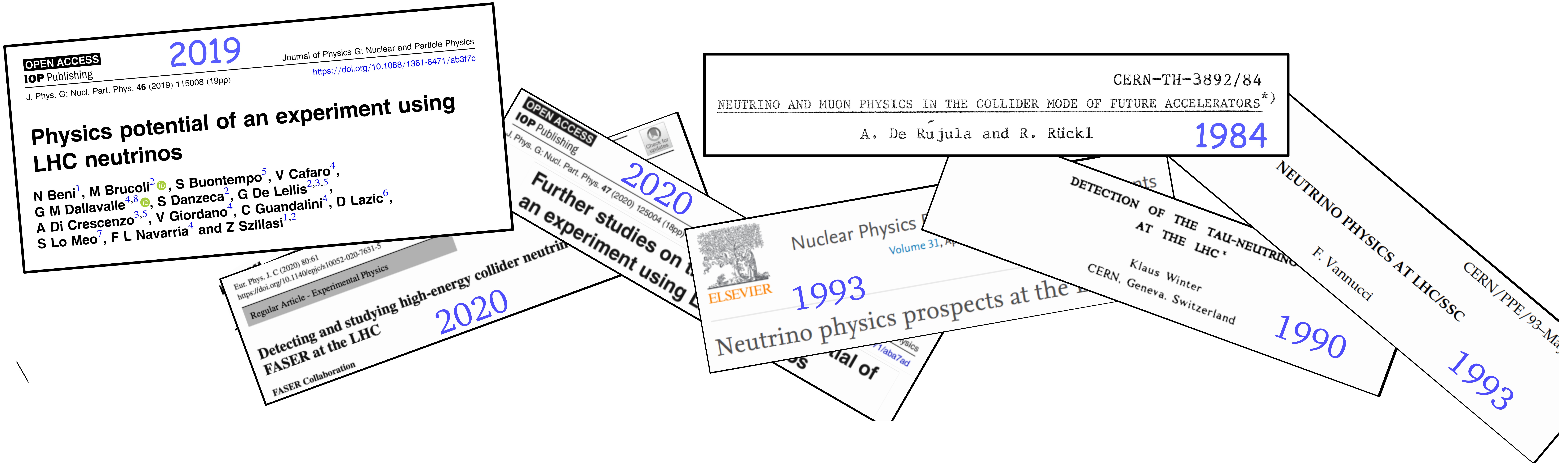
Primi risultati dell'esperimento SND@LHC

G.Marco Dallavalle (INFN Bologna)
per la Collaborazione SND@LHC

Origine dell’esperimento

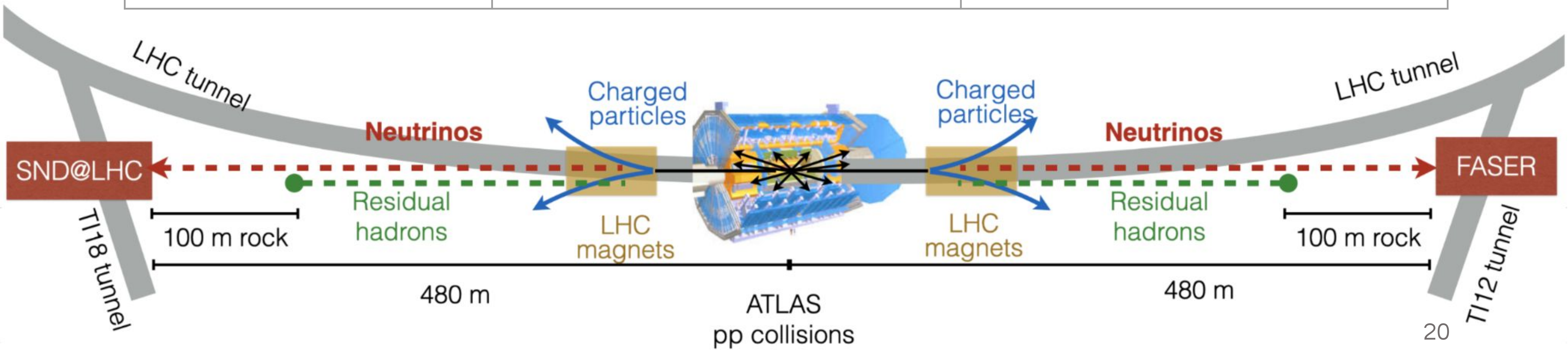
- Già a fine anni ’80, pre LHC, si pensava alla possibilità di utilizzare collisioni protone-protone (pp—>νX) per produrre **neutrini di alta energia in laboratorio**

- In LHC reale al CERN, ~30 anni dopo, misure specifiche durante il RUN2 hanno individuato locazioni in cui i fondi radioattivi sono adatti a esperimenti con neutrini



Per il RUN3 di LHC, il CERN ha approvato due esperimenti con neutrini

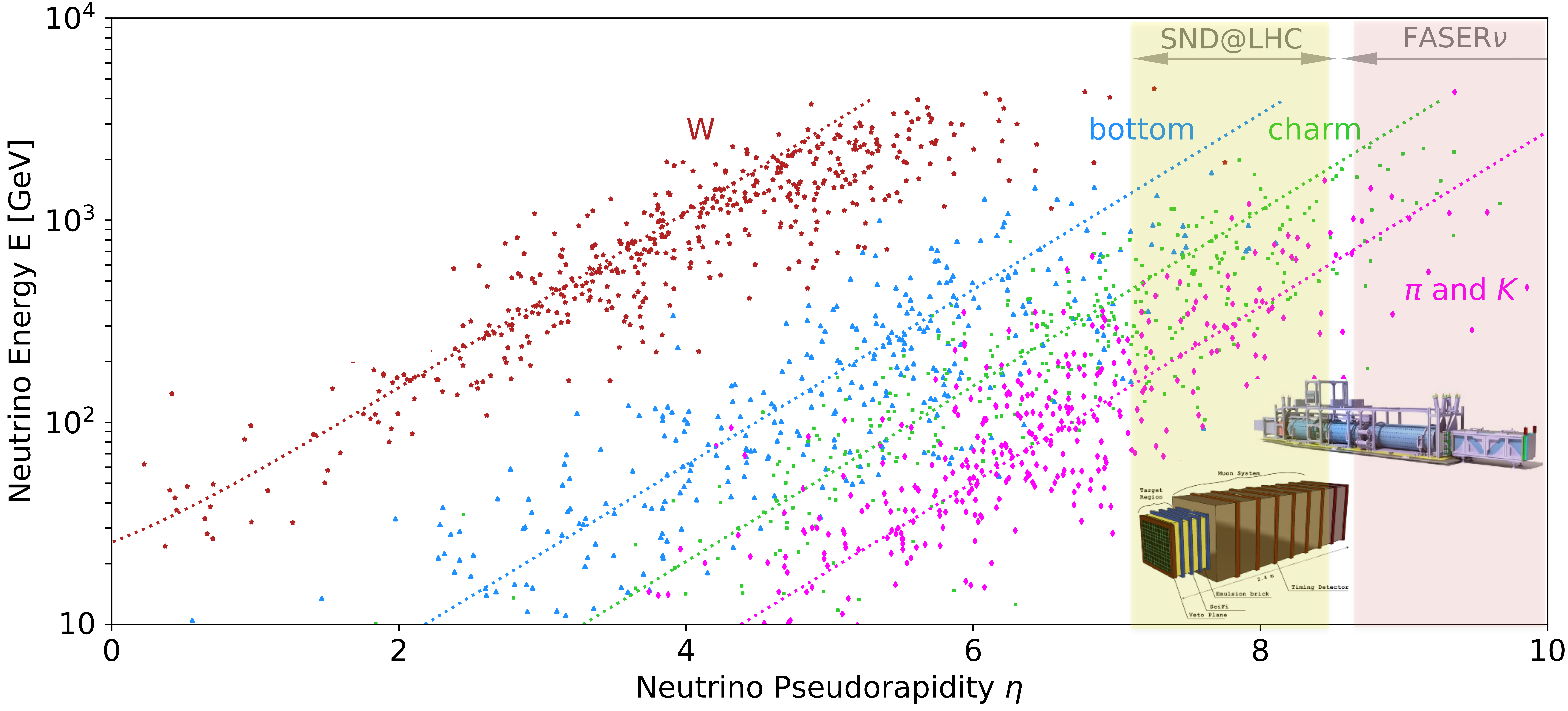
	SND@LHC	FASER
Location	**Off-axis**: $7.2 < \eta < 8.4$ Enhances **charm** parentage	**On-axis**: $\eta > 8.8$ Enhances **statistics**
Target	**800 kg** of tungsten	**1100 kg** of tungsten
Hybrid Detector technology	**Emulsion vertex detector**, electromagnetic and hadronic **calorimeters**	**Emulsion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



Esperimenti complementari

- in presa dati dal 2022

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



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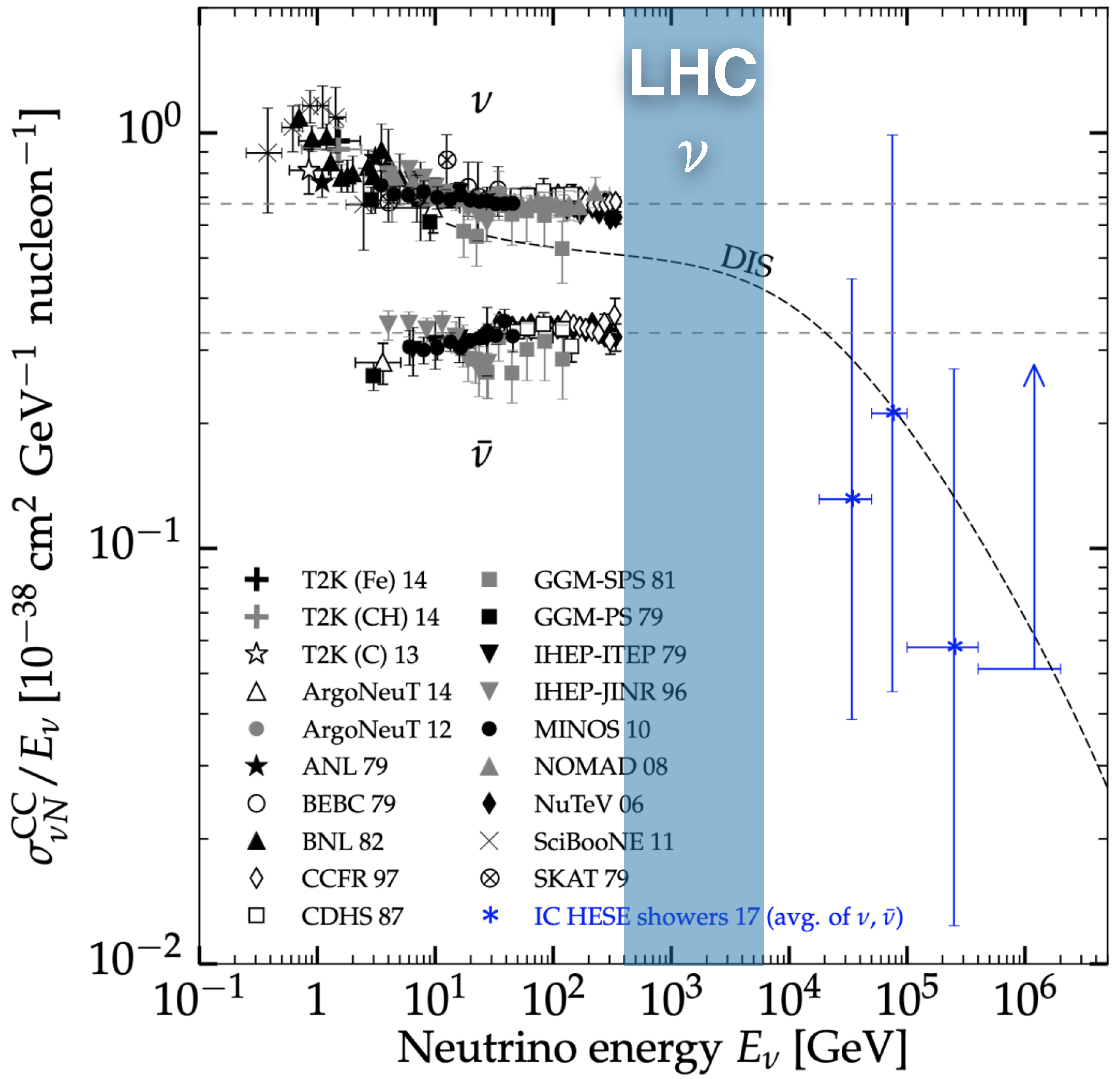
Fisica di SND@LHC

Adapted from Juan Rojo's
CERN TH seminar 11/2023

Interazione neutrino-Nucleone

PRL 122 041101 (2019)

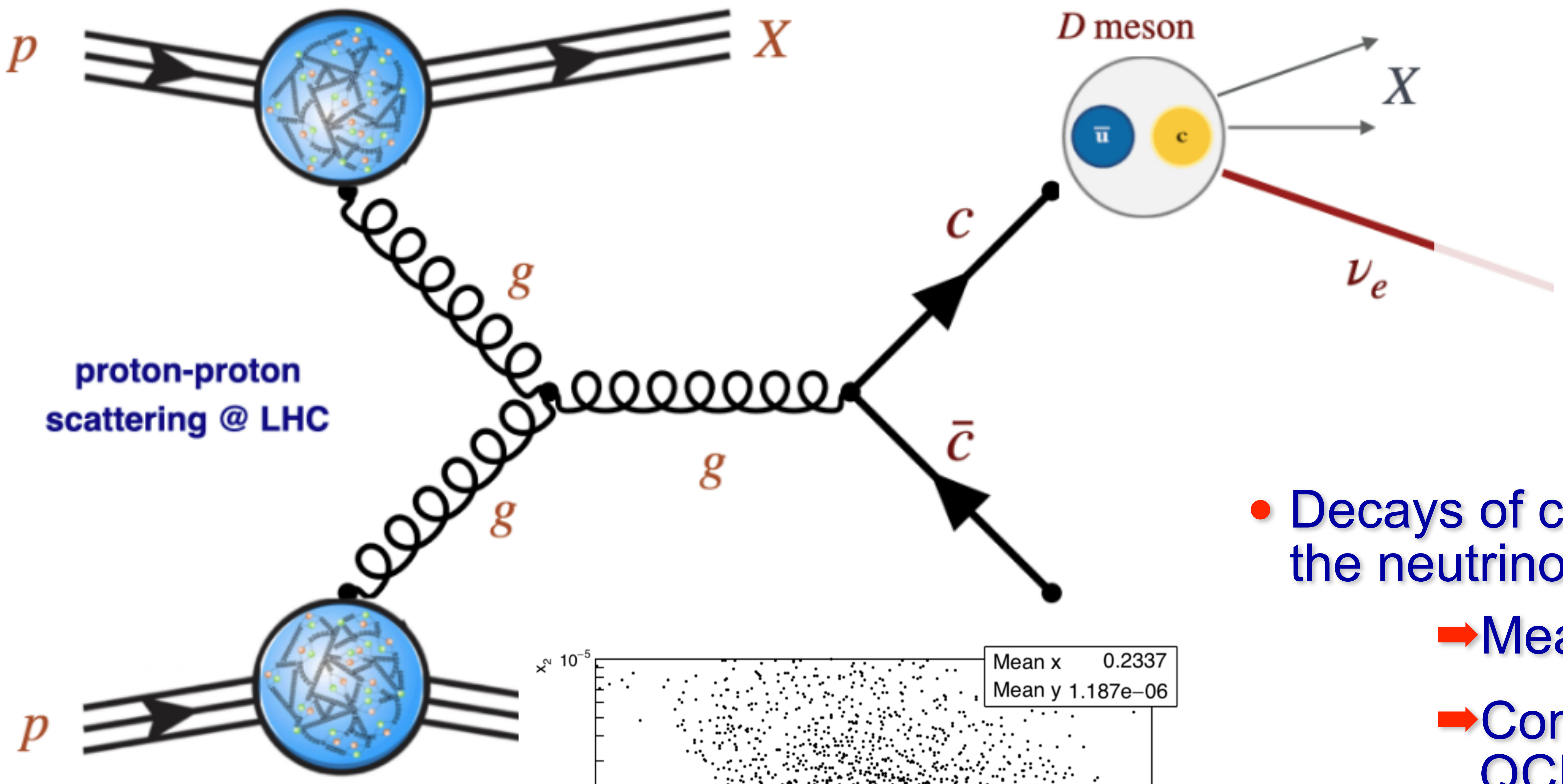


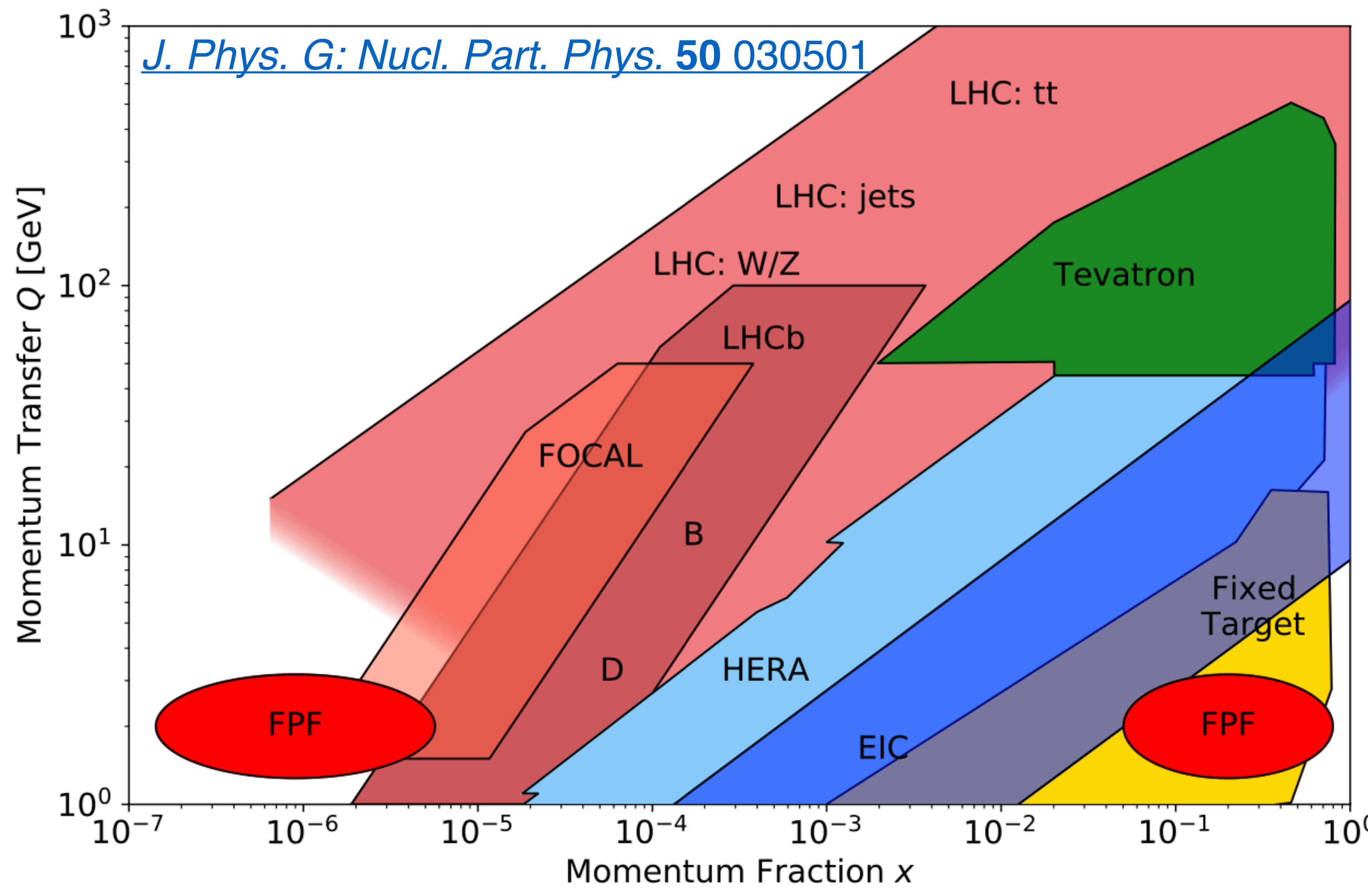
- LHC estende le misure in laboratorio fino alle energie di astrofisica
  - ➡ per tutti e tre i sapori
- un campione significativo di ν_τN
  - ➡ ad ora 20 eventi osservati da DONUT e OPERA, 7 candidati da IceCube

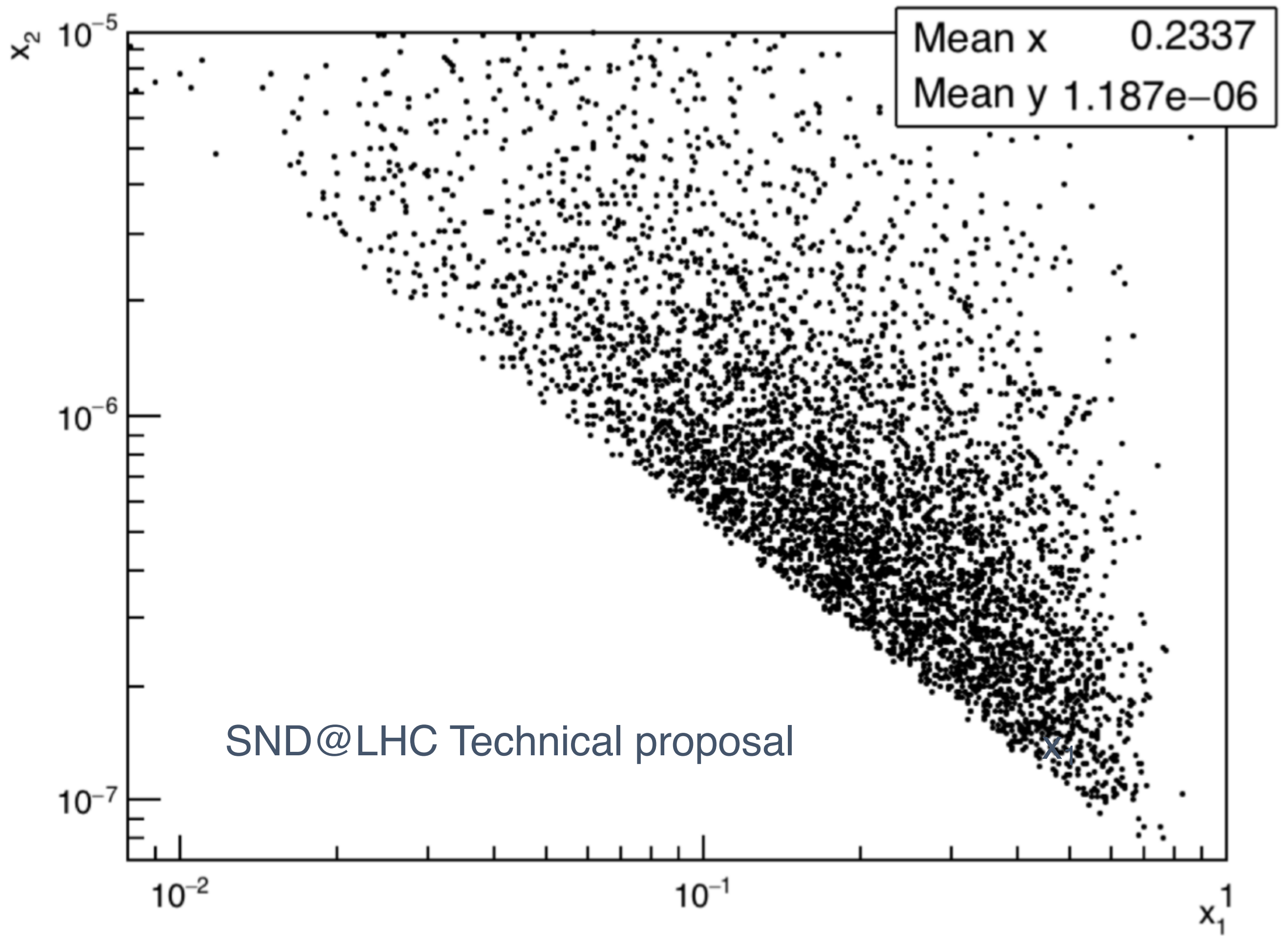
previsioni di DPMJET +FLUKA +GENIE per RUN3 (250 /fb)

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

QCD





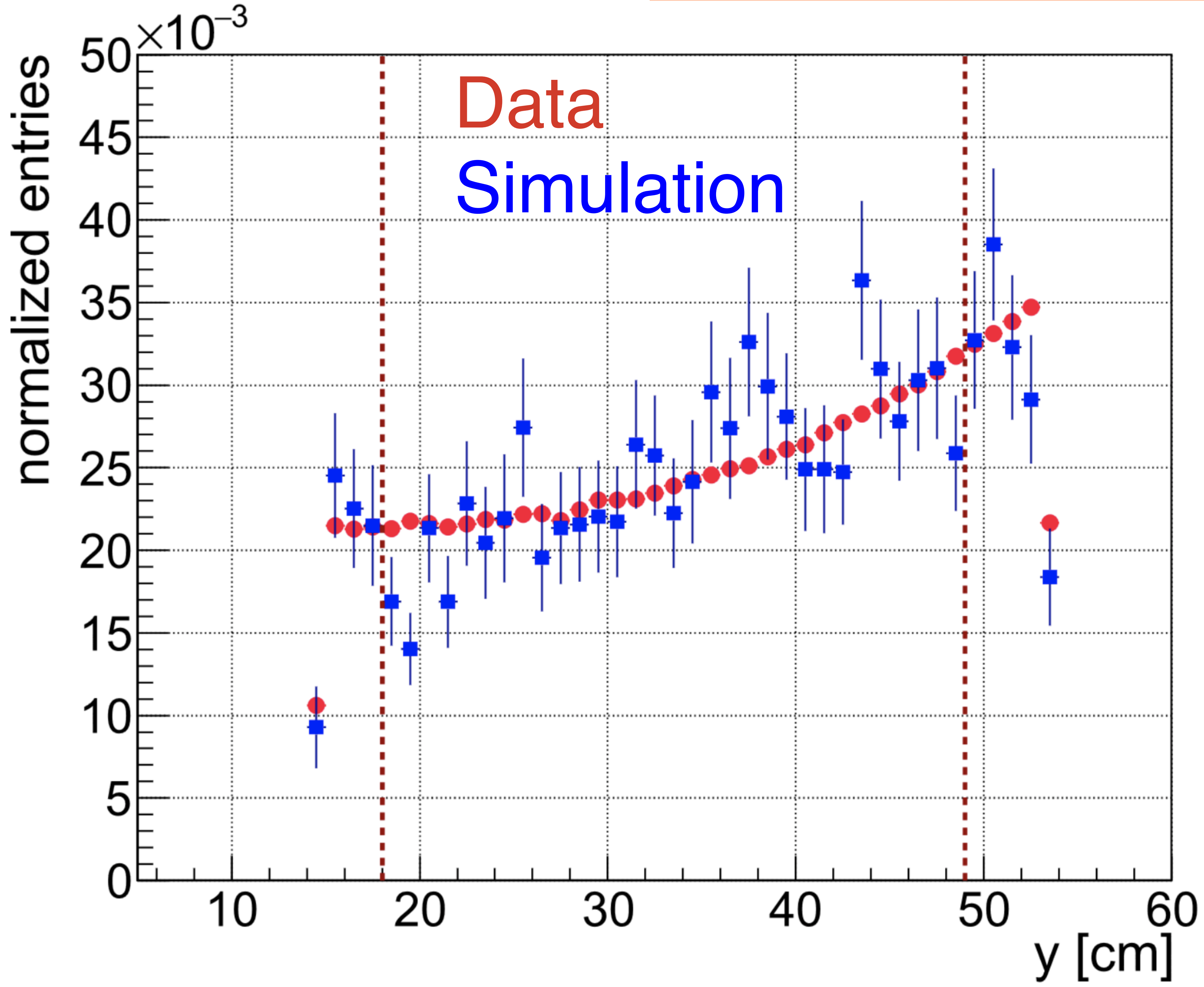


- Decays of charm hadrons contribute significantly to the neutrino flux.
  - ➡Measure forward charm production with ν_es.
  - ➡Constrain **gluon PDF at very small x :** QCD calculations highly uncertain
- Implications for FCC-pp: much of the FCC-pp physics will be produced at very small x.


SND@LHC
Veto
plastic scintillators
Target/ECAL
W+emulsions
SciFi tracker
HCAL/Muon System
Fe+plastic scintillators

Misura del flusso di muoni

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

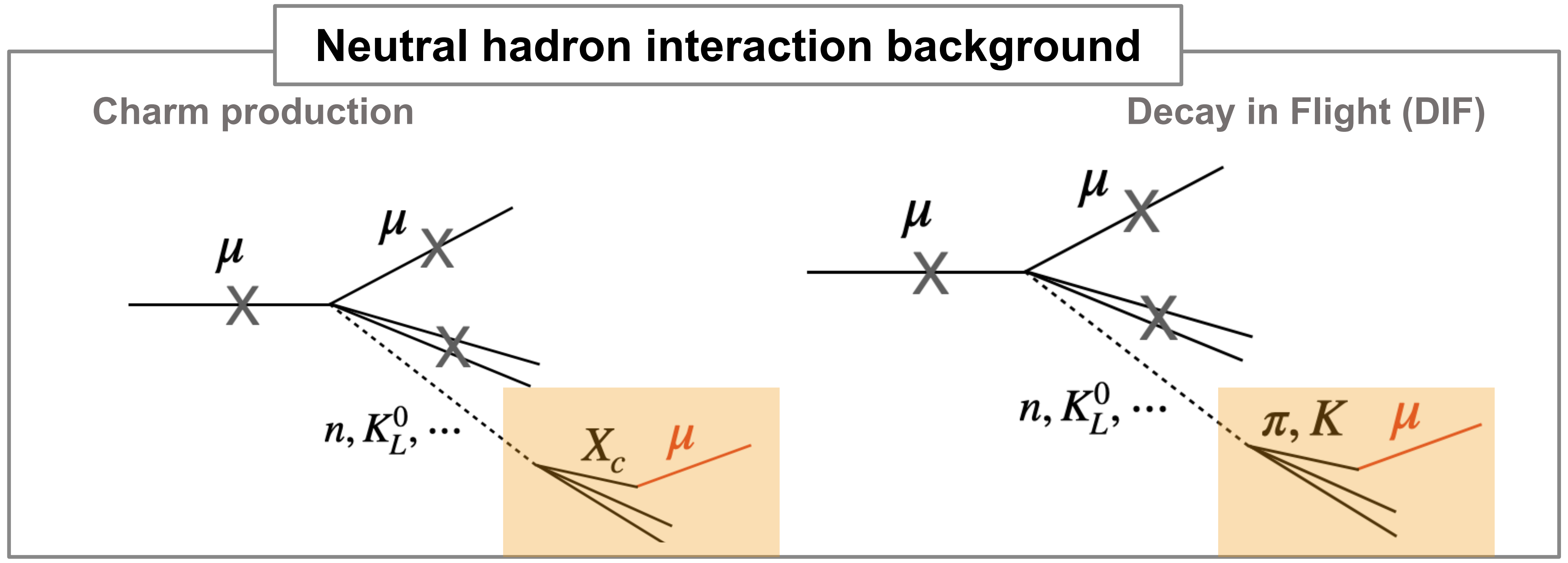


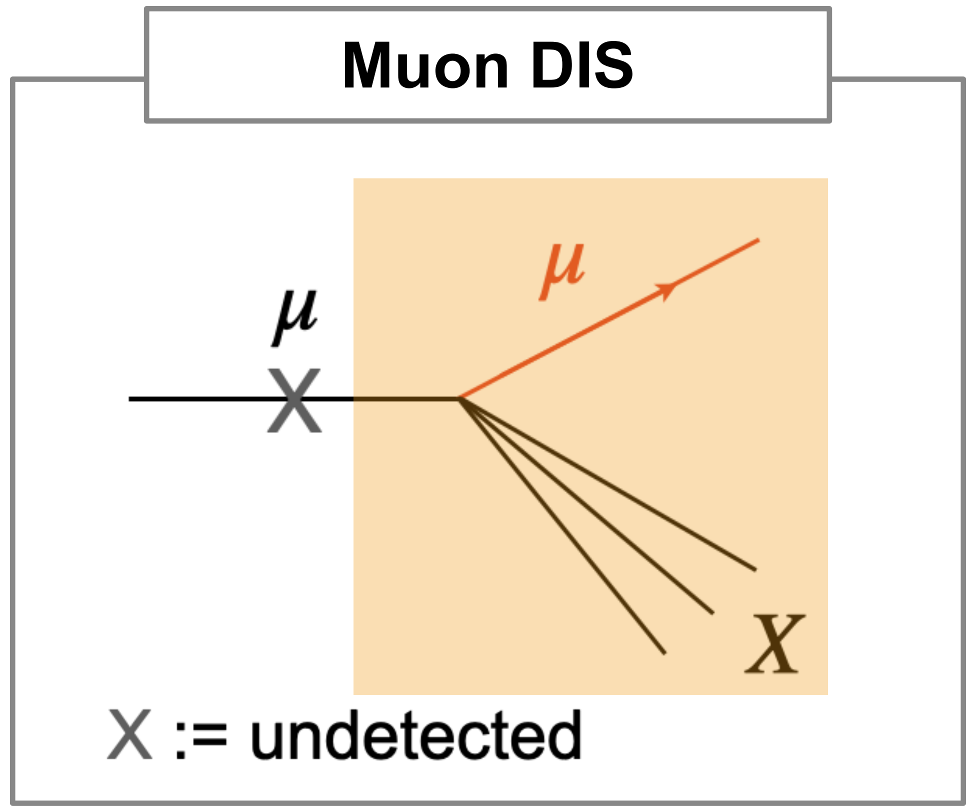
- Misure indipendenti con SciFi, con le emulsioni e con il (DownStream) Muon System danno risultati consistenti

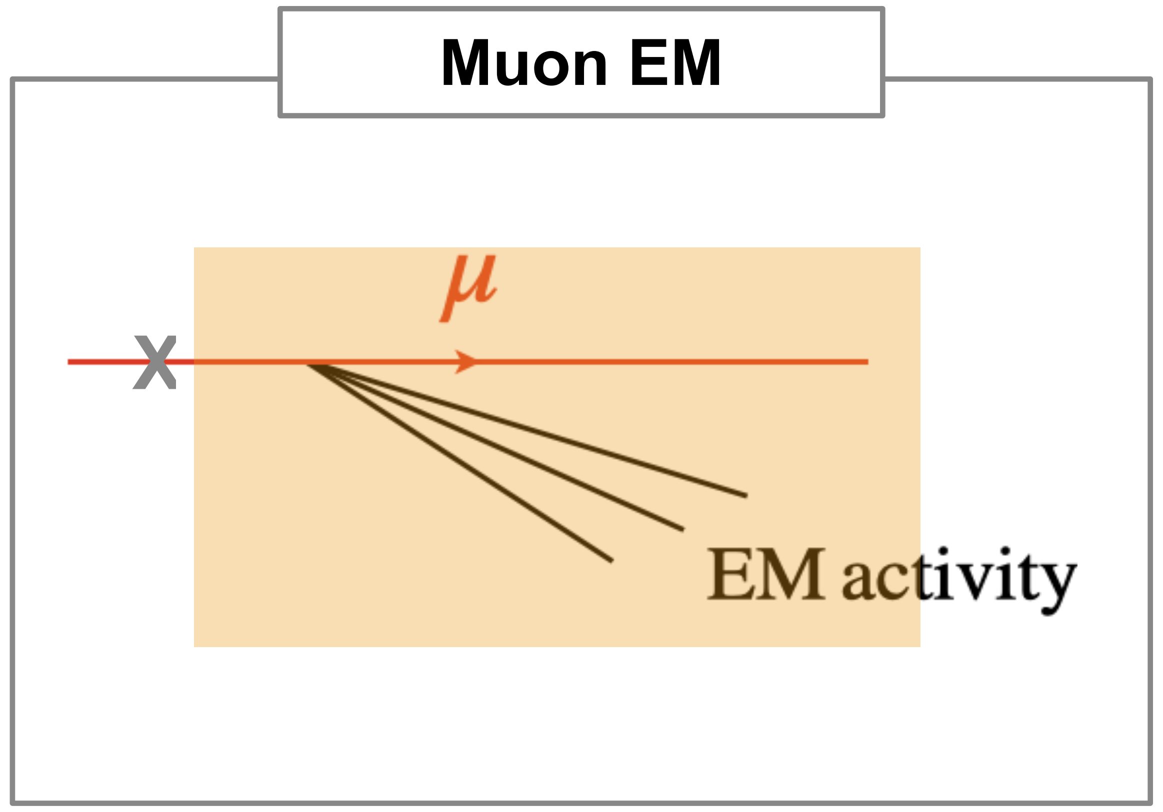
System	Muon flux [10^4 fb/cm^2] same fiducial area
SciFi	$2.06 \pm 0.01(\text{stat.}) \pm 0.12(\text{sys.})$
DS	$2.02 \pm 0.01(\text{stat.}) \pm 0.08(\text{sys.})$

- Backgrounds to neutrino signals in SND@LHC are mainly due to muons.

  ➡ Precise measurements of the muon flux allow for validating and constraining our background model.







:= within SND@LHC acceptance

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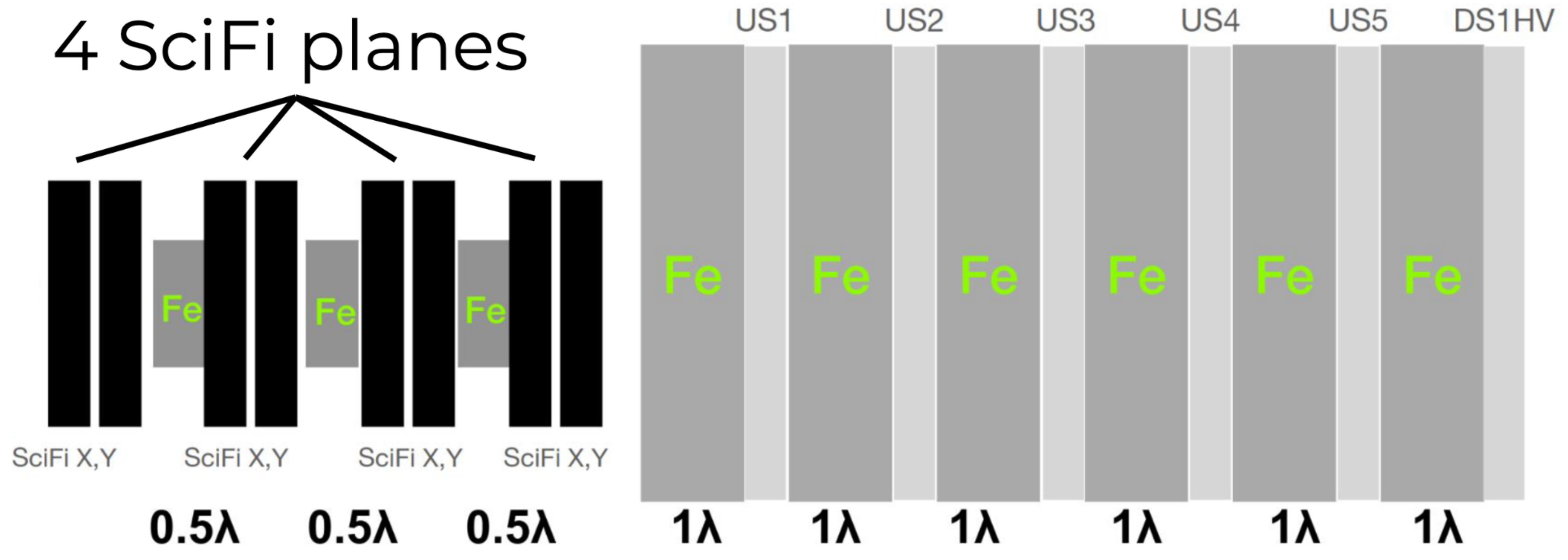
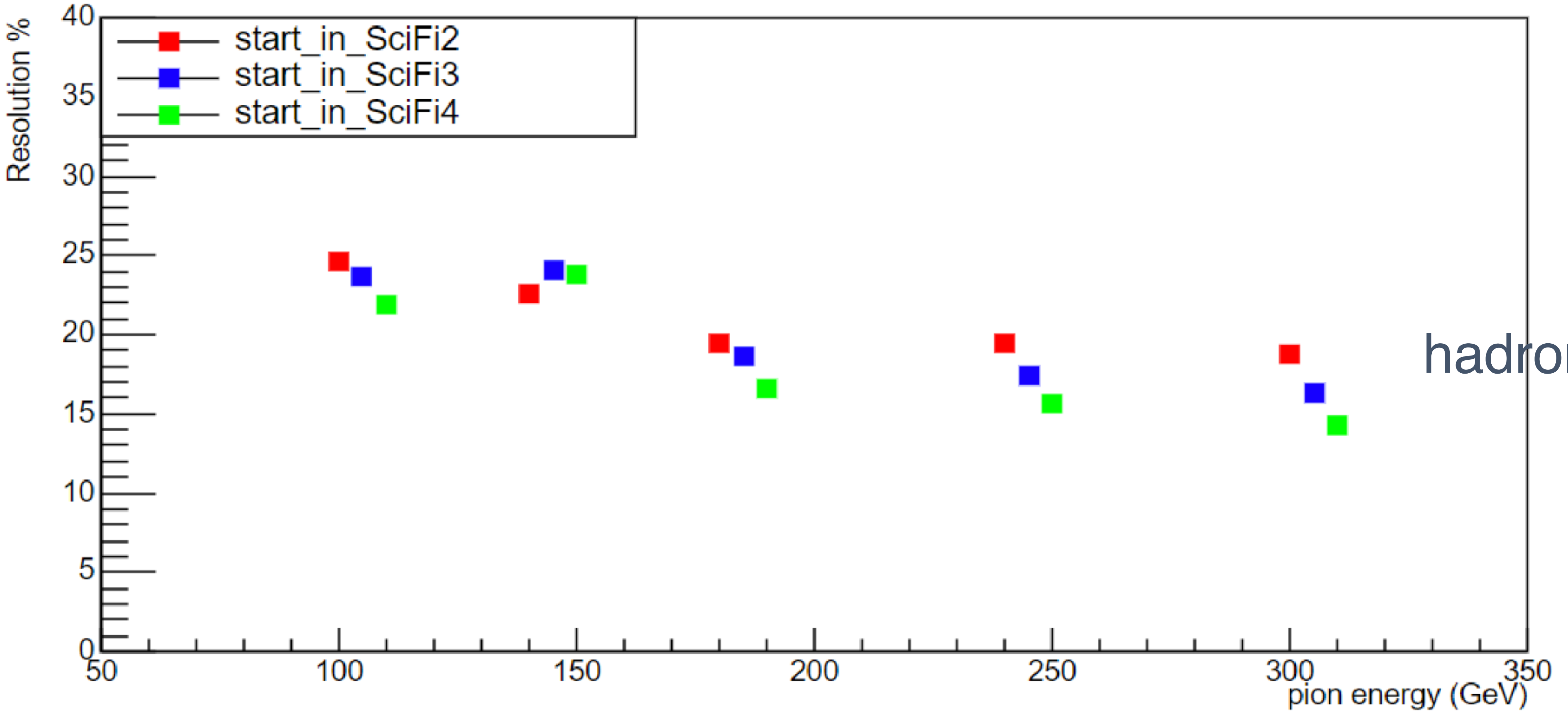
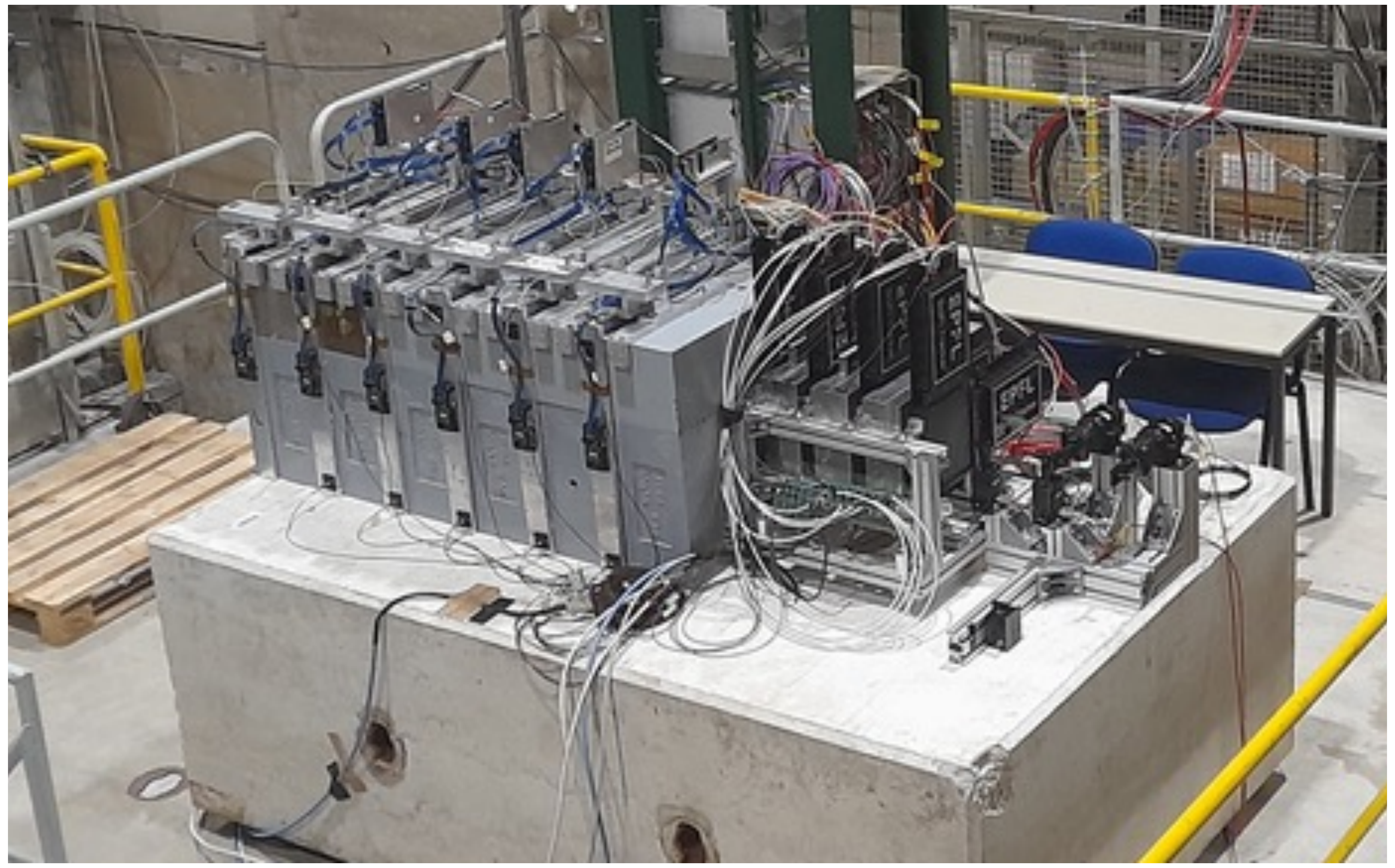
Calibrazione fine della calorimetria

- Le interazioni di neutrini di alta energia hanno uno sciame adronico nello stato finale. La misura di uno sciame deve essere indipendente dalla posizione di interazione del neutrino lungo il target.





hadrons ⟶



- HADRON TEST BEAM in August 2023.
  - ➡ Exact replica of the hadron calorimeter.
  - ➡ Downsized mockup of the target.
    - ➡ Narrow beam spot.
  - ➡ Calibrated calorimeter response.
    - ➡ Confirmed expected performance.
- ELECTRON TEST BEAM in 2024.
  - ➡ Data analysis ongoing.

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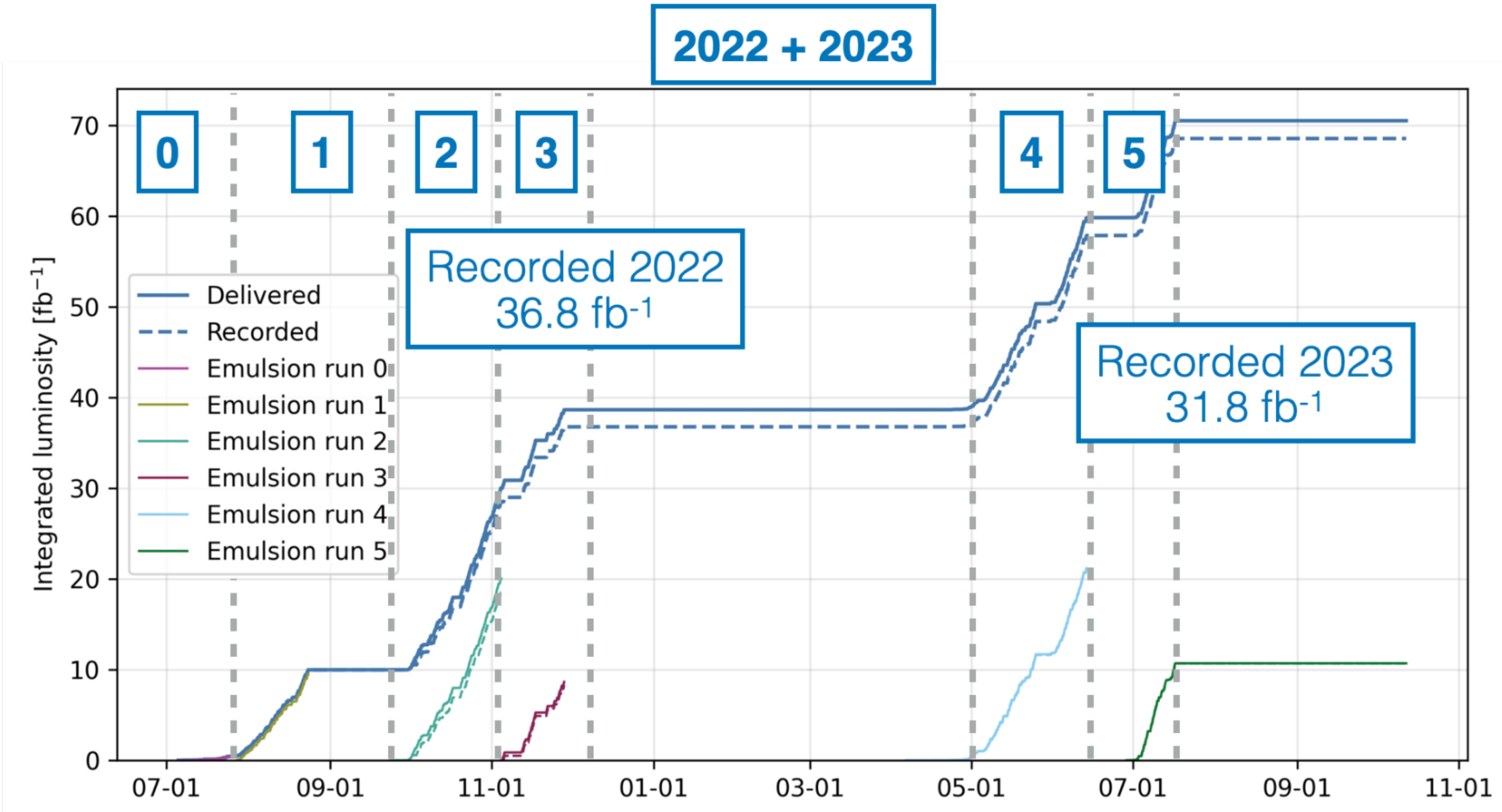
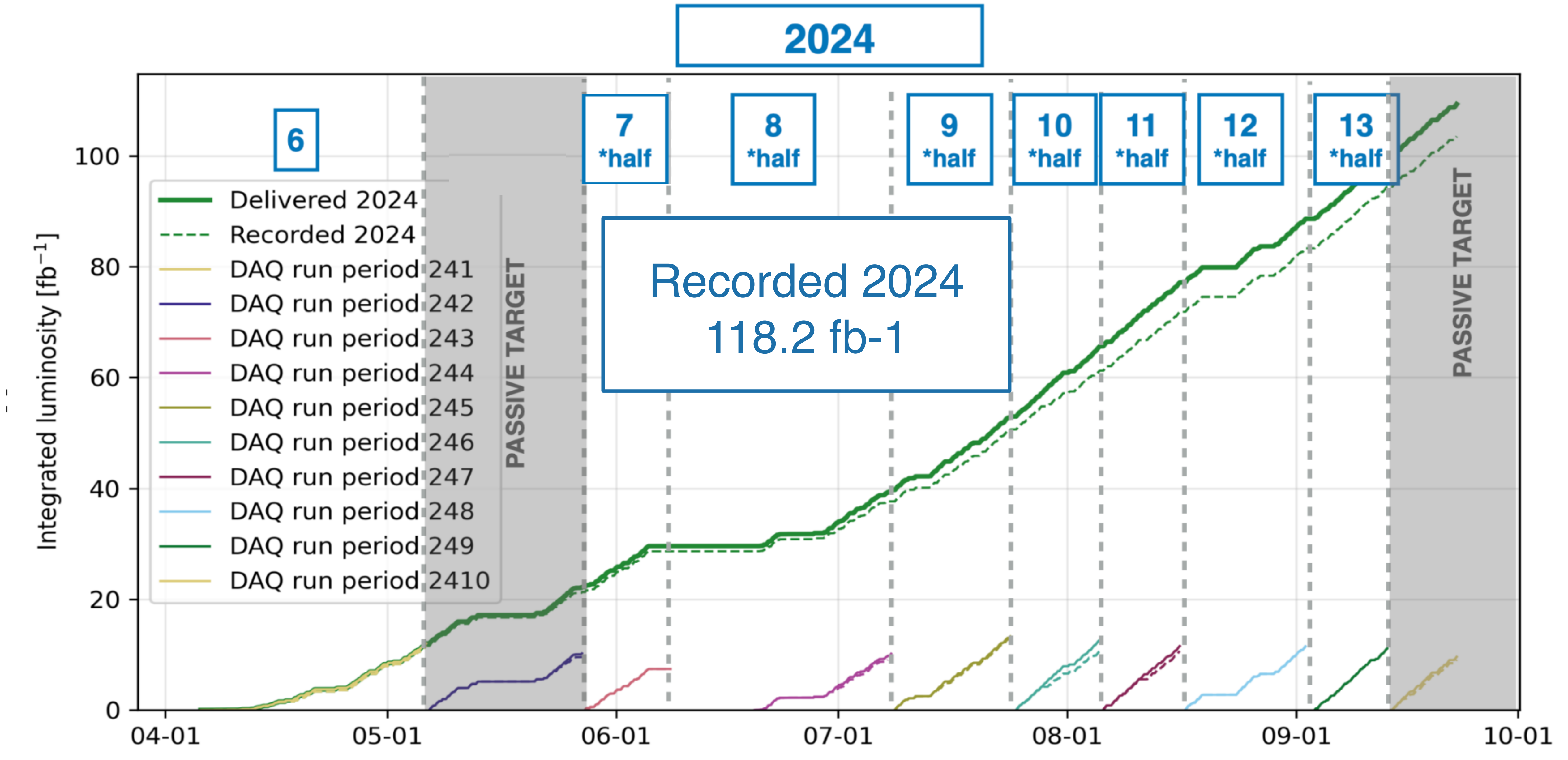
SND@LHC Data





- LHC delivered 195 /fb in 2022-2024
- SND@LHC recorded 187 /fb
  - ➡ 96% uptime
  - ➡ target (W+emulsion) replaced each 20 (10) /fb in 2022-2023 (2024)

SND@LHC 2023

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

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

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full 2022 data sample (36.8 /fb)

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

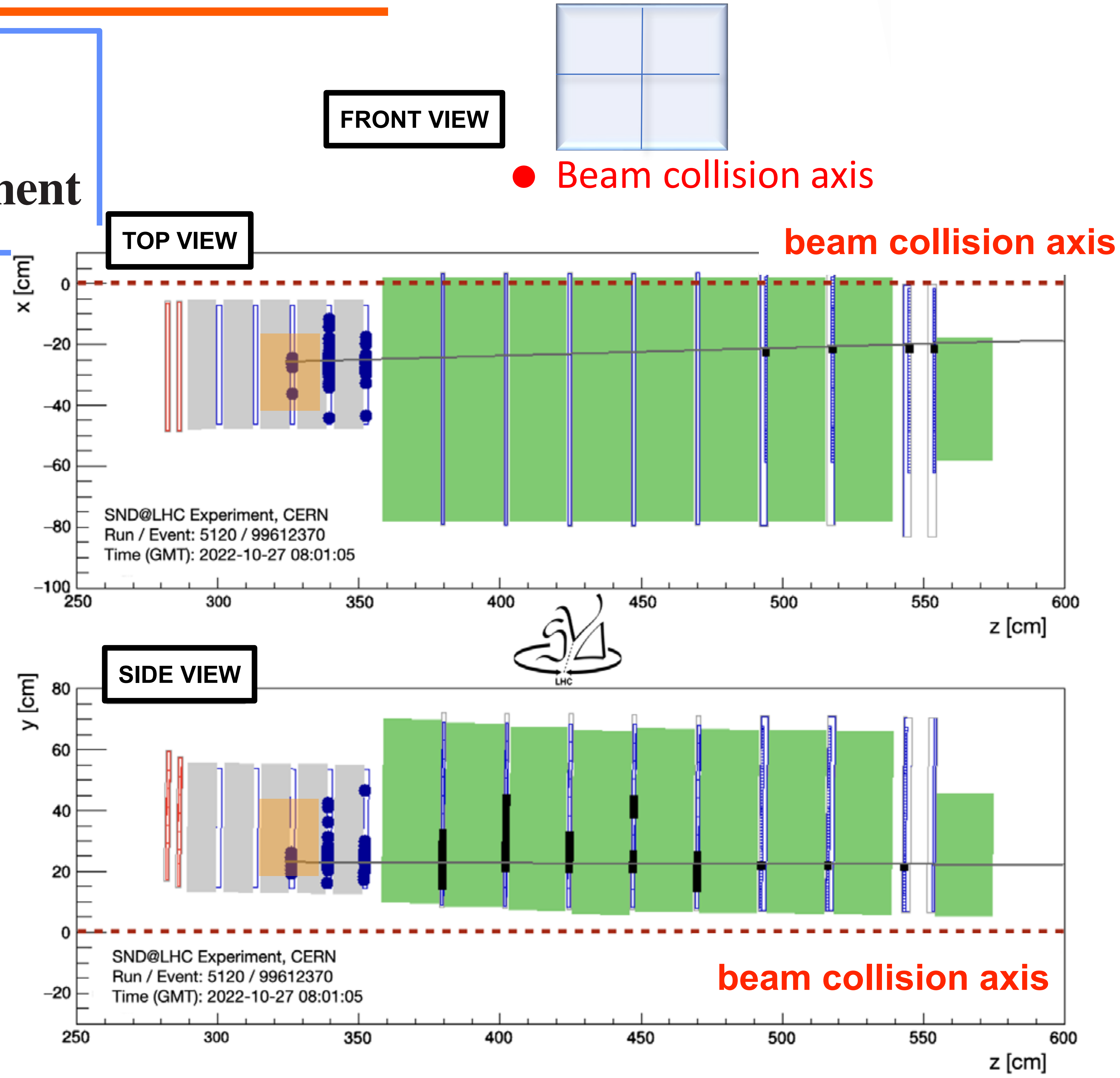
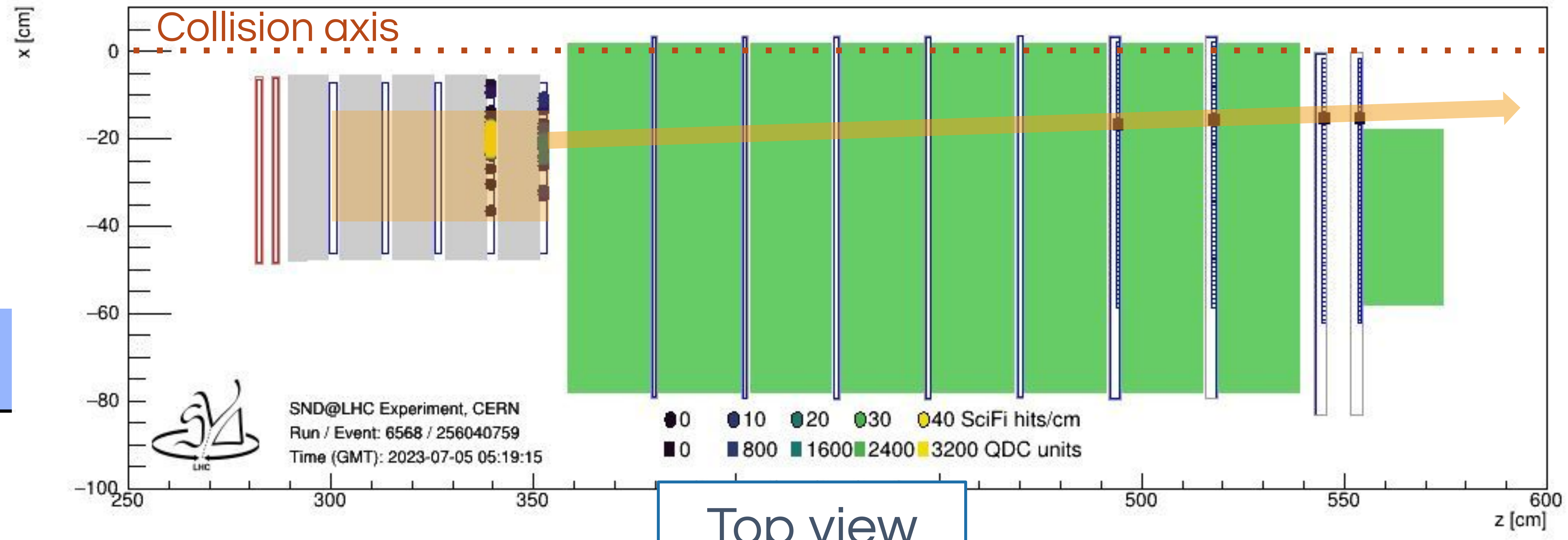


FIG. 2. Display of a ν_μ CC candidate event. Hits in the SciFi, and hadronic calorimeter and muon system are shown as blue markers and black bars, respectively, and the line represents the reconstructed muon track.

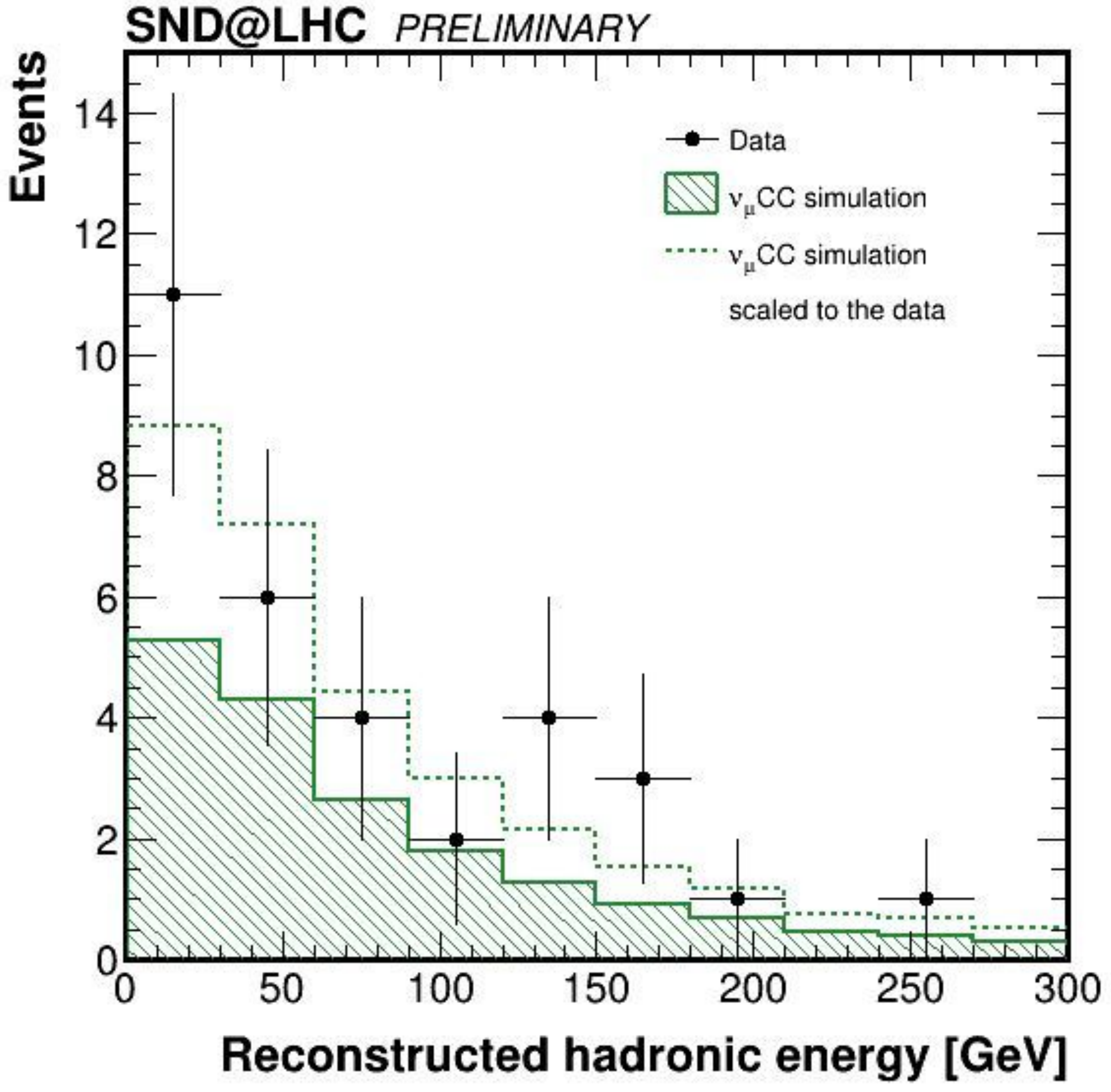
SND@LHC ν_μ analysis update

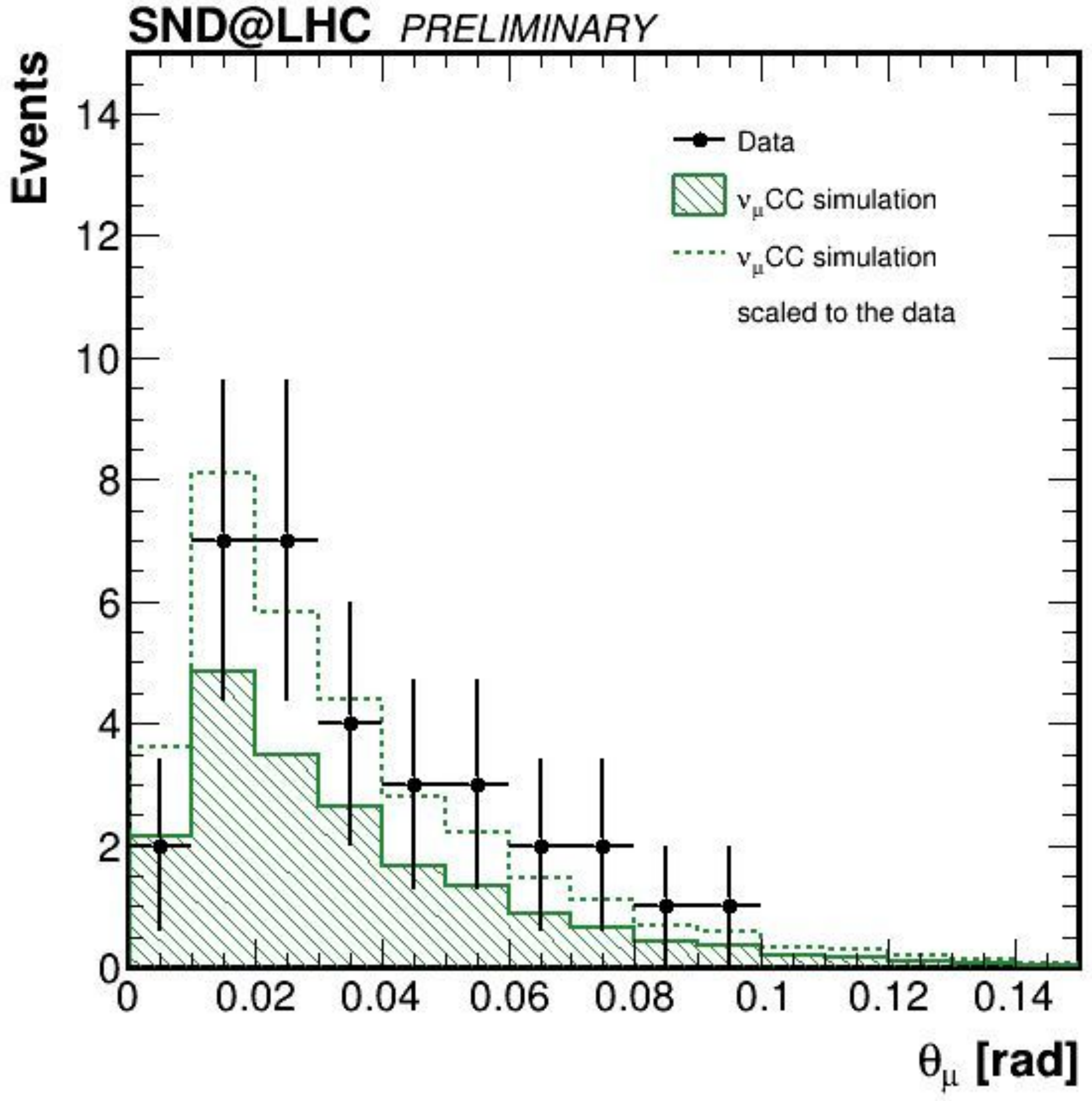
- 2022/23 data sample 68.6/fb
- fiducial volume extended
- preliminary:

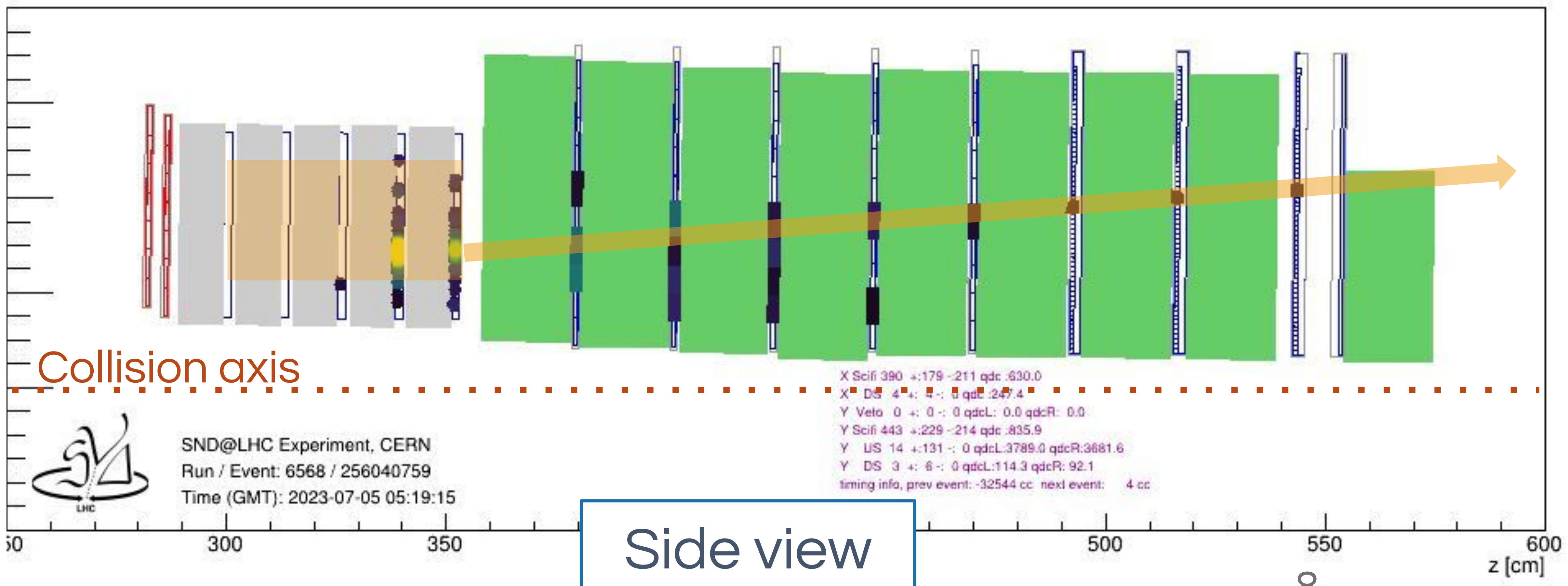
	background	observed	S/N
ν_μ CC	$1.53^{+0.25}_{-0.25}$	32	17



Top view



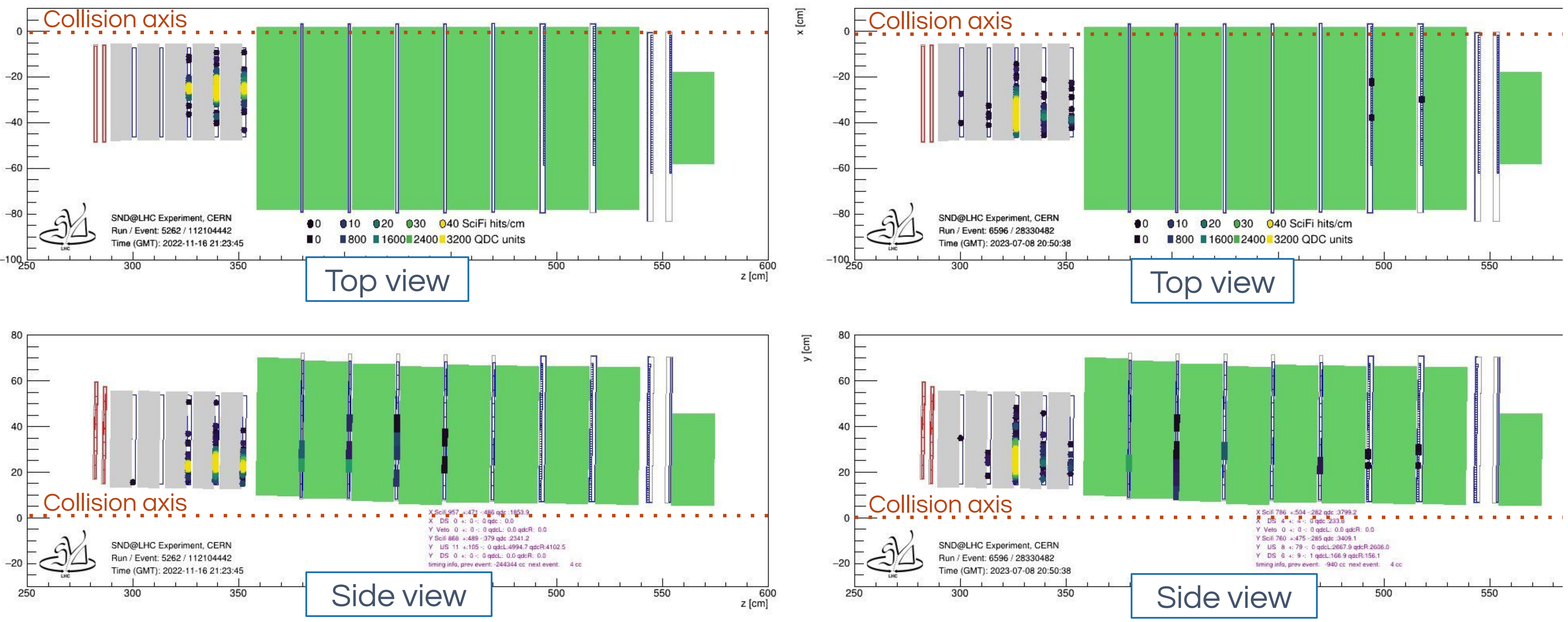




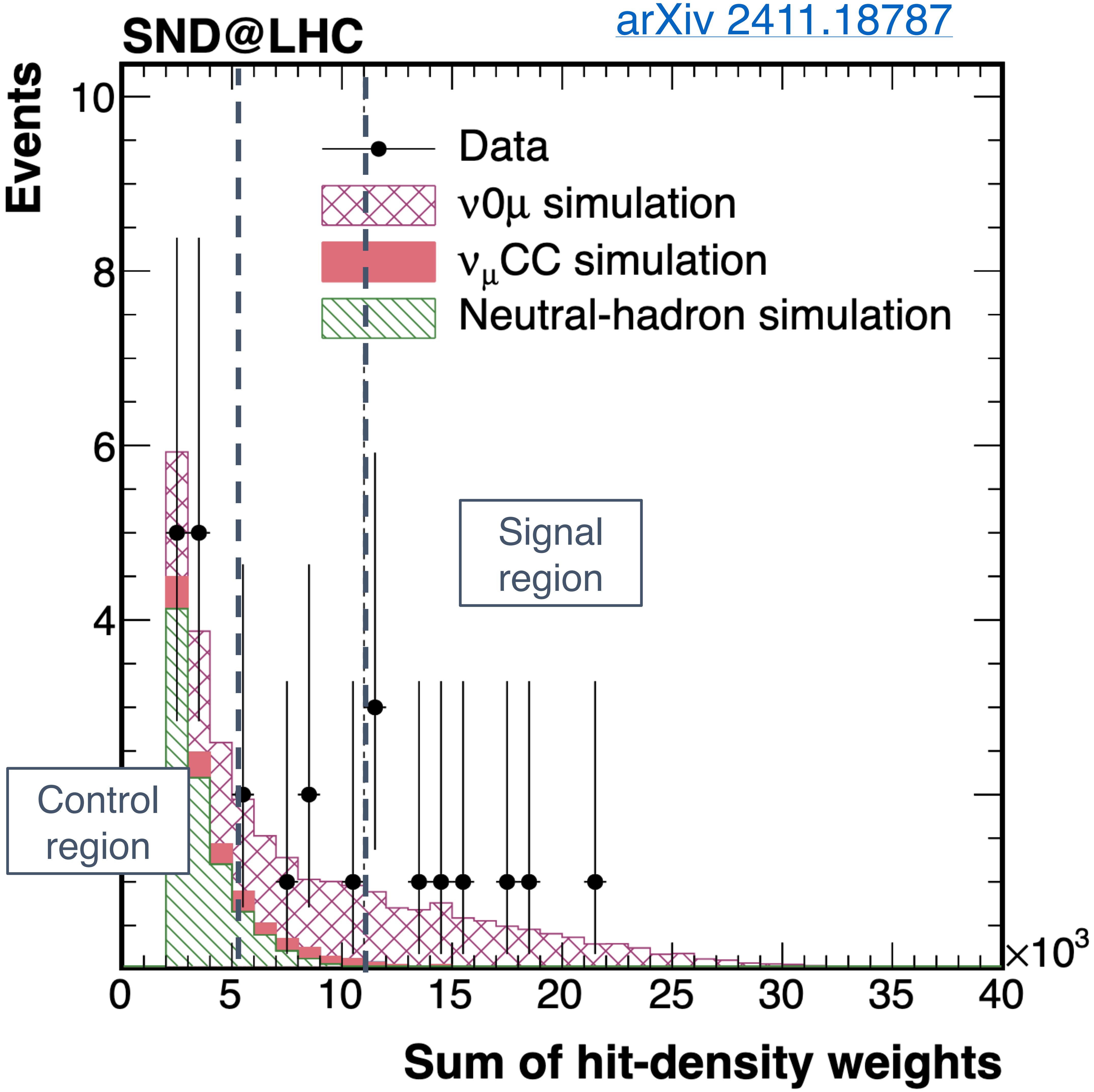
Side view

Observation of 0μ events in SND@LHC

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



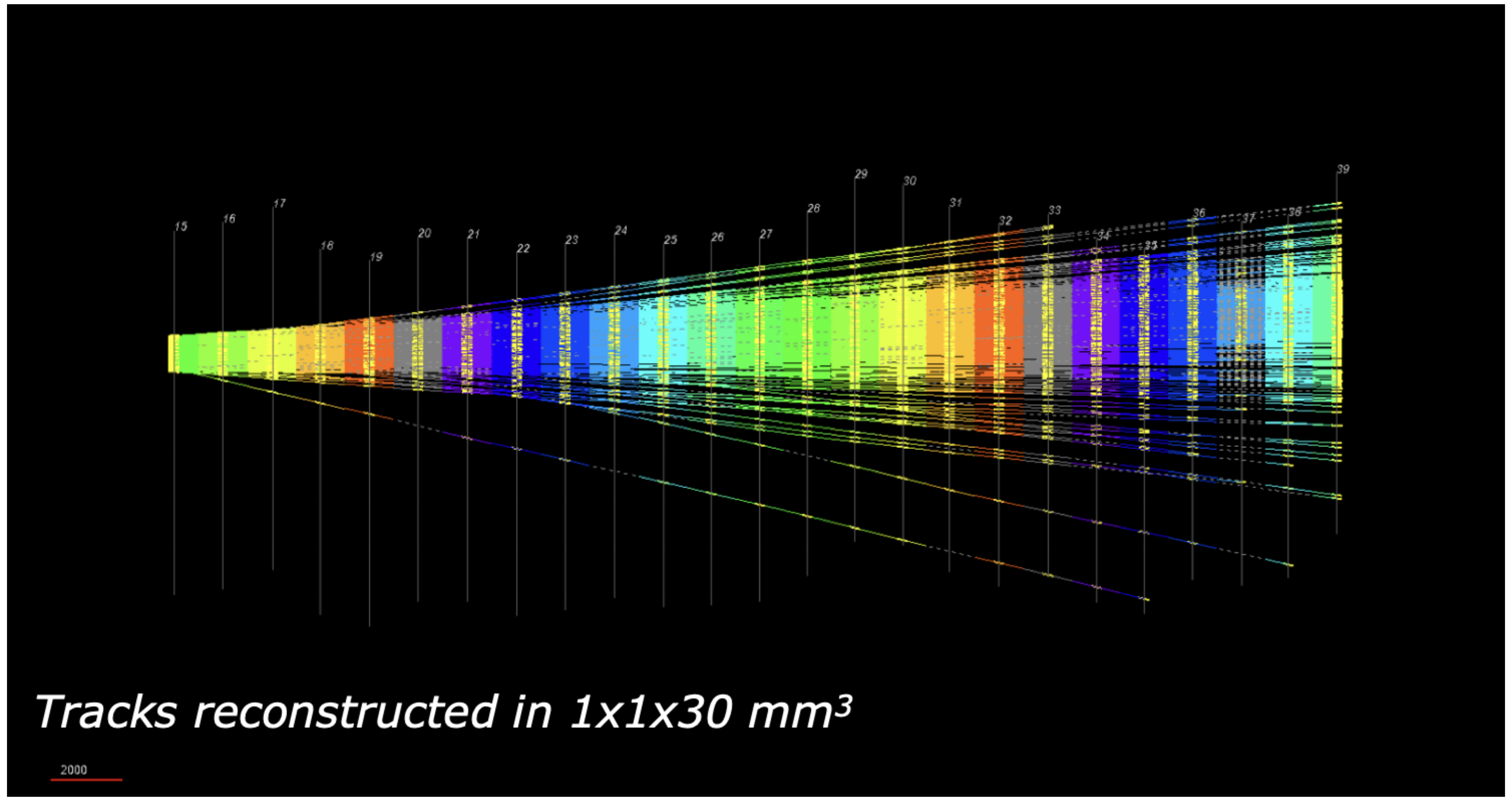
arXiv 2411.18787



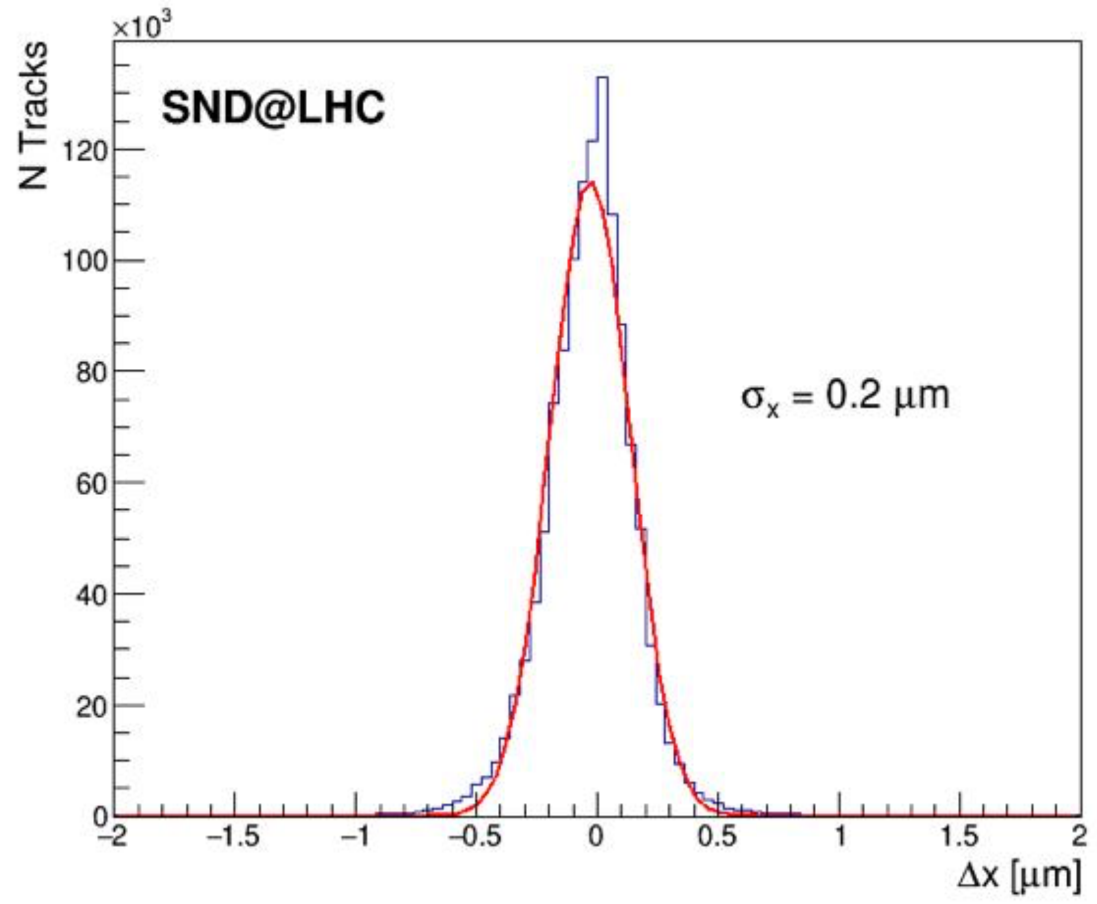
	background	observed	significance
0μ	$0.32^{+0.06}_{-0.06}$	9	6.4 σ

emulsion target analysis

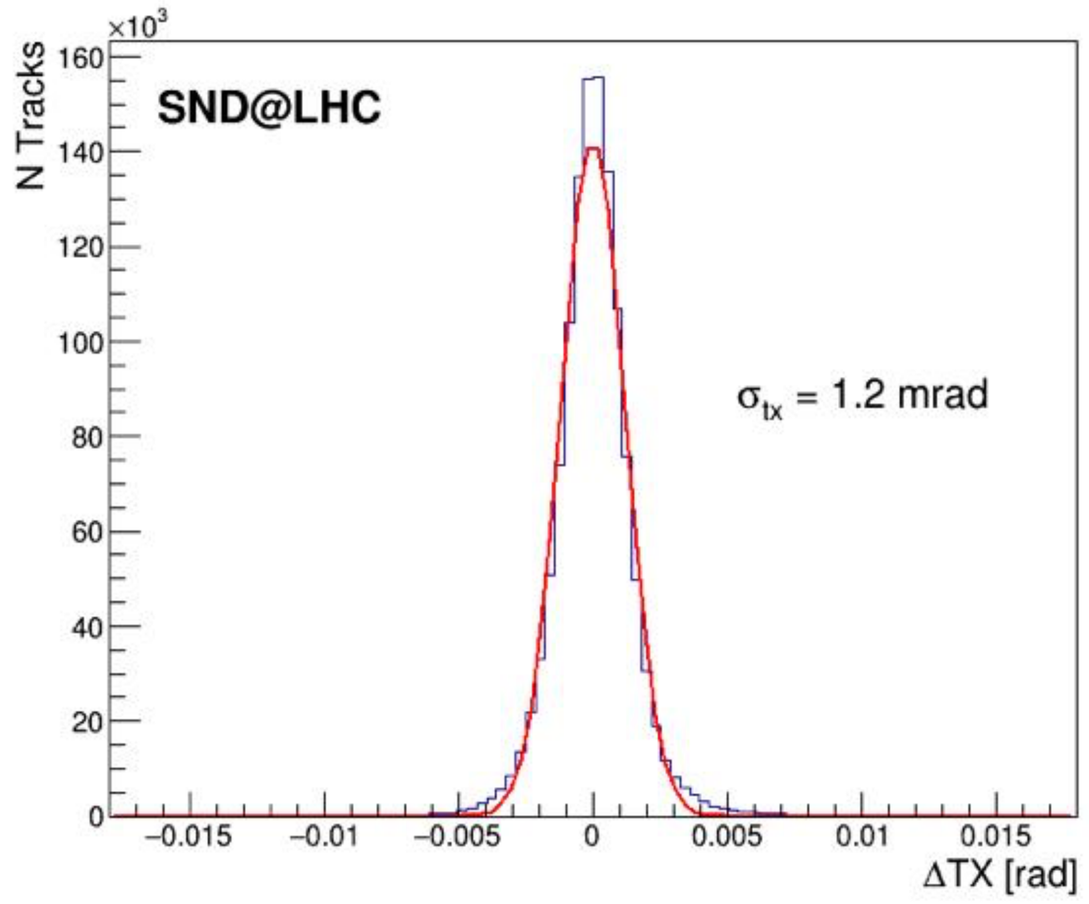
- Emulsion scanning with automated microscopes in 6 laboratories: CERN, Napoli, Bologna, Nagoya, LNGS, Santiago
- Track density up to 4×10^5 tracks/cm2 (10^3 x OPERA)
  - ➡ Full revision of alignment, tracking, vertexing procedures
    - ➡ Excellent tracking resolution achieved



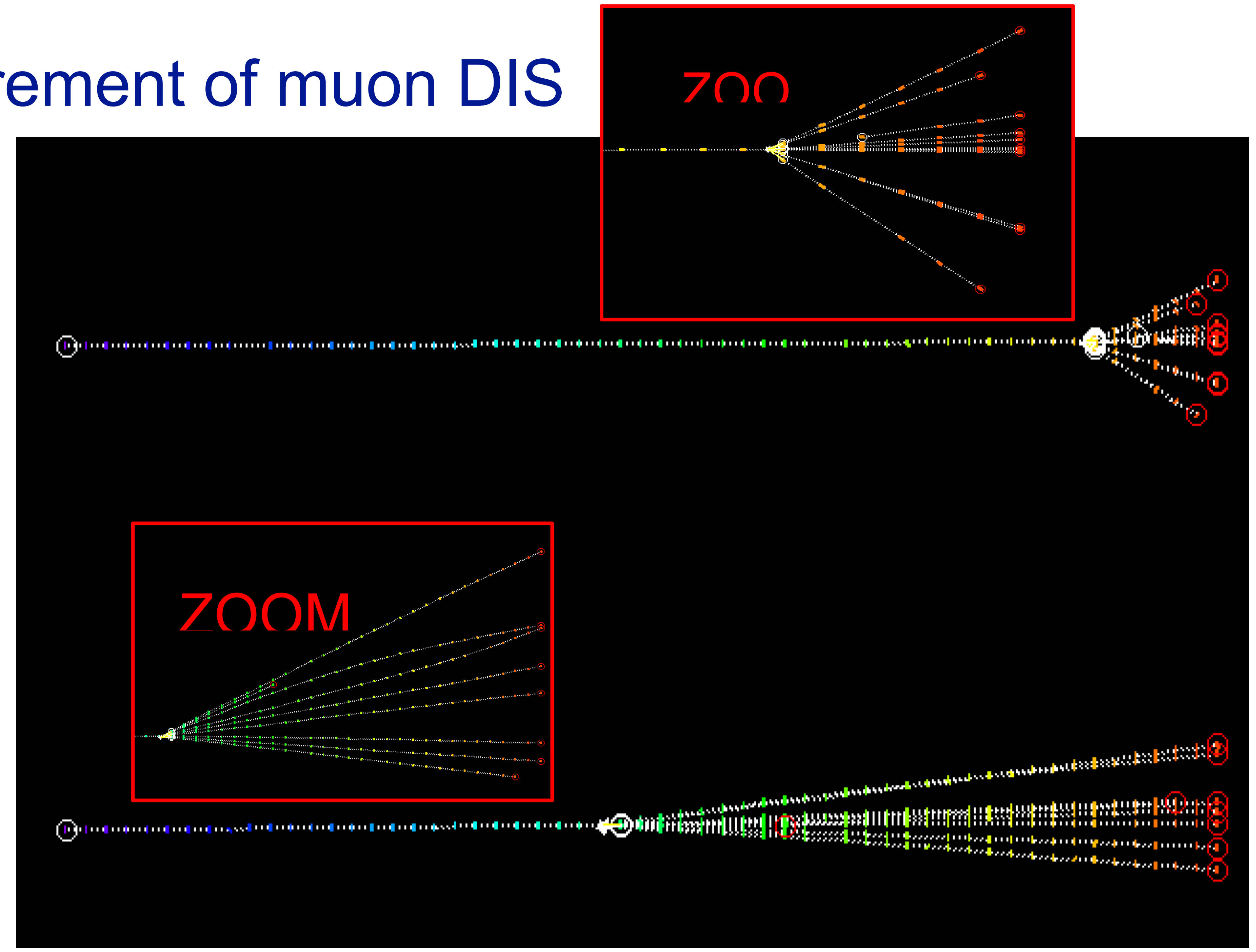
POSITION RESOLUTION $0.2\mu m$



ANGULAR RESOLUTION 1.2 mrad



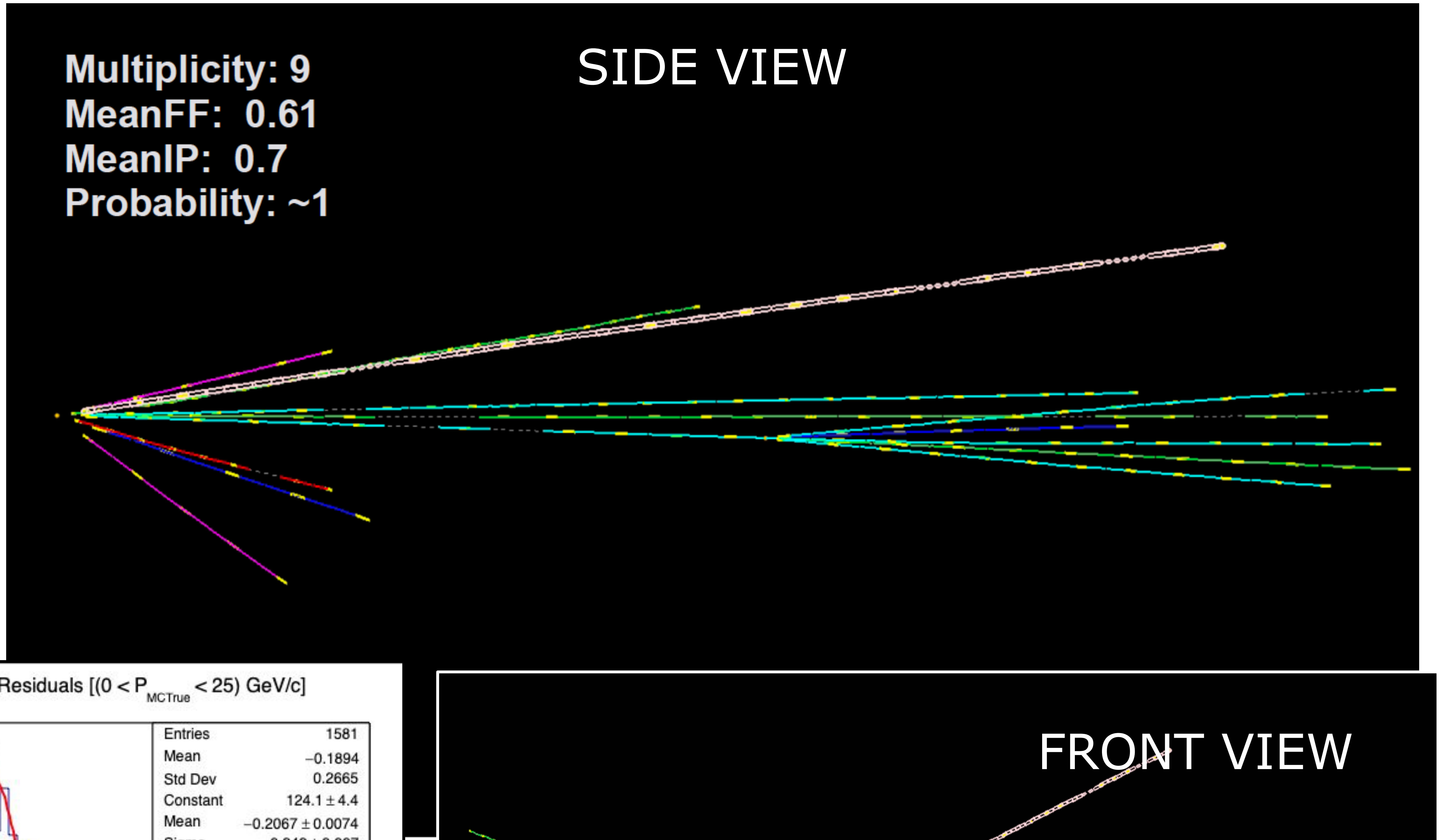
measurement of muon DIS

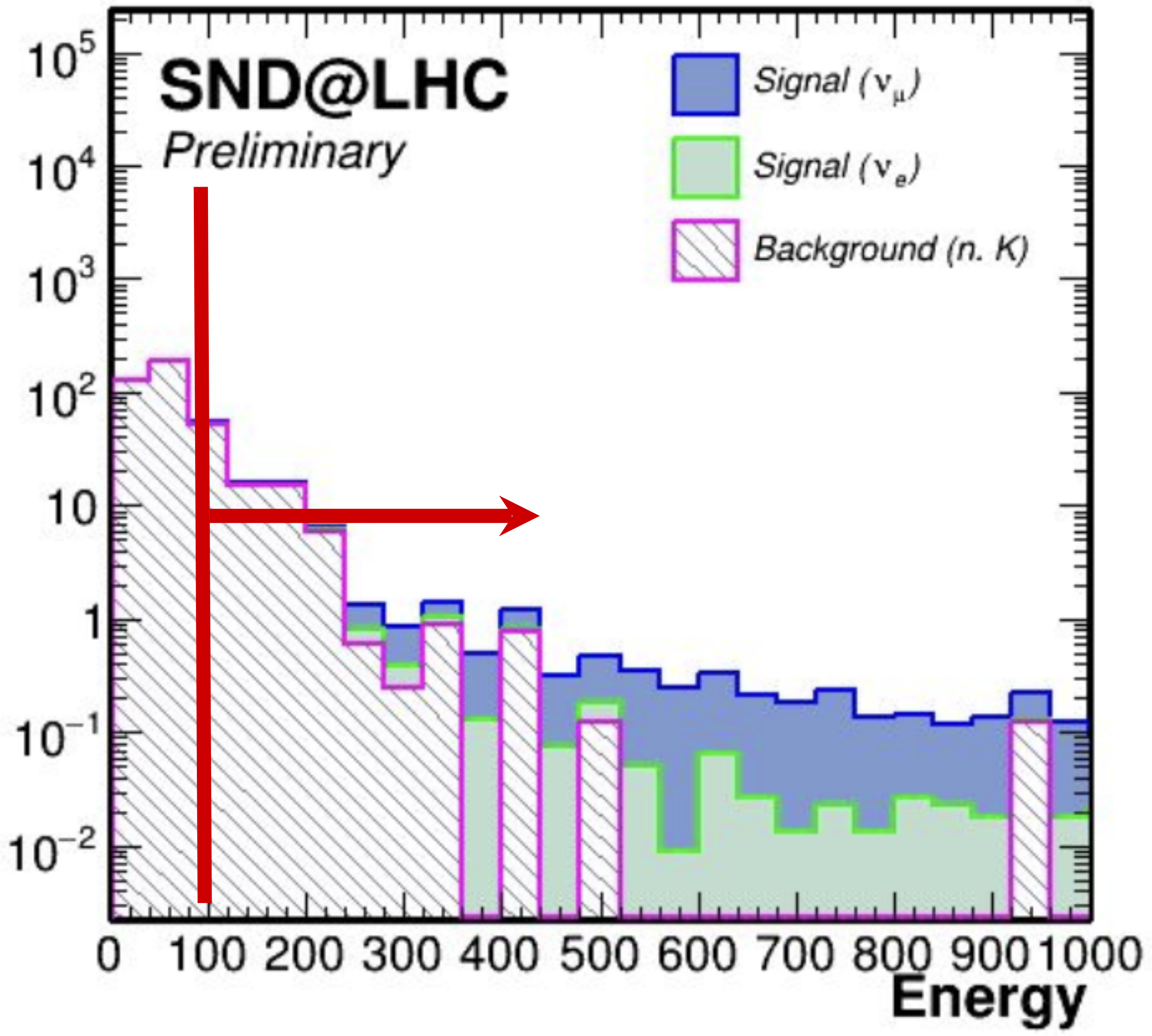


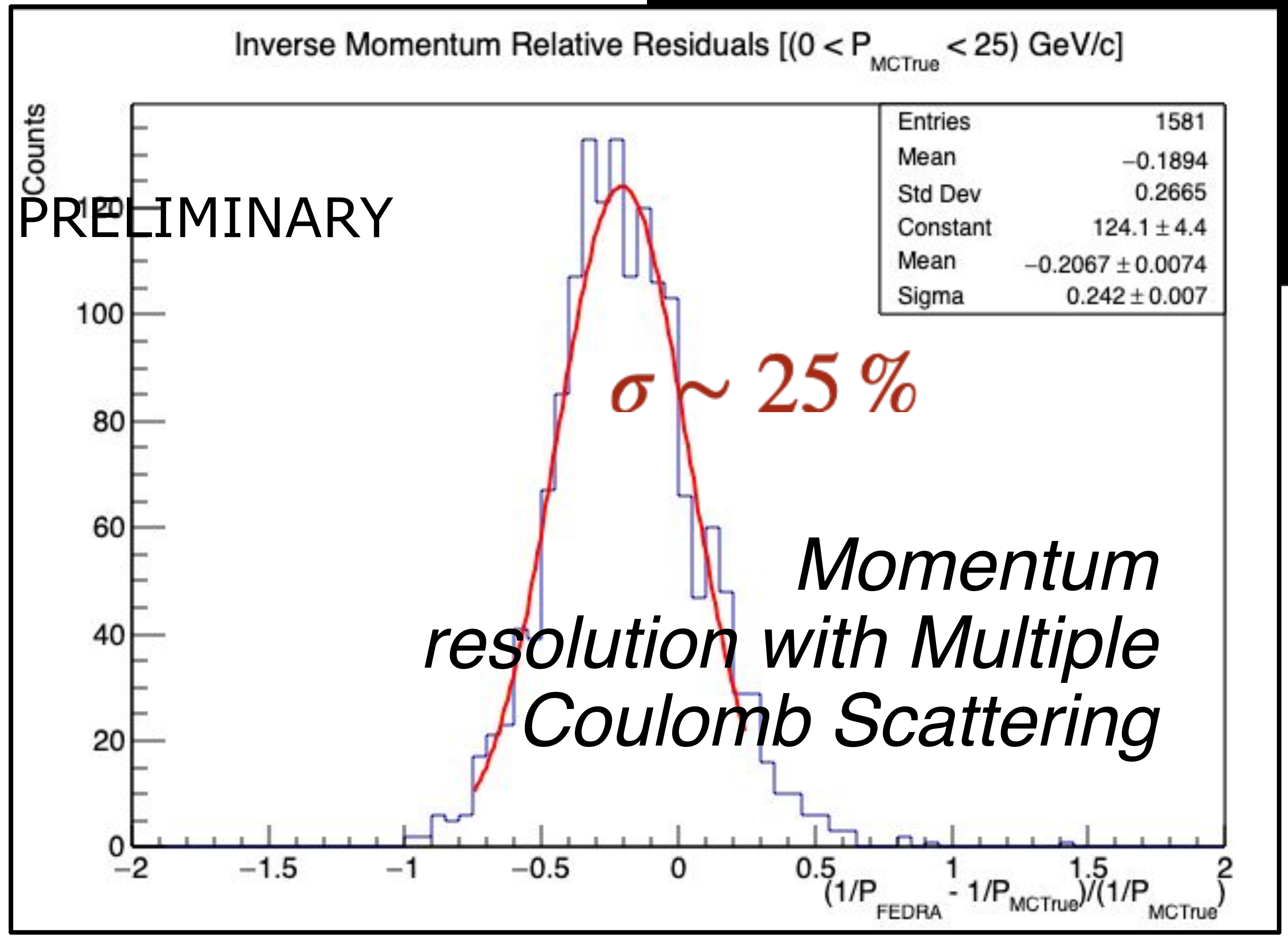
Neutrino interactions in emulsions

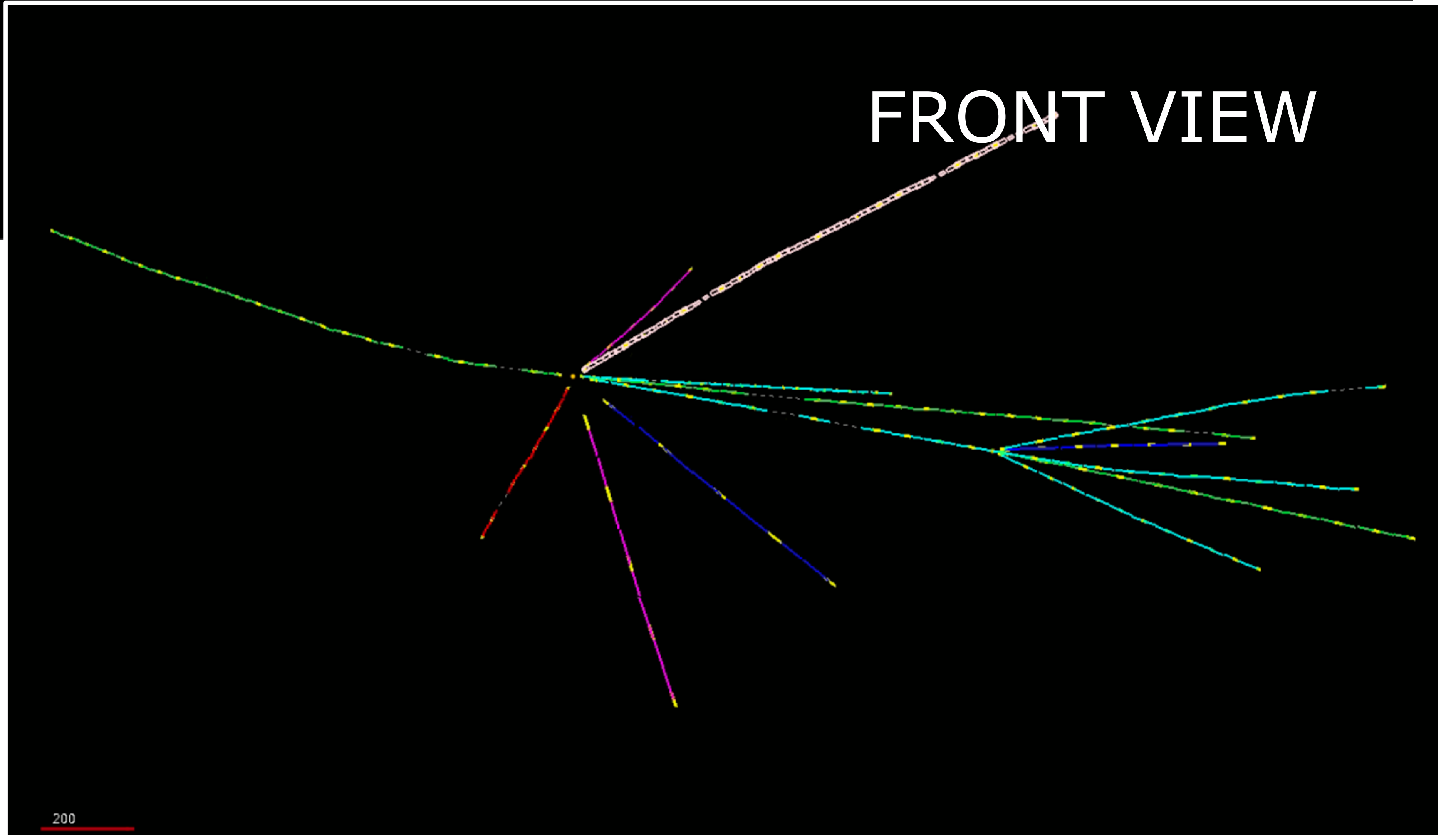
- Identification of neutrino interactions in the emulsion target:
  - charged vertex
  - track multiplicity>3
  - impact parameter<3.5um
  - fraction of crossed films>0.1
  - vertex probability>0.1
- Kinematical selection Erec>300 GeV

Expected signal/noise ratio: 2/1



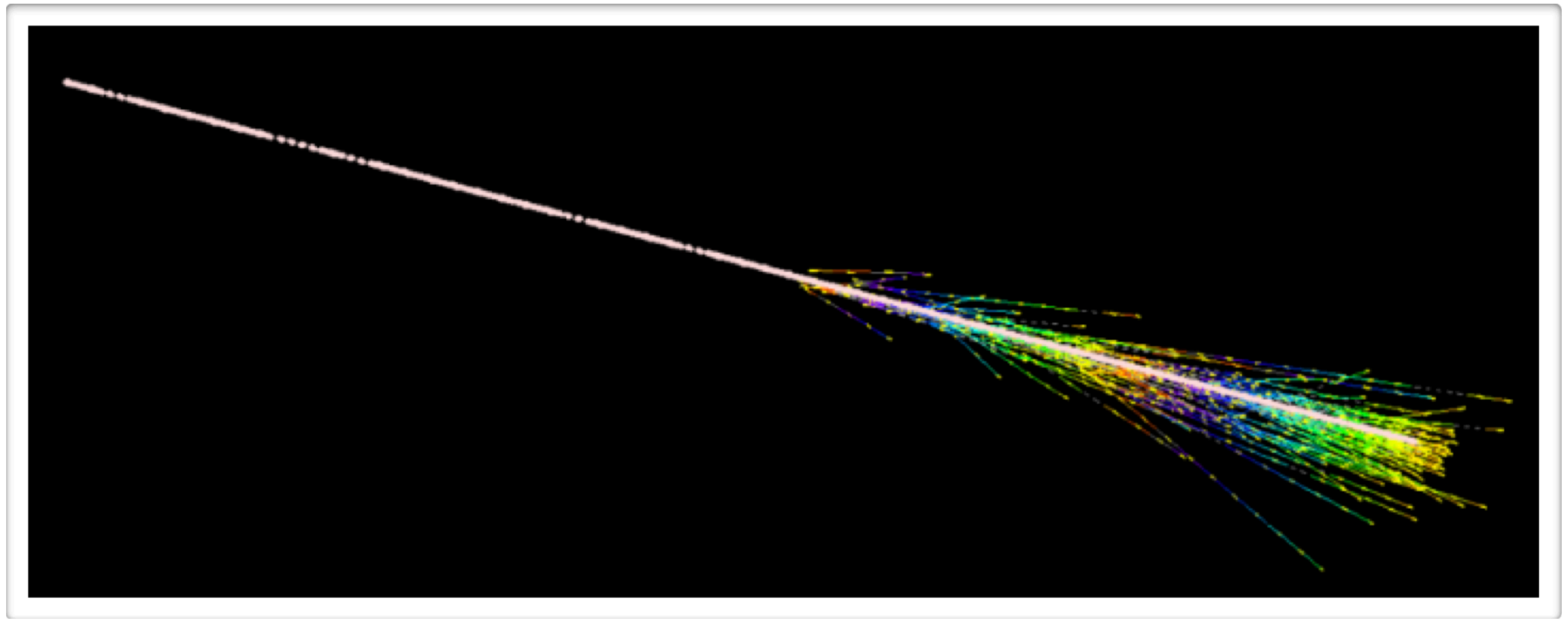


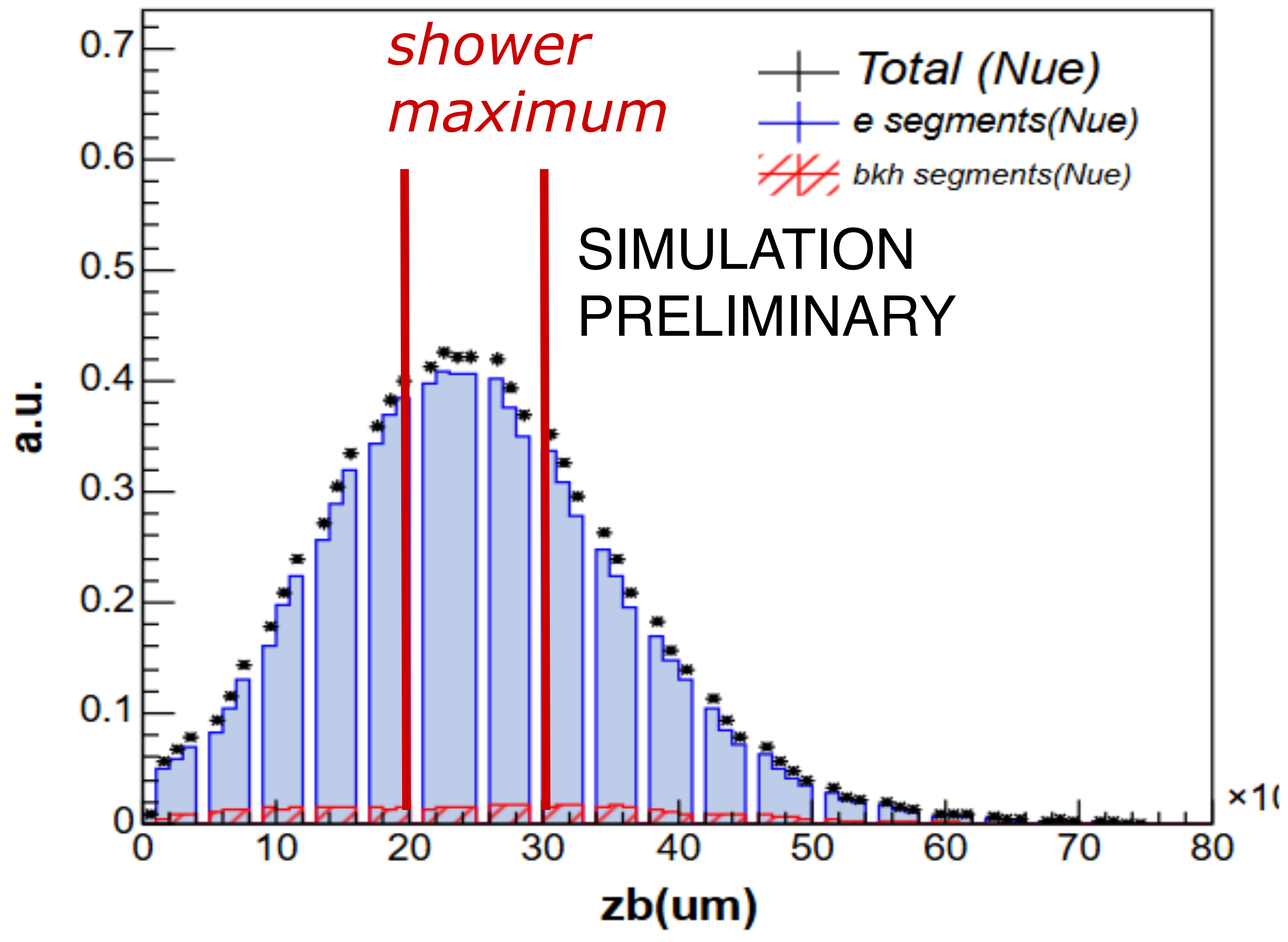


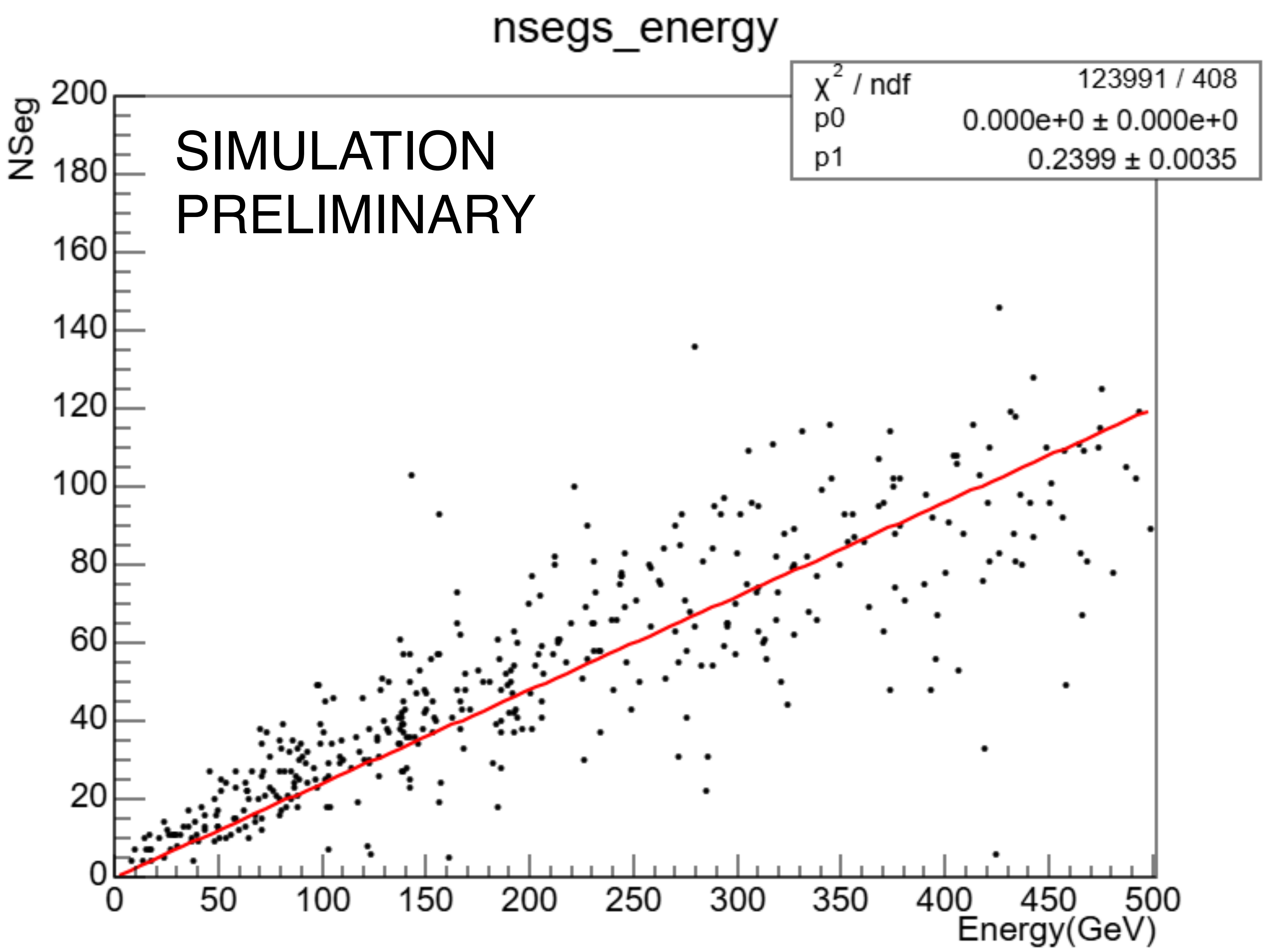


Electron ID in emulsion target

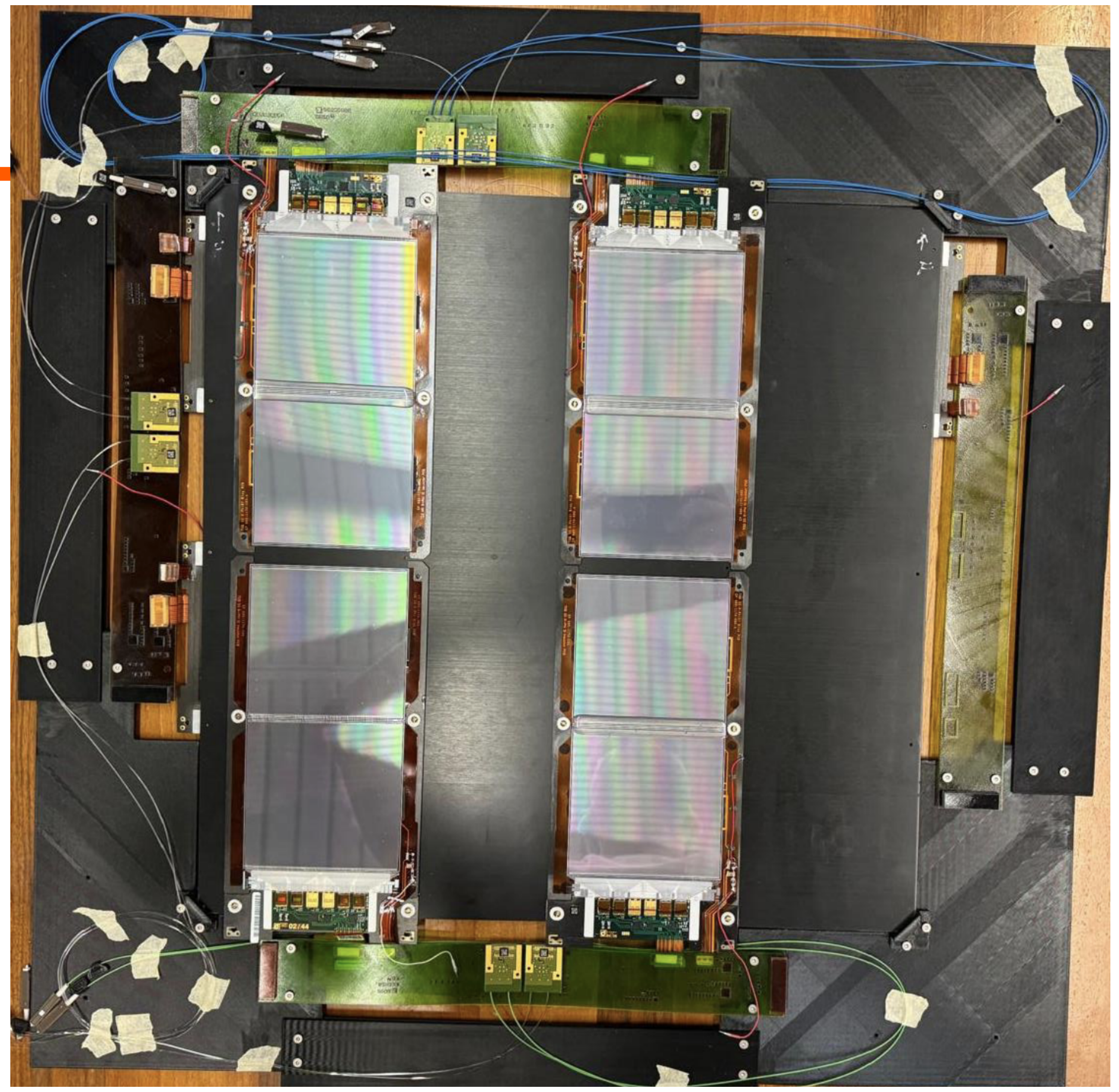
- Electron ID based on EM shower identification
- Electron energy estimate based on number of segments at the shower maximum proportional to electron energy



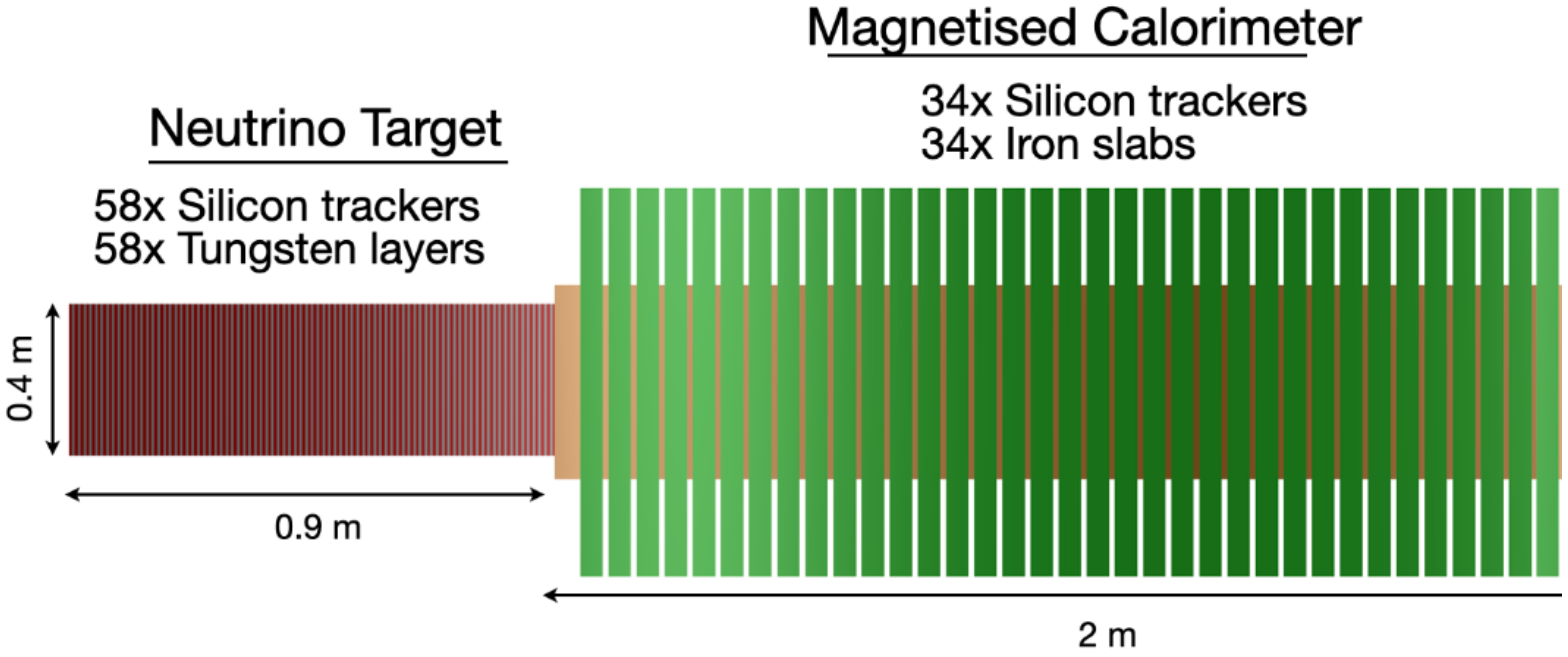


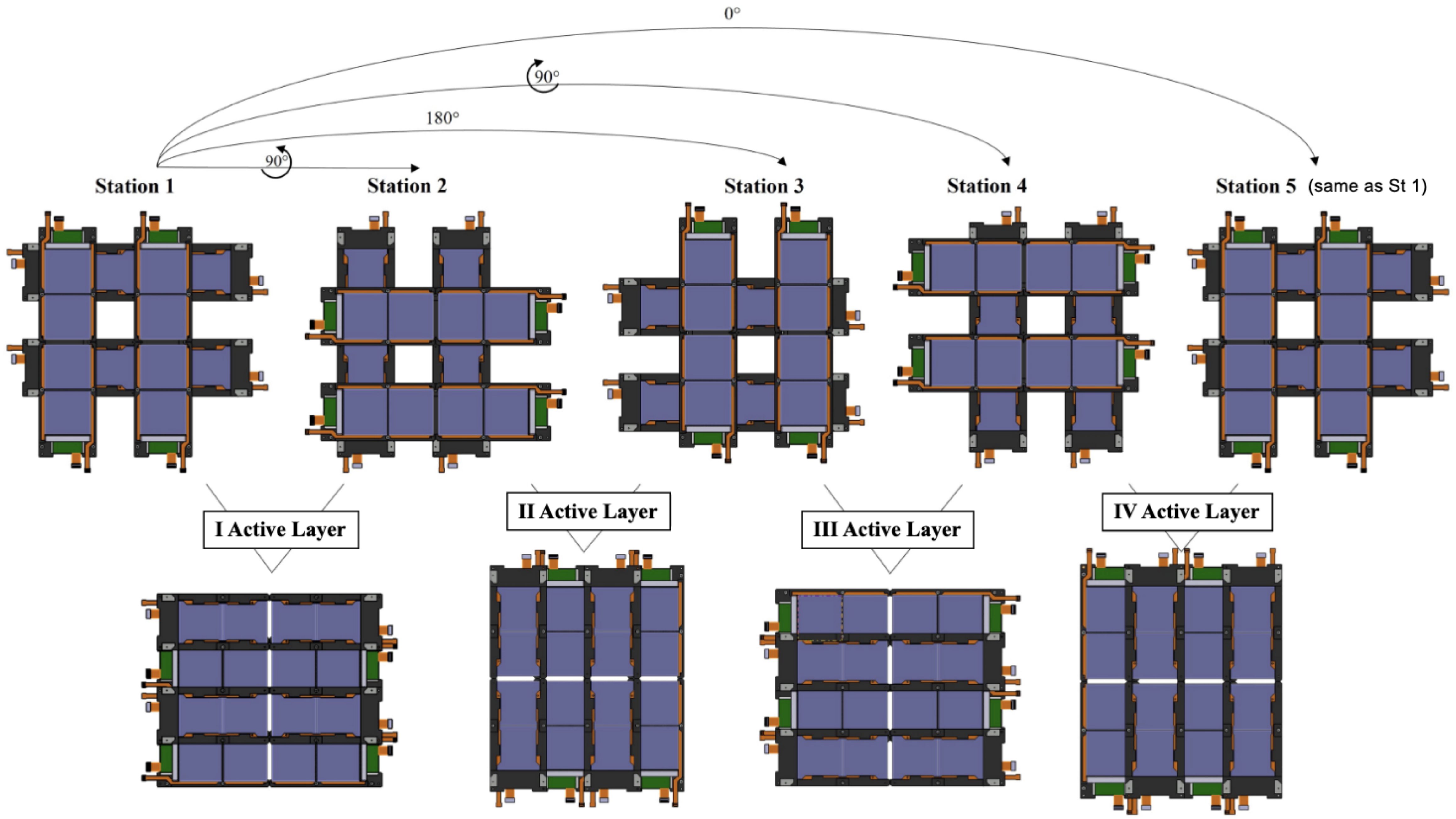


SND@HL-LHC: Silicon strips



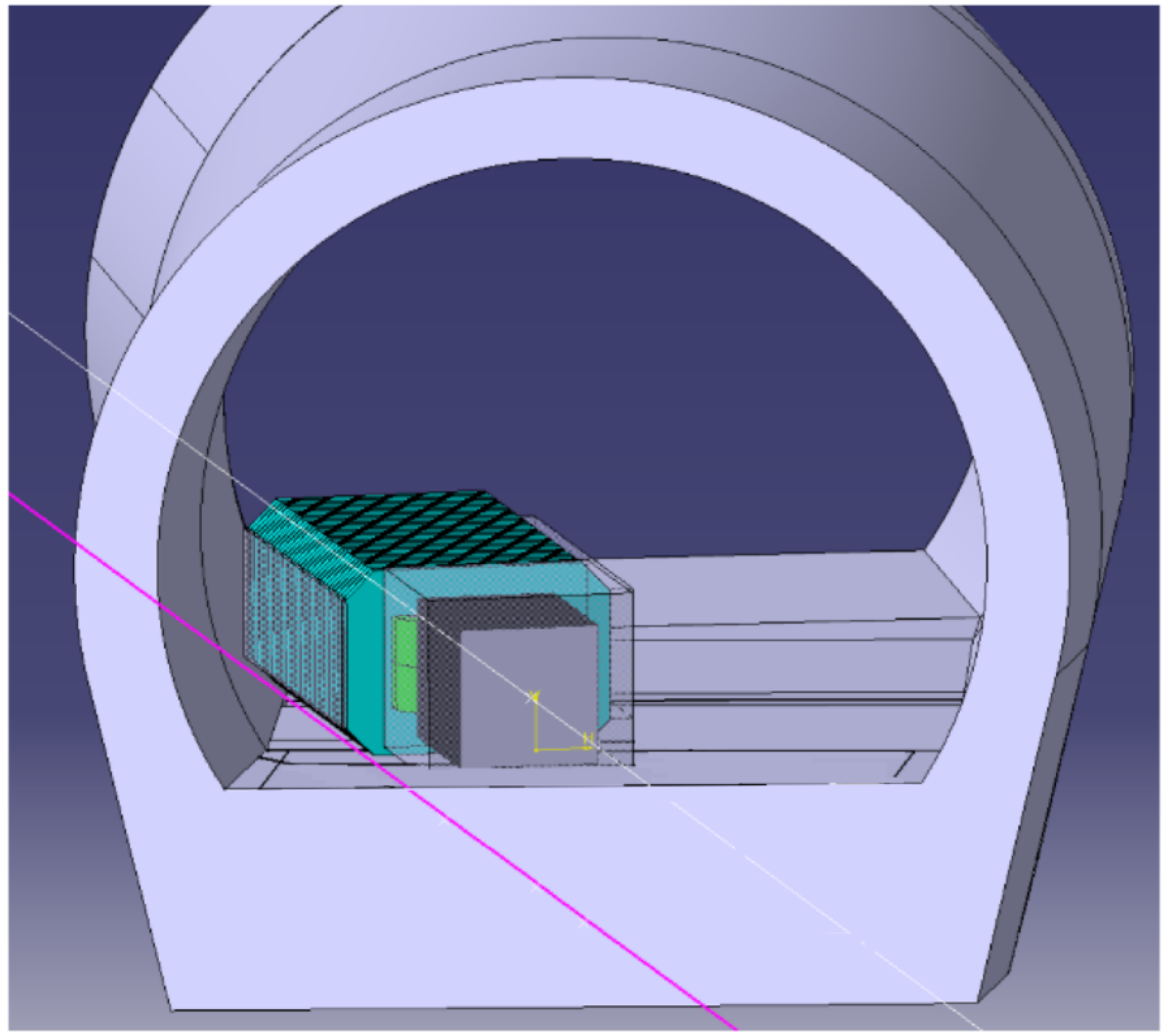
- Running the emulsion detector during the HL-LHC is unfeasible.
- will use silicon-strip modules inherited from the CMS outer barrel tracker.
    - ➡ 122 micron strip pitch; 1680 modules available.
- The calorimeter will be magnetised for muon momentum and charge measurement.
- Technical Proposal submitted



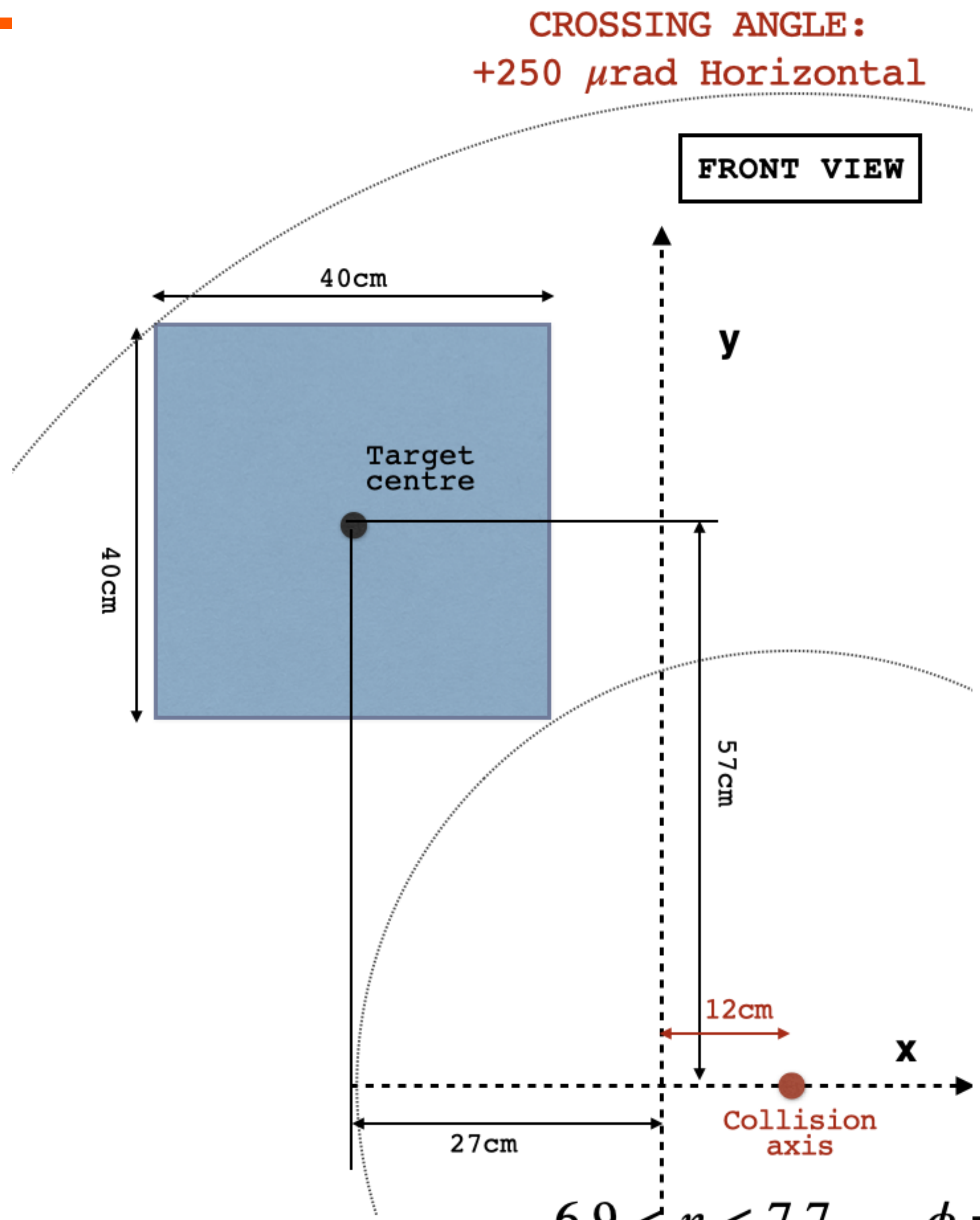


CERN-LHCC-2024-014

Detector location



CERN-LHCC-2024-014



$6.9 < \eta < 7.7$ $\phi = 0.066$

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- The detector will be moved upstream and upward to fit in the existing space.
- If there is an opportunity to excavate a trench on the tunnel floor, an increase in the event yield by a factor of 7 is possible.

	CC DIS Interactions (3k fb^{-1}, 1.3 ton)	
Flavour	**total (DPMJET)**	**cc-bar (DPMJET)**
$\nu_\mu + \bar{\nu}_\mu$	1.5x10^4	2.4x10^3
$\nu_e + \bar{\nu}_e$	3.4x10^3	2.7x10^3
$\nu_\tau + \bar{\nu}_\tau$	2.8x10^2	2.8x10^2
Total	**1.9x10^4**	**5.4x10^3**

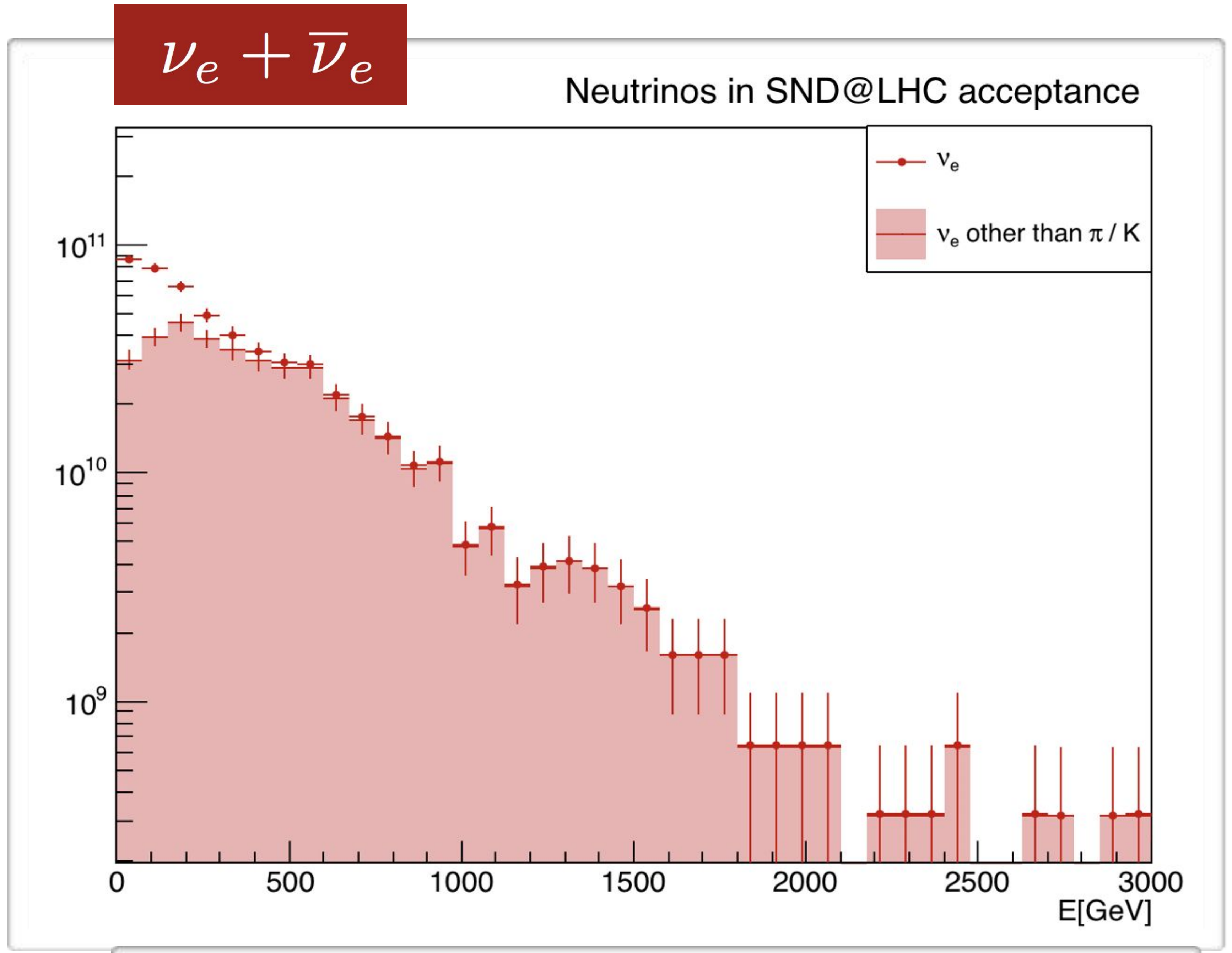
Summary

- Dal 2022 due esperimenti a LHC dedicati allo studio di ν_e , ν_μ , ν_τ da collisioni pp:
  - ➡ SND@LHC in $7.2 < \eta < 8.4$
  - ➡ FASER in $\eta > 8.8$
- Questi neutrini “forward” accrescono il potenziale di Fisica di LHC:
  - ➡ allow for studying νN interactions at energies in the E_ν TeV range
  - ➡ carry information on parton fractional momenta down to 10^{-6} and can constrain QCD uncertainties
- SND@LHC ha raccolto 187 fb-1 nel 2022-2024
  - ➡ Observation of collider muon neutrinos (2023)
  - ➡ Observation of neutrinos without final state muons (2024)
- Per HL-LHC l’esperimento sarà potenziato con
  - ➡ silicon strip modules from the CMS outer barrel
  - ➡ magnetised calorimeter

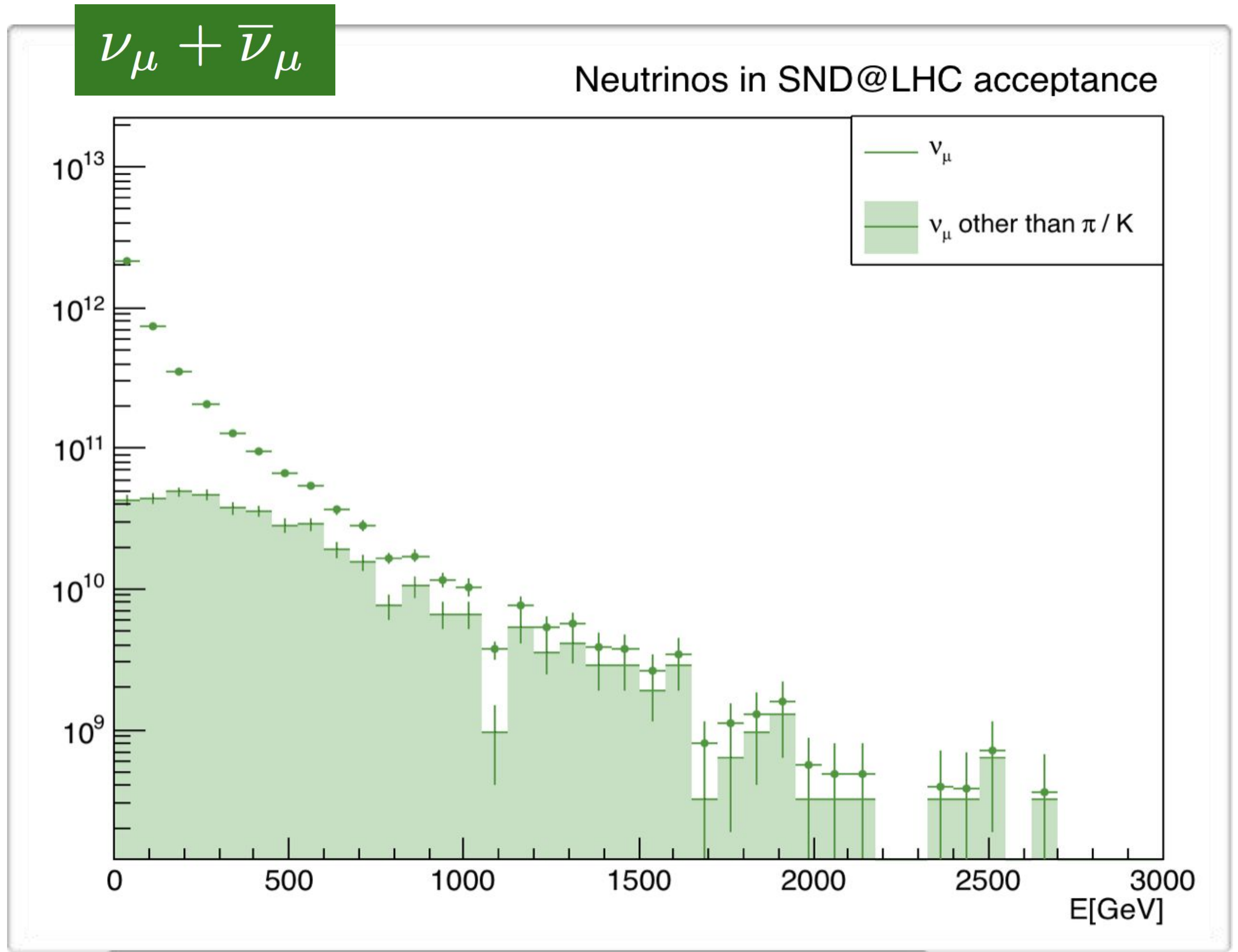
additional material

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

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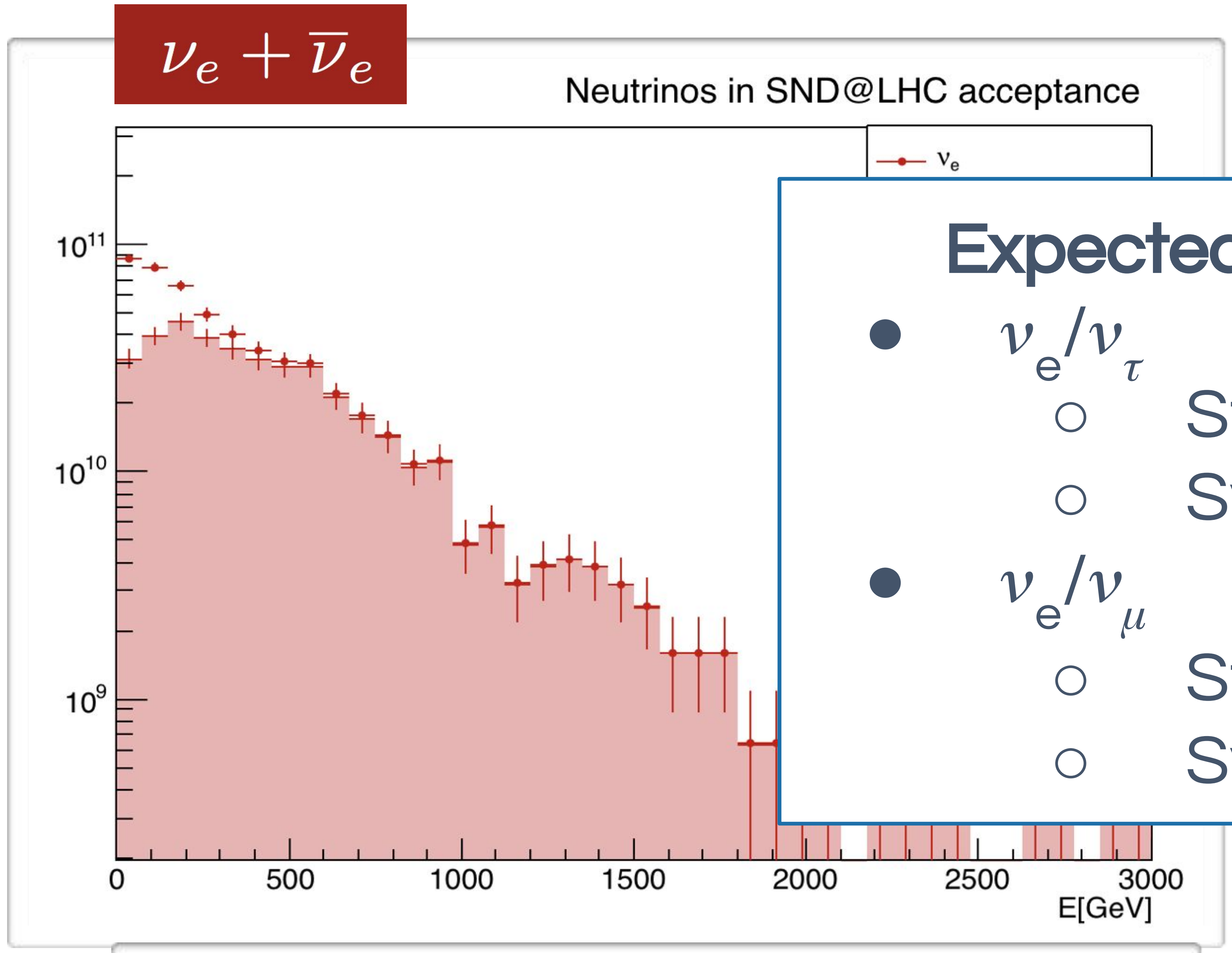

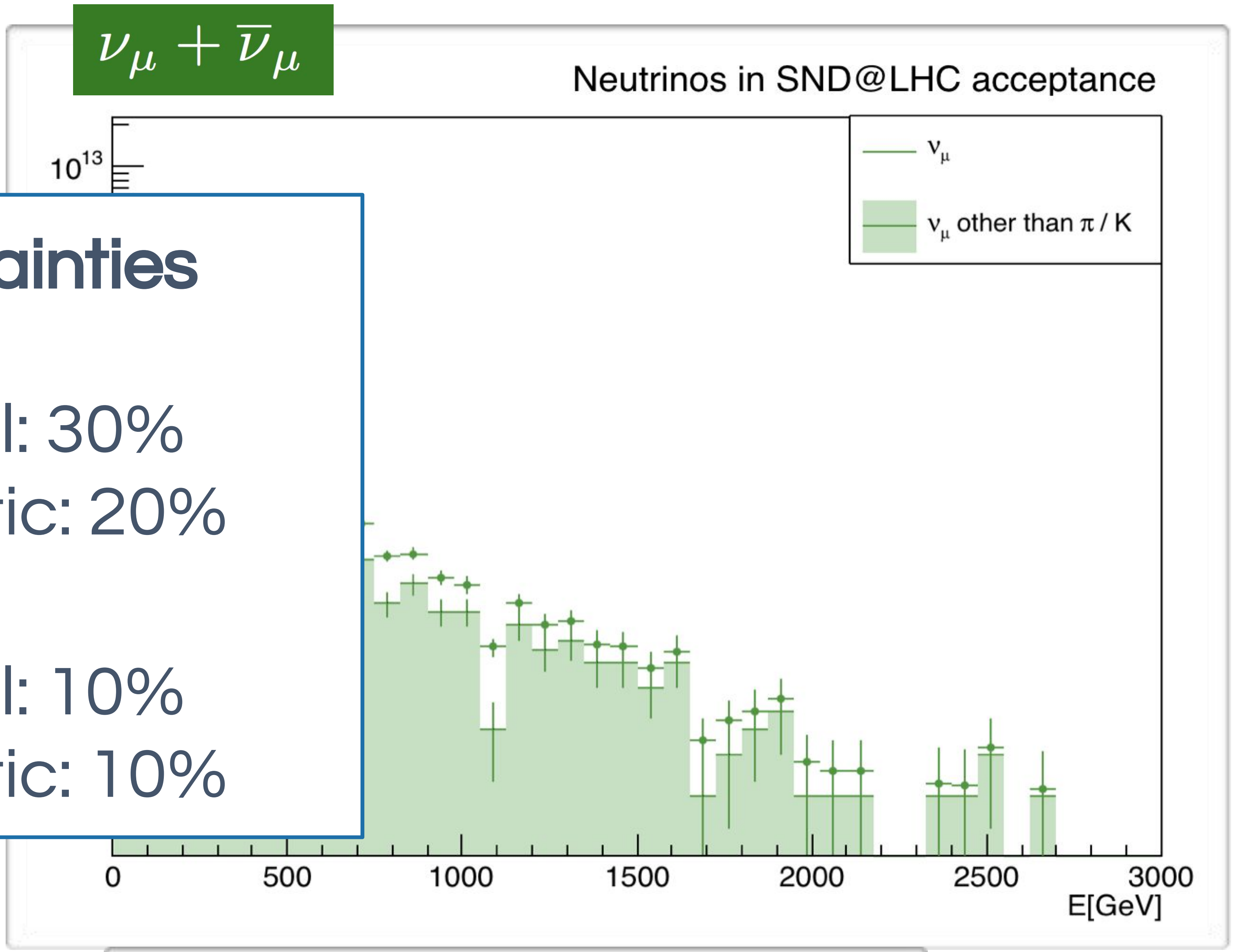

Expected uncertainties

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

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

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π/K contamination

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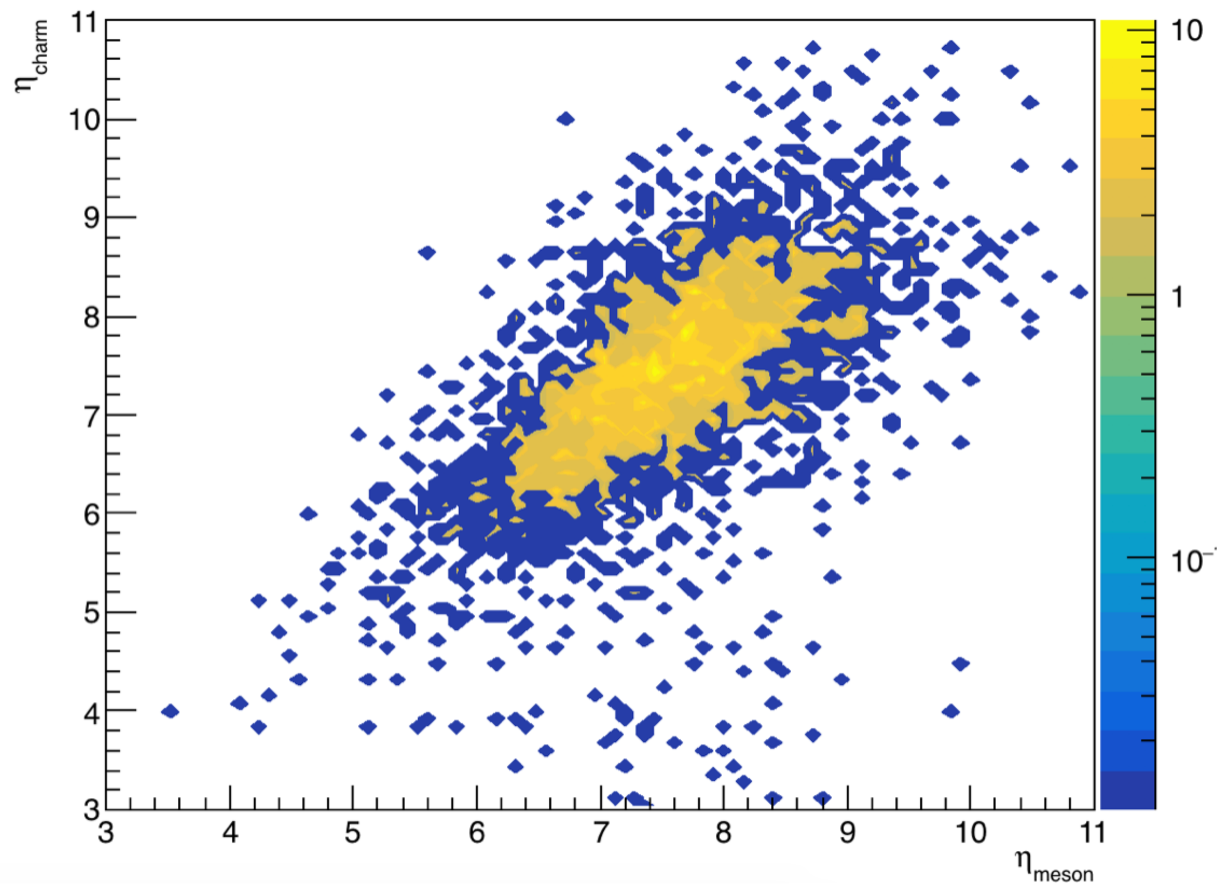
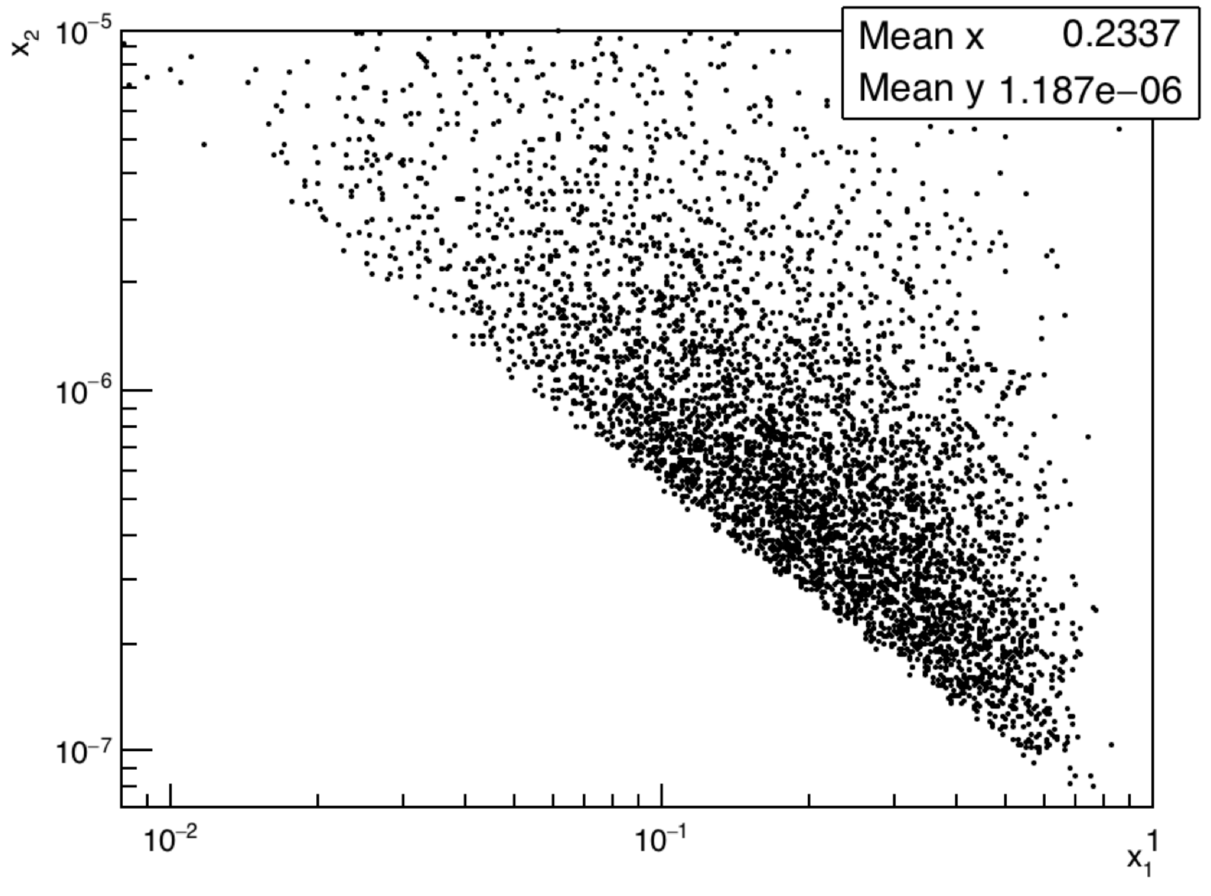
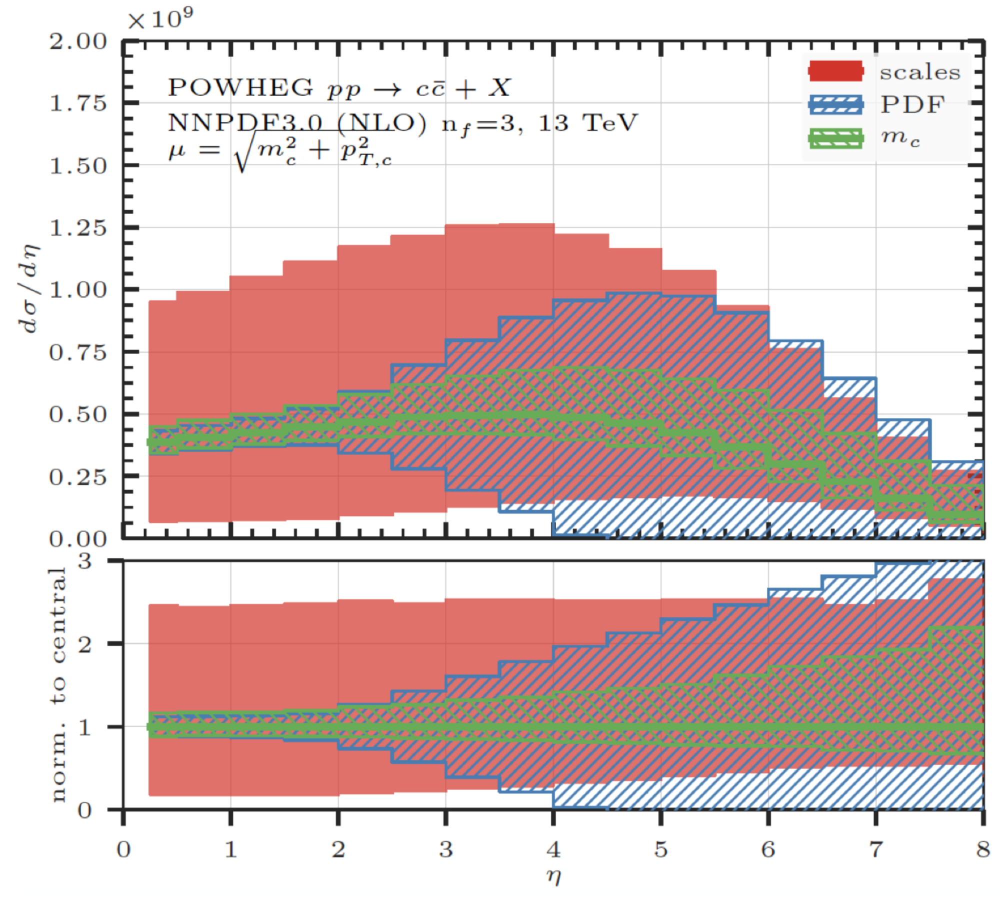
Neutrino physics: QCD

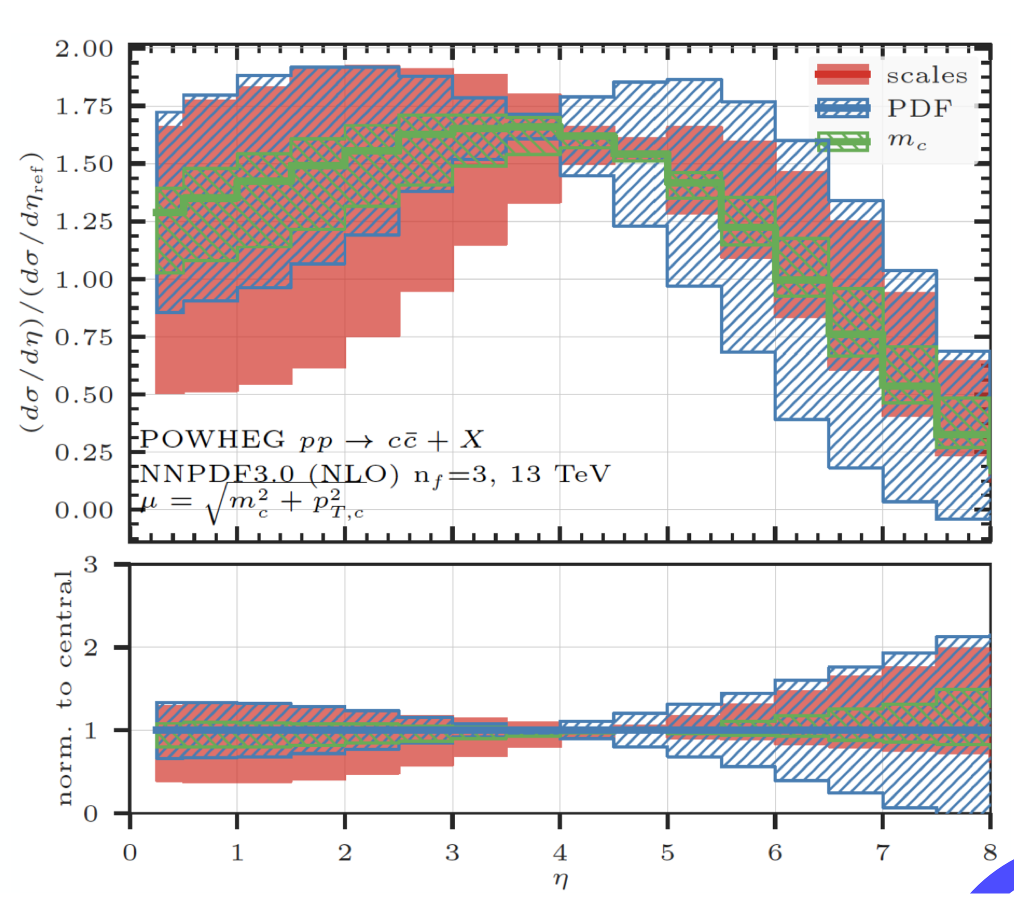
[LHCC-P-016] [M. V. Garzelli,SND@LHC open session 16/06/2022]

- 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]

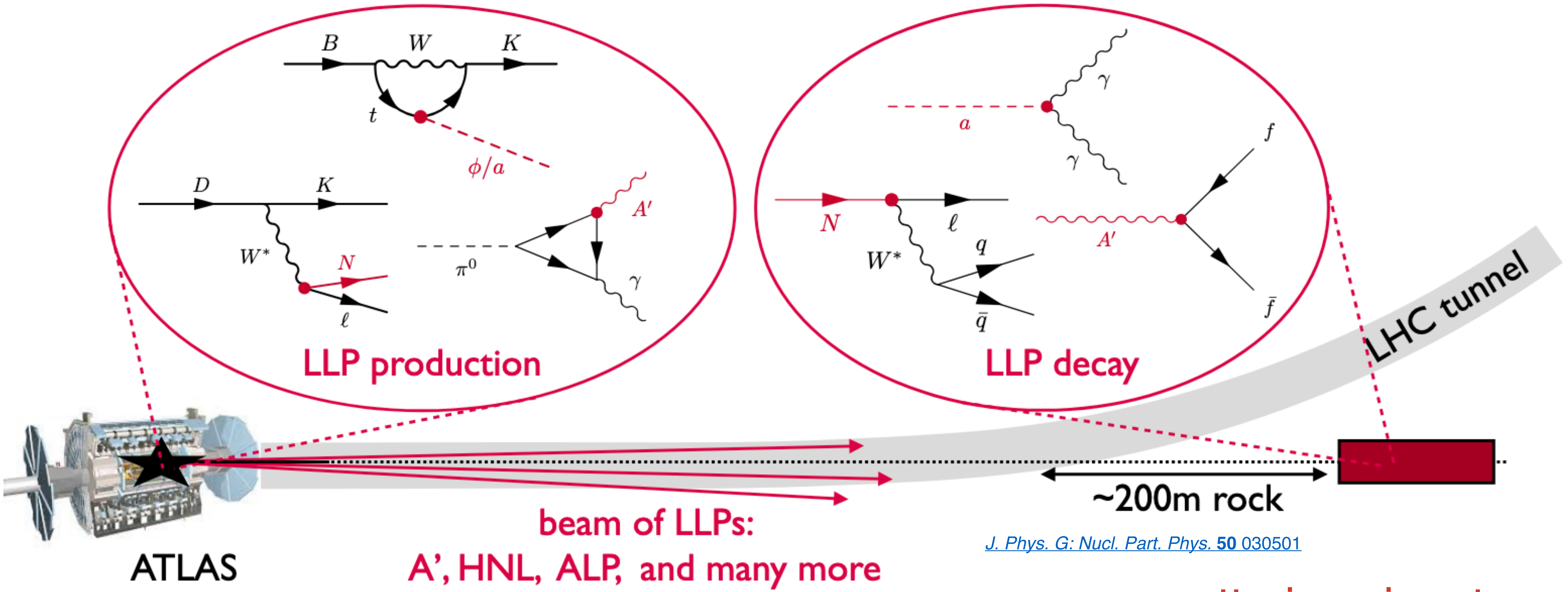








Beyond the Standard Model



J. Phys. G: Nucl. Part. Phys. **50** 030501

+ scattering signatures

Beyond the Standard Model

- Search for new, feebly interacting, Long-lived particles (LLP) **decaying** within the detector or **scattering** off the target.

Experiment timeline

Scattering and Neutrino Detector at the LHC

Letter of Intent

August 2020

TECHNICAL PROPOSAL

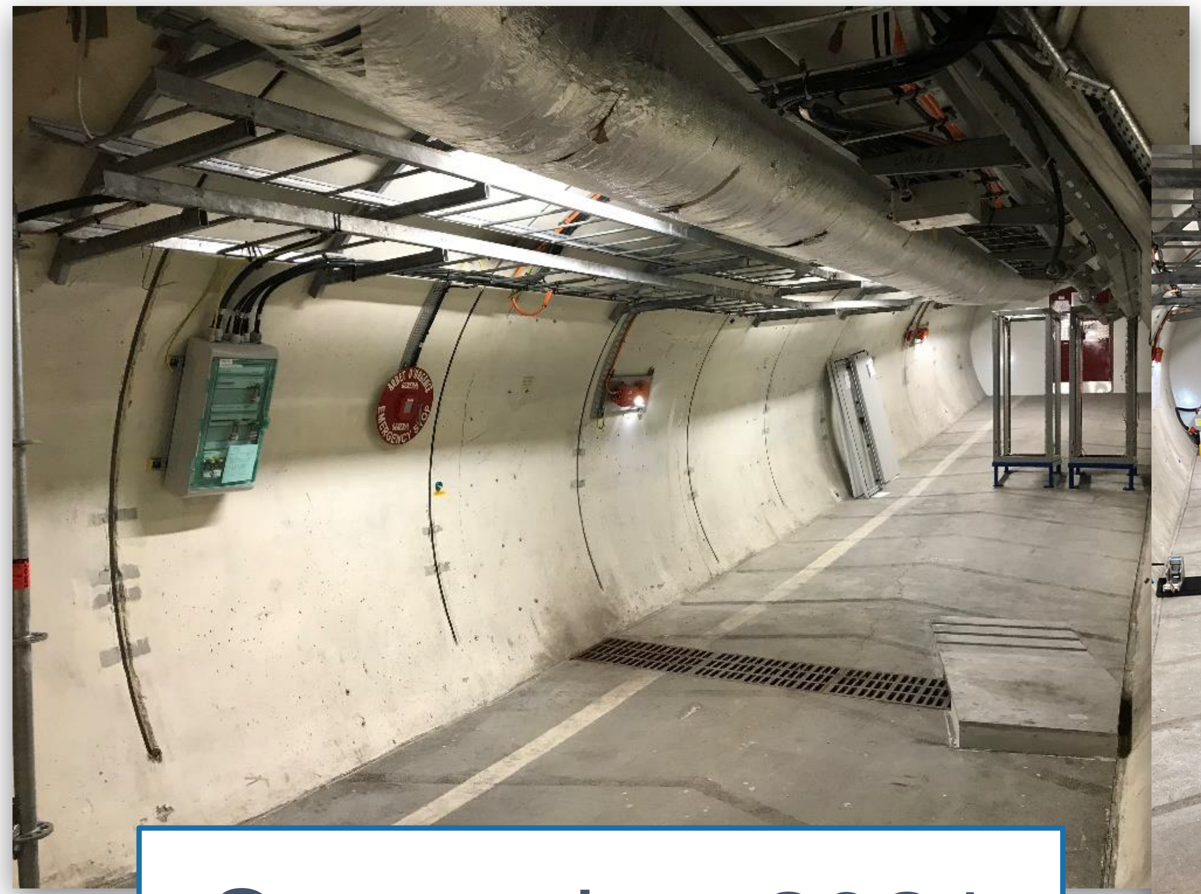
SND@LHC

January 2021

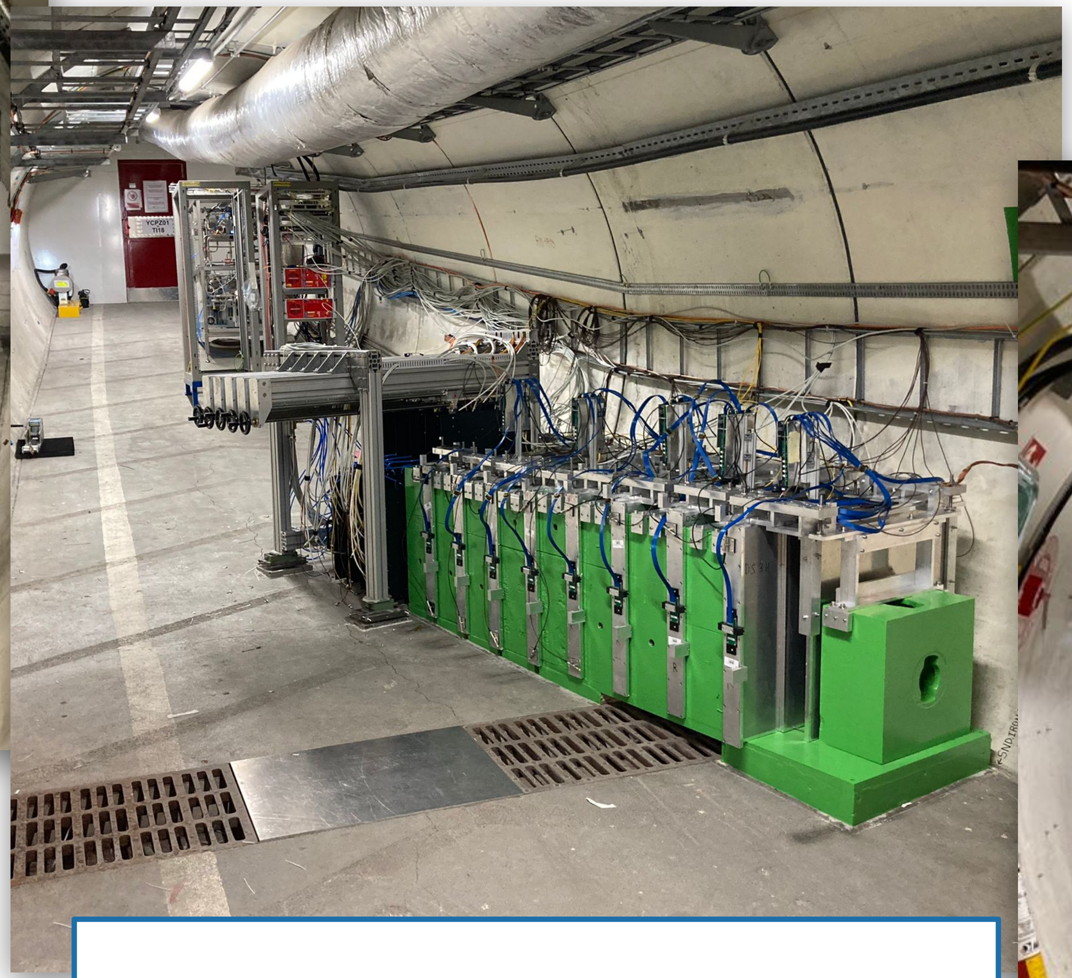
CERN approves new LHC experiment

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

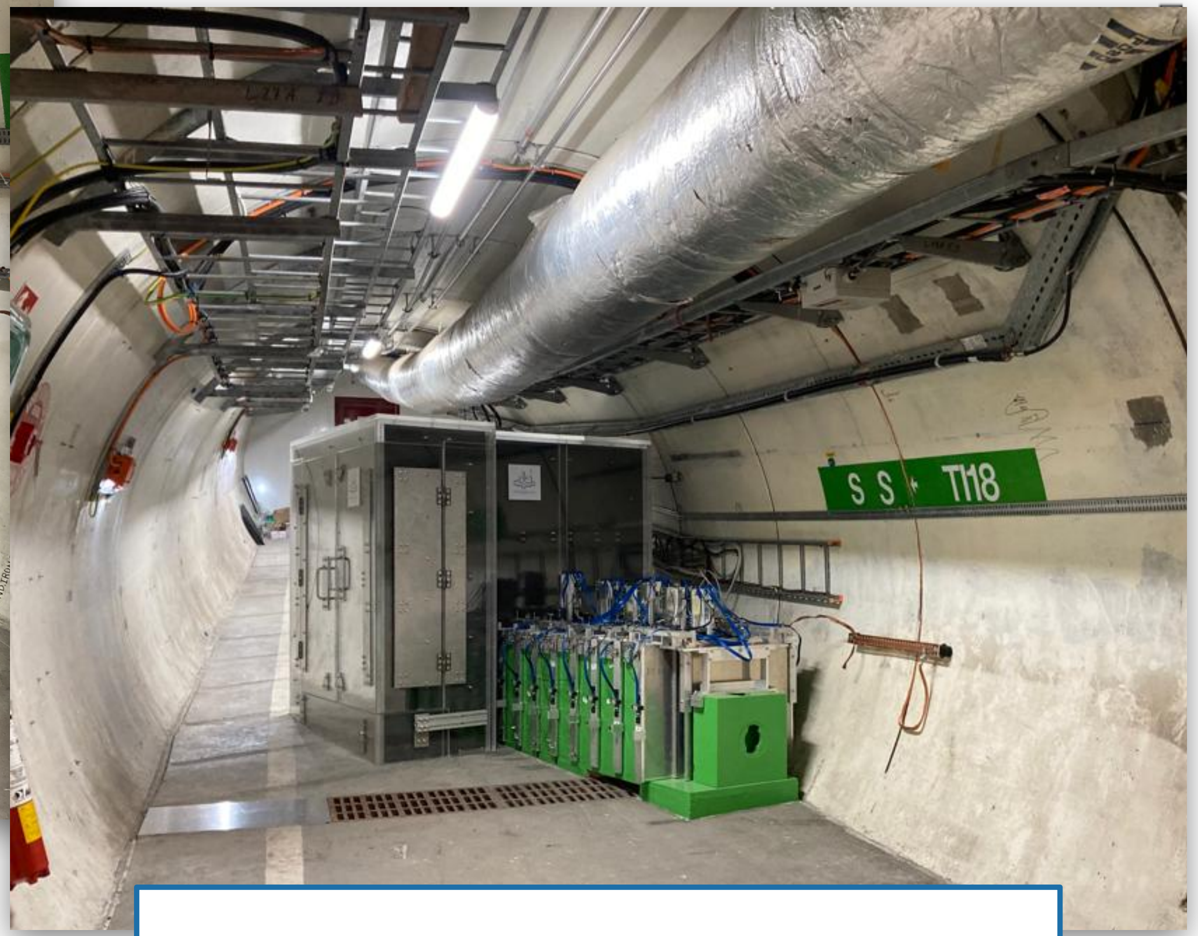
March 2021



September 2021

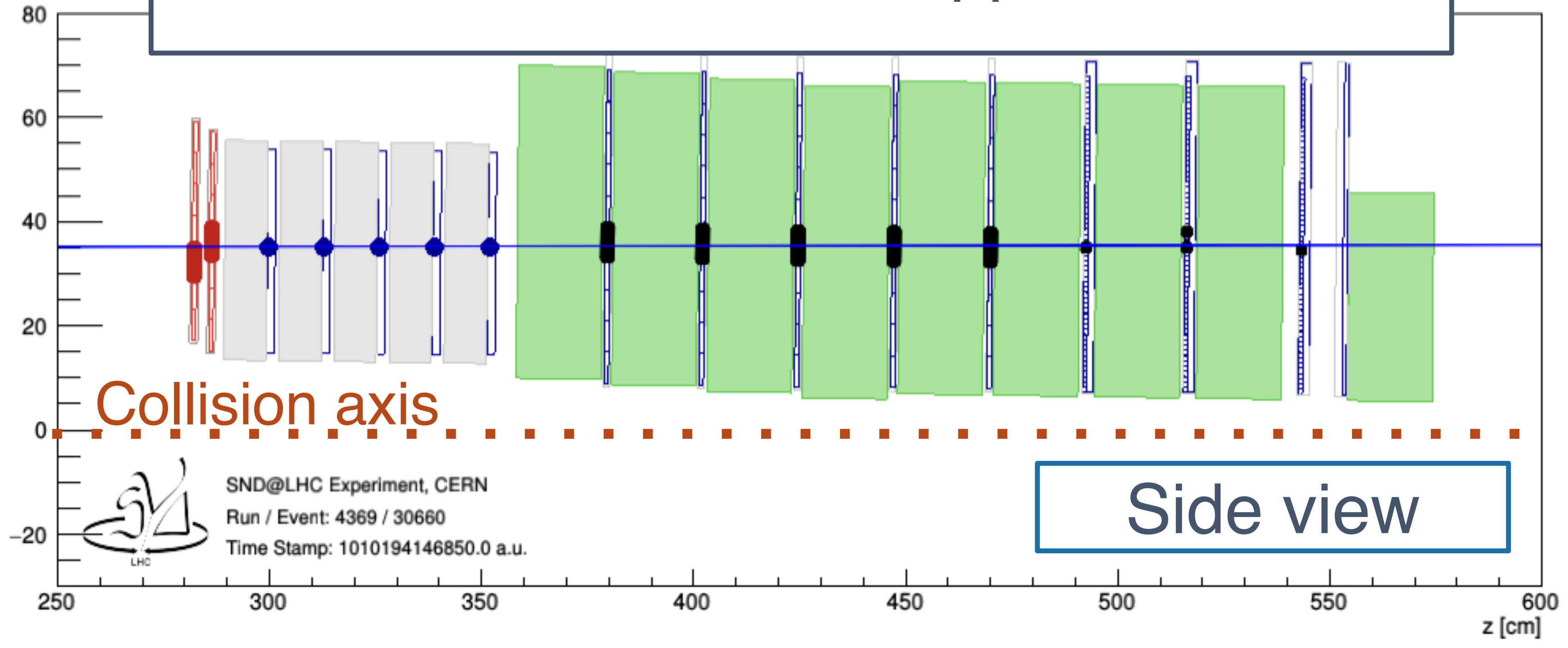


December 2021



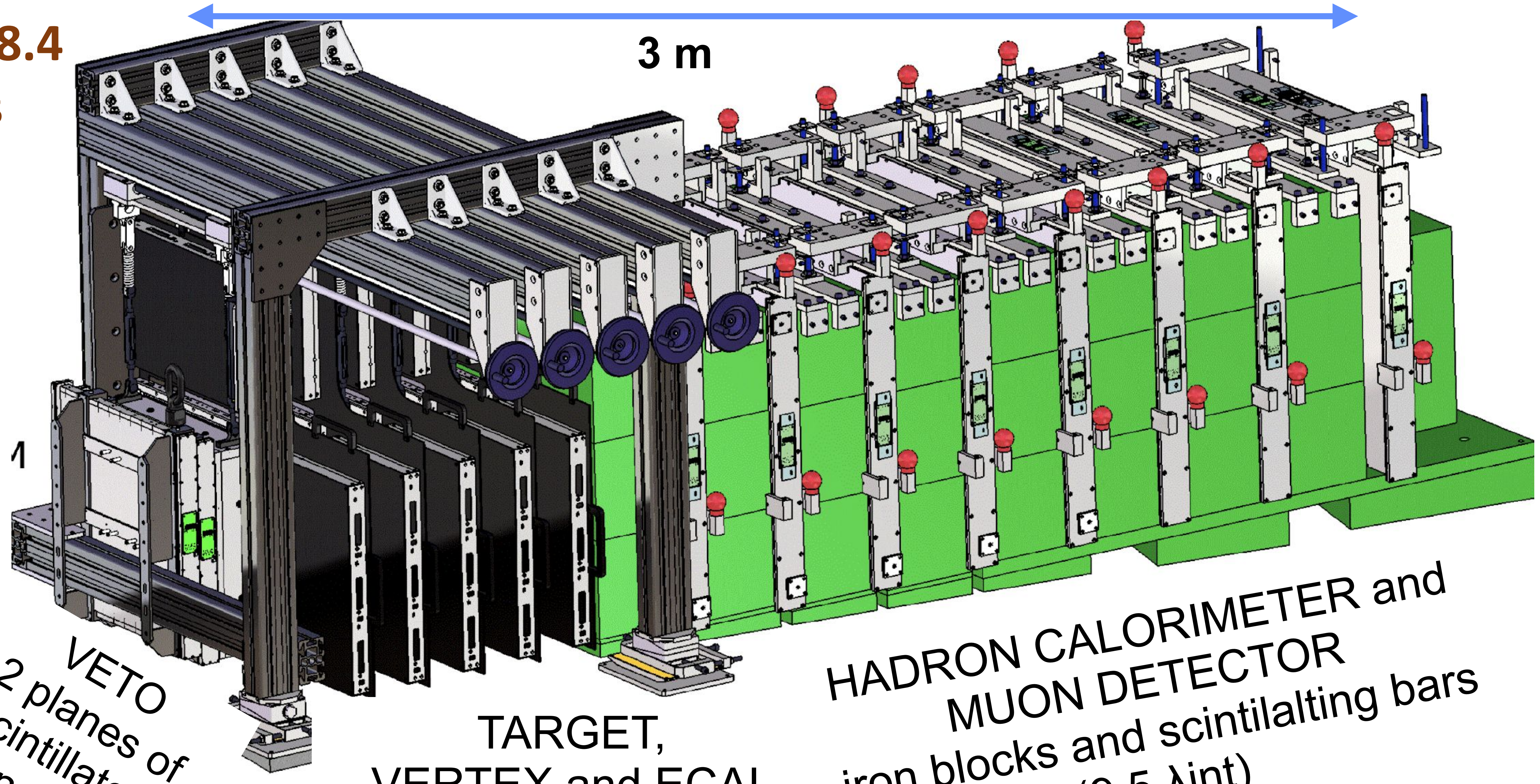
March 2022

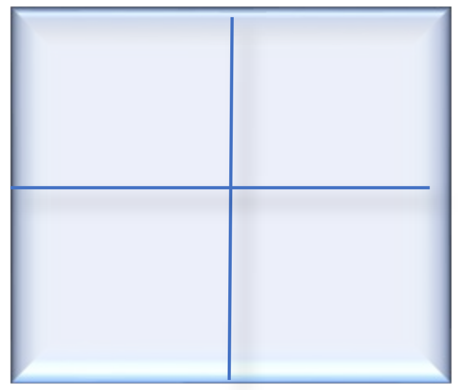
Muon from 13.6 TeV pp collision



July 2022

SND@LHC 2022-24





● Beam collision axis

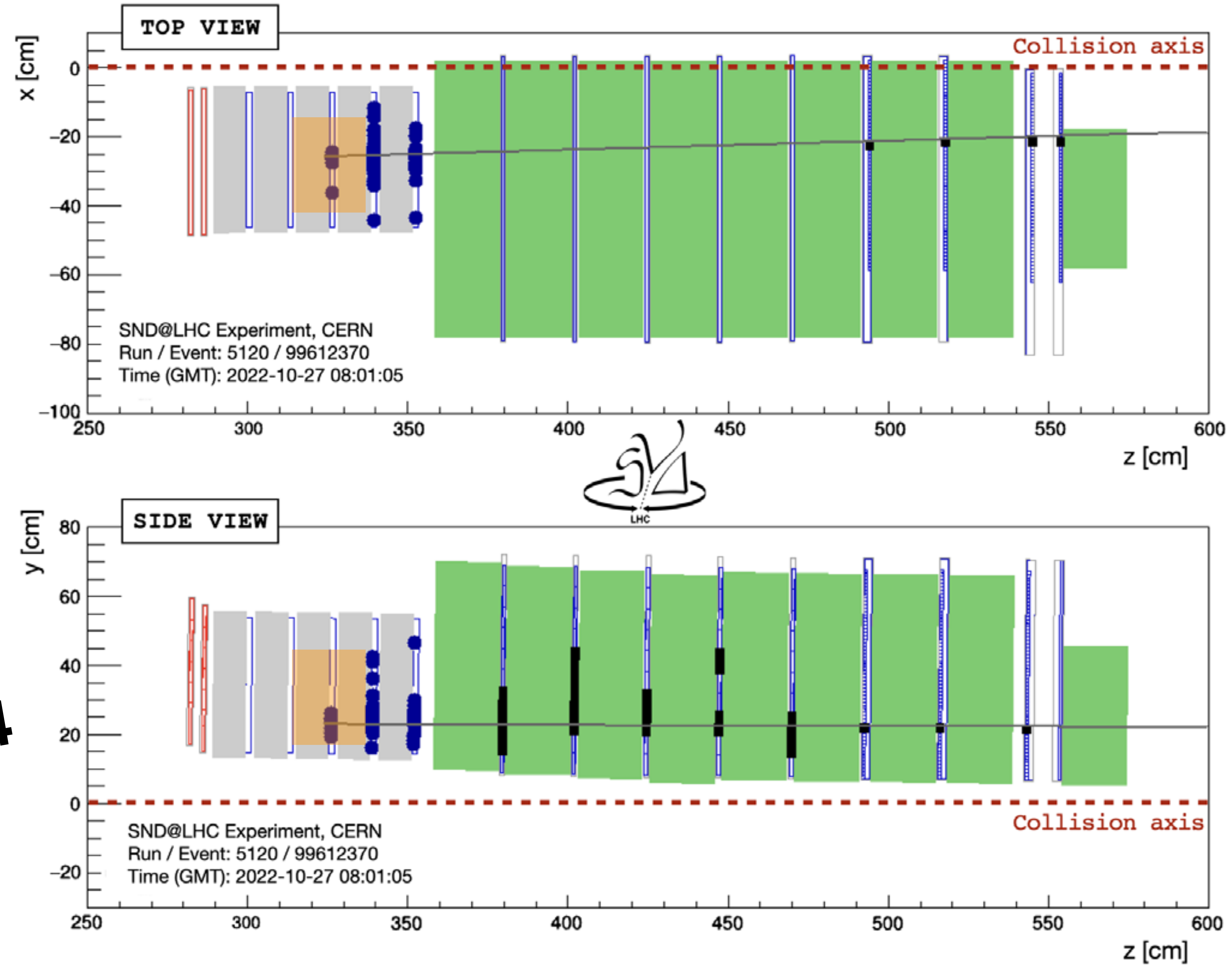
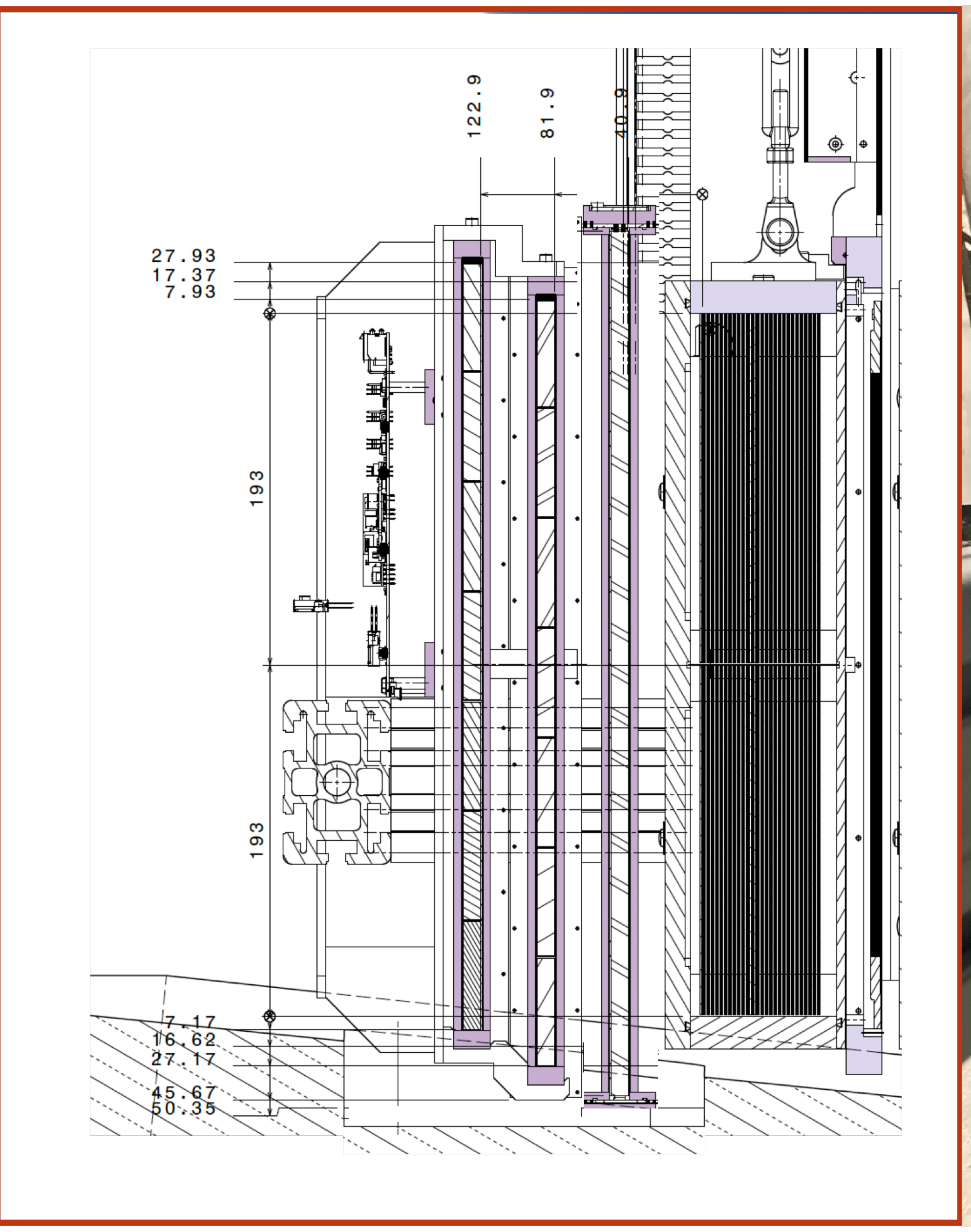


FIG. 2. Display of a ν_μ CC candidate event. Hits in the SciFi, and hadronic calorimeter and muon system are shown as blue markers and black bars, respectively, and the line represents the reconstructed muon track.

Acceptance and efficiency with the new veto configuration

Upgraded layout: third plane with vertical bars

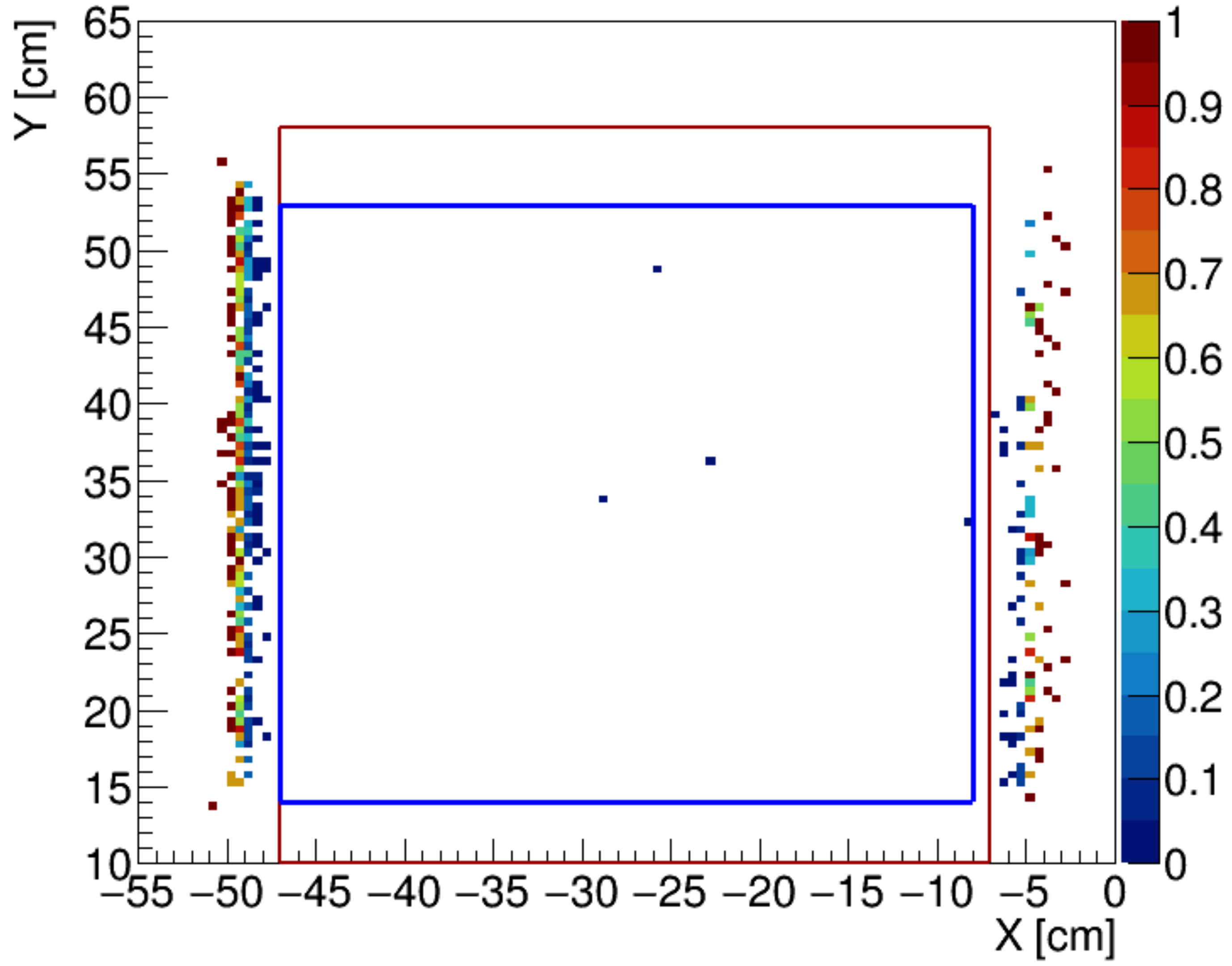


- 8×10^8 selected muons with a reconstructed SciFi track
- Particles from the IP1 side. Efficiency of 99.2% for all muons with a reconstructed SciFi track

Installation and performance of the 3rd Veto plane at the SND@LHC detector

https://arxiv.org/pdf/2502.10188

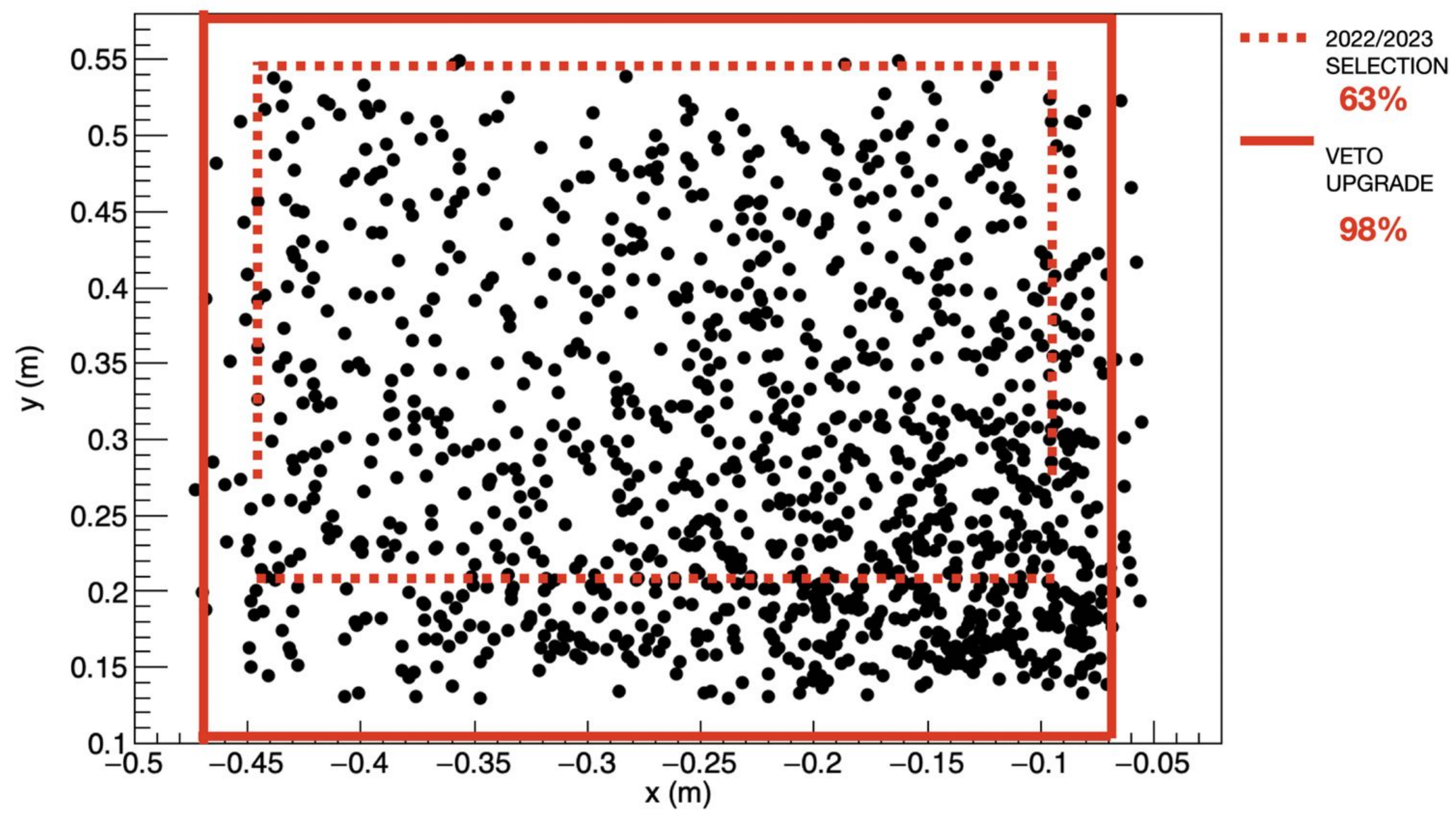
Extrapolated position from SciFi



Inefficiency down to the level of 10^{-9}

8.7e-09

XY position of ν interactions



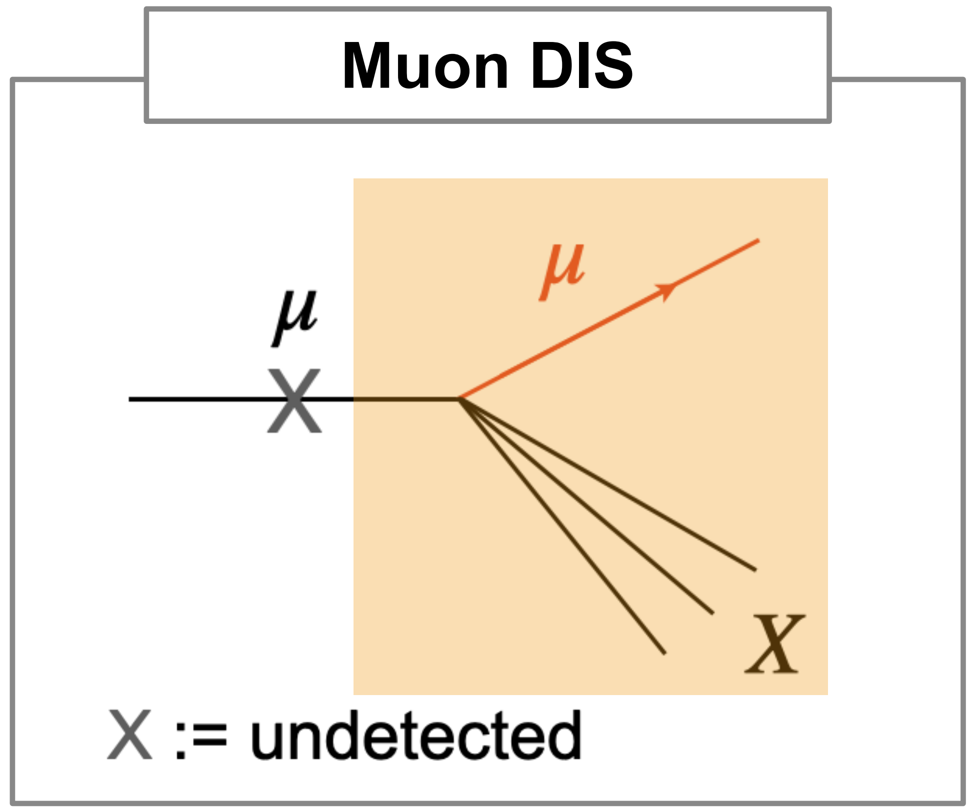
SND@LHC backgrounds

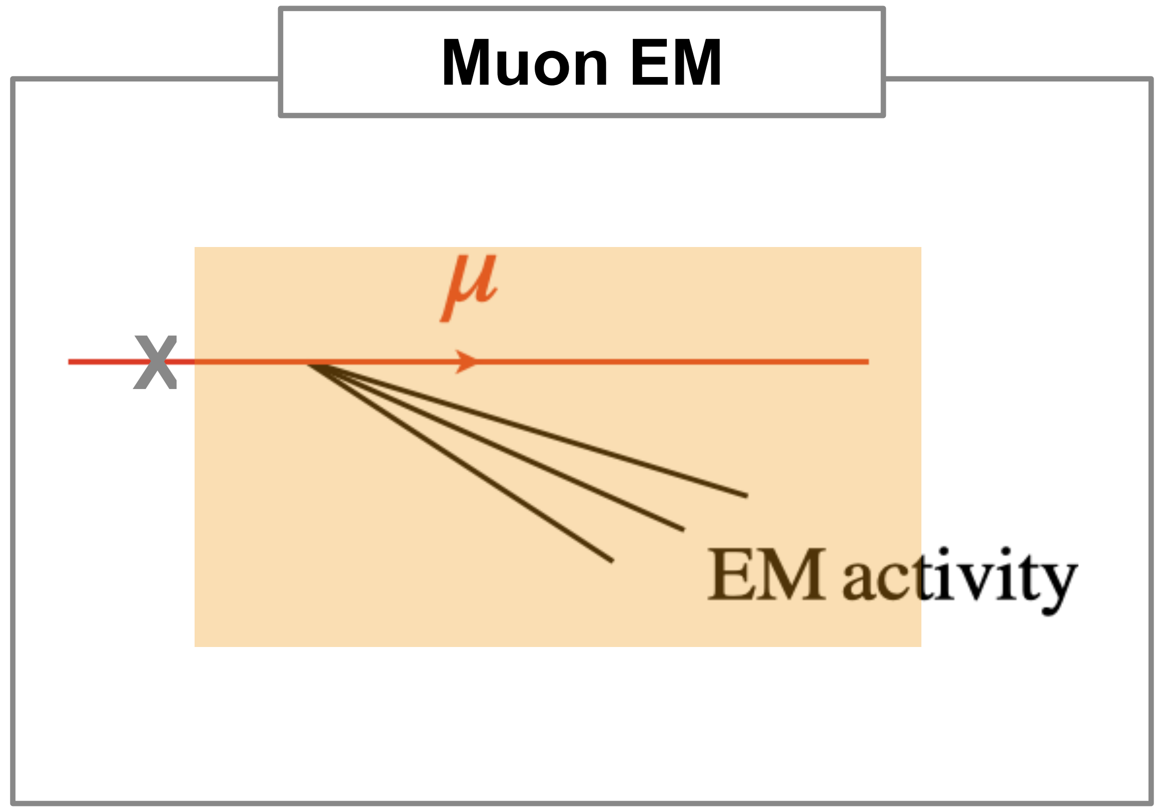
2023

Phys. Rev. Lett. 131, 031802

Entering muons

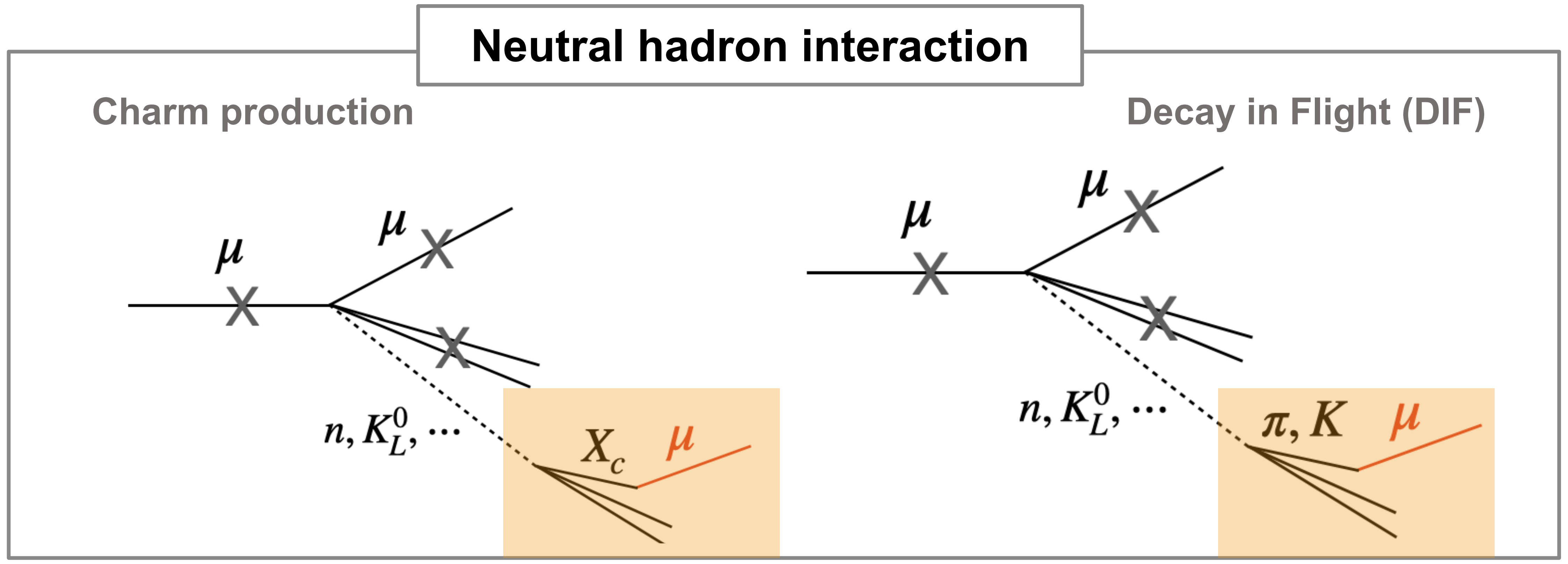
- Incoming muon track may be missed due to detector inefficiency.
- Shower induced by DIS or EM activity.
- Number of muons in acceptance: 5×10^{8}
  SNDLHC-NOTE-2023-001
- Detector inefficiency: 5×10^{-12}
  - Two veto and two scintillating fibre planes.
- **Negligible** background with tight fiducial 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 **$(8.6 \pm 3.8) \times 10^{-2}$** background events due to neutral hadrons.



:= within SND@LHC acceptance

Search for shower-like (0μ) neutrino events

arXiv 2411.18787

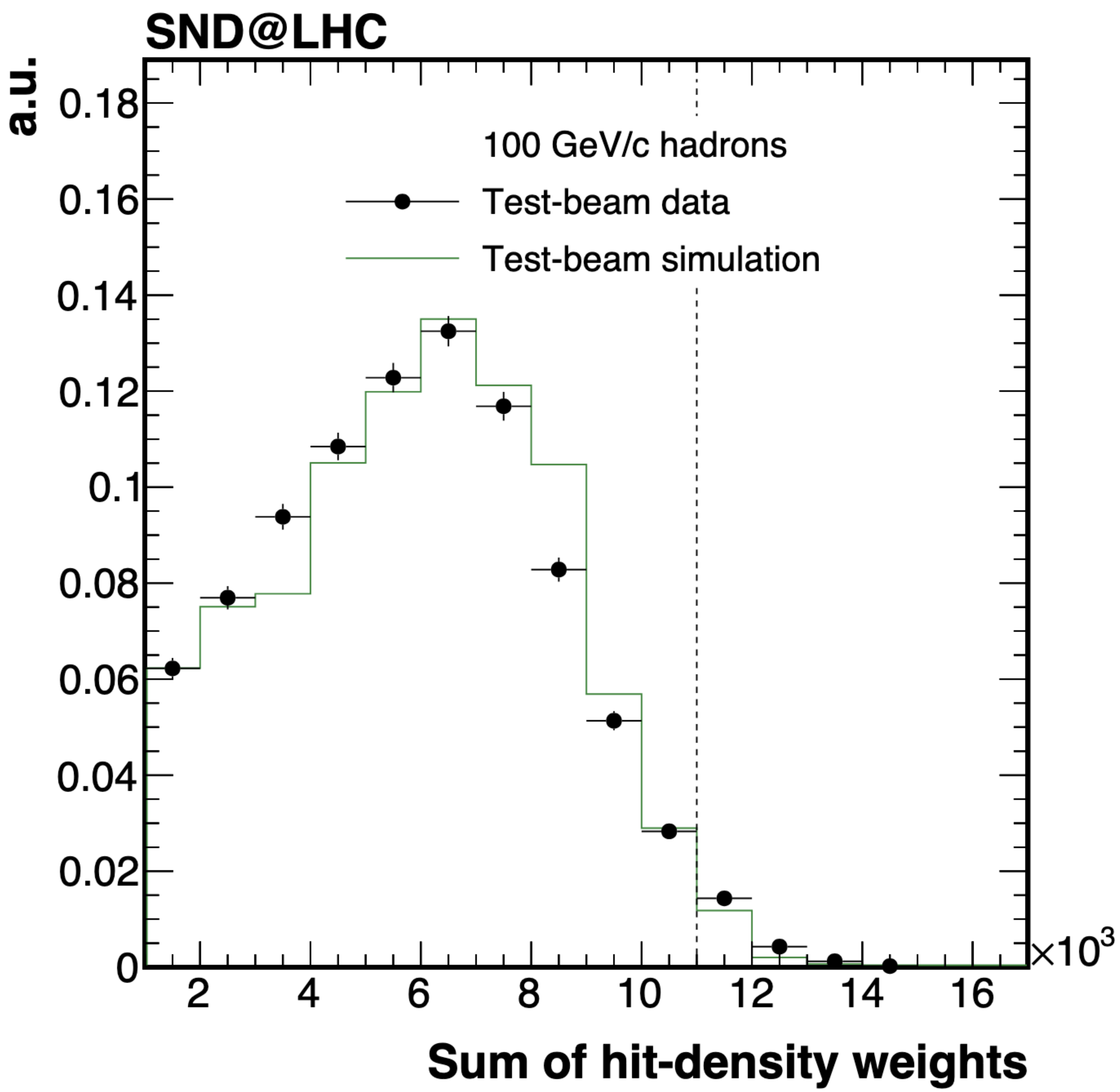
Signal: ν_eCC and NC interactions

Fiducial volume

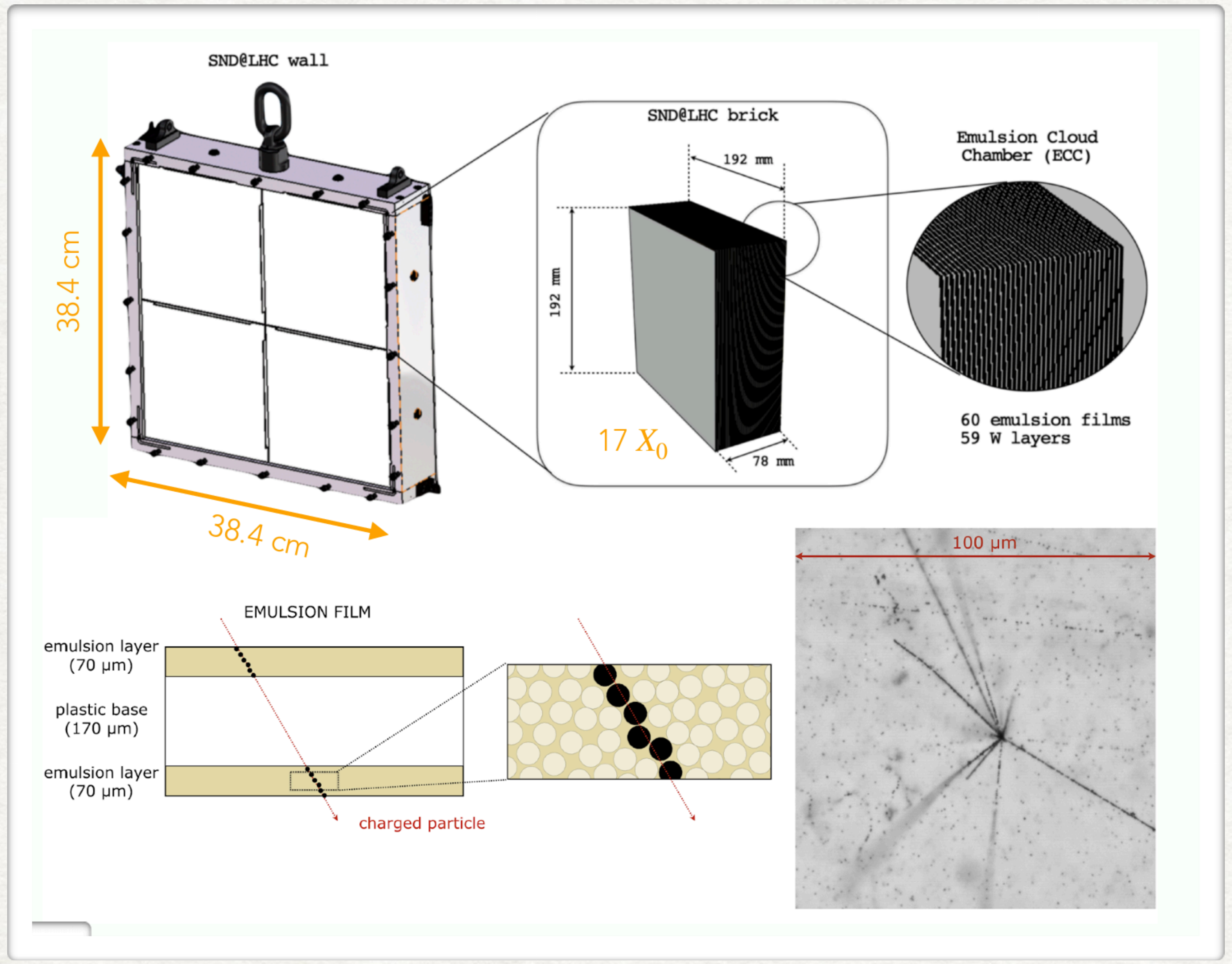
- No hits in the veto detector.
- Reject side-entering backgrounds.
- Signal acceptance: 12%

0μ neutrino event identification

- Large scintillating fibre detector activity.
- Large HCal activity.
- No hits in last two muon system planes.
  - No reconstructable muon.
- Sum of hit-density weights > 11×10^3.
  - Selects events with a high density of hits in the Scintillating Fibre detector
  - Optimized for maximum expected significance
  - Validated with test-beam data
- Signal selection efficiency: 19%

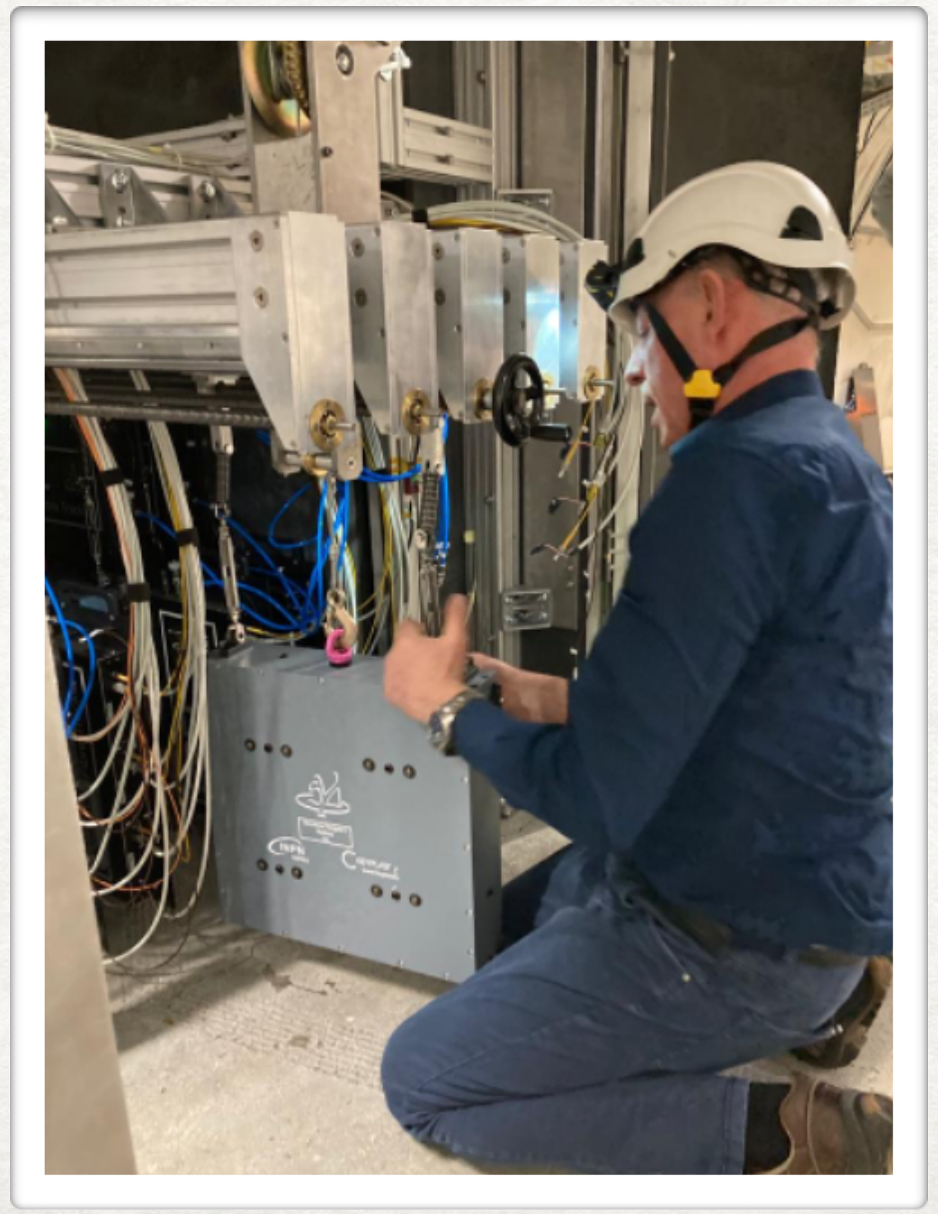


EMULSION TARGET



- Full target system equipped with 5 Tungsten/emulsion walls
- Total mass: ~800 kg
- Number of emulsion films: 1200
- Limit to the integrated track density: 4×10^5 tracks corresponding to 20 (10) fb^{-1} in 2022-2023 (2024)
- Emulsion development in the CERN emulsion facility
- Emulsion scanning with automated optical microscopes in several scanning stations (CERN, Bologna, Gran Sasso, Nagoya, Napoli, Santiago)

- **36 walls** assembled
- **5700 emulsion** films developed
- **210 m²** emulsion films developed



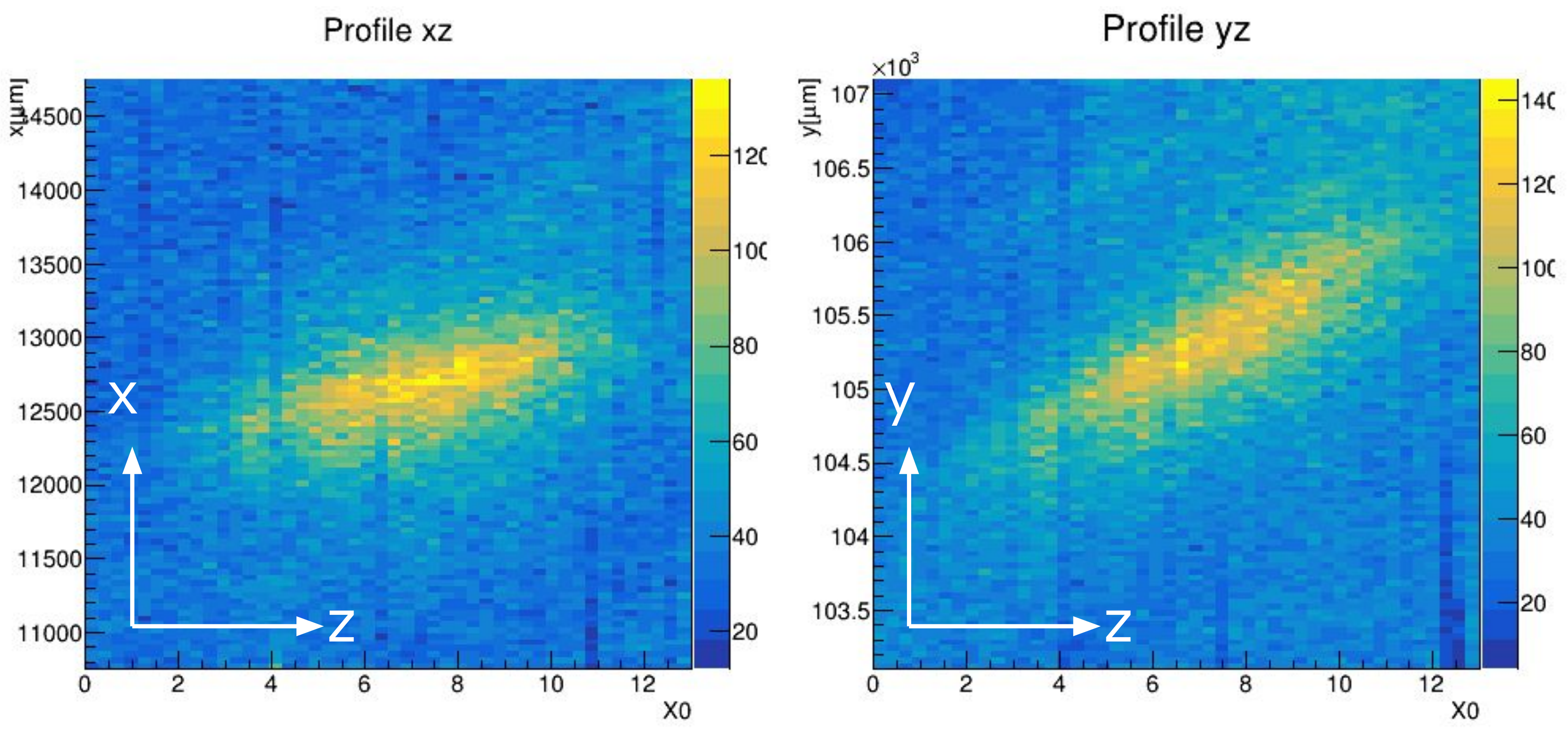
ν_e CC observation in emulsions

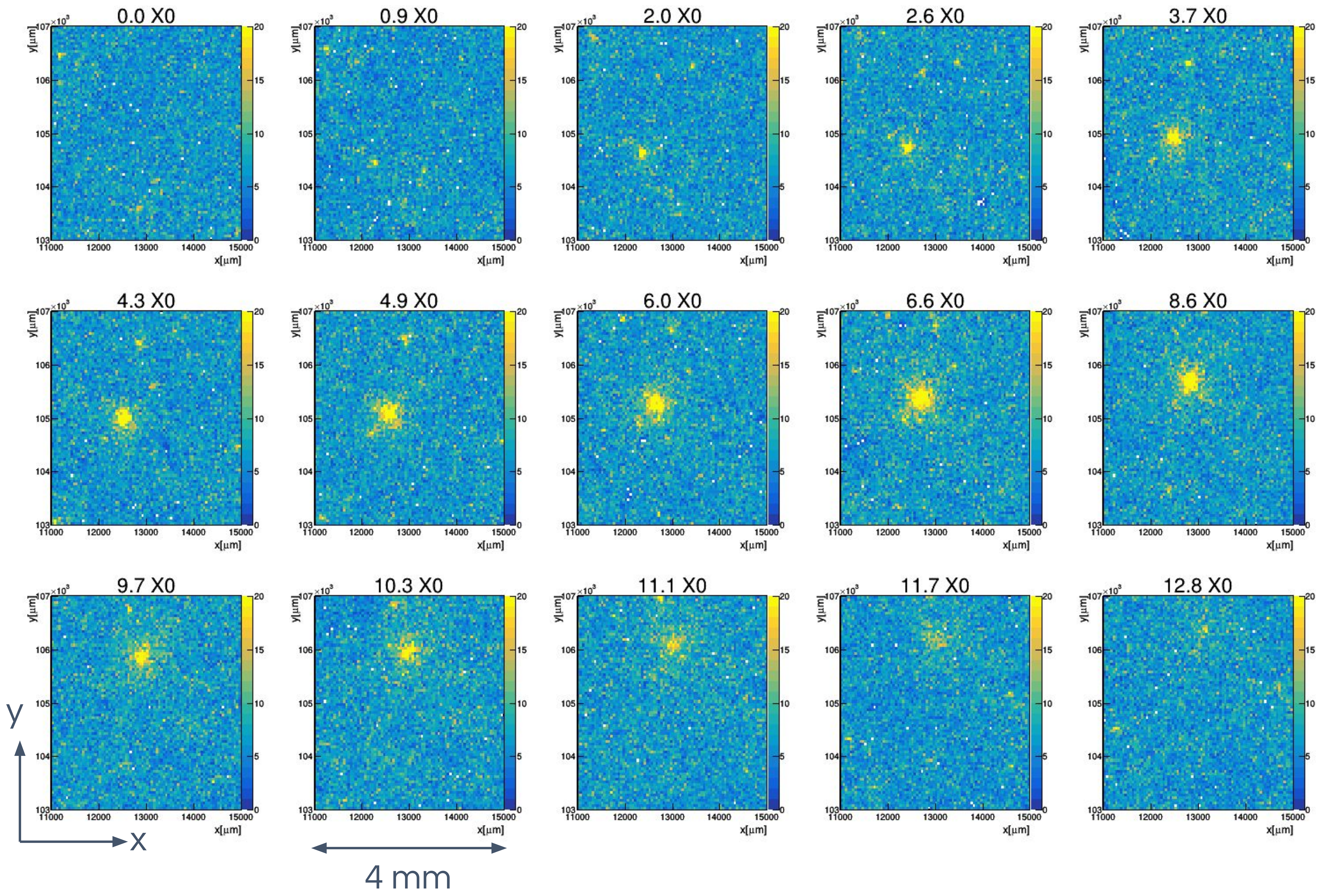
Strategy

- 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.

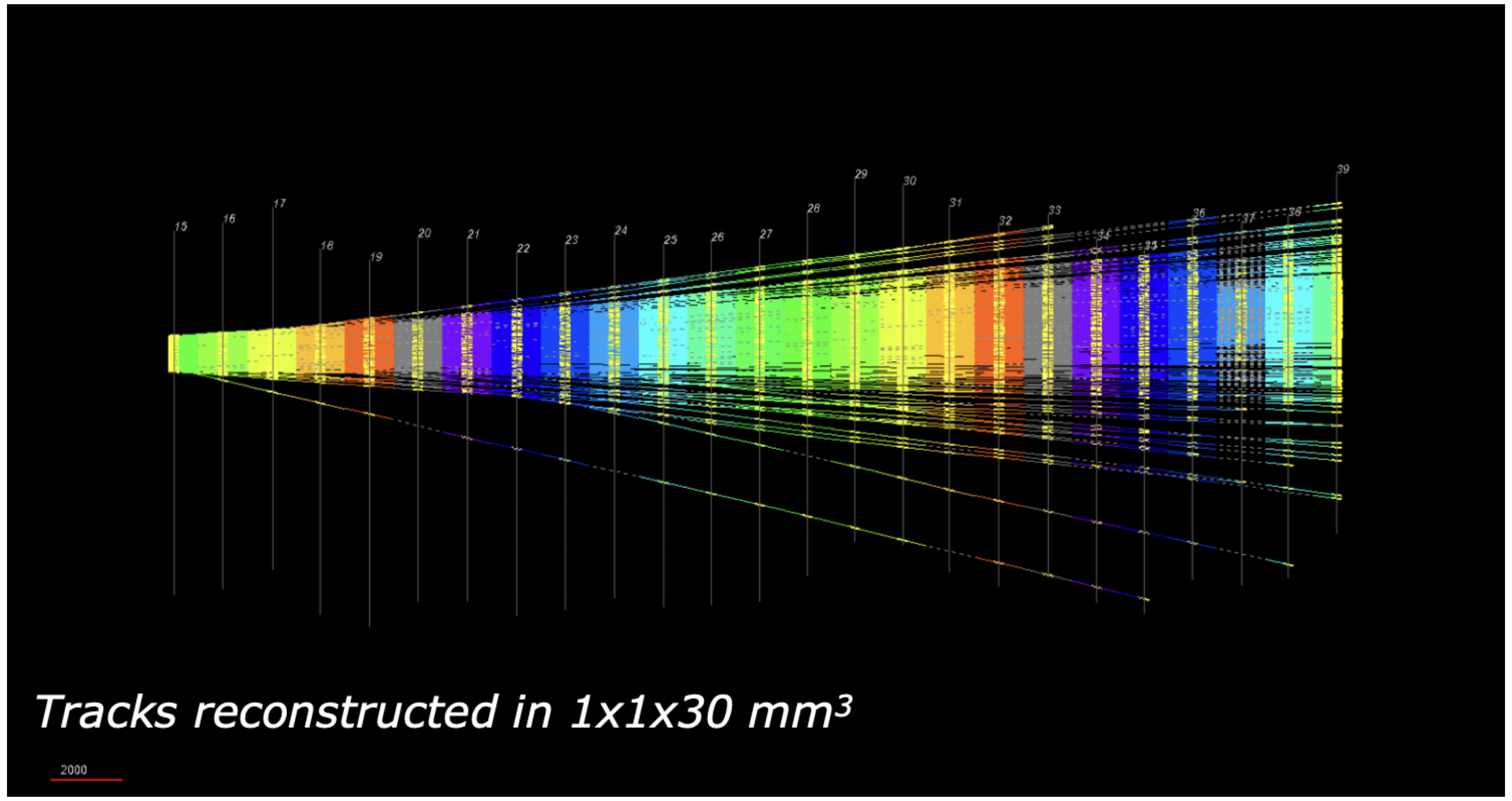


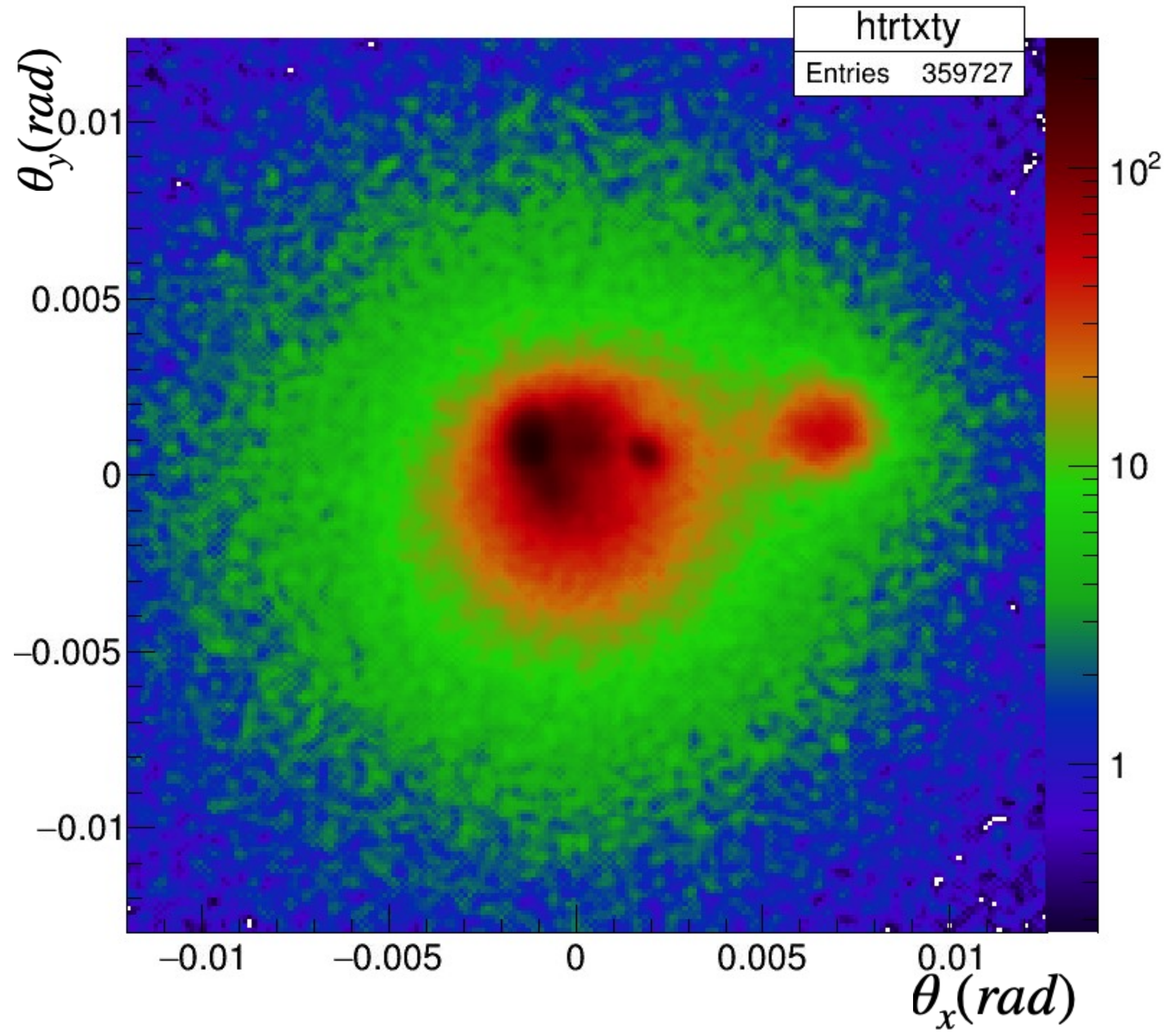


M.Dallavalle, IFAE 2025, Cagliari

Emulsion scanning and analysis

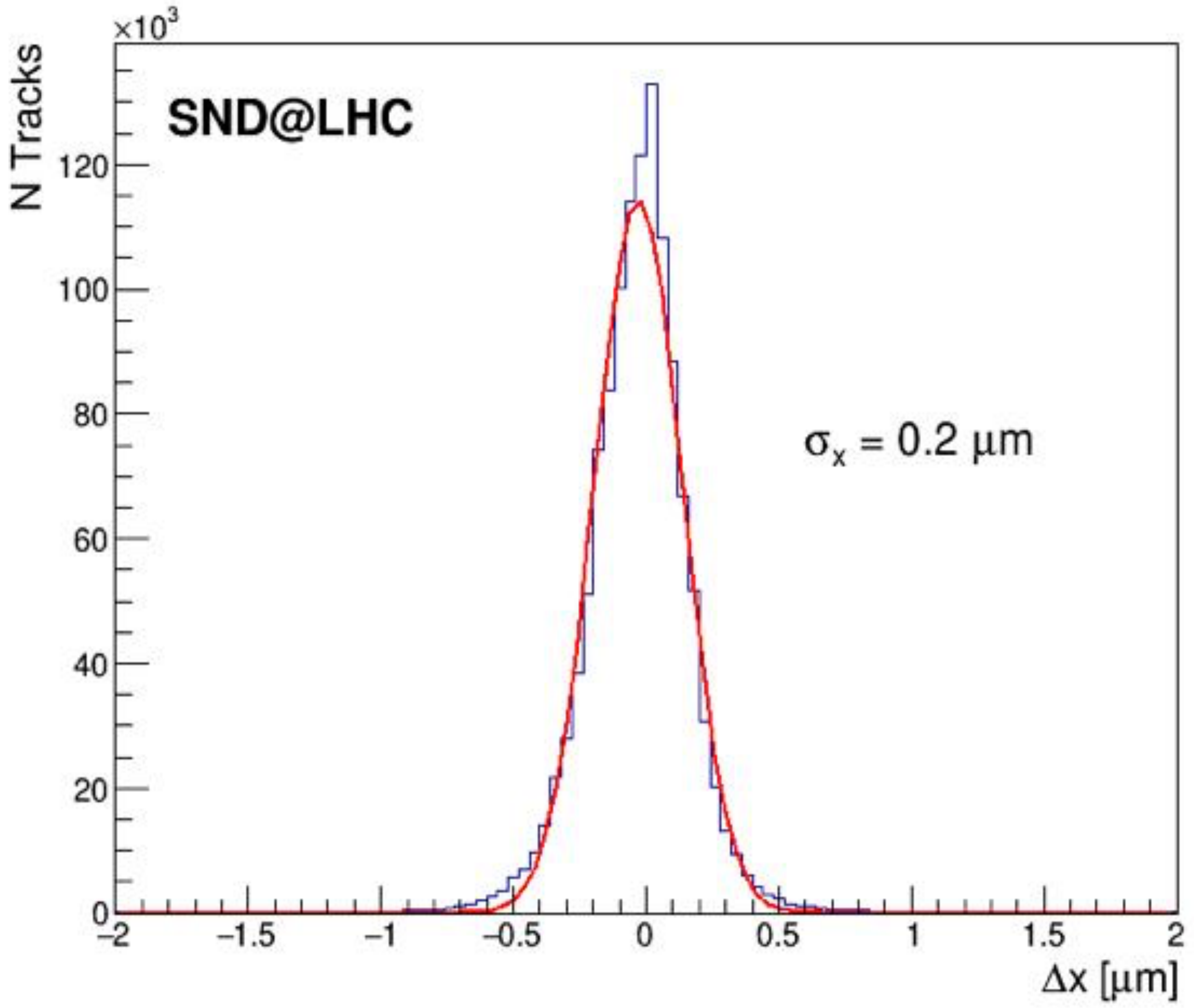
- Emulsion scanning is performed with fully automated microscopes in six laboratories: CERN, Bologna, Napoli, Nagoya, Gran Sasso, Santiago
- Track density up to $4x10^5$ tracks/cm^2 (factor 10^3 larger wrt OPERA)
- Full revision of alignment, tracking, vertexing procedures
- Excellent tracking resolution achieved



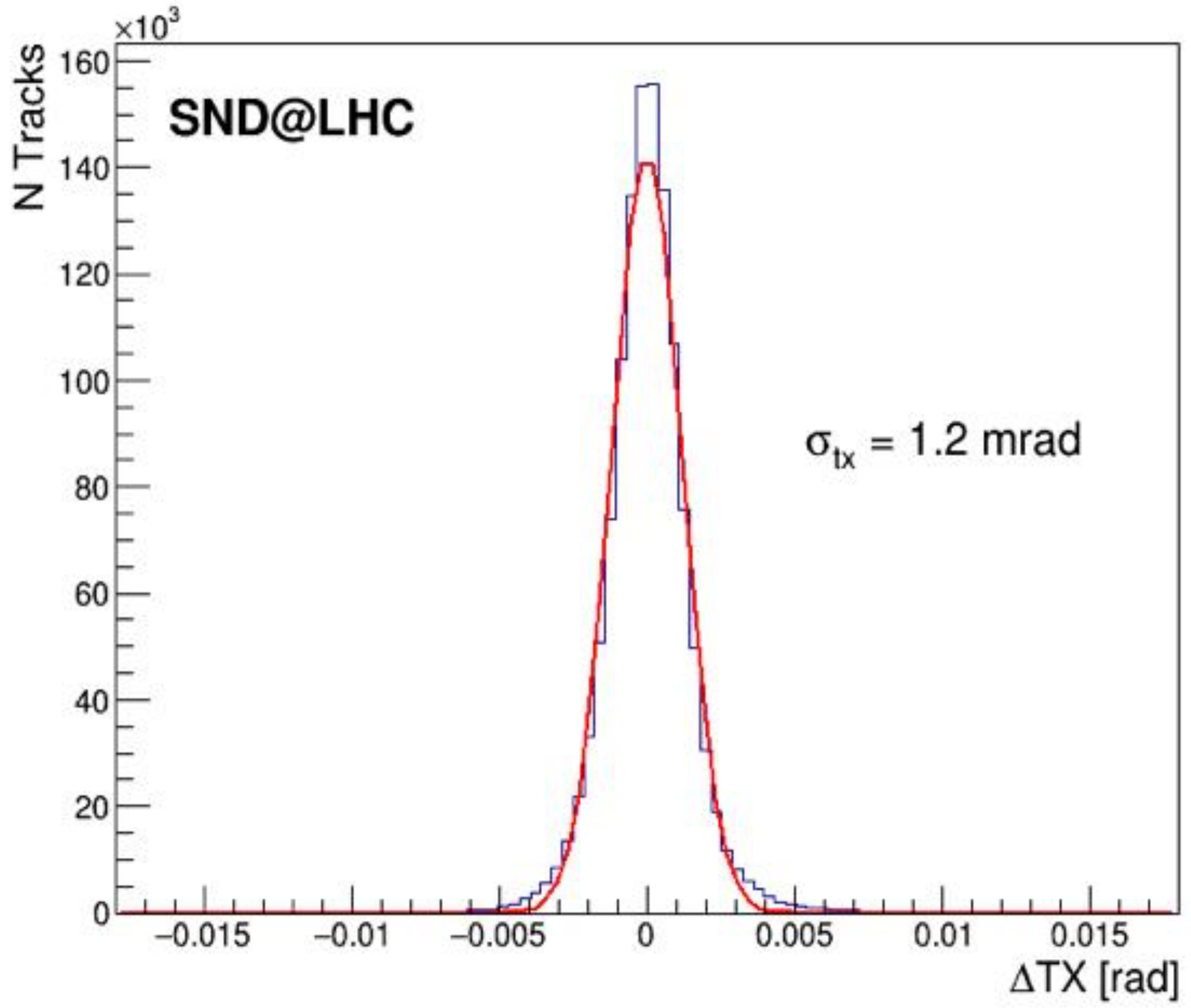


Beam core structure clearly visible with passing-through tracks

POSITION RESOLUTION $0.2\mu m$



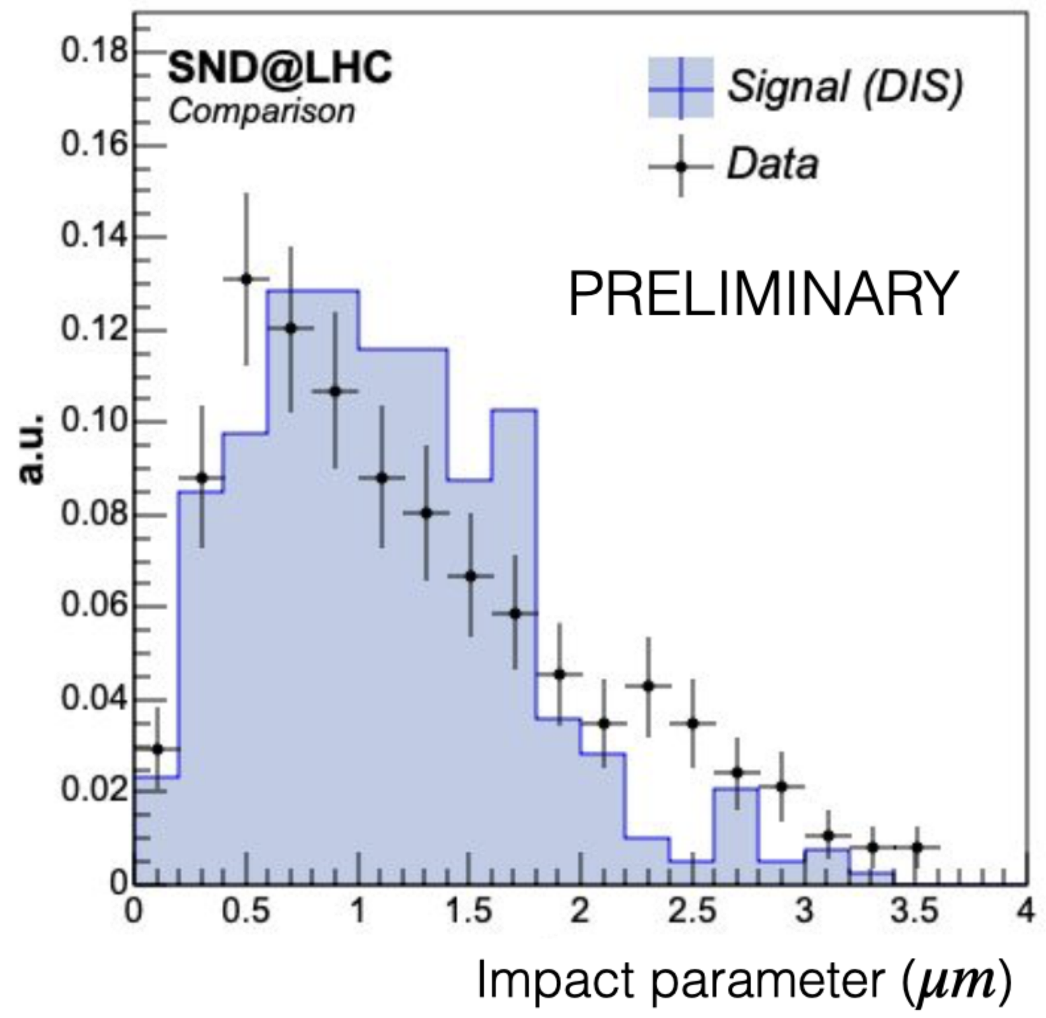
ANGULAR RESOLUTION 1.2 mrad

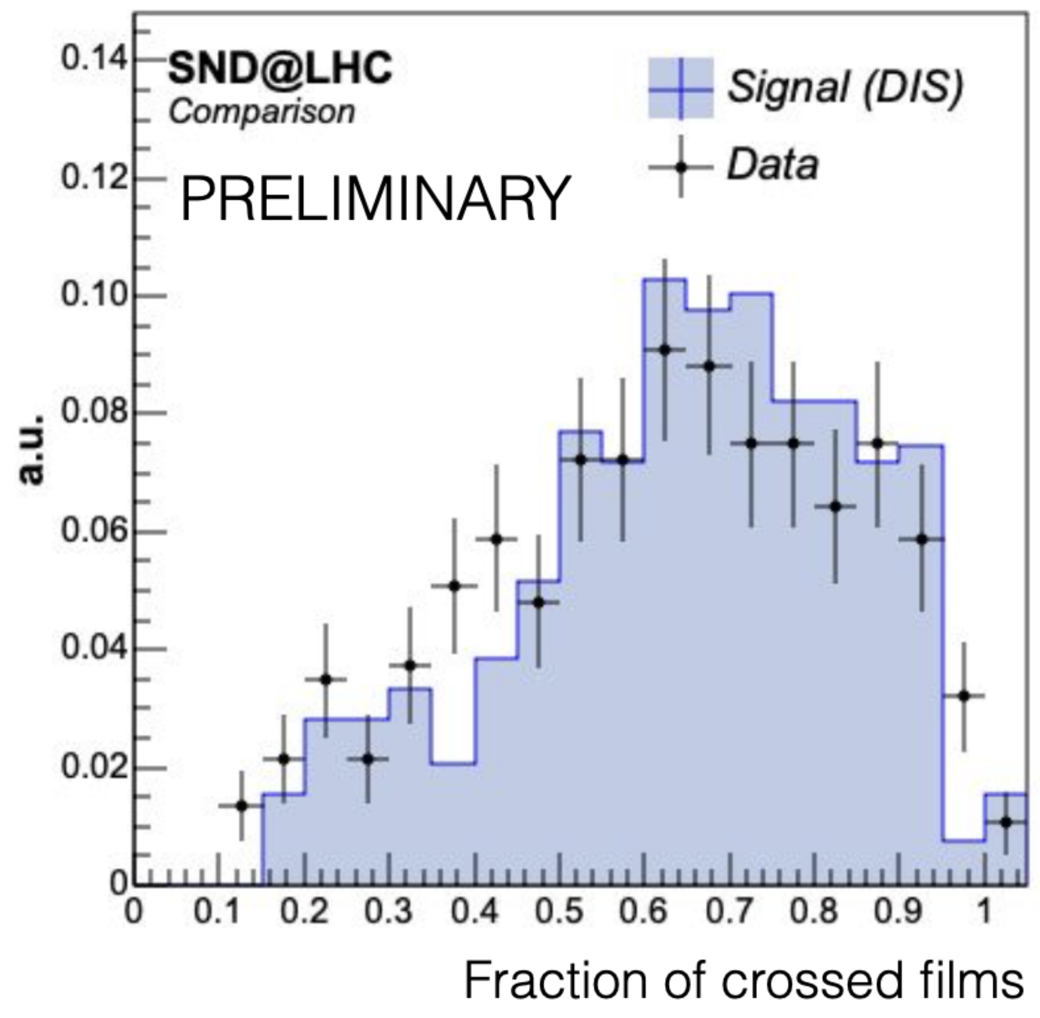


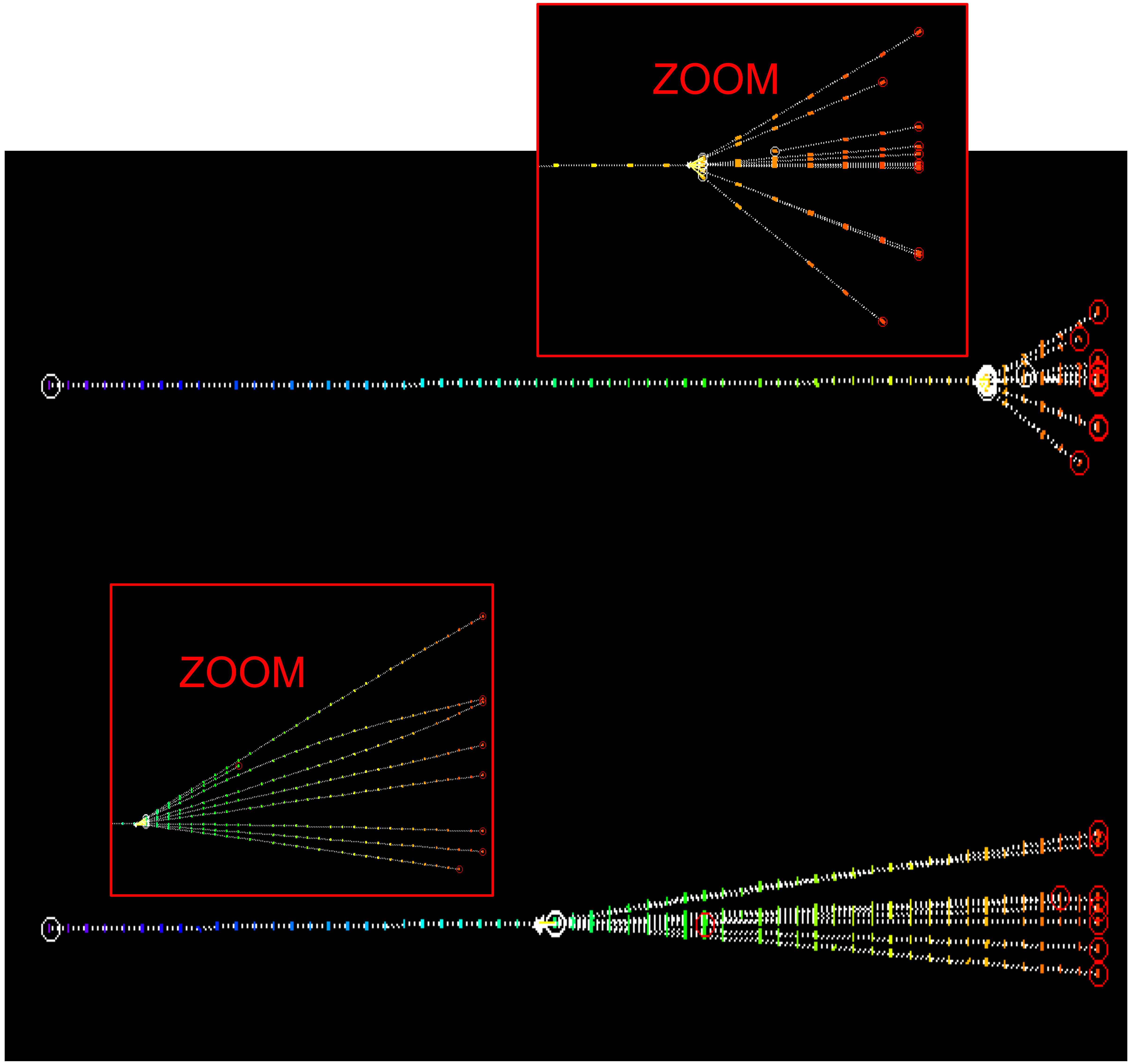
Observation of muon DIS in emulsion data

Identification of **muon DIS** in the emulsion target with cut-based approach on topological variables:

- charged vertex
- track multiplicity>3
- impact parameter<3.5um
- fraction of crossed films>0.1
- vertex probability>0.1

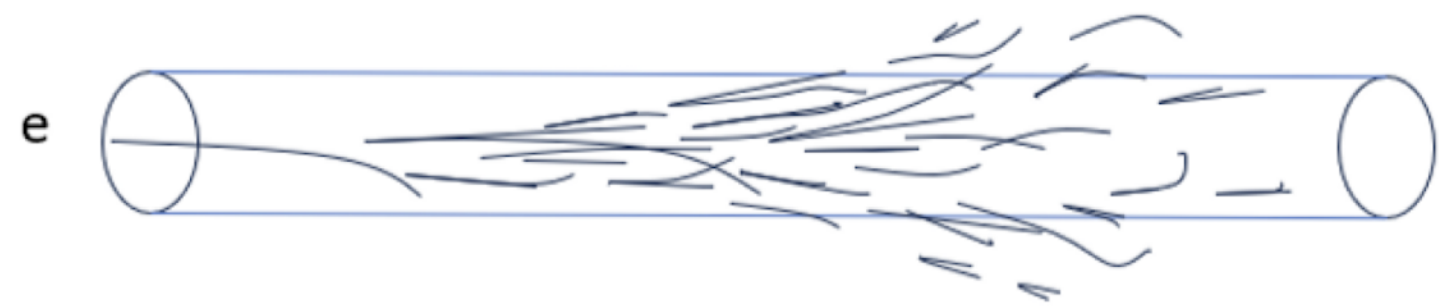






Electron ID and energy measurement

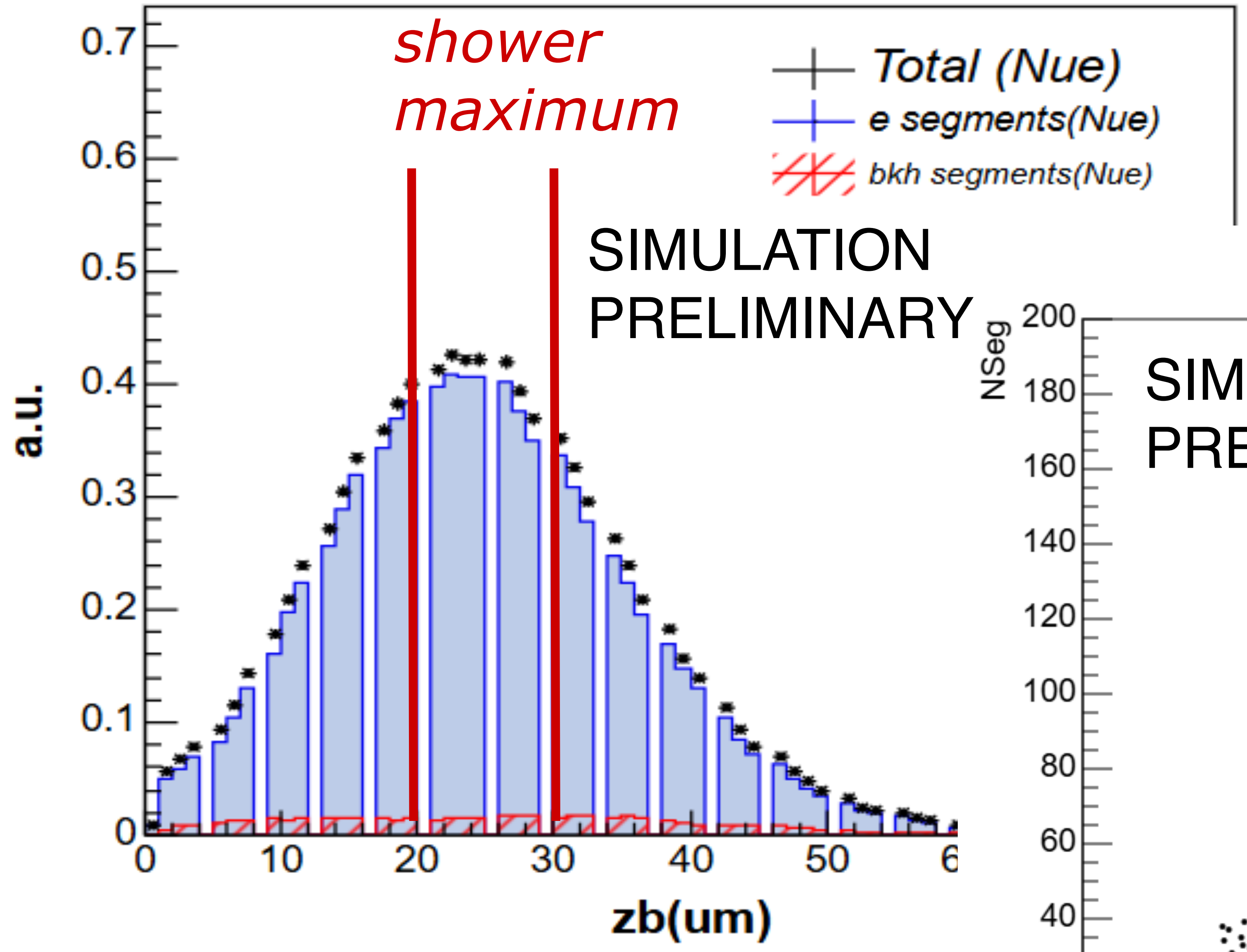
- Electron ID based on em shower identification
- Electron energy estimate based on calorimetric measurement
- Number of segments at the shower maximum proportional to electron energy

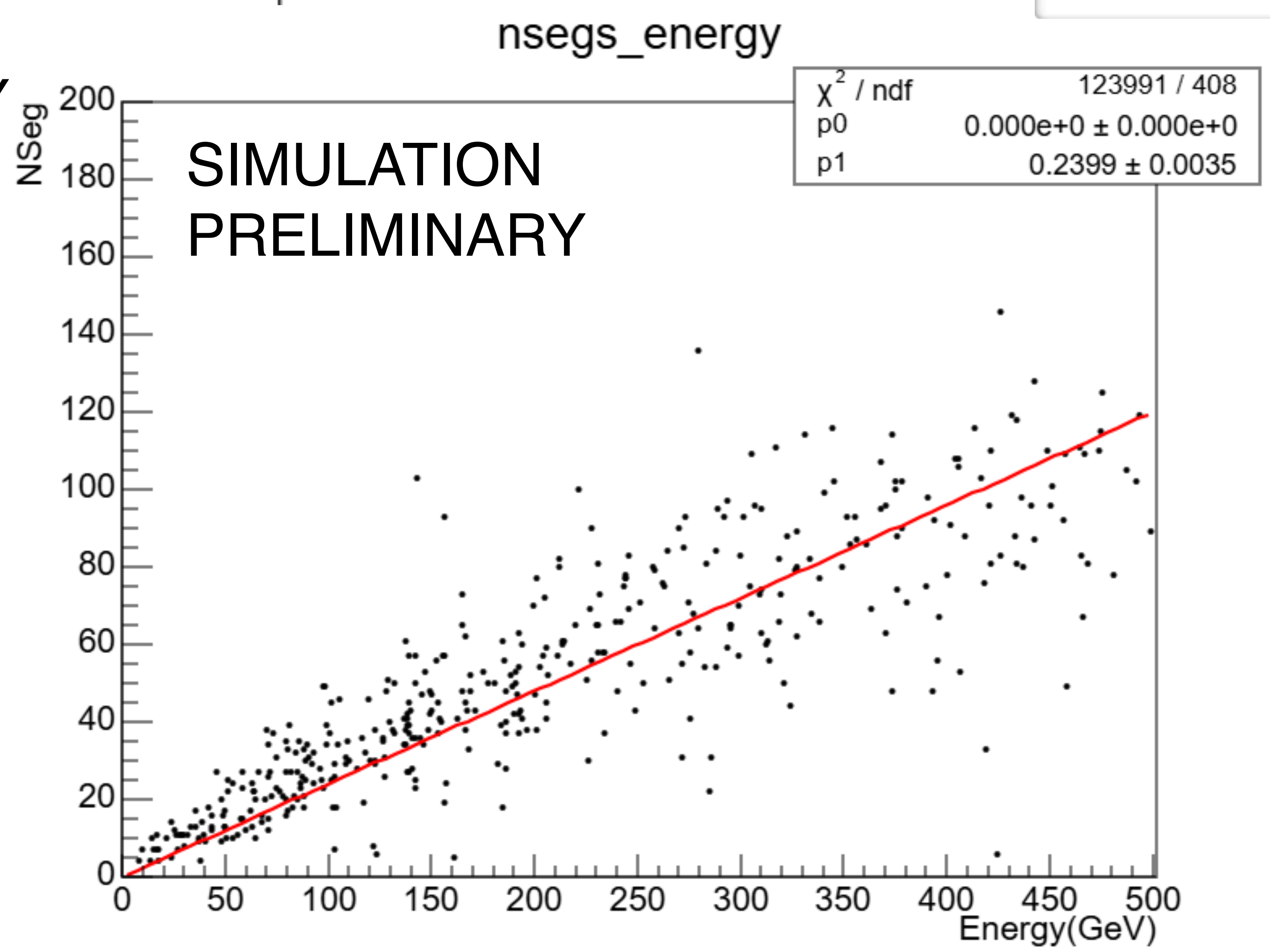


$\delta_{pos} < 100\mu m$

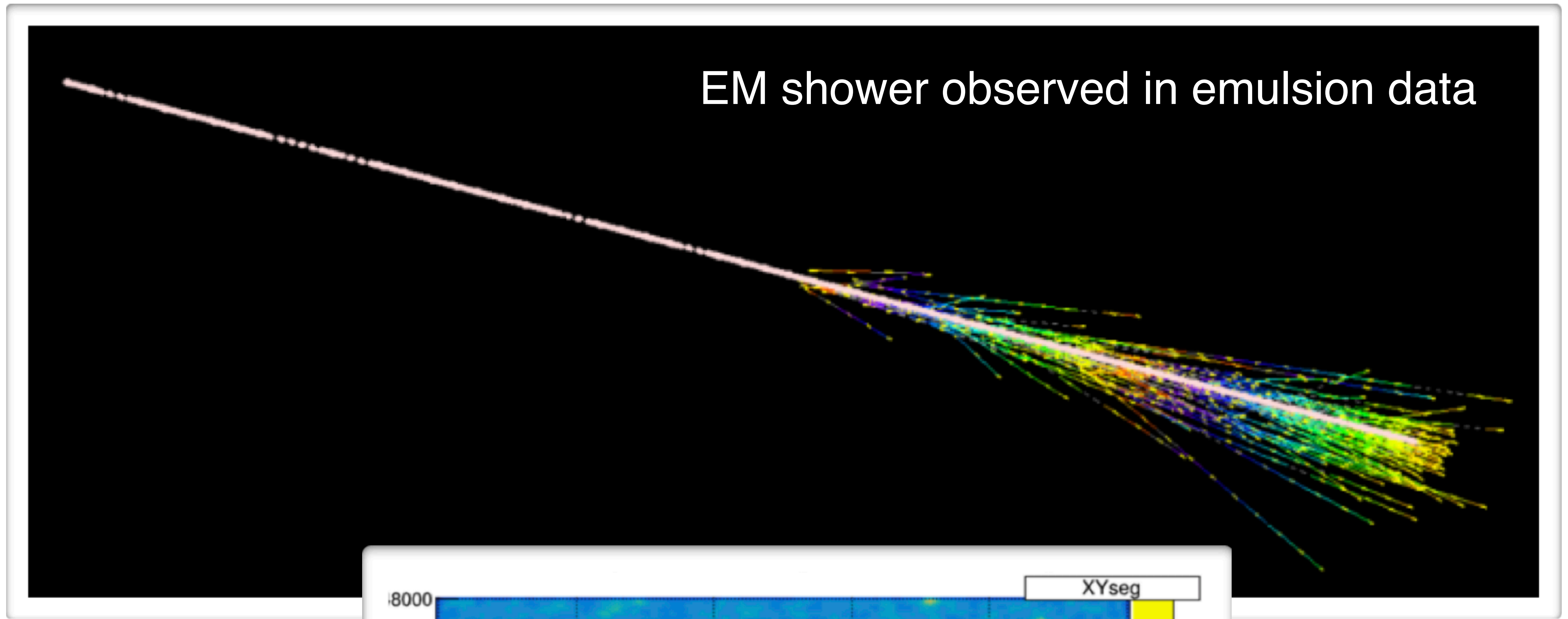
$\delta_{\theta} < 10mrad$

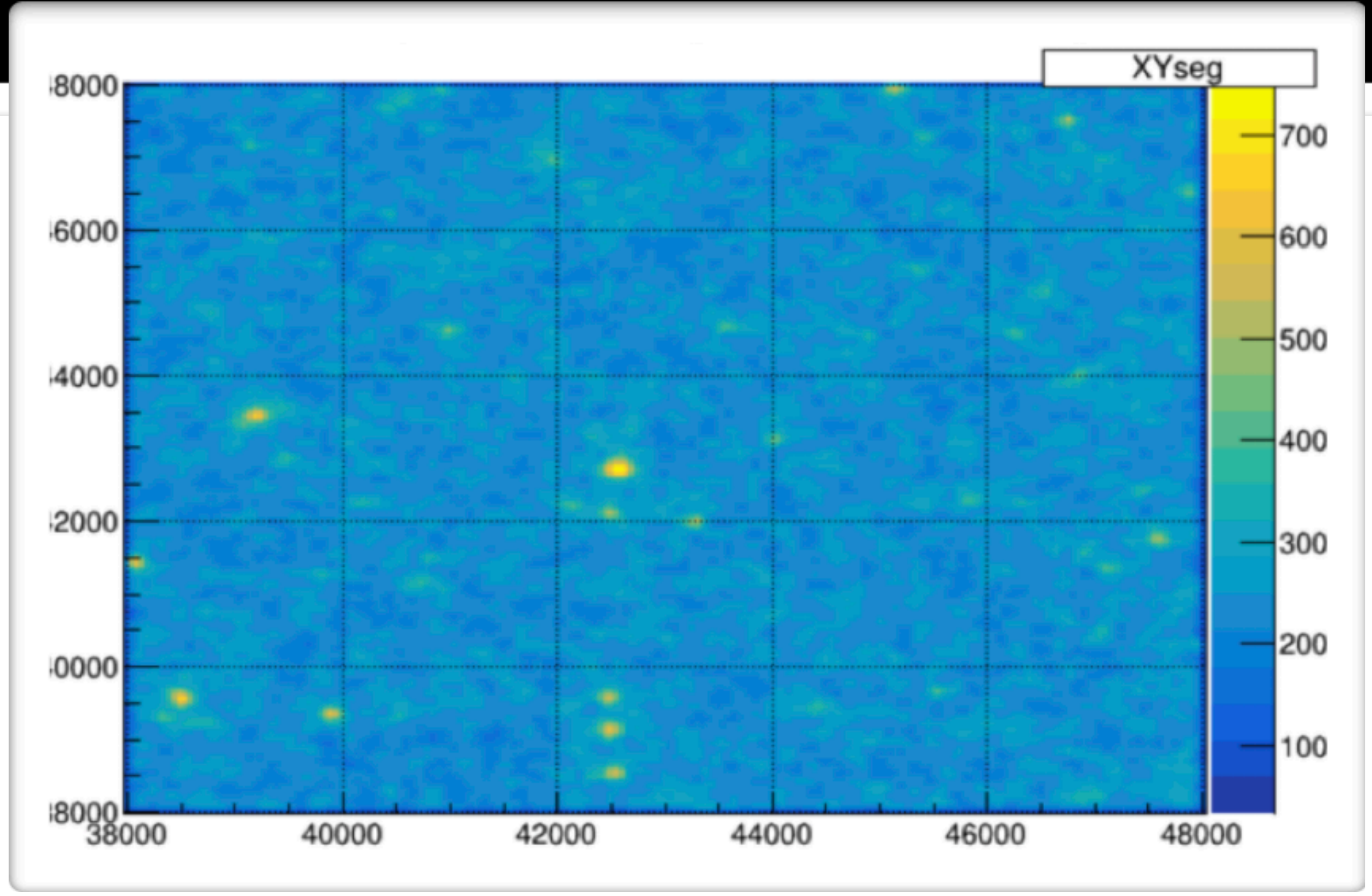
$d_{min} < 50\mu m$





- EM shower search based on observation of high density spots

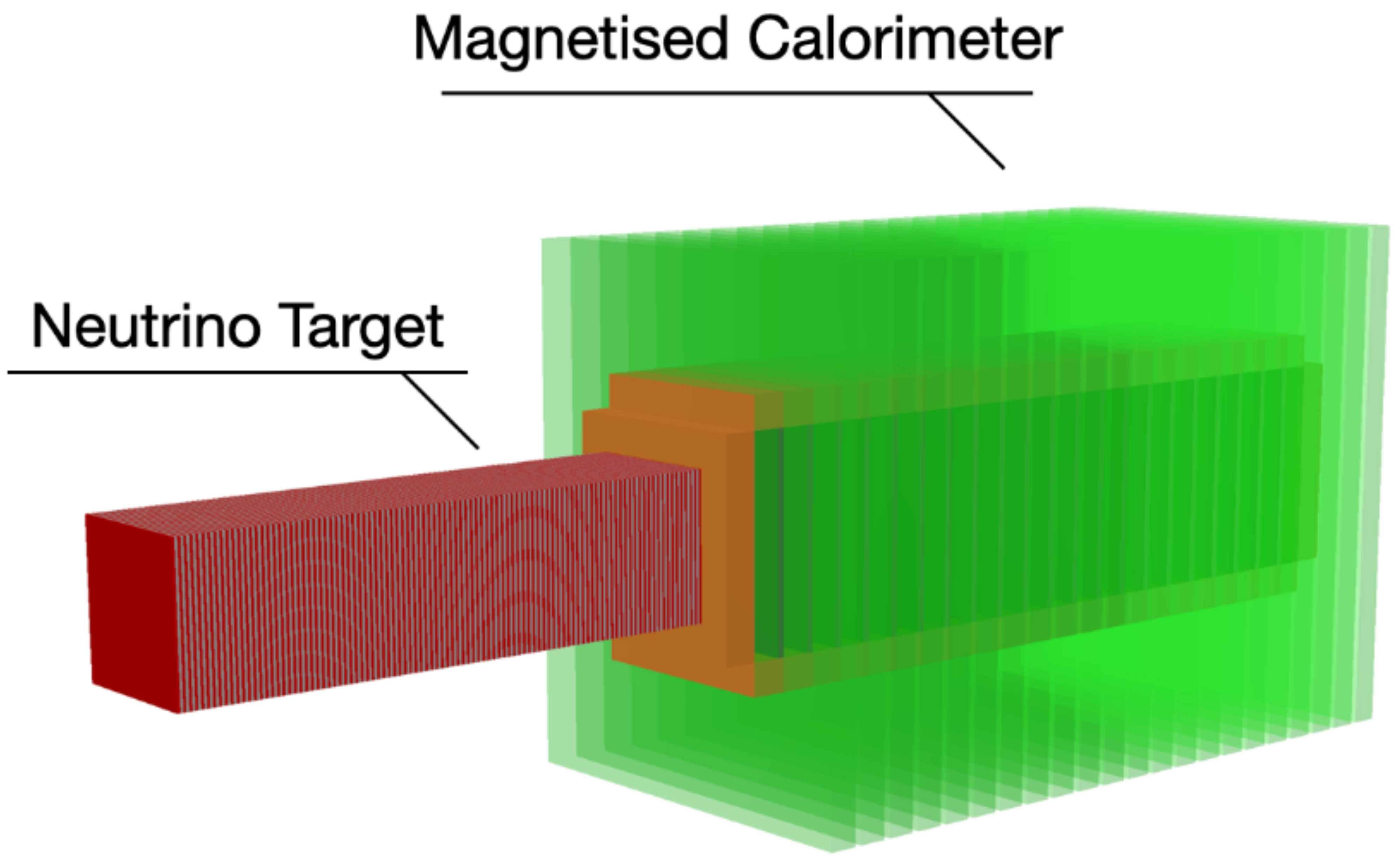


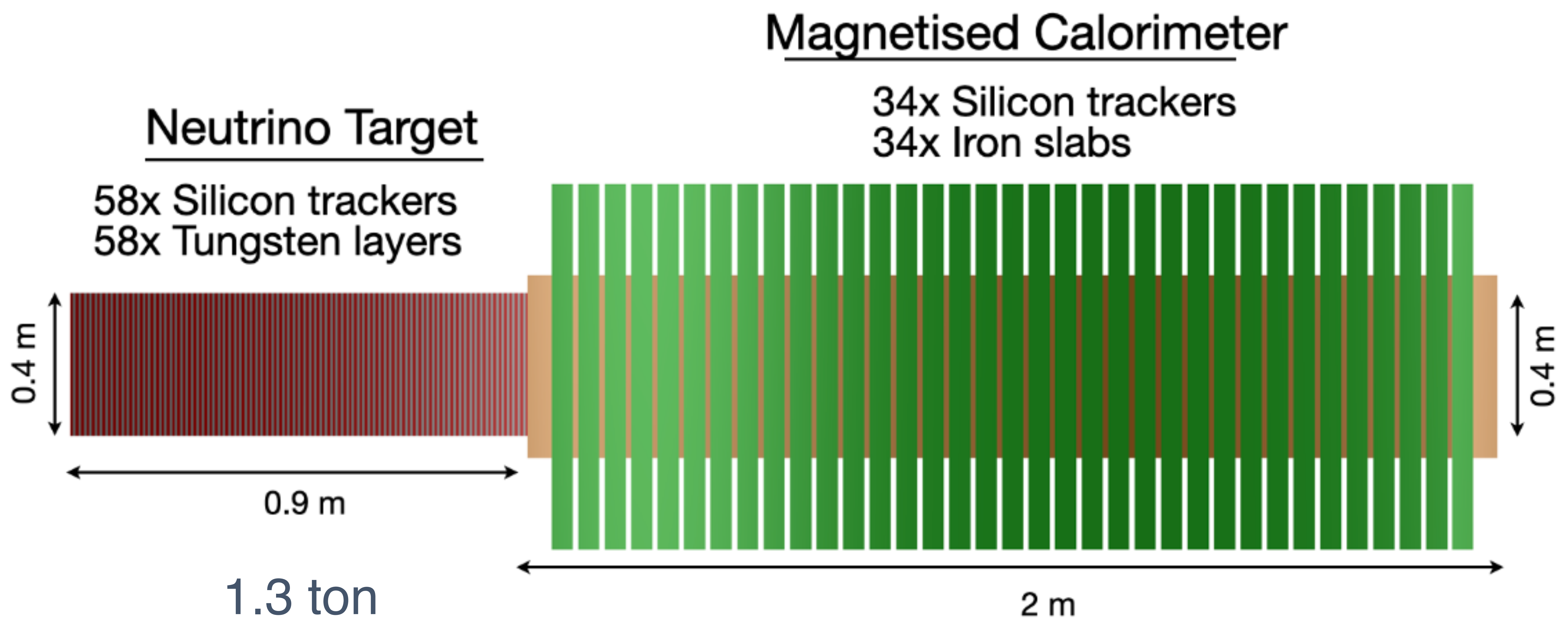


EM shower observed in emulsion data

SND@HL-LHC

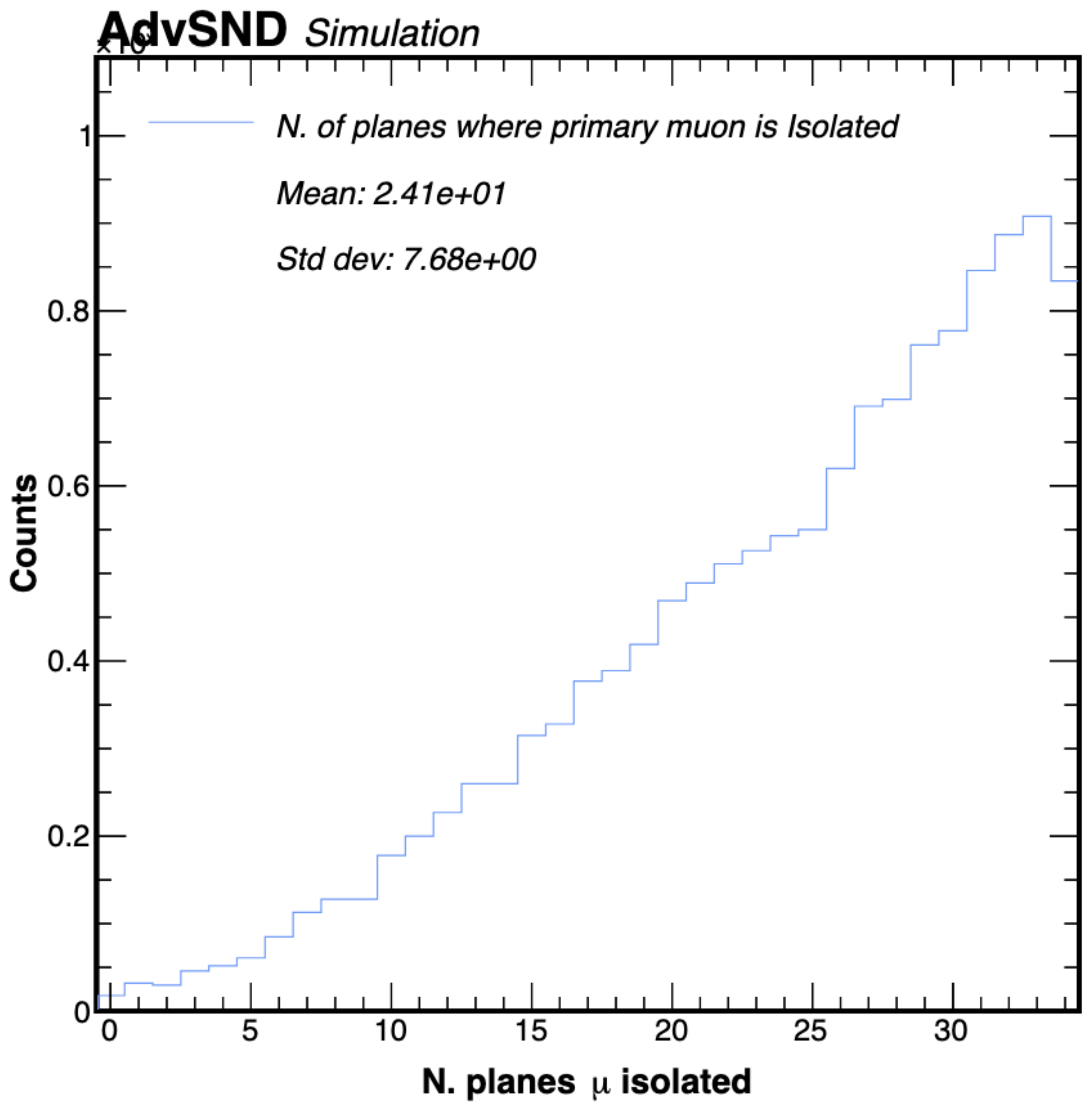
- Running the emulsion detector during the HL-LHC is unfeasible.
- HL-LHC phase of the experiment will use silicon-strip instrumentation.
- The calorimeter will be magnetised for muon momentum and charge measurement.
- Technical Proposal submitted

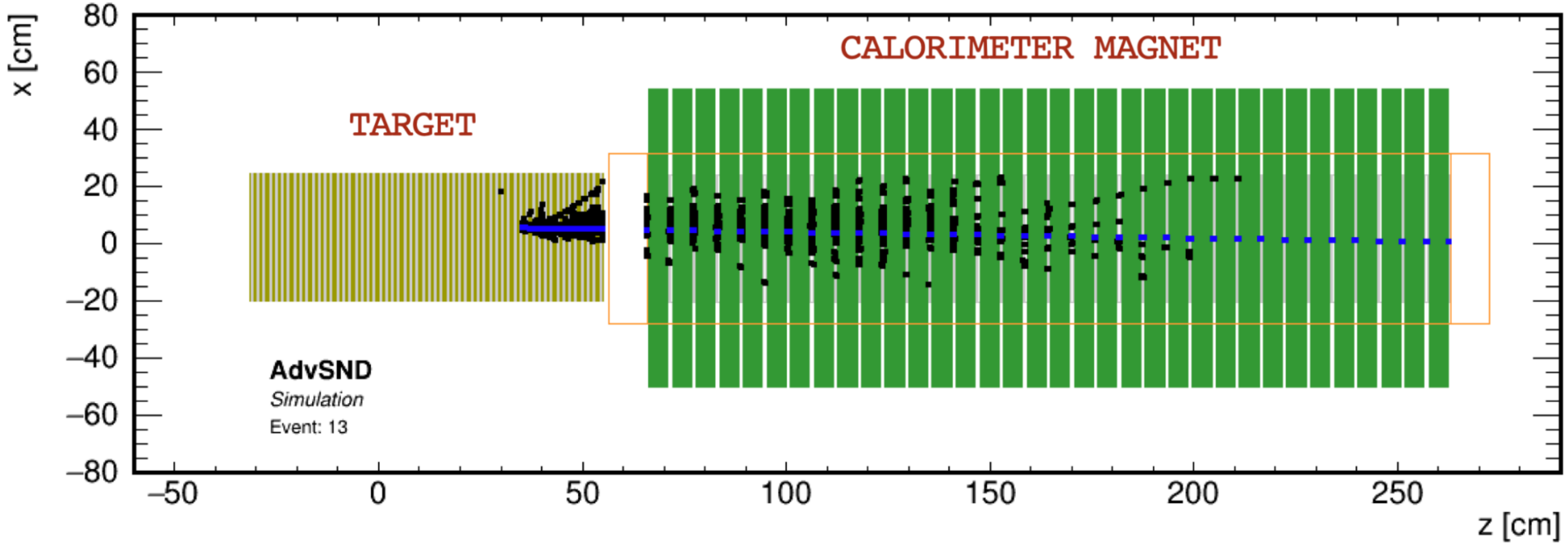




CERN-LHCC-2024-014

Muon neutrino identification



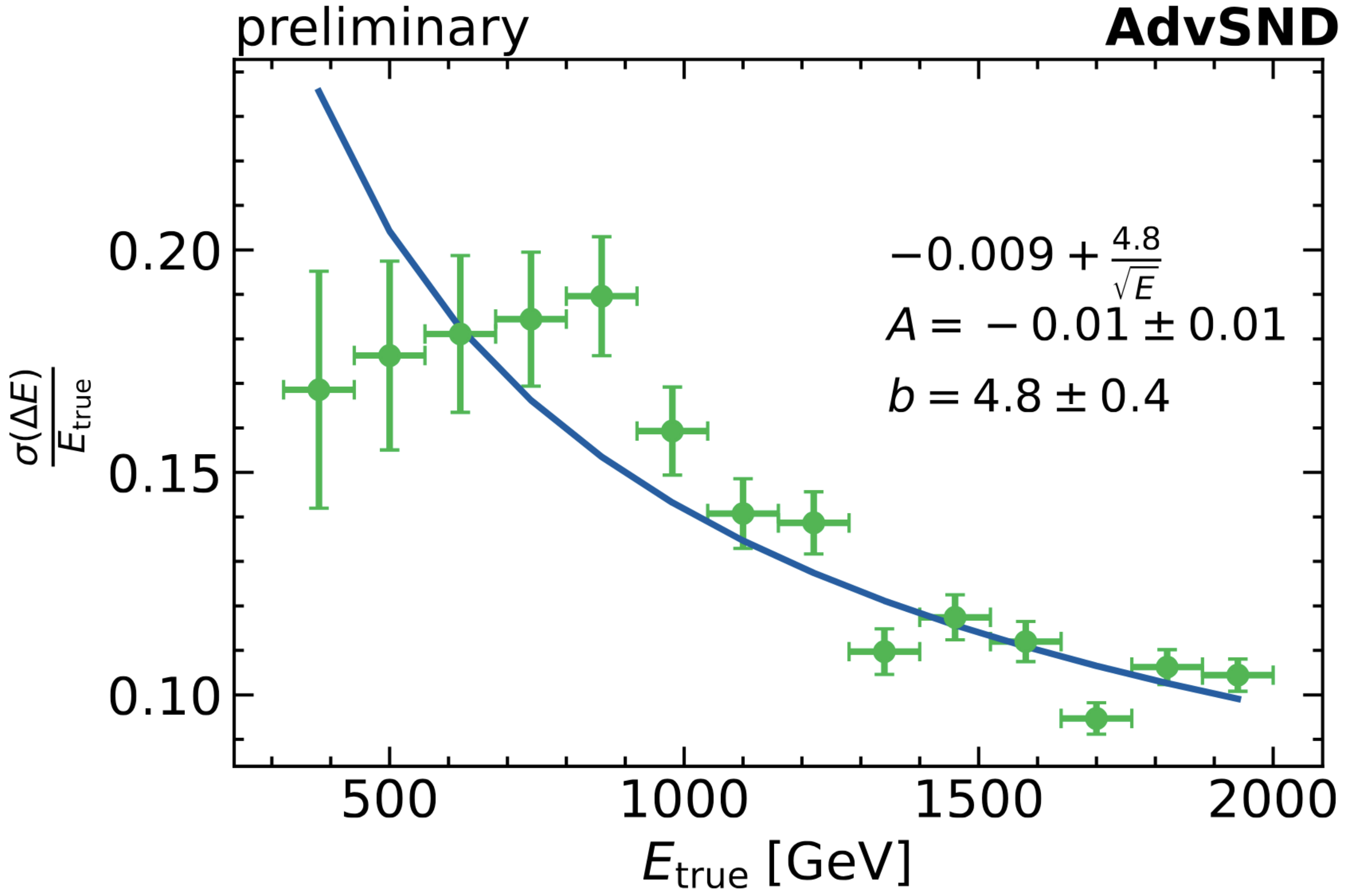


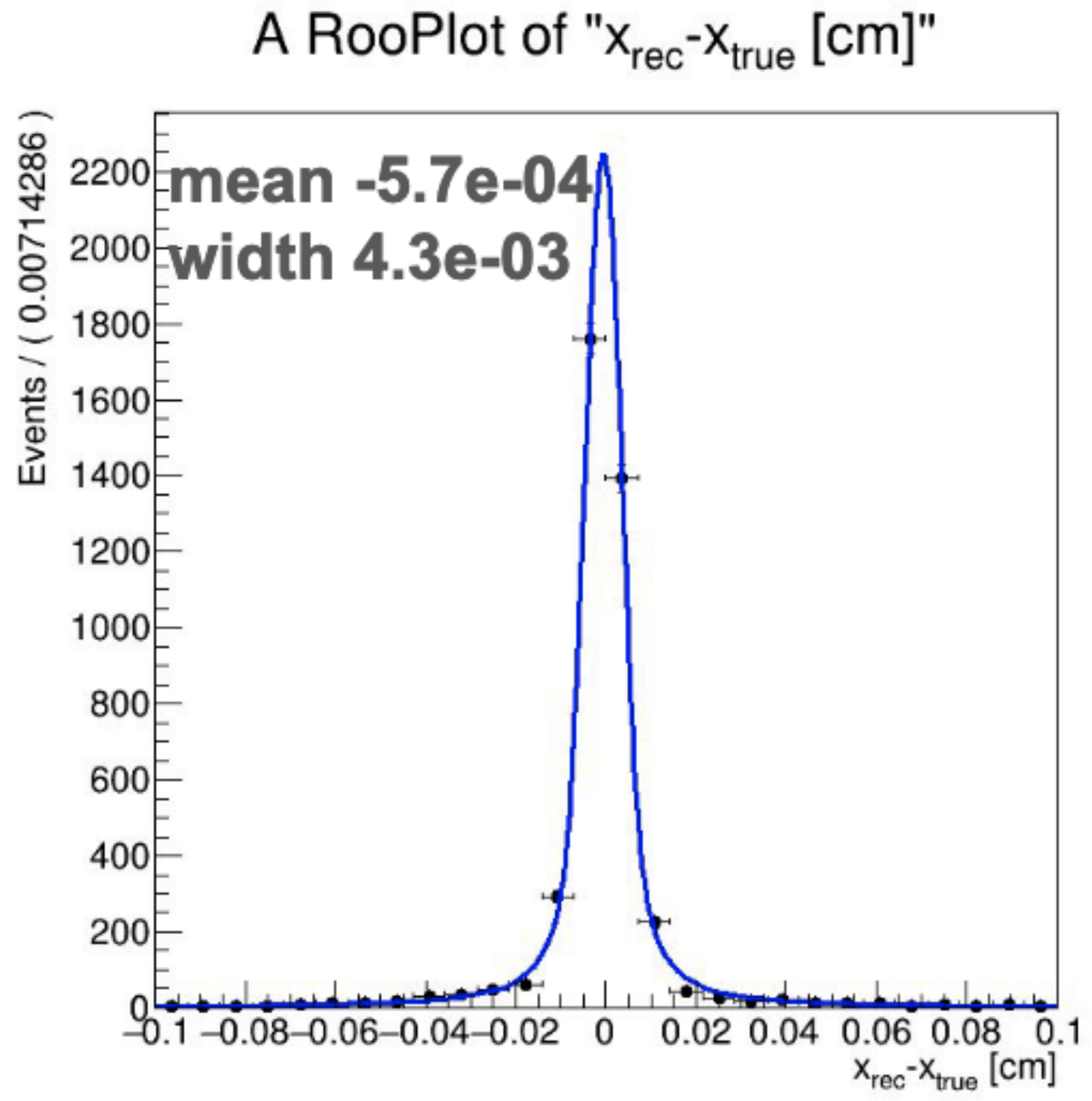
Muon geometrical acceptance is around 72%

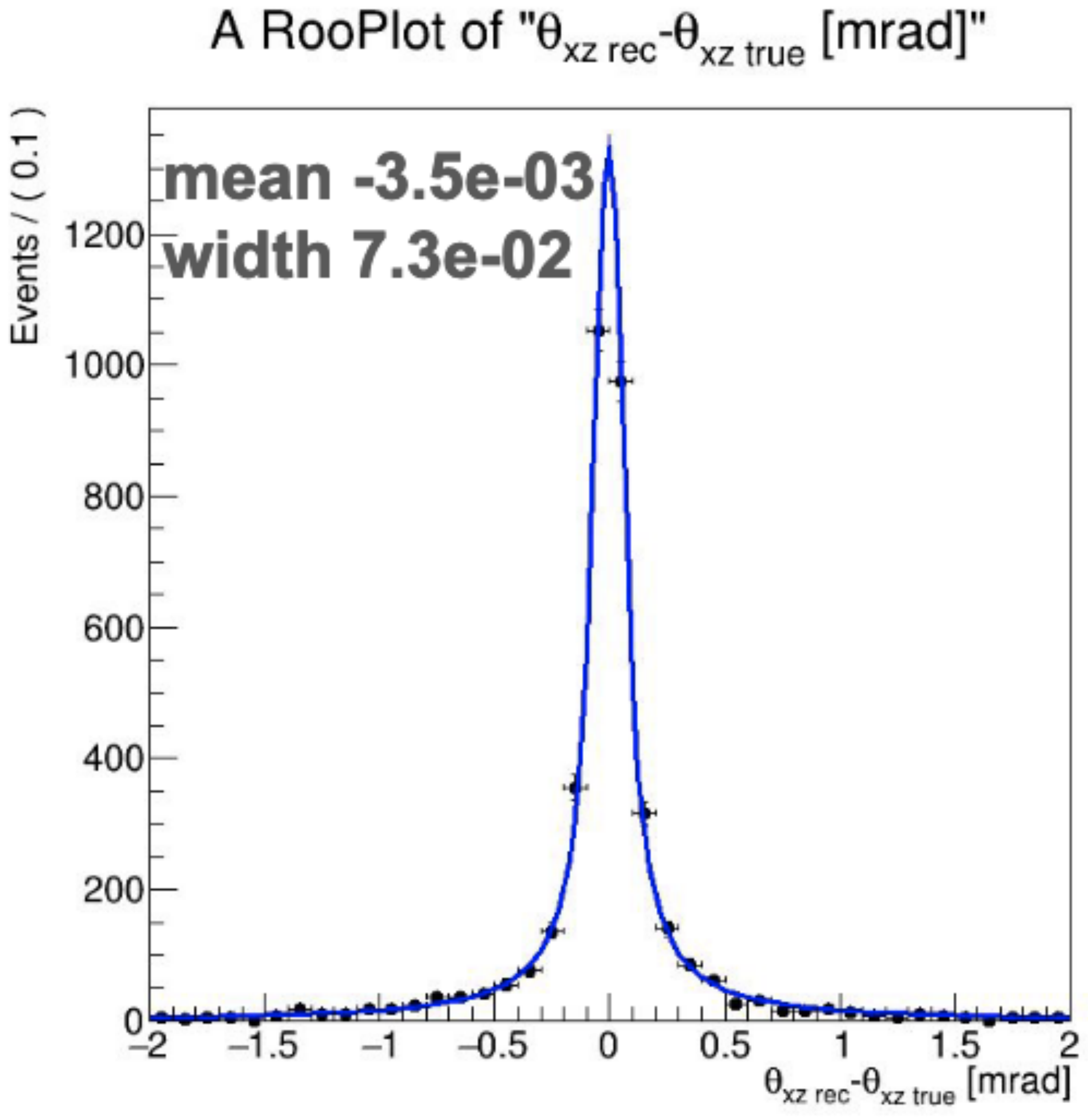
Muon hits are isolated in 24 planes on average

CERN-LHCC-2024-014

Expected SND@HL-LHC performance

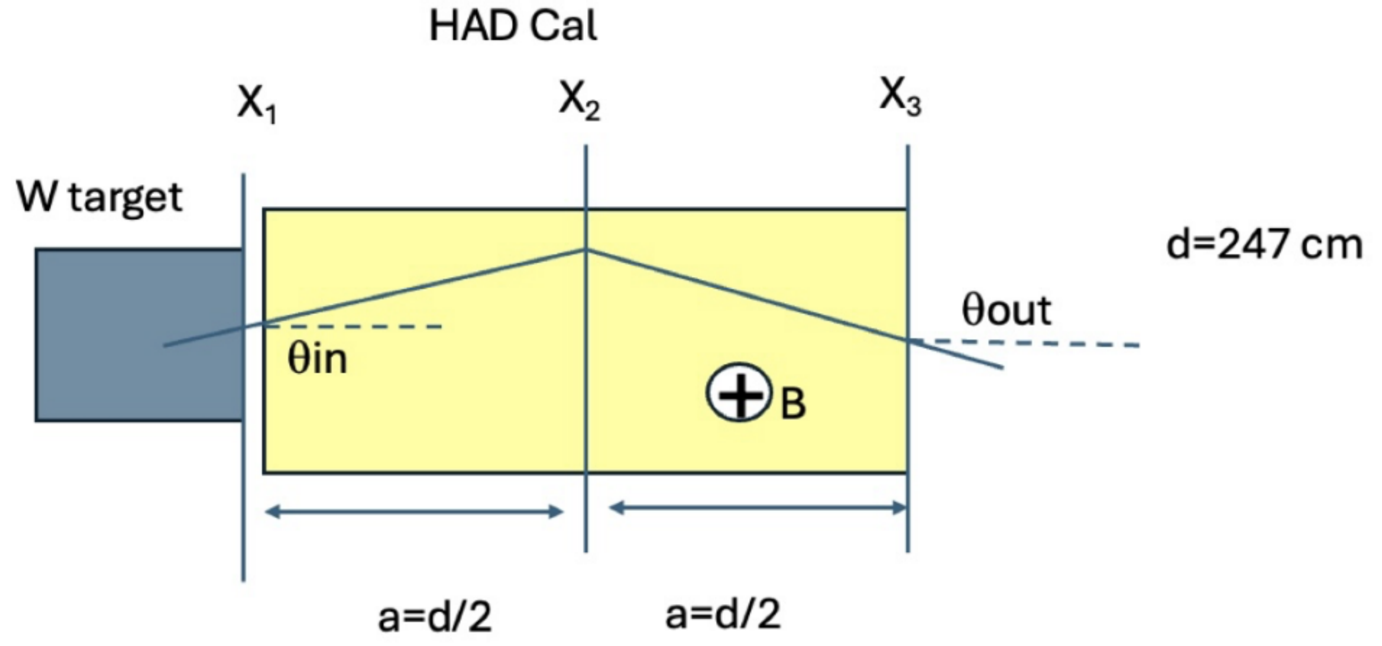


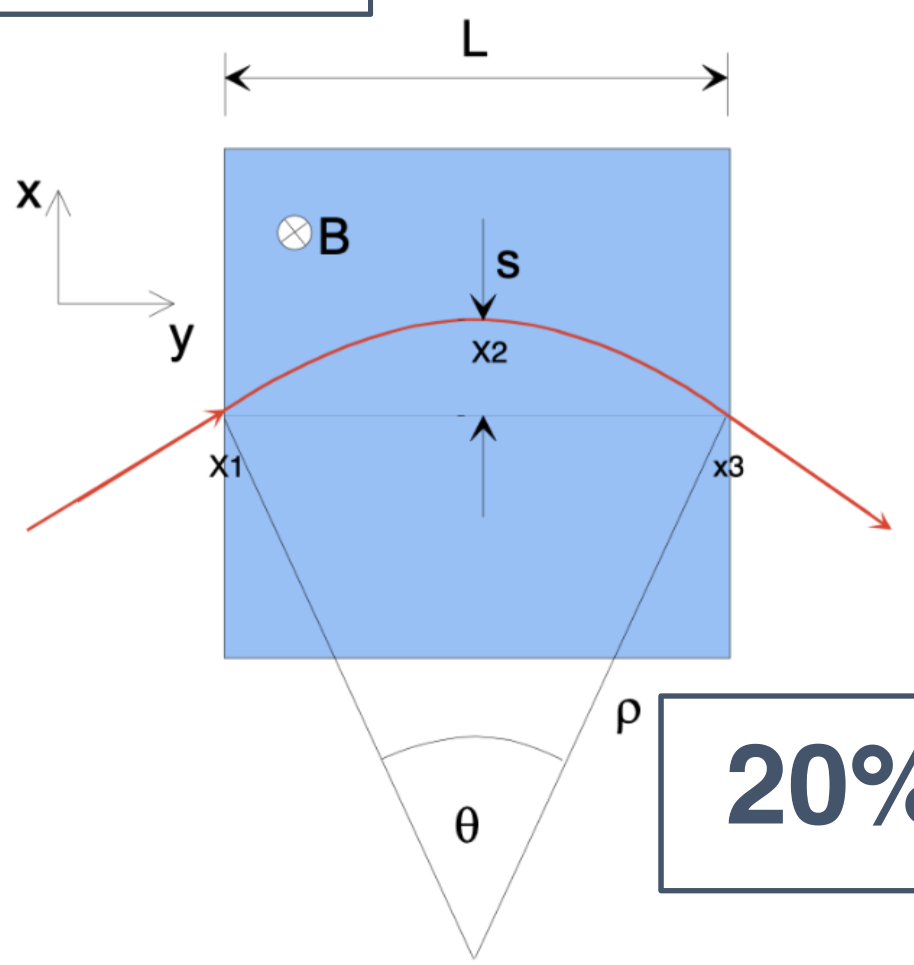




10 – 20% Hadron energy resolution

40 micron and 0.1 mrad tracking





$$s = \rho\left(1 - \cos\frac{\theta}{2}\right) \simeq \rho\frac{\theta^2}{8} = 0.3\frac{BL^2}{8p}$$

$$\frac{\Delta p}{p} = \frac{\Delta s}{s} = \sqrt{\frac{3}{2}}\frac{8p\sigma_x}{0.3BL^2}$$

20% Muon momentum resolution at 1 TeV

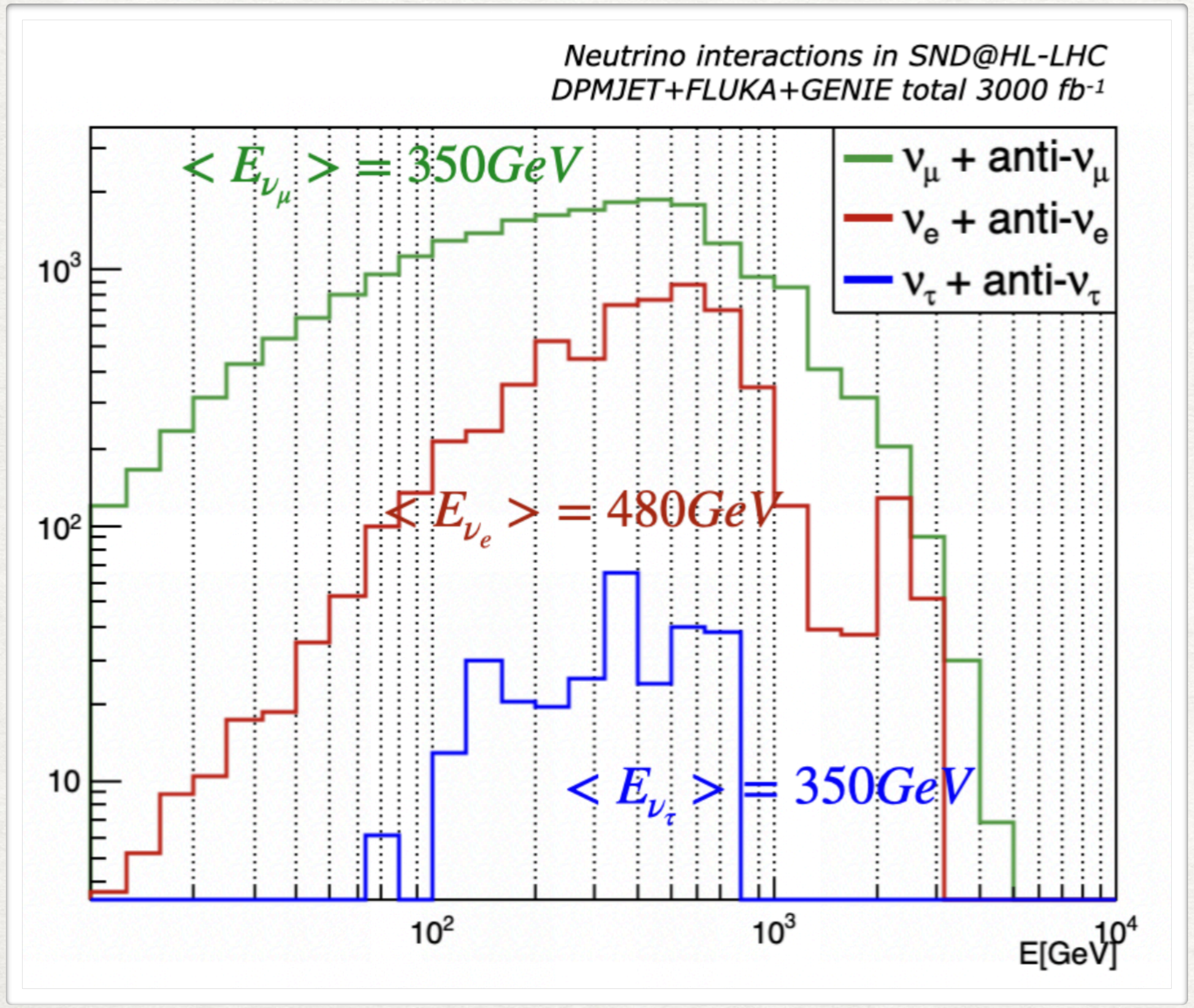
1.7 T over 1.7 m

CERN-LHCC-2024-014

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



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

13 times more statistics wrt Run3

- If there is an opportunity to excavate a trench on the tunnel floor (~50 cm), an further increase in the event yield by a factor of 7 is possible

LHC Run3 **HL-LHC**

Measurement	Uncertainty Stat.	Uncertainty Sys.	Uncertainty Stat.	Uncertainty Sys.
Gluon PDF	5%	35%	2%	5%
ν_e/ν_τ ratio for LFU test	30%	22%	6%	10%
ν_e/ν_μ ratio for LFU test	10%	10%	2%	5%
Charm-tagged ν_e/ν_μ ratio for LFU test	-	-	10%	$<$ 5%
ν_μ and $\bar{\nu}_\mu$ cross-section	-	-	1%	5%

Prospects for 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.