# Direct searches for heavy neutrinos



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Stockholm, 7 March 2017

# Where are the new physics?

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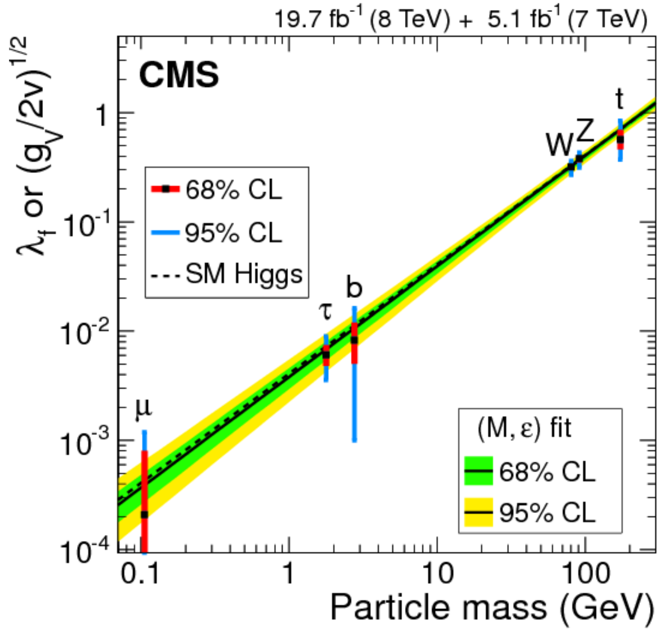
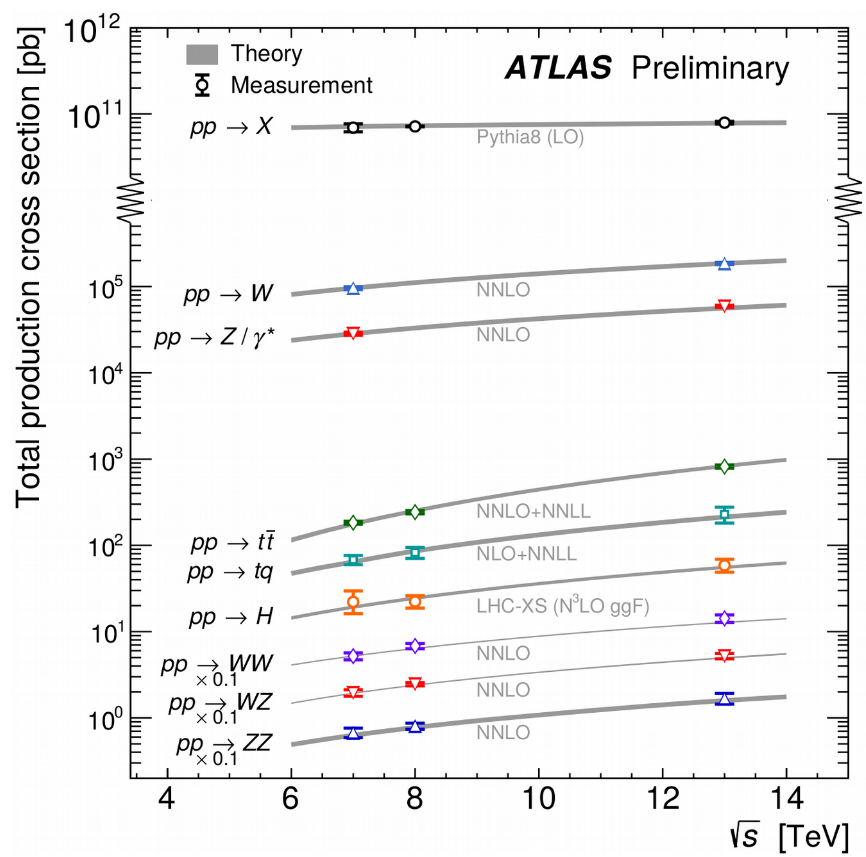
No new physics so far at the LHC **even at the highest energies**

- The SM is a triumph up to the TeV scale



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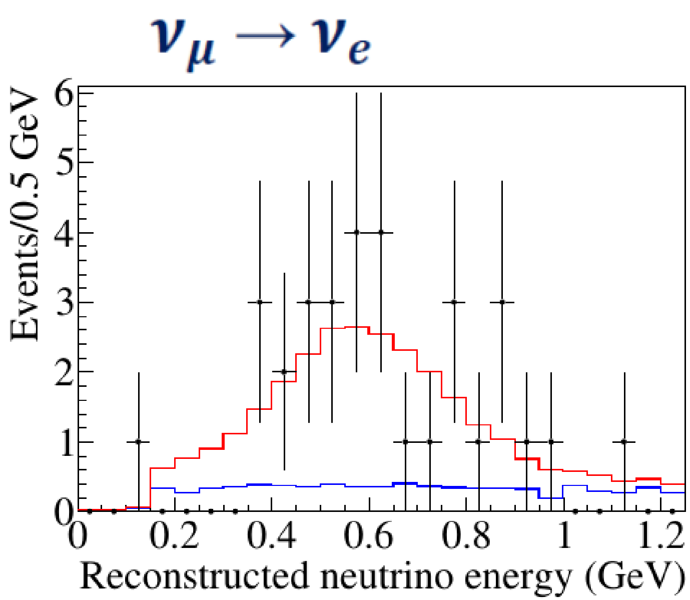
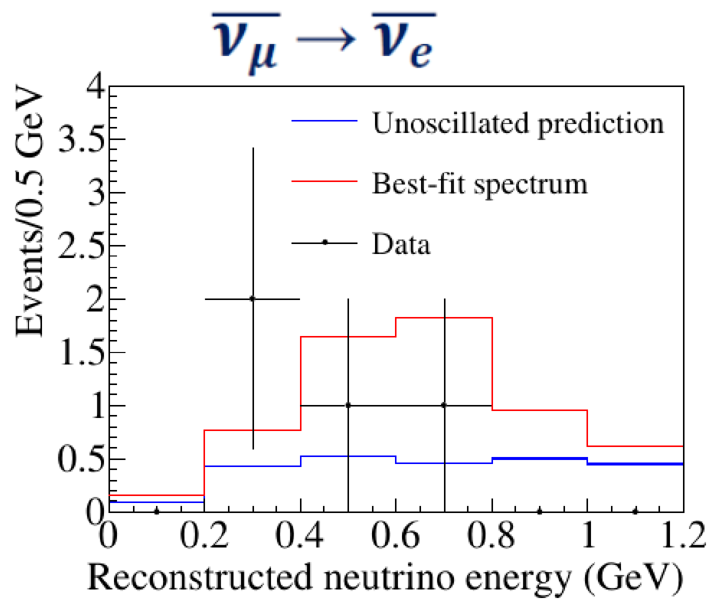
T2K might be seeing **CP violation in the neutrino sector**

- Can reasonably expect 3σ level confirmation within 10 years




arXiv:1701.00432 (2017)

**Observed 32 events**

Expect 24.2 if $\delta_{CP}$= 0

28.7 if $\delta_{CP}$= -π/2

**Observed 4 events**

Expect 6.9 if $\delta_{CP}$= 0

6.0 if $\delta_{CP}$= -π/2

(assuming normal hierarchy)

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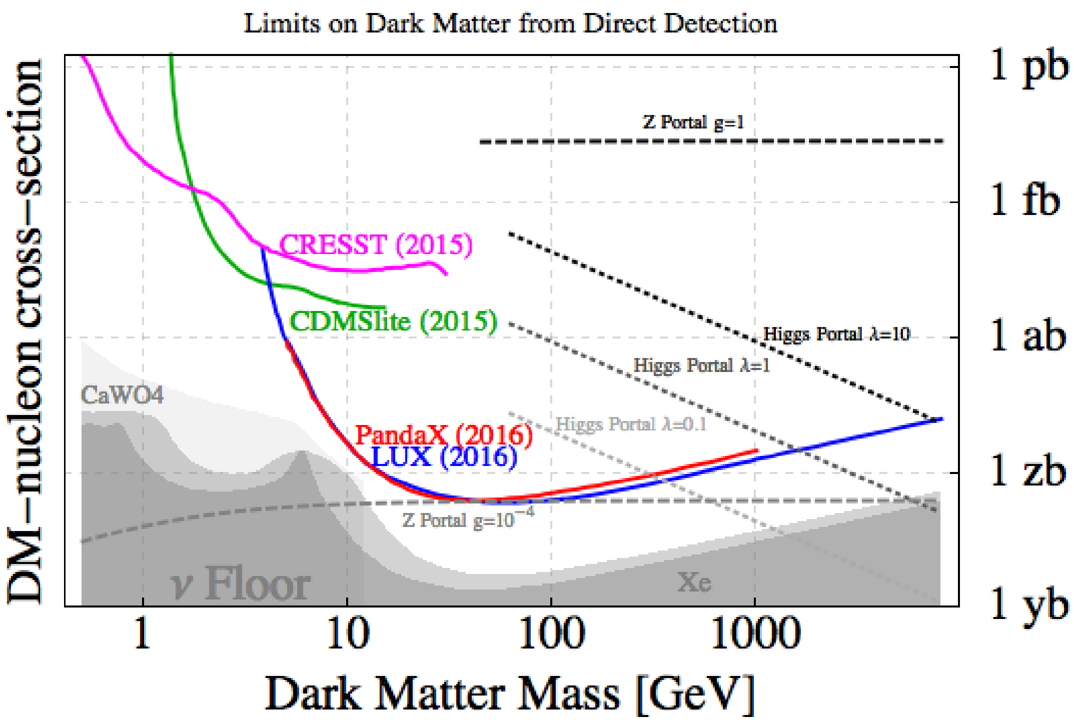
**No dark-matter interactions** seen on Earth

- Renewed interest in light dark matter scenarios



# Neutrino masses

# Neutrino masses

## The Nobel Prize in Physics 2015

Photo: A. Mahmoud
**Takaaki Kajita**
**Prize share:** 1/2

Photo: A. Mahmoud
**Arthur B. McDonald**
**Prize share:** 1/2

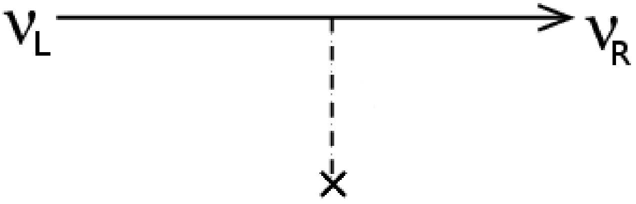
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

There is no unique way to incorporate neutrino masses in the Standard Model

Almost certainly implies the existence of

- new mass-generation mechanism
- new phenomena such as right-handed neutrinos

Mass ⟺ Coupling with Higgs vev




Dirac only (like $e^-$, $e^+$)

$M_R = 0$

$m_D \neq 0$

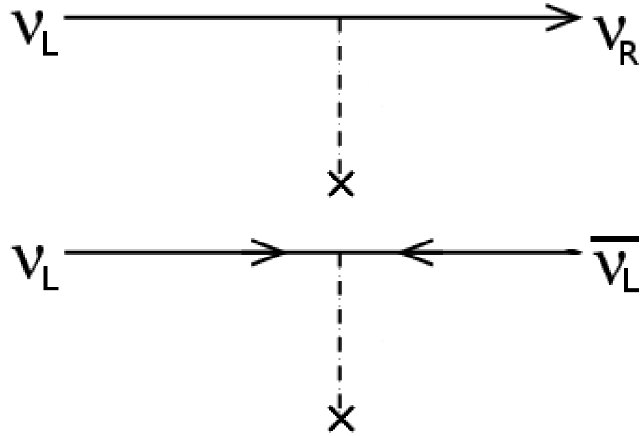
| | $\nu_L$ | $\nu_R$ | $\bar{\nu}_L$ | $\bar{\nu}_R$ |
|---|---|---|---|---|
| $I_{weak}=$ | ½ | 0 | ½ | 0 |

**4 states of equal masses**

**Some have I=1/2 (active)**

**Some have I=0 (sterile)**

Mass ⟺ Coupling with Higgs vev




Majorana mass ($M_R$)

→ Allowed for neutrinos!

Dirac only (like $e^-$, $e^+$)

$M_R = 0$
$m_D \neq 0$

m ↑

$\nu_L$ $\nu_R$ $\bar{\nu}_L$ $\bar{\nu}_R$

$I_{weak}=$ ½ 0 ½ 0

4 states of equal masses

Some have I=1/2 (active)

Some have I=0 (sterile)

Majorana only

$M_R \neq 0$
$m_D = 0$

m ↑

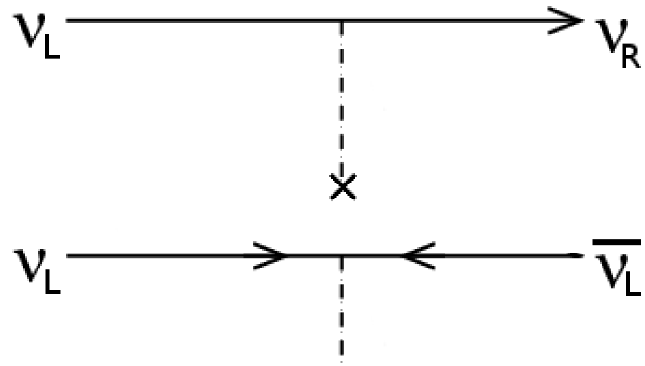
$\nu_L$ $\bar{\nu}_L$

$I_{weak}=$ ½ ½

2 states of equal masses

All have I=1/2 (active)

Mass ⟺ Coupling with Higgs vev




Majorana mass ($M_R$)

➔ Allowed for neutrinos!

Dirac ($m_D$) and Majorana ($M_R$)

➔ Splitting of the mass states

**seesaw mechanism**

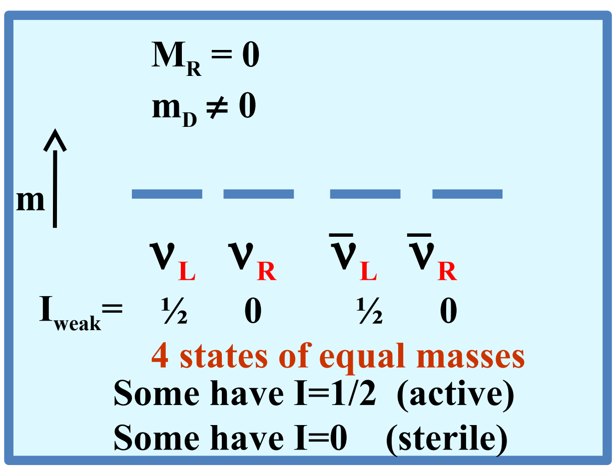
$$\tan 2\theta = \frac{2\, m_D}{M_R - 0} \qquad \ll 1$$

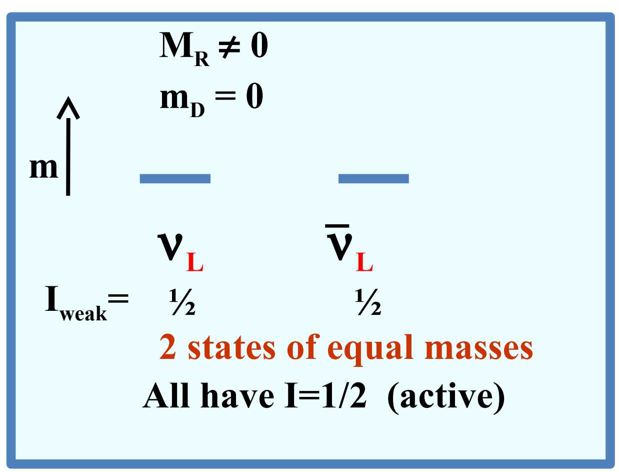
$$m_\nu = \tfrac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

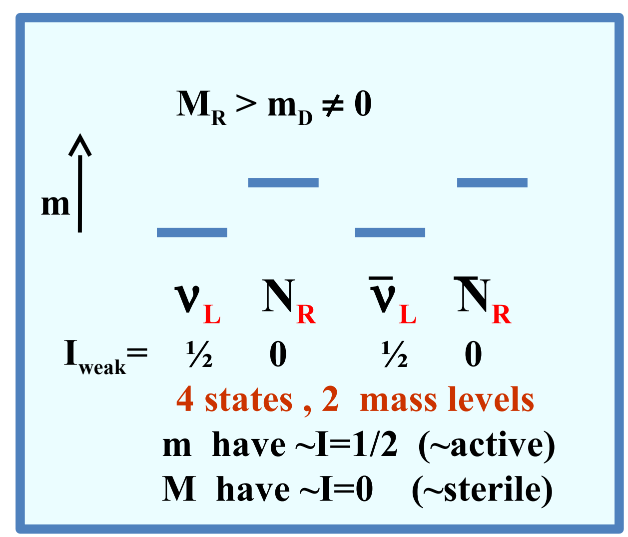
$$M = \tfrac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

Dirac only (like $e^-$, $e^+$) | Majorana | Dirac + Majorana



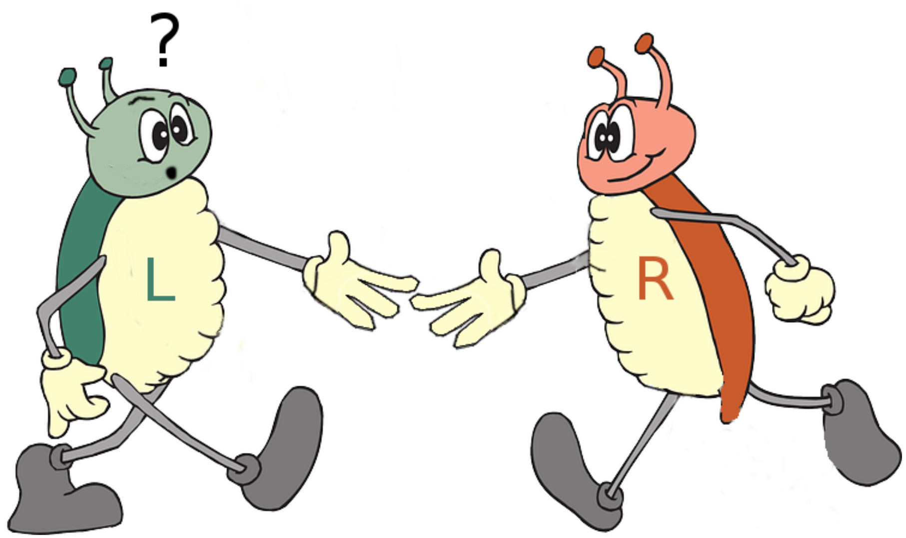



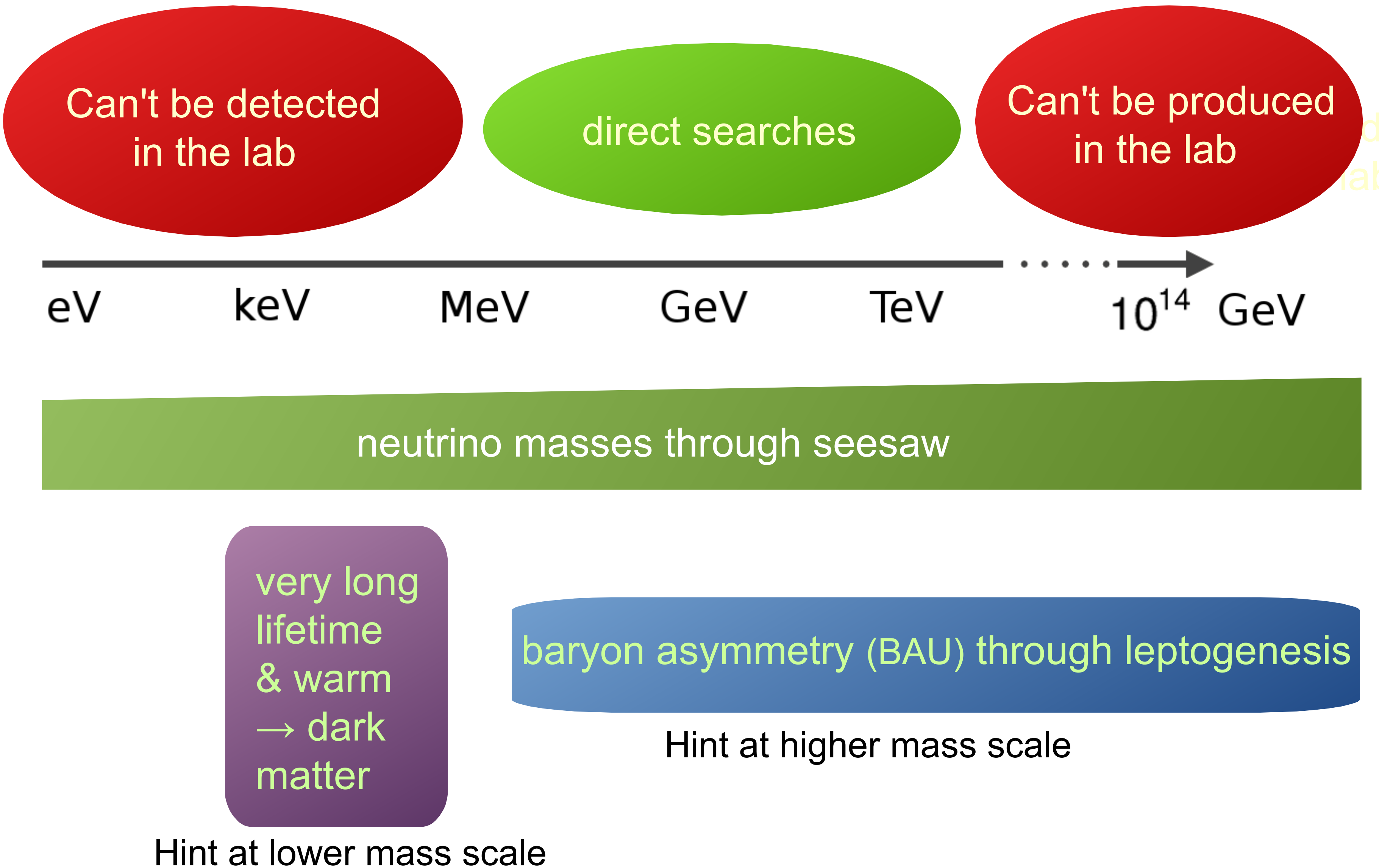
| | |
|---|---|
| $\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$ | $(e)_R \quad (\mu)_R \quad (\tau)_R$ <br> $(\nu_e)_R \quad (\nu_\mu)_R \quad (\nu_\tau)_R$ |

# N

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

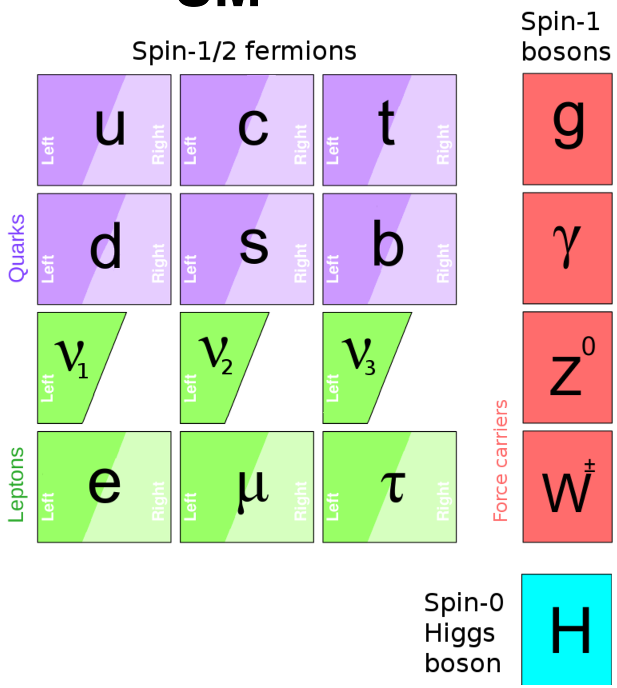


# N mass scale??

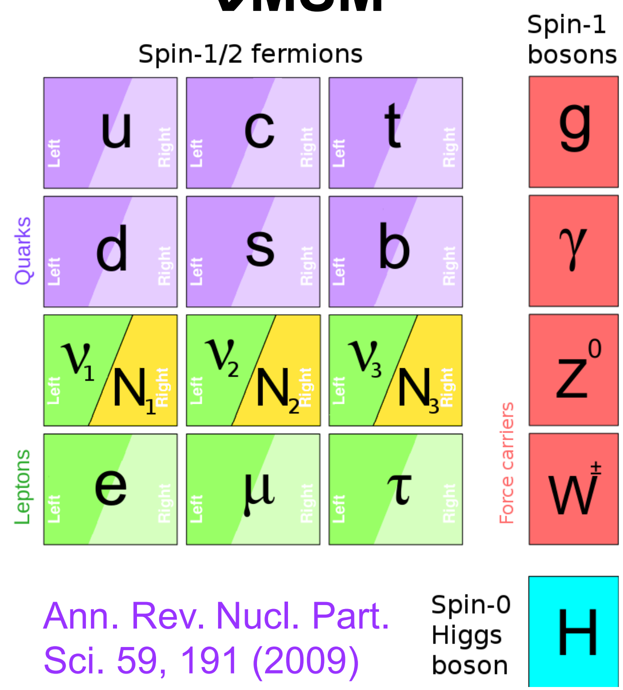

Can't be detected in the lab
direct searches
Can't be produced in the lab
eV
keV
MeV
GeV
TeV
$10^{14}$ GeV
neutrino masses through seesaw
very long lifetime & warm → dark matter
baryon asymmetry (BAU) through leptogenesis
Hint at higher mass scale
Hint at lower mass scale

# Still just 3 missing pieces

**SM**




**νMSM**

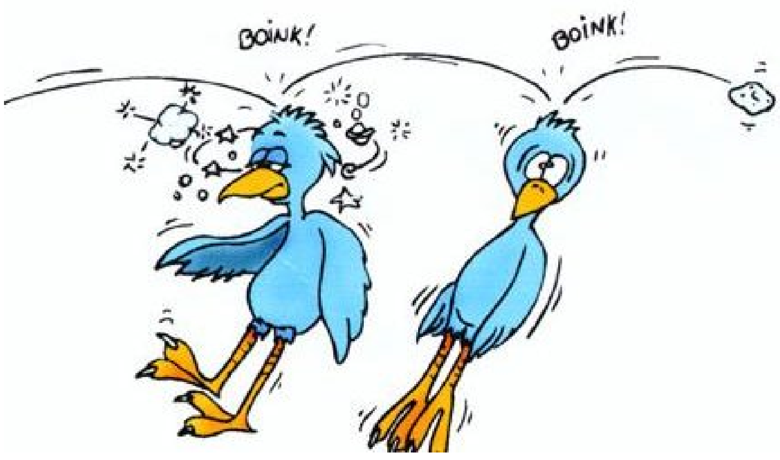


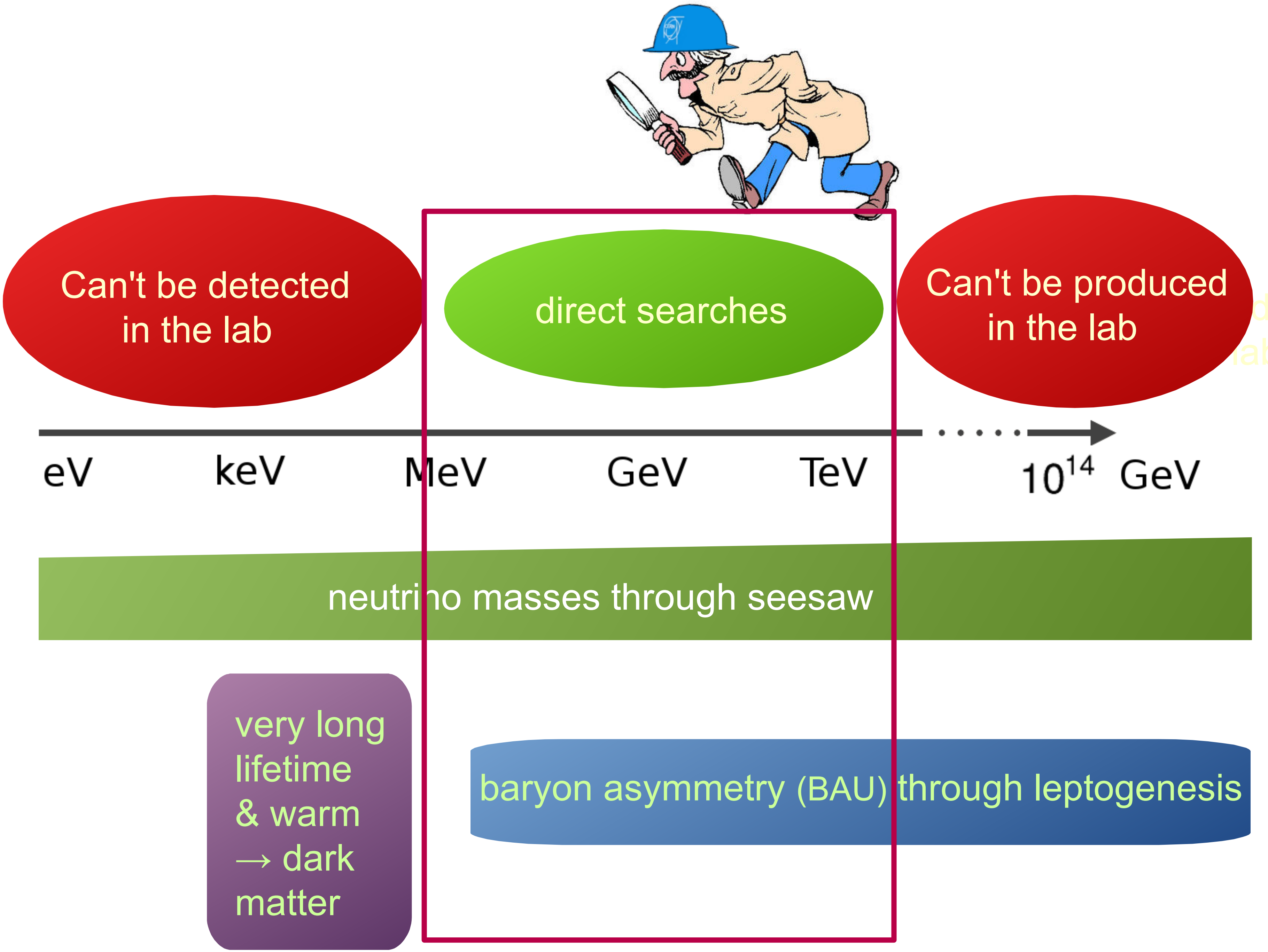

Ann. Rev. Nucl. Part. Sci. 59, 191 (2009)

**$N_1$** mass ~keV
→ **dark matter**

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

- Guided by <u>experimental</u> evidence for new physics

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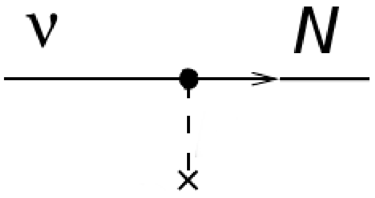
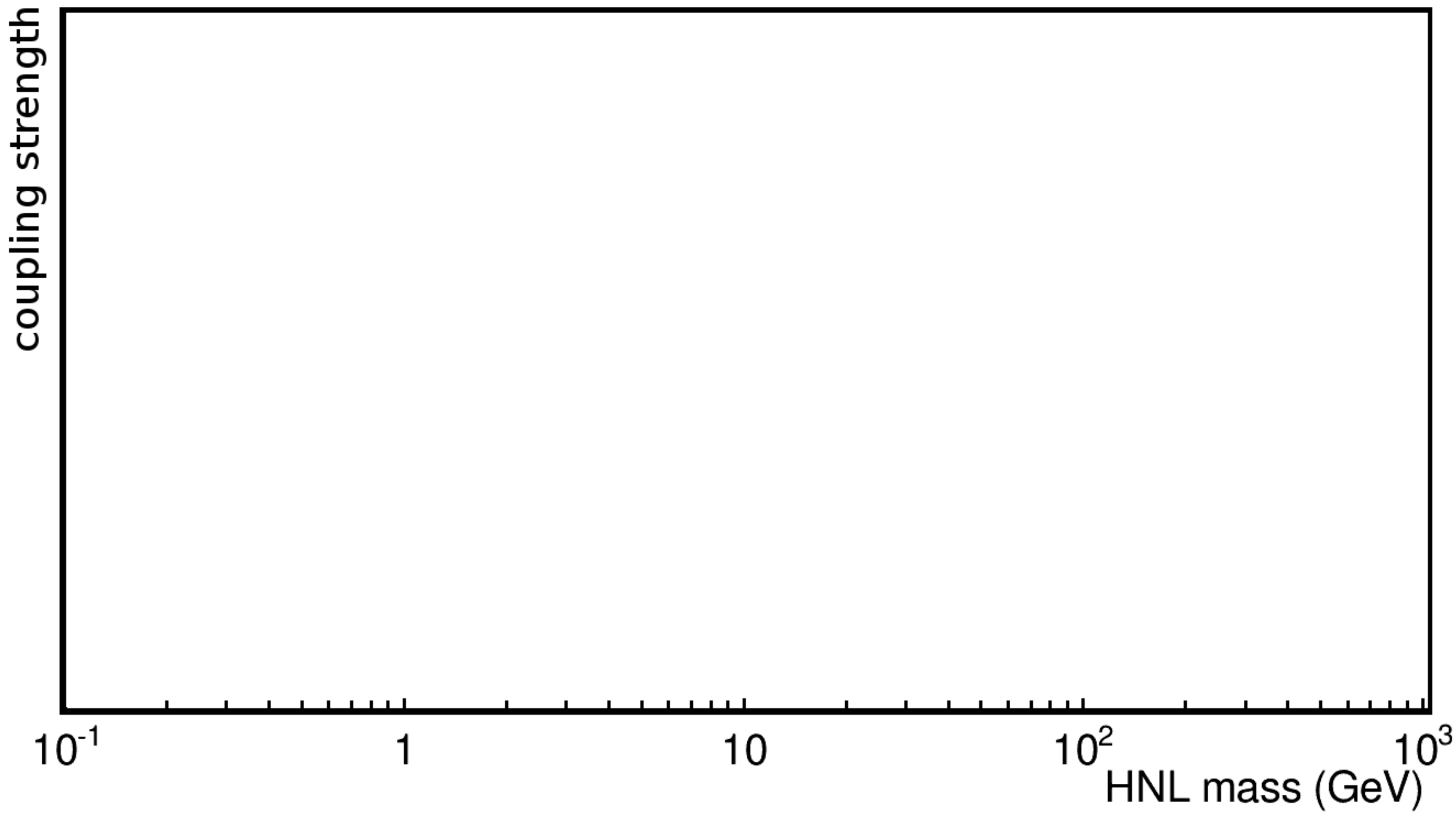
# N production and detection in the lab




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

- High-intensity beams
- Displaced decays



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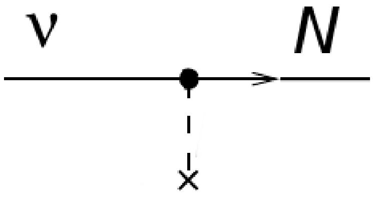


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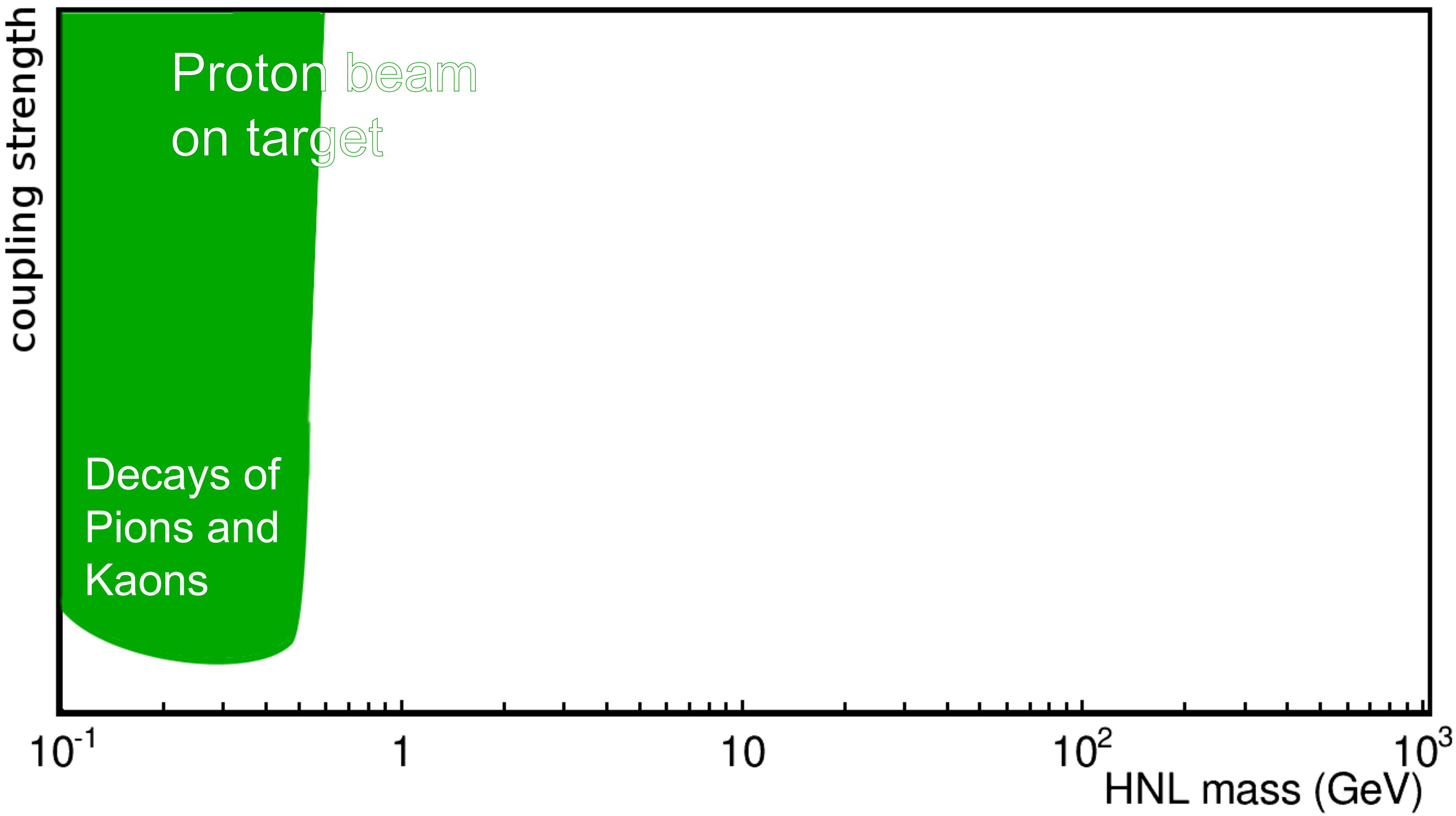

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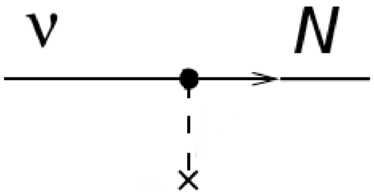


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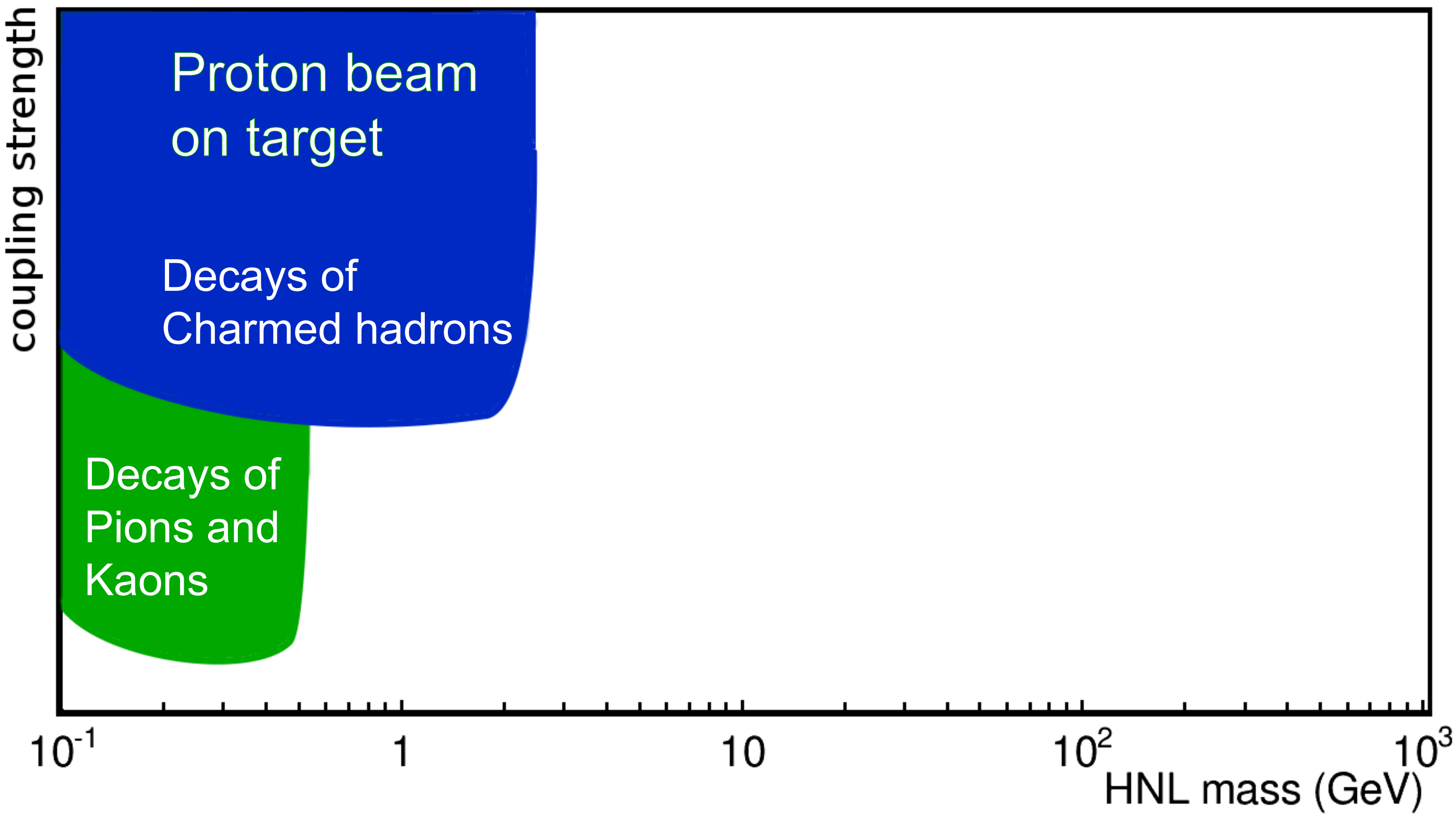

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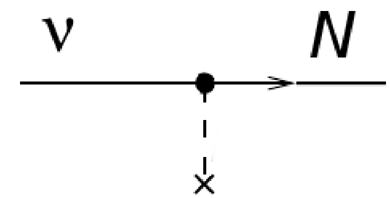


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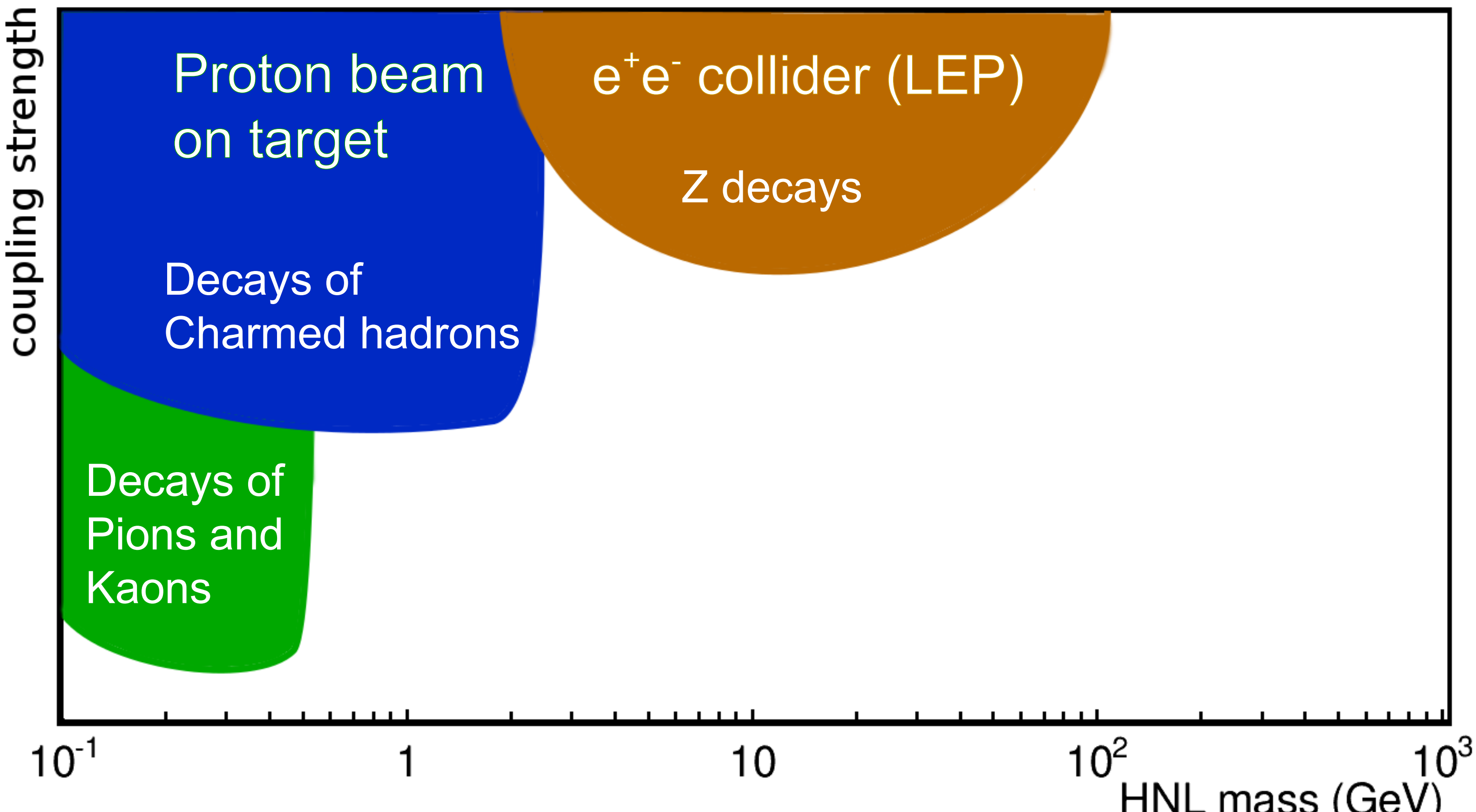

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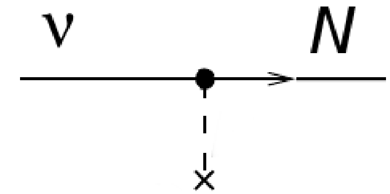


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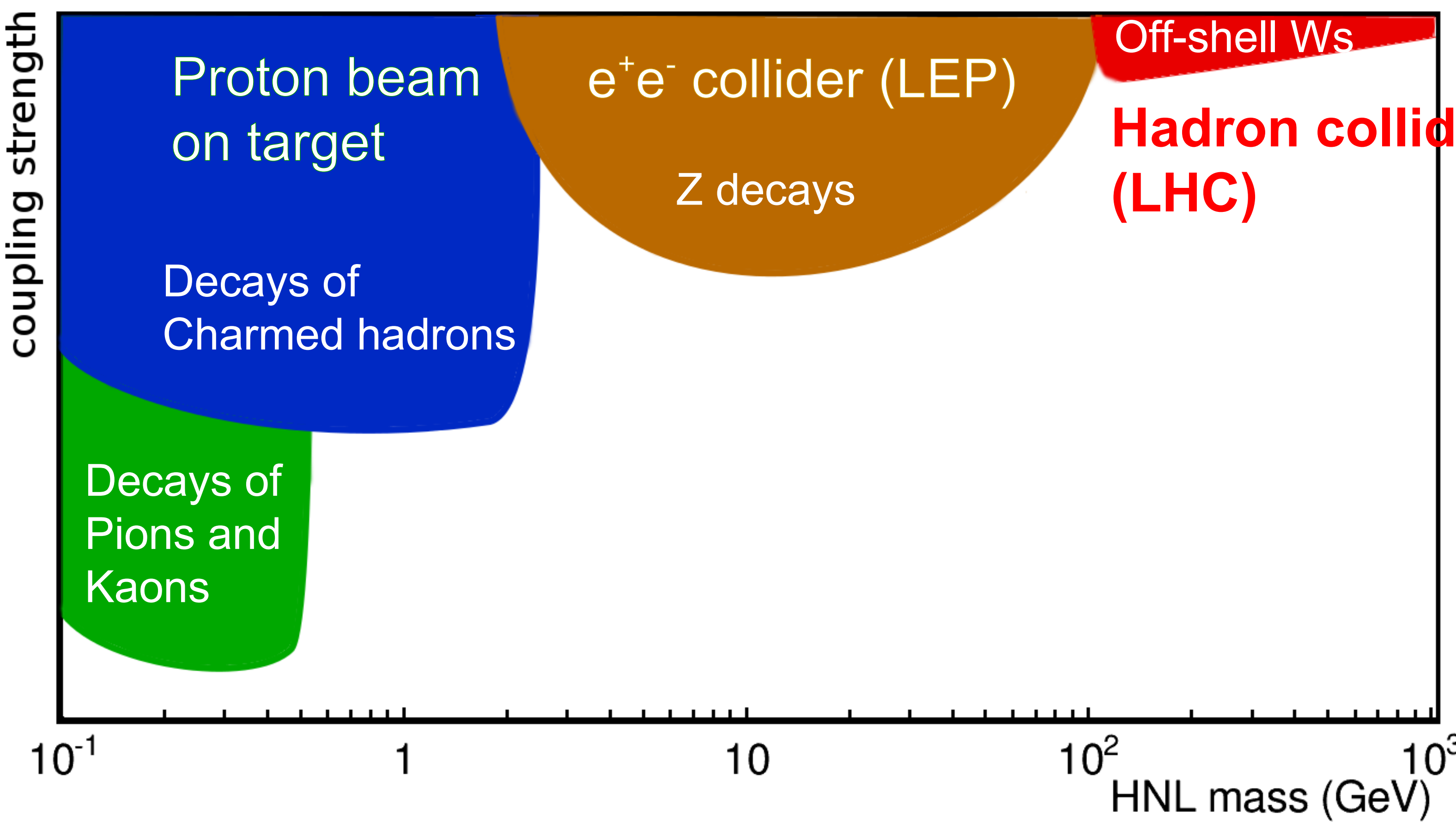

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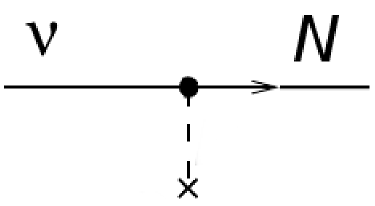


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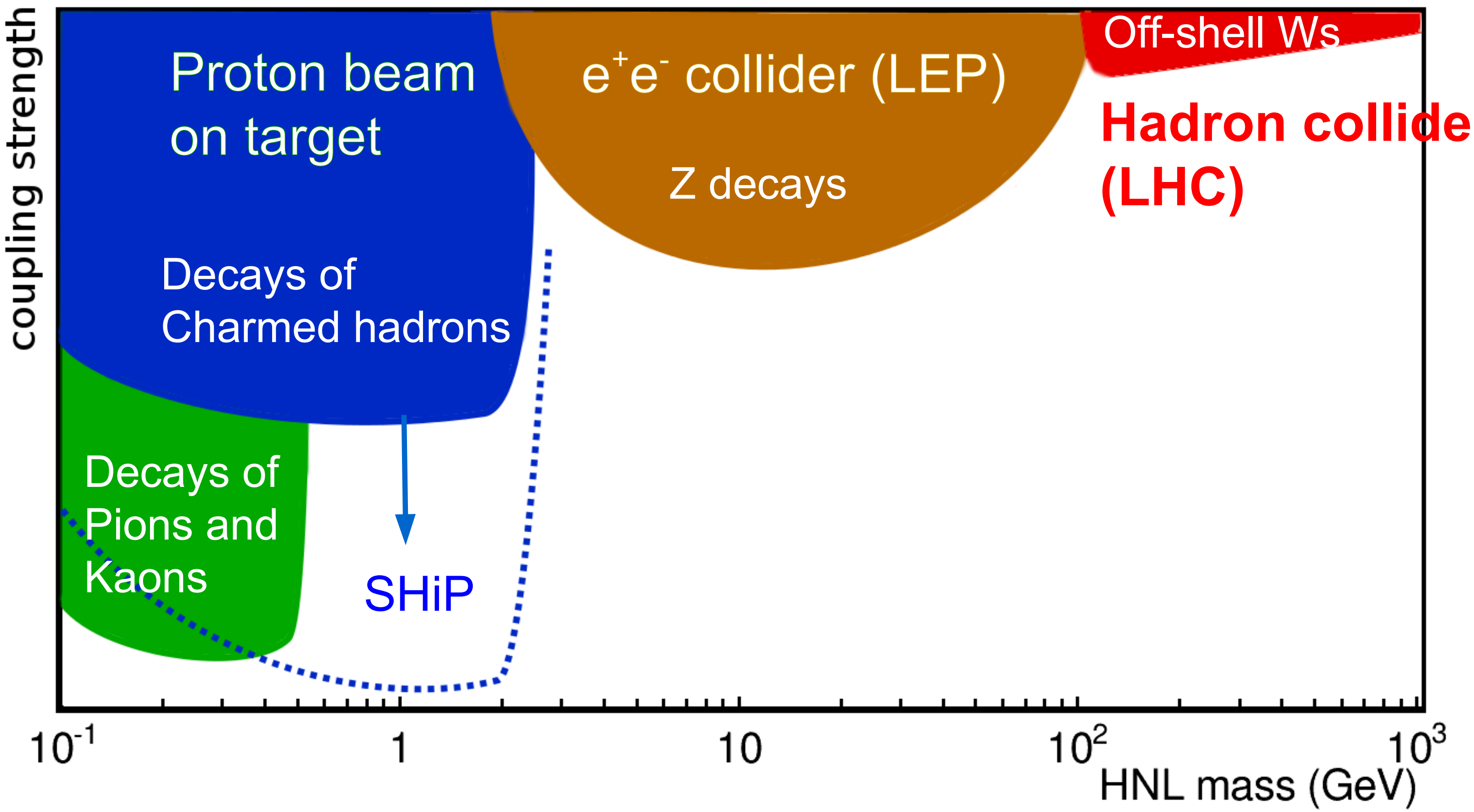

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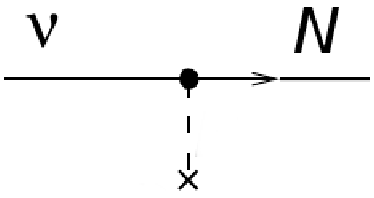


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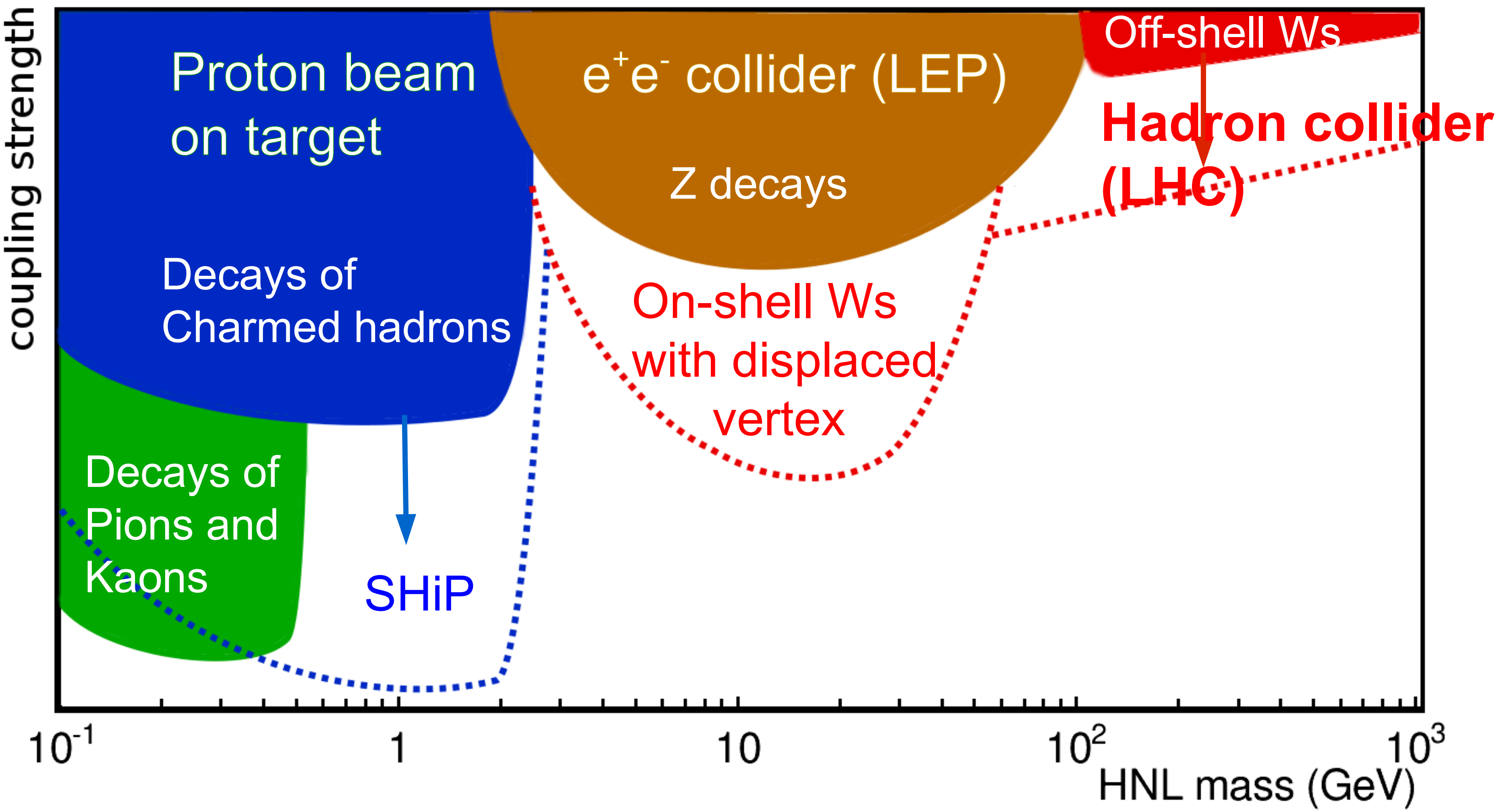

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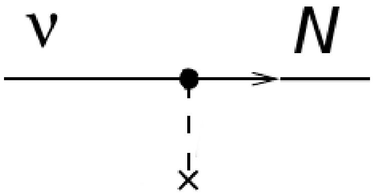


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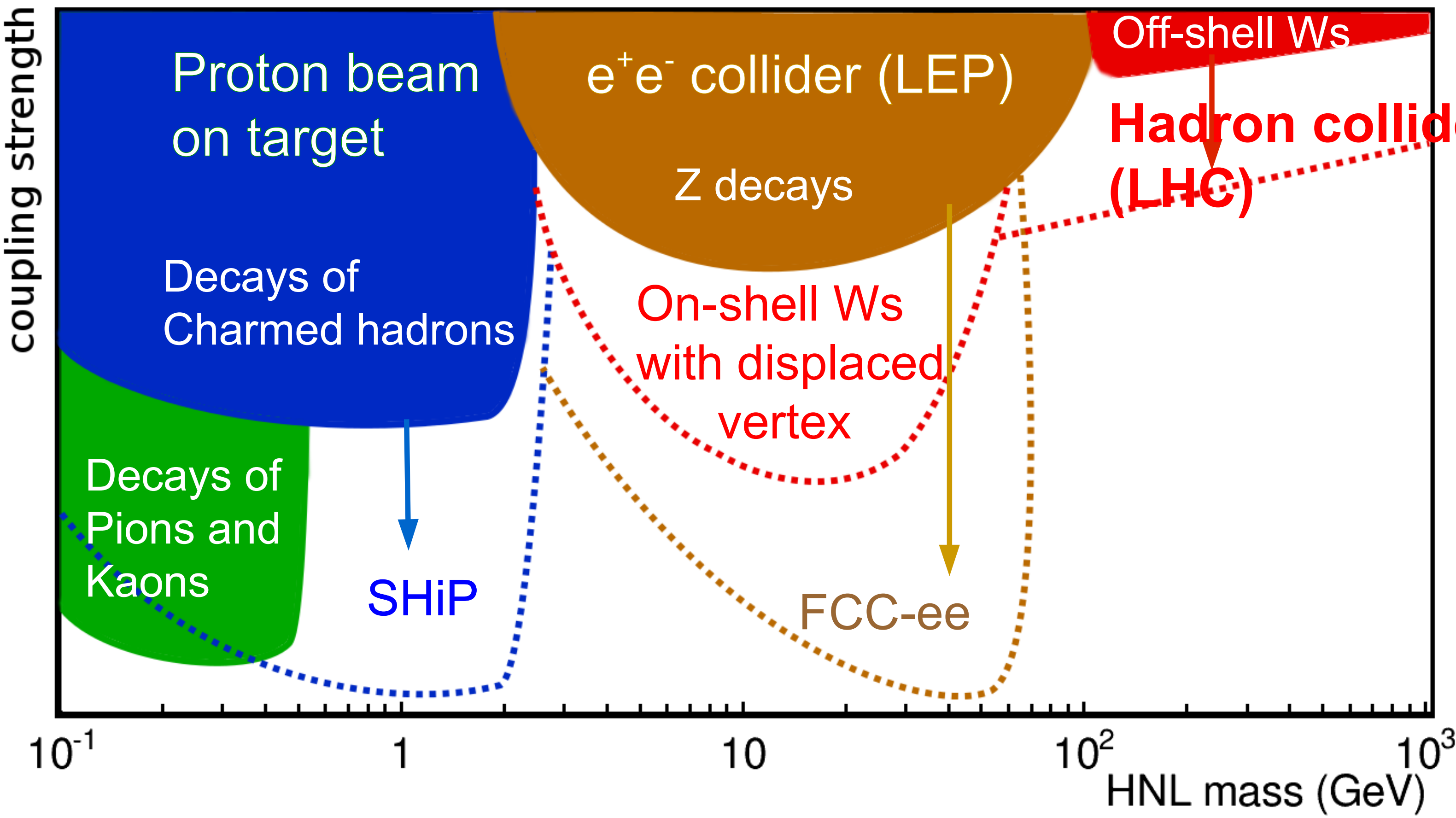

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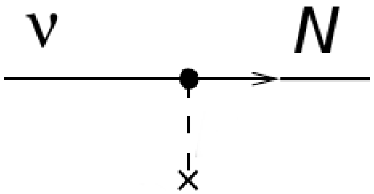


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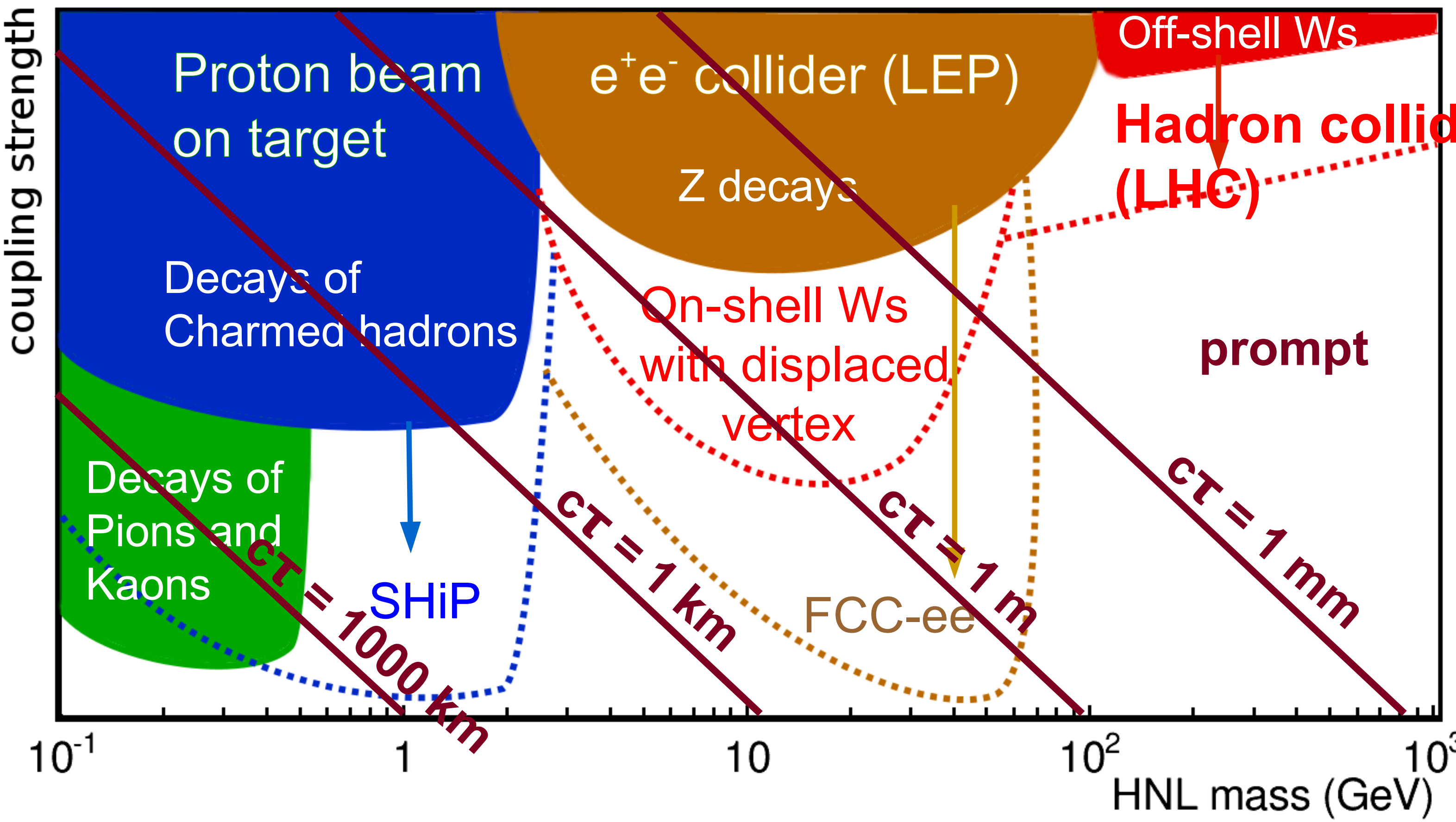
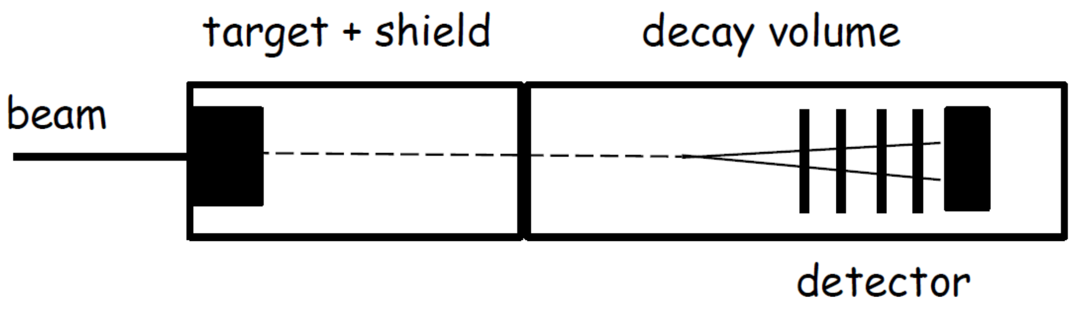


# N searches at fixed-target facilities




- 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

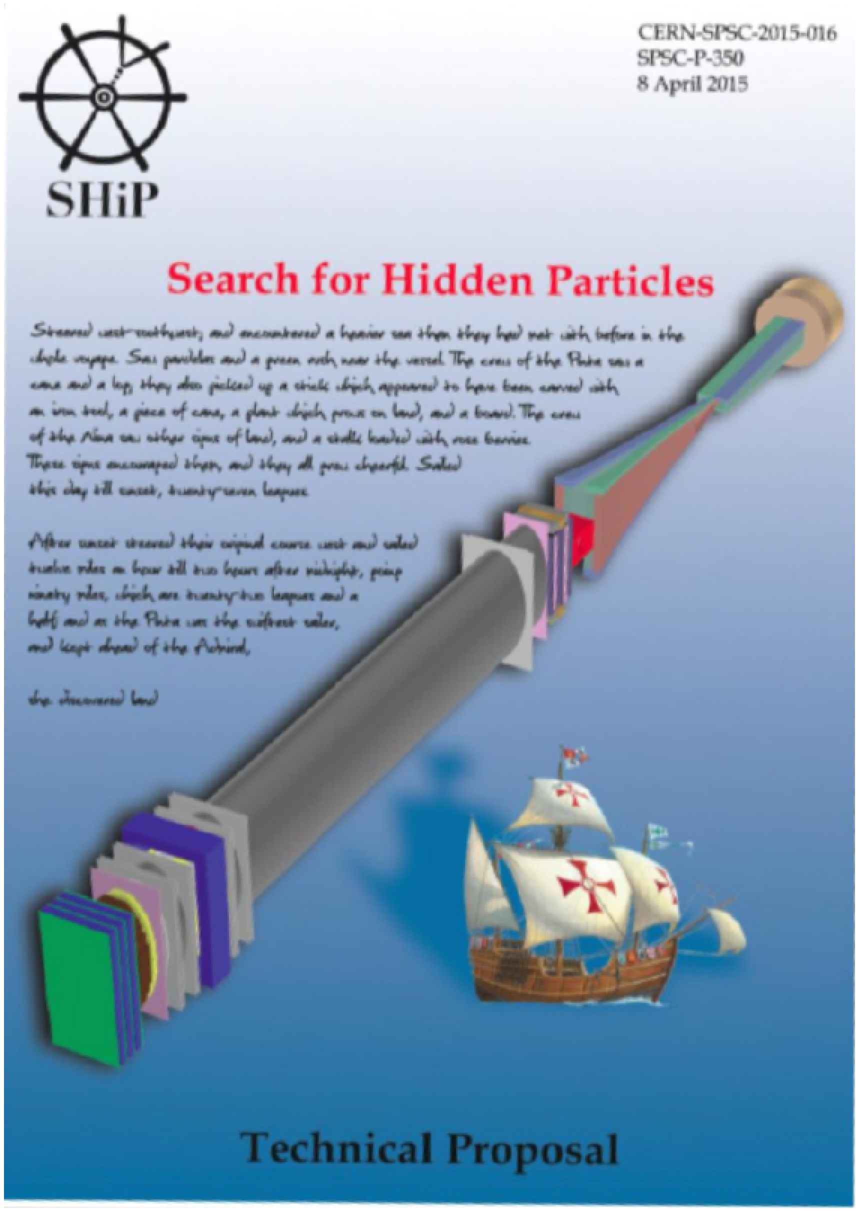
# Proton fixed-target experiments – comparison

| | PS191 | CHARM | NuTeV | SHiP current design |
|---|---|---|---|---|
| Beam energy (GeV) | 19.2 | 400 | 800 | 400 |
| Protons on target | $0.9 \cdot 10^{19}$ focused | $2.4 \cdot 10^{18}$ dumped | $2.5 \cdot 10^{18}$ focused | $2 \cdot 10^{20}$ dumped |
| Distance (m) | 128 | 480 | 1400 | 80 |
| Off-axis angle | $2.2^{o}$ | $0.6^{o}$ | 0 | 0 |
| Decay volume | 12 m helium | 35 m air | 34 m helium | 60 m vacuum |

SHiP strategy

- dedicated beam line and target area
- decay volume as close as possible to target
- highly efficient background rejection systems

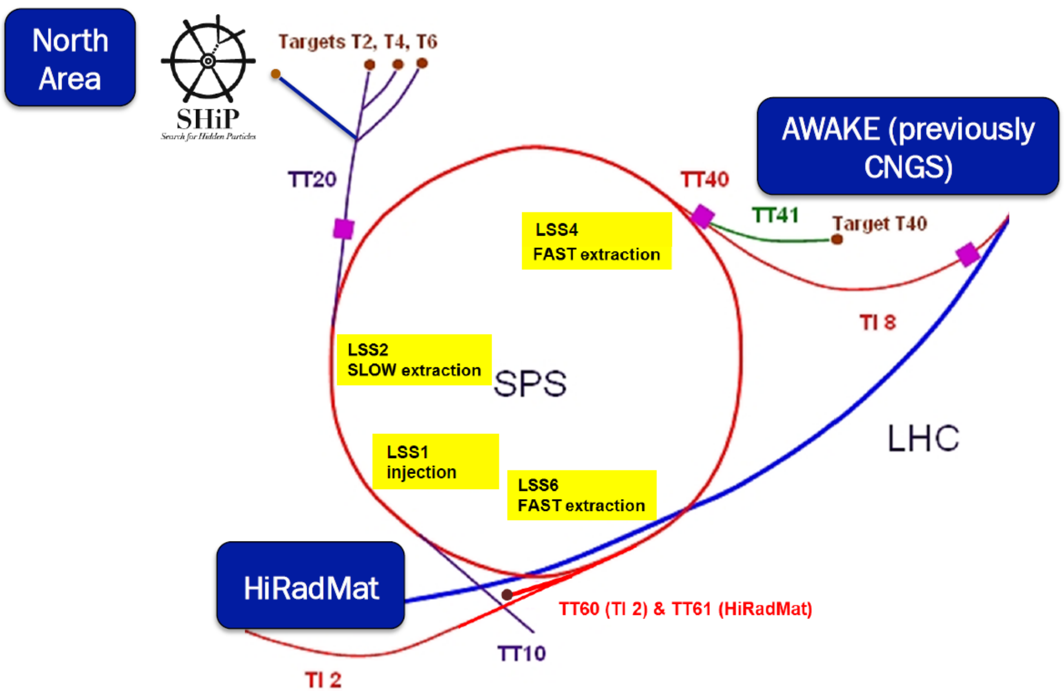
# SHiP

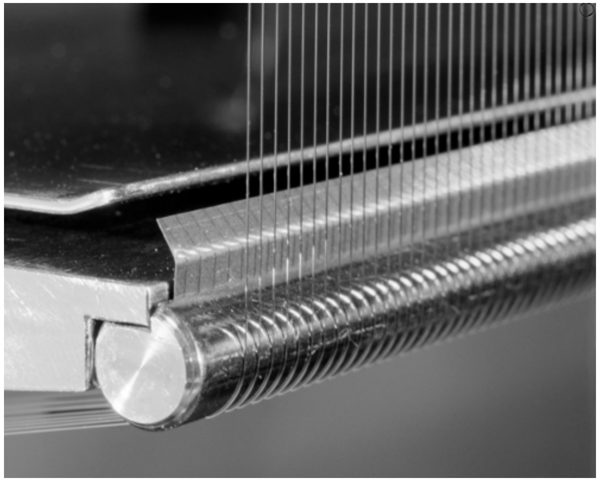



- Proposed experiment at the CERN SPS
- Collaboration of 250 members from 46 institutes
- Technical proposal arXiv:1504.04956 (2015)
- Physics case signed by 80 theorists Rep. Prog. Phys. 79 (2016)
- SPSC recommended Comprehensive Design study by 2019 → decision about approval in 2019/2020
  - Physics 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)
  - testing silicon crystal channelling to reduce beam losses and related radioactivity

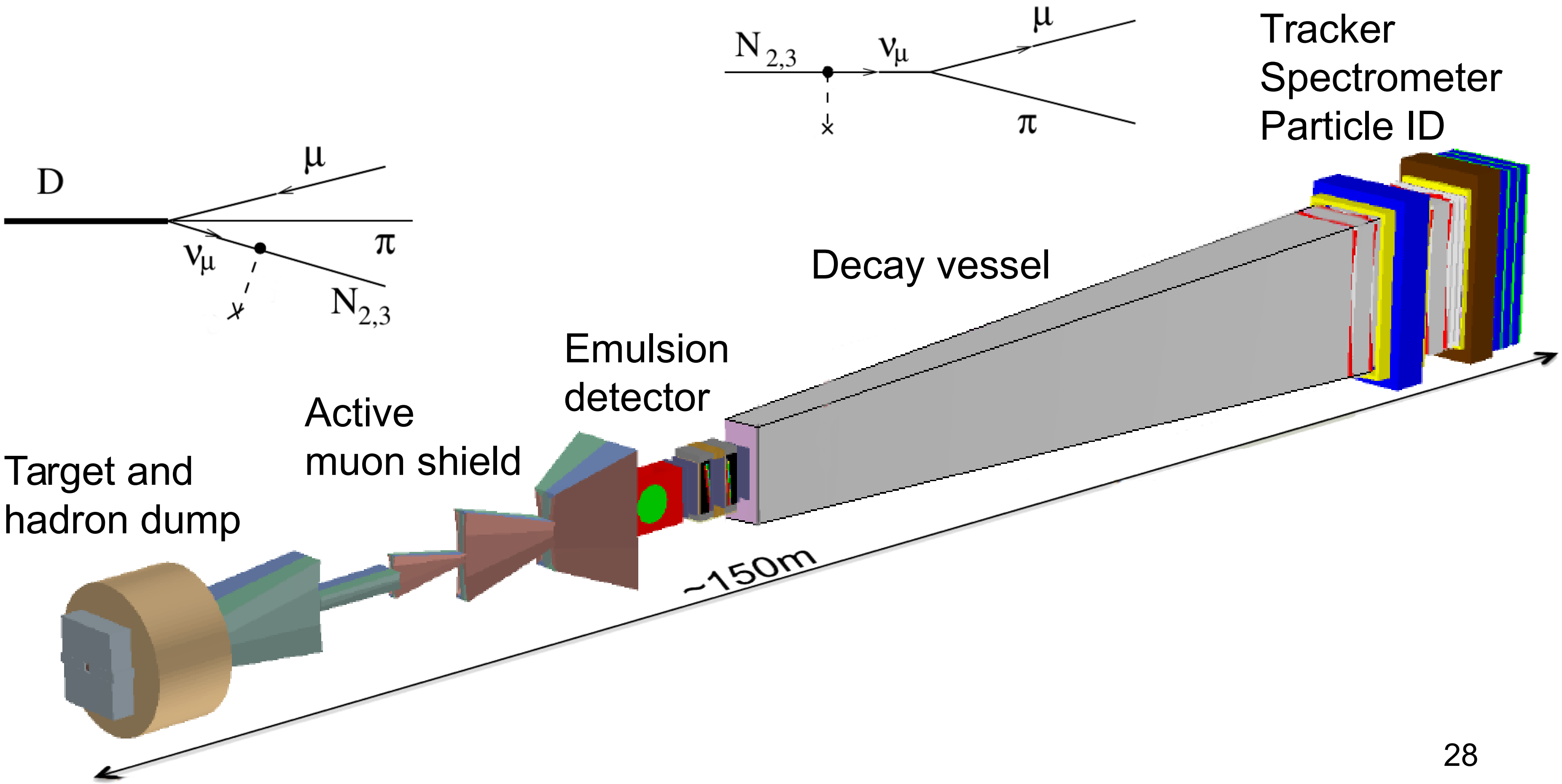


60 μm wires part of the SPS electrostatic septa

# SHiP – detector

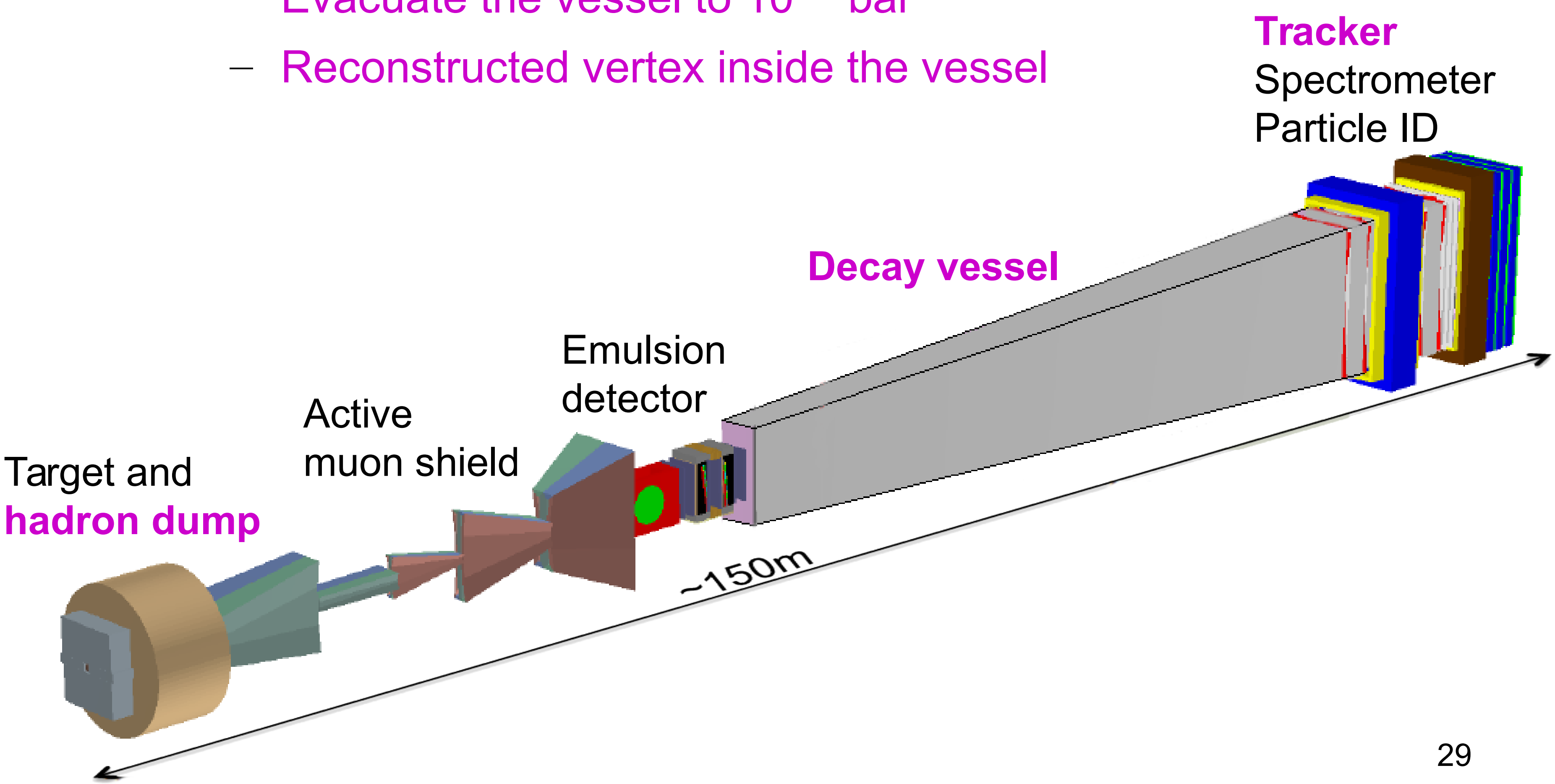
## Designed for **large acceptance** and **zero backgrounds**



# SHiP – detector

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

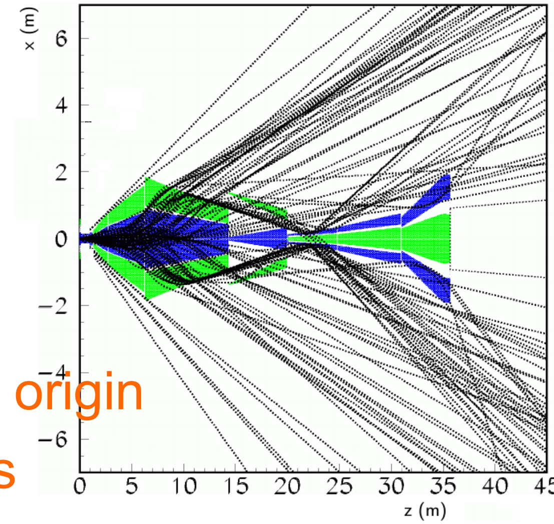
- Vertices from neutrinos
  - Stop pions and kaons before they decay
  - Evacuate the vessel to $10^{-6}$ bar
  - Reconstructed vertex inside the vessel



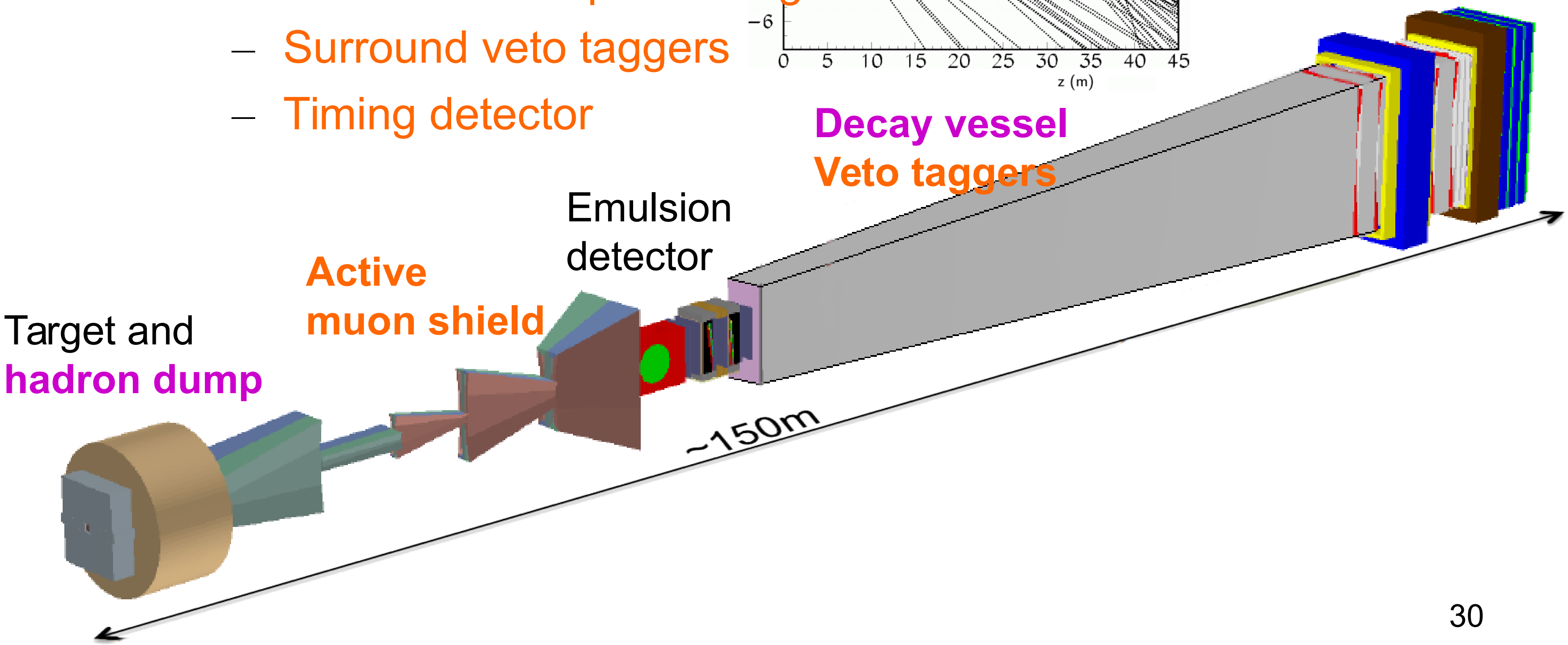
# SHiP – detector

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

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



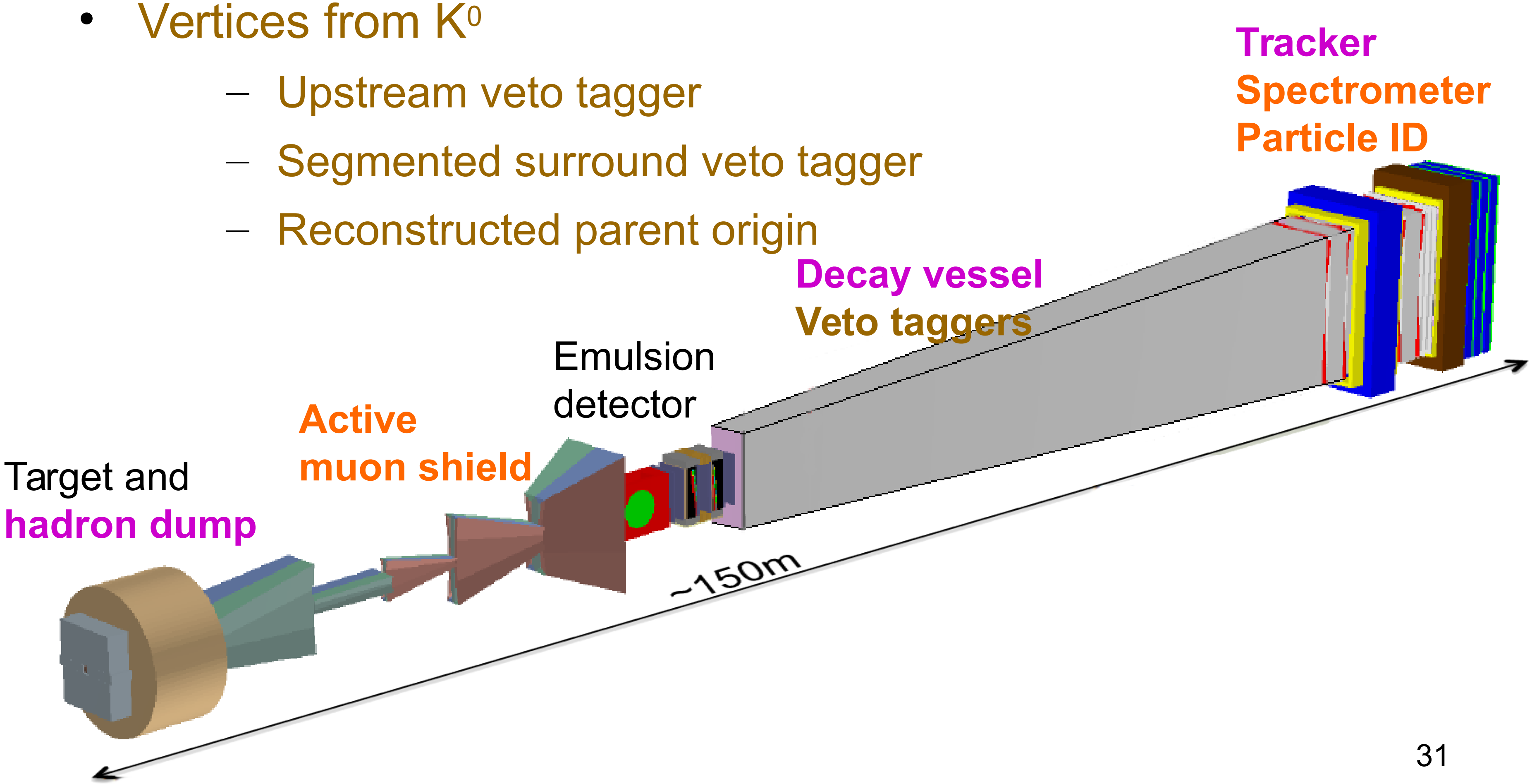

design minimises:
- muons in vessel
- length
- weight



# SHiP – detector

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

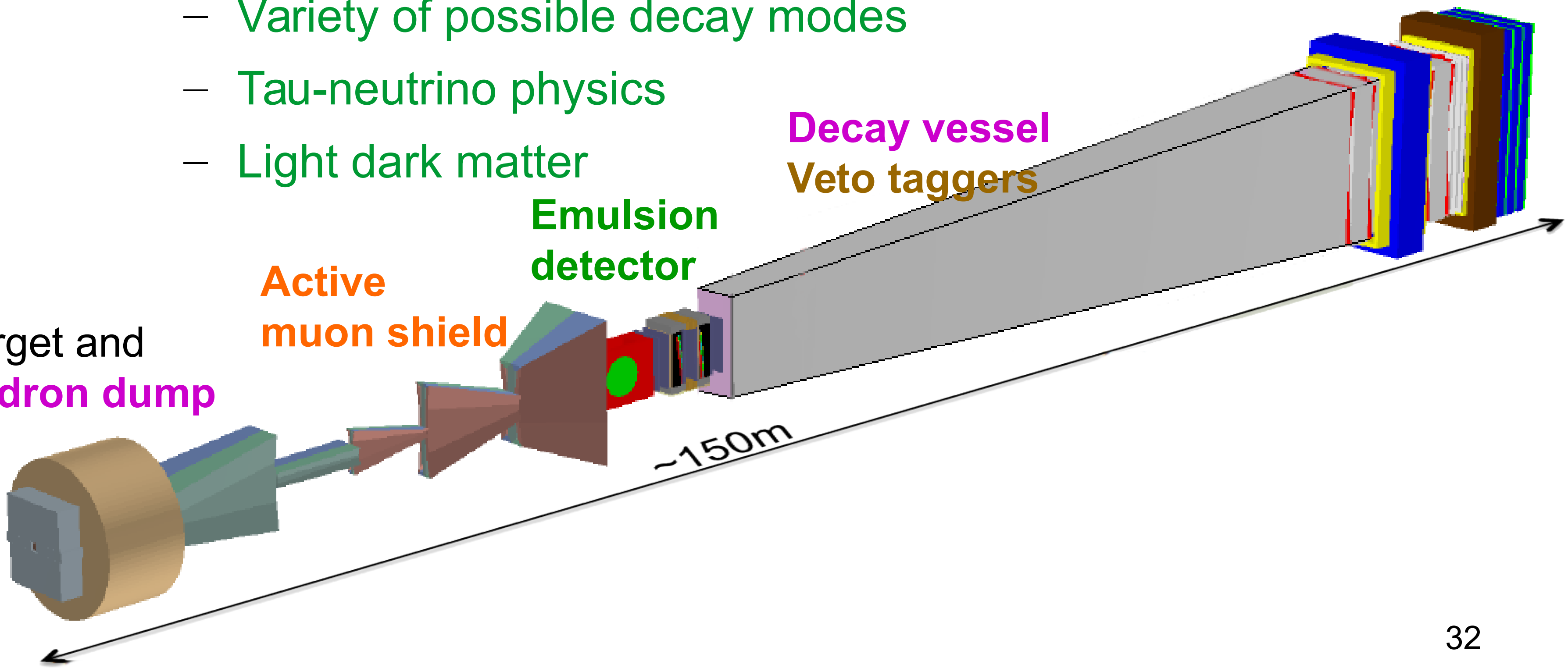
- Vertices from neutrinos
- Muon crossings
- Vertices from $K^0$
  - Upstream veto tagger
  - Segmented surround veto tagger
  - Reconstructed parent origin



# SHiP – detector

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

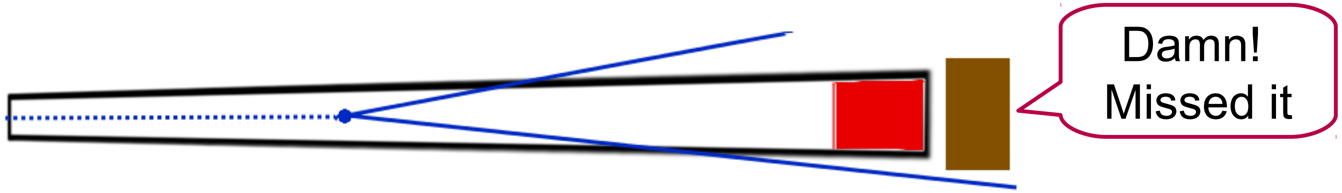
- Vertices from neutrinos
- Muon crossings
- Vertices from $K^0$
- Wide physics programme
  - Variety of possible decay modes
  - Tau-neutrino physics
  - Light dark matter



# 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:

- 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 → μπ once both tracks are reconstructed

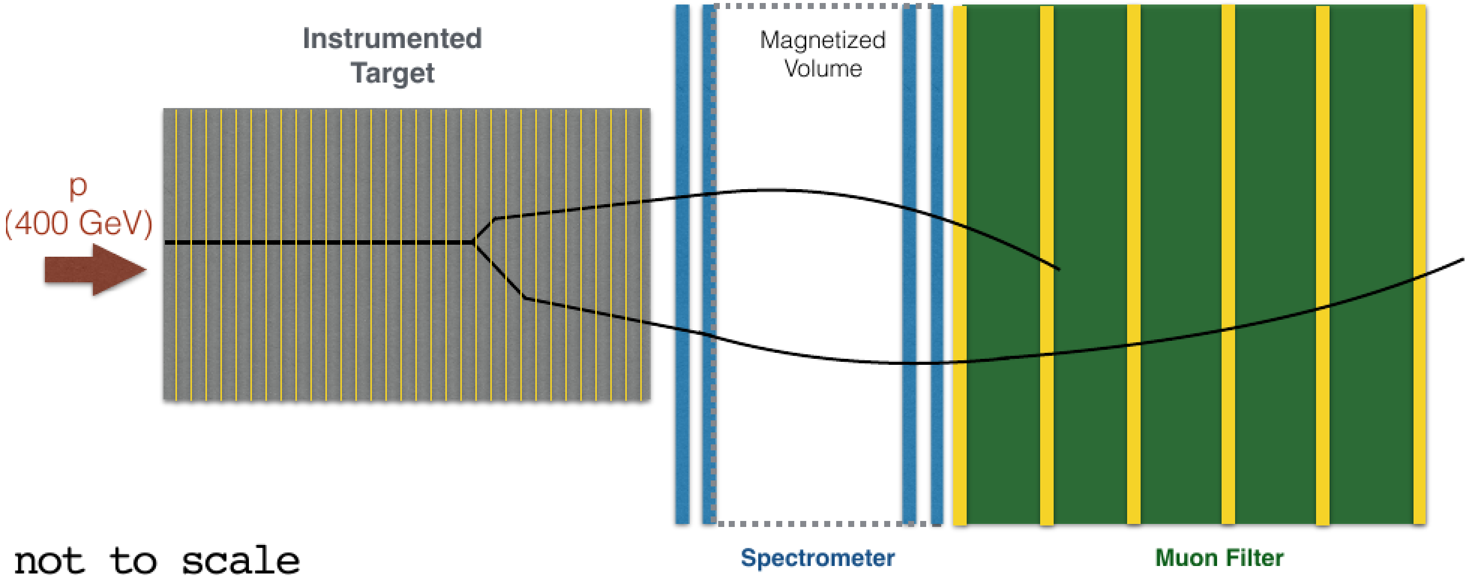
< 0.1 background events remaining

# 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

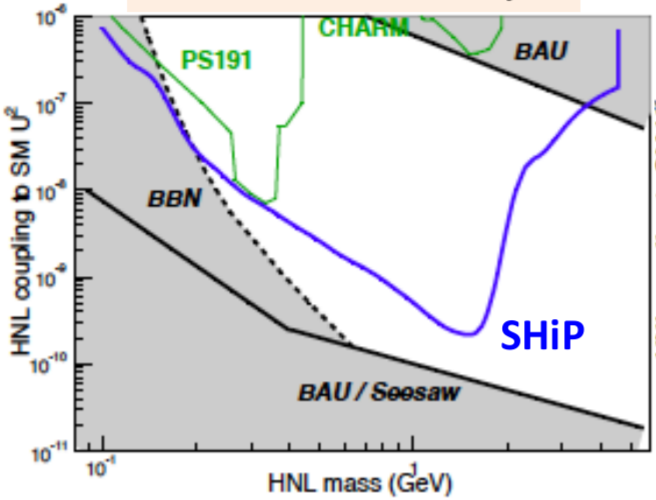
- Instrumented replica of the SHiP target
- Inclusive charm production $d^2\sigma/dE d\theta$ measurement – important for HNL signal acceptance estimate
- Measurement of muon flux at high energies and large angles – important for muon shield design



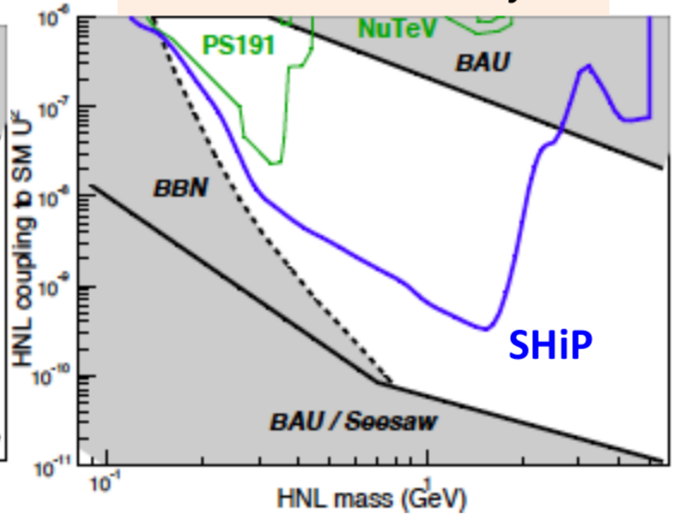

not to scale

# SHiP – sensitivity to new physics

*$U^2_e : U^2_\mu : U^2_\tau \sim 52:1:1$*
*Inverted hierarchy*




*$U^2_e : U^2_\mu : U^2_\tau \sim 1:16:3.8$*
*Normal hierarchy*

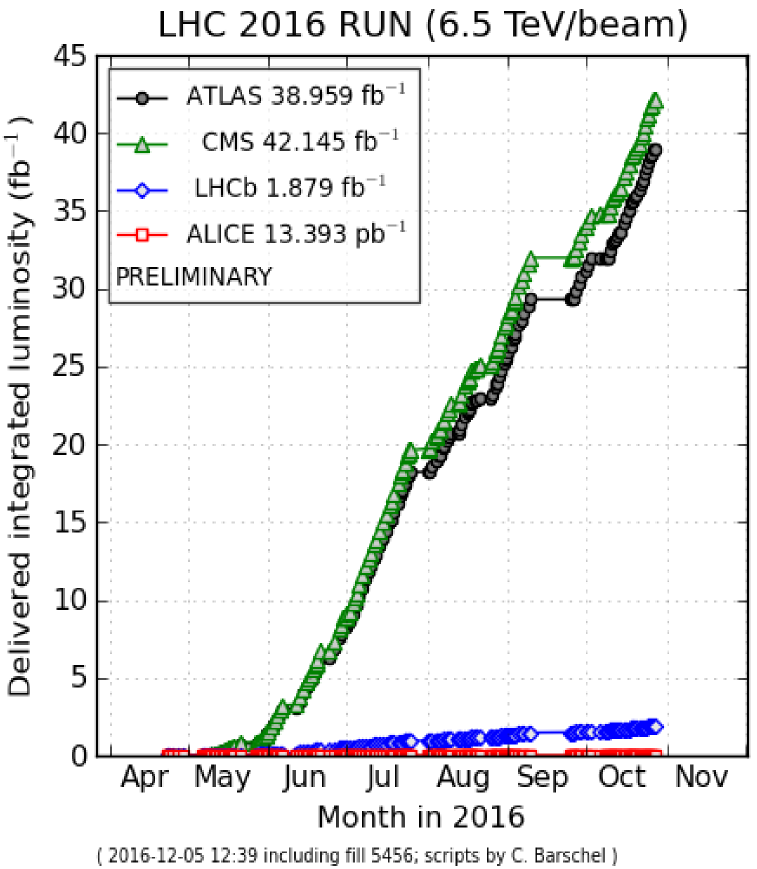



$\sim 5 \cdot 10^{16}$ neutrinos from charm decays

- N probed in large unexplored regions
  - expected from models accounting for neutrino masses, baryon asymmetry, and dark matter
- Also hidden sectors
  - Dark photons
  - Hidden scalars
  - Light dark matter, etc...

# Exploring higher N masses

- *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



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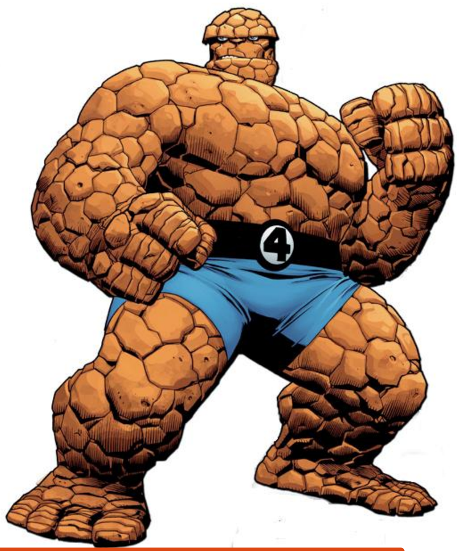
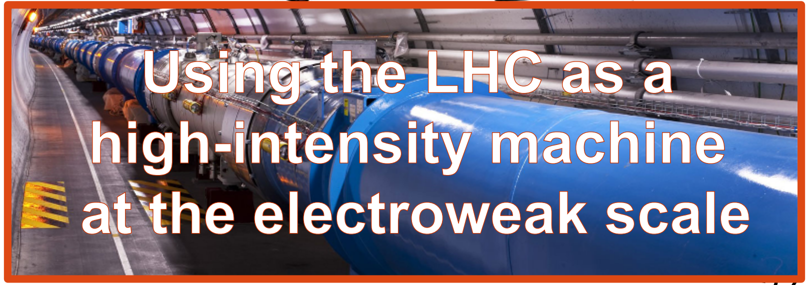
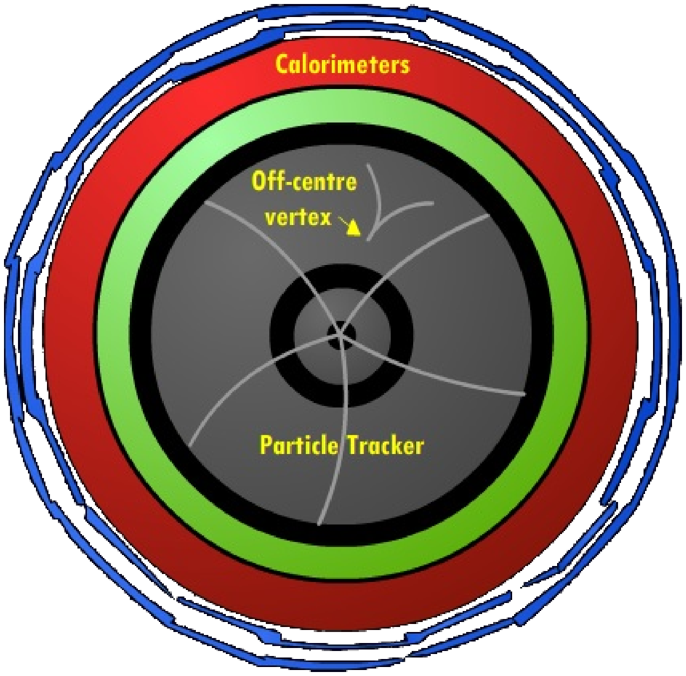
High-energy frontier

High-intensity frontier





# N searches at colliders



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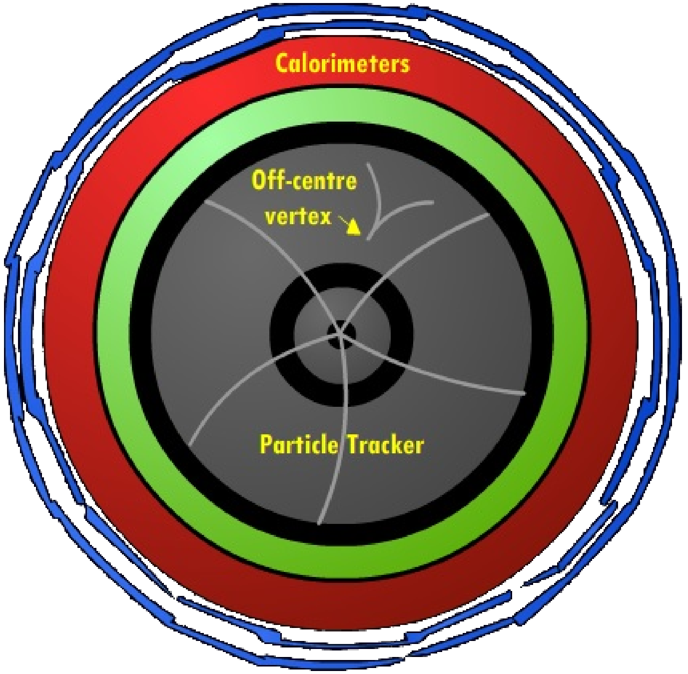
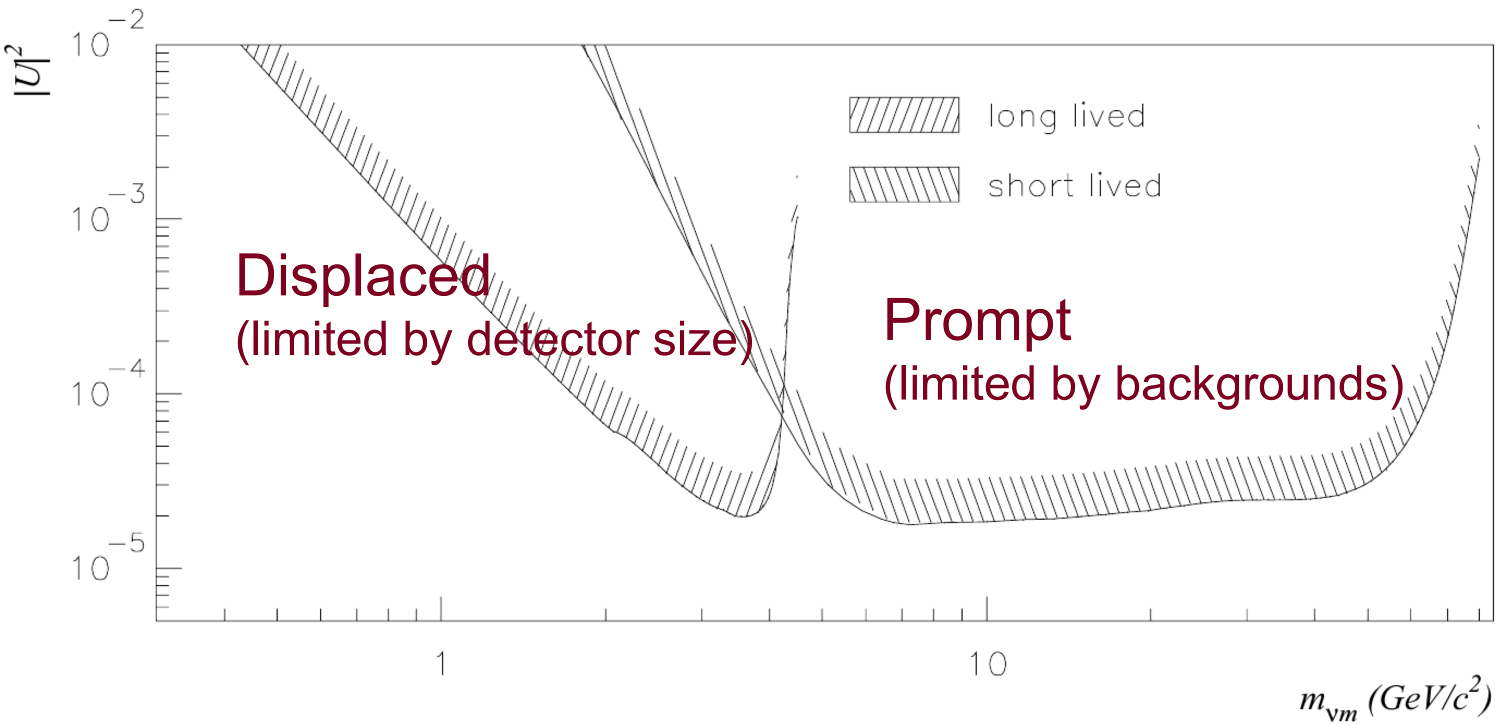
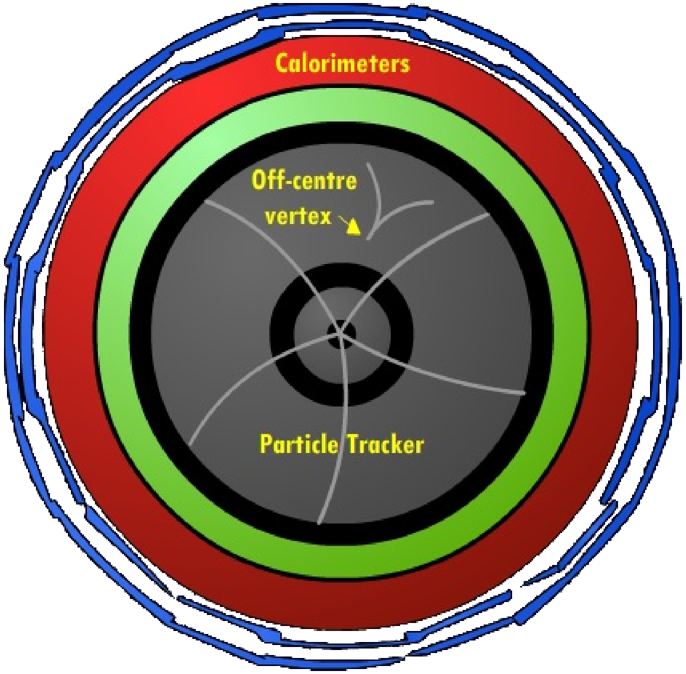



- LEP1: ~$10^6$ νs from $Z$ decays
  - displaced vertex for $m_N < 4$ GeV
  - Delphi set current best constraints in range $2 < m_N < 80$ GeV Z. Phys. C 74, 57 (1997)



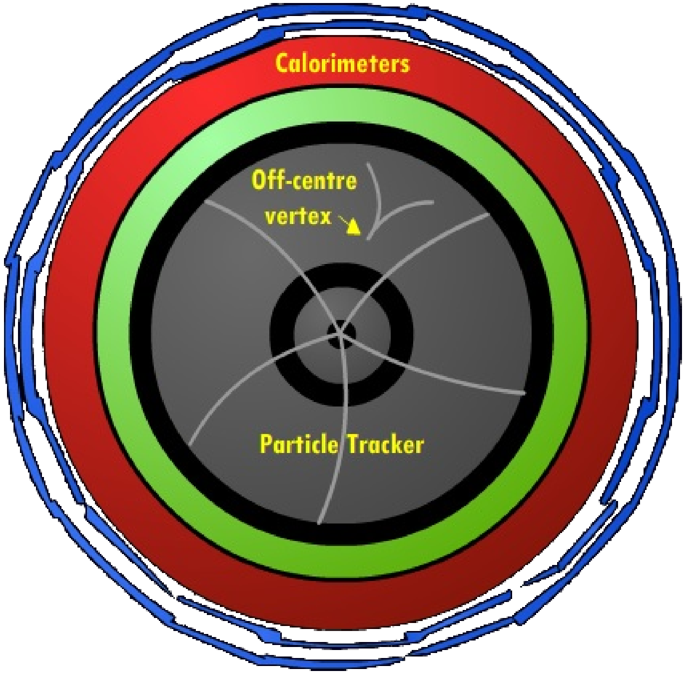
# N searches at colliders



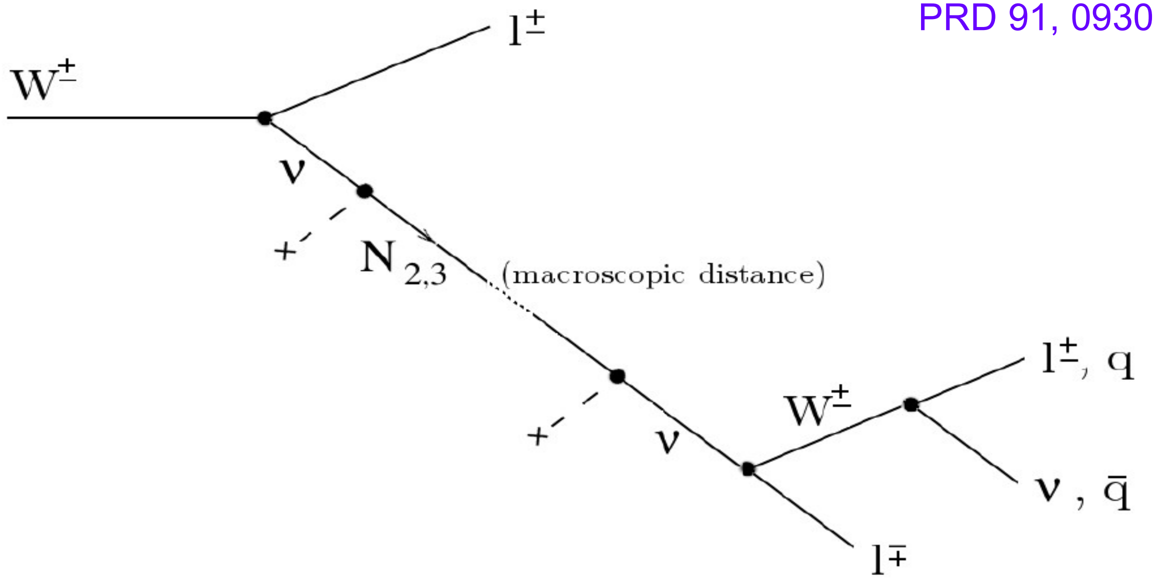

- LEP1: ~$10^6$ νs from *Z* decays
- Tevatron: ~$5 \cdot 10^6$ νs from *W* decays
  - cannot use *Z*s due to trigger requirements
  - not enough *W*s for displaced vertices with masses above backgrounds

# N searches at colliders

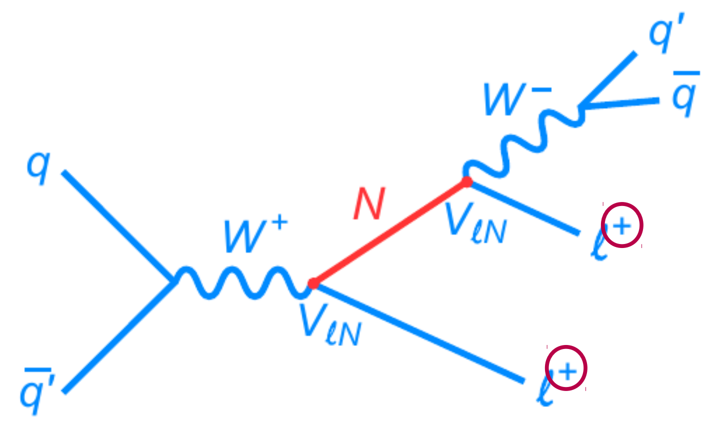
- LEP1: ~$10^6$ νs from $Z$ decays
- Tevatron: ~$5 \cdot 10^6$ νs from $W$ decays
- LHC: ~$10^{10}$ νs from $W$s
  - >$10^9$ υs per year in ATLAS or CMS
  - Displaced HNL decays for $m_N$ < 30 GeV → reach down to very low mixing




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



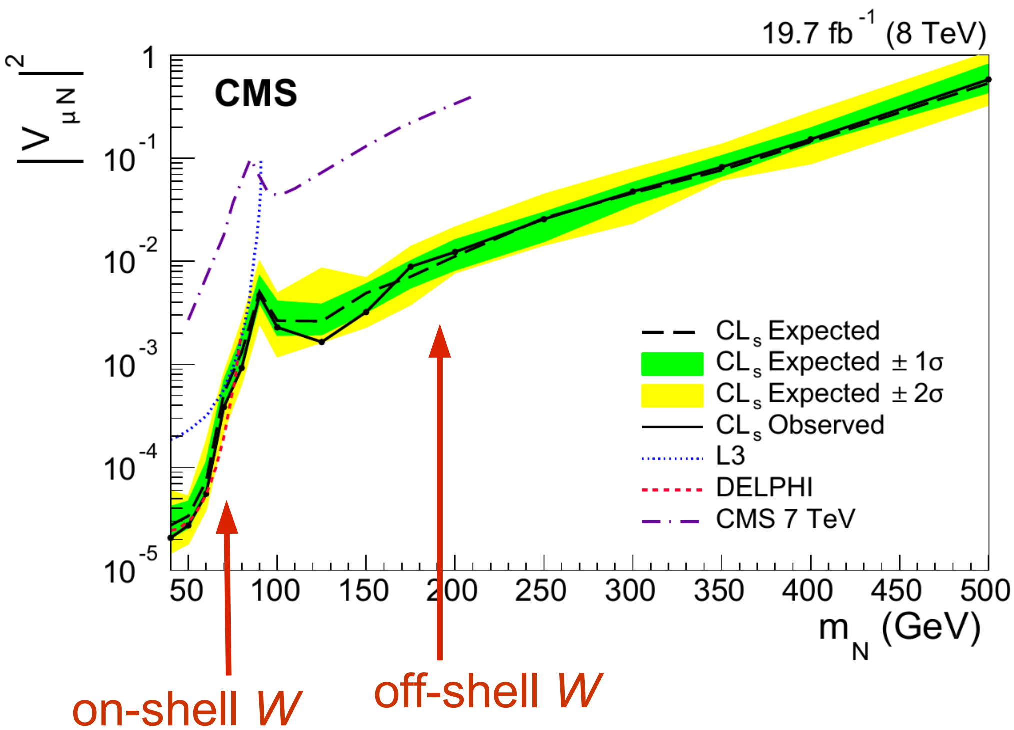
# LHC – prompt high-pT signature




## 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)

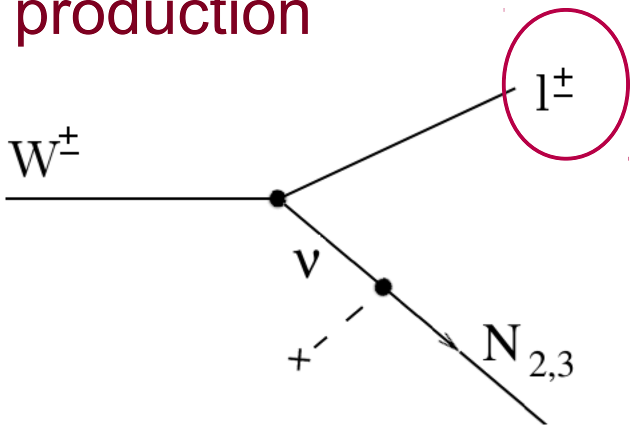



- Models of leptogenesis point to lower mass, lower mixing

  → on-shell W

# LHC – N from on-shell *W*s

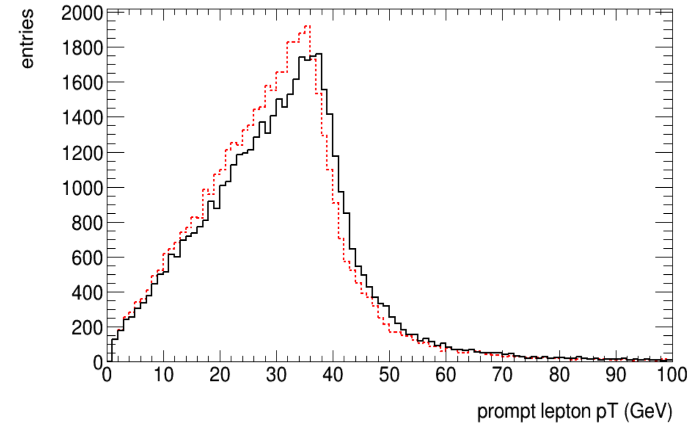
production



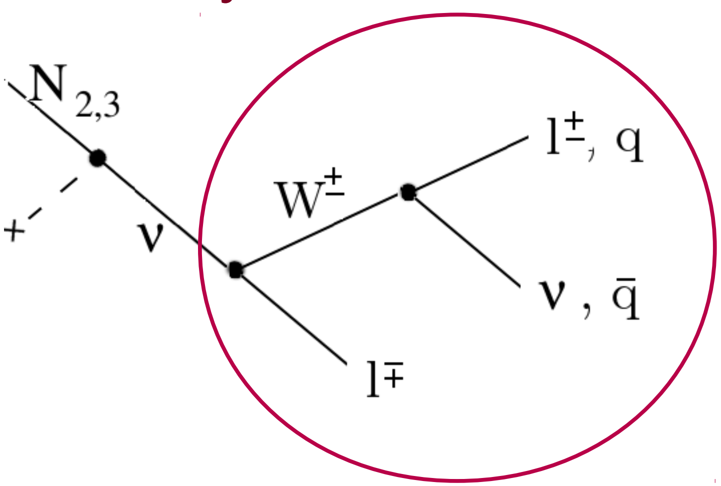

Prompt lepton essential for trigger

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

(generator-level pT distributions)

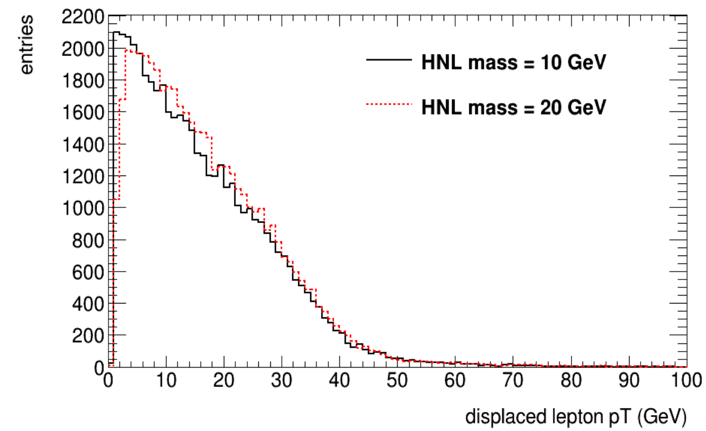



decay

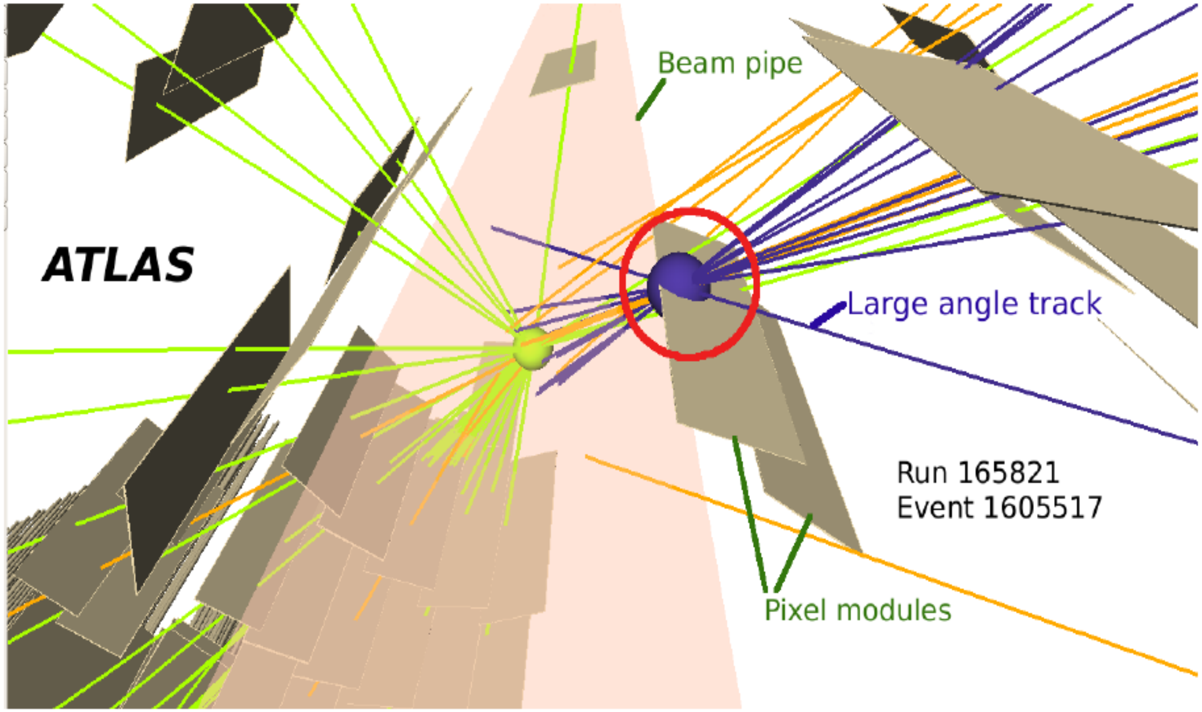



**1) Prompt three-leptons**
($m_N \geq 20$ GeV)

**2) Displaced vertex (DV)**
($3 \leq m_N \leq 30$ GeV)



# LHC – DV signature



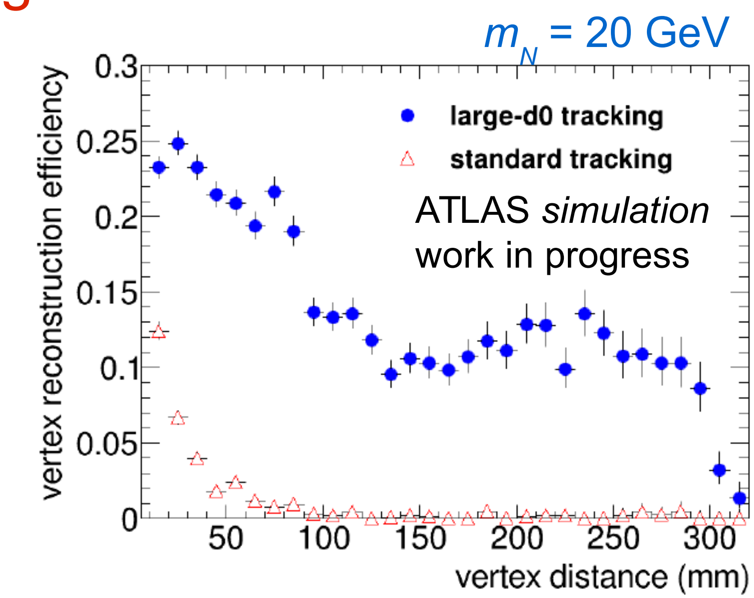

Similar to previous work using DV in ATLAS and CMS inner detectors

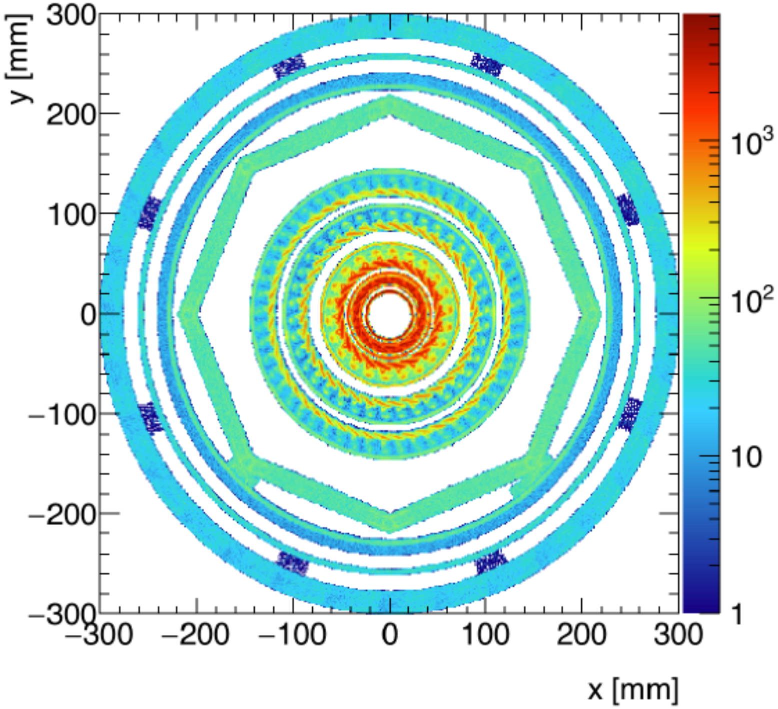
PLB 707, 478 (2012)
PLB 719, 280 (2013)
JHEP 02, 085 (2013)
PRL 114, 061801 (2015)
PRD 91, 052012 (2015)
PRD 91, 012007 (2015)
PRD 92, 072004 (2015)

- 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

# Example of typical DV selection in ATLAS and CMS
## aiming at zero backgrounds

- Single-lepton trigger (~35% efficient)
- Special reconstruction of tracks with large impact parameter
- Vertex at distance 3–300 mm

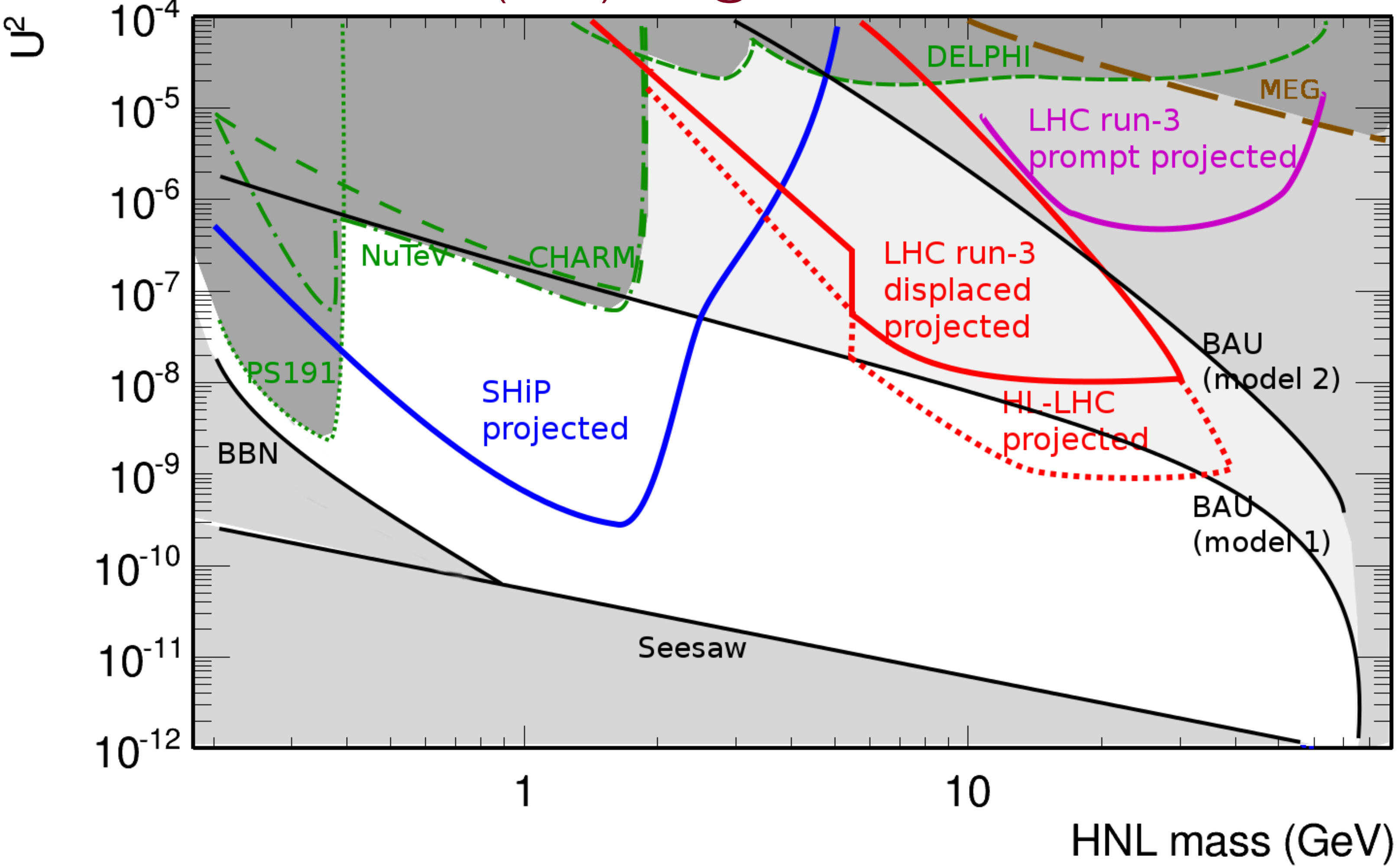



- Lepton identification criteria for particles forming the vertex
- Vertex mass > 2 GeV to reduce backgrounds from metastable hadrons
- Material map veto to reduce backgrounds from hadronic interactions (~50% efficient)

# 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 HNLs to participate in BAU)

# Conclusions

- SHiP can probe the existence of new particles which can shed light on the puzzles of **neutrino masses**, **dark matter**, and **matter-antimatter asymmetry**
- SHiP might be the only way to discover heavy neutrinos in the mass range 0.4–2.5 GeV
- Higher masses can be probed already today at the LHC using a displaced-vertex signature
  - (and later at the HL-LHC and FCC)

**Hot stuff!**

- **CP violation in neutrino oscillations**
- **Search for heavy neutrinos**