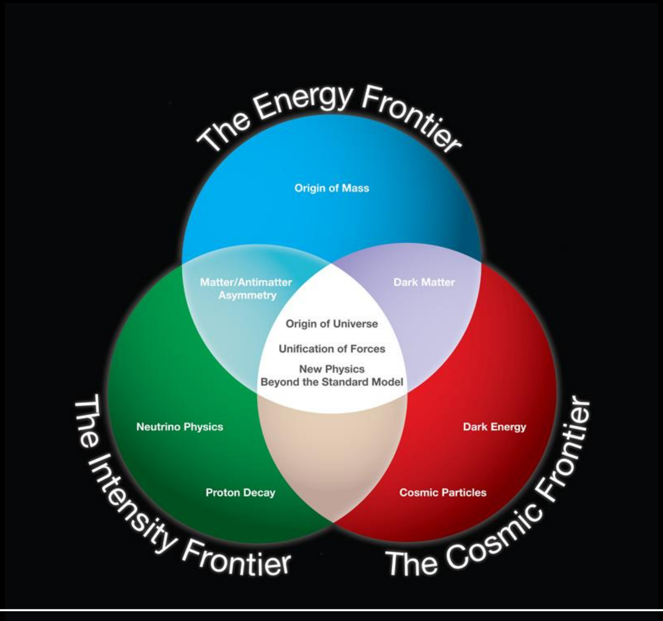
Search for New Physics at the High Intensity Frontier

Gaia Lanfranchi
LNF-INFN



Weizmann Institute – November 9th 2017

Preamble

With the **discovery at the Large Hadron Collider (LHC) at CERN** 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).

These results, indicate that **there might be no New Physics with a direct and sizeable coupling to Standard (Model) particles up to energies ~10^5 TeV** unless specific flavour structures/symmetries are postulated.

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?

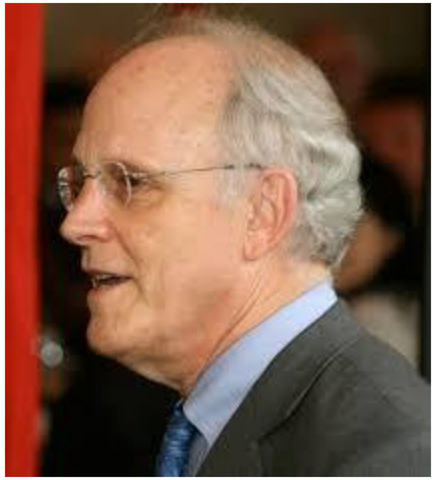
What leading physicists expected from the LHC in 2008

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.



What leading physicists expected from the LHC in 2008

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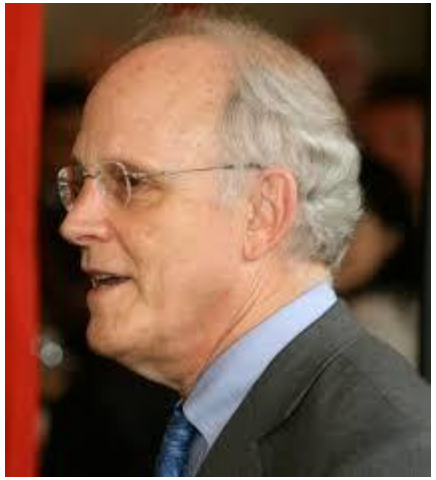

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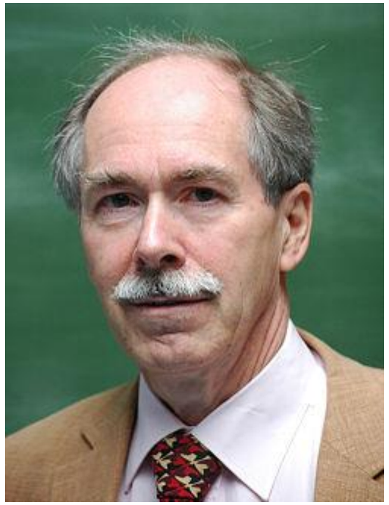

Gerardus ’t Hooft: "a Higgs, or more"

(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"

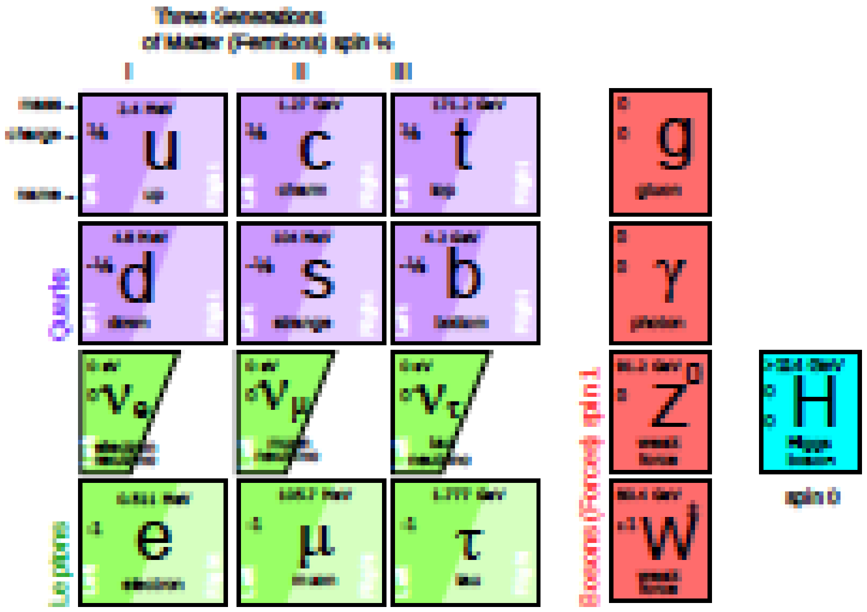
If we don't get the Higgs, that would in fact be a bit more interesting, but *I am hoping that there will be lots of new particles and resonances that no one ever expected.* That will be really exciting.

2017, 9 years later:

2017, 9 years later:

Higgs discovered with mass ~ 125.5 GeV.
No new particles found.

The Standard Model is in excellent shape!



\+ Einstein gravity

- ✓ 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.

The masses of the top quark (~172.5 GeV) and of the Higgs boson (125.5 GeV) the Nature has chosen, make the Standard Model a self-consistent (effective field) theory all the way up to the quantum gravity Planck scale, even in absence of New Physics at the TeV scale.

The theory is mathematically consistent and does not loose predictability up to very high energies, $M_{Planck} \sim 10^{19}$ GeV.

…. Is this the end of the story ?……

NO!

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

What is the scale of New Physics?

Masses of right handed neutrinos
$10^{-9} – 10^{15}$ GeV

Mass of Dark Matter particle
$10^{-31} – 10^{20}$ GeV

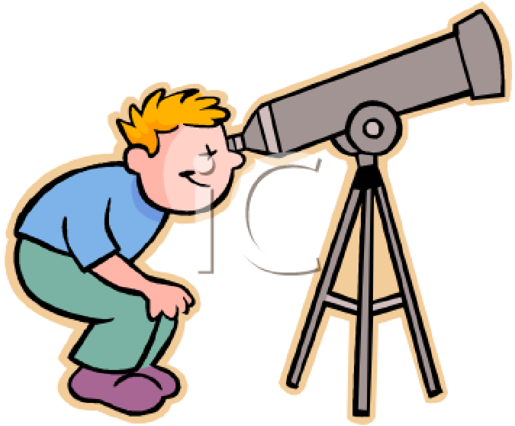
Mass of new particles required for baryogenesis
$10^{-2} - 10^{15}$ GeV

Mass of New Particles for Higgs hierarchy
$10^{3} – 10^{18}$ GeV

Today – more than ever - we must keep a broad view

What is the scale of New Physics?

- ✓ So far the experimental efforts have been concentrated on the discovery of **new particles with masses at (or slightly above) the Higgs mass** and **sizeable couplings with Standard Model (SM) particles**.



? New Physics ?

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? New Physics ?

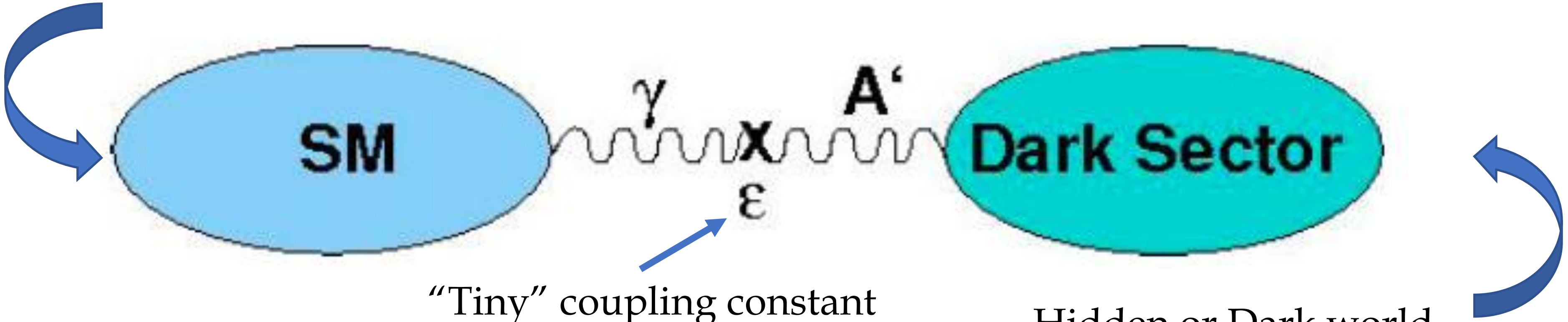
New Physics !

✓ Another viable possibility (largely unexplored) is that new particles are **below the Higgs mass and couple very weakly with SM particles** and are "dark" or "hidden"

What is the scale of New Physics?

- ✓ These particles could be **light, long-lived, and mix with SM particles that not carry electromagnetic charge,** like for example Higgs (Dark scalar or pseudo-scalar), photons (Dark Photon) and neutrinos (Heavy Neutrinos).

Standard Model world (our world)

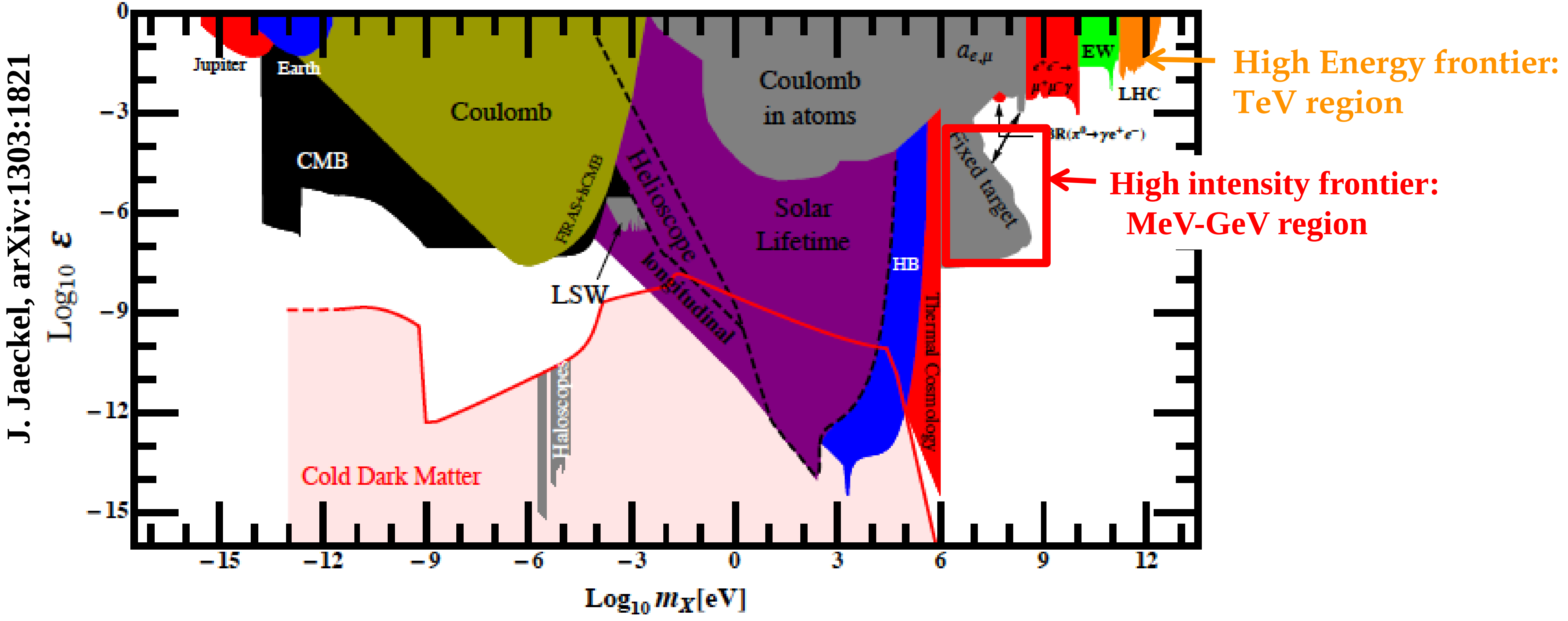


"Tiny" coupling constant between the two worlds ("kinetic mixing")

Hidden or Dark world that could explain all the open problems in particle physics

Below the Higgs mass... but where?

kinetic mixing of a dark photon-ordinary photon versus mass of dark photon

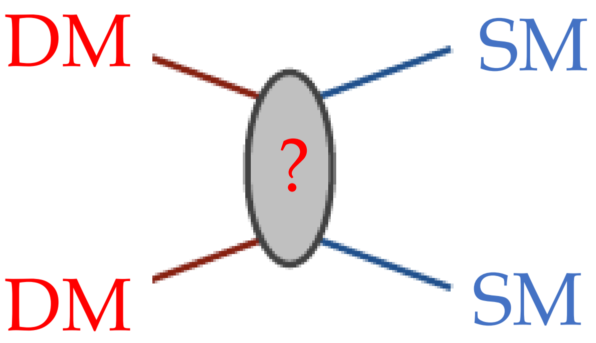


…. lost among the orders of magnitude ….

MeV-GeV region: Light Dark Matter with thermal origin

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

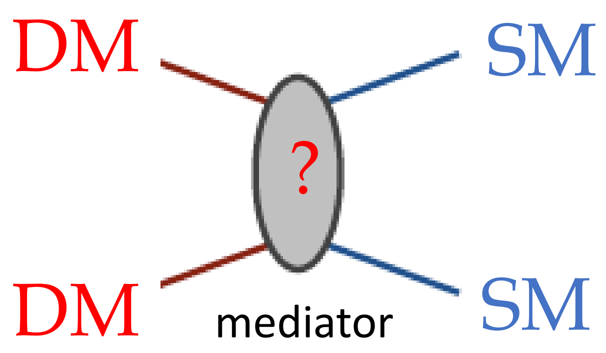
- Dark Matter interacts with SM to stay in equilibrium
- eventually Dark Matter particles can't find each other to annihilate
- and a (minimal) DM abundance is left over the present day.

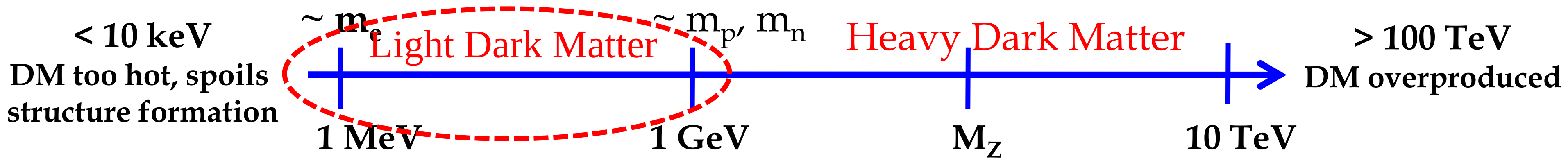


DM annihilation cross-section necessary to obtain the observed Dark Matter density:

$$\boldsymbol{\sigma\, v\, (\mathrm{relic}) = 3\times10^{-26}\ \mathrm{cm}^3/\mathrm{s}}$$

MeV-GeV region: Light Dark Matter with thermal origin

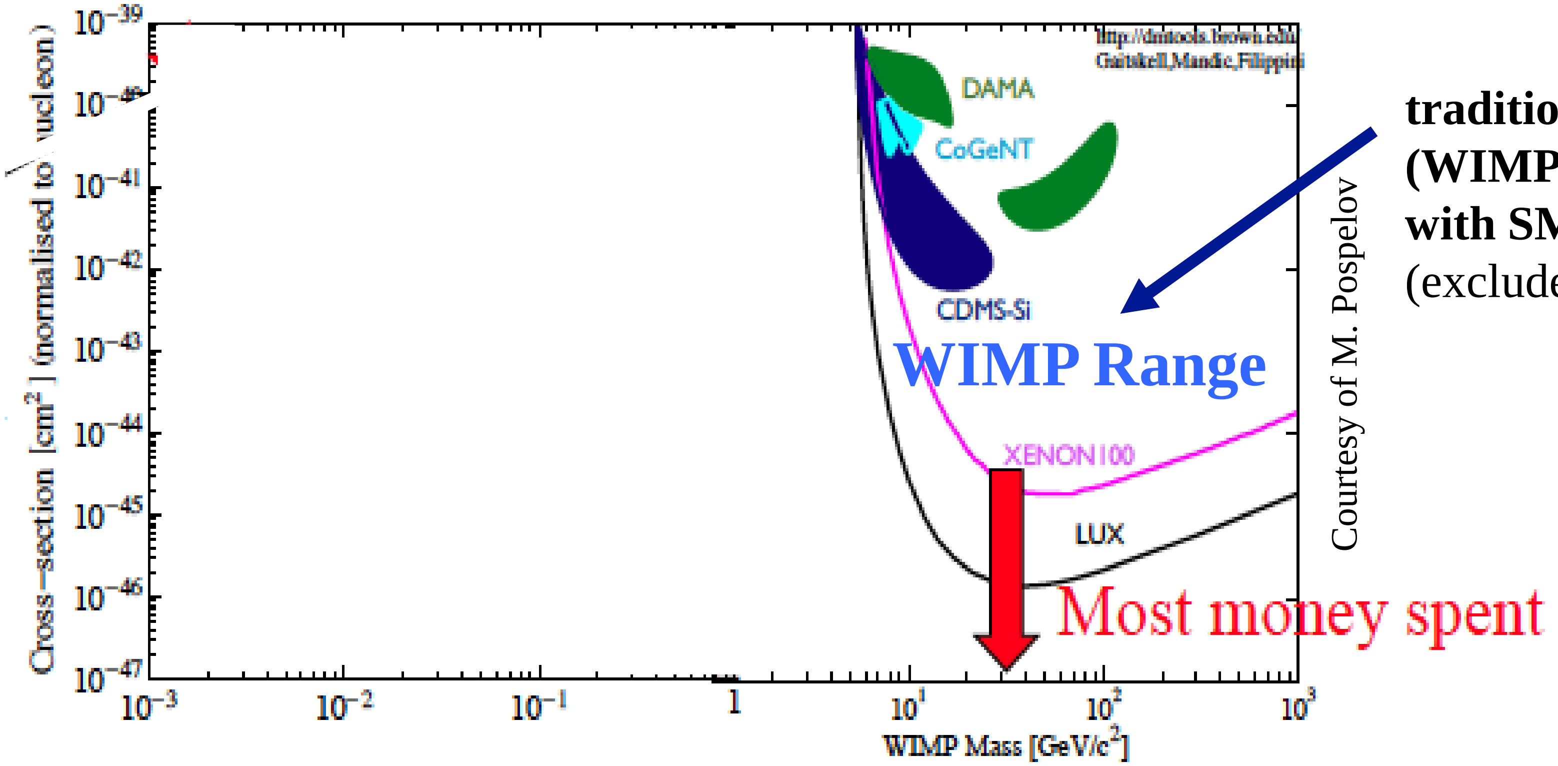




The equilibrium can be reached:

- either with **an heavy DM particle (~**TeV) **with a Standard Model mediator** (excluded by current limits)
- or with **Light Dark Matter (LDM) particle (~MeV-GeV)** with a **light new mediator (hence new forces).**

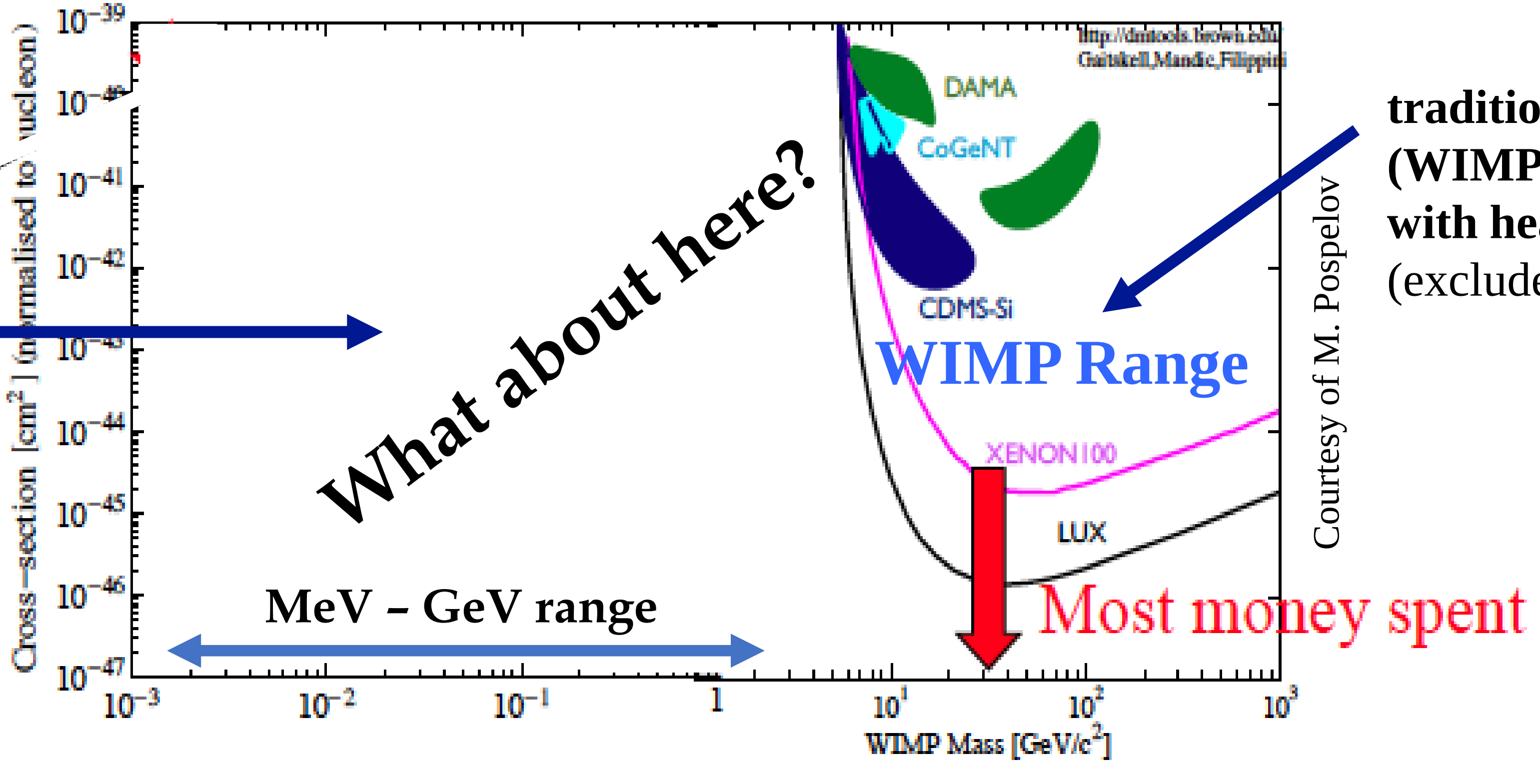
MeV-GeV region for Light Dark Matter with thermal origin



traditional heavy DM
(WIMP at TeV)
with SM mediator
(excluded by current limits)

MeV-GeV region for Light Dark Matter with thermal origin

Light Dark Matter with **light mediators (hence new forces) that couple very weakly to SM and are therefore *hidden* or *dark***

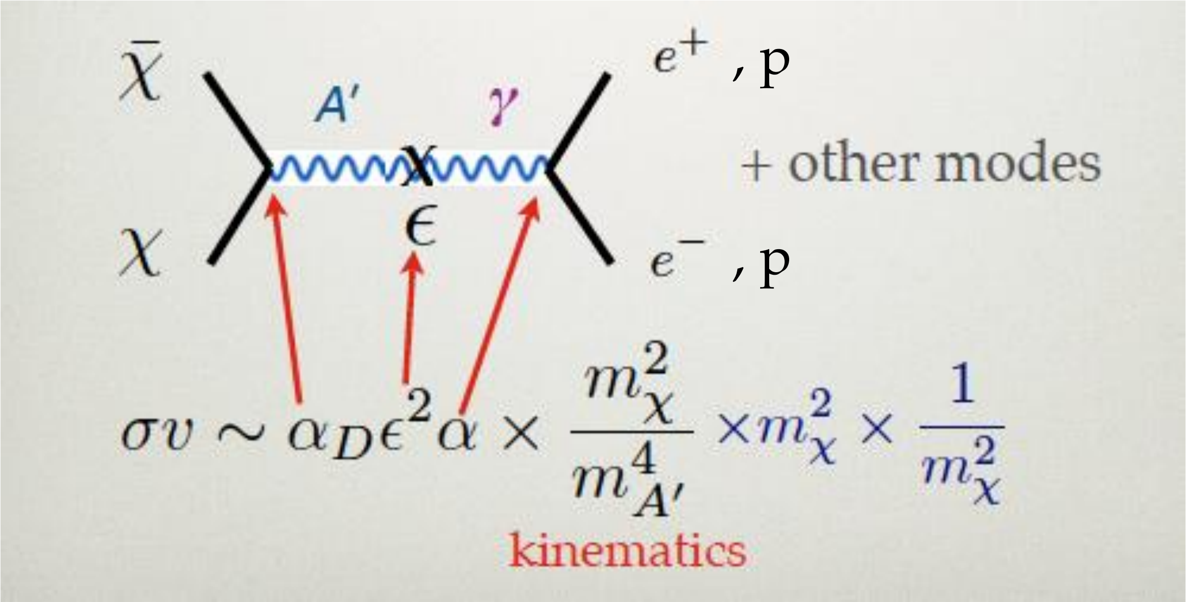


traditional heavy DM (WIMP at TeV)
with heavy mediator
(excluded by current limits)

How we can study Dark Matter and related mediators with mass in this range?

Light Dark Matter: connection between relic density and production of LDM at the accelerators

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



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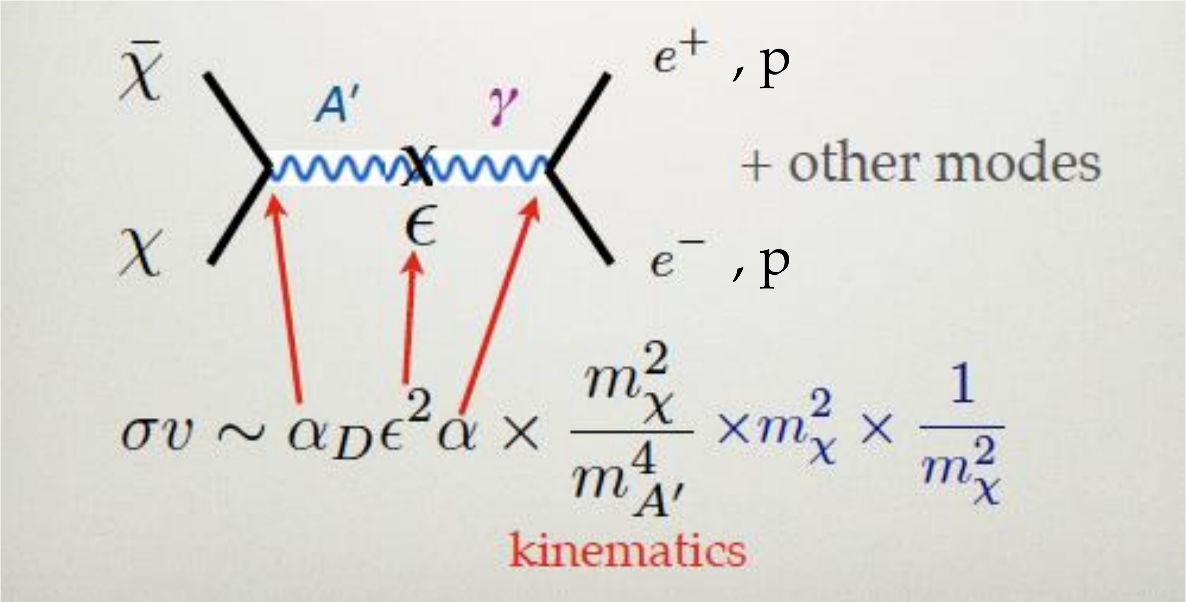


Production of DM (and mediators) at accelerators via, eg, electron or proton bremsstrahlung

Direct annihilation is controlled by the same couplings relevant for DM production at accelerators, leading to well defined predictions, once we assume the thermal origin target

Production of Hidden Particles

Proton or electron beams

fixed target

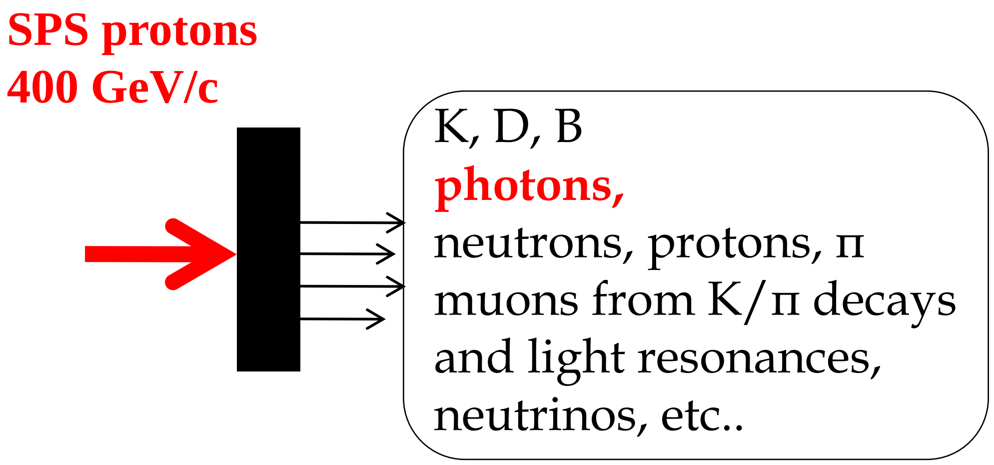
Standard Model Particles

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

Dark Sector Particles

Use K, D, B decays and photons to search for light mediators or Light DM in the MeV-GeV region

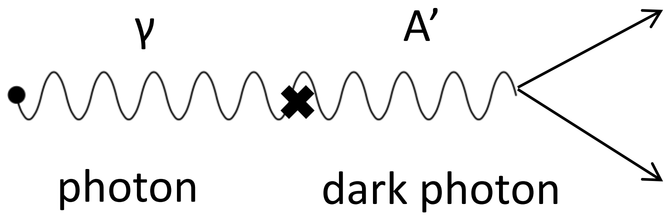
Production of Dark Photons via kinetic mixing



Eg: Production of Dark Photons:

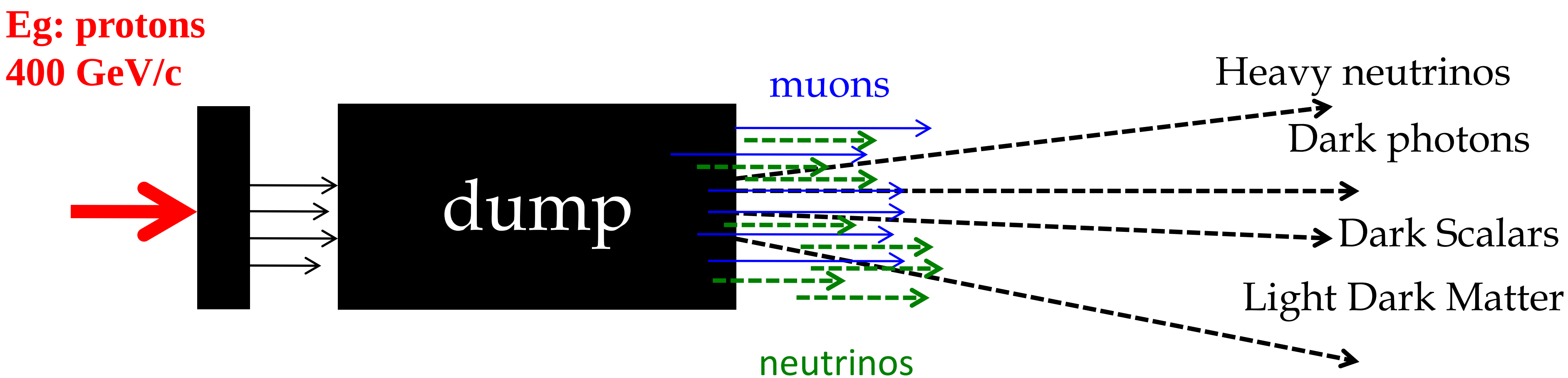
Photon produced in light meson resonances, bremsstrahlung, and QCD processes.

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



….Background, background, background…..

A dump with suitable length stops all beam-induced backgrounds but neutrinos and muons:



Any kind of feebly-interacting long-lived particle or LDM (put here your favored model);

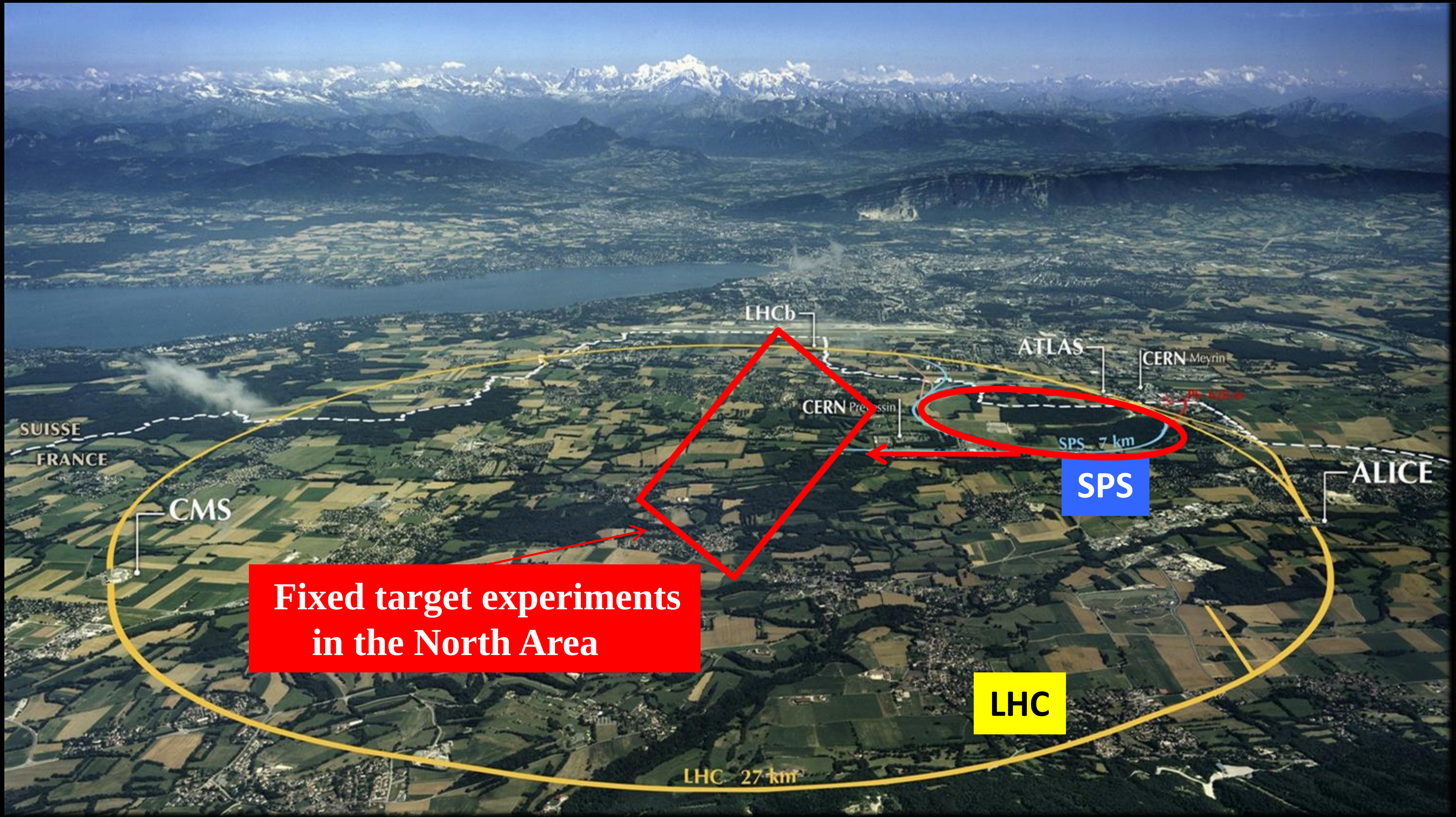
Background is the name of the game !

How to produce and detect Hidden Particles in the MeV-GeV range?

1) Light and feebly-interacting particles can be **originated by the decay of beauty, charm and strange hadrons and by photons produced in the interaction of protons with a target**. As the heavy quark cross-sections increase steeply with the energy, **a high-intensity, high-energy proton beam is required to improve over the current results**:
→ To date the world best line to produce high intensity fluxes of beauty and charm hadrons and photons through the interactions of protons on a high-Z target is a 400 GeV/c proton beam line extracted from the CERN SPS .

2) The smallness of the couplings implies that the hidden sector mediators are also **very long-lived (up to several km) compared to the bulk of the Standard Model particles**:
→The decays to SM particles can optimally be detected only using an experiment with decay volume tens of meters long..

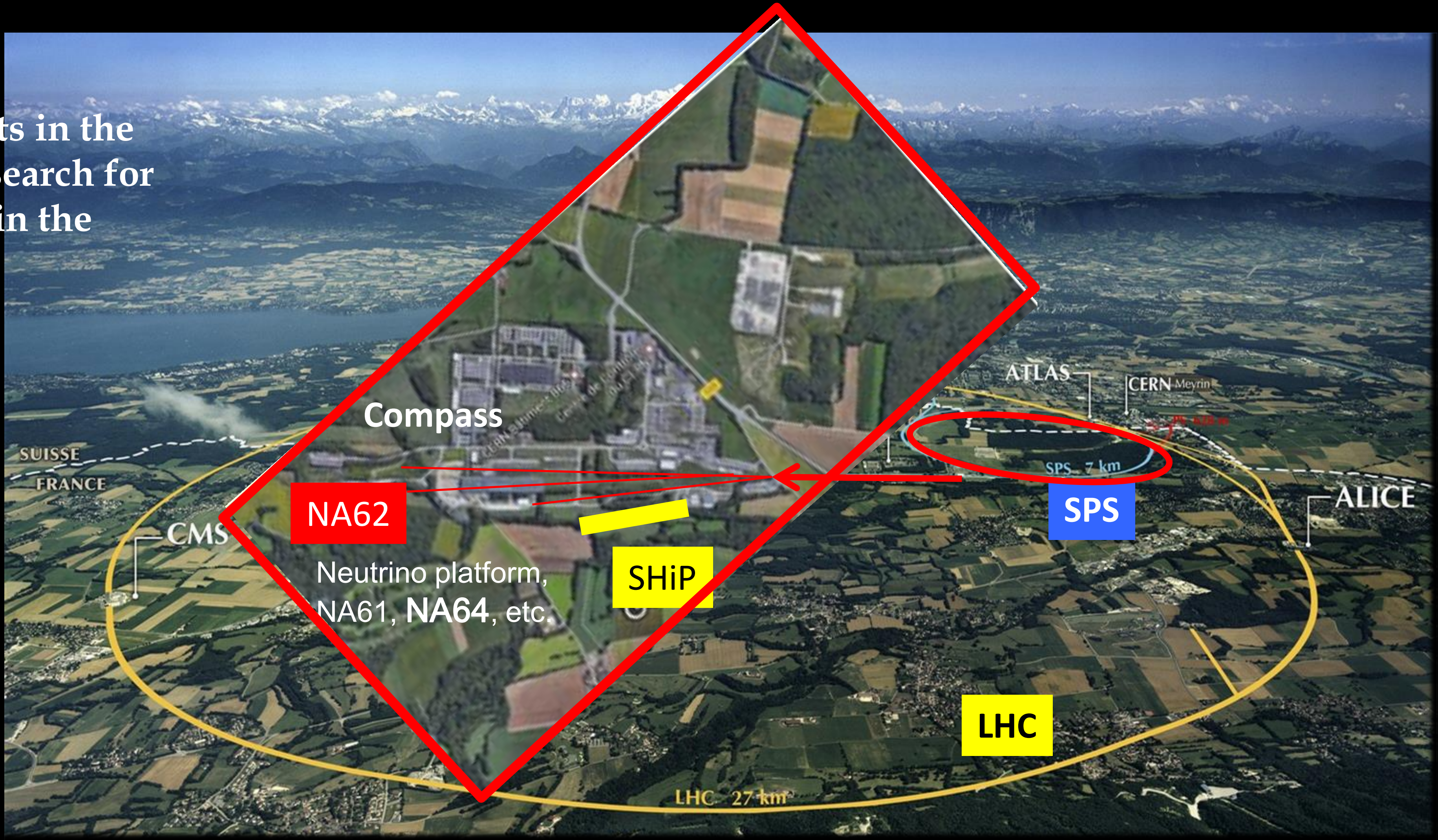
The CERN accelerator complex



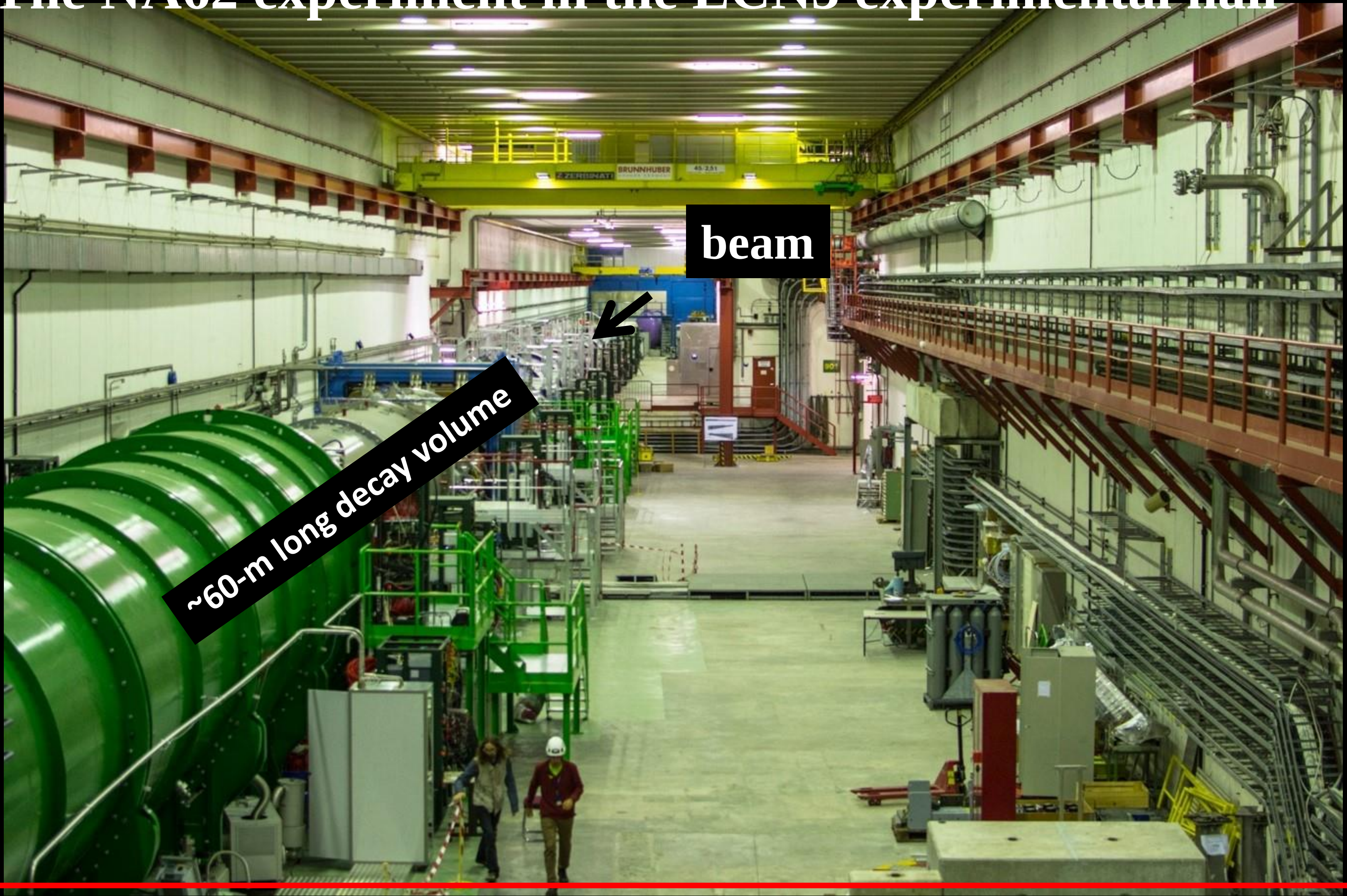
2015: 2-3 10^{19} pot delivered to the North Area.
Highest energy proton beam delivered for fixed target experiments in the world

Fixed Target Experiments @ CERN

Three experiments in the North Area will search for hidden particles in the coming years:
NA62 (running),
NA64 (running)
SHiP (proposed)

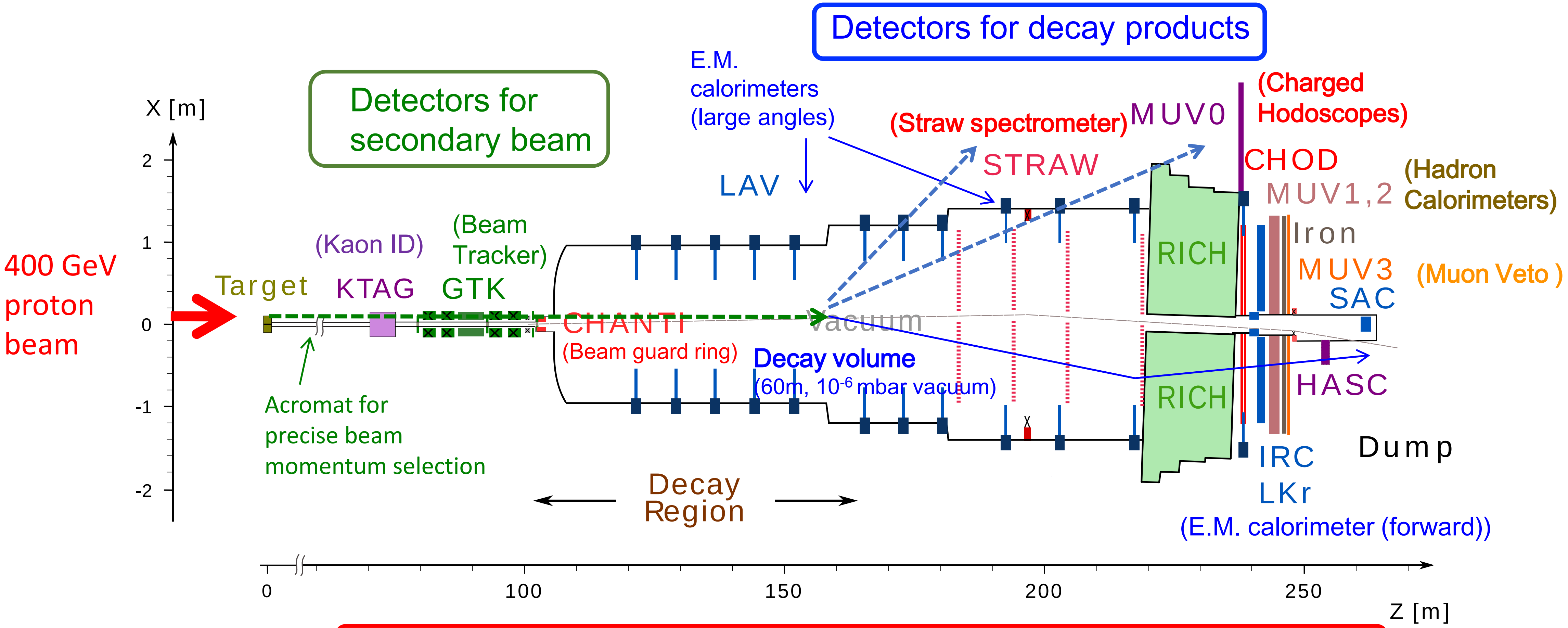


The NA62 experiment in the ECN3 experimental hall



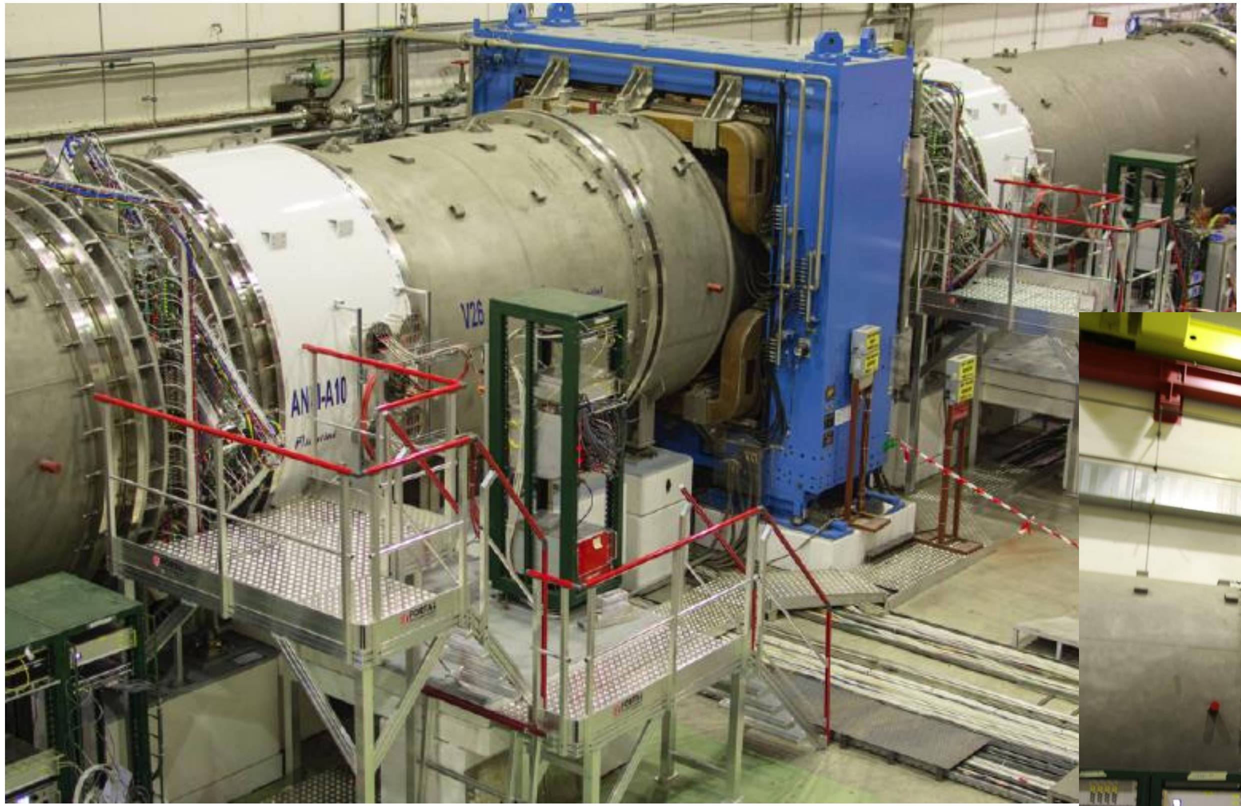
The NA62 detector, served by the P42 400 GeV proton line and designed to measure the branching fraction of the rare decay $K^+ \rightarrow \pi^+ \nu$ vbar, is perfectly suited to search for hidden particles

The NA62 experiment: conceptual scheme

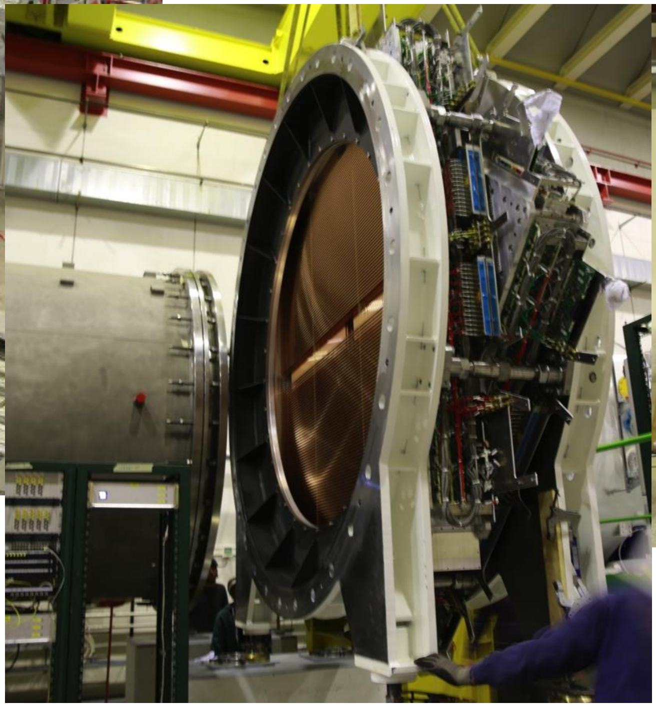


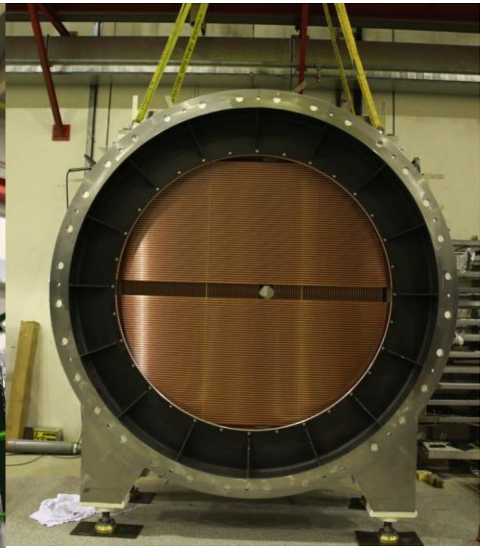
NA62 ~ (2.0-3.0)x10^{18} protons-on-target/year @ 400 GeV/c

The NA62 experiment: the real apparatus

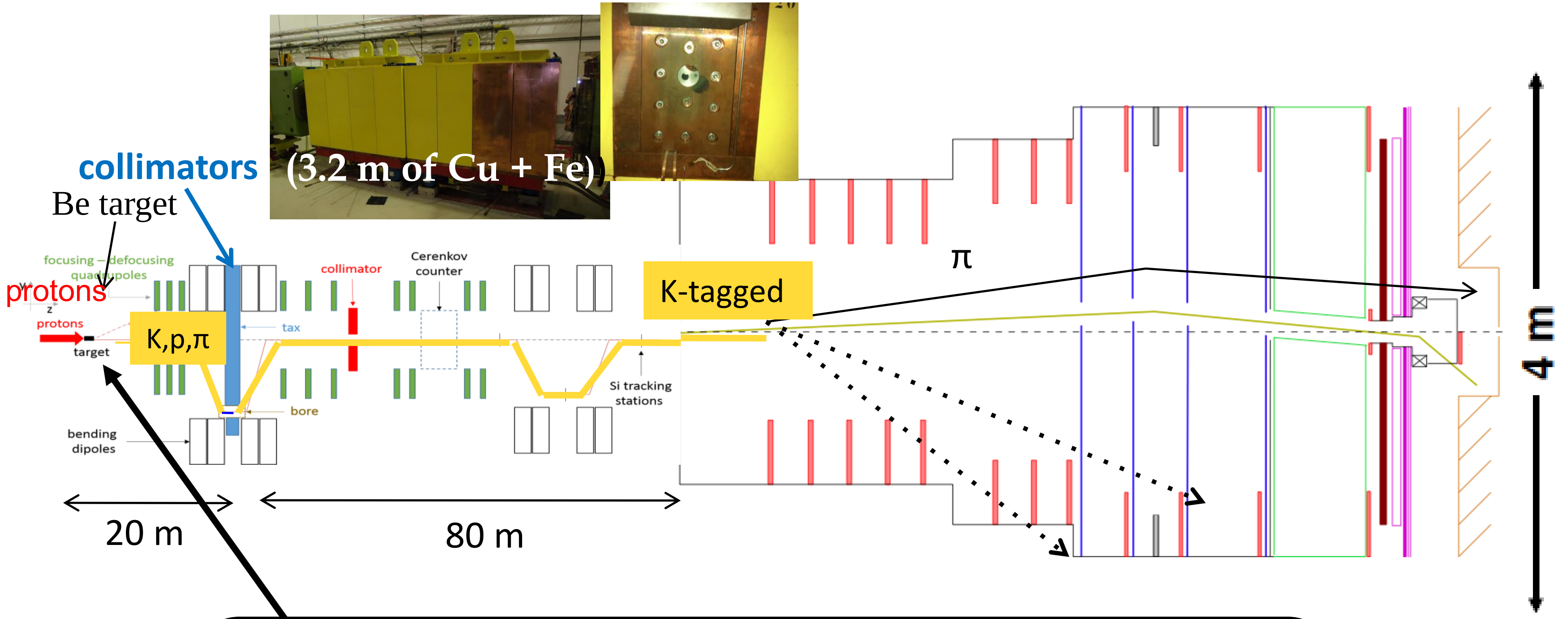


The tracking stations





NA62 in kaon (normal) operation mode

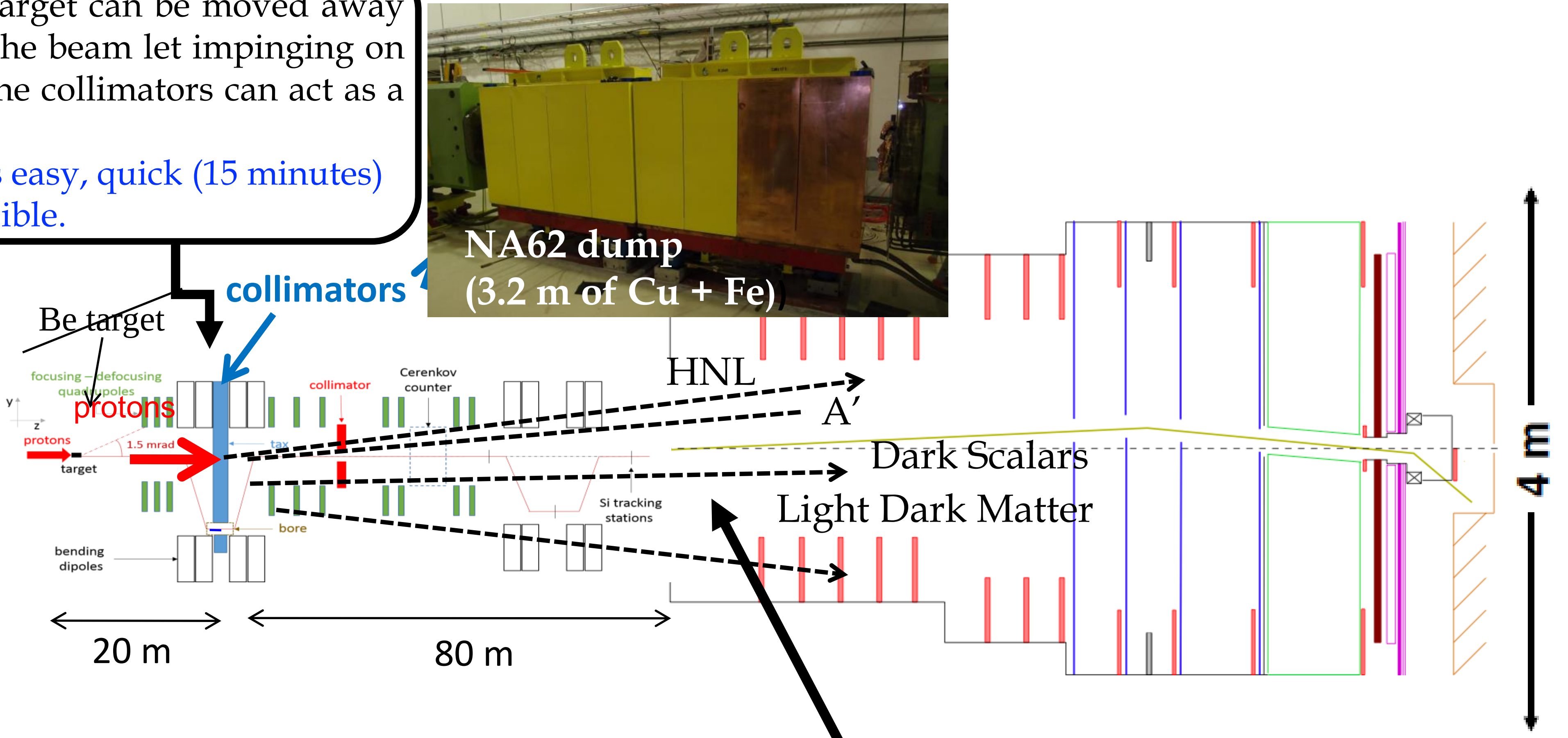


The 400 GeV/c proton beam impinges on a Be-target producing a mixed beam of K, pions, protons. A magnetic system and two 1.6-m long, water-cooled, copper collimators (TAXes) select a monochromatic beam of 75 GeV/c momentum.

NA62 in “dump” operation mode

In dump mode the target can be moved away from the beam and the beam let impinging on the copper. Hence: the collimators can act as a dump.

→ this operation is easy, quick (15 minutes) and fully reversible.



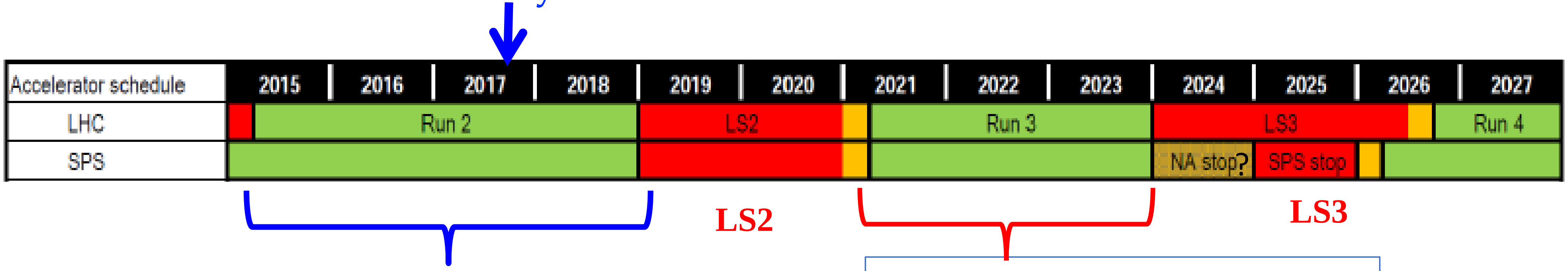
Heavy Neutrinos, Dark Photons, Dark scalars, and ALPS can be originated by charm, beauty and photons produced in the interaction of protons with the dump.

NA62 in kaon and dump modes: scientific scheduling

NA62 has the main goal of measuring the BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) with 10% accuracy;

- **Before LS2 (2017-2018)** many searches in the hidden sector will be performed using the kaon beam.
- **After LS2 (2021++)** there is a window of opportunity to run NA62 in beam-dump mode to collect at least 10^{18} pot to search for hidden particles from charm, beauty decays, and photons.

today



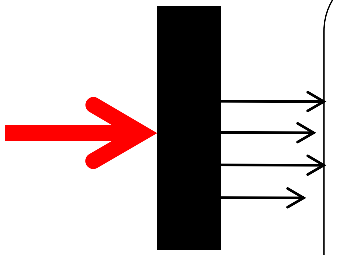
NA62: $K^+ \rightarrow \pi^+ \nu \nu$, LFV/LFU modes
Hidden sector from K decays

NA62 in dump mode and kaon physics

Goal: integrate at least ~10^{18} protons on target in dump mode by 2023
(corresponding to ~ 3 months of dedicated data taking in 2021-2023)

Production of Dark Photons via kinetic mixing

SPS protons
400 GeV/c

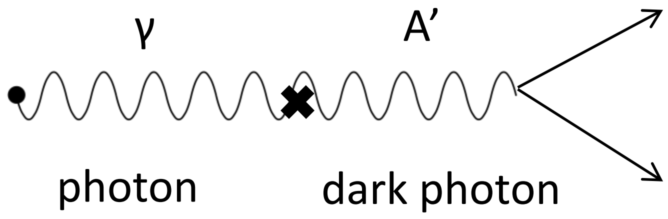


K, D, B
photons,
neutrons, protons, π
muons from K/π decays
and light resonances,
neutrinos, etc..

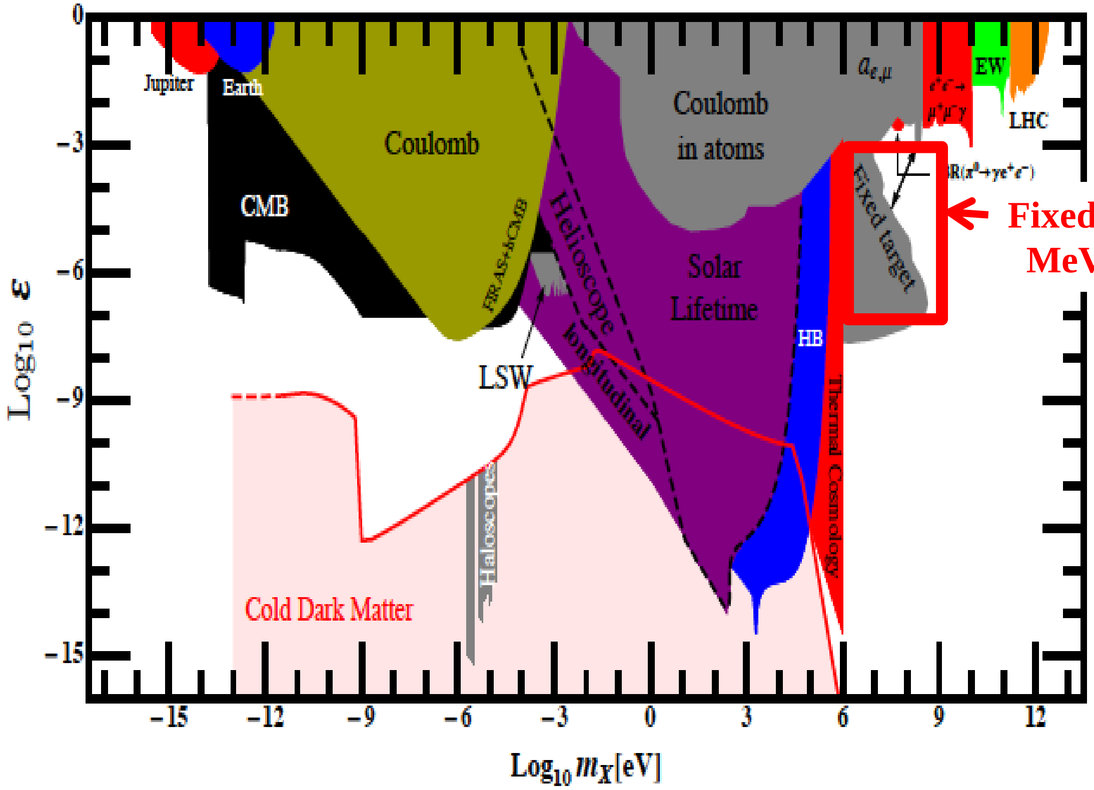
Production of Dark Photons:

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.)



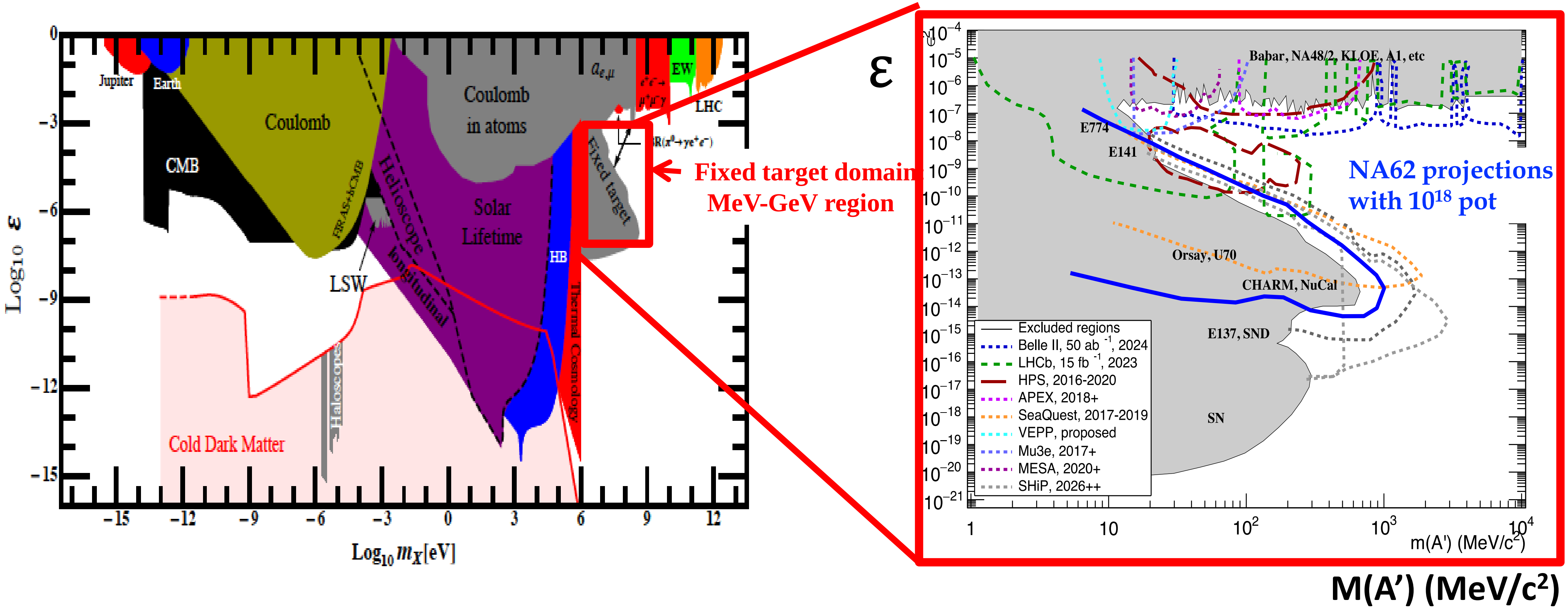
Search for Dark Photons decaying to SM particles @ NA62



Fixed target domain:
MeV-GeV region

Search for Dark Photons decaying to SM particles @ NA62

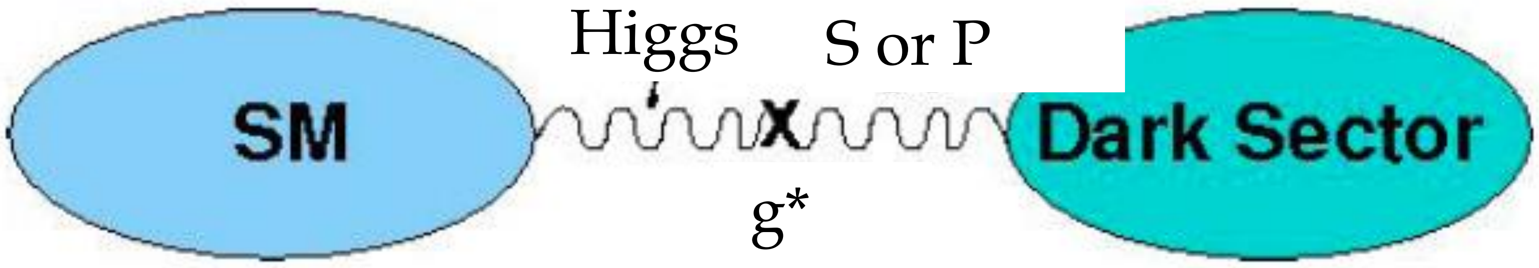
90% CL exclusion limit



A lot of experimental results expected on the Dark Photon in the near future

(Pseudo)-Scalar Portal: Dark (Pseudo)-Scalars

The discovery of the Higgs provides strong evidence that fundamental scalar bosons exist in nature:
- timely and well-motivated to search for additional scalar or pseudo-scalar particles that could be mediators of light Dark Matter



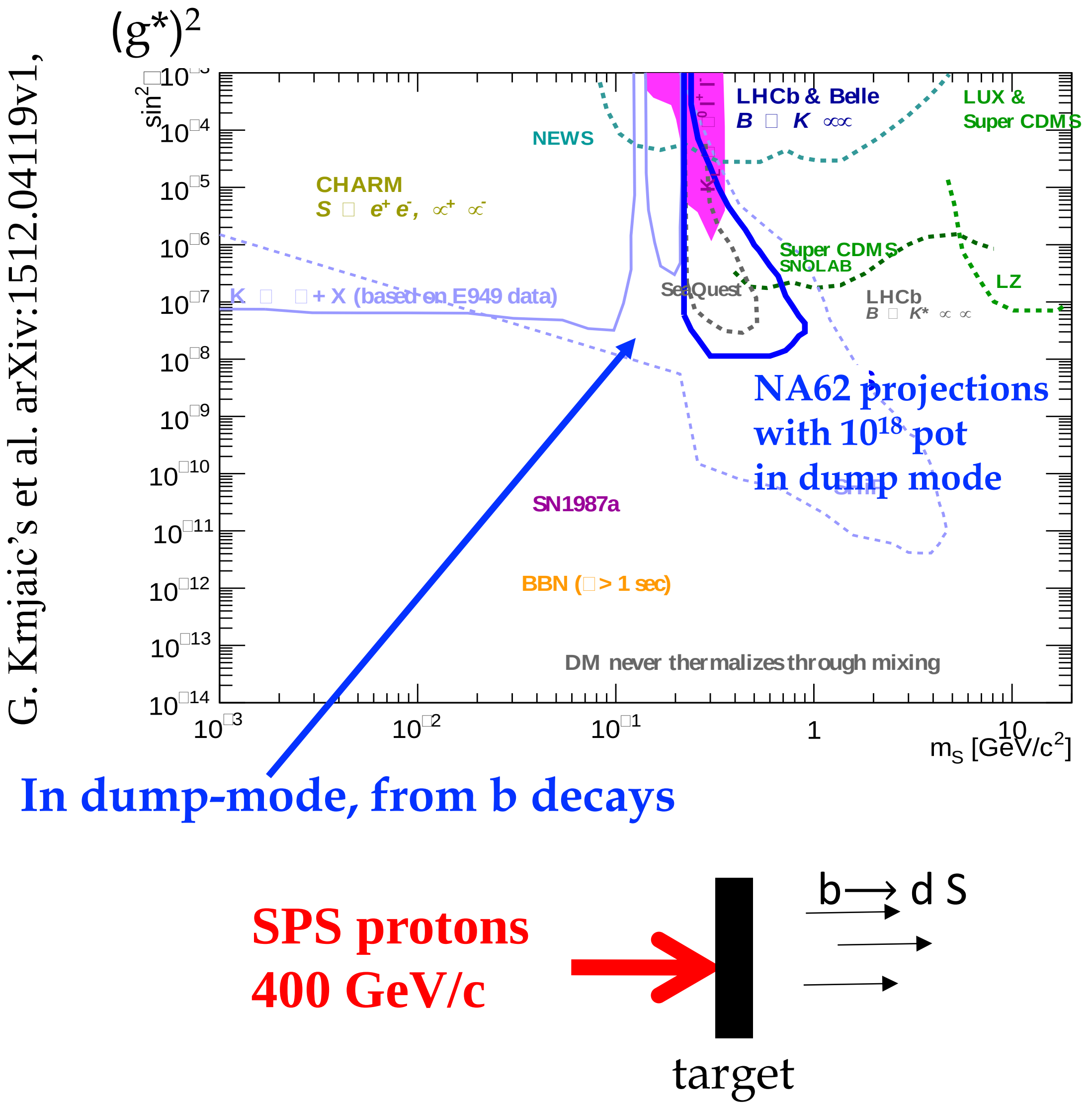
At the SPS energy we cannot produce directly the Higgs because it is too heavy, we can produce it only indirectly via decays of quarks.

At SPS energies:

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

Search for Dark (Pseudo)-Scalars: NA62 in dump and kaon mode

Secluded DM annihilation via mediators (only possibility compatible with CMB and rare mesons decays constraints), mediators then decay to SM particles



Axion and Axion-Like Particles

- **Pseudo-scalar particles can be Pseudo Nambu-Goldstone bosons of a spontaneously broken U(1) symmetry:**
  - The prime example is the axion introduced to solve the strong CP problem in QCD: m~ 10^{-5} eV
  - Other pseudo-scalar particles can feature very similarly to the axion but with larger mass: ALPS

- **Axions and ALPs can couple to: gauge bosons, fermions, gluons**

  - gauge bosons, eg: photons:

$$\mathcal{L} \supset \frac{1}{4}\, g_{a\gamma\gamma}\phi F^{\mu\nu}F_{\mu\nu}$$

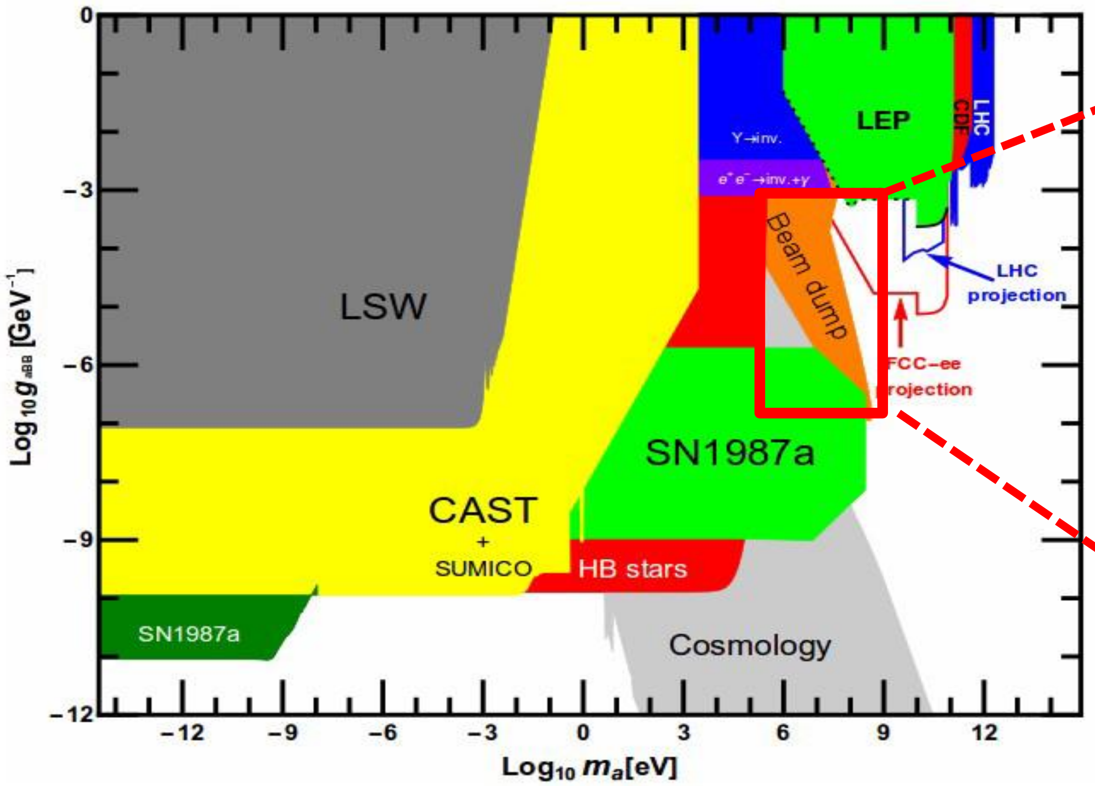
$$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f_a}$$

  - fermions:

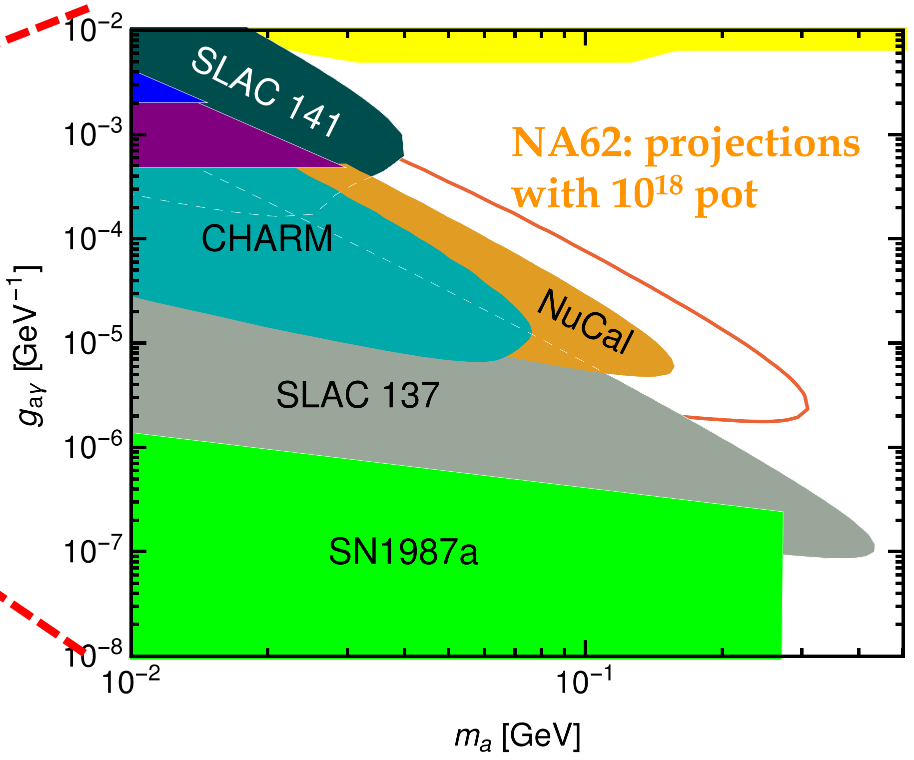
$$\mathcal{L} \supset \frac{\partial_\mu \phi}{f_a}\, \bar{\psi}\gamma^\mu\gamma^5\psi$$

- **In both cases their interactions are suppressed by a scale $1/f_a$, scale of the spontaneous symmetry breaking.**

- Search for ALPs with photon coupling @ NA62 in dump mode



ALP ⟶ γ γ



ALPS production via Primakov effect at target

See also Dobrich et al., JHEP 02 (2016) 018 for details.

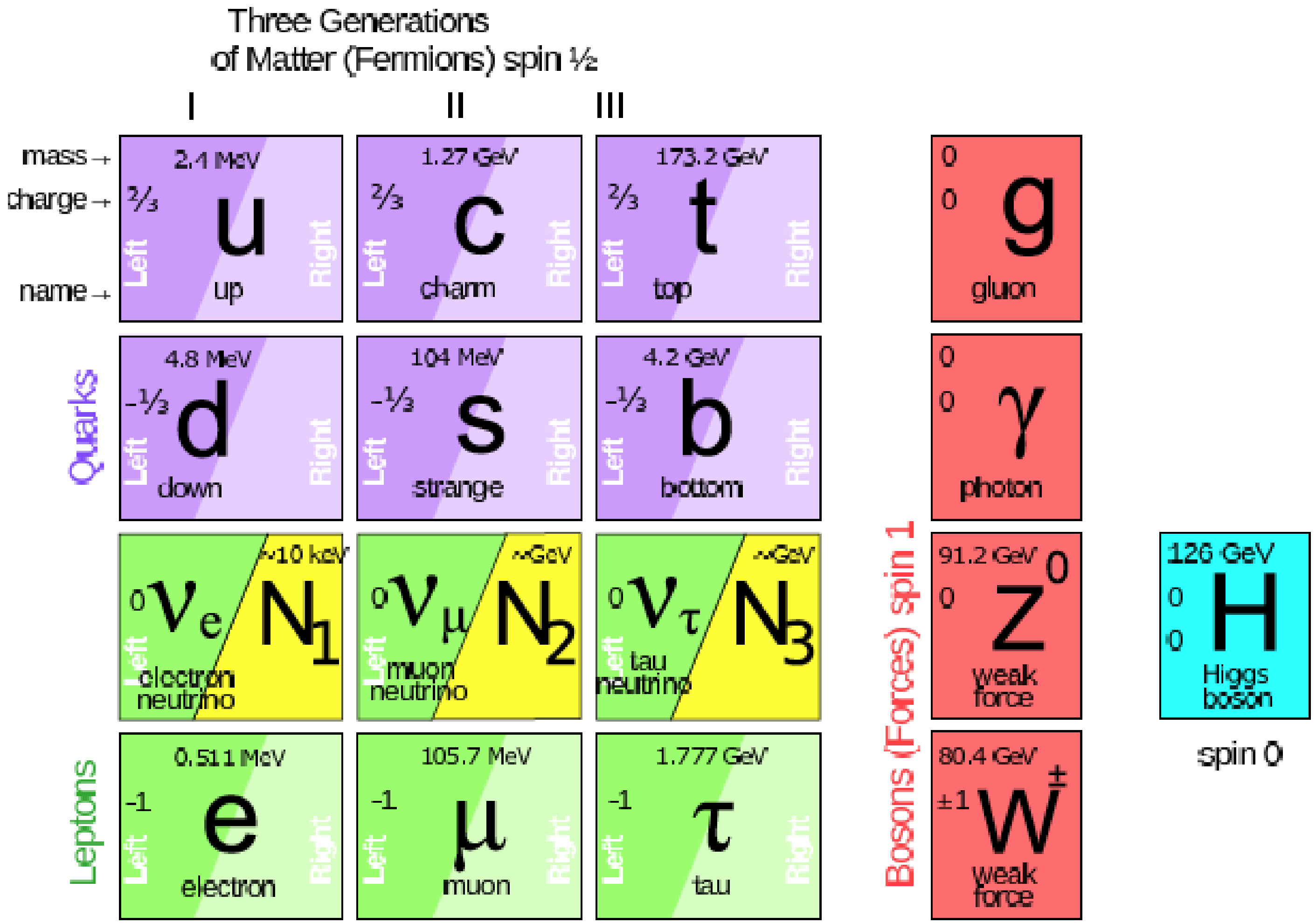
The Neutrino Portal: the νMSM

SHiP

Add three right handed neutrinos to the SM pattern

Suitable values of m_N and U_{2f} allow to simultaneously explain:

- oscillations induced by massive states N2, N3
- dark matter: N1 with mass keV
- BAU: leptogenesis due to Majorana mass term

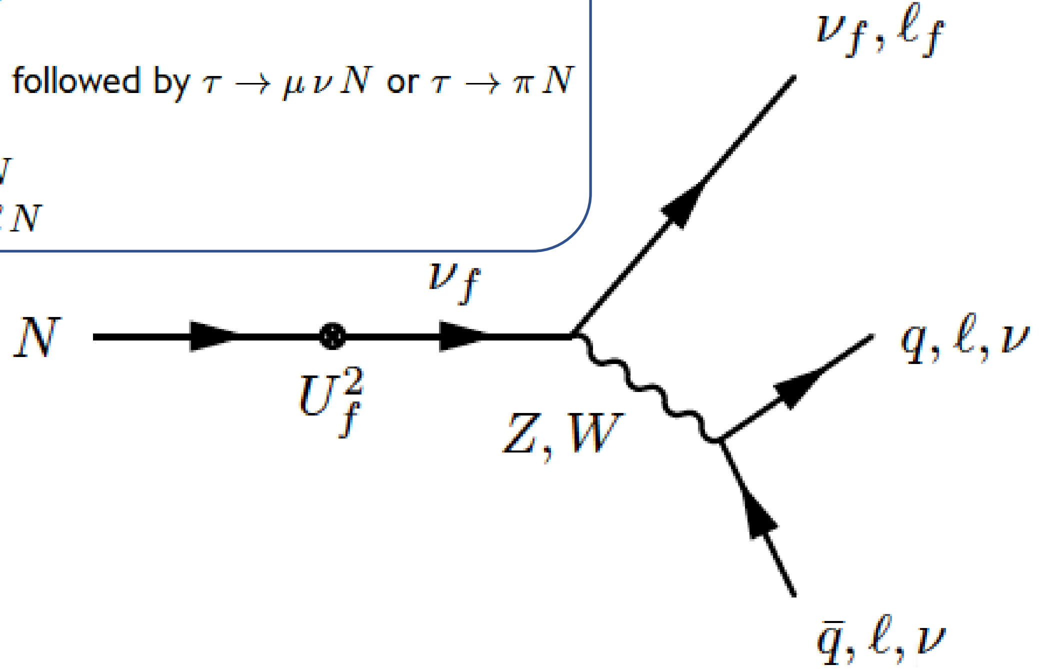


Asaka, Blanchet, Shaposhnikov, Phys.Lett. B631 (2005) 151-156

The Neutrino Portal: the νMSM

HNLs can be produced in decays where a neutrino is replaced by a N (kinetic mixing, U^2);
Main neutrino sources at fixed target: c and b mesons.

Production processes
- $D \to K \ell N$
- $D_s \to \ell N$
- $D_s \to \tau \nu_\tau$ followed by $\tau \to \mu \nu N$ or $\tau \to \pi N$
- $B \to \ell N$
- $B \to D \ell N$
- $B_s \to D_s \ell N$



Decay channels

$N \to H^0 \nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$

$N \to H^\pm \ell^\mp$, with $H = \pi, \rho$

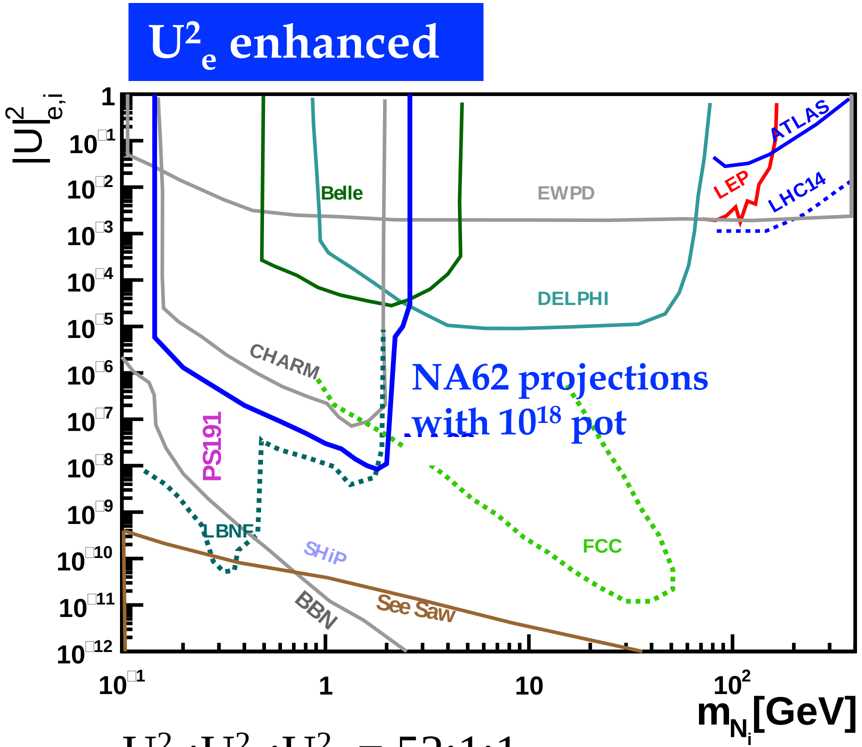
$N \to 3\nu$

$N \to \ell_i^\pm \ell_j^\mp \nu_j$

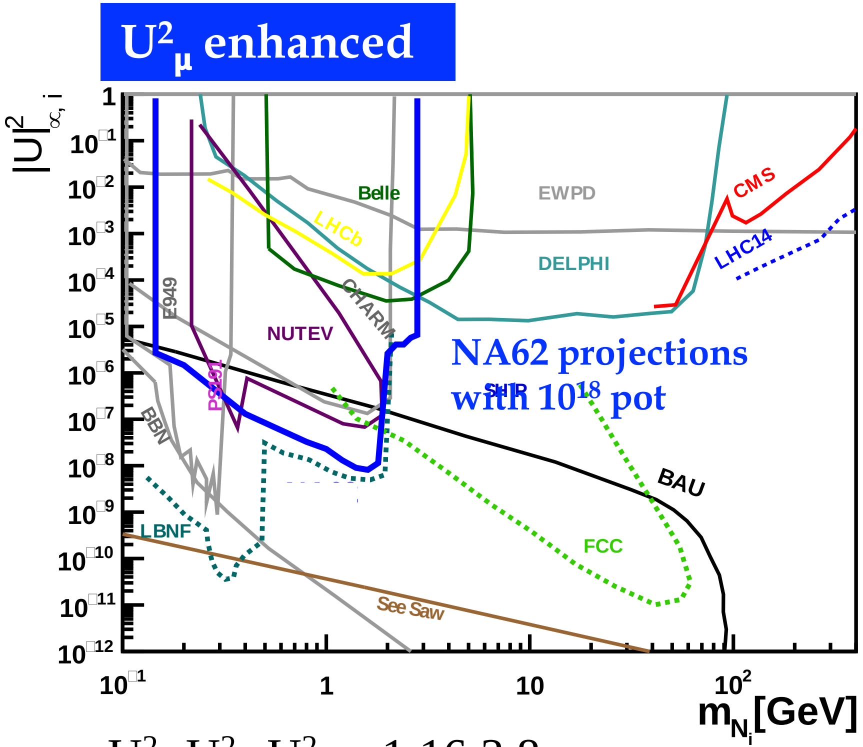
$N \to \nu_i \ell_j^\pm \ell_j^\mp$

They can then decay again to SM particles through mixing (U^2) with a SM neutrino. This (now massive) neutrino can decay to a large amount of final states through emission of a Z^0 or W boson

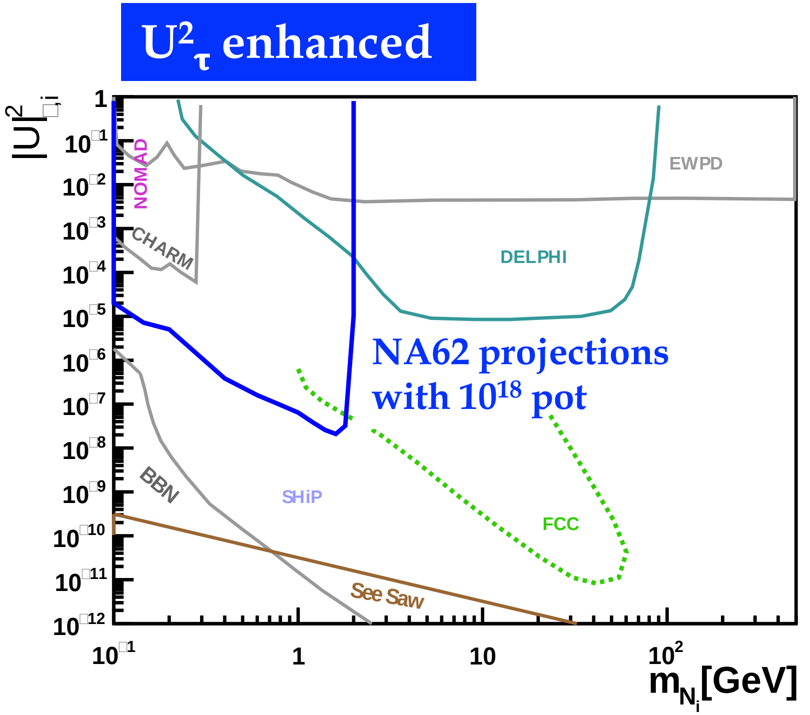
Search for Heavy Neutral Leptons @ NA62 in dump-mode



$U^2_e:U^2_\mu:U^2_\tau = 52:1:1$
Normal hierarchy of active **ν** masses



$U^2_e:U^2_\mu:U^2_\tau = 1:16:3.8$
Normal hierarchy of active **ν** masses

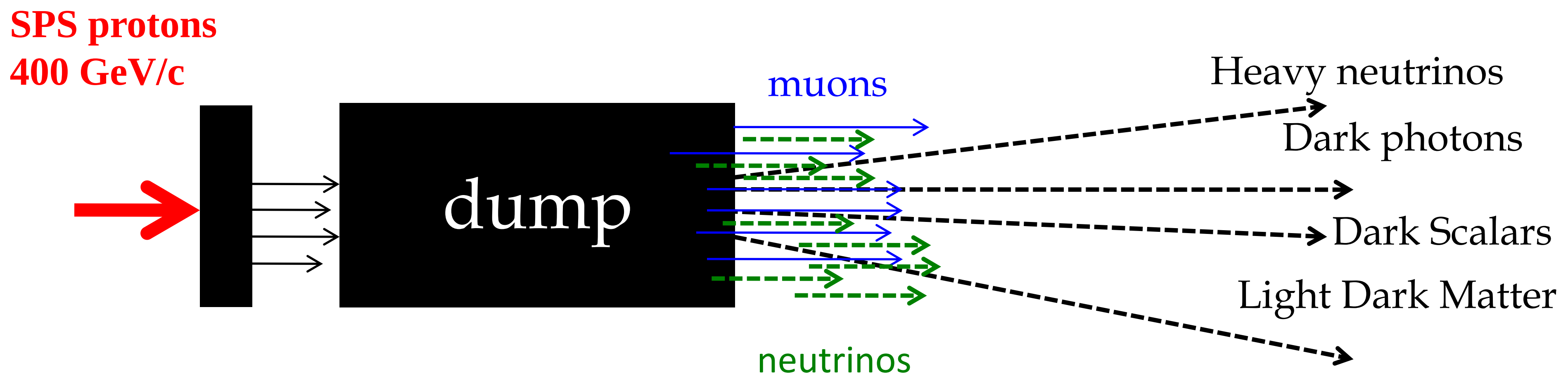


$U^2_e:U^2_\mu:U^2_\tau = 0.061:1:4.3$
Normal hierarchy of active **ν** masses

These sensitivities assume to detect all 2-track final states, including open channels, and **zero background.**

….Background, background, background…..

A dump with suitable length stops all beam-induced backgrounds but neutrinos and muons:



Any kind of feebly-interacting long-lived particle or LDM (put here your favored model);

Background is the name of the game !

NA62-DUMP: data driven background estimate

In November 2016, few hours long run taken in dump mode, 2×10^{15} pot collected for ALPs search and in preparation for the longer physics runs in dump mode in 2021-2023:

- This small dataset already provides crucial information on the background level;
- More data in short runs have been collected in 2017 and will be collected in 2018.

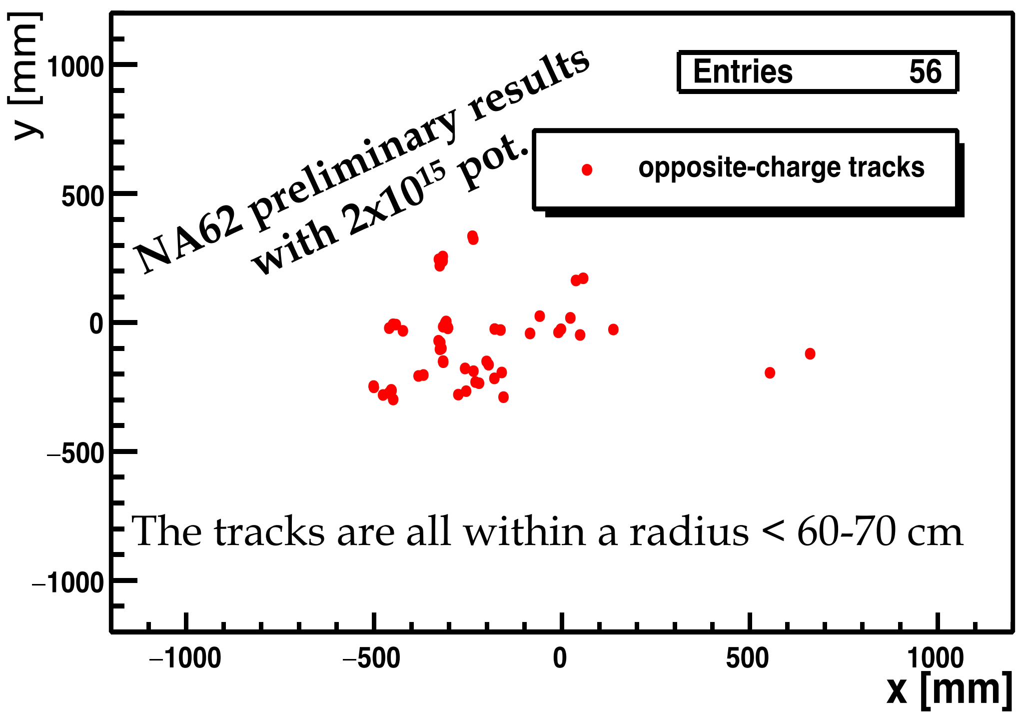
Very simple selection applied to search for generic 2-track final states:

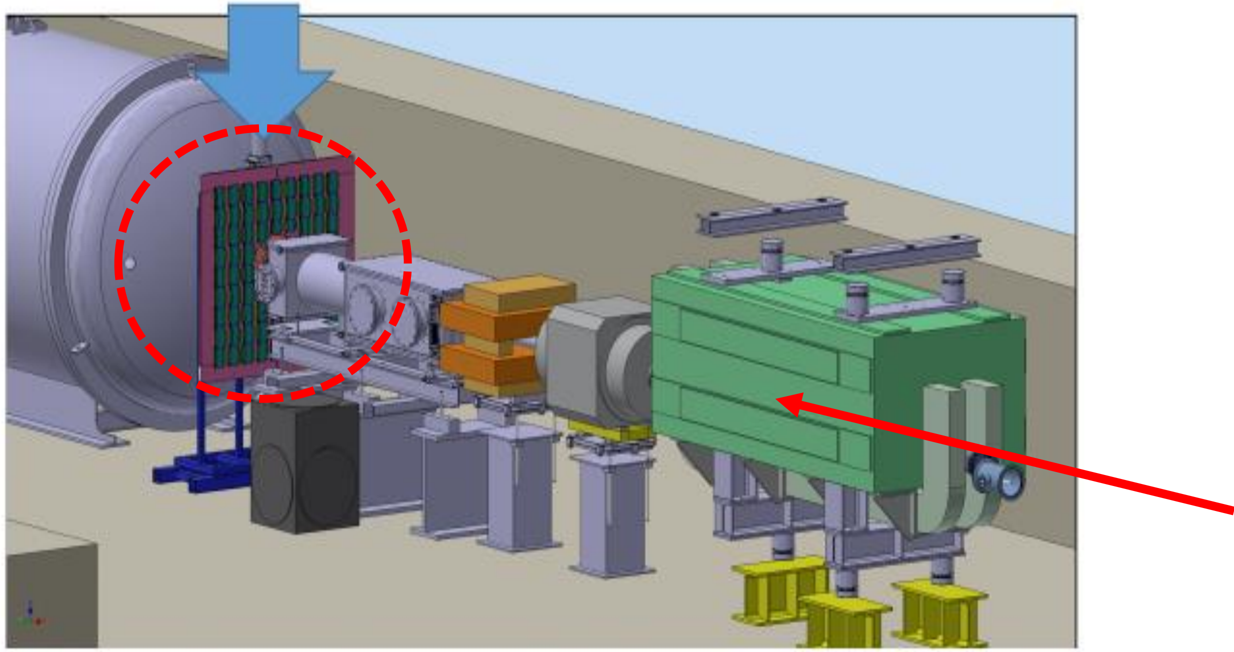
- Good quality tracks and 2-track vertices
- No further activity in time with the 2-track candidates
- Particle Identification information
- Isolation of the vertex: no further track close to the selected vertices.

Results: no background left for fully reconstructed final states pointing backwards to the dump, O(20) events left for partially reconstructed final states.

NA62-DUMP: residual background in dump mode

Extrapolation of the 2-tracks of the remaining o(20) events at the beginning of the decay vessel:
⟶ they are all concentrated either in the "empty" zone not covered by any detector in NA62

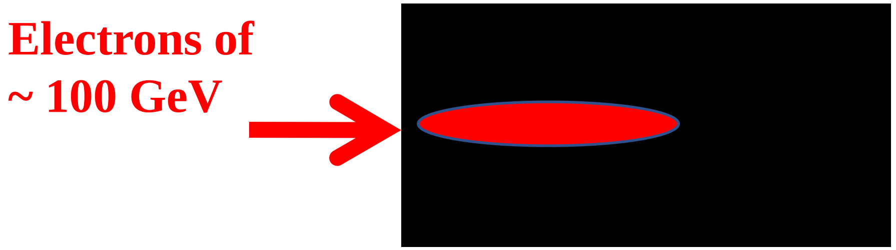




Adding a new detector in front of the decay vessel
(missing in the current setup) the background can be reduced (almost) to zero

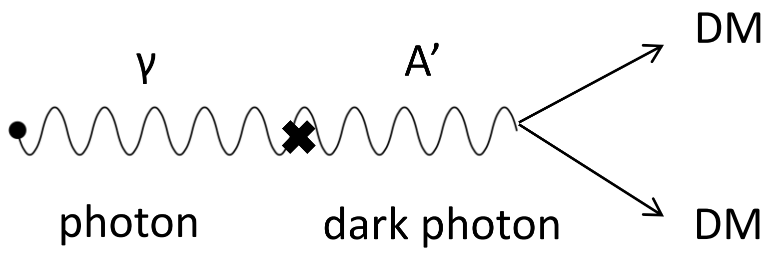
Production of Dark Photons via kinetic mixing

Active dump



:Eg: Production of Dark Photons

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



Any discrepancy between the energy of the electron measured before and in the active dump would be sign of the production of some non-interacting particles, as for example Dark Matter

Fixed Target Experiments @ CERN: NA64

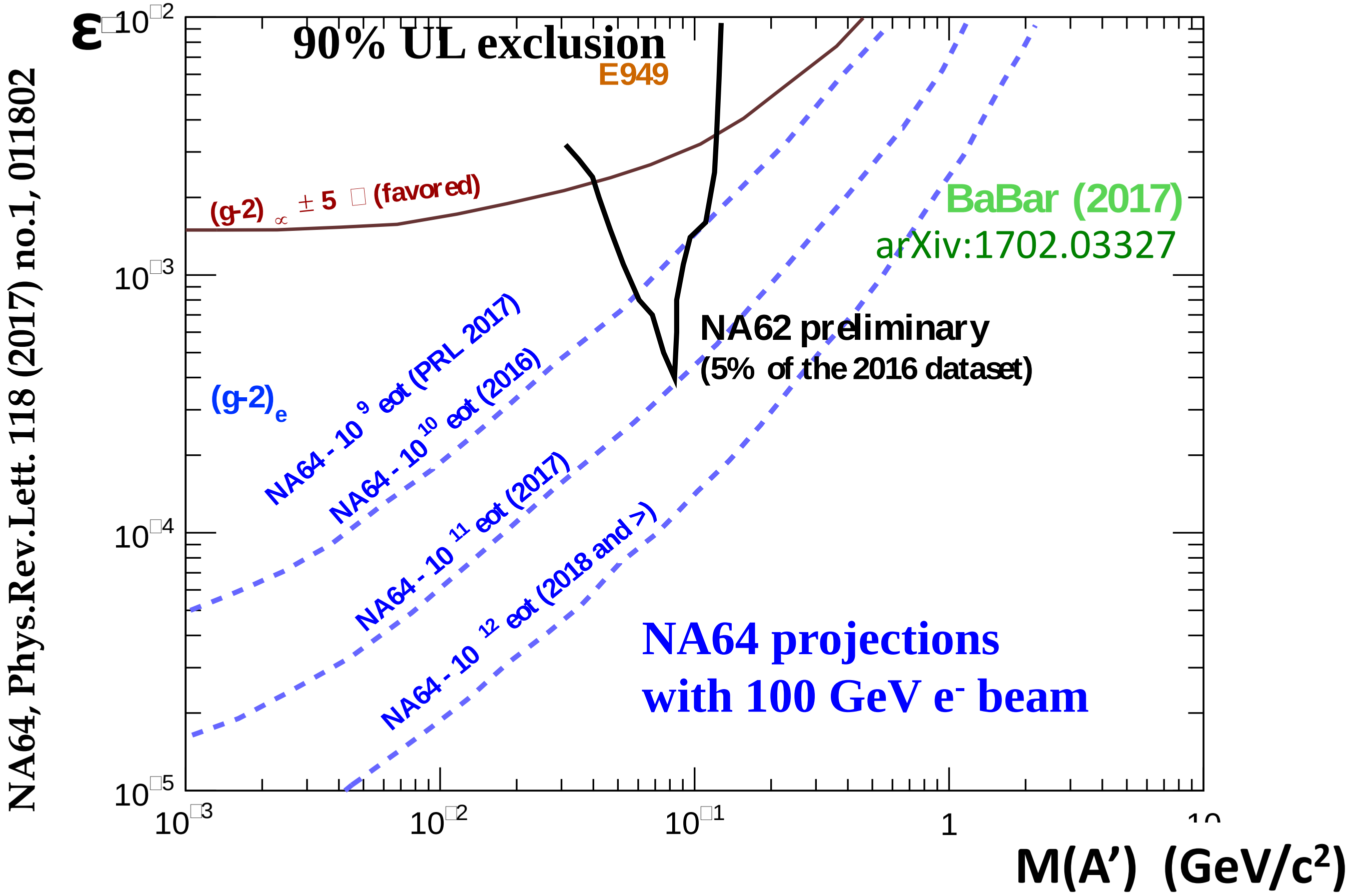
Approved in March'16 for dark photon to invisible searches with 100 GeV e^- beam; electron beam dump, search for missing energy.

Current status: running

https://na64.web.cern.ch/

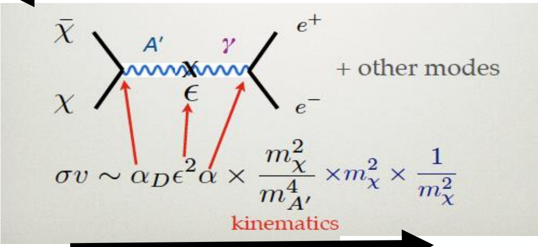
Dark Photons in invisible modes: NA64 current and future sensitivities

Searches for A’ ⟶ Light Dark Matter (invisible states)



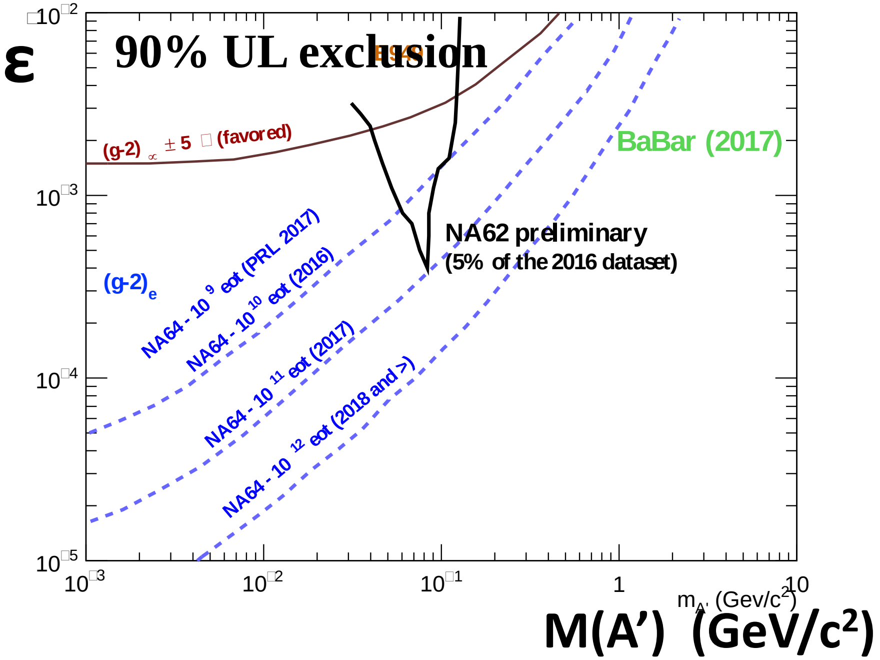
Dark Photons in invisible modes: beam dump vs direct searches

Beam dump

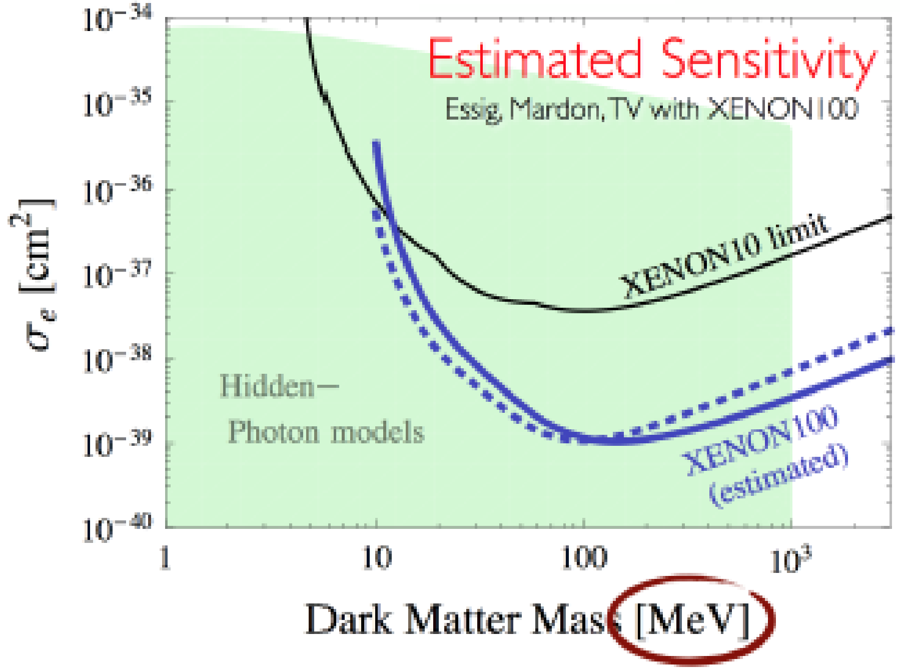


Direct searches

Beam dump



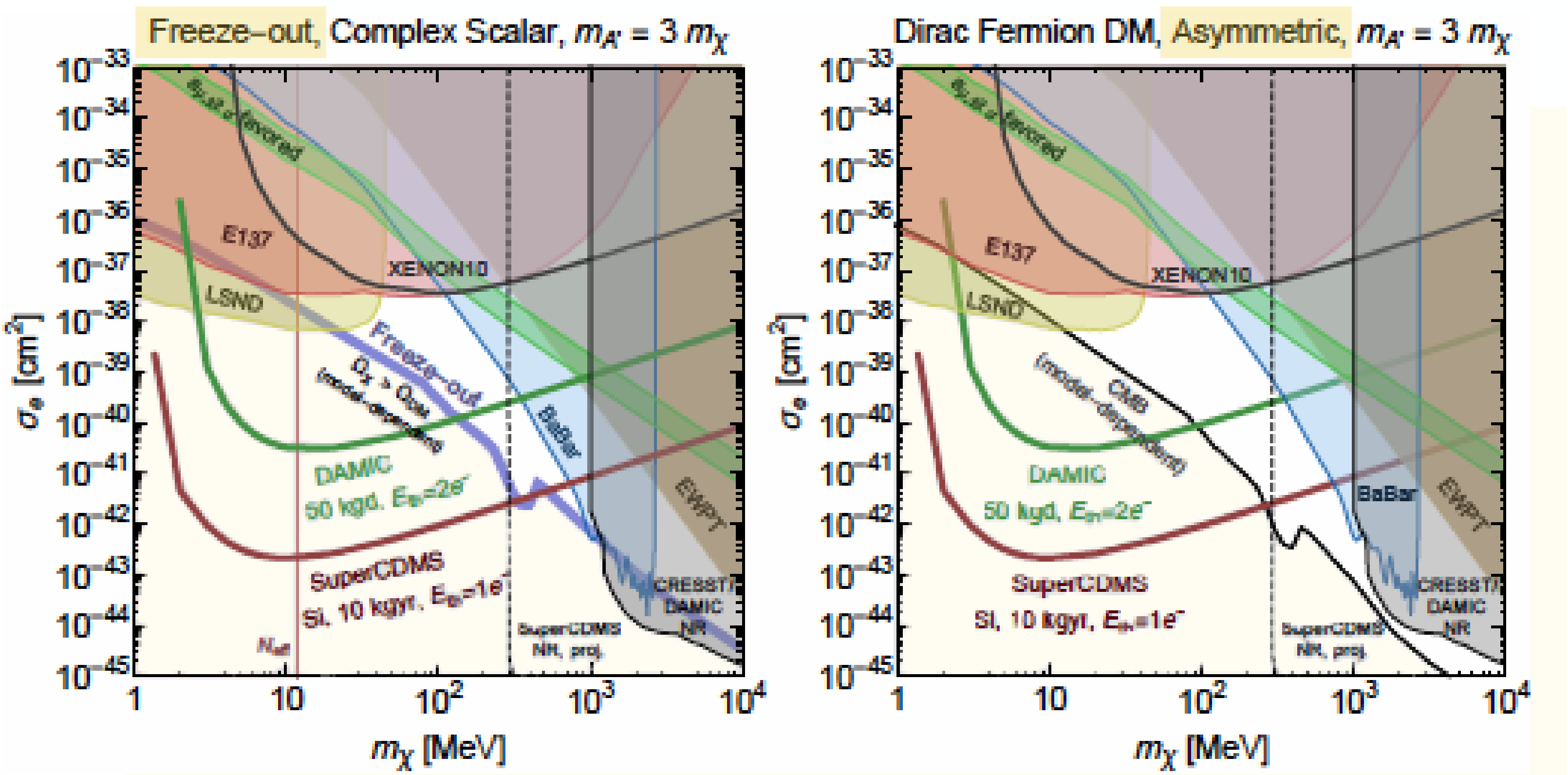
Direct searches



$\sigma_e = 16\,\pi\,\alpha\,\alpha_D\,\varepsilon^2\, m^2_{reduced}/(m^4_{A'})$

with: $m_{reduced} = m_e{*}m_{DM}/(m_e+m_{DM})$

Dark Photons in invisible modes: beam dump vs direct searches



[Essig, Fernandez-Serra, Mardon, Soto, TV, Yu, 2015 (upcoming)]

Presented by
T. Volyansky
at EPS 2015

For specific models, direct DM searches and beam-dump results can be directly comp

Perspectives for searches for Hidden Sector particles:

From CHARM, NuTeV (1980++)….

Perspectives for searches for Hidden Sector particles:

…to NA62, NA64 (now)…

From CHARM, NuTeV (1980++)….

Perspectives for searches for Hidden Sector particles:

…. to next generation's experiments
(SHiP/LBNF, 2026++)

…to NA62, NA64 (now)…

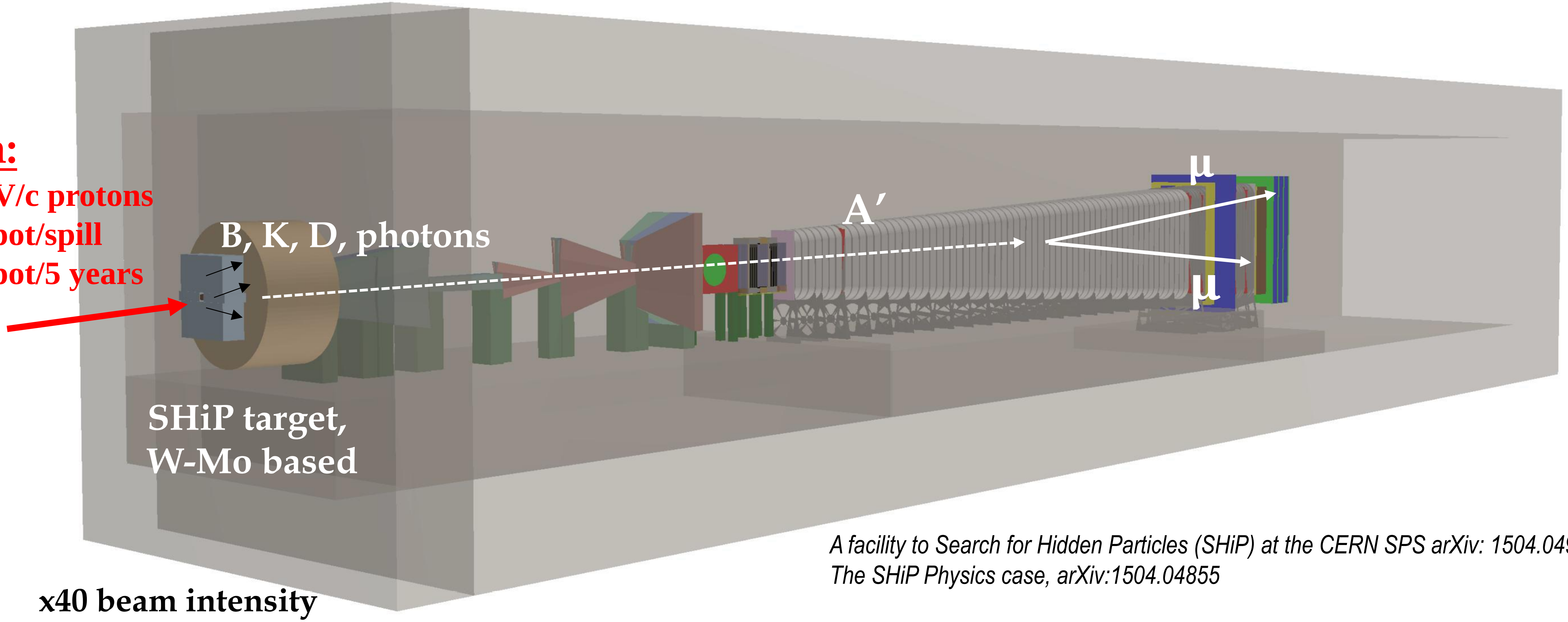
From CHARM, NuTeV (1980++)….

The SHiP project: a dedicated experiment to Search for Hidden Particles

(one of the projects proposed for the next European Strategy for Particle Physics in 2019-2020)

Beam:

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

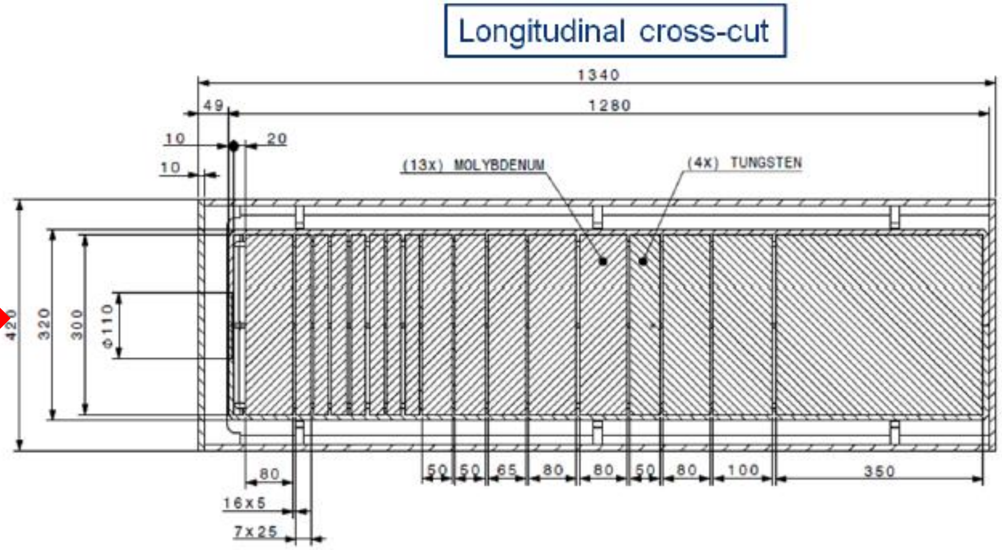


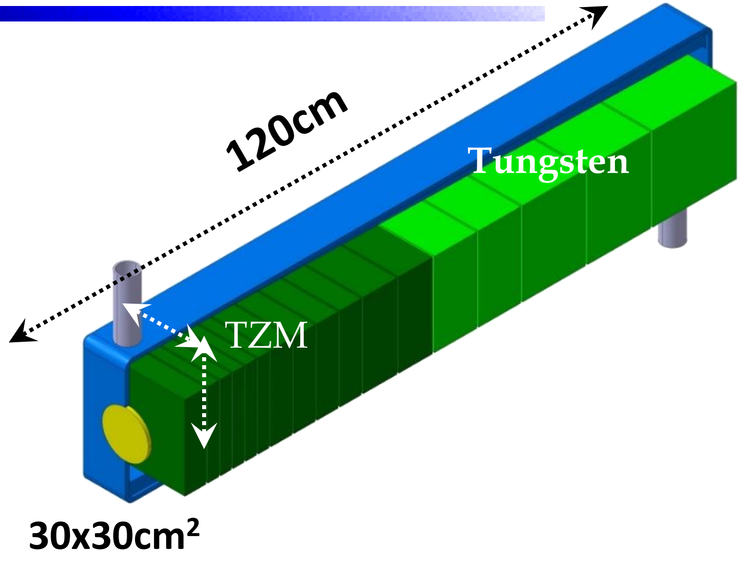
A facility to Search for Hidden Particles (SHiP) at the CERN SPS arXiv: 1504.04956
The SHiP Physics case, arXiv:1504.04855

x40 beam intensity
x15 larger acceptance
Optimized for hidden sector physics

The SHiP target:

Proton beam
400 GeV/c





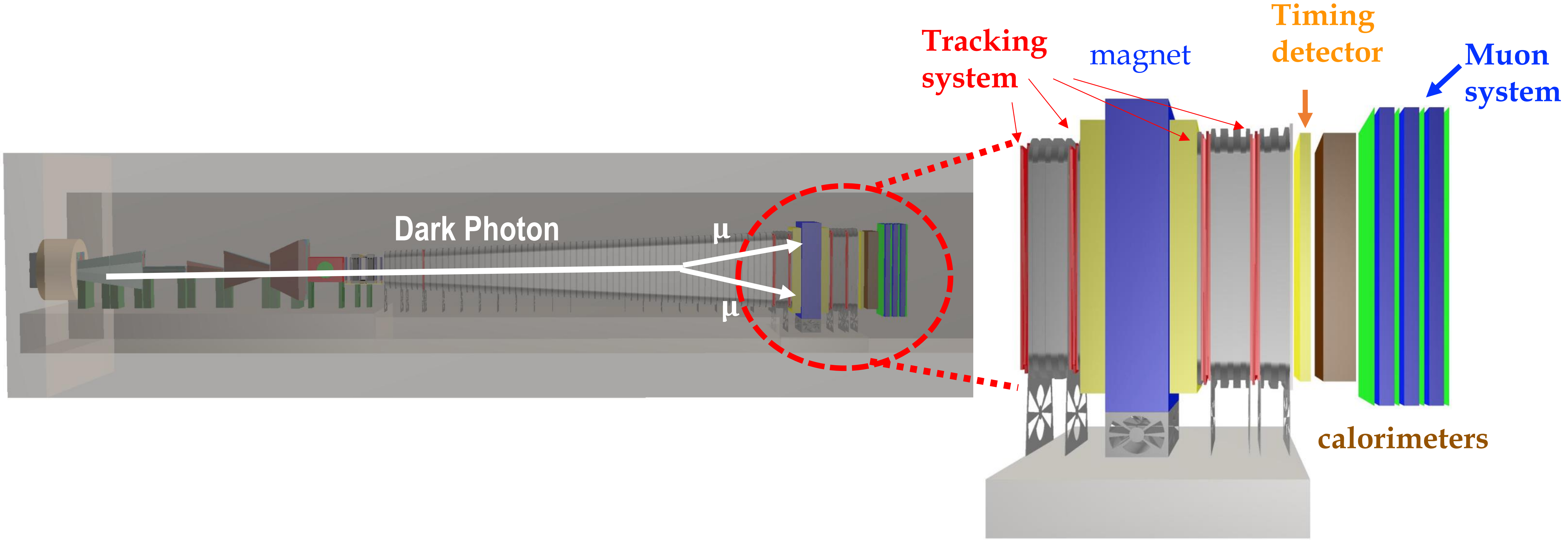
- 10 nuclear interaction lengths long production target (~ 120 cm)
- High-Z target, hybrid solution composed of TZM (Molybdenum alloy) & pure W
  - 30x30 cm^2, segmented target
  - 58 cm TZM (13 layers) + 58 cm W (4 layers)

SHiP target configuration: main parameters

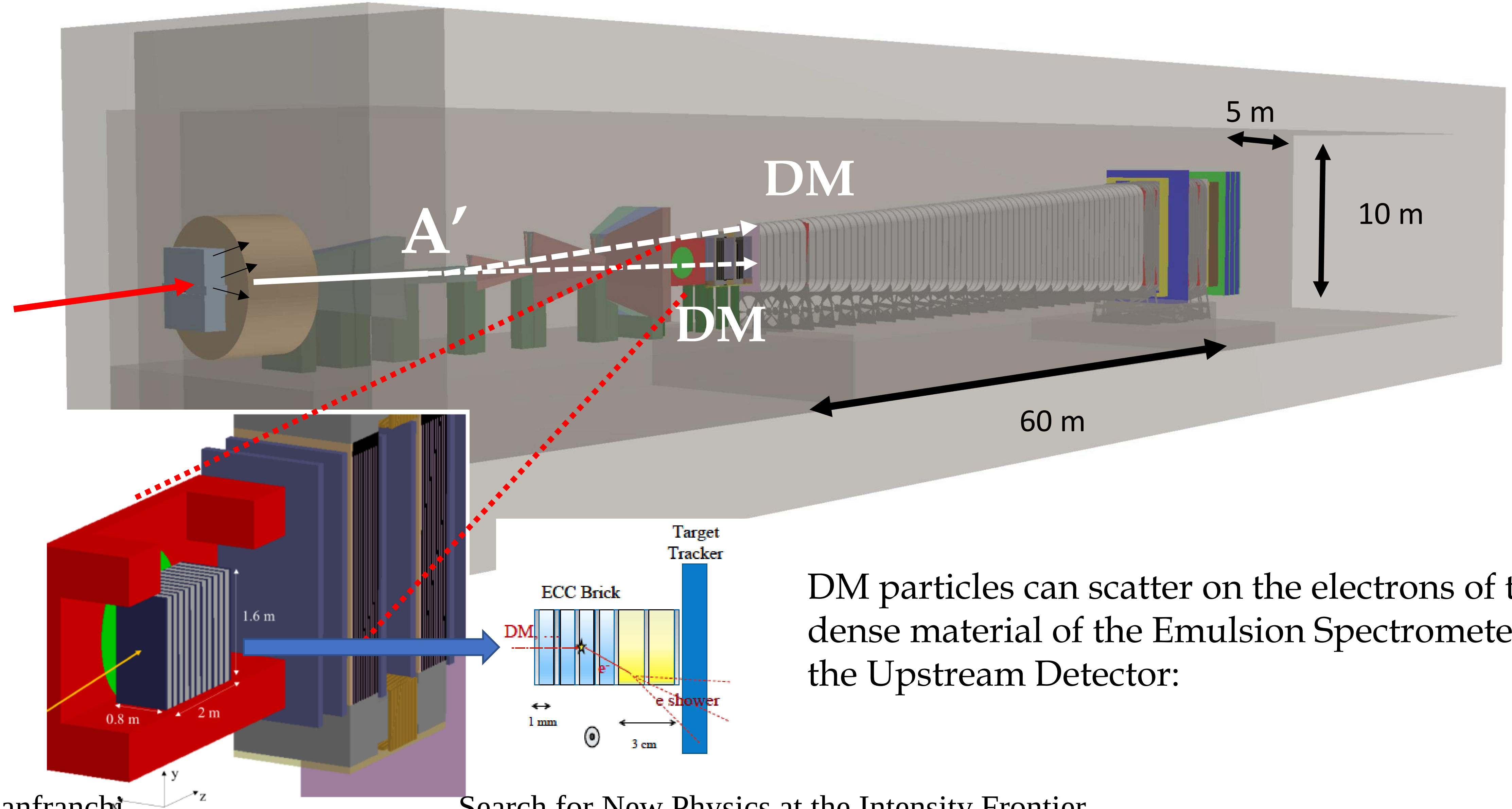
- SHiP target is a high pulse intensity "spallation" target
- 90% of the beam energy (**2.56 MJ**) is deposited in the target
  - SC-averaged beam power (**355 kW**) similar to SNS and JSNS
  - Pulse-averaged power is similar to ESS (**2.6 MW**), but more challenging due to high intensity pulse

	Baseline
Beam	protons
Momentum [GeV/c]	400
Beam Intensity [10^{13} p/cycle]	4.0
Magnetic cycle length [s]	7.2
Spill duration [s]	1.0
Expected r.m.s. spot size (H/V) [mm]	6/6
Average beam power on target (deposited) [kW]	**355 (320)**
Average beam power on target during spill (deposited) [kW]	**2560 (2300)**

SHiP: detection of decay products of hidden mediators

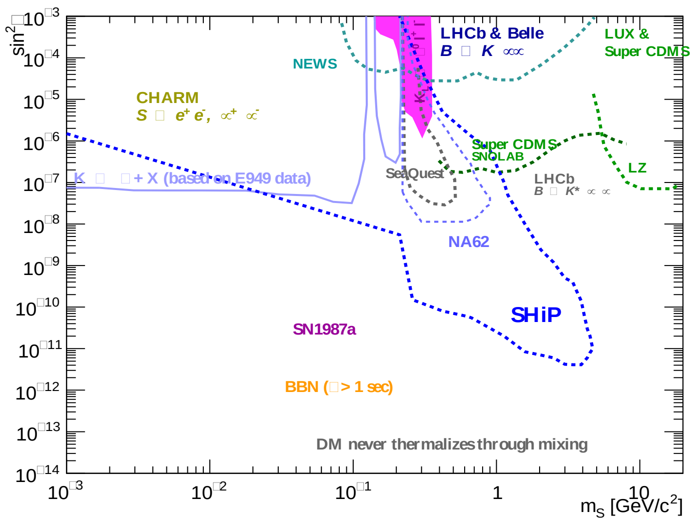


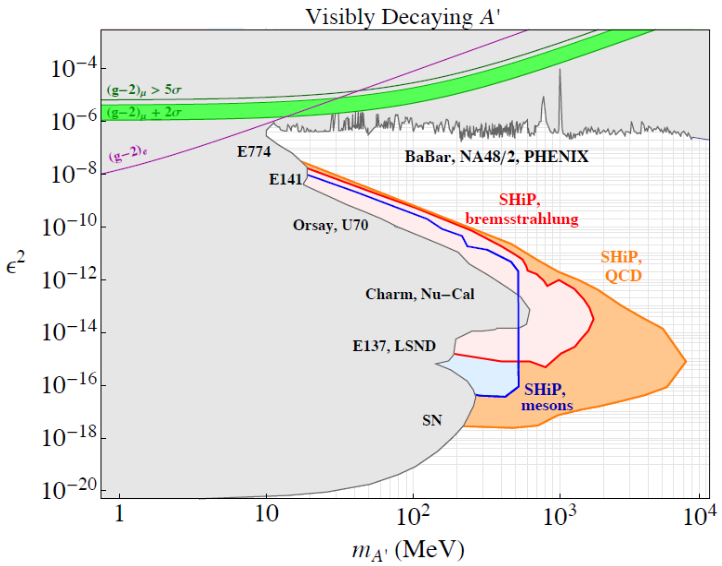
SHiP: Light Dark Matter direct detection

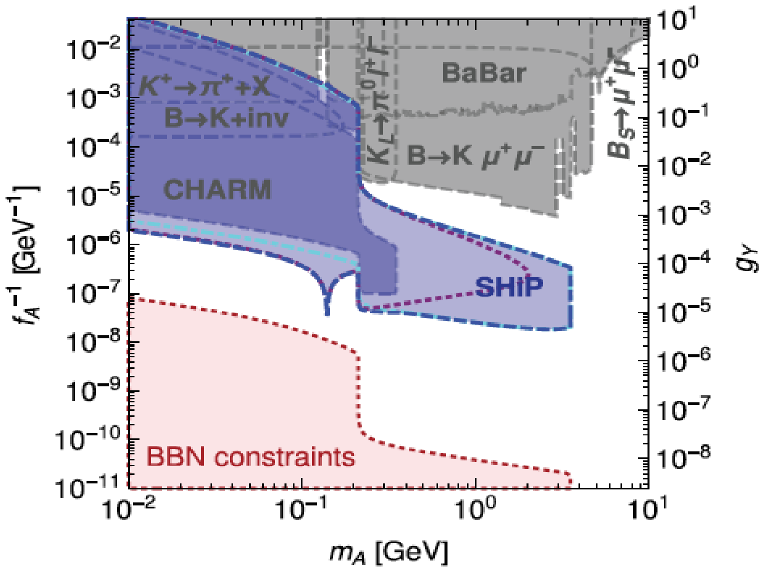


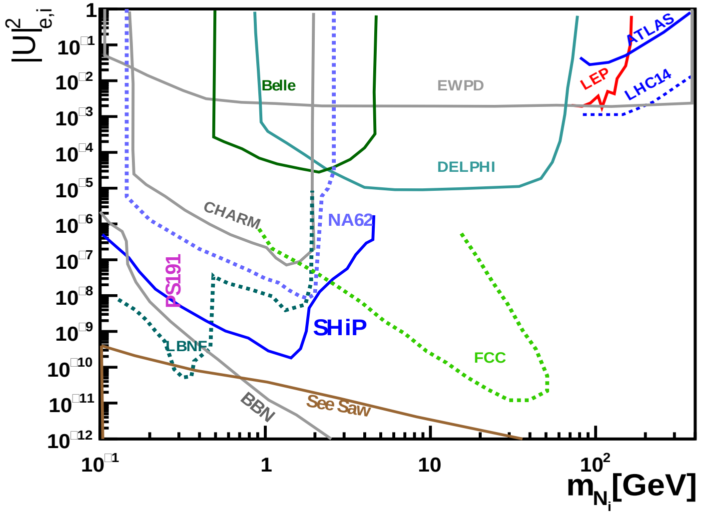
DM particles can scatter on the electrons of the dense material of the Emulsion Spectrometer in the Upstream Detector:

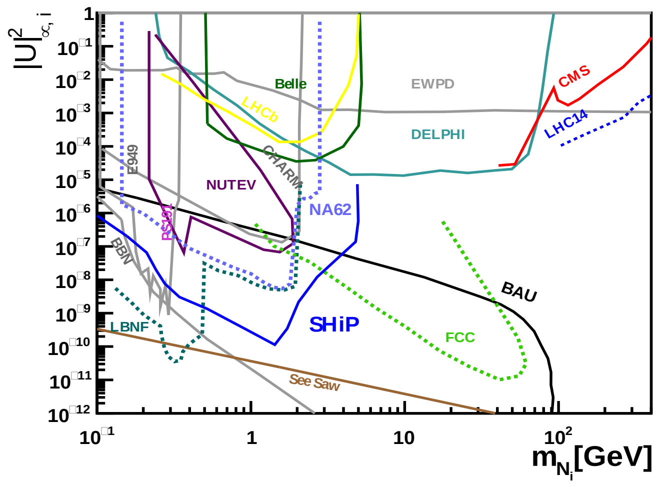
(a taste of the) SHiP Physics Reach

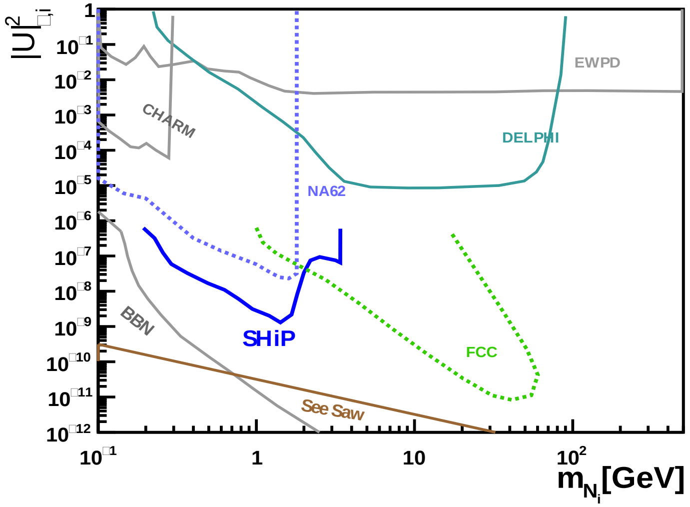












Physics Beyond Colliders: A new initiative at CERN

http://pbc.web.cern.ch/

Projects discussed in this framework:
NA62 in dump mode, **NA64** (electron dump),
SHiP (proton dump), and others
(IAXO, ALPS-II, proton and deuteron EDM, etc.)

Organization **PBC@work** **Resources**

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. The mandate of the study team may be found here.

Using the LHC to Search for Hidden Particles

Three new proposals in the last 12 months to search for hidden particles using the high-intensity flux of and photons produced in some of the LHC interaction points.

CODEX-b @ LHCb

arXiv:1708.09395v1 [hep-ph] 30 Aug 2017

Searching for Long-lived Particles: A Compact Detector for Exotics at LHCb

Vladimir V. Gligorov,[1] Simon Knapen,[2,3] Michele Papucci,[2,3] and Dean J. Robinson[4]

[1] LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France
[2] Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA
[3] Department of Physics, University of California, Berkeley, CA 94720, USA
[4] Physics Department, University of Cincinnati, Cincinnati OH 45221, USA

We advocate for the construction of a new detector element at the LHCb experiment, designed to search for displaced decays of beyond standard model long-lived particles, taking advantage of a large shielded space in the LHCb cavern that is expected to soon become available. We discuss the general features and putative capabilities of such an experiment, as well as its various advantages and complementarities with respect to other detectors and searches. For two well-motivated benchmark beyond standard model theories – Higgs decay to dark photons and B meson decays via a Higgs mixing portal – the reach either complements or exceeds that predicted for other LHC experiments.

I. INTRODUCTION

FASER @ ATLAS

UCI-TR-2017-08

arXiv:1708.09389v1 [hep-ph] 30 Aug 2017

FASER: ForwArd Search ExpeRiment at the LHC

Jonathan Feng,[1,*] Iftah Galon,[1,†] Felix Kling,[1,‡] and Sebastian Trojanowski[1,2,§]

[1] Department of Physics and Astronomy, University of California, Irvine, CA 92697-4575 USA
[2] National Centre for Nuclear Research, Hoża 69, 00-681 Warsaw, Poland

Abstract

New physics has traditionally been expected in the high-p_T region at high-energy collider experiments. If new particles are light and weakly-coupled, however, this focus may be completely misguided: light particles are typically highly concentrated within a few mrad of the beam line, allowing sensitive searches with small detectors, and even extremely weakly-coupled particles may be produced in large numbers there. We propose a new experiment, ForwArd Search ExpeRiment, or FASER, which would be placed downstream of the ATLAS or CMS interaction point (IP) in the very forward region and operated concurrently there. Two representative on-axis locations are studied: a far location, 400 m from the IP and just off the beam tunnel, and a near location, just 150 m from the IP and right behind the TAN neutral particle absorber. For each location, we examine leading neutrino- and beam-induced backgrounds. As a concrete example of light, weakly-coupled particles, we consider dark photons produced through light meson decay and proton bremsstrahlung. We find that even a relatively small and inexpensive cylindrical detector, with a radius of $\sim$ 10 cm and length of 5 – 10 m, depending on the location, can discover dark photons in a large and unprobed region of parameter space with dark photon mass $m_{A'} \sim$ 10 – 500 MeV and kinetic mixing parameter $\epsilon \sim 10^{-6} - 10^{-3}$. FASER will clearly also be sensitive to many other forms of new physics. We conclude with a discussion of topics for further study that will be essential for understanding FASER's feasibility, optimizing its design, and realizing its discovery potential.

MATHUSLA @ surface (top of ATLAS)

Physics Letters B 767 (2017) 29–36

Contents lists available at ScienceDirect

Physics Letters B

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ELSEVIER

New detectors to explore the lifetime frontier

John Paul Chou[a], David Curtin[b,*], H.J. Lubatti[c]

[a] Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08854, USA
[b] Maryland Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, MD 20742, USA
[c] Department of Physics, University of Washington, Seattle, WA 98195, USA

ARTICLE INFO

Article history:
Received 1 November 2016
Received in revised form 5 January 2017
Accepted 20 January 2017
Available online 25 January 2017
Editor: G.F. Giudice

ABSTRACT

Long-lived particles (LLPs) are a common feature in many beyond the Standard Model theories, including supersymmetry, and are generically produced in exotic Higgs decays. Unfortunately, no existing or proposed search strategy will be able to observe the decay of non-hadronic electrically neutral LLPs with masses above $\sim$ GeV and lifetimes near the limit set by Big Bang Nucleosynthesis (BBN), $c\tau \lesssim 10^7$–10^8 m. We propose the MATHUSLA surface detector concept (MAssive Timing Hodoscope for Ultra Stable neutraL pArticles), which can be implemented with existing technology and in time for the high luminosity LHC upgrade to find such ultra-long-lived particles (ULLPs), whether produced in exotic Higgs decays or more general production modes. We also advocate a dedicated LLP detector at a future 100 TeV collider, where a modestly sized underground design can discover ULLPs with lifetimes at the BBN limit produced in sub-percent level exotic Higgs decays.

The interest @ CERN is growing……

.. and not only at CERN !

- SLAC Dark Sector Workshop 2016: Community Report – arXiv: 1608.08632
- Maryland Dark Sector Workshop 2017: Cosmic Visions – arXiv:1707.04591

Large (and continuously growing) "hidden sector" community:
Ex: current and proposed experiments searching for **Dark Photons**

Searches for A' → visible states

Name	Where	Source	Intensity	Production mode	Detection mode	Status
Belle-II	Super KEK-B	$e^+e^- \to \Upsilon(3S)$	> 100 fb^{-1} @ $\Upsilon(3S)$	$\Upsilon(3S) \to \gamma A'$	$A' \to e^+e^-, \mu^+\mu^-$	Commis. 2018
Apex	JLAB	e^-, 2 GeV	10^9 EOT (W)	A'-strahlung	$A' \to e^+e^-$	Commis. 2018
HPS	CEBAF12 @ JLAB	e^-,1-2 GeV	10^{14} EOT (W)	A'-strahlung	$A' \to e^+e^-$	Running 2016-20
MAGIX	MESA @ Mainz	e^-, 155 MeV	10^{18} EOT (Xe gas)	A'-strahlung	$A' \to e^+e^-$	Commis. 2020
Mu3e	πE5 line @ PSI	μ^-, 28 MeV	10^{15-16} μ^-	$\mu \to \nu\nu A'$	$A' \to e^+e^-$	Commis. 2017
ATLAS/CMS	LHC @CERN	pp 8, 13 TeV	few fb^{-1}	$H \to 4l$ + MET	$A' \to \mu^+\mu^-$	Running
LHCb	LHC @CERN	pp,13 TeV	15 fb^{-1}	$D^* \to DA'$	$A' \to e^+e^-, \mu^+\mu^-$	Running
NA62	SPS @CERN	p, 400 GeV	2 10^{18} POT	Meson, A'-strahlung	$A' \to e^+e^-, \mu^+\mu^-$	Running -2018
SeaQuest	Main Inj. @ FNAL	p, 120 TeV	1.5	Meson, A'-strahlung	$A' \to \mu^+\mu^-$	Proposed 2017-19
SHiP	SPS @CERN	p, 400 GeV	2 10^{20} POT	Meson, A'-strahlung	$A' \to e^+e^-, \mu^+\mu^-$	Proposed 2026

Searches for A' → Light Dark Matter (invisible states)

Name	Where	Source	Intensity	Production mode	Detection mode	Status
Babar	PEP-II @ SLAC	$e^+e^- \to \Upsilon(3S)$	57 fb^{-1}	$\Upsilon(3S) \to \gamma A'$	Single-γ trigger	ICHEP 2016
VEPP-3	VEPP-3 @ Budker Inst.	e^+, 500 MeV	1.5 MHz $\gamma\gamma$	$e^+e^- \to A'\gamma$	detect $\gamma + M_{\rm miss}$	Proposed
PADME	BTF @ Frascati INFN	e^+, 550 MeV	15 Hz $\gamma\gamma$	$e^+e^- \to A'\gamma$	detect $\gamma + M_{\rm miss}$	Approved, 2017-19
MMAPS	CESR @ Cornell	e^+, 5.3 GeV	2.2 MHz $\gamma\gamma$	$e^+e^- \to A'\gamma$	detect $\gamma + M_{\rm miss}$	Not funded
NA64	SPS @ CERN	e^-, 100 GeV	$e^-N \to e^-NA'$	10^9–10^{12} EOT	detect $e^- + E_{\rm miss}$	Running, 2016-17
LDMX	LCLS-II @ SLAC	e^-, 4 GeV	$e^-N \to e^-NA'$	10^{15}–10^{16} EOT	detect $e^- + E_{\rm miss}$	Proposed, 2020

Direct detection of LDM via the process A' → LDM → LDM scattering in the detector

Name	Where	Source	Intensity	Production mode	Detection mode	Status
SBND	FNAL	p, 9 GeV	2 10^{20} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 110 m	Under study
T2K	Tokai-Kamioka	p, 30 GeV	10^{21} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 280 m	Running
COHERENT	SNS @ Oak Ridge	p, 1 GeV	10^{23} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 20 m 2°-OA	Proposed
SHiP	SPS @CERN	p, 400 GeV	2 10^{20} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 100 m	Proposed 2026
LBNF	DUNE @FNAL	p, 120 GeV	3 10^{21} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 500 m	Under study 2020

Very lively communities in Europe and US !

What is the scale of New Physics?

Masses of right handed neutrinos
10^{-9} – 10^{15} GeV

Mass of Dark Matter particle
10^{-31} – 10^{20} GeV

Mass of new particles required for baryogenesis
10^{-2} - 10^{15} GeV

Mass of New Particles for Higgs hierarchy
10^{3} – 10^{18} GeV

We really do not know.
Today – more than ever - we must keep a broad view

Conclusions

"I think Nature is smarter than physicists. We should have the courage to say: Let Nature tell us what is going on.

Our experience of the past has demonstrated that in the world of the infinitely small, it is extremely silly to make predictions as to where the next physics discovery will come from and what it will be.

In a variety of ways, this world will always surprise us all.
The next breakthrough might come from beta decay, or from underground experiments, or from accelerators.

We have to leave all this spectrum of possibilities open and just enjoy this extremely fascinating science."

Carlo Rubbia

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

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- Thank you for your attention !-