SND@LHC

THE SCATTERING AND NEUTRINO DETECTOR AT THE LHC

A. Di Crescenzo
Università Federico II and INFN

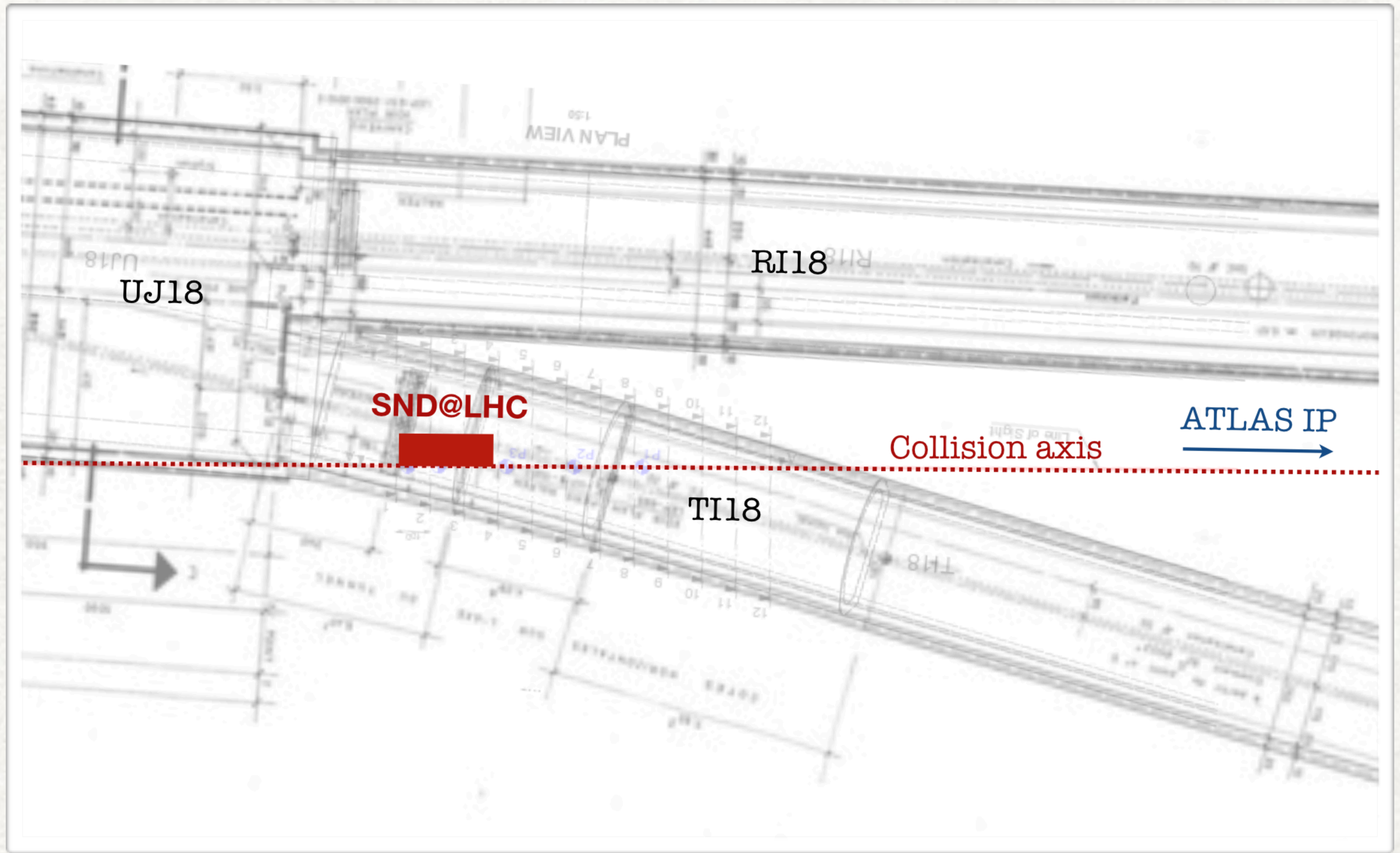
On behalf of the SND@LHC Collaboration

Neutrino physics at LHC - 2021 January 15th

OVERVIEW

- The SND@LHC experiment
- Event reconstruction
- Simulation and background estimation
- Neutrino expectations in Run 3
- 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
- Outlook

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}

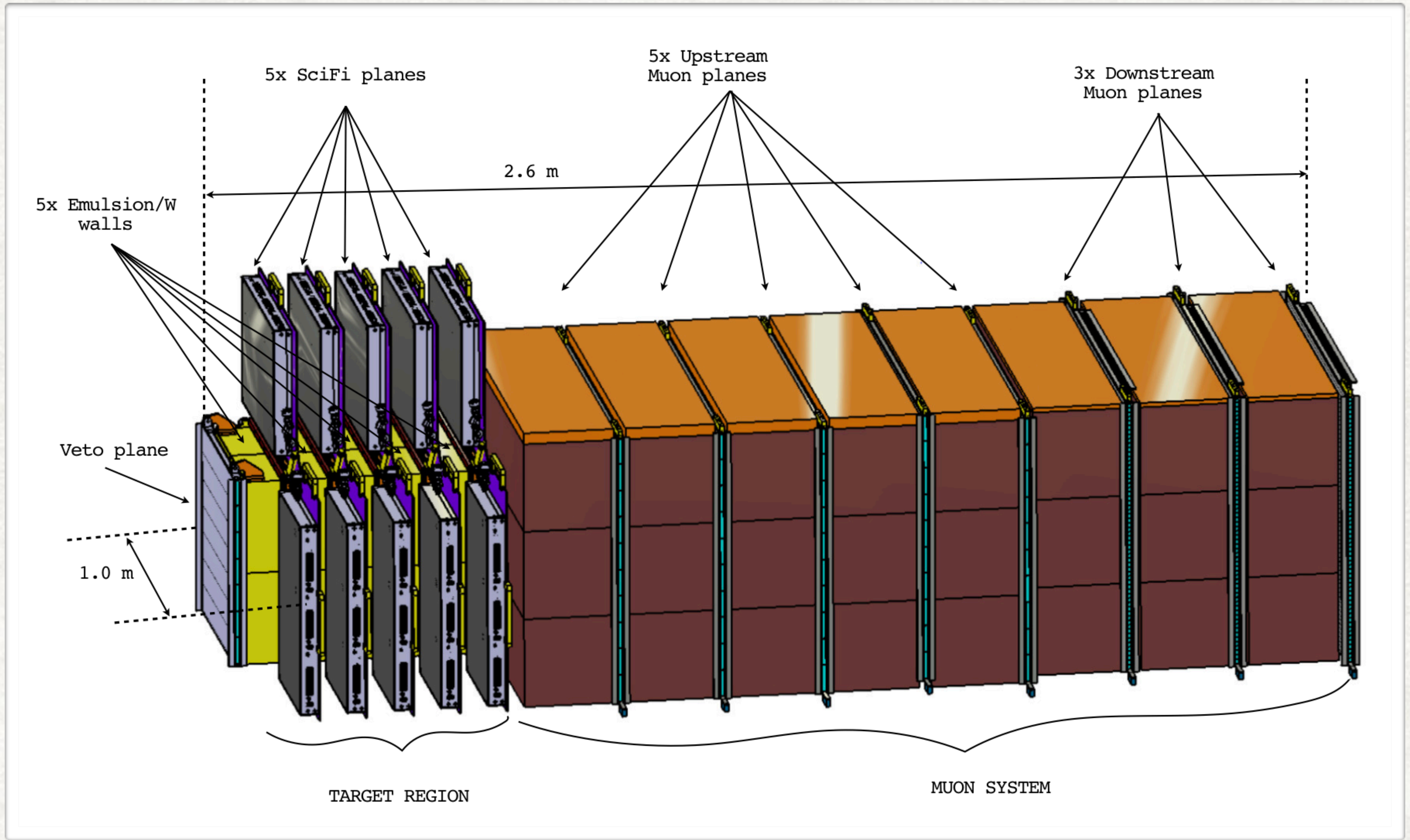
THE SND@LHC CONCEPT

Hybrid detector optimised for the identification of three neutrino flavours

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



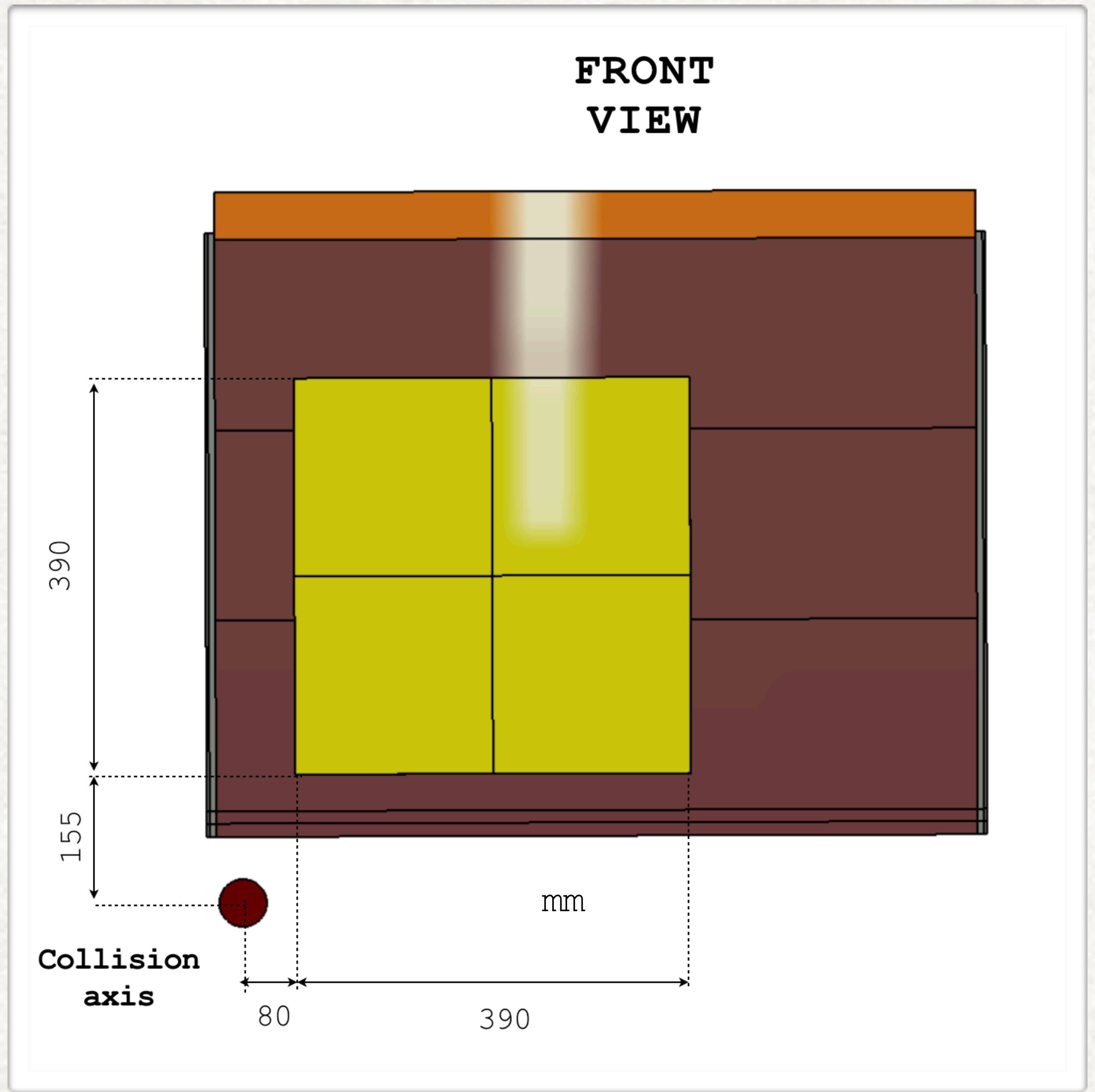
THE DETECTOR LAYOUT

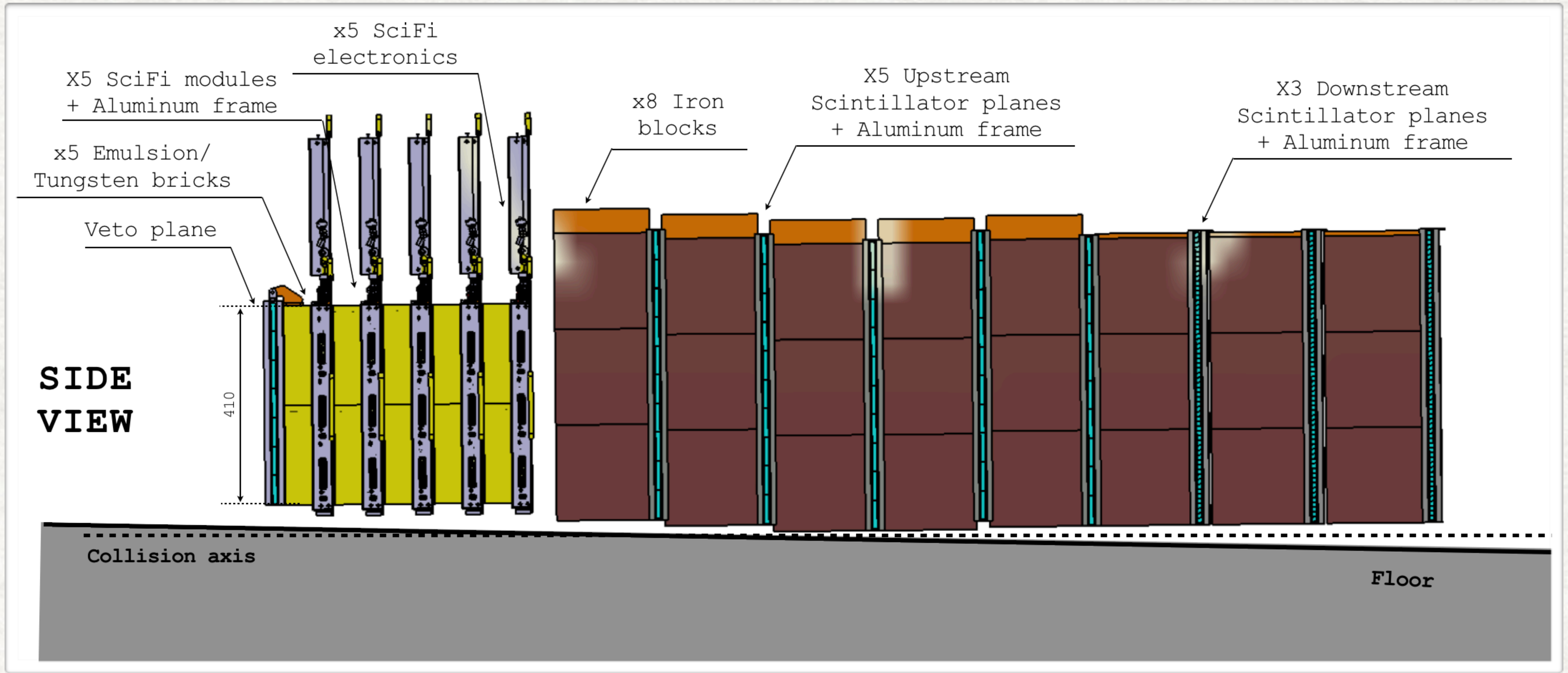
- Angular acceptance: $7.2 < \eta < 8.6$
- Target material: Tungsten
- Target mass: 830 kg
- Surface: 390x390 mm^2

Off axis location

Electromagnetic calorimeter
~40 X_0

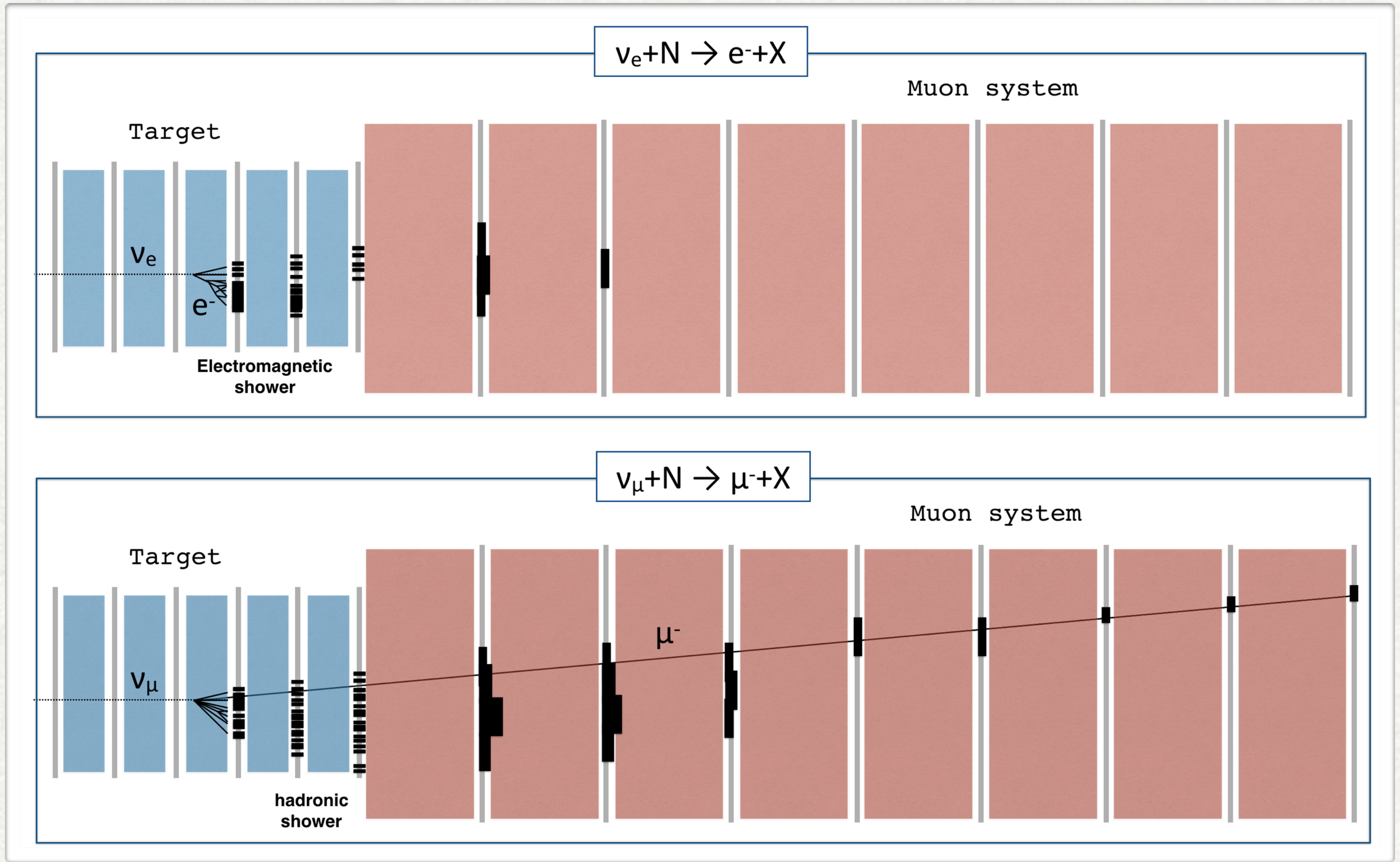
Hadronic calorimeter
~9.5 λ



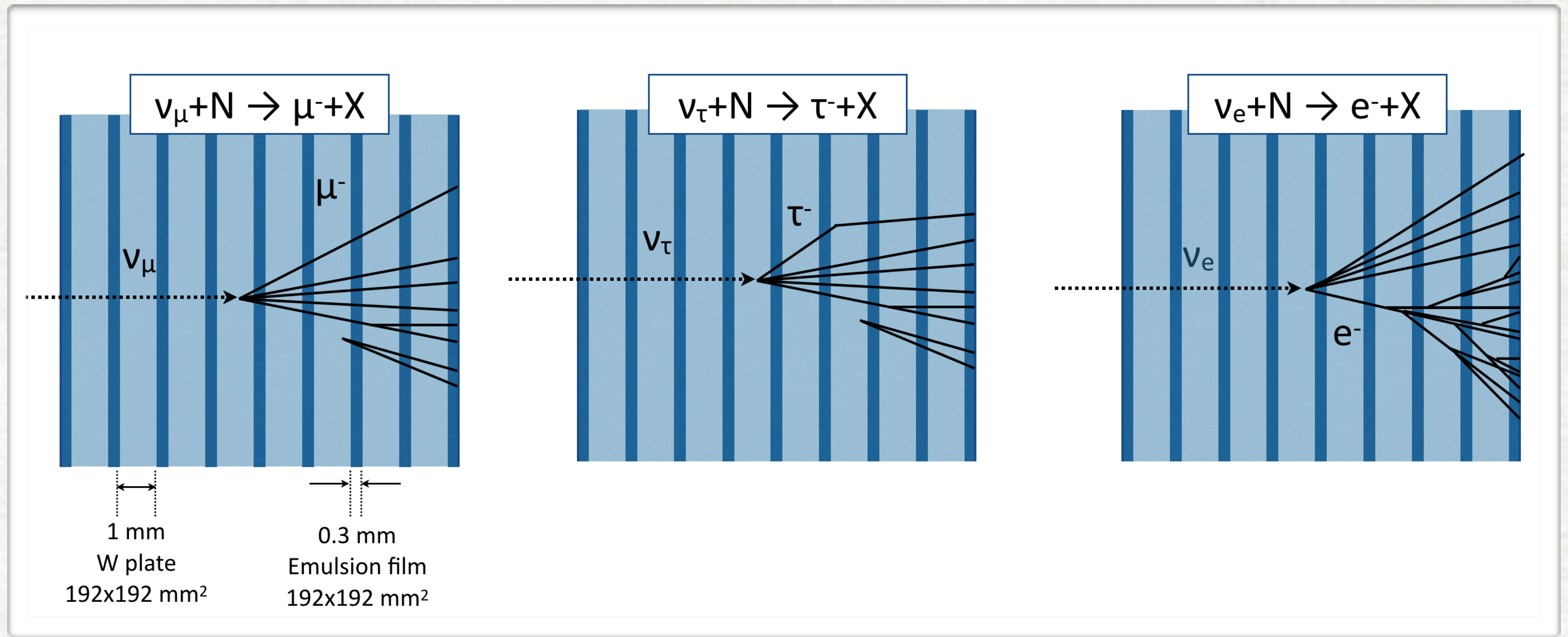


EVENT RECONSTRUCTION

- **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



SIMULATION

- PRODUCTION

- PROPAGATION

- DETECTOR

SIMULATION

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

Francesco Cerutti & Marta Sabaté Gilarte
(CERN-EN-TI-BMI)

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

- PROPAGATION

- DETECTOR

SIMULATION

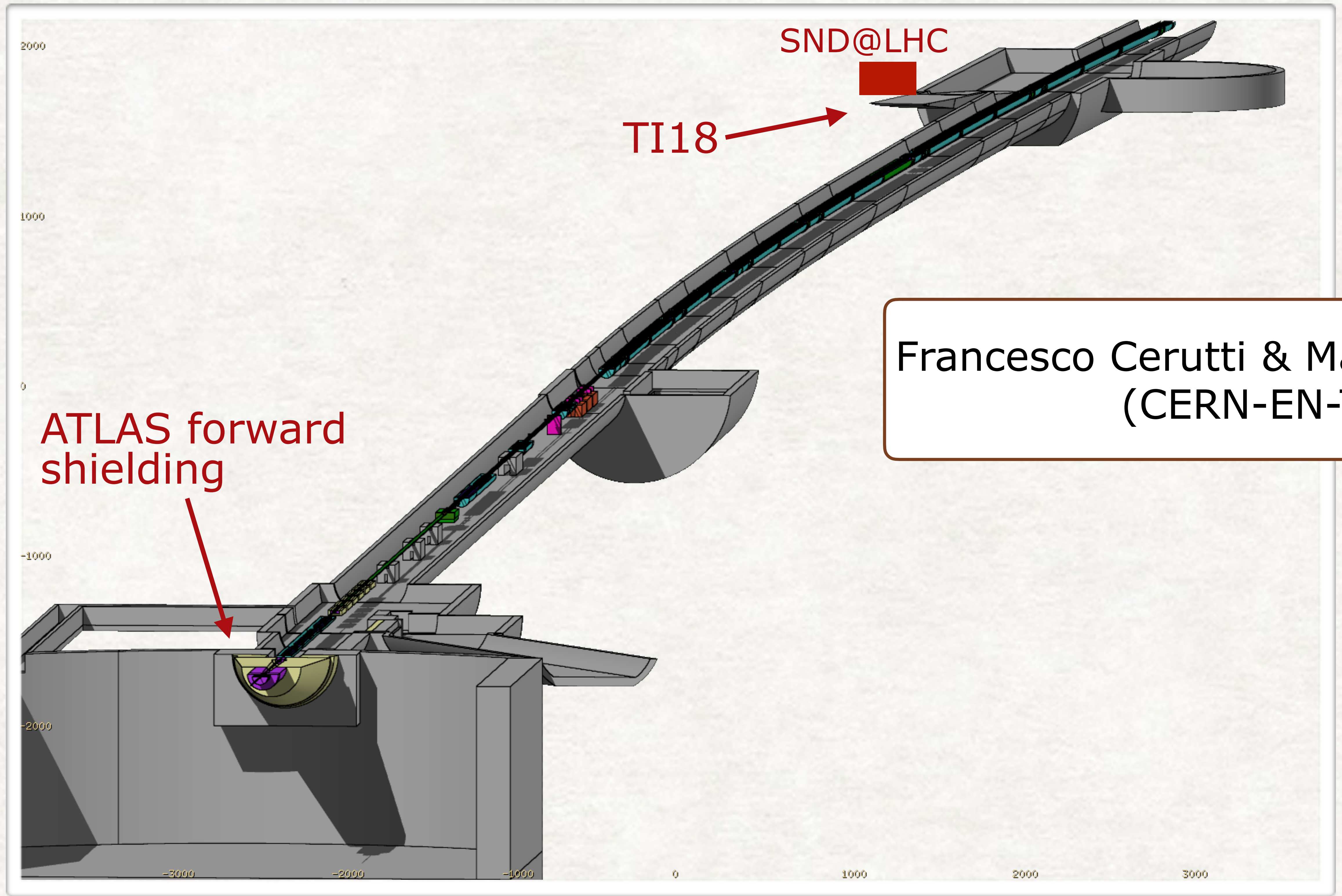
- PRODUCTION →
  - pp collisions at LHC with **DPMJET III - v10** (embedded in FLUKA)
  - √s = 13 TeV

Francesco Cerutti & Marta Sabaté Gilarte
(CERN-EN-TI-BMI)

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



Francesco Cerutti & Marta Sabaté Gilarte
(CERN-EN-TI-BMI)

SIMULATION

- PRODUCTION

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

Francesco Cerutti & Marta Sabaté Gilarte
(CERN-EN-TI-BMI)

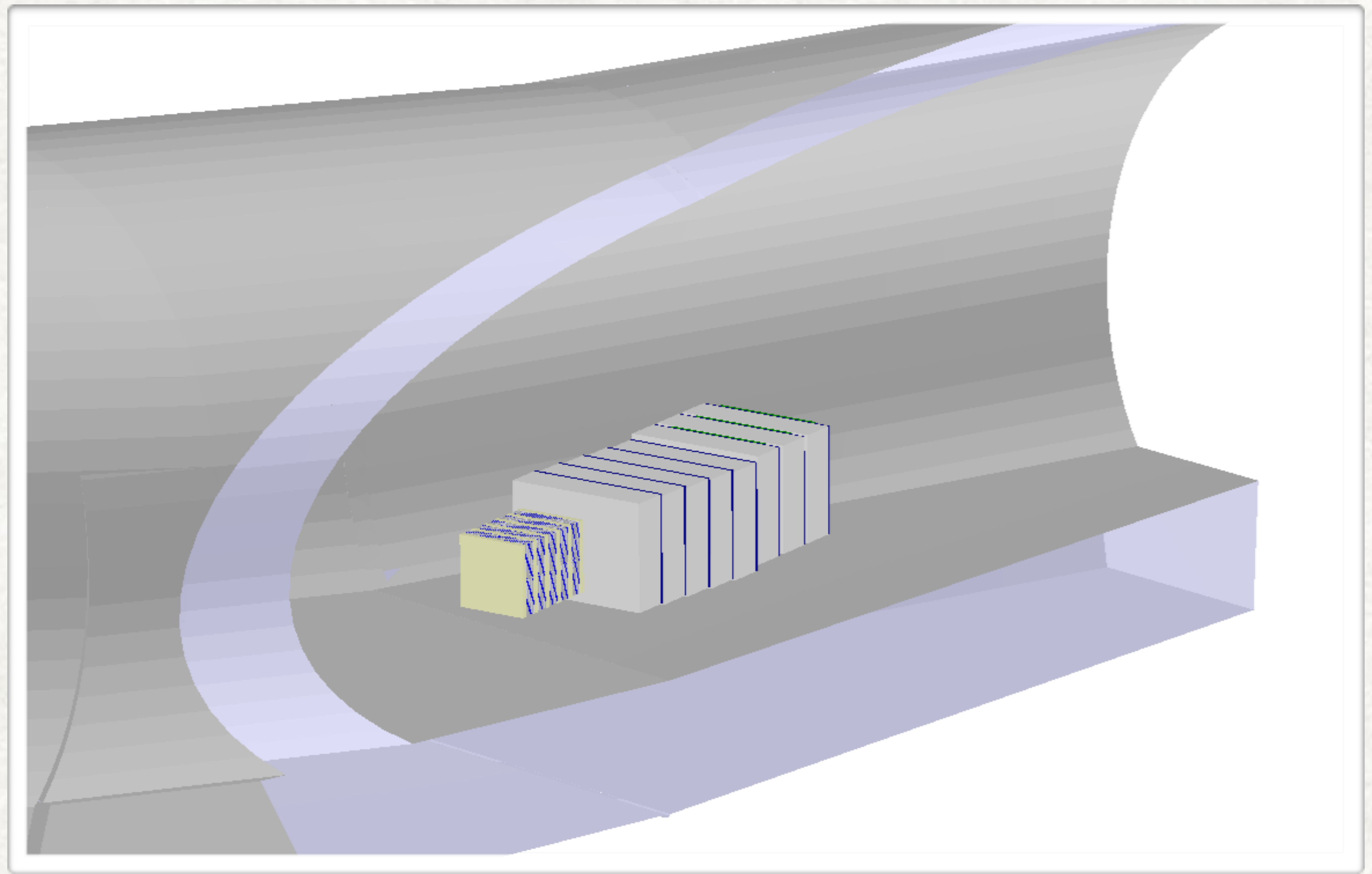
SND@LHC can perform measurements of heavy quark production in the forward region and set constraints to production mechanisms in unexplored region

- 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

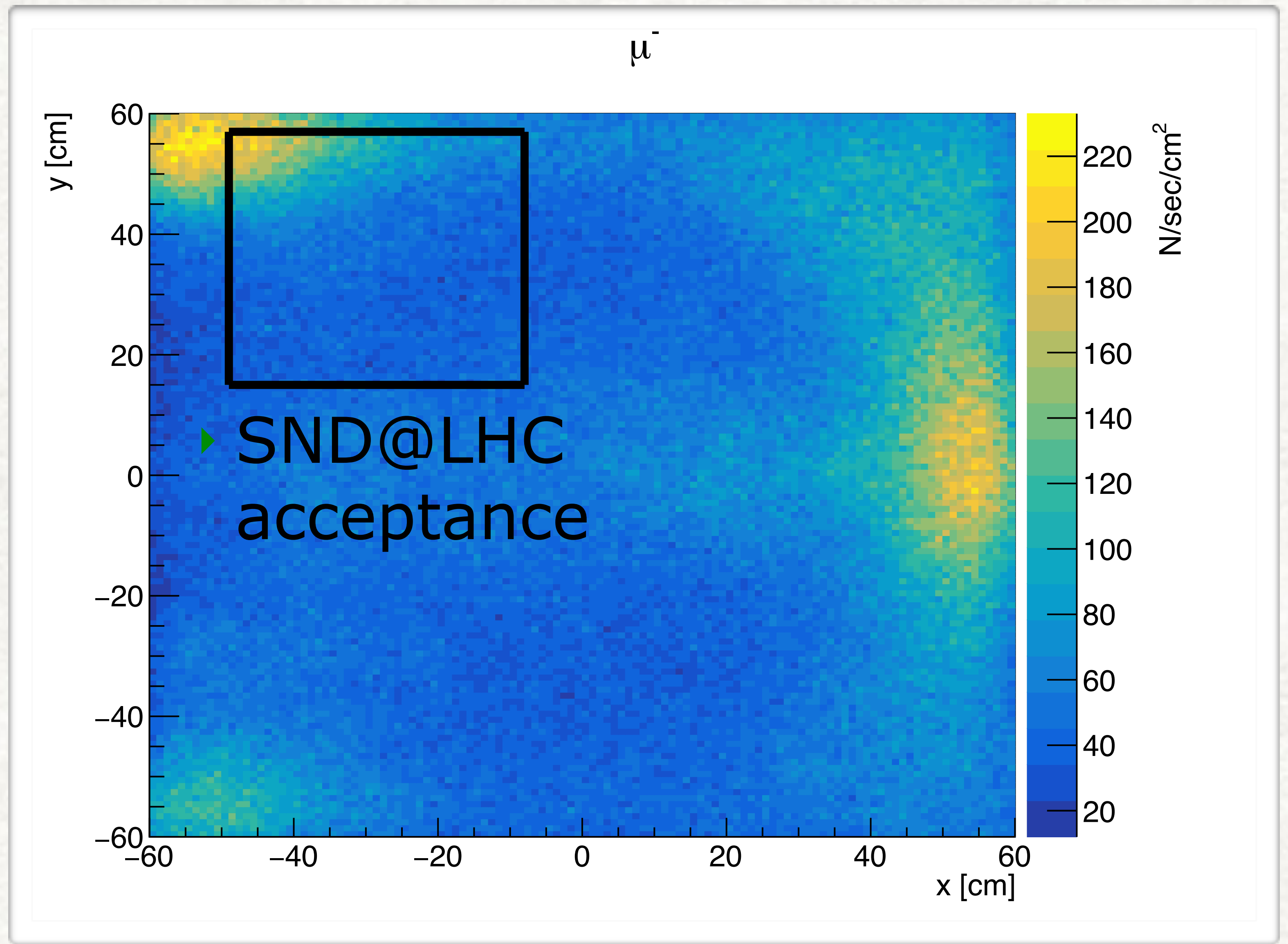
- Neutrino interactions in SND@LHC material simulated with **GENIE**
- Detector geometry and surrounding tunnel implemented in **GEANT4**

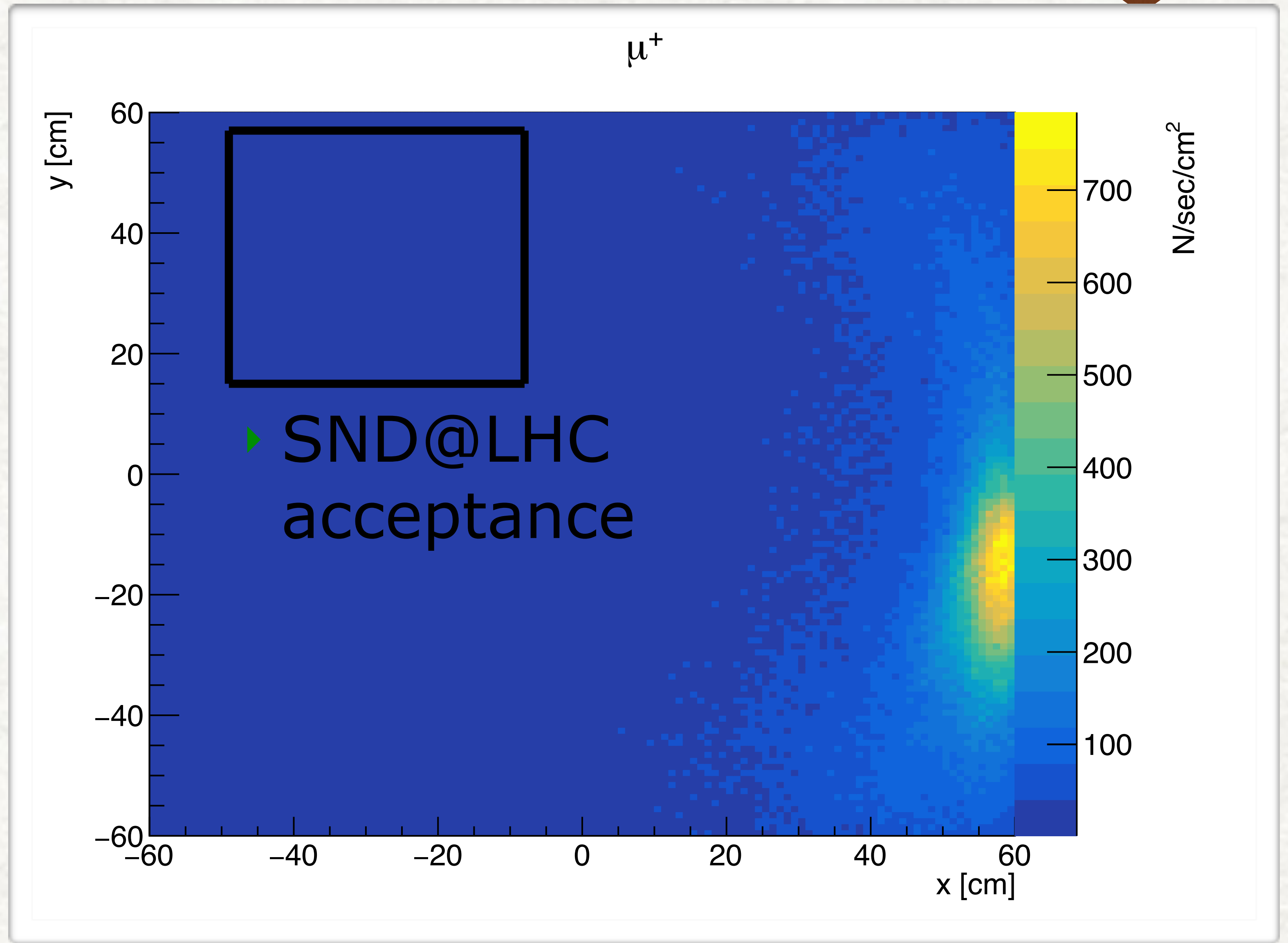


BACKGROUND ESTIMATION

Muon background

- Rates at the SND@LHC location: $2 \times 10^4 / cm^2 / fb^{-1}$





SND@LHC can perform precise measurements on muon yield and angle to validate predictions and constraint simulations in an unexplored region

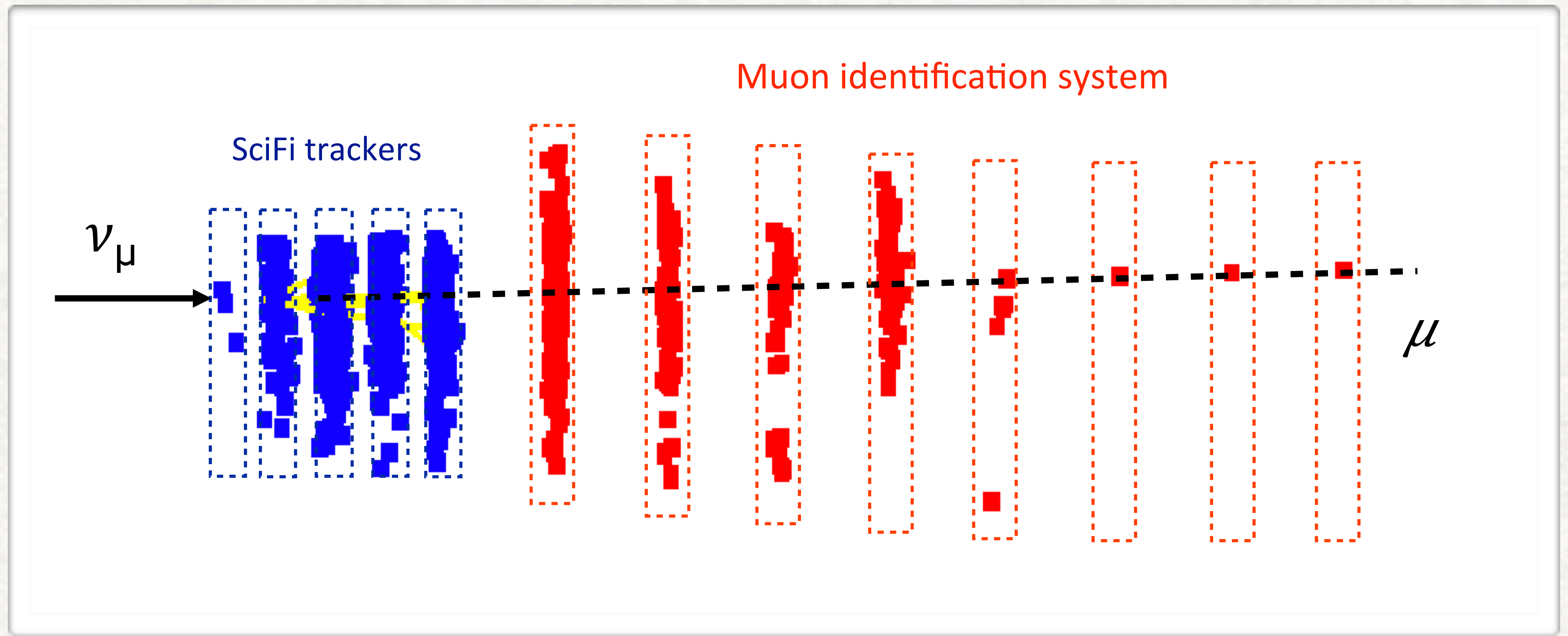
- Measurements performed by FASER in agreement with FLUKA predictions within errors

From FASER TP
https://cds.cern.ch/record/2651328

	normalized flux, main peak [fb cm^{-2}]
TI18	$(1.2 \pm 0.4) \times 10^4$
TI12	$(1.9 \pm 0.2) \times 10^4$

KEY FEATURES

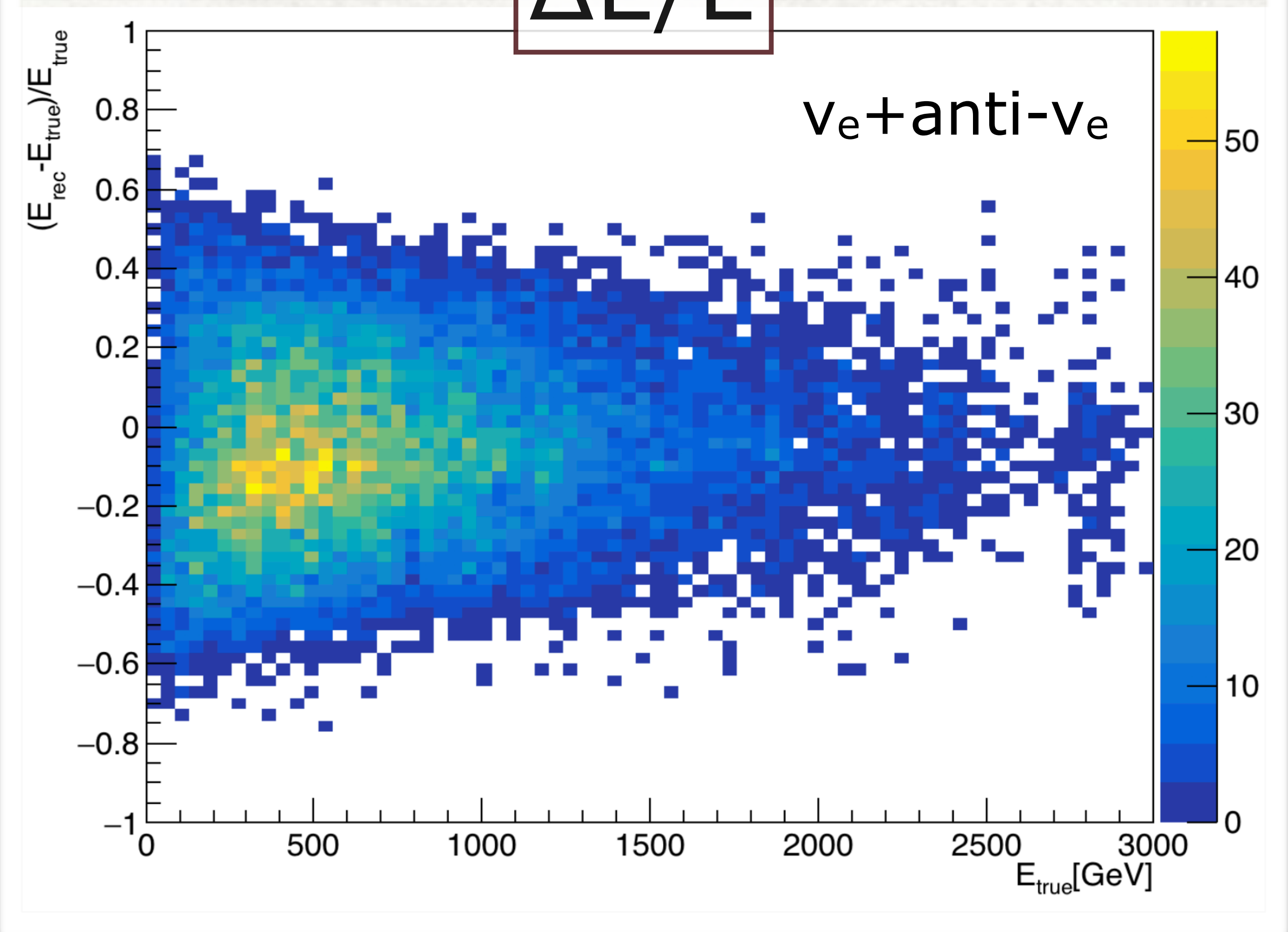
- Muon identification
  - ν_μ CC interactions identified thanks to the identification of the muon produced in the interaction
  - Muon ID at the neutrino vertex crucial to identify charmed hadron production, background to ν_τ detection



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

- Energy measurement
  - Estimation of hadronic and electromagnetic energy combing information from SciFi (target region) and Scintillator bars (Muon System)
  - The detector acts as a non-homogeneous sampling calorimeter

ΔE/E

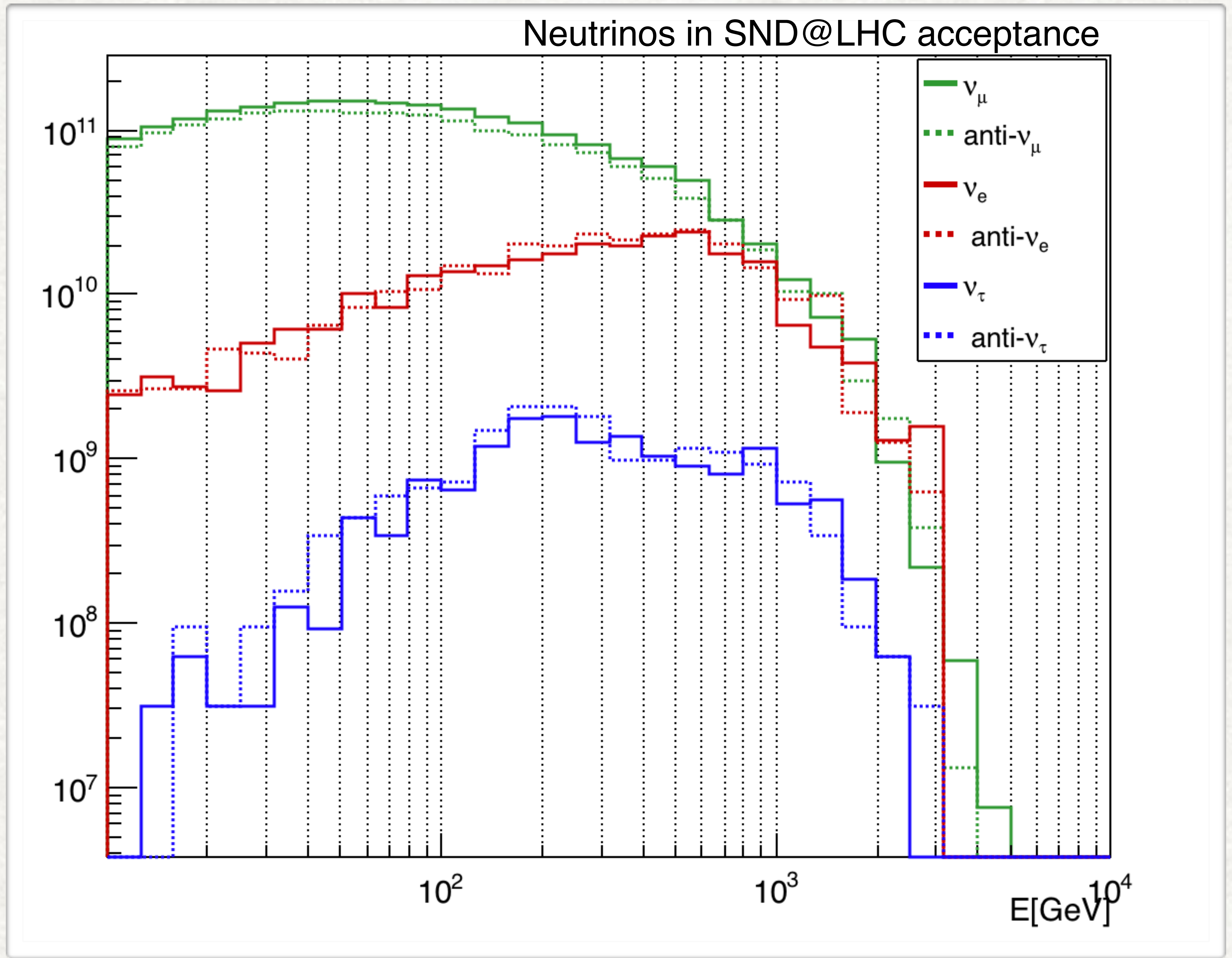


Average resolution on ν_e energy: 22%

- Precise measurement pseudo-rapidity of neutrinos coming from the IP
  - Micrometric reconstruction of neutrino interaction vertex in the target

EXPECTED NEUTRINOS IN ACCEPTANCE

- Neutrino energy spectra



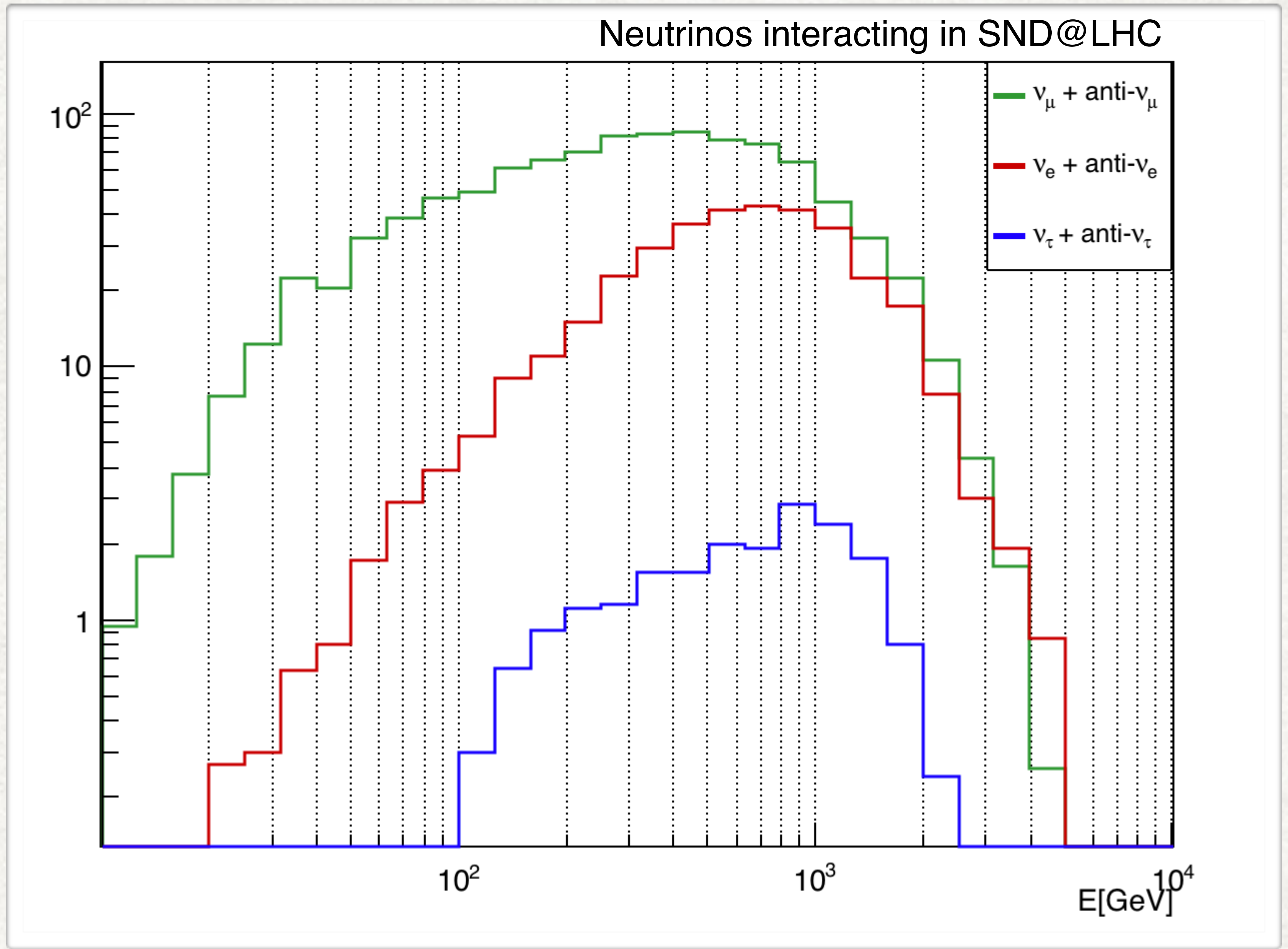
- Expectations in 150 fb^{-1}

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

EXPECTED NEUTRINO DIS INTERACTIONS

- Spectra of neutrinos interacting in SND@LHC



- Expectations in 150 fb^{-1}

Flavour	CC neutrino interactions $\langle E \rangle$ (GeV)	CC Yield	NC neutrino interactions $\langle E \rangle$ (GeV)	NC 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

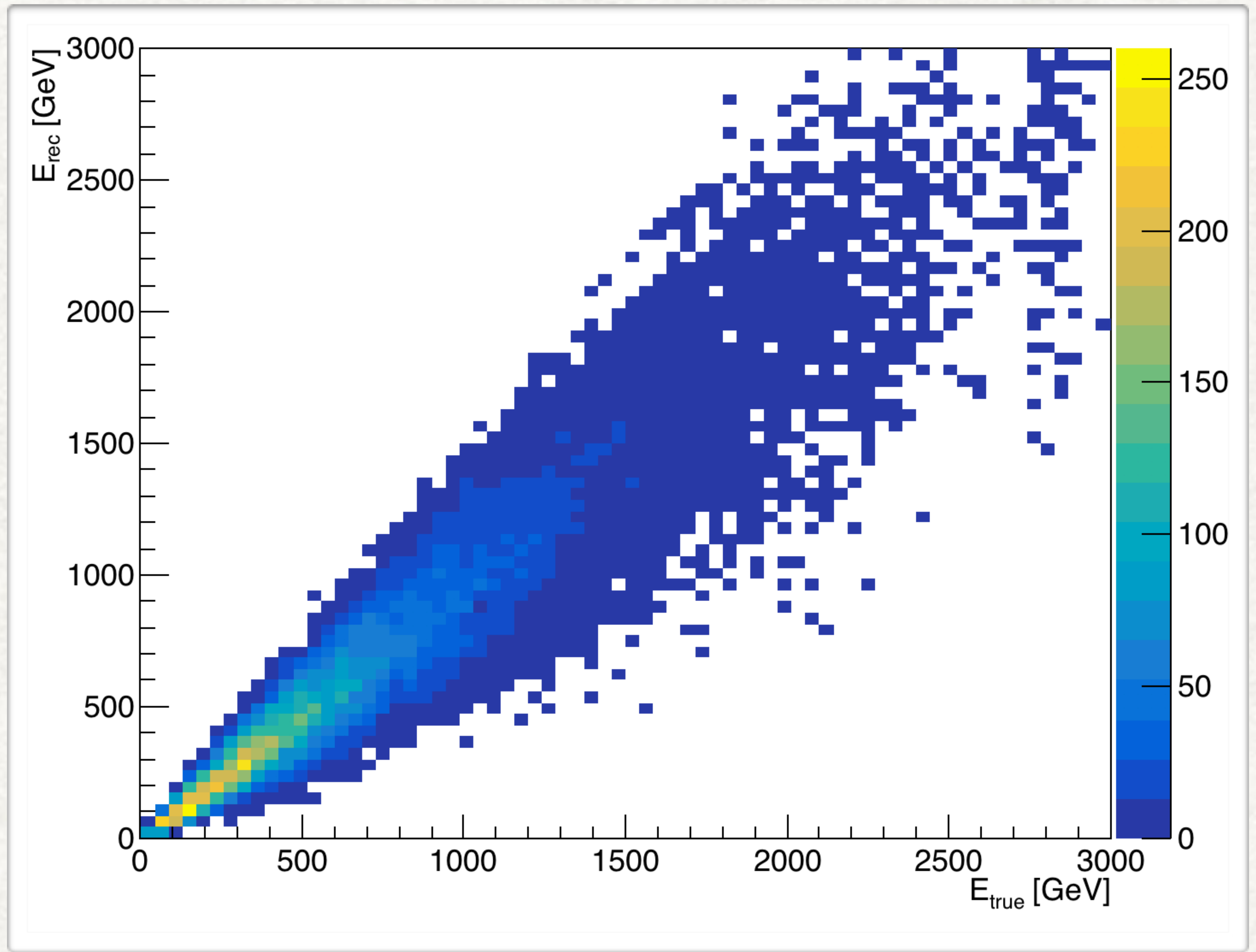
NEUTRINO PHYSICS PROGRAM IN RUN 3

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

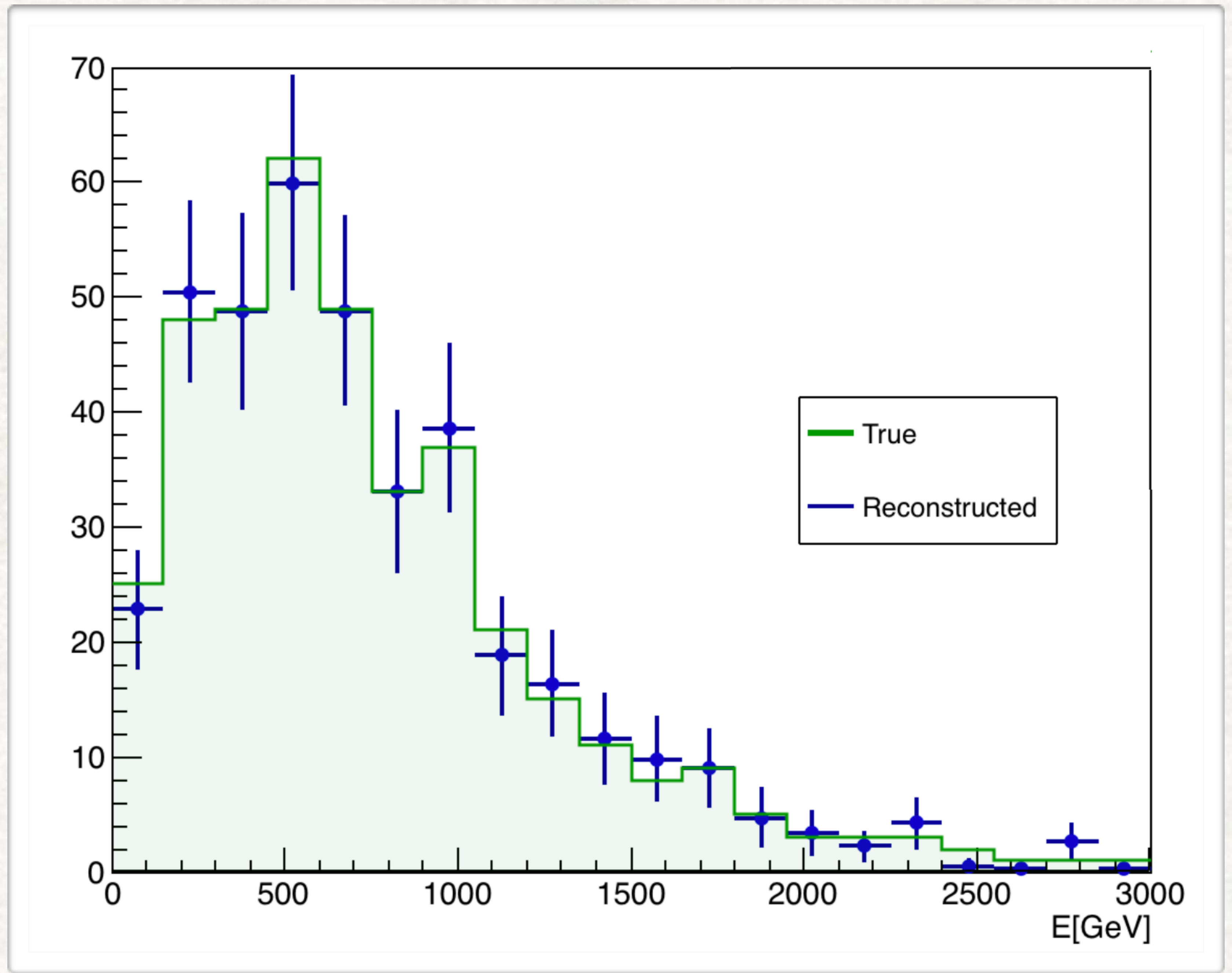
1. MEASUREMENT OF *pp*⟶ν_eX CROSS-SECTION

- 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
- An unfolding procedure was applied to the *measured* spectrum of ν_e+anti-ν_e to retrieve reconstructed ν_e+anti-ν_e energy spectrum

Unfolding procedure based on RooUnfold
(http://hepunx.rl.ac.uk/~adye/software/unfold/RooUnfold.html)



- Response matrix (E_{rec} vs E_{true}) estimated with full simulation

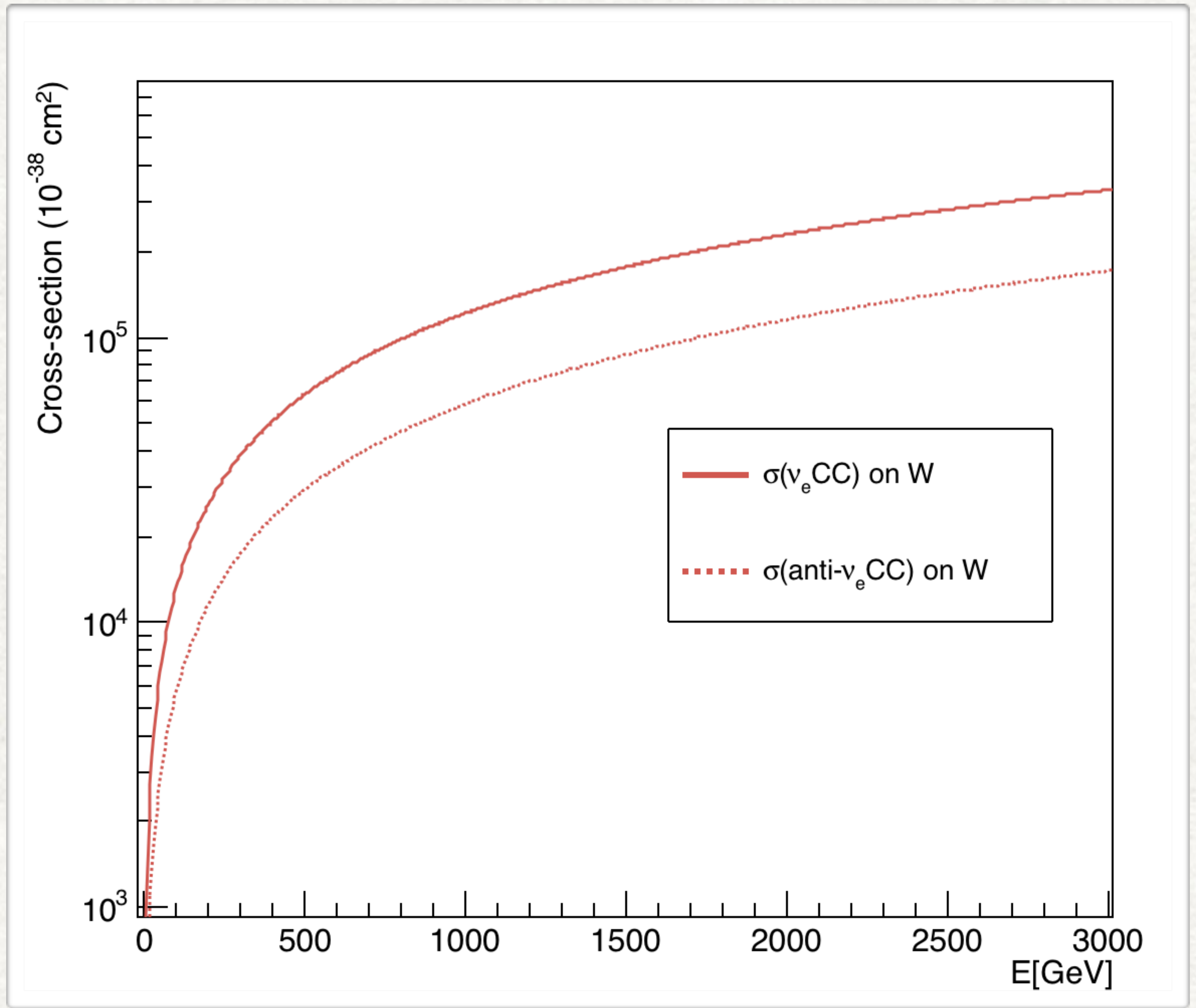


Errors: statistical (number of entries in each bin) + systematic (unfolding procedure)

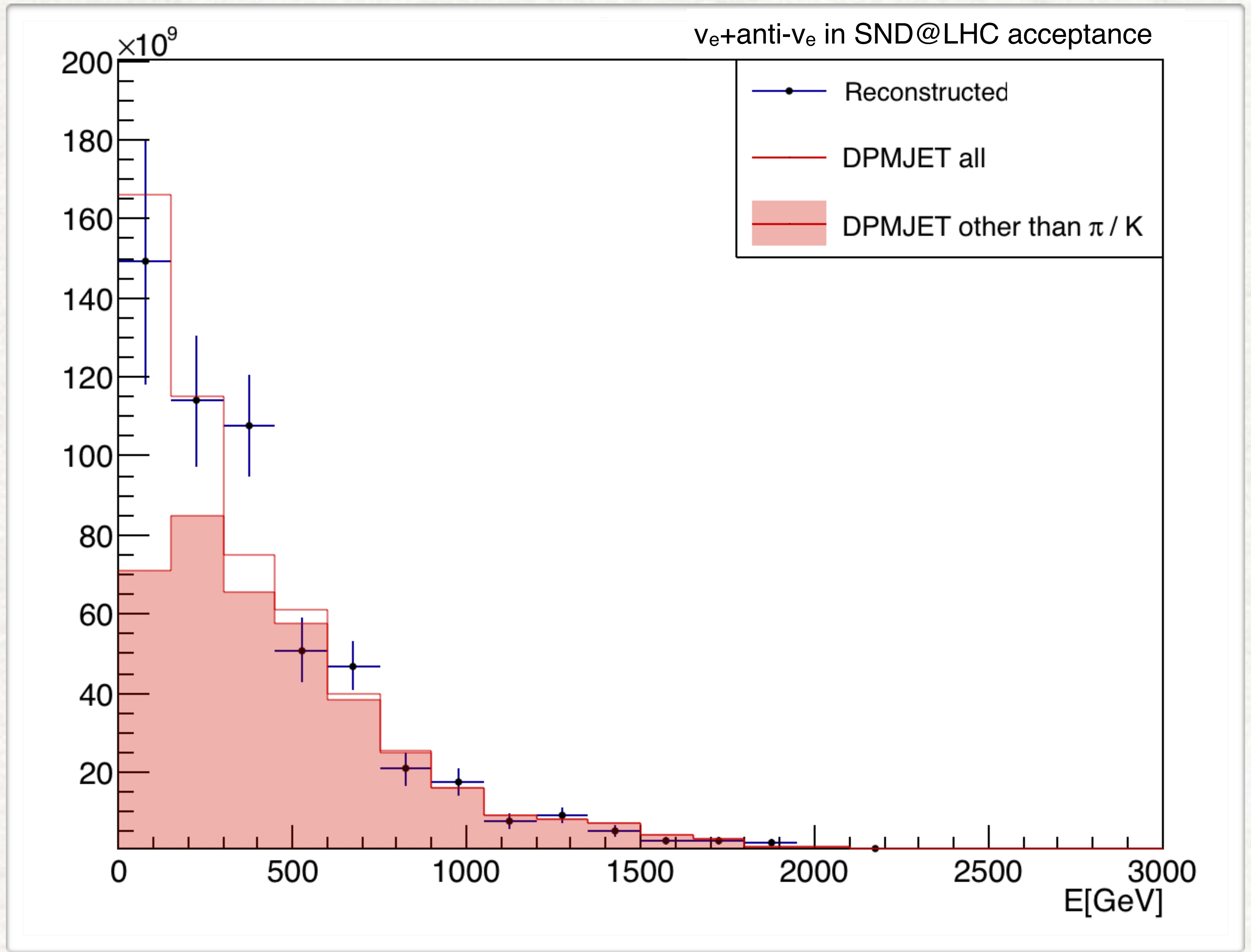
1. MEASUREMENT OF $pp \longrightarrow \nu_e X$ CROSS-SECTION

- 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

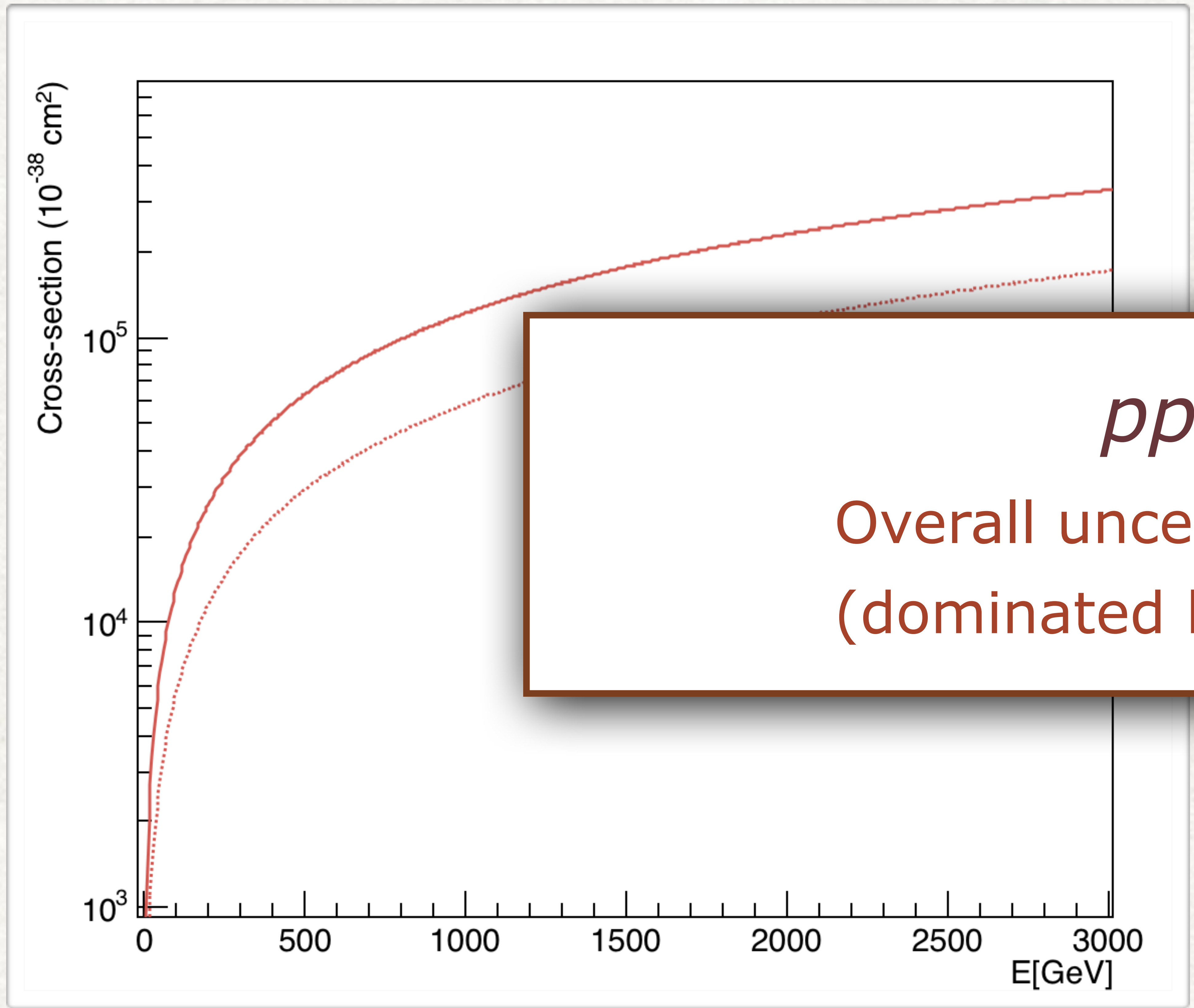


Errors: statistical (collected statistics)
+ systematic (unfolding procedure)

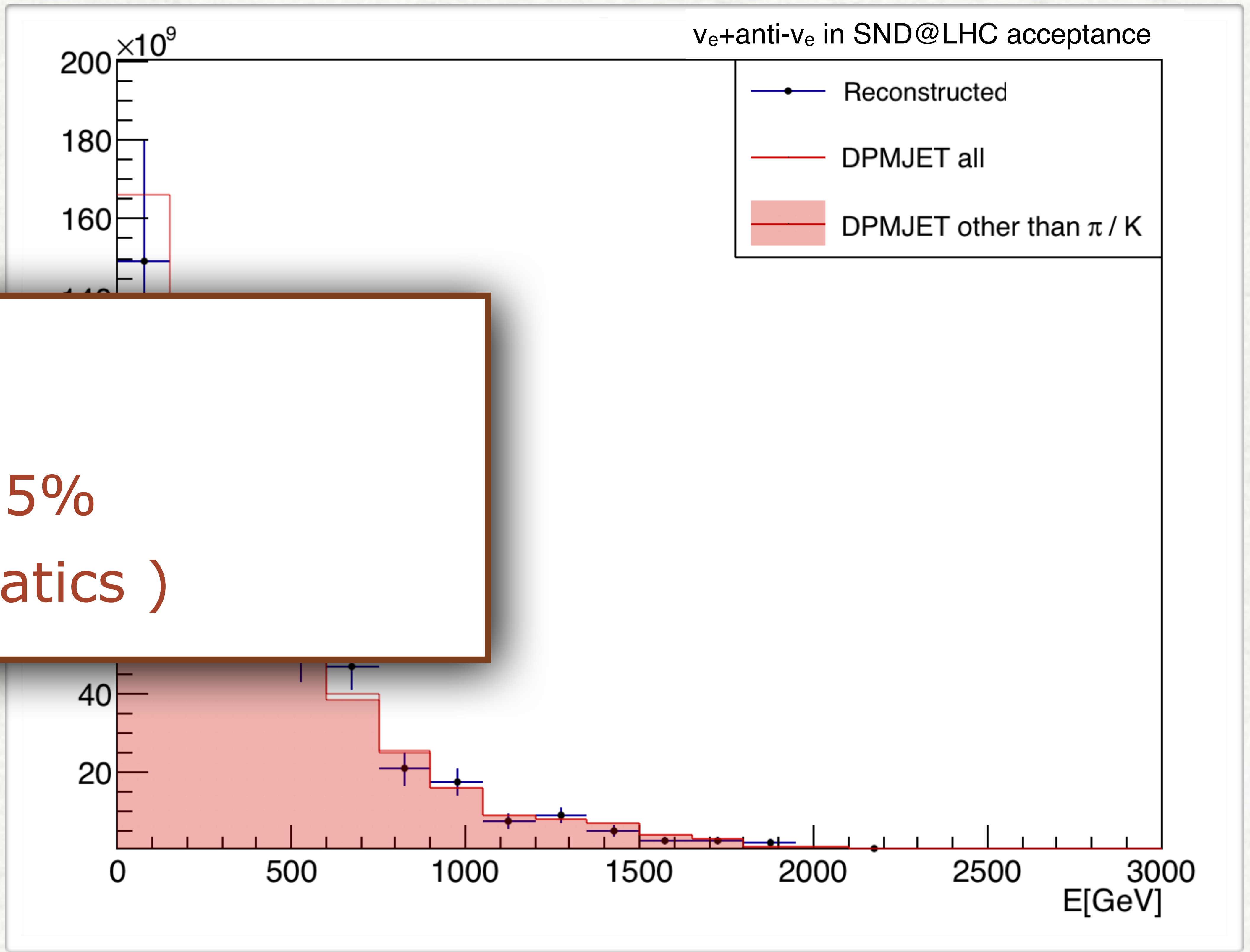
1. MEASUREMENT OF $pp \rightarrow \nu_e X$ CROSS-SECTION

- 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)

$pp \rightarrow \nu_e X$

Overall uncertainty ~15%

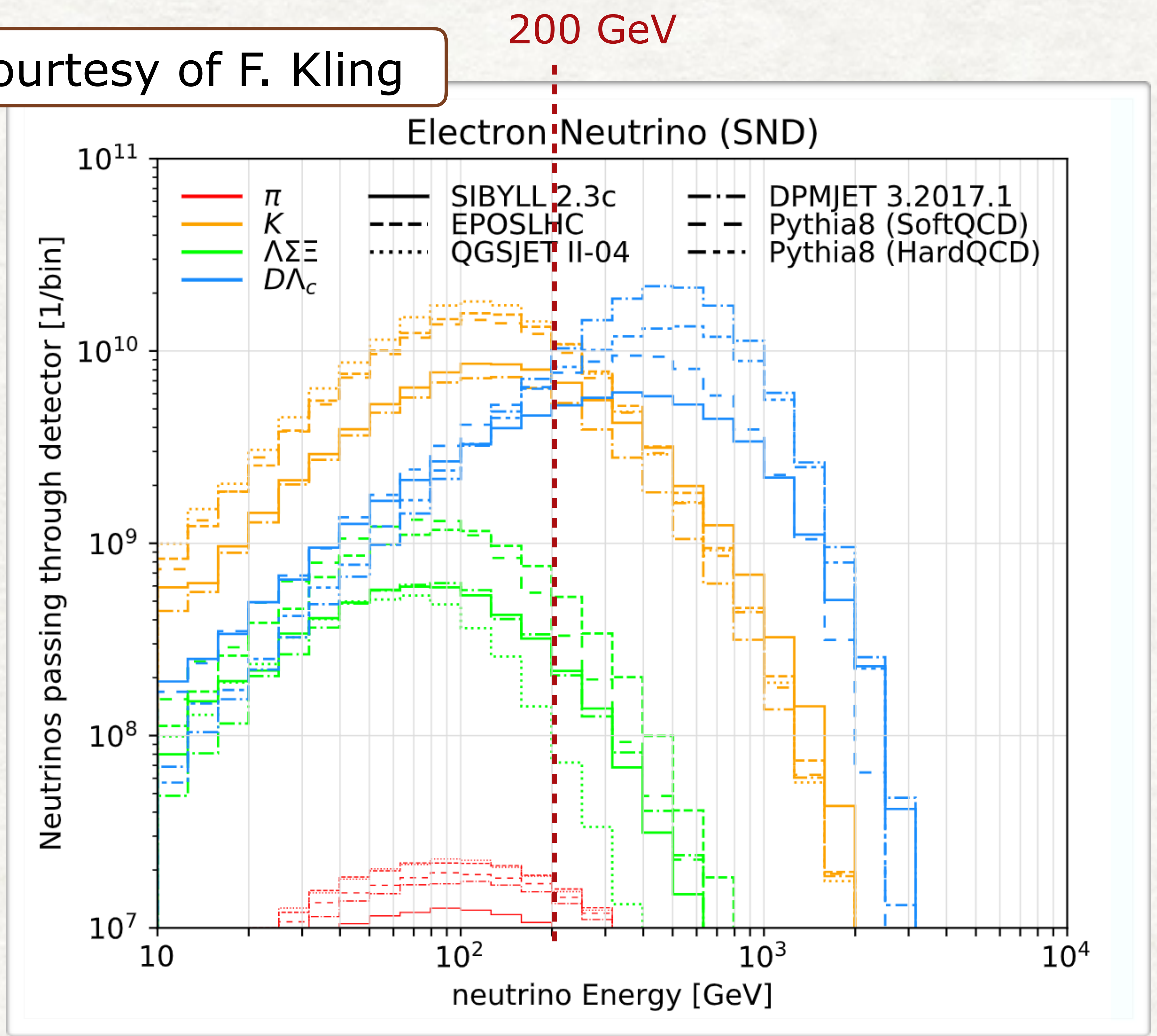
(dominated by systematics)

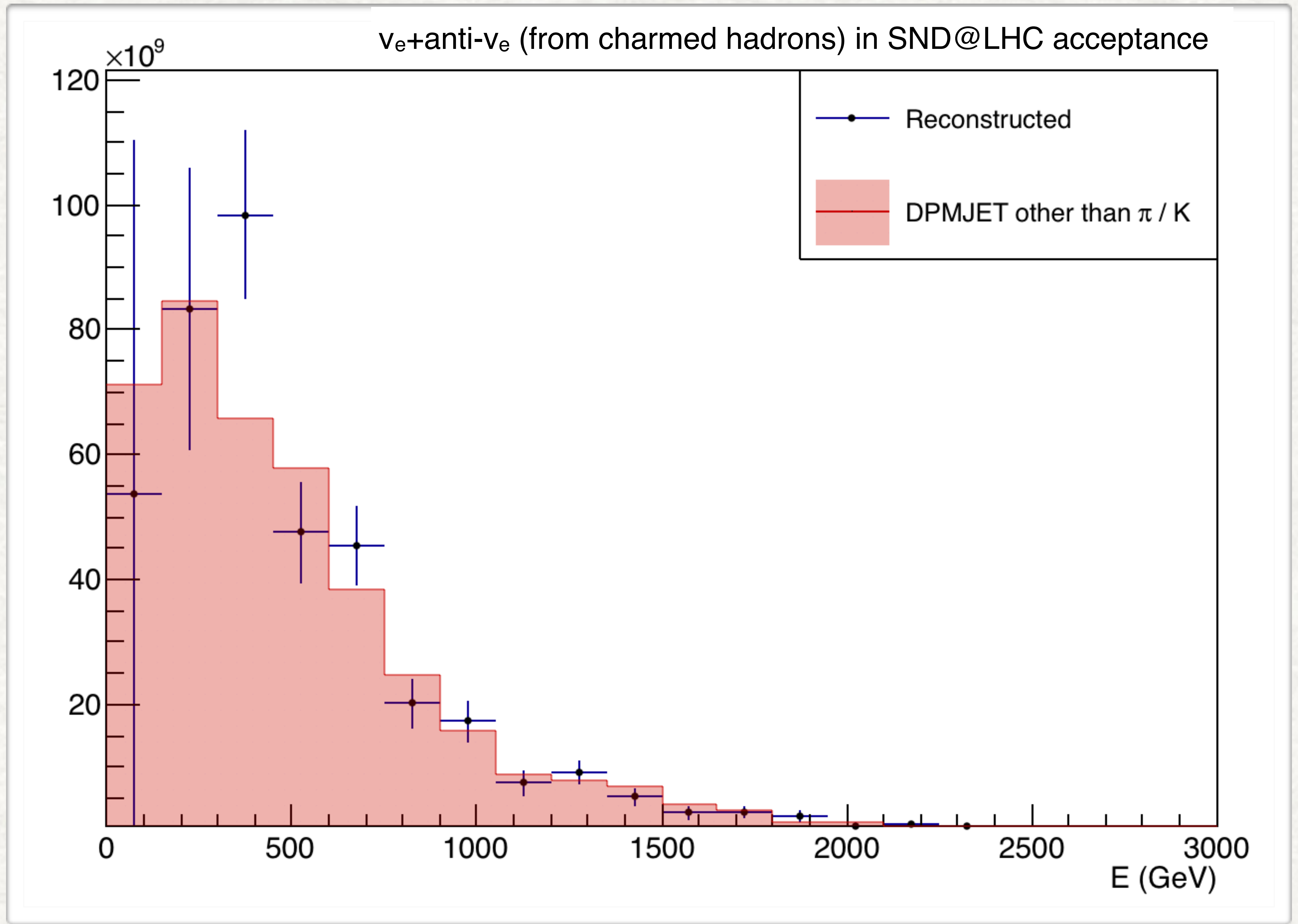
KAON CONTRIBUTION TO ν_e

- In order to extract the ν_e+anti-ν_e component from charmed hadron decay, a statistical subtraction of K component has to be performed
- The K component dominates at low energies (E<200 GeV)
- Predictions from different generators show large uncertainties (factor 2)

- This operation affects the low energy portion of the spectrum where the number of observed neutrino is lower
- The subtraction of the K component introduces an additional systematic error of **~20%**

Courtesy of F. Kling



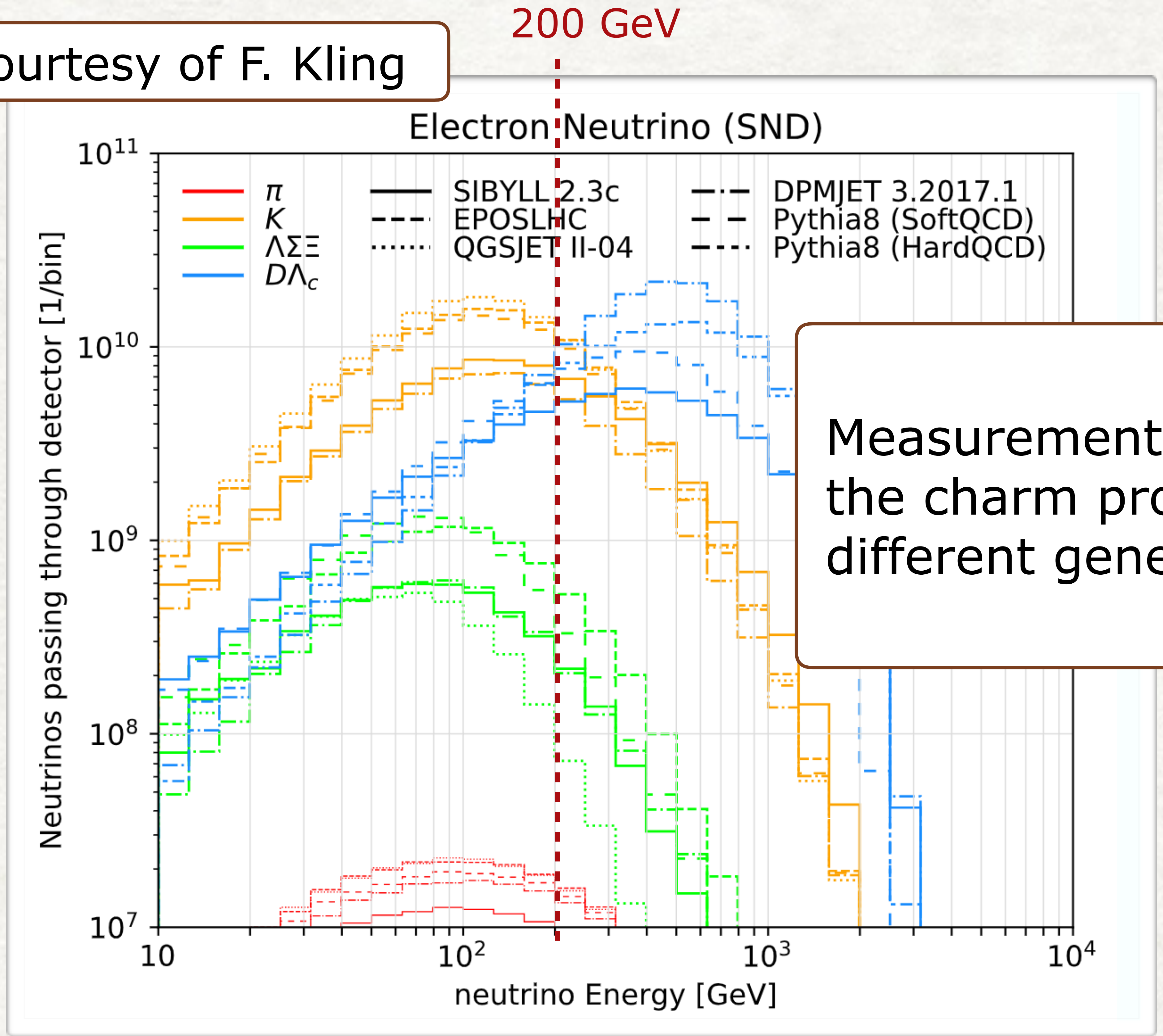


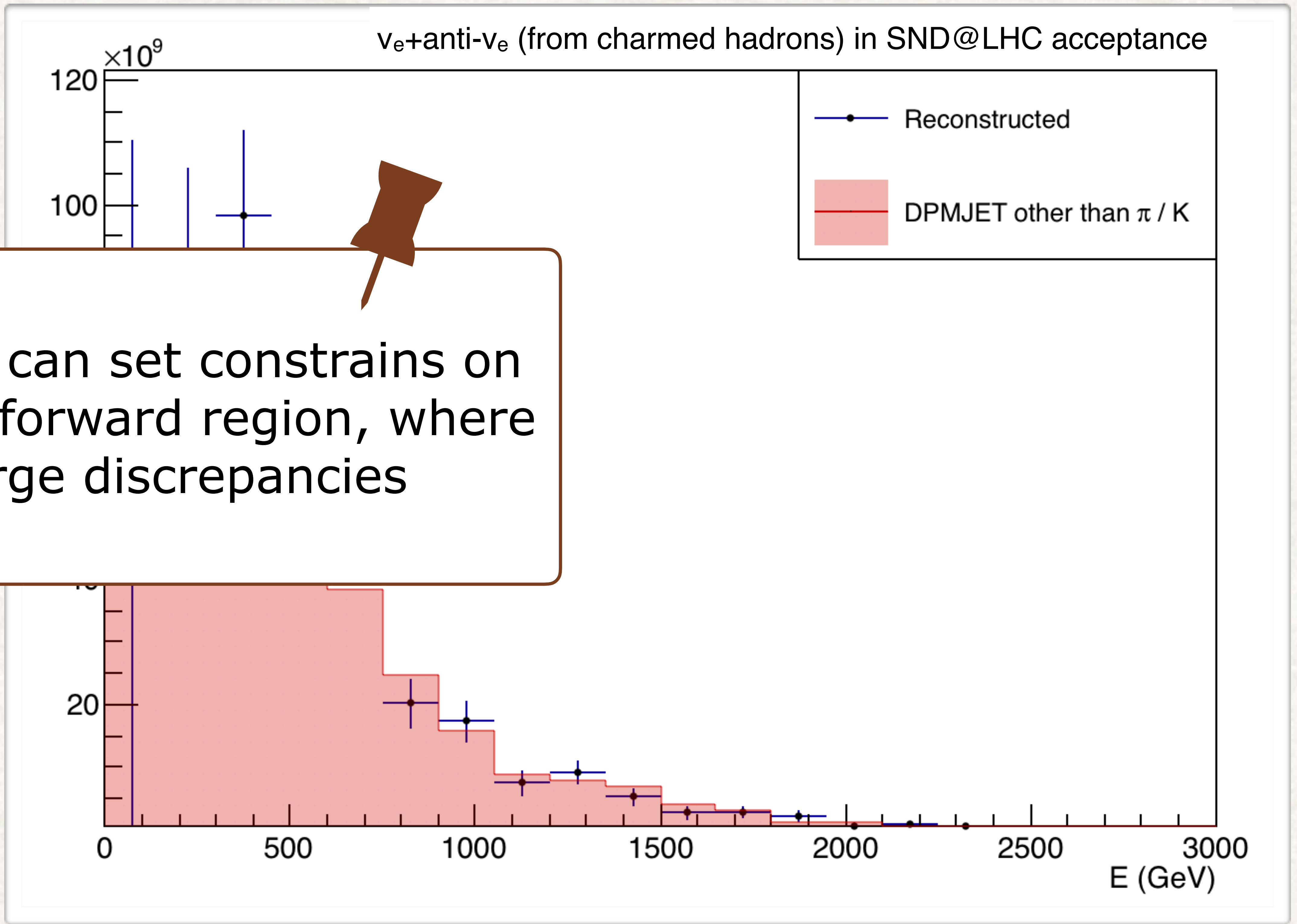
KAON CONTRIBUTION TO ν_e

- In order to extract the ν_e+anti-ν_e component from charmed hadron decay, a statistical subtraction of K component has to be performed
- The K component dominates at low energies (E<200 GeV)
- Predictions from different generators show large uncertainties (factor 2)

- This operation affects the low energy portion of the spectrum where the number of observed neutrino is lower
- The subtraction of the K component introduces an additional systematic error of **~20%**

Courtesy of F. Kling



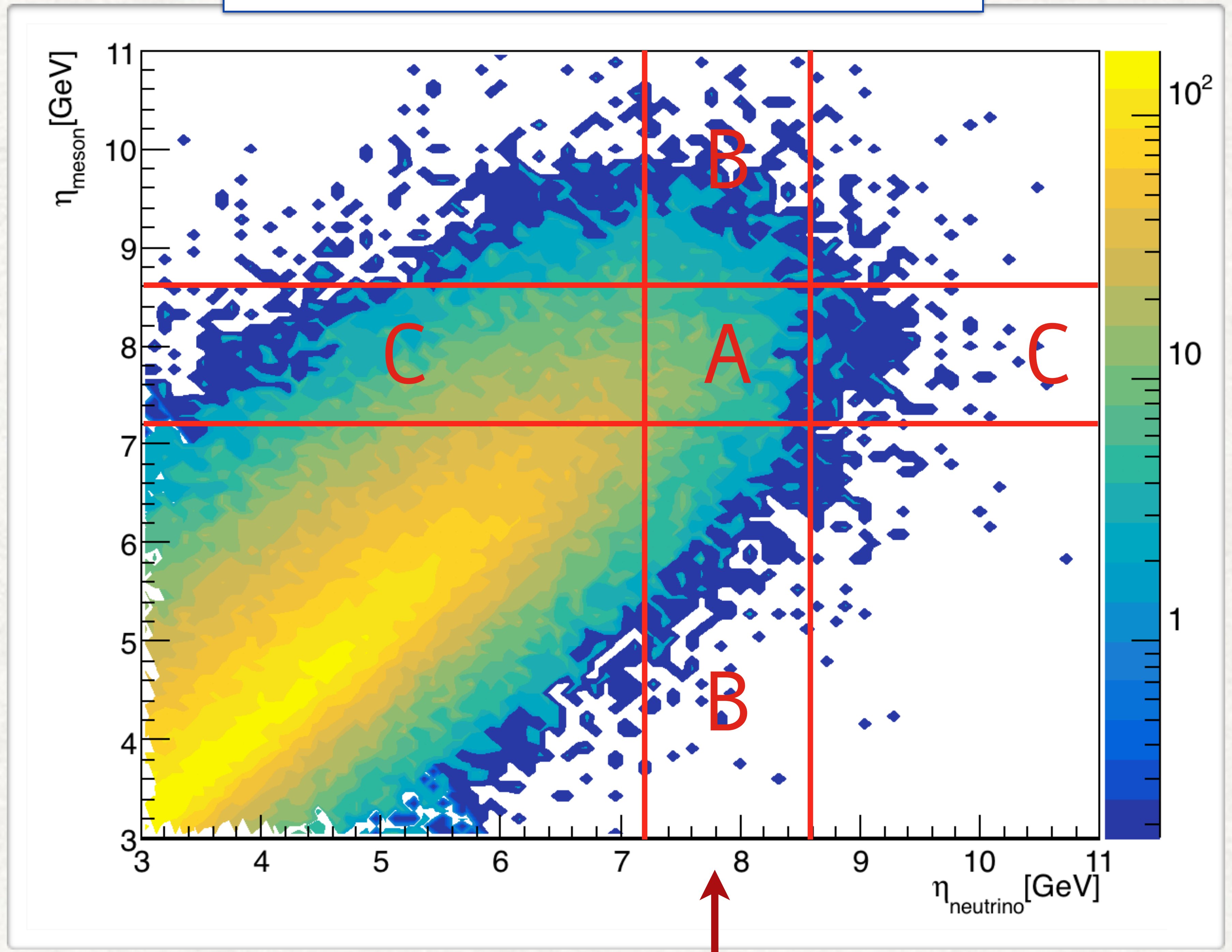


Measurements at SND@LHC can set constrains on the charm production in the forward region, where different generators show large discrepancies

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: $7.2 < \eta_{meson} < 8.6$



Neutrinos in SND@LHC acceptance

Study performed by F. Tramontano
Details in his talk

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

N_A/N_{A+B}

N_A/N_{A+C}

Branching ratio of charmed mesons to ν_e

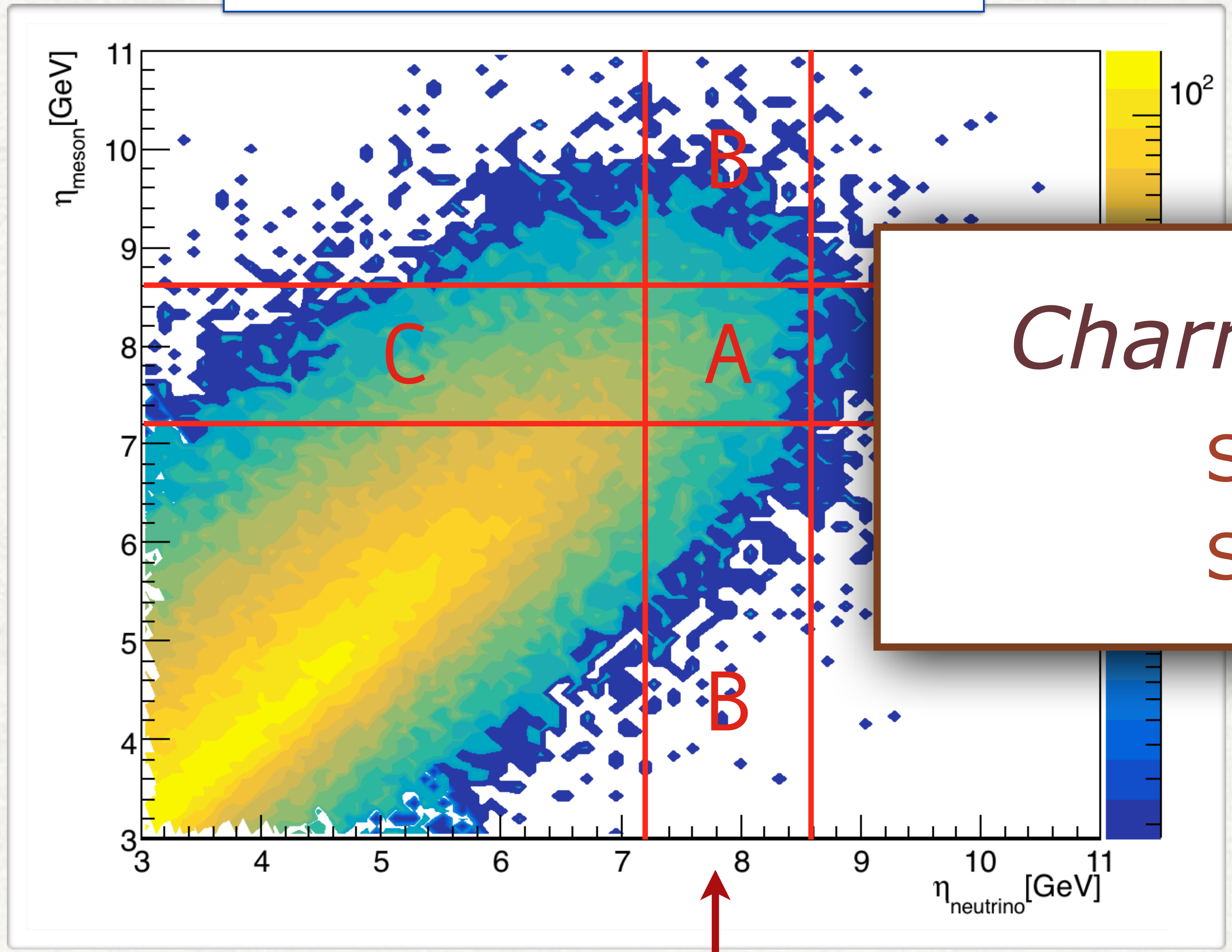
- Fractions f_{AB} and f_{AC} evaluated using leading order computations+Pythia8 parameters for cc-bar production at 13 TeV

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

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: $7.2 < \eta_{meson} < 8.6$



Neutrinos in SND@LHC acceptance

Study performed by F. Tramontano
Details in his talk

N_A/N_{A+B}

Branching ratio of charmed mesons to ν_e

Charmed hadron production

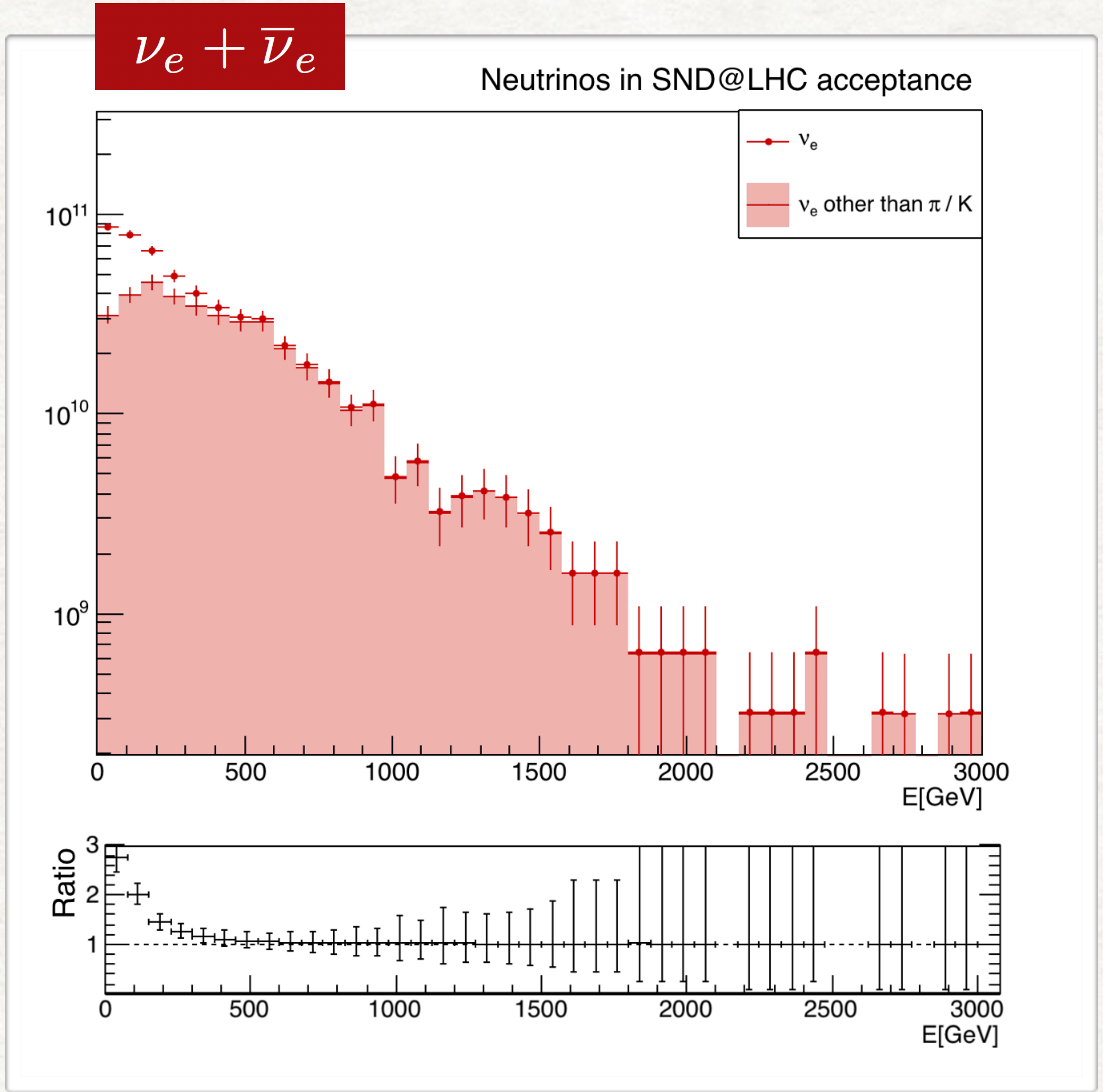
Statistical uncertainty ~5%

Systematic uncertainty ~35%

- 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%**

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)



- 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

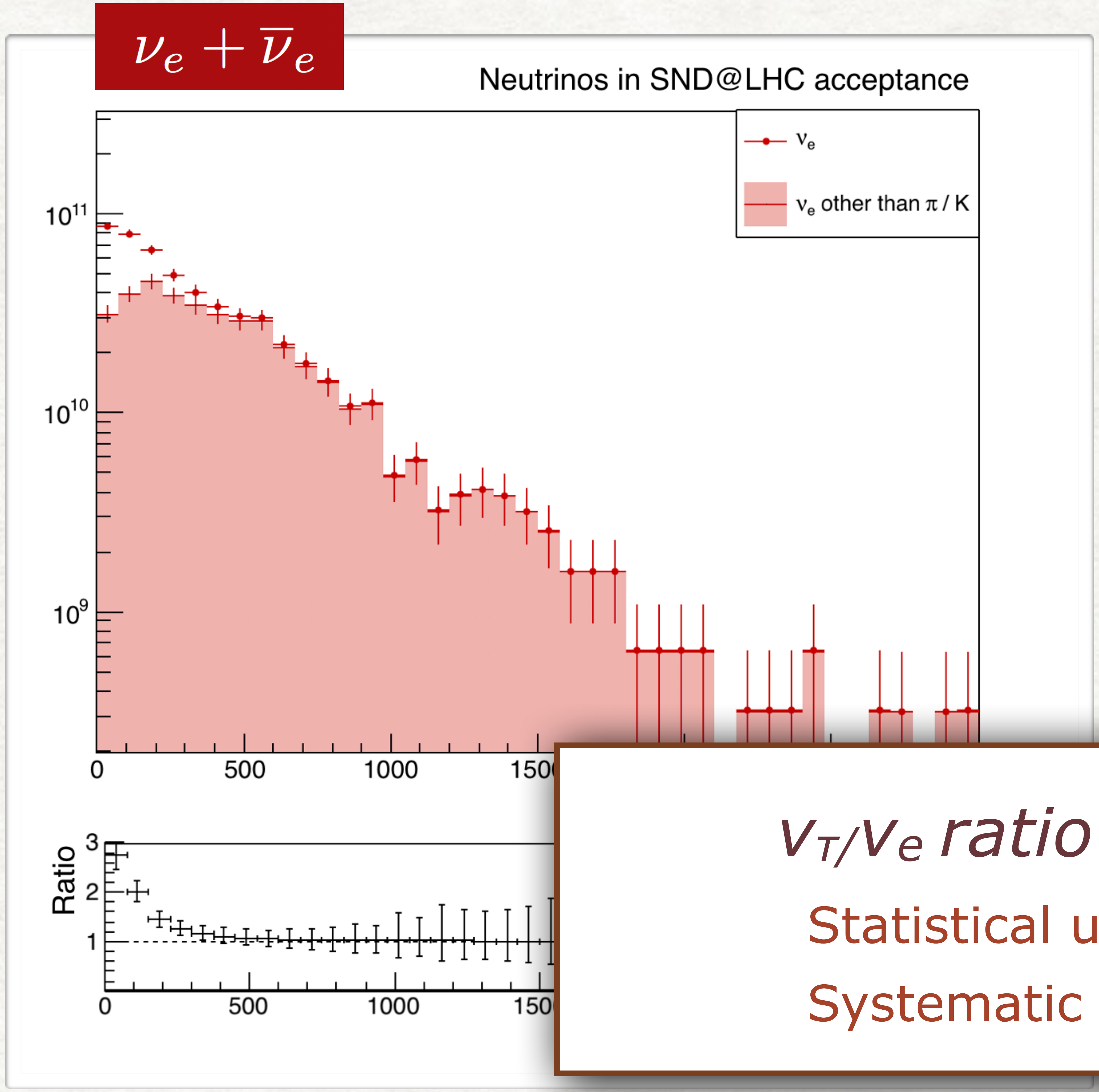
$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)},$$

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

- Statisical error due to low ν_τ statistics :**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)



- 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

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

as discrepancy between values

rwig generators: **20%**

statistics :**30%**

ν_τ/ν_e ratio for LFU test

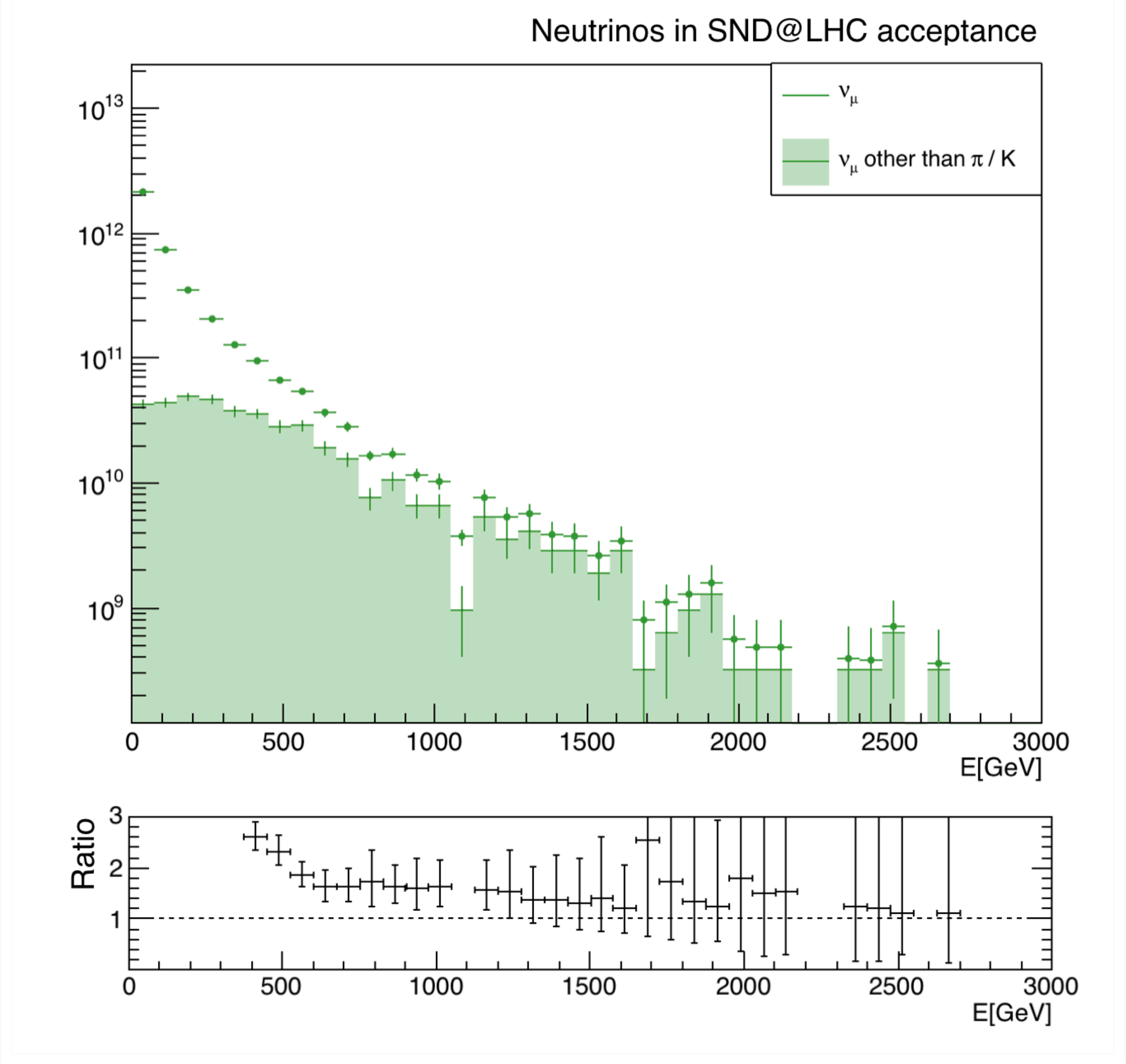
Statistical uncertainty ~30%

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

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



$N(\nu_\mu + \overline{\nu}_\mu)[E > 600\, GeV] = 290$ in 150 fb^{-1}

$N(\nu_e + \overline{\nu}_e)[E > 600\, GeV] = 190$ 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

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

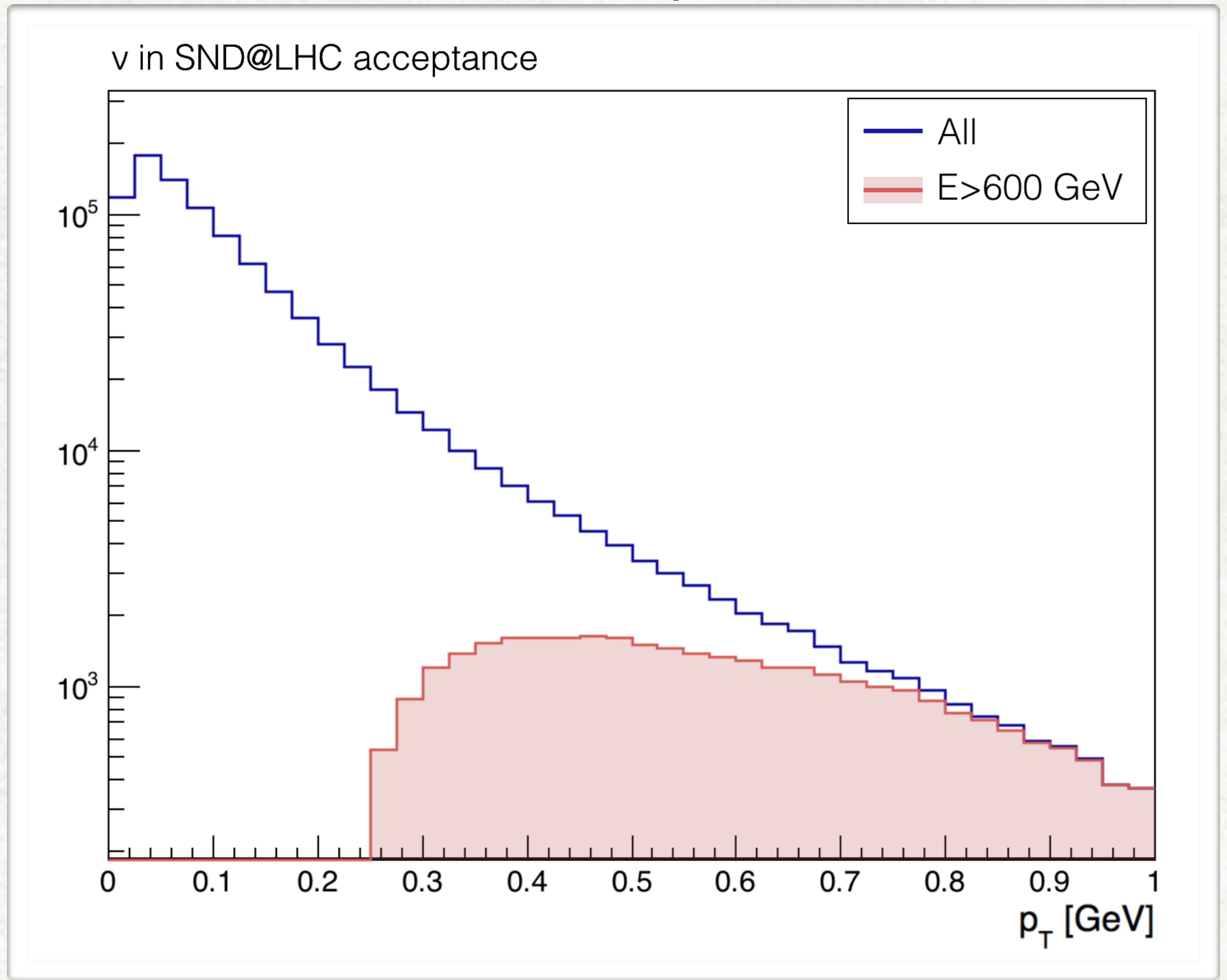
UNCERTAINTY IN PION/KAON CONTAMINATION

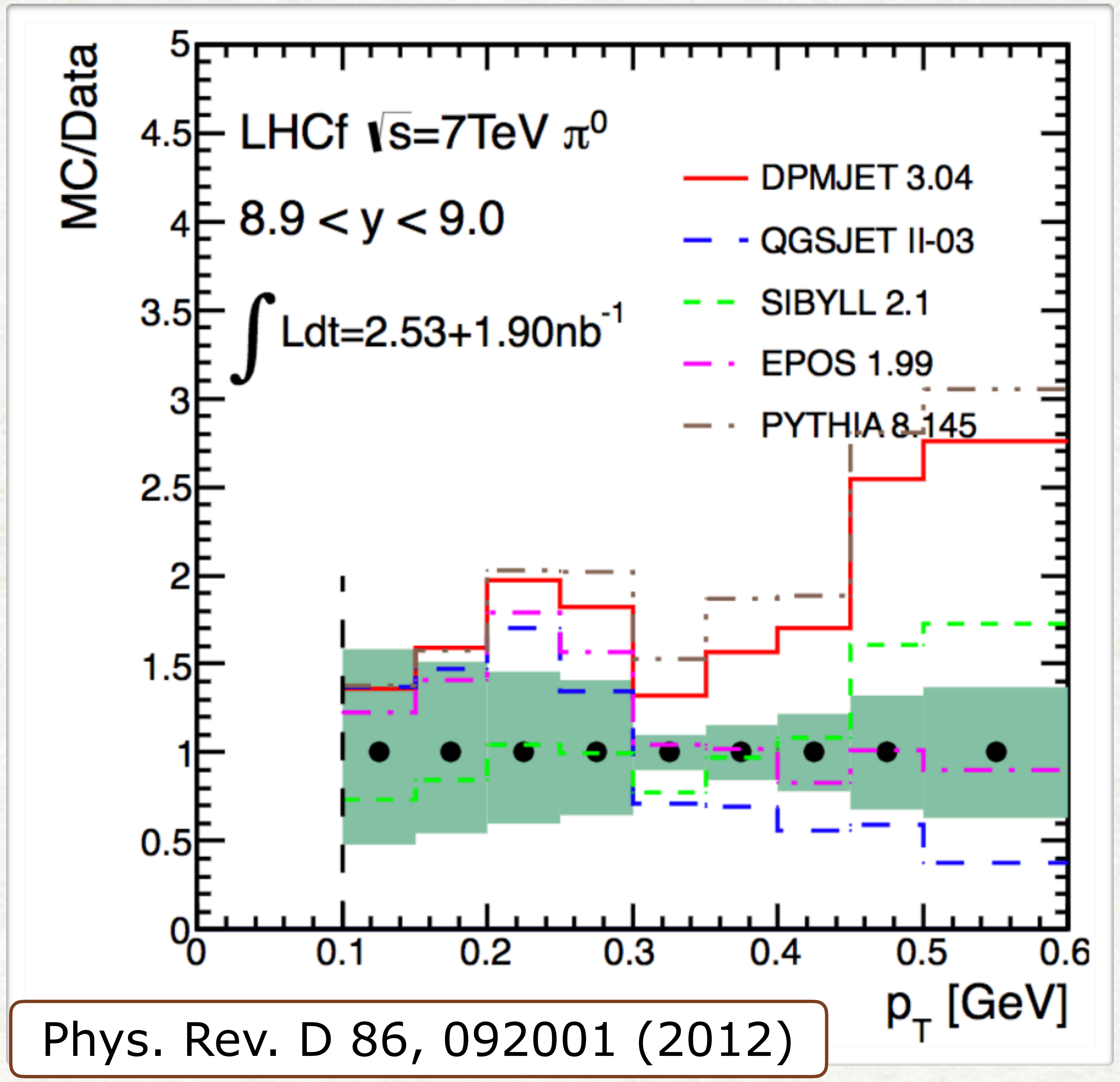
- The uncertainty in the knowledge of π/k contamination has two contributions:

1. Production of π/k
2. Propagation along beamline

- Simulation of light meson production in forward region constrained by LHCf collaboration
- Agreement better than **10%** with EPOS generator for p_T>300 GeV

- Neutrinos in SND@LHC acceptance with E>600 GeV have p_T>250 GeV





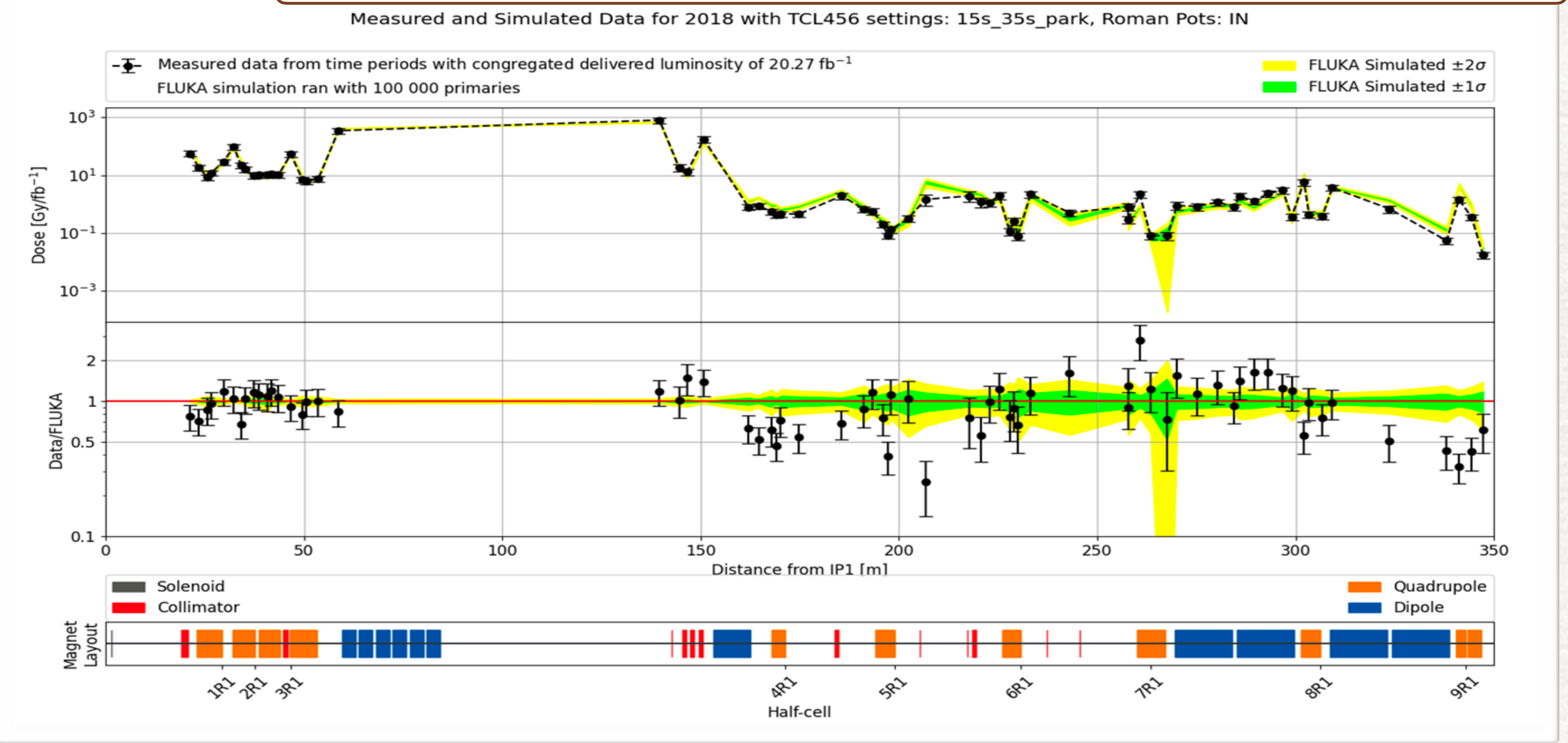
Phys. Rev. D 86, 092001 (2012)

UNCERTAINTY IN PION/KAON CONTAMINATION

- The uncertainty in the knowledge of π/k contamination has two contributions:

1. Production of π/k
2. Propagation along beamline

Courtesy of D. Prelipcean and G. Lerner (CERN-EN-TI-BMI)



- Charged meson propagation performed with FLUKA and show very good agreement with measurements performed along the beamline

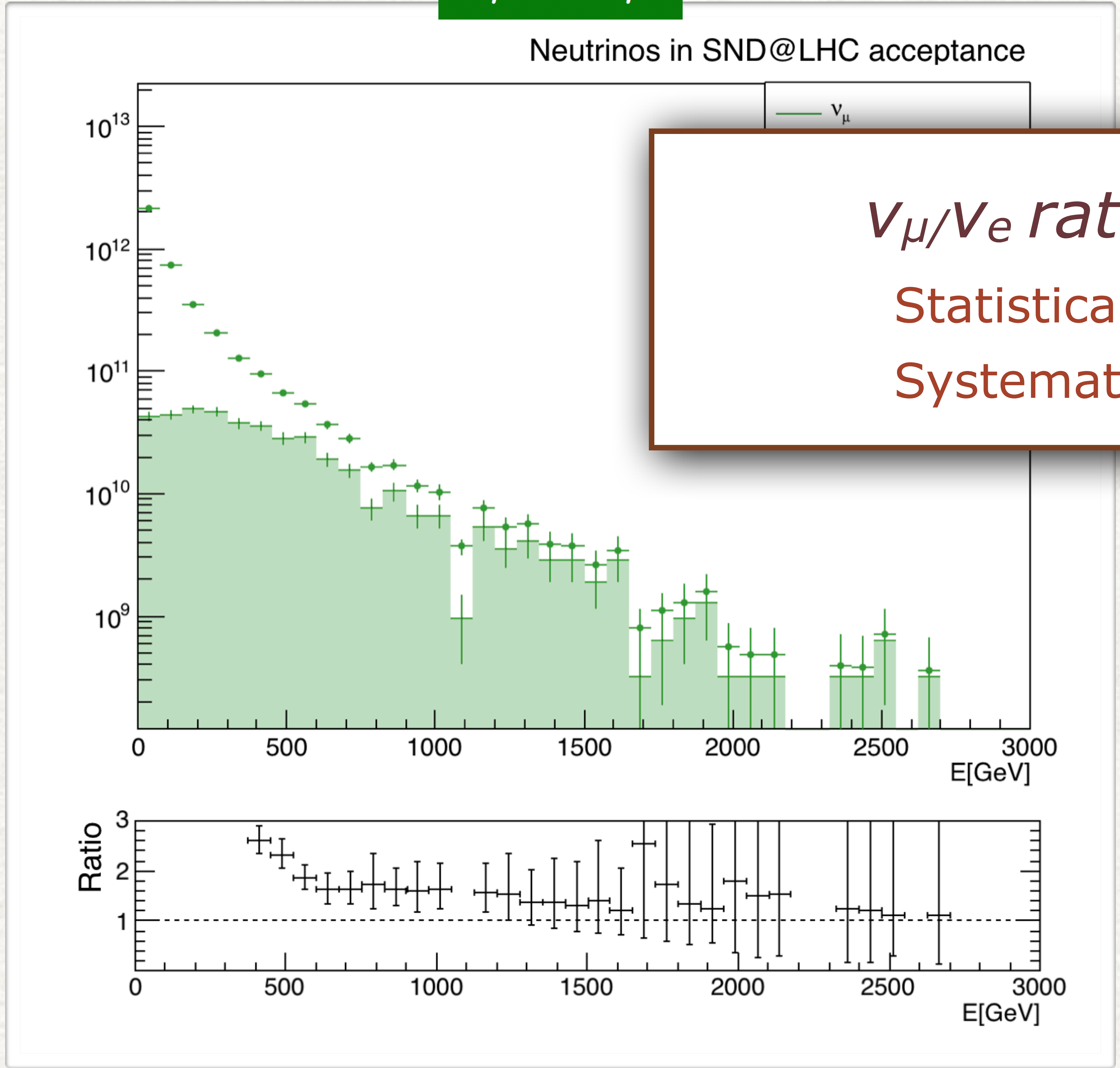
- Measurements performed by FASER in TI18 in agreement with FLUKA predictions ($2\text{x}10^4/\text{cm}^2/\text{fb}^{-1}$) within errors

- SND@LHC will measure particle flux in TI18 with high accuracy, using different detectors

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

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



$N(\nu_\mu + \overline{\nu}_\mu)[E > 600\, GeV] = 290$ in 150 fb^{-1}

... $)[E > 600\, GeV] = 190$ in 150 fb^{-1}

ν_μ/ν_e ratio for LFU test

Statistical uncertainty ~10%

Systematic uncertainty ~10%

...ratio can be used as a test

...and *Br* since charmed

...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

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

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

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

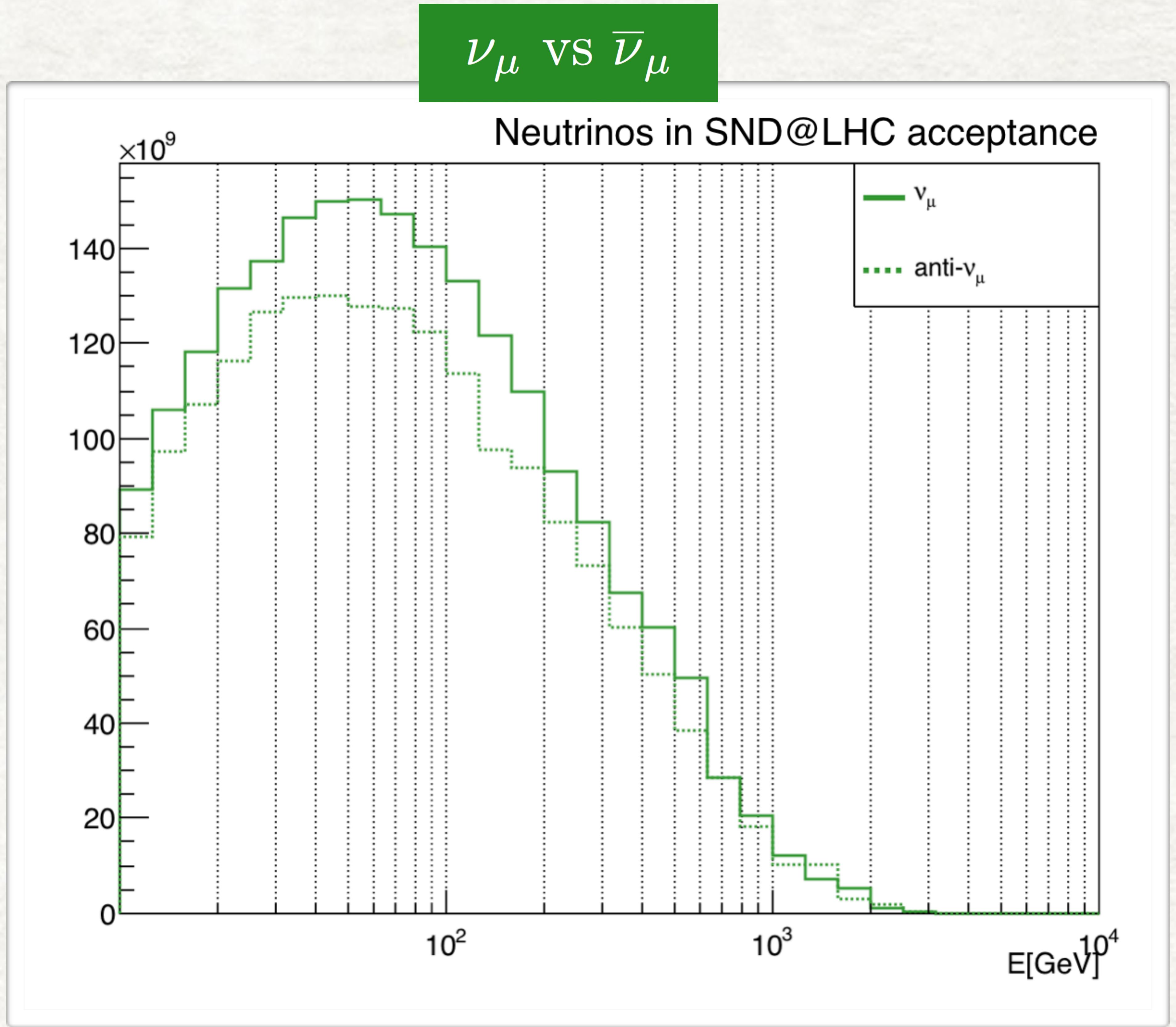
- In case of DIS, *P* can be written as

Rept.Prog.Phys. 79 (2016) 12, 124201

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

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



- **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%**

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

Rept.Prog.Phys. 79 (2016) 12, 124201

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

where λ originates from unequal
protons Z and neutrons (A-Z) i
Introduces a correction factor of

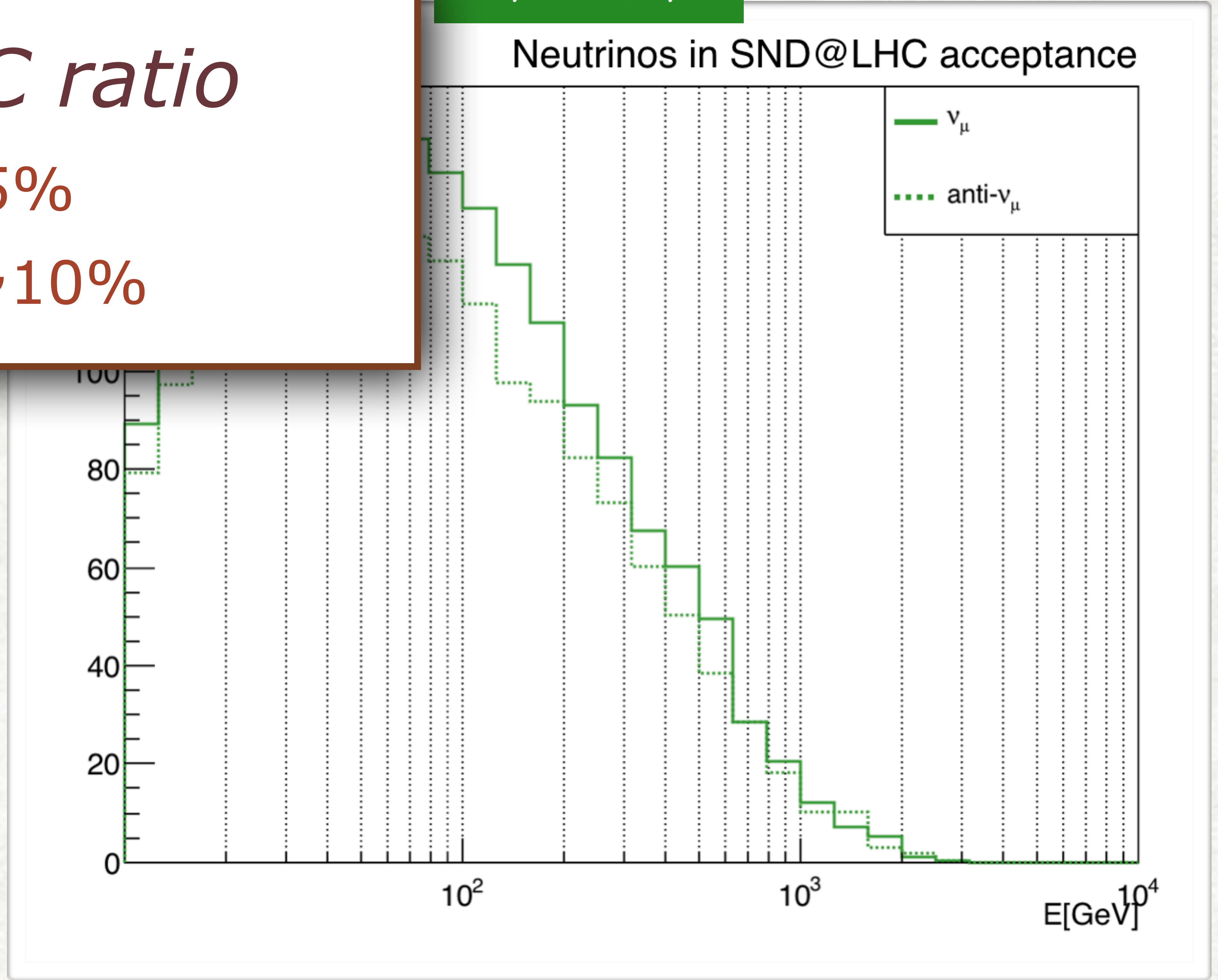
For a Tungsten target λ=0.04

Measurement of NC/CC ratio

Statistical uncertainty ~5%

Systematic uncertainty ~10%

ν_μ vs $\bar{\nu}_\mu$



- **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%**

NEUTRINO PHYSICS IN RUN 3

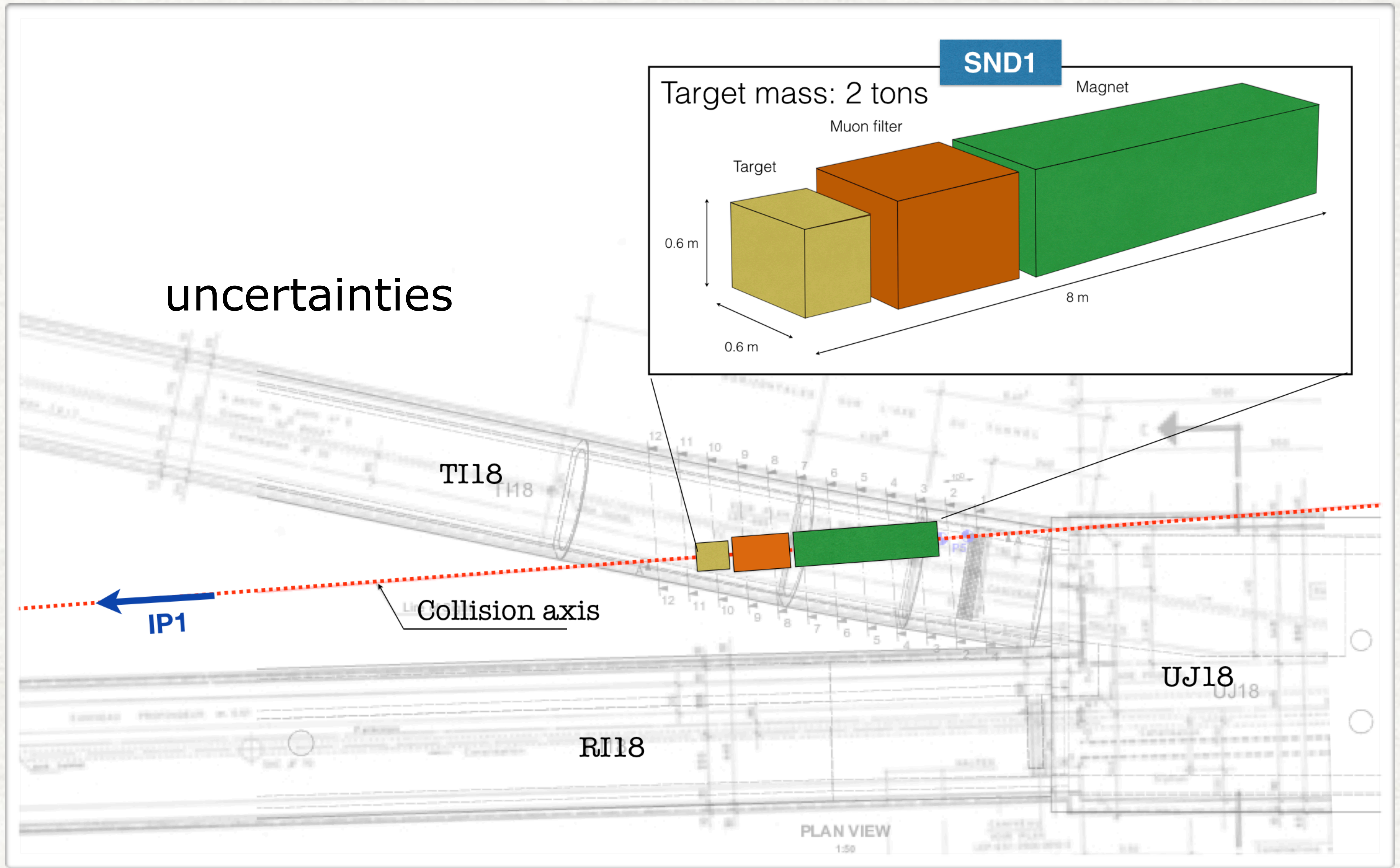
- Summary of SND@LHC performances

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%

OUTLOOK

- Upgrade of the detector in view of an extended run during Run 4:
  - Magnetised region to measure charge of the muon (ν_μ/anti-ν_μ, ν_τ/anti-ν_τ in the $\tau \rightarrow \mu$ channel)
  - Larger target region
  - Replace emulsions with electronic trackers

- Increase the statistics by a factor ~50
- Tau neutrino physics with high statistics
- Explore different pseudo-rapidity regions
- Overlap with LHCb η range to reduce systematic uncertainties

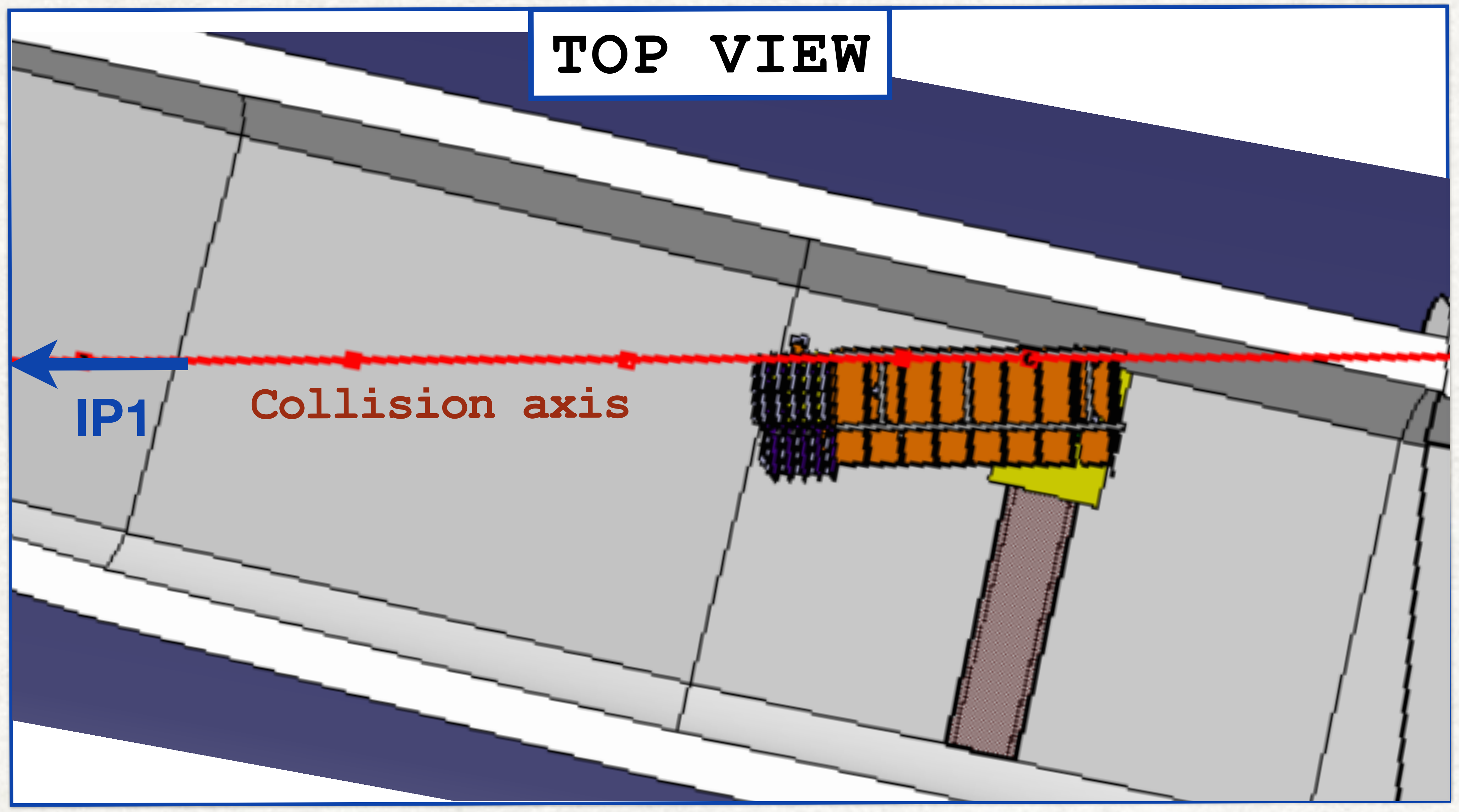


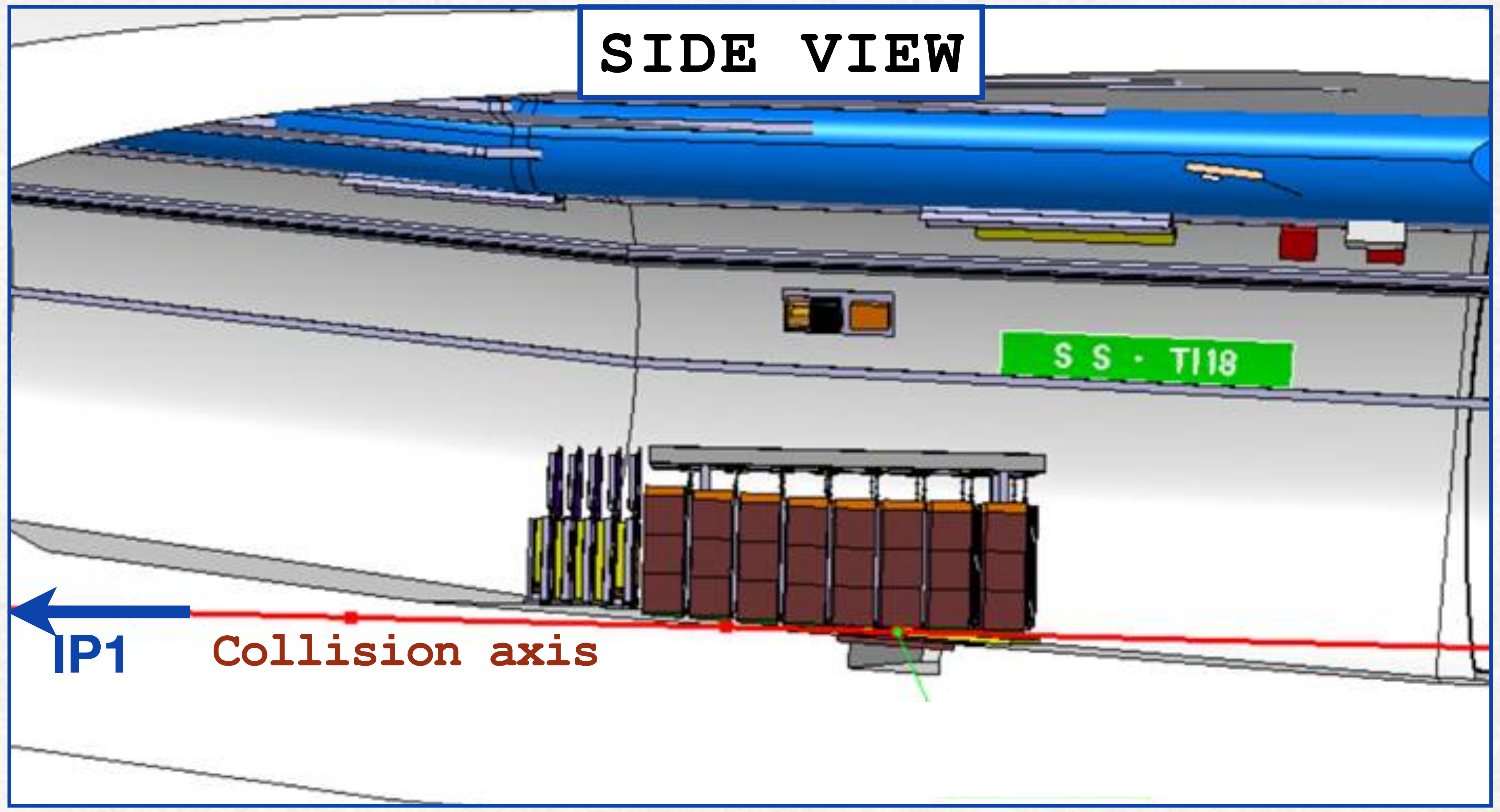
BACKUP SLIDES

GEOMETRICAL CONSTRAINTS

- Constraint on the detector design from the tunnel and the uphill floor
- No civil engineering foreseen

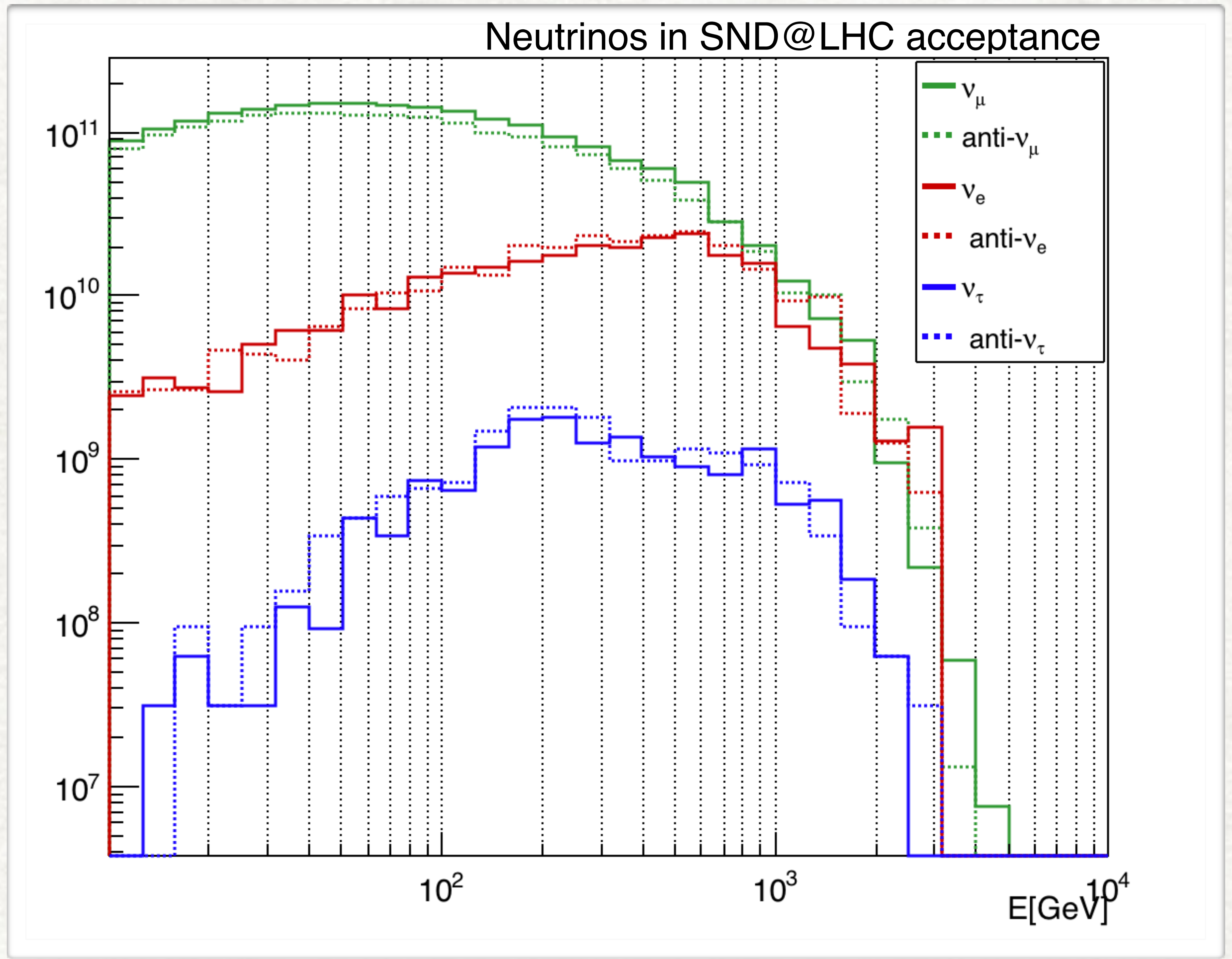
- Enough length for the muon identification and hadronic energy measurement (~10 lengths)
- Intercept a relatively large integrated flux to get a reasonable phi-angle acceptance

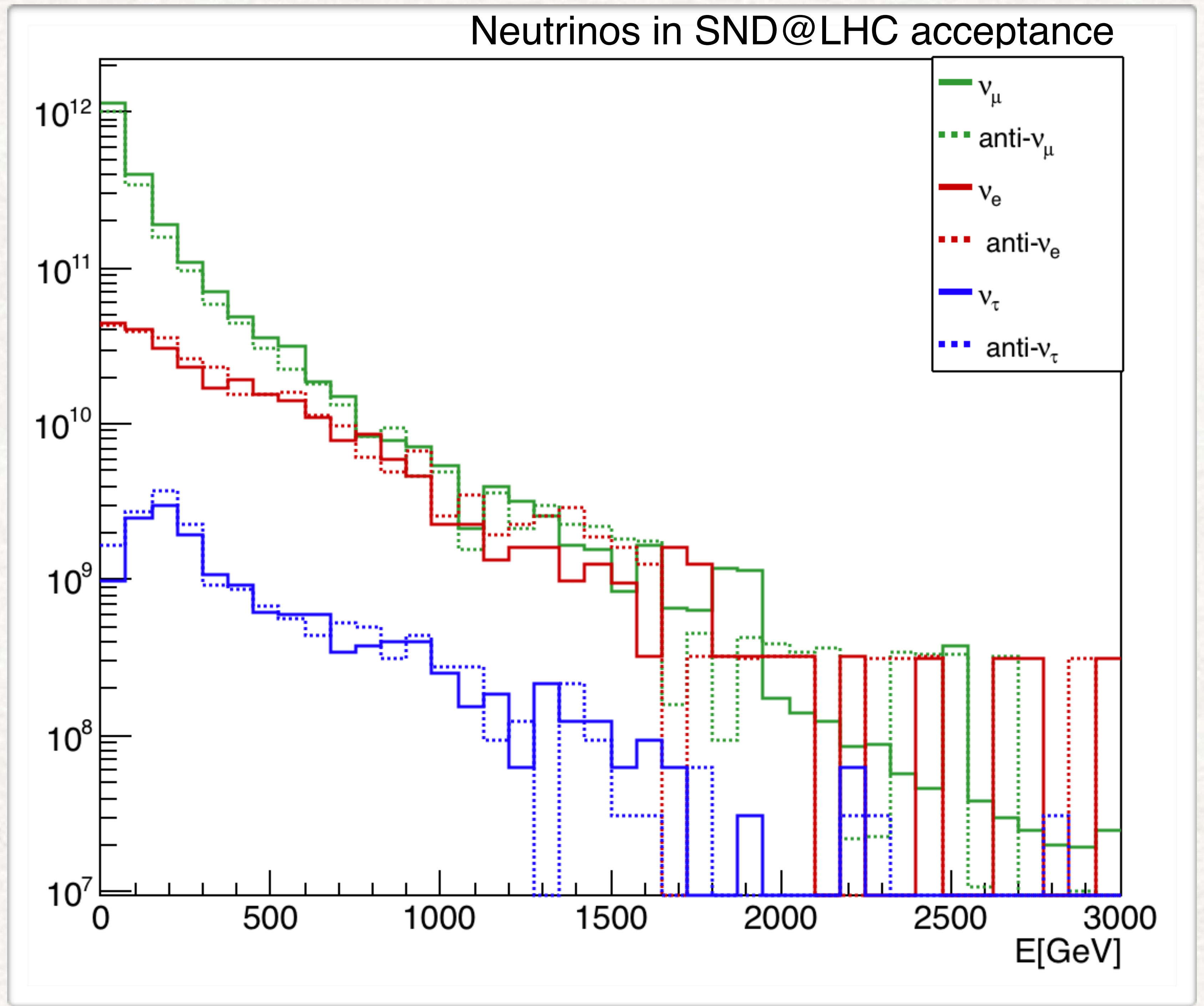




NEUTRINO EXPECTATIONS: Fluxes

- Neutrino spectra in the SND@LHC acceptance





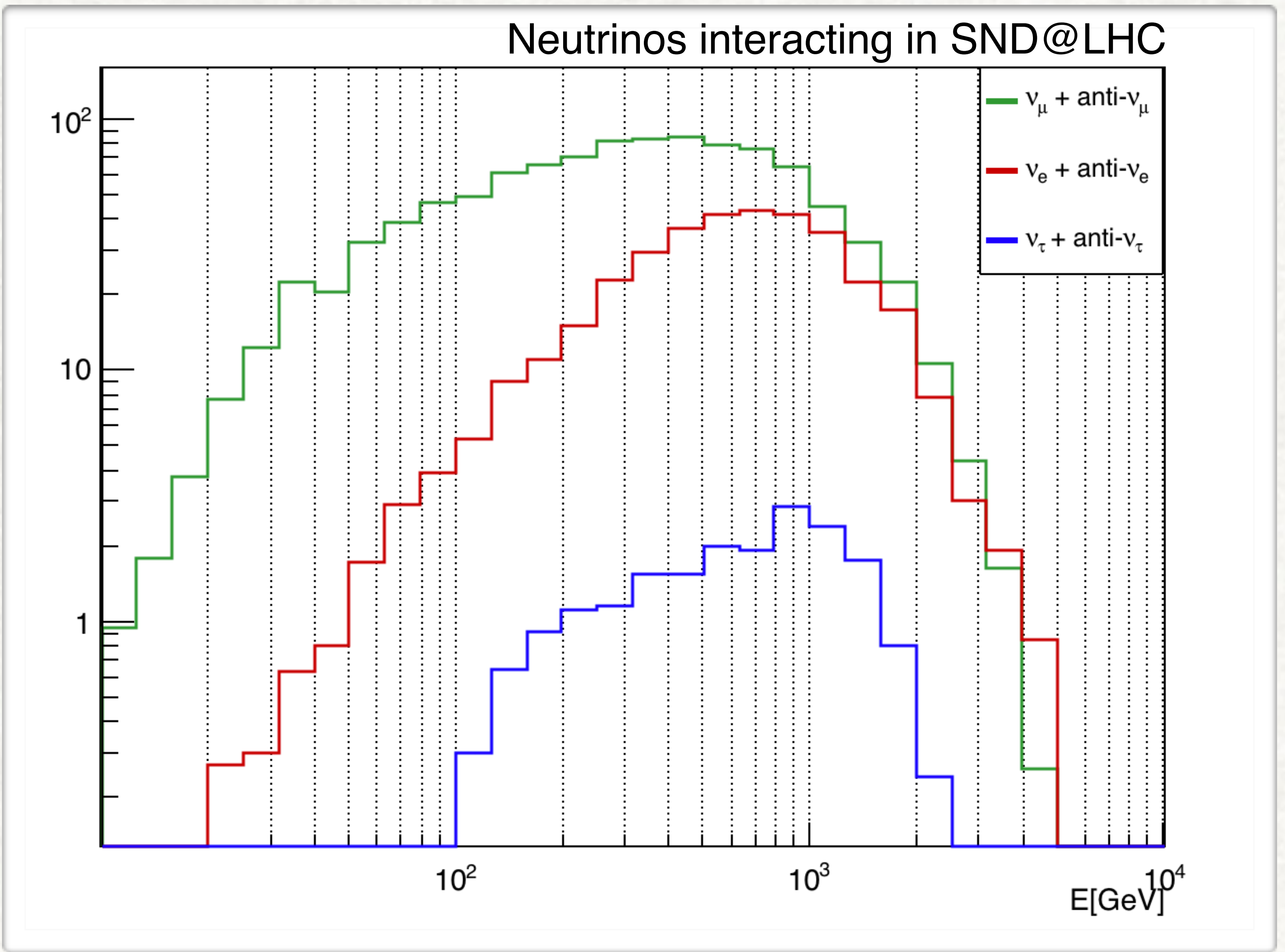
- Expectations in 150 fb^{-1}

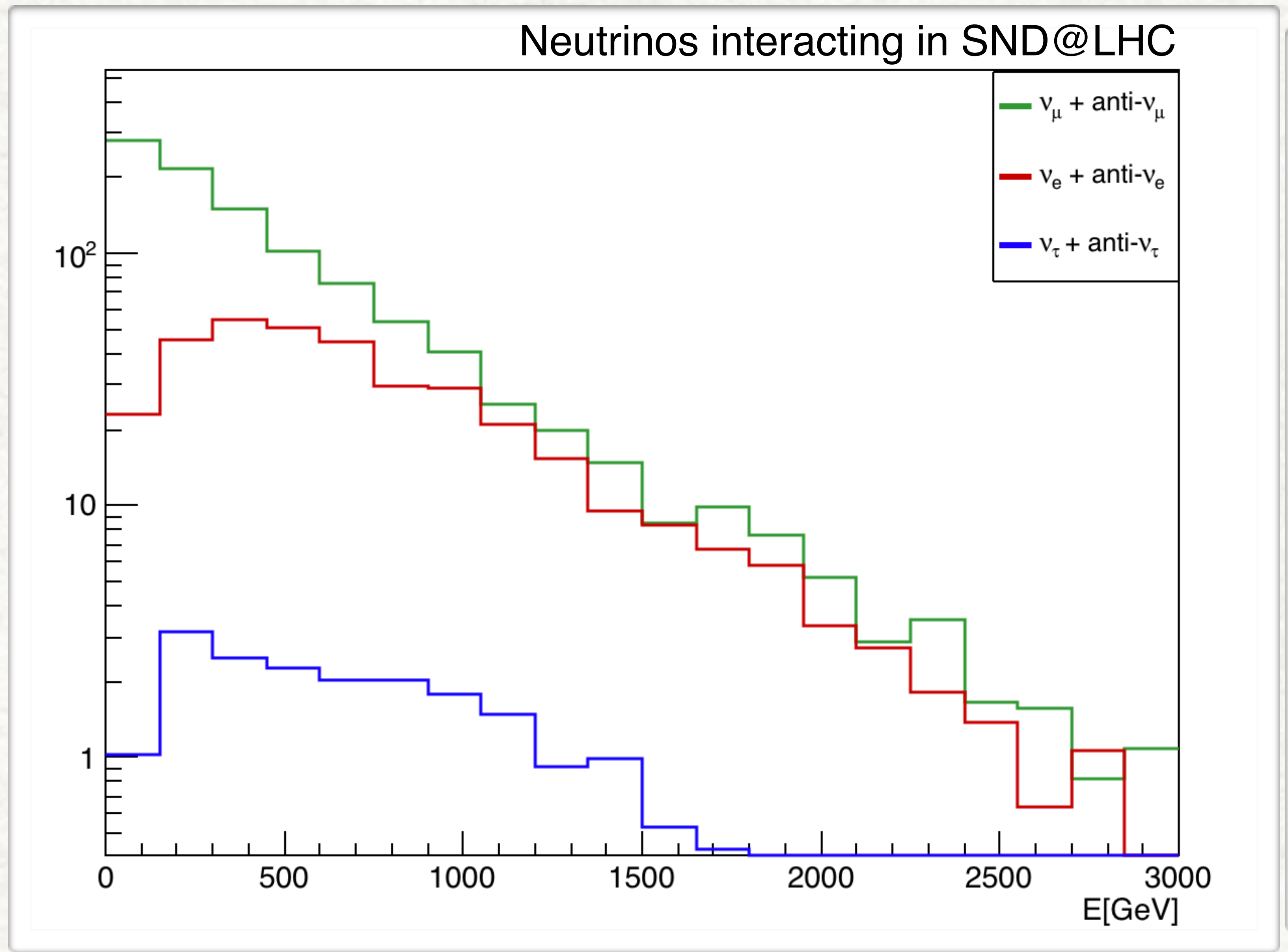
Flavour	Neutrinos in acceptance $\langle E \rangle$ (GeV)	Yield
ν_μ	145	2.1×10^{12}
$\bar{\nu}_\mu$	145	1.8×10^{12}
ν_e	395	2.6×10^{11}
$\bar{\nu}_e$	405	2.8×10^{11}
ν_τ	415	1.5×10^{10}
$\bar{\nu}_\tau$	380	1.7×10^{10}
TOT		4.5×10^{12}

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

NEUTRINO EXPECTATIONS: Interactions

- Spectra of neutrinos interacting in SND@LHC





- Expectations in 150 fb^{-1}

Flavour	CC neutrino interactions $\langle E \rangle$ (GeV)	CC Yield	NC neutrino interactions $\langle E \rangle$ (GeV)	NC 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