NEUTRINO PHYSICS AT CERN

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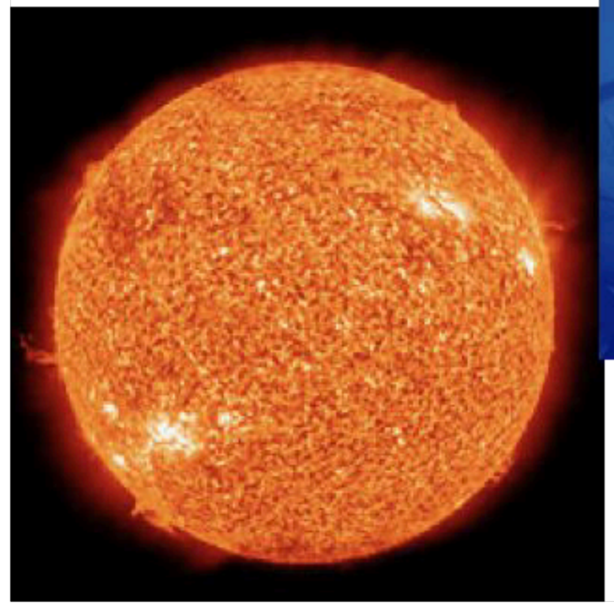
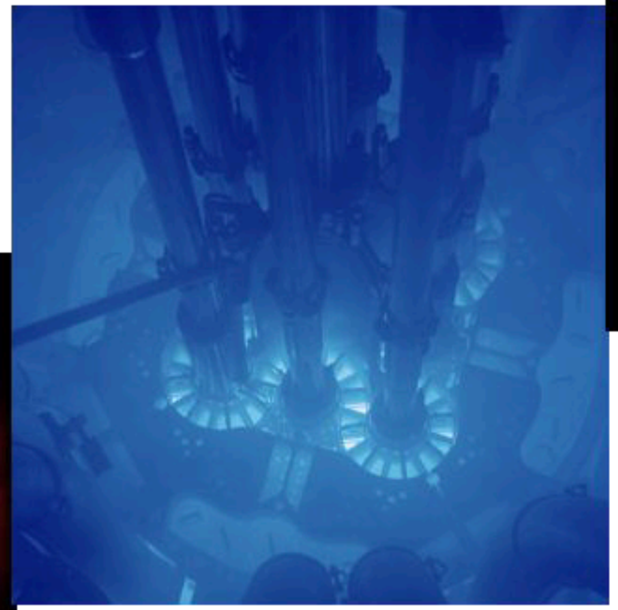
INFN Bari - 23 October 2025

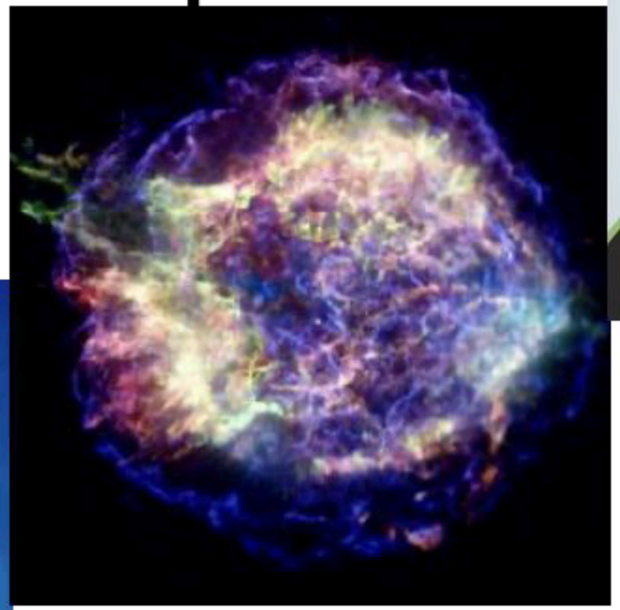
MOTIVATION

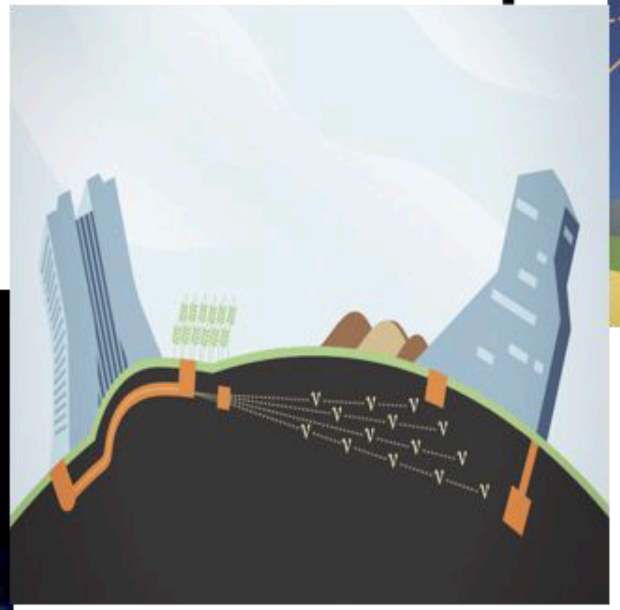
We have detected neutrinos a variety of source across a large energy range

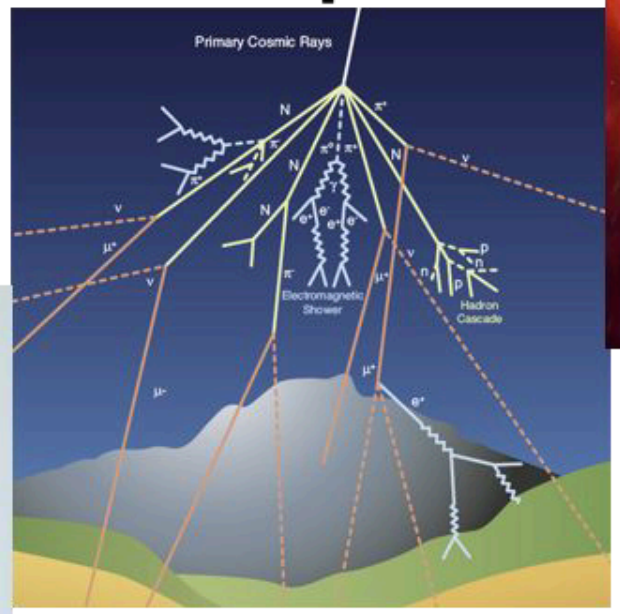
Each detection led to profound insights across the fields of particle physics, nuclear physics, and astrophysics

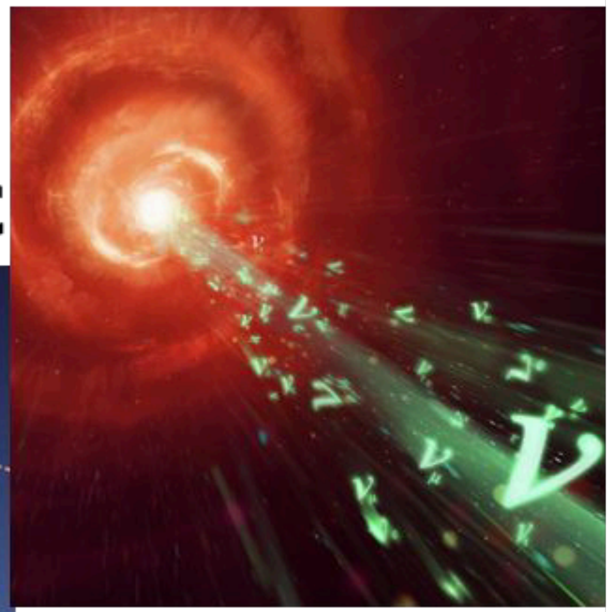




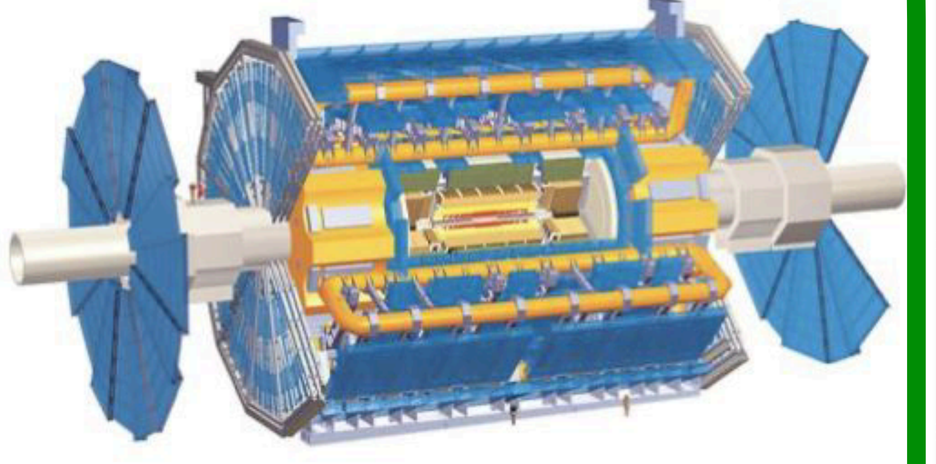








Only recently we have observed the first neutrinos from a new source: **particle colliders**

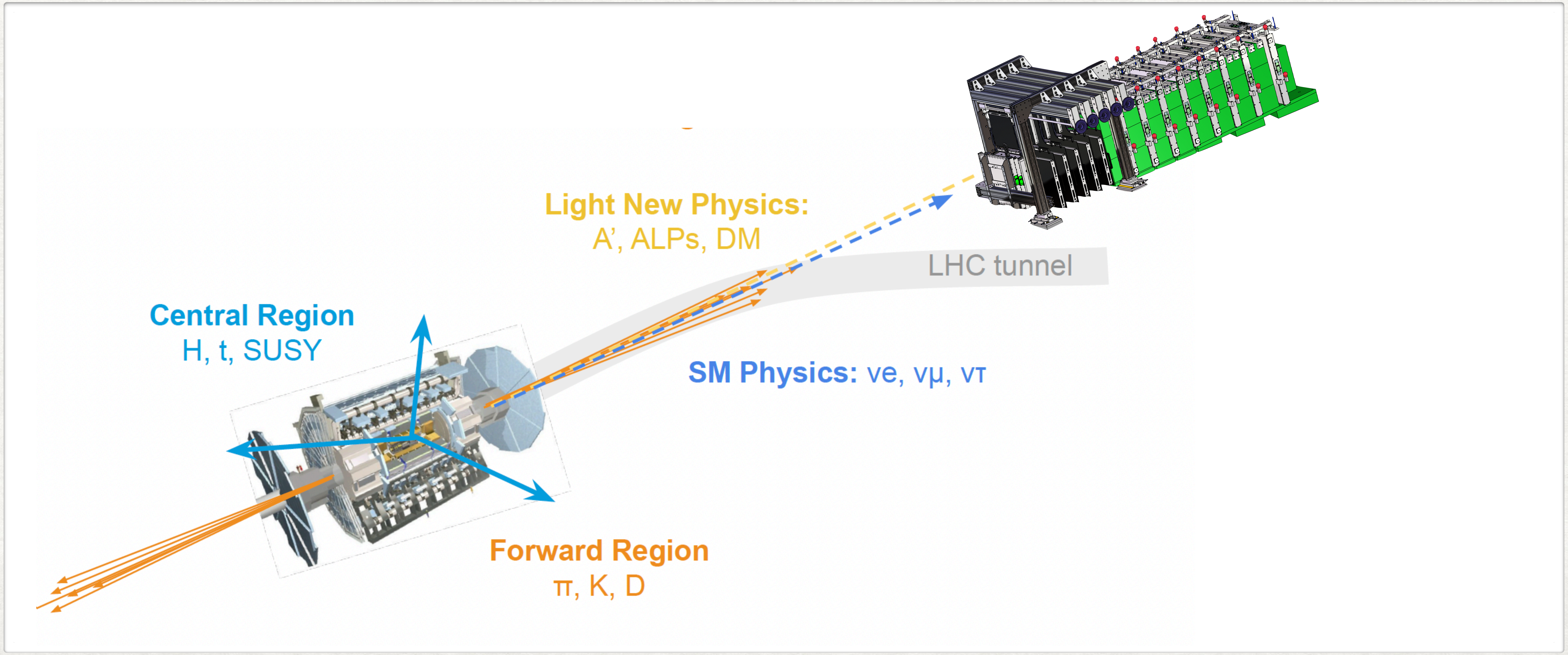


MOTIVATION

The LHC produces an intense and strongly collimated beam of highly energetic particles in the forward direction

10^{17} π^0, 10^{16} η, 10^{15} D, 10^{13} B within 1 mrad of beam

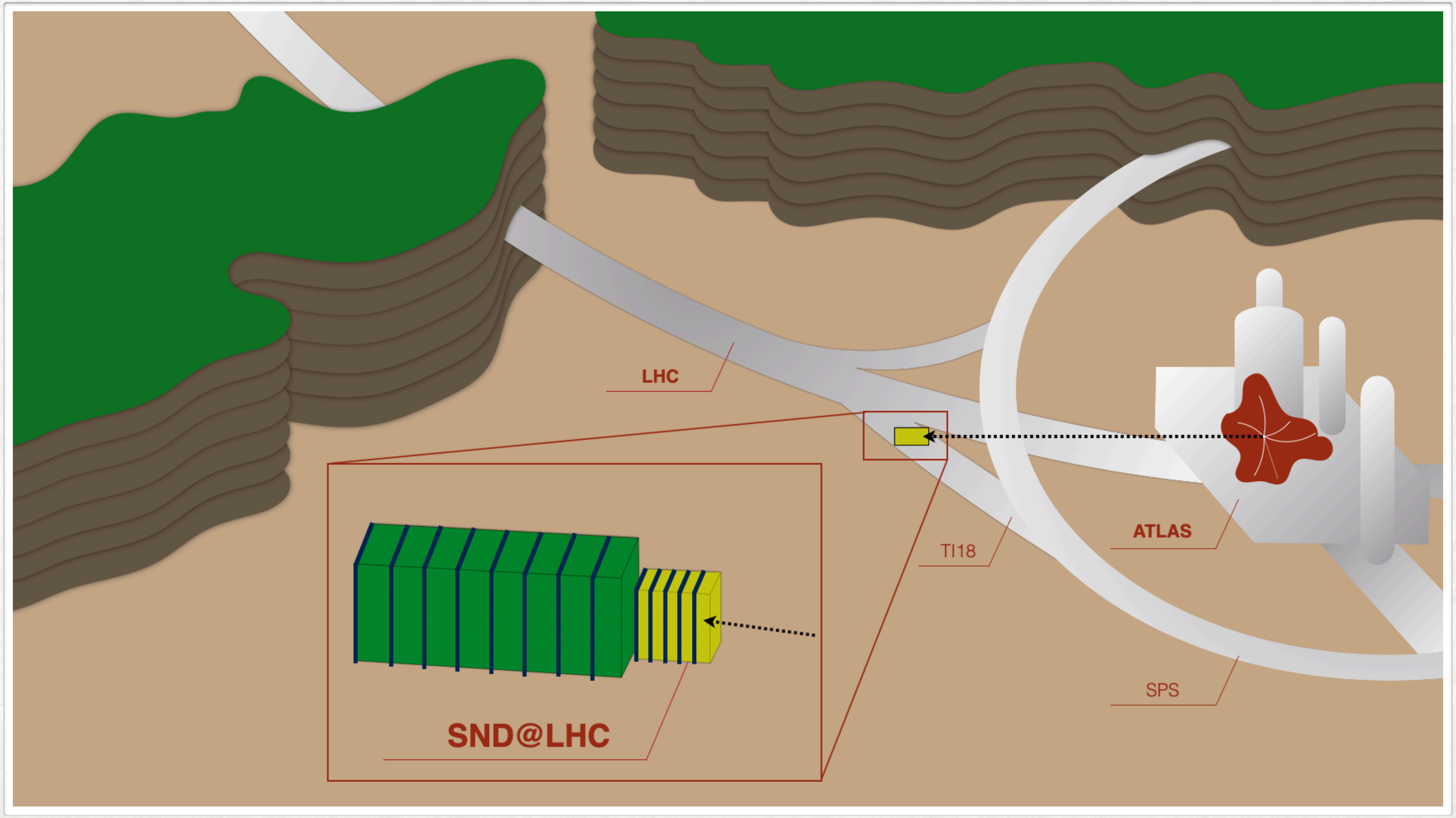
Can we do something with that?



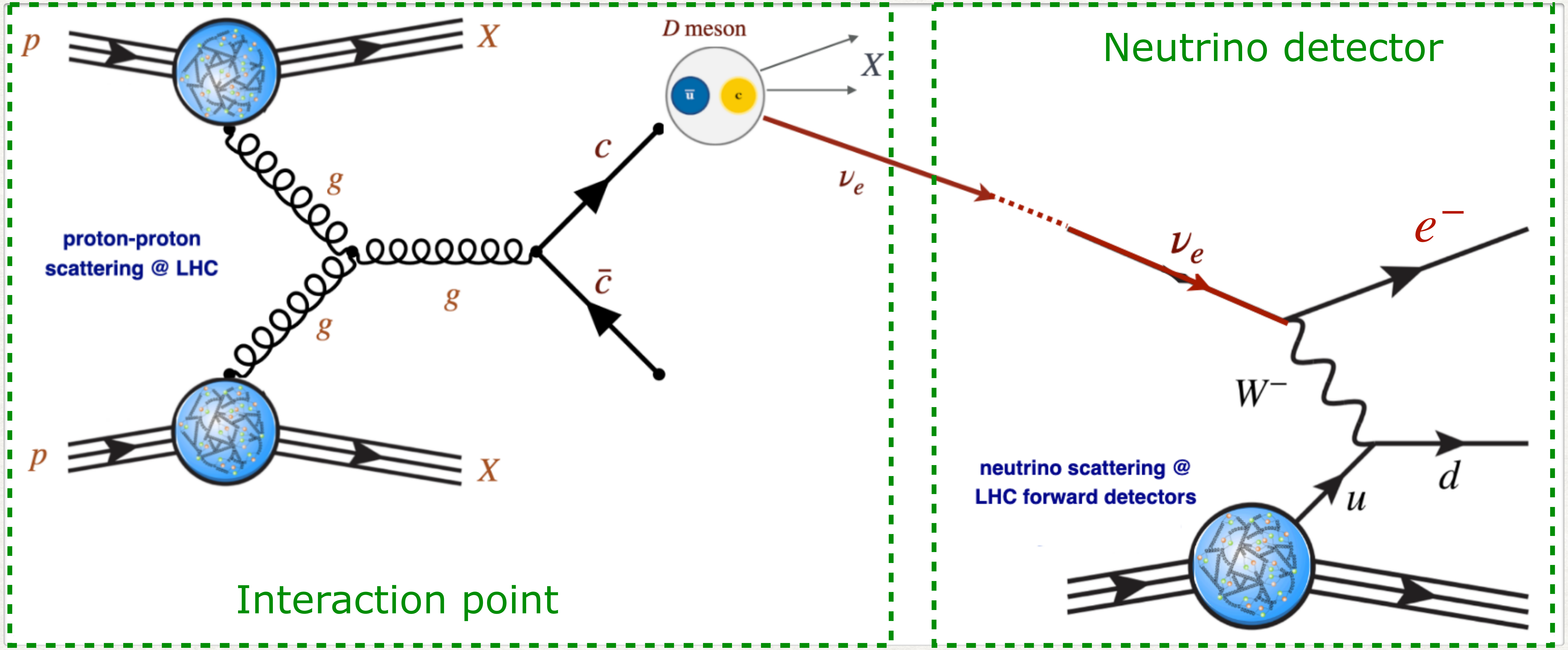
LOCATION

There is potential for forward physics experiments along beam axis
Two new experiments are exploiting this potential during Run3 of the LHC: **SND@LHC** and **FASER**

THE SCATTERING AND NEUTRINO DETECTOR

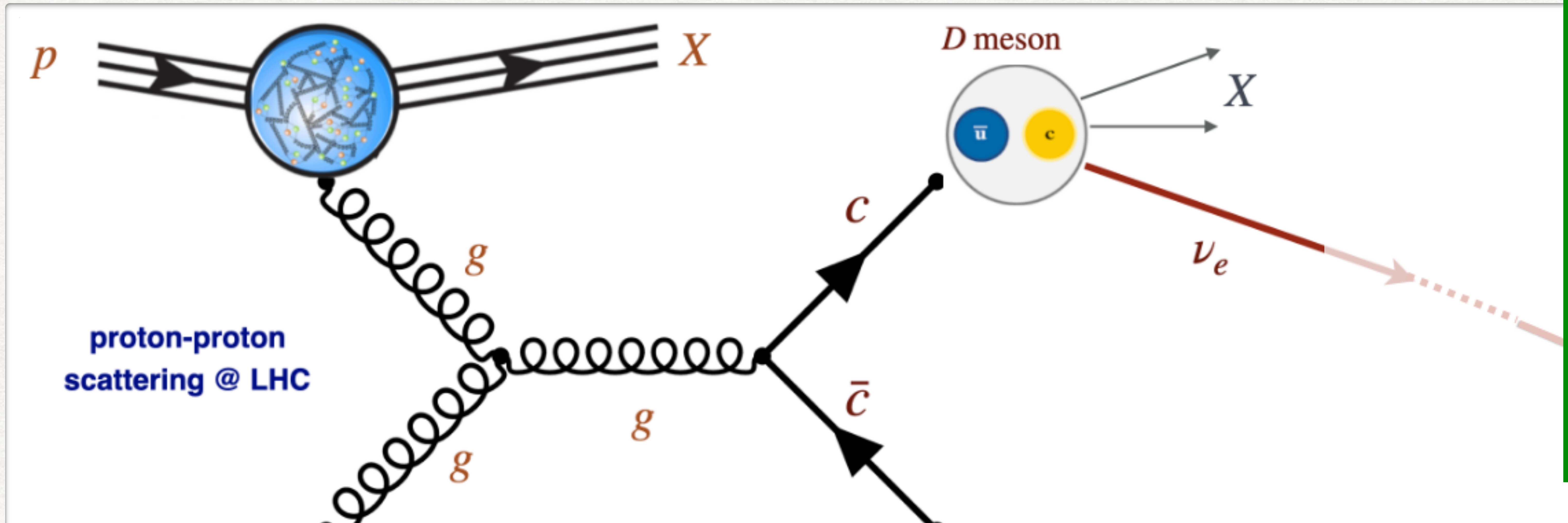


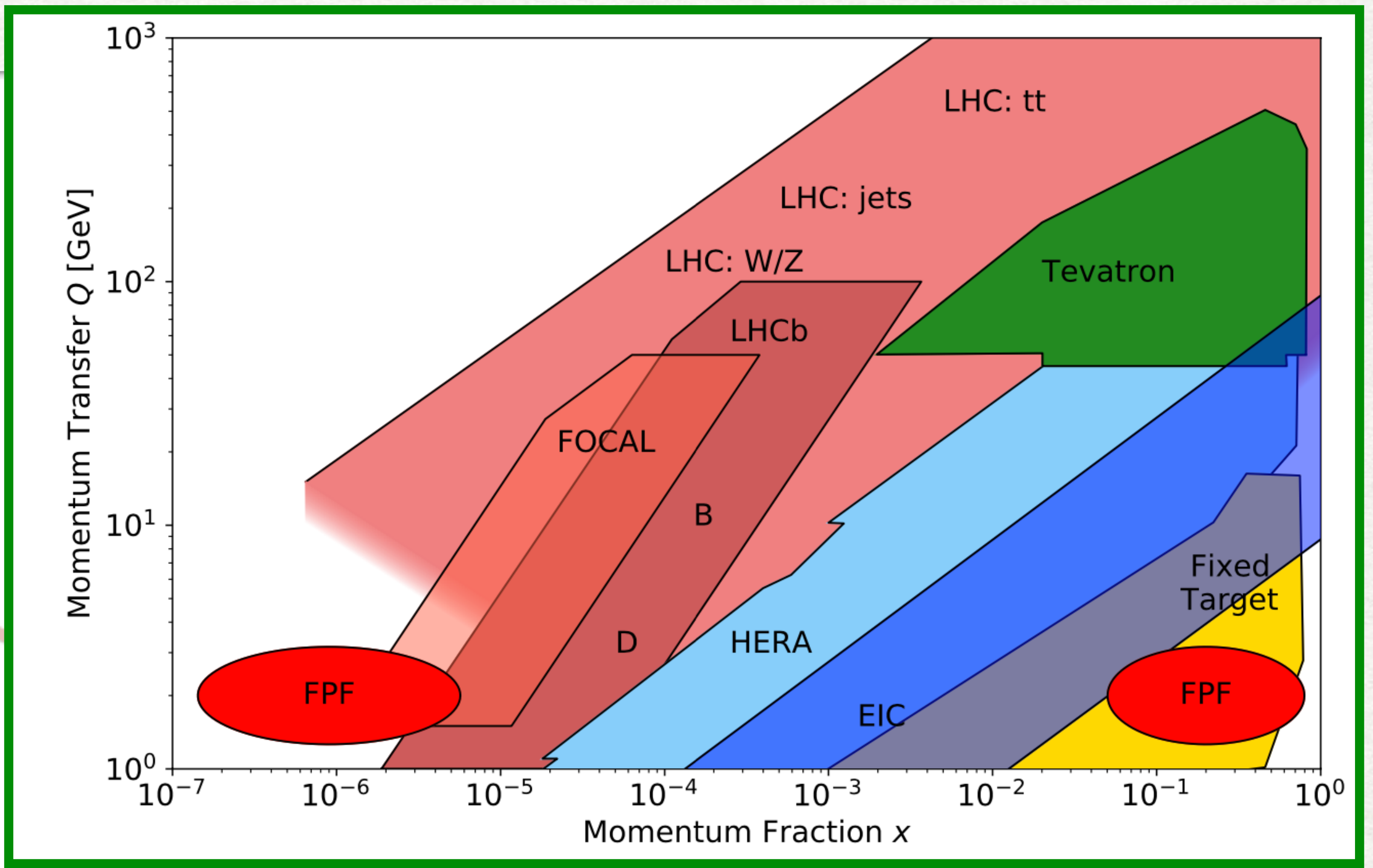
SND@LHC PHYSICS GOALS

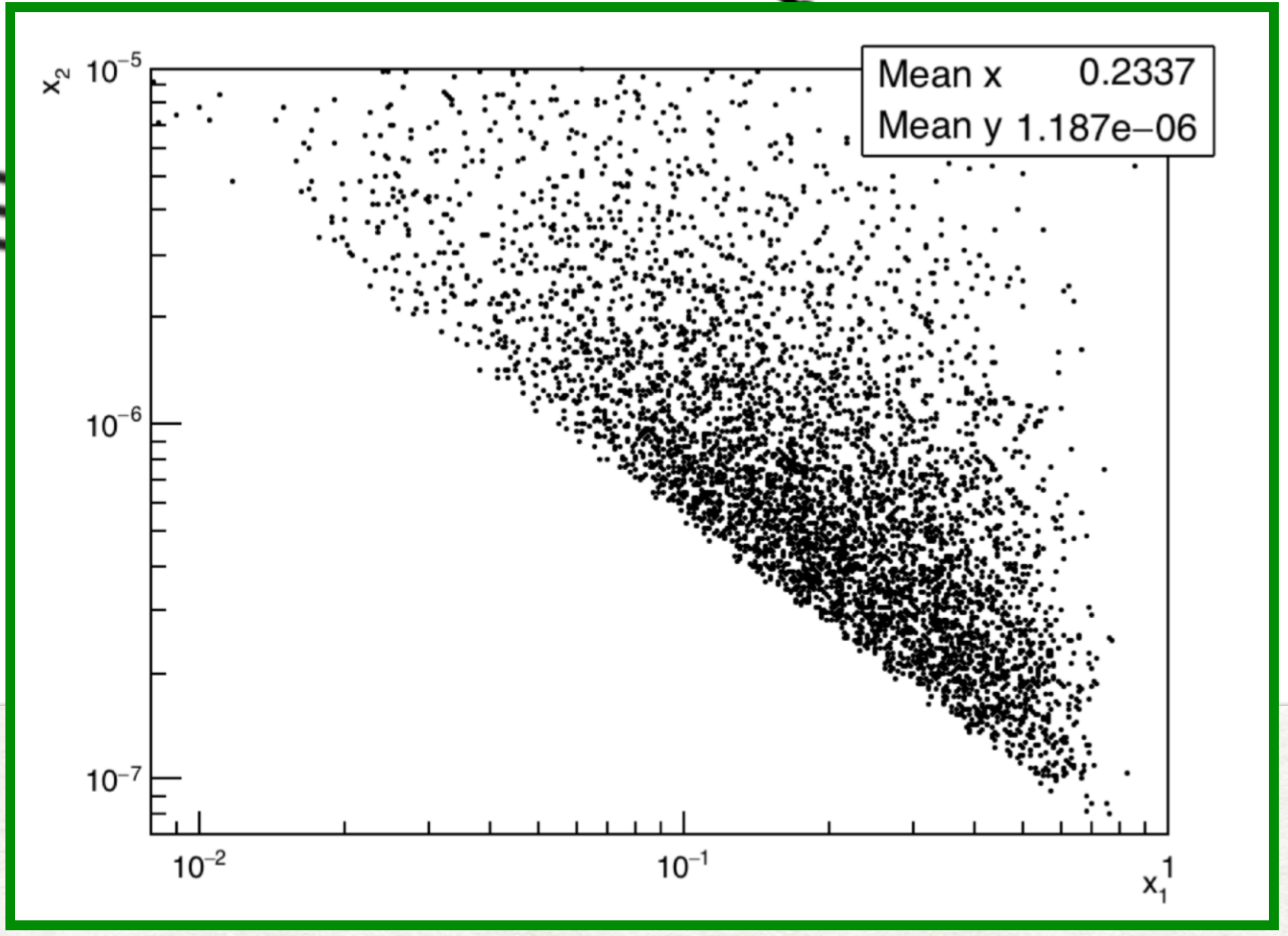


SND@LHC PHYSICS GOALS

1. Quantum cromodynamics





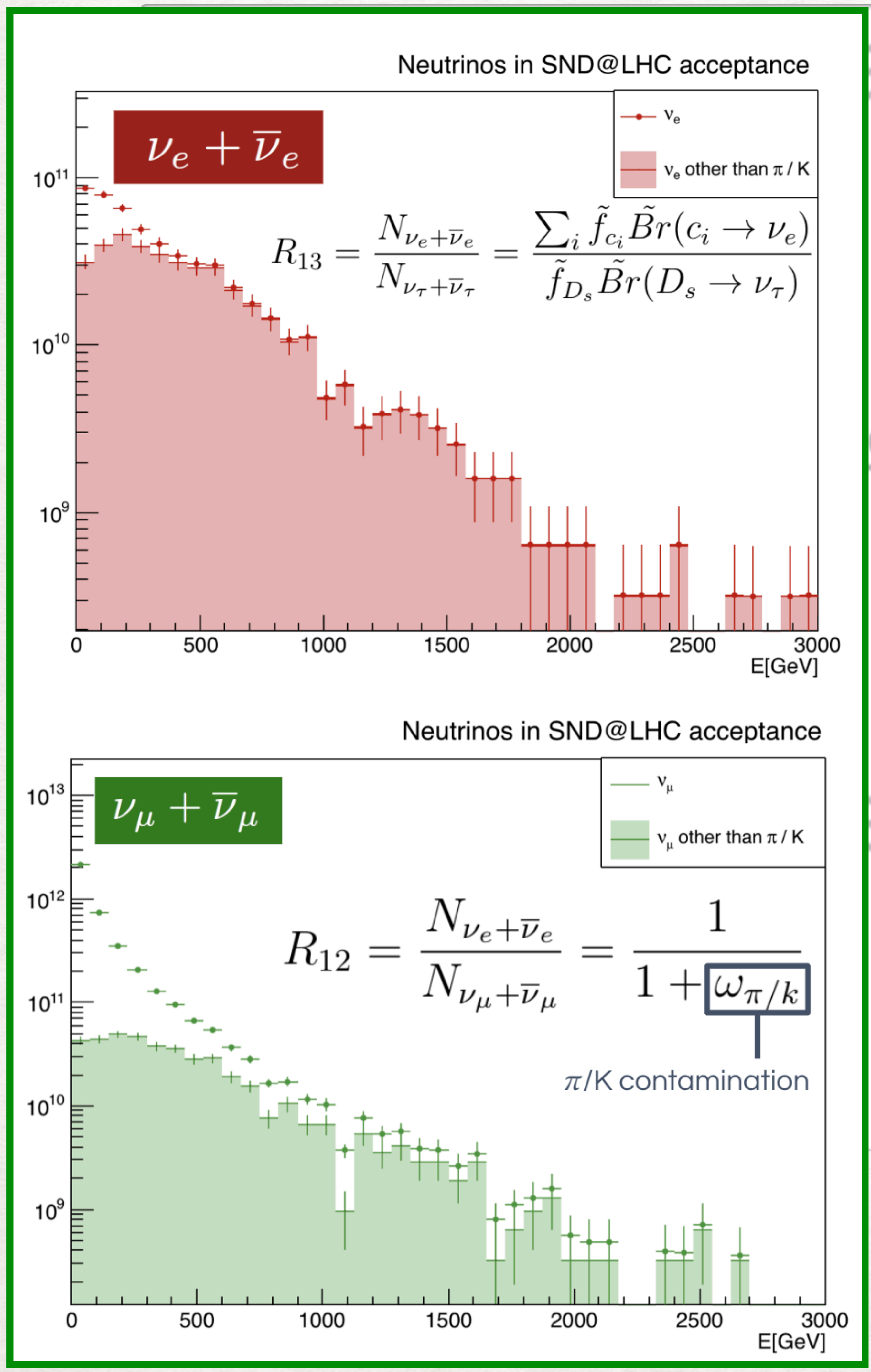


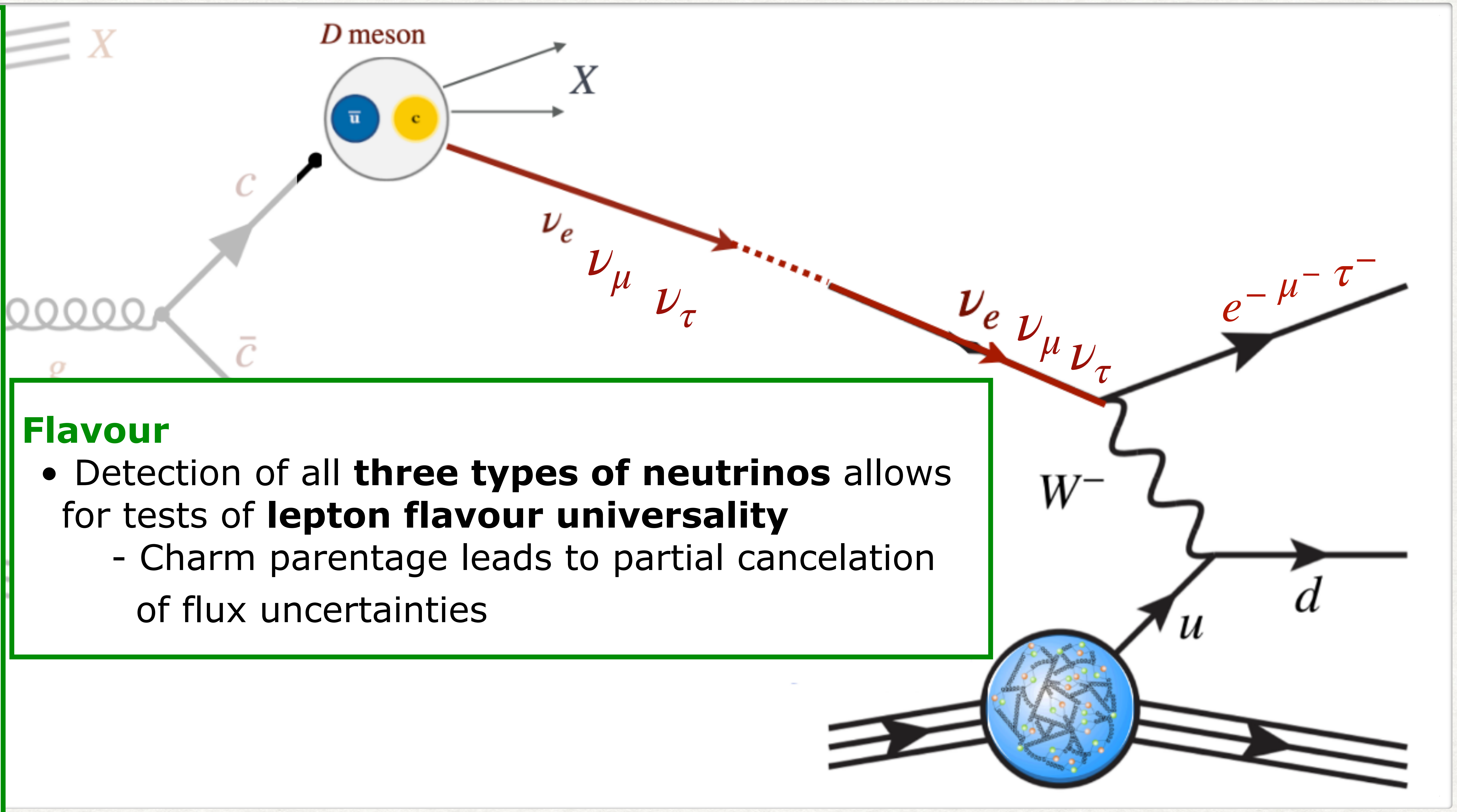
QCD

- Decays of **charm** hadrons contribute significantly to the neutrino flux in SND@LHC
  - Measure forward charm production with ν_es
    - Constrain **gluon PDF** at very **small x**

SND@LHC PHYSICS GOALS

2. Lepton flavor universality



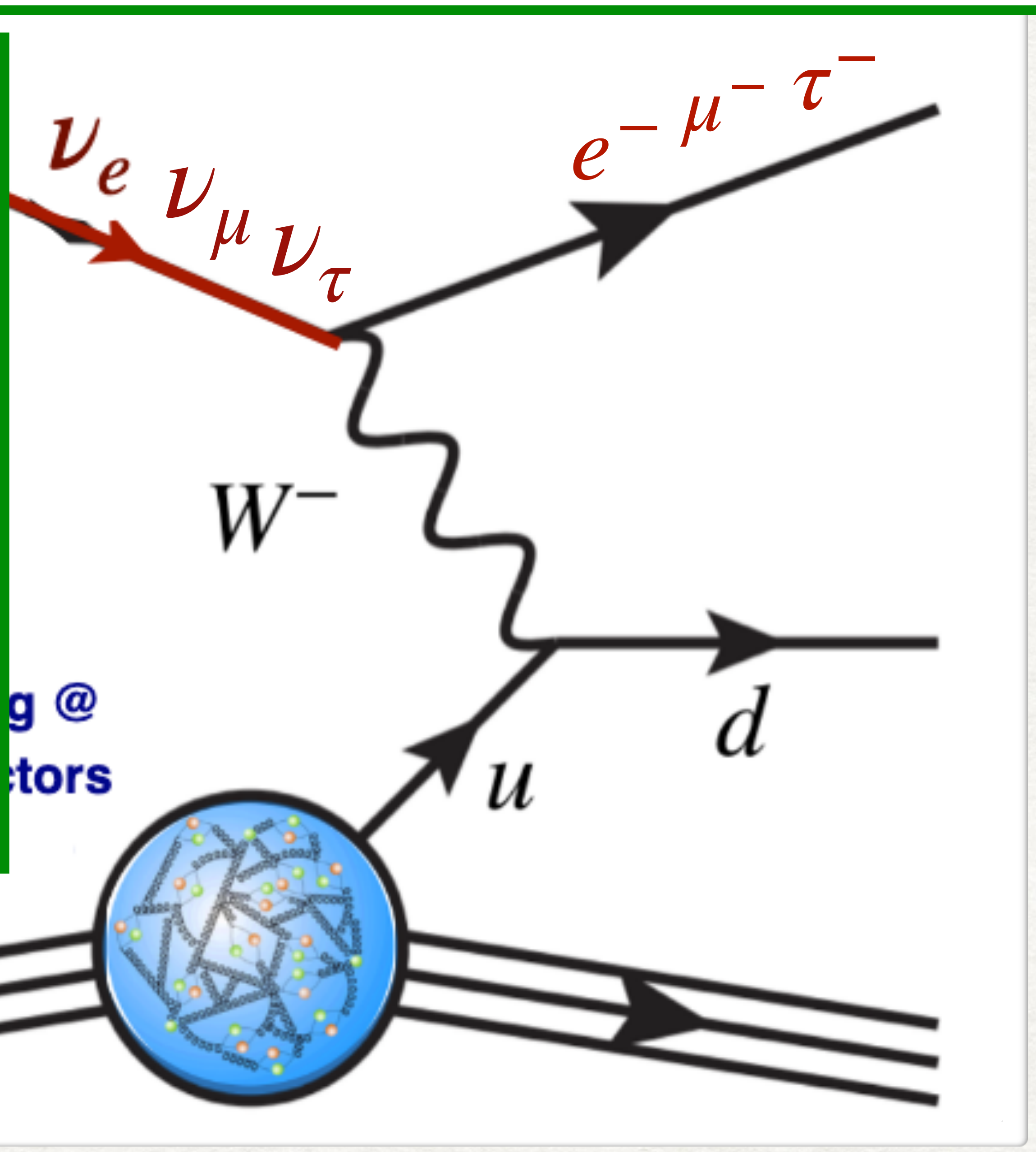


Flavour

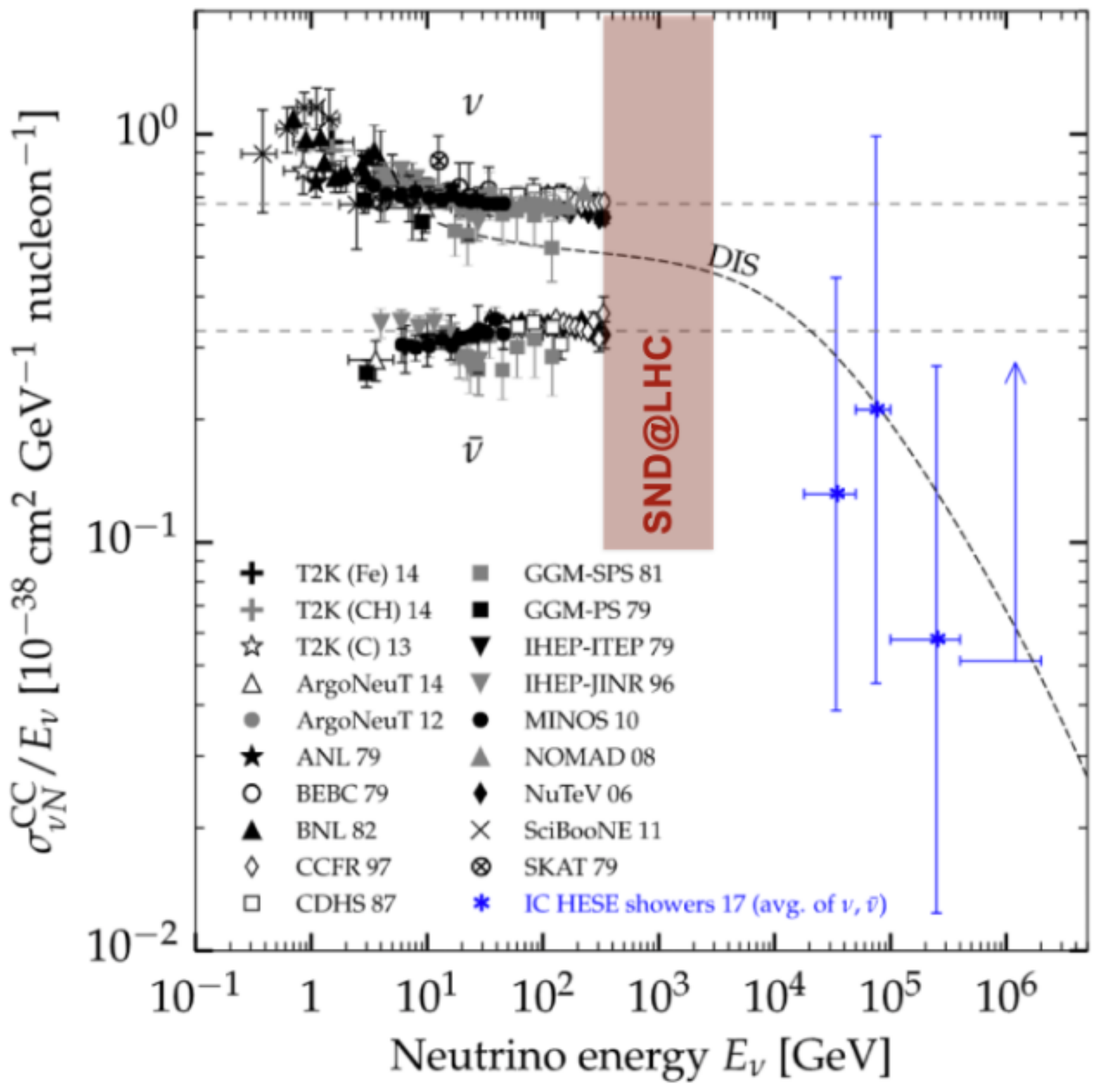
- Detection of all **three types of neutrinos** allows for tests of **lepton flavour universality**
  - Charm parentage leads to partial cancelation of flux uncertainties

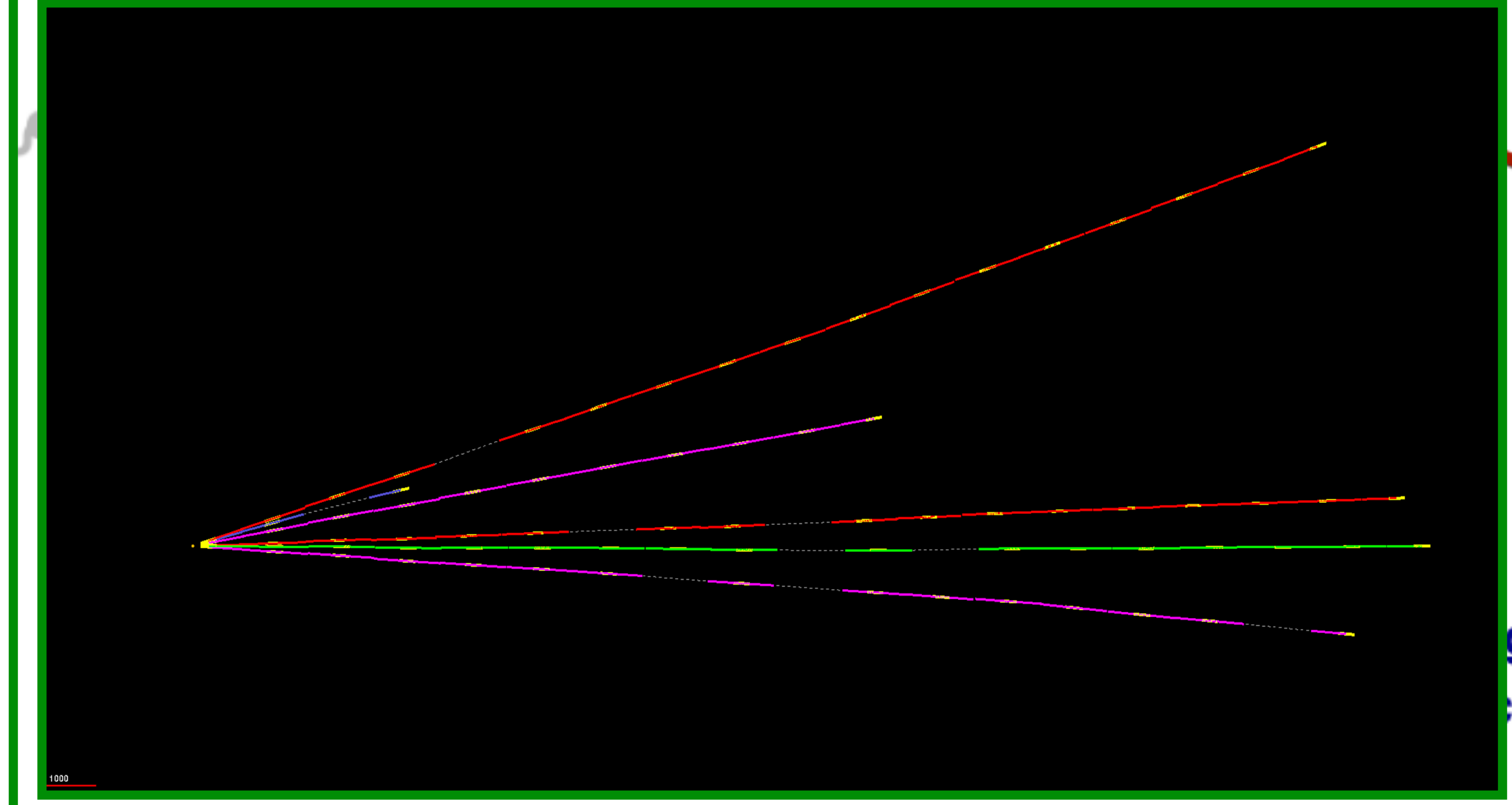
SND@LHC PHYSICS GOALS

3. Neutrino interactions



PRL 122 (2019) 041101





Neutrino interactions

- Measure **neutrino interactions** in unexplored ~TeV energy range
  - Large yield of ν_τ will likely double existing data
    - About 20 events observed by DONuT and OPERA
    - 7 astrophysical ν_τ candidates observed by IceCube

THE SND@LHC CONCEPT

Hybrid detector optimised for the identification of three neutrino flavours and for the detection of feebly interacting particles

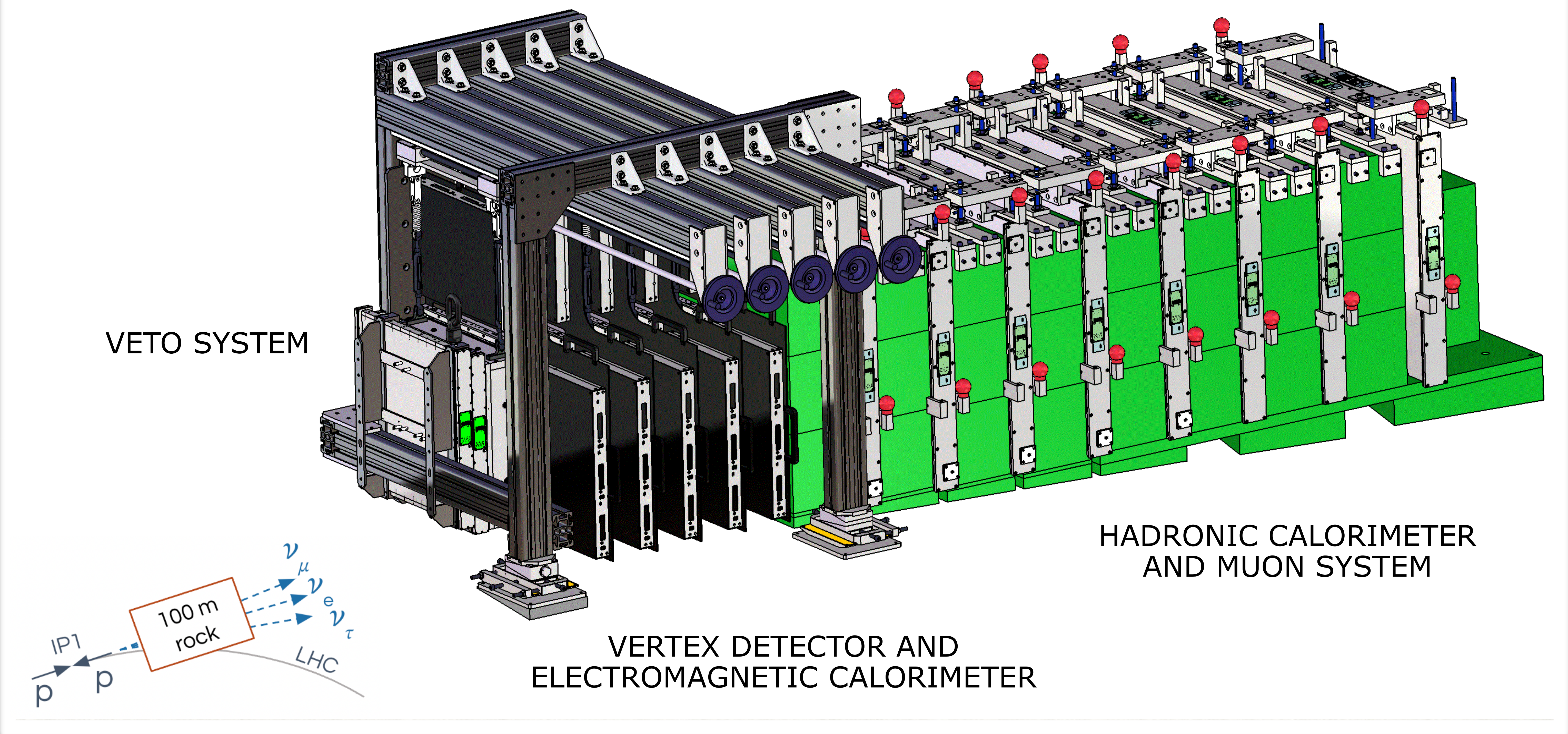
VETO PLANE:
- two (2022–2023) / three (2024-) 1 cm-thick scintillator planes

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-thick Fe blocks + scintillator planes
- Last 3 planes have finer granularity to track muons
- 9.5 λ_{int}

OFF-AXIS LOCATION
- Rapidity range: 7.2 < η < 8
- Enhances ν flux with **charm** origin

JINST 19 (2024) P05067



EXPERIMENT TIMELINE

August 2020

Scattering and Neutrino Detector at the LHC

Letter of Intent

January 2021

TECHNICAL PROPOSAL

SND@LHC

March 2021

CERN approves new LHC experiment

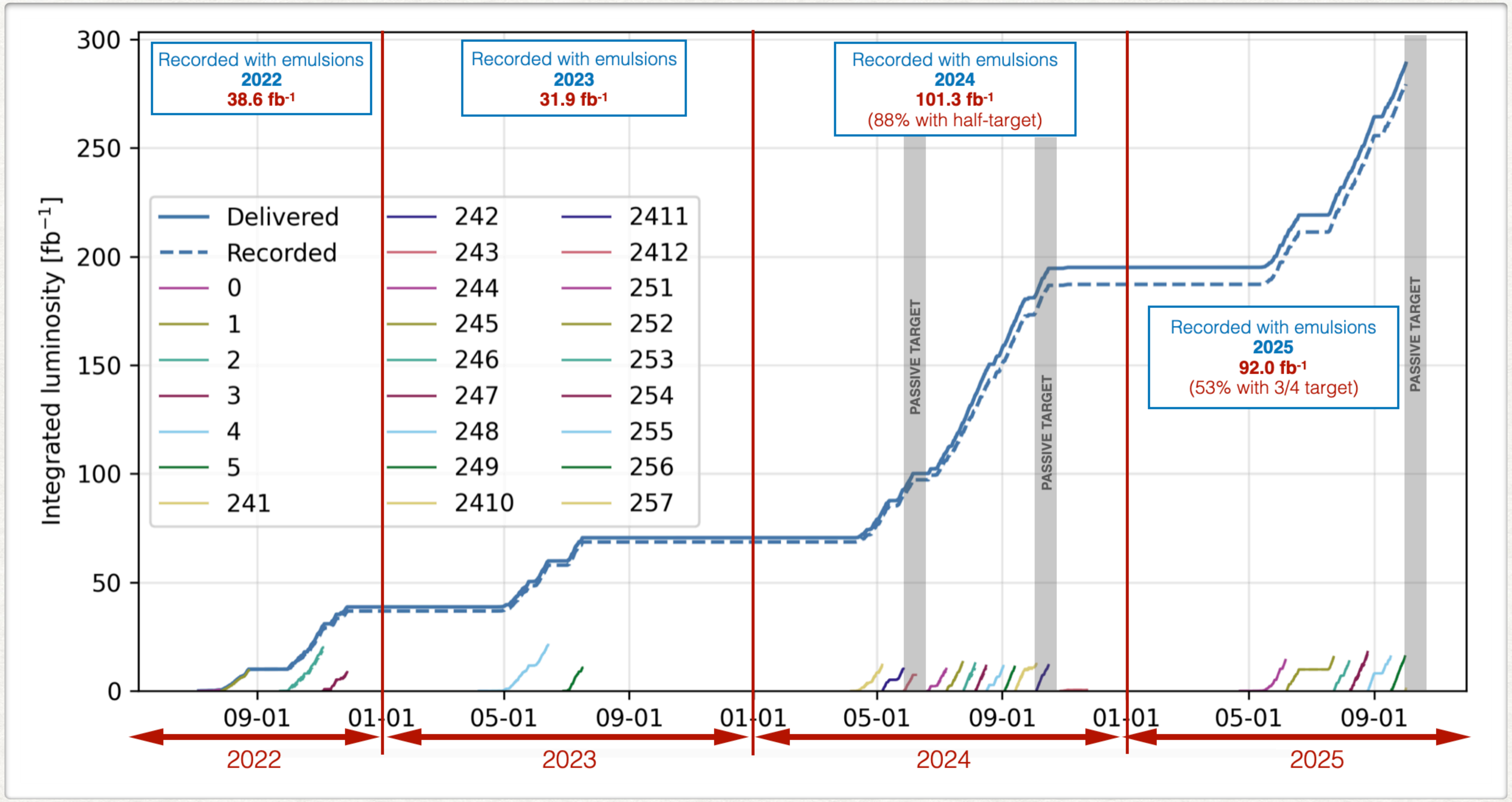
SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility's ninth experiment

September 2021

December 2021

March 2022

DATA TAKING IN RUN3



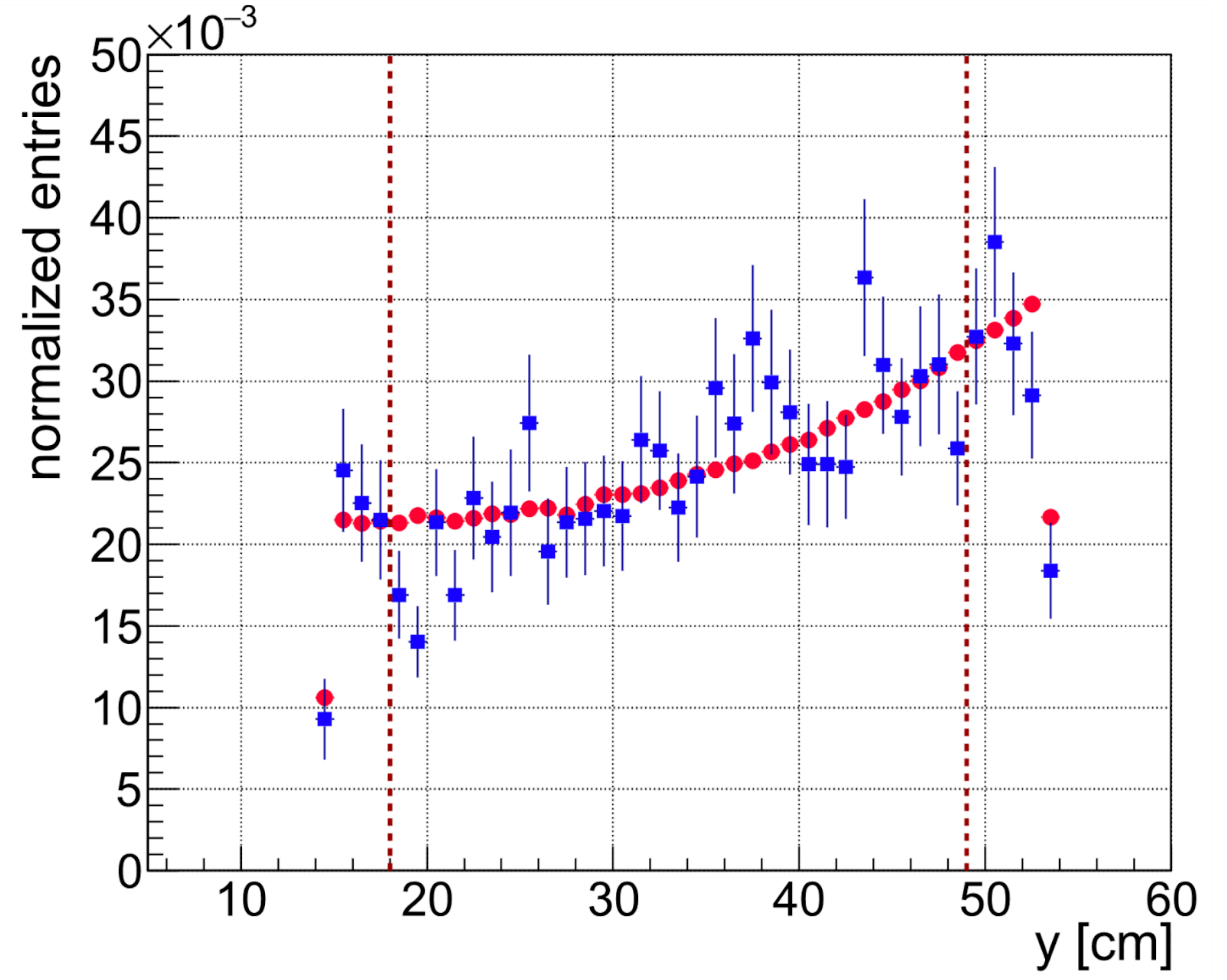
- Delivered luminosity in 2022-2025: 306.9 fb^{-1}
- Integrated luminosity in 2022-2024: 297.2 fb^{-1}
- 20 emulsion targets exposed (215 m^2)

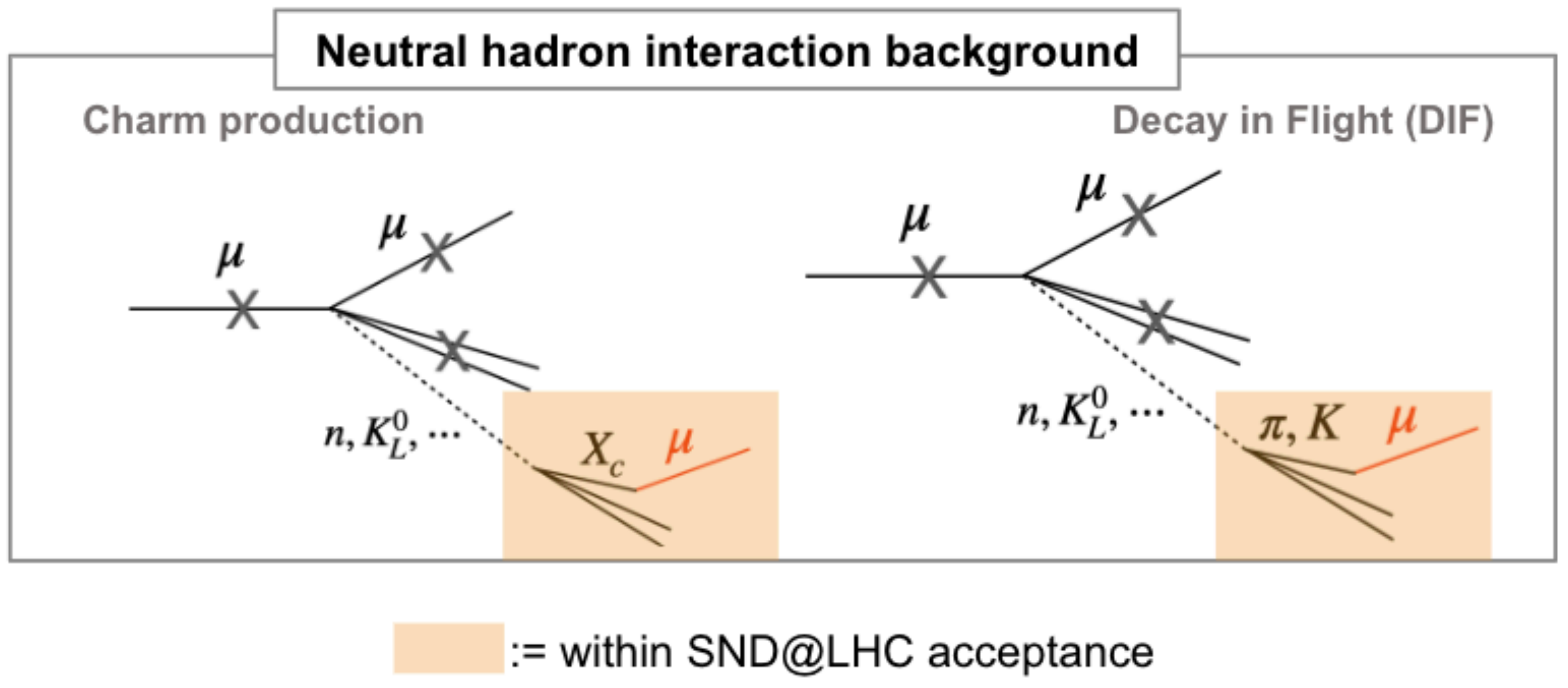
97% efficiency

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

MUON NEUTRINO OBSERVATION

PRL 131 (2023) 031802

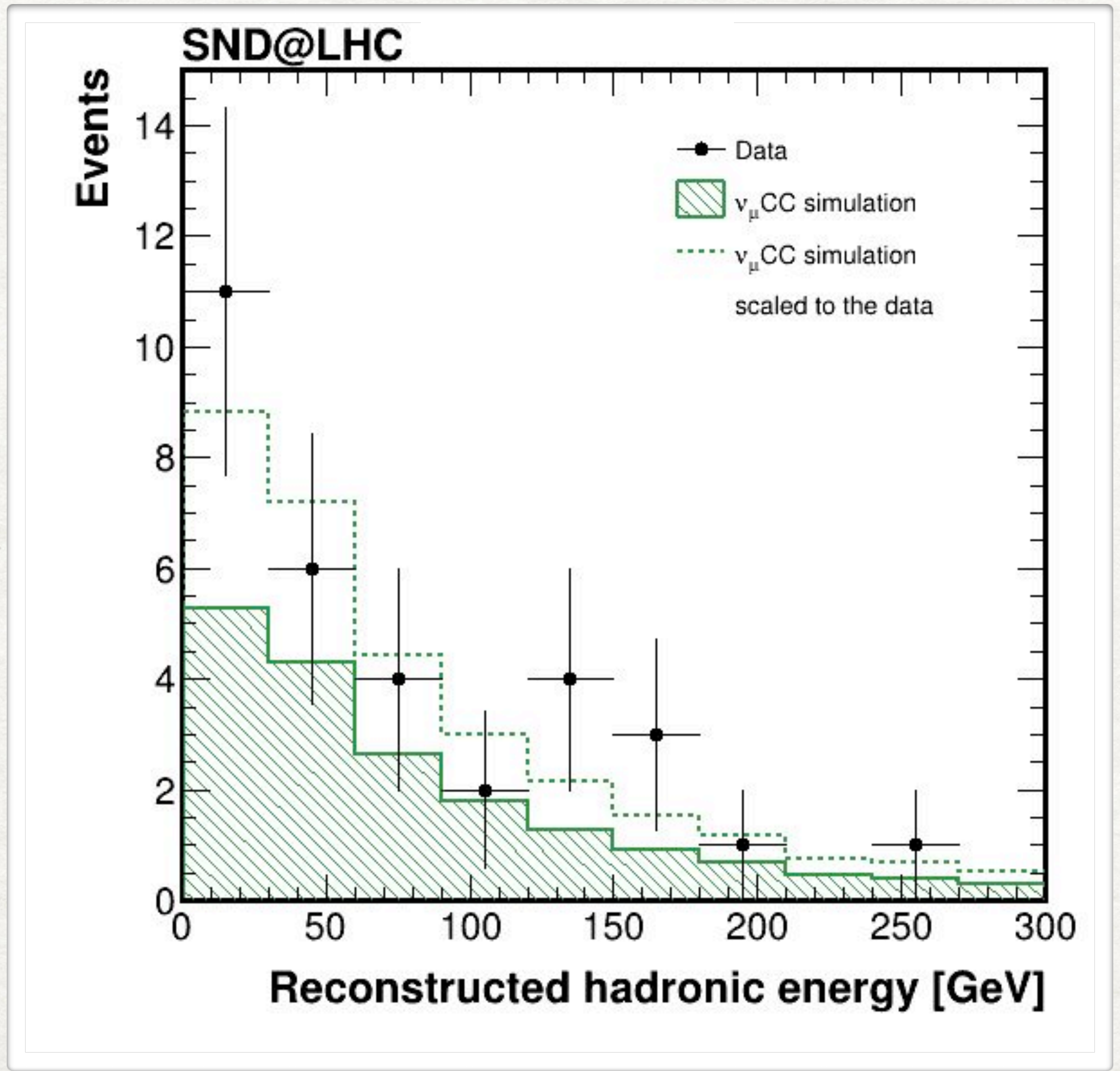
- First observation of muon neutrinos produced at colliders based on **2022** data published last year
- **8** observed **ν_μ candidates**
- Observation significance **7σ**

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

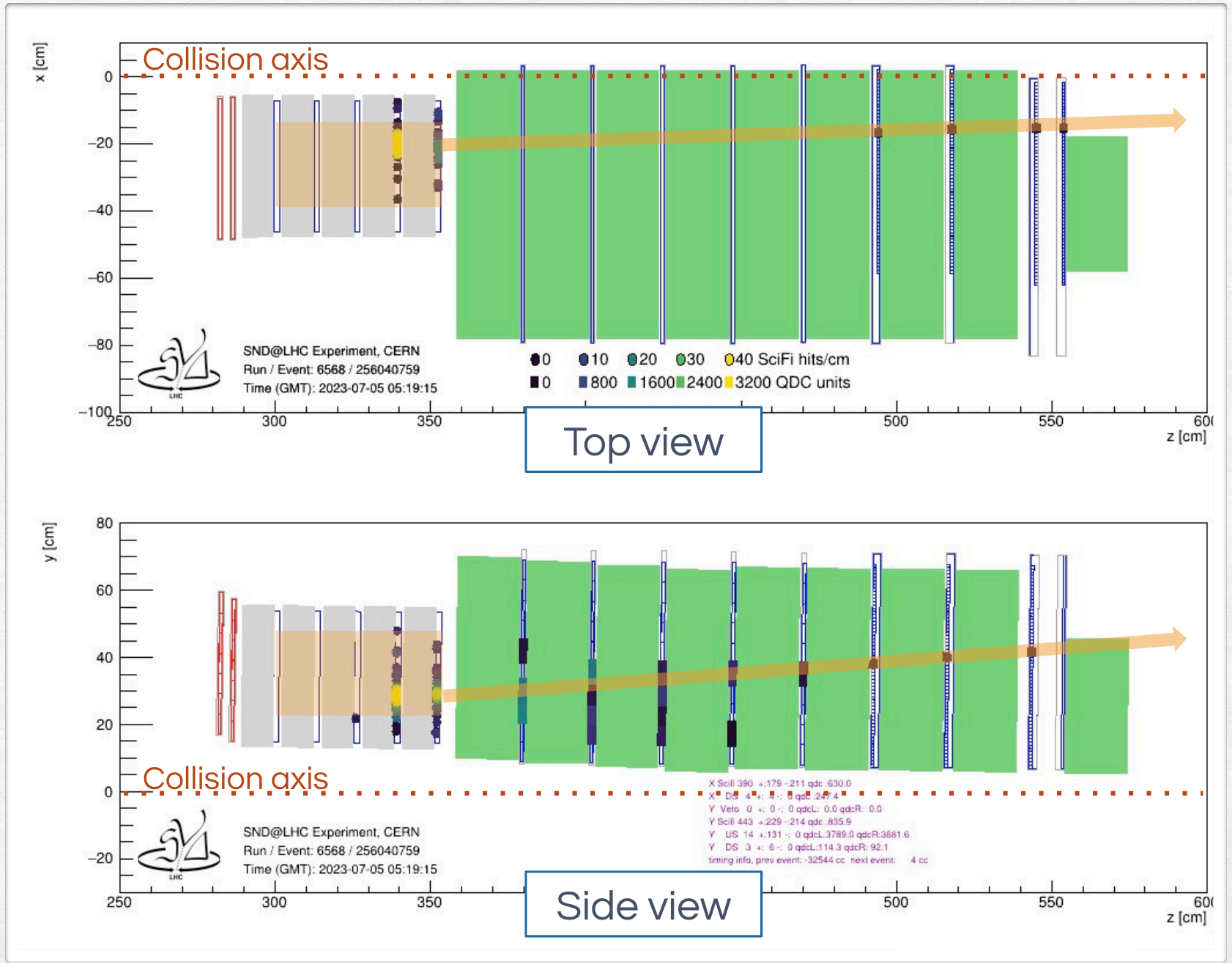
Editors' Suggestion

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

- Updated results using **2022+2023** data:
- **32** observed **ν_μ candidates**
- Measurement of the hadronic energy



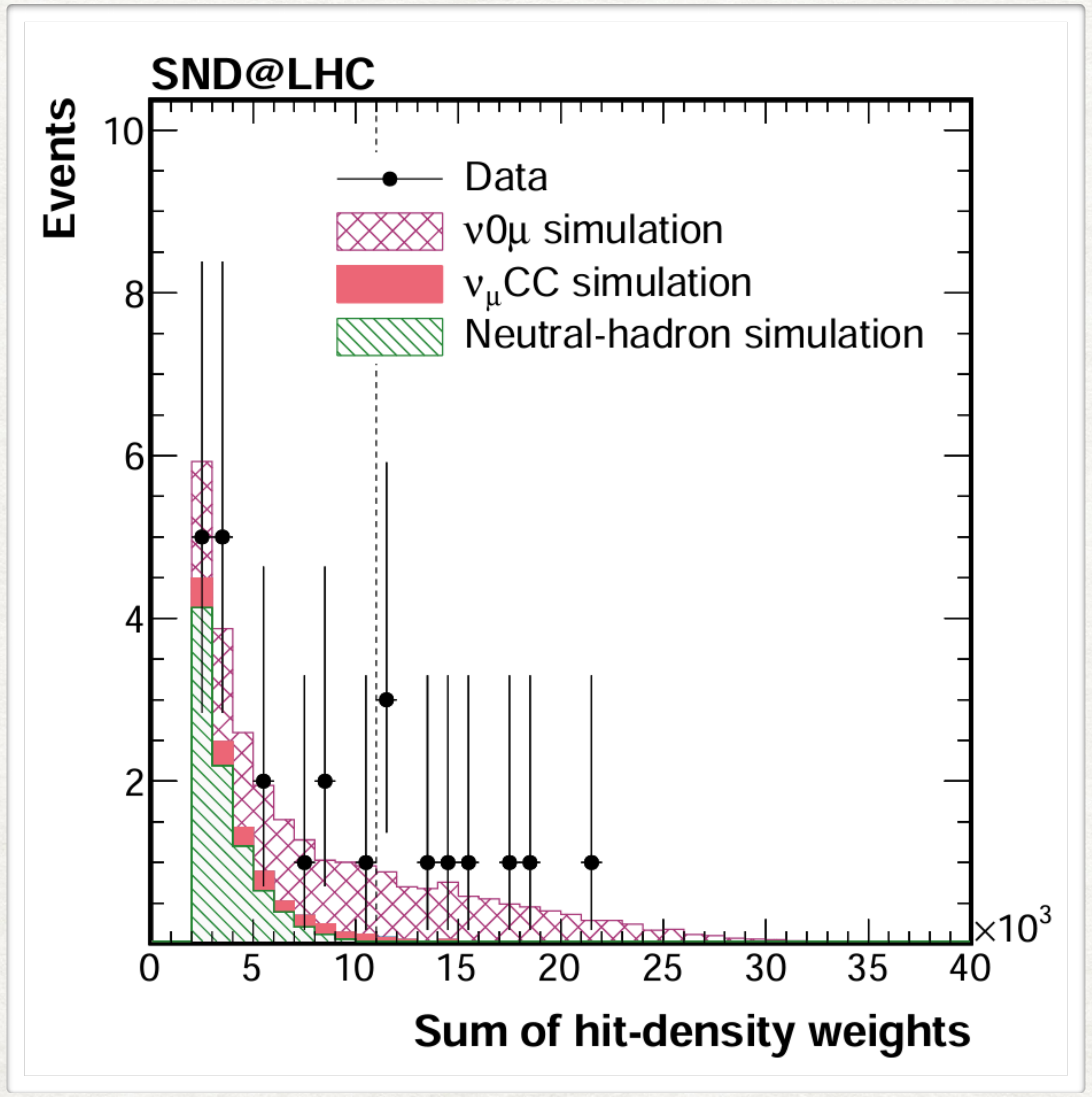
- Display of a ν_μ CC candidate event



0μ NEUTRINO OBSERVATION

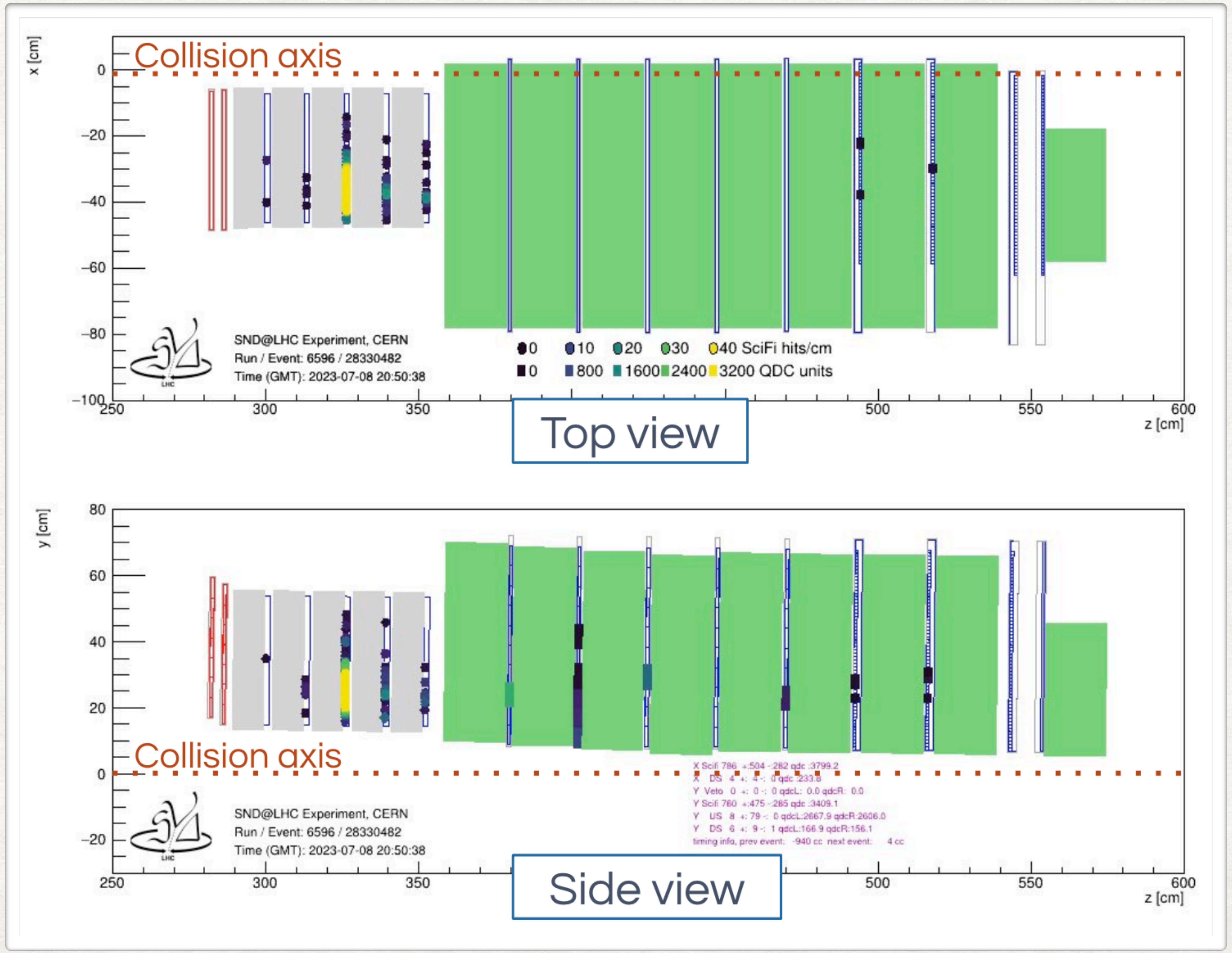
PRL 134 (2025) 231802

- First observation of neutrino interactions without a muon in the final state based on **2022-2023** data
- **9** observed **0μ ν-candidates**
- Observation significance **6.4σ**
- Evidence for **ν_e interactions** at 6.1σ



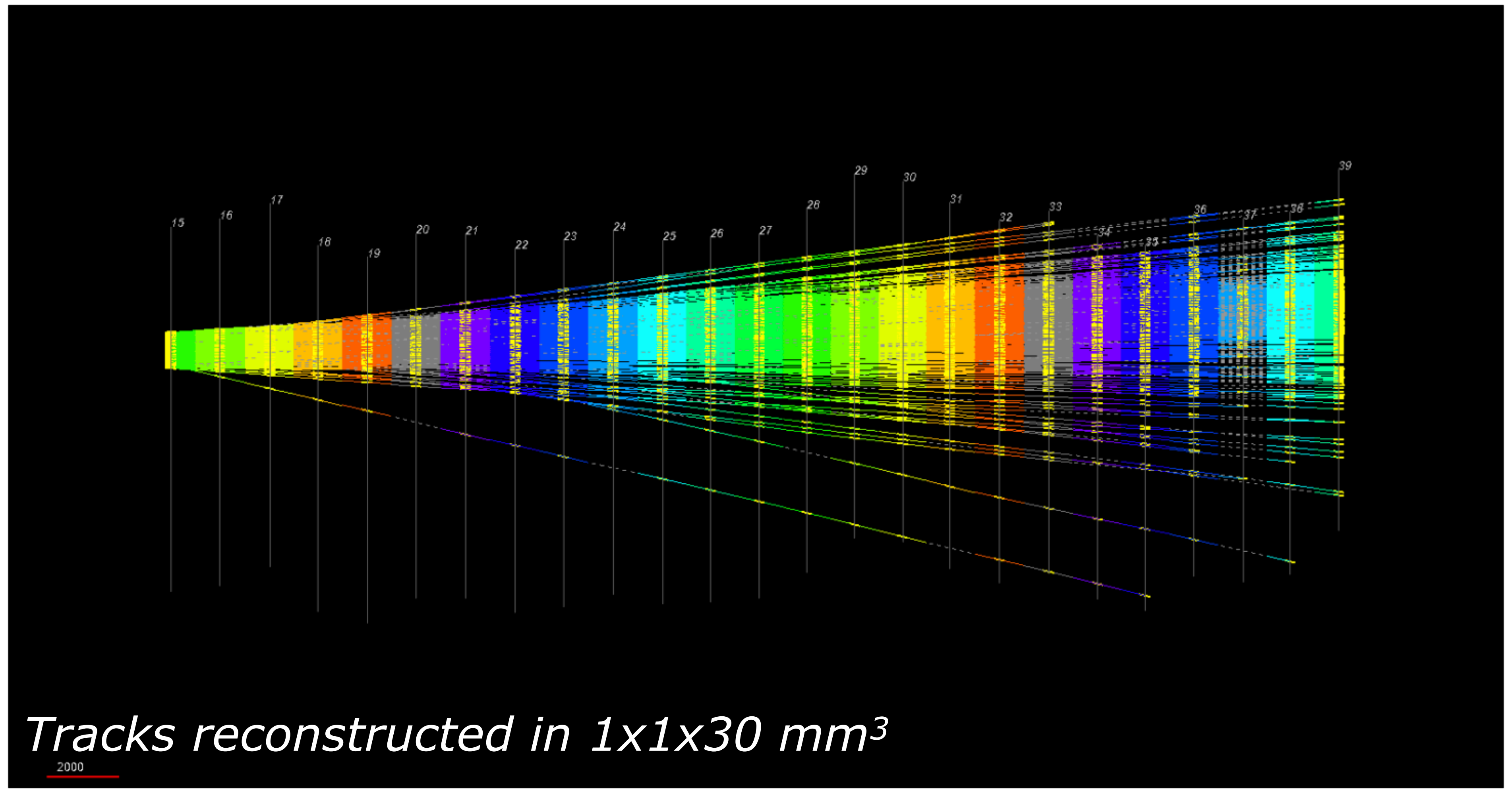
Observation of collider neutrinos without final state muons with the SND@LHC experiment

- Display of a 0μ ν-candidate event



EMULSION SCANNING AND ANALYSIS

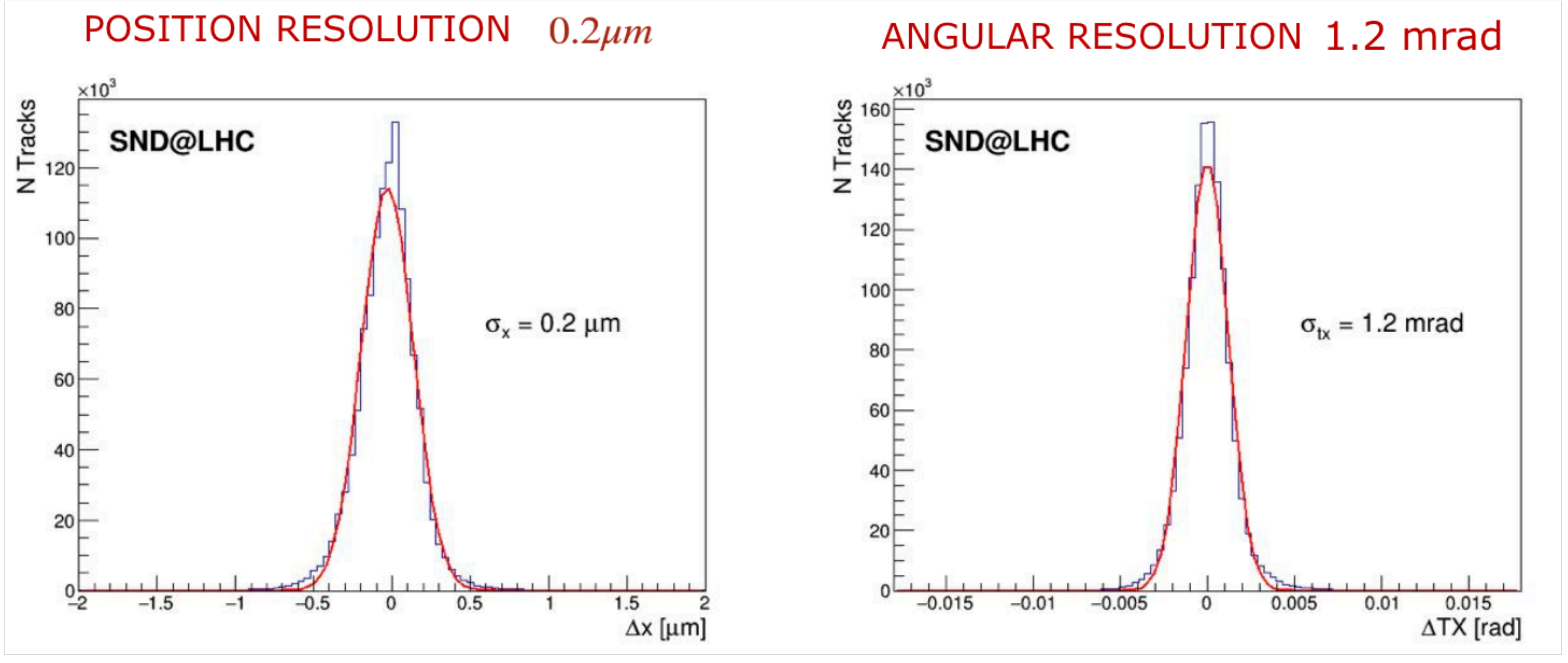
- Emulsion scanning is performed with fully automated microscopes in seven laboratories: CERN, Bologna, Napoli, Nagoya, Gran Sasso, Salerno, Santiago
- Track density up to 4×10^5 tracks/cm^2
- Full revision of alignment, tracking, vertexing procedures

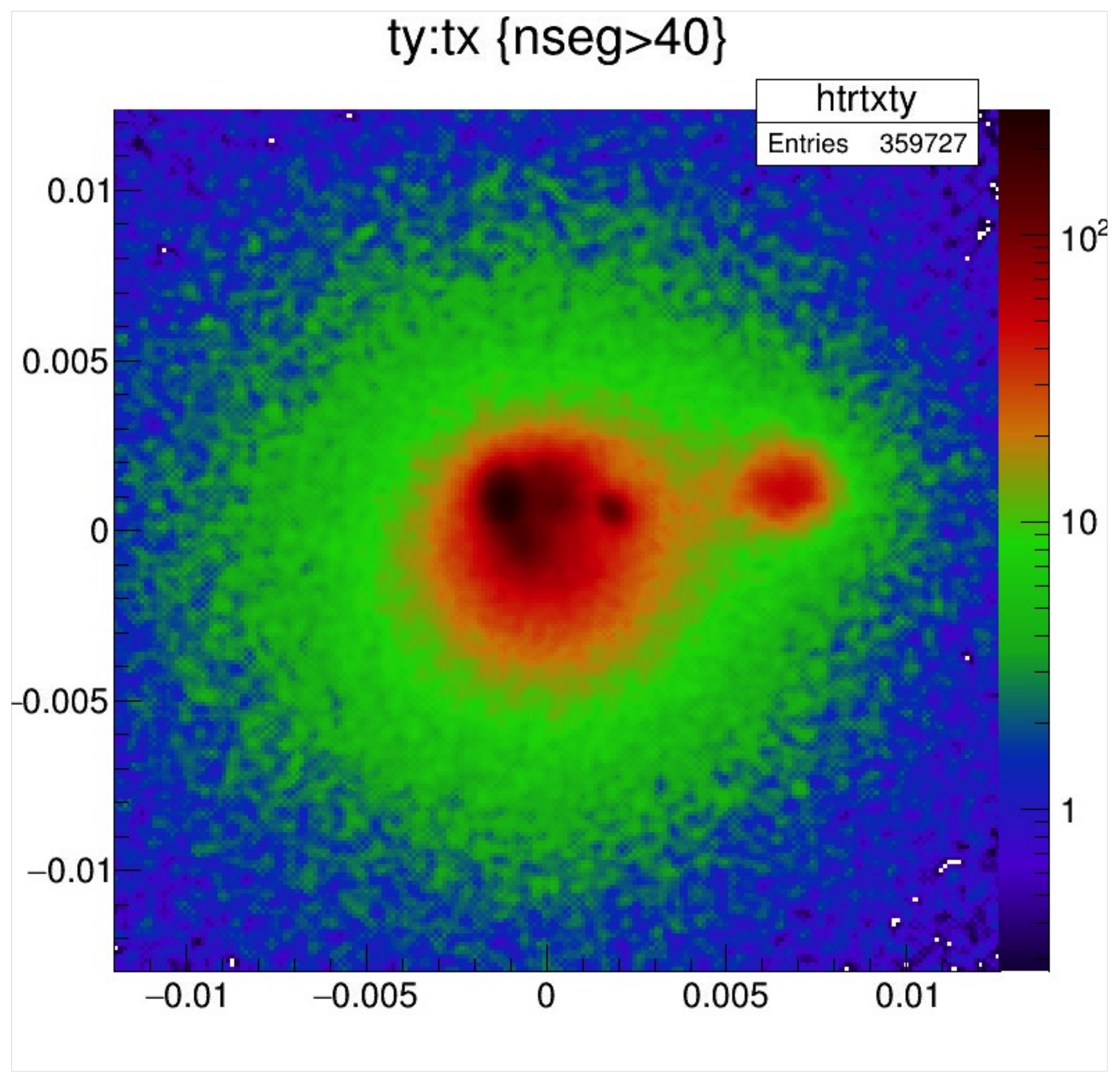


Tracks reconstructed in 1x1x30 mm^3

Status of emulsion scanning:
800 kg x 55 fb^{-1}

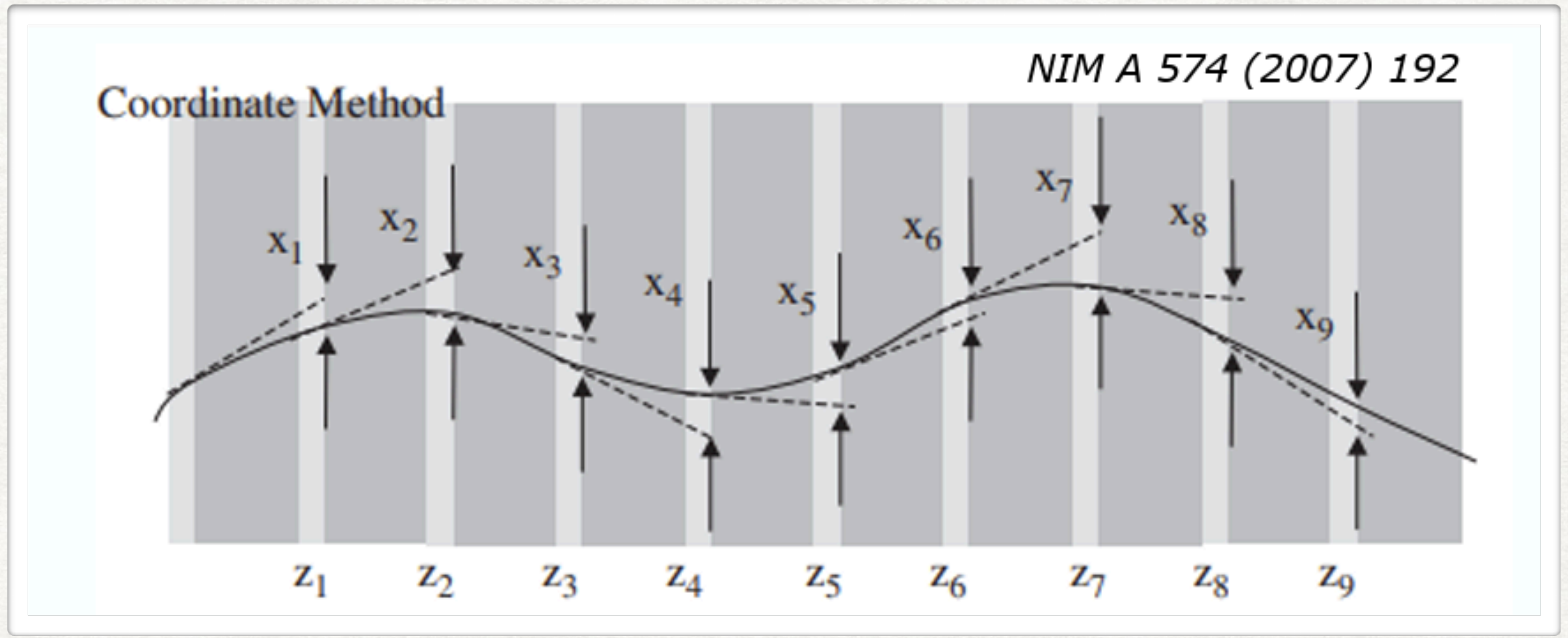
Angular distribution of reconstructed muon tracks

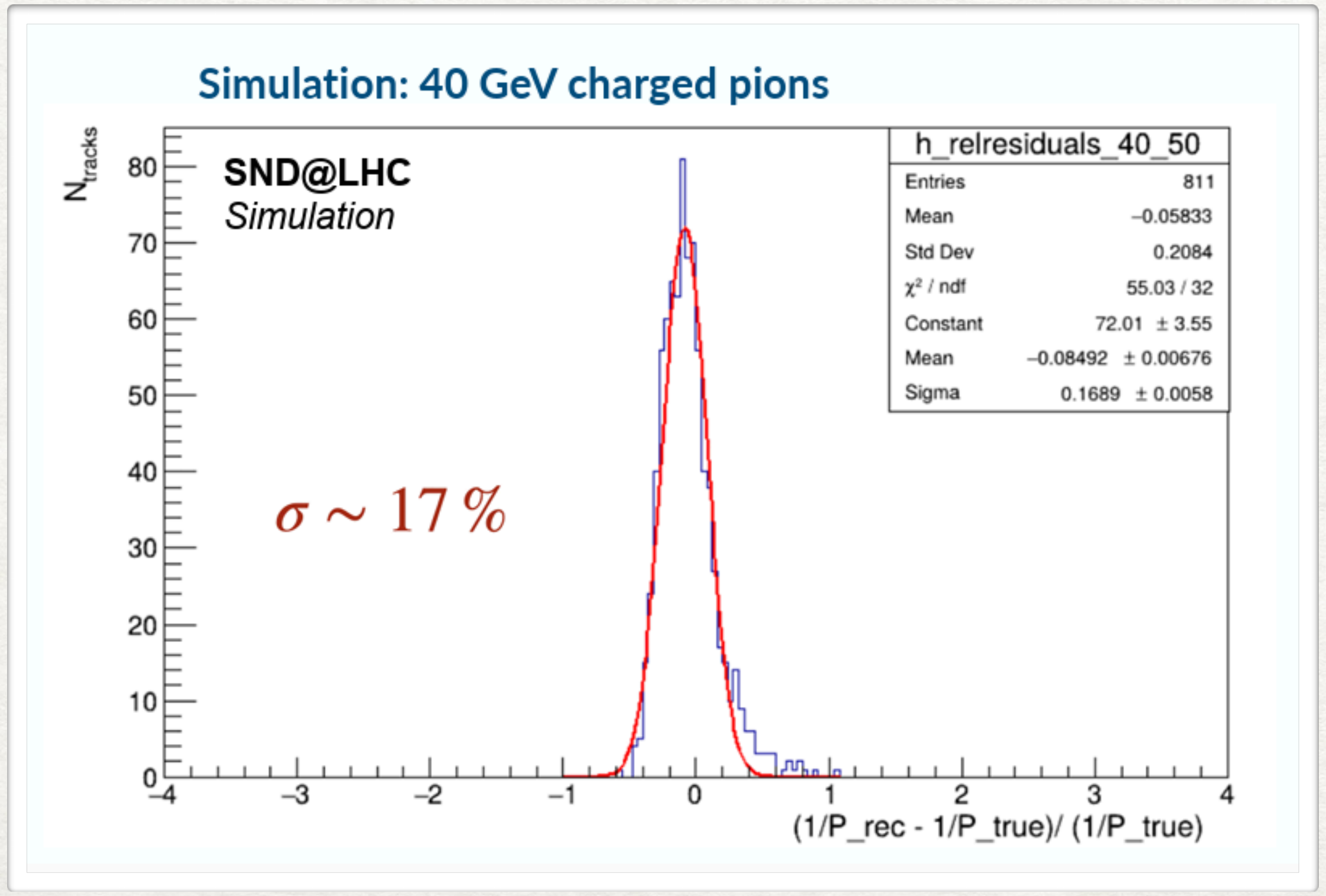


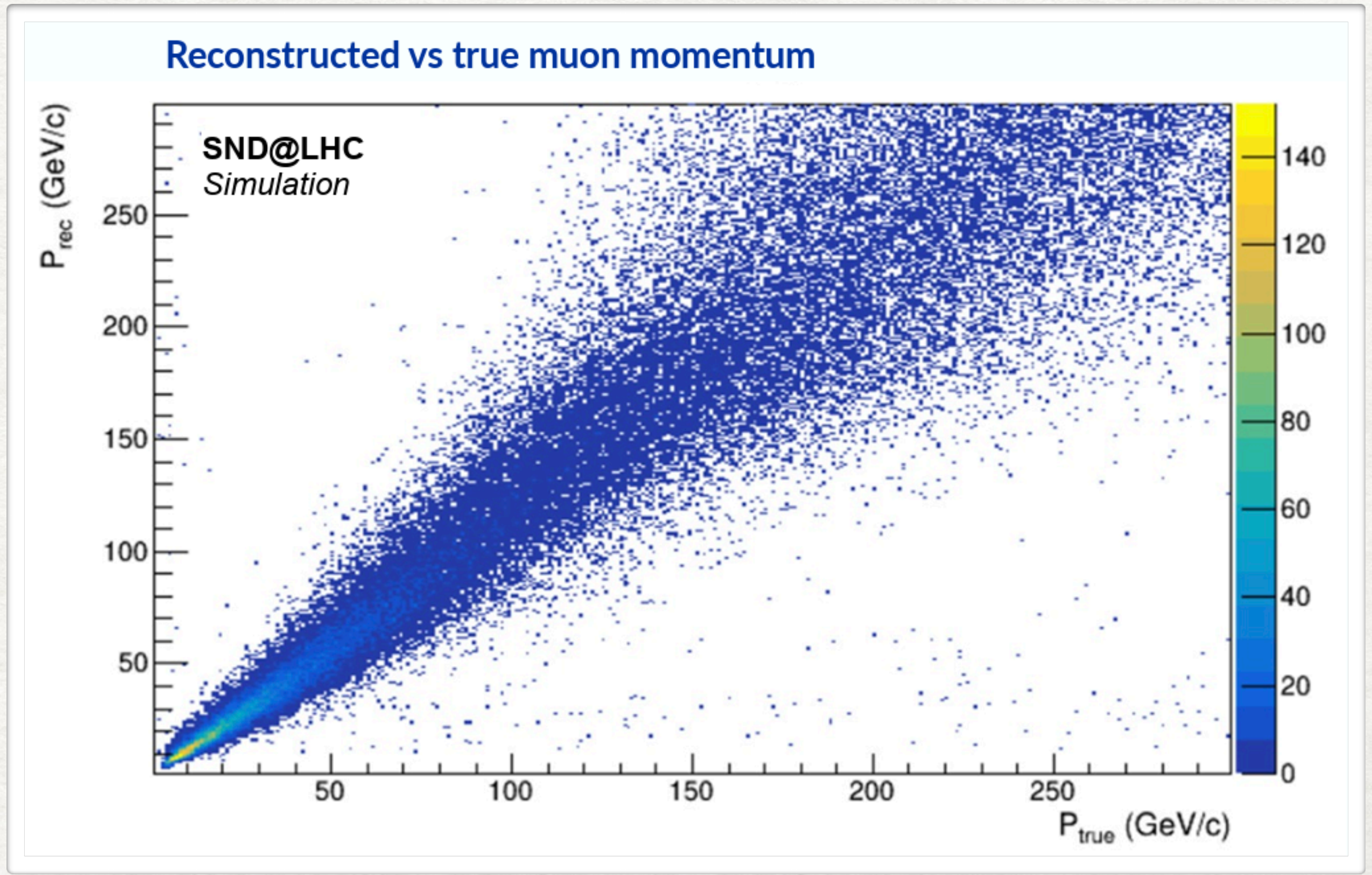


MOMENTUM MEASUREMENT IN EMULSION

- Momentum measurement of charged particles
- Deflection induced by MCS used to infer particle's momentum
- Estimated resolution on charged pions: 15÷25%
- Neutrino energy has a strong correlation with the reconstructed momentum of charged particles at the primary vertex
- Neutrino energy resolution 20÷40%

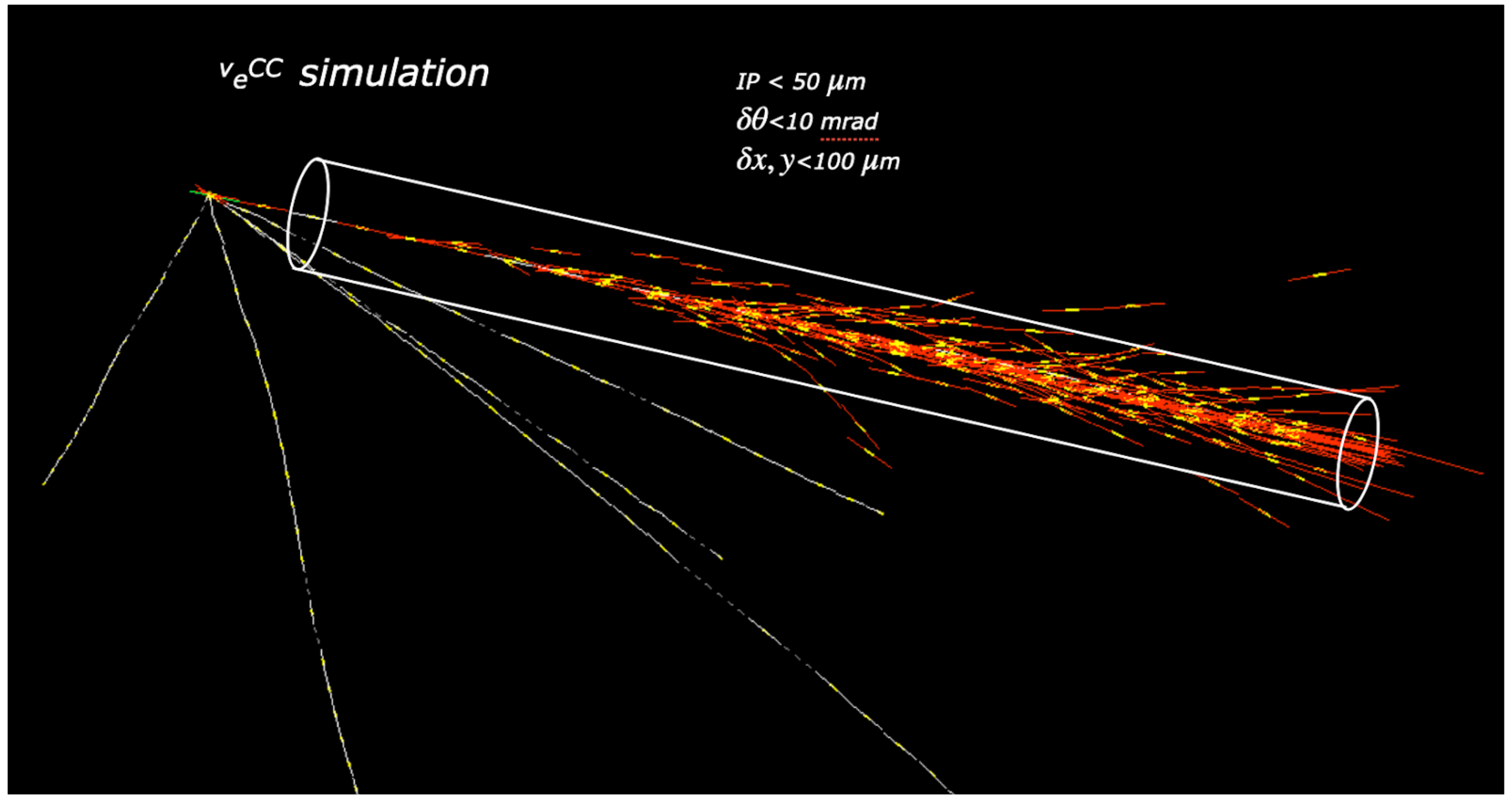






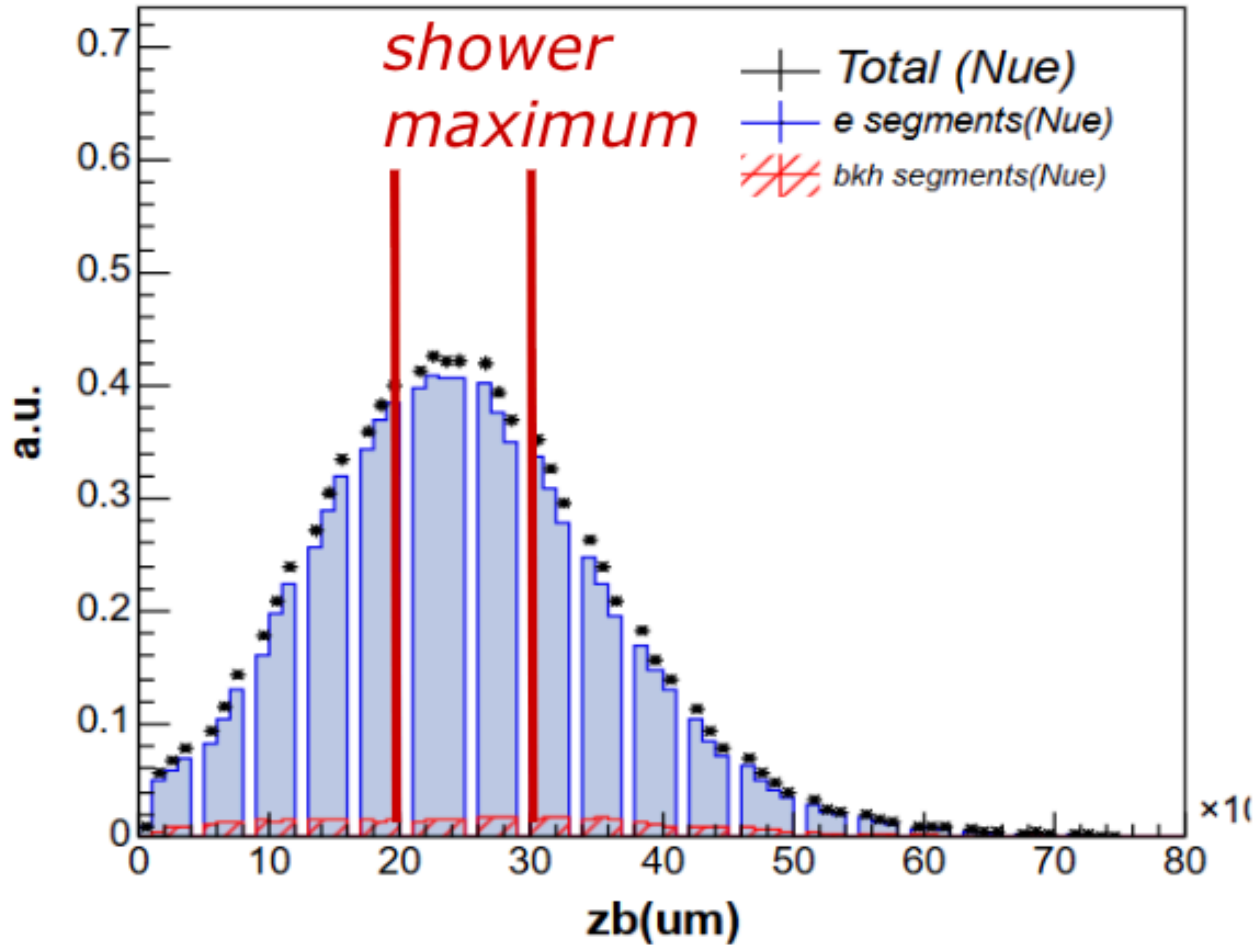
ELECTRON ID AND ENERGY MEASUREMENT

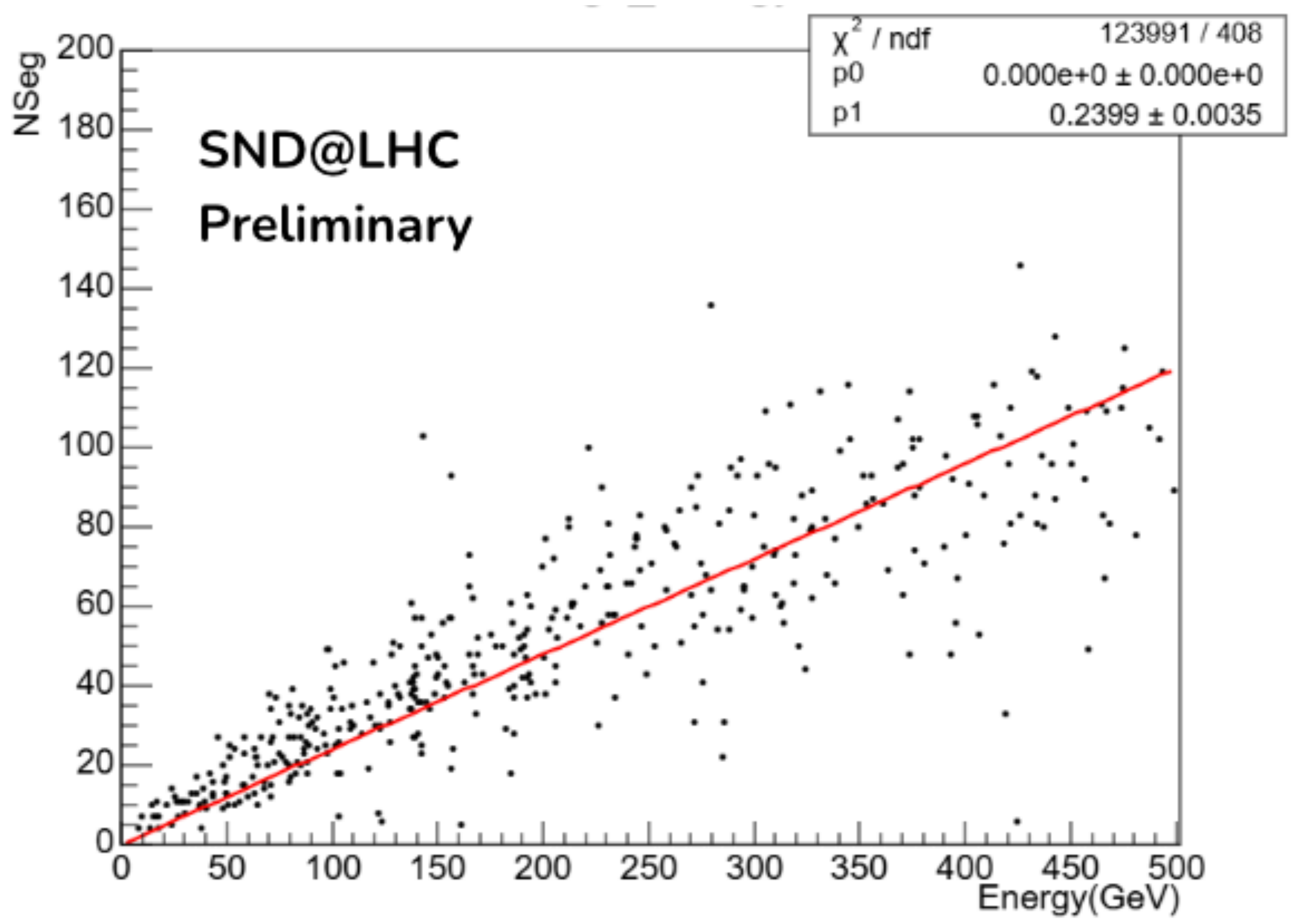
- Electron ID based on em shower identification
- Electron energy estimate based on calorimetric measurement

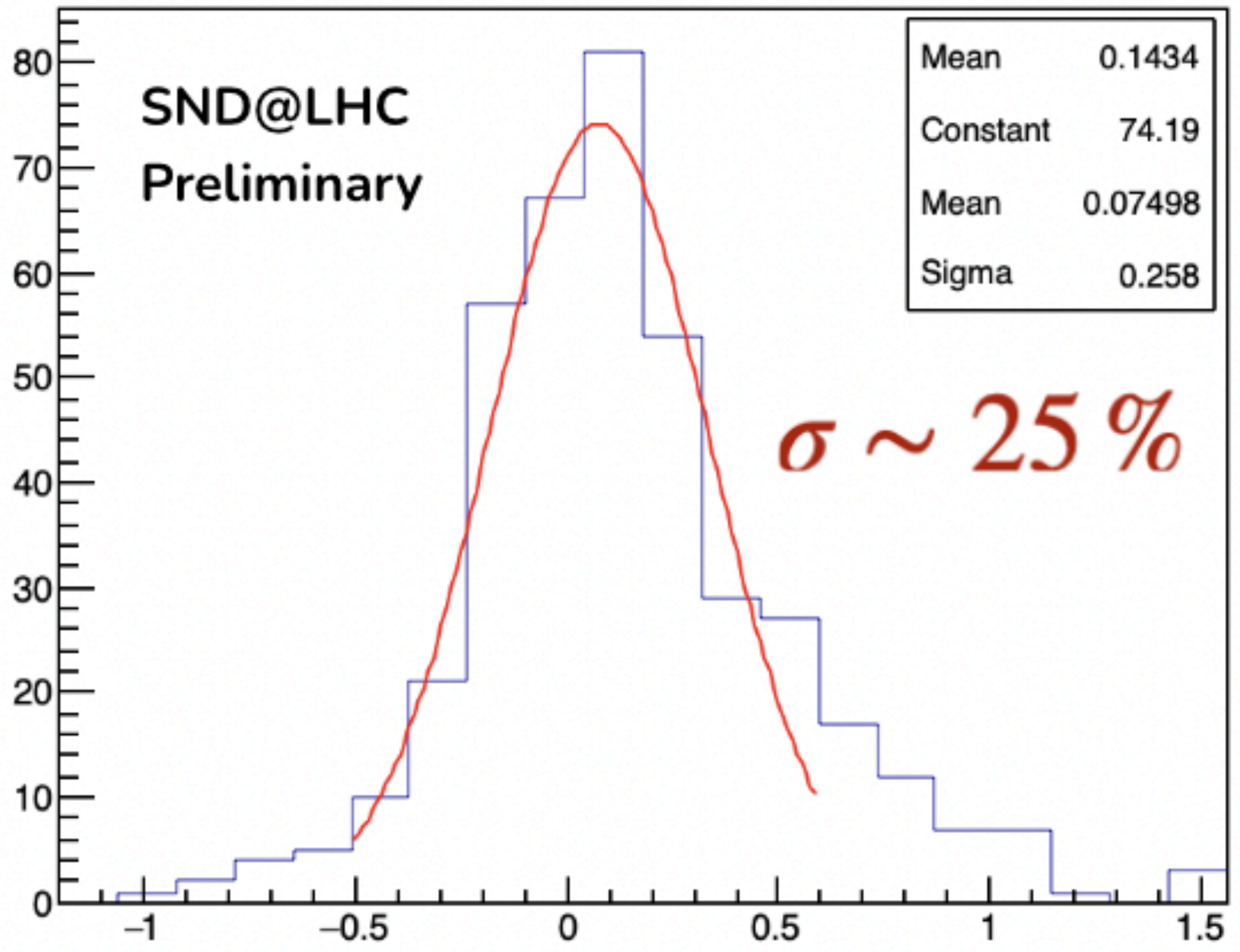


- Number of segments at the shower maximum proportional to electron energy

- Electron energy resolution

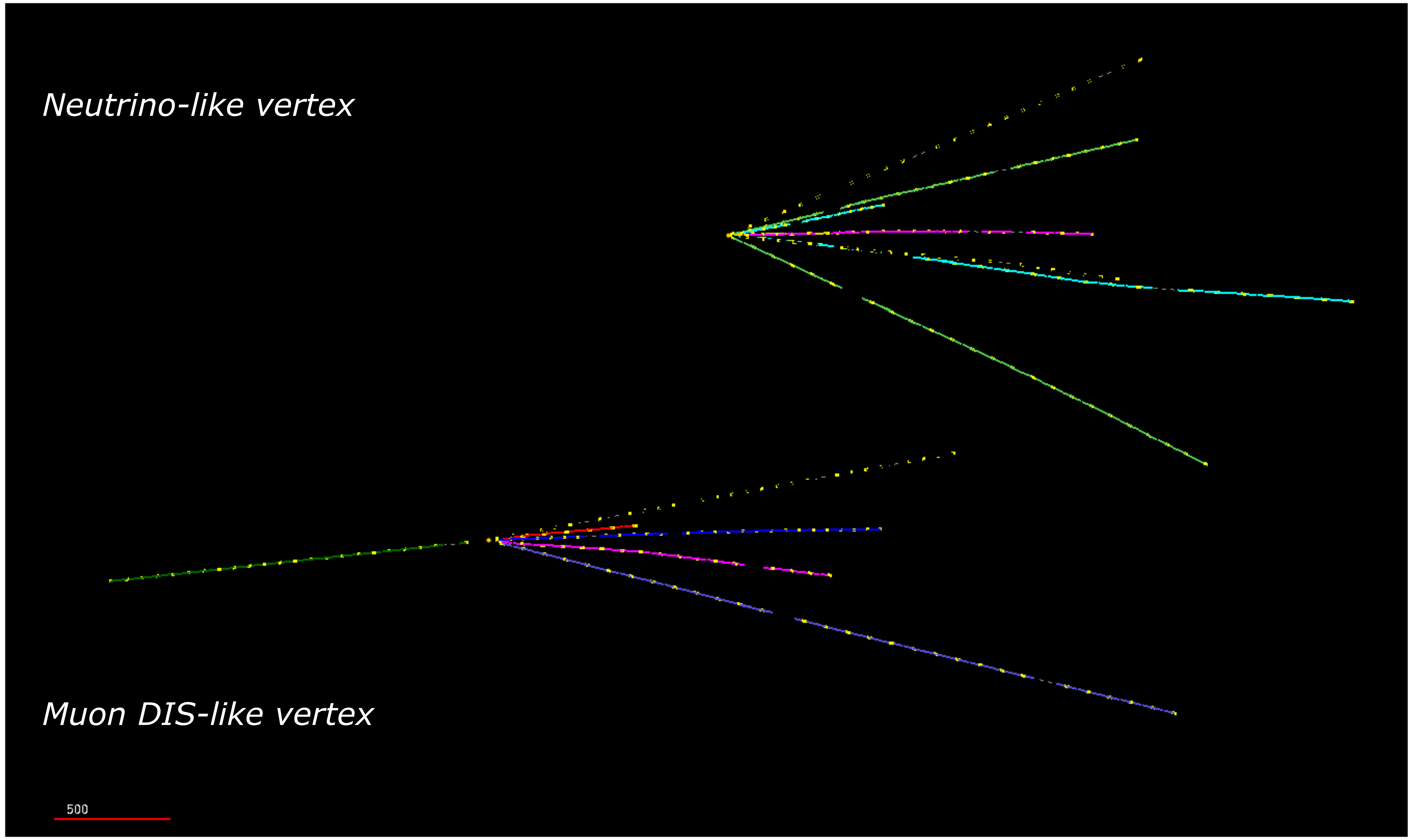


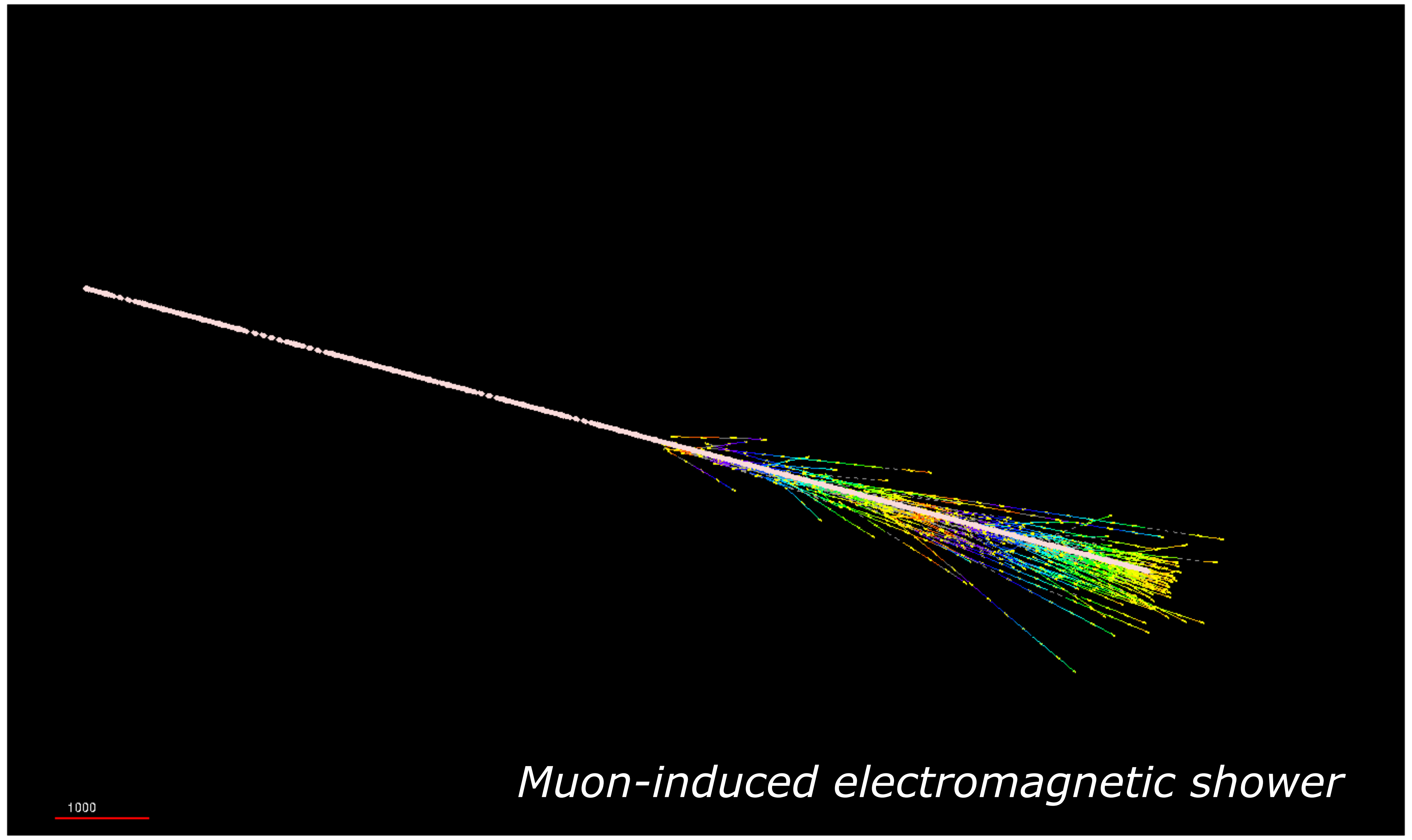




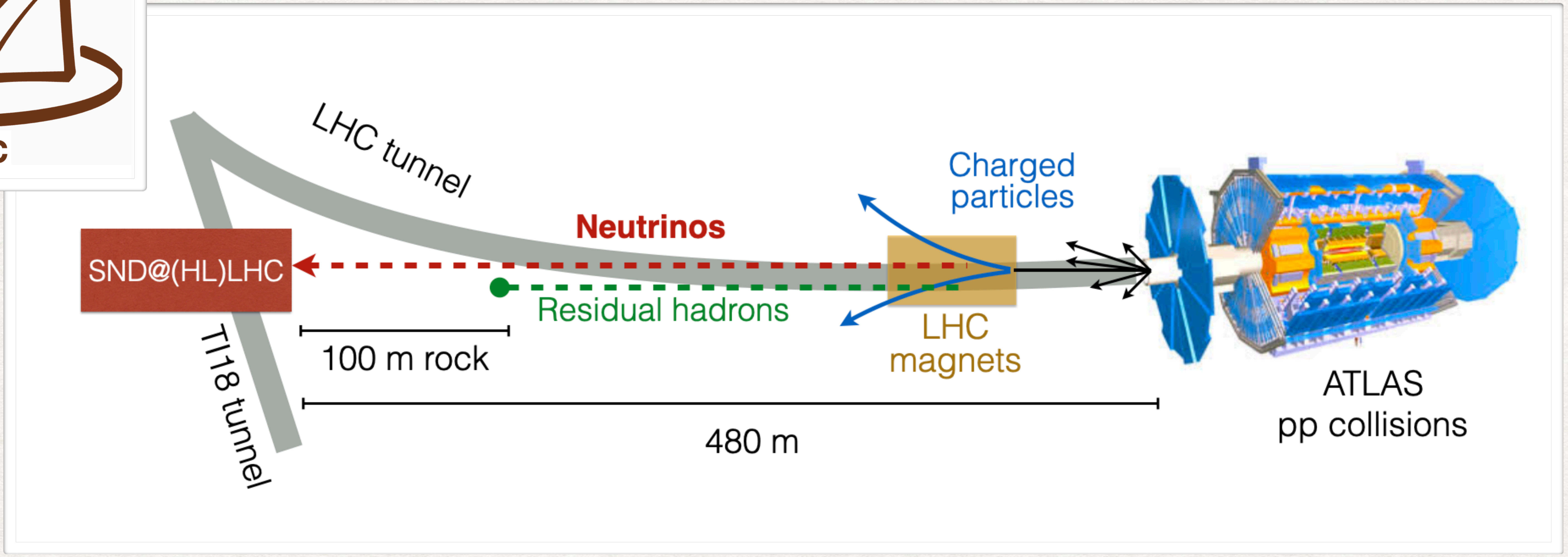
EMULSION DATA RECONTRUCTION

- Reconstruction of neutral and charged vertices
- Identification of electromagnetic showers





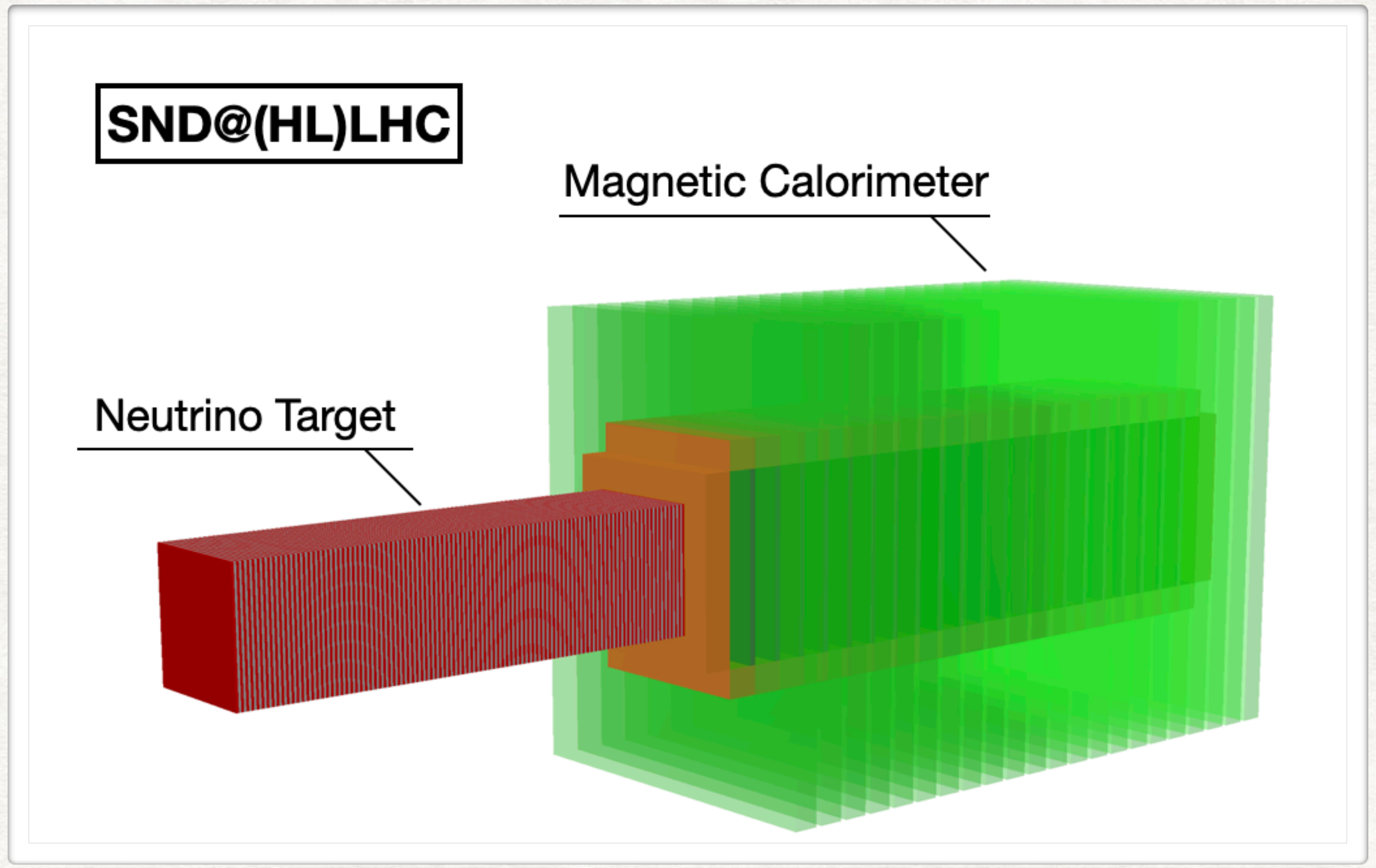
NEUTRINO PHYSICS AT THE **ENERGY** FRONTIER: **SND@LHC** IN HI-LUMI ERA



SND IN THE HI-LUMI ERA

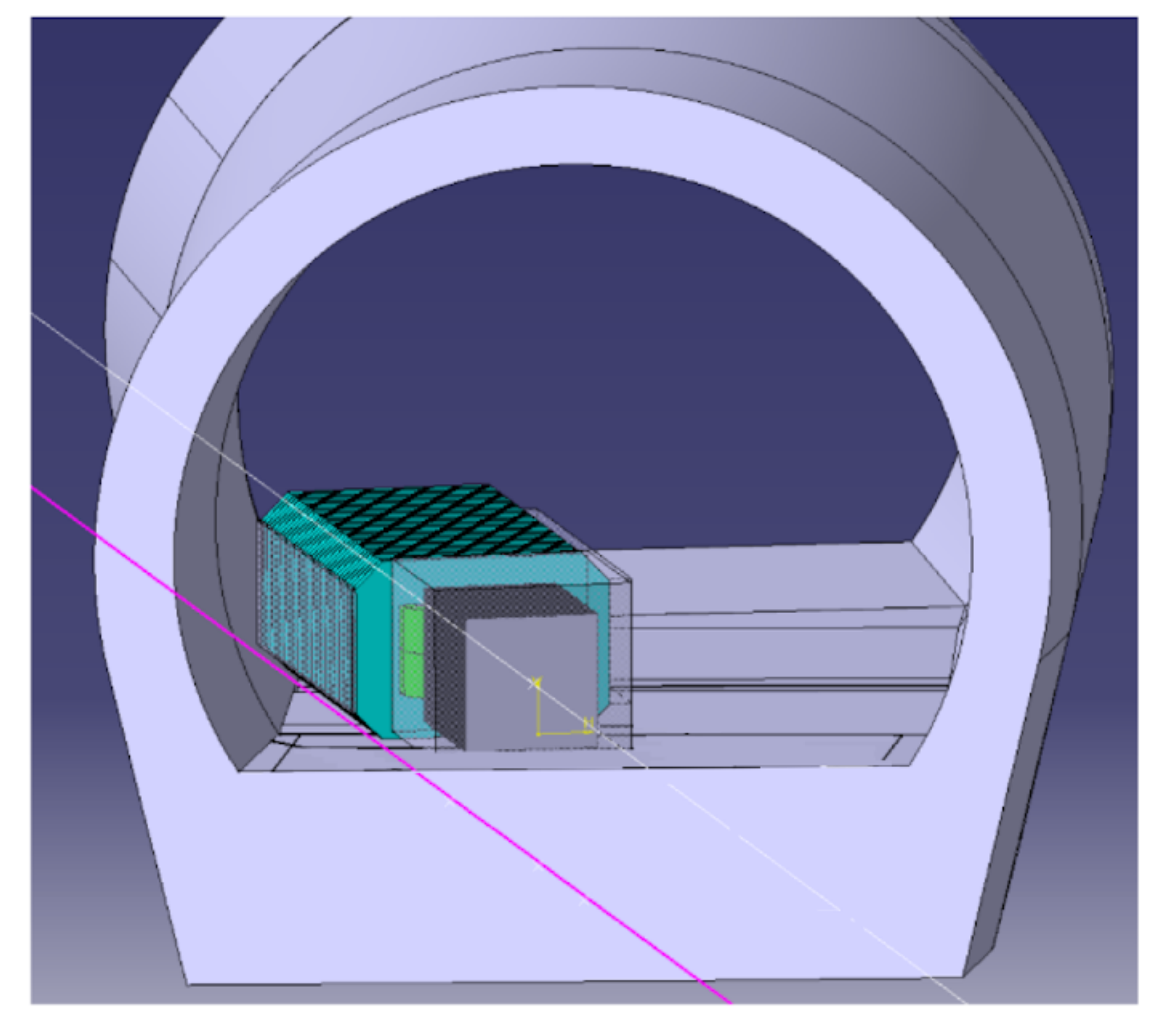
Motivation

- Exploit the High-Lumi LHC to perform neutrino physics measurements in the TeV energy range with unprecedented statistics
- Upgrade the SND@LHC detector to cope with high background rates
- Improve detector performances in energy measurement and charge separation



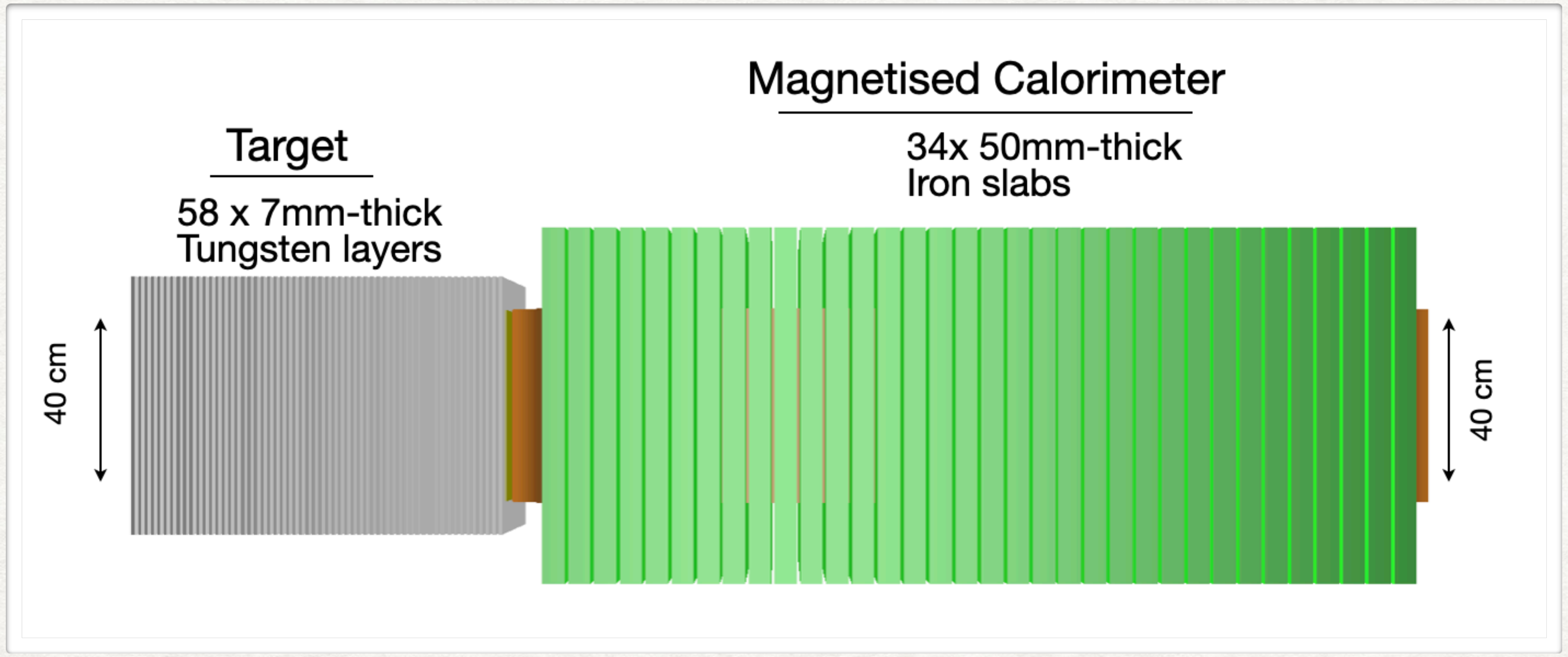
Main features of the detector

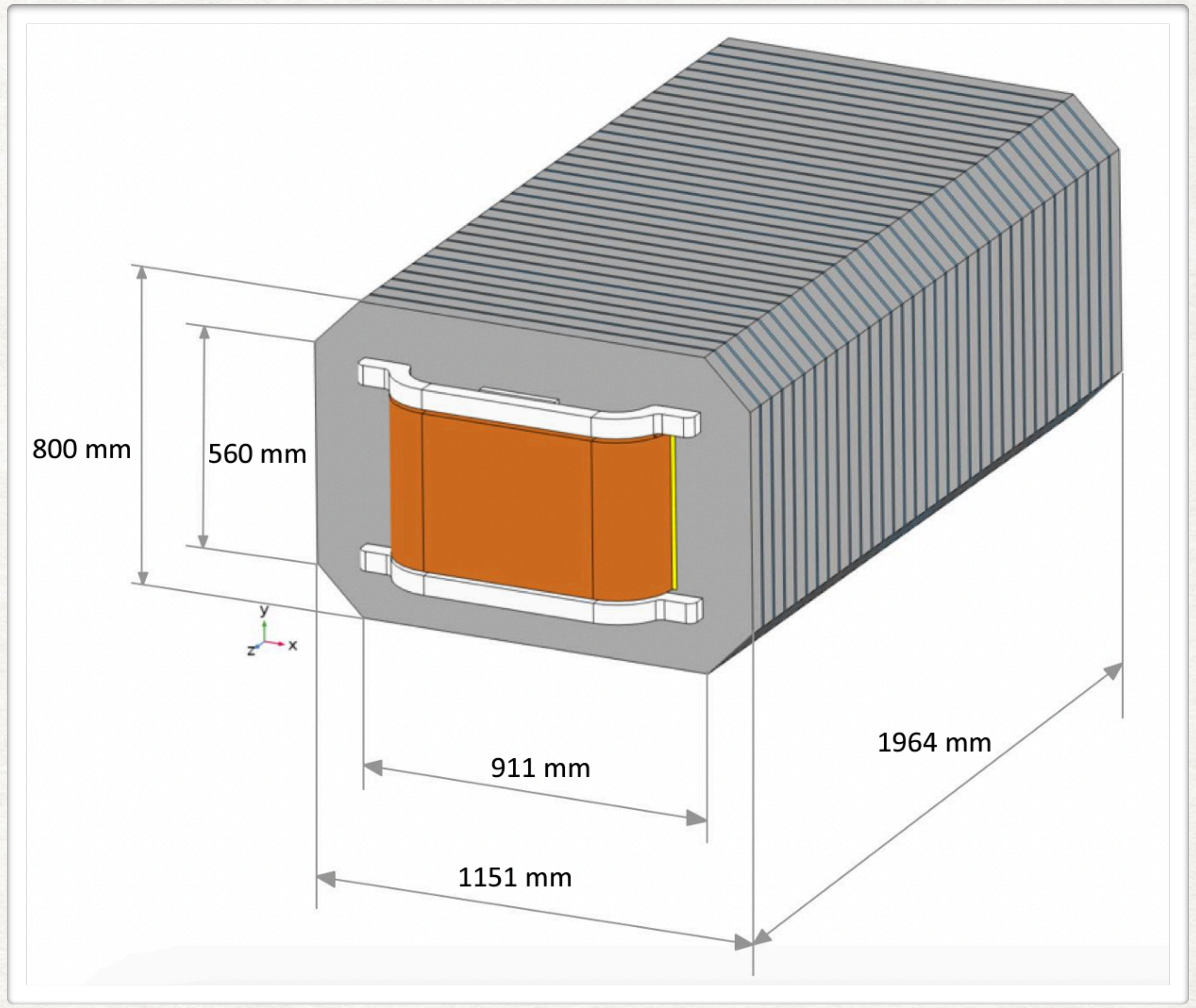
- Electronic vertex detector
- Silicon tracker as vertex detector
- Iron-core muon spectrometer
- Improved hadron calorimeter and timing detectors.



Letter of Intent: https://cds.cern.ch/record/2895224
Addendum: https://cds.cern.ch/record/2909524/
Technical Proposal: https://cds.cern.ch/record/2926288/

SND@HL-LHC: DETECTOR LAYOUT





TARGET

- Active surface: 40x40 cm^2
- Material: W
- Total mass: 1.3 tons
- Sensitive layers: Silicon strips

MAGNETIZED HCAL

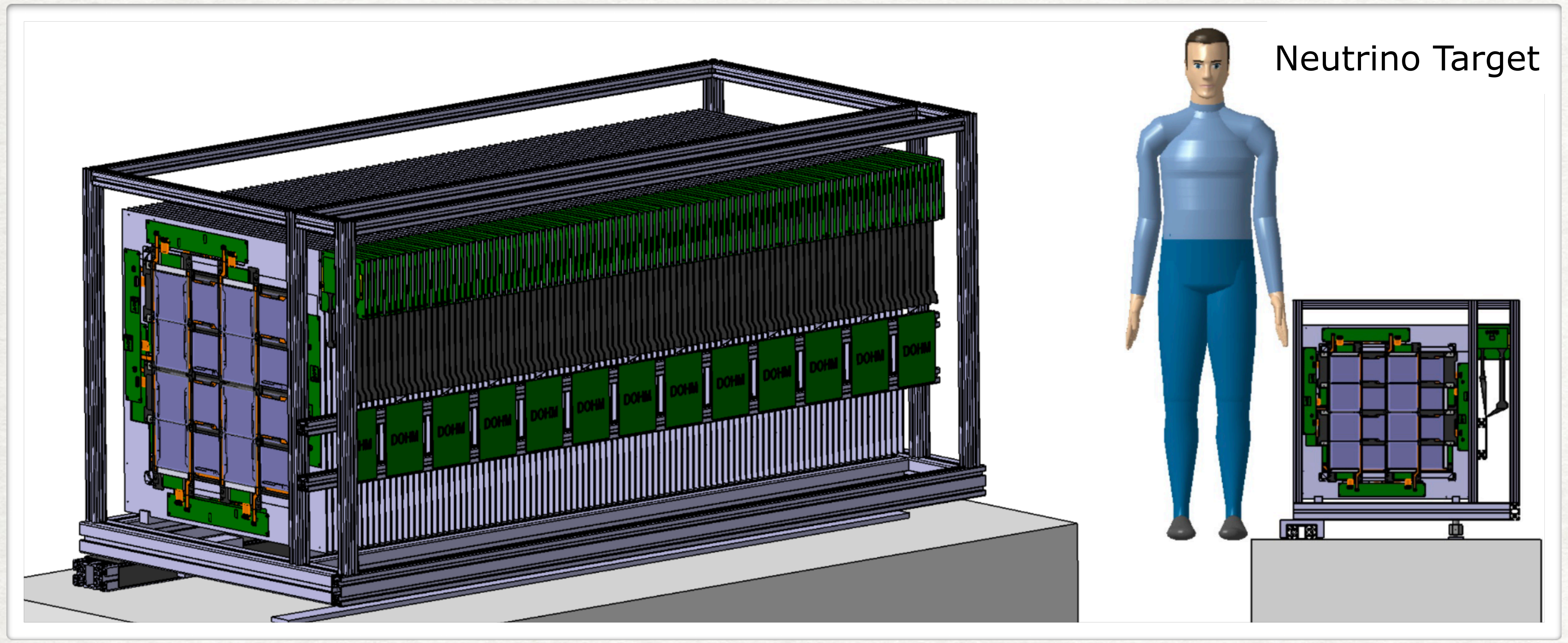
- Active surface: 40x40 cm^2
- Material: Fe
- Sensitive volume mass: 2.1 tons
- Sensitive layers: Silicon strips

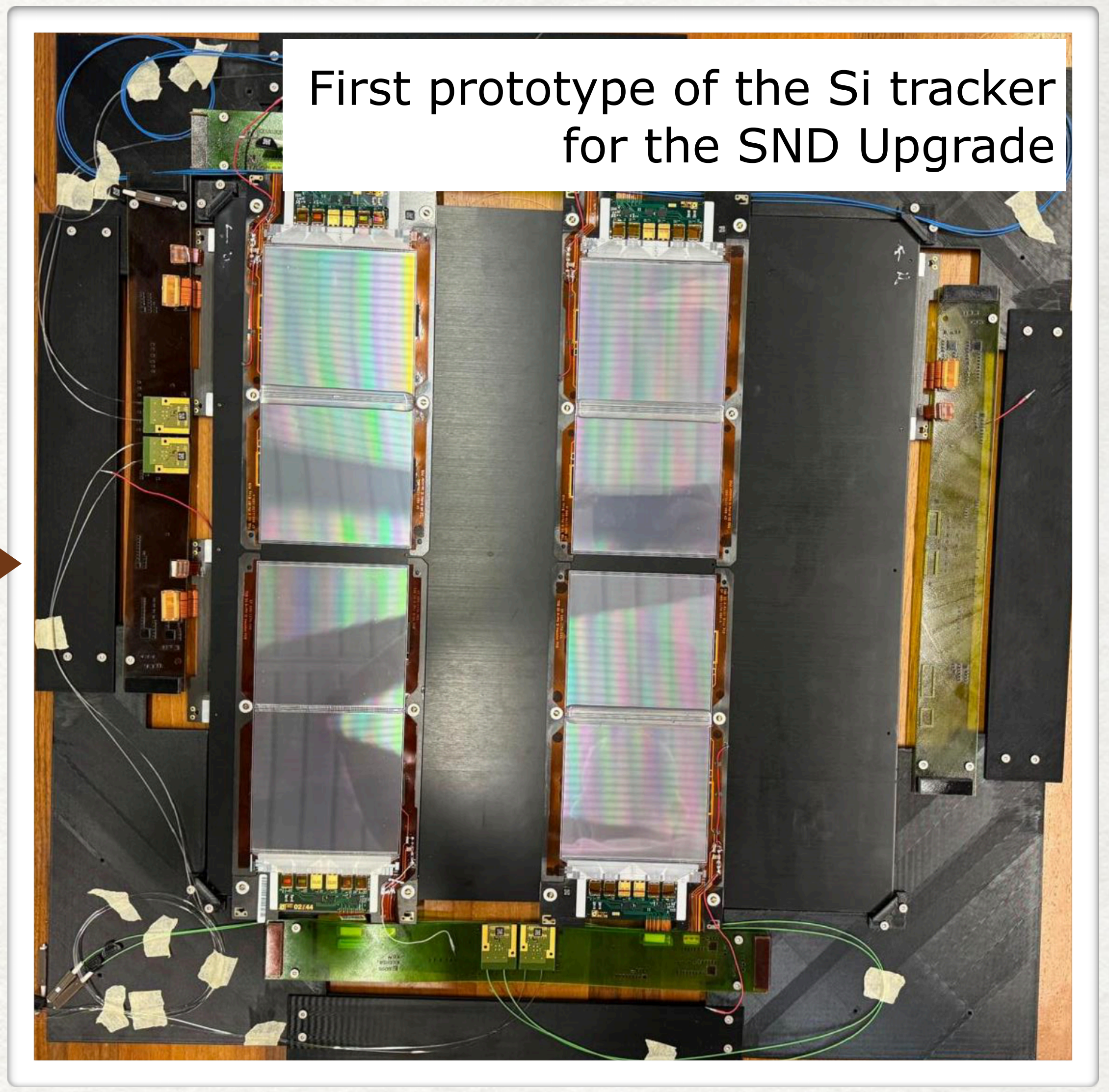
IRON CORE MAGNET

- Horizontal magnetic field 1.75 T
- Coil mass (copper): 0.86 tons
- Overall mass: 12 tons

SND@HL-LHC: SILICON STRIPS DETECTOR PLANES

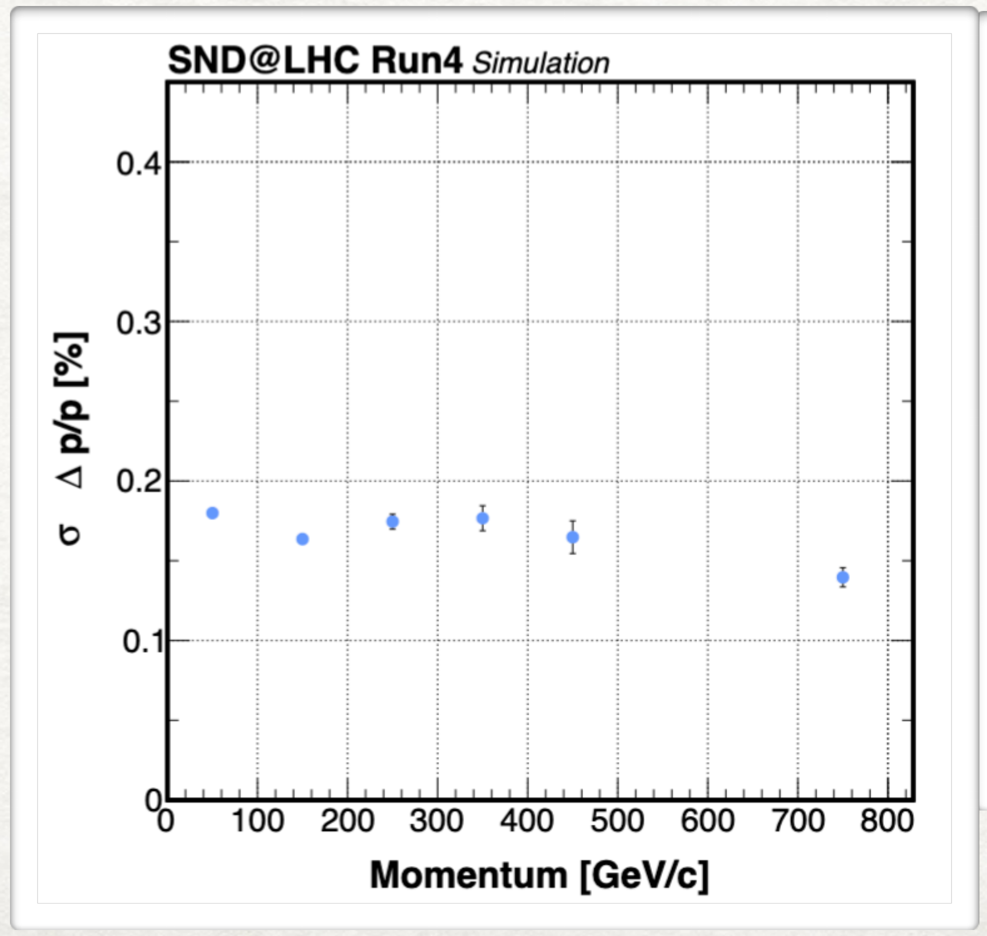
- Detector modules inherited from the CMS outer barrel tracker
- Eight modules per plane. 1680 modules available
- 122 micron strip pitch

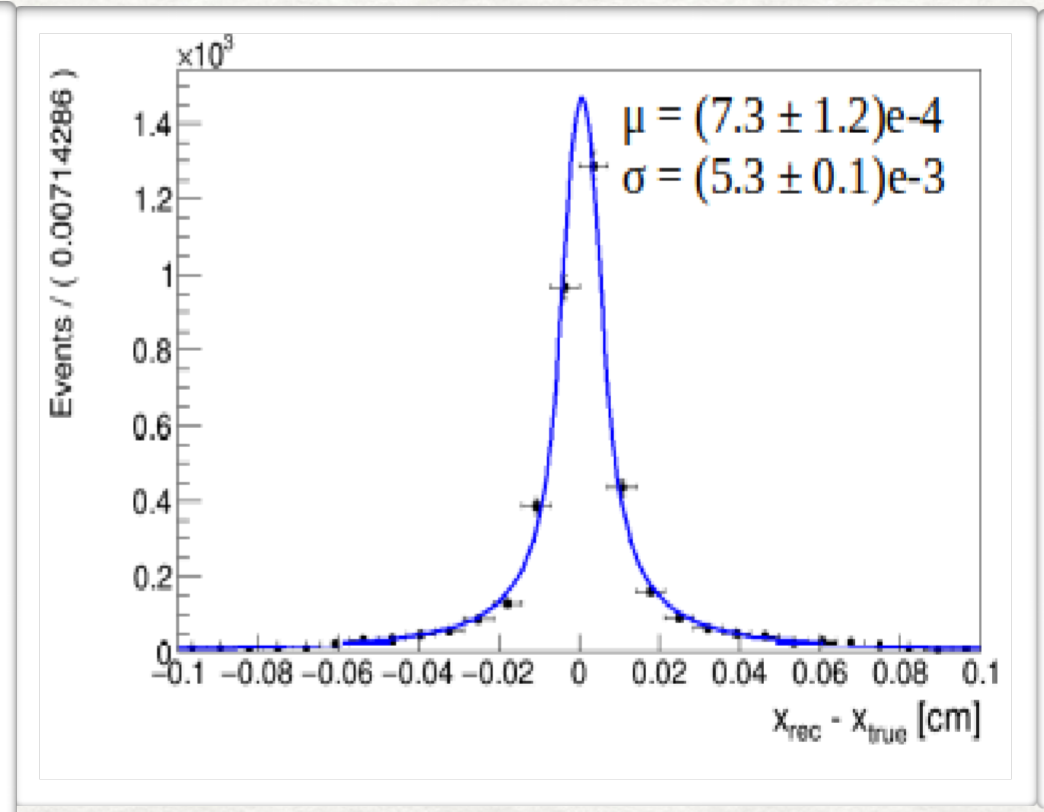


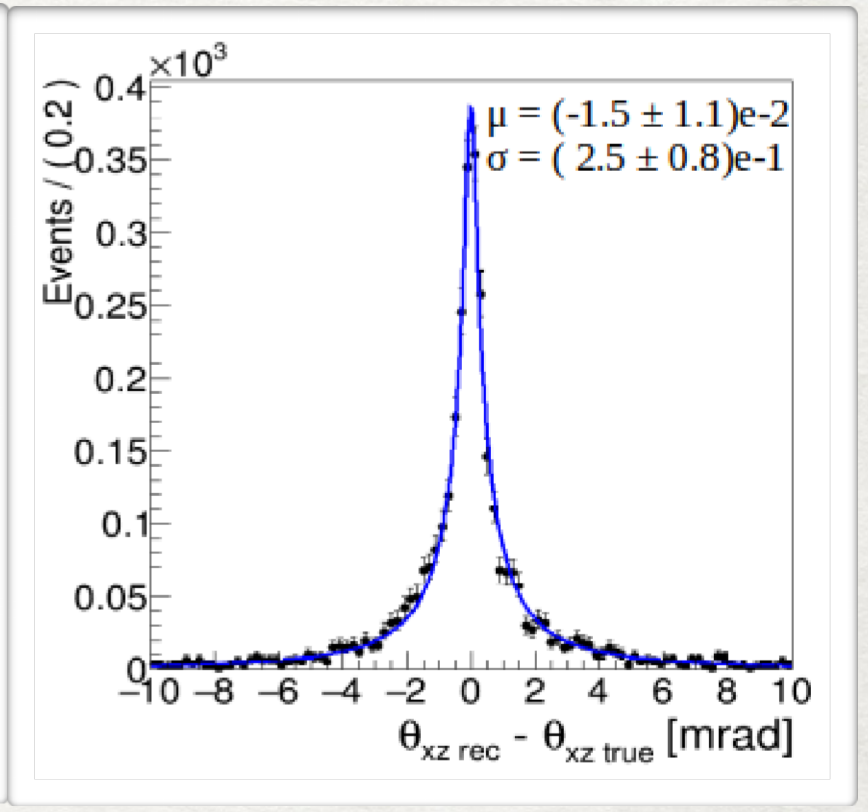


Detector performances

- Tracking resolution: 50 μm and 20 mrad
- Hadronic energy resolution: 10÷20 %
- Muon momentum resolution: <20% up to 1TeV



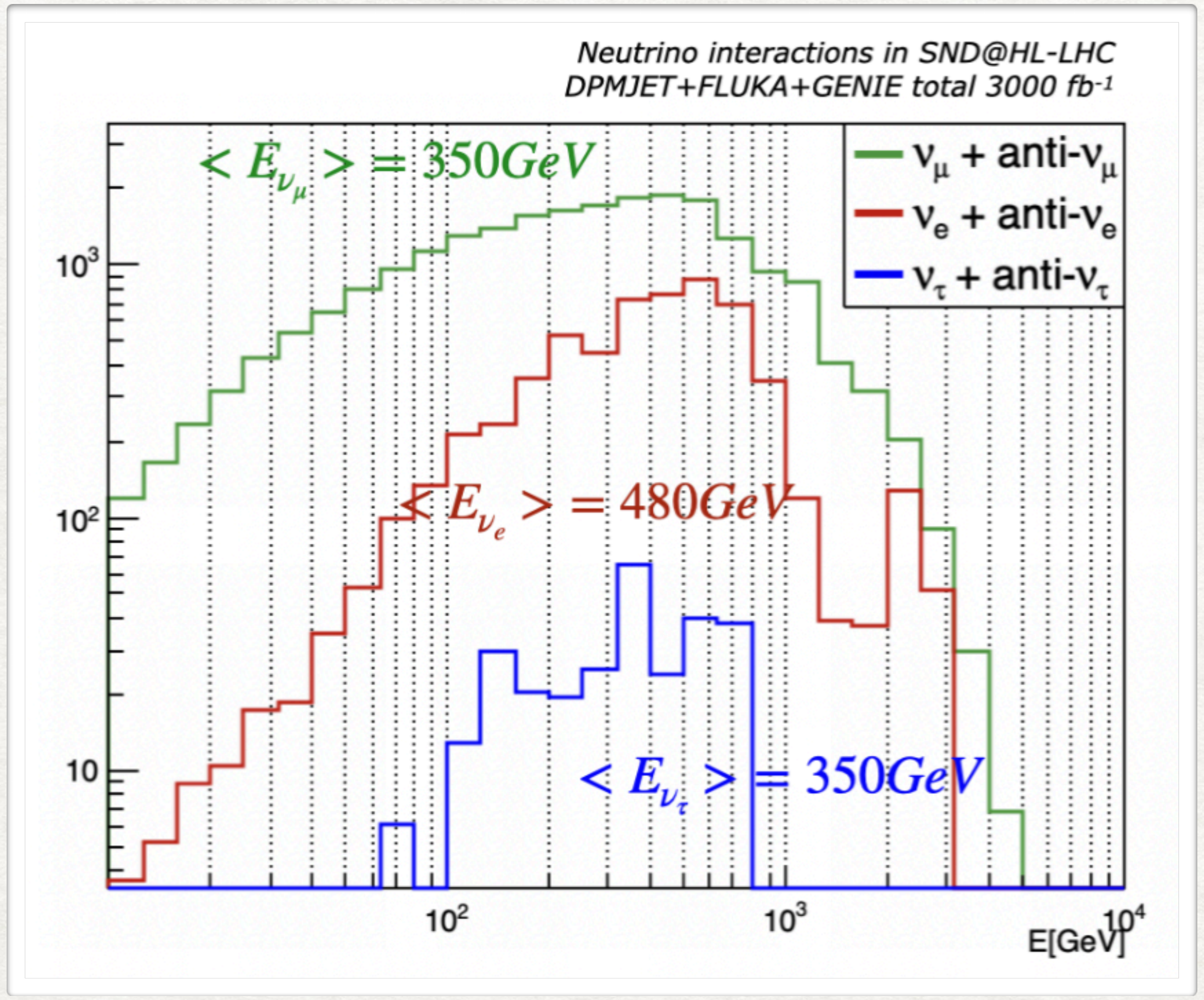




SND IN THE HI-LUMI ERA

Physics performances

- Measurement of **charm production** with neutrinos
- Constrain **gluon PDF** at very **small x**
- **(Tau) neutrino** physics with high statistics
- Beyond Standard Model searches



HL-LHC

Flavour	Target	HCAL	Target+HCAL
$\nu_\mu+\bar{\nu}_\mu$	1.5×10^4	8.8×10^3	2.4×10^4
$\nu_e+\bar{\nu}_e$	3.4×10^3	2.1×10^3	5.5×10^3
$\nu_\tau+\bar{\nu}_\tau$	2.8×10^2	1.7×10^2	4.5×10^2
Tot	1.9×10^4	1.1×10^4	3.0×10^4

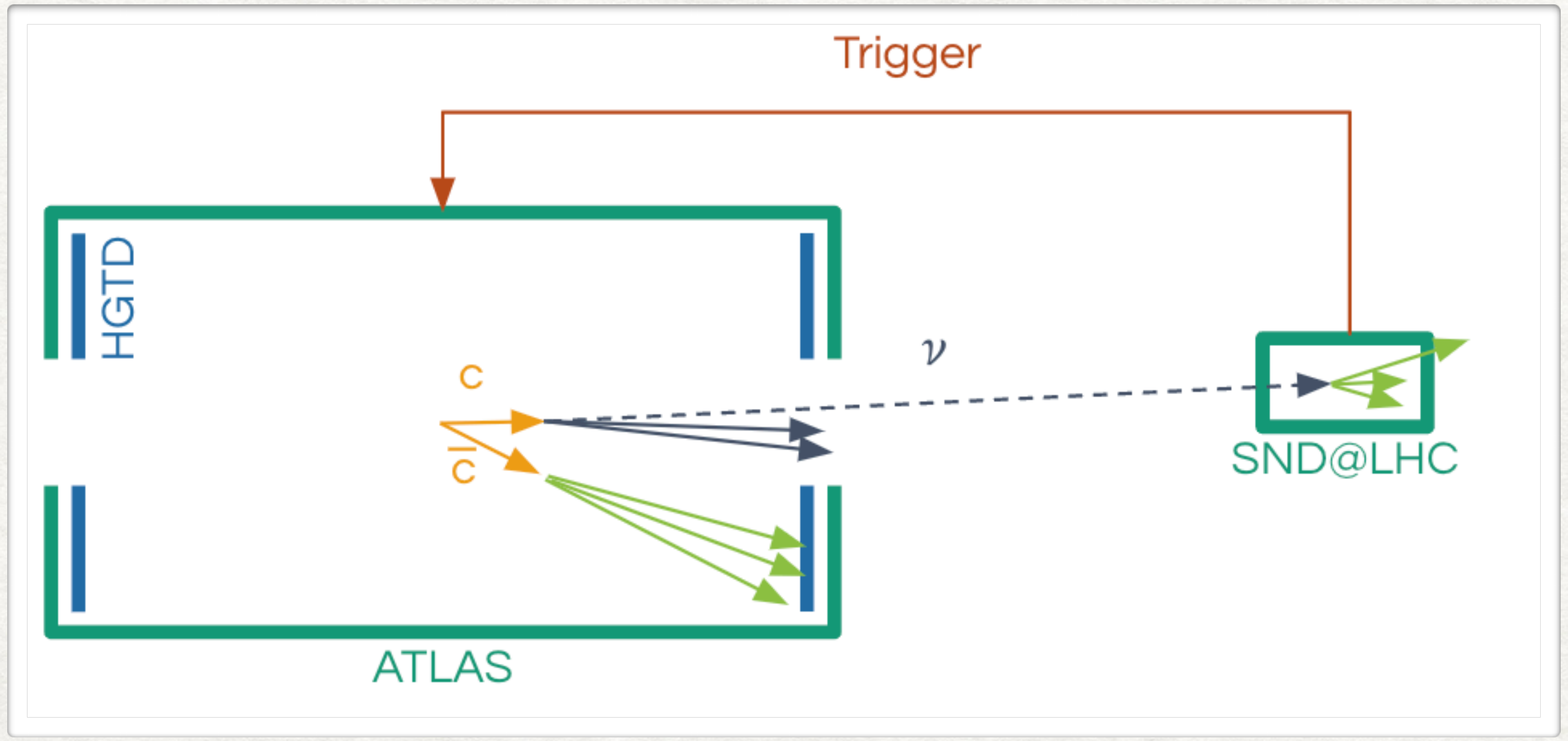
7 time more statistics

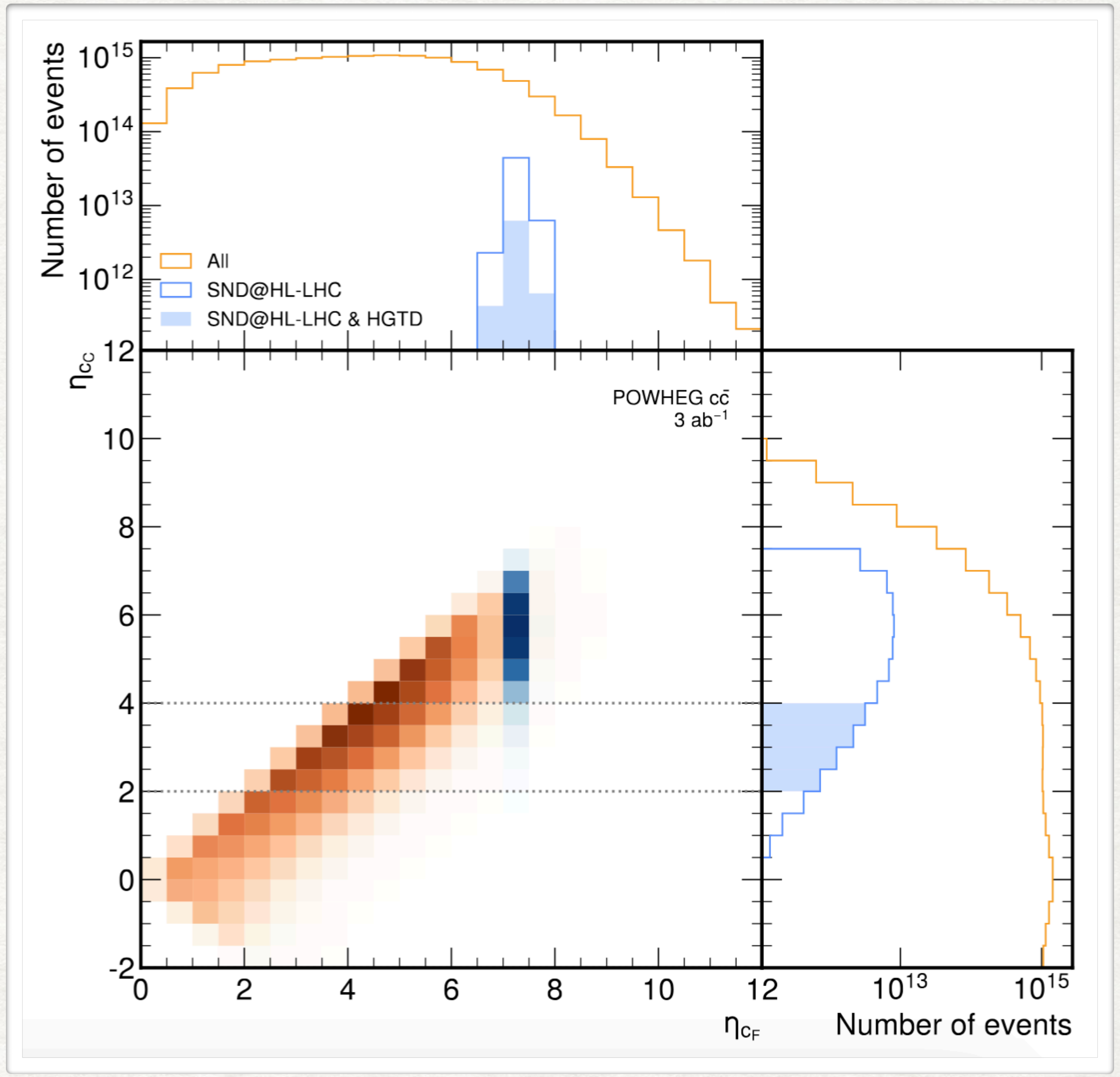
LHC Run3 **HL-LHC**

Measurement	Uncertainty Stat.	Uncertainty Sys.	Uncertainty Stat.	Uncertainty Sys.
Charmed hadron yield	5%	35%	1%	5%
ν_e/ν_τ ratio for LFU test	30%	22%	5%	10%
ν_e/ν_μ ratio for LFU test	10%	10%	1%	5%
ν_μ and $\bar{\nu}_\mu$ cross-section	-	-	1%	5%

SND@HL-LHC:CHARM-TAGGED NEUTRINOS

- A sizeable fraction of the interacting neutrinos originate in open charm production
- In around 10% of these events, the associated charm quark is emitted within the acceptance of ATLAS: over 500 events expected
- A charm-tagged neutrino sample would allow for clean flavour ratio measurements
- Requires fast timing detectors to resolve the pile-up, and sending a trigger signal to ATLAS

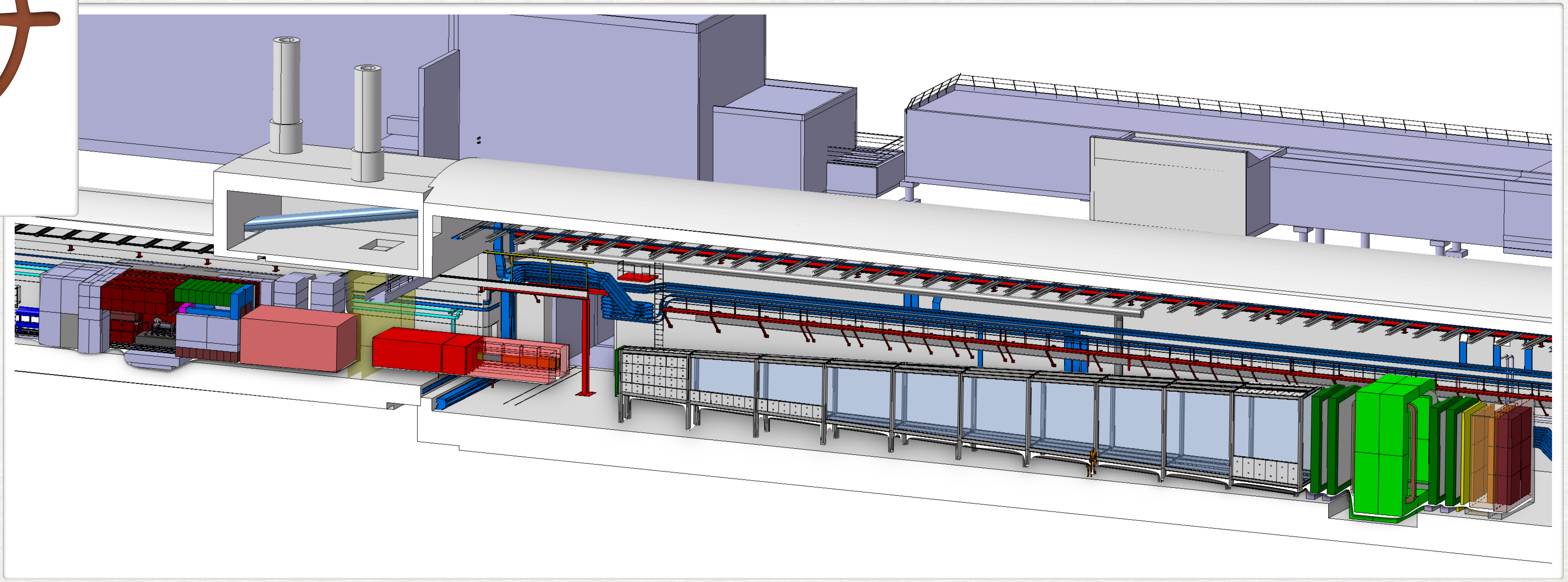




NEUTRINO PHYSICS AT THE **INTENSITY** FRONTIER

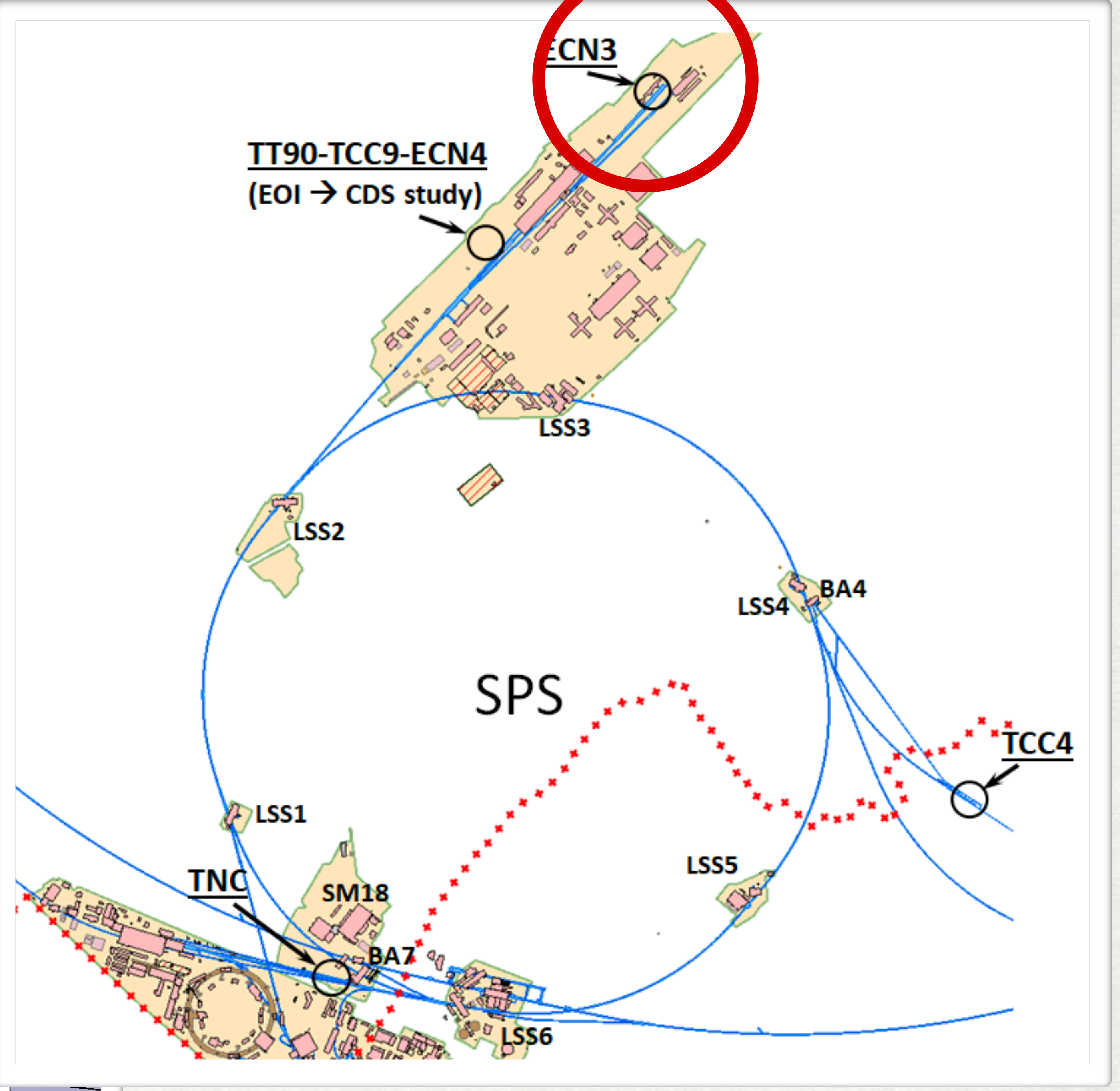
THE **SHIP** EXPERIMENT

SHiP

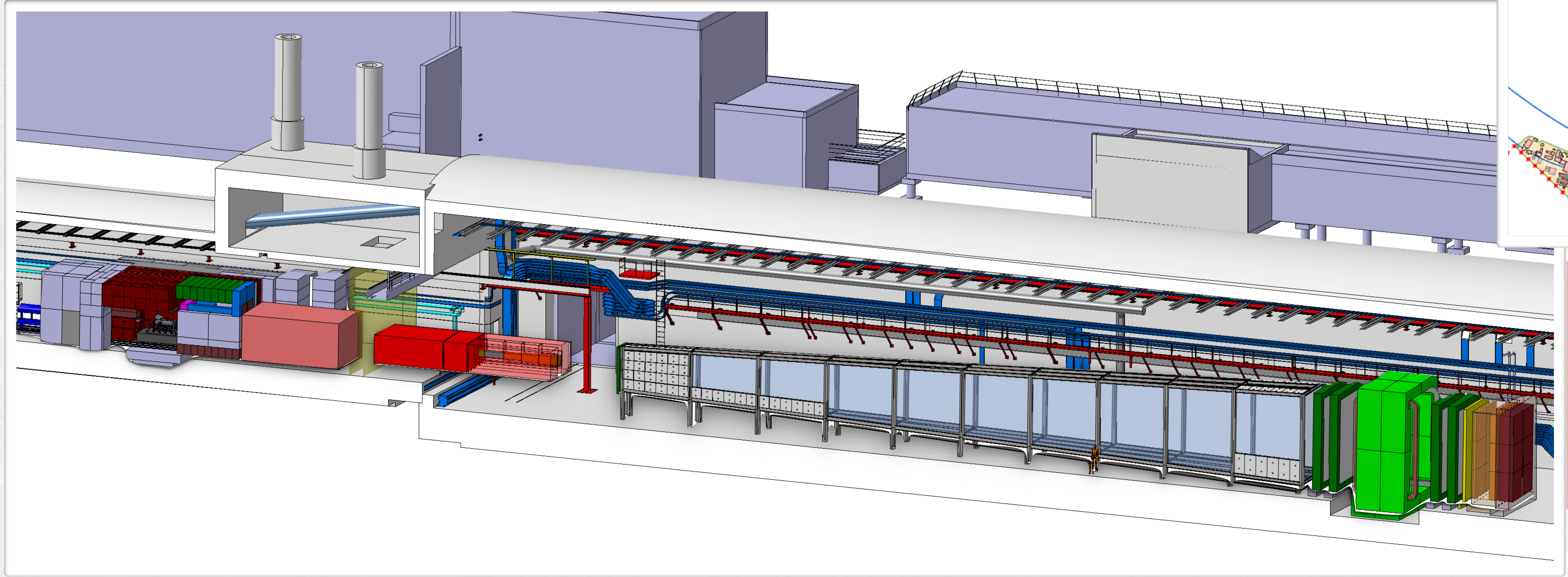


SEARCH FOR HIDDEN PARTICLES (SHIP) AT A DEDICATED BEAM DUMP FACILITY (BDF)

- High intensity upgrade of CERN **SPS (400 GeV)** proton facility
- General purpose *beam-dump* facility
- Dedicated beamline towards **ECN3**
- SPS energy and intensity produce large amounts of charmed and beauty hadrons, necessary to search for Hidden Sector particles up to O(GeV)



BDF/SHiP approved by the CERN Research Board in March 2024



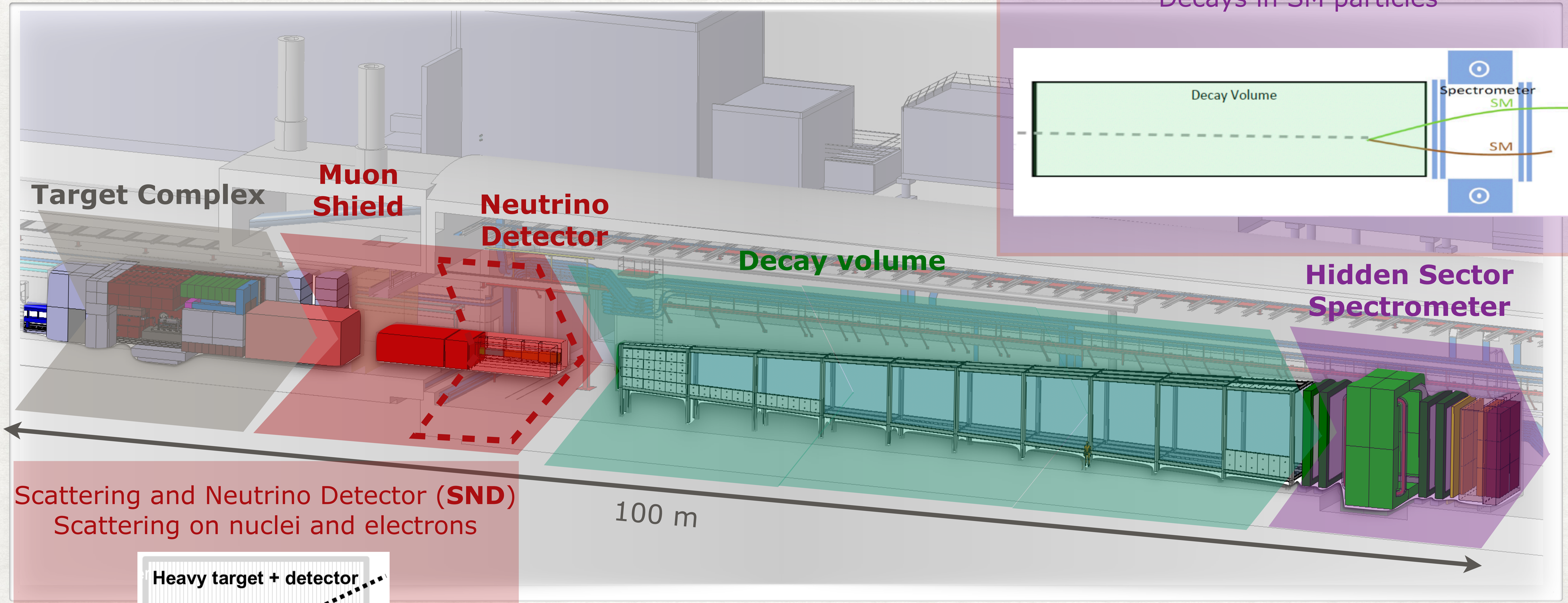
4x10^{19} pot/year
~2x10^{17} *charm* hadrons
(> 10 larger than HL-LHC)
~2x10^{12} *beauty* hadrons
~2x10^{15} tau leptons
O(10^{20}) photons with E>100 MeV
~10^{16} tau neutrinos

EPJC (2022) 82:486

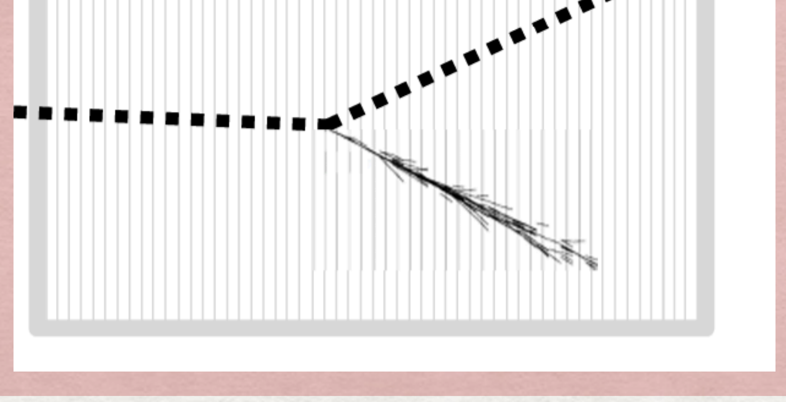
Proposal, BDF/SHiP at the ECN3 high-intensity beam facility, CERN-SPSC-**2023**-033
Letter of Intent, BDF/SHiP at the ECN3 high-intensity beam facility, CERN-SPSC-**2022**-032
Technical Proposal, A Facility to Search for Hidden Particles (SHiP) at the CERN SPS, CERN-SPSC-**2015**-016

EXPERIMENTAL SETUP

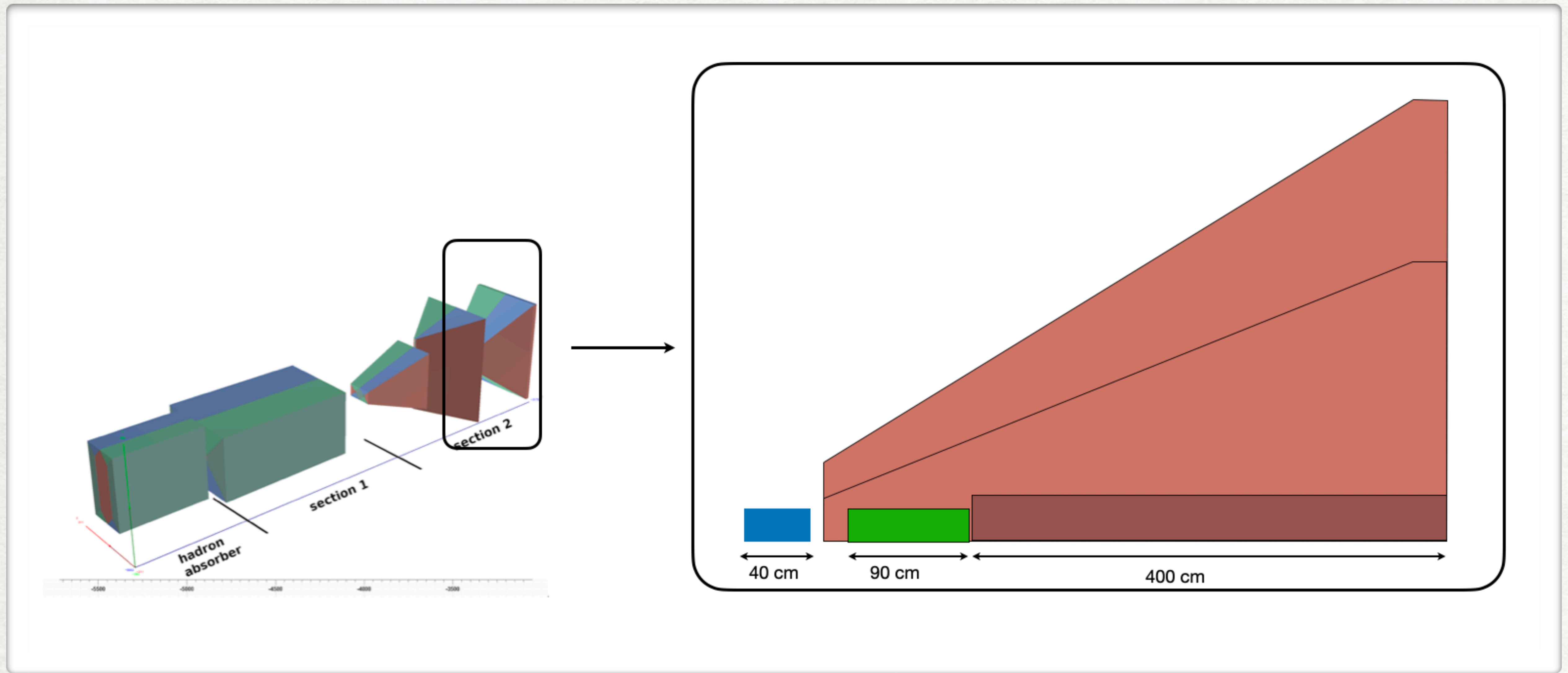
Search for **Hidden Sector** particles
Decays in SM particles



Scattering and Neutrino Detector (**SND**)
Scattering on nuclei and electrons



THE SND DETECTOR



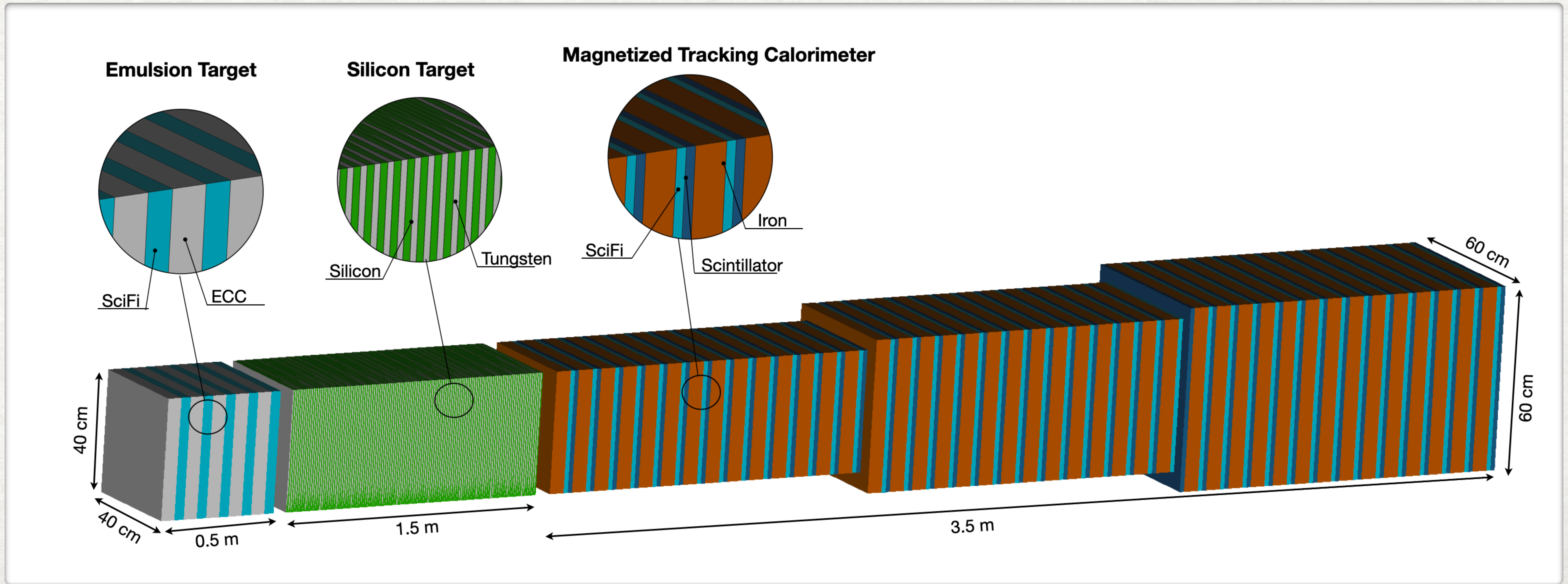
New concept for SND:

- Detector embedded in the last section **muon shield**
- Closer to the target, higher neutrino fluxes
- Magnetized Iron interleaved with trackers and used as HCAL

- Profit of the experience gained in SND@LHC with **emulsions** in high-density environment
- R&D and prototyping for **Silicon detectors** in common with the SND Upgrade for HL-LHC

- **Vertex Detector & ECAL:**
  - *Emulsion Target*:
    - Emulsion Cloud Chamber: Emulsioni + W
    - SciFi planes
  - *Silicon Target*:
    - Silicon planes + W

- **HCAL & Muon Spectrometer**
  - Magnetized Iron + SciFi + Scintillators



NEUTRINO PHYSICS WITH SND@SHIP

- Large number of interacting neutrinos in SND@SHiP

- **Tau neutrino physics**
  - First observation of $\bar{\nu}_\tau$
  - ν_τ e $\bar{\nu}_\tau$ cross-section measurement

- **Measurement of neutrino DIS cross-section**
  - First measurement of F_4 and F_5 structure functions
  - E_ν<10 GeV input for neutrino oscillation physics
  - Cross-sections at high energy input for cosmic neutrino studies

- **Lepton flavor universality**
  - Measurement of ratios ν_e/ν_τ , ν_e/ν_μ , ν_μ/ν_τ

- **Charm production in neutrino interactions**
  - Measurement of the *strange* quark content
  - $|V_{cd}|$ measurement

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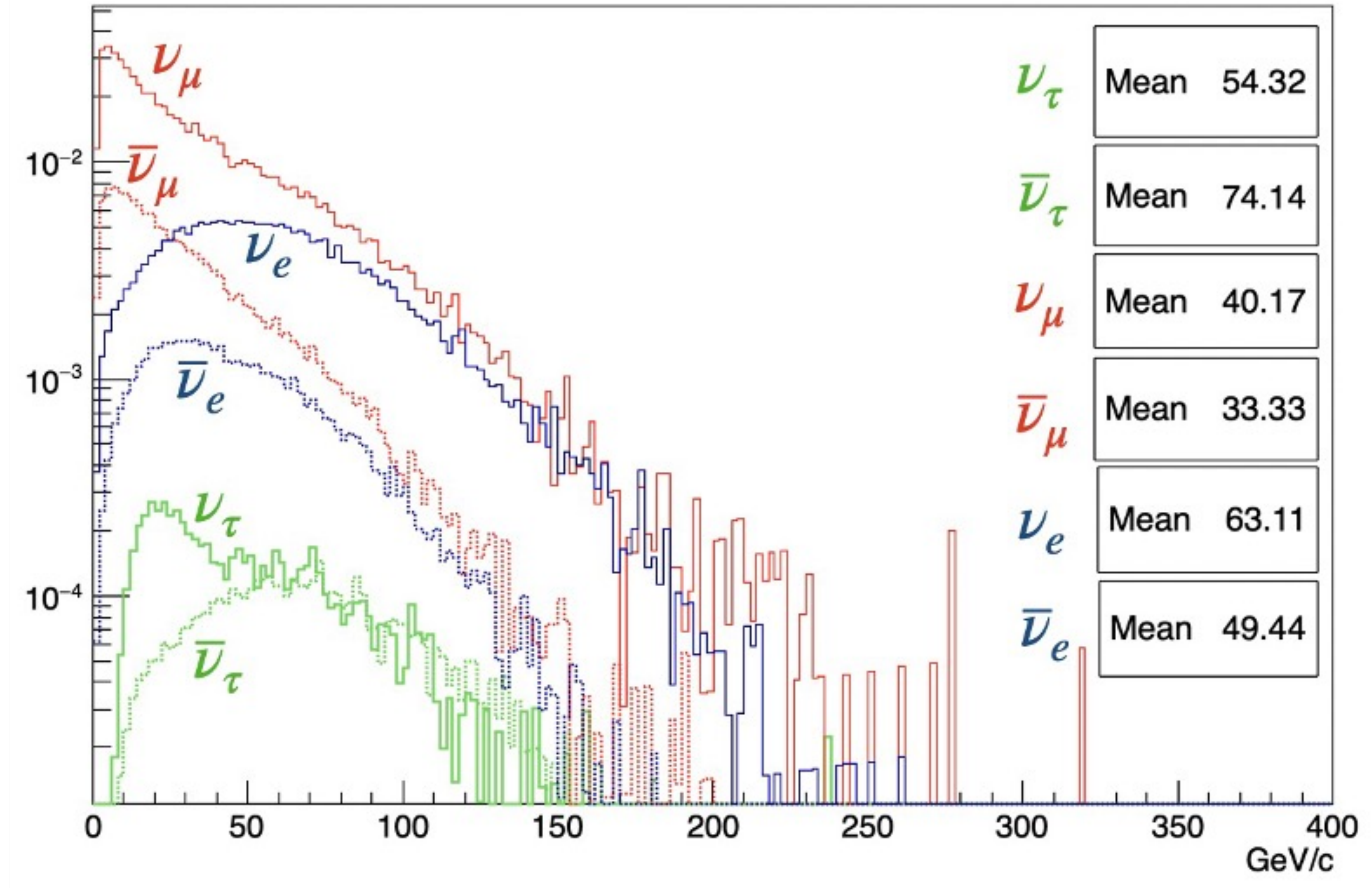
Interacting neutrinos in SND@SHiP



	CC DIS
N_{ν_e}	2.0×10^6
N_{ν_μ}	5.8×10^6
N_{ν_τ}	5.9×10^4
$N_{\overline{\nu}_e}$	4.0×10^5
$N_{\overline{\nu}_\mu}$	1.3×10^6
$N_{\overline{\nu}_\tau}$	4.3×10^4

Interacting neutrinos SND@SHiP in 6x10^{20} pot

Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	3×10^3	2×10^3
$\tau \to h$	18×10^3	
$\tau \to 3h$	7×10^3	
$\tau \to e$	5×10^3	
total	35×10^3	

Tau neutrinos e anti-neutrinos detected in 6x10^{20} pot

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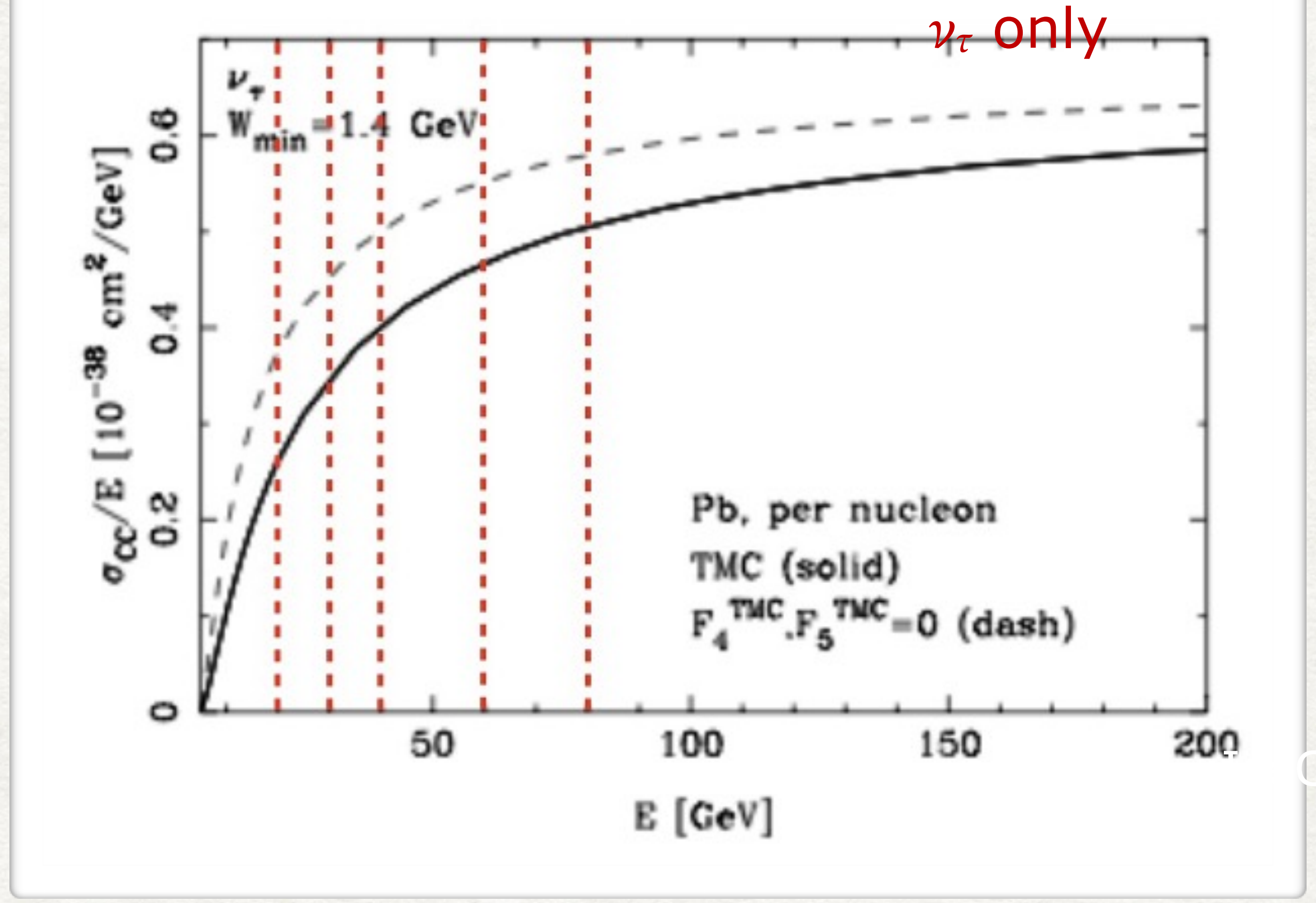
$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right]F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2M^2x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\Bigg),$$

Al LO F_4=0, $2xF_5$=F_2
Al NLO F_4~1% a 10 GeV

bins with 5%
ν_τ only



F4 and F5 measurement with ~5% accuracy

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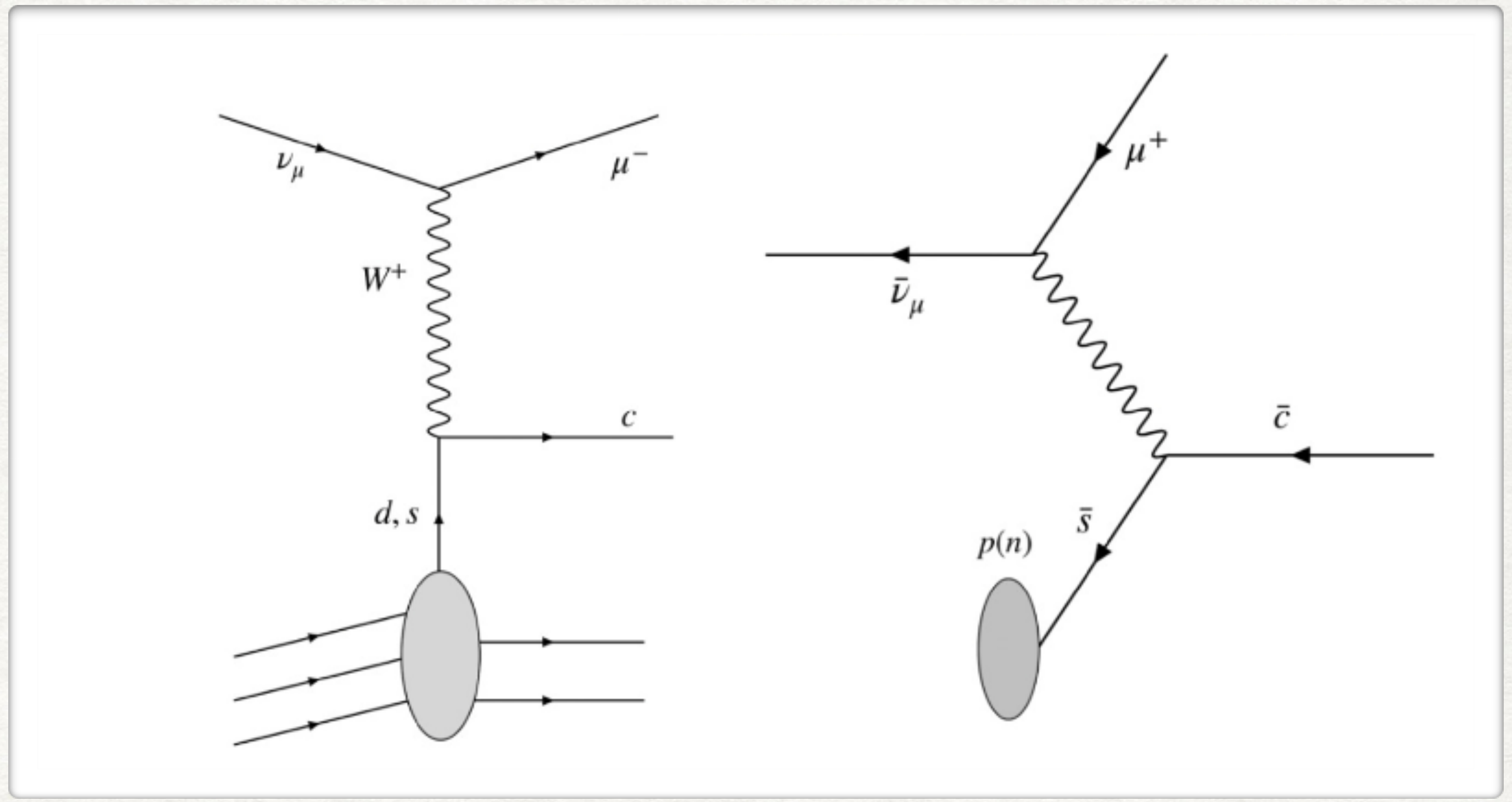
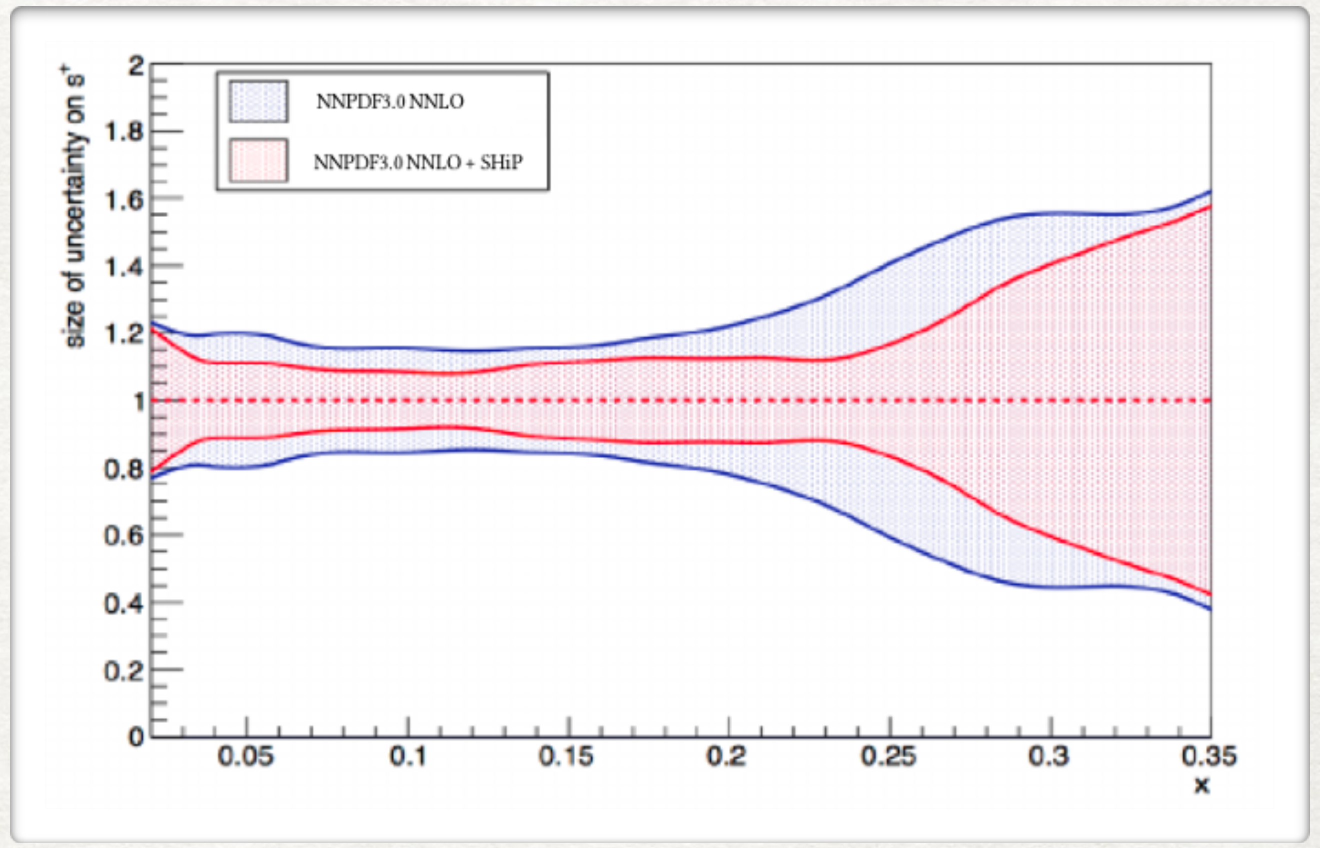


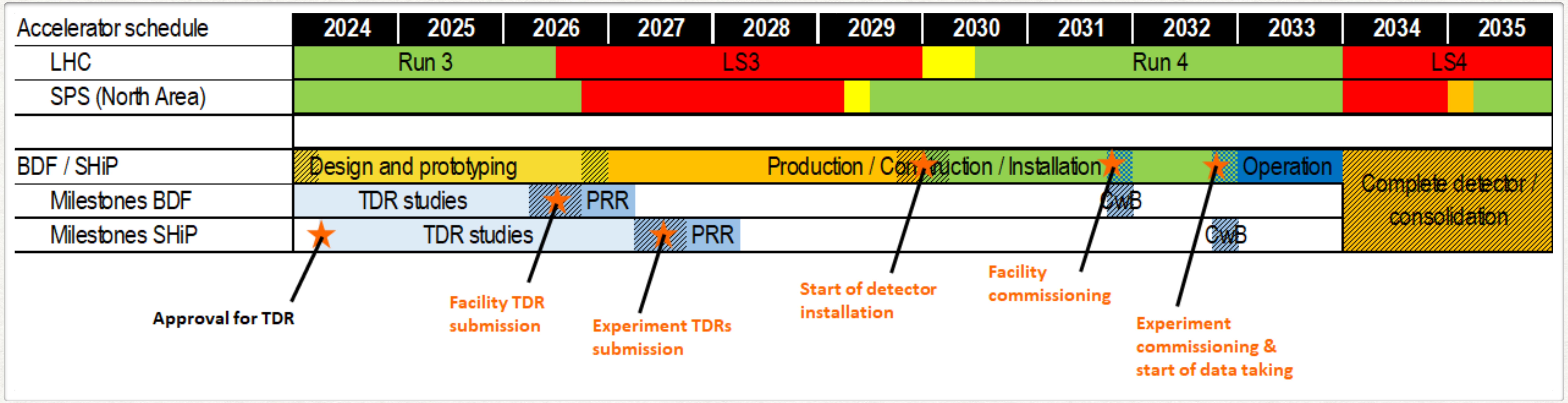
Charm production via anti-neutrinos dominated by s-bar quarks
Charm production via neutrinos shared ~50/50 between d (valence) and s (sea)

	Charm CC DIS
N_{ν_e}	1.2×10^5
N_{ν_μ}	2.8×10^5
N_{ν_τ}	3.2×10^3
$N_{\overline{\nu}_e}$	2.1×10^4
$N_{\overline{\nu}_\mu}$	5.0×10^4
$N_{\overline{\nu}_\tau}$	2.5×10^3

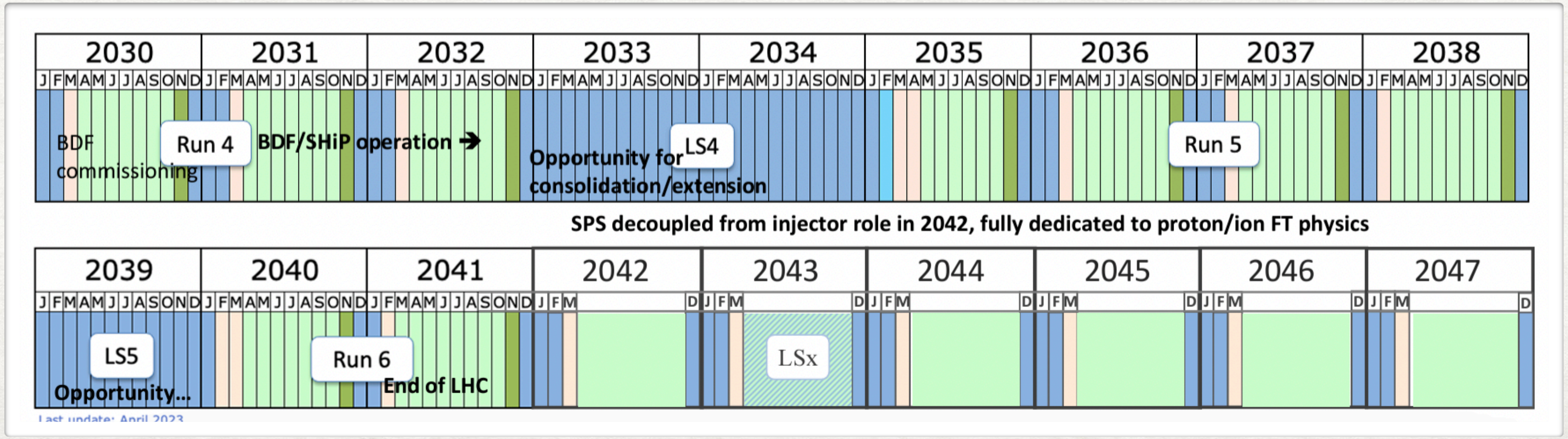


Rep. Prog. Phys. 79 (2016) 124201
based on 2 ×10^{20} pot

SHIP TIMELINE



- ~2 years for Detector Technical Design Reports (TDRs)
- Start data taking in 2032



IT'S TIME FOR NEUTRINO PHYSICS AT CERN