Beyond colliders: dark sector searches at beam dumps

E. Graverini (*École Polytechnique Fédérale de Lausanne*)

Joint annual meeting of the SPS and ÖPG, Zurich, August 2019

(B)SM landscape in 2019

Fundamental questions of particle physics:

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

found no answers at the LHC nor elsewhere.

No theory guidance on the mass of new particles.

(B)SM landscape in 2019

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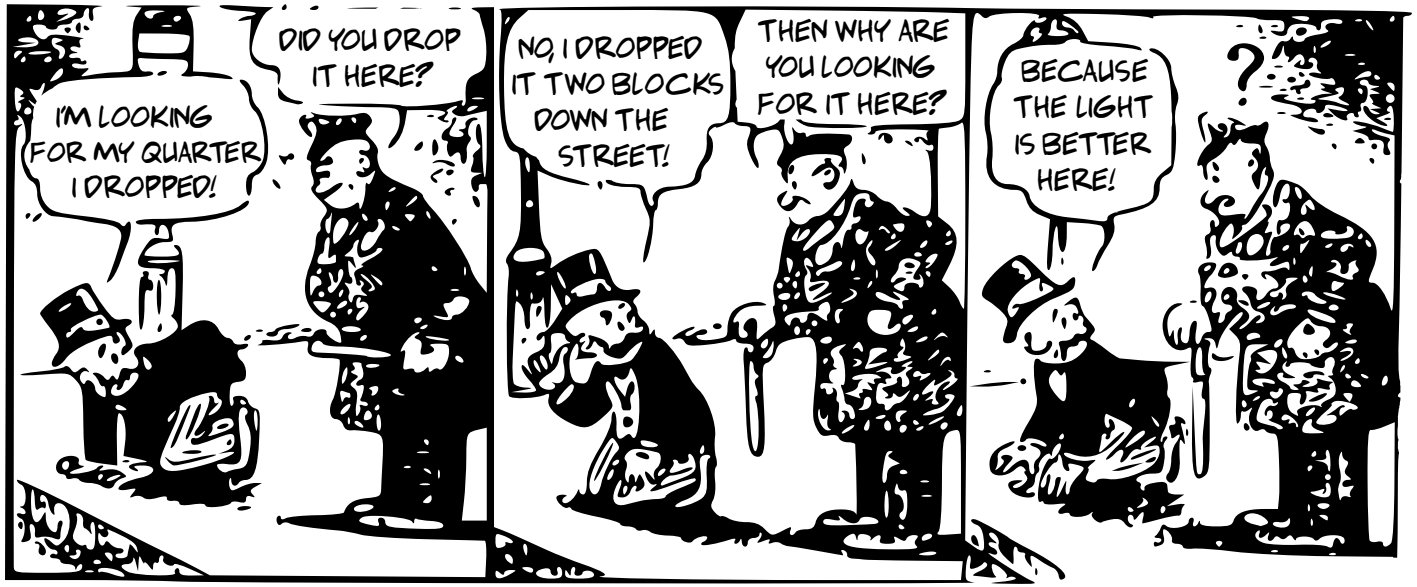
What is the energy scale of New Physics?

- **Dark matter:**
  10^{-22} eV (superlight scalars) to $\geq 10^{20}$ GeV (wimpzillas & co.)
- **Neutrino masses/oscillations:**
  right-handed seesaw neutrinos up to 10^{15} GeV
- **$\cancel{CP} \to$ baryogenesis:**
  new particle(s) from 10 MeV to 10^{15} GeV



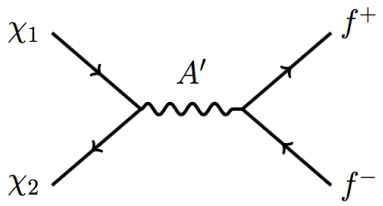
Dark matter, dark mediators... a dark sector?

- Dark matter mediated by EW, H interactions heavily constrained
- Lee-Weinberg bound: $m_{DM} > 2$ GeV
  - $\rightarrow$ can be lifted by introducing new light boson mediators
    - DM-SM coupling reduced, DM annihilation cross-section increased

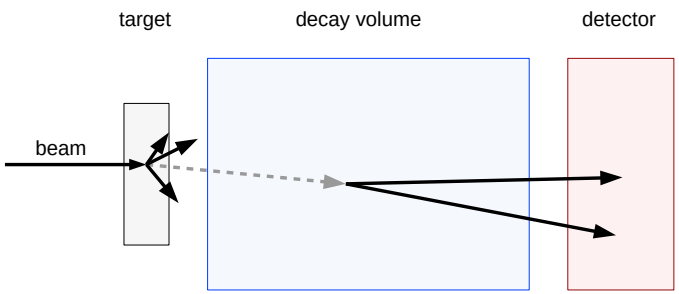
$$\mathcal{L}_{\text{world}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{portal}} + \mathcal{L}_{\text{DS}}$$

- "mediators" as "portals" to a "Dark Sector"
  - feebly interacting ("FIPs") and low mass

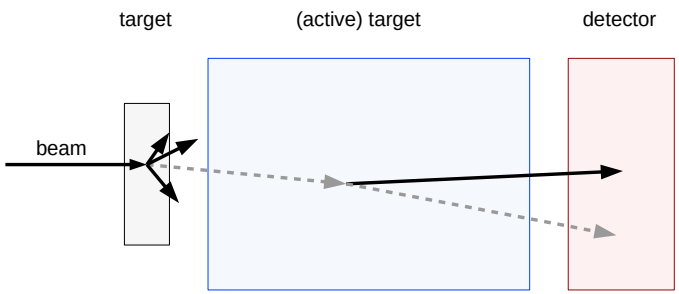
Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$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



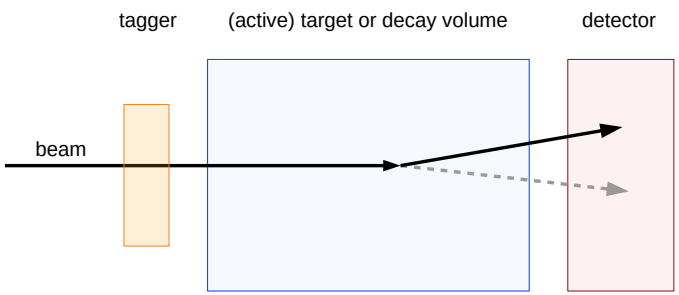
Discovery strategies



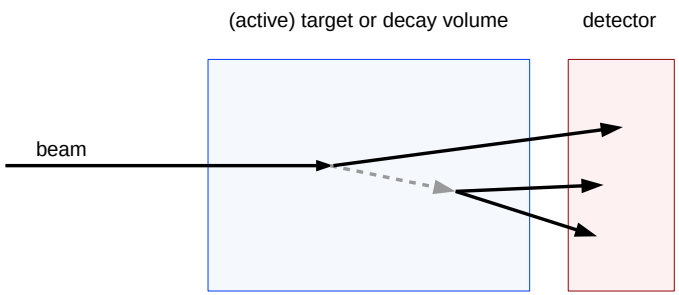
hidden particle decaying into visible particles



hidden particle scattering



missing energy or momentum



displaced vertex and/or peculiar final state

- **Requirements:**
  - sensitivity to extremely small couplings U^2
  - small or no background
- $E_{\text{miss}}/p_{\text{miss}}$ techniques sensitive to U^2, others U^4

Proton beam dumps

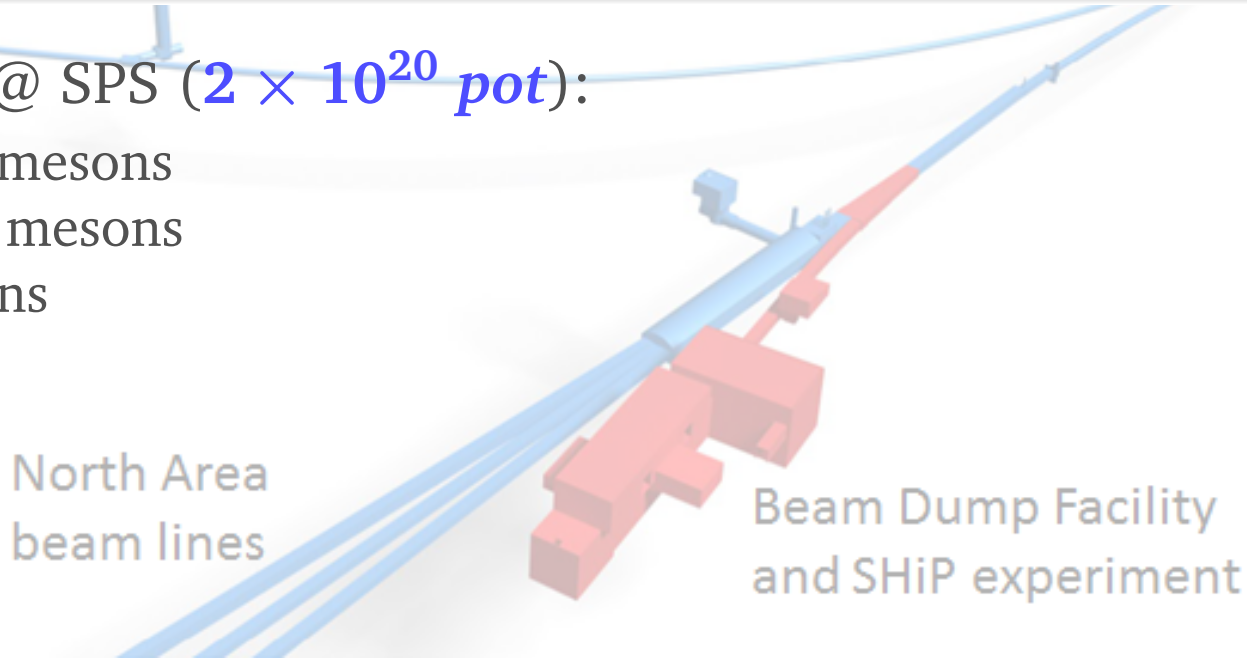
- long tradition of beam dump searches with far (CHARM, NuTeV) and near detectors (PS191)
- decays of charm and beauty: reach $m \lesssim 5$ GeV
  - dump proton beam to remove light mesons before they decay

The SPS provides a unique high-intensity beam of 400 GeV protons: ideal setting for a CERN-based **Beam Dump Facility** (BDF)

[CERN-PBC-REPORT-2018-001]

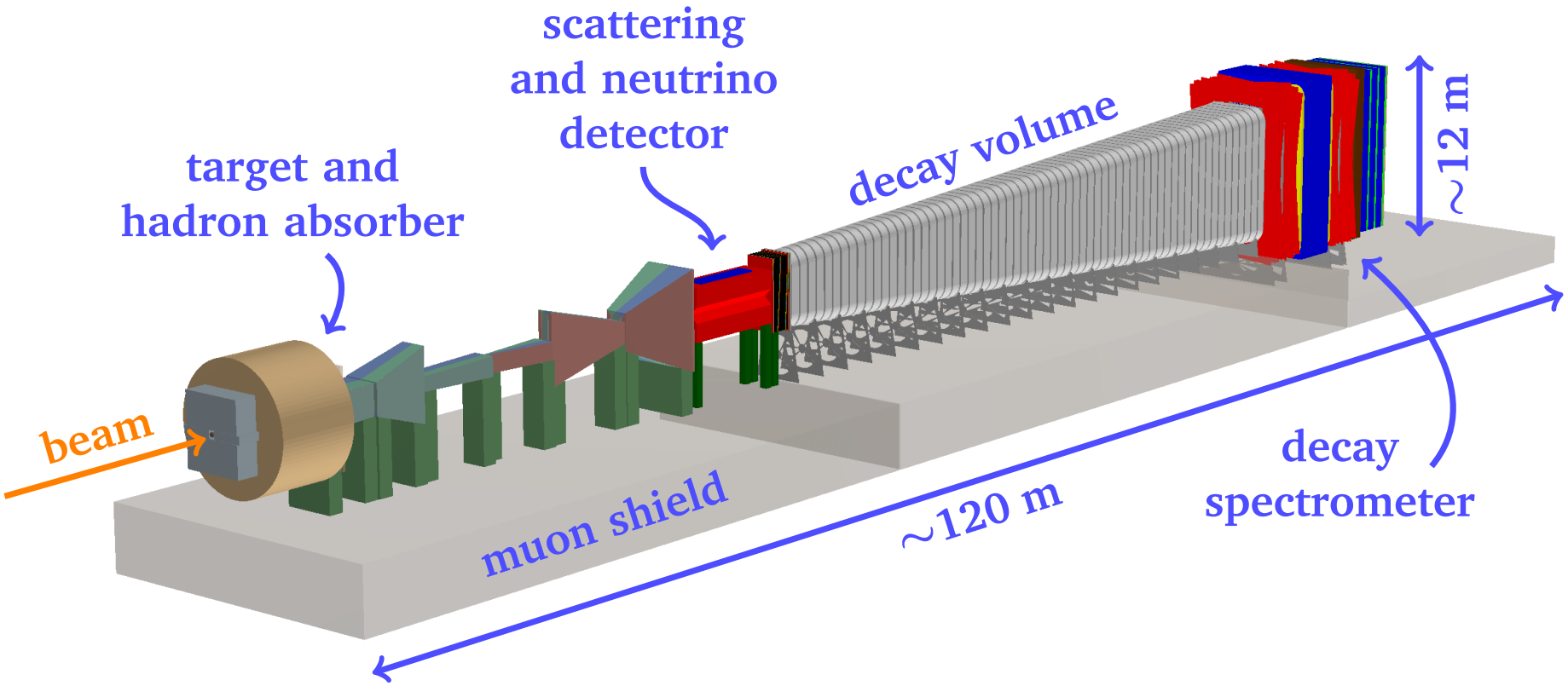
5 years of BDF @ SPS ($\mathbf{2 \times 10^{20}}$ ***pot***):

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



SHiP

[ins-det:1504.04956, JINST 14(2019)03 P03025, CERN-SPSC-2019-010]

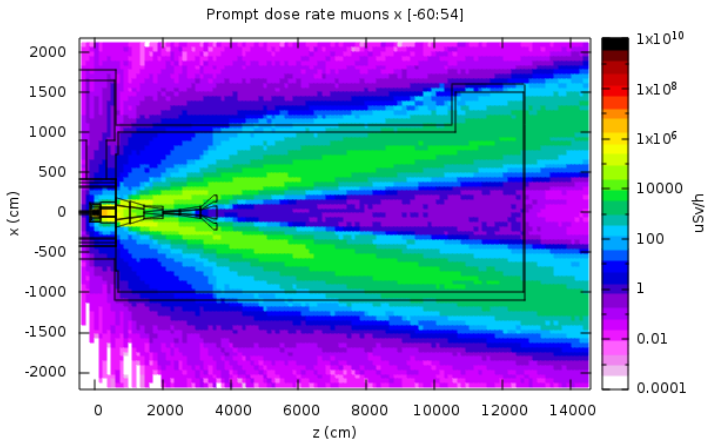


- **discovery experiment for weakly coupled LLPs**, with a complementary detector for ν physics and LDM scattering
- large geometrical acceptance: long volume close to dump
- zero background with spectrometry, PID and VETO taggers

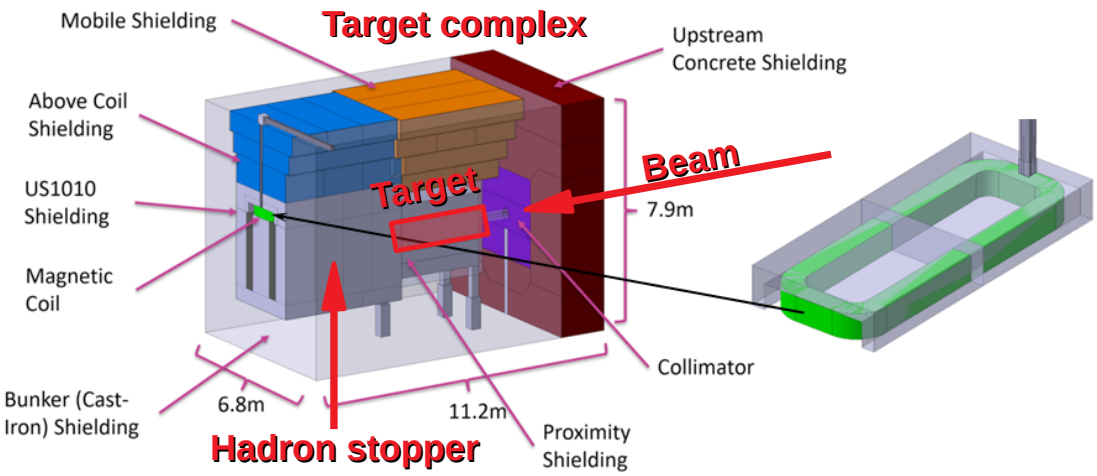
Target and shielding

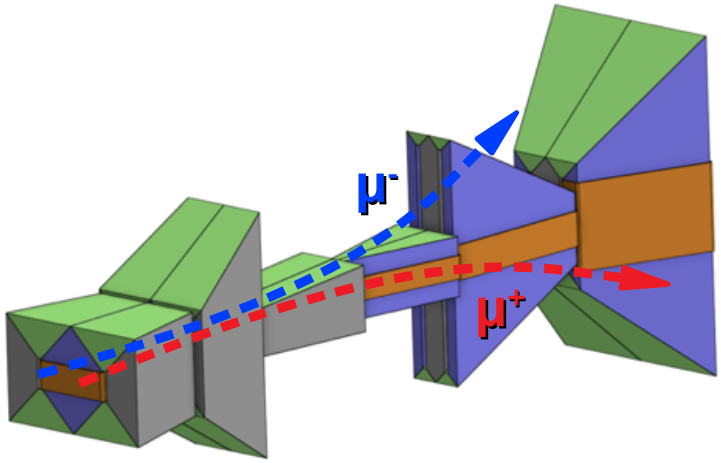
[JINST 12(2017)05 P05011]

- heavy target to absorb pions
- magnetized hadron stopper: immediately separate $\mu^{\pm}$
- muon shield config optimised with ML
  $\Longrightarrow$ μ rate reduced to $\sim$ 25 kHz



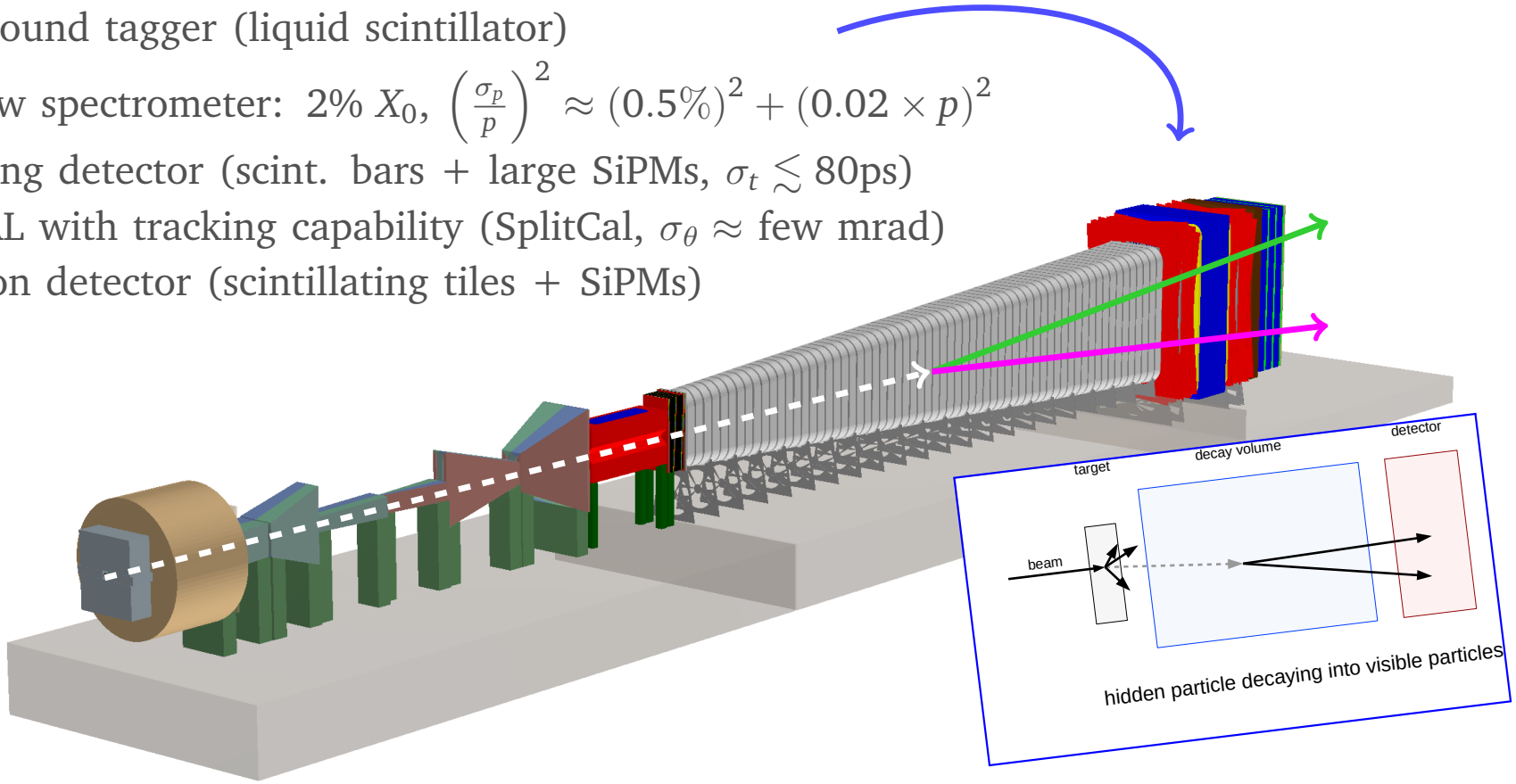
- μ simulation validated with existing data from Hyperon and NA62
- and with dedicated exp. in 2018 using replica of BDF target, 10^{11} *pot*





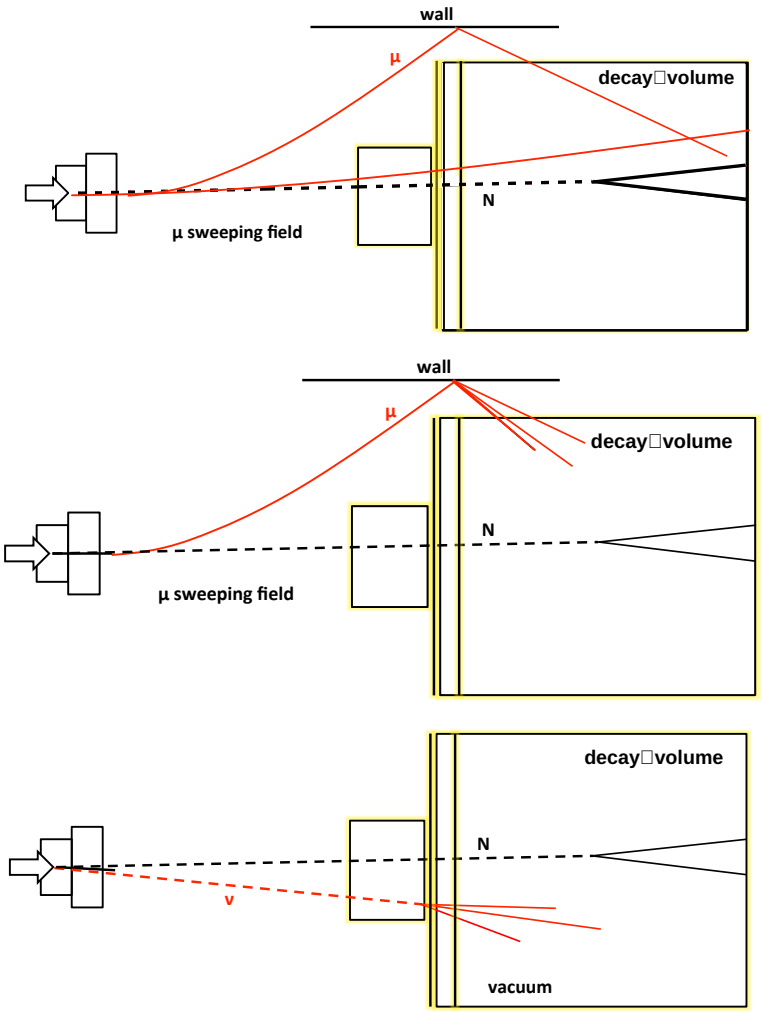
SHiP Decay Spectrometer

- surround tagger (liquid scintillator)
- straw spectrometer: 2% X_0, $\left(\frac{\sigma_p}{p}\right)^2 \approx (0.5\%)^2 + (0.02 \times p)^2$
- timing detector (scint. bars + large SiPMs, $\sigma_t \lesssim 80$ps)
- ECAL with tracking capability (SplitCal, $\sigma_\theta \approx$ few mrad)
- muon detector (scintillating tiles + SiPMs)



- mass, charge, flavour information available at observation
  $\Longrightarrow$ narrow down physics models

Background for decay signatures @ SHiP



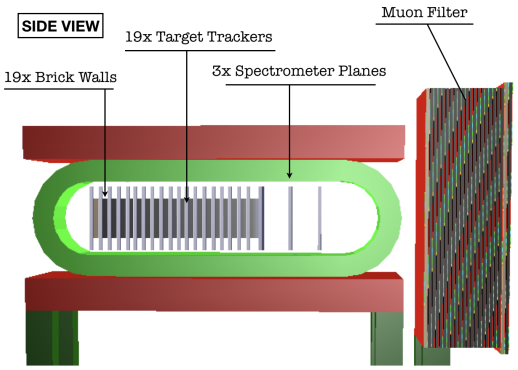
- Muon combinatorial
- Muon inelastic
- **ν interactions:**
  - 10 years of SHiP simulated, increasing to 100
  - ν-air: keep pressure $\sim$ 1 mbar
  - ν-material: some K_L, combination of tracks from primary and secondary interactions
  - vetoed by topology & signal selection

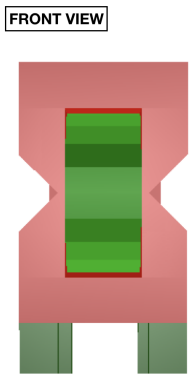
0 background $\Longrightarrow$ 2 candidates are a **discovery**

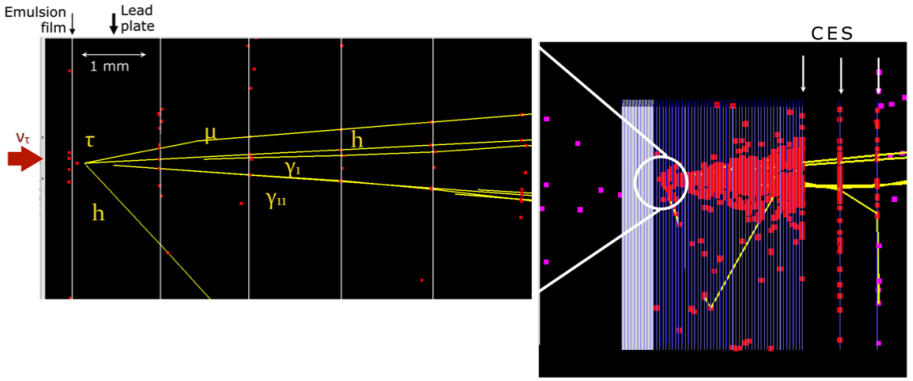
SHiP Scattering and Neutrino Detector

- distinguish ν_e, ν_μ, ν_τ and hadrons
  - measure charge
- ν_f cross sections measurements relevant for flavour anomalies
- first $\bar{\nu}_\tau$ observation
- Target (emulsion chambers + target tracker) + Downstream spectrometer + Muon filter

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







- ideal laboratory also for Light Dark Matter scattering signatures!

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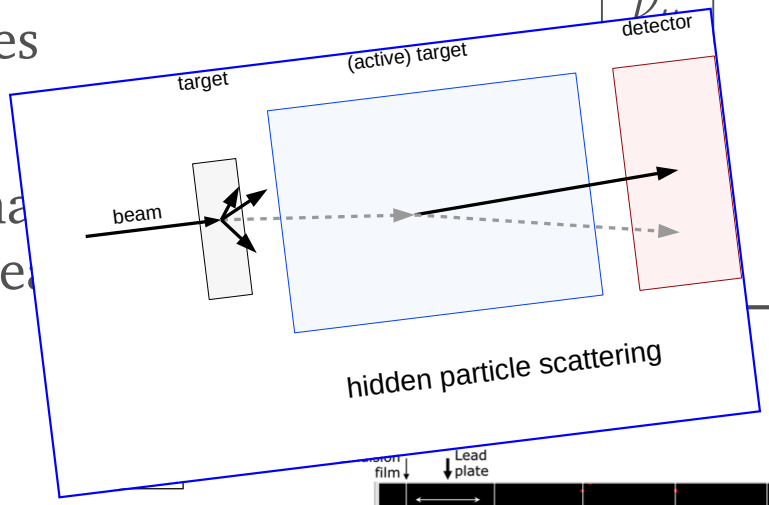
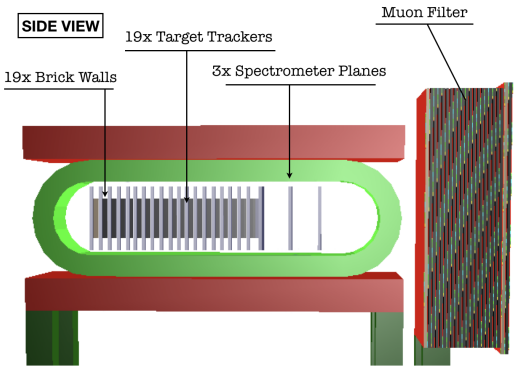
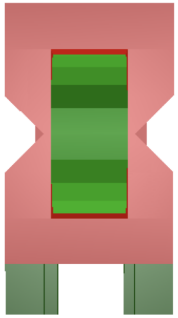
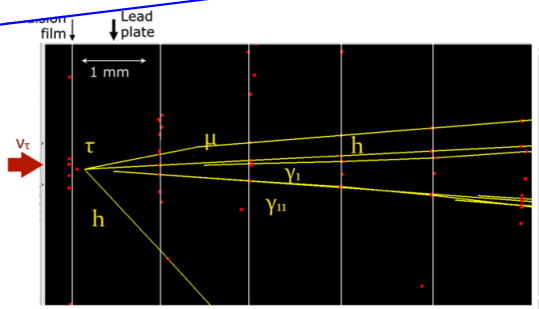
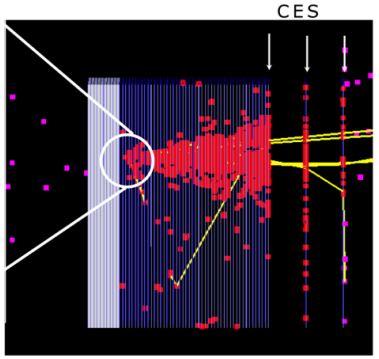






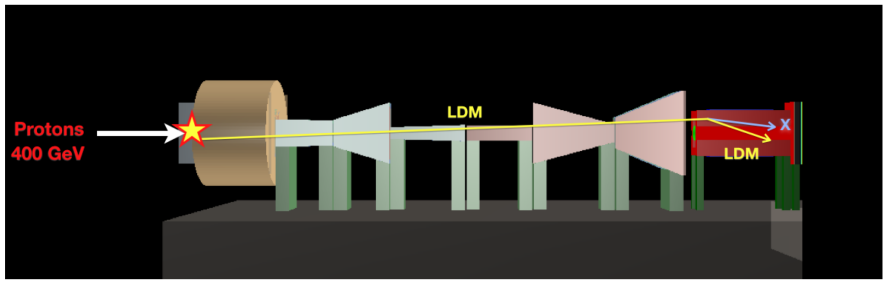


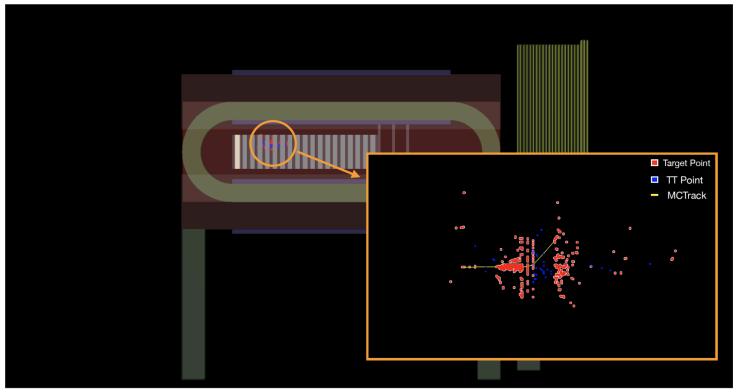


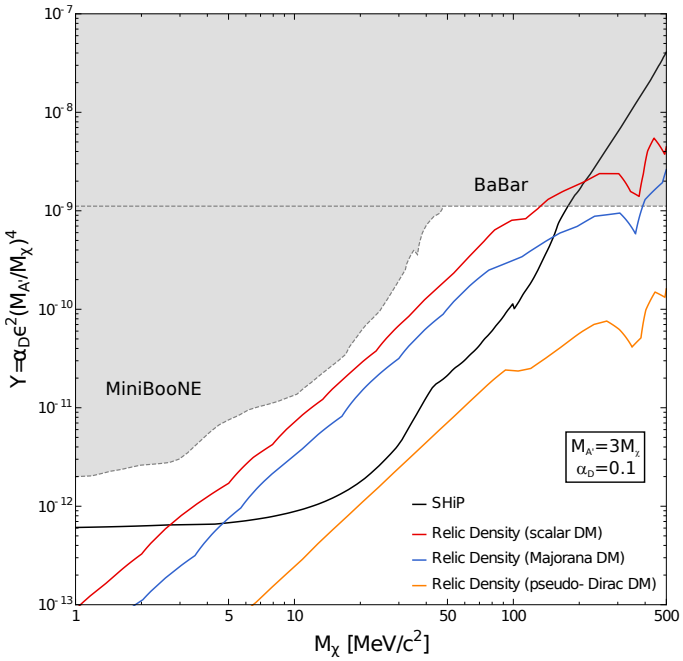
- ideal laboratory also for Light Dark Matter scattering signatures!

SHiP SND: invisible decays

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



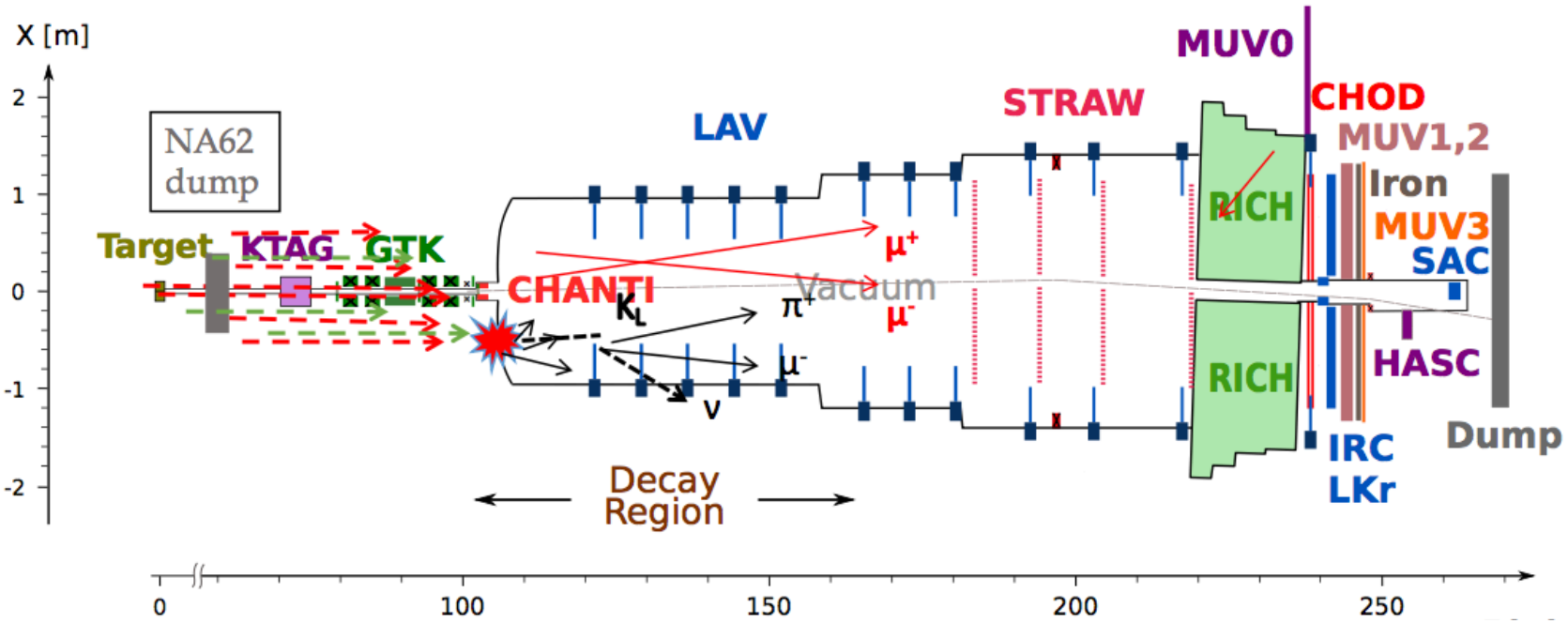




- $\chi_2 \to \chi_1 \gamma' (\to \ell\ell)$ can be searched with the Decay Spectrometer

NA62

[A. Ceccucci, ESPPU 2019]



- built to measure $\mathcal{B}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$ [PLB 791 (2019) 156]
- can quickly switch between beam and dump (collimators)
- studies on $\mu-$ and $\nu-$halo BG in dump mode ongoing
- in beam mode: $K^+ \to \mu^+ N$ with N decaying visibly or invisibly, $K^+ \to \pi^+ \left(\pi^0 \to \gamma\gamma'\right)$ [JHEP 1905 (2019) 182, PLB 778 (2018) 137, PLB 772 (2017) 712]

NA62

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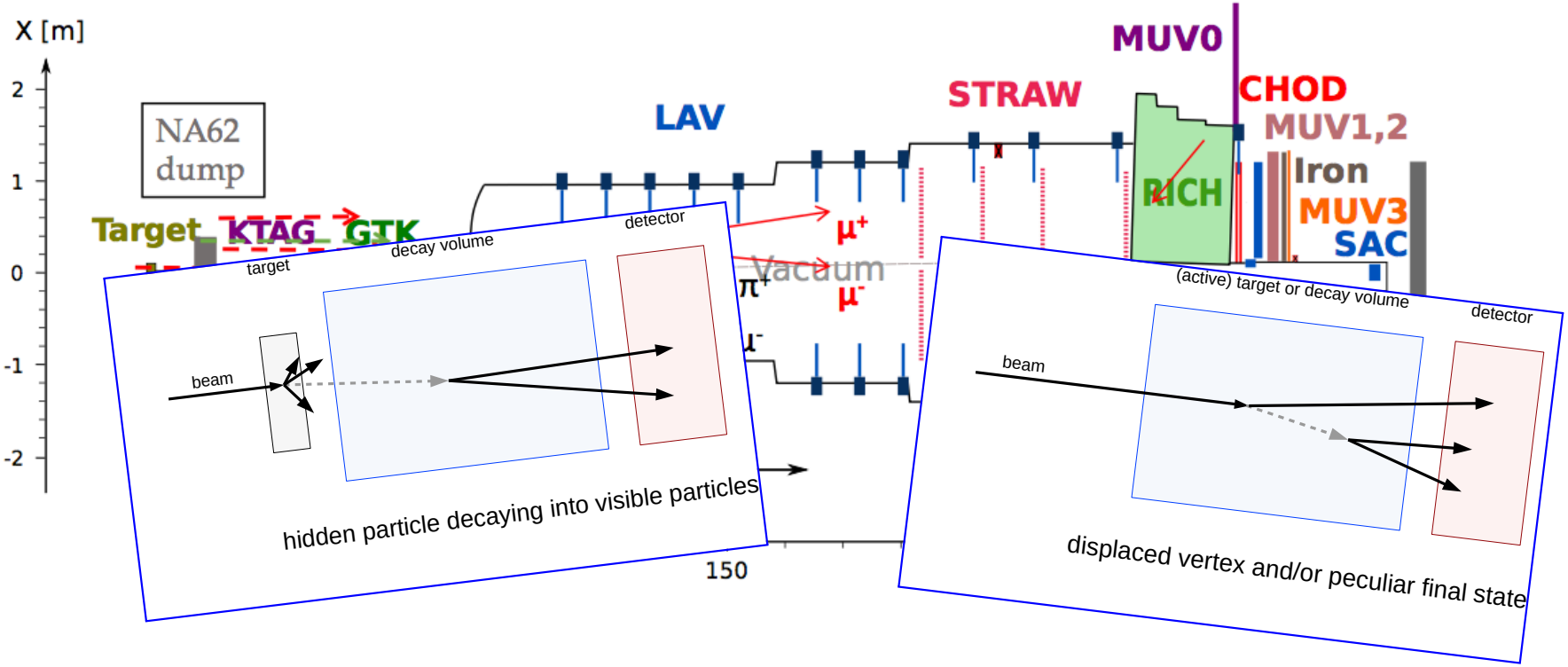

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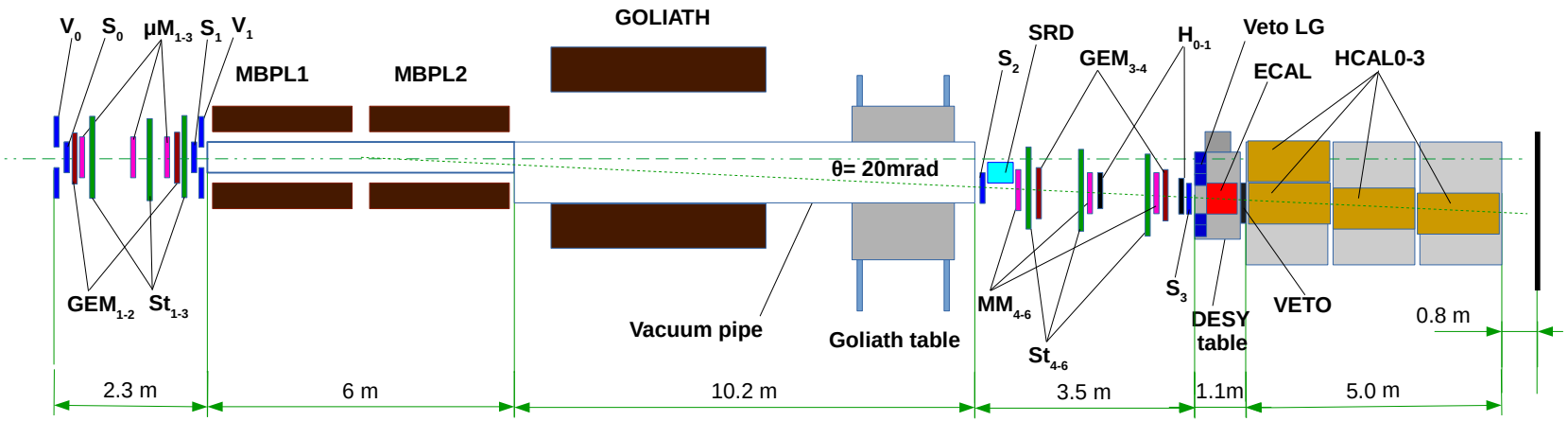
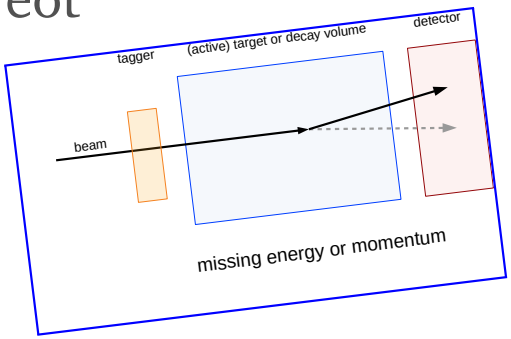
NA64(++)

[S. Gninenko, SPSC 2017] [see E. Depero's talk!]



- NA64 approved in 2016 to search for NP in missing energy
  - ruled out γ' explanation for $(g-2)_\mu$ with 10^{11} eot
- NA64++: 5×10^{12} eot after LS2
  - extend γ' search to muon beams
  - configurable to look for visible signatures too

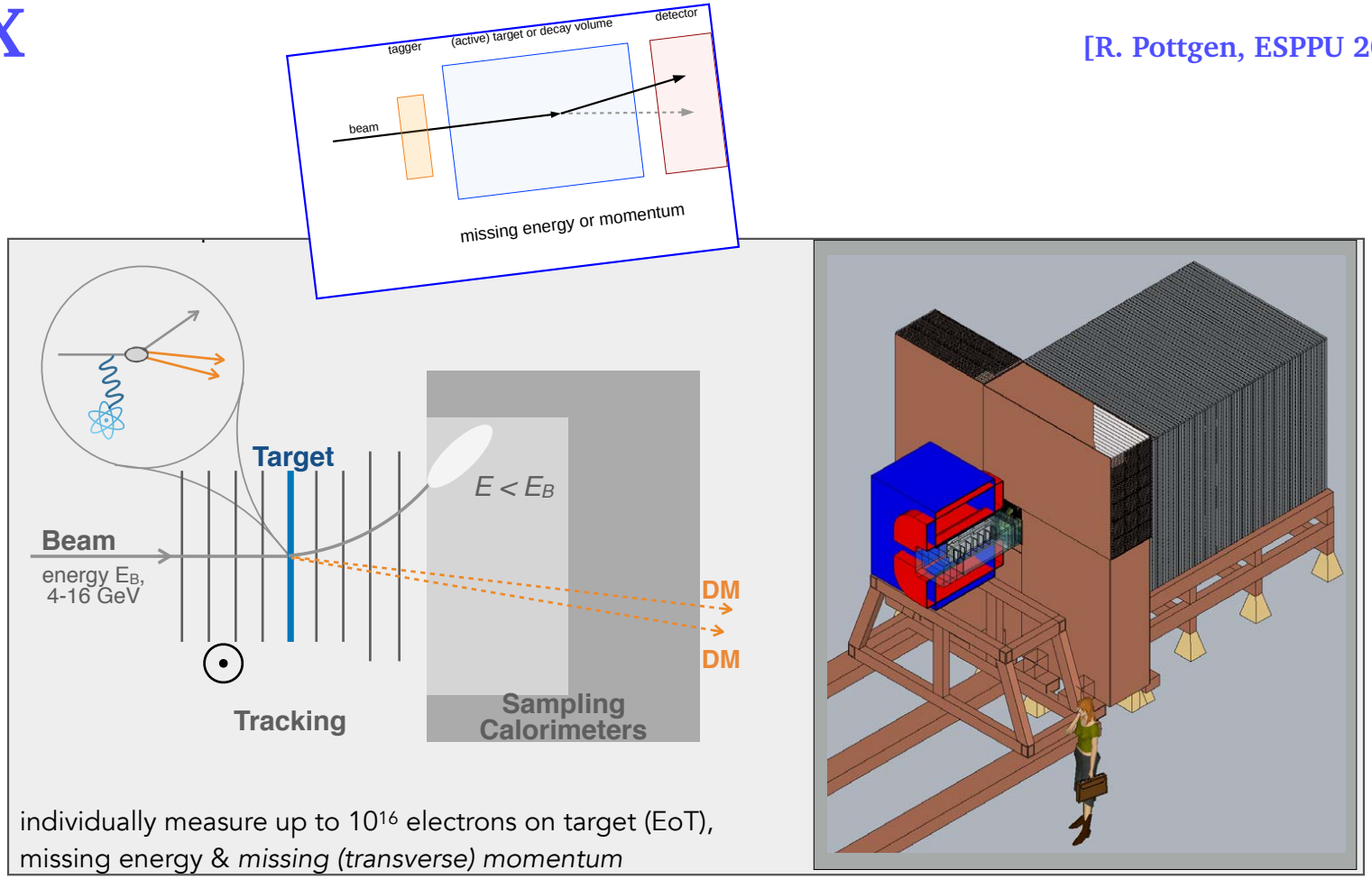


- Studied as possible application for the AWAKE plasma wakefield acceleration scheme

[CERN-PBC-REPORT-2018-004]

LDMX

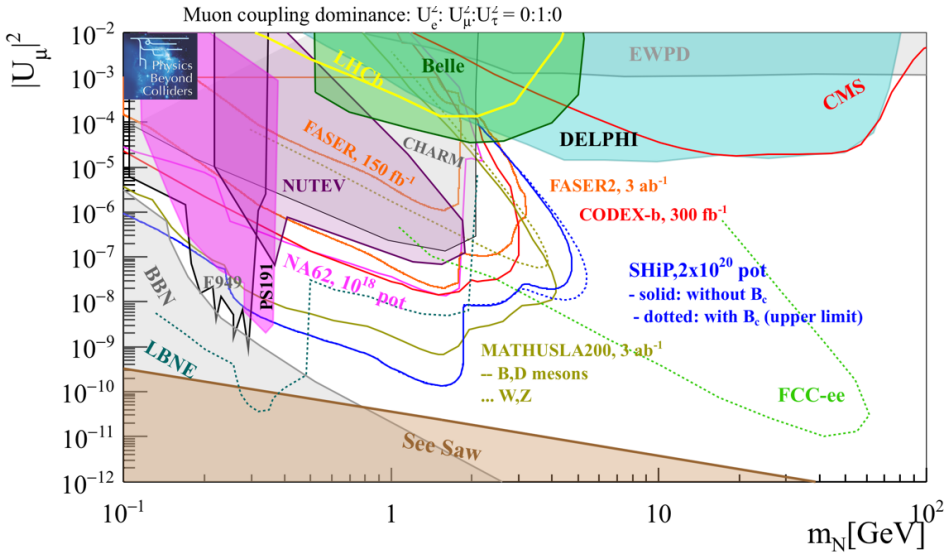
[R. Pottgen, ESPPU 2019]

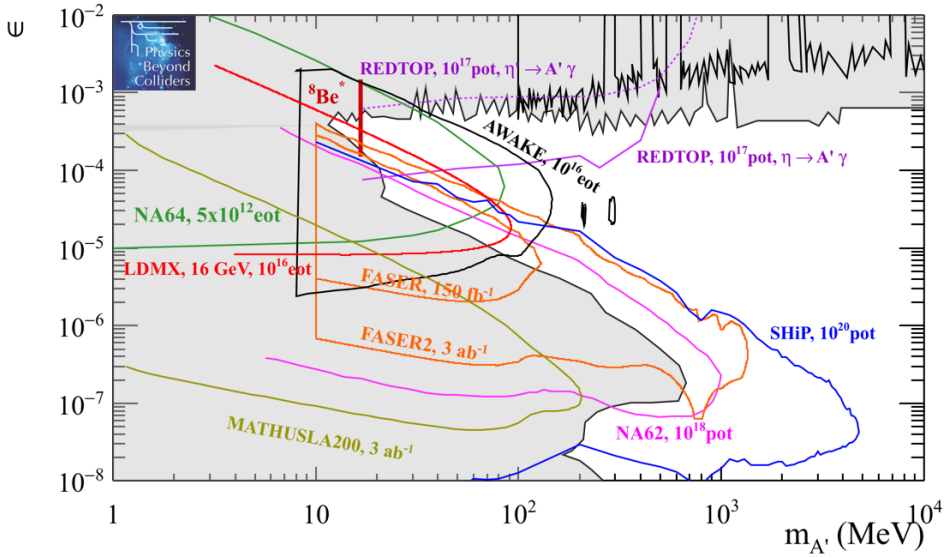


- small scale experiment to measure up to 10^{16} eot
- missing energy & missing momentum techniques
- potential beam lines: JLab CEBAF, SLAC S30XL, CERN eSPS

[hep-ex/1808.05219]

Performance: visible decays

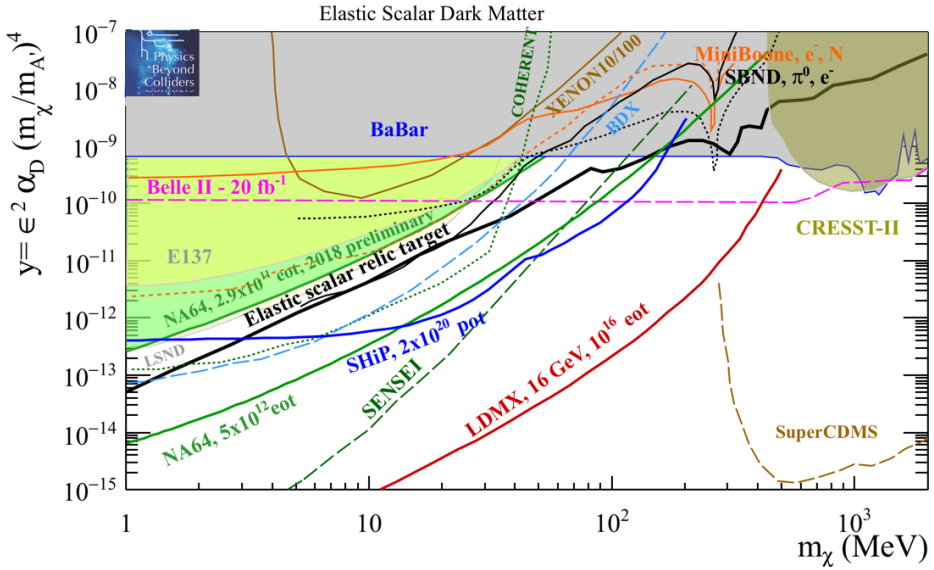


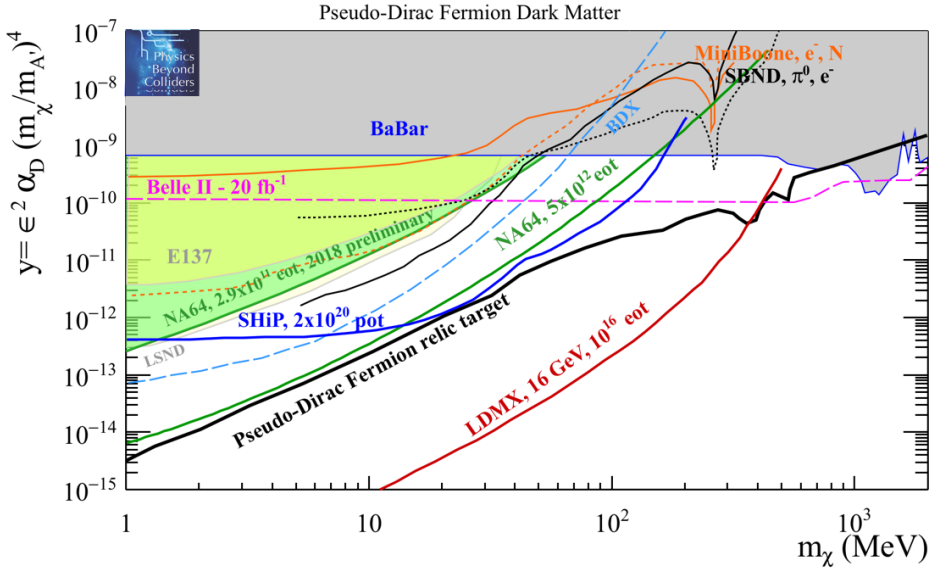


- HNL (heavy meson decays), dark photon (decays + bremsstrahlung + QCD)
- Time scale:
  - NA62 (10^{18} pot): 5 years.
  - SHiP (2×10^{20} pot): 6 + 5 years.
- See F. Redi's next talk for collider-based experiments!

[1504.04956, 1504.04855, 1811.00930, 1901.09966]

Performance: invisible decays / missing energy





- scattering *vs.* missing E approaches offer complementary insights
- Time scale:
  - NA64 (5×10^{12} eot): 5 years.
  - SHiP (2×10^{20} pot): 6 + 5 years.
  - LDMX (10^{16} pot): beam selection + 5 years.

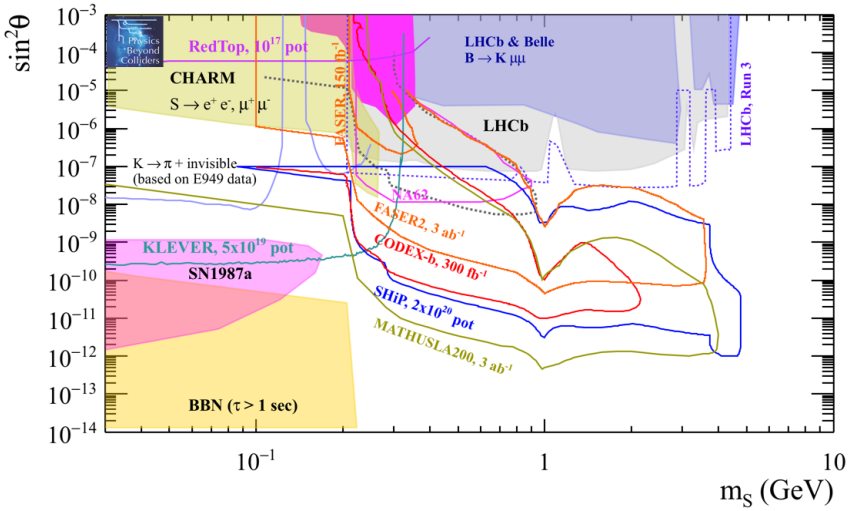
[1901.09966 and refs. therein]

Conclusions

- current data leave open a wide window on the unknown
- Dark Sector exploration very well justified
  - active theory community, formulating benchmark models
  - ...that can be thoroughly tested within 15 years!
- CERN's new "Physics Beyond Colliders" WG largely devoted to DS
- **short term:**
  - existing experiments such as NA62 and NA64 will have results soon, while serving as training grounds towards dedicated beam dump explorations with *e.g.* BDF/SHiP and AWAKE++
- **medium/long term:**
  - future facilities like BDF/SHiP and eSPS/LDMX will grant significant progress towards the exploration of the dark sector
- nice **complementarity** with dark sector programme at the LHC
  - and at the FCC-*ee*!

Spare slides

Visible decays



[1504.04956, 1504.04855, 1811.00930, 1901.09966]

- scalar (K and B decays)
- Time scale:
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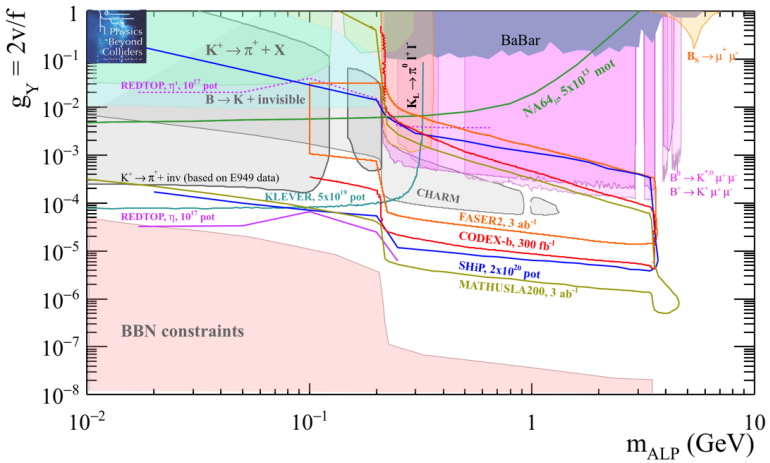
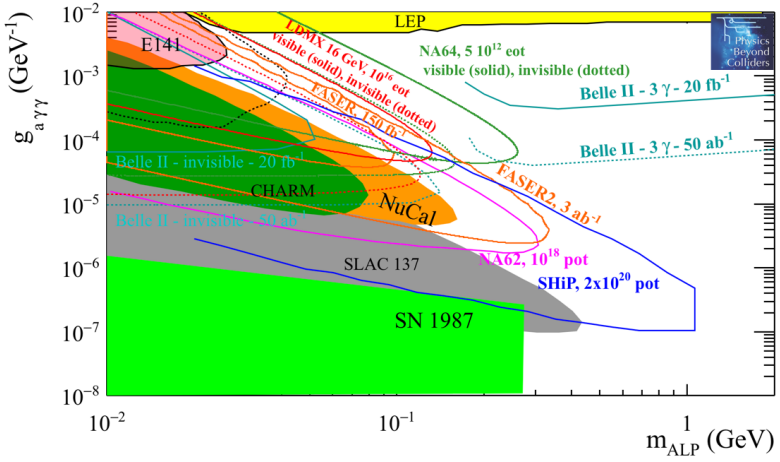
Visible decays





[1504.04956, 1504.04855, 1811.00930, 1901.09966]

- from left: ALPs coupled to fermions, ALPs coupled to photons
- Time scale:
  - NA62 (10^{18} pot): 5 years.
  - SHiP (2×10^{20} pot): 6 + 5 years.
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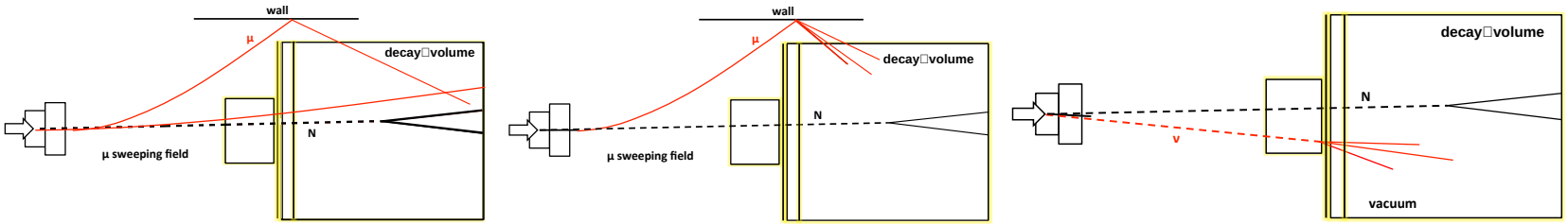
Background for decay signatures @ SHiP



- **Muon combinatorial:**
  - $10^{16} \xrightarrow{\text{selection}} 10^{9} \xrightarrow{\text{timing}} 10^{-2}$ candidates in 5 years @ $90\%CL$
  - ML used to generate large sample of dangerous μ
- **Muon inelastic:**
  - 5 years of SHiP simulated
  - ~~correlation~~ between VETO and selection: $< 6 \times 10^{-4}$ @ $90\%CL$
- **ν interactions:**
  - 10 years of SHiP simulated, increasing to 100
  - ν-air: $< 10^{-2}$ with pressure ~ 1 mbar
  - ν-material: $5 \times 10^{5} \begin{cases} \xrightarrow{\text{cuts (fully reco)}} 0 \\ \xrightarrow{\text{cuts (part. reco)}} 2 \xrightarrow{\text{opening angle}} 0 \end{cases}$ @ $90\%CL$