SHiP experiment challenges, IHEP/UCAS Beijing, 26.01.2026

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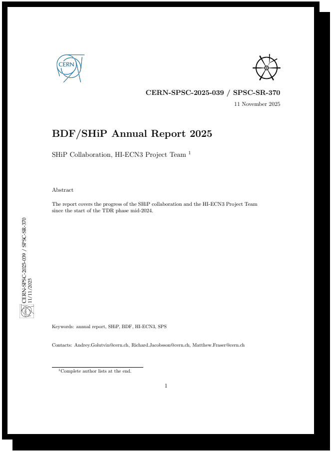
SHiP
Search for Hidden Particles

Outline

- Setting the scene
- The Active Muon Shield
- The Scattering Detector
- Background Tagging
- Decay Spectrometer
- Summary and outlook



CERN-SPSC-2025-039 / SPSC-SR-370

11 November 2025

BDF/SHiP Annual Report 2025

SHiP Collaboration, HI-ECN3 Project Team [1]

Abstract

The report covers the progress of the SHiP collaboration and the HI-ECN3 Project Team since the start of the TDR phase mid-2024.

Keywords: annual report, SHiP, BDF, HI-ECN3, SPS

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[1]Complete author lists at the end.

1

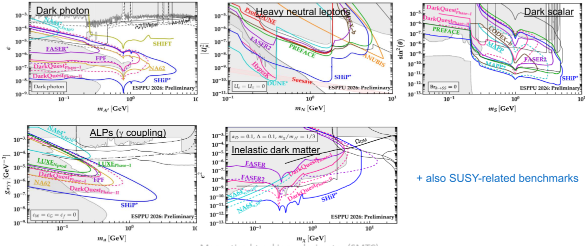
CERN-SPSC-2025-039 / SPSC-SR-370 11/11/2025

(only 62 pages)

Setting the scene

Search for Hidden Particles — also known as **Feebly Interacting Particles**

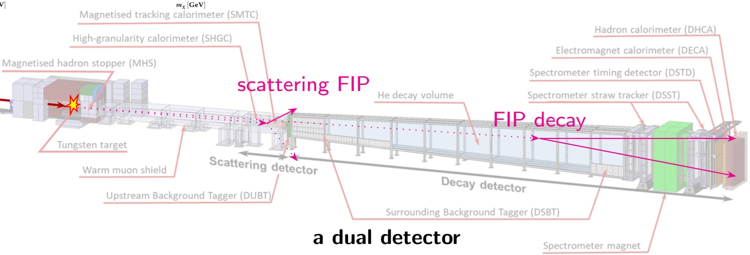
heavy neutral leptons, axion-like particles, dark photons/scalars, ...



+ also SUSY-related benchmarks

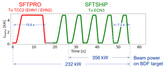
p (400 GeV)

10^6 spills/yr



a dual detector

Nominal Design Parameter	Value
Beam type	proton
Beam momentum [GeV/c]	400
Beam pulse intensity [$\times 10^{13}$ p]	4.0
Spill length [s]	1
Beam pulse power [kW]	2560
Average beam power [kW] (7.2 s)	356
POT [$\times 10^{20}$ p over 15 years]	6.0



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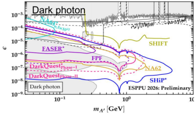
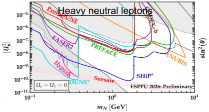
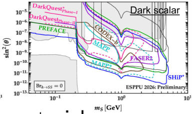
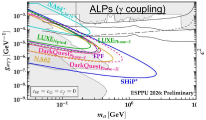
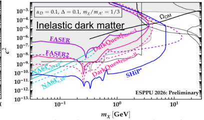


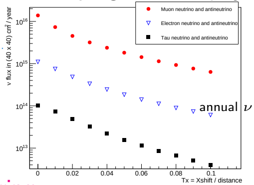








+ rich program of ν **physics**

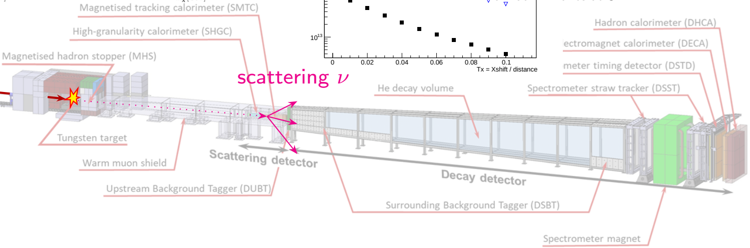


annual ν fluxes at SD

p (400 GeV)

scattering ν

10^6 spills/yr



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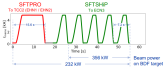


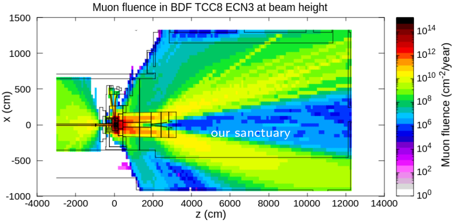
Setting the scene

Search for **Hid**den **P**articles

our challenge: suppress bkg !

from ν and μ

must suppress μ flux by $\sim 10^6$



graph by Dominika Wasik, CERN

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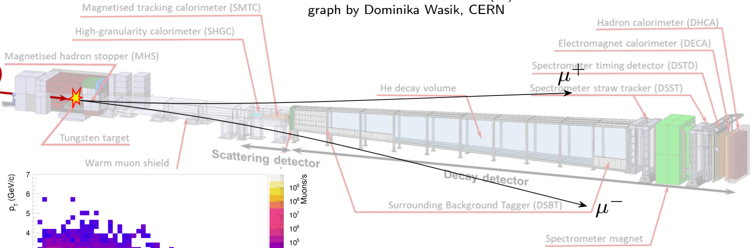

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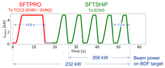
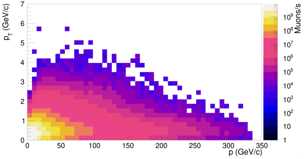




A. Akmete et al., JINST 12 (2017) P05011

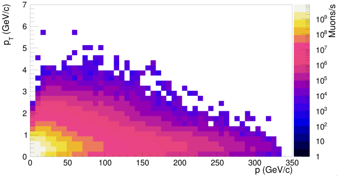
An important enemy of SHiP: the muon flux out of BDF

MC simulation

In a 2018 campaign, we simulated about 65 billion p-N events, $N = p,\ n$ (with enhancements of various processes, resonances to dimuons, c-, b-production, ...).

Stored about 0.5 billion muons that exited from the 4.5 m HA with at least 10 GeV.

At BDF/SHiP we expect ∼18 billion muons to come out of the 4.5 m HA with at least 10 GeV at each SPS 1 s spill



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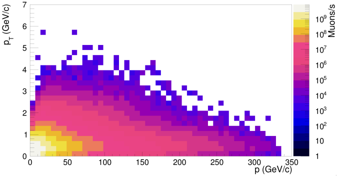
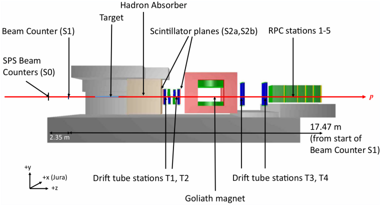
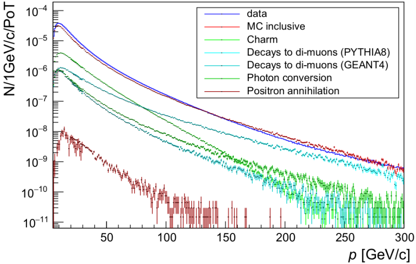


Experimental studies



SPS muon flux experiment performed to validate FairShip full simulation doi: 10.1140/epjc/s10052-020-7788-y

Remarkable agreement obtained



The Active Muon Shield

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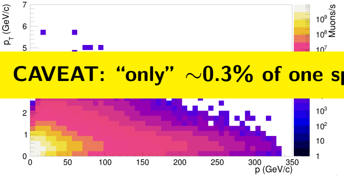
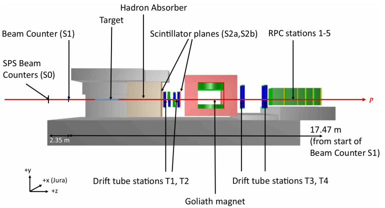


CAVEAT: “only” ∼0.3% of one spill

Experimental studies



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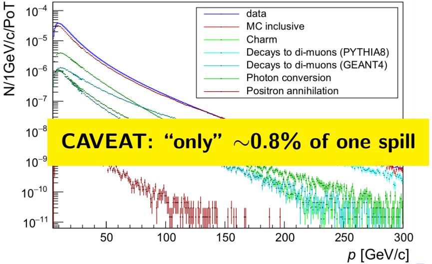
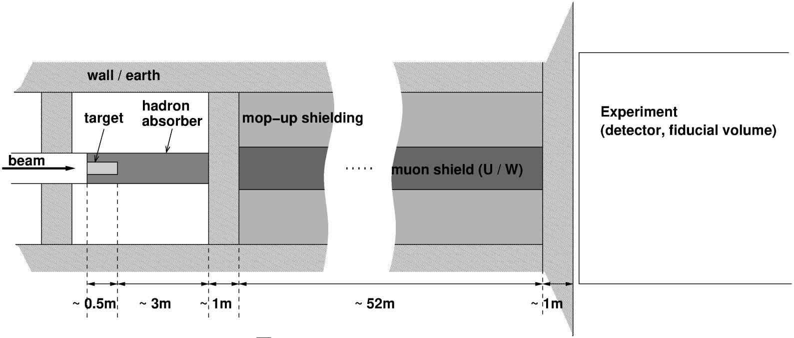


CAVEAT: “only” ∼0.8% of one spill

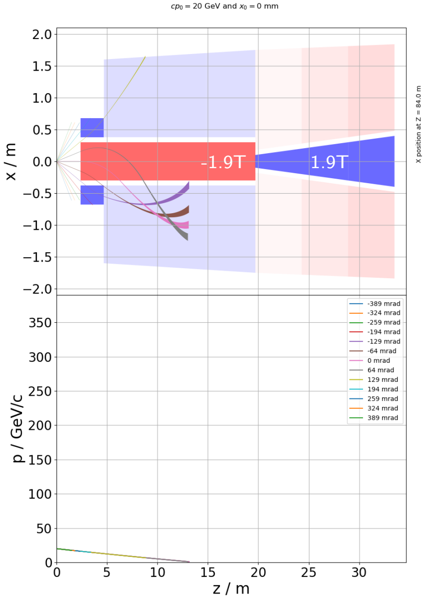
Setting the scene

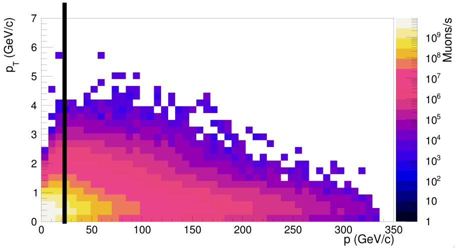
Original expression of interest (2013): **passive** muon shield



⇒ **explore magnetic sweeper (active!)**

The Active Muon Shield: alternate polarity scheme JINST 12 (2017) P05011

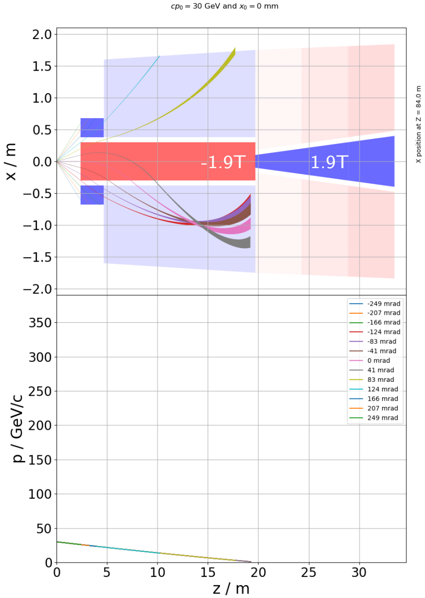


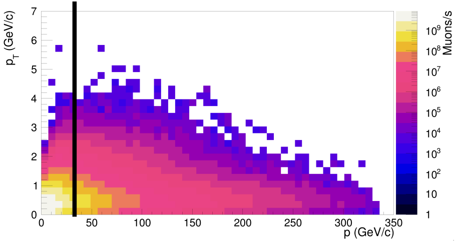


$\mathrm{atan}(p_x/p_z)$ scanned along the vertical line

Simple toy program for illustration

- xz trajectory (no y)
- constant B_y by area
- non-stochastic energy loss
- mult. scatt. cumulative σ shown as an envelope





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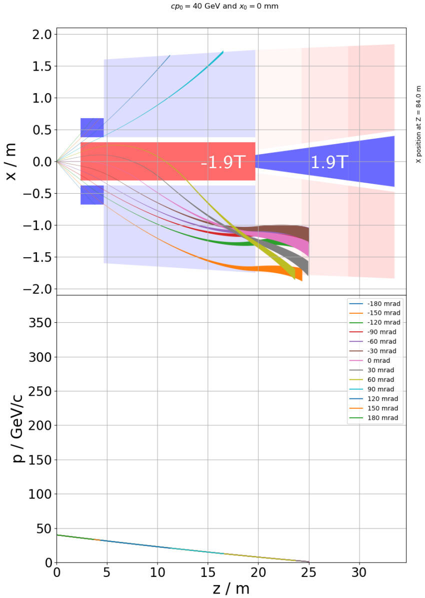

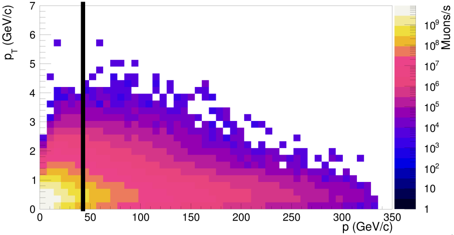

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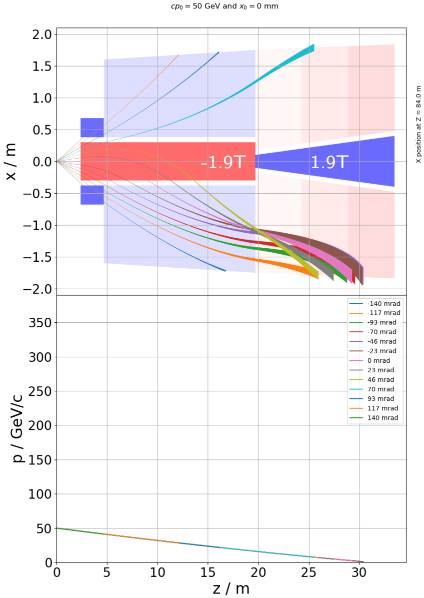

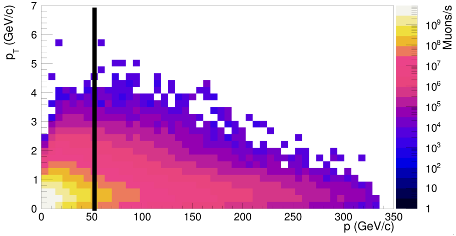

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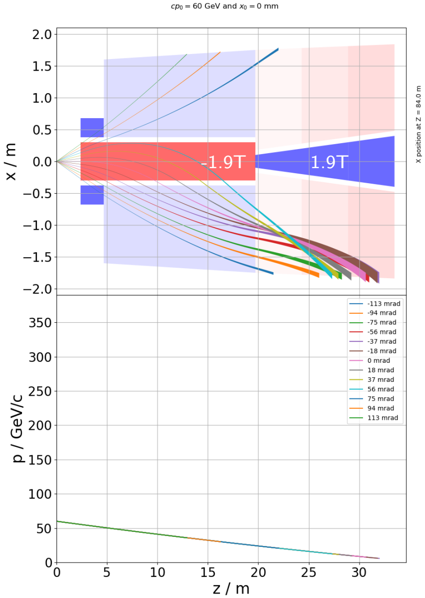

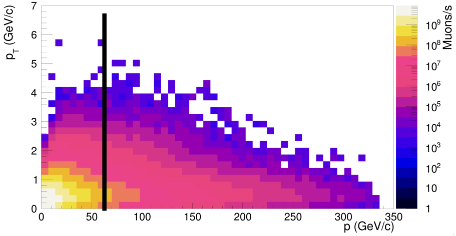

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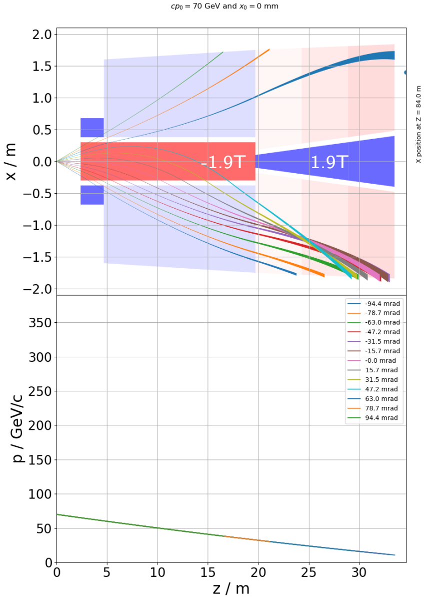

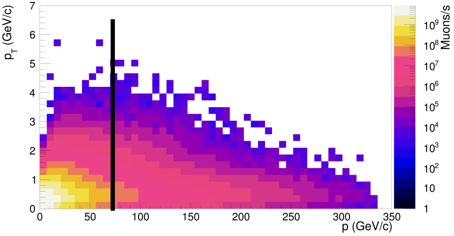

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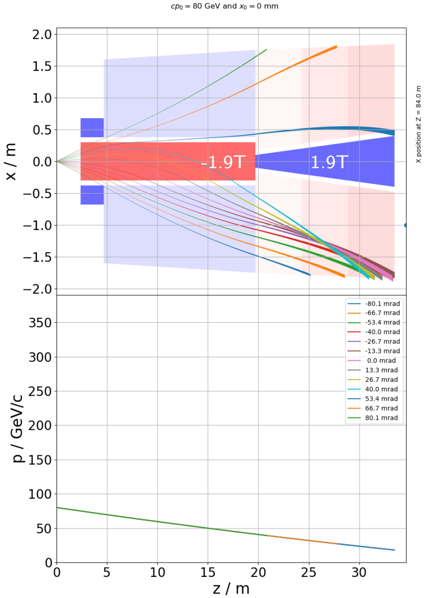

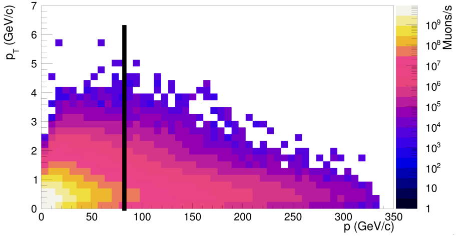

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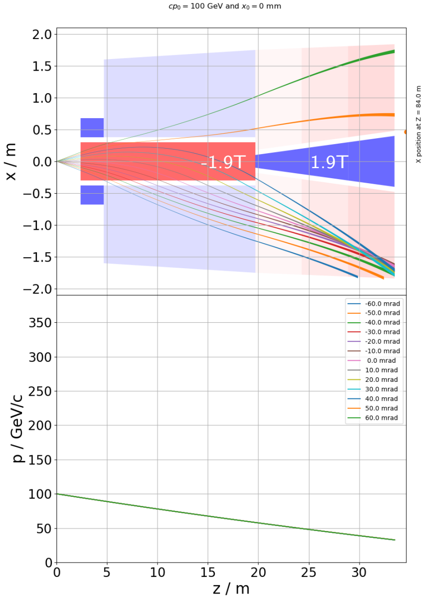

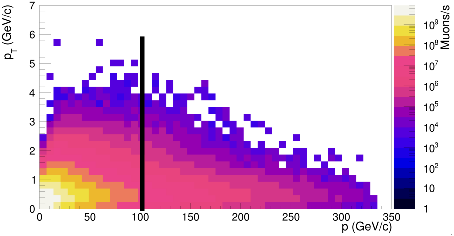

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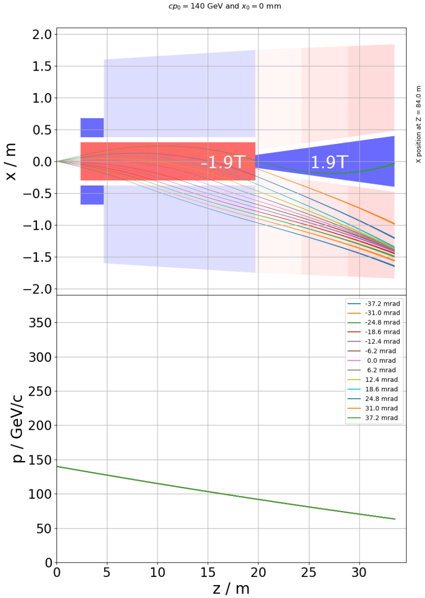

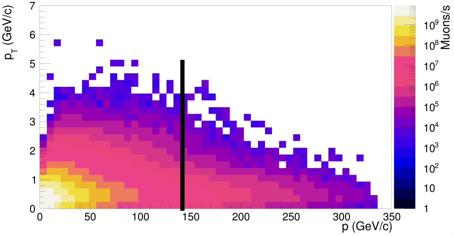

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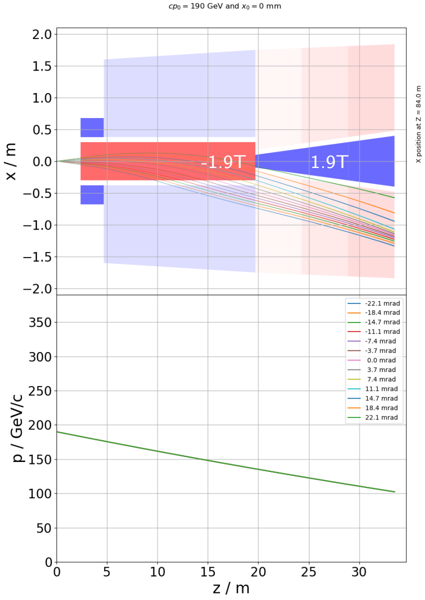

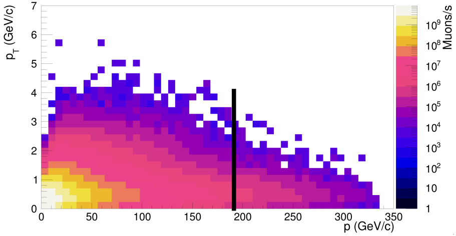

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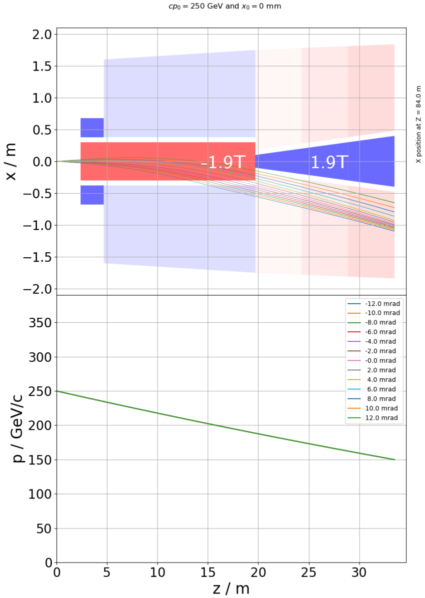

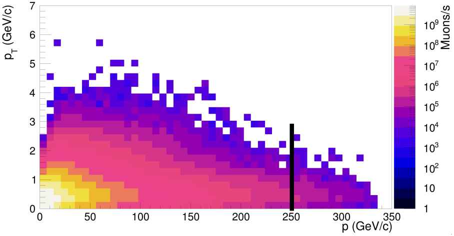

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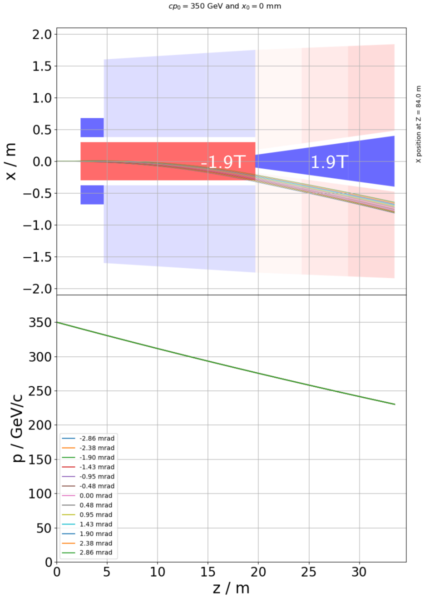

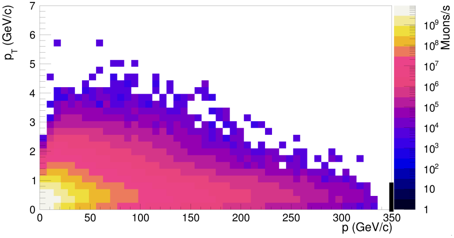

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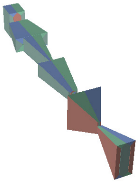
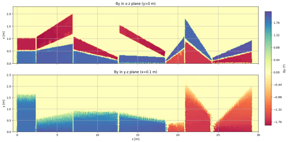
Muon Shield variants

Minimal Iron Yoke

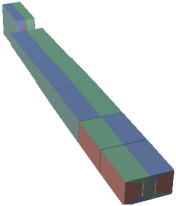
Only warm coils, saturated iron

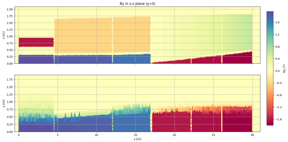




Tuned Return Yoke

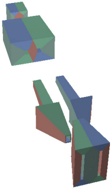
Only warm coils, allow for dilution of iron with non-magnetic shielding material

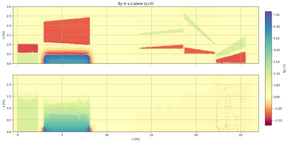




Hybrid (with SC)

Superconducting coil in section 1, then minimal saturated iron with warm coils





All three optimized using MuonsAndMatter framework at UZH

Luis Felipe Cattelan, Guglielmo Frisella, Melvin Liebsch, Shah Rukh Qasim

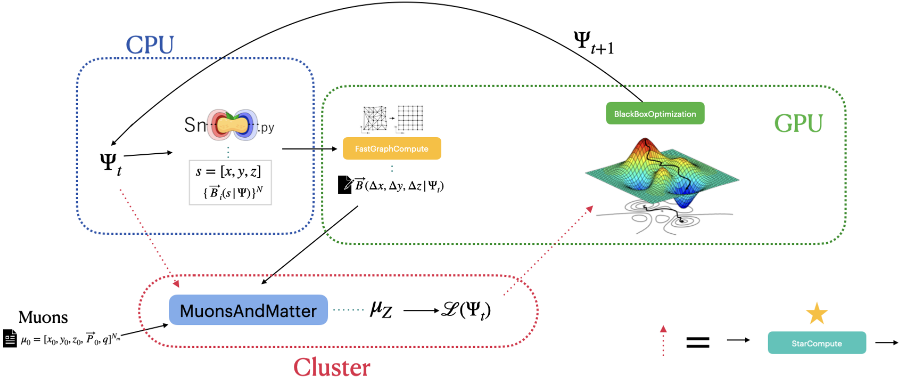
The Active Muon Shield: Optimization framework

Luis Felipe Cattelan, Guglielmo Frisella, Melvin Liebsch, Guillermo Mendizabal, Shah Rukh Qasim

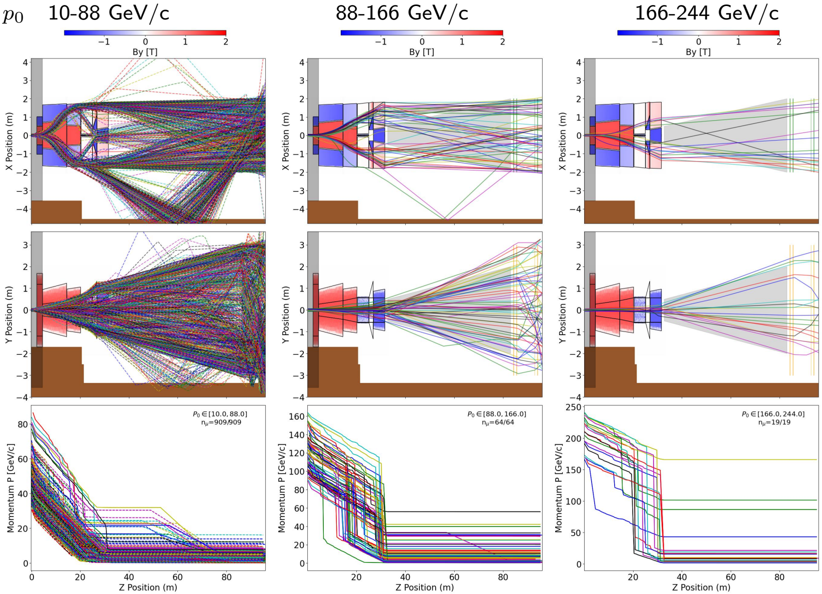
Optimized 2 warm variant and 1 hybrid variant

- Using a μ bkg sample (few millions)
- Standalone Geant4 simulation
- With "field maps on the fly" (snoo.py)
- Run on dedicated CPU and GPU clusters (at UZH)

but then check perf. over $5 \cdot 10^8$



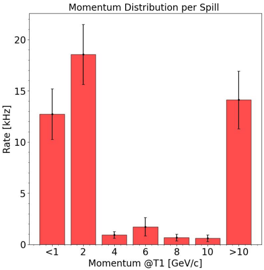
The Active Muon Shield: some results



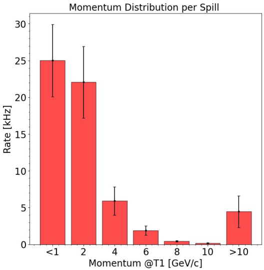
Achieved sufficient performance with all variants
(∼50 kHz in tracker station T1, no p cut)

Guglielmo Frisella

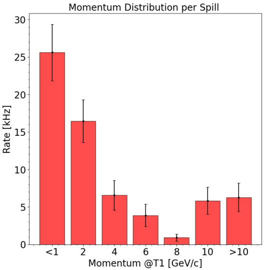
Minimal Iron



Tuned return yoke

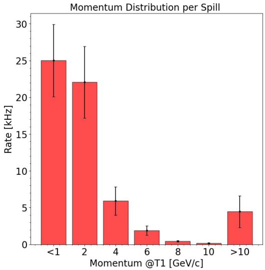


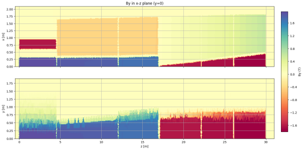
Hybrid

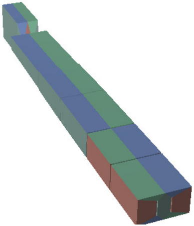


The Active Muon Shield: some results

Achieved sufficient performance with all variants
($\sim$50 kHz in tracker station T1, no p cut)



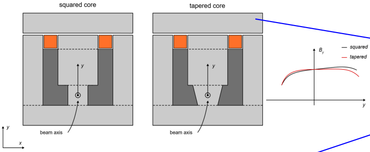


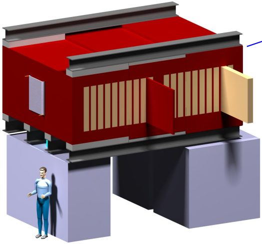


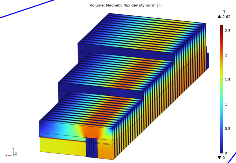
The TRY variant was chosen (end of 2025)

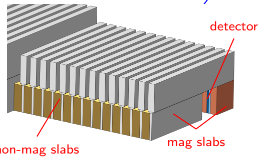
Conceptual design studies

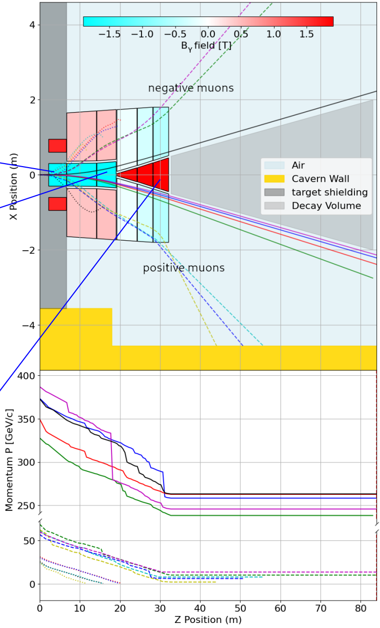
- MHS, taken over by CERN/TE-MSC-NCM Vittorio Ferrentino, Melvin Liebsch
- Started Scatt. Det. integration studies Vincenzo Loschiavo
- Started developing concept of 4.8 m long TRY magnet Pablo Santos Diaz







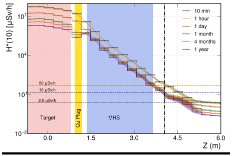


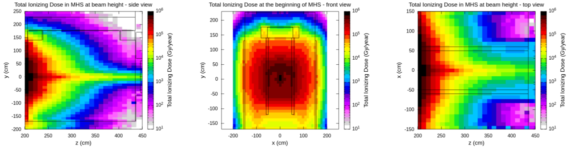


sometimes called Hadron Absorber, HA

- first magnet of the muon shield, but embedded in target complex
- same for all variants of MS
- reduced MHS length from 4.5 m to 2.3 m, based on radiation studies
- preserves space for experiment

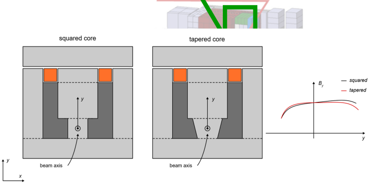
May be beneficial for muons shield variant with a SC magnet (allows coming closer to target, thus use reduced transverse dimensions)

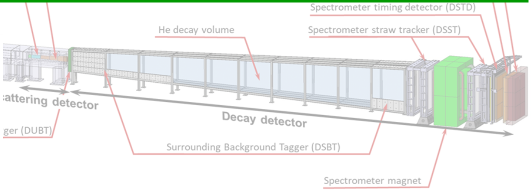




Olin Pinto

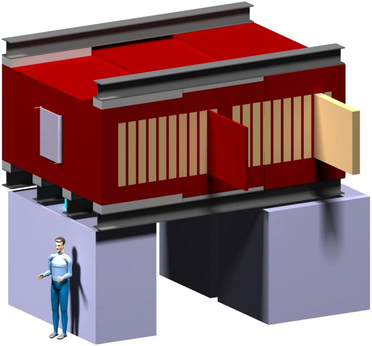
Dominika Wasik

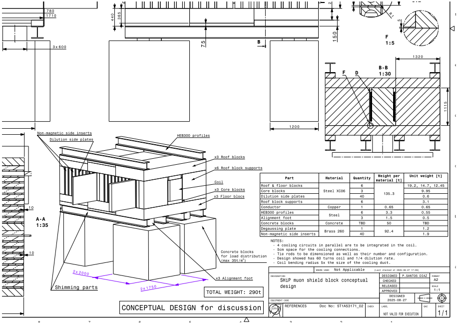




Conceptual design of a template Tuned Return Yoke magnet

Pablo Santos Diaz





Part	Material	Quantity	Weight per material [t]	Unit weight [t]
Roof & floor blocks	Steel XC06	6	135.3	19.2, 14.7, 12.45
Core blocks		3		9.95
Dilution side plates		40		0.6
Roof block supports		6		3.1
Conductor	Copper	1	0.65	0.65
HEB300 profiles	Steel	6	3.3	0.55
Alignment foot		3	1.5	0.5
Concrete blocks	Concrete	TBD	50	TBD
Degaussing plate	Brass 260	1	92.4	1.2
Non-magnetic side inserts		40		1.9

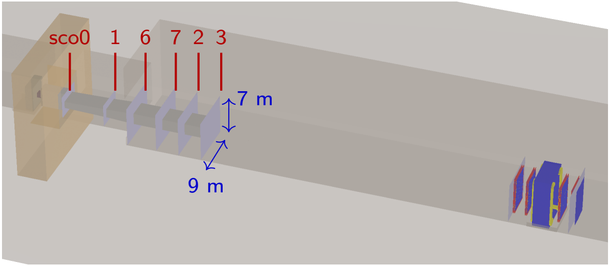
Magnet yoke:

- High quality low-C iron for core, floor/roof, and side slabs (in red)
- Non magnetic dense material for **insertable slabs** (light brown) adequately chosen stainless steel grade
- About 200-300 tons per magnet (5-6 magnets)

Coils: $\sim$ 30-60 kA, water cooled, $\sim$ 10-50 kW, $I_{\text{nom}} \approx 250$ A, 1-3 tons

The Active Muon Shield: monitoring system

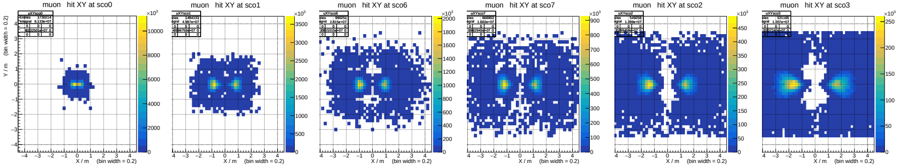
What will be the muon rates inside/around the MS ?

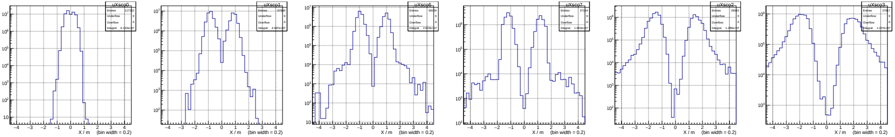


Here an example, with some scoring planes.

→ color scale × 0.74 to get rate in Hz/cm^2

→ ordinate log scale × 1.5 to get rate in Hz/mm

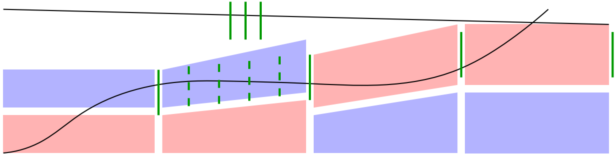




Challenge: Measure full muon tajectories and p all along

In both planes, multiple scattering heavily smears the trajectories.

Muons lose about 1.5 GeV/m.

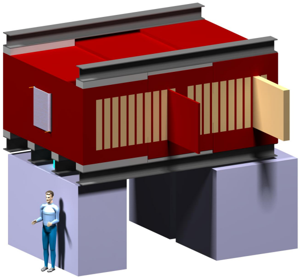


Where to place detectors ?

How many planes are needed ?

At what distance from each other ?

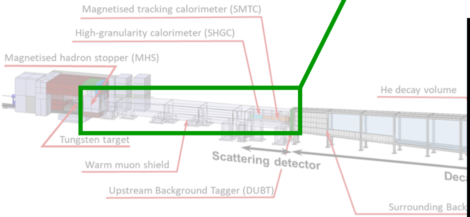
Which type of detectors ?
(technology, resolution, rate capability)

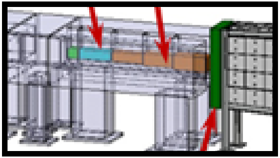


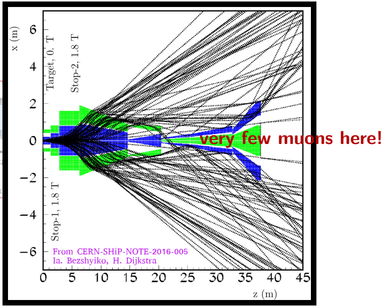
The Scattering Detector

Muon shield and Scattering (LDM & neutrino) Detector

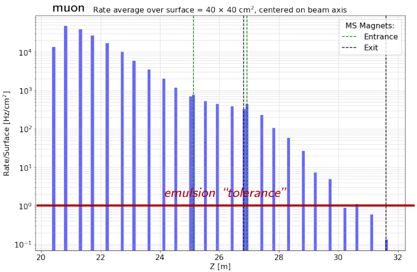
- Full-warm muon shield fills whole space between target and decay volume
- Integrate Scattering Detector inside the Muon Shield magnets







The Scattering Detector



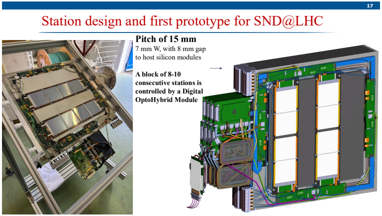
	CC DIS (W)	Charm CC DIS (W)	CC DIS (Fe)	Charm CC DIS (Fe)
N_{ν_e}	6.8×10^4	4.1×10^3	1.6×10^5	9.8×10^3
N_{ν_μ}	2.0×10^5	8.7×10^3	4.6×10^5	2.0×10^4
N_{ν_τ}	2.1×10^3	1.2×10^2	5.1×10^3	2.8×10^2
$N_{\bar{\nu}_e}$	1.4×10^4	7.4×10^2	3.7×10^4	1.9×10^3
$N_{\bar{\nu}_\mu}$	4.4×10^4	1.7×10^3	1.1×10^5	4.1×10^3
$N_{\bar{\nu}_\tau}$	1.5×10^3	8.6×10^1	3.8×10^3	2.1×10^2

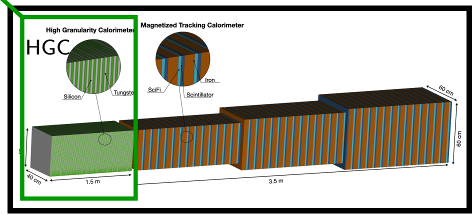
Table 2: Neutrino interaction yields per year in the SND High Granularity Calorimeter, and in the Magnetised Tracking Calorimeter.

- Originally, focused on emulsions for SD, great spatial resolution, resolve dble-vertex/kink in $\nu_{\tau(\bar{\tau})}$ events
- What if μ rate is too high for emulsions ? $\rightarrow$ exploring new method, exploiting high statistics
- Use kinematical cuts (missing p, origin) and shower patterns $\rightarrow$ measure distributions, disentangle signal & bkg contributions
  - Missing momentum wrt ν direction-of-flight
  - Muon momentum, use μ sagitta to give the charge
  - Energy of hadrons and longitudinal shower profile
  - Additional use of impact param with silicon

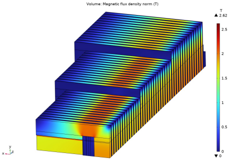
High-Granularity Calorimeter + Magnetized Tracking Calorimeter

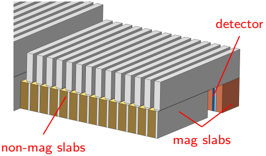
- W slabs and Si μstrip sensors (pitch $\sim 100\ \mu$m, $\sim 30\ \mu$m resol) $B \approx 0$ T
- W thickness being optimised
- Currently assuming $\sim$ 120 W slabs, 40 cm x 40 cm x 3.5 mm $\rightarrow \approx$ 1.3 tons.

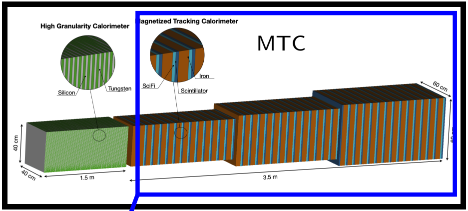




High-Granularity Calorimeter + Magnetized Tracking Calorimeter







- Magnetized Fe slabs and scintillators → tracking (p_μ) and calorimetric energy $B \gtrsim 1.5$ T
  - Scint. pads for energy measurement, 1 cm thick, 5 cm x 5 cm, avoid saturation effects,
  - SciFi 5-6 layers/view, $\varnothing 0.25$ mm, for good tracking capabilities of isolated tracks.
- Assuming now 42 planes, 40 cm x 40 cm to 60 cm x 60 cm.
- Fe: 5 cm thick magnetised slabs, $\sim$ 4.2 tons, $>$ 10 int. lengths → good hadronic calorimeter

The Decay Volume

- Moved from 1 mbar vacuum to 1 bar He balloon
- a central part of optimization of the initial setup

⇒ ν interactions inside fiducial volume increased, but bkg seems still ok

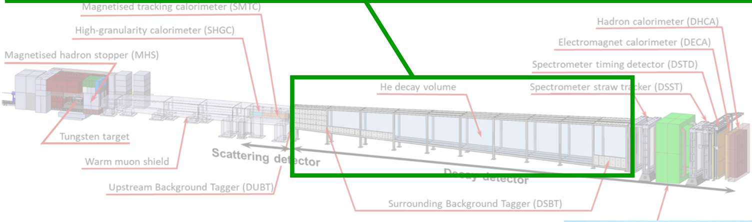
was dominated by interactions in the thick envelope

⇒ surrounding material drastically reduced (less inelastic)

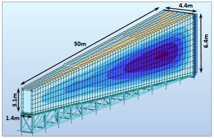
must revisit bkg tagging strategy

⇒ straw tracker no longer in vacuum

simpler, but more mult. scatt in exit window and He



Going from a 300’000 kg steel vessel to a ∼300 kg polymer fabric



⇒

Background Tagging

Given the change in Decay Volume design, we must revisit our BT strategy

Reminder: main sources of bkg are

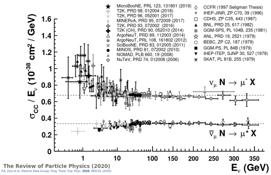
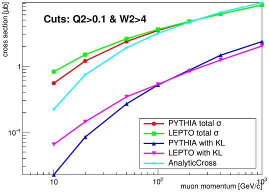
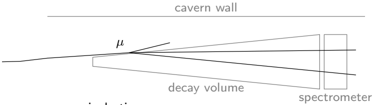
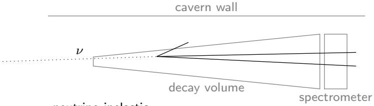


Figure 51.1: Measurements of per nucleon ν_μ and $\bar{\nu}_\mu$ CC inclusive scattering cross sections divided by neutrino energy as a function of neutrino energy. Note the transition between logarithmic and linear scales occurring at 100 GeV. Neutrino cross sections are typically twice as large as their corresponding antineutrino counterparts, although this difference can be larger at lower energies. NC cross sections (not shown) are generally smaller compared to the CC case.

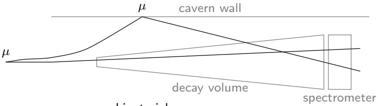




muon inelastic



neutrino inelastic

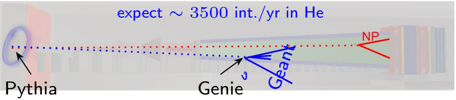


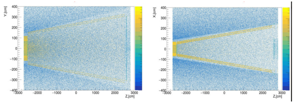
muon combinatorial

Does NOT depend on muon shield config

Depends on muon shield config

1) ν-induced bkg:



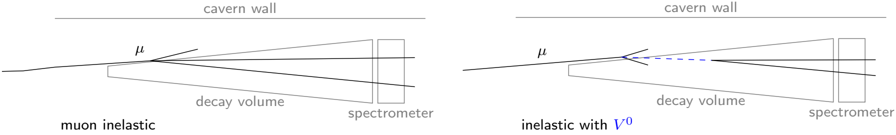


- Large samples of int. can easily be obtained ($>$ 15yr expected rate)
- Liq.scint.+He @ ECN3: 1.2×10^8 generated (corresponds to $\sim$ 50yr)
  - Assuming the full detector configuration (with current UBT/SBT):

    After basic event selection
    $\rightarrow$ 0.2 / 0.7 bkg evts in 15yr
    for fully / partially rec'ed

Cut	Value
Good daughters	nDoF>25, χ^2/nDoF $<$ 5, $p_{\text{track}} > 1$ GeV
Number of "good" candidates per event	1
DOCA	$<$ 1 cm
Vertex distance from vessel's wall	$>$ 5 cm (transverse), 20 cm (longitudinal)
IP (f.r.)	$<$ 10 cm
IP (p.r.)	$<$ 250 cm

- **2026**: must repeat these studies with He balloon
  - ν bkg studies independent of MS optimization (no need to wait for final MS)
  - A full optimisation of selection using multivariate techniques will be carried out, after completing bkg sample production with final decay volume geometry.



2) μ-induced background

- Extensive simulation campaigns to evaluate this bkg.
- After applying the fiducial, DOCA, and IP cuts, and imposing Background Tagger cuts, no bkg event is found for either 1 mbar air in the decay volume or helium at 1 atm.
- Assuming factorisation between BT and IP cuts to enhance stats $\rightarrow$ less than 0.2 partially rec events over full running period
- However, challenges:
  - Statistics! Unlike the ν bkg, the μ bkg cannot be simulated with full stats.
  - Muon shield has strong impact on this bkg.
- Addressing the limited simulated stats (producing larger bkg samples) are one of main physics study goals for 2026.

Background Tagging

3) Combinatorial μ background

After applying track selection (3 stations hit, $N_{\text{meas}} > 25$, $p > 1\,\text{GeV}/c$) → obtain sample of ~ 2900 tracks.

Form 2-track vertices:

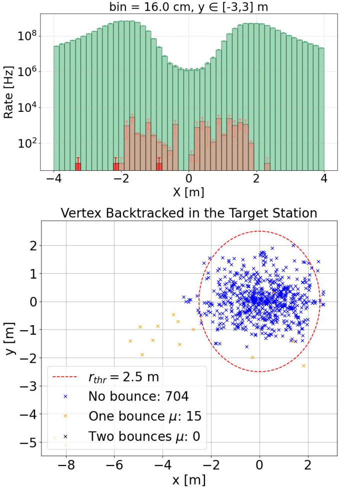
	left over	rate/spill (Hz)
Opposite charge pairs	2100918	$(2.4 \pm 0.02) \times 10^9$
DOCA	7146	$8.7 \pm 1.6 \times 10^6$
Vertex inside FV	709	$1.4 \pm 1.1 \times 10^5$
Target impact param.	690	$1.4 \pm 1.1 \times 10^5$

We want to achieve a rate $< 1/(15 \cdot 10^6)$, i.e. per spill, a rate $< 6.7 \cdot 10^{-8}$ (Hz).

The main suppression factor is obtained by timing cut:

$$\text{expect suppression} \sim \frac{340 \text{ ps}}{1 \text{ s}} = 3.4 \cdot 10^{-10}$$

⇒ background taggers must suppress comb. vertices by at least $10^{3\ldots4}$ (indiv. muons by at least ~ 100)



Guglielmo Frisella

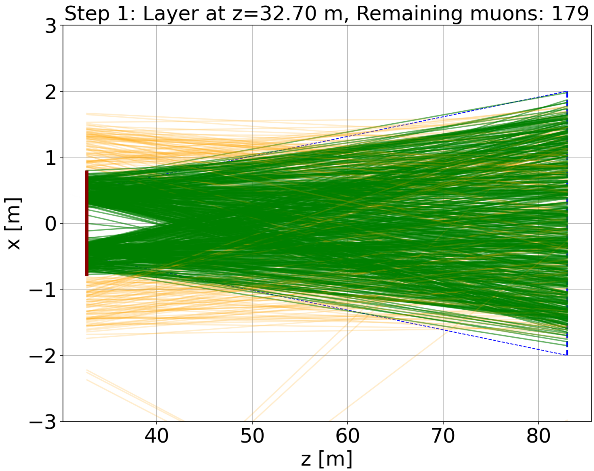
Background Tagging

Considering several technologies for the background taggers:

- Scintillator tiles, see SD
- Scintillating fibres, see SD
- Straws (drift)

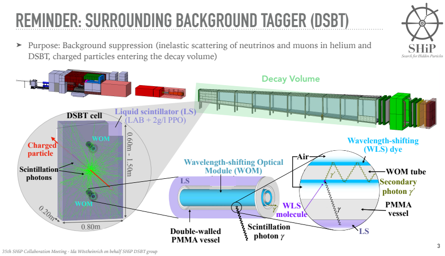
Detailed requirements and geometry yet to be defined

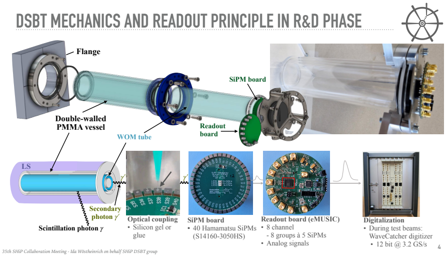
Will need good rate capability, good spatial resolution and timing to reduce false vetoes



Guglielmo Frisella

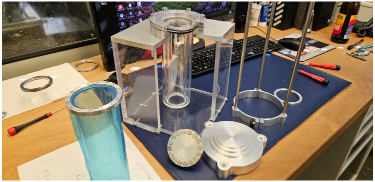
Surrounding background tagger





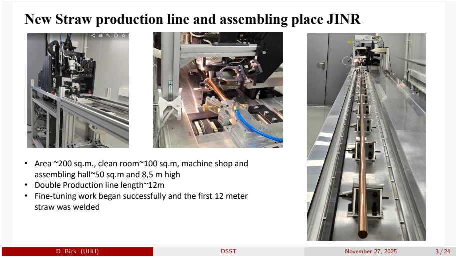
WOM INTEGRATION

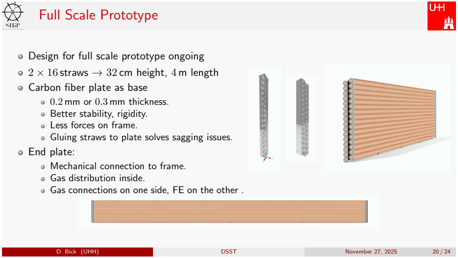
SHiP
Search for Hidden Particles

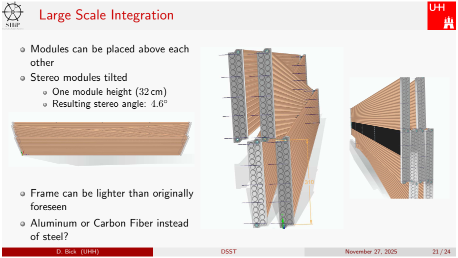


- Used for activity detection around the fiducial volume
- Tag neutrino and muon material interactions
- Currently being revisited in view of light He balloon

Decay Spectrometer: straw tracker

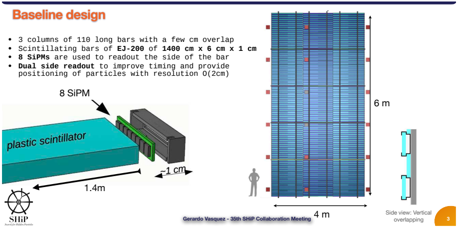


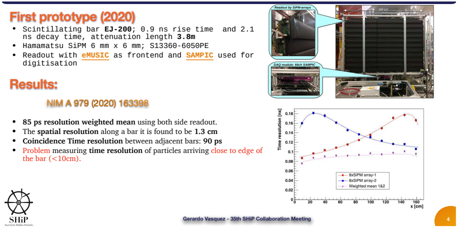


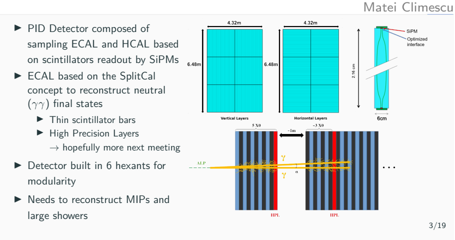


- ultrasonic welded straws
- 36 μm PET (Au-Cu coated inside)
- 2 cm diameter straws
- 4 m long
- drift time $\sim$ 800 ns
- spatial resolution $\sim$ 120 μm
- (no longer needs to be in vacuum)

Decay Spectrometer: Timing + Particle identification







- Essential for combinatorial background rejection
- Used as reference time for the straw drift time
- Time resolution < 100 ps

- Used mostly for e, γ/π^0, $h^{\pm}$ identification
- Important for a number of FIP decay modes

Summary and outlook

- HI-ECN3 and SHiP approved in 2024
- SHiP opens a new window in the search for physics beyond the SM
- In 2025, introduced important changes (GHe-cooled W target, He decay volume, ...) and chose the muon shield variant
- This year, optimize and define SHiP-2026 detector setup
  - focus on decays to charged particle tracks in our spectrometer acceptance (fully reconstructed decays)
  - based on perf/bkg simulation studies with new W target
- Timeline
  - Technical Design Reports in 2026-2028
  - muon shield ready for commissioning with beam in 2031
  - detector ready for commissioning with beam in 2032
  - first physics run in 2033 (just before LHC Long Shutdown 4)

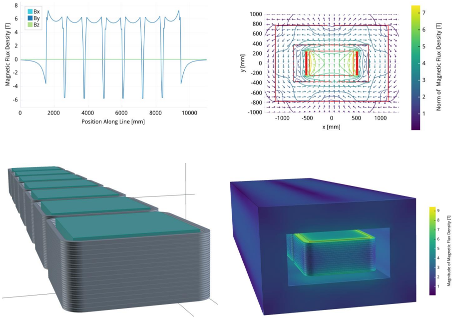
New contributions very welcome !!!

RESERVE SLIDES

Muon Shield "hybrid" variant superconducting magnet in section 1

Square coil assembly with inner and outer iron yoke

Quantity	Symbol	Value	Unit
Tape width	w	12	mm
Tape thickness (50 µm cu surr.)	d_{cd}	0.15	mm
Operating temperature	T_{op}	30	K
Coil former		1000 x 1000	mm x mm
Corner radius		100	mm
Radial winding thickness	d_r	34.5	mm
Turns per coil	N	230	-
Operating current	I_{op}	550	A
Peak B-field on coils	B_m	7.7	T
Tape length per pancake coil	L_c	905	m
Inductance for one coil-stack	L_{stack}	70	H
Number of coils	N_c	224	-
Tape length, total	l_{tot}	203	km
Magnetic energy	E_m	84.0 (23.3)	MJ (kWh)
Total inductance	L_{tot}	587	H
Inner iron yoke		900x900x500	mm^3
Outer iron yoke		2300x1550x7800	mm^3
Stray field (4 m from center)	$B_{4\,m}$	35	mT



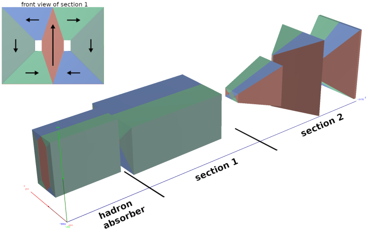
4 2025-10-06 HTS coils for SHiP KIT

→ R&D program to assess the feasibility of a 5 T magnet based on non-insulated gen-2 (high temperature superconducting) **HTS coils** was launched.
R&D program started (KIT, CERN) with REBCO tape

4.1 km in width of 4 mm, 0.6 km of 12 mm, lengths of 100, 150 and 300 m

Why a SC magnet ? (for section 1, after HA)

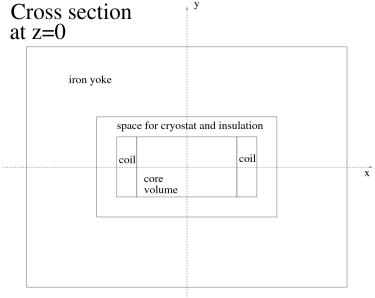
- **Compact, reduces distance to target**
  - expt fits better into existing TCC8/ECN3
  - same signal yields with smaller transverse size
  - more space for Scattering Detector
  - more $\int B_y dz$ in section 1 $\rightarrow$ more flexibility
    - rates in SD region are smaller!
    - separation between μ flames at UBT is larger



- **Key requirements:**
  - $B_y \approx 5$ T over 7 m x 1 m x 0.6 m (LxHxW).
  - Field non-uniformity is acceptable, static operation.
  - Core material = Fe, or whatever prefered.
  - Core/yoke gap of 0.2 m is acceptable (cryostat).
  - No strong reqs on coil curvature.
  - Stored energy around 70 MJ

These are rather mild requirements for a gen2 NI Rebco coil! (see later talks)

Cross section at z=0



Tried to identify the main challenges

Scientific and technological challenges:

- Performance, as a muon shield, with realistic assumptions
  size of core volume, stray fields, coil longitudinal segmentation
- Particle fluences out of BDF:
  - Radiation damage to HTS coils
  - Energy deposited in HTS coils

  } backup slides
- Stresses in the HTS coils ⇐ **identified as main technological challenge**
  → SHiP started R&D program with KIT
  CERN procured/delivered to KIT 4.7 km of REBCO tape thanks TE-MSC-HSD!
  4.1 km in width of 4 mm, 0.6 km of 12 mm, lengths of 100, 150 and 300 m.

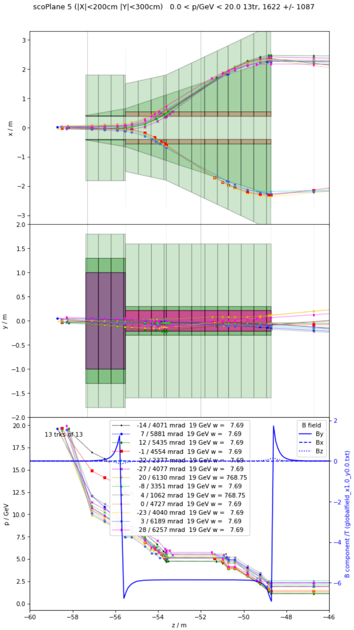
Organizational challenges:

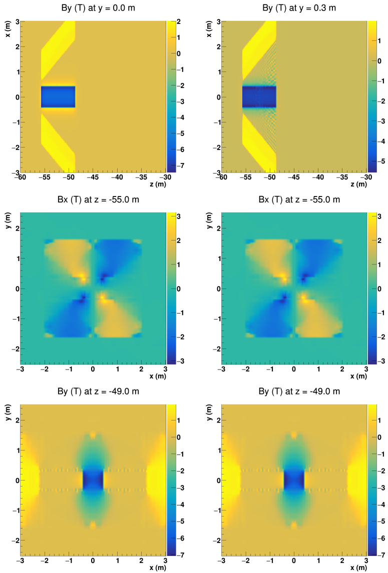
- Cost / funding — $+\mathcal{O}$(10 MCHF), see later
- Time line — start with beam in 2031
- Expert partners — big project requires collaborative effort

SC magnet: way forward

Preliminary studies have shown that there may be a solution with a single SC magnet in the MS behind the HA: a 35 T m magnet with controlled return field and materials in the Y=0 plane.

Hybrid option: challenges





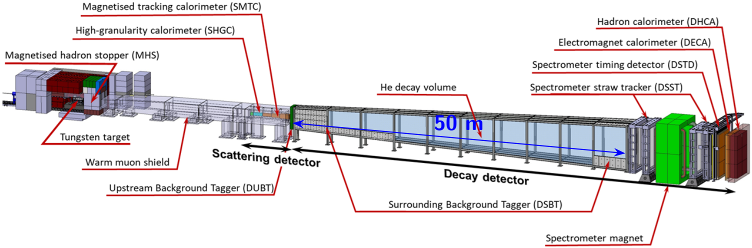
SC magnet: way forward

Preliminary studies have shown that there may be a solution with a single SC magnet in the MS behind the HA: a 35 T m magnet with controlled return field and materials in the Y=0 plane.

Such a solution would allow freeing up entirely a distance $\Delta \approx 20$ m between this magnet and the Decay Volume, possibly allowing also use of emulsions. (see backup slides for more)

Therefore, we will explore the gain in physics from such a single magnet solution.

Given the longer time scale, one could also discuss a more complex (and higher field ?) SC magnet.

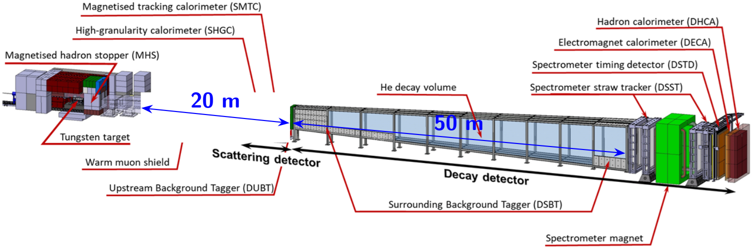


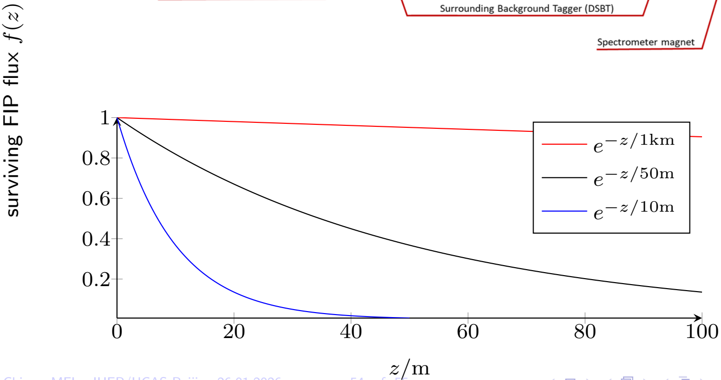
Magnetised tracking calorimeter (SMTC)
High-granularity calorimeter (SHGC)
Magnetised hadron stopper (MHS)
Tungsten target
Warm muon shield
Upstream Background Tagger (DUBT)
Scattering detector
He decay volume
50 m
Decay detector
Surrounding Background Tagger (DSBT)
Hadron calorimeter (DHCA)
Electromagnet calorimeter (DECA)
Spectrometer timing detector (DSTD)
Spectrometer straw tracker (DSST)
Spectrometer magnet

Very coarsely: The **SD** physics yield goes like $N \propto Z_{\rm SD}^2$. But one could also increase the size, length, mass...

The **DD** physics yield depends on avge decay distance ℓ: $N \propto (e^{-Z_{\rm DV,start}/\ell} - e^{-Z_{\rm DV,end}/\ell}) \quad \propto (Z_{\rm DV,end} - Z_{\rm DV,start})$ if $\ell \gg Z_{\rm SST}$

but more beneficial in case of short ℓ ?





SC magnet: way forward

Preliminary studies have shown that there may be a solution with a single SC magnet in the MS behind the HA: a 35 T m magnet with controlled return field and materials in the Y=0 plane.

Such a solution would allow freeing up entirely a distance $\Delta \approx 20$ m between this magnet and the Decay Volume, possibly allowing also use of emulsions. (see backup slides for more)

Therefore, we will explore the gain in physics from such a single magnet solution.

Given the longer time scale, one could also discuss a more complex (and higher field ?) SC magnet.

The challenge will be to control the return field in the side regions and the material budget at the plane where B_y flips sign.