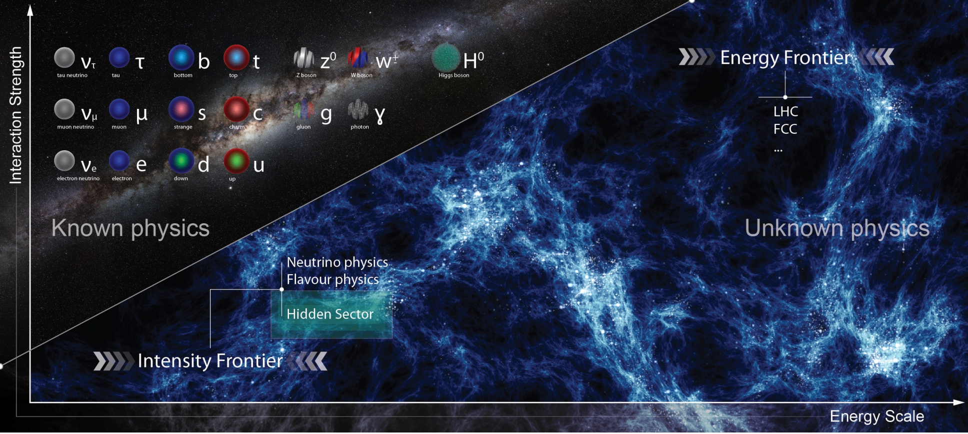


SND@LHC:

scattering and neutrino detector at the LHC for ν cross section measurement and LDM searches

Lesya Shchutska
EPFL

Uppsala University Seminar
June 4, 2020

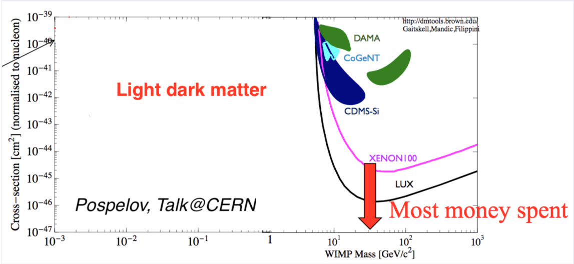
Explaining BSM phenomena

Our questions with no answer so far:

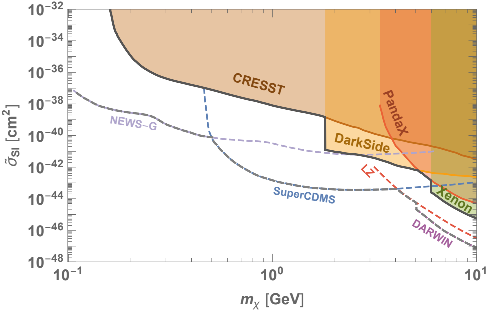
- what is dark matter?
- where has the antimatter gone?
- how do neutrinos acquire a mass?

What is the energy scale of New Physics?

- not the one we are focusing on currently, as e.g. for dark matter:



Light dark matter

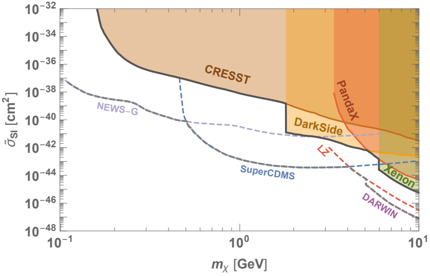


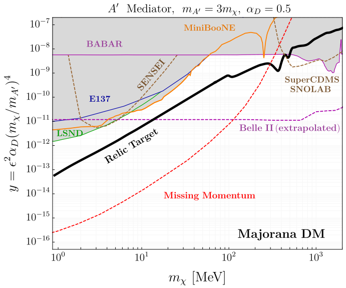
- weakly interacting dark matter is heavily constrained
- Lee-Weinberg bound $m_{DM} > 2$ GeV
  - can be lifted by introducing new light boson mediators
  - DM-SM coupling reduced, DM annihilation cross section increased
- "mediators" as "portals" to a "dark sector"
  - feebly interacting ("FIPs") and low mass

arXiv:1909.08632

Example: dark photon framework

Translation between direct detection and accelerator searches:

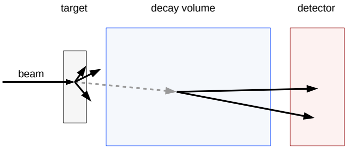




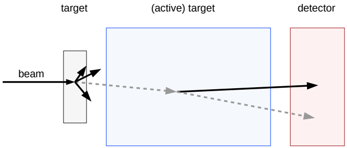
- dark photon A' as a mediator, and DM particles χ:
  - α_D - a coupling constant between A' and χ
  - ϵ - mixing parameter between A' and SM photon
  - m_χ and $m_{A'}$ - the masses of two new particles
  - parameter $y = \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$
  - in the $(m_{A'}, y)$ plane, the relic abundance curves are invariant under a change of the the α_D and the mass ratio

arXiv:1909.08632 arXiv:1808.05219

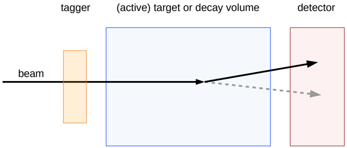
Man-made Light dark matter



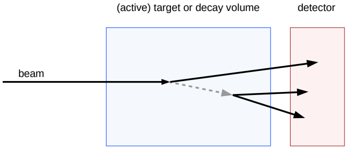
hidden particle decaying into visible particles



hidden particle scattering



missing energy or momentum



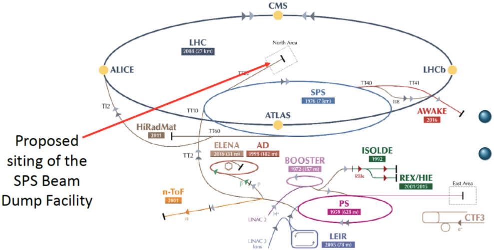
displaced vertex and/or peculiar final state

- provides sensitivity to extremely small couplings ϵ^2
- imperative: small or no background
- $E^{\rm miss}/p^{\rm miss}$ techniques sensitive to ϵ^2, others to ϵ^4

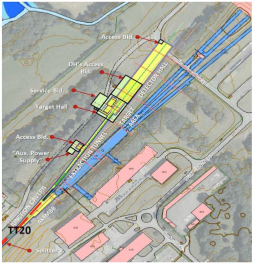
Physics beyond colliders

Search for Hidden Particles @ CERN-based Beam Dump Facility (BDF)

(CERN-PBC-REPORT-2018-001)

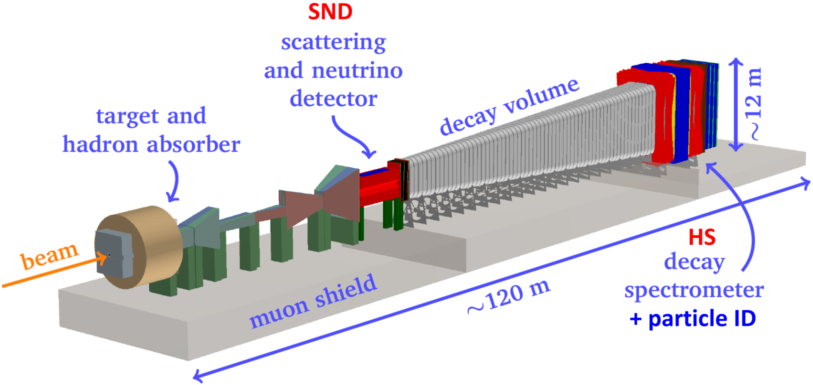


- slow extraction (1 sec)
- high intensity proton beam:
  - 4×10^{13} p/spill
  - 4×10^{19} pot/year
  - 2×10^{20} pot/5 years
- 5 years of BDF@SPS:
  - 10^{18} charm mesons
  - 10^{14} beauty mesons
  - 10^{16} τ leptons



existing tunnels
existing buildings
new installations

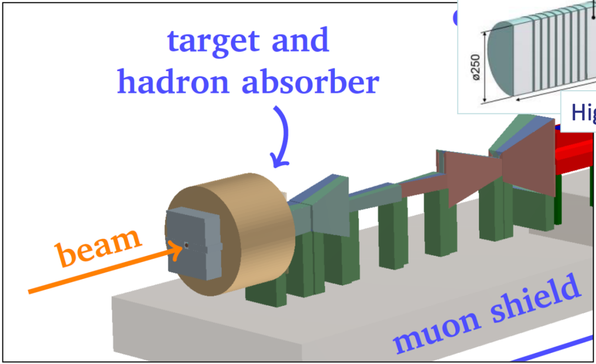
SHiP experiment

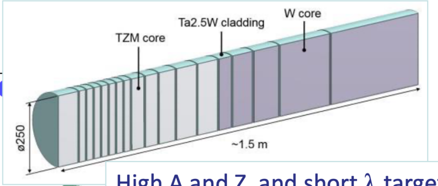


Dual detector system:

1. Hidden Sector detector (HS)
   - for new, weakly coupled, long-lived particles from the Hidden Sector
2. Scattering and Neutrino Detector (SND)
   - neutrino physics and Light Dark Matter searches

SHiP experiment: general requirements



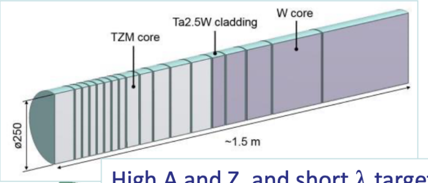


High A and Z, and short λ target

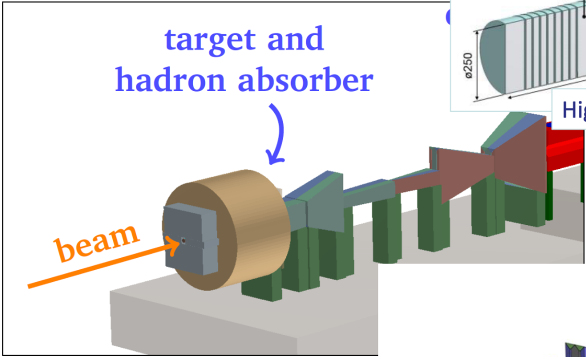
5 years of BDF@SPS ($2*10^{20}$pot):

- 10^{18} charm mesons
- 10^{14} beauty mesons
- 10^{16} tau leptons

SHiP experiment: general requirements

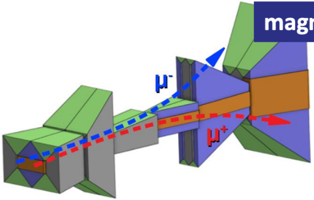


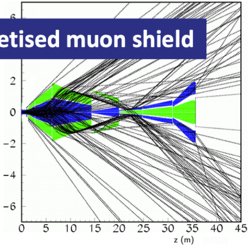
High A and Z, and short λ target



Hadron absorber
Strongly reduce the huge flux of SM particles, in particular pion and kaons before decay

magnetised muon shield



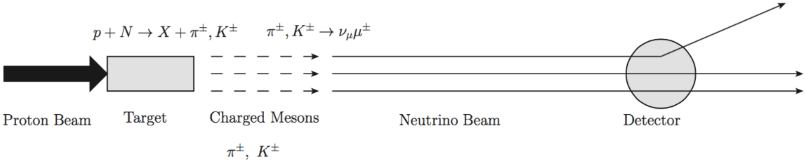


- μ rate reduced to ≈ 25 kHz
- μ spectrum validated with dedicated experiment in 2018

Scattering and Neutrino detector concept

High ν flux is expected @ BDF:

- unique opportunity to perform studies on ν_τ, ν_μ, ν_e (+ cc)@SHiP SND



ν physics potential:

- first ever observation of $\overline{\nu}_\tau$
- ν_τ and $\overline{\nu}_\tau$ physics with high statistics wrt state of the art
- ν-induced charm production studies
- ν_f cross section measurements

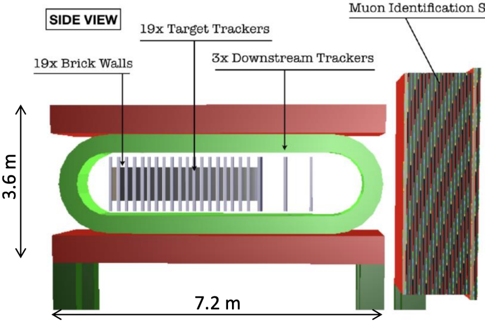
of ν CC DIS int. in SND target in 2x10[20] pot

	$\bar{E}$ [GeV]	CC DIS int.
ν_e	59	1.1×10^6
ν_μ	42	2.7×10^6
ν_τ	52	3.2×10^4
$\bar{\nu}_e$	46	2.6×10^5
$\bar{\nu}_\mu$	36	6.0×10^5
$\bar{\nu}_\tau$	70	2.1×10^4

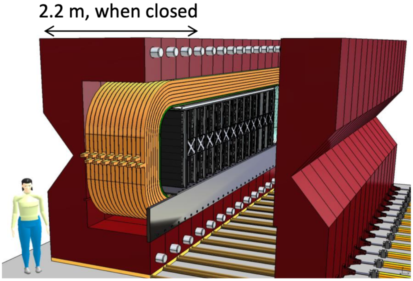
Experimental requirements:

- reconstruct ν interactions $\Longrightarrow$ Emulsion Cloud Chamber technique + TT
- tag ν flavor $\Longrightarrow$ ECC technique + μ ID system
- tag ν and $\overline{\nu}$ $\Longrightarrow$ magnetized target

Scattering and Neutrino detector



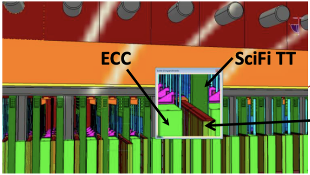
SHiP Progress Report
CERN-SPSC-2019-010 / SPSC-SR-248

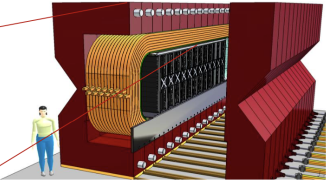


Experimental requirements:

- reconstruct ν interactions $\Longrightarrow$ Emulsion Cloud Chamber technique + TT
- tag ν flavor $\Longrightarrow$ ECC technique + μ ID system
- tag ν and $\overline{\nu}$ $\Longrightarrow$ magnetized target

The SND magnetized target



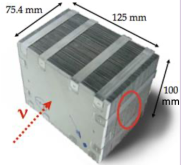


Compact Emulsion Spectrometer (CES)

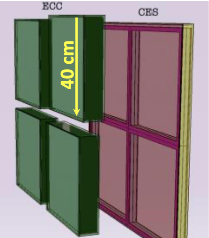
B field (H dir) ≈ 1.2 T

target mass ≈ 8 ton

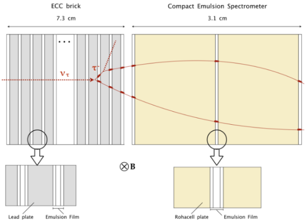
≈ 230 events in 1 ECC exp.
vtx definition @ μm resolution
ECC thickness ≈ 10 X_0 (shower ID)



ECC brick à la OPERA

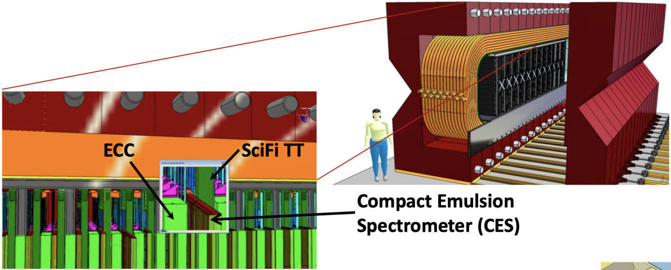


SND target wall



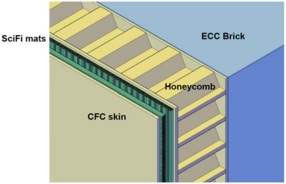
Techniques successfully exploited in the OPERA experiment

The SND magnetized target



B field (H dir)
≈ 1.2 T

Conceptual view (SciFi)



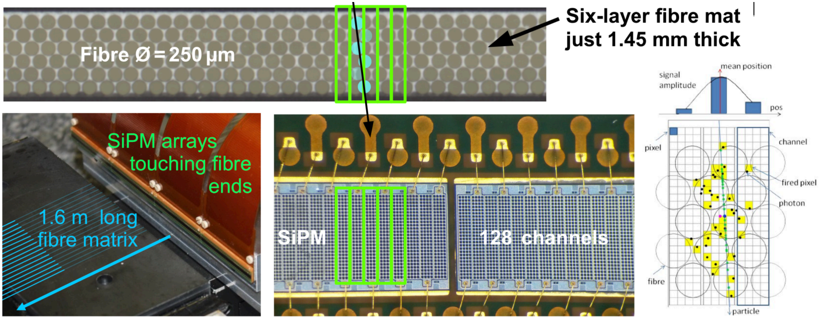
ν SciFi target tracker characteristics

provide time stamp and link μ track information from the target to the magnetic spectrometer with:

- $\sigma_{x,y} \sim 30 - 50\mu$m resolution
- 6 scintillating fibre layers, total thickness 3 mm $\sim 0.05\ X_0$
- multichannel SiPM at one end, ESR foils as mirrors at the other

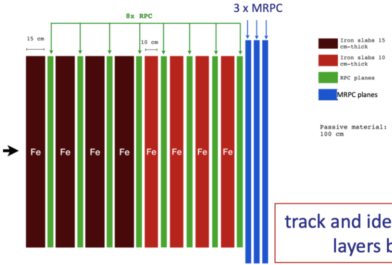
ECC+TT combination provides a total chargeID efficiency of $\sim 65\%$ for μ produced in ν_μ CC interactions

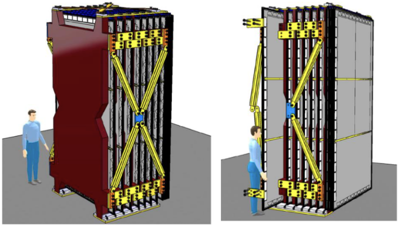
SciFi detector as Target Tracker



- staggered layers of 250 μm thin, double-clad scintillating fibres, to form 6-layered hexagonal packed mat
- read out by the SiPM arrays covering one fibre mat end
- signal is shared between the adjacent SIPM array channels allowing for a resolution better than pitch$/\sqrt{12}$
- mirror opposite to readout end increases the light yield by $\geq 65\%$ for the hits close to the mirror

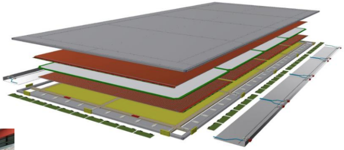
The SND muon identification system

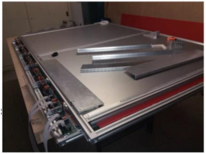




track and identify muons, and tag interactions (ν, μ) in the last layers before entrance window to HS decay volume

RPCs sensitive area of ~2×4 m^2
geometrical acceptance ~60%
$\varepsilon\mu ID$= 96.7%
Hadrons' mis-identification 1.5%.





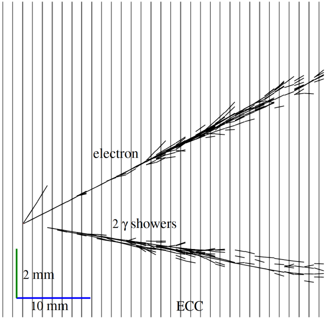
RPC prototypes built and successfully operated for muon flux and charm production measurement at SPS in 2018

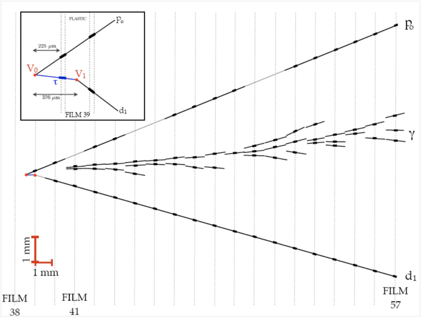
SciFi modules construction for LHCb upgrade

Movie with the sound (400 MB)

Neutrino identification

- ν_e: electron shower identification in the brick (left)
- ν_τ: disentanglement of τ production and decay vertices (right)
- ν_μ: muon reconstruction in the muon ID system



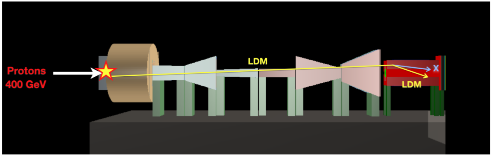


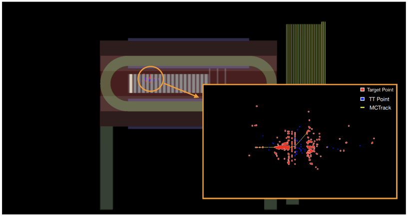
Tau event in the emulsion

More events online

Light dark matter identification

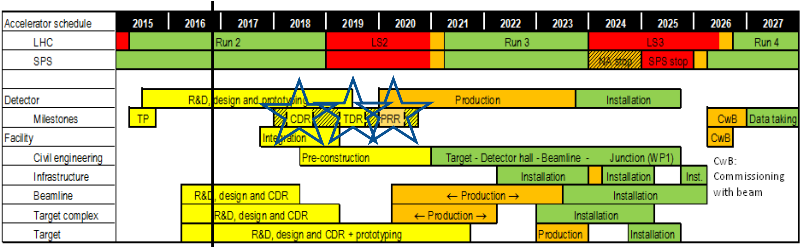
- benchmark: $A' \to \chi\chi$, $\chi e \to \chi e$ scattering in the emulsion target
- expect single EM shower w/o associated tracks:
  - $\overline{\nu}_e N \to eX$ background reduced by tagging extra activity at the vertex
  - $\nu_e e \to \nu_e e$ slightly kinematically different
  - if an excess is observed can switch to bunched beam and use TOF
  - excess can be observed in real time using target tracker (R&D ongoing)





SHiP timeline?

Flashback to 2016:



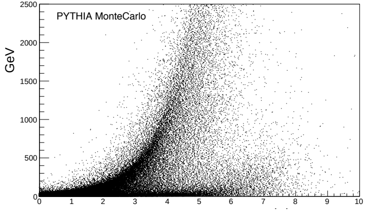
Now:

- CDR (Comprehensive design report) is out: http://cds.cern.ch/record/2704147
- no decision on BDF (CDR: https://cds.cern.ch/record/2703984) from CERN yet
- from decision to beginning of data taking: $\sim$ 6 years
- full dataset: $+5$ years

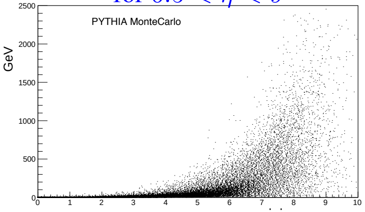
Meanwhile: Neutrinos in the LHC collisions

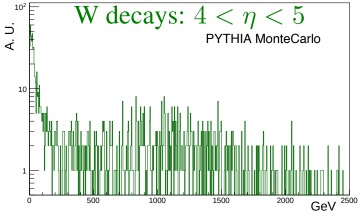
Neutrinos from W and b, c decays:

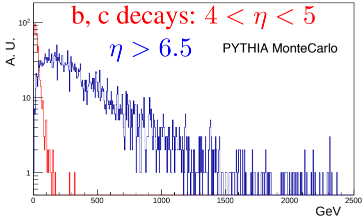
W decays: $\mathcal{B}(\rightarrow \nu_\tau) \approx 33\%$



b, c decays: $\mathcal{B}(\rightarrow \nu_\tau) \approx 5\%$
for $6.5 < \eta < 9$





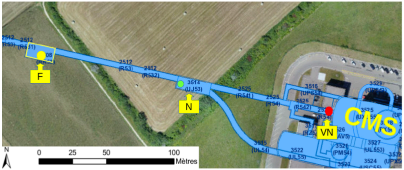


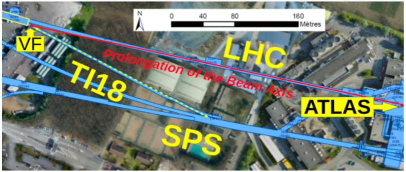
To get most energetic neutrinos need to be close to the beam axis!

arXiv:1804.04413, "CMS-XSEN: LHC Neutrinos at CMS. Experiment Feasibility Study", Buontempo, Dallavalle, De Lellis, Lazic, Navarria

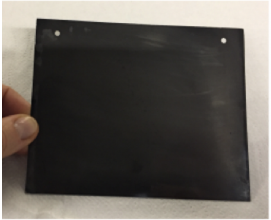
Investigation of background in different locations

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

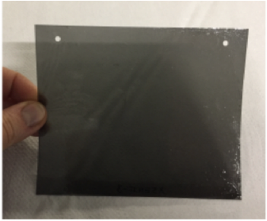




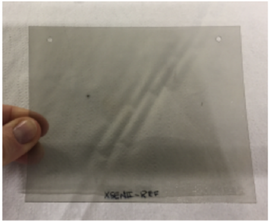
Results of emulsions exposure:



After 1.6 fb^{-1} under Q1 in S45



After 4.9 fb^{-1} in RR53



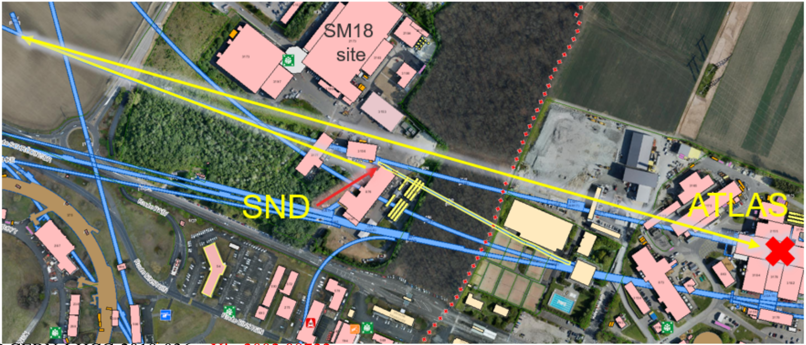
Reference

J. Phys. G: Nucl. Part. Phys. 46 (2019) 11500, "Physics Potential of an Experiment using LHC Neutrinos", Beni et al

Old LEP injection tunnels

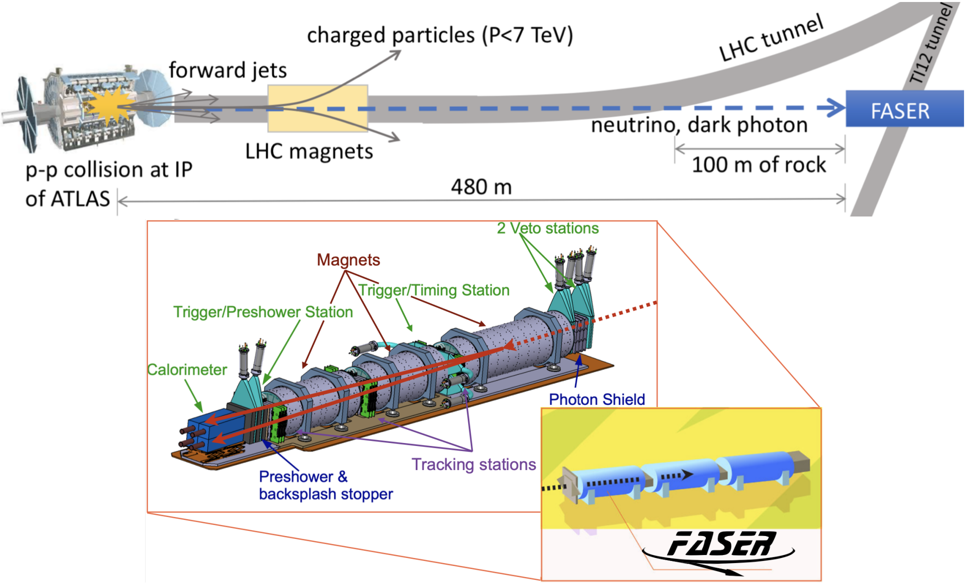
At the same time FASER studied sites near IP1: the decommissioned LEP injection tunnels are quite well protected

- FASER is being installed in TI12
- TI18 available for other measurements
- TI12 and TI18 are located symmetrically around IP1
- the backgrounds are reduced due to LHC magnetic bend and absorption in 100 m of rock:

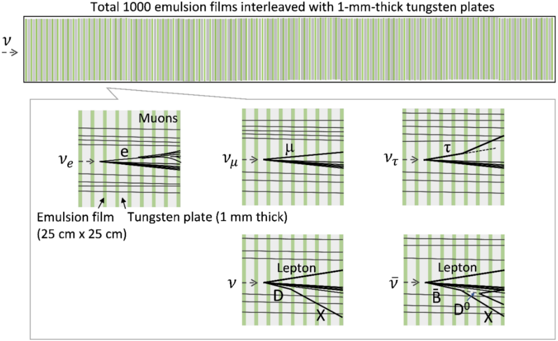


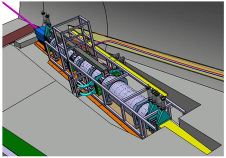
FASER TP CERN-LHCC-2018-036 arXiv:2002.08722

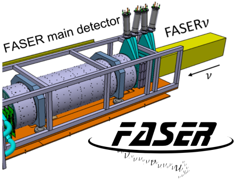
FASER: light and weakly interacting particles



FASERν: ν interactions



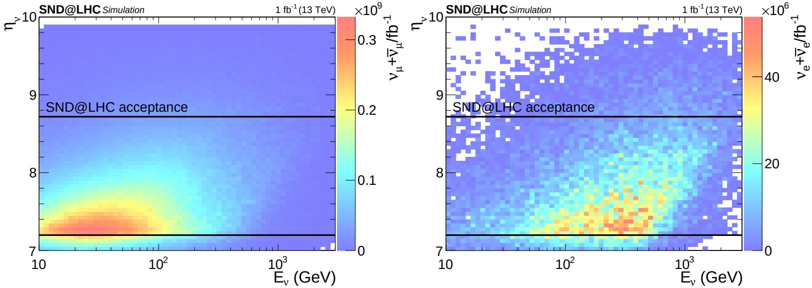




- a proposed extension to FASER
- fully passive detector: emulsion films with tungsten plates
- $\eta > 9.2$, 1.2 tonnes, 285 X_0, 10.1 λ_{int}
- pilot run with 30 kg detector in 2018 in TI18: 12.5/fb collected
- affordable muon background rate!
- analysis is ongoing: ~ 30 ν candidates are expected

arXiv:1908.02310 *Josh McFayden @ PBC*

Simulation of the transportation through machine elements and rock



- ν_μ are more abundant:
  - produced in $\pi^\pm$, $K^\pm$ decays
  - and in charm, beauty decays
- ν_e and ν_τ are more rare:
  - produced mainly in charm, beauty decays
- off-axis region ($\eta < 9$) is richer in ν from c and b

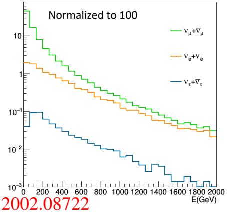
arXiv:2002.08722

Detectable neutrinos with 150/fb

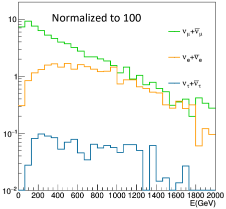
Table 2: (Third column) Integrated neutrino flux for 25 fb^{-1} for the different neutrino flavours at the target region. (Fifth column) Expected number of CC interactions for the different neutrino flavours for 25 fb^{-1}. (Sixth Column) Expected number of CC interactions for the different neutrino flavours for 150 fb^{-1} in the updated detector configuration.

Neutrino flavour	⟨E⟩ GeV (incident)	Neutrino Flux	⟨E⟩ GeV (interacting)	CC Interactions Initial config	CC Interactions Updated config
ν_μ	150	4.6×10^{11}	460	62	975
ν_e	390	5.9×10^{10}	710	21	332
ν_τ	420	3.0×10^{9}	720	1	18
$\bar{\nu}_\mu$	150	4.0×10^{11}	480	27	429
$\bar{\nu}_e$	390	6.2×10^{10}	740	11	174
$\bar{\nu}_\tau$	360	2.9×10^{9}	720	0	7
TOT		9.87×10^{11}		122	1935

Incoming ν



Interacting ν

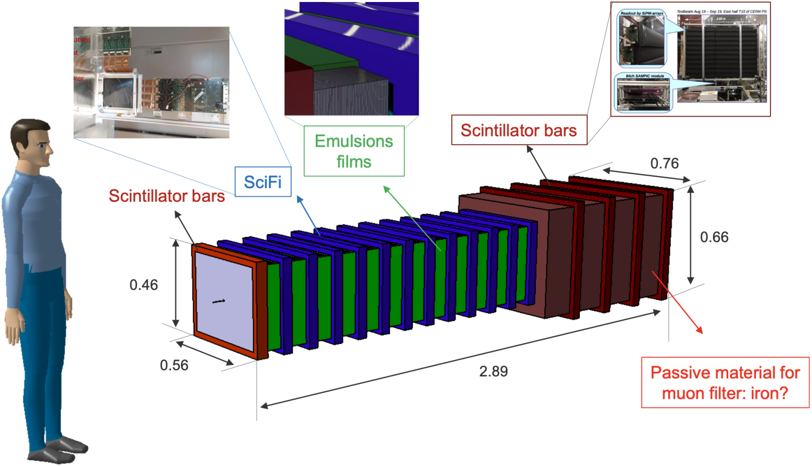


- total target mass $\sim$850 kg
- with 25/fb expect to detect about 120 ν interactions
- with 150/fb expect to get almost 2000 ν interactions

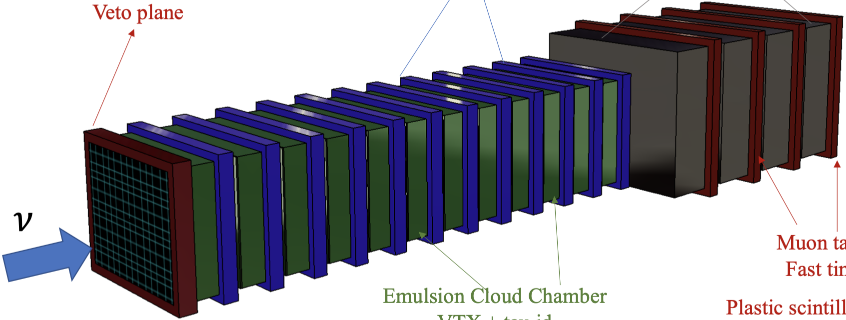
arXiv:2002.08722

SND@LHC staged approach

- 2021: commissioning of the electronic detectors on surface
- 2022: data taking with an intermediate detector configuration
- 2023: addition of more SciFi layers



SND detector setup

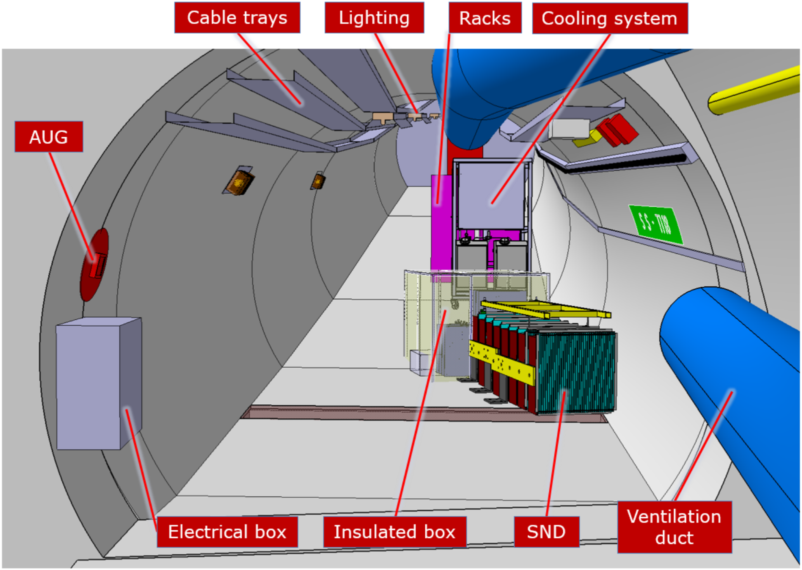


TI18

Where?

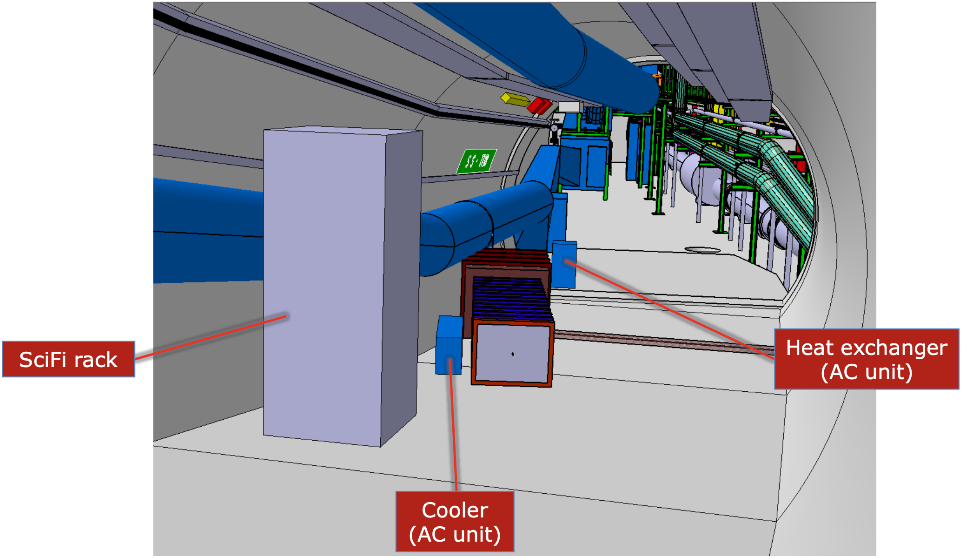
TI18

Preliminary integration



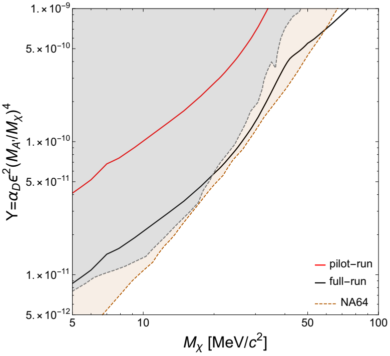
arXiv:2002.08722

Preliminary integration



LDM sensitivity

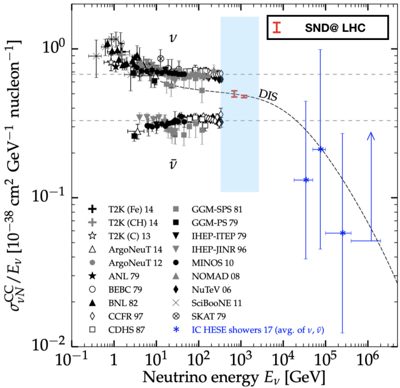
- PBC and EPS benchmark dark photon scenario:
  - $\alpha_D = 0.1, \dfrac{m_\chi}{m_{A'}} = \dfrac{1}{3}$
- signal production:
  - rare meson decays
  - proton bremsstrahlung
  - Drell Yan production
- signal in the detector:
  - dark photon decays promptly to 2 DM particles
  - consider scattering off atomic electrons
  - no scattering off the nuclei at the moment



arXiv:2002.08722

Neutrino cross section measurement

- while finding or not DM is a long shot, neutrinos are for sure there
- unprecedented access to ν_e, ν_μ, ν_τ at TeV energies:
  - expected neutrino interactions in η range (7.1, 8.1): 350/ton
  - expected neutrino interactions in η range (8.0, 9.5): 950/ton
- further optimisation of detector layout to maximise ν interactions



Current developments and next steps

Detector layout is being optimized, key features to consider:

- sampling fraction of SciFi with ECC bricks:
  - currently sensitive layer is every $10X_0$: too coarse?
- timing detector granularity:
  - target time resolution of 50 ps achieved with scintillator strips
  - consider more granular detector – depending on event occupancy
- SciFi timing performance:
  - timing measurement developed for SHiP (not available in LHCb yet)
  - value measured with cosmics 350 ps
  - recent DESY testbeam data indicate improved timing resolution in EM showers

Also discuss the **services in the tunnel and transportation options**:

- need to provide cooling & ventilation, powering & lighting, signals, readout and networking, etc
- and some smart way to assemble the detector in the tunnel!

34 cm clearance:

Muscle considerations:

Table 1: The most restrictive sub-components to be transported

Part	Dimensions (cm)	Unit weight (kg)	Number of units
Veto plane	100 x 100 x 25	20	1
Muon detector			
SAMPIC boards	50 x 50 x 30	10	6
SAMPIC Power Supply	50 x 30 x 30	8	1
HV+LV supplies, crate	50 x 50 x 30	20	1
Veto plane	60 x 60 x 20	4	1
Muon timing plane	80 x 80 x 20	6	5
Muon x,y plane	80 x 80 x 20	8	6
SciFi			
Modules	100 x 100 x 25	15	4
Power supplies, crates, switch	50 x 50 x 30	20	6
Iron block	80 x 20 x 20	230*	32
Rack	50 x 50 x 170	25	2
Chiller	100 x 60 x 40	80	2
Emulsion brick	39.7 x 42.6 x 8.5	9	4

*It can be divided in smaller pieces to reduce weight and can pass below the LHC machine