SND@LHC

THE SCATTERING AND NEUTRINO DETECTOR AT THE LHC

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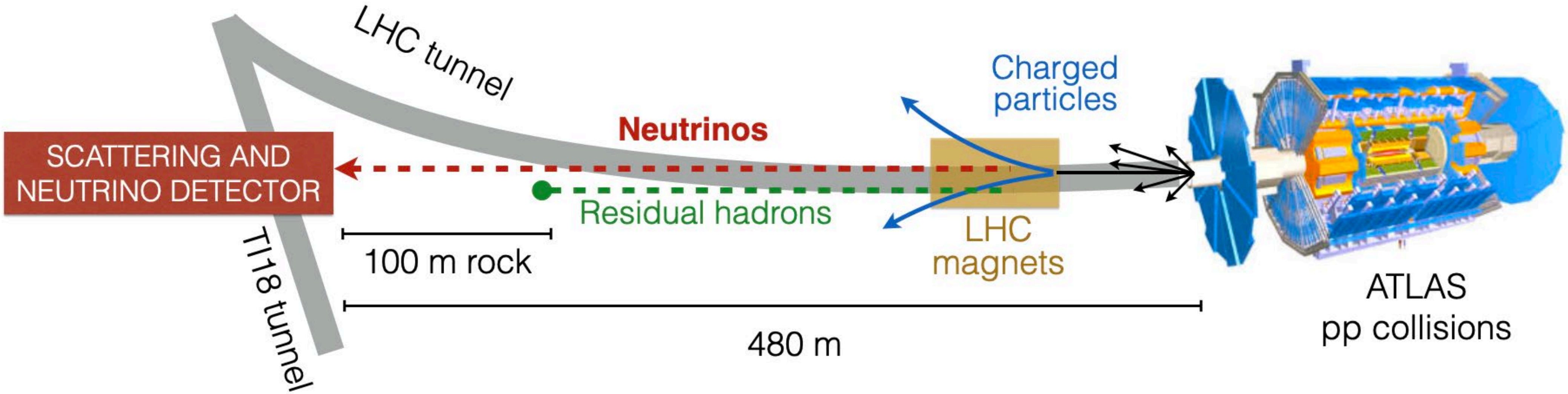
On behalf of the SND@LHC Collaboration

XIV International Conference on Beauty, Charm and Hyperon Hadrons(BEACH 2022),
9 June 2022

OVERVIEW



- Introduction to the SND@LHC experiment
- Detector overview
- Commissioning and installation
- Plans for event reconstruction and physics measurements

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

Approved by the Research Board on March 2021

https://snd-lhc.web.cern.ch/

NEUTRINOS AT THE LHC

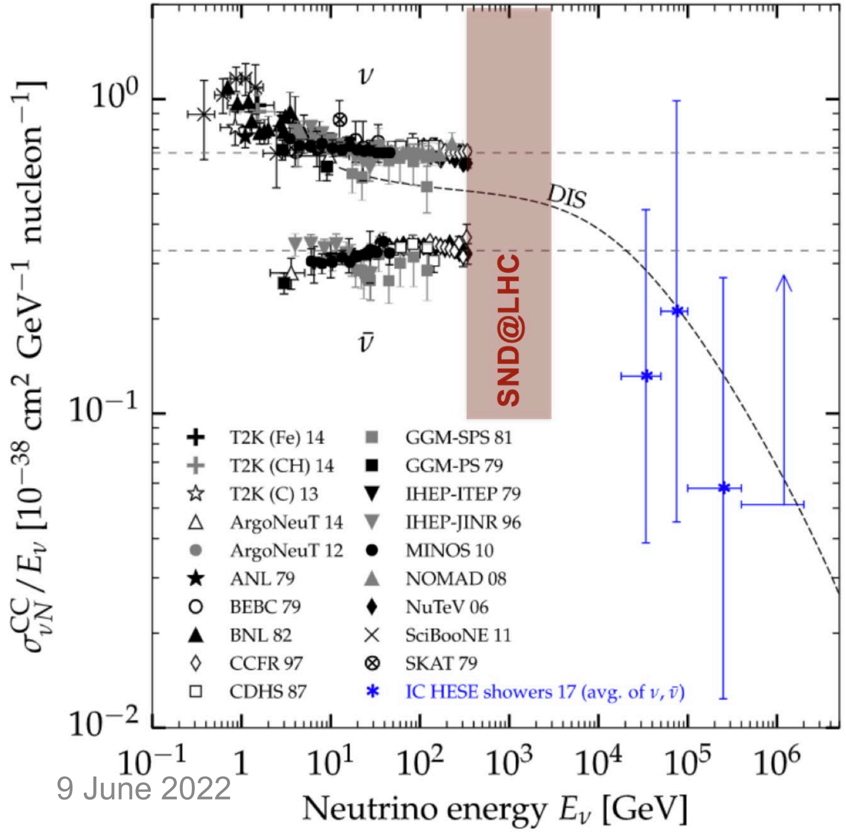
OPEN ACCESS
IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 46 (2019) 115008 (19pp)
https://doi.org/10.1088/1361-6471/ab3f7c

Physics potential of an experiment using LHC neutrinos

OPEN ACCESS
IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 47 (2020) 125004 (18pp)
https://doi.org/10.1088/1361-6471/aba7ad

Further studies on the physics potential of an experiment using LHC neutrinos

PRL 122 (2019) 041101



CERN is unique in providing energetic **ν** (from LHC) and measure pp →**ν**X in an unexplored domain

- High energies, large **ν**N cross sections
- Neutrinos from a colliders, in an unexplored energy region

PHYSICS PROGRAM

Neutrino and QCD physics:

1. Measurement of the $pp \to \nu_e X$ cross-section
2. Heavy flavour production in pp collisions
3. Lepton flavour universality in neutrino interactions

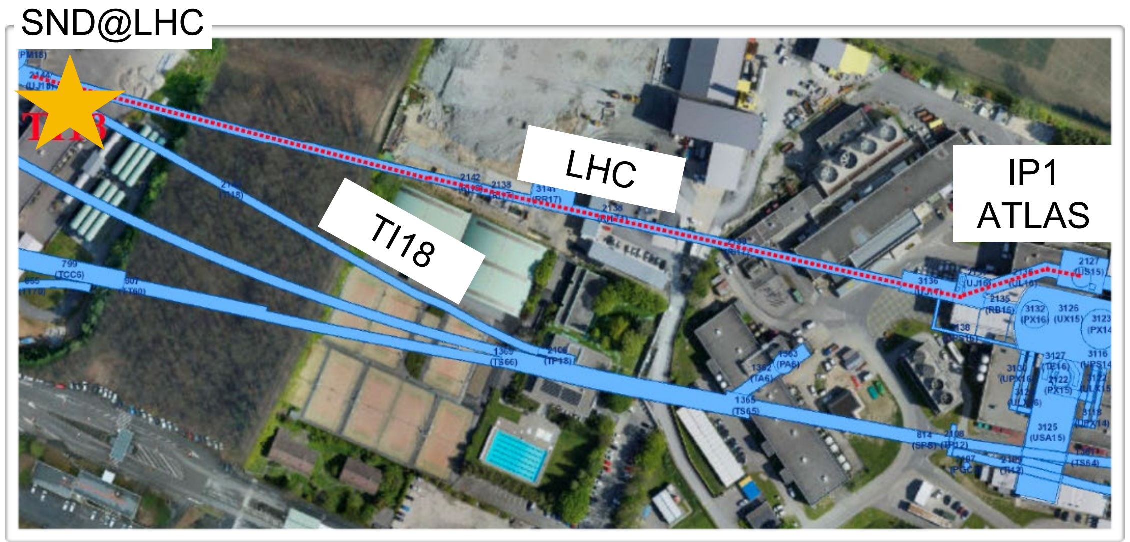
Collected data useful for estimation of very high energy neutrino yields from cosmic rays

Internal consistency checks for the detector:

4. Measurement of the NC/CC ratio

Measurement	Uncertainty	
	Stat.	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%

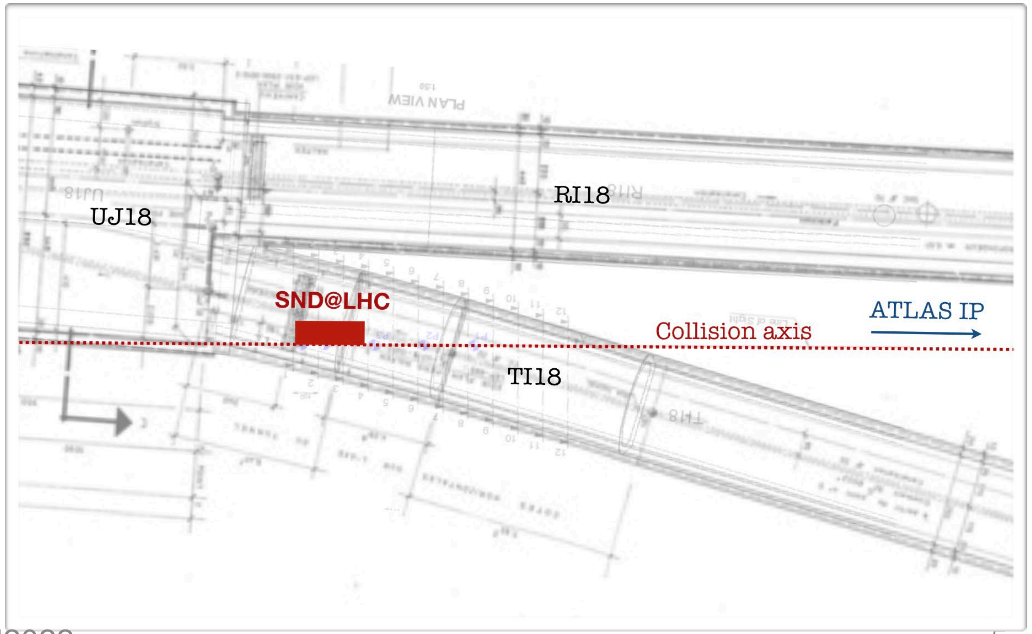
LOCATION



- 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: $7.2<\eta< 8.4$
- First phase: operation in Run 3 to collect 290 fb^{-1}



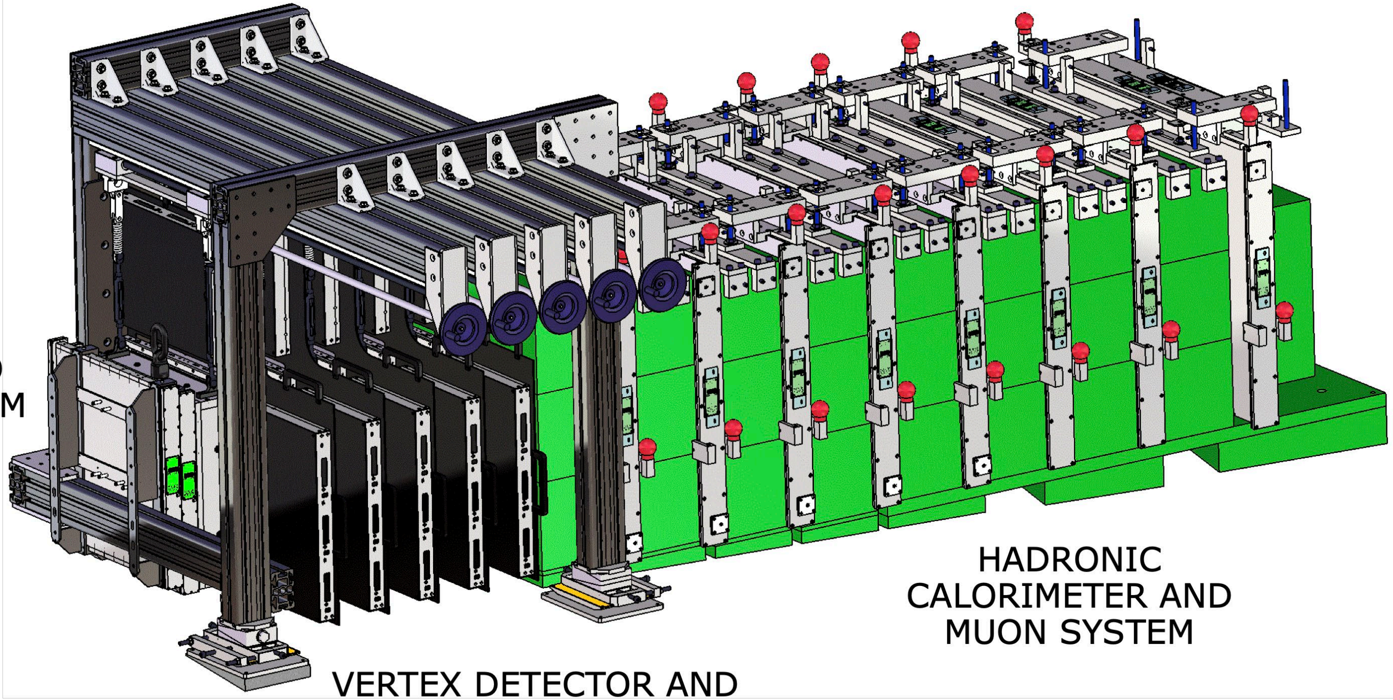
THE SND@LHC CONCEPT

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

VETO SYSTEM:
tag penetrating muons

VERTEX DETECTOR + EM CAL:
- Emulsion cloud chambers (Emulsion+Tungsten) for neutrino interaction detection
- Scintillating fibers for timing information and energy measurement

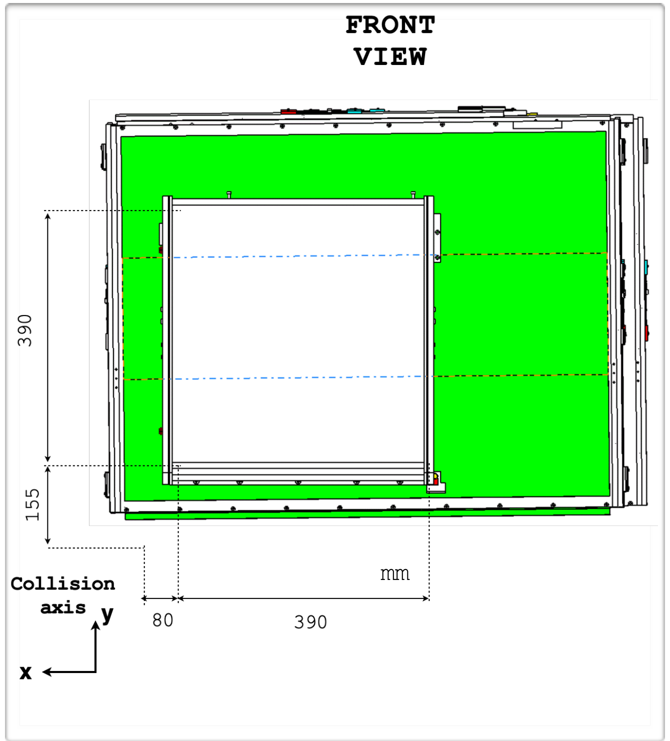
HAD CAL + MUON SYSTEM:
iron walls interleaved with plastic scintillator planes for fast time resolution and energy measurement



THE DETECTOR LAYOUT

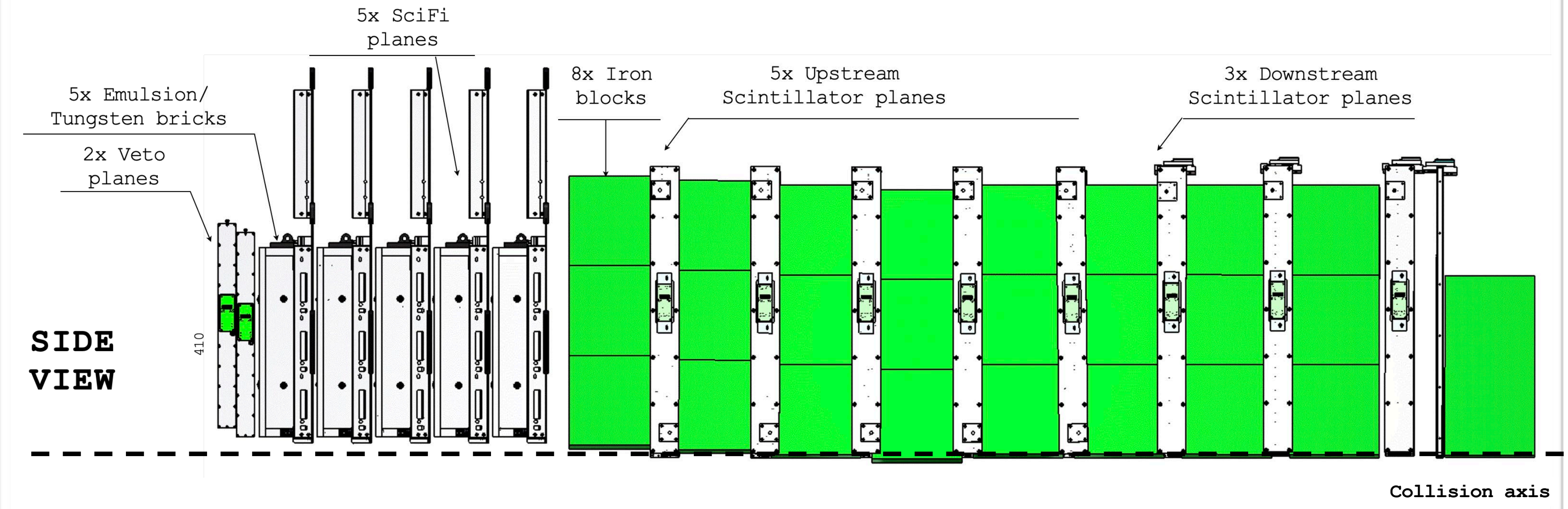
- Angular acceptance: 7.2< η < 8.4
- Target material: Tungsten
- Target mass: 830 kg
- Surface: 390x390 mm^2

Off axis location

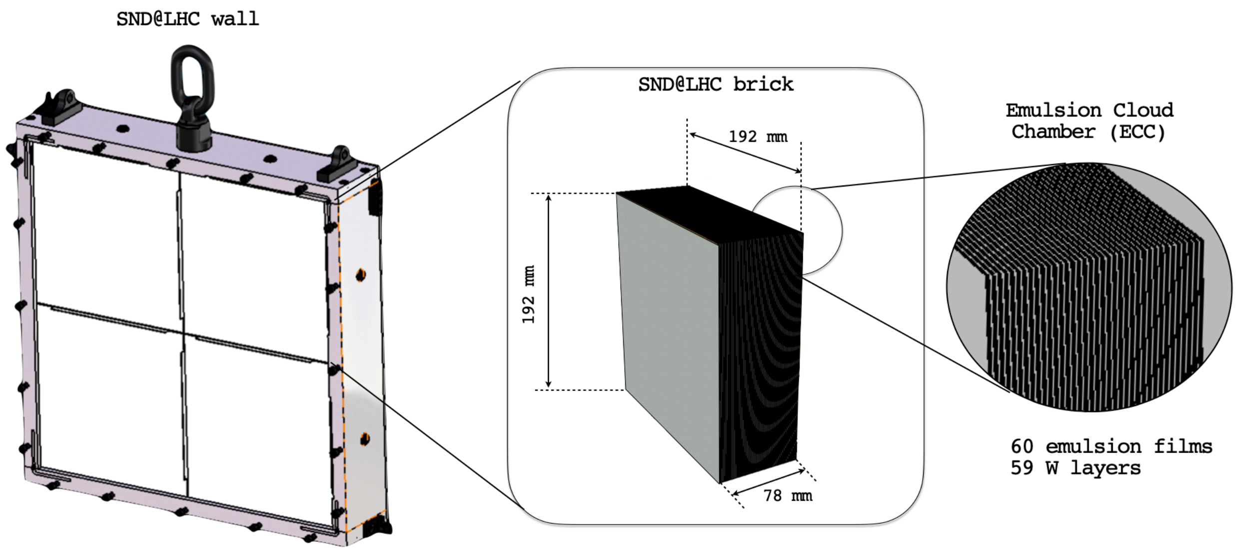


Electromagnetic calorimeter
~40 X_0

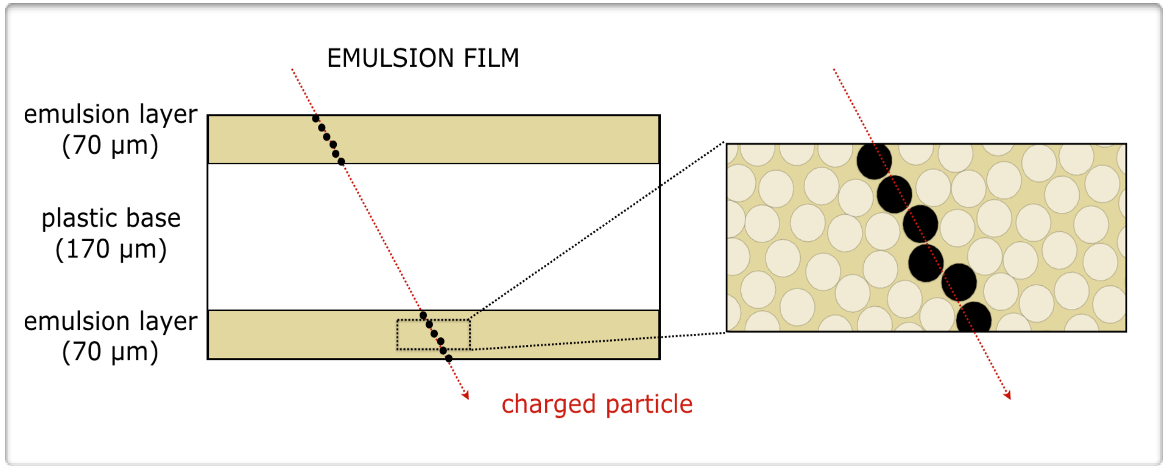
Hadronic calorimeter
~10 λ

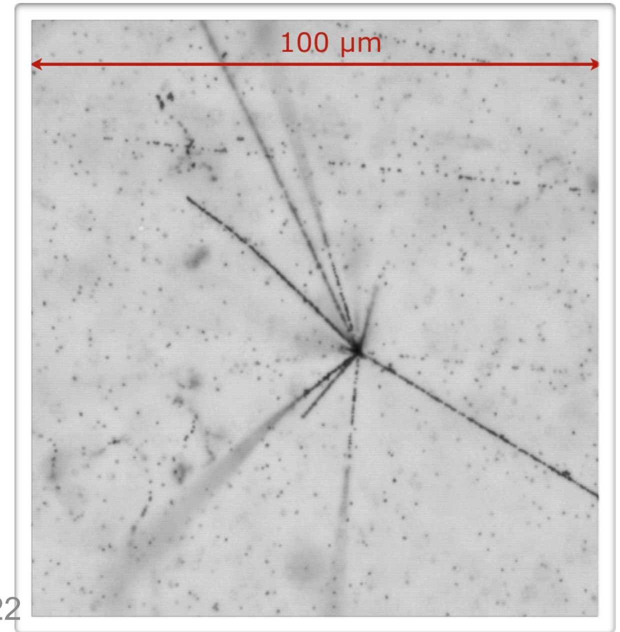


EMULSION TARGET



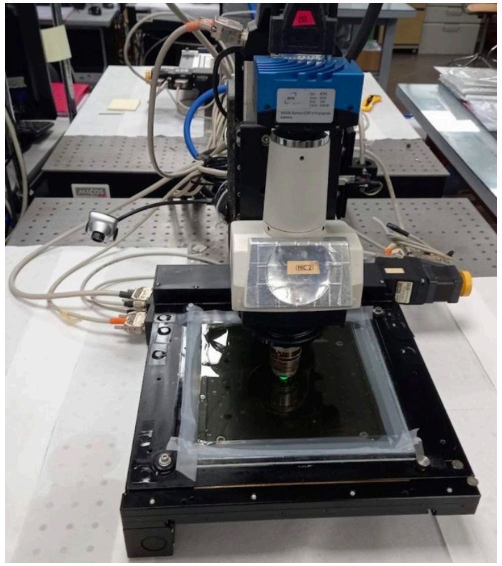
Target assembled according to the Emulsion Cloud Chamber (ECC) technique: Tungsten layers (1mm-thick) alternated to nuclear emulsion films

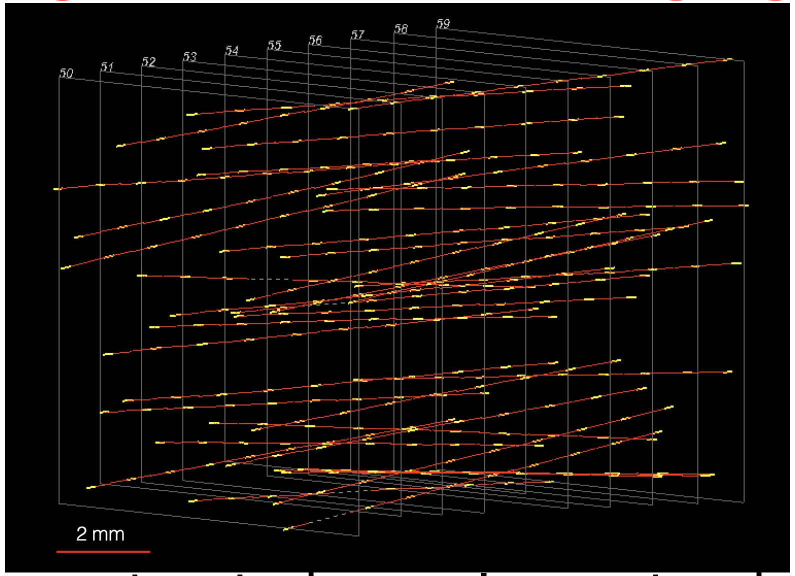




Sub-micrometric position resolution
Milliradian angular resolution

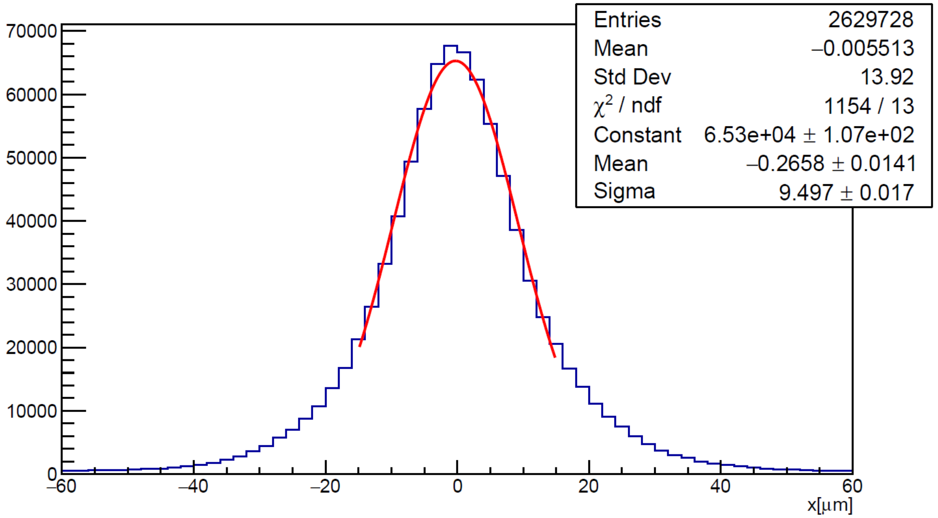
EMULSION SCANNING AND ANALYSIS

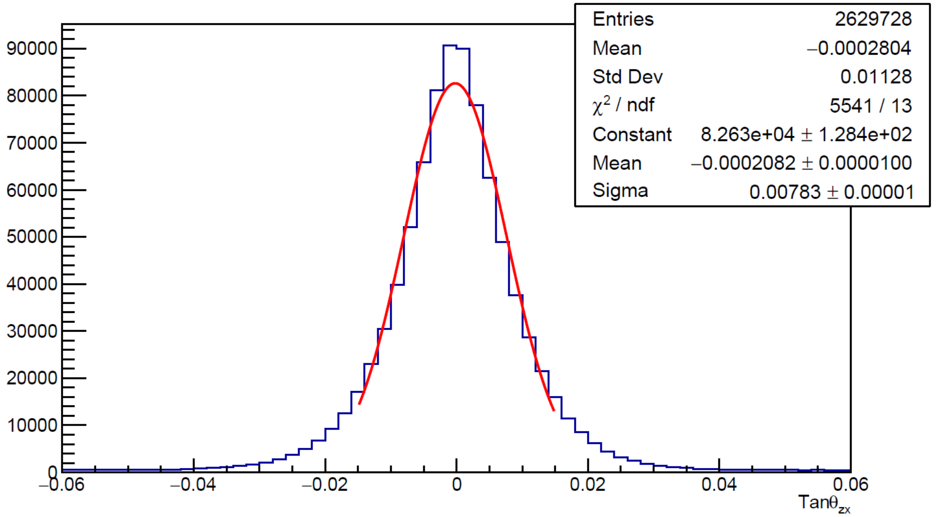




- Automated optical system for the scanning of emulsion films @Napoli Laboratory

Reconstructed cosmic-ray tracks in the SND@LHC wall used in the commissioning



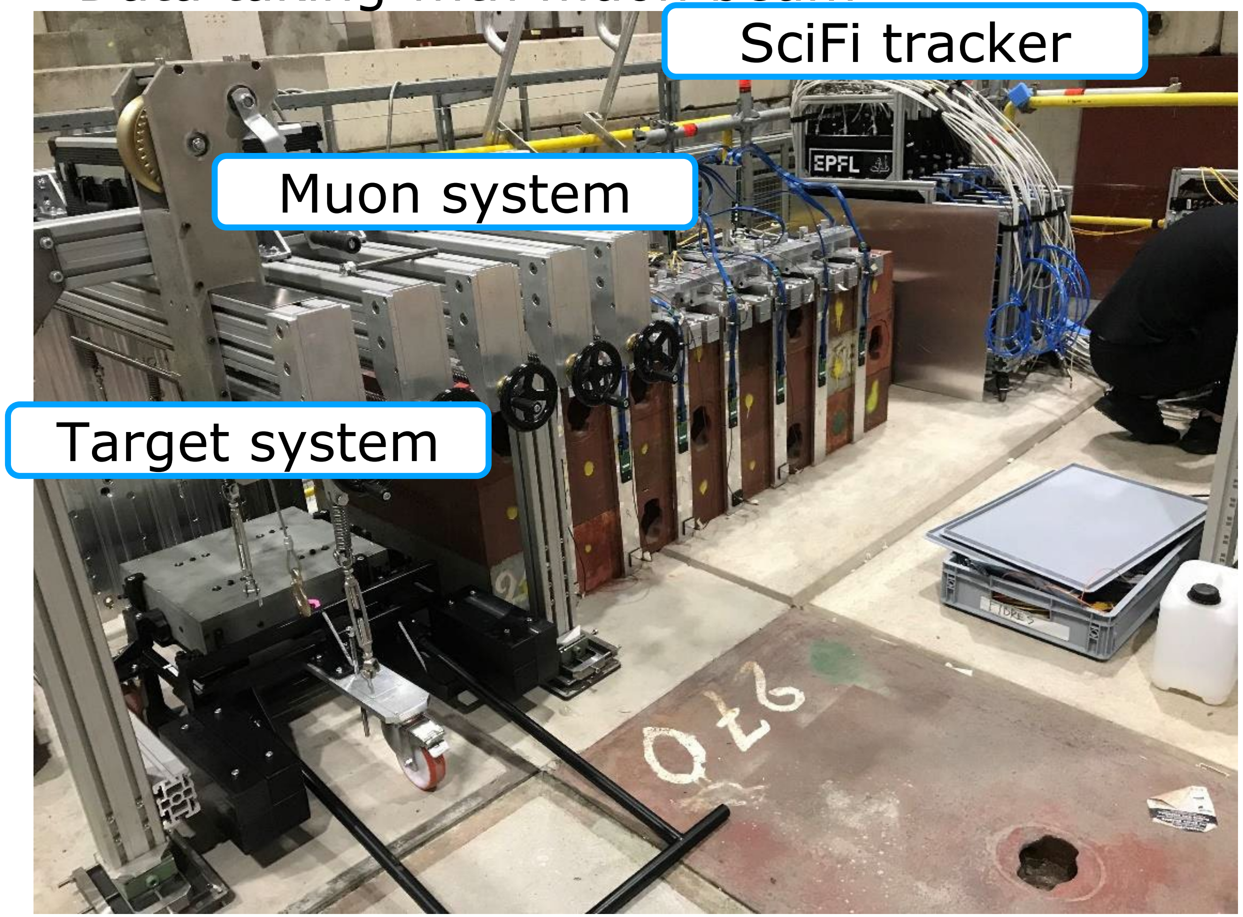


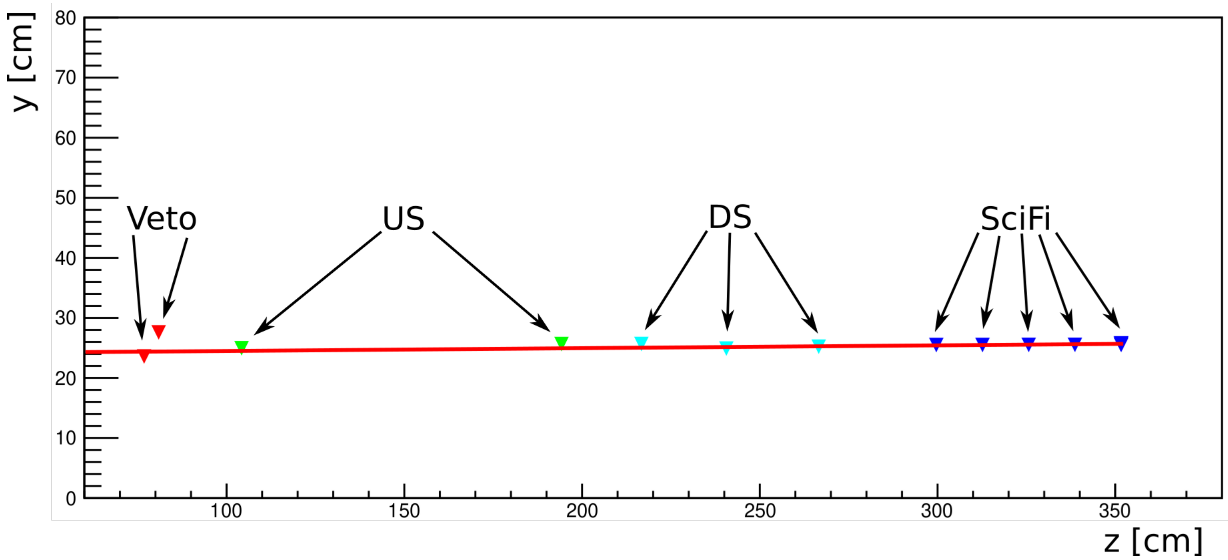
DETECTOR COMMISSIONING ON SURFACE

- Full assembly of the detector at H6 in the North Area
- Target on a 2.5 degree slope to simulate the TI18 floor inclination

Sept 2021

- Successful mechanical test of all subsystems
- Data taking with muon beam

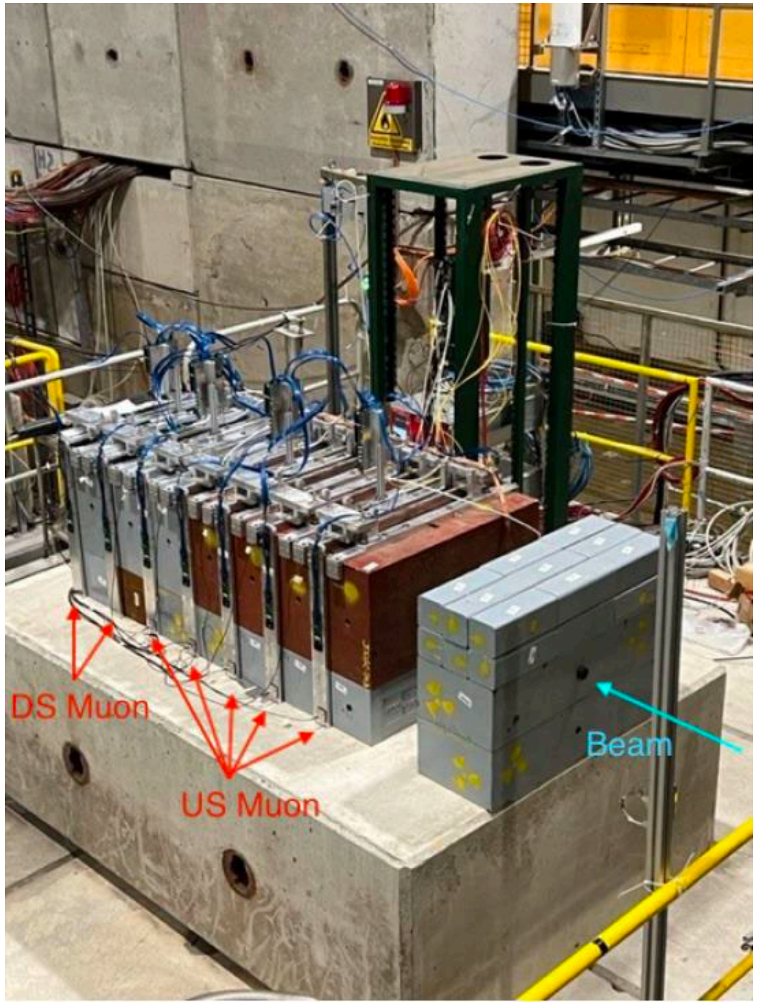


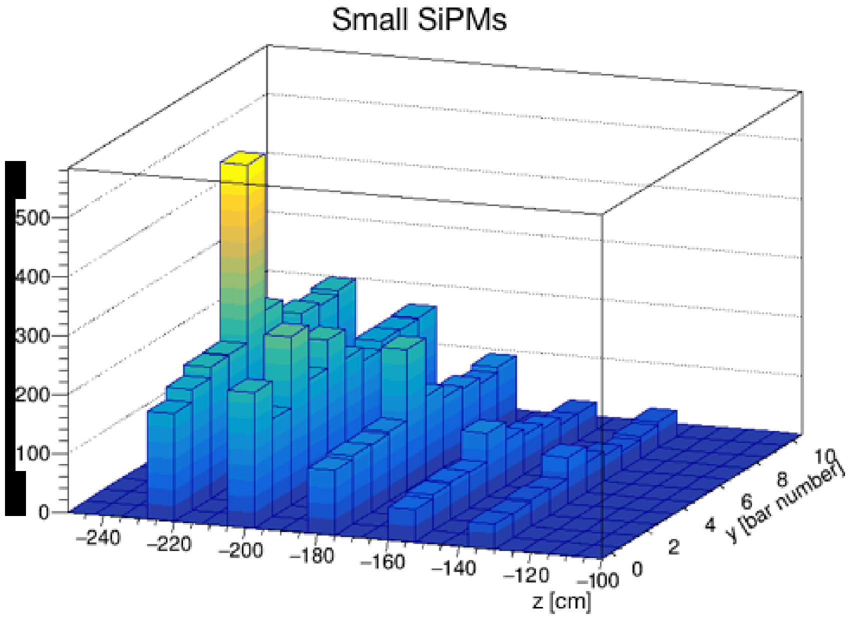


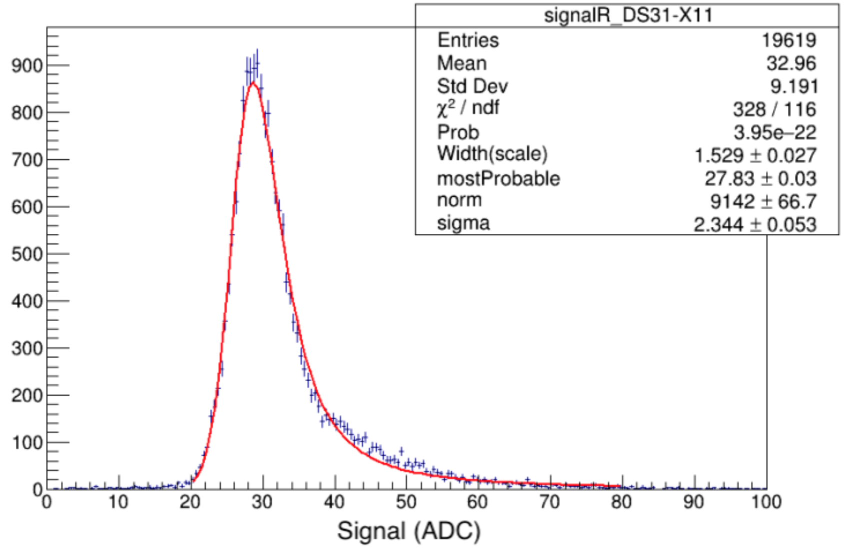
TEST BEAM WITH MUON SYSTEM

- Installation of the whole muon system at H8 in the North Area
- Energy calibration with 140, 180 240, 300 GeV pion beam

Oct 2021



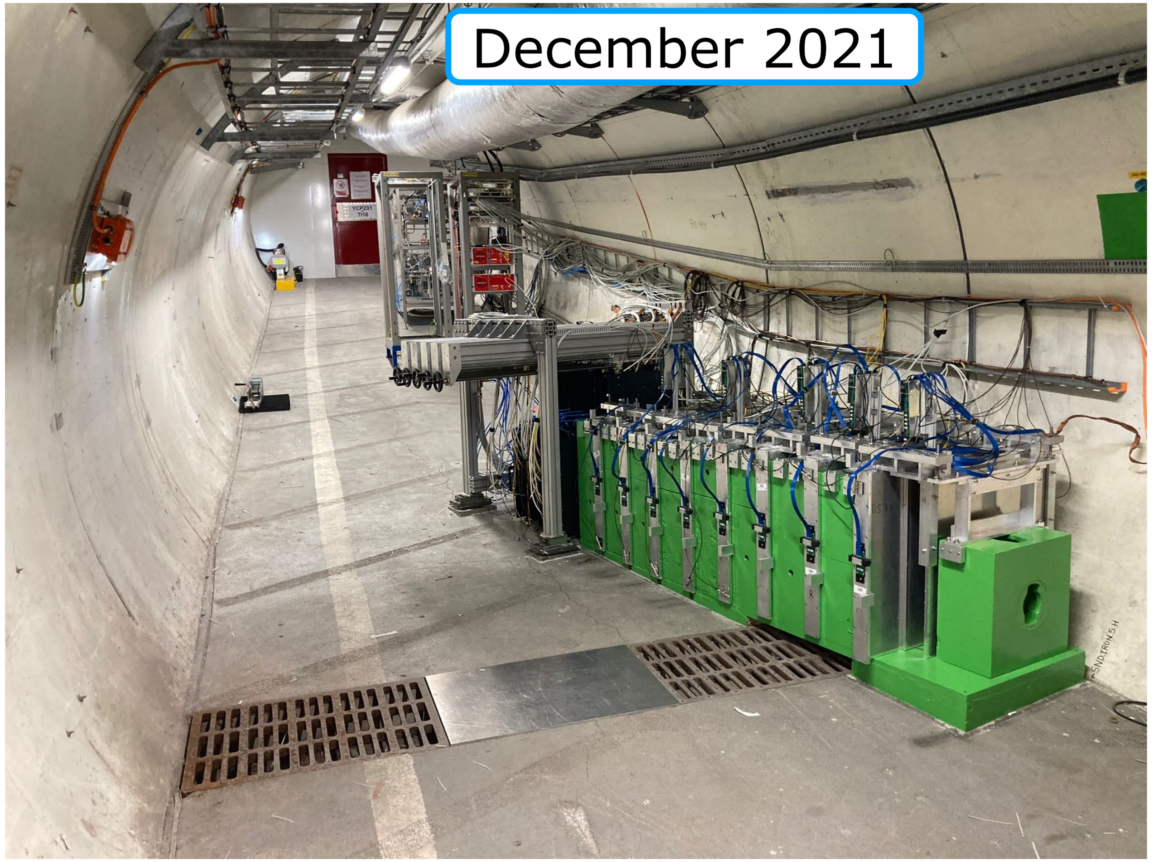




DETECTOR INSTALLATION IN TI18

- Installation in TI18 started on November 1st

- Electronic detector installed on December 3rd

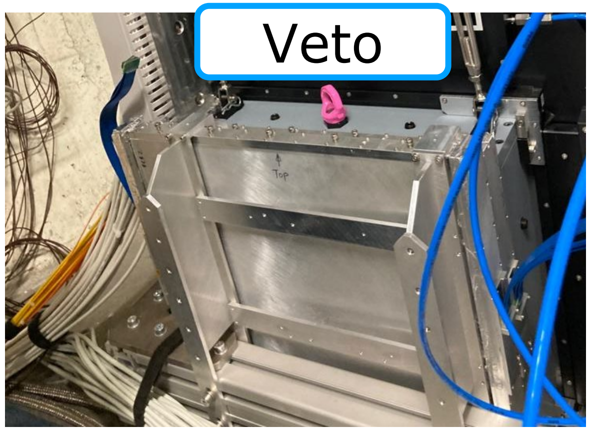


SUBDETECTORS IN TI18

Target wall

SciFi planes

Veto



Had Calo/
muon system

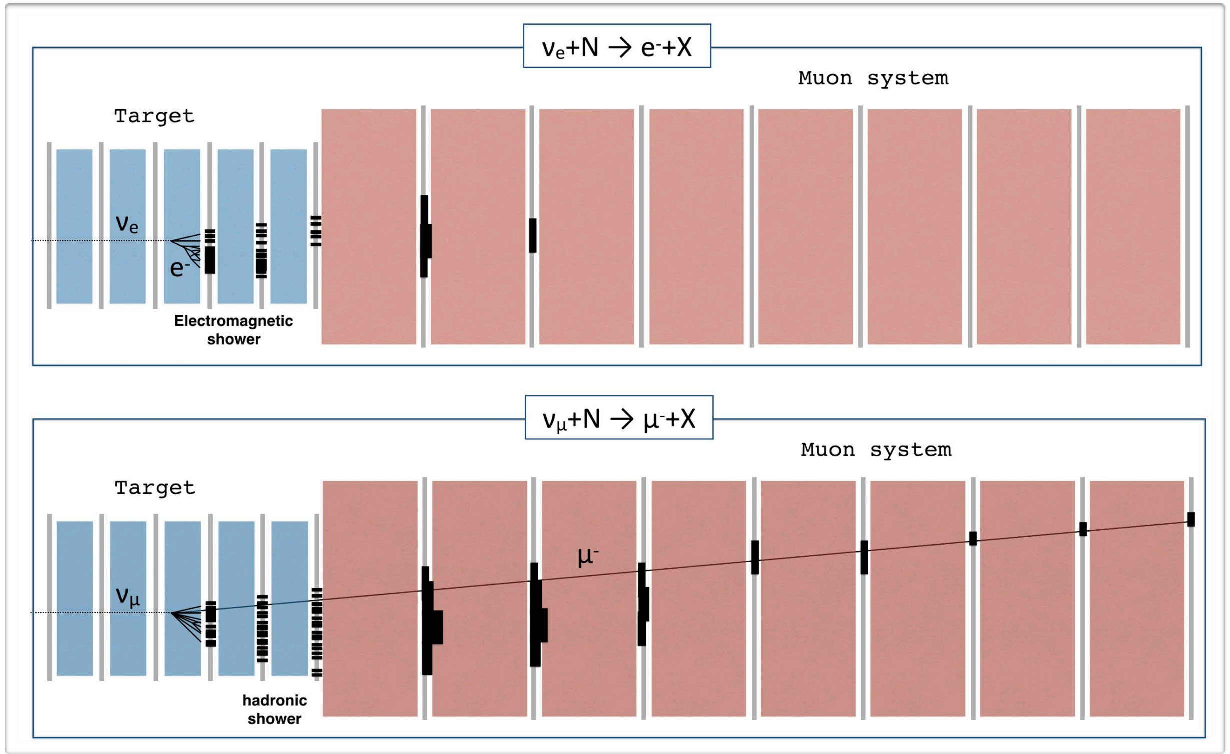
FULL DETECTOR INSTALLATION

Neutron shield installation: March 2022

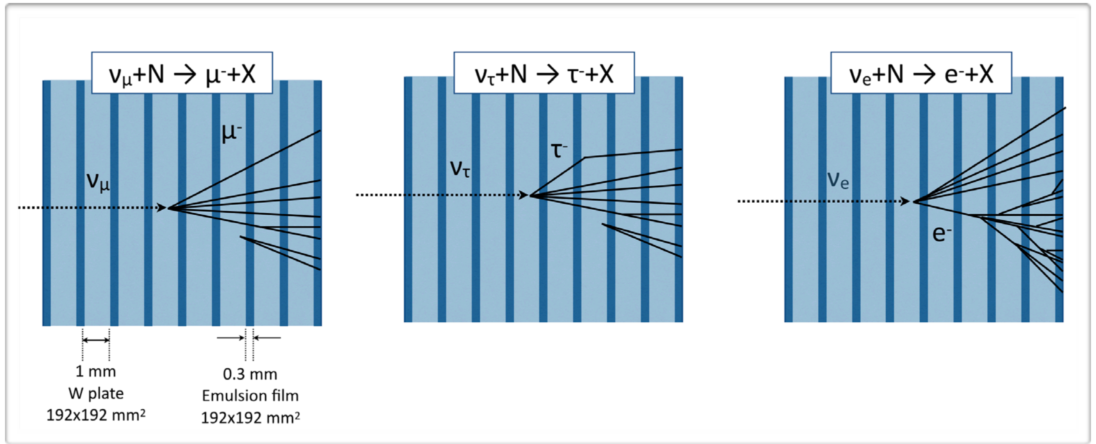
Final completion of the installation: 7 April 2022

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 em showers (SciFi)
  - Measure neutrino energy (SciFi+Muon)

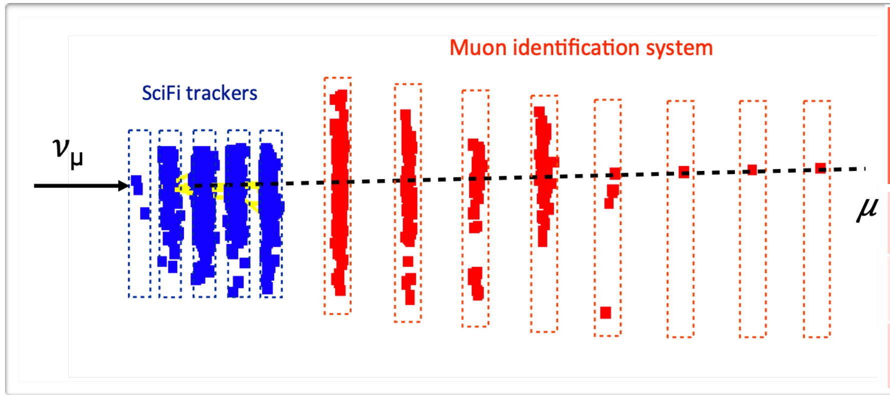


- **SECOND PHASE: nuclear emulsions**
- Event reconstruction in the emulsion target
  - Identify e.m. showers
  - Neutrino vertex reconstruction and 2ry search
  - Match with candidates from electronic detectors (time stamp)
  - Complement target tracker for e.m. energy measurement
  - Electron/pion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



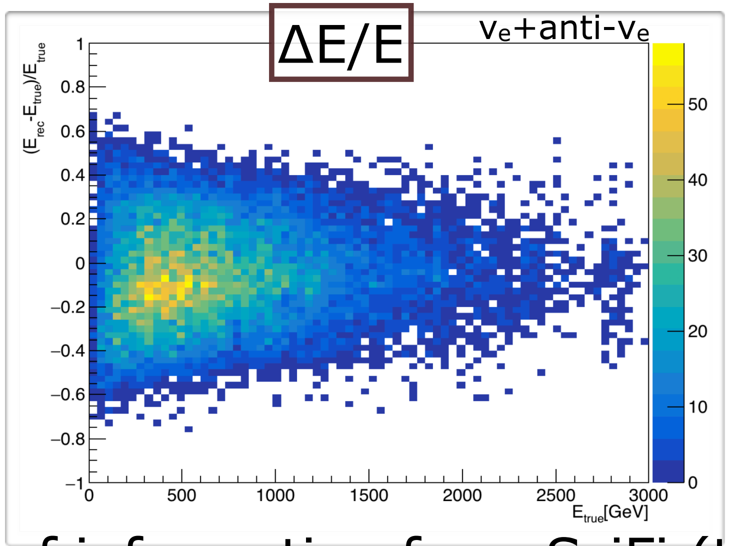
KEY FEATURES

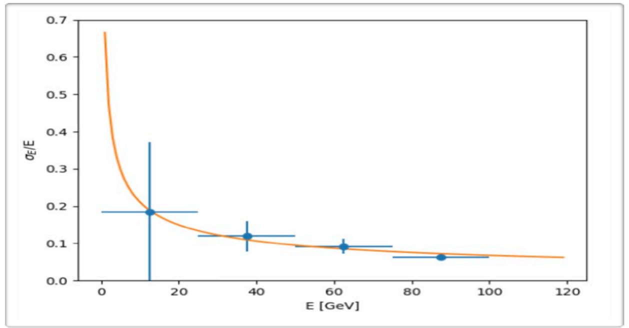
- **Muon identification**
  - ν_μ CC interactions identified thanks to the identification of the muon produced in the interaction
  - Muon ID at the neutrino vertex crucial to identify charmed hadron production, background to ν_τ detection



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

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





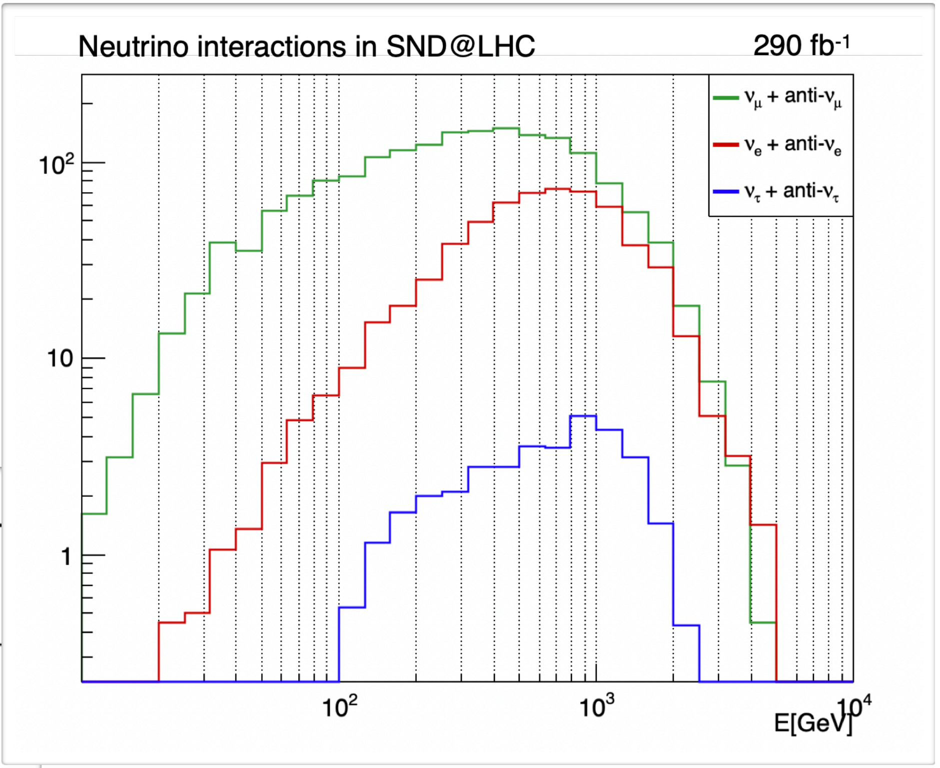
- Performance of SciFi tracker as sampling calorimeter, using a CNN
- Electron energy resolution

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

NEUTRINO EXPECTATIONS

- Integrated luminosity: **290 fb^{-1}**
- Upward/downward crossing angle: **0.43/0.57**

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



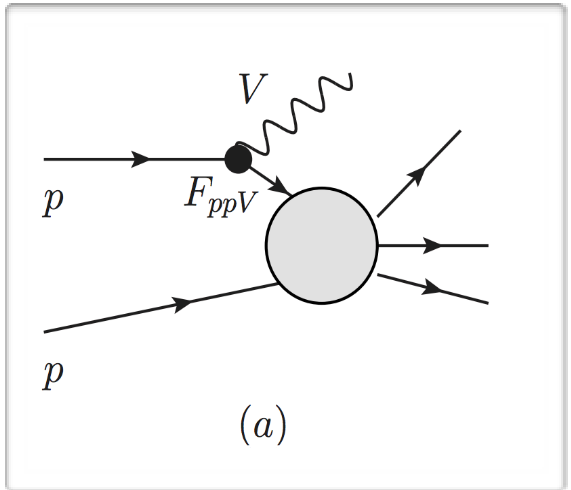
Flavour	Neutrinos in acceptance $\langle E \rangle$ [GeV]	Yield	CC neutrino interactions $\langle E \rangle$ [GeV]	Yield	NC neutrino interactions $\langle E \rangle$ [GeV]	Yield
ν_μ	120	3.4×10^{12}	450	1028	480	310
$\bar{\nu}_\mu$	125	3.0×10^{12}	480	419	480	157
ν_e	300	4.0×10^{11}	760	292	720	88
$\bar{\nu}_e$	230	4.4×10^{11}	680	158	720	58
ν_τ	400	2.8×10^{10}	740	23	740	8
$\bar{\nu}_\tau$	380	3.1×10^{10}	740	11	740	5
TOT		7.3×10^{12}		1930		625

FEEBLY INTERACTING PARTICLES

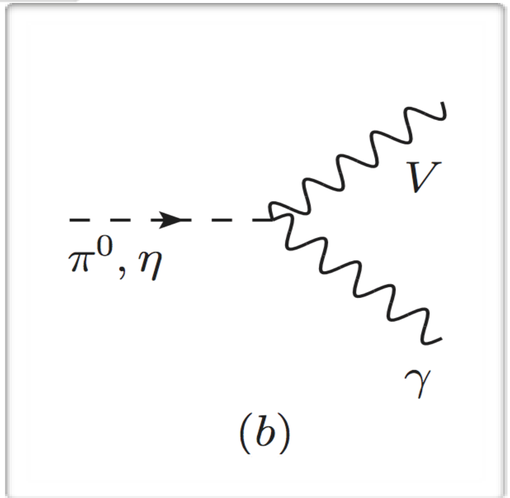
- SND@LHC experiment can explore a large variety of Beyond Standard Model (BSM) scenarios describing Hidden Sector

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

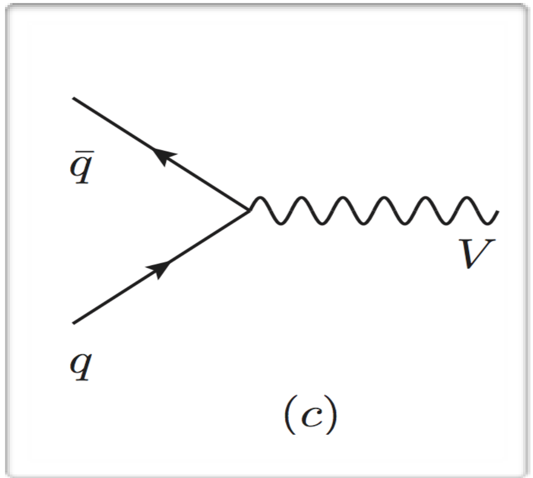
$$\mathcal{L}_{\text{leptophob}} = -g_B V^\mu J^B_\mu + g_B V^\mu (\partial_\mu \chi^\dagger \chi + \chi^\dagger \partial_\mu \chi),$$



Proton bremsstrahlung

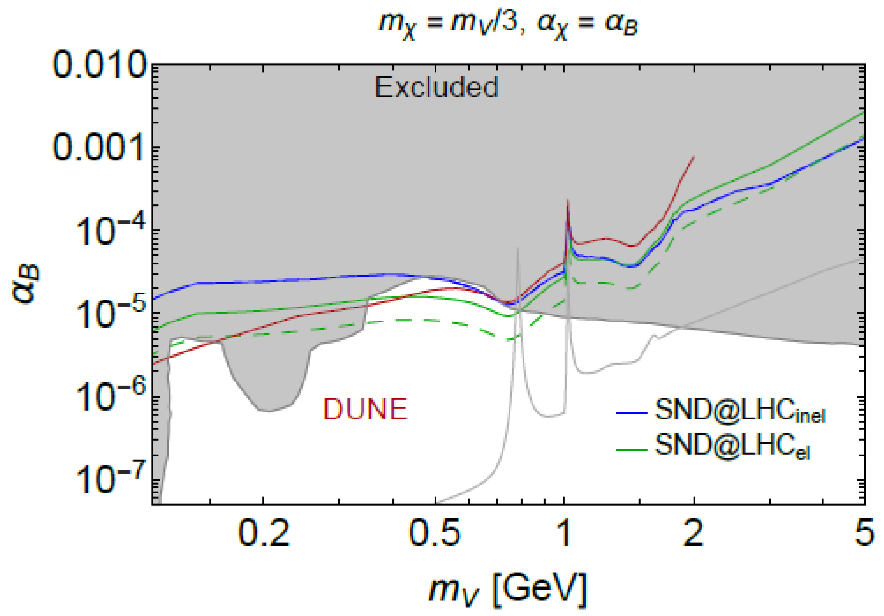


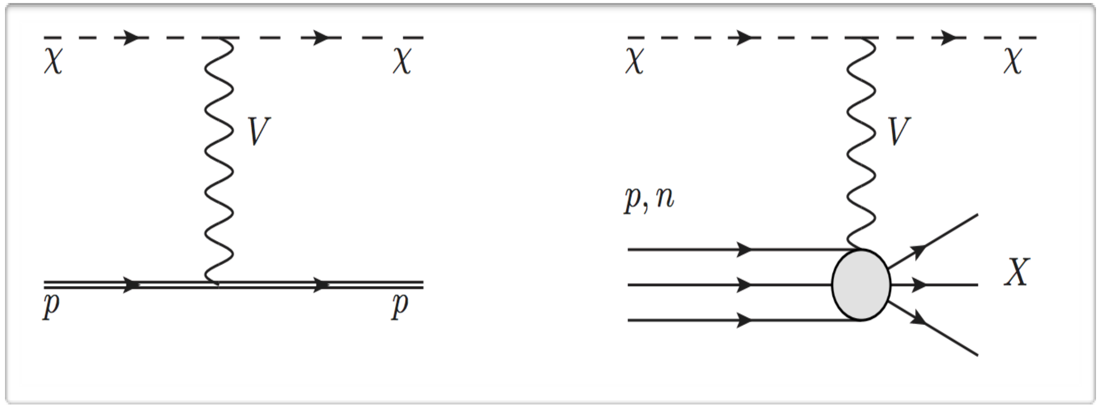
Meson decay

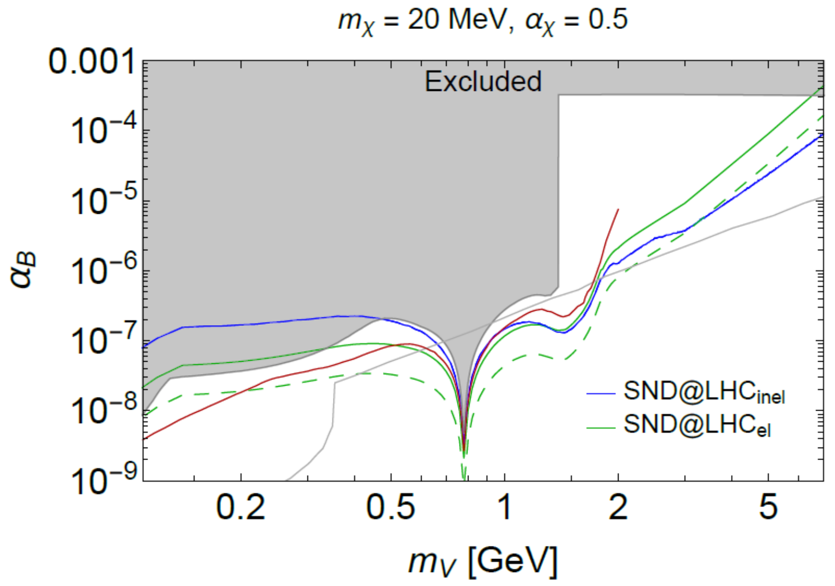


Drell-Yan process

FEEBLY INTERACTING PARTICLES







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

- Elastic signature: isolated proton, to be reconstructed in emulsions
- Inelastic signature: hadron shower, similar to NC neutrino event signature

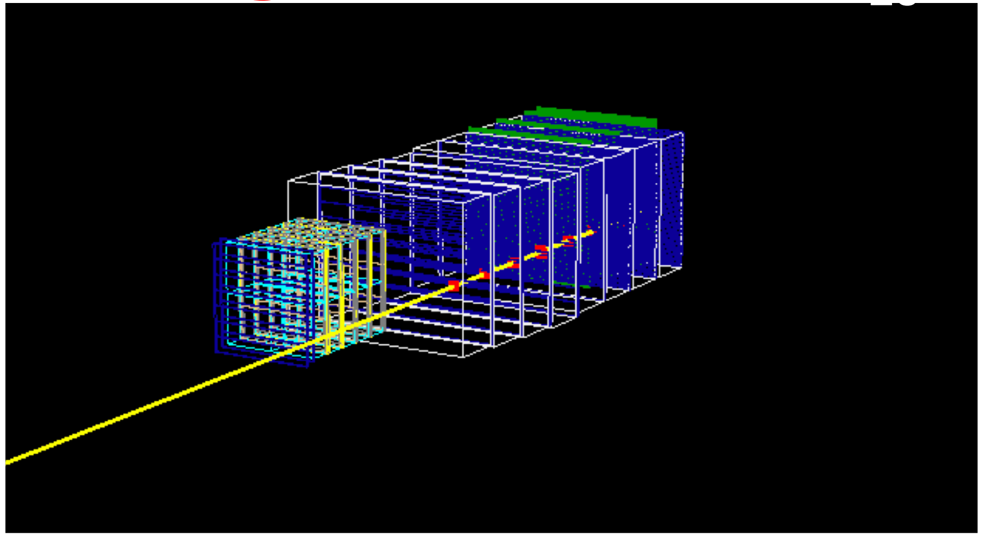
High Energ. Phys. **2022,** 6 (2022)

EARLY MEASUREMENTS

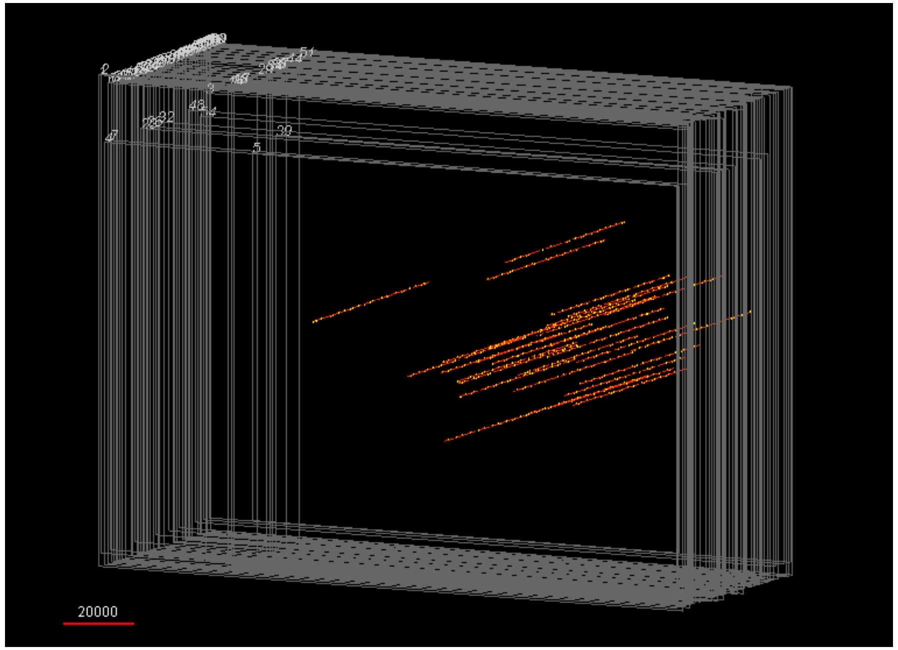
1. Muon (and muon-induced) background measurement with electronic detectors
   - Muon rates at the detector location
   - Reconstruction of muon direction and sense.
   - Comparison with simulations

2. Study of neutrino interactions with information from electronic detectors only

3. Analysis of nuclear emulsions
   (1/20 of the target instrumented with emulsion films extracted in July 2022)
   - Evaluation of background in the emulsion target
   - Definition of replacement frequency



Simulated muon passing through the muon system

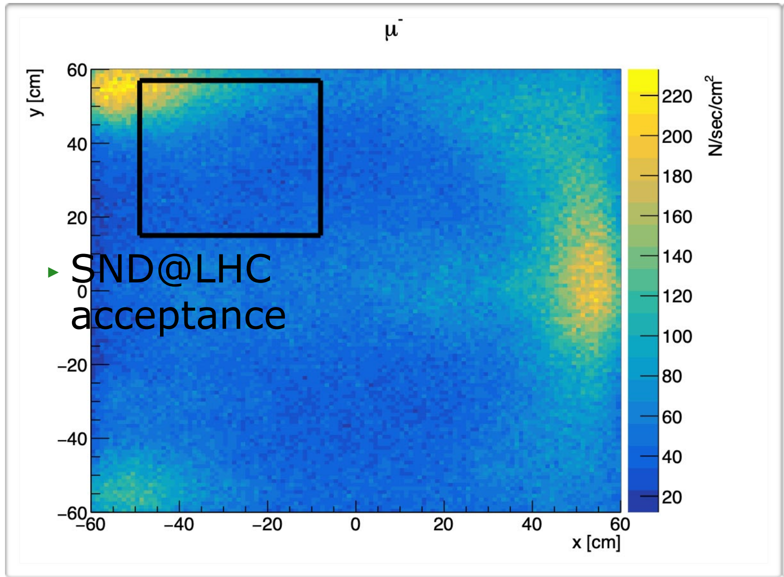


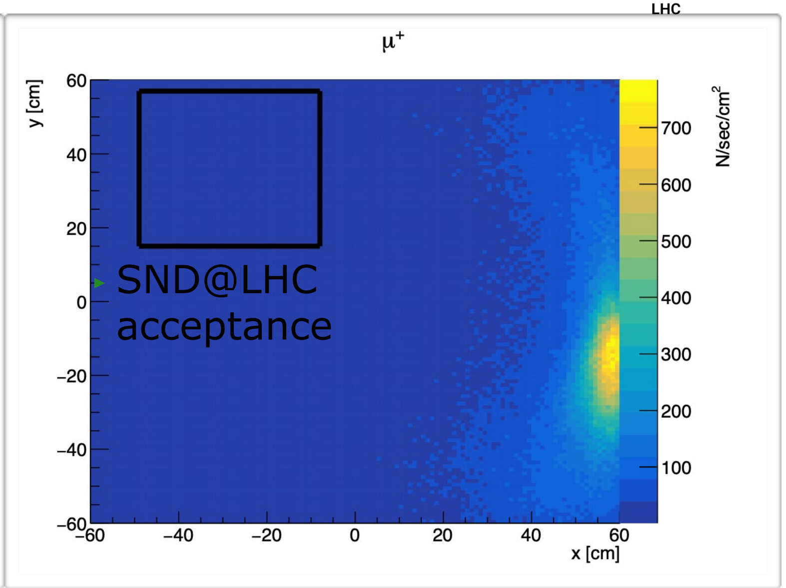
Simulated muons reconstructed in the emulsion target

MUON BACKGROUND ESTIMATION

- Rates at the SND@LHC location: $4x10^4/cm^2/fb^{-1}$

Possibility of performing precise measurements on muon yield and angle to validate predictions and constraint simulations in an unexplored region





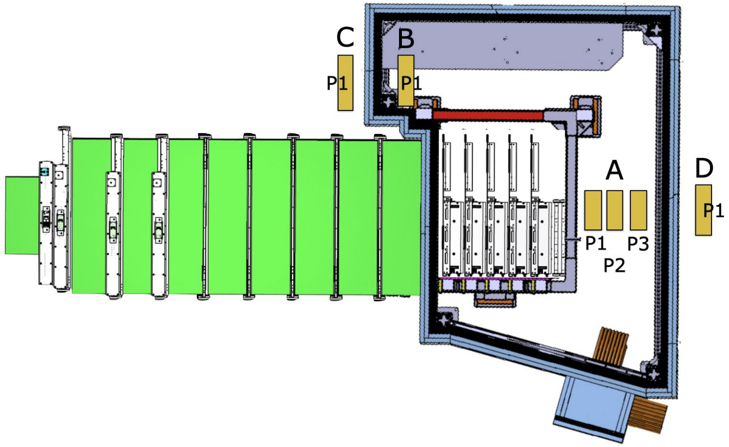
- Measurements performed by FASER

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	$(1.9 \pm 0.2) \times 10^4$

Tentative emulsion replacement frequency : every 25 fb^{-1}

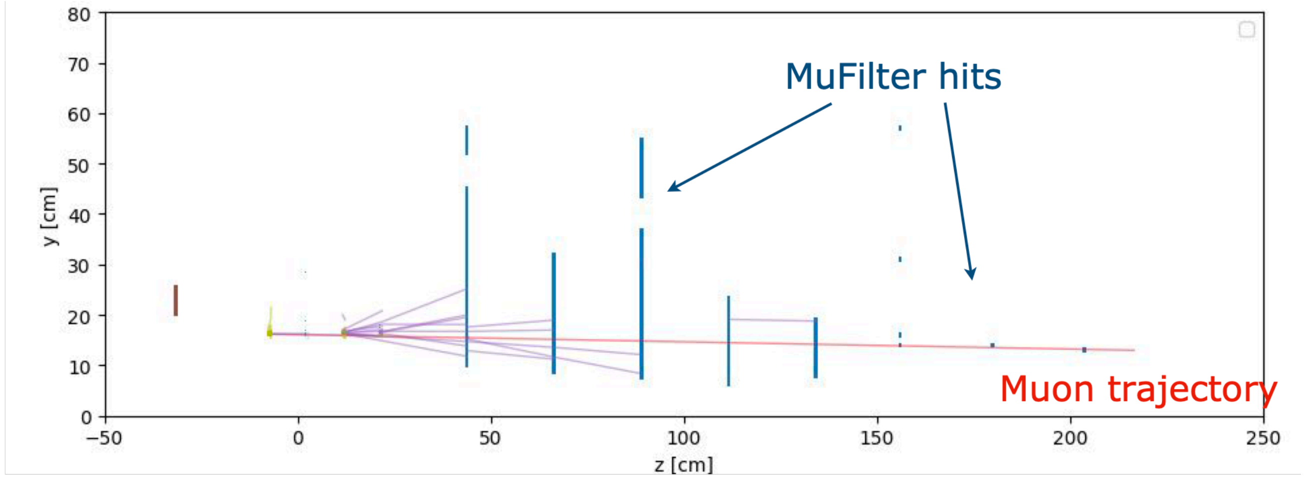
Periodic checks with small emulsion packages



NEUTRINO SIGNAL STUDIES

ELECTRONIC DETECTORS

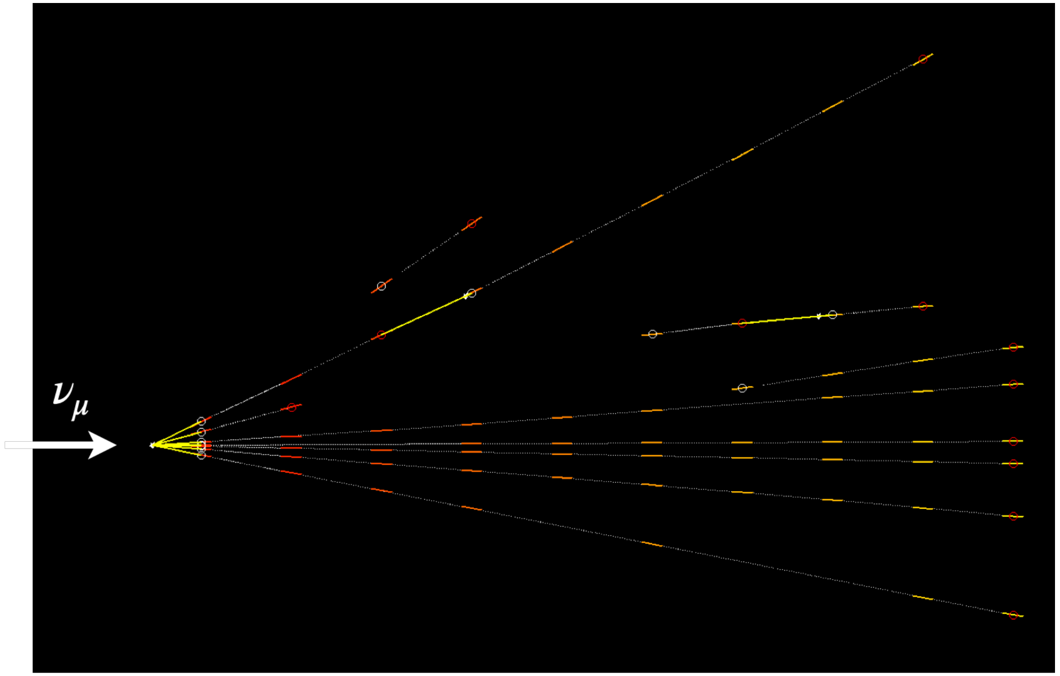
- Flavour identification
- Muon ID with muon system using Hough transformation



Simulated ν_μ interaction

EMULSION DATA

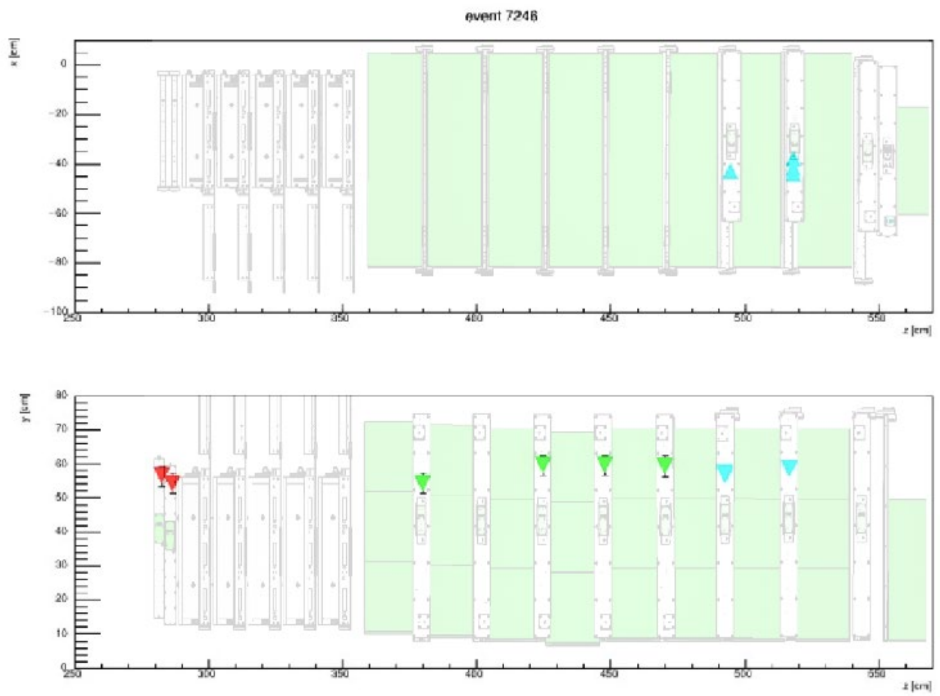
- Neutrino vertex reconstruction in high occupancy environment



Simulated ν_μ interaction in the emulsion target

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 installation completed in April 2022
- Started taking data from the beginning of LHC RUN3!



First muon from beam "splash" April 22

Preliminary

THANK YOU

BACKUP SLIDES
WITH MORE DETAILED INFORMATION

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

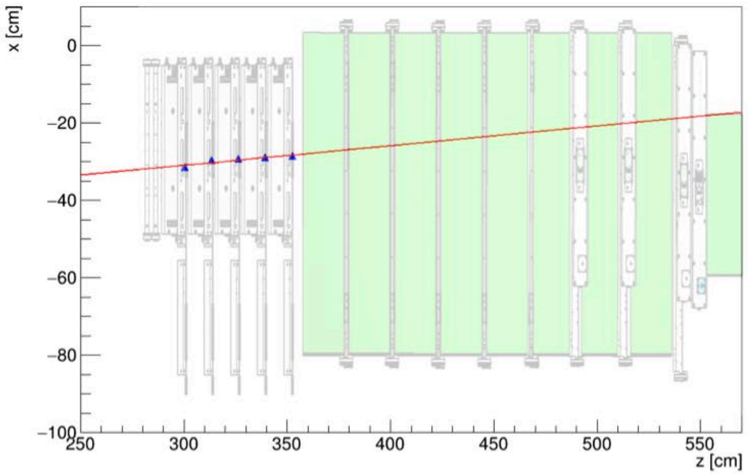
- Detector installation completed in December 2021

- Currently registering first detector hits from start of LHC RUN3!

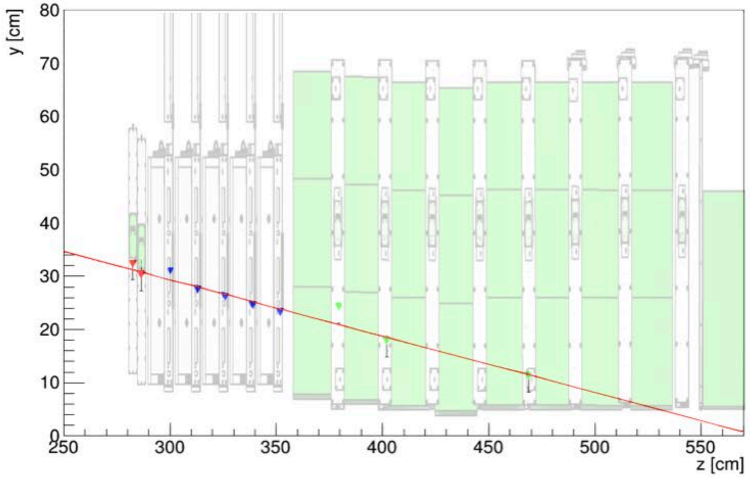
DETECTOR COMMISSIONING IN TI18

EV 215120

TOP VIEW

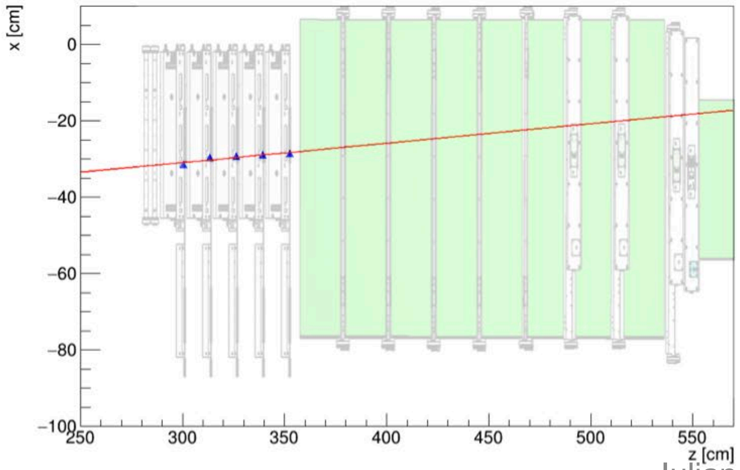


SIDE VIEW

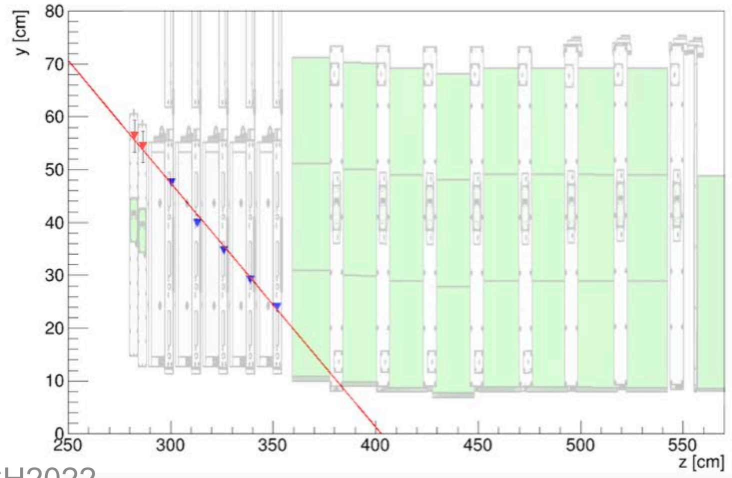


EV 261930

TOP VIEW



SIDE VIEW

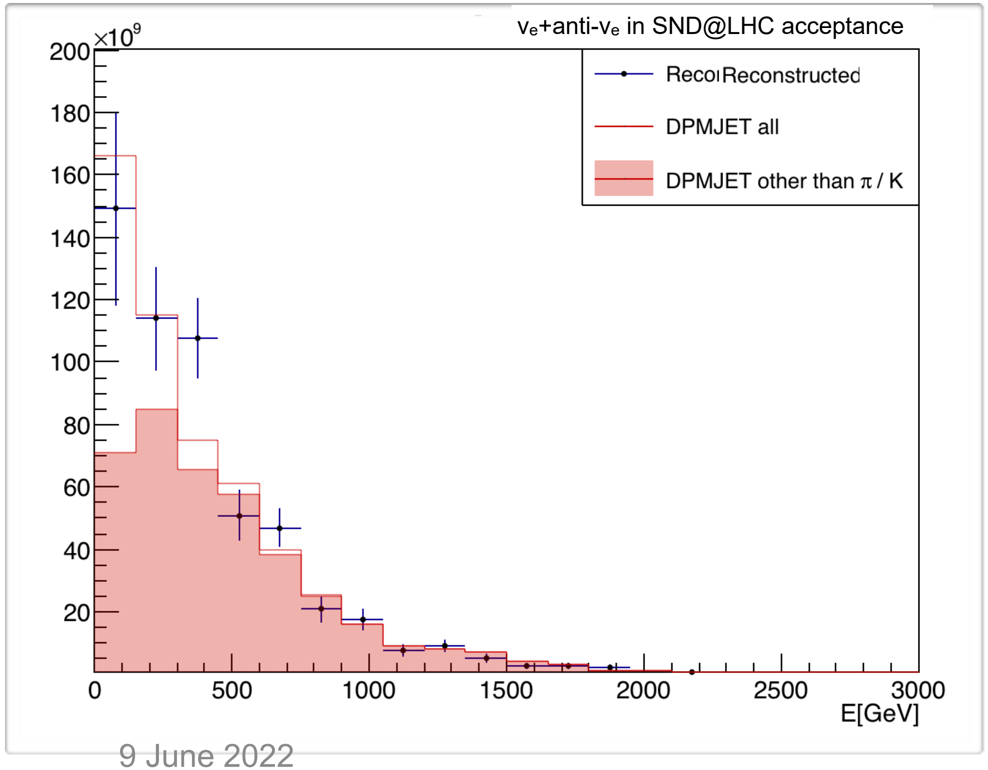


1. MEASUREMENT OF $pp \to \nu_e X$ CROSS-SECTION

2. CHARMED HADRON PRODUCTION

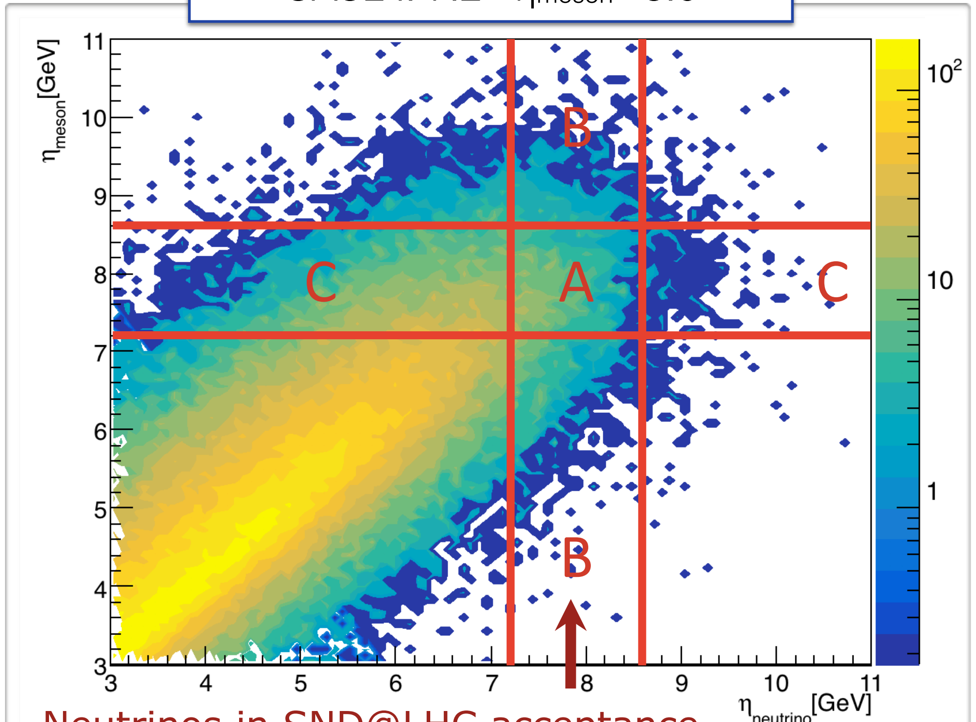
- Simulation predicts that 90% ν_e+anti-ν_e come from the decay of charmed hadrons
- Electron neutrinos can be used as a probe of the production of charm in the relevant pseudo-rapidity range after unfolding the instrumental effects

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



- Correlation between pseudo-rapidity of the electron (anti-)neutrino and the parent charmed hadron

CASE I: 7.2< η_{meson} <8.6

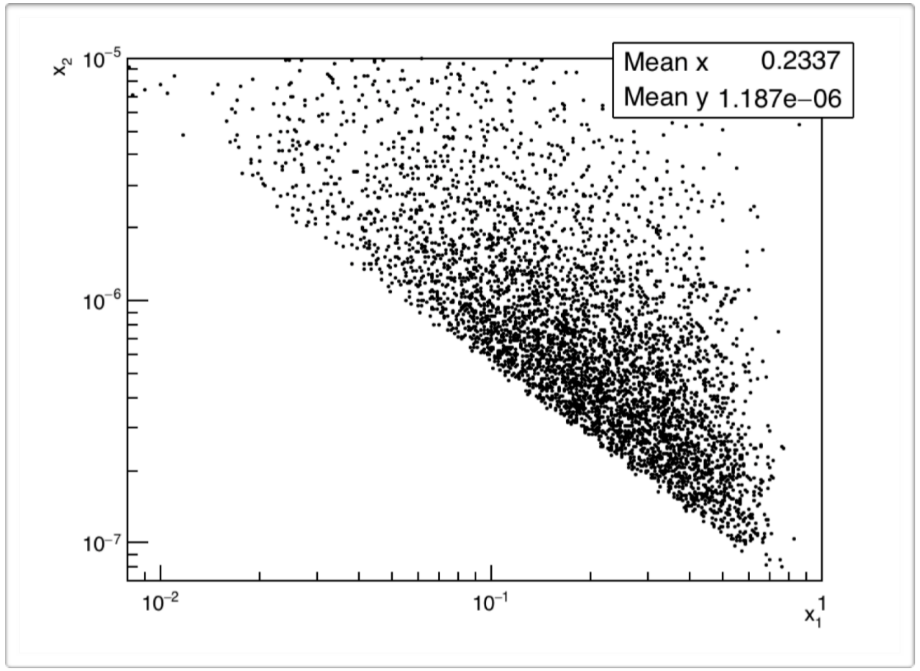


Neutrinos in SND@LHC acceptance

QCD MEASUREMENTS

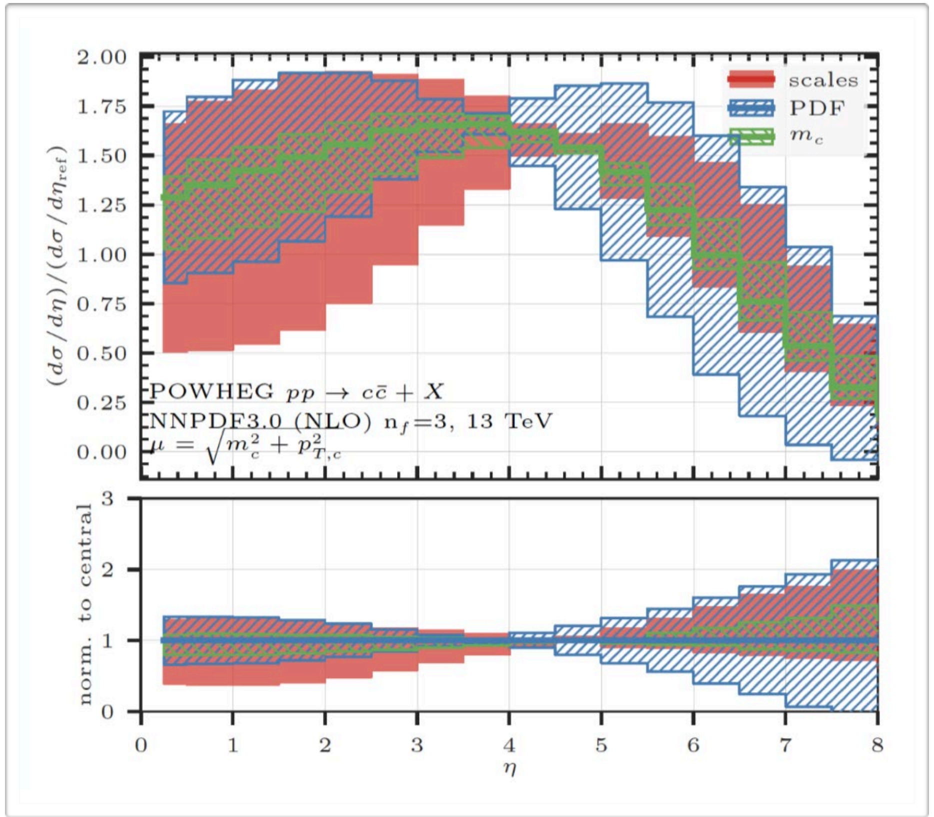
The dominant partonic process for associated charm production at the LHC is gluon-gluon scattering

Average lowest momentum fraction: 10^{-6}



Correlation between x1 and x2 for events in the SND@LHC acceptance

Extraction of gluon PDF in very small x-region relevant for Future Circular Colliders



Ratio between the cross-section measurements at different energies and pseudo-rapidities

$$R = \frac{d\sigma/d\eta(13\,TeV)}{d\sigma/d\eta_{ref}(7\,TeV)}$$

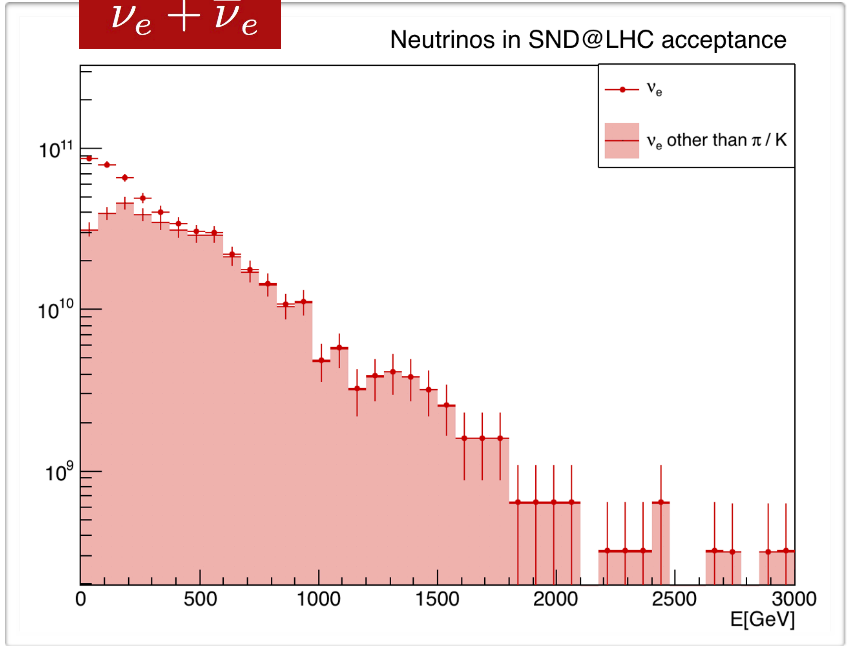
$\eta_{ref} = 4.5$

Reduction of scale uncertainties
Constraint the PDF with data

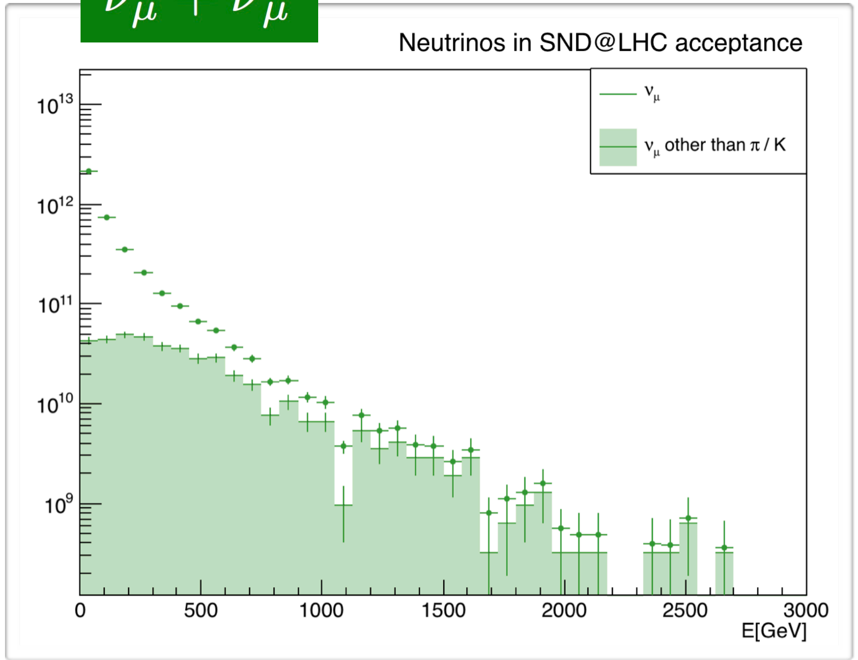
3. LEPTON FLAVOUR UNIVERSALITY TEST

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

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



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



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

- Sensitive to ν-nucleon interaction cross-section ratio of two neutrino species

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

contamination from π/k

- The measurement of the ν_e/ν_μ ratio can be used as a test of the LFU for E>600 GeV

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

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

For a Tungsten target λ=0.04

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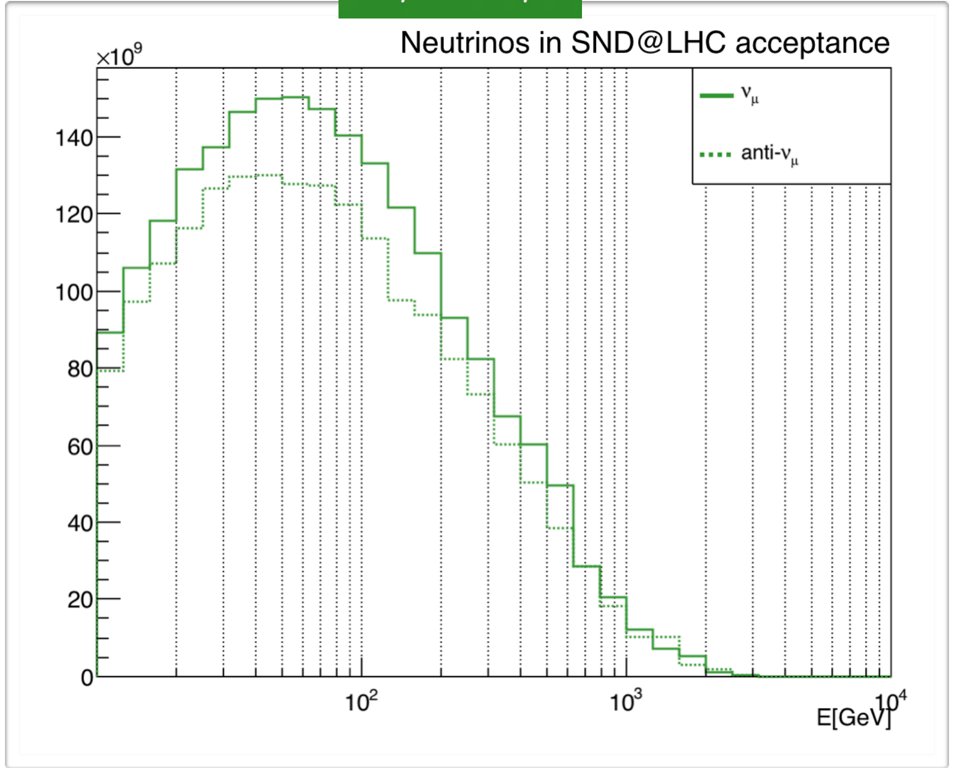
- P measurement used as an internal consistency check

ν_μ vs $\overline{\nu}_\mu$



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%

ADVANCED SND@LHC

- Upgrade of the detector in view of an extended run during Run 4:
- Two off-axis forward detectors:

- **AdvanceSND-Near**: 4<η<5

Overlap with LHCb pseudo-rapidity coverage

Reduction of systematic uncertainties

Provide normalization for neutrino physics studies

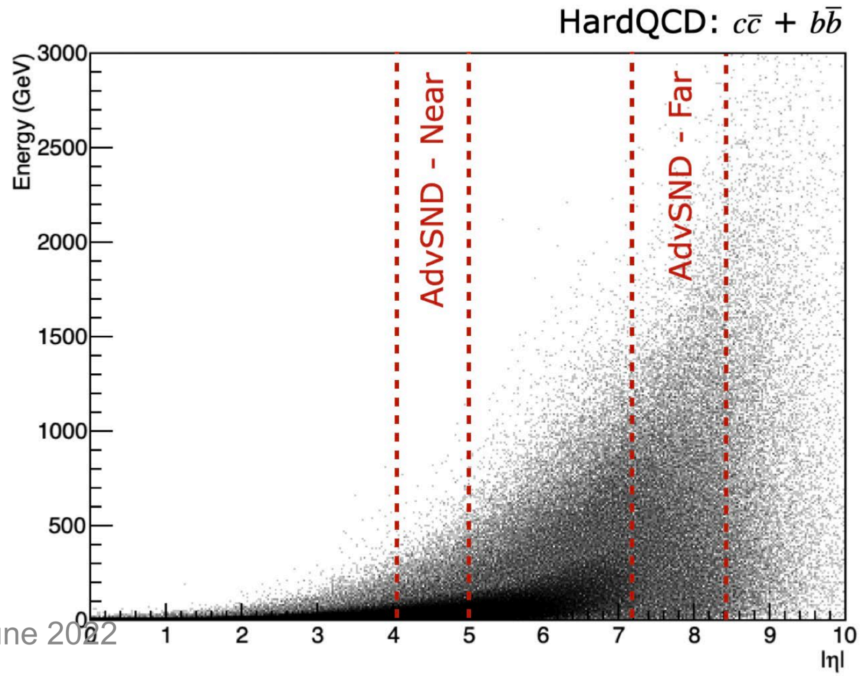
Neutrino cross-section measurements

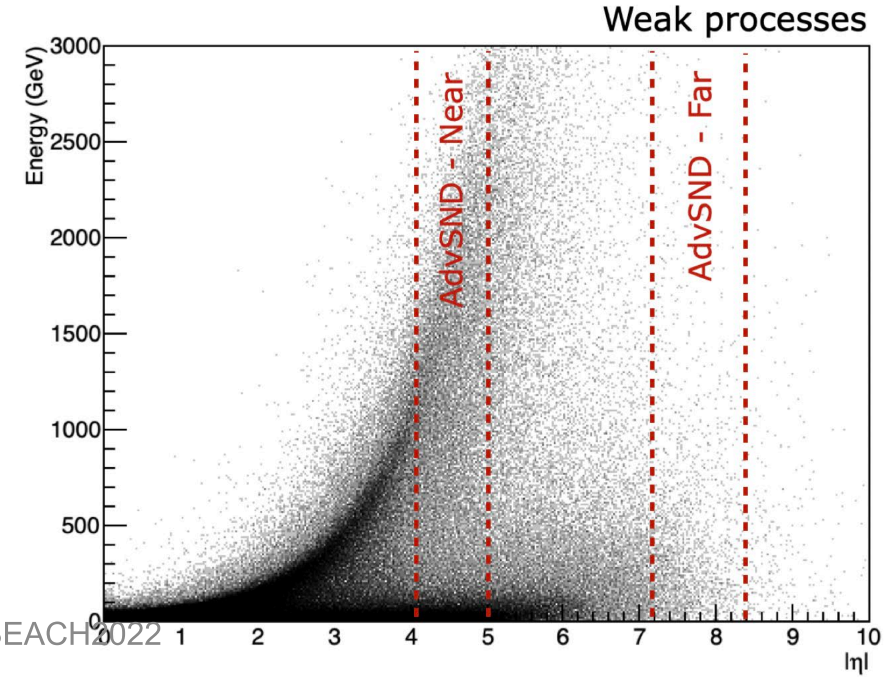
- **AdvancedSND-Far**: 7.2< η <8.4

Overlap Acceptance similar to SND@LHC

Charm production measurements

Lepton flavour universality

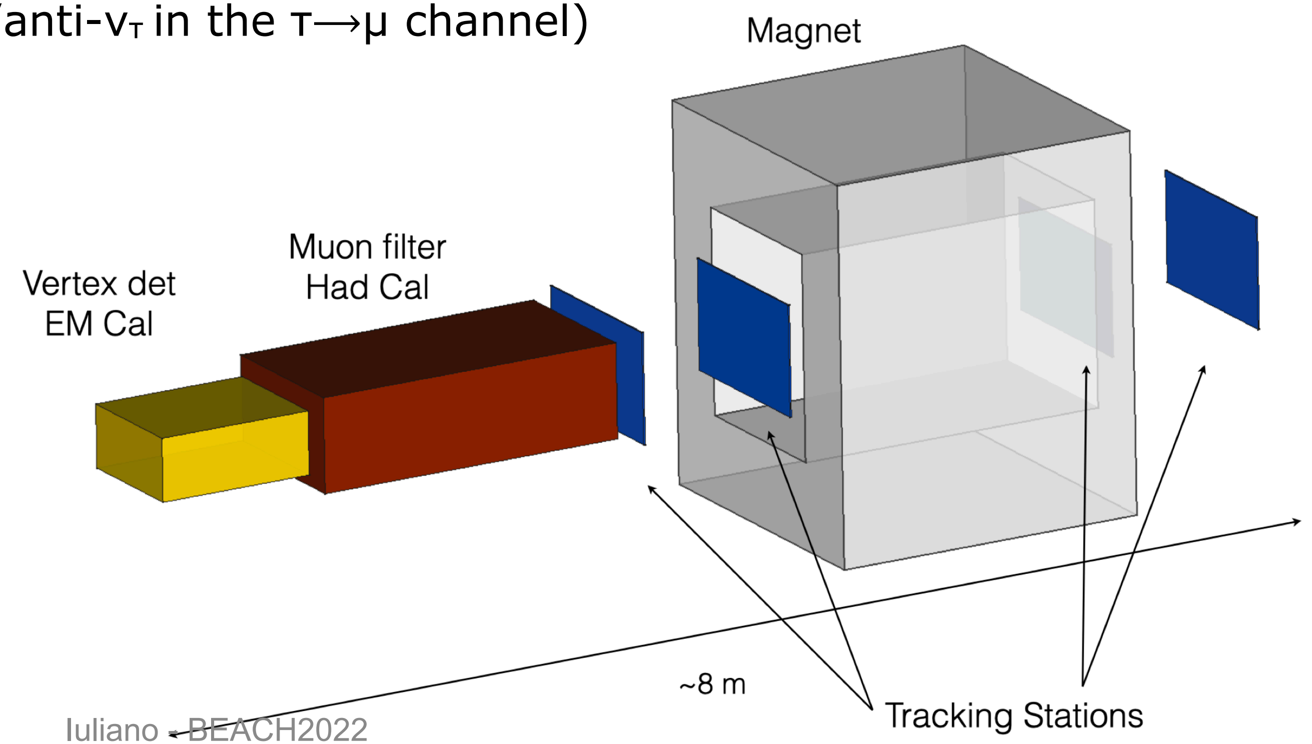




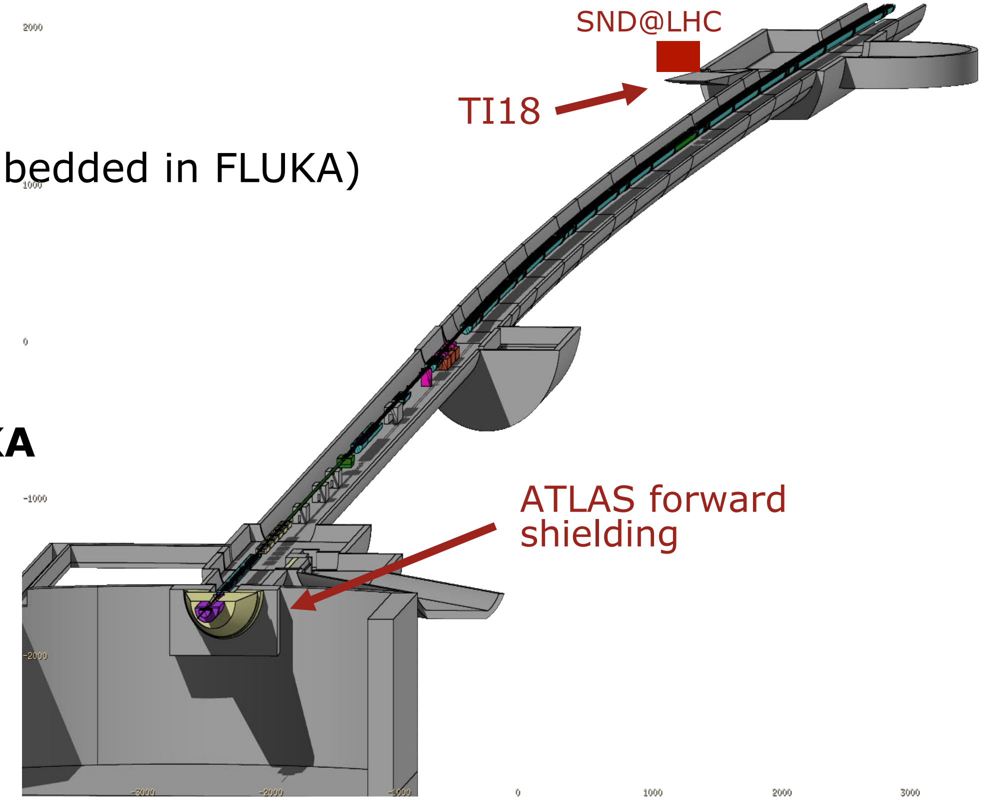
ADVANCED SND@LHC: DETECTOR LAYOUT

1) Target region:
  - Vertex identification and electromagnetic calorimeter
  - Thin sensitive layers interleaved with Tungsten plates
  - Replace emulsions with electronic trackers to cope with high intensity muon rates
2) Muon ID system and hadronic calorimeter
  - 10 interaction lengths
3) Magnet with two high-resolution tracking stations
  - measure charge of the muon (ν_μ/anti-ν_μ, ν_τ/anti-ν_τ in the $\tau \longrightarrow \mu$ channel)
  - 1 T field over 2 m length

	AdvSND - NEAR	AdvSND - FAR
η	[4.0, 5.0]	[7.2, 8.4]
mass (ton)	5	5
surface (cm^2)	120×120	100×55
distance (m)	55	630



SIMULATION



PRODUCTION

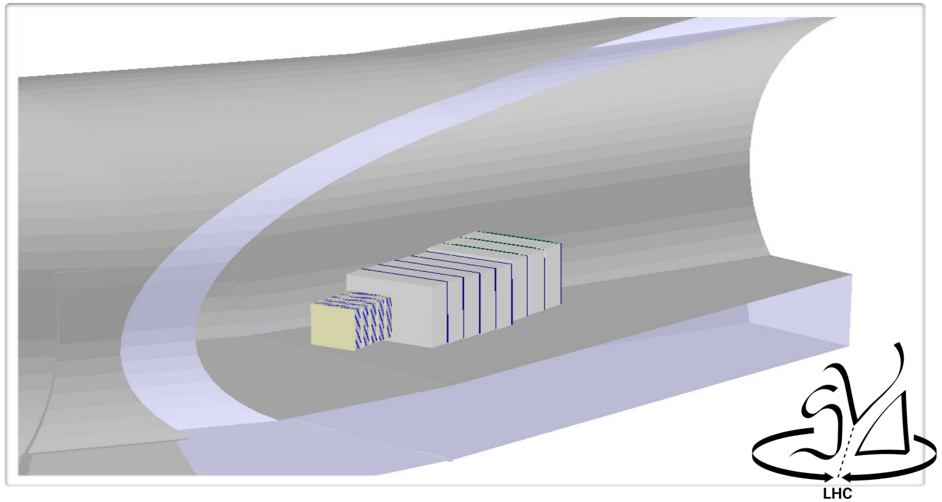
- pp collisions at LHC with **DPMJET III - v10** (embedded in FLUKA)
- $\sqrt{s}$ = 13 TeV

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

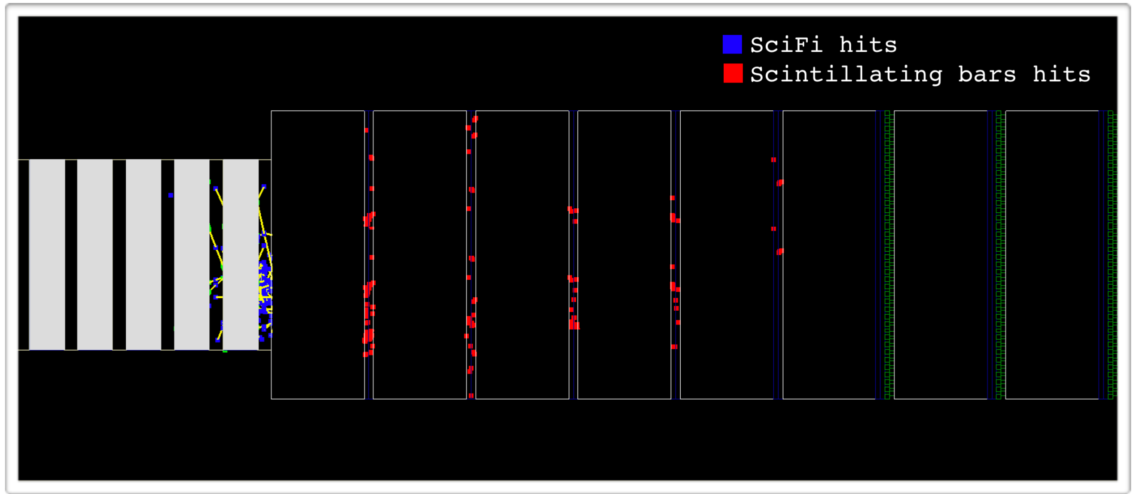
- Neutrino interactions in SND@LHC material simulated with **GENIE**
- Detector geometry and surrounding tunnel implemented in **GEANT4**



ν_e ENERGY ESTIMATION

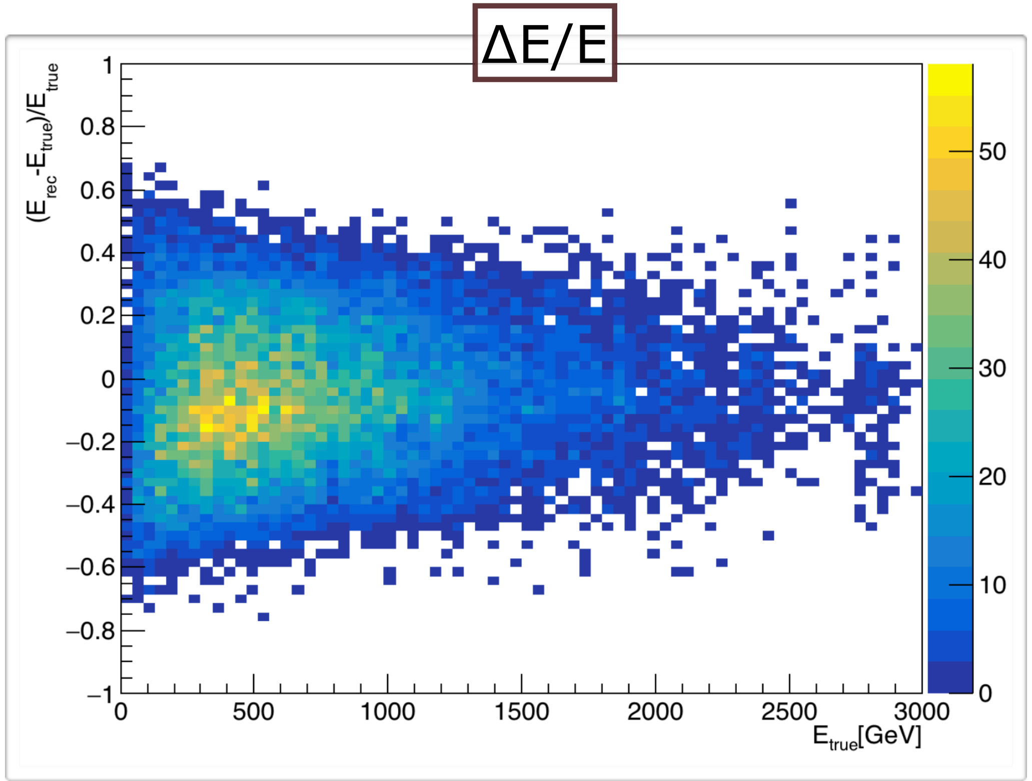
- Estimation of ν_e energy combing information from SciFi (target region) and Scintillator bars (Muon System)
- The detector acts as a non-homogeneous calorimeter

$$E_{rec} = A + B \times Nhits_{SciFi} + C \times Nhits_{Bars}$$



- Monte Carlo hits used in the current estimation
- Parameters A, B and C estimated via a gradient descent minimisation algorithm

Average resolution: 22%

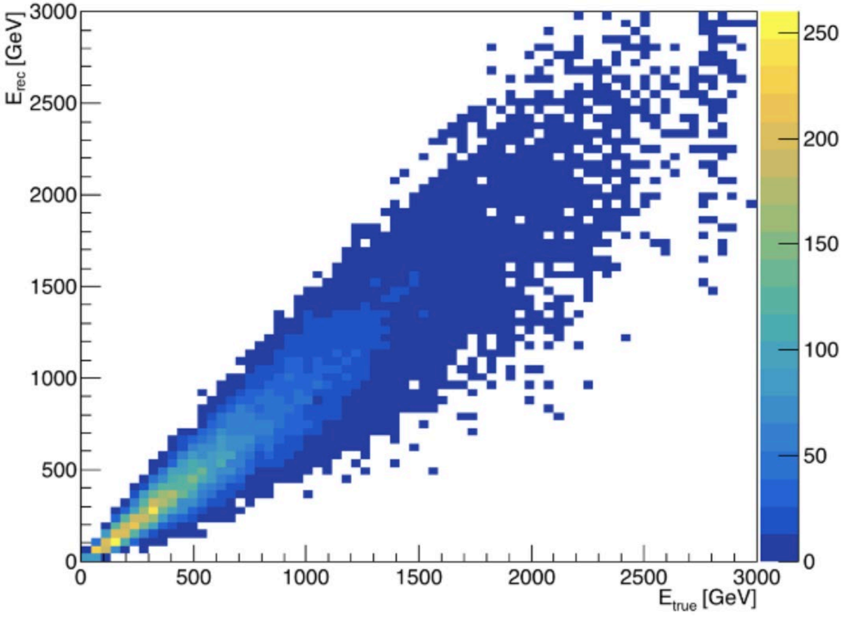


1. MEASUREMENT OF $pp \longrightarrow \nu_e X$ CROSS-SECTION

STEP 2: Unfolding of the data to get reconstructed ν_e+anti-ν_e energy spectrum

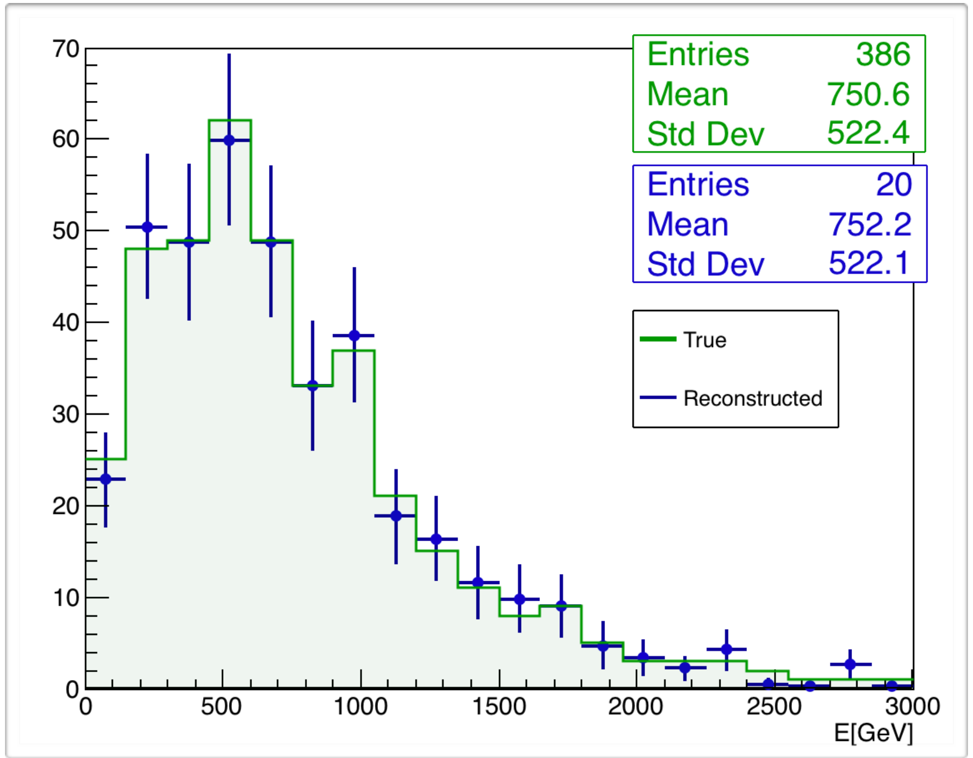
- **RooUnfold** class used to remove know effects of resolution (http://hepunx.rl.ac.uk/~adye/software/unfold/RooUnfold.html)
- Method: **Iterative Bayes theorem**
- Input: measured energy spectrum, response matrix
- Output: reconstructed energy spectrum, bin-to-bin χ^2, bin-to-bin covariance matrix

Bin-by-bin χ^2/NDF =16.12/18



- Bin-by-bin response matrix

- Reconstructed energy spectrum

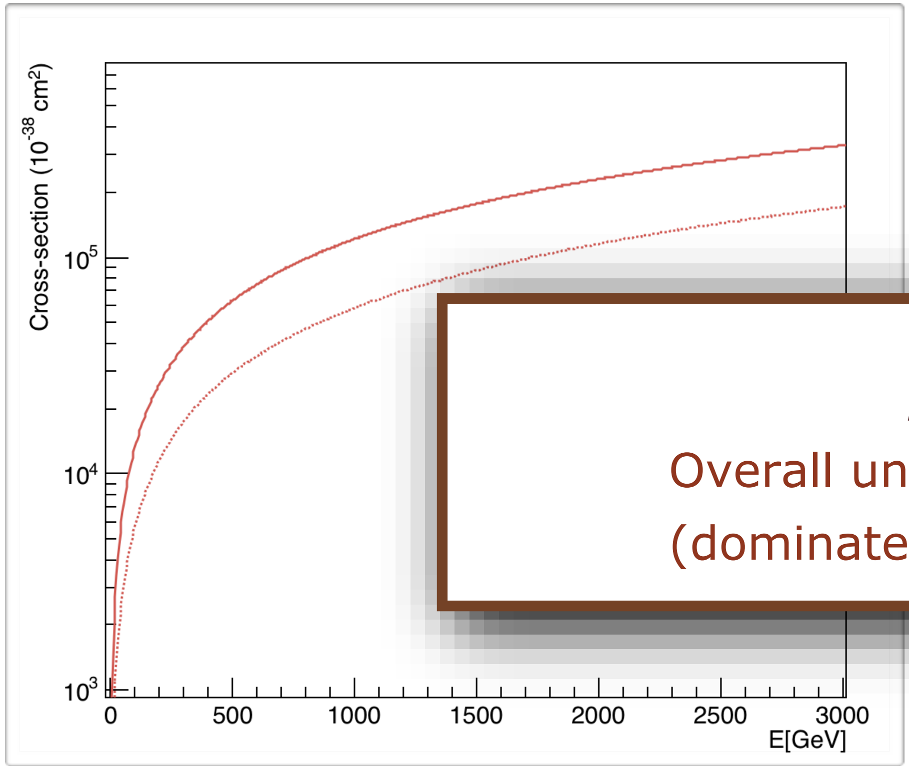


Errors: statistical (number of entries in each bin) + systematic (unfolding procedure)

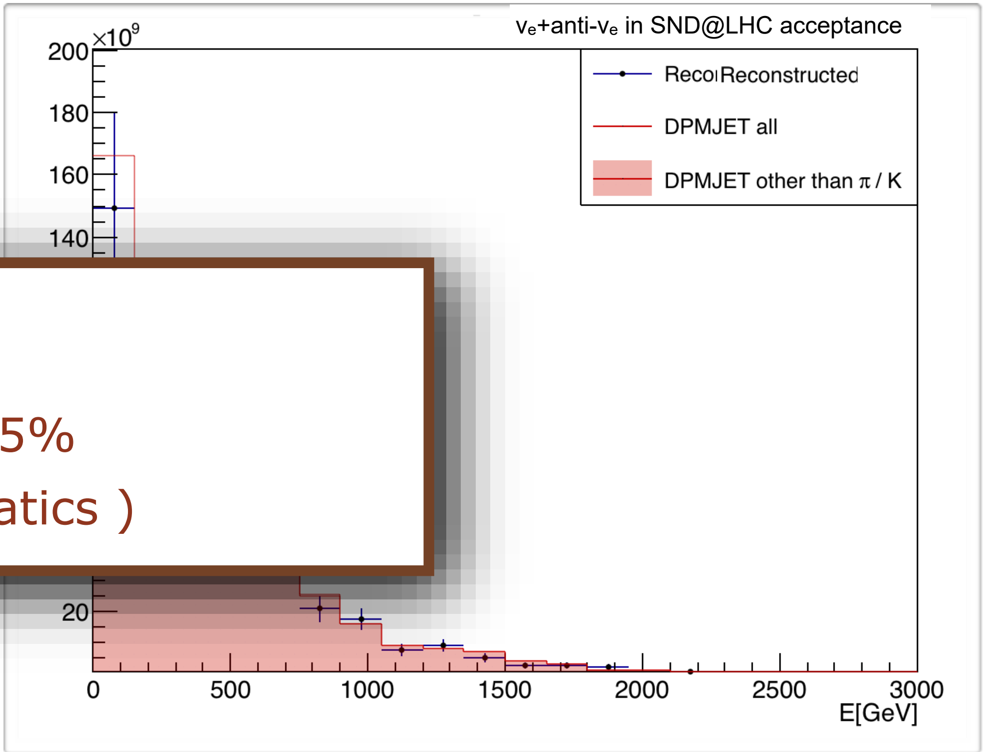
1. MEASUREMENT OF *pp*⟶ν_eX CROSS-SECTION

- 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



pp⟶ν_eX

Overall uncertainty ~15%

(dominated by systematics)

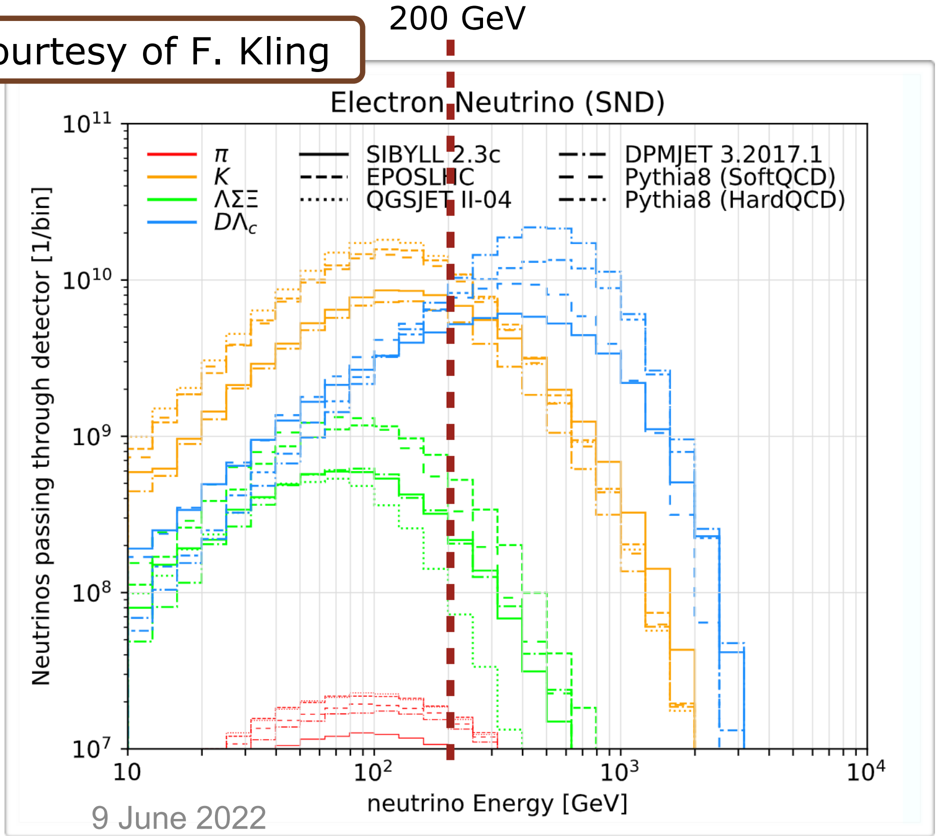
Errors: statistical (collected statistics) + systematic (unfolding procedure)

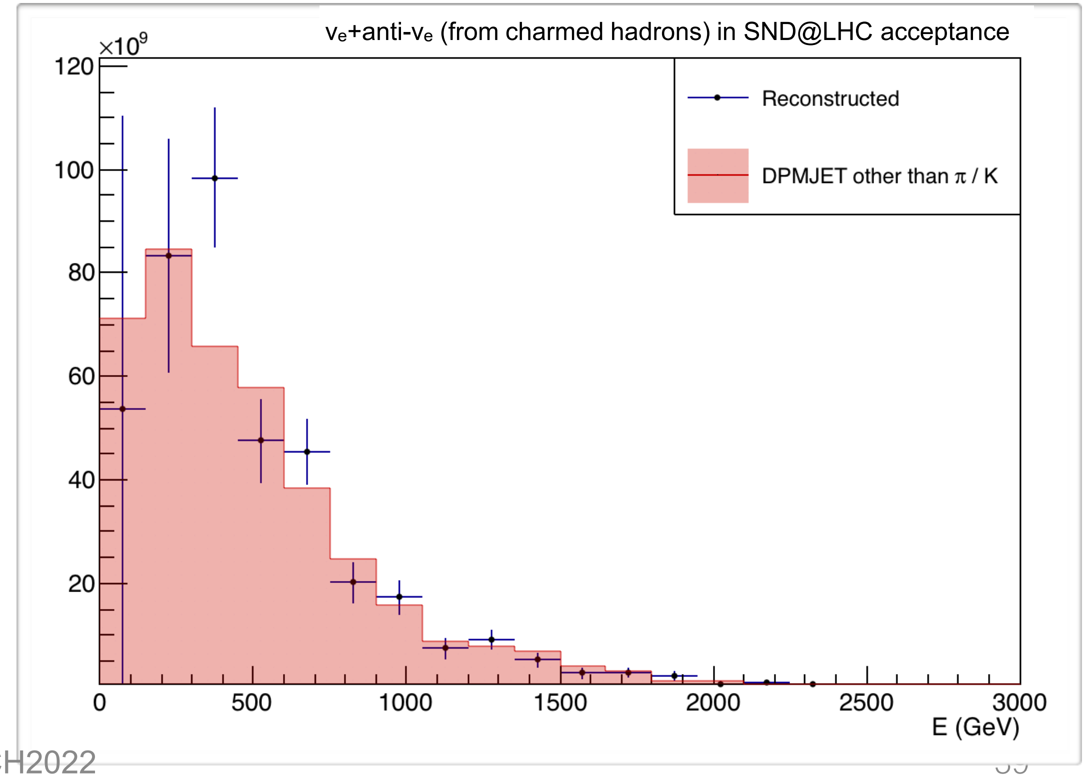
KAON CONTRIBUTION TO ν_e

- 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





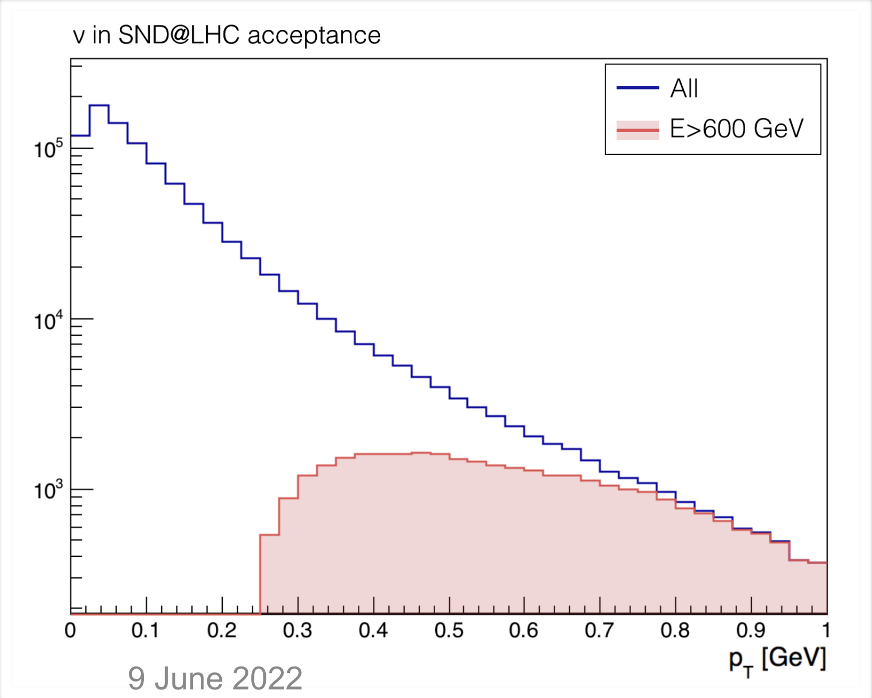
UNCERTAINTY IN PION/KAON CONTAMINATION

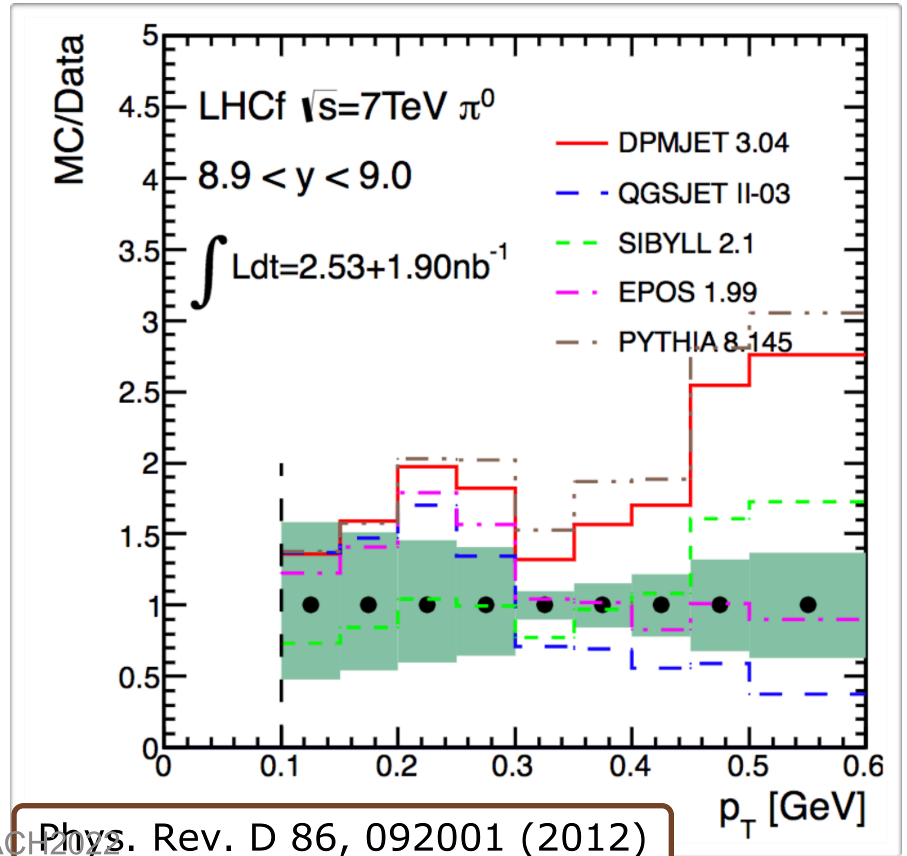
- The uncertainty in the knowledge of π/k contamination has two contributions:

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 MeV





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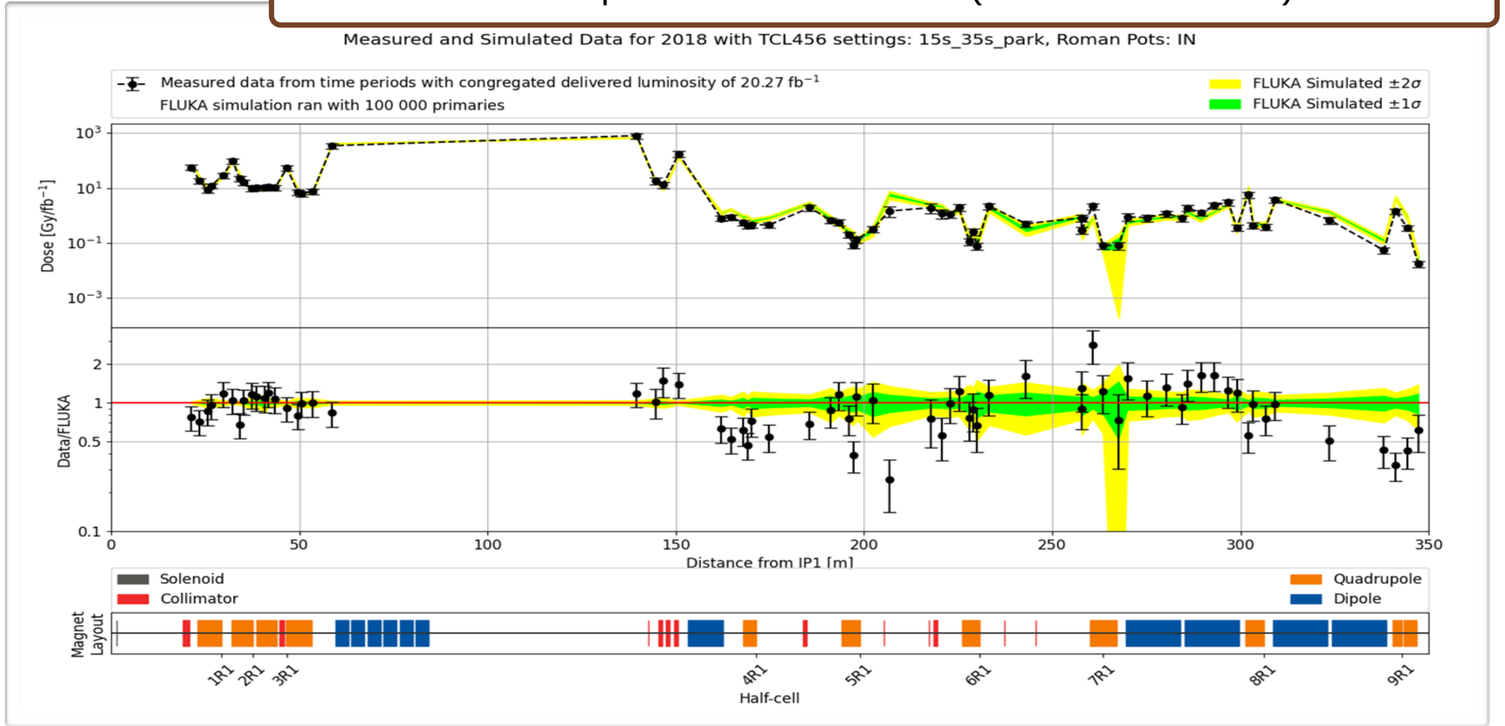
UNCERTAINTY IN PION/KAON CONTAMINATION

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

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

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

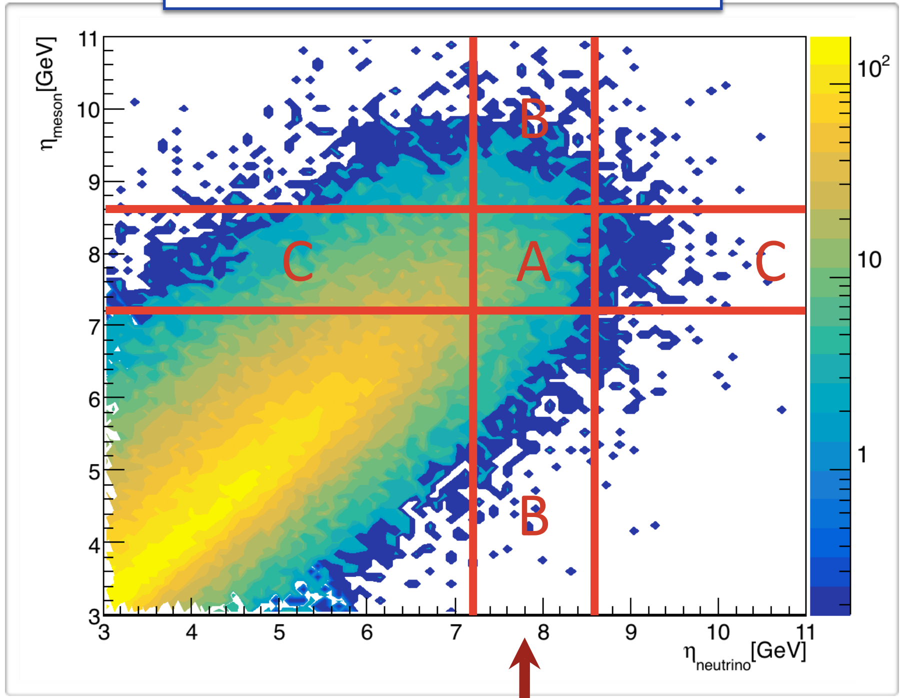
- Measurements performed by FASER in TI18 in agreement with FLUKA predictions ($2x10^4/cm^2/fb^{-1}$) within errors

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

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

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

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

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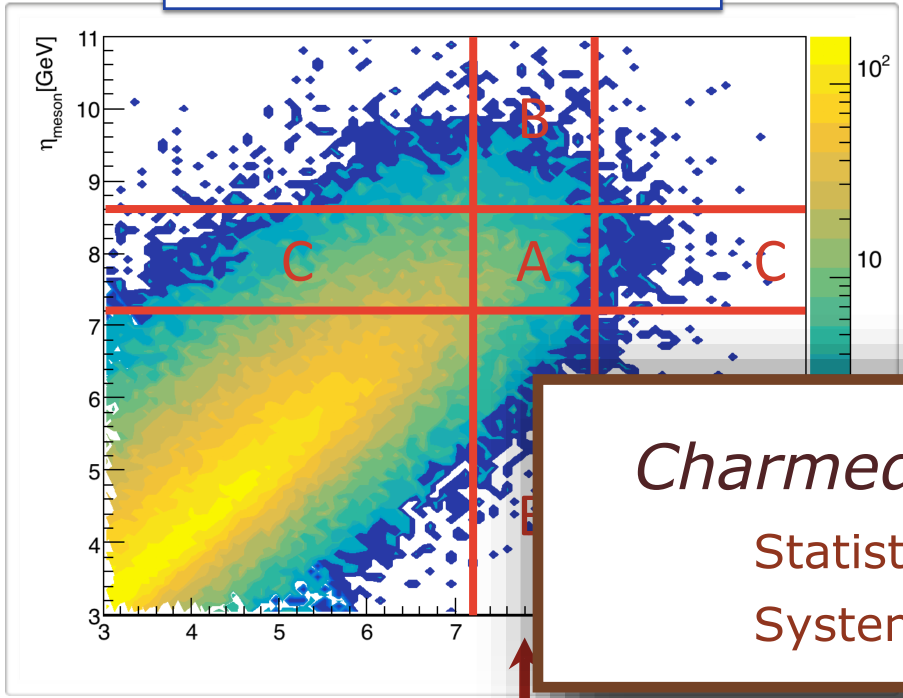


Neutrinos in SND@LHC acceptance

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

Charmed hadron production

Statistical uncertainty ~5%

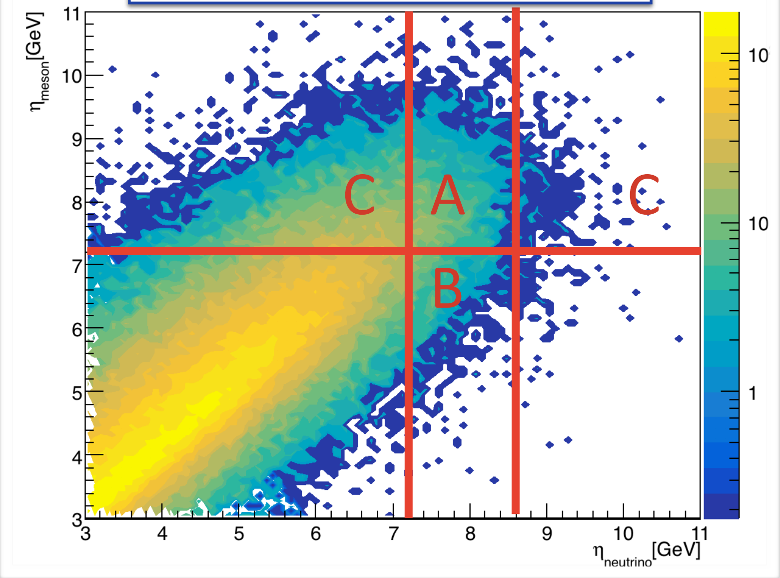
Systematic uncertainty ~35%

ing leading order
s for cc-bar

- 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

CASE II: $\eta_{meson} > 7.6$

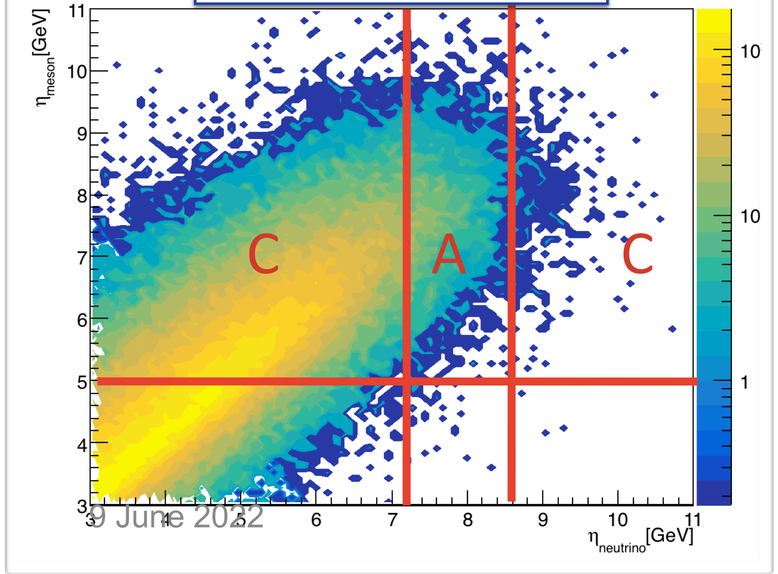


$$\textbf{CASE II} \quad N(c\text{–mesons}) = N(\nu_e + \bar{\nu}_e)^{\text{charm}} \times \frac{f_{AB}}{f_{AC}} \times \frac{1}{Br(c \to \nu_e)}$$

CASE II			
Parameter	value	f_{AB}	f_{AC}
all	default	0.66	0.23
m_c [GeV/c^2]	(1.25, 1.65)	(0.74, 0.62)	(0.25, 0.23)
$\hat{\mu}$	(0.5, 2.0)	(0.73, 0.61)	(0.25, 0.21)
primordialKTsoft	(0.7, 1.1)	(0.67, 0.66)	(0.23, 0.23)
primordialKThard	(1.6, 2.0)	(0.66, 0.66)	(0.23, 0.23)
primordialKTremnant	(0.2, 0.6)	(0.66, 0.65)	(0.23, 0.23)

Error f_{AB}/f_{AC}: 20%

CASE III: $\eta_{meson} > 5$



$$\textbf{CASE III} \quad N(c\text{–mesons}) = N(\nu_e + \bar{\nu}_e)^{\text{charm}} \times \frac{1}{f_{AC}} \times \frac{1}{Br(c \to \nu_e)}$$

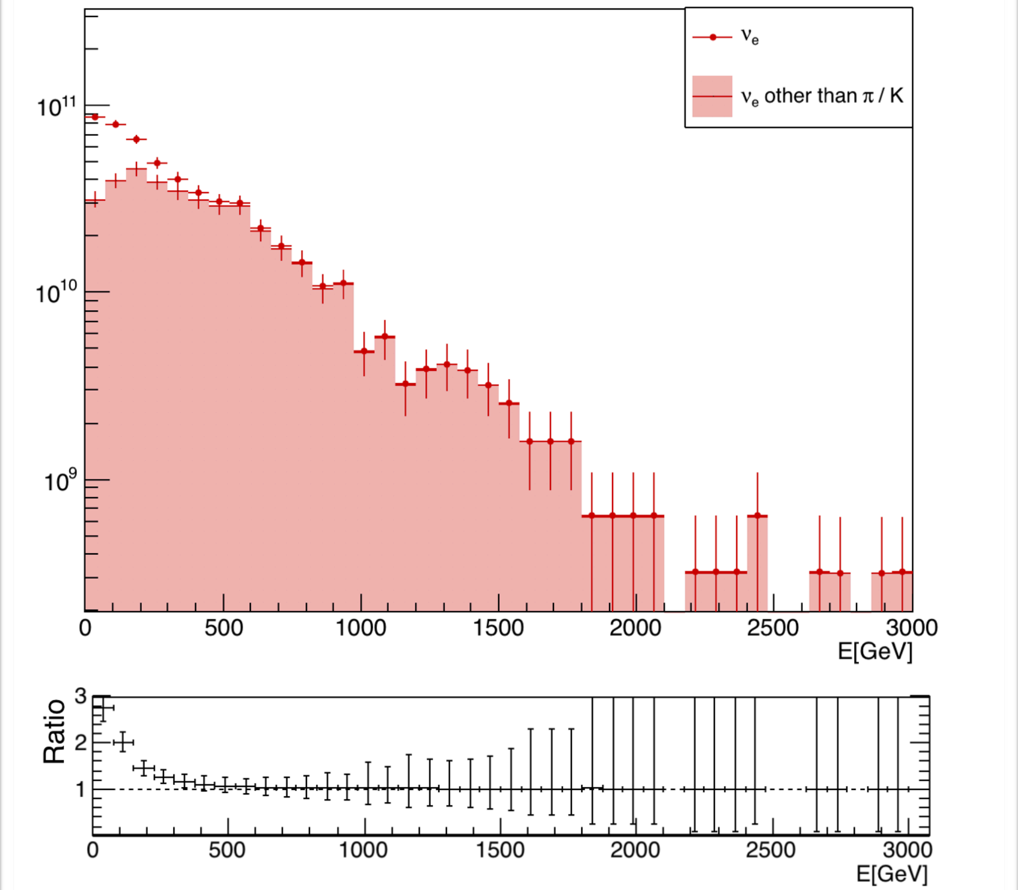
CASE III		
Parameter	value	f_{AC}
all	default	0.058
m_c [GeV/c^2]	(1.25, 1.65)	(0.074, 0.052)
$\hat{\mu}$	(0.5, 2.0)	(0.081, 0.048)
primordialKTsoft	(0.7, 1.1)	(0.058, 0.058)
primordialKThard	(1.6, 2.0)	(0.059, 0.059)
primordialKTremnant	(0.2, 0.6)	(0.058, 0.058)

Error $1/f_{AC}$: 20%

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

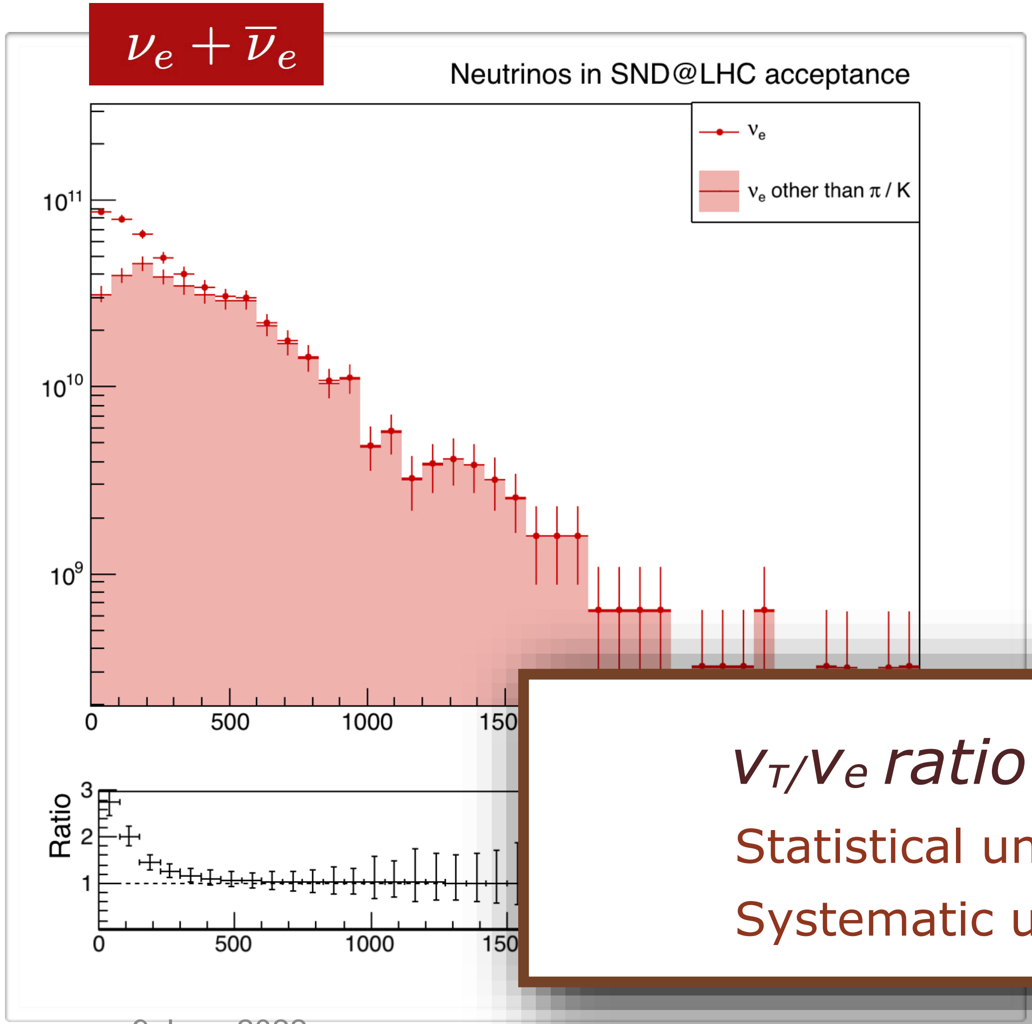
$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)},$$

- 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%**

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)



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as discrepancy between values

vig generators: **20%**

statistics :**30%**

ν_τ/ν_e ratio for LFU test

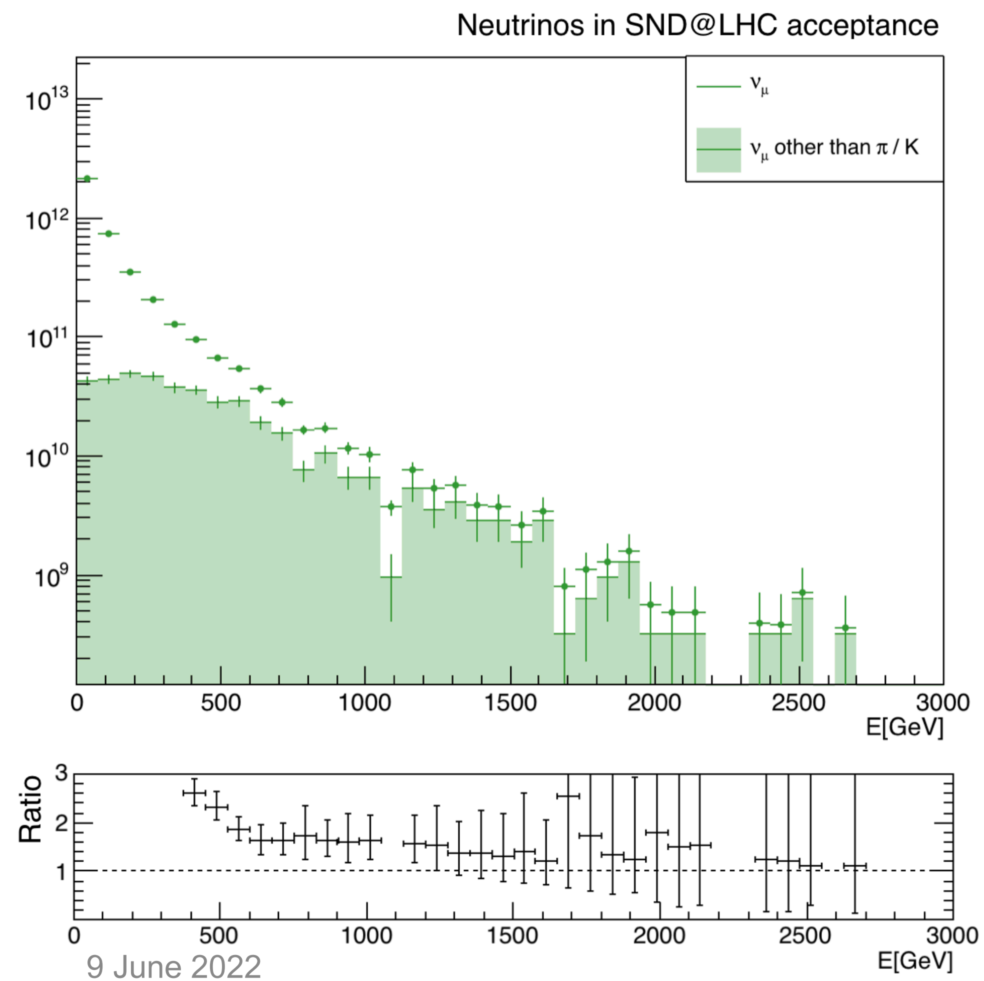
Statistical uncertainty ~30%

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

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



$$N(\nu_\mu + \overline{\nu}_\mu)[E > 600\,GeV] = 294 \quad \text{in 150 fb}^{-1}$$
$$N(\nu_e + \overline{\nu}_e)[E > 600\,GeV] = 191 \quad \text{in 150 fb}^{-1}$$

- 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%

3. LEPTON FLAVOR UNIVERSALITY

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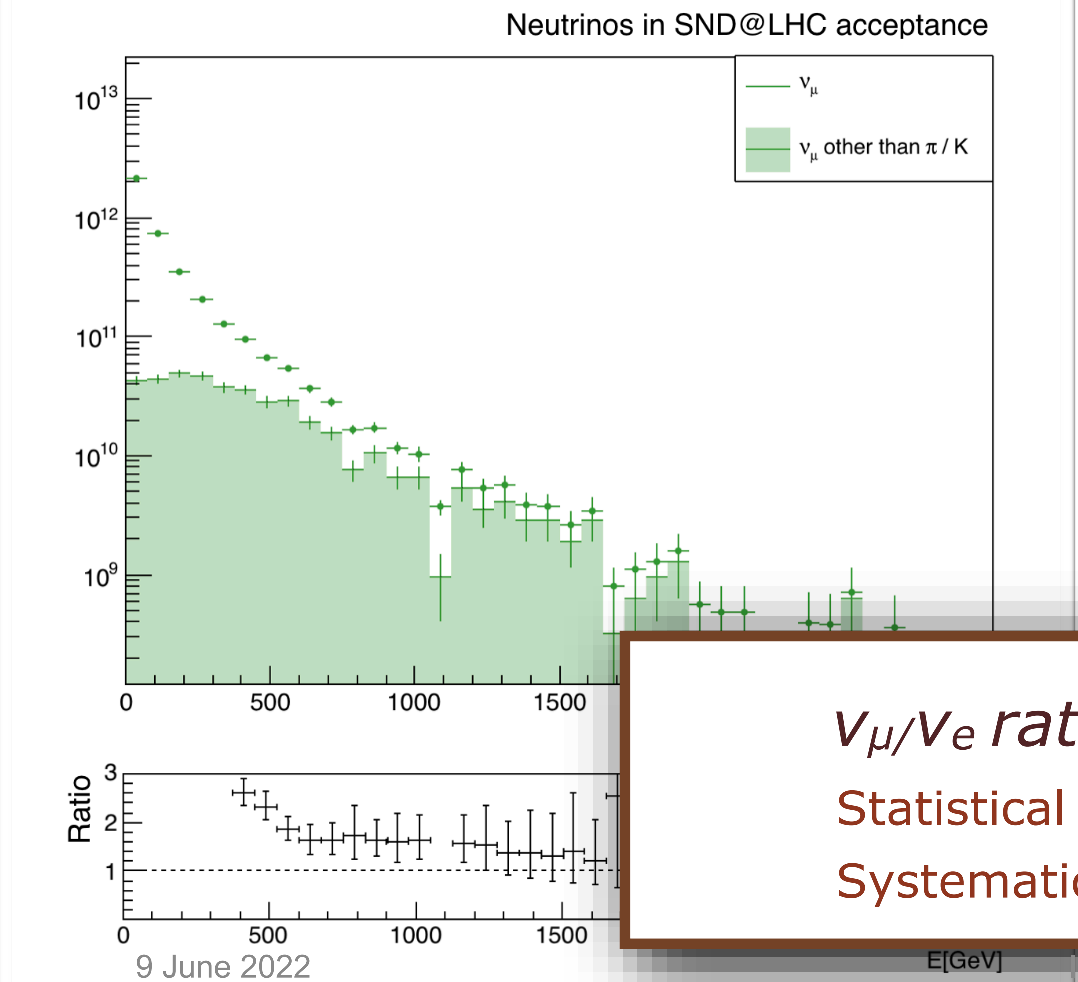
$\nu_\mu + \overline{\nu}_\mu$



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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

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

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  - In case of DIS, P can be written as

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

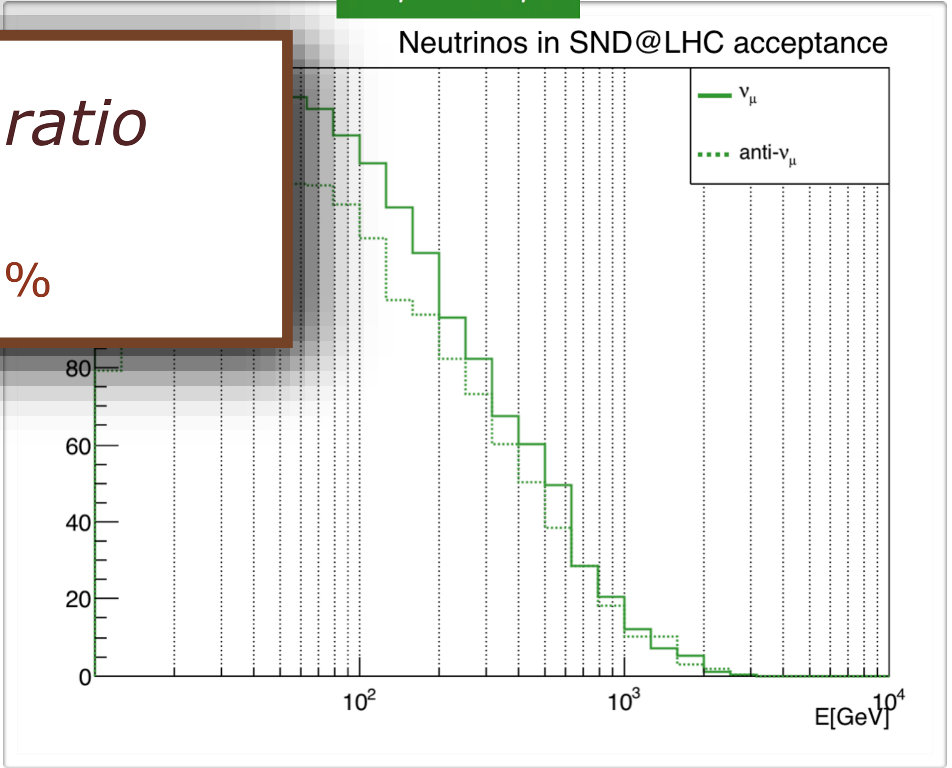
where λ originates from unequ
protons Z and neutrons (A-Z)
Introduces a correction factor c
For a Tungsten target λ=0.04

Measurement of NC/CC ratio

Statistical uncertainty ~5%

Systematic uncertainty ~10%

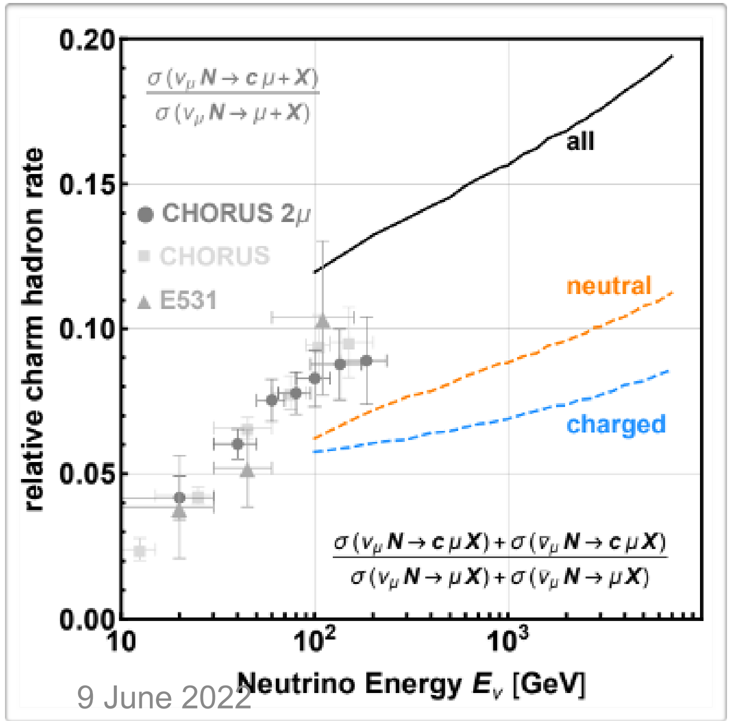
ν_μ vs $\bar{\nu}_\mu$

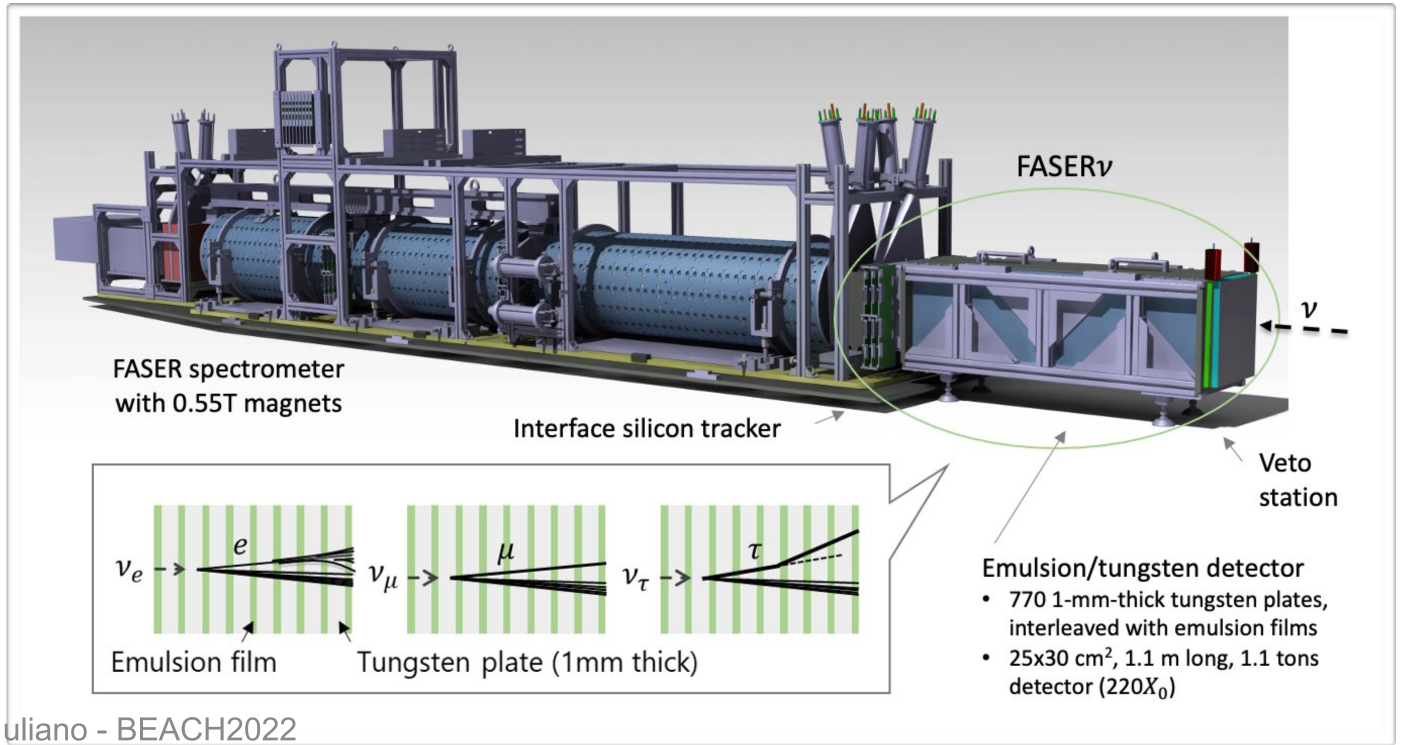


- **Statistical** uncertainty on P given by the number of observed CC and NC interactions: **5%**
- **Systematic** uncertainty:
  - asymmetry between neutrino and anti-neutrino spectra mainly in n muon neutrino spectra at low energies. Contribution to the error on P: **<2%**
  - CC to NC migration and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

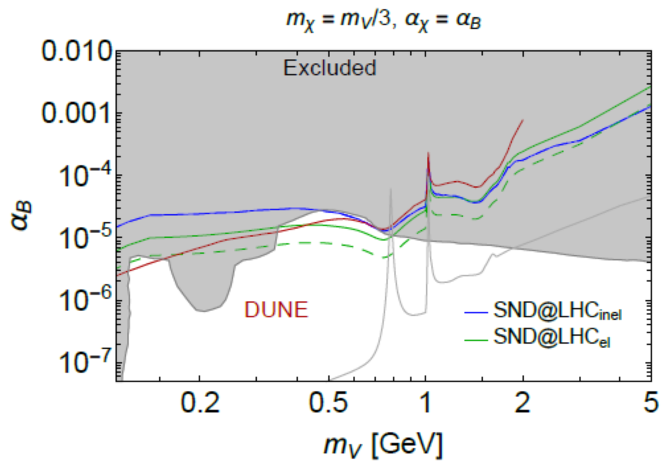
COMPLEMENTARITY WITH FASERnu

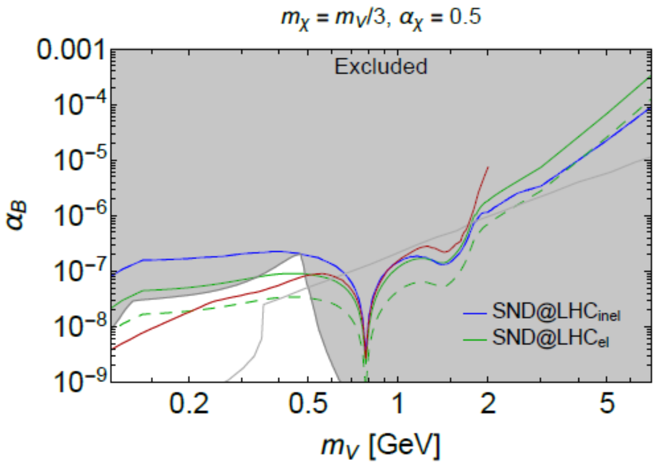
- Pseudo-rapidity range: η >8.8
- Main physics goals:
  - ~2000 ν_e, 7000 ν_μ, 50 ν_τ CC interactions expected [Eur. Phys. J. C 80 (2020) 61]
  - NC measurements could constrain neutrino non-standard interactions [Phys. Rev. D 103, 056014 (2021)]
  - Neutrino CC interaction with charm production ($\nu s \rightarrow lc$)
  - Study the strange quark content

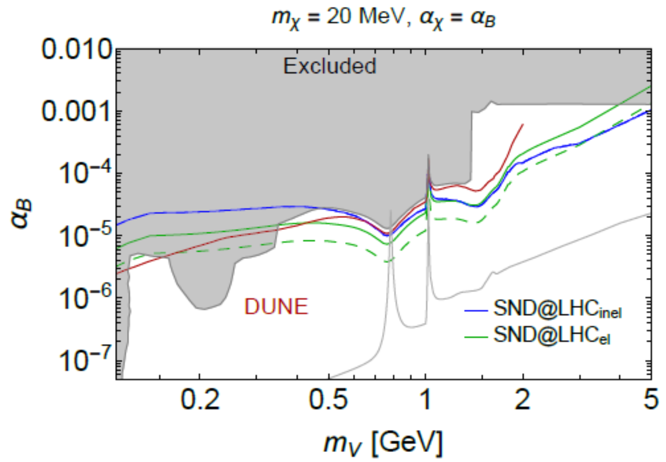


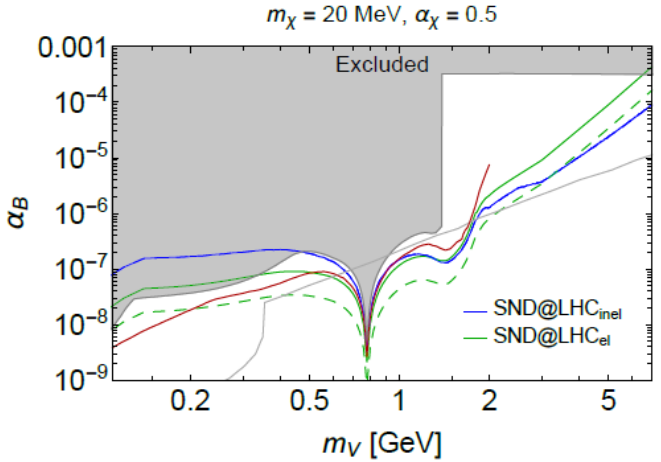


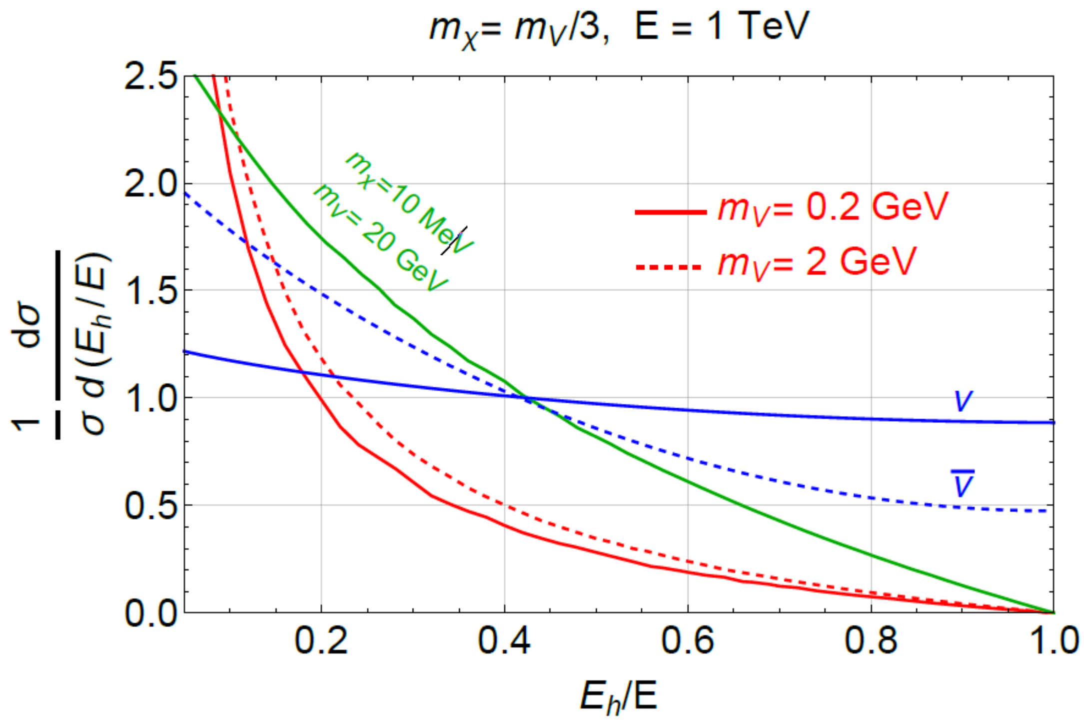
FEEBLY INTERACTING PARTICLES











Spectra of neutrinos vs dark matter in inelastic scattering events. The green line shows the special case of light X and massive V

Neutrino-induced charm production