STANDARD MODEL AT THE LHC

Rome, May 7-10, 2024

Istituto Nazionale di Fisica Nucleare
Sezione di Roma

Sapienza Università di Roma

Collider Neutrinos

(results from FASER and SND@LHC)

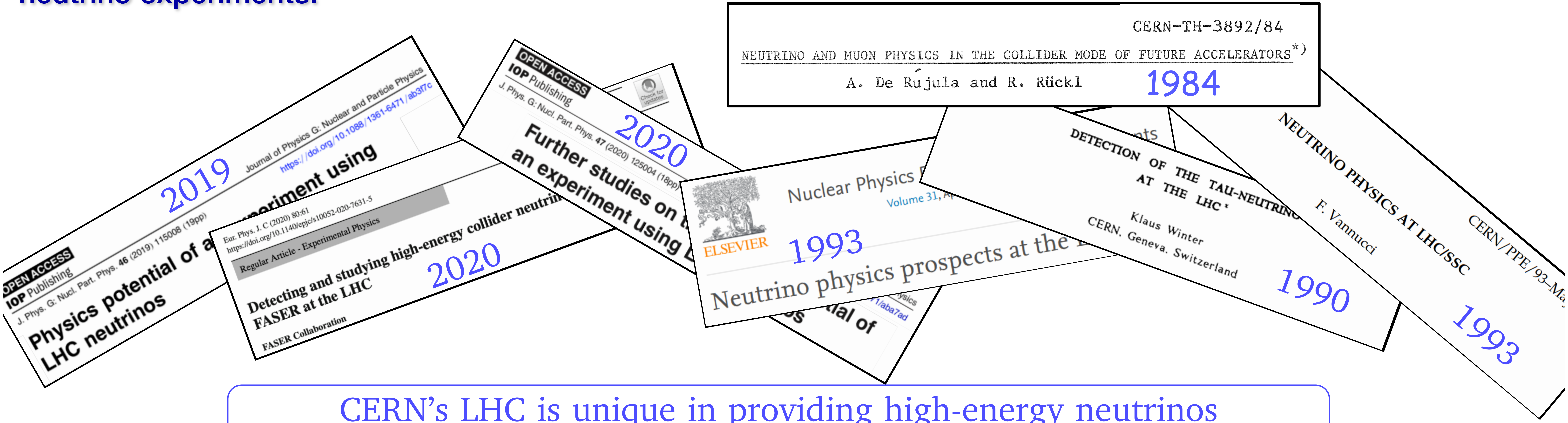
Marco Dallavalle

(INFN Bologna, SND@LHC Collaboration)

Motivation

Since the 1980s, before the LHC design phase, it was proposed to use the intense neutrino flux from pp collisions (pp—>νX)

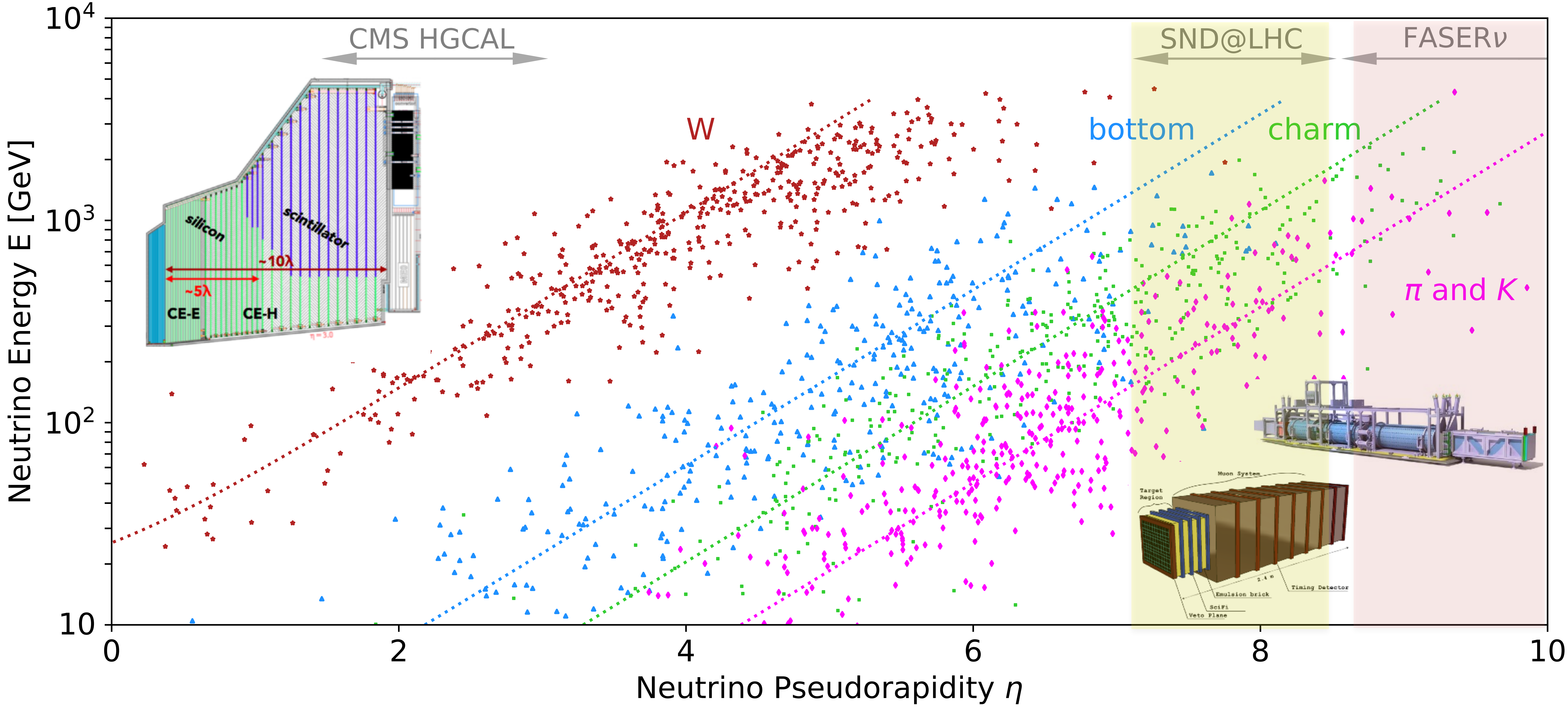
However, only in the last decade, it was shown that the backgrounds in the real CERN's LHC are low enough for neutrino experiments.



CERN's LHC is unique in providing high-energy neutrinos and measuring $pp \to \nu X$ in an unexplored domain

High Energy Neutrinos from LHC pp collisions

P. Foldenauer,[1,*] F. Kling,[2,3,†] and P. Reimitz[4,‡] arXiv:2108.05370v2 [hep-ph] 23 Dec 2021

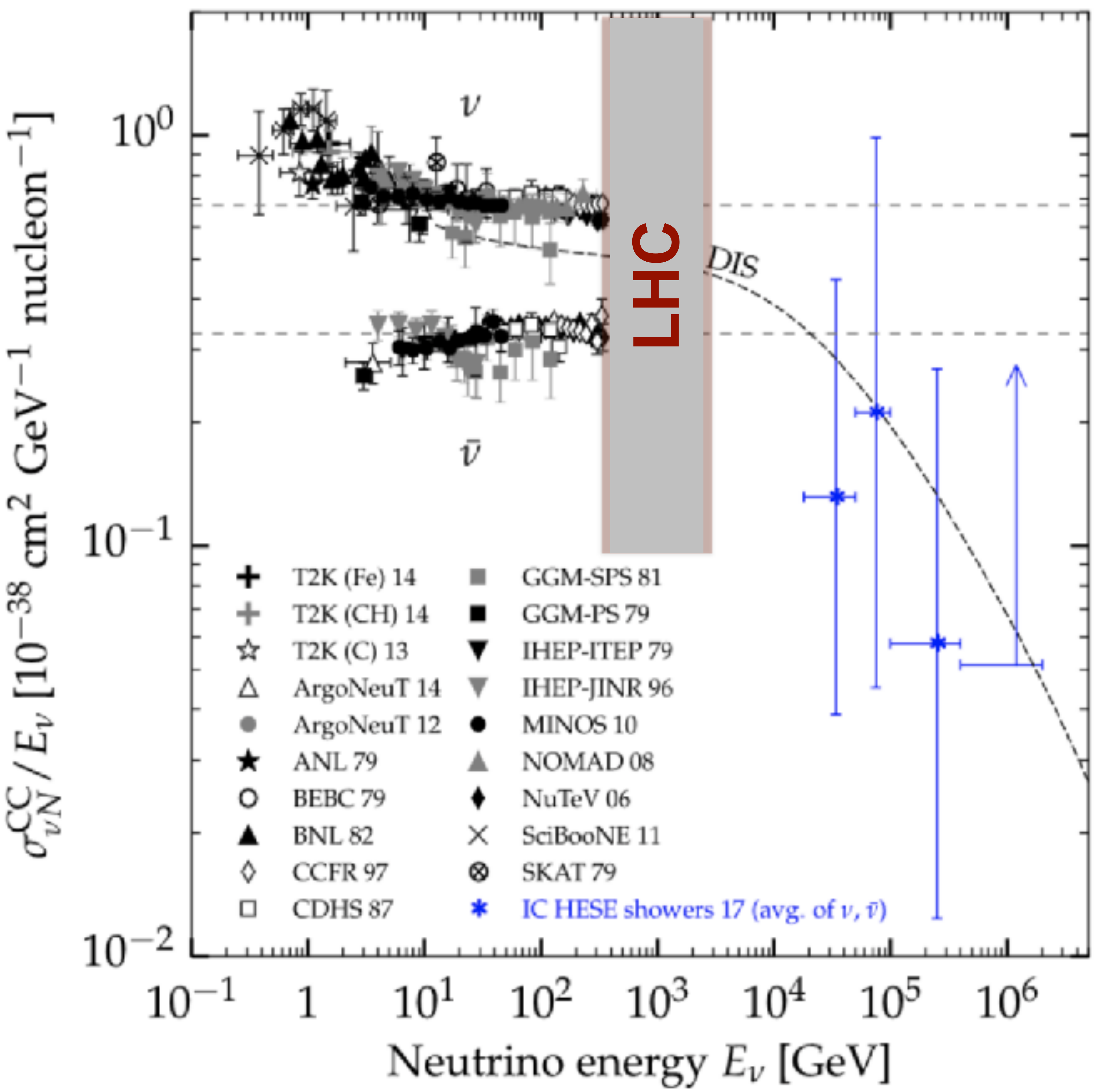


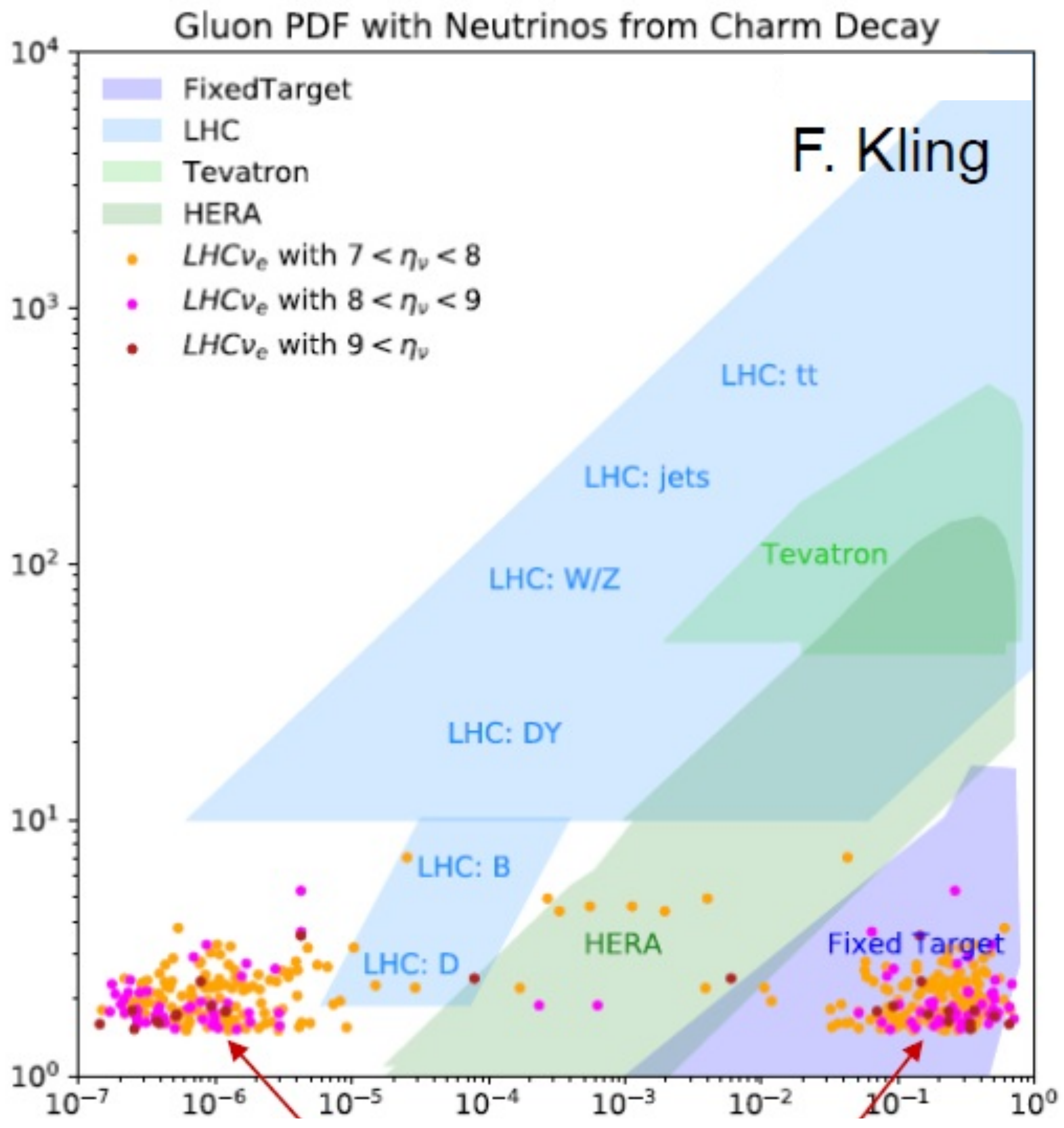
M.Dallavalle, SM@LHC, Rome, May 2024

Physics potential in new domains

- **all three flavour**
  - it will be the largest sample of ν_τ
- **Explore ν interactions at unprecedent lab energies**
- **ν_e from forward charm production; their rate constrain gluon PDF at very small x**
  - relevant for FCC and astroparticle exp.

Bustamante and Connoly, PRL 122 (2019)041101



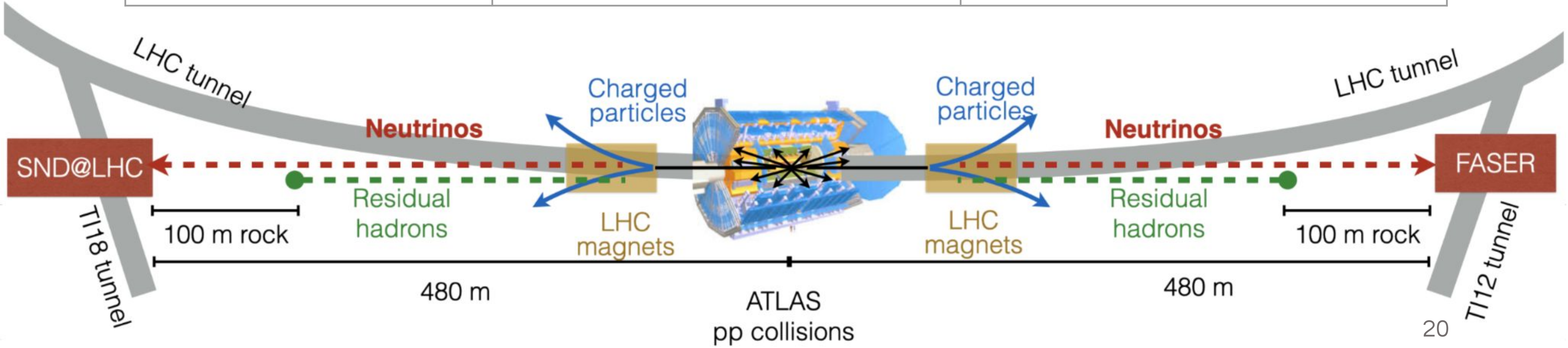


gluon momentum fraction x

M.Dallavalle, SM@LHC, Rome, May 2024

Two complementary LHC ν experiments

	SND@LHC	FASER
Location	**Off-axis**: $7.2 < \eta < 8.4$ Enhances **charm** parentage	**On-axis**: $\eta > 8.8$ Enhances **statistics**
Target	**800 kg** of tungsten	**1100 kg** of tungsten
Hybrid Detector technology	**Emulsion vertex detector**, electromagnetic and hadronic **calorimeters**	**Emulsion vertex detector** and **spectrometer**



both experiments started to take data in 2022

expected neutrino interactions in LHC Run3 (250 fb^{-1})

M.Dallavalle, SM@LHC, Rome, May 2024

Expected number of CC interactions in FASERν with 250 fb^{-1}

Generators: light hadrons	Generators: charm hadrons	FASERν at Run 3: $\nu_e + \bar{\nu}_e$	FASERν at Run 3: $\nu_\mu + \bar{\nu}_\mu$	FASERν at Run 3: $\nu_\tau + \bar{\nu}_\tau$
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}

https://arxiv.org/abs/2402.13318

SND@LHC

- Model neutrino production in pp collisions with **DPMJET**.
- Propagation to SND@LHC with **FLUKA** model of the LHC.
- GENIE neutrino interaction model.
- Neutrino interactions in SND@LHC / 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

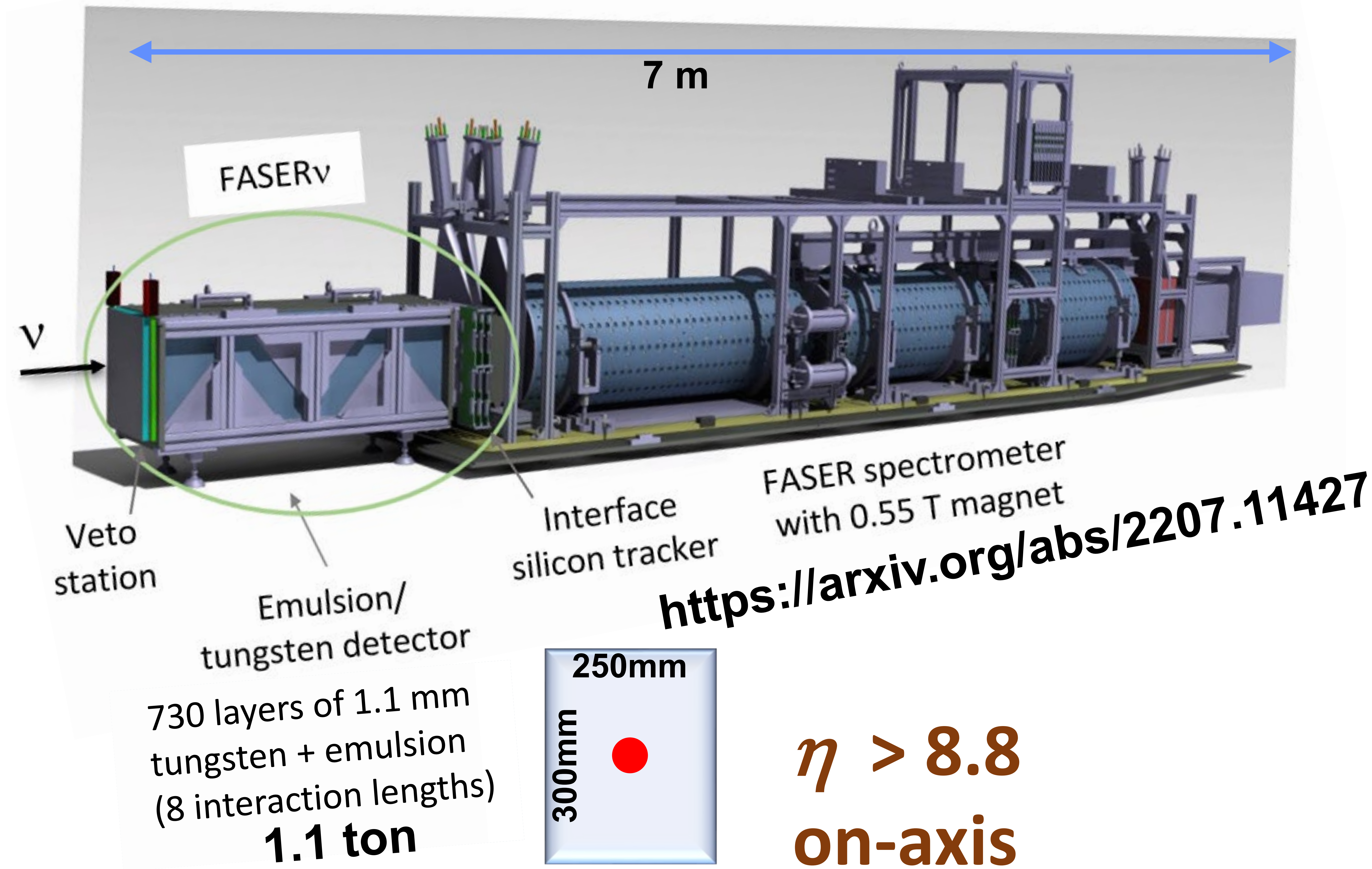
both experiments expressed interest in taking data also in LHC Run4 (680 fb^{-1})

FASER 2023

M.Dallavalle, SM@LHC, Rome, May 2024

PHYSICAL REVIEW LETTERS 131, 031801 (2023)

First Direct Observation of Collider Neutrinos with FASER at the LHC



η > 8.8
on-axis

full 2022 data sample

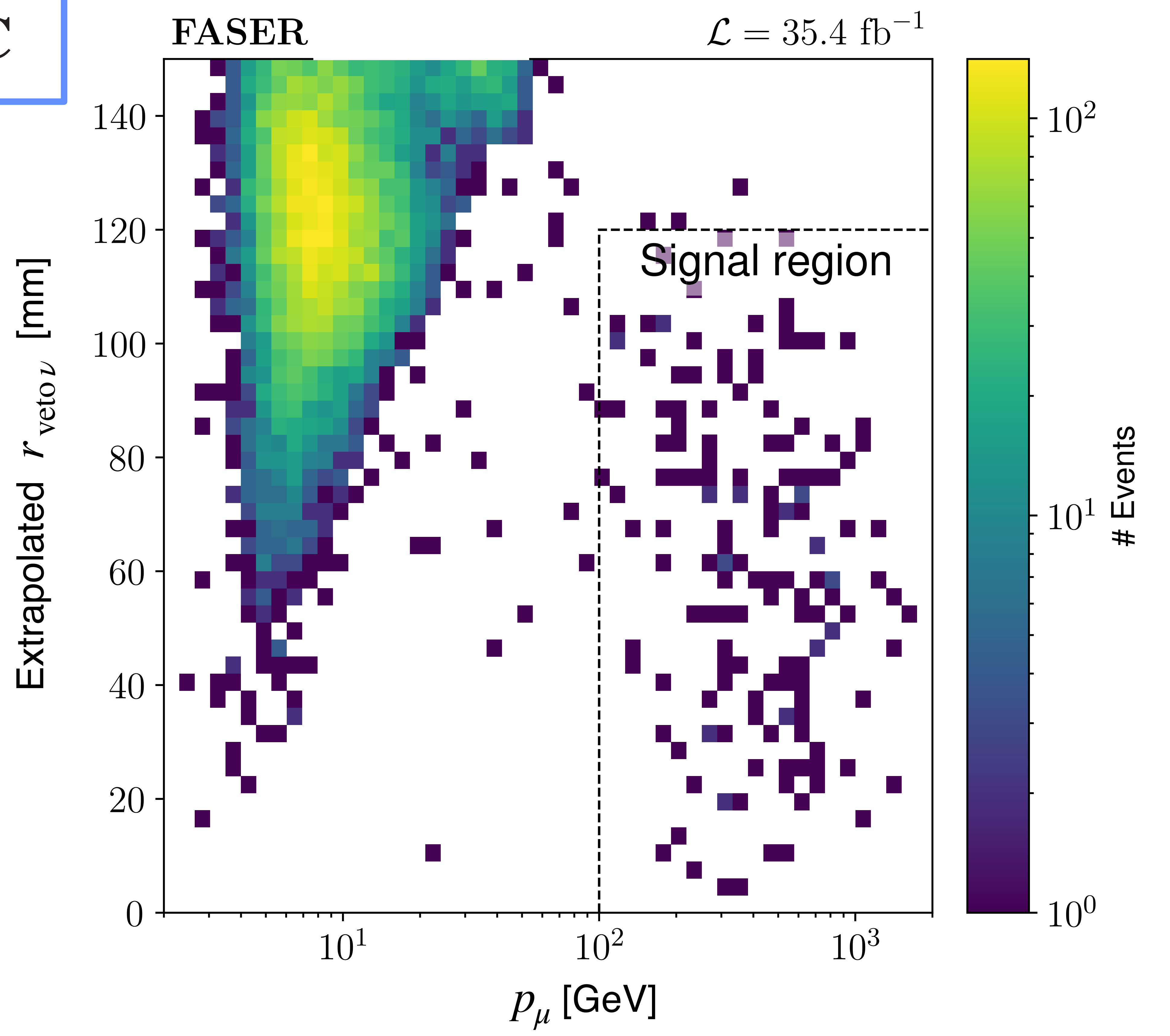


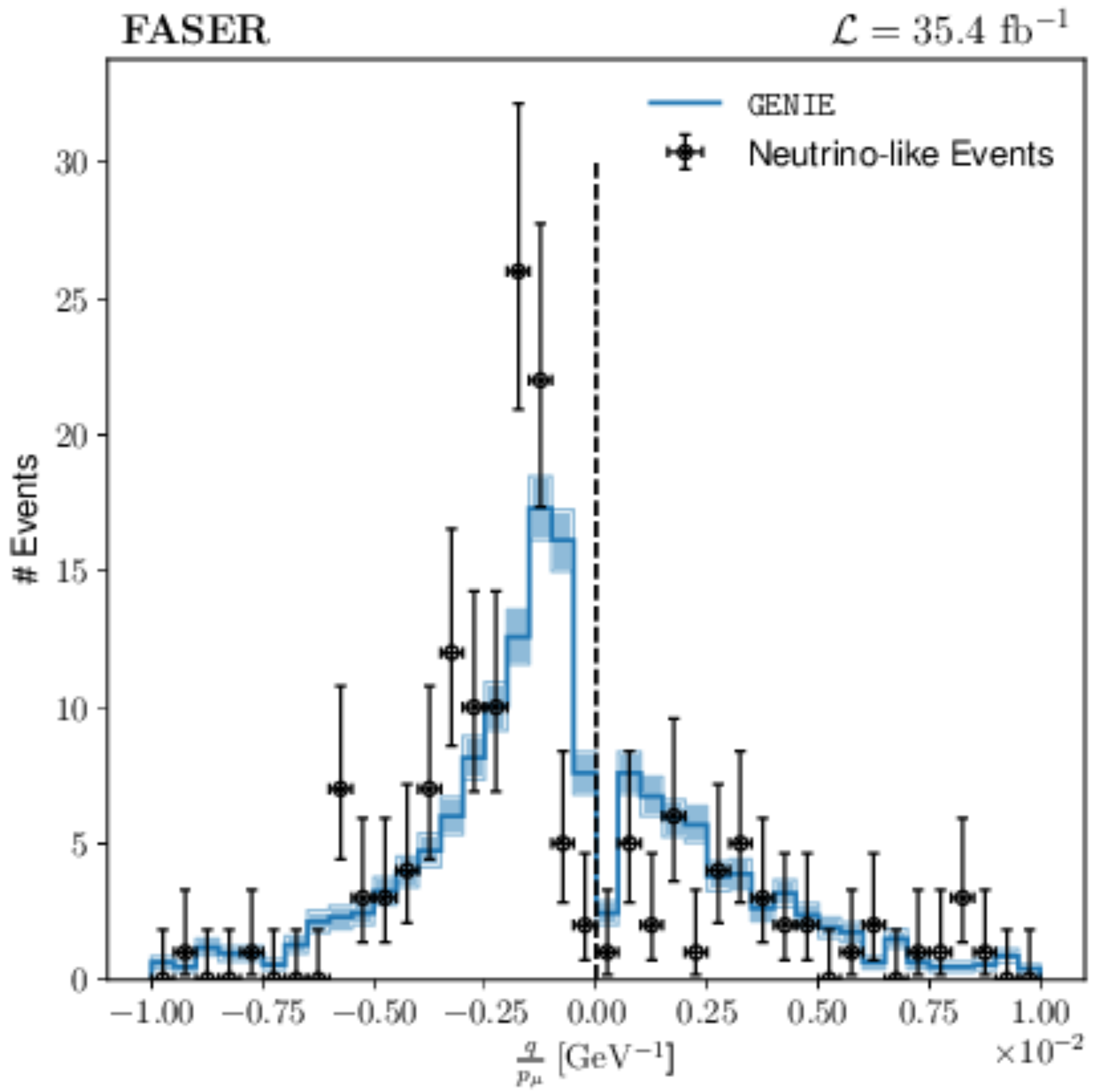
FIG. 2. The selected signal region in extrapolated radius $r_{\text{veto}\nu}$ and reconstructed track momentum p_μ is depicted. The region with lower momenta and larger radii is dominated by background events consisting of charged particles that miss the FASERν scintillator station.

selection: no signal in Veto, interaction in target, track in spectrometer with p>100 GeV

153 $^{+12}_{-13}$ muon neutrino interactions

16 standard deviations above the background-only hypothesis

neutrino, anti-neutrino separation in FASER



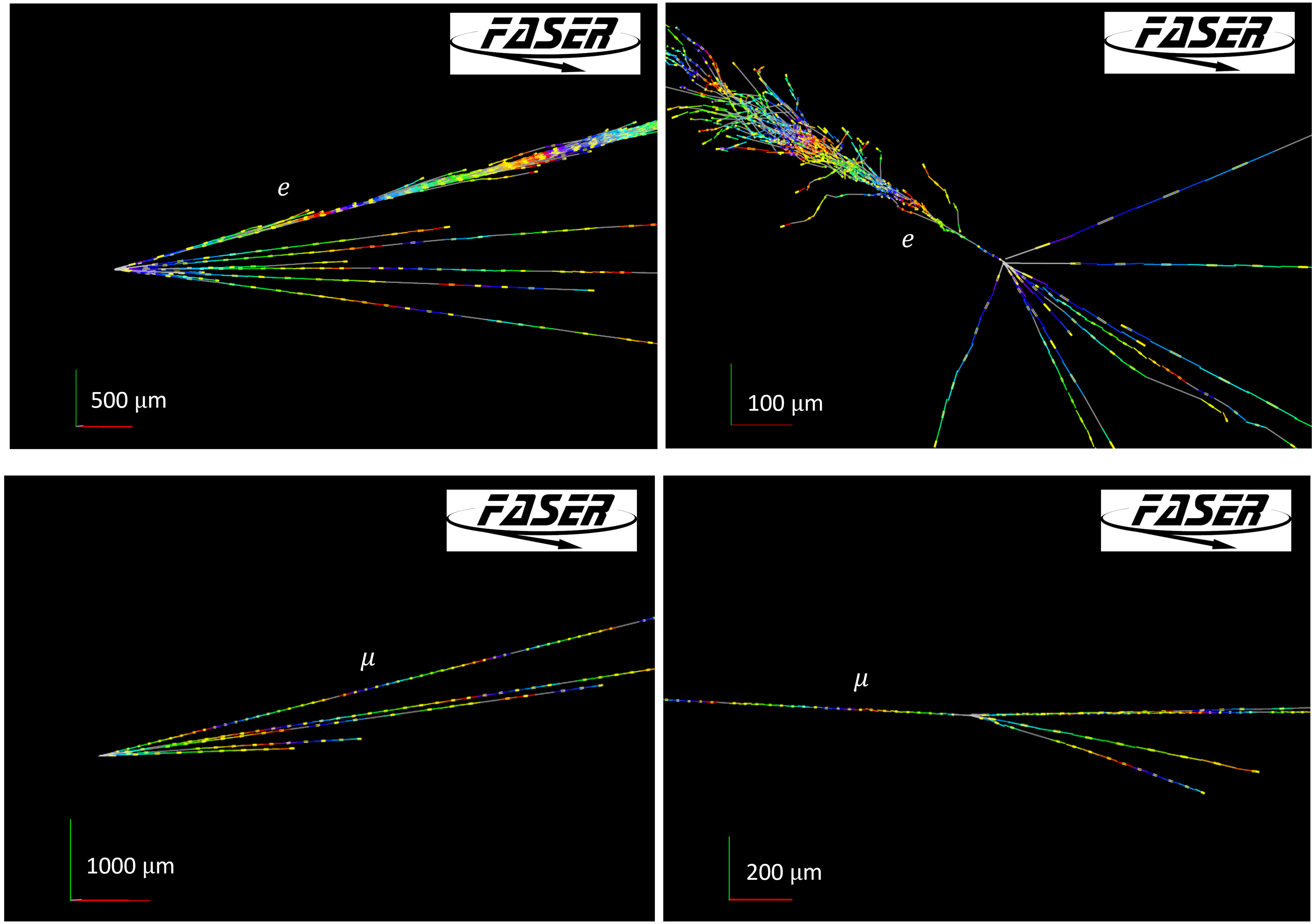
FASERν 2024

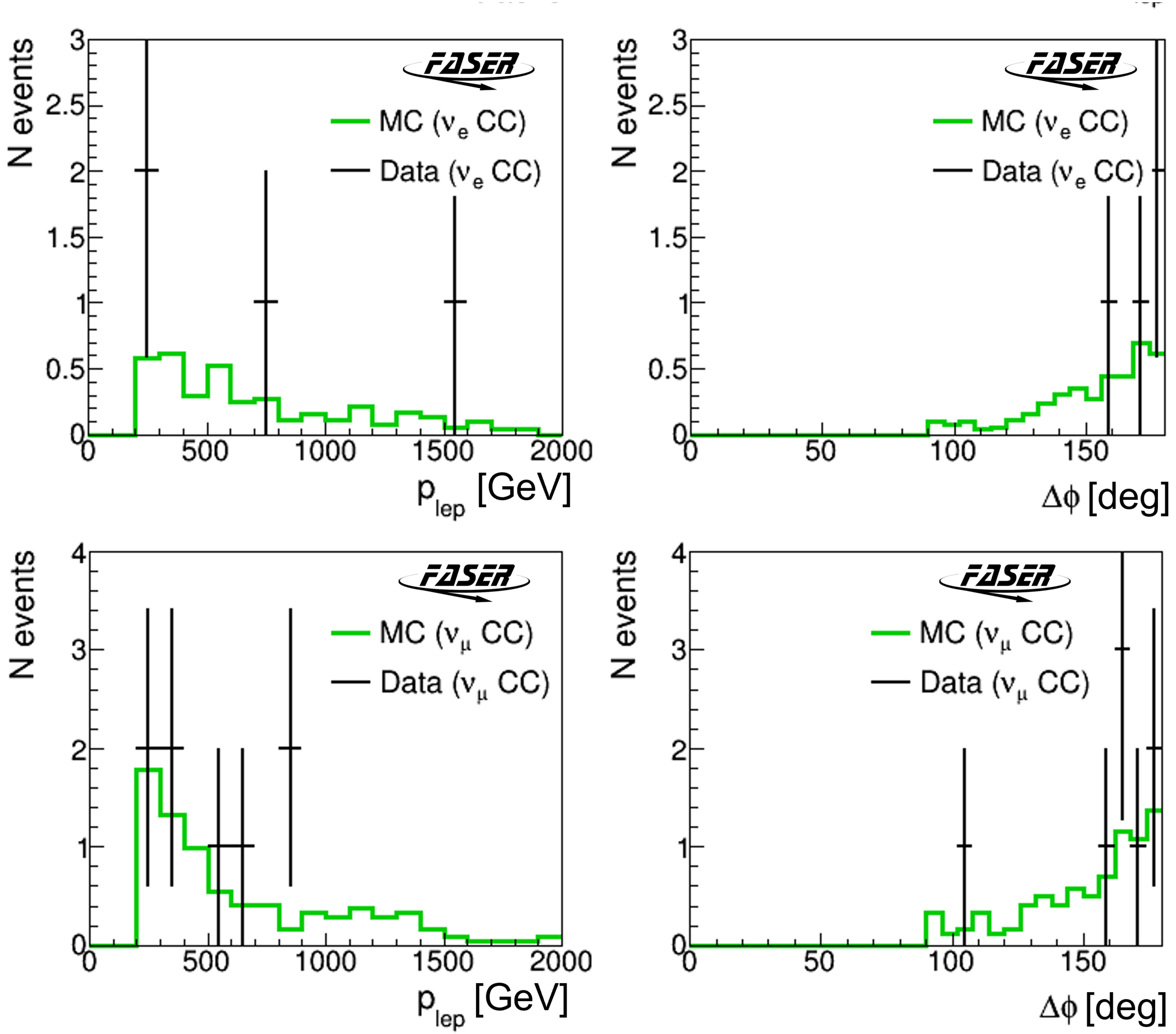
https://arxiv.org/pdf/2403.12520.pdf

rotated view | **beam view**

ν_e CC candidate

ν_μ CC candidate





Δϕ between
high-E charged lepton and
remaining particle system

First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector

	background	expected	observed	significance
ν_e CC	$0.025^{+0.015}_{-0.010}$	1.1-3.3	4	5.2 σ
ν_μ CC	$0.22^{+0.09}_{-0.07}$	6.5-12.4	8	5.7 σ

https://arxiv.org/pdf/2403.12520.pdf

results from 128.6 Kg of the target integrating 9.5 fb^{-1} in 2022

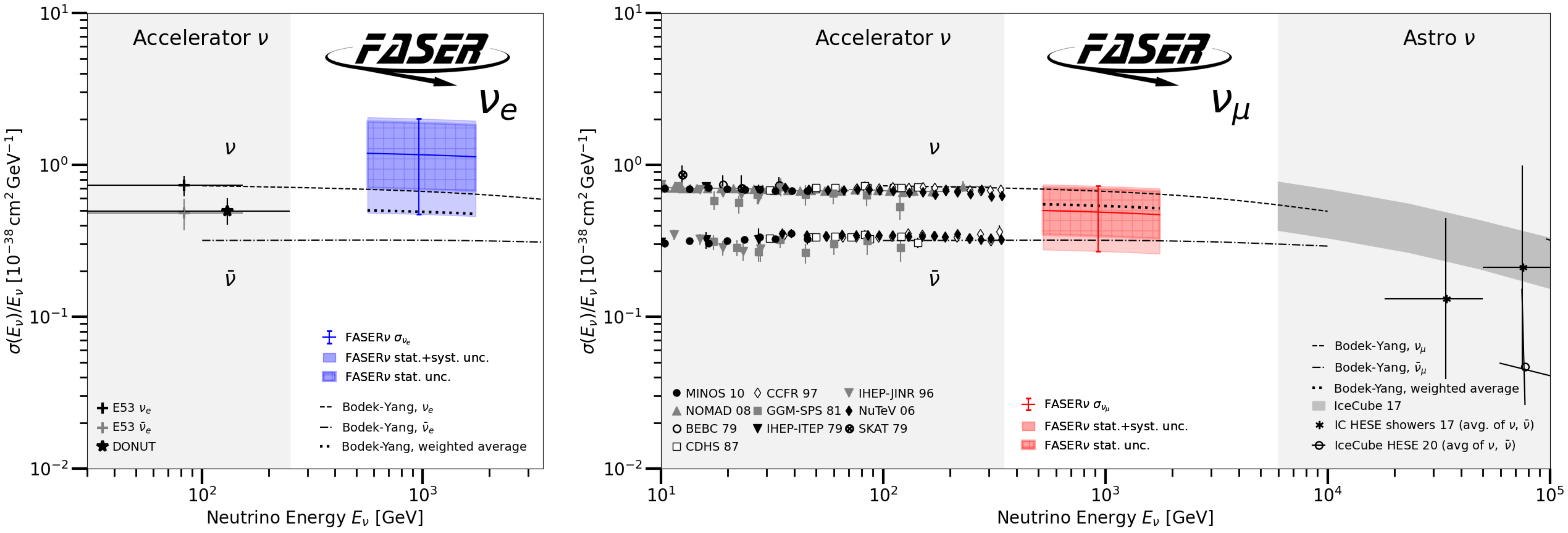


Figure 13: The measured cross section per nucleon for ν_e (left) and ν_μ (right). The dashed contours labelled "Bodek-Yang" are cross sections predicted by the Bodek-Yang model, as implemented in GENIE.

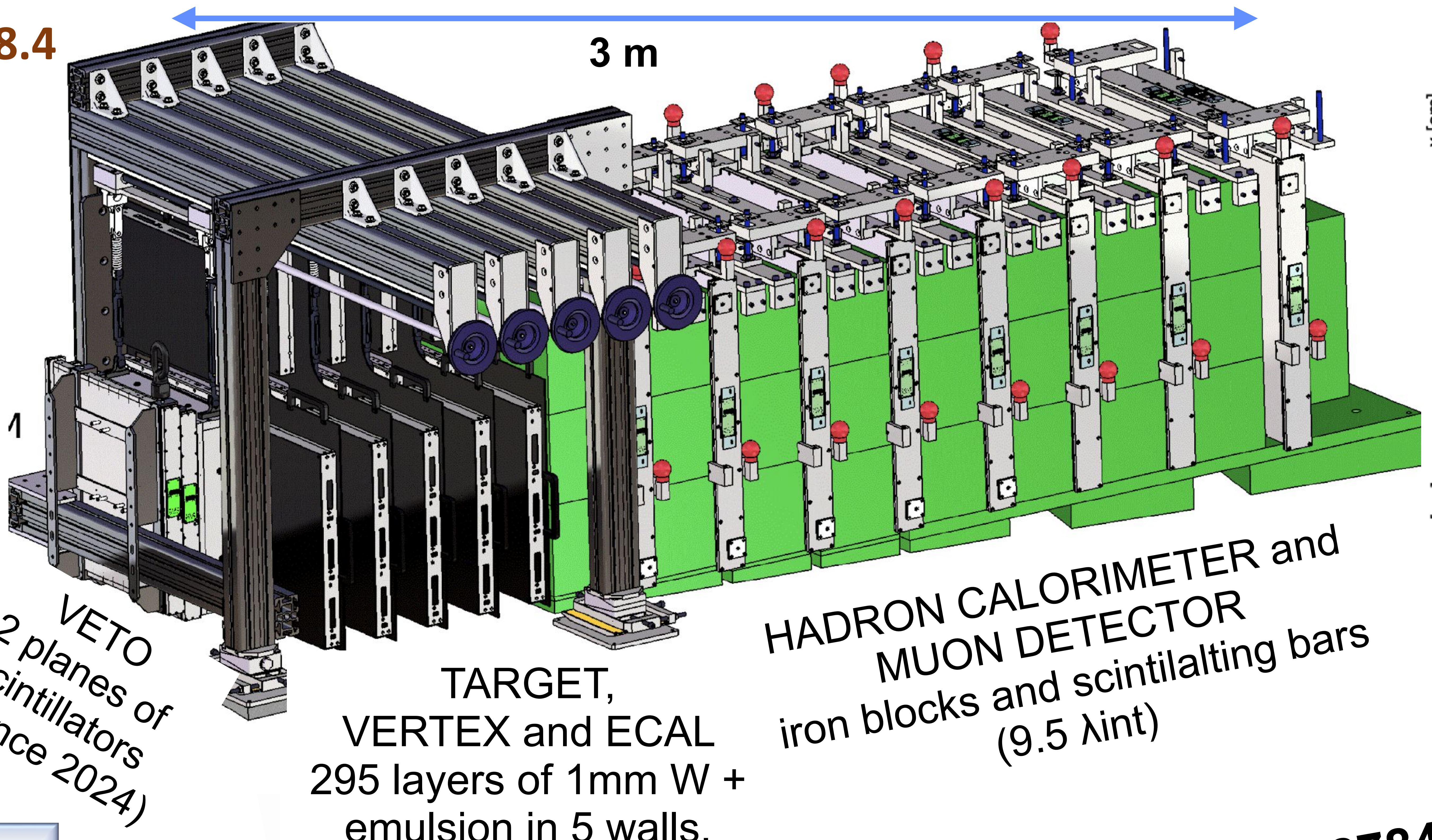
SND@LHC 2023

PHYSICAL REVIEW LETTERS **131**, 031802 (2023)

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

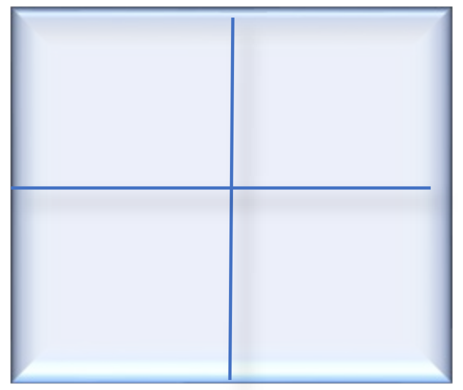
M.Dallavalle, SM@LHC, Rome, May 2024

7.2 < η < 8.4
off-axis



0.83 ton

https://arxiv.org/abs/2210.02784



● Beam collision axis

full 2022 data sample

very clean interactions in the inner fiducial volume of the target (signal acceptance 7.5%)

	background	observed	significance
ν_μ CC	$0.086^{+0.038}_{-0.038}$	8	6.8 σ

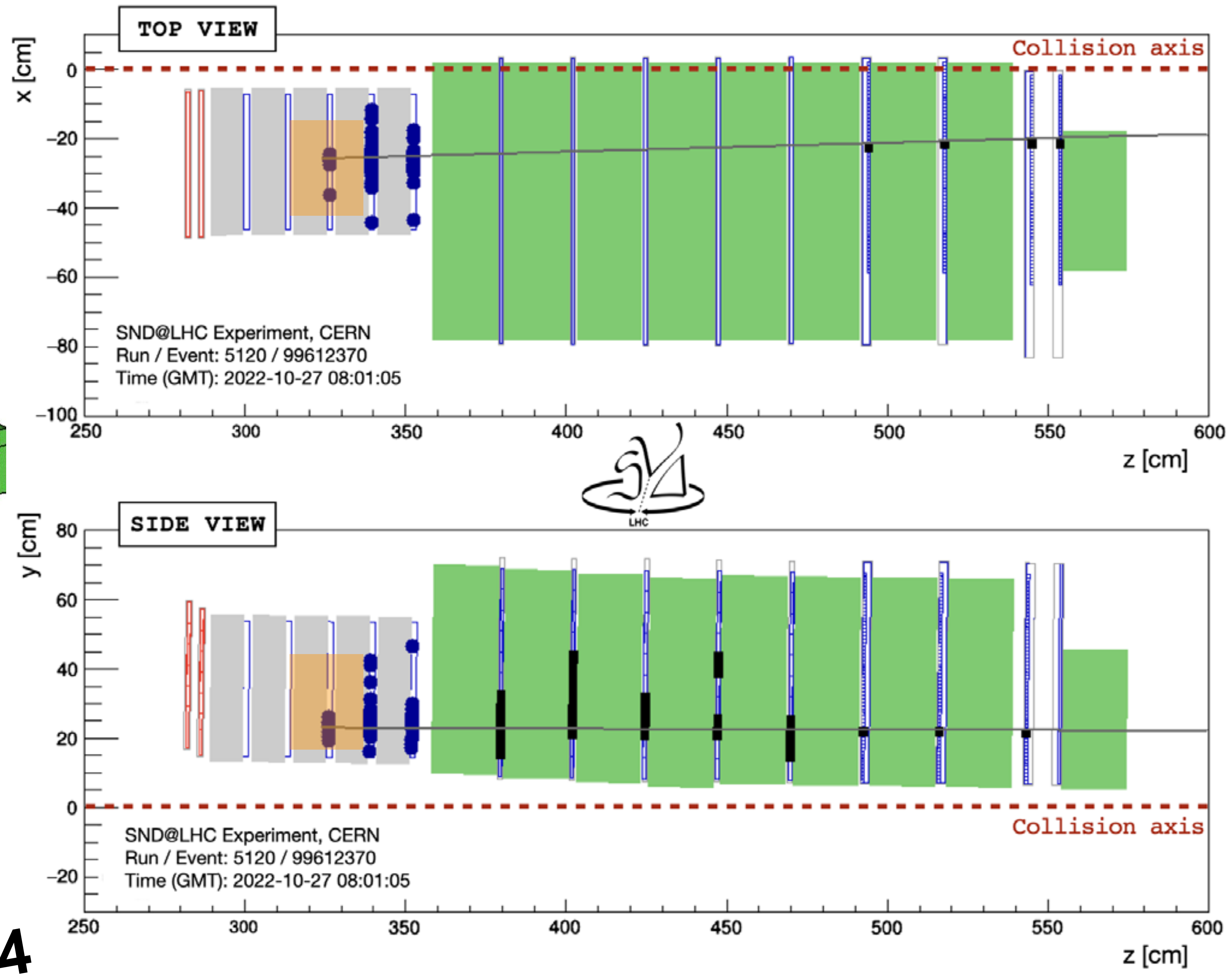


FIG. 2. Display of a ν_μ CC candidate event. Hits in the SciFi, and hadronic calorimeter and muon system are shown as blue markers and black bars, respectively, and the line represents the reconstructed muon track.

SND@LHC ν_μ analysis update 2024

	background	observed	significance
ν_μ CC	$0.25^{+0.06}_{-0.06}$	32	12 σ

(C.Vilela at the 58th Recontres de Moriond, QCD, April 2024)

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

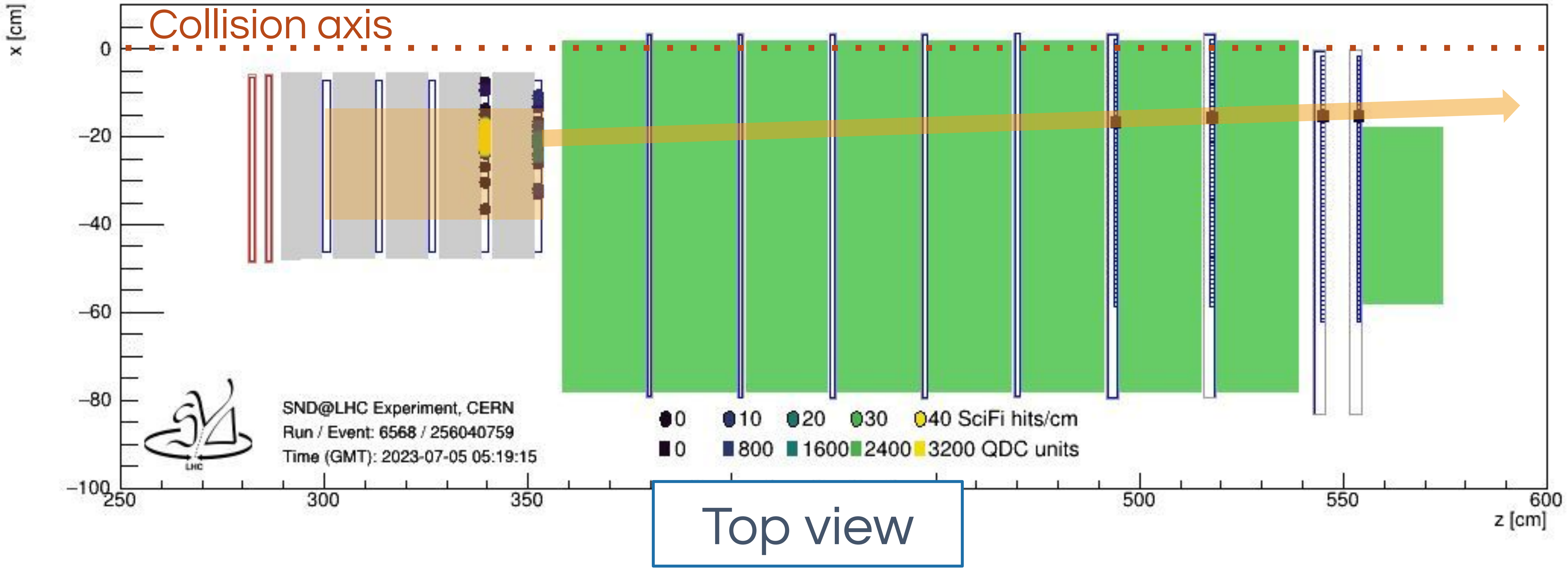
Event selection

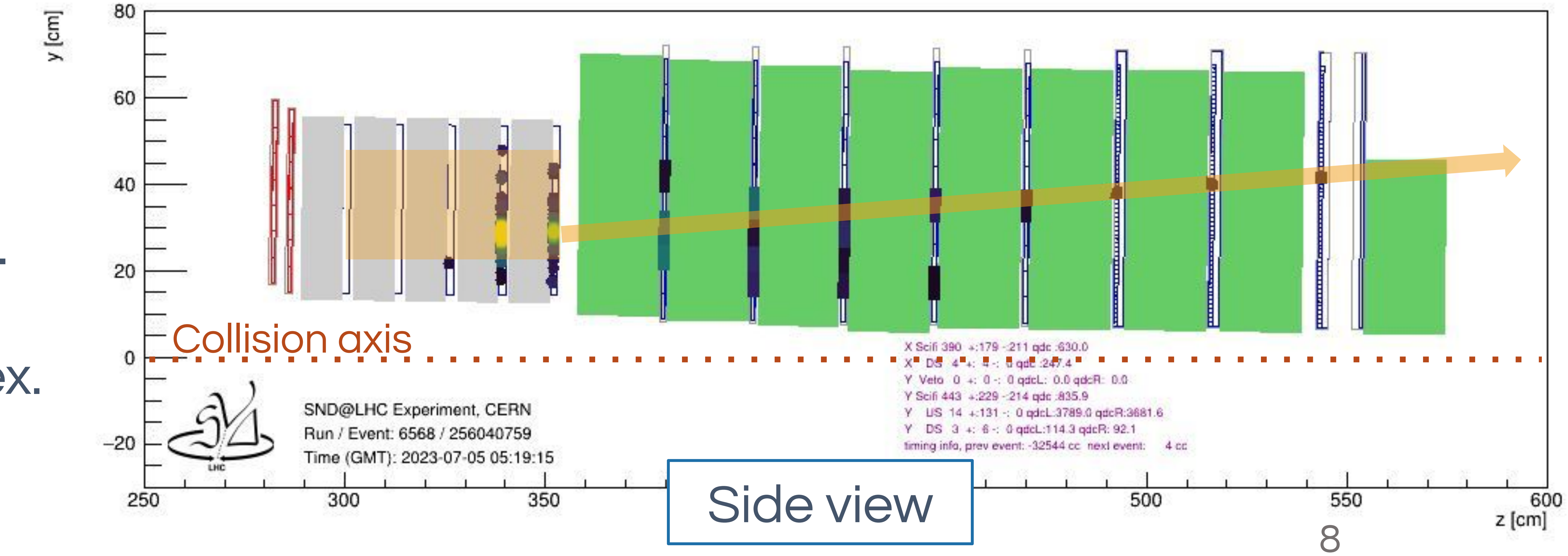
Fiducial volume

- Reject events in first wall.
  - Previously used only walls 3 and 4.
- Reject side-entering backgrounds.
- Signal acceptance: 18%
  - Up from 7.5%.

Muon neutrino identification

- Large scintillating fibre detector activity.
- Large HCal activity.
- One muon track associated to the vertex.
- Signal selection efficiency: 35%

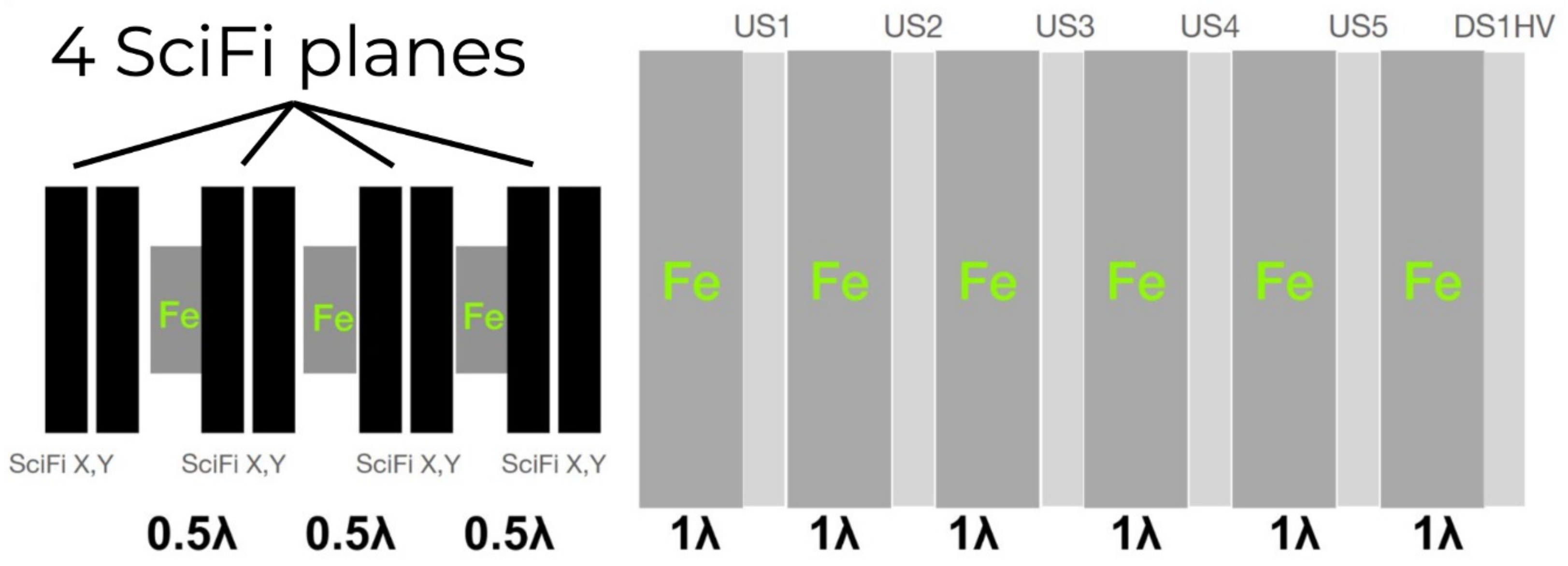




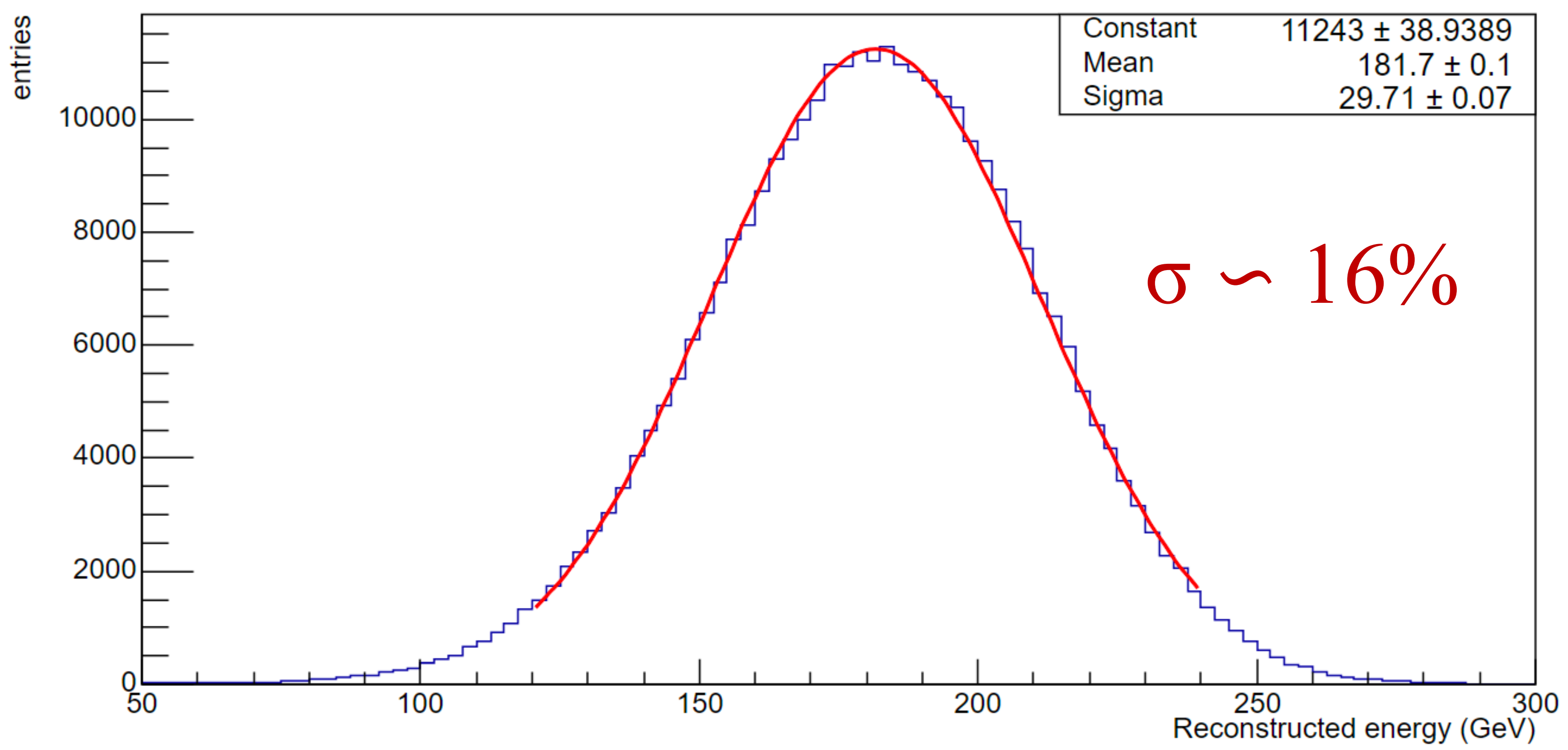
8

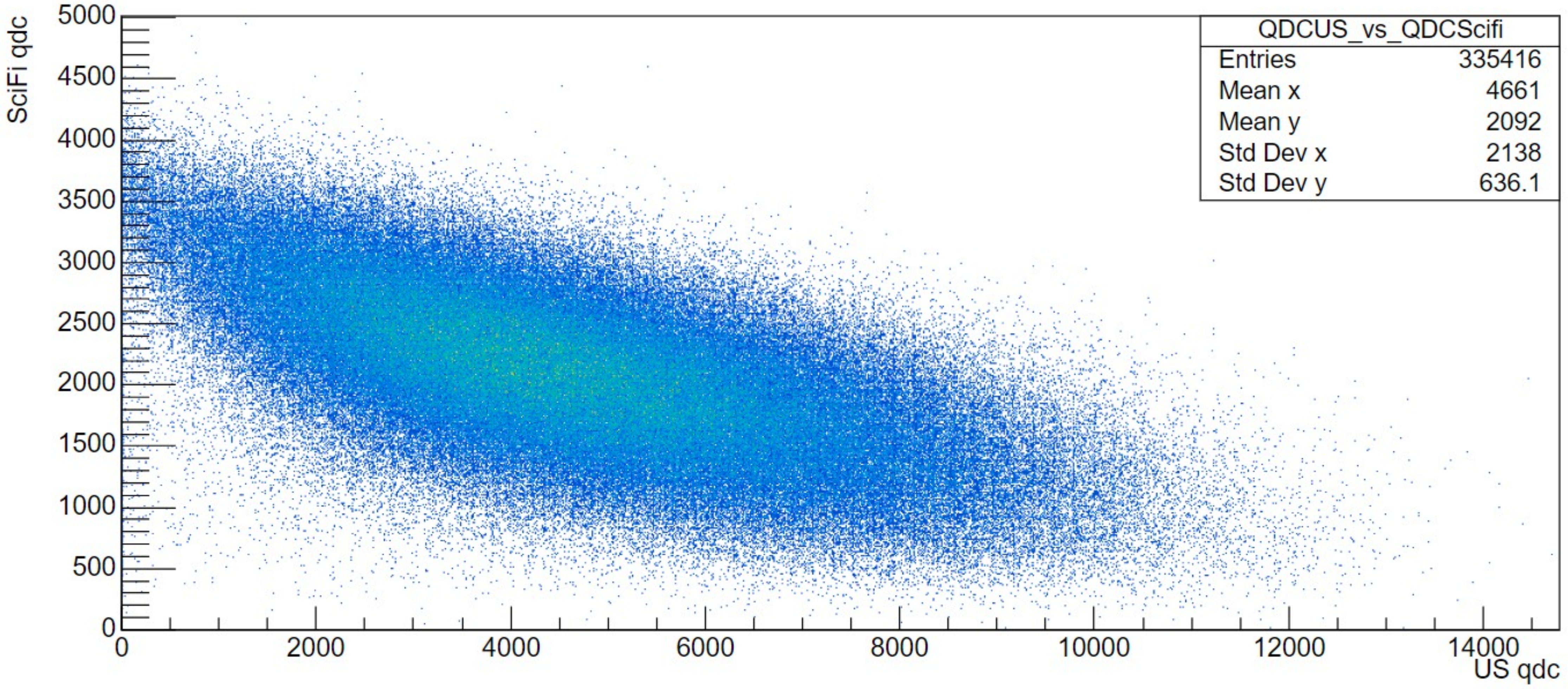
SND@LHC calibration of hadron energy measurement

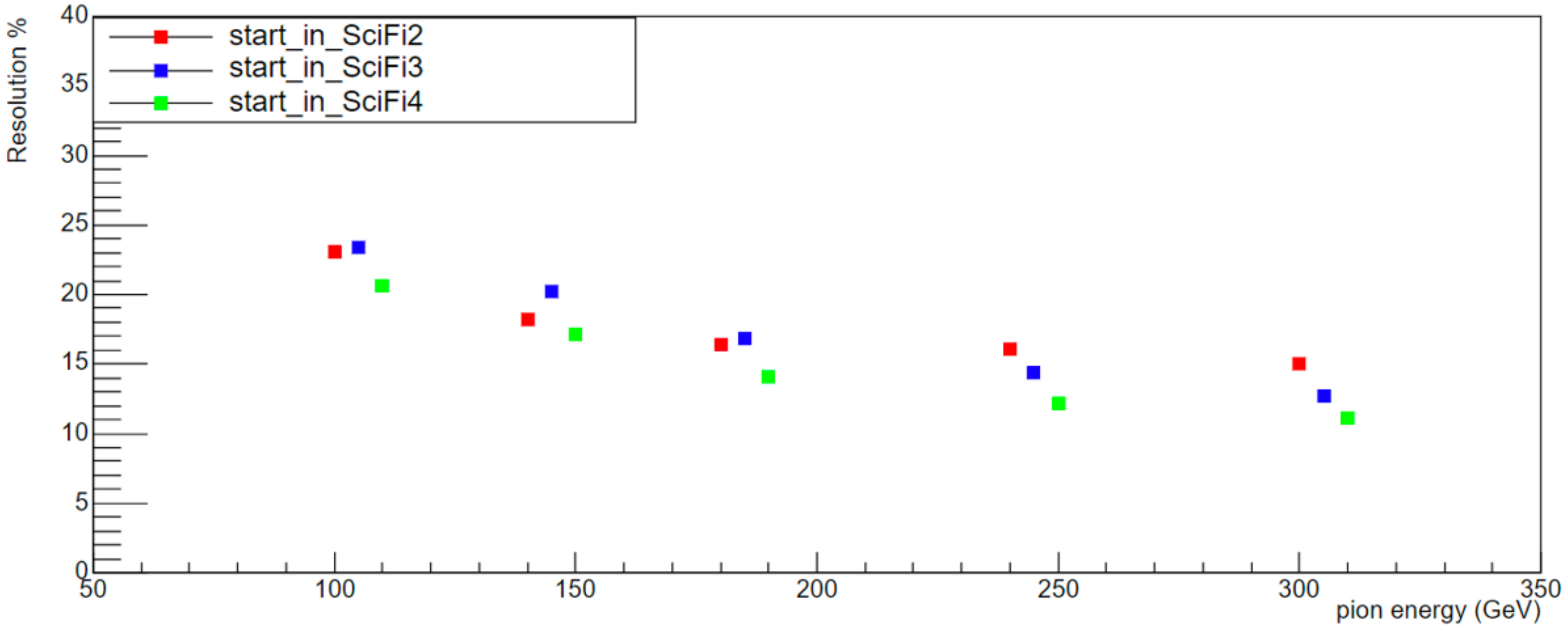
- in summer 2023 with hadron beams from SPS



Reconstructed energy for 180 GeV π

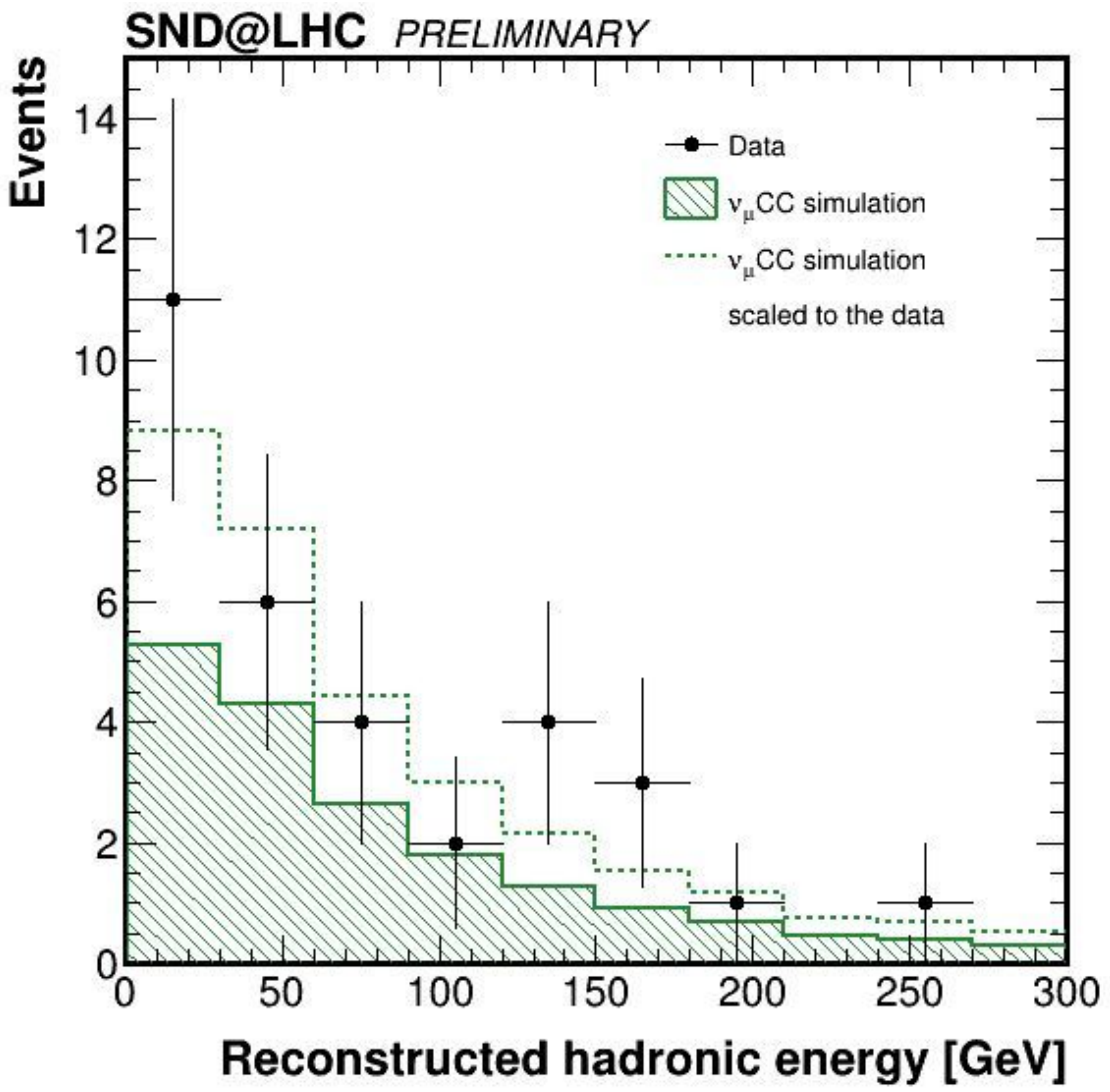


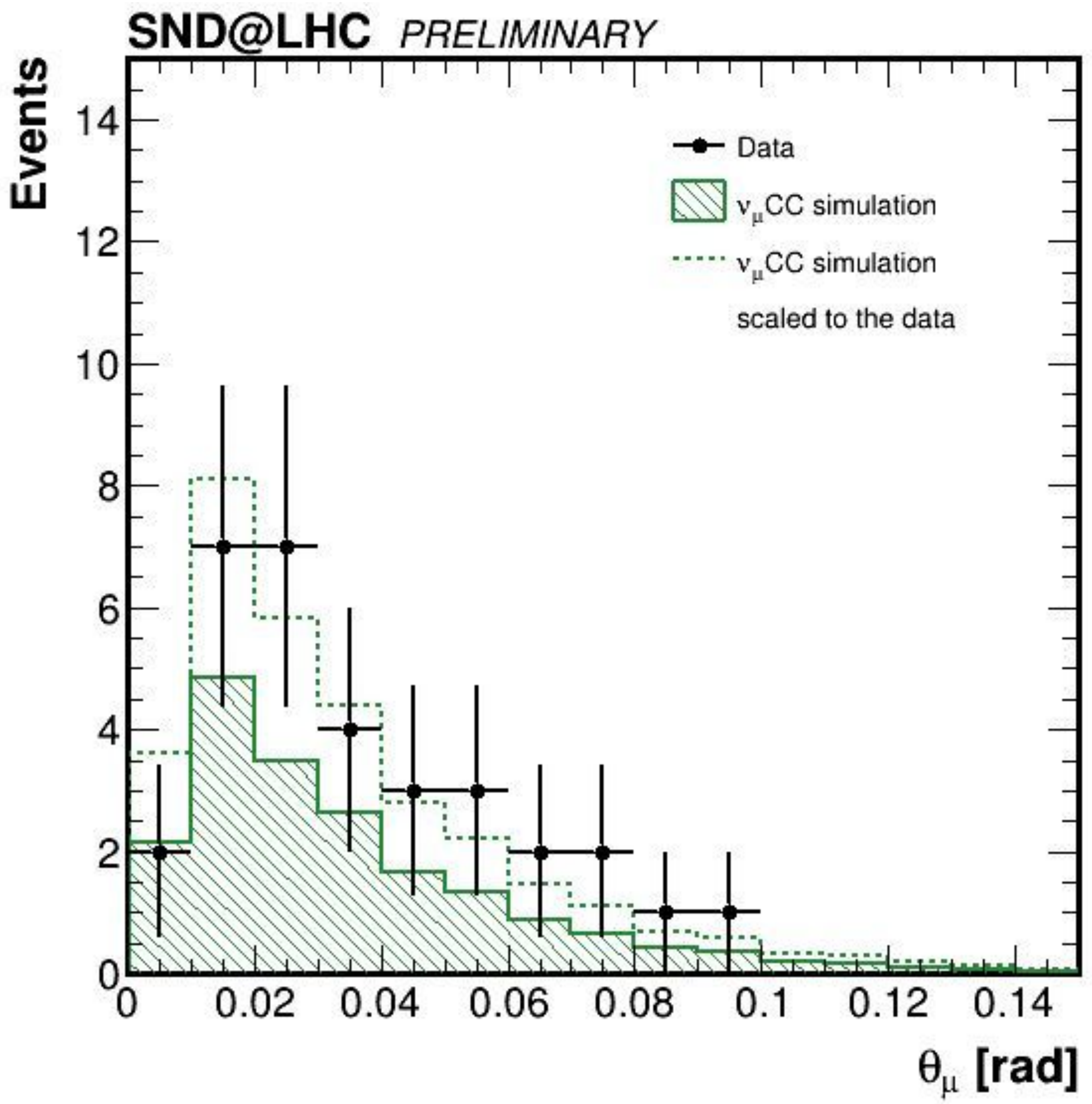




M.Dallavalle, SM@LHC, Rome, May 2024

SND@LHC new ν_μ results 2024

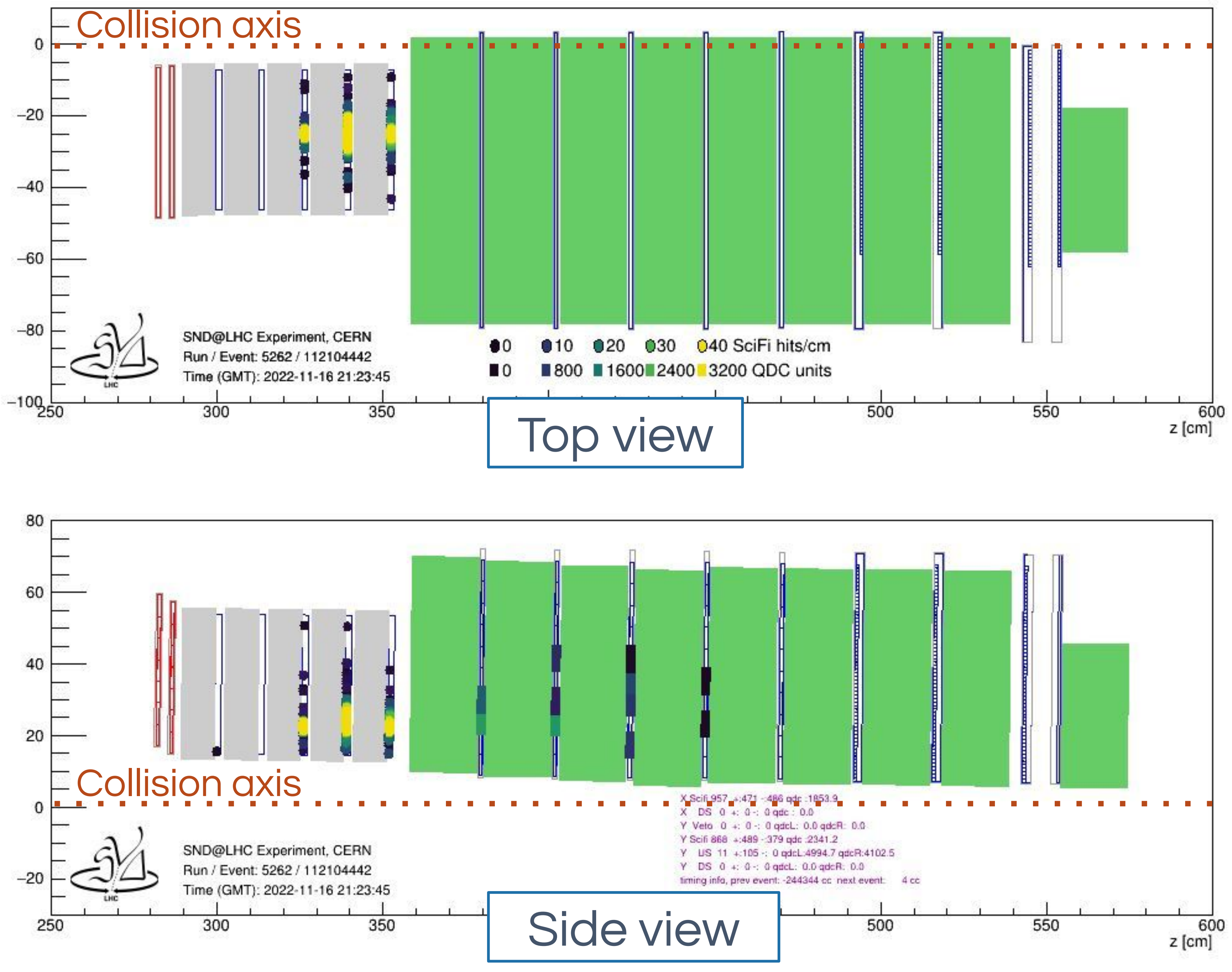


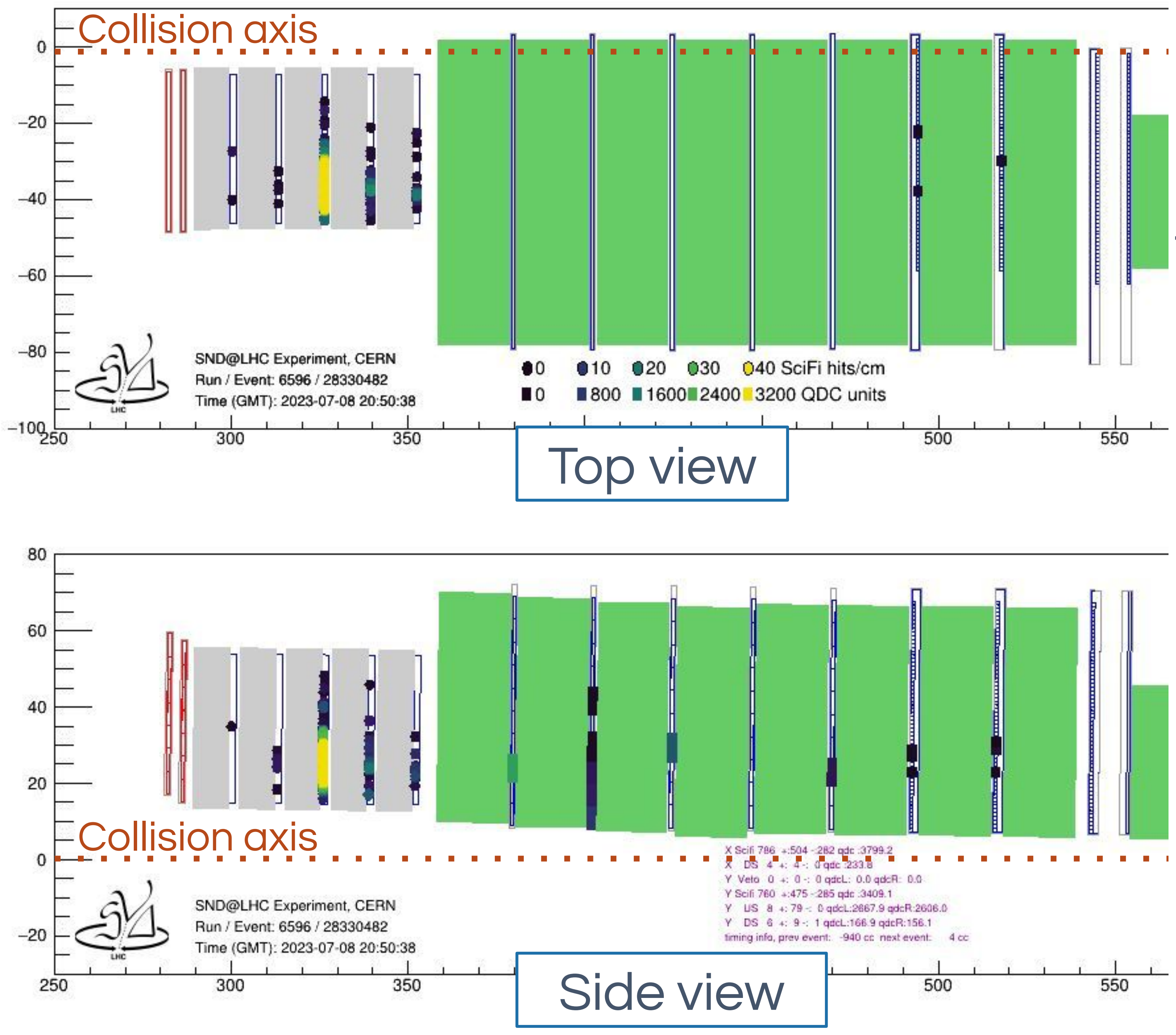


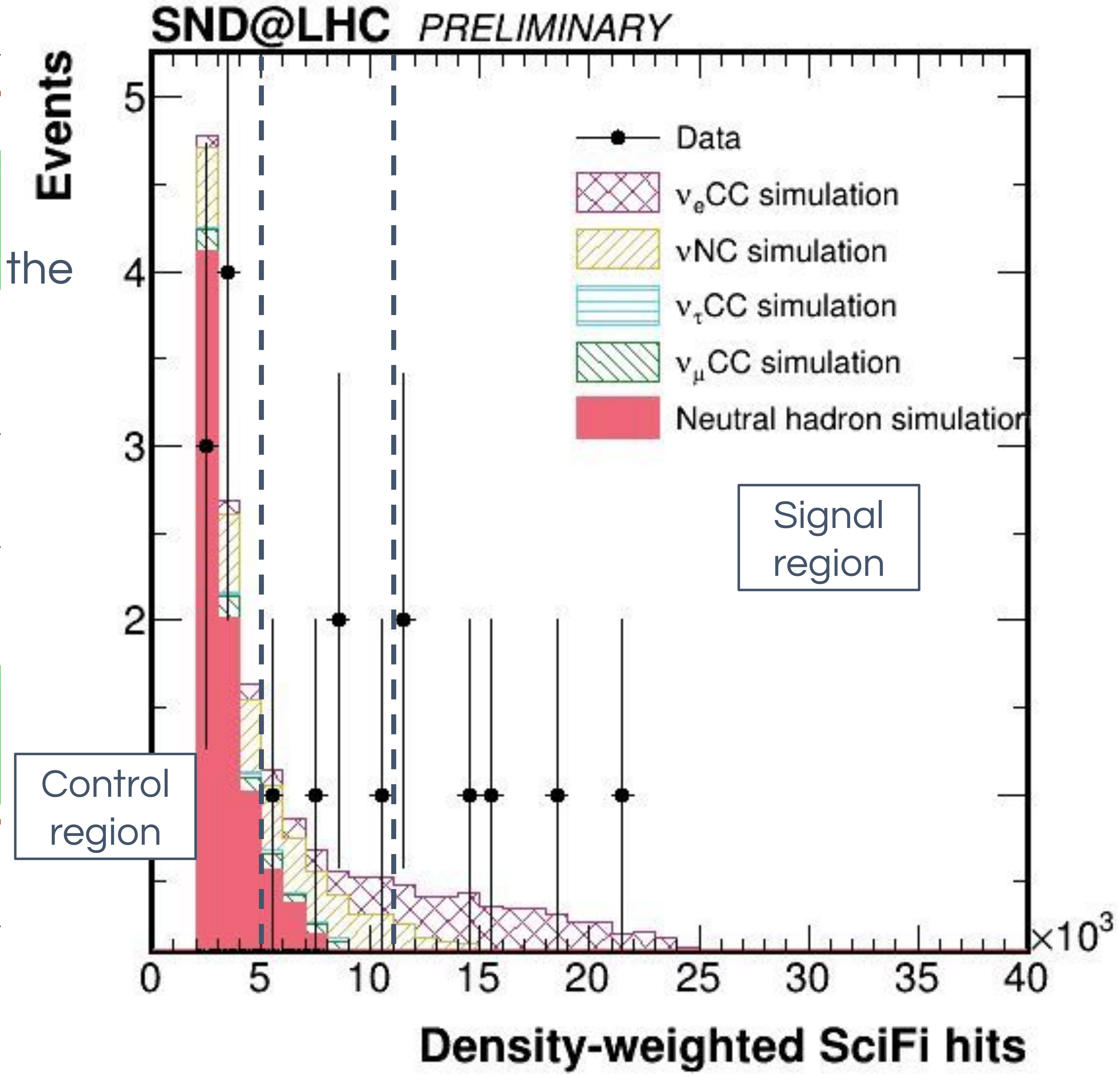
Next: determination of hadronic shower direction will allow for complete reconstruction of event kinematics and measurement of incoming neutrino energy

0μ events SND@LHC

ν_e CC interactions (+ ν_τ CC 0μ) and Neutral Currents







	background	observed	significance
0μ	$0.13^{+0.04}_{-0.04}$	6	5.8 σ

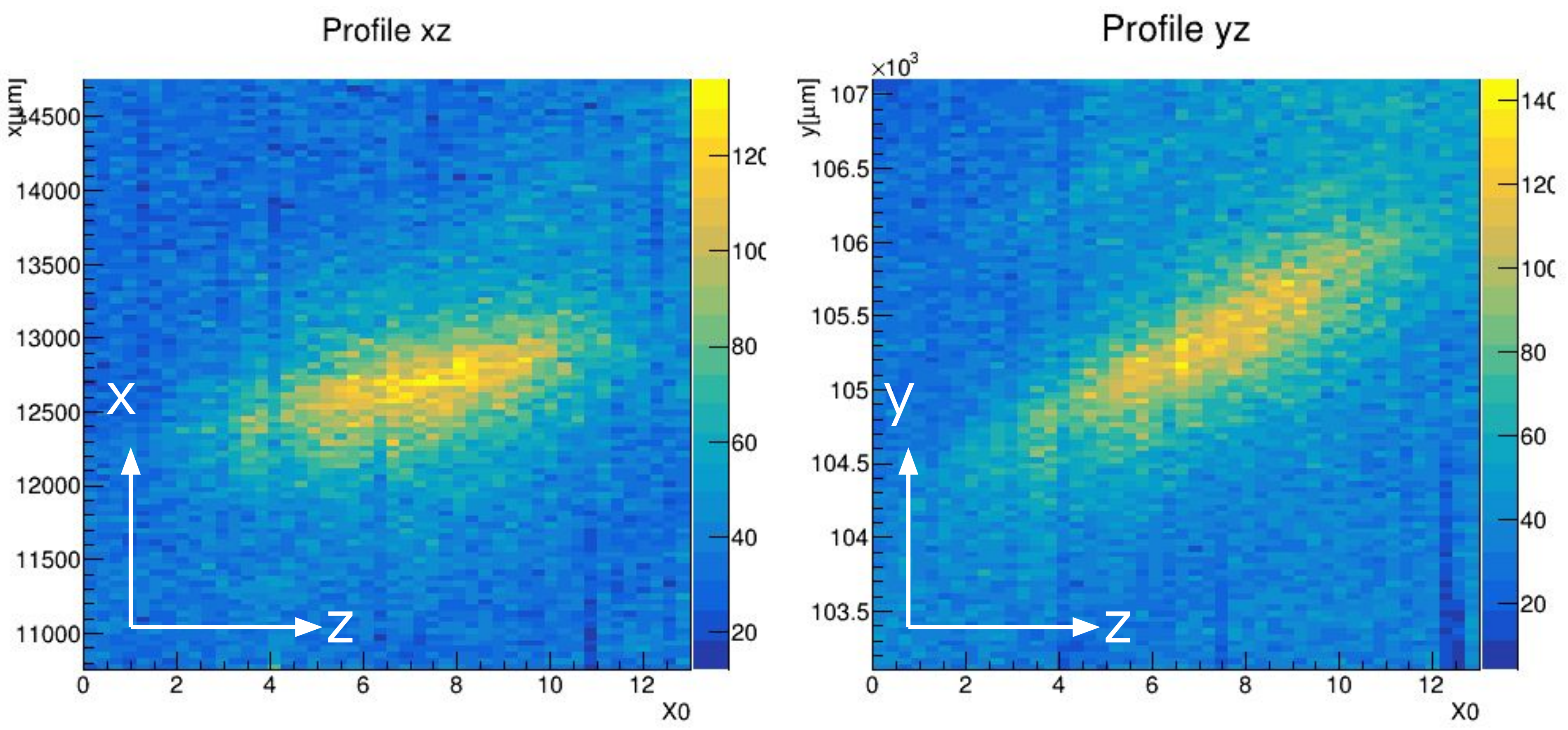
ν_e CC observation in emulsions

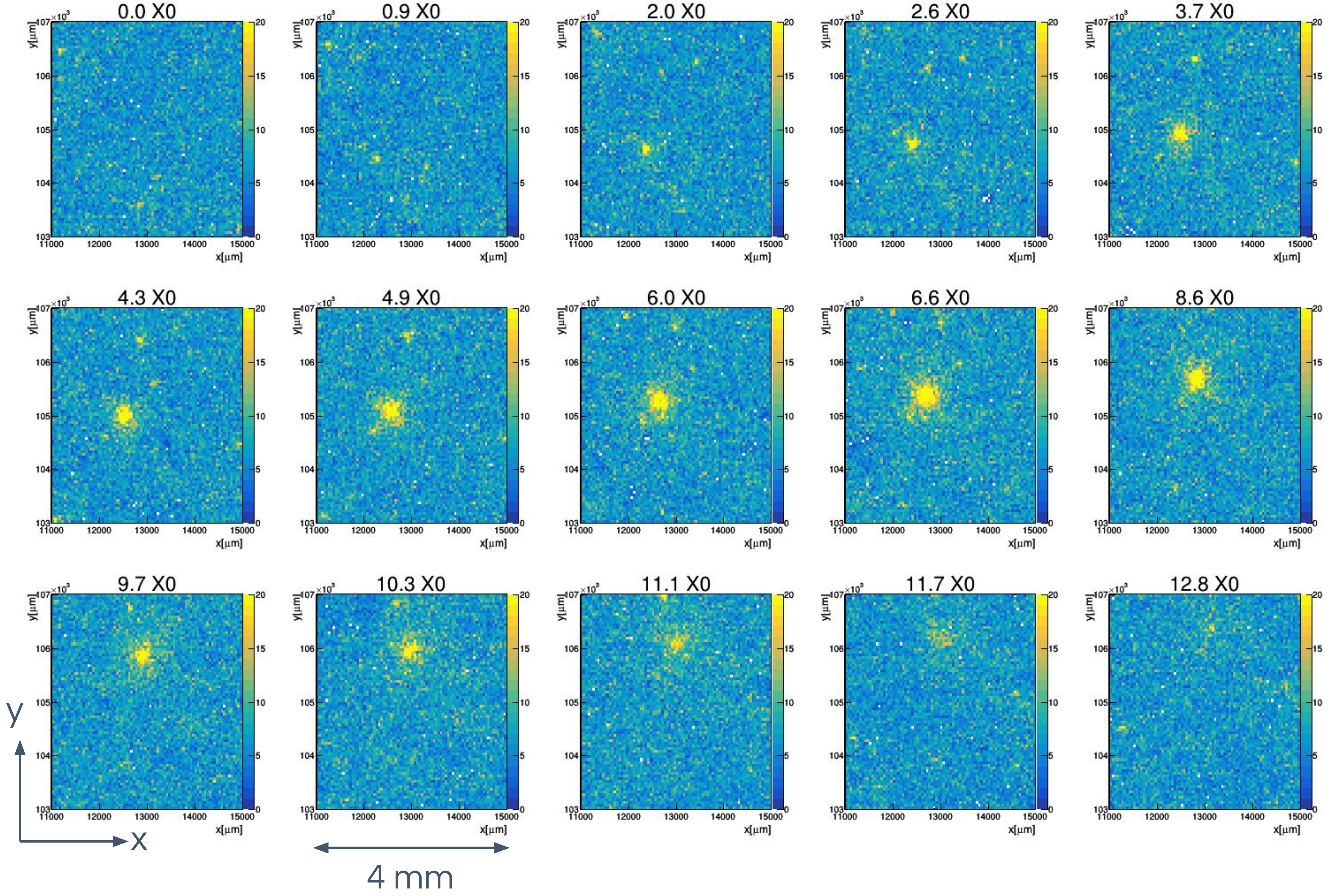
Strategy

- Identify regions of high track density in the emulsions.
- Consistent with the expectation of electromagnetic shower development.
- Search for neutral vertices associated to identified showers.

Status

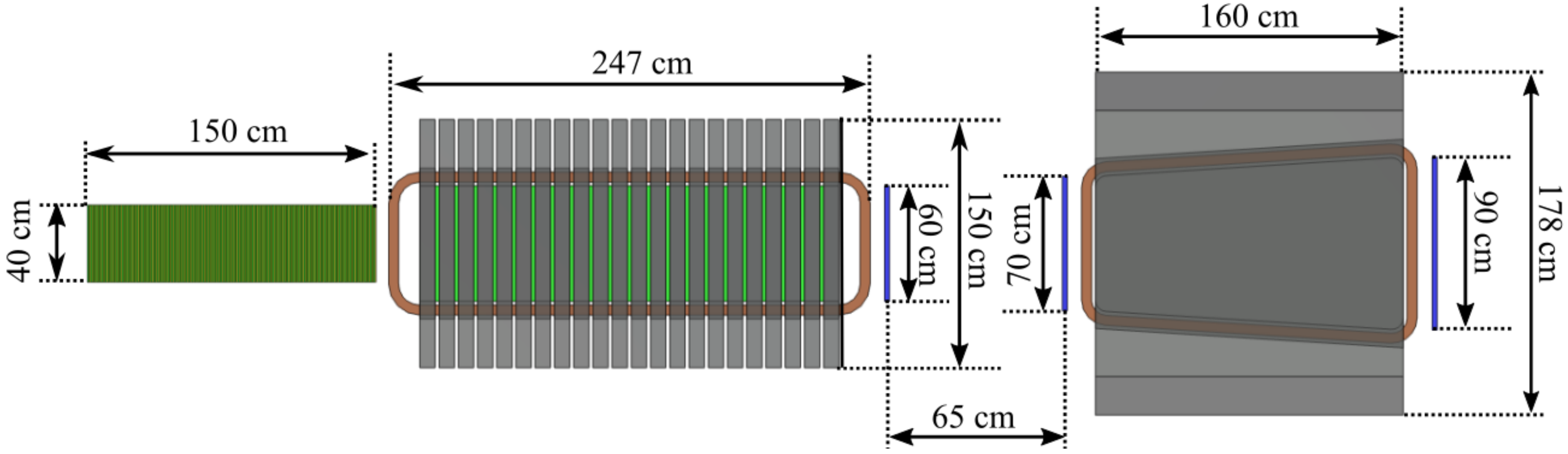
- Electromagnetic shower patterns identified.
- Vertex association ongoing.





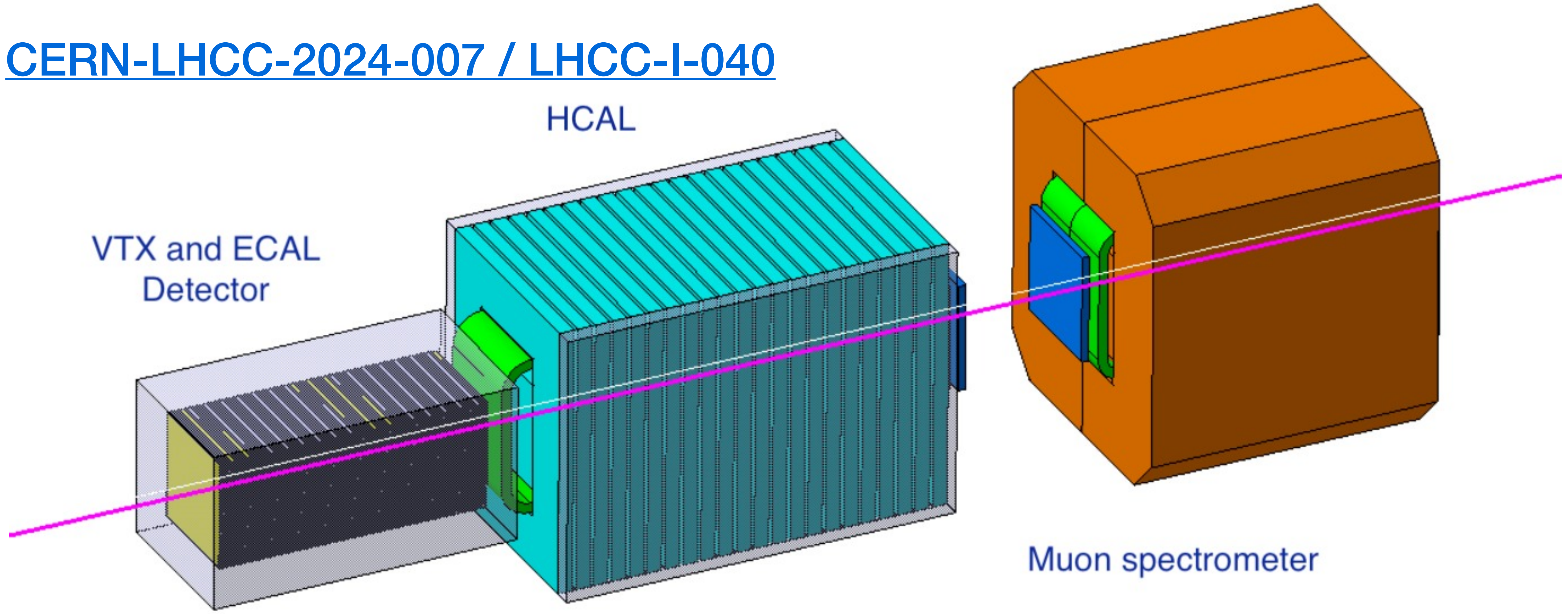
SND@LHC upgrade for LHC Run4 (AdvancedSND)

- sligthy closer to the collision axis $\eta > 7.9$
- a new target of 2 tons with up to 120 layers of tungsten and silicon detectors to replace emulsions
- tenfold increase in statistics
- improved spectrometer capabilities, to separate neutrino and anti-neutrino CC interactions
- possibility of triggering the ATLAS event read-out when a neutrino is tagged in AdvSND



AdvSND Letter of Intent:

CERN-LHCC-2024-007 / LHCC-I-040



CONCLUSIONS

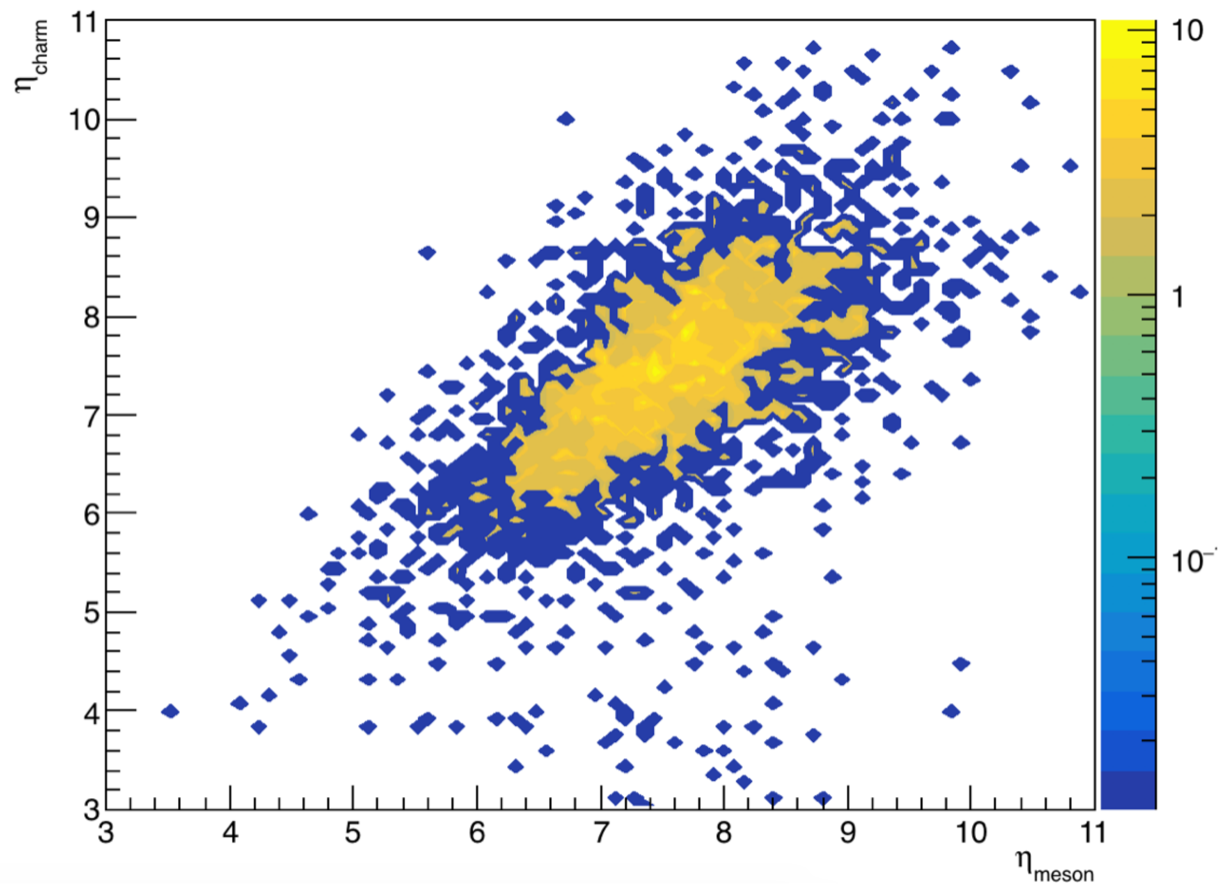
- Since 2022 two experiments study very forward ν_e , ν_μ , ν_τ from LHC collisions (pp—>νX):
  - SND@LHC in *7.2 < η < 8.4*, FASER in *η > 8.8*
  - those neutrinos expand the Physics reach of LHC:
    - carry information on parton fractional momenta down to 10^{-6} and can contrain QCD uncertainties
    - allow for studying νN interactions for all three flavors at energies in the E_ν TeV range
- the experiments already collected 70 fb^{-1} in 2022-23 and will collect 250 fb^{-1} by the end of LHC Run3
- First measurements are coming out:
  - both experiments neatly detected ν_μ and ν_e events over a negligible background
  - FASER has performed a first measurement of ν_μN and ν_eN CC interaction cross sections
- the experiments plan to continue data taking also in HL-LHC

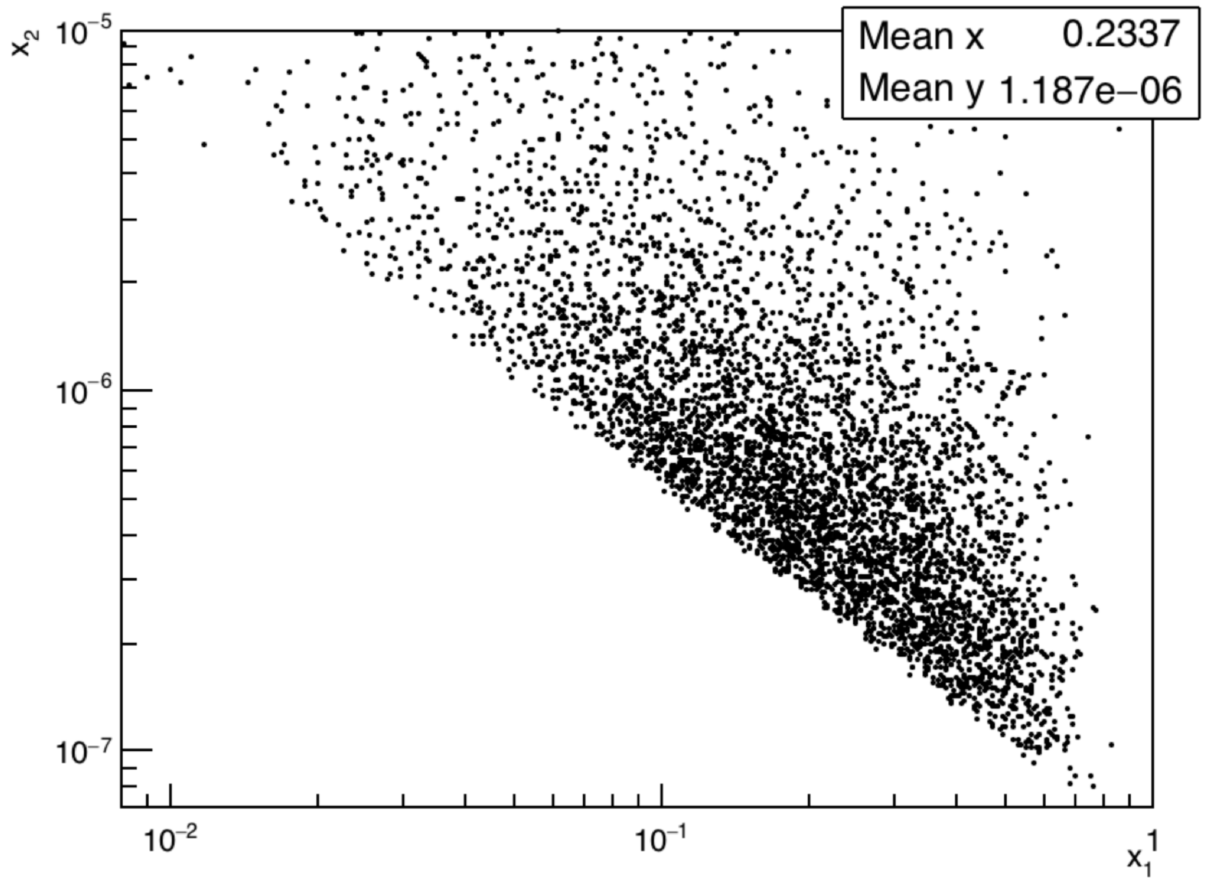
additional material

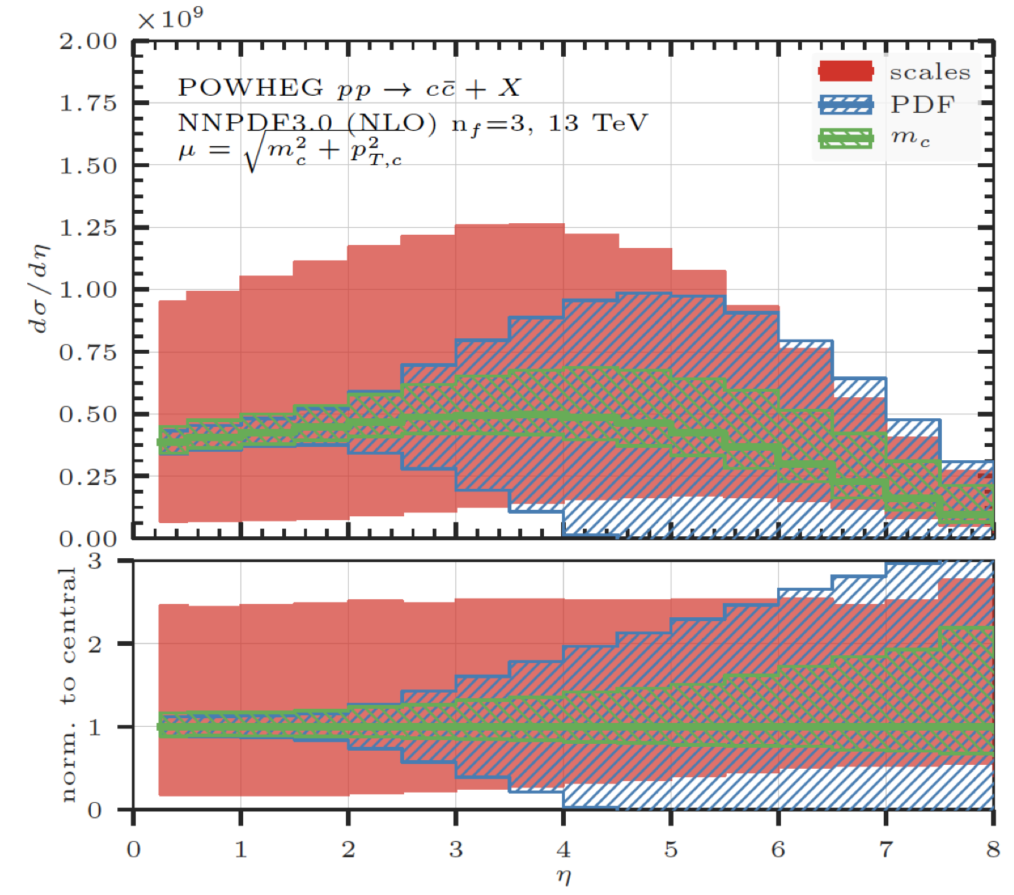
Neutrino physics: QCD

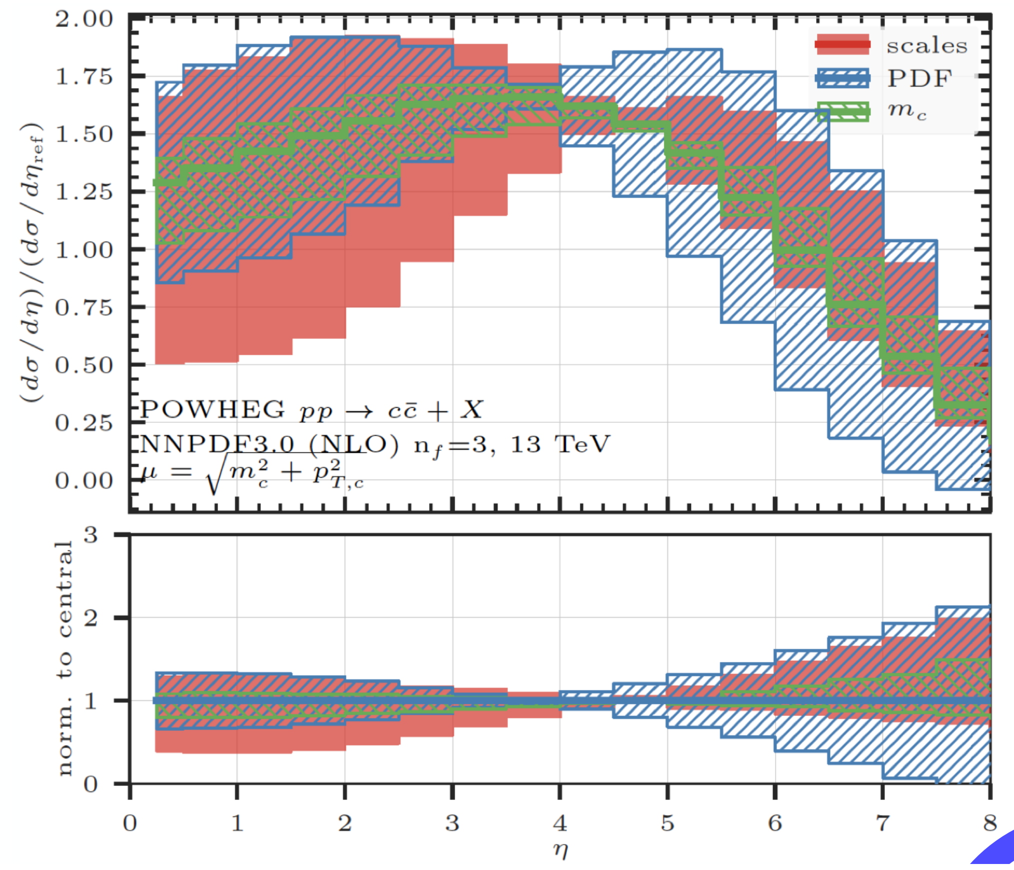
[LHCC-P-016] [M. V. Garzelli,SND@LHC open session 16/06/2022]

- measurement of the charmed hadrons can be translated into measurement of the corresponding open charm production
  - angular correlation between charmed hadron and parent charm
- charm production at LHC dominated by gluon-gluon scattering
- average lowest momentum fraction accessible at SND@LHC $\sim 10^{-6}$
  - here, gluon PDF completely unknown, theory work ongoing on resummation
- constrain PDF with SND@LHC data
  - taking ratio of cross-sections at different energies/rapidities reduces scale uncertainty [JHEP 11 (2015) 009]
  - use LHCb measurement in $\eta < 4.5$, $\sqrt{s} = 7, 13$ TeVs [Nucl. Phys. B871 (2013) 1-20] [JHEP 03 (2016) 159]





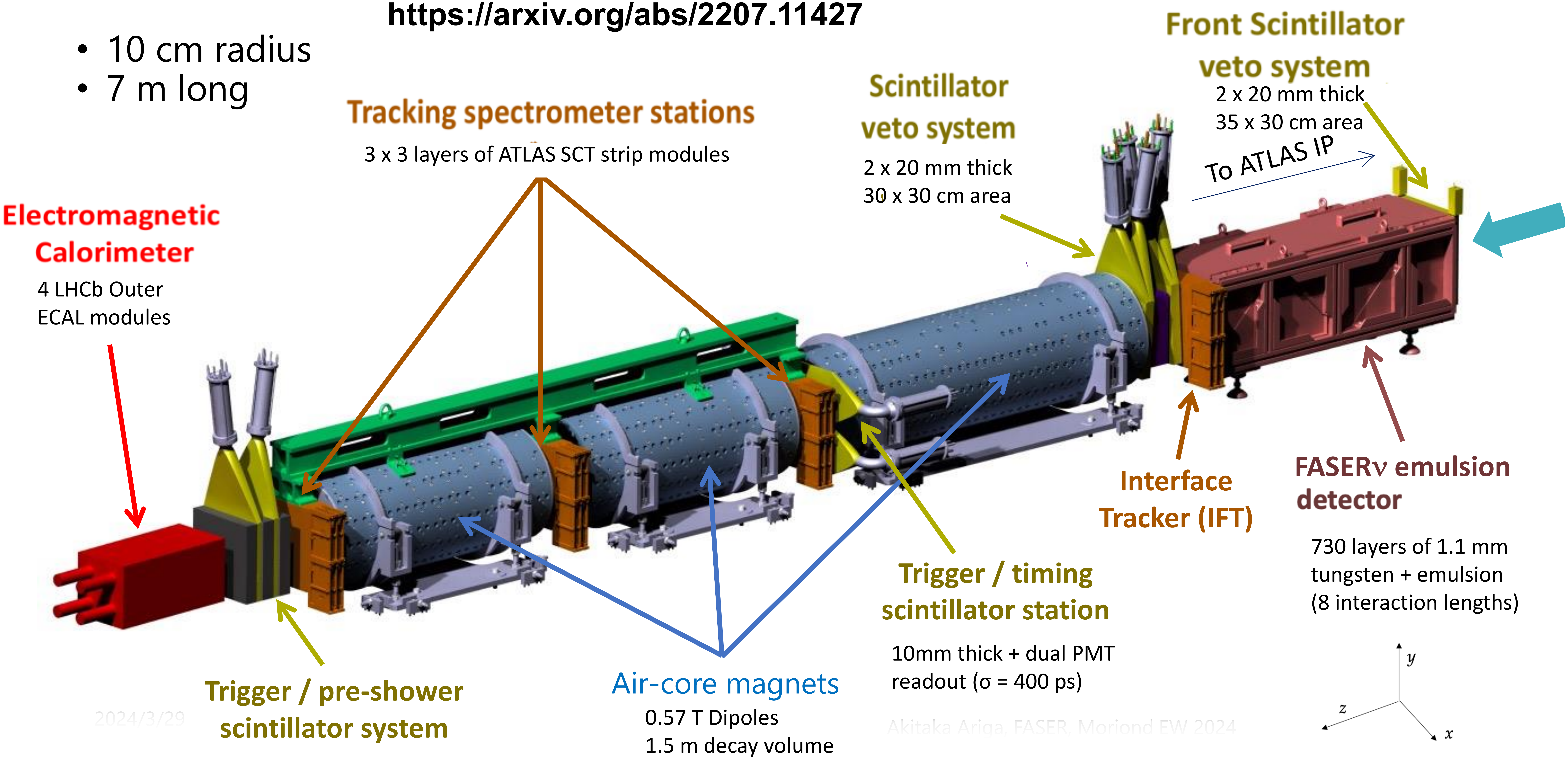




FASER detector

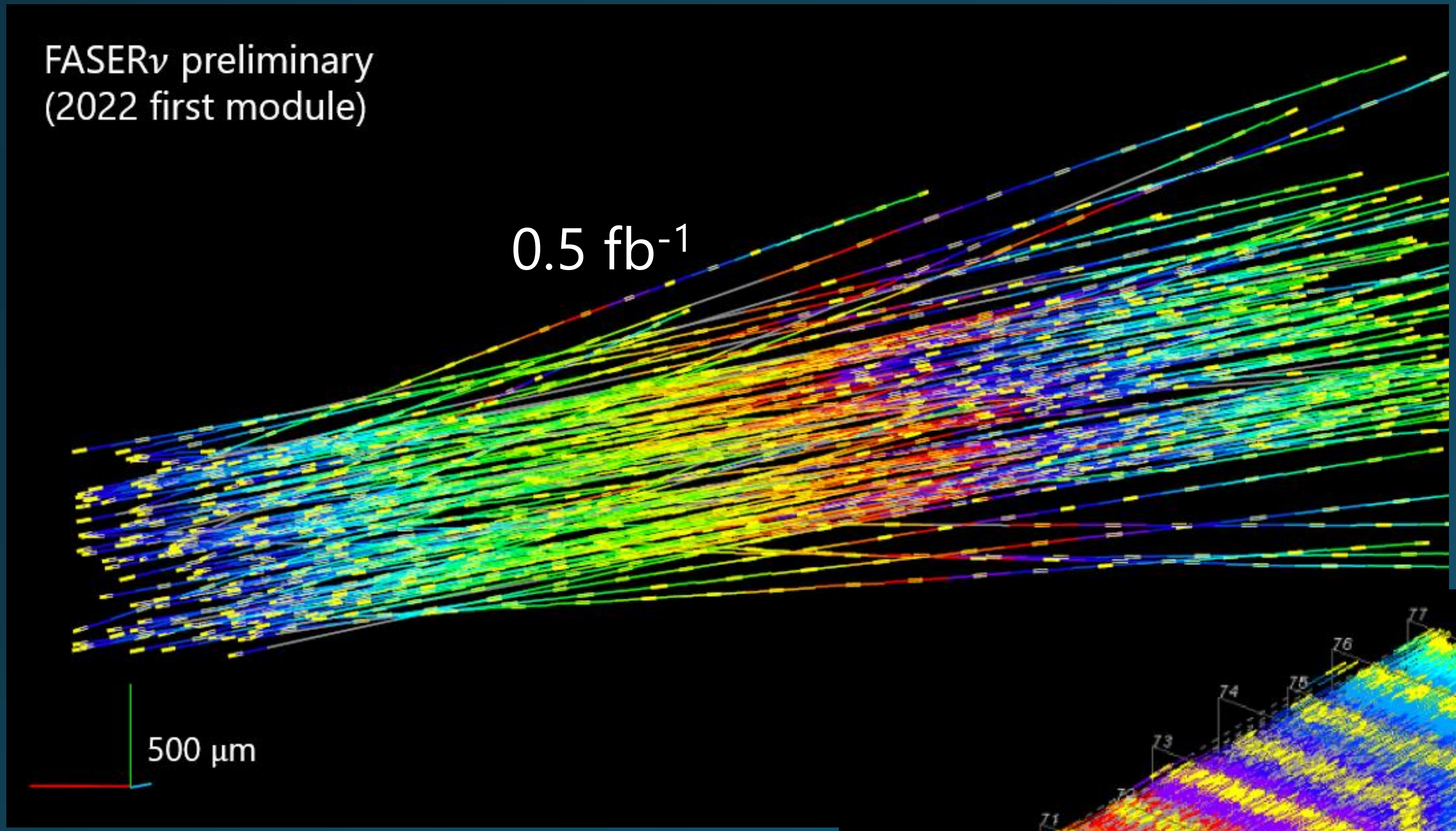
https://arxiv.org/abs/2207.11427

- 10 cm radius
- 7 m long

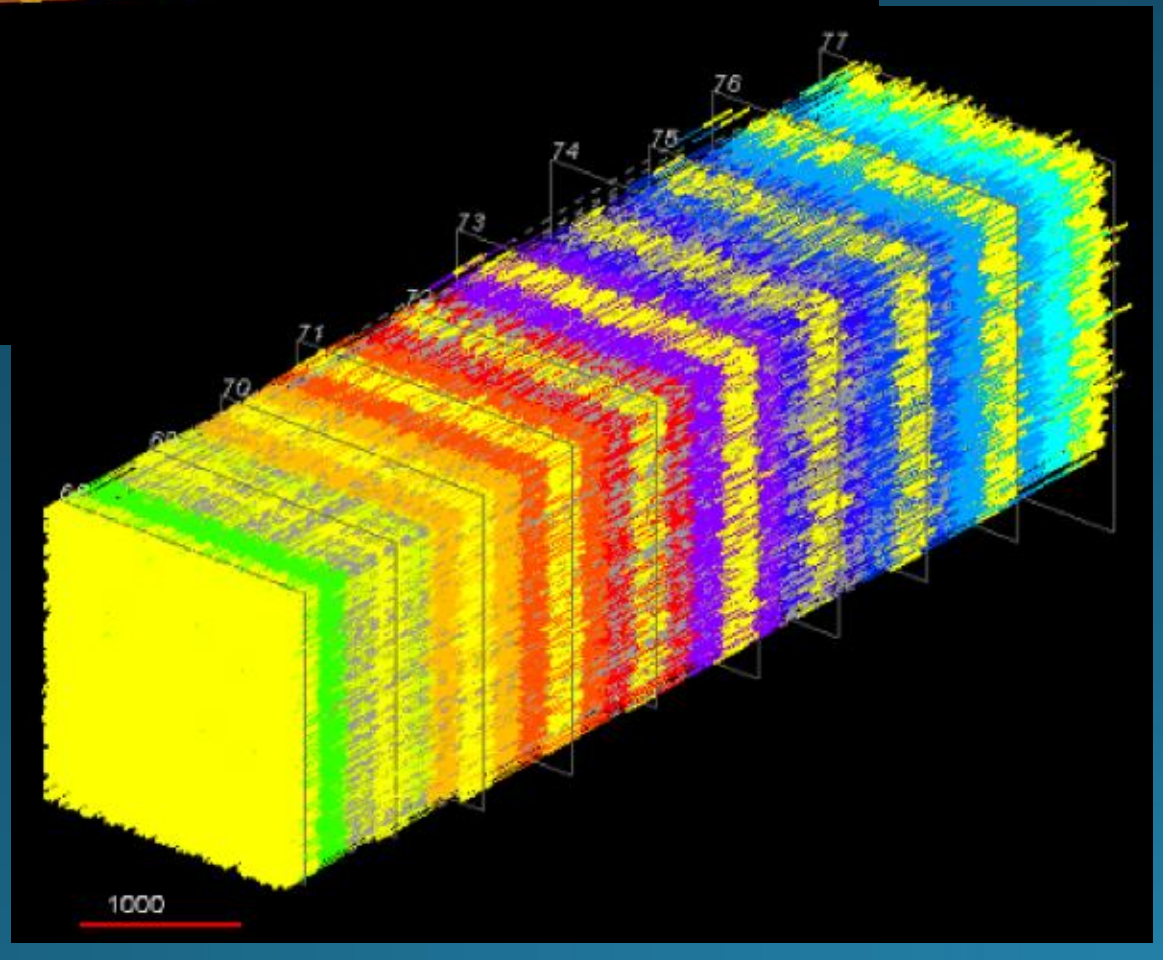


Muons at FASER site

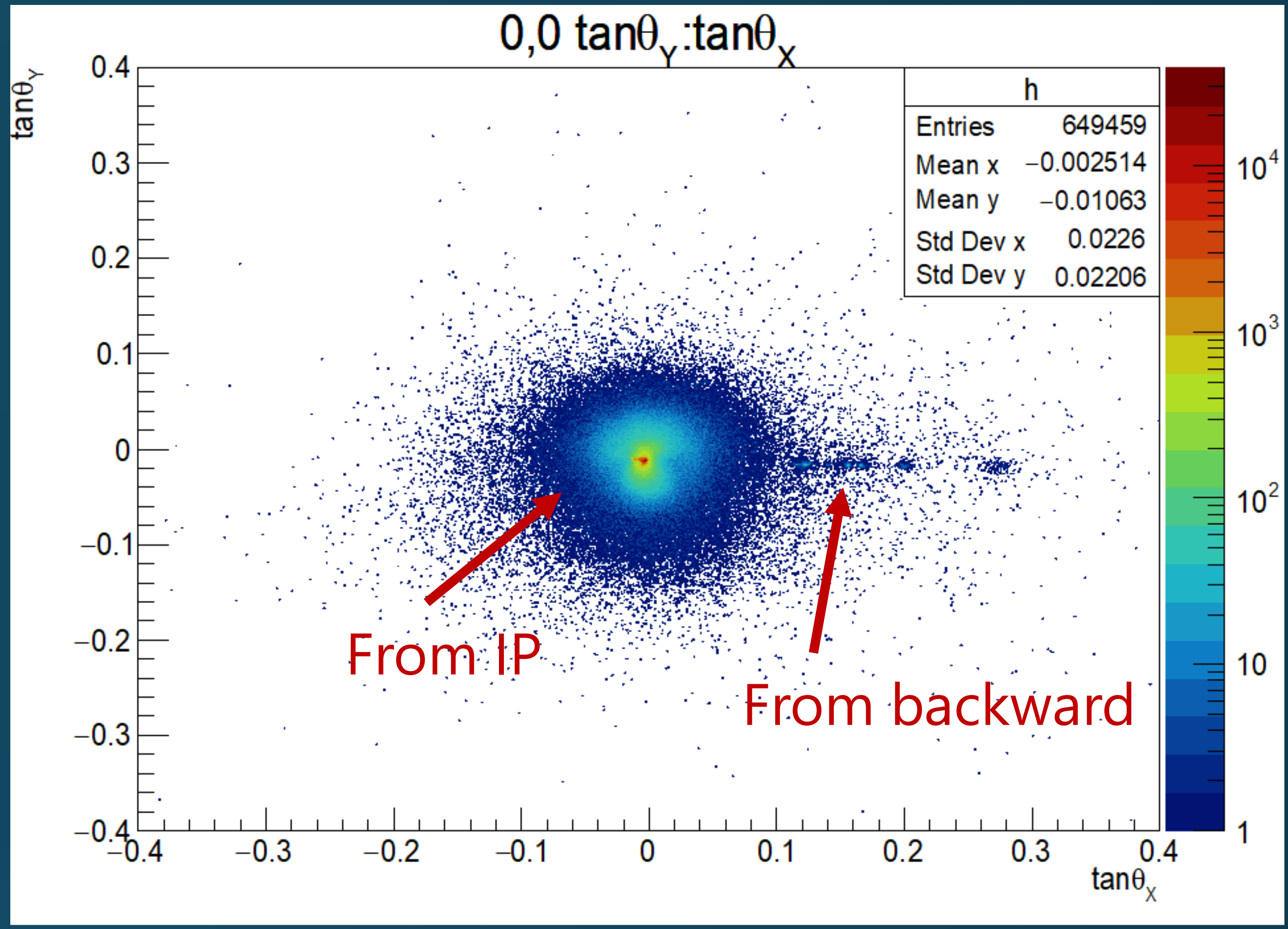
- Muons brings rich info to validate beamline simulation
- Eventually we could validate hadron production models at p-p collisions

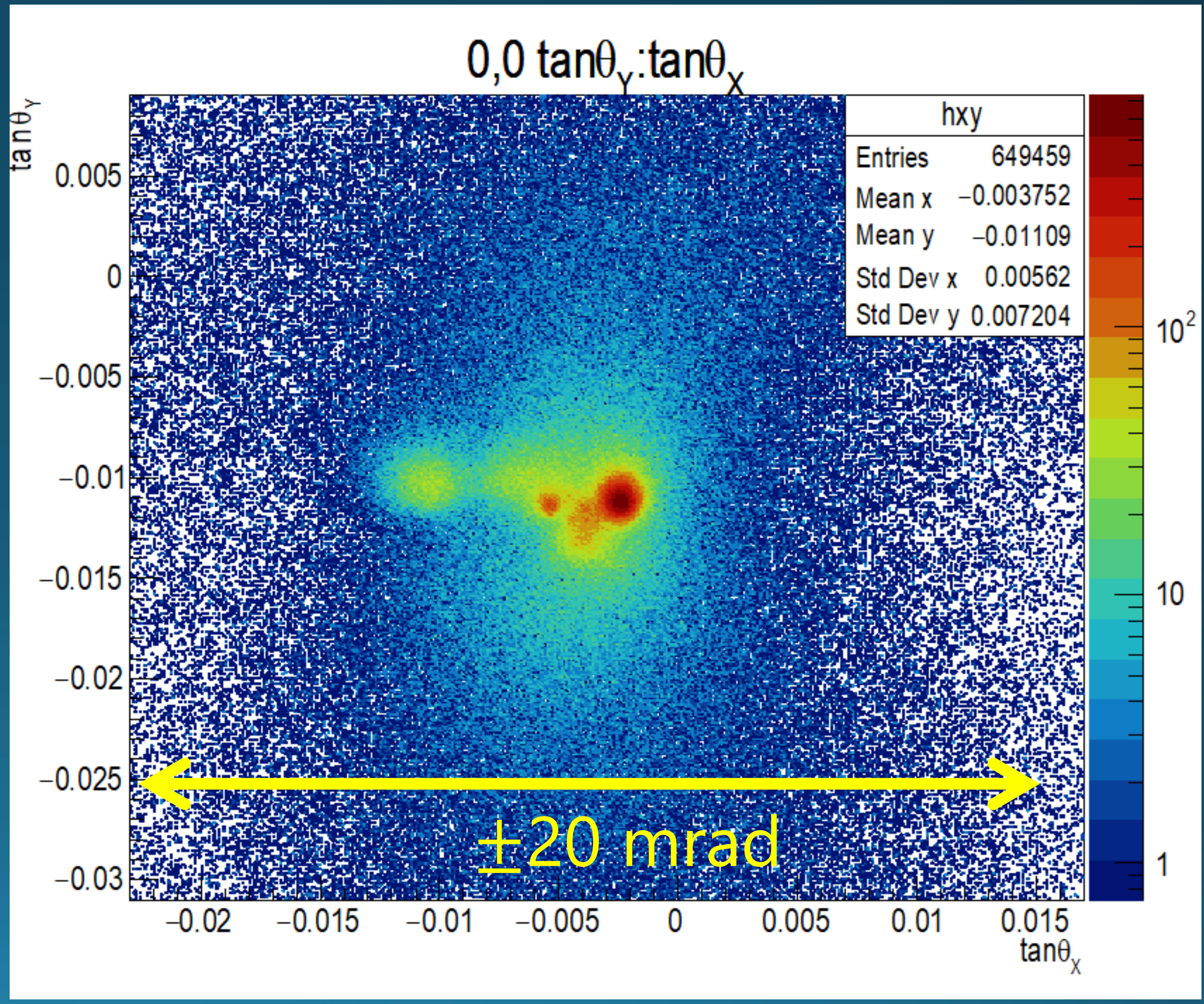


10 fb-1



Angular distribution (Data)





FASER preliminary

A.Ariga, FASER collab., Moriond EW 2024

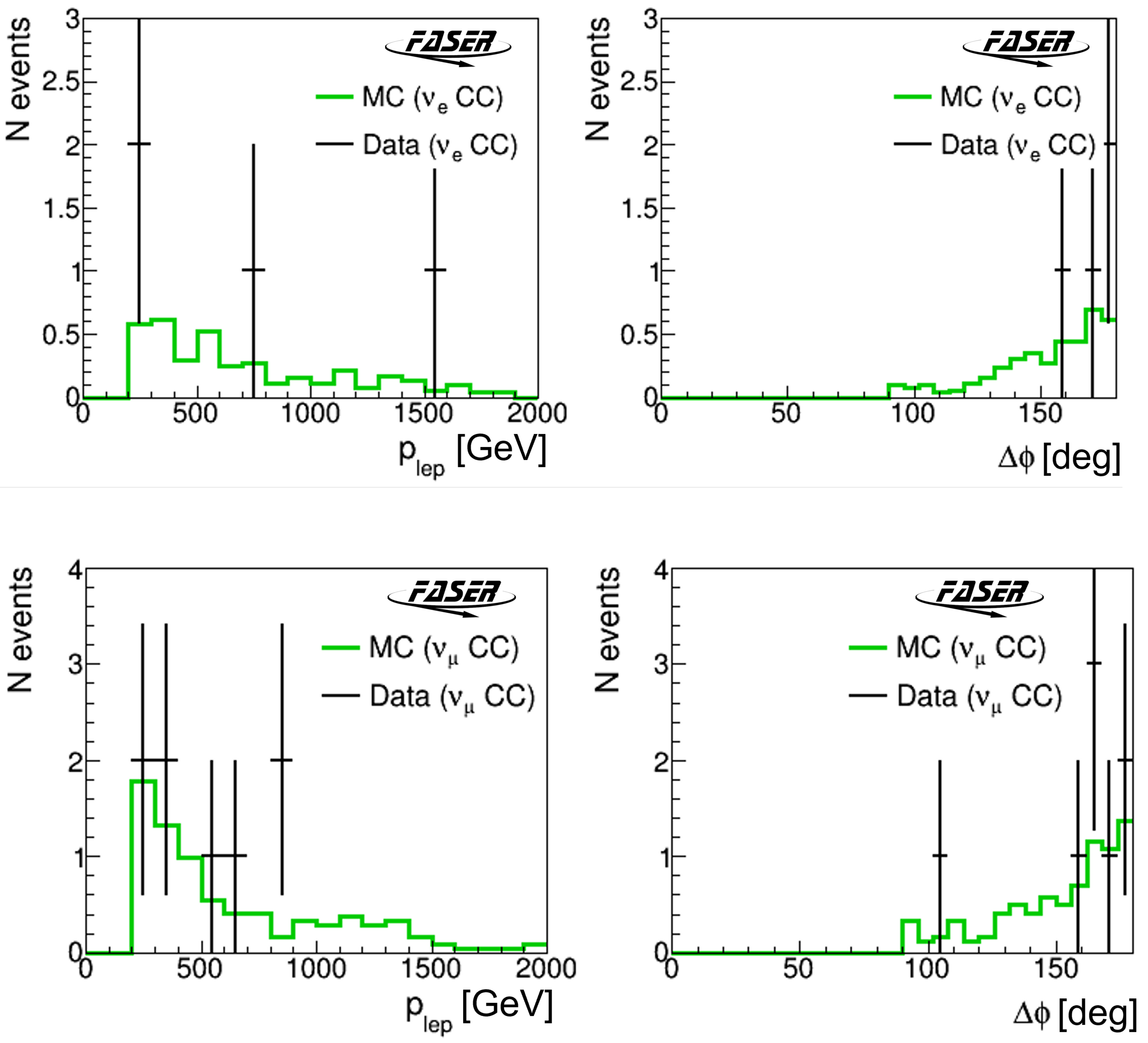
FASERν https://arxiv.org/pdf/2403.12520.pdf

M.Dallavalle, SM@LHC, Rome, May 2024

Table 3: The number of MC reconstructed events of neutral-hadron interactions satisfying the ν_e and ν_μ CC event selection. The scaling factor shows the ratio of the data luminosity to the MC luminosity.

Hadron type	K_L	n	Λ
Events simulated (E_h >200 GeV)	13497	13191	13902
Events selected as ν_e CC	0	0	0
Events selected as ν_μ CC	6	11	5
Scaling factor (data/MC)	1/232	1/256	1/423

Hadron type	K_S	$\bar{n}$	$\bar{\Lambda}$
Events reconstructed (E_h >200 GeV)	7113	5827	5368
Events selected as ν_e CC	1	0	0
Events selected as ν_μ CC	3	3	4
Scaling factor (data/MC)	1/436	1/569	1/630

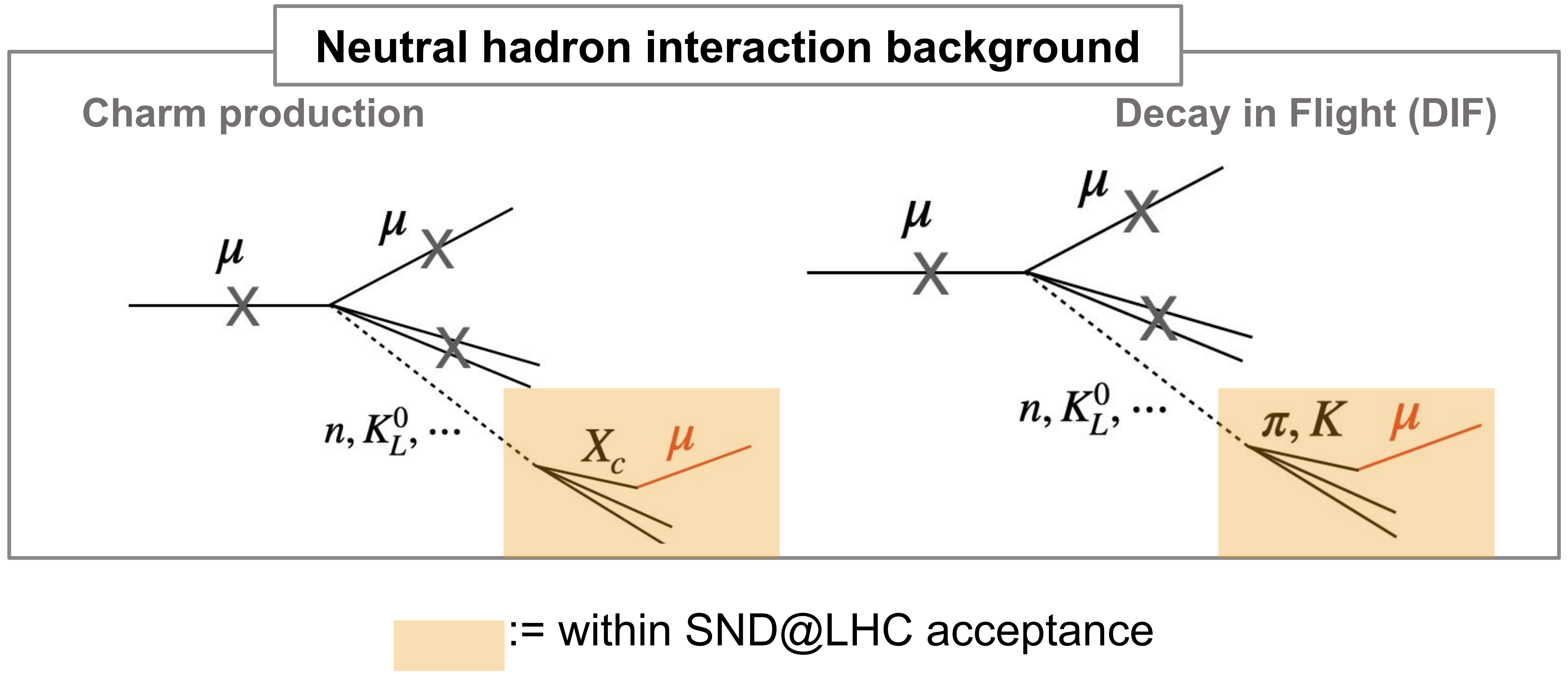


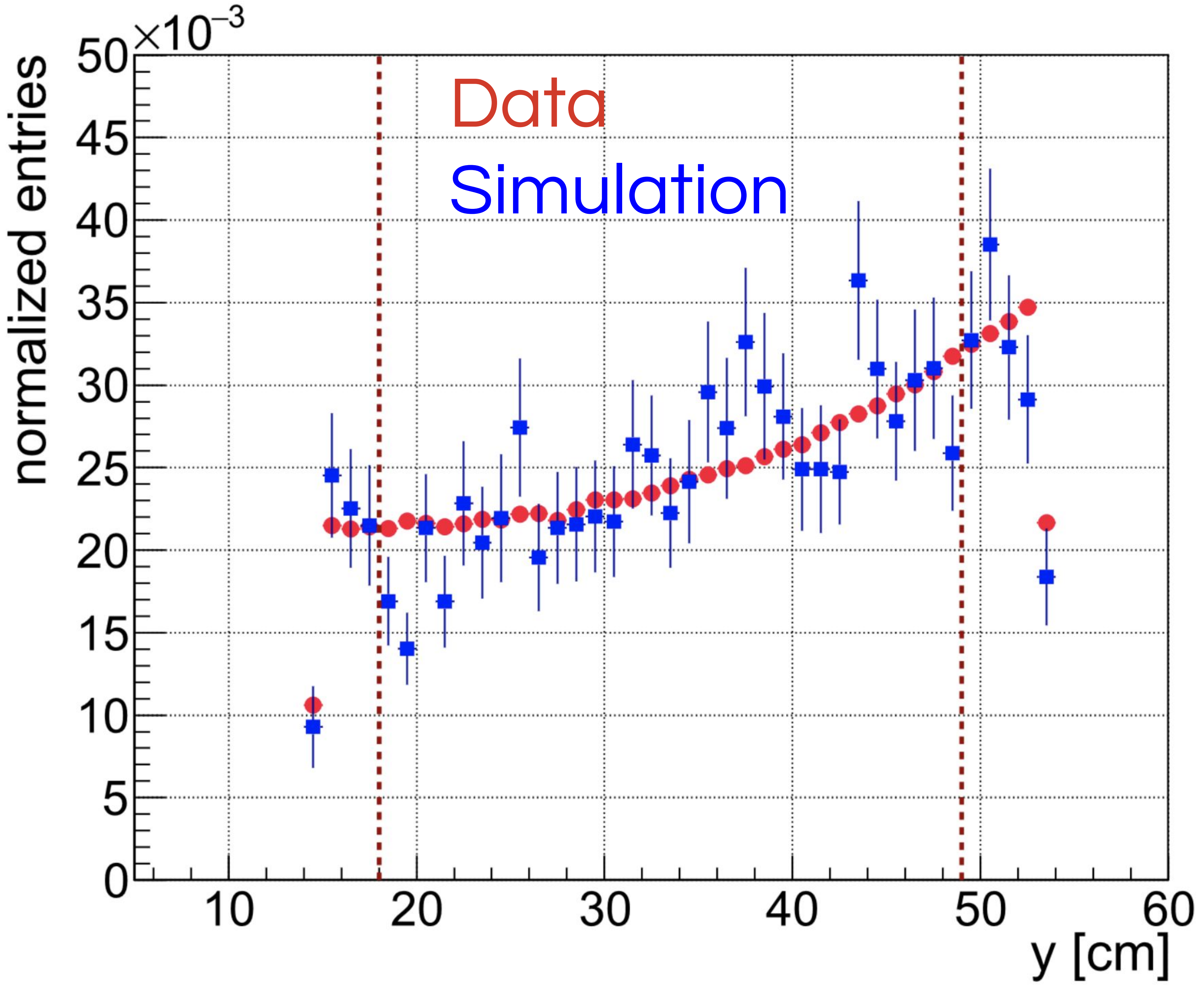
Δφ between lepton and hadronic system

Muon flux measurement

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

- Backgrounds to neutrino signals in SND@LHC are mainly due to muon interactions in the tunnel walls.
- Precise measurements of the muon flux allow for validating and constraining our background model.



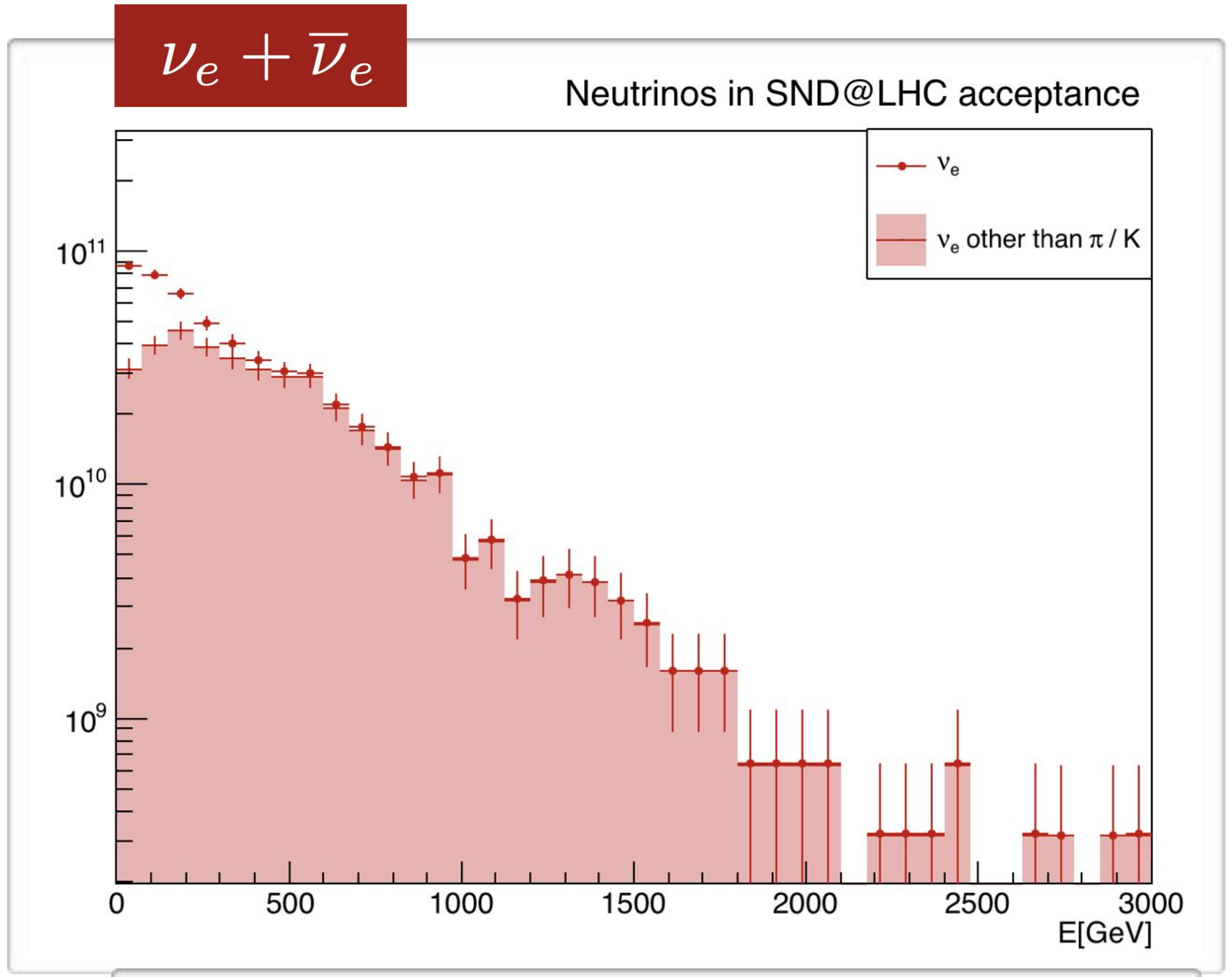


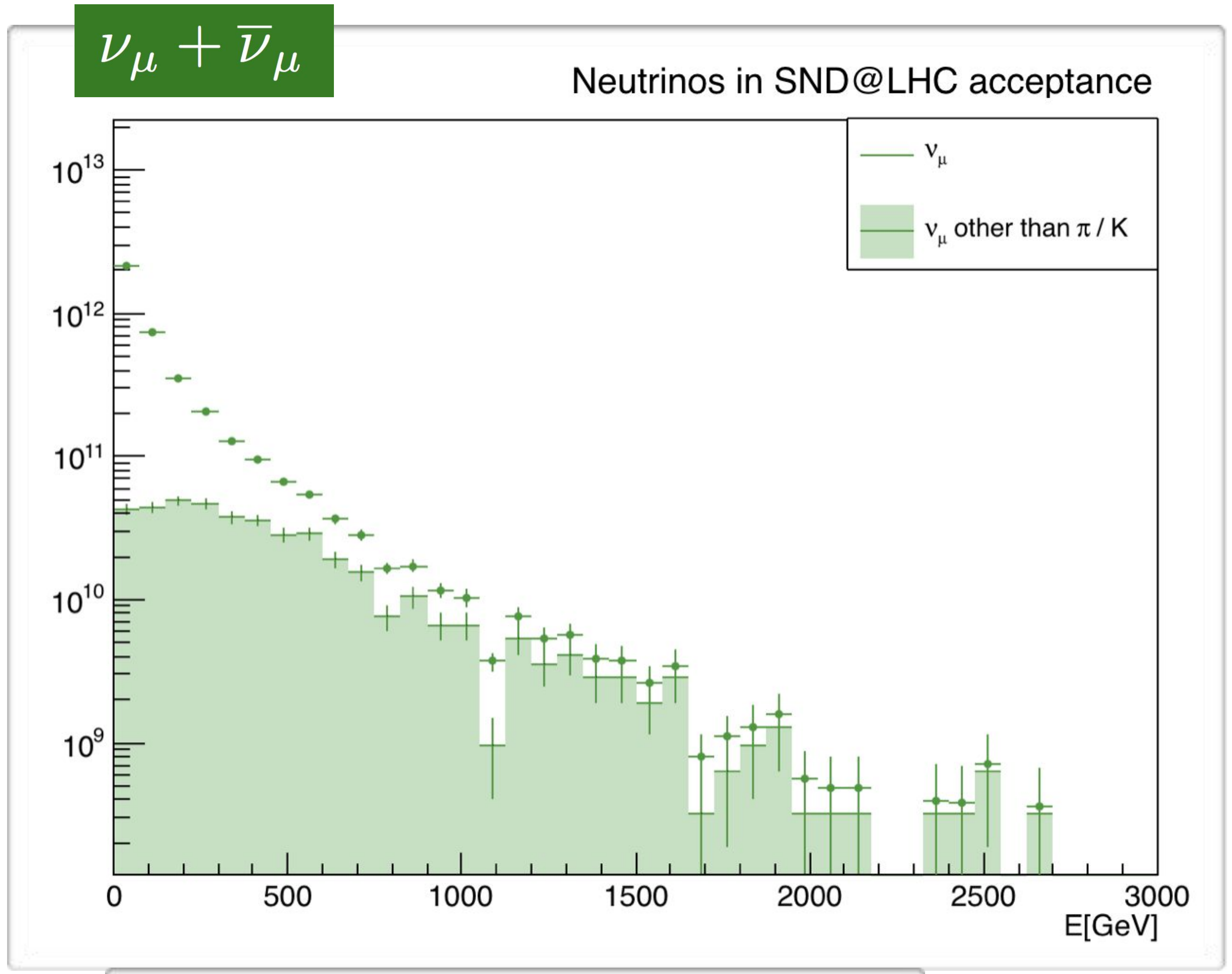
System	Muon flux [10^4 fb/cm^2] same fiducial area
SciFi	$2.06 \pm 0.01(\text{stat.}) \pm 0.12(\text{sys.})$
DS	$2.02 \pm 0.01(\text{stat.}) \pm 0.08(\text{sys.})$

- Measurements with the SciFi tracker, downstream muon system and emulsion detectors give consistent results.

Lepton Flavour Universality tests

- Charm hadron decays contribute to the flux of all three types of neutrinos at SND@LHC.
- The detector has excellent flavour identification capabilities.
- Unique opportunity to test lepton flavour universality with neutrinos.
  - Take ratios of event rates: ν_e/ν_τ and ν_e/ν_μ.





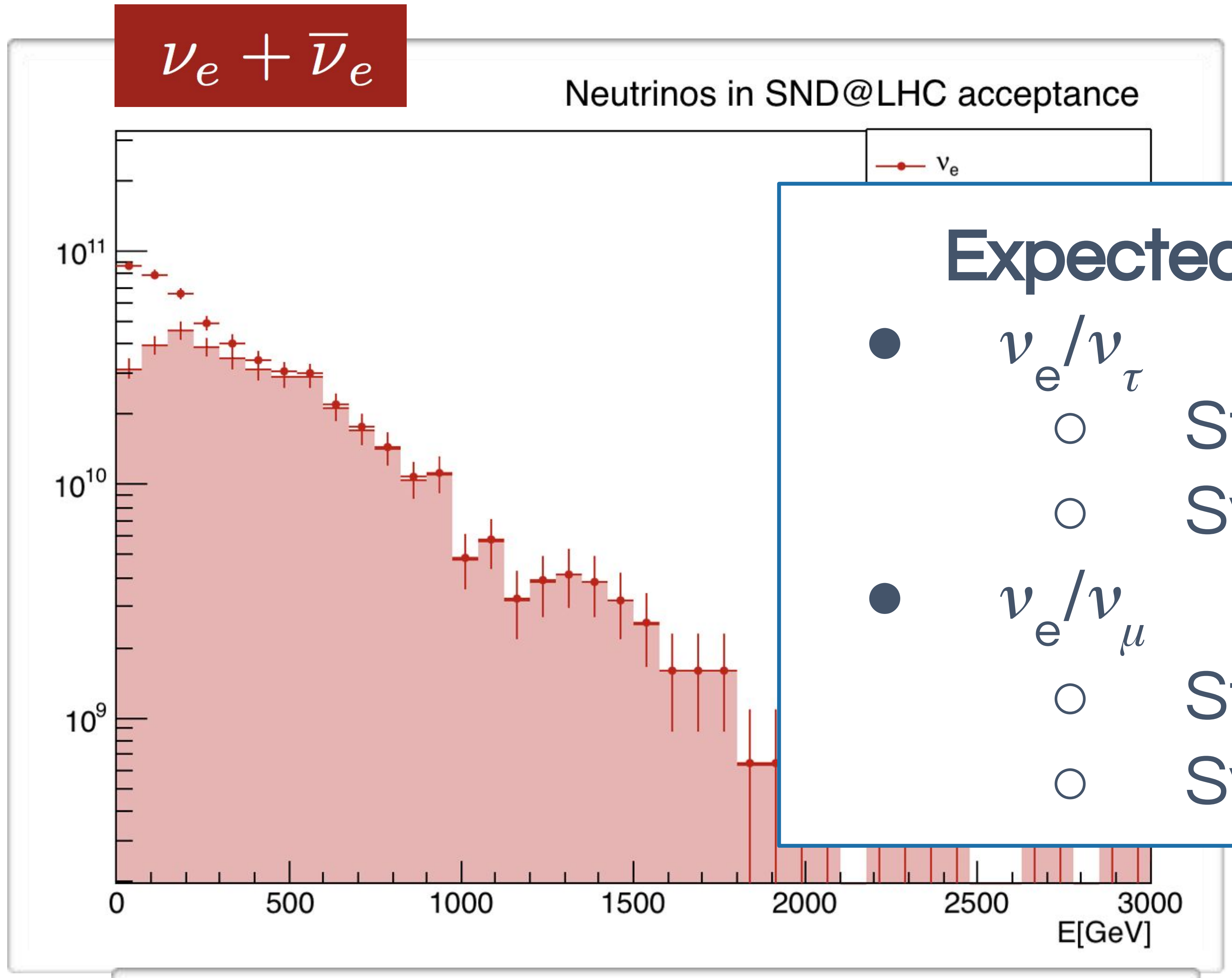
$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)},$$

$$R_{12} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\mu+\overline{\nu}_\mu}} = \frac{1}{1+\boxed{\omega_{\pi/k}}}.$$

π/K contamination

Lepton Flavour Universality tests

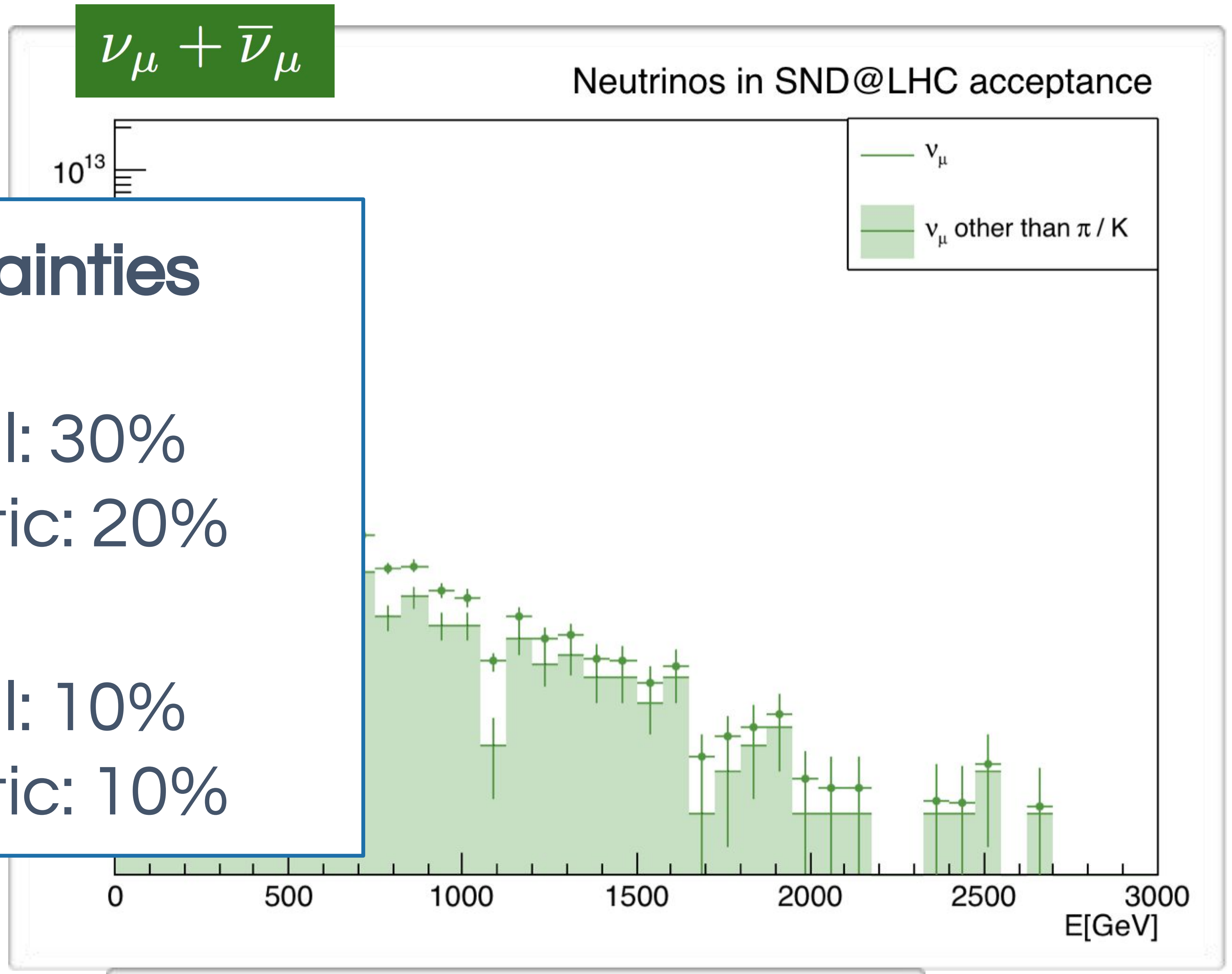
- Charm hadron decays contribute to the flux of all three types of neutrinos at SND@LHC.
- The detector has excellent flavour identification capabilities.
- Unique opportunity to test lepton flavour universality with neutrinos.
  - Take ratios of event rates: ν_e/ν_τ and ν_e/ν_μ.



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

Expected uncertainties

- ν_e/ν_τ
  - Statistical: 30%
  - Systematic: 20%
- ν_e/ν_μ
  - Statistical: 10%
  - Systematic: 10%



$$R_{12} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\mu+\overline{\nu}_\mu}} = \frac{1}{1 + \boxed{\omega_{\pi/k}}}.$$

π/K contamination

M.Dallavalle, SM@LHC, Rome, May 2024

AdvSND with 3000 fb^{-1} at HL-LHC

Flavour	ν in acceptance All	ν in acceptance not from π/K	CC DIS All	CC DIS not from π/K	NC DIS All	NC DIS not from π/K
ν_μ	8.6×10^{13}	8.2×10^{12}	1.2×10^5	3.3×10^4	3.6×10^4	1.0×10^4
$\bar{\nu}_\mu$	7.0×10^{13}	9.6×10^{12}	4.4×10^4	1.8×10^4	1.6×10^4	6.5×10^3
ν_e	1.3×10^{13}	9.1×10^{12}	4.2×10^4	3.6×10^4	1.3×10^4	1.1×10^4
$\bar{\nu}_e$	1.3×10^{13}	9.2×10^{12}	1.9×10^4	1.7×10^4	7.0×10^3	6.1×10^3
ν_τ	7.3×10^{11}	7.3×10^{11}	2.1×10^3	2.1×10^3	6.7×10^2	6.7×10^2
$\bar{\nu}_\tau$	9.4×10^{11}	9.4×10^{11}	1.2×10^3	1.2×10^2	4.6×10^2	4.6×10^2
Tot	1.8×10^{14}	3.8×10^{13}	2.3×10^5	1.1×10^5	7.3×10^4	3.5×10^4

Table 10: Number of neutrinos in the Target acceptance, CC DIS and NC-DIS neutrino interactions, assuming 3000 fb^{-1}, as estimated with DPMJET+FLUKA and GENIE generators.

AdvSND Letter of Intent:

CERN-LHCC-2024-007 / LHCC-I-040