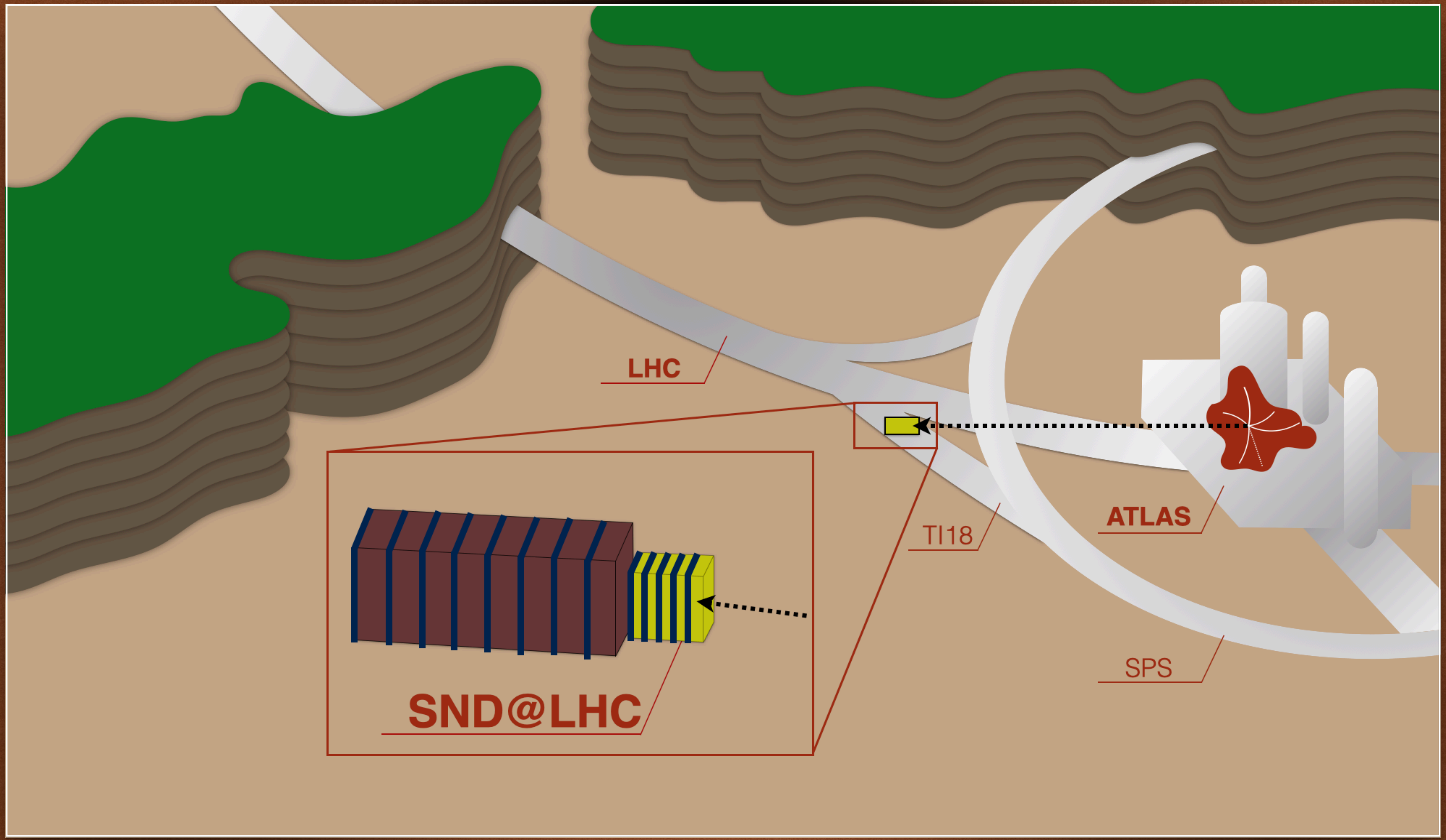
THE PHYSICS OF THE SND@LHC EXPERIMENT



A. Di Crescenzo
Università Federico II and INFN
antonia.di.crescenzo@cern.ch

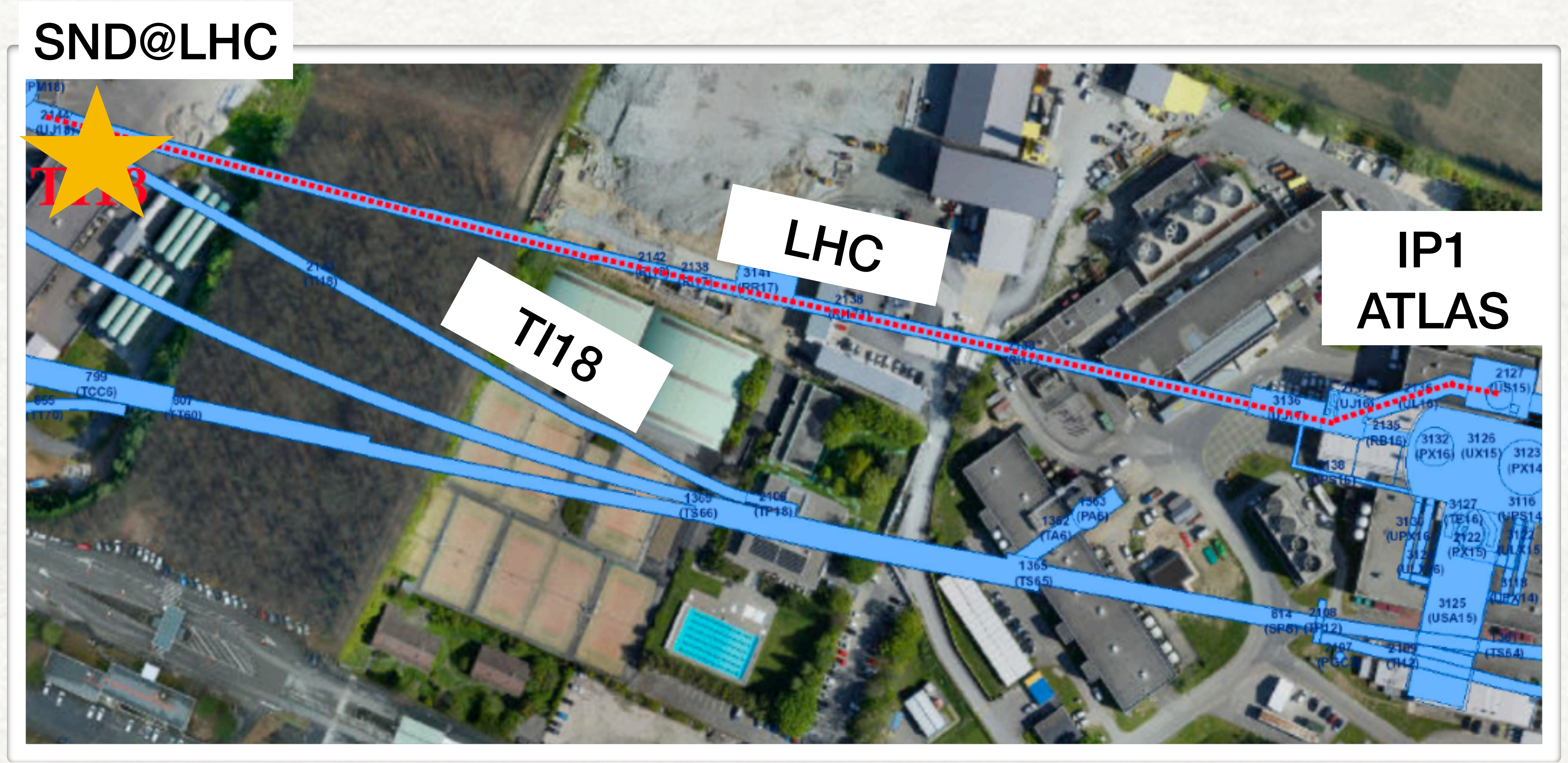
OVERVIEW

- **SND@LHC: S**cattering and **N**eutrino **D**etector at the **LHC**

- The SND@LHC experiment
- Event reconstruction
- Neutrino expectations
- Neutrino physics program
- Search for feebly interacting particles
- Analysis items to be addressed

SND@LHC Technical Proposal
https://cds.cern.ch/record/2750060/files/LHCC-P-016.pdf

LOCATION

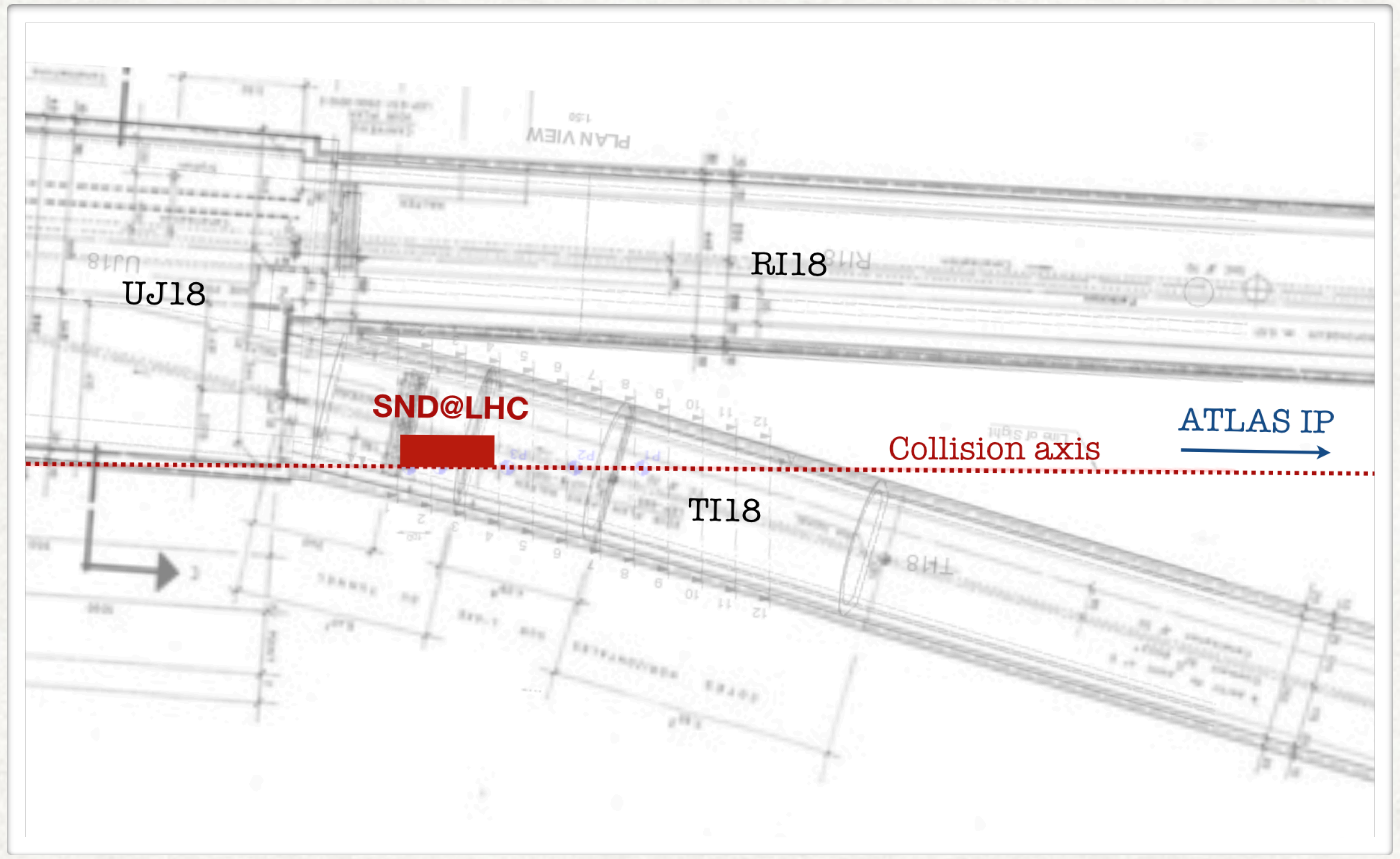


- About 480 m away from the ATLAS IP
- Tunnel TI18: former service tunnel connecting SPS to LEP
- Symmetric to TI12 tunnel where FASER is located

- Charged particles deflected by LHC magnets
- Shielding from the IP provided by 100 m rock

- Angular acceptance: $7.2<\eta< 8.6$

- First phase: operation in Run 3 to collect 150 fb^{-1}



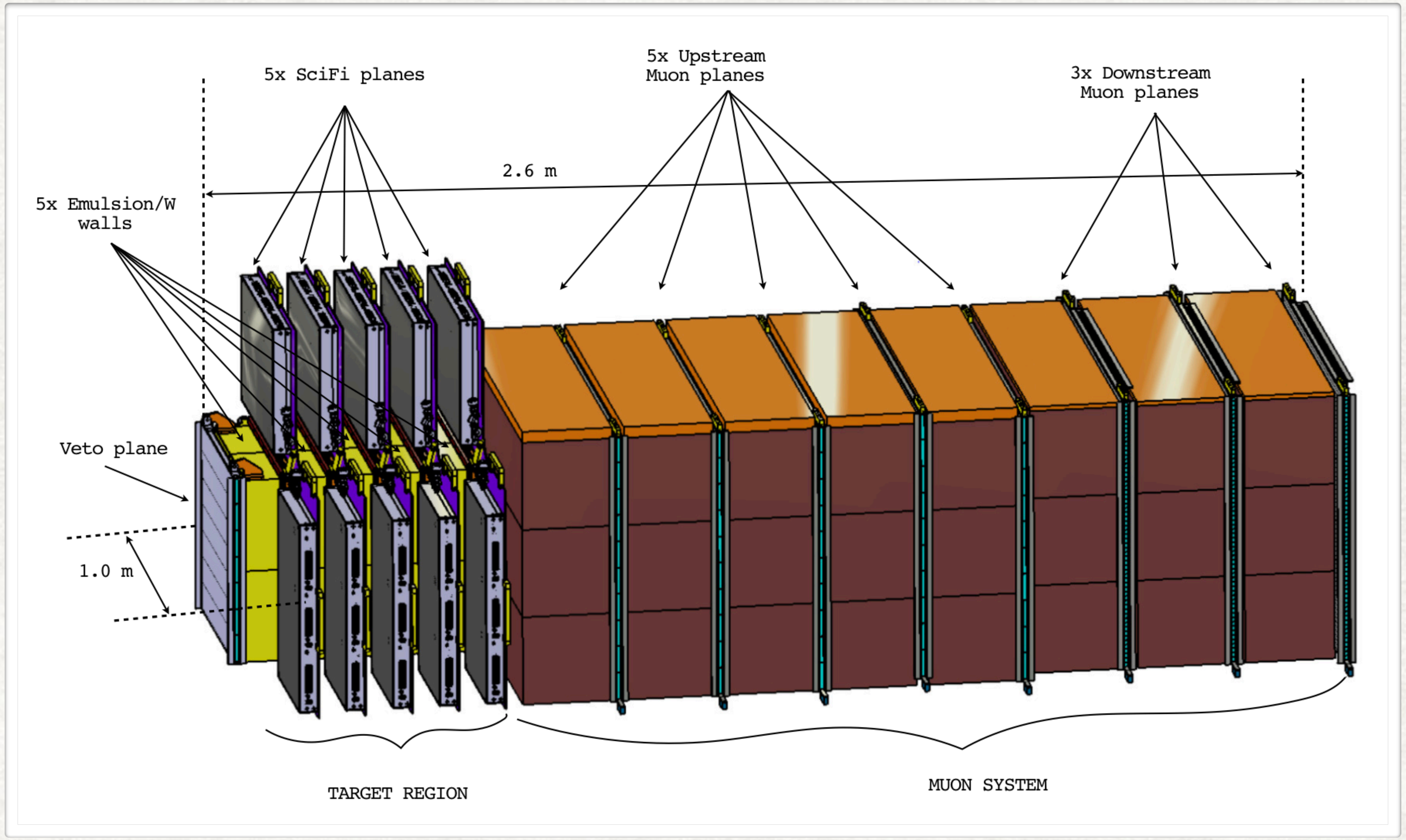
THE SND@LHC CONCEPT

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

VETO PLANE:
tag penetrating muons

TARGET REGION:
- Emulsion cloud chambers (Emulsion+Tungsten) for neutrino interaction detection
- Scintillating fibers for timing information and energy measurement

MUON SYSTEM:
iron walls interleaved with plastic scintillator planes for fast time resolution and energy measurement



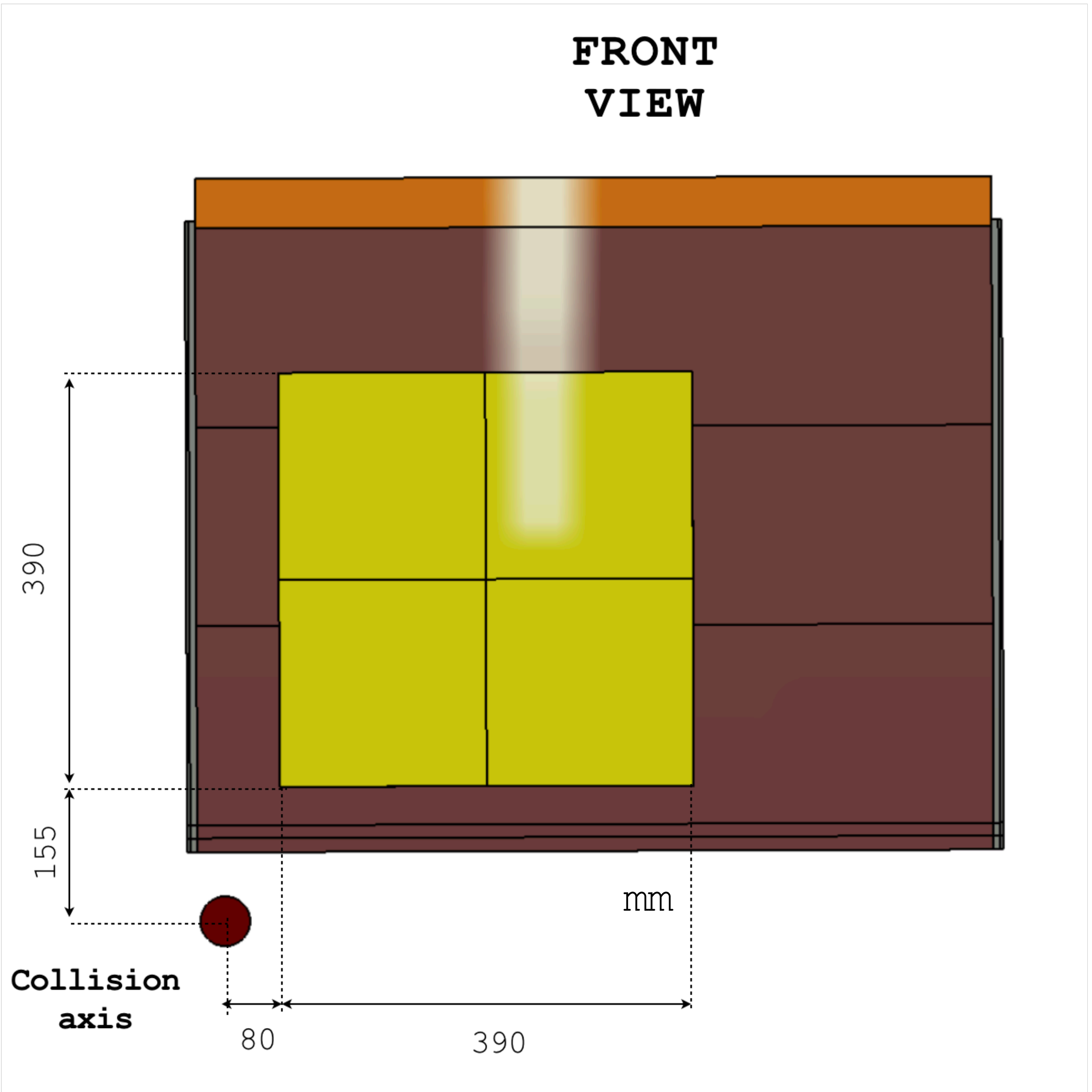
THE DETECTOR LAYOUT

- Angular acceptance: $7.2 < \eta < 8.6$
- Target material: Tungsten
- Target mass: 830 kg
- Surface: 390x390 mm^2

Electromagnetic calorimeter
~40 X_0

Hadronic calorimeter
~10 λ

Off axis location



Veto plane for charged particles in front of the target region

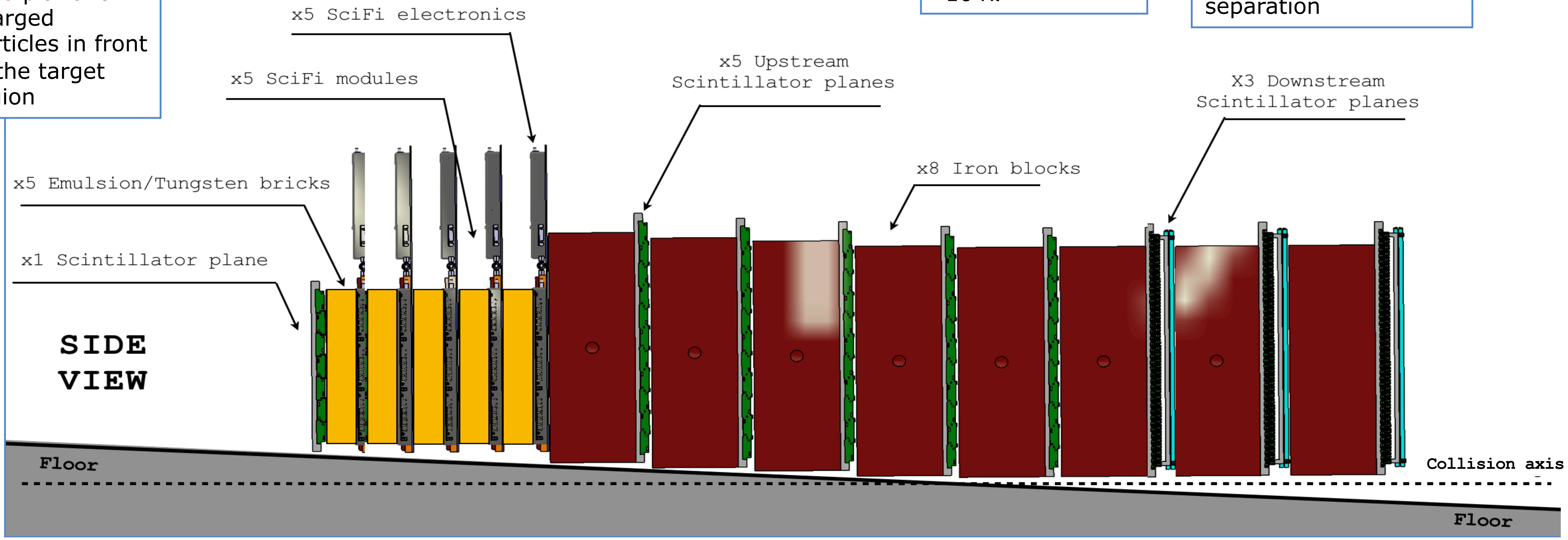
Emulsion Cloud Chamber, emulsion and W absorbers for micrometric accuracy in the detection of τ and FIPs, EM shower energy measurement.

SciFi with timing, provide time stamp to emulsion, records TOF information of events in the target region, track matching with ECCs. EM shower measurement as sampling calorimeter every ~17 X_0.

Muon system – hadronic calorimeter 8 λ, sampling every λ, with target region ~10 λ.

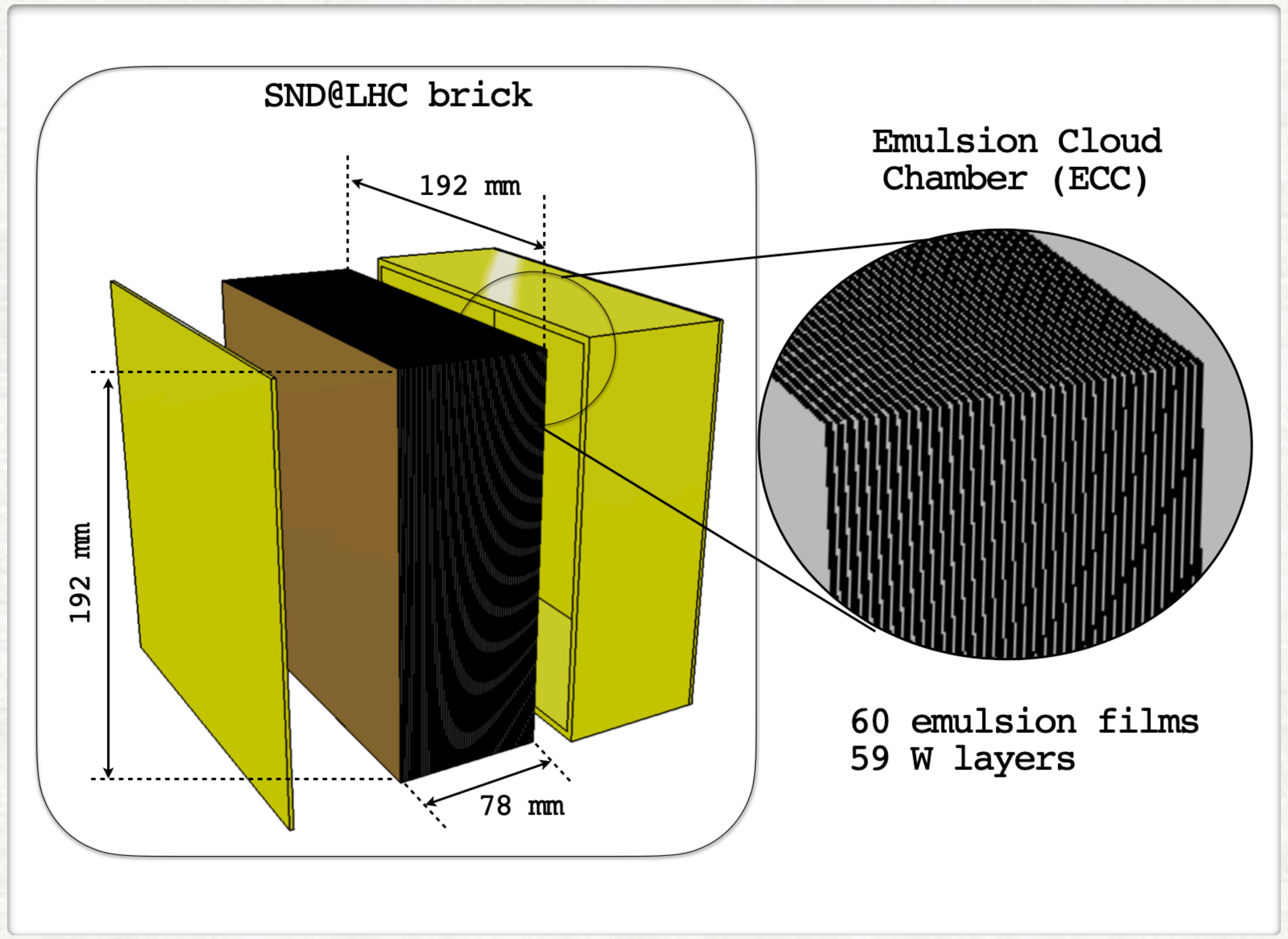
Timing upstream for the muon filtering

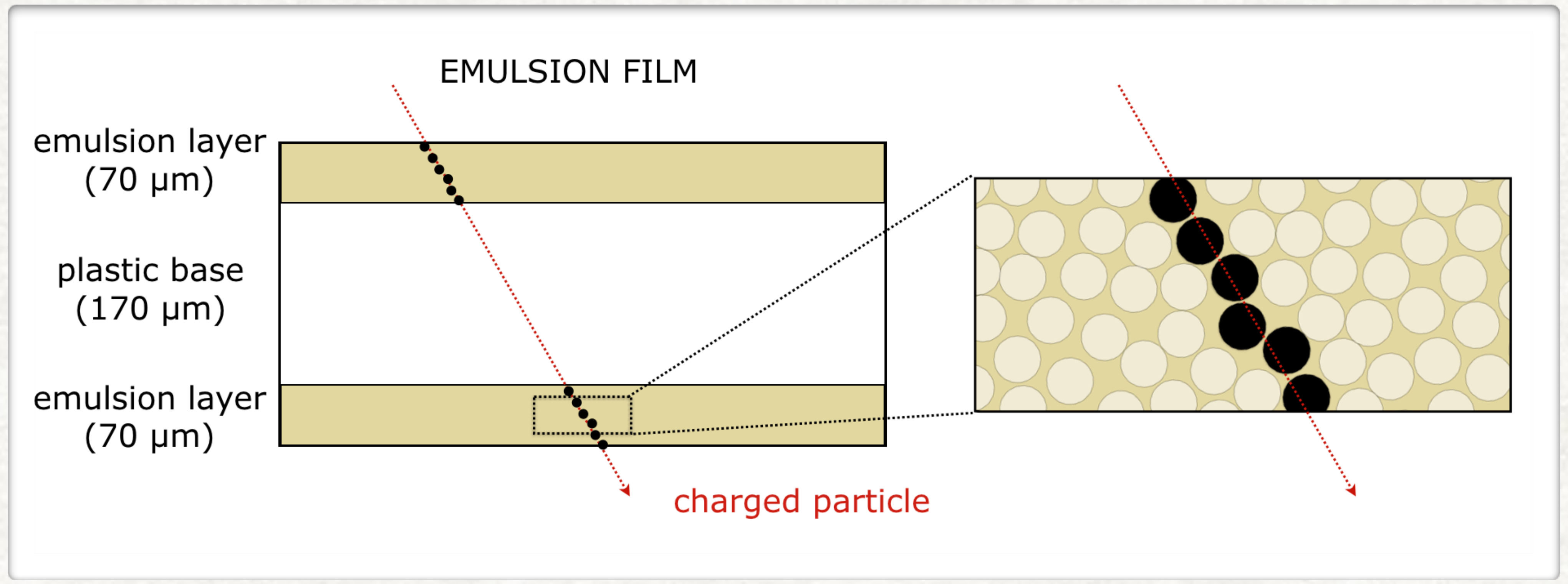
Timing downstream, double X-Y planes with higher granularity for muon-hadron separation

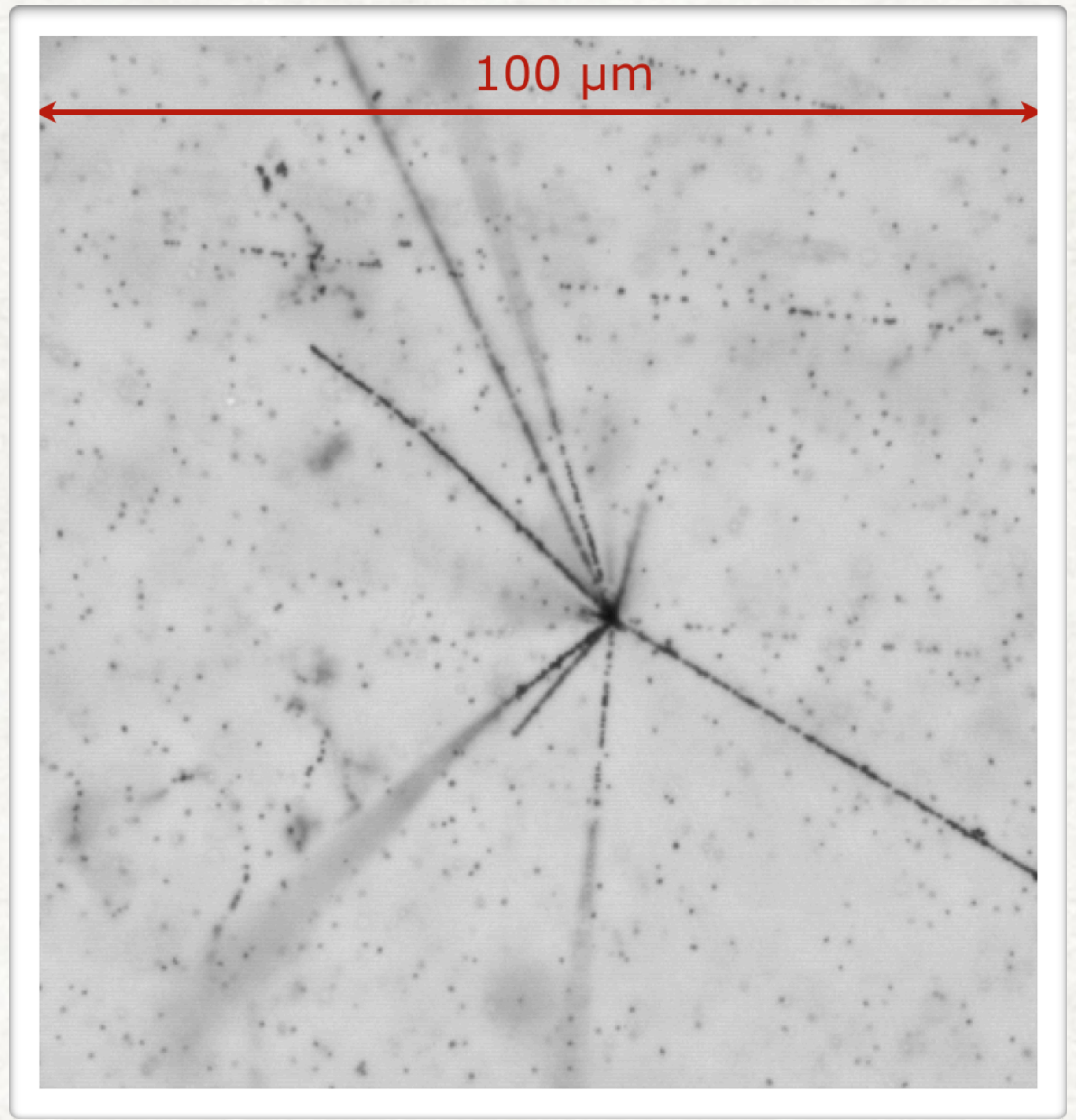


EMULSION TARGET

Target assembled according to the Emulsion Cloud Chamber (ECC) technique:
Tungsten layers (1mm-thick) alternated to nuclear emulsion films





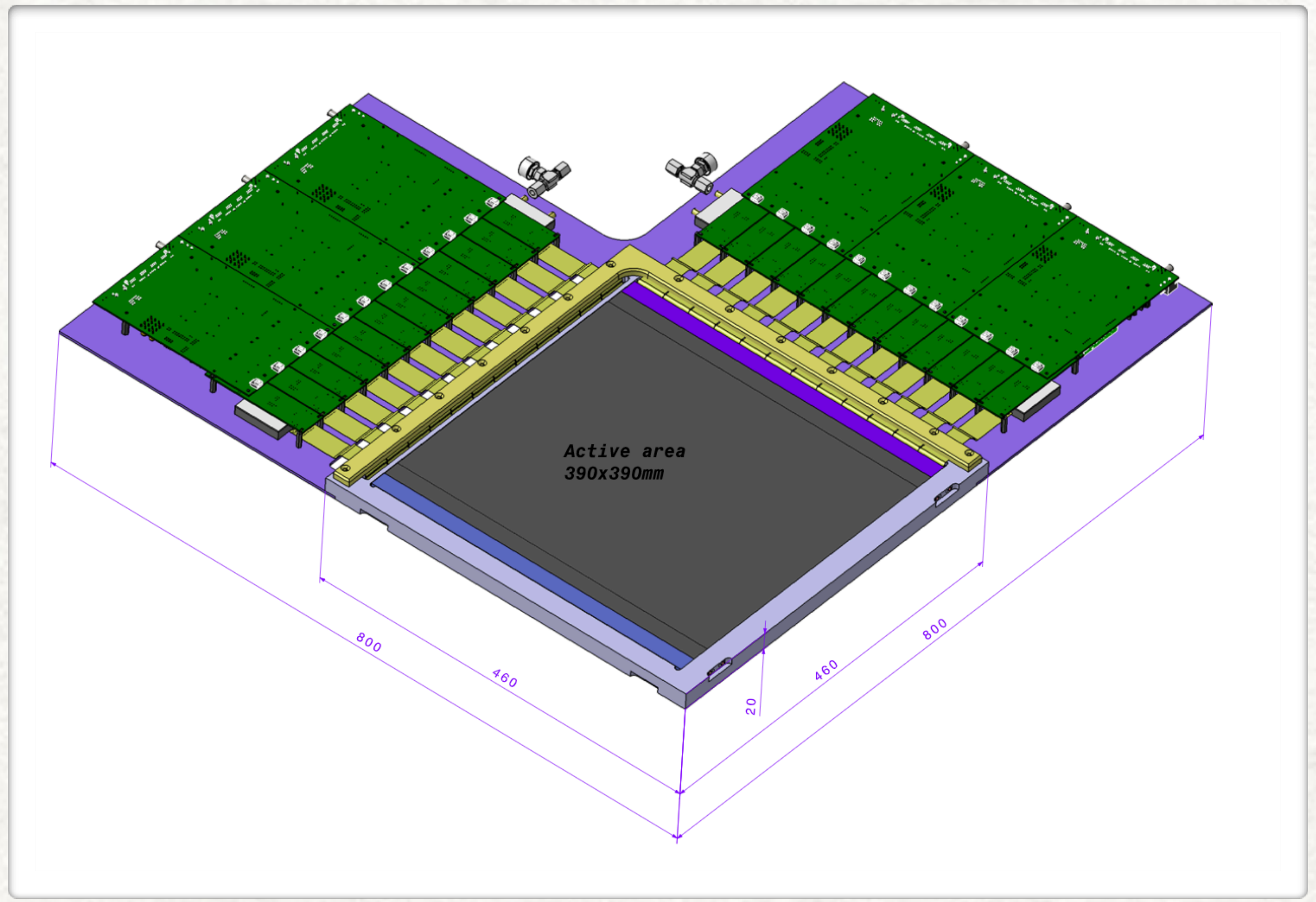


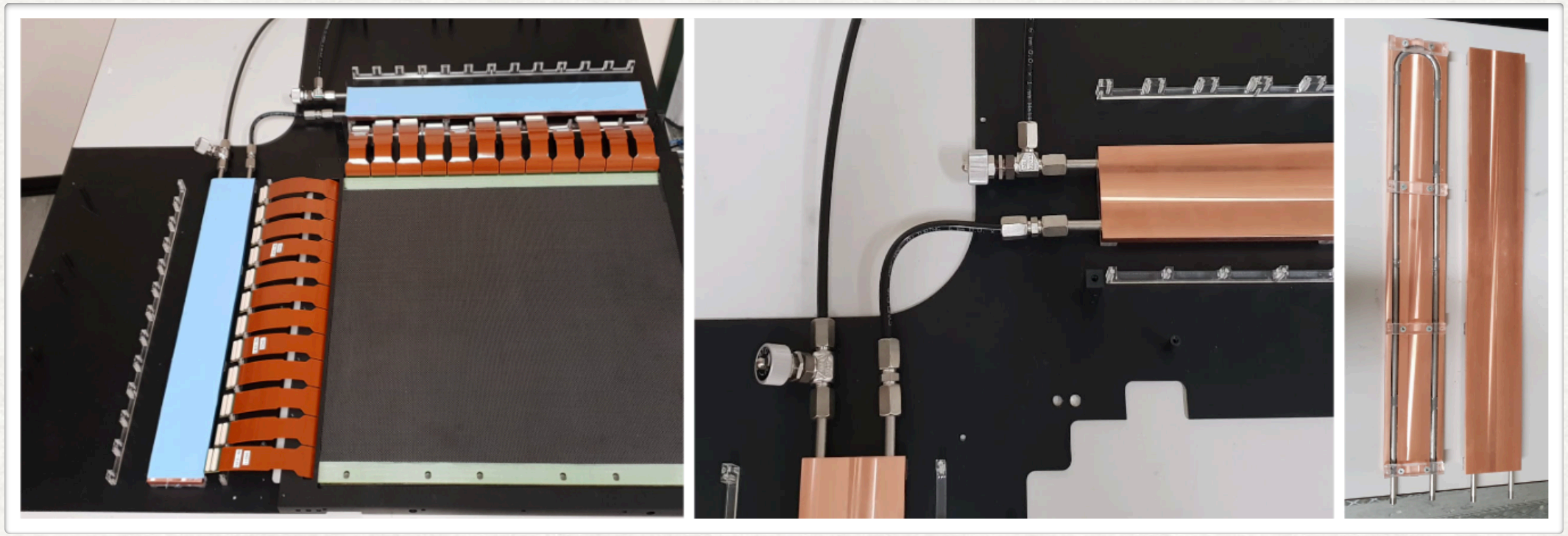
Sub-micrometric position resolution

SCINTILLATING FIBRES

Five XY SciFi modules in production:
- Active surface 390x390 mm^2

→ Time stamp to interactions reconstructed the emulsion
→ Time of Flight measurement of events recorded in the target
→ Sampling calorimeter for electromagnetic shower measurement



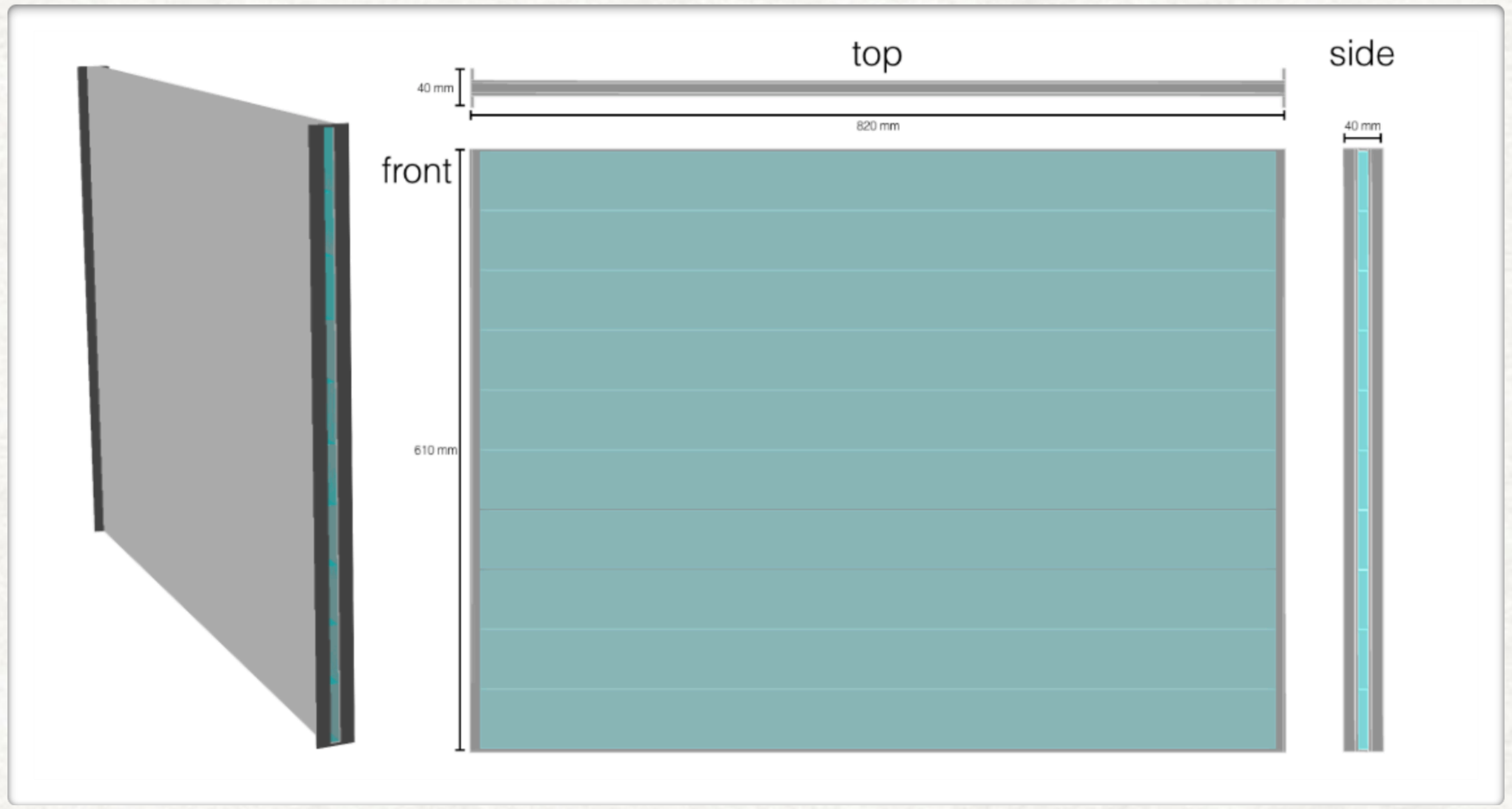


Modules under construction @EPFL

MUON STATIONS

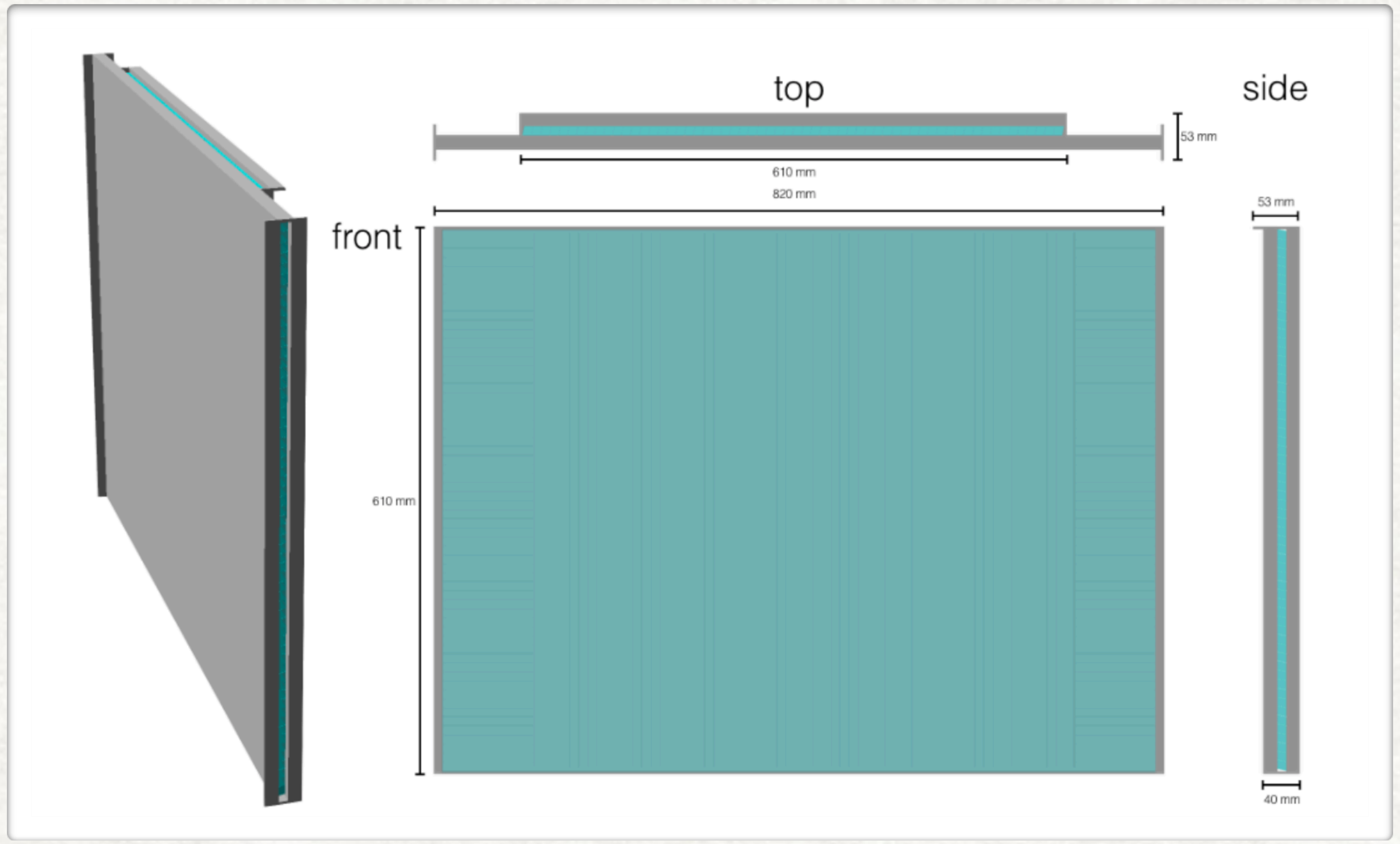
UPSTREAM
- Five planes
- 10 bars/plane

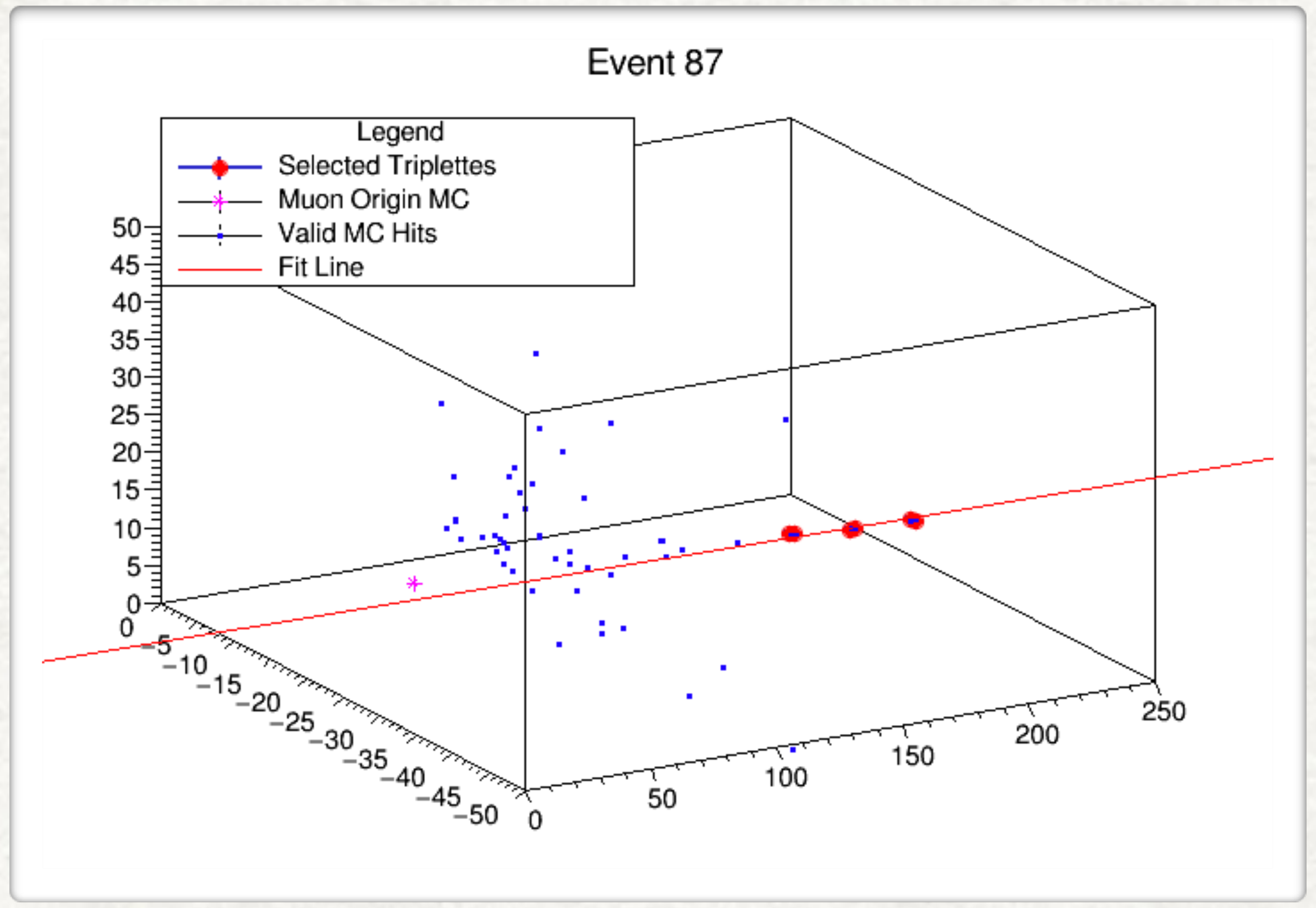
→ Hadronic calorimeter



DOWNSTREAM
- Three planes
- Two layers/plane
- 60 bars/layer

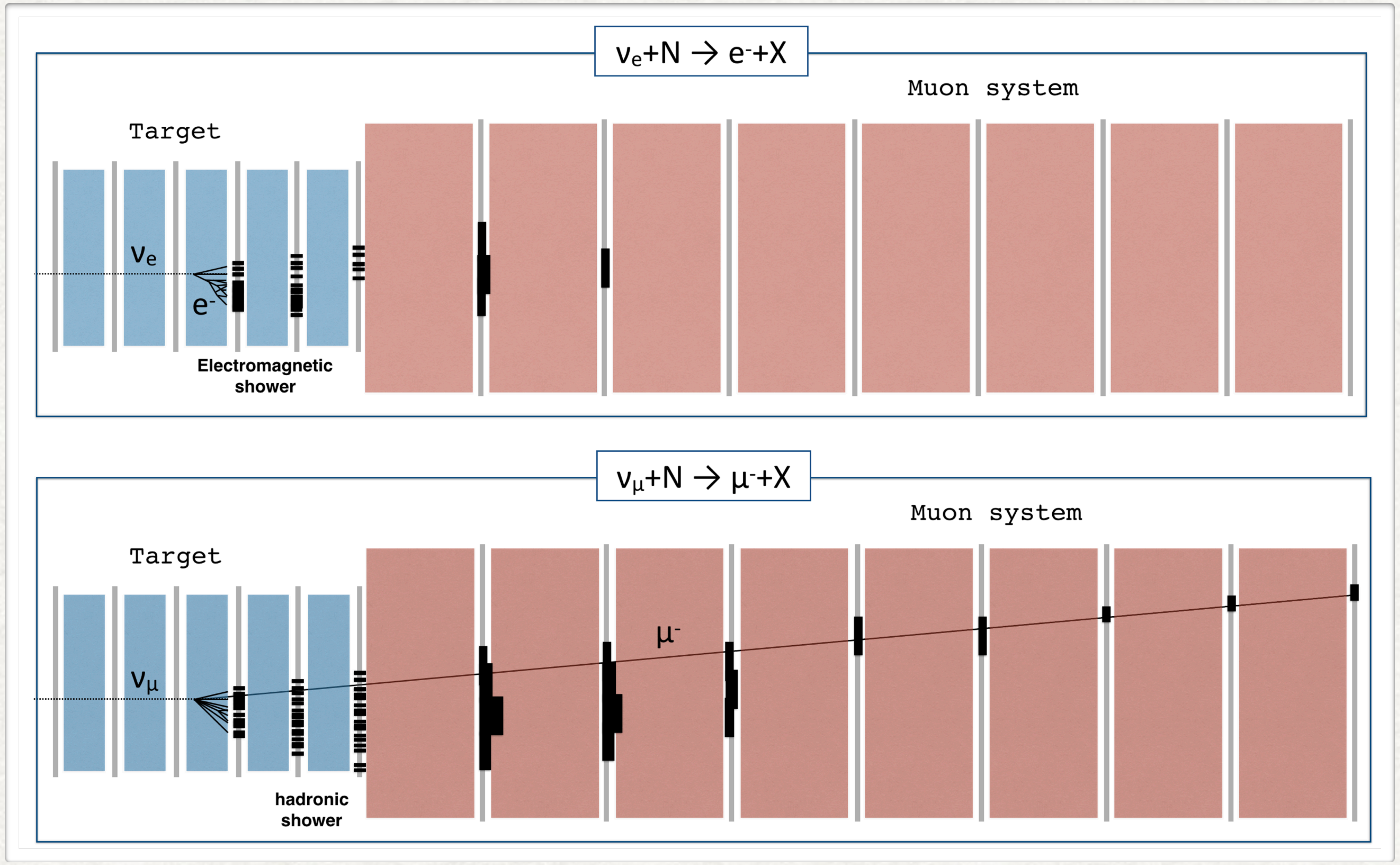
→ Muon identification



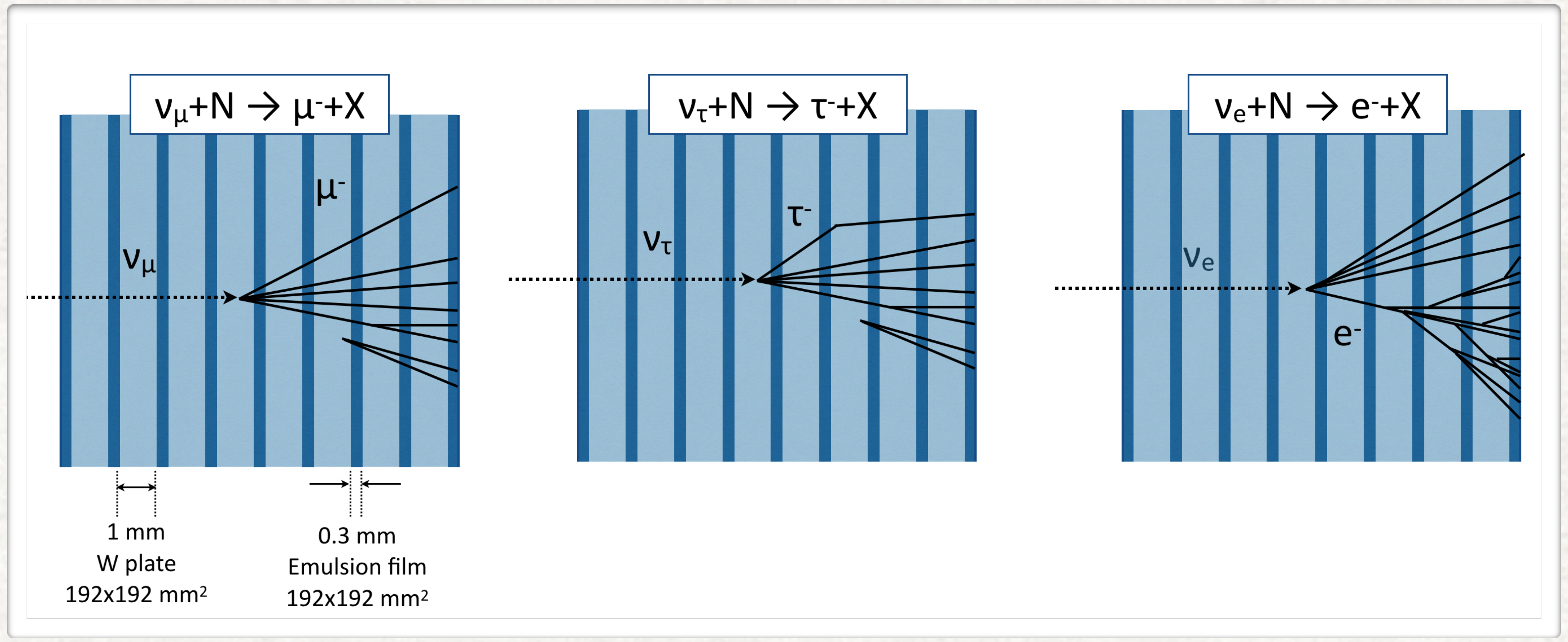


EVENT RECONSTRUCTION

- **FIRST PHASE: electronic detectors**
- Event reconstruction based on Veto, Target Tracker and Muon system
  - Identify neutrino candidates
  - Identify muons in the final state
  - Reconstruction of electromagnetic showers (SciFi)
  - Measure neutrino energy (SciFi+Muon)

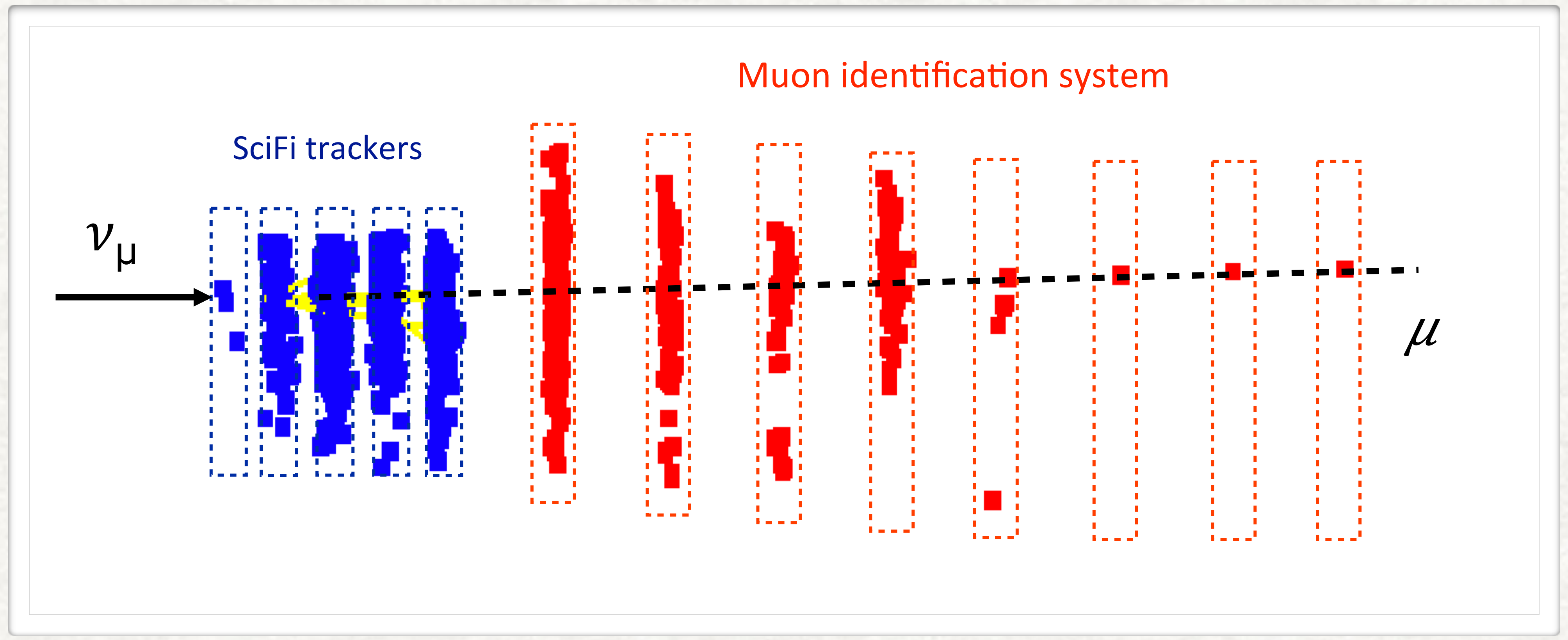


- **SECOND PHASE: nuclear emulsions**
- Event reconstruction in the emulsion target
  - Identify e.m. showers
  - Neutrino vertex reconstruction and 2ry search
  - Match with candidates from electronic detectors (time stamp)
  - Complement target tracker for e.m. energy measurement



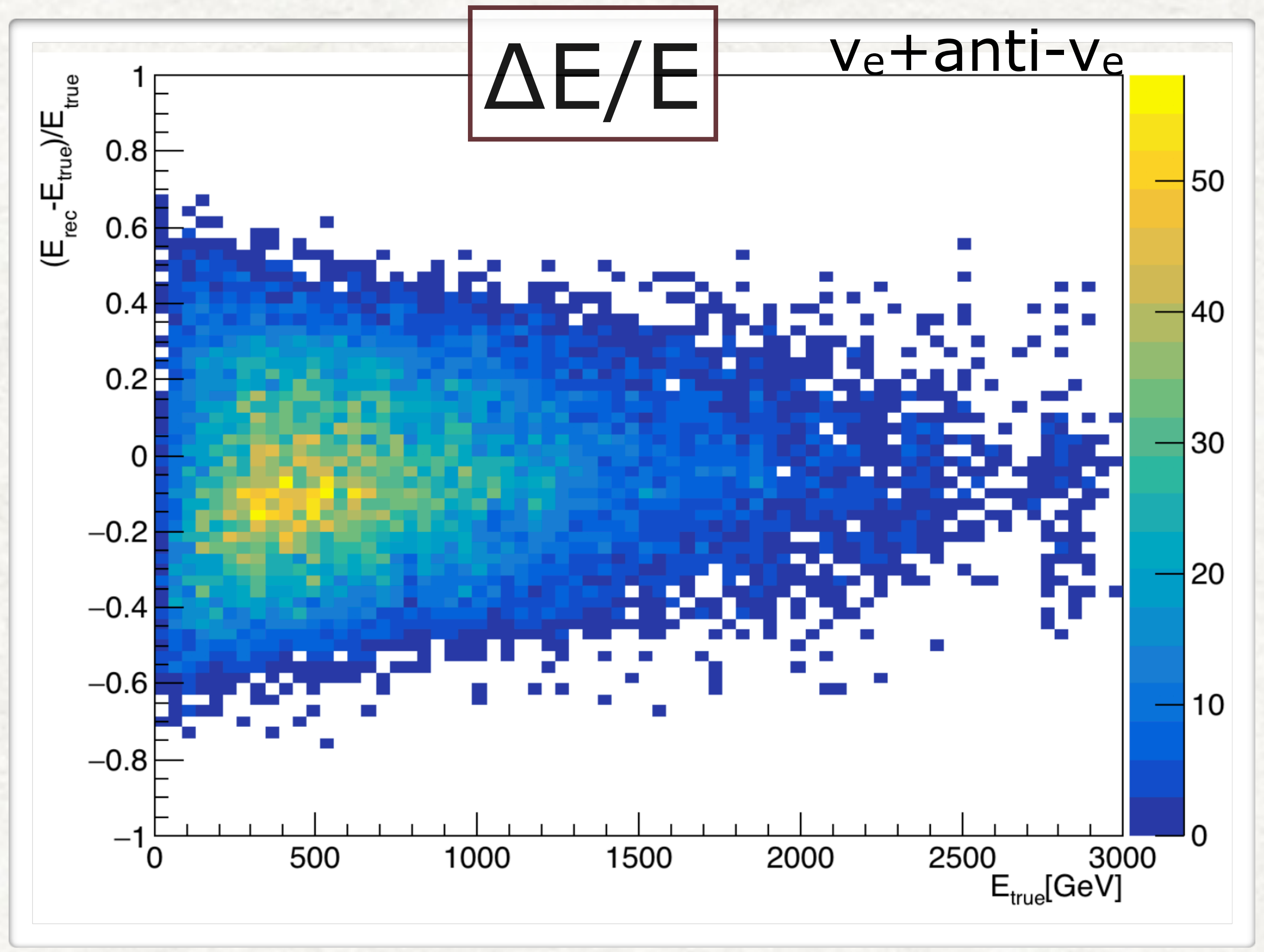
KEY FEATURES

- Muon identification
  - ν_μ CC interactions identified thanks to the identification of the muon produced in the interaction
  - Muon ID at the neutrino vertex crucial to identify charmed hadron production, background to ν_τ detection

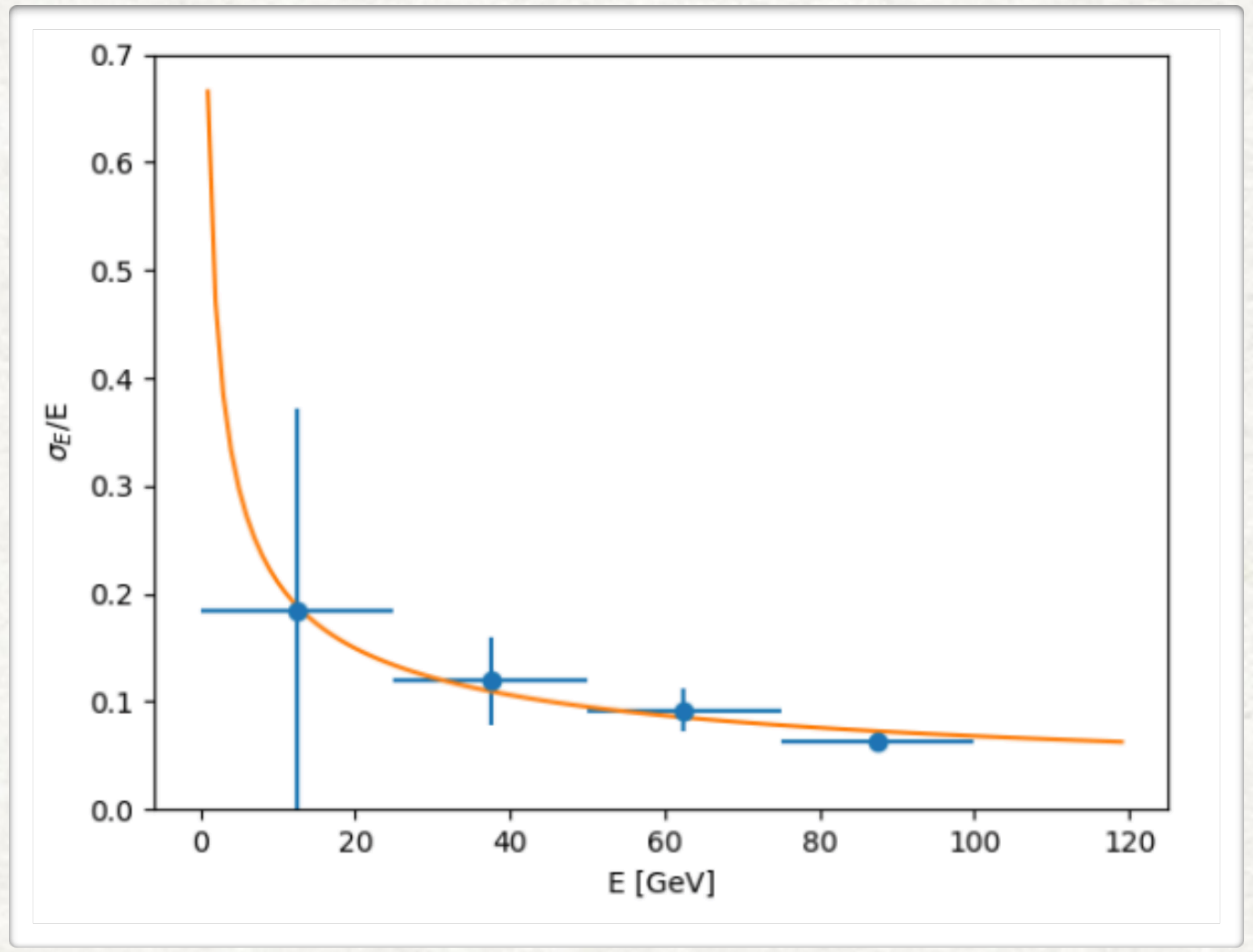


	% evts CC-DIS	% evts NC-DIS
0μ	31.1	99.6
1μ	67.6	0.27
2μ	1.1	0.06

- Energy measurement
  - The detector acts as a non-homogeneous sampling calorimeter



- Combing information from SciFi (target region) and Scintillator bars (Muon System)
- Average resolution on ν_e energy: 22%



- Performance of SciFi tracker as sampling calorimeter, using a CNN
- Electron energy resolution

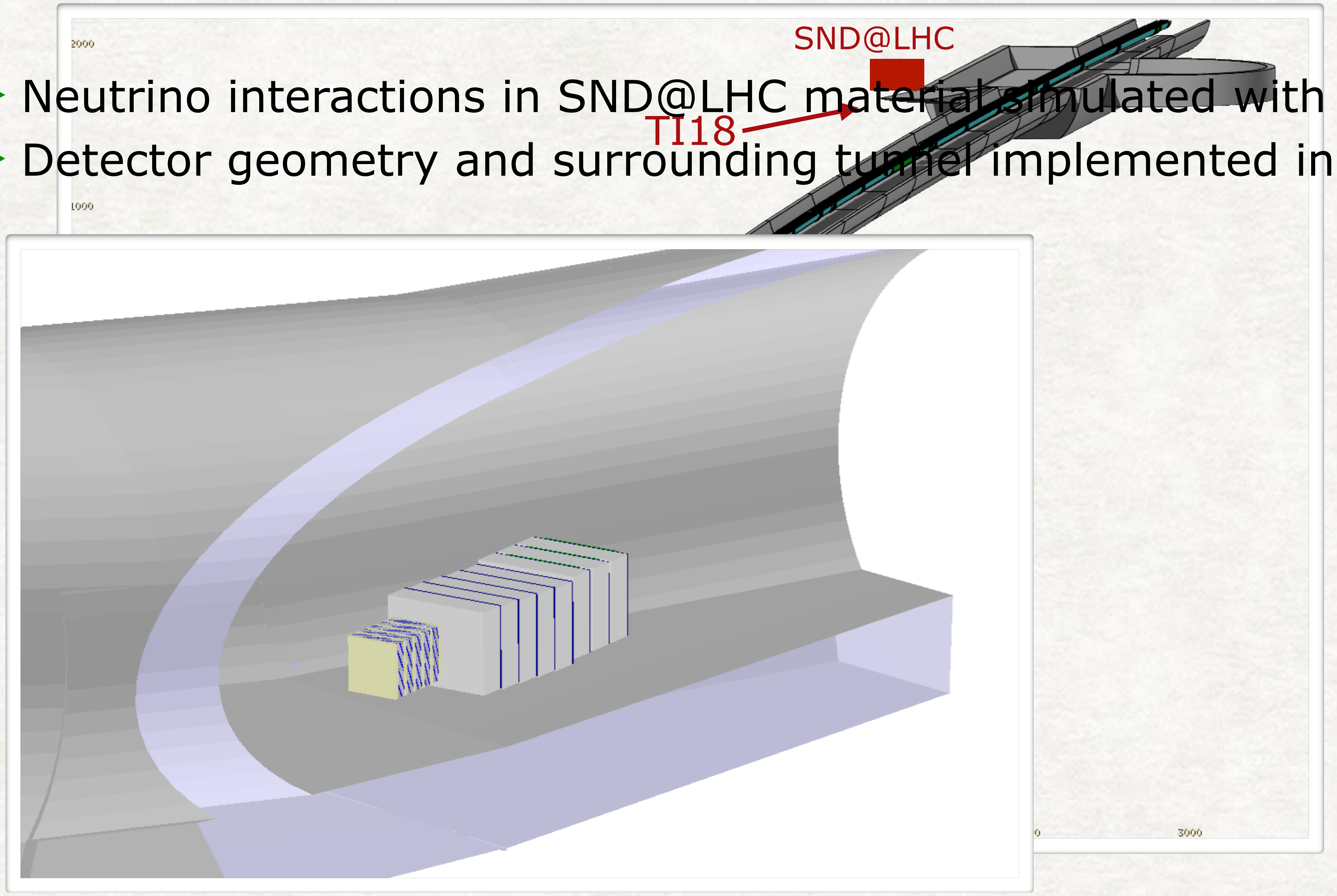
SIMULATION

- PRODUCTION
  - pp collisions at LHC with **DPMJET III - v10** (embedded in FLUKA)
  - $\sqrt{s}$ = 13 TeV

SND@LHC can perform measurements of heavy quark production in the forward region and set constraints to production mechanisms in unexplored region

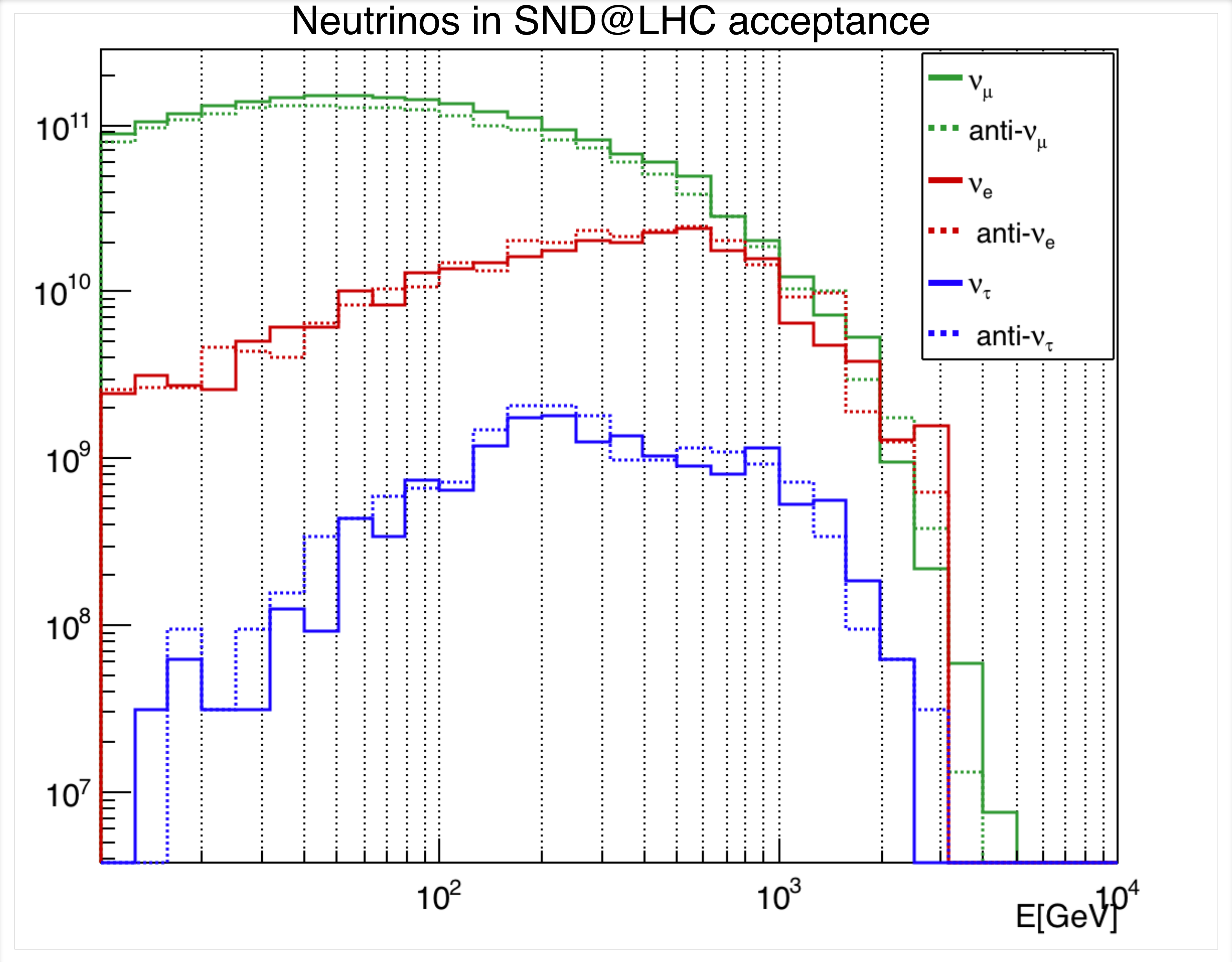
- PROPAGATION
  - Detailed simulation of LHC beam line with **FLUKA**
  - Prediction of neutrino yields and spectra at SND@LHC location
  - Prediction of muon population in the upstream rock, 75m from SND@LHC

- DETECTOR
  - Neutrino interactions in SND@LHC material simulated with **GENIE**
  - Detector geometry and surrounding tunnel implemented in **GEANT4**



NEUTRINO EXPECTATIONS AT THE TARGET

- Neutrino energy spectra in SND@LHC acceptance



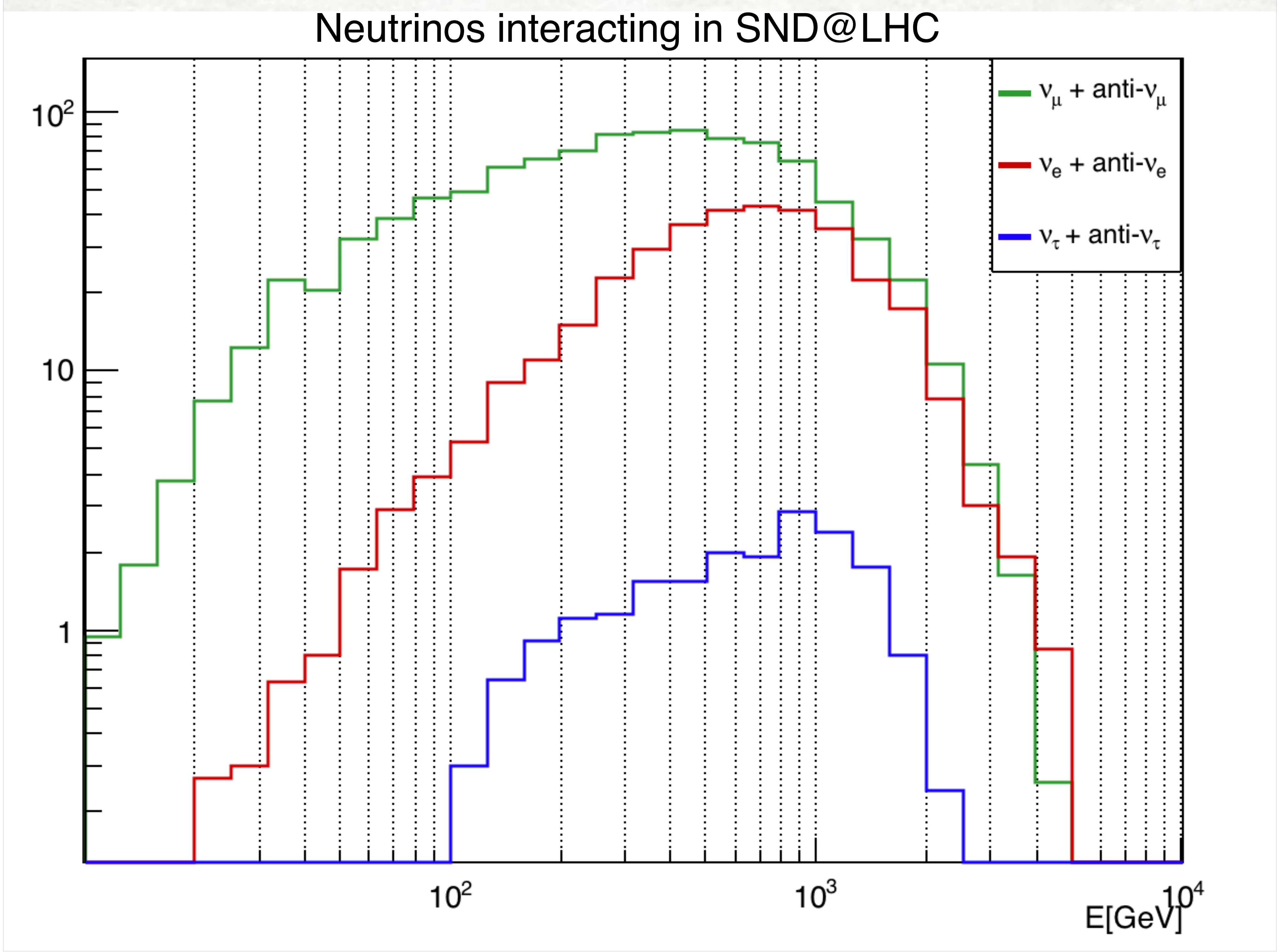
- Expectations in 150 fb^{-1}

Flavour	Neutrinos in acceptance $\langle E \rangle$ (GeV)	Yield
ν_μ	145	2.1×10^{12}
$\bar{\nu}_\mu$	145	1.8×10^{12}
ν_e	395	2.6×10^{11}
$\bar{\nu}_e$	405	2.8×10^{11}
ν_τ	415	1.5×10^{10}
$\bar{\nu}_\tau$	380	1.7×10^{10}
TOT		4.5×10^{12}

- Neutrino production in LHC pp collisions performed with **DPMJET3** embedded in FLUKA
- Particle propagation towards the detector through **FLUKA** model of LHC accelerator

NEUTRINO INTERACTIONS

- Interacting neutrino energy spectra



Flavour	CC neutrino interactions $\langle E \rangle$ (GeV)	Yield	NC neutrino interactions $\langle E \rangle$ (GeV)	Yield
ν_μ	450	730	480	220
$\bar{\nu}_\mu$	485	290	480	110
ν_e	760	235	720	70
$\bar{\nu}_e$	680	120	720	44
ν_τ	740	14	740	4
$\bar{\nu}_\tau$	740	6	740	2
TOT		1395		450

- **GENIE** used to simulate neutrino interactions in the detector target

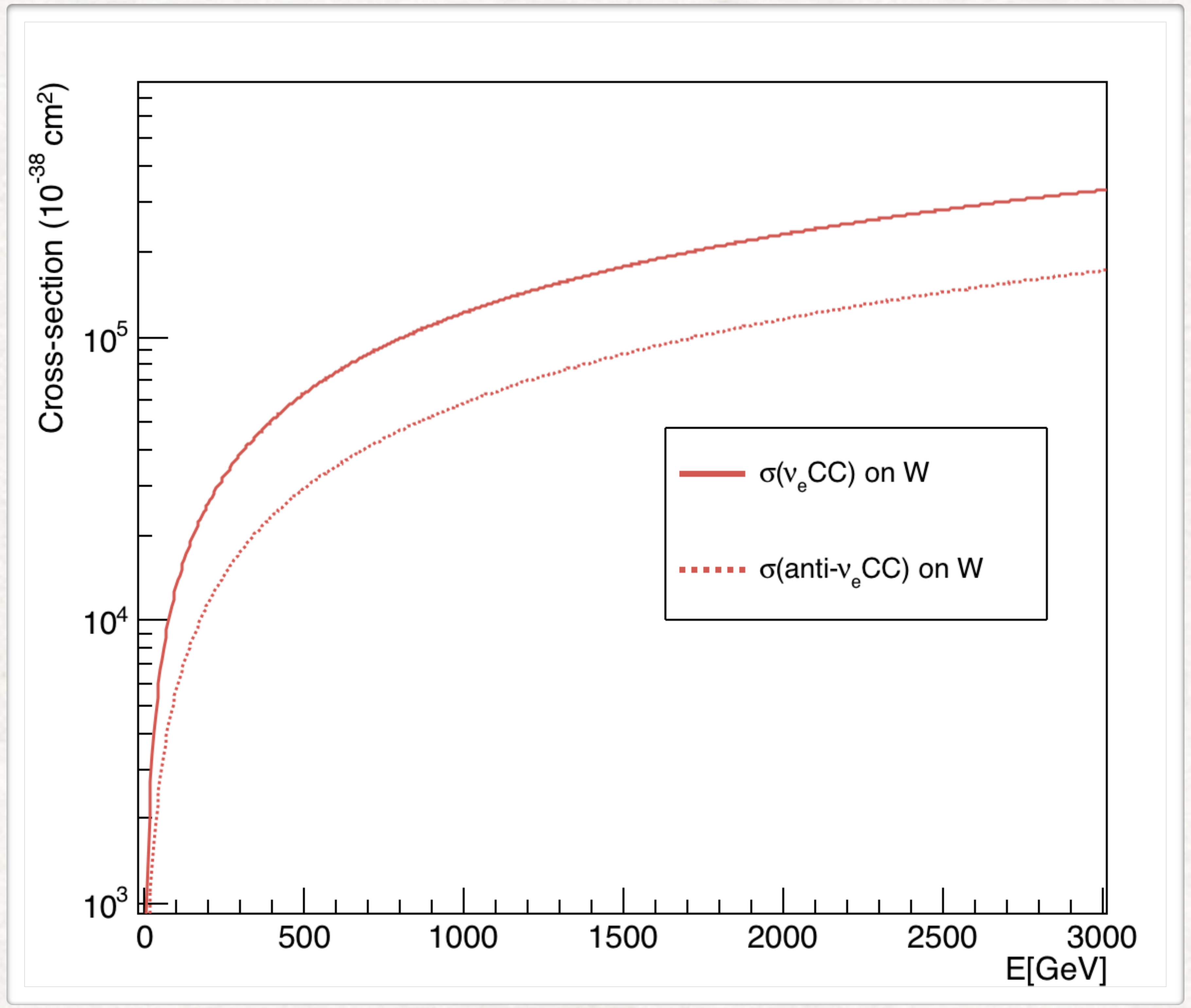
NEUTRINO PHYSICS PROGRAM IN RUN 3

1. Measurement of the $pp \longrightarrow \nu_e X$ cross-section
2. Heavy flavour production in pp collisions
3. Lepton flavour universality in neutrino interactions
4. Measurement of the NC/CC ratio

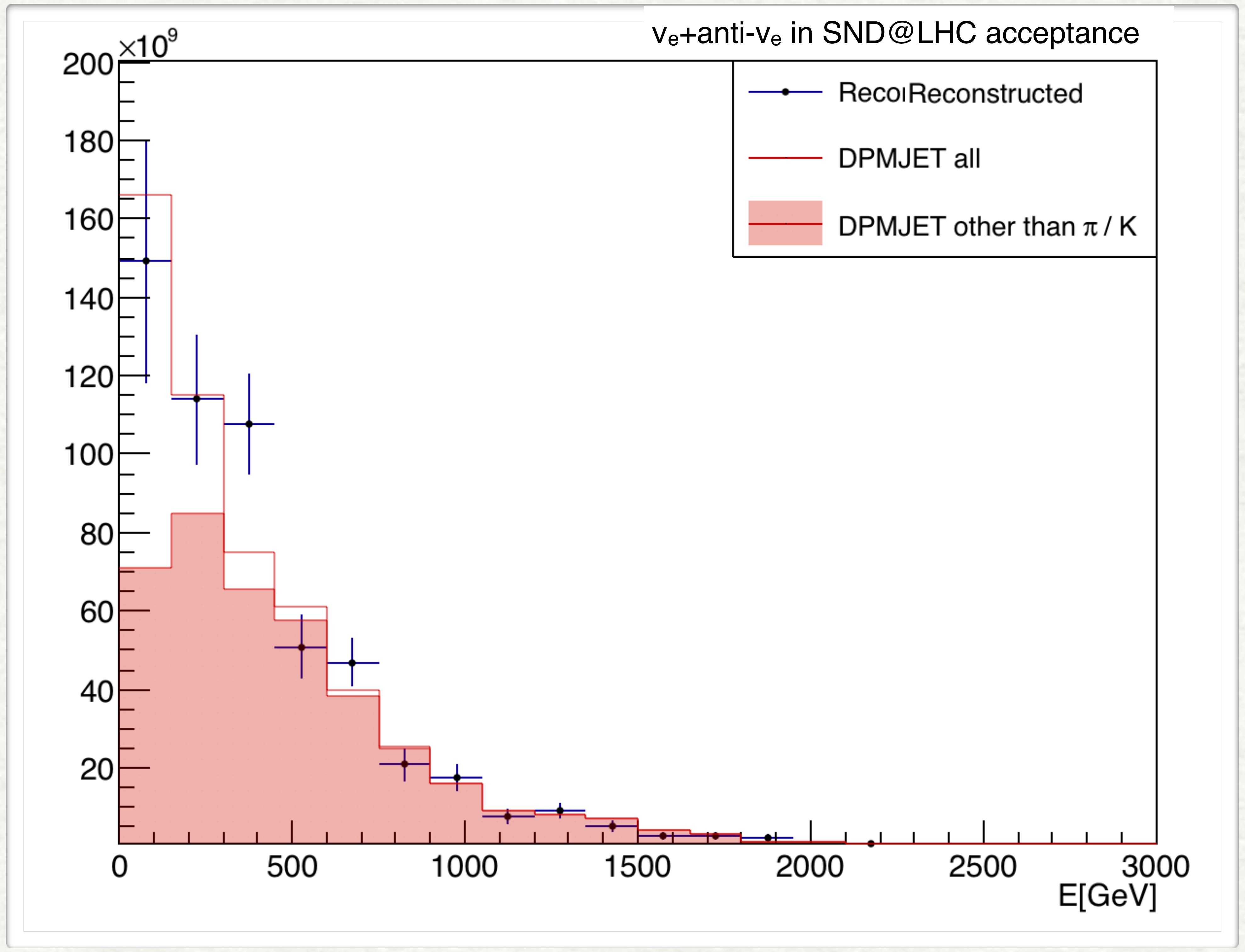
1. MEASUREMENT OF *pp*⟶ν_eX CROSS-SECTION

- Simulation predicts that 90% ν_e+anti-ν_e come from the decay of charmed hadrons
- Electron neutrinos can be used as a probe of the production of charm in the relevant pseudo-rapidity range after unfolding the instrumental effects
- Apply deconvolution of neutrino cross section to get ν_e+anti-ν_e flux in SND@LHC acceptance

- Genie cross-sections on target material



- Reconstructed spectrum of ν_e+anti-ν_e flux in SND@LHC acceptance



Errors: statistical (collected statistics) + systematic (unfolding procedure)

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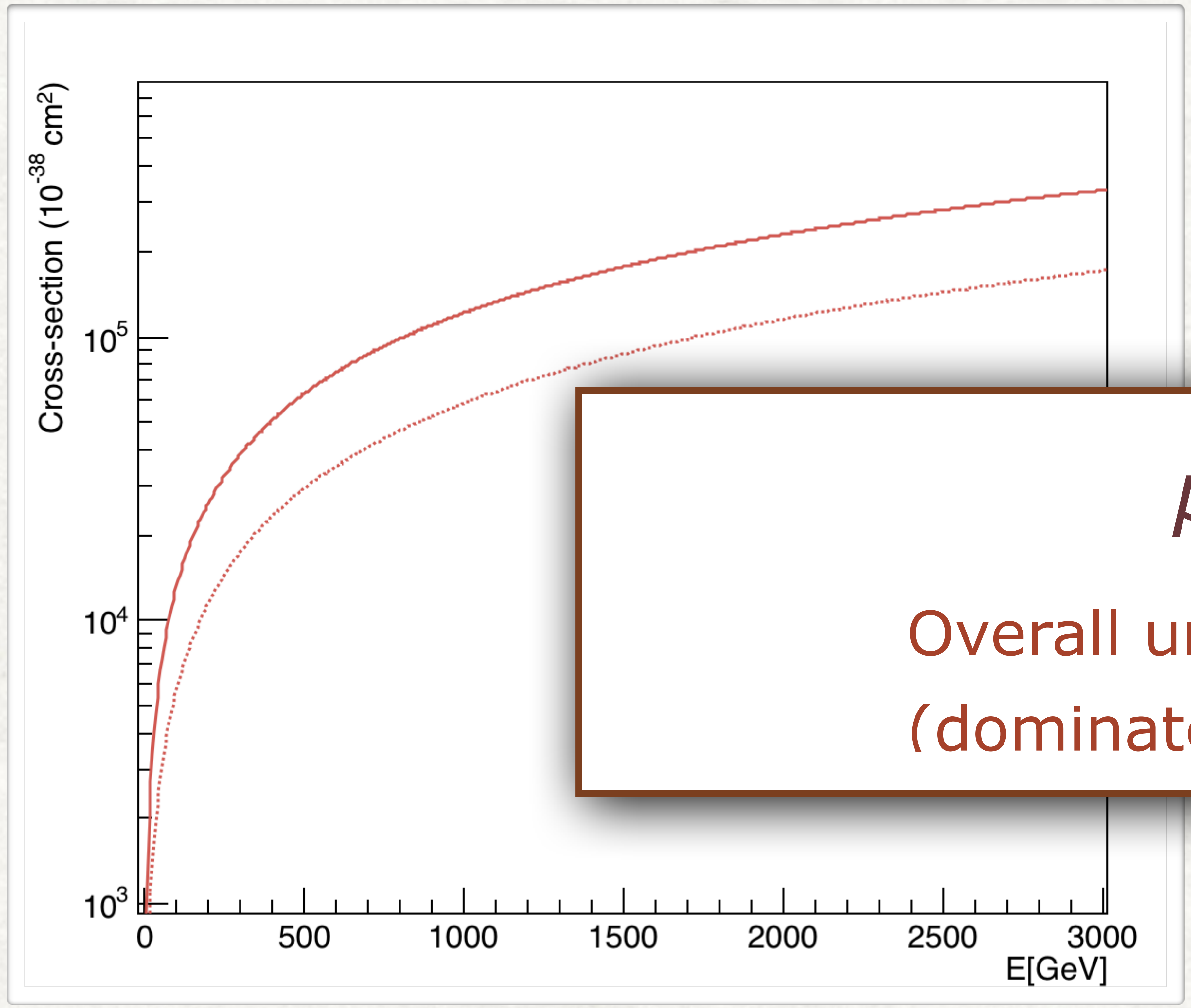

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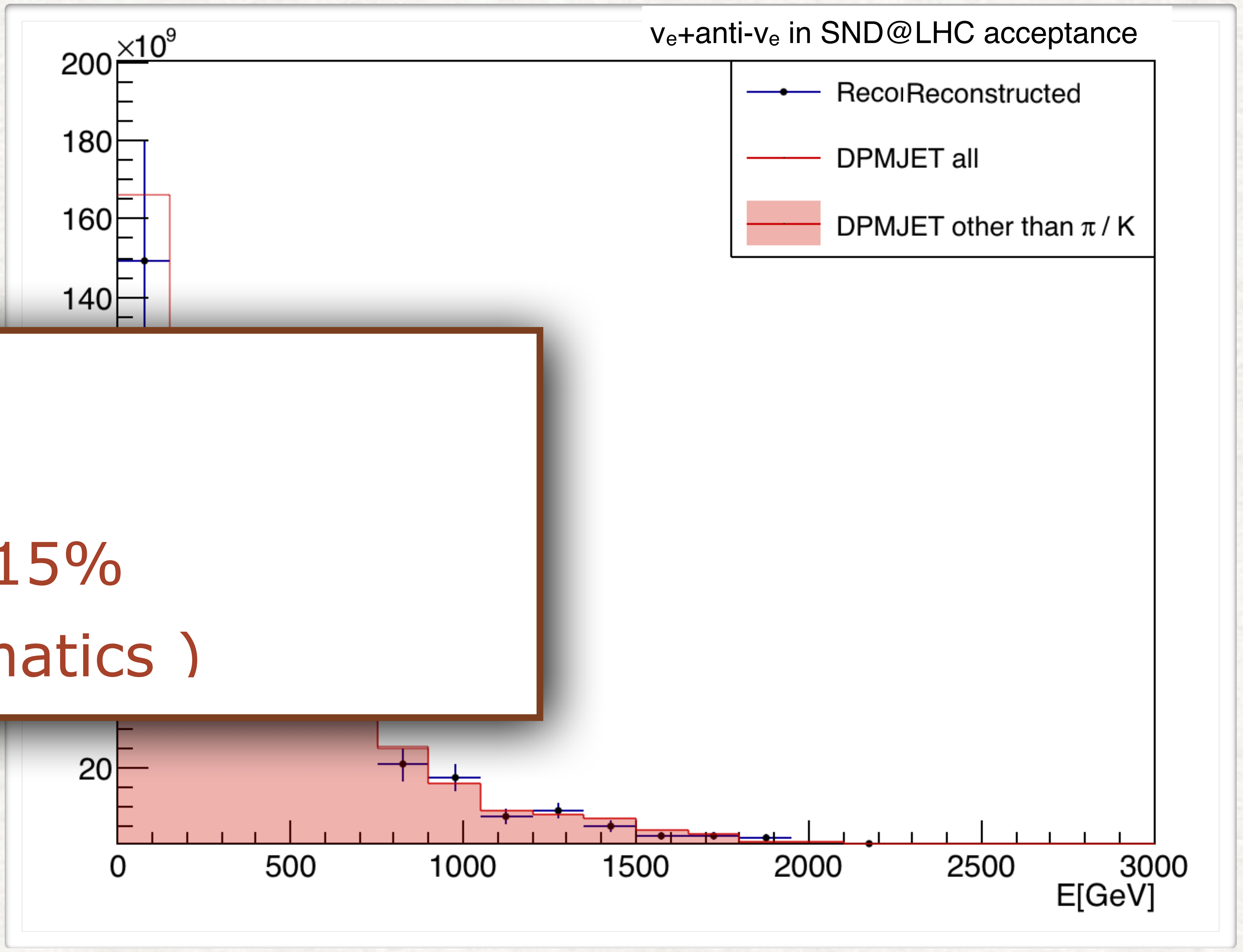


pp⟶ν_eX

Overall uncertainty ~15%

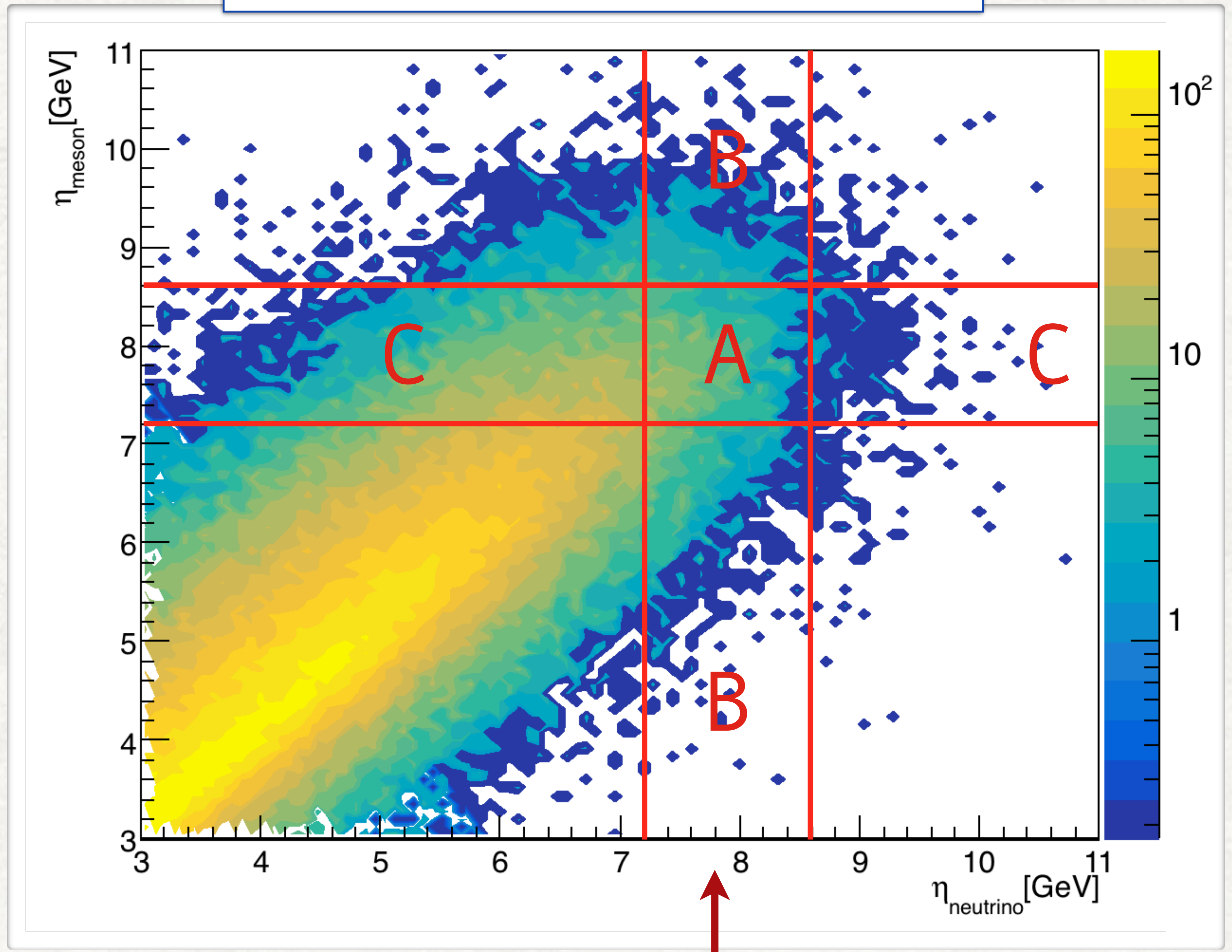
(dominated by systematics)

Errors: statistical (collected statistics) + systematic (unfolding procedure)

2. CHARMED HADRON PRODUCTION

- Correlation between pseudo-rapidity of the electron (anti-)neutrino and the parent charmed hadron
- Evaluation of the migration by defining regions in the pseudo-rapidity correlation plot

CASE I: 7.2< η_{meson} <8.6



Neutrinos in SND@LHC acceptance

N_A/N_{A+B}

$$N(c\text{−mesons}) = N(\nu_e + \overline{\nu}_e)^{\text{charm}} \times \frac{f_{AB}}{f_{AC}} \times \frac{1}{Br(c \to \nu_e)}$$

N_A/N_{A+C}

Branching ratio of charmed mesons to ν_e

- Fractions f_{AB} and f_{AC} evaluated using leading order computations+Pythia8 parameters for cc-bar production at 13 TeV

- Variation of parameters that describe charm production and hadronisation show that the ratio f_{AB}/f_{AC} is stable within **20-30%**

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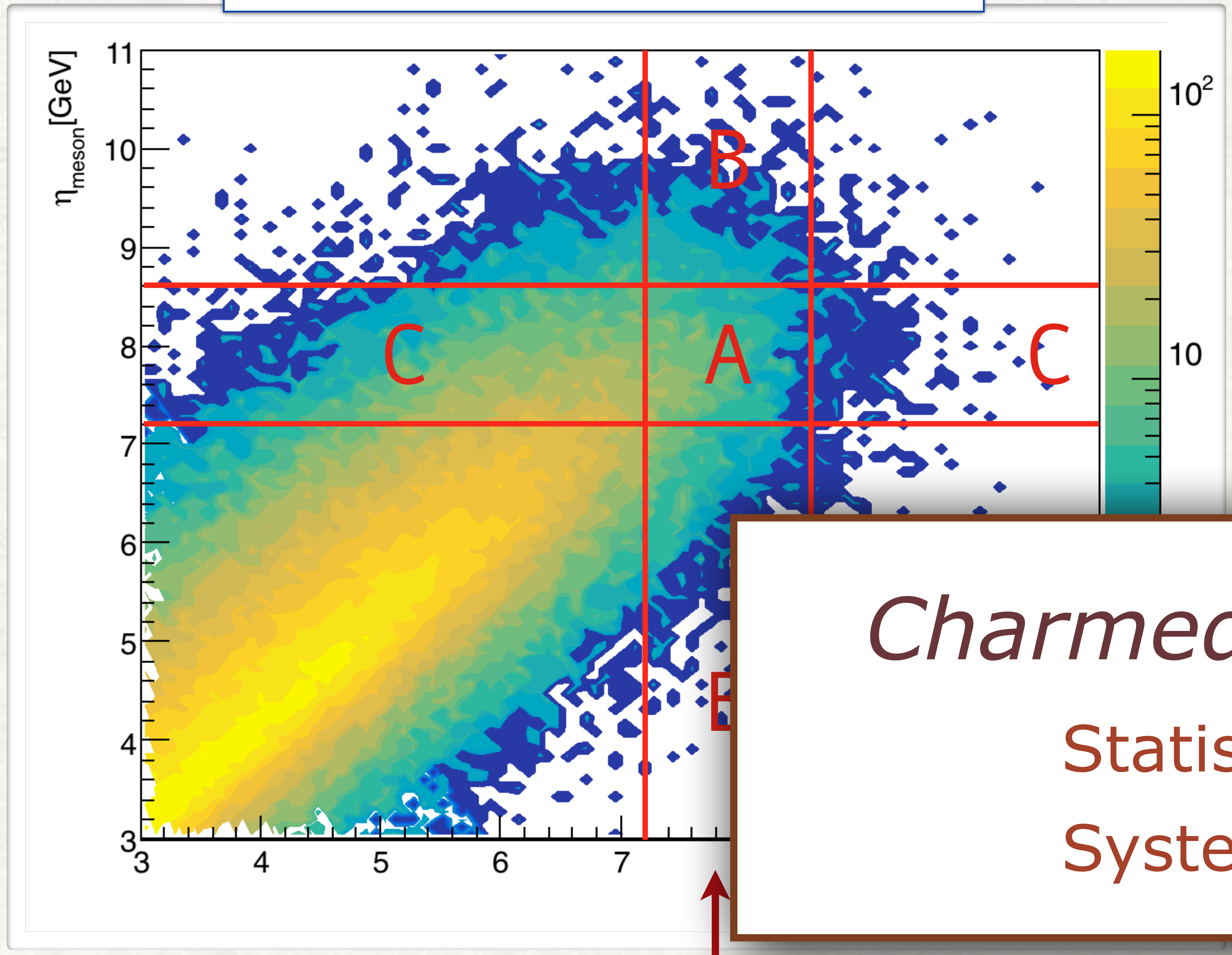

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N_A/N_{A+C}

Branching ratio of charmed mesons to ν_e

ing leading order
ers for cc-bar

Charmed hadron production

Statistical uncertainty ~5%

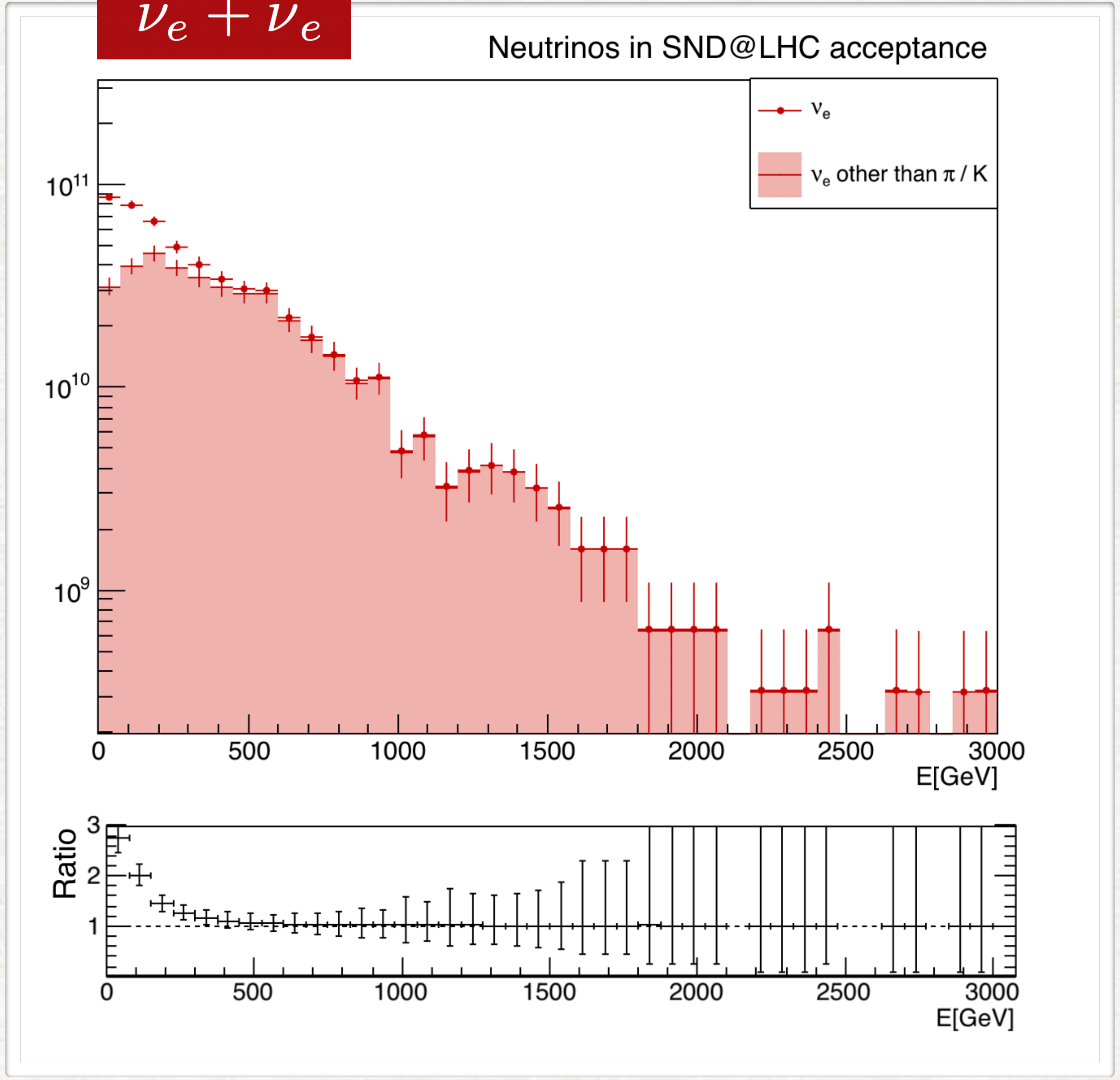
Systematic uncertainty ~35%

- Variation of parameters that describe charm production and hadronisation show that the ratio f_{AB}/f_{AC} is stable within **20-30%**

3. LEPTON FLAVOUR UNIVERSALITY TEST

- The identification of three neutrino flavours in the SND@LHC detector offers a unique possibility to test the Lepton Flavor Universality (LFU)

$\nu_e + \overline{\nu}_e$



- ν_τ are produced essentially only in D_s decays
- ν_e are produced in the decay of all charmed hadrons (essentially D0, D, Ds, Λc)
- The ratio depends only on charm hadronisation fractions and branching ratios
- Sensitive to ν-nucleon interaction cross-section ratio of two neutrino species

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

- Error on f_c and *Br* evaluated as discrepancy between values obtained in Pythia8 and Herwig generators: **20%**

- Statistical error due to low ν_τ statistics :**30%**

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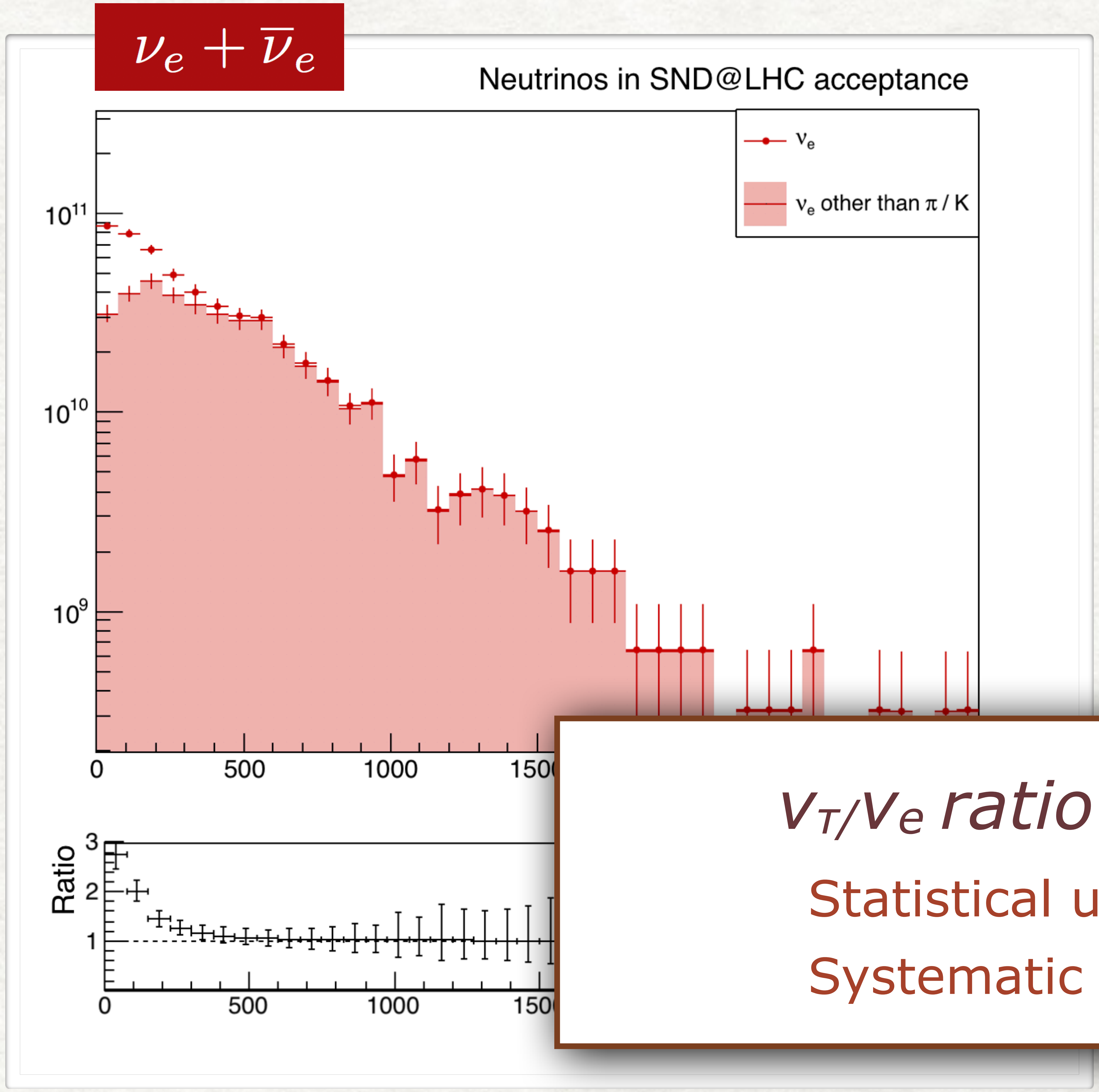

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as discrepancy between values

rwig generators: **20%**

$_\tau$ statistics :**30%**

ν_τ / ν_e *ratio for LFU test*

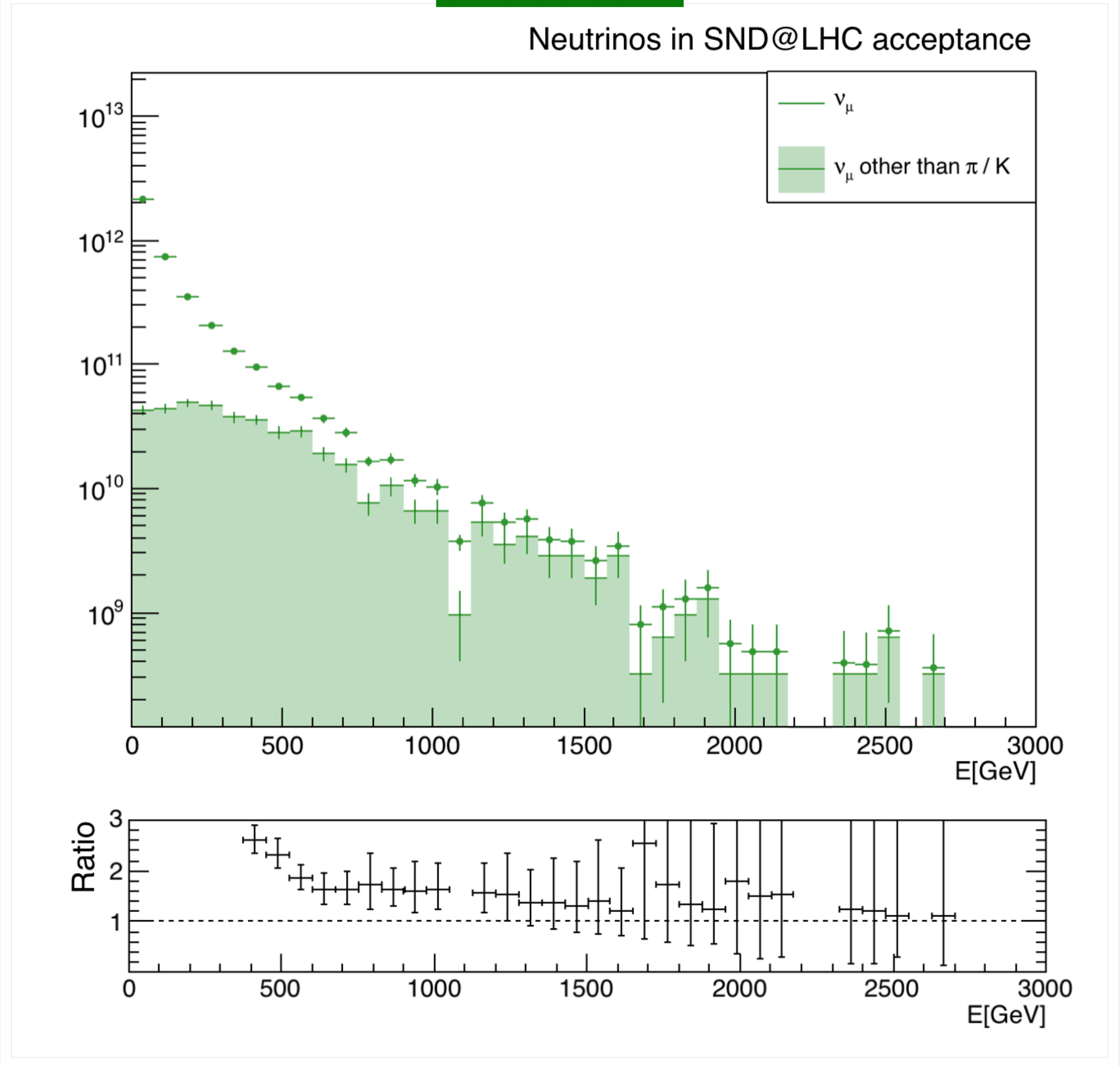
Statistical uncertainty ~30%

Systematic uncertainty ~20%

3. LEPTON FLAVOR UNIVERSALITY

- The ν_μ spectrum at lower energies is dominated by neutrinos produced in π/k decays
- For E>600 GeV the contamination of neutrinos from π/k keeps constant (~35%) with the energy

$\nu_\mu + \overline{\nu}_\mu$



$$N(\nu_\mu + \overline{\nu}_\mu)[E > 600\, GeV] = 294$$ in 150 fb^{-1}

$$N(\nu_e + \overline{\nu}_e)[E > 600\, GeV] = 191$$ in 150 fb^{-1}

- The measurement of the ν_e/ν_μ ratio can be used as a test of the LFU for E>600 GeV
- No effect of uncertainties on f_c and *Br* since charmed hadrons decay almost equally in ν_μ and ν_e

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

contamination from π/k

- Statistical error: 10%
- Systematic error: uncertainty in the knowledge of π/k contamination: 10%

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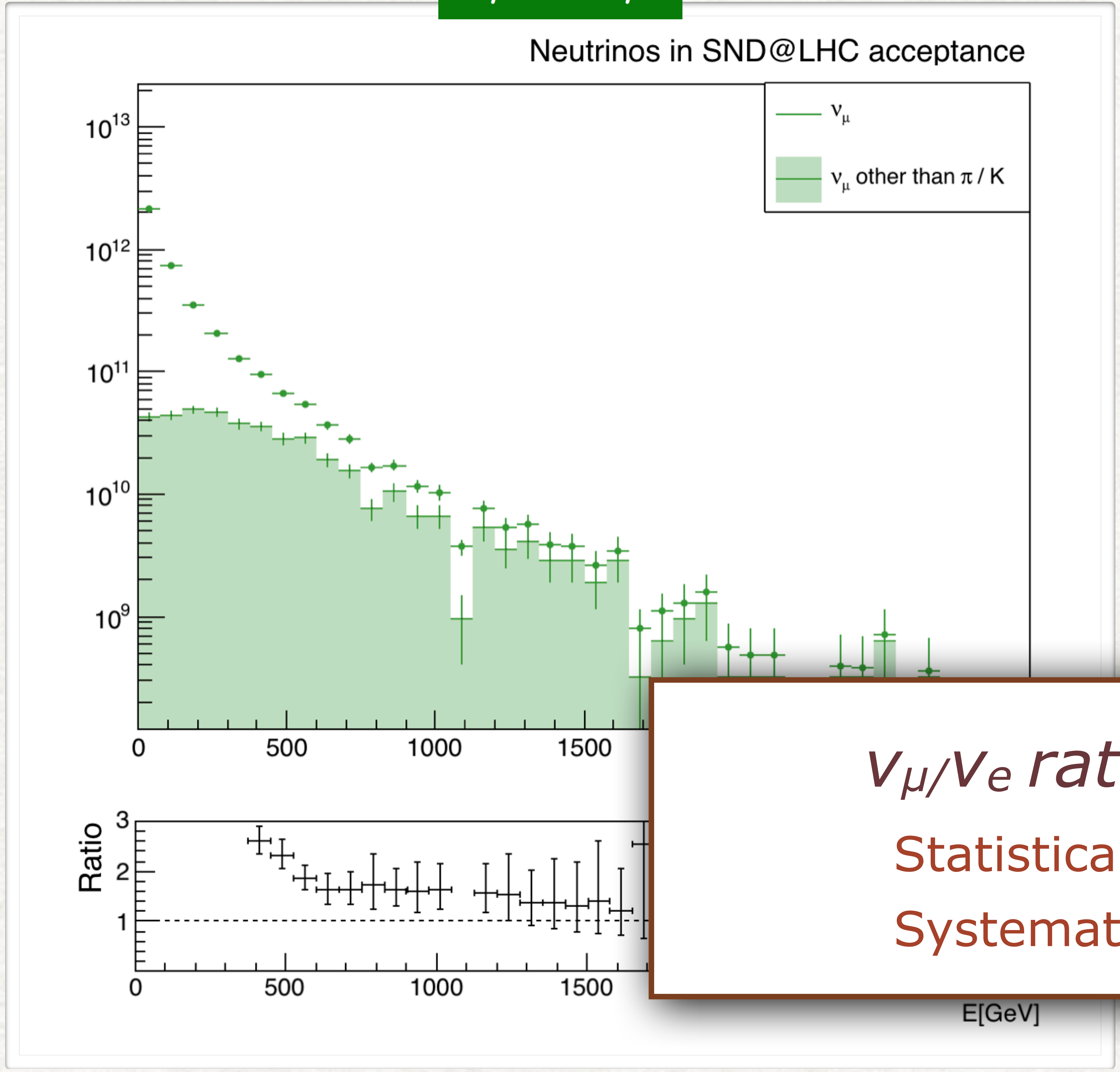

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contamination from π/k

n the knowledge of π/k

ν_μ/ν_e ratio for LFU test

Statistical uncertainty ~10%

Systematic uncertainty ~10%

4. MEASUREMENT OF NC/CC RATIO

- Lepton identification for the three different flavors allows to distinguish CC to NC interaction at SND@LHC
- If differential neutrino and anti-neutrino fluxes are equal, the NC/CC ratio can be written as

$$P = \frac{\sum_i \sigma_{NC}^{\nu_i} + \sigma_{NC}^{\bar{\nu}_i}}{\sum_i \sigma_{CC}^{\nu_i} + \sigma_{CC}^{\bar{\nu}_i}}$$

  - In case of DIS, *P* can be written as

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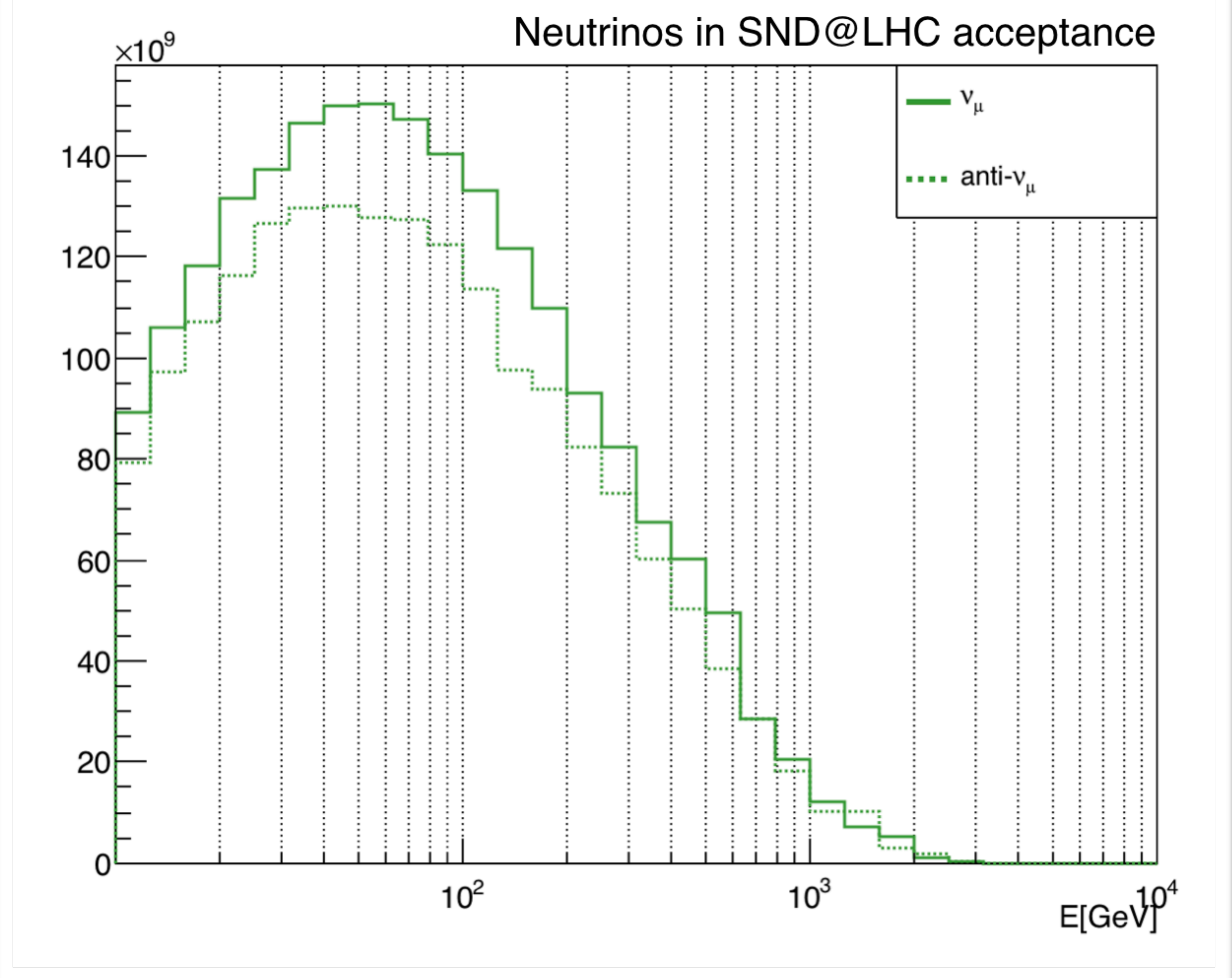
$$P = \frac{1}{2}\left\{1 - 2\sin^2\theta_W + \frac{20}{9}\sin^4\theta_W - \lambda(1 - 2\sin^2\theta_W)\sin^2\theta_W\right\}$$

where λ originates from unequal numbers of protons Z and neutrons (A-Z) in the target
Introduces a correction factor of ~1%

For a Tungsten target λ=0.04

ν_μ vs $\overline{\nu}_\mu$



- **Statistical** uncertainty on P given by the number of observed CC and NC interactions: **5%**
- **Systematic** uncertainty:
- asymmetry between neutrino and anti-neutrino spectra mainly in n muon neutrino spectra at low energies. Contribution to the error on P: **<2%**
- CC to NC migration and neutron background subtraction: **10%**

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protons Z and neutrons (A-Z)…
Introduces a correction factor …

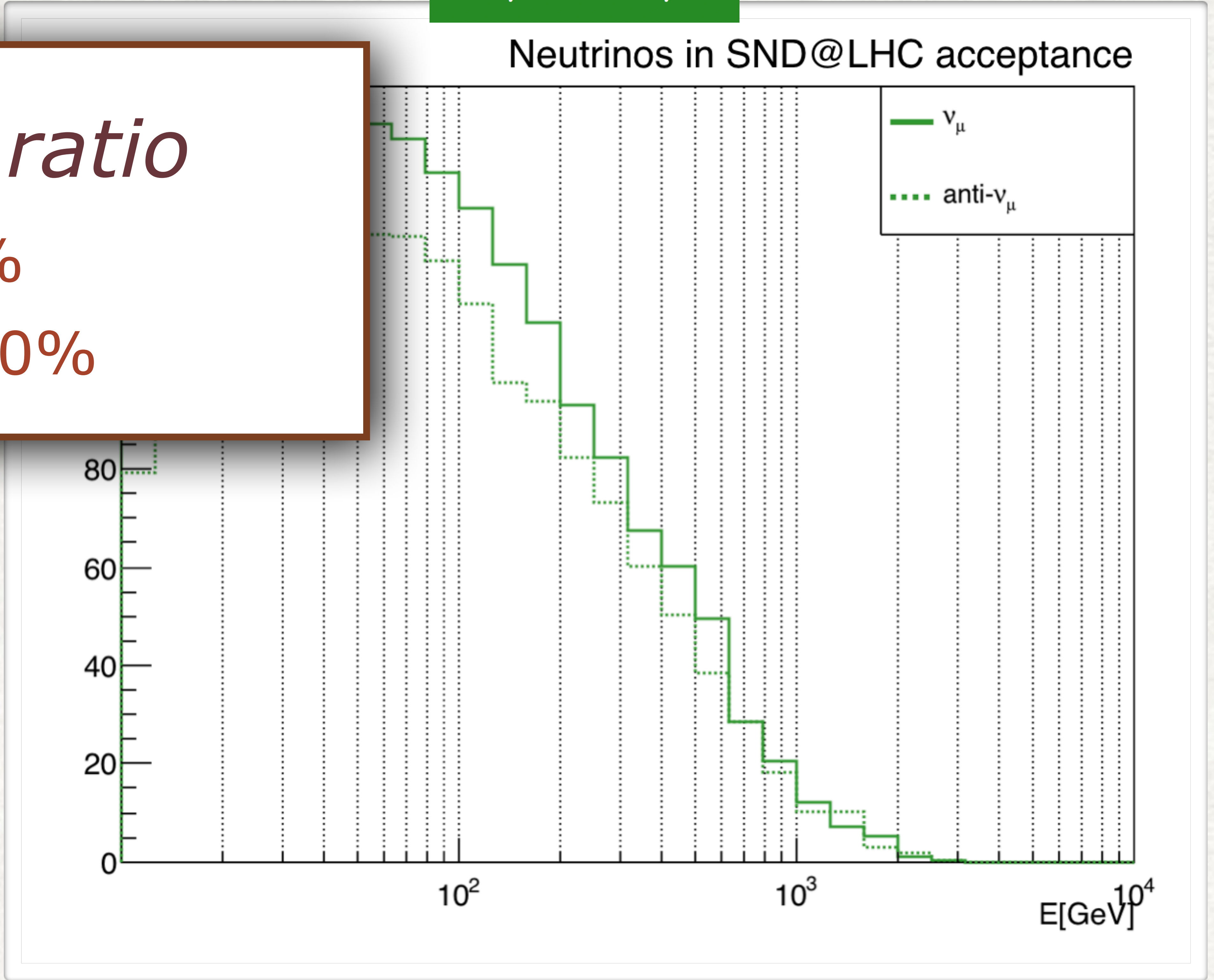
For a Tungsten target λ=0.04

Measurement of NC/CC ratio

Statistical uncertainty ~5%

Systematic uncertainty ~10%

ν_μ vs $\overline{\nu}_\mu$



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NEUTRINO PHYSICS IN RUN 3

- Summary of SND@LHC performances

Measurement	Uncertainty Stat.	Uncertainty Sys.
$pp \to \nu_e X$ cross-section	5%	15%
Charmed hadron yield	5%	35%
ν_e/ν_τ ratio for LFU test	30%	20%
ν_e/ν_μ ratio for LFU test	10%	10%
Measurement of NC/CC ratio	5%	10%

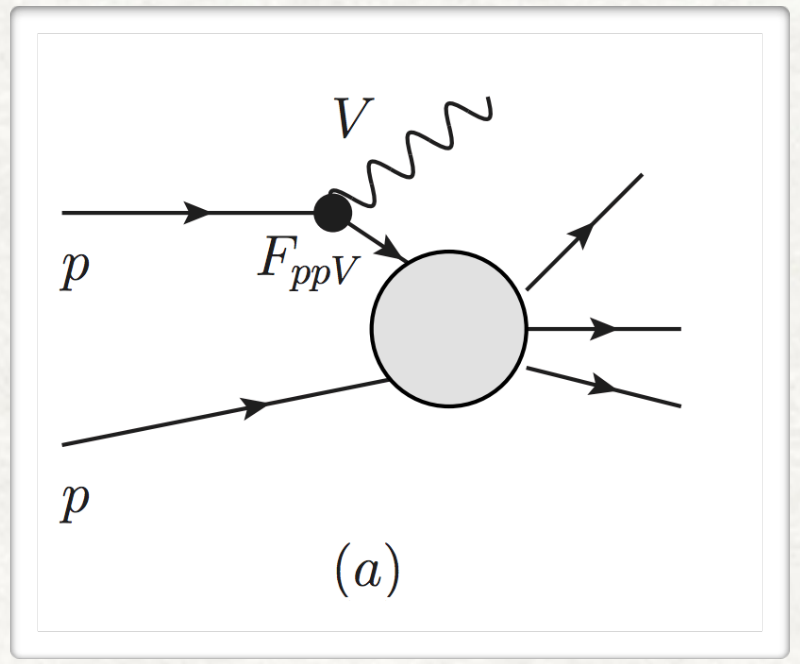
FLEEBLY INTERACTING PARTICLES

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

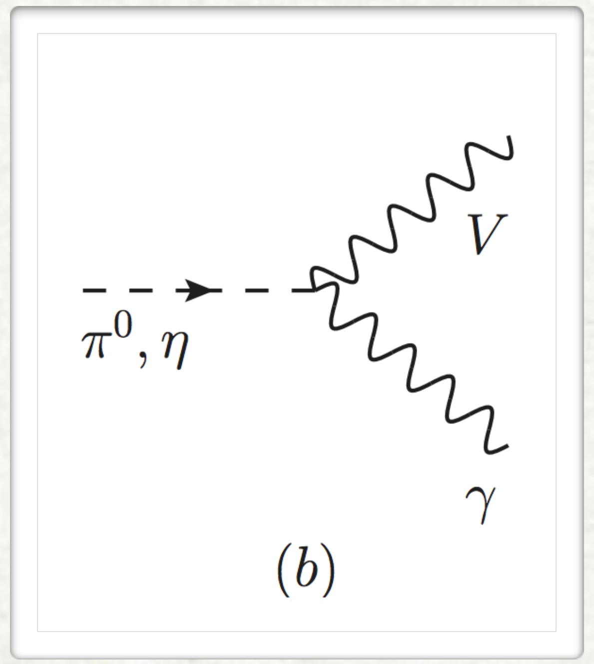
Production: we consider a scalar χ particle coupled to the Standard Model via a leptophobic portal,

$$\mathcal{L}_{\text{leptophob}} = -g_B V^\mu J^B_\mu + g_B V^\mu (\partial_\mu \chi^\dagger \chi + \chi^\dagger \partial_\mu \chi), \quad J^B_\mu = \frac{1}{3}\sum_q \bar{q}\gamma_\mu q$$

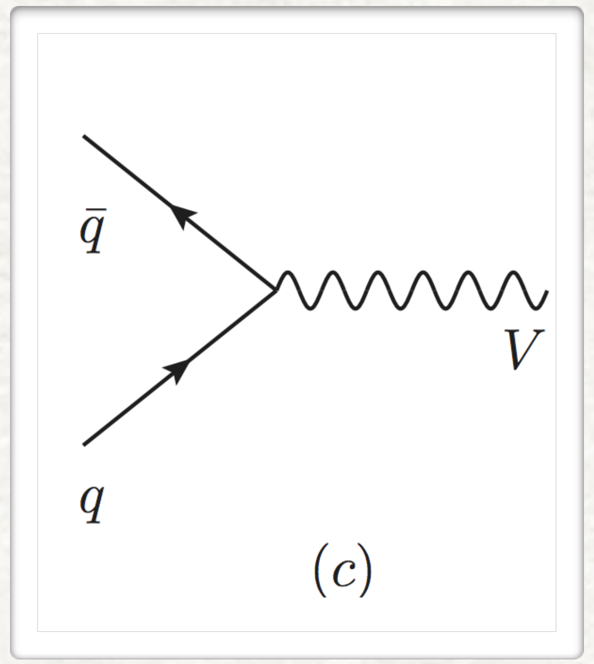
i.e. with a vector mediator V that can be produced at LHC via



Proton bremsstrahlung



Meson decay

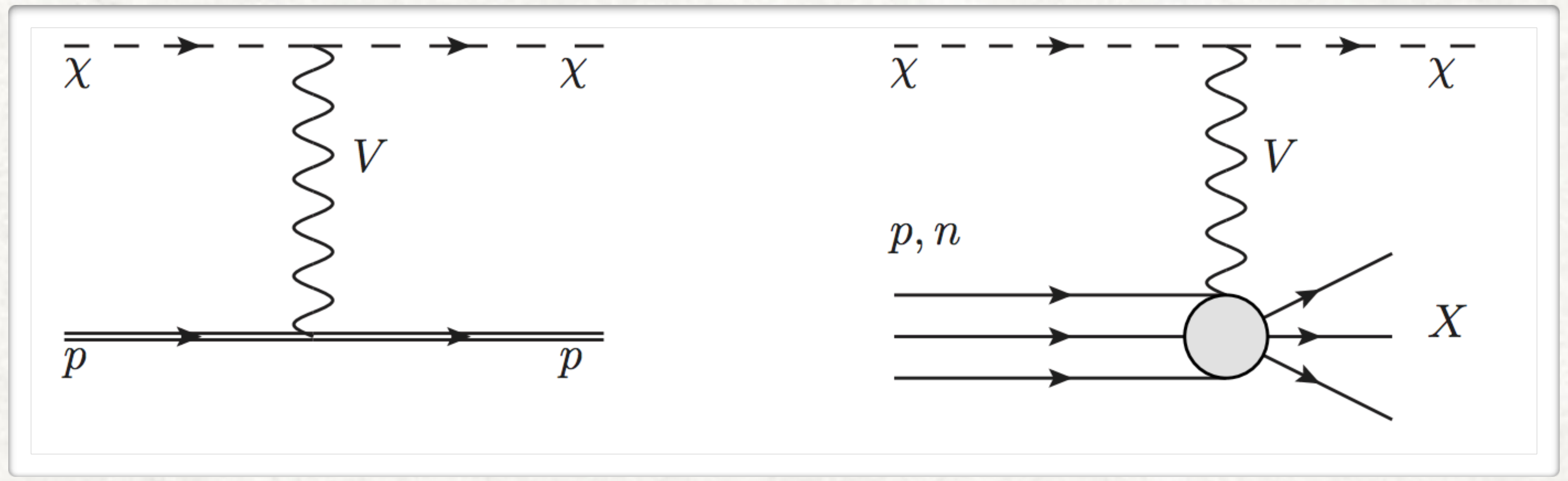


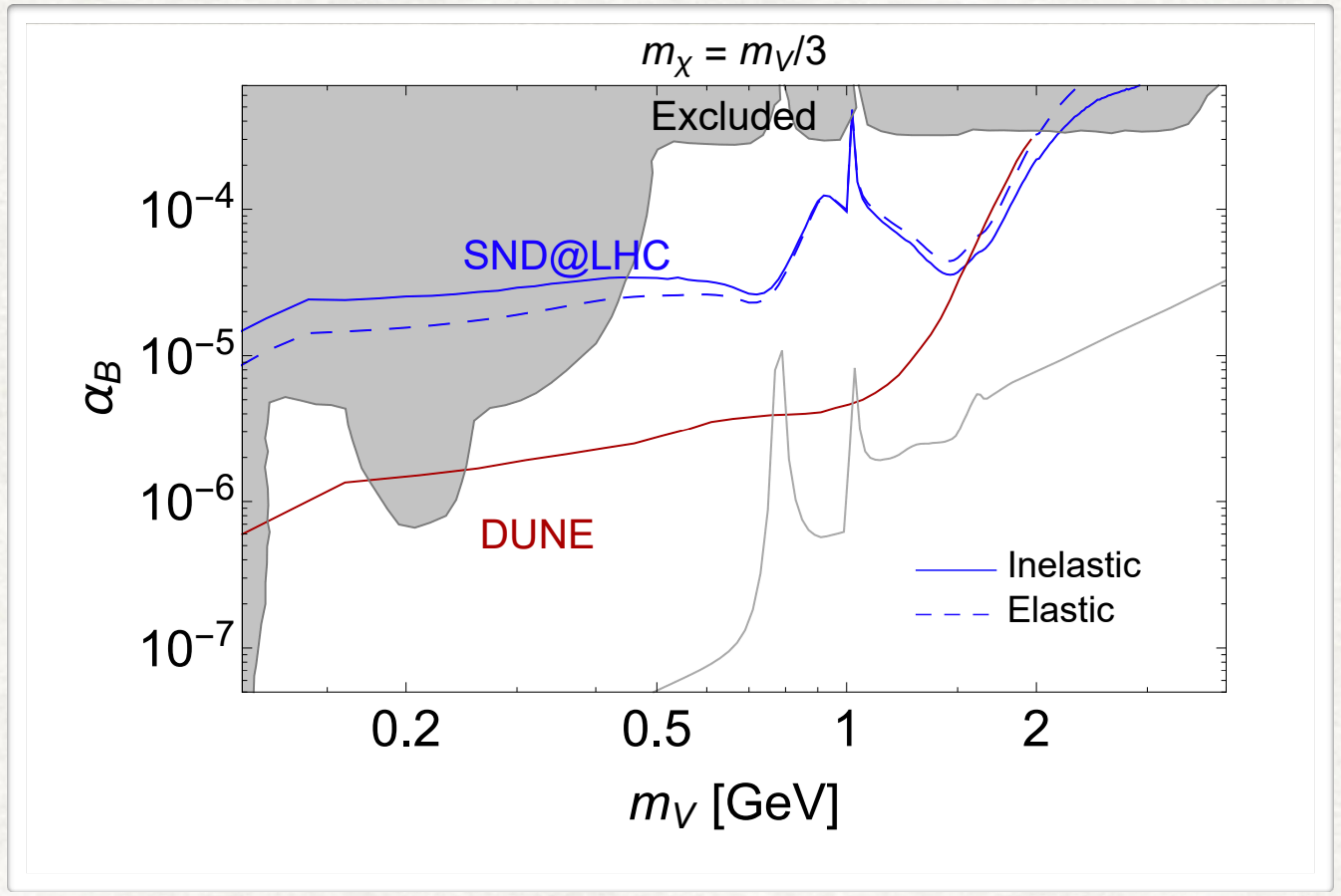
Drell-Yan process

$$p + p \to VX,\ V \to \chi + \bar{\chi}$$

FLEEBLY INTERACTING PARTICLES

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

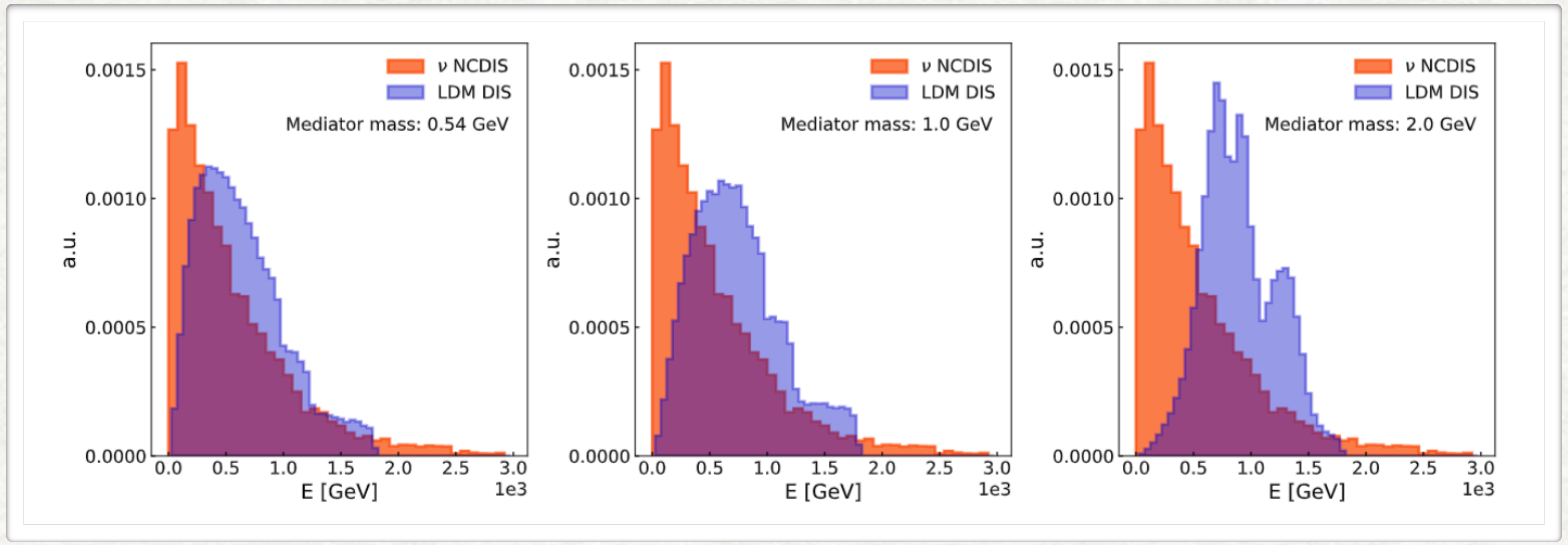




Background yield in the elastic scattering $\chi + N \to \chi + N$

	$\chi p \to \chi p$ Selection eff.	Background
NC DIS	2.8×10^{-3}	1.26
NC RES	1.7×10^{-1}	0.48

DIS: background suppression exploiting kinematical features



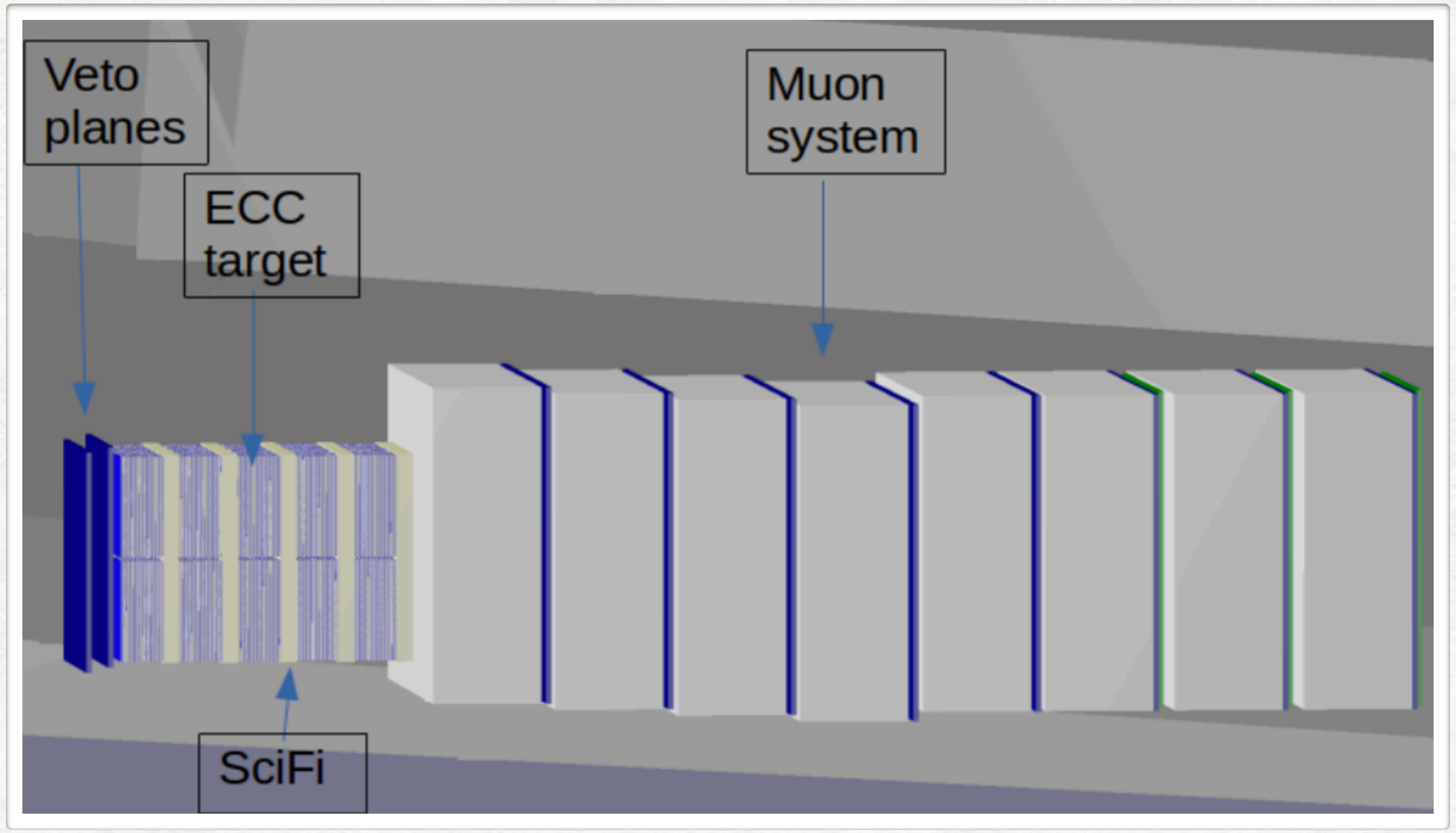
ANALYSIS ITEMS TO BE ADDRESSED

A few (uncovered) items

1. Digitisation of SciFi planes and realistic simulation of their response
2. Electron/muon neutrino identification with electronic data
3. Matching between emulsions and SciFi
4. Electron neutrino energy measurement combining emulsion+Scifi data
5. Muon neutrino energy measurement combining SciFi+Muon system data

DIGITISATION OF SCIFI PLANES AND REALISTIC SIMULATION OF THEIR RESPONSE

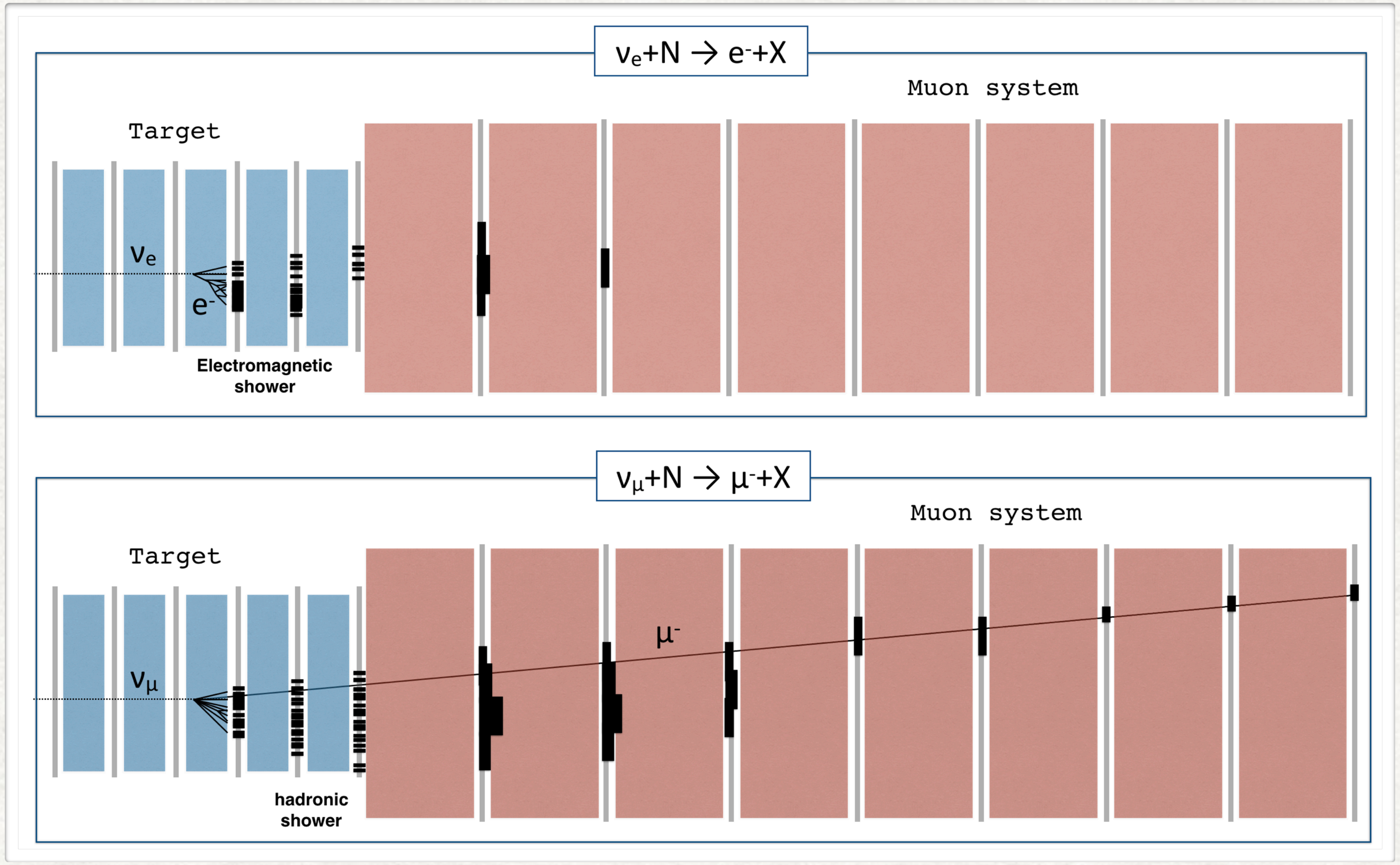
Detector simulation performed in Geant4, implemented in the FairShip framework



- Implementation of the SciFi digitisation
- Simulation of the detector response
- Implementation of track reconstruction algorithms

ELECTRON/MUON NEUTRINO IDENTIFICATION

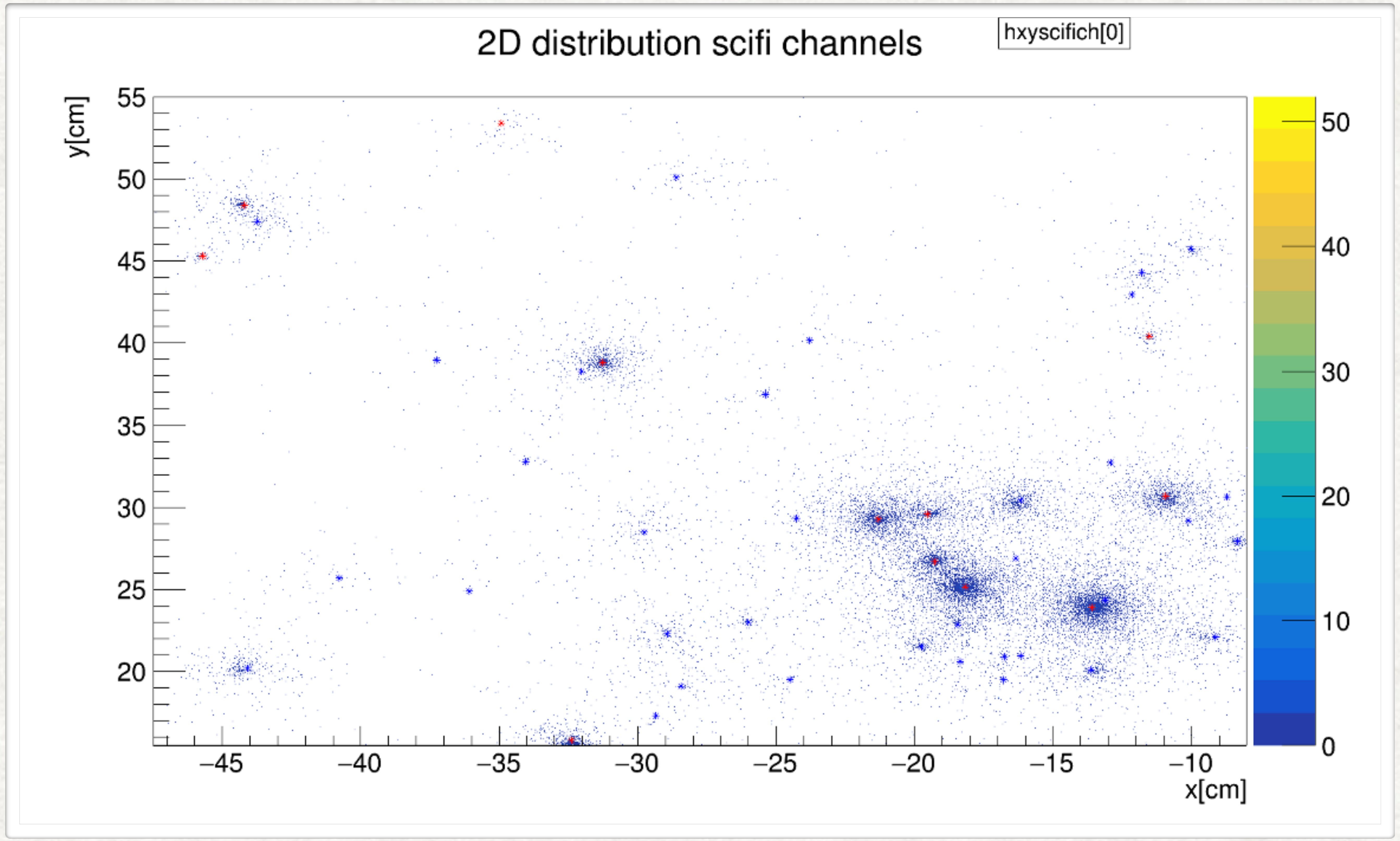
Neutrino flavour identification with electronic detector data only:
- important tool while waiting for emulsions to be extracted, scanned and analysed
- to be used in early 2022 where a small fraction of emulsion films will be installed



- Quasi-online analysis based on the response of Veto, SciFi planes, Muon System
- Asses detector performances measuring the NC/CC ratio
- Perform very first measurement of TeV neutrino interactions @LHC

MATCHING BETWEEN EMULSIONS AND SCIFI

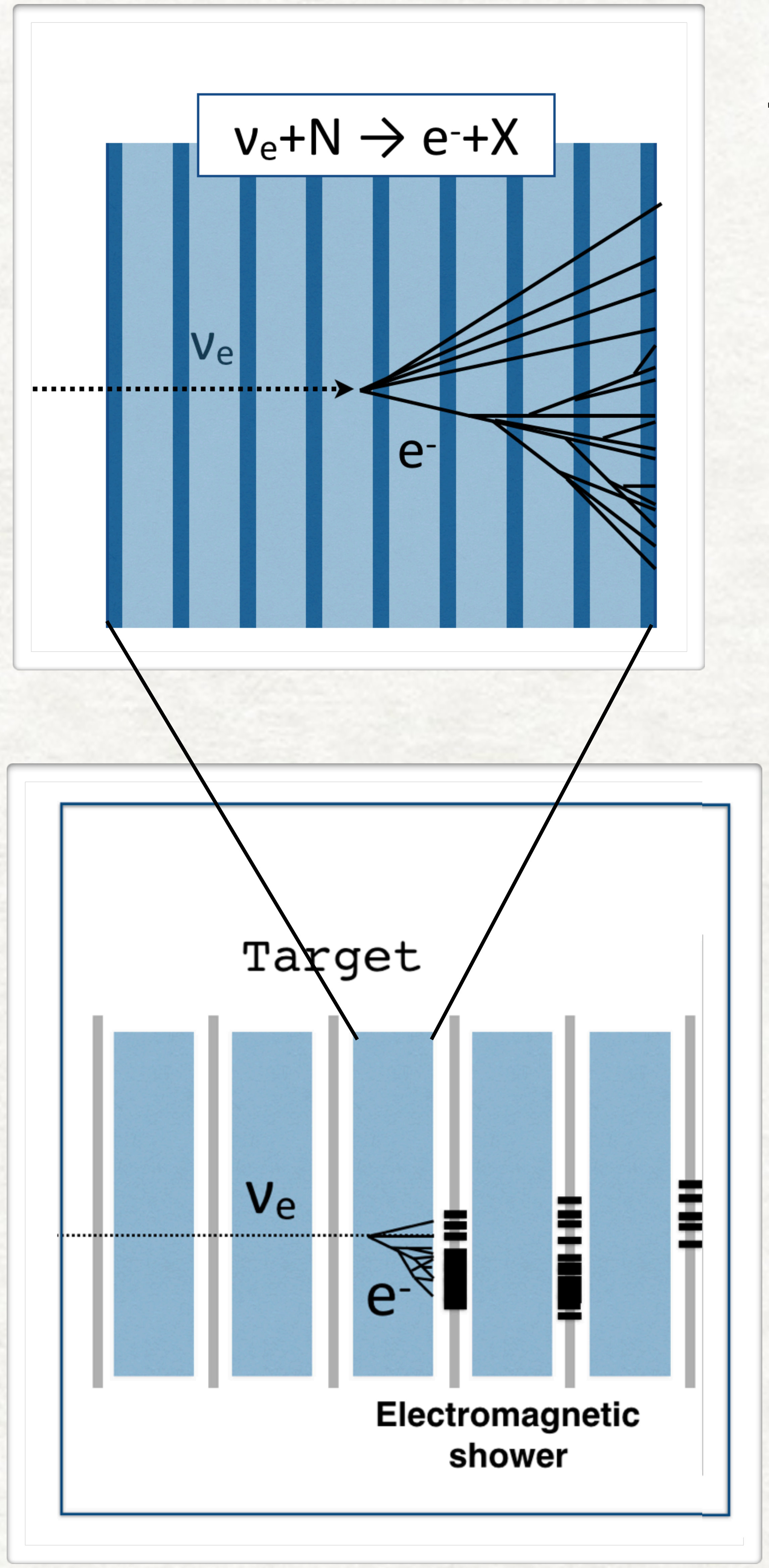
Expected neutrino CC DIS interactions in a single wall in 25fb^{-1}: 35 ν_μ, 12 ν_e



Hit map on the SciFi plane immediately downstream of the emulsion/tungsten wall

- Matching between tracks reconstructed in emulsion and events reconstructed in the SciFi immediately downstream
- Evaluate the effect of muon background (passing through tracks with high density)
- Evaluate the effect of neutron background (additional interactions in the target)

ELECTRON NEUTRINO ENERGY MEASUREMENT



Emulsion/
Tungsten wall

→ Sampling calorimeter every ~0.3 X_0

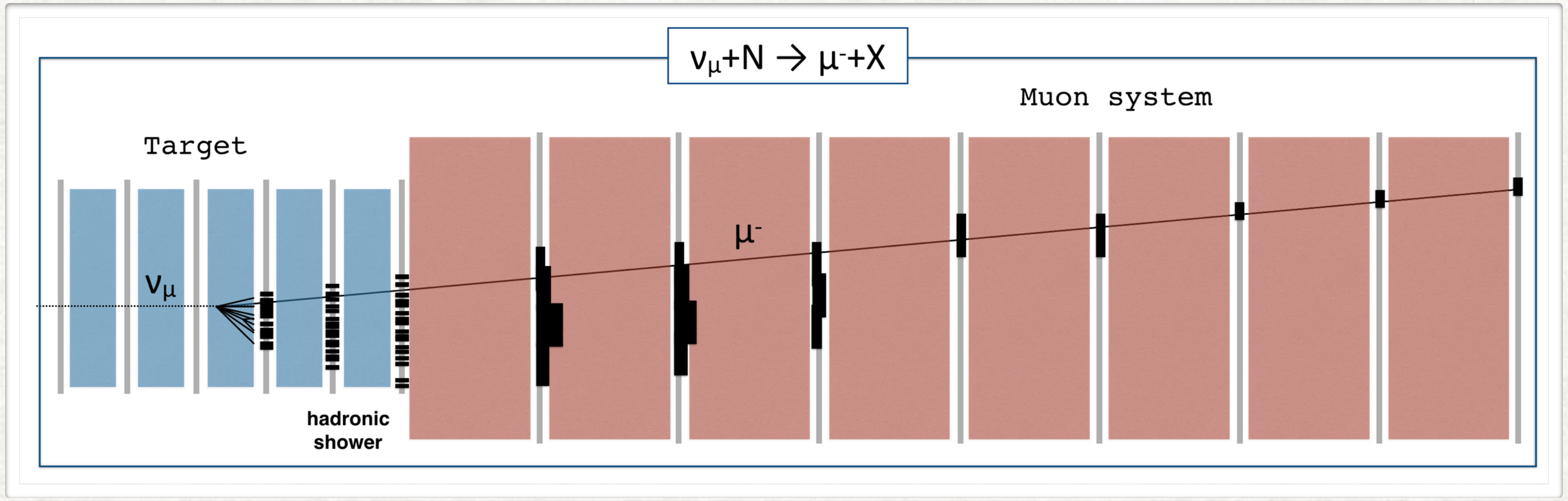
Target:
5 walls+5 SciFi planes

→ Sampling calorimeter every ~17 X_0

- Combine information reconstructed in the emulsion/lead target with SciFi data
- Measure the electromagnetic component of the neutrino interaction
- Combine electromagnetic with hadronic components → measure the electron neutrino energy

MUON NEUTRINO ENERGY MEASUREMENT

- Combine SciFi data and Muon system information to retrieve electromagnetic+hadronic components



- The momentum of the outgoing muon can be estimated by balancing the transverse momentum of the hadronic system
- Dedicated algorithms based on multivariate techniques will be used to extract the neutrino energy

CONCLUSIONS

- SND@LHC is a recently approved experiment at CERN aiming at:
  - measuring neutrinos produced at the LHC in an unexplored pseudo-rapidity region
  - searching for feebly interacting particles
- Detector under construction
- Data taking will start in early 2022
- A few important items in the analysis to be addressed, room for contributions