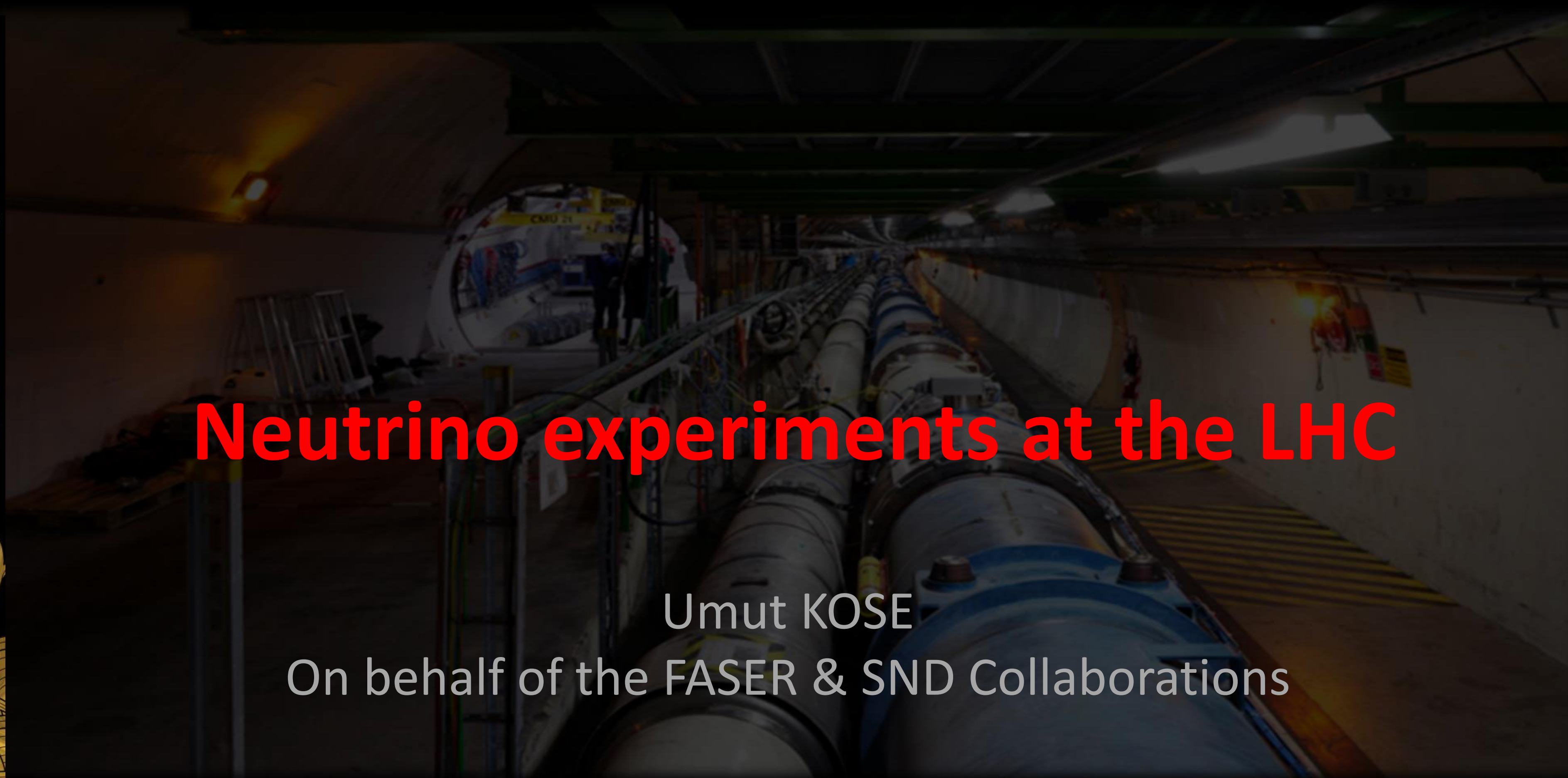


Neutrino experiments at the LHC

Umut KOSE

On behalf of the FASER & SND Collaborations

22nd Conference on Flavor Physics and CP Violation

FPCP 2024, 27-31 May 2024

History

- Neutrinos detected from many sources, but not from colliders

- Neutrinos at collider were considered in 80s and 90s but never realized:
  - A. De Rujula, R. Ruckl, Neutrino and muon physics in the collider mode of future accelerators (1984)
  - Klaus Winter, Detection of the tau neutrino at the LHC (1990)
  - F. Vannucci, Neutrino physics at LHC/SSC (1993)
  - A. De Rujula, E. Fernandez, J.J. Gomez-Cadenas, Neutrino fluxes at future hadron colliders (1993)
  - H. Park, The estimation of neutrino fluxes produced by proton-proton collisions at $\sqrt{s}$ = 14 TeV of the LHC (2011)

- Two experiments were approved: FASER (2019) and SND (2021) to study for high energetic neutrinos as well as to search light and extremely weakly interacting long-lived particles produced in forward region at the Large Hadron Collider (LHC) at CERN

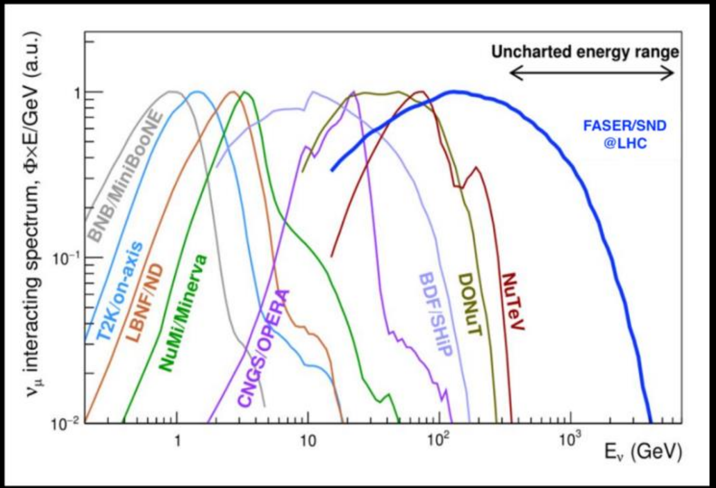
- First neutrino interaction candidates at collider/LHC observed by the FASERν pilot run in 2018* (using 29 kg emulsion-W module, collecting 12.2 fb^{-1}) FASER Collaboration: arXiv:2105:06197

- A new era in collider neutrino physics allowing to explore unexplored energy region

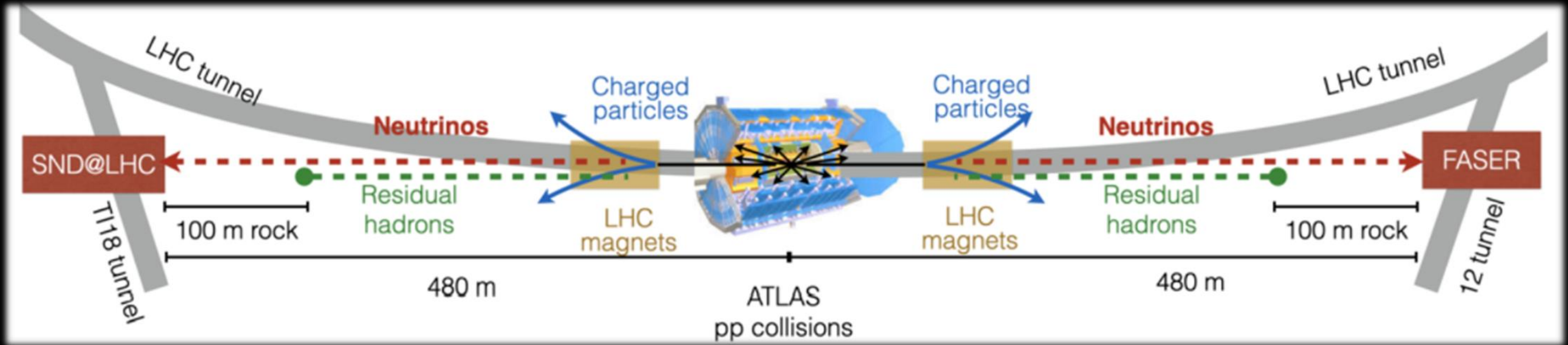
- LHC Run3 physics run started in 2022

* Two FASERν pilot run in 2018 to study the charged particle flux and for neutrino detections as a proof of principle.

LHC as Neutrino Beam Line



- Huge flux of neutrinos at LHC produced at collision points in the far forward direction, from a variety of sources: pion, kaon, hyperon and charm decays.
  - Intense: ~10^{12} neutrino in LHC Run3
  - Highly collimated, beam size $\approx O(10cm)$
  - ~TeV neutrinos/antineutrinos in all flavours



- FASER/FASERν and SND are dedicated to study unexplored energy regime (TeV neutrinos)
- Study production, propagation and interactions of high energy neutrinos
- Probing neutrino related models to new physics

Physics potential: high energy neutrino interactions

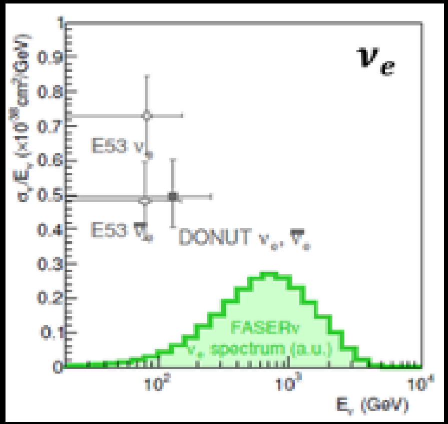
- Cross section measurements of different flavor at TeV energies.

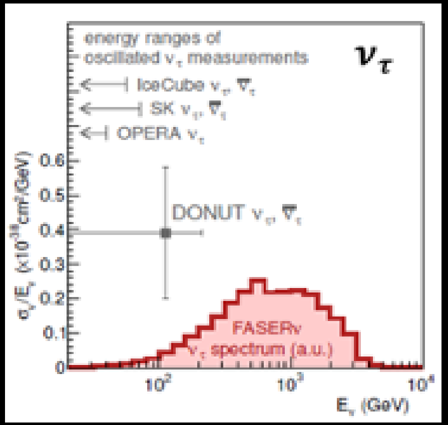
FASER Collaboration, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310
SND Collaboration, CERN-LHCC-2021-003 / LHCC-P-016

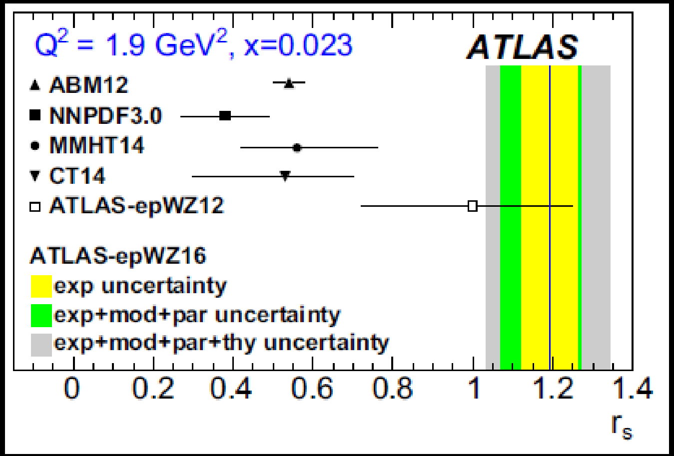
- Test lepton flavour universality in neutrino interactions by comparing cross-sections
- Neutrino CC interaction with charm production ($\nu s \rightarrow lc$):
    - Study the strange quark content: $r_s = \frac{s+\bar{s}}{2\bar{d}}$
    - Probe inconsistency between the predictions and the LHC data

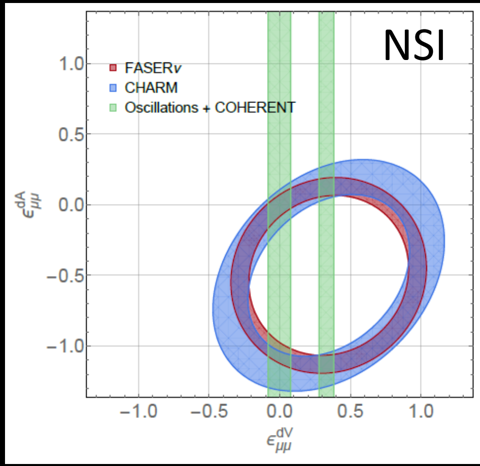
      Eur. Phys. J. C77 (2017) 367
    - to date no charmed hadron observed in $\nu_e CC$ interactions
- Search for anomalous b-quark production in neutrino interactions
- Neutrino NC measurements could constrain neutrino non-standard interactions.

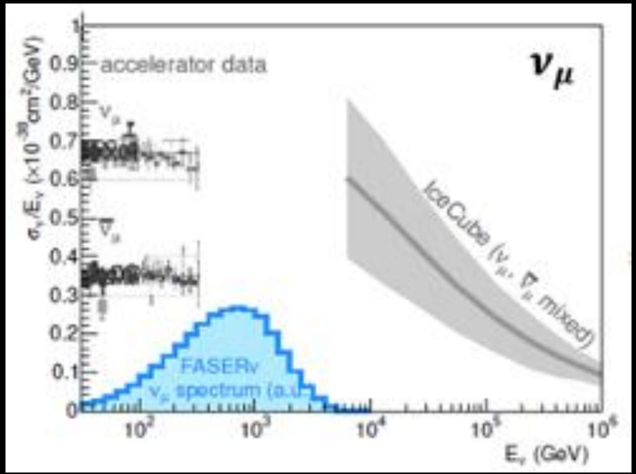
A. Ismail, R.M. Abraham, F. Kling ,Phys. Rev. D 103, 056014 (2021), arXiv:2012.10500





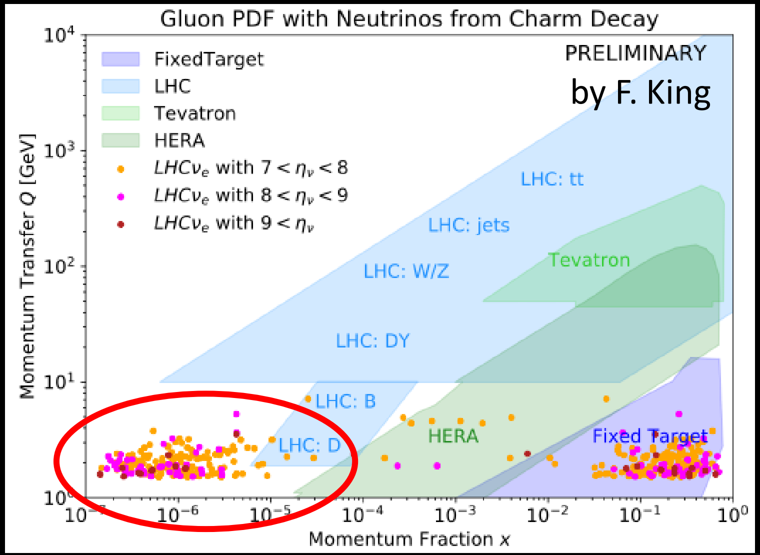


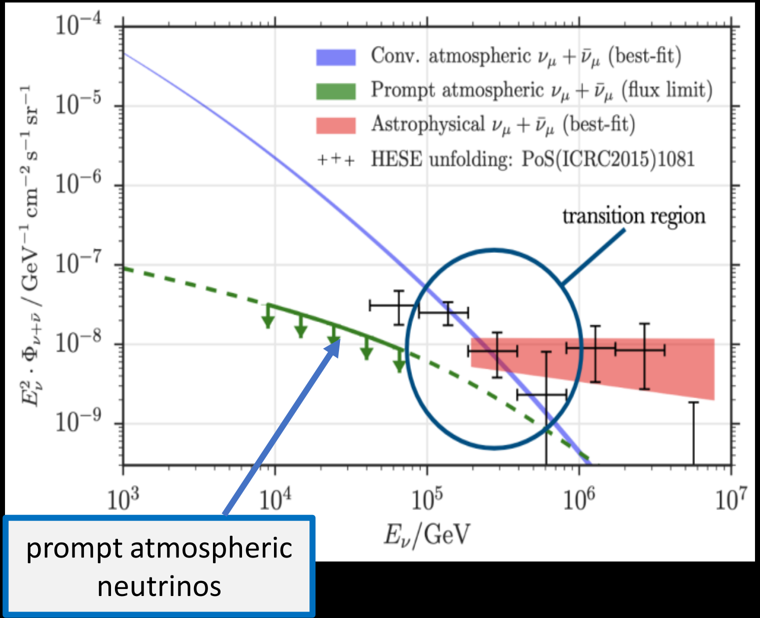




Physics potential: Forward particle production

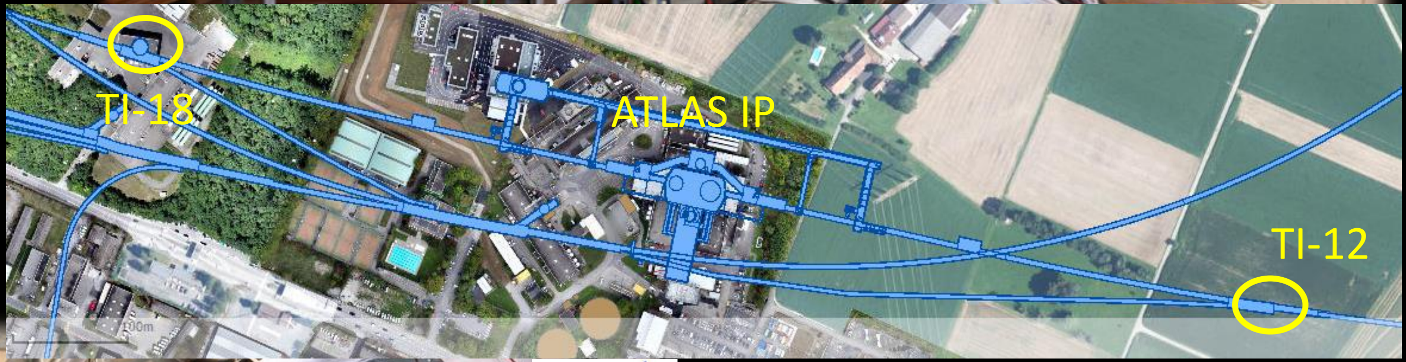
- Neutrinos produced in the forward direction at the LHC originate from the decay of hadrons, mainly pions, kaons, and charm particles.
- Forward particle production is poorly constrained by other LHC experiments. Neutrino flux measurement both at SND and FASER will provide complimentary constraints that can be used to validate/improve MC generators.
- Neutrinos from charm decay could allow to test transition to small-x factorization, constrain low-x gluon PDF and probe intrinsic charm contributing to QCD → **relevant for FCC**
- Having precise measurements of the cosmic neutrino flux in high energy neutrino telescopes, accelerator measurements of high energy and large rapidity charm production are needed. As 7+7 TeV p-p collision corresponds to 100 PeV proton interaction in fixed target mode, a direct measurement of the prompt neutrino production would provide important basic data for current and future prompt atmospheric high-energy neutrino telescopes, such as ICECUBE.

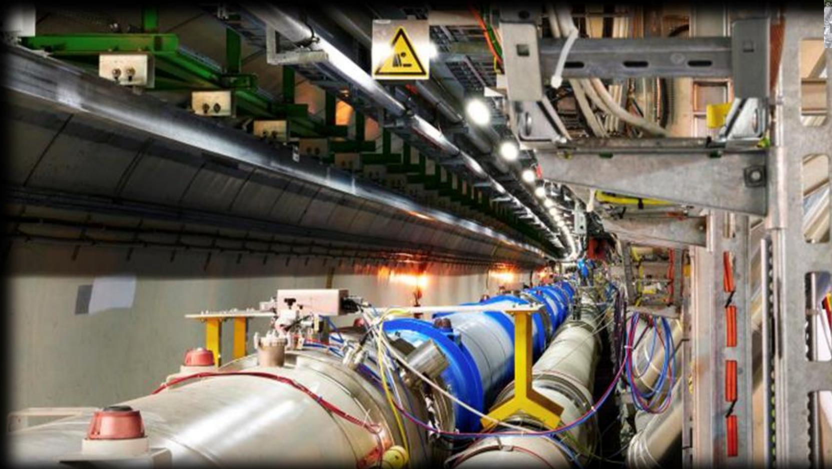




LHC Neutrino Experiments

- **@480 m away from ATLAS IP**
- **FASER @ TI-12 and SND @ TI-18**
- **FASER located at on-axis ($\eta > 8.8$) along the LoS allows increasing statistics, while SND located at off-axis ($7.2 < \eta < 8.4$) enhances charm contributions**
- **Muon background levels low at both sites**
- **Starting data taking since 2022**





Expected neutrino event rate in LHC Run3

- Neutrino production:
  - For light hadrons (pions, kaons and hyperons) EPOS-LHC, QGSJET II-04, SIBYLL2.3d, PYTHIA8, DPMJET
  - For charm hadrons POWHEG+PYTHIA8, DPMJET
- Propagation to detectors BDSIM/FLUKA model of the LHC
- Neutrino interactions with tungsten/emulsion GENIE
- Propagation in the detector GEANT4
- LHC Run3 with an integrated luminosity of 250 fb^{-1}

Flavour	Neutrinos in acceptance ⟨E⟩ [GeV]	Neutrinos in acceptance Yield	CC neutrino interactions ⟨E⟩ [GeV]	CC neutrino interactions Yield	NC neutrino interactions ⟨E⟩ [GeV]	NC neutrino interactions Yield
ν_μ	130	3.0×10^{12}	452	910	480	270
$\bar{\nu}_\mu$	133	2.6×10^{12}	485	360	480	140
ν_e	339	3.4×10^{11}	760	250	720	80
$\bar{\nu}_e$	363	3.8×10^{11}	680	140	720	50
ν_τ	415	2.4×10^{10}	740	20	740	10
$\bar{\nu}_\tau$	380	2.7×10^{10}	740	10	740	5
TOT		4.0×10^{12}		1690		555

CERN-LHCC-2021-003 / LHCC-P-016

Neutrino CC interactions

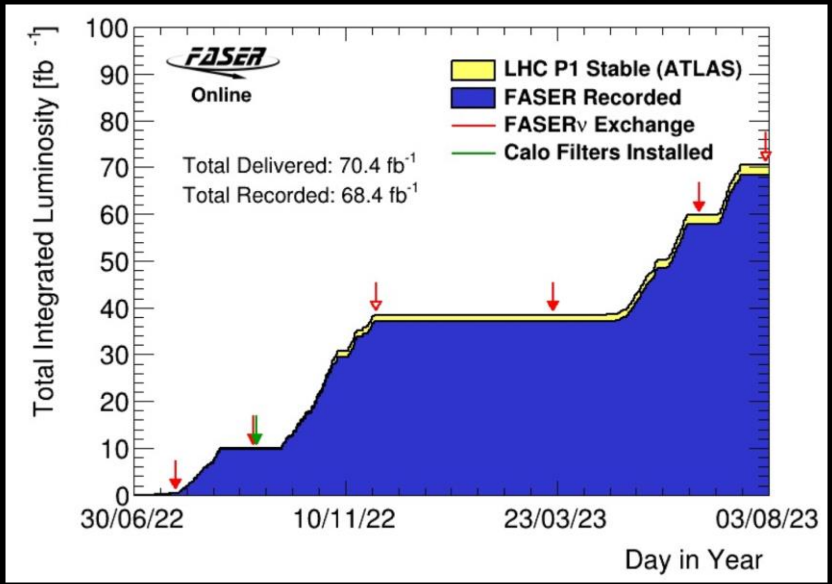
Generators: light hadrons	Generators: charm hadrons	FASERν at Run 3: $\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
EPOS-LHC	–	1149	7996	–
SIBYLL 2.3d	–	1126	7261	–
QGSJET 2.04	–	1181	8126	–
PYTHIAforward	–	1008	7418	–
–	POWHEG Max	1405	1373	76
–	POWHEG	527	511	28
–	POWHEG Min	294	284	16
Combination		1675^{+911}_{-372}	8507^{+992}_{-962}	28^{+48}_{-12}

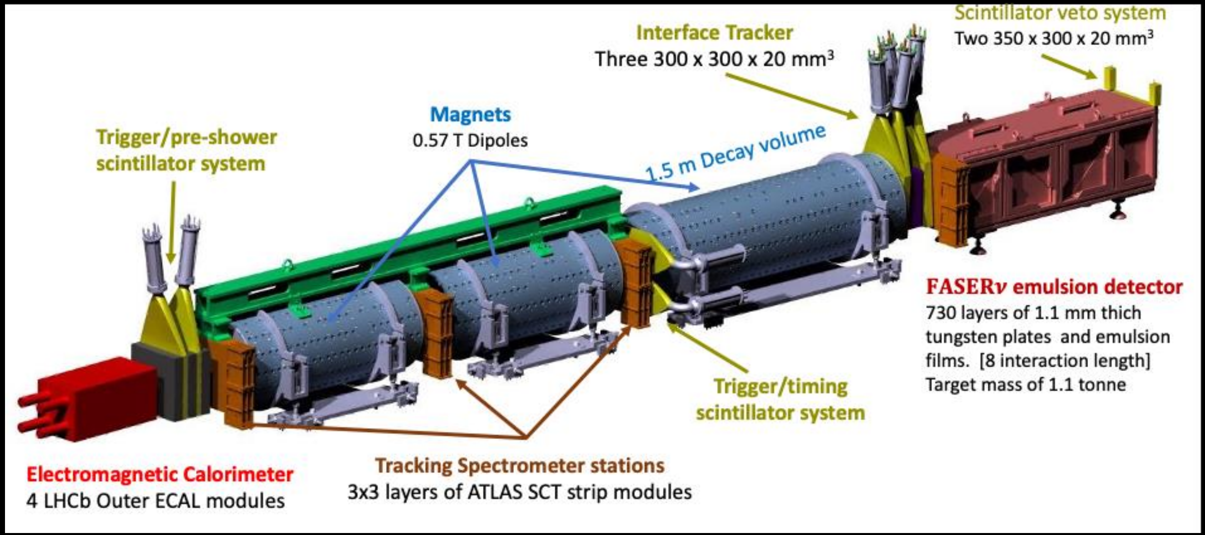
FASER Coll. arXiv:2402.13318

Directly observed $\nu_\tau CC$ interactions: 9 at DONUT and 10 at OPERA experiments

FASER Detector and its operation in LHC Run3

- Small detector: 10 cm radius of active volume, 7 m long
- Angular acceptance: $\eta > 9$, on-axis
- FASERν neutrino detector (Emulsion+Tungsten):
  - Target mass: 1.1 tons; 8 interaction length
- Successfully operated throughout 2022/2023
  - Continuous data taking; Largely automated; Trigger rate up to 1.5 kHz and DAQ dead-time of < 2%
- Recorded ~97% of delivered luminosity
- Emulsion detector exchanged five times during LHC Technical Stops
  - Needed to keep detector occupancy an acceptable level for analysis ($\mathcal{O}(10^6)$ tracks/cm)
- Calorimeter gain optimised for:
  - Low E (<300 GeV) before 2nd exchange
  - High E (up to 3 TeV) after the exchange



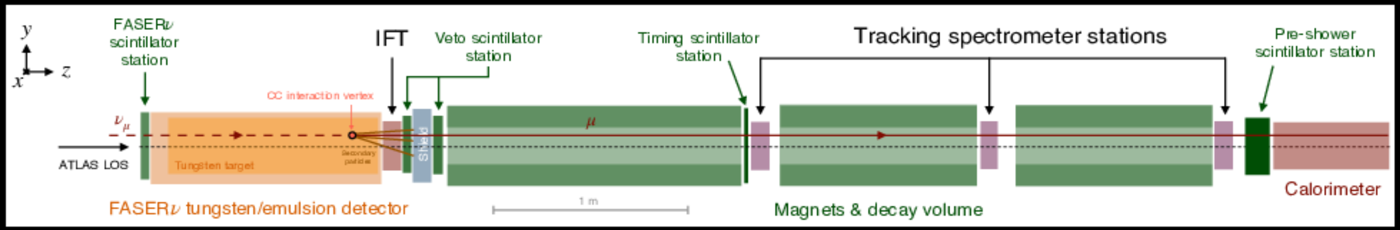


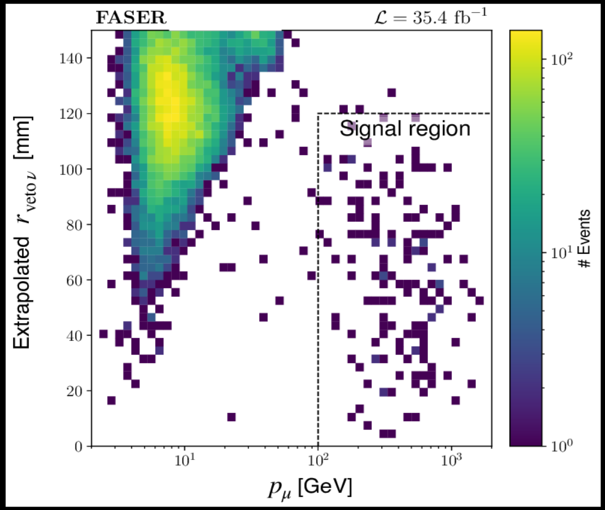
arXiv:2207.11427

Nearly 70 fb^{-1} of data recorded with data taking efficiency of 97%

First Direct Observation of Collider Neutrinos with FASER at the LHC

- Dataset collected at $\sqrt{s} = 13.6\ TeV$ from July to November 2022 corresponding to integrated lumiosity of 35.4 fb^{-1} used for the first direct observation of neutrino interactions using FASER electronic detector.

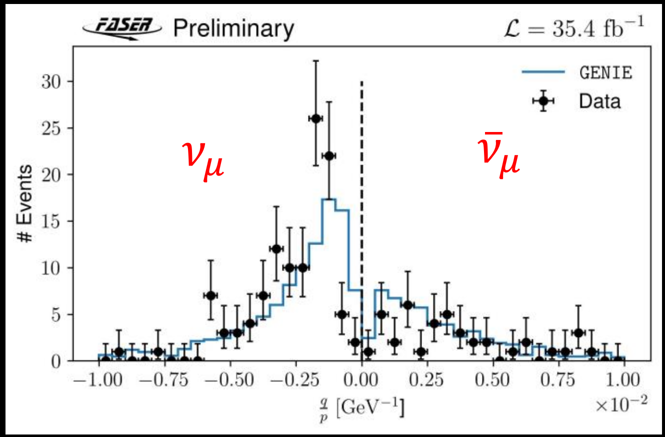


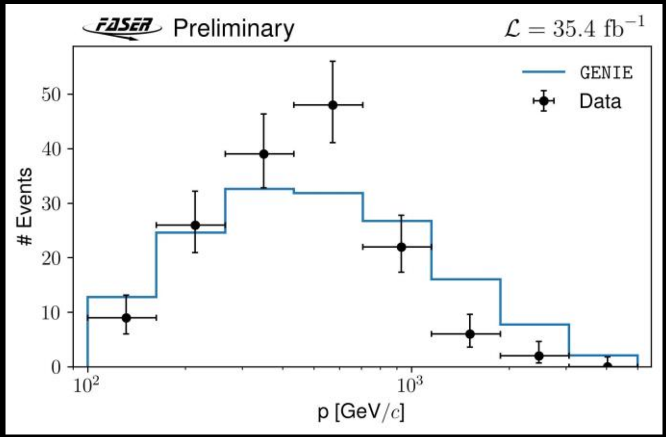


- Expecting 151 ± 41 neutrino events from GENIE simulation
  - Uncertainty from difference between generators (DPMJET & SIBYLL).
  - No experimental errors were included.

- Background:
  - Neutral hadrons: 0.11 ± 0.06 events
  - Muon scattering: 0.08 ± 1.83 events
  - Veto inefficiency: negligible

- Unblinded results:
  - 153 events in the signal region
  - Signal significance of 16σ

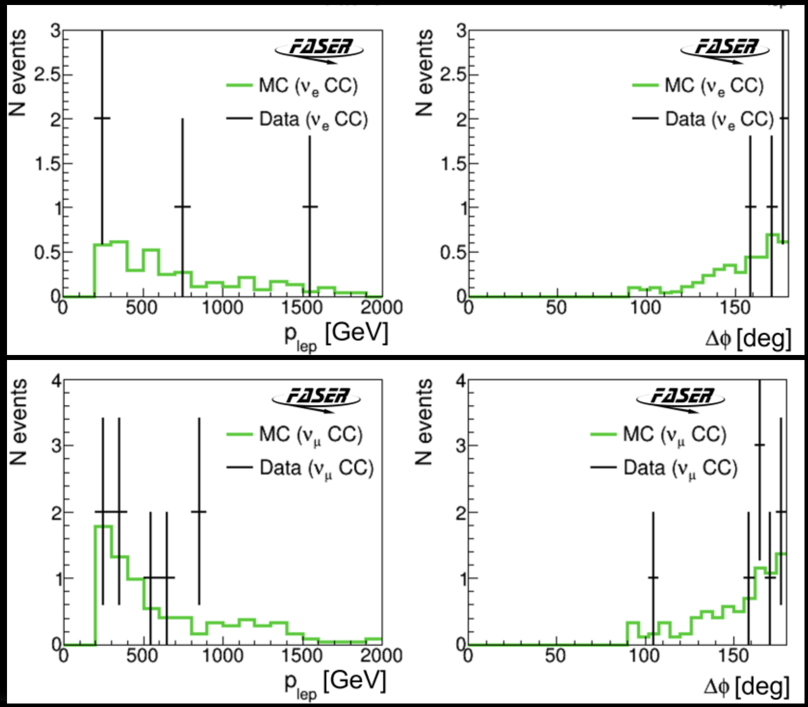




Phys. Rev. Lett. 131, 031801 (2023)

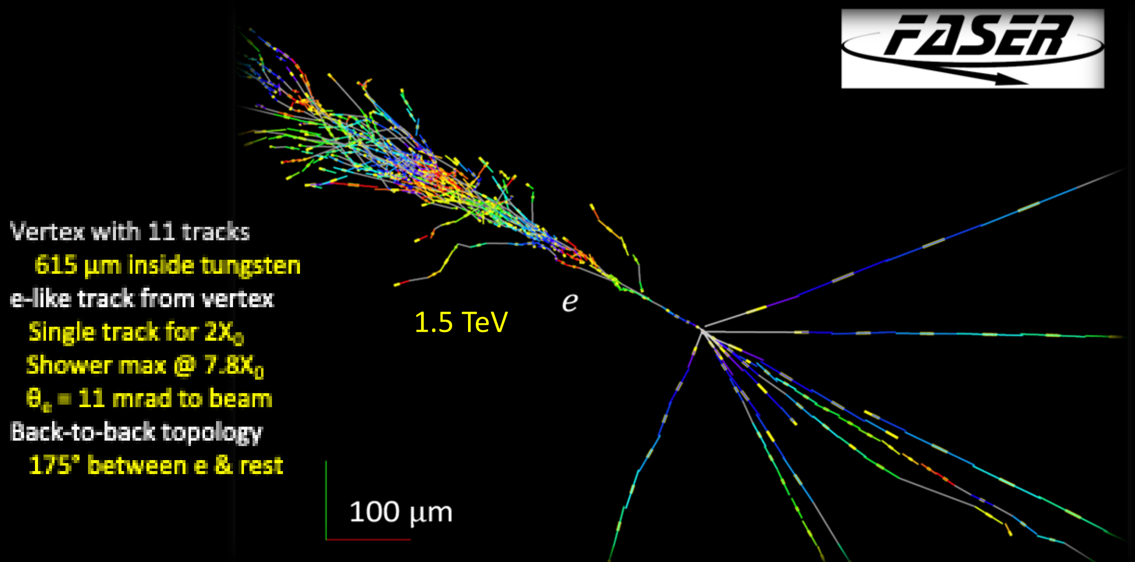
First direct observation of ν_e interactions at the LHC

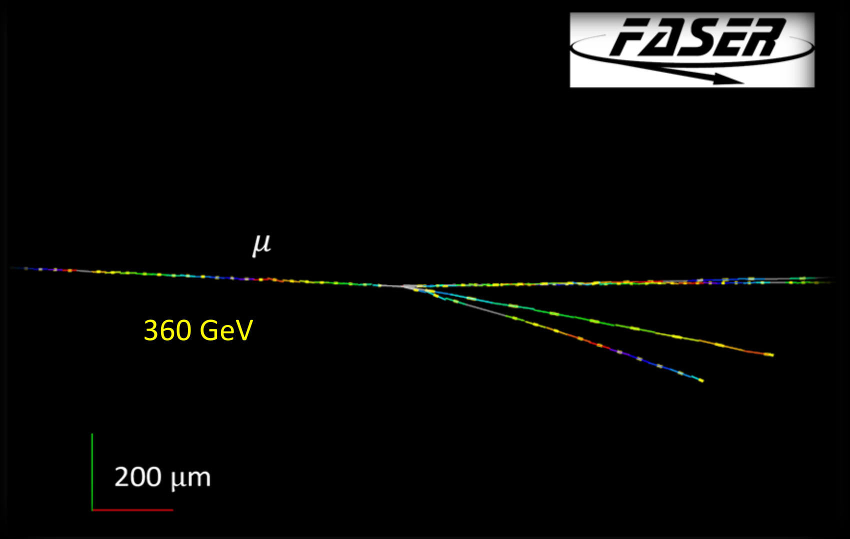
- Analysed dataset was collected by exposing to 9.5 fb^{-1} pp collision data from July to November 2022 at $\sqrt{s} = 13.6\ TeV$.
- A subset of the FASERν module corresponding to 128.6 kg analyzed
- Selecting vertices with associated lepton candidate, e or μ, with E_{lep} > 200 GeV



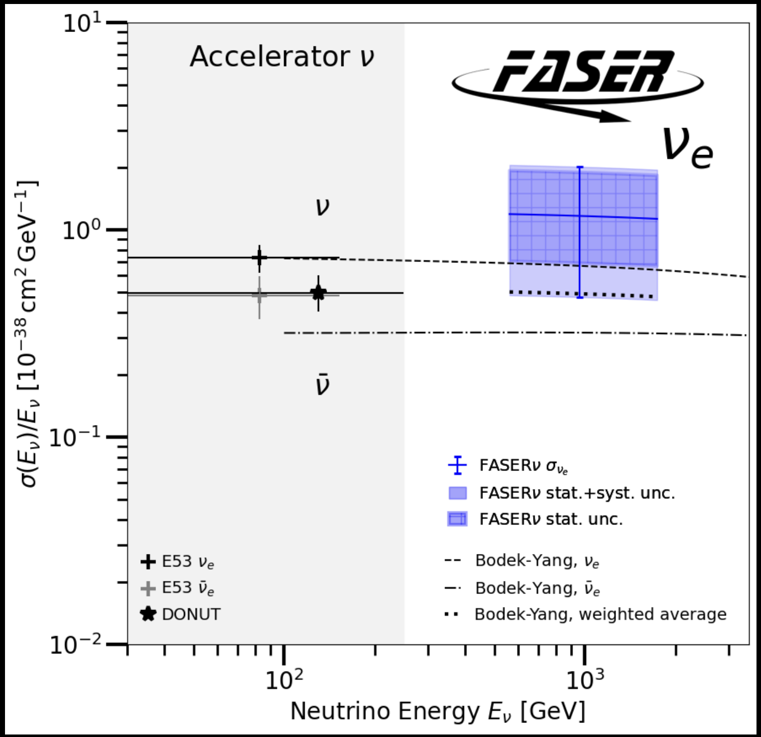
arxiV:2403.12520

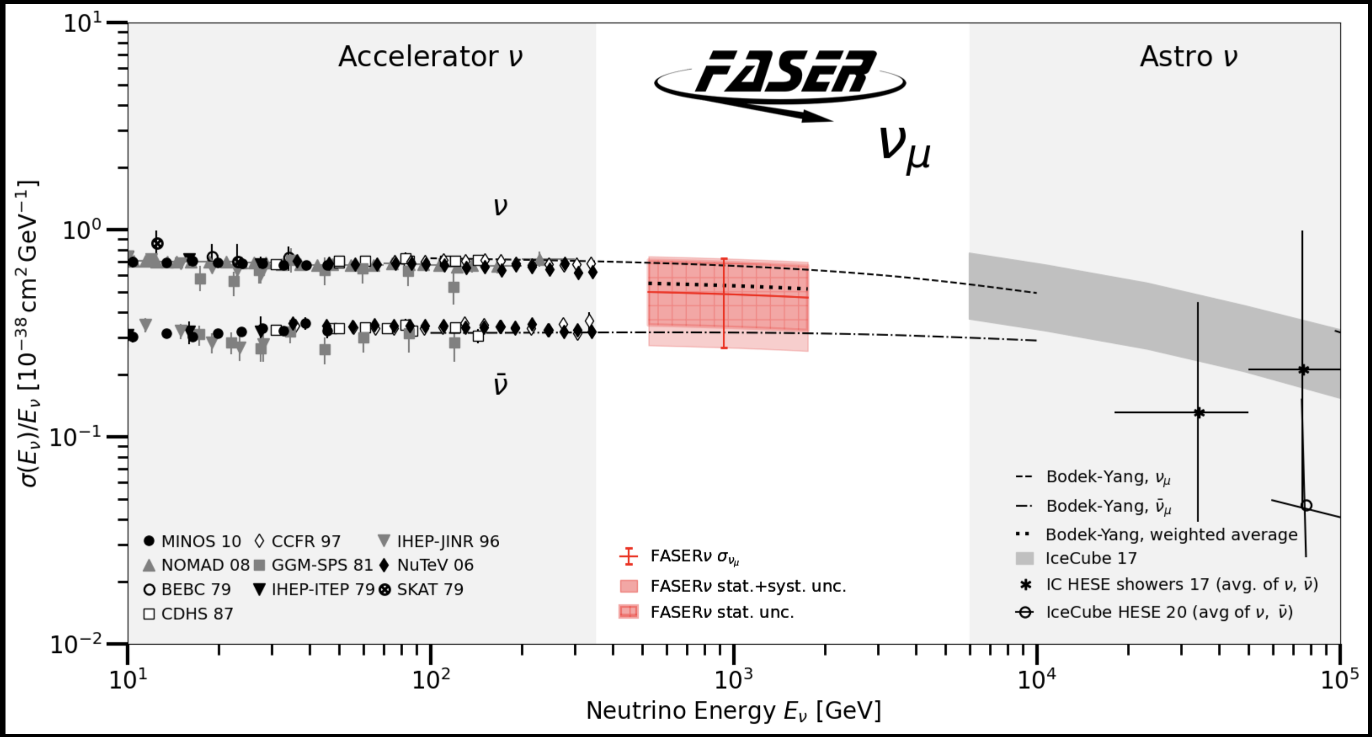
	Background	Expected	Observed	Significance
$\nu_e CC$	$0.025^{+0.015}_{-0.010}$	1.1 – 3.3	4	5.2σ
$\nu_\mu CC$	$0.22^{+0.09}_{-0.07}$	6.5 – 12.4	8	5.7σ





First measurement of the ν_e and ν_μ interaction cross-sections





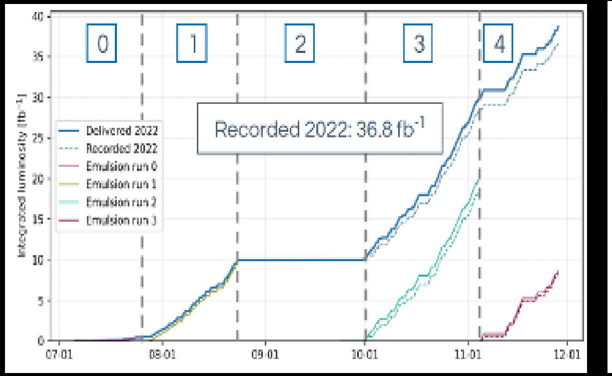
arxiV:2403.12520

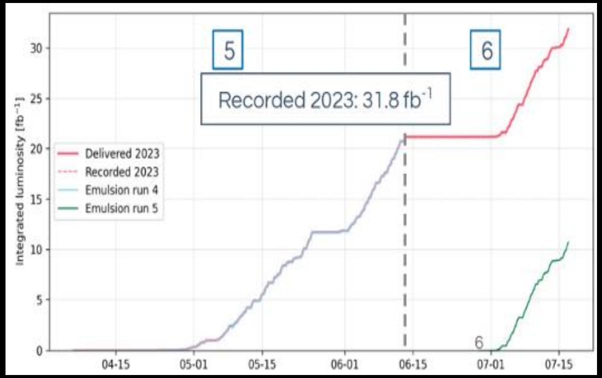
- The interaction cross-section per nucleon measured over an unexplored energy range
- Relative measurement with respect to theoretical curve
- 2% of the data used
- More measurements to come with higher statistics

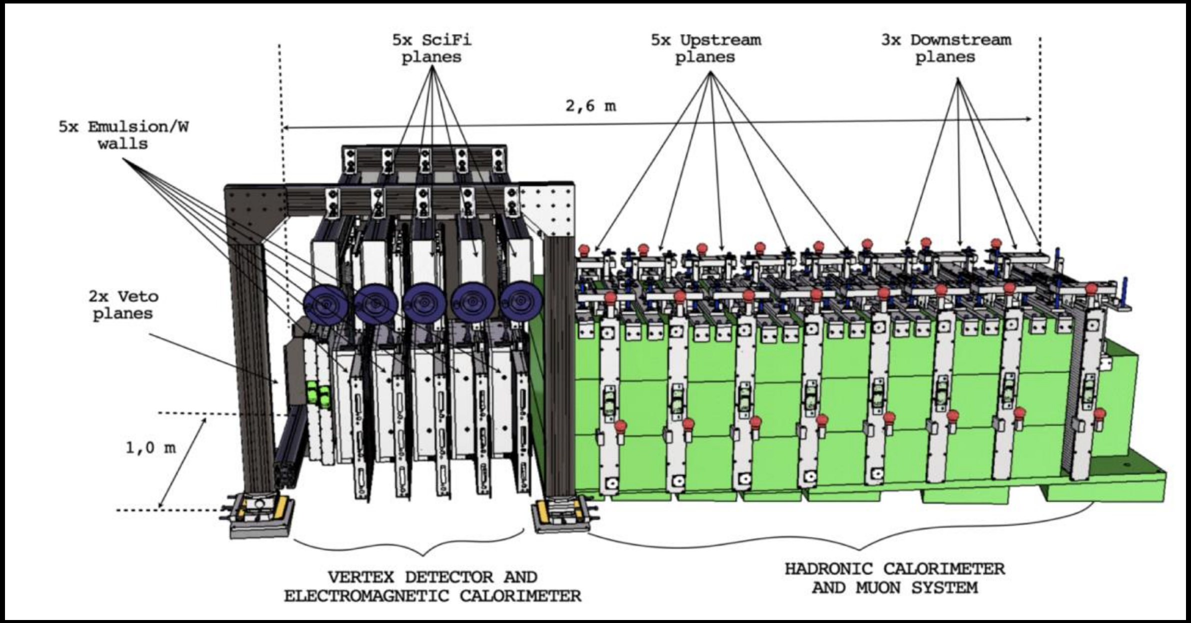
	Energy range [GeV]	σ_{obs}/E_ν [$cm^2 GeV^{-1}$]
$\nu_e - N$	560 – 1740	$(1.2^{+0.8}_{-0.7})\times10^{-38}$
$\nu_\mu - N$	520 - 1760	$(0.5^{+0.2}_{-0.2})\times10^{-38}$

SND Detector and its operation in LHC Run3

- Angular acceptance: $7.2 < \eta < 8.4$
- Target mass: 830 kg, 3 interaction length
- Five Emulsion+Tungsten (60 emsulsion films interleaved with 59 tungsten sheets) interleaved with SciFi trackers, followed by hadron calorimeter and muon system
- Exchanging 6 times SND emulsion modules
- About 68.6 fb^{-1} of p-p collisions recorded by the electronic detectors, with 97% detector uptime efficiency







Observation of Collider Muon Neutrinos with SND

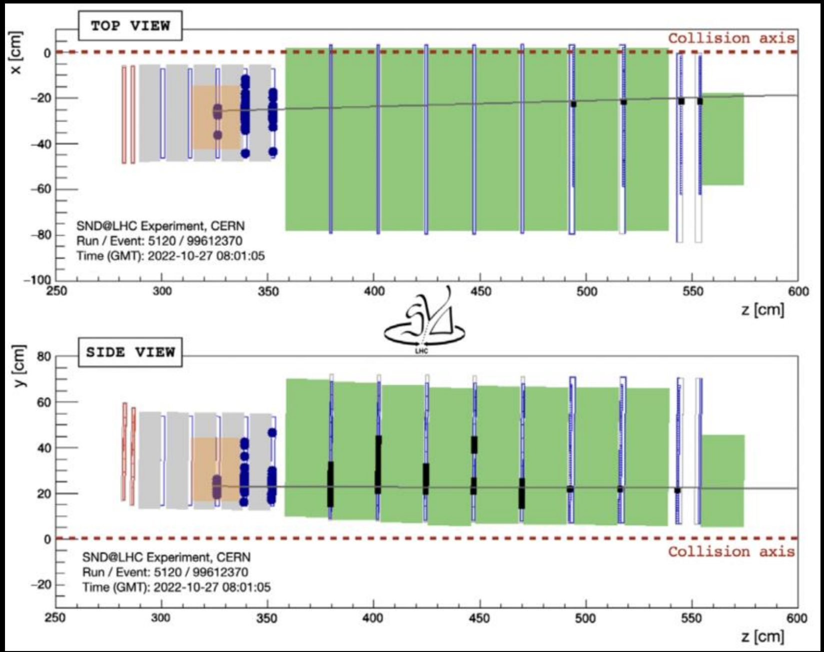
- 2022 data sample: (limited fiducial volume)
  - FLUKA/GENIE, 157±37 $\nu_\mu CC$ interactions expected in whole target
  - Hits in an inner XY detector region of 25 × 26 cm^2
  - Using Em+W walls of 3 and 4, overall efficiency of 7.5 %
  - Selecting events with large hadronic activity in the SciFi and HCAL, selection efficiency of 2.5%

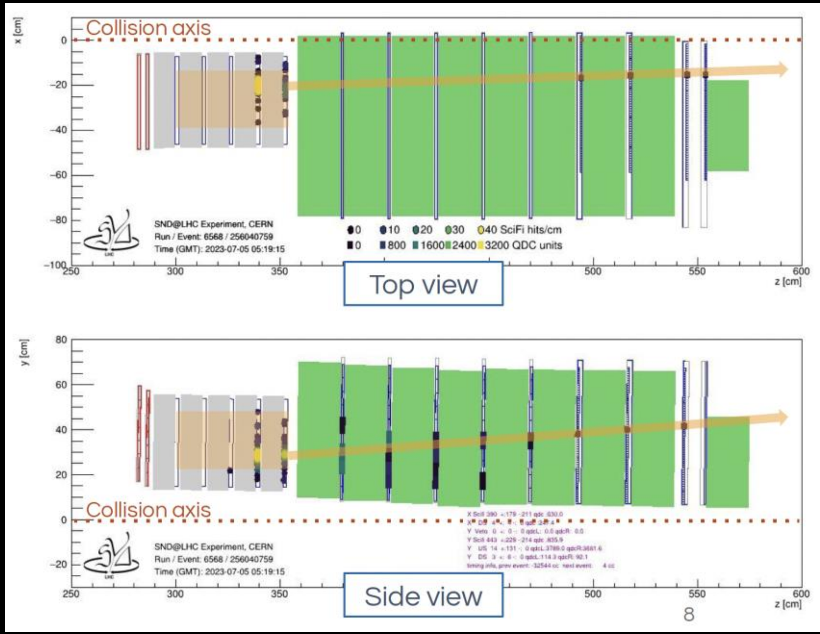
	Data	Signal simulation
All	8.4×10^9	157
Fiducial volume	4.9×10^5	11.9
One muon-like track	17	6.1
Large SciFi activity	13	5.1
Large hadronic activity	12	4.7
Low muon system activity	8	4.2

Phys. Rev. Lett 131, 031802

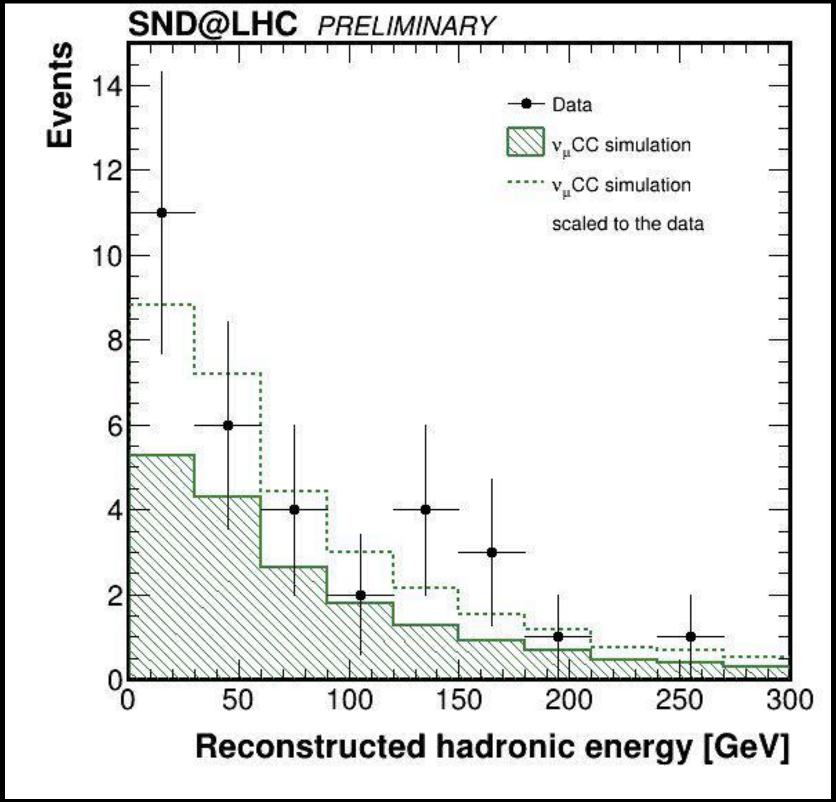
- 2022-2023 data sample: extending fiducial volume
  - Reject events in the first wall, overall signal acceptance 18%
  - Large activities on SciFi and HCAL
  - One muon track associated to the vertex
    - Signal selection efficiency 35%

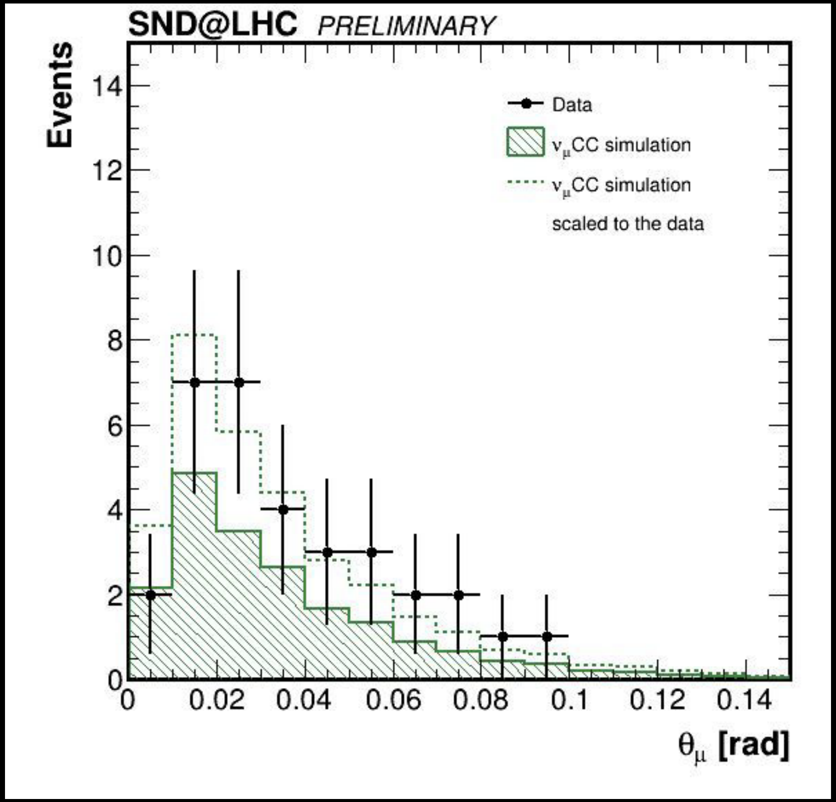
Data sample	Integrated Luminosity	Background	Expected	Observed	Significance
2022	36.8 fb^{-1}	0.086±0.038	4.2	8	6.8σ
2022 – 2023	68.6 fb^{-1}	0.25±0.06	19.1 ± 4.1	32	12σ





Muon Neutrino event kinematics (2022-2023 data sample)





- Kinematics of muon neutrino candidates are in agreement with the signal prediction
- Determination of hadronic shower allows for complete reconstruction of event kinematics and neutrino energy → in progress

Search for shower like (0μ) neutrino events in SND

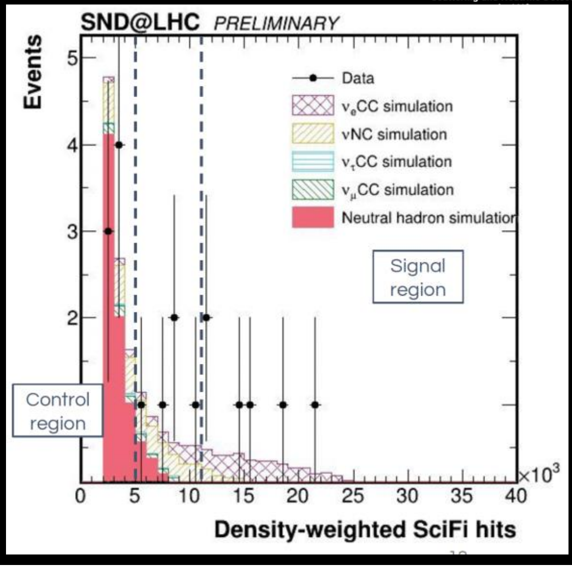
Signal: $\nu_e CC$ (+ $\nu_\tau CC\ 0\mu$) and NC interactions

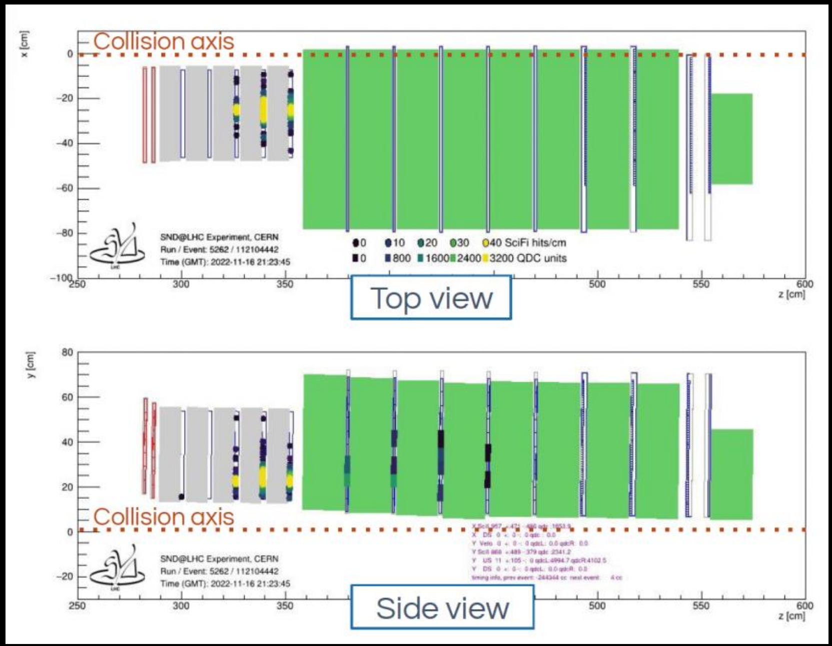
Fiducial volume: no hits in veto, and rejecting side entering
→ signal acceptance 12%

Selection: Large activity on SciFi and HCAL, no reconstructable muon, density number of hits larger than $11\text{x}10^3$
→ selection efficiency 42%

Background: Neutral hadron, $\nu_\mu CC$ and $\nu_\tau CC$ interactions

	Background	Expectation	Observation	Significance
0μ	0.13 ± 0.04	4.66	6	5.8σ

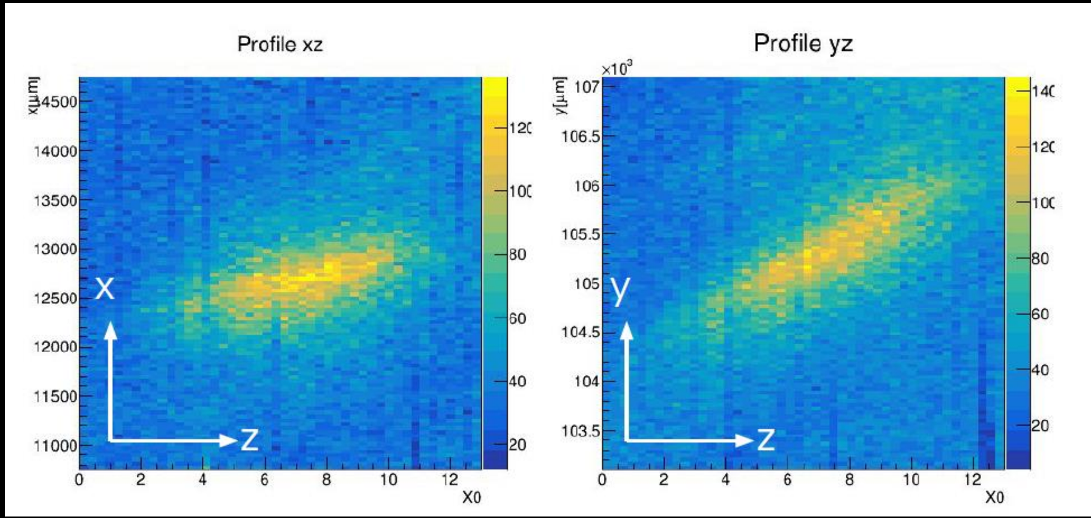




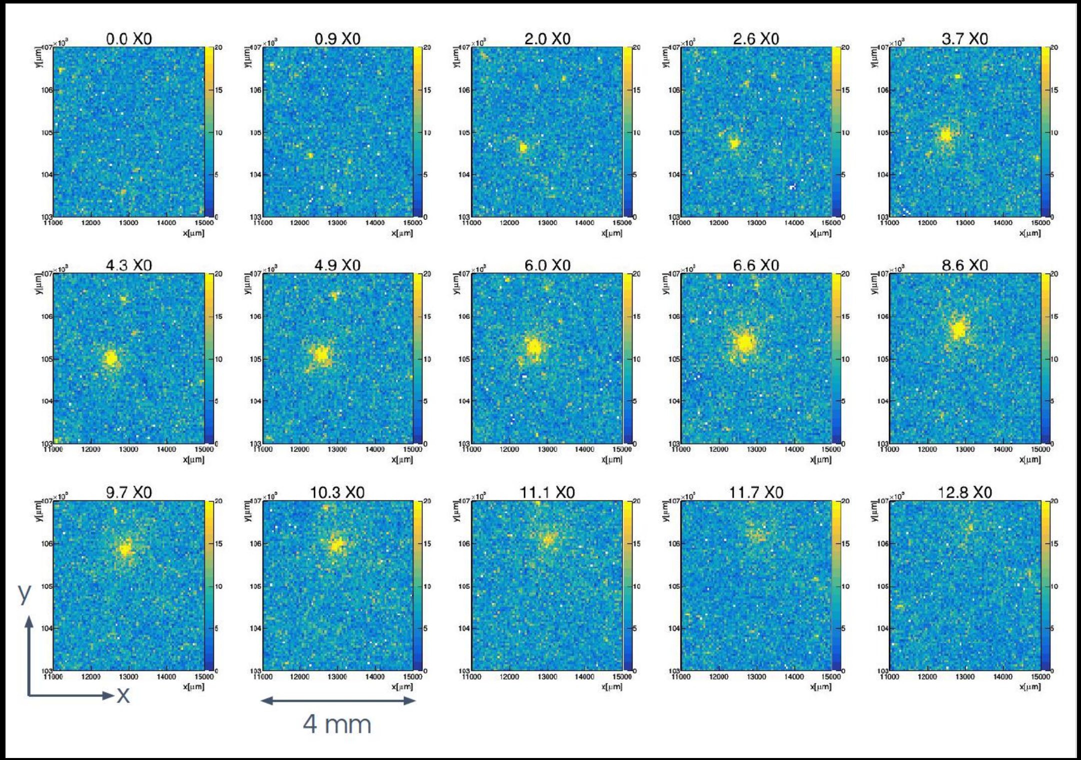
$\nu_e CC$ search in emulsion at SND

- Identifying regions with high track density in emulsions
- Consistency with the expectation of EM shower development
- Search for neutral vertices associated to identified shower

- EM shower patterns identified
- Vertex association in progress



Shower profile



Example of shower development:

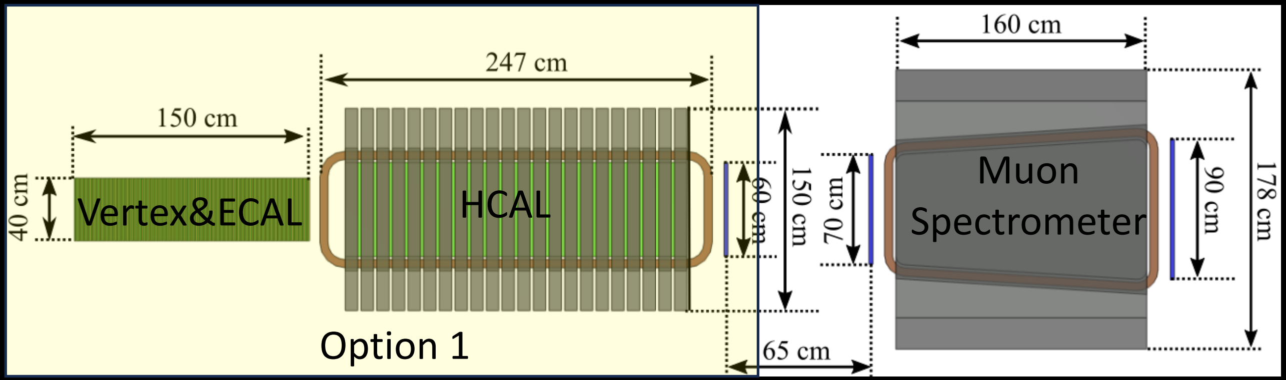
- 4x4 mm2 region with 100μm binning
- Radiation length of W plate: 3.504 mm
- Maximum width reached at plate 6.6 X0

LHC Run4

Both FASER and SND expressed their interest in taking data exploring further TeV neutrinos in LHC Run4, with expected total integrated luminosity of 680 fb^{-1}

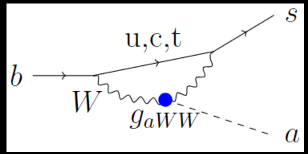
- Expecting to collect 5000 ν_e, 25000 ν_μ and 100 ν_τ interactions at **FASERν**

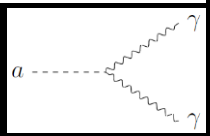
- With the HL-LHC operating at luminosity five times larger than the current run
  → frequent replacement of Emulsion/Tungsten modules and require access to service tunnels
  → **FASER/FASERν** approved, discussion ongoing on possible upgrade of neutrino detector **at LHC Run4**
  → **SND** submitted Letter of Intent for LHC Run 4 with upgraded detector, **AdvSND**: replacing emulsion+W with high precision vertex detector using W as target.



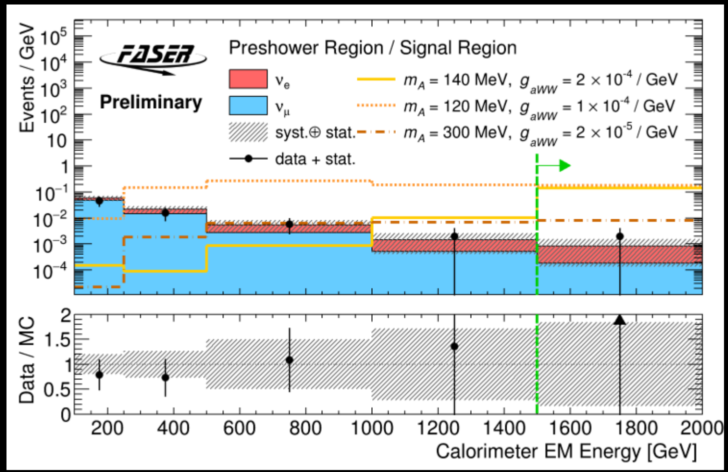
[FASER Coll. arXiv:2402.13318]
[AdvSND Coll. CERN-LHCC-2024-007]

Axion-like particles (ALPs) search in FASER

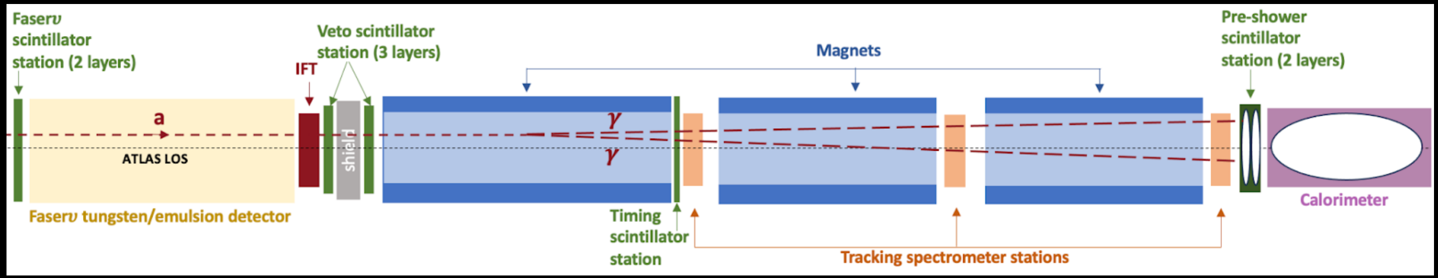




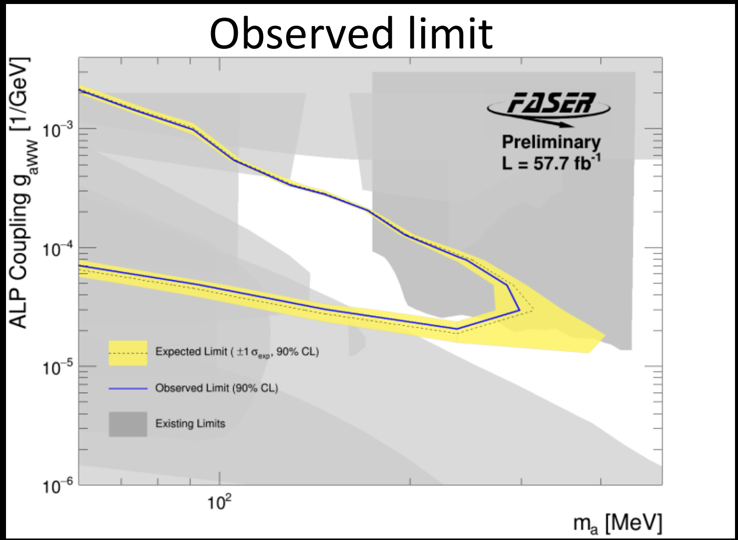
- Sensitive to ALPs produced by B meson decays and decay into two high energy photons (~TeV) → mass range $50 - 500\ MeV$ and $g_{aWW} \sim 10^{-5} - 10^{-3}$ GeV^{-1}
- Dataset collected at $\sqrt{s} = 13.6\ TeV$ in 2022 and 2023 corresponding to integrated lumiosity of 57.7 fb^{-1}



- Selection: No signal in 5 veto counter and timing scintillator; evidence of EM shower in preshower counters; significant energy deposition (>1.5TeV) in EM calorimeter; in time with LHC



- Background: 0.42 ± 0.38 events from neutrinos,
- One event observed in unblinded signal region
- Preshower deposit consistent with EM shower
- Calorimeter energy of 1.6 GeV
- World-leading constraints on ALPs are obtained for masses up to 300 MeV and couplings around 10^{-4} GeV^{-1}, testing a previously unexplored region of parameter space.



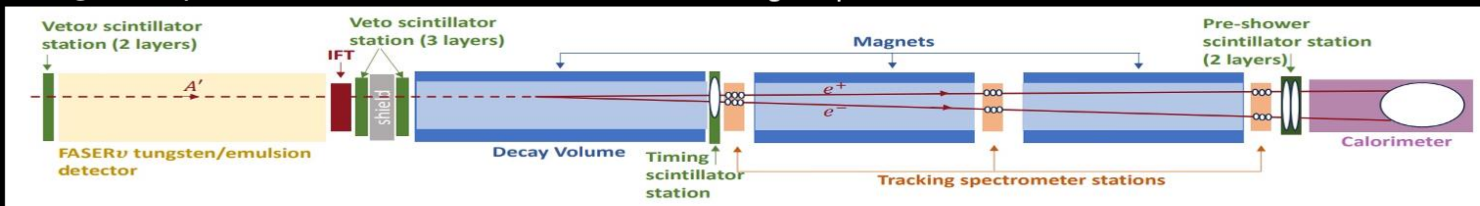
Conf note: CERN-FASER-CONF-2024-001

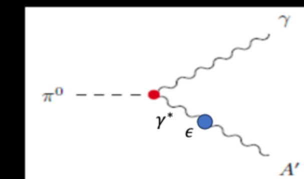
Dark Photon Search in FASER

- Mainly produced at the LHC through $\pi^0 \rightarrow A'\gamma$,$\eta \rightarrow A'\gamma$ and dark bremsstrahlung pp $\rightarrow ppA'$
- FASER is sensitive in parameter space with $m_{A'} \sim 100\ MeV$ and $\epsilon{\sim}10^{-5}$, searching for $A' \rightarrow e^- e^+$
- Dataset collected at $\sqrt{s} = 13.6\ TeV$ in 2022 corresponding to integrated lumiosity of 27.0 fb^{-1}

No signal in any of the five veto scintillators

Timing and preshower consistent with ≥2 MIPs





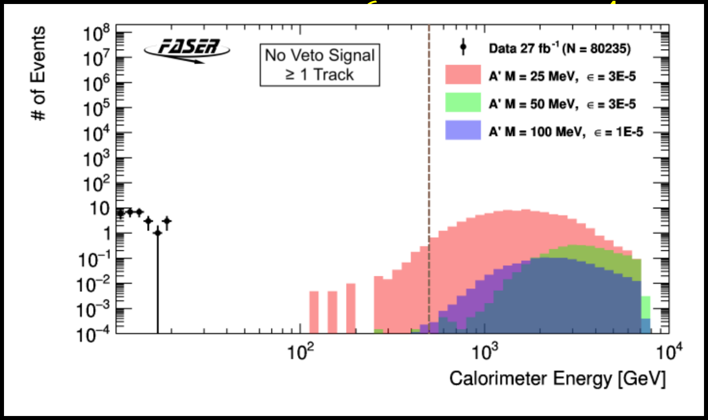
Event time is consistent with a colliding bunch at ATLAS IP

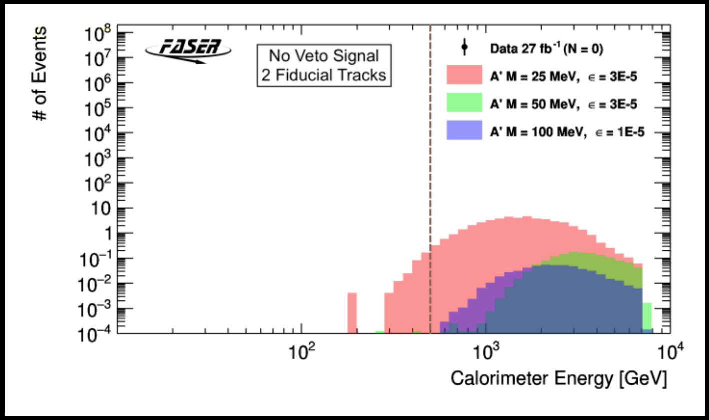
Exactly two good tracks in fiducial volume (p > 20 GeV and r < 95 mm, extrapolating to r < 95 mm at vetos)

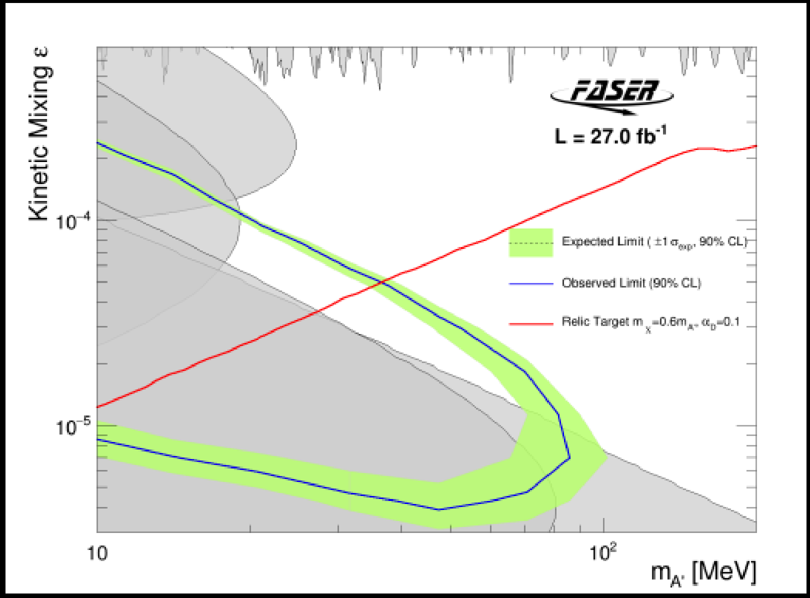
Total calorimeter energy E > 500 GeV

Phys. Lett. B 848 (2024) 138378

- Total background: $(2.3 \pm 2.3) \times 10^{-4}$ events (mainly from neutrinos)
- No events seen in unblinded signal region
- At the 90% confidence level, FASER excludes the region of



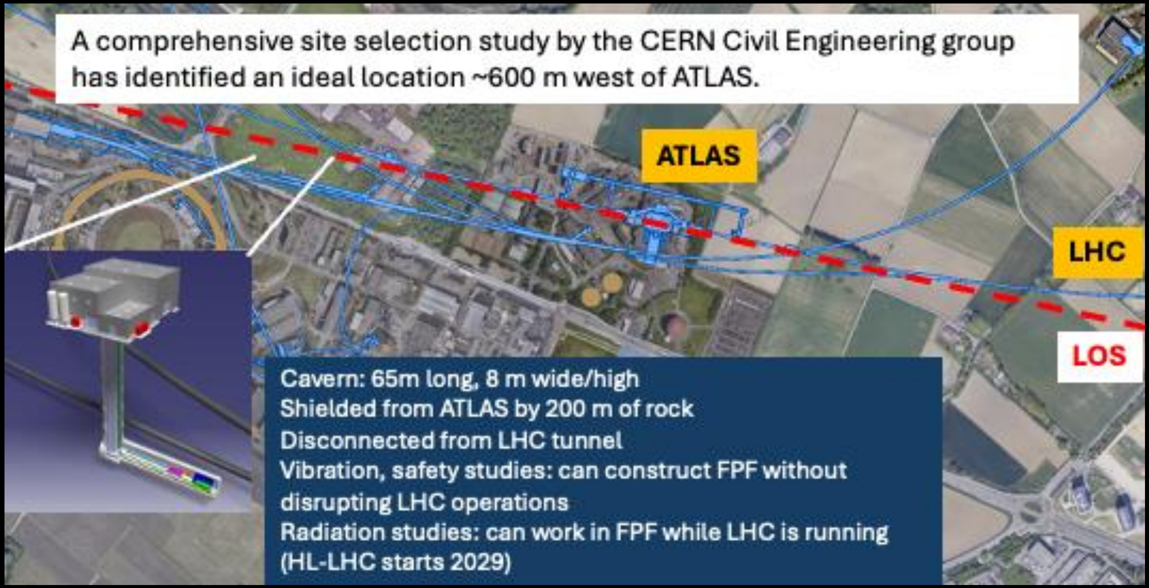




Future programs at the LHC: Forward Physics Facility (FPF)

- FPF studied in context of PBC for last 3 years
- FPF is proposed new facility to fully exploit the LHC's physics potential in the forward direction during the HL-LHC era
  - BSM physics searches, neutrino physics, QCD and astro-particle physics
- High statistics highest energy $\nu/\bar{\nu}$:
  - $\mathcal{O}$(10tonne) detectors with HL-LHC
  - $\mathcal{O}(10^5)$ ν_e, $\mathcal{O}(10^6)$ ν_μ and $\mathcal{O}(10^4)$ ν_τ interactions

  with energies from $\mathcal{O}(100)$ GeV to a few TeV

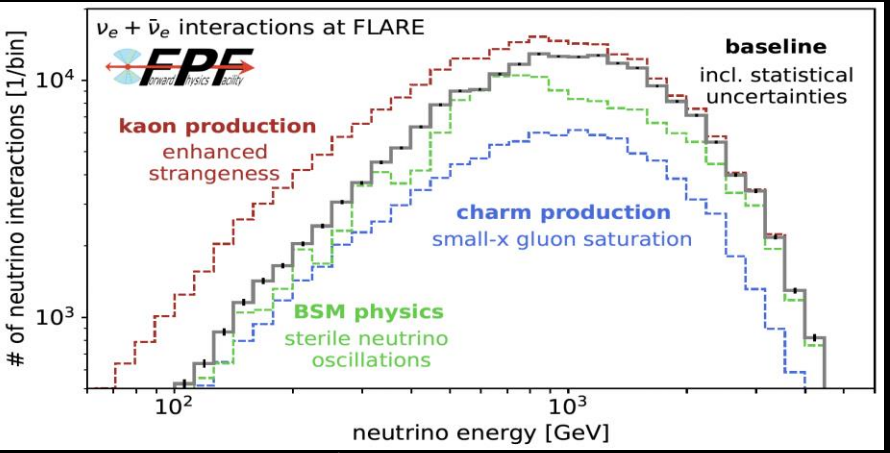


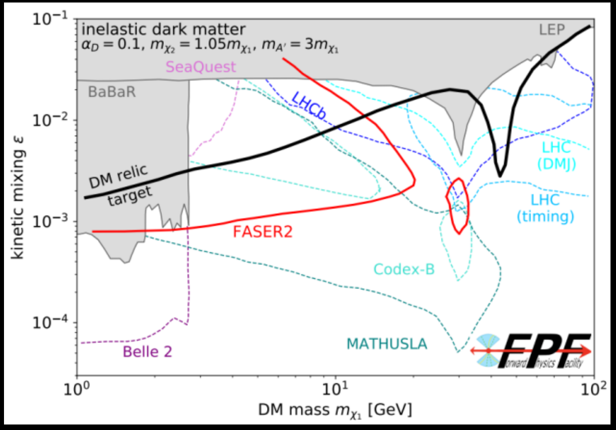
Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

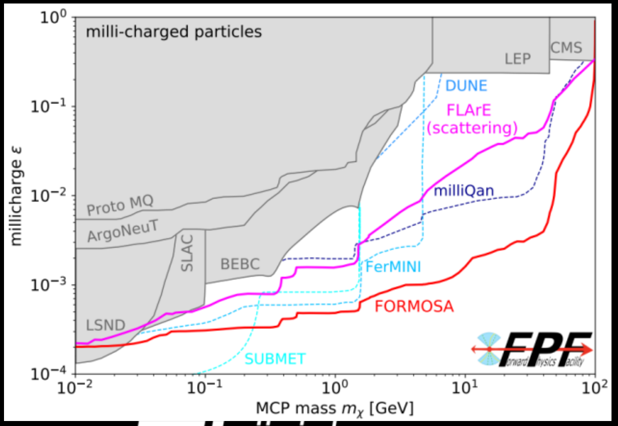
J. Phys. G 50 (2023) 030501, 1-410 https://cds.cern.ch/record/2851822/

arXiv:2203.05090

Detectors at FPF: AdvSND, FASER2, FASERν2, FLArE and FORMOSA







Conclusions

- High energetic neutrinos (at TeV level) in all flavor are produced in proton-proton collisions at the LHC at forward region
- FASER at on-axis ($\eta > 8.8$) and SND at off-axis ($7.2 < \eta < 8.4$) successfully took data in first year of Run 3 at the LHC
  - Experiments already collected about 70 fb^{-1} in 2022 and 2023, by the end of LHC Run3 reaching 250 fb^{-1}
- Neutrino search at LHC

  Opens new window for high-energy neutrino study

  First direct observation of collider neutrinos both on FASER and SND

  153 $\nu_\mu CC$ interactions in FASER spectrometer

  32 $\nu_\mu CC$ interactions in SND electronic detectors

  The first measurement of $\nu_e N$ and $\nu_\mu N$ charged current interaction cross-sections by FASERν

  Observing for the first time the highest energy, 1.5 TeV, $\nu_e CC$ interaction

  4 $\nu_e CC$ and 8 $\nu_\mu CC$ candidates observed in subset of FASERν data (2% of data)
- Search for long-lived particles beyond standard model:
  - First results for "Dark Photon" and "Axion-like Particles" search by FASER
- Both experiment will continue their exploration at LHC Run4

Thank you

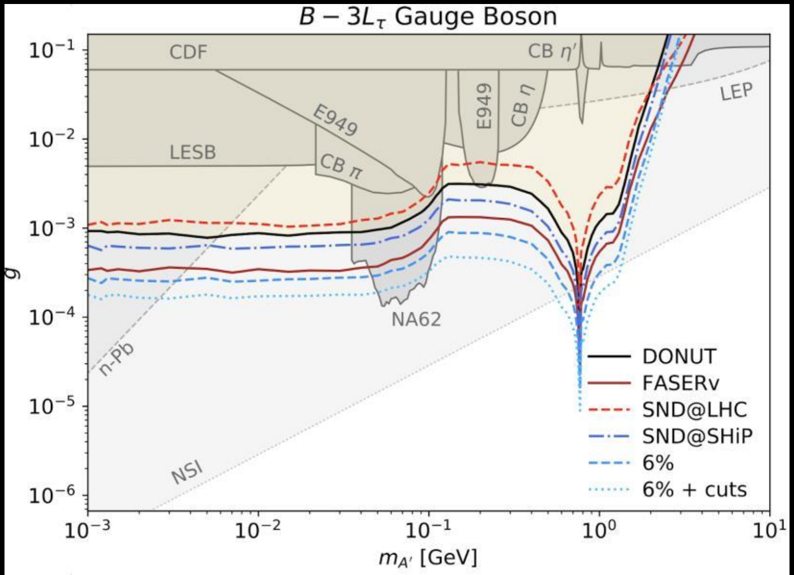
FASER supported by

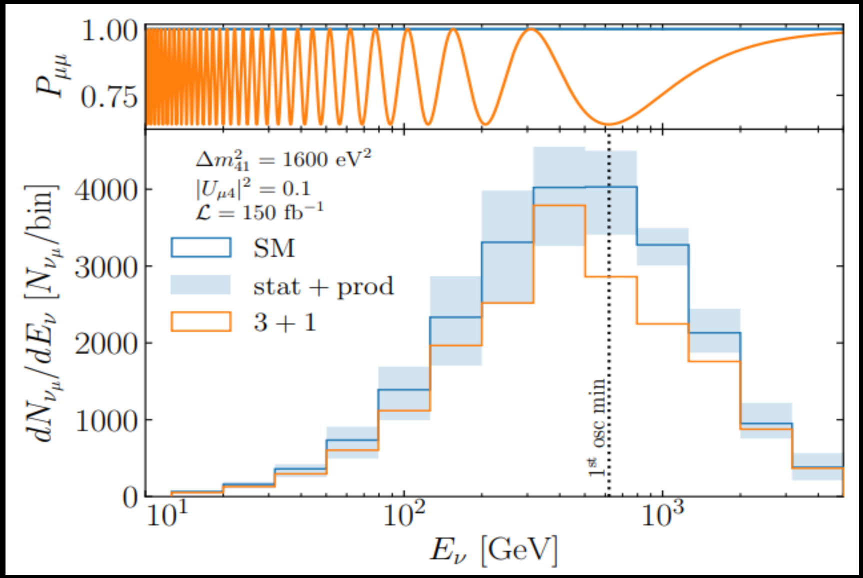
Back-Up

Physics potential: Beyond standard model physics

The tau neutrino flux is small in Standard Model. A new light weakly coupled gauge bosons decaying into tau neutrinos could significantly enhance the tau neutrino flux.
F. Kling, Phys. Rev. D 102, 015007 (2020), arXiv:2005.03594

In SM, no neutrino oscillations are expected. However, sterile neutrinos with mass ~40 eV can cause oscillations. FASERν could act as a short-baseline neutrino experiment. FASER Collaboration, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310





Lepton Flavour Universality tests

- Charm hadron decays contribute to the flux of all three types of neutrinos
  - Being at off-axis SND would get more neutrinos from charm hadron decays
  - $\nu_\tau + \bar{\nu}_\tau$ produced in $D_s \to \tau\, \nu_\tau$ and subsequent decay of τ lepton
  - $\nu_e + \bar{\nu}_e$ produced in the decay of all charmed hadrons: D, D^0, D_s and Λ_c
  - $\nu_\mu + \bar{\nu}_\mu$ mainly produced in π, K decays
- Emulsion detector has excellent flavour identification capabilities

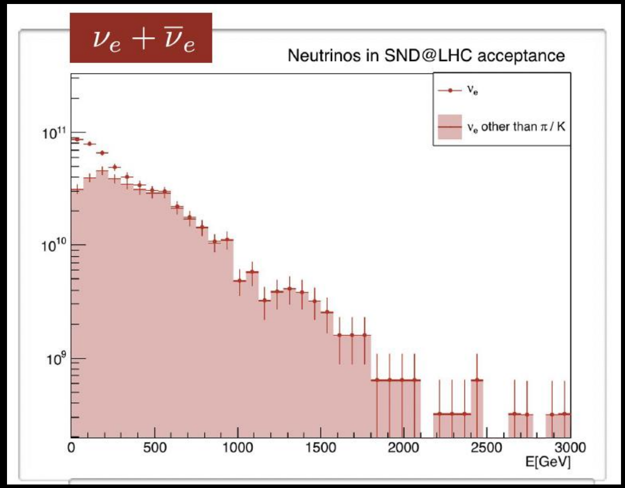
- Testing lepton flavour universality with neutrinos by studying the ratios of event rates $\frac{\nu_e}{\nu_\mu}$ and $\frac{\nu_e}{\nu_\tau}$

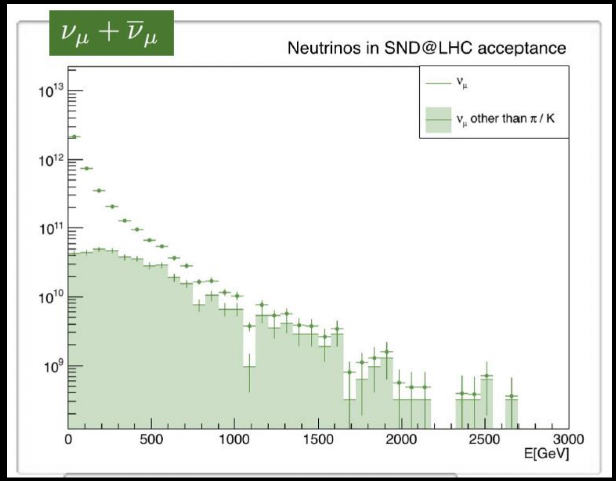
$$R_{13} = \frac{N_{\nu_e+\bar{\nu}_e}}{N_{\nu_\tau+\bar{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i}\widetilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s}\widetilde{Br}(D_s \to \nu_\tau)}$$

Expected uncertainties:
30% statistical & 20% systematics

$$R_{12} = \frac{N_{\nu_e+\bar{\nu}_e}}{N_{\nu_\mu+\bar{\nu}_\mu}} = \frac{1}{1 + w_{\pi/K})}$$

Expected uncertainties:
10% statistical & 10% systematics

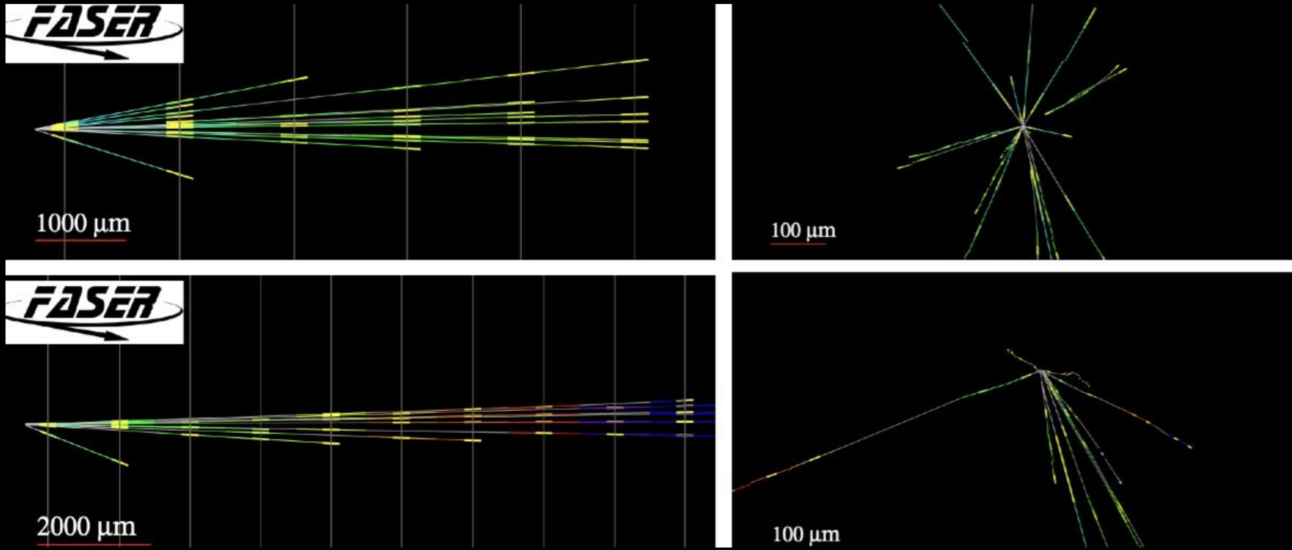




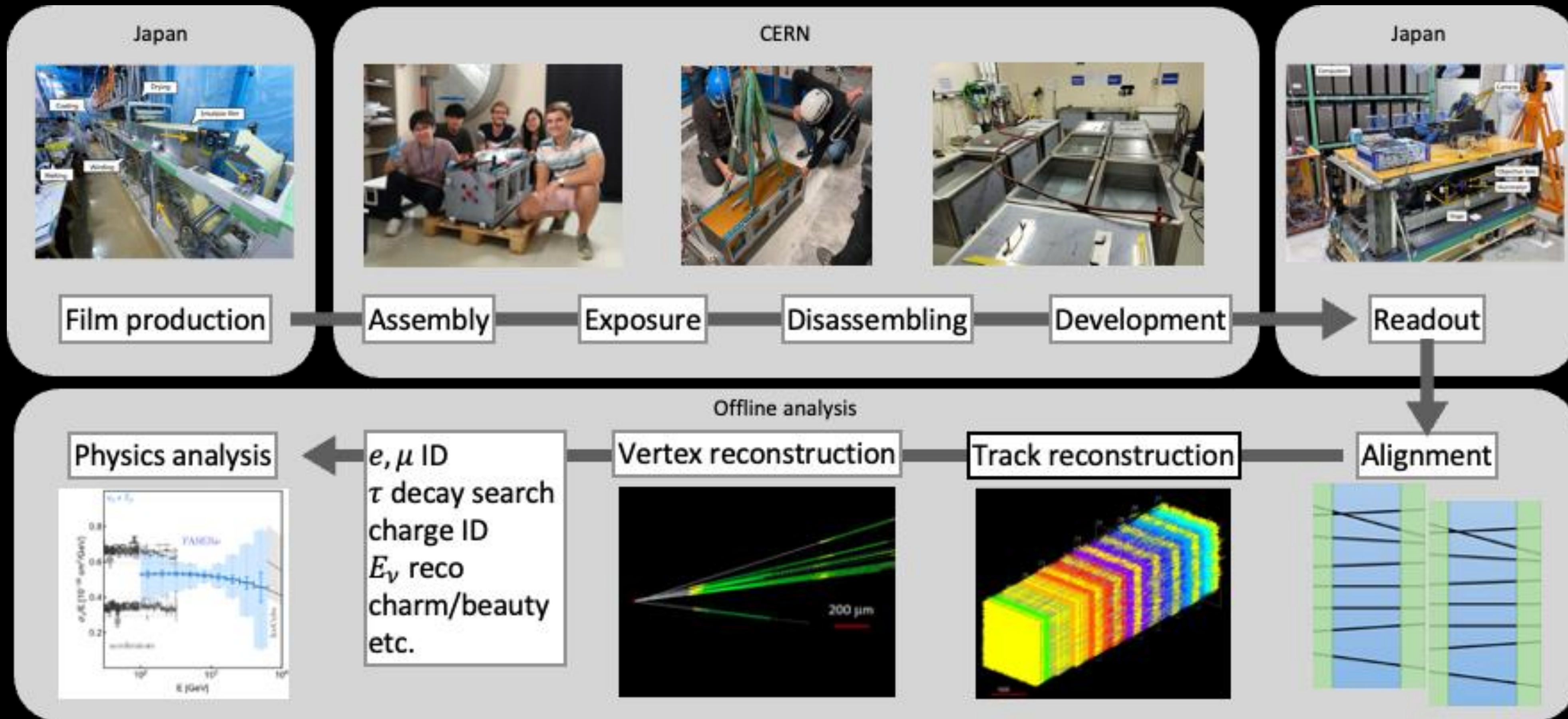
FASERν pilot run in 2018

- The pilot runs were taken place for charged particles flux measurement and neutrino detection at tunnels TI12 and TI18, 480 m from ATLAS in 2018. Both tunnels are symmetric to ATLAS.
- For neutrino detection: ~30 kg mass emulsion:
  - Lead (1-mm-thick, 100 layers) and Tungsten (0.5-mm-thick, 120 layers)
  - Installed in TI18
  - 12.2 fb^{-1} of data collected in Sep - Oct. 2018 (~1. 5months)

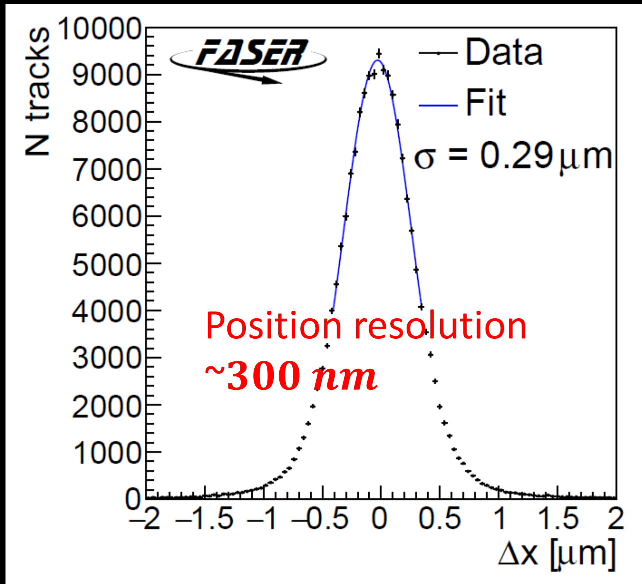
- 18 neutral vertices passed the vertex selection criteria
- Expected # of neutrino signal = $3.3^{+1.7}_{-0.95}$
- Expected # of background = 11.0 events.
- The background-only hypothesis is disfavored with a statistical significance of 2.7σ



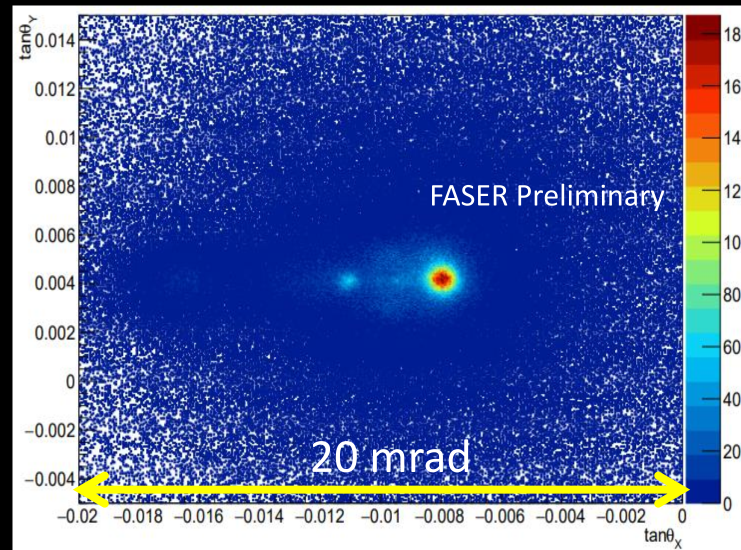
Emulsion film production to physics analysis in FASERν



FASERν Detector Performance

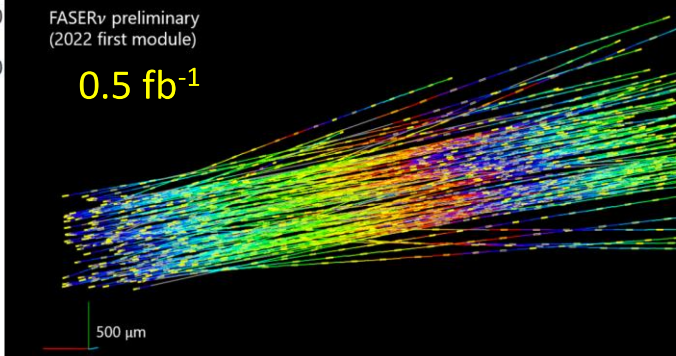


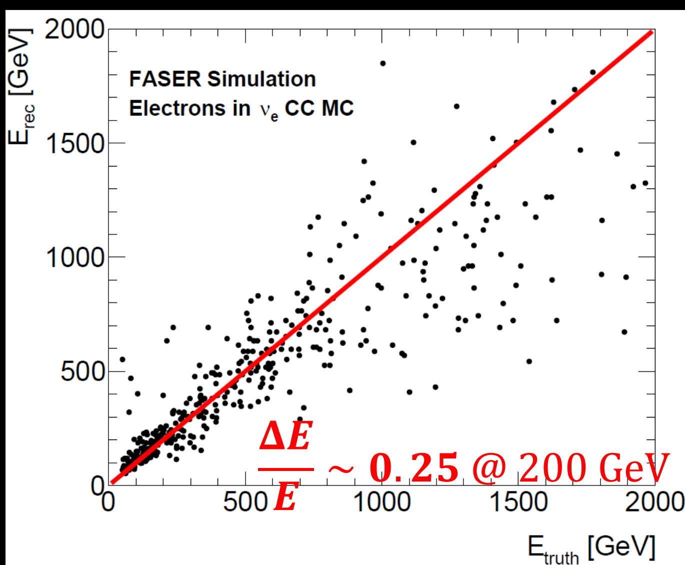
BG muon angular distribution (Data)



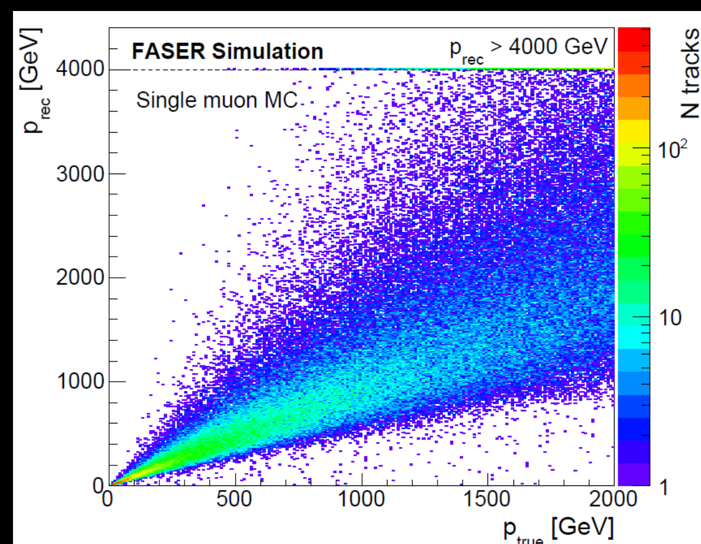
Angular spread of muon peaks

$\sim \mathbf{0.4\ mrad}$





Electron energy reconstruction



Muon momentum measurement by MCS

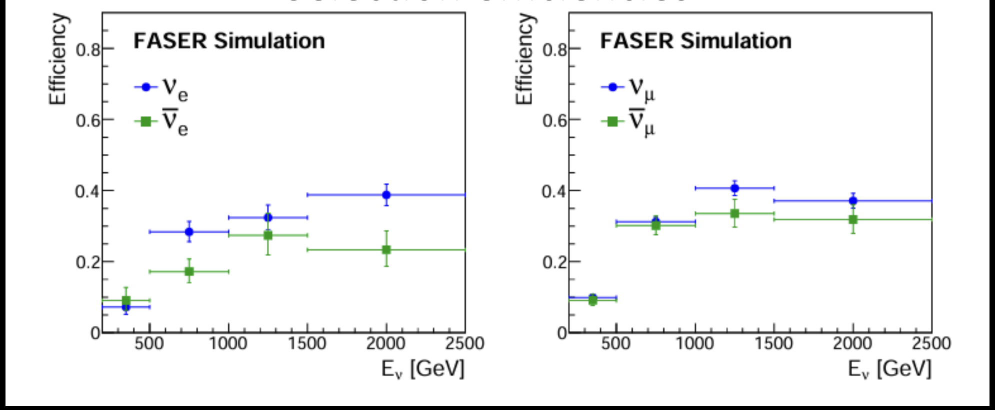
$$\frac{\Delta P^{RMS}}{P} \sim \mathbf{0.3} \text{ @ 200 GeV}$$

FASERν Analysis

Selection criteria:

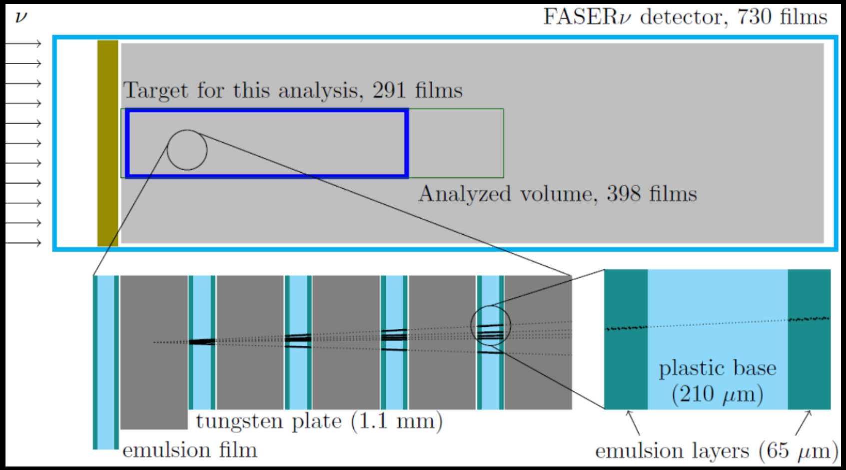
- Vertex reconstruction with $N_{track} \geq 5$ and $N_{track}(\tan\theta \leq 0.1) \geq 4$
- Lepton requirements with E_e or $p_\mu > 200\ GeV$ and $tan\theta_e$ or $tan\theta_\mu > 0.005$
- Back-to-back topology: $\Delta\phi > 90°$

Selection efficiencies



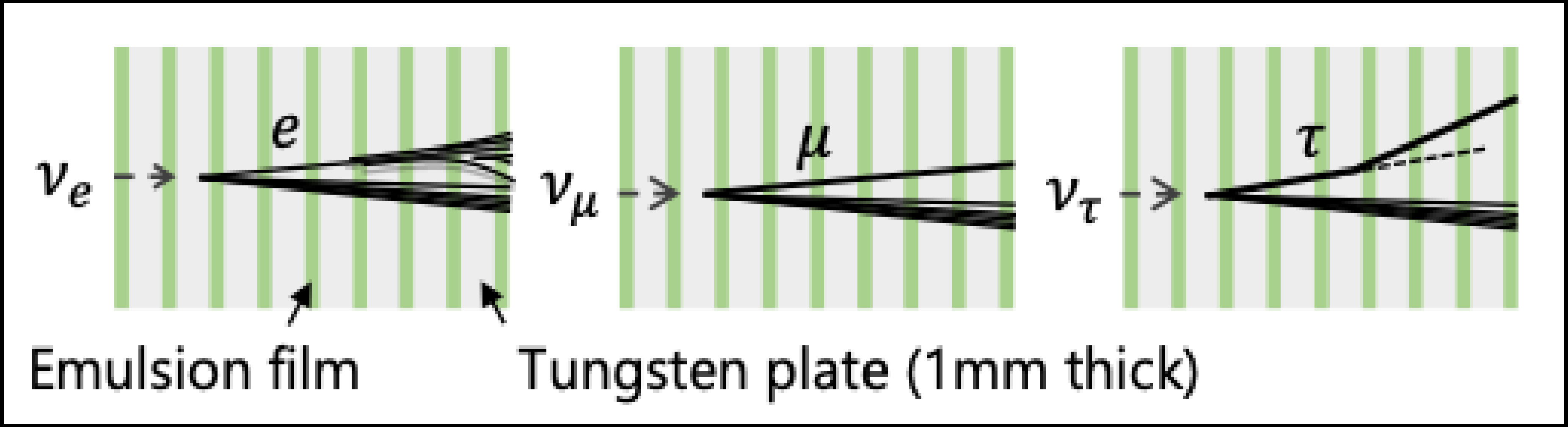
$$N_{obs} = \frac{L\rho l}{m_{nucleon}} \int \sigma(E)\phi(E)\varepsilon(E)dAdE$$

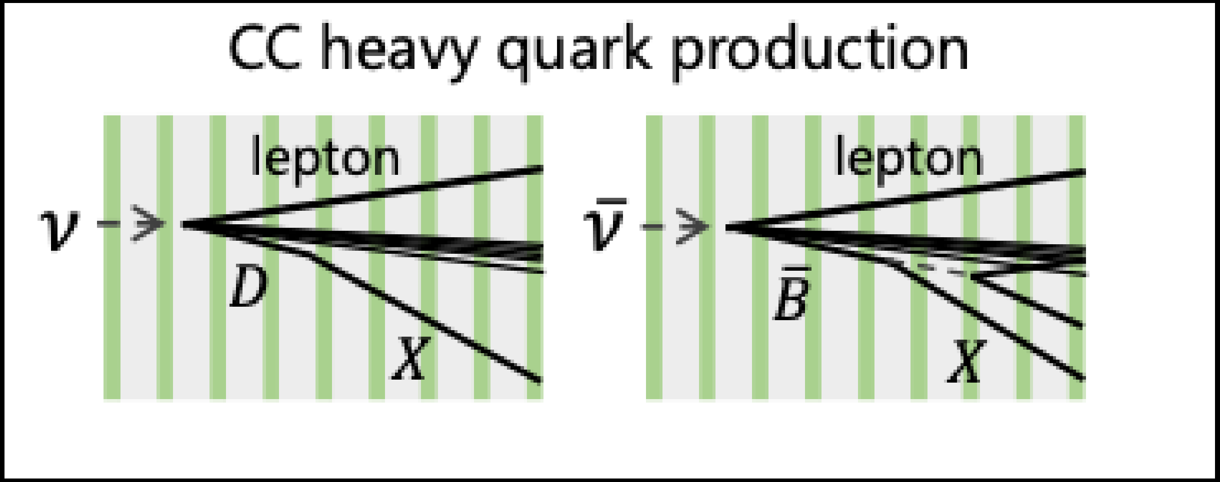
- ν_e and ν_μCC sections measured in a single energy bin
- $\sigma_{obs} = \alpha\sigma_{theory}$
- The α is measured to be $2.4^{+1.8}_{-1.3}$ for ν_e and $0.9^{+0.5}_{-0.3}$ for ν_μ



Source	Relative uncertainty	
	ν_e	ν_μ
Luminosity	2.2%	2.2%
Tungsten thickness	1%	1%
Interactions with emulsions	$^{+3.6}_{-0}$%	$^{+3.6}_{-0}$%
Flux uncertainty	$^{+70}_{-22}$%	$^{+16}_{-9}$%
Line of sight position	$^{+2.1}_{-2.4}$%	$^{+1.9}_{-2.5}$%
Efficiency from hadronization	$^{+22}_{-5}$%	$^{+23}_{-5}$%
Efficiency from reconstruction	20%	20%
Efficiency from MC statistics	4.9%	2.8%
Total	$^{+70}_{-22}$% (flux)	$^{+16}_{-9}$% (flux)
	$^{+30}_{-21}$% (other)	$^{+31}_{-21}$% (other)

Neutrino interaction identification





Search for shower like (0μ) neutrino events in SND

Neutral hadron background

- Define background dominant control region
- Scale background prediction to the number of observed events in the control region
  - Observed neutral hadron background is 1/3 of the predicted value

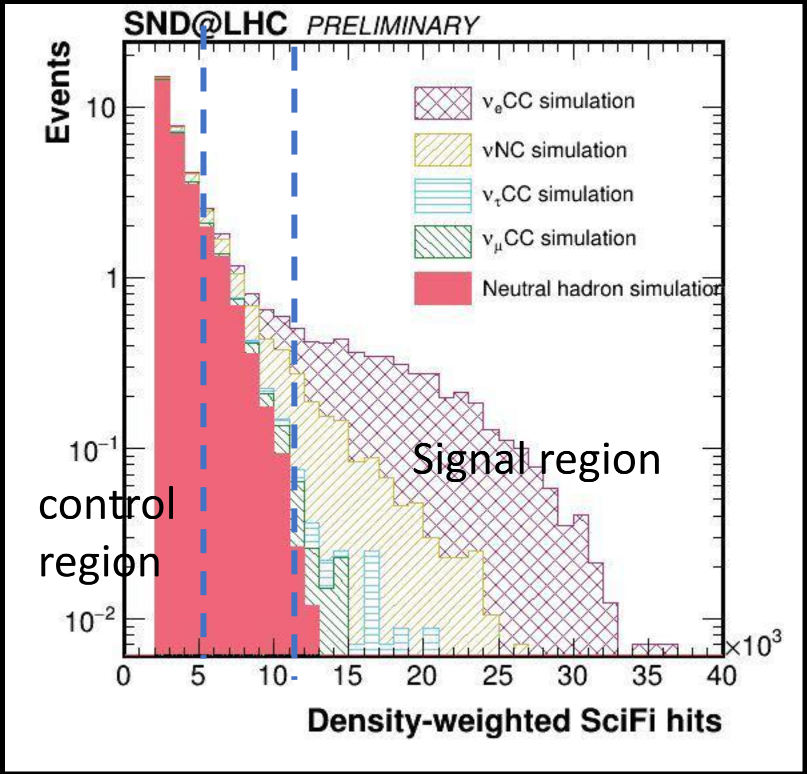
Neutrino background:

- Muon neutrino CC interactions are the dominant background
- Tau neutrino CC interactions

- Total expected background: 0.13±0.04 events

Number of observed events: 6

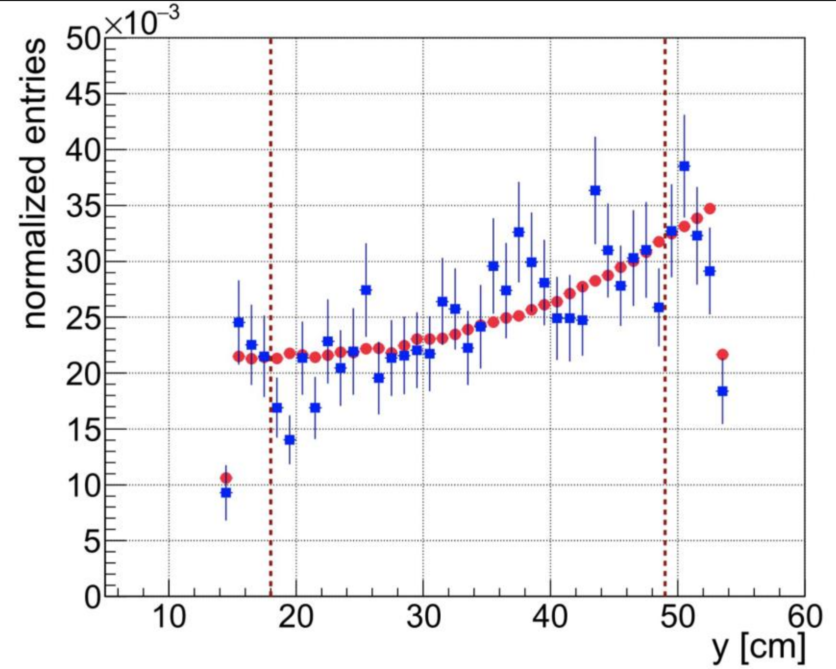
Observation significance 5.8 σ

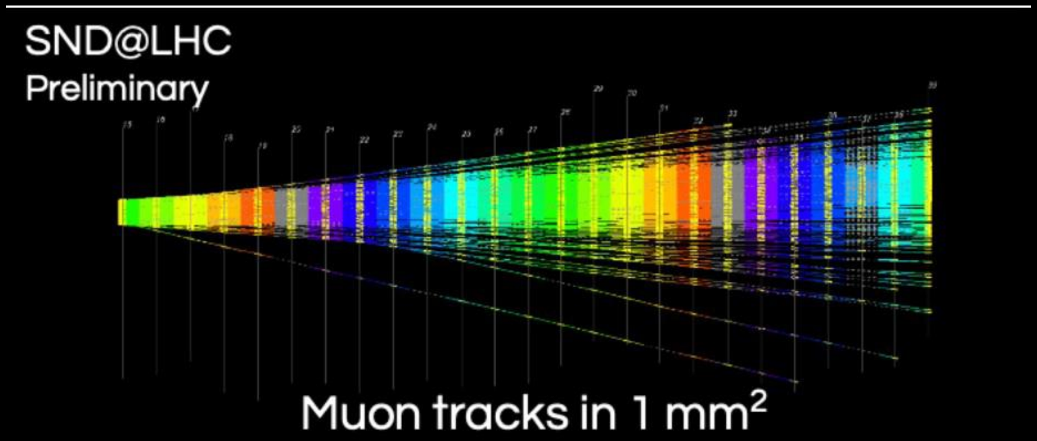


Muon Flux measurement in SND

- Using SciFi tracker and the Downstream Stations of the muon system
  - same fiducial area (31 x 31 cm^2)

- Data/MC simulation an agreement at the level of 20-25%





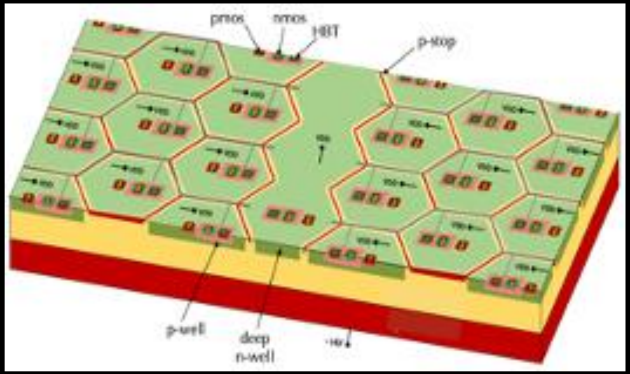
System	Muon flux $[10^4\ fb/cm^2]$
Sci-fi	$\mathbf{2.06 \pm 0.01(stat.) \pm 0.12(sys.)}$
Downstream muon system	$\mathbf{2.02 \pm 0.01(stat.) \pm 0.08(sys.)}$

[Eur. Phys. J. C (2024) **84**: 90](#)

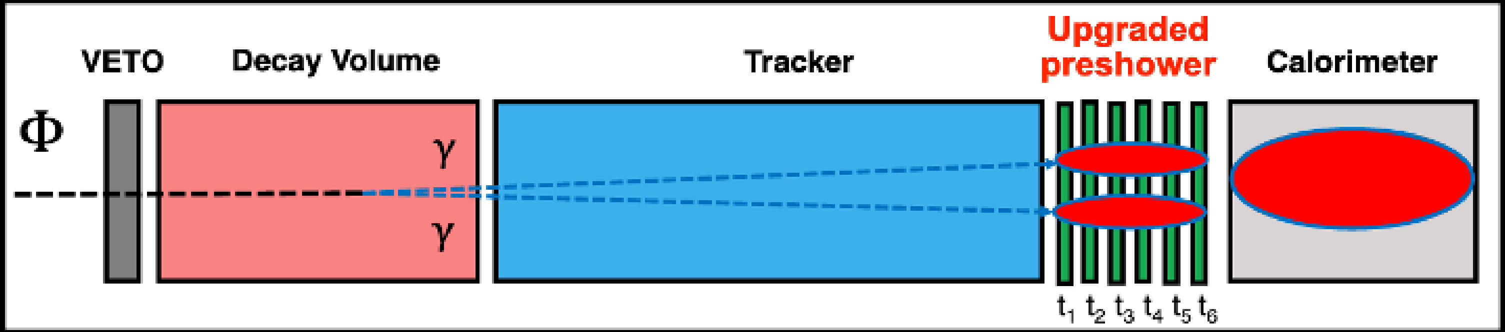
Improving ν background suppression in ALPs search

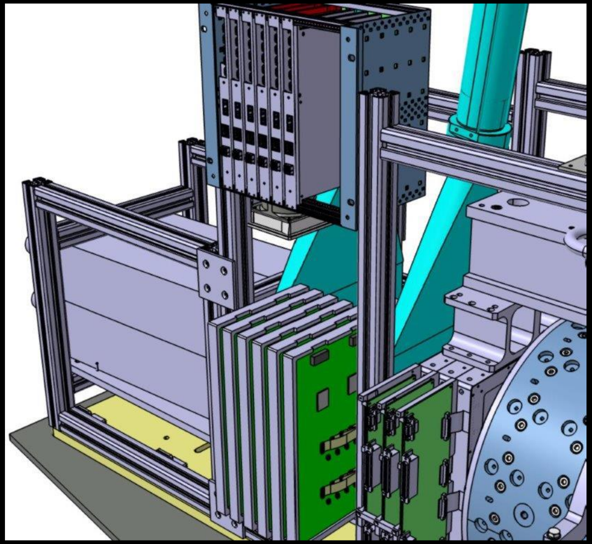
Resolve diphoton events by upgraded pre-shower calorimeter with high X-Y granularity

- 6 layers of high-granularity
- Si pixels with W absorber
- Separate photons at ~200 µm
- To be installed before 2025 (Run3)



Main specifications	
Pixel Size	65 µm side (hexagonal)
Pixel dynamic range	0.5 ÷ 65 fC
Cluster size	O(1000) pixels
Readout time	< 200 µs
Power consuption	< 150 mW/cm^2
Time resolution	< 300 ps



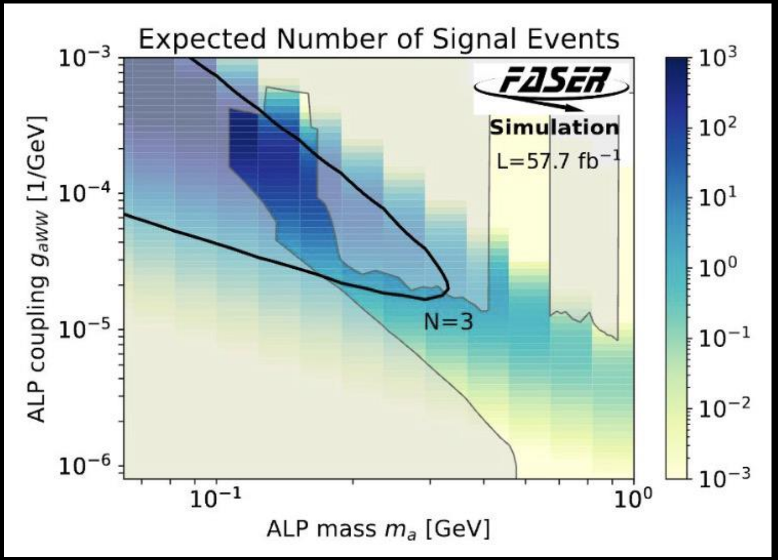


FASER preshower: CERN-LHCC-2022-006

ALPs selection in FASER

- Data: Luminosity of 57.7 fb^{-1}
- Signal: Two high energetic photon pairs from ALP decay

- No signal in any of the 5 veto scintillators
- No signal in the timing scintillator
- Evidence of EM Shower in preshower detector
- Significant energy deposit in electromagnetic calorimeter



Selection	Efficiency	Cum. Efficiency
$m_a = 140$ MeV, $g_{aWW} = 2 \times 10^{-4}$ GeV^{-1}		
Veto Signal nMIP < 0.5	99.6%	99.6%
Timing Scintillator Signal nMIP < 0.5	97.8%	97.4%
Preshower Ratio > 4.5	85.7%	83.5%
Second Preshower nMIP > 10	98.6%	82.3%
Calo $E > 1.5$ TeV	91.6%	75.4%

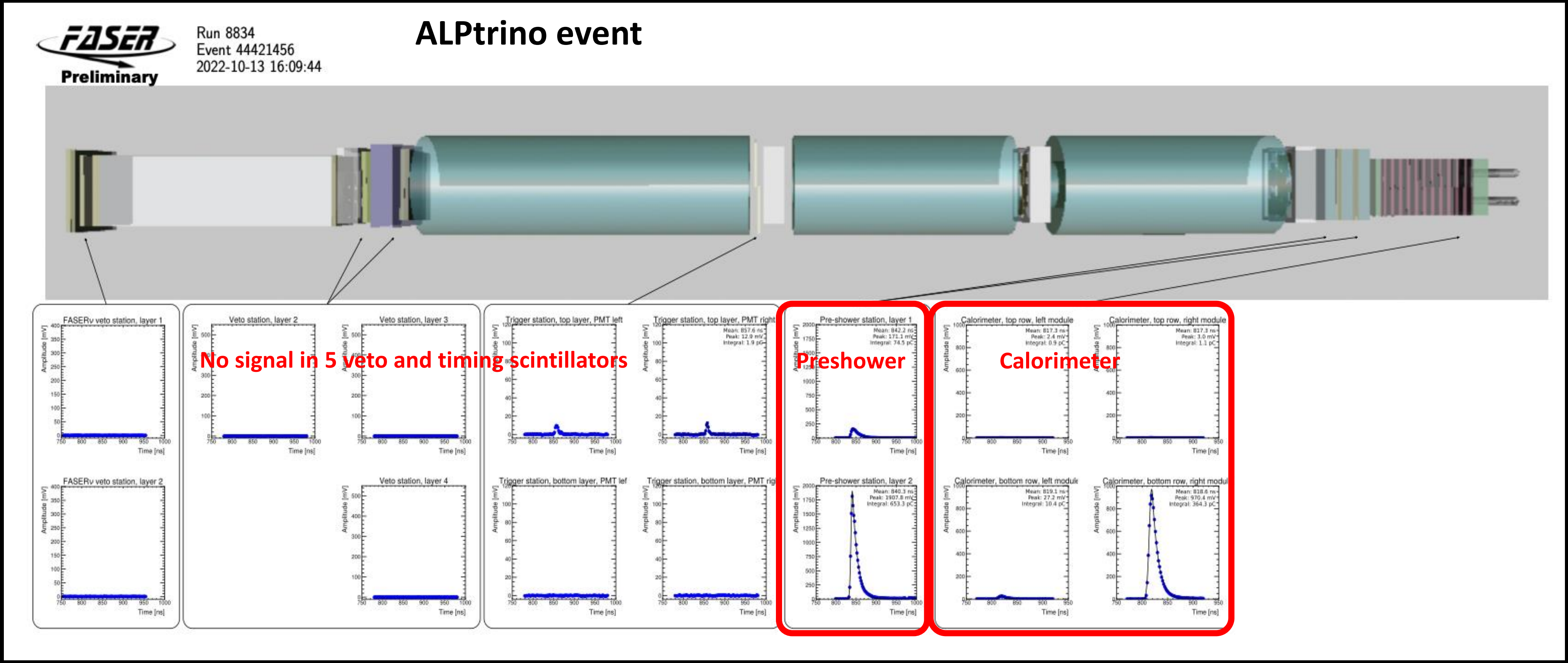
Signal Sample	Flux	Stat.	Luminosity	Calorimeter	Second Preshower Layer	Preshower Ratio
$m_a = 140$ MeV $g_{aWW} = 2 \times 10^{-4}$ GeV^{-1}	59.4%	1.8%	2.2%	3.6%	0.6%	7.9%
$m_a = 120$ MeV $g_{aWW} = 10^{-4}$ GeV^{-1}	57.3%	3.5%	2.2%	16.3%	0.6%	6.9%
$m_a = 300$ MeV $g_{aWW} = 2 \times 10^{-5}$ GeV^{-1}	58.0%	2.9%	2.2%	15.8%	0.6%	8.4%

Backgrounds

- Neutral hadrons
- Large-angle muons
- Cosmic events
- Neutrinos
- The main background in this analysis arises from non-negligible charge current neutrino interactions

Source	Event Rate
Neutrino Background	0.42 $\pm$ 0.32 (flux) $\pm$ 0.14 (calo. energy) $\pm$ 0.06 (PS ratio) $\pm$ 0.02 (PS 1 nMIP) $\pm$ 0.05 (stat.) **Total: 0.42 $\pm$ 0.38 (90.6%)**
ALP ($m_a = 140$ MeV, $g_{aWW} = 2 \times 10^{-4}$ GeV^{-1})	70.7 ± 42.0 (theo.) ± 6.4 (exp.) ± 1.3 (stat.)
ALP ($m_a = 120$ MeV, $g_{aWW} = 1 \times 10^{-4}$ GeV^{-1})	91.1 ± 52.2 (theo.) ± 16.2 (exp.) ± 3.2 (stat.)
ALP ($m_a = 300$ MeV, $g_{aWW} = 2 \times 10^{-5}$ GeV^{-1})	4.0 ± 2.3 (theo.) ± 0.6 (exp.) ± 0.1 (stat.)
Data	**1**

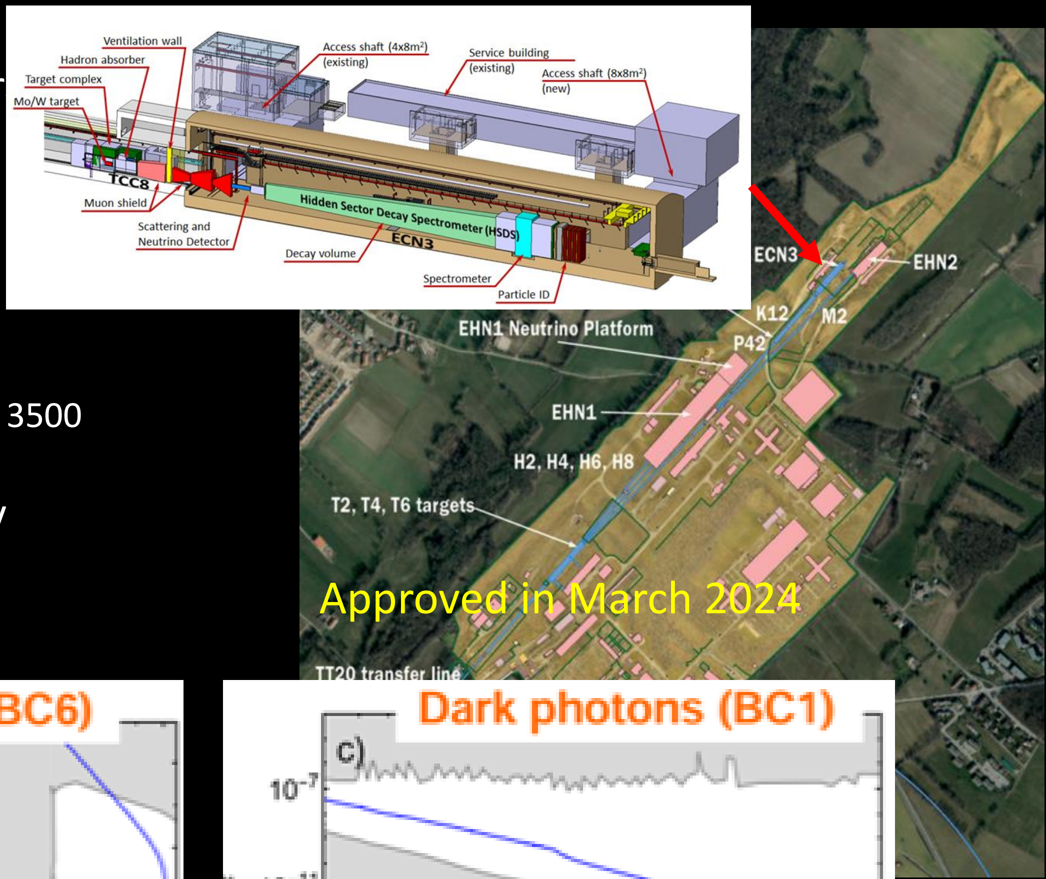
ALPs search: event display of selected event

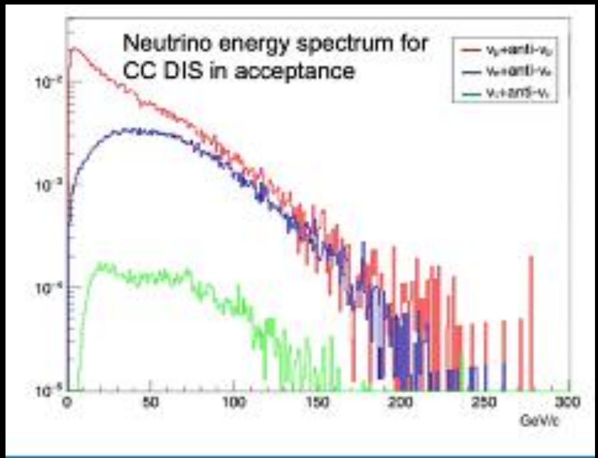


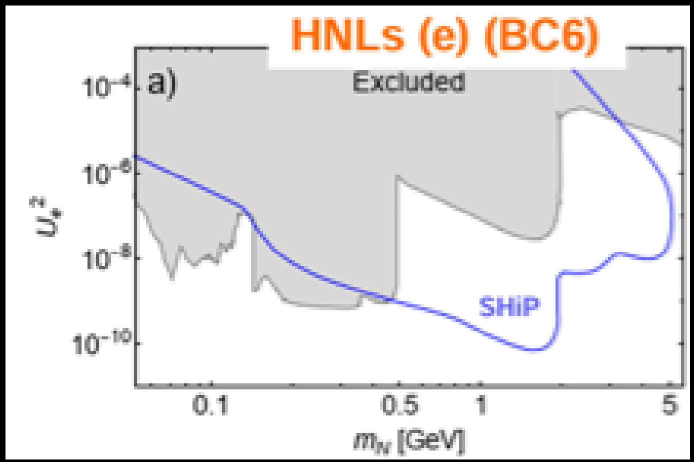
- The waveforms for signals in the scintillators and calorimeter modules are shown in blue.
- A clear signal in the second preshower layer equivalent to 146 MIPs can be seen.
- The event has been triggered by the calorimeter modules, with an overall reconstructed energy of 1.6 TeV.

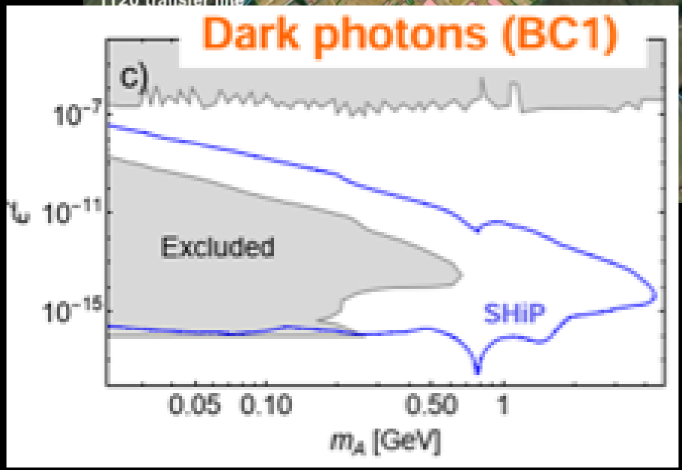
Future programs at CERN: Beam Dump Facility/Search for Hidden Particles (BDF/SHIP)

- 400 GeV protons on W/Mo target: 4×10^{19} pot/year for 15 years
- Expected luminosity > $4 \times 10^{45}\ cm^2/year$
- BDF/SHIP (annually yield)
  - $\sim 2 \times 10^{17}$ charmed hadrons,
  - $\sim 2 \times 10^{12}$ beauty hadrons,
  - $\sim 2 \times 10^{15}$ tau leptons
  - $O(10^{20})$ photons above 100 MeV
  - Large number of seutrinos detected with 3tons emulsion-W target: 3500 $\nu_\tau + \bar{\nu}_\tau$, $2 \times 10^5\ \nu_e + \bar{\nu}_e$ and $7 \times 10^5\ \nu_\mu + \bar{\nu}_\mu$
- Search for light dark matter and associated mediators, feebly interacting particles (Dark photons, HNL, ALP, etc), neutrino physics (x-section, LFU, etc)









Richardson: BDF/SHIP ECN3, Plenary ECFA meeting, 2023

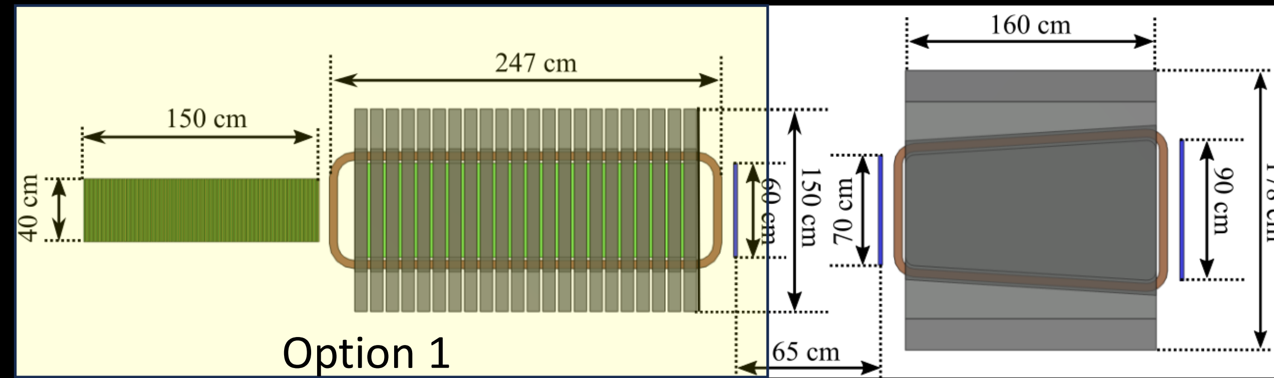
CERN-SPSC-2022-032 / SPSC-I-258

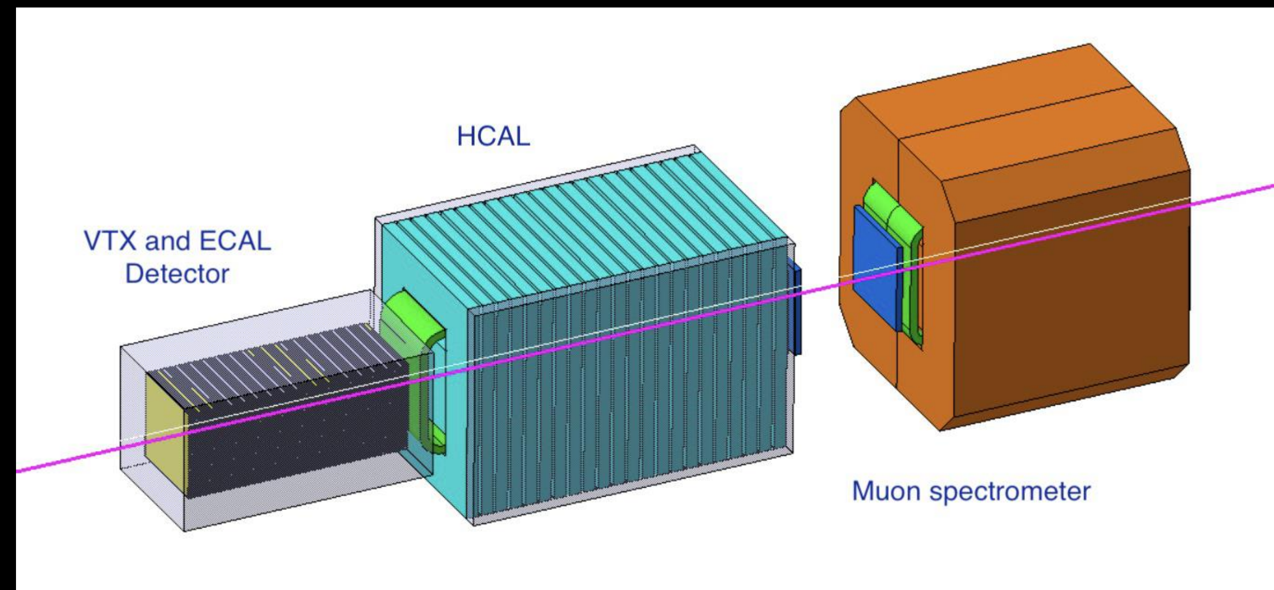
AdvSND for LHC Run4

New target design,

- Tungsten as a target
  - 7 mm or 3.5 mm
- High precision vertex detector
  - Silicon strip modules of outer barrel tracker of CMS
  - Pixel planes
- Up to 2.6 to 1.7 tons with 100 to 130 Tungsten+Scifi layers

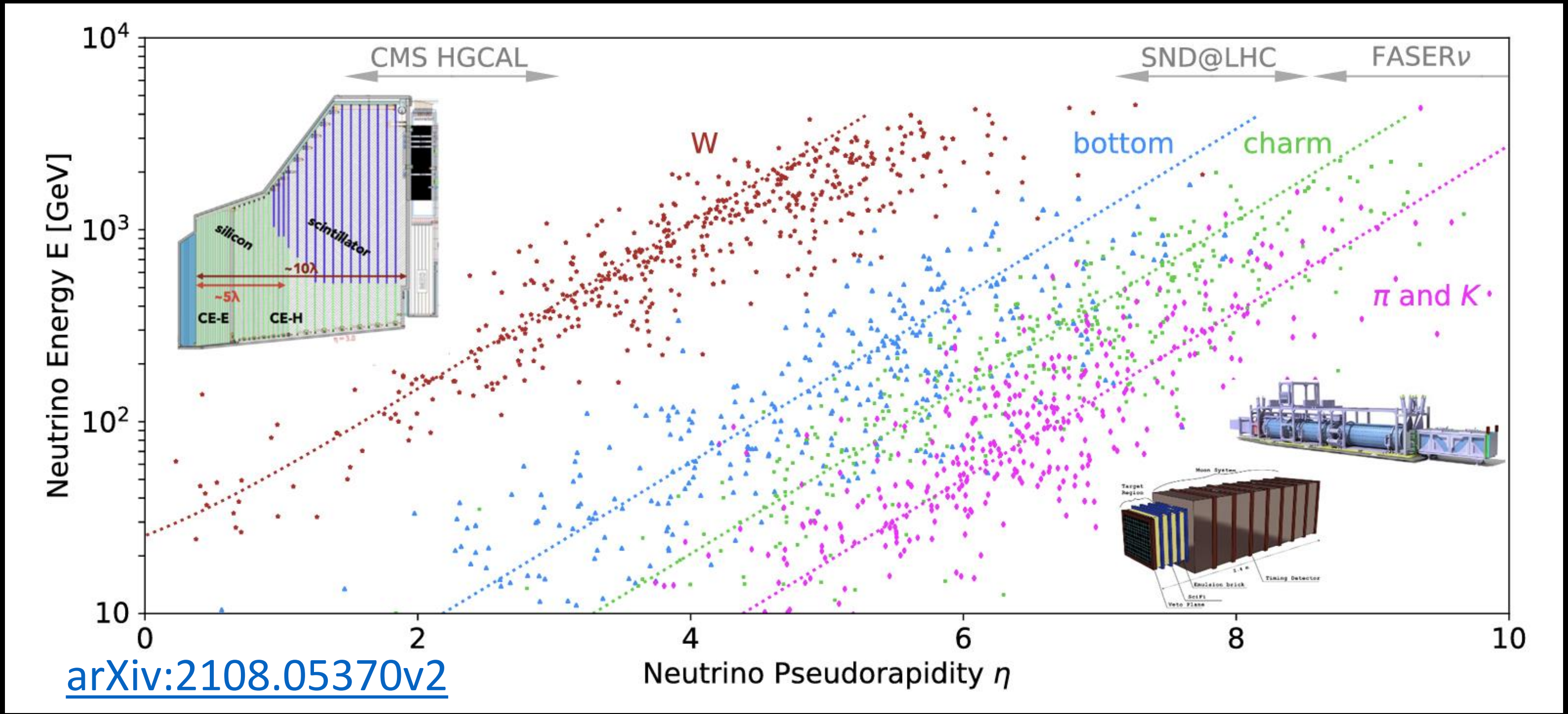
[AdvSND Coll. CERN-LHCC-2024-007]



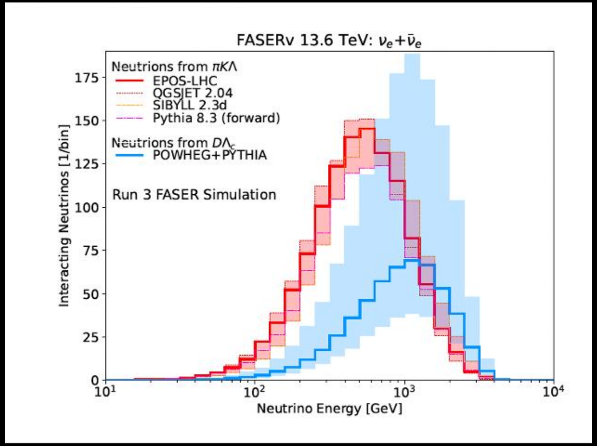


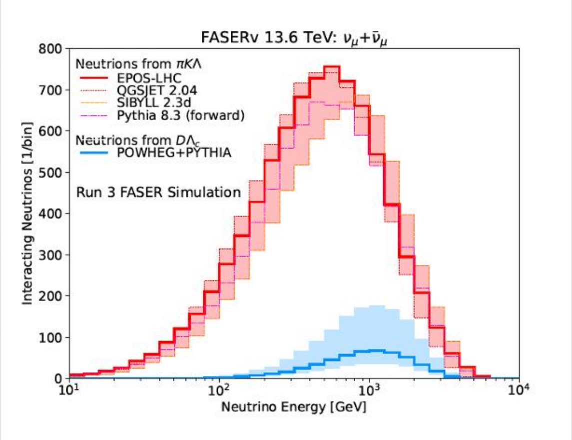
Discussion within **FASER/FASERν** is ongoing on possible upgrade of neutrino detector **at LHC Run4**

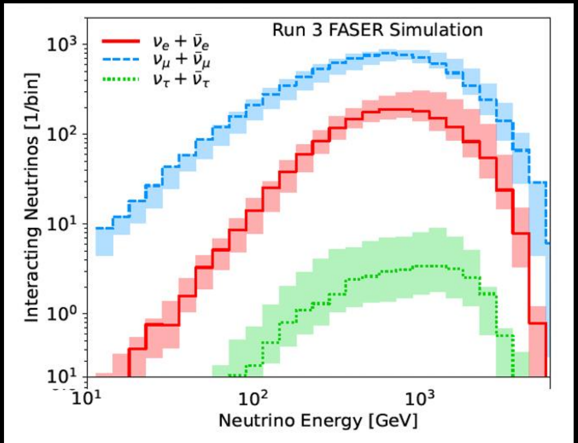
High energy neutrino distribution at the LHC



arXiv:2108.05370v2







FASER Coll. arXiv:2402.13318

FPF physics snapshoot