TeV Neutrinos at the LHC

Albert De Roeck
Imperial College Londen
CERN, Geneva, Switzerland

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ON ELEMENTARY PARTICLE PHYSICS
MOSCOW STATE UNIVERSITY

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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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- The Forward Physics Facility proposal/ Neutrinos in lake Geneva..
- 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.

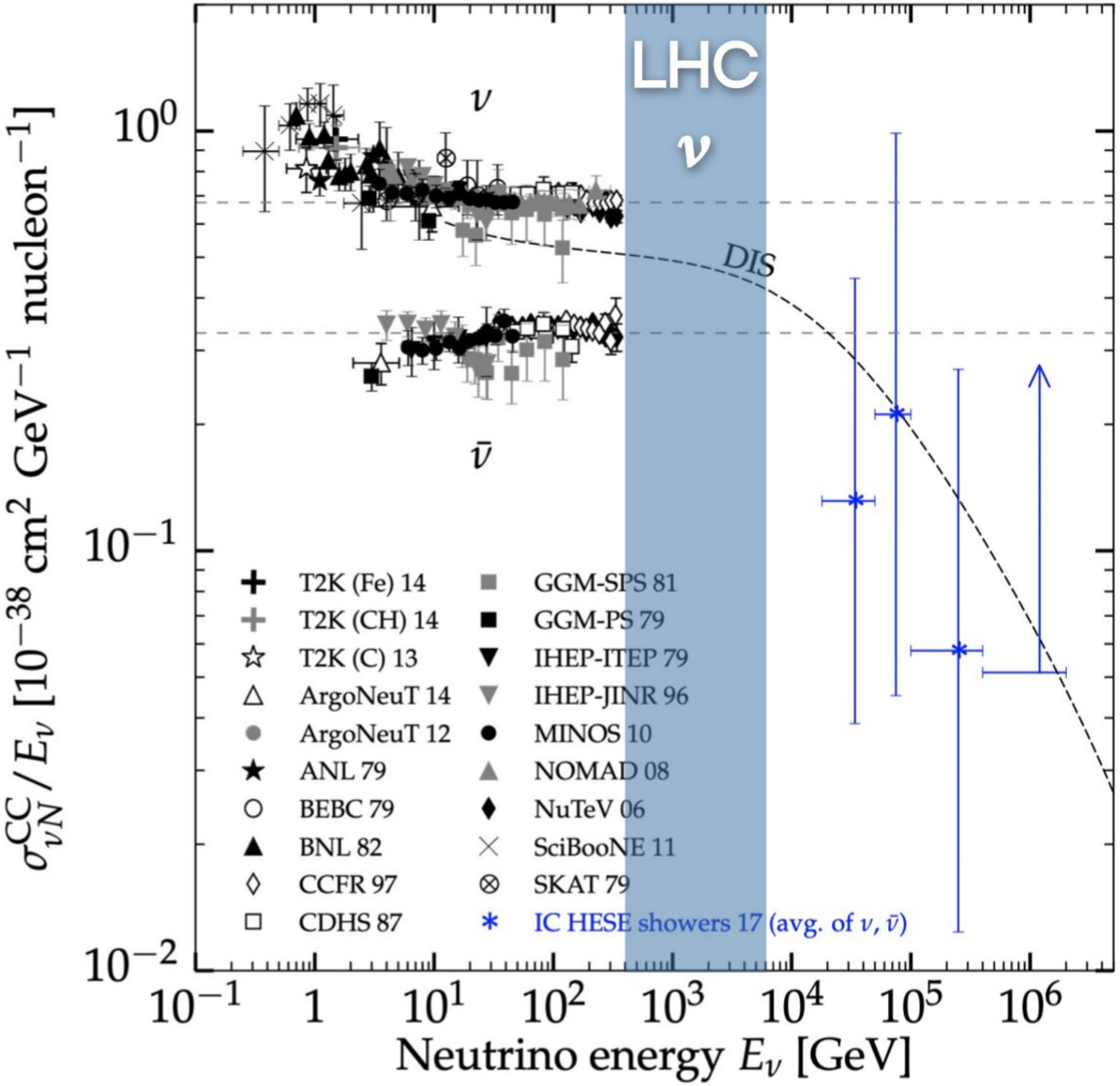
- **Large flux** of neutrinos in the forward region.
- Very **high neutrino energy** ($\sigma_\nu \propto E_\nu$).

⇒ 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

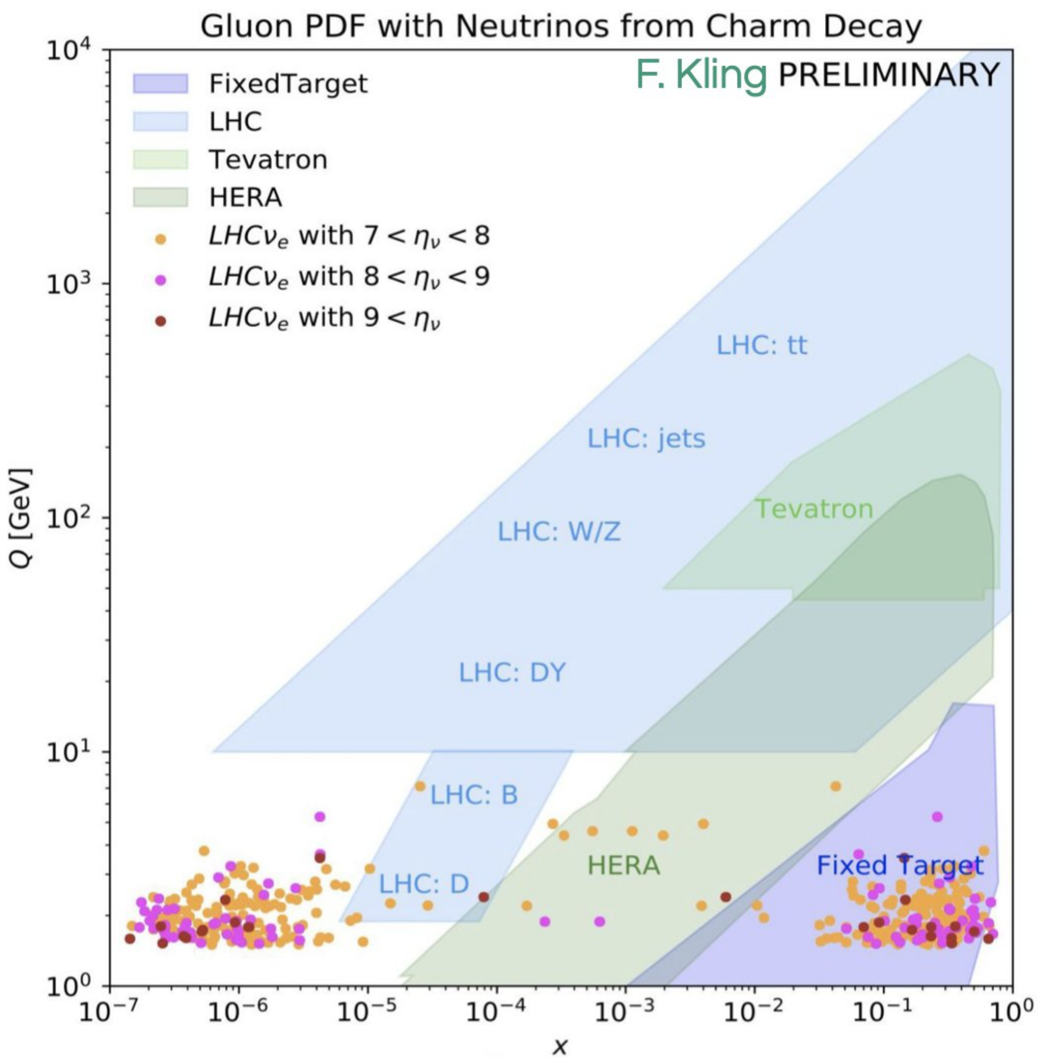
- Decays of **charm** hadrons contribute significantly to the neutrino flux.
  ⇒ Measure **forward charm production** with neutrinos.
  ⇒ Constrain **gluon PDF** at very **small x**.

Flavour

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

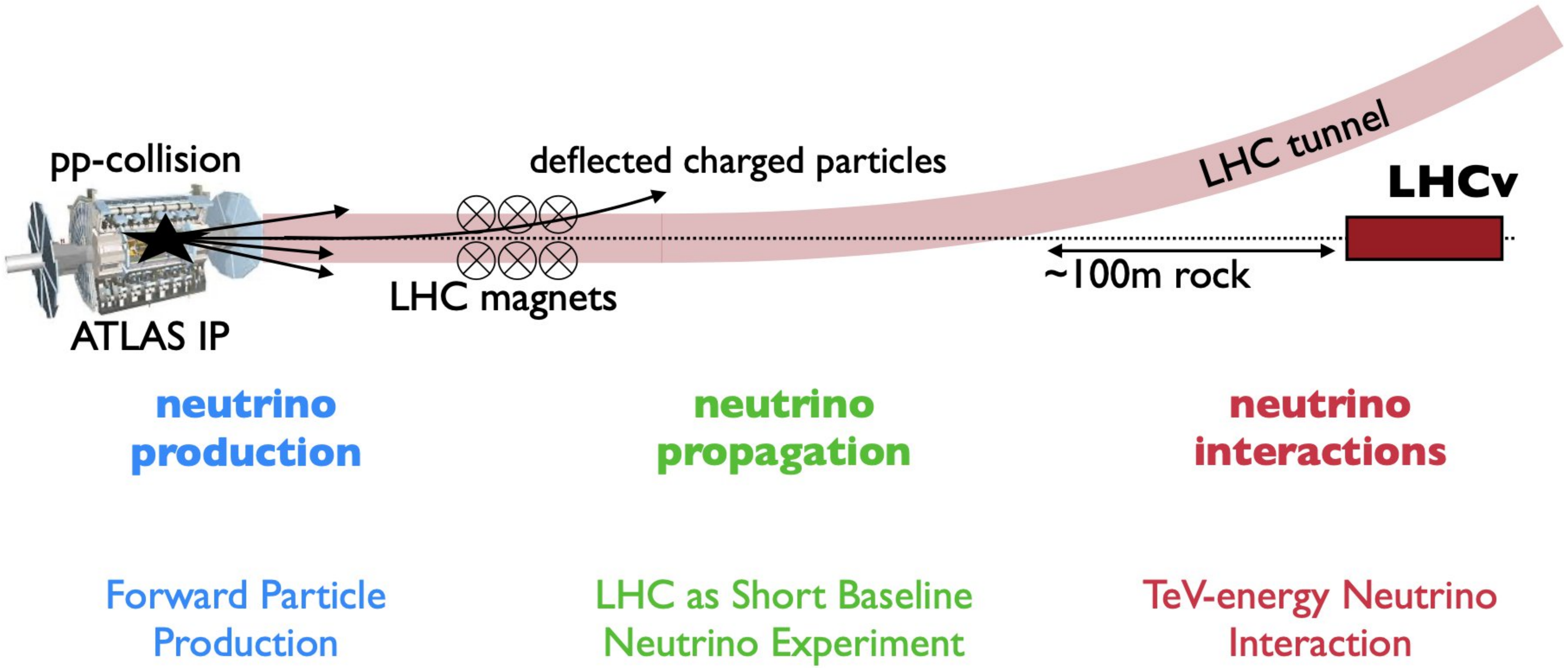
Beyond the Standard Model

- 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



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

High intensity neutrino 'beam'
High energy neutrinos

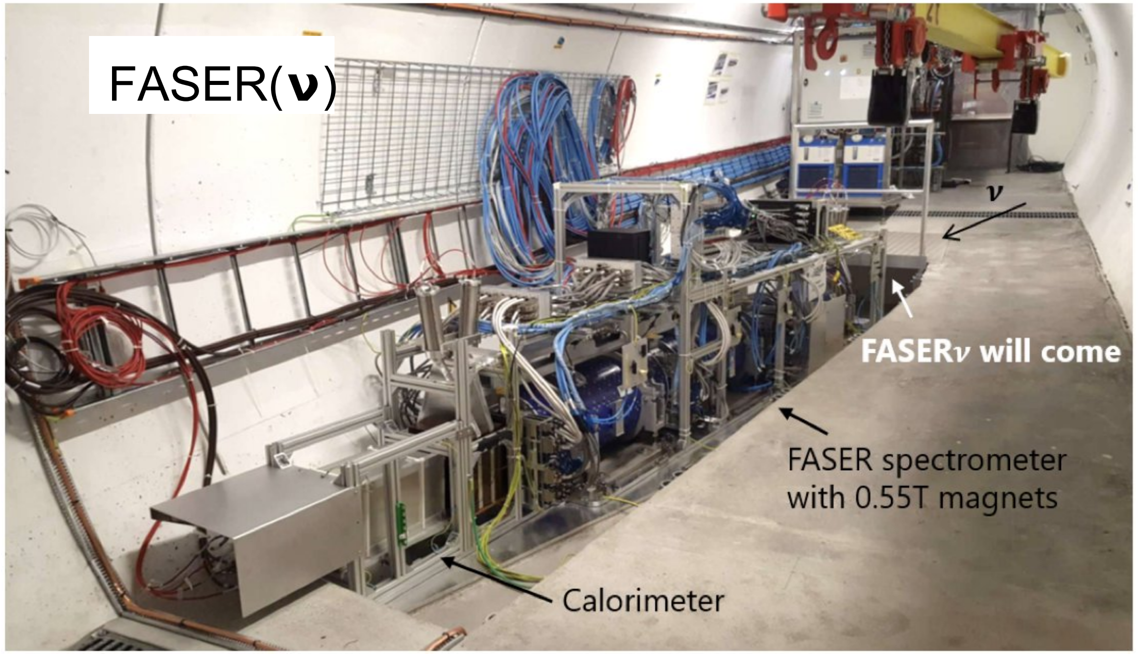
Neutrino Detectors at the LHC

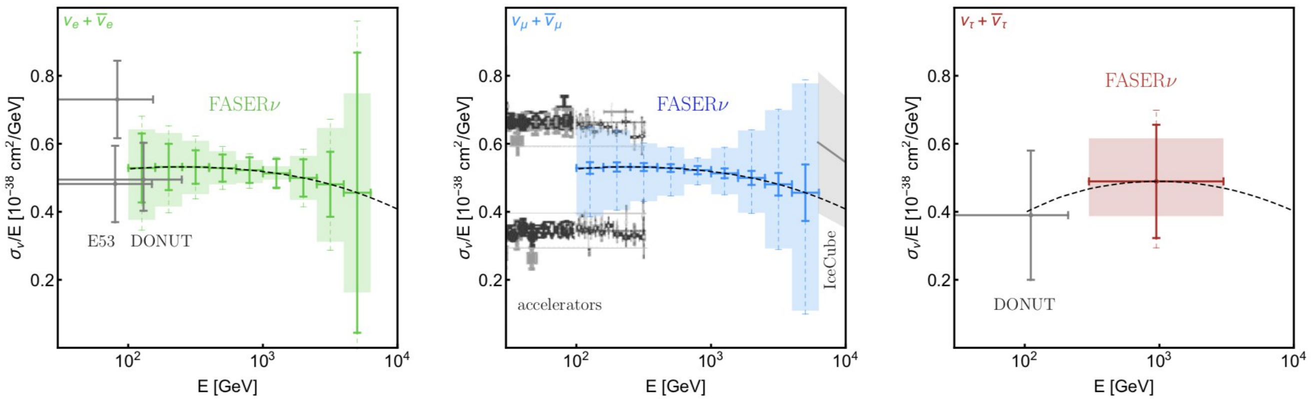
SND@LHC: approved March '21

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

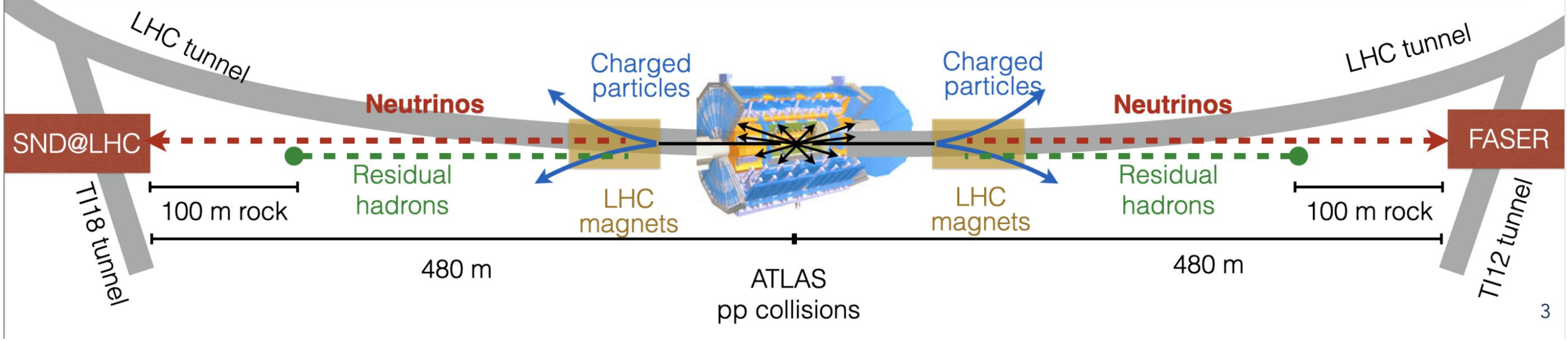
Brookhaven National Laboratory, Upton, New York, US

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: $7.2 < \eta < 8.4$ (● 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



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

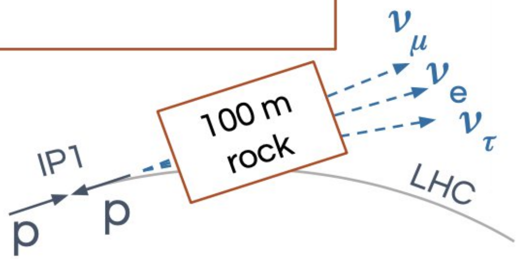
Scattering and Neutrino Detector @ the LHC

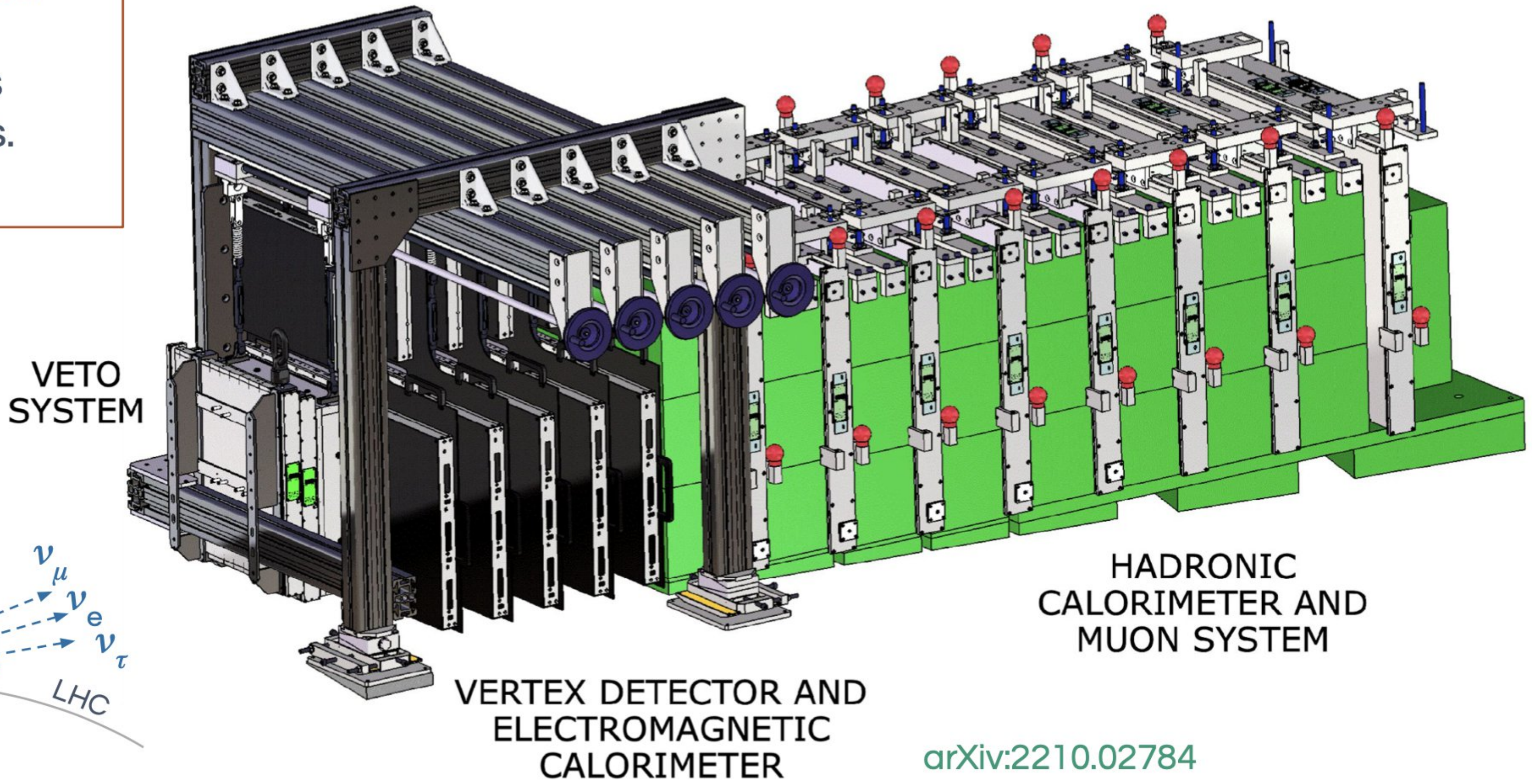
Veto system
Two 1 cm thick scintillator planes.

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

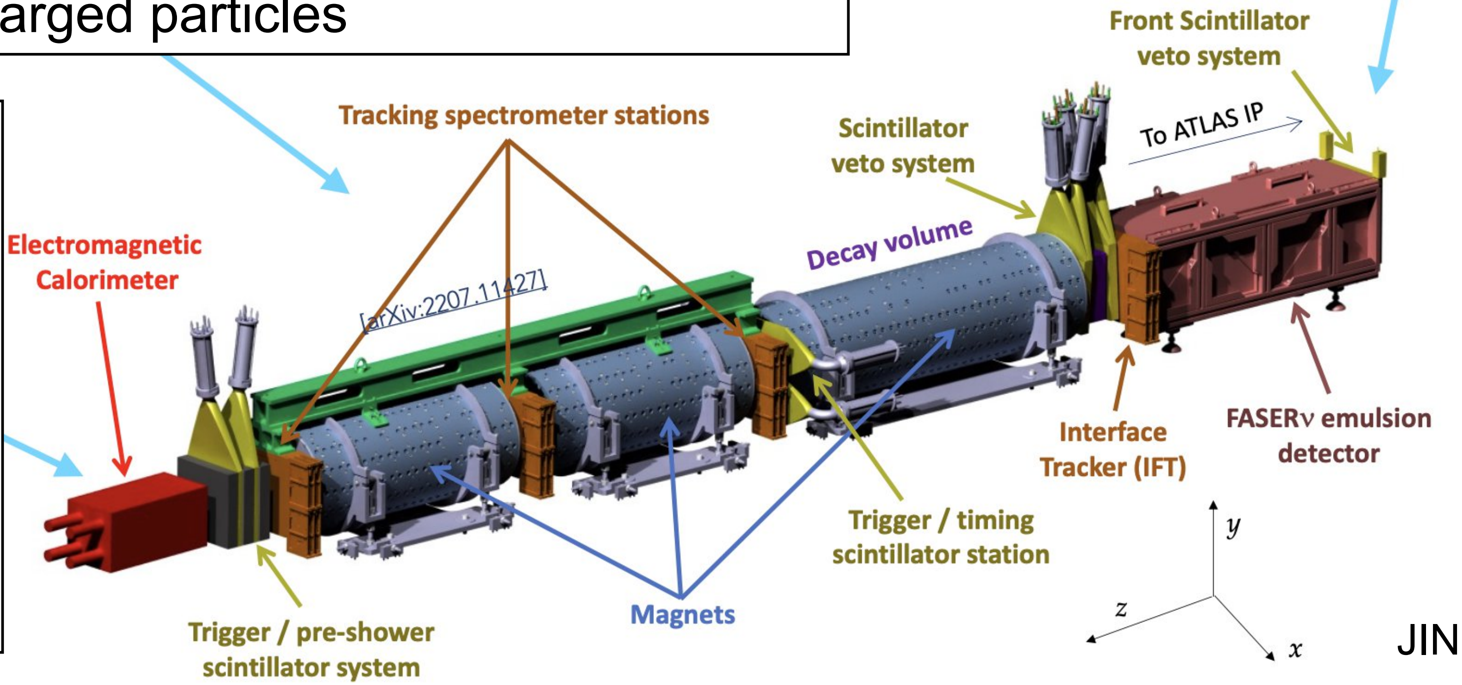
- Dipole magnets separate collimated oppositie charged particles and measure the charge and momentum of the μ from ν interactions
- Silicon strip trackers to measure position, charge & momentum of the charged particles

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

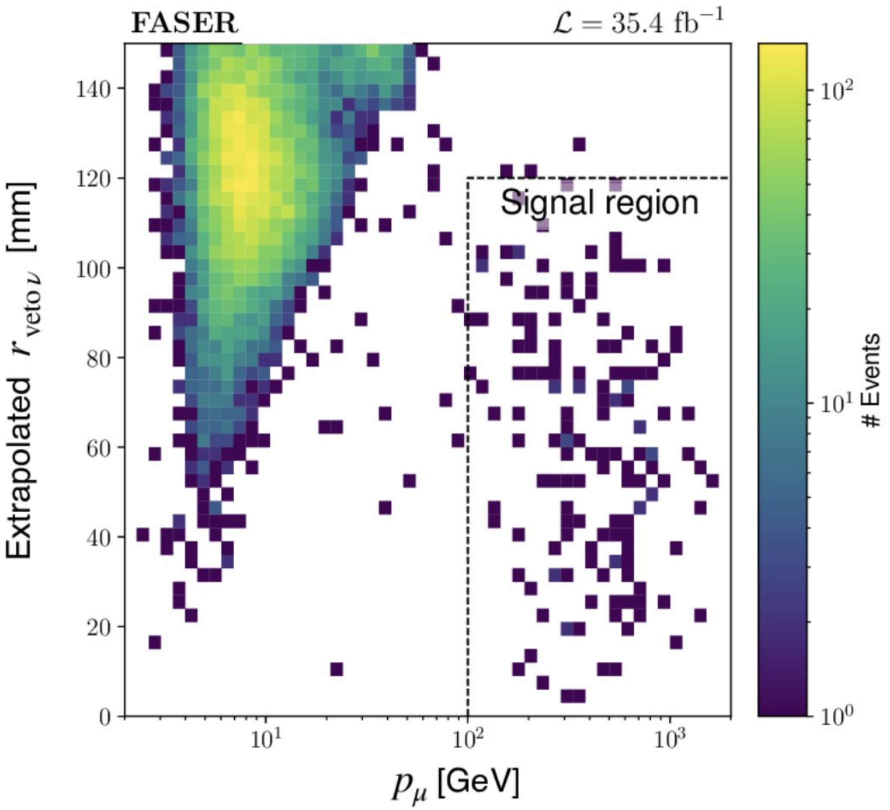
JINST 19 P05066 (2024)

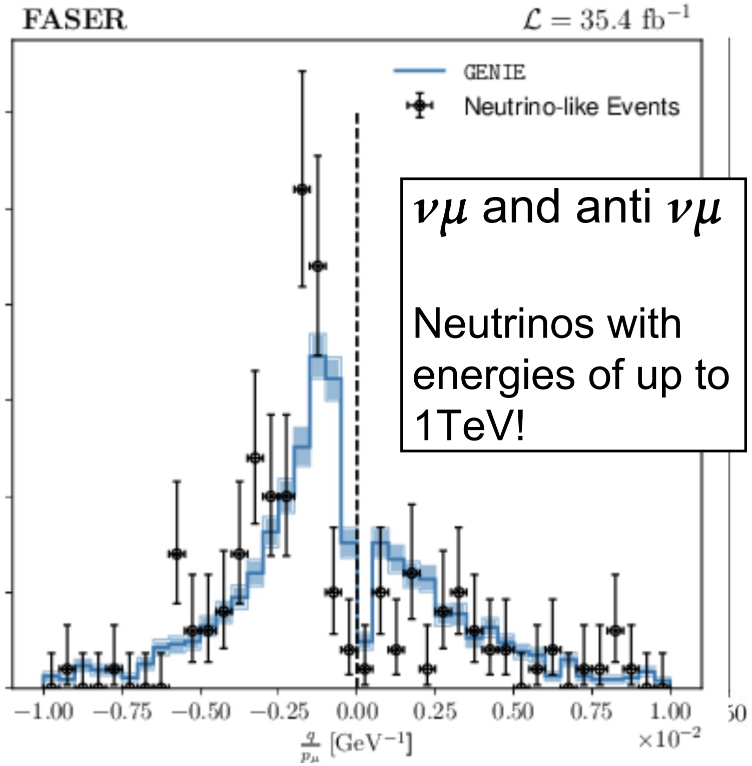
First Direct Observation of Collider Neutrinos

- 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





- 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

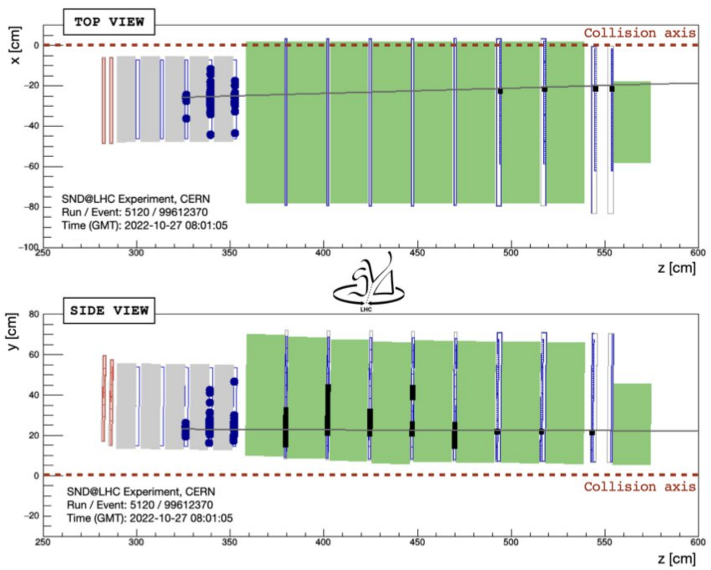
Editors' Suggestion

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

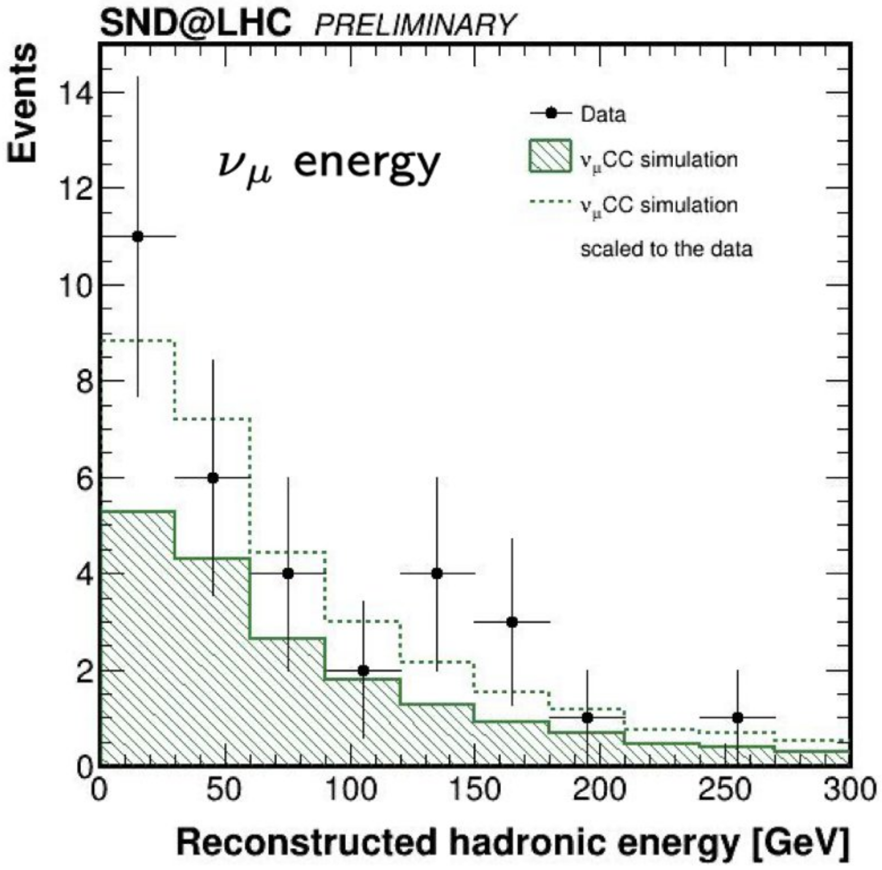
SND@LHC Updated Muon Neutrino Results

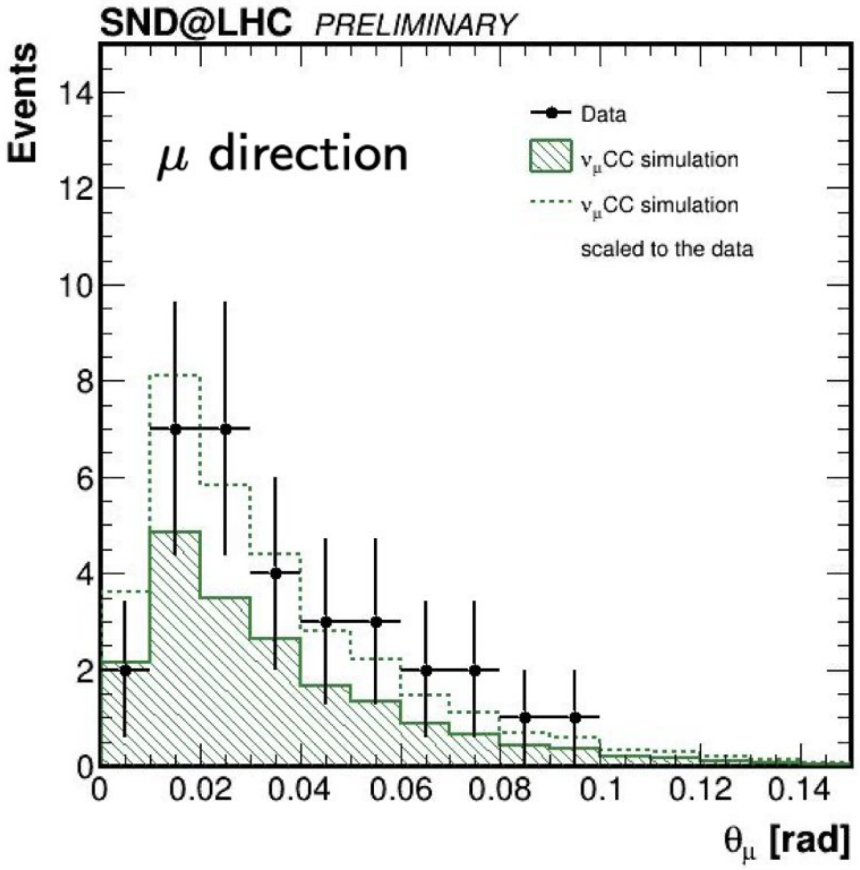
New this year
Updated analysis with 2023 data and extended fiducial volume.

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

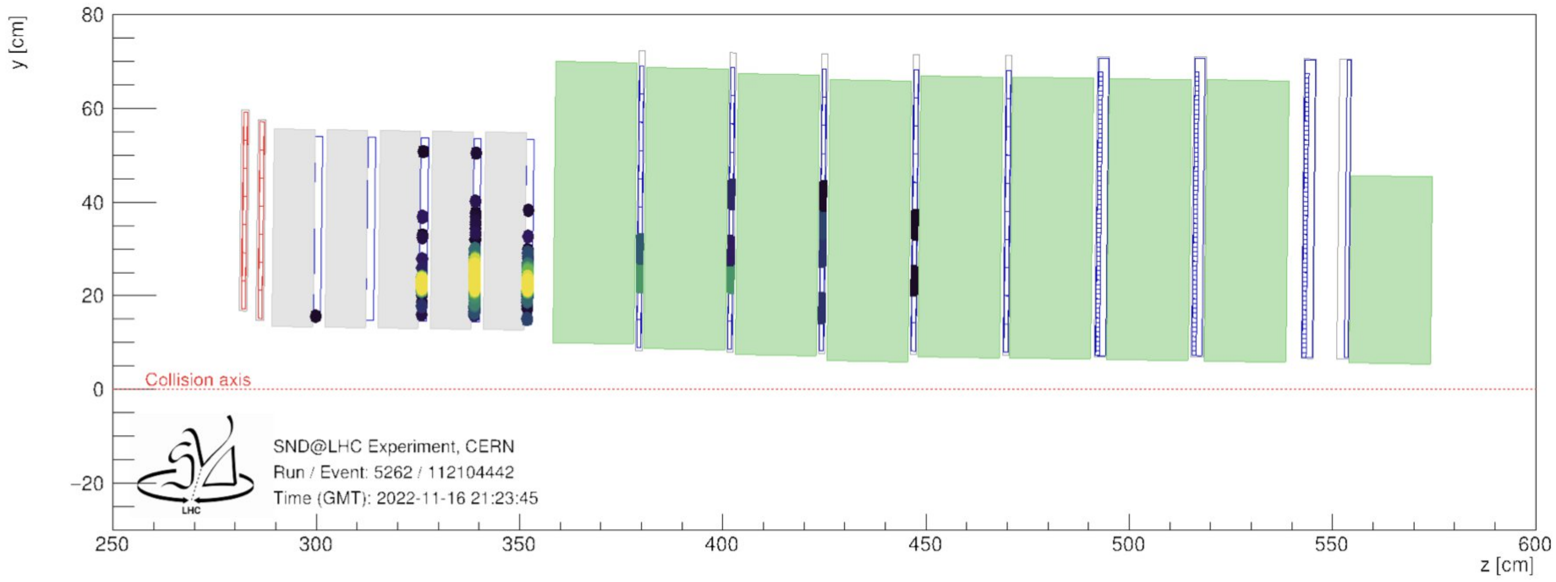
12σ significance

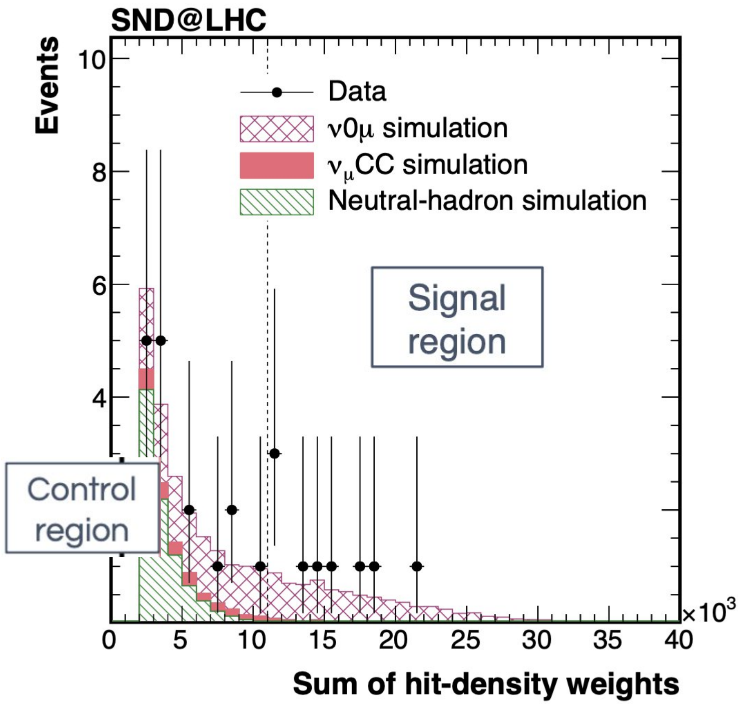
Observation of 0μ Events in SND@LHC

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

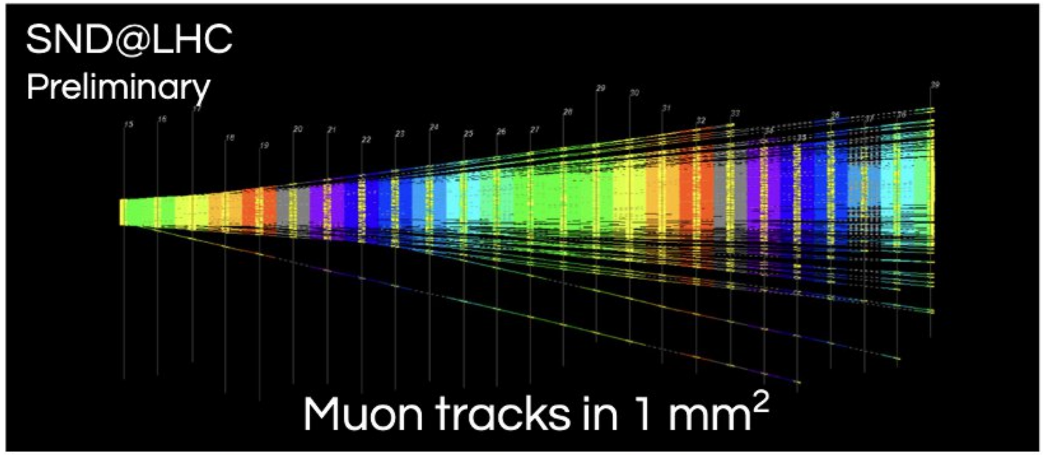
2411.18787



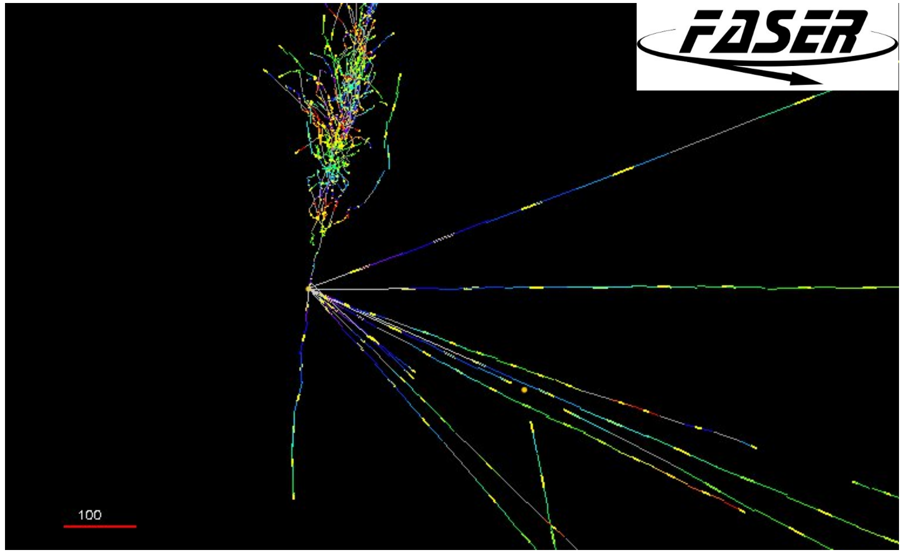


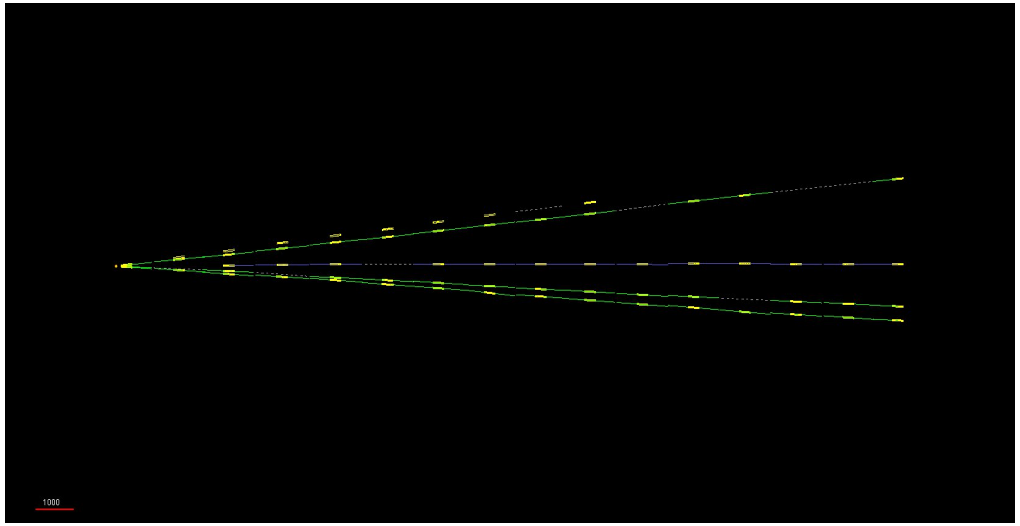
Emulsion Detector Data Analysis

- Emulsion data takes time to be scanned and measured. Mostly 2022/2023 data so far.
- 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





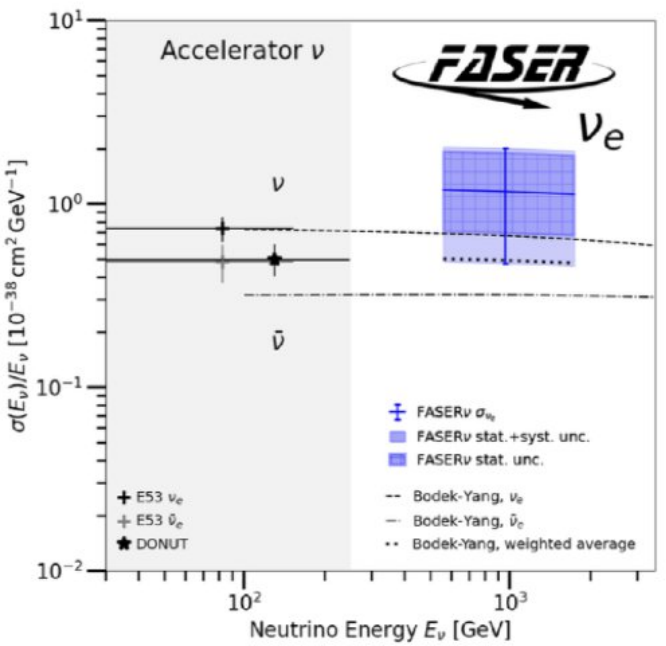
- Replacing of the emulsions is strongly affected by muon background (esp. in 2024)

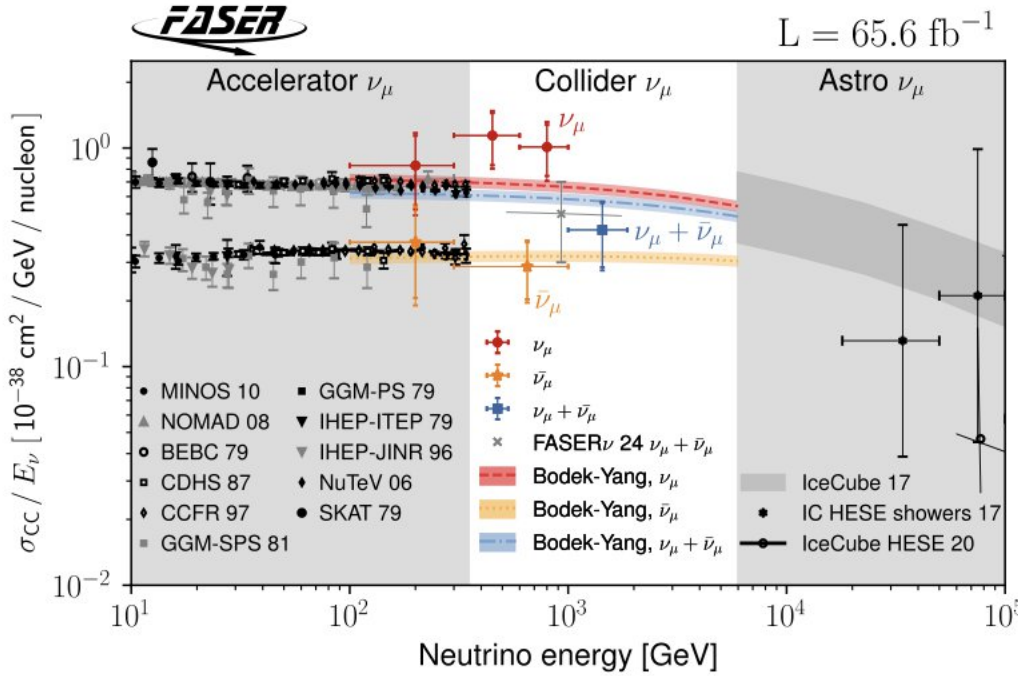
Measurement of ν_e and ν_μ Interaction Cross Sections

- 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

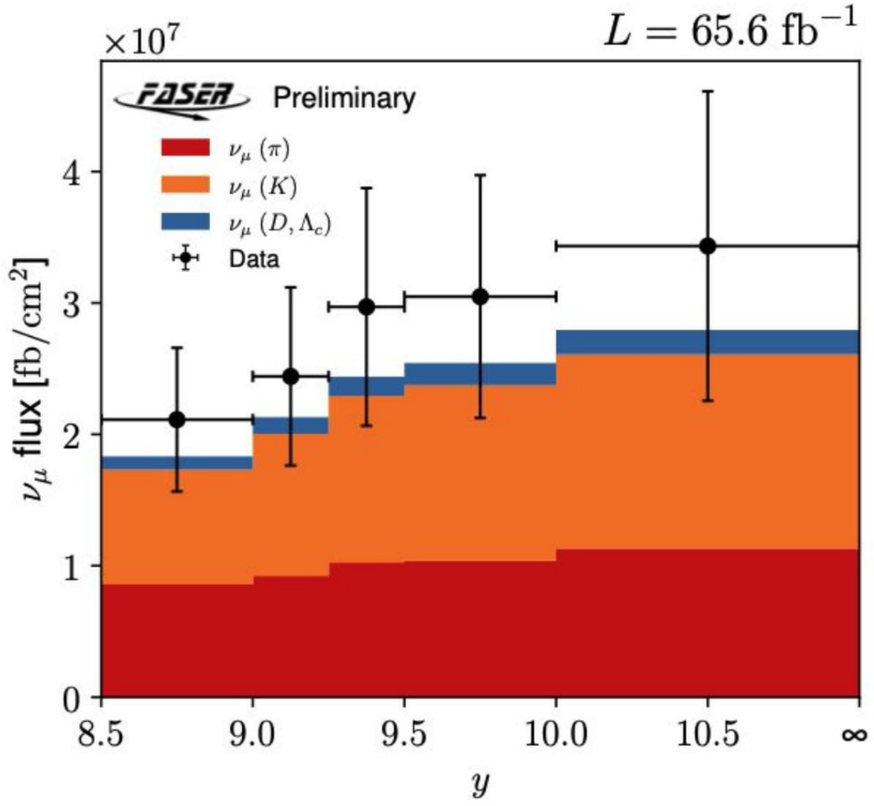
2412.03186

Muon Neutrino Flux as Function of Rapidity

study of collider ν_μ neutrinos: FASER electronic detector

CERN-FASER-CONF-2025-001

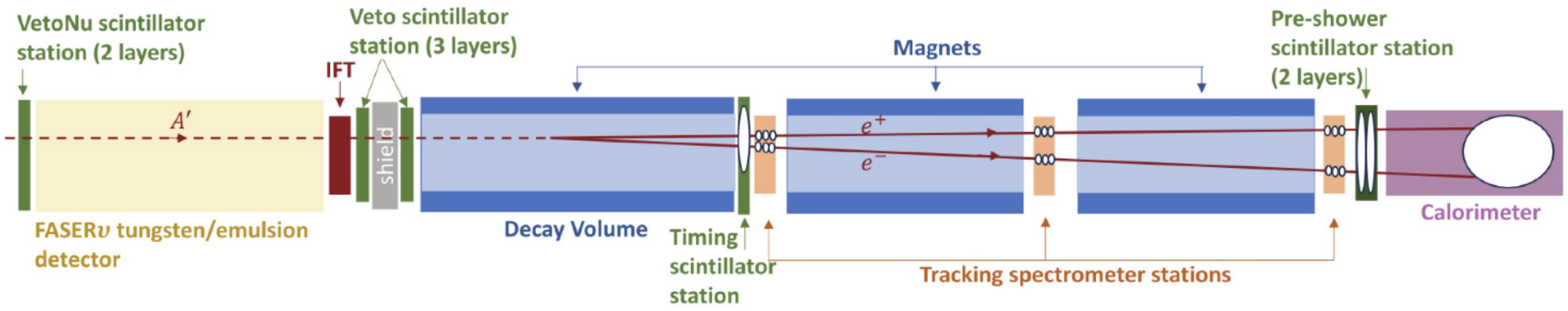
Measurements: ν_μ flux as a function of the rapidity y



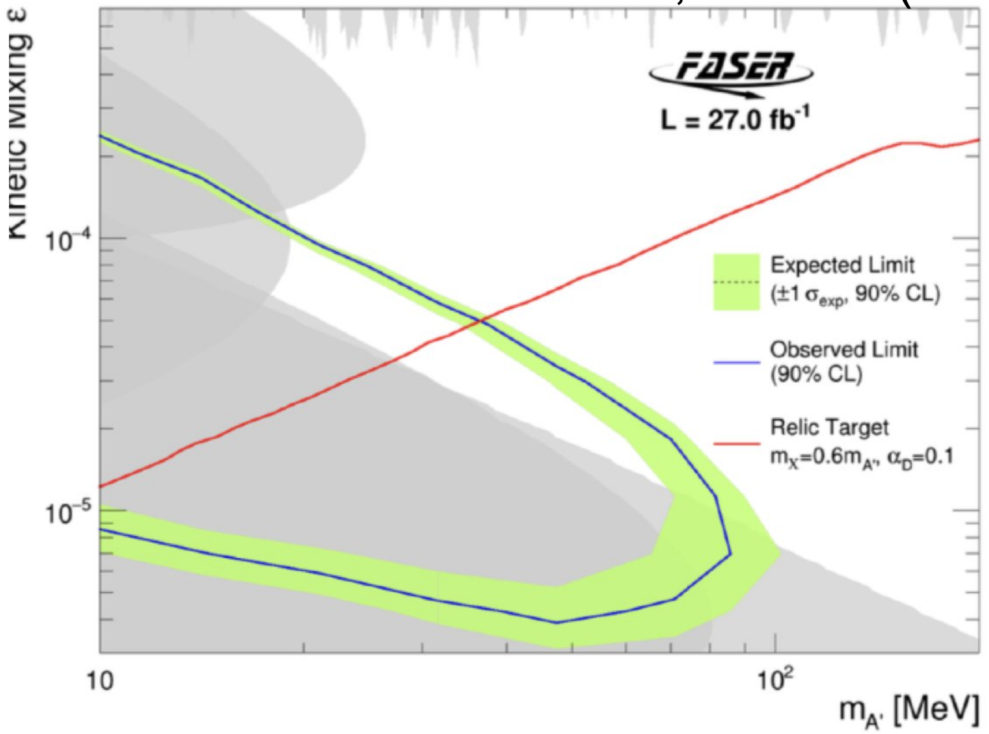
Rapidity bin	[8.5, 9.0]	[9.0, 9.25]	[9.25, 9.5]	[9.5, 10]	[10, ∞)
Uncertainty Sources					
MC Stat. unc.	1.5	1.2	1.0	1.1	1.0
Geant4 + GENIE unc.	1.3	4.3	3.5	3.6	1.8
Neutrino Flux Modeling unc.	38.3	29.4	19.5	23.0	22.4
LOS unc.	29.9	3.5	0.2	9.0	12.7
Mass	3.3	2.3	1.6	1.9	1.5
Luminosity	6.9	4.8	3.4	4.0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

Neutrino flux modeling is the dominant source of uncertainty

BSM Searches with FASER: Dark Photons



PLB 848, 138378 (2024)

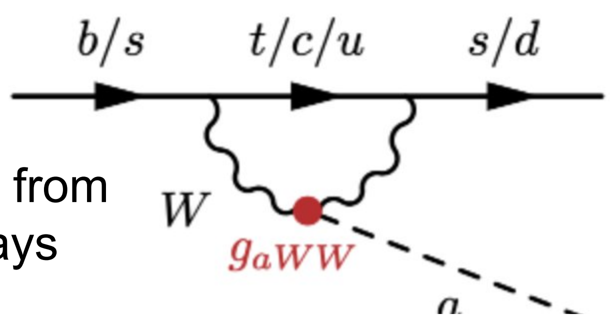


- Dark Photons: U(1) gauge group
  Signature: decay into e+e- pair in decay volume

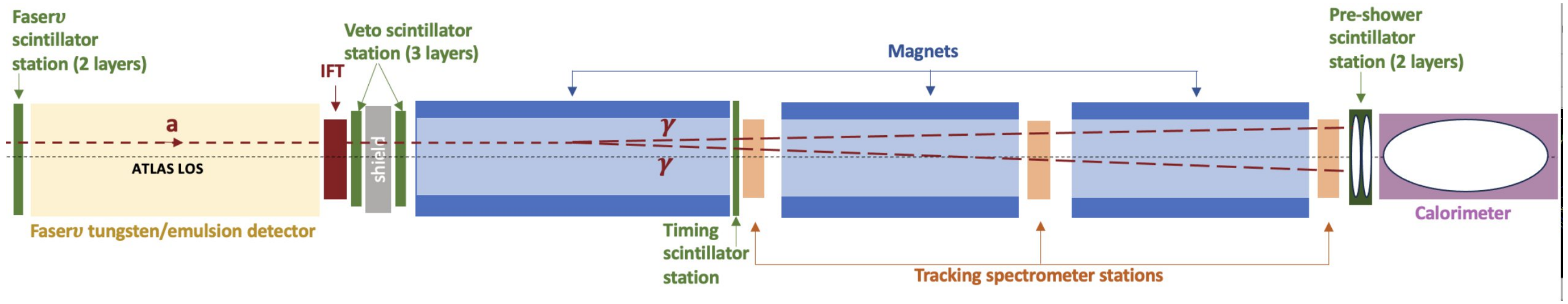
- Selection
  - 2 opposite-sign tracks & 500 GeV in calorimeter
  - No signal in veto counters
  - Signal in downstream scintillators

0 events observed / expected

BSM Searches with FASER: ALPs



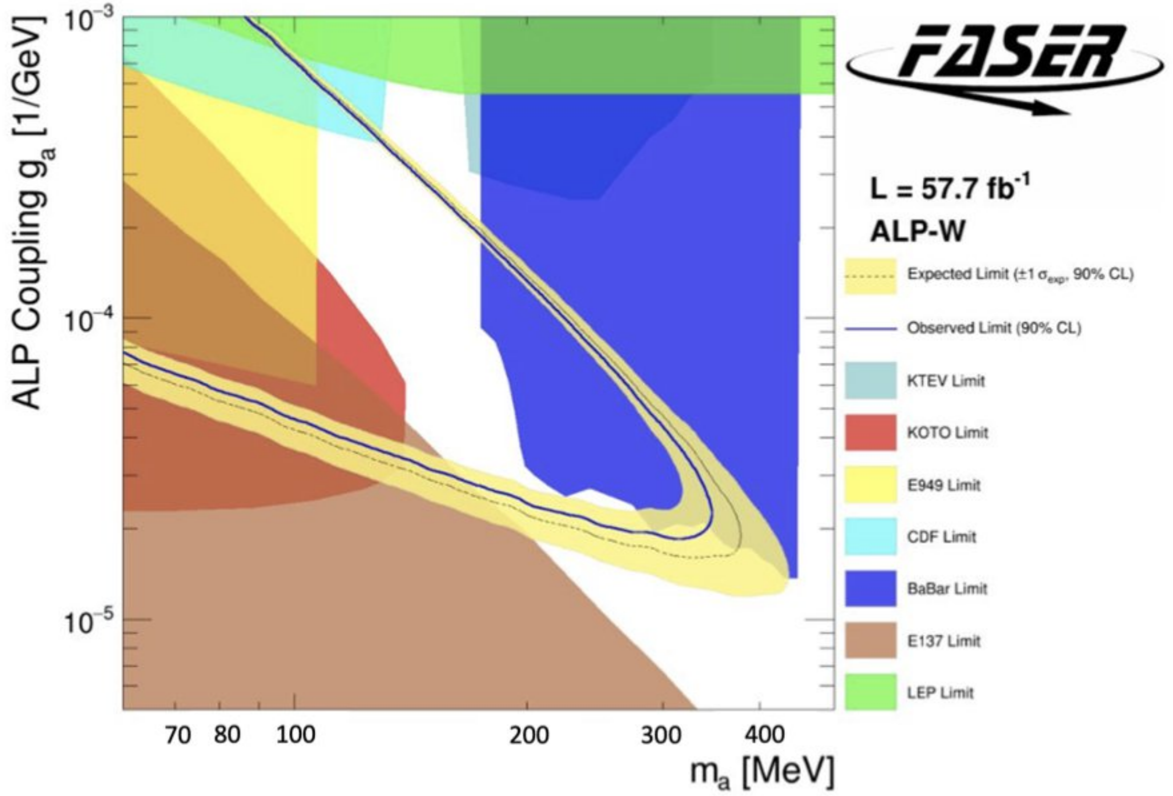
Mainly from B decays



- 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 …

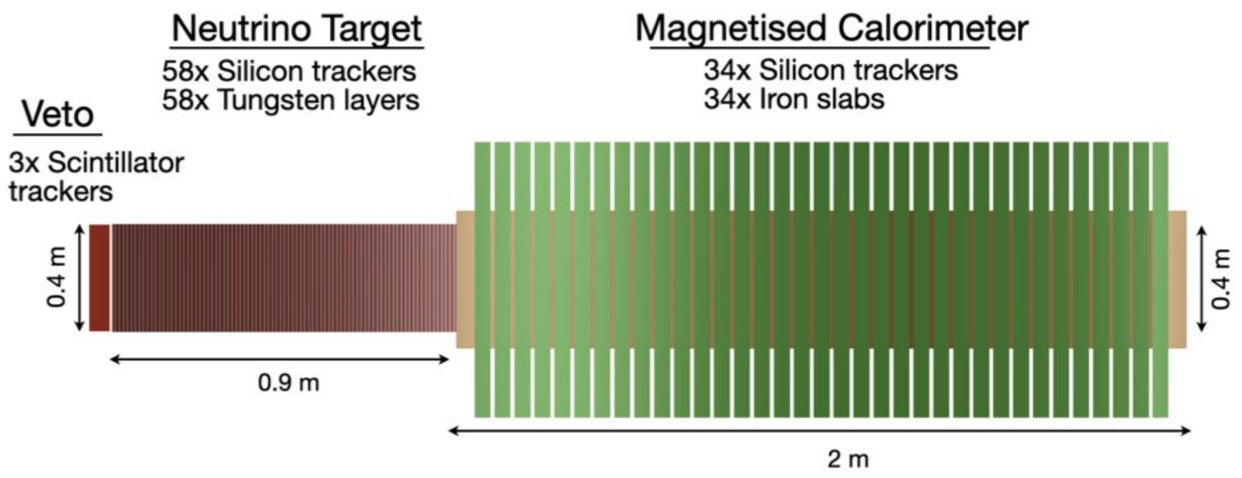
Expected number of CC neutrino interactions for 3000 ab^{-1}

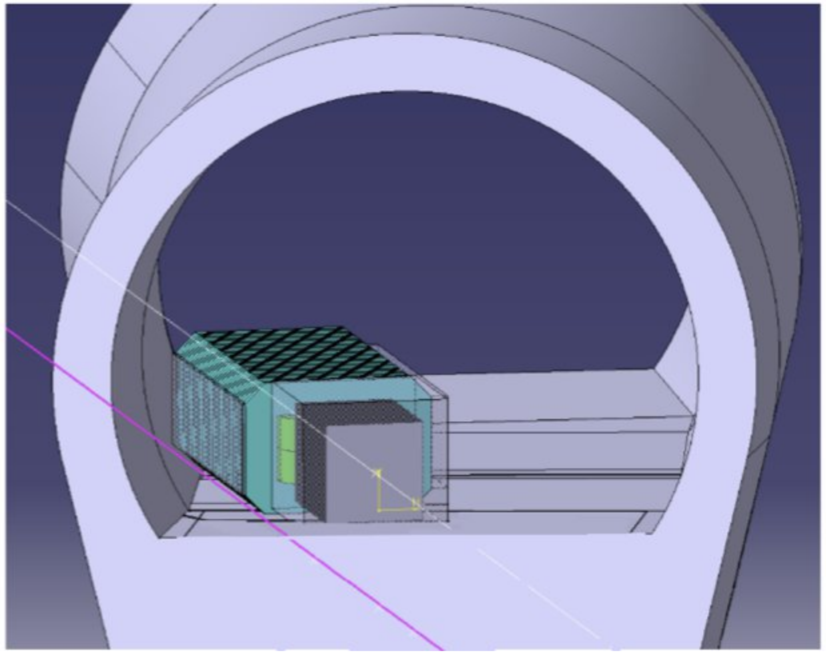
$2.10^4\ \nu\mu$

$3.10^3\ \nu_e$

$3.10^2\ \nu\tau$

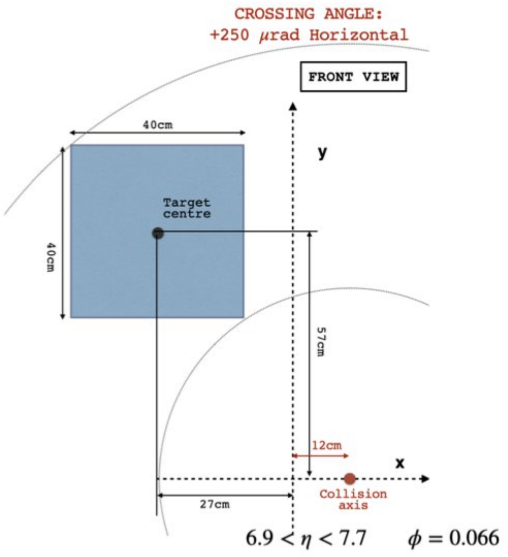
See talk D. Morozova



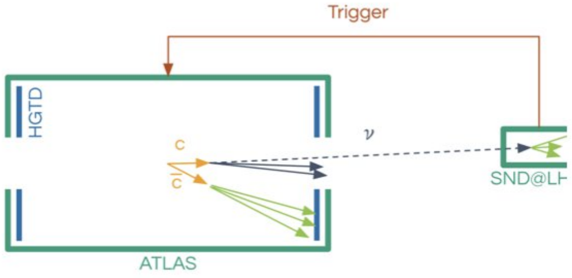


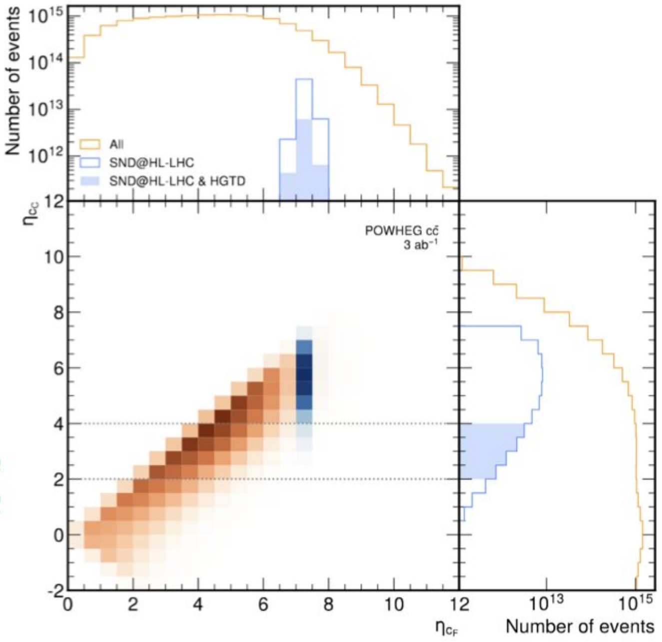
SND@LHC Upgrade Proposal for HL-LHC (~2030)

- **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.



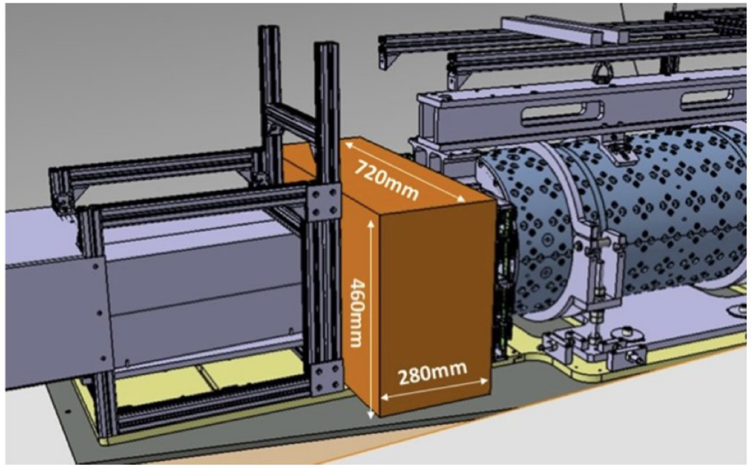
Flavour	CC DIS Interactions (3k fb-1, 1.3 ton)	
	total (DPMJET)	cc-bar (DPMJET)
$\nu_\mu + \bar{\nu}_\mu$	1.5x10⁴	2.4x10³
$\nu_e + \bar{\nu}_e$	3.4x10³	2.7x10³
$\nu_\tau + \bar{\nu}_\tau$	2.8x10²	2.8x10²
Total	**1.9x10⁴**	**5.4x10³**

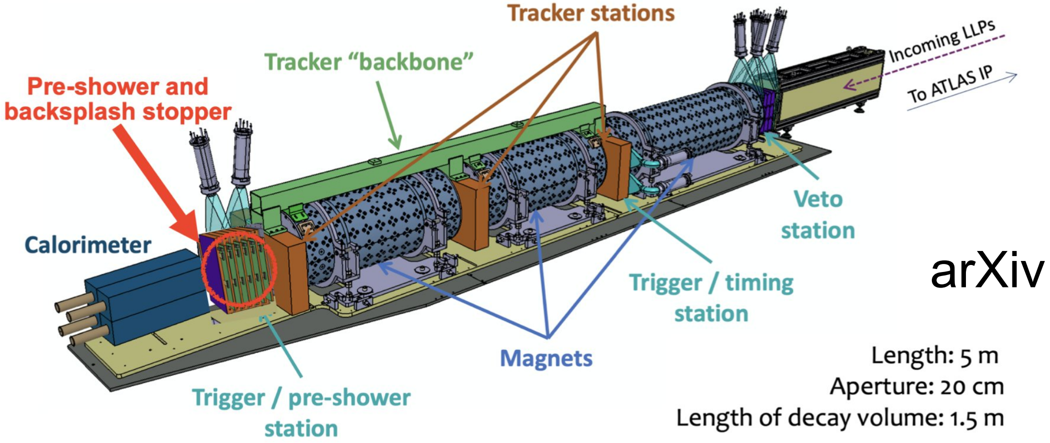




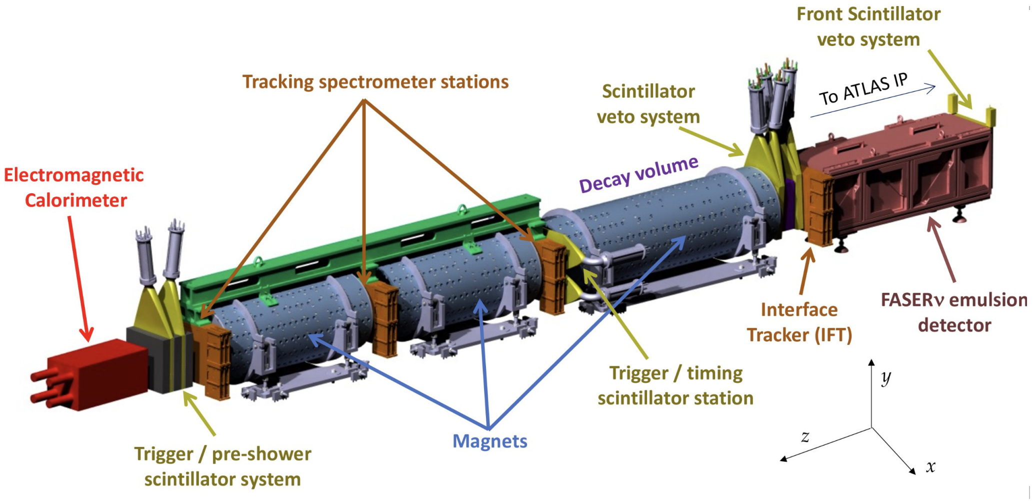
FASER Upgrade for Run-3 and Run-4

- 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



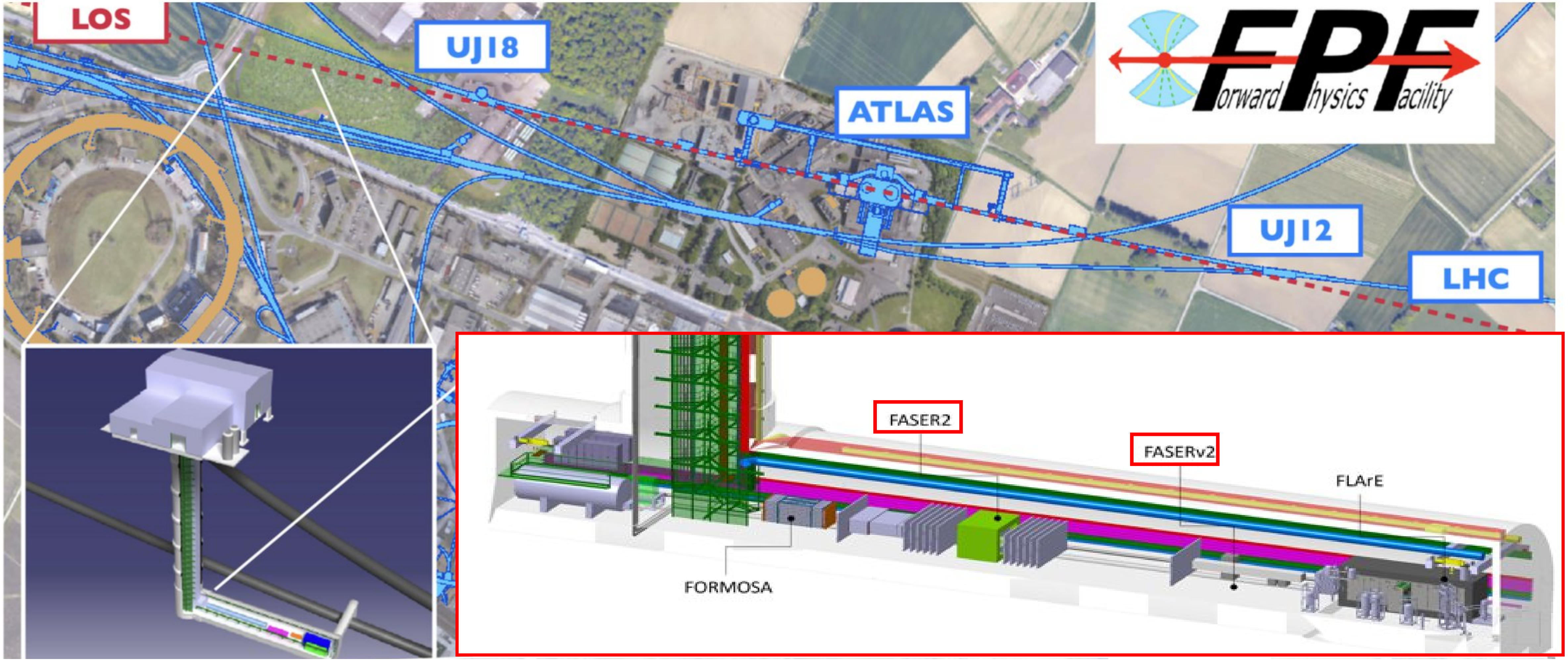
- FASER is approved for Run-4
  Expected luminosity: 680 fb^{-1}

- 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

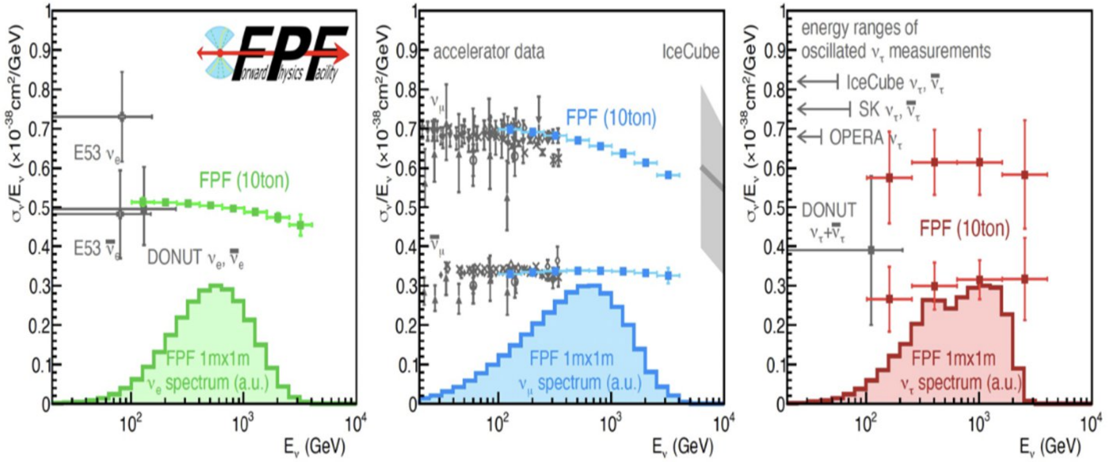
2203.05090
2411.04175
2503.19010

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



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

Neutrinos at the Forward Physics Facility

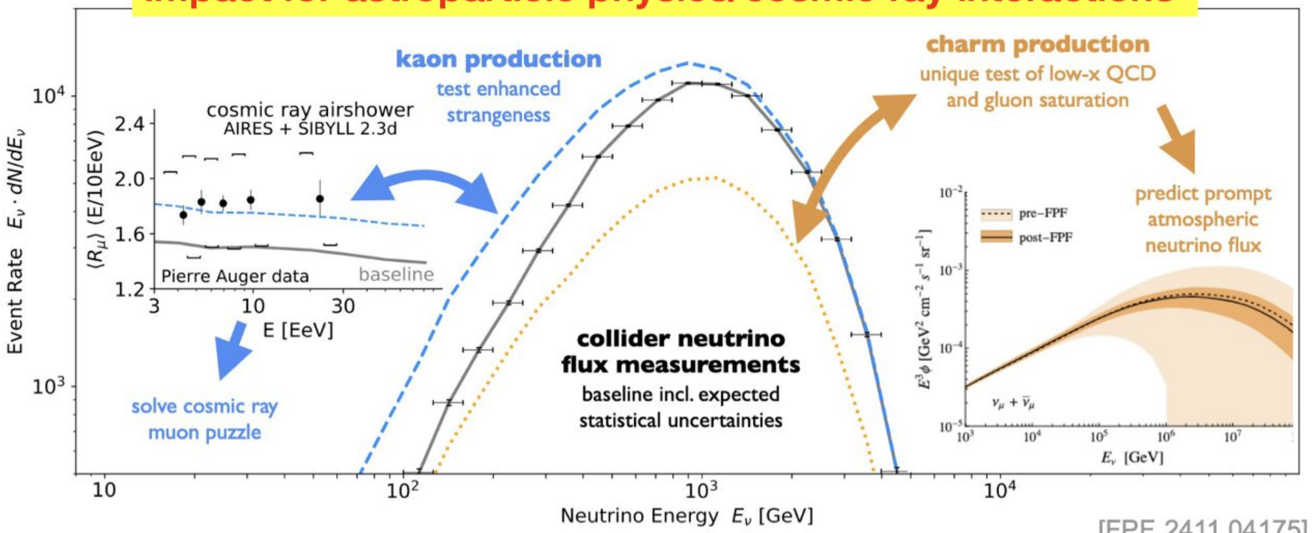


J.Phys.G 50 (2023) 3, 030

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 ($x{\sim}10^{-7}$ – 0.1, DIS)
  - astroparticle physics

Impact for astroparticle physics/cosmic ray interactions



[FPF 2411.04175]

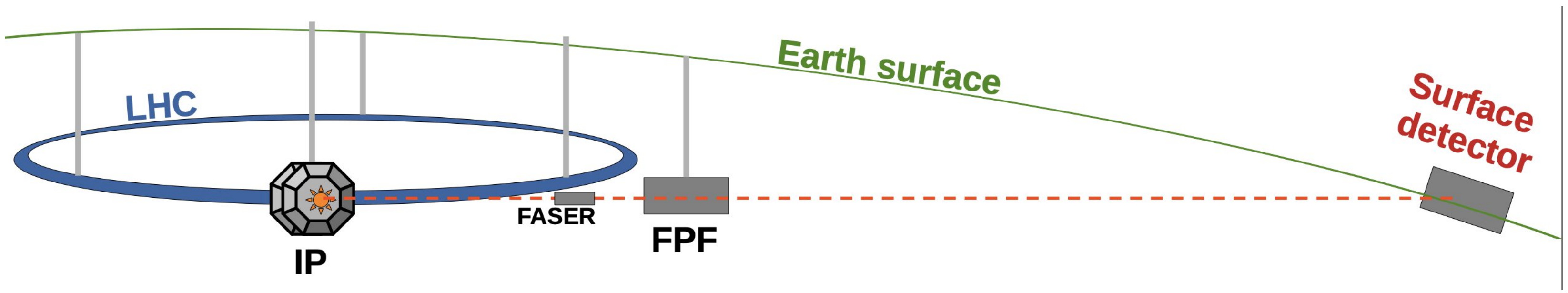
cosmic ray muon puzzle: observed 8σ excess of muons compared to predictions from hadronic interaction models

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)



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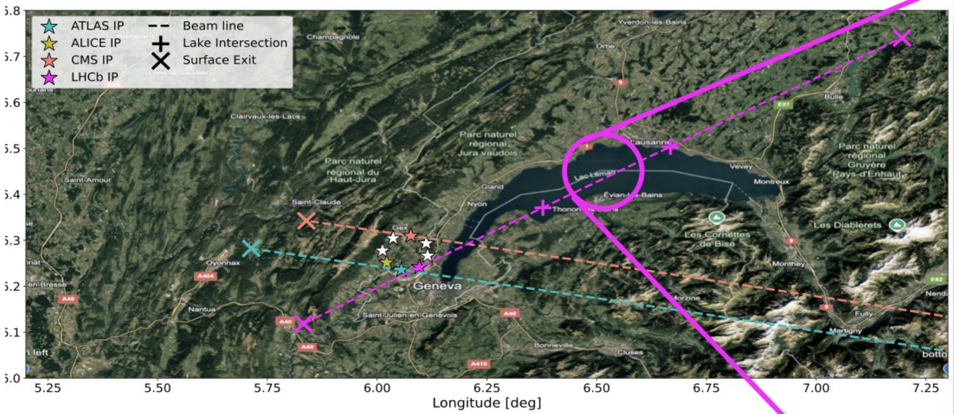
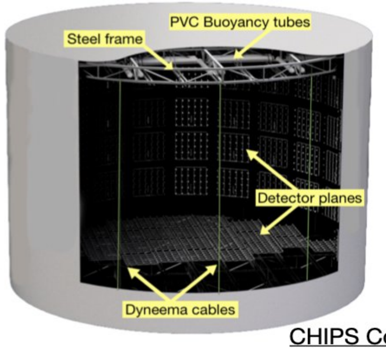
2501.06142

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

UNDINE: UNDerwater Integrated Neutrino Experiment





CHIPS Collab. 2024

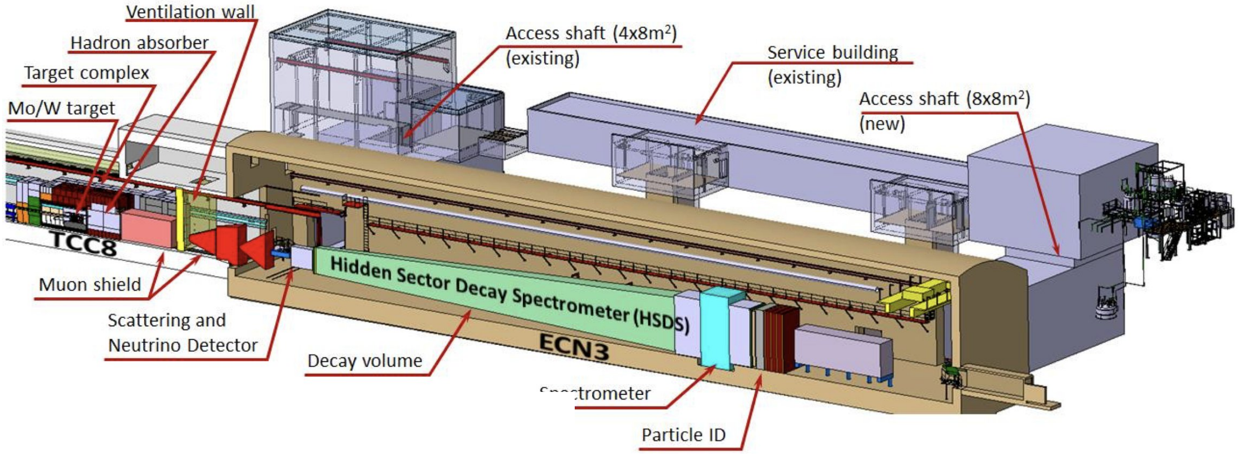
- A suite of CHIPS-style water Cherenkov detectors deployed in a modular fashion
- Benchmark lake detector: 5 CHIPS modules (~30 kT)

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

What exactly can we measure, apart from cross sections?

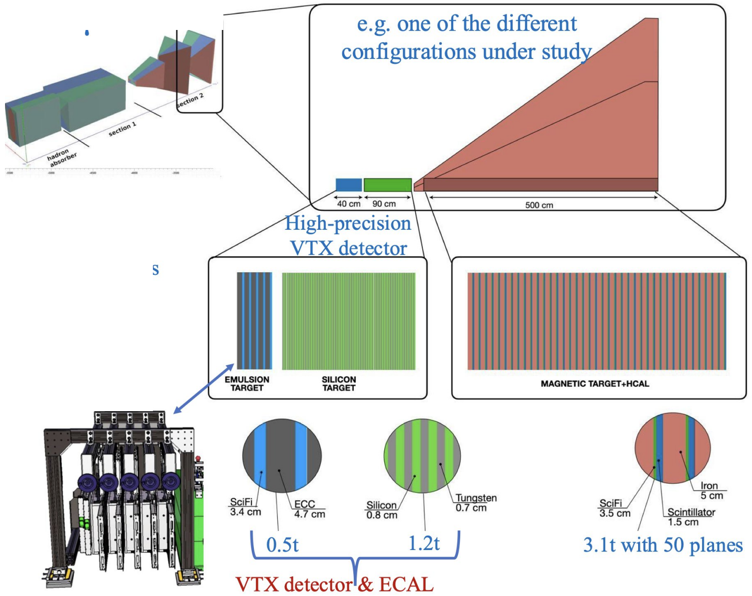
SHiP a Future (Neutrino)Experiment @ CERN

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: $4x10^{19}$ 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

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. Samples of $10^5 - 10^6$ neutrinos events should be collected.

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

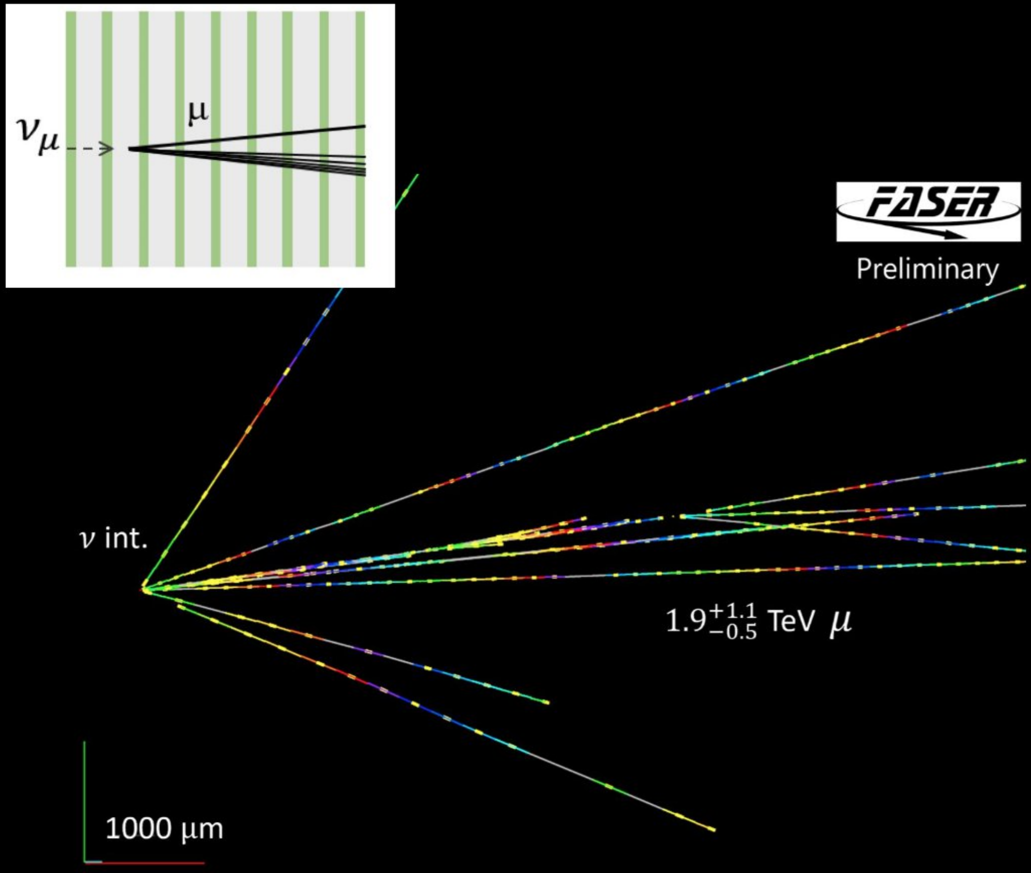
- In addition: The CERN neutrino platform as a central point for neutrino experiment development; The SHiP experiment planned for data taking in early 2030's; auxiliary experiments such as NA61; A new experiment with tagged neutrino beam (NuScope?)…

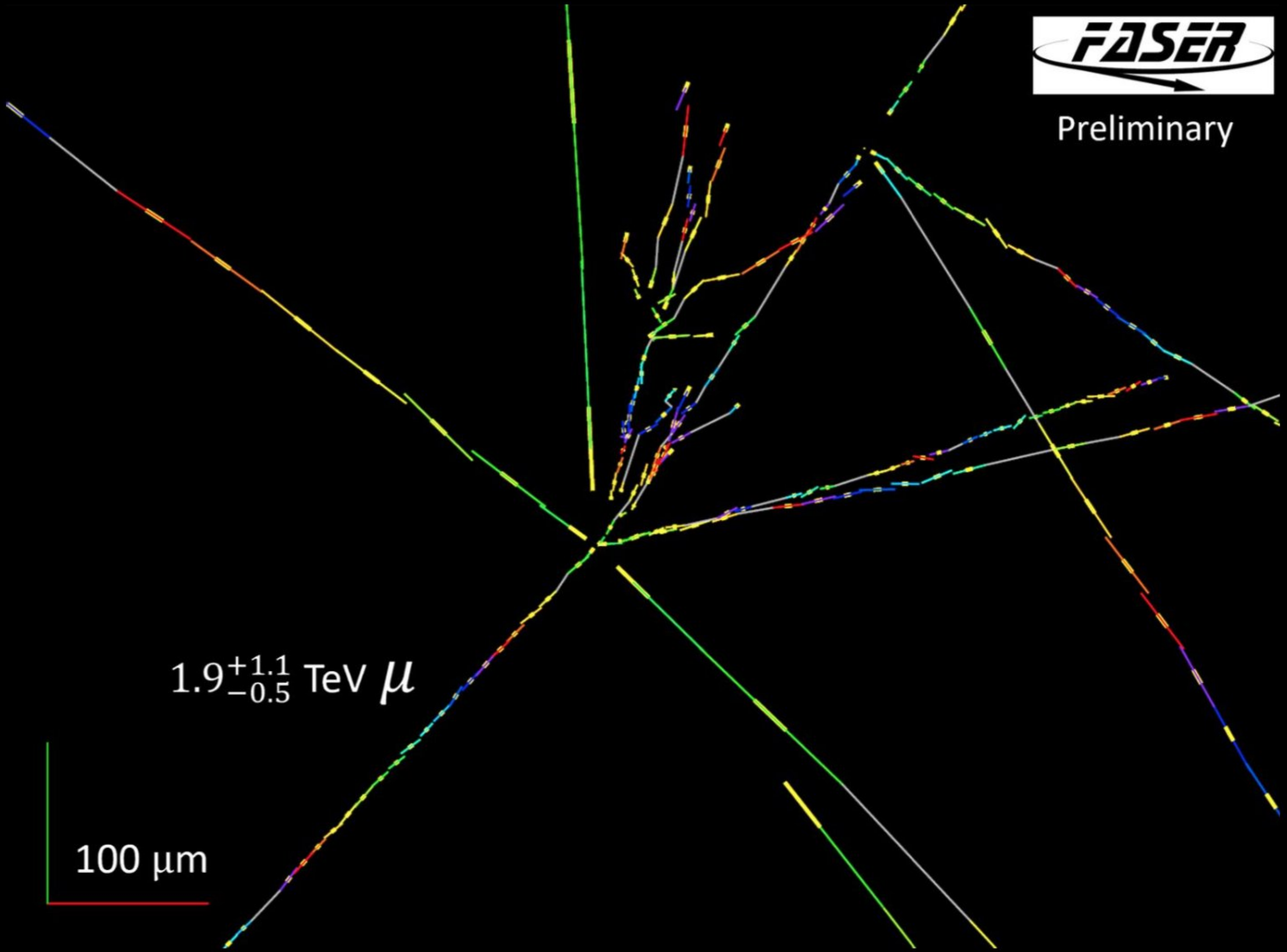
Backup

FASER

SND@LHC

Event display of ν_μ event candidate





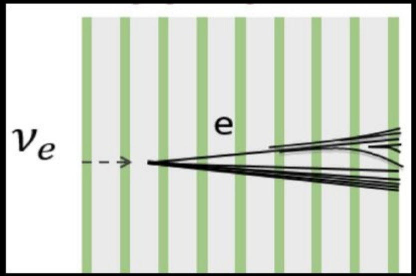
Tilted view

A subset of the FASERν volume is used, corresponding to a target mass of 314.7 kg, collecting 9.5 fb^{-1} of LHC proton-proton collision data in 2022 at a centre-of-mass energy of 13.6 TeV.

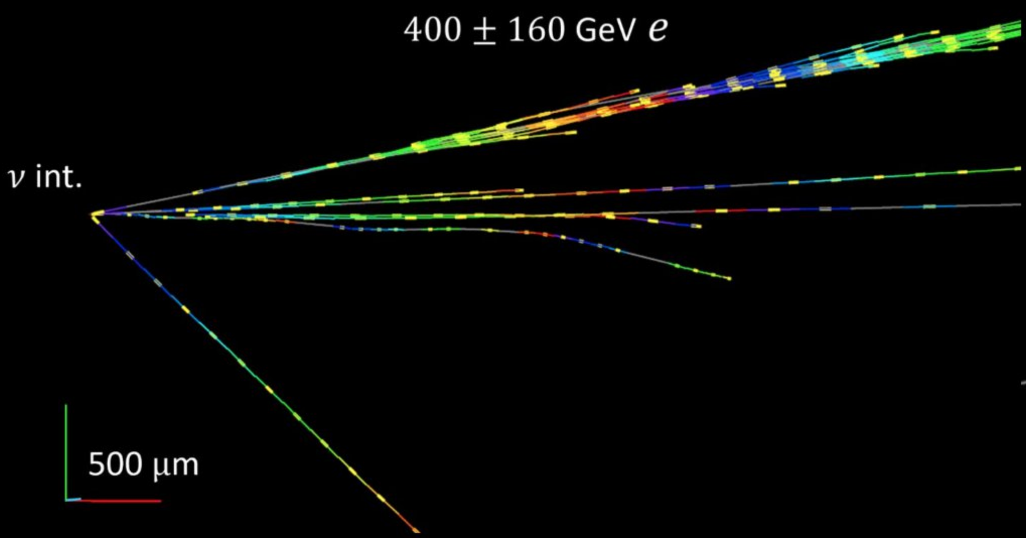
	ν_e CC	ν_μ CC
Expected signal	2.8–7.2	16.2–28.7
Expected background	$0.06^{+0.04}_{-0.02}$	$0.54^{+0.22}_{-0.17}$
Observed events	5	20

CERN-FASER-CONF-2025-002

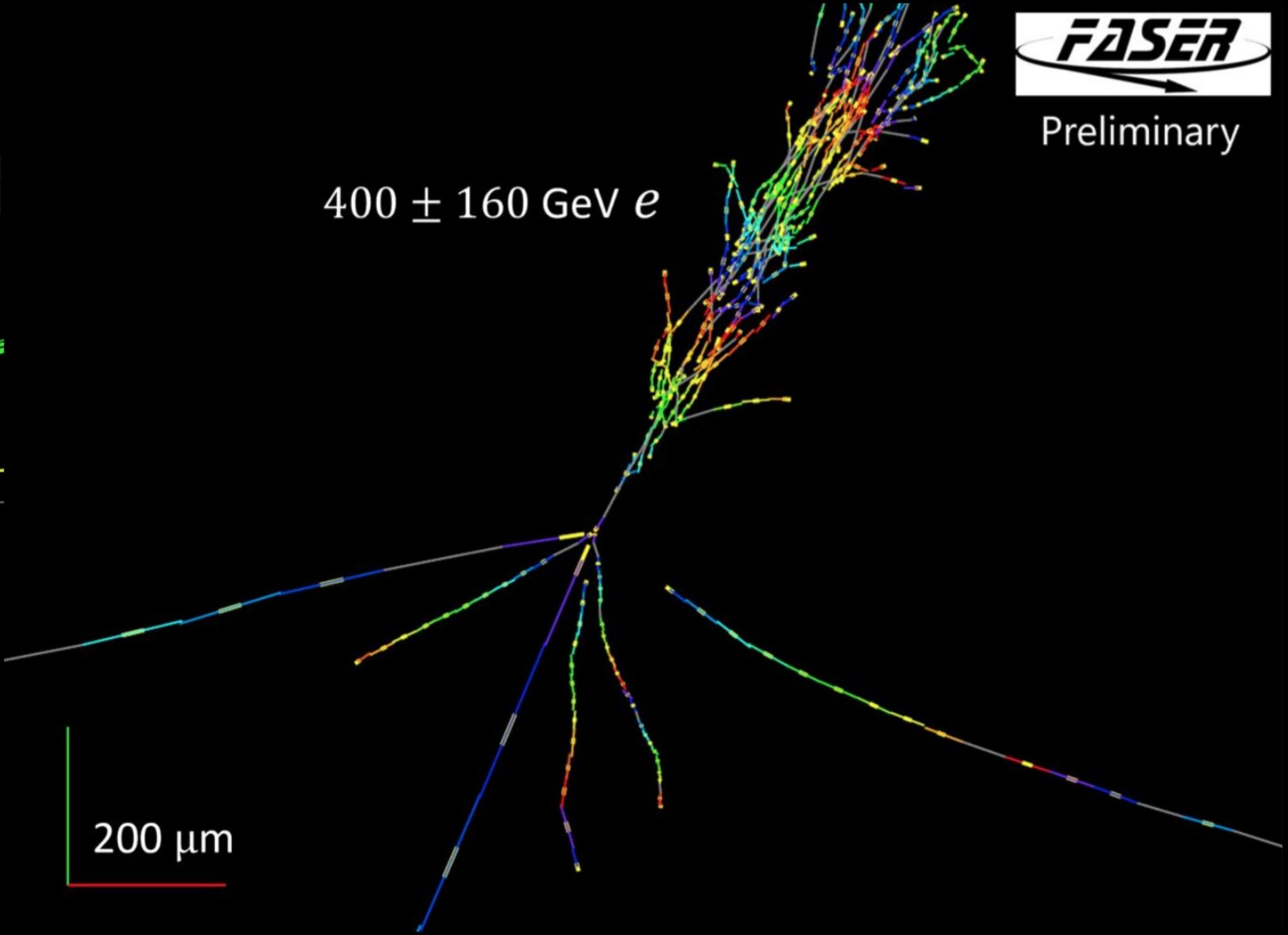
Event display of ν_e event candidate



FASER Preliminary



Tilted view



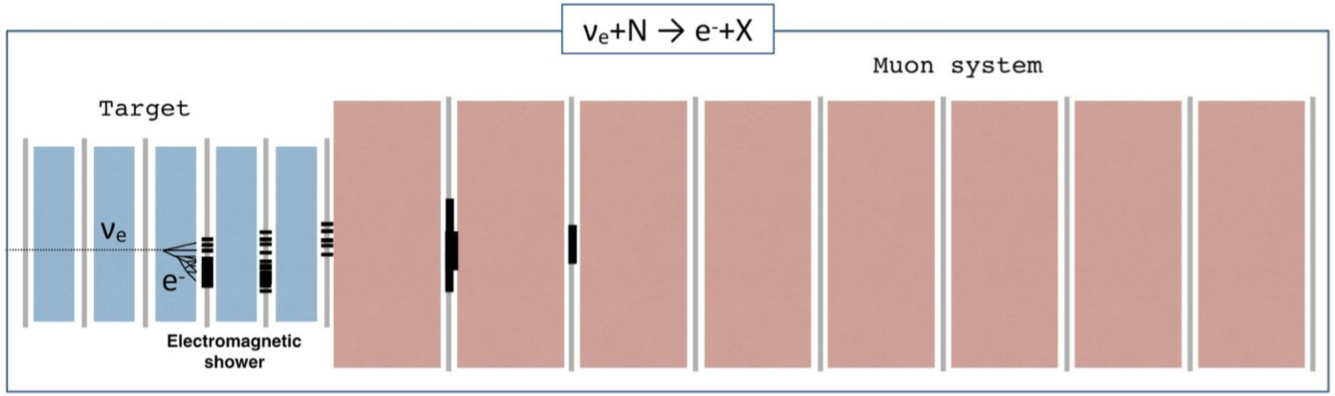
FASER Preliminary

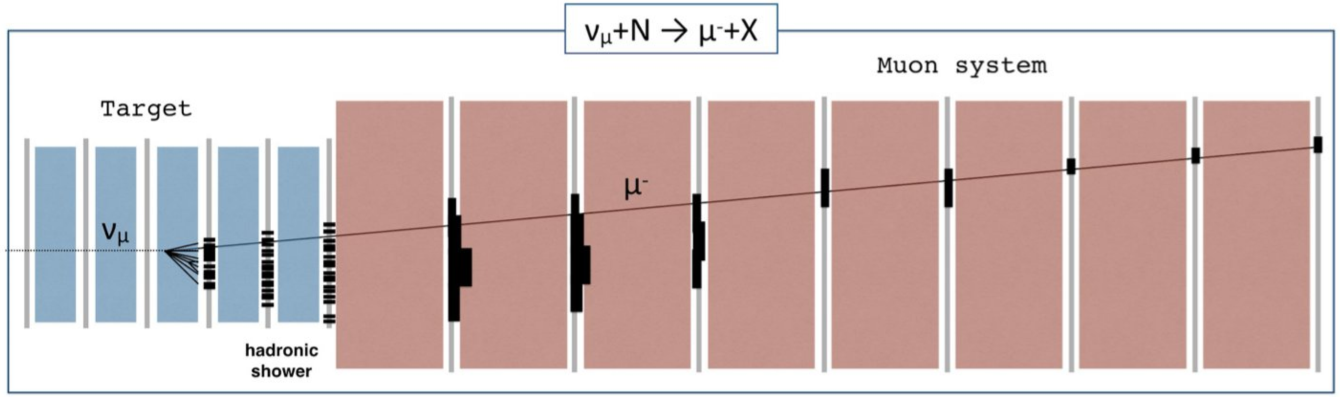
Beam view

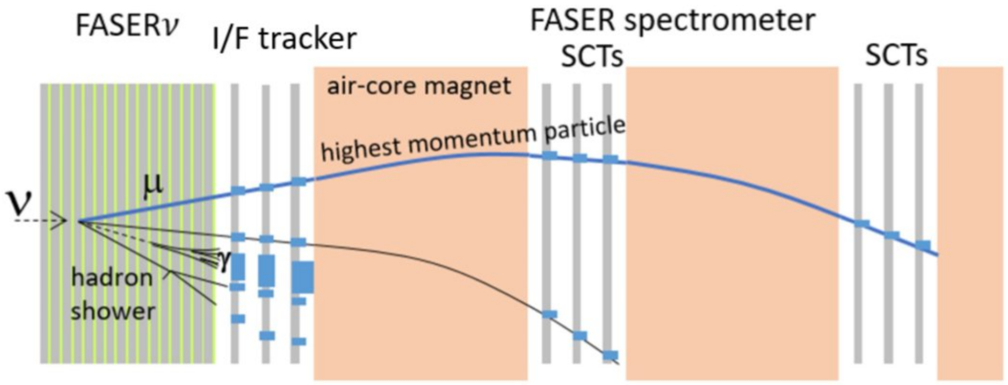
Neutrino Event Reconstruction Strategies

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**.







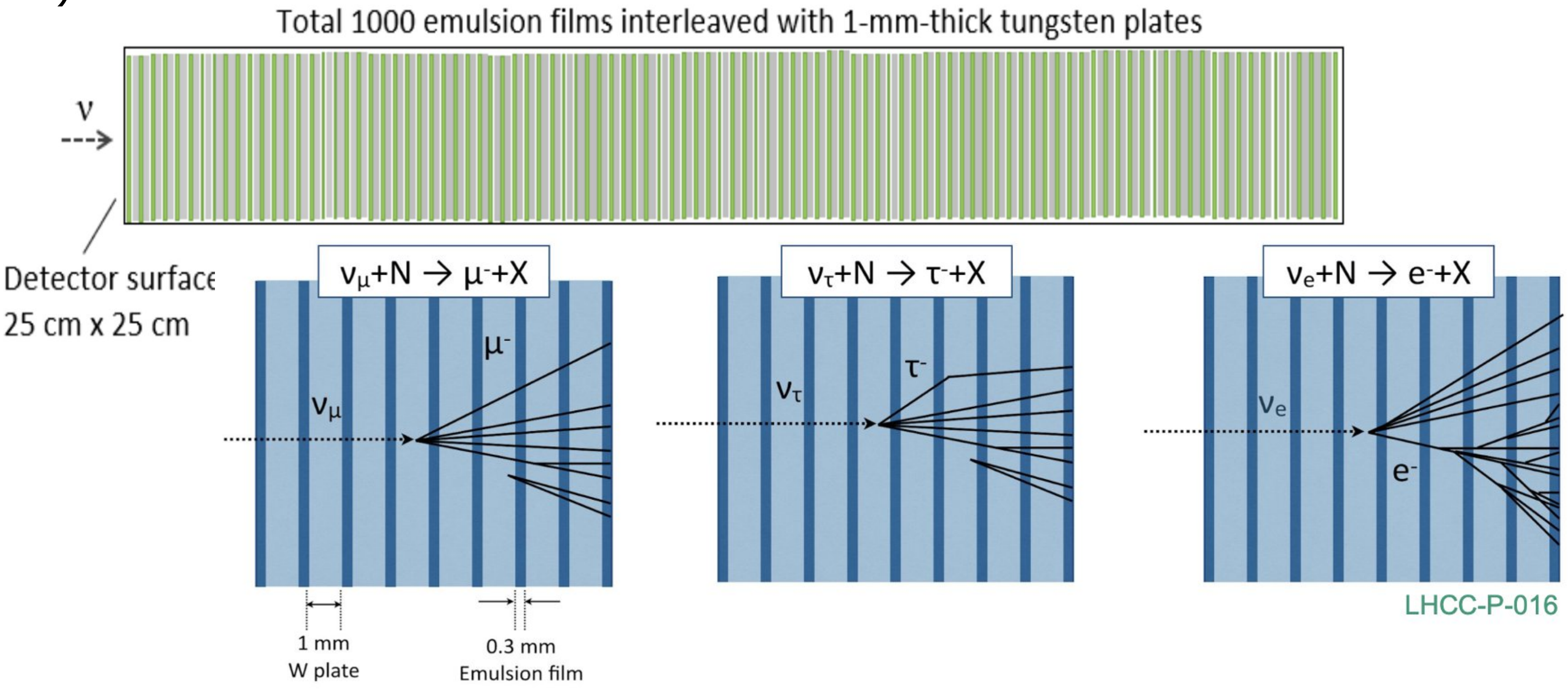
FASER

- 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)

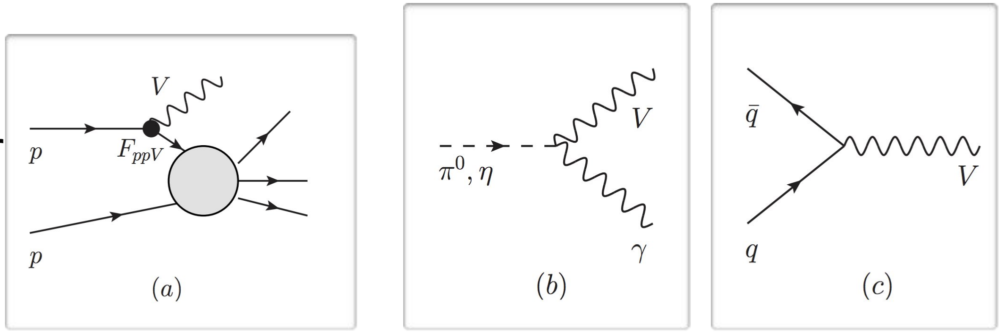


More BSM Searches Channels to Come…

Eg. SND@LHC sensitivity for light dark matter

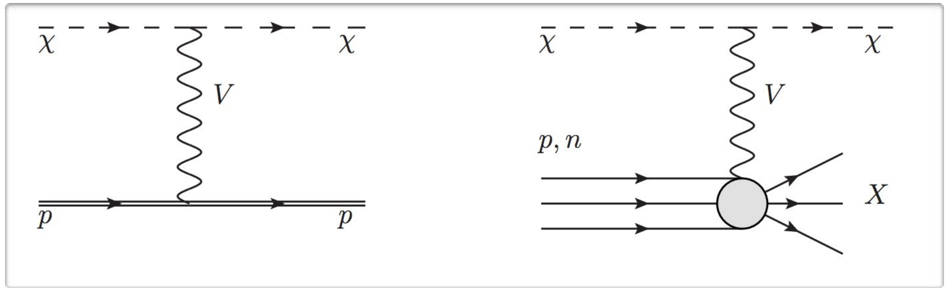
Production: consider a scalar χ particle coupled to the Standard Model via a leptophobic portal,

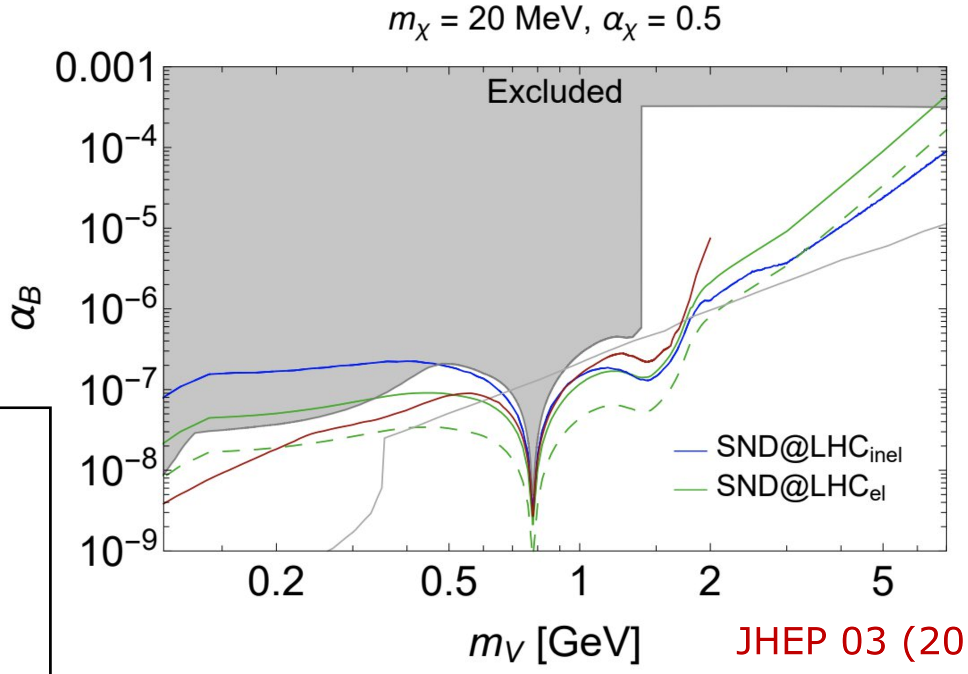
$$\mathcal{L}_{\text{leptophob}} = -g_B V^\mu J^B_\mu + g_B V^\mu (\partial_\mu \chi^\dagger \chi + \chi^\dagger \partial_\mu \chi),$$



Proton bremsstrahlung | Meson decay | Drell-Yan process

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





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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…

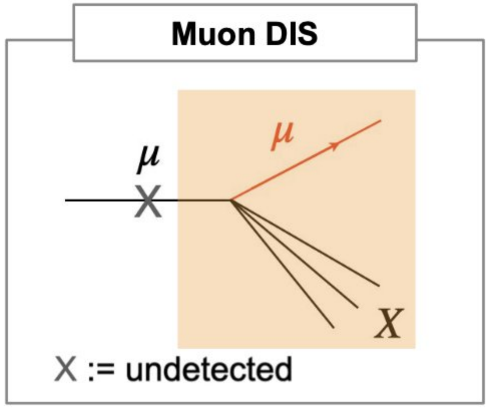
SND@LHC backgrounds

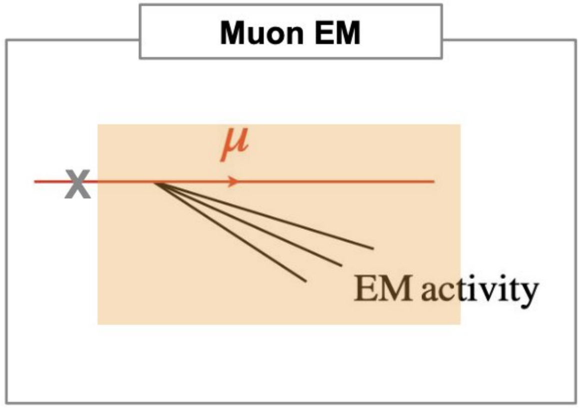
Entering muons

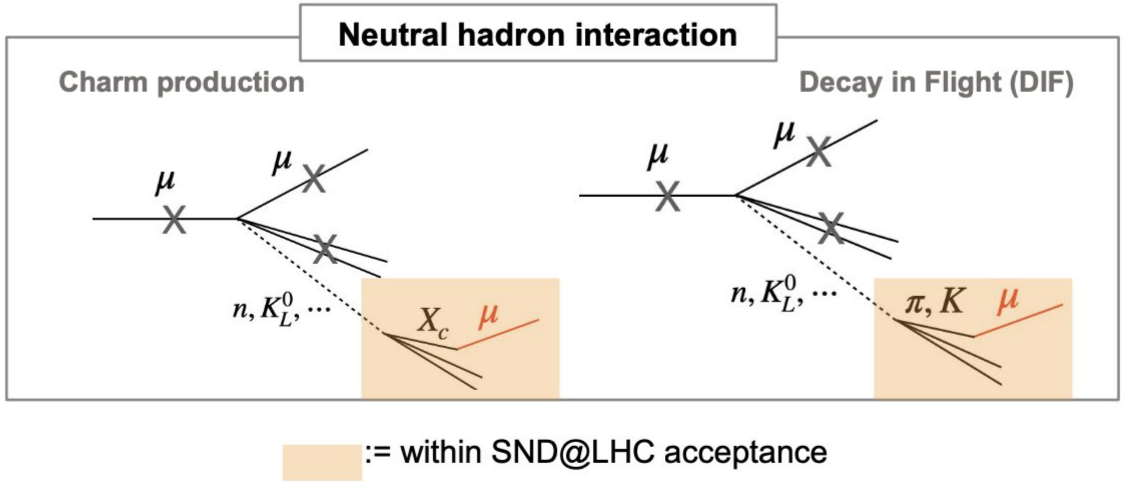
- Incoming muon track may be missed due to detector inefficiency.
- Shower induced by DIS or EM activity.
- Number of muons in acceptance: 5×10^{8}
  SNDLHC-NOTE-2023-001
- Detector inefficiency: 5×10^{-12}
  - Two veto and two scintillating fibre planes.
- **Negligible** background with tight fiducial 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)** $\times 10^{-2}$ background events due to neutral hadrons.



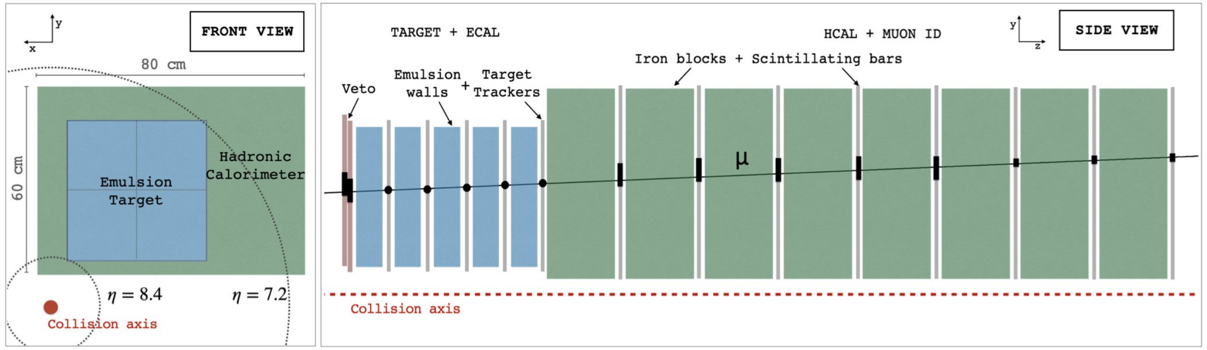




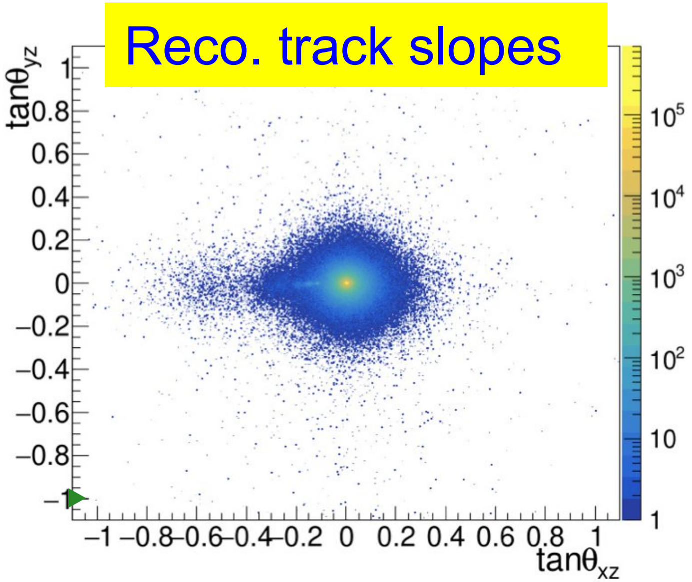
SND@LHC backgrounds

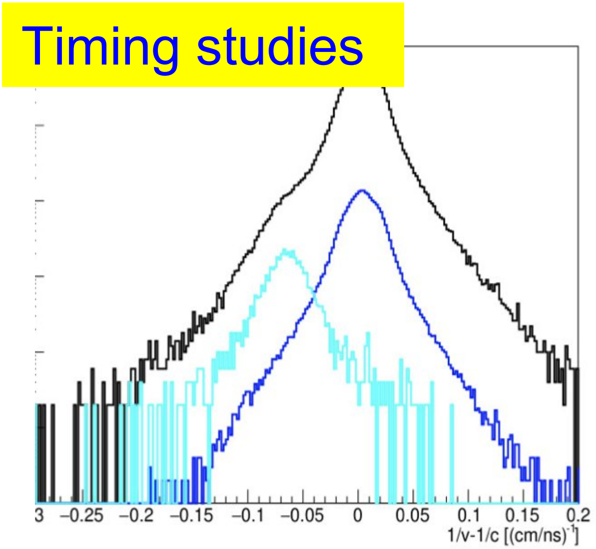
CERN-EP-2023-222

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

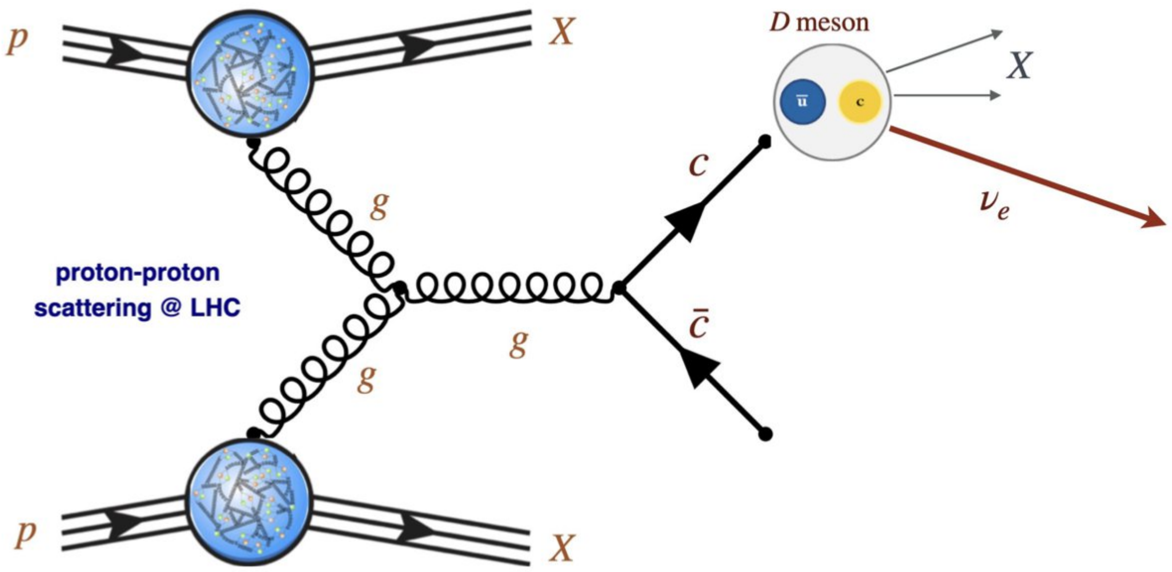




system	sample	muon flux $[10^4\ \mathrm{fb/cm^2}]$	$1-\frac{\mathrm{sim}}{\mathrm{data}}$ [%]
on the level of eff. corrected data and generator MC flux			
SciFi	data	$2.06 \pm 0.01(\mathrm{stat.}) \pm 0.12(\mathrm{sys.})$	22 ± 9
	sim	$1.60 \pm 0.05(\mathrm{stat.}) \pm 0.19(\mathrm{sys.})$	
DS	data	$2.35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

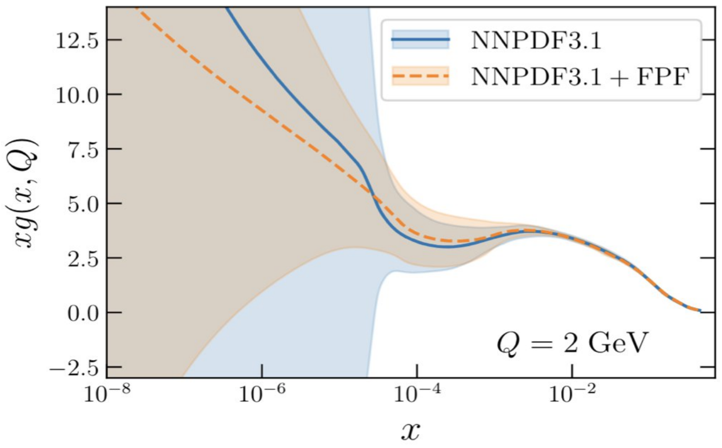
Data-MC difference ~ 25%

Neutrinos as a probe for charm production

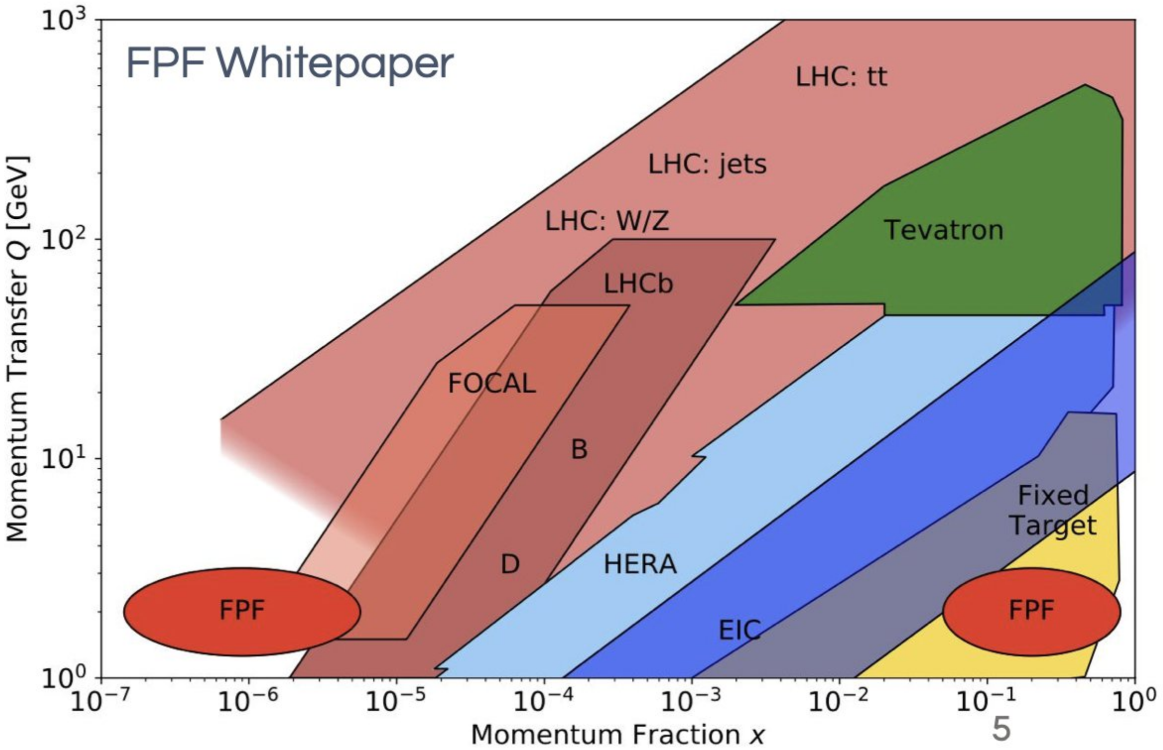


- Dominant partonic process: **gluon-gluon** scattering.
- SND@LHC will constrain the gluon PDF in the **very small x** region.
  - Only LHC neutrinos have sensitivity in this region.
- Relevant for **FCC-pp, ultra-high energy neutrinos** and **cosmic rays.**

Electron neutrinos, 2% uncertainty in inclusive event rates

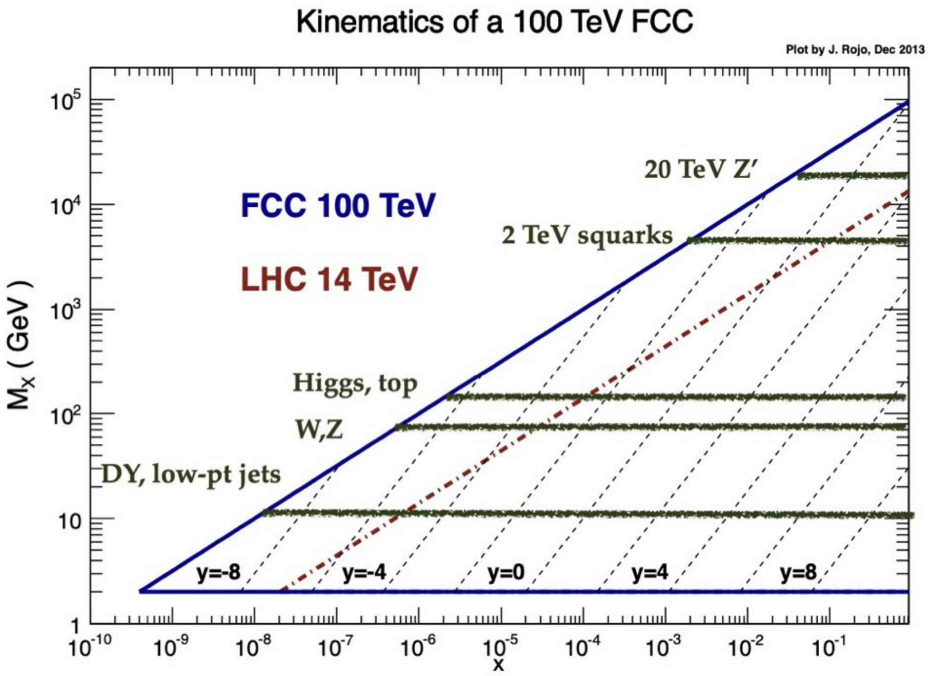


$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$

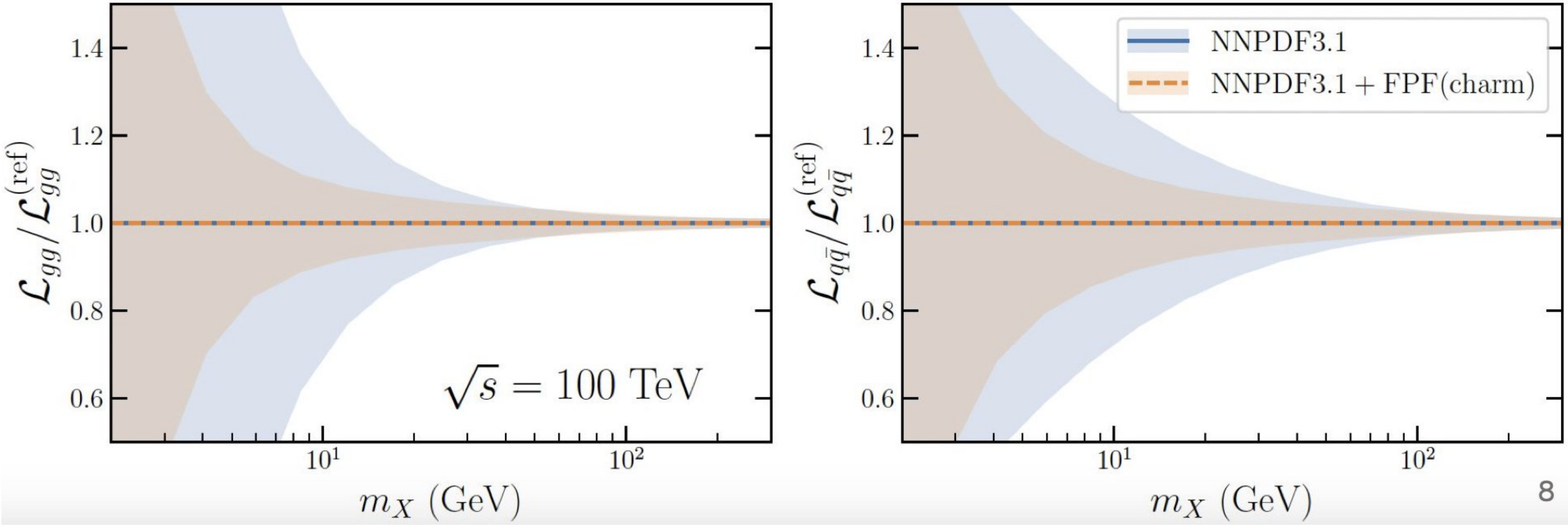


Implications for FCC-pp

- 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.



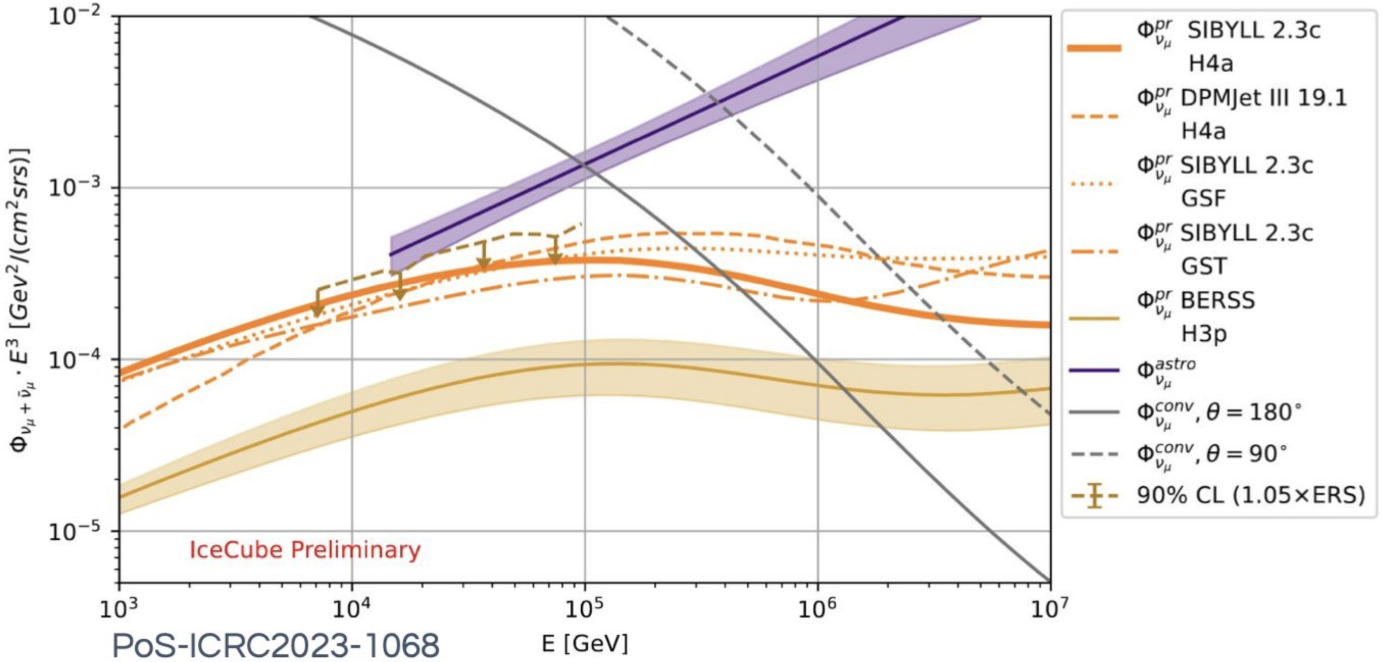
J. Rojo CERN-TH Colloquium 11/2023



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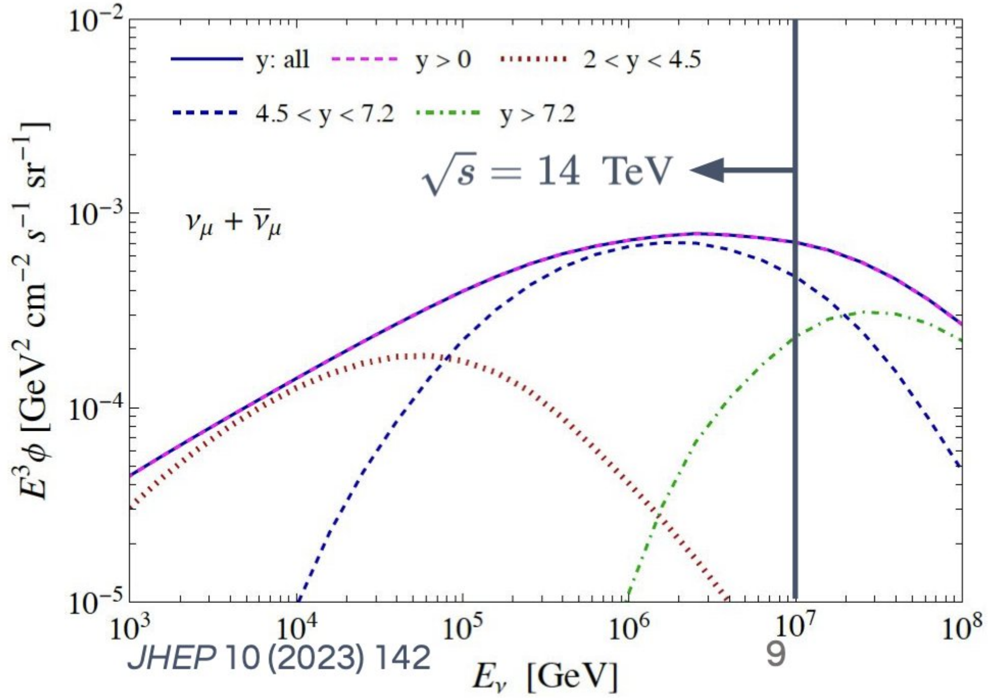
Prompt flux of atmospheric neutrinos broken down by charm hadron rapidity in the pp collision frame.



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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***.

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

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 $\bar{\nu}$ to reduce impact of charm production uncertainties.
  - Same strategy as in ***QCD*** measurements.