SHiP sensitivity to Dark Photons decaying to visible final states

Gaia Lanfranchi – LNF-INFN
(on behalf of the SHiP Collaboration)

Dark Sector Workshop - SLAC – 28-30/4/2016

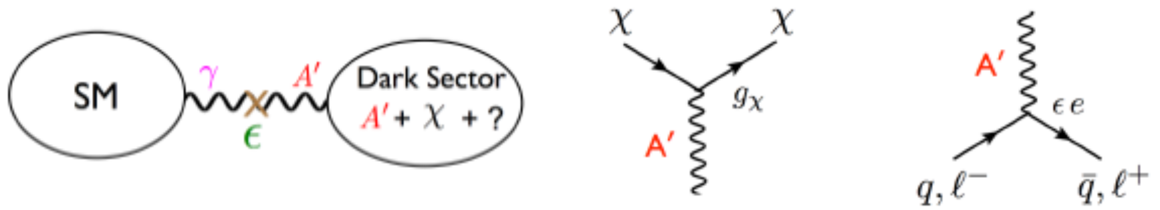
Introduction

In the simplest realizations of the dark sector, a **new U(1)' symmetry** is introduced. The associated gauge boson, called dark photon (A'), couples to the weak hyper charge with a **mixing strength ε**.
An effective interaction between the dark photon and the electromagnetic current arises after electroweak symmetry breaking.

To accommodate the recent anomalies in cosmic rays (PAMELA, FERMI, AMS-2), the **dark photon mass is constrained to lie in the MeV/c^2 to GeV/c^2 range**.

Which is the SHiP sensitivity to Dark Photons to visible final states?

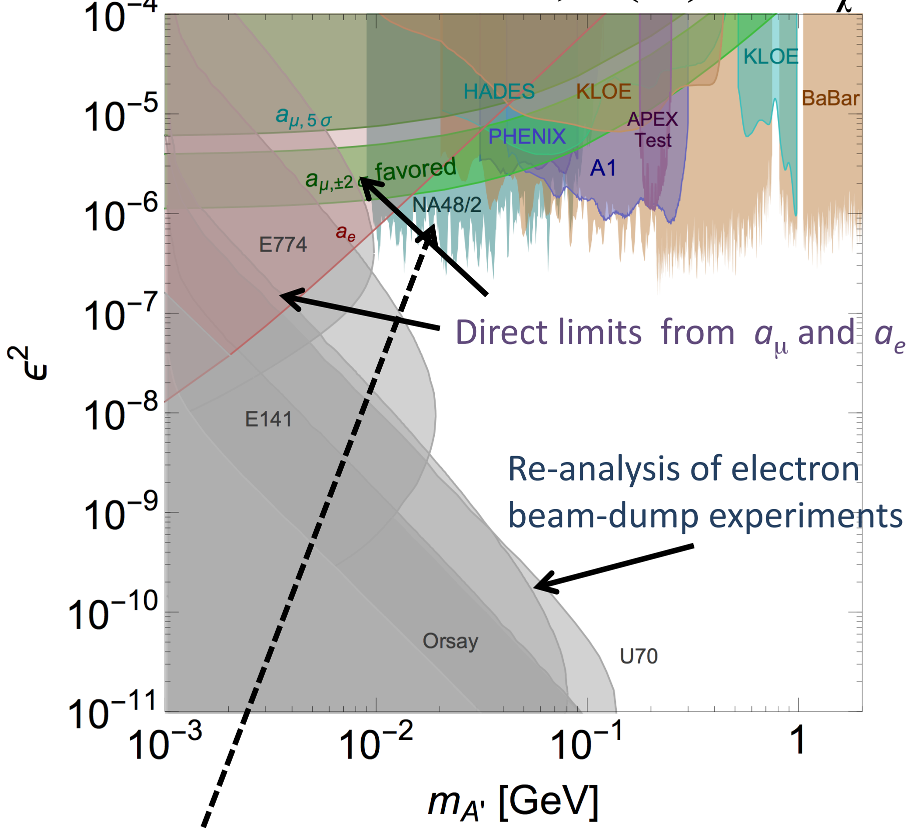
Current (world-wide) experimental situation



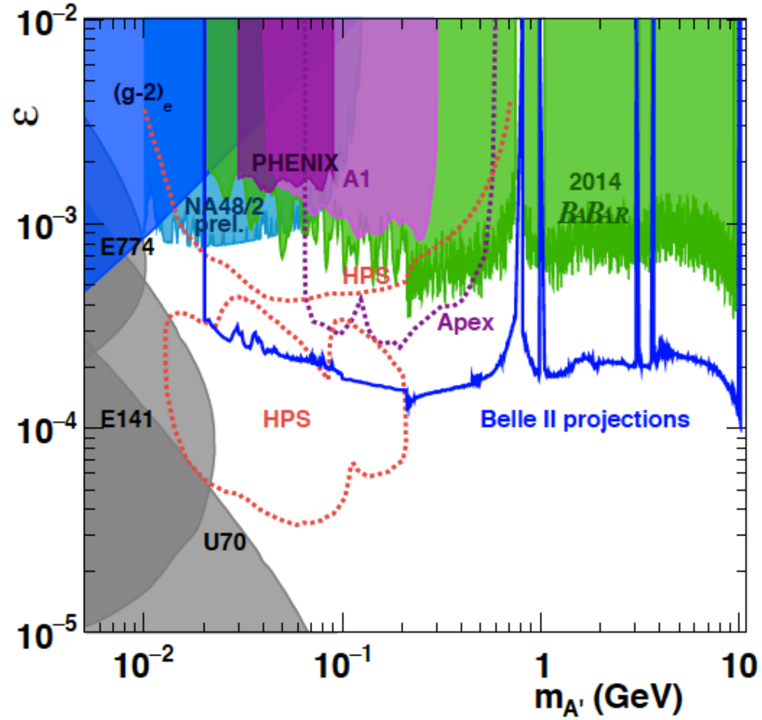
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

$m_\chi \sim m_{A'} \sim \text{MeV} - 5\ \text{GeV}$

A′ → visible channels, **m(A′) < 2 m$_\chi$**



planned experiments: HPS, Apex, Belle-II

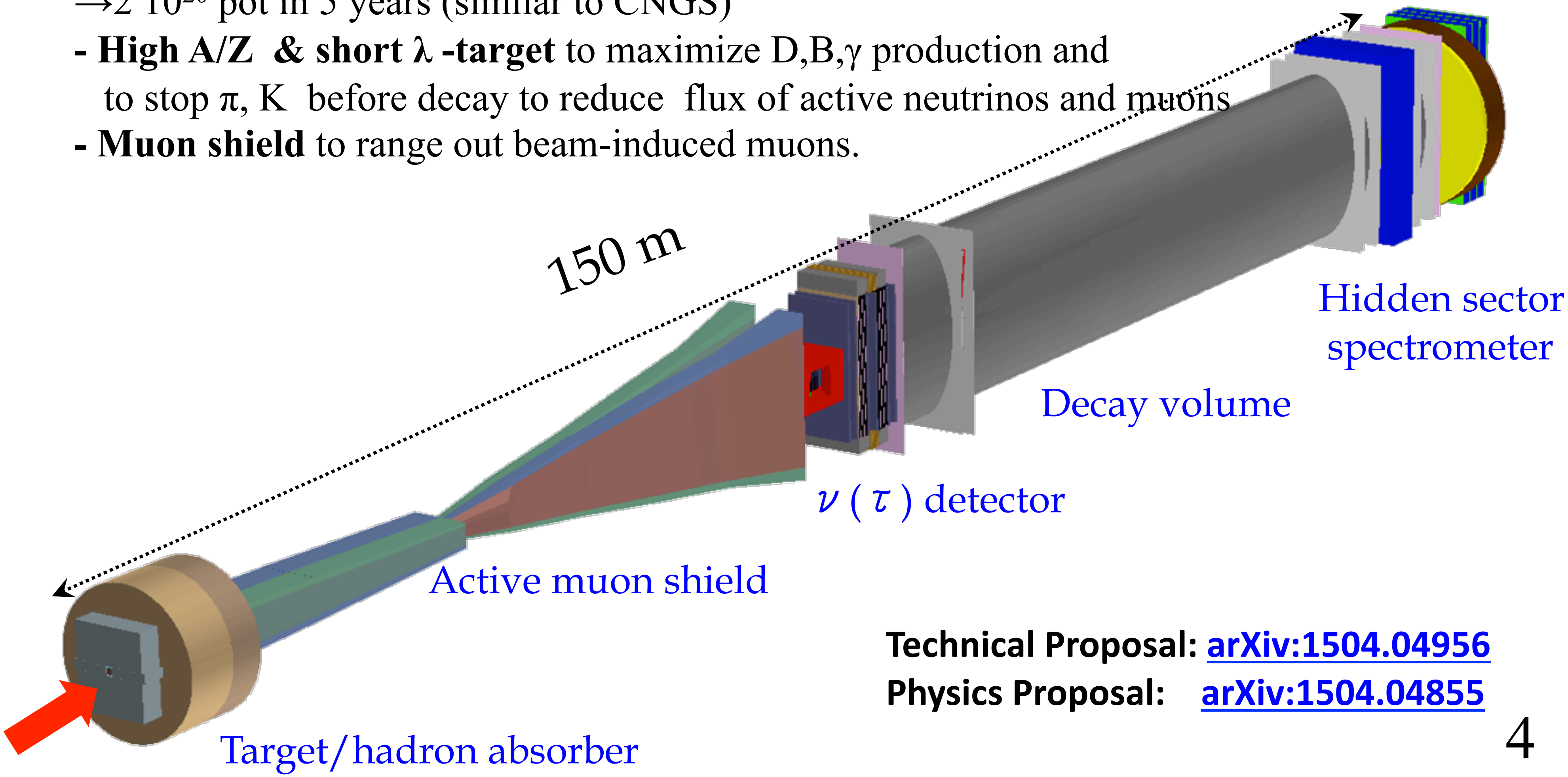


The A′→ visible channel as responsible of the (g-2)$_\mu$ anomaly has been already ruled-out.

The SHiP experiment at the CERN SPS
(see A. Golutvin's talk for details)

Proton fixed-target (beam dump like) experiment at the CERN SPS
- **SPS:** 4×10^{13} proton on target /7s @ 400 GeV , 1 sec spills (slow extraction)

  $\rightarrow 2\ 10^{20}$ pot in 5 years (similar to CNGS)
- **High A/Z & short λ -target** to maximize D,B,γ production and to stop π, K before decay to reduce flux of active neutrinos and muons
- **Muon shield** to range out beam-induced muons.



Technical Proposal: arXiv:1504.04956
Physics Proposal: arXiv:1504.04855

Dark photon production:

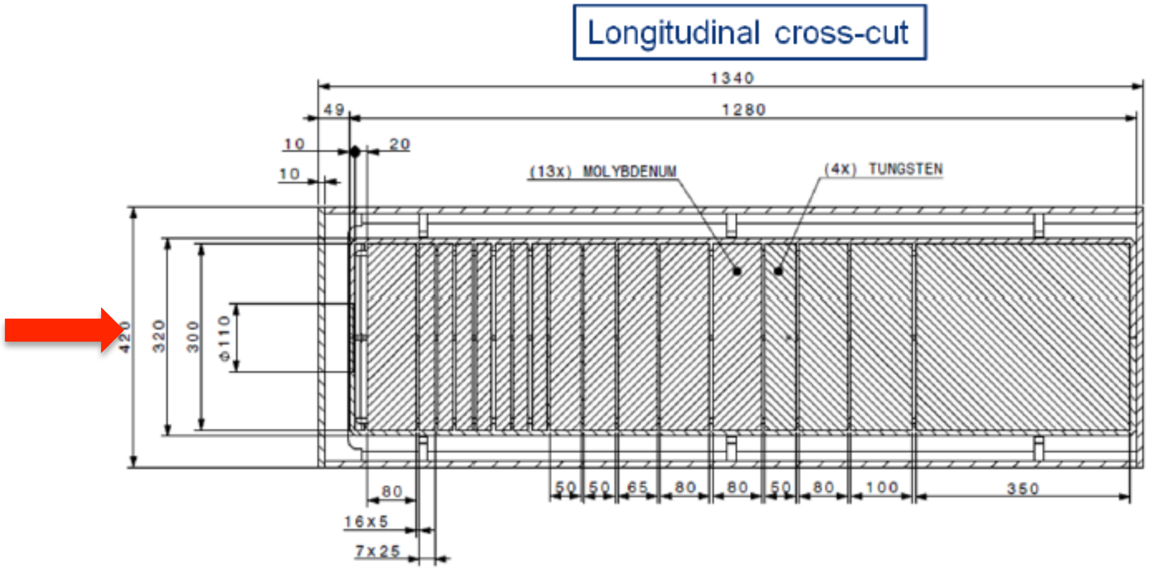
Production mechanisms at a proton beam dump facility:

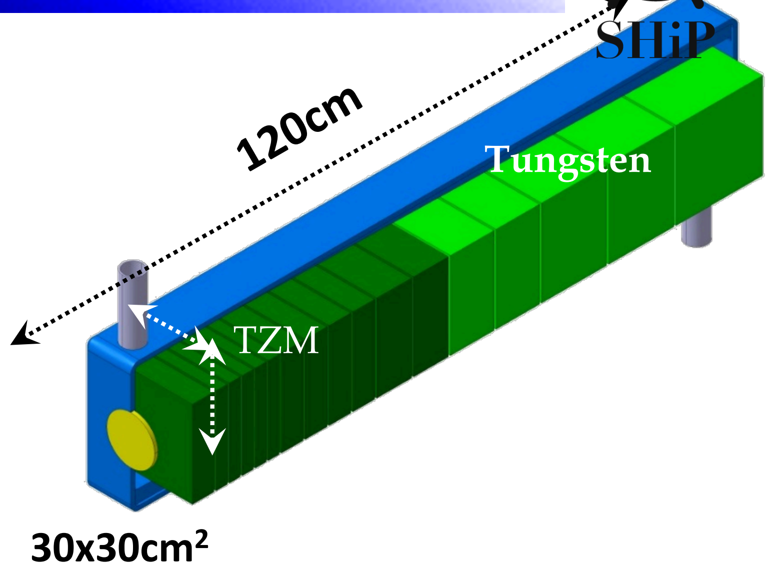
1) Meson decays: (π^0,η, η', ω) $\rightarrow \gamma$ A' (decay of K, D,B subdominant)

2) (Quasi) elastic scattering of incident protons on nucleons in the target can lead to production of vector states via **bremsstrahlung process**
pp $\rightarrow$ ppV **($\sigma \sim Z^2$)**

3) For large m(A'), **direct perturbative QCD production** of vector states via the underlying q + q $\rightarrow$ V ; q + g $\rightarrow$ q + V processes should become dominant.
($\sigma \sim \sigma_0$ x $A^{0.7}$)

The SHiP target:





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

SHiP target configuration: main parameters

SHiP

- 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)**

Dark photon decays to visible final states

SHiP

Dark photons decay to pair of SM particles by mixing again with the SM photon. The dark photon decay width to leptons is given by

$$\Gamma_{A'\to l^+l^-} = \frac{1}{3}\epsilon^2 \alpha m_V \left(1 + \frac{2m_l^2}{m_V^2}\right)\sqrt{1 - \frac{4m_l^2}{m_V^2}},$$

The partial decay width to hadrons is given by:

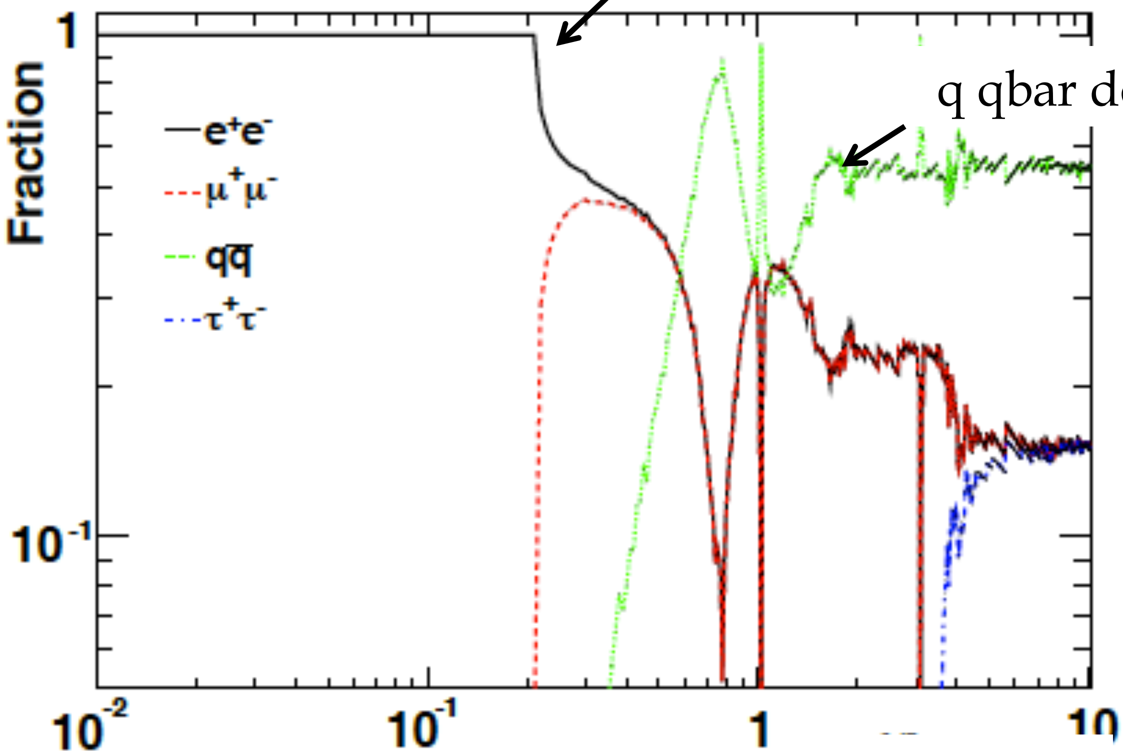
$$\Gamma_{V\to\mathrm{hadrons}} = \frac{1}{3}\alpha\epsilon^2 m_V \sqrt{1 - \frac{4m_\mu^2}{m_V^2}}\left(1 + \frac{2m_\mu^2}{m_V^2}\right) R(s = m_V^2).$$

where

$$R(\sqrt{s}) = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}.$$

Branching fraction predictions for A′ → l+ l- and A′ →q qbar as a function of m(A′):

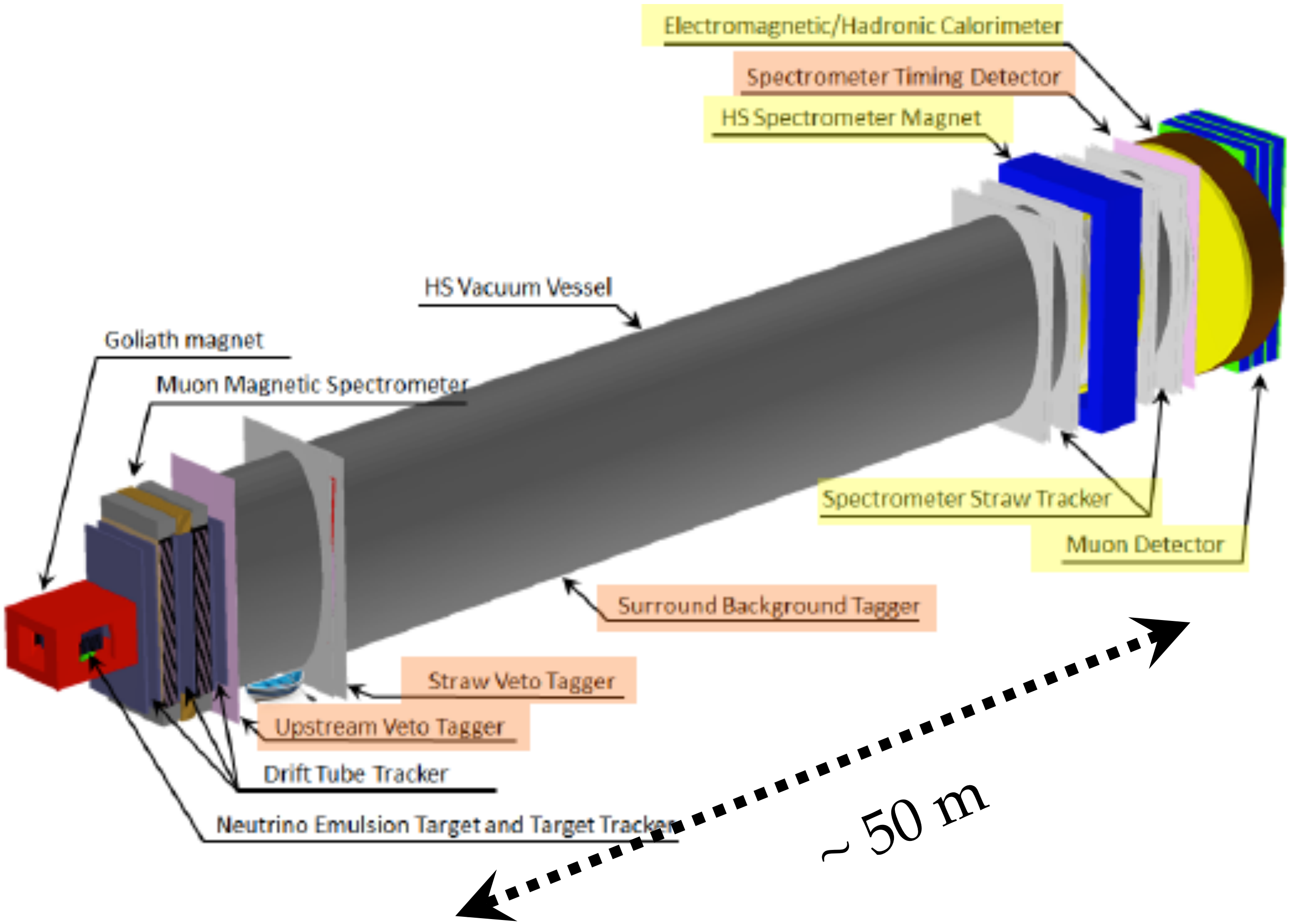
e^+e^- dominant below 2 m_μ



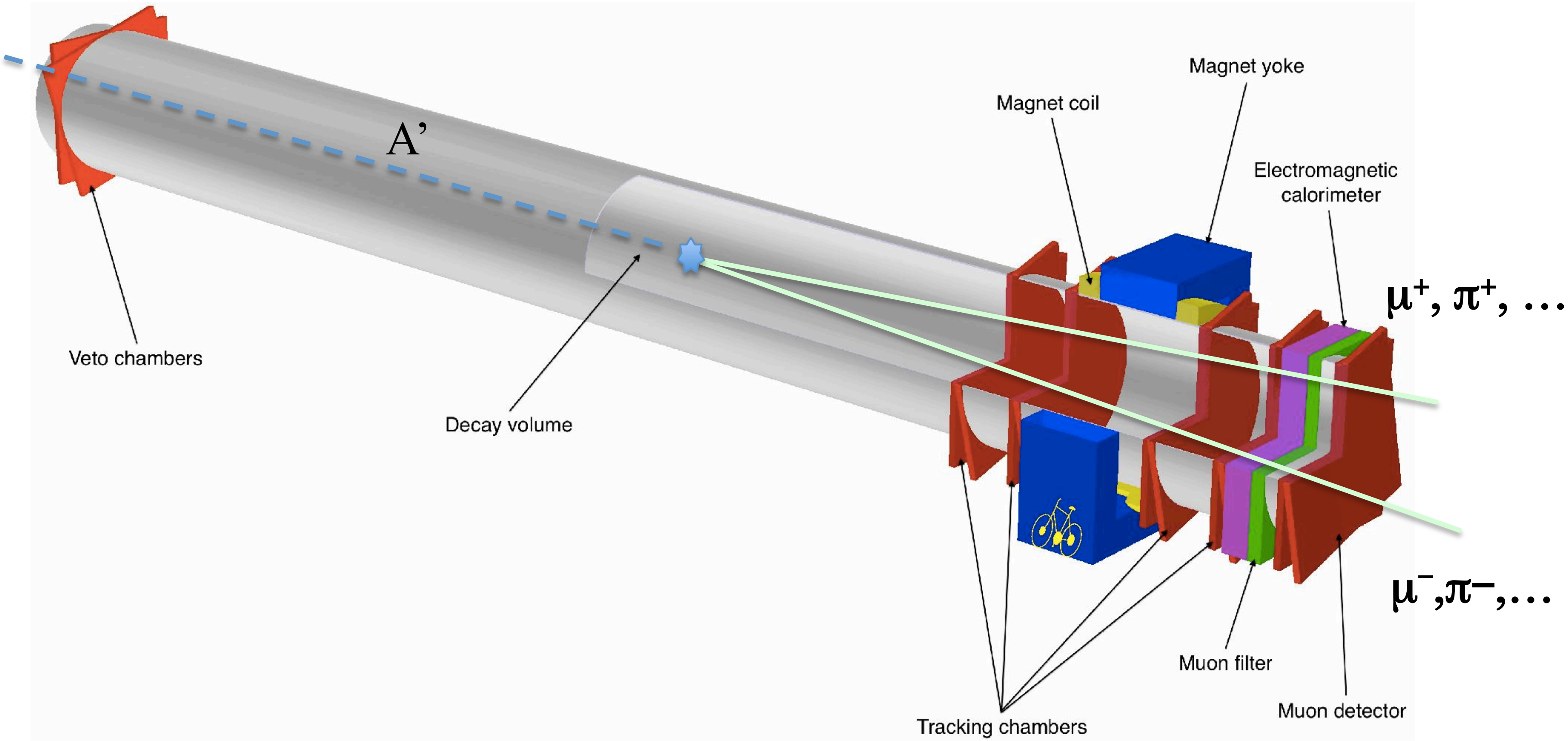
q qbar dominant above $2m_{charm}$

M(A’) (GeV)

The SHiP detector



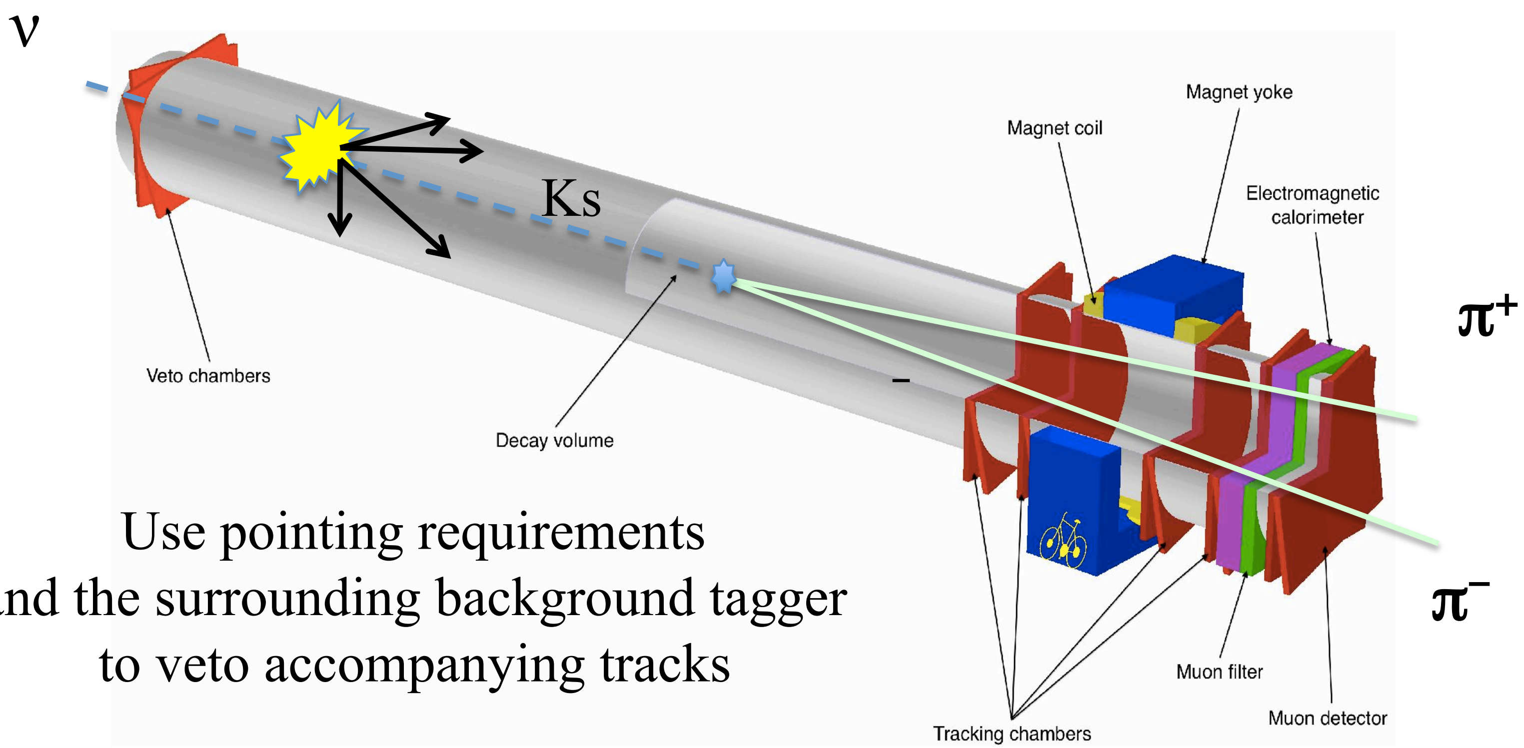
The SHiP detector: A' →μμ decay



Backgrounds:

Inelastic scattering of neutrino/muon beam-induced background with the detector material:

Background source	Decay modes
ν or μ + nucleon $\rightarrow X + K_L$	$K_L \rightarrow \pi e \nu, \pi \mu \nu, \pi^+\pi^-, \pi^+\pi^-\pi^0$
ν or μ + nucleon $\rightarrow X + K_S$	$K_S \rightarrow \pi^0\pi^0, \pi^+\pi^-$
ν or μ + nucleon $\rightarrow X + \Lambda$	$\Lambda \rightarrow p\pi^-$
n or p + nucleon $\rightarrow X + K_L$, etc	as above

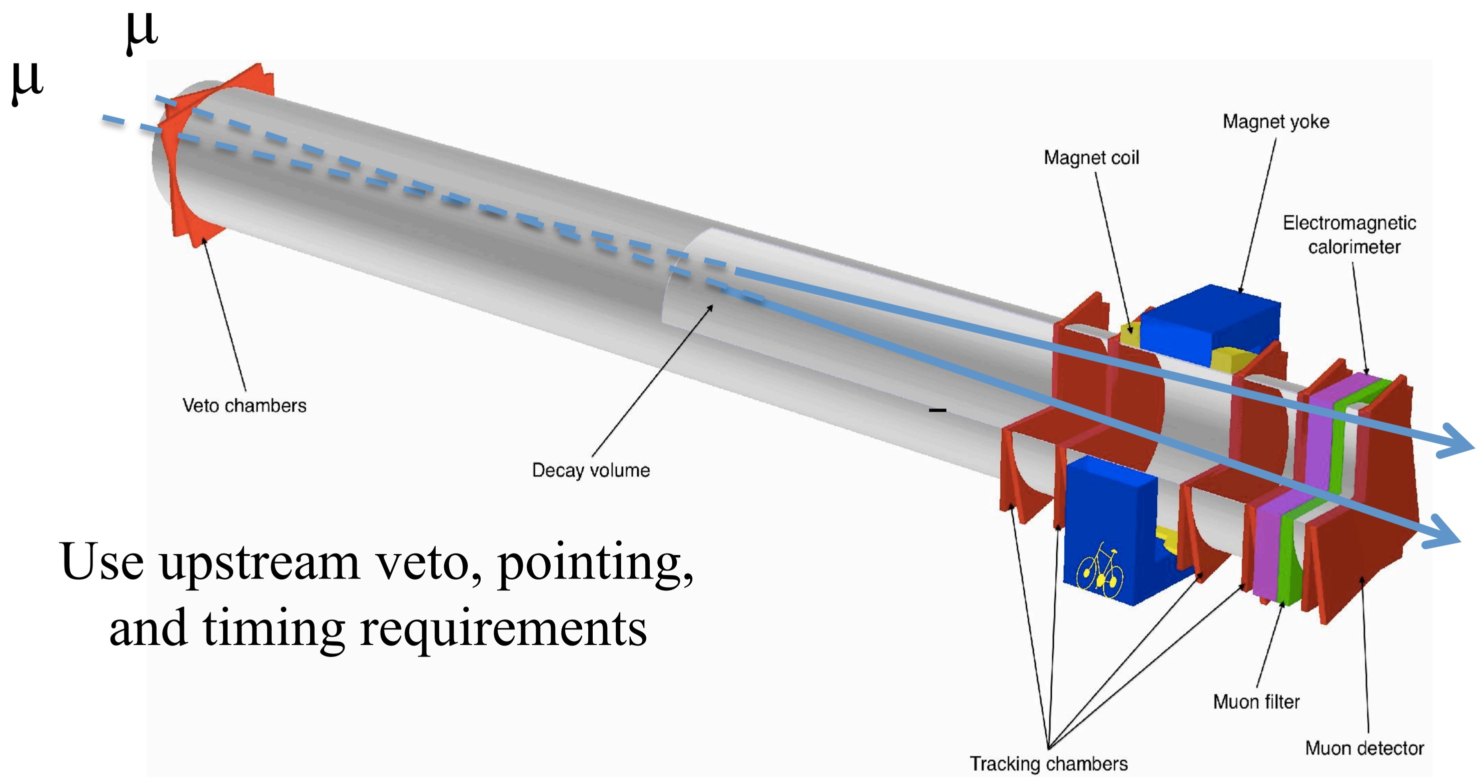


Use pointing requirements
and the surrounding background tagger
to veto accompanying tracks

Backgrounds:

Beam-induced combinatorial muon background:

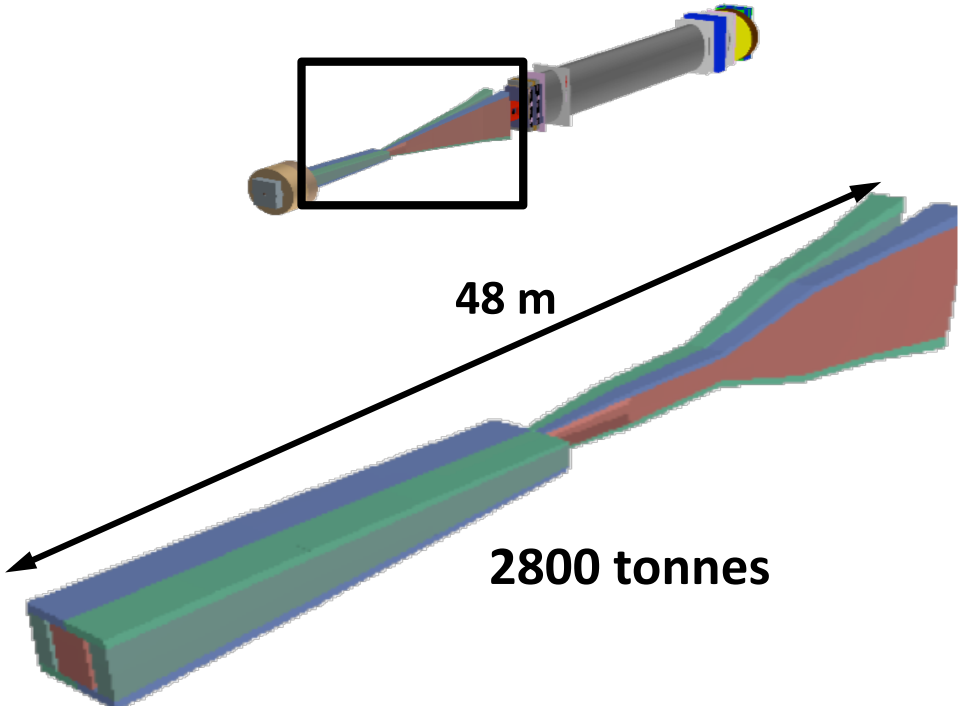
Random combinations of residual muon flux from proton interactions in the target can mimic signal if they form a (fake) vertex in the fiducial volume.
For 4×10^{13} pot/spill 1 sec long, several kHz of muons after the active filter are expected in acceptance: → **effectively rejected via a short time-coincidence.**

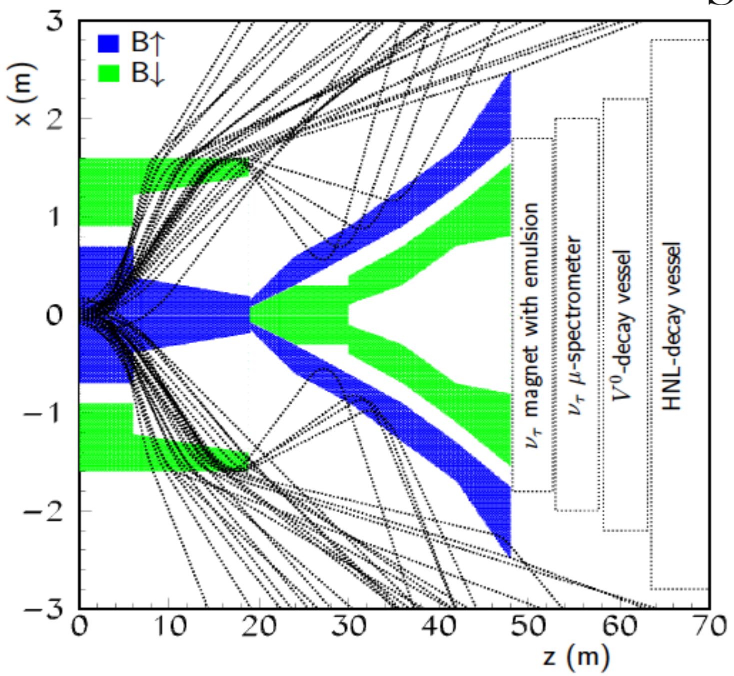


Use upstream veto, pointing, and timing requirements

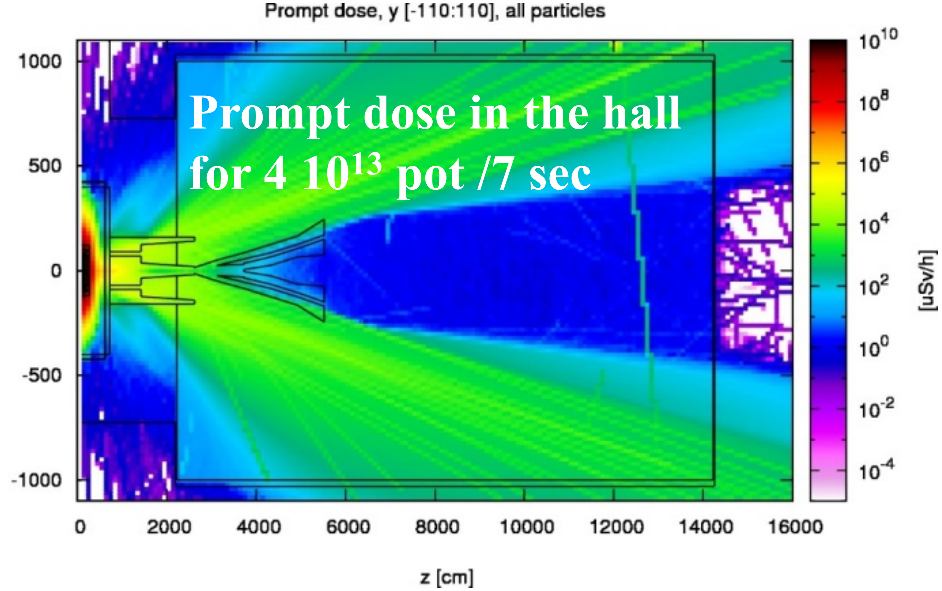
SHiP active muon shield:

It ranges out beam-induced muons:





- Shield based entirely on magnetic sweeping
- Residual flux on detectors 7 10^3 muons/ spill
- Negligible occupancy

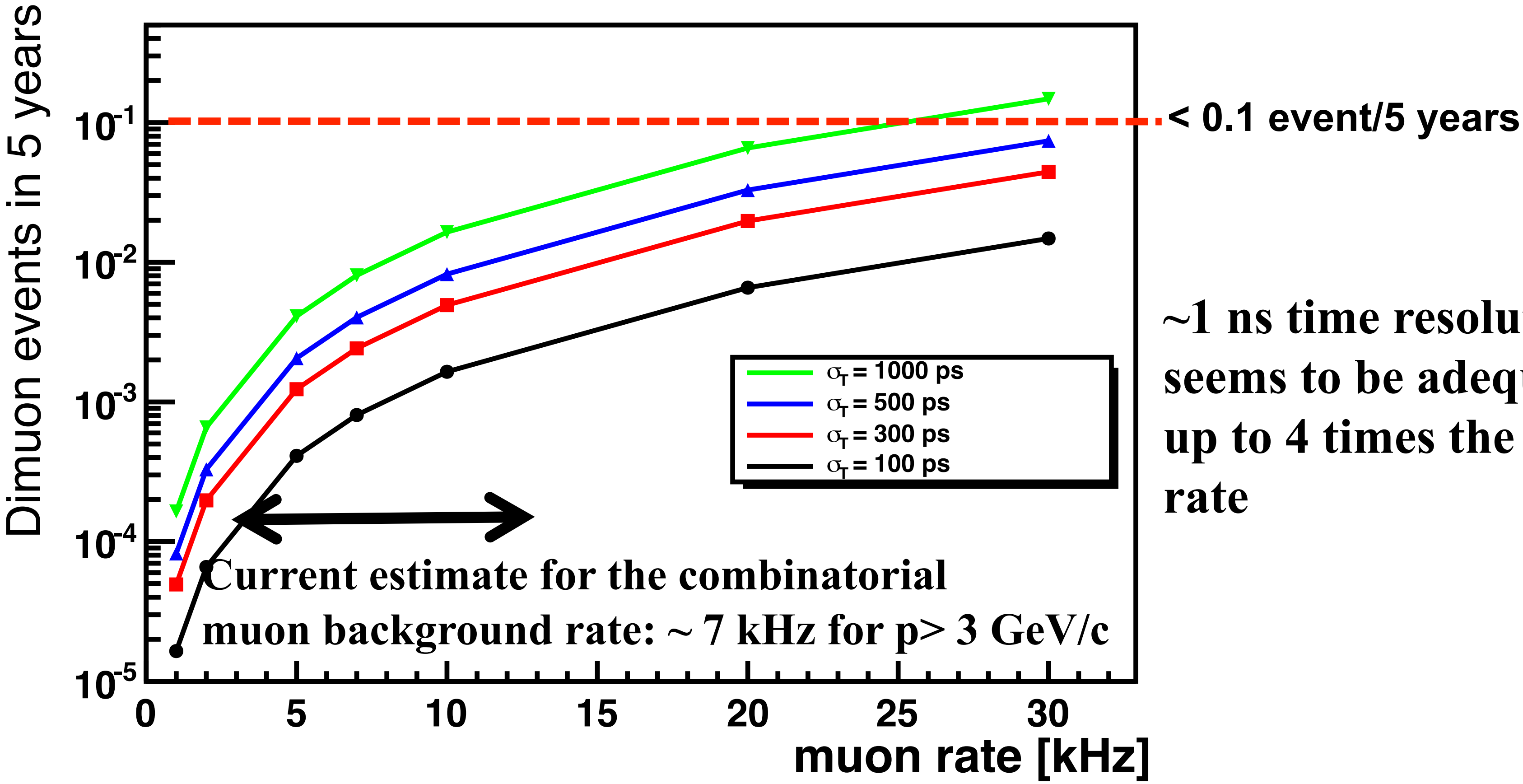


Challenges: flux leakages, constant field profile, modeling magnet shape

SHiP active muon shield: residual muon flux

SHiP

Reconstructed, selected and not-vetoed di-muon events in 5 years in time window $\Delta T = 3.29\ \sigma_T$ (99.9%) as a function of the muon flux after the active filter.

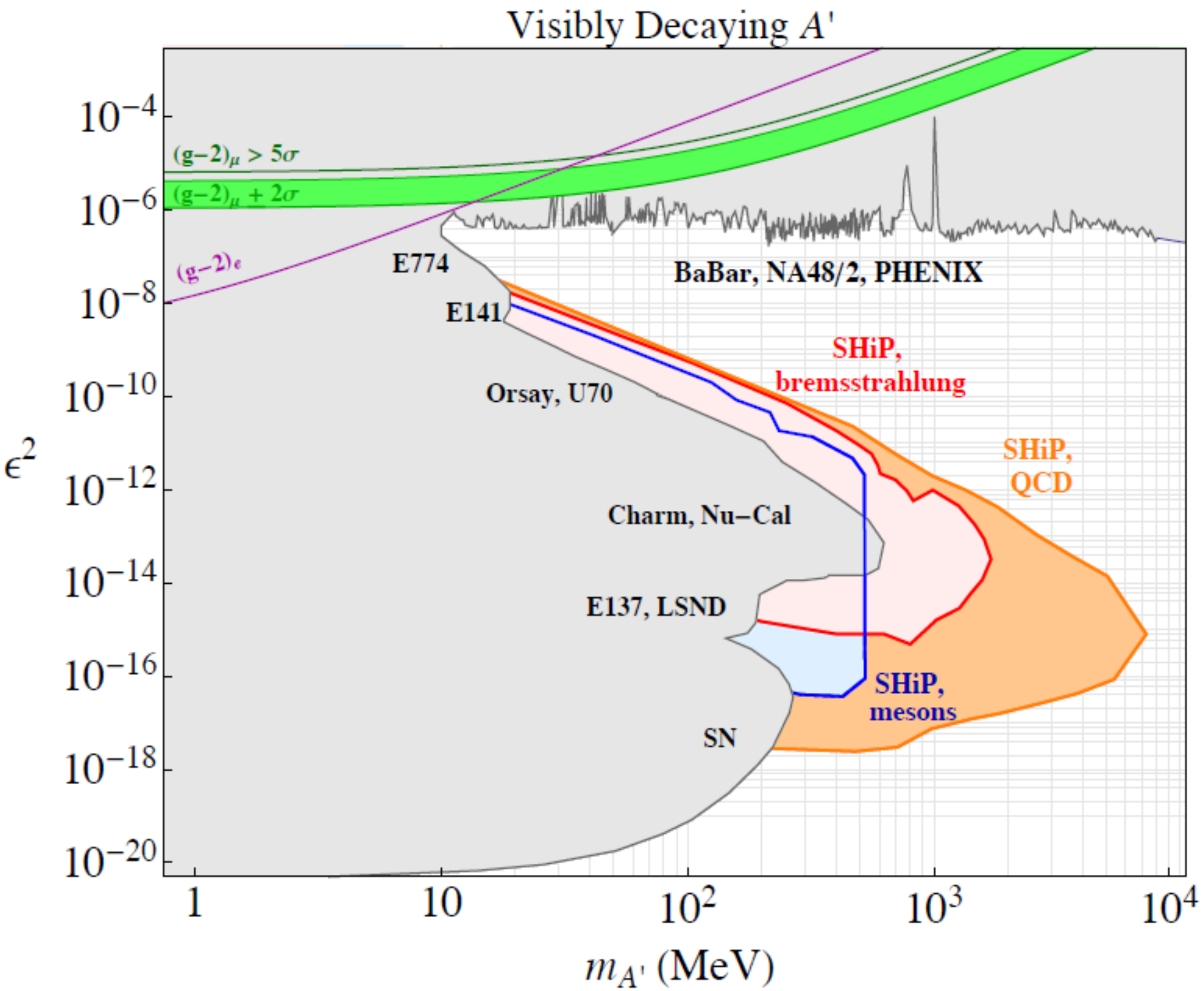


~1 ns time resolution seems to be adequate up to 4 times the current rate

Residual muon flux after active shield
can be effectively removed using timing information.

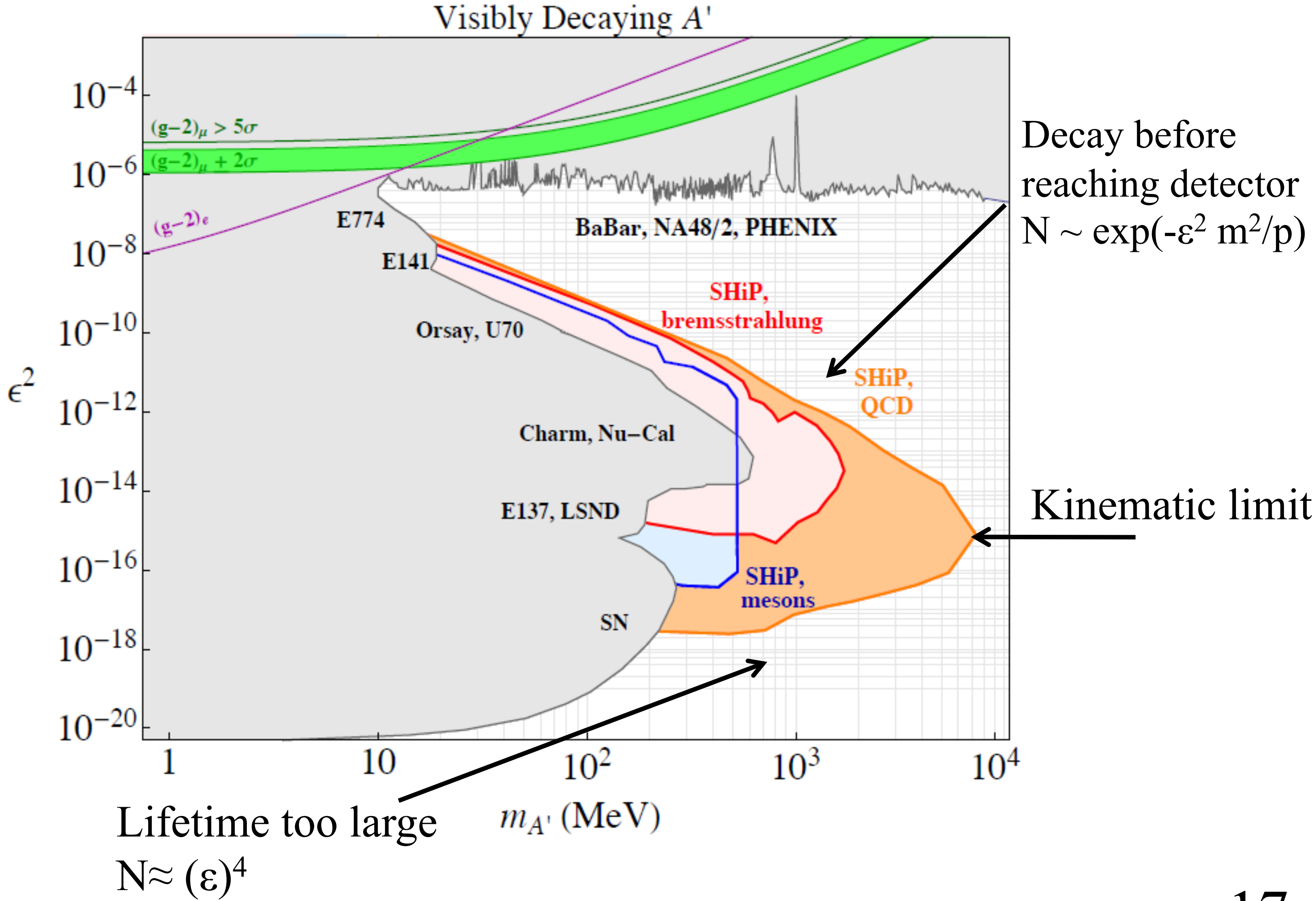
SHiP sensitivity to the A’ → visible

2 10^{20} pot in 5 years of running

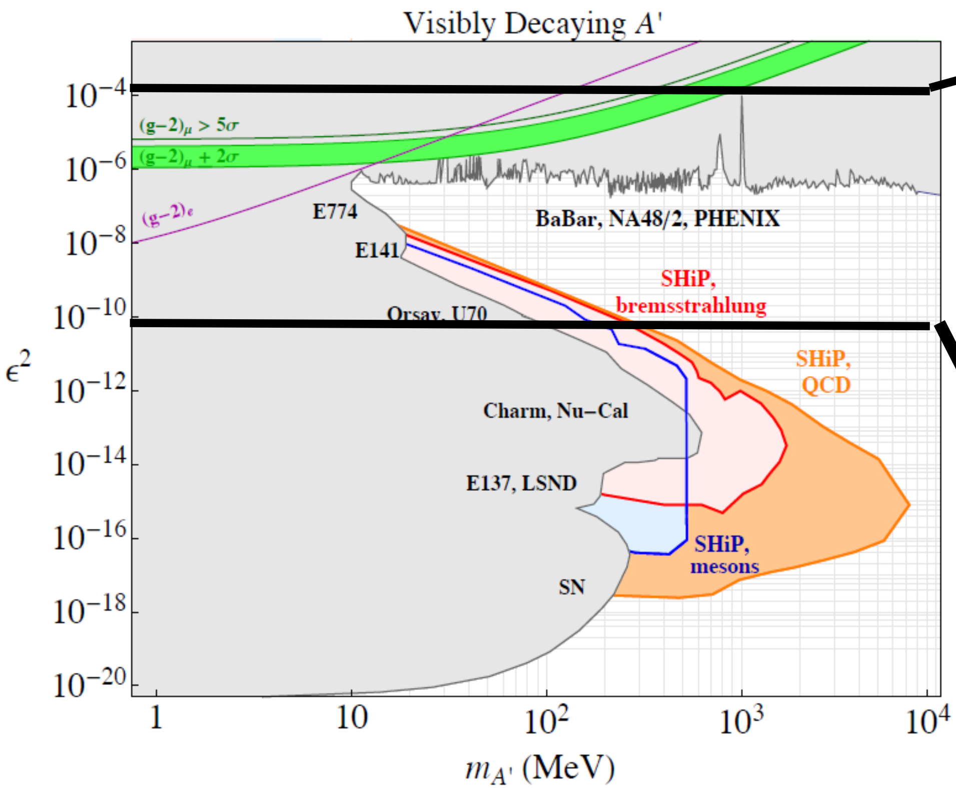


SHiP sensitivity to the A' → visible

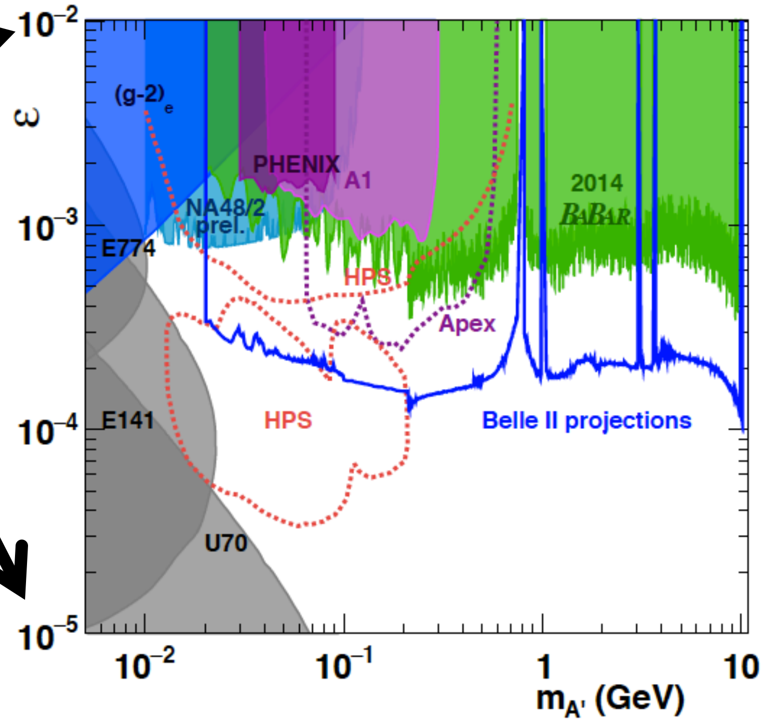
2 10^{20} pot in 5 years of running



Sensitivity to A′ → visible: SHiP vs HPS, APEX and Belle-II



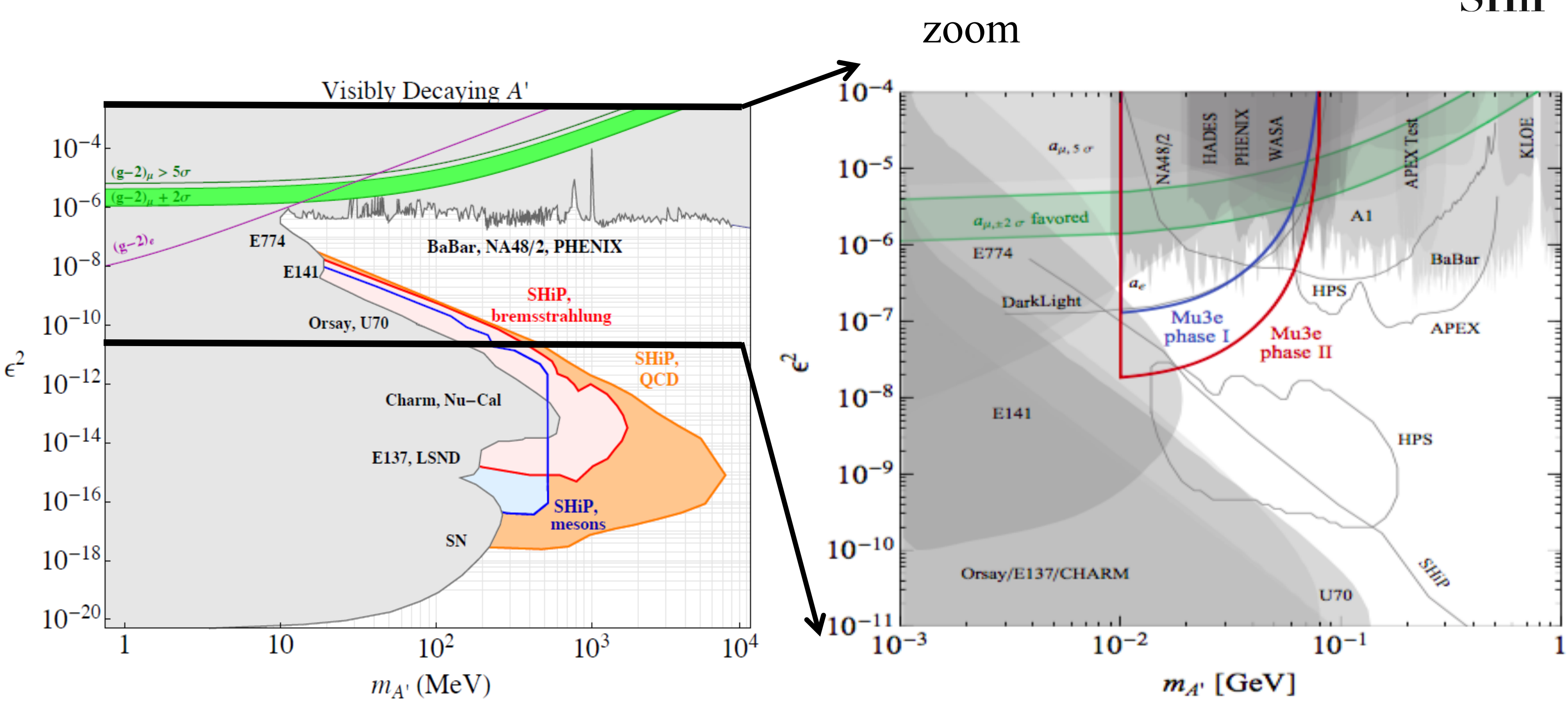
zoom



SHiP will have sensitivity in a range that cannot be covered by any current or planned experiment

Caveat: these limits are valid in the assumption that A' does not decay in dark matter

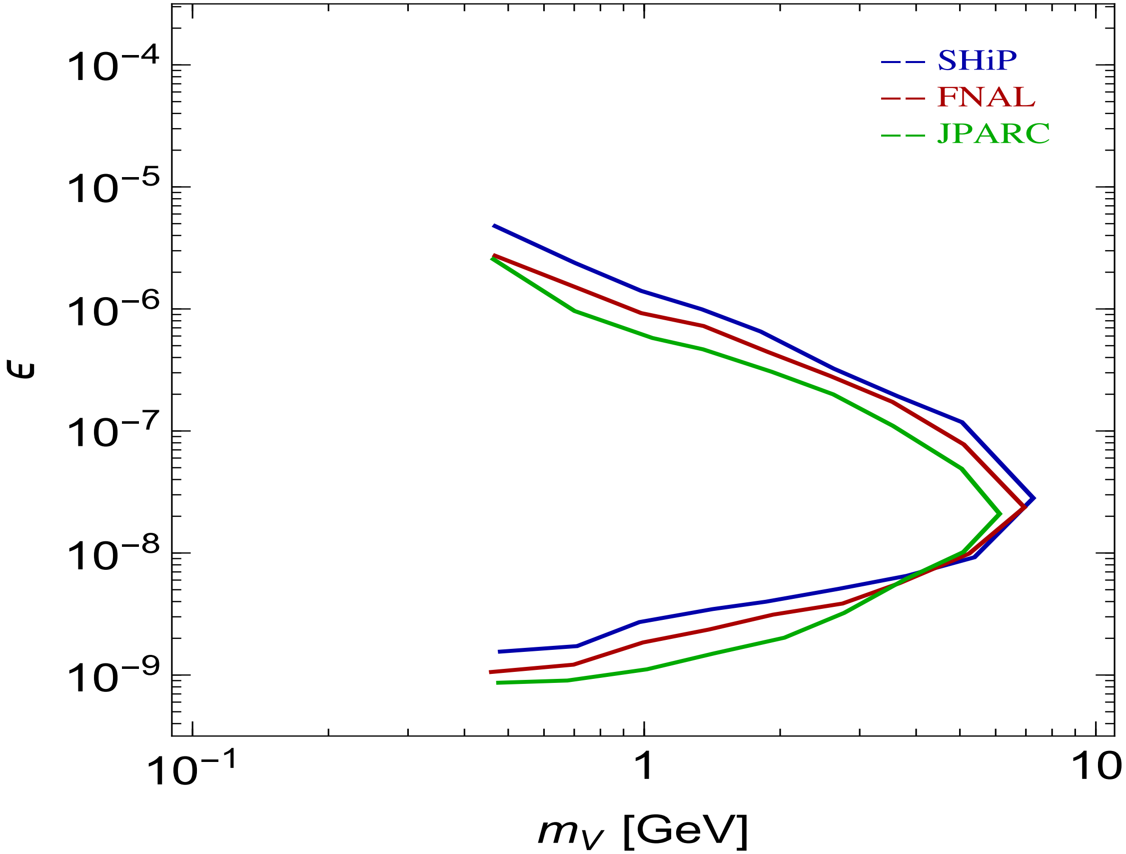
Sensitivity to A′ → visible: SHiP vs Mu3e phase-I and phase-II



SHiP will have sensitivity in a range that cannot be covered by any current or planned experiment

Caveat: these limits are valid in the assumption that A' does not decay in dark matter

Sensitivity to A′ → visible: SHiP@SPS vs SHiP@FNAL or SHiP@JPARC



Assumptions: all protons of each facility are given to SHiP-like experiment:

- **SPS @ CERN:** 8.5 10^{19} pot/year, 400 GeV/c, slow extraction (1 sec spills),
- **FNAL:** 120 GeV
  - fast extraction (10 μsec spill) → 1.1 10^{21} pot/year, x100 muon combinatorial background
  - slow extraction (7.5 10^{13} pot/2.4 sec) → 5.9 10^{20} pot/year (max limit for high-Z target)
- **JPARC:** 30 GeV, 5x10^{14} pot/ 2 sec (excluded due to excessive heat on target)

Sensitivity to A′ → visible: SHiP@SPS vs SHiP@ILC

At the ILC the beam is dumped after each collision providing a platform for the design of an experiment to search for dark photons produced through the bremsstrahlung mechanism.

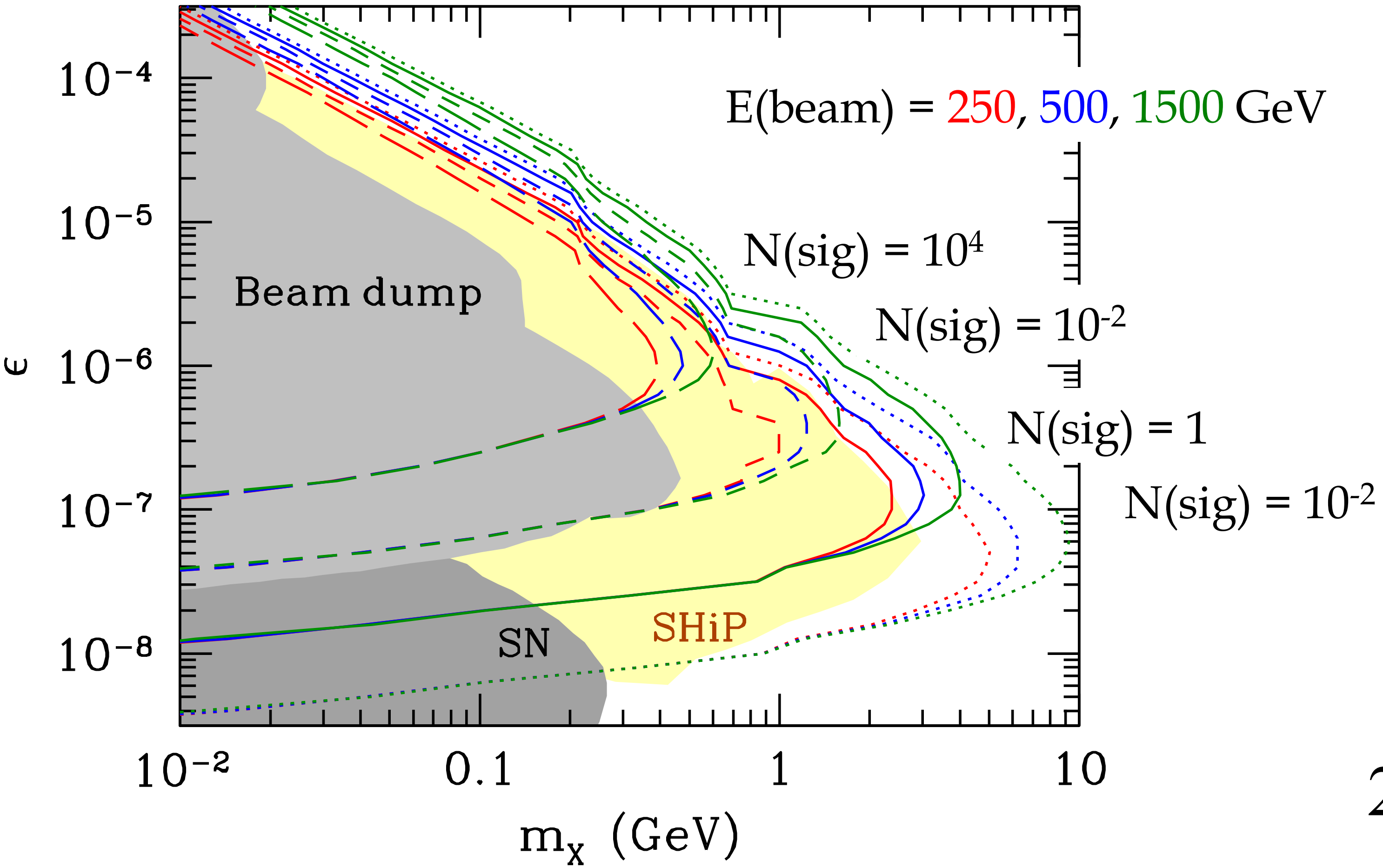
Assumptions:

N (eot) = 4 10^{21}

L dump = 11 m

L shield = 50 m

L decay = 50 m



Conclusions

- SHiP is a proposed experiment at the CERN SPS.
- If approved, SHiP will start to operate in 2026 and will cover a broad spectrum of hidden sector searches.
- The SHiP sensitivity to dark photons to visible final states will cover a range that cannot be covered by any existing or planned experiment.

For a complete description of the status of the SHiP experiment at CERN see A. Golutvin (SHiP spokesperson)'s talk on Friday morning, Rich Dark Sector session.