Neutrinos at the LHC

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CERN, Geneva, Switzerland

Milano, 21st June 2024

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- Dedicated experiments since 2022: FASER(ν) and SND@LHC
  - Results on neutrino detection/scattering
  - Searches for BSM physics
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- Neutrinos @ Central Detectors: Searches for Heavy Neutral Leptons
- Summary and outlook

Neutrinos at the Large Hadron Collider

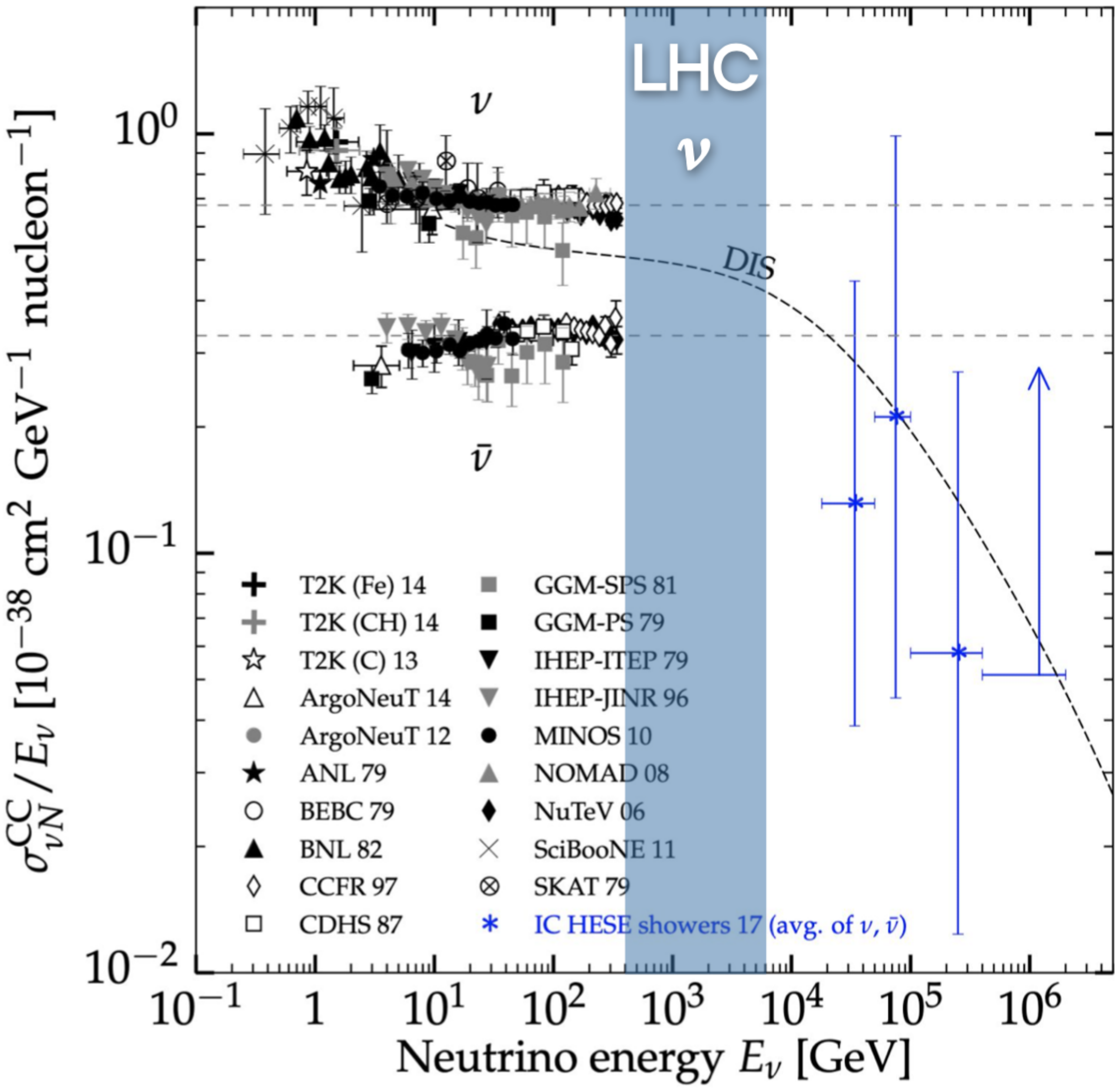
- Initial studies on **neutrino detection at the LHC** date back to the 80s.
  CERN-1984-010-V-2.571; Nucl. Phys. B405, 80; LPNHE-93-03
  - Back then, seen as an opportunity to discover the ν_τ.

- **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

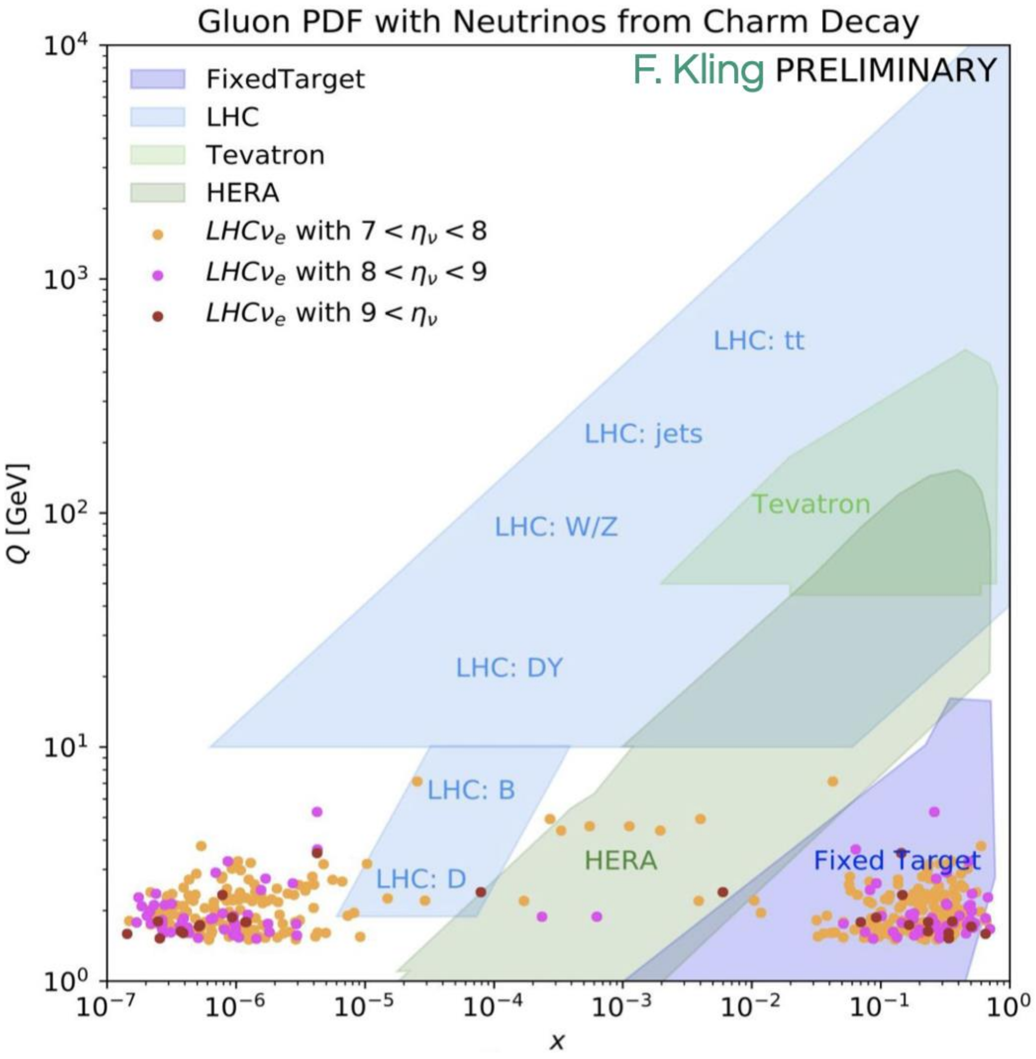
- Decays of **charm** hadrons contribute significantly to the neutrino flux.
  ⇒ Measure **forward charm production** with neutrinos.
  ⇒ Constrain **gluon PDF** at very **small x**.

Flavour

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

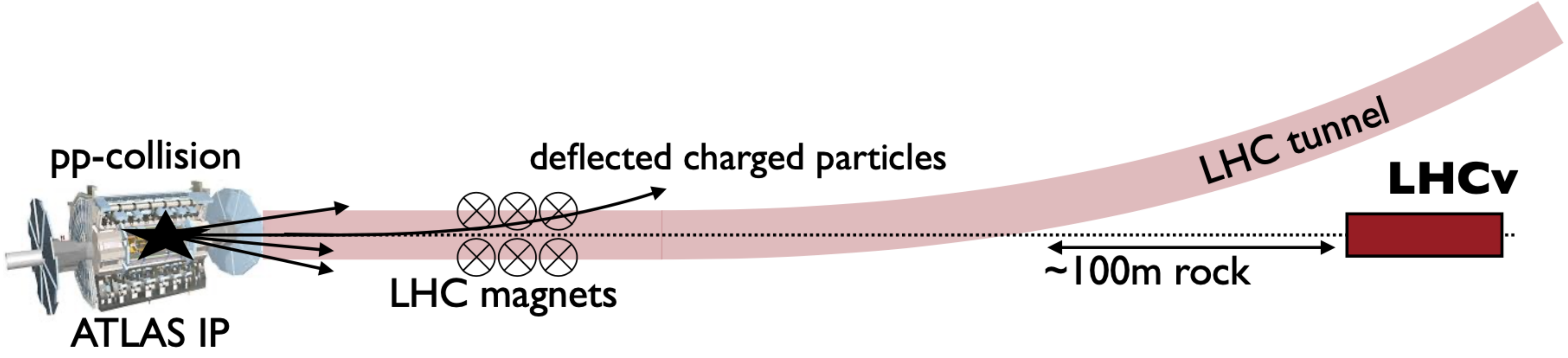
Beyond the Standard Model

- 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

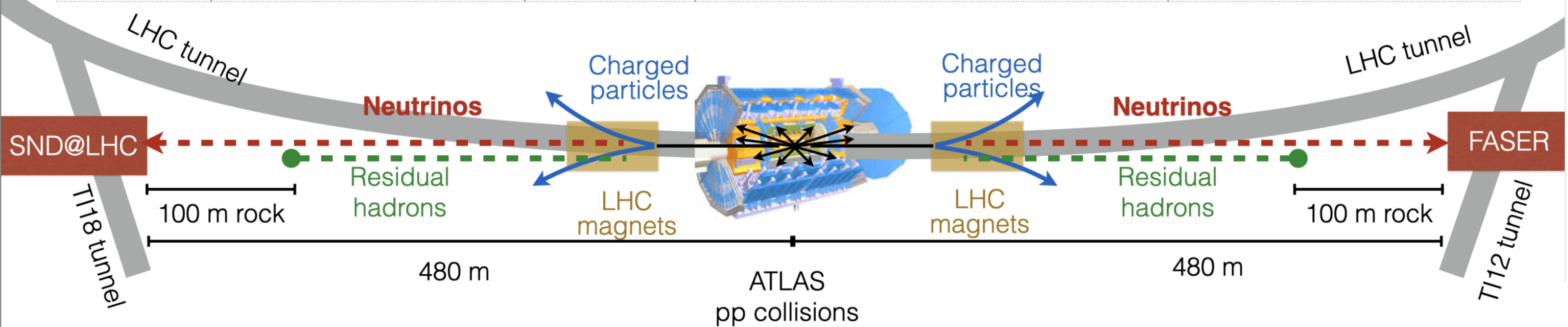
TeV-energy Neutrino Interaction

~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

	Acceptance	Target	Physics	Detector
SND@LHC	Off-Axis: $7.2 < \eta < 8.4$ (● Beam collision axis)	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



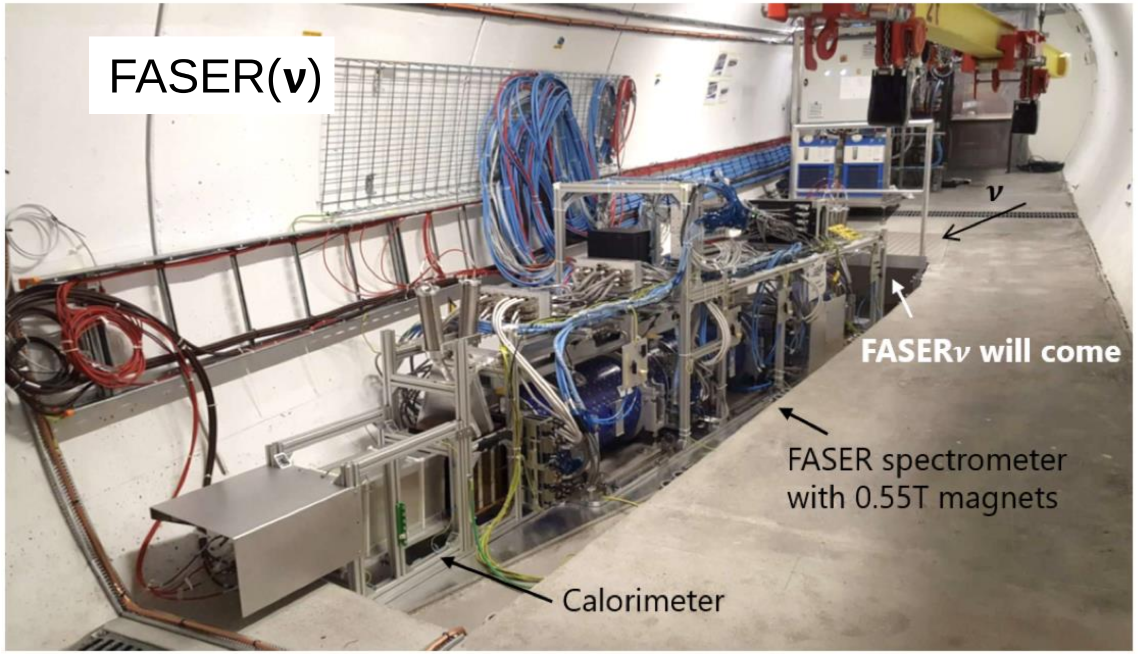
Neutrino Detectors at the LHC

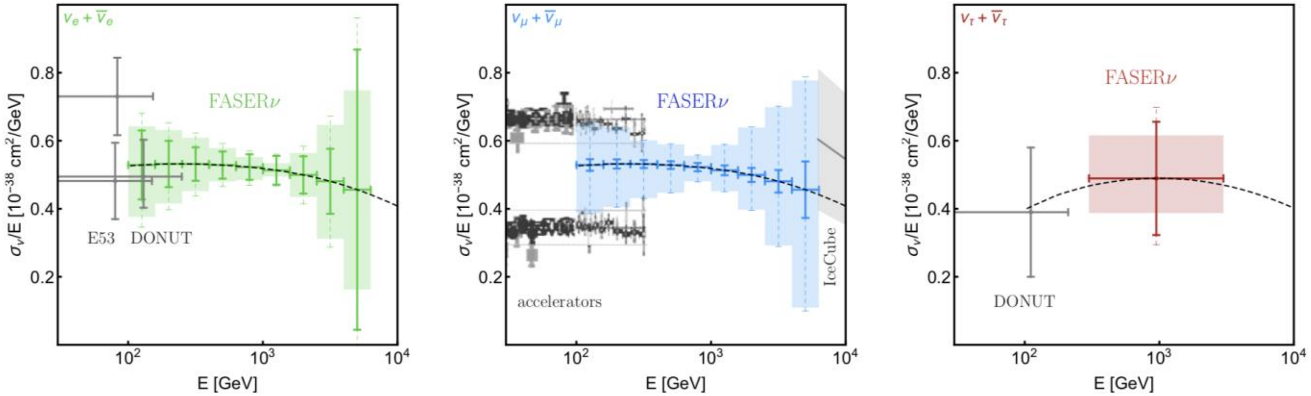
SND@LHC: approved March ‘21

SND= Scattering and Neutrino Detector

FASER(ν): approved March ‘19

FASER= ForwArd Search ExpeRiment





Prospects for Run 3 2022-2025

The Dawn of Collider Neutrino Physics

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

July 19, 2023 • *Physics* 16, 113

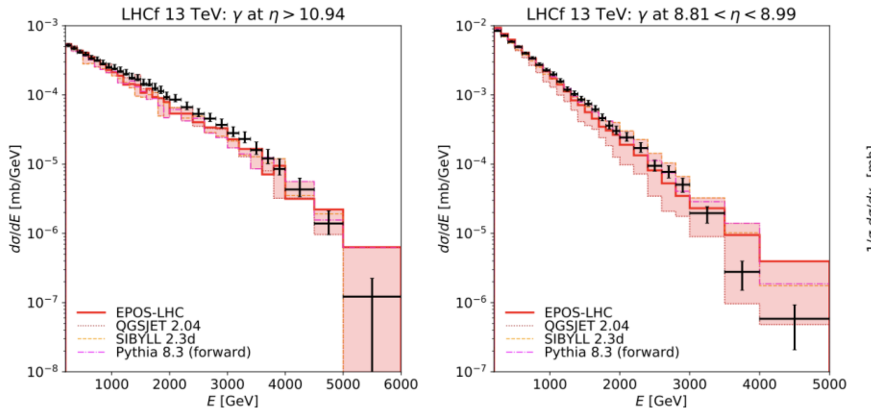
The first observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.

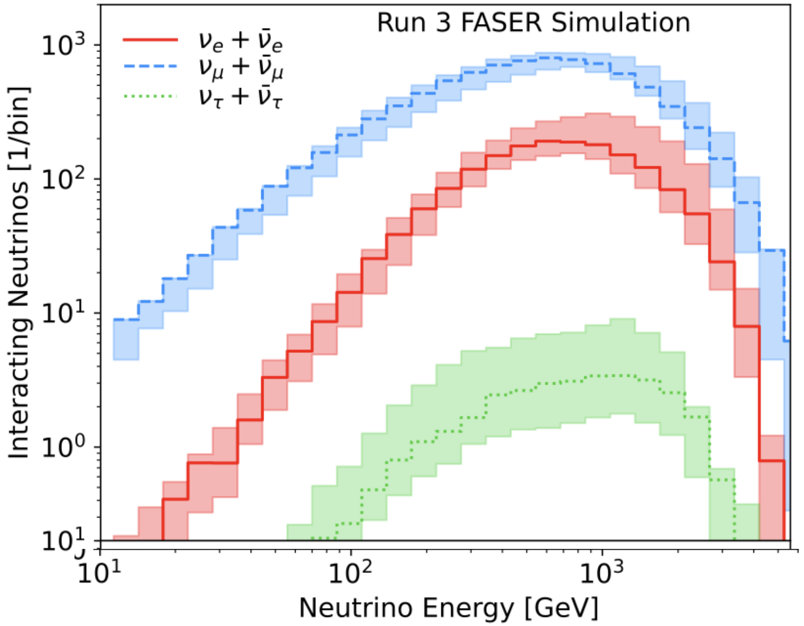
Neutrino Rate Predictions for the LHC

2402.13318

Neutrino rates from hadron decays

- Using phenomenological models EPOS-LHC, Sibyll, QGSJET, PYTHIAforward and POWHEG/PYTHIA (for charm)
- Model predictions are compared to data eg. from LHCf





Generators		FASERν at Run 3			FASERν at Run 4		
light hadrons	charm hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
EPOS-LHC	–	1149	7996	–	3382	23054	–
SIBYLL 2.3d	–	1126	7261	–	3404	21532	–
QGSJET 2.04	–	1181	8126	–	3379	22501	–
PYTHIAforward	–	1008	7418	–	2925	20508	–
–	POWHEG Max	1405	1373	76	4264	4068	255
–	POWHEG	527	511	28	1537	1499	91
–	POWHEG Min	294	284	16	853	826	51
Combination		1675^{+911}_{-372}	8507^{+992}_{-962}	28^{+48}_{-12}	4919^{+2748}_{-1141}	24553^{+2568}_{-3219}	91^{+163}_{-41}

O(10)% uncertainty for $\boldsymbol{\nu_\mu}$ and larger for other $\boldsymbol{\nu}$ flavors

The FASER(ν) Detector

Decay Volume & Tracking Spectrometer

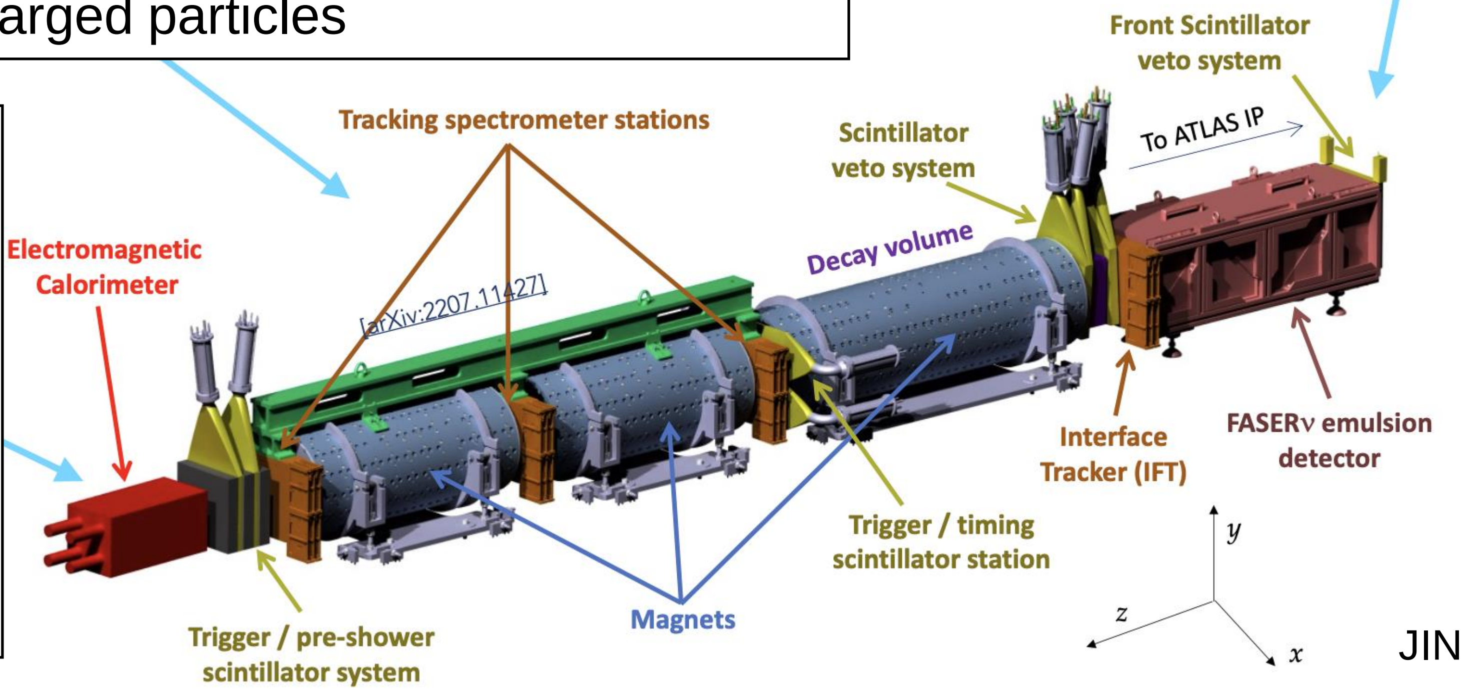
- Dipole magnets separate collimated oppositie charged particles and measure the charge and momentum of the μ from ν interactions
- Silicon strip trackers to measure position, charge & momentum of the charged particles

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)

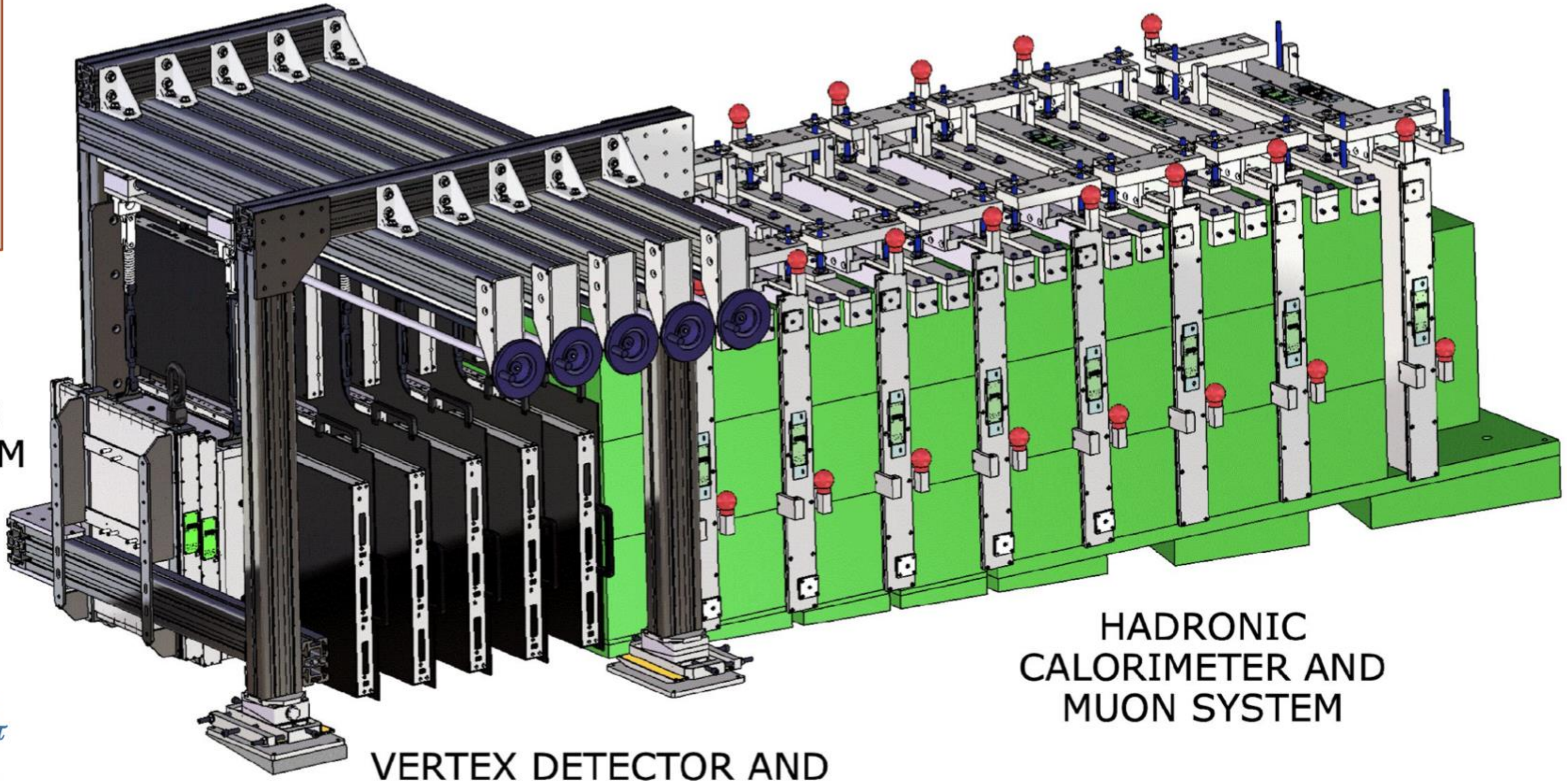
Scattering and Neutrino Detector @ the LHC

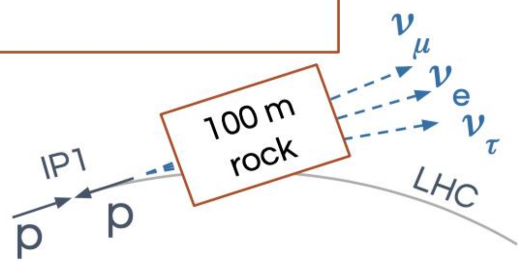
Veto system
Two 1 cm thick scintillator planes.

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: $7.2 < \eta < 8.4$



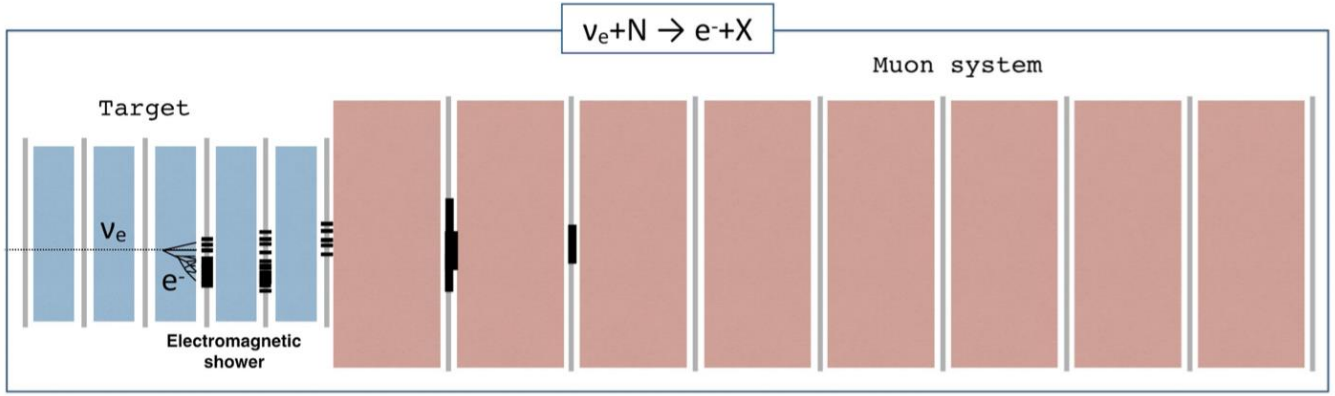


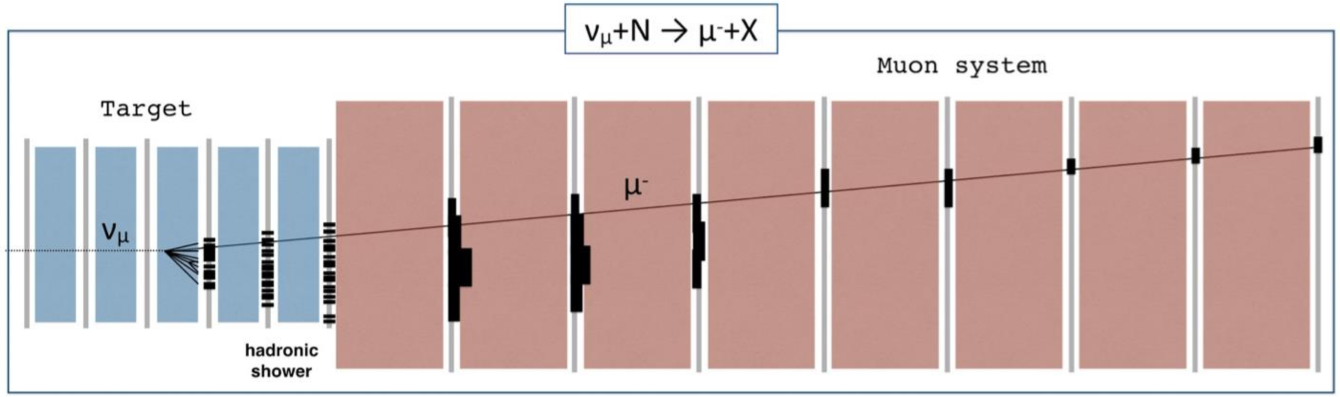
arXiv:2210.02784

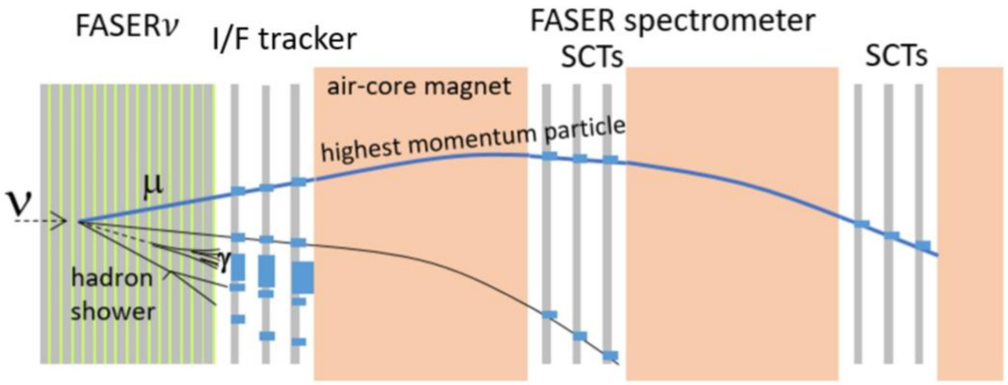
Neutrino Event Reconstruction Strategies

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**.







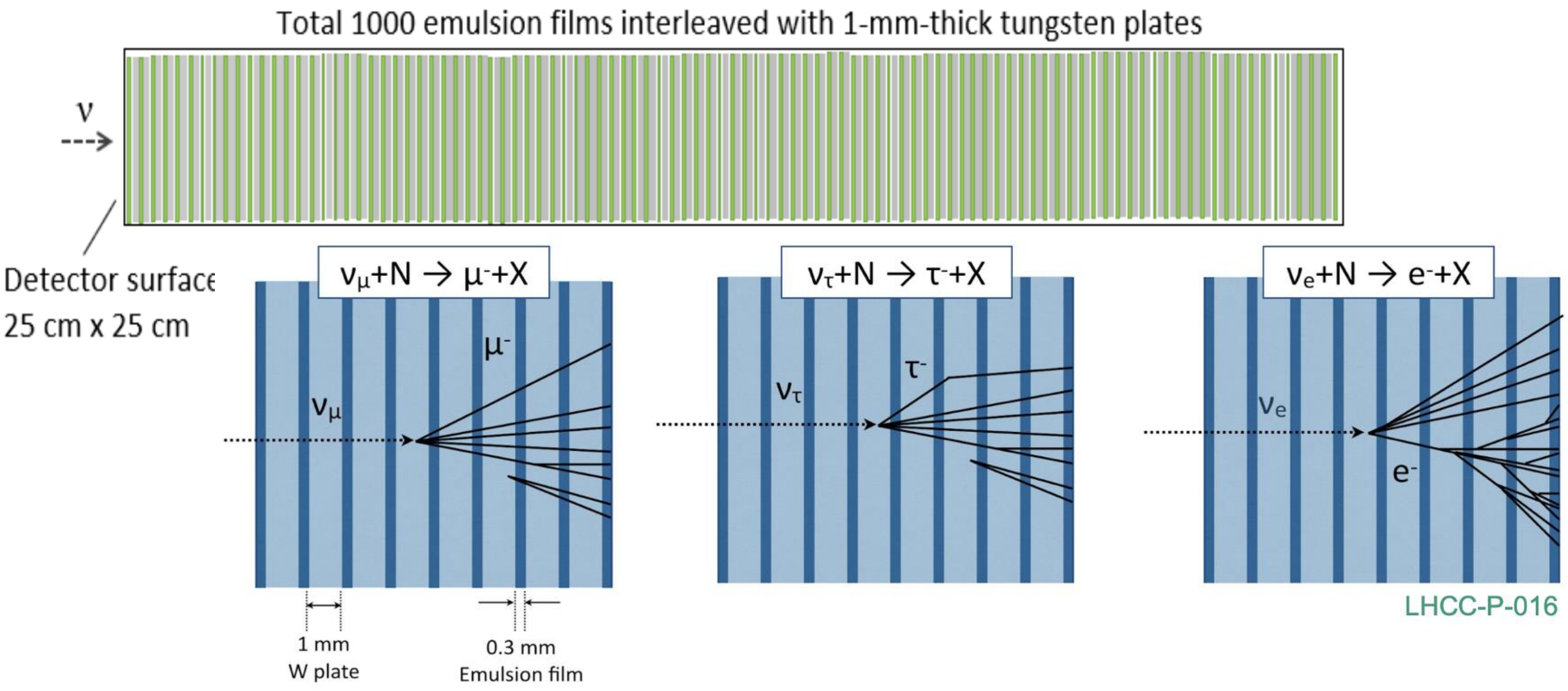
FASER

- 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

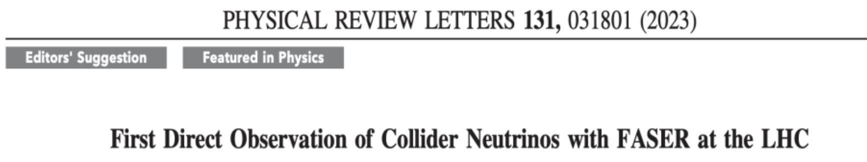
Identification of the Neutrino Flavor

- 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)



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

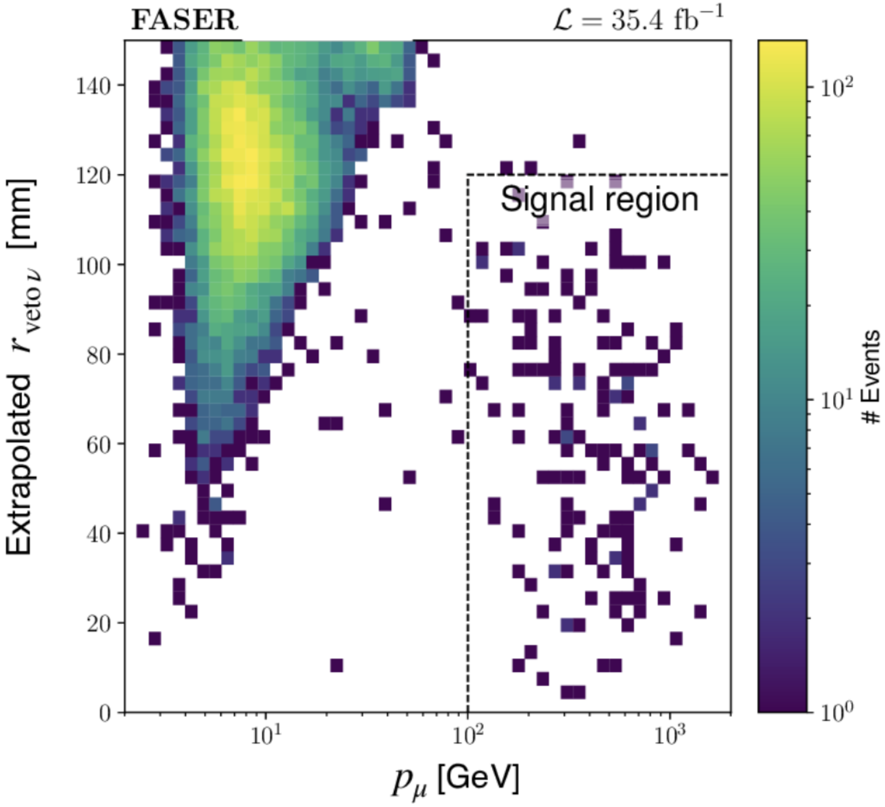

PHYSICAL REVIEW LETTERS 131, 031801 (2023)

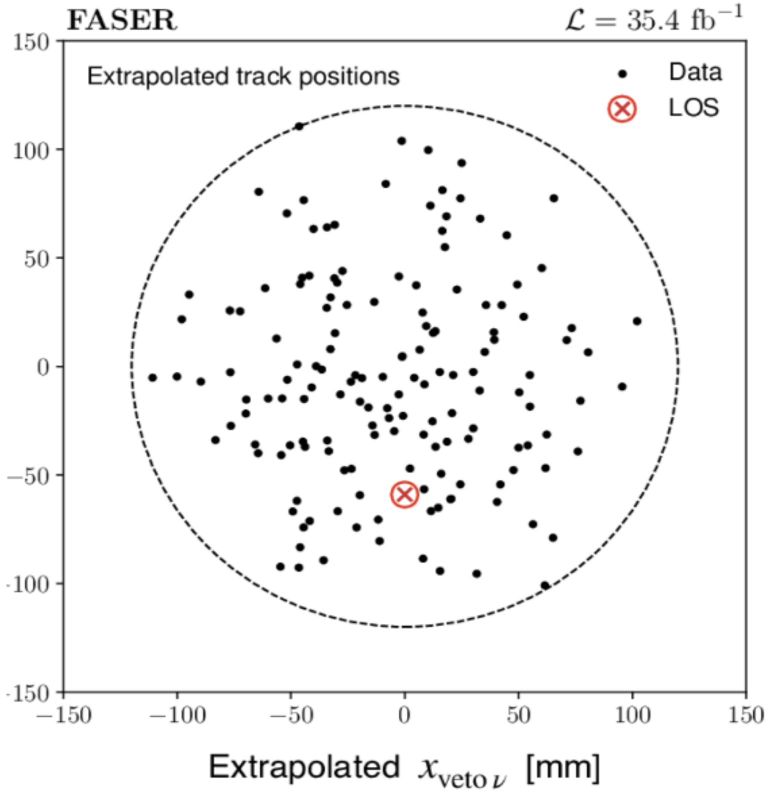
Editors' Suggestion | Featured in Physics

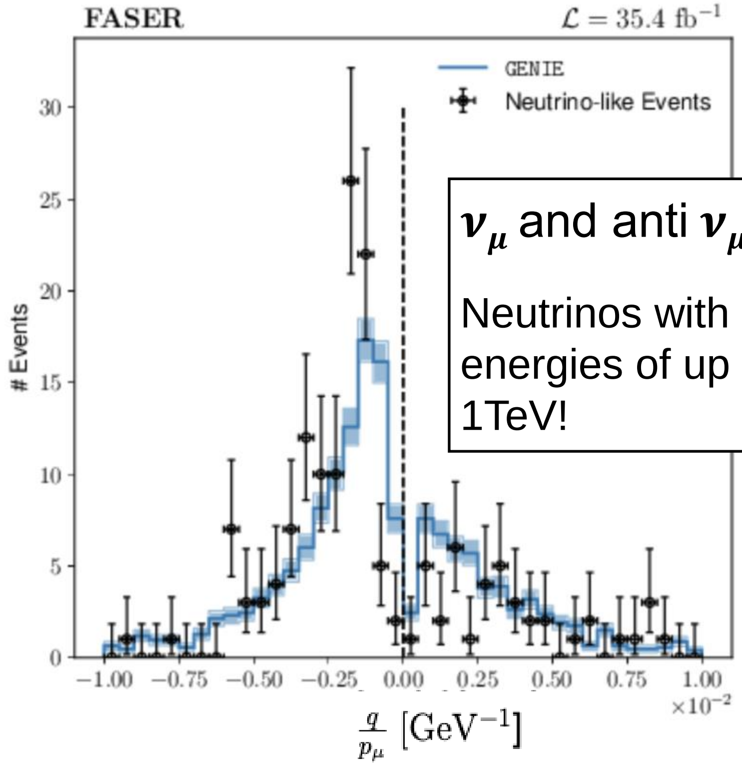
First Direct Observation of Collider Neutrinos with FASER at the LHC

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

16$\boldsymbol{\sigma}$ significance





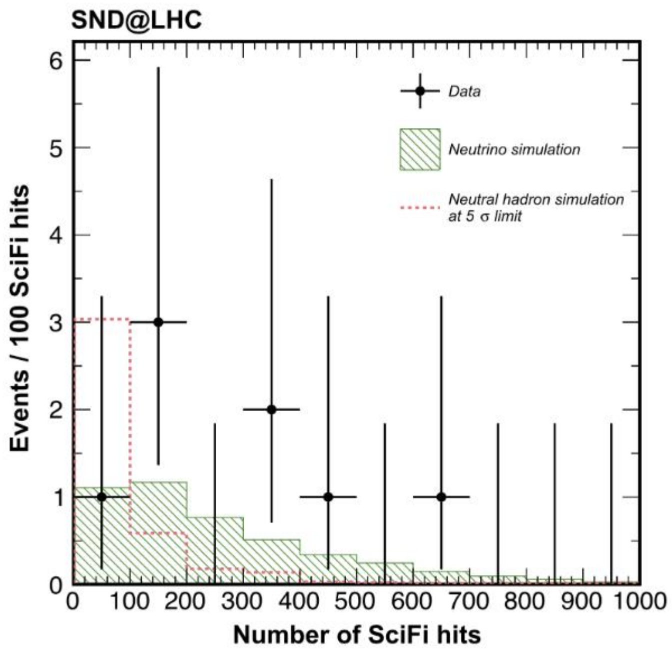


$\boldsymbol{\nu_\mu}$ and anti $\boldsymbol{\nu_\mu}$

Neutrinos with energies of up to 1TeV!

- q: assigned track charge

Observation of Collider Muon Neutrinos



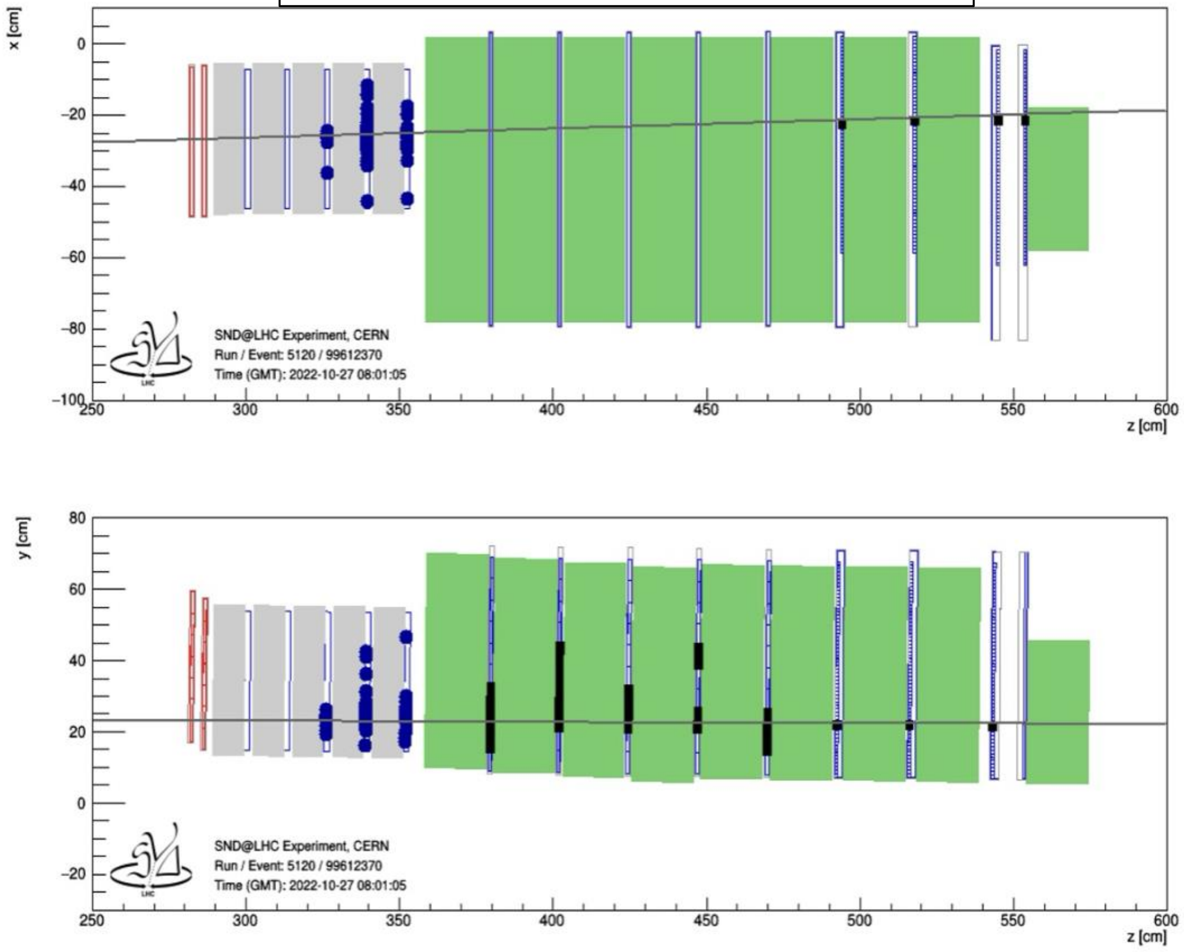
- ν_μ with electronic detectors only
- 2022 data
- 8 events observed events
- 8.6×10^{-2} background
  $\rightarrow$ 6.8 σ significance

Editors' Suggestion

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

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

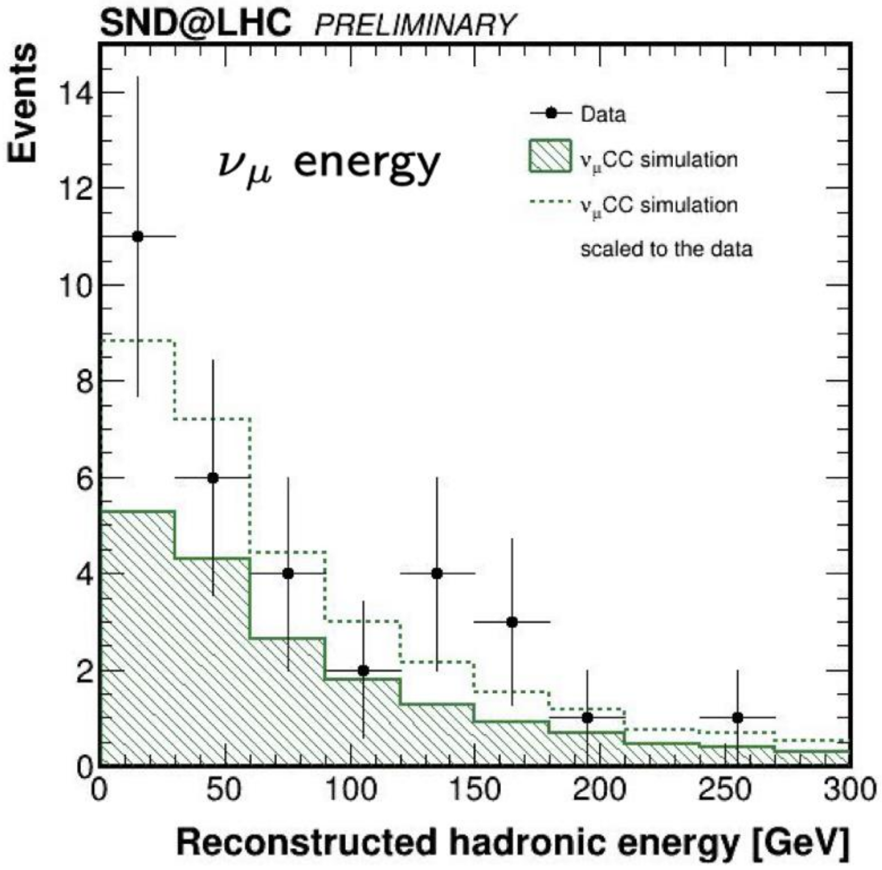
Phys. Rev. Lett. **131**, 031802 (2023) – Published 19 July 2023

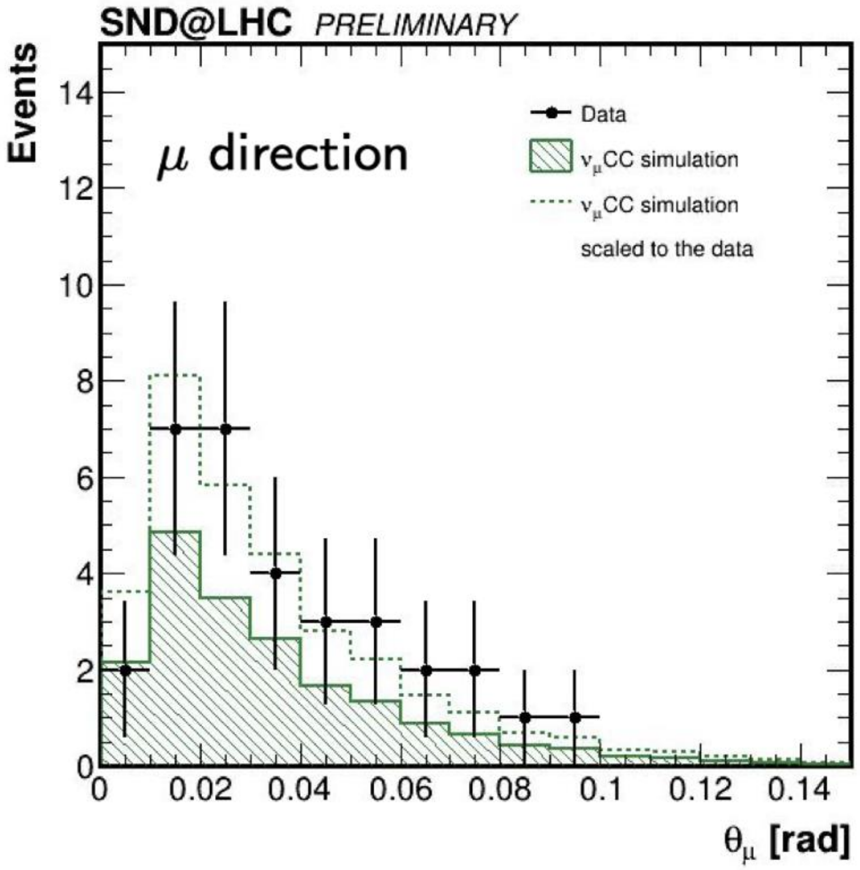


Updated Muon Neutrino Results

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





Kinematics of muon neutrino candidates in agreement with signal prediction

Number of events observed: 32

12σ

Observation of 0μ Events in SND@LHC

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

Neutral hadron background

- Define background-dominated control region.
- Scale the background prediction to the number of observed events in the control region.
  - Observed neutral hadron background is ⅓ of the predicted value.
- Events **expected in signal region: 0.01**

Neutrino background

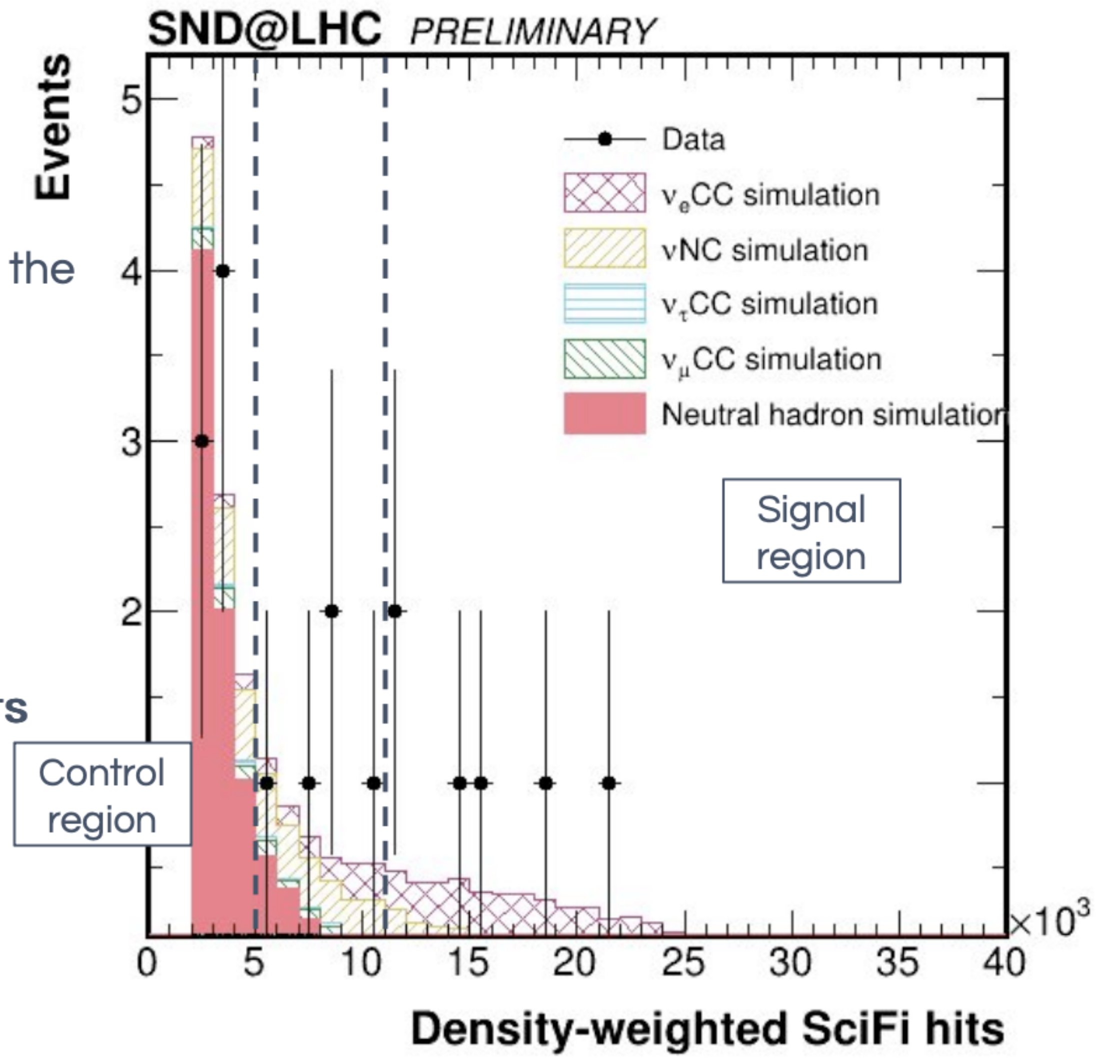
- Muon neutrino CC interactions are the dominant background, with **0.12** expected events.
- Tau neutrino CC1μ interactions expected: 0.002

0μ observation significance

- **Total expected background: 0.13 ± 0.11 events**
- **Expected signal: 4.7 events**
- **Expected significance: 4.9 σ**

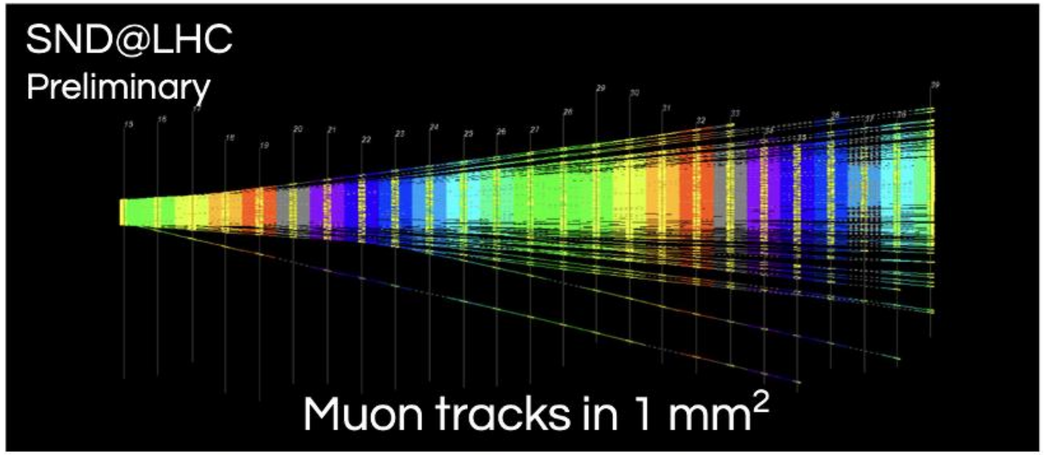
Number of events observed: 6
Observation significance: 5.8 σ

Paper in preparation

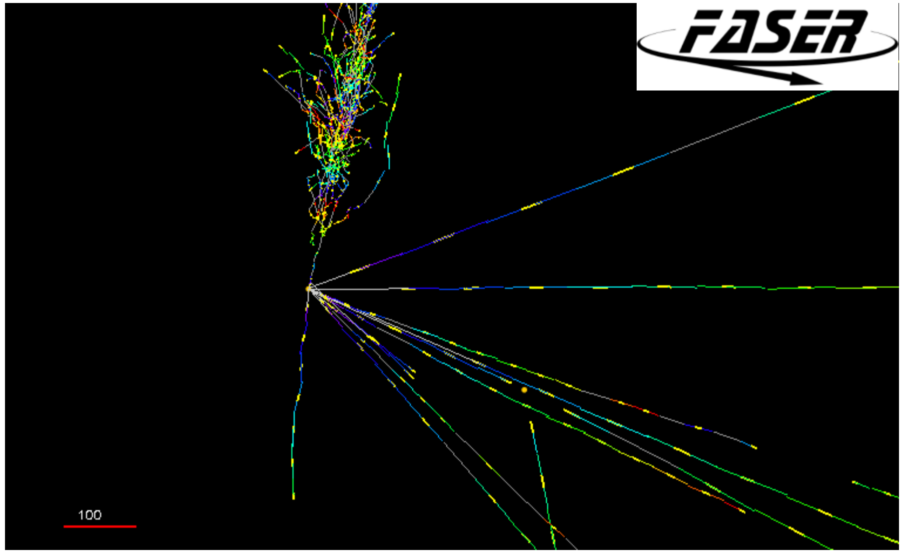


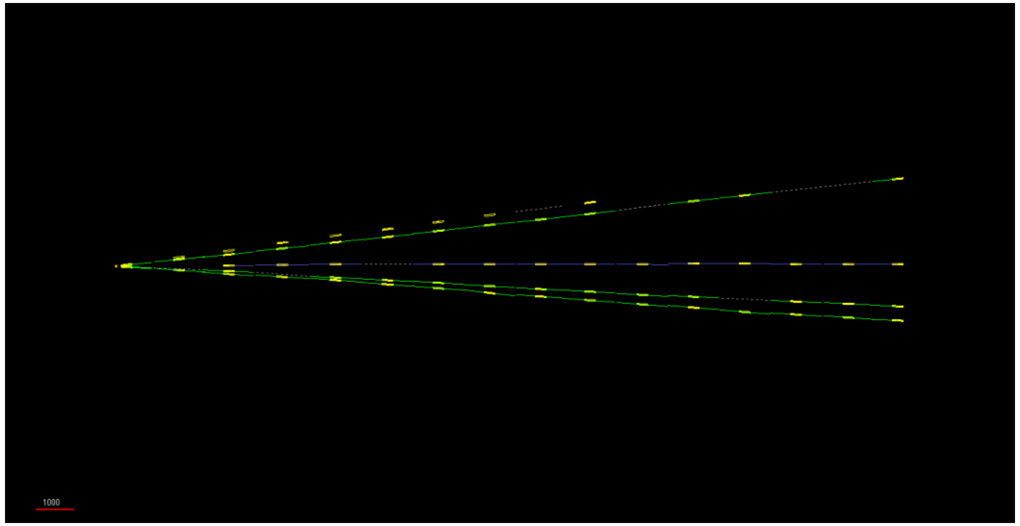
Emulsion Detector Data Analysis

- ➢ 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…



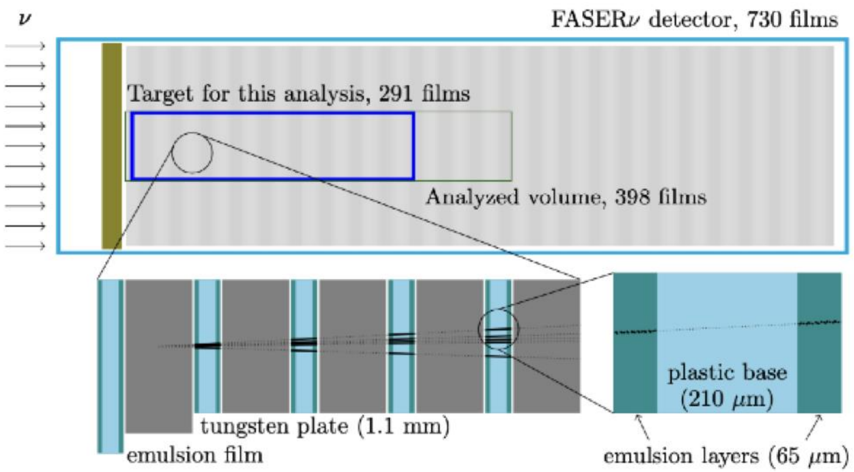
10^5 tracks/cm^2 in 10 fb^{-1} exposure





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

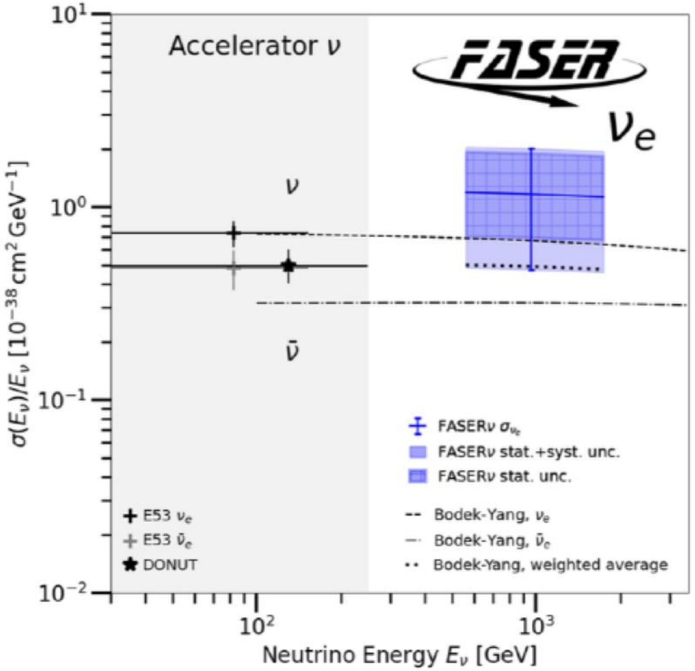
Measurement of ν_e and ν_μ Interaction Cross Sections

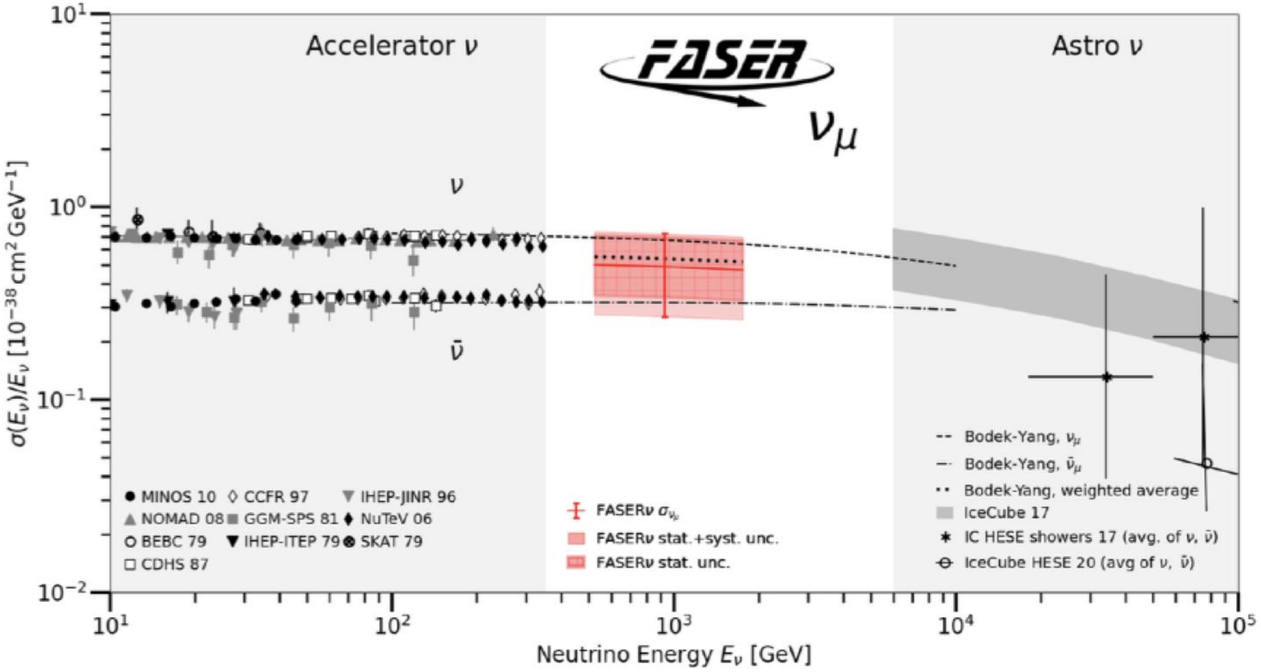


Analysed target mass of 128.6 kg

- Using the emulsion detector of FASER
- Only a small fraction of the 2022 data analysed so far
- Candidate vertices reconstructed in emulsion films.
  Electron energy measured from shower multiplicity.
  Muon momentum measured from track RMS
  (via multiple scattering)
- Electron neutrinos observed 4(5.2 σ)
- Muon neutrinos observed 8 (5.7σ)

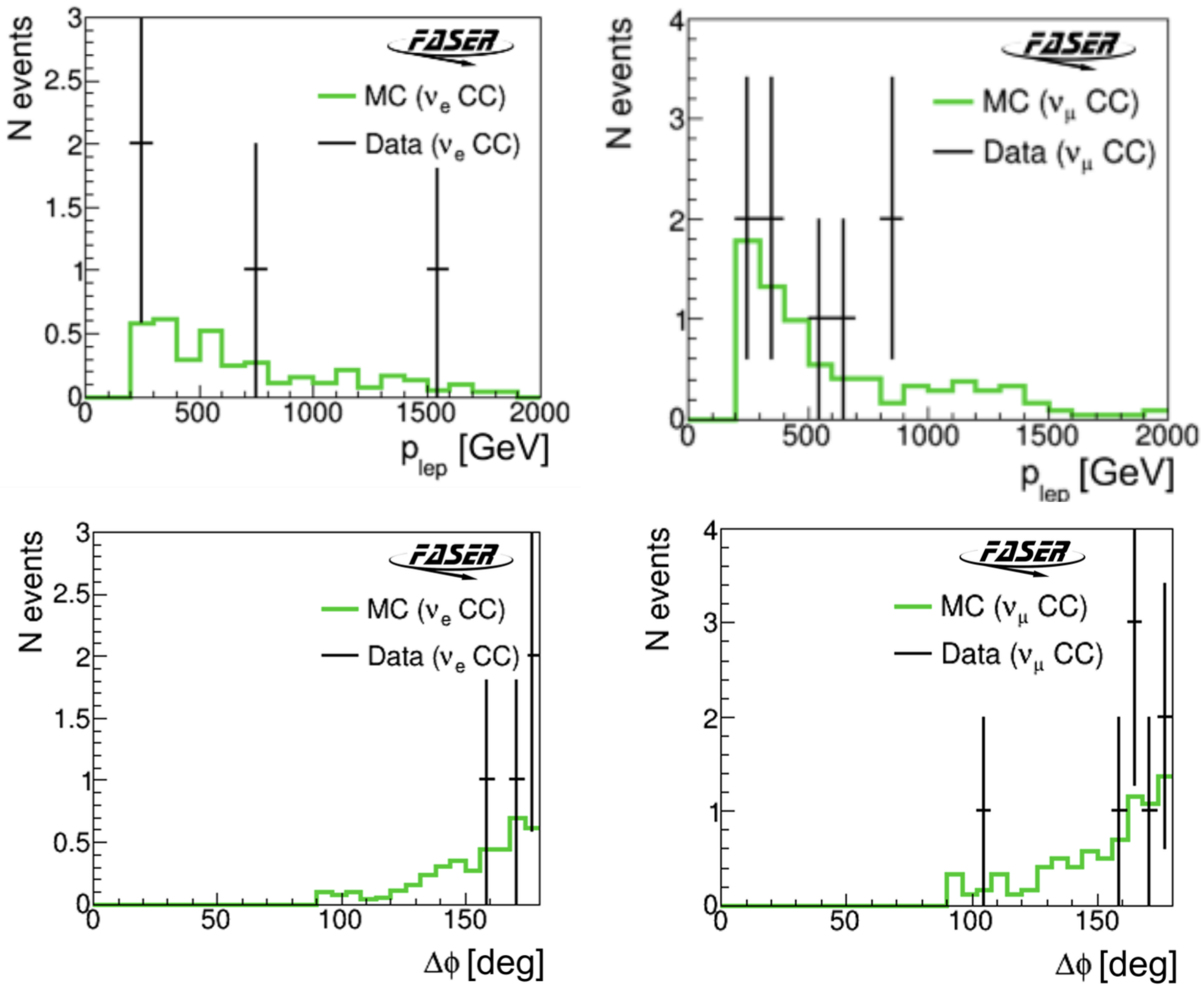
2403.12520



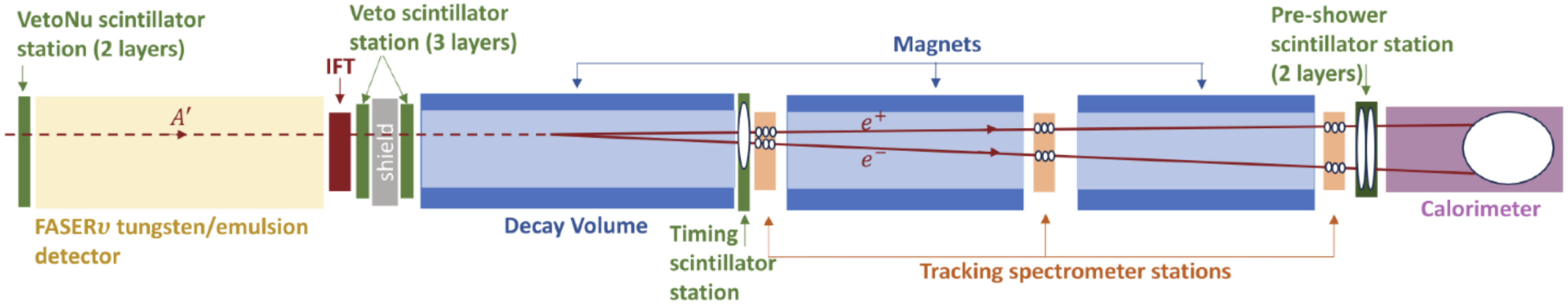


Analysing Emulsion Data

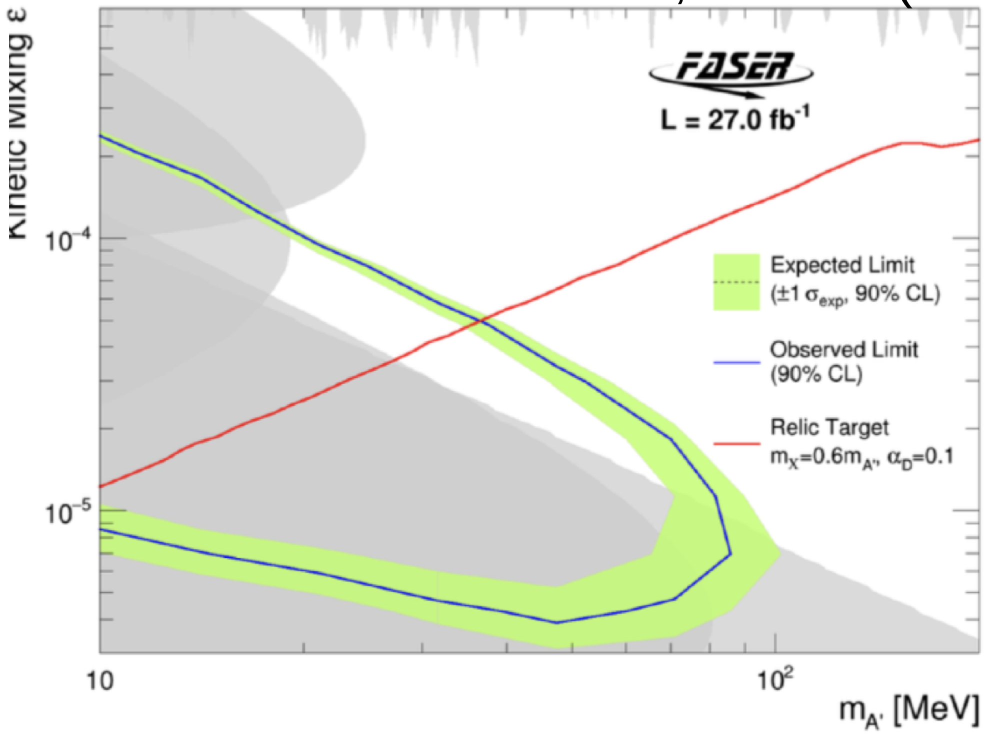
- Electron neutrino events observed: 4 (5.2σ)
- Muon neutrino events observed: 8 (5.7σ)
- **first direct observation of electron neutrinos produced at a particle collider**
- Expected background:
  - Elec. 0.025 +/- 0015 (neutral hadrons)
  - Muon 0.22 +/0.09 (Neutral hadrons, NC)



BSM Searches with FASER: Dark Photons



PLB 848, 138378 (2024)

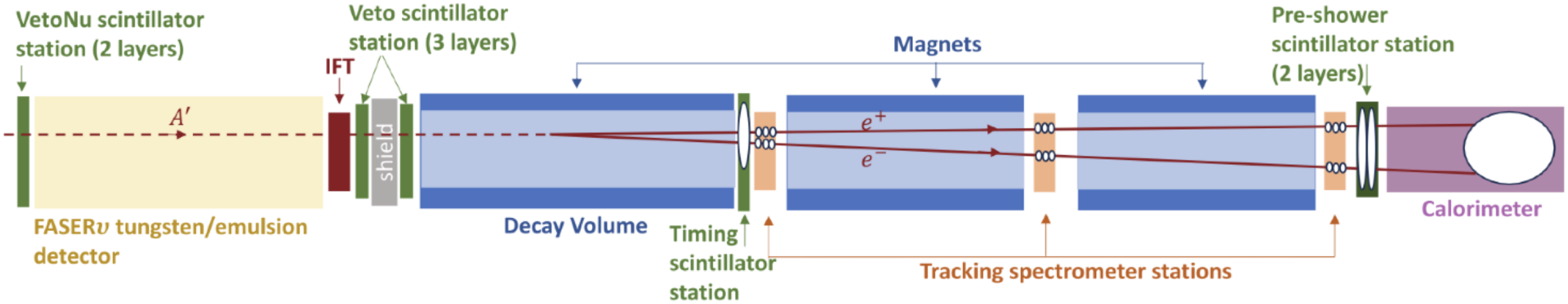


- Dark Photons: U(1) gauge group
  Signature: decay into e+e- pair in decay volume

- 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: Dark Photons

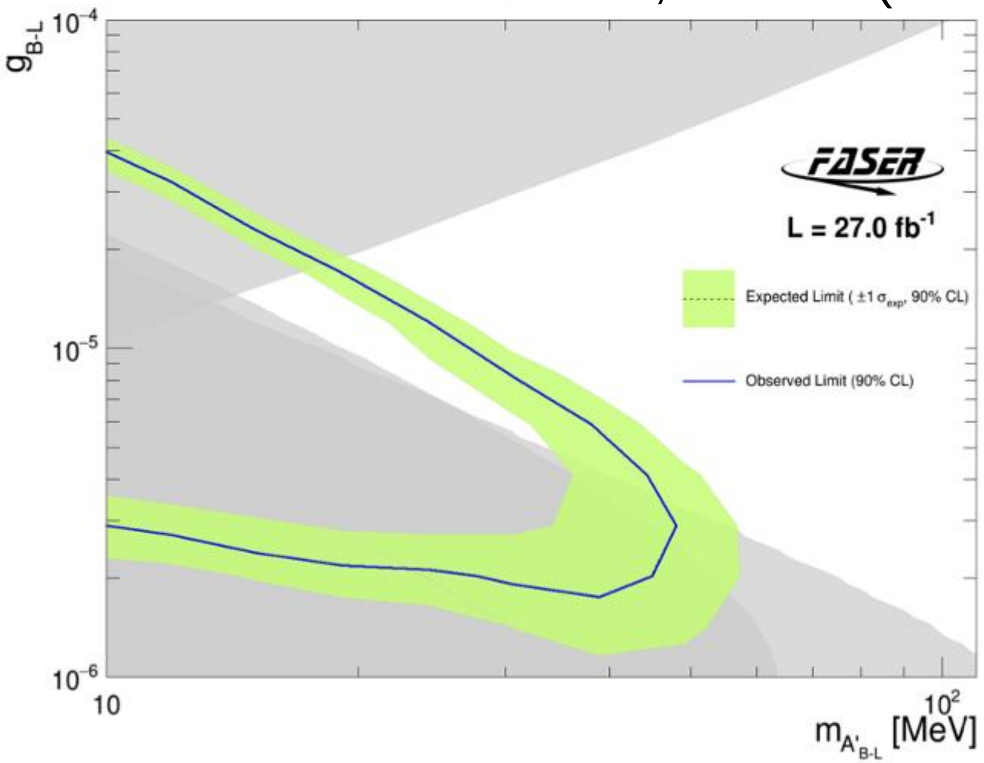


PLB 848, 138378 (2024)

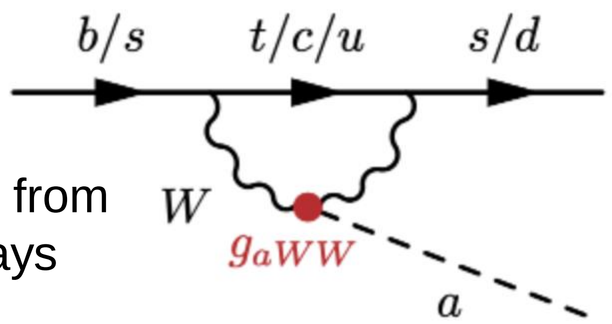
- Dark Photons: $U(1)_{B\text{-}L}$ gauge group
  Signature: decay into e+e- pair in decay volume

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

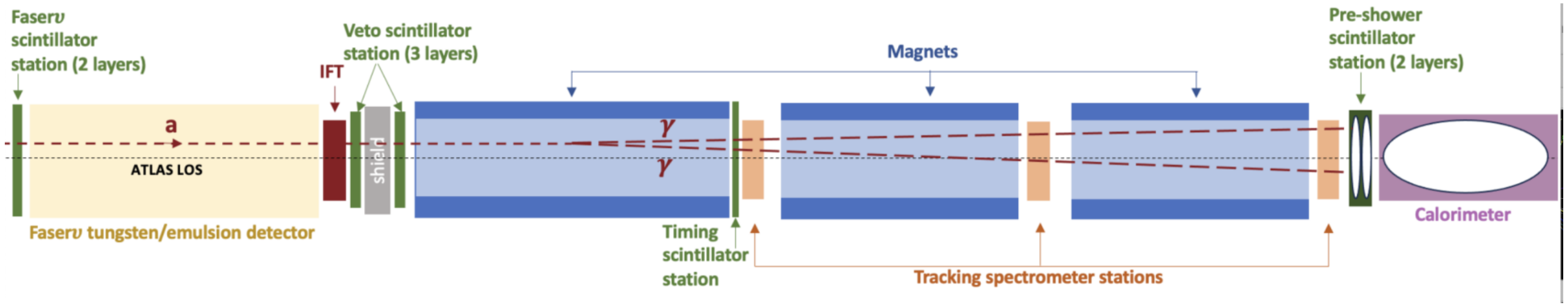
0 events observed / expected



BSM Searches with FASER: ALPs



Mainly from B decays

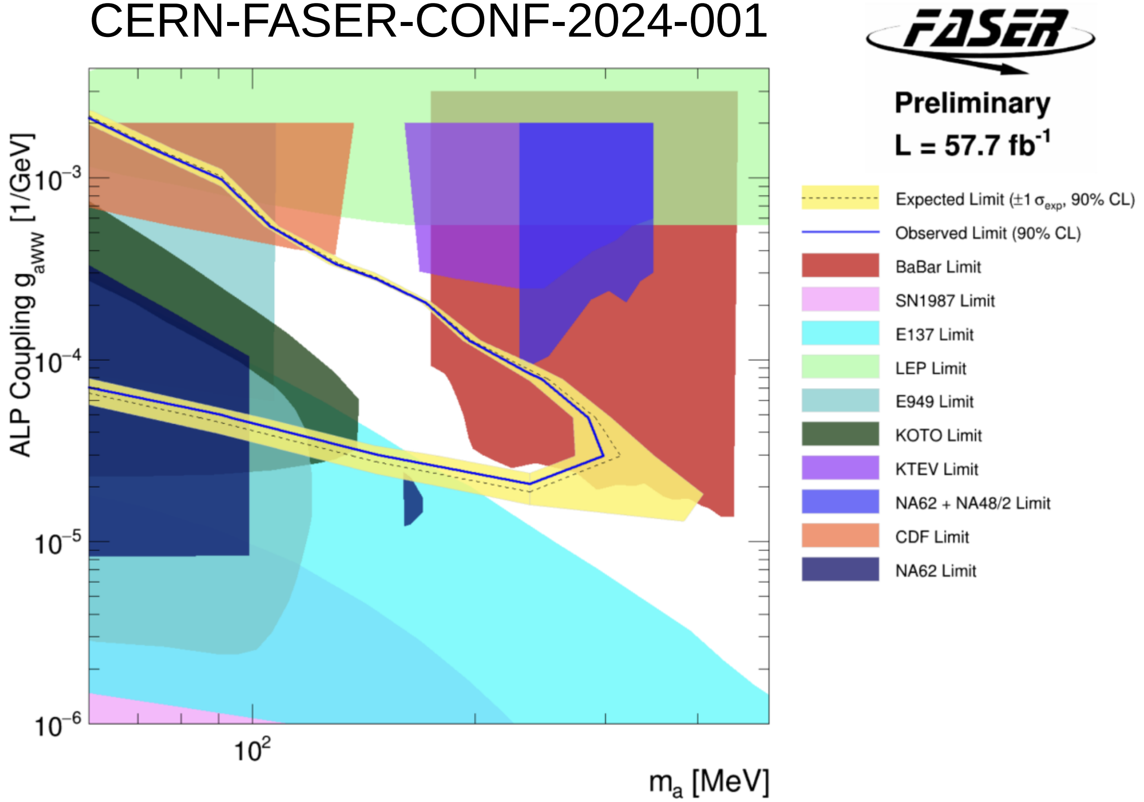


- Currently sensitive to axion-like particles (ALPs) coupling to $SU(2)_L$ gauge bosons

- 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

CERN-FASER-CONF-2024-001

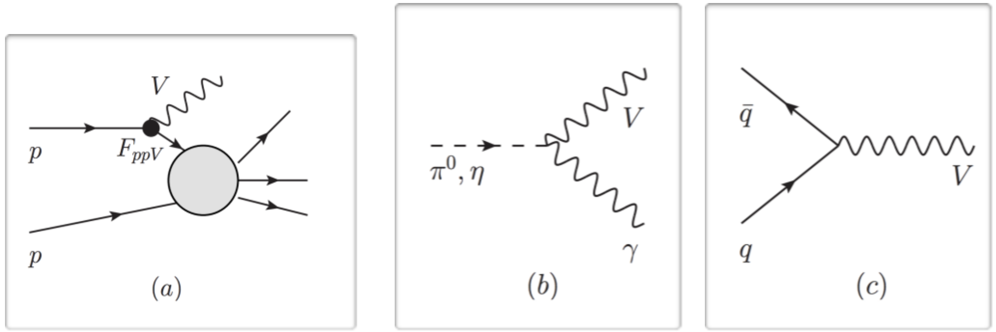


More BSM Searches Channels to Come…

- Eg. SND@LHC sensitivity for light dark matter

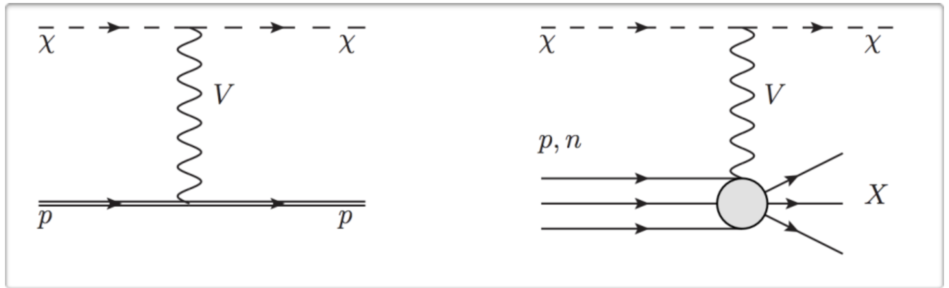
Production: consider a scalar χ particle coupled to the Standard Model via a leptophobic portal,

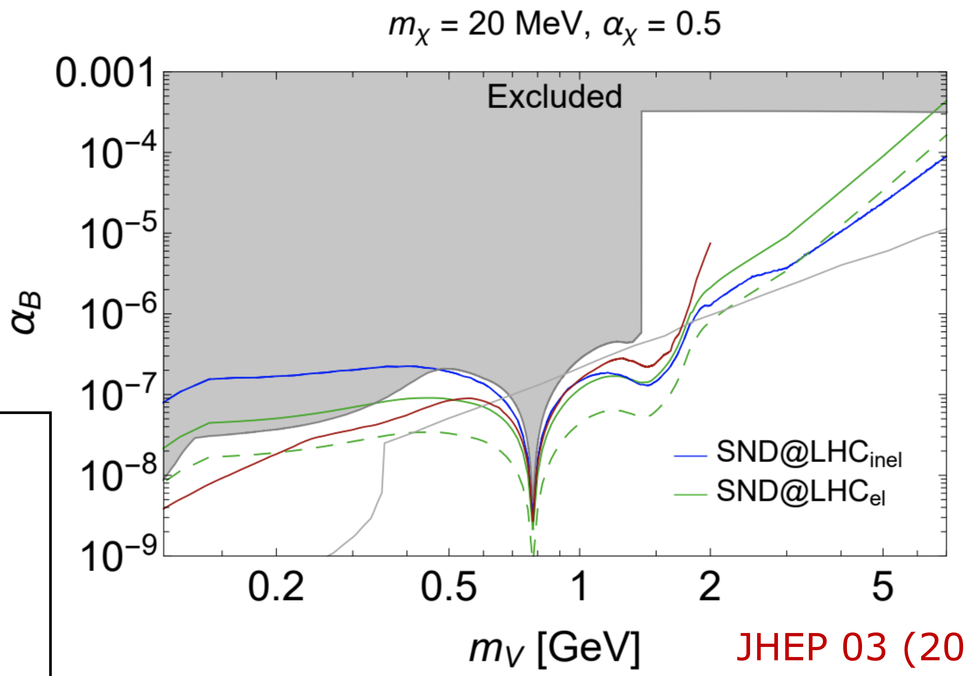
$$\mathcal{L}_{\text{leptophob}} = -g_B V^\mu J^B_\mu + g_B V^\mu (\partial_\mu \chi^\dagger \chi + \chi^\dagger \partial_\mu \chi),$$



Proton bremsstrahlung | Meson decay | Drell-Yan process

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





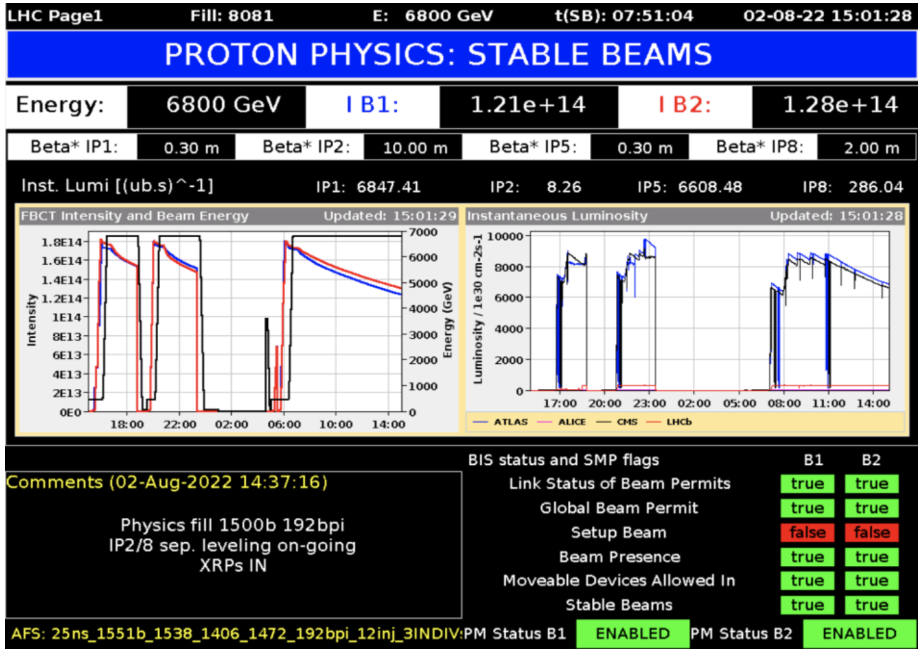
JHEP 03 (2022) 006

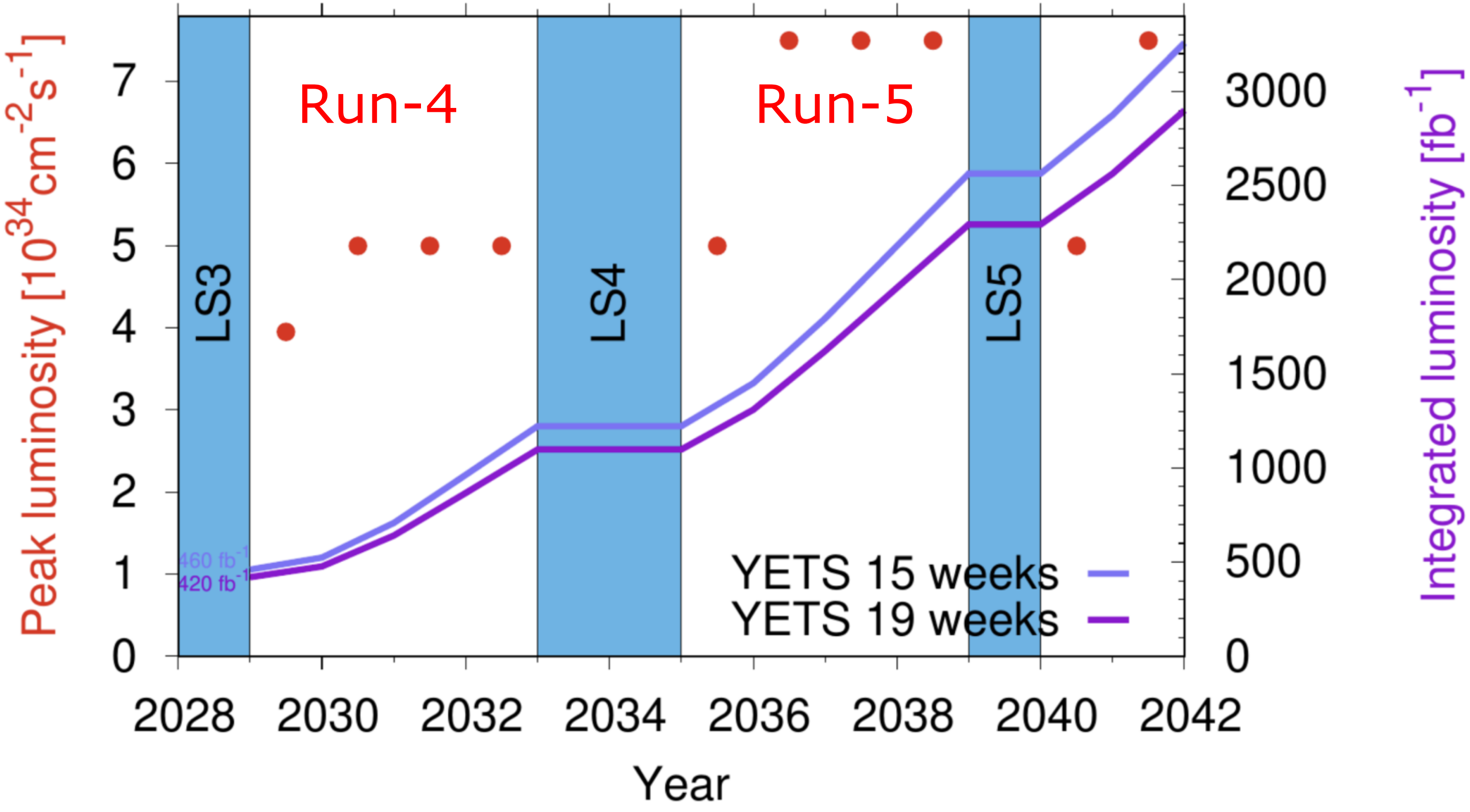
- More channels to explore by SND@LHC and FASER Higgs-like scalars, Heavy Neutral Leptons, final state radiation effects, Quirks, LFV with tau excess, exotic interactions…

Future LHC Running

- Currently Run-3 (2022-2025) is ongoing –> ~250 fb^{-1} expected luminosity

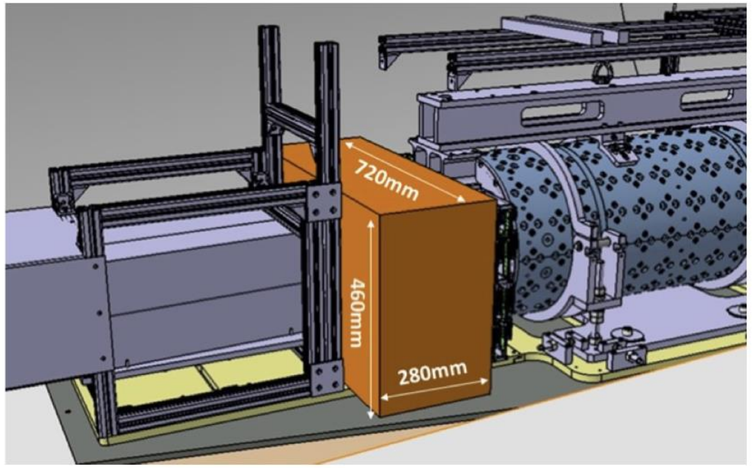
- Next: High Luminosity LHC starts with Run-4 (2029-2032) and Run-5 (2035-2038)
  Both SND@LHC and FASER plan upgrades for these future runs

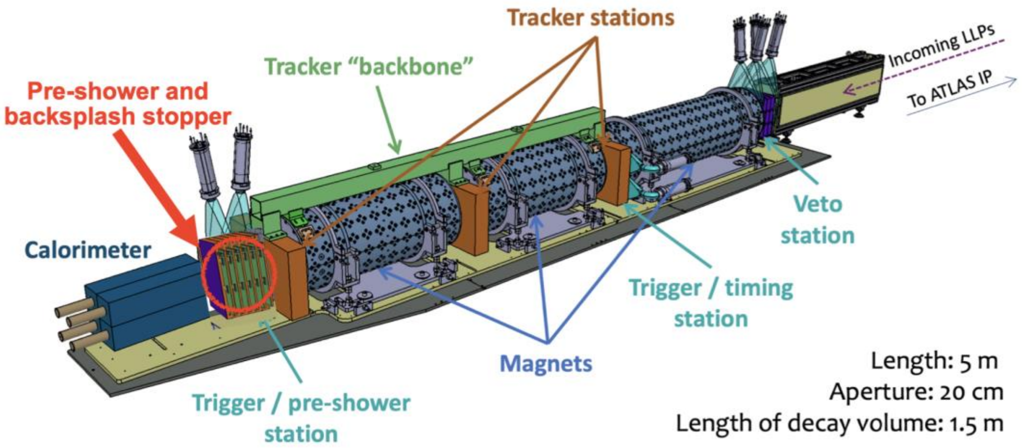


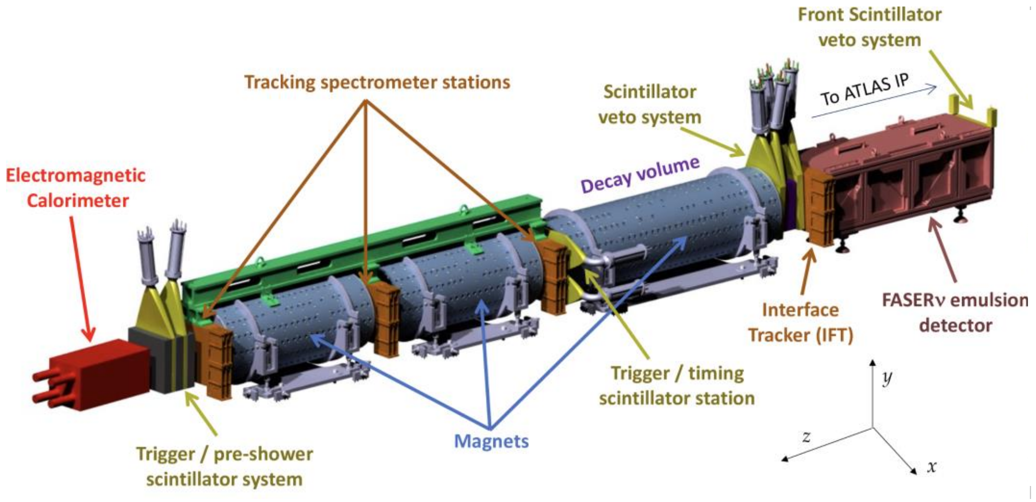


FASER Upgrade for Run-3 and Run-4

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







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

- The target will not have emulsion film for this Run-4, as too frequent target exchange would be required due to the higher luminosity… (LHCC-I-039)

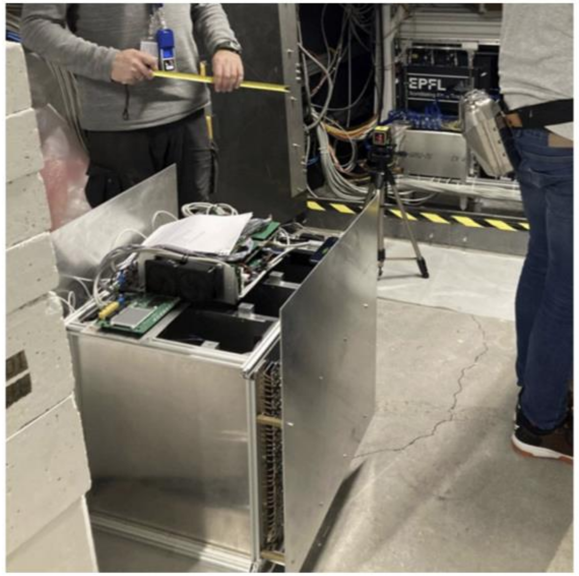
SND@LHC Upgrades Installed for 2024

Veto detector upgrade

- Installed a 3rd plane veto plane in the detector.
  - Additional redundancy to mitigate the impact of detector inefficiency.
- Floor was excavated so that veto system could be lowered.
  - Better coverage of the target.
- This upgrade will allow for a significant increase of the fiducial volume used in neutrino data analyses.

New muon telescope

- Technology demonstrator: sealed resistive-plate chambers.
- Will allow for measuring the muon flux outside of the SND@LHC acceptance.
  - Further validation of the background model.



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

CERN-LHCC-2024-007

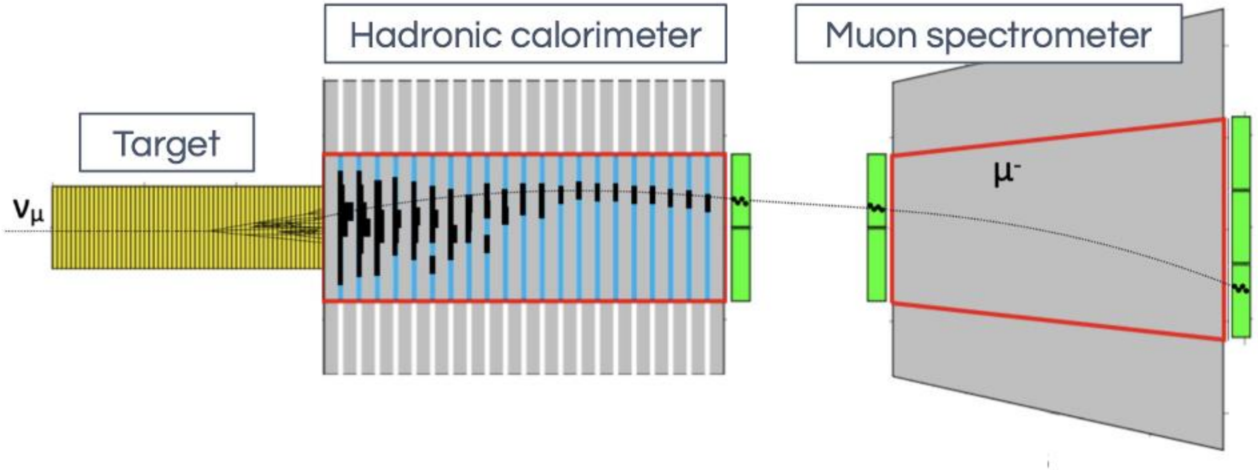
- Electronic vertex detector
  Silicon tracker option under consideration
- Improved hadron calorimeter and timing detectors
- Iron-core muon spectrometer
- Better acceptance, including the LOS of the LHC…

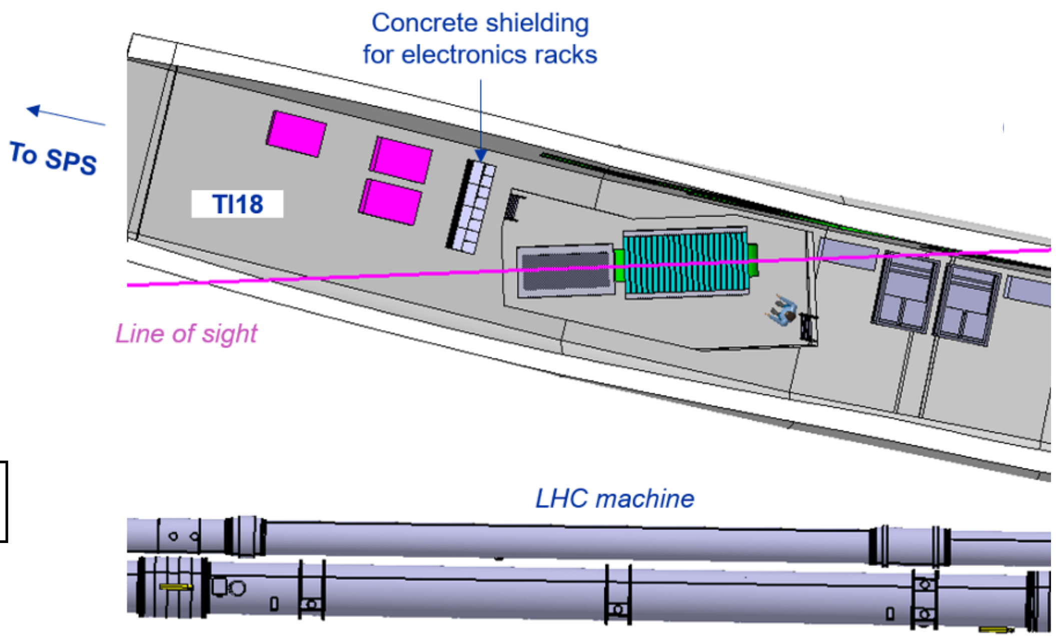
Expected # of neutrino interactions for 3000 fb^{-1}

$2.10^5\ \nu_\mu$

$6.10^4\ \nu_e$

$3.10^3\ \nu_\tau$

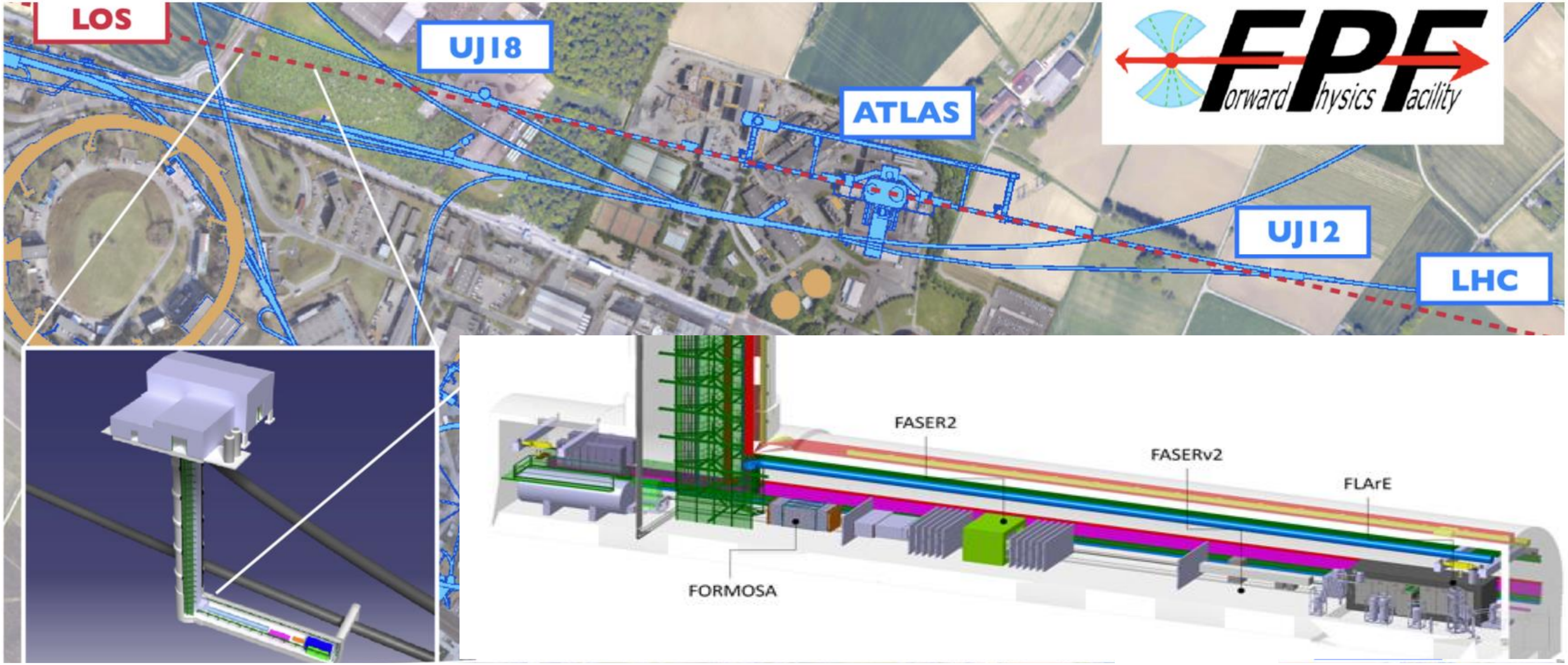




Recently: Focus on "Compact upgrade version" ->

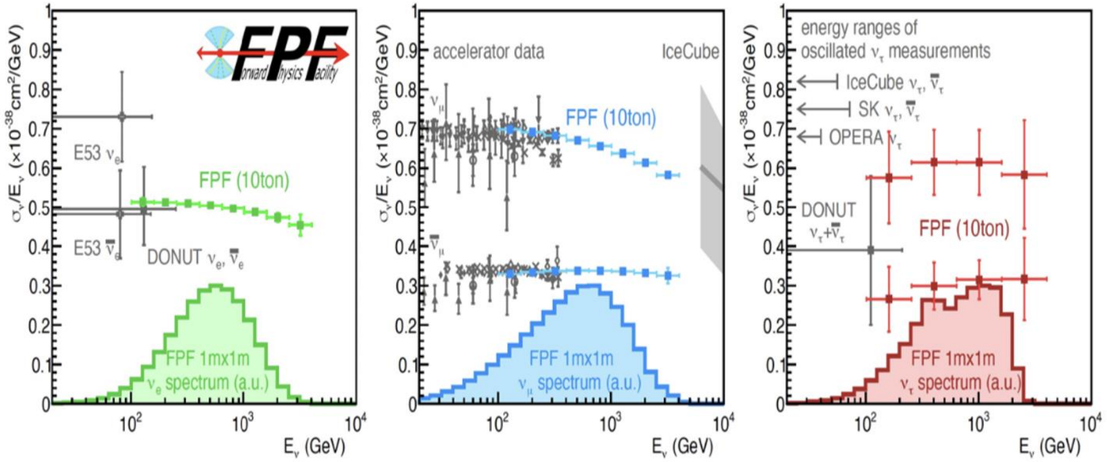
Proposal: The Forward Physics Facility

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



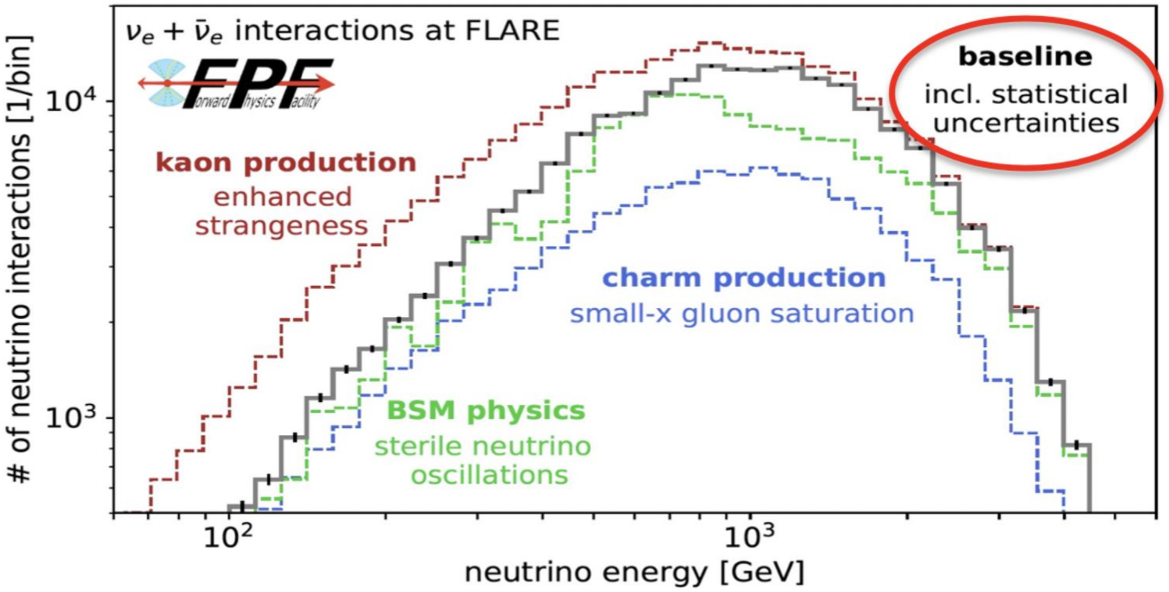
- A new underground area with a complementary suite offorward experiments operating concurrently with the HL-LHC. Positive outcome of geological drilling studies so far.

Neutrinos at the Forward Physics Facility



Assuming a 10 ton detector with acceptance $\eta > 6.9$ and 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



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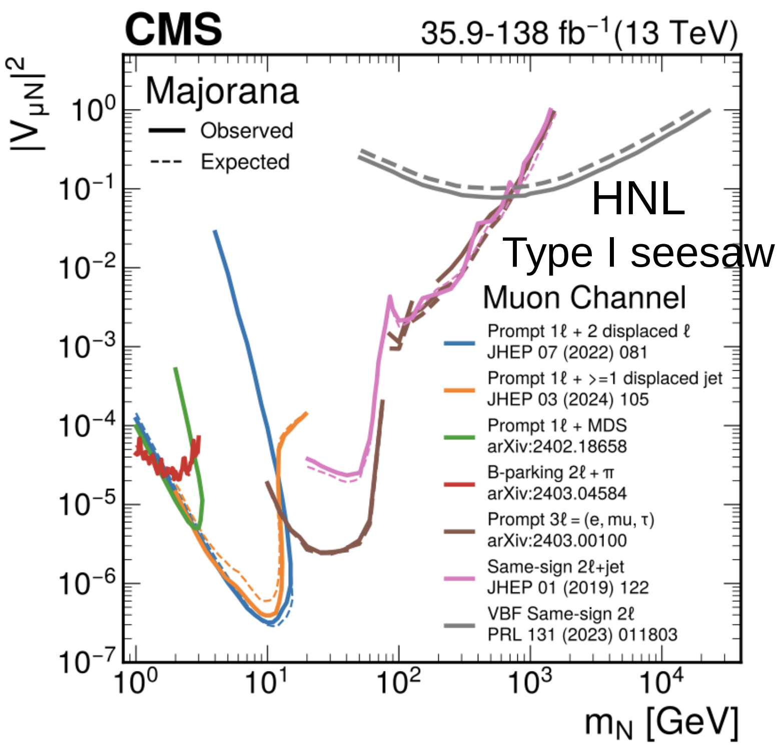
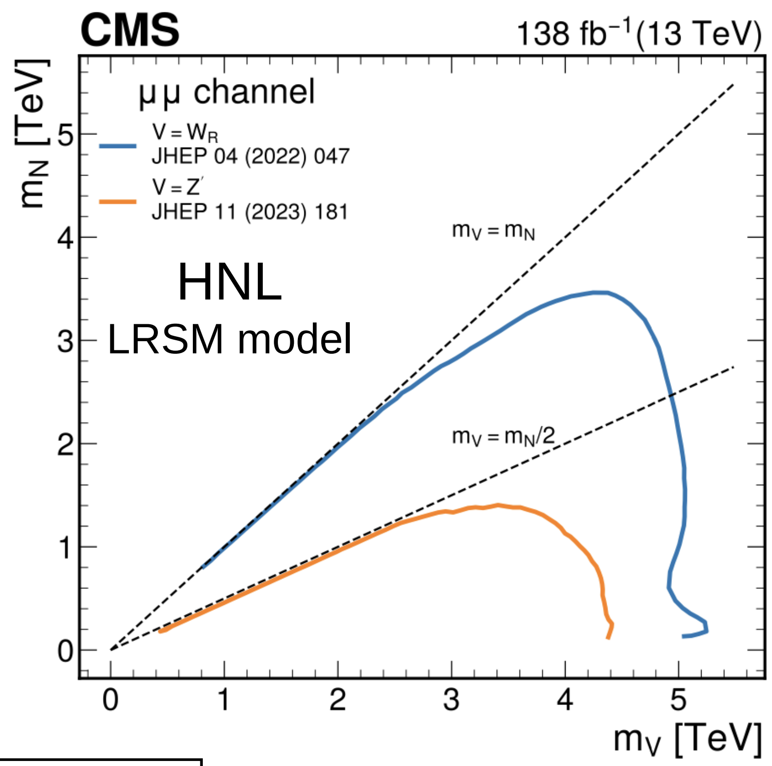
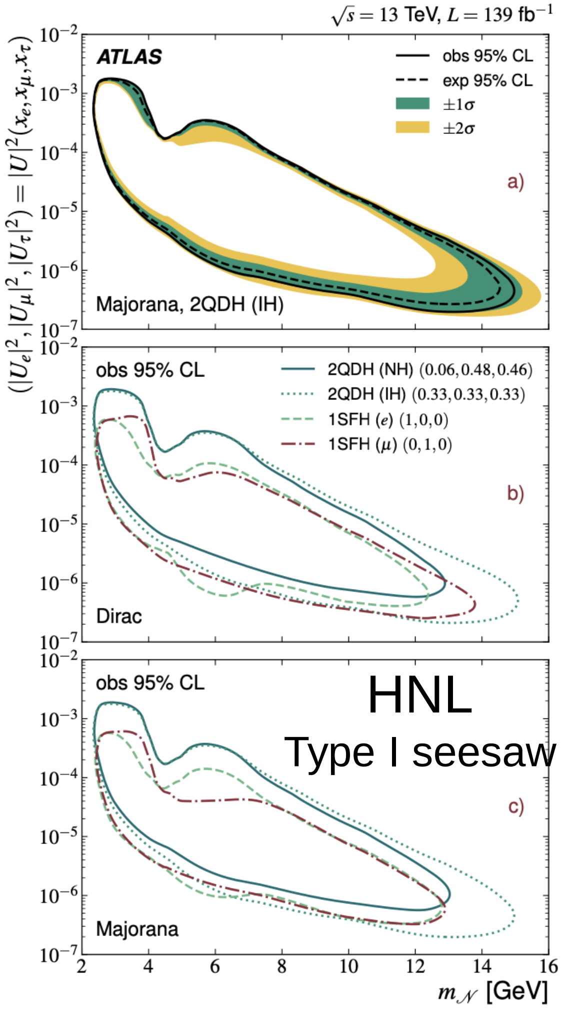
- …or instead a large detector around/inside Lake Geneva?? -> See poster C. Delgado et al, #452

Neutrinos at the (Central) Collider Experiments

- ATLAS, CMS, LHCb, (ALICE). These have no chance to measure Standard Model neutrino interactions but they can hunt for BSM unstable neutrinos such as HNLs (see talks of M. Shaposhnikov and E. F. Martinez).
- Recent result and summary plots: 2405.17605 & 2204.11988







- With and without displaced decays
- Neutrinos from B's and W's

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 ALPs

- 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 can be collected

- A facility is being studied for the neutrino –and other physics- at the LHC: the Forward Physics Facility FPF.

- Meanwhile the more central LHC detectors continue their search for new neutrinos such as Heavy Neutral Leptons…

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 FASERν detector in the LHC-FASER experiment - Haruhi Fujimori #387

Many Thanks to J. Boyd, C. Vilela, G. Di Lellis…

backup

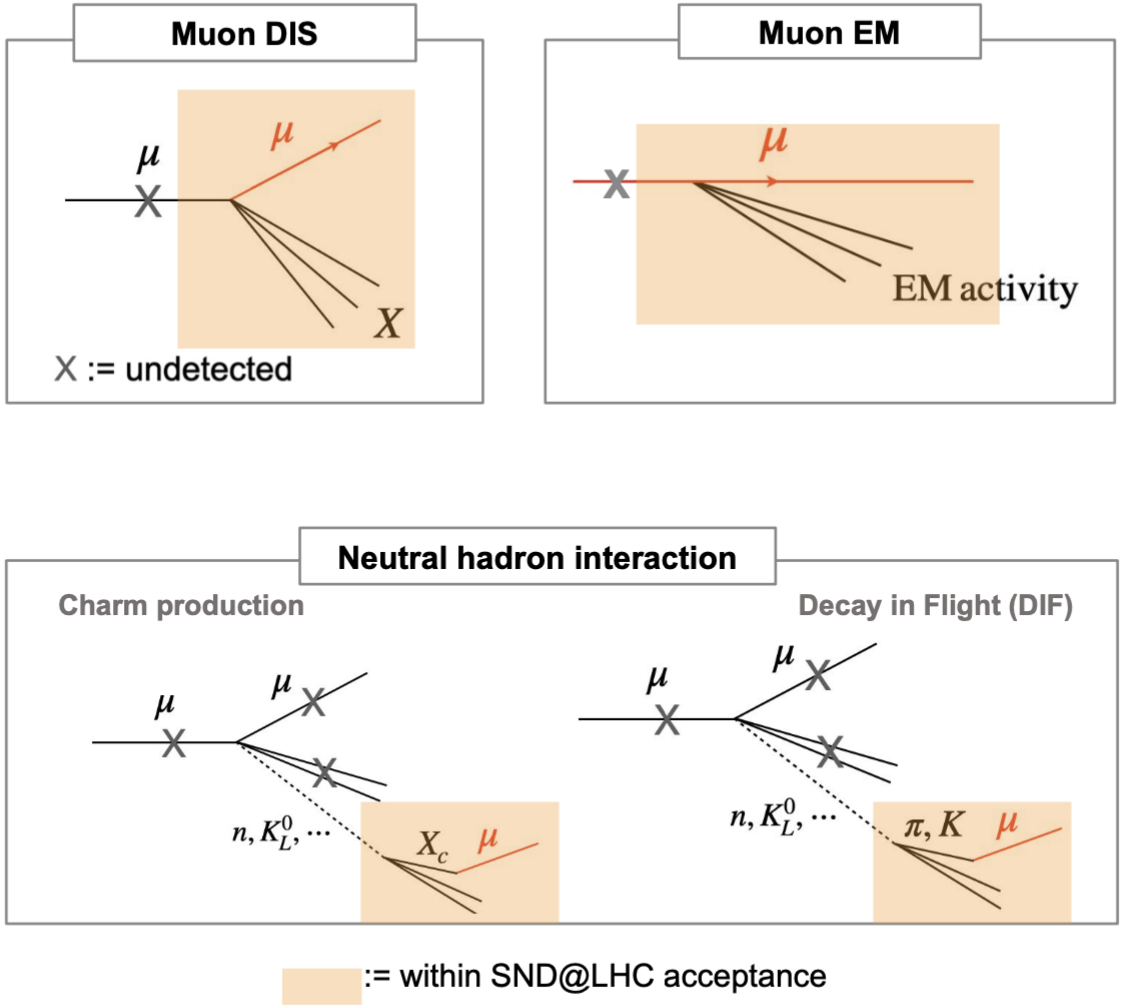
SND@LHC backgrounds

Entering muons

- Incoming muon track may be missed due to detector inefficiency.
- Shower induced by DIS or EM activity.
- Number of muons in acceptance: 5×10^{8}
  SNDLHC-NOTE-2023-001
- Detector inefficiency: 5×10^{-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.



Muon neutrino analysis summary

- Analysis updates
  - Extended fiducial volume (walls 2 and 5).
  - 2022+2023 luminosity.

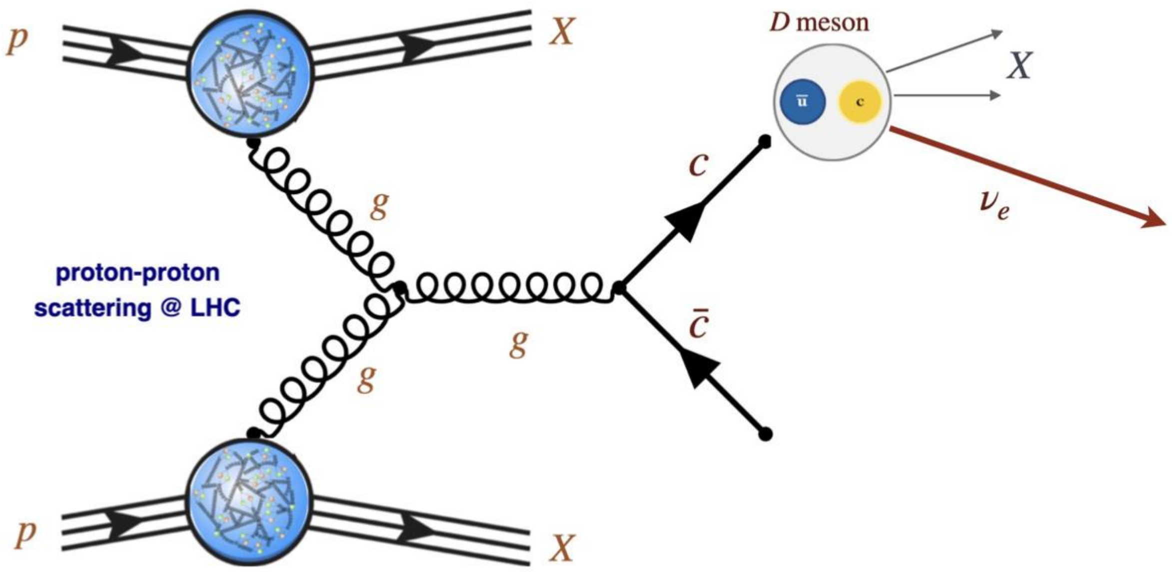
- **Hadron background expectation**
  - Neutral Kaons:
    - QGSP: 0.14
    - FTFP: 0.12
  - Neutrons:
    - QGSP: 0.13
    - FTFP: 0.10
  - **Total:**
    - QGSP: 0.27
    - FTFP: 0.22
    - Average: 0.25 +- 0.05 (model syst) +- 0.03 (MC stats)

- **Neutrino expectation**
  - **Muon neutrino CC: 19.1 ± 4.1**
  - **Other CC: 0.12**
  - **NC: 0.03**

- **Observed events: 32**
  - **Significance: 12 σ**

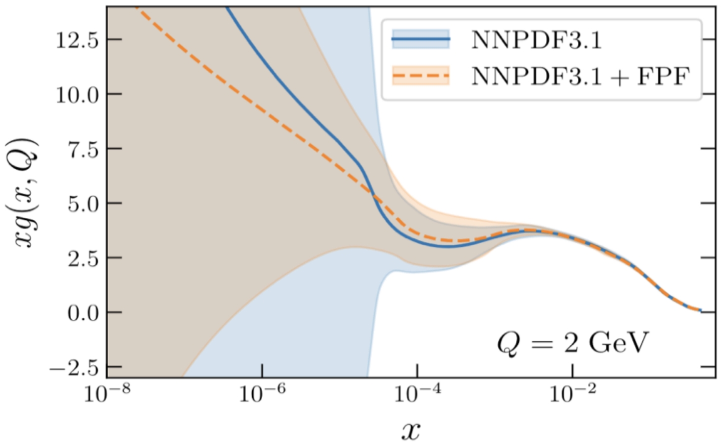
Neutrinos as a probe for charm production

J. Rojo

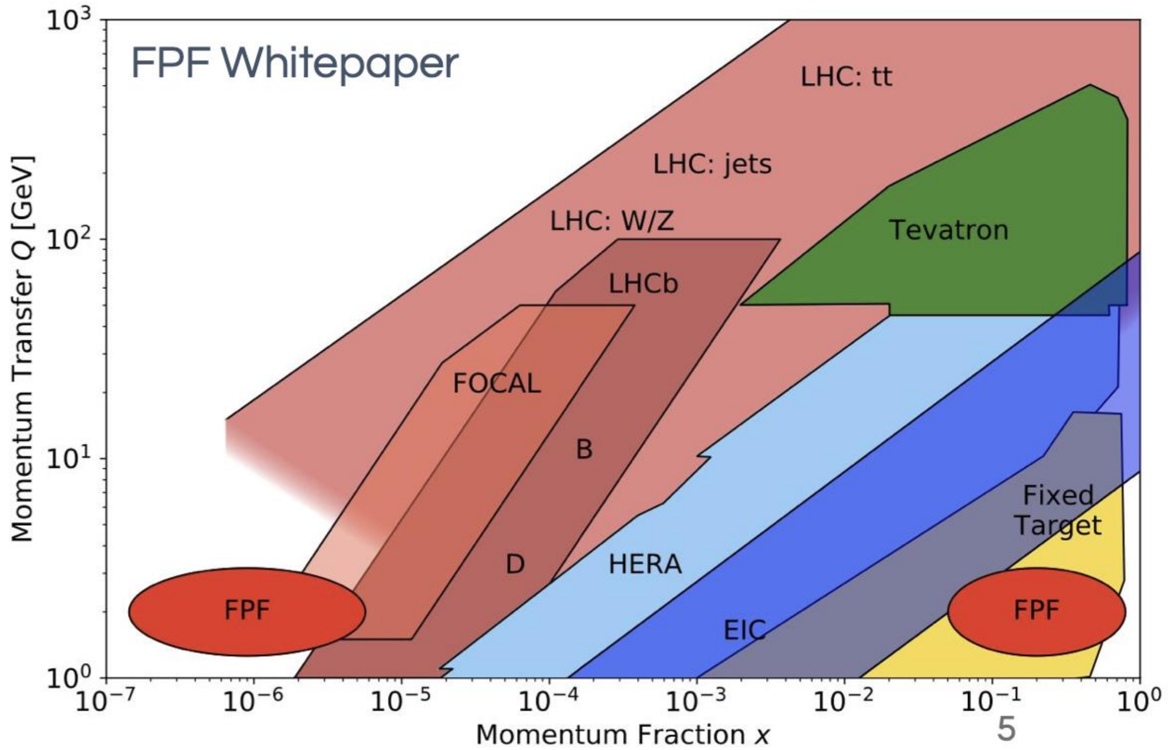


- Dominant partonic process: **gluon-gluon** scattering.
- SND@LHC will constrain the gluon PDF in the **very small x** region.
  - Only LHC neutrinos have sensitivity in this region.
- Relevant for **FCC-pp, ultra-high energy neutrinos** and **cosmic rays.**

Electron neutrinos, 2% uncertainty in inclusive event rates

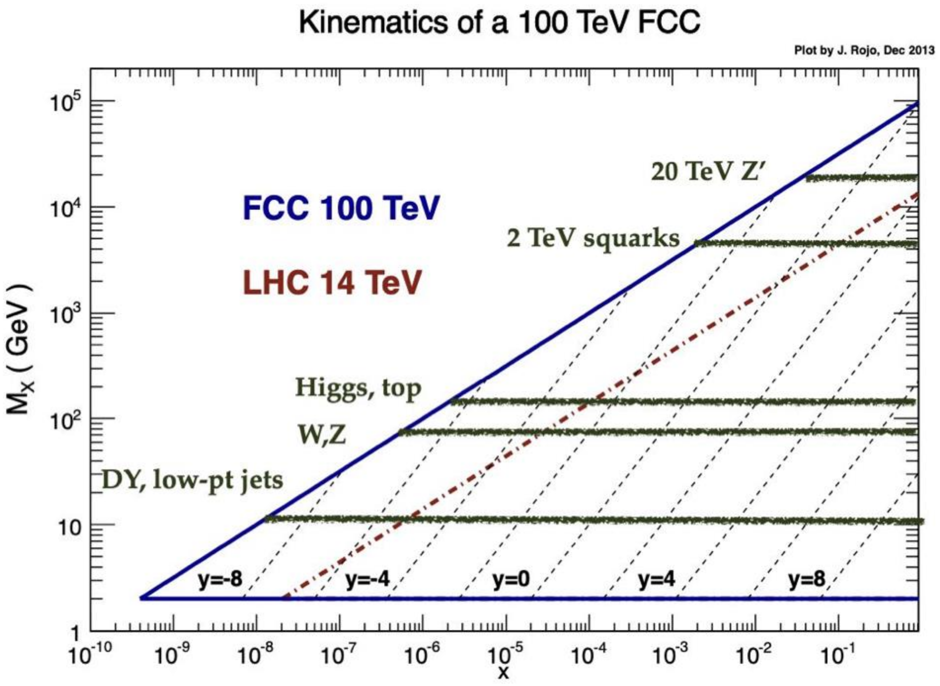


$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$

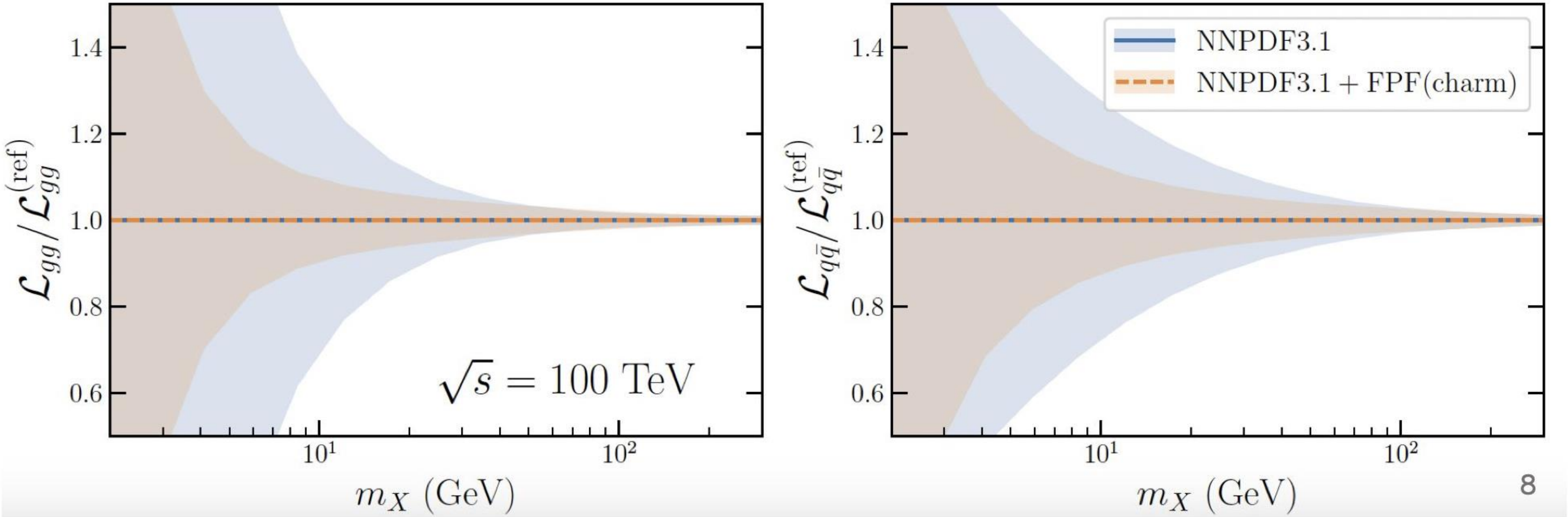


Implications for FCC-pp

- 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.



J. Rojo CERN-TH Colloquium 11/2023

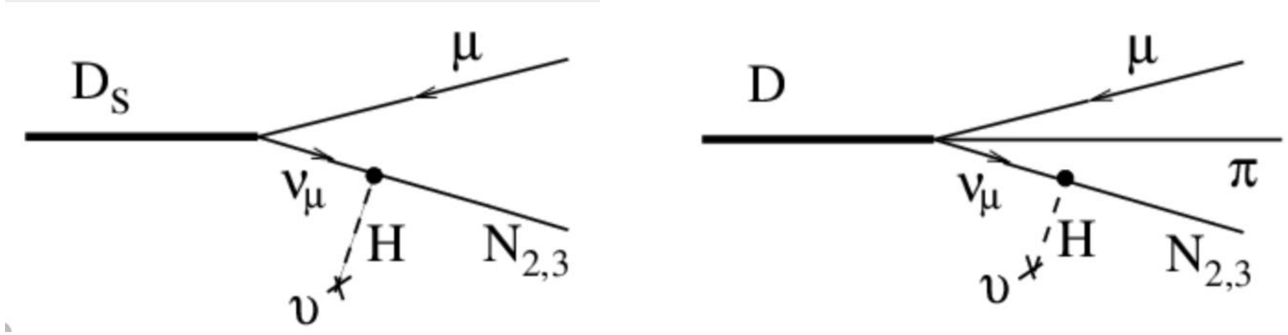


J. Rojo

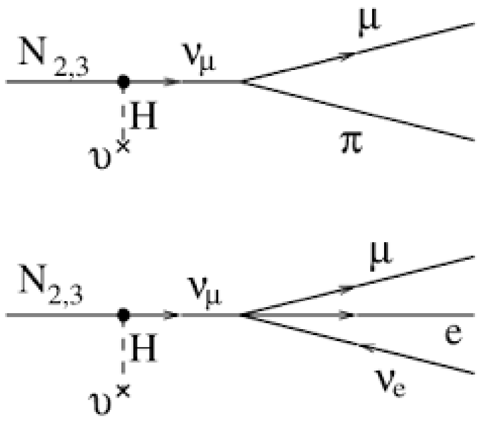
FEEBLY INTERACTING PARTICLES

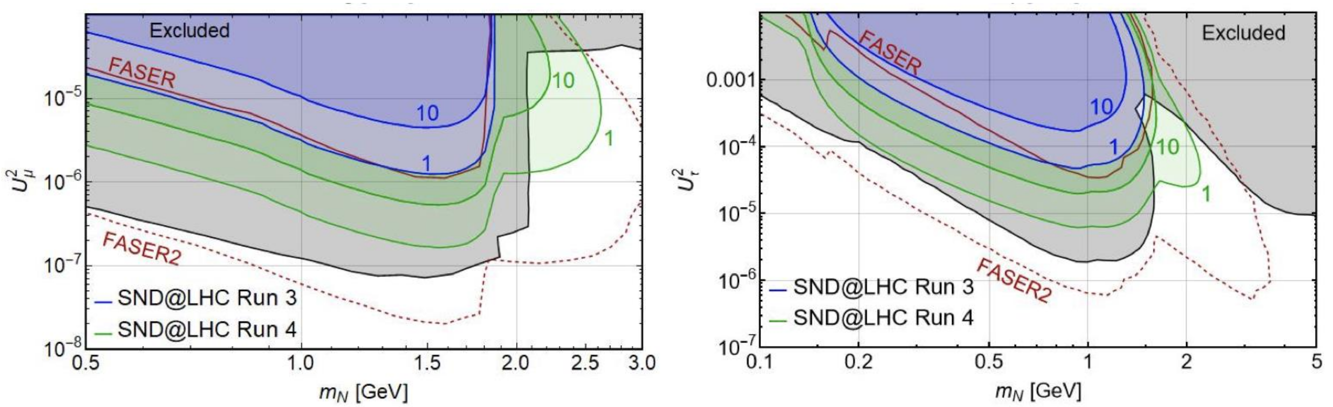
- SND@LHC/FASER can explore a large variety of Beyond Standard Model (BSM) scenarios describing Hidden Sector

Production: Mixing of neutrinos with Heavy Neutral Leptons (HNLs). Examples:



Detection: with decays of the N into charged particles or the decay $N \to \pi^0 \nu$.





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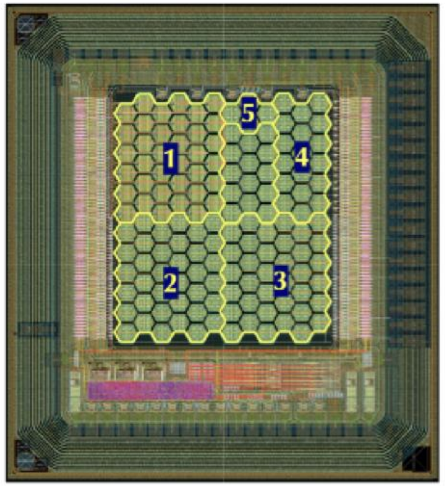
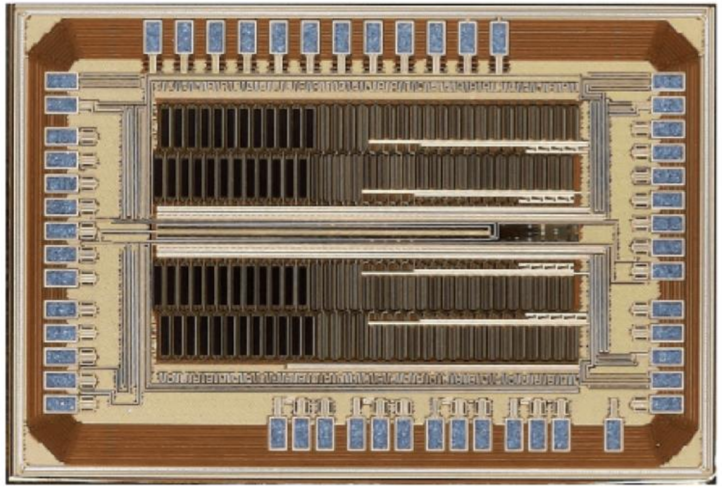
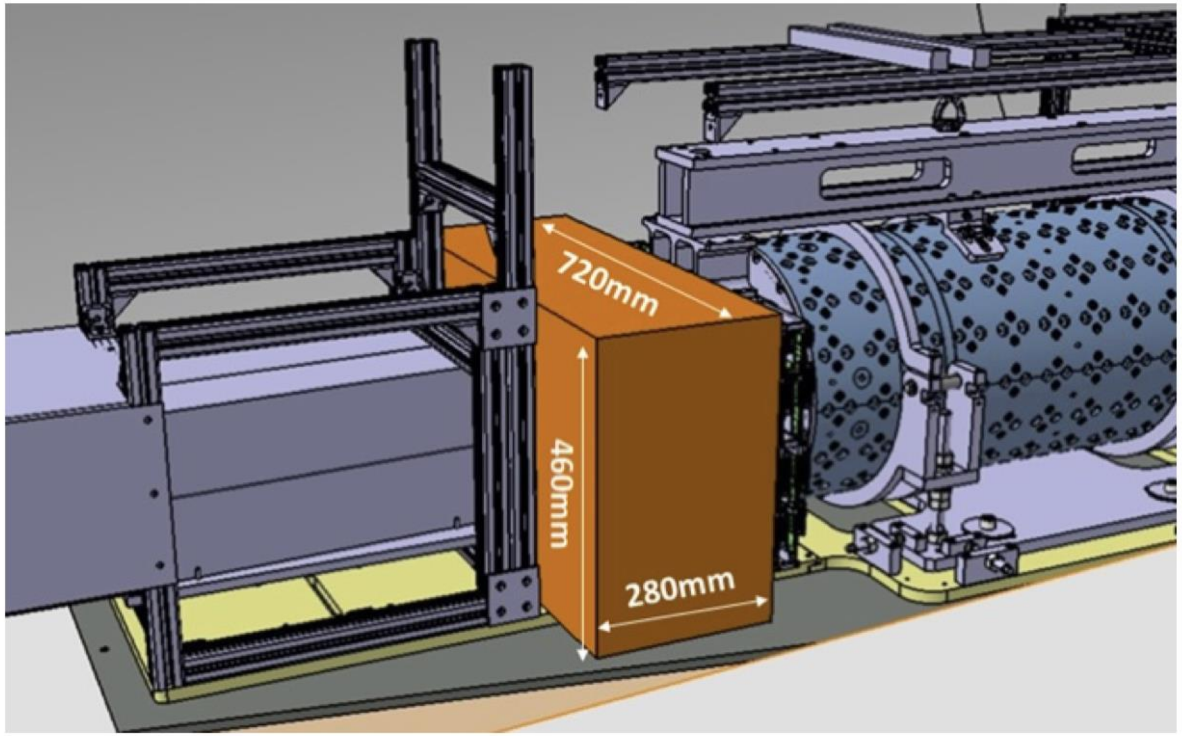
- Preshower upgrade
  - Layers of high-granularity Si pixels with W absorber
  - Identify photons separated by ~200 μm
  - Installation before 2025
- Improve ability to identify photons, reject neutrino backgrounds
- FASER approved to run during HL-LHC Run4
  - Will record large dataset with upgraded FASER
- FASER-2: significant R&D for the Forward Physics Facility ongoing!







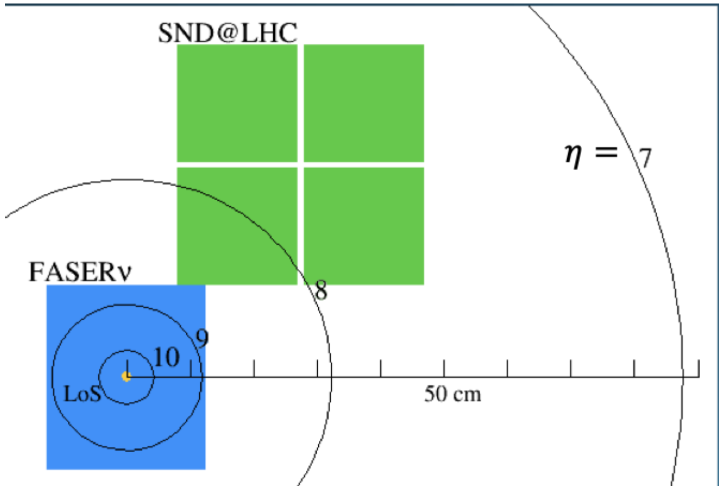
Neutrinos at FASER(ν) and SND@LHC

Number of neutrino events (150 fb^{-1})

10.1103/PhysRevD.104.113008

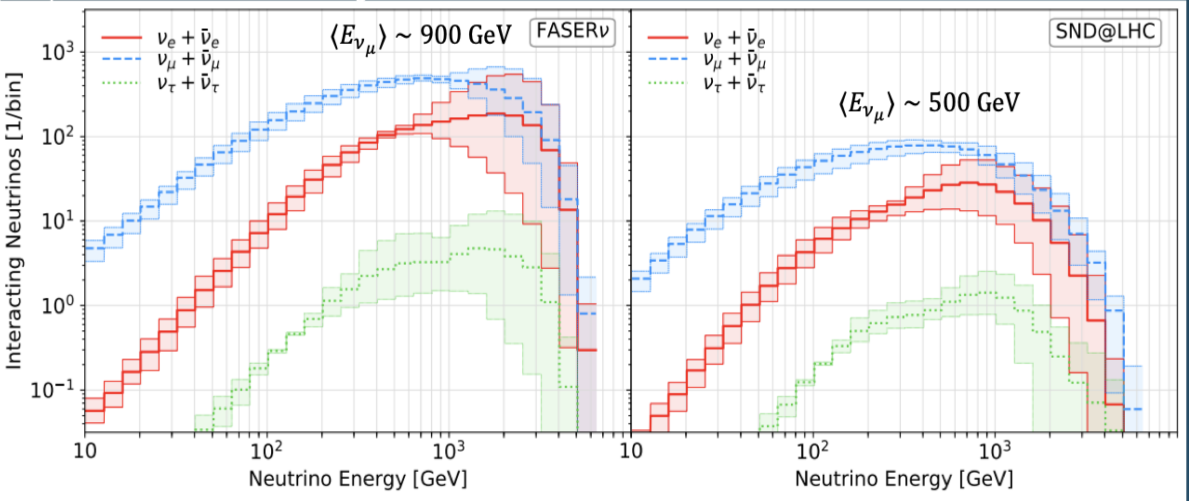
Generators		FASERν			SND@LHC		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	901	4783	14.7	134	790	7.6
DPMJET	DPMJET	3457	7088	97	395	1034	18.6
EPOSLHC	Pythia8 (Hard)	1513	5905	34.2	267	1123	11.5
QGSJET	Pythia8 (Soft)	970	5351	16.1	185	1015	7.2
Combination (all)		1710^{+1746}_{-809}	5782^{+1306}_{-998}	$40.5^{+56.6}_{-25.8}$	245^{+149}_{-111}	991^{+132}_{-200}	$11.3^{+7.3}_{-4.0}$
Combination (w/o DPMJET)		1128^{+385}_{-227}	5346^{+558}_{-563}	$21.6^{+12.5}_{-6.9}$	195^{+71}_{-61}	976^{+146}_{-185}	$8.8^{+2.7}_{-1.5}$

Line-of-sight to experiment



Neutrino energies (150 fb^{-1})

Expected CC interactions with 150 fb^{-1}

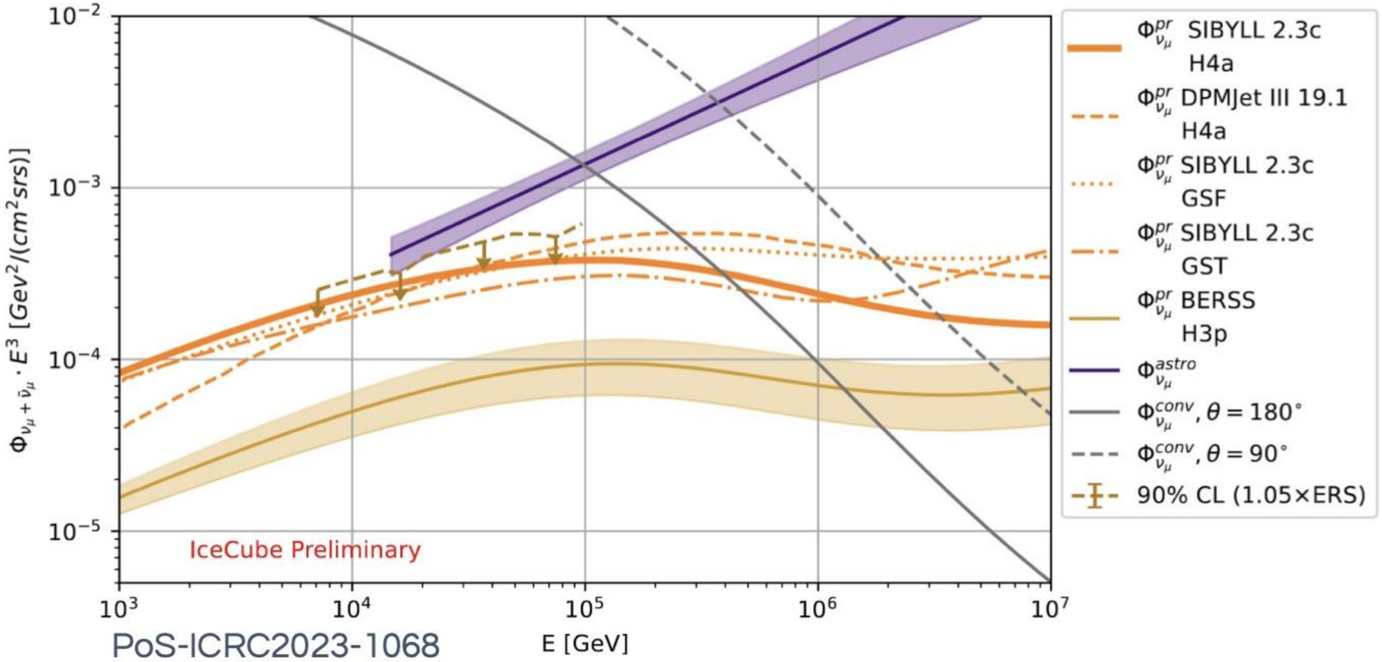


	FASERν	SND@LHC
Target mass	1100 kg	800 kg
Location	On axis	Off axis
Features	High energy & high statistics	More neutrinos from charm decay

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.



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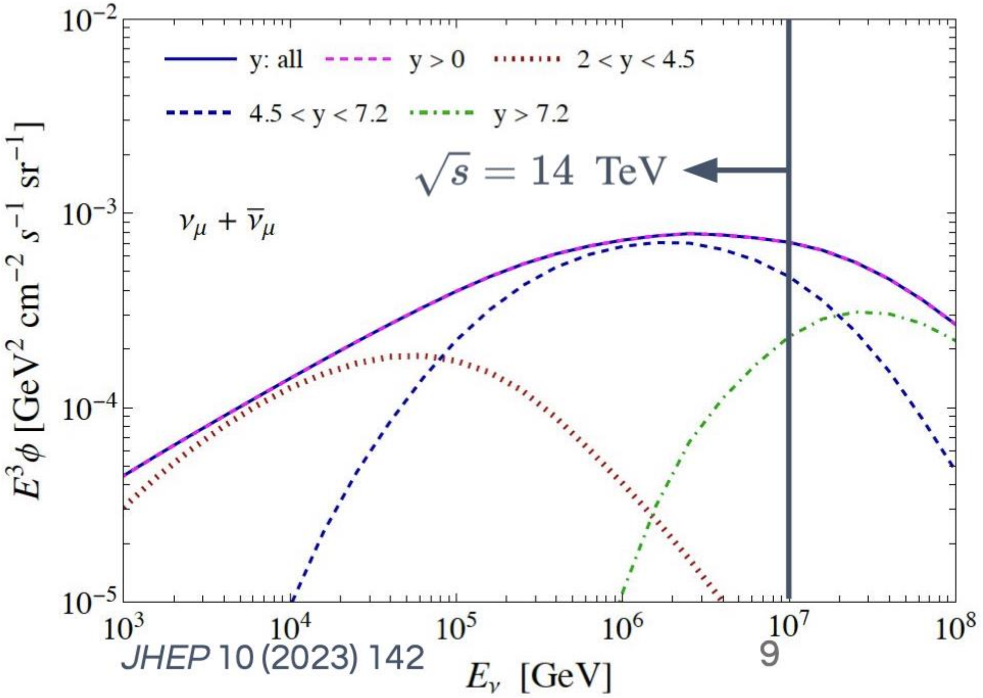
Prompt flux of atmospheric neutrinos broken down by charm hadron rapidity in the pp collision frame.



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