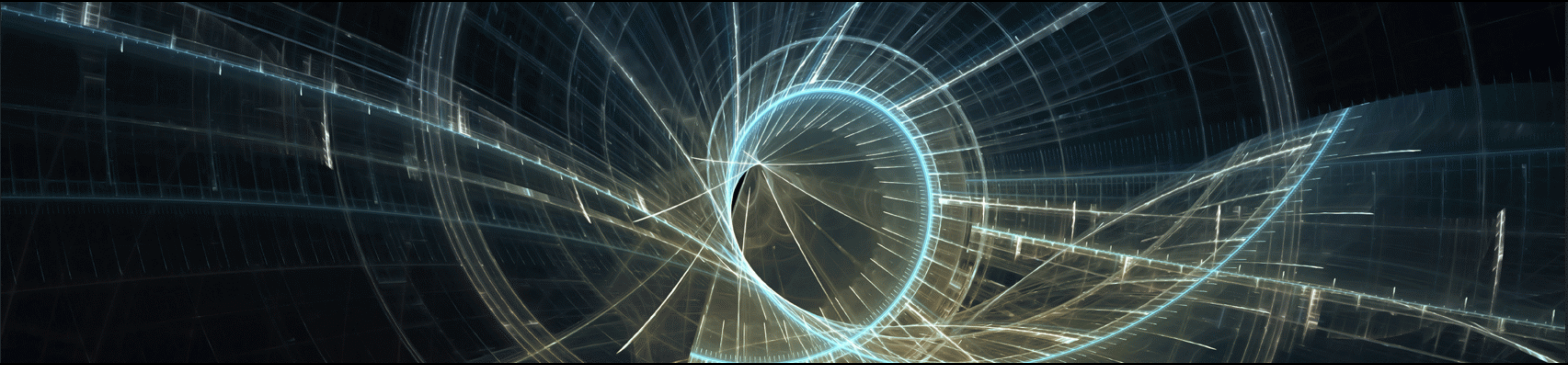
The SHiP experiment at CERN

SHiP = Search for Hidden Particles



Gaia Lanfranchi - CERN & INFN

Neckarzimmern (Heidelberg) 20 March 2019

Outline

- ✓ The current particle physics landscape
- ✓ The SHiP physics programme
- ✓ The SHiP beam line
- ✓ The SHiP detector
- ✓ The SHiP physics reach
- ✓ Conclusions and outlook

The current particle physics landscape

The current particle physics landscape

With the **discovery at the Large Hadron Collider (LHC)** of the Higgs boson, the main missing block for the experimental validation of the Standard Model is now in place.

An additional **LHC result of great importance (and totally unexpected) is that a large new territory has been explored and no unambiguous signal of New Physics has been found (so far). This is true for direct searches of new particles, for flavor physics, for direct detection of dark matter.**

A very unexpected situation.

…really unexpected!

Google

Expectations for New Physics at the LHC
http://lhc2008.web.cern.ch/lhc2008/nobel/
Nobel expectations for new physics at the LHC, 2008

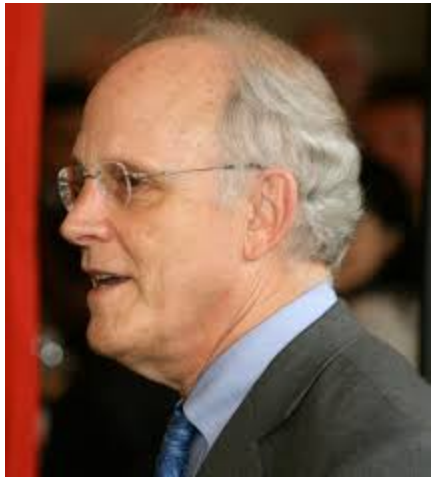
What did leading figures in particle physics expect from the LHC in 2008?

What leading physicists expected from the LHC in 2008

http://lhc2008.web.cern.ch/lhc2008/nobel/

David Gross: "a super world"

(Nobel prize in Physics in 2014, with D. Politzer and F. Wilczek)



I expect new discoveries that will give us clues about the unification of the forces, and maybe solve some of the many mysteries that the Standard Model (SM) leaves open.
I personally expect supersymmetry to be discovered at the LHC; and that enormous discovery, if it happens, will open up a new world – a super world.

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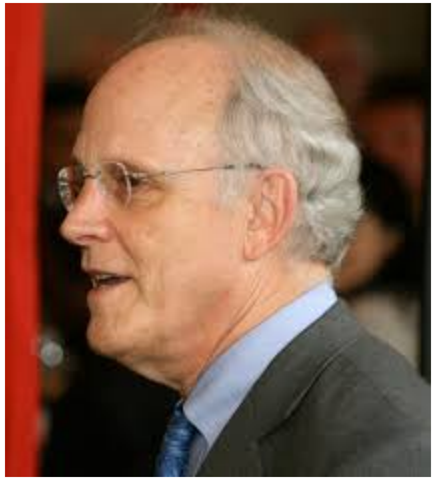

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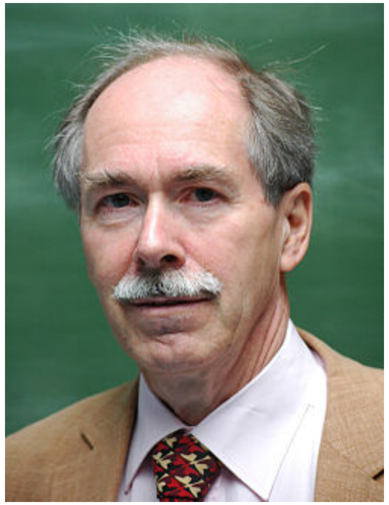

Gerardus 't Hooft: "a Higgs, or more"

(Nobel prize in Physics in 1999, with M. Veltman)

The first thing we expect - we hope to see - is the Higgs. I am practically certain that the Higgs exists. My friends here say it is almost certain that if it exists, the LHC will find it…
My real dream is that the Higgs comes up with a set of particles that nobody has yet predicted and doesn't look in any way like the particles that all of us expect today. That would be the nicest of all possibilities. We would then really have work to do to figure out how to interpret those results.

What leading physicists expected from the LHC in 2008

http://lhc2008.web.cern.ch/lhc2008/nobel/

George Smoot: "the nature of dark matter"

2006 Nobel Prize in Physics with J. Mather

I am looking forward to hearing about the Higgs, because I'd like to see the Standard Model completed and understood….

…. *But what I am really looking forward to is supersymmetry or something that shows what dark matter is made of, so I have really high hopes, perhaps too high hopes*.

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Douglas Osheroff: "lots of new particles"

shared the 1996 Nobel Prize in Physics with David Lee and Robert Richardson for their discovery of superfluidity in helium-3"

If we don't get the Higgs, that would in fact be a bit more interesting, but *I am hoping that there will be lots of new particles and resonances that no one ever expected.* That will be really exciting.

2019, 11 years later:

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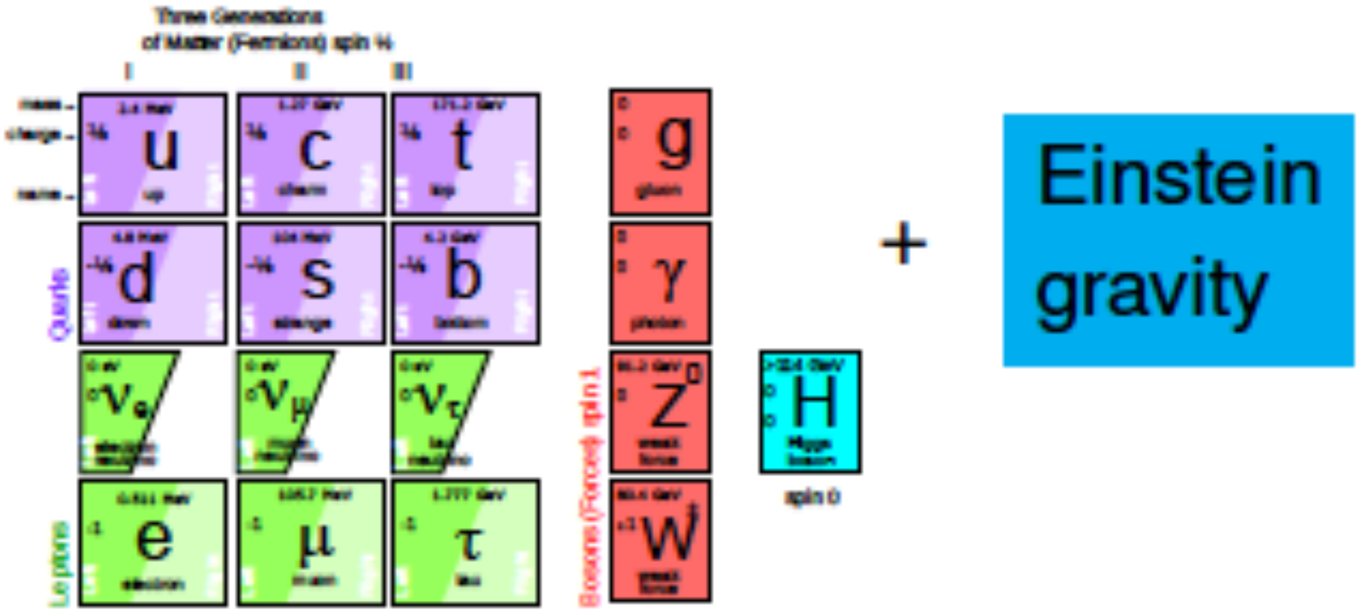
?

The Standard Model is in excellent shape!



- ✓ SM works in all laboratory/collider experiments
- ✓ LHC 2012 – final piece of the model discovered: the Higgs boson
  - Mass measured   125 GeV –
  - Perturbative and predictive for high energies
- ✓ Add gravity:
  - get cosmology
  - get Planck scale $M_{Planck} = 1.22\ 10^{19}$ GeV as the highest energy to worry about.

“….But where is everybody?”

N. Arkani-Hamed

Where did the expectation of NP at the TeV scale come from?

Hierarchy problem, Naturalness and Super- Symmetry

Hierarchy problem and Naturalness:

From a "natural" point of view we should have just one fundamental scale that explains everything. In reality our Universe has, at least, two (three) outstanding scales highly hierarchical

1. The electro-weak scale (Higgs mass, ~100 GeV)
2. [the GUT scale (~10^{14} GeV)] – not really associated to a fundamental interaction.
3. the Gravitational force scale (Planck scale, ~10^{19} GeV).

How are these scales connected? Which are the consequences in particle physics?

Hierarchy problem, Naturalness and Super- Symmetry

The Higgs is (presumably) the only fundamental scalar particle in the SM. Its potential is given by:

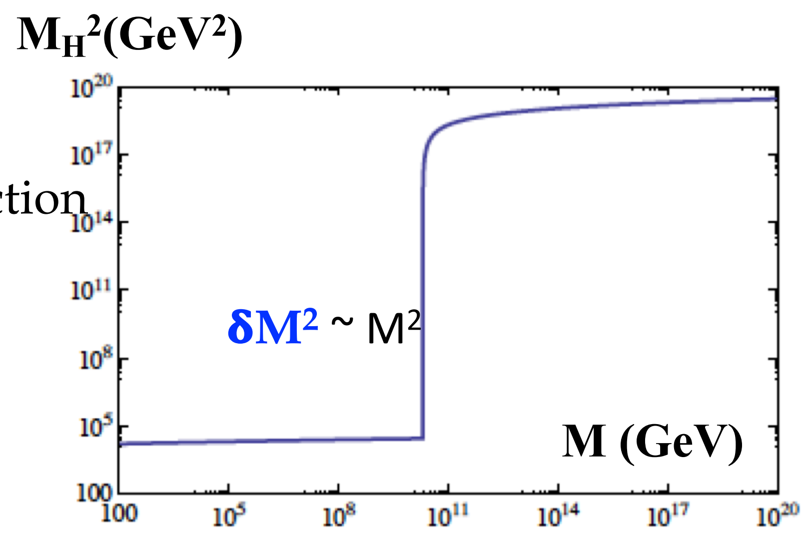
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

The Higgs boson has a mass

$$M_H^2 = 2\lambda v^2$$

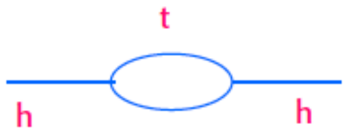
If there is a new mass scale at a high mass M, the quadratic sensitivity produces a jump in the running mass:

eg: **M ~ 10^{10} GeV, λ ~ 1 , jump: δM ~(λ M)^2/ 16 π^2**



A possible way to cure this HUGE quantum correction is to assume New Physics nearby the Higgs mass that compensates this large correction and explains the small measured value of the Higgs mass:

$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$



Gildener, Weinberg'76; Maiani'79; 't Hooft'79.......

Hence: we must have NP at the TeV scale, hence SUSY!

The same physics at the TeV scale should also modify flavor physics observables, if no symmetries are postulated (main goal of LHCb);
the same physics at the TeV scale should provide a good DM candidate (WIMP).

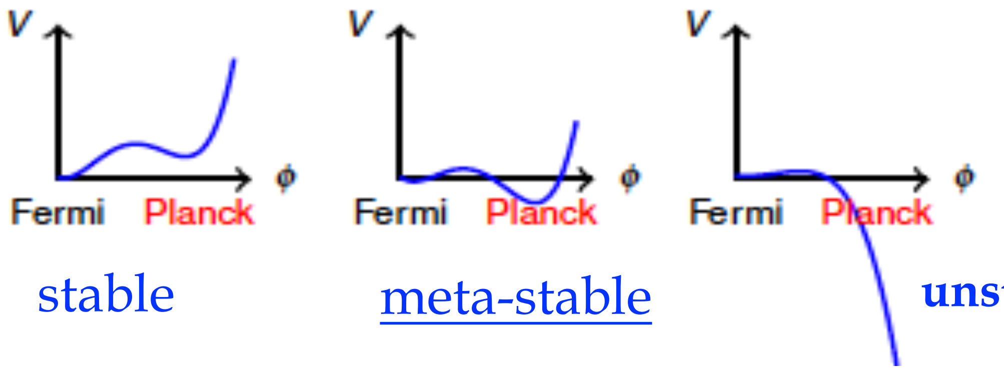
Morever the Standard Model is (meta)-stable until the Plack scale !

The Standard Model is renormalizable

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

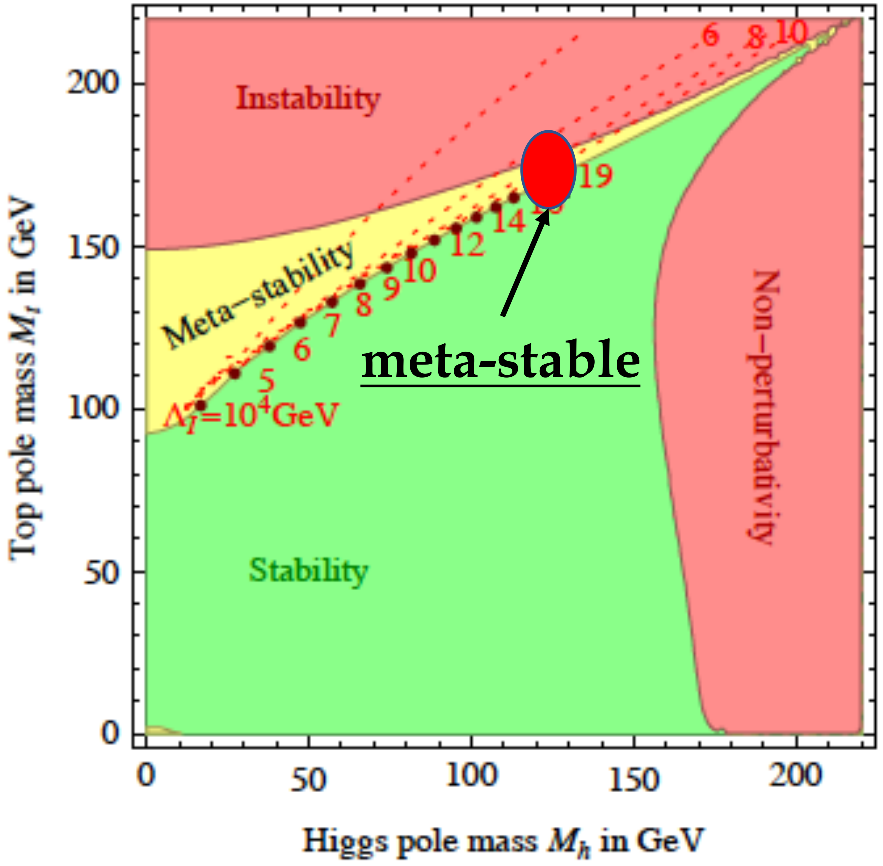
Due to renormalization the coupling $\boldsymbol{\lambda} = f\,(m_H, mTop)$
varies with the energy and changes the shape of the Higgs potential:

Higgs potential $V(\phi) \simeq \lambda(\phi)\frac{\phi^4}{4}$



stable   meta-stable   **unstabl**e

Higgs and Vacuum Stability



The masses of the top quark (~172.5 GeV) and of the Higgs boson (125.05 GeV) the Nature has chosen make the Higgs potential (meta)-stable up to the Planck scale. Hence: the Standard Model is a self-consistent and (meta)-stable (effective) quantum field theory all the way up to the quantum-gravity Planck scale.

Is this the end of the story?

Experimental evidence for New Physics beyond the Standard Model

1) Observations of neutrino oscillations:
$\longrightarrow$ in the Standard Model neutrinos are massless and do not oscillate.

2) Evidence for Dark Matter
$\longrightarrow$ Standard Model does not have particle candidate for DM.

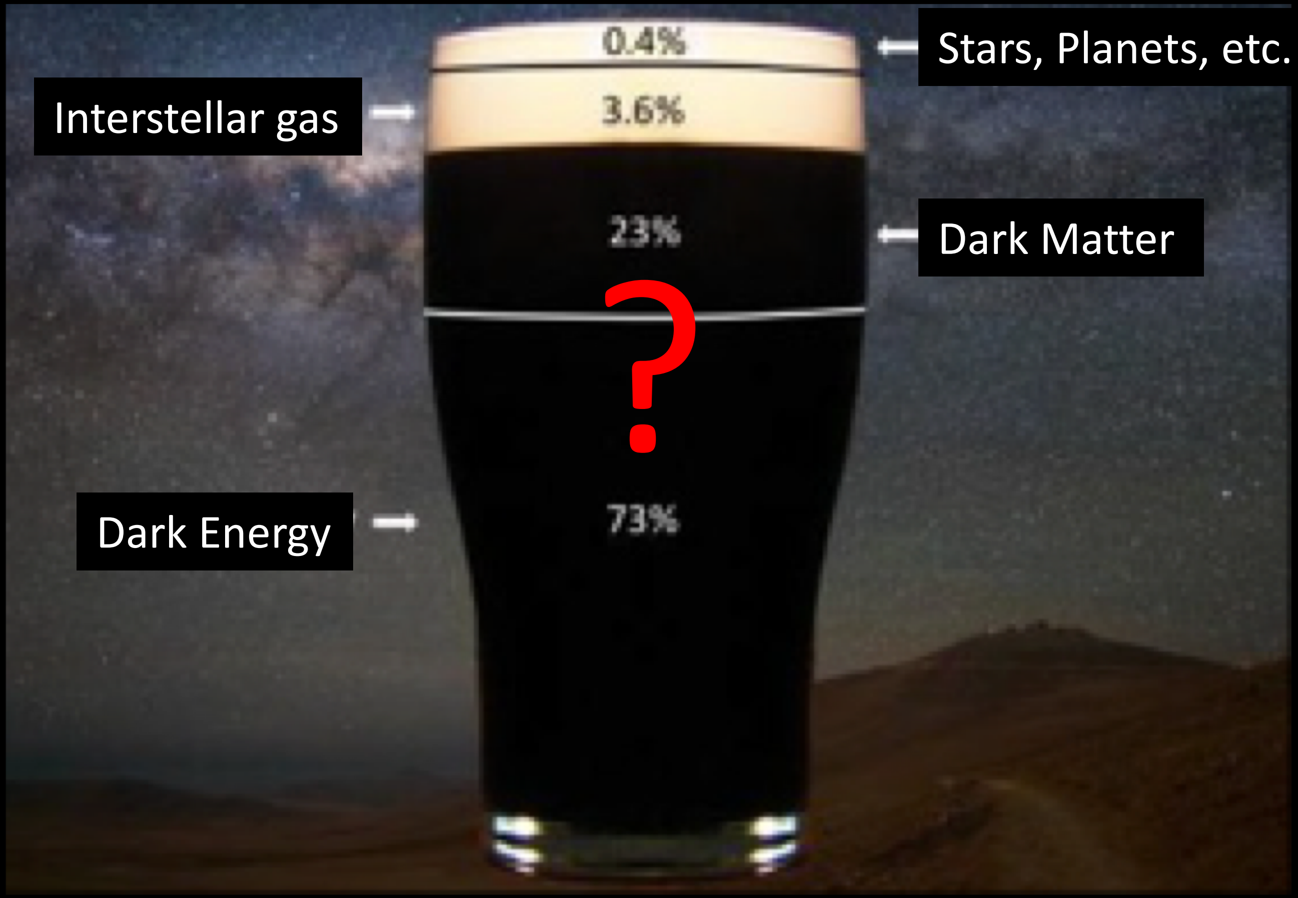
3) No antimatter in the Universe in amounts comparable with matter:
$\longrightarrow$ baryon asymmetry of the Universe is too small in the SM.

4) Cosmological inflation is absent in canonical variant of the SM.

5) Accelerated expansion of the Universe (?):
$\longrightarrow$ though can be "explained" by a cosmological constant.

Hence: we do need New Physics !

We are living in a Dark World



(hence: us!)

Courtesy of S. Gori

And our basic understanding of Quantum Field Theory is failing…

Compare with Absent Ether

- ✓ Electromagnetic Waves
- ✓ Waves require a medium
- ✓ Medium must be detectable
  by looking for relative velocity

- ✓ Michelson-Morley: no shift in relative velocity seen

- ✓ Simple Ugly Fix: Ether drifts along with the Earth

- ✓ Big Ugly Fix: Fitzgerald-Lorentz contraction

- ✓ Correct Fix: Einstein relativity

Courtesy of M. Strassler

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- ✓ Higgs boson
- ✓ Light scalars must be protected from higher scales
- ✓ Protection mechanism: New particles at mass scale of the scalar
- ✓ LHC: no sign of non-SM particles at TeV scale (so far)
- ✓ Simple Ugly fix: tune parameters a small amount; Naturalness delayed.
- ✓ Big Ugly fix: any exotic implementation of SUSY or proxies.
- ✓ Correct Fix: ???

Courtesy of M. Strassler

The correct fix?

Very lively discussions in the particle physics community.
Many options/plausible solutions on the table, each one with pros' and cons'.

1) SUSY is hiding behind signatures that have not been considered so far - feebly-interacting long-lived particles?
2) SUSY is more complex than previously anticipated (split-SUSY, neutral naturalness, ...)
3) The stability of the Higgs mass is ensured by a dynamical mechanism (relaxion) that also foresees a light, feebly-interacting long-lived scalar particle;

....

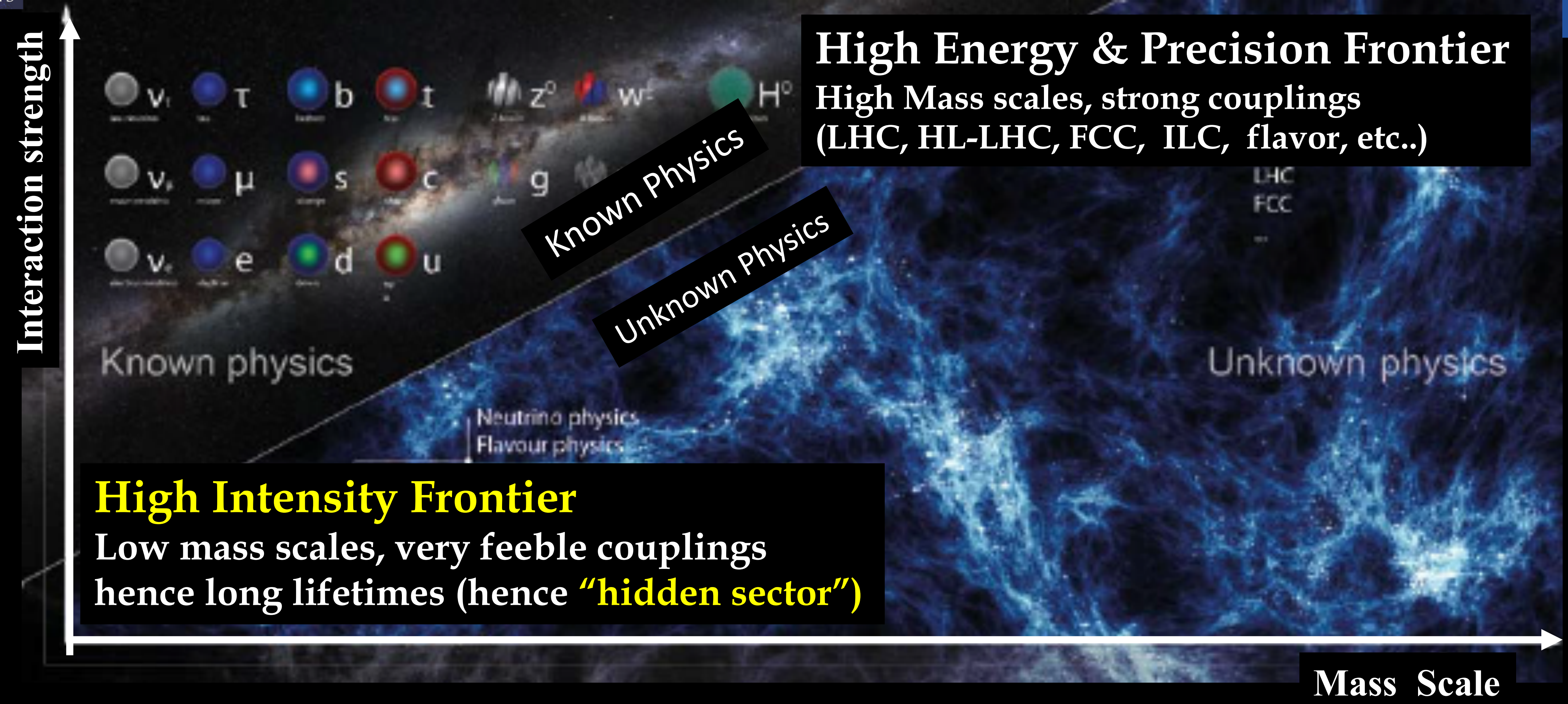
.....

n) The hierarchy problem could be solved in a unified theory of Quantum Gravity
all the other experimental BSM facts - Dark Matter, Neutrinos' masses and Baryogenesis
can be solved with New Physics below the EW scale (hence below the Higgs scale)
with particles very feebly (hence long-lived) interacting with the Standard Model world.

Several paradigms on the table, many of them require the presence of light and "feebly–interacting" particles (hence long-lived) with the Standard Model world. Noone of them – apart SUSY – can indicate an energy scale.

We need a multi-scale approach.

Search for New Physics at the Intensity Frontier



Many TeV-scale ideas/models have been scrutinized
Need a systematic investigation in the low (MeV-GeV) mass range with the High Intensity Frontier

Outstanding Physics Questions in Particle Physics could be answered by feebly-interacting particles

1) Nature of Dark Matter:

traditional WIMPs (100-1000 GeV) mediated by weak force but thermal origin is equally compelling with low-mass (MeV-GeV) WIMP with new (light) feebly interacting mediators;
other popular possibilities: oscillating axions as solution of strong CP problem and DM candidates; Self-interacting DM could require vector or scalar light (MeV-GeV) mediators, …

2) Origin of neutrino masses and oscillations

- Right handed neutrinos via see-saw mechanism;
- traditional solution: RHN at the GUT scale but possibility for RHN below the EW scale (but above BBN) hence between 100 MeV – 100 GeV.

3) Mechanism of Baryogenesis:

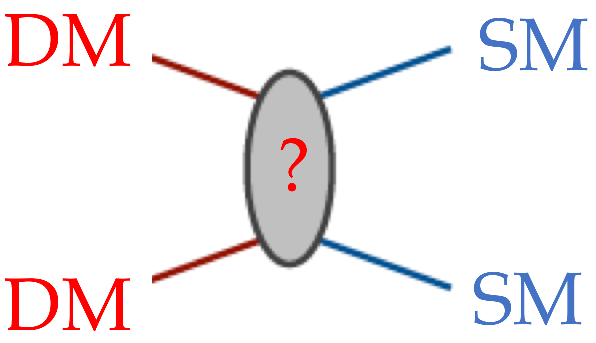
- through leptogenesis, deeply linked to RHN and to their mass; several models in literature: freeze-out scenario for RHN at the GUT scale, freeze-in scenario for RHN at or below the EW scale.

Scale of NP is unknown: we need a multi-scale approach.

Ex.1: Dark Matter with thermal origin

As universe cools below DM mass, density decreases as exp{-m/T}

- Dark Matter interacts with SM to stay in equilibrium
- eventually Dark Matter particles can't find each other to annihilate
- and a (minimal) DM abundance is left over the present day.

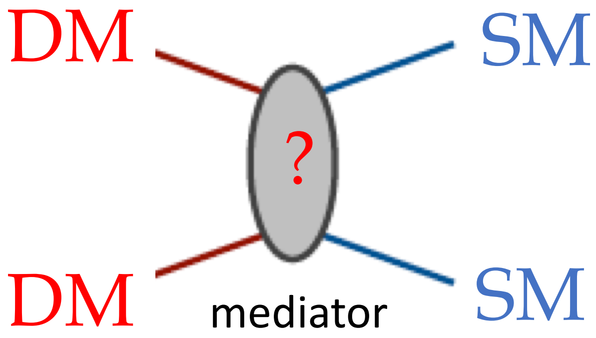


$$\Omega_{\rm DM} h^2 \sim \frac{10^9\ {\rm GeV}^{-1}}{M_{\rm pl}} \frac{1}{\langle \sigma v \rangle}$$

DM annihilation cross-section necessary to obtain the observed Dark Matter density:

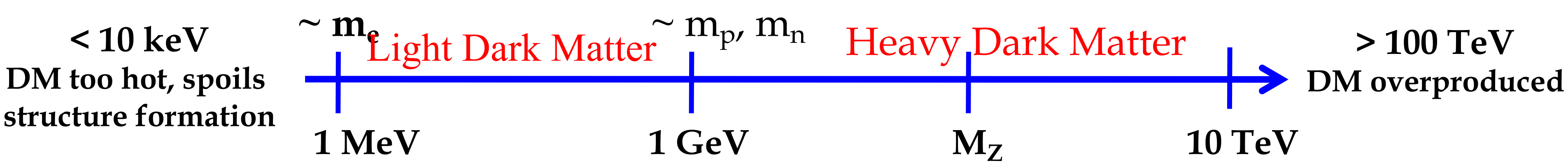
σ v (relic) = 3x10^{-26} cm^3/s

Ex 1: Dark Matter with thermal origin



$$\Omega_{DM} h^2 \sim \frac{10^9 \text{ GeV}^{-1}}{M_{pl}} \frac{1}{\langle \sigma v \rangle}$$

$$< \sigma\, v > \propto \frac{M(DM)^2}{M\,(mediator)^4}$$

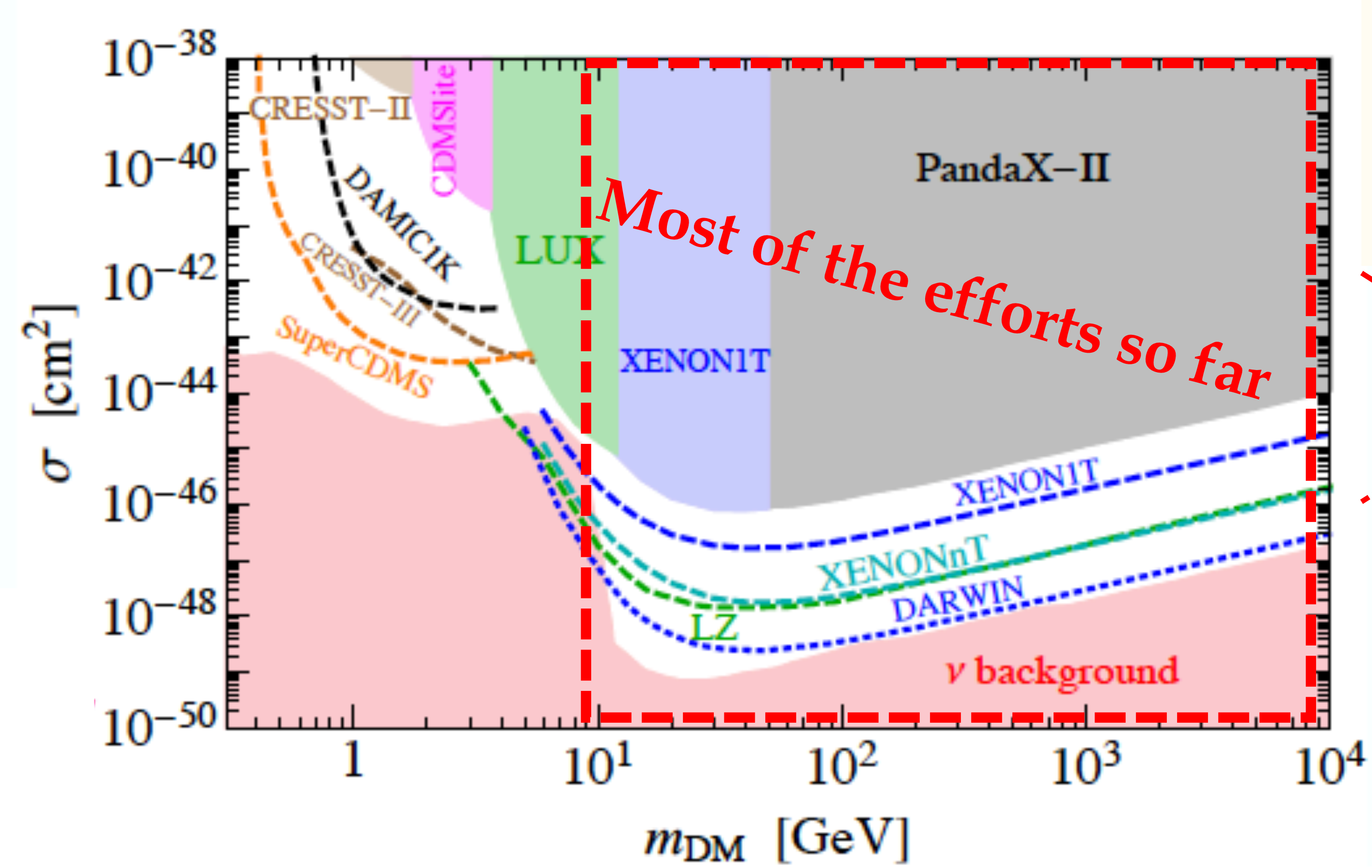


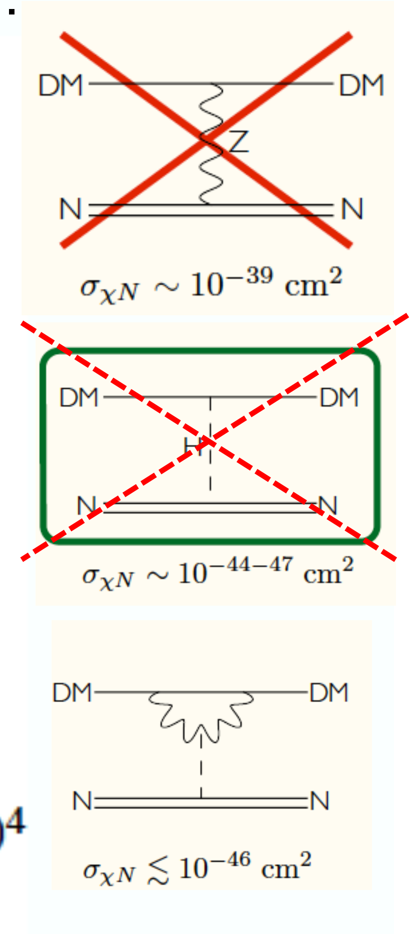
The equilibrium can be reached:

- with **an heavy DM particle (~100 GeV) with a SM gauge boson as mediator: standard WIMP searches.**
- with **Light Dark Matter (LDM) particle** (**~MeV-GeV)** with a **light new mediator (hence new forces).**

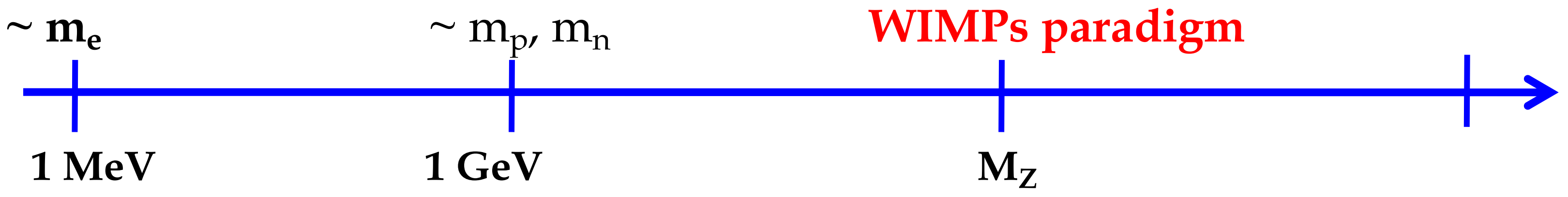
Ex.1: (Light) Dark Matter with thermal origin

DM candidates with thermal origin can have mass between 10 keV and 100 TeV.





< 10 keV
DM too hot, spoils structure formation



> 100 TeV
DM overproduced

Ex.1: (Light) Dark Matter with thermal origin

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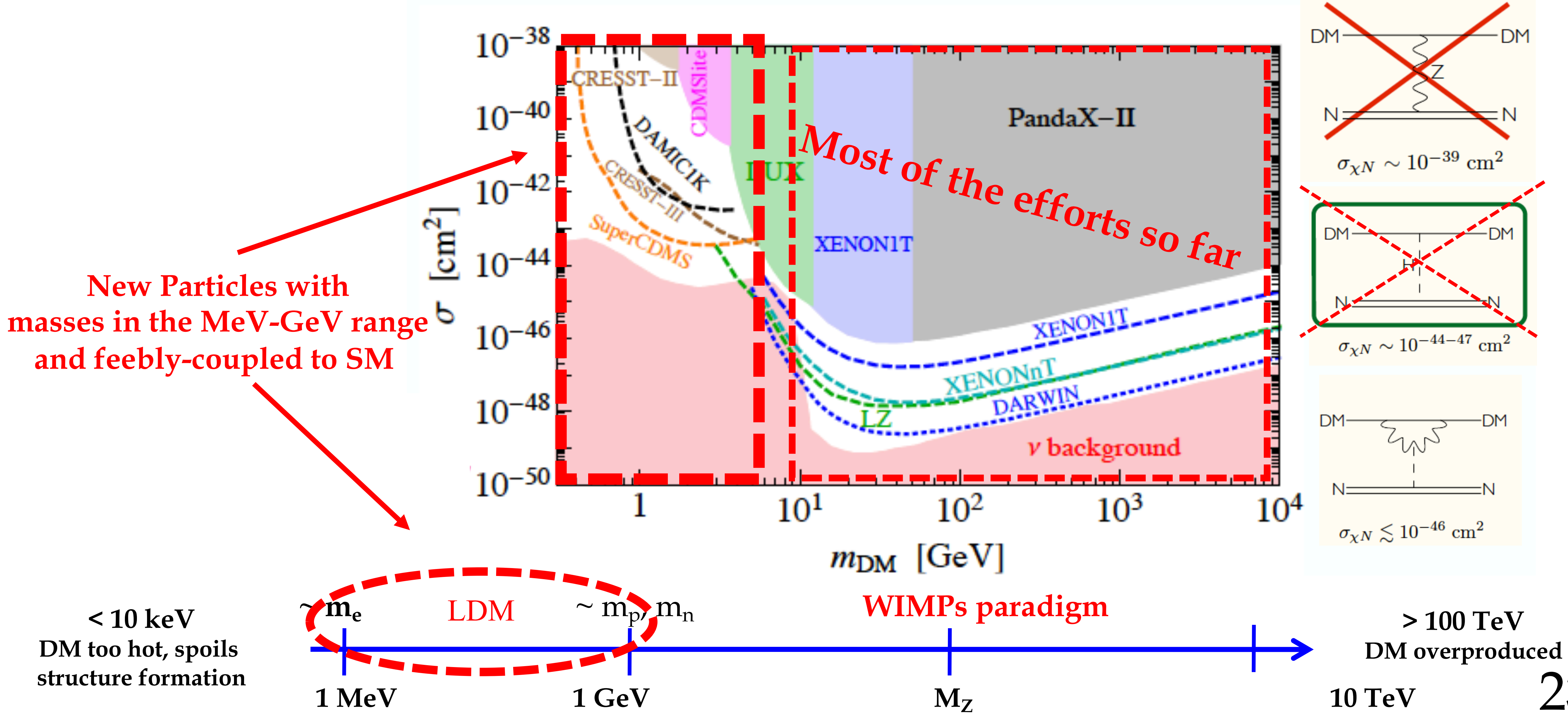


Ex. 2: Neutrinos masses and oscillations

At the beginning of the SM Weimberg did not introduce masses for neutrinos probably because at that time they were thought to be massless but neutrinos have mass.
Possible origin of this mass – existence of righ-handed neutrinos (singlet fermions, sterile neutrinos,…) with mass M_N and Yukawa couplings to the SM leptons and Higgs boson.

The see-saw formula:

$$m_\nu = -M_D \frac{1}{M_N} [M_D]^T, \quad M_D = Fv,$$

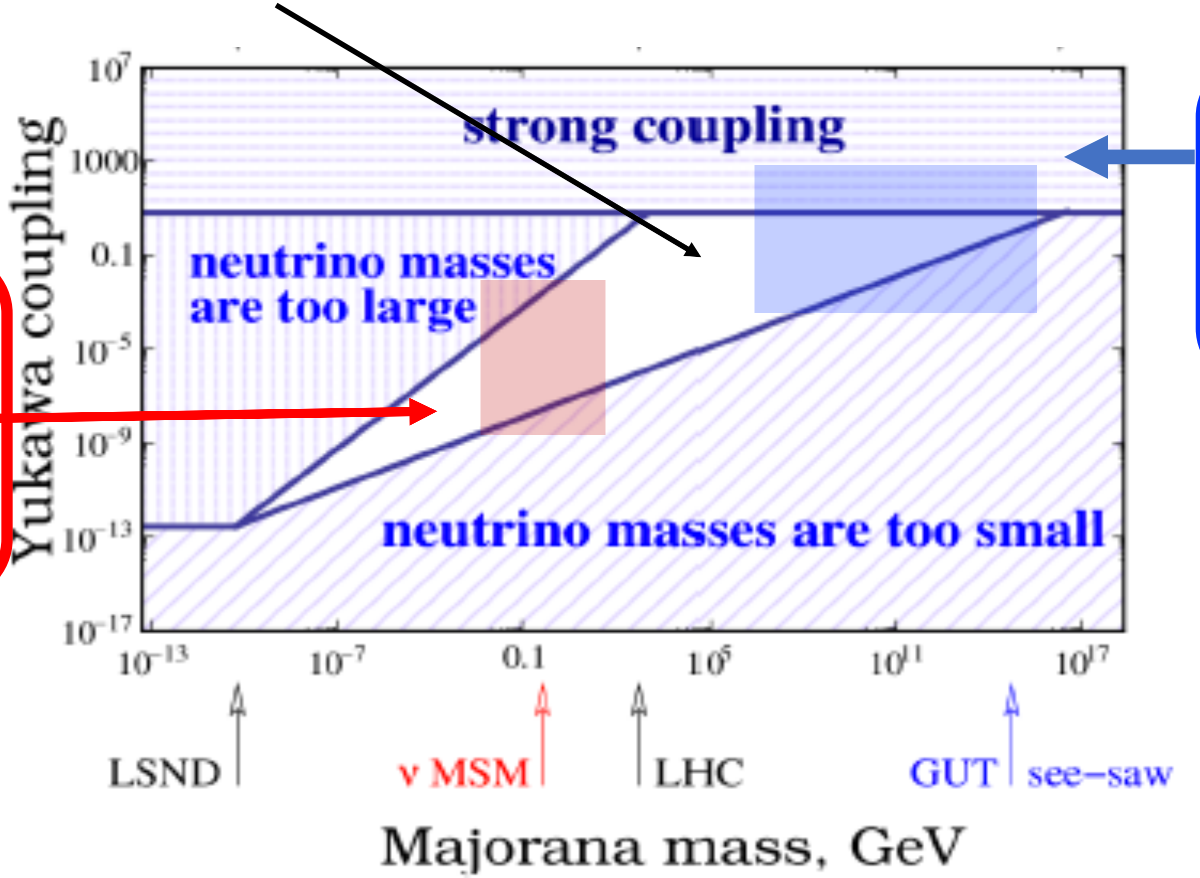
Coming from

$$F\bar{L}NH + M_N \bar{N}^c N, \quad \langle H \rangle = v = 246 \text{ GeV}$$

Tells nothing about the scale of M_N

Ex 2: Neutrinos masses and oscillations

Right handed neutrinos responsible of the neutrinos' mass generation
can have any coupling/mass in the white area, assuming a soft U(1)_L breaking



Alternative choice:
EW "see-saw" (νMSM)

It is "natural" to assume that the masses of the RH neutrinos are at EW scale

Standard choice:
GUT see-saw

It "natural" to assume that Yukawa couplings of the RH neutrinos are similar to SM Yukawa.

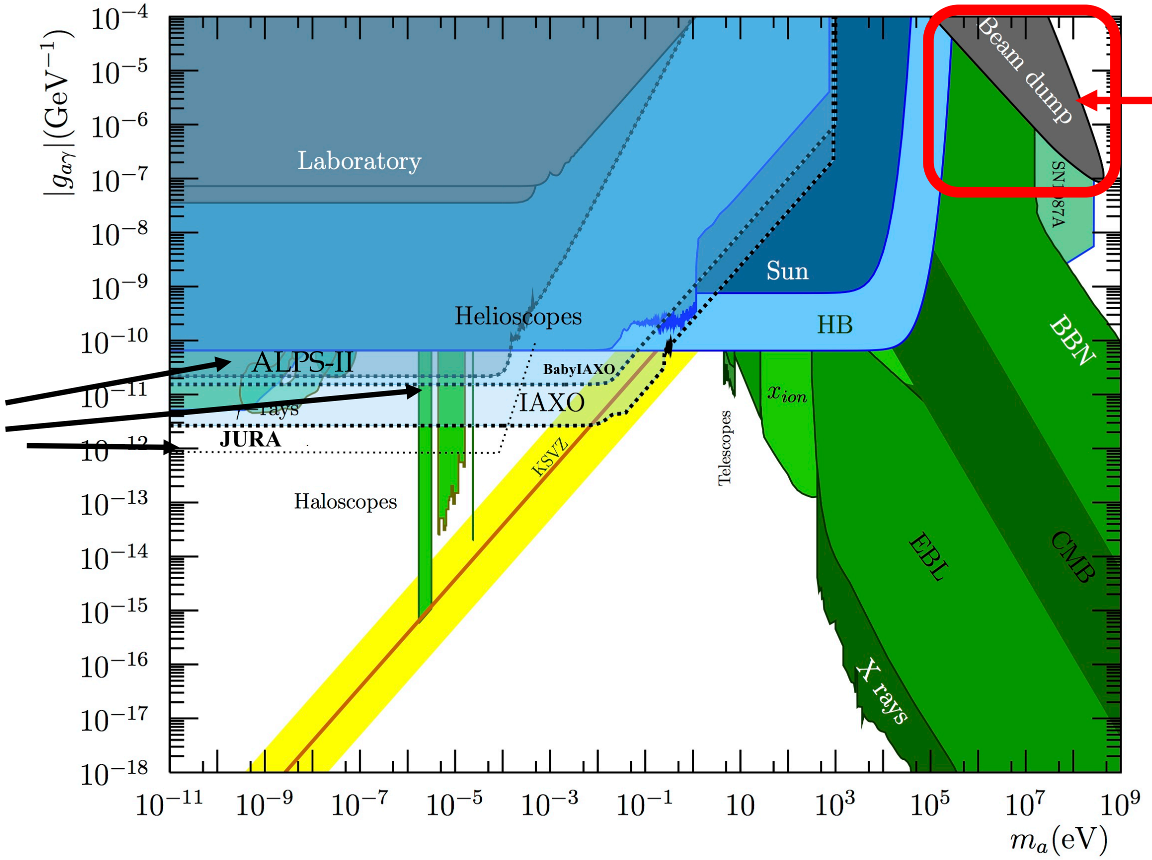
If 2 RHN have a mass degeneracy of o(10^{-2}) (as in the case of a soft $U(1)_L$ breaking) they could also explain baryogenesis

Example n.3: Axions and Axion-Like Particles

Axion = Pseudo-Nambu Goldstone Boson associated to Peccei-Quinn symmetry, a global U(1), introduced to address the Strong QCD problem. Vast range of masses and couplings possible, with fixed relation.

Axion-Like Particle (ALP): a generalized version of the axion (at the cost of the original motivation from the strong CP problem). No direct relation between coupling and mass.

Very lively community in the sub-eV range



Interest to explore the MeV-GeV region at accelerator-based experiments

Generic Benchmark Cases

HNLs, LDM & Light mediators, ALPs must be SM singlets, hence options limited by SM gauge invariance:
According to generic quantum field theory, the lowest dimension canonical operators are the most important:

PBC report, arXiv:1901.09966

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Sterile Neutrino, N	$y_N LHN$

This is the set of the simpler fields and renormalizable interactions that can be added to the SM

Large consensus in the community to use these portals as generic benchmark cases to compare sensitivities
This is the bulk of the SHiP Physics programme.

The SHiP physics programme

The SHiP Physics Programme

Any kind of feebly-interacting long-lived particle emerging from the interaction of 400 GeV protons with a heavy target:

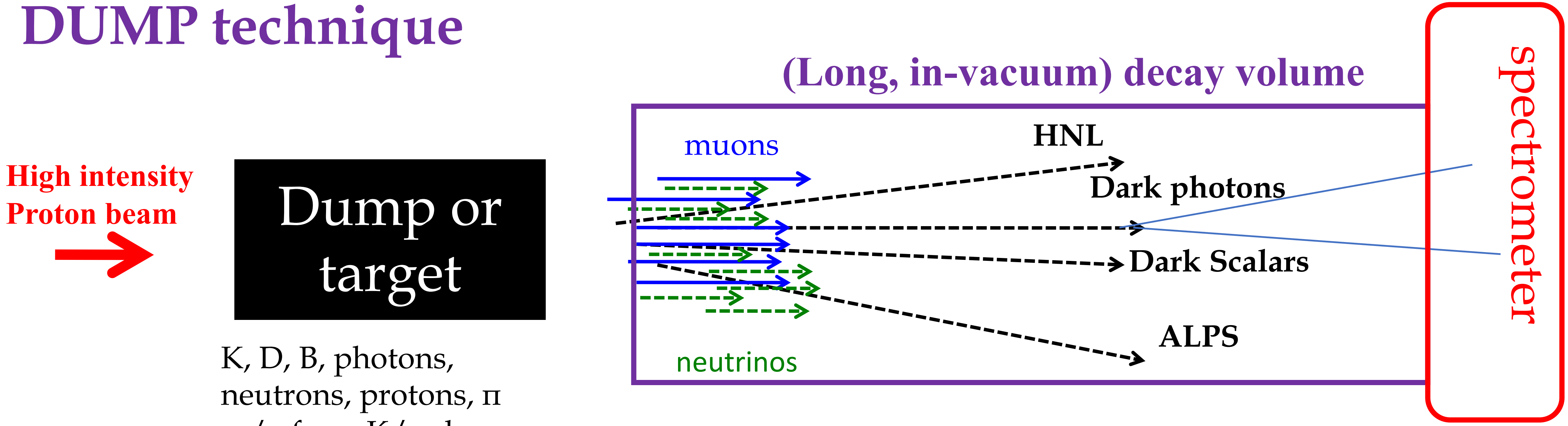
1) Dark Photons: could be the light mediator between Light Dark Matter(LDM) and the SM particles
2) Heavy Neutral Leptons below the EW scale: could be the RHN responsible of the neutrino mass generation mechanism and baryogenesis;
3) Light Dark Scalars or pseudo-scalars: could be the responsible of the Higgs stabilization mechanism (relaxion) or mediators between DM and SM particles or…
4) Long-lived SUSY particles (neutralino with RPV parity)….
5) Light Dark Matter detection via scattering on a dense medium

Tau neutrino physics:

- only 13 nu_tau observed so far: 8 by DONUT, 5 by OPERA
- SHiP can detect o(10^3) $\boldsymbol{\nu_\tau}$ interactions, unambiguously observe the anti- $\boldsymbol{\nu_\tau}$ and measure all the $\boldsymbol{\nu_\tau}$ cross-sections.

How to search for feebly-interacting long-lived particles?

DUMP technique

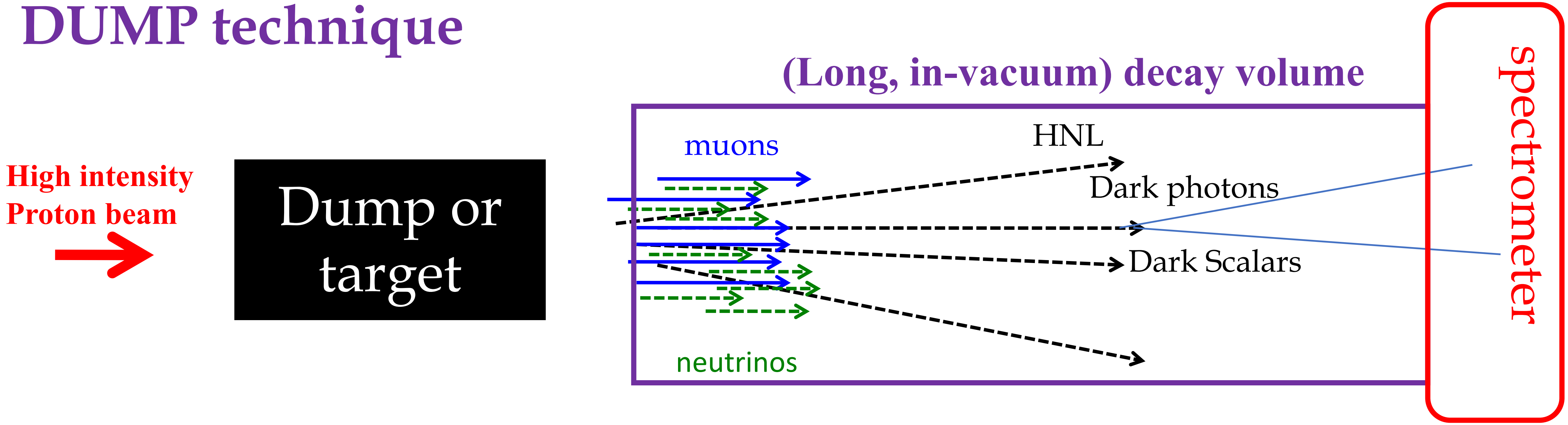


K, D, B, photons, neutrons, protons, π
μ/ν from K/π decays and light resonances, neutrinos, etc..

Feebly interacting long-lived particles at the SPS energy can be produced by strange, charm and beauty decays or by photons .The couplings are very feeble leading to very long lifetimes (up to hundreds of km).

How to search for feebly-interacting long-lived particles?

DUMP technique



Fundamental ingredients:

- Very intense proton beam of moderate energy (to avoid too long lifetimes due to boost effect) but enough to produce many charm and beauty quark (cross-section increase with the energy)
- High-Z material target to enhance heavy quark production and stop pions/kaons before decay in muons (main background)
- Long and in-vacuum decay volume where a non-negligible fraction of long-lived particles can decay
- Exceptional background rejection to enhance sensitivity for very rare processes (main backgrounds: muons and neutrinos)

How to search for feebly-interacting long-lived particles?

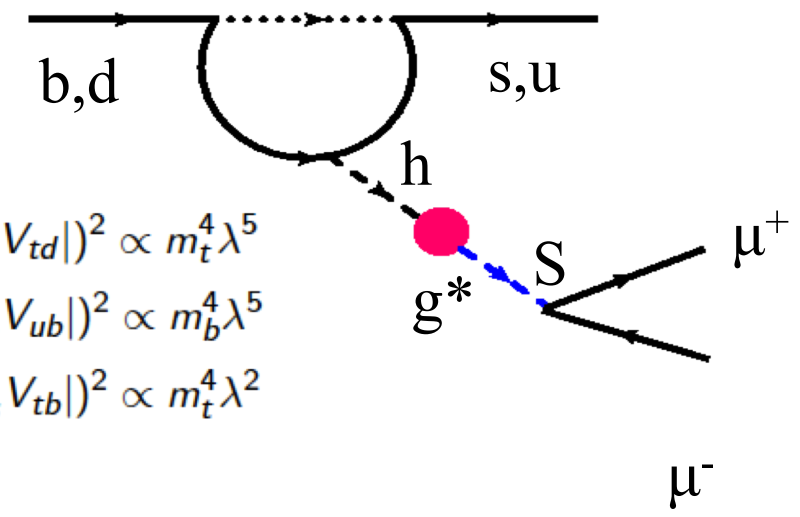
Dark Scalars

High intensity Proton beam

Dump or target

Use the processes:

$B \rightarrow K\ S$
$K \rightarrow \pi\ S$



$$\Gamma(K \to \pi\phi) \sim (m_t^2 |V_{ts}^* V_{td}|)^2 \propto m_t^4 \lambda^5$$

$$\Gamma(D \to \pi\phi) \sim (m_b^2 |V_{cb}^* V_{ub}|)^2 \propto m_b^4 \lambda^5$$

$$\Gamma(B \to K\phi) \sim (m_t^2 |V_{ts}^* V_{tb}|)^2 \propto m_t^4 \lambda^2$$

At SPS energies:

σ (pp → ssbar X) /sigma (pp→ X) ~ 0.15
σ (pp→ c cbar X) /sigma (pp→ X) ~ $2\ 10^{-3}$
σ (pp → b bbarX) /sigma (pp→ X) ~ $1.6\ 10^{-7}$

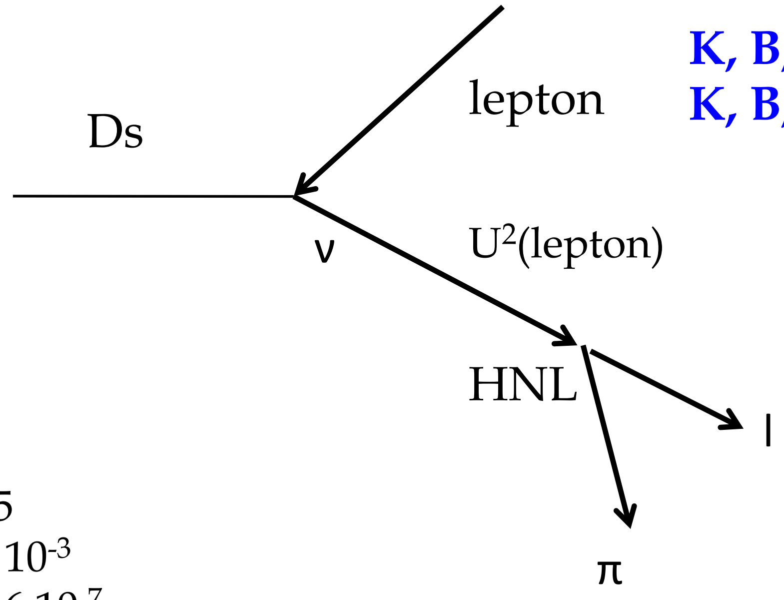
Feebly interacting long-lived particles at the SPS energy can be produced by strange, charm and beauty decays or by photons. The couplings are very feeble leading to very long lifetimes (up to hundreds of km).

How to search for feebly-interacting long-lived particles?

Heavy Neutral Leptons or RHN

High intensity Proton beam →

Dump or target



Use the processes:

K, B, Bs, D, Ds → lepton HNL
K, B, Bs, D, Ds → semi-leptonic modes

At SPS energies:

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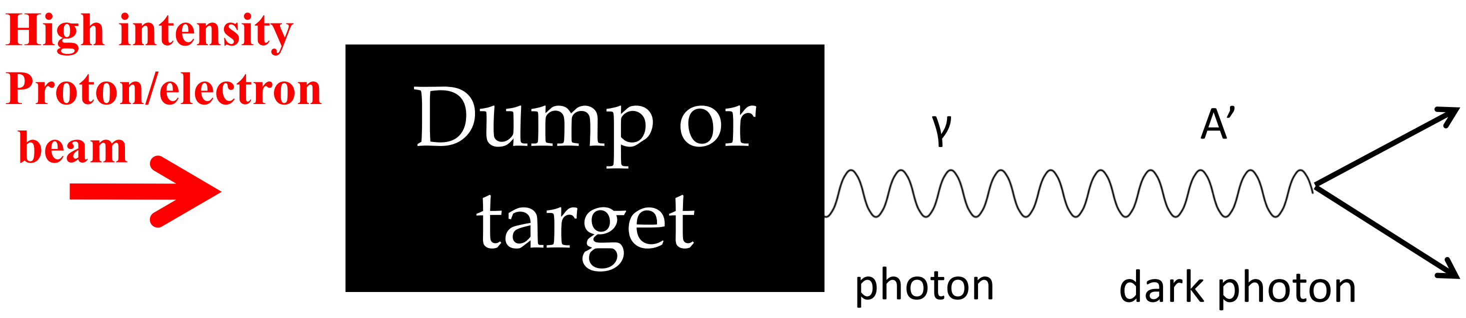
How to search for feebly-interacting long-lived particles?

Dark Photons



Photon produced in light meson resonances, bremsstrahlung, and QCD processes.

Search for massive particle mixing with the photon and decaying to visible final states (e+ e- , μ+μ-, etc.)

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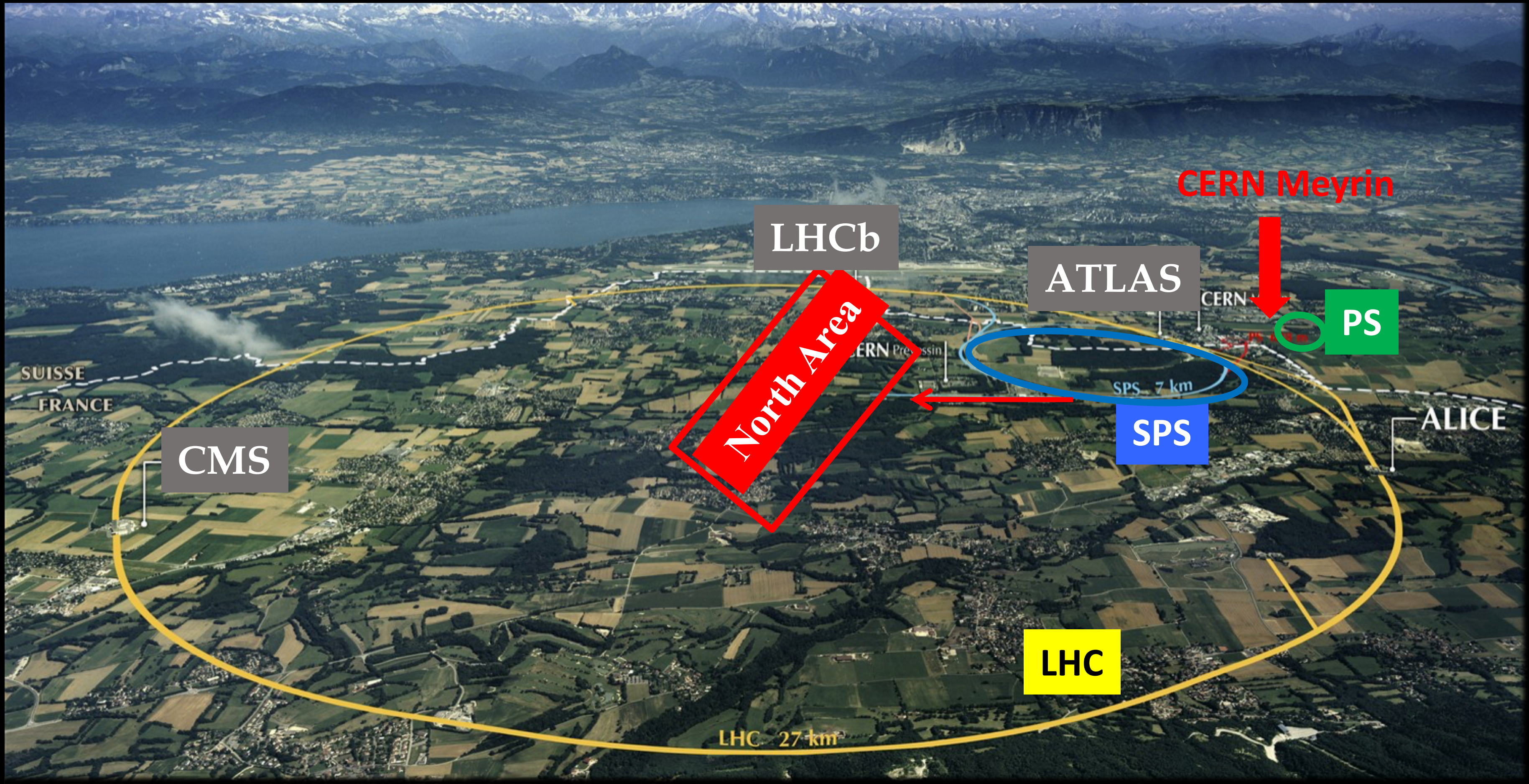
The CERN Accelerator Complex and Sites

Feebly interacting long-lived particles require high-energy high-intensity beams



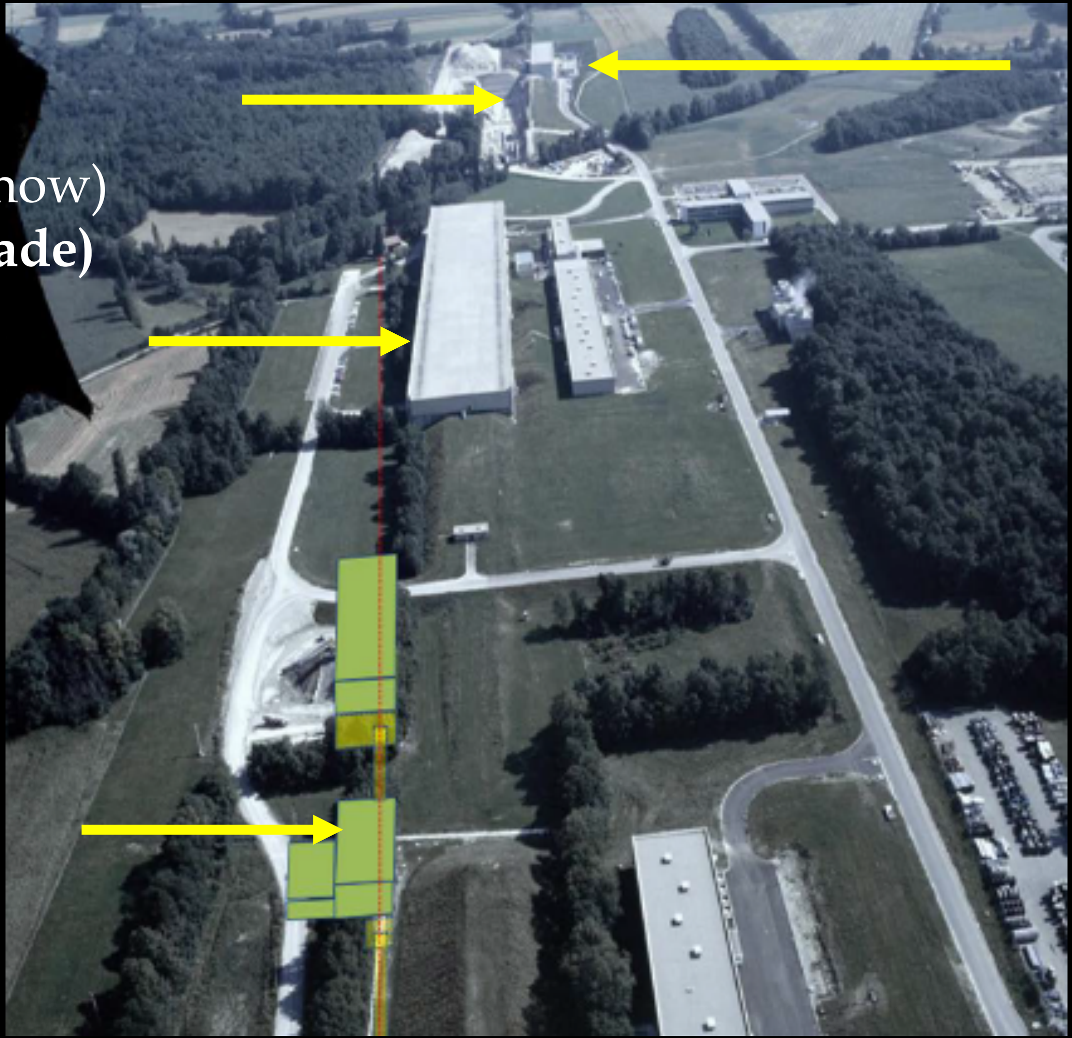
CERN can provide the highest energy proton, electron and muon beams in the world.

Aerial picture of the North Area - Prevessin

NA62 $^{++}$ @ K12
400 GeV p beam
up to 1-2x10^{18} pot/year (now)
up to 10^{19} pot/year (upgrade)

NA64^{++}(e) @ H4
(100 GeV e- beam
up to 5x10^{12} eot/year)

SHiP @BDF
400 GeV p
up to 4x10^{19} pot/year
(40 times the intensity of the NA62 beam)

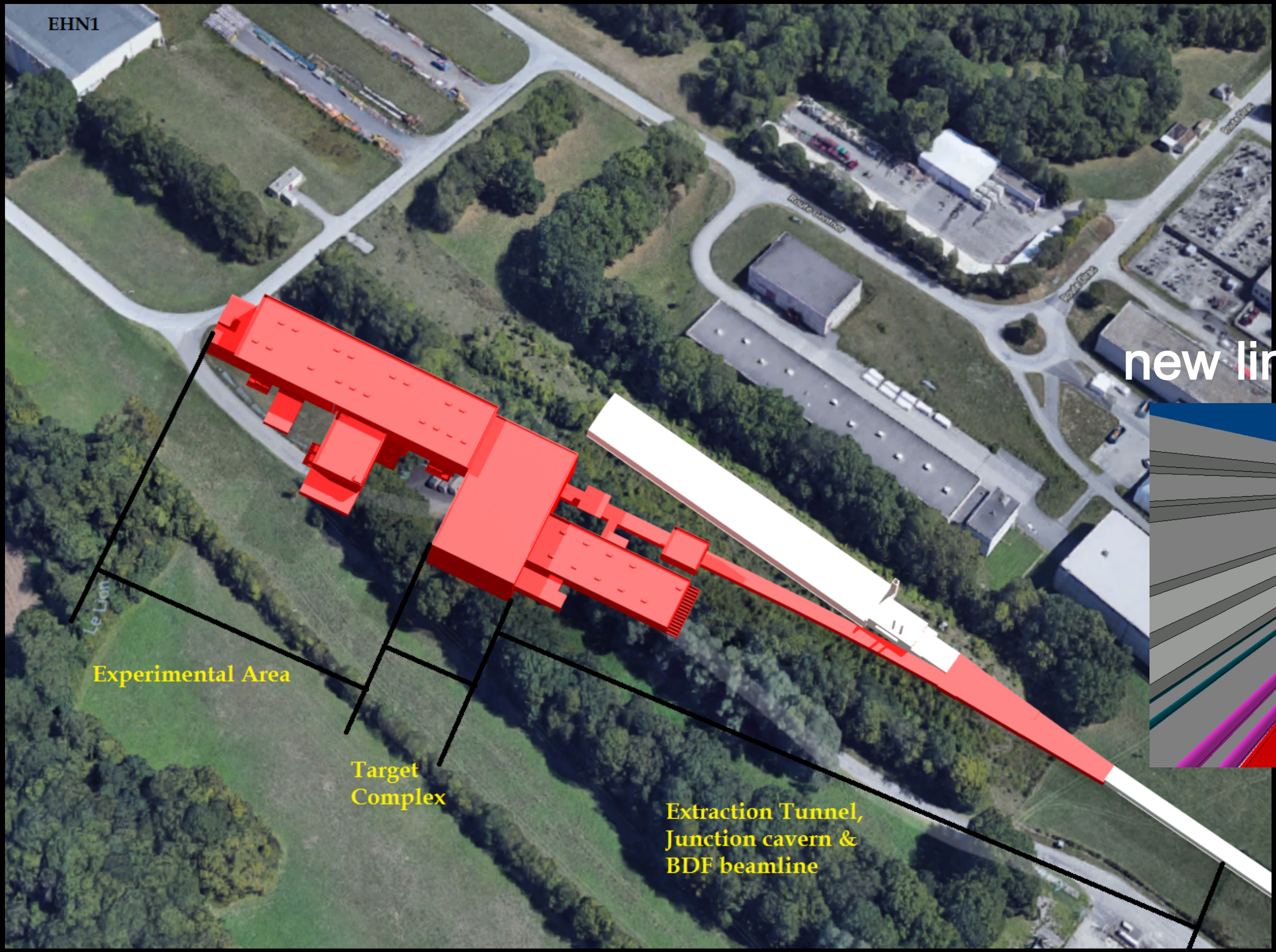


NA64^{++} (μ) @ M2
100-160 GeV muons,
up to 10^{13} μ/year

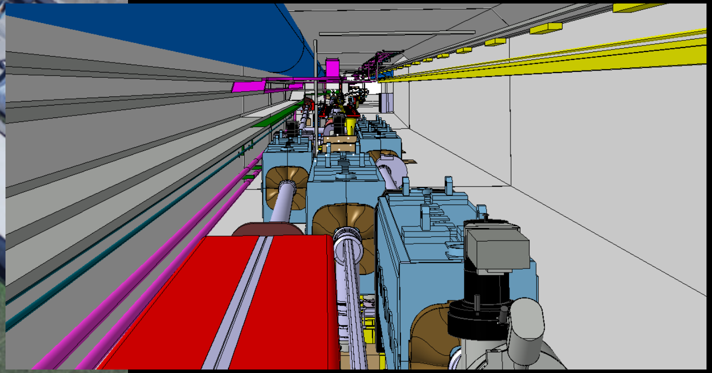
From the Physics Beyond Colliders Report, input to the ESPP

The "Hidden Sector Campus" (HSC)

Beam Dump Facility in the North Area



new line branching off in TDC2



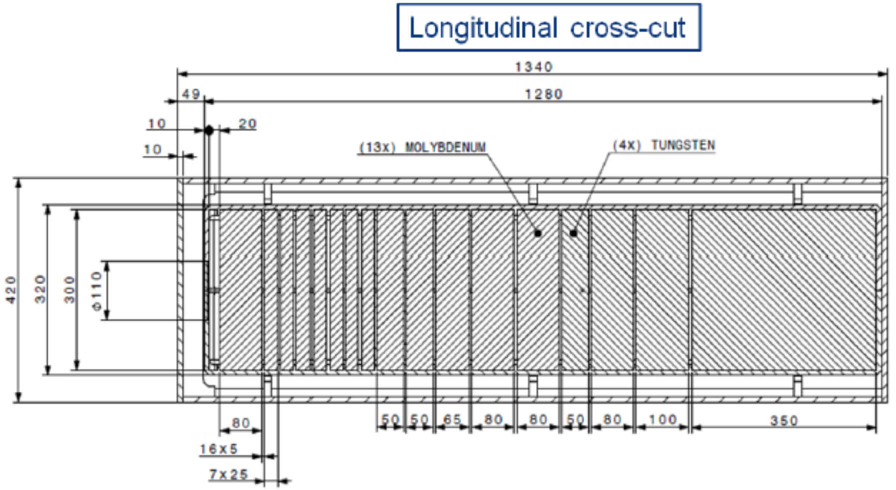
Brand new high-intensity proton beamline proposed in the North Area
~500 pp Yellow Report in preparation.

The SHiP Target

- SHiP target is a high pulse intensity "spallation"

Target: 90% of the beam energy (**2.56 MJ**) is deposited in the target

  - Pulsed power is similar to ESS (**2.5 MW**), but more challenging due to high intensity pulse; **355 kW** average power.

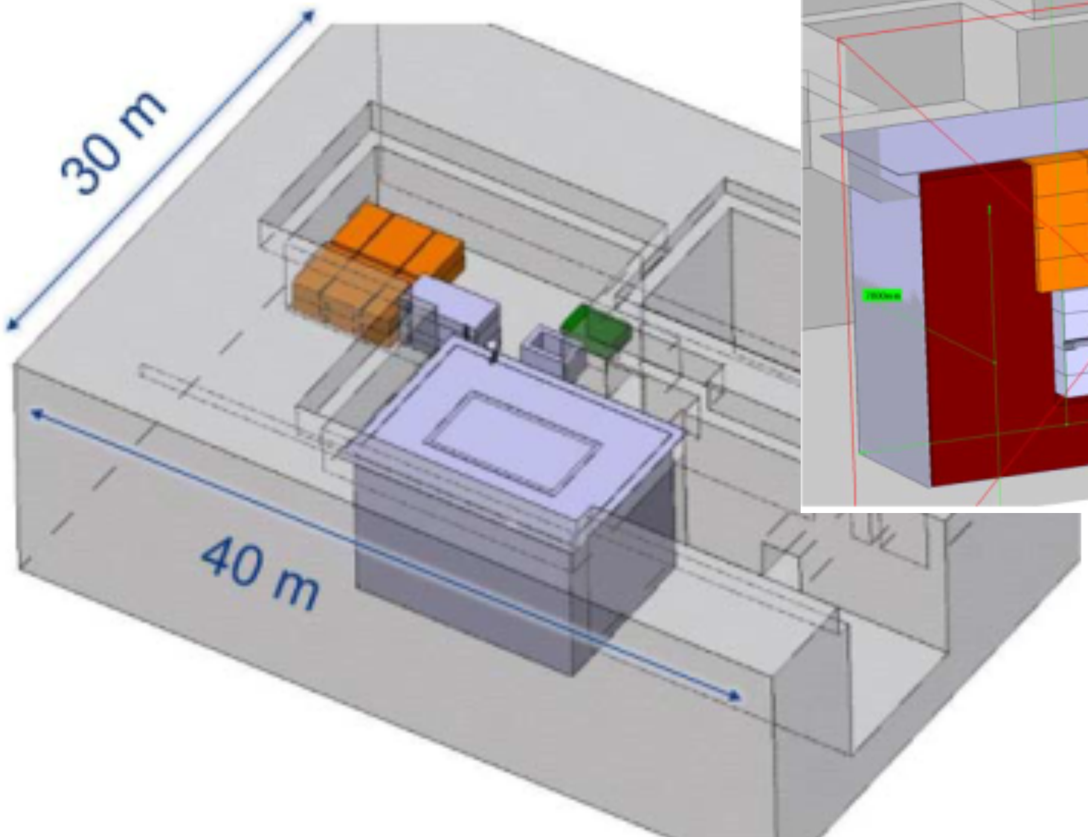


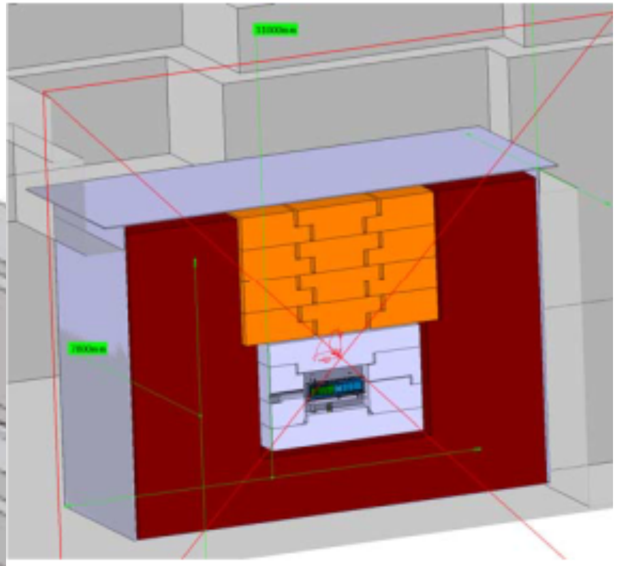
Proton beam
400 GeV/c

- 10 nuclear interaction length long production target (~ 120 cm)
- High-Z target, hybrid solution composed of TZM (Molybdenum alloy) & pure W

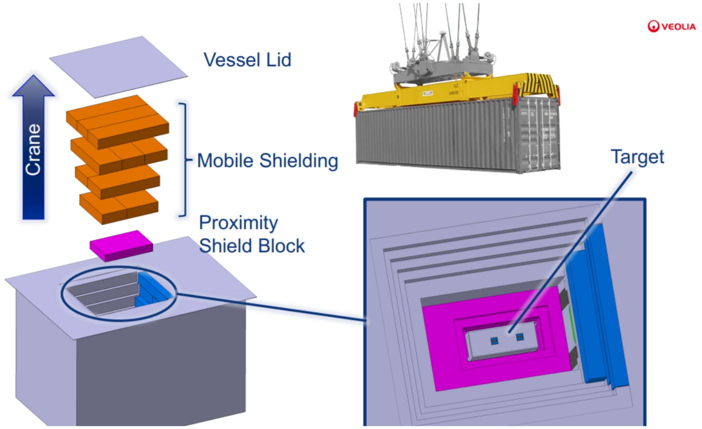
Beam Dump Facility: Target Complex

- ✓ Target is located 15 m underground, relatively close to the CERN fence (~70 m)
- ✓ Cast-iron shielding encloses production target (460 m3)
- ✓ Target bunker inside an active circulation He-vessel
- ✓ Fully remote handling/manipulation as basis of design

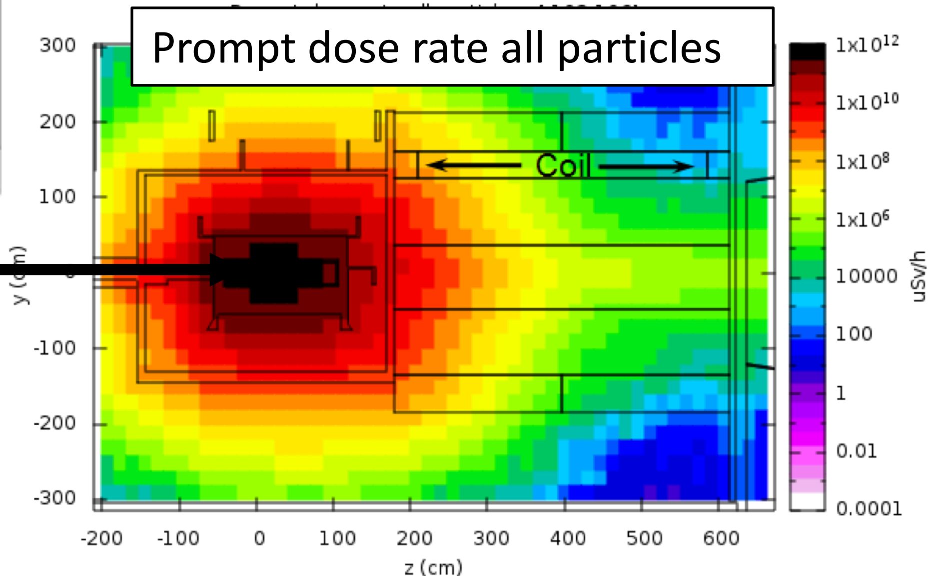




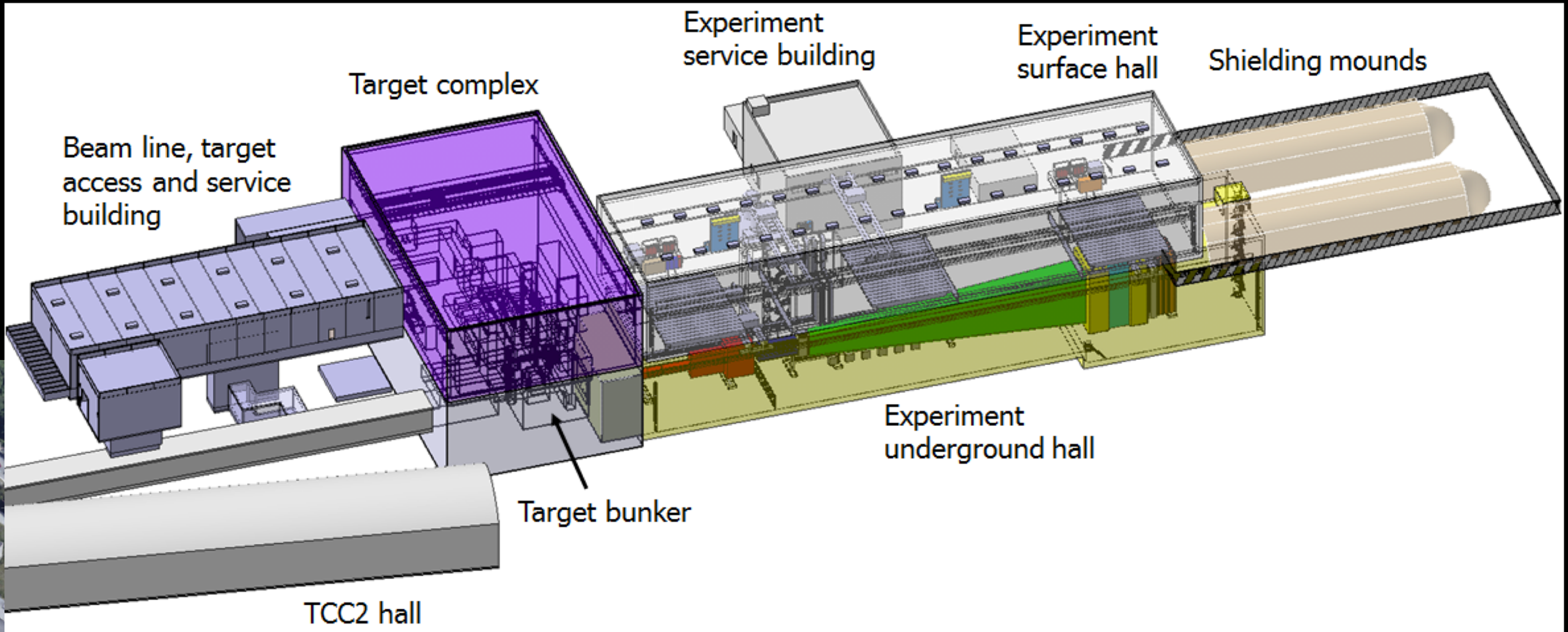
Crane concept – target access

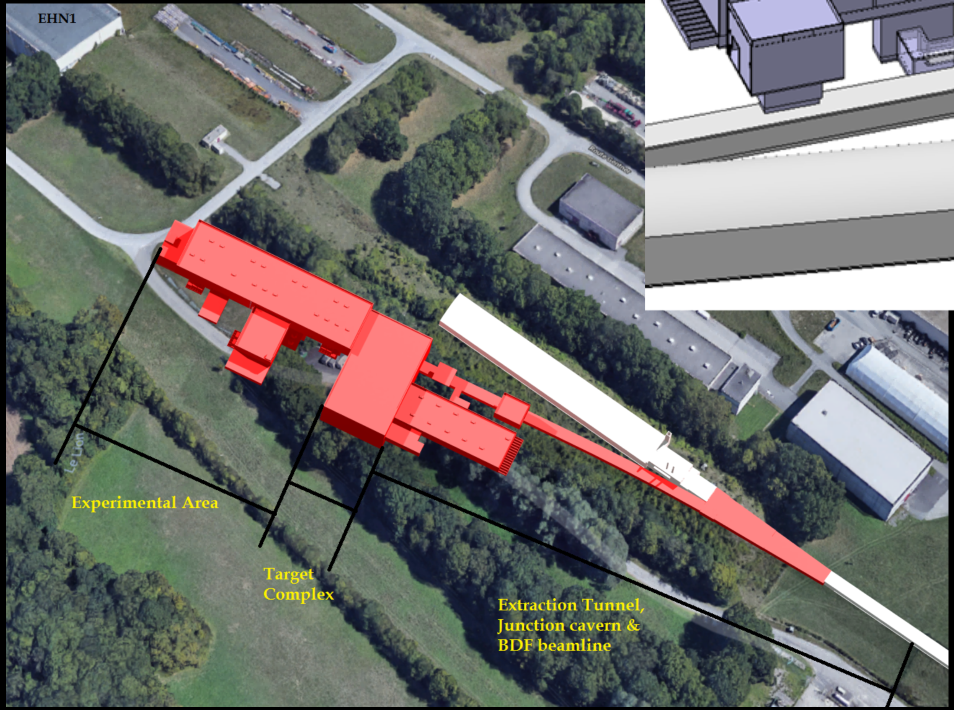


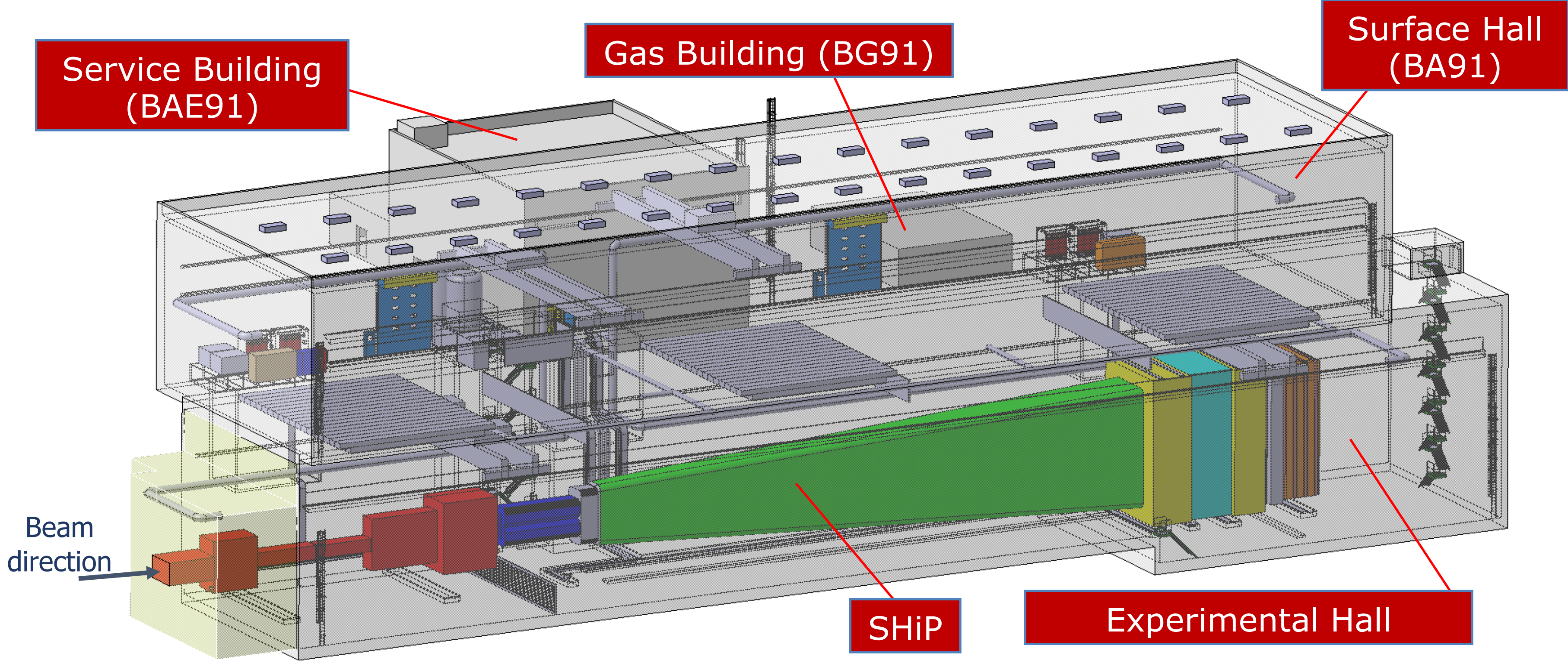
beam

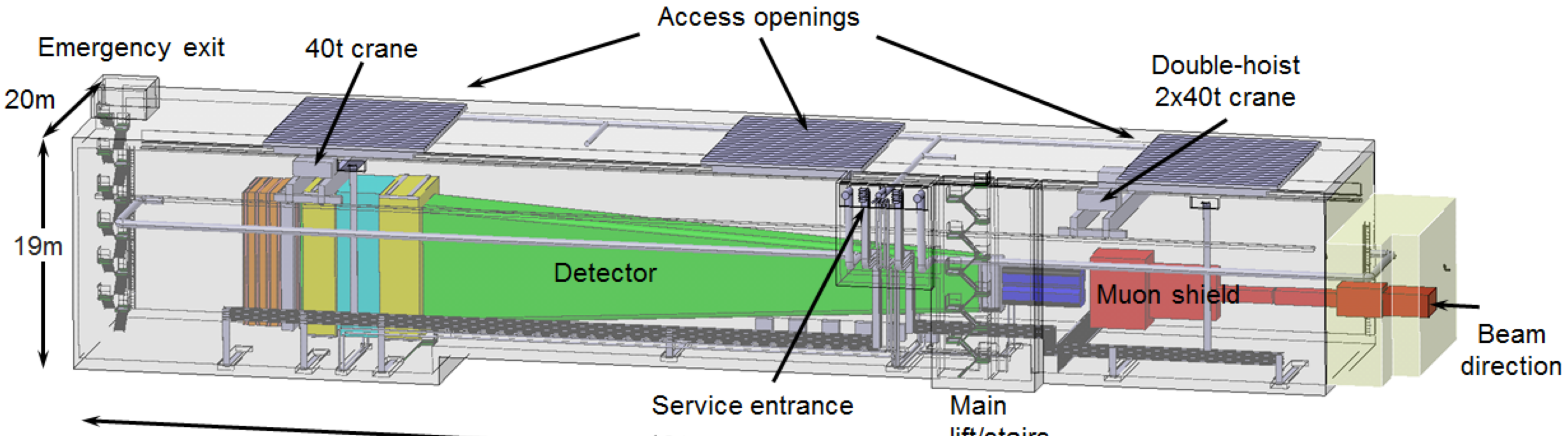


SHiP Experimental Area: overview

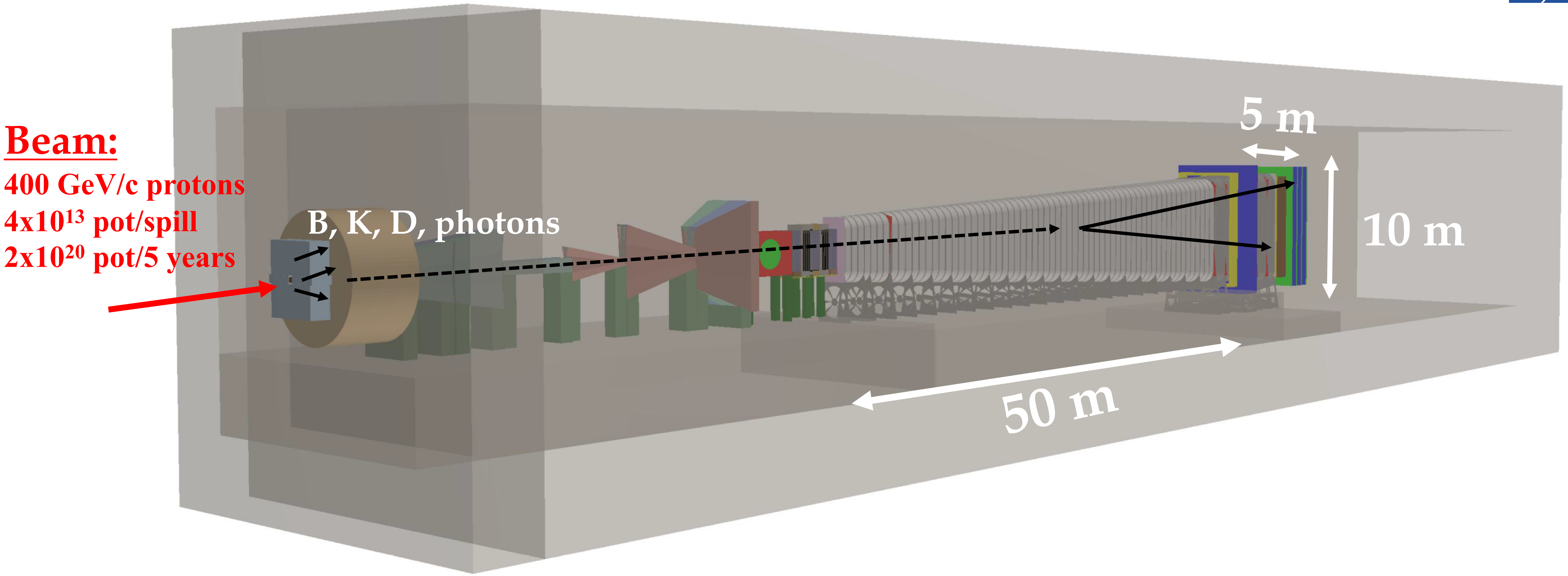





Service Building
(BAE91)
Gas Building (BG91)
Surface Hall
(BA91)
Beam
direction
SHiP
Experimental Hall

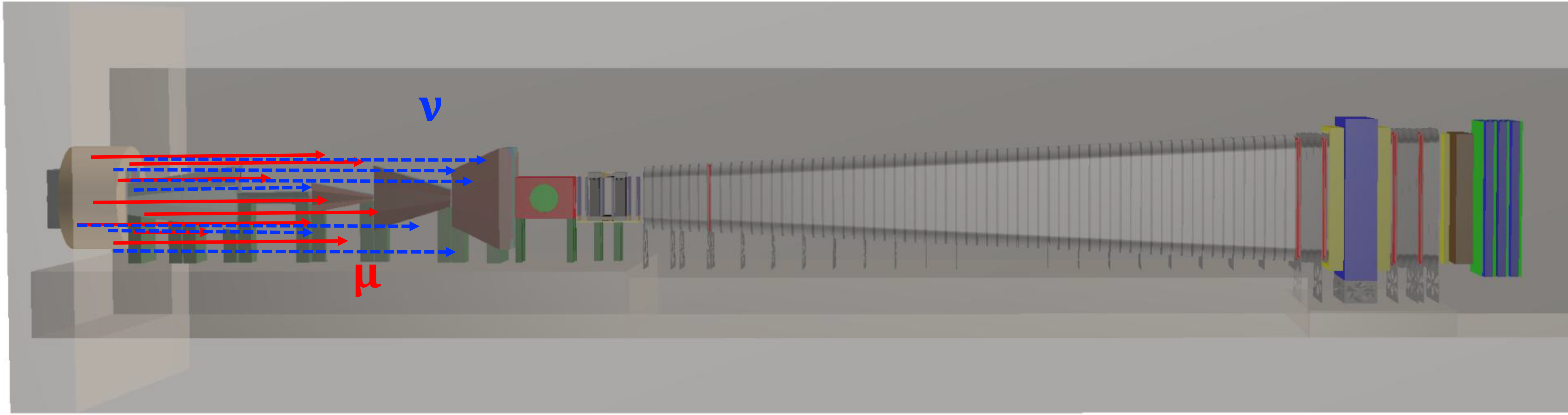

Access openings
Emergency exit
40t crane
Double-hoist
2x40t crane
20m
19m
Detector
Muon shield
Beam
direction
Service entrance
Main

SHiP experiment @ BDF



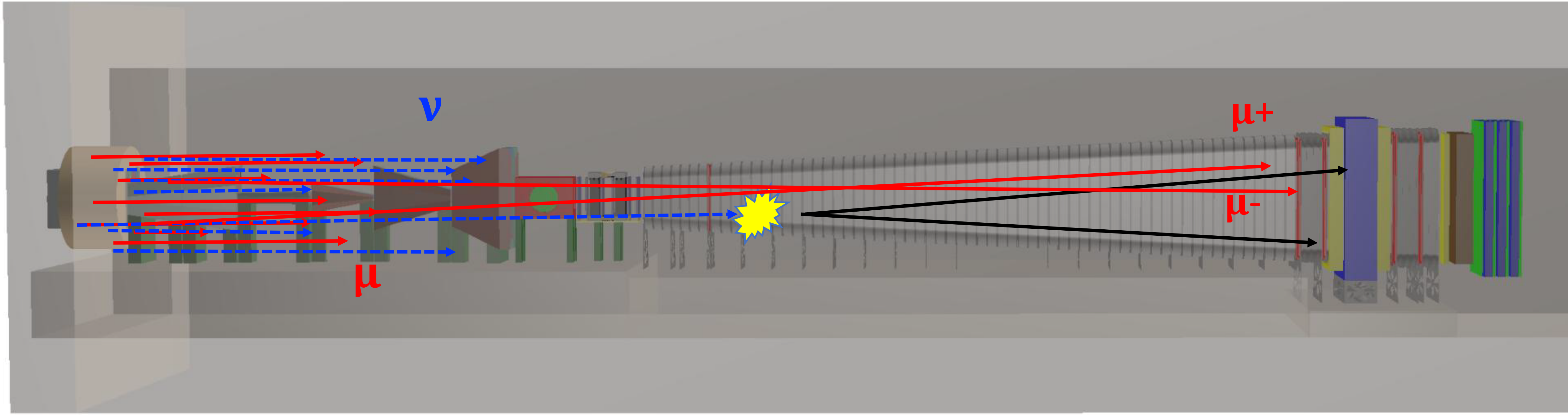
- ✓ Hidden particles have very feeble couplings, hence they are (very) long-lived:
  - The 60m-long, in-vacuum SHiP decay volume allows us to be sensitive to extremely low couplings
- ✓ Hidden particles from D and B decays have large p_T:
  - SHiP large geometrical acceptance maximizes detection of decay products

….Background, background, background……



- ✓ The proton interactions on the dump, along with the signals, give rise to a copious direct production of short lived resonances, and pions and kaons.
- ✓ While the length of the dump (~11 λ_I target + 5 m hadron absorber) is sufficient to absorb the hadrons and the electromagnetic radiation, the decays of pions, kaons and short-lived resonances result in a large flux (several tens of GHz) of muons and neutrinos.

....Background, background, background......



Two types of background expected:

1) neutrino and muon inelastic interactions with the detector material, namely with the decay vessel;

⟶ mostly in-time tracks, not pointing backwards to the target;

⟶ main detectors to reduce this background: VETO detectors (surrounding background tagger, Upstream Veto)

2) muon combinatorial background:

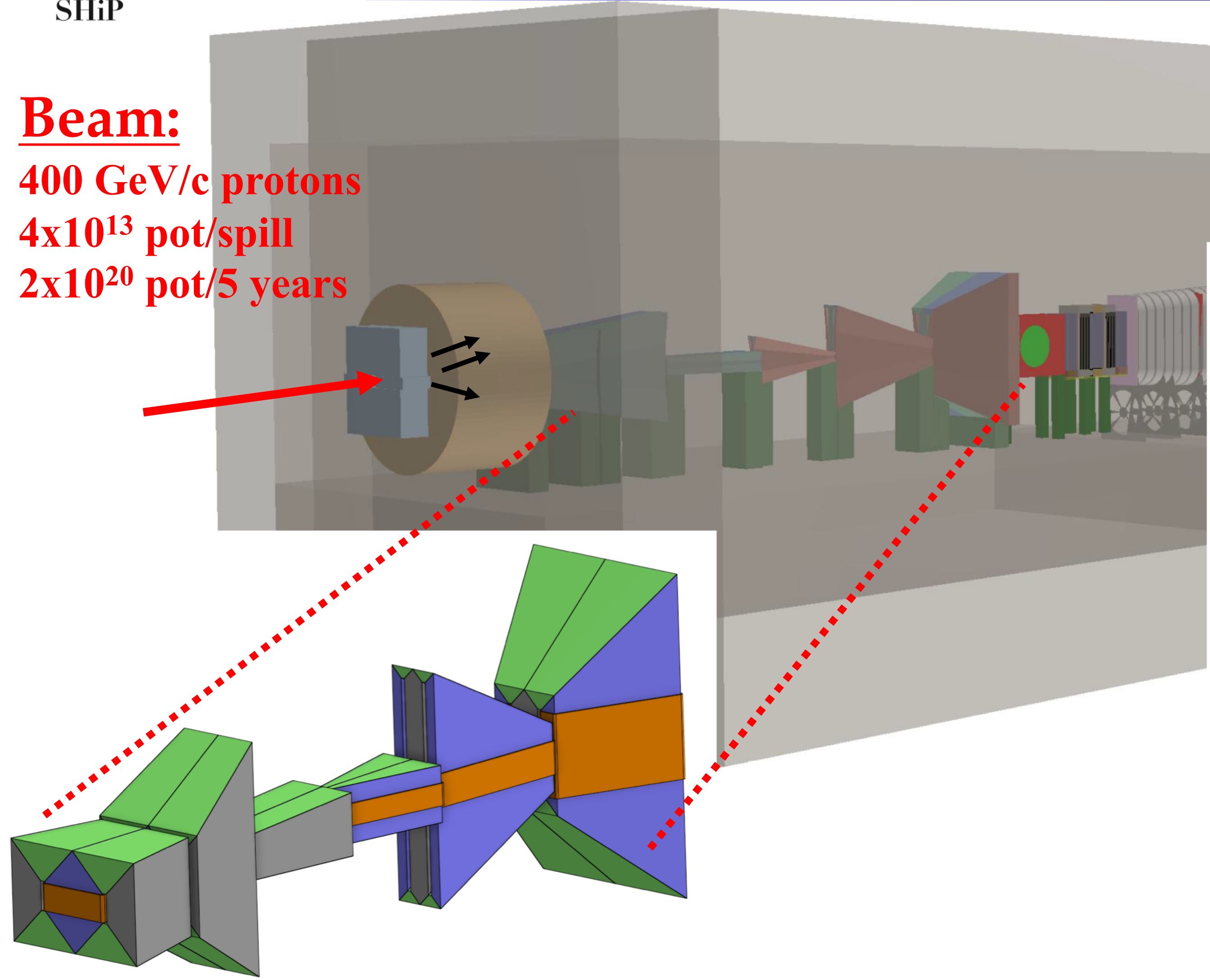
⟶ mostly out-of-time tracks, not pointing backwards to the target

⟶ main detectors to reduce this background: Timing Detector (and muon system with timing capabilities)

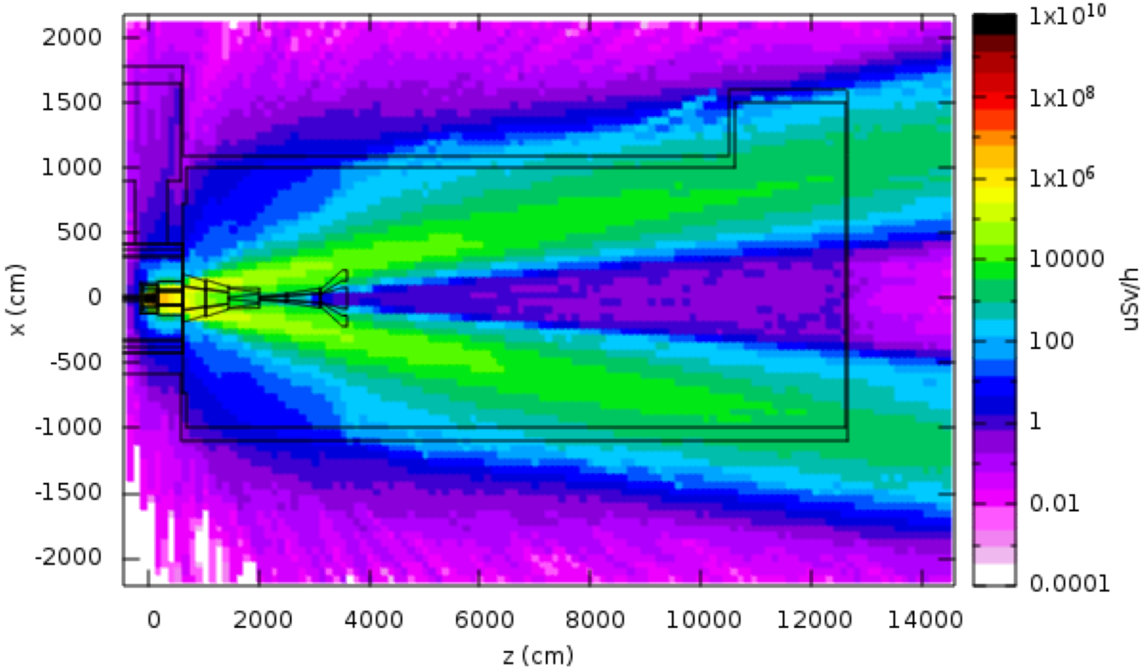
SHiP @ BDF: Active Muon Shield

Beam:

400 GeV/c protons
$4x10^{13}$ pot/spill
$2x10^{20}$ pot/5 years



Prompt dose rate muons



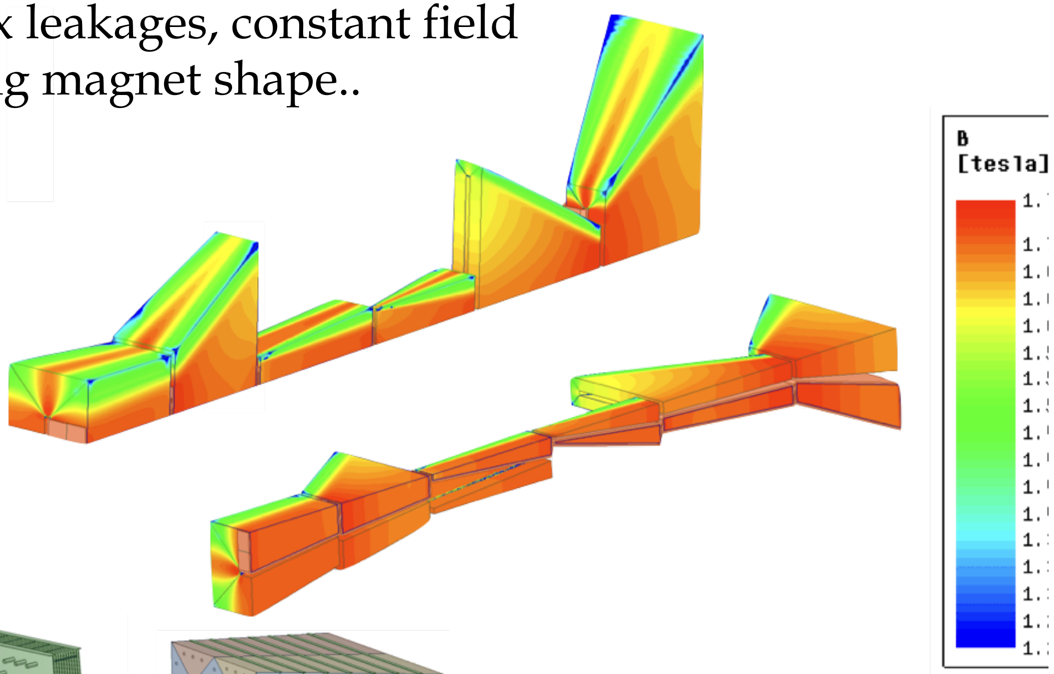
Active Muon Shield:

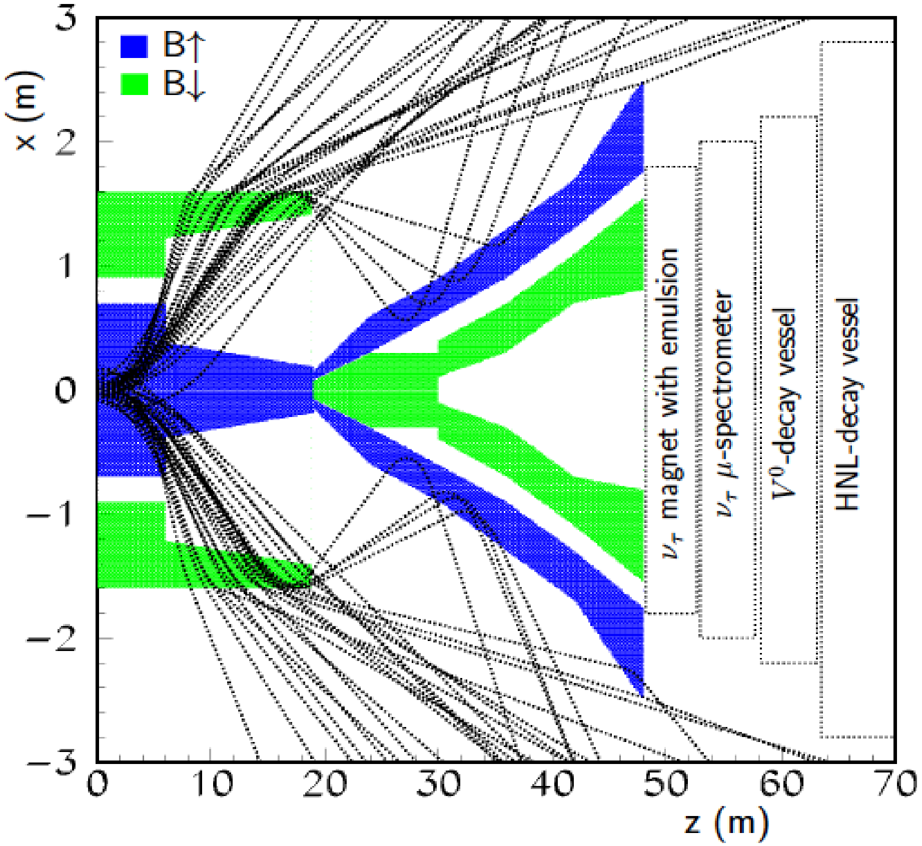
sweeps out muons emerging from the target: reduces by 6 orders of magnitude the rate of muons

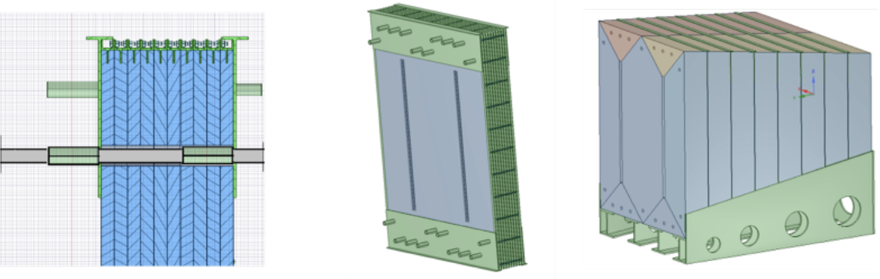
SHiP @ BDF: Active Muon Shield

35 m long, Grain Oriented steel, allowing a high magnetic flux density at a very limited current.

Challenges: flux leakages, constant field profile, modeling magnet shape..







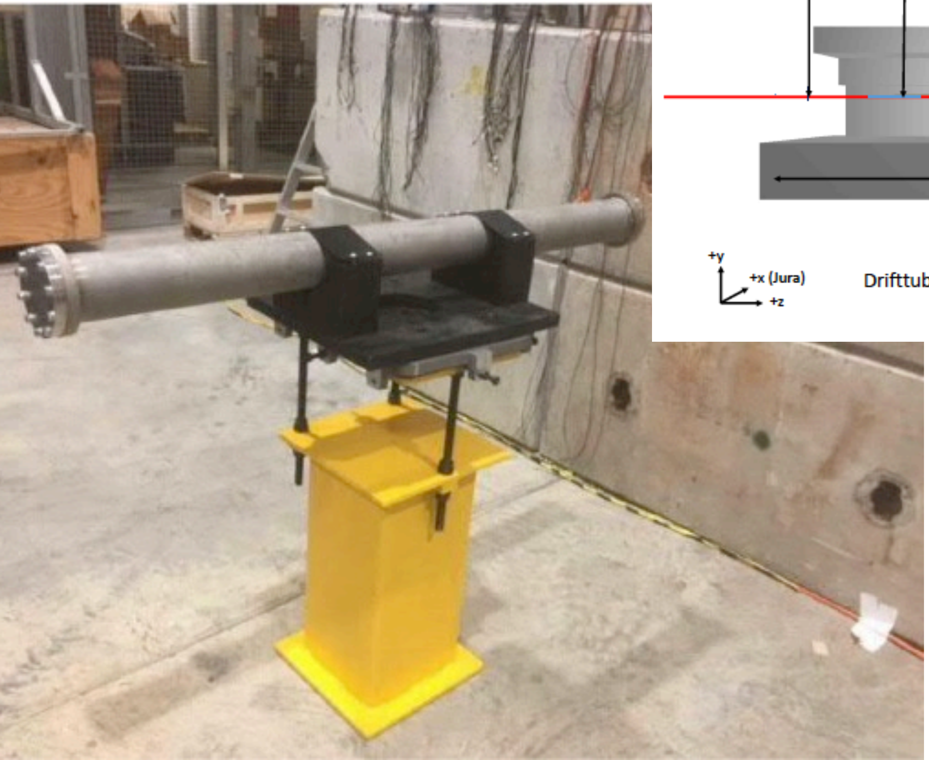
GO steel sheets are packed into sections about 50 mm thick

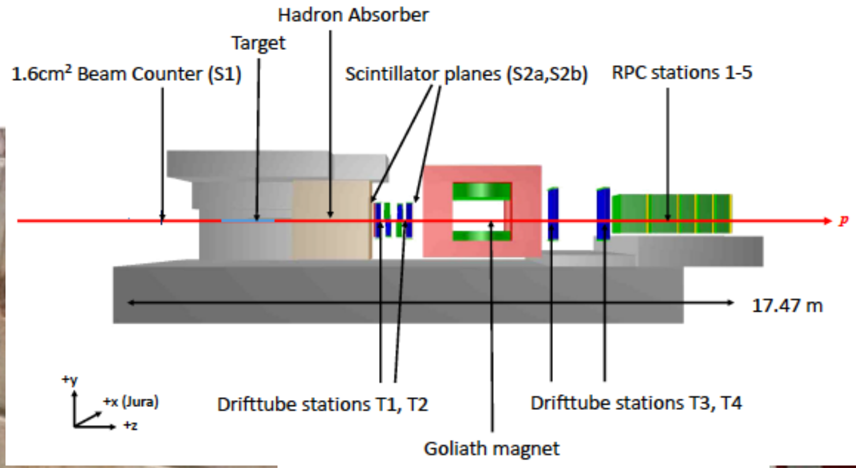
Reduced the muon flux by 6 orders of magnitude: o(100) GHz → 100 kHz
(currently being designed in Russia and UK)

Measurement of the muon flux for muon shield design

About 5 x10^{11} protons on (SHiP) target collected in the H4 area of CERN SPS, in a 1-month long test beam (July 2018)
Crucial measurements of rates and (p,pT) distributions of muons emerging from SHiP target to validate active shield design.
Measurements show an overall good agreement with simulation, paper in preparation.

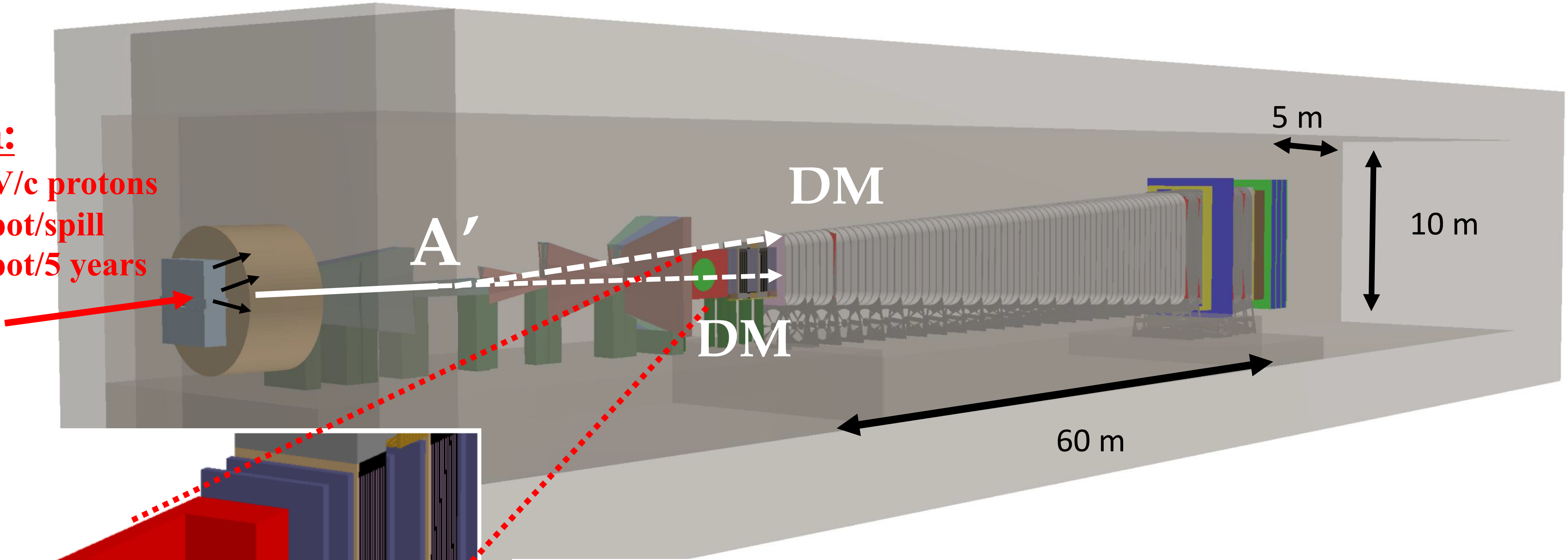
This is a major step forward for SHiP!

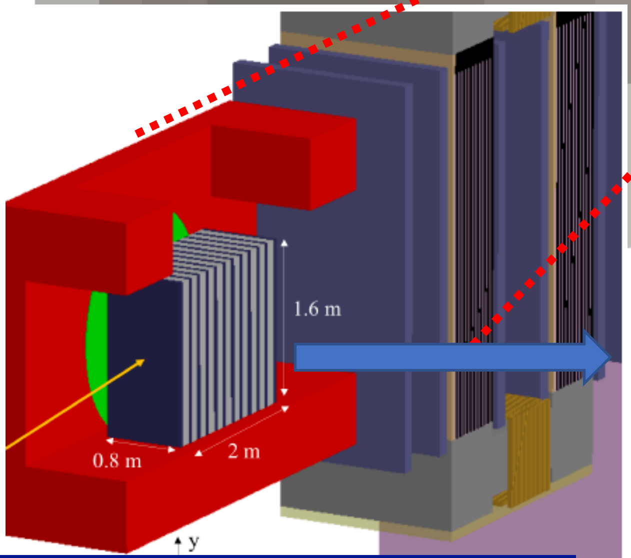




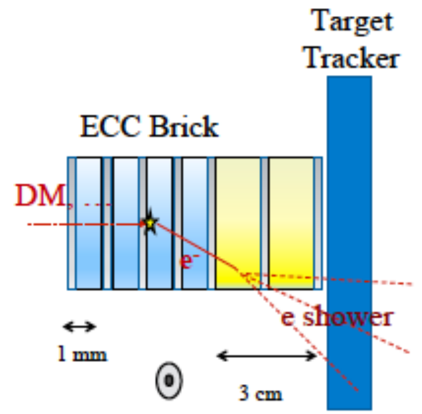
SHiP: neutrino and LDM detector

Beam:
400 GeV/c protons
4×10^{13} pot/spill
2×10^{20} pot/5 years



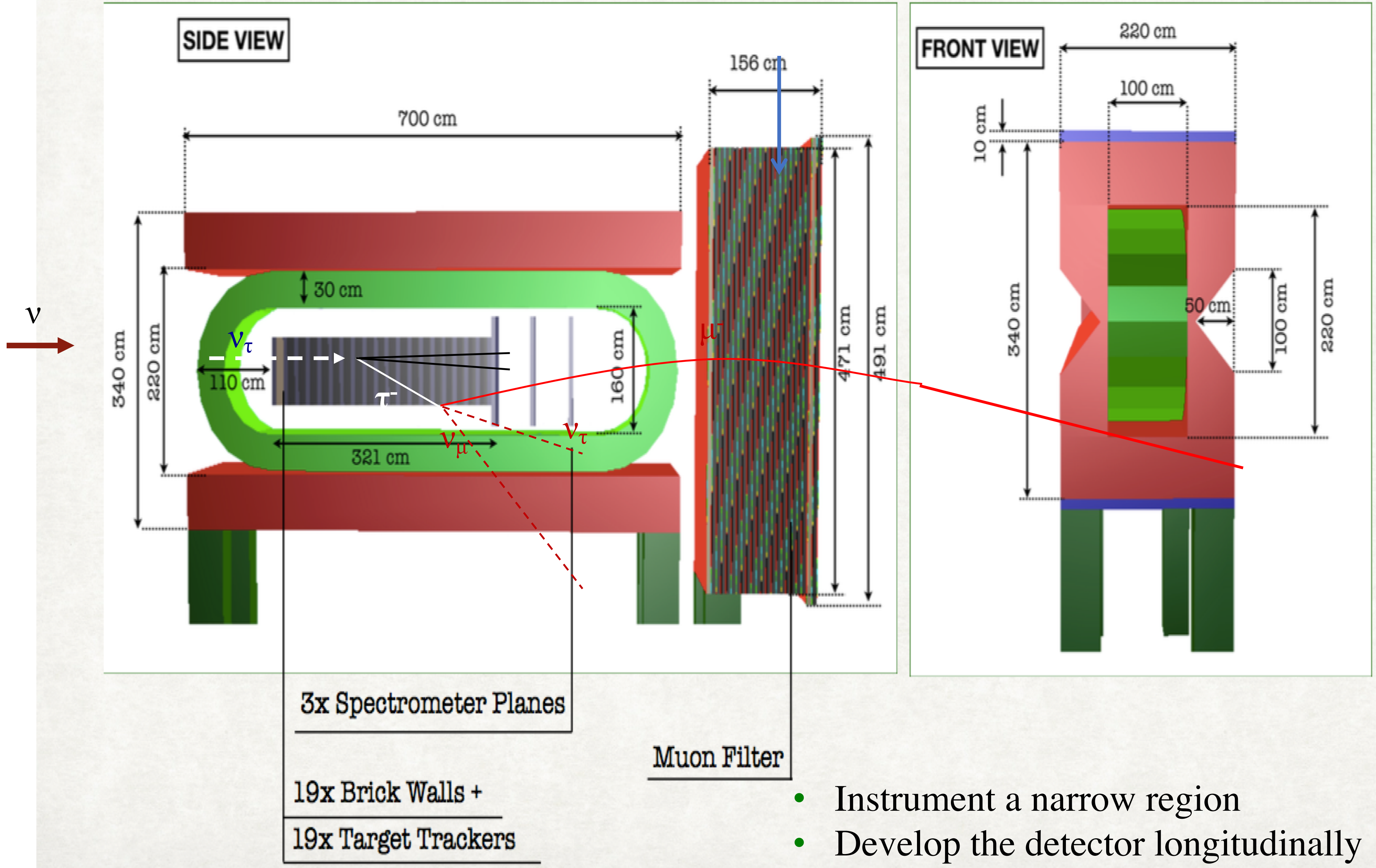


SHiP Upstream Detector



DM particles can scatter on the electrons of the dense material of the Emulsion Spectrometer in the Upstream Detector.
The same detector will do tau neutrino physics.

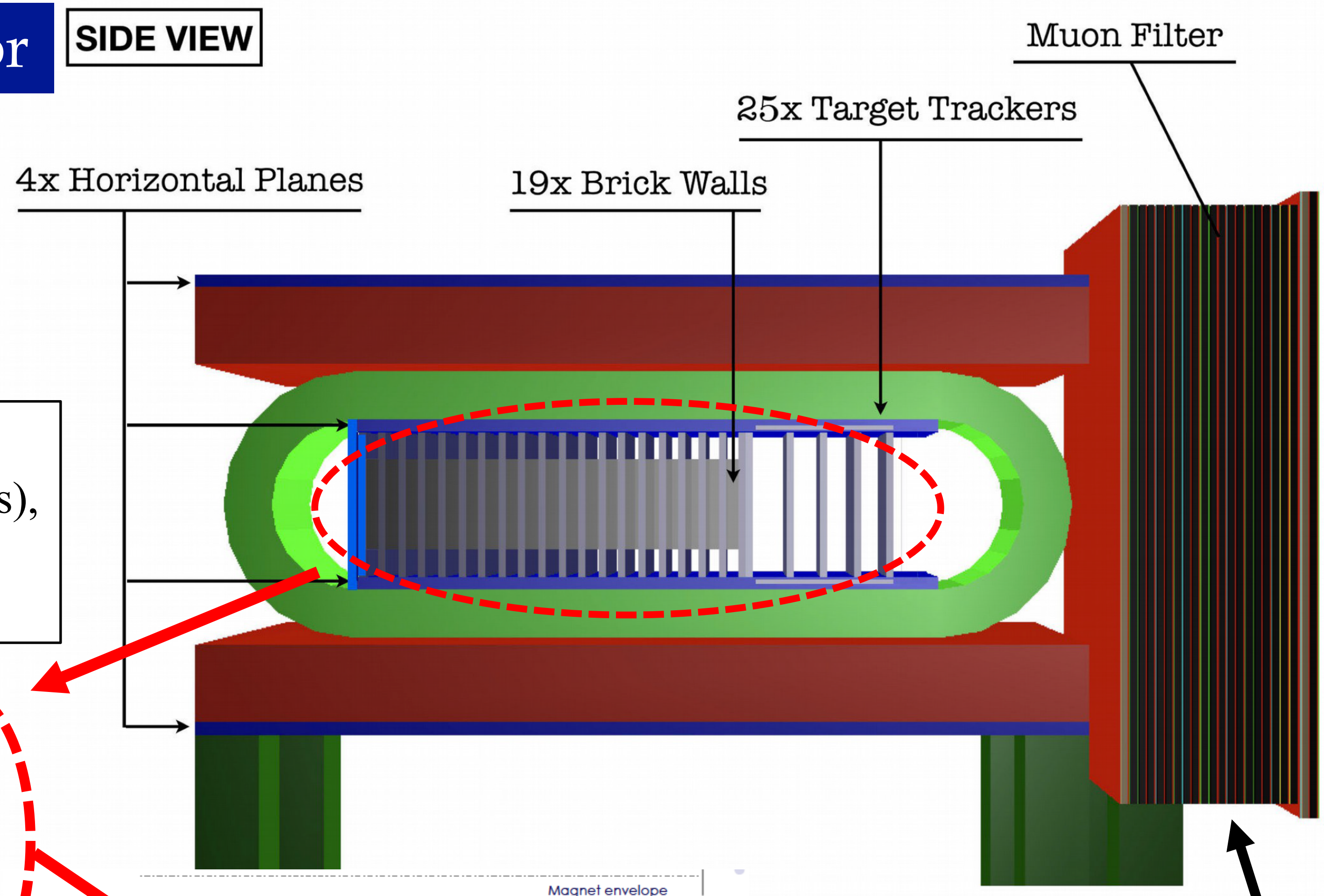
CONCEPT OF THE ν/iSHiP DETECTOR



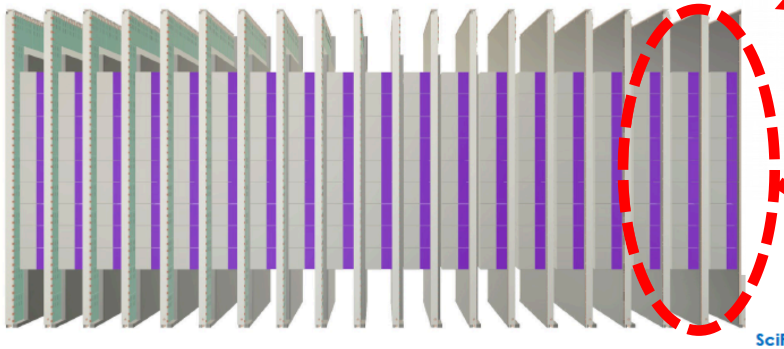
- Instrument a narrow region
- Develop the detector longitudinally

SHiP Upstream Detector

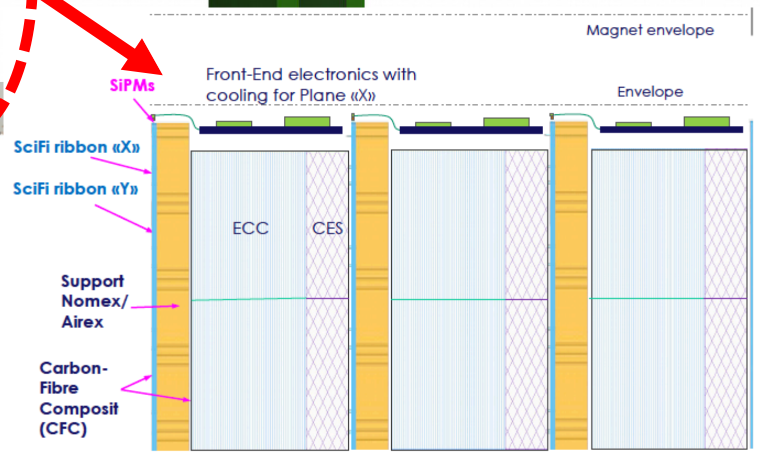
SIDE VIEW



<u>19 layers of high precision tracker</u>
(scintillating fibers or GEM/muRWELLs),
910x1430x30 mm^3
separated by emulsions bricks



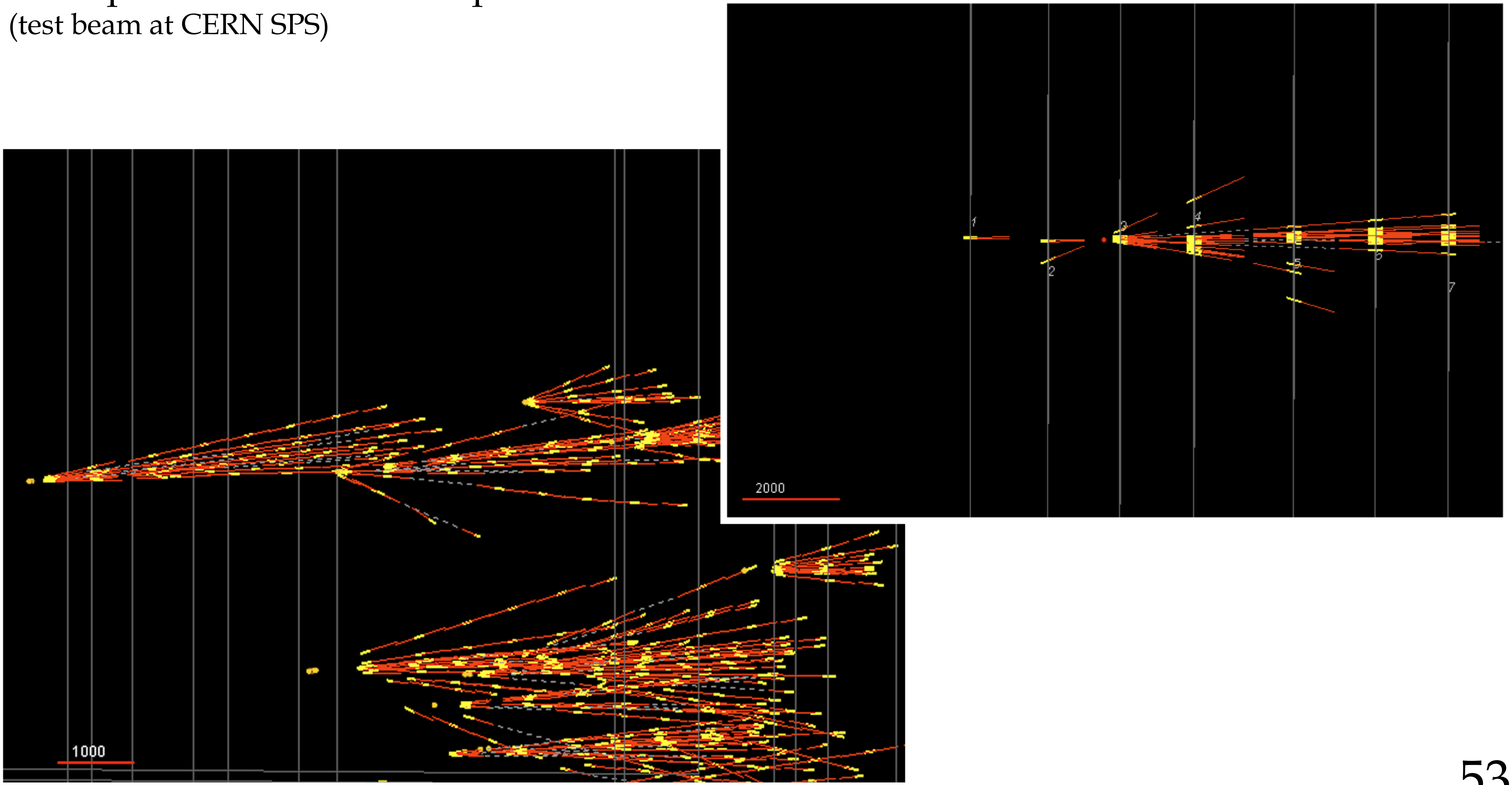
13 March 2019 iSHiP- SciFi tracker



<u>Upstream Muon Detector:</u>
16 RPC layers (3 cm)
+ 15 Fe layers (10 cm)

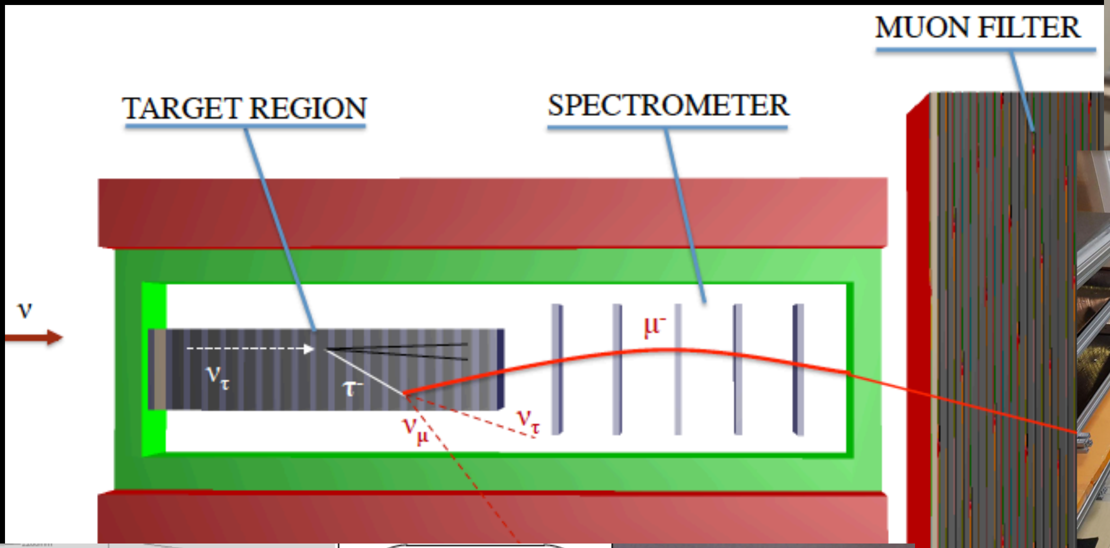
Example of interactions of protons in the bricks

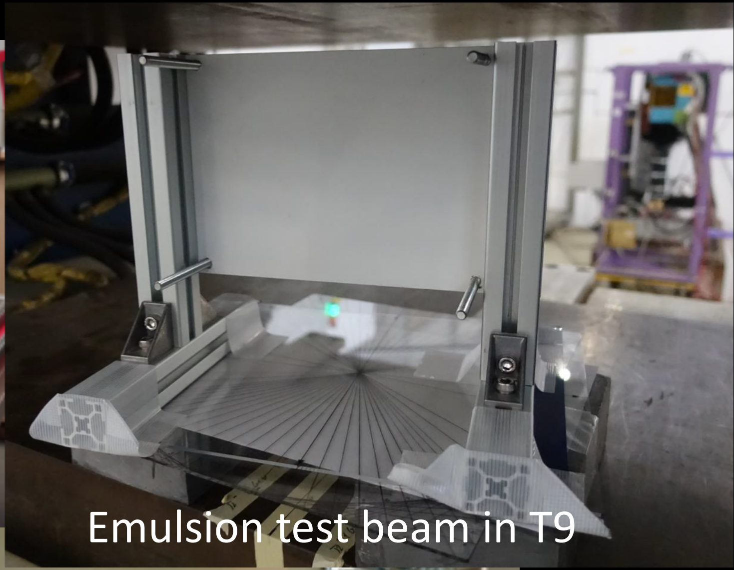
(test beam at CERN SPS)

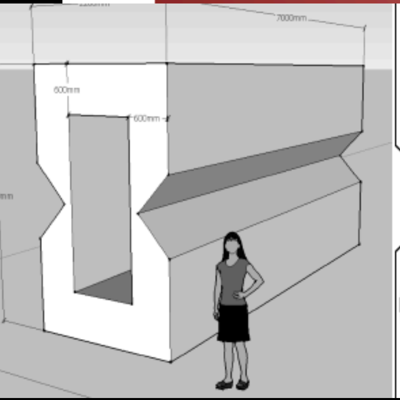


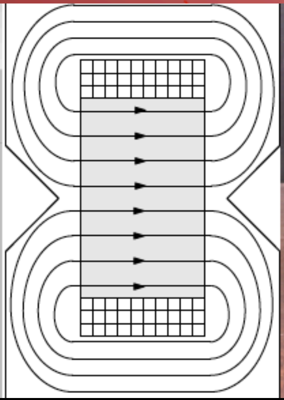
SHiP Upstream Detector: prototypes

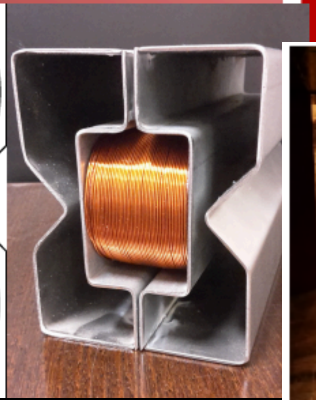
Bulgaria, Germany, Italy, Japan, Korea, Russia and Turkey





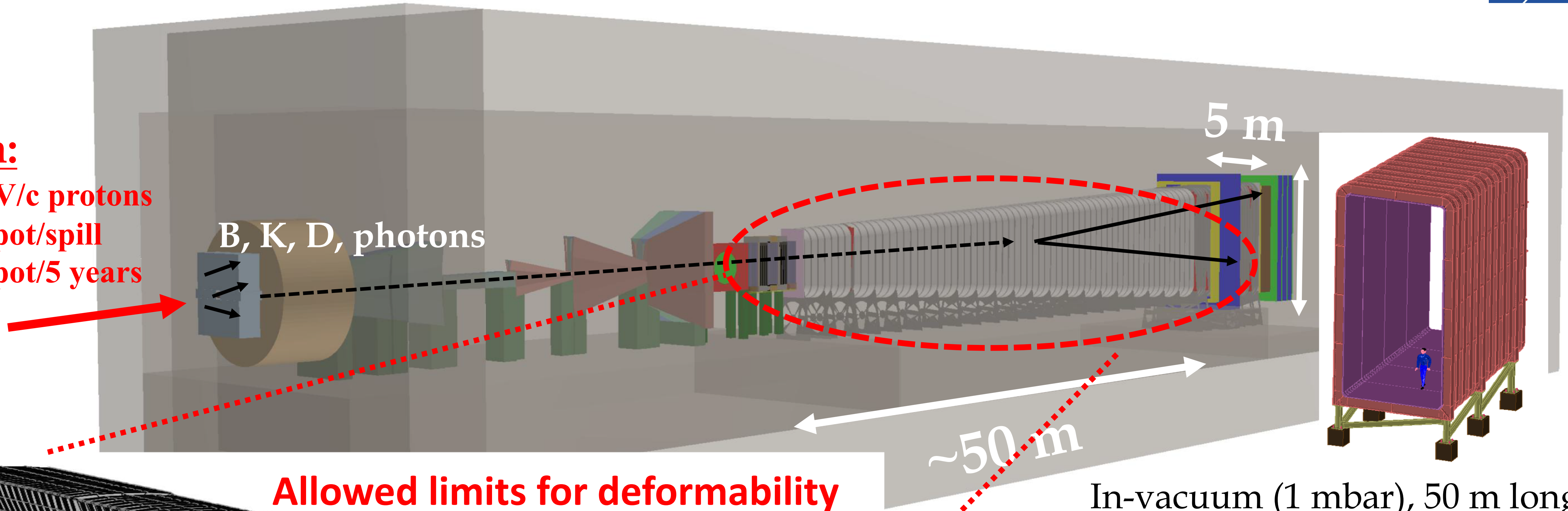




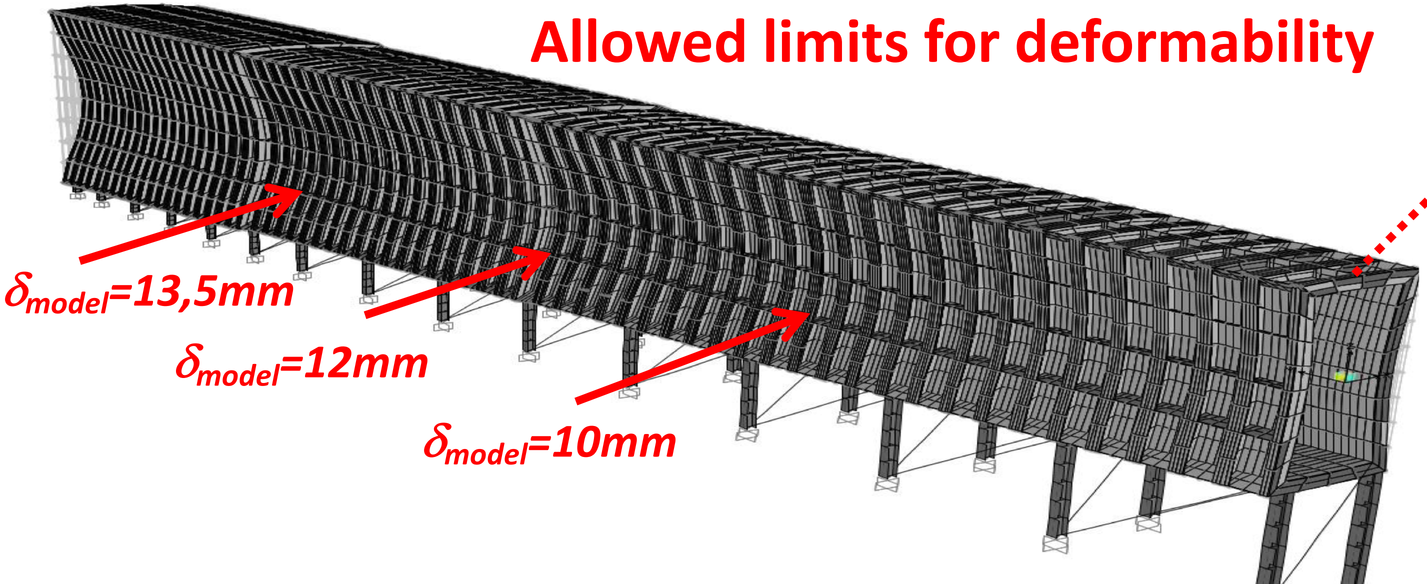


SHiP: long, in-vacuum decay volume

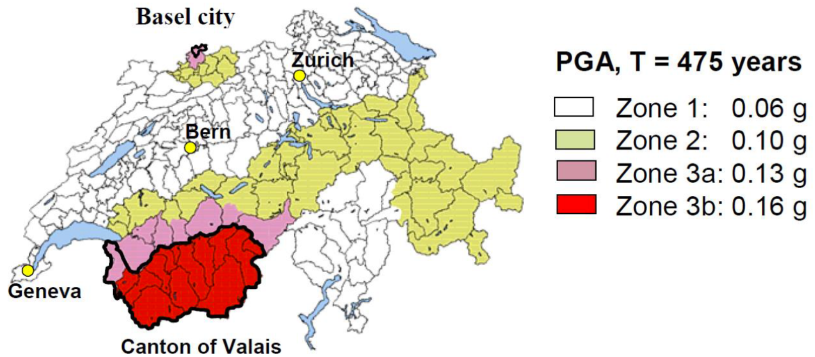
Beam:
400 GeV/c protons
$4x10^{13}$ pot/spill
$2x10^{20}$ pot/5 years



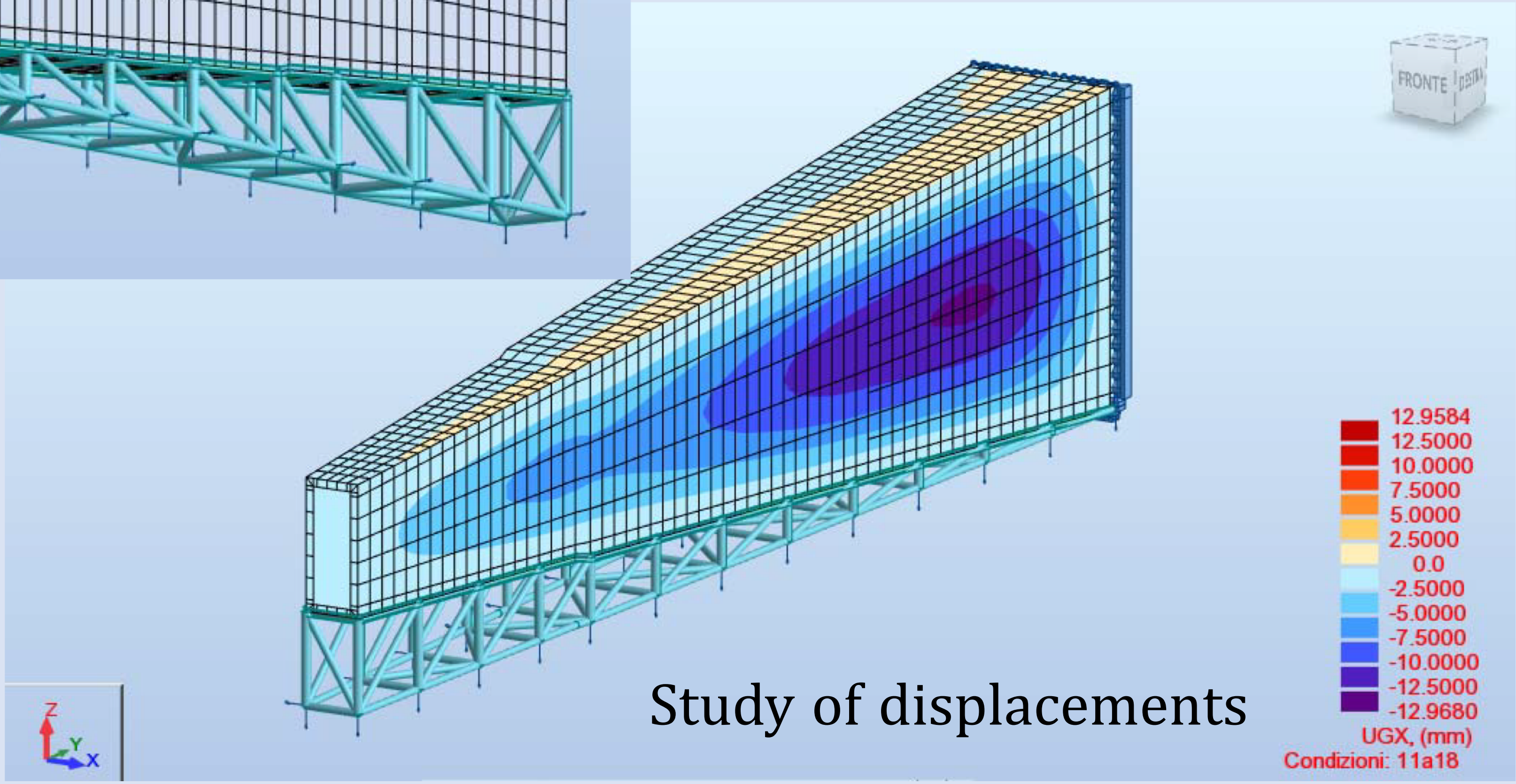
In-vacuum (1 mbar), 50 m long decay volume



Define seismic load



SHiP: decay vessel

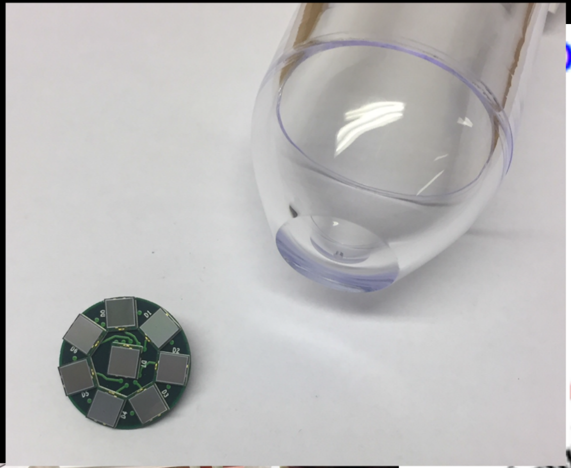
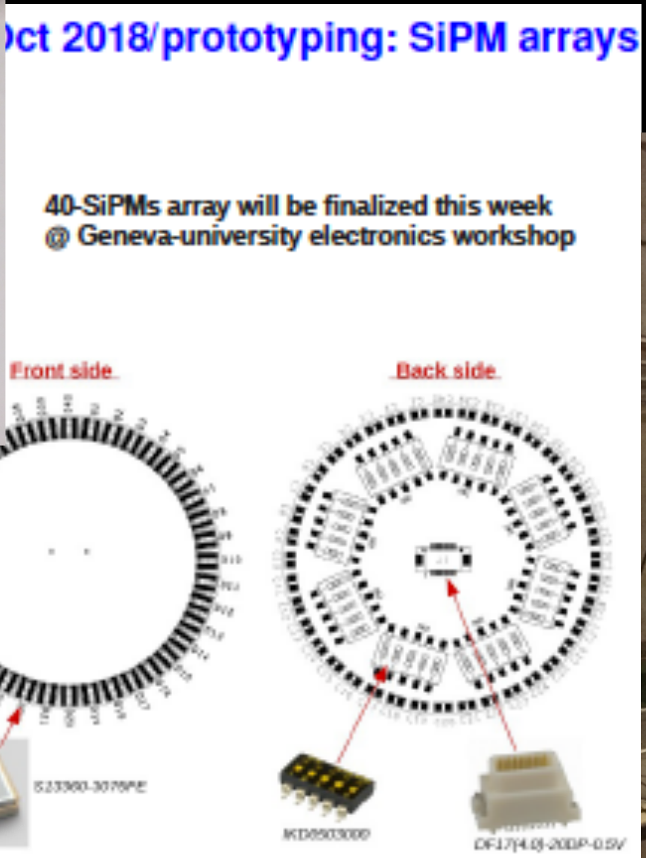


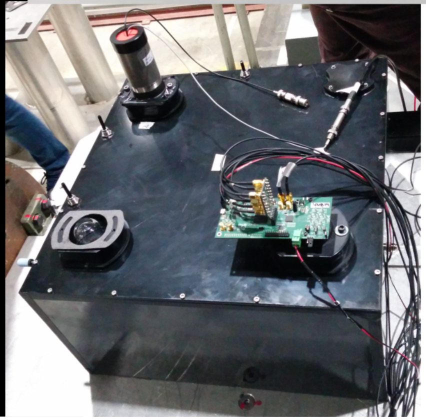
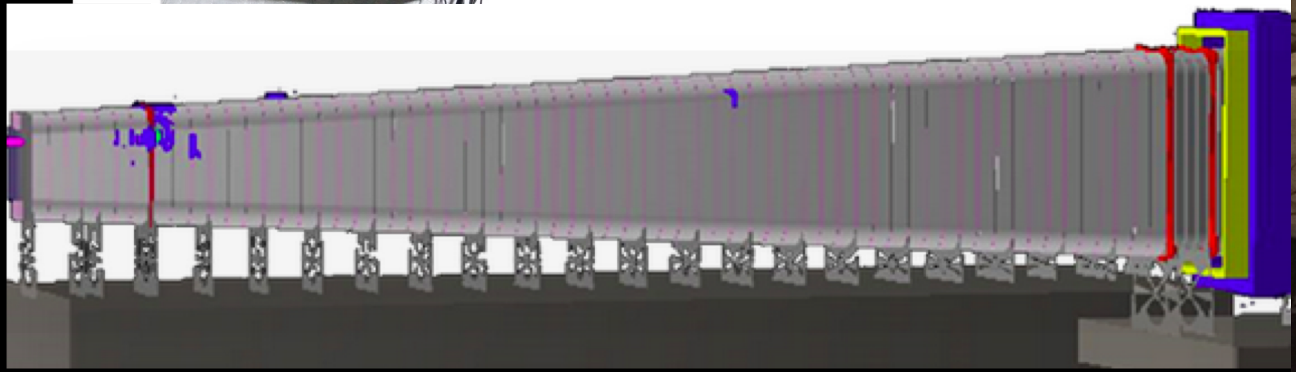
Steel-made structure designed to be as light and slim as possible (has to fit within the boundaries of the muon flux). Detailed study of displacements/seismic loads on going.

Study of displacements

… surrounded by an active (liquid scintillator) veto

Berlin, Mainz, Kyev, Geneva

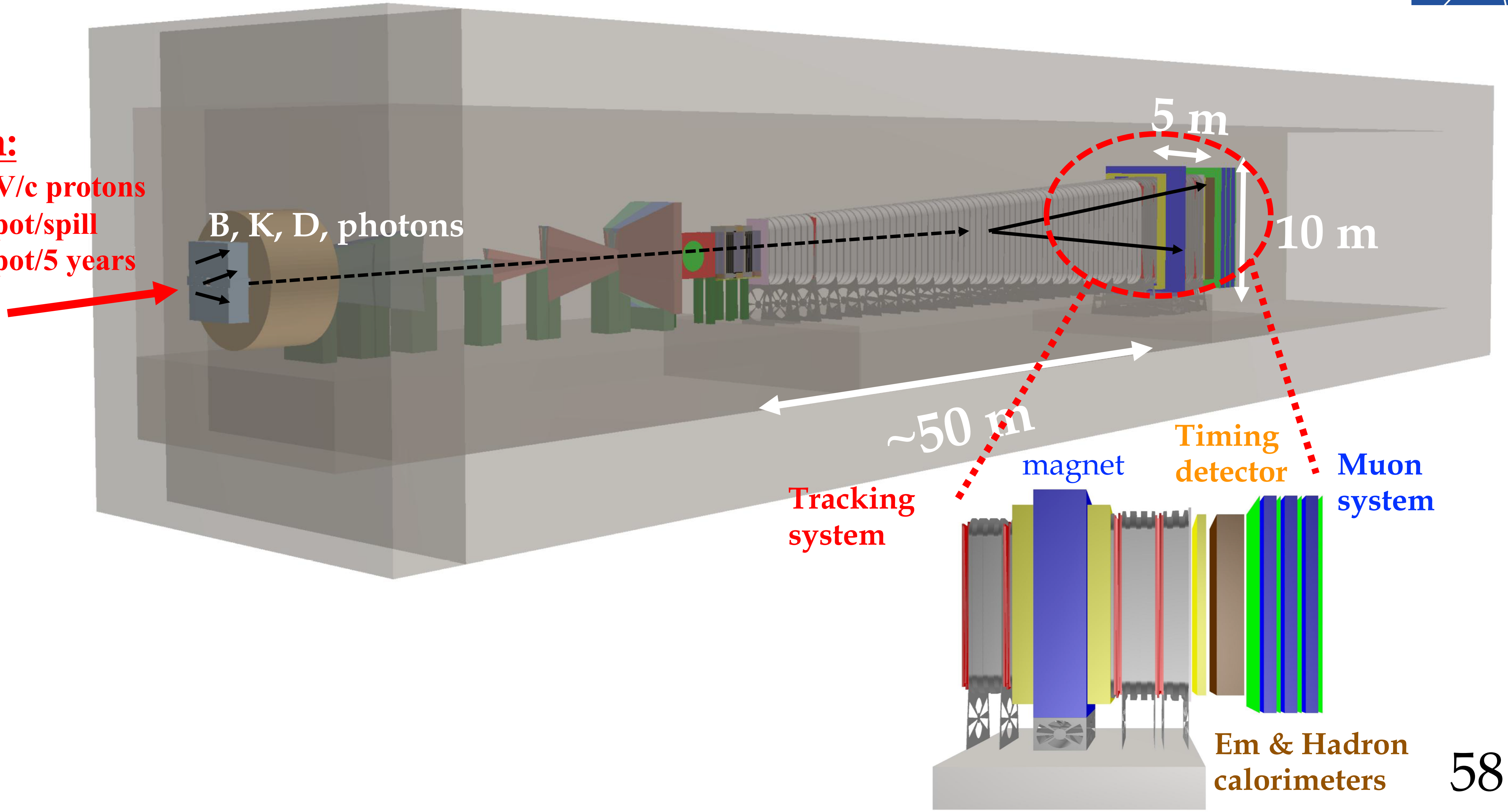



Active medium: liquid scintillator modules, linear alkylbenzene(LAB), with Wavelength-shifter Optical Modules read out by SiPM-arrays

Provides hermetic coverage and powerful veto for neutrino and muon inelastic interactions

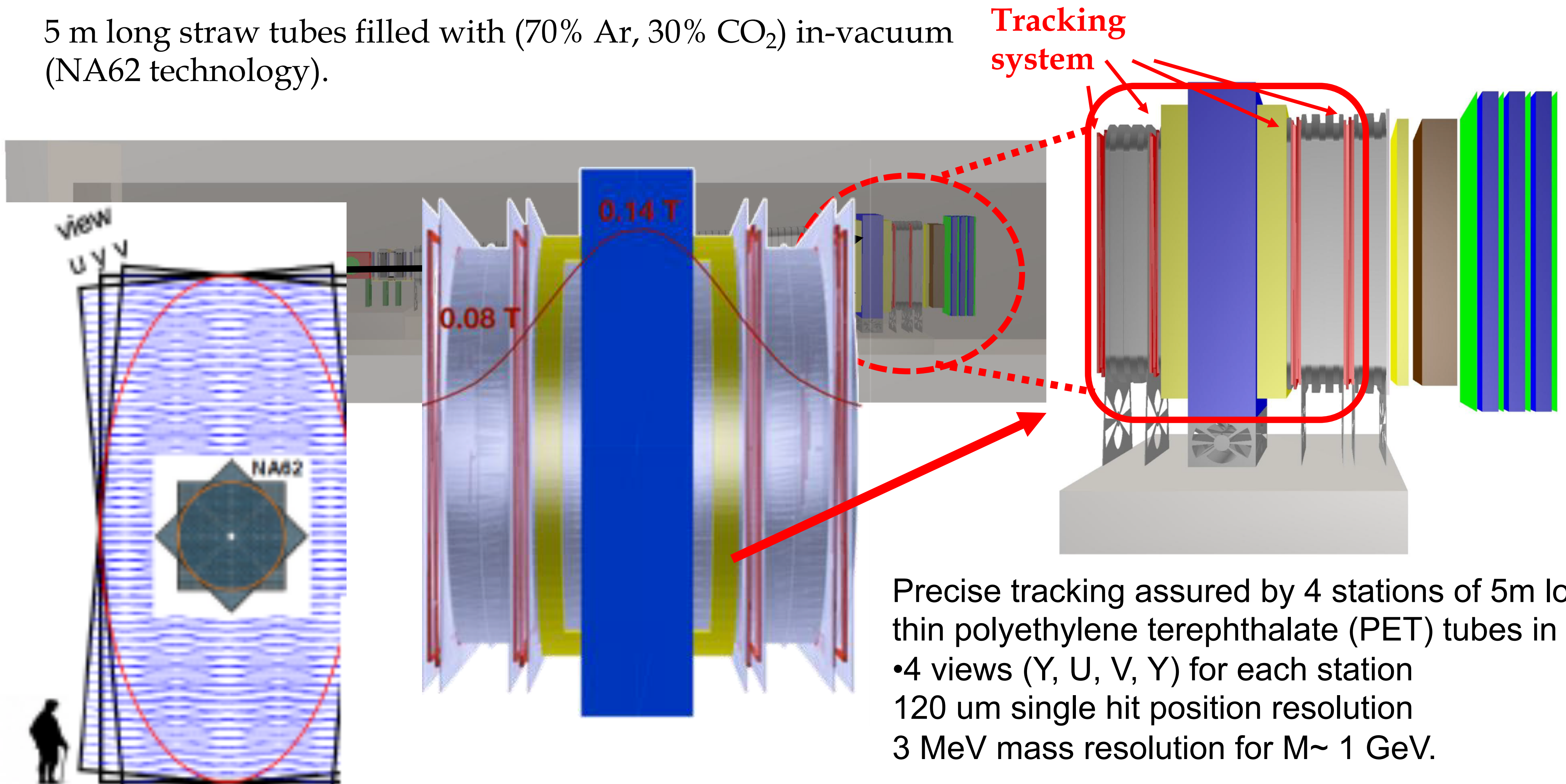
SHiP @ BDF: Hidden Sector Spectrometer

Beam:
400 GeV/c protons
4×10^{13} pot/spill
2×10^{20} pot/5 years



SHiP: Tracking system

5 m long straw tubes filled with (70% Ar, 30% CO_2) in-vacuum (NA62 technology).



Precise tracking assured by 4 stations of 5m long thin polyethylene terephthalate (PET) tubes in vacuum:

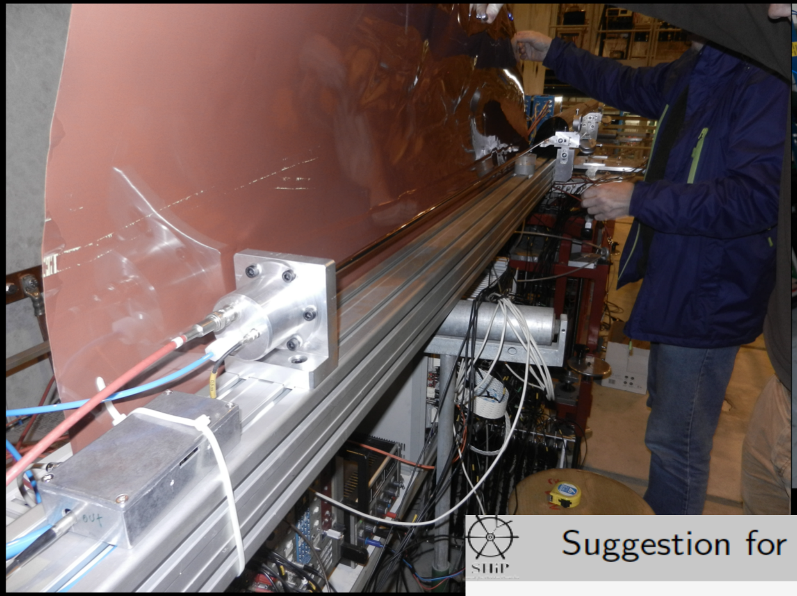
- 4 views (Y, U, V, Y) for each station

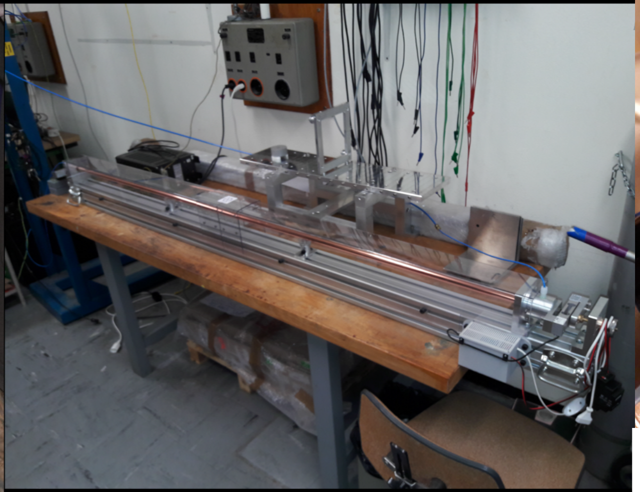
120 um single hit position resolution

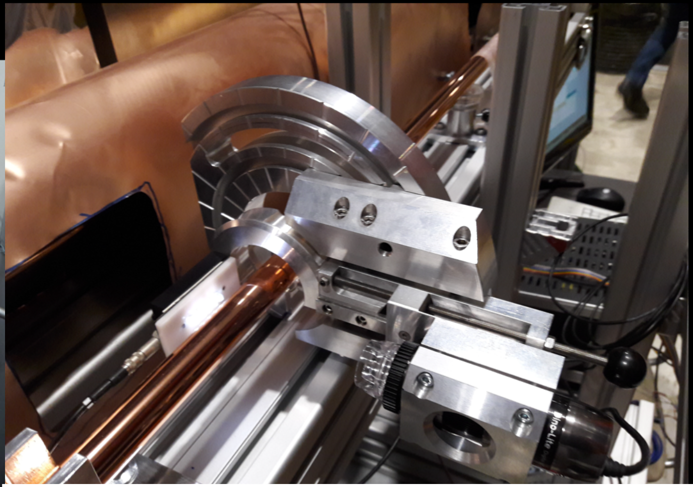
3 MeV mass resolution for M~ 1 GeV.

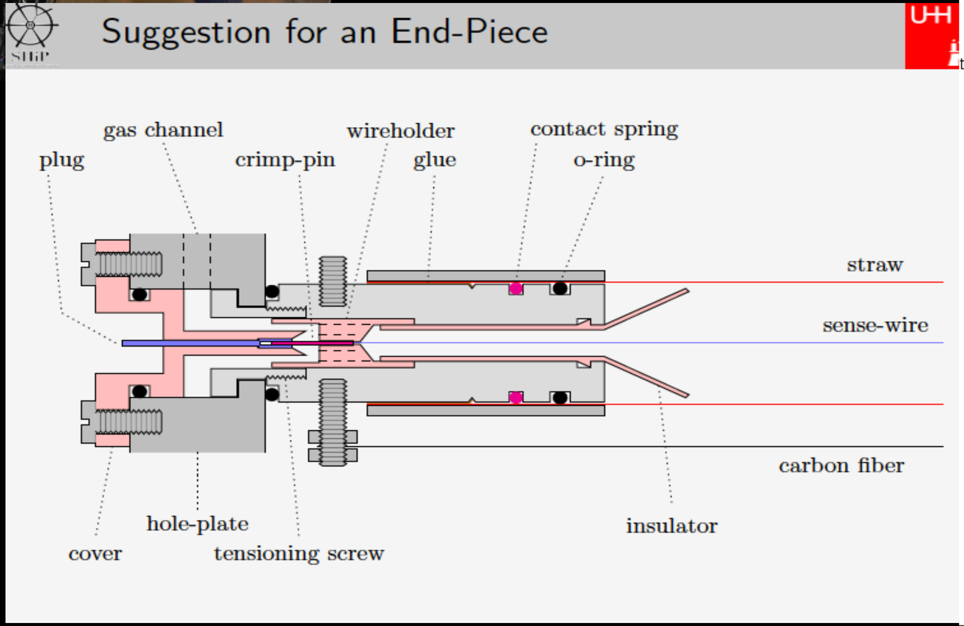
Tracking System: prototypes

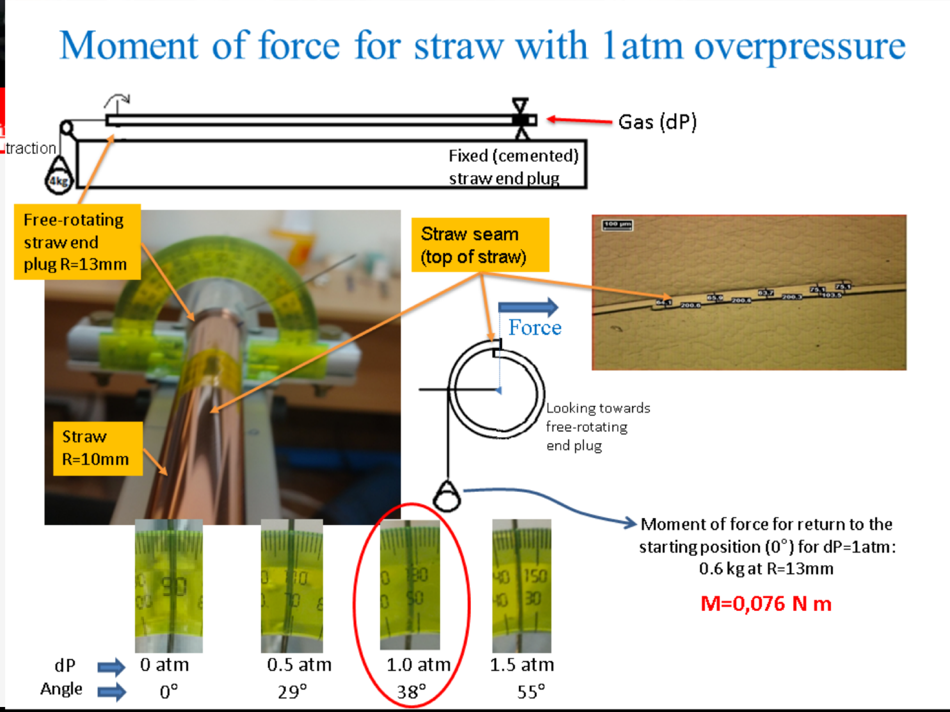
CERN, Dubna, Hamburg, Juelich, Kyev, ….





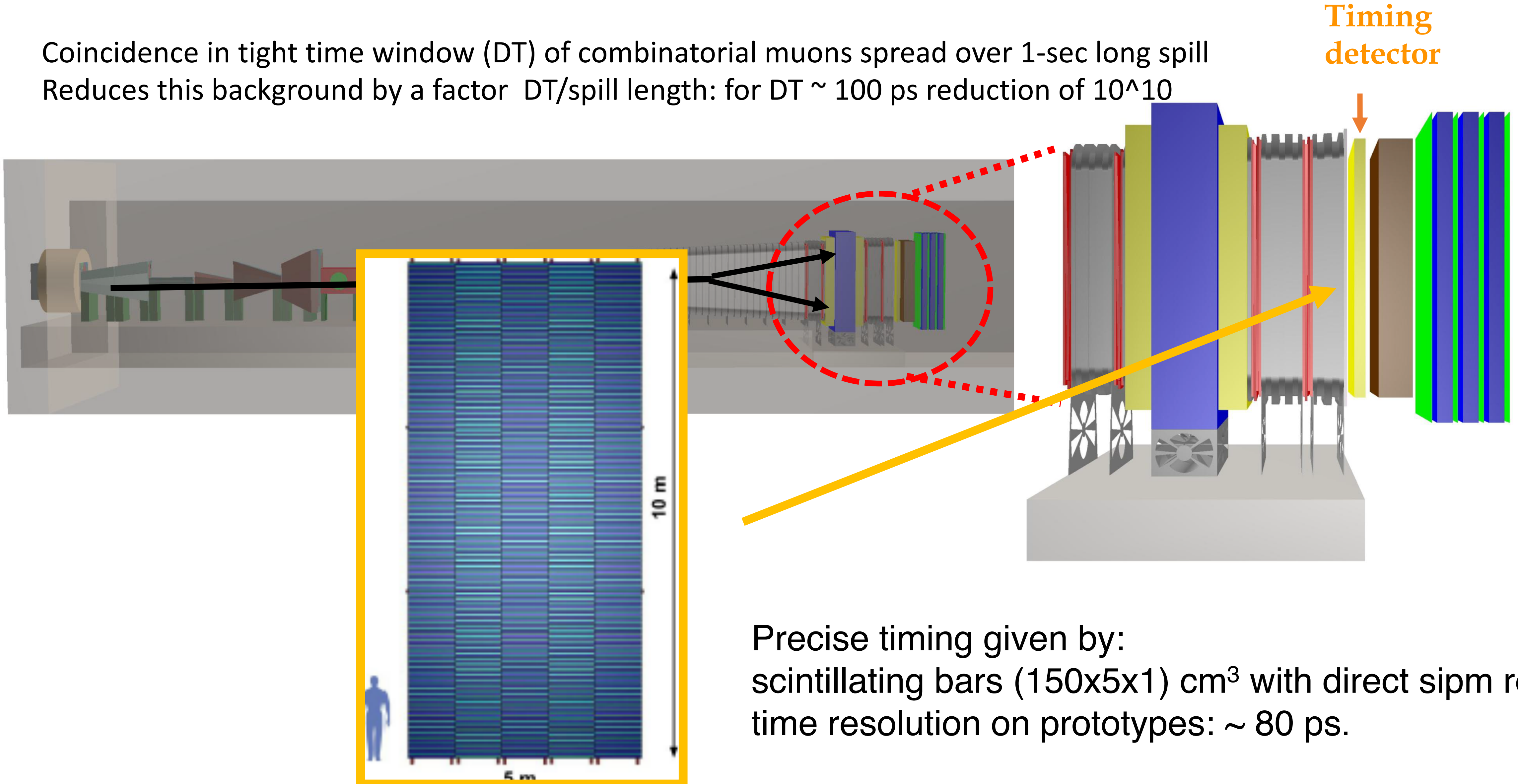






SHiP: Timing detector

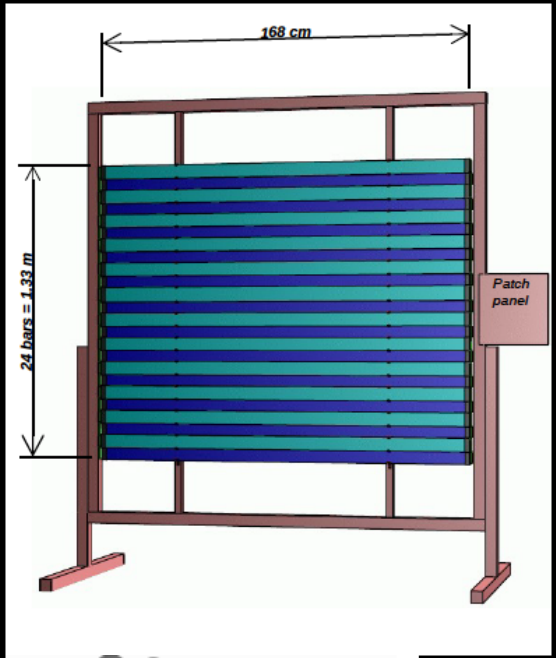
Coincidence in tight time window (DT) of combinatorial muons spread over 1-sec long spill
Reduces this background by a factor DT/spill length: for DT ~ 100 ps reduction of 10^10

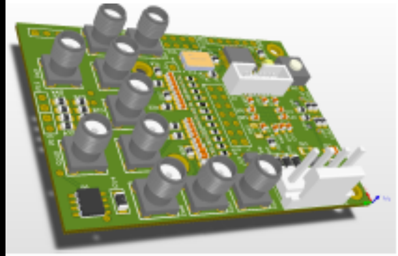


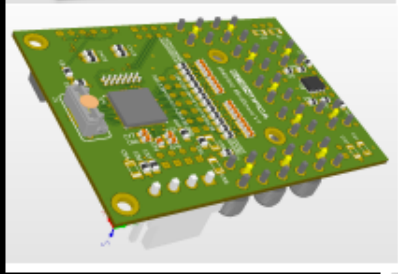
Precise timing given by:
scintillating bars (150x5x1) cm^3 with direct sipm readout
time resolution on prototypes: ~ 80 ps.

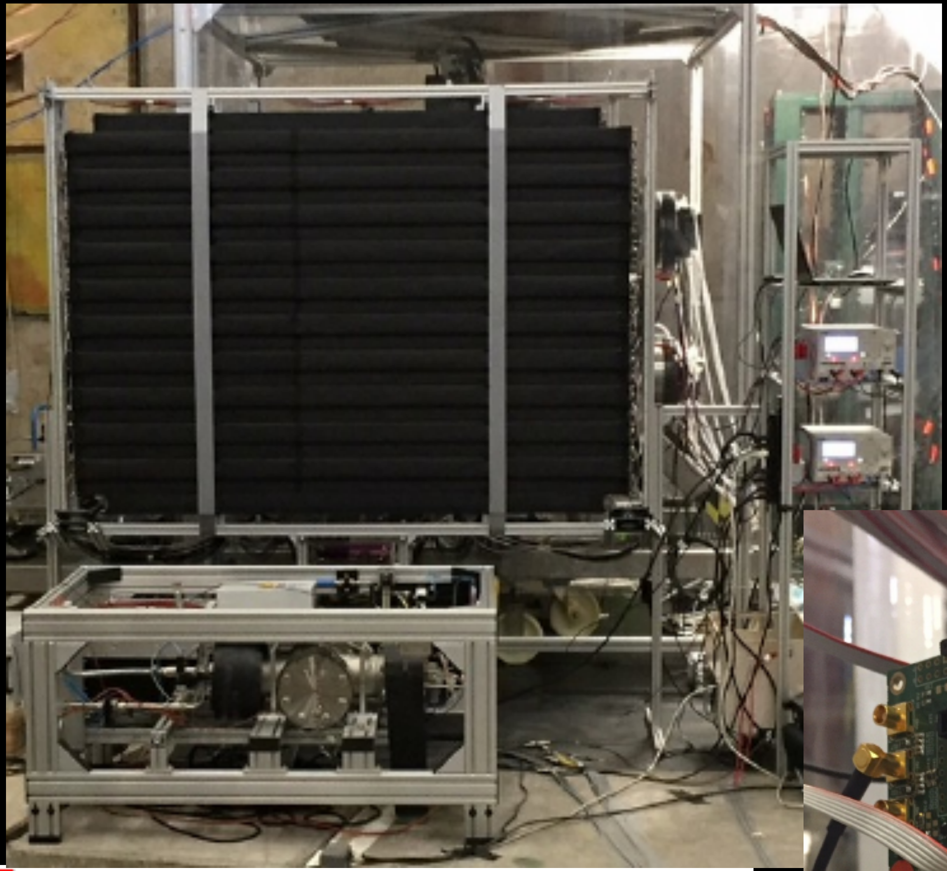
Timing Detector: large size module tested at T9, CERN PS

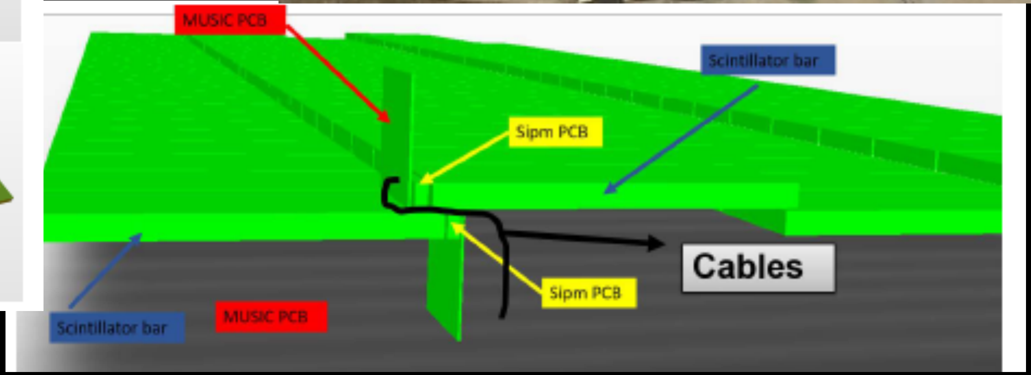
Prototype for 2018 test beam







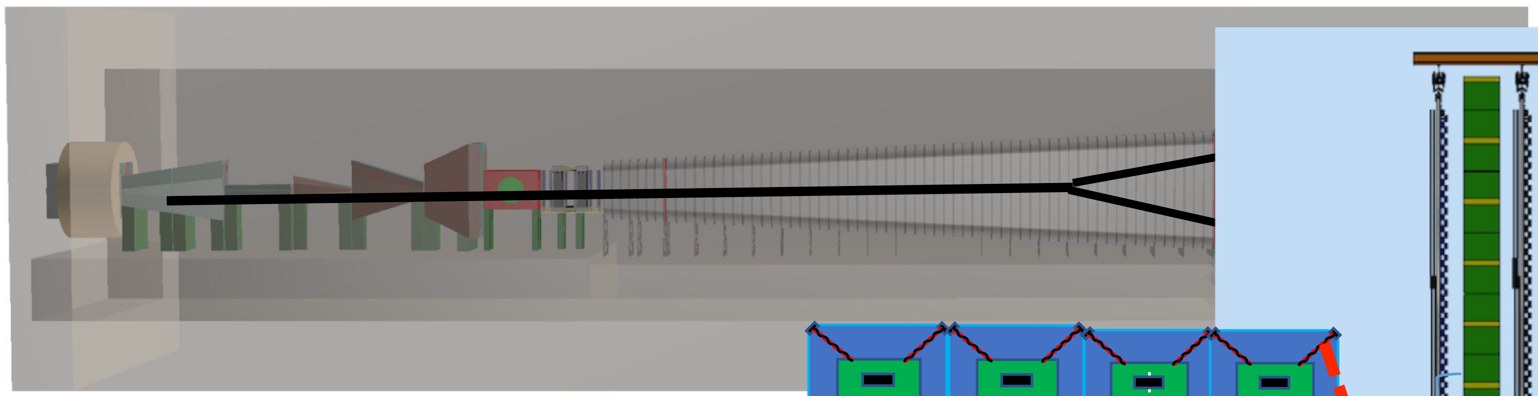


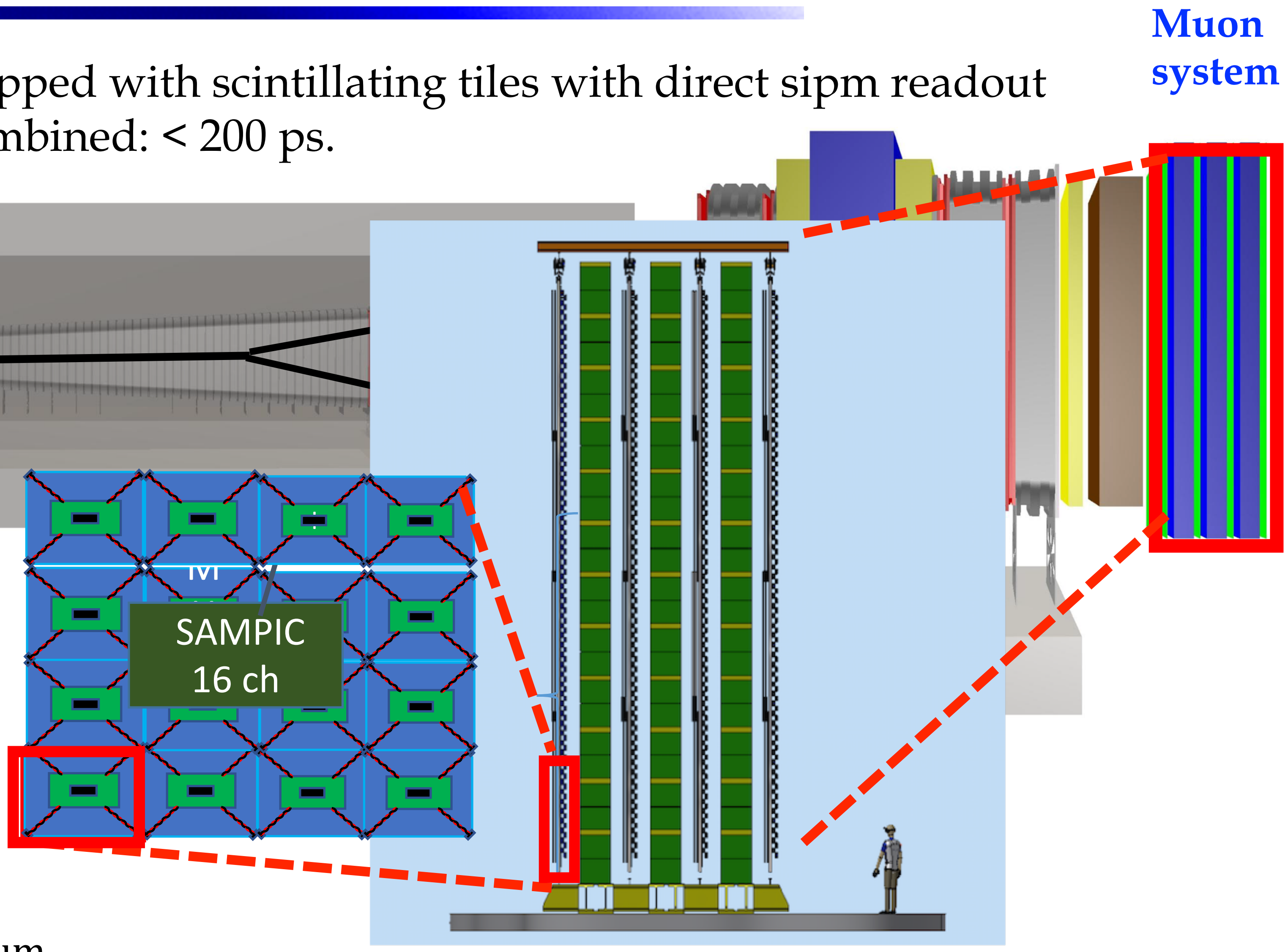


Muon System

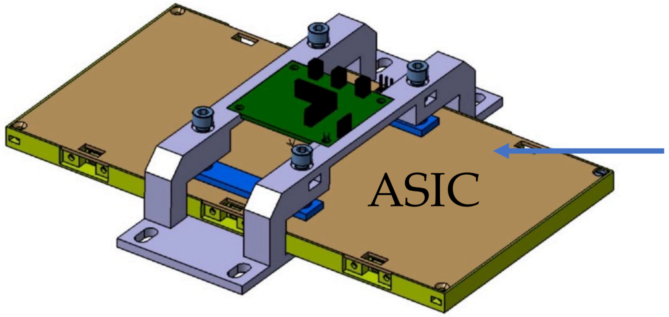
Italy, Russia, LAL for FEE, …..

Muon system: 4 stations equipped with scintillating tiles with direct sipm readout
Time resolution 4 stations combined: < 200 ps.



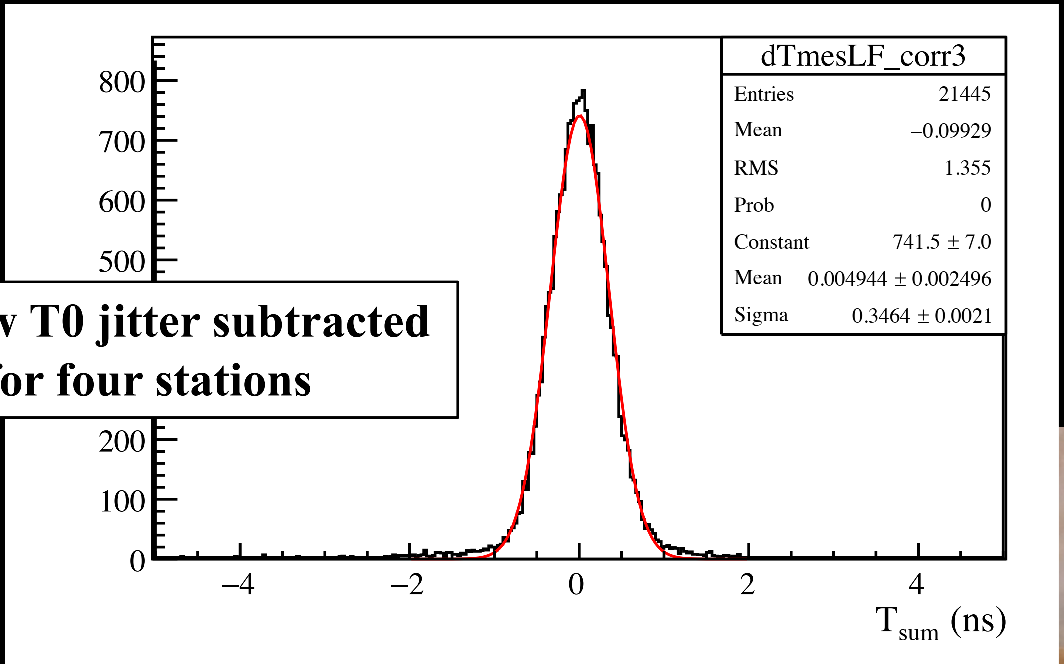


Eljen EJ 200 scintillator tile wrapped in aluminized Mylar

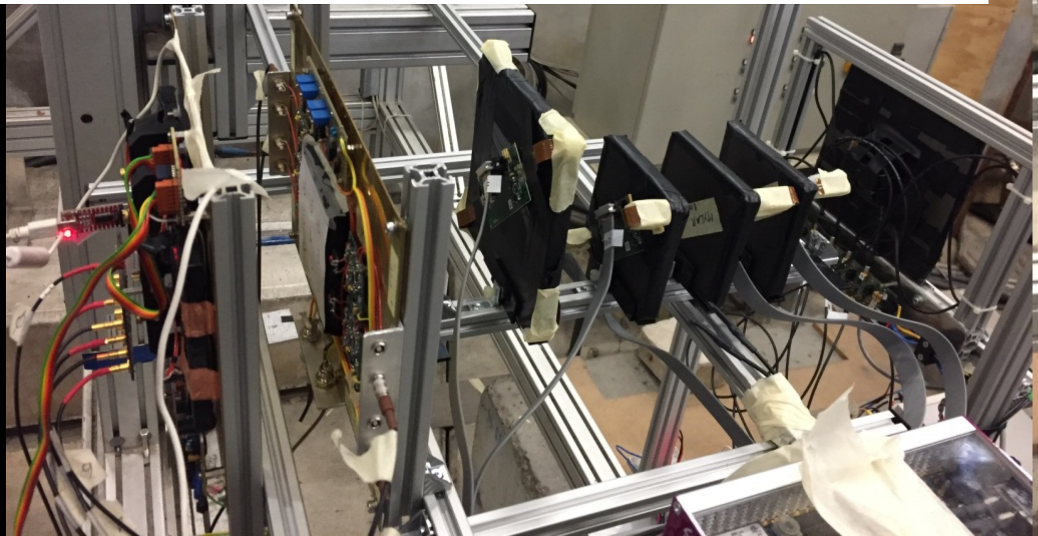


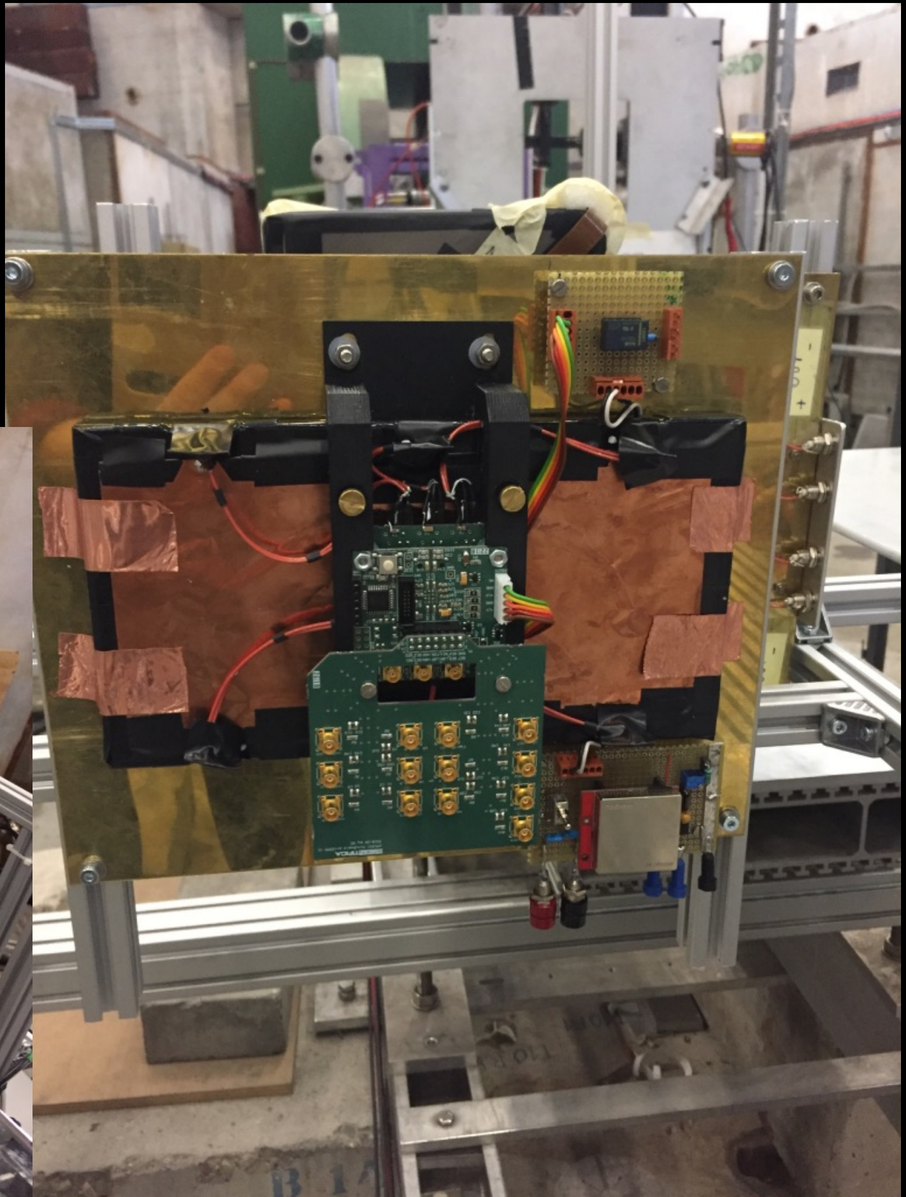
6 Hamamatsu S14160 4x4 mm, 50 um

SHiP Muon System: prototypes tested in the T9 area, CERN PS

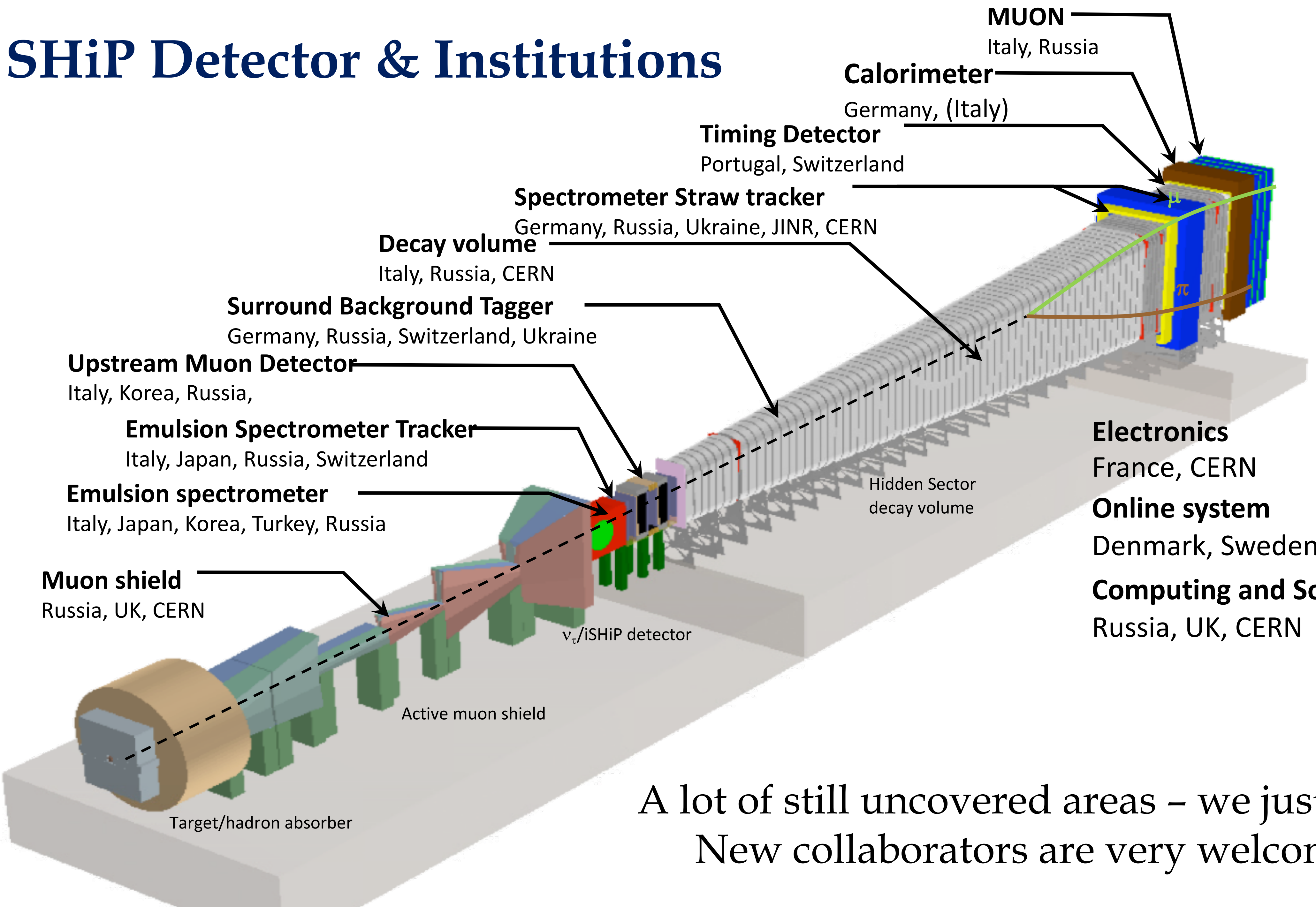


σ(t) ~ 300 ps w T0 jitter subtracted
σ(t) ~ 150 ps for four stations





SHiP Detector & Institutions



Electronics
France, CERN

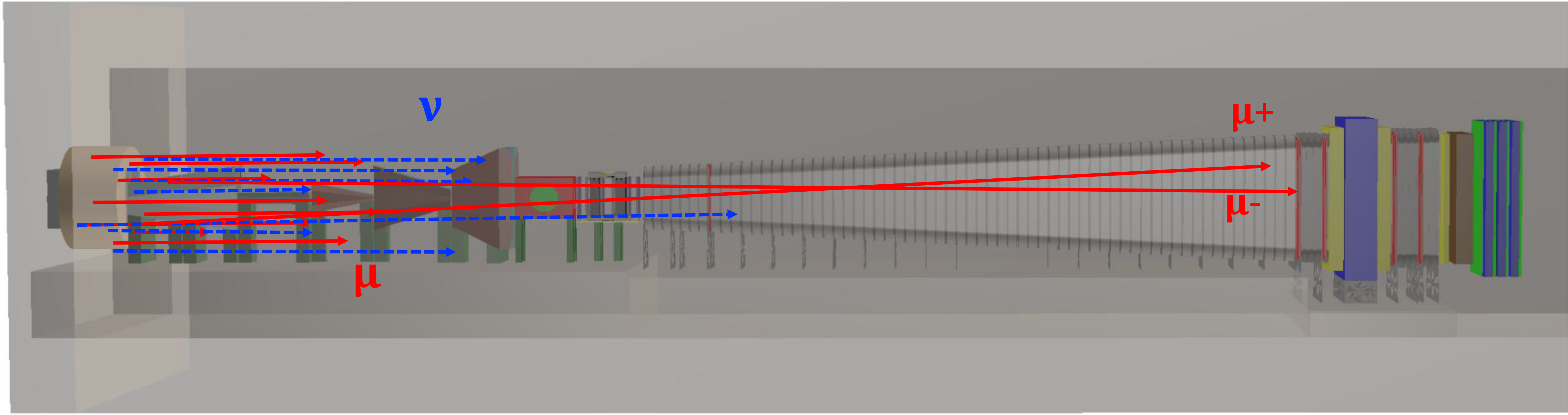
Online system
Denmark, Sweden, UK, CERN

Computing and Software
Russia, UK, CERN

A lot of still uncovered areas – we just started
New collaborators are very welcomed.

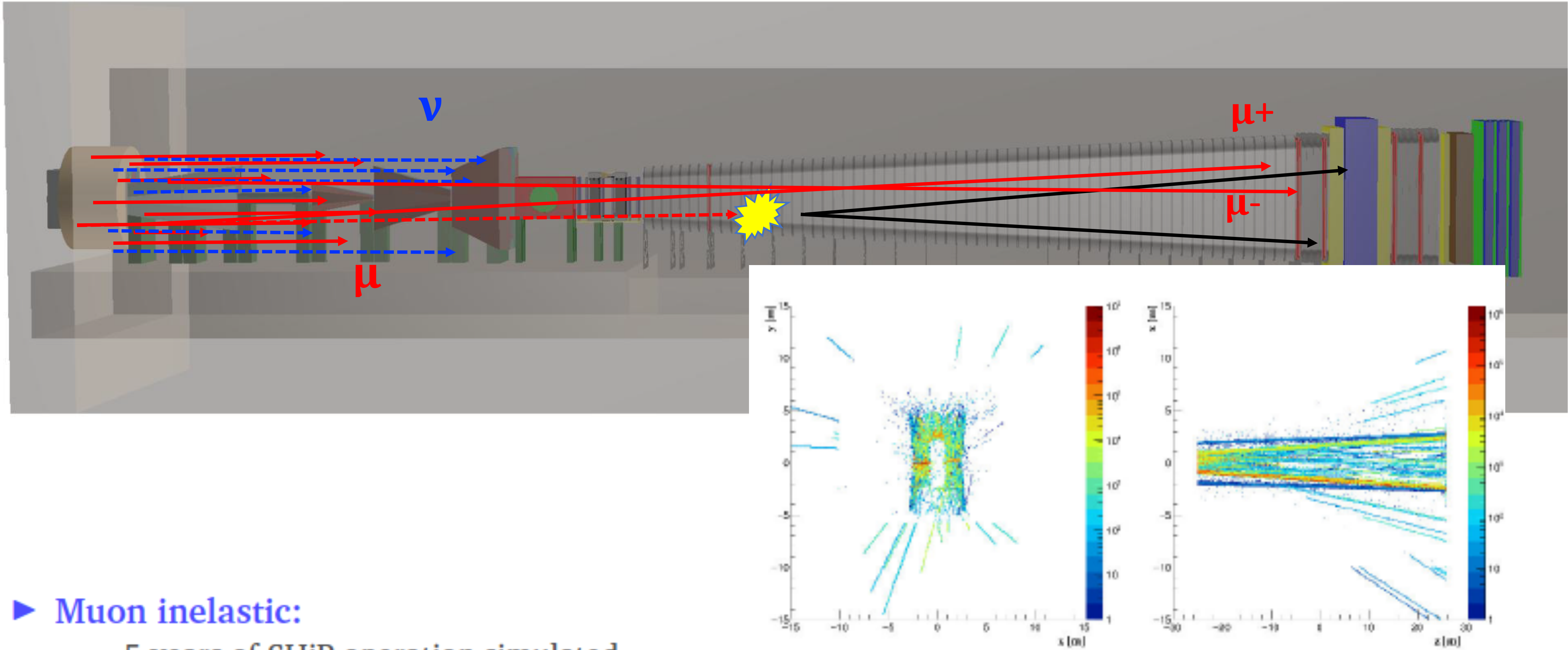
Background, background, background

....Background, background, background......



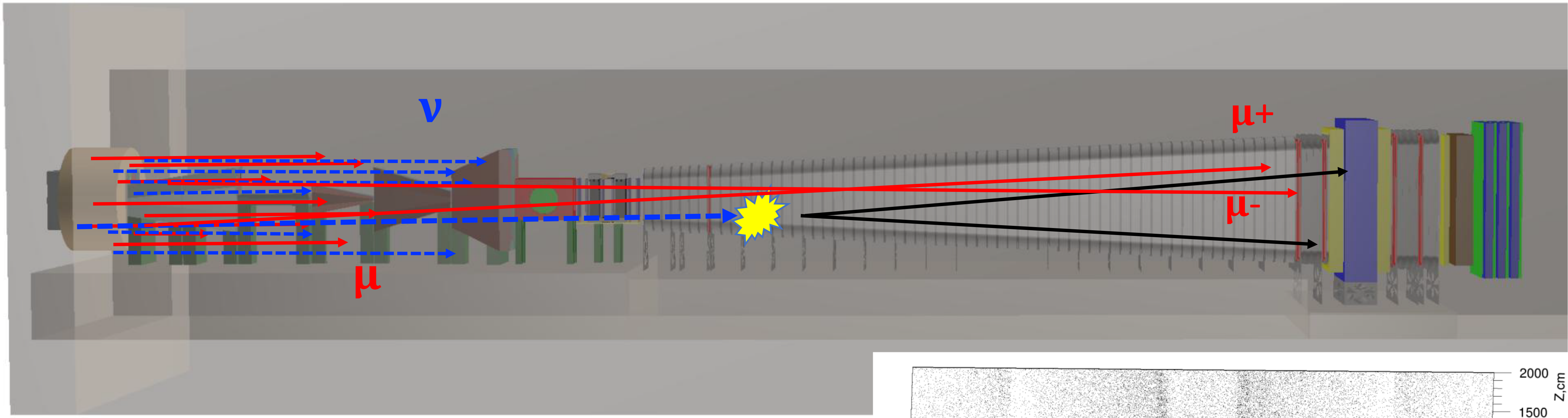
- **Muon combinatorial:**
  - $10^{16} \xrightarrow{\text{selection}} 10^{9} \xrightarrow{\Delta t<340\text{ps}} 10^{-2}$ candidates in 5 years @ $90\%CL$
  - ML used to generate large sample of dangerous μ

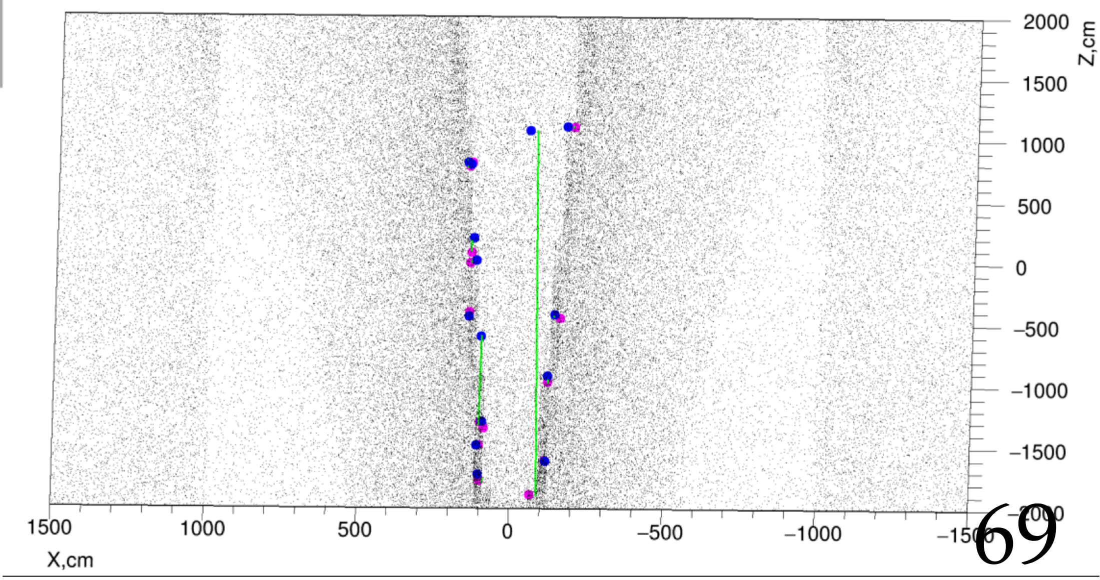
….Background, background, background……



- **Muon inelastic:**
  - 5 years of SHiP operation simulated
  - ~~correlation~~ between VETO and selection: $< 6 \times 10^{-4}$ @ 90%*CL*

….Background, background, background……





- **ν interactions:**
  - 10 years of SHiP simulated, increasing to 100
  - ν-air: $< 10^{-2}$ in 5 years with pressure ~ 1 mbar
  - ν-material: $5 \times 10^5 \begin{cases} \xrightarrow{\text{cuts (fully reco)}} 0 \\ \xrightarrow{\text{cuts (part. reco)}} 2 \xrightarrow{\text{opening angle}} 0 \end{cases}$ @90%CL

The SHiP Physics Reach

Generic Benchmark Cases

HNLs, LDM & Light mediators, ALPs must be SM singlets, hence options limited by SM gauge invariance:
According to generic quantum field theory, the lowest dimension canonical operators are the most important:

PBC report,
arXiv:1901.09966

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Sterile Neutrino, N	$y_N L H N$

This is the set of the simplest fields and renormalizable interactions that can be added to the SM

Large consensus in the community to use these portals as generic benchmark cases to compare sensitivities
This is the bulk of the SHiP Physics programme.

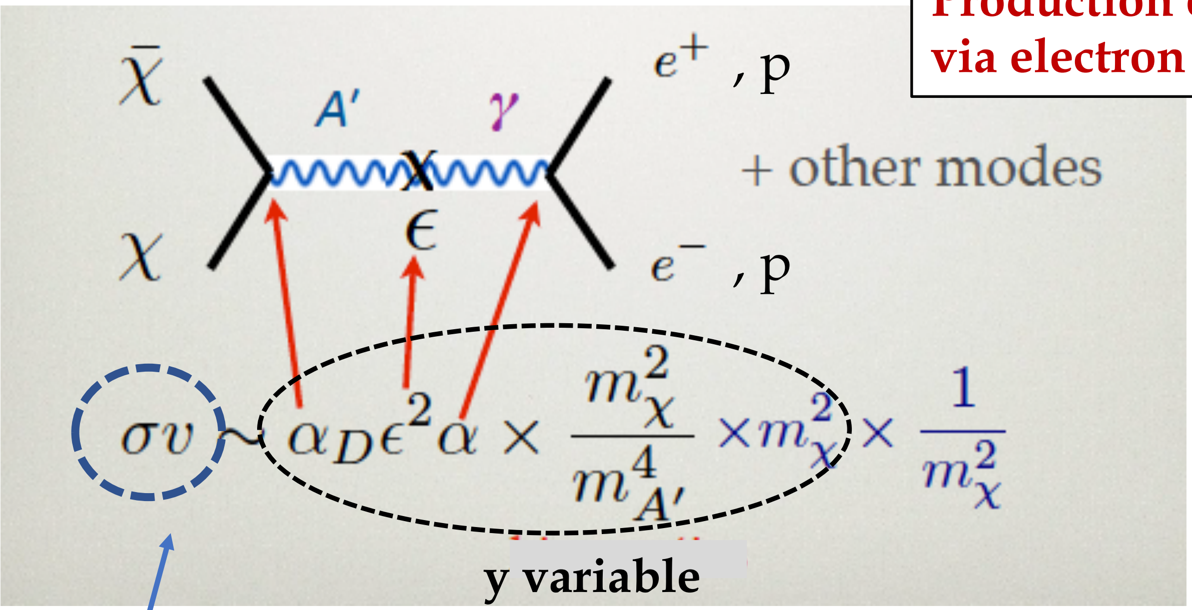
Dark Photon coupled to Light Dark Matter: connection with DM direct detection and cosmological bounds

Model where minimally coupled viable WIMP dark matter model can be constructed. The parameter space for this model is $\{m_{A'}, \epsilon, m_\chi, \alpha_D\}$. Vector mediator survives CMB constraints. Light vector mediator could also explain the positron excess observed by PAMELA, AMS…

$$A' \to \chi\chi$$

Production of DM at accelerators via electron or proton bremsstrahlung

Direct DM scattering with e/protons: Direct Detection experiments



Courtesy of P. Schuster

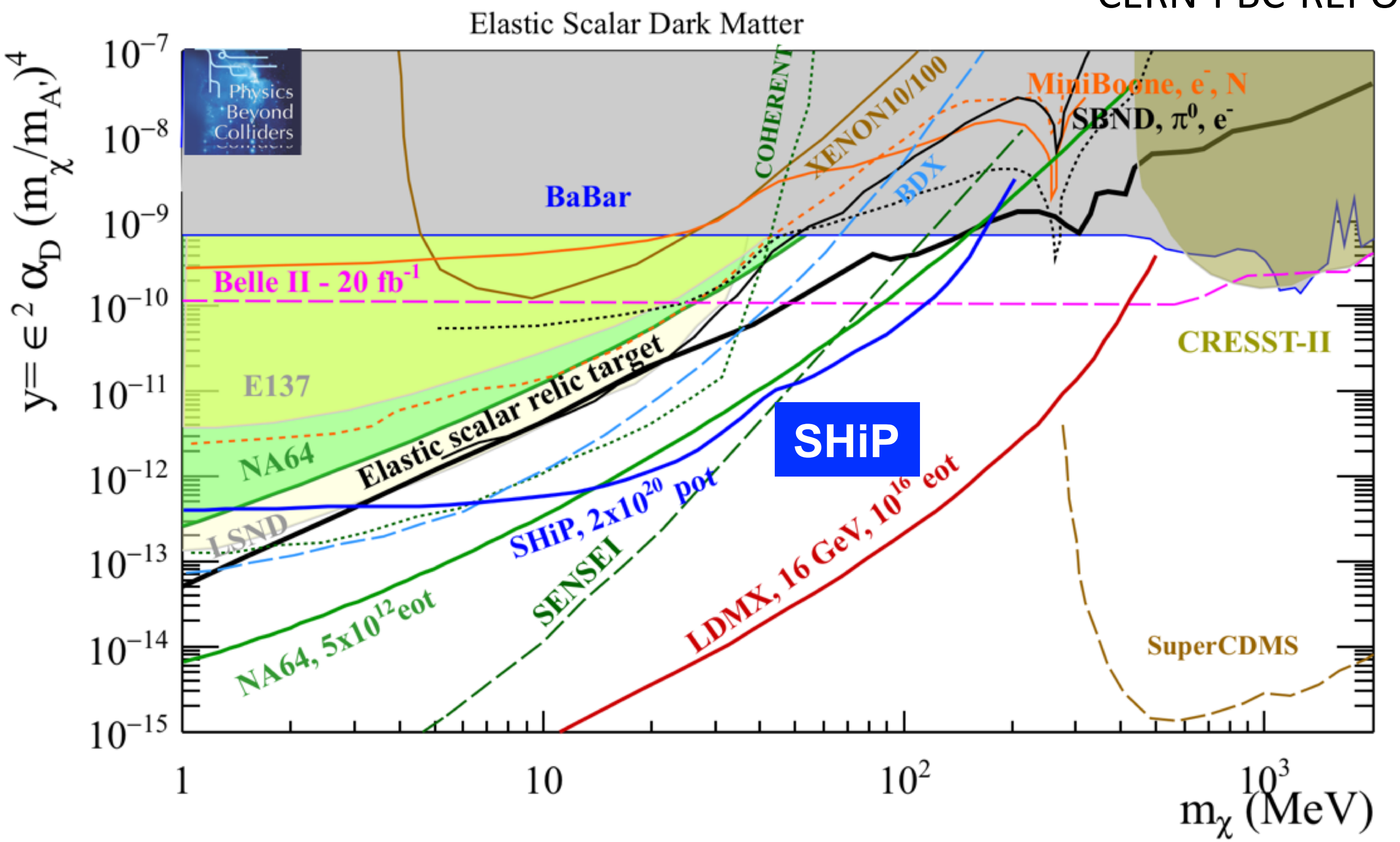
$$\Omega_{DM} h^2 \sim \frac{10^9\ \text{GeV}^{-1}}{M_{pl}} \frac{1}{\langle \sigma v \rangle}$$

Direct DM annihilation (main process to get the thermal relic abundance)

Dark Photon coupled to Light Dark Matter

Model where minimally coupled viable WIMP dark matter model can be constructed.
The parameter space for this model is: $\{m_{A'}, \epsilon, m_\chi, \alpha_D\}$

CERN-PBC-REPORT-2018-007



$A' \to \chi\chi$

$m(A') = 3\, m(\chi)$
$\alpha(D) = 0.1$

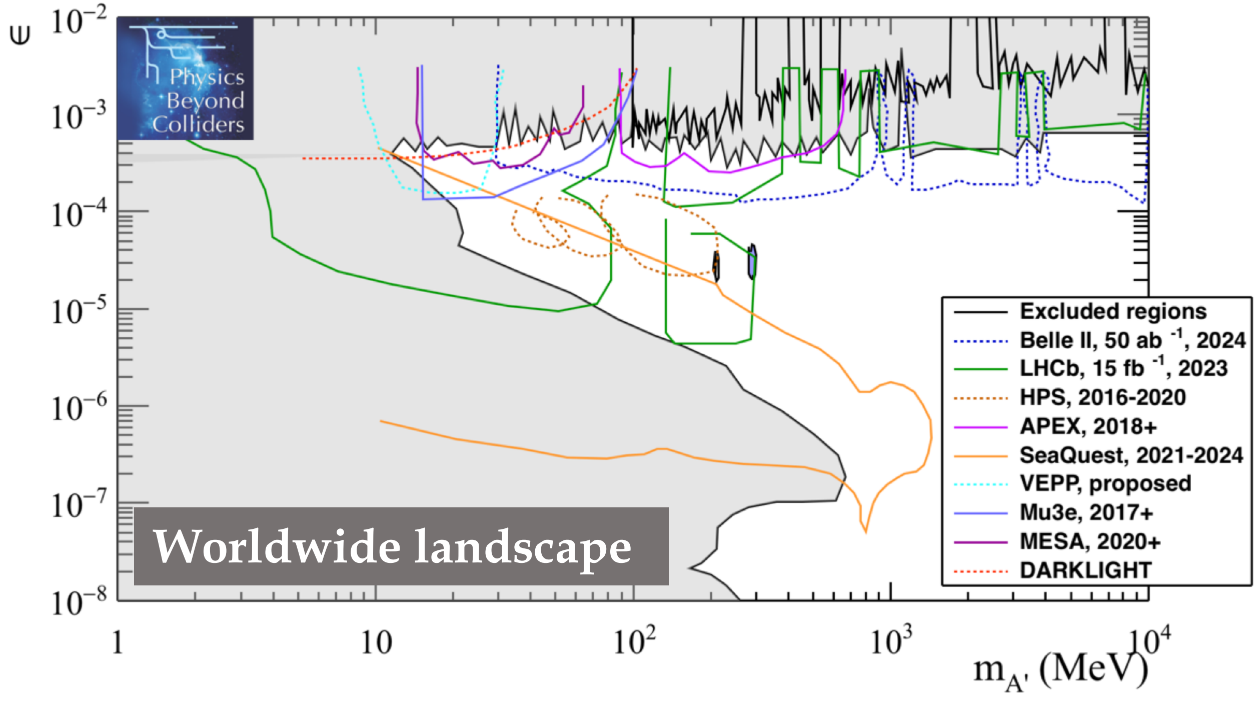
Nice complementarity
between accelerator-based proposals, colliders and Light DM direct detection experiments.

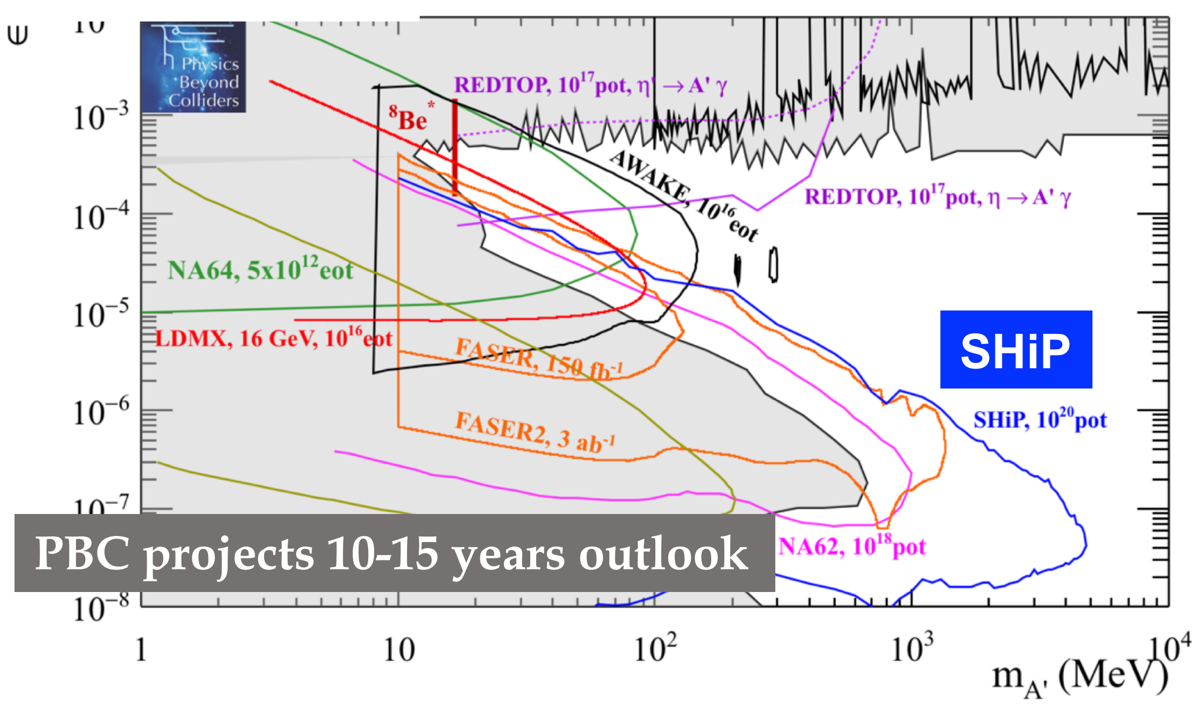
Dark Photon coupled to SM particles

The SM is augmented by a single new state A'. DM is assumed to be either heavy or contained in a different sector. . Clearly a mixed case is possible with DP decaying to DM and visible final states: In that cases the rates to visible final states will depend on the assumption on alphaD. For simplicity here we assume alphaD=0.

$$A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, ...$$

CERN-PBC-REPORT-2018-007



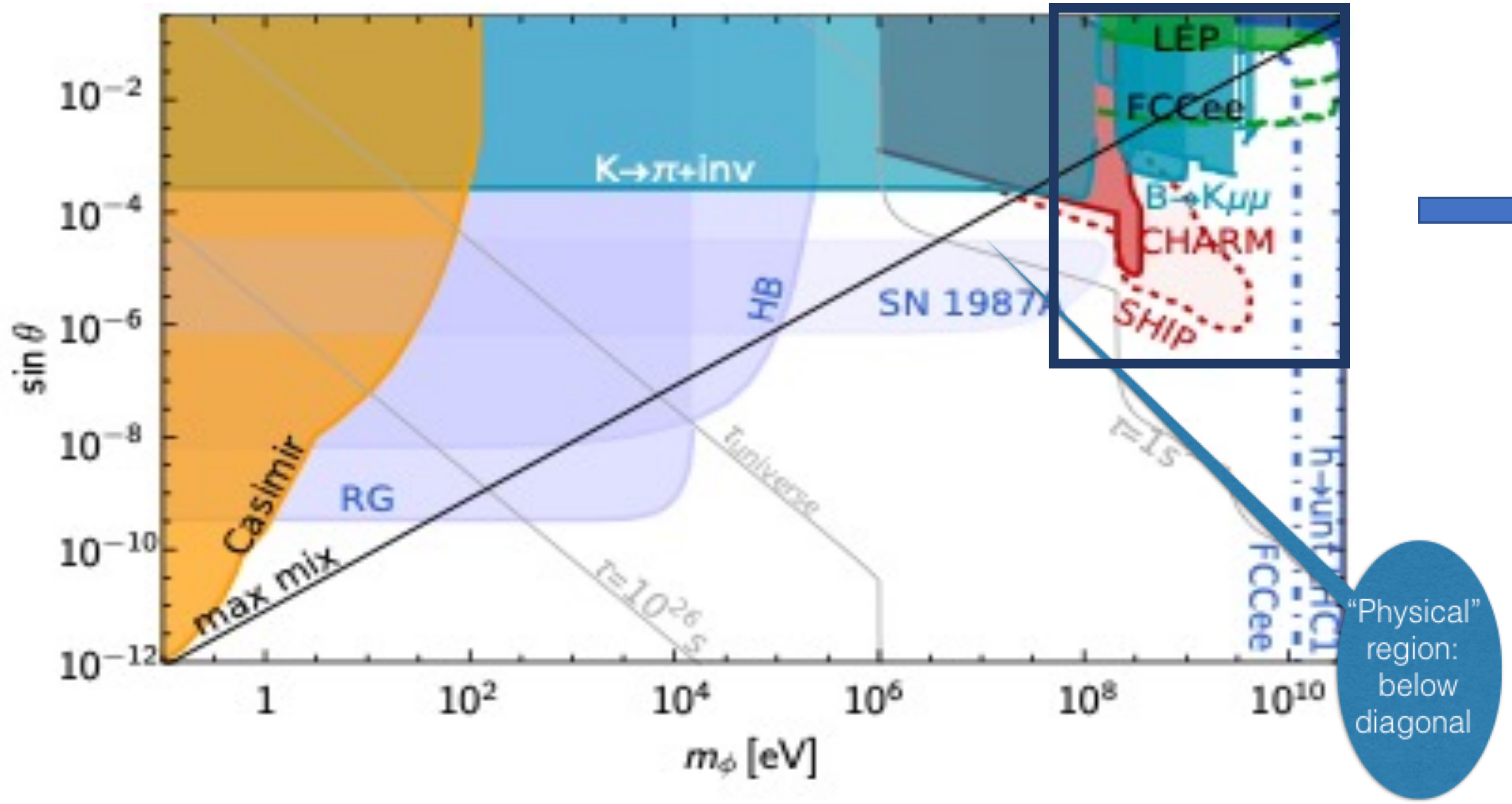


Nice complementarity/competition
with experiments in Japan, FNAL, JLAB, Mainz, PSI…..

Dark Scalar (relaxion) coupled to the Higgs

The Higgs portal couples the dark sector to the Higgs boson via the bilinear H†H operator of the SM. The minimal scalar portal model operates with one extra singlet field S and two types of couplings, μ and λ.

1807.10842

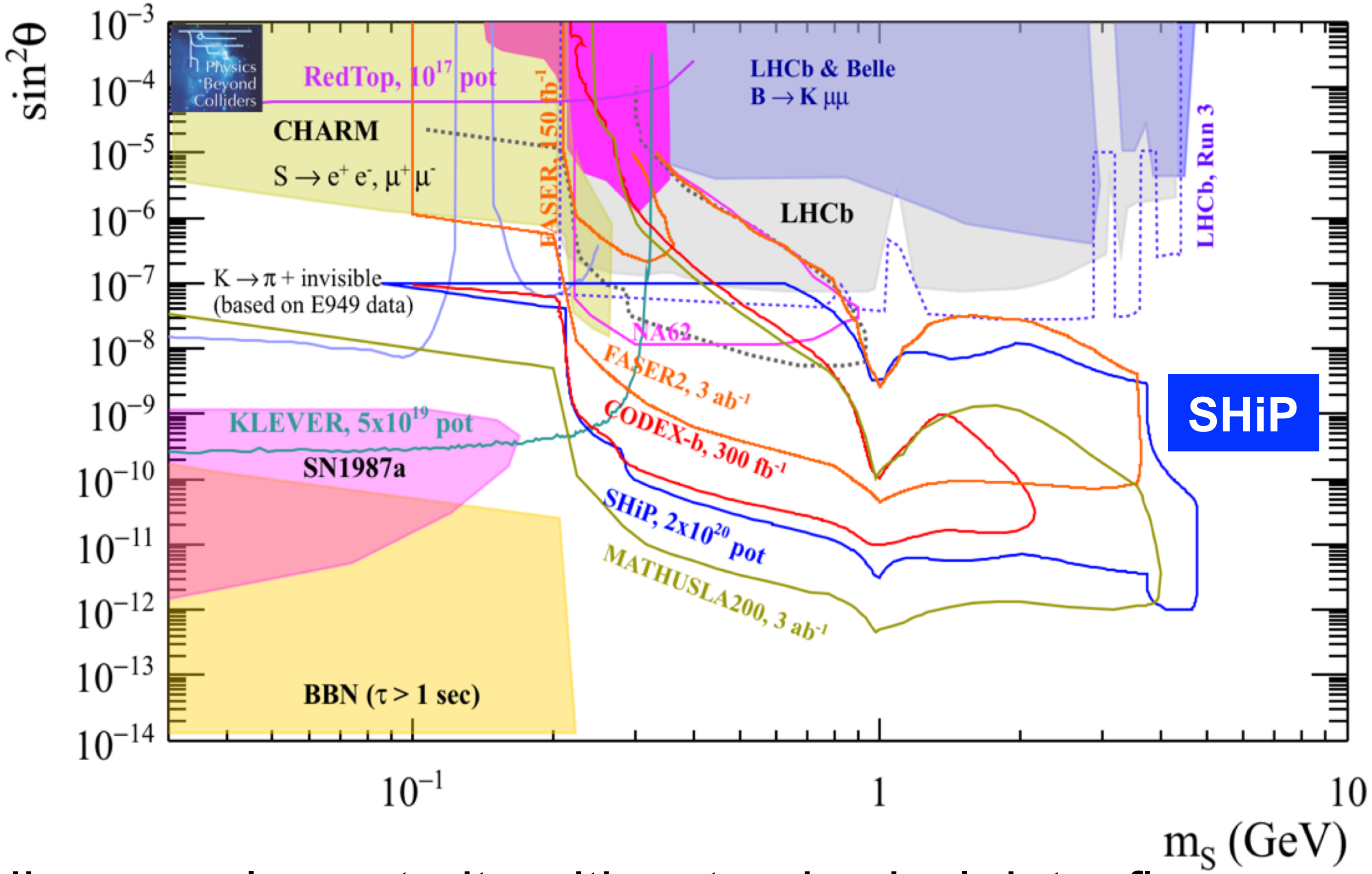


Nice complementarity with astrophysical data, flavor results

Dark Scalar (relaxion) coupled to the Higgs

The Higgs portal couples the dark sector to the Higgs boson via the bilinear H†H operator of the SM. The minimal scalar portal model operates with one extra singlet field S and two types of couplings, μ and λ.

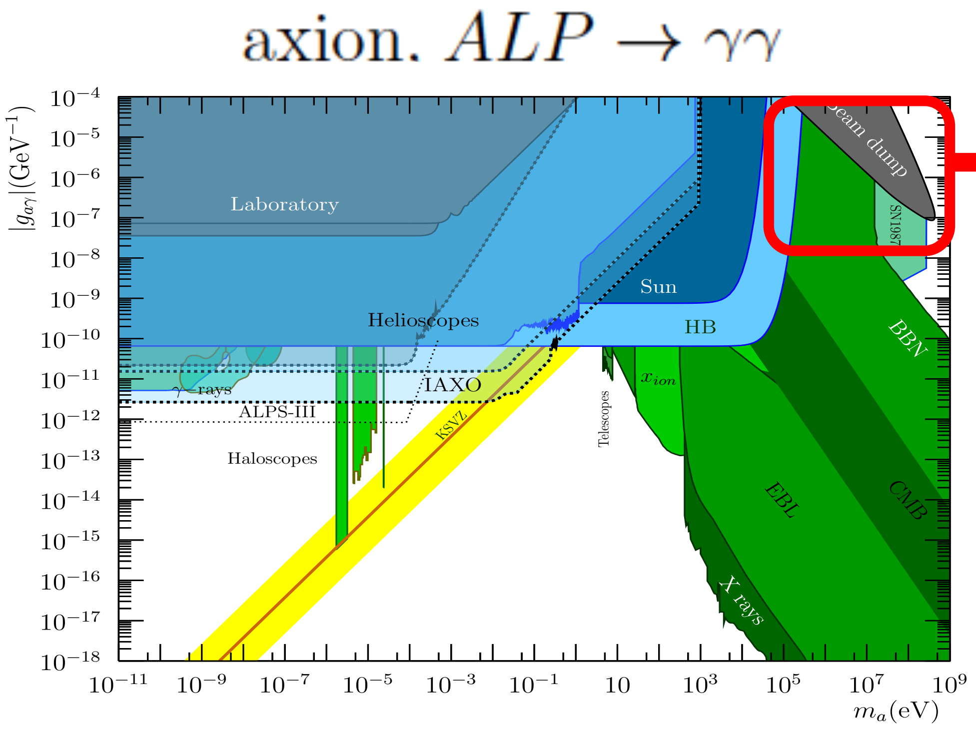
CERN-PBC-REPORT-2018-007



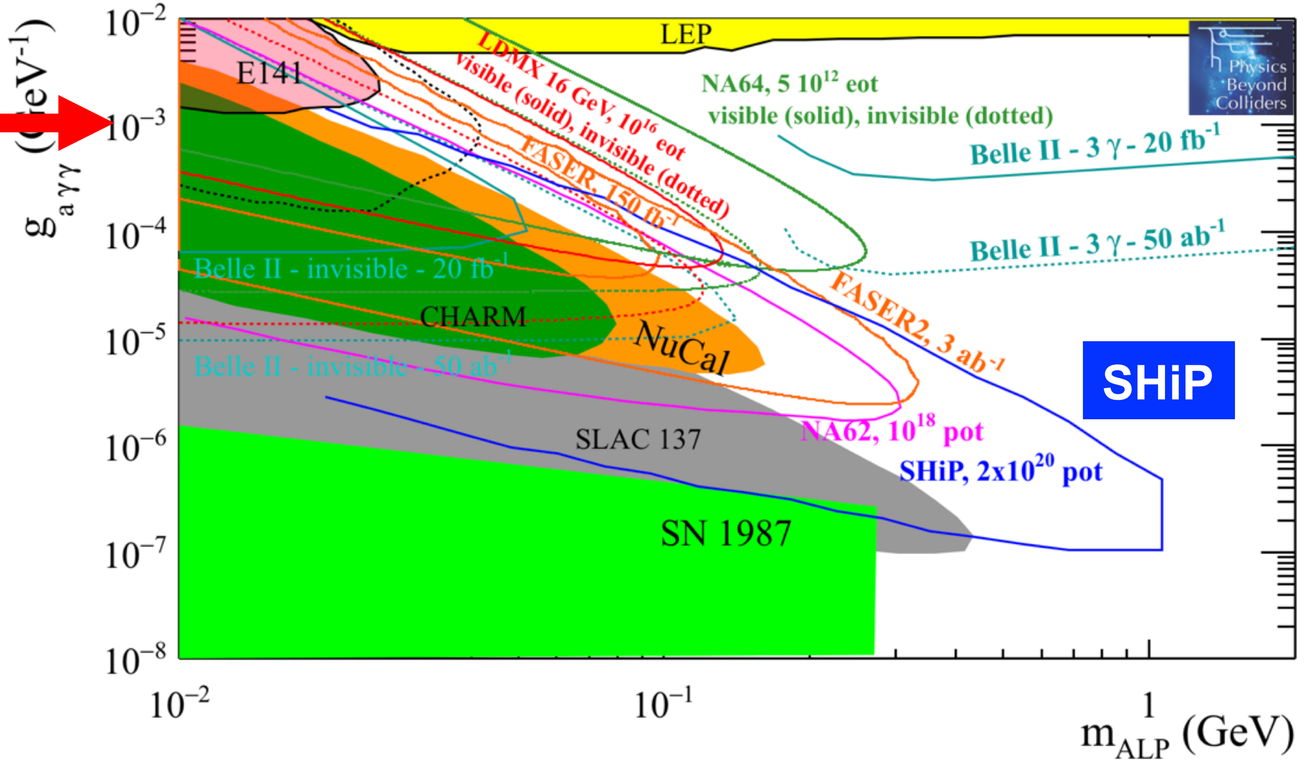
Nice complementarity with astrophysical data, flavor results

Axions / ALPs with photon coupling

Search for axions/ALPs: extremely lively and established field, mostly in the sub-eV mass range
Need of a systematic investigation in the MeV-GeV range.



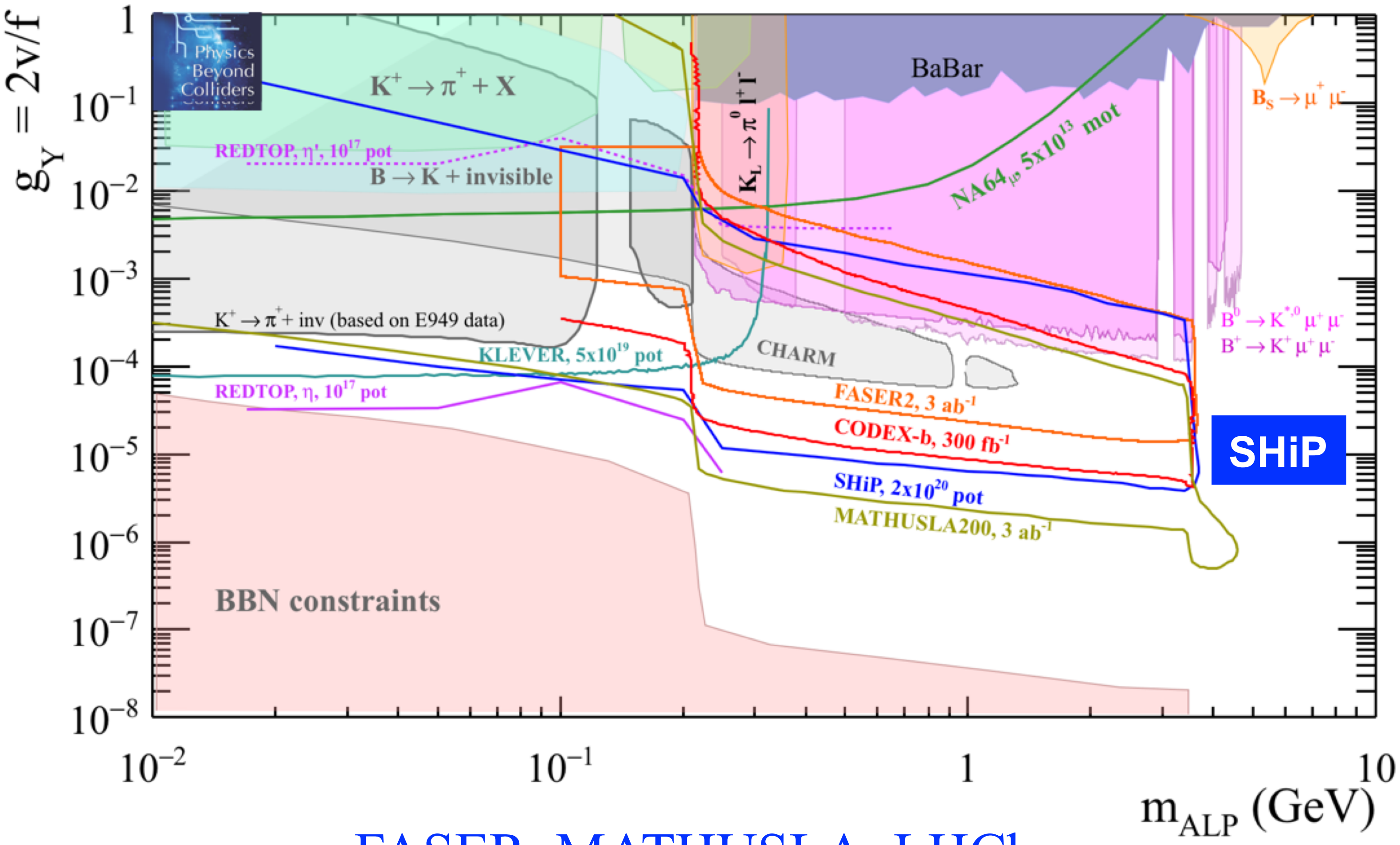
zoom in the MeV-GeV range



Nice complementarity of accelerator-based experiment
with experiments in the sub-eV range and cosmological bounds

Axion portal - fermion couplings
Accelerator-based experiments' reach: low mass range

PBC report, 1901.09966

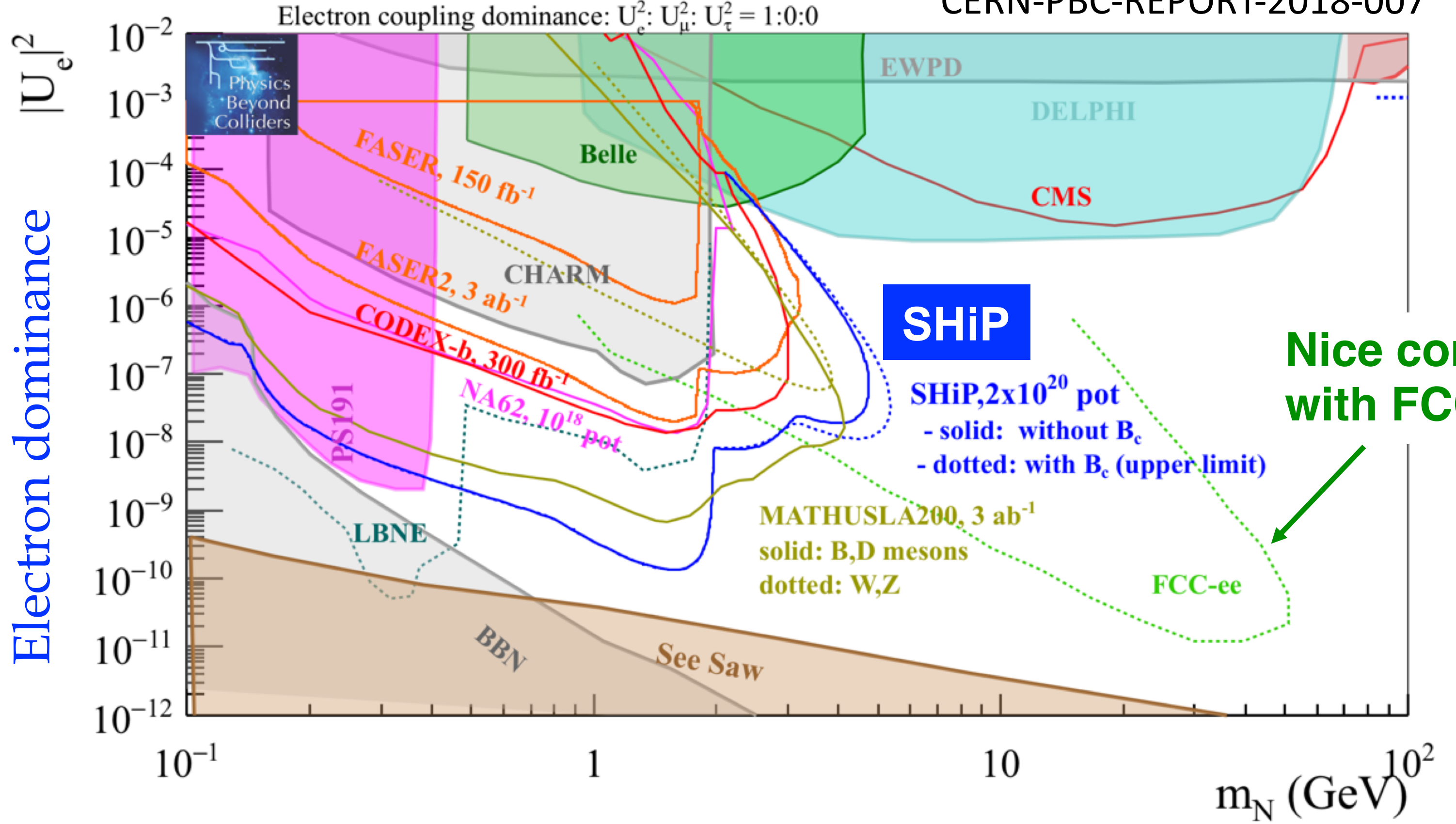


FASER, MATHUSLA, LHCb…

Right Handed Neutrinos below the EW scale

Neutrino portal extension of the SM is motivated by the fact that it can be tightly related with the neutrino mass generation mechanism: Heavy Neutral Leptons or HNLs.

CERN-PBC-REPORT-2018-007



Nice complementarity with FCC-ee, CEPC, ILC, CLIC,..

SHiP in the framework of the Physics Beyond Colliders activity at CERN

The Physics Beyond Colliders mandate

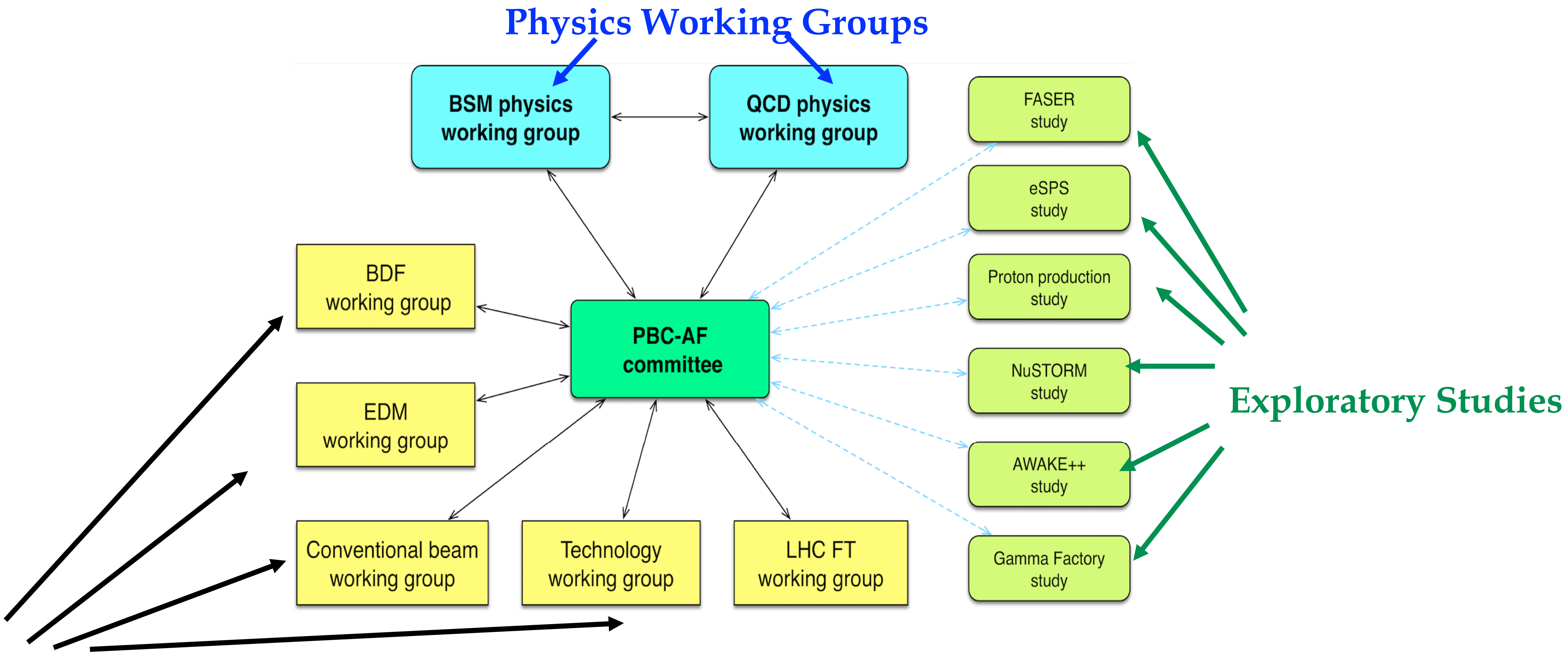
https://pbc.web.cern.ch/

"Physics Beyond Colliders is an exploratory study aimed at exploiting the full scientific potential of CERN's accelerator complex and its scientific infrastructure through projects complementary to the LHC, HL-LHC and other possible future colliders. These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments."

Deliverables for the European Strategy Update:

- PBC summary report – arXiv: 1902.00260
- QCD WG Report – arXiv: 1901.04482
- BSM WG Report – arXiv: 1901.09966
- Experiments' proposals & beam lines Yellow Reports (~15 inputs to ESU)

Physics Beyond Colliders Structure



Evaluation of new proposals;
Optimization/upgrade of existing beam lines;
Technology support to proposals sited elsewhere;
Comprehensive Design Studies for mature projects

Physics Beyond Colliders: a multi-scale approach

Since the TeV scale is very well explored at the LHC, focus on the sub-eV, MeV-GeV and multi-TeV scales:

sub-eV NP :
Axions with helioscopes, LSW and EDM rings

MeV-GeV NP:
Hidden Sector at accelerator-based experiments

Multi-TeV NP:
Ultra-rare/forbidden decays, EDM ring.

Proposal	Main Physics Cases	Beam Line	Beam Type	Beam Yield
sub-eV mass range:				
IAXO	axions/ALPs (photon coupling)	–	axions from sun	–
JURA	axions/ALPs (photon coupling)	laboratory	LSW	–
CPEDM	p, d oEDMs	EDM ring	p, d	–
	axions/ALPs (gluon coupling)		p, d	–
LHC-FT	charmed hadrons oEDMs	LHCb IP	7 TeV p	–
MeV-GeV mass range:				
SHiP	ALPs, Dark Photons, Dark Scalars LDM, HNLs, lepto-phobic DM, ..	BDF, SPS	400 GeV p	$2 \cdot 10^{20}$/5 years
NA62^{++}	ALPs, Dark Photons, Dark Scalars, HNLs	K12, SPS	400 GeV p	up to $3 \cdot 10^{18}$/year
NA64^{++}	ALPs, Dark Photons, Dark Scalars, LDM	H4, SPS	100 GeV e^-	$5 \cdot 10^{12}$ eot/year
	$+ L_\mu - L_\tau$	M2, SPS	160 GeV μ	$10^{12} - 10^{13}$ mot/year
	+ CP, CPT, leptophobic DM	H2-H8, T9	$\sim$ 40 GeV π, K, p	$5 \cdot 10^{12}$/year
LDMX	Dark Photon, LDM, ALPs,...	eSPS	8 (SLAC) -16 (eSPS) GeV e^-	$10^{16} - 10^{18}$ eot/year
AWAKE/NA64	Dark Photon	AWAKE beam	30-50 GeV e^-	10^{16} eot/year
RedTop	Dark Photon, Dark scalar, ALPs	CERN PS	1.8 or 3.5 GeV	10^{17} pot
MATHUSLA200	Weak-scale LLPs, Dark Scalar, Dark Photon, ALPs, HNLs	ATLAS or CMS IP	14 TeV p	3000 fb^{-1}
FASER	Dark Photon, Dark Scalar, ALPs, HNLs, $B - L$ gauge bosons	ATLAS IP	14 TeV p	3000 fb^{-1}
MilliQan	milli charge	CMS IP	14 TeV p	300-3000 fb^{-1}
CODEX-b	Dark Scalar, HNLs, ALPs, LDM, Higgs decays	LHCb IP	14 TeV p	300 fb^{-1}
>> TeV mass range:				
KLEVER	$K_L \to \pi^0 \nu \bar{\nu}$	P42/K12	400 GeV p	$5 \cdot 10^{19}$ pot /5 years
TauFV	LFV τ decays	BDF	400 GeV p	$o(2\%)$ of the BDF proton yield
CPEDM	p, d EDMs	EDM ring	p, d	–
	axions/ALPs (gluon coupling)		p, d	–
LHC-FT	charmed hadrons MDMs, EDMs	LHCb IP	7 TeV p	–

Non Accelerator-based

Accelerator-based

arXiv: 1901.09966

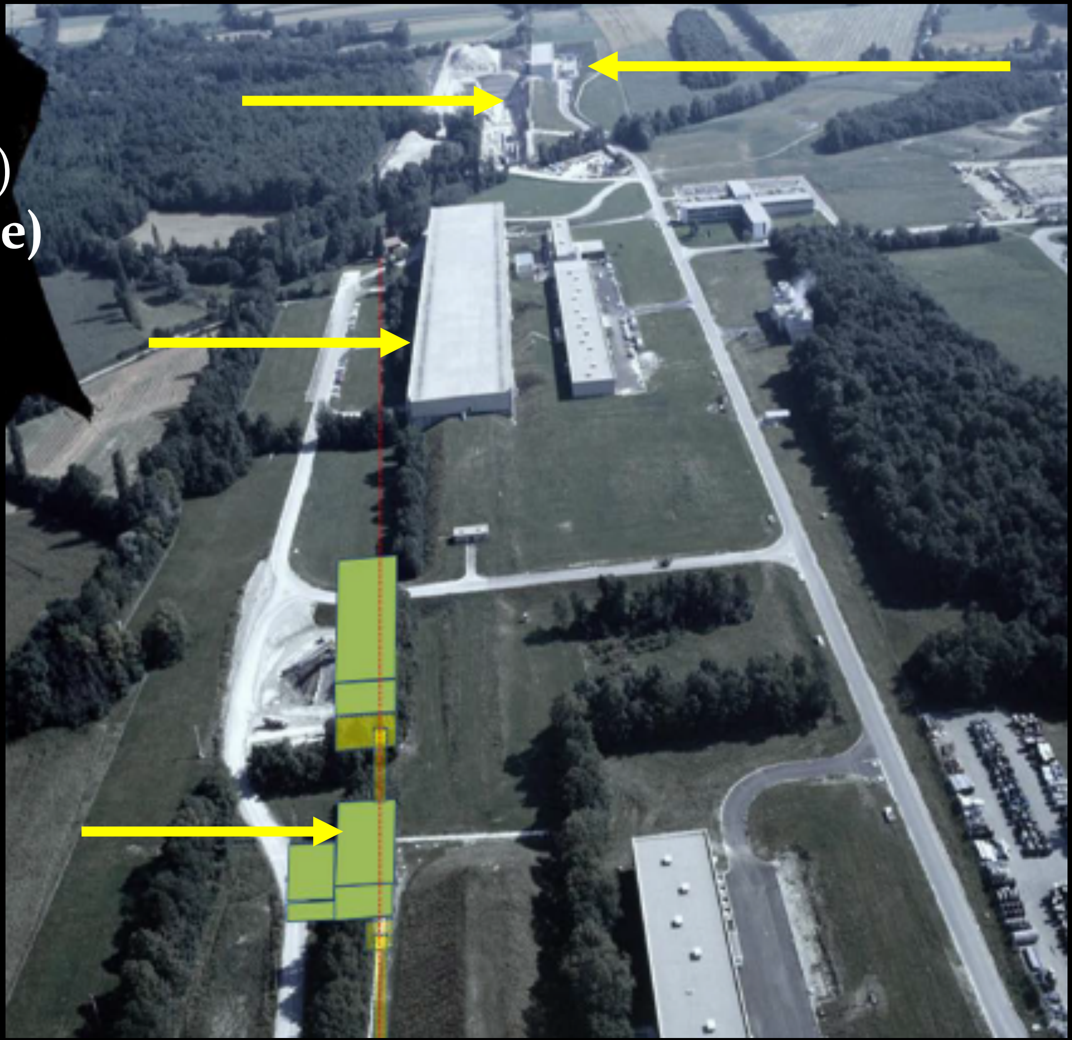
A multi-scale approach.

(some) PBC Proposals in the North Area

NA62^{++} @ K12
400 GeV p beam
up to 3×10^{18} pot/year (now)
up to 10^{19} pot/year (upgrade)

NA64^{++}(e) @ H4
(100 GeV e- beam
up to 5×10^{12} eot/year)

SHiP @ BDF
400 GeV p
up to 4×10^{19} pot/year



NA64^{++} (μ) @ M2
100-160 GeV muons,
up to 10^{13} μ/year

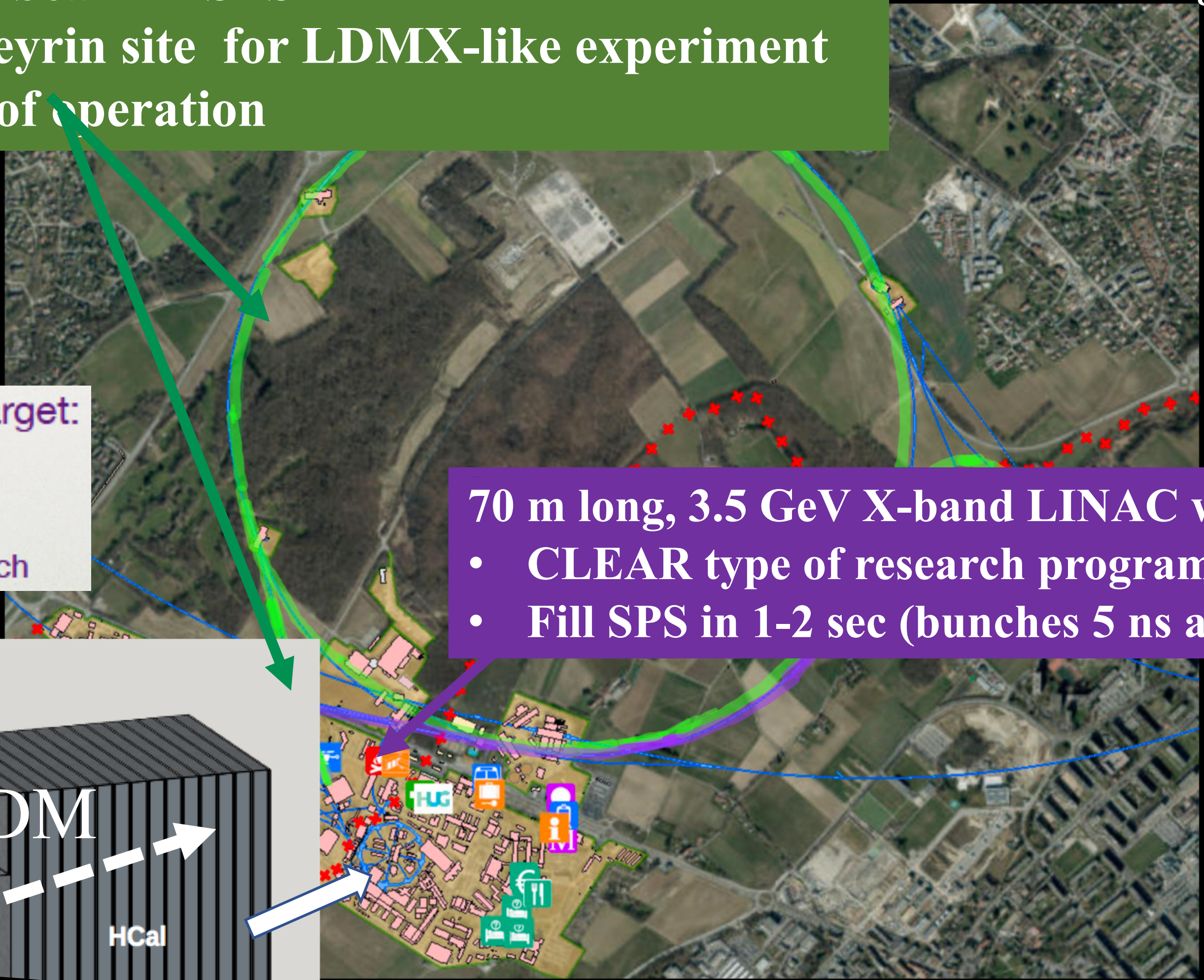
Beam-Dump and Missing Energy techniques

The "Hidden Sector Campus" (HSC)

LDMX @ eSPS: Meyrin area

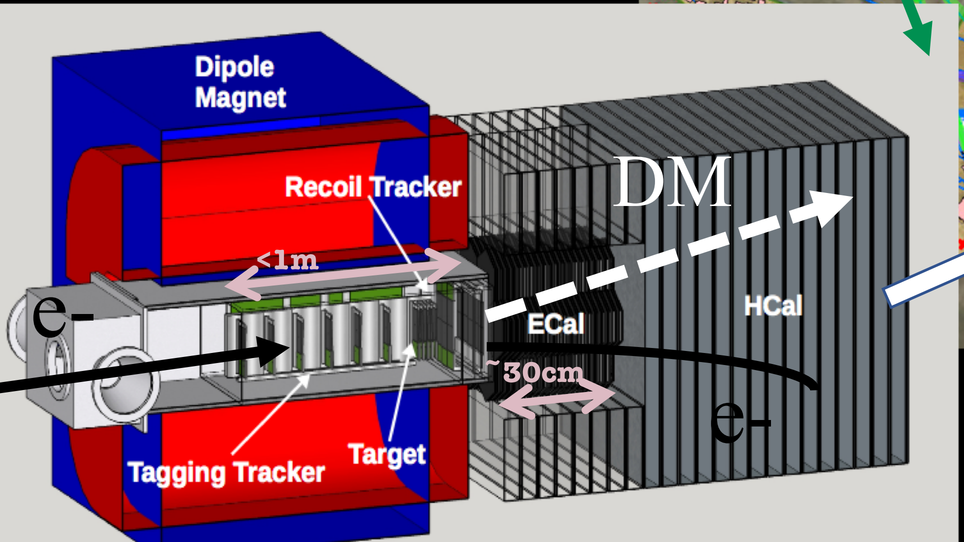
GREEN: ~16 GeV electron beam in SPS
slow extraction towards Meyrin site for LDMX-like experiment
Up to 10^{16} eot in o(1) year of operation

Missing momentum technique



70 m long, 3.5 GeV X-band LINAC with excellent beam quality
- **CLEAR type of research programme.**
- **Fill SPS in 1-2 sec (bunches 5 ns apart) via TT60;**

Electron beam impinging on target:
- multi-GeV electrons
- 1-200 MHz bunch spacing
- Ultra-low O(1-5) electrons per bunch

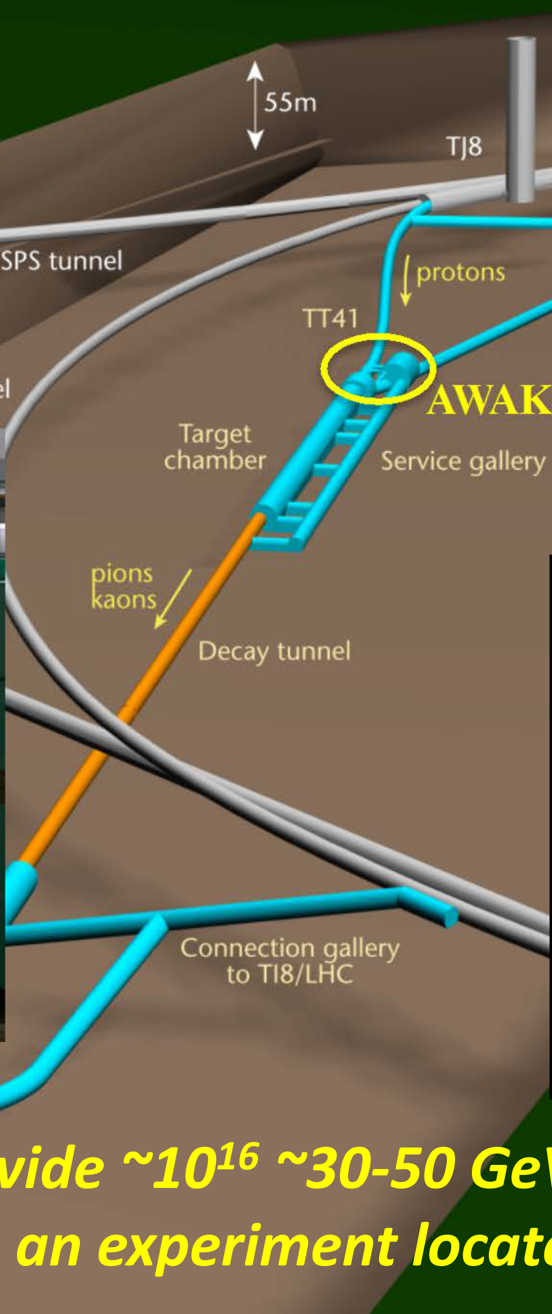


EoI sent to SPSC in October 2018:
https://cds.cern.ch/record/2640784

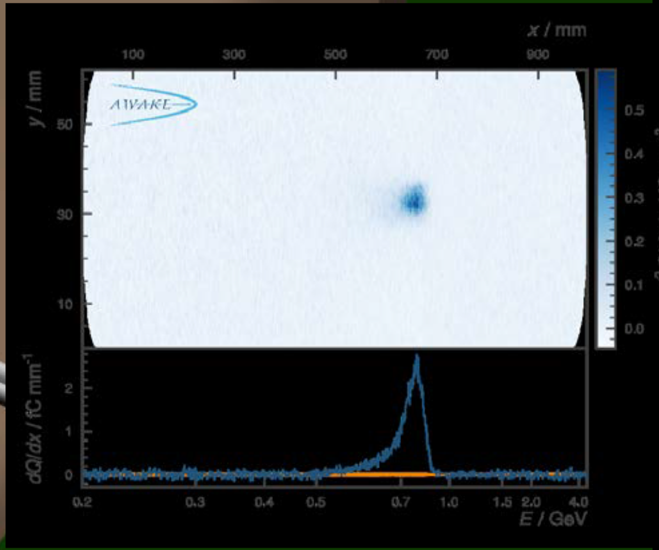
Electron-Dump at AWAKE

Beam Dump technique

R&D for electron acceleration with a plasma cell excited by SPS proton bunches

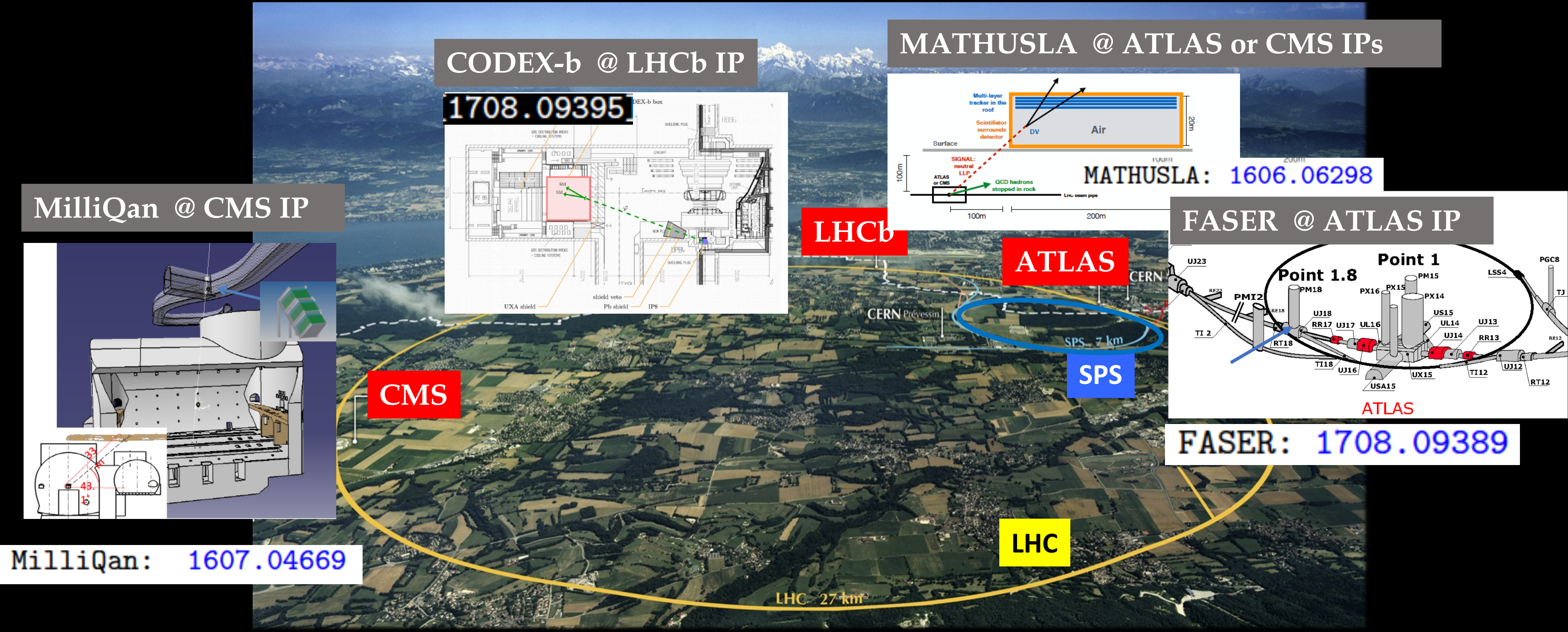


First accelerated e- seen in 2018!



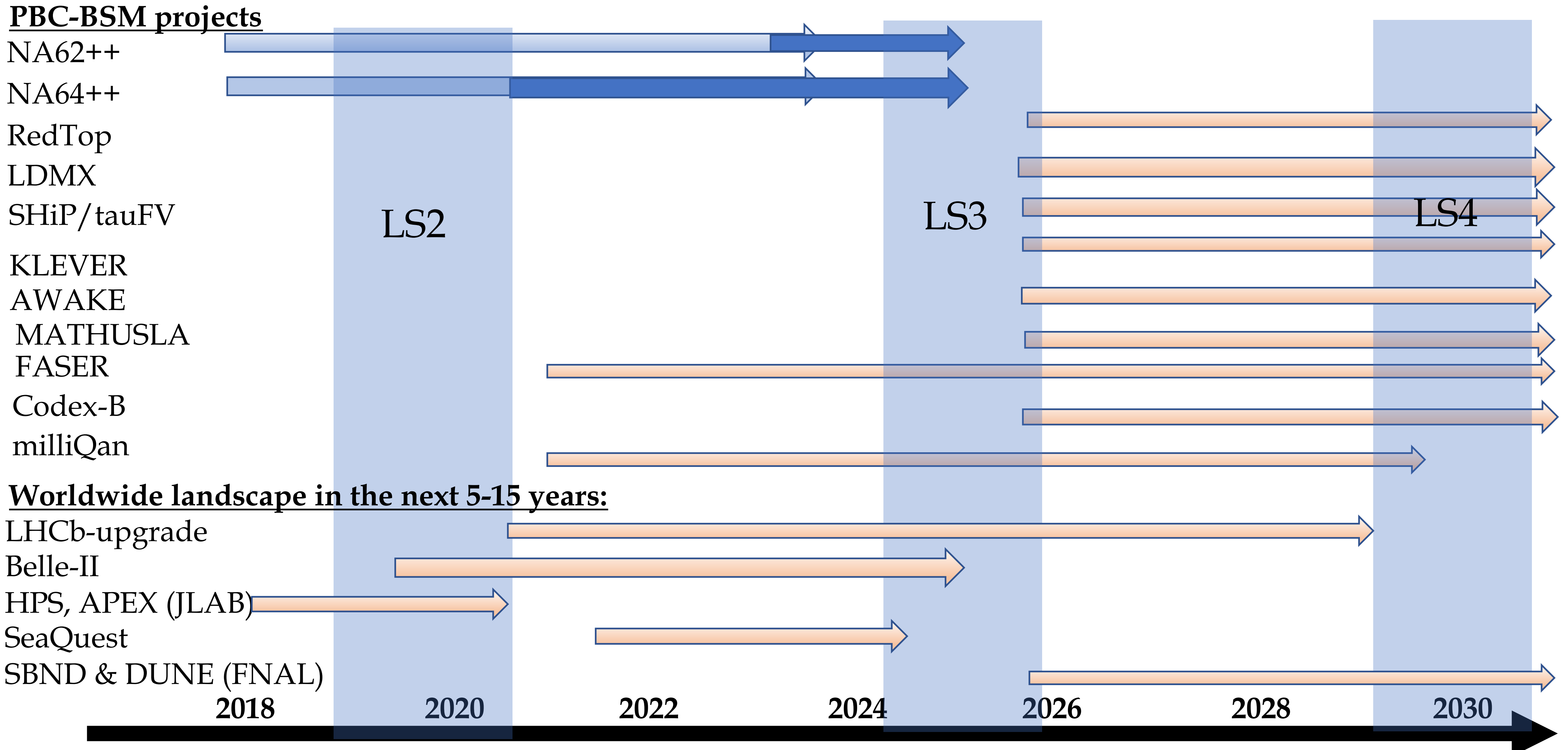
Could provide ~10^{16} ~30-50 GeV pulsed e's/year in the post-LS3 era to an experiment located in the CNGS decay tunnel

MilliQan, MATHUSLA, FASER, CODEX-b @ LHC IPs

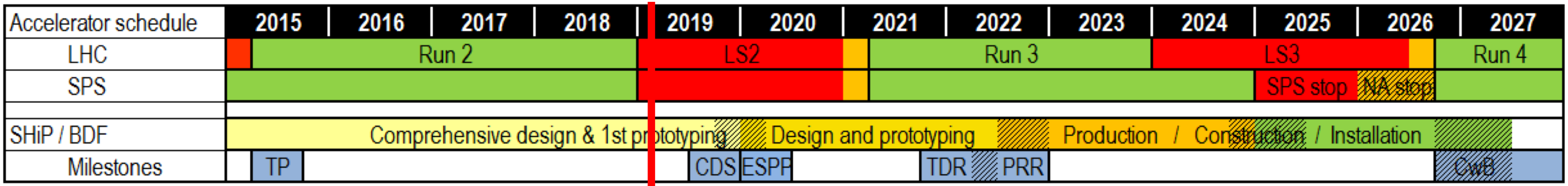


Timescale of accelerator-based PBC projects

All projects could be built and operated on 10-15 year timescale



SHiP: Next steps



2015: SHiP Technical Proposal sent to the SPSC

End 2018: SHiP and BDF Projects submitted to the ESPP

End 2019: Comprehensive Design Study

May 2020: ESPP outcome

End 2020-2021: Approval?

2027: Earliest possible date to start if approved in 2021.

today

The next two years will be extremely important for SHiP

Granada Symposium for the European Strategy Update
13-16 May 2019

European Strategy Update

Feebly interacting long-lived particles very popular topic across the ESPP inputs. Lively discussions expected in Granada…..

- BSM at colliders:

160 - HE-LHC
152 - HL-LHC
151 – Heavy Ions
145 - CLIC
135 - FCC-int
120 – Muon collider
101 - FCC-ee
94 - FASER
77 - ILC
75 - MATHUSLA
29 - CEPC

- Dark Matter and Dark Sector:

1 - Sterile Neutrinos at CERN (NA62/SHiP)
9 - NA64
12 – SHiP
36 - Dark Sector Physics with primary electron beam (eSPS)
42 - Physics Beyond Colliders
50 - Particle Physics with AWAKE

- Flavor:

11 – Belle-II experiment at super KEK-B
28 – REDTOP
153 - KLEVER

Conclusions

- ❑ SHiP physics programme aims to address open questions in particle physics in a complementary way to the LHC, HL-LHC, FCC , CEPC, ILC, and other initiatives in the world (e.g. DM direct detection, flavor, astrophysical data).

- ❑ This programme aims at exploiting the unique CERN scientific infrastructure and accelerator complex on a 5-15 year timescale. SHiP, is approved, could start taking data in 2027++.

- ❑ A preliminary set of comparative plots, based on theoretically and phenomenologically motivated models, shows the scientific potential and the impact that SHiP could have on the international landscape in the next o(10-15) years in the quest for New Physics .

- ❑ SHiP along with the projects presented in the Physics Beyond Colliders framework could be a very attractive option while preparing the next big machine.

CERN

Physics Beyond Colliders

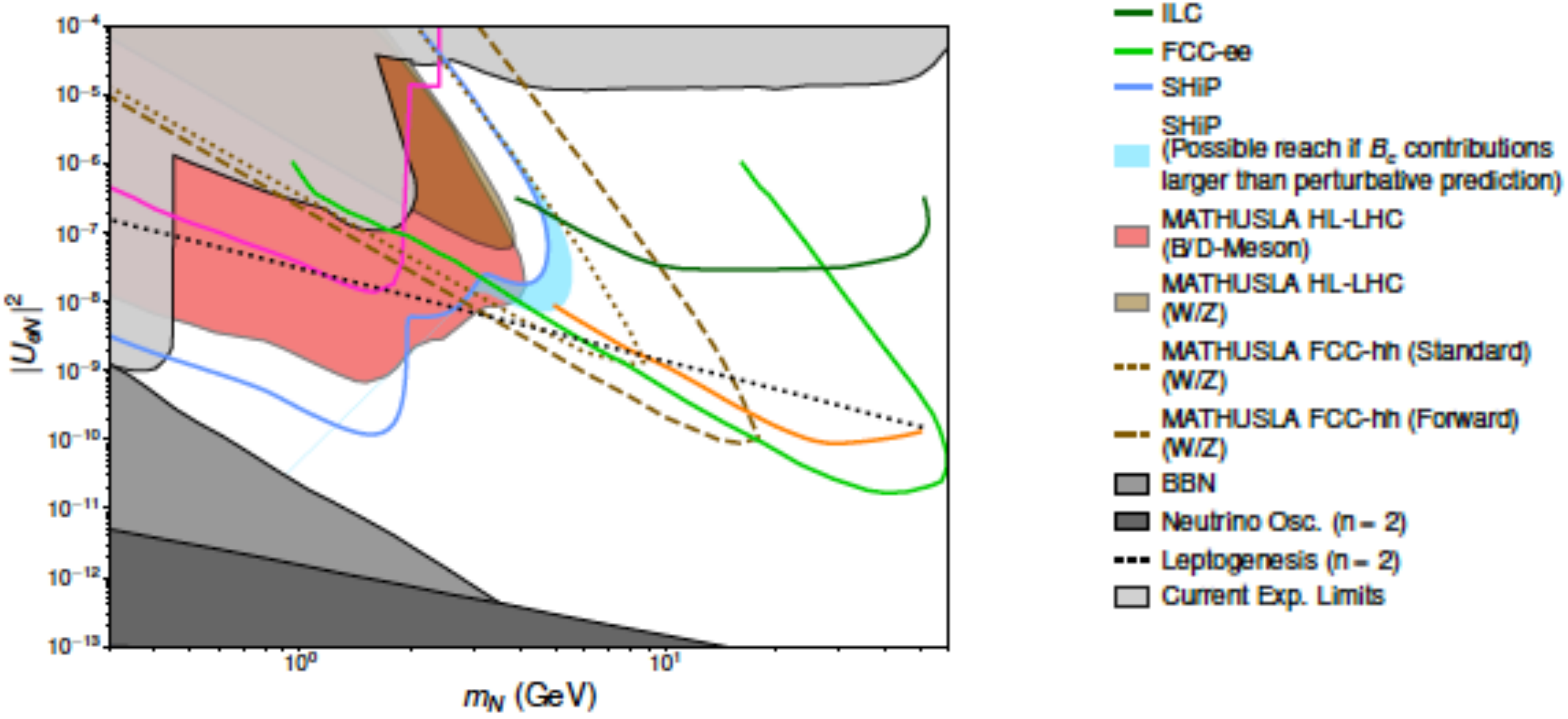
SHiP

Thank you for your attention.

SPARES

Right Handed Neutrinos below the EW scale:

+ ILC, CEPC, FCC-ee

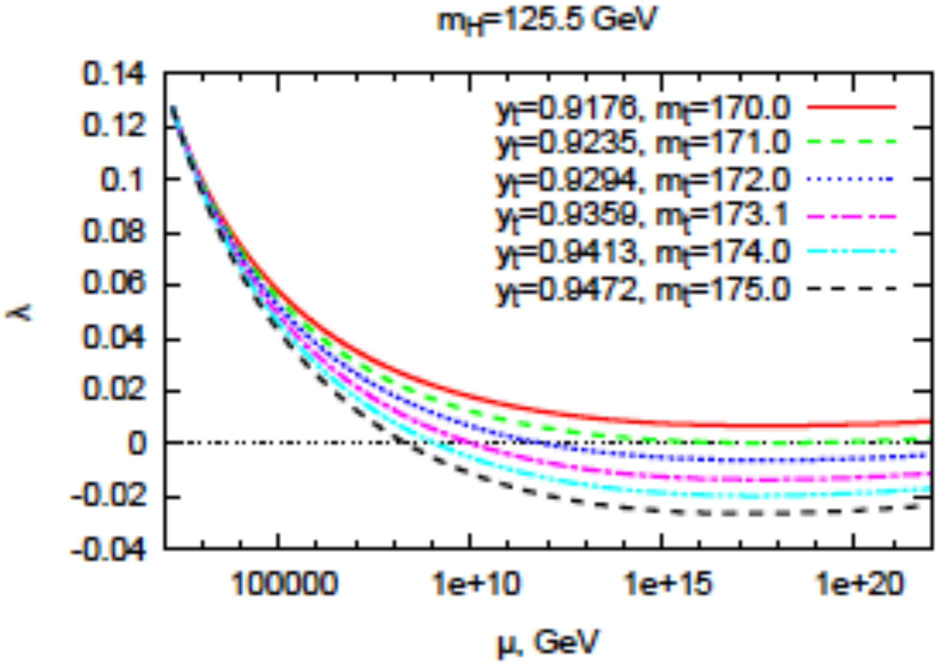


MATHUSLA Physics Case – arXiv 1806.07396

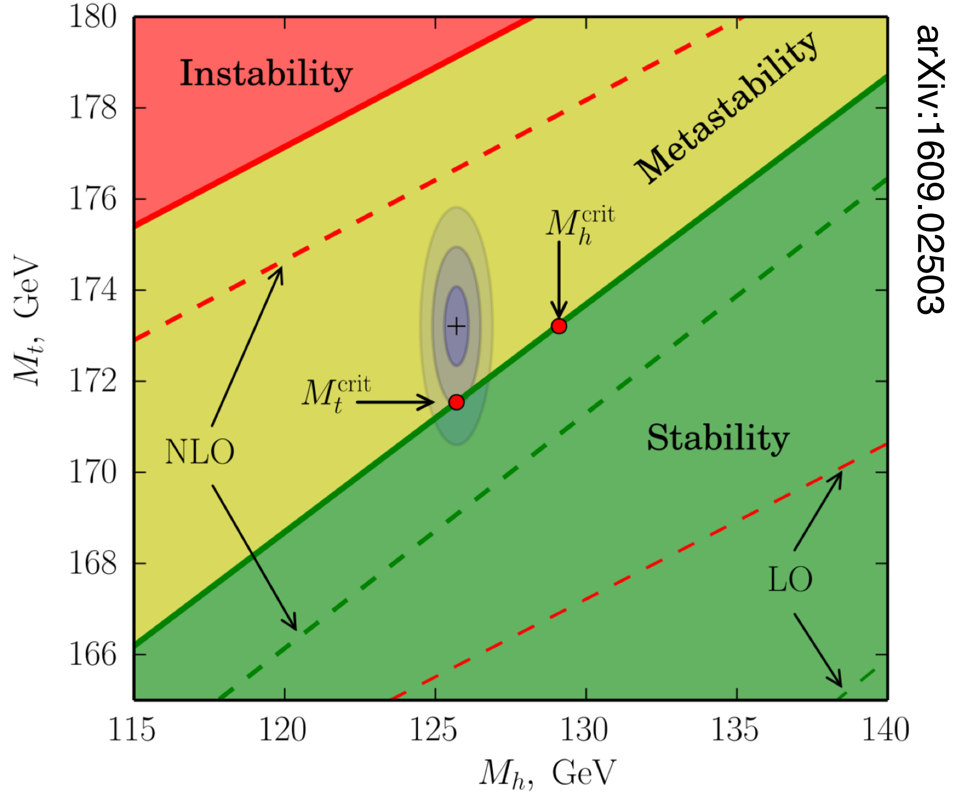
A "metastable" world

M_H = 125.09 GeV and M_{top} = 173.1 GeV are two special numbers.

Coupling λ evolution:



Phase diagram of vacuum stability obtained at three loops (NNLO).



The experimental value: 125.09 +- 0.21 +- 0.11 GeV is impressively close to the critical value

….Too elegant to be by chance…..

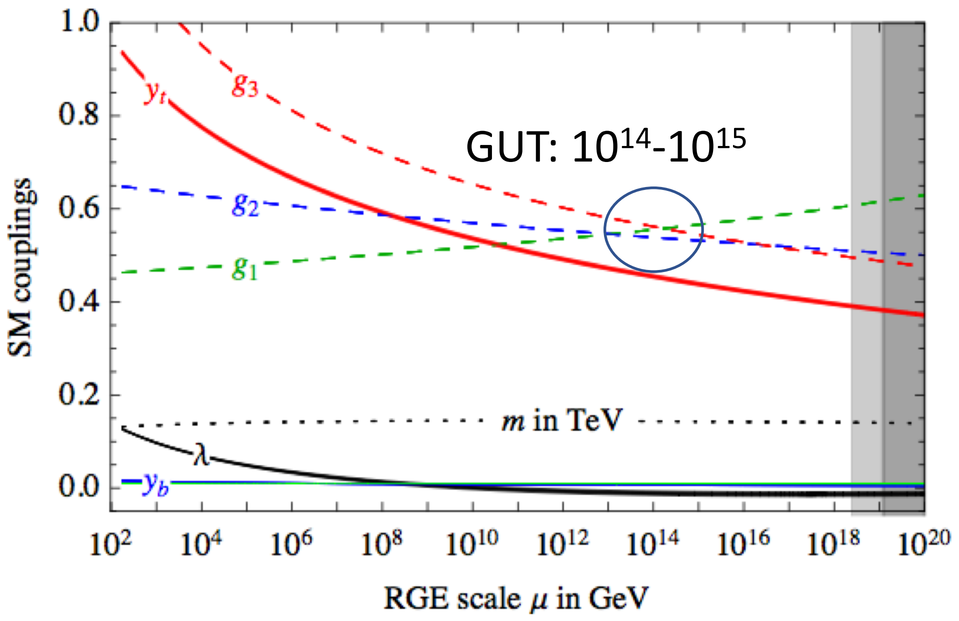
The Grand Unification Theory

The Standard Model has three gauge symmetries:
the colour SU(3), the weak isospin SU(2) and the hypercharge U(1) symmetry corresponding to the three fundamental forces:

$$\mathcal{L}\ (\text{Standard Model}) = SU(3) \times SU(2) \times U(1)$$

Due to renormalization the coupling constants of each of these symmetries, (g1, g2 and g3) vary with the energy at which they are measured.
Around 10^{16} GeV these couplings become *approximately* equal

This has led to the speculation that above this energy the three gauge symmetries of the SM are unified in one single gauge symmetry with A single gauge group and just one coupling constant.
Below this energy the symmetry is spontaneously broken to SM symmetries



This is called Grand Unified Theory (GUT)

Higgs mass and New Physics

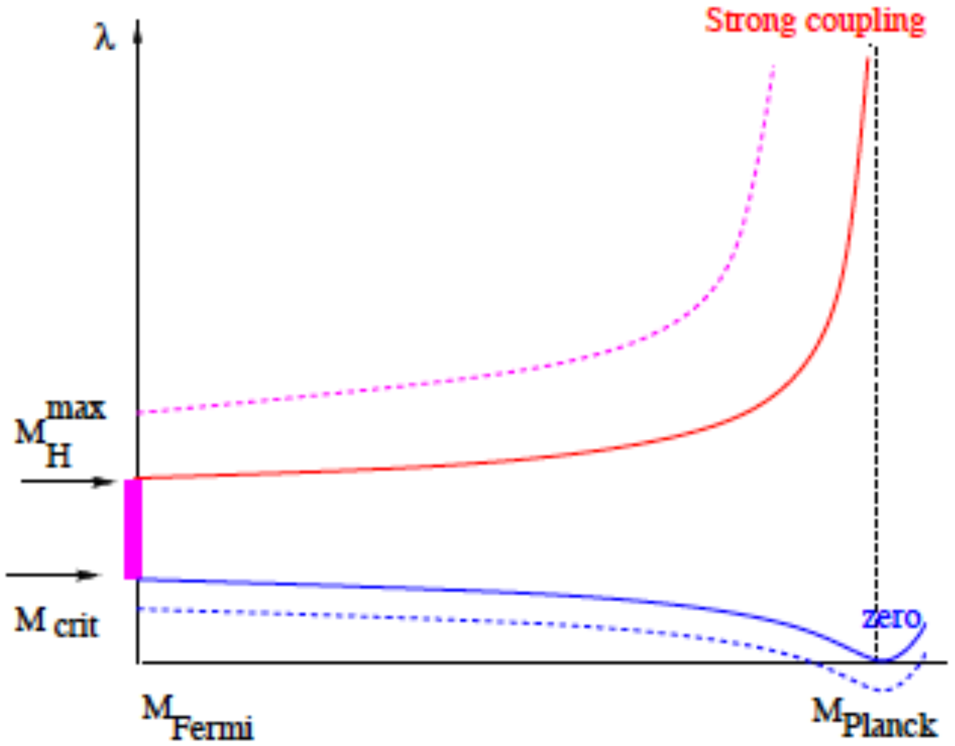
Higgs self-coupling λ at the Planck scale:

behavior is determined by the masses of the Higgs boson and mostly the top mass (m_{top}, $m_t = y_t v/\sqrt{2}$): $m_H = \sqrt{2\lambda}\, v$

$$m_{\max} = [173.5 + \frac{m_t - 171.2}{2.1} \times 0.6 - \frac{\alpha_s - 0.118}{0.002} \times 0.1]\ \text{GeV}\ ,$$

$$m_{\min} = [126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5]\ \text{GeV}\ ,$$

for mH = m_min = M_{crit} the running evolution of the Self-coupling crosses zero EXACTLY at the Planck scale (no gravity implied, this just a pure prediction of SM)



The value of the Higgs mass was not unexpected :

See for example, arXiv:0912.0208

Asymptotic safety of gravity and the Higgs boson mass

Mikhail Shaposhnikov

Institut de Théorie des Phénomènes Physiques, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

Christof Wetterich

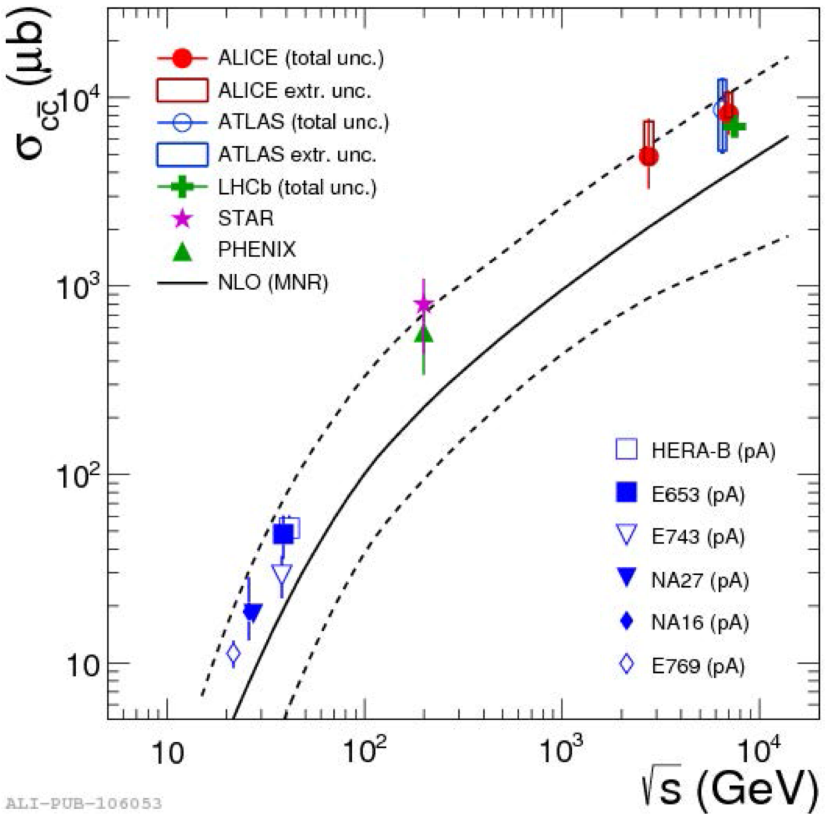
Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, D-69120 Heidelberg, Germany

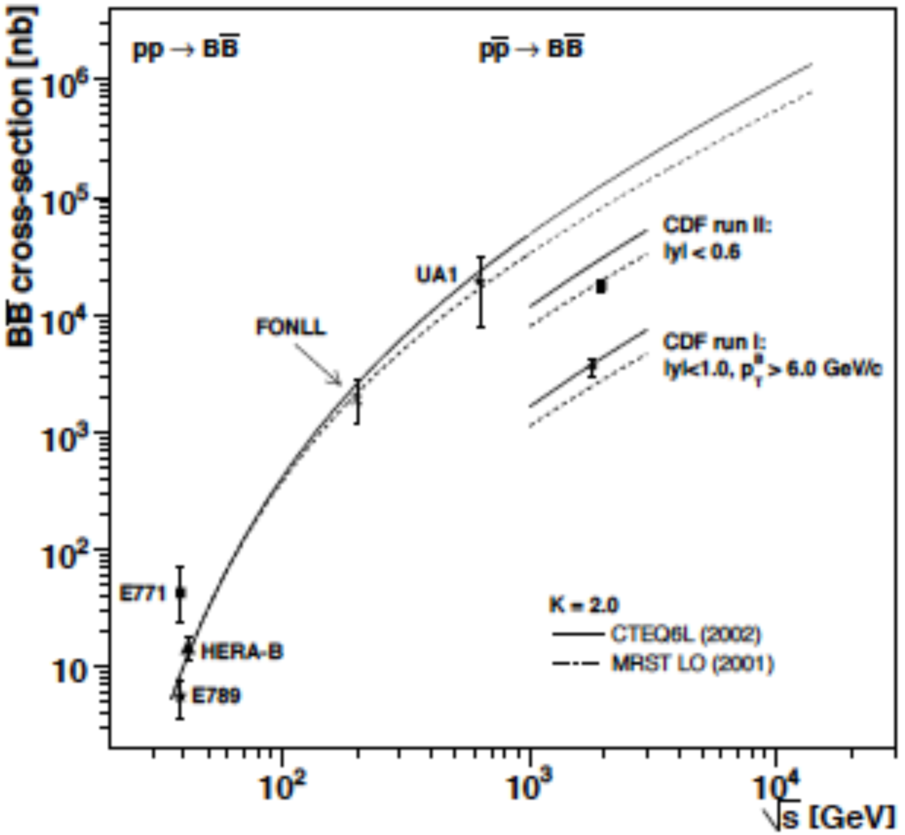
12 January 2010

Abstract

There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\text{min}} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\text{min}} < m_H < m_{\text{max}} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

Beauty and charm production cross-sections versus sqrt(s)





At SPS energies:

σ (pp → ssbar X) / sigma (pp→ X) ~ 0.15

σ (pp→ c cbar X) / sigma (pp→ X) ~ $2\ 10^{-3}$

σ (pp → b bbarX) / sigma (pp→ X) ~ $1.6\ 10^{-7}$