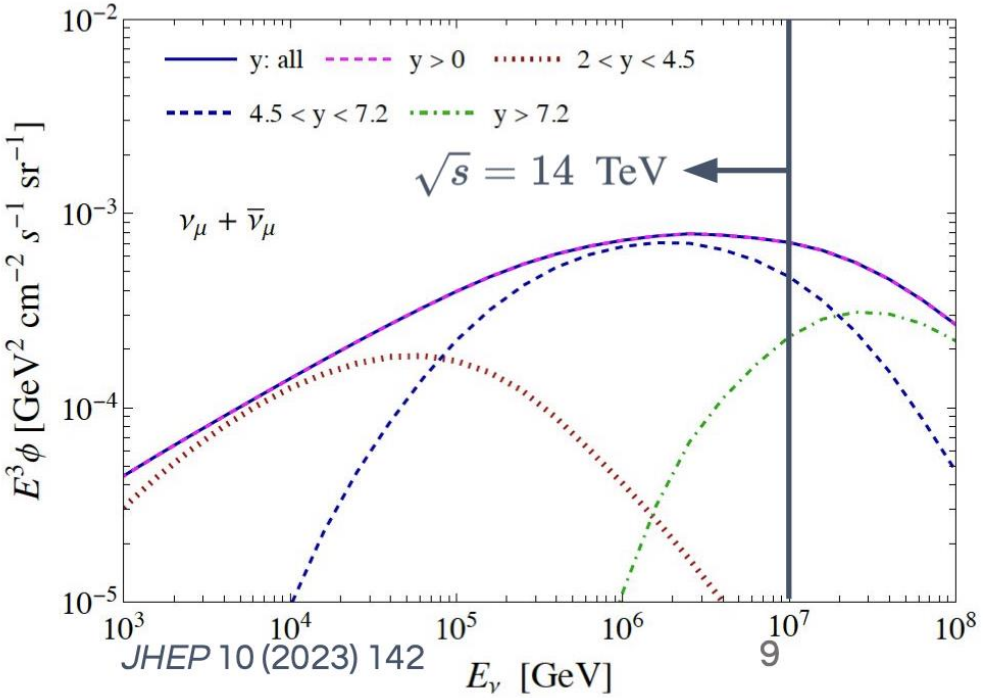
- The ***prompt*** flux of atmospheric neutrinos, originating from charm decays, is not known.
  - This is an important component in the ***transition region*** between ***atmospheric*** and ***astrophysical*** neutrino flux.
- LHC neutrinos originating from ***charm*** hadrons with rapidities > ~ 7 correspond to atmospheric neutrino energies up to **10^7 GeV**, in the ***transition region***.

Current IceCube limits on the prompt neutrino flux, along with model predictions.



PoS-ICRC2023-1068

Prompt flux of atmospheric neutrinos broken down by charm hadron rapidity in the pp collision frame.



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Lepton flavour universality

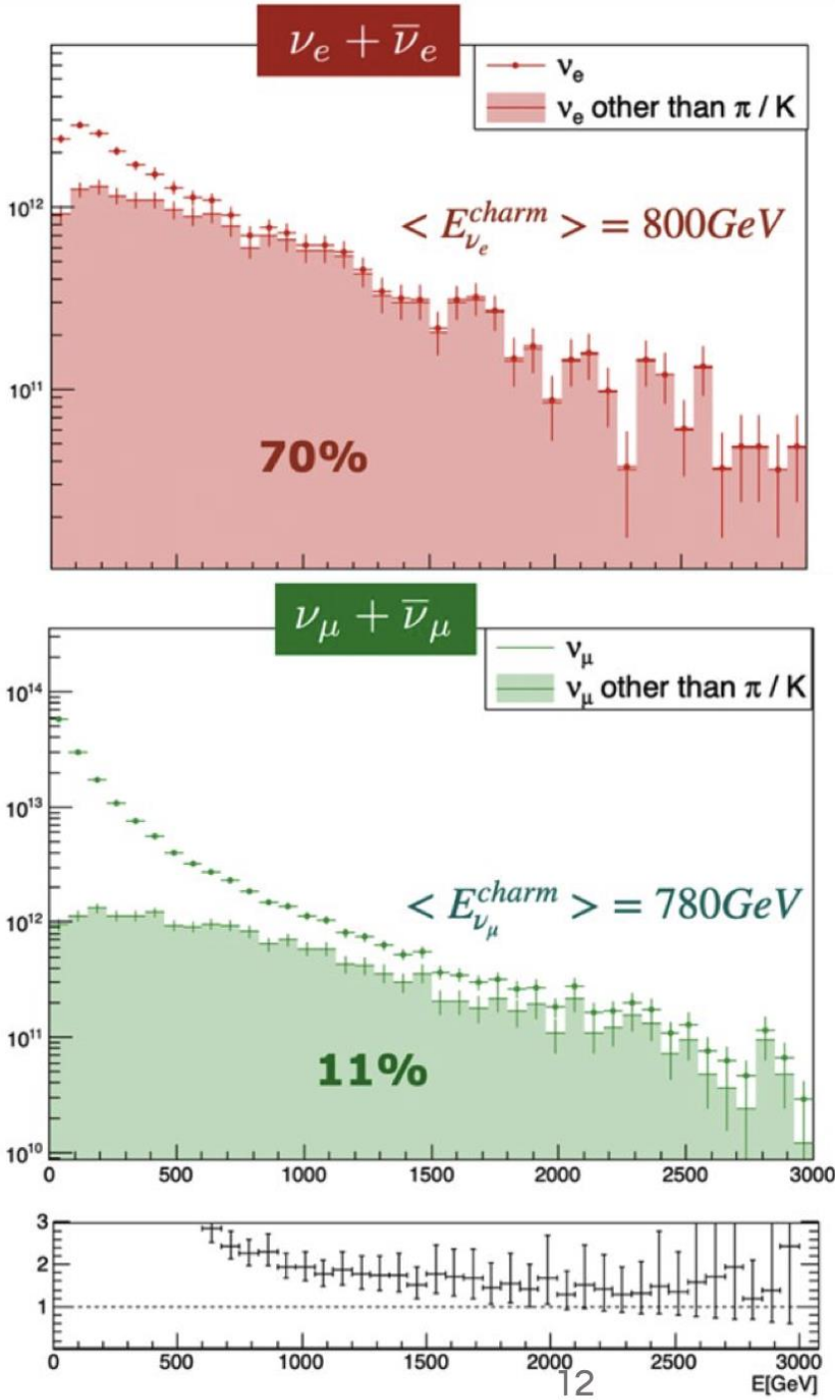
- Significant ***charm*** hadron contribution to the flux of ***all neutrino flavours***.
- Overall flux normalization ***cancels out*** in flavour ***ratios***.
- This enables the test of ***LFU*** with ***neutrinos***.

$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)} \qquad R_{12} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\mu+\overline{\nu}_\mu}} = \frac{1}{1+\boxed{\omega_{\pi/k}}}$$

π/K contamination

- Uncertainty on Run 3 R_{13} determination is dominated by low ν_τ statistics.

- Expect systematic uncertainty reduction in Run 4:
- Improved forward π flux ***measurements*** at 13 TeV with ***LHCf***.
  - Same strategy as in neutrino ***cross section*** measurements.
- ***Bin*** data in η, ν energy, and ν vs $\overline{\nu}$ to reduce impact of charm production uncertainties.
  - Same strategy as in ***QCD*** measurements.



Neutrino constraints on the gluon PDF

- Constraining the gluon PDF requires observables where the theory systematics cancel out. Make use of ***ratios***:
  - To a reference pseudorapidity bin
  - Between CoM energies
  - Between correlated observables

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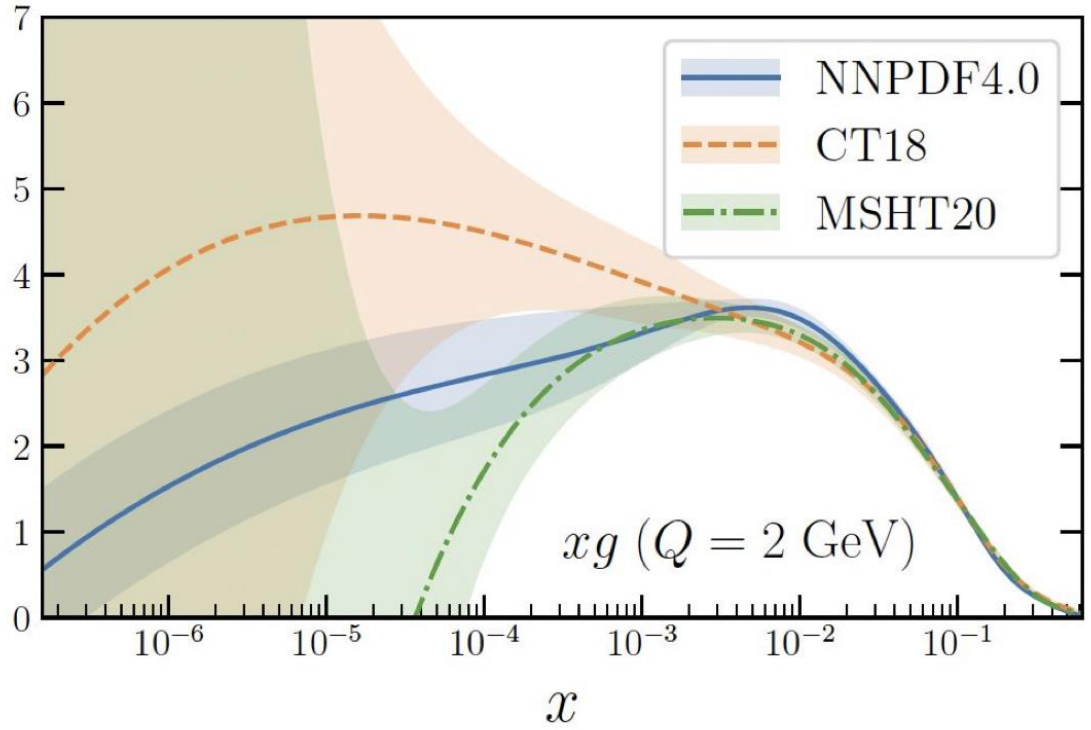
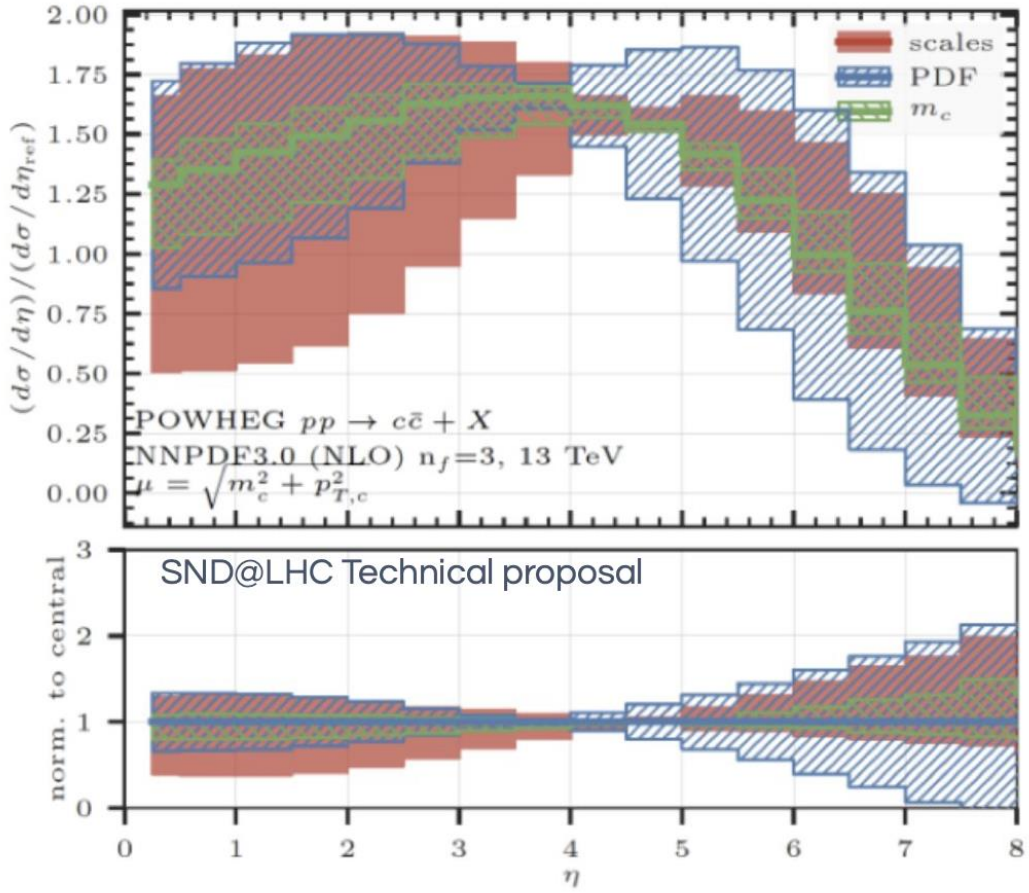


SND@LHC TP approach:
LHCb charm production data as ***reference***.



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