

Search for Hidden Particles



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Thanks to the theory support from M. Shaposhnikov, D. Gorbunov

CHIPP PhD Winter School, Grindelwald
January 23, 2015



i.e. How to fix most SM problems w/o introducing new physic principles

Leptons and quarks get their mass through the Yukawa interaction:

$$\mathcal{L} = m \psi_L^\dagger h \psi_R + c.c.$$

Three Generations of Matter (Fermions) spin $\frac{1}{2}$			
	I	II	III
mass →	2.4 MeV	1.27 GeV	173.2 GeV
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
name →	u up Left Right	c charm Left Right	t top Left Right
Quarks			
	d down Left Right	s strange Left Right	b bottom Left Right
	ν_e electron neutrino Left Right	ν_μ muon neutrino Left Right	ν_τ tau neutrino Left Right
Leptons			
	e electron Left Right	μ muon Left Right	τ tau Left Right
Bosons (Forces) spin 1			
	Z^0 weak force Left Right	W^+ weak force $+1$ Left Right	H Higgs boson spin 0
	0.511 MeV	105.7 MeV	1.777 GeV
	-1	-1	± 1

Neutrinos need a right-handed partner to get their masses like the other SM fermions!



i.e. How to fix most SM problems w/o introducing new physic principles

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Bosons (Forces) spin 1				
	ν_e N_1 electron neutrino	ν_μ N_2 muon neutrino	ν_τ N_3 tau neutrino	Z^0 weak force Left Right
	0.511 MeV	105.7 MeV	1.777 GeV	W^\pm weak force Left Right
	-1	-1	-1	80.4 GeV
				H^0 Higgs boson spin 0

Neutrinos need a right-handed partner to get their masses like the other SM fermions!

Three extra N field could exist (*sterile neutrinos*). They would be $SU(2)$ singlets, as they are still unobserved.

Sterile neutrinos would mix to $\nu_{e,\mu,\tau}$ with very small couplings $U_{e,\mu,\tau}^2$.

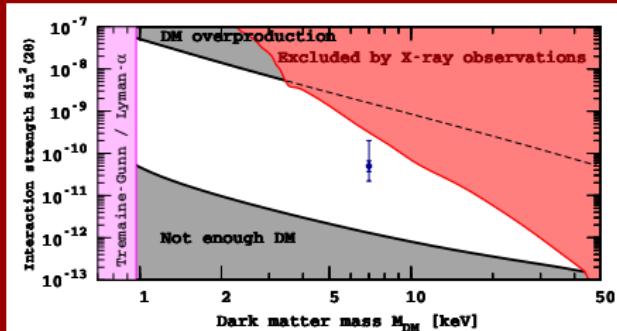


i.e. How to fix most SM problems w/o introducing new physic principles

Suitable values of m_N and U_f^2 allow to simultaneously explain:

- ν oscillation: two massive states N_2 , N_3 give mass to active νs through the Seesaw mechanism
- dark matter: N_1 , likely to have mass in the keV region, could have a lifetime greater than the age of the Universe
- matter-antimatter asymmetry: baryogenesis induced by leptogenesis if N has a Majorana mass term.

Two recent observations provide hints of the **existence of a 7 keV dark matter (N_1) candidate** [E. Bulbul et al. 2014] [A. Boyarsky et al. 2014].



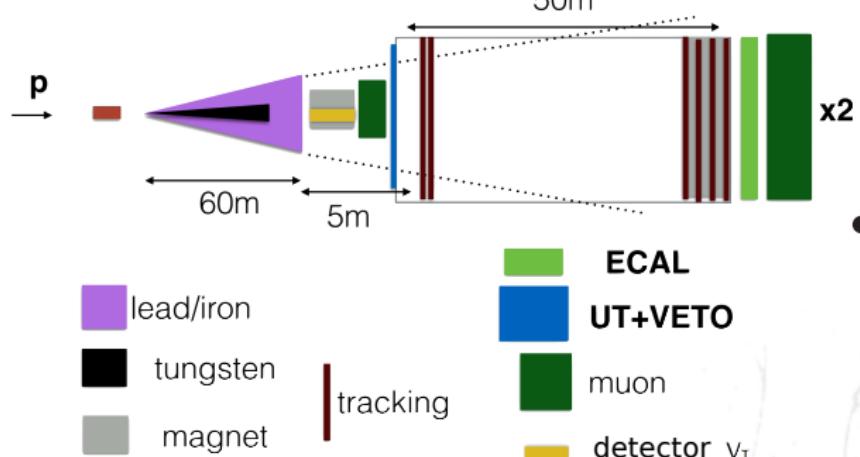


Search for Hidden Particles [W. Bonivento et al. 2013]

Small hints of a 7 keV DM candidate are not enough to confirm or rule out the ν MSM: need to look for N_2, N_3 !

A proposed fixed-target experiment at the SPS (400 GeV protons) aimed at the study of **long-lived weakly interacting particles**.

- $\times 10\,000$ statistical sensitivity to Heavy Neutral Leptons & co.
- $\times 200$ statistical sensitivity to ν_T



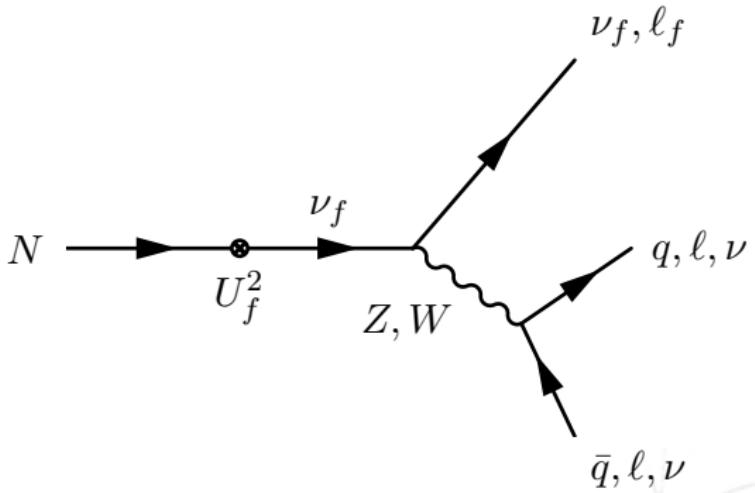
SHiP

HNL mixing to Standard Model

i.e. How to detect sterile neutrinos



HNLs can be produced in decays where a ν is replaced by a N (kinetic mixing, low BR). Main neutrino sources in SHiP: c and b mesons.



They can then decay again to SM particles through **mixing** (U^2) with a SM neutrino. This (now **massive**) neutrino can decay to a large amount of final states through emission of a Z^0 or W^\pm boson.

Estimating SHiP's physics reach

HNL production \times Experimental acceptance



- Number of detected HNL events:

$$\Phi(p.o.t) \times \sigma(pp \rightarrow NX) \times \mathcal{P}_{vtx} \times \mathcal{BR}(N \rightarrow \text{visible}) \times \mathcal{A}$$

with

$$\sigma(pp \rightarrow NX) \propto \chi_{cc}, \chi_{bb}, U_f^2$$

$$\mathcal{BR}(N \rightarrow \text{visible}) \propto U_f^2$$

- HNL production:
 - χ_{cc}, χ_{bb} from simulations
 - $\mathcal{BR}(m_N, U_f^2)$ parametrised according to theory [Gorbunov, Shaposhnikov 2007]
- Now we only need to compute the **daughters acceptance** \mathcal{A} :
 - HNLs kinematics obtained from simulation
 - every decay channel with **detectable** daughters is simulated

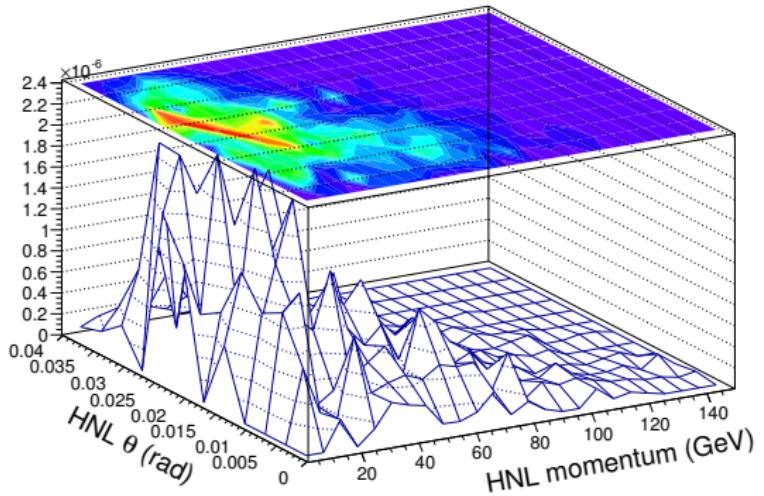
Estimating SHiP's physics reach



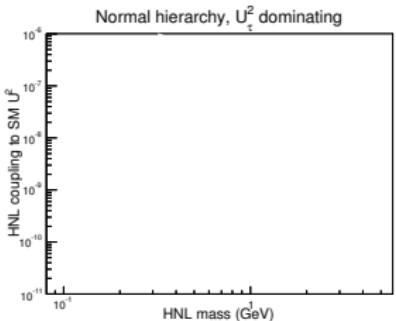
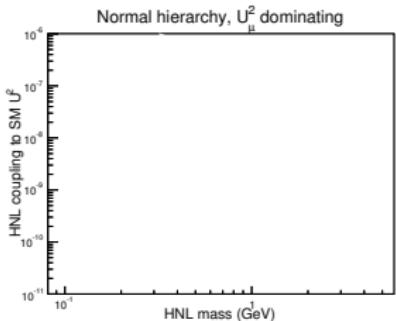
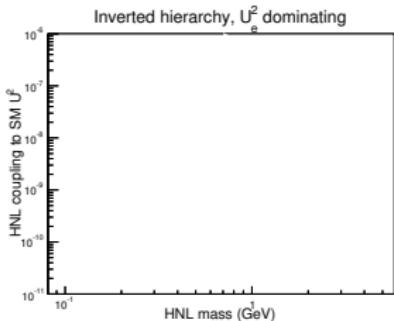
$$\Phi(p.o.t) \times \mathcal{BR}(pp \rightarrow NX) \times \mathcal{P}_{vtx} \times \mathcal{BR}(N \rightarrow \text{visible}) \times \mathcal{A}$$

- Pythia8 used to retrieve the spectrum of c and b mesons in SHiP.
Heavy neutrinos produced in kinematically-allowed decay chains.
- HNL spectra are re-weighted by the probability that HNLs decay with a vertex inside SHiP's tracking volume: $\mathcal{P}_{vtx} \sim \int_{SHiP} e^{-l/c\gamma\tau} dl$

Weighted PDF for model 2, $m_N = 1.8$ GeV, $U_\mu = 10^{-9}$



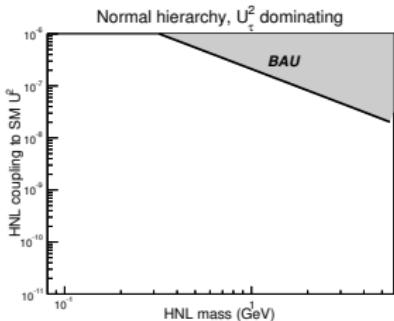
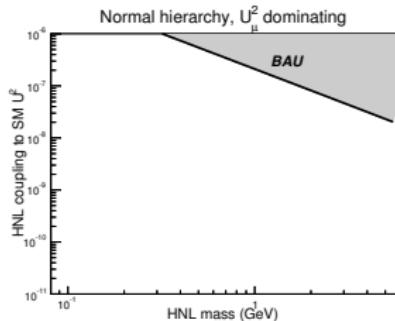
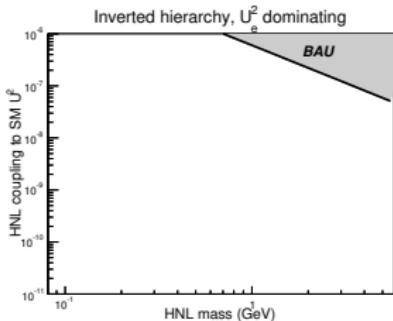
The parameter space of the ν MSM



Results must be interpreted according to the **hierarchy of ν masses** and to the relative strength of the U_e^2 , U_μ^2 and U_τ^2 couplings.

Three “extreme” benchmark models [Gorbunov, Shaposhnikov 2007] will be shown.

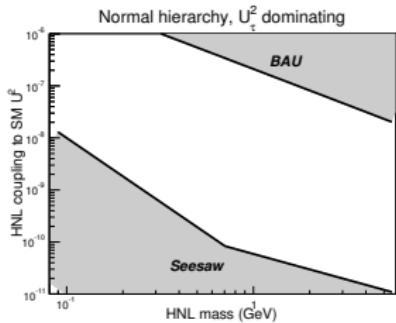
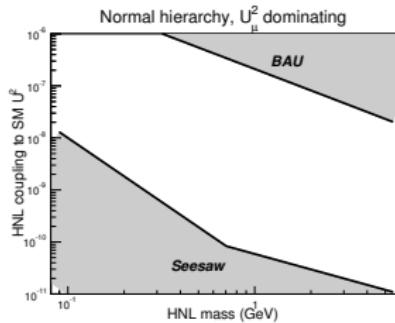
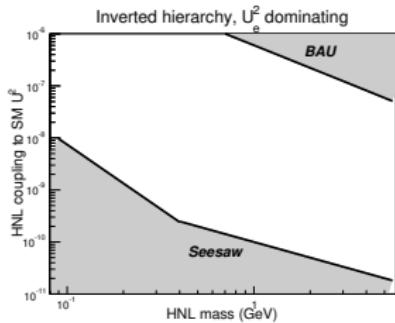
The parameter space of the ν MSM



The **cosmologically interesting** parameter space is limited by physical constraints:

1. by the requirement that sterile neutrinos explain the **matter-antimatter asymmetry** (baryogenesis induced by leptogenesis)

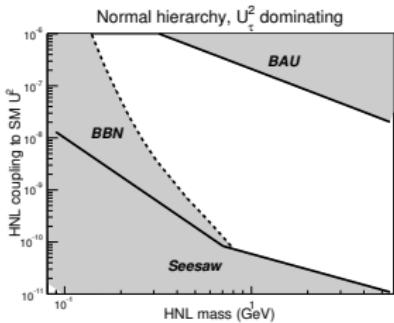
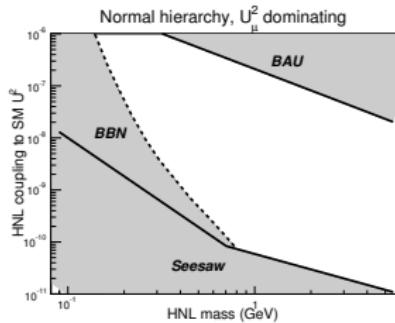
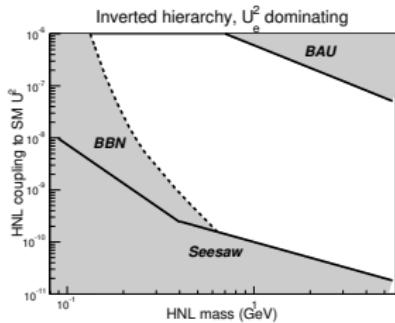
The parameter space of the ν MSM



The **cosmologically interesting** parameter space is limited by physical constraints:

2. by the **Seesaw** mechanism: adding an extra singlet neutrino field allows to extend the Lagrangian with a Majorana mass term. The active and sterile neutrino masses are then inversely proportional

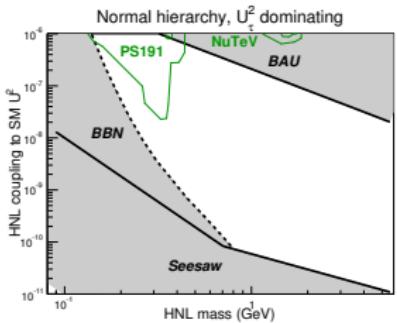
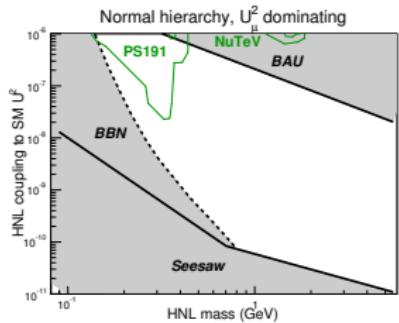
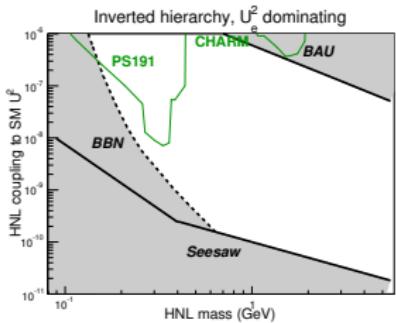
The parameter space of the ν MSM



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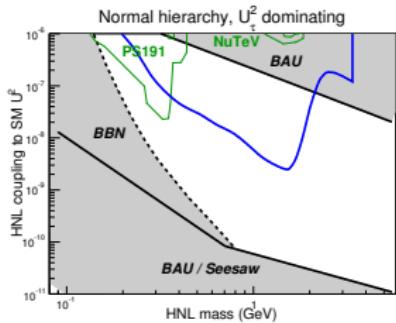
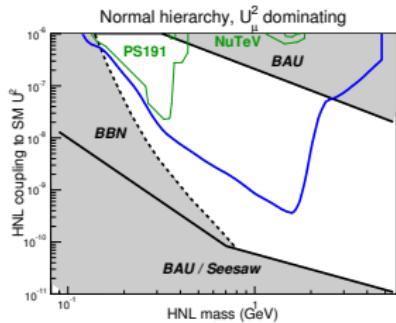
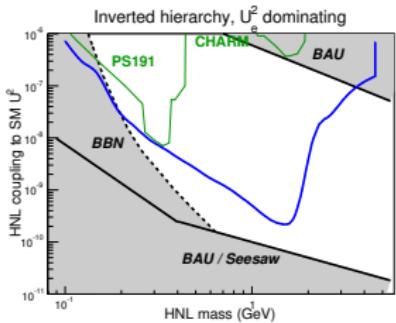
3. at low M_N , by **Big Bang Nucleosynthesis** constraints (observations of the relative abundance of primordial nuclei)

The parameter space of the ν MSM



Searches already performed by e.g. PS191, CHARM, NuTeV, but **most** of the parameter space is **still unexplored!**

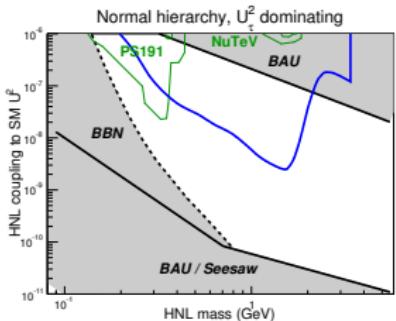
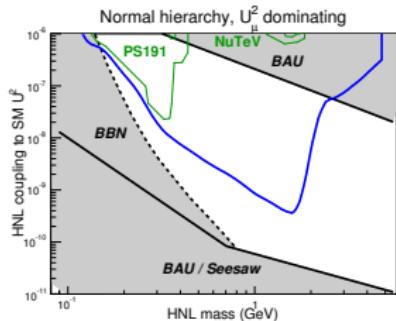
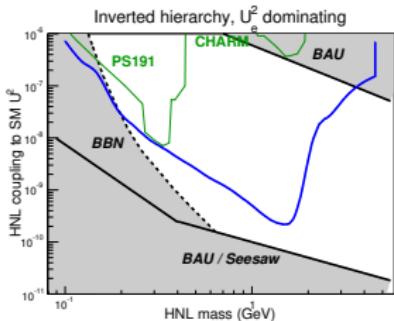
The parameter space of the ν MSM



Searches already performed by e.g. PS191, CHARM, NuTeV, but **most** of the parameter space is **still unexplored!**

Blue lines: area of the ν MSM parameter space that can be ruled out if no event is observed in SHiP (90% C.L.).

The parameter space of the ν MSM



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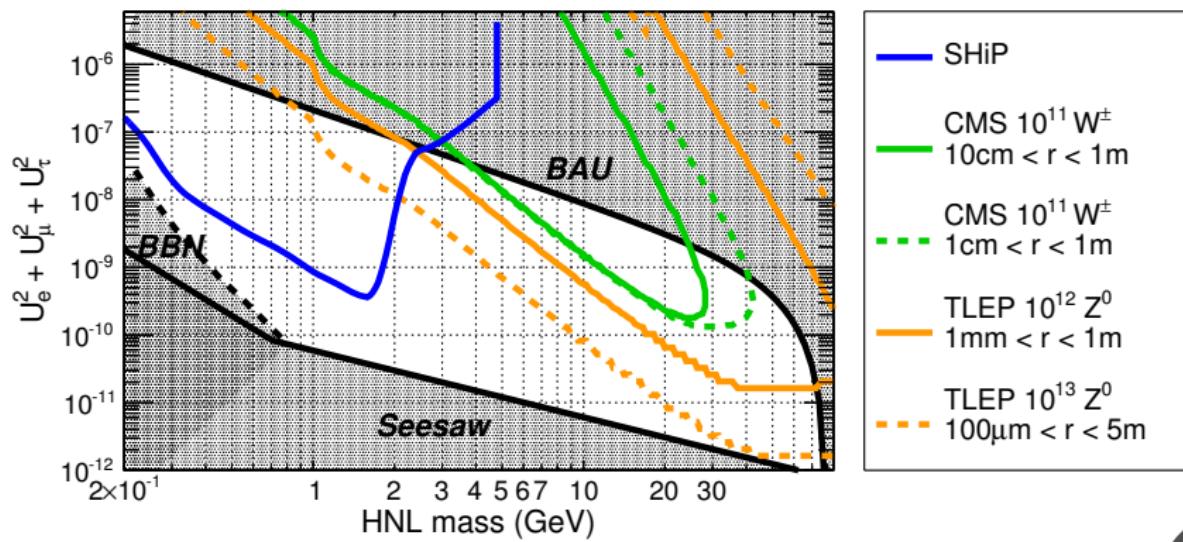
- the remaining area below $m_N \simeq 350$ keV can be covered by NA62.
- what about $m_N \gg 1$ GeV?

Extending the search to higher mass



i.e. How to close the ν MSM parameter space

- Possible N sources for $m_N \gg 1$ GeV: W^\pm, Z^0
- $W \rightarrow \ell N$ at LHC: extremely large BG, difficult triggering/analysis.
- $Z \rightarrow \nu N$ at e^+e^- collider [A. Blondel et al. 2014]: clean signature, low BG.



Extending the search to higher mass

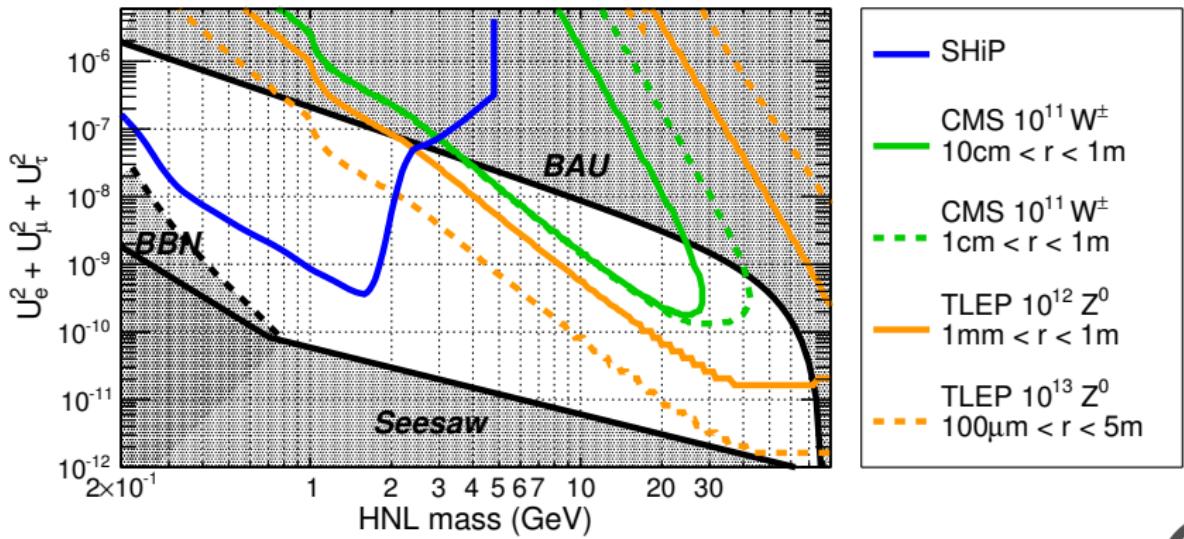
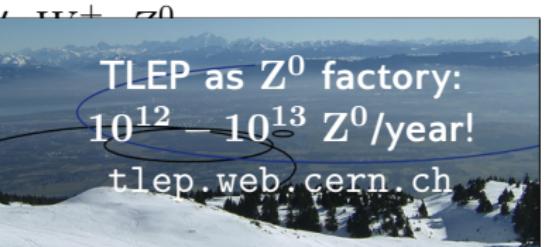
i.e. How to close the ν MSM parameter space



- Possible N sources for $m_N \gg 1$ GeV

- $W \rightarrow \ell N$ at LHC: extremely large BG

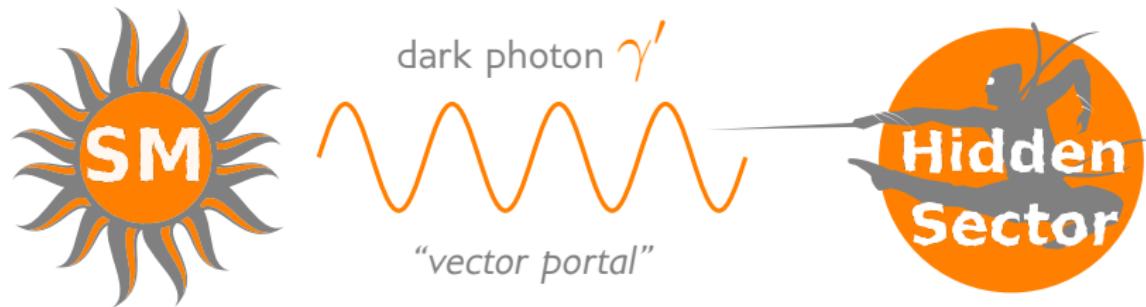
- $Z \rightarrow \nu N$ at e^+e^- collider [A. Blondel et al.]
low BG.



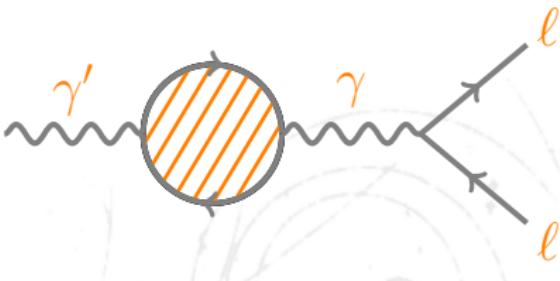
The vector portal to the hidden sector



Most BSM models predict a set of SM-neutral unobserved particles that do not interact with SM except through a “messenger” particle.

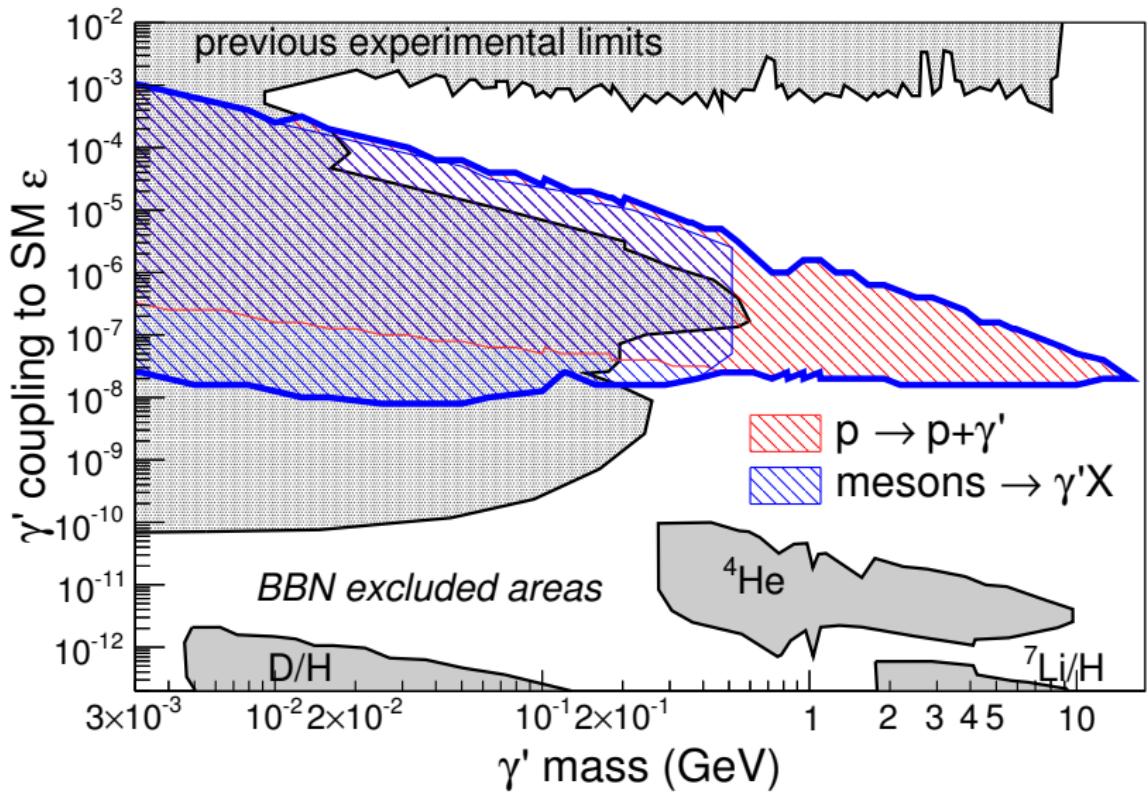


Sensitivity to γ' investigated as for HNLs: γ' mixes to γ through loops of particles charged under both the SM and HS. Extra production mode: **proton bremsstrahlung** [S. Andreas 2013] [Blümlein, Brunner 2013].



SHiP's contribution to the vector portal

Previous limits and cosmological constraints from [A. Fradette et al. 2014]



Conclusions



- Three fundamental questions left open by the Standard Model can be answered by the ν MSM, with no need for new physic principles
 - searches for N_2, N_3 are necessary to confirm or rule out the ν MSM
 - design of the dedicated SHiP experiment
- SHiP's discovery potential was investigated
 - most of the parameter space can be covered by SHiP ($m_N < 2 - 3$ GeV) and by future Z factories ($m_N > 3$ GeV)
- SHiP can be used to look for signatures of other BSM physics
 - SHiP's physics reach into the vector portal determined

A scenic winter landscape featuring a large, rugged mountain peak in the background. In the foreground, there's a church with a tall steeple and several houses with snow-laden roofs. Bare trees are scattered throughout the scene, their branches heavy with snow.

Thanks!

References I



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- [2] T. Asaka, S. Blanchet, and M. Shaposhnikov. "The nuMSM, dark matter and neutrino masses". In: *Phys.Lett.* B631 (2005), pp. 151–156.
- [3] M. Bicer et al. "First Look at the Physics Case of TLEP". In: *JHEP* 1401 (2014), p. 164. DOI: 10.1007/JHEP01(2014)164. arXiv: 1308.6176 [hep-ex].
- [4] M. Bicer et al. "First Look at the Physics Case of TLEP". In: *JHEP* 1401 (2014), p. 164. DOI: 10.1007/JHEP01(2014)164. arXiv: 1308.6176 [hep-ex].

References II

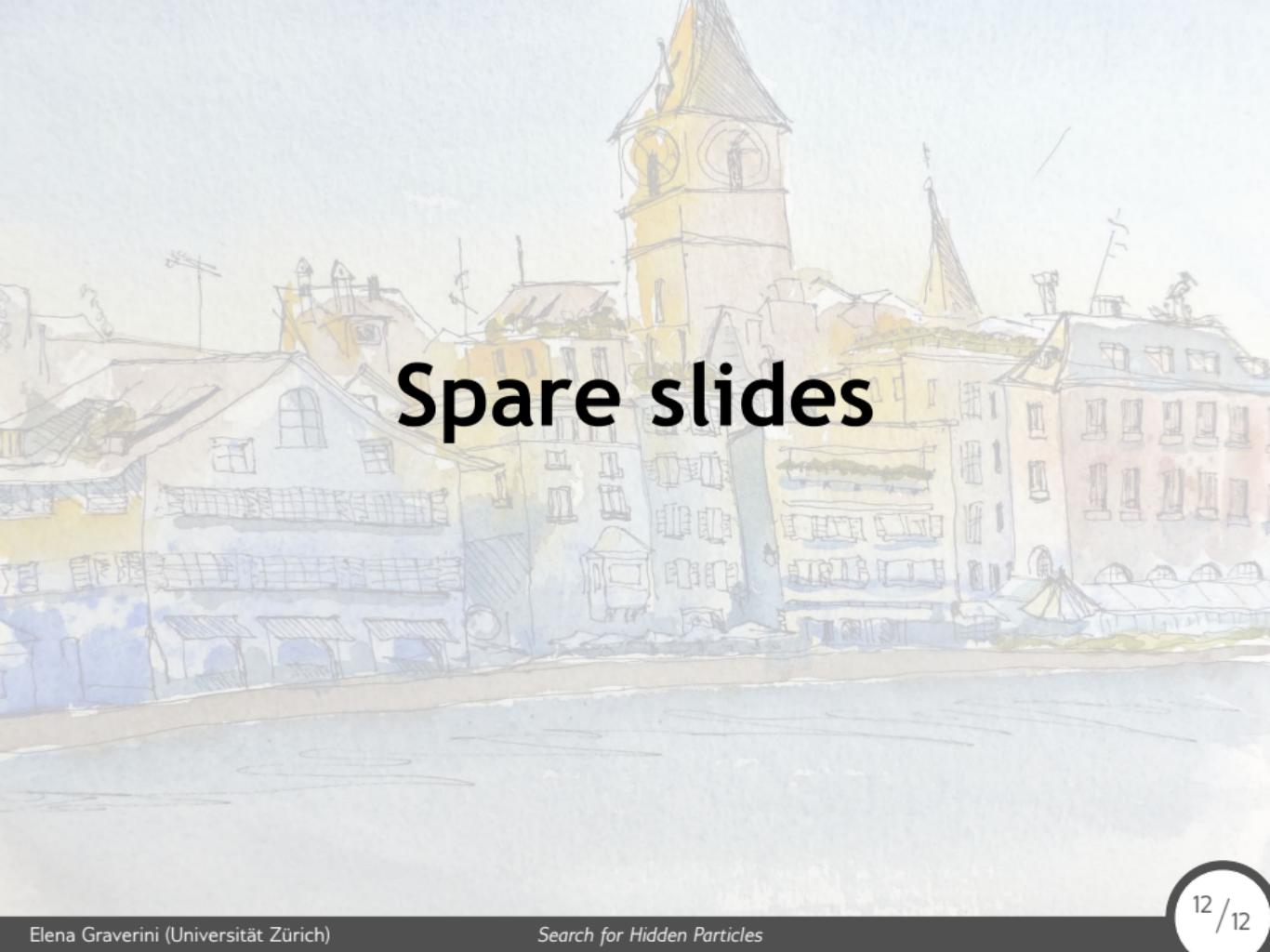


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References III



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Spare slides

Backgrounds



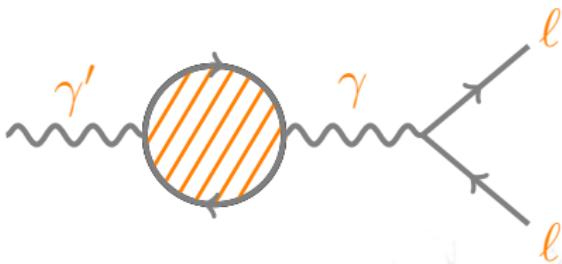
- **SHiP:** it is designed to be a zero-BG experiment: evacuated decay volume, veto chambers, event topology... Active or passive muon shielding.
- **CMS:** every event with either three leptons or one lepton and two jets in the final state!
- **TLEP:** W^*W^* , Z^*Z^* and $Z^*\gamma^*$ backgrounds suppressed by displacement of the secondary vertex.

Dark photons in short



The vector portal [5]

- Extra $U(1)'$ symmetry with gauge boson γ' (*dark photon*)
- $U(1)'$ broken by Higgs-like mechanism \rightarrow non-zero $m_{\gamma'}$
- Mix to γ through kinetic mixing to particles charged under both $U(1)$ and $U(1)'$: $\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_{hidden} + \frac{\varepsilon}{2} A'_{\mu\nu} F^{\mu\nu}$



Estimating SHiP's physics reach



1. Production: 10^{20} p.o.t.

HNL: $D_s \rightarrow \ell N$, $D \rightarrow K \ell N$

γ' : $p \rightarrow p\gamma'$, meson decays $\rightarrow \gamma' X$

2. (p, θ) -PDF weighted with the probability that the particle decays inside the SHiP volume (\mathcal{P}_{vtx})

3. Vertex acceptance: $\int_{SHiP} e^{-l/c\gamma\tau} dl$

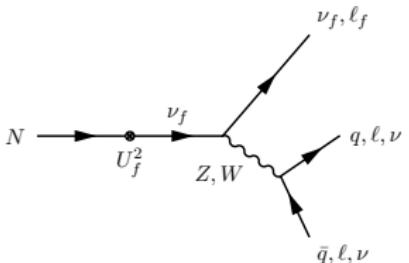
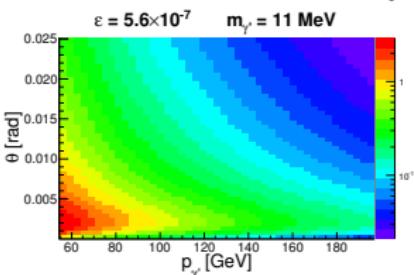
4. Simulate decays and compute daughters acceptance (\mathcal{A})

5. Count the number of events:

$$N = \Phi(p.o.t) \times BR_{prod} \times U_f^2 \times BR_{visible} \times \mathcal{P}_{vtx} \times \mathcal{A}$$

where U_f^2 is the mixing angle to SM particles.

HNL reach at TLEP: $Z^0 \rightarrow \nu N$, similar procedure.



HNL lifetime



and branching ratios

For a given N mass, its lifetime was computed on the basis of the widths of its kinematically allowed decay channels, according to the formulas in [11]. I included all the main N decay channels:

- $N \rightarrow H^0 \nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$
- $N \rightarrow H^\pm \ell^\mp$, with $H = \pi, \rho$
- $N \rightarrow 3\nu$
- $N \rightarrow \ell_i^\pm \ell_j^\mp \nu_j$
- $N \rightarrow \nu_i \ell_j^\pm \ell_j^\mp$

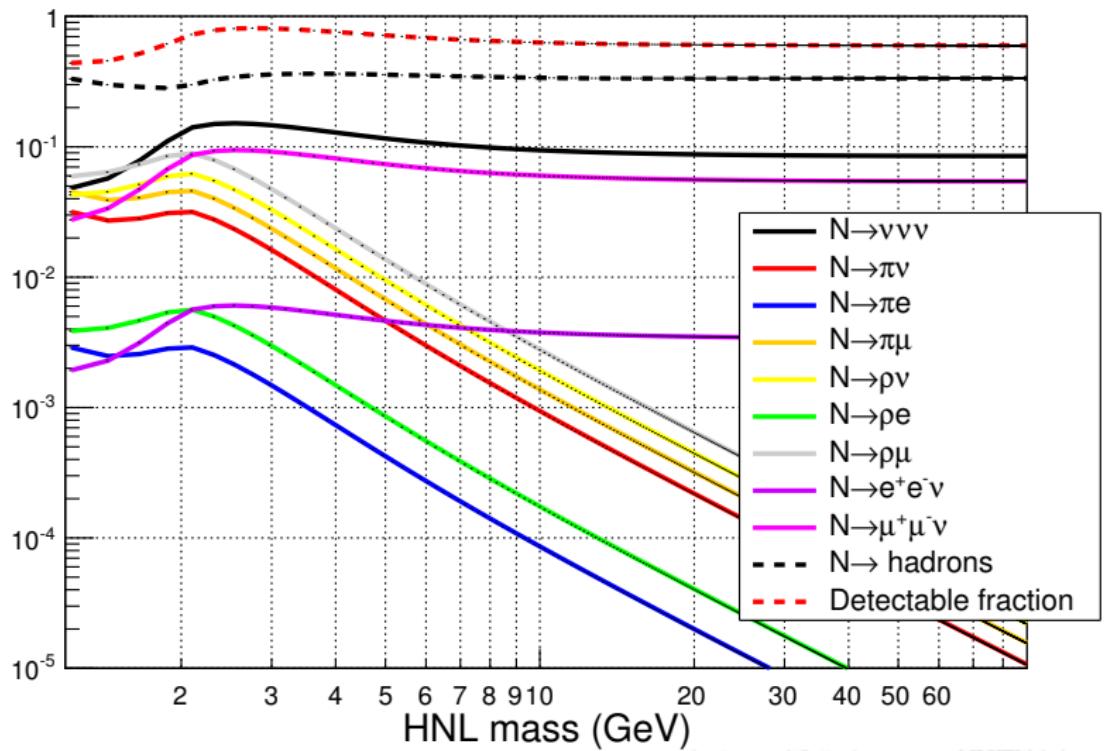
The formulas in [11] are valid up to $m_N \simeq 1$ GeV. For $m_N \gg \lambda_{QCD}$, the two quarks do no longer hadronise together and should be considered free. In this regime ($m_N \geq 2$ GeV) I extrapolated the three-body leptonic formulas to the quark case to compute the total hadronic decay width.

HNL lifetime

and branching ratios



Branching ratios for HNL (model: $U^2 = [6.25e-10, 1e-08, 2.5e-09]$)





All decay channels into ≥ 2 charged particles were taken to be **visible**.

Decay chains such as $N \rightarrow \rho^0 \nu$ followed by $\rho^0 \rightarrow \pi^+ \pi^-$ were taken into account, with the pion pair as final state particles.

Final-state π^0 s were taken not to be detectable, even if the photon pair could be reconstructed with a high-granularity calorimeter. For decay chains like $N \rightarrow \rho^\pm \ell$ with $\rho^\pm \rightarrow \pi^\pm \pi^0$, the requirement that the two photons fall into the acceptance of a toy detector of radius 2.5 m decreases the final-state detection efficiency to $\sim 27\%$, while it is $\sim 37\%$ for a (π^\pm, ℓ) final state.

How to estimate the number of expected events

For SHiP



1. Charm mesons are the main source of HNLs in SHiP
2. Simulate protons on target \implies store an ntuple of charm mesons with their secondary vertices
3. Fix the model (fix the U_f^2) and the HNL mass m_N
4. According to the dominating U_f^2 , simulate the $D_s \rightarrow \ell N$ and $D^{\pm,0} \rightarrow K^{0,\mp} \ell^\pm N$ decays or the $D_s \rightarrow \tau \nu_\tau$, $\tau \rightarrow \mu \nu N$ decay chain
5. Momentum and angle of the outgoing N are stored in a binned bi-dimensional PDF
6. Each bin of the PDF is weighted with the probability that a N with that kinematics decays into SHiP's fiducial volume, and the total probability \mathcal{P}_{vtx} is computed as the integral of the weighted PDF

How to estimate the number of expected events

For SHiP



7. For each of the kinematically allowed decays into detectable daughters, decays inside SHiP's fiducial volume are simulated to compute SHiP's acceptance to the daughters (\mathcal{A}). Decaying N are sampled from the weighted PDF. The total branching ratio $BR(\text{visible})$ into detectable particles is computed.
8. For each of the two fiducial volumes, the number of expected events is computed as:

$$N_{\text{events}} = N_{\text{p.o.t.}} \times 2\chi_{cc} \times BR(\text{production}, f) \times U_f^2 \\ \times \mathcal{P}_{\text{vtx}} \times BR(\text{visible}) \times \mathcal{A}$$

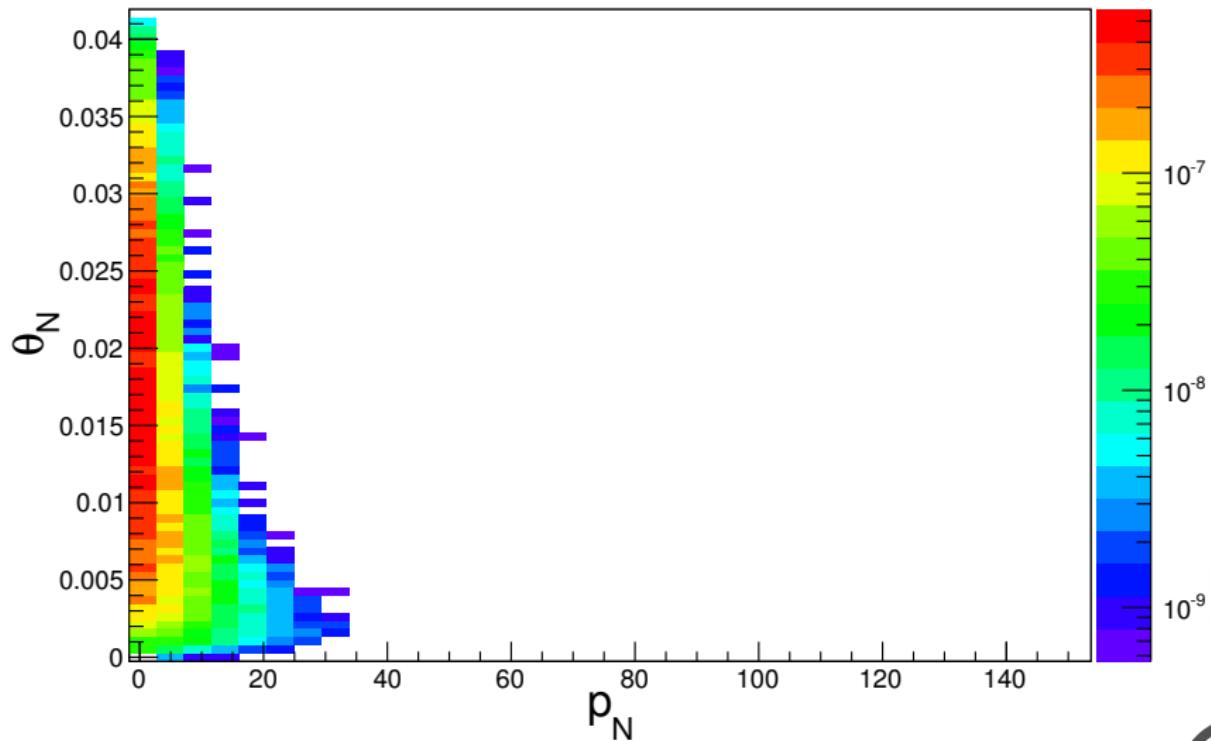
It depends on the three mixing angles U_f^2 and on m_N .

How to estimate the number of expected events



For SHiP

weightedPDF_vol1_m0.51_couplegs1.75e-09_2.8e-08_6.65e-09



How to estimate the number of expected events



For TLEP, assuming running as Z^0 factory

The expected statistic is $10^{12} - 10^{13} Z^0/\text{year}$. The following considerations is applicable to any e^+e^- collider capable of producing a large quantity of Z^0 bosons.

The only production channel considered is $Z^0 \rightarrow \nu\bar{\nu}$, with one neutrino mixing to N . An onion-like detector is assumed.

1. Fix the model (fix the U_f^2) and the HNL mass m_N
2. The Z^0 decays in place to νN . The boost to the N is then:

$$\gamma = \frac{m_Z}{2m_N} + \frac{m_N}{2m_Z}$$

How to estimate the number of expected events

For TLEP, assuming running as Z^0 factory



3. Compute the N lifetime τ . Compute the probability \mathcal{P}_{vtx} that it decays inside the tracking volume:

$$\mathcal{P}_{vtx} = \frac{1}{c\gamma\tau} \int_{R_{min}}^{R_{max}} e^{-\frac{r}{c\gamma\tau}} dr$$

where R_{min} corresponds to the minimum SV displacement
(\sim inner tracker resolution)

4. Compute the total branching ratio BR (*visible*) into lepton pairs (ee , $\mu\mu$ and $e\mu$). The detector efficiency is assumed to be 100%
5. The number of expected events is computed as:

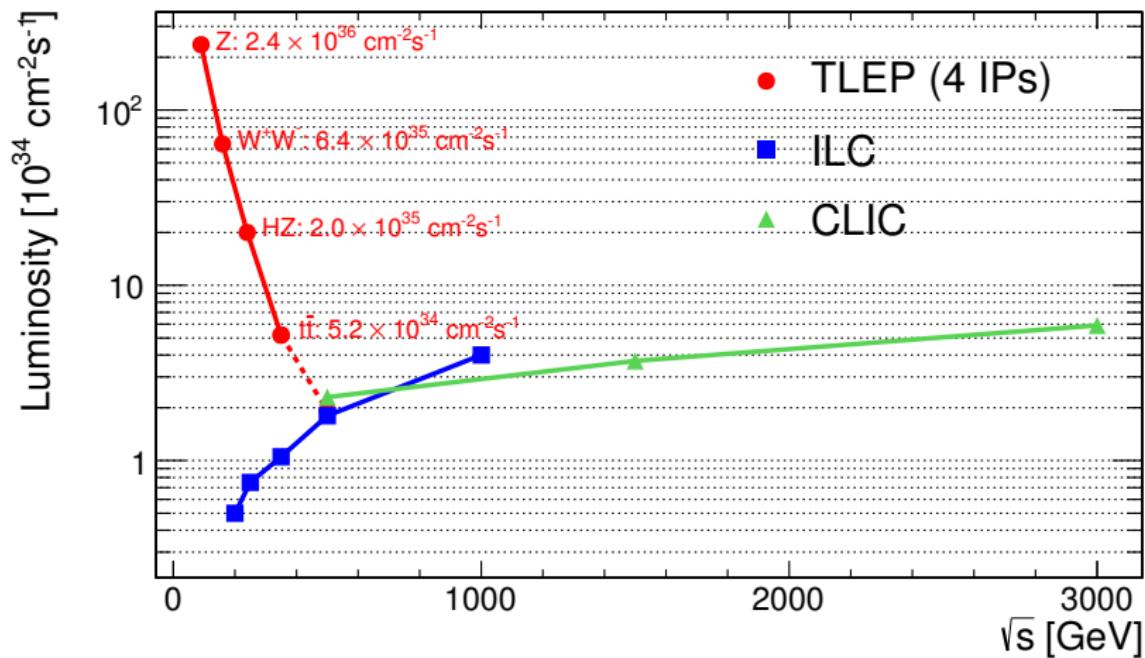
$$N_{events} = N_{Z^0} \times BR(Z^0 \rightarrow 2\nu) \times 2 \times \sum_f U_f^2 \\ \times \mathcal{P}_{vtx} \times BR(\text{visible})$$

How to estimate the number of expected events

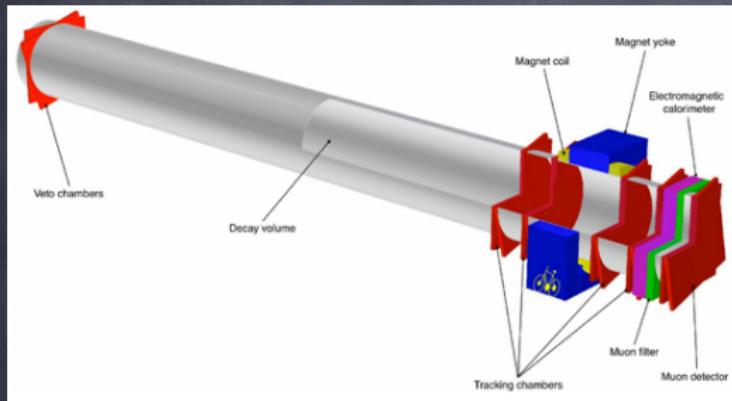


For TLEP, assuming running as Z^0 factory

Expected luminosity is large at the Z^0 mass [4]:



Decay Volume



- Vacuum tank (similar to NA62) with $1e-2$ mbar (instead of $1e-5$ mbar)
- NA62-like straw chambers, 120um resolution and 0.5% X_0/X
- LHCb-like magnet 0.5Tm over 5m
- LHCb-like shashlik calorimeter
- Veto chambers at the entrance of the vacuum tank to veto muons and strangeness from surroundings

Geometry

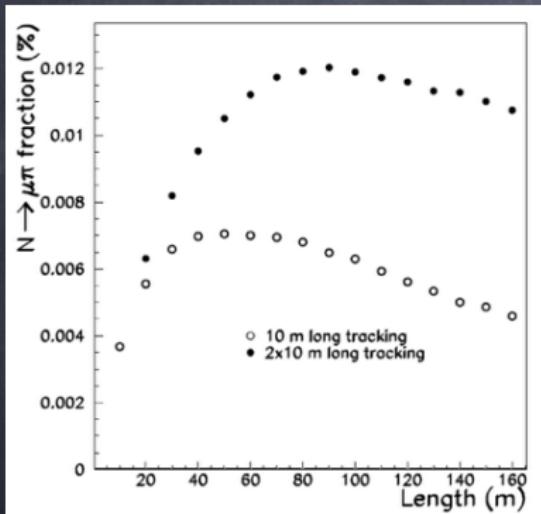


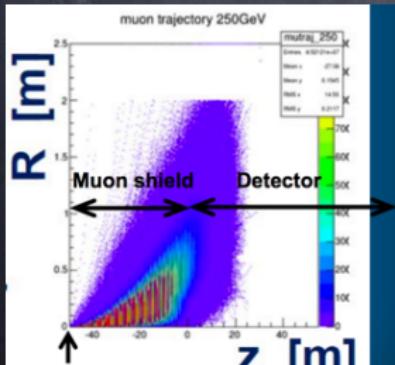
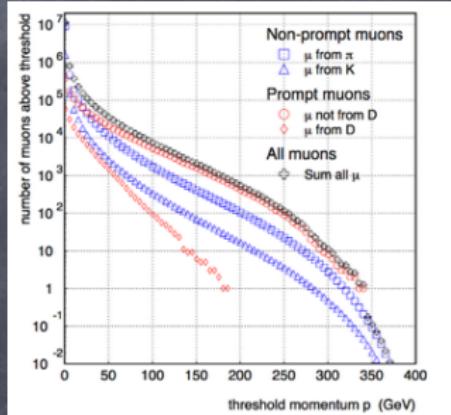
Figure 8: Fraction of HNL in the detector acceptance as a function of the length of the fiducial volume. Open circles: a single spectrometer following a fiducial volume of a given length. Full circles: two spectrometers in series, each following a fiducial volume of half the given length. The spectrometer length is fixed to 10 m.

Muon Shield

N. Serra, Flavour Physics Conference, Vietnam, 01.08.2014

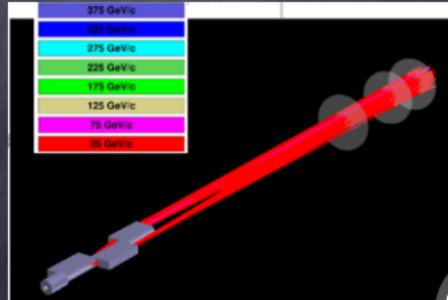
Muon rate 5×10^9 muons/spill

- Acceptable rate $< 10^5$ muons per spill
- Main source of muons from η , η' , ω , etc...
- Studying solution with passive or active filter



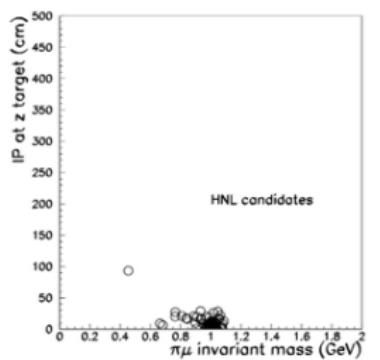
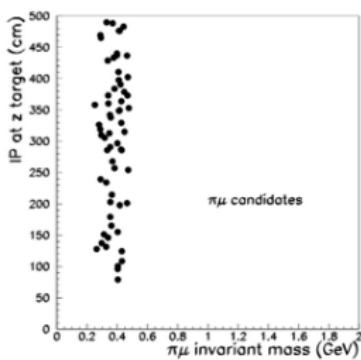
Elena Graverini (Universität Zürich)

Search for Hidden Particles



Background rejection

- 2×10^4 neutrino interactions per 2×10^{20} POT in the decay volume at atmospheric pressure, negligible at 10^{-2} mbar
- K_L production from $\nu + A \rightarrow K_L(\rightarrow \mu\nu\pi)X$
- 10% ν interactions produce Λ and K^0 in acceptance
- Majority of the decays in the first 5m of the decay volume
- Muon filter to reduce background from muon DIS to a negligible level

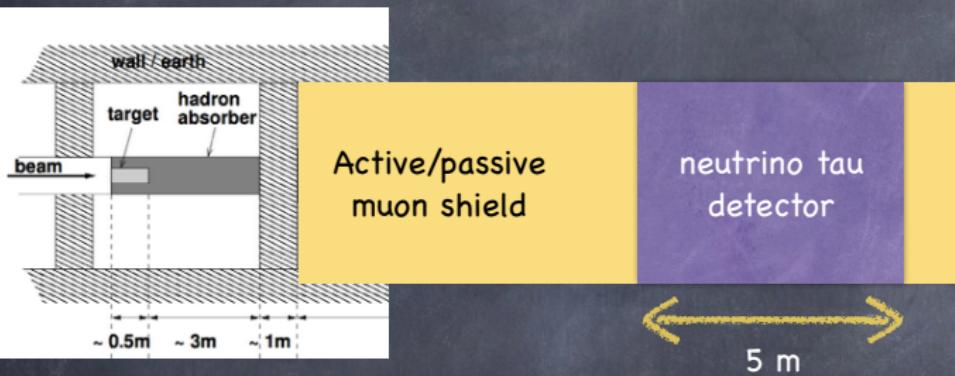


Fighting hard to design
a zero background
experiment



Activity	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Operation	LHC operation	■														
	SPS operation	■	■													
Detector	Facility HW commissioning/dry runs on availability															
	SHIP facility commissioning with beam															
Civil Engineering	SHIP facility operation															
	SHIP Technical Proposal	■	■													
Infrastructure Systems	SHIP Project approval		■													
	Technical Design Reports and R&D		■	■	■	■	■	■	■	■	■	■	■	■	■	■
Beam Line	TDR approval			■	■	■										
	Detector production															
Target complex/target	Detector installation															
	Pre-construction activities(Design, tendering, permits)		■	■	■	■	■	■	■	■	■	■	■	■	■	■
Target complex/target	CE works for extraction tunnel, target complex															
	CE works for TDC2 junction cavern															
Target complex/target	CE works for filter tunnel and detector hall															
	Installation in TT20 (150m)															
Target complex/target	Installation for new beam line to target															
	Installation in target complex, filter tunnel															
Target complex/target	Installation in detector hall															
	Design studies, specs and tender docs		■	■	■	■	■	■	■	■	■	■	■	■	■	■
Target complex/target	Integration studies															
	Technical Design Report															
Target complex/target	Manufacturing new components															
	Refurbishment existing components															
Target complex/target	TT20 dismantling (150m)															
	TT20 re-installation and tests															
Target complex/target	New beam line to target installation and tests															
	Muon filter installation															
Target complex/target	Target complex design studies, specs and tender docs															
	Target complex integration studies															
Target complex/target	Target complex services - design and manufacturing															
	Target studies and prototyping															
Target complex/target	Target production and installation															

Tau neutrinos

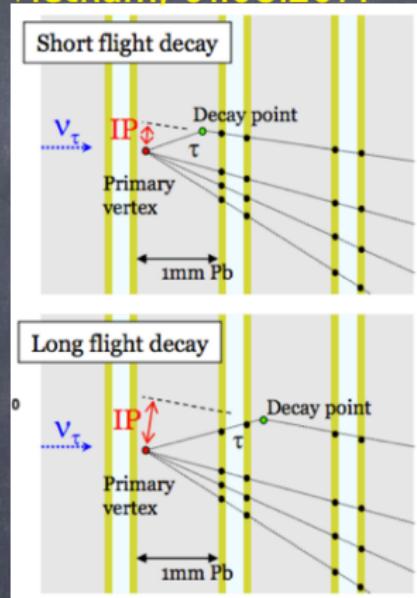
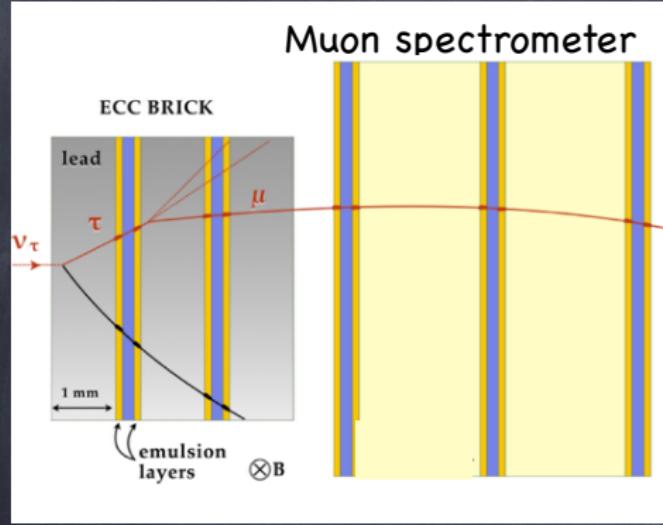


- The same optimization for sterile neutrinos in the GeV region also maximises the flux of ν_τ
- Source of ν_τ and $\bar{\nu}_\tau$ is $D_s \rightarrow \tau \nu_\tau$
- Also high rate of ν_e from charm

Tau neutrino detector

N. Serra, Flavour Physics Conference, Vietnam, 01.08.2014

Muon spectrometer



- ν_τ target: Opera-like bricks, laminated lead and nuclear emulsions (for micrometric resolution)
- 750 Opera-like bricks, to be replaced 10 times
- Muon spectrometer to measure charge and momentum and give time stamp

Working hypotheses

- Detector located ~60m from the proton target
- Charm production cross-sections in p-W affected by large uncertainties
- Compare with DONUT to extrapolate the expected numbers
- Energy dependence of σ_{cc} and v_τ cross-section, acceptance: production ~ 0.36, detector acceptance ~ 0.2, energy dependence of the v_τ cross-section ~0.52 → DONUT/SHIP ~ 26
- 2×10^{20} pot for SHIP compared to 3.6×10^{17} DONUT → ~ 550 in favour of SHIP
- Overall rate SHIP/DONUT ~ 20
- DONUT observed 9 events with a background of 1.5 → 7.5 ± 3 (40% error)
- 150 events expected with the same mass (260 kg)
- Measurement of v_τ and anti- v_τ cross-section, including the study of structure functions sets the scale for the mass: ~ 6 tons for ~ 3400 v_τ interactions
- Assume OPERA-like bricks (8.3 kg) and wall target structure: ~ 750 bricks