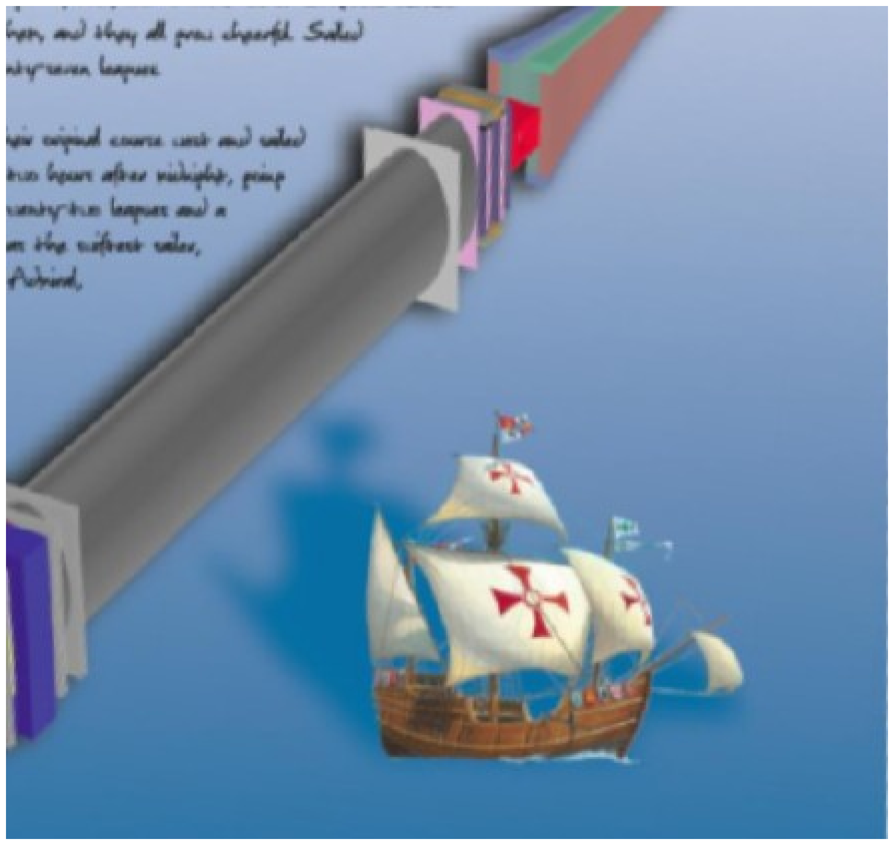
# SHiP and the search for light new physics

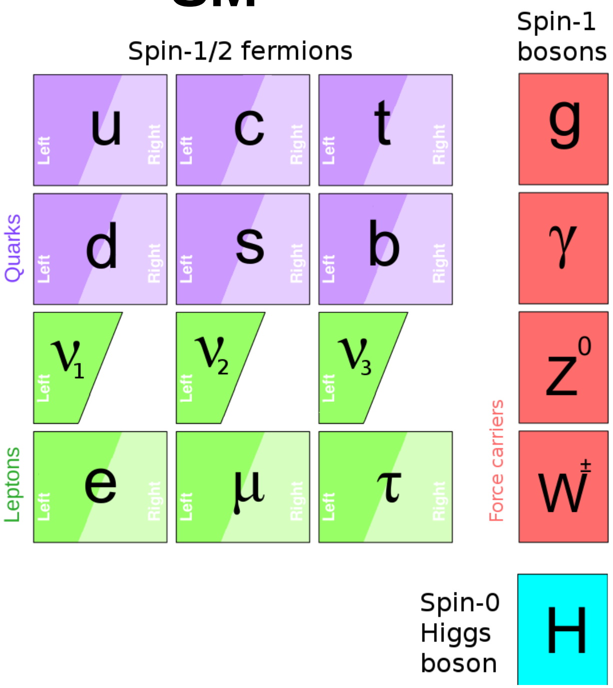
Philippe Mermod

Workshop of the LHC LLP Community, CERN, 24 April 2017

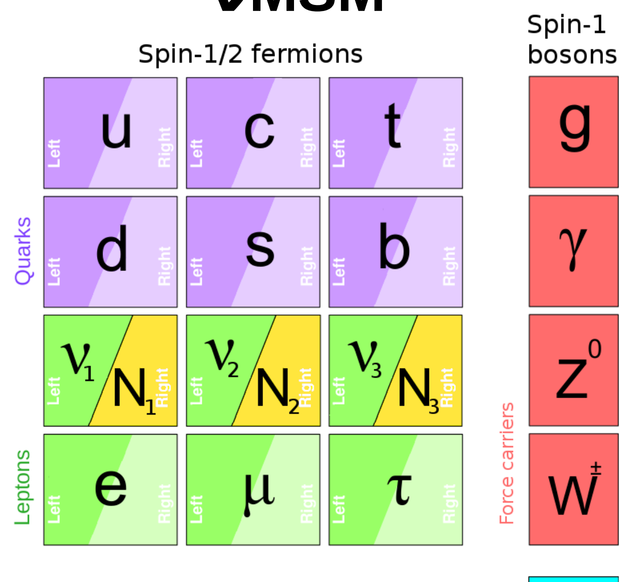


# Still 3 missing pieces

**SM**




**νMSM**

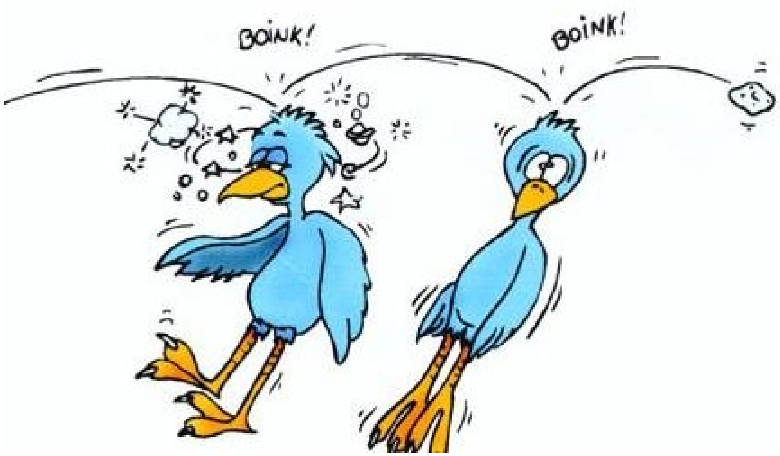



Ann. Rev. Nucl. Part. Sci. 59, 191 (2009)

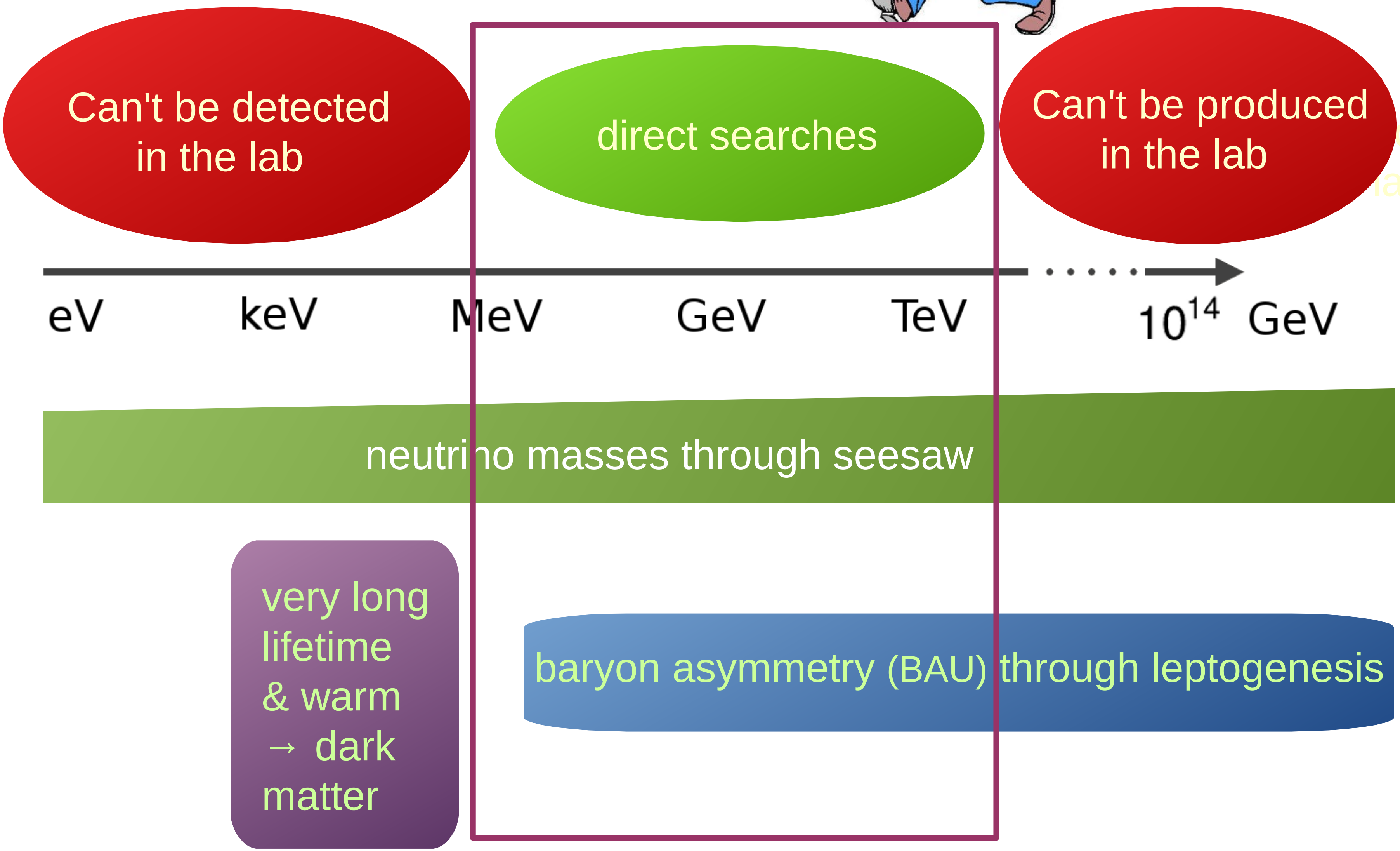
$\mathbf{N_1}$ mass ~keV
→ **dark matter**

$\mathbf{N_{2,3}}$ mass ~GeV
→ **seesaw**
→ **leptogenesis**

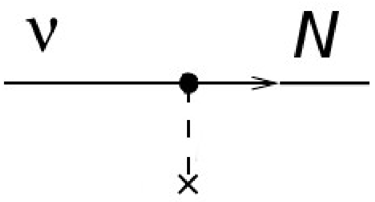
- Guided by experimental evidence for new physics
- No new mass scale introduced



# Right-handed neutrinos (N)?

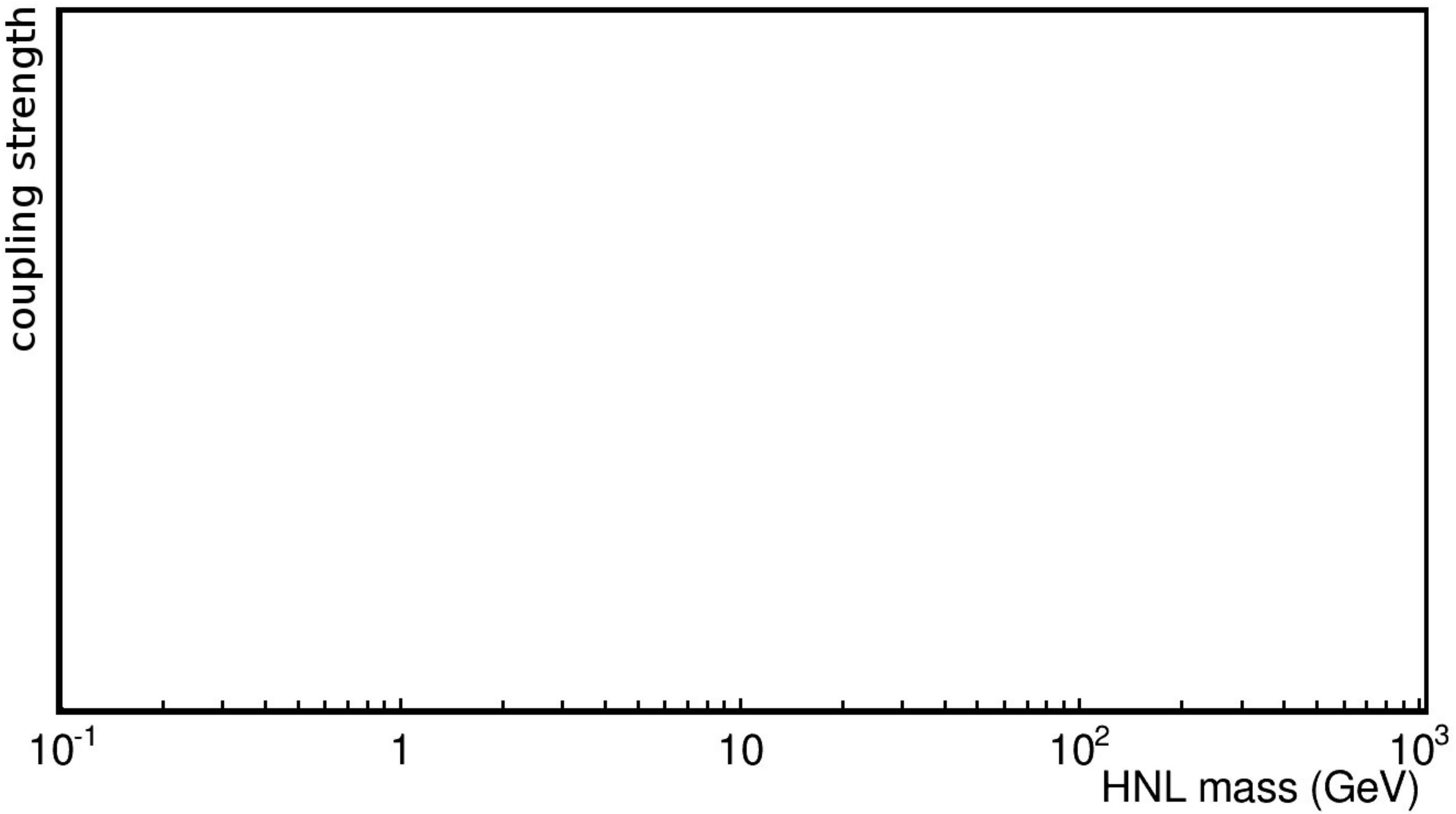


# N production and detection in the lab (1)

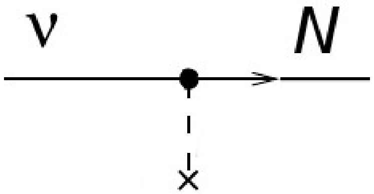



Very small mixing for BAU and to evade existing experimental constraints

- High-intensity beams
- Displaced decays



# N production and detection in the lab (2)




Very small mixing for BAU and to evade existing experimental constraints ⇒

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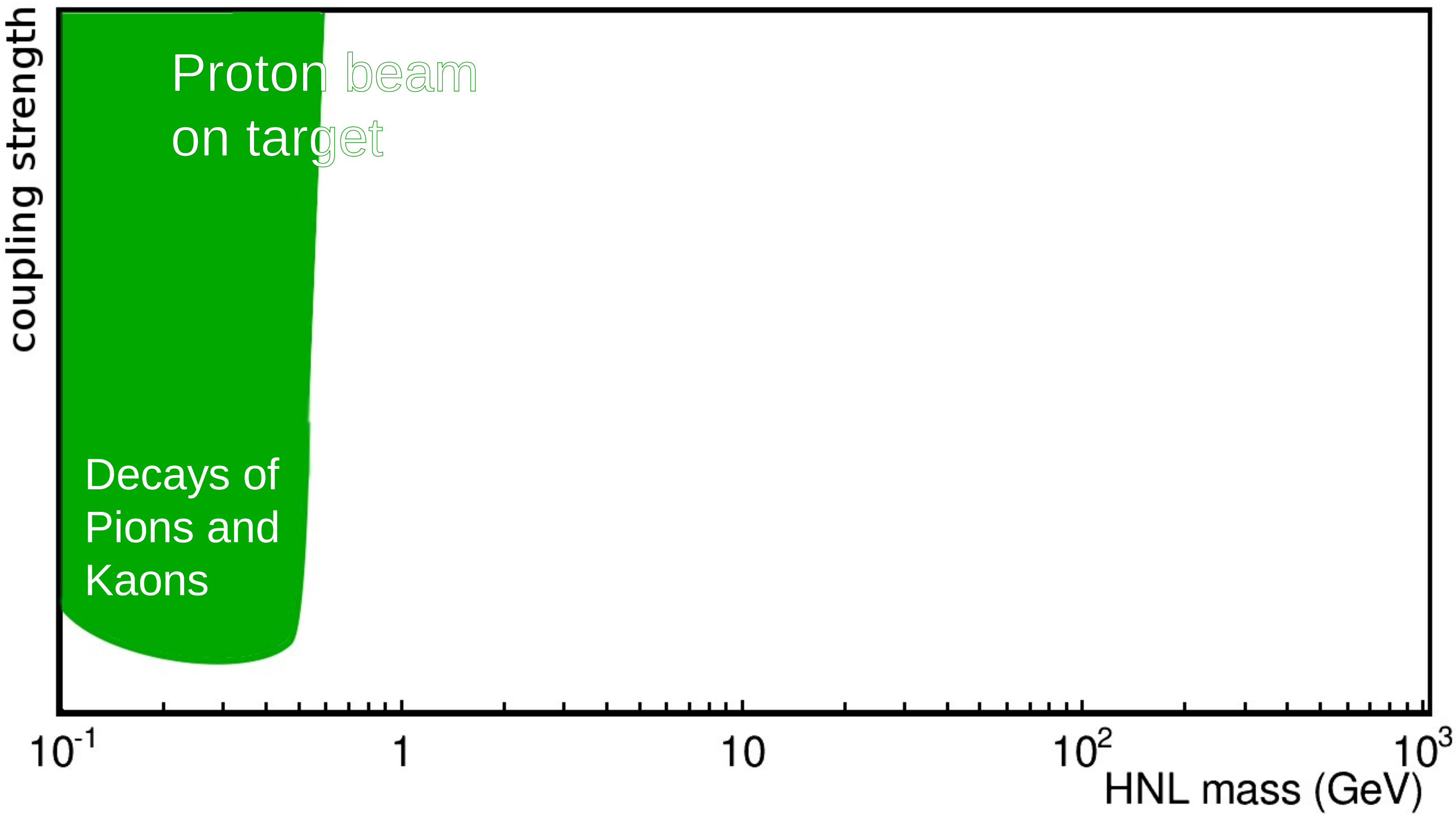
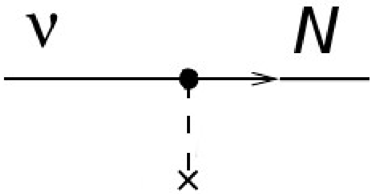


# N production and detection in the lab (3)




Very small mixing for BAU and to evade existing experimental constraints ⇒

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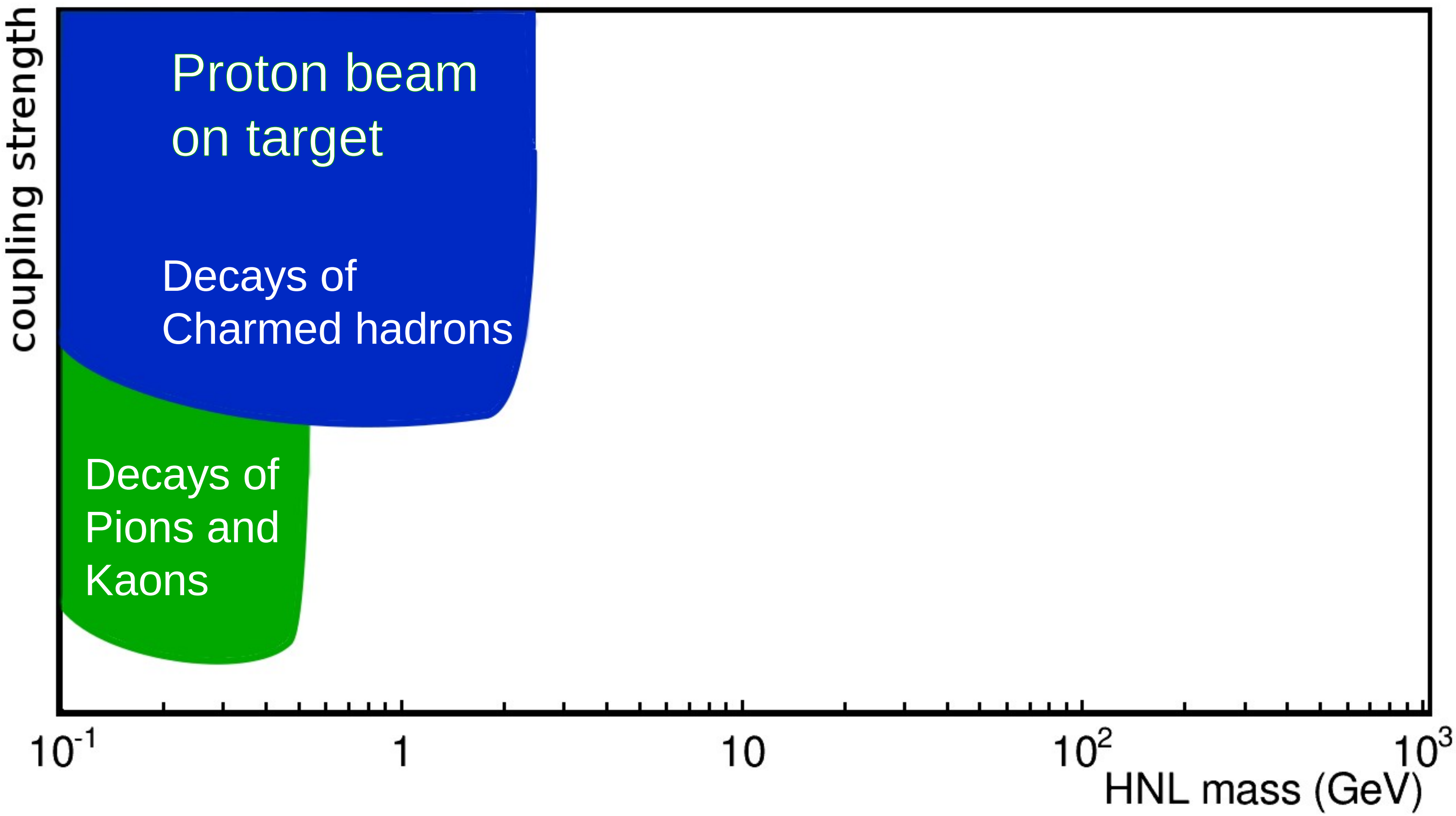
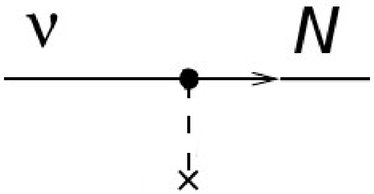


# N production and detection in the lab (4)




Very small mixing for BAU and to evade existing experimental constraints ⇒

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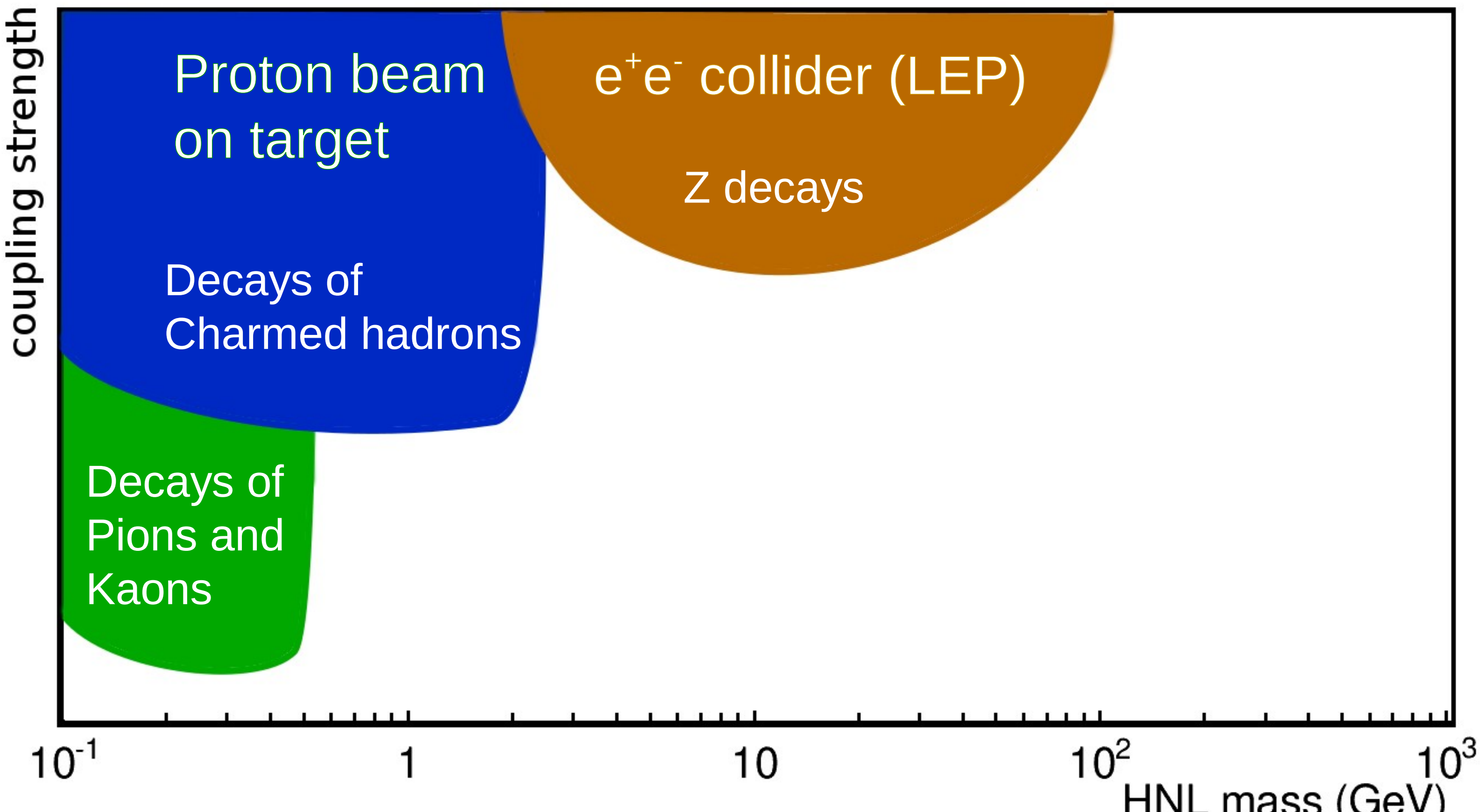
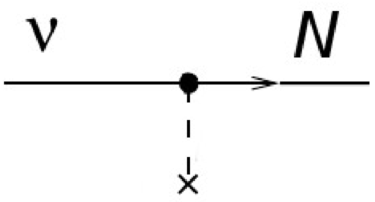


# N production and detection in the lab (5)




Very small mixing for BAU and to evade existing experimental constraints

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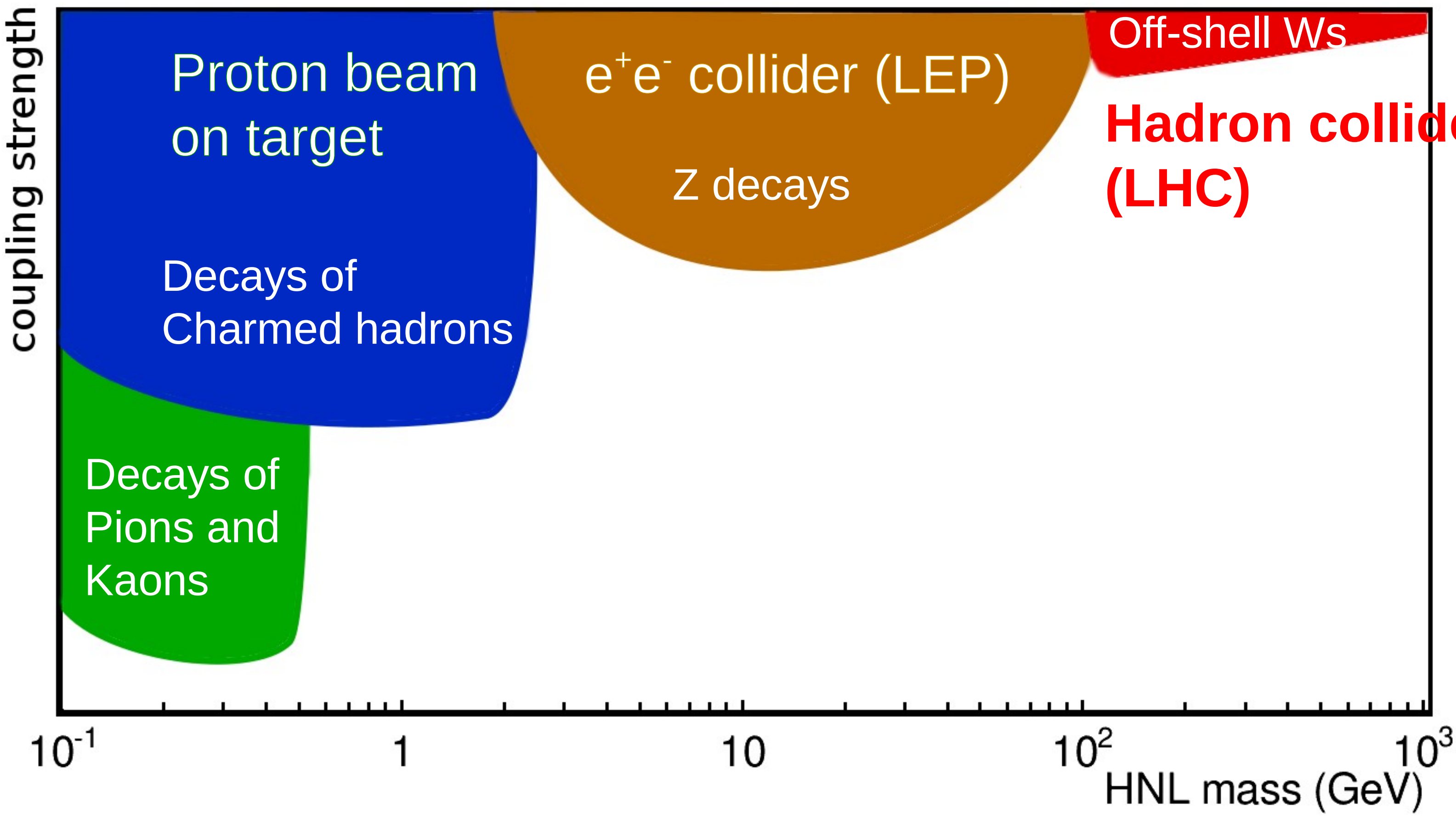
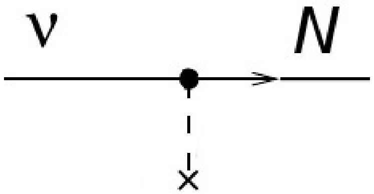
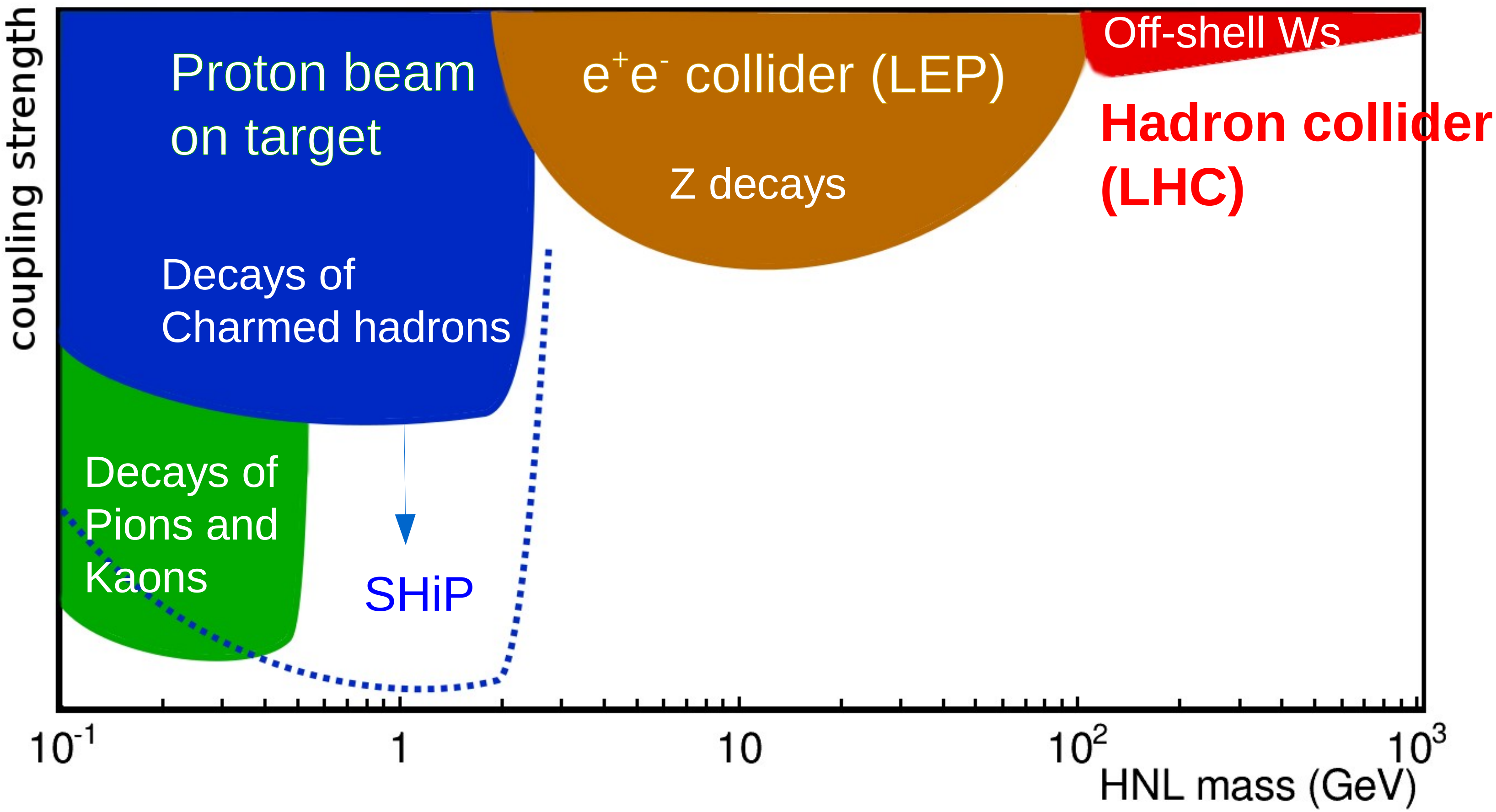


# N production and detection in the lab (6)

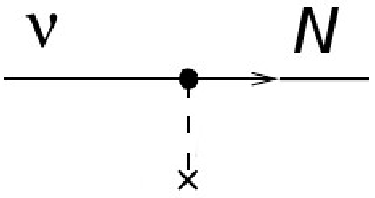



Very small mixing for BAU and to evade existing experimental constraints ⇒

- High-intensity beams
- Displaced decays

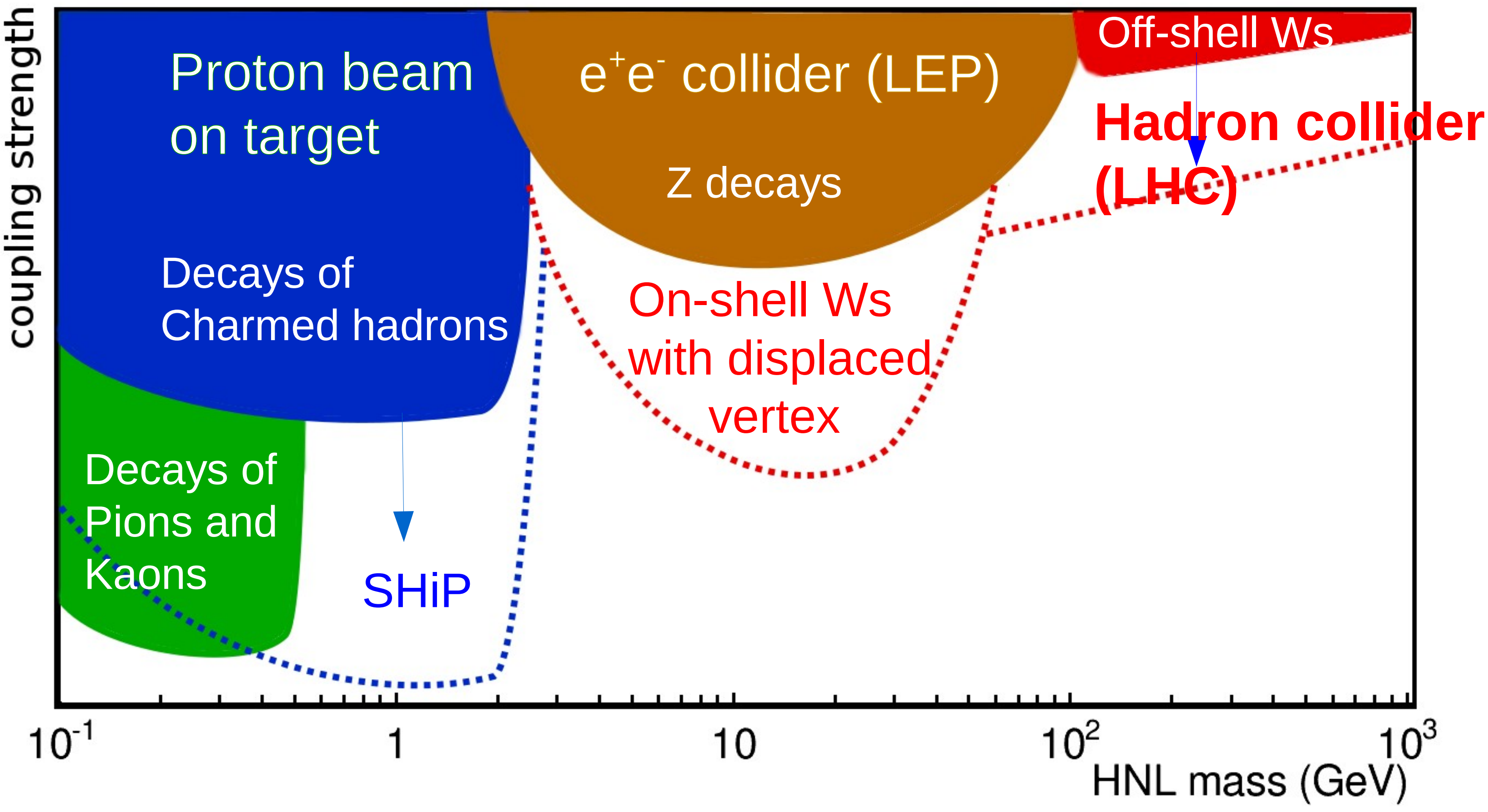


# N production and detection in the lab (7)

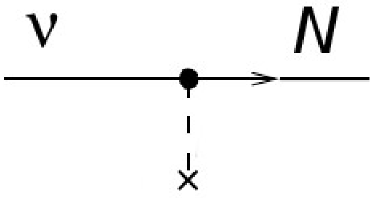



Very small mixing for BAU and to evade existing experimental constraints ⇒

- High-intensity beams
- Displaced decays

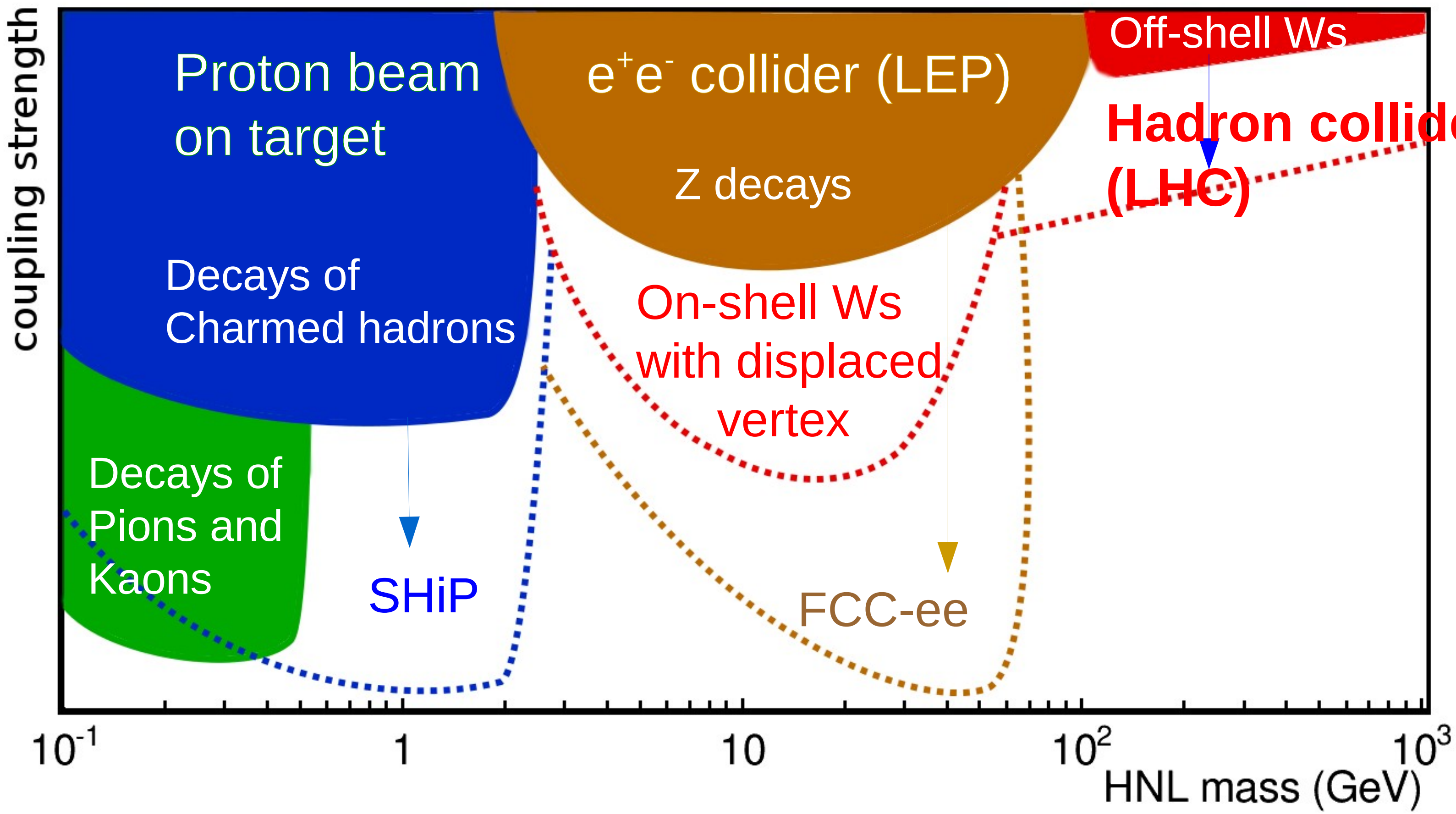


# N production and detection in the lab (8)

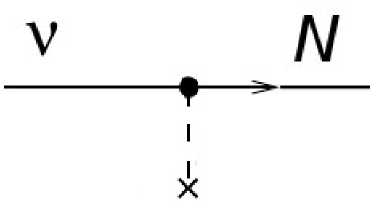



Very small mixing for BAU and to evade existing experimental constraints ⇒

- High-intensity beams
- Displaced decays

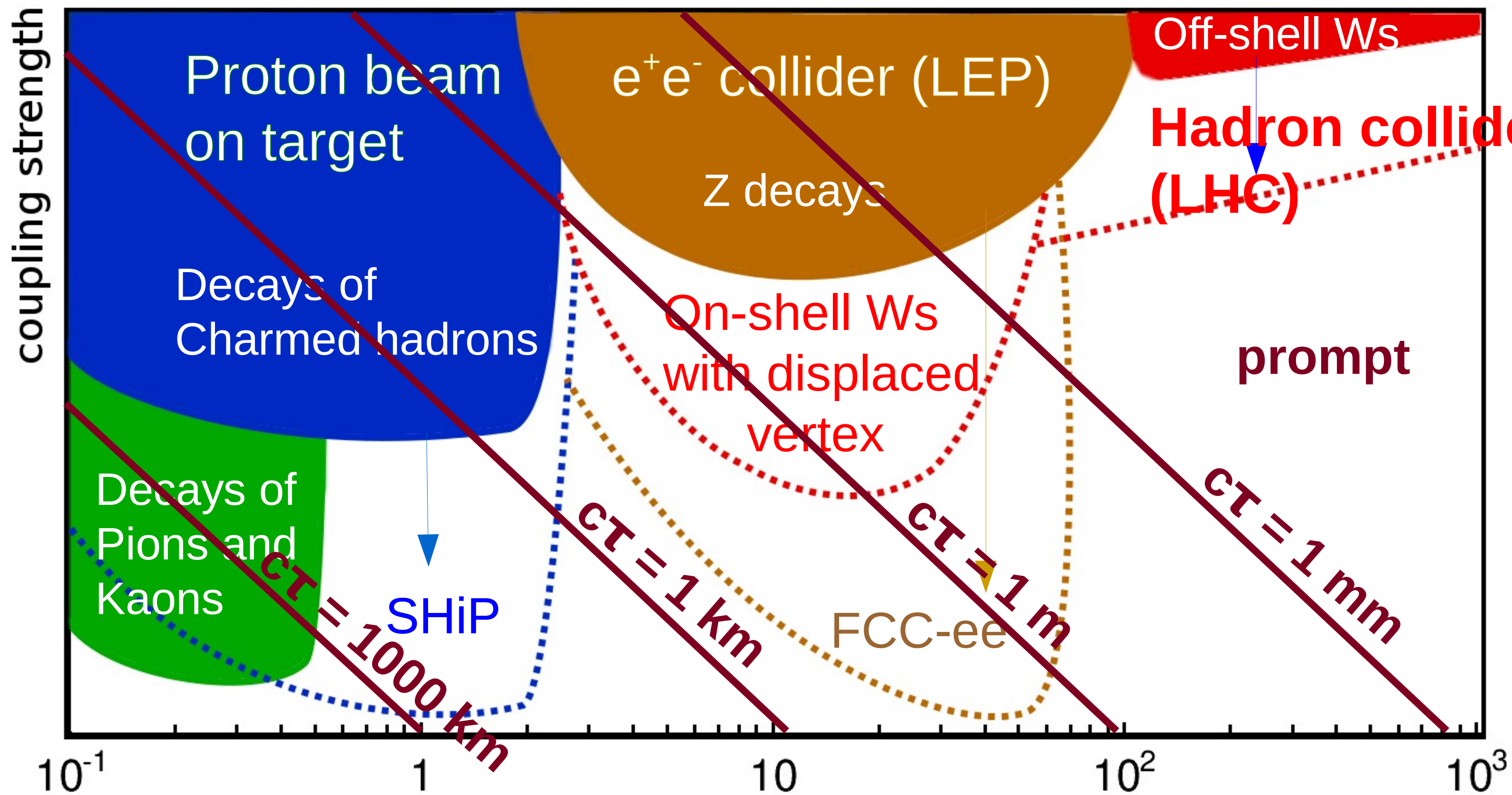


# N production and detection in the lab (9)

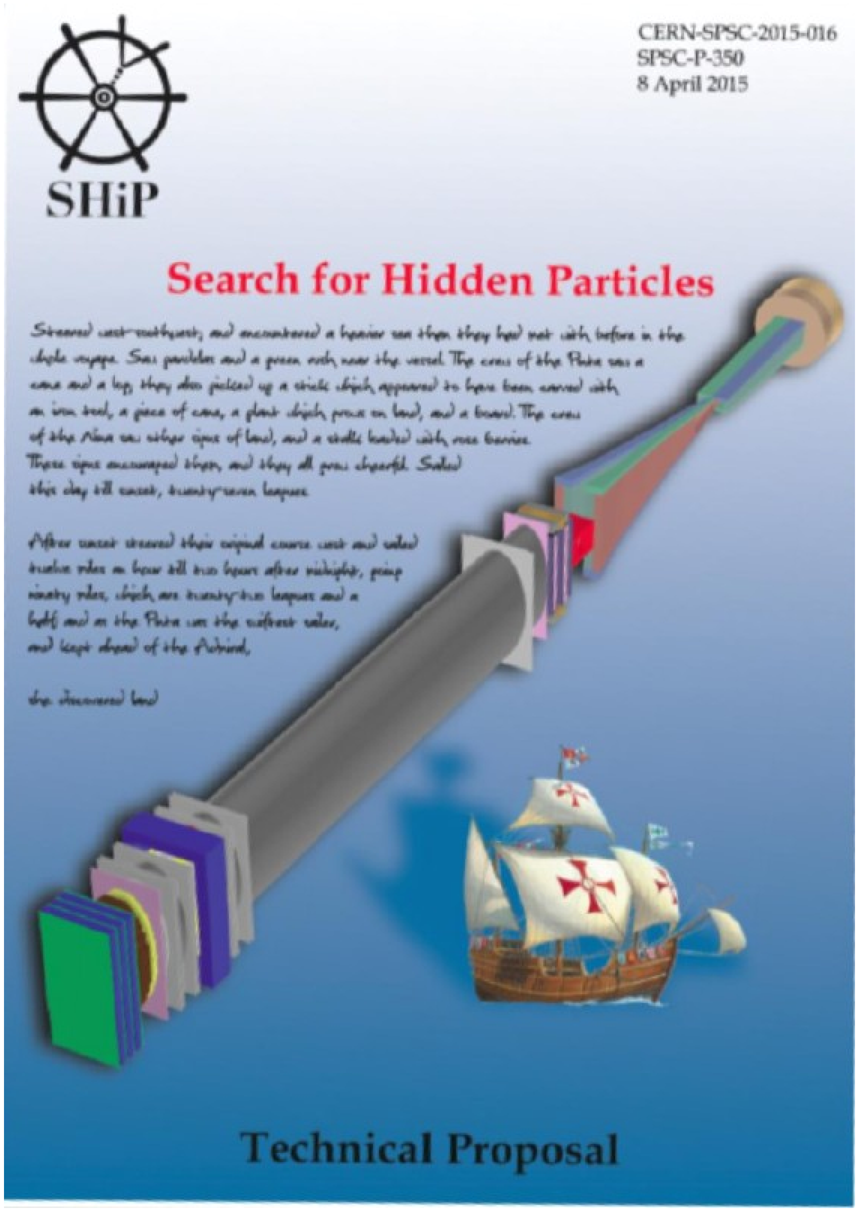



Very small mixing for BAU and to evade existing experimental constraints ⇒

- High-intensity beams
- Displaced decays



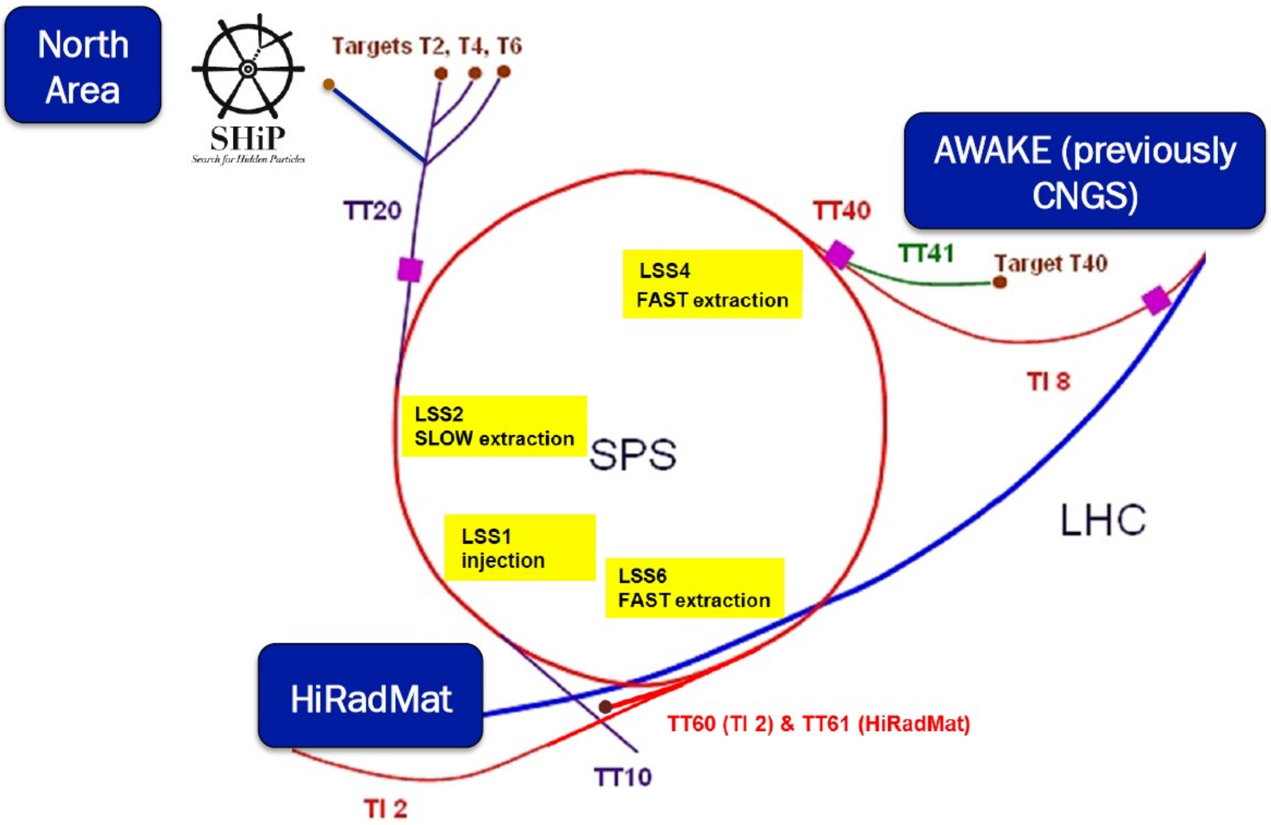
# Search for Hidden Particles (SHiP)




- Proposed experiment at the CERN SPS
- Collaboration of 250 members from 46 institutes
- Technical proposal arXiv:1504.04956 (2015)
- Physics case signed by 80 theorists Rep. Prog. Phys. 79 (2016)
- SPSC requested a comprehensive design study by 2019 → decision about approval in 2019/2020
  - Physics runs around 2026
- Major actor in the CERN Physics Beyond Colliders study group

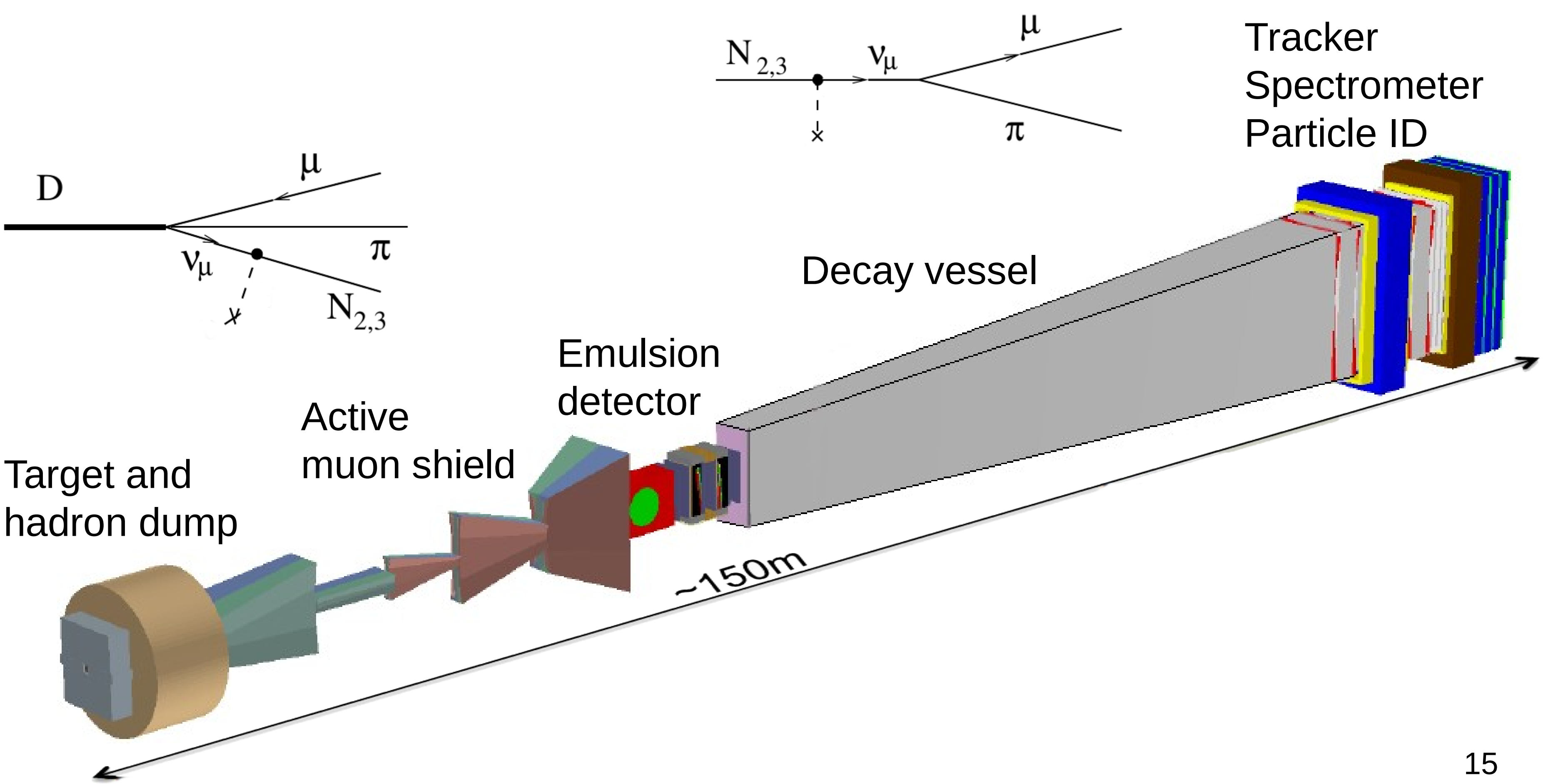
# SHiP – facility

- 400 GeV protons from the CERN SPS
  - Aim: $2 \cdot 10^{20}$ protons on target in 5 years
- New beam line and target complex
- Slow extraction technique (debunching)



# SHiP – detector (1)

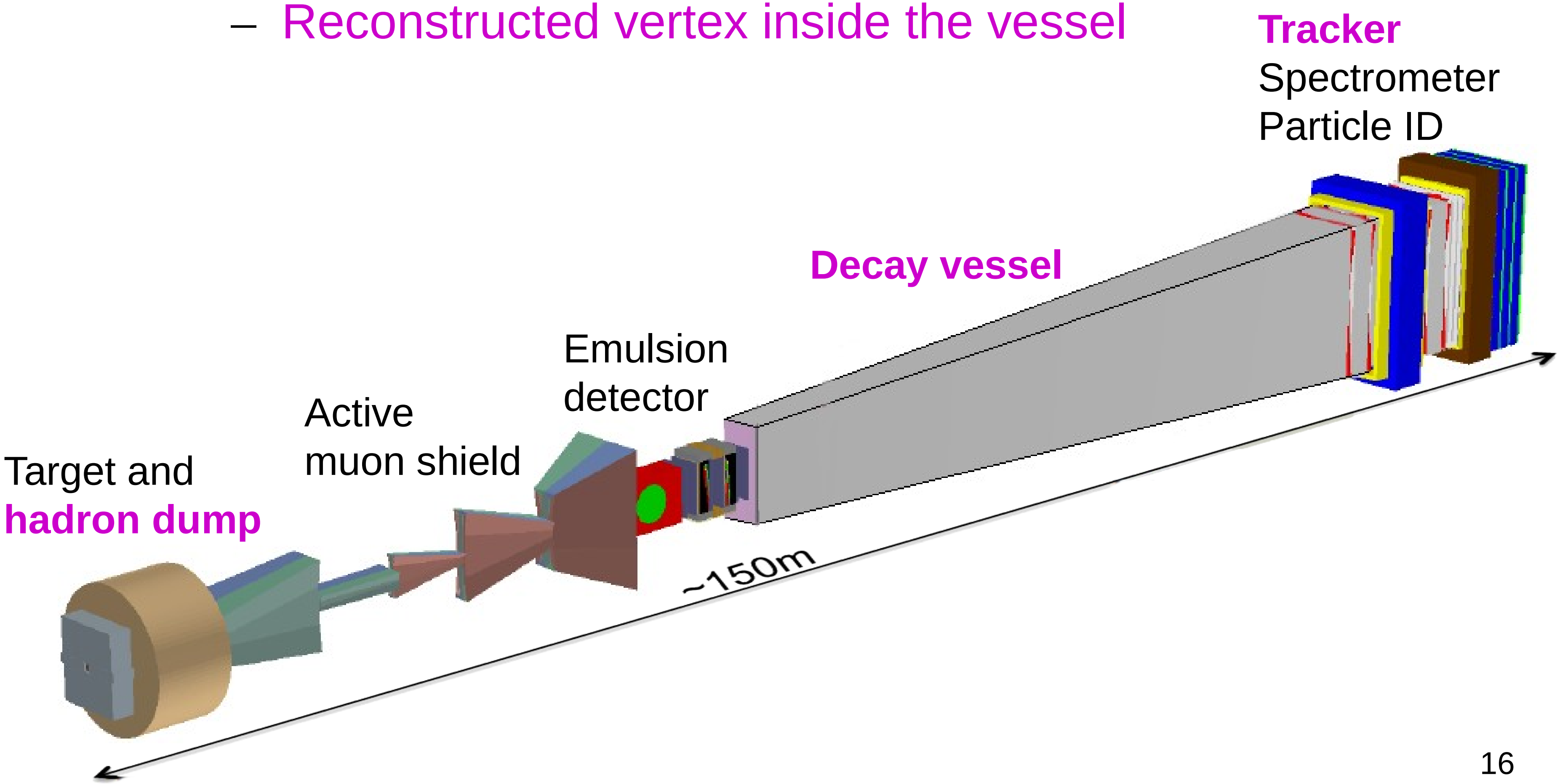
Designed for **large acceptance** and **zero backgrounds**



# SHiP – detector (2)

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

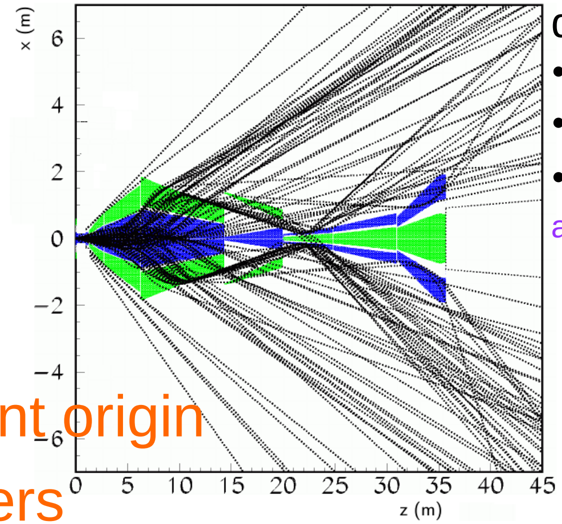
- Vertices from neutrinos
  - Stop pions and kaons before they decay
  - Evacuate the vessel to $10^{-6}$ bar
  - Reconstructed vertex inside the vessel



# SHiP – detector (3)

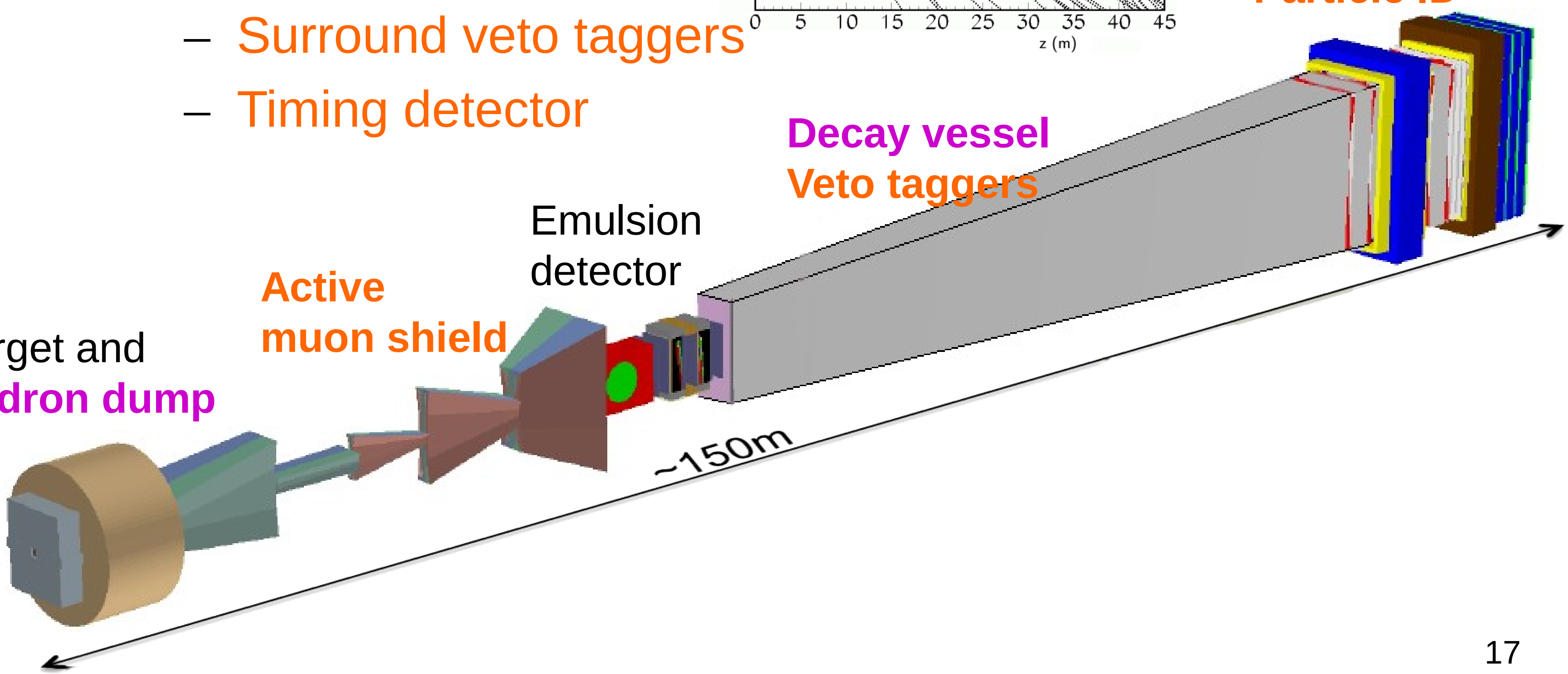
Designed for **large acceptance** and **zero backgrounds**

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




design minimises:
- muons in vessel
- length
- Weight

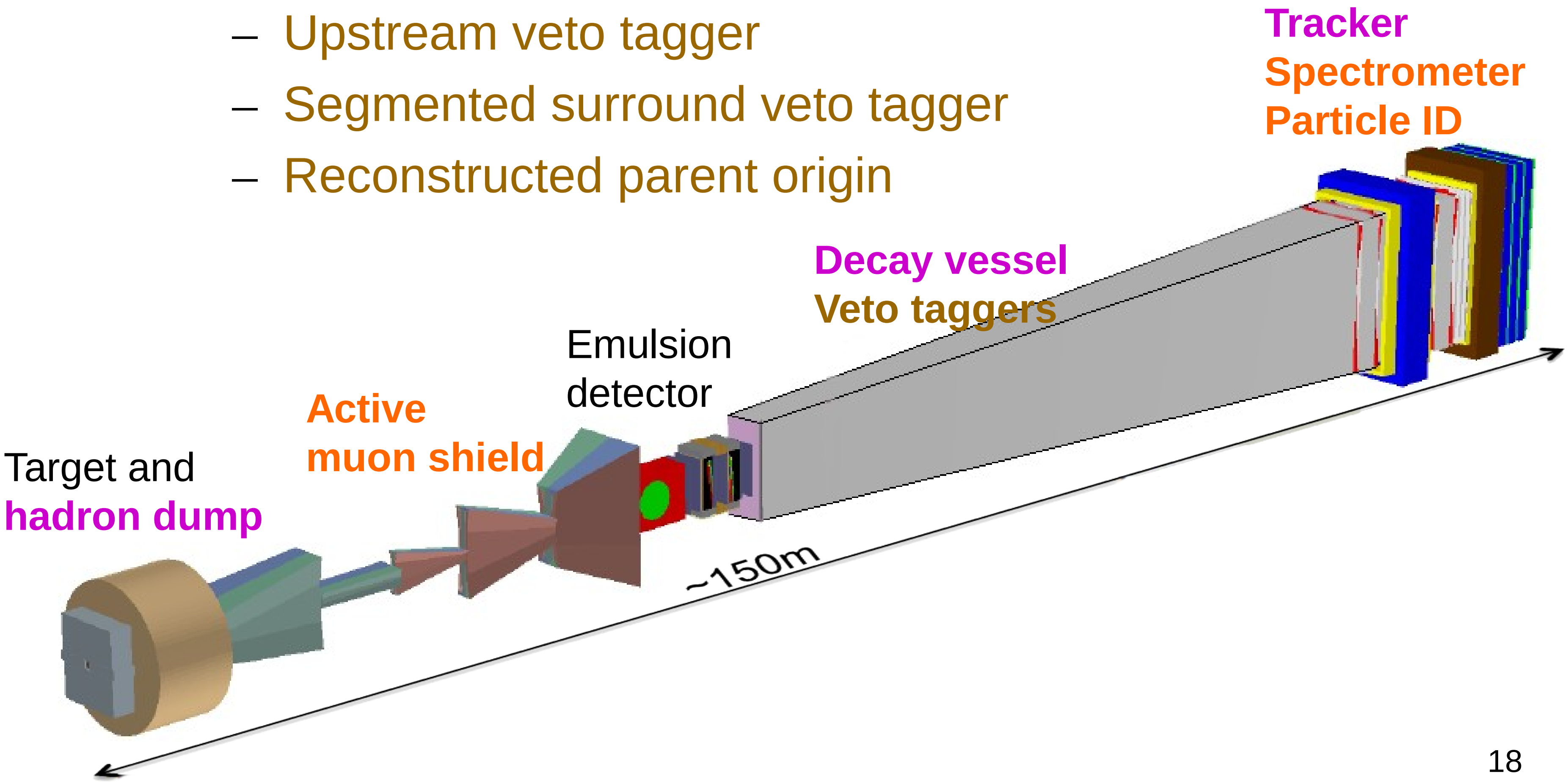
arXiv:1703.03612



# SHiP – detector (4)

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

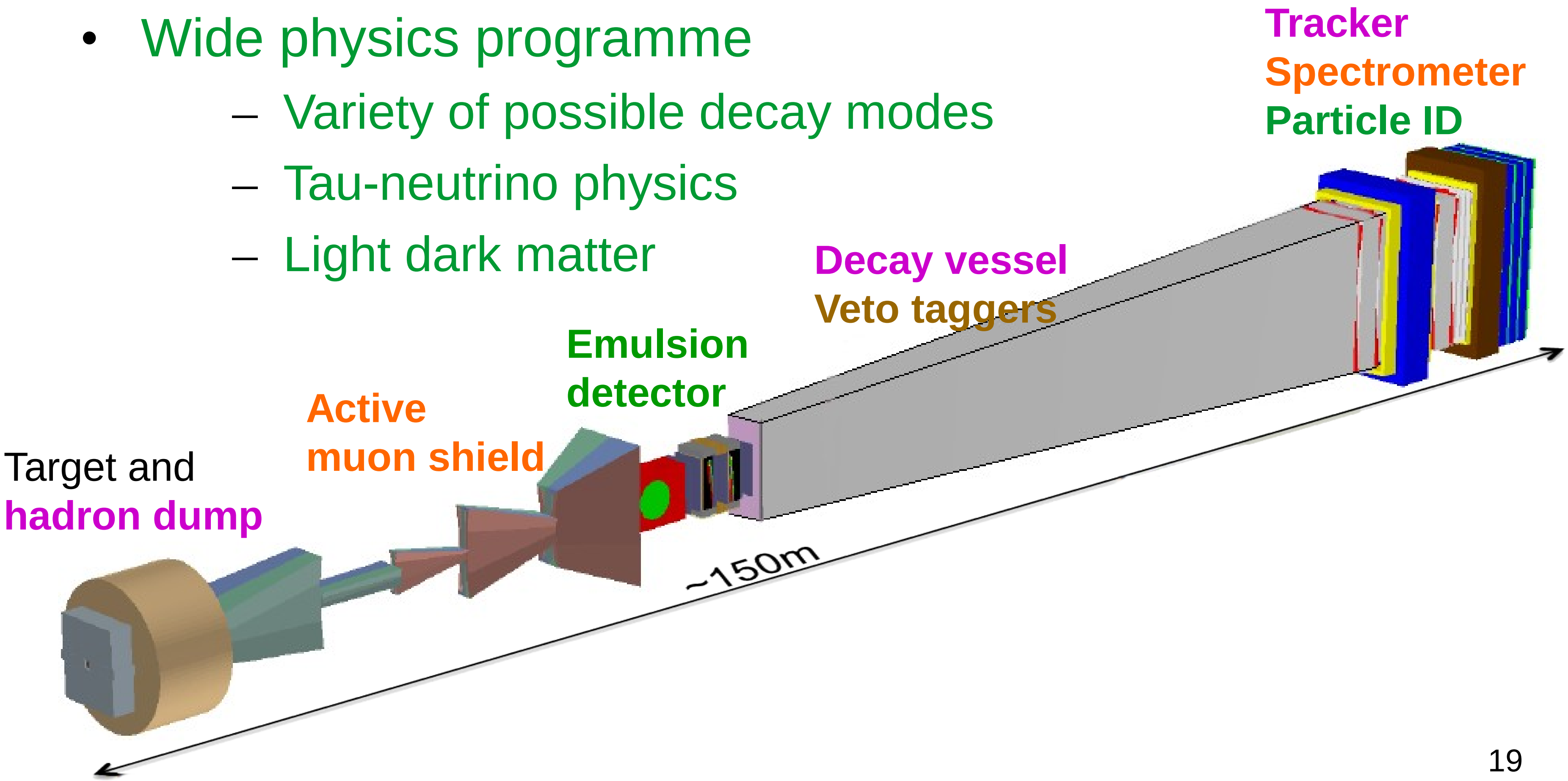
- Vertices from neutrinos
- Muon crossings
- Vertices from $K^0$
  - Upstream veto tagger
  - Segmented surround veto tagger
  - Reconstructed parent origin



# SHiP – detector (5)

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

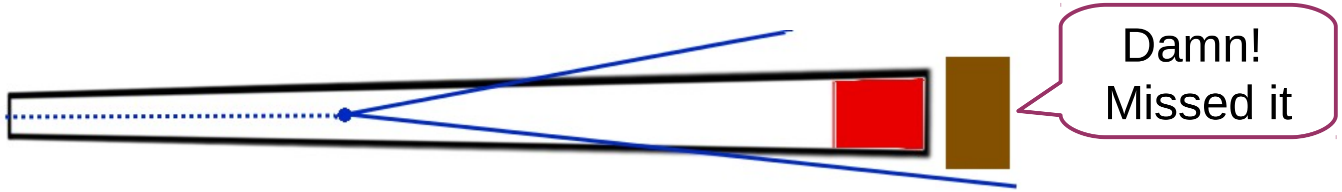
- Vertices from neutrinos
- Muon crossings
- Vertices from $K^0$
- Wide physics programme
  - Variety of possible decay modes
  - Tau-neutrino physics
  - Light dark matter



# Example of typical SHiP event selection

Start with two high-quality tracks in spectrometer

– typically $10^{-5}$ probability once N decays inside the vessel




For these require:

- Vertex with DOCA < 30 cm inside the decay volume
- Identify one muon and one pion
- Matched hits in timing detector within 300 ps window
- No hit in the upstream veto tagger and in surround veto near the vertex
- Reconstructed parent pointing to target within 2.5 m distance

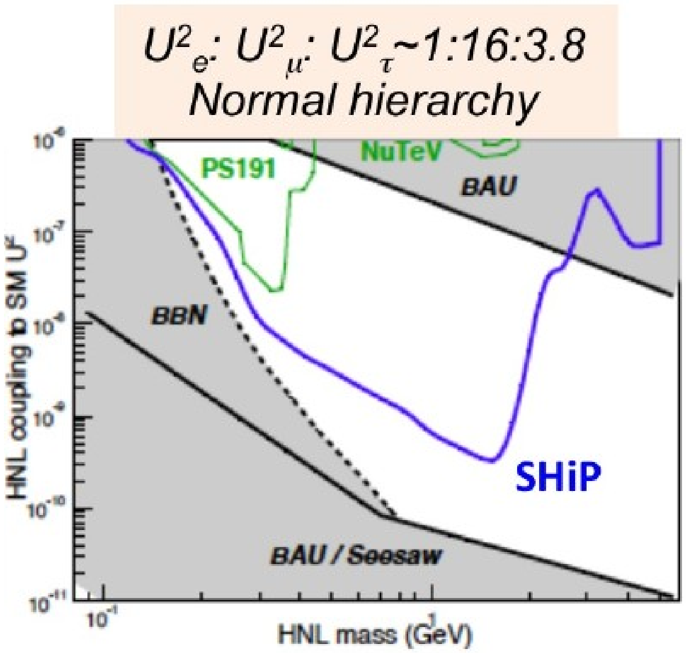
~70% efficiency for $N \rightarrow \mu\pi$ once both tracks are reconstructed

< 0.1 background events remaining

# SHiP can probe many types of weakly-coupled particles produced in hadron decays

Rep. Prog. Phys. 79 (2016)

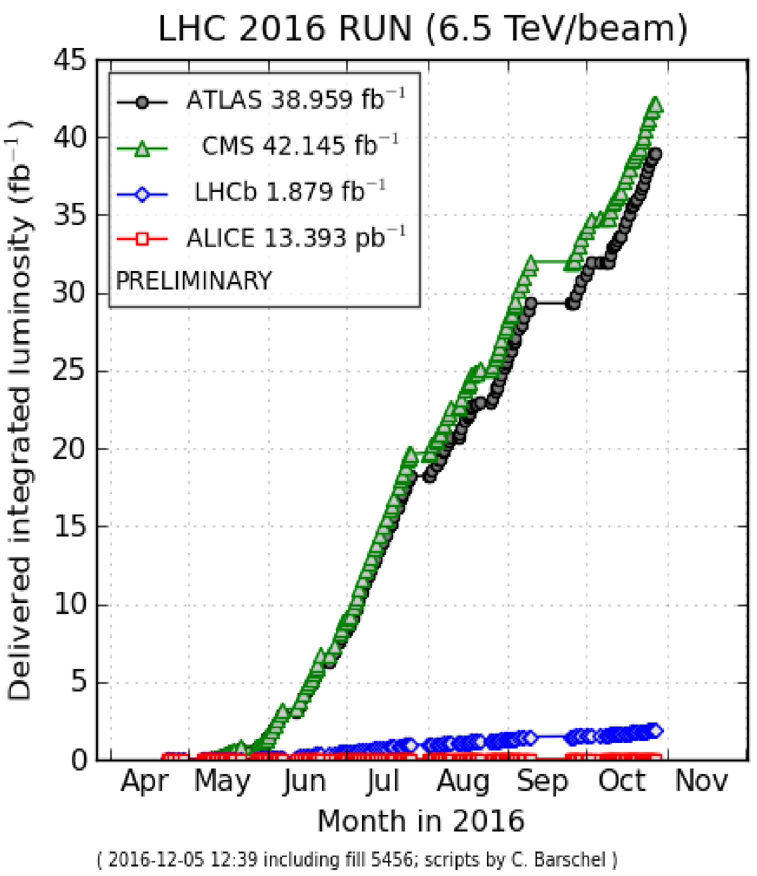
- Neutrino portal – $N_{2,3}$
- Vector portal – dark photons
- Scalar portal – hidden-sector scalars
- Axion-like particles
- Light SUSY – neutralinos, sgoldstinos...
- Tau-neutrino physics
- Light dark matter
- Etc...




Sensitivity to $N_{2,3}$ with ~$5 \cdot 10^{16}$ neutrinos from charm decays

# Exploring higher N masses (1)

- *B factory* → up to 5 GeV
  - Belle
  - LHCb
  - SHiP
- *Z factory* → up to 90 GeV
  - LEP1
  - FCC-ee
- *W factory* → up to TeV scale
  - LHC
  - FCC-hh

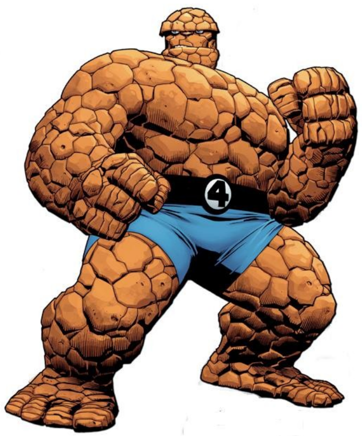


# Exploring higher N masses (2)

- ***B factory*** → up to 5 GeV
  - Belle
  - LHCb
  - SHiP
- ***Z factory*** → up to 90 GeV
  - LEP1
  - FCC-ee
- ***W factory*** → up to TeV scale
  - LHC
  - FCC-hh

High-energy frontier

High-intensity frontier



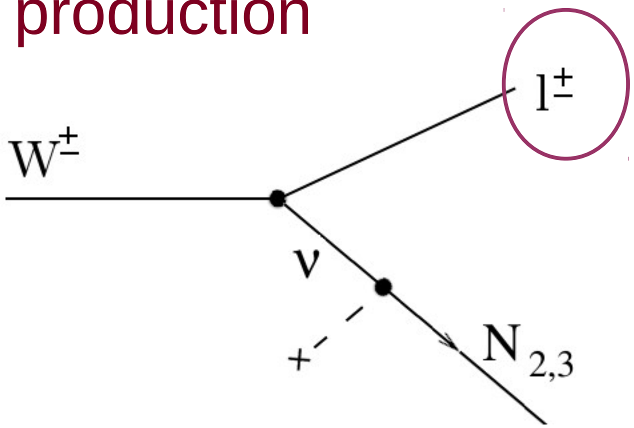
**Using the LHC as a high-intensity machine at the electroweak scale**

Sensitivity studies in
PRD 89, 073005 (2014)
PRD 91, 093010 (2015)

$>10^9$ $\nu$s from *W*s per year in ATLAS or CMS
→ displaced N decays for $m_N < 30$ GeV

# N at the LHC – on-shell *W*s and displaced-vertex signature

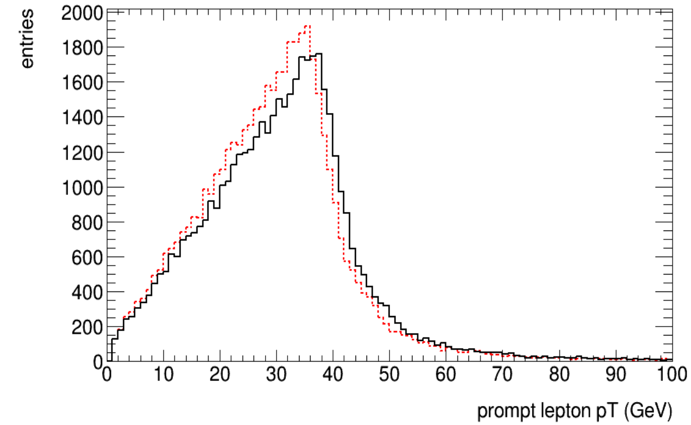
production



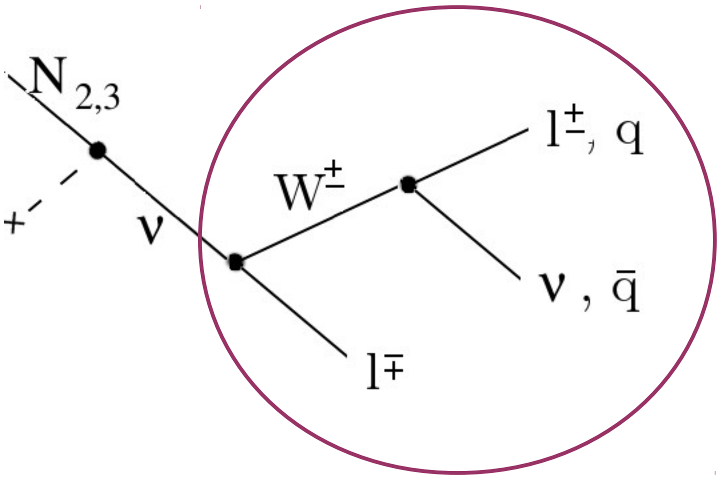

Prompt lepton essential for trigger

Low-pT objects → **large QCD backgrounds**

(generator-level pT distributions)




decay

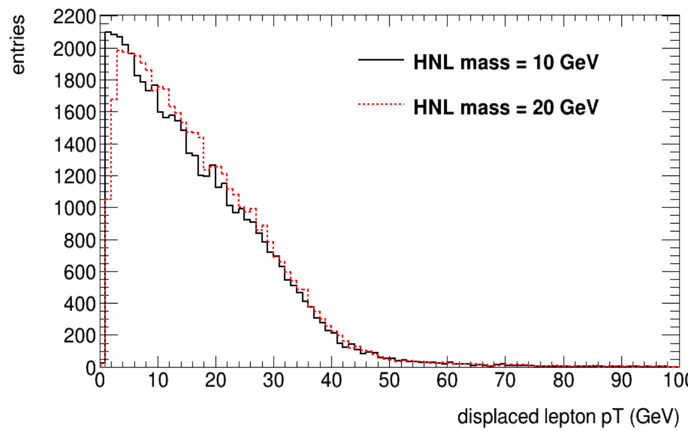



**1) Three prompt leptons with no opposite-sign same-flavour**

($m_N \geq 20$ GeV)

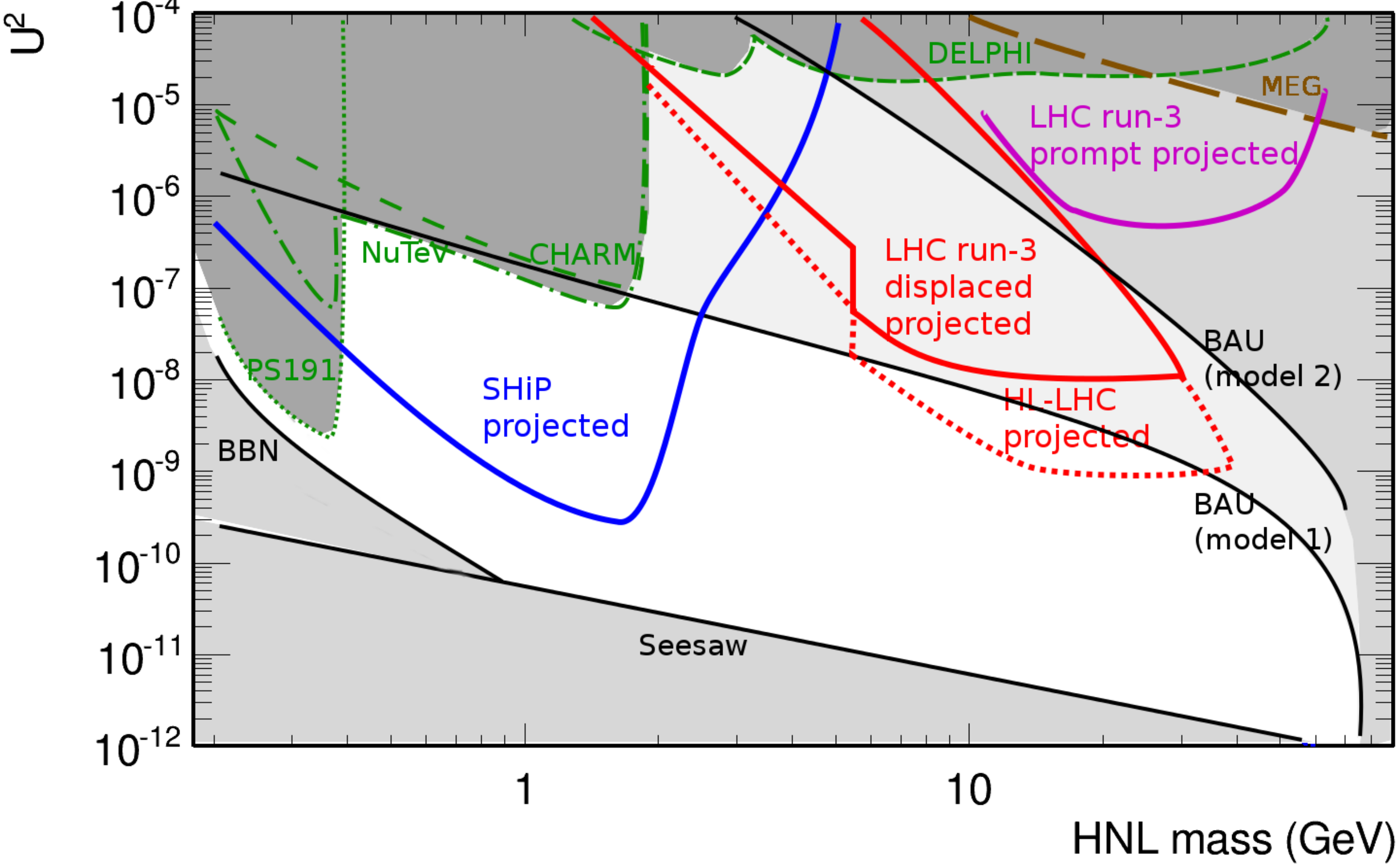
**2) Displaced vertex (DV)**

($3 \leq m_N \leq 30$ GeV)



# Heavy neutrinos at CERN in a 10-year timesecale

assume SHiP technical proposal
assume 300 (3000) fb⁻¹ @ 14 TeV in ATLAS and CMS

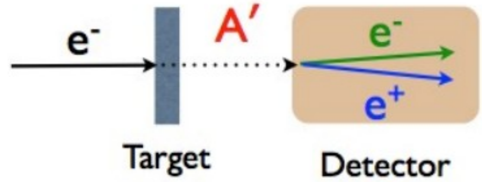


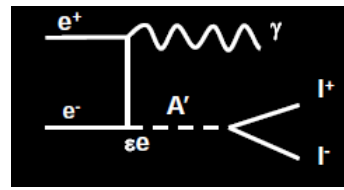

model 1: PRD 87, 093006 (2013) ($N_1$ does not participate in BAU → dark matter)

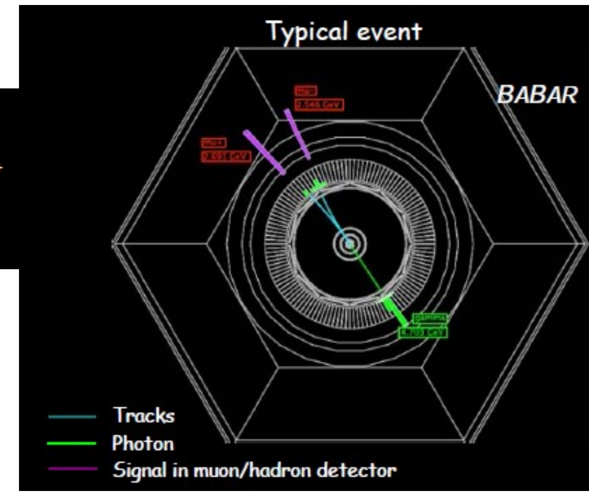
model 2: PRD 90, 125005 (2014) (allow all three Ns to participate in BAU)

# Dark photon (1)

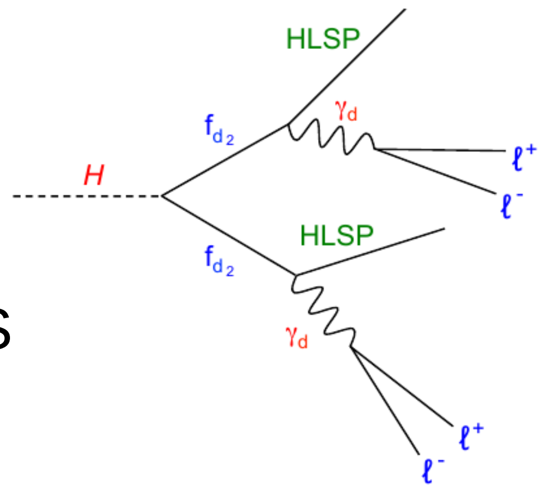
- Vector portal
  - Electron beam dump
  - Proton beam dump
  - electron-positron colliders (Babar, Belle)
  - LHCb

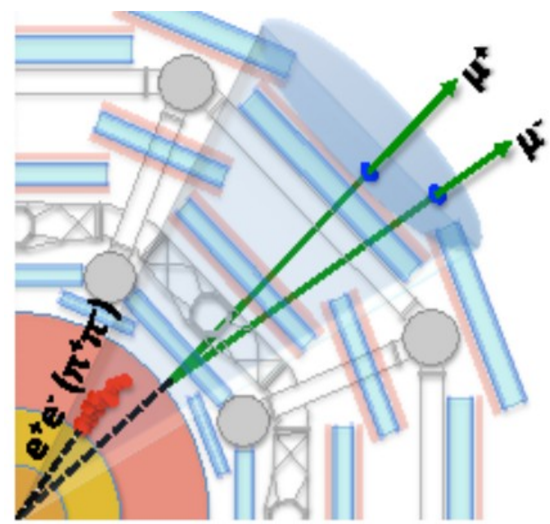



- Higgs portal
  - ATLAS and CMS



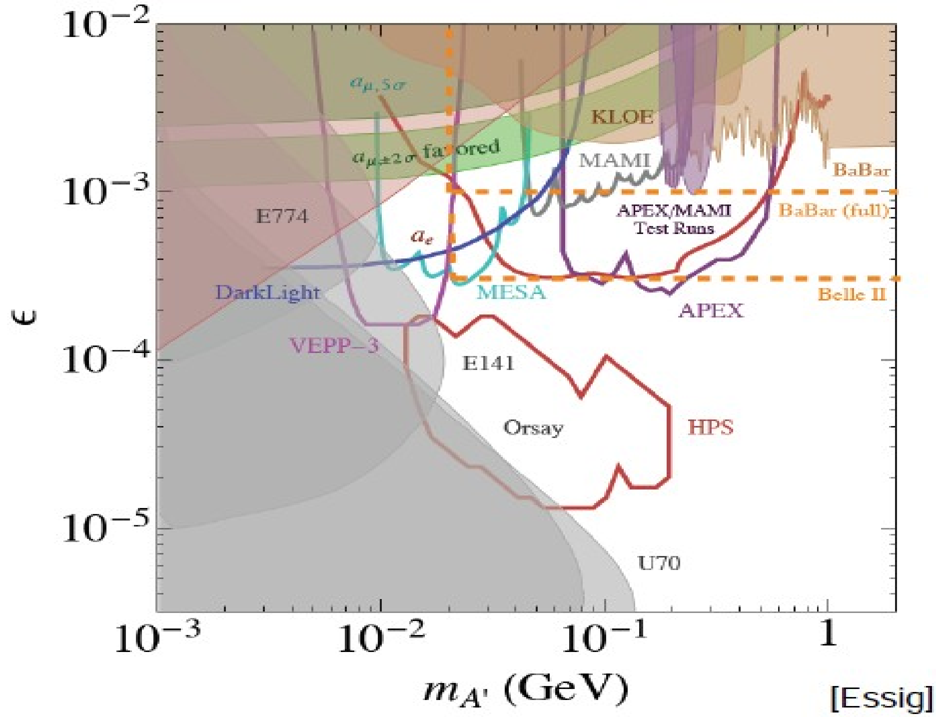
# Dark photon (2)

- Vector portal
  - Electron beam dump
  - Proton beam dump
  - electron-positron colliders (Babar, Belle)
  - LHCb

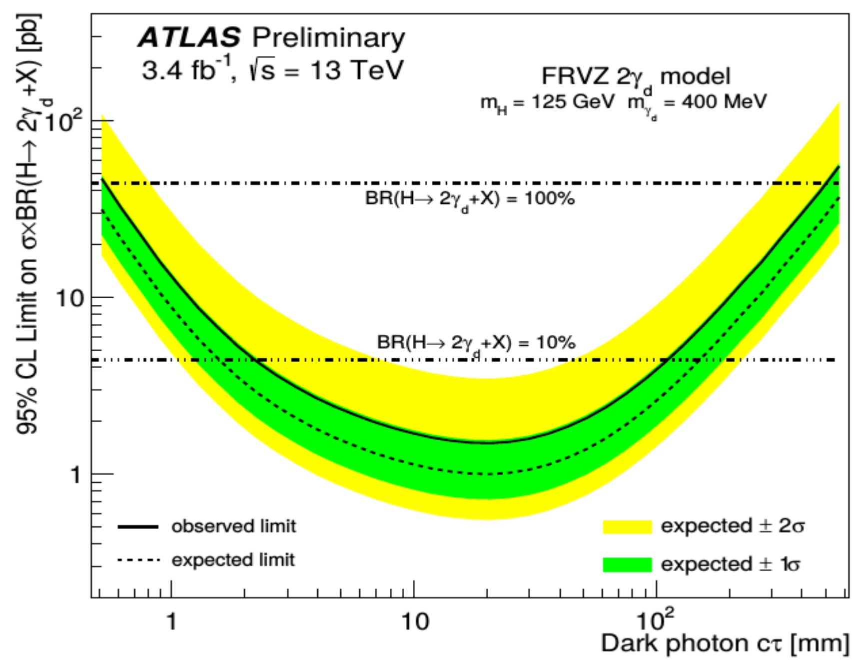
➔ Direct constraints on mixing to the photon

- Higgs portal
  - ATLAS and CMS

➔ Constraints on Higgs decay branching ratio



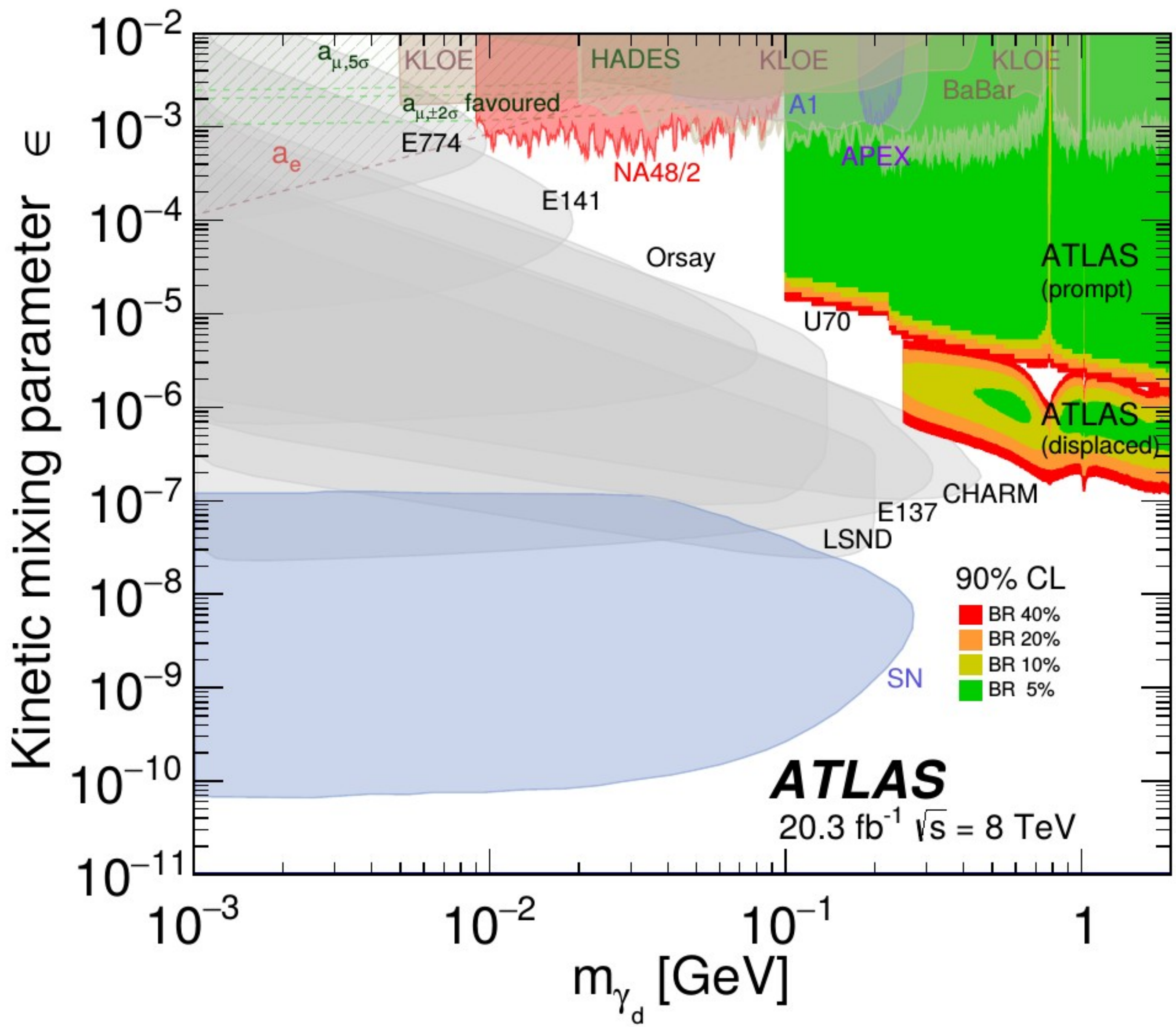

[Essig]




ATLAS-CONF-2016-042

# Dark photons at ATLAS and CMS

ATLAS ArXiv:1511.05542 (2015), CMS arXiv:1506.00424 (2015), ATLAS-CONF-2016-042, ATLAS-CONF-2016-103

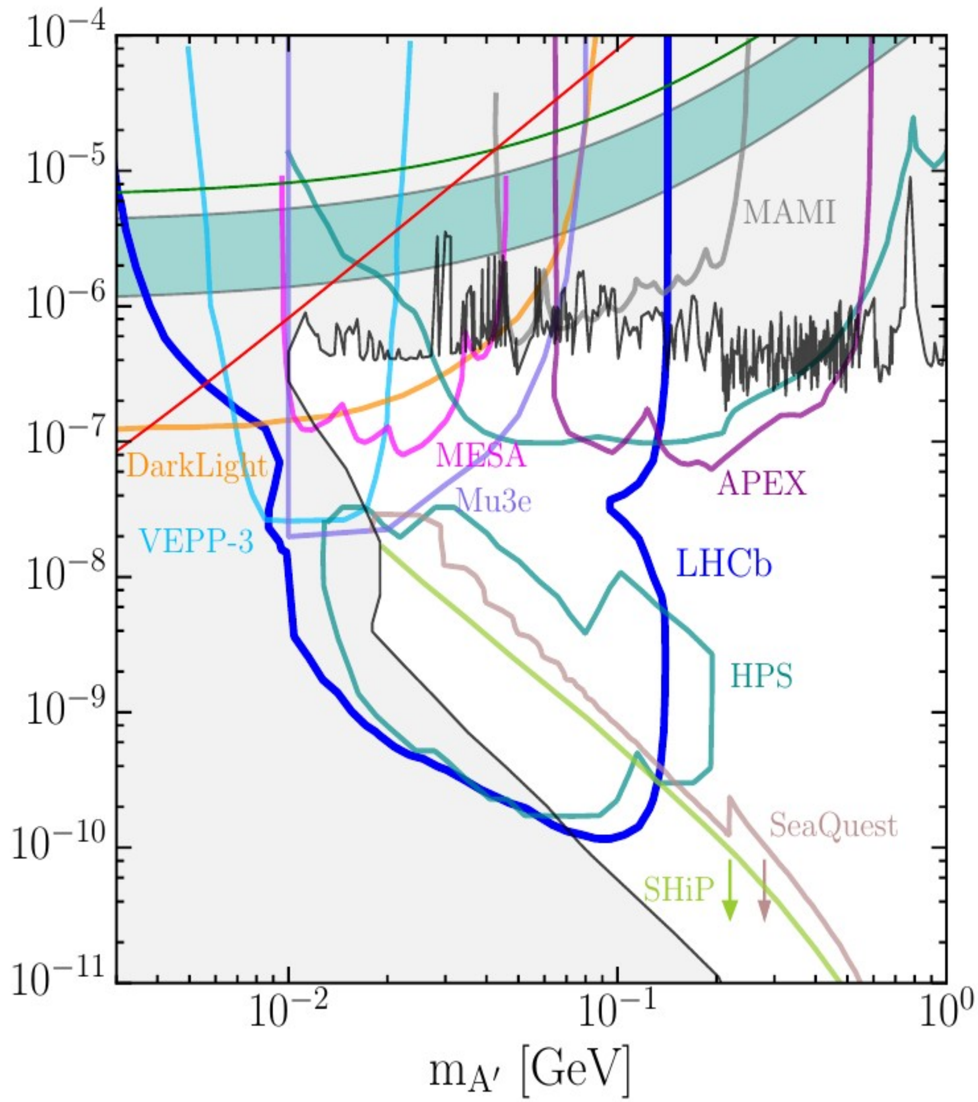



Remember : LHC limits rely on assumption of Higgs decay to hidden fermions

# Dark photons at LHCb

- Produced in charm meson decays $D^{*0} \rightarrow D^0\gamma$
- Identification of prompt and displaced vertices of low-momentum lepton pairs, requiring:
  - Precise tracking
  - Triggerless readout planned for Run-3

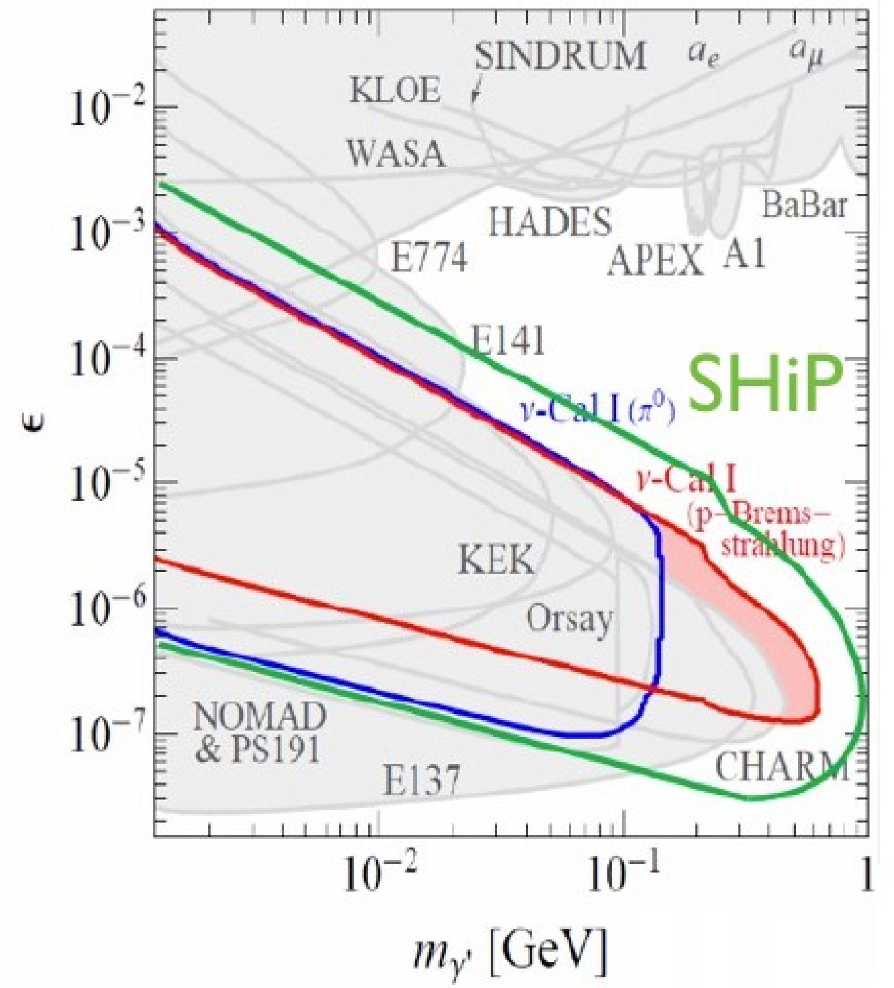
Projected sensitivity (PRD 92, 115017 (2015))



# Dark photons at SHiP

- Production dominated by
  - $p \rightarrow p\gamma$
  - $\pi^0 \rightarrow \gamma\gamma$
  - $\eta \rightarrow \gamma\gamma$
- Dark photon decays to $e^+e^-$ and $\mu^+\mu^-$
- Large expected improvement at high mass and low coupling (long lifetimes)

Projected sensitivity



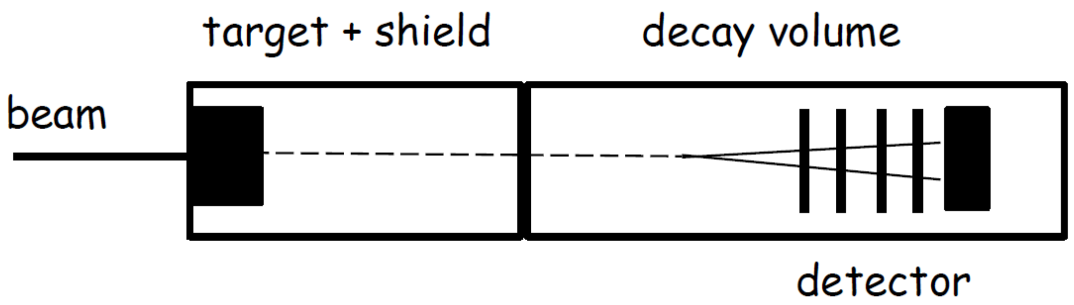
# Summary and outlook

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 – B-factories, LHC
  - Fixed target – APEX, HPS, SHiP
- Wide experimental programme for many years to come!

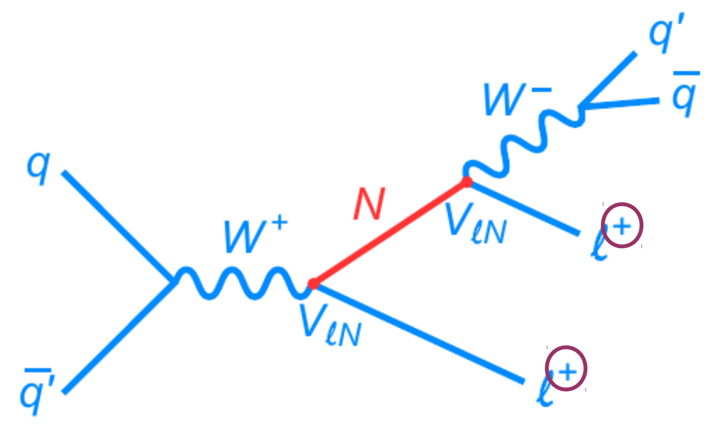
# Extras

# N searches at fixed-target facilities




- Strategy: high-intensity proton beam on a target, produce large amounts of neutrinos from hadron decays
- $m_N$ up to 0.4 GeV probed through pion and kaon decays
  - **PS191 experiment** at CERN Phys. Lett. B 203, 332 (1988)
- $m_N$ up to 2 GeV probed through charmed meson decays
  - **CHARM experiment** at CERN Phys. Lett. B 166, 473 (1986)
  - **NuTeV experiment** at Fermilab Phys. Rev. Lett. 83, 4943 (1999)
- With high-energy beams, $m_N$ up to 4 GeV can be probed to some extent through $B$ decays

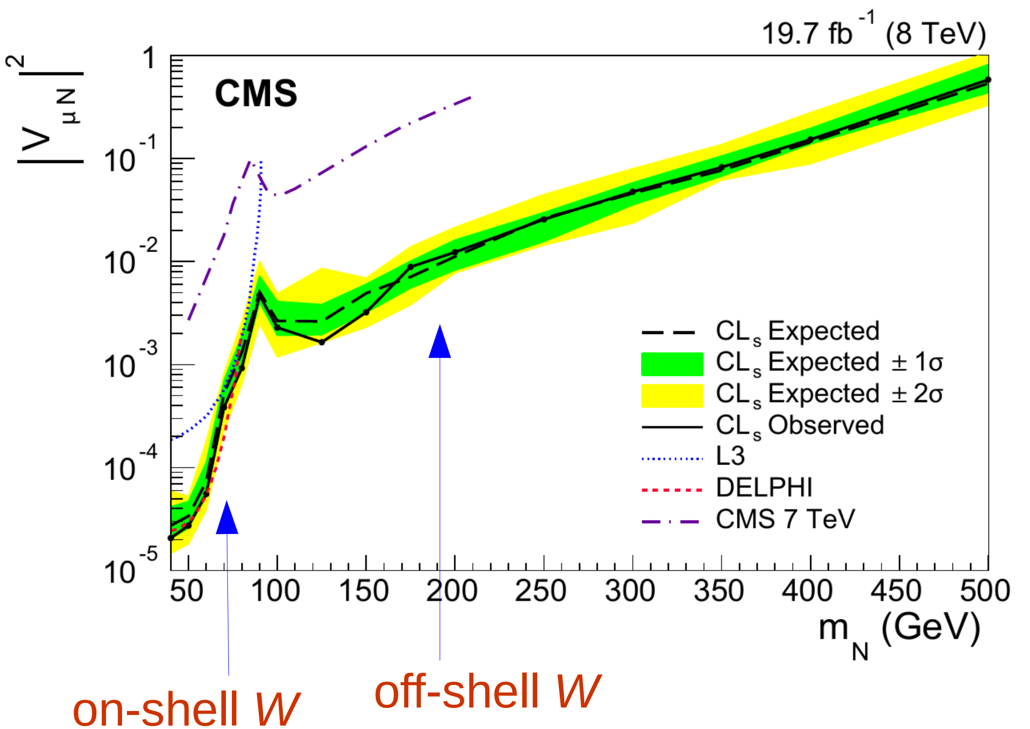
# N at the LHC – prompt high-pT signature




## Same-sign leptons + two jets

- Exploit Majorana nature of the neutrino
- Investigated in both ATLAS and CMS

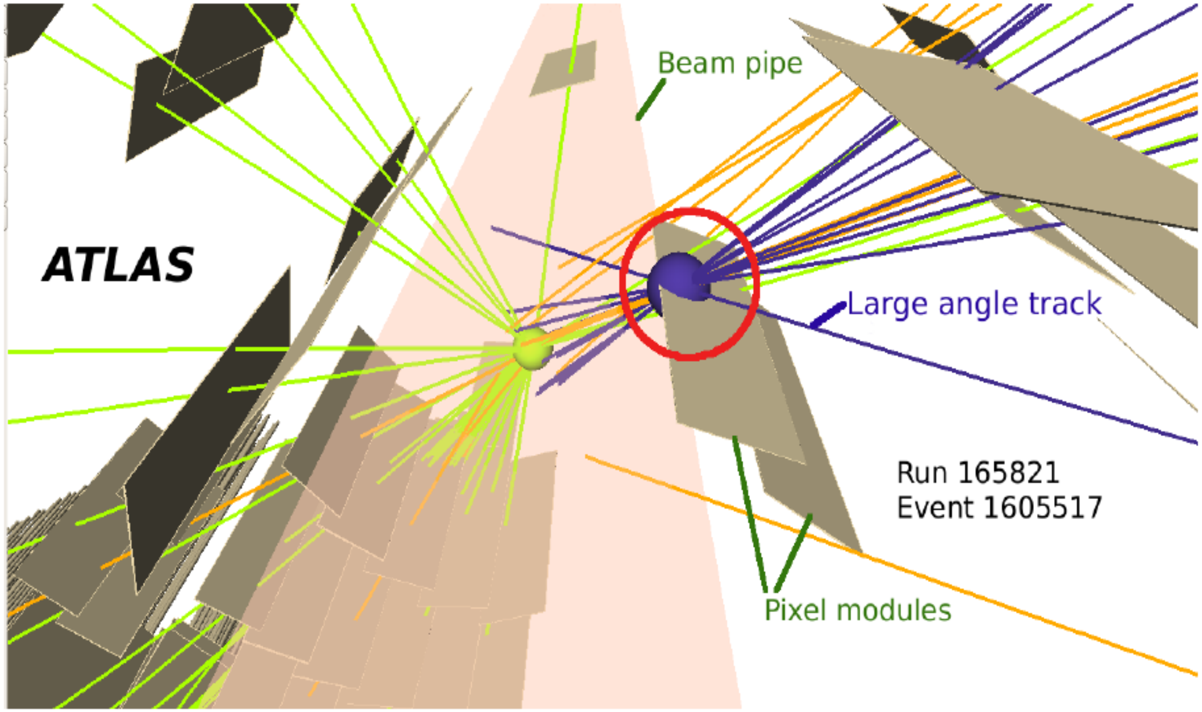
PLB 717, 109 (2012); JHEP 07, 162 (2015); PLB 748, 144 (2015)




- Models of leptogenesis point to lower mass, lower mixing

  → on-shell *W*

# LHC – DV signature




Similar to previous work using DV in ATLAS and CMS inner detectors

PLB 707, 478 (2012)
PLB 719, 280 (2013)
JHEP 02, 085 (2013)
PRL 114, 061801 (2015)
PRD 91, 052012 (2015)
PRD 91, 012007 (2015)
PRD 92, 072004 (2015)

- So far no sensitivity to N due to high pT thresholds (trigger on MET or particles from DV, interpratation in SUSY models)
- Adequate track and vertex reconstruction tools, similar backgrounds
- The N signature is unique, it has a prompt lepton for triggering and a DV with low-pT tracks and low mass