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Prospect to search Heavy Neutral Leptons

Nico Serra (Universität Zürich)

CERN Council Open Symposium on the Update of
European Particle Physics Strategy 2019
13th-16th May - Granada (Spain)

European Strategy Update

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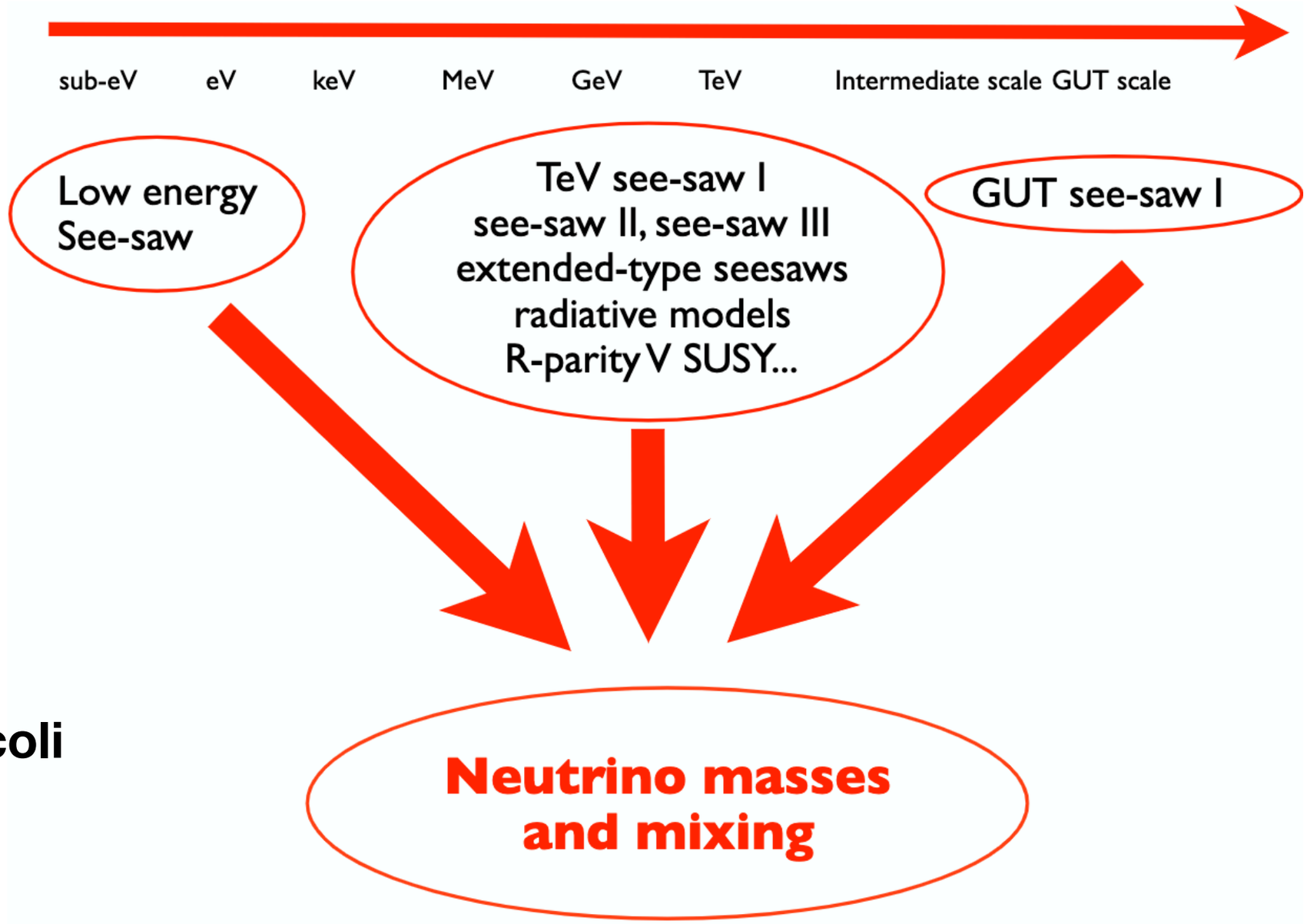
Fundamental Questions

- HNLs are in general introduced to naturally explain neutrino masses and oscillations

- It is common to add to this Lagrangian a Majorana mass term:
  - Helps to explain smallness of neutrino masses
  - Matter anti-matter asymmetry in the Universe (Leptogenesis)
  - Dark Matter HNLs (discussed in the talk by Christoph Weniger)

- There are many models (e.g. nuMSM, Left-Right symmetric model, SUSY, …)

HNLs



Talk by
Silvia Pascoli

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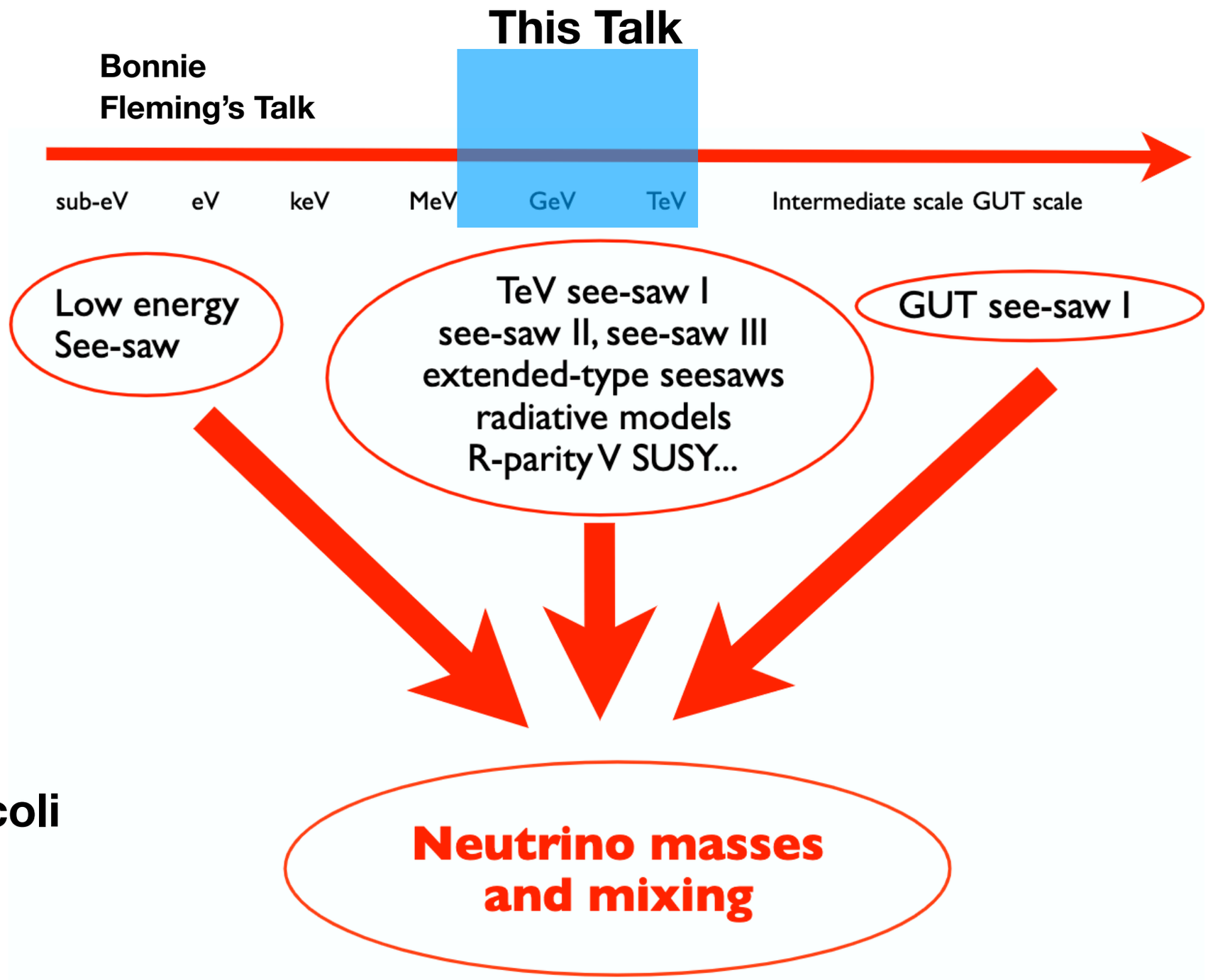
HNLs



Talk by Silvia Pascoli

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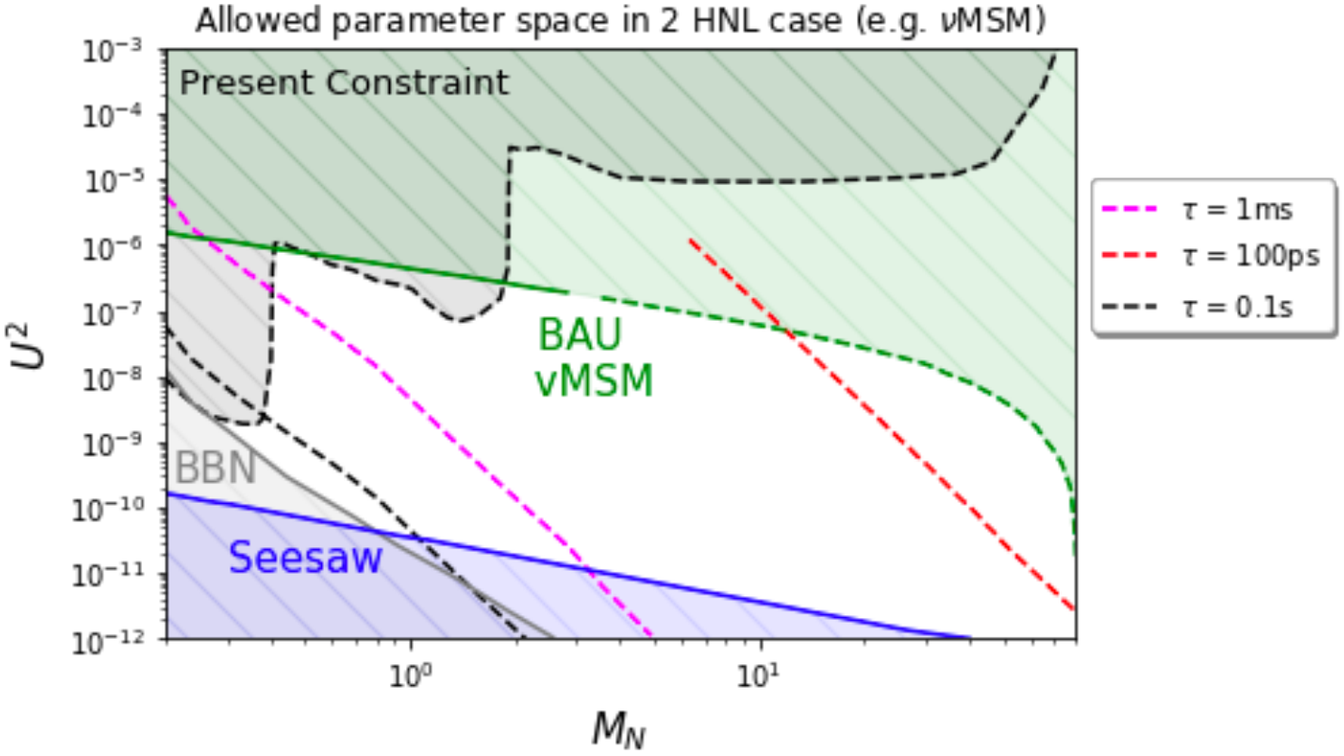
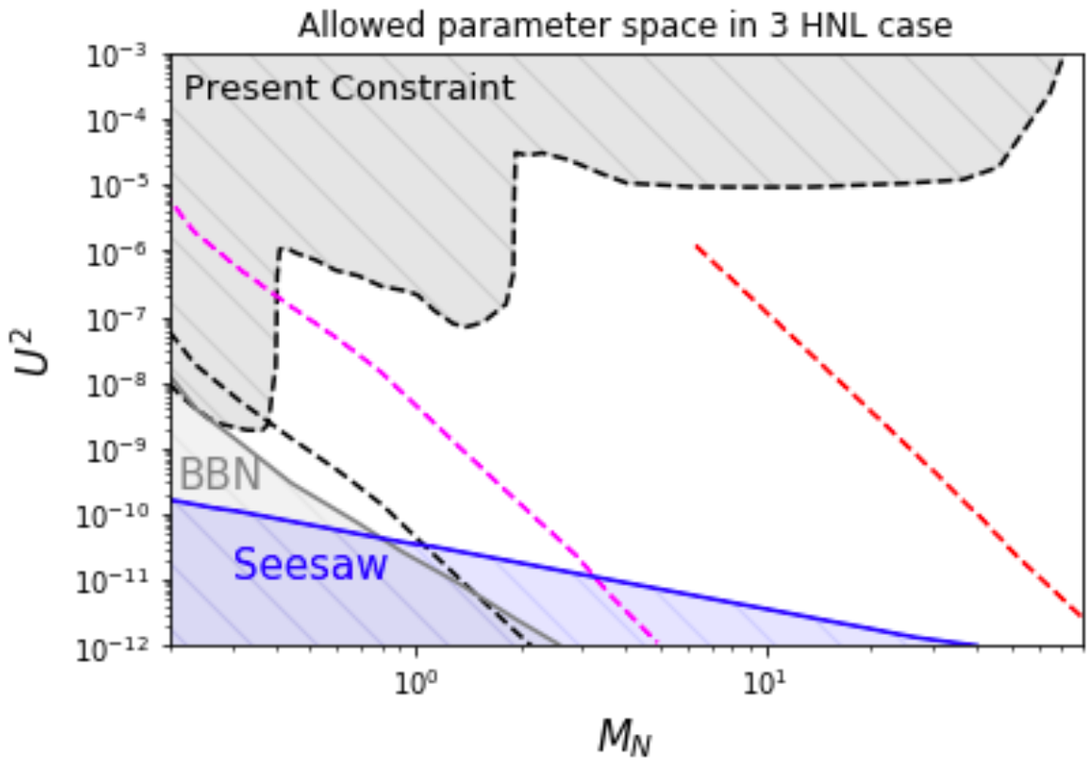
HNLs

- HNLs in the GeV region can explain the BAU (Akhmedov, Rubakov, Smirnov 9803255, Shaposhnikov et al. 050513/0804.4542 nuMSM) and simultaneously neutrino oscillations
- A generalised L symmetry explains a range of couplings making them observable experimentally (Shaposhnikov 0605047 , Kersten/Smirnov 0705.3221)
- Signatures such as 0v2beta decays (see talk by Susanne Mertens) can be induced by HNLs (Hernandez 1606.06719), in other models such as nuMSM are suppressed

Blondel et al, arXiv:1411.5230
Eijima, Shaposhnikov, Timiryasov arXiv:1808.10833



Hernandez et al., arXiv:1606.06719 and references therein
Abada et al., arXiv:1810.12463 and references therein



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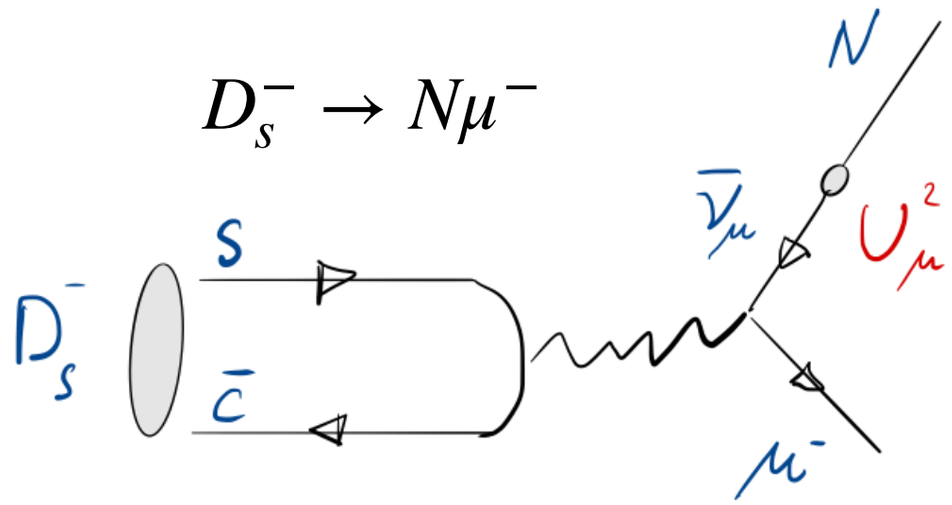
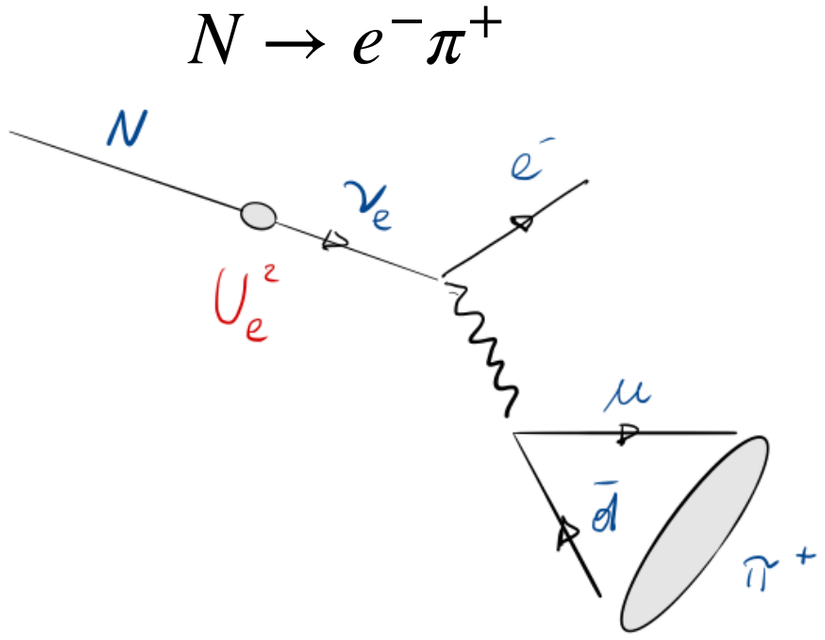
HNL Production

- The production of sterile neutrinos happens via mixing of sterile neutrinos with active neutrinos, i.e. it is suppressed by a factor U^2
- If the mass is small enough they can be produced in semileptonic meson decays (pions, kaons, D-mesons, B-mesons)
- The decay is also mediated by the mixing with active neutrinos





Gorbunov, Shaposhnikov, arXiv:0705.1729

- These processes can violate Lepton Number and Lepton Flavour
- Direct searches for these decays proportional to U^4

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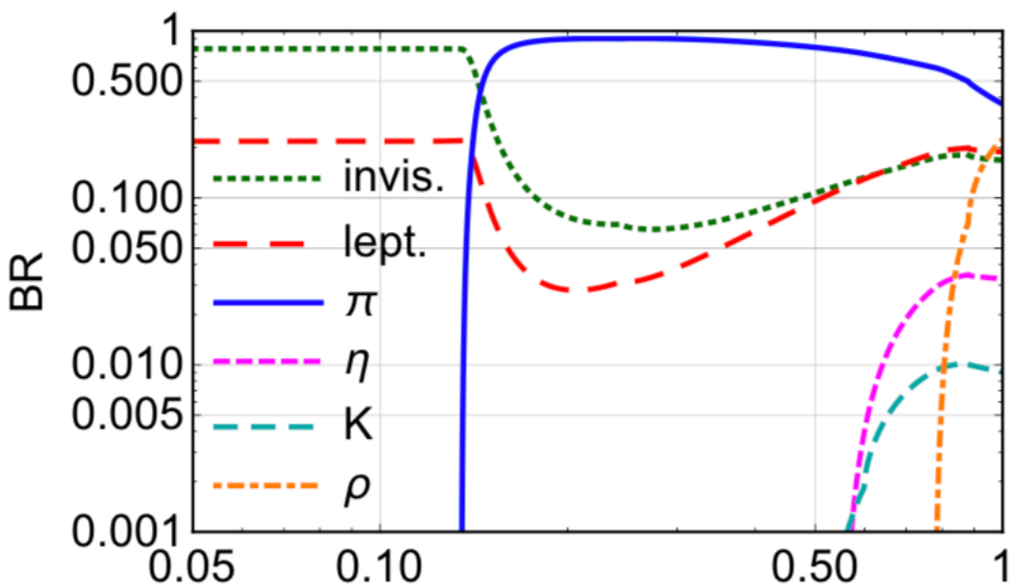
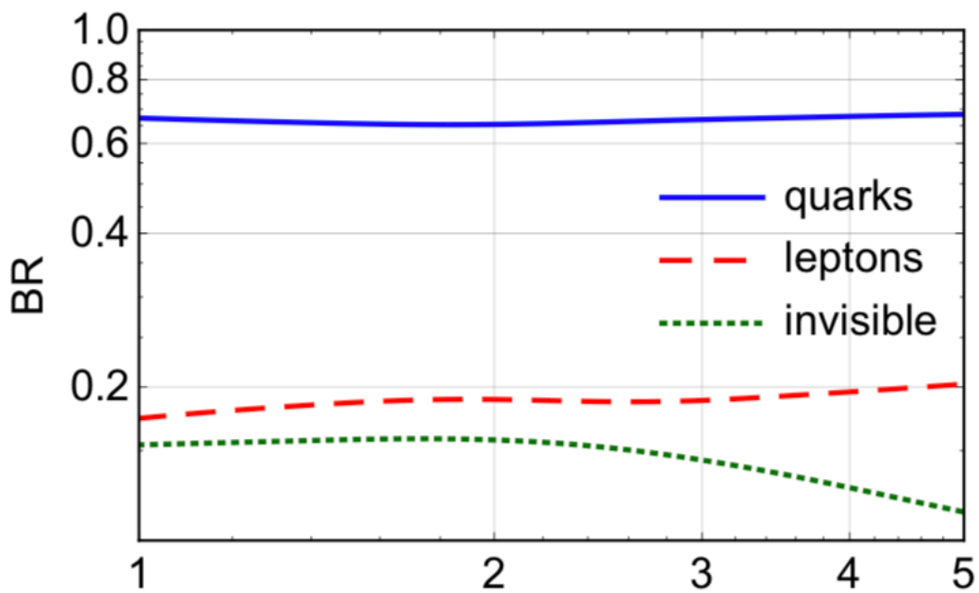
Low mass HNLs

Production for $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 1 : 1$

SHiP Coll., CERN-SPSC-2019-010
Bondarenko et al., arXiv: 1805.08567



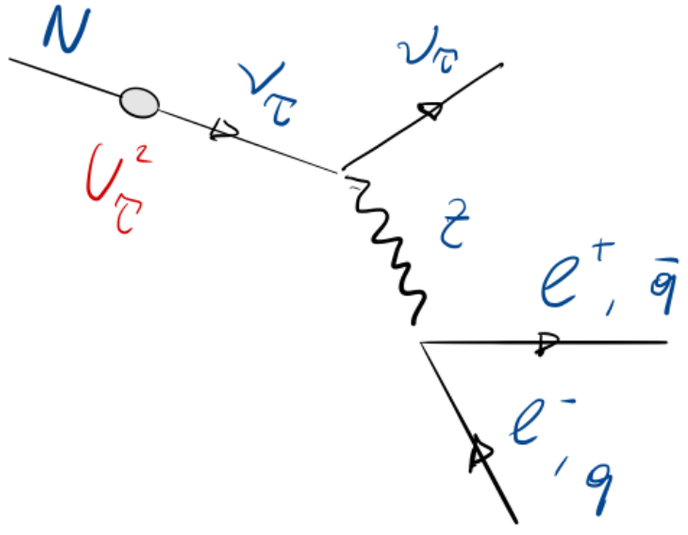


Decays

$N \to \ell h$

$N \to \nu \ell^+ \ell^-$

- If U_τ^2 coupling dominates neutral current decays most important



$N \to \nu_\tau \mu^+ \mu^-$

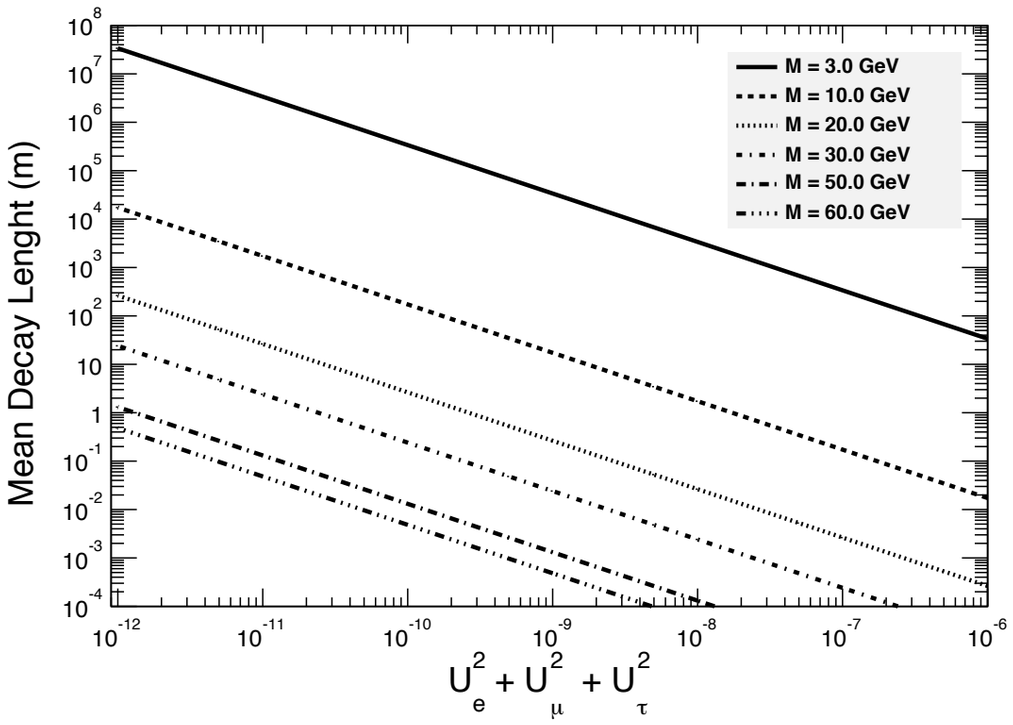
$N \to \nu_\tau \rho^0$

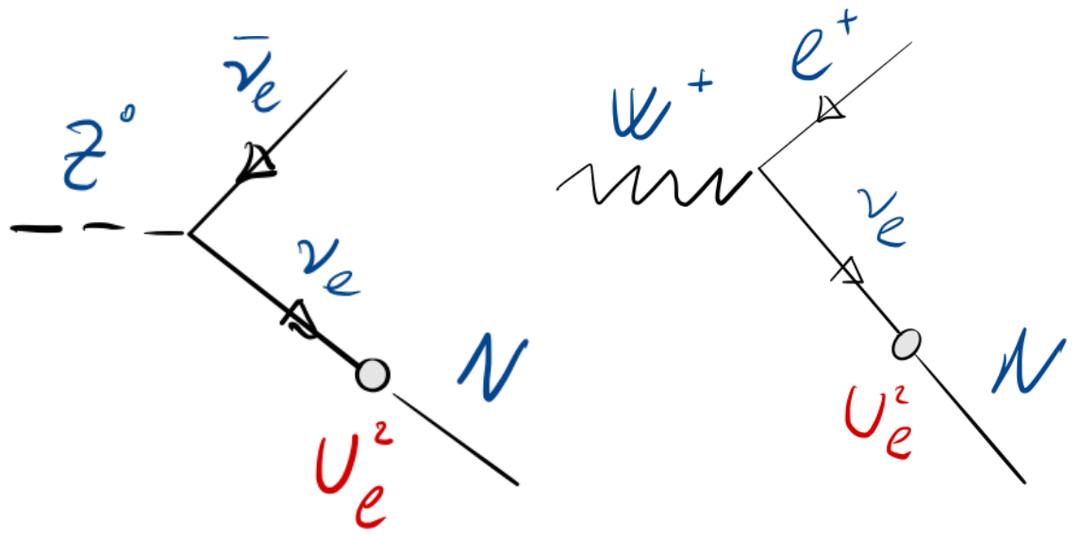
High mass HNLs

- At high masses you have that the lifetime becomes short and the sterile neutrino decays immediately
- Can be searched for at colliders, e.g. ATLAS/CMS and FCCee

$$L \sim \frac{3[\mathrm{cm}]}{|U|^2 \times (m_N[\mathrm{GeV}])^6}$$

Blondel et al., arXiv:1411.5230





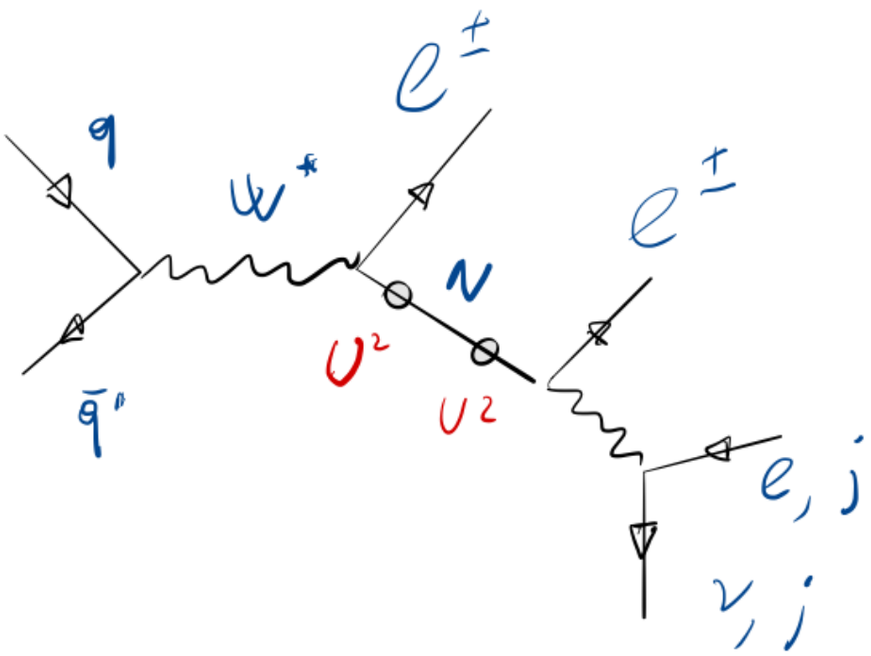
- At high energies HNLs decay as:

$$N \to \nu \ell^+ \ell^- \qquad N \to \nu jj \qquad N \to \ell jj$$

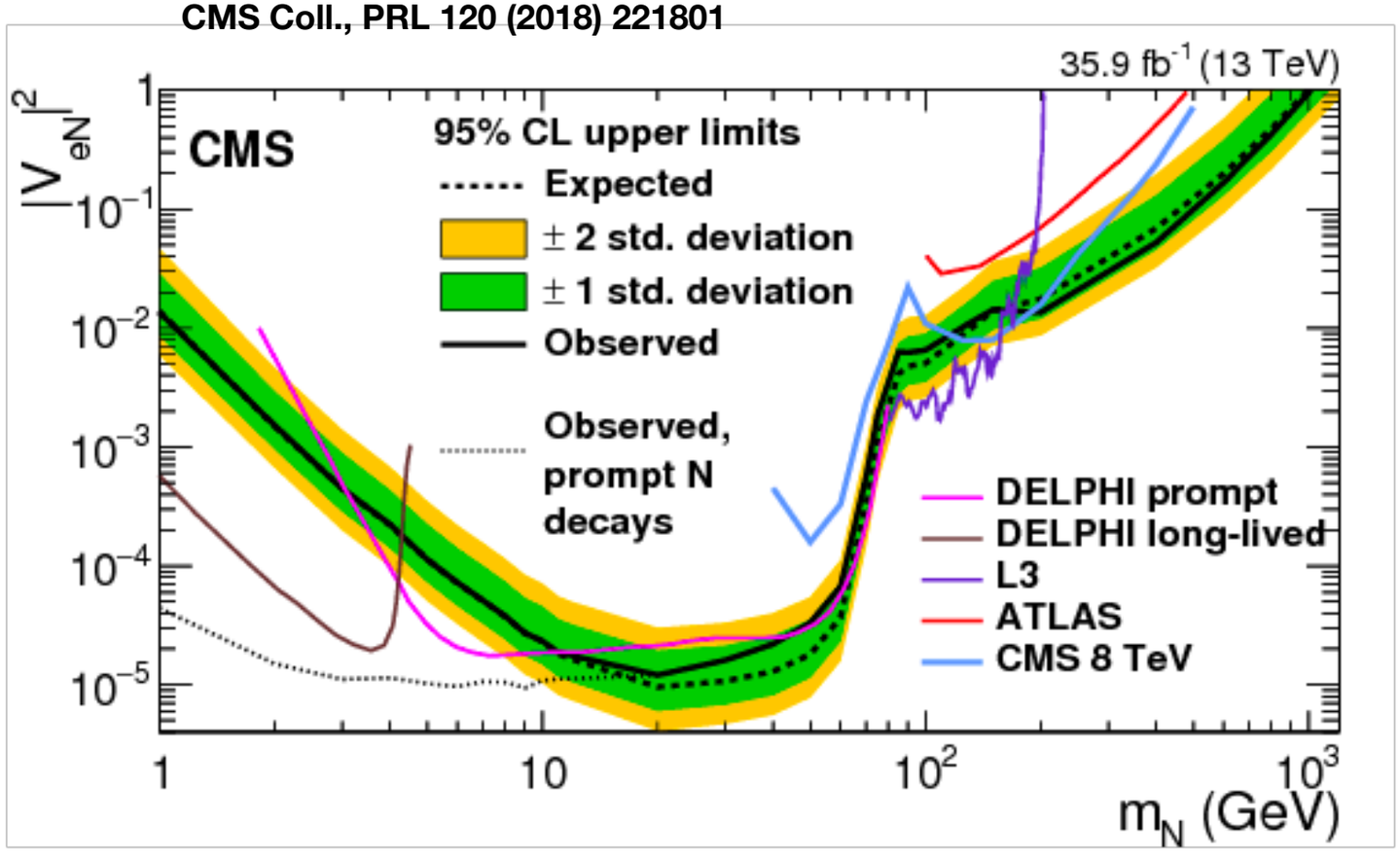
- For boosted displaced leptons see Izaguirre/Shuve [1504.02470]
- For Higgs decays mediated by HNLs see Dev et al. [1207.2756]; Das et al. [1704.00880]

Higher Masses

- For masses masses larger than the mass of the Z, HNL can be produced by decays of virtual W and/or Z (limits from e.g. ATLAS/CMS) with loss in sensitivity



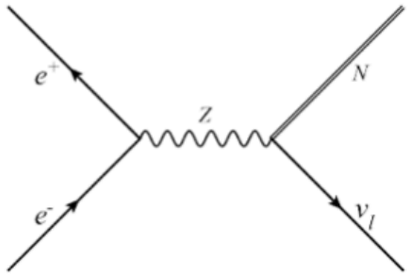
CMS Coll., PRL 120 (2018) 221801



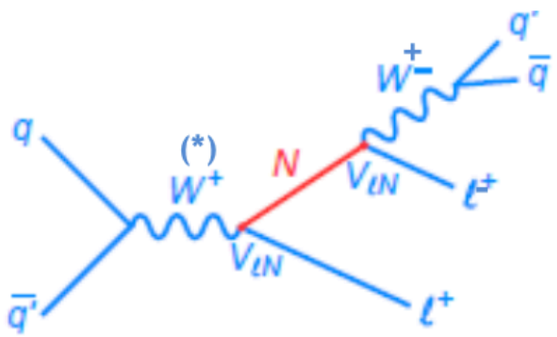
- At high mass the same-sign dilepton and 2 jets has better acceptance
- At low mass the tri-lepton and missing E_T has better sensitivity due to bkg

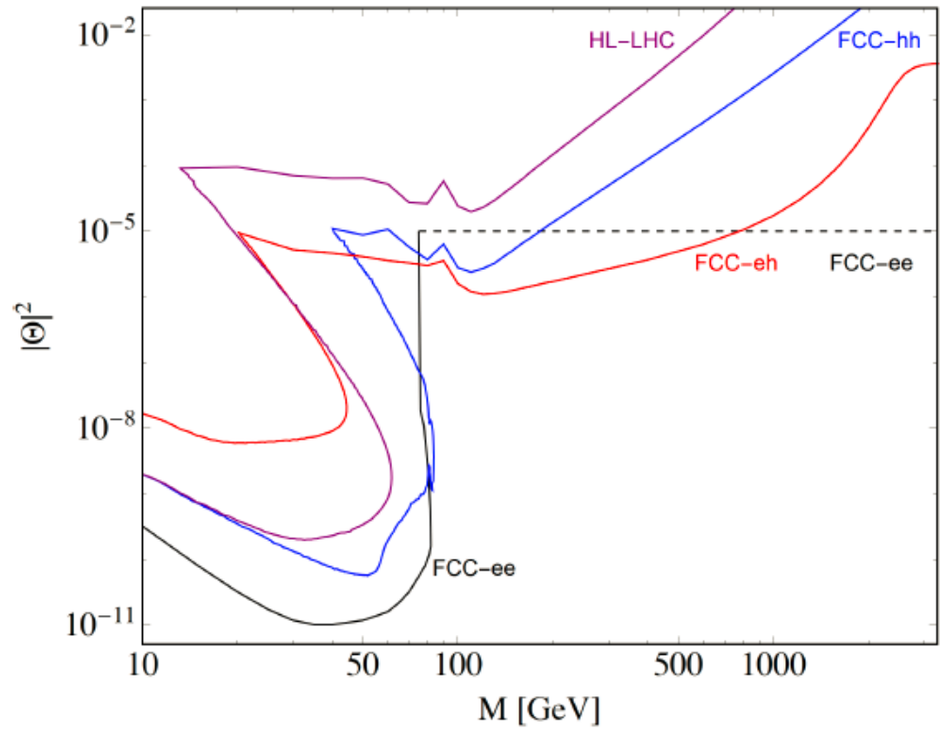
FCC

FCC-ee Z



FCC-hh





Blondel et al., arXiv:1411.5230
Updated plot from Drewes et al., 1609.09069
Antusch et al., 1710.03744
c.f. also Cai et al., 1711.02180

FCC-ee
-- EWPO : sensitivity 10^{-5} up to very high masses
-- high sensitivity to single N(→ $l_2^{\pm}$W) in Z decay
FCC-hh
-- production in W-> $l_1^{\pm}$ + N(→ $l_2^{\pm}$W)
with initial and final lepton charge and flavour
FCC e-p
-- production in CC $e^{\pm}$ p → X N(→ $l^{\pm}$W) high mass
Complementarity:
discovery + studies of FNV and LFV!

The capability to probe massive neutrino mechanisms for generating the matter-antimatter asymmetry in the Universe should be a central consideration in the selection and design of future colliders. *(from the neutrino town meeting report to the ESPP)*

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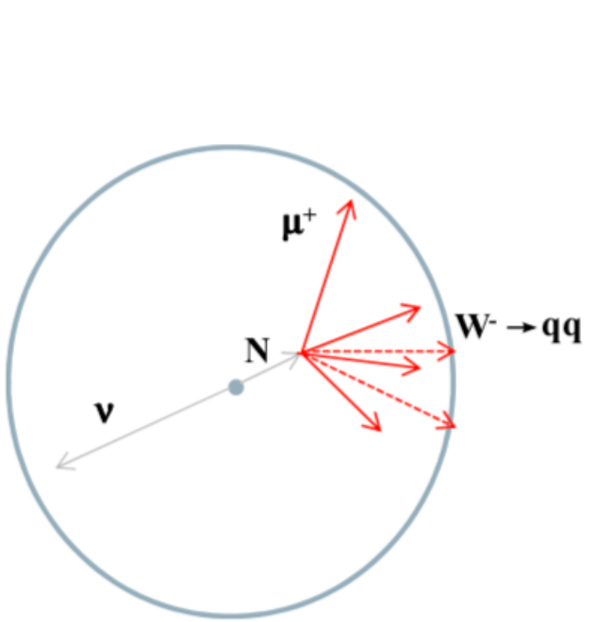
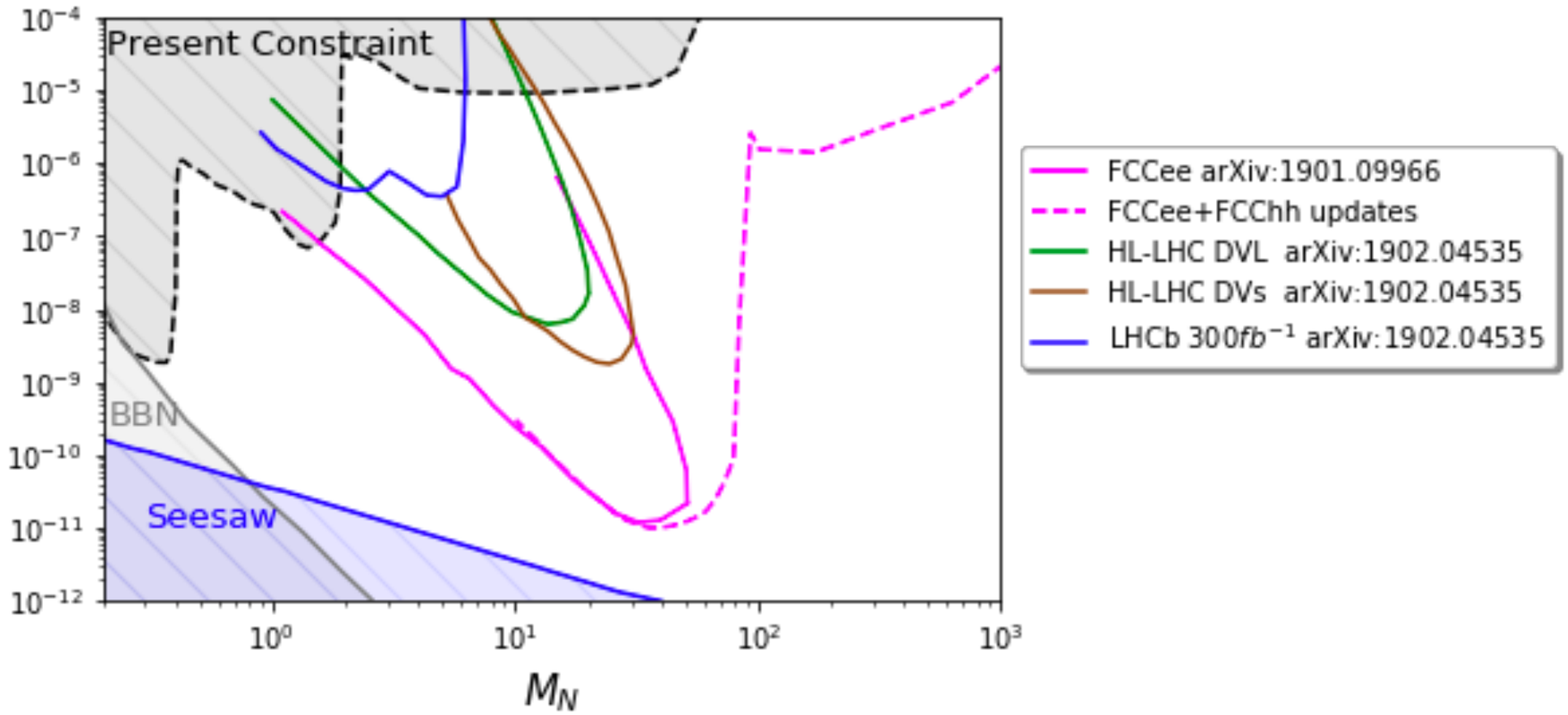
Displaced Vertexes

- Main signatures are two (displaced) charged leptons or one charged lepton and two jets or two displaced jets
- These searches are complementary with other planned/proposed experiments
- FCCee has a large large potential for HNL searches because of clean environment and clean signatures





Blondel et al., arXiv:1411.5230
Updated plot from Drewes et al., 1609.09069
Antusch et al., 1710.03744
c.f. also Cai et al., 1711.02180

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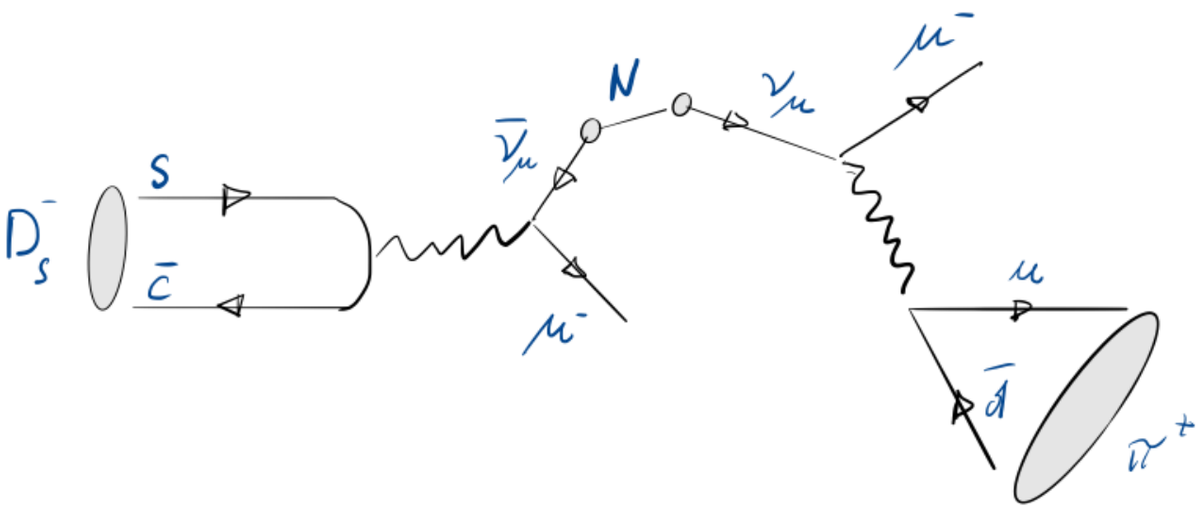
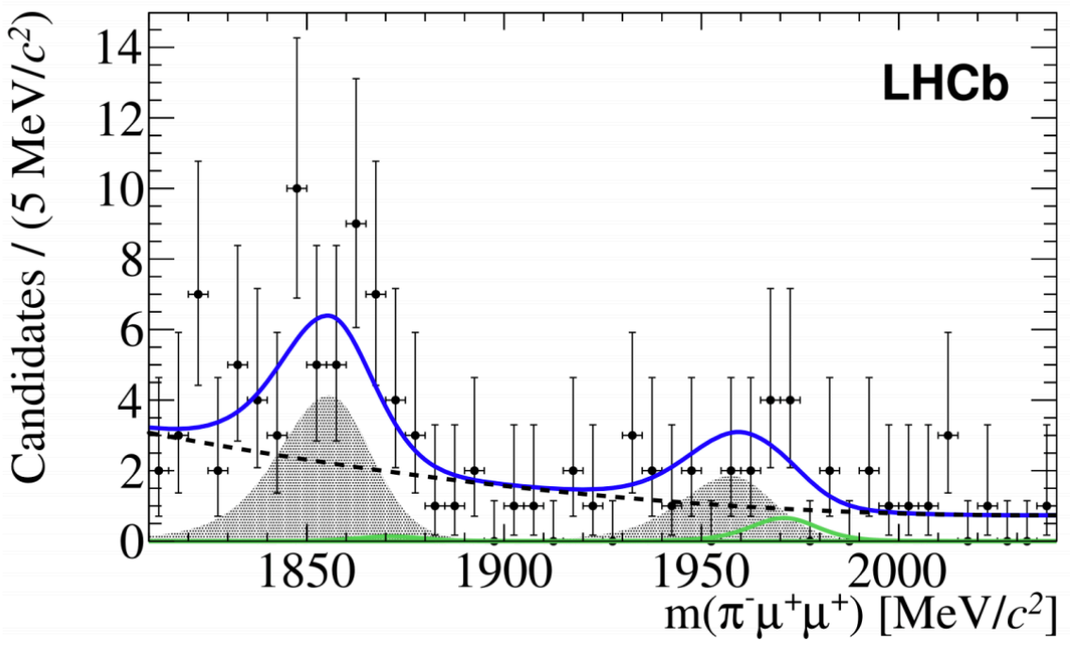
LHCb Limits

- Similarly HNLs can be produced as virtual particles in heavy flavour decays, resulting in LNV decays, analogous to neutrinoless double beta decays (limits from e.g. LHCb)





$\mathcal{B}\left(B^- \to D^0\pi^+\mu^-\mu^-\right) < 1.6 \times 10^{-6}$ at 95% C.L. — **LHCb Coll., J. Phys.: Conf. Ser. 447, 012062 (2013)**

$\mathcal{B}\left(B^- \to \pi^+\mu^-\mu^-\right) < 4.0 \times 10^{-9}$ at 95% C.L. — **LHCb Coll., Phys. Rev. Lett. 112, 131802 (2014)**

$\mathcal{B}\left(D_s^+ \to \pi^-\mu^+\mu^+\right) < 1.2 \times 10^{-7}$ at 90% C.L. — **LHCb Coll., Phys. Lett. B 724, 203 (2013)**

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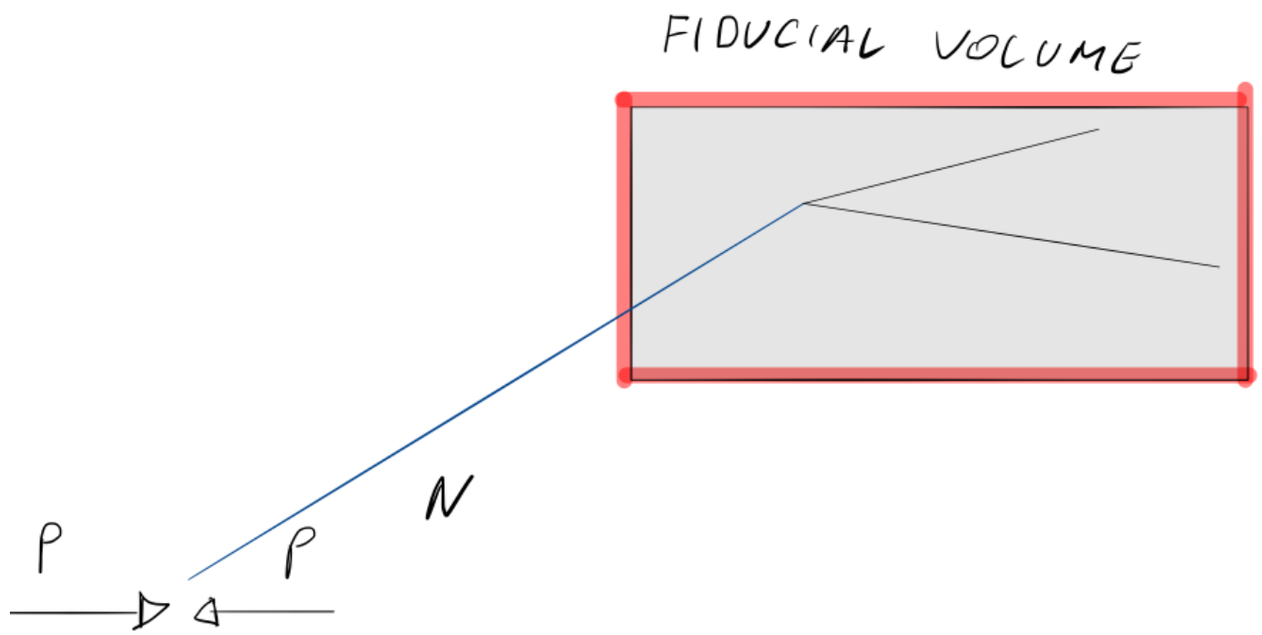
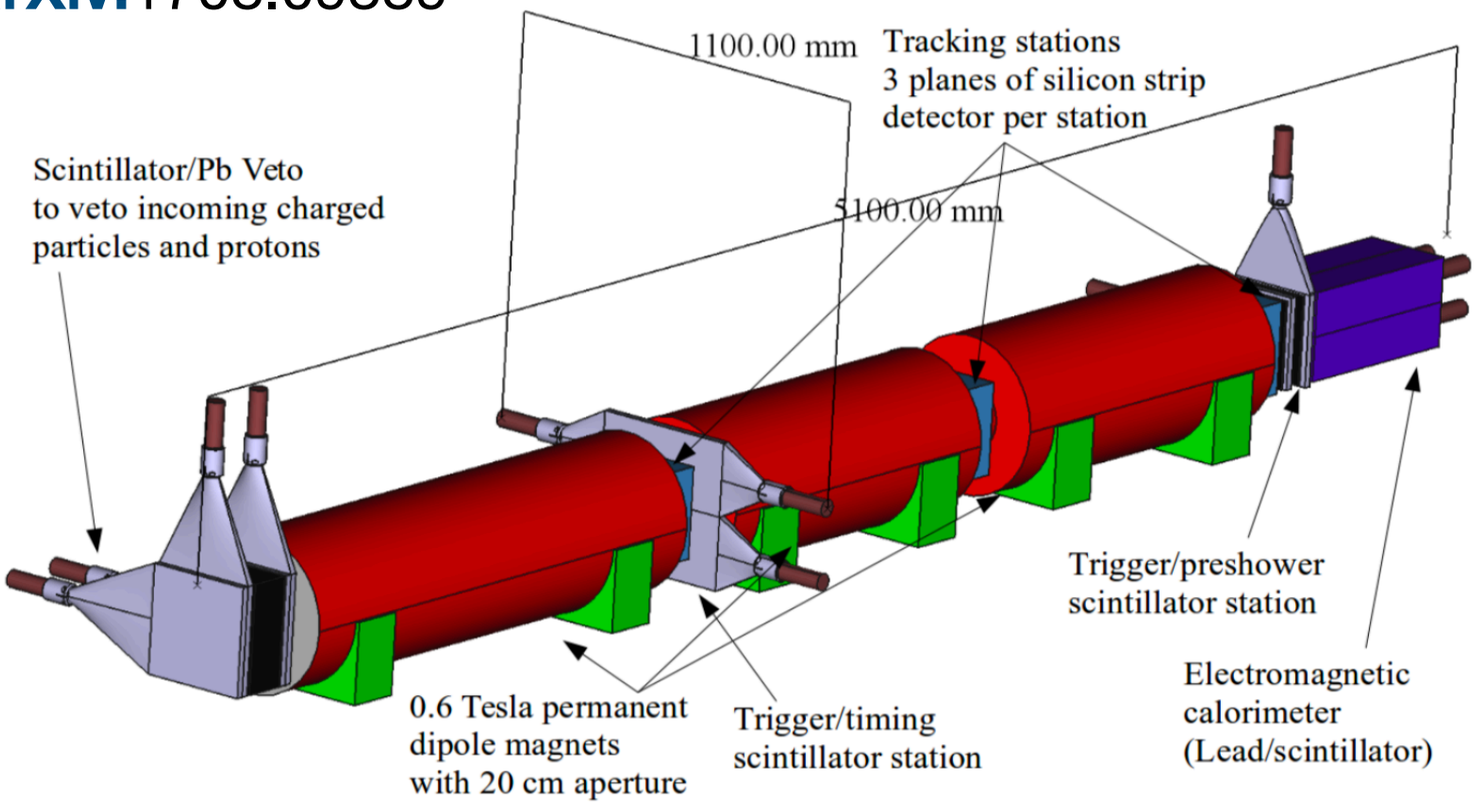
LHC interaction points

- The LHC produces a large number of Beauty and Charm which can decay into HNLs (with long lifetime)
- The idea is to have a (large) fiducial volume relatively with vetoes, timing and tracking capabilities
- The experimental signature of HNLs (as well as of any Hidden Sector Particles) is an excess of vertexes (aiming to have zero bkg)
- The physics sensitivity is given by the interplay between:
  - Size of the fiducial volume
  - Distance from pp interaction point
  - Momentum measurement/particle identification



FASER

arXiv:1708.09389



- Located 480 m downstream of ATLAS in service tunnel (R=10 cm, L=1.5m)
- FASER II (HL-LHC era) R=1m. L=5m (need civil engineering work)
- FLUKA demonstrated low radiation levels and background
- Further background studies and detector optimisation ongoing

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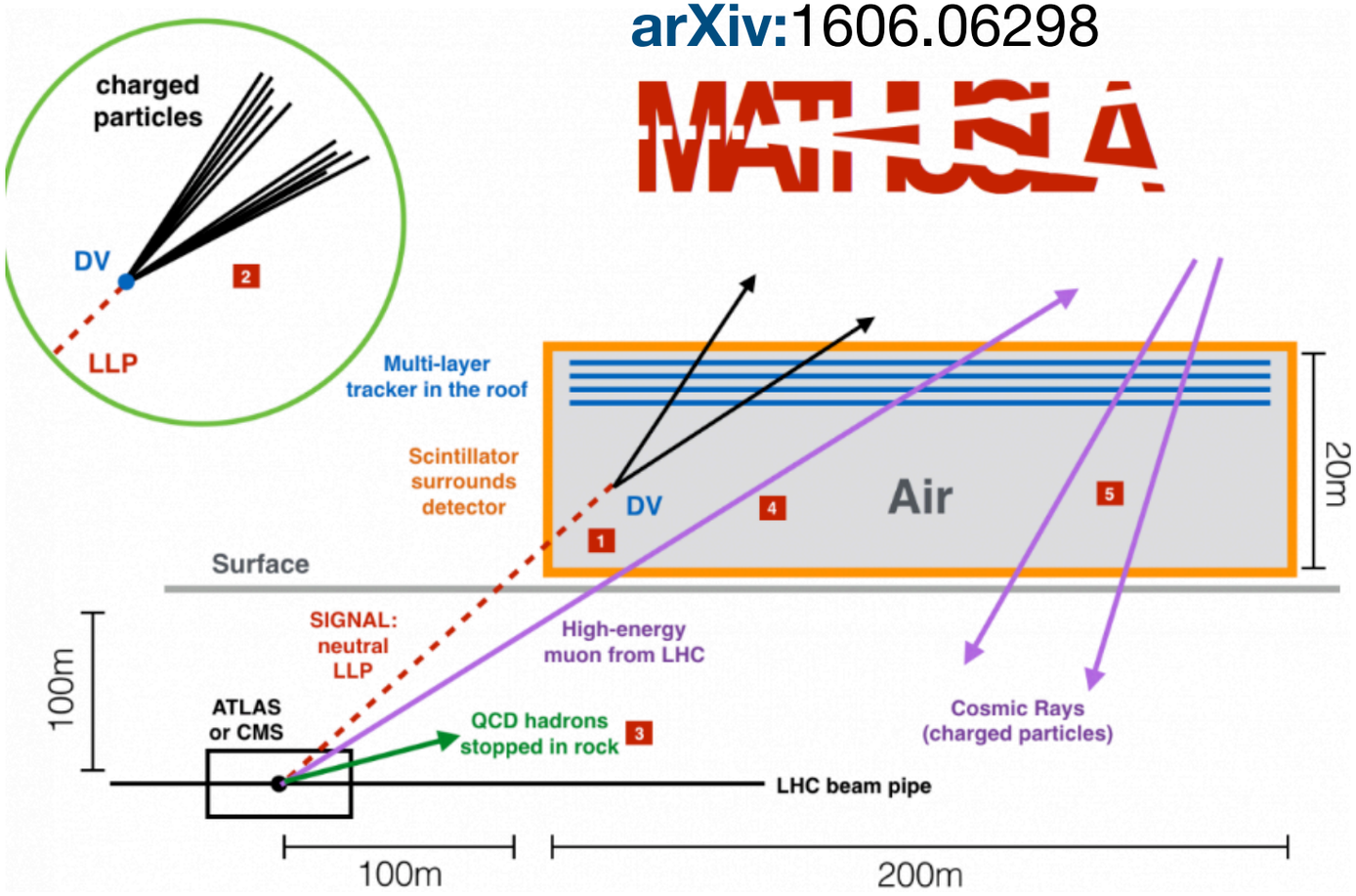
MATHUSLA

arXiv:1606.06298



- Location of detector to be finalised (probably smaller detector)
- Tracking with RPC or Extruded Scintillators $\sigma(T) \sim 1ns, \sigma(X) \sim 1cm$
- Layer of detector in the floor considered for additional veto capabilities
- Preliminary background studies with toy simulation (indicate zero bkg)
- Ongoing studies with full simulation for comics (10^{15} interactions in total)
- MATHUSLA-like test stand (3x3x5 m^3) taking data
- Full scale detector in the HL-LHC era

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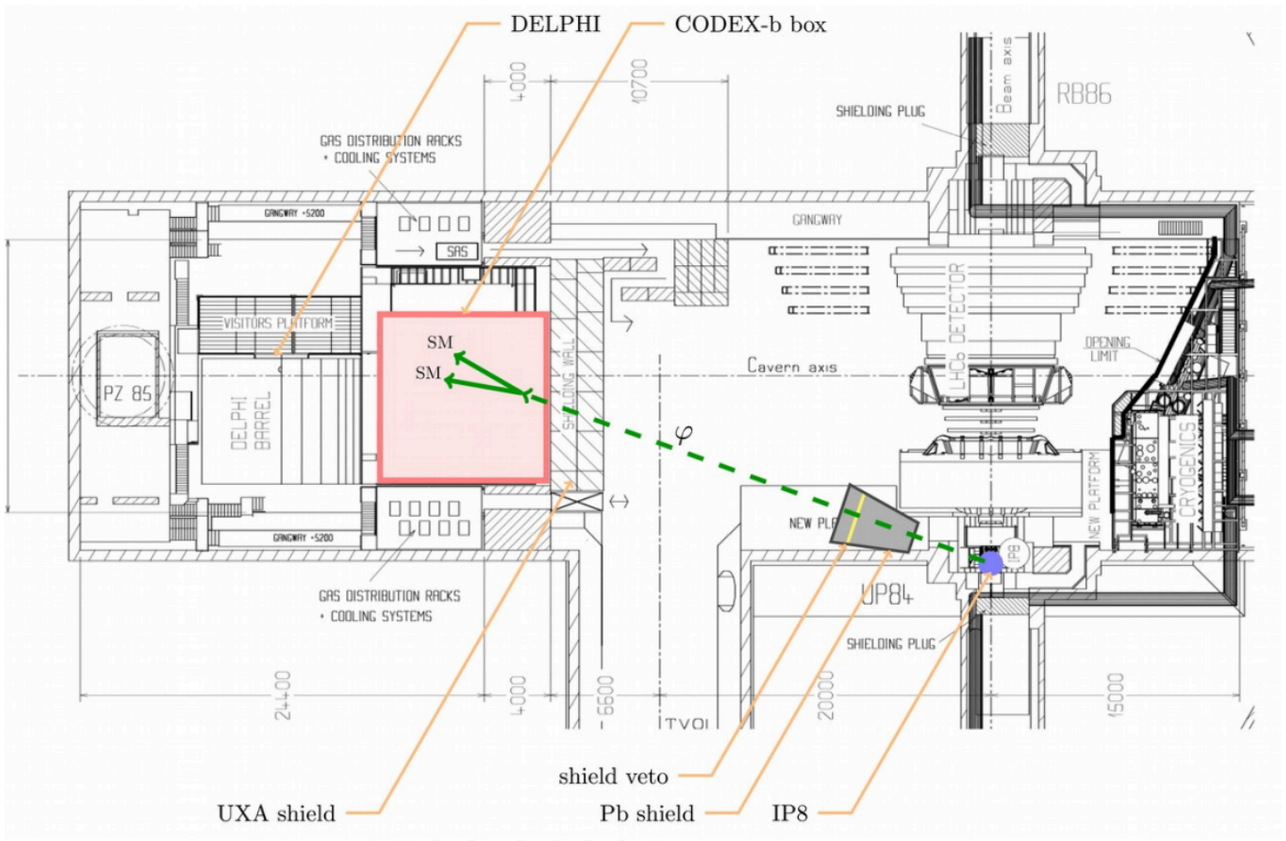
CODEX-b



arXiv:1708.09395

- CODEX-b consisting of tracking detector and vetos
- CODEX-b located in the LHCb cavern, behind 3m concrete from IP8
- Location available from Run3 of LHCb (2021), can be interfaced to LHCb trigger and reconstruction stream
- Fiducial volume of 10x10x10 m^3
- Data-driven background estimate ongoing

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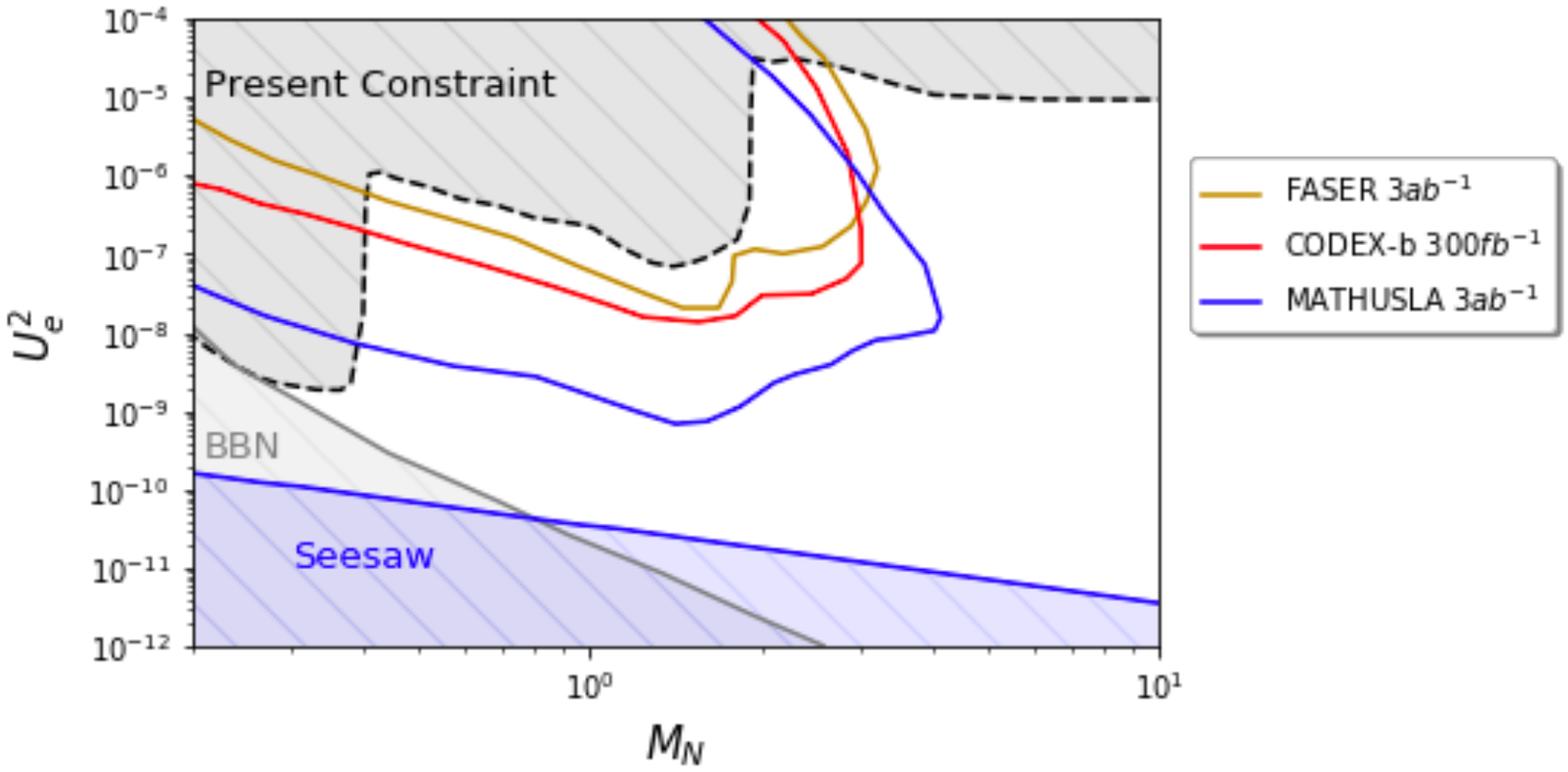
Sensitivity to HNLs

Sensitivity curves from
Physics Beyond Colliders WG, arXiv:1901.09966



- Estimates assume zero background (to be demonstrated)
- All estimates assume full LH-LHC integrated luminosity
- MATHUSLA and CODEX-b signature are displaced vertex
- FASER in addition can perform measurements to characterise the signal

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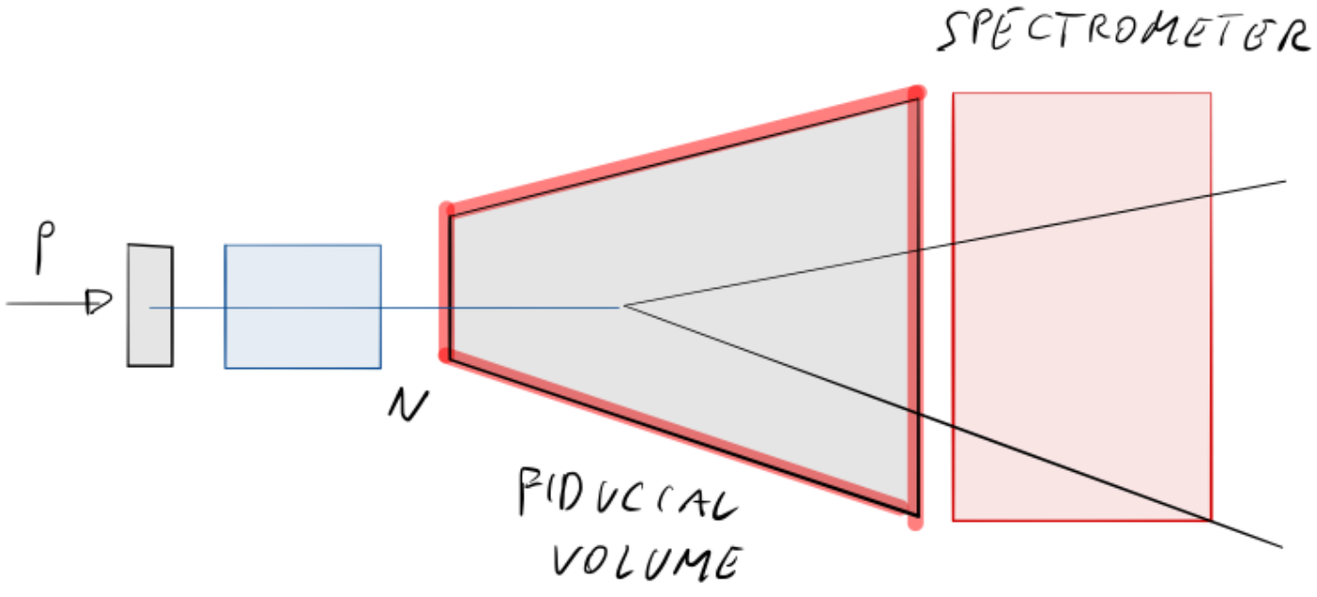
Proton Beam Dump

- To test small values of U^2 the best way is to use c-/b-hadrons (apart for the phase space that can be tested by FCCee)
- If we are optimistic and assume we can discover these decays we certainly wants to make measurements on these particles to answer questions such as:
  - What is the mass of these particles
  - How many of these particles do we have
  - Are the parameters the right one to explain v-oscillation/leptogenesis
- In general proton beam dump experiment allow large fiducial volume and many sub-detectors allowing to measure mass and decay channels



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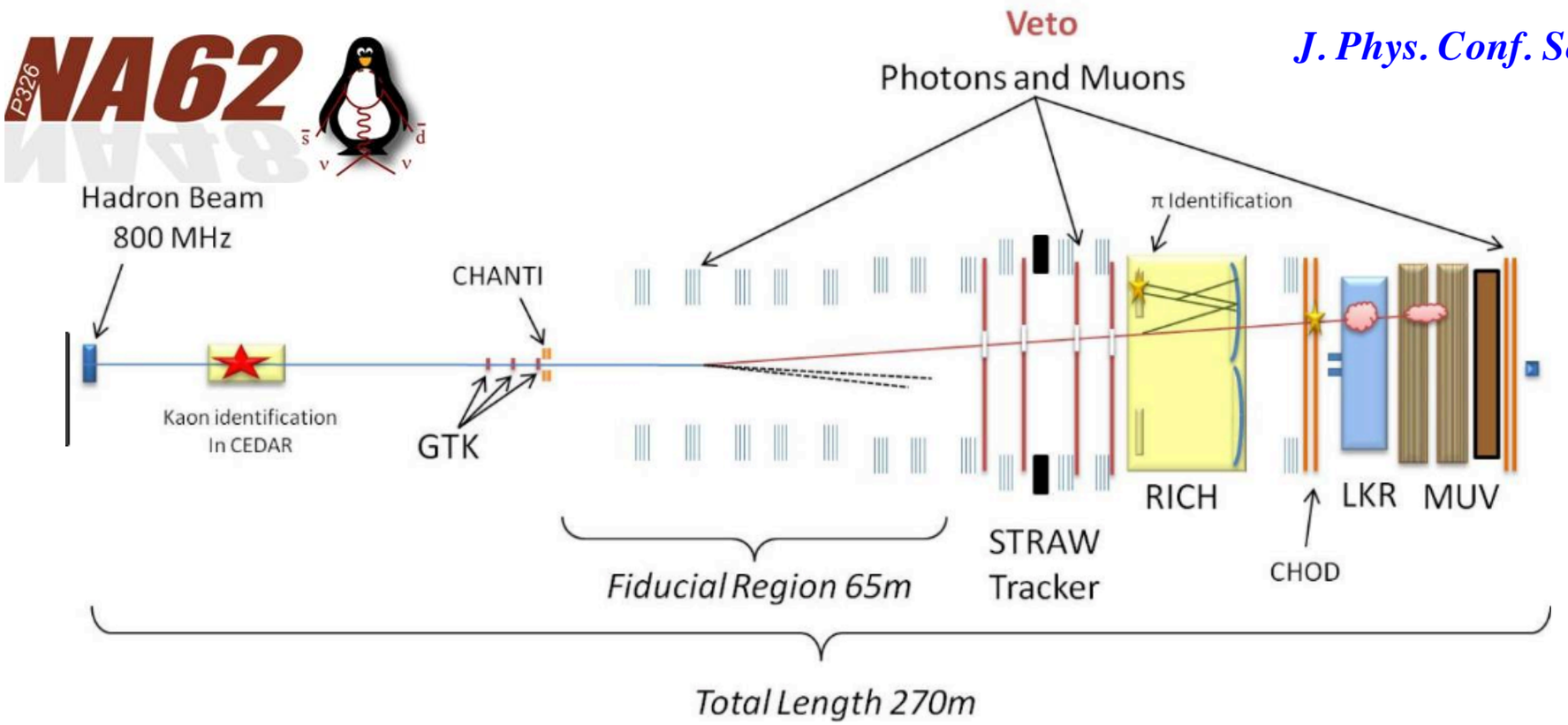
NA62 experiment



J. Phys. Conf. Ser. **873 (2017) 012015**

- Experiment at SPS of CERN
- Main goal of NA62 is to measure ultra-rare K-decays such as $K^+ \to \pi^+ \nu\bar{\nu}$
- Possible to operate NA62 in beam-dump mode, acquaring about 10^{18} PoT
- NA62 Collaboration preparing a plan for Run3 (2021-2023)
- Already collected about 10^{16} PoT in dump mode, demonstrated that background is under control for fully reconstructed mode
- Possibility to add veto detector to extend the sensitivity to partially reconstructed mode

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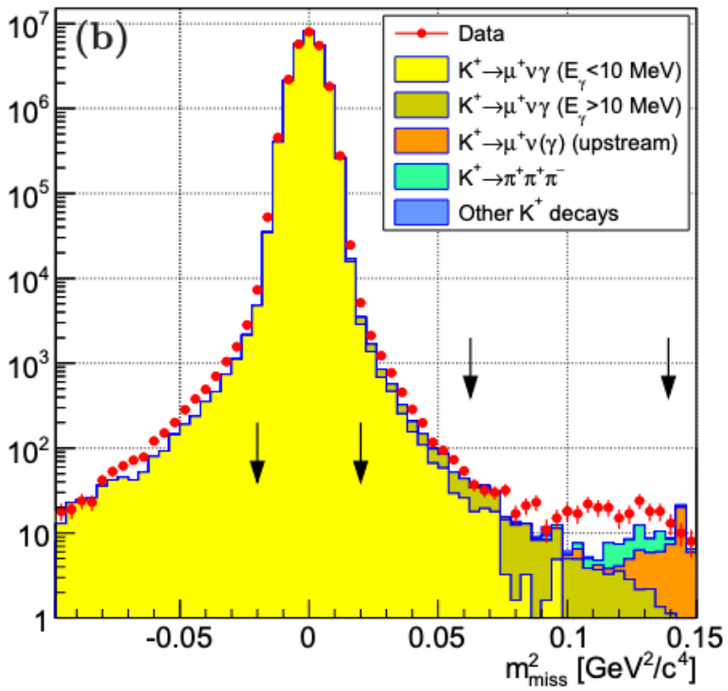
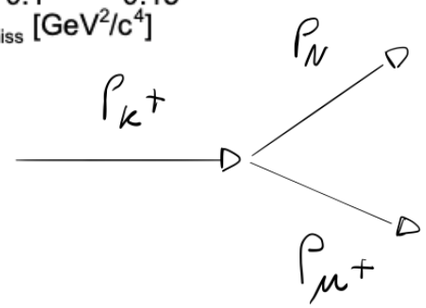
HNL at NA62

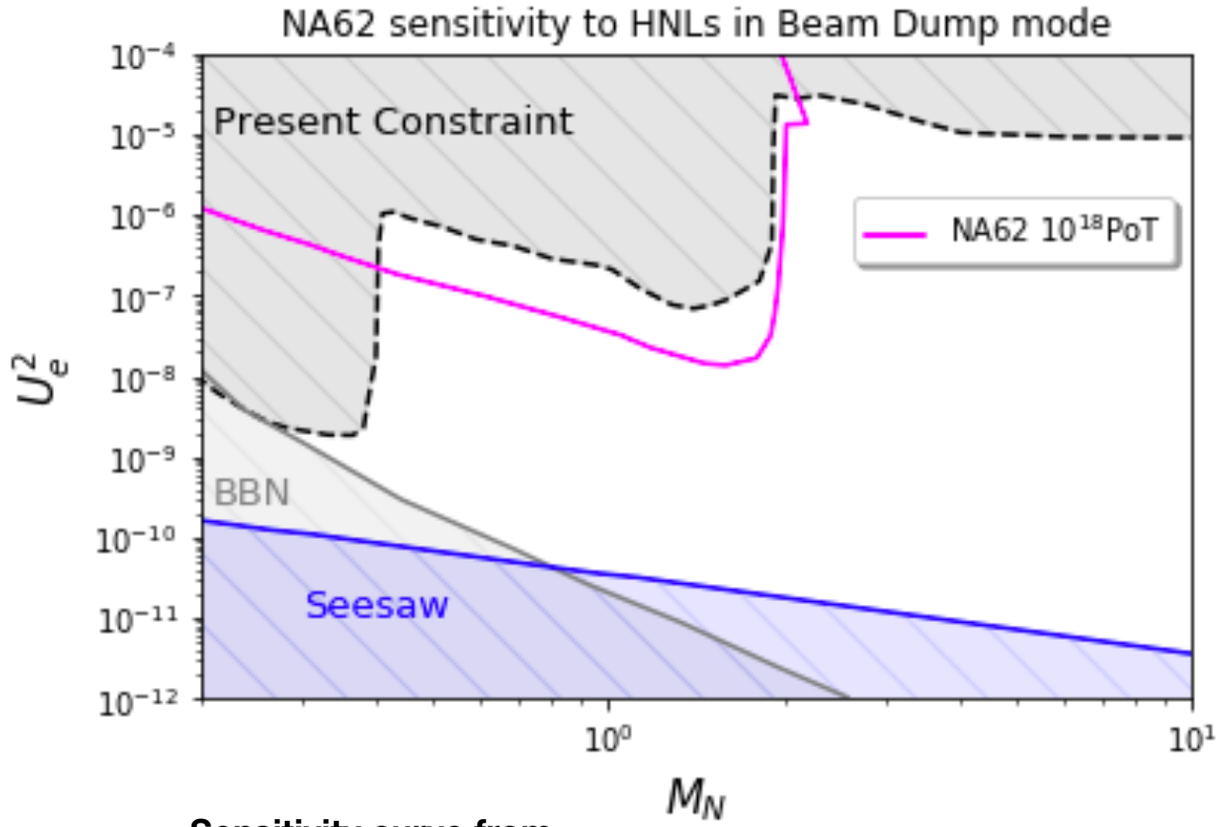
NA62 Coll., Phys.Lett.B (12/01/2018)



$$K^+ \to \mu^+ N$$

$$m_N^2 = (p_{K^+} - p_{\mu^+})^2 = m^2_{miss}$$





Sensitivity curve from
Physics Beyond Colliders WG, arXiv:1901.09966

- NA62 is searching for HNLs coming from K with missing mass techniques
- Results with1% of the nominal beam intensity arXiv:1712.00297
- Possibility to probe the region below the K with full data
- NA62 running in beam dump mode has potential to improve present constraints for HNL coming from heavy mesons

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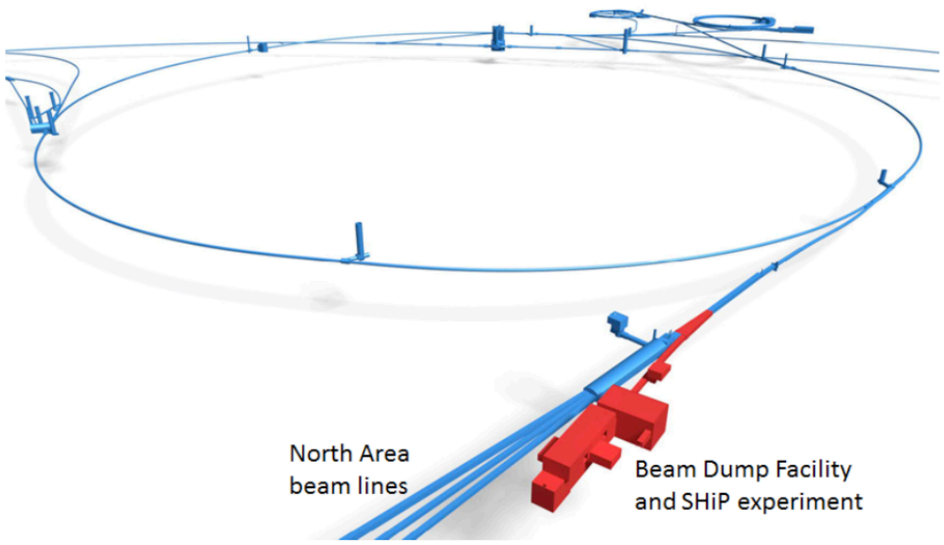
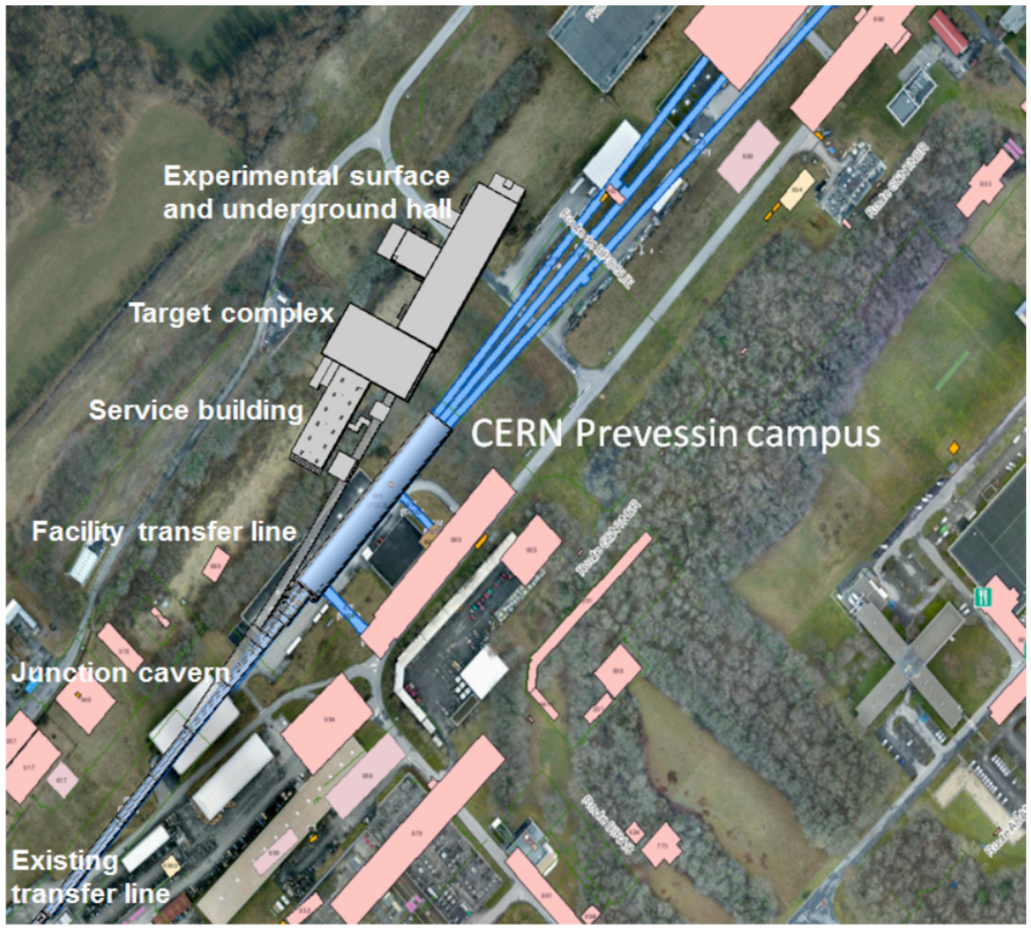
Beam Dump Facility

Table 2: Key beam parameters foreseen for BDF/SHiP

Momentum [GeV/c]	400
Beam Intensity per cycle	4.2×10^{13}
Cycle length [s]	7.2
Spill duration [s]	1
Expected r.m.s. spot size (H/V) [mm]	6/6
Avg. beam power on target [kW]	355
Avg. beam power on target during spill [kW]	2560
Protons on target (PoT)/year	4×10^{19}
Total PoT in 5 year's data taking	2×10^{20}



See talk of Mike Lamont in the Accelerator Session



CERN-PBC-REPORT-2018-001

- Proposal for Beam Dump Facility in the North area of CERN compatible with present and planned activities
- Consolidation and upgrade of SPS would allow data taking in Run4 (2026)

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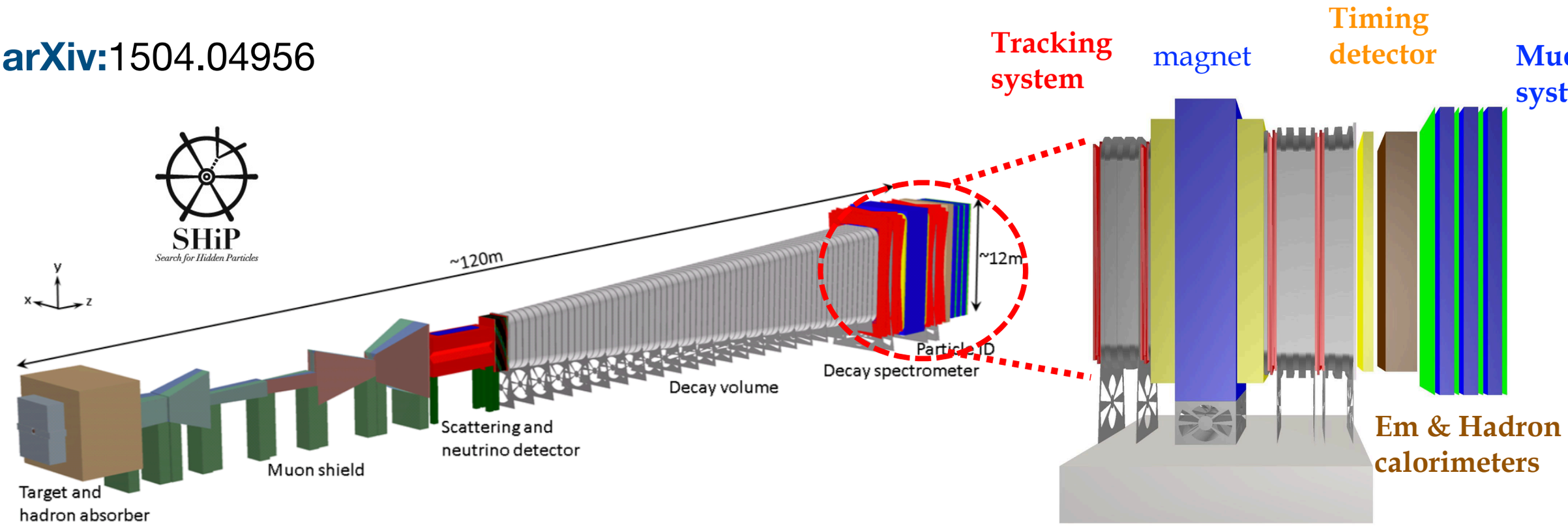
SHiP Experiment

arXiv:1504.04956



- Heavy target followed by Hadron Absorber
- Muon shield to reduce the muon rate to less than 100KHz
- Pyramidal Frustrum fiducial volume
- Decay Spectrometer consisting of Tracking System, Timing Detector, Calorimeter System and Muon Detector
- Experiment optimised for acceptance while minimising background

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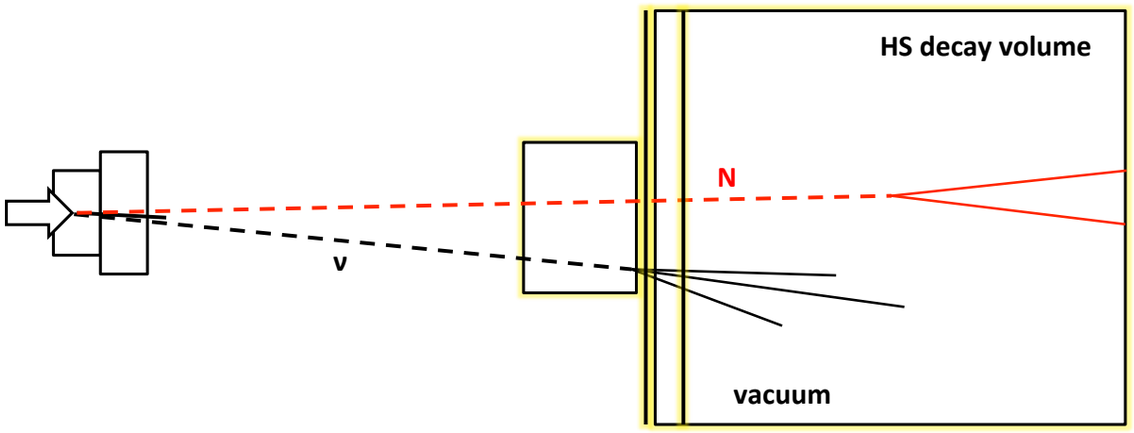
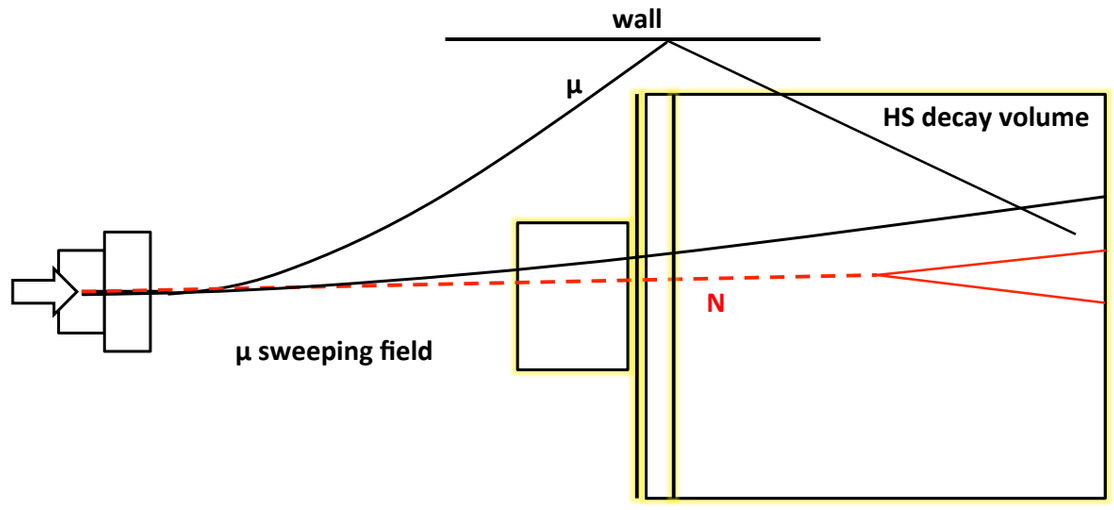
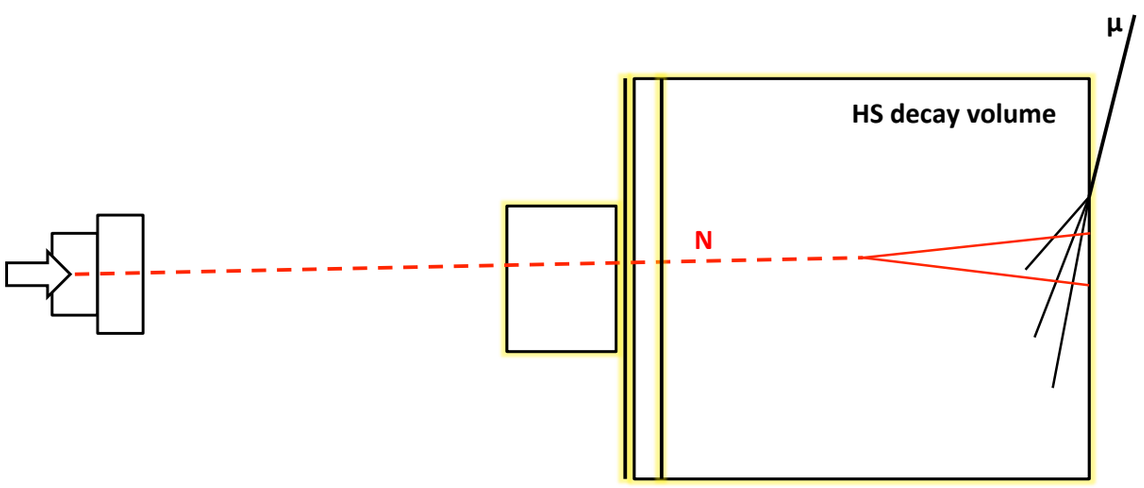
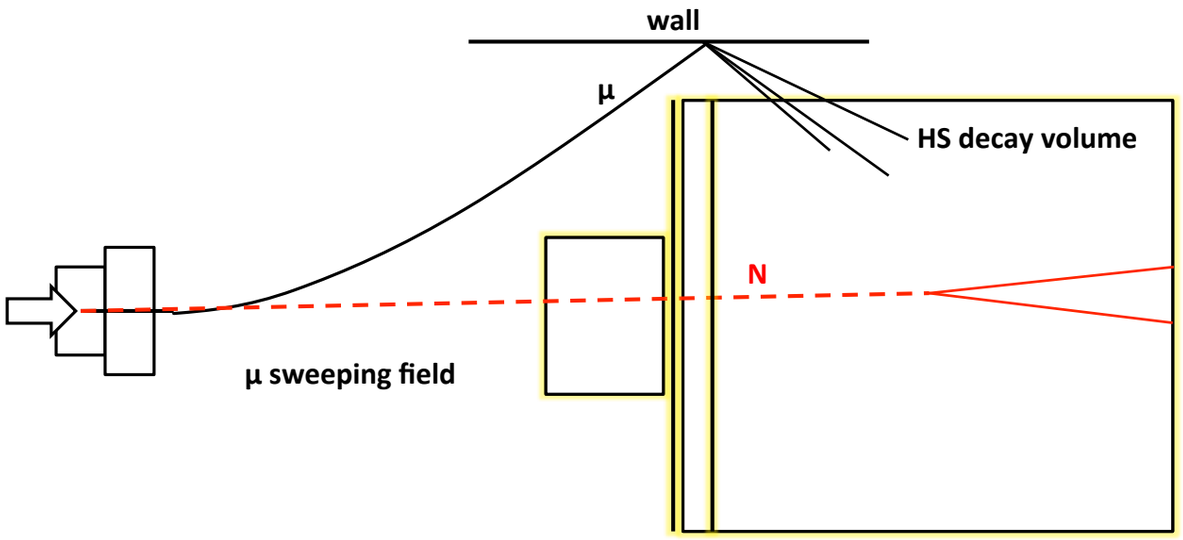
SHiP Experiment









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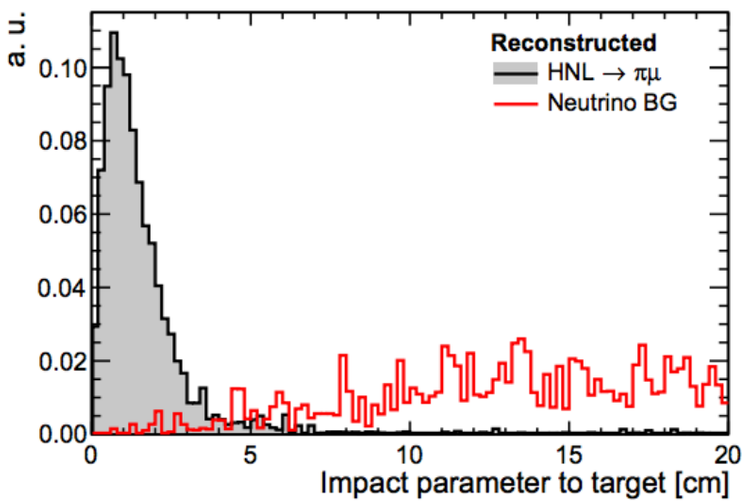
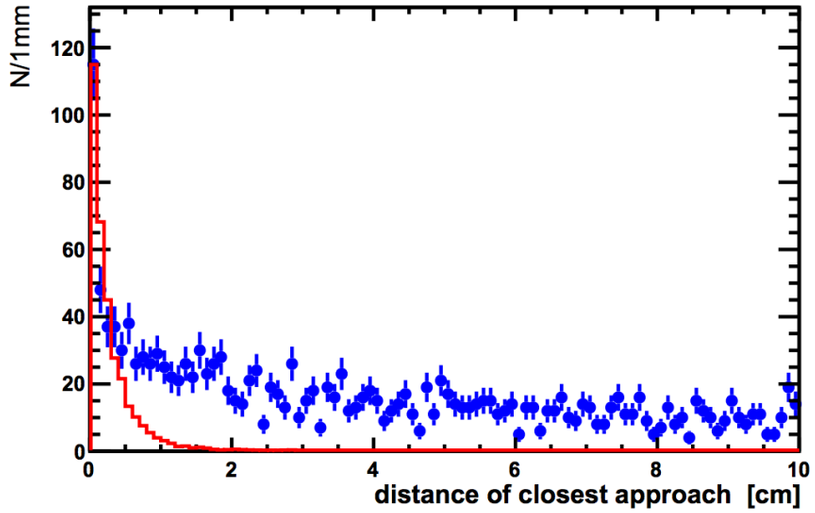
SHiP Experiment

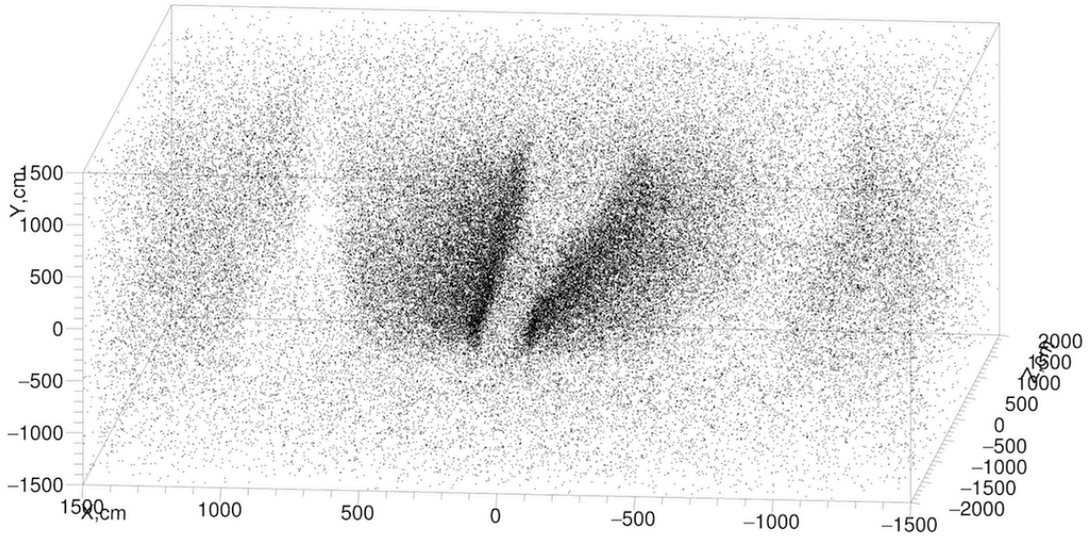
Cut	Value
Track momentum	$> 1.0\,\mathrm{GeV}/c$
Dimuon distance of closest approach	< 1 cm
Dimuon vertex position	(> 5 cm from inner wall)
IP w.r.t. target (fully reconstructed)	< 10 cm
IP w.r.t. target (partially reconstructed)	< 250 cm

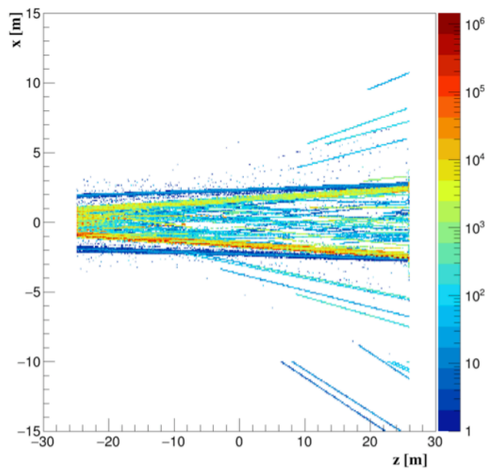
Timing cut around 350 ps

Various veto cuts considered









SHiP Coll., CERN-SPSC-2019-010

- All backgrounds simulated with full Monte Carlo (Pythia6,8/GEANT4/Genie)
- Demonstrated capability of having less than 0.1 bkg events
- Possible to measure the background data driven in the experiment itself

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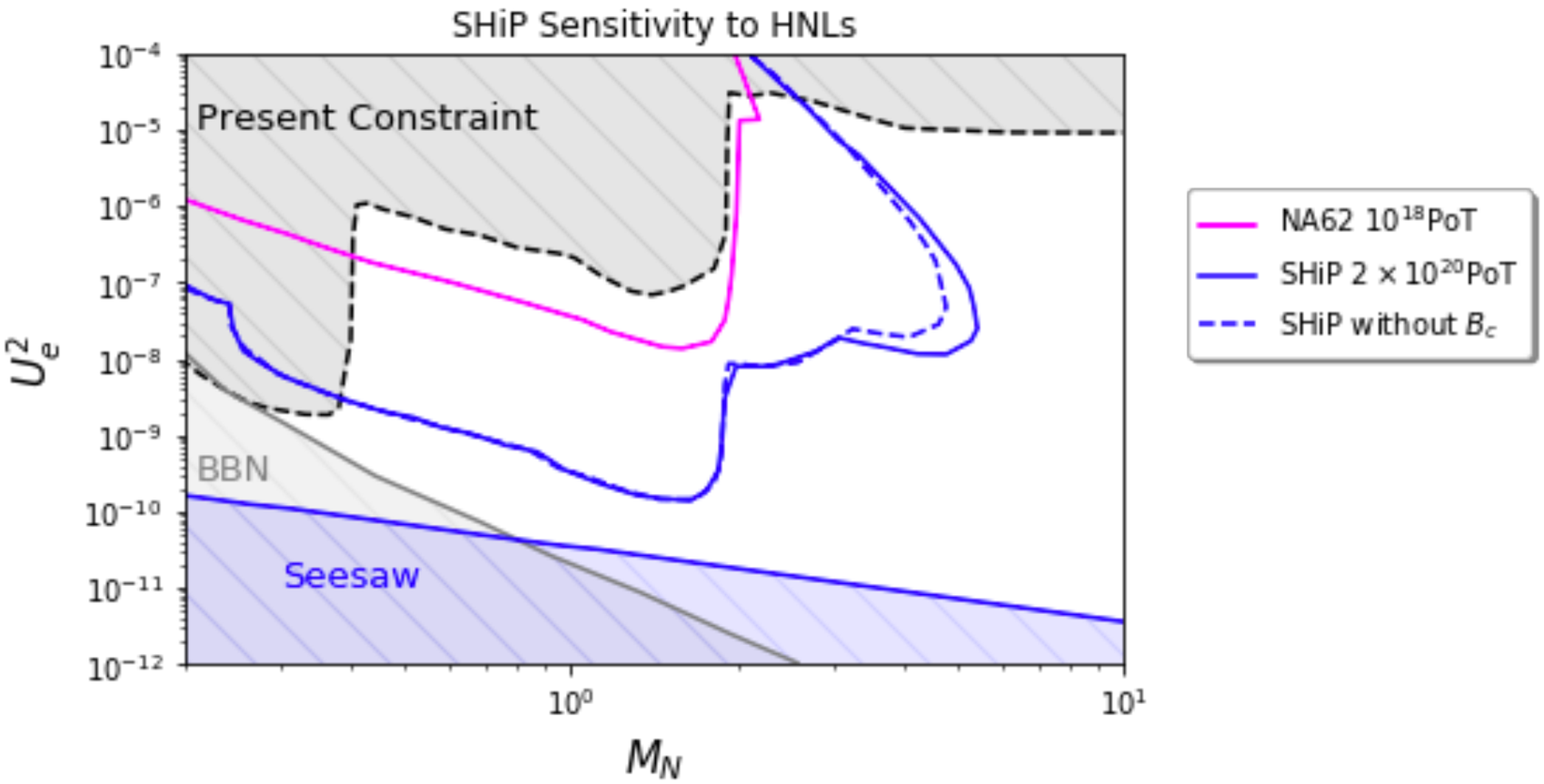
SHiP Experiment

Sensitivity curves from
Physics Beyond Colliders WG, arXiv:1901.09966



- NA62^{++} equivalent beam dump sample collected every few days
- One signal event corresponds to 3σ (also for partially reconstructed)
- In case of discovery momentum, invariant mass and particle identification allow to measure branching ratios and flavour structure

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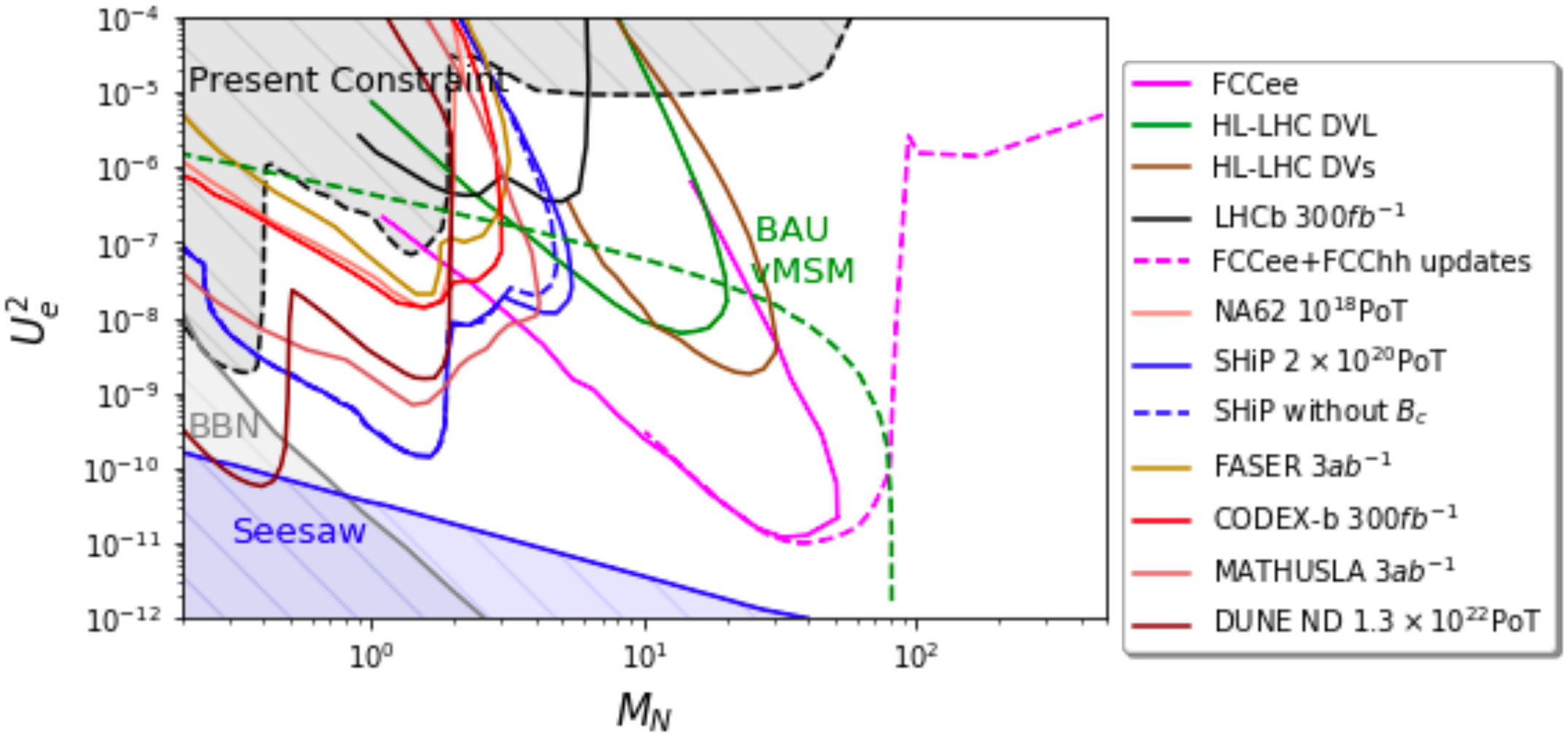
All Together

Sensitivity curves from
Physics Beyond Colliders WG, arXiv:1901.09966
HL-LHC from arXiv:1902.04535
LBNF near detector from arXiv:1905.00284

FCC from
Blondel et al., arXiv:1411.5230
Updated plot from Drewes et al., 1609.09069
Antusch et al., 1710.03744
c.f. also Cai et al., 1711.02180



- Very similar sensitivity for U_μ^2
- For U_τ^2 sensitivity to partially reconstructed decays is crucial

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Conclusions

- HNLs in the multi-GeV region well justified from theory point of view
  - Can provide explanation to neutrino masses and oscillations
  - Mechanism for leptogenesis
  - Test LFV and LNV

- HL-LHC, DUNE ND, FCCee and Beam Dump Experiments have the possibility to constraint very interesting region:
  - About 2-3 orders of magnitude in mass
  - About 2-3 orders of magnitudes in couplings

- In case of discovery important to measure mass and branching ratios to check compatibility with neutrino oscillation and leptogenesis

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Incomplete Reference List

- This talk was based on the contribution to the EPPSU: 1, 12, 42, 45
  https://indico.cern.ch/event/765096/contributions/

Disclaimer: all relevant papers written on this subject do not fit in many pages, the following is just a list of papers I have used while preparing this talk

- vMSM

Asaka, Blanchet, Shaposhnikov arXiv:0503065 ; Asaka, Shaposhnikov arXiv:0505013; Shaposhnikov, Tkachev arXiv:0604236; Shaposhnikov arXiv:0605047

- RH neutrinos at low mass, seesaw, 0nu2beta decays

Kersten, Smirnov arXiv:0705.3221; Moffat, Pascoli, Weiland arXiv:1712.07611; Bezrukov arXiv:0505247; Blennow arXiv:1005.3240 Pavon, Pascoli, Chan-fai arXiv:1209.5342; Faessler arXiv:1408.6077

- HNL and Leptogenesis

Abada et al. arXiv:1810.12463; Drewes, Eijima arXiv:1606.06221; Hernandez et al. arXiv:1606.06719; Asaka, Shaposhnikov arXiv:0505013 Boyarsky et al. arXiv:0901.0011; Eijima, Shaposhnikov, Timiryasov arXiv:1808.10833

- HNL Production, decays and sensitivity:

Gorbunov, Shaposhnikov, arXiv:0705.1729; Bondarenko et al. arXiv:1902.06240; Kyrylo et al. 1805.08567; Boiarska et al. arXiv:1902.06240; Blondel et al., arXiv:1411.5230; Ballet et al., arXiv:1905.00284

- Experiment Proposals:

Physics Beyond Colliders WG arXiv:1901.09966 and references therein

Backup Slides

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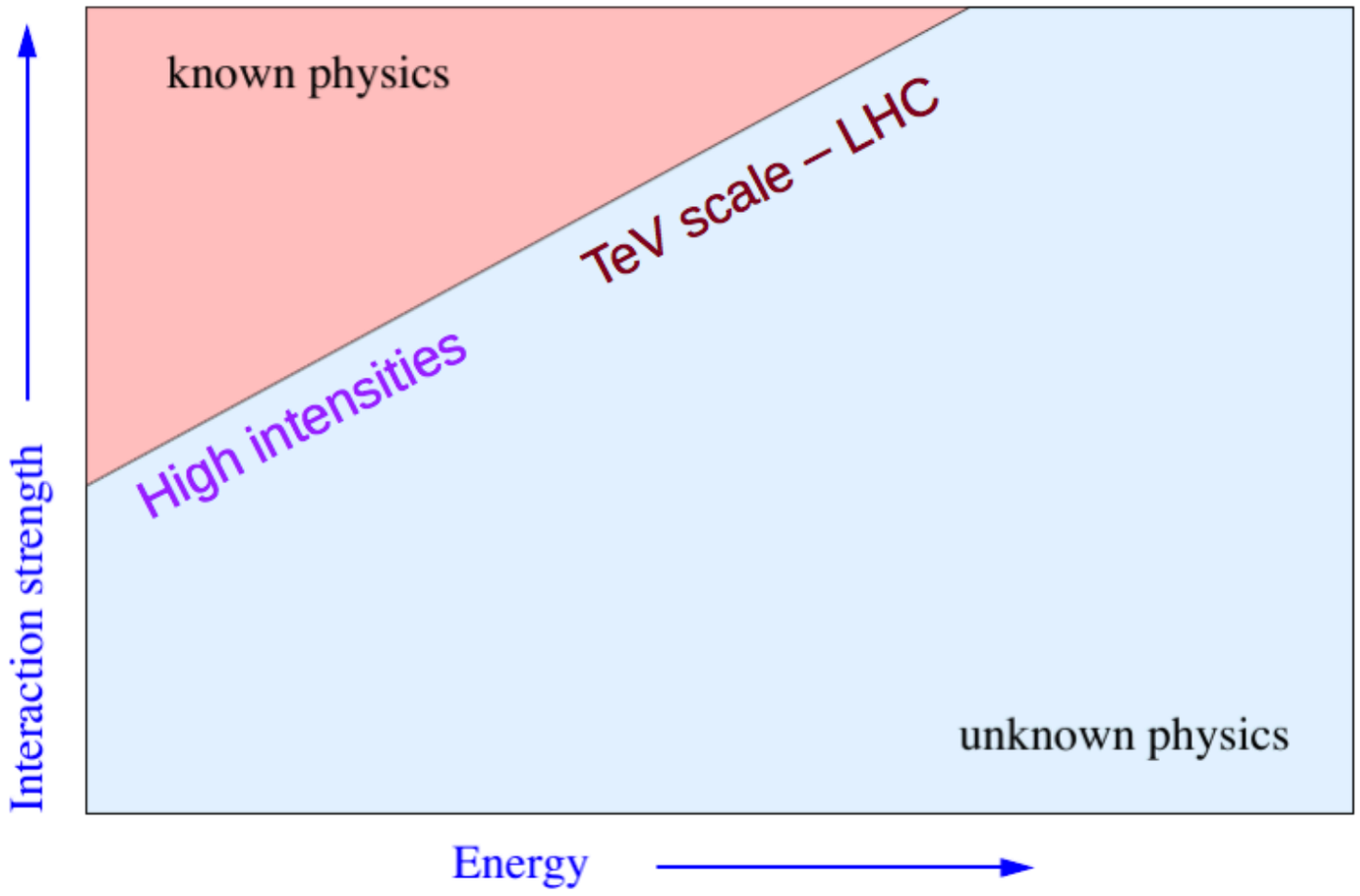
Motivation

- Naturalness as a guiding principle of Nature is nowadays put into question
- We should therefore not forget that we have a 2D problem (Mass VS Coupling)



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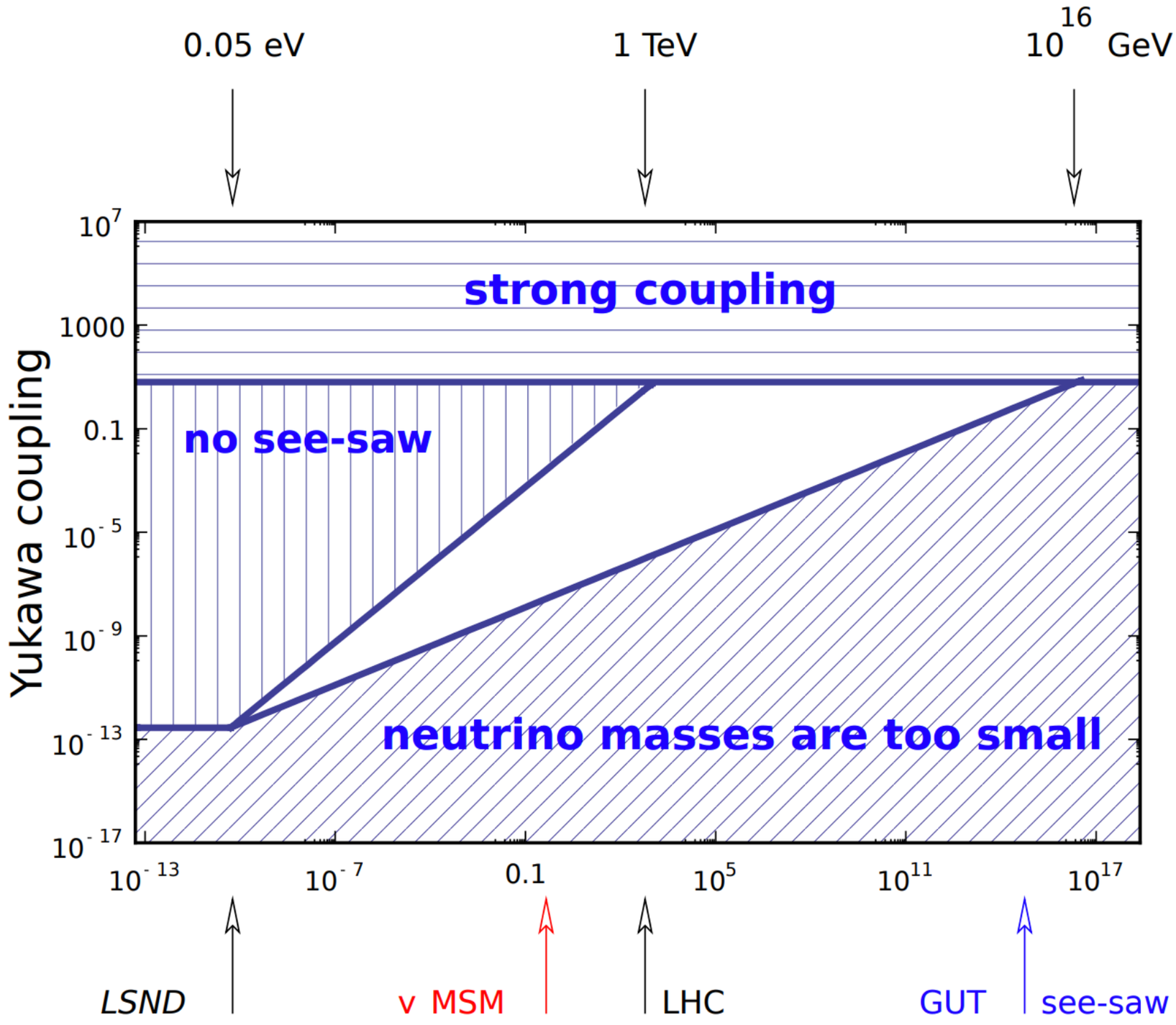
Majorana Mass



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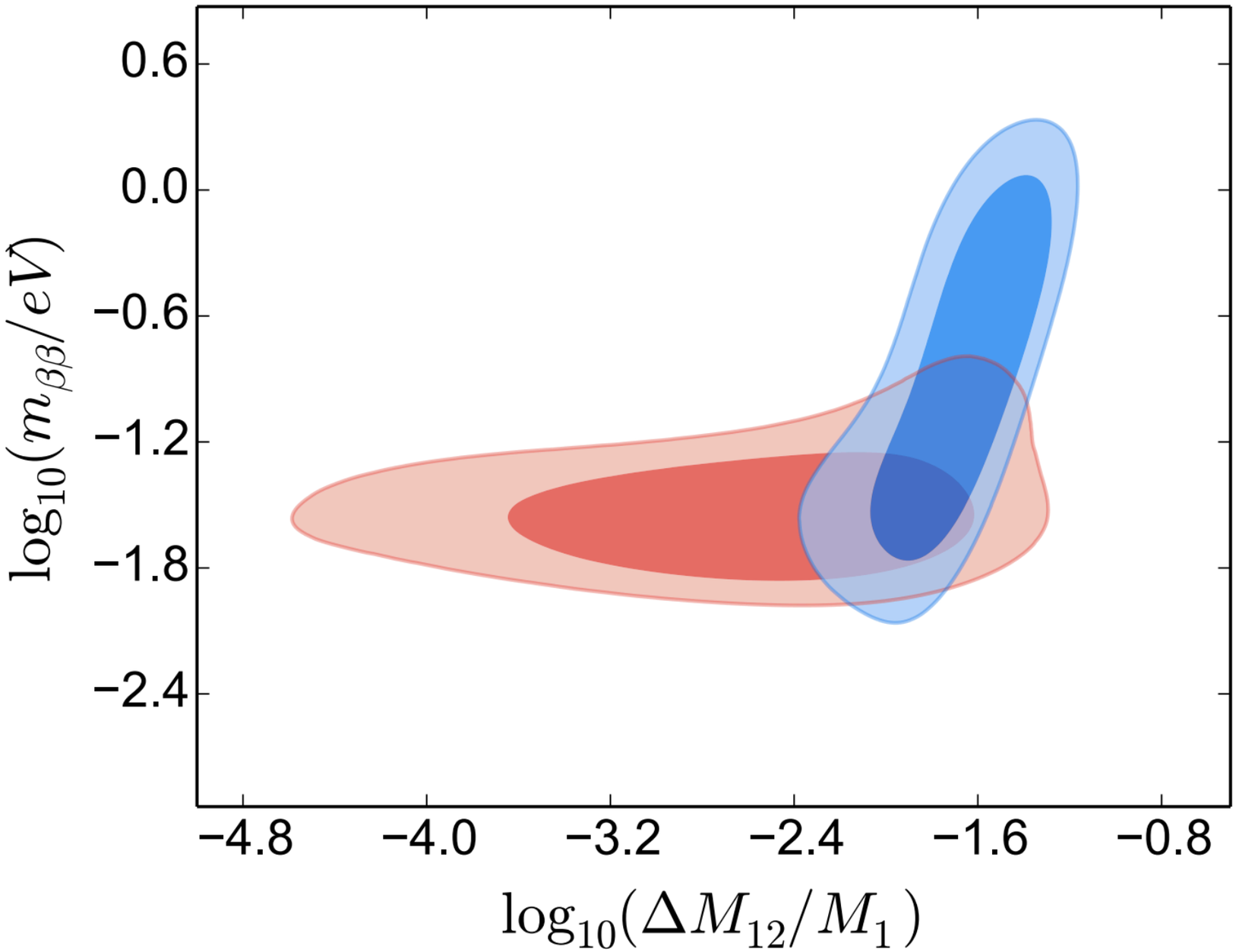
0v2beta VS DM/M



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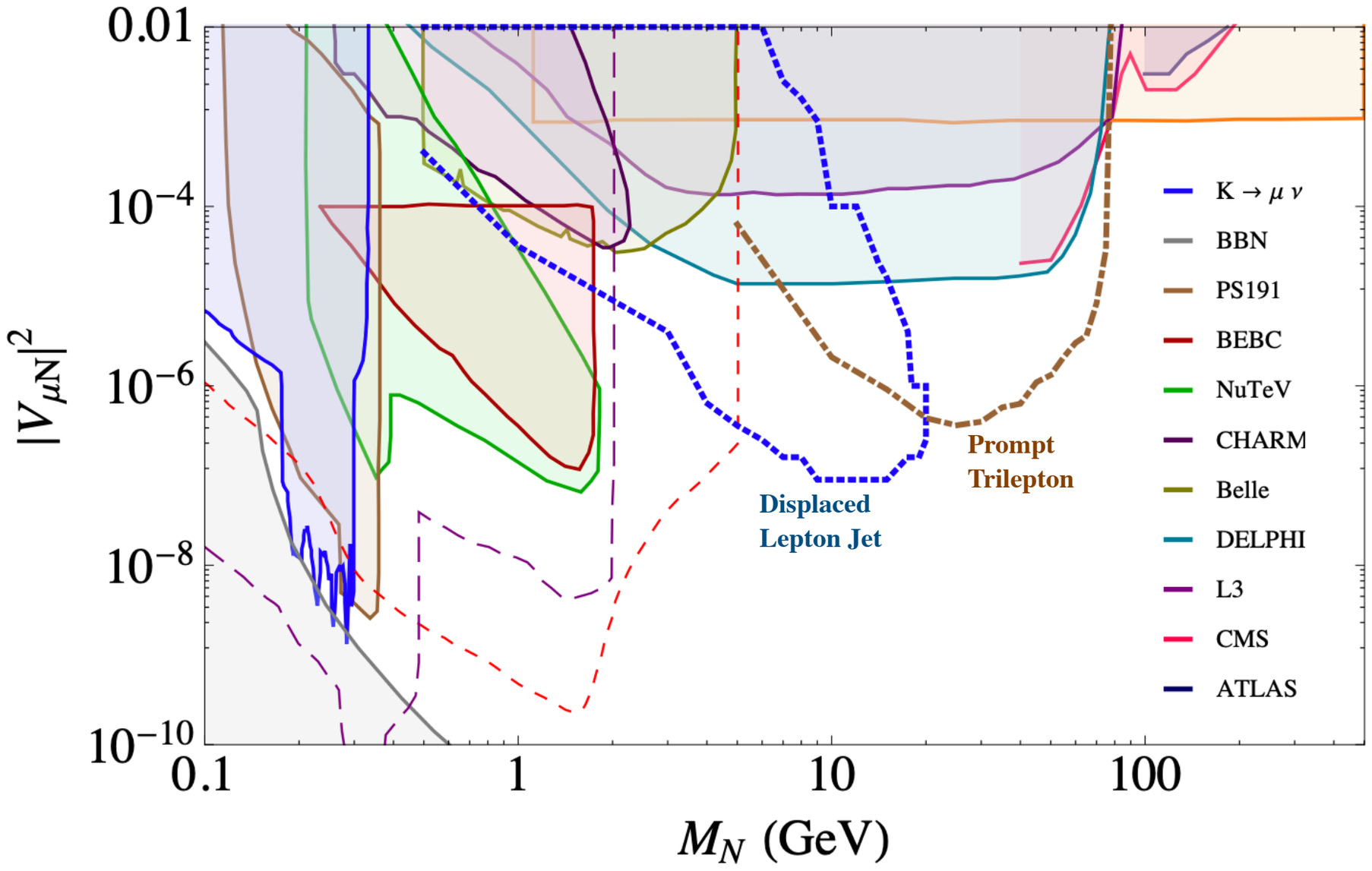
Boosted Leptons



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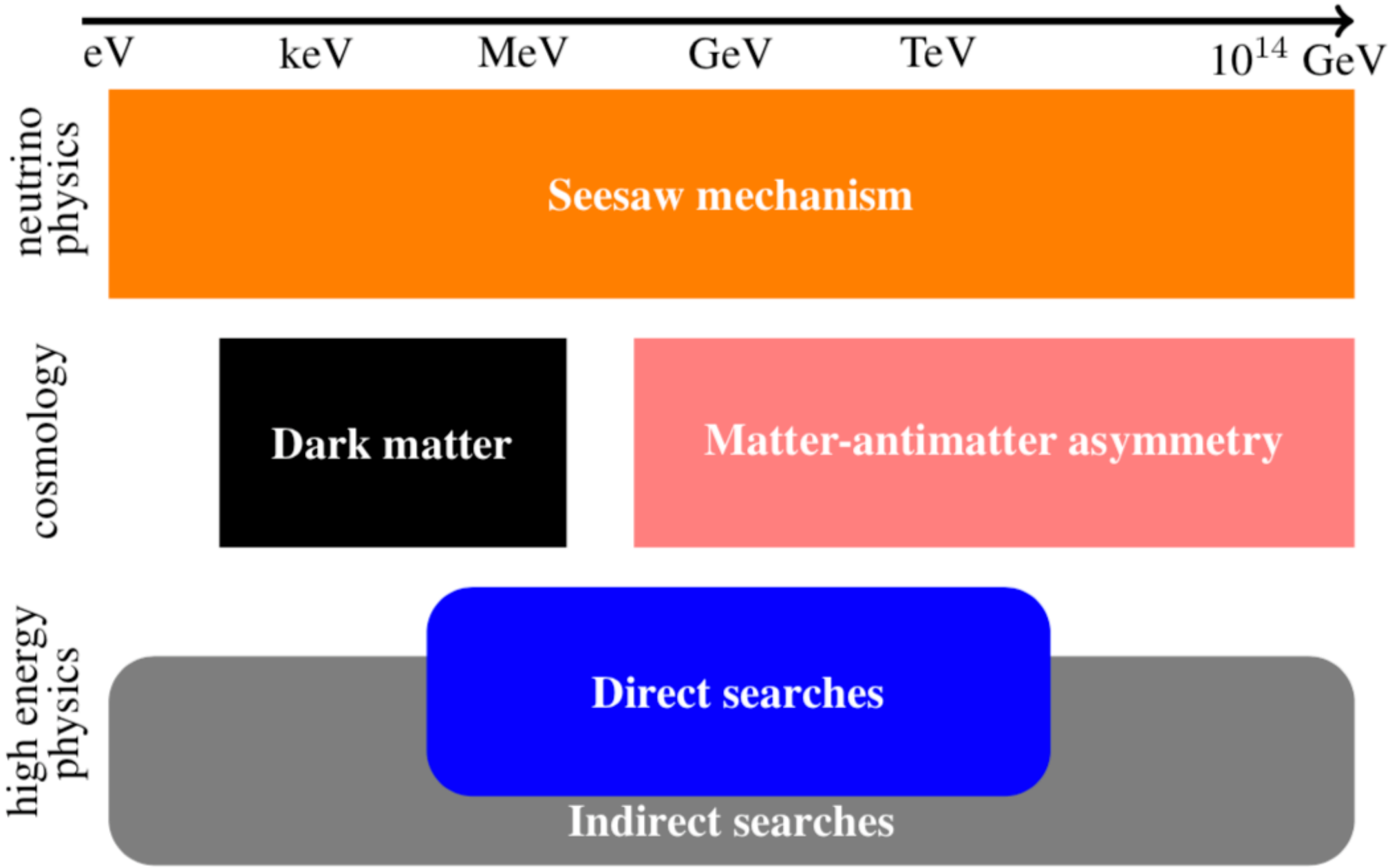
HNL Mass



M. Drewes arXiv:1510.07883

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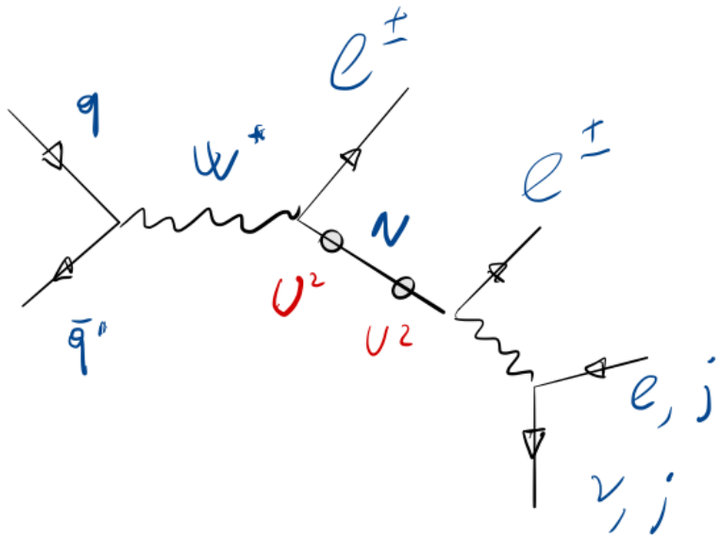
HNLs @ CMS



Same-sign di-leptons + 2 jets

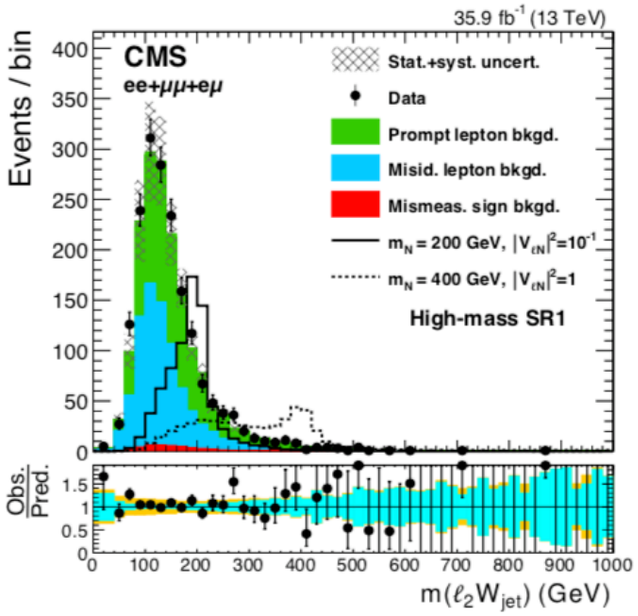
- Fully reconstructed N mass peak
- N has to be heavy (jet P_T >30 GeV)
- Sensitive to LNV N-decays

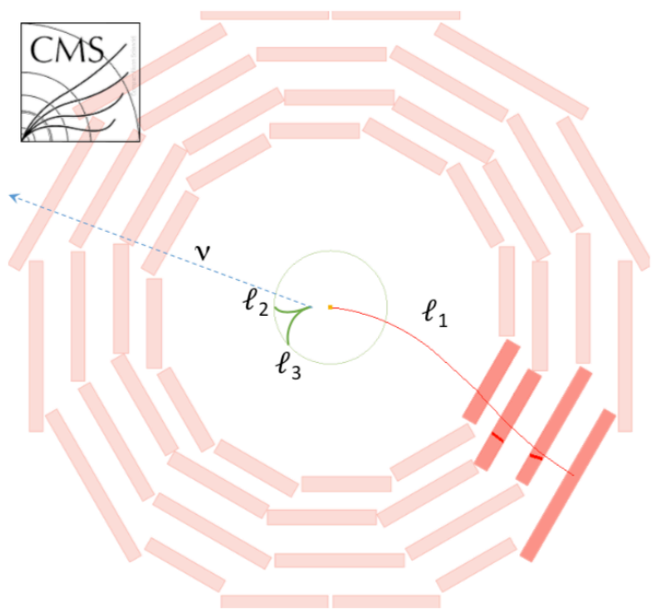
Tri-leptons + missing E_T

- No clear mass peak
- Sensitive to light N (lepton P_T > 5GeV)
- Sensitive to LN-conserving N-decays

CMS Coll., PRL 120 (2018) 221801

Prompt same-sign dilepton search: coupling to muons





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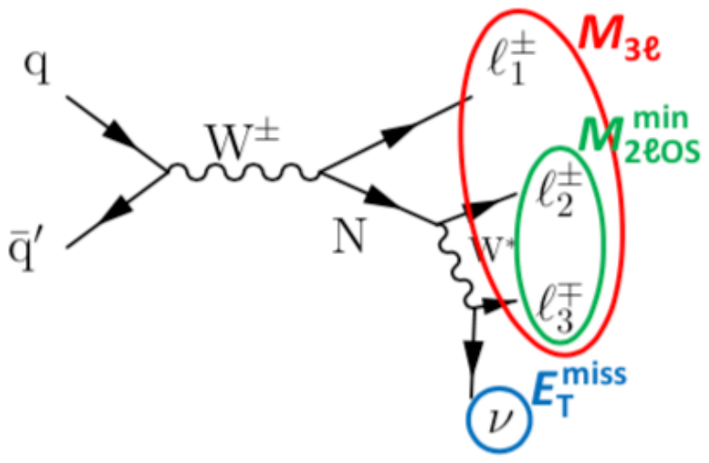
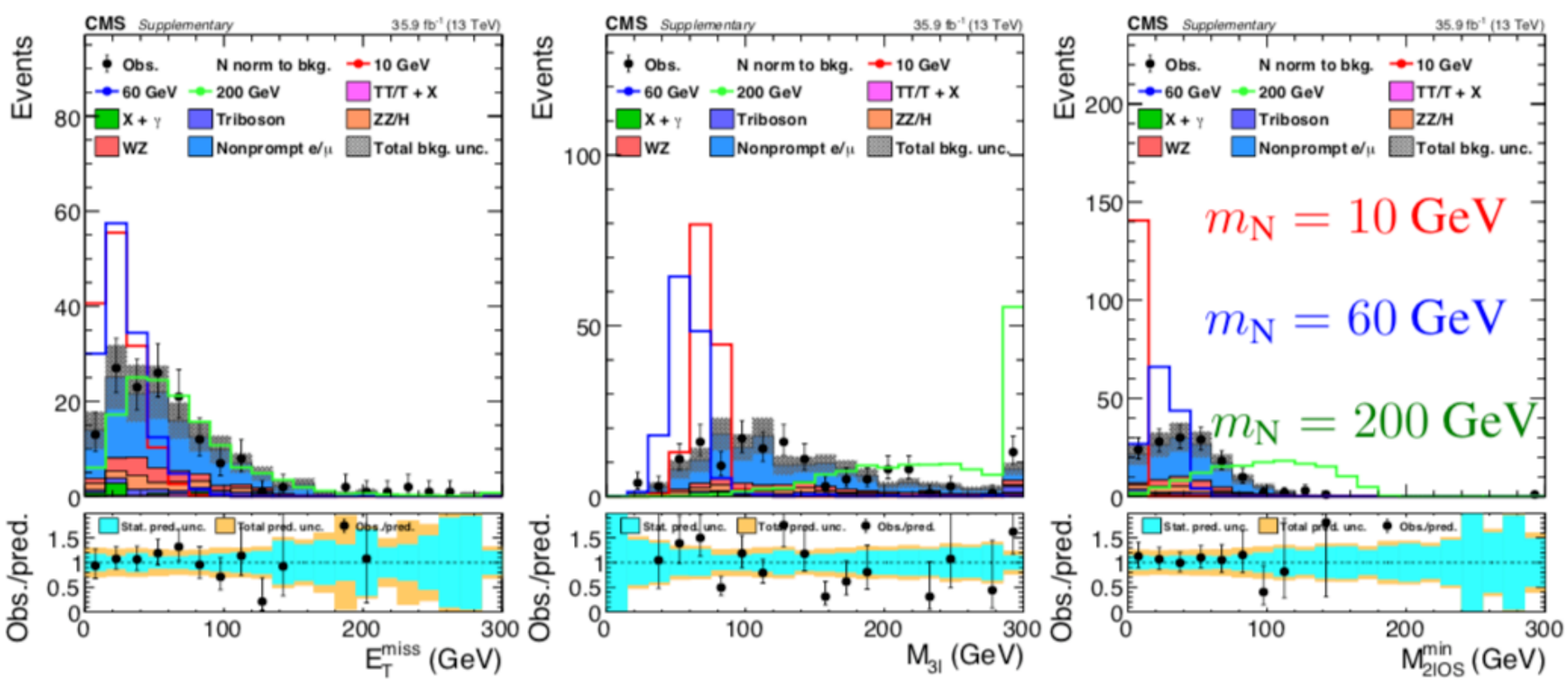
HNLs @ CMS

Search variables: low mass N ($< m_{\mathrm{W}}$)



Key differences wrt previous searches:

- softer leptons (from 5 GeV)
- low $E_{\mathrm{T}}^{\mathrm{miss}} < 75$ GeV
- low $M_{3\ell} < 80$ GeV
- $M_{2\ell\mathrm{OS}}^{\mathrm{min}}$ as a proxy for M_{N}



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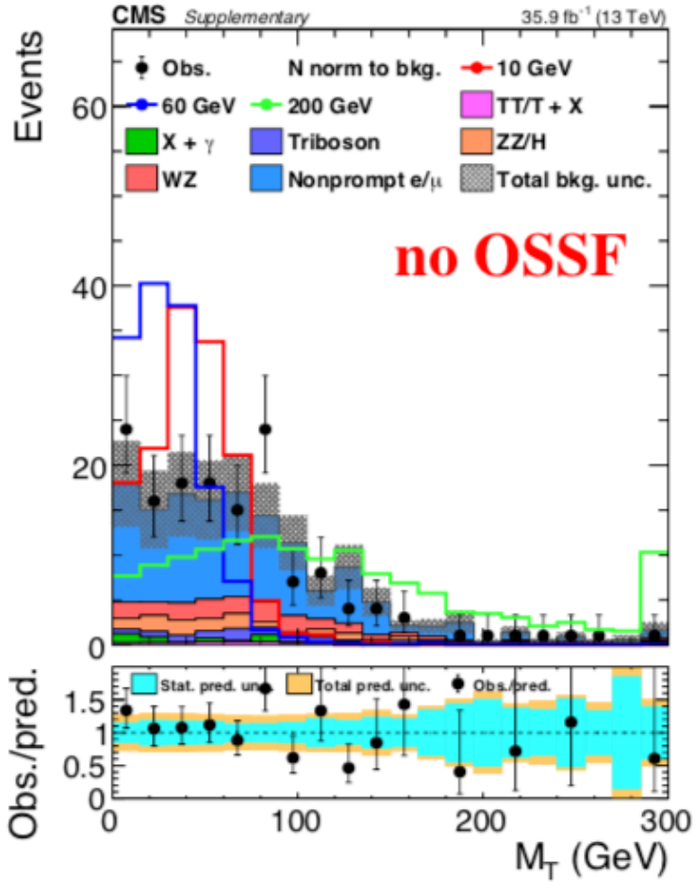
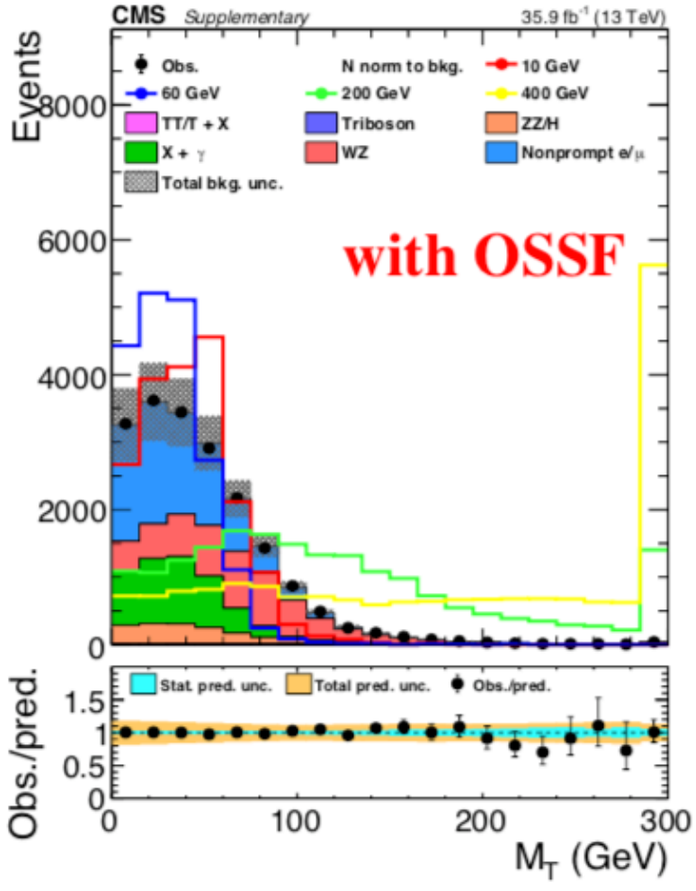
Backup Slides

Search variables: high mass N $(> m_{\mathrm{W}})$

Phase-space is more similar to previous searches, e.g. electroweak SUSY:

- higher lepton p_{T} thresholds ($p_{\mathrm{T}} > 55, 15, 10$ GeV)
- veto a Z boson
- use $M_{2\ell\mathrm{OS}}^{\mathrm{min}}$ and M_{T} shapes to differentiate signal and background
- but do not make any selection on $E_{\mathrm{T}}^{\mathrm{miss}}$





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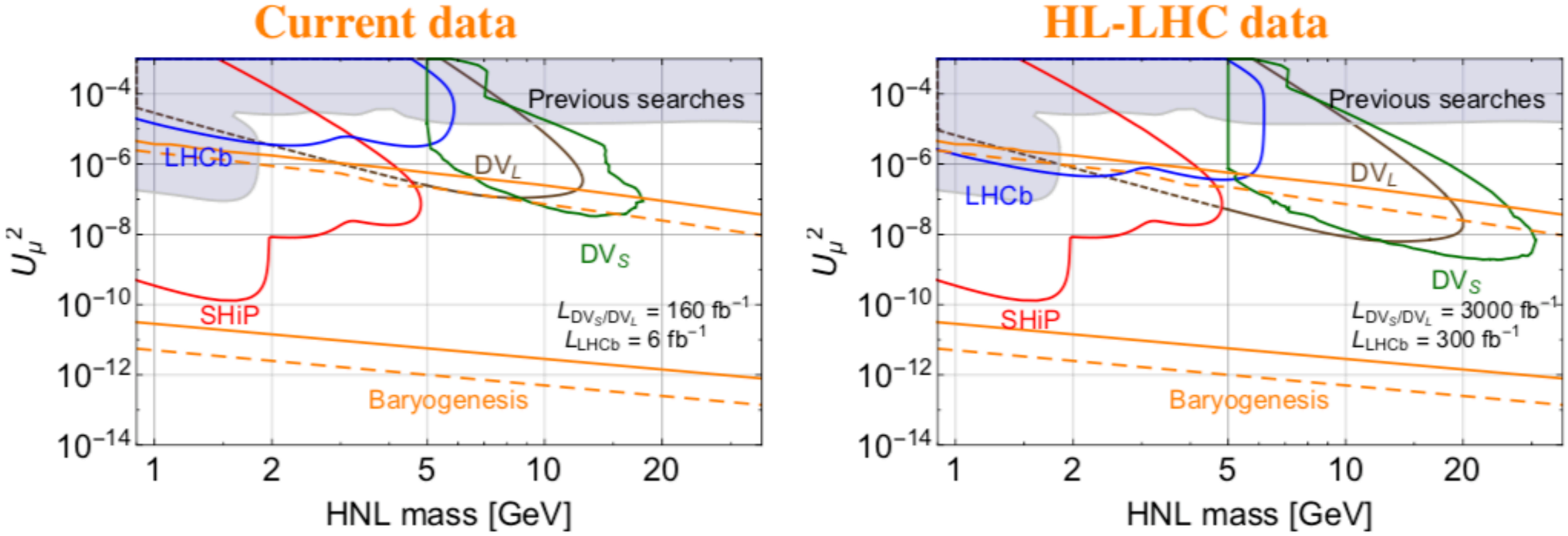
Search for DV



- a displacement kills SM bkg, signal acceptance estimated with gen-level info:
  - **DV$_S$**: a displaced vertex search in a tracker at ATLAS or CMS
  - **DV$_L$**: a search with muon system at CMS (3 m decay volume)
  - **LHCb reach**: an inclusive HNL search in B decays

Boiarska et al. arXiv:1902.04535

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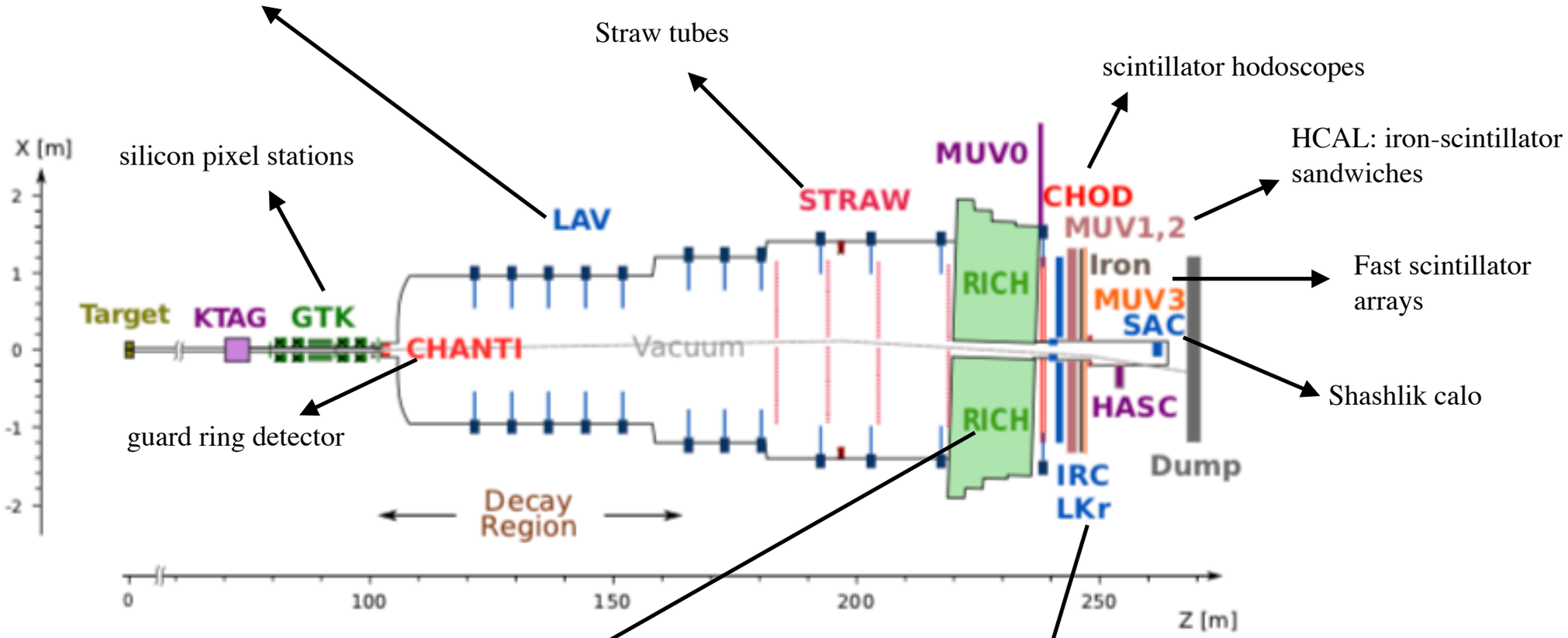
NA62 Detector

Large angle electromagnetic calorimeters

lead glass blocks surround (VETO)



RICH counter filled with Neon
separates π, μ and e up to 40 GeV/c

ECAL filled with liquid krypton

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PBC WG

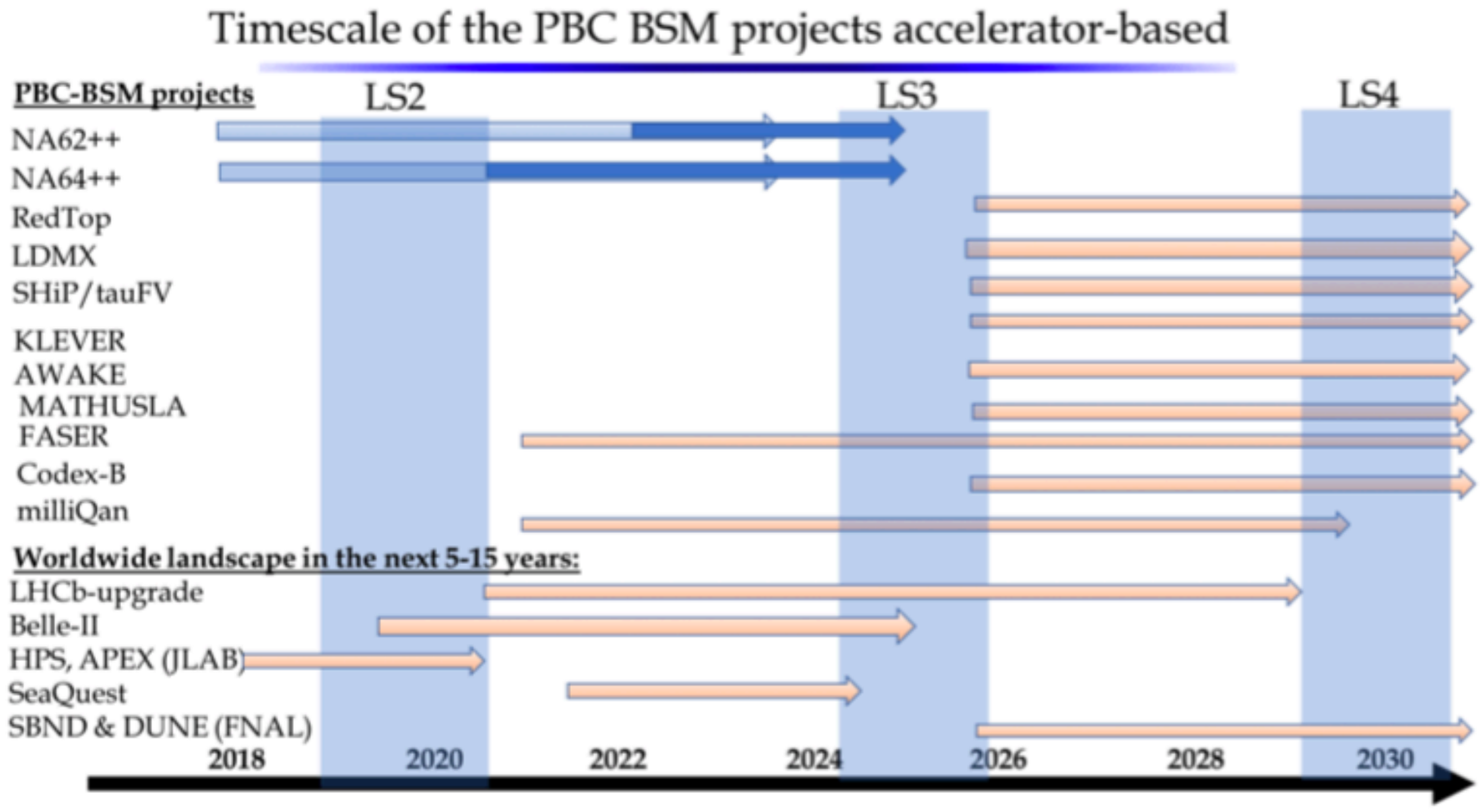

Figure 2: Tentative timescale for PBC projects exploring the MeV-GeV mass range compared to other similar initiatives in the world that could compete on the same physics cases.

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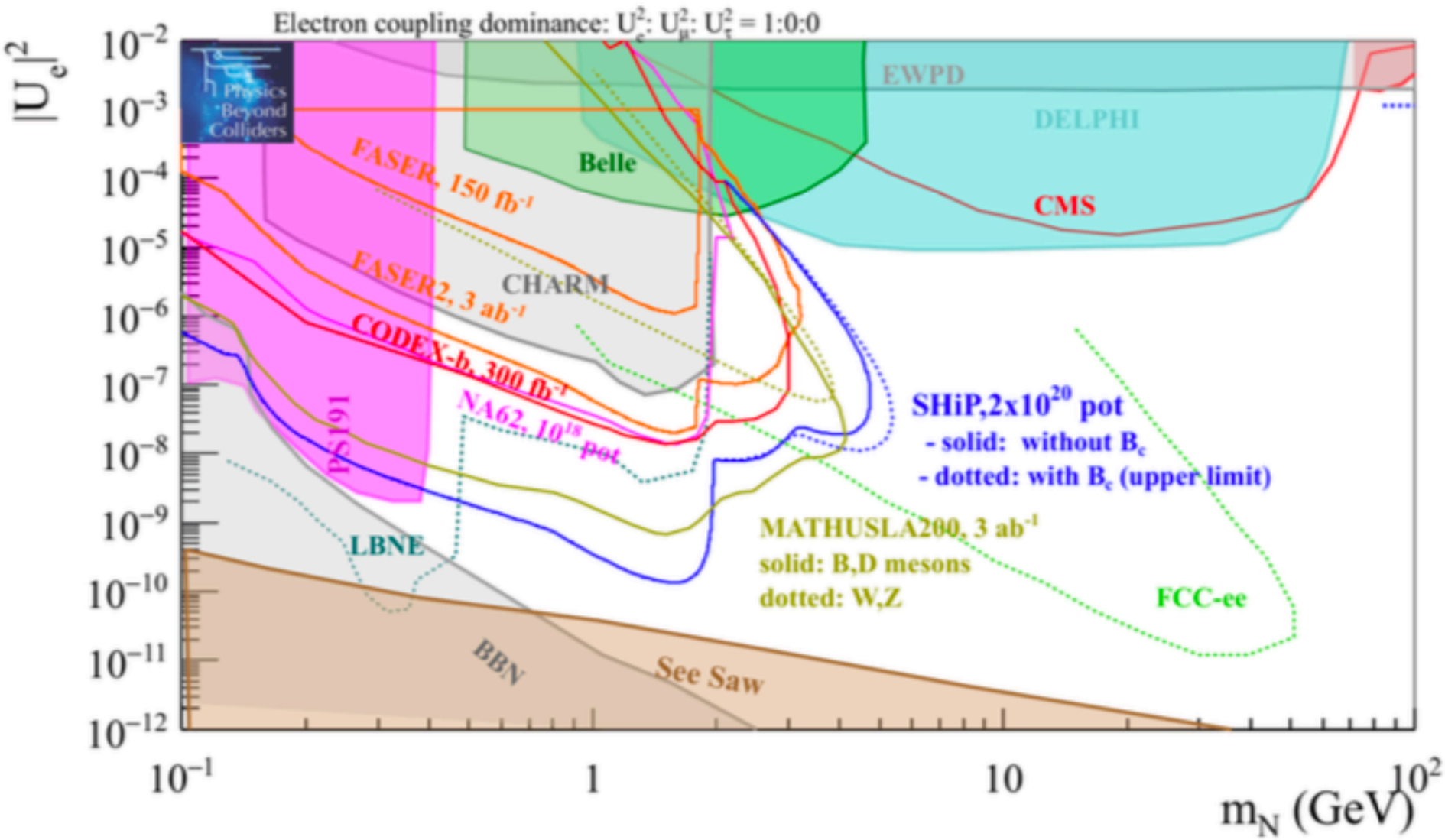
PBC Sensitivity



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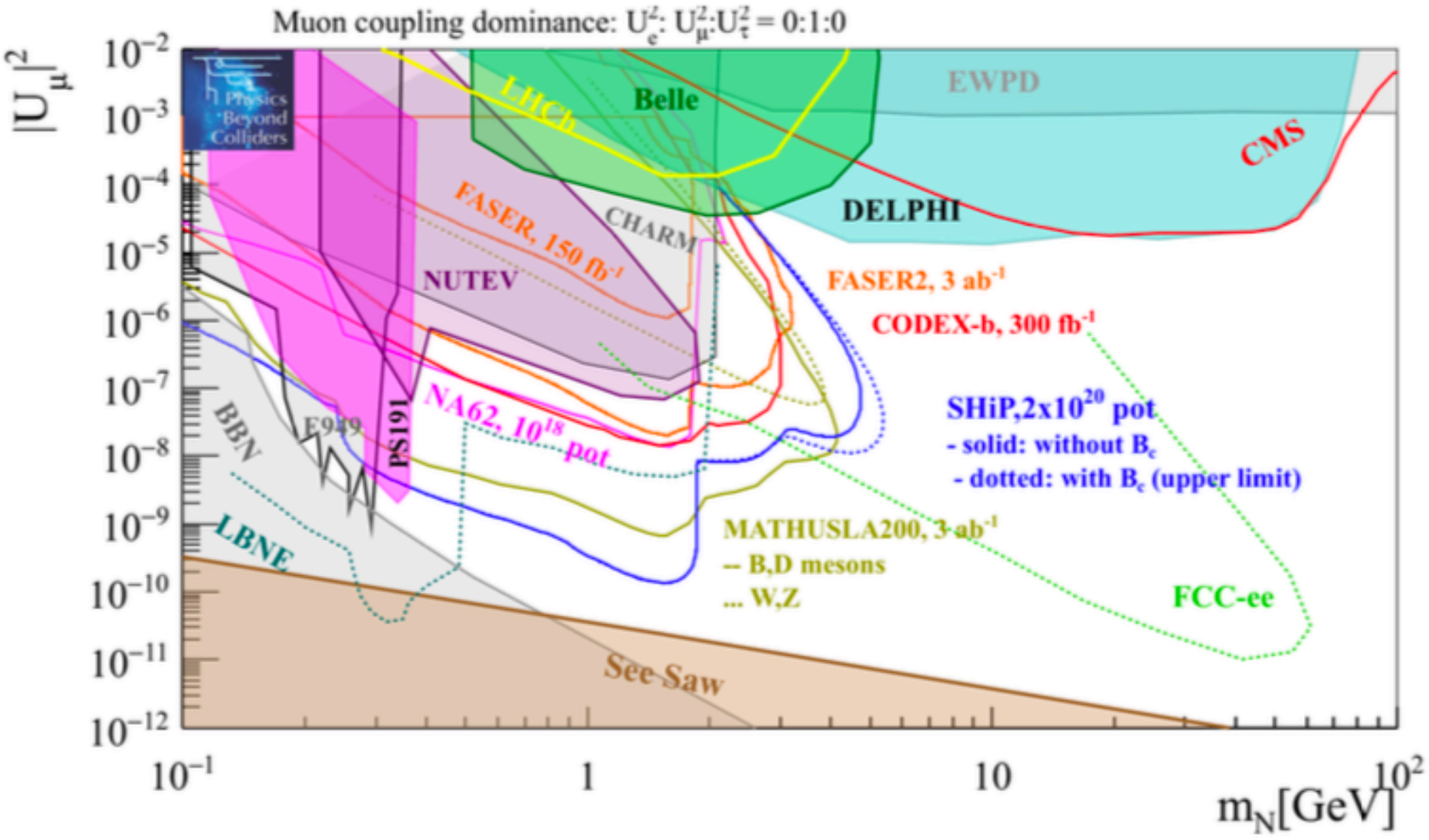
PBC Sensitivity



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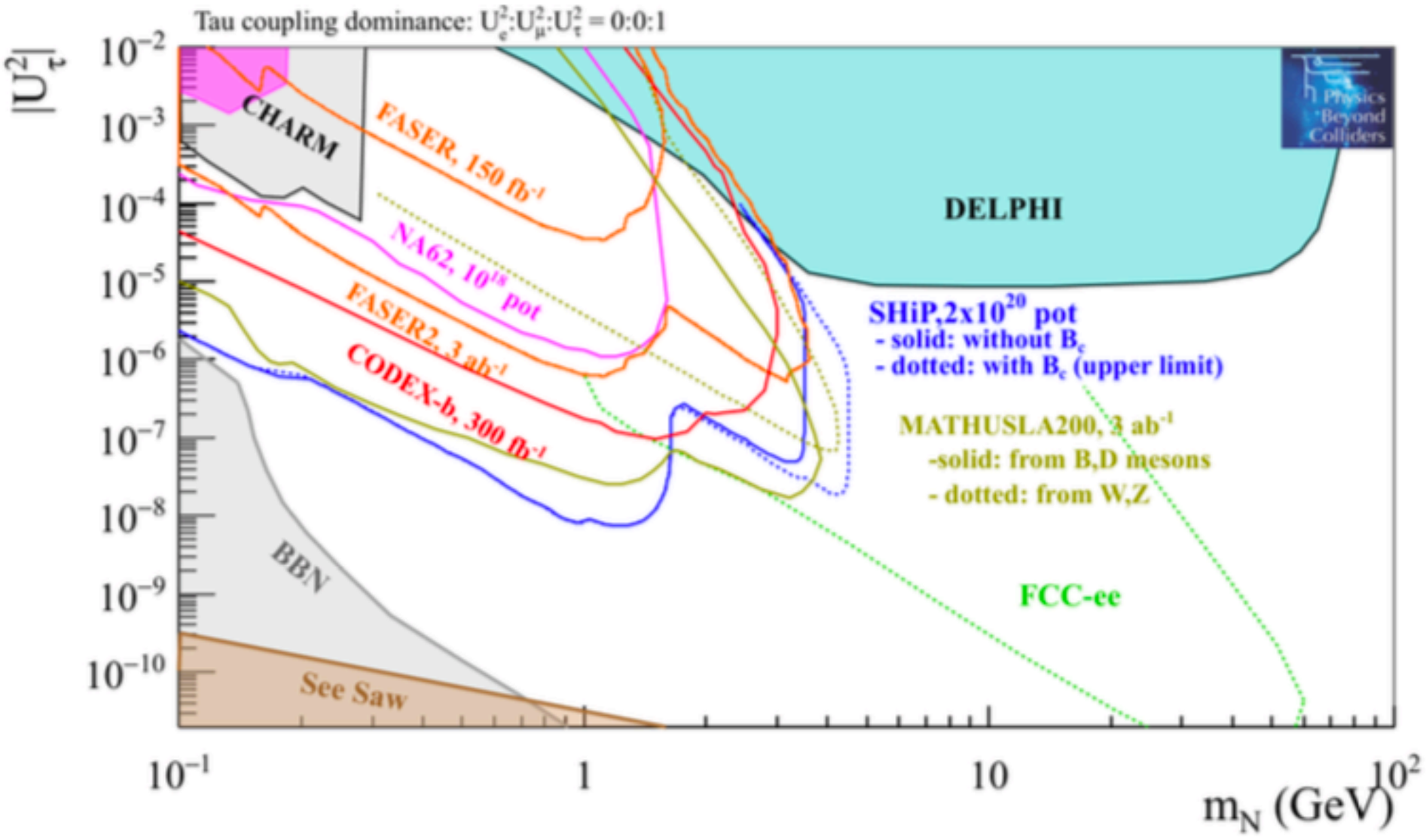
PBC Sensitivity



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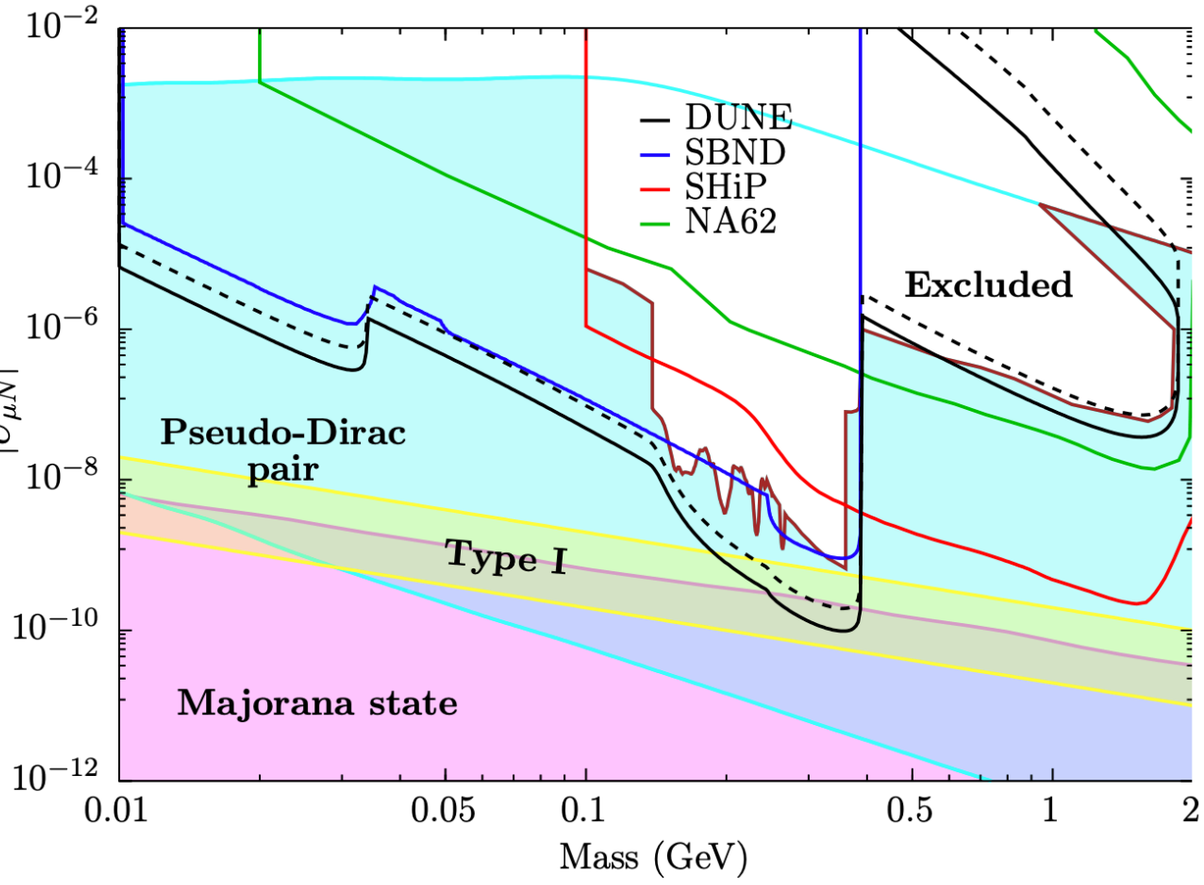
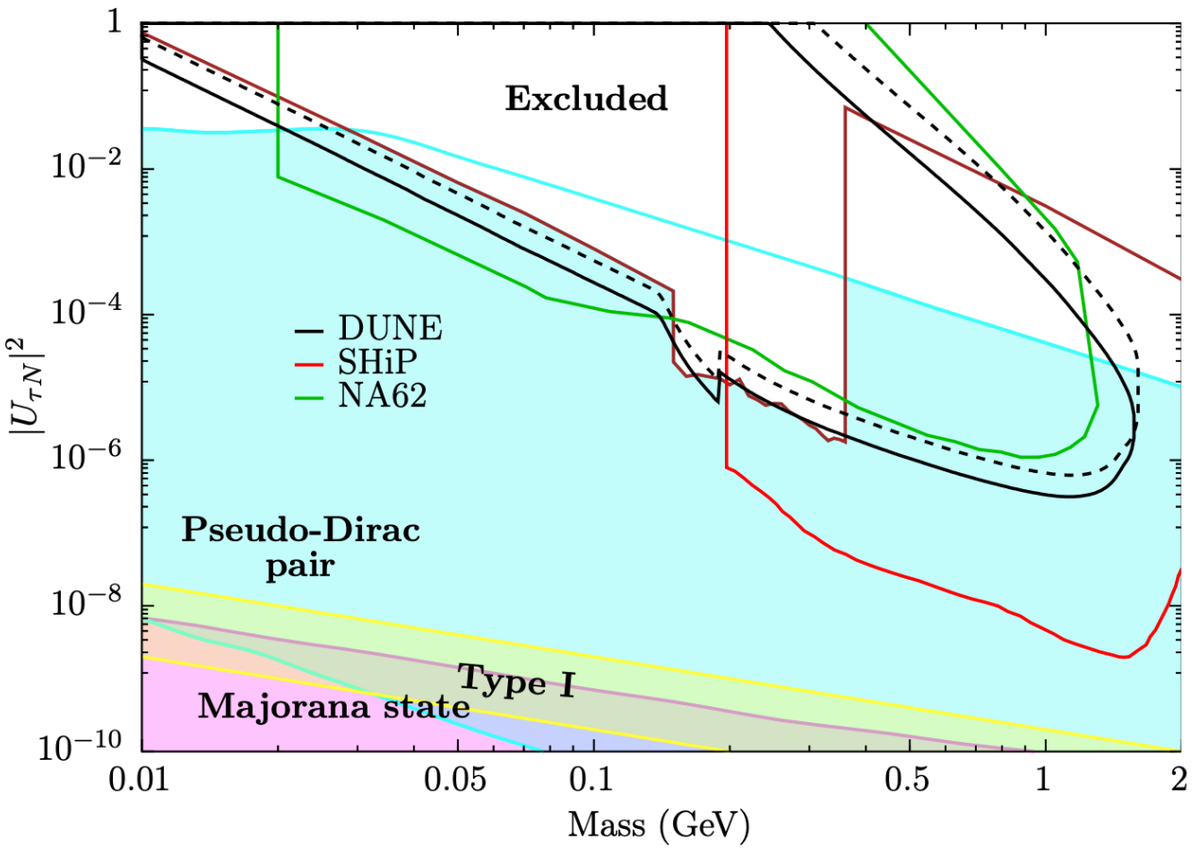
DUNE ND





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SHiP Muon Spectrum

- *Collecting 5x10^{11} proton to validate the muons flux simulations*
- *Analysis of data in progress*

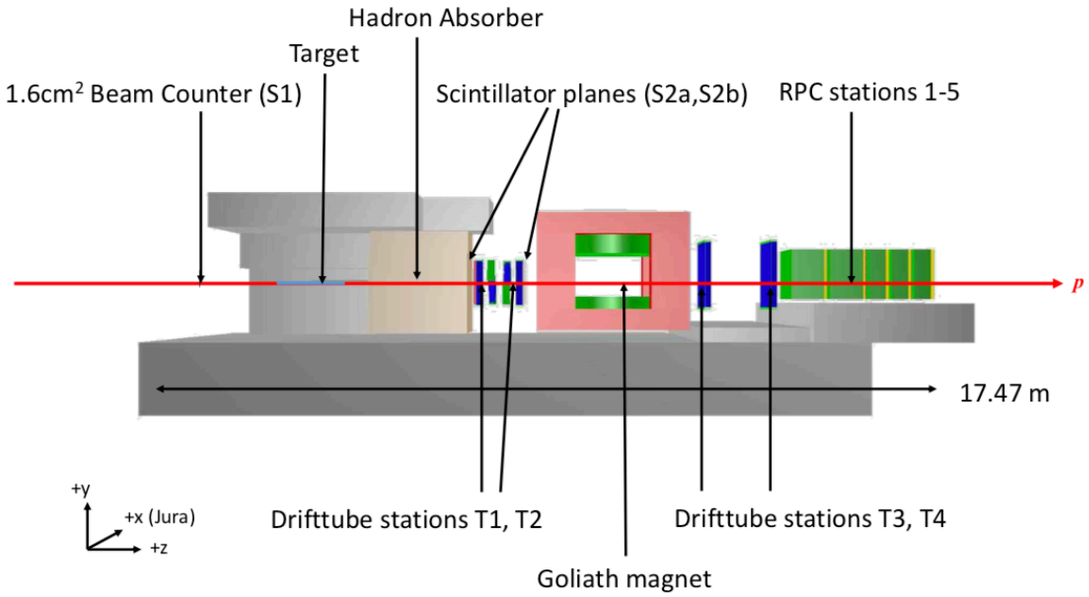

Figure 34: Layout of the spectrometer to measure the μ-flux

Figure 35: Replica of the SHiP target and the experimental setup as seen from behind.

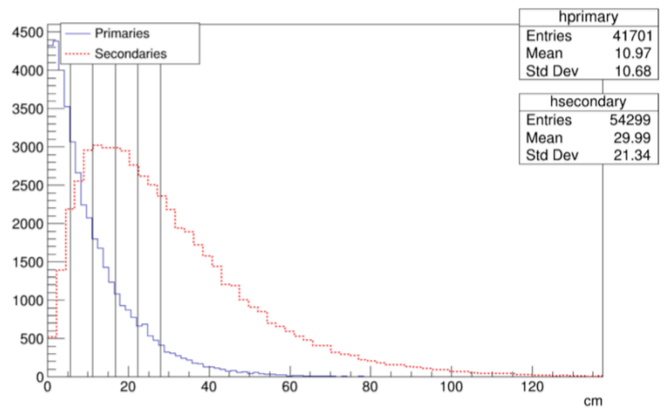

Figure 37: Distribution along the z-axis of charmed hadrons production vertices in a lead target.

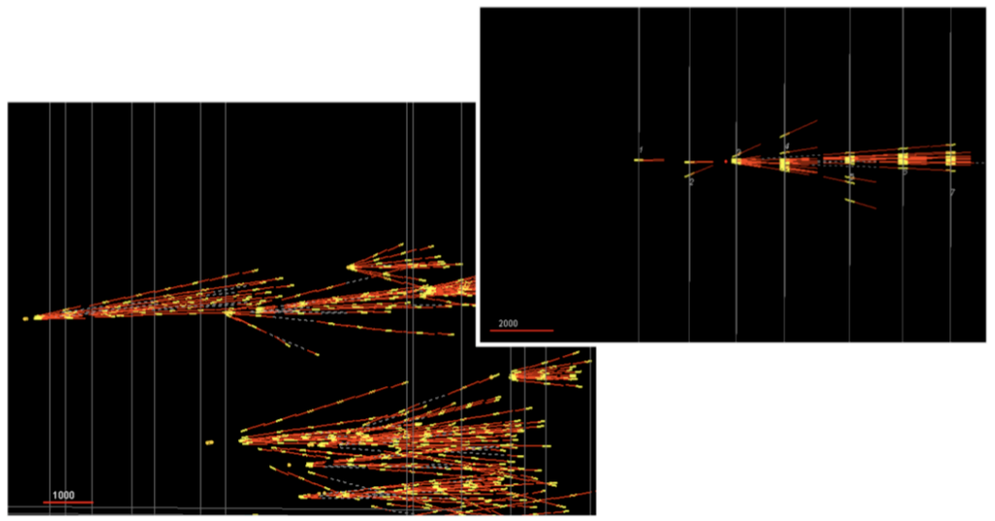

Figure 39: Proton interaction vertices reconstructed in the ECC brick.

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Target

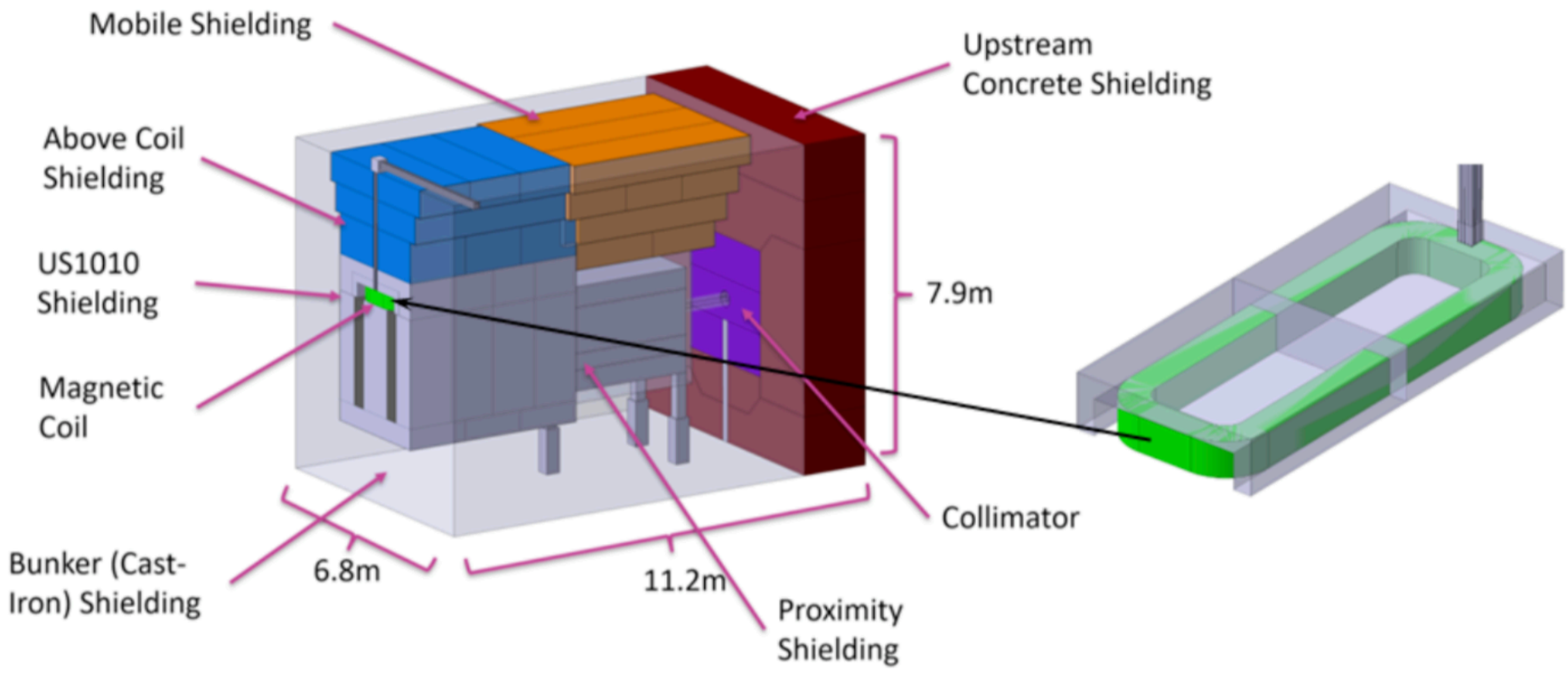

Figure 10: View of the magnetised section of the target shielding with the yoke configuration and the coil. The coil is embedded in specially designed shielding blocks which restrains the coil during operation and which provides crane lifting points should an intervention be necessary.

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Magnet

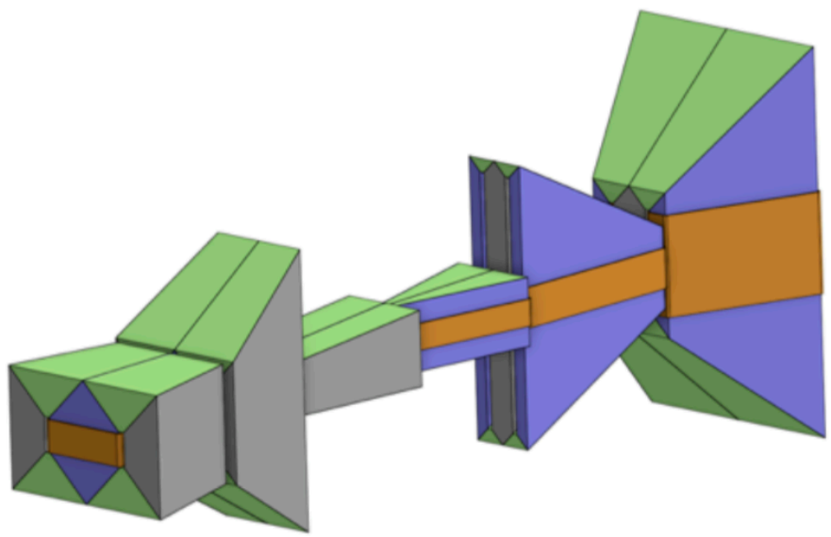

Figure 14: 3D view of the optimised muon magnetic shield.

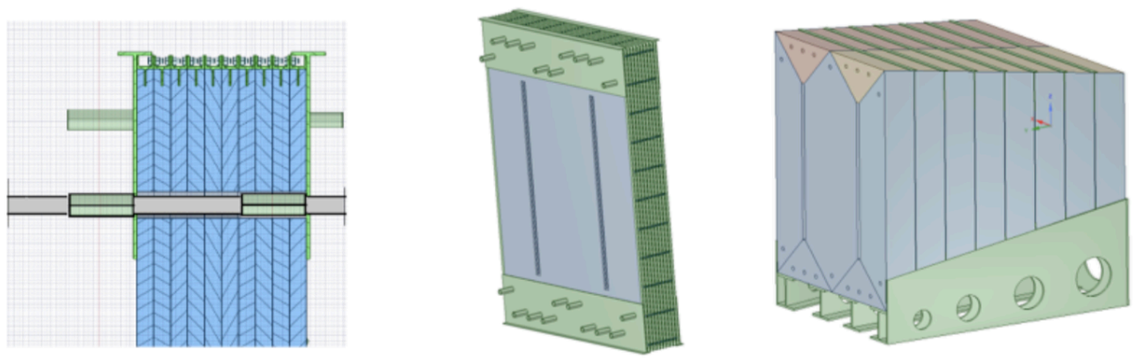

Figure 16: Preliminary mechanical design of magnets. GO steel sheets are packed into sections about 50 mm thick (left). Packs are bolted together into rectangular block about 50 cm thick (left, central). blocks of different dimensions are installed on the support beams (right).

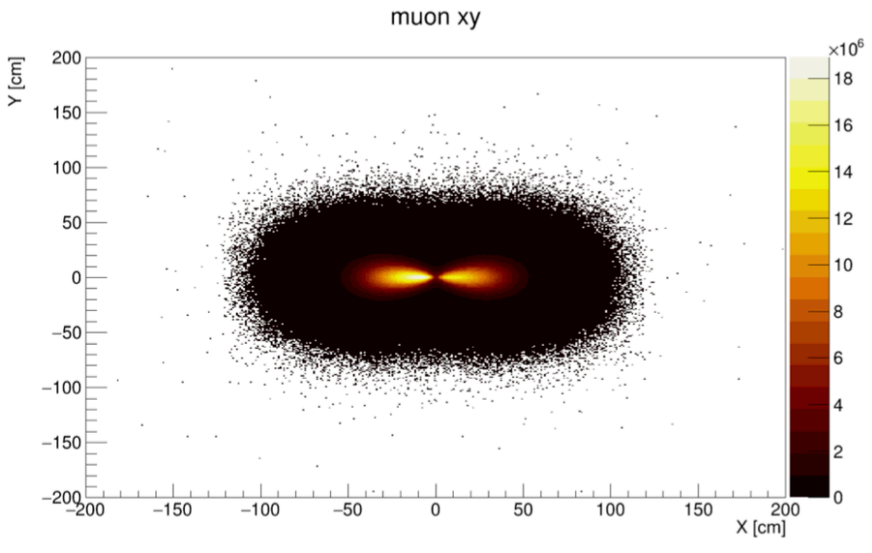

Figure 31: Position of muons leaving the magnetized hadron absorber.

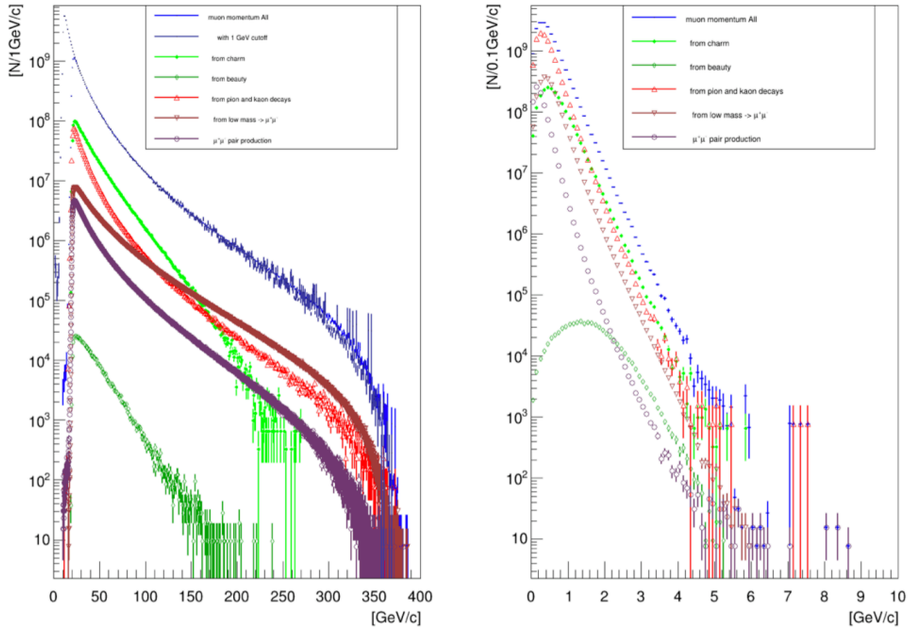

Figure 30: Momentum distributions of muons leaving the hadron absorber, total momentum (left) and transverse momentum (right). Different contributions are shown. The rates are normalized to 5×10^{13} protons on target.

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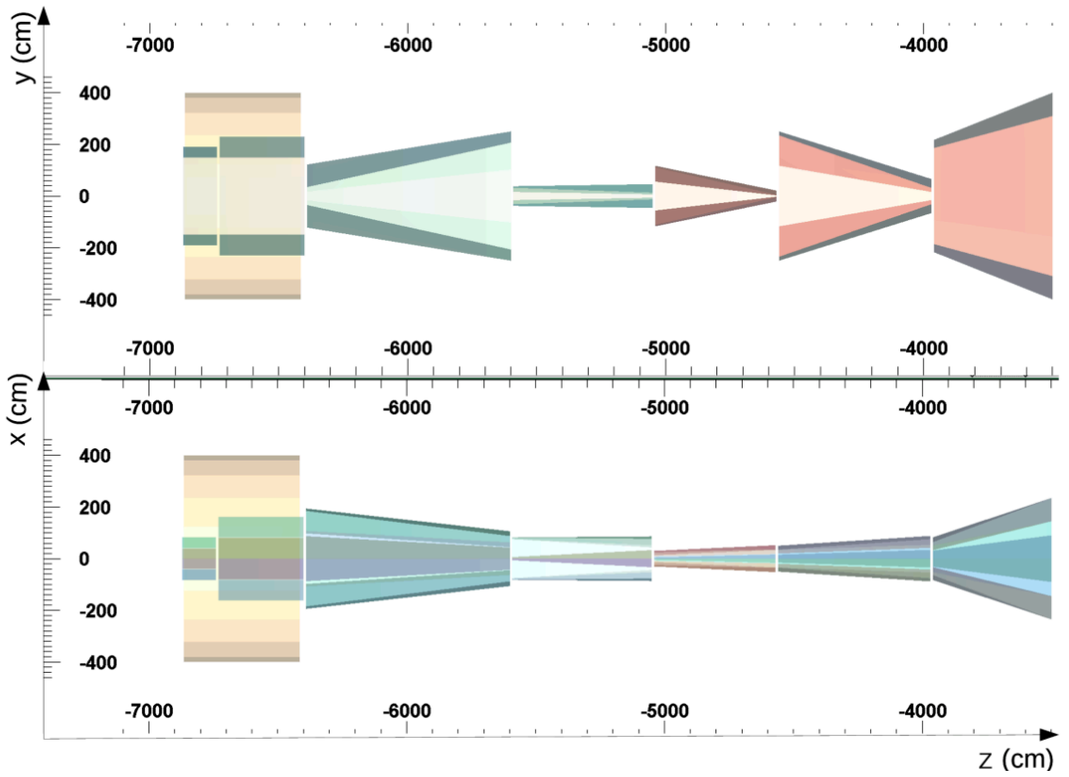
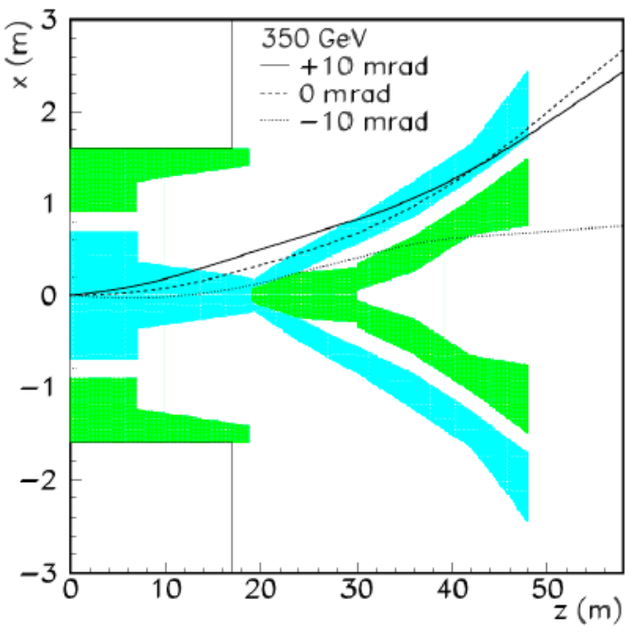
Muon Shield

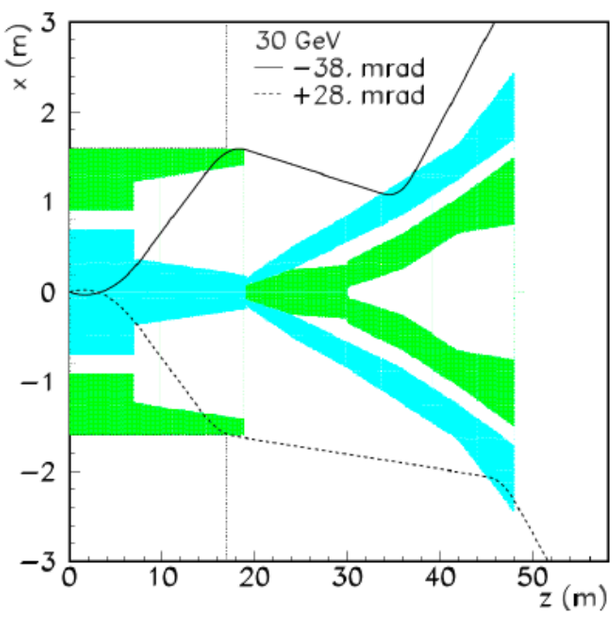
- Global optimisation of the magnetic field (with Machine Learning) still ongoing

Challenging Aspects:
- Narrow separation between field directions
- Aiming to 1.8T to minimize length (with grain oriented steel sheets)
- Have reliable muon sample to optimise with



The active muon shield in the SHiP experiment
JINST 12 P05011 2017





Running the simulation with material

- ~3×10^9 muons/spill with magnets off
- With the magnet on 3×10^5 muons/spill
- ~6.5×10^4 muons/spill with p>3GeV

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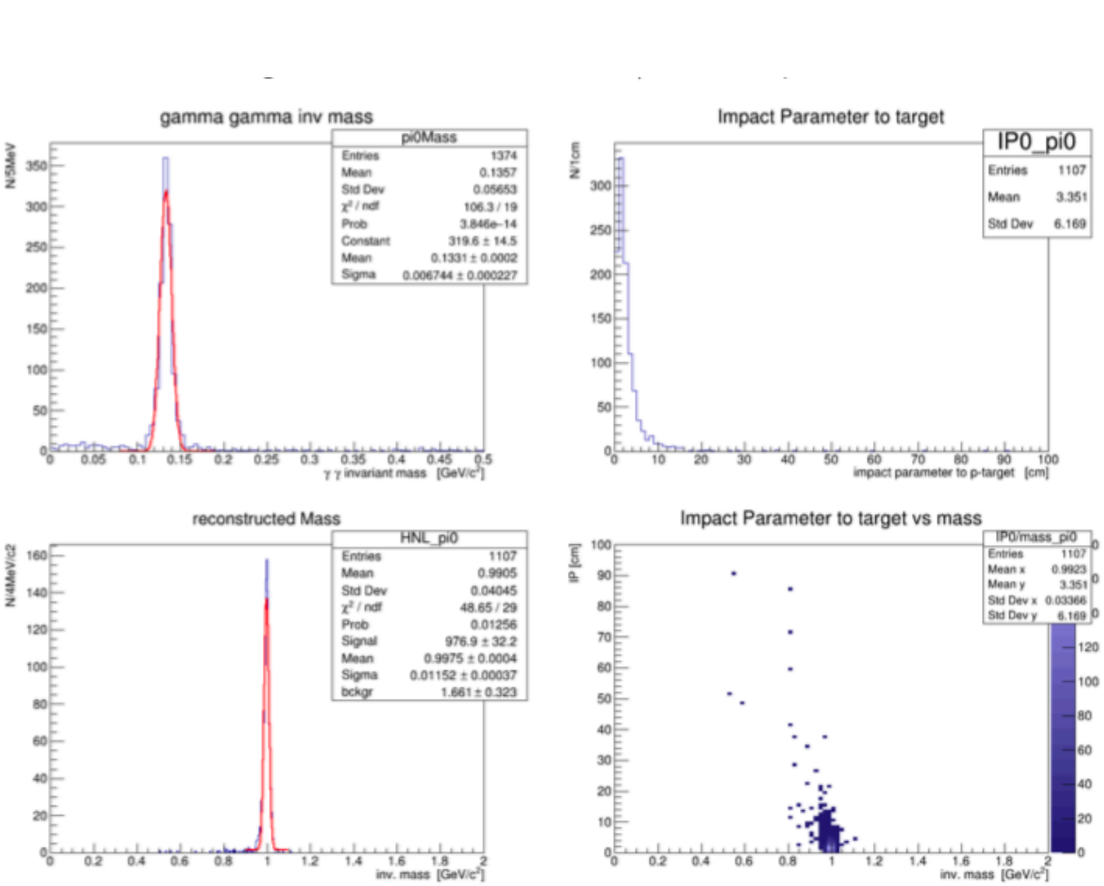

Figure 28: Reconstruction of 1 GeV/c^2 HNL $\to \mu^- \rho^+ (\to \pi^+ \pi^0 (\to \gamma\gamma))$.

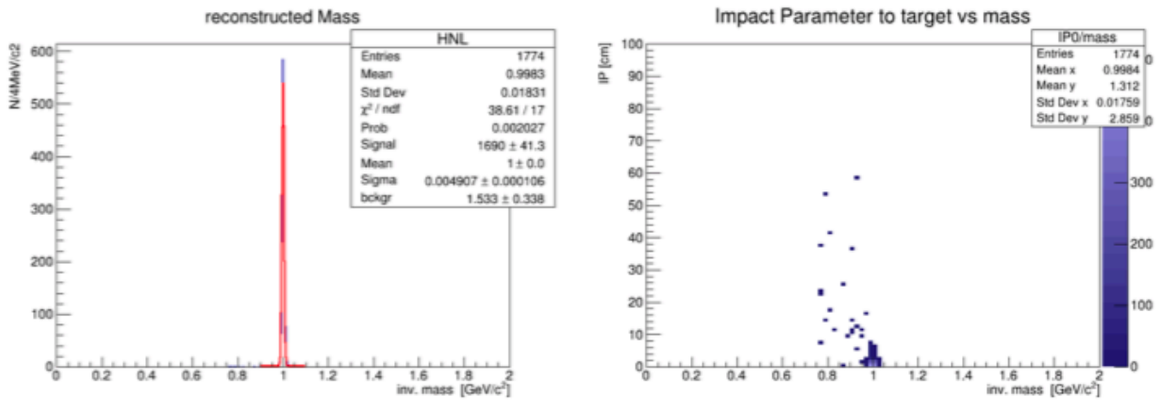

Figure 27: Reconstruction of 1 GeV/c^2 HNL $\to \mu^- \pi^+$.

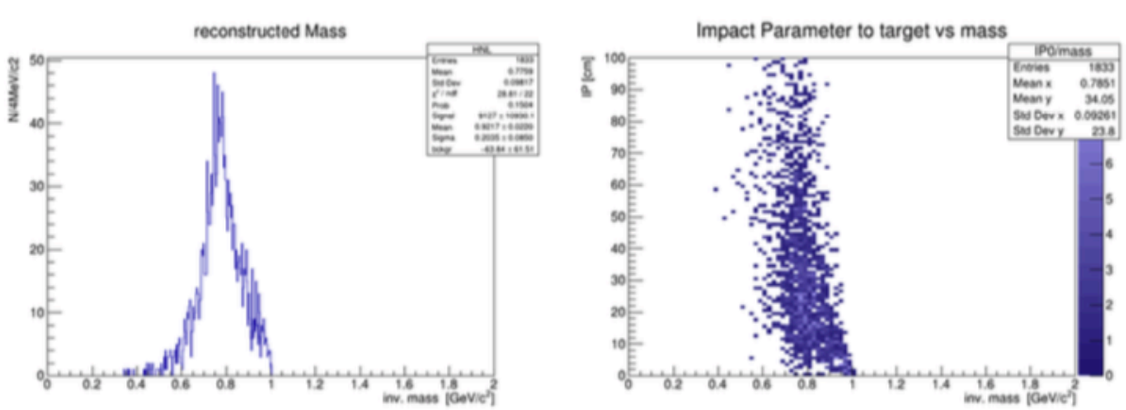

Figure 29: Reconstruction of 1 GeV/c^2 HNL $\to \nu \rho^0 (\to \pi^+ \pi^-)$.

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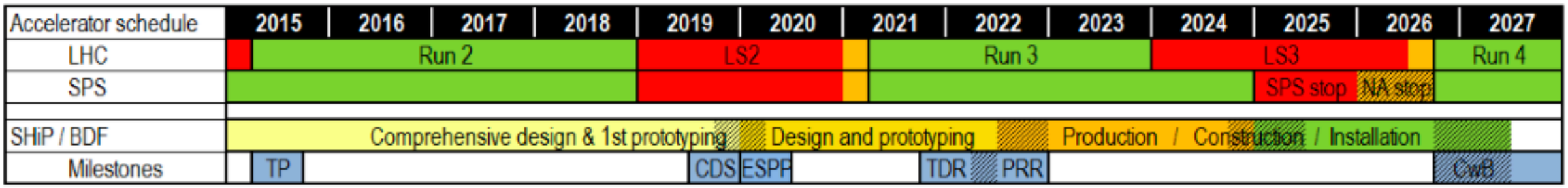

Figure 83: Global project schedule for the Beam Dump Facility and the SHiP detector. CDS, TDR, PRR mark the submission of the Comprehensive Design Study report, submission of Technical Design Reports, and Production Readiness Reviews for the SHiP detector, and CwB marks commissioning with beam.

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