SND@LHC

A new **S**cattering and **N**eutrino **D**etector **at the LHC**

Blois 2023: 34th Rencontres de Blois on "Particle Physics and Cosmology"

Gaston d'Orléans - May 18th 2023

C. Battilana (Università ed INFN Bologna)

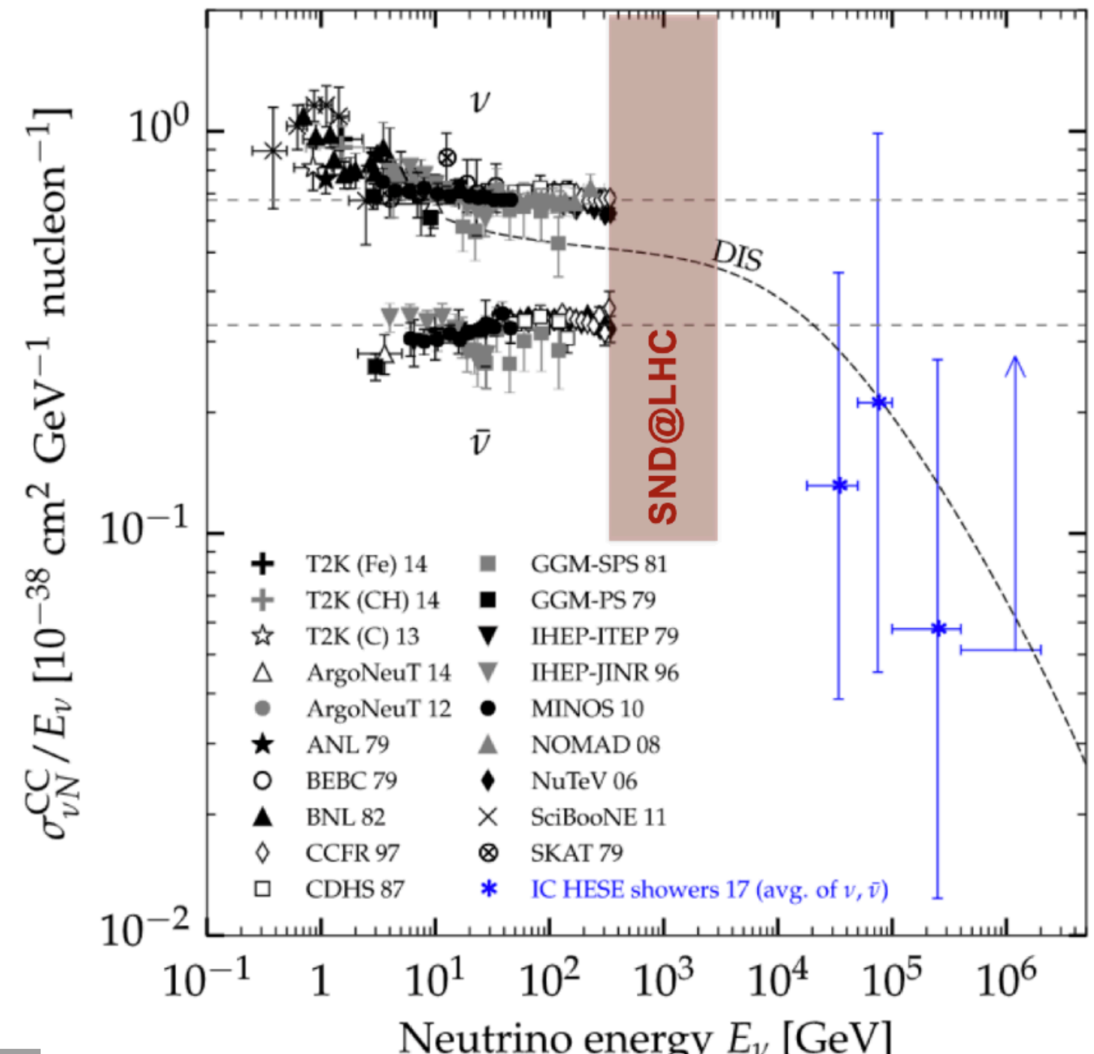
on behalf of the SND@LHC collaboration

Neutrino Experiments at the LHC

Proposals for **studying high-energy neutrinos at LHC** date back to the early 90's

- **Measure** pp → ν X in an **uncovered energy domain**
- **Achievable** with rather **small-size detectors** [*]
  - **Large ν fluxes** from pp collisions **at high η**
  - **E_ν [10^2 – 10^3] GeV**, $\sigma_\nu \propto E_\nu$
- **Two experiments** presently operating
  - **FASER ν** on-axis ($\eta > 9$) [C. Cavanagh talk]
  - **SND@LHC** slightly off-axis ($7.2 < \eta < 8.4$)

PRL 122 (2019) 041101



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IOP Publishing **2019** 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

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IOP Publishing **2020** 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

[*]

SND@LHC: Physics Programme

LHCC-P-016

arXiv 2210.02784

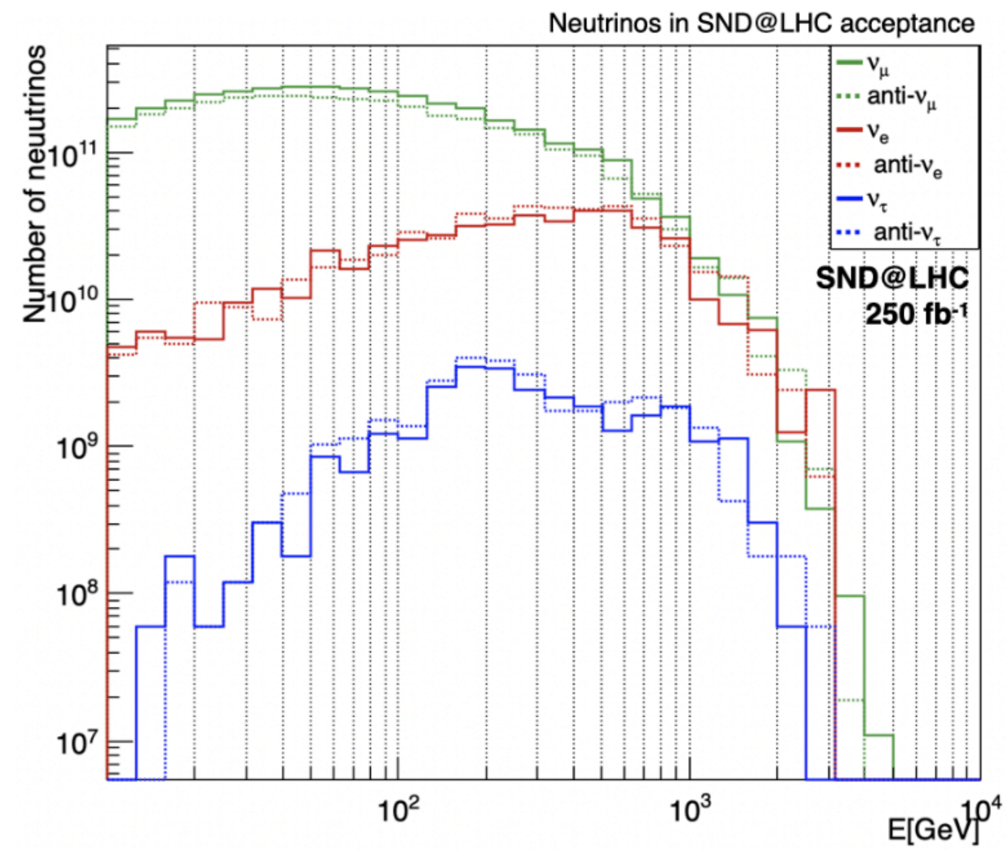
- Measure **charm production** at high **high** η ($gg \rightarrow c\bar{c}$)
  - Due to η acceptance, ν s mostly coming from charmed hadrons decay

J. Phys. G 47 (2020) 125004

- **Probe gluon PDF** low momentum fraction ($x \sim 10^{-6}$)
  - FCC detectors
  - Extra-galactic ν observation (atmospheric ν background)

- **Test lepton flavour universality** using ν s:
  - **SND@LHC** is designed to **distinguish all ν flavours**

- Direct **search of feebly-interacting particles (FIPs)**
  - E.g.: Dark scalars, Heavy Neutral Leptons, Dark Photons



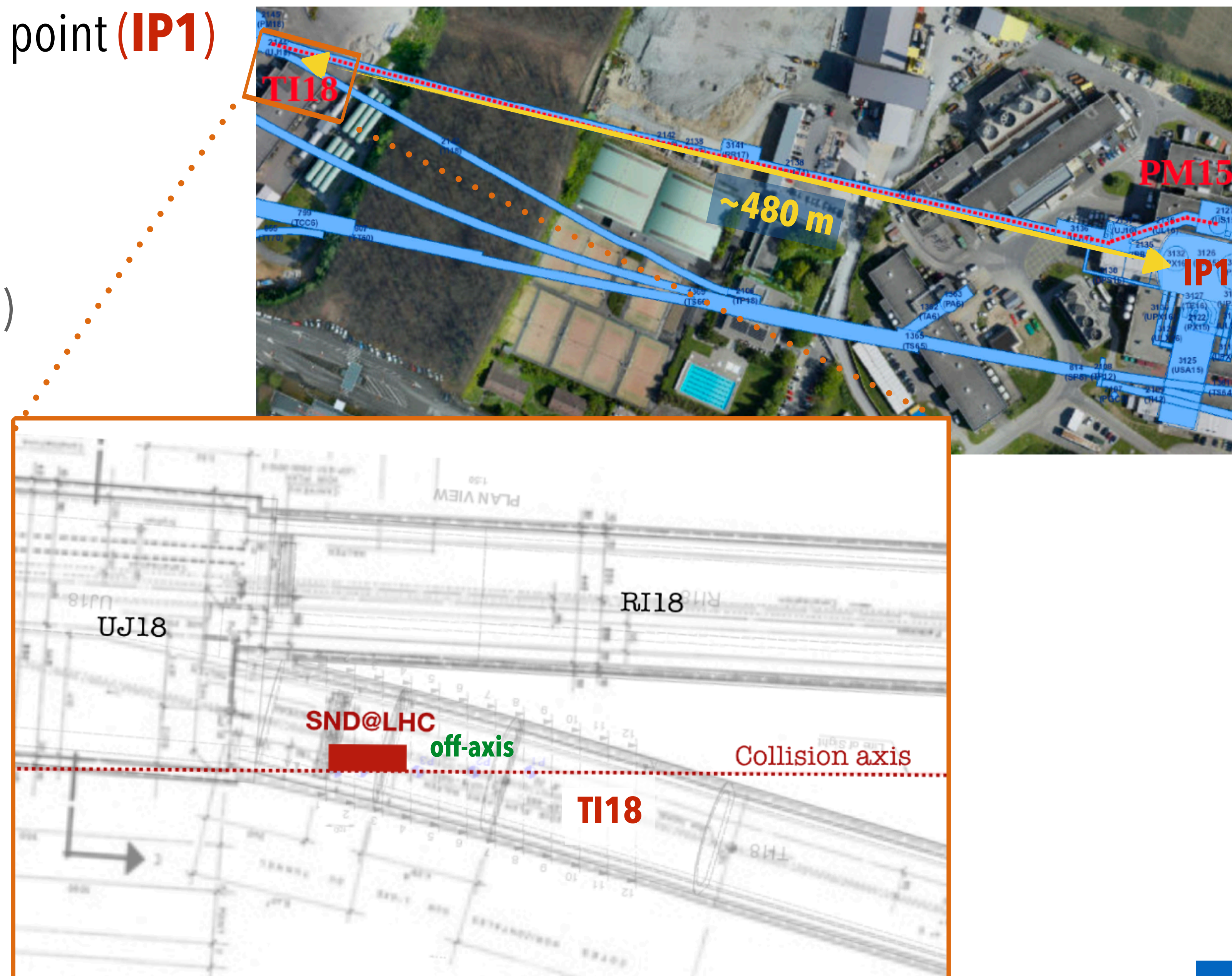
Run 3: 250 fb^{-1}

Flavour	Neutrinos in acceptance $\langle E \rangle$ [GeV]	Neutrinos in acceptance Yield	CC neutrino interactions $\langle E \rangle$ [GeV]	CC neutrino interactions Yield
ν_μ	130	3.0×10^{12}	452	910
$\bar{\nu}_\mu$	133	2.6×10^{12}	485	360
ν_e	339	3.4×10^{11}	760	250
$\bar{\nu}_e$	363	3.8×10^{11}	680	140
ν_τ	415	2.4×10^{10}	740	20
$\bar{\nu}_\tau$	380	2.7×10^{10}	740	10
TOT		4.0×10^{12}		1690

SND@LHC: Detector Location

SND@LHC is **located** in the **TI18** service tunnel (SPS to LEP transfer line, then dismissed)

- **~480 m** away **from ATLAS** interaction point (**IP1**)
- **Shielding**:
  - **~ 100 m** of rock
  - **LHC magnets** (deflect charged particles)
- **Angular acceptance: 7.2 < η < 8.4**



SND@LHC: Detector Location

SND@LHC is **located** in the **TI18** service tunnel (SPS to LEP transfer line, then dismissed)

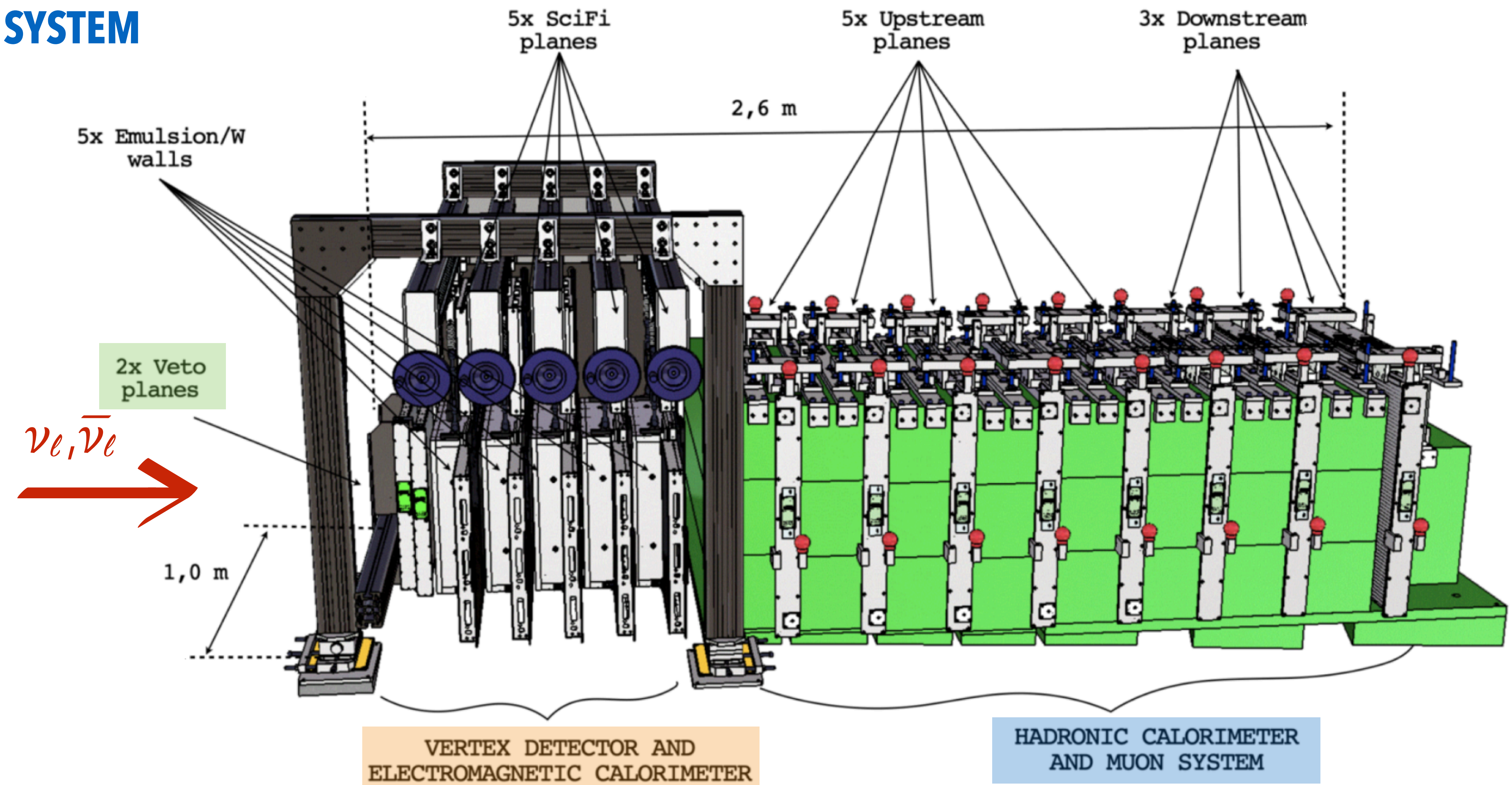
Machine to IP1 (left) – SND@LHC in TI18 (right)

SND@LHC: Detector Layout

arXiv 2210.02784

Angular acceptance: $7.2 < \eta < 8.4$

- **Veto system**
- **Target, Vertex detector, EM CAL**
- **HAD CAL, MUON SYSTEM**



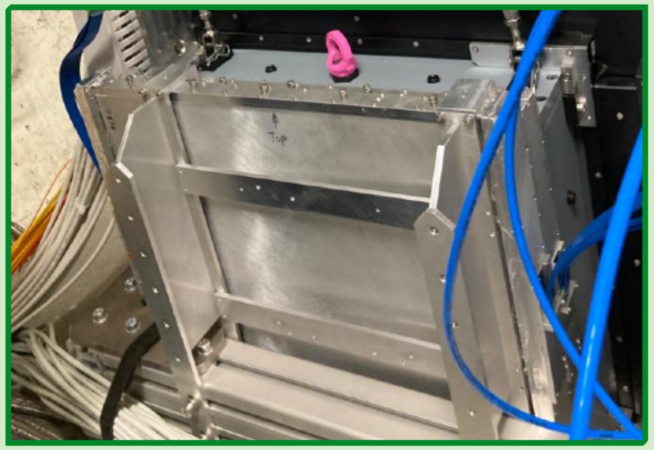
~40 X_0 ~10 λ

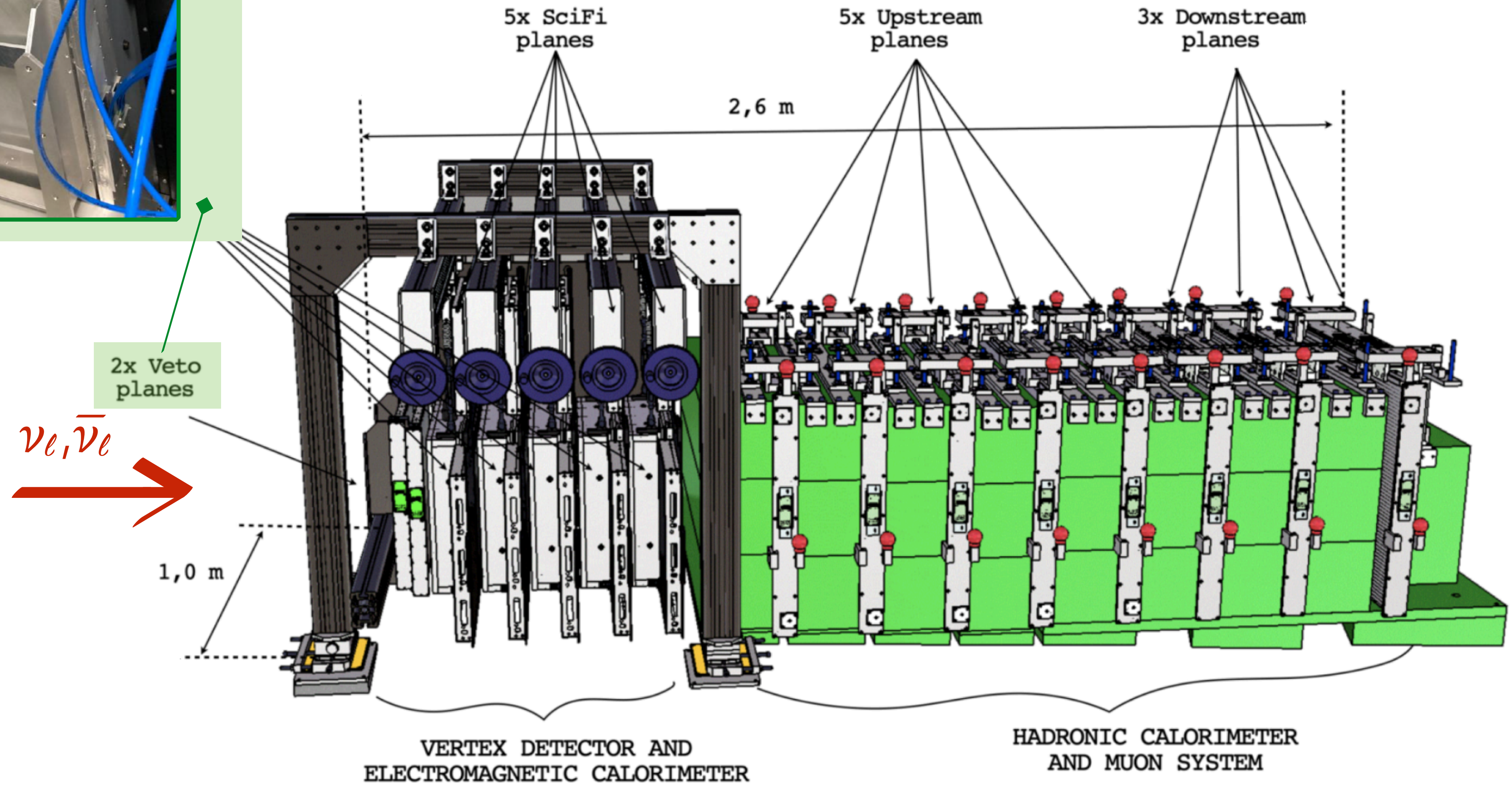
SND@LHC: Detector Layout

arXiv 2210.02784

VETO

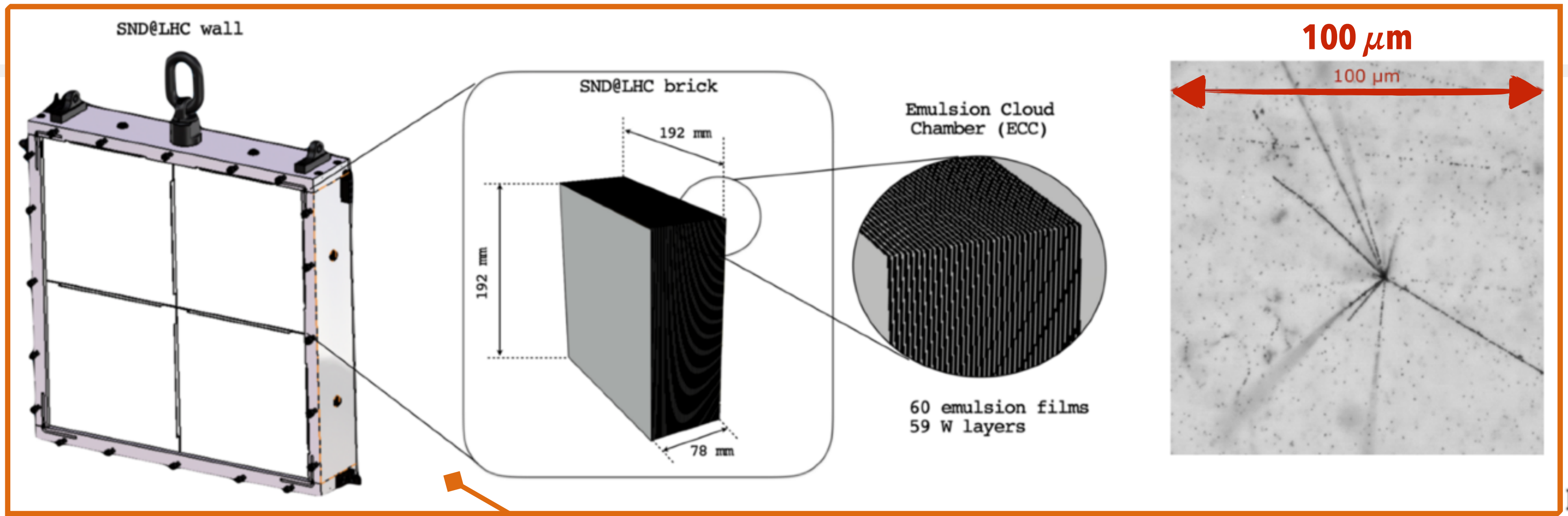
- **Goal:** charged particle identification
- 2 planes of stacked **scintillator bars**

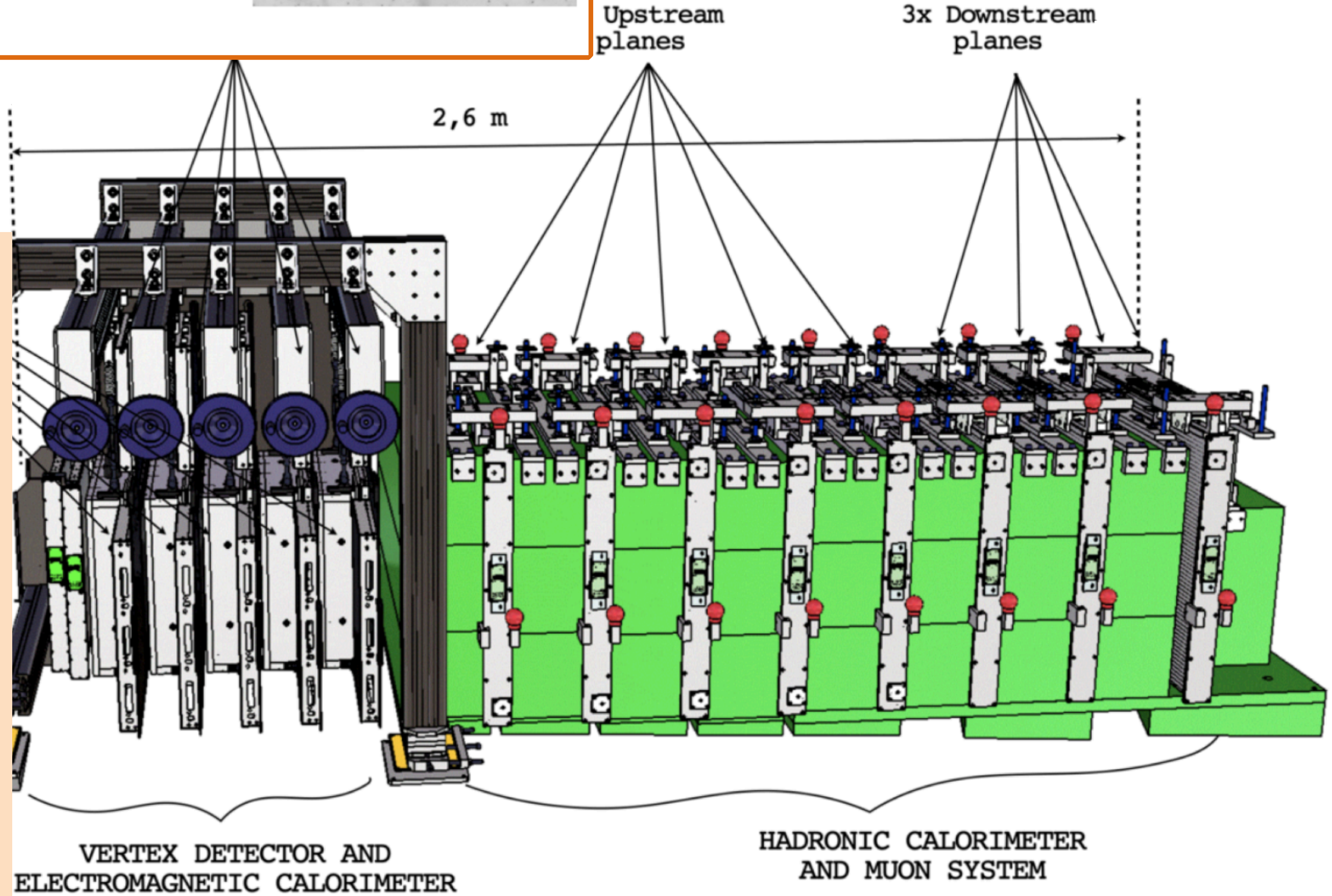




SND@LHC: Detector Layout

arXiv 2210.02784





Emulsion Cloud Chambers (ECC)

- **Goal: tracking** and **vertex ID**
  - **Sub-micrometric** resolution
- **Geometry**
  - 5 **walls** of 2x2 **bricks**
  - Shielding
    (protect from neutrons, stabilise T and humidity)
- **Brick layout**
  - 60 layers of 300 μm-thick **emulsions**
  - Interleaved by **1 mm tungsten** plates
- **Target mass** ~830 kg

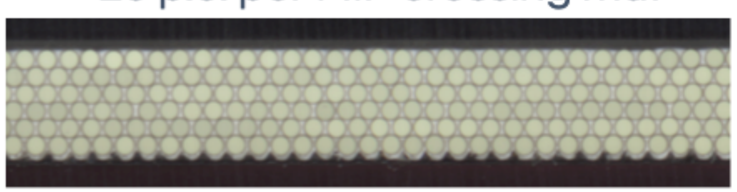
SND@LHC: Detector Layout

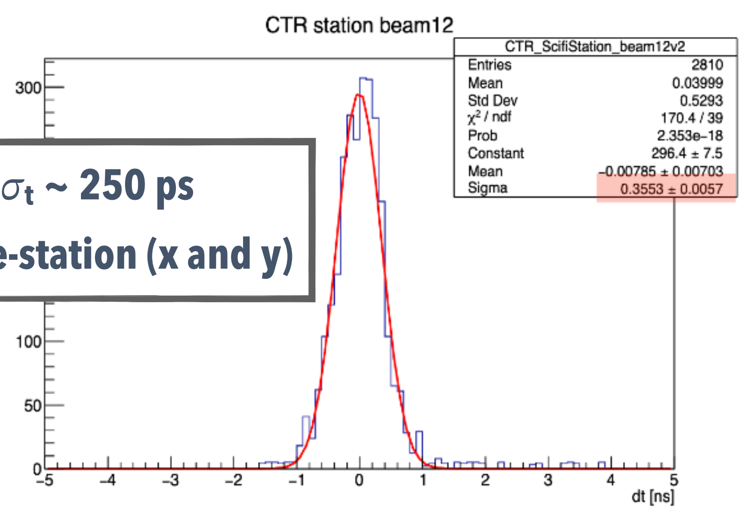
arXiv 2210.02784

SciFi

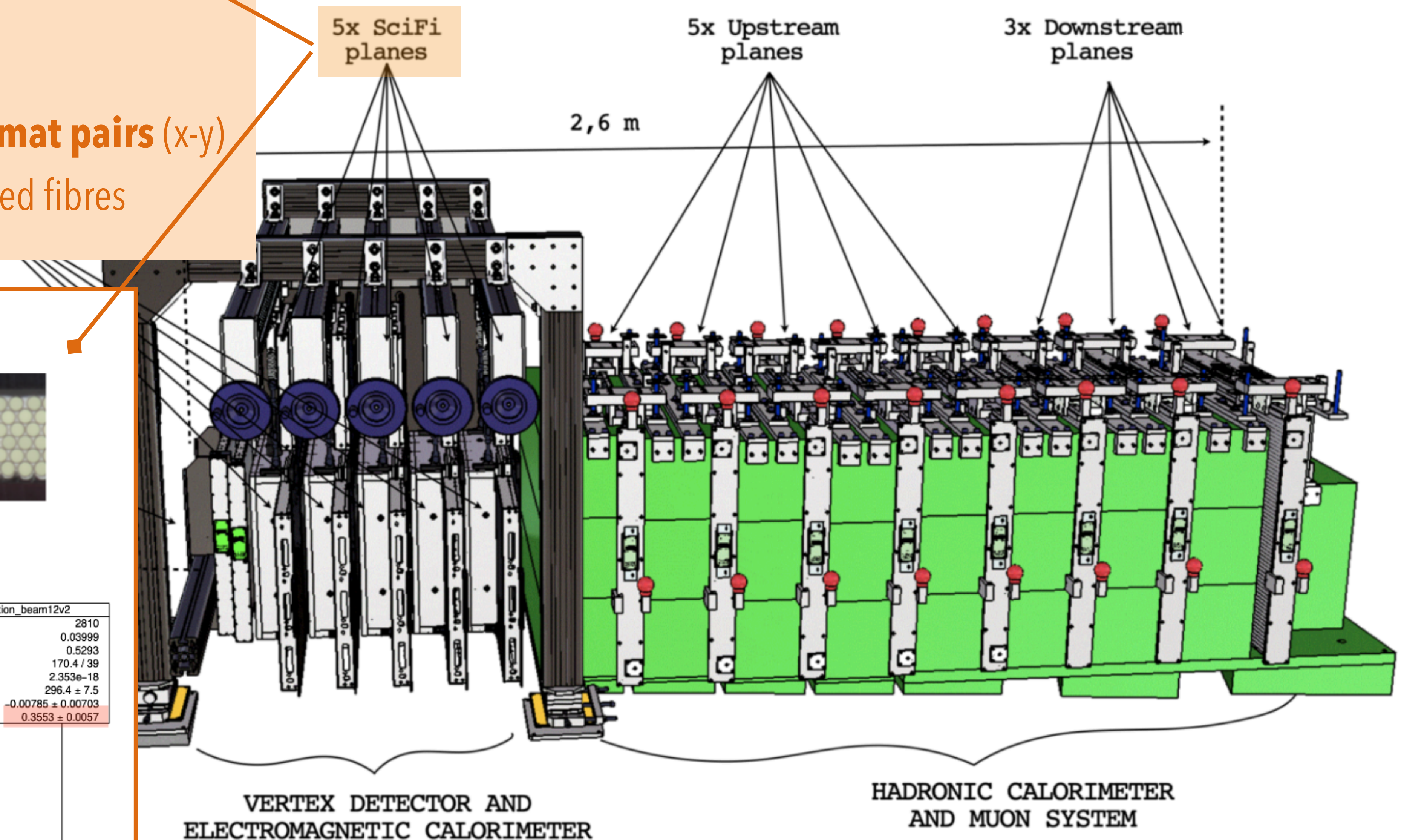
- **Goals:**
  - **Precise timing** information
  - **EM energy** measurement
  - Spatial information
- **Geometry**
  - 5 planes of **scintillating fibres mat pairs** (x-y)
  - **Mats** built of **6 layers** of staggered fibres

~25 p.e. per MIP crossing mat





σ_t ~ 250 ps
single-station (x and y)



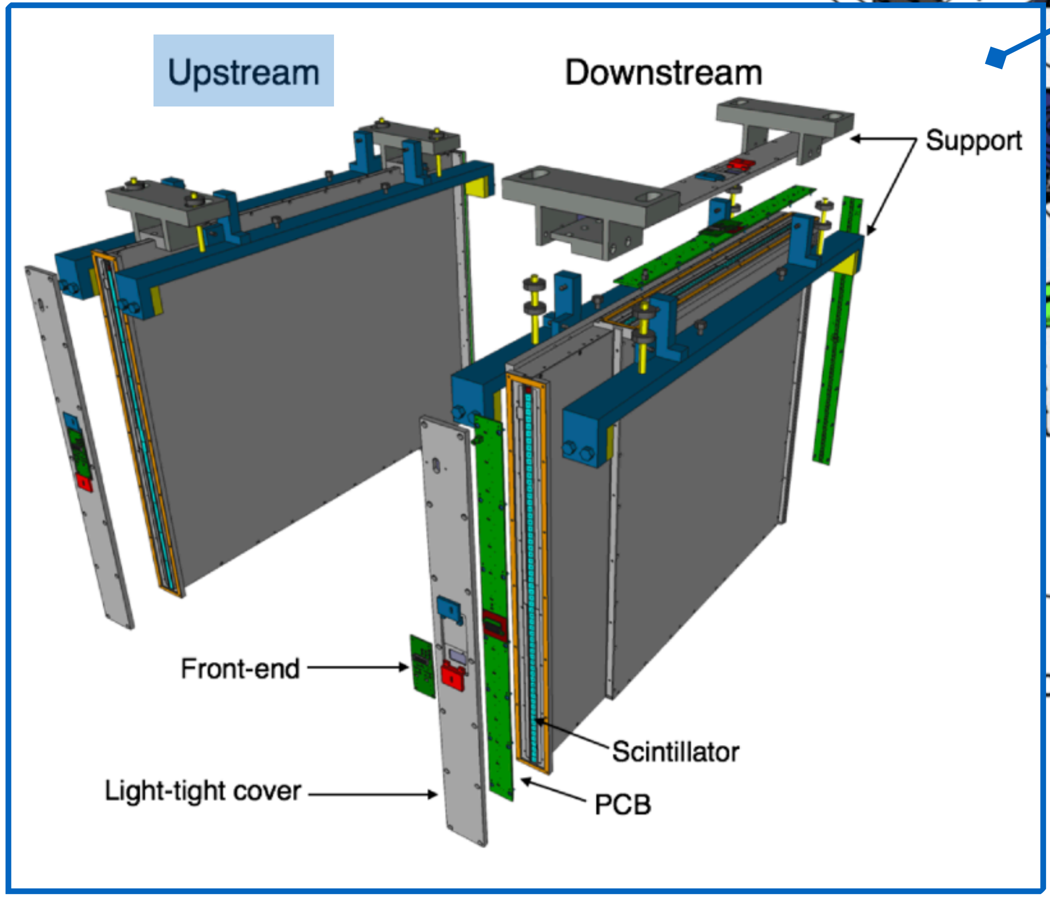
SND@LHC: Detector Layout

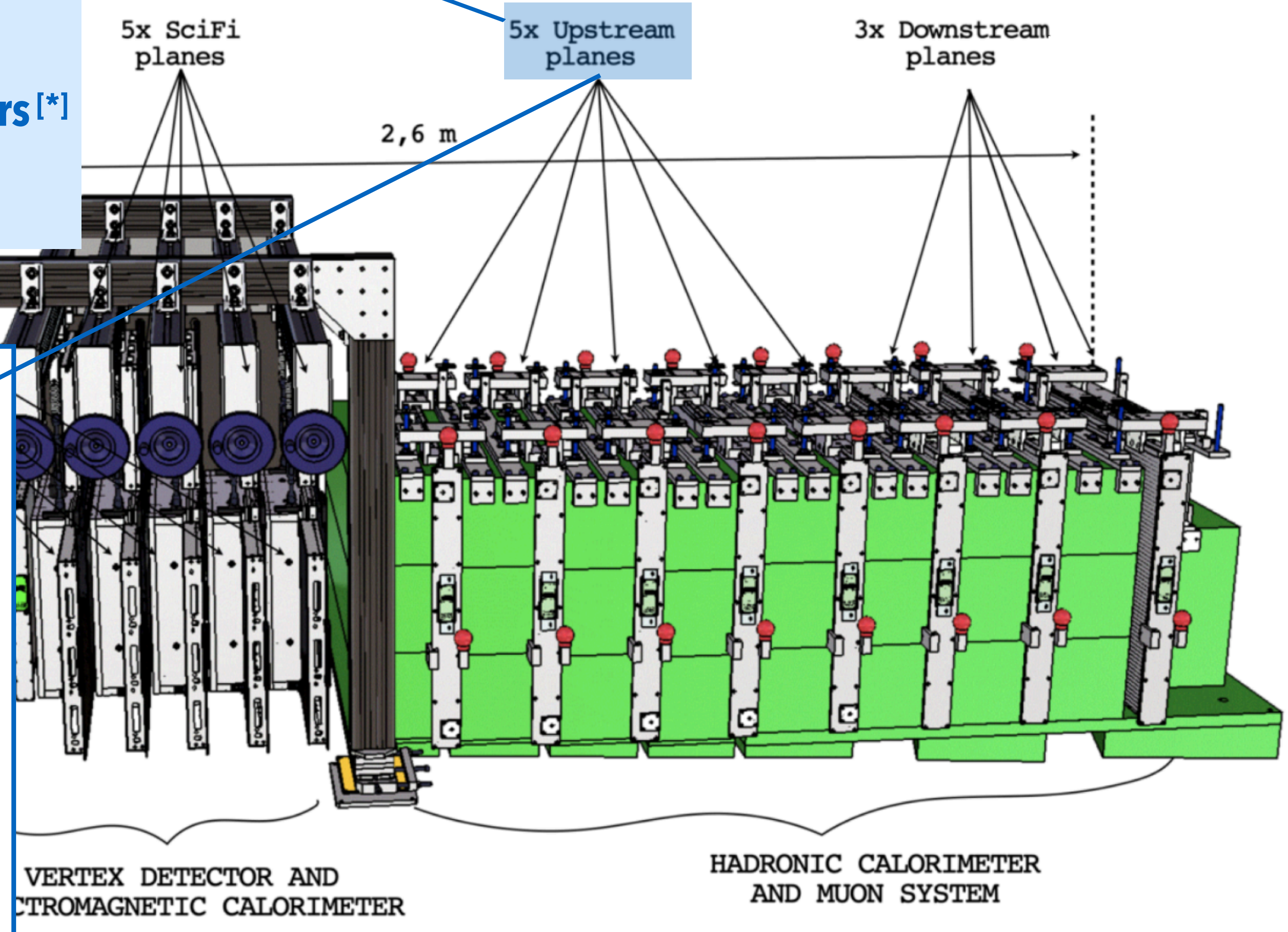
arXiv 2210.02784

Hadronic calorimeter

- **Goals:**
  - Timing information
  - **Hadronic energy** measurement
  - Spatial information
- **Geometry**
  - **5 stations** of horizontal **scintillation bar layers** [*]
  - Readout **on both ends** of a bar

[*] **interleaved with 20 cm Fe blocks**





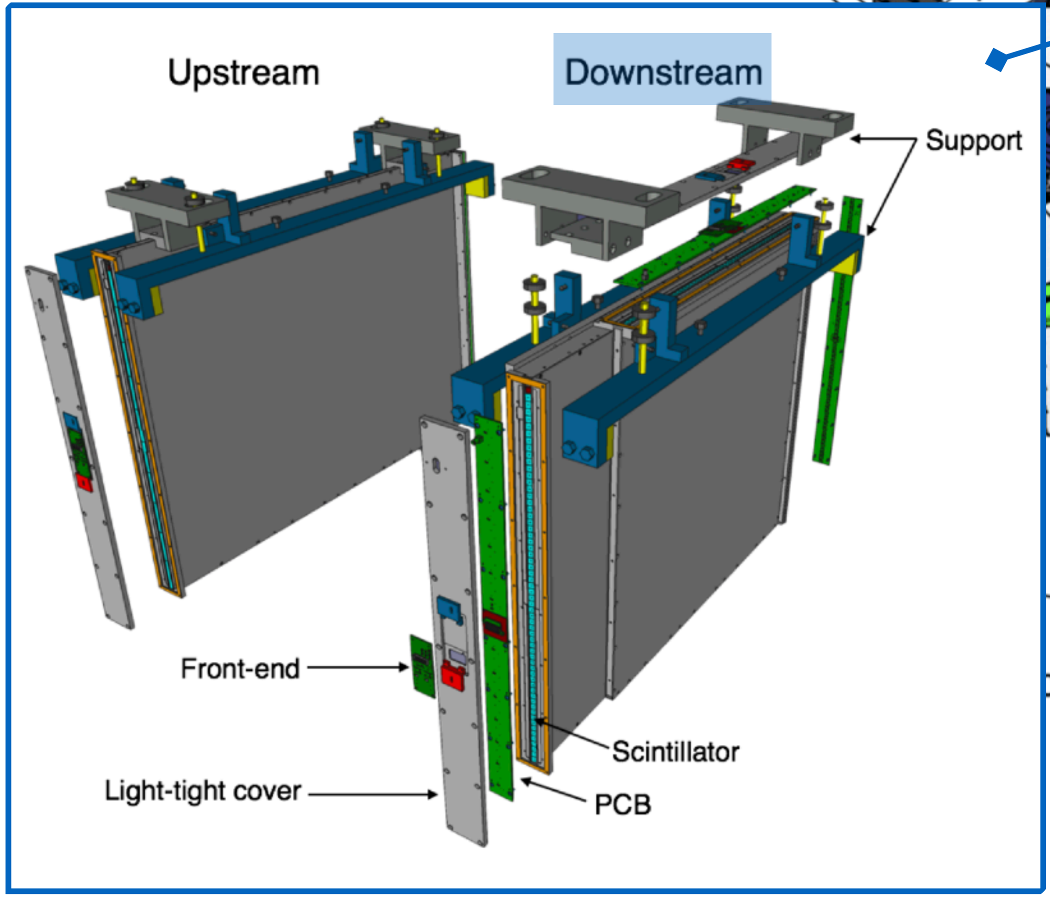
SND@LHC: Detector Layout

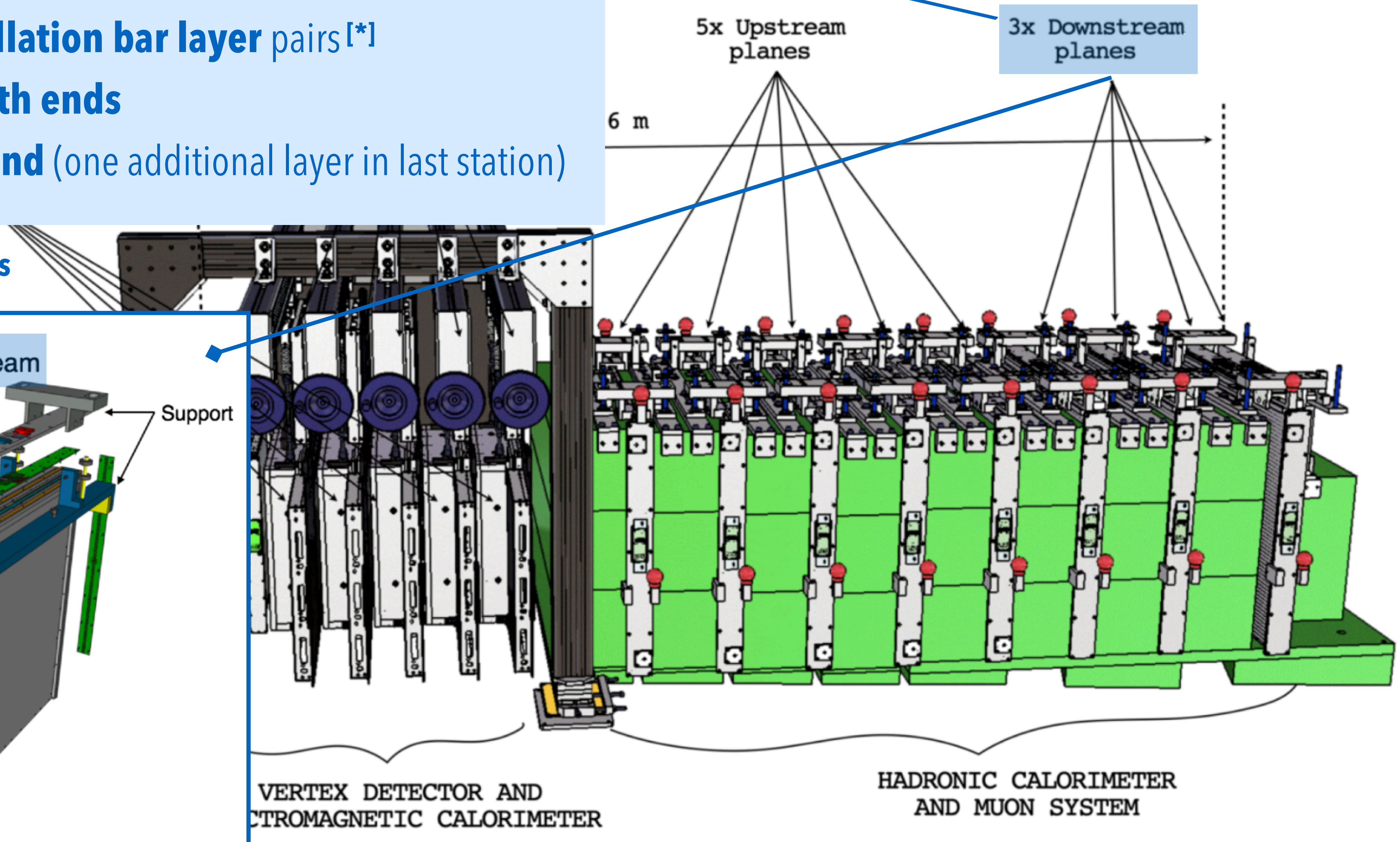
arXiv 2210.02784

Muon system

- **Goals:**
  - Timing information
  - **Muon tracking** and **isolation**
- **Geometry**
  - **3 stations** of orthogonal **scintillation bar layer** pairs [*]
  - Horizontal bars **read out on both ends**
  - Vertical bars **read out on one end** (one additional layer in last station)

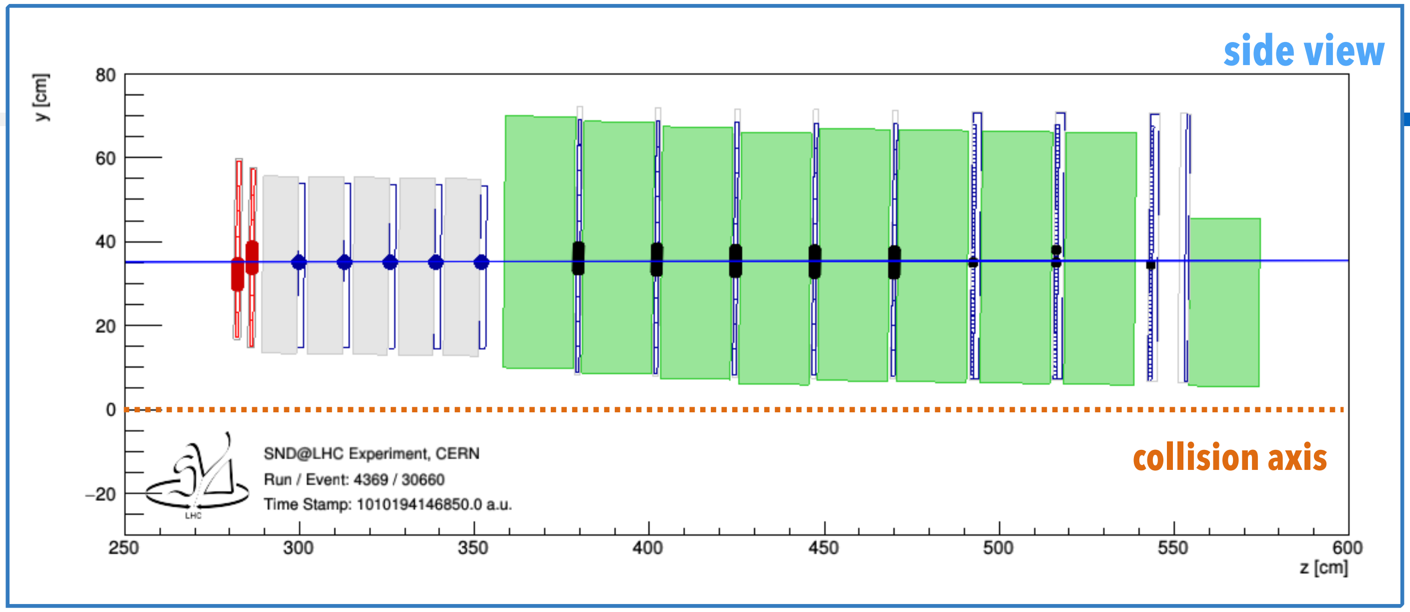
[*] **interleaved with 20 cm Fe blocks**





SND@LHC: Some Cornerstones

SND@LHC Event Display (6th of July 2022)



August 2020 *Letter of intent*

January 2021 *Technical Proposal*

March 2021 *Approval by CERN Research Board*

April 2022 *Beams Back in LHC*

July 2022 Run 3 starts ($\sqrt{s}$ 13.6 TeV)

September 2021

December 2021

March 2022

Data Acquisition and **Event Reconstruction**

Readout and DAQ

- **Trigger-less acquisition** system
- **Timestamp-based event building** from DAQ
- Multiple levels of noise filtering (FE thresholds, DAQ)

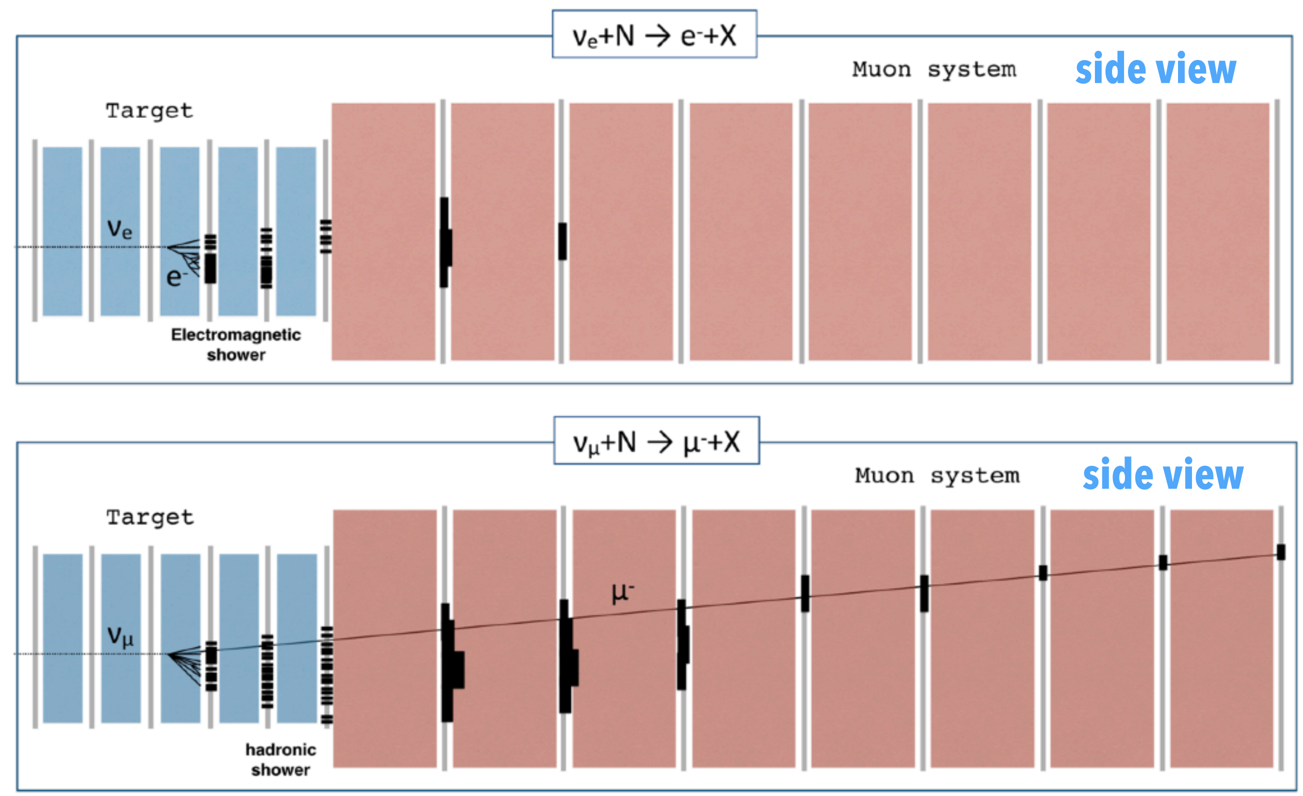
Two-staged Reconstruction

First phase: electronic detectors (event)

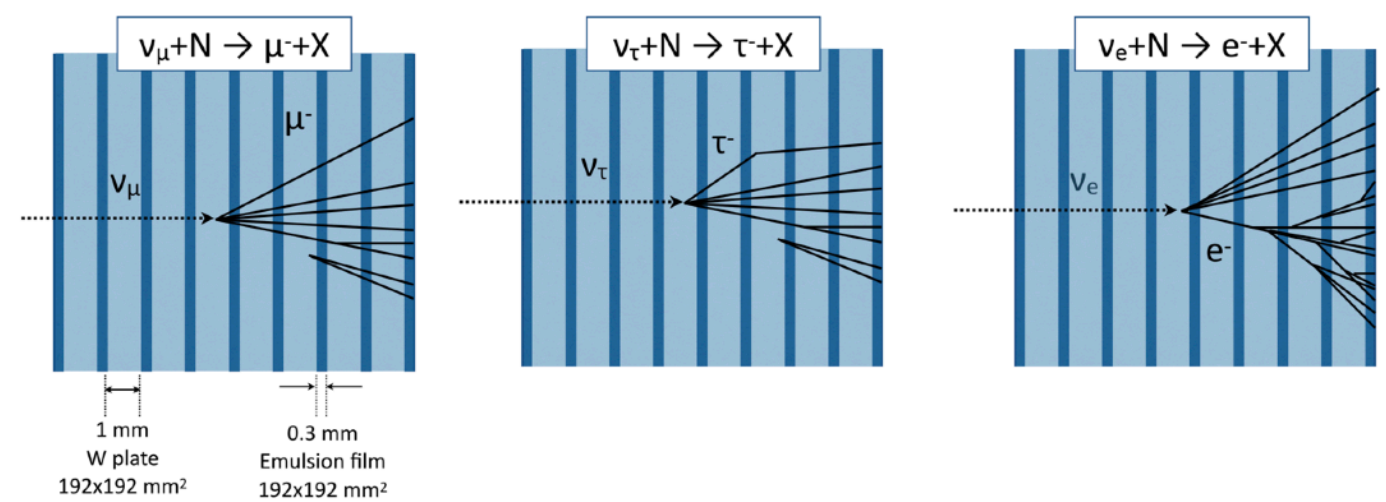
- **Tagging** of incoming charged particles (Veto, SciFi)
- **Muon identification** (Muon System)
- **Calorimetric energy measurement** (SciFi, HCAL)

Second phase: nuclear emulsions (~20 fb^{-1})

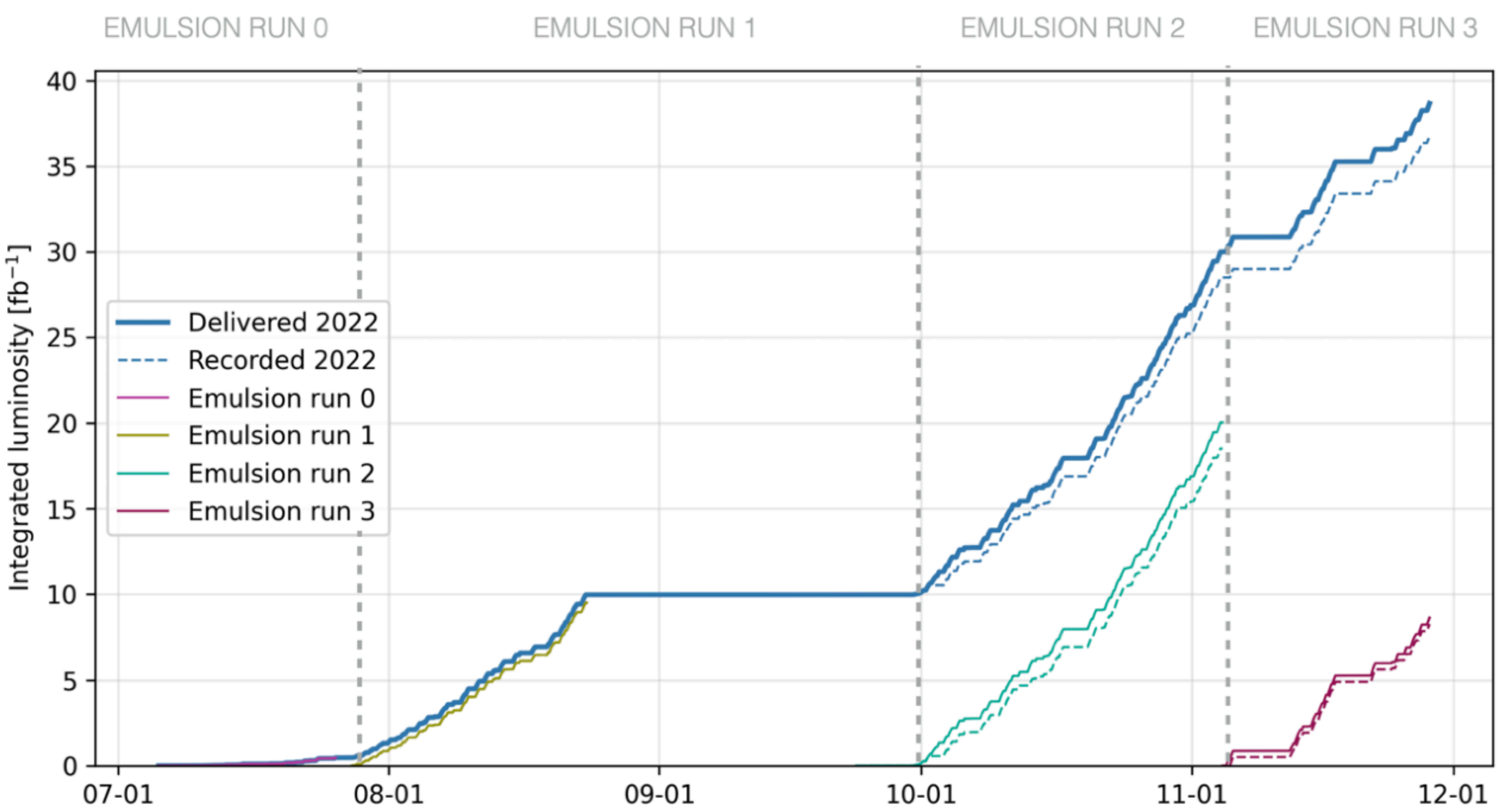
- Extract, develop, scan, and analyse emulsion data
- Reconstruct ν **primary** and **secondary vertices**
- **Match emulsion** and **electronics** reconstruction
  - Timestamp
  - Complement EM energy measurement



Discriminate between $\nu_{\mu,e,\tau}$ flavours

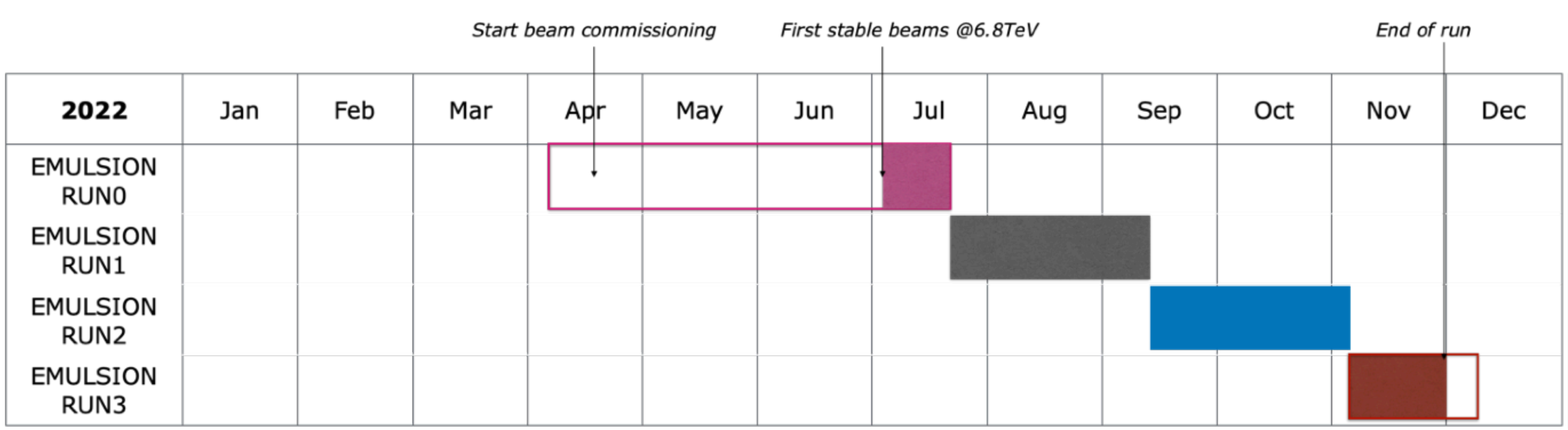


Overview of the 2022 Data-Taking



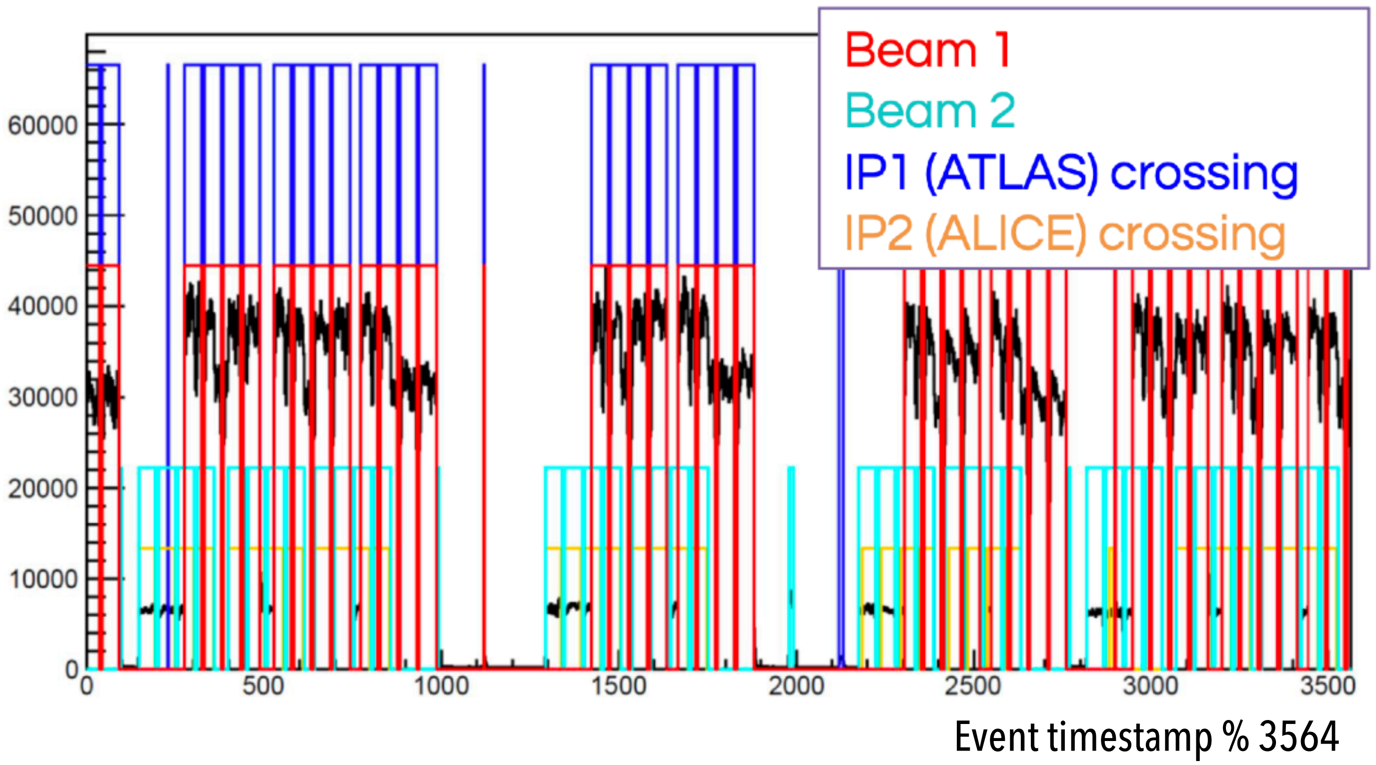
- **Delivered lumi. (IP1):** 38.7 fb^{-1}
- **Recorded lumi.:** 36.8 fb^{-1} ⇠ **95%**
- **4 emulsion runs**

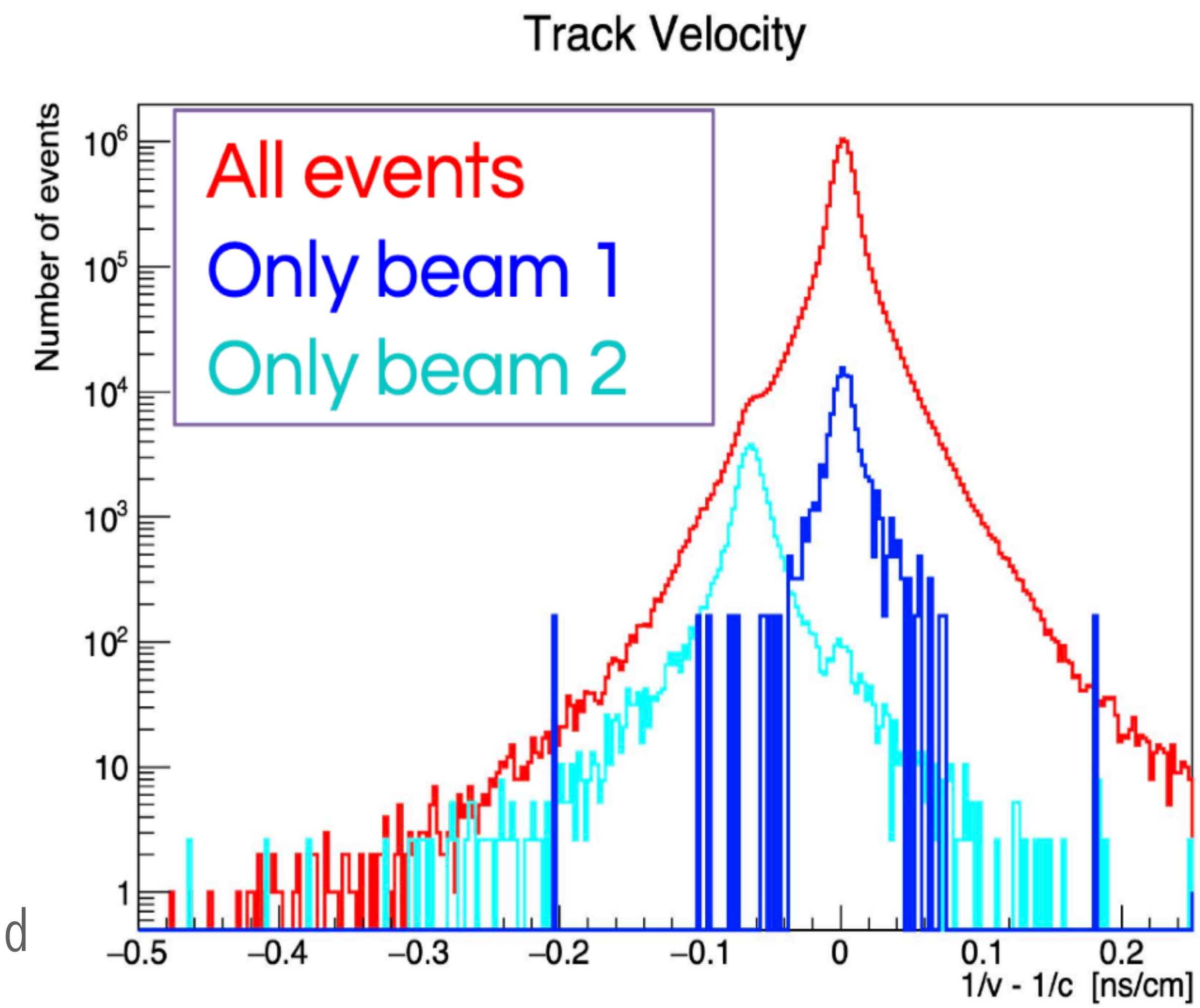
Emulsions replaced three times over the 2022 run



INSTRUMENTED TARGET MASS	INTEGRATED LUMINOSITY
39 kg	0.46 fb^{-1}
807 kg	9.5 fb^{-1}
784 kg	20.0 fb^{-1}
792 kg	8.6 fb^{-1}

Performance studies with Run3 data (highlights)



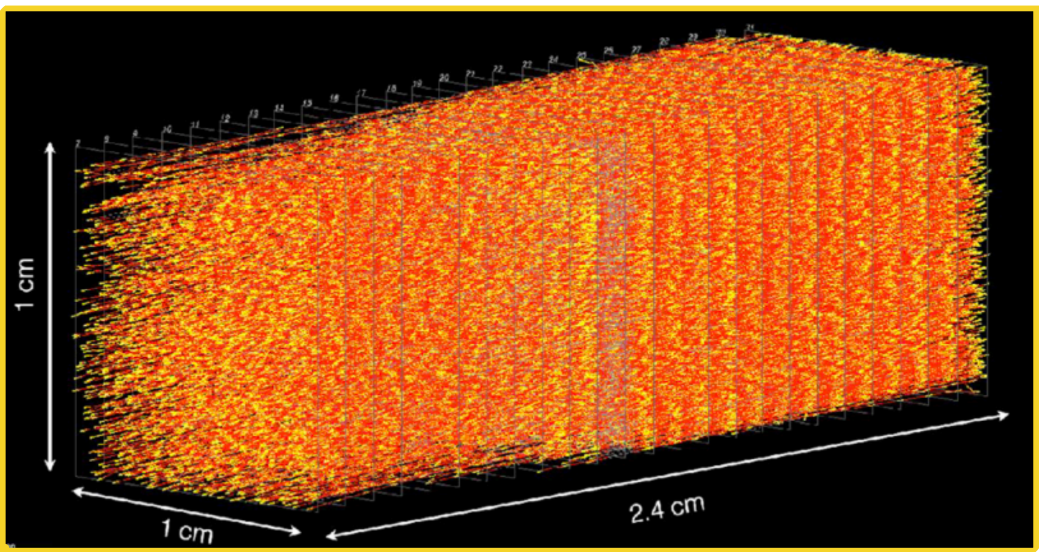


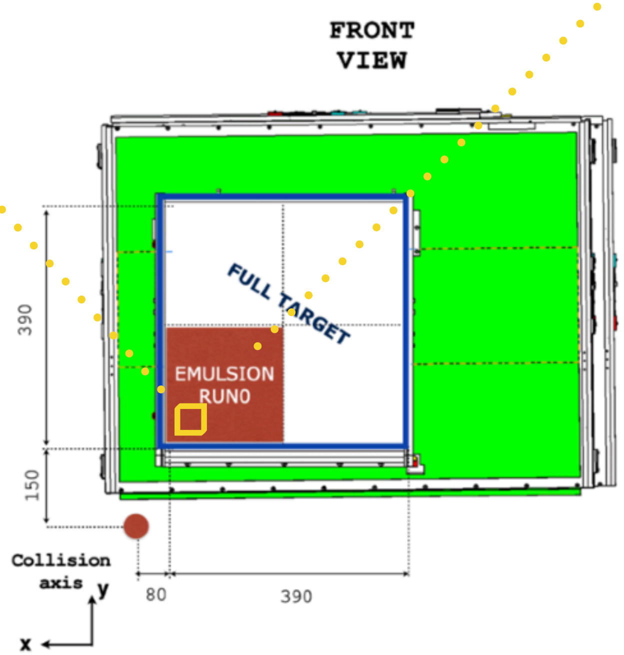
- **Event rates** were mapped to the LHC filling scheme
  - Study non-colliding bunches to asses non-collision background
- **Results: beam 1 background < 1.0%** – **beam 2 background < 1.5%**
- Can clearly **tag events entering from the downstream detector end**

Performance studies with Run3 data (highlights)

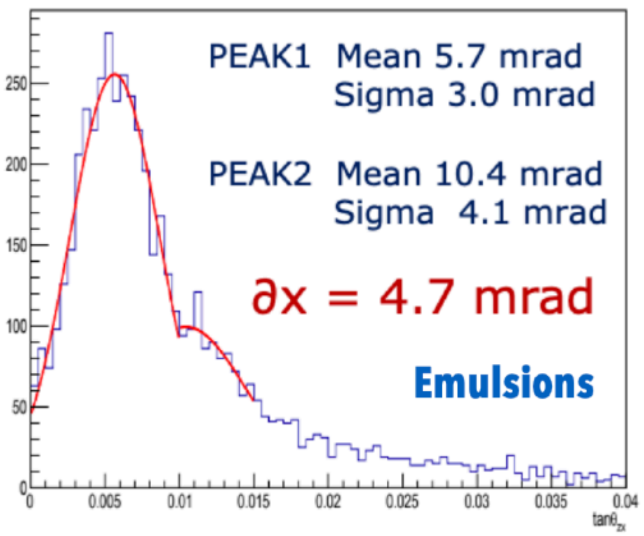
2022 data also used to **study detector performance** and **measure muon flux**

Emulsion tacks: 1 cm^2 x-y section – RUN0 (0.5 fb^{-1})

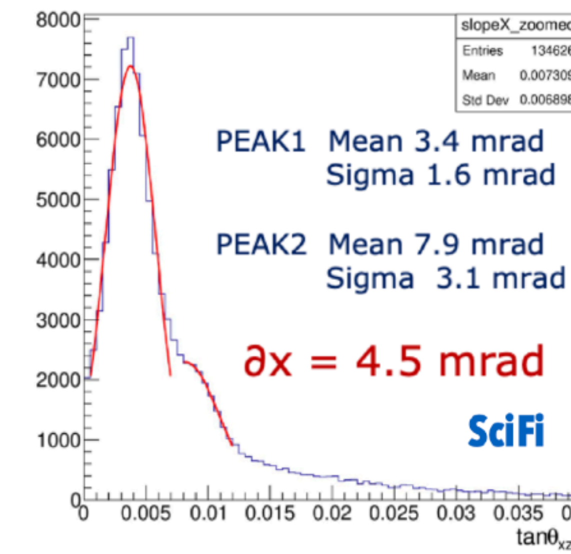




SND@LHC Preliminary



SND@LHC Preliminary



Comparison of **Emulsions/SciFi distributions** with early data **in good agreement**, preliminary flux measurement agree within 10%

- Input to **target replacement strategy definition**

SND@LHC Preliminary

Refined muon flux studies performed with later 2022 data:

- Using data from **SciFi** and **Muon system**
- Accounting for higher order corrections (e.g. efficiency)
  - SciFi: ***2.06 · 10^4 cm^{-2} / fb^{-1}***
  - Muon system: ***2.35 · 10^4 cm^{-2} / fb^{-1}***
  - Data/MC disagreement **~20 - 25%**

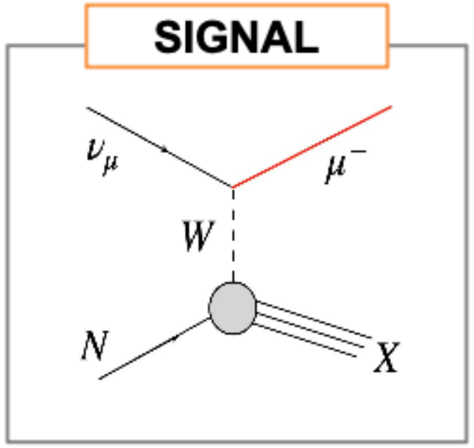
Observation of ν_μ using electronic detectors

arXiv 2305.09383

Dataset: full 2022 run, **36.8 fb^{-1}**

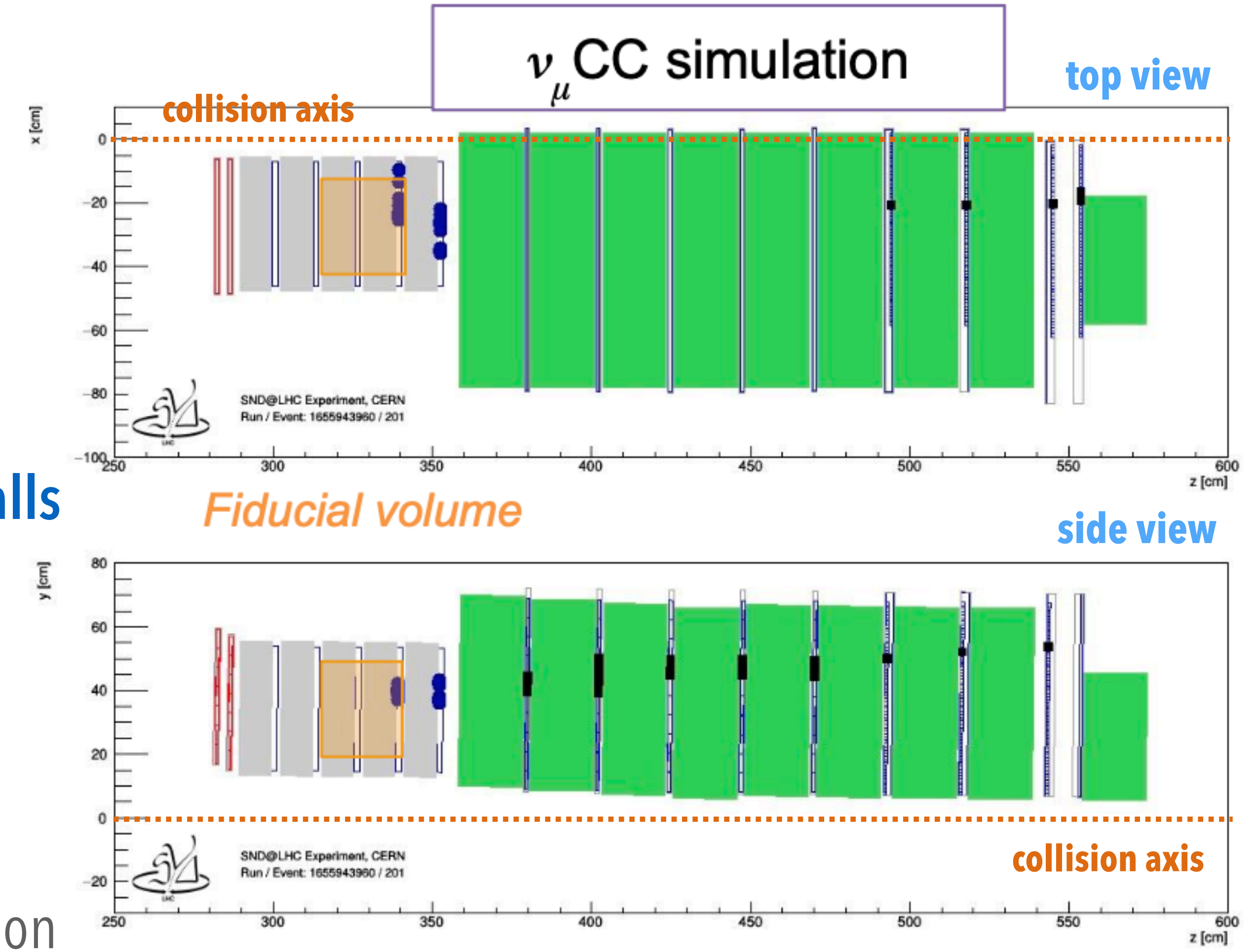
Analysis strategy

- Look for ν_μ **charged current interaction** (CC) events
- **Maximise S/B**, counting-based approach
- **Challenge**
  - must reach negligible background out of **~10^9 μ events**
  - apply cuts with **strong rejection power**

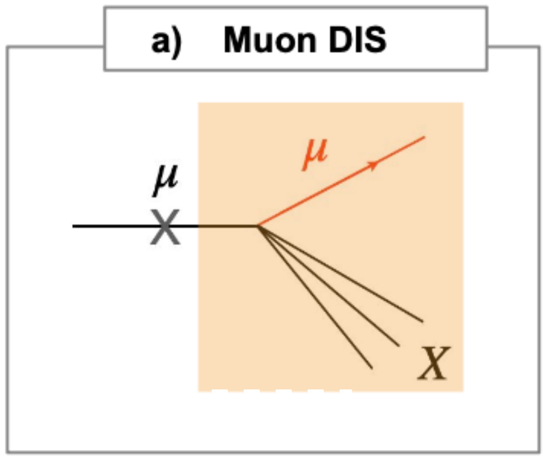


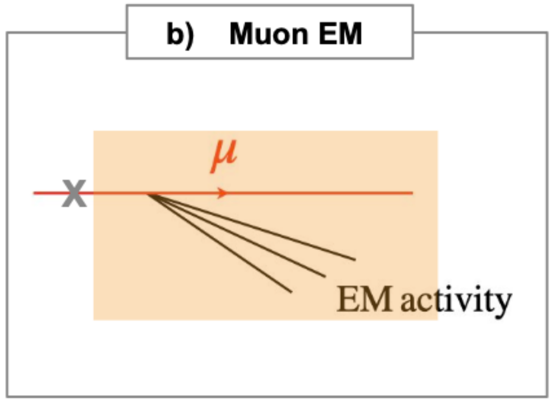
Signal selection

- **Fiducial volume cuts**
  - require **neutral vertex** event from the **3rd or 4th target walls**
  - select **x-y fiducial area** (25 x 26 cm^2) to reject background entering from edges
- **Neutrino ID**
  - require **large hadronic activity in SciFi and HCAL**
  - **timing compatible with upstream event** from IP1 collision
  - **reconstructed** and **isolated muon track** (muon system)



Background estimation





Muon-induced background

"undetected" muons

(~2.1·10 ^{4} cm $^{-2}$ fb × 36.8 fb $^{-1}$ × 650 cm $^{-2}$)

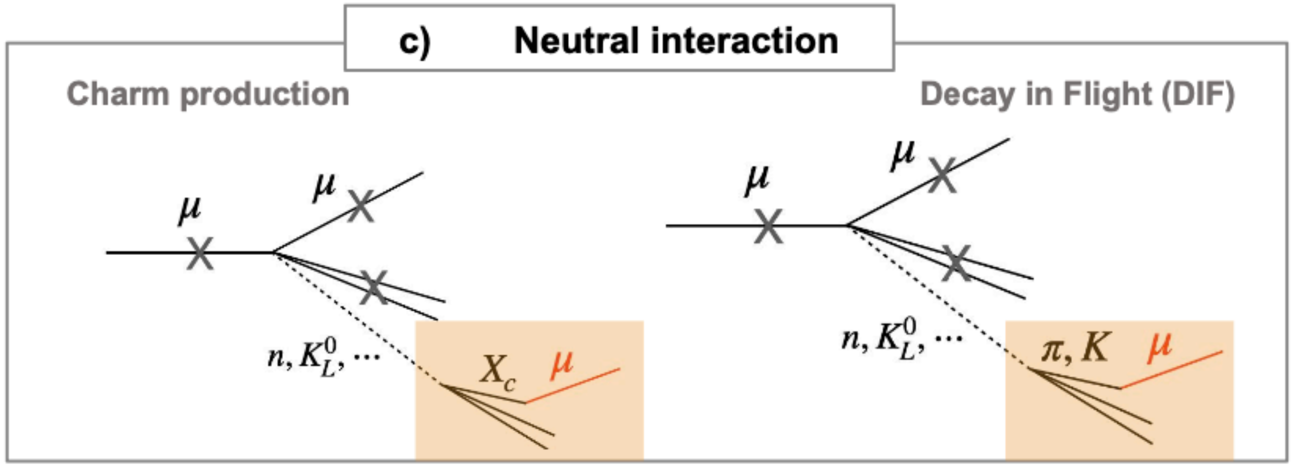
5.0×10 ^{8}

~5.3×10 $^{-12}$

$$N_{\mu}^{bkg} = N_{\mu} \times (1 - \epsilon_{Veto}) \times (1 - \epsilon_{SciFi1}) \times (1 - \epsilon_{SciFi2})$$ ~ 3 × 10 $^{-3}$

Veto inefficiency

SciFi inefficiency



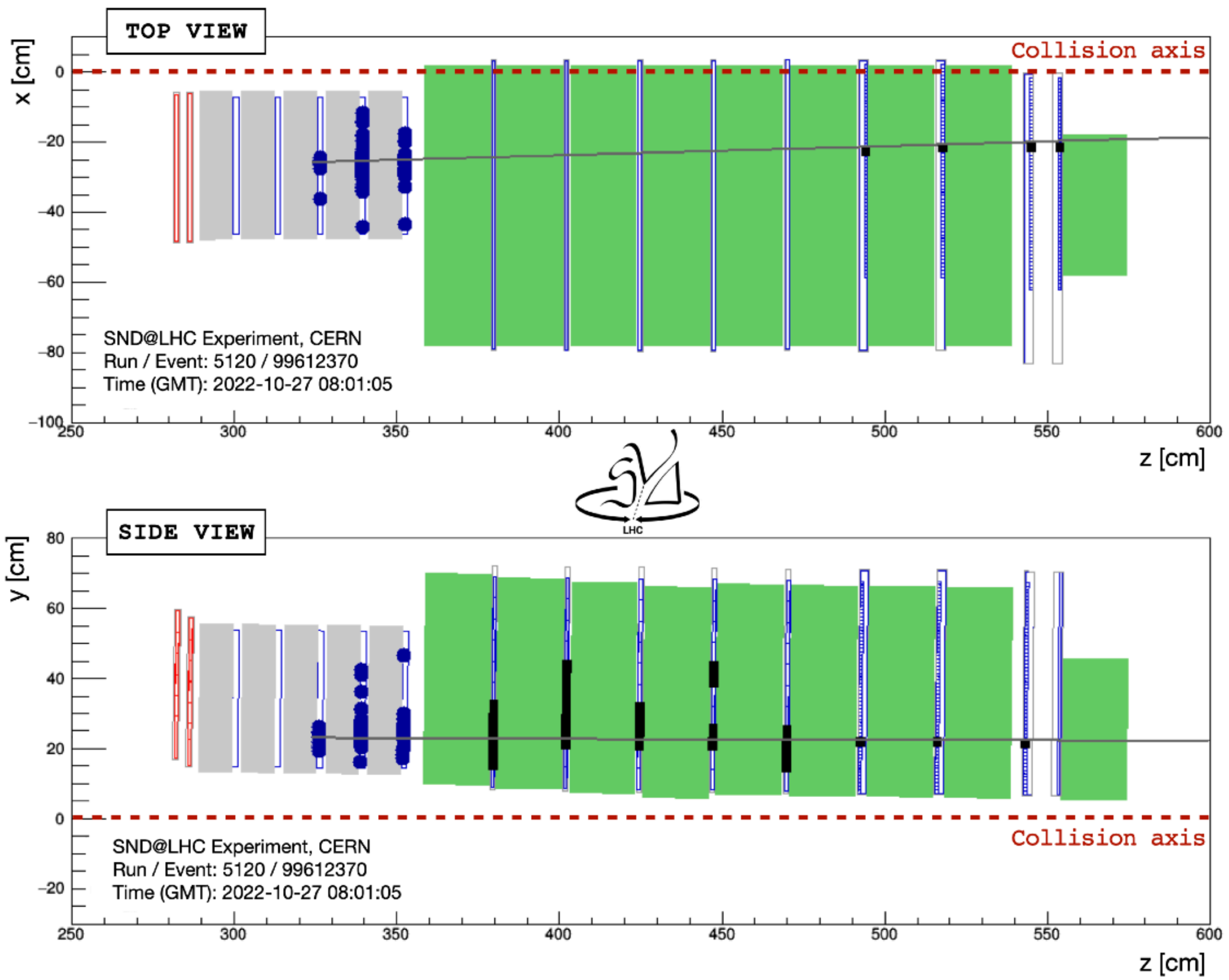
Muon-induced neutral interactions

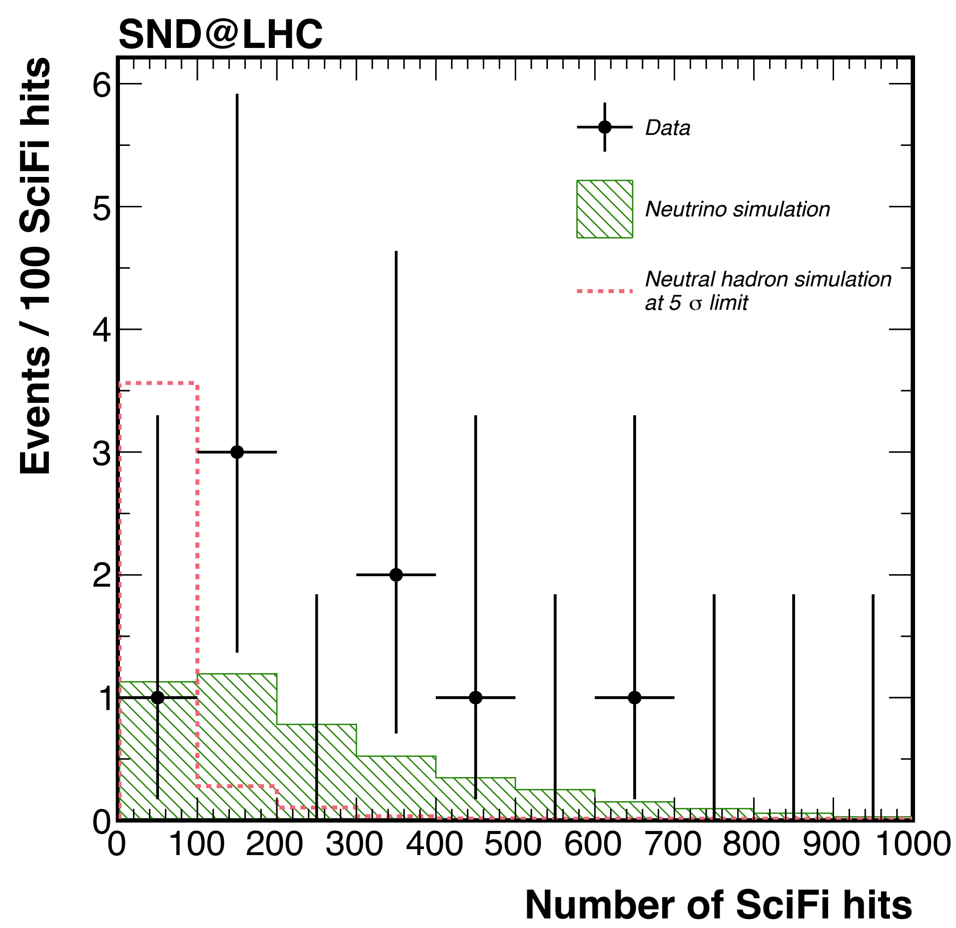
assessment of systematics ongoing

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

= (7.6 ± 3.1) × 10 $^{-2}$

Observed candidates, analysis result





- Observed **8 ν_μ** CC candidates
- Observation **significance 7.0 σ**

Summary

- **After approval** by the CERN Research Board in March 2021 the SND@LHC detector was **built** and **installed** in **TI18** ***over just a one year span***
- **Operating since the start of the LHC Run 3**, has collected 36.8 fb^{-1} **(95% uptime efficiency)**
- **Incoming muon flux** was measured using **SciFi**, **Muon system** and **Emulsions**
- **Attempted the observation of incoming ν_μ** solely **based on electronics detectors**
  - **Observed 8 ν_μ CC candidates** against an **expected background** of **$(7.6 \pm 3.1)\times10^{-2}$**
  - **Observation significance 7.0 σ**

Exciting times have started!

SND@LHC *Web Page*

Thank you!

Backup

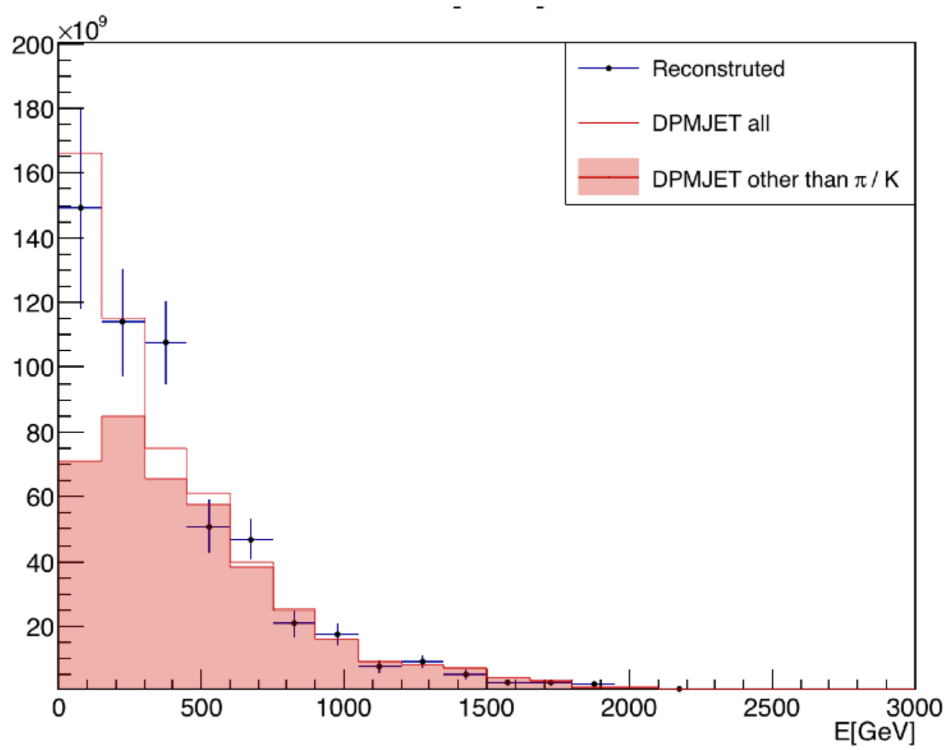
Neutrino Physics Summary - Run3

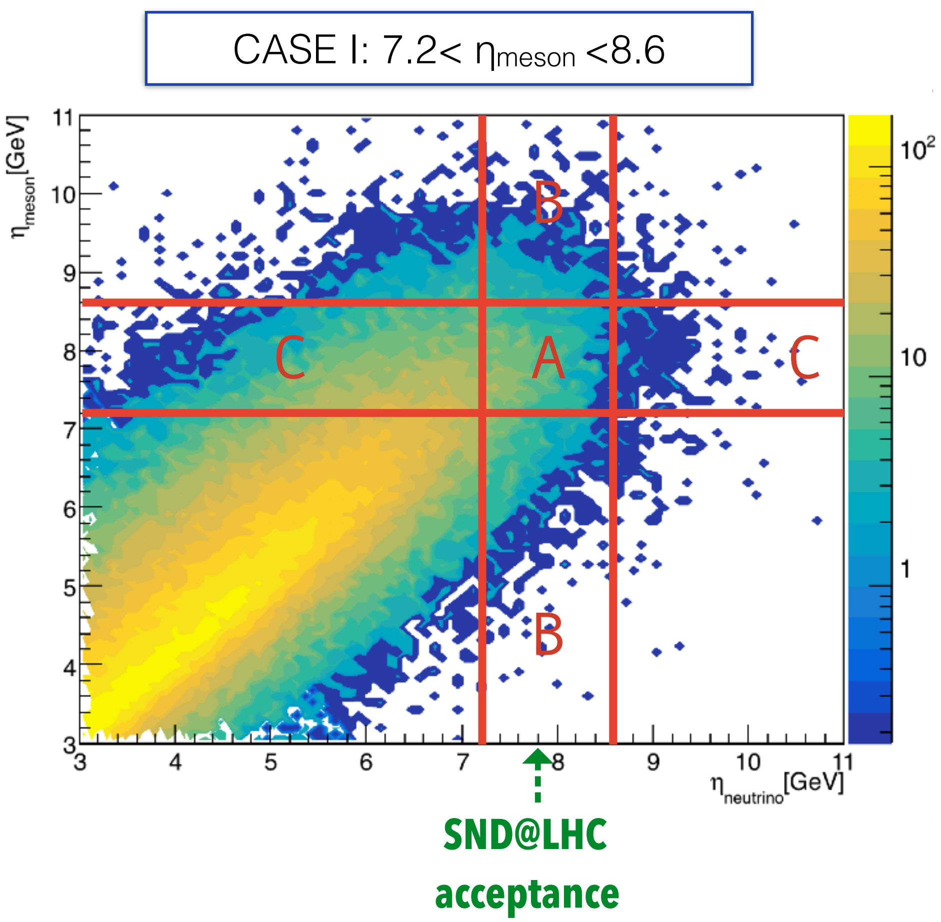
LHCC-P-016

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%

Measure of $pp \to \nu_e X$ cross-section, then charm production

LHCC-P-016





$pp \to \nu_e X$ cross section

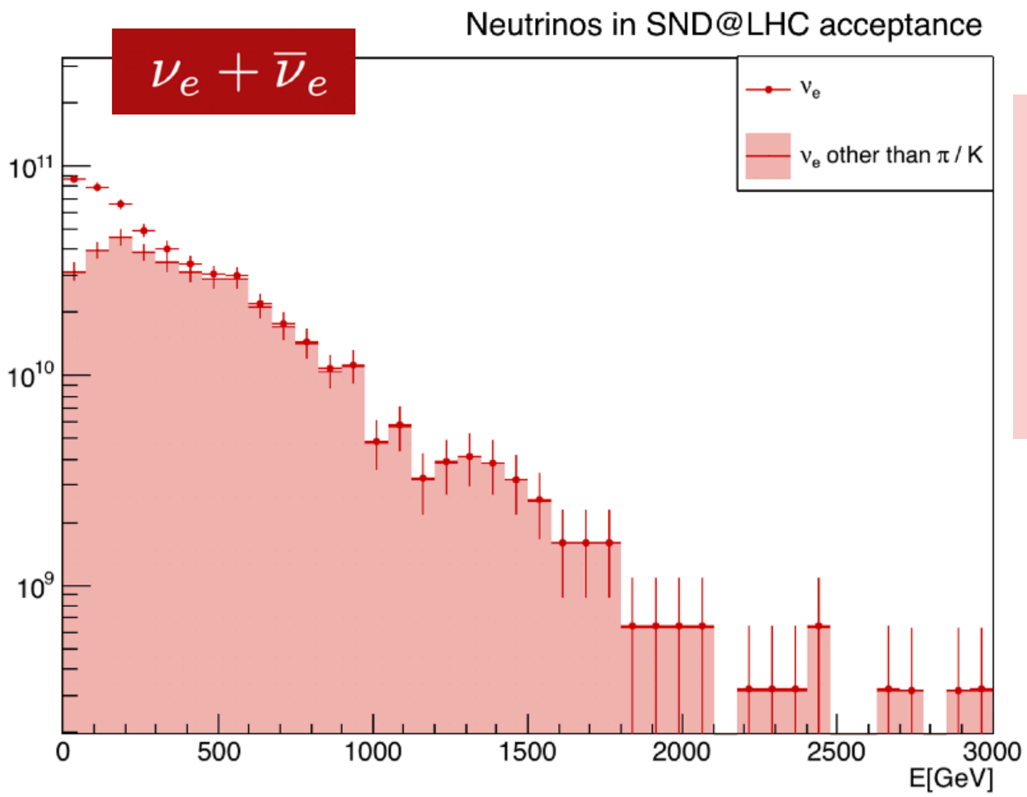
- Simulation prediction: **~90% of ν_e come from charm decays**
- Unfold detector response to get energy spectrum
- Assume SM σ_e

charm production

- Apply statistical subtraction of π/K component to the above result
- Exploit correlation between neutrino and parent hadron
- Use different generators to assess systematics

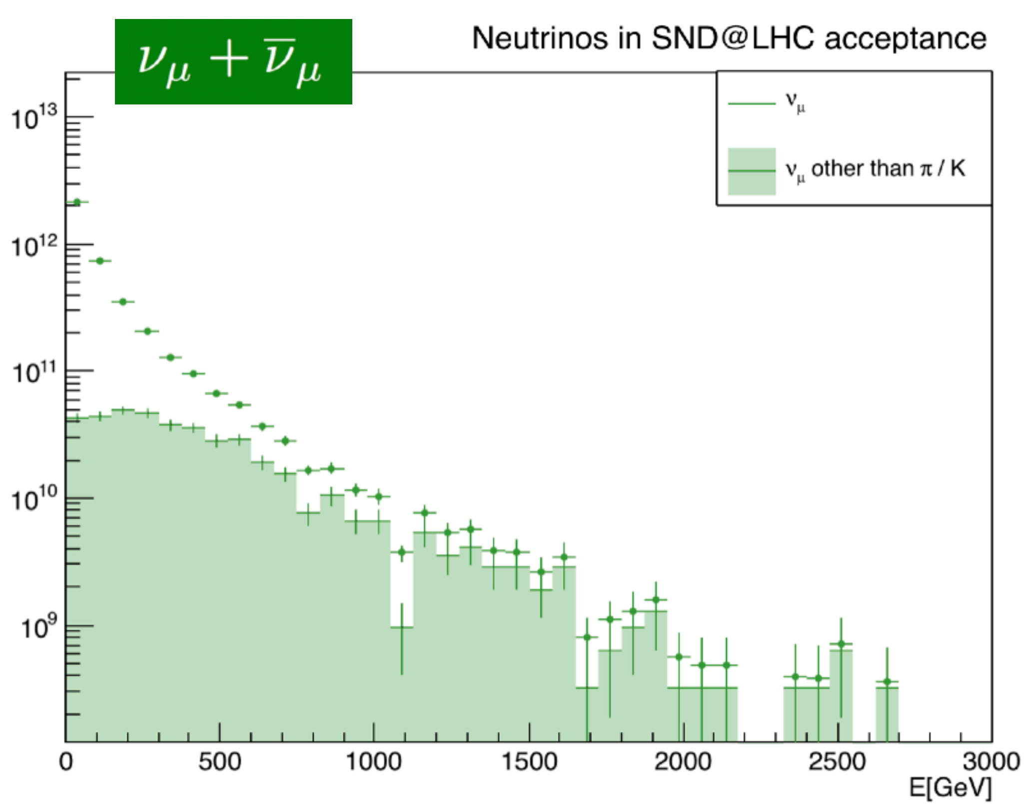
Lepton Flavour Universality Test

LHCC-P-016



- ν_τ essentially only coming from D_s decays
- ν_e coming from decay of all charmed hadrons (essentially D_0, D, D_s, Λ_c)
- R_{13} only depends only on charm hadronisation fractions and Brs

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



- ν_μ produced also in decays of π/K
  - Above 600 GeV, ~flat contamination around 35%
- Decay modes are essentially the same
  - negligible systematic from Brs and charm hadronisation

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

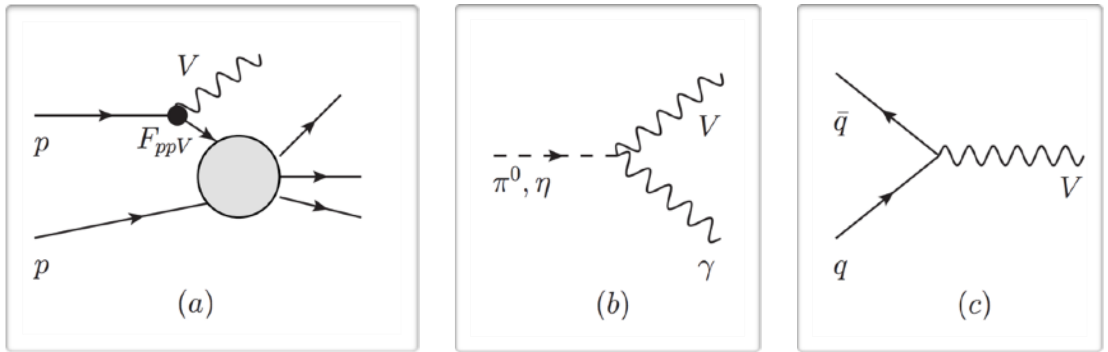
contamination from π/k

Feebly interacting particles (example)

JHEP03 (2022) 006

Production example: a scalar χ particle coupled to the SM via a leptophobic portal:

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

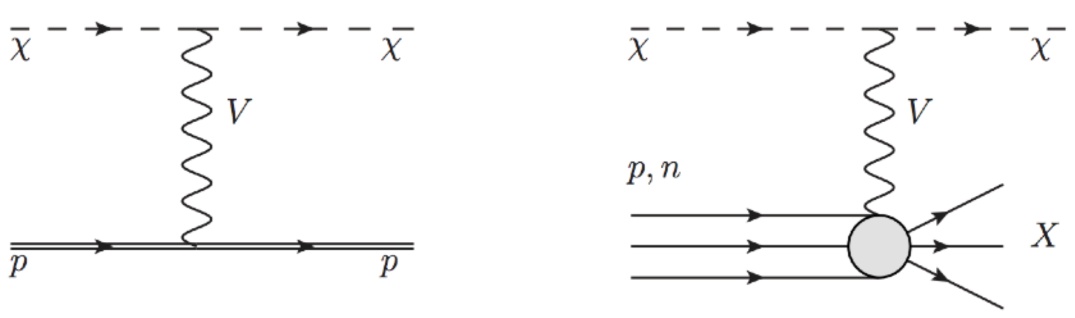


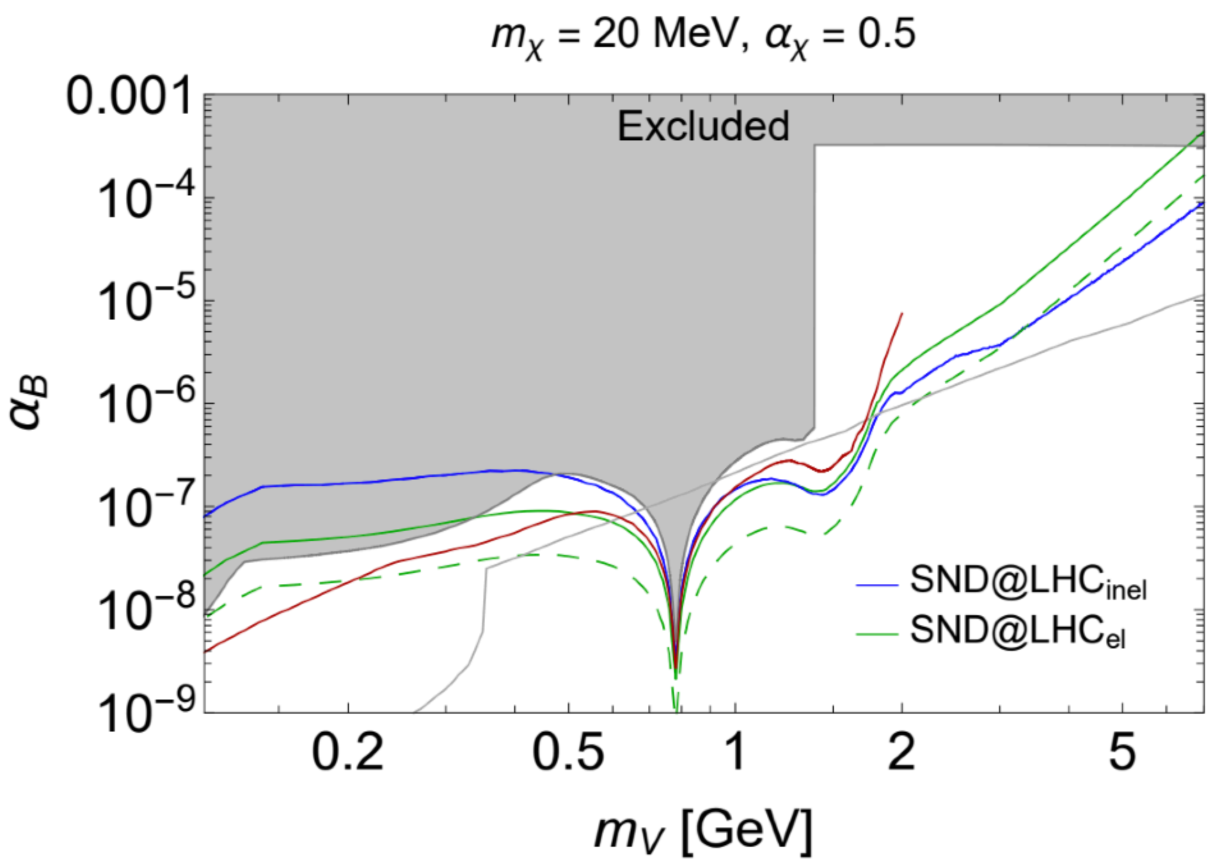
Proton bremsstrahlung

Meson decay

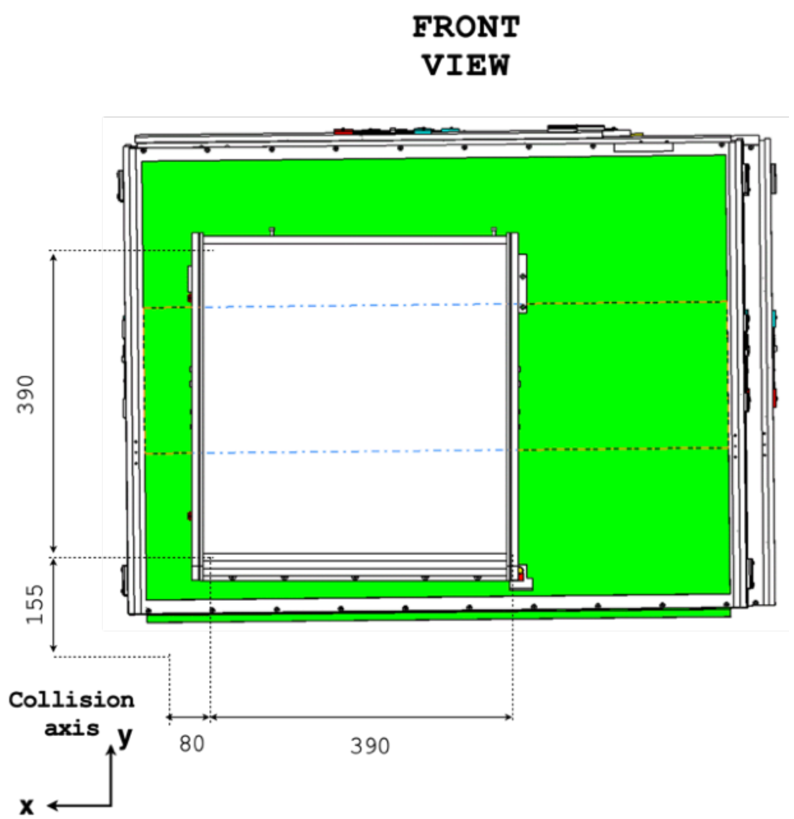
Drell-Yan

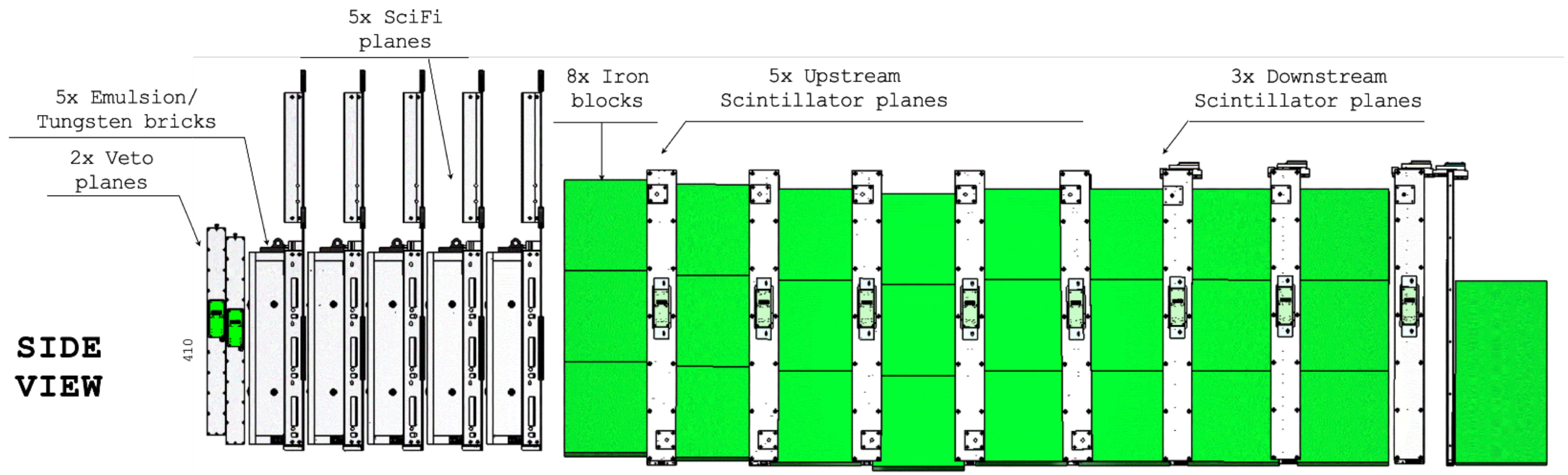
Detection: χ elastic/inelastic scattering off nucleons of the target





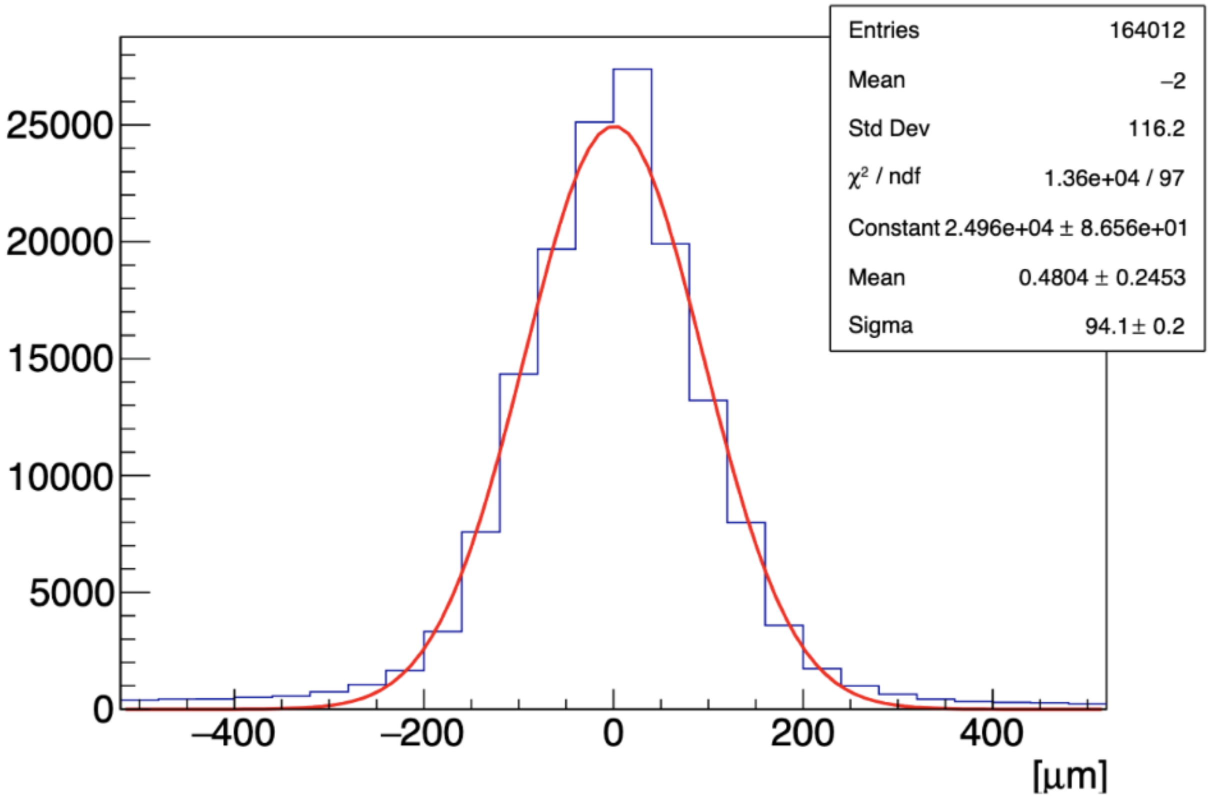
SND@LHC: Detector Layout (additional details)





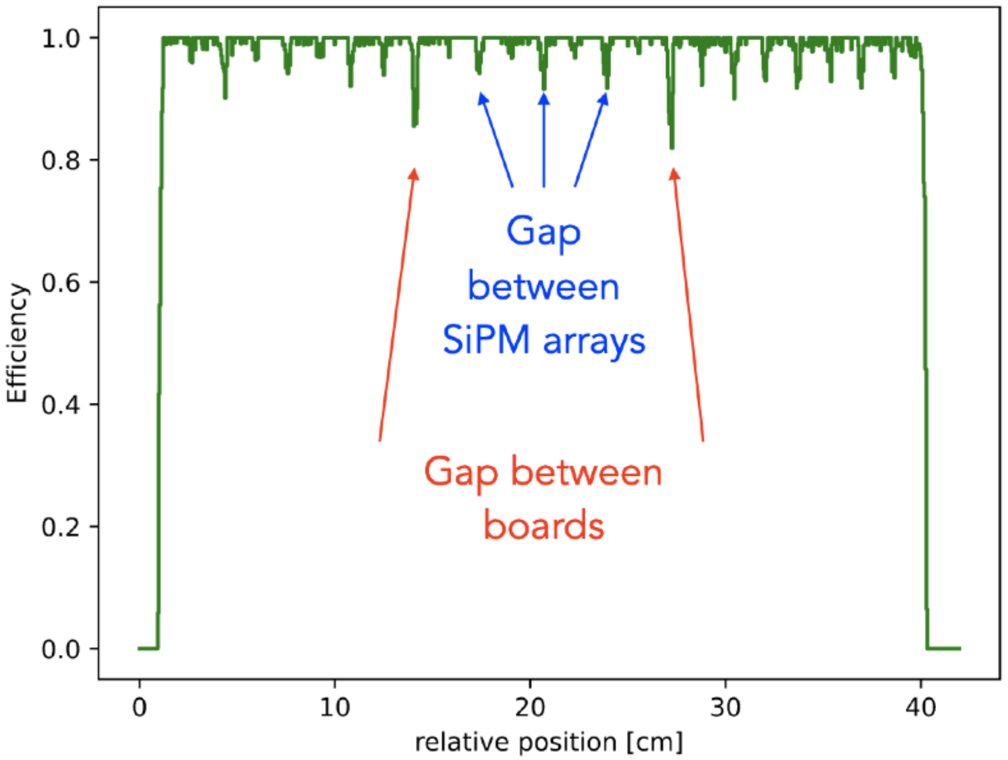
Further SciFi Performance studies

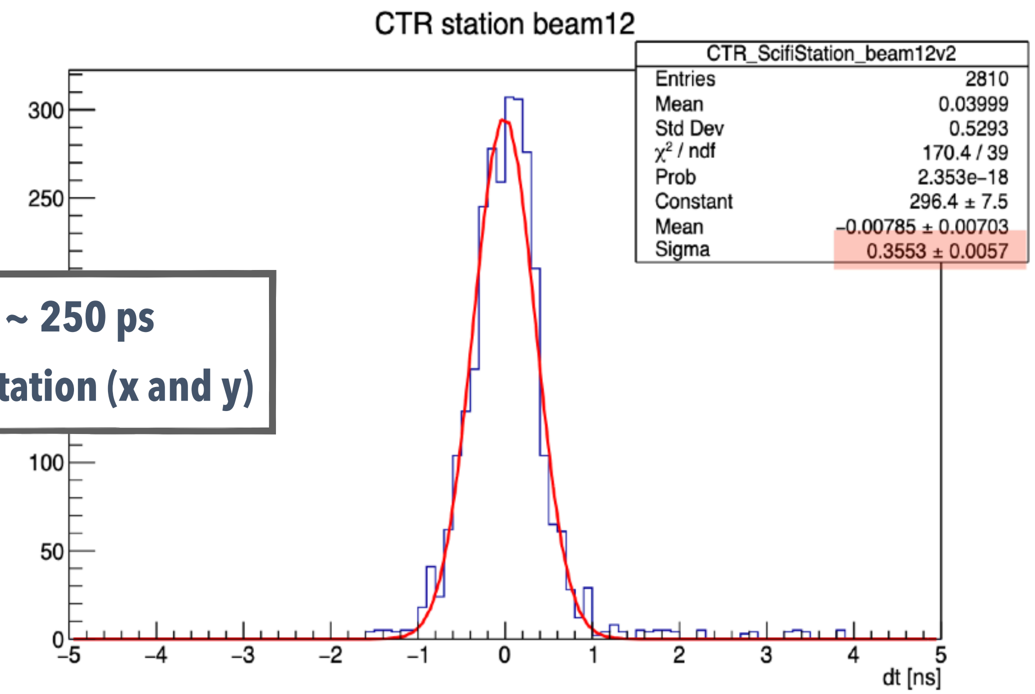
Muon test beam data



Measured without any material between stations

Run 3 **SND@LHC Preliminary**



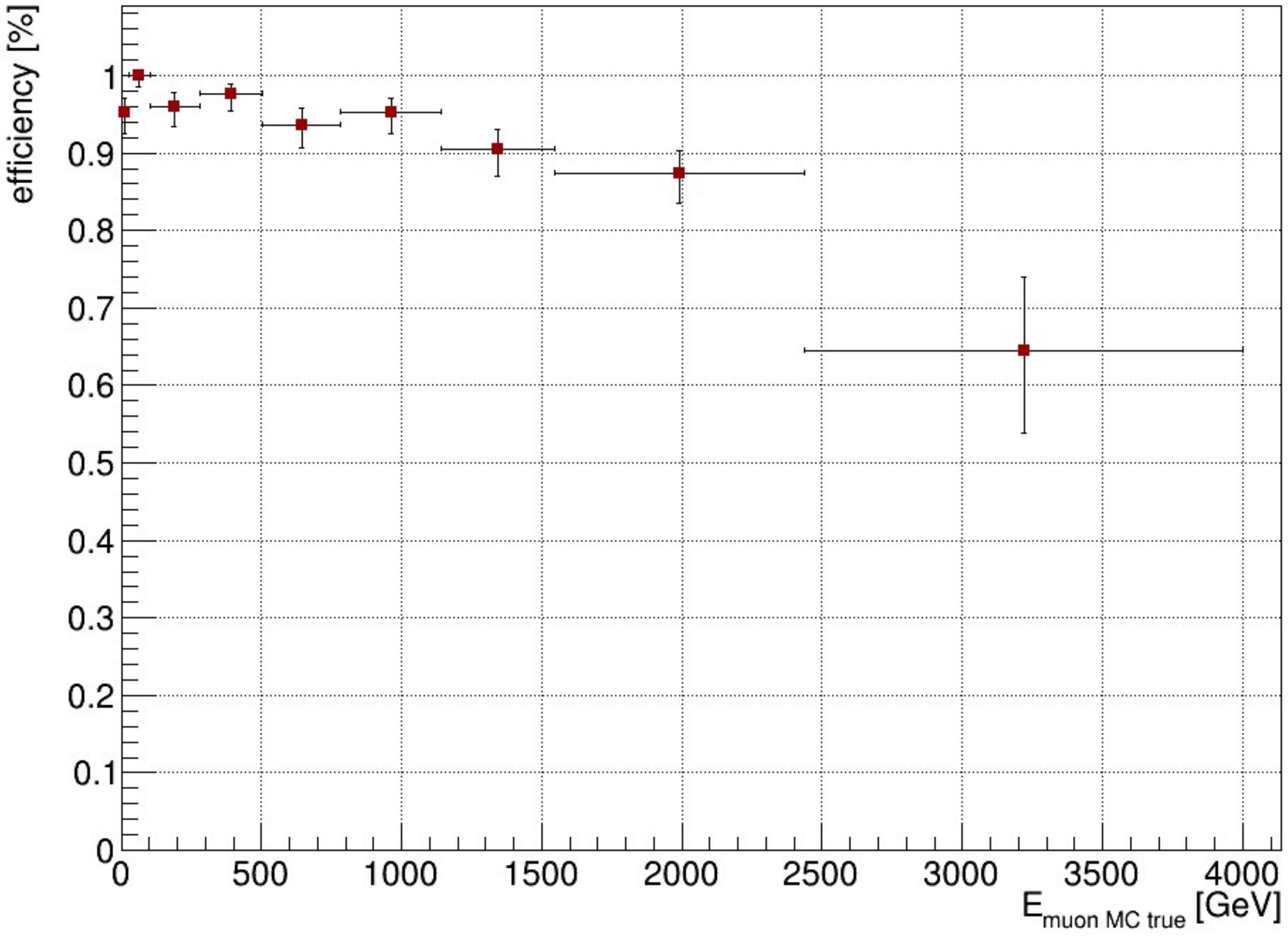


σ_t ~ 250 ps
single-station (x and y)

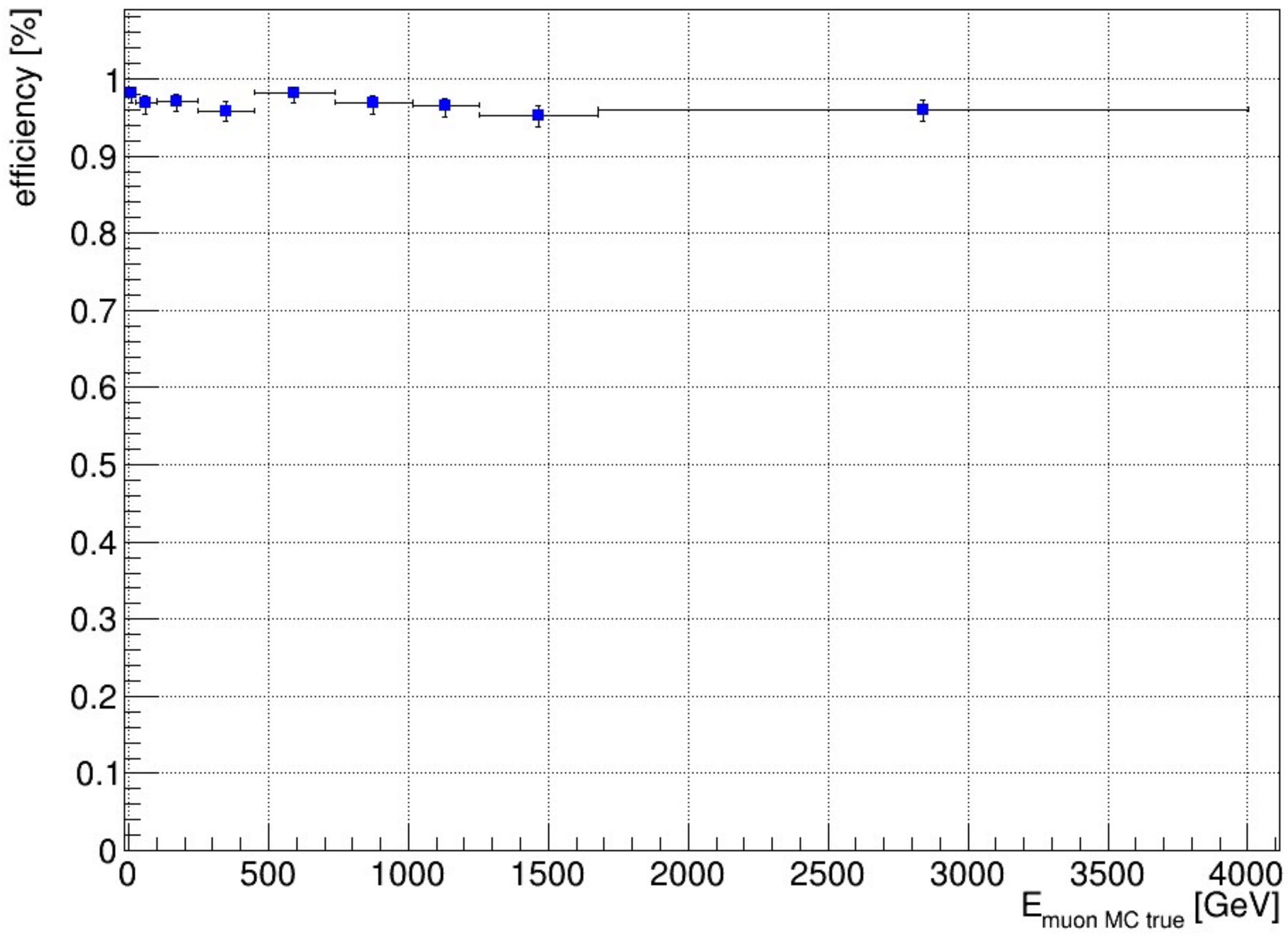
Muon tracking efficiency

SND@LHC Preliminary

SciFi + Simple tracking



Muon system + Hough transform



SND@LHC at HL-LHC

Upgrade of SND@LHC in view of an extended run during Run 4:

- Extension of the physics case
- New technologies and detector layout
- Two detectors

  AdvSND-Far (7.2< <8.4)

  possible locations: TI18, Future Forward Facility

  AdvSND-Near (4< <5)

  possible locations: existing caverns close to IPFiducial volume cuts