Hidden sector searches at NA62 and SHiP

Philippe Mermod, on behalf of the SHiP Collaboration

NUFACT, Uppsala, 29 September 2017

Where are the new physics?

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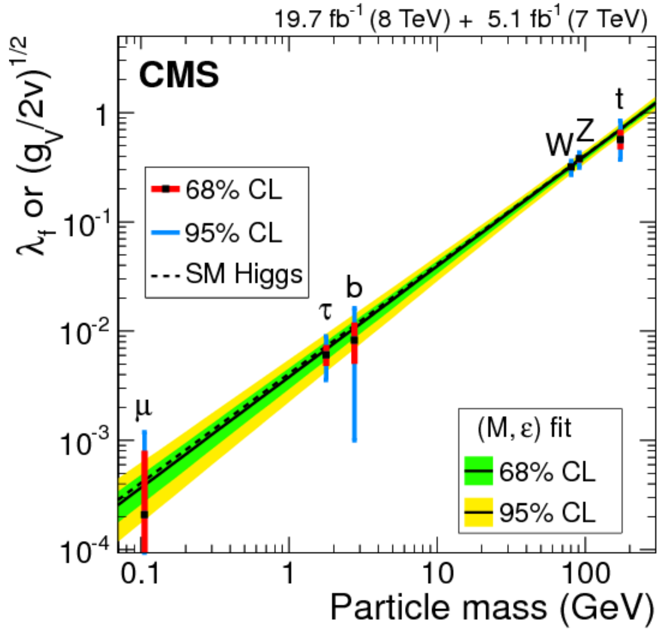
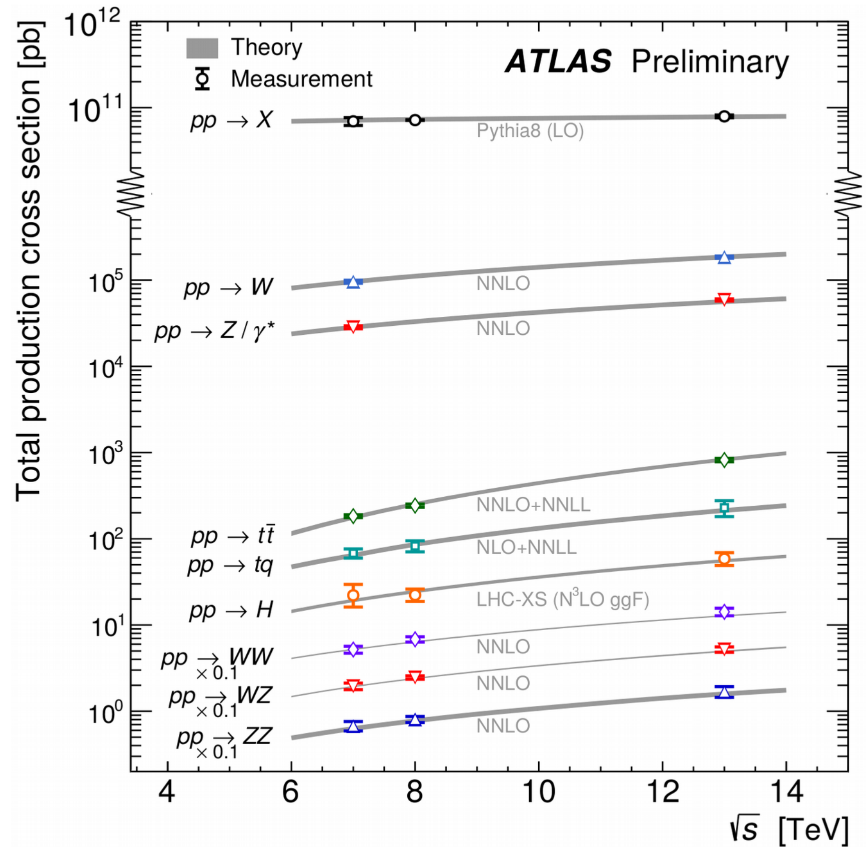
No new physics so far at the LHC **even at the highest energies**

- The SM is a triumph up to the TeV scale





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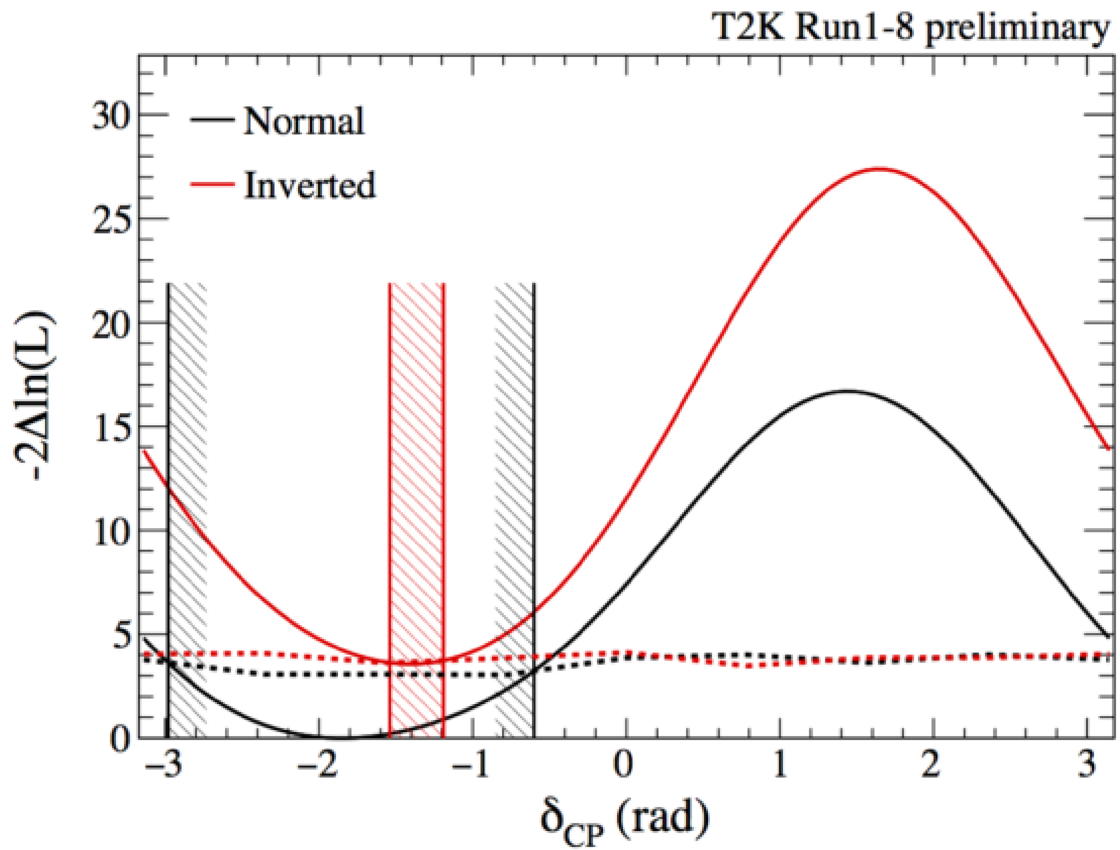
T2K might be seeing **CP violation in the neutrino sector**

- Can reasonably expect 3σ level confirmation within 10 years



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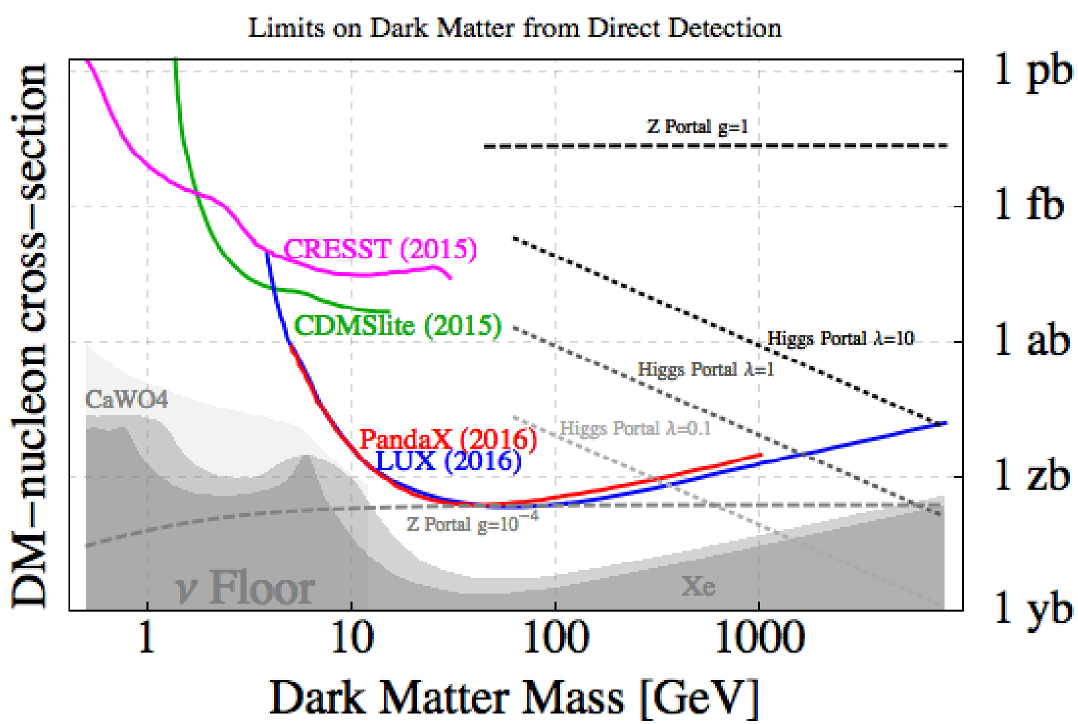
No dark-matter interactions seen on Earth

- Renewed interest in light dark matter scenarios



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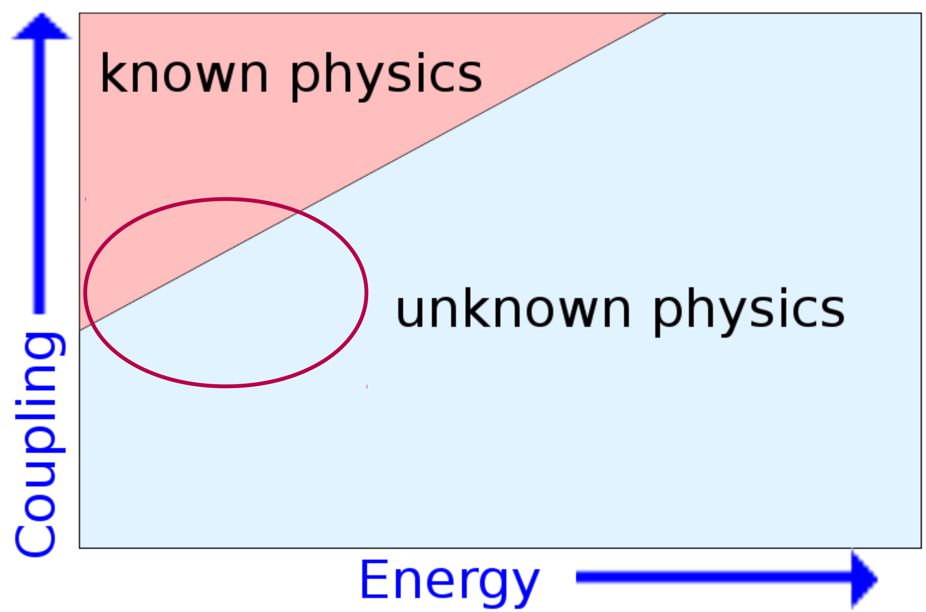
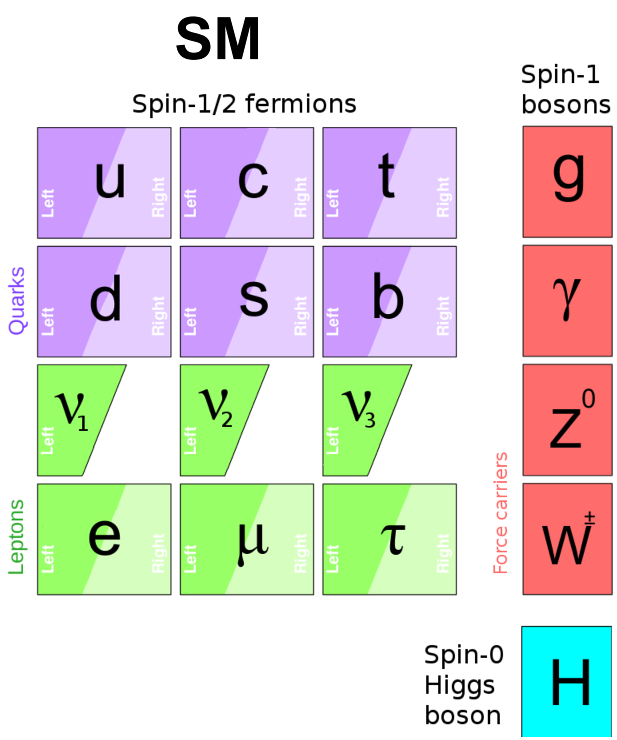
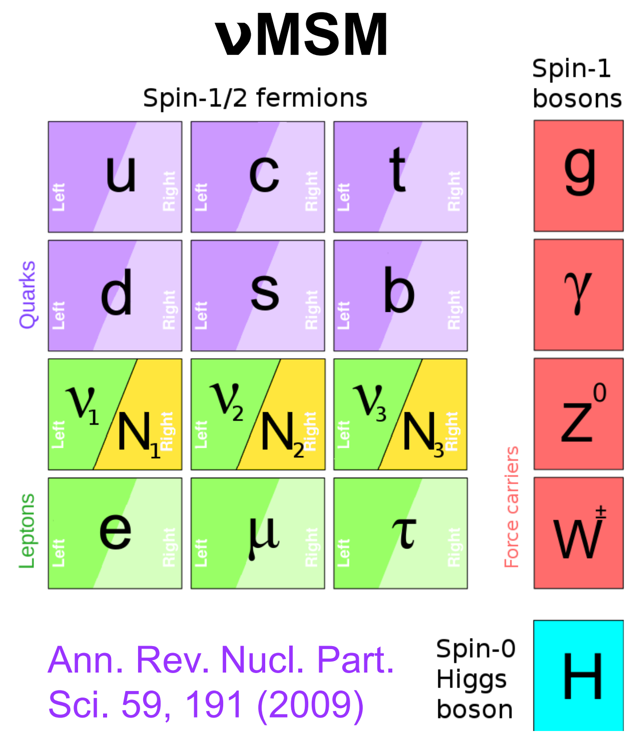
Probing *hidden sectors*:
light particles with low coupling to the SM



Still 3 missing pieces to the SM





Ann. Rev. Nucl. Part. Sci. 59, 191 (2009)

N

Heavy neutral lepton (HNL)
Right-handed neutrino
Heavy neutrino
Majorana neutrino
Sterile neutrino, etc.

N_1 mass ~keV

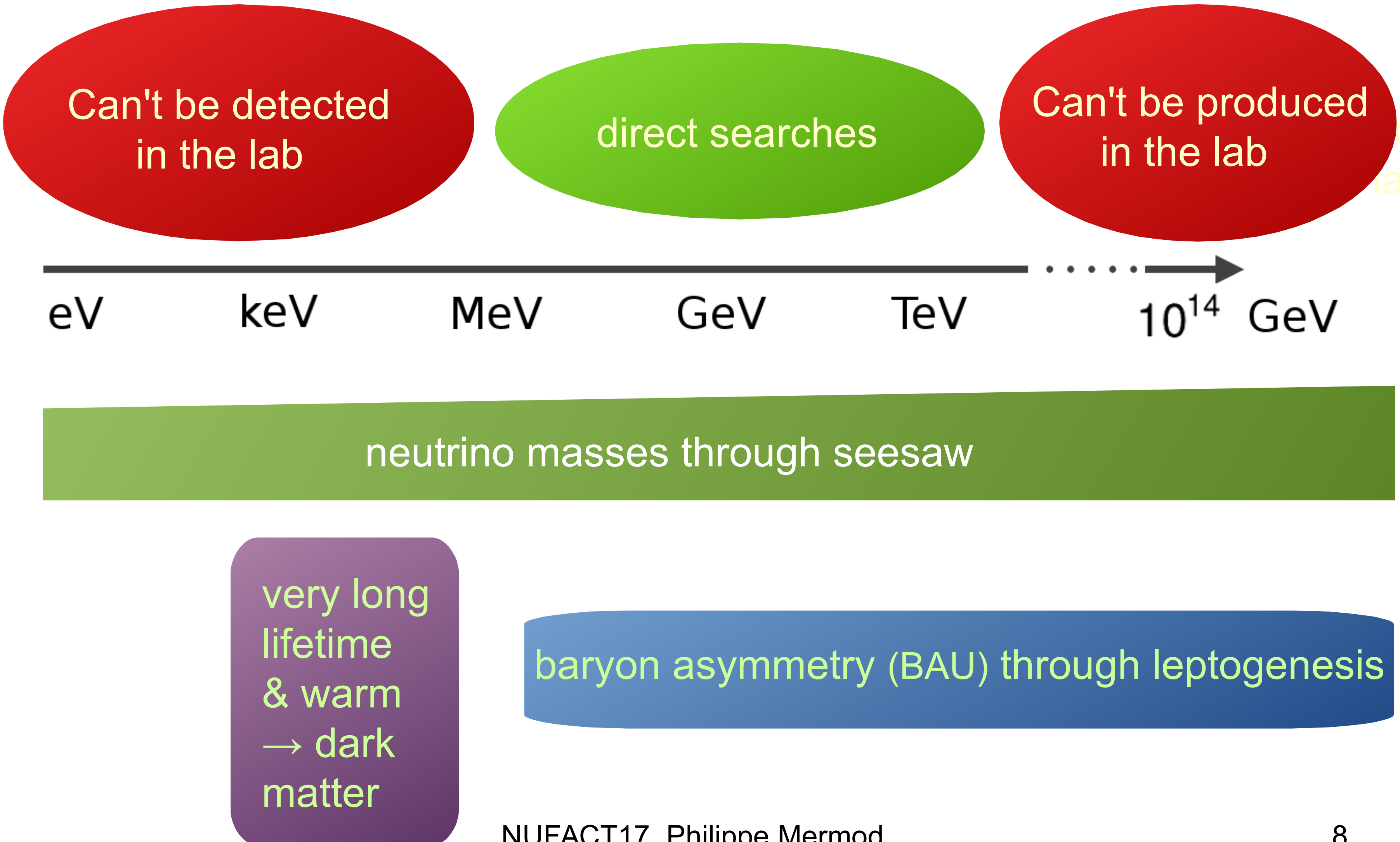
→ **dark matter**

$N_{2,3}$ mass ~GeV

→ **seesaw**

→ **leptogenesis**

No new mass scale introduced


Can't be detected in the lab
direct searches
Can't be produced in the lab
eV
keV
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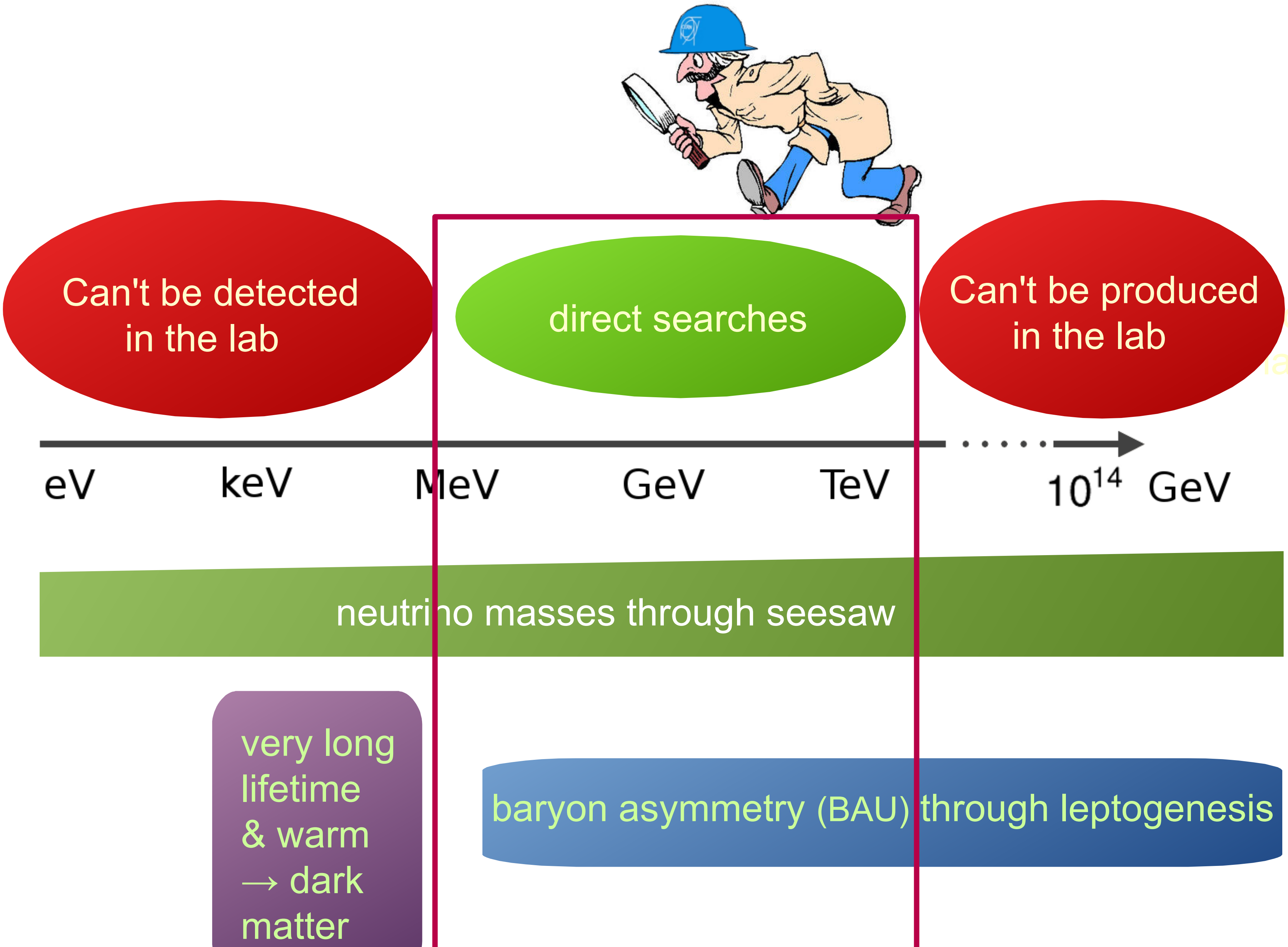
GeV
TeV
10^{14} GeV
neutrino masses through seesaw
very long lifetime & warm → dark matter
baryon asymmetry (BAU) through leptogenesis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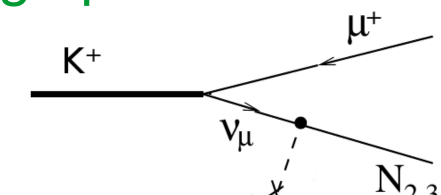
Probing hidden sectors with very small couplings to SM

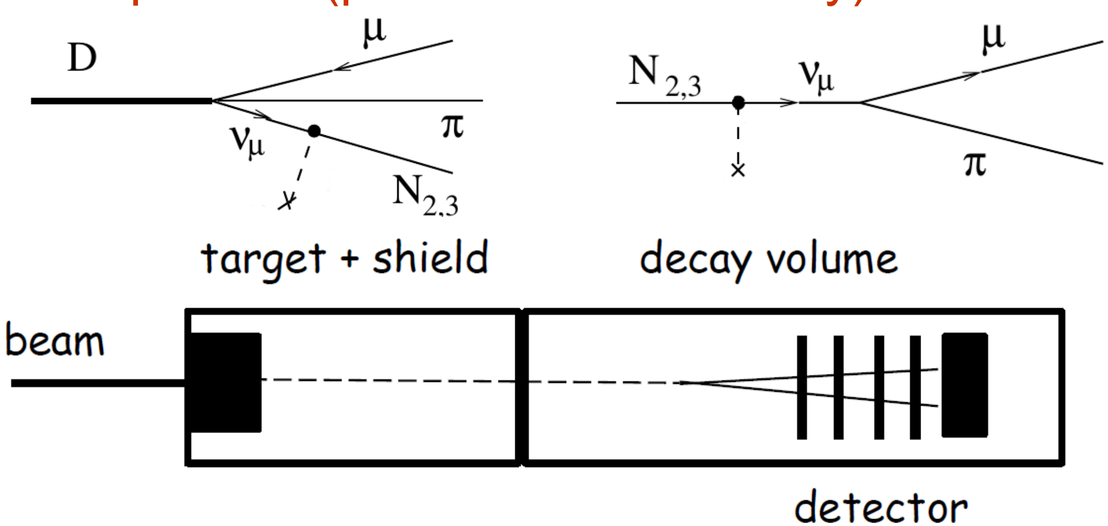
- High fluxes
- Displaced decays

Searches with proton beams

- masses up to 0.45 GeV probed through pion and kaon decays
  - **PS191** Phys. Lett. B 203, 332 (1988)
  - **NA62** in beam mode (production)

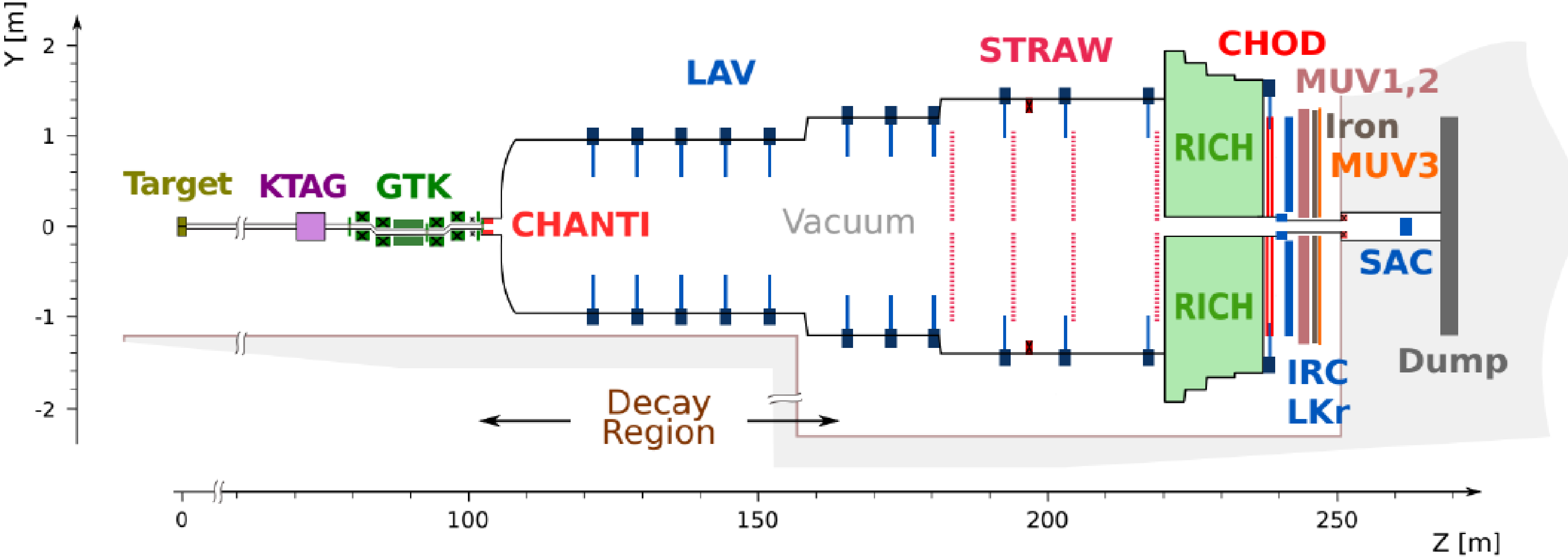


- masses up to 2 GeV probed through charmed meson decays
  - **CHARM** Phys. Lett. B 166, 473 (1986)
  - **NuTeV** Phys. Rev. Lett. 83, 4943 (1999)
  - **NA62** in dump mode (production and decay)
  - **SHiP**



The NA62 experiment

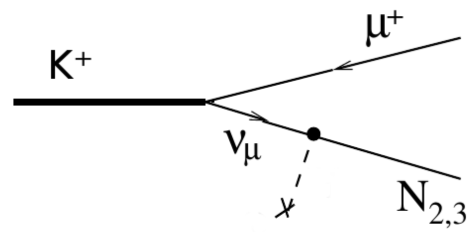
JINST 12, P05025 (2017)



Normal operation

- 400 GeV protons on target → collimated 75 GeV K^+ beam
- Tag K^+ in the beam
- Vacuum vessel as decay volume
- Reconstruct K^+ decay kinematics with high precision

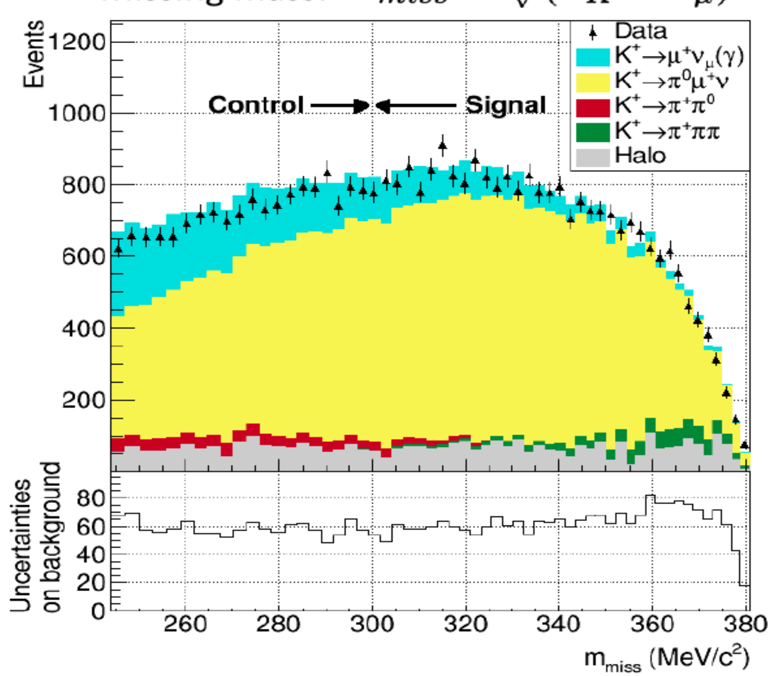
N search at NA62 in beam mode



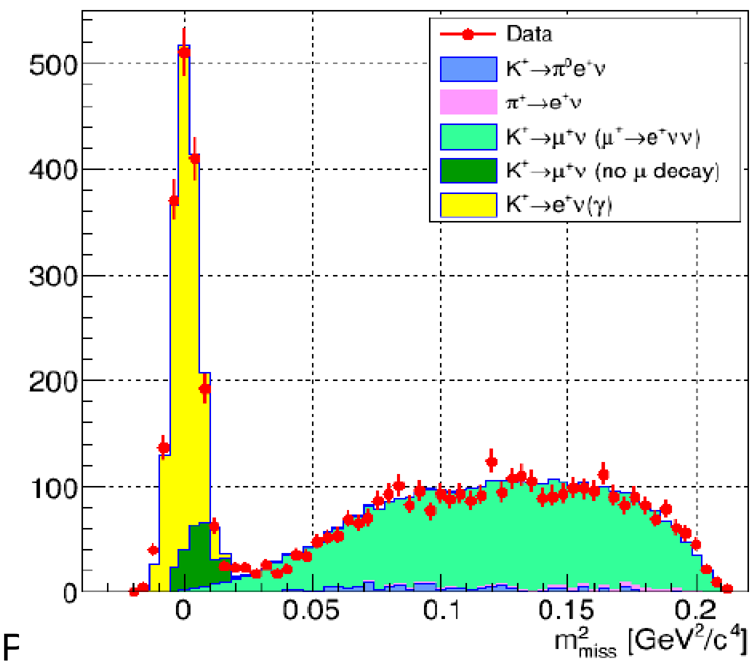
- Analysed datasets
  - 2007: 60 millions K^+, muon channel
  - 2015: 300 millions K^+, electron channel
- Look for excess in missing mass spectrum
- Probe couplings $U^2 \sim 10^{-7}$ for $m_N \sim 0.2 – 0.45$ GeV

$K^+ \to \mu^+ N$ arxiv:1705.07510

Missing mass: $m_{miss} = \sqrt{(P_K - P_\mu)^2}$



$K^+ \to e^+ N$



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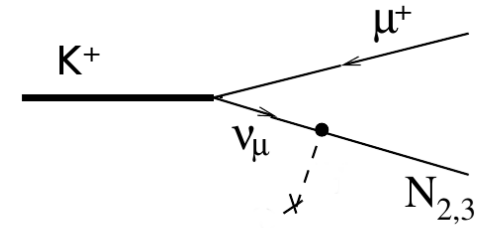

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$K^+ \rightarrow \mu^+ N$ arxiv:1705.07510

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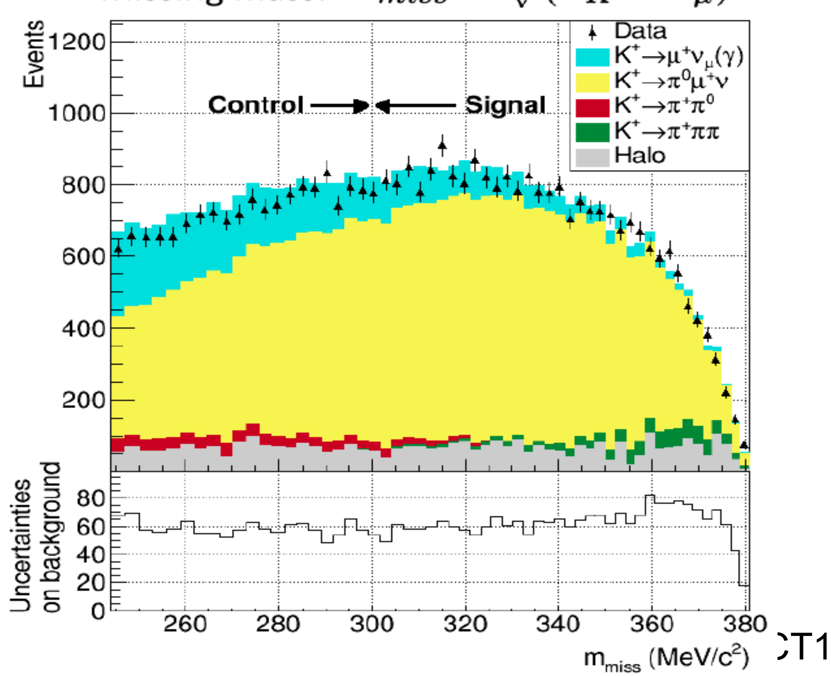
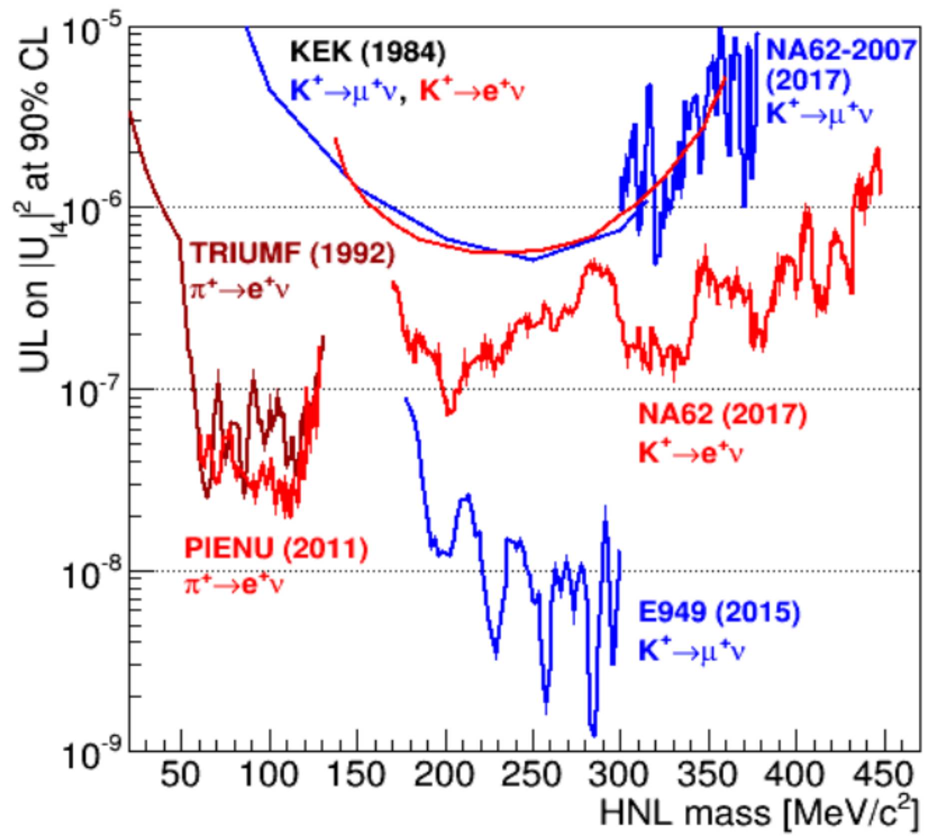
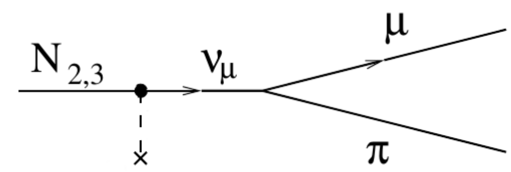
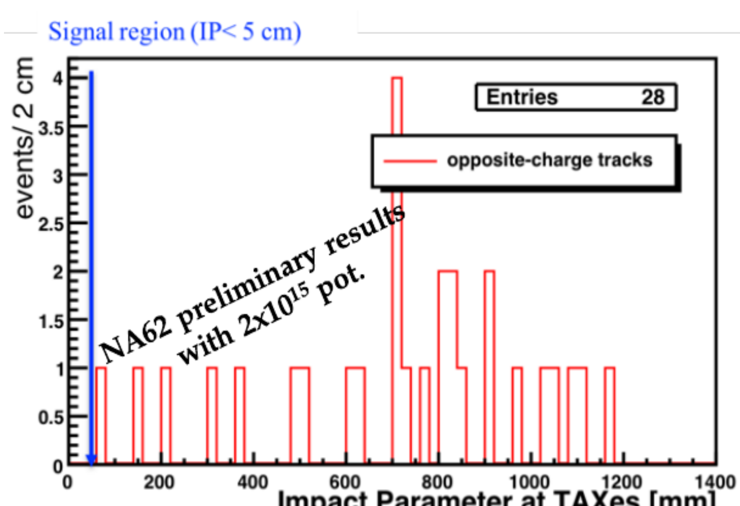


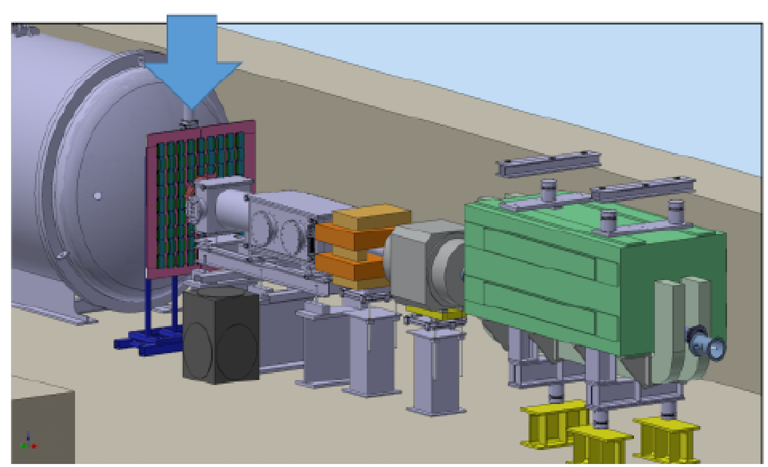


N search at NA62 in dump mode



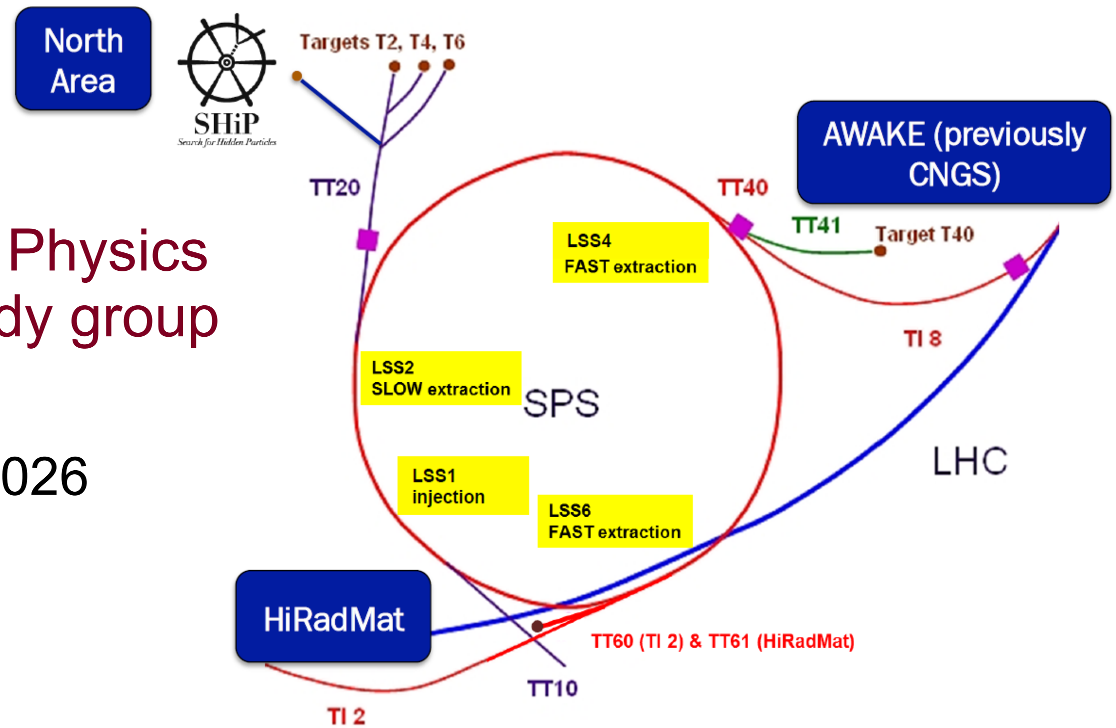
- Proposed NA62 operation in dump mode
  - Target removed, beam dumped directly on Cu collimator
  - Long-lived neutral particle decays in vacuum vessel
- Goal: integrate ~10^{18} pot in dump mode
  - ~3 months of dedicated data taking in 2021–2023
- Test run in dump mode ($2 \cdot 10^{15}$ pot) used to study backgrounds
  - Considered opposite-charge track vertices within 1 ns window
  - Background events do not point to the proton interaction and can be further rejected by adding an upstream veto detector





Search for Hidden Particles (SHiP)

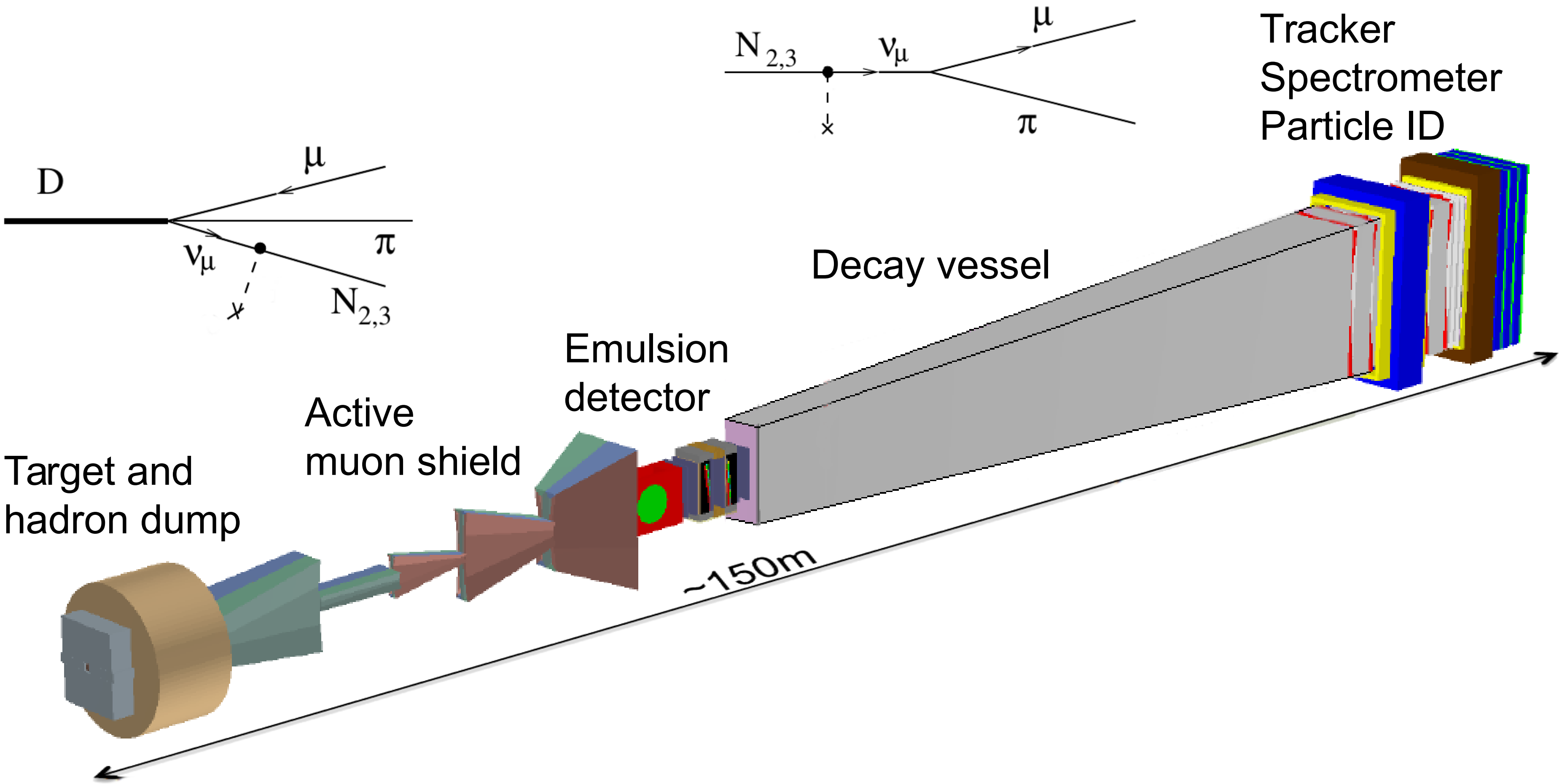
- Proposed facility: 400 GeV protons from the CERN SPS
  - New beam line and target complex
  - Aim at $2{\cdot}10^{20}$ pot in 5 years ($\rightarrow \sim 5{\cdot}10^{16}$ νs from charm decays)
- Collaboration of 250 members from 46 institutes
- Technical proposal arXiv:1504.04956 (2015) Physics paper Rep. Prog. Phys. 79 (2016)



- Major actor in CERN Physics Beyond Colliders study group
  - Approval ~2020
  - Physics runs ~2026

SHiP – detector

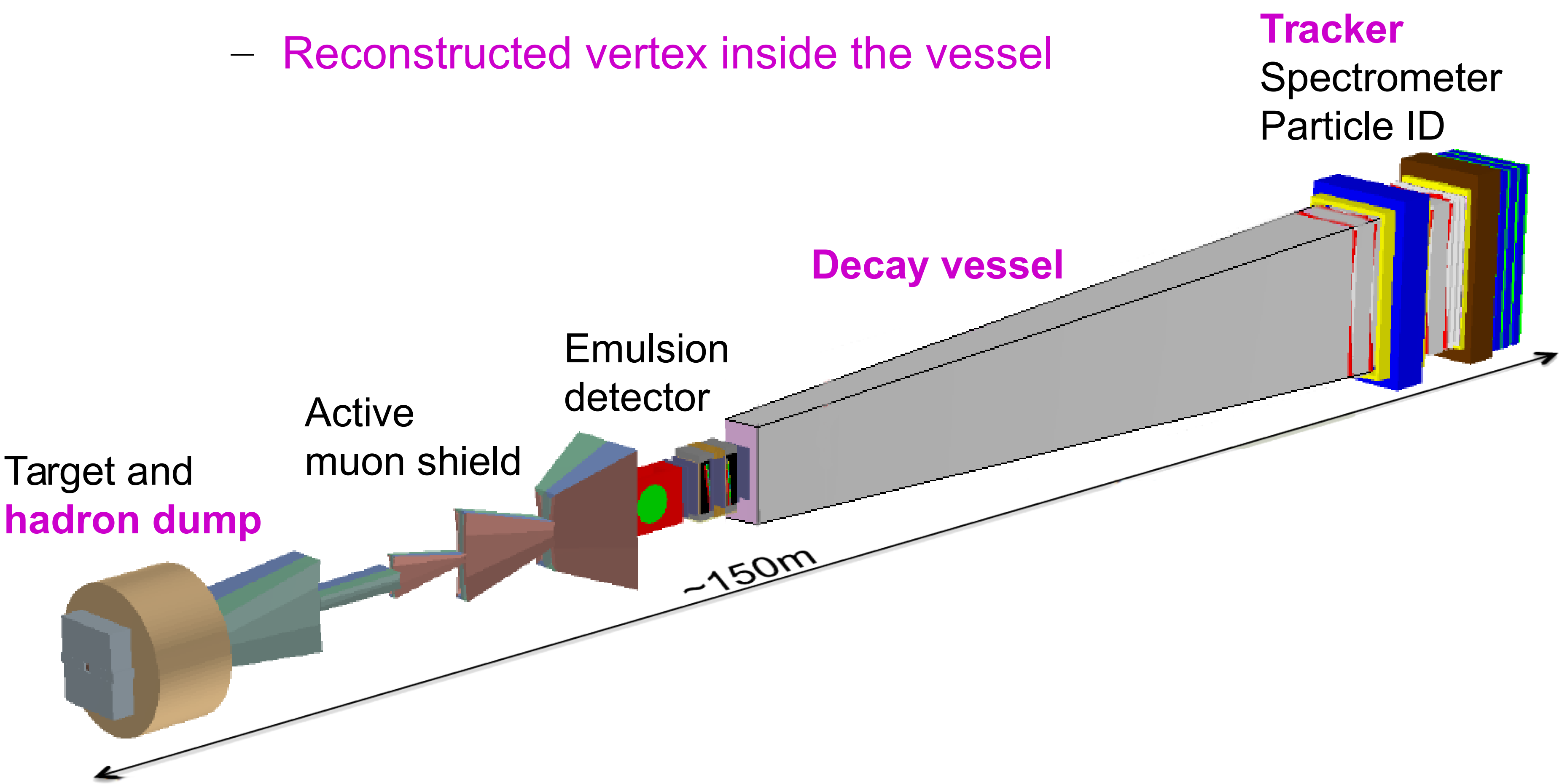
Designed for **large acceptance** and **zero backgrounds**



SHiP – detector

Designed for **large acceptance** and **zero backgrounds**

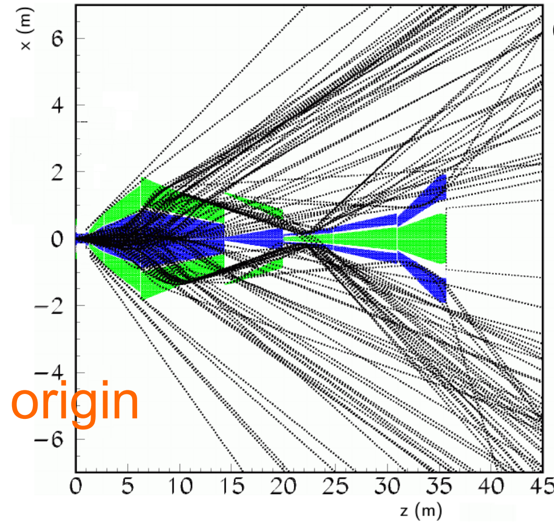
- Vertices from neutrinos
  - Stop pions and kaons before they decay
  - Evacuate the vessel
  - Reconstructed vertex inside the vessel



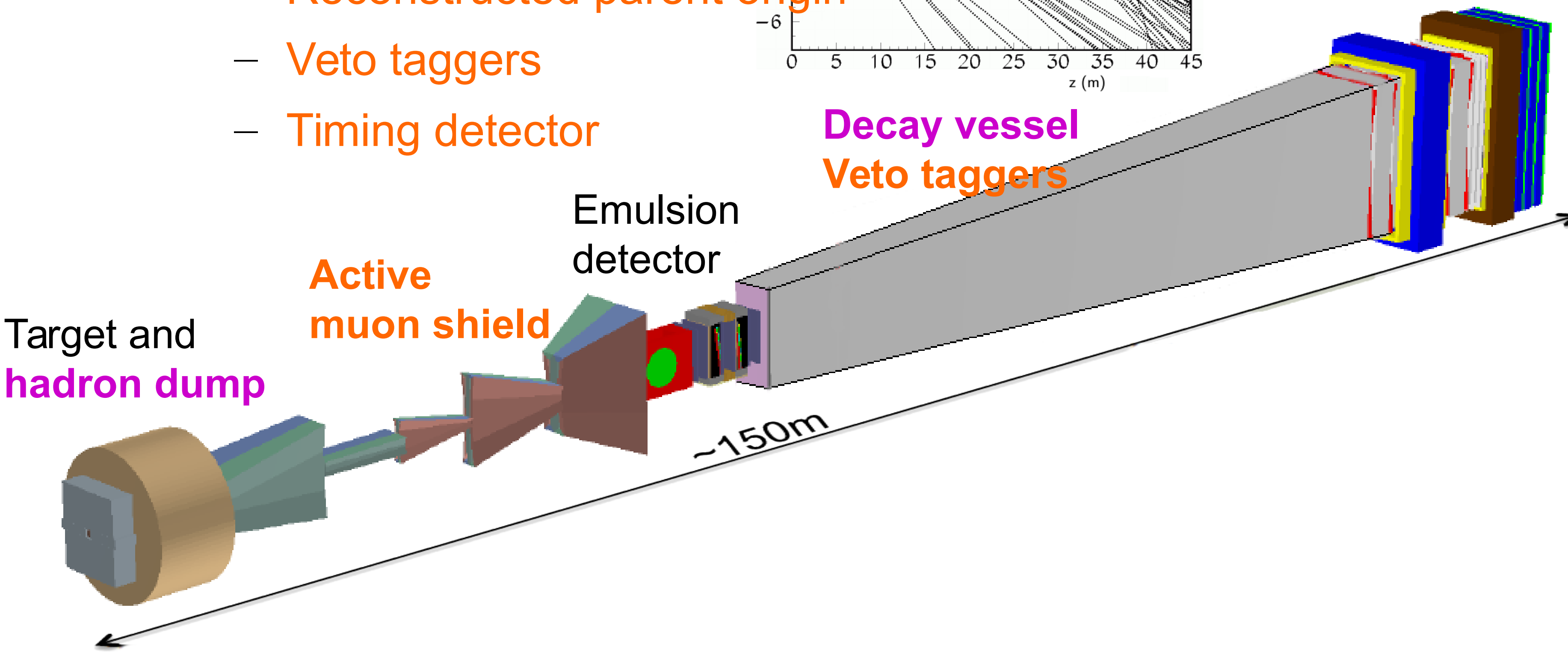
SHiP – detector

Designed for **large acceptance** and **zero backgrounds**

- Vertices from neutrinos
- Muon crossings
  - Magnetic shield
  - Particle ID
  - Reconstructed parent origin
  - Veto taggers
  - Timing detector



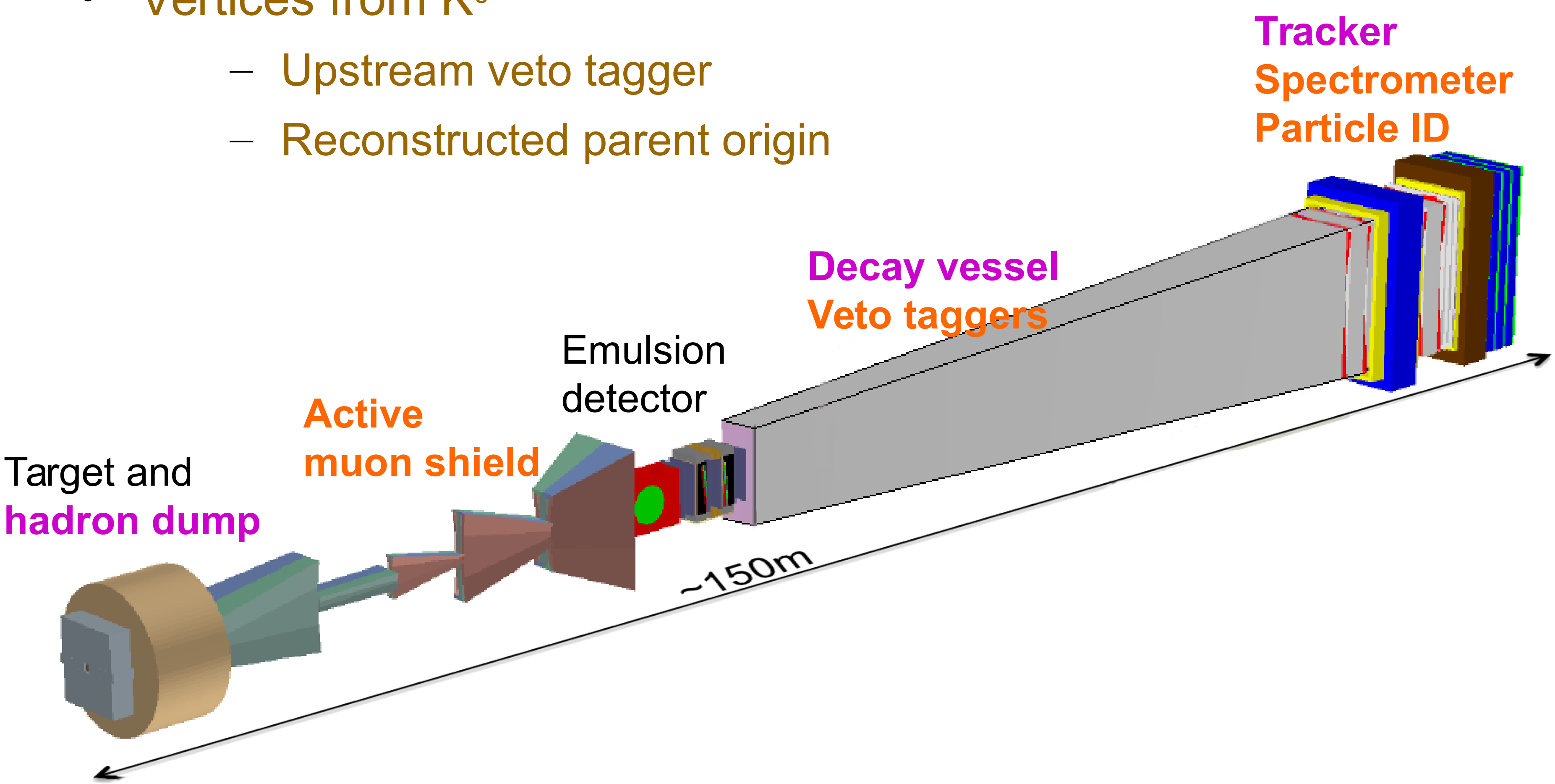
design minimises:
- muons in vessel
- length
- weight



SHiP – detector

Designed for **large acceptance** and **zero backgrounds**

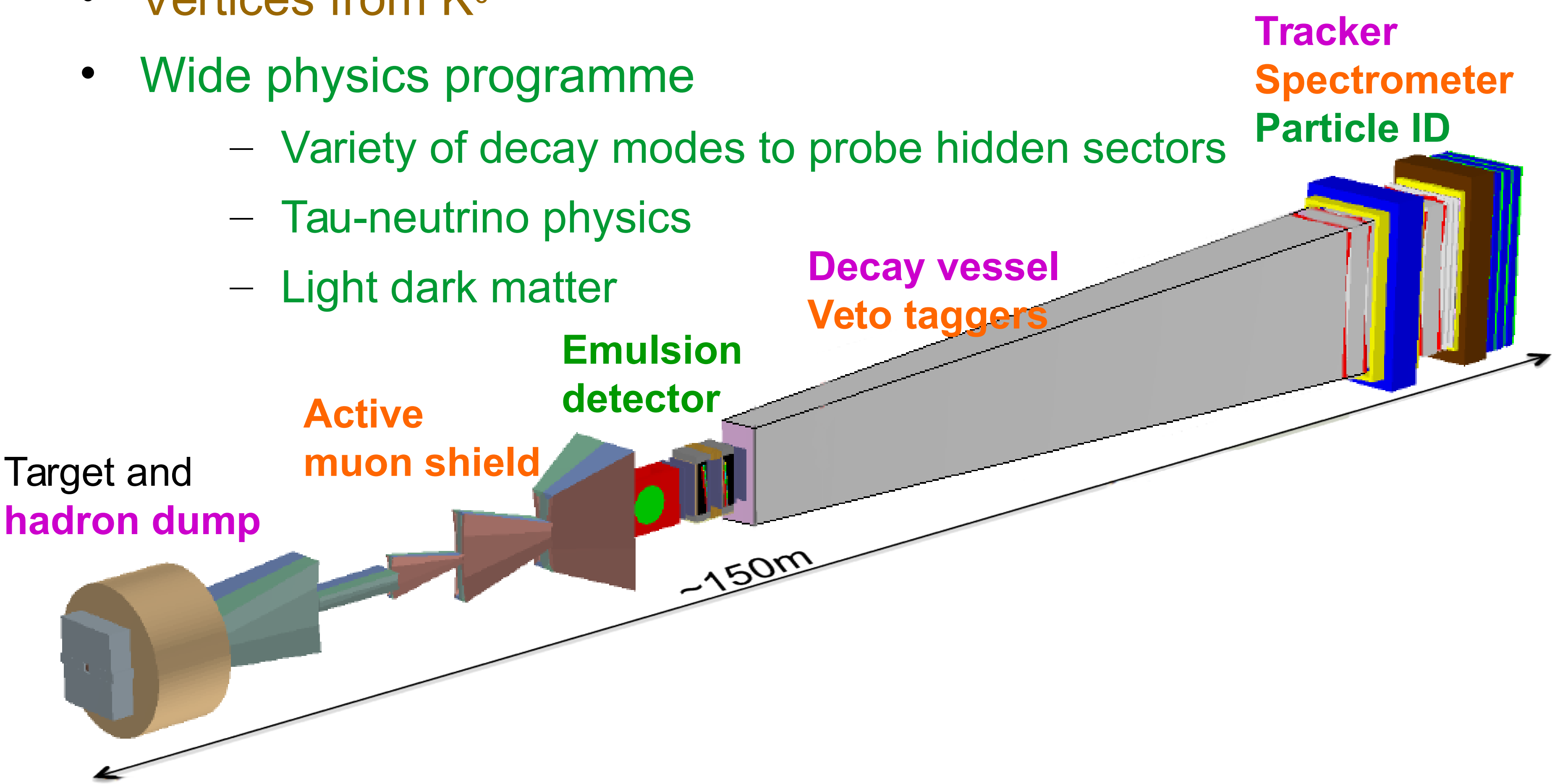
- Vertices from neutrinos
- Muon crossings
- Vertices from K^0
  - Upstream veto tagger
  - Reconstructed parent origin



SHiP – detector

Designed for **large acceptance** and **zero backgrounds**

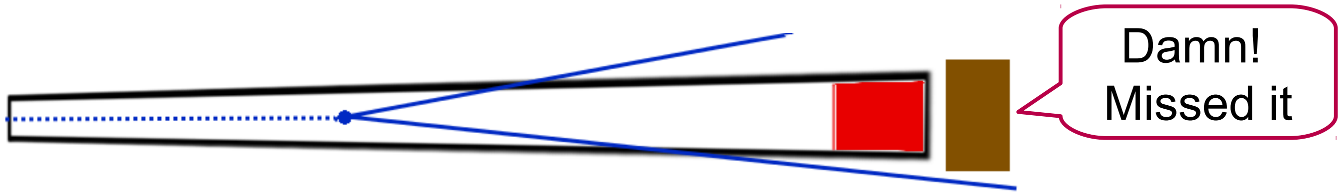
- Vertices from neutrinos
- Muon crossings
- Vertices from K^0
- Wide physics programme
  - Variety of decay modes to probe hidden sectors
  - Tau-neutrino physics
  - Light dark matter



Example of typical SHiP event selection

Start with two high-quality tracks in spectrometer

– Typically 6% probability once N decays inside the vessel



For these require:

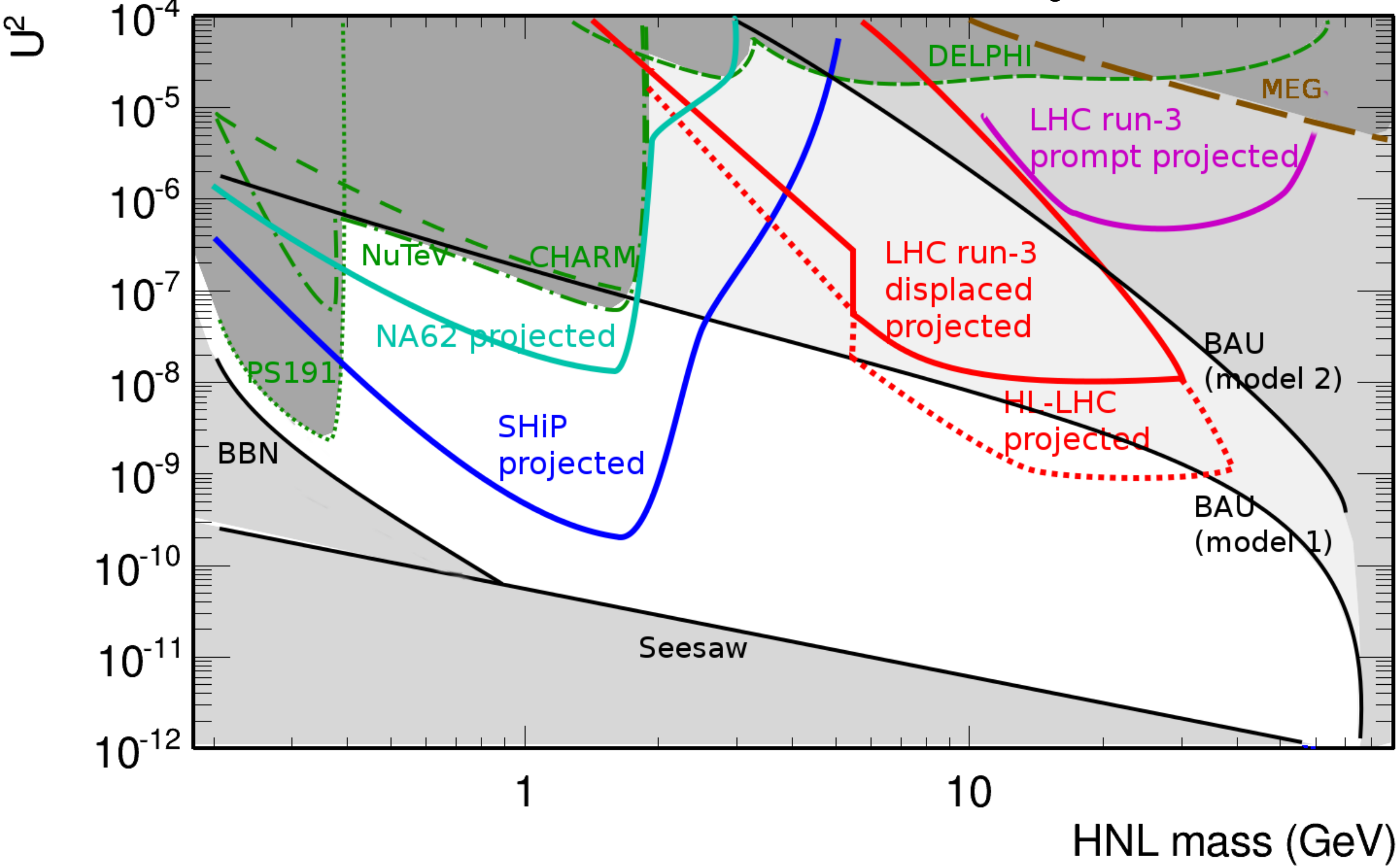
- Crossing within small distance inside decay volume
- One muon and one pion
- Matched hits in timing detector within narow time window
- No matched hit in upstream and surround veto taggers
- Reconstructed parent pointing to target

~70% efficiency for N $\rightarrow$ $\mu\pi$ once both tracks are reconstructed

< 0.1 background events remaining

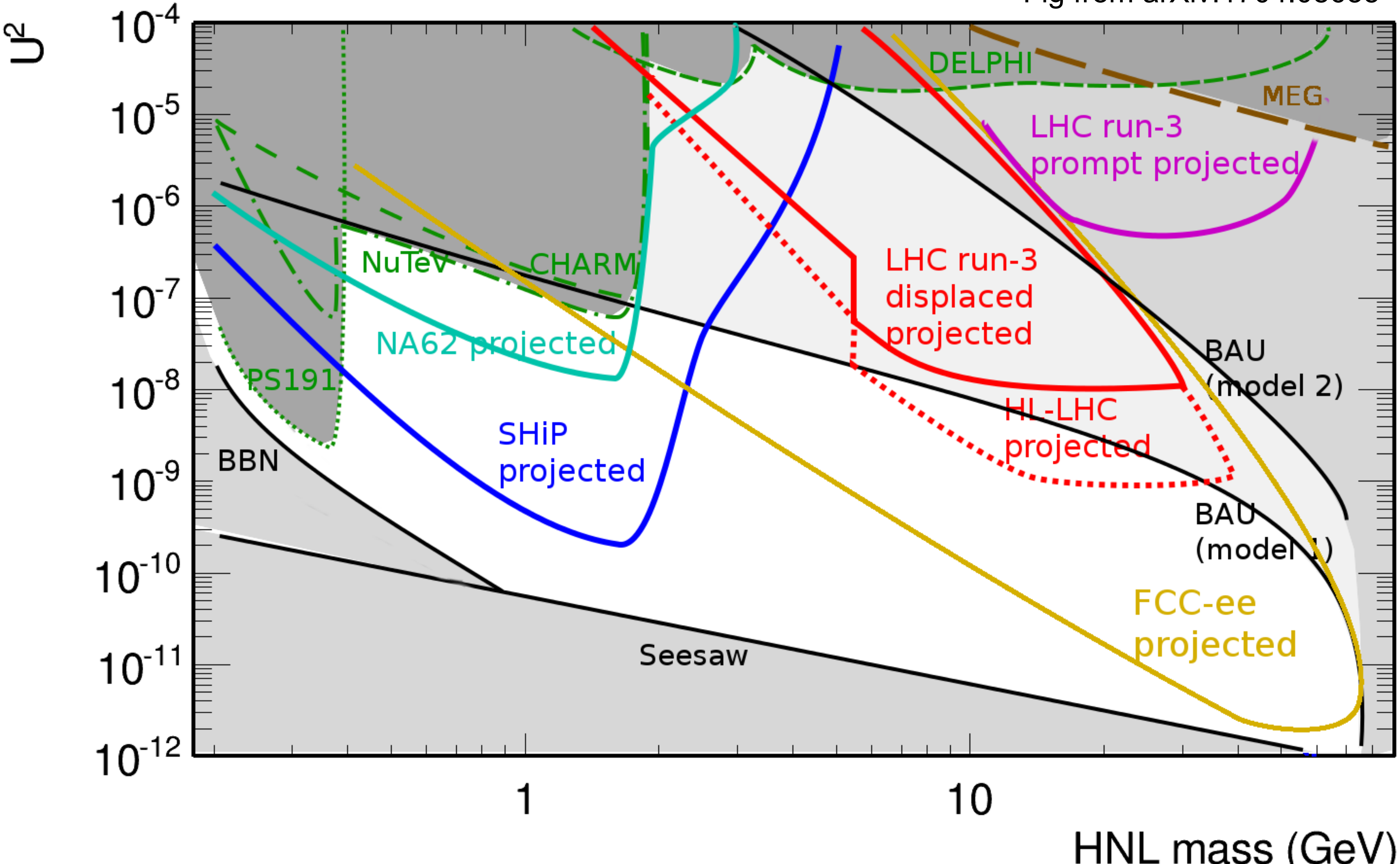
N at CERN in a 10-year timesecale

Fig from arXiv:1704.08635



N at CERN in a 10-year timesecale … and beyond

Fig from arXiv:1704.08635



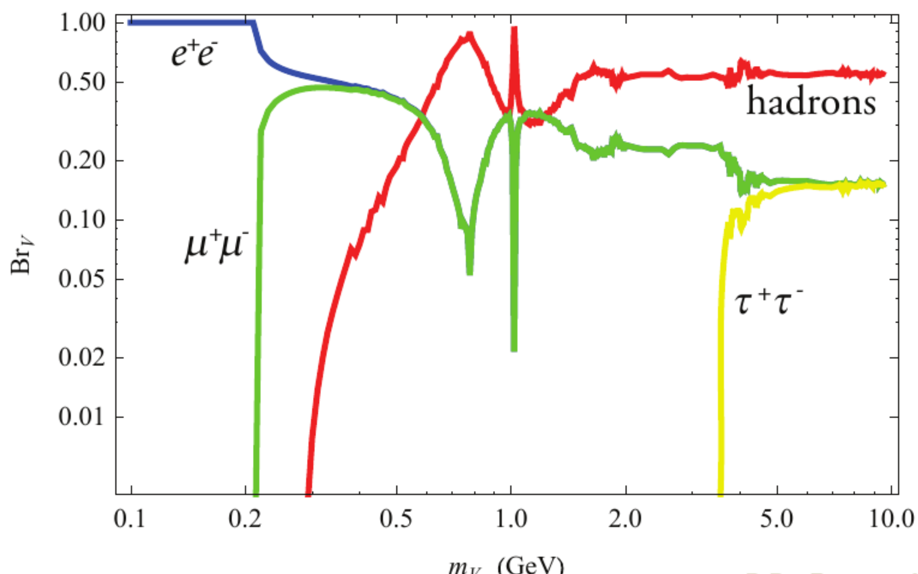
Dark photon

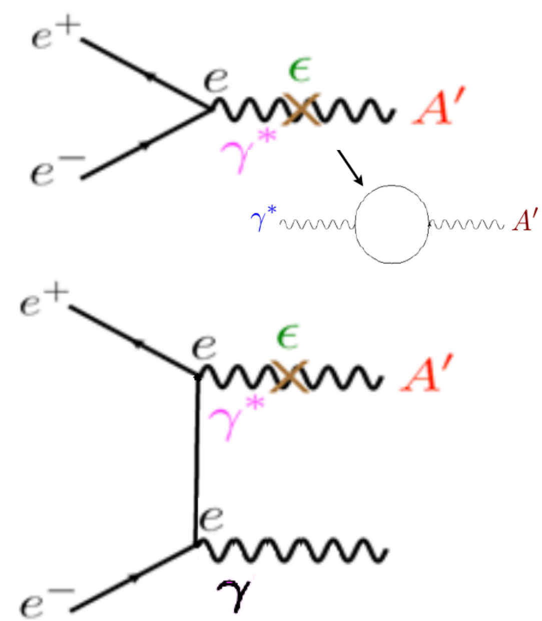
hidden sector charged under U(1)'

A'
Dark photon (γ^D)
Hidden / heavy photon
Mirror photon
Dark *Z* (Z^D)
U-boson, etc.

- g-2, dark matter, positron excess, parity...
- Production via kinetic mixing with the photon
  - Coupling to charged particles suppressed by ε
- Decay to fermion pairs
  - Search for resonances

$$\epsilon \sim 10^{-6} - 10^{-2}$$
$$m_{A'} \sim \mathrm{MeV} - \mathrm{GeV}$$



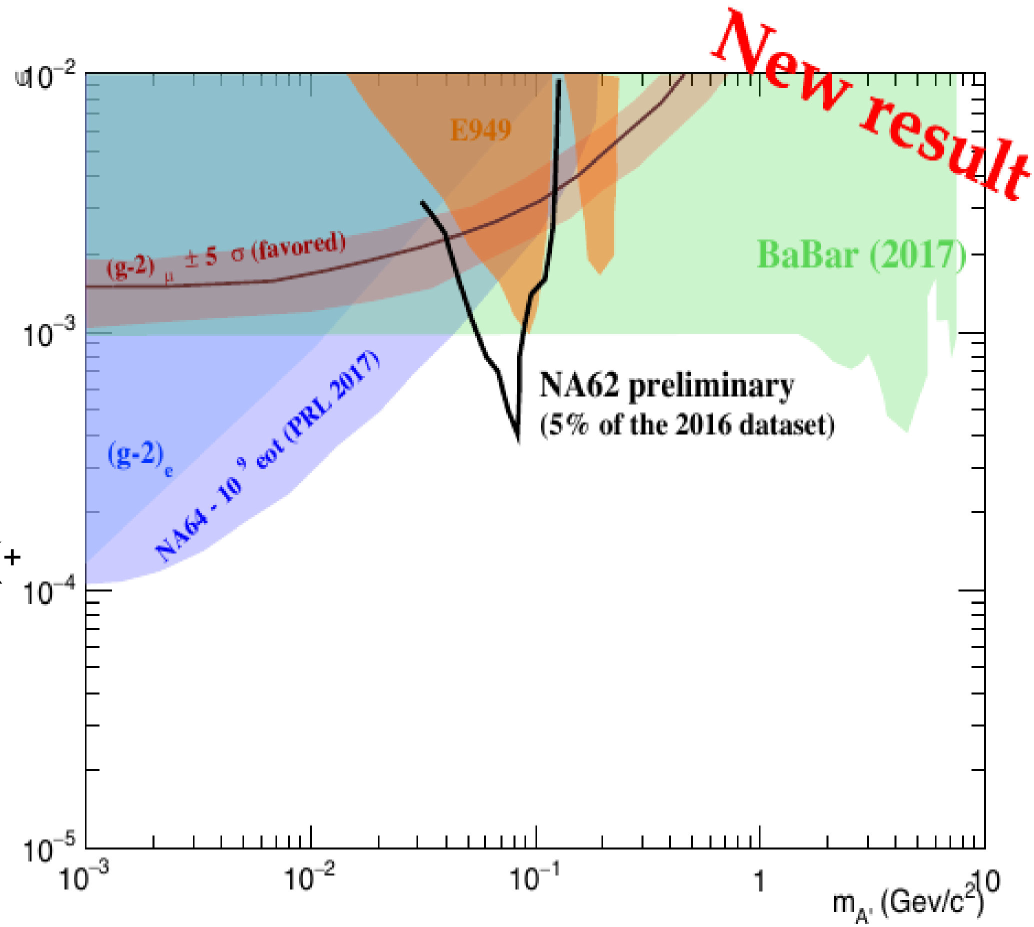


BB, Pospelov, Ritz

Dark photons at NA62 in beam mode

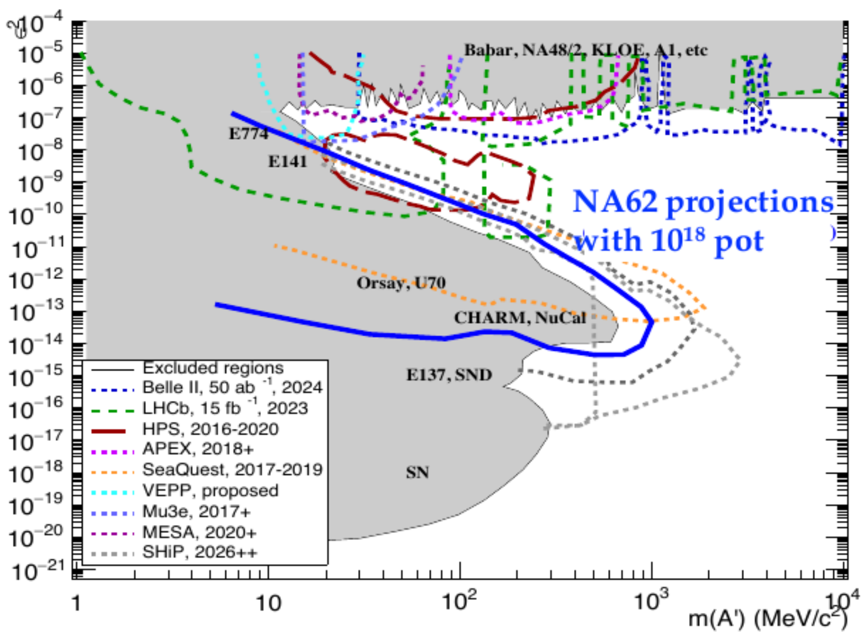
Use the decay $K^+ \to \pi^+ \pi^0$ (BR ~21%)

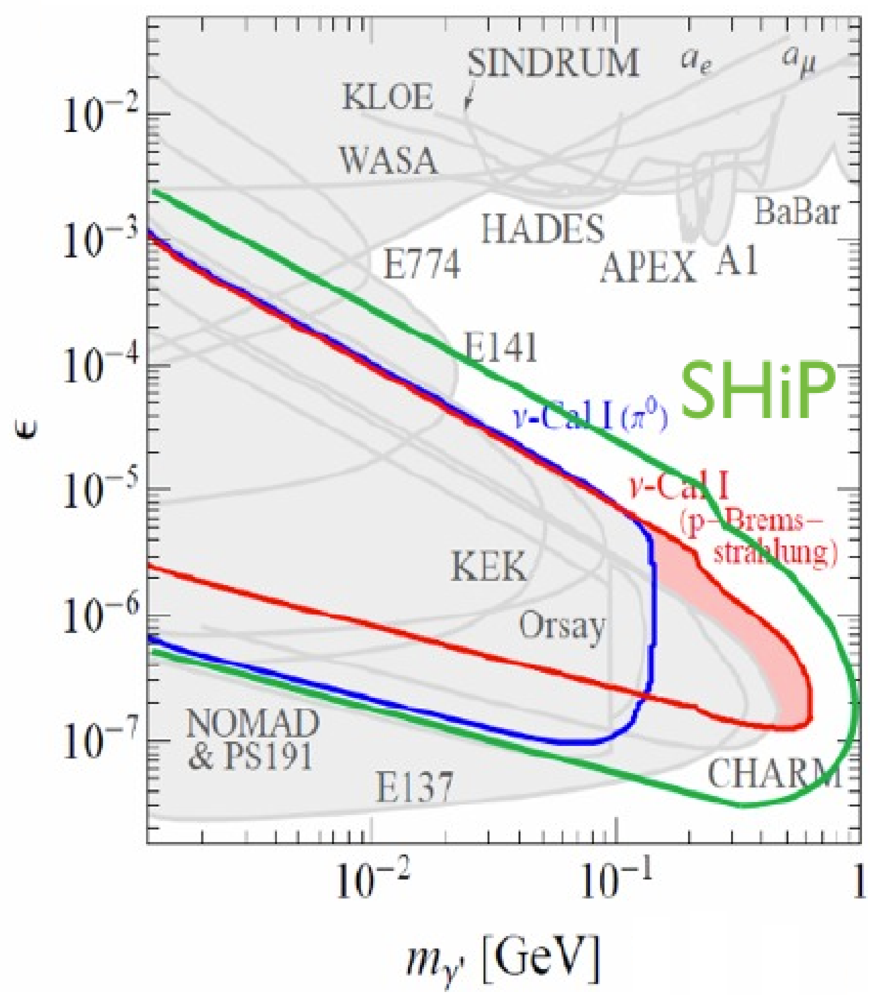
- $\pi^0 \to \gamma A'$
- Reconstruct K^+, π^+, γ
- Constrain A' using π^0 mass
- Sensitivity improves linearly with number of K^+



Dark photons at NA62 in dump mode and at SHiP

- Production dominated by
  - $p \rightarrow p\gamma$
  - $\pi^0 \rightarrow \gamma\gamma$
  - $\eta \rightarrow \gamma\gamma$
- Reconstruct e^+e^- and $\mu^+\mu^-$ vertex from A' decay





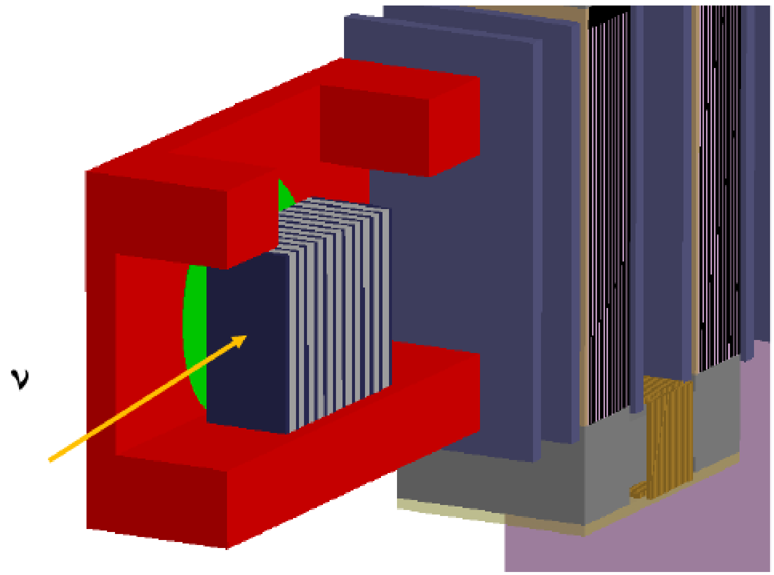
Summary and outlook

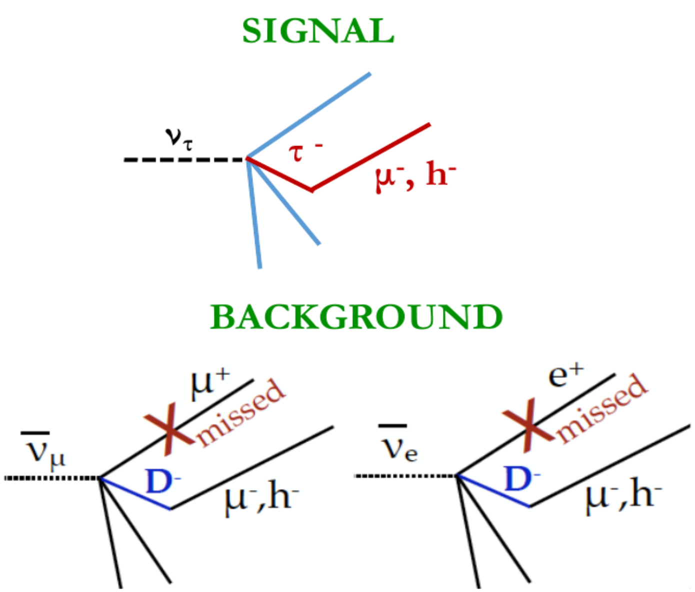
In the absence of new physics at the TeV scale, searches for **light new physics** are gathering momentum

- Possibly key to explaining dark matter, baryon asymmetry, neutrino masses...
- Probing low couplings to the SM, which means:
  - High-intensity beams
  - Long lifetimes → displaced decay signatures
- Complementary approaches with high-intensity beams:
  - Colliders – LHC, HL-LHC
  - Fixed target – NA62, SHiP
- Wide experimental programme for many years to come

Extras

SHiP – tau-neutrino physics





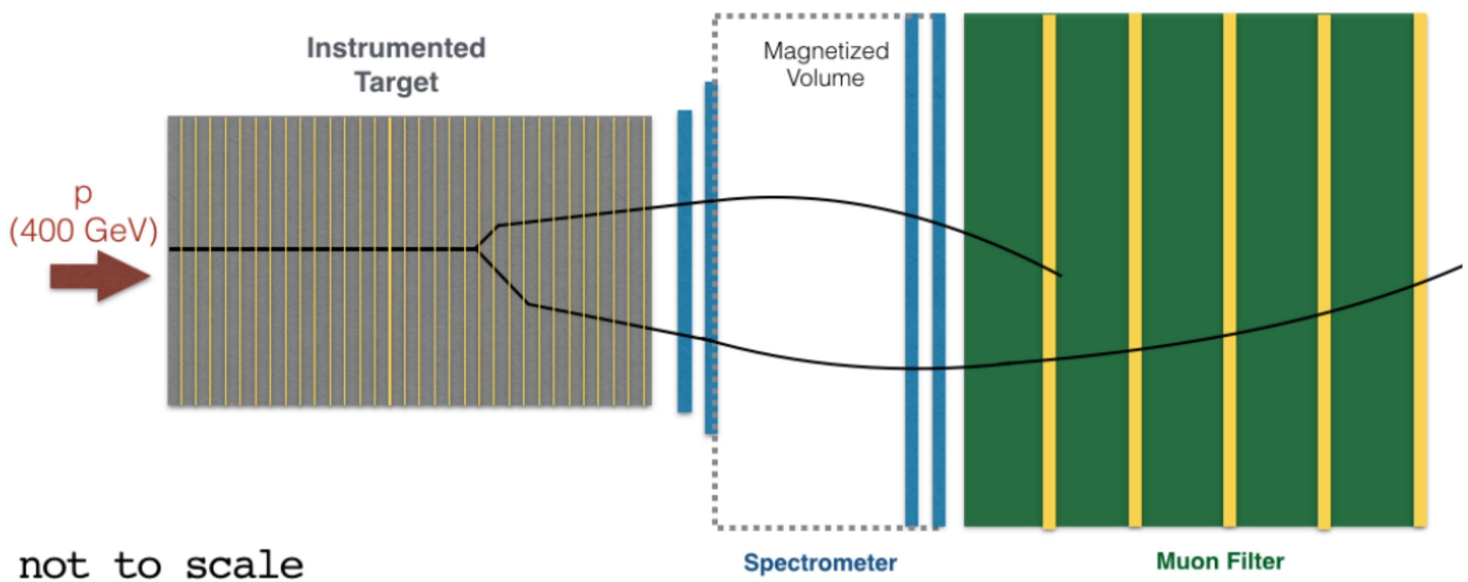
- An OPERA-like tau-neutrino emulsion detector
- Current status of tau-neutrino measurements:
  - DONUT observed 9 events (from charm), OPERA 5 events (from oscillations)
- SHiP can increase by 200 the current tau neutrino sample, discover anti-tau-neutrinos, measure structure functions and constrain strange PDFs (with ν_μ)

SHiP – controlling the fluxes

Charm – no data available for protons at ~400 GeV

Need to validate cascade production→ proposal to perform direct measurements with dedicated experiment in 2018

- Instrumented replica of the SHiP target
- Inclusive charm production $d^2\sigma/dEd\theta$ measurement – important for HNL signal acceptance estimate
- Measurement of muon flux at high energies and large angles – important for muon shield design



not to scale