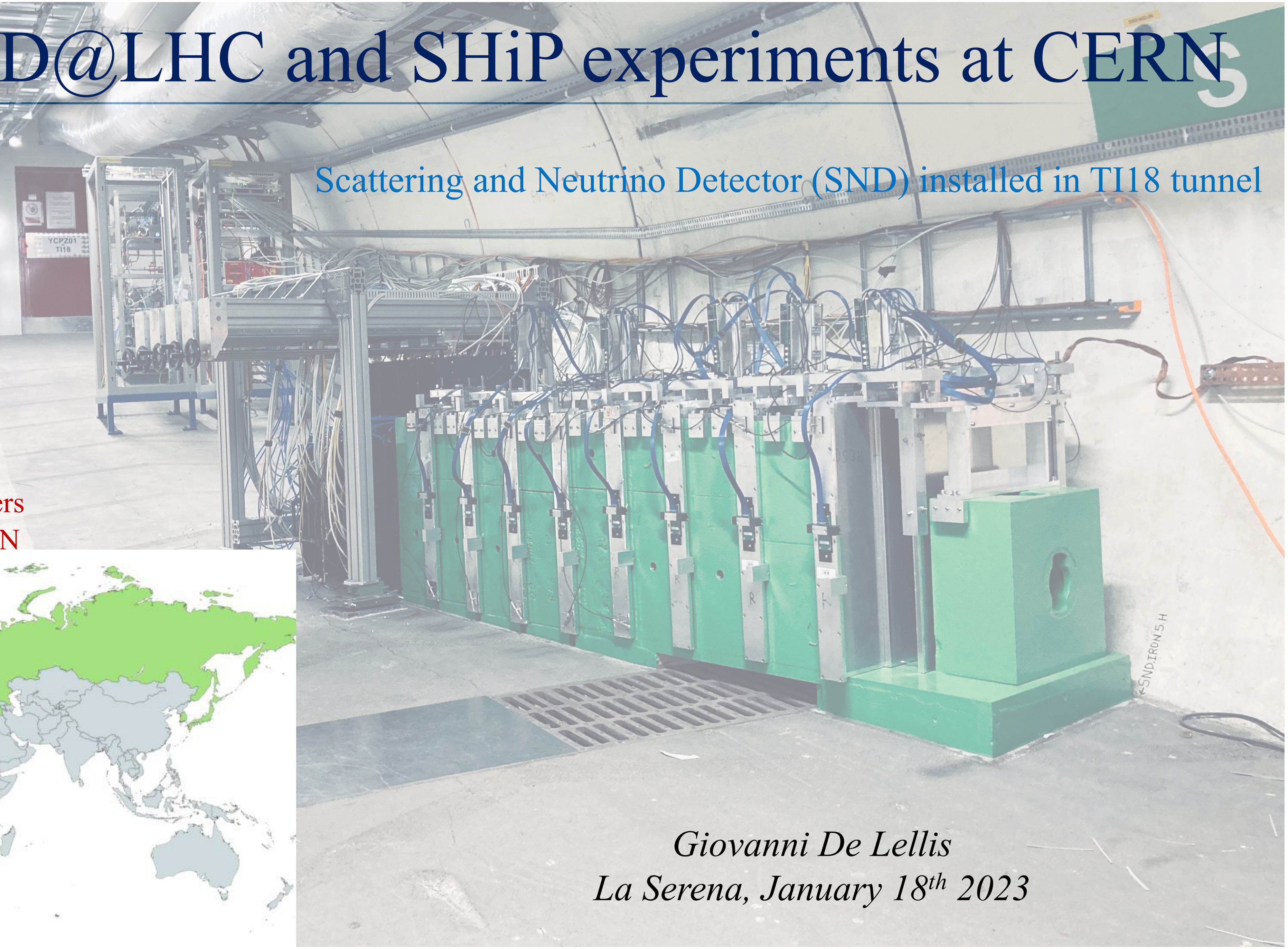
The SND@LHC and SHiP experiments at CERN

Scattering and Neutrino Detector (SND) installed in TI18 tunnel



LHC
Scattering and Neutrino Detector at the LHC

SND@LHC Collaboration: 180 members
22 Institutes in 13 Countries and CERN

Giovanni De Lellis

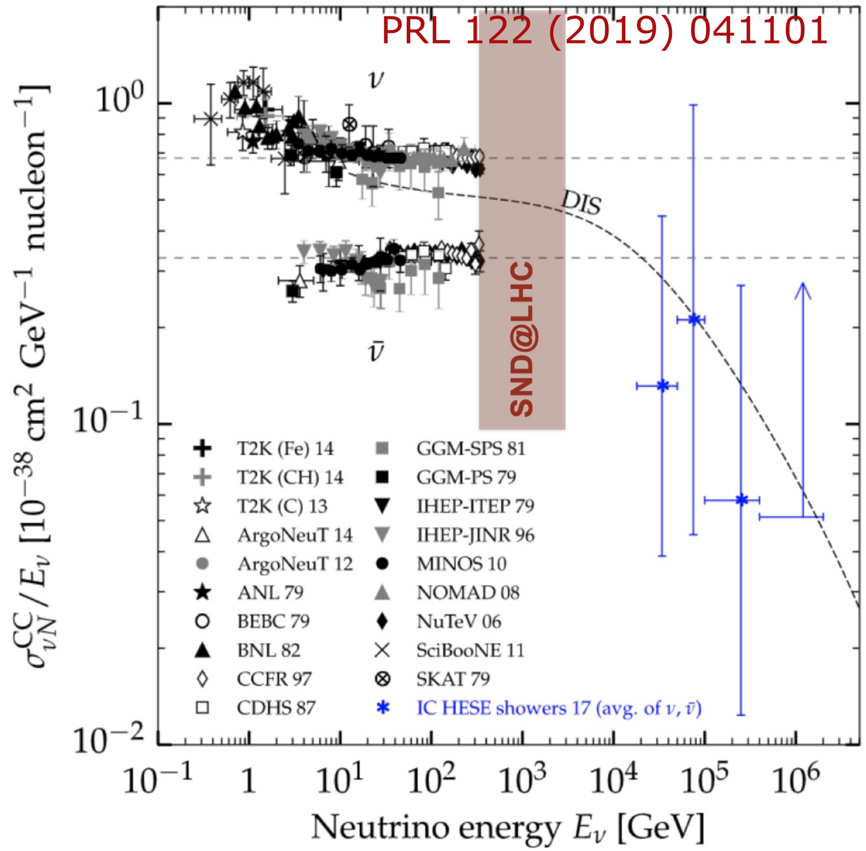
La Serena, January 18th 2023

MOTIVATION

Neutrino physics at the LHC

- A. De Rujula and R. Ruckl. 1984, Neutrino and muon physics in the collider mode of future accelerators
- Klaus Winter, 1990, observing tau neutrinos at the LHC
- A. De Rùjula, E. Fernandez and J. J. Gòmez-Cadenas, 1993, Neutrino fluxes at LHC
- http://arxiv.org/abs/1804.04413 April 12th 2018, First paper on feasibility of studying neutrinos at LHC

LHC
Scattering and Neutrino Detector 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

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]

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

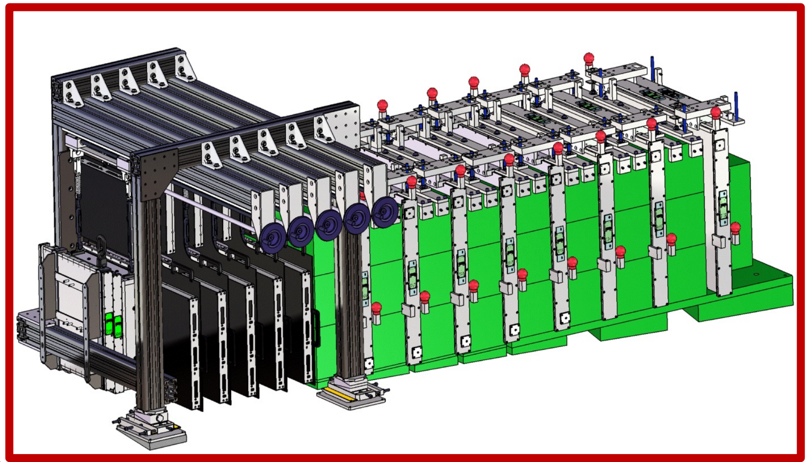
To cite this article: N Beni *et al* 2020 *J. Phys. G: Nucl. Part. Phys.* **47** 125004

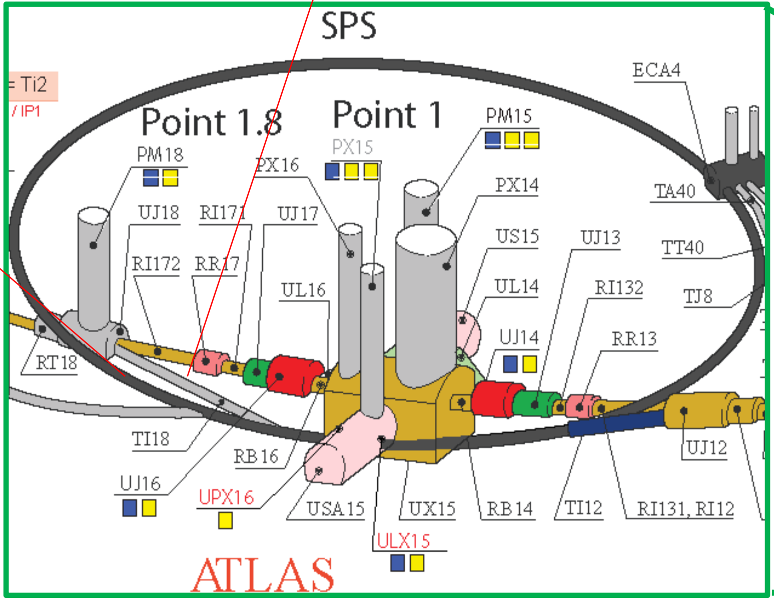
CERN is unique in providing energetic **ν** (from LHC) and measure pp → **ν**X in an unexplored domain

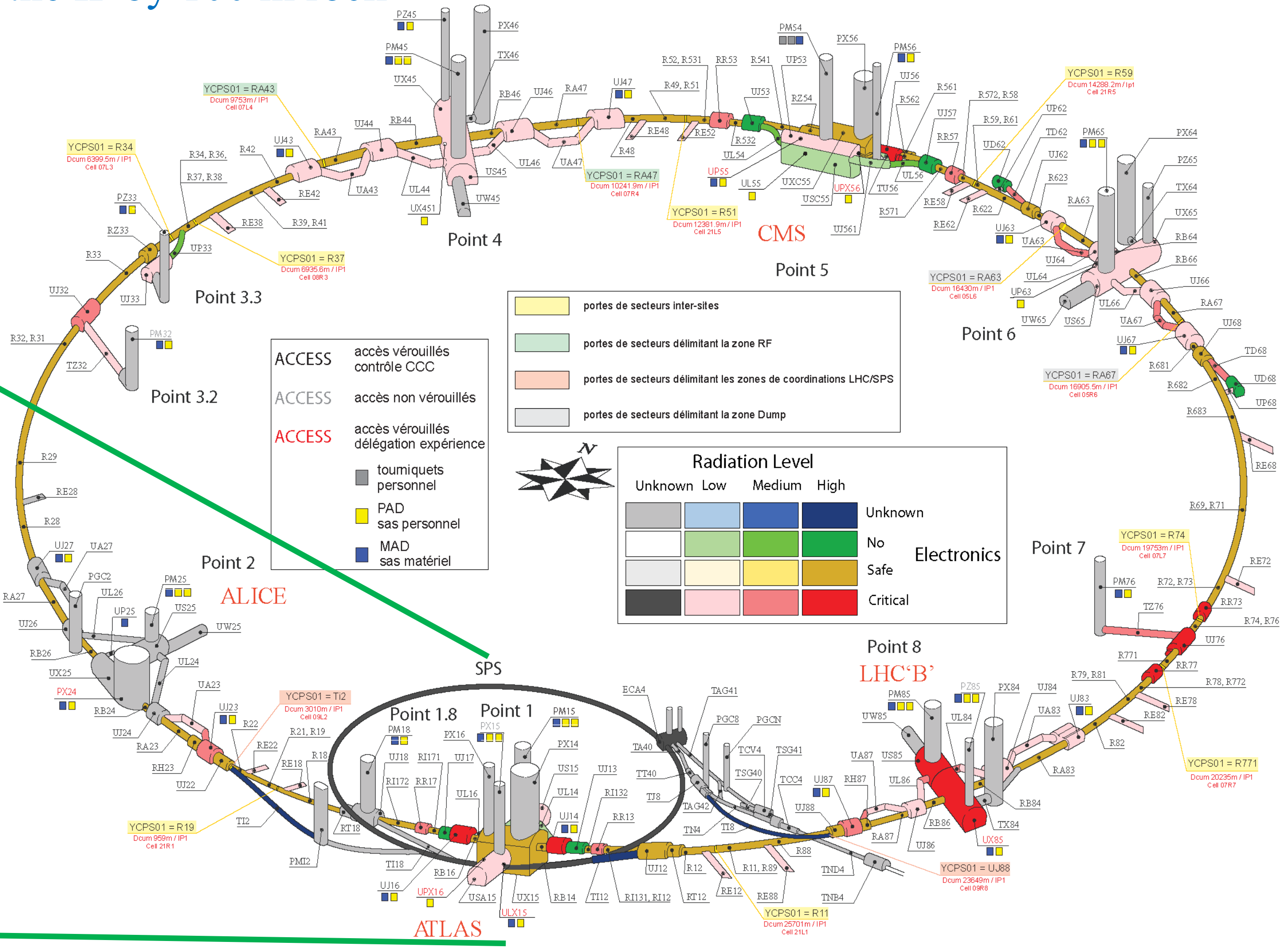
Location: TI18, transfer tunnel connecting SPS to LEP

Scattering and Neutrino Detector at the LHC

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







Experiment concept

Hybrid detector optimised for the identification of all three neutrino flavours

LHC
Scattering and Neutrino Detector at the LHC

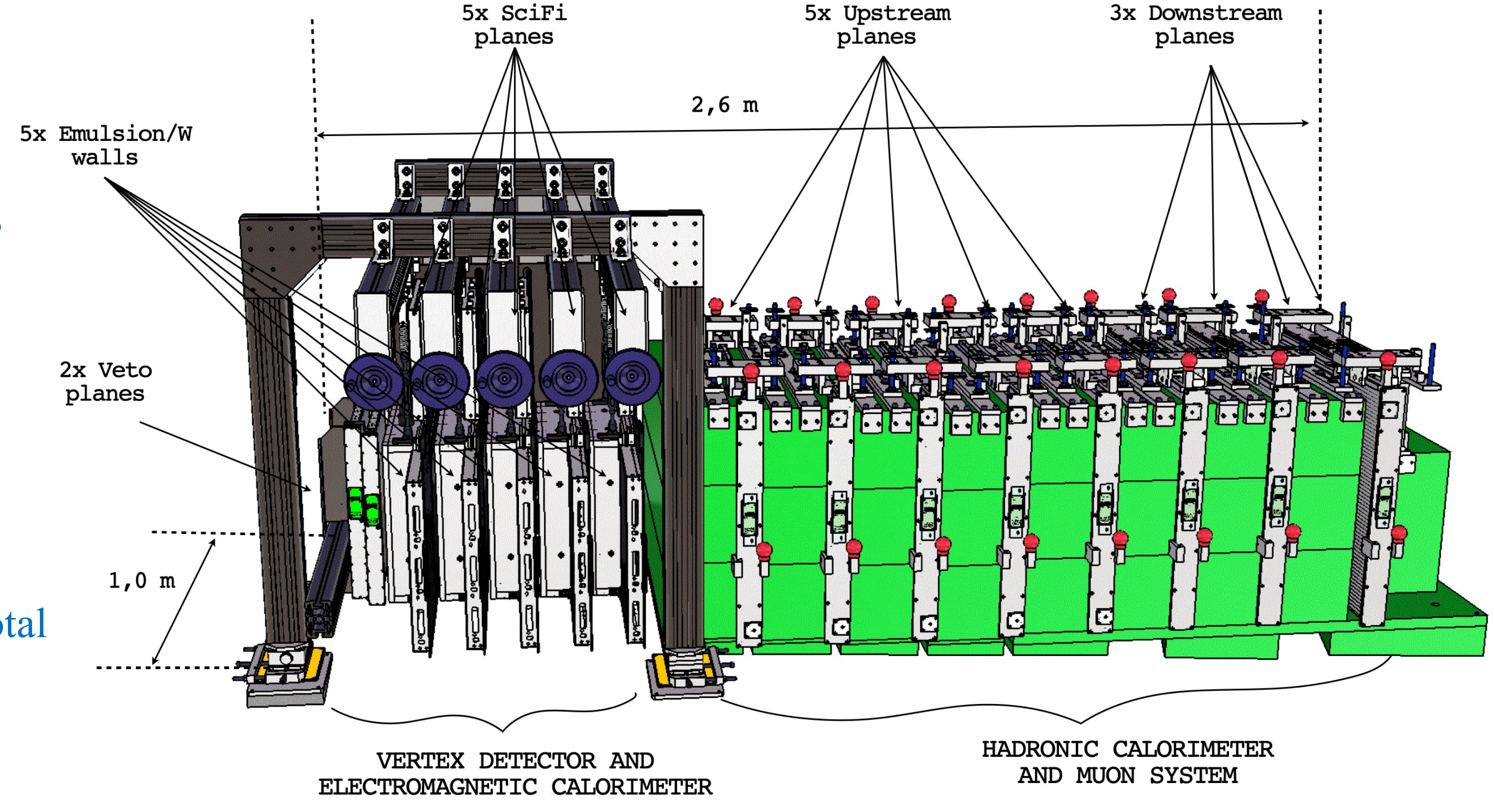
VETO PLANE:
tag penetrating muons

NEUTRINO TARGET & VERTEX DETECTOR:
Emulsion cloud chambers (60 emulsion films, 300μm thick, interleaved by 1mm thick tungsten plates)

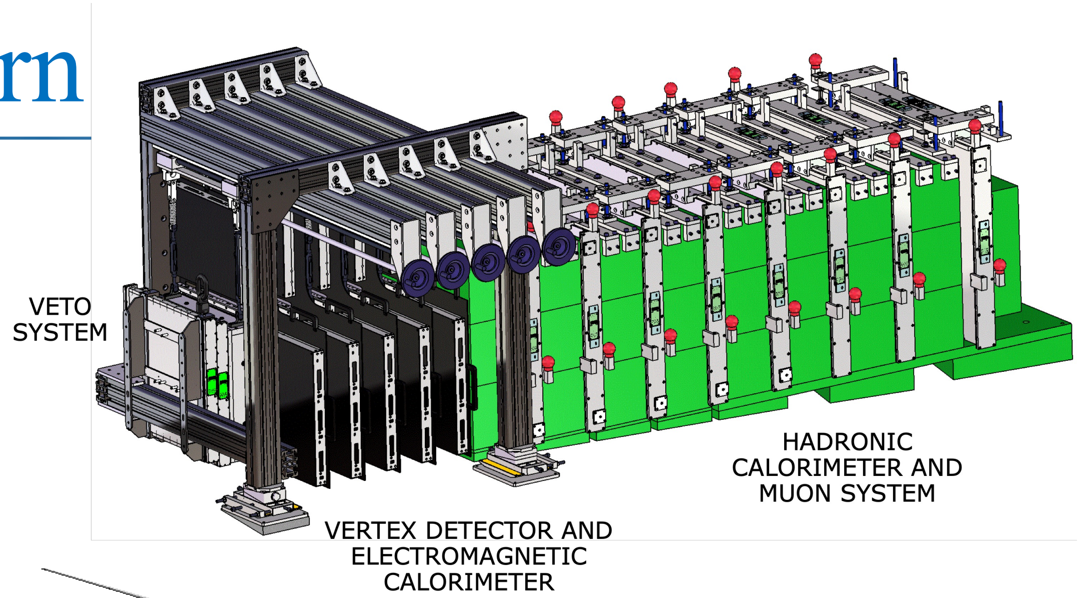
E.M. CAL
250μm Scintillating fibres for timing information and e.m. energy measurement in combination with emulsion

HADRONIC CALO:
iron walls interleaved with plastic scintillator planes for a total of about 11 λ

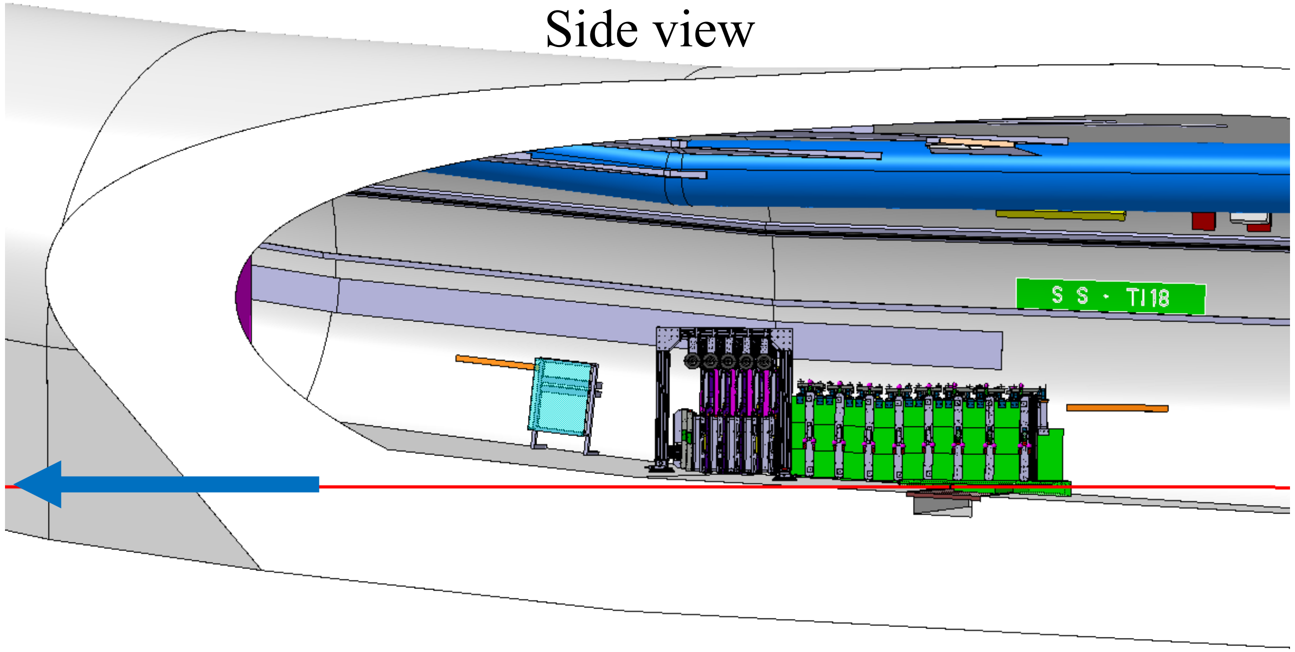
MUON IDENTIFICATION SYSTEM:
3 most downstream plastic scintillator stations based on fine-grained bars, meant for the muon identification and tracking



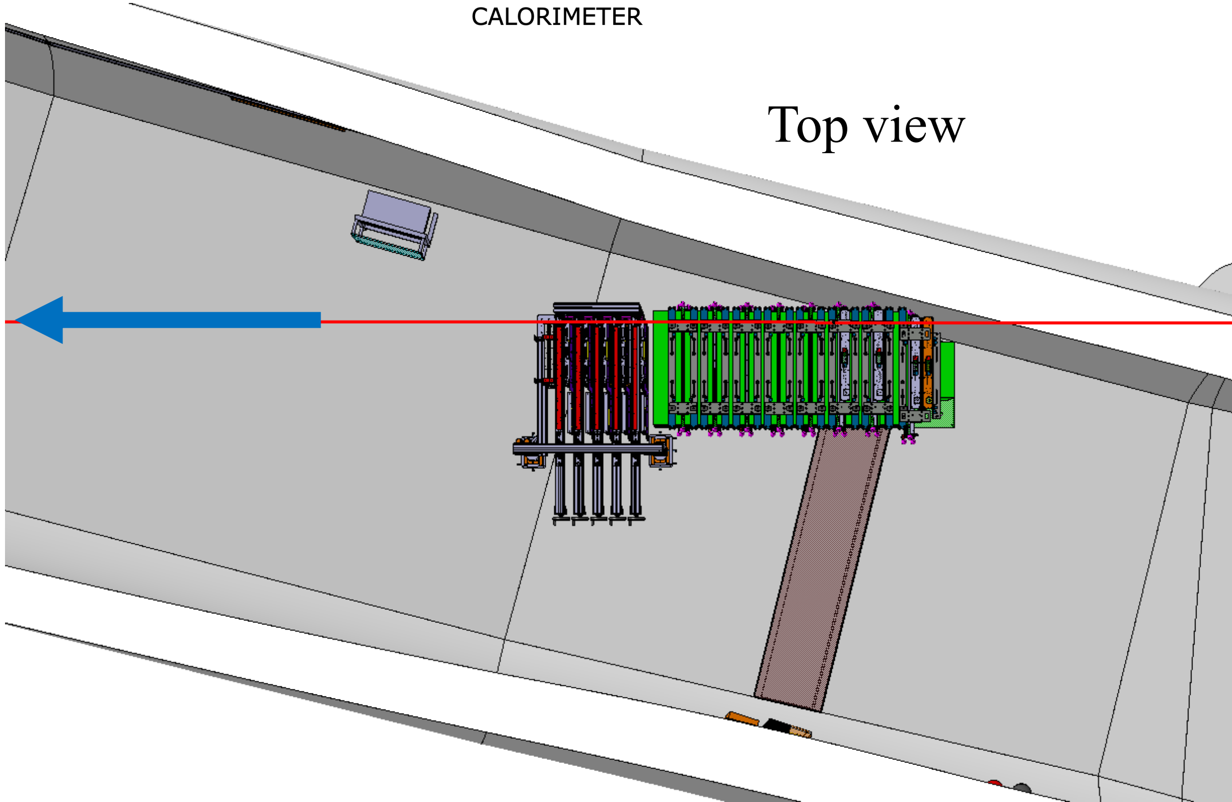
SND@LHC in the TI18 cavern



Side view



Top view



Physics goals

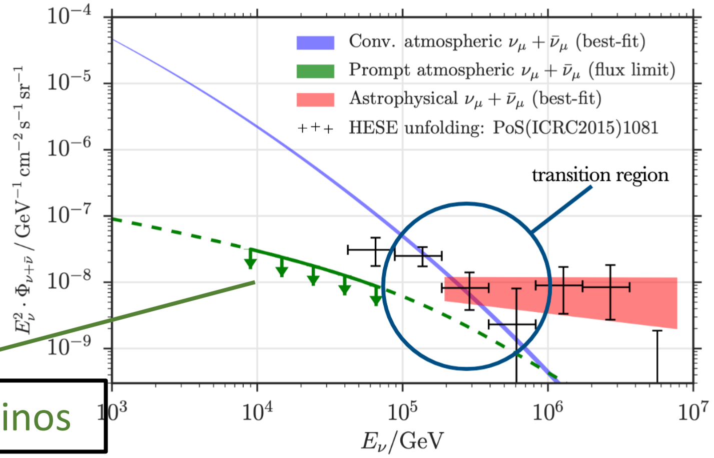
Scattering and Neutrino Detector at the LHC

- Study neutrino interactions (cross-section, LFU, ..) in a new energy domain
- Systematic uncertainty on the cross-section measurement dominated by the uncertainty on the neutrino flux
- Studying the neutrino source, i.e. using neutrinos as probes, e.g. in some angular region ν_e production dominated by charm decays → measuring charm production in pp collisions in the forward region
- Interest for the charm measurement in pp collision at high η for FCC detectors
- Prediction of very high-energy neutrinos produced in cosmic-ray interactions → experiments also acting as a bridge between accelerator and astroparticle physics

IceCube Collaboration, six years data, Astrophysics J. 833 (2016) 3, https://iopscience.iop.org/article/10.3847/0004-637X/833/1/3/pdf

7+7 TeV *p*-*p* collisions correspond to 100 PeV proton interaction for a fixed target

prompt atmospheric neutrinos



LHC

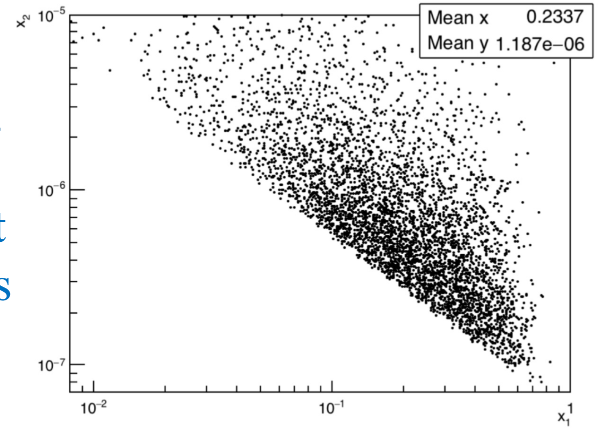
Scattering and Neutrino Detector at the LHC

Physics goal: charm production

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

Measurement	Uncertainty Stat.	Sys.
$pp \to \nu_e X$ cross-section	5%	15%
Charmed hadron yield	5%	35%

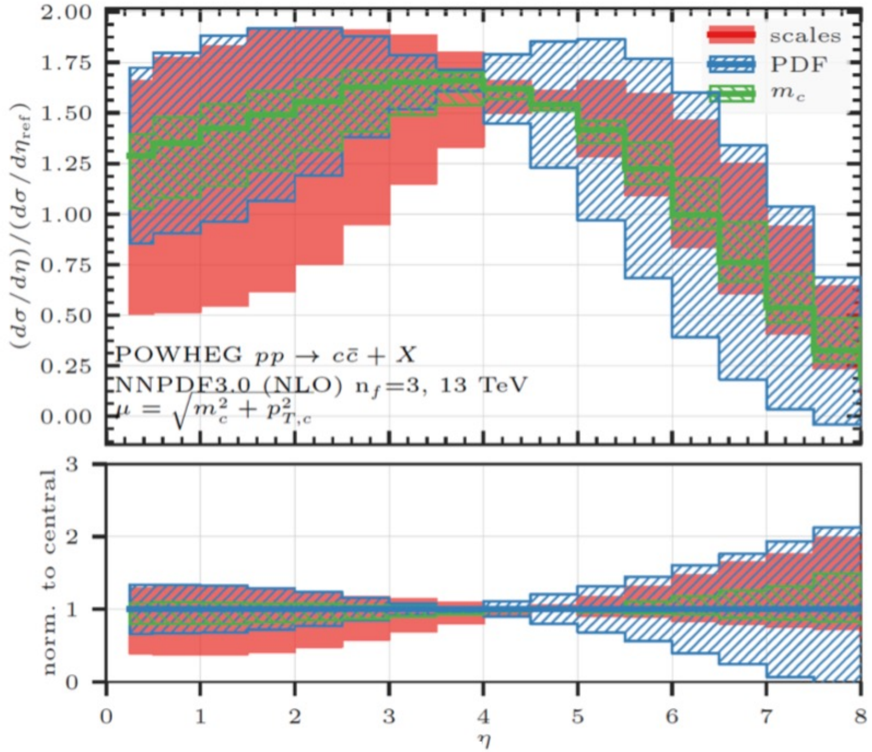
Gluon PDF in an *x*-region relevant for FCC and atmospheric neutrinos



- 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

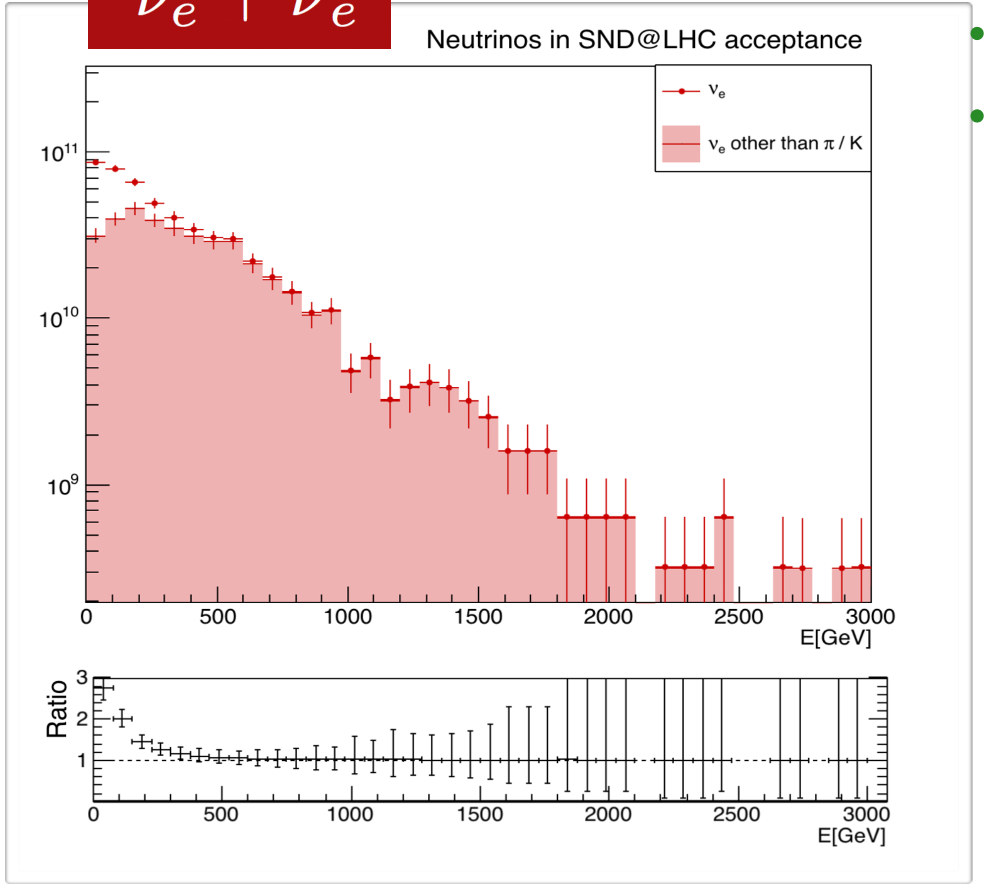


$$R = \frac{d\sigma/d\eta(13\,TeV)}{d\sigma/d\eta_{ref}(7\,TeV)} \qquad \eta_{ref} = [4, 4.5]$$

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

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

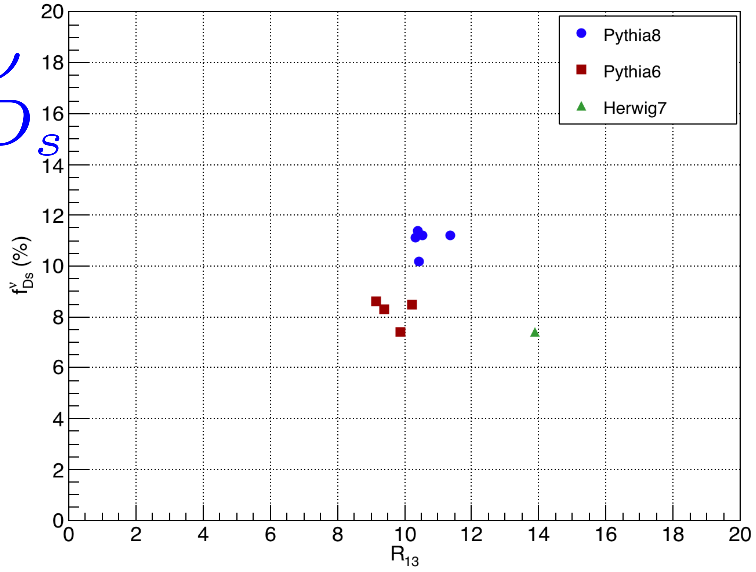


$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)},$$

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

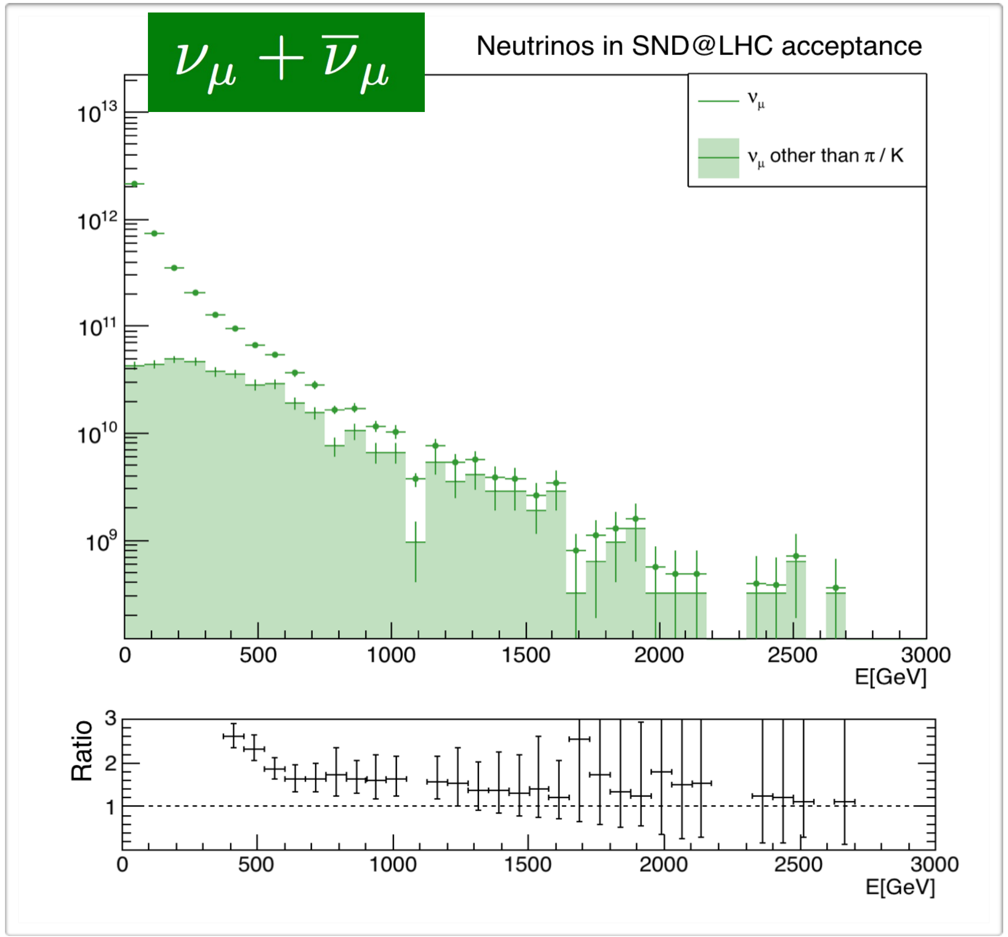
- Error on f_c evaluated as the discrepancy between Pythia8 and Herwig7 generators: **22%**
- **20%** error due to ν_τ statistics

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



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 keeps constant (~35%) with the energy



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

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

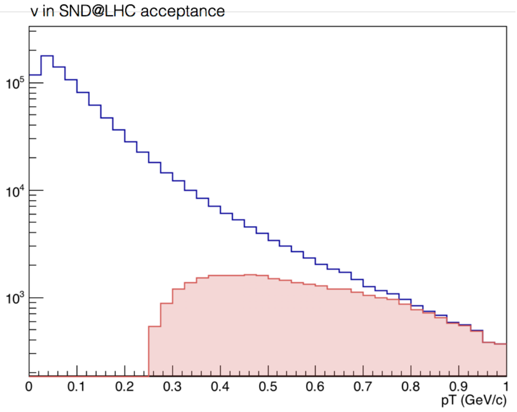
$$R_{12} = \frac{\nu_e}{\nu_\mu}$$

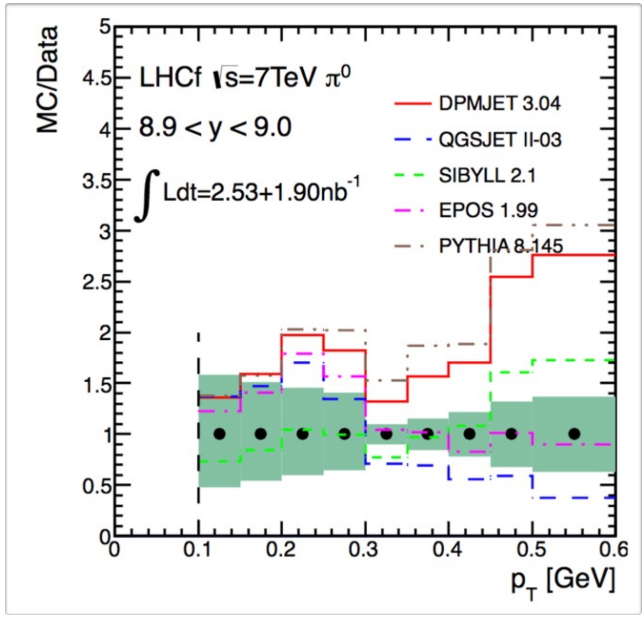
- ν_e/ν_μ as a LFU test in ν int for E>600 GeV
- No effect of uncertainties on f_c (and Br) since charmed hadrons decay almost equally in ν_μ and ν_e

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

contamination from π/k

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

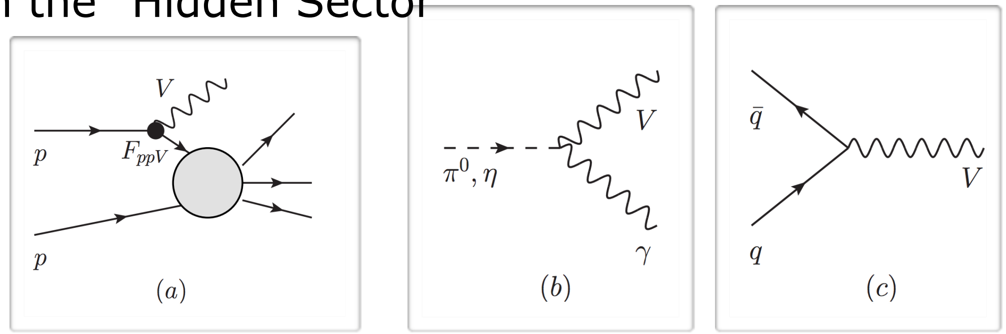




Phys. Rev. D 86, 092001 (2012)

FEEBLY INTERACTING PARTICLES

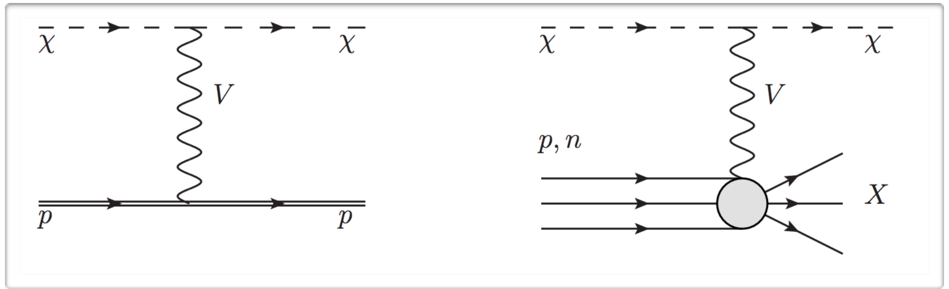
- SND@LHC can explore a large variety of BSM scenarios within the "Hidden Sector"

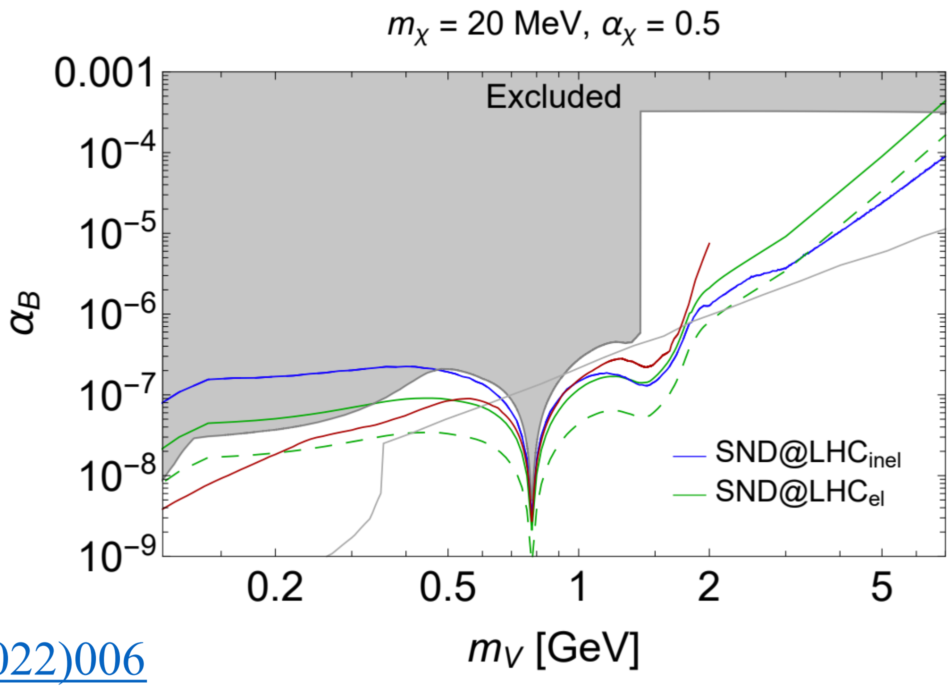


Proton bremsstrahlung | Meson decay | Drell-Yan process

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

Detection: χ elastic/inelastic scattering off target nucleons





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

Summary of the experiment main milestones

• Letter of Intent	Aug 27th, 2020
• Technical Proposal	Jan 22nd, 2021
• Approval by CERN RB:	Mar 2021
• Experimental area & infrastructure:	Jun 28 – end Aug
• Detector construction completion:	Oct 13
• Detector surface commissioning:	Sep - Oct
• Test beams:	Sep 1-5, Oct 1-6
• Start of detector installation in TI18:	Nov 1
• Turn on and global commissioning:	Dec 7
• Detector commissioning and debugging:	Jan-Feb 2022
• Installation of the neutron shield:	Mar 15
• Installation of the first emulsion films:	Apr 7
• First data from “splash”/collision:	Apr, May
• First 13.6 TeV collisions:	July 5th
• Full target installation:	July 26th

Experimental area preparation in TI18 in Summer 2021

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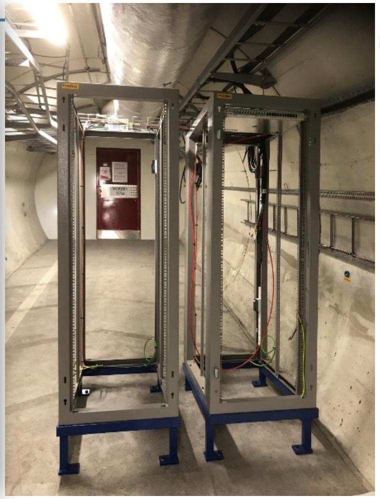
at the LHC

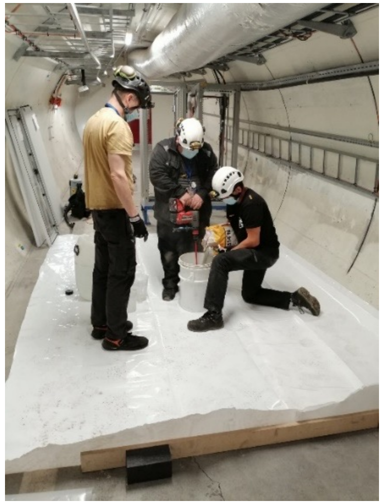
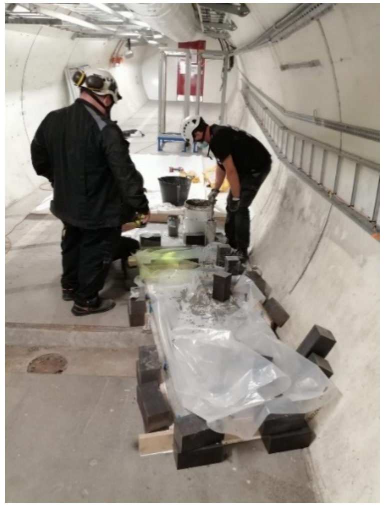


Survey and positioning of baseplates for muon filters

Underground racks

Optical fibres between surface and underground racks

Formworks and grouting of baseplates


Detector installation in TI18

- Started on November 1st 2021
- Electronic detector completed on December 3rd 2021
- Neutron shield completed on March 15th 2022
- First emulsion films in the target on April 7th 2022

September 2021

December 2021

March 2022

Detector paper published on https://arxiv.org/abs/2210.02784 submitted to the JINST Joint Issue on the LHC experiment upgrades for Run3

Neutron shield construction and installation

LHC
Scattering and Neutrino Detector
at the LHC


Nov 26^{th} 2021


Angle cutting for floor slope


Installation of aluminum frame


Evaporator installation


Door hinges installed


On March 4^{th} 2022

Detector in TI18

LHC
Scattering and Neutrino Detector
at the LHC

Detector in TI18 pointing towards IP1

LHC

Scattering and Neutrino Detector
at the LHC

EMULSION TARGET #3

- Transportation from **Emulsion Lab** to PM15 by CERN internal transport
- Transportation of trolleys from **PM15** to TI18 by hand + electric kart
- Uncabling and removal of SciFi planes
- Extraction of Target#2 walls and installation of Target#3 walls
- Re-installation of SciFi stations and test
- Transportation of Target#2 trolleys on surface
- RP measurements
- Transportation of Target#2 trolleys to the lab by CERN Internal Transport

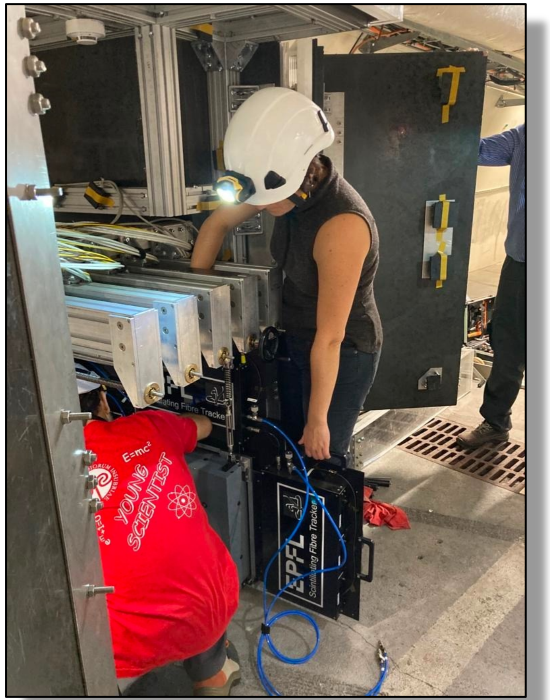
November 4th

Total time required for underground operations: **4 hours**

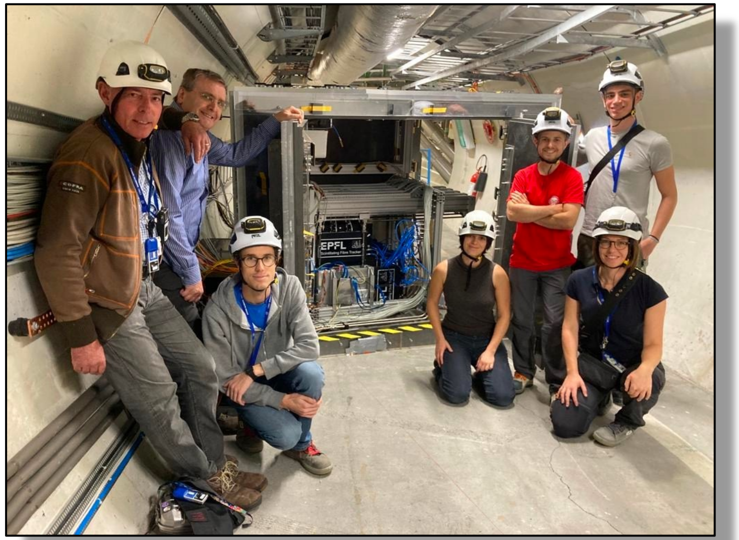
Integrated luminosity: 9.2 fb^{-1}

Transport

Target replacement



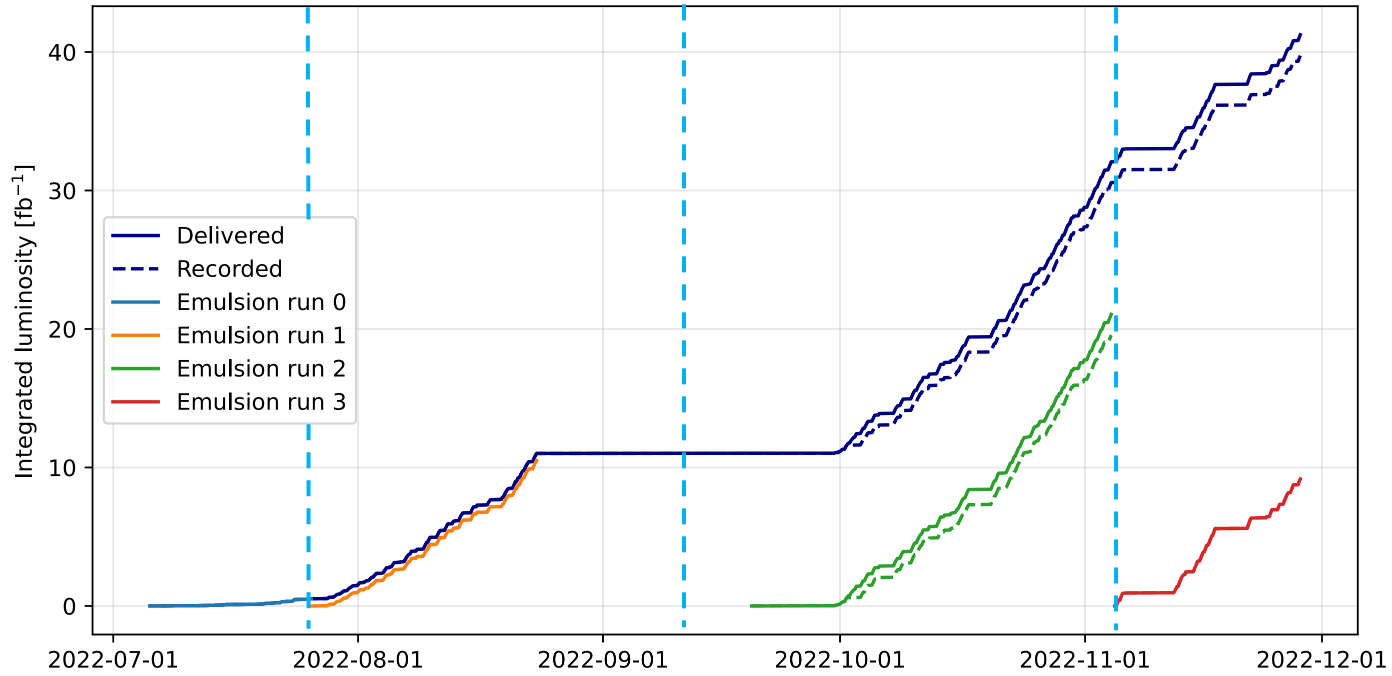
SciFi installation



Target#3 walls installed

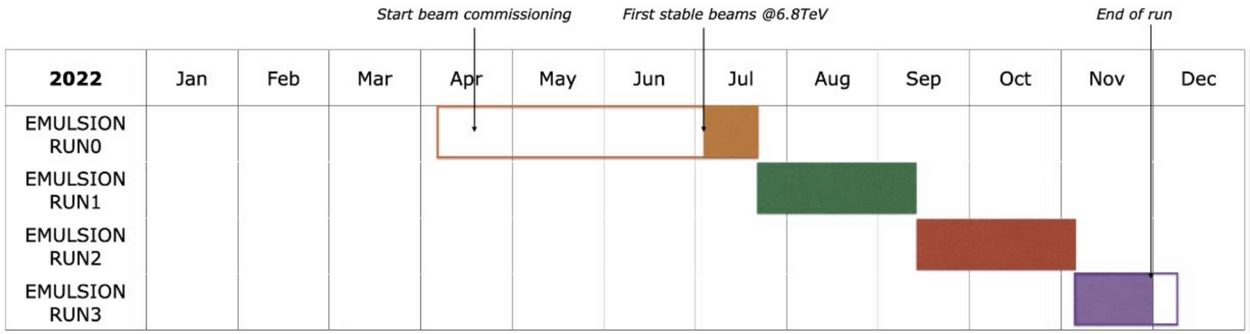
Start of data taking

Integrated luminosity in Run 3
for the different emulsion batches



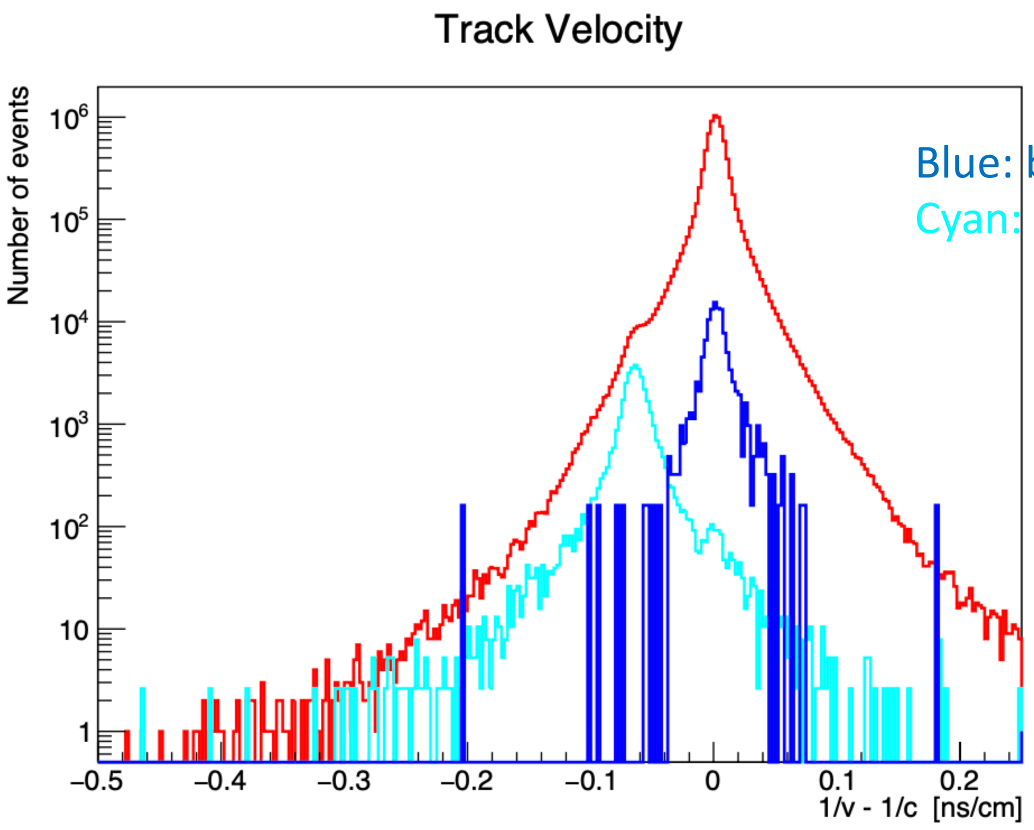
Delivered: 41.2 fb^{-1}

Recorded: 39.7 fb^{-1} (96%)



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

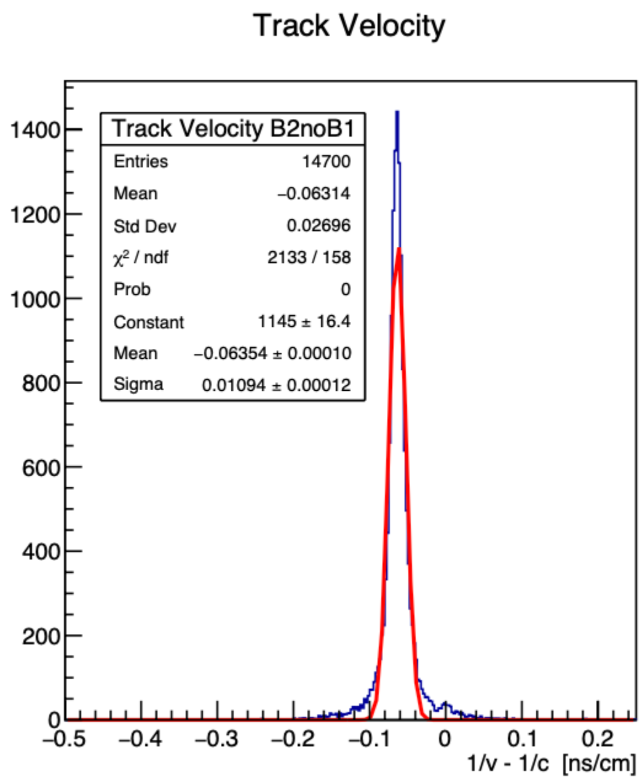
Use bunch structure to study event features: the track direction



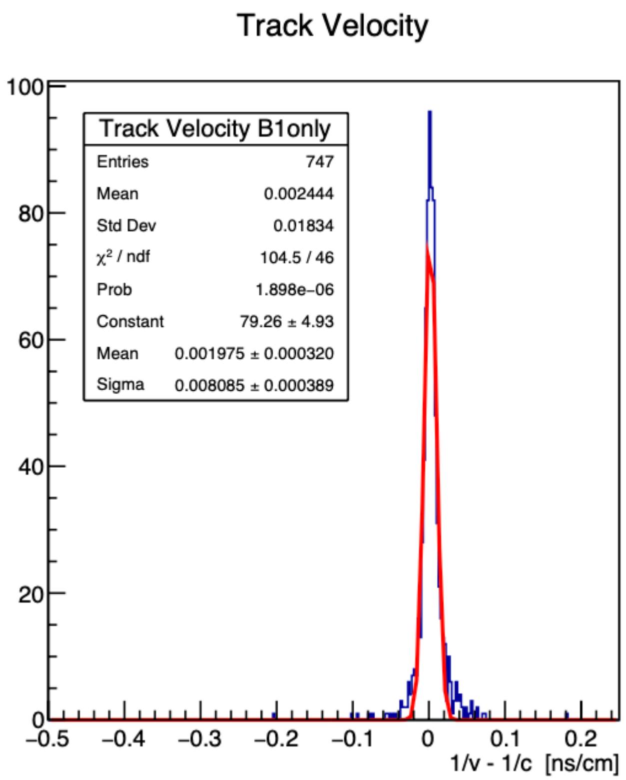
Blue: beam 1

Cyan: beam 2

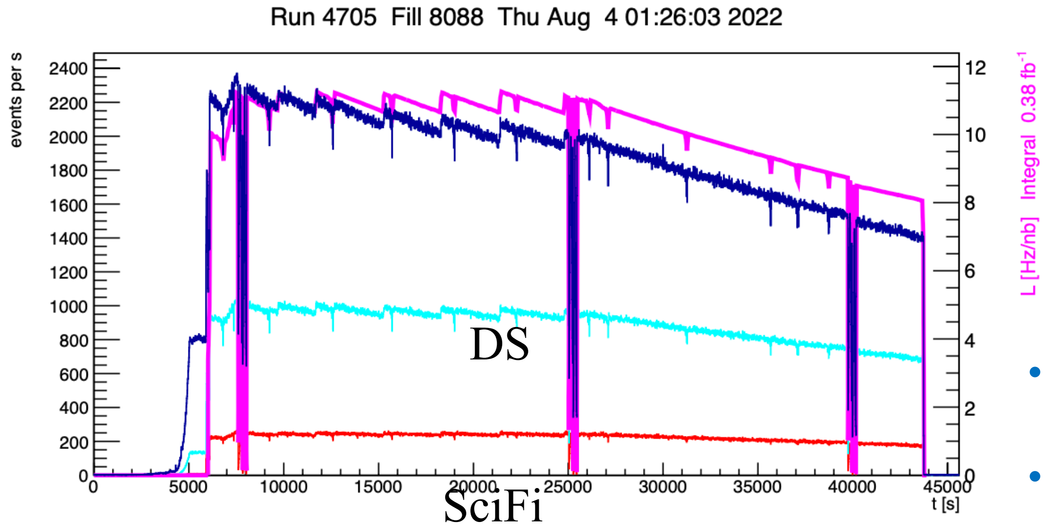
Beam 2



Beam 1

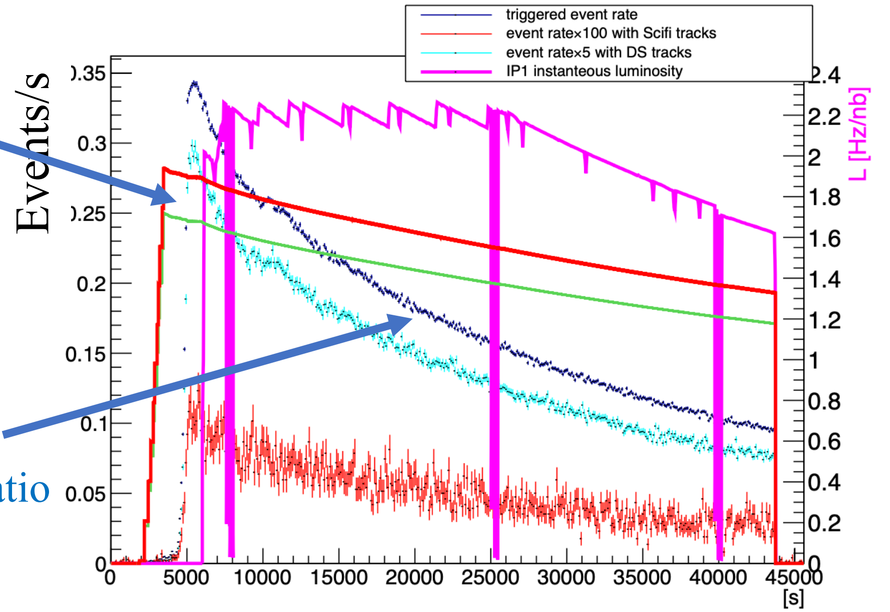


Use bunch alignment to study “background” features



events associated to bunches from beam 2

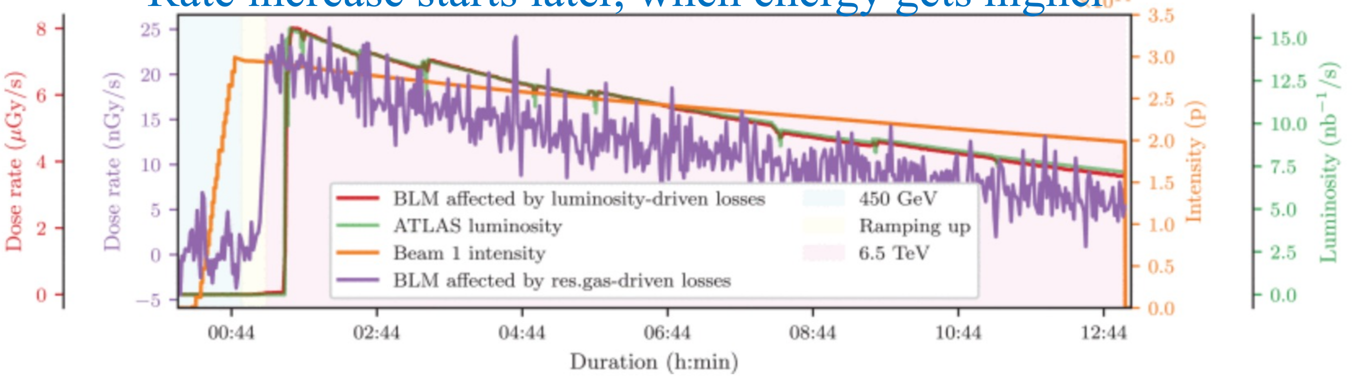
Beam intensity



- Rate decrease due to intensity and vacuum conditions
- Much larger DS/SciFi track ratio

fixed number of collisions by beam tuning despite the drop in beam current

Rate increase starts later, when energy gets higher



https://ieeexplore.ieee.org/document/8976238

track type	beam 1	beam 2	no beam
	Run 4705		
Scifi	1.41%	0.44%	0.02%
DS	1.10%	1.13%	0.04%
	Run 4654		
Scifi	1.30%	0.41%	0.01%
DS	0.98%	1.03%	0.02%
	Run 4661		
Scifi	1.20%	0.34%	0.01%
DS	0.90%	0.86%	0.05%

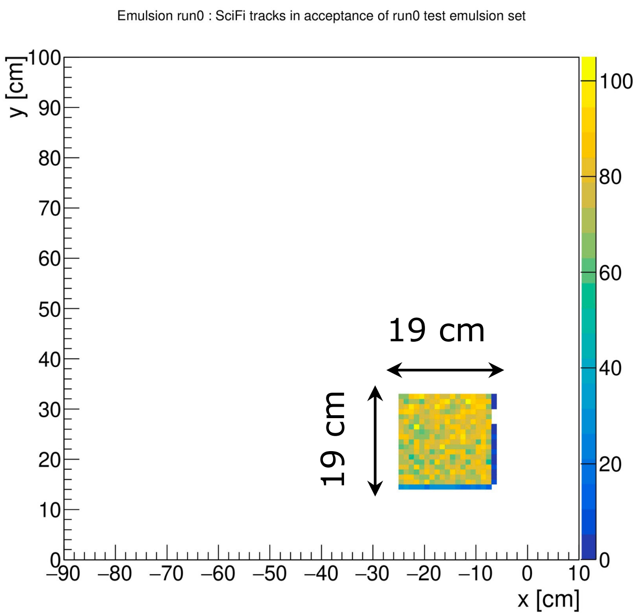
Table 1: Background rates for different runs.

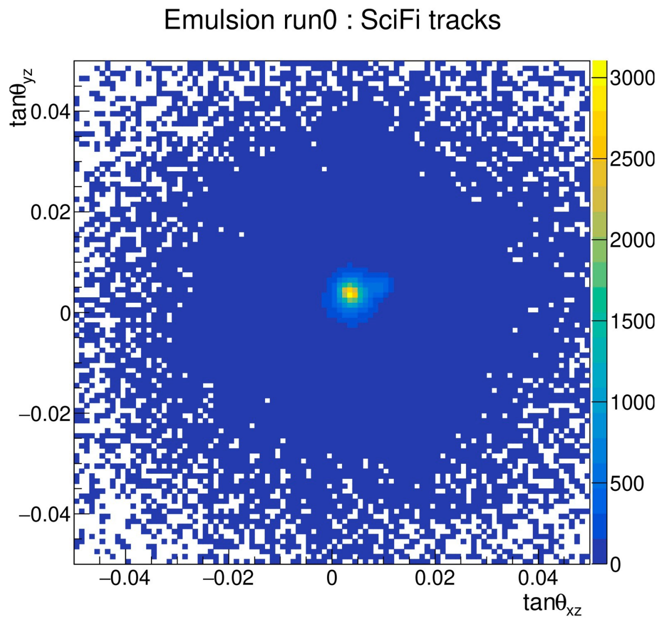
Background target tracks < 2%

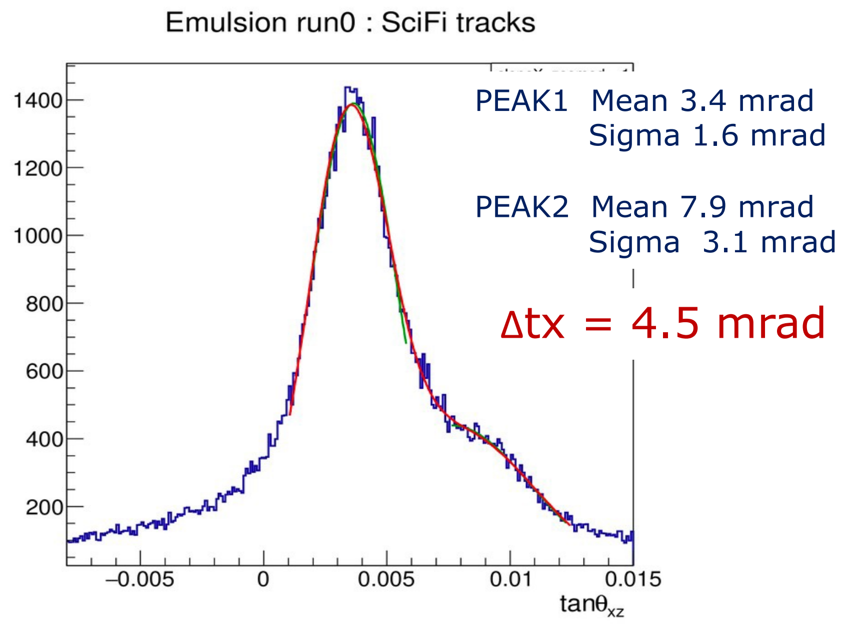
EMULSION / SCIFI COMPARISON

SciFi

Measured rates on BRICK1 surface
1.4x10⁴ fb/cm²

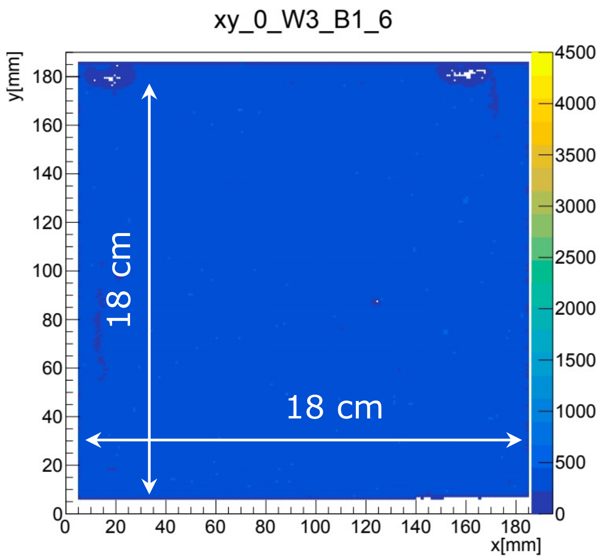


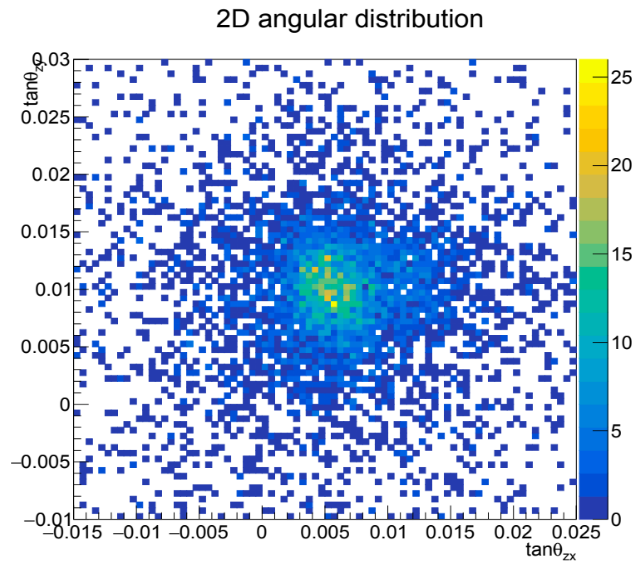


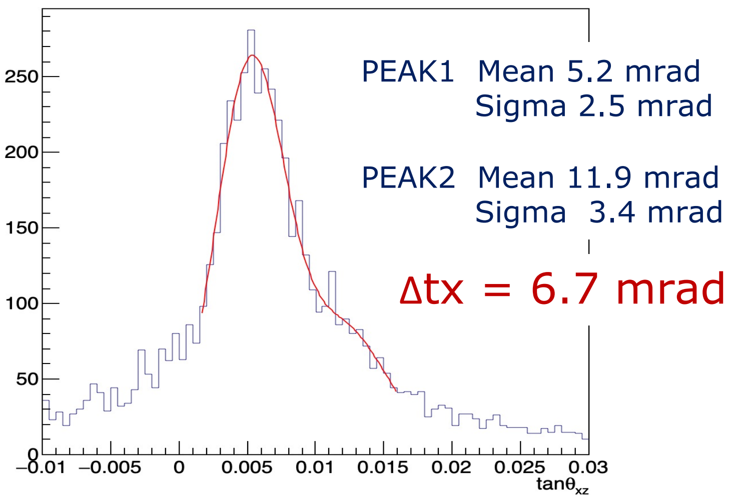


EMULSIONS

Measured rates in BRICK1
1.5 x10⁴ fb/cm²

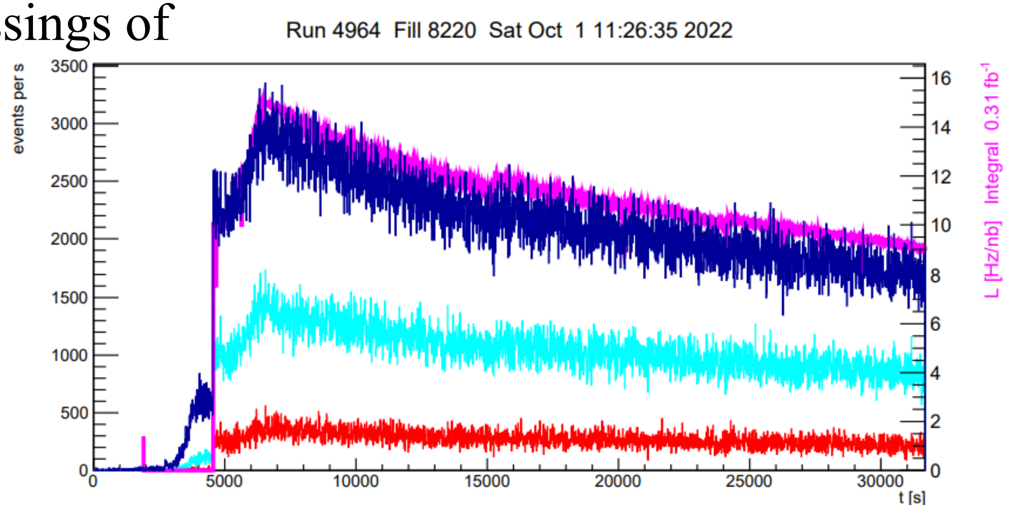


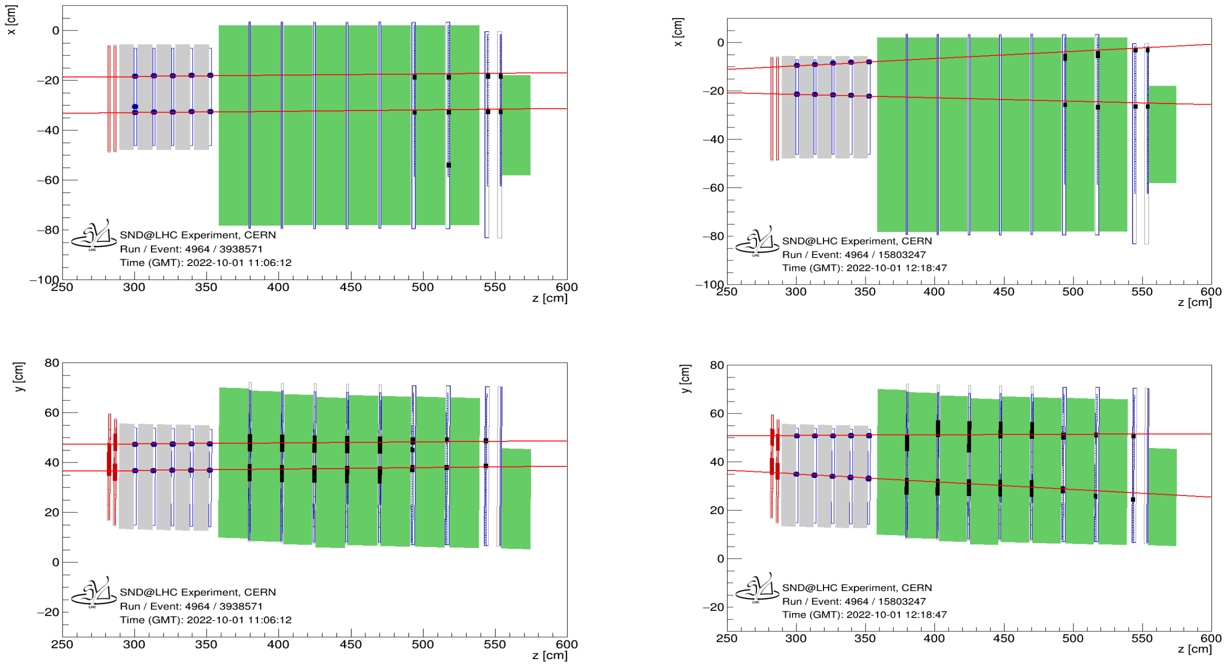




Multi-track events

- Run 4964: $\int Ldt = 0.31fb^{-1}$, $\sigma_{inelastic} = 80\ mb$, 2448 bunch crossings of 3564, $N_{collisions} = 25\times10^{12}$, $T = 26\times10^3 s$, $N_{xings} = 0.72\times10^{12}$
- Efficiency corrected average over this run: 300 tracks/s
- Single muon per bunch crossing: $\mu = 1.1\times10^{-5}$
- Probability for k-track event from pile-up: $\frac{\mu^k e^{-\mu}}{k!}$
- 2 μ per bunch xing: $p_2 = \frac{1}{2}\mu^2$
- 3 μ per bunch xing: $p_3 = \frac{1}{6}\mu^3$
- Expect $N_{2\ track} = 43$,
  observed 224
- Additional rate could be due to trident process,
  muon pair production in rock, concrete, tungsten.
- Hypothesis supported by 3-track events

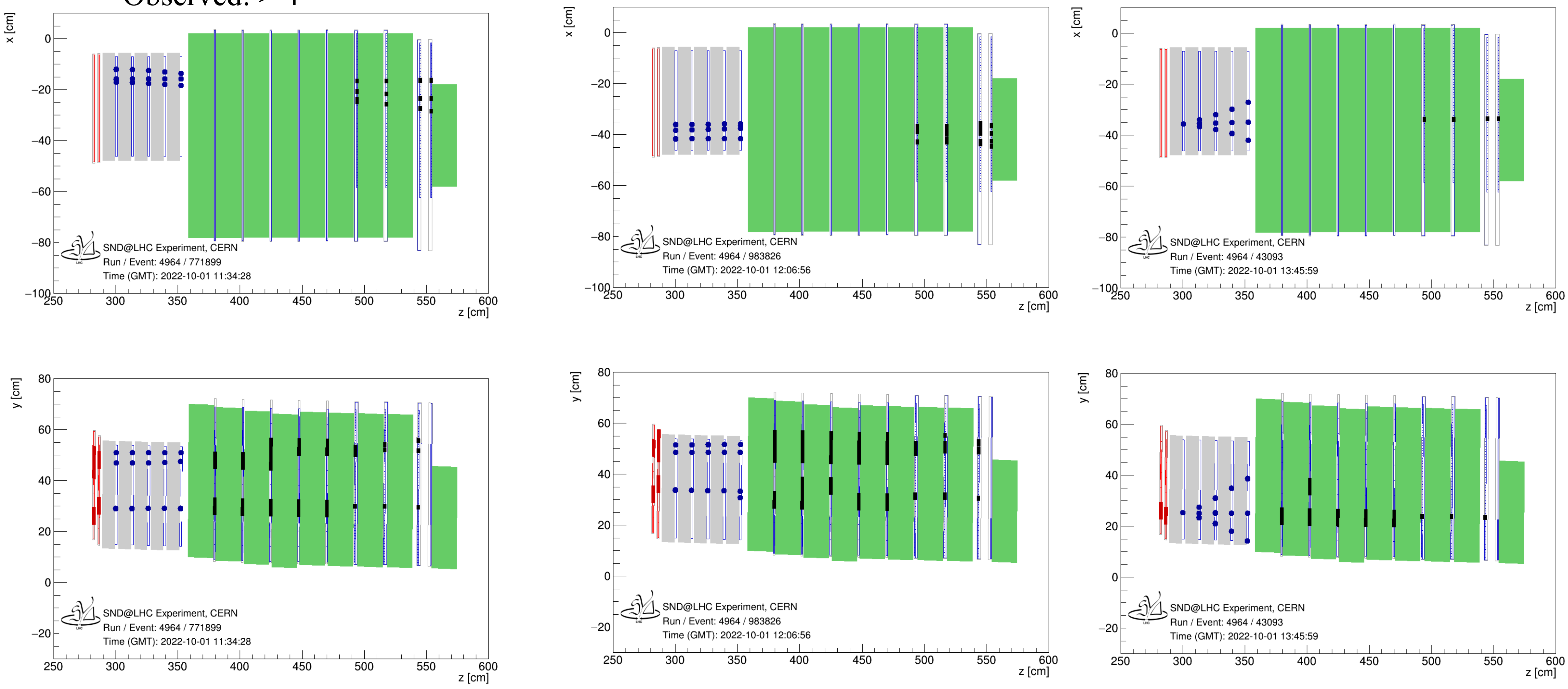




Three-track events

Expect: $N_{3\ track} = 2 \times 10^{-4}$

Observed: > 4



SND@LHC UPGRADE TOWARDS HL-LHC

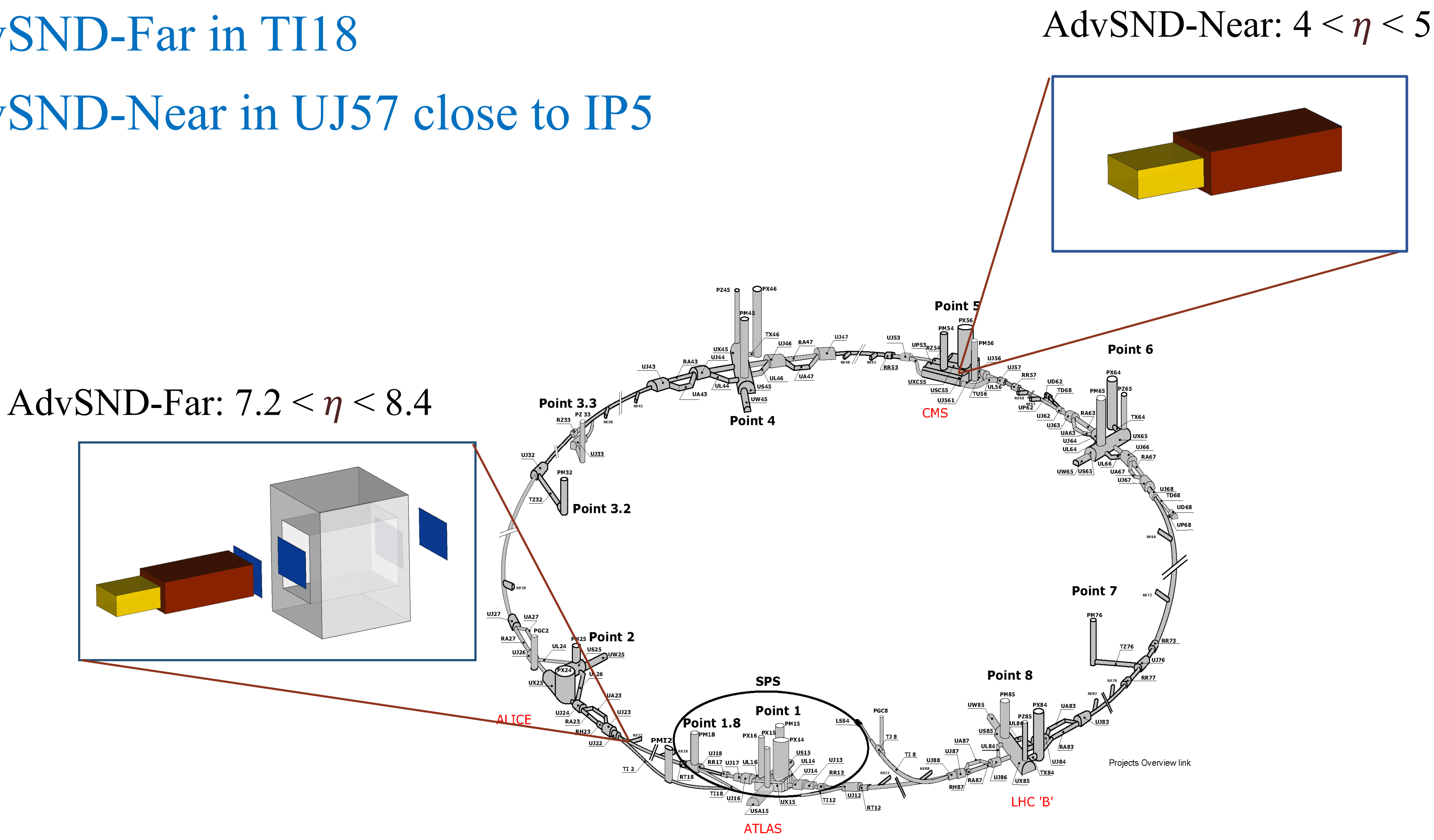
LHC

Scattering and Neutrino Detector
at the LHC

Construction during LS3 (2026-2028) and data taking from 2029

Detector(s) concept to extend the physics case

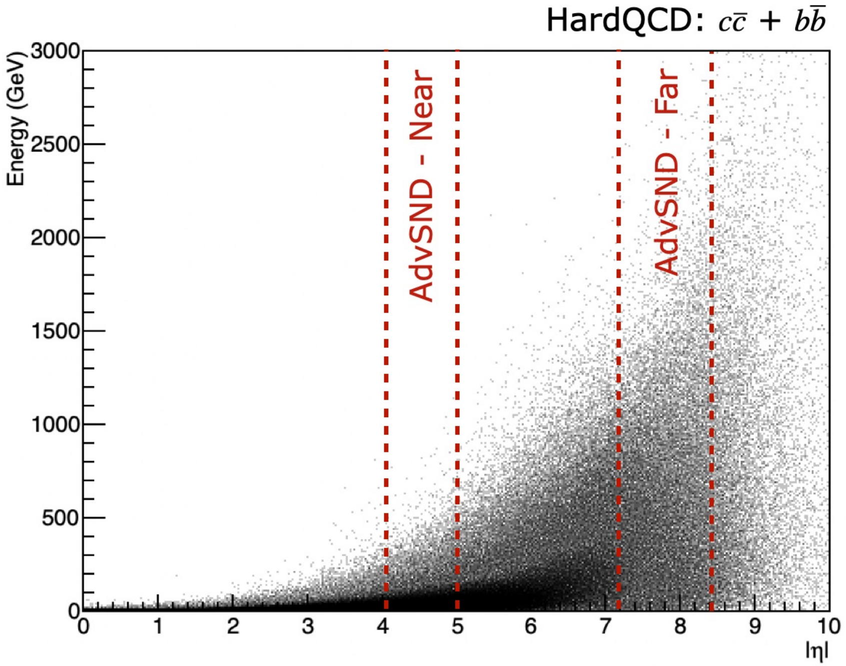
- Two detectors
  - AdvSND-Far in TI18
  - AdvSND-Near in UJ57 close to IP5



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

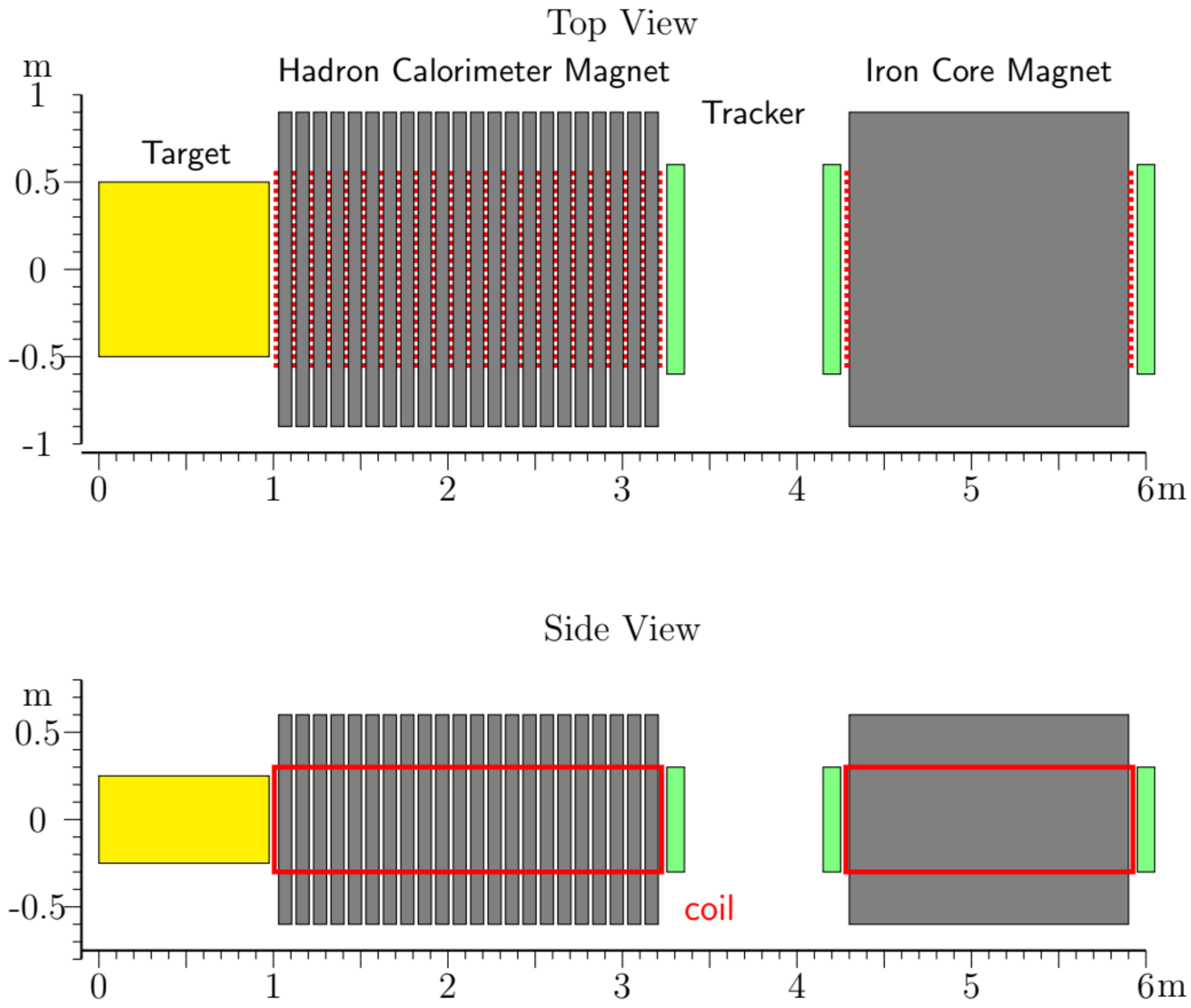
- **AdvSND-Far**: $7.2 < \eta < 8.4$
  - Same acceptance as SND@LHC
  - Measurements with (much) reduced systematics
  - Separate neutrinos from anti-neutrinos
  - Charm production measurements
  - Lepton flavour universality



Muon spectrometer design for the FAR detector

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



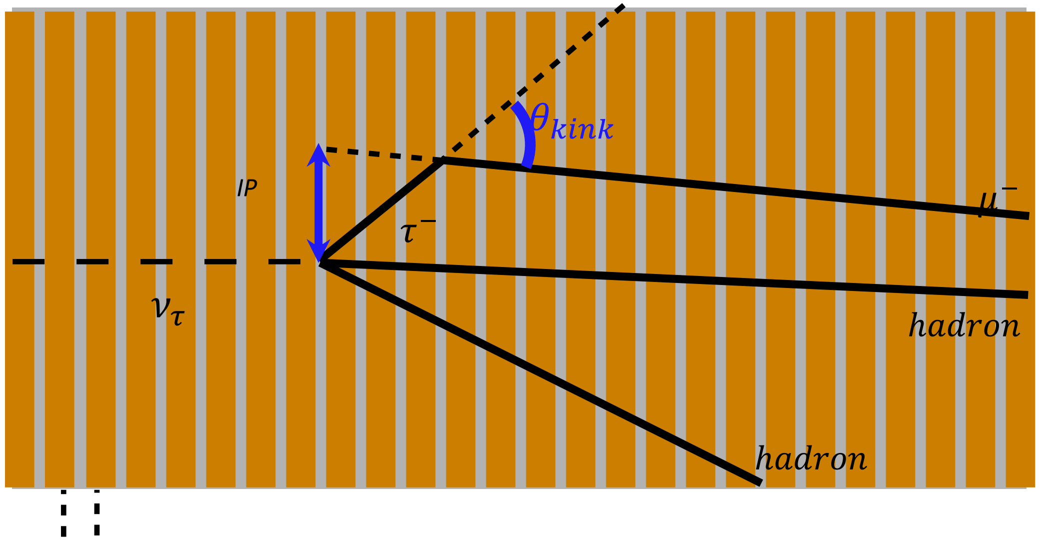
Challenges for the vertex detector

Impact parameter ***<IP> ~ 100 μm***

AdvSND-Near

τ decay length ***<Lτ> ~ 3 mm***

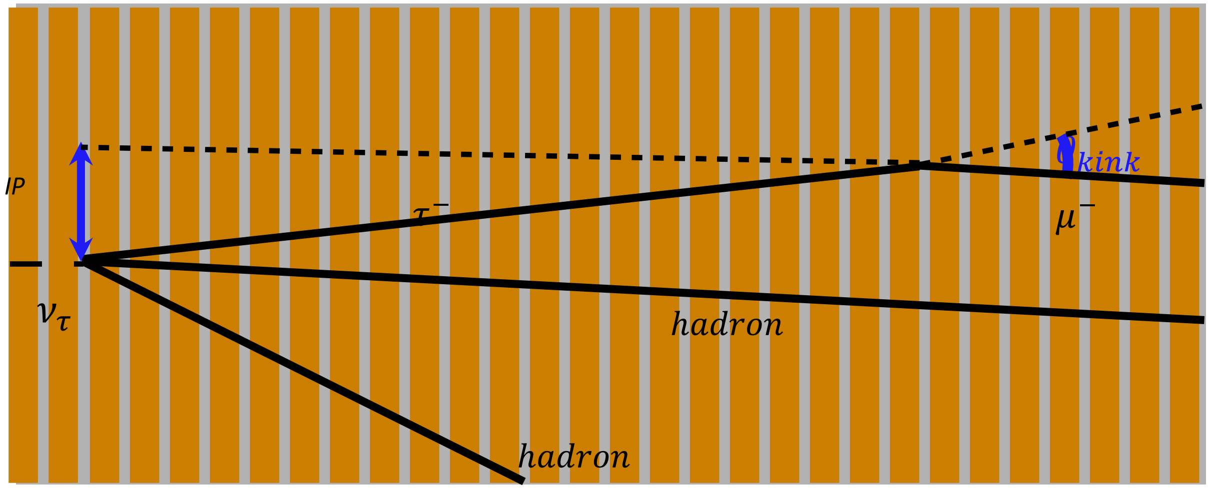
kink angle ***$<\theta_{kink}>$ ~ 30 mrad***



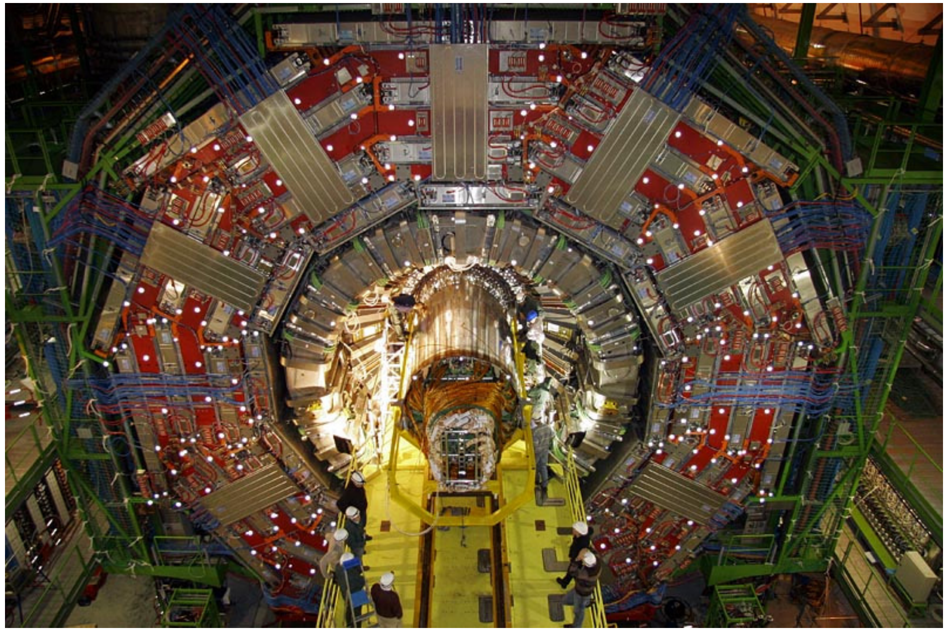
AdvSND-Far

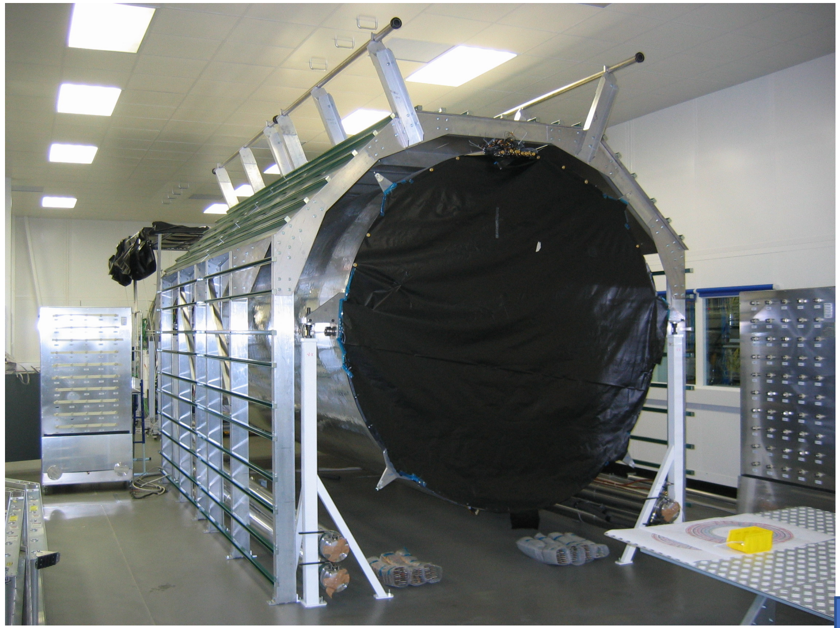
τ decay length ***<Lτ> ~ 3.5 cm***

kink angle ***$<\theta_{kink}>$ ~ 3 mrad***

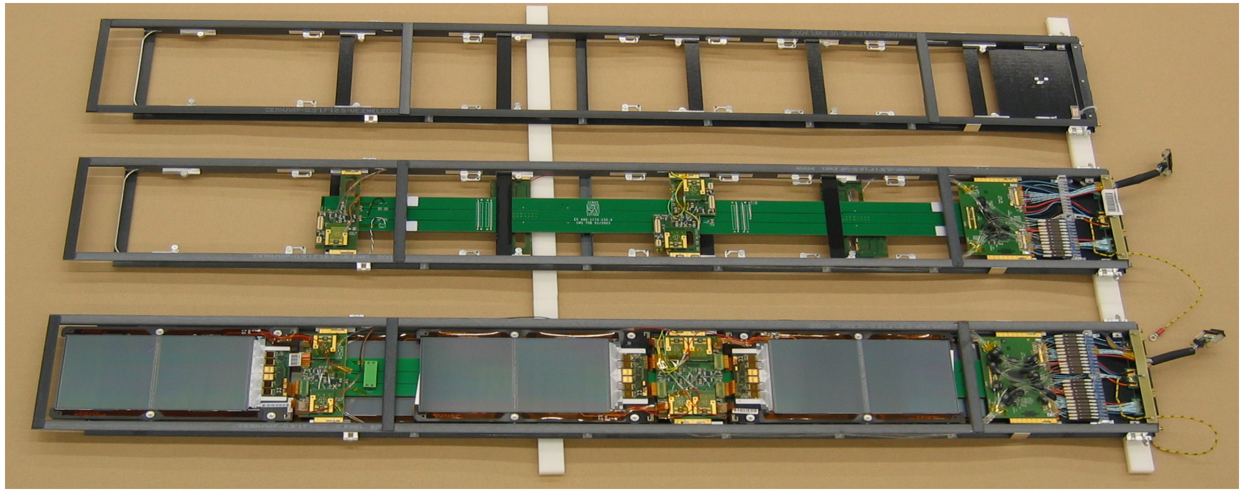


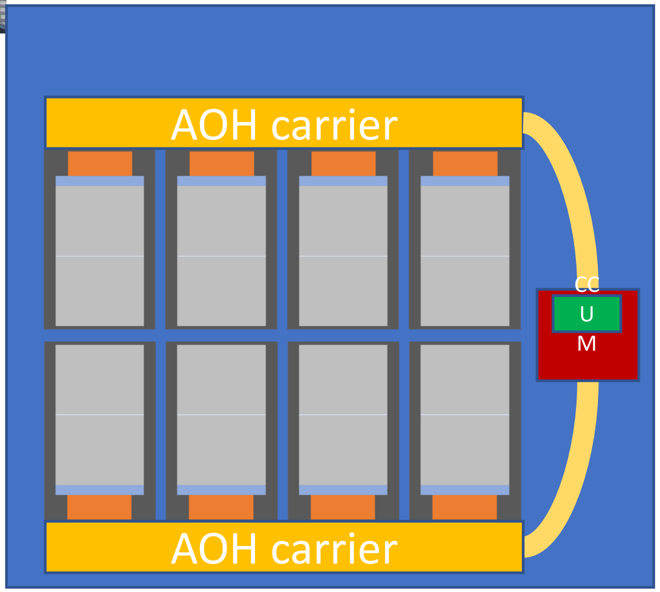
One option for the FAR: vertex detector with silicon strips





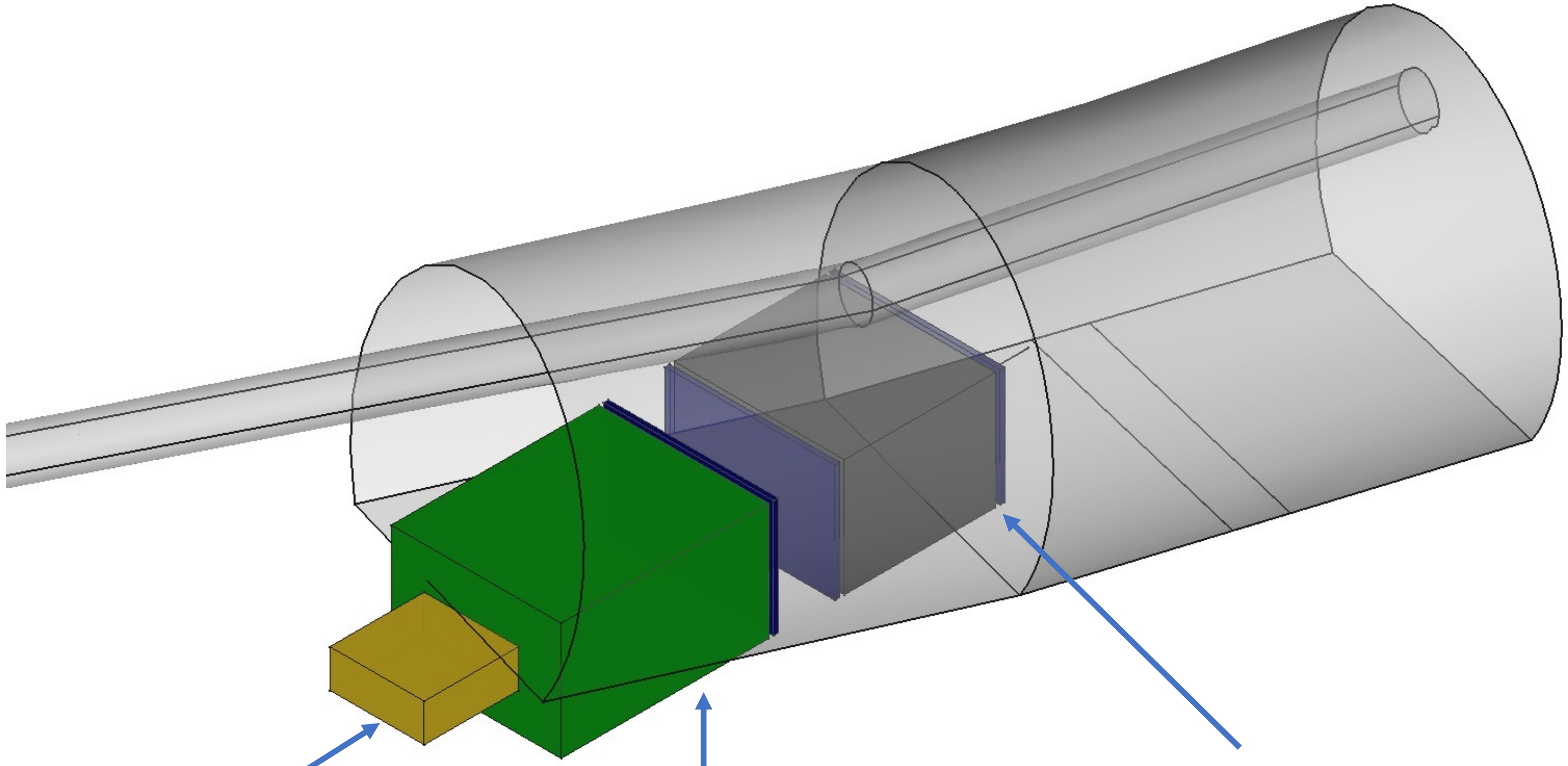
Silicon strips of the CMS TOB





Preliminary integration studies in TI18

LHC
Scattering and Neutrino Detector
at the LHC



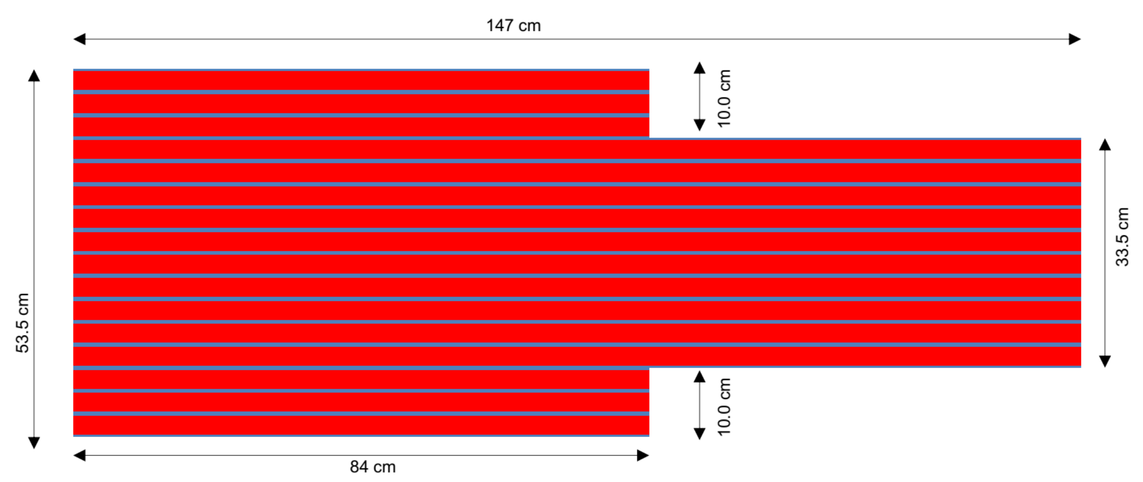
NEAR detector concept

- 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)

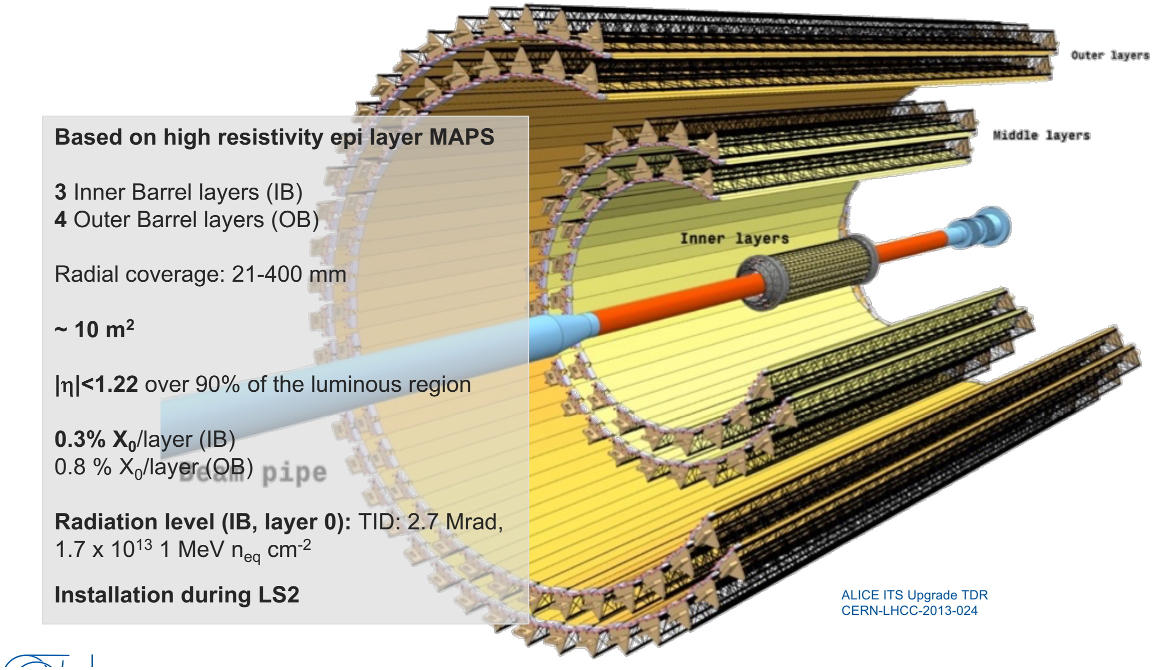
τ flight length shorter ~ 3 mm → Very high segmentation. ALICE Monolithic Active Pixel Sensors (MAPS) seem optimal

Arranging modules in layers

Layer arrangement



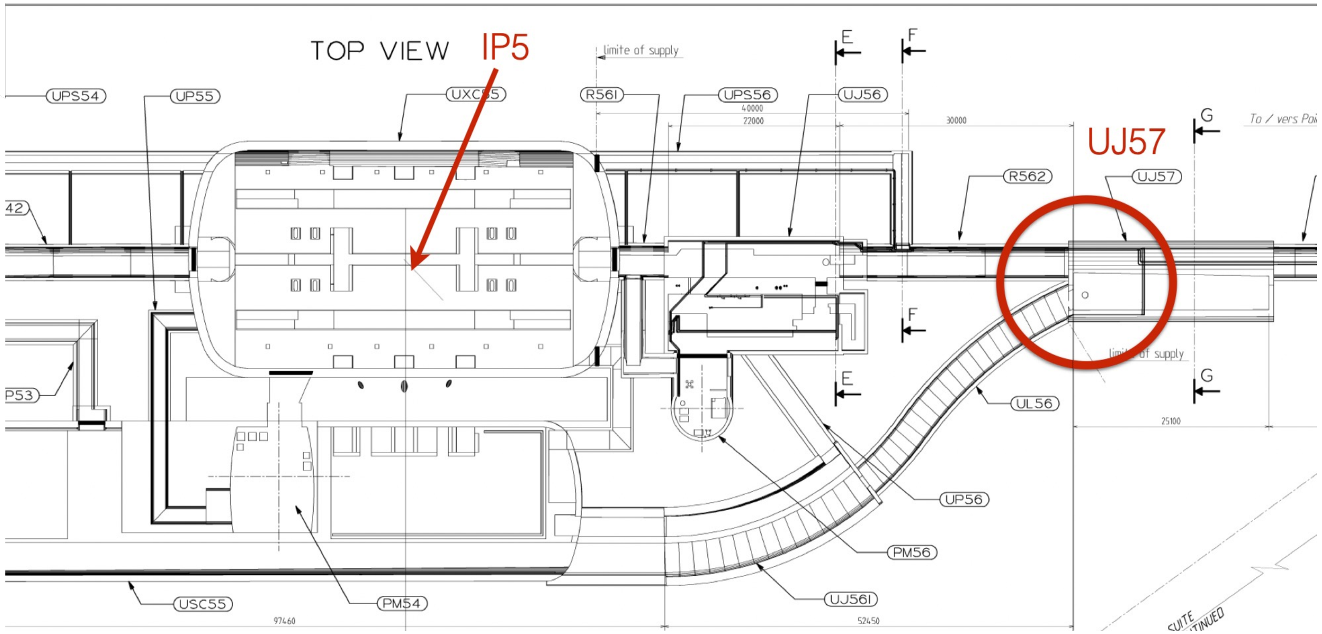
× 9 layers

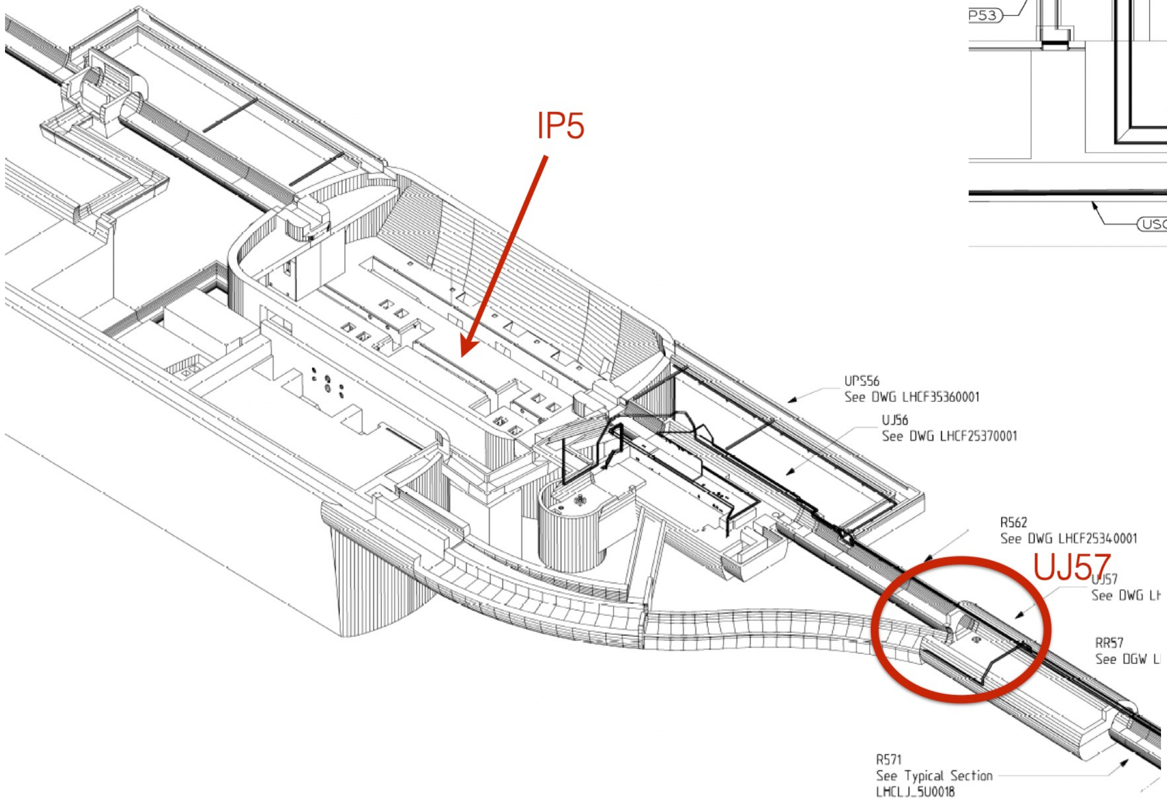


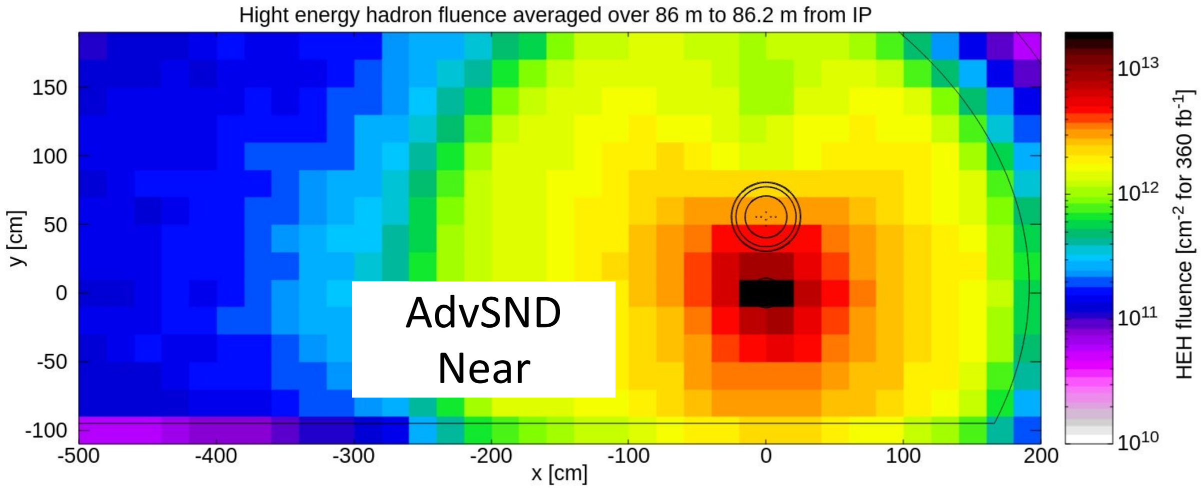
ALICE ITS upgrade

Preliminary studies for the NEAR Detector

UJ57 tunnel at 86 m from CMS IP





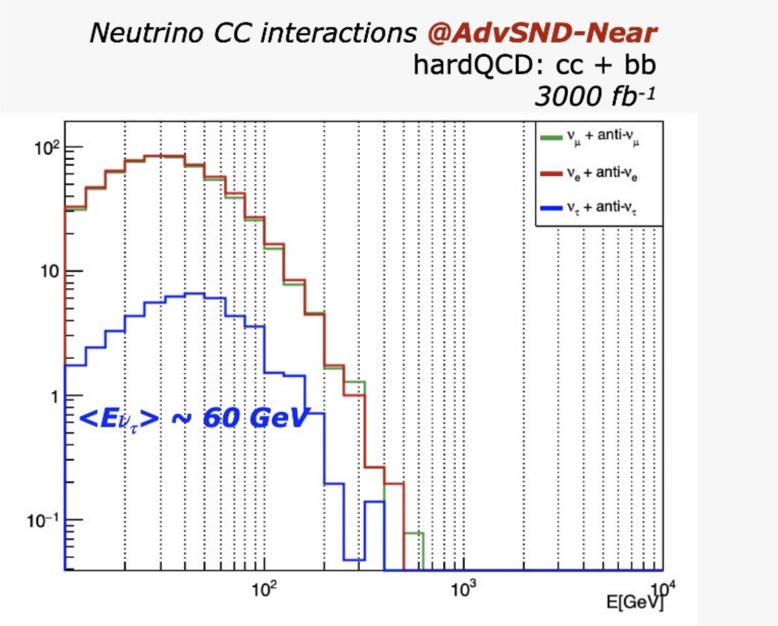


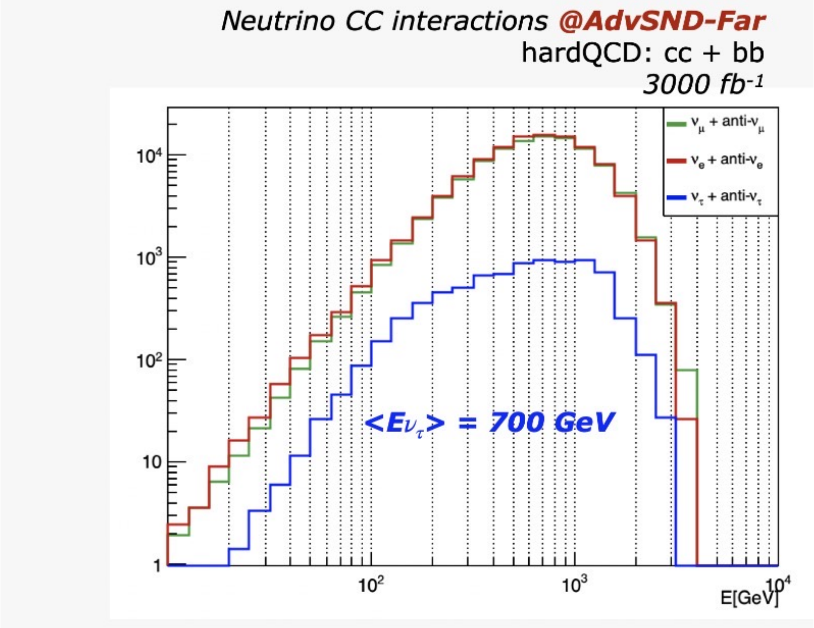
High-energy hadron fluence in the UJ57 tunnel

NEAR and FAR detector: neutrinos from c and b

AdvSND - NEAR

Flavour	ν in acceptance hardQCD: $c\bar{c}$	ν in acceptance hardQCD: $b\bar{b}$	CC DIS hardQCD: $c\bar{c}$	CC DIS 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}	





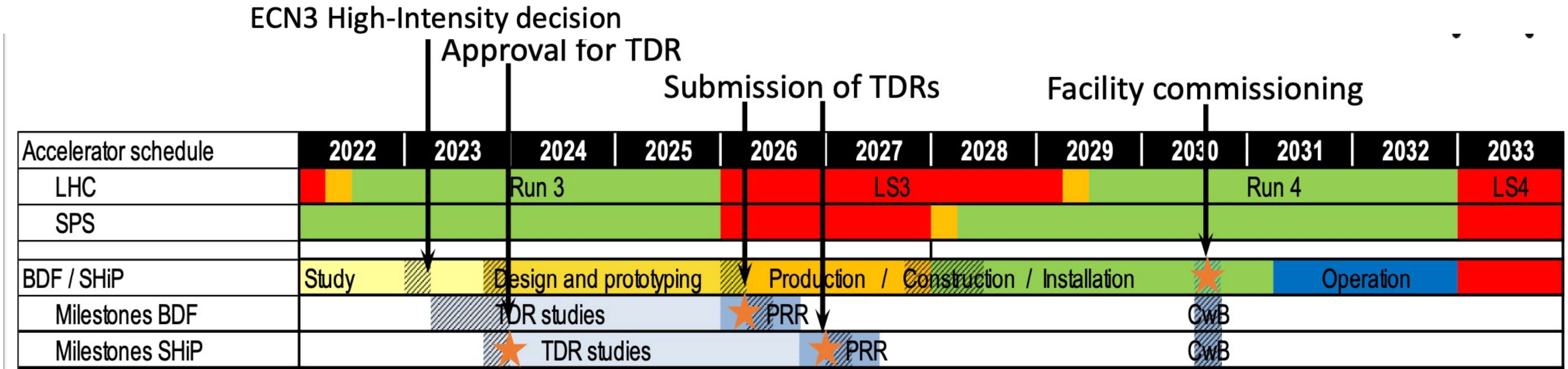
AdvSND-FAR

Flavour	ν in acceptance hardQCD: $c\bar{c}$	ν in acceptance hardQCD: $b\bar{b}$	CC DIS hardQCD: $c\bar{c}$	CC DIS 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}	

Concluding remarks on SND@LHC

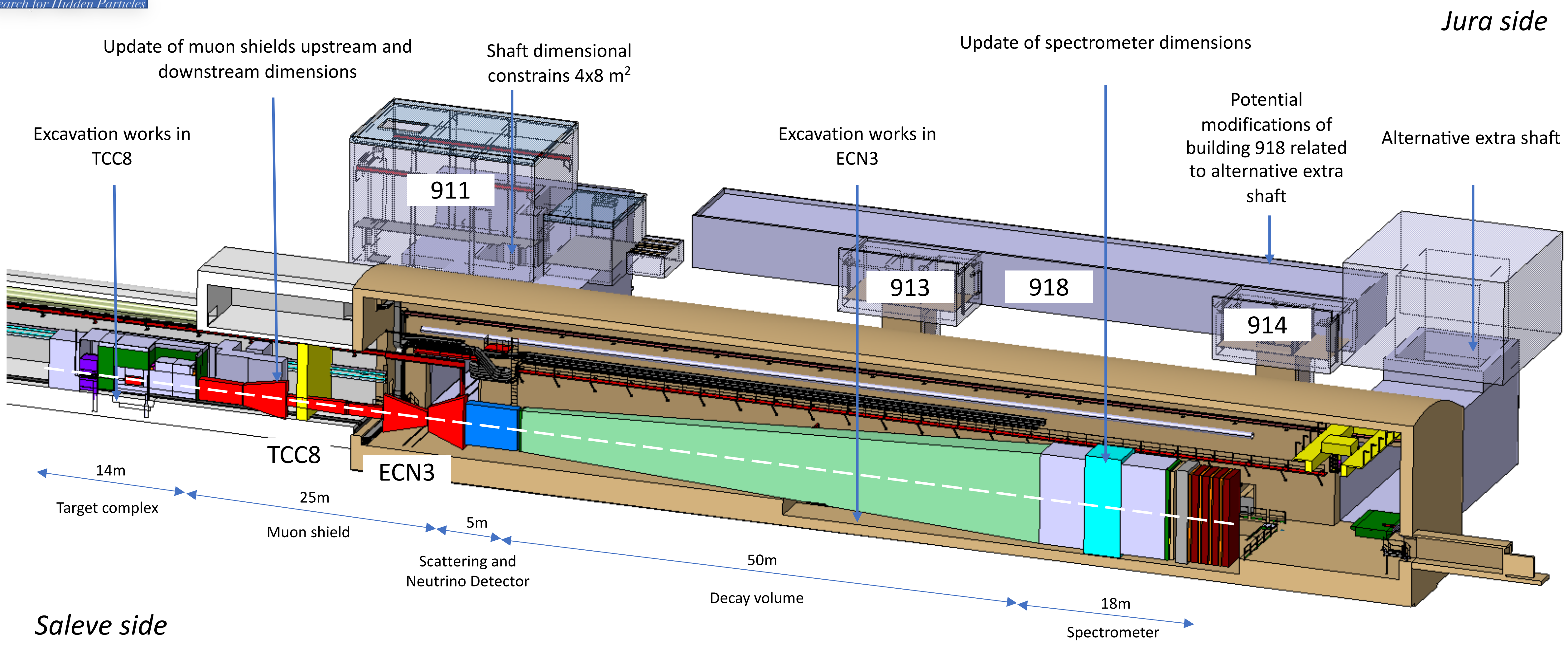
- Successful operation of the detector over the first year of Run 3, to record about 41 fb^{-1}
- Muon rates show good agreement between emulsion and electronic trackers
- Multi-track event rates hinting for additional physics processes on top of the pileup
- In 2023 new campaign for the improvement of the energy calibration
- In 2023 a Letter of Intent will be submitted for the SND@LHC upgrade towards the High-Luminosity LHC

SHiP (Search for Hidden Particles) proposal timeline



Long-lived particles and neutrinos with the SHiP experiment

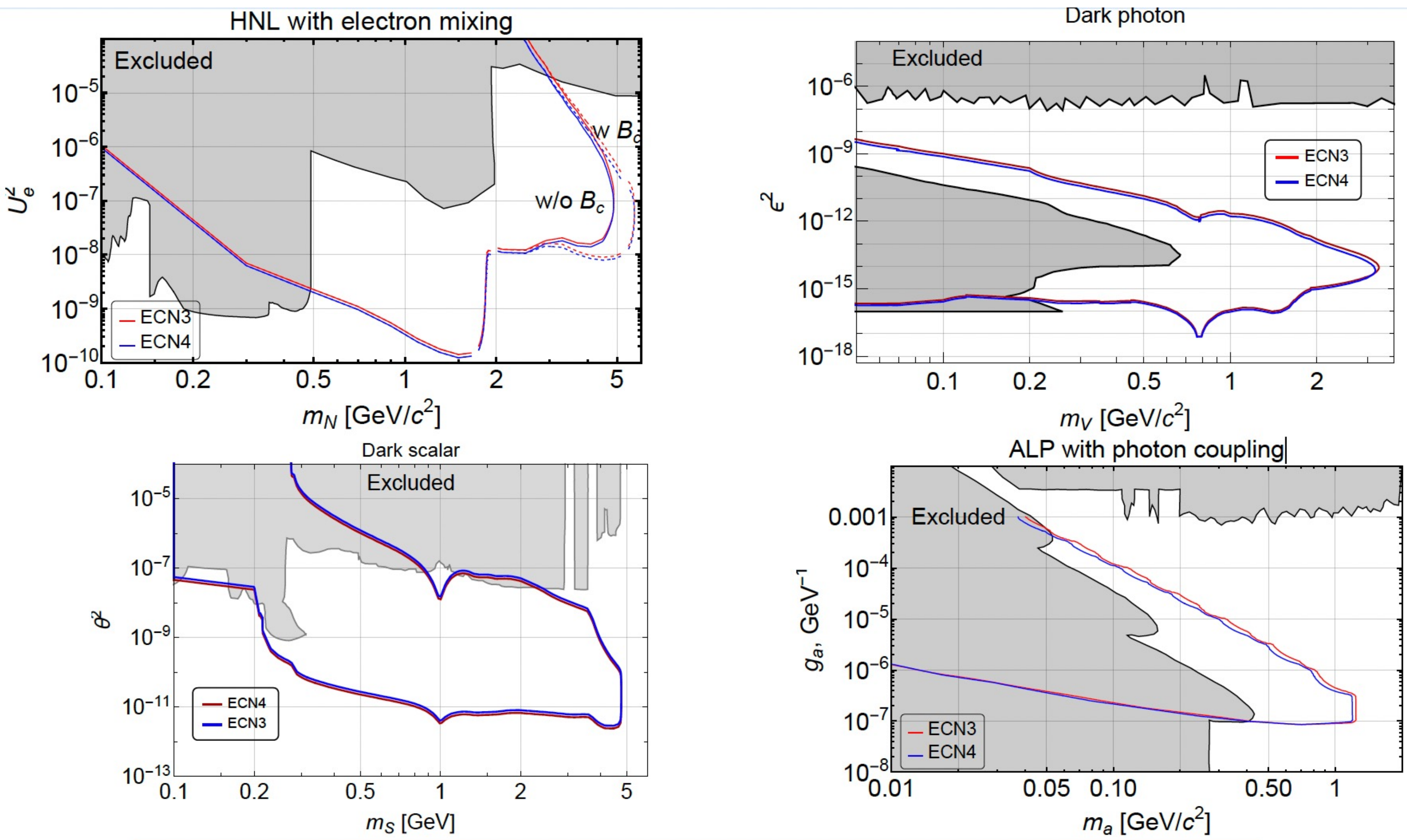
BDF/SHiP integration in TCC8/ECN3



SHiP
Search for Hidden Particles

Sensitivity to the dark sector assuming 2 x 10^{20} pot

LHC
Scattering and Neutrino Detector
at the LHC



Background suppression

Pythia/Geant simulation with complete description of detector and infrastructure

- ✓ *$\mathcal{O}(10^{11})$ muons (>1 GeV/c) per spill of $4\text{x}10^{13}$ protons*
- ✓ *4.5×10^{18} neutrinos and $3\text{x}10^{18}$ anti-neutrinos in acceptance in 2×10^{20} pot*

LHC

Scattering and Neutrino Detector at the LHC

SHiP Search for Hidden Particles

5 Key points for the suppression:

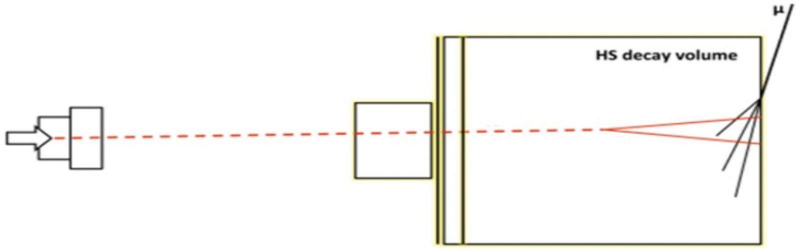
(a) Hadron stopper (5m thick iron) and (b) magnetic muon shield (25 m long)

(c) Background taggers UBT and SBT surrounding the decay volume

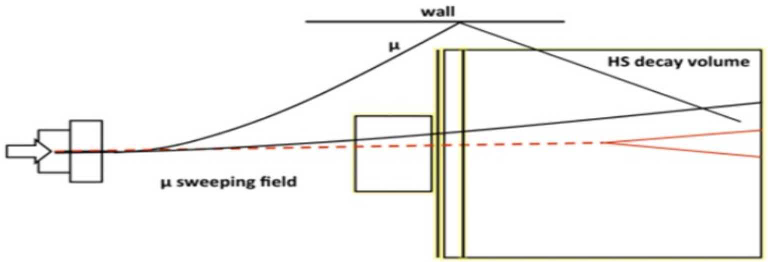
(d) Evacuated Decay Volume

(e) Reconstruction cuts: *fiducial volume, vertex quality, pointing to the dump target, timing window, PID*

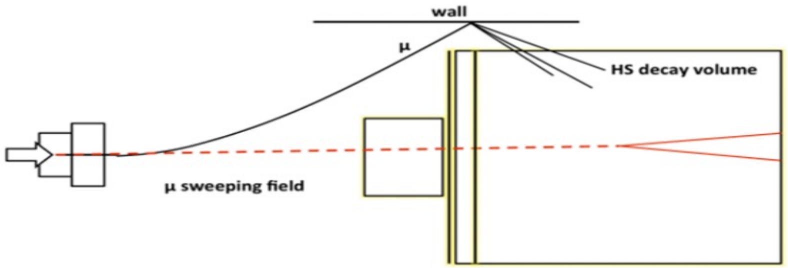
Backgrounds in decay search (fully reconstructible/partially with neutrinos) in 2×10^{20} pots/5 years



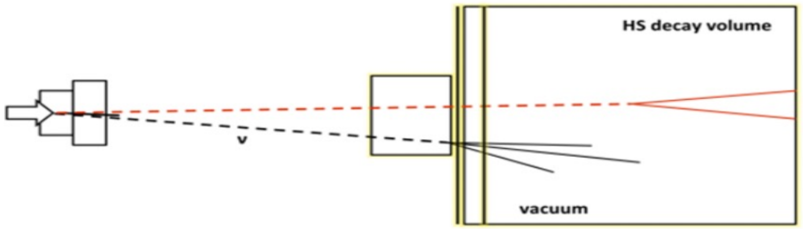
Cosmics: negligible



Muon combinatorial: $1.2\times10^{-2} \pm 1.2\times10^{-2}$



Muon DIS: 6×10^{-4}



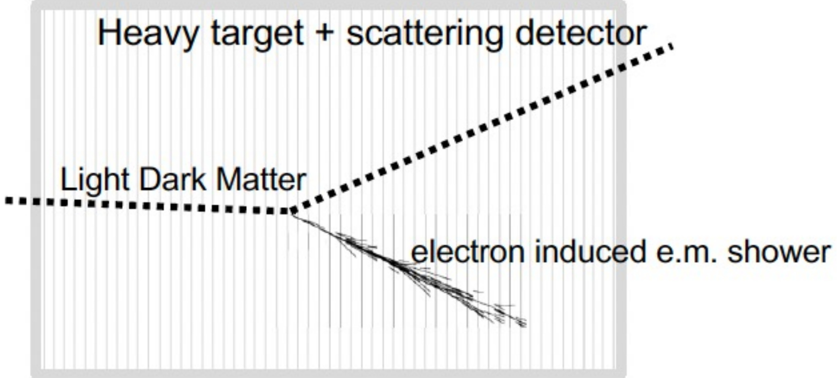
Neutrino DIS: 0.1 (fully) / 0.3 (partial)

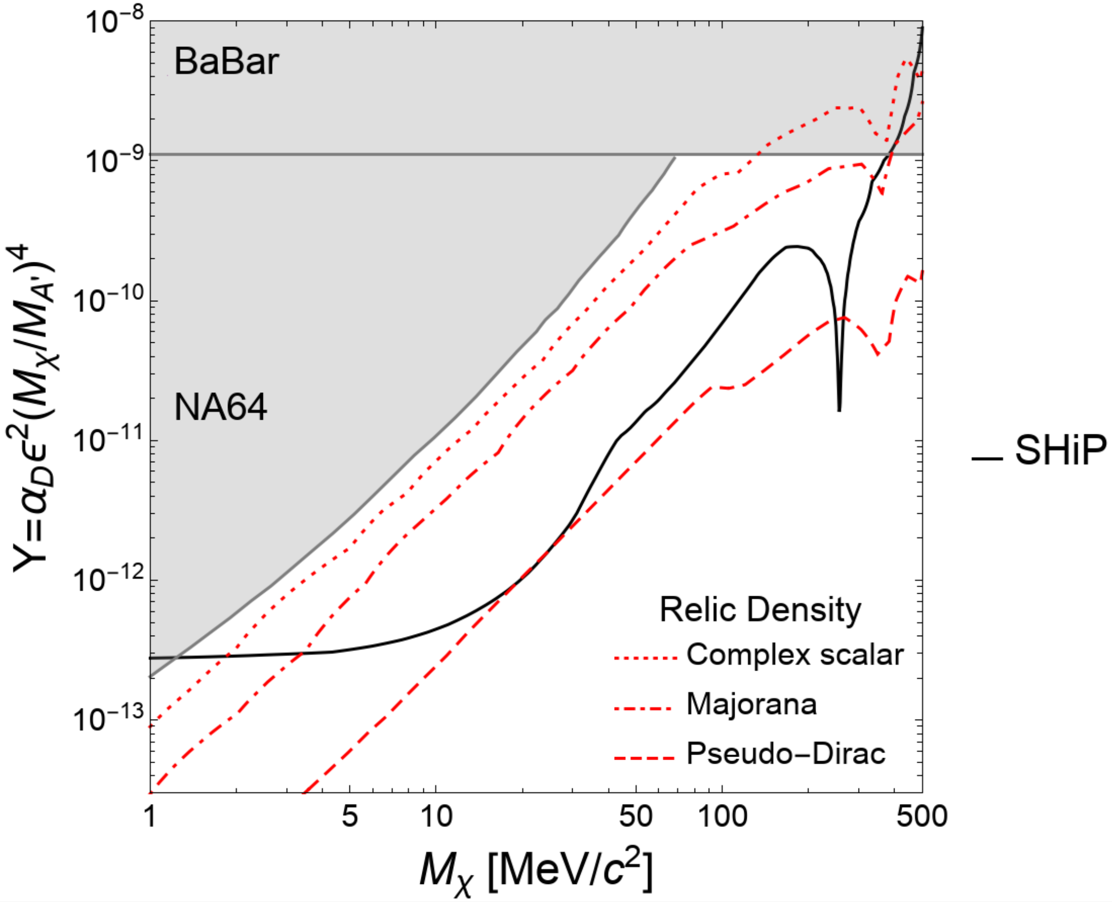
Sensitivity to light dark matter with the neutrino detector

	CC DIS interactions	CC DIS w. charm prod.
N_{ν_e}	8.6×10^5	5.1×10^4
N_{ν_μ}	2.4×10^6	1.1×10^5
N_{ν_τ}	2.8×10^4	1.5×10^3
$N_{\overline{\nu}_e}$	1.9×10^5	9.8×10^3
$N_{\overline{\nu}_\mu}$	5.5×10^5	2.2×10^4
$N_{\overline{\nu}_\tau}$	1.9×10^4	1.1×10^3

Extensive Neutrino Physics program and Charm physics with neutrinos

https://www.sciencedirect.com/science/article/pii/S0370157304002984





	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	68	41	60	38	207
Quasi - elastic scattering	9	9			18
Resonant scattering	-	5			5
Deep inelastic scattering	-	-			-
Total	77	55	60	38	230