Neutrino physics at LHC :

The SND@LHC experiment at CERN

LHC
Scattering and Neutrino Detector
at the LHC

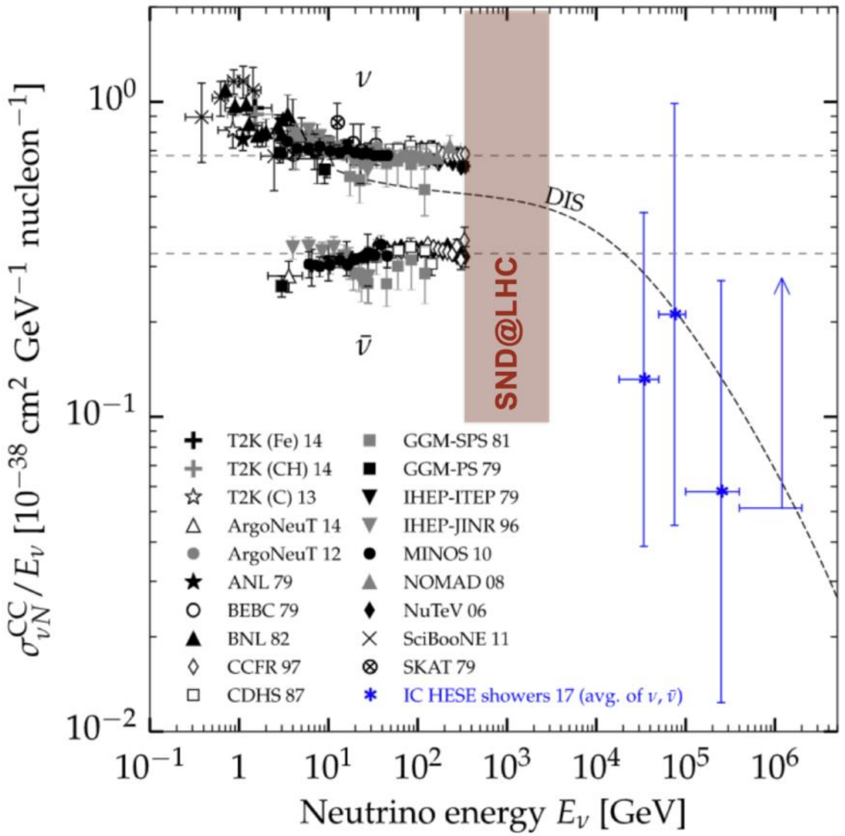
T. Camporesi,
CERN, EP Dep.
April 7, 2023

UNIVERSITY OF IOANNINA

MOTIVATION

Neutrino physics at the LHC

- A. De Rùjula, R. Rükl, 1984, Neutrino And Muon physics in the collider mode of future accelerator,CERN-TH-3892-84
- Klaus Winter, 1990, observing tau neutrinos at the LHC
- A. De Rùjula, E. Fernandez and J. J. Gòmez-Cadenas, 1993, Neutrino fluxes at LHC
- F. Vannucci, 1993, neutrino physics at the LHC
- http://arxiv.org/abs/1804.04413 April 12th 2018, First paper on feasibility of studying neutrinos at 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

N Beni[1], M Brucoli[2], S Buontempo[5], V Cafaro[4], G M Dallavalle[4,8], S Danzeca[2], G De Lellis[2,3,5], A Di Crescenzo[3,5], V Giordano[4], C Guandalini[4], D Lazic[6], S Lo Meo[7], F L Navarria[4] and Z Szillasi[1,2]

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

Recall the basics

Number of ν Events

- neutrino interaction cross section plays a critical role in determining number of ν interactions expect to collect

$$N_\nu(E) \sim \Phi_\nu(E) \times \sigma_\nu(E) \times \text{target}$$

ν flux

(# neutrinos)

depends on your ν source

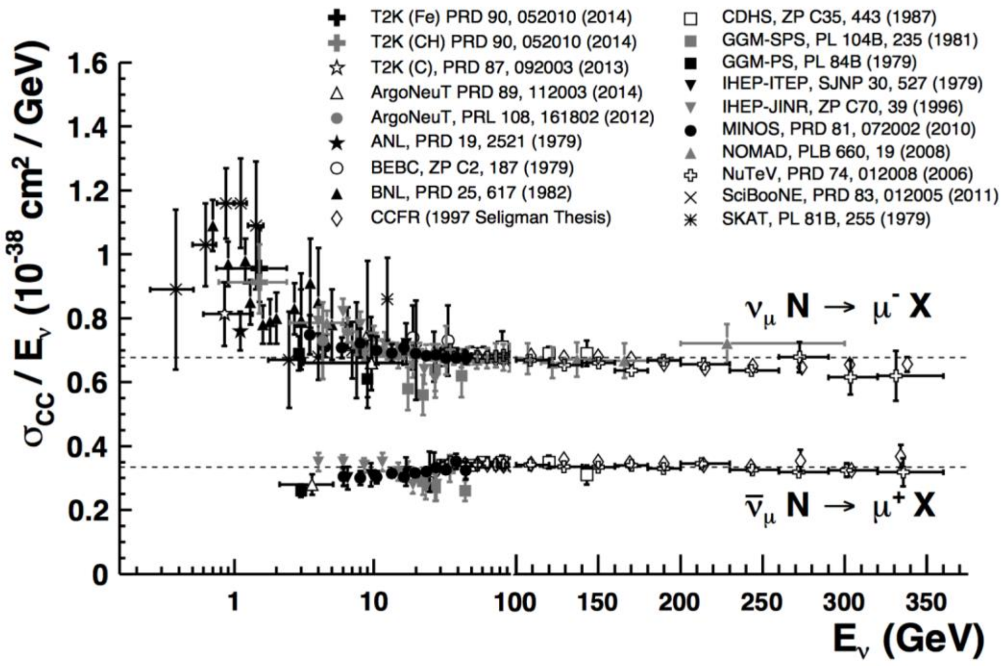
ν cross section

tiny (~10^{-38} cm^2)

$\sigma_\nu^{tot} \sim E_\nu$

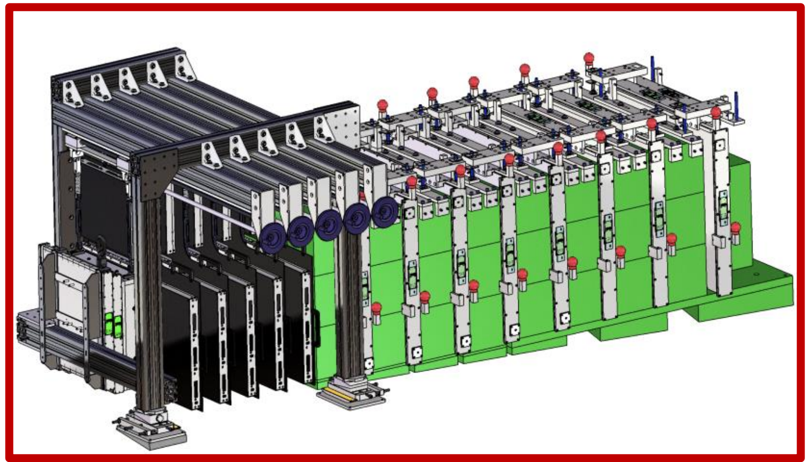
at 1 GeV $\sigma(\nu N) \sim 10^{-38}$ cm^2,
compare to $\sigma(pp) \sim 10^{-26}$ cm^2

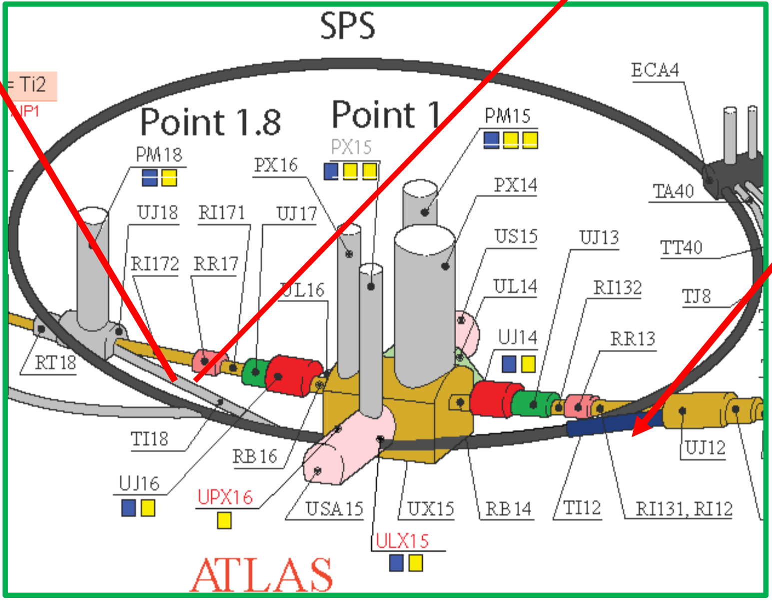
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$



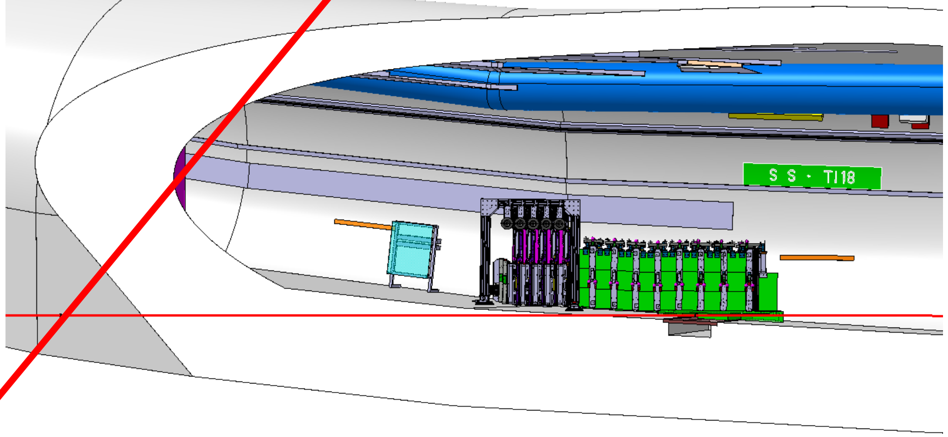
Location: TI18, transfer tunnel connecting SPS to LEP

- 480 m away from the IP
- Charged particles deflected by LHC magnets
- Shielding from the IP provided by 100 m rock
- Off LHC beam axis Angular acceptance: 7.2<η< 8.4
- Complementary to FASERν (9.<η)

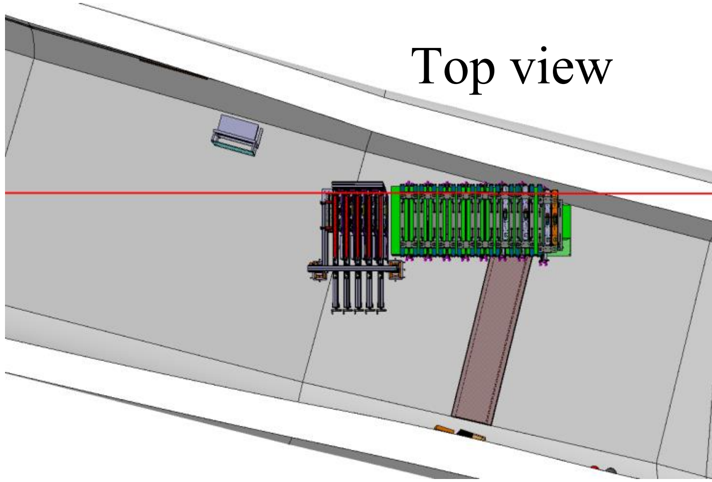


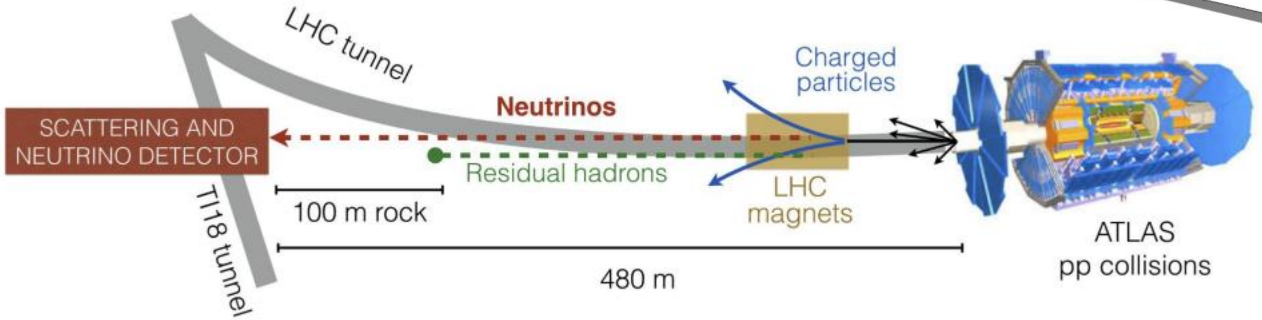


Side view



Top view





Experiment timeline

Scattering and Neutrino Detector at the LHC

Letter of Intent

August 2020

TECHNICAL PROPOSAL

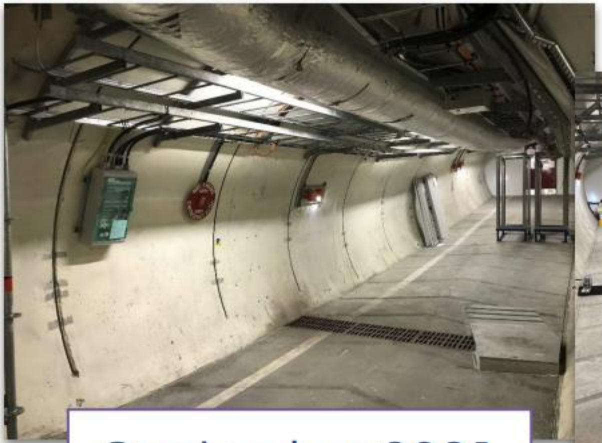
SND@LHC

January 2021

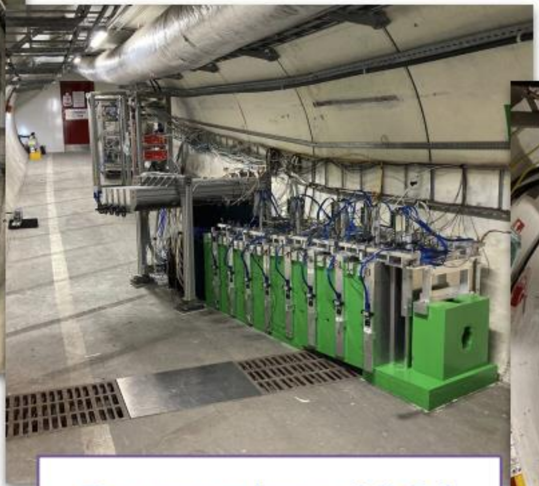
CERN approves new LHC experiment

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

March 2021



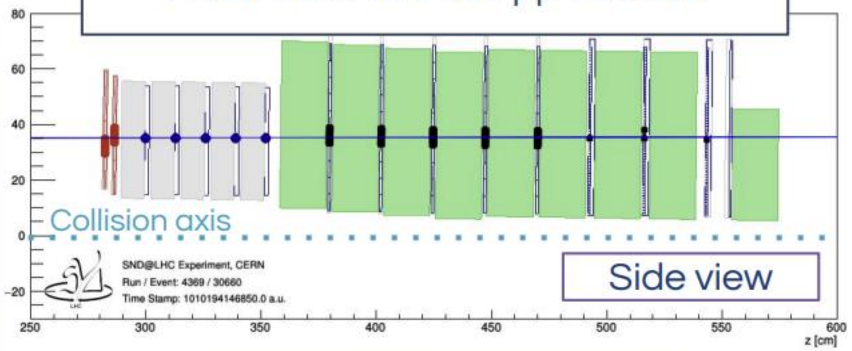
September 2021



December 2021

March 2022

Muon from 13.6 TeV pp collision



July 2022

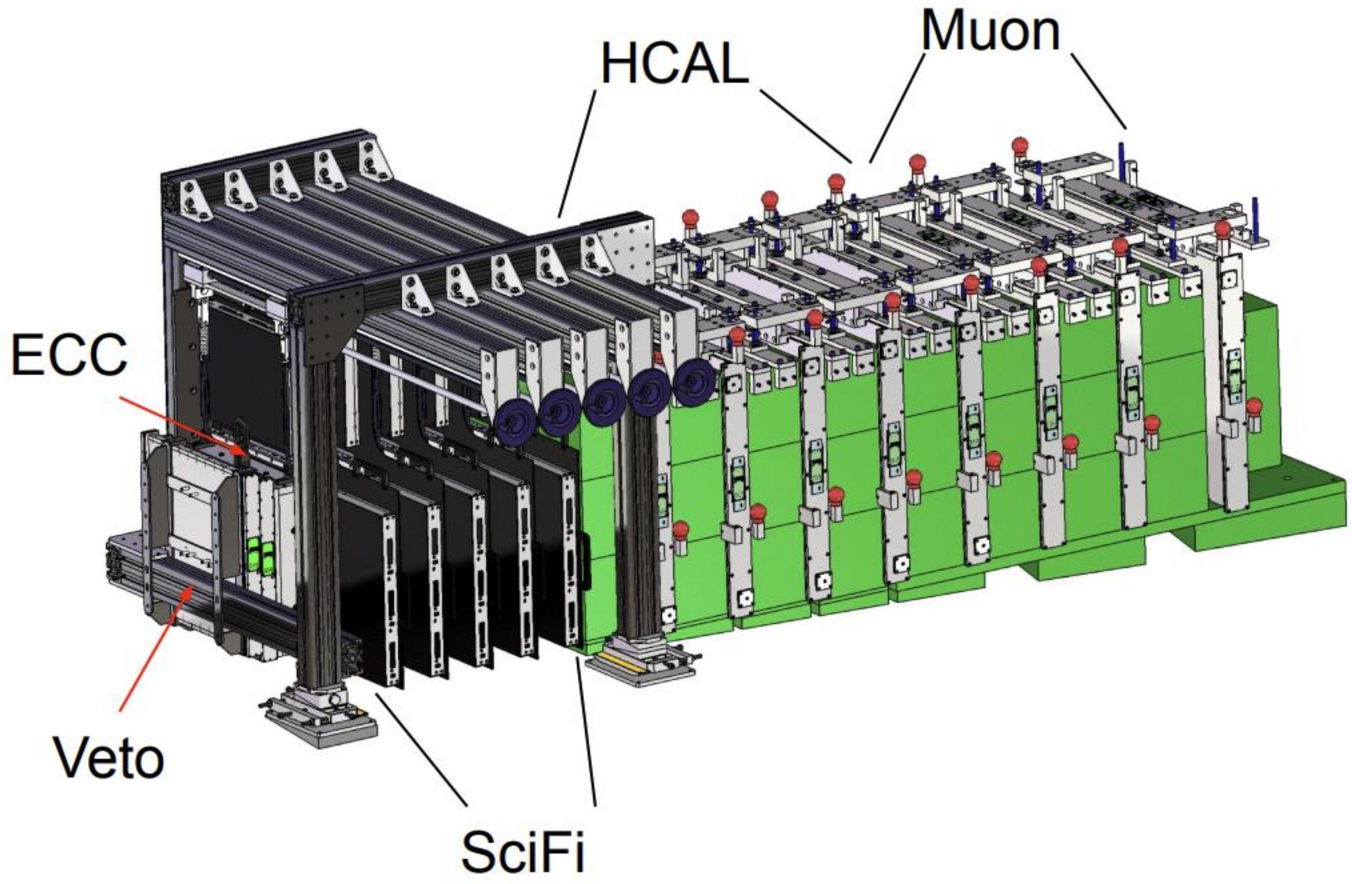
Experiment Concept

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(ECC) (Emulsion+Tungsten) for neutrino interaction detection
- Scintillating fibers for timing information and energy measurement

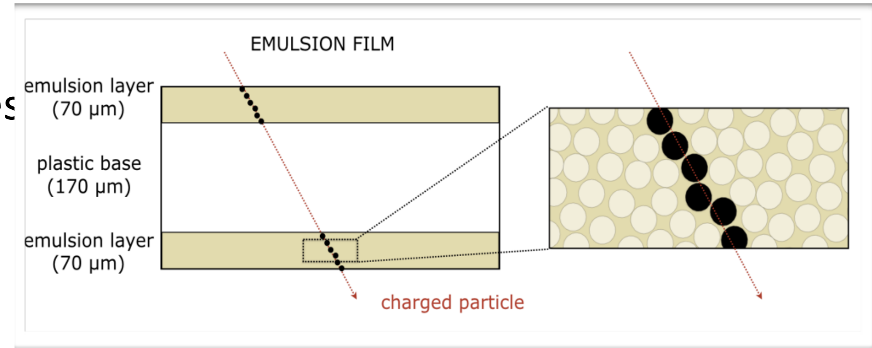
HAD CAL + MUON SYSTEM:
iron walls interleaved with plastic scintillator planes for fast time resolution and energy measurement



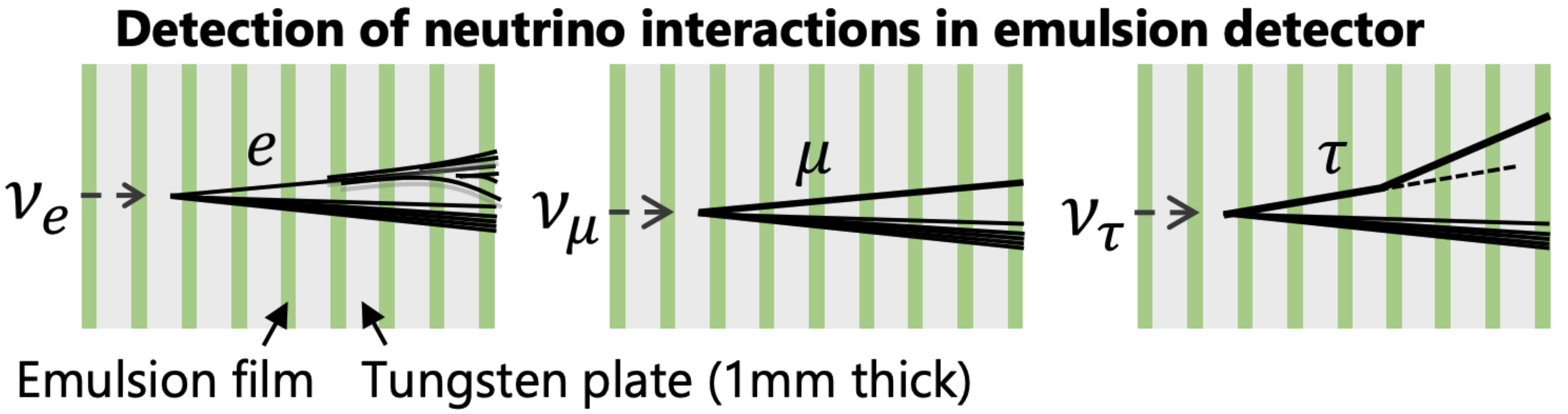
https://arxiv.org/abs/2210.02784 (detector paper)

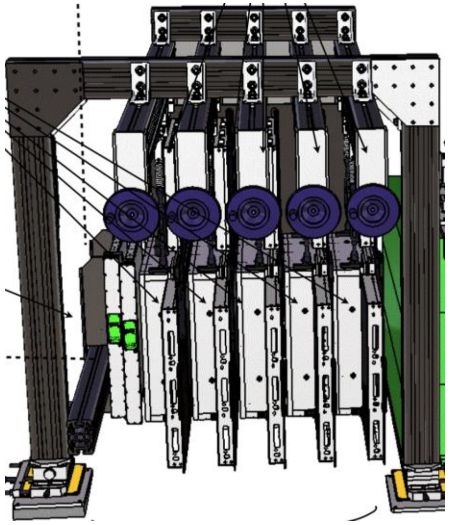
Neutrino target

Angular acceptance: 7.2< η < 8.4
5 Walls comprising 60 Emulsions interleaved with 1 mm tungsten plates: 5x60 planes
Total emulsion surface 44m^2
Total weight of W target 830 Kg
Surface: 390x390 mm^2

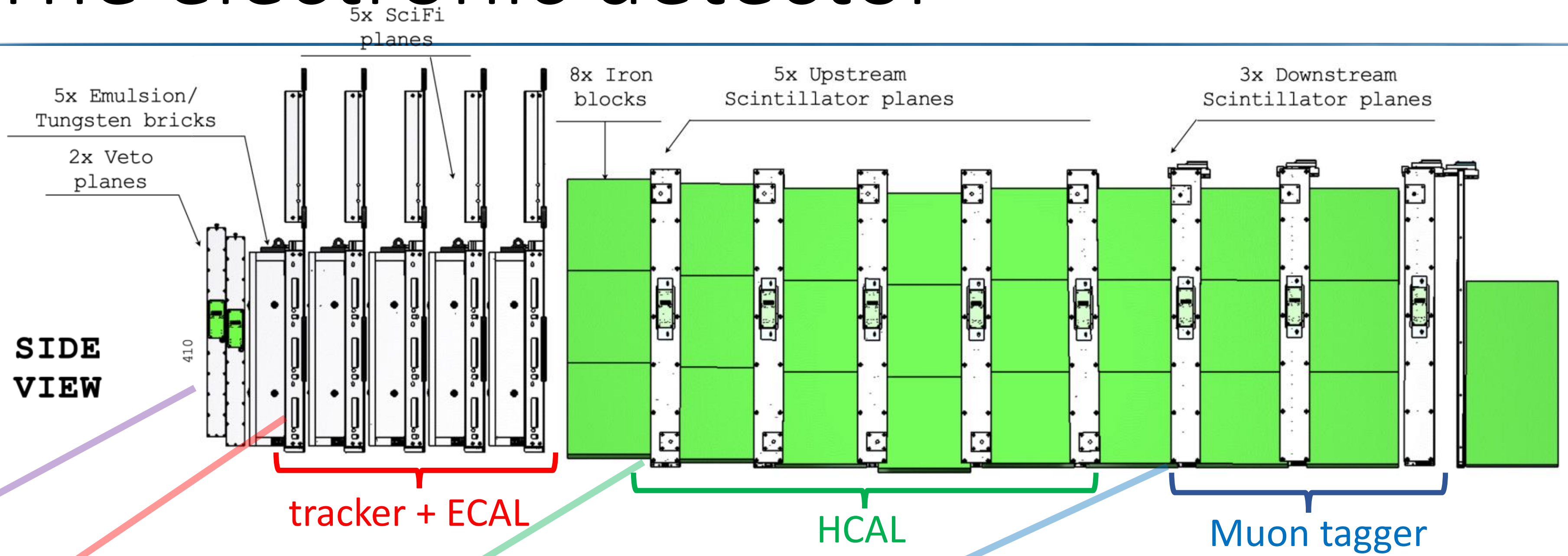


Submicron resolution
Milliradians angular resolution





The electronic detector



Veto plane (two planes of vertical 1x6 cm Sci bars) : time stamp of entering particle (expect less than 1 charge particle per bunch crossing)

SCiFI tracker (XY stacks of 250 mm thick square fibers readout by SIPM) postioned avter each WALL : measure position of charged particles and time stamp them. Position resolution 50 µm and time resolution on single hit 250 ps .
Acts as single particle tracker and EM Calorimeter

SCI bars in HCAL ‘upstream detector ‘ (6x1 cm vertical scintillator bars) readout by SIPMs at each end : sample energy of shower and time stamp it

SCI bars in ‘Downstream detector’ (3 planes of stacked vertical and horizontal 1x1 cm Sci bars) readout by SIPMs measure

Triggerless operation

Every element (Veto scintillator planes (2) , SCI-FI target tracker planes (10), HCAL scintillator bars (5), Muon stations (6) is readout by SIPM and the reaodut (TOPFET chip) record time (T0 given by the LHC bunch crossing signal) and Pulse HeIght and sent to a ‘EVENT builder’

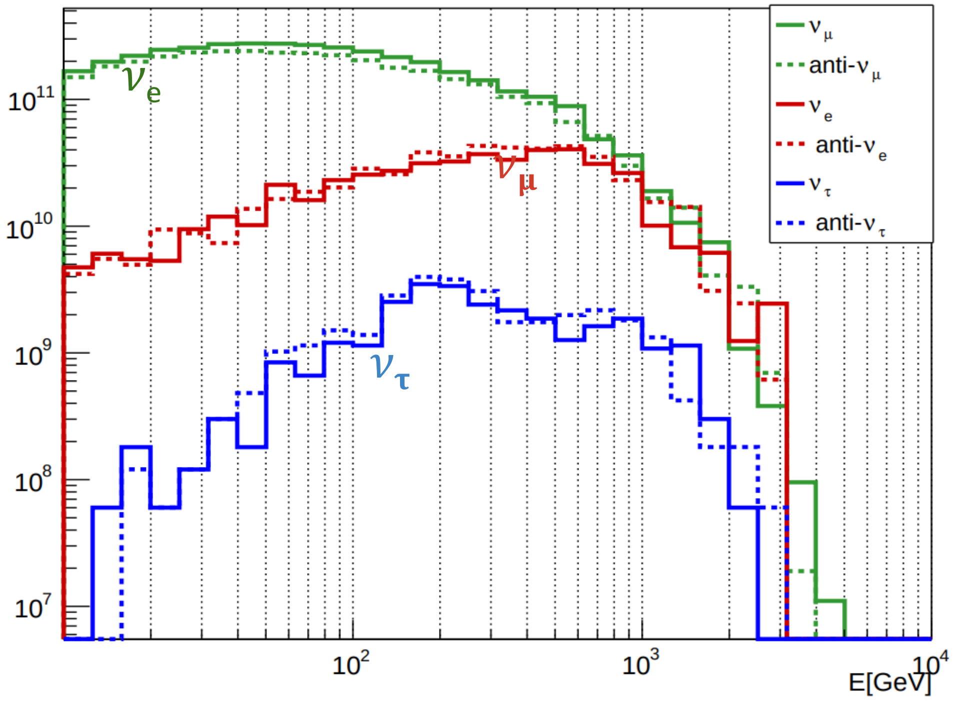
The typical single detector time resolution is : 450 ps

The event builder groups all the elements which are at the same time : an event is saved if there are more than N_{min} element at the same time (else rejects it as electronic noise)

The time of the event is defined by the SCI-FI. Eventually the final time ‘stamp’ of an event which accumulates ≥ 10 ‘elements’ the resolution will approach or exceed 100 ps and will be good enough to assess if the event comes from ‘prompt’ particles from the iP (the spread of the LHC luminous region is 200ps) .

Physics programme

- Measurement of charm production at high pseudorapidity (gg → cc): 97% of neutrinos come from Charm decays
- Probe gluon PDF at low momentum fraction x ~ 10^{-6}. Relevant for
  - FCC detectors
  - Extra-galactic neutrino observation (atmospheric neutrino background)
- Test lepton flavour universality with neutrinos
  - Thanks to the ability to distinguish all neutrino flavours
- Direct search of feebly-interacting particles (Scattering elastic/inelastic, Decay)



~ 75% ν_μ 25% ν_e

and ~30-40 ν_τ

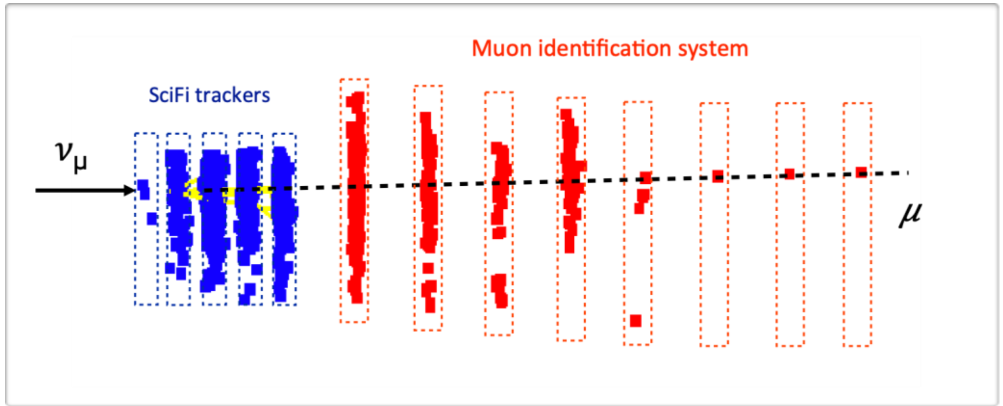
Technical Proposal

Detector paper

Key detetcor Features

•Muon identification

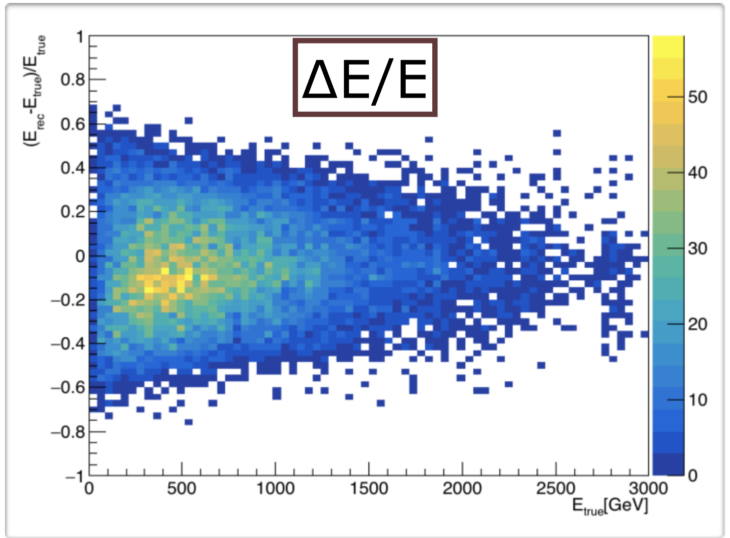
- ν_μ CC interactions identified thanks to the identification of the muon produced in the interaction
- Muon ID at the neutrino vertex crucial to identify charmed hadron production, background to ν_τ detection



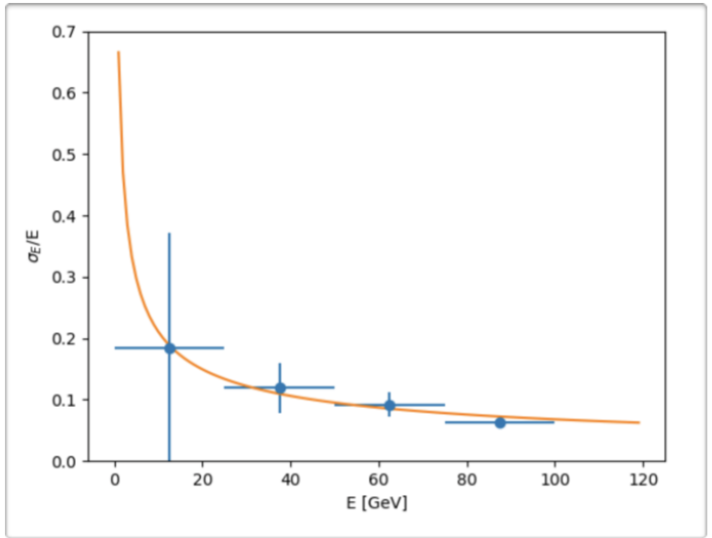
•Energy measurement

- The detector acts as a non-homogeneous sampling calorimeter

ν_e+anti-ν_e



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



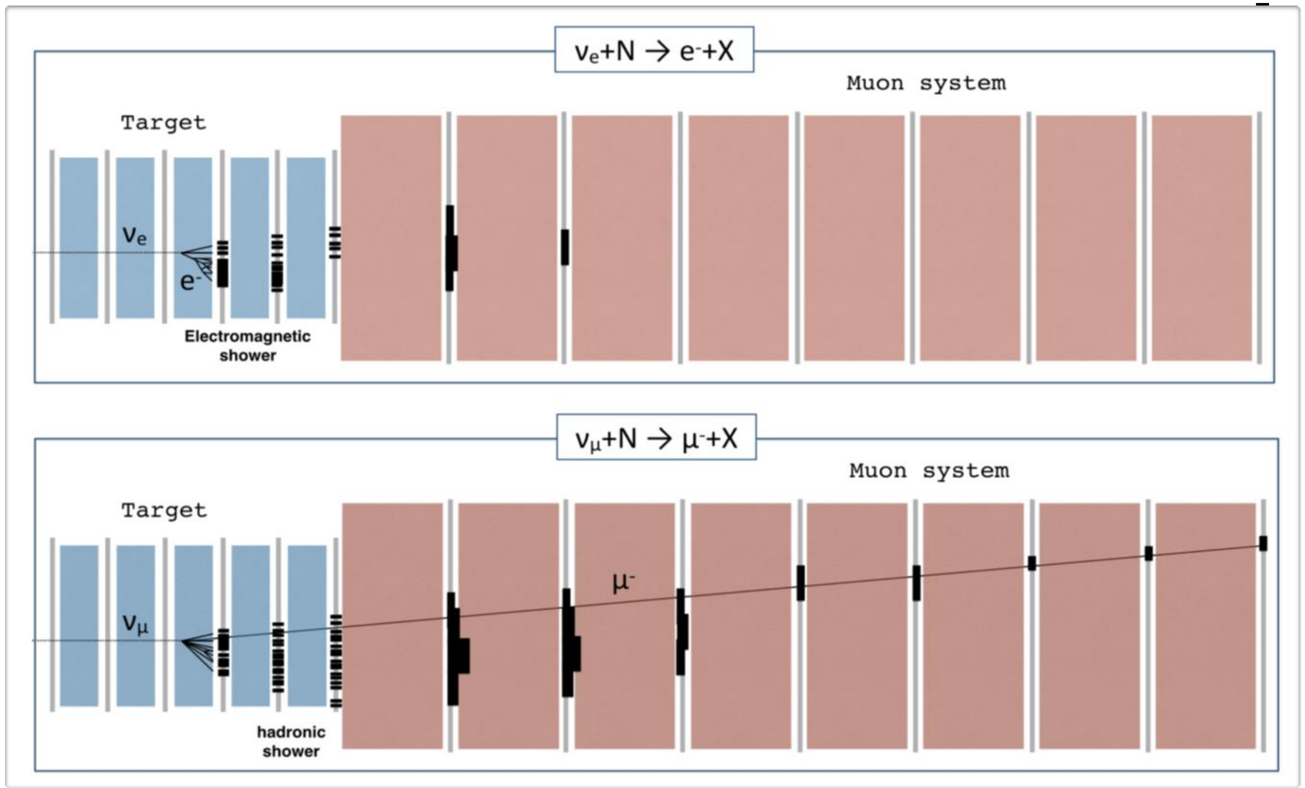
- Performance of SciFi tracker as sampling calorimeter, using a CNN
- Electron energy resolution

EVENT RECONSTRUCTION

FIRST PHASE: electronic detectors

Event reconstruction based on Veto, Target Tracker (TT) and Muon system/HCAL

- ν candidates
- μ ID
- E.m. shower reconstruction (SciFi)
- ν energy (SciFi+Muon system/HCAL)

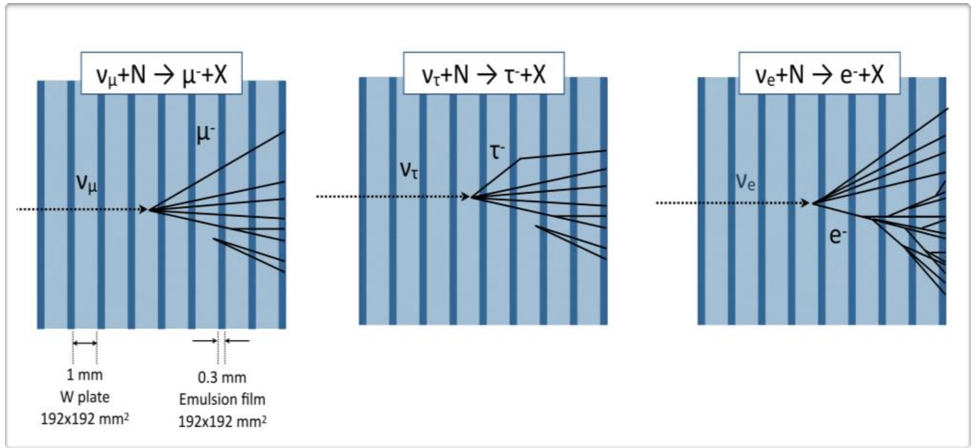


SECOND PHASE: nuclear emulsions

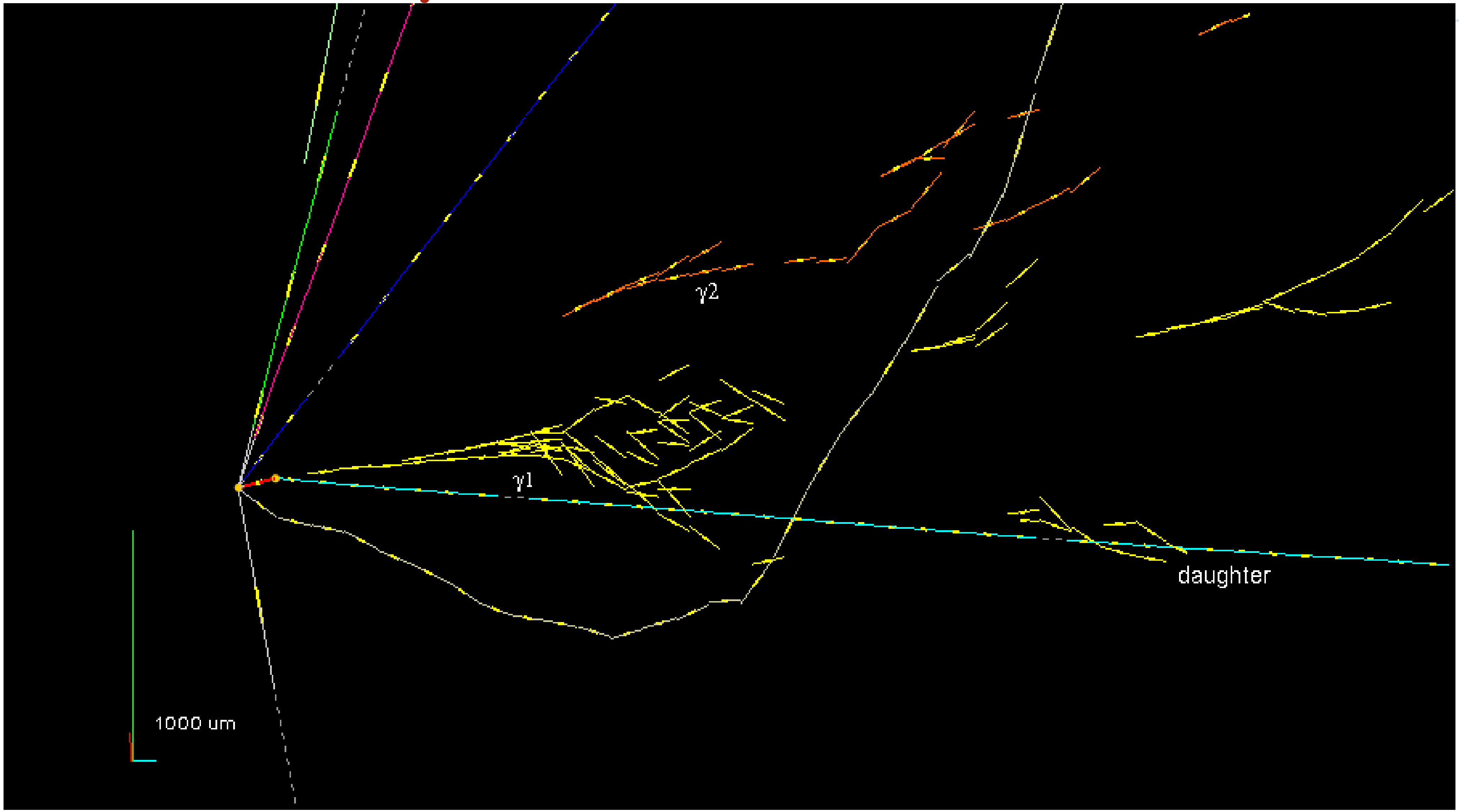
After subtracting the through going muon tracks

Event reconstruction in the emulsion target

- Align with traversing muons (then subtract them!)
- E.m. shower id with e/π^0 separation
- ν and 2ry vertex reconstruction
- Match emulsion and elec. Det. (time stamp)
- Complement TT for e.m. energy measurement



THE FIRST ν_τ CANDIDATE IN OPERA

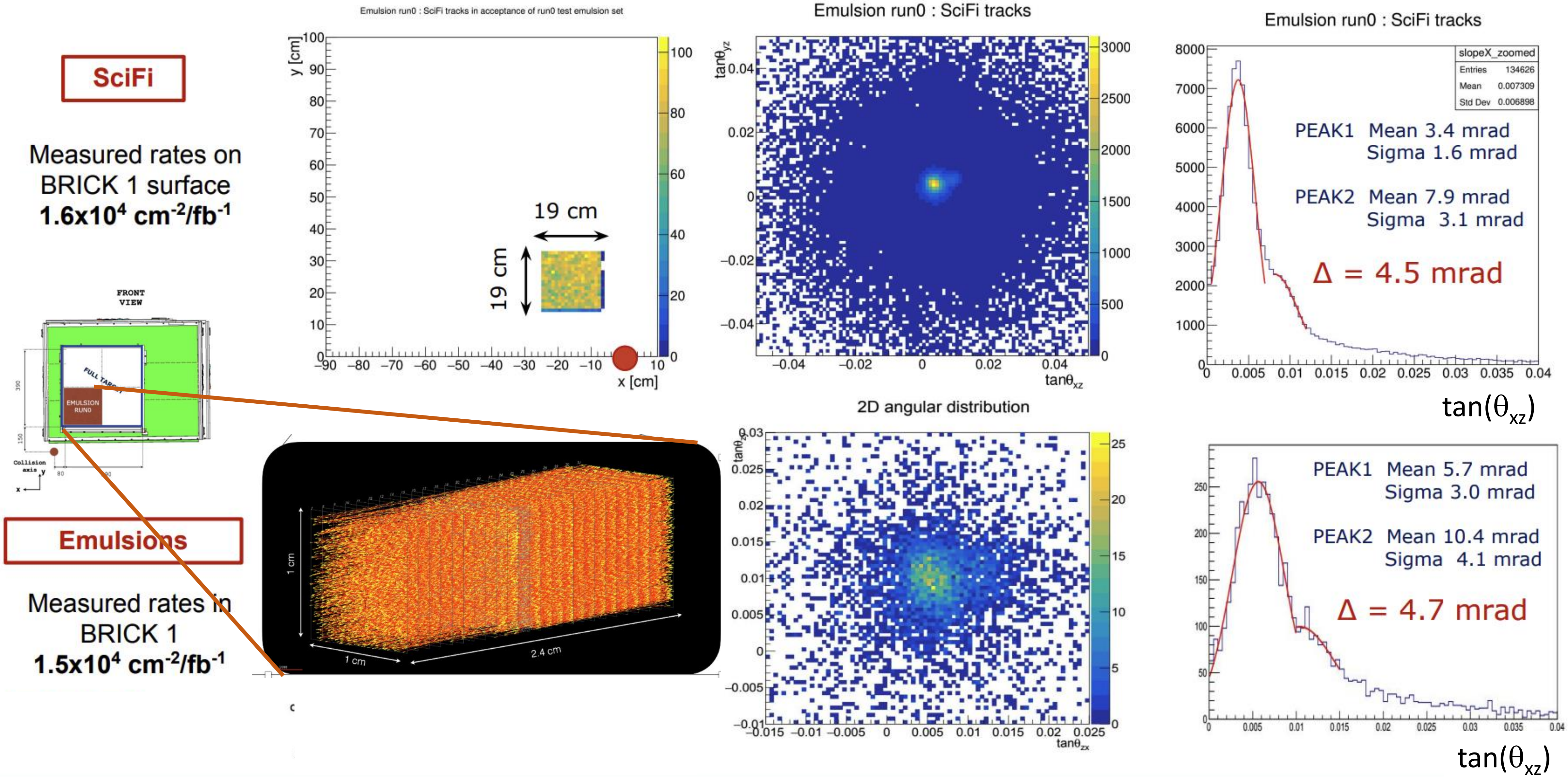


Physics Letters B691 (2010) 138

Emulsions / SciFi comparison

SciFi

Measured rates on BRICK 1 surface
1.6×10^4 cm^{-2}/fb^{-1}



Emulsions

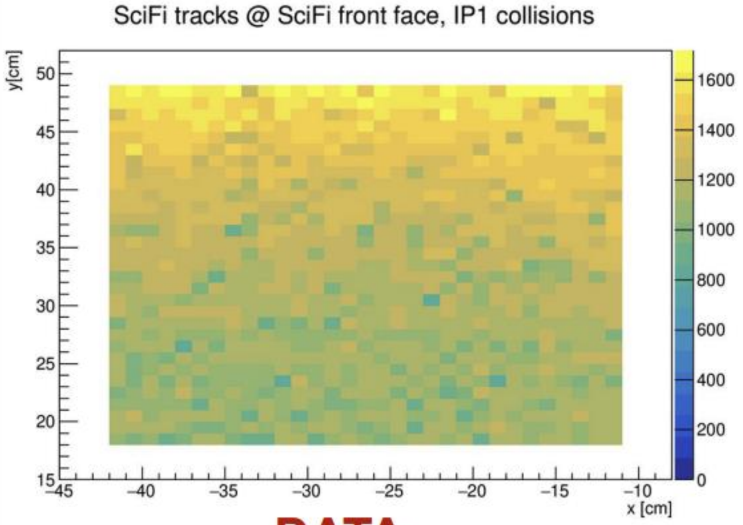
Measured rates in BRICK 1
1.5×10^4 cm^{-2}/fb^{-1}

Data/MC comparison

FLUKA: tracking through LHC optics and surrounding rock

F. Cerutti, M.S. Gilarte
CERN-SY/STI

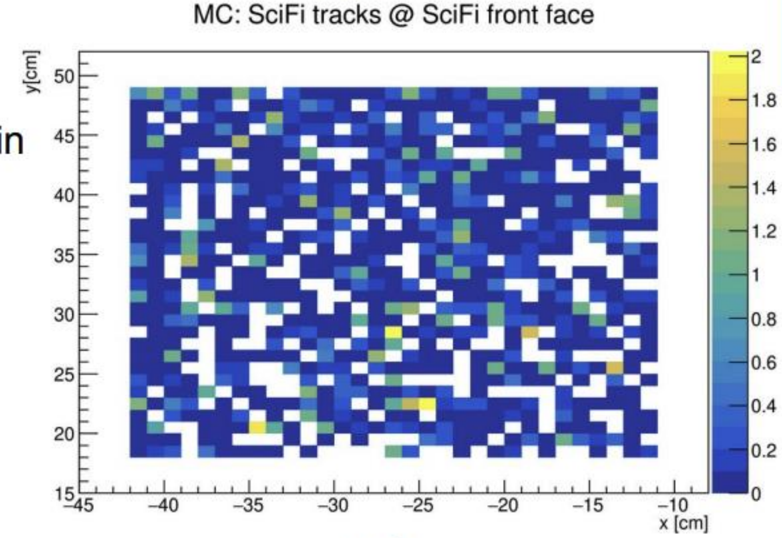
DATA



Measured muon track rate in SciFi (31x31 cm^2):

$(1.60 \pm 0.01_{stat})\times10^4$ cm^{-2}/fb^{-1}

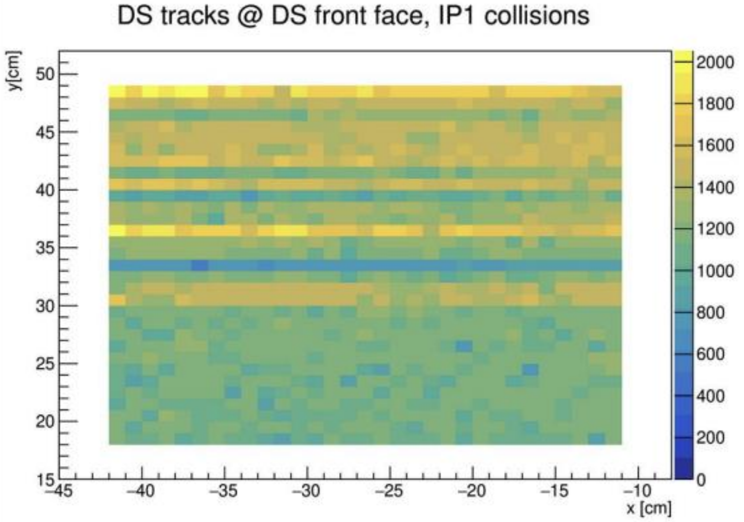
MC



Expected muon track rate in SciFi (31x31 cm^2):

$(1.57 \pm 0.10_{stat})\times10^4$ cm^{-2}/fb^{-1}

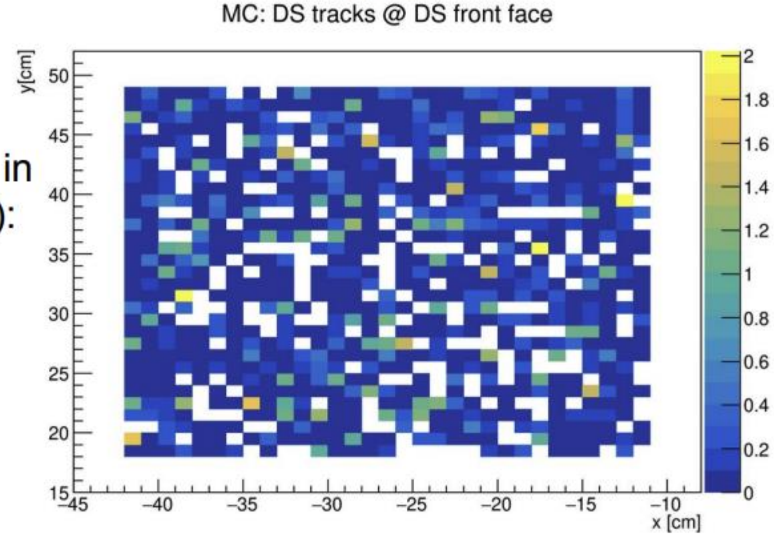
DATA



Measured muon track rate in Muon system (31x31 cm^2):

$(1.67 \pm 0.01_{stat})\times10^4$ cm^{-2}/fb^{-1}

MC



Expected muon track rate in Muon system (31x31 cm^2):

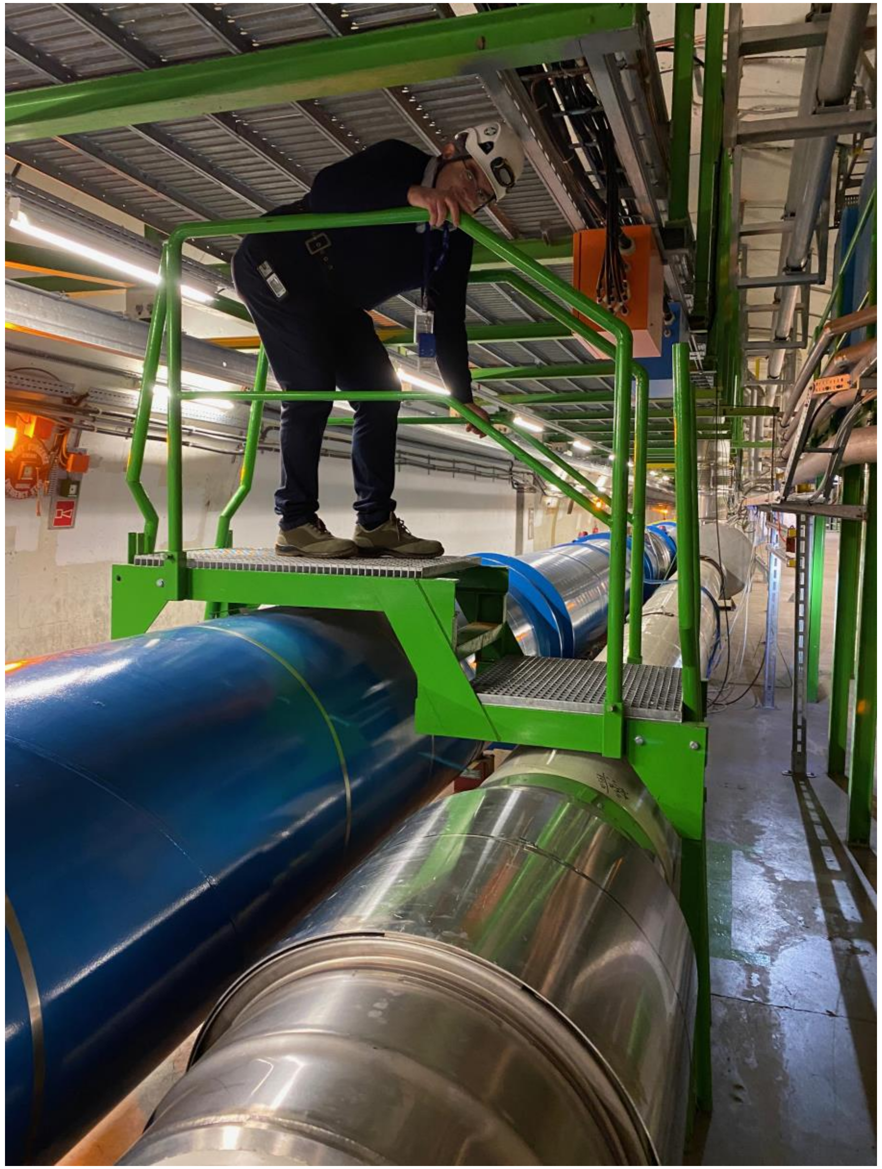
$(1.59 \pm 0.10_{stat})\times10^4$ cm^{-2}/fb^{-1}

Fully installed detector pointing to the IP

LHC
Scattering and Neutrino Detector at the LHC

View of the machine towards the IP1 (left) and of the detector in TI18 (right)

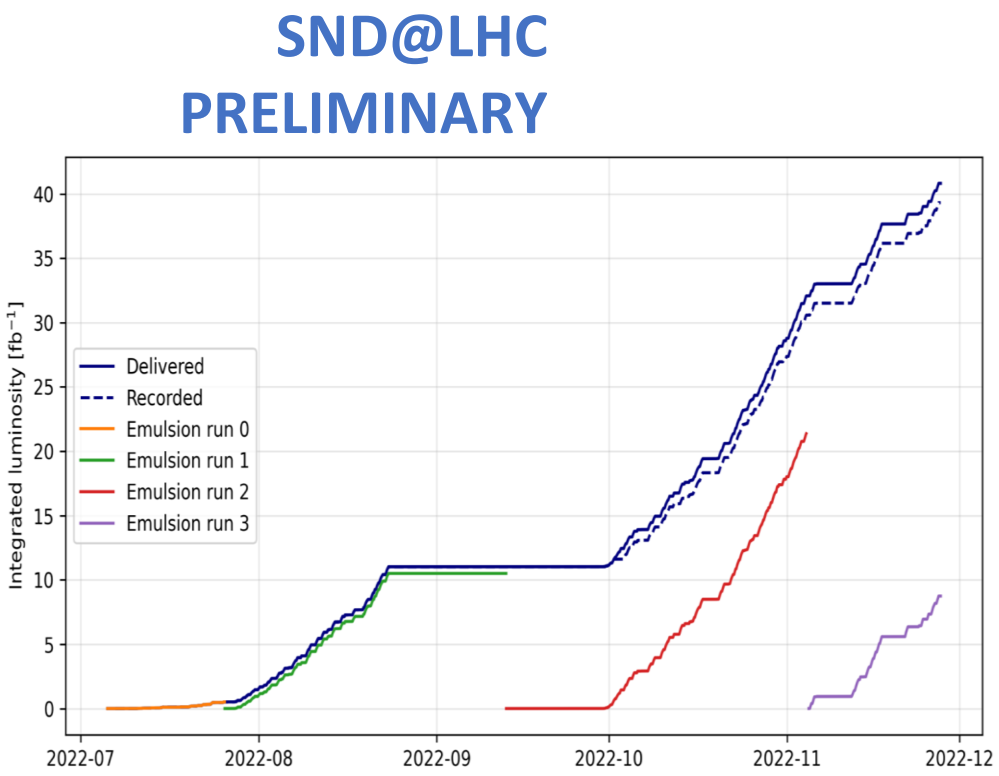
Human sized detector

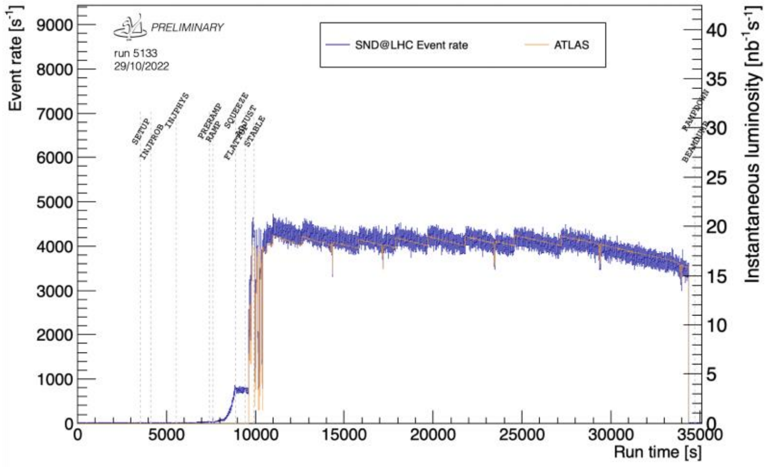


Run 3 data taking

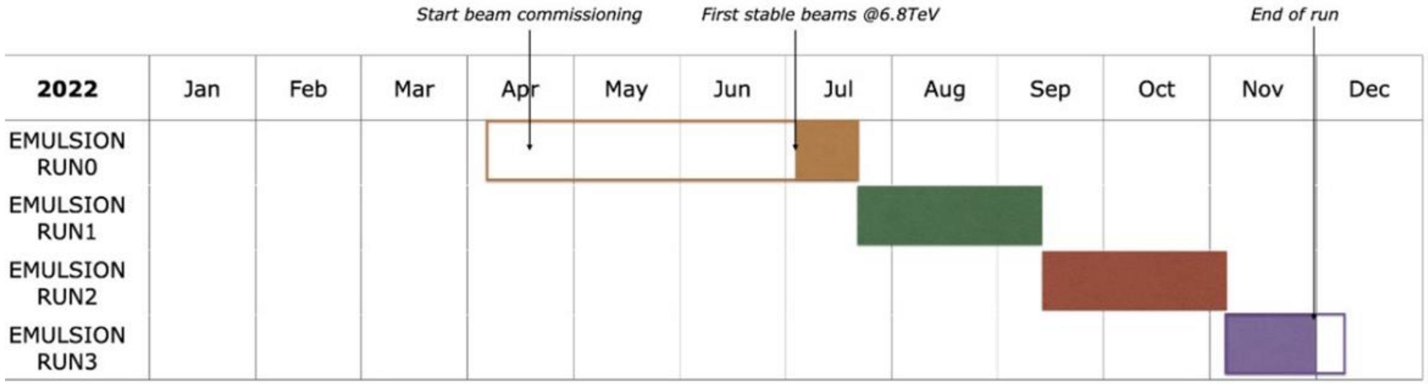
Delivered: 41.25 fb^{-1}
Recorded: 39.74 fb^{-1} (96%)

Quoted values don't account for the new ATLAS integrated luminosity estimation (5.4% less)





Typical fill: event rate vs ATLAS online lumi

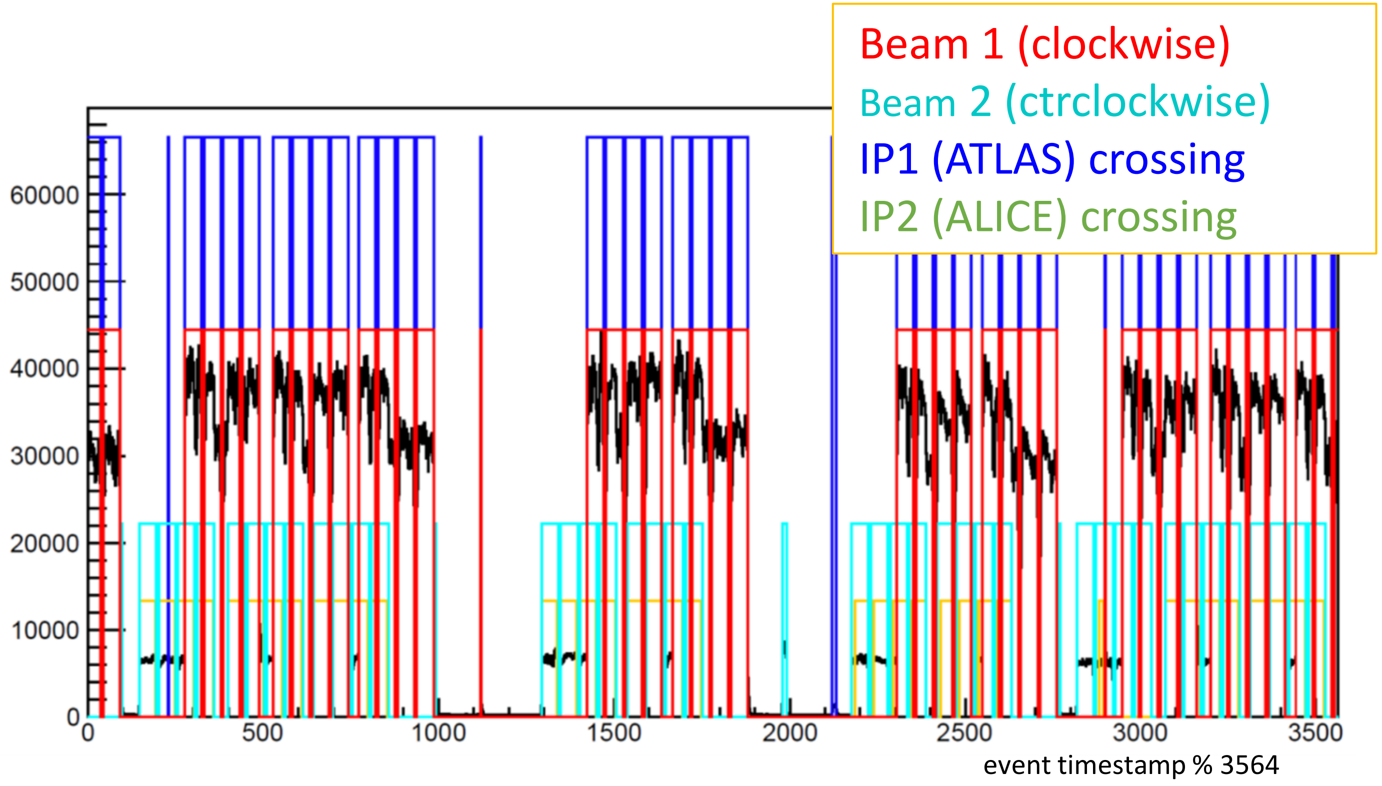


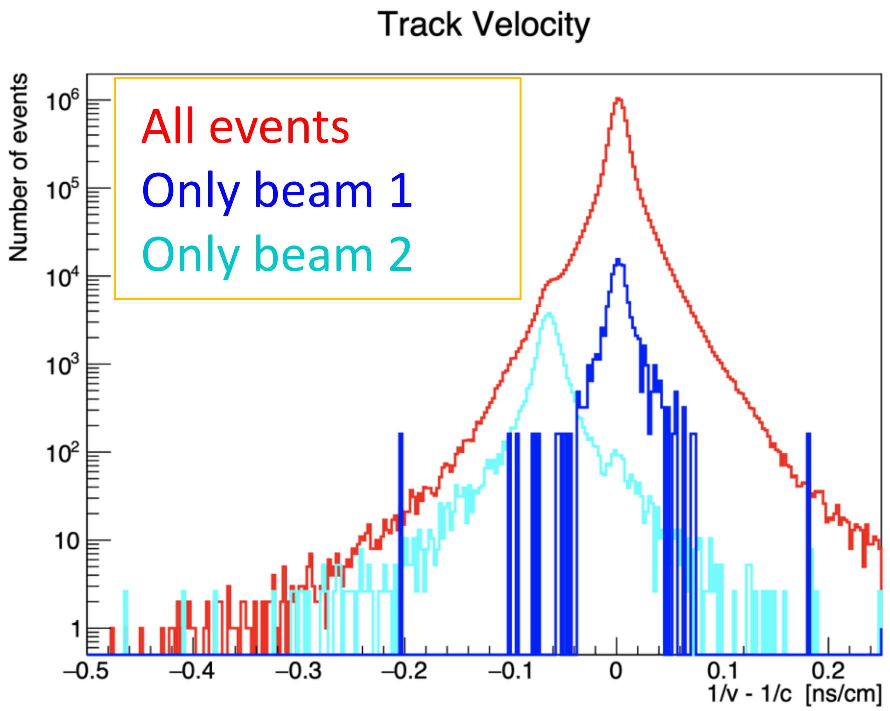
	INSTRUMENTED TARGET MASS	INTEGRATED LUMINOSITY
EMULSION RUN0	39 kg	0.5 fb^{-1}
EMULSION RUN1	807 kg	10.5 fb^{-1}
EMULSION RUN2	784 kg	21.1 fb^{-1}
EMULSION RUN3	792 kg	9.2 fb^{-1}

Bunch structure

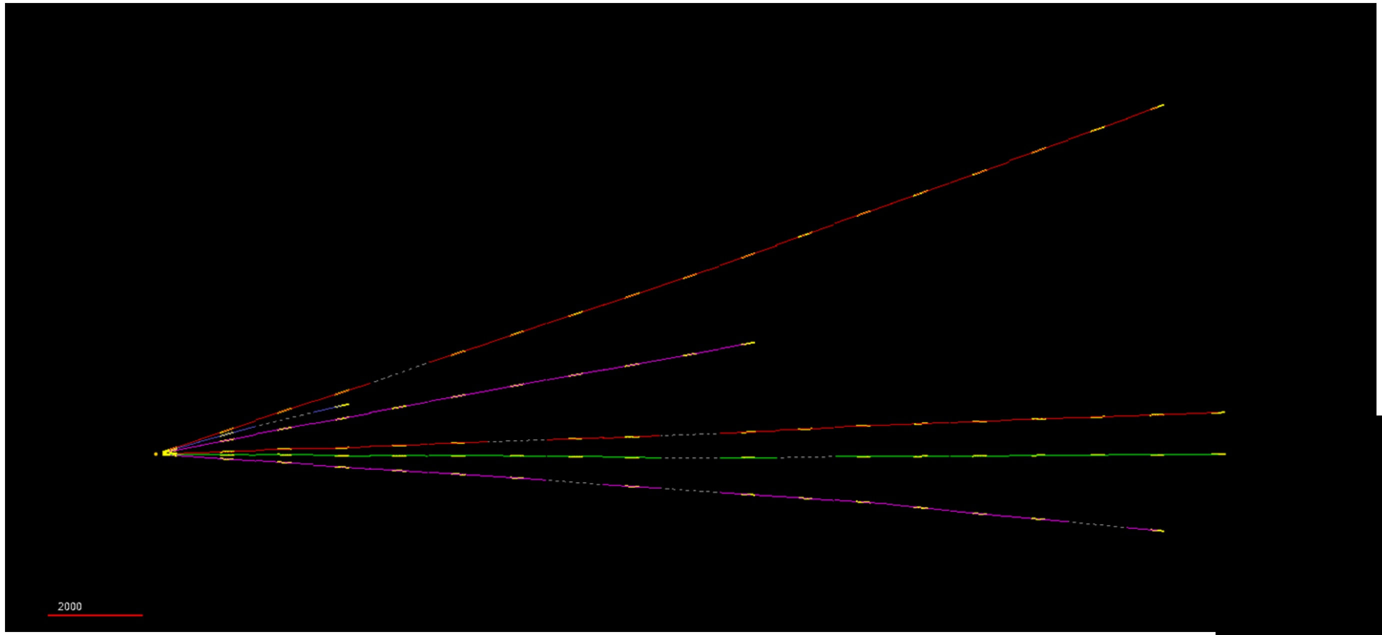
- Event rate at SND@LHC follow the LHC filling scheme
- Events associated to non-colliding bunches used to measure non-collision backgrounds
  - Significant event rate induced by Beam 2 non-colliding bunches
    - These events enter the detector from the downstream end
    - Clearly observed in track direction measurements

tracks from beam 1 <1.5%
tracks from beam 2 <1.0%



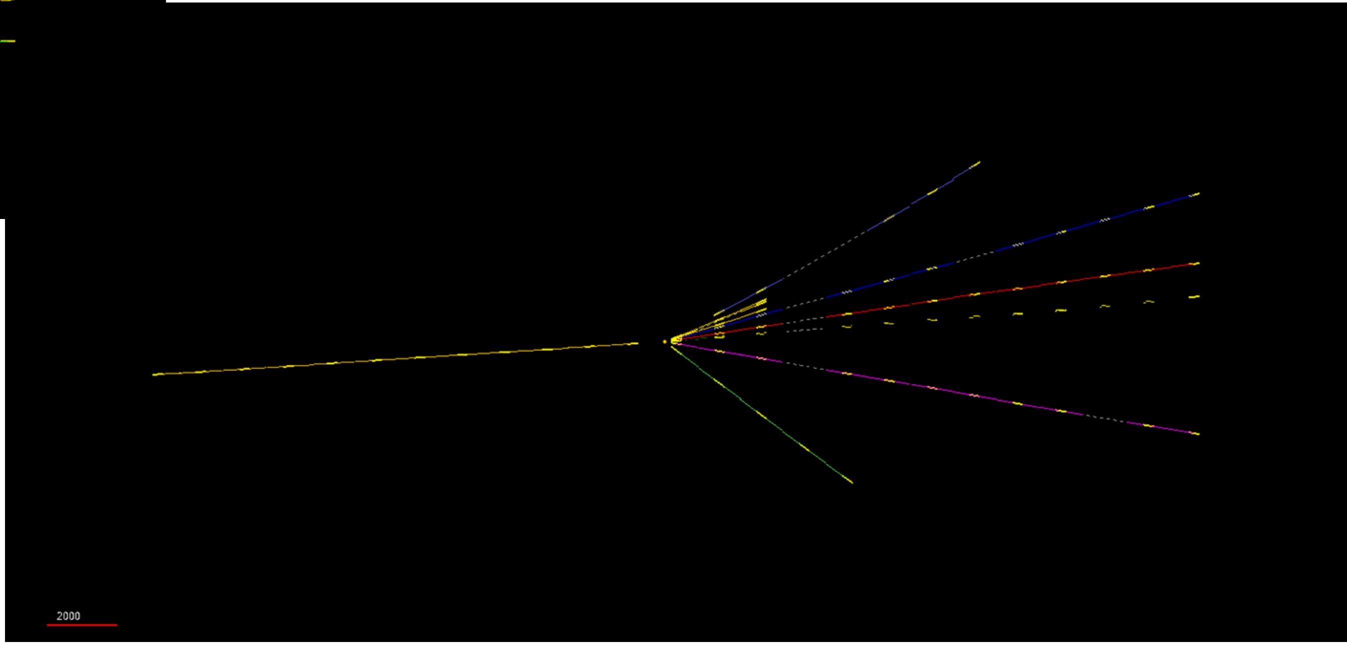


Vertex reconstruction in emulsion data



← Neutral-like particle interaction

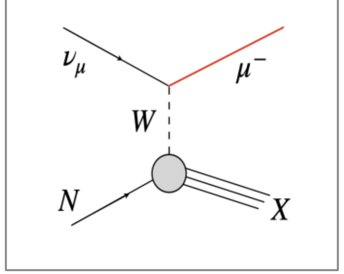
Charged-like particle interaction →



Neutrino observation with electronic detectors

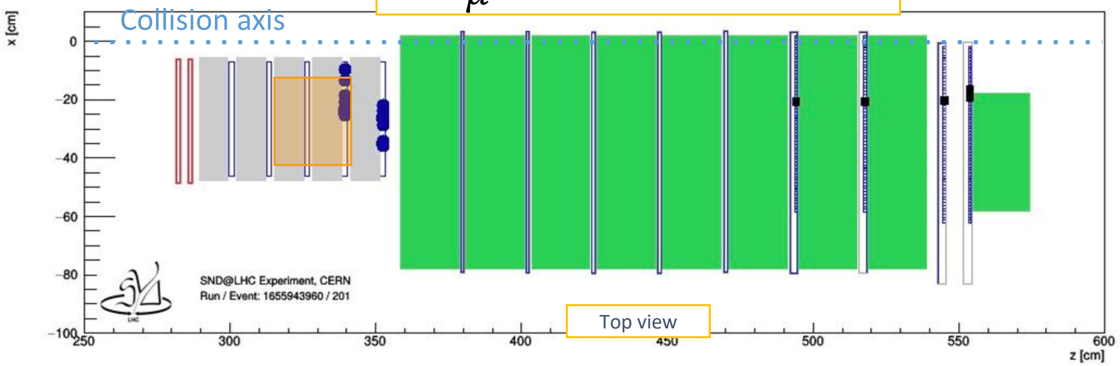
- Analysis strategy:
  - Full Run 3 **2022 dataset**, 39 fb^{-1}
  - Observe ν_μ **Charged Current** interactions with **electronic detectors only**
  - **Maximise S/B**, counting-based approach
  - ~10^9 muon events: apply **cuts with a strong rejection power** to reach a negligible background level

SIGNAL

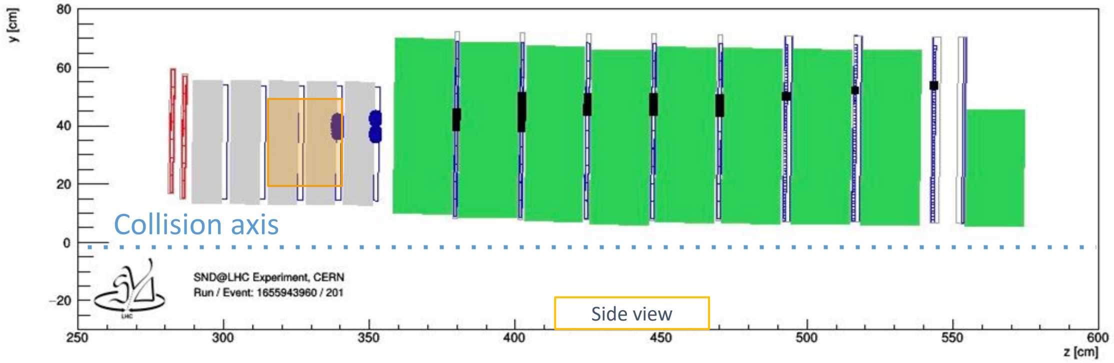


- Signal selection:
  - **Fiducial Volume (1, 2)** cuts
    - Require an event from a **neutral vertex**, located in the 3rd or 4th target wall
    - Select fiducial cross-sectional area to reject entering backgrounds
  - **Neutrino ID** cuts
    - Require large EM activity in SciFi and hadronic activity in the HCAL
    - Event produced upstream (timing)
    - **Muon** reconstructed and **isolated** in the Muon system

ν_μCC simulation



Fiducial volume



Neutrino observation with electronic detectors

SND@LHC PRELIMINARY

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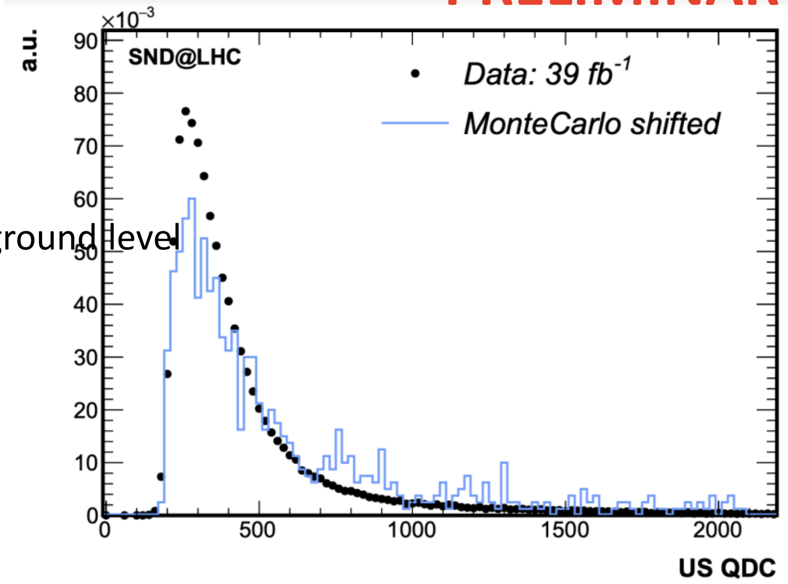
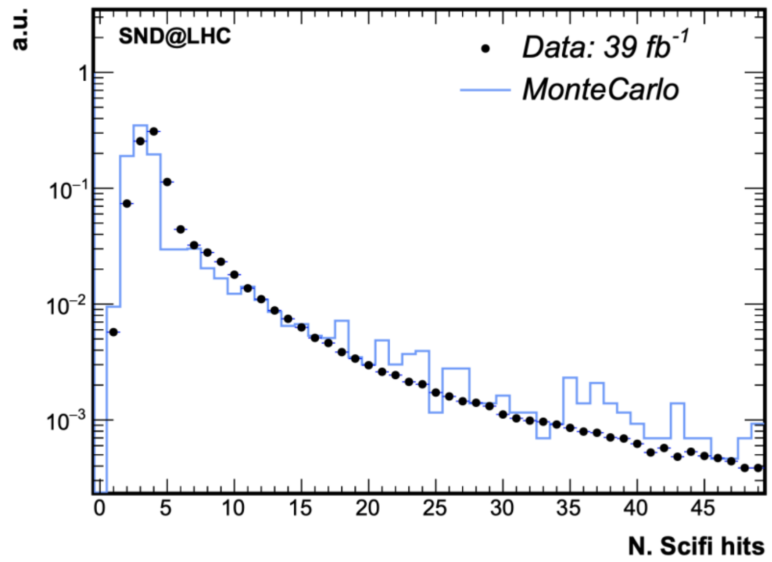
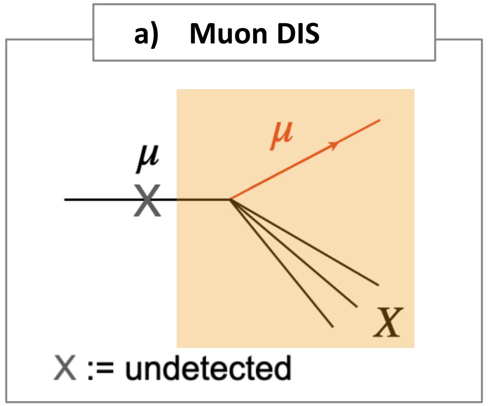
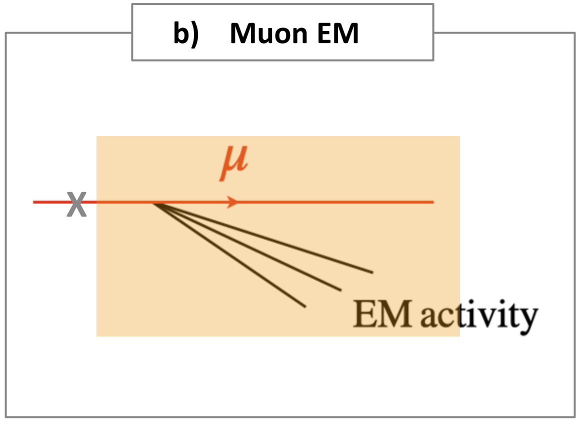




Background estimates (I)

SND@LHC PRELIMINARY





:= within SND@LHC acceptance

- Muon induced background

  Number of undetected muons entering the target (2022 Run3 data)

$$N_\mu^{bkg} = N_\mu \times (1 - \epsilon_{Veto}) \times (1 - \epsilon_{SciFi1}) \times (1 - \epsilon_{SciFi2})$$ **<10^-2^** *totally negligible*

Total number of muons in target acceptance — N_μ

Veto inefficiency — $(1 - \epsilon_{Veto})$

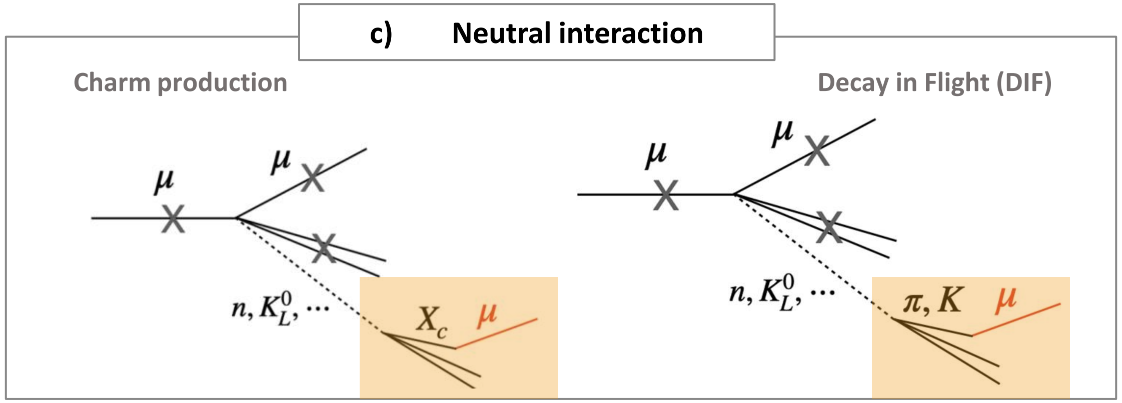
SciFi plane inefficiency — $(1 - \epsilon_{SciFi1})$, $(1 - \epsilon_{SciFi2})$

$$N_\mu = \frac{28 \times 10^6}{fb^{-1}} \times 39\ fb^{-1} = 1.1 \times 10^9$$

$$(1 - \epsilon_{Veto}) \times (1 - \epsilon_{SciFi1}) \times (1 - \epsilon_{SciFi2}) < 10^{-11}$$

Background estimates (II)

SND@LHC PRELIMINARY



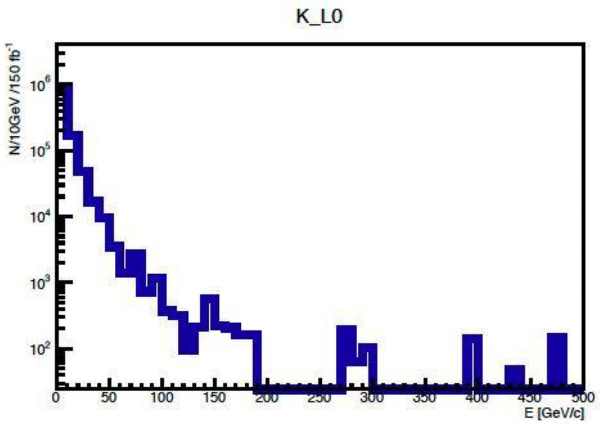
:= within SND@LHC acceptance

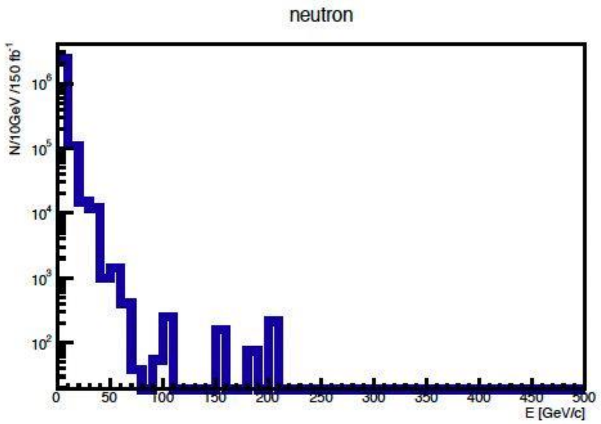
- Muon-induced neutral interactions

$$N^{\text{bkg}}_{\text{neutrals}} = N_{\text{neutrals}} \times P_{\text{inel}} \times \epsilon_{\text{sel}}$$

~ 0.12 (K^0_L) + 0.06 (neutrons) **~ 0.2**

Systematic uncertainty estimation is ongoing

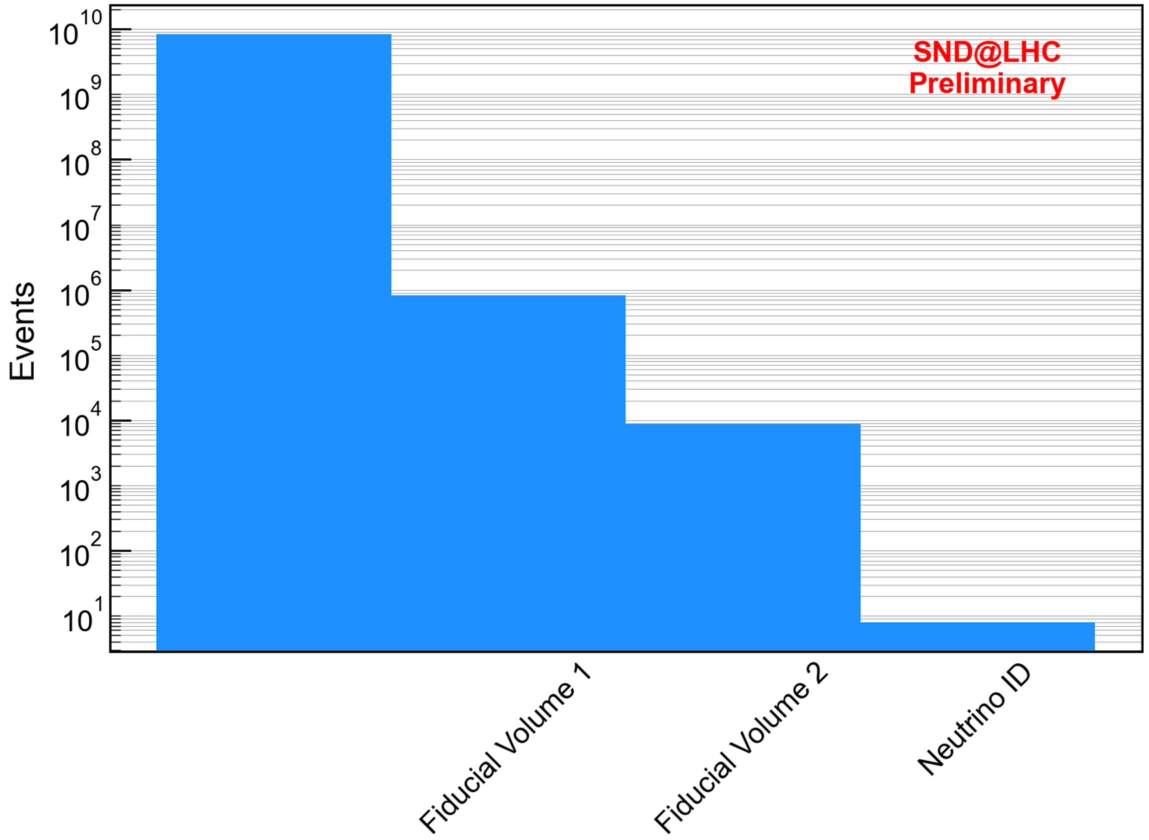


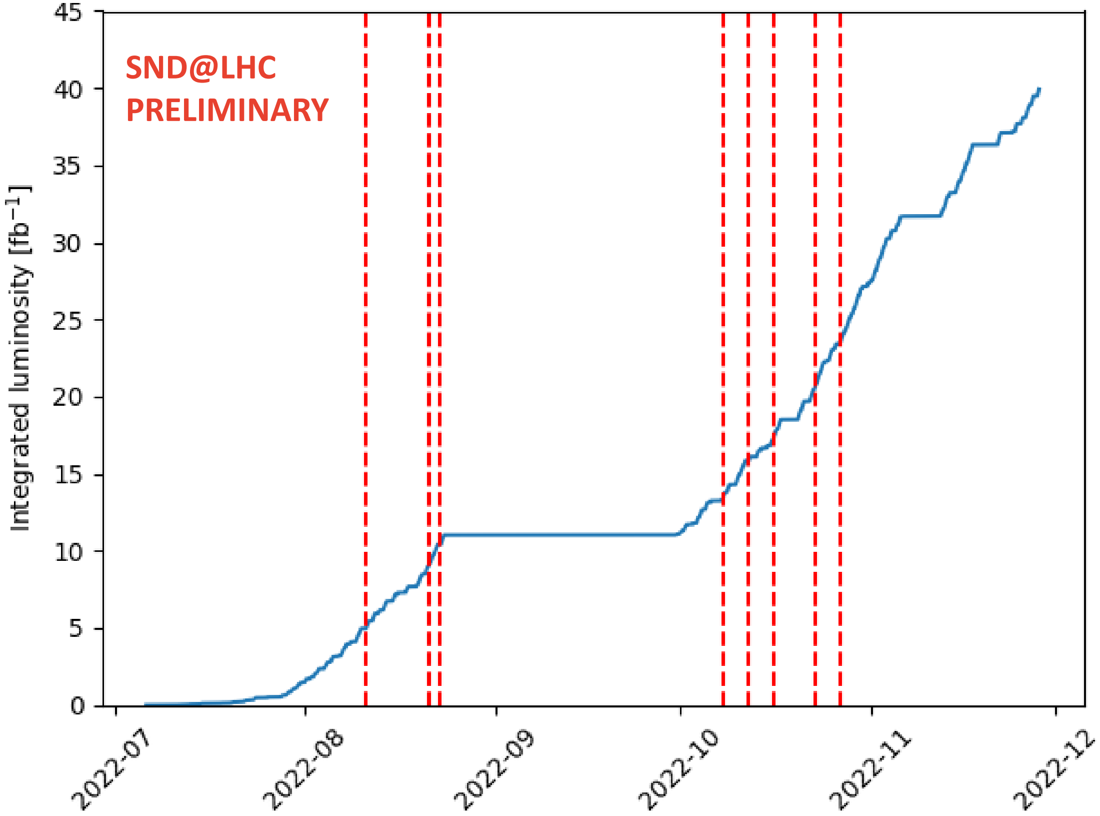


Observed candidates

SND@LHC
PRELIMINARY

- Observed ν_μ **candidates**: 8 (expected 5)
- Preliminary estimate of background yield: 0.2

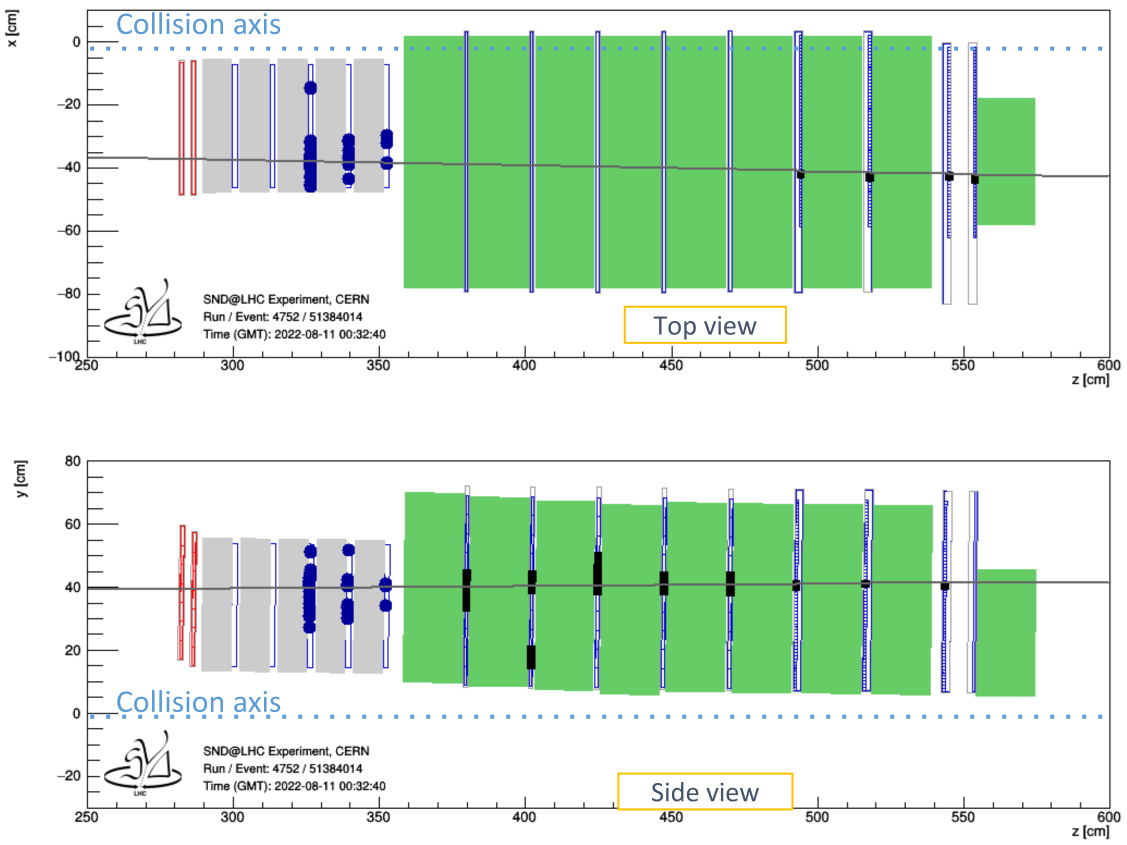




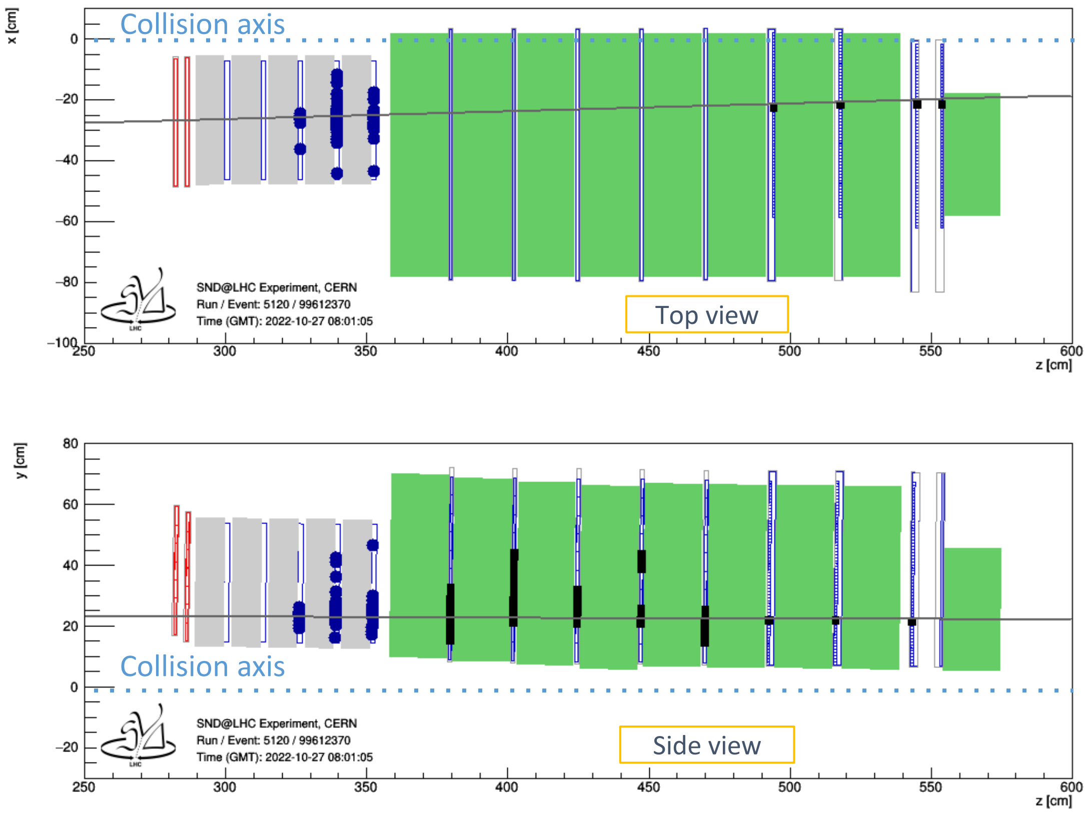
Selected candidates

ν_μCC candidate events in Run 3 data

Aug 11th 2022



Oct 27th 2022



Unusual for an LHC experiment :
A one page author list

Observation of muon neutrino interactions at SND@LHC

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(Dated: April 6, 2023)

We report the direct observation of muon neutrino interactions at SND@LHC, a particle experiment at the LHC Collider. SND@LHC covers the pseudo-rapidity region of $7.2 < \eta < 8.4$, which is inaccessible to the other LHC experiments. Neutrino candidate events are identified in a 13.6 TeV center-of-mass energy pp collision data set of 39.74 fb^{-1} taken by the active electronic components of the SND@LHC detector. The candidates are required to have a track propagating through the entire length of the muon detector and to be consistent with the topology of a muon neutrino charged-current interaction. After applying selection cuts 8 ν_μ CC interaction candidate events remain. The backgrounds from muons and neutrals amount to 0.2 events, which implies a $> 5\sigma$ significance for this observation.

Introduction - The possibility of detecting neutrinos produced at colliders has been pointed out some time ago [1]. Proton-proton (pp) collisions at a center-of-mass energy of 13.6 TeV during LHC Run 3, with an expected

New era of collider neutrinos started!

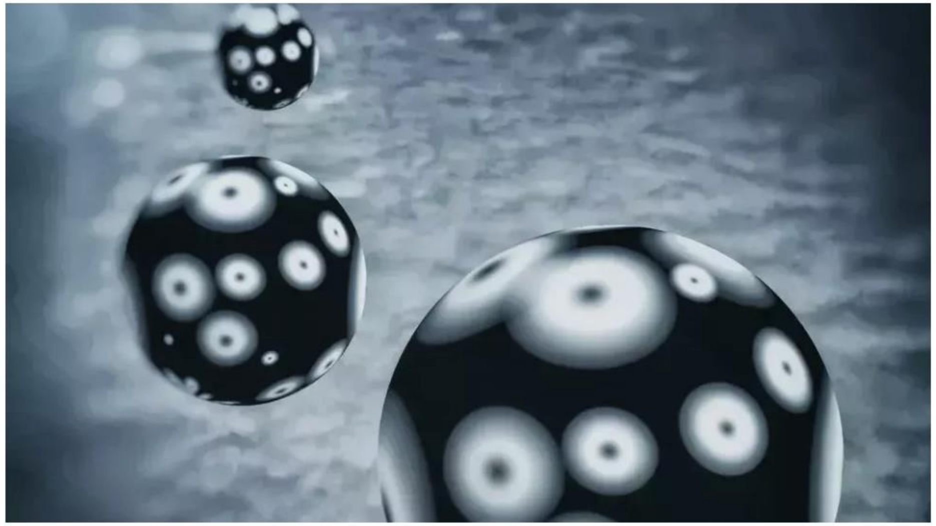
LHC
Scattering and Neutrino Detector at the LHC

'Ghostly' neutrinos spotted inside the world's largest particle accelerator for the first time

News By Ben Turner published 15 days ago

Signatures of neutrinos, or ghostly particles that rarely interact with others, were tentatively spotted in the Large Hadron Collider in 2021. Now, physicists have confirmed they are real.

Comments (0)



An artist's illustration of three neutrinos, ghostly particles which barely interact with other forms of matter. (Image credit: Shutterstock)

CERNCOURIER | Reporting on international high-energy physics

Physics ▾ | Technology ▾ | Community ▾ | In focus | Magazine

NEUTRINOS | NEWS

Collider neutrinos on the horizon

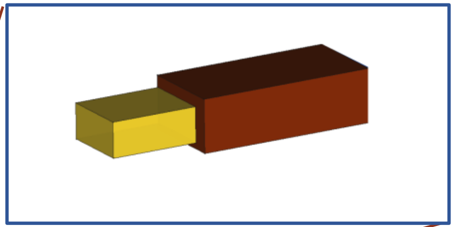
2 June 2021

Stay tuned! We have just rediscovered the Neutrino!
The era of neutrino measurement at LHC has begun

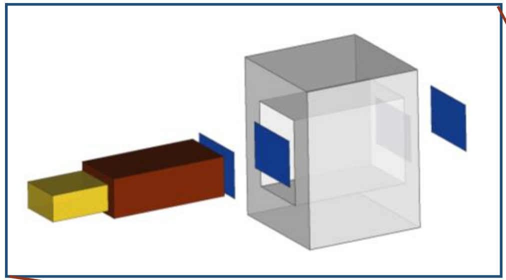
SND@LHC UPGRADE TOWARDS HL-LHC

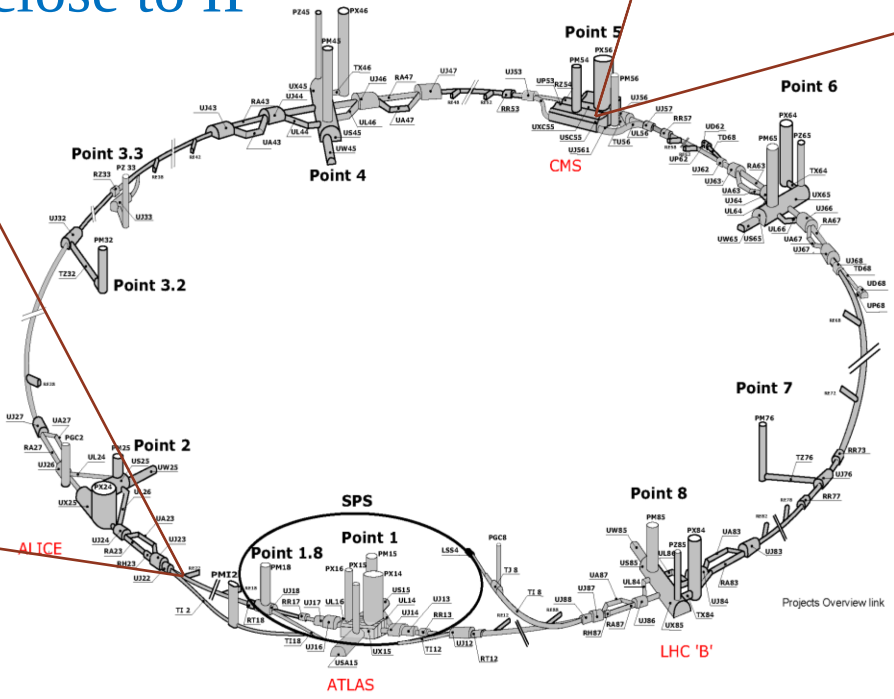
- Two detectors
  - AdvSND-Far
  - Location: TI18
  - AdvSND-Near
  - Location: existing caverns close to IP

AdvSND-Near: $4 < \eta < 5$



AdvSND-Far: $7.2 < \eta < 8.4$





Advanced SND@LHC

- **AdvSND-Near:** $4 < \eta < 5$

 - Overlap with LHCb η coverage where charm was measured

 - Reduce systematic uncertainties for the FAR

 - ν cross-section measurement

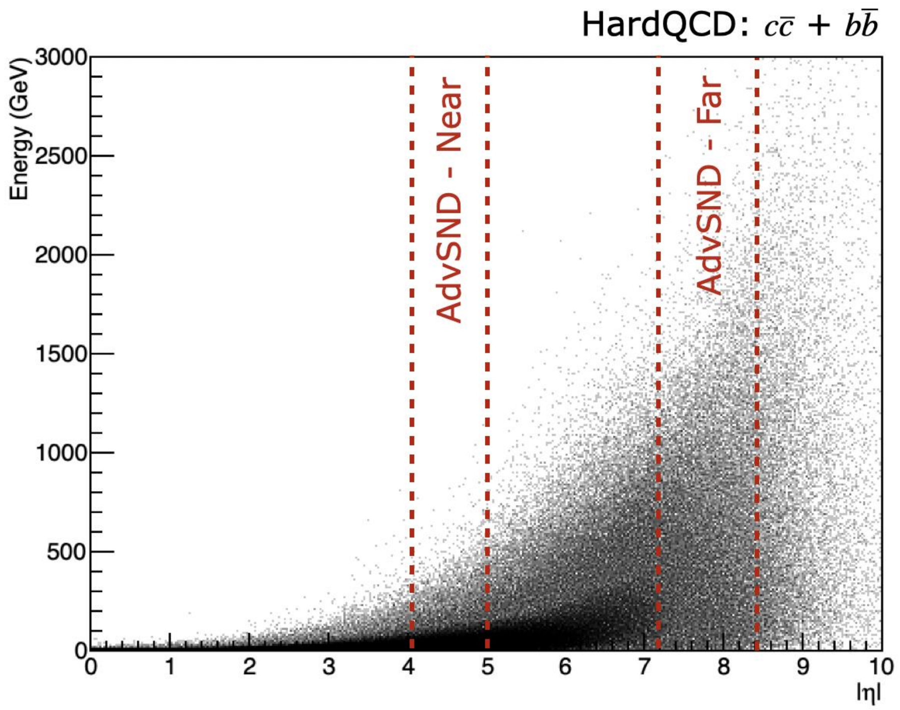
- **AdvSND-Far**: $7.2 < \eta < 8.4$

 - Same acceptance as SND@LHC

 - Measurements with (much) reduced systematics

 - Charm production measurements

 - Lepton flavour universality



Replace emulsions with silicon detector

Add Magnetic field

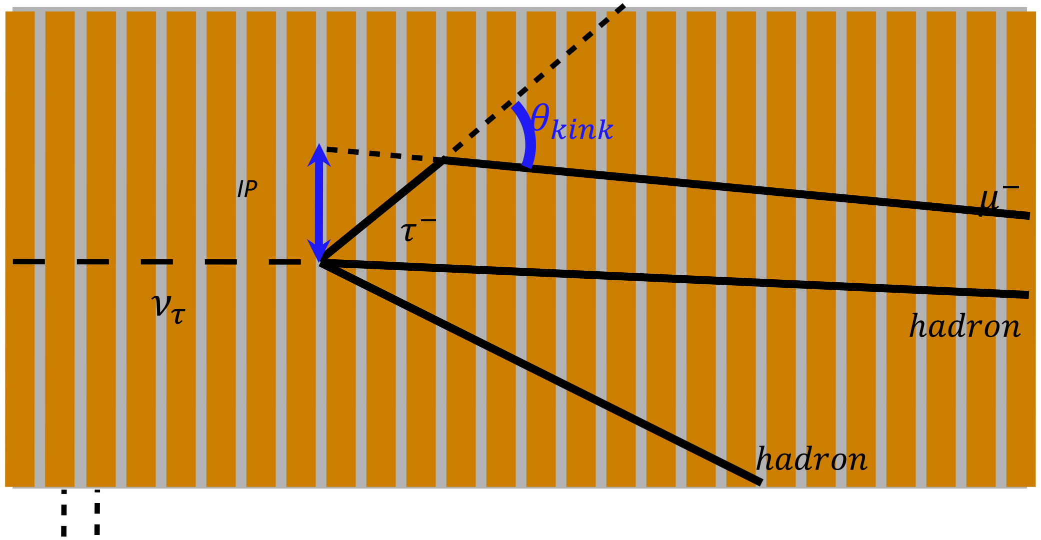
Challenges for the vertex detector

Impact parameter ***<IP> ~ 100 μm***

AdvSND-Near

τ decay length ***<Lτ> ~ 3 mm***

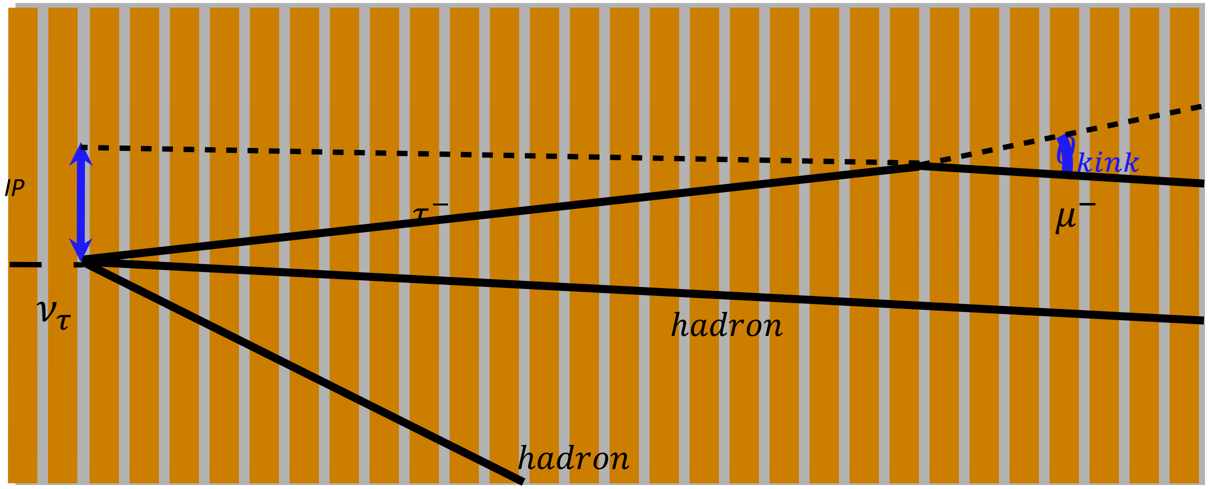
kink angle ***<θ_{kink}> ~ 30 mrad***



AdvSND-Far

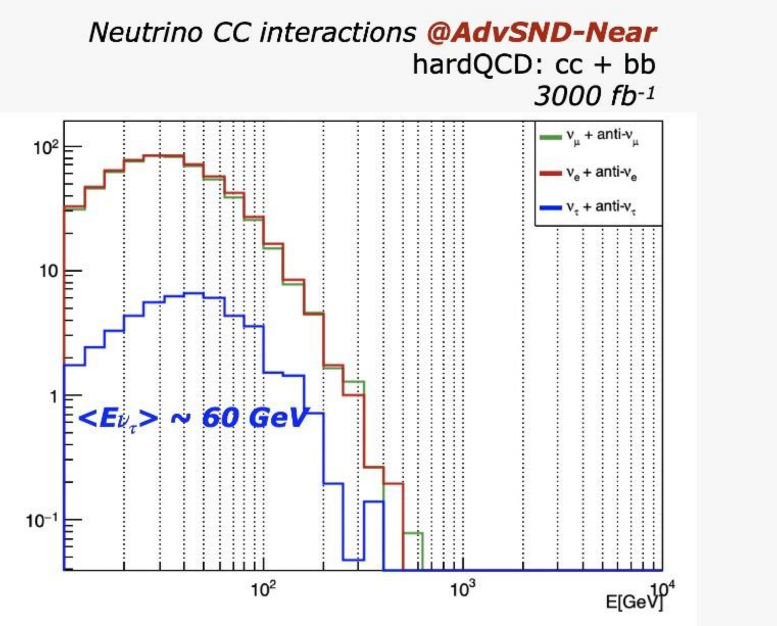
τ decay length ***<Lτ> ~ 3.5 cm***

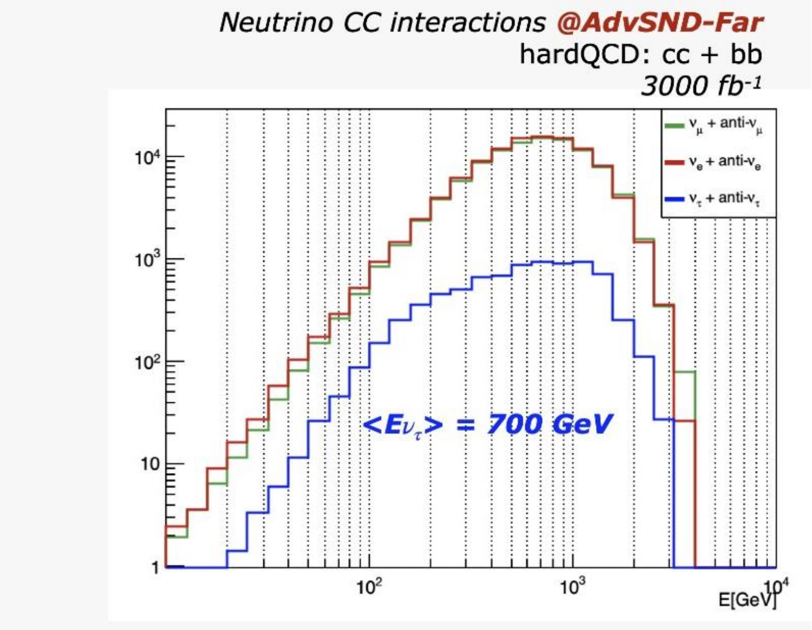
kink angle ***<θ_{kink}> ~ 3 mrad***



NEAR and FAR detector: neutrinos from c and b

AdvSND - NEAR				
	ν in acceptance		CC DIS	
Flavour	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$
$\nu_\mu + \bar{\nu}_\mu$	2.1×10^{12}	3.3×10^{11}	980	200
$\nu_e + \bar{\nu}_e$	2.2×10^{12}	3.3×10^{11}	1000	200
$\nu_\tau + \bar{\nu}_\tau$	2.7×10^{11}	1.4×10^{11}	80	50
Tot	5.4×10^{12}		2.5×10^{3}	





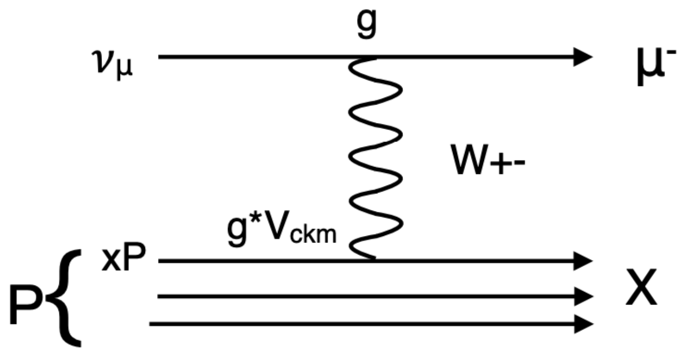
AdvSND-FAR				
	ν in acceptance		CC DIS	
Flavour	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$	hardQCD: $c\bar{c}$	hardQCD: $b\bar{b}$
$\nu_\mu + \bar{\nu}_\mu$	6.3×10^{12}	1.5×10^{11}	1.2×10^{4}	200
$\nu_e + \bar{\nu}_e$	6.7×10^{12}	1.7×10^{11}	1.2×10^{4}	220
$\nu_\tau + \bar{\nu}_\tau$	7.1×10^{11}	4.7×10^{10}	880	40
Tot	1.4×10^{13}		2.5×10^{4}	

LHC
Scattering and Neutrino Detector at the LHC

Backup

neutrino DIS

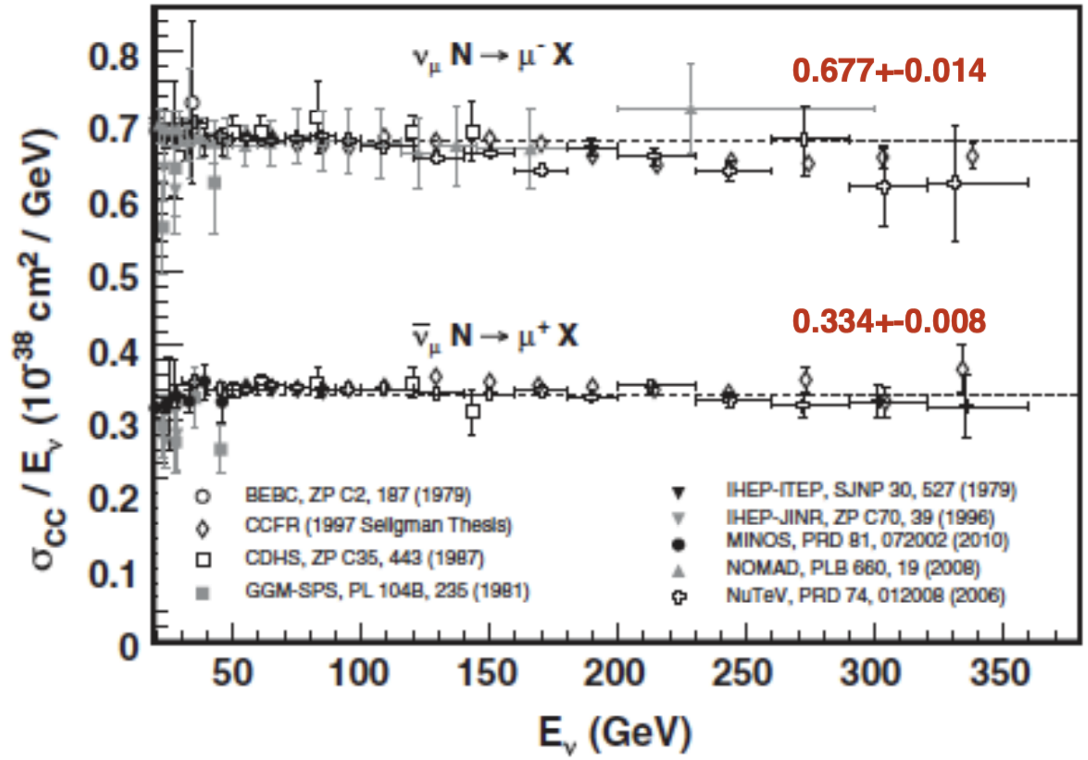
Deep Inelastic Scattering



$$y = E_{had} / E_{\nu}$$

$$x \equiv \frac{-q^2}{2P \bullet q} = \frac{Q^2}{2M_N E_{had}}$$

$$Q^2 = -m_{\mu}^2 + 2E_{\nu} \bullet (E_{\mu} - p_{\mu} \mathrm{Cos}\,\theta_{\mu})$$

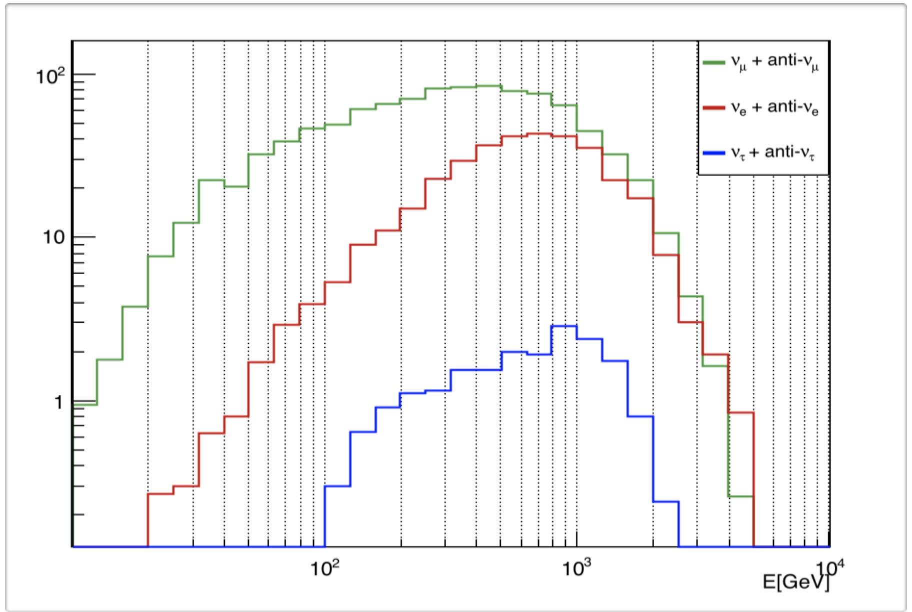


$$d\sigma(\nu q)/dy \propto G_F^2 M_N x E_{\nu} \qquad d\sigma(\bar{\nu} q)/dy \propto G_F^2 M_N x E_{\nu} (1-y)^2$$

NEUTRINO DIS INTERACTIONS

$7.2 < \eta < 8.4$, $0.4 < \vartheta < 1.5$ mrad

- **DPMJET3** embedded in FLUKA for neutrino production@LHC
- Particle propagation towards the detector through the LHC **FLUKA** model
- **GENIE** used to simulate neutrino interactions in the detector target



Interacting Neutrinos

~ 75% ν_μ 25% ν_e

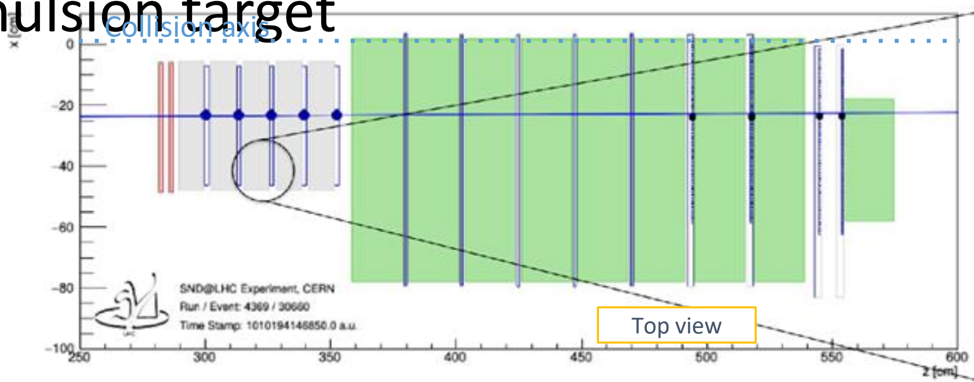
- Expectations in 290 fb^{-1} (43/57 upward/downward crossing angle)

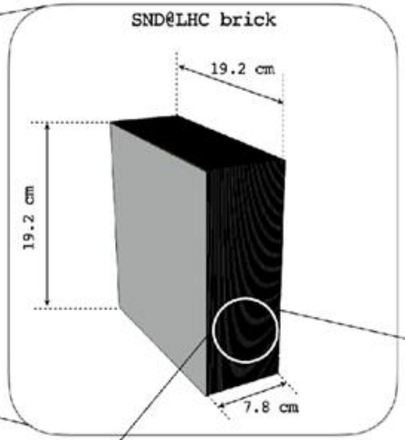
	CC neutrino interactions		NC neutrino interactions	
Flavour	⟨E⟩ [GeV]	Yield	⟨E⟩ [GeV]	Yield
ν_μ	450	1028	480	310
$\bar{\nu}_\mu$	480	419	480	157
ν_e	760	292	720	88
$\bar{\nu}_e$	680	158	720	58
ν_τ	740	23	740	8
$\bar{\nu}_\tau$	740	11	740	5
TOT		1930		625

~ 30 ν_τ CC interactions expected

Muon flux measurement

Track reconstruction performed in electronic detectors and emulsion target

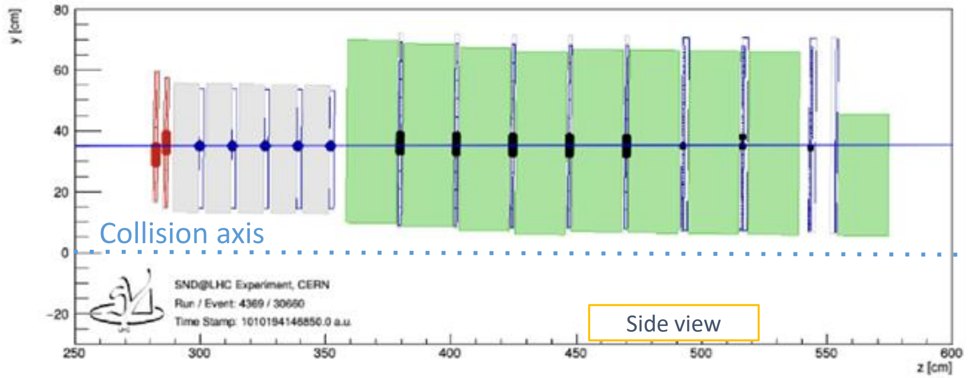


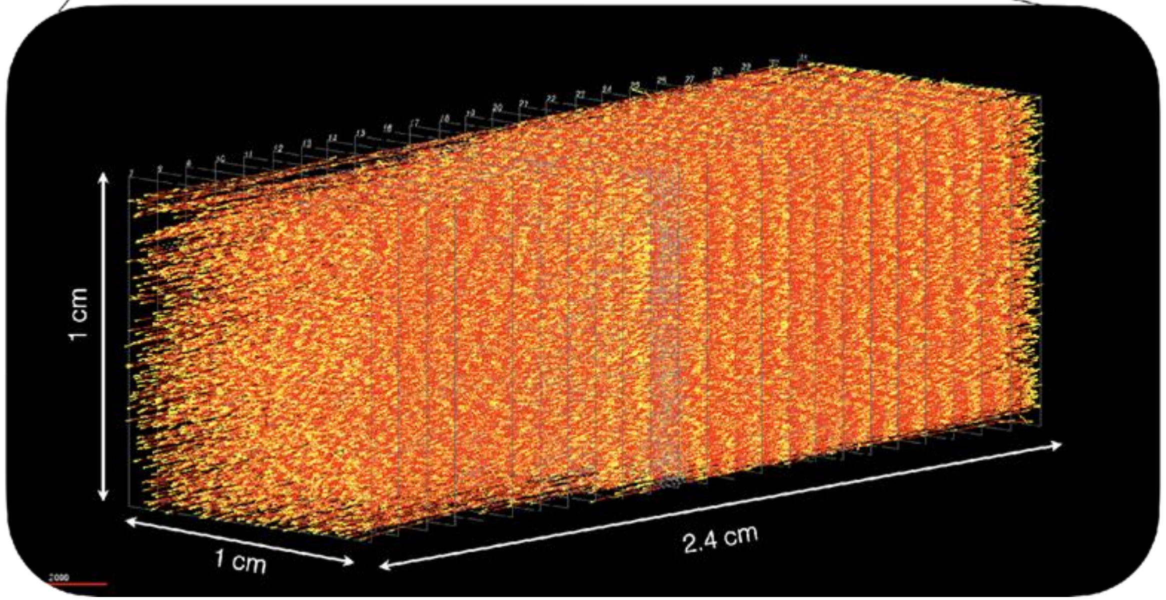


Emulsion reconstruction

Muon tracks in 1x1 cm^2

integrated in EMULSION RUN0 (7/4/22 - 26/7/22)





Electronic detector reconstruction

Muon tracks from pp collisions @13.6 TeV (6/7/22 - 26/7/22)

BSM physics: Feebly interacting Particles

FIPs may be produced in the pp scattering at the LHC interaction point, propagate to the detector and decay or scatter inside it.

SND@LHC has sensitivity to physics beyond the Standard Model considering the scatterings of light dark matter particles χ via leptophobic $U(1)B$ mediator, as well as decays of Heavy Neutral Leptons, dark scalars and dark photons.

The excellent spatial resolution of nuclear emulsions and the muon identification system makes SND@LHC also suited to search for the decay of neutral mediators decaying in two charged particles

The background from neutrino interactions can be rejected by making a time-of-flight (TOF) measurement (the timing of the SND detectors are referred to the LHC collision clock and TOF resolution is limited by the 'size ' of the LHC bunch overlap 'size' of 200ps.
The hybrid nature of the apparatus, which combines emulsion trackers and electronic detectors, makes it possible to disentangle the scattering of massive FIPs and neutrinos, with a significance that depends on the particle mass.

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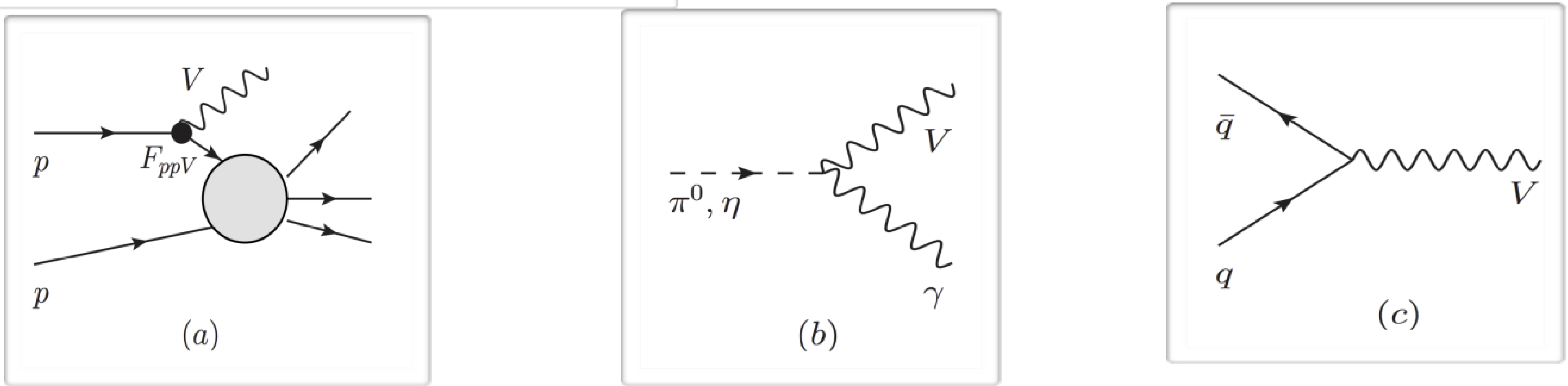
https://link.springer.com/article/10.1007/JHEP03(2022)006

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,

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

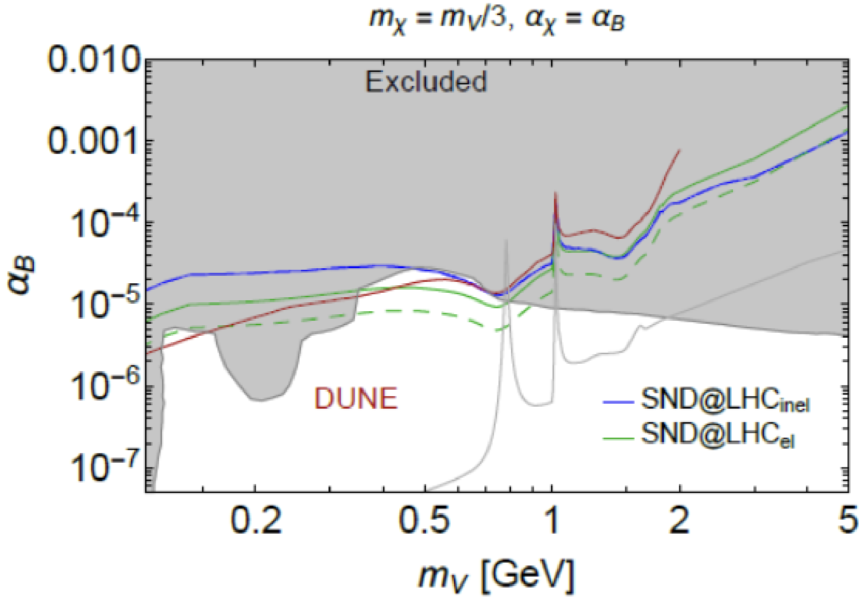


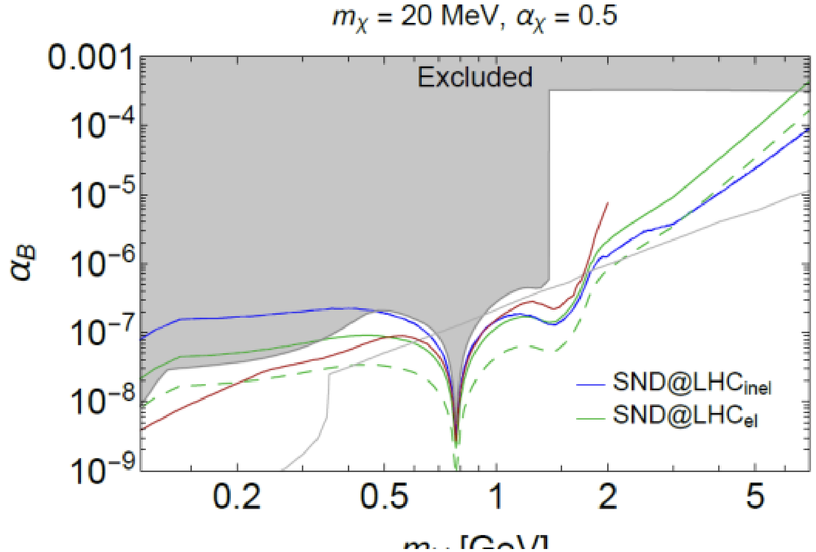
Proton bremsstrahlung

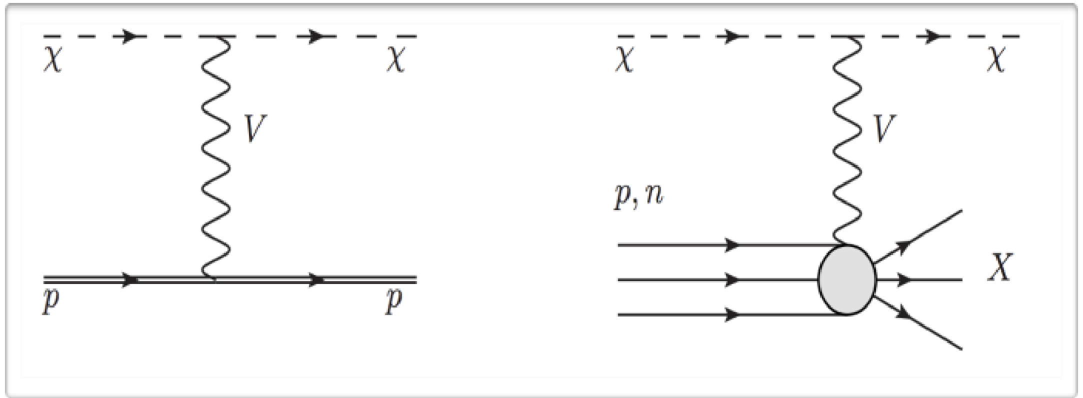
Meson decay

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

LHC
ttering and Neutrino Detector at the LHC

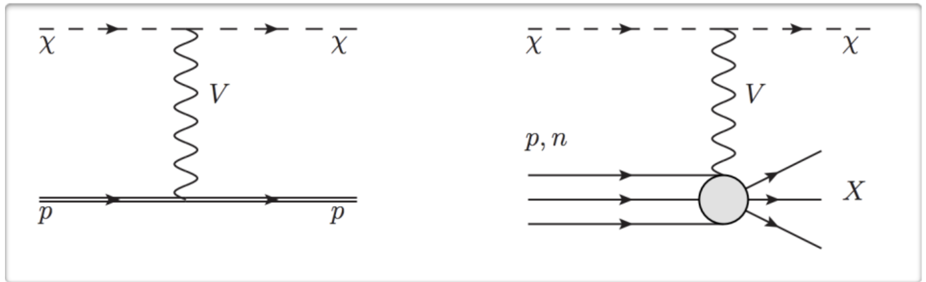
Search for Feebly Interacting particles

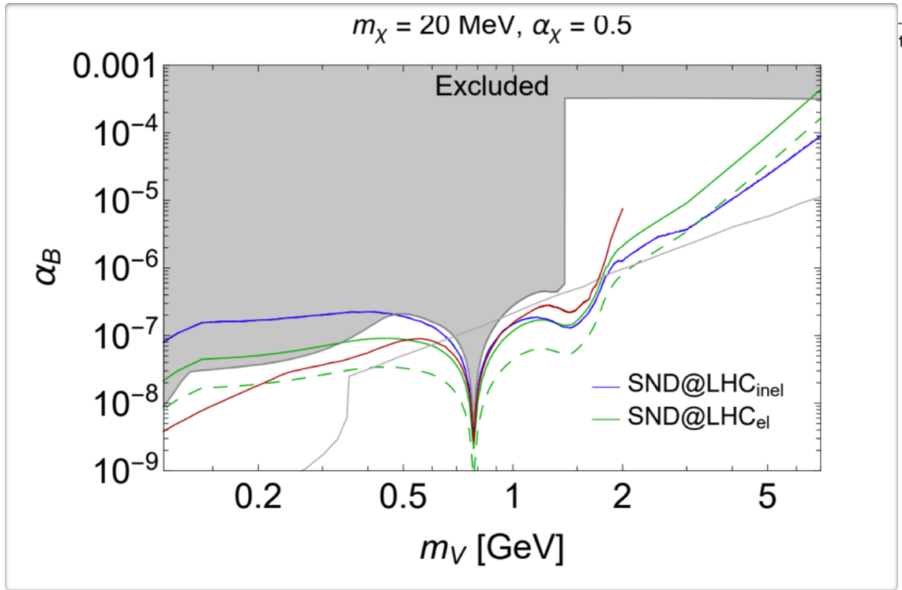
- Explore a variety of Beyond Standard Model (BSM) scenarios within the Hidden Sector

1. Scattering

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

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

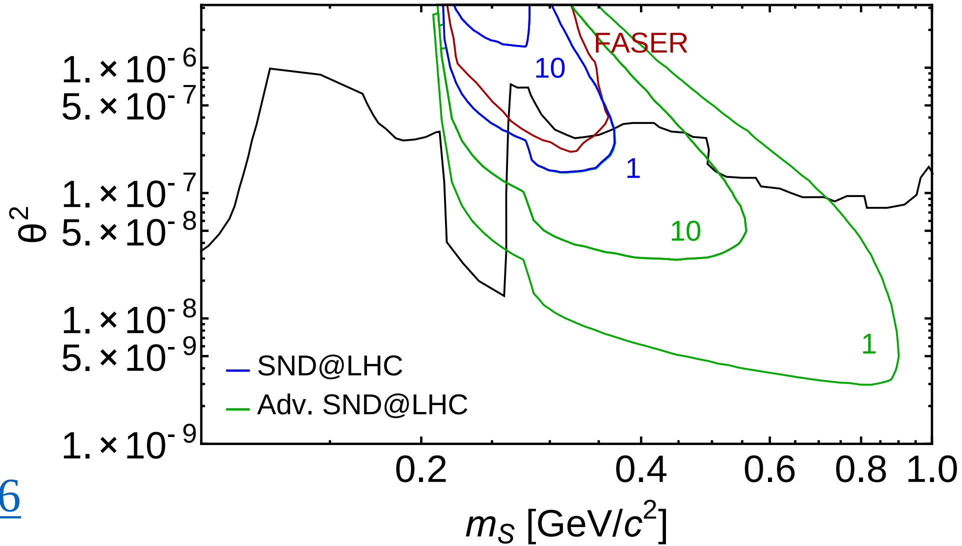




2. Decay of dark scalars, HNLs, dark photons

Production: dark scalars produced in the decay of B mesons, HLNs in the decay of B and D mesons, dark photons via leptophobic mediator

Detection: Decays into a pair of charged tracks or monophotons



https://link.springer.com/article/10.1007/JHEP03(2022)006

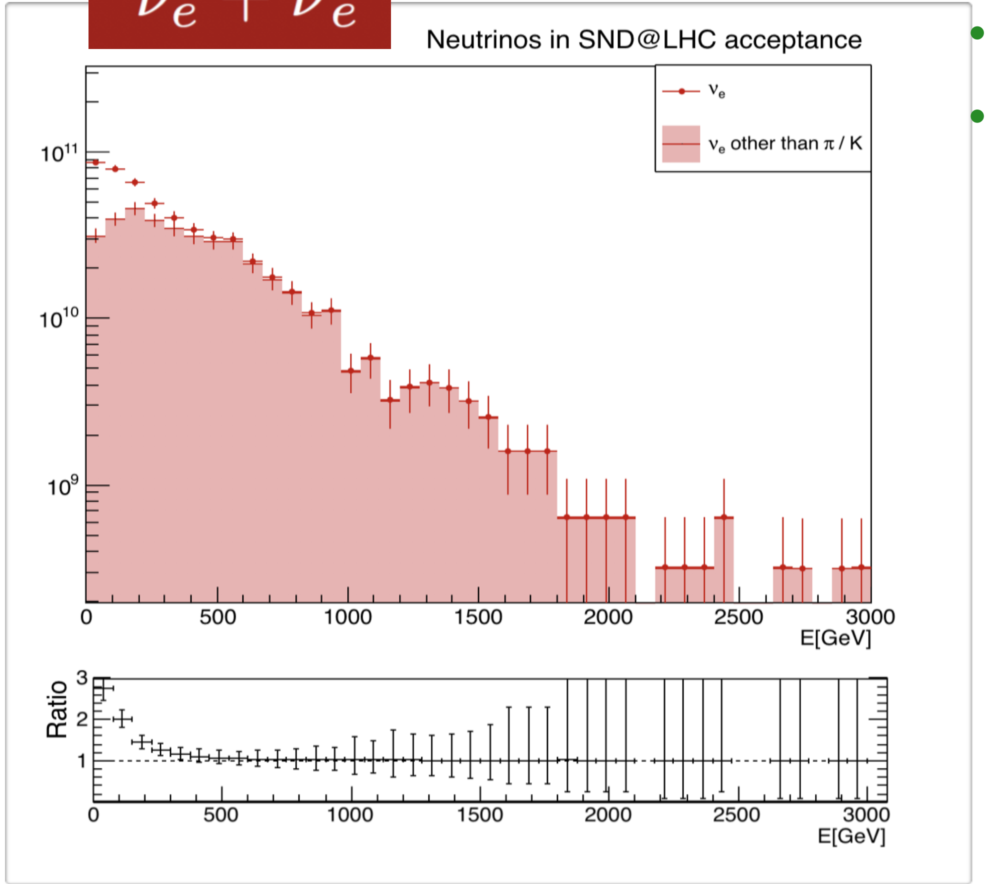
3. Lepton flavour universality test in ν interactions

- The identification of 3 ν flavours offers a unique possibility to test LFU in ν interactions
  - ν_τs produced essentially only in D_s decays
  - ν_es produced in the decay of all charmed hadrons (D^0, D, D_s, Λ_c)
  - The ratio depends only on charm hadronisation fractions
  - Sensitive to ν-nucleon cross-section ratio

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

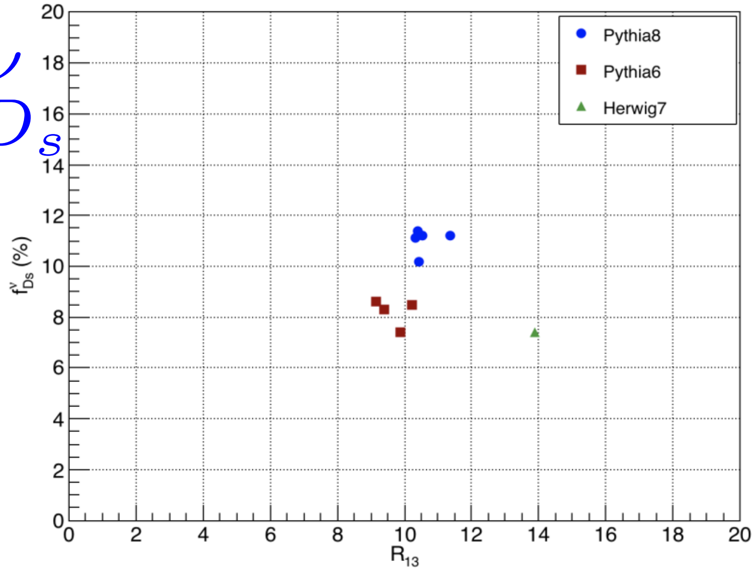
$$R_{13} = \frac{\nu_e}{\nu_\tau}$$

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



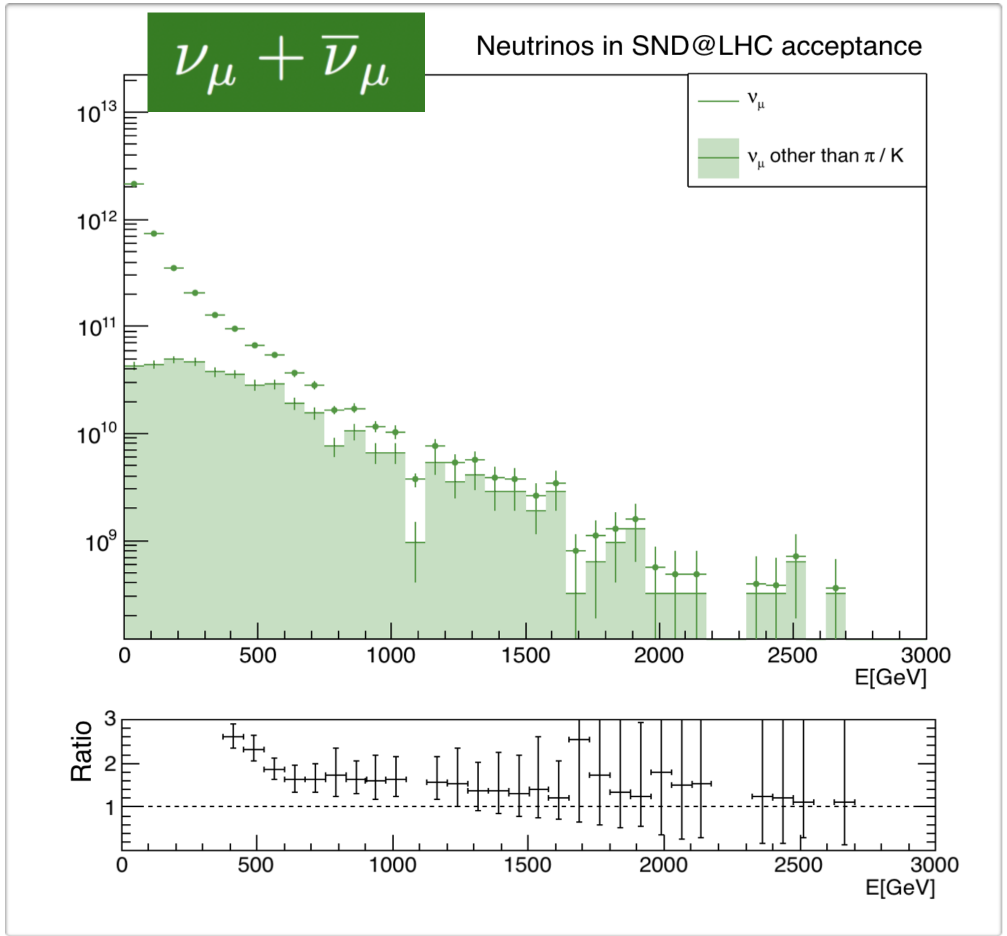
- Error on f_c evaluated as the discrepancy between Pythia8 and Herwig7 generators: **22%**
- **20%** error due to ν_τ statistics

$f^{\nu}_{D_s}$



3. Lepton flavour universality test in ν interactions

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



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

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

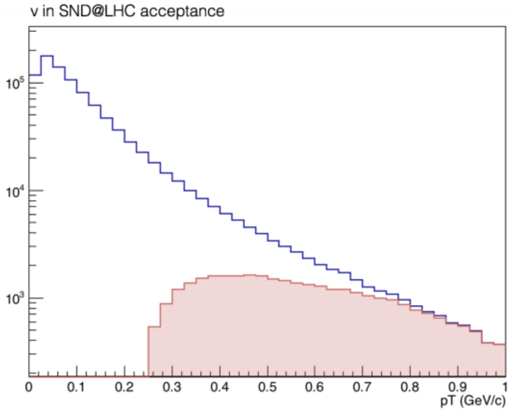
$$R_{12} = \frac{\nu_e}{\nu_\mu}$$

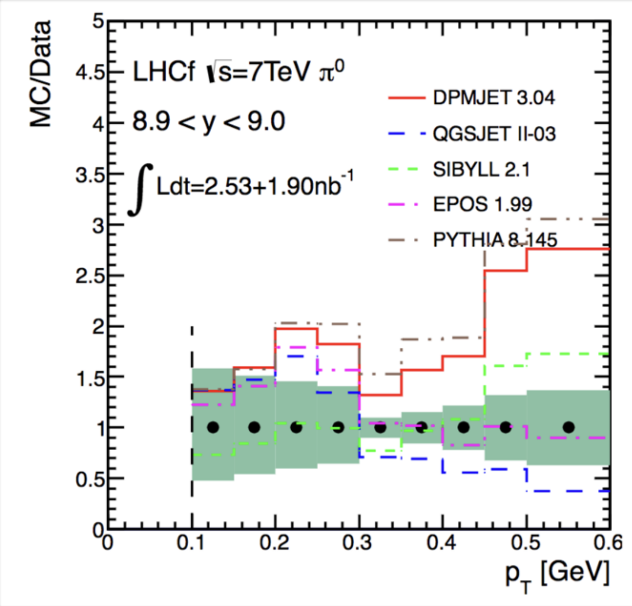
- ν_e/ν_μ as a LFU test in ν int for E>600 GeV
- No effect of uncertainties on f_c (and *Br*) since charmed hadrons decay almost equally in ν_μ and ν_e

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

contamination from π/k

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





Phys. Rev. D 86, 092001 (2012)

4. The NC/CC RATIO as a consistency check

- Lepton identification allows to distinguish between CC and NC interactions
- If differential ν and anti-ν fluxes are equal, the NC/CC ratio can be written as

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

- For DIS, P can be written as

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

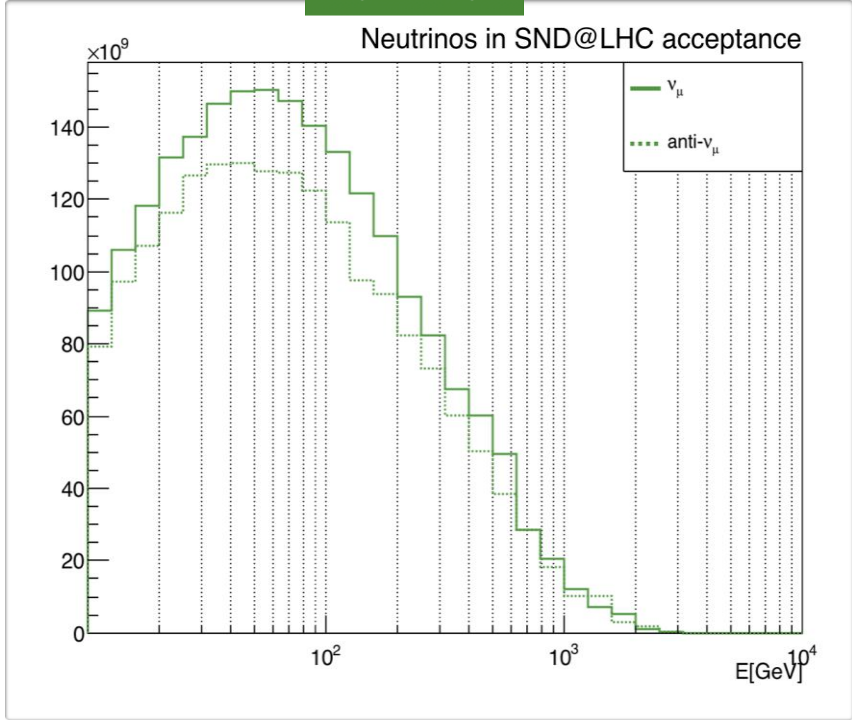
- where λ originates from the non-isoscalarity of the target, a correction factor of ~1%

- For a Tungsten target λ=0.04

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

Important internal consistency test

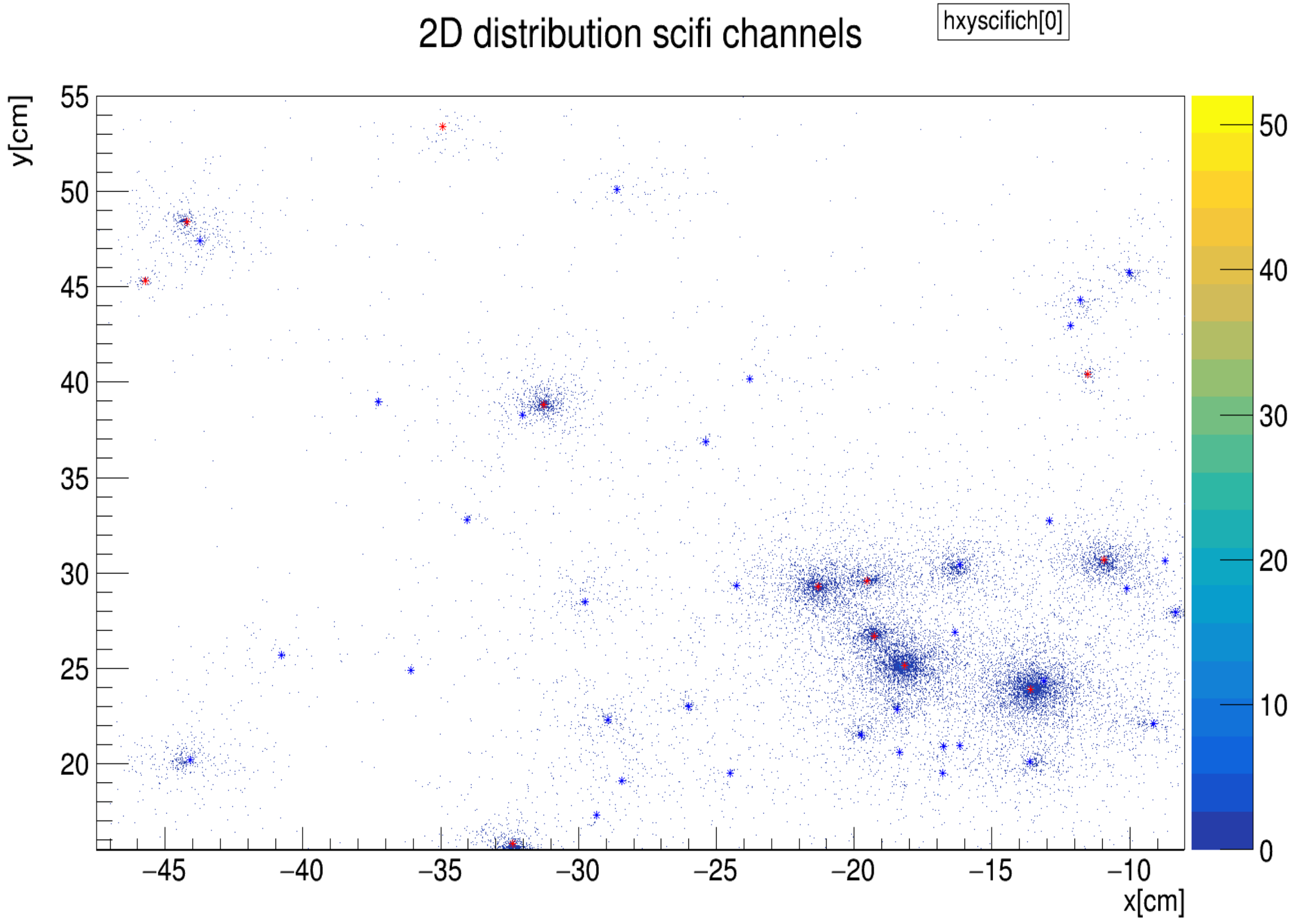
ν_μ vs $\overline{\nu}_\mu$



SCINTILLATING FIBRES

Emulsion-SciFi alignment

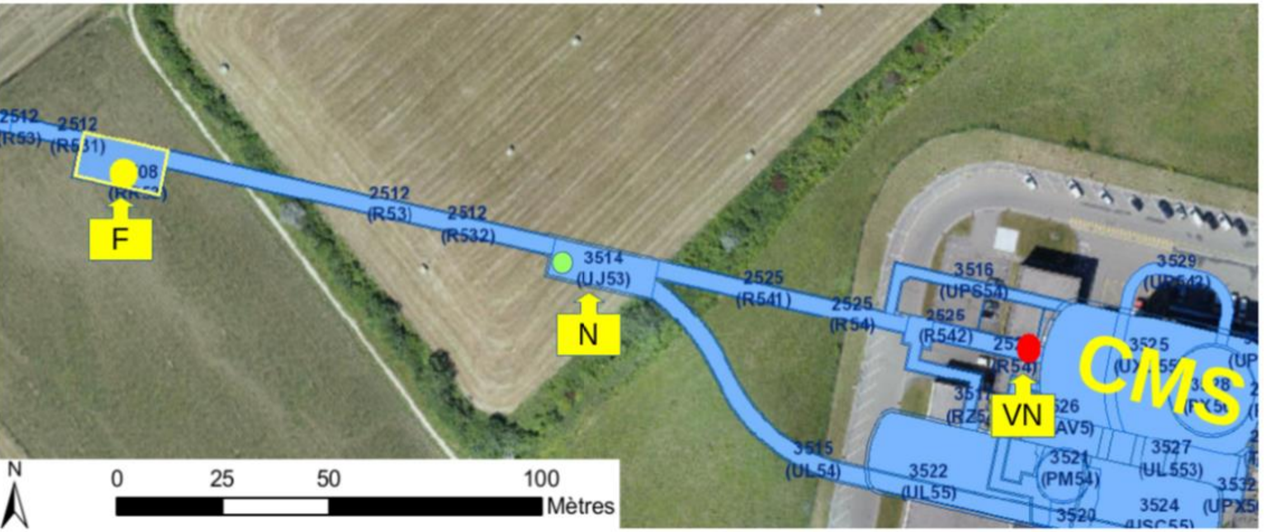
Expected neutrino CC DIS interactions in a single wall in 25fb^{-1}: 35 ν_μ, 12 ν_e

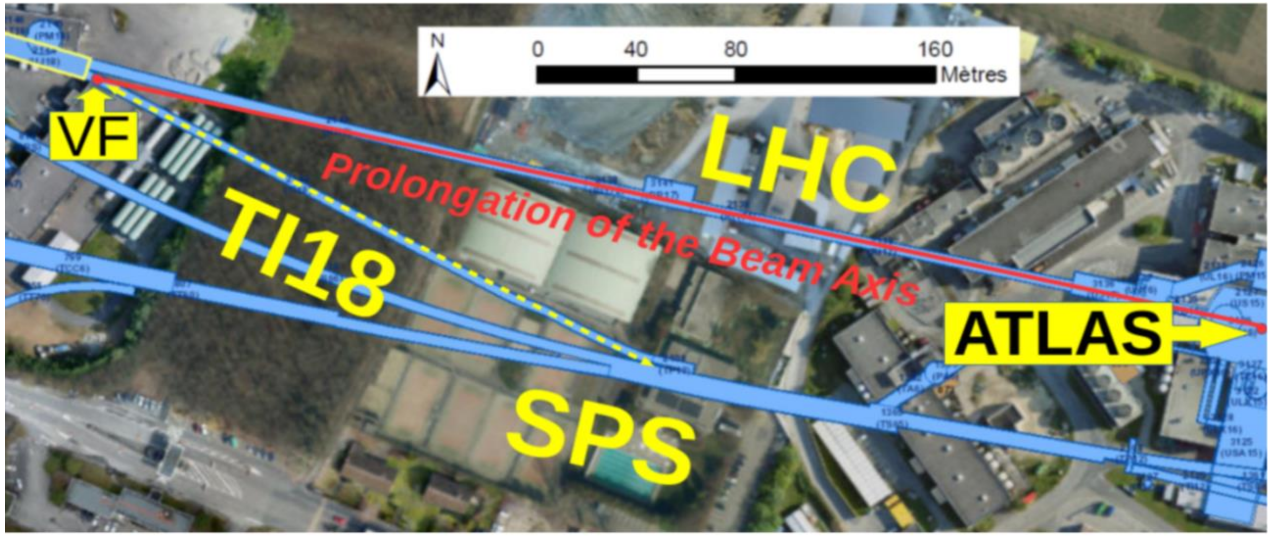


Hit map on the SciFi plane immediately downstream of the emulsion/tungsten wall

Investigating the background for a neutrino detector in different locations with a measurement campaign

VN = Q1 in S45 at 25m
N = UJ53 and UJ57 at 90-120m
F = RR53 at 237m
VF = TI18 at 480m





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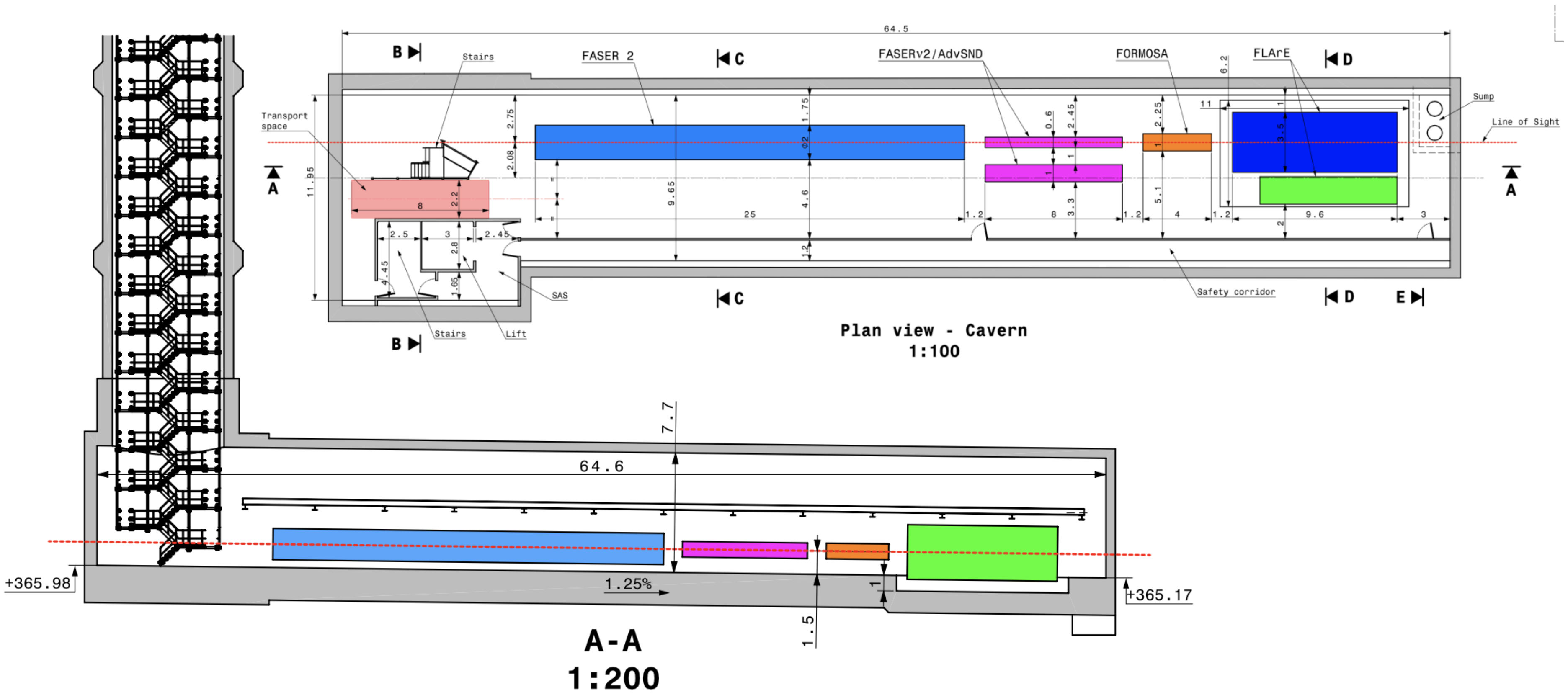
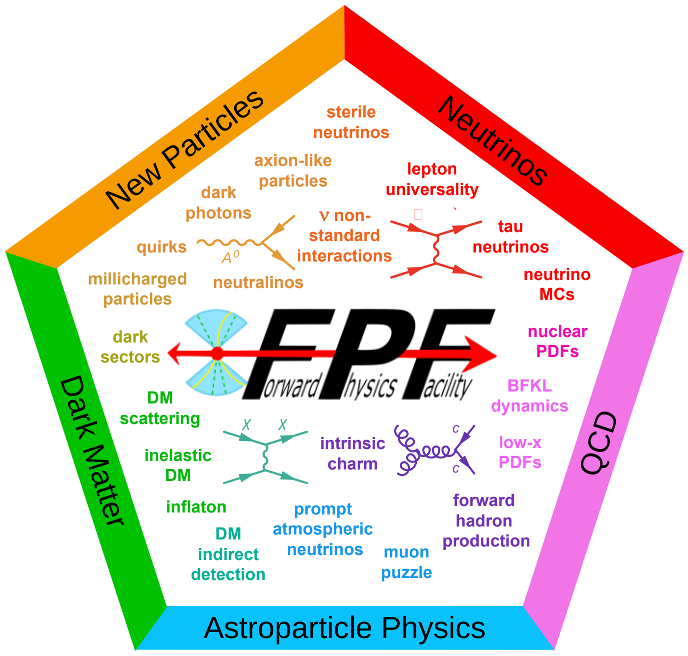
FPF: New facility for larger detectors

Forward Physics Facility (FPF) is a proposed new facility to house several new experiments on the collision axis line-of-sight in the HL-LHC era. Baseline option considered is a new cavern ~600m from IP1 in the SM18 area, which could house 5 new experiments, including FASER2 and FASERv2. Preliminary costing of 40MCHF for facility (CE works + services). Broad physics program covering dark sector searches, neutrino physics and QCD.
Facility being studied within the Physics Beyond Collider sudy group.
FPF physics case described in white paper: https://arxiv.org/pdf/2203.05090.pdf

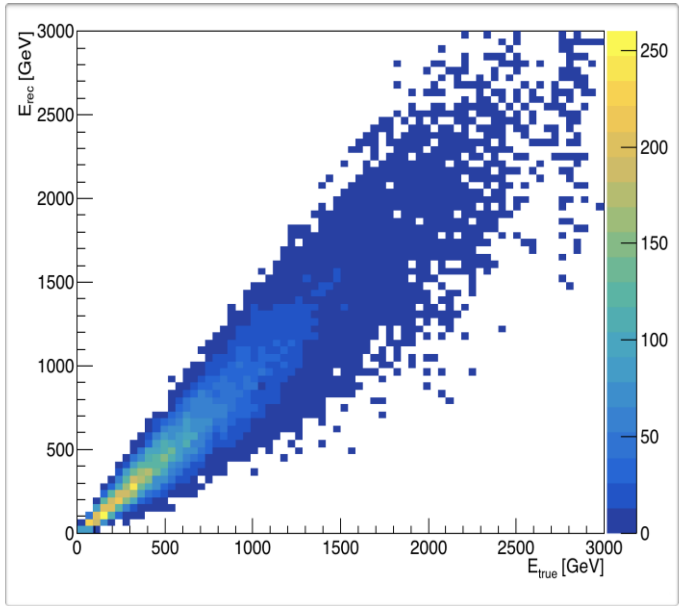


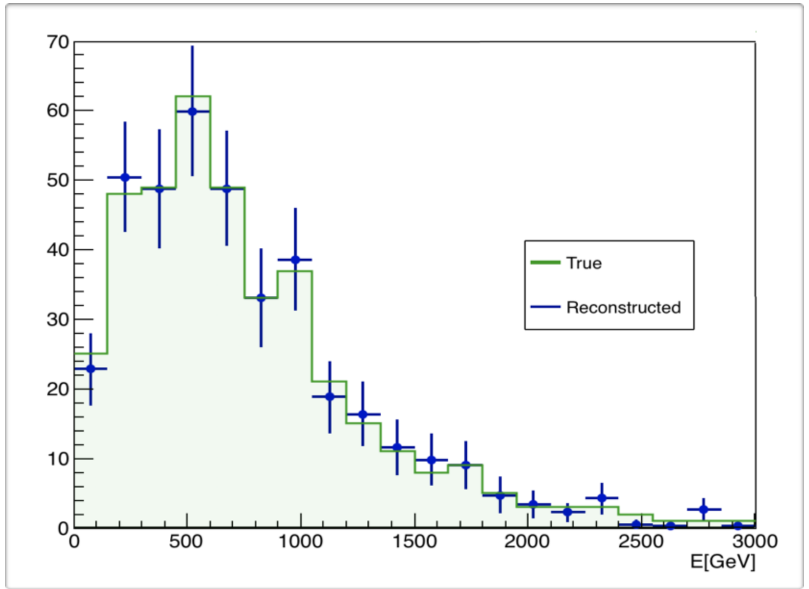


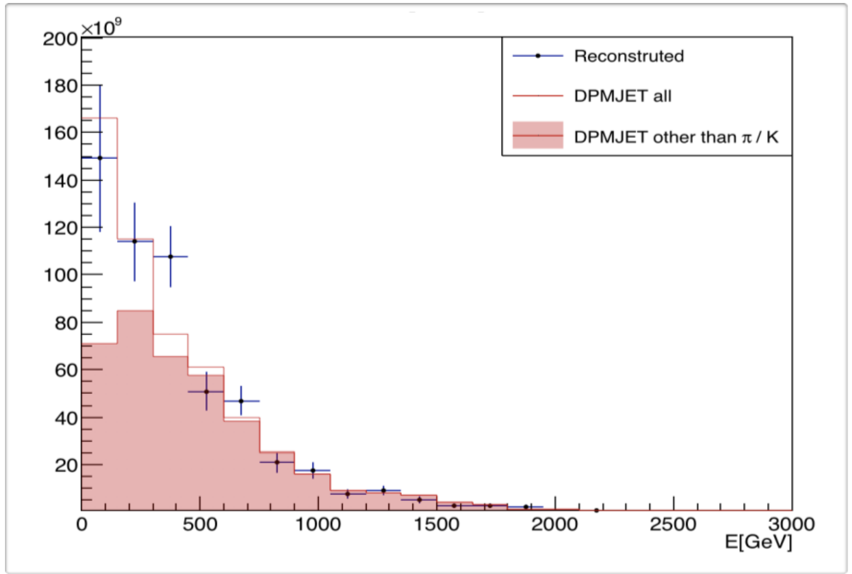
1. MEASUREMENT OF pp⟶ν_eX CROSS-SECTION

- 90% ν_e & anti-ν_e from the decay of charmed hadrons
- ν_e as a probe of charm production in this η range after unfolding instrumental effects
- Unfolding applied to the *measured* energy spectrum to retrieve the reconstructed energy
- Deconvolution of neutrino (SM) cross-section to get the flux in SND@LHC acceptance

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







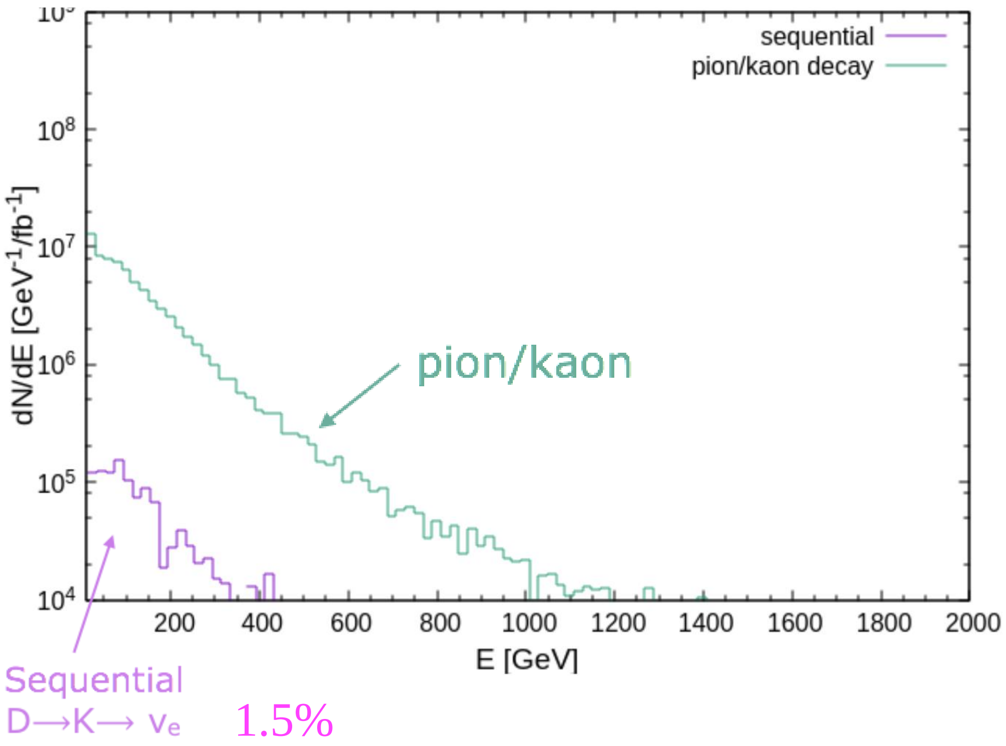
Uncertainty: 15%

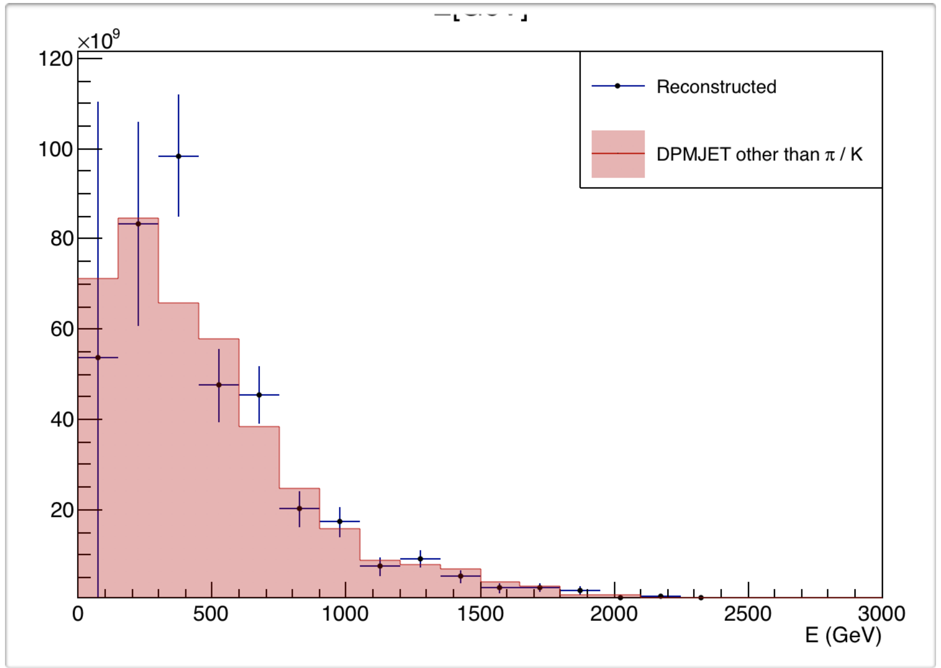
statistical (collected statistics) + systematic (unfolding procedure)

Subtraction of the Kaon contribution to ν_es

- Kaon component dominates at low energies (E<200 GeV)
- Different generators show different predictions (factor up to ~ 2)
- Subtraction in the low energy region where the number of observed neutrinos is lower
- Procedure introduces an additional systematic uncertainty of **~20%** on the overall yield

Electron neutrinos in SND@LHC acceptance

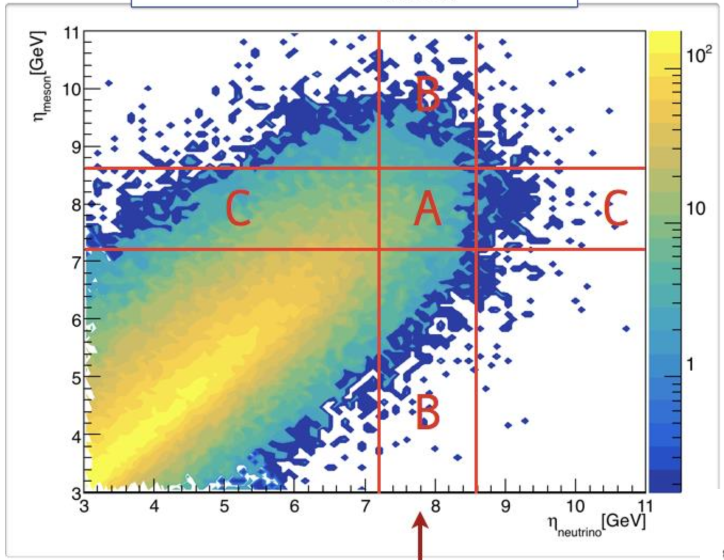




2. CHARMED HADRON PRODUCTION

- 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}

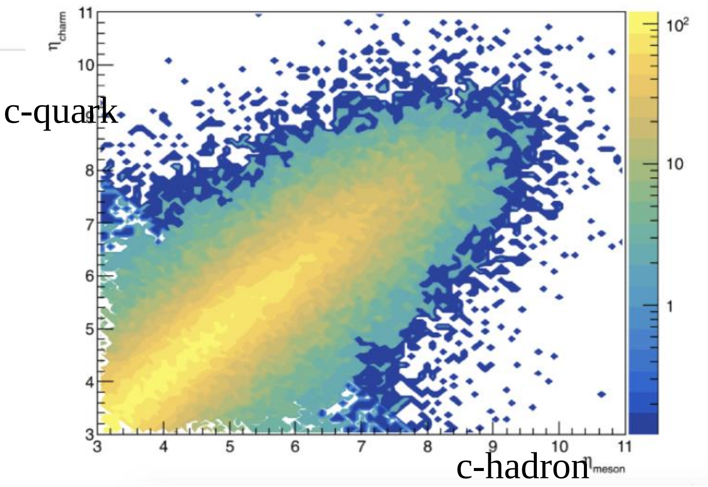
N_A/N_{A+C}

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%**

Statistical uncertainty ~5%

Systematic uncertainty ~35%



The measurement of charmed hadrons can be translated into a measurement of the corresponding open charm production in the same pseudo-rapidity range given the straight correlation between the hadron and its parent charm quark

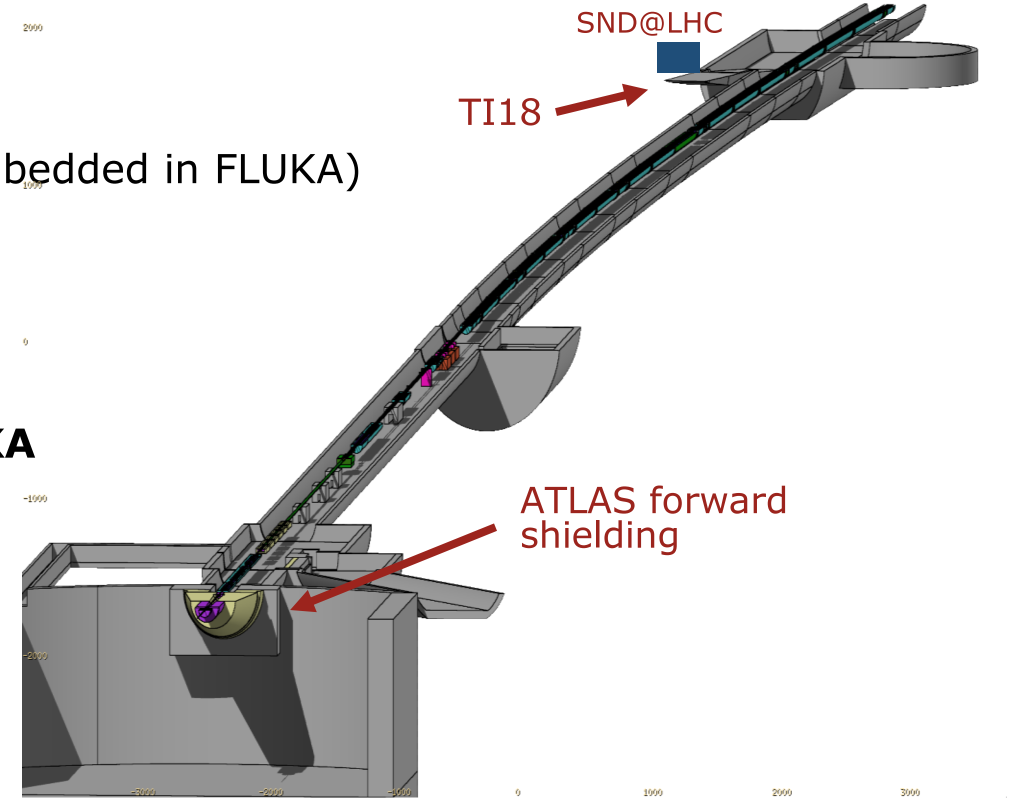
SIMULATION

- PRODUCTION

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

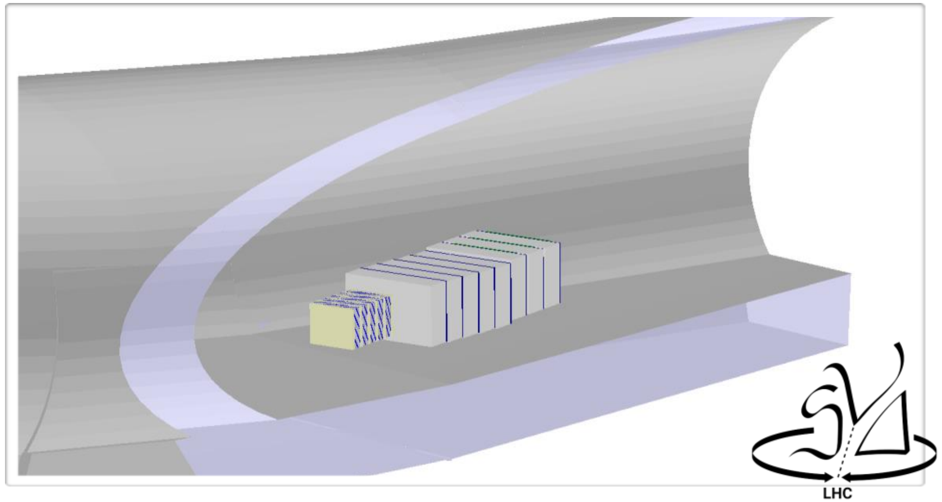
- PROPAGATION

  - 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



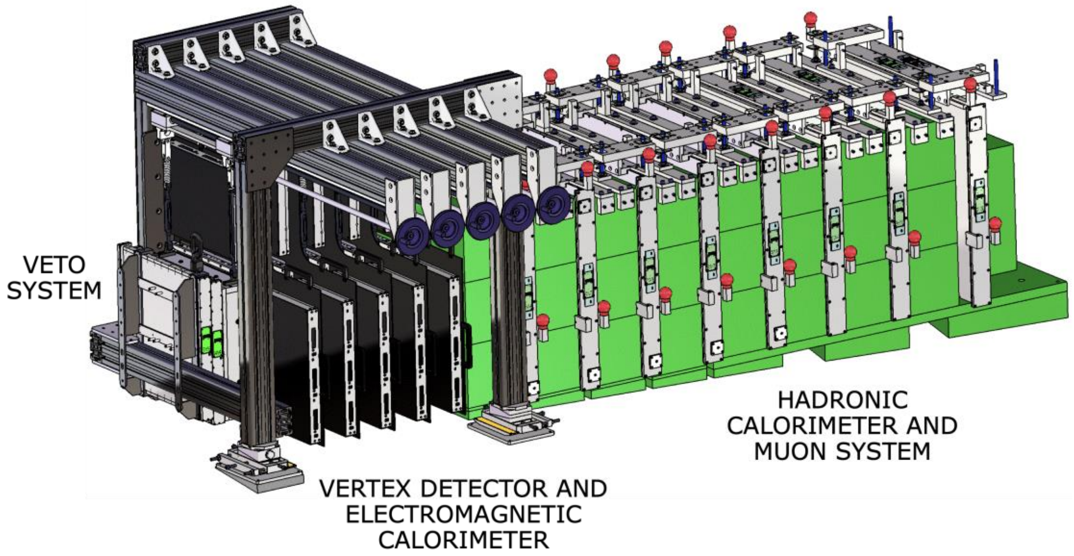
- DETECTOR

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



Detect all three neutrinos

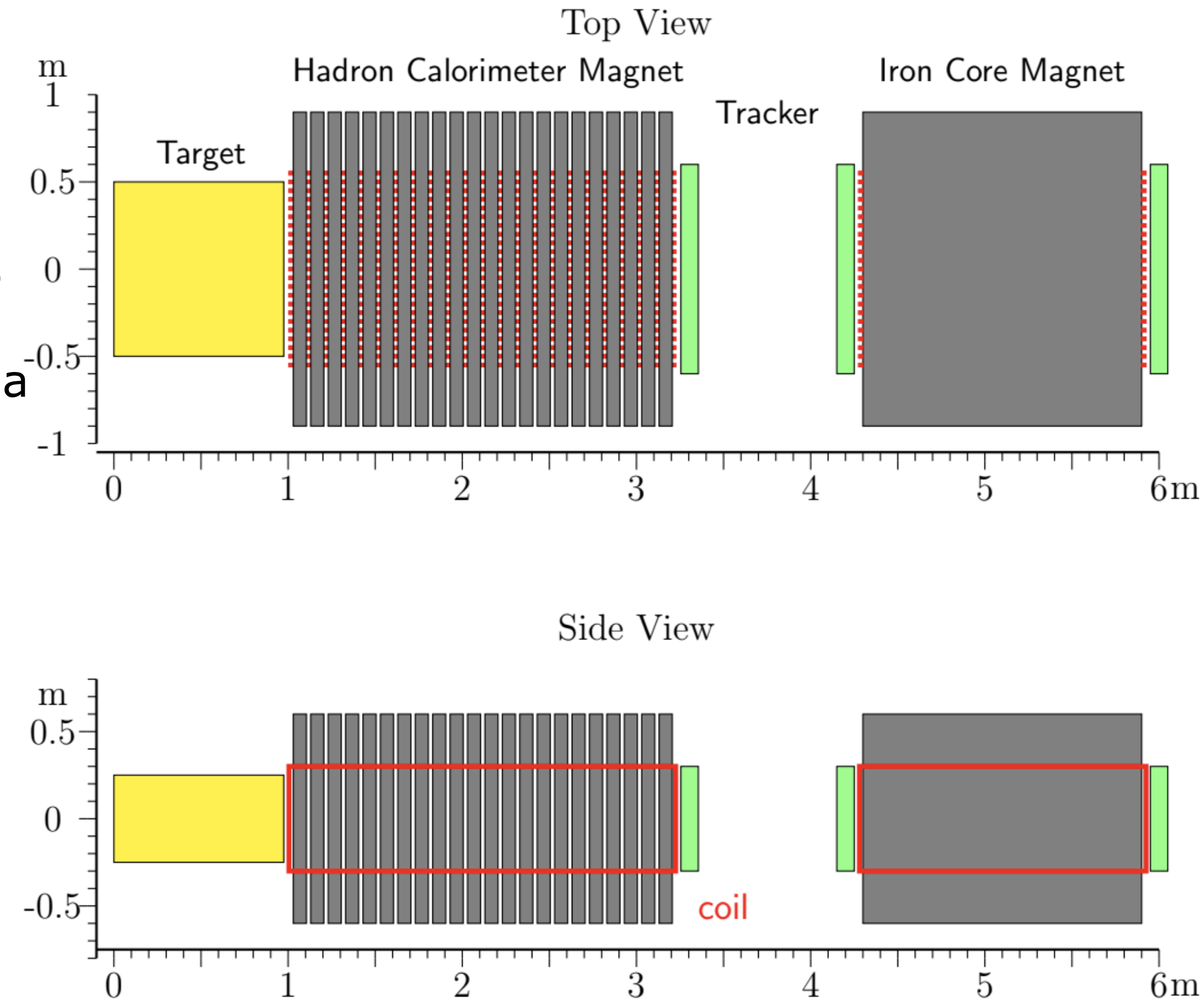
- Neutrino target with a vertex detector embedded
  - High spatial resolution for tau neutrinos
- E.m. and hadronic calorimeter for the energy measurement. Important for the cross-section measurement and for the background reduction
  - Target thin unless it can also act as a calorimeter
- A muon identification system and a magnetic spectrometer for ν/anti-ν separation: ν_μ and ν_τ when $\tau \rightarrow \mu$



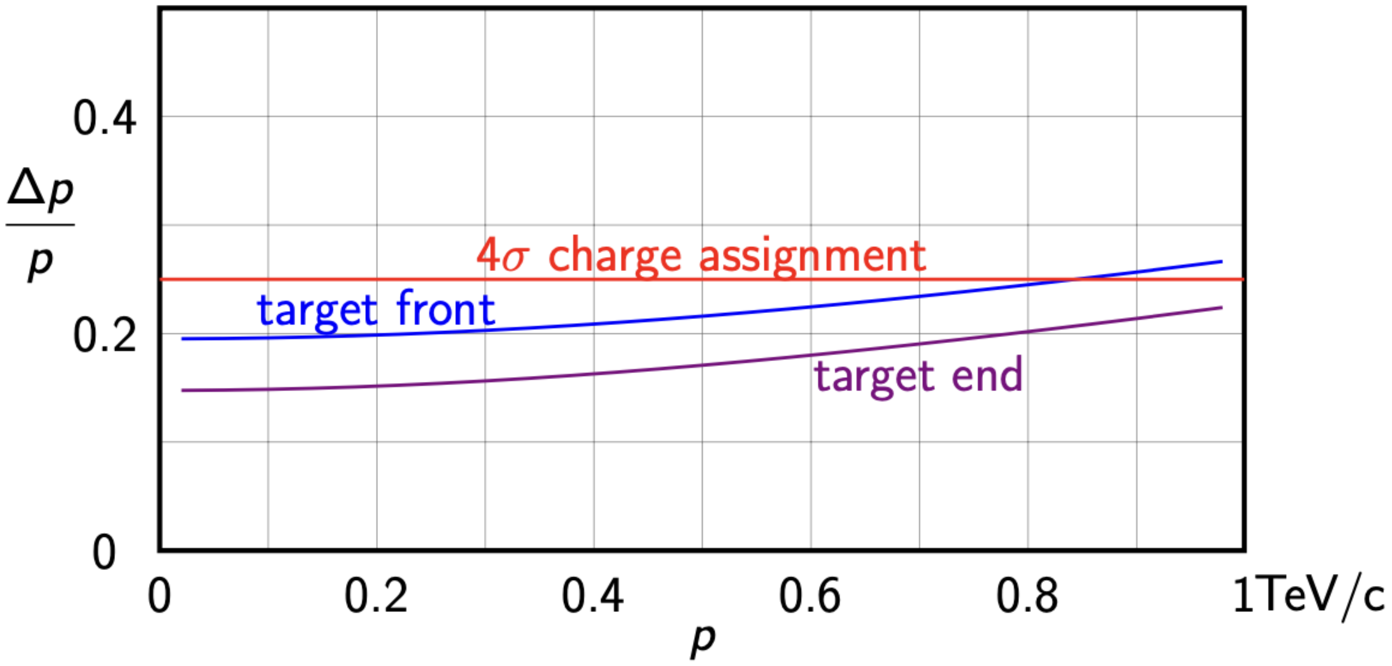
Muon spectrometer to separate ν ant anti-ν

Iron core magnet

- Two magnetised volumes
  - Upstream one acting also as hadronic calorimeter
  - Downstream one only as a magnetic spectrometer
- Three tracking chambers to measure muon track coordinates
- B = 1.5 T
- Total iron mass: 57 t
- Power consumption: 1kW



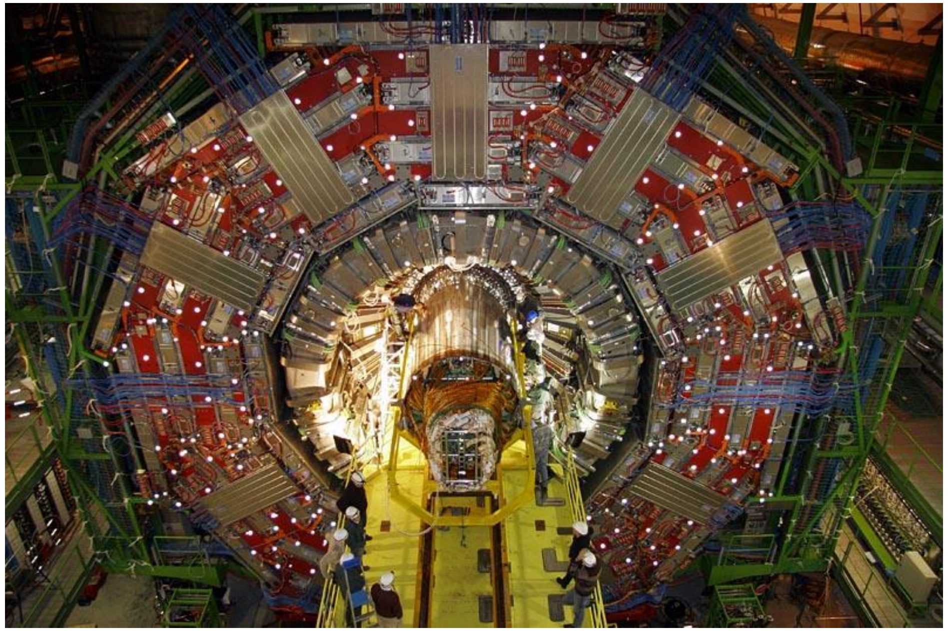
Momentum charge measurement



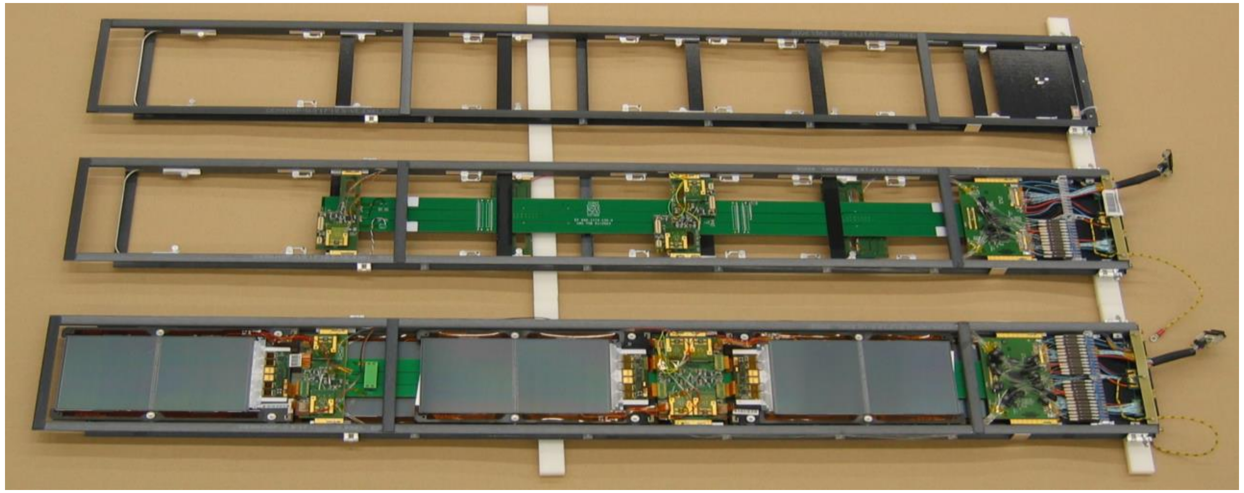
The momentum resolution of the spectrometer for muons originating from the front and from the end of the target. For a momentum resolution $\Delta p/p$ below 0.25 at least a 4σ separation from infinite momentum and thus a charge assignment is achieved.

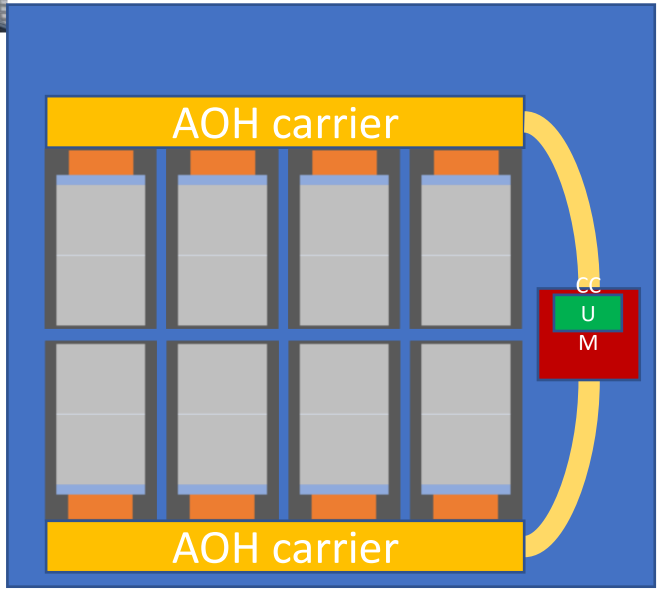
One option for the FAR: vertex detector with silicon strips

LHC
Scattering and Neutrino Detector
at the LHC



Silicon strips of the CMS TOB



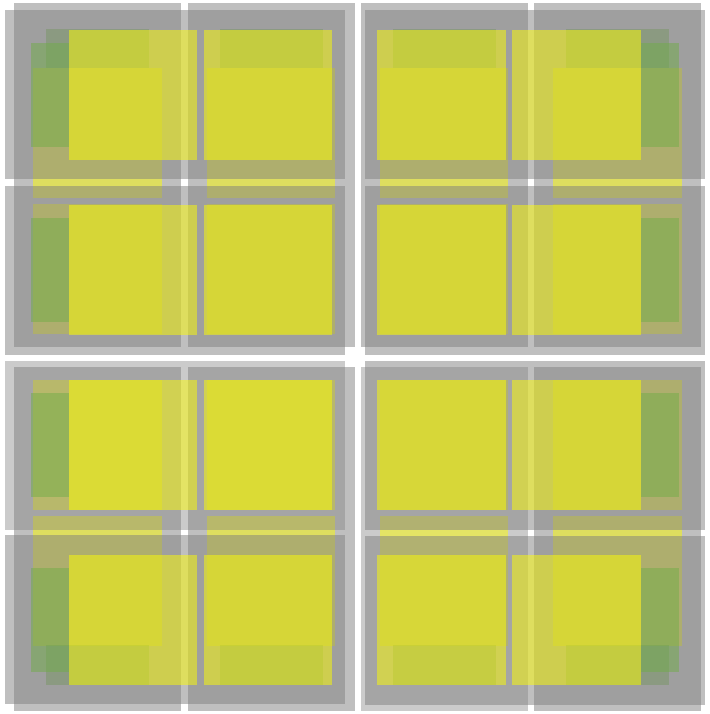


Arranging modules in a layer (Duccio Abbaneo)

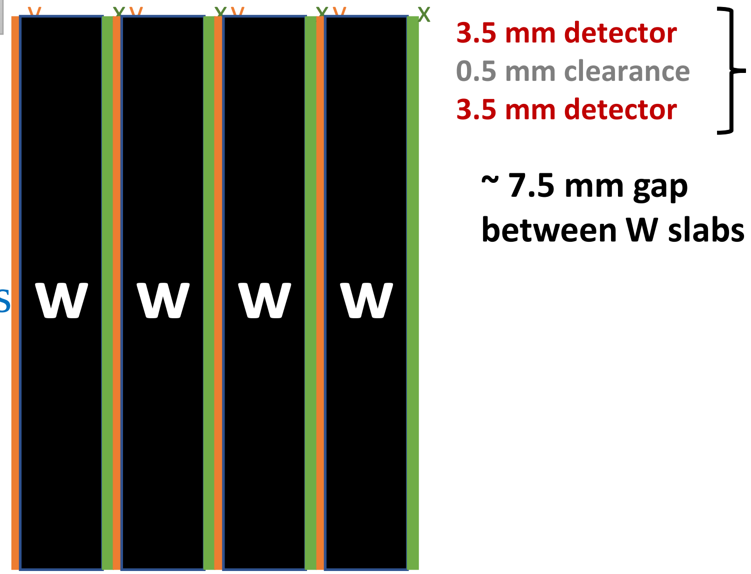
Outer envelope 49.29 × 49.29 cm^2 = 2430 cm^2

... as good as it can get

Surface with 0 coordinates	469 cm^2 ⟶ **673 cm^2**	
Surface with 1 coordinate	956 cm^2 ⟶ **769 cm^2**	**20% decrease**
Surface with 2 coordinates	894 cm^2 ⟶ **987 cm^2**	**10% increase**



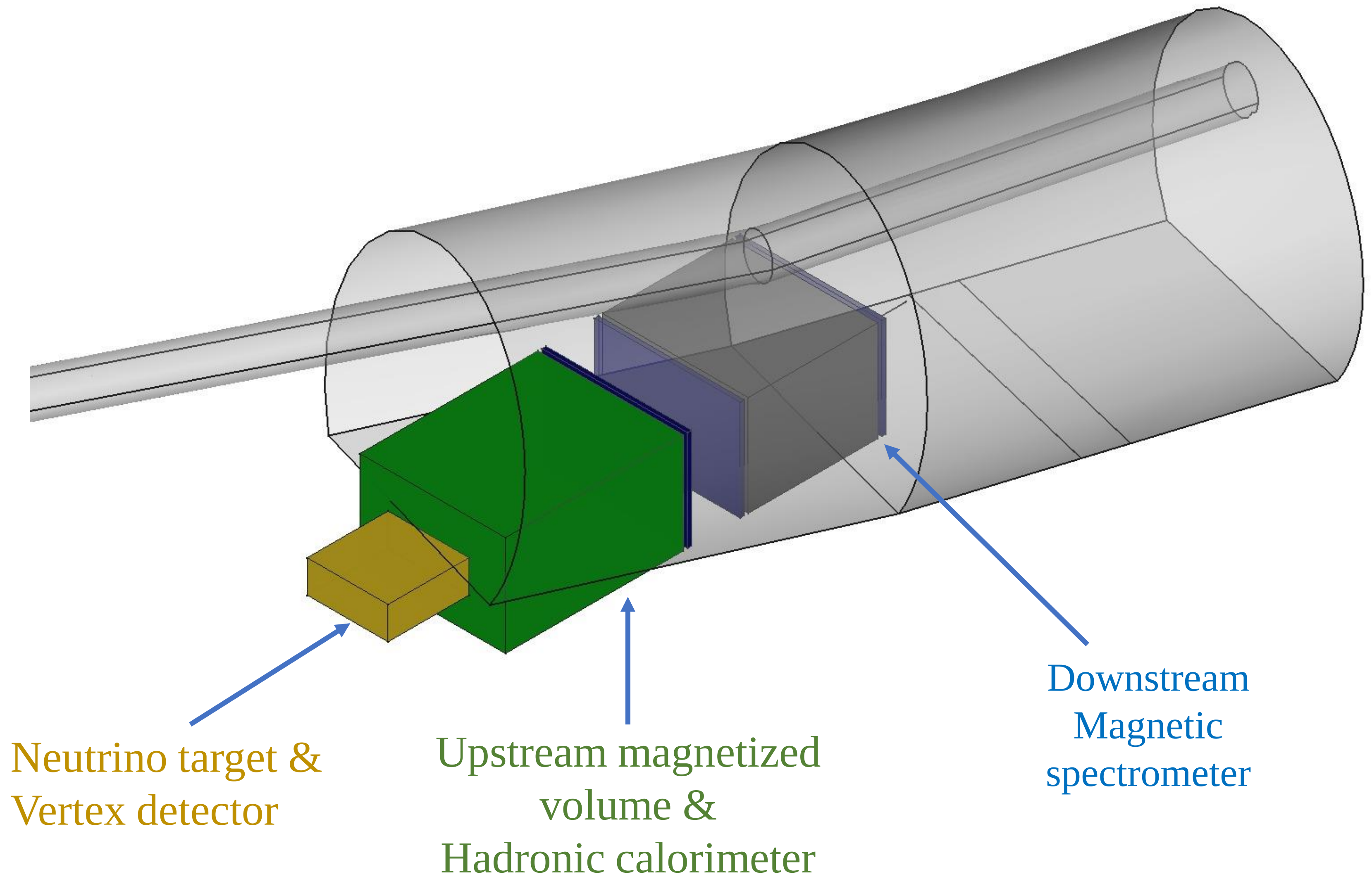
Available from the TOB for ~80 detection layers



Assuming 7.5 mm W layers → 60 cm W for about 40 x 40 cm^2
For 1 total mass of 1.8 tons and 1.2m length
Exploit silicon as a (particle flow) calorimeter

Simulation needed to assess the viability of this option (7.5mm step) for a tau neutrino detector at the energy of the FAR

Preliminary integration studies in TI18

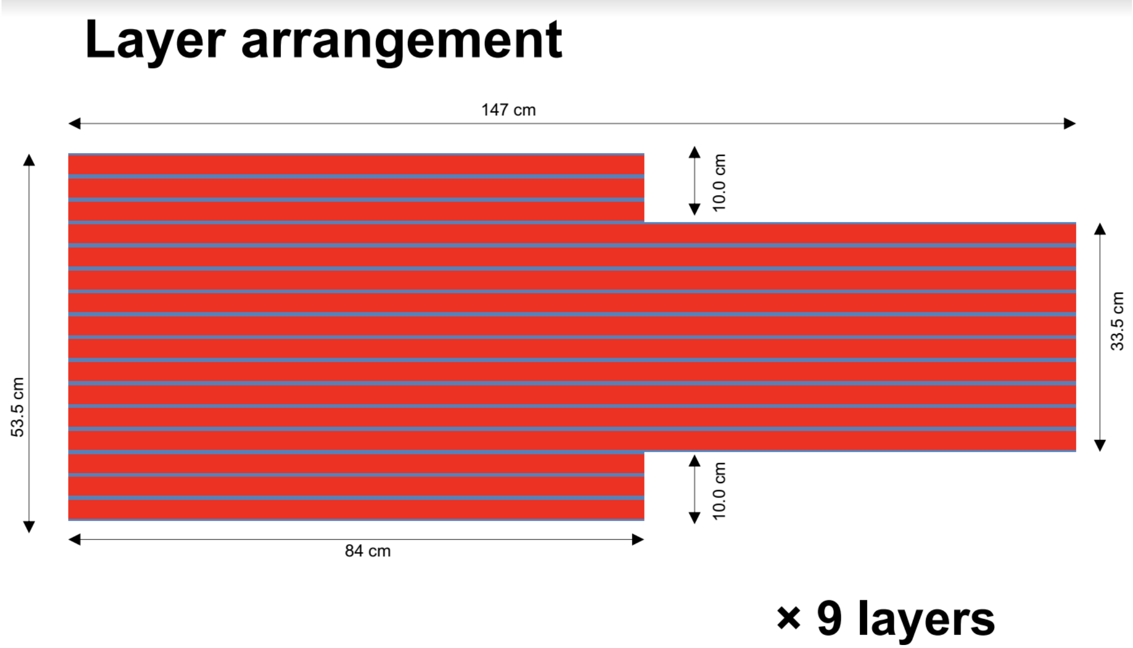


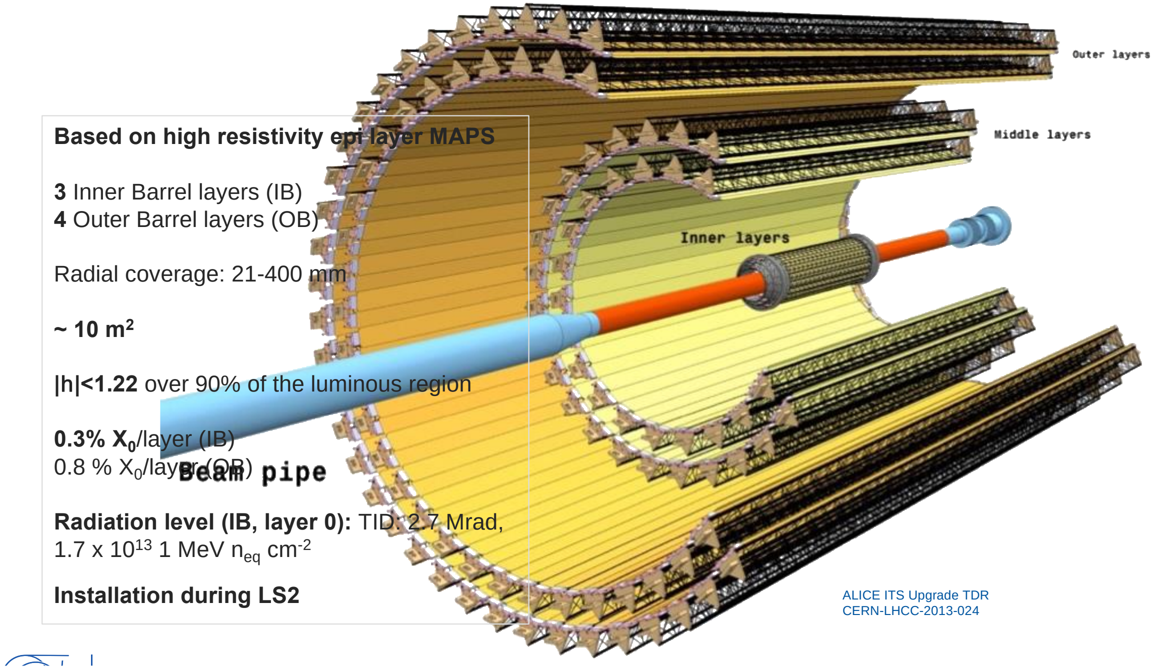
NEAR detector concept

- Geometrical constraints: 85 m away from IP → 1.1 to 3.0 m off-axis
- Difficult to fit a magnet: inclusive ν/anti-ν measurements
- Detector concept similar to the current SND@LHC, except for the environmental conditions
- Lower (w.r.t. FAR) energies for ν originated by a given parent (b and c)
- $4 < \eta < 5$ coverage. Angle [13, 36] mrad to compare with ~ 1 mrad → factor 10 lower energy

τ flight length shorter ~ 3 mm → Very high segmentation. ALICE Monolithic Active Pixel Sensors (MAPS) seem optimal

Arranging modules in layers

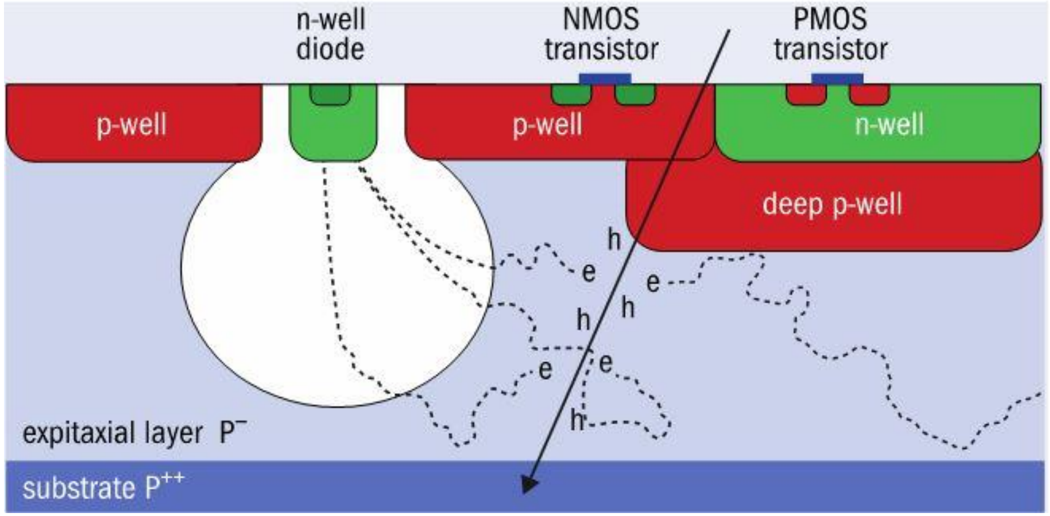




ALICE ITS upgrade

Monolithic Active Pixel Sensors (MAPS)

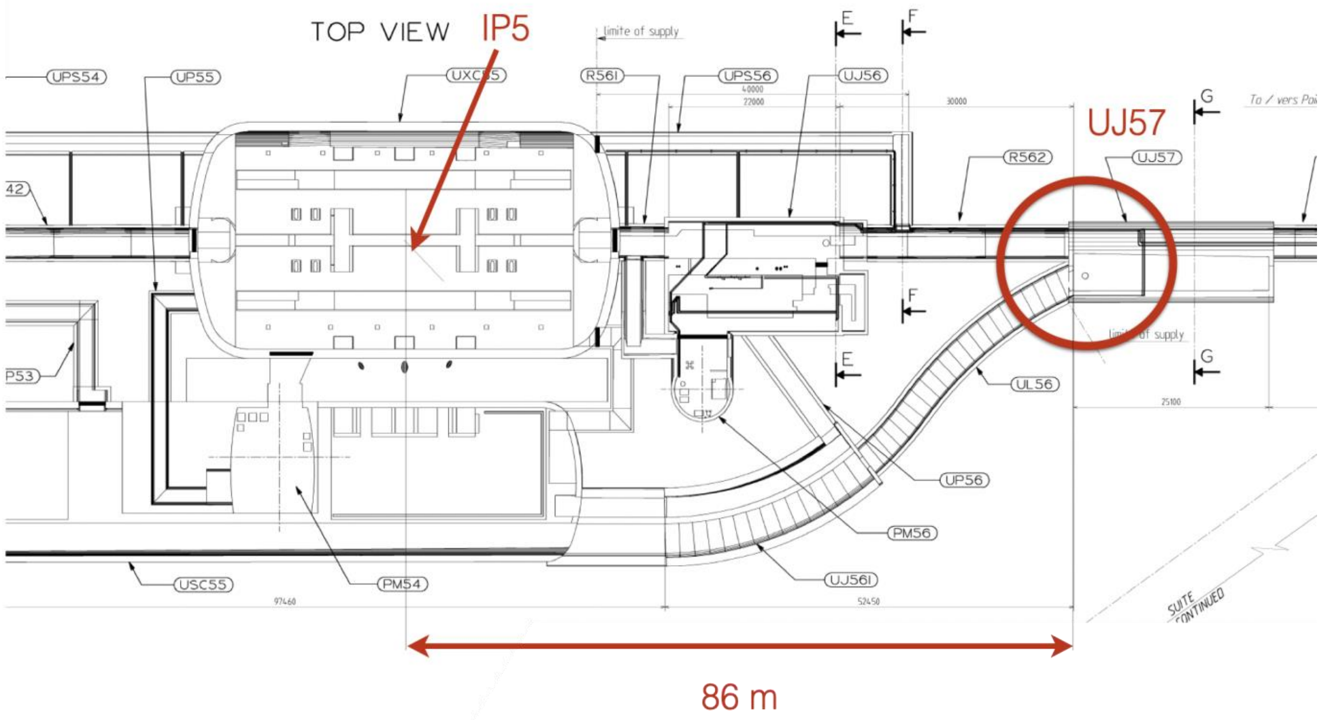
- Sensor and readout in one same piece of silicon
  - Advantages
    - High granularity/precision
    - Minimal material/thickness
    - Low power density
  - Limitations
    - Radiation tolerance
    - Rate capability

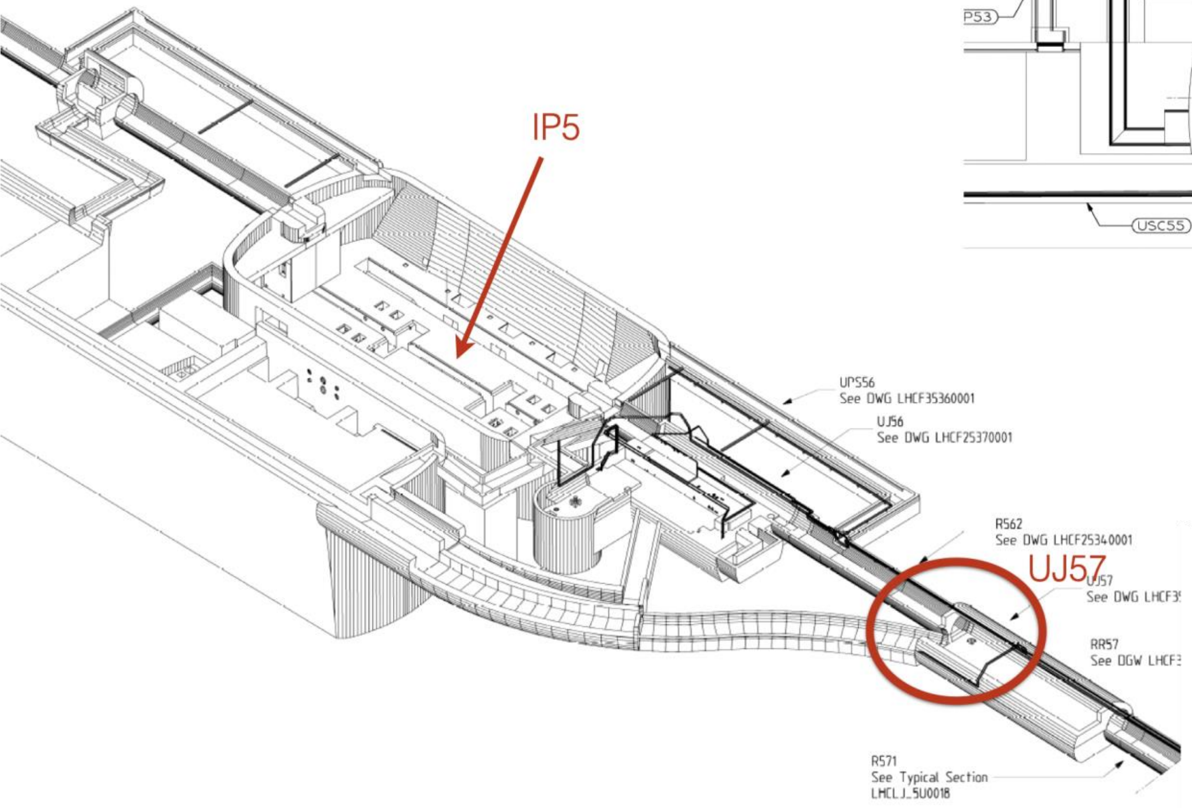


Preliminary studies for the NEAR Detector

UJ57 tunnel at 86 m from CMS IP

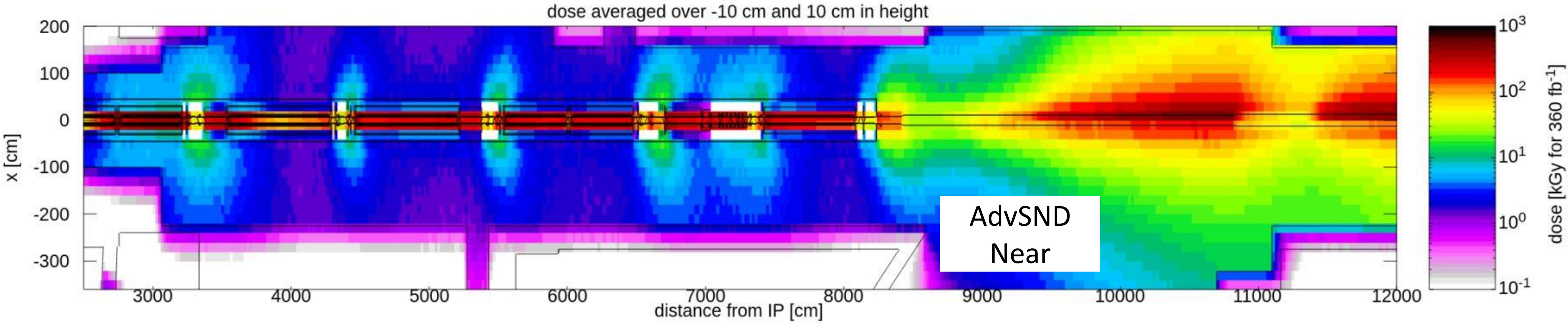
Sufficiently close to allow triggering CMS (and hence have 4pi view of the event)



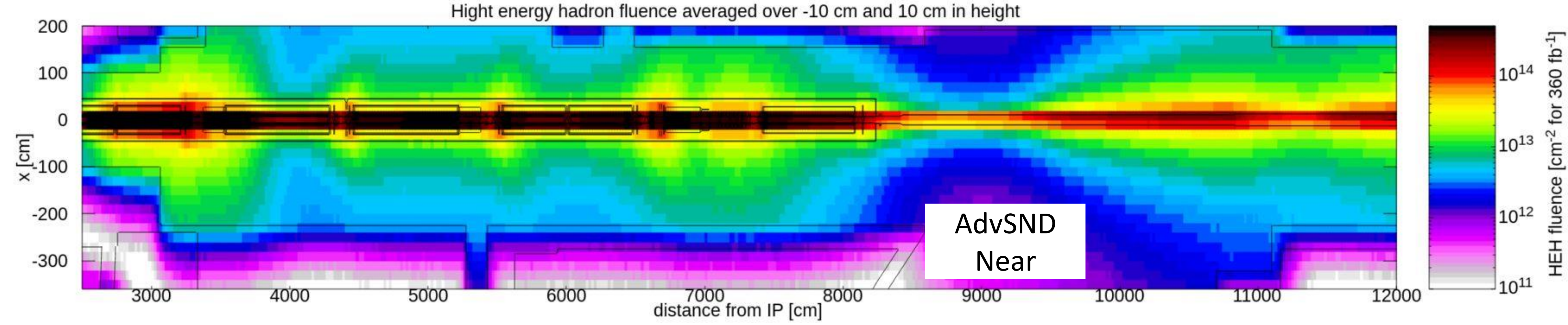


Dose and particle fluence right of IP5 (FLUKA)

- Dose map in HL-LHC, right of IP5

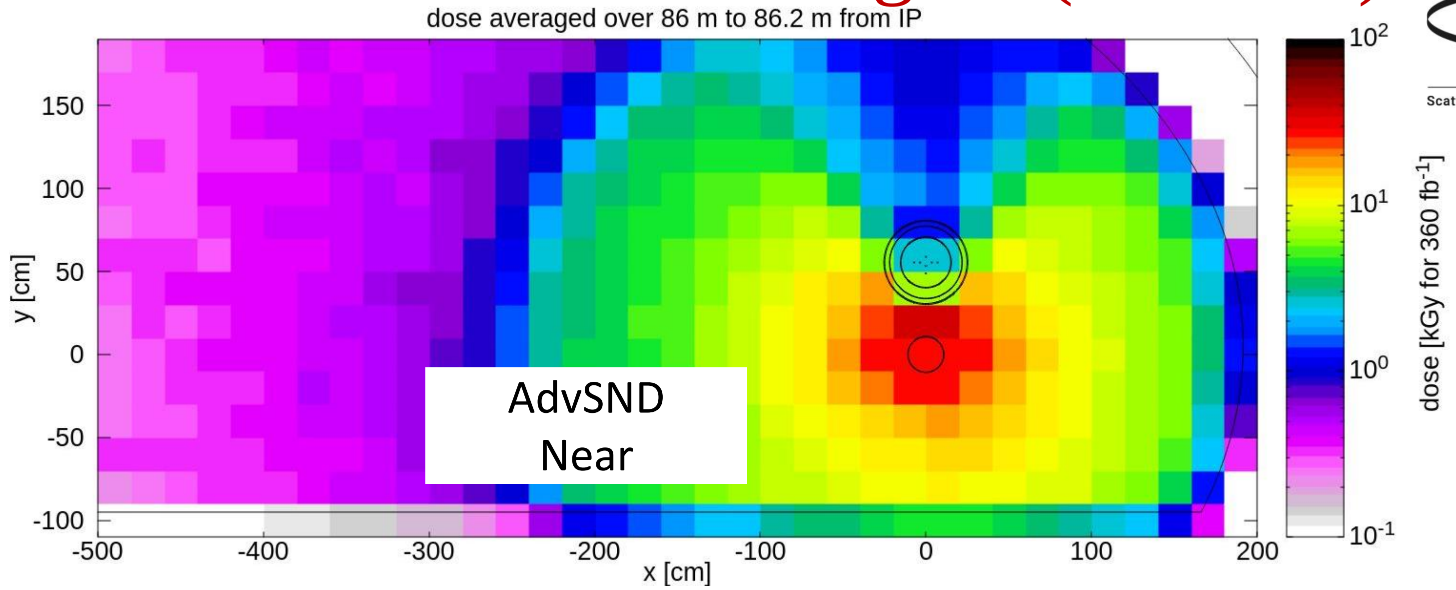


- High energy hadron fluence in HL-LHC, right of IP5



Dose and particle fluence in the NEAR detector region (FLUKA)

- Dose in UJ57 tunnel, 86 m (right) from IP5



- High energy hadron fluence in UJ57 tunnel, 86 m (right) from IP5