Exploring intensity frontier of new physics with cosmological observations and accelerator experiments

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Outline

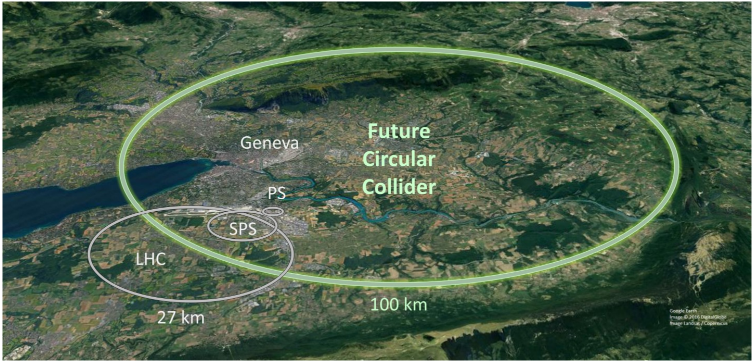
- Intensity frontier experiments: what are they
- One of their main goal: search for feebly-interacting particles (FIPs)
- Our understanding of the parameter space of GeV-scale FIPs: is it mature enough?

Introduction

Intensity frontier experiments and feebly-interacting particles

Intensity frontier experiments I

– Mid-2030s: HL-LHC
– Mid 2040s: FCC-ee (?)

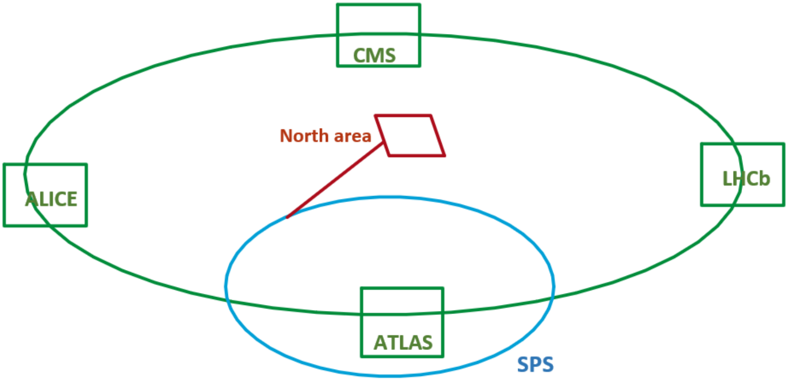


FCC image selection

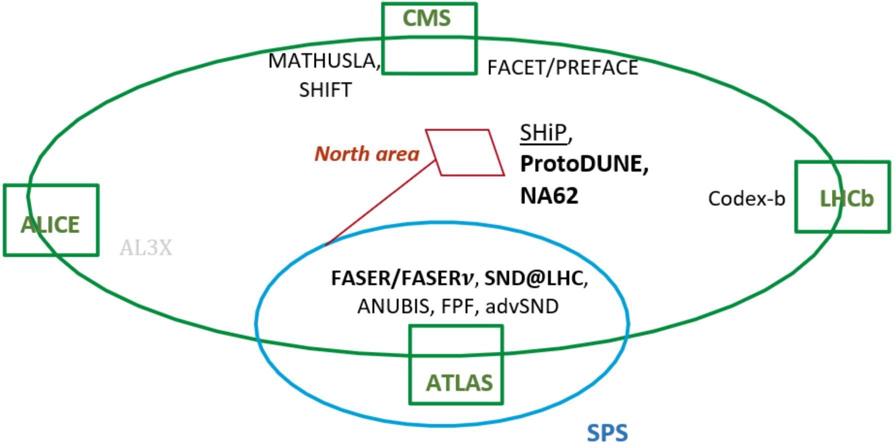
Do we have something earlier?

Intensity frontier experiments II

- LHC: 4 main experiments
- SPS: 400 GeV protons



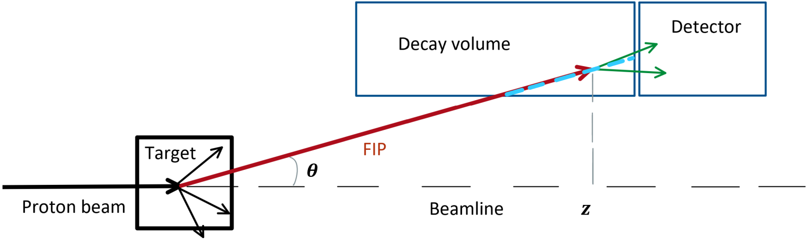
Intensity frontier experiments III



Intensity frontier experiments

[1901.09966], [2305.01715]

Intensity frontier experiments IV



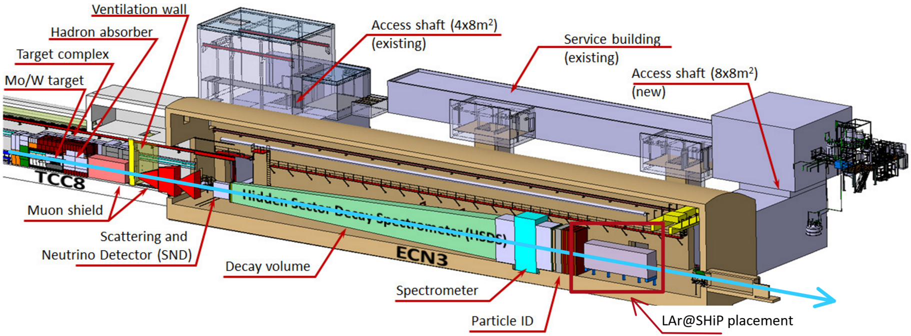
Typical intensity frontier experiment:

- Displaced large decay/scattering volume
- Low background environment

Main goals:

- Neutrino physics
- Kaon physics
- New physics at intensity frontier

SHiP experiment I



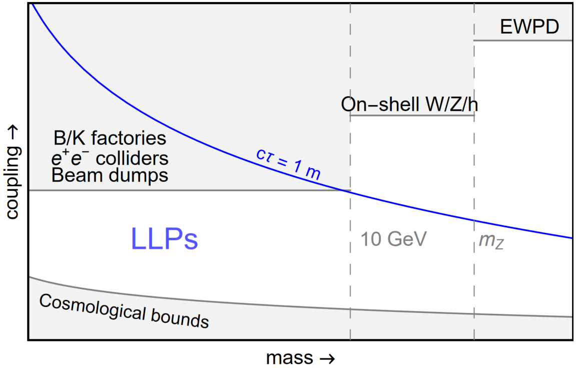
SHiP experiment – highlights:

- Proton beam with $E_p = 400$ GeV and a large beam intensity: $N_{\text{PoT,year}} = 4 \cdot 10^{19}$. Expected running time: $\simeq 2030 - 2045$
- Background-free experiment for many scenarios
- May search for decays and scattering signatures

See TDR

New physics at the intensity frontier I

- Consider a new physics particle with mass $\boldsymbol{m}$ and coupling $\boldsymbol{g}$
- Masses $\boldsymbol{m} \ll \boldsymbol{\Lambda}_{\mathrm{EW}}$: past experiments excluded large $\boldsymbol{g}$
- Such particles are called **Feebly Interacting Particles** (FIPs)



- If the particle is unstable: $\boldsymbol{c\tau \propto m^{-\alpha} g^{-2}} \Rightarrow$ unexplored parameter space corresponds to **Long-Lived Particles** (LLPs)

New physics at the intensity frontier II

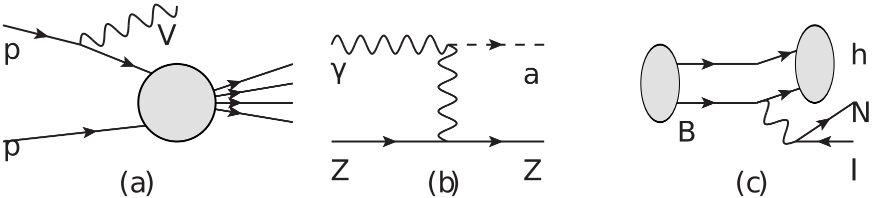
"Portals" – lowest-dimensional gauge-invariant operators with LLPs:

Model	(Effective) Lagrangian	What it looks like
HNL N	$Y\bar{L}\tilde{H}N + \text{h.c.}$	Heavy neutrino with interaction suppressed by $U \sim Yv_h/m_N \ll 1$
Higgs-like scalar S	$c_1 H^\dagger H S^2 + c_2 H^\dagger H S$	A light Higgs boson with interaction suppressed by $\theta \sim c_2 v_h/m_h$
Vector mediator V	$-\frac{\epsilon}{2}B_{\mu\nu}V^{\mu\nu} + gV^\mu J_{\mu,B}$	A massive photon/vector meson with interaction suppressed by ϵ/g
ALP a	$ag_a G^{\mu\nu}\tilde{G}_{\mu\nu} + \dots$	A $\pi^0/\eta/\eta'$-like particle with the interaction suppressed by $f_\pi g_a$

Simple extensions of these models: couple N, S, V, a to dark sector (DM, dark QCD, etc.)

[1901.09966], [2305.01715]

GeV mass range: why is it special? I



Reason 1: huge production rates

– GeV-scale LLPs may be produced in

- Decays of mesons ($\boldsymbol{\pi^0, \ldots, B}$)
- Proton bremsstrahlung/fragmentation
- Primakov processes

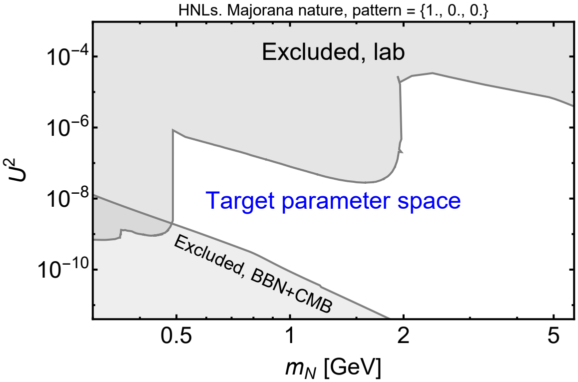
Thousands of events with FIPs may be observed

It can be used to extract unique information about FIPs

GeV mass range: why is it special? II

Reason 2: complementarity of cosmological and lab proves

- LLP lifetime scaling: $\boldsymbol{\tau_{\mathrm{LLP}} \propto m^{-\alpha} g^{-2}, \alpha > 0}$
- Cosmological observations (BBN, CMB) may probe lifetimes $\boldsymbol{\tau_{\mathrm{LLP}} \gtrsim 10^{-2}}$ **s.** They cross lab constraints at some small mass
- Astrophysical constraints (like SN) may also show up in the mass range $m \lesssim 100$ MeV



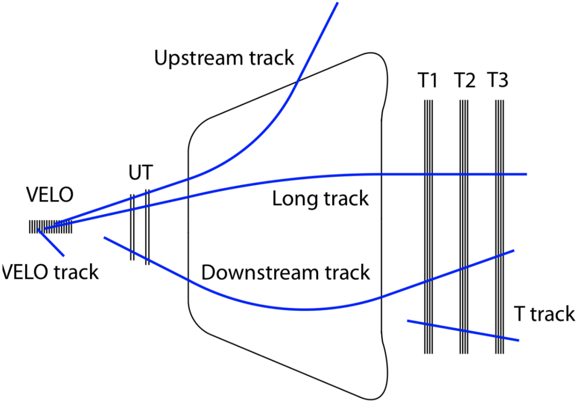
Synergy between lab and cosmic/astrophysical probes in GeV range

Defines target parameter space from above and below

GeV mass range: why is it special? III

Reason 3: limitations of LHC searches

- Recently, a lot of new trigger schemes at the LHC have been conducted to search for FIPs:
  - Downstream algorithm at LHCb [2312.14016]
  - Muonless showers in muon chambers [2402.01898]
  - . . .
- These searches have limitations for GeV-scale particles: small decay volume, non-negligible backgrounds



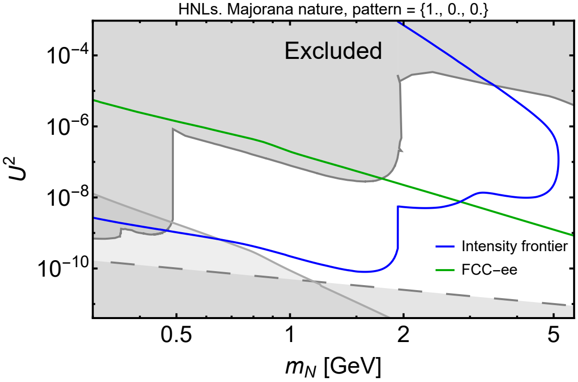
GeV mass range: why is it special? IV

Bonus: complementarity to the domain probed with FCC-ee

- FCC-ee is not a B, D factory:

$$N_{B,D}^{\text{FCC-ee}} \ll N_{B,D}^{\text{intensity frontier}} \quad (1)$$

  So it cannot efficiently probe the parameter space of FIPs produced by B decays
- On the other hand, it may search for the particles produced in Z decays

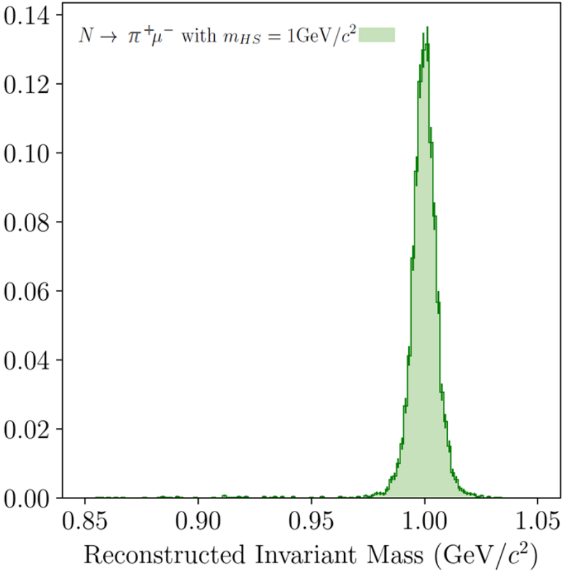


LLPs with intensity frontier experiments: what we can extract? I

By observing interactions of FIPs, we may:

- Reconstruct the FIP invariant mass
- Identify decay/scattering modes $\Rightarrow$ distinguishing various FIPs

10-1000 events are required, depending on the signature (this is why we need large intensity!)

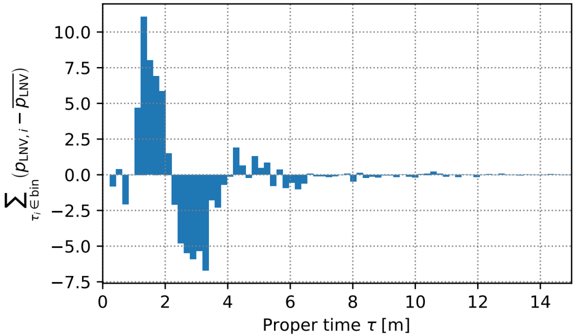


LLPs with intensity frontier experiments: what we can extract? II

Example: HNLs may exist in pairs $N_{1,2}$ forming a quasi-degenerate particle

Motivated by HNL-induced BAU and neutrino oscillations [0605047]

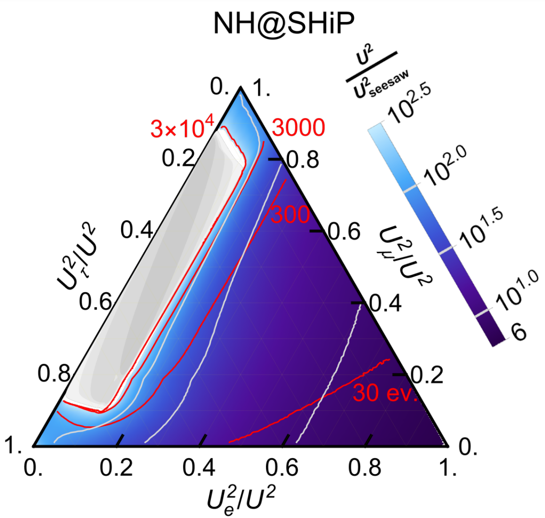
– Seeing $\mathcal{O}(1000)$ events, it may be possible to resolve oscillations $\boldsymbol{N_1 \leftrightarrow N_2}$ and measure $\boldsymbol{\Delta m}$ by distinguishing lepton number violating and lepton number conserving events
This information is encoded in the angular distribution of the decay products (due to helicity conservation)



[1912.05520]

LLPs with intensity frontier experiments: what we can extract? III

- By reconstructing HNL decay modes, we may extract mixings with neutrinos $\boldsymbol{U_\alpha^2/U^2}$
- On the other hand, varying $\boldsymbol{\theta_{ij}}$, $\boldsymbol{\delta_{\mathrm{CP}}}$, $\boldsymbol{\Delta m_{ij}^2}$ within uncertainty range, obtain the region of possible $\boldsymbol{U_\alpha^2/U^2}$ for the given ν mass hierarchy
- 100 – 1000 events are required to test the neutrino hierarchy and extract the Majorana phase

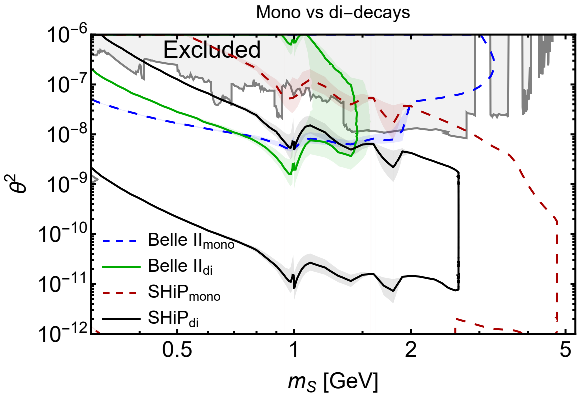


2312.05163

LLPs with intensity frontier experiments: what we can extract? IV

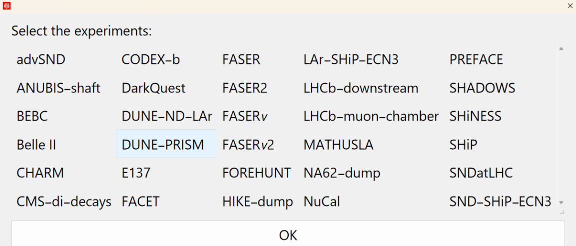
Another example: di-decays

- Consider a particle that couples linearly and quadratically to SM fields
- At intensity frontier experiments, we may observe mono- and di-decays
- Di-decays may allow identifying LLP's production modes and distinguishing from solely linearly coupled FIPs



Example: LLPs X having the hXX coupling [2503.01760]

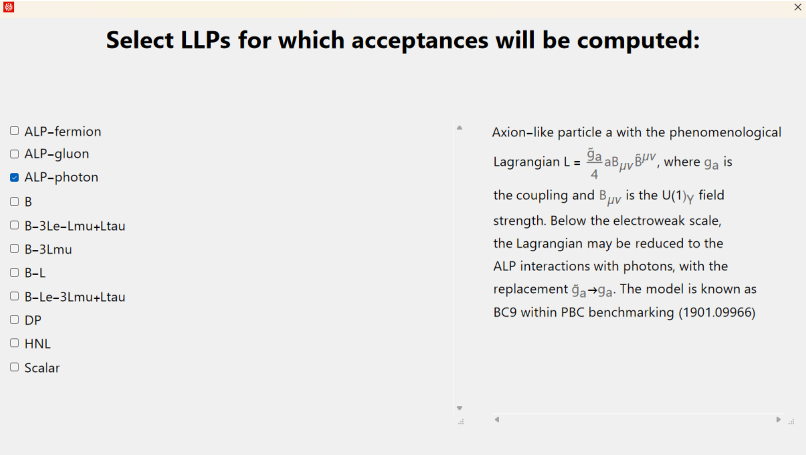
Compute the sensitivity to your model I



Recipe to calculate the sensitivity to your model:

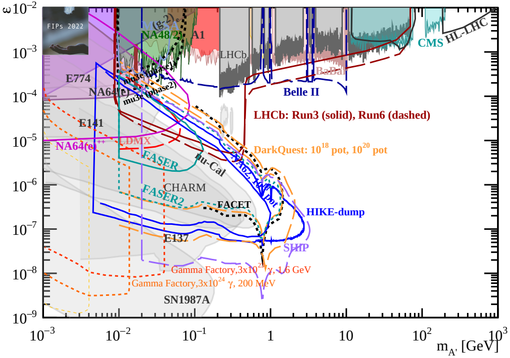
1. Consider available event samplers with LLPs [2105.07077], [2201.05170], [2305.13383]
2. Implement experimental setup

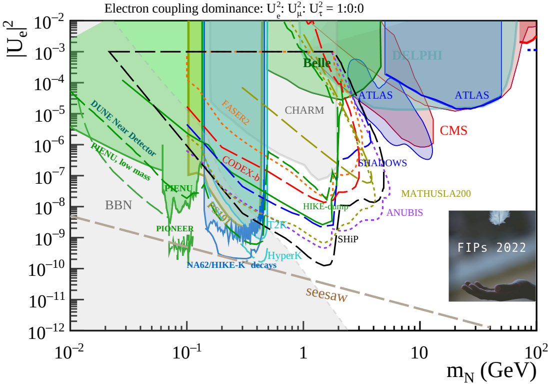
Compute the sensitivity to your model II



3. Directly calculate the sensitivity with event generators or translate the generated events to the full simulation framework

Challenges I





Examples of nice summary plots with the LLP parameter space from [2305.01715]

Can we take these plots as they are? No

Challenges II

Can we take these plots as they are? No

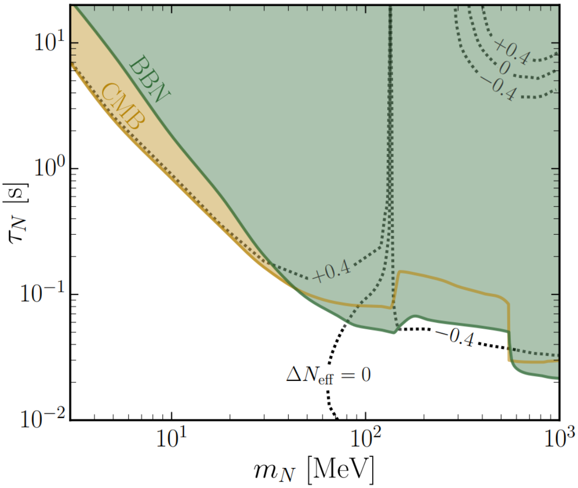
- **Reason 1: status of the cosmological constraints**
  - How do they behave under the variation of the cosmic setup?
  - Contradictory predictions of previously existing approaches on the impact of LLPs on neutrinos
- **Reason 2: unaccounted theoretical uncertainties in the LLP phenomenology**
  - May be orders of magnitude and even not quantifiable

Challenges

Challenge 1: from cosmology

Cosmological constraints/sensitivities I

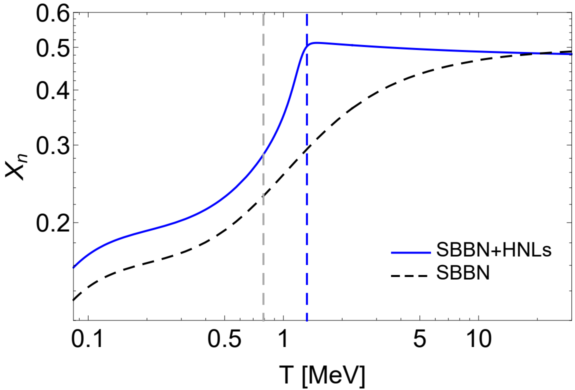
- LLPs may be efficiently produced in the primordial plasma
- Cosmological probes/bounds: earliest observable imprint of the LLP on the Early Universe (BBN, CMB)
- Crucial to understand the boundary of the constraint (when LLPs affected the Universe around neutrino decoupling time)
- Especially important in light of ongoing observations by Simons observatory



Cosmological constraints/sensitivities II

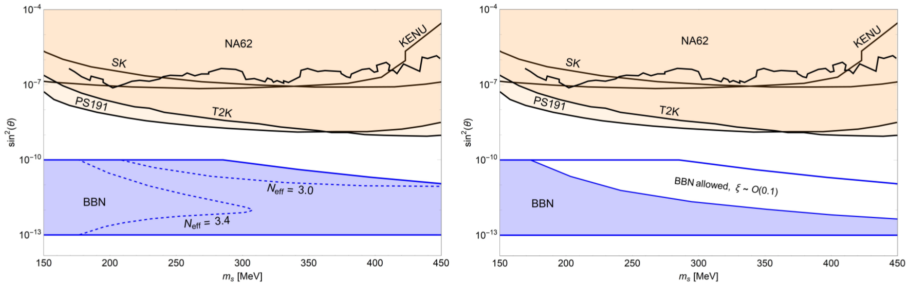
– Example: short-lived HNLs with mass $m_N \gtrsim m_\pi$. The main impact on BBN: meson-driven $p \leftrightarrow n$ conversion [2008.00749]

– The main impact on CMB: affect on N_{eff} via decays into neutrinos, mesons, and EM particles [2103.09831]



– Effect on $\boldsymbol{N_{\text{eff}}}$: requires solving neutrino Boltzmann equations

Relaxing cosmological constraints: varying cosmic setup



– For the same HNL interactions at accelerators, one can relax BBN constraints by varying the cosmic setup

– Example: add huge asymmetry in the sectors of neutrinos and HNLs – wash out the impact of HNLs on the expansion of the Universe an $\boldsymbol{n} \leftrightarrow \boldsymbol{p}$ rates
Partially discussed in [2005.06721]

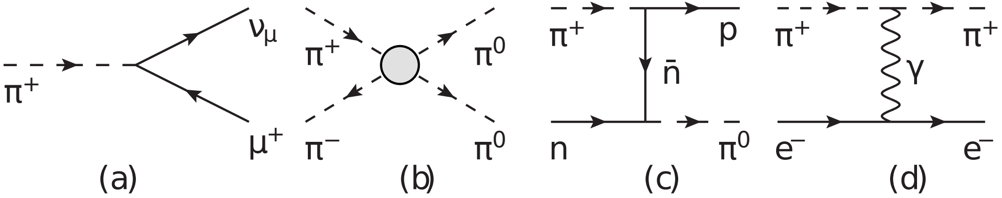
In preparation

Impact on neutrinos I

Previously existed solvers of neutrino Boltzmann equation [0008138], [2103.09831], [2104.11752], [2109.11176]

- Used the same approach of solving the neutrino Boltzmann equation
- Delivered qualitatively contradictory results for LLPs decaying into high-energy neutrinos ($\boldsymbol{\Delta N_{\mathrm{eff}} > 0}$ or $\boldsymbol{< 0}$?)
- In case of LLPs decaying into **metastable particles** (mesons/muons), missed important processes governing their interactions with the plasma

Impact on neutrinos II



- Consider LLPs decaying into **metastable particles**: $\boldsymbol{\mu, \pi^{\pm}/K}$
- Before decaying (a), they may participate in
  - Elastic scattering off EM particles (d)
  - Interactions with nucleons (c)
  - Self-annihilations (b)
- (b), (c) dominate at MeV temperatures, leading to non-trivial influence on neutrinos
- In particular, decays into $\boldsymbol{K^{\pm}}$ may induce $\boldsymbol{\nu\text{-}\bar{\nu}}$ asymmetry in energy distribution

More information in companion papers [2411.00892], [2411.00931]

Impact on neutrinos III

Incorporate the metastable dynamics into existing neutrino Boltzmann solvers – non-trivial task:

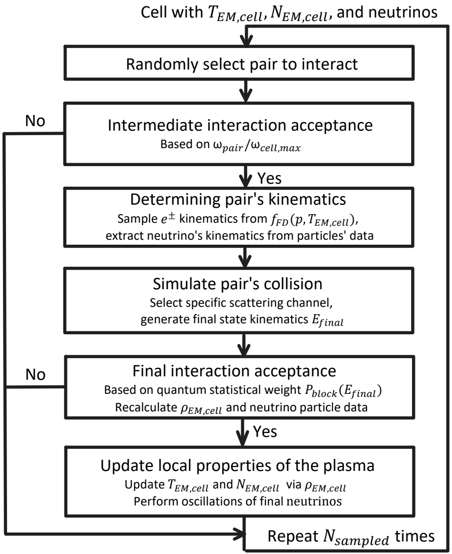
- Very sensitive to the analytic reducibility of the collision integral
  The approach breaks down in case of, e.g., decays into jets or complicated NSI
- Extremely complicated to implement every model
  Need to achieve stability of the solver and define the integration phase space case-by-case
- Unrealistic to use for heavy LLPs with mass $m \simeq 1$ GeV decaying into neutrinos: computational time scales as

$$t_{\text{comp}} \propto E_{\nu,\max}^{k+2}, \quad k \geq 2 \tag{2}$$

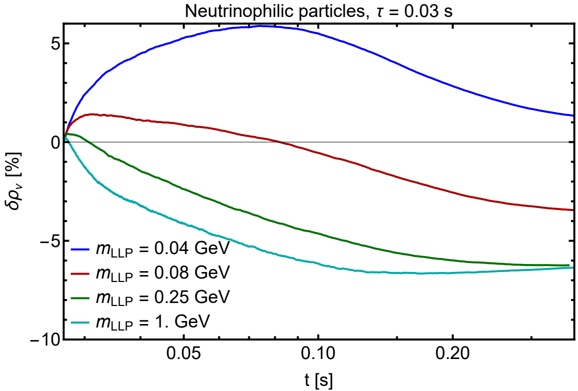
Impact on neutrinos IV

- New approach to solve the neutrino Boltzmann equation – neutrino DSMC
- Idea: replace the collision integral with the system of νs, $e^{\pm}$, LLPs, and simulate their interactions
- Account for the instant thermalization of the EM plasma, ν oscillations, Pauli principle
- Cross-checked against existing methods in the case of well-defined setups, very fast and versatile

More information in companion papers [2409.15129], [2409.07378]



Impact on neutrinos V

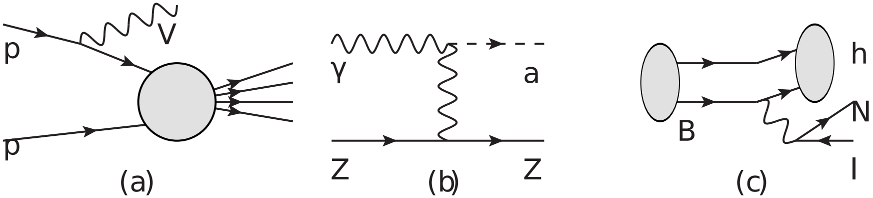


– Application of DSMC: **generic LLPs with mass $m \gg 3T$ decaying into SM species at MeV temperatures always decrease N_{eff}**
– May be applied to other systems (evaporating PBHs, SN)
In preparation

Challenges

Challenge 2. Theoretical uncertainties in LLP phenomenology

LLP phenomenology: outline I



- LLP's phenomenology: production and decay/scattering modes
- **Complexity 1**: variety of modes, depending on the LLP interactions
- **Complexity 2**: $\boldsymbol{m_{\mathrm{LLP}} \simeq 1}$ **GeV** is around $\boldsymbol{\Lambda_{\mathrm{QCD}}}$
  We have to match two descriptions of their production and decays: perturbative QCD and hadronic bound states (mesons, nucleons)

Mixing I

Main challenge – mixing with mesons

- Interaction Lagrangian of a LLP X:

$$\mathcal{L} = X^a \cdot \mathcal{O}_a[\psi_{\mathrm{SM}}] \tag{3}$$

- Expansion of $\mathcal{O}_a[\psi_{\mathrm{SM}}]$ in terms of bound states $\mathcal{Y}$:

$$\mathcal{O}_a = \overbrace{c_1(\mathcal{Y}, \partial\mathcal{Y}, \partial^2\mathcal{Y})_a}^{\text{1-particle}} + \overbrace{c_2(\mathcal{Y}^2, (\partial\mathcal{Y})^2, \mathcal{Y}\partial\mathcal{Y})_a}^{\text{2-particle}} + \dots \tag{4}$$

- $X^a\mathcal{Y}_a$ – induced resonant mixing. Every process with $\mathcal{Y}$ may involve X by replacing

$$\psi_{\mathcal{Y}} \to \theta_{\mathcal{Y}X}\psi_X, \quad \theta_{\mathcal{Y}X} = \frac{c_1}{m_X^2 - m_{\mathcal{Y}}^2 - i m_{\mathcal{Y}}\Gamma_{\mathcal{Y}}} + \dots \tag{5}$$

Mixing II

Main challenge – mixing with mesons

LLP	Mixing with $\mathcal{Y}$
Dark photon	ρ^0, ω, ϕ and their excitations
V coupled to J^μ_B	ω, ϕ and their excitations
Higgs-like scalar S	f_0 and its excitations
ALP a	π^0, η, η' and their excitations
HNL N	–

- Most of the “simplest” LLPs have mixing
- It makes it necessary to carefully know the meson spectroscopy in the mass range $M \lesssim 2$ GeV, which is far from being true [2407.18348]

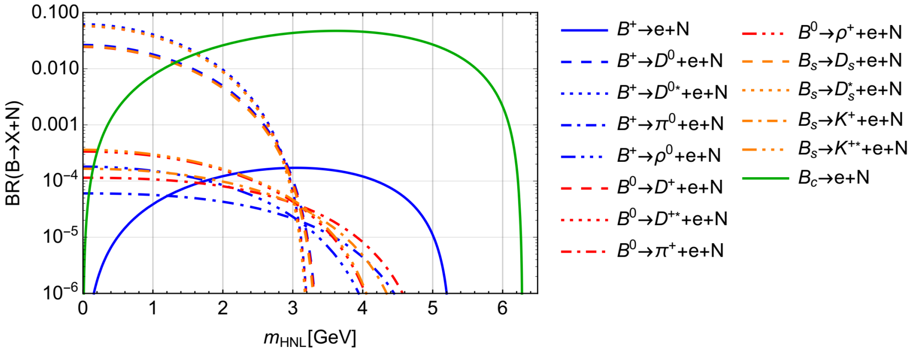
Mixing III

Main challenge – mixing with mesons

How to (partially) overcome the problem:

- Use experimental data from which it is possible to extract the production/decay rate
- Use phenomenological Lagrangians incorporating as many mesonic resonances as possible

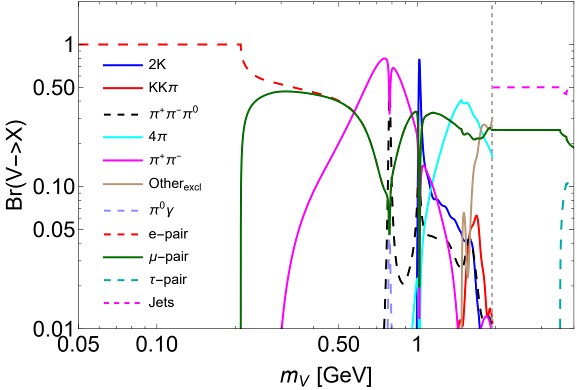
LLP phenomenology: examples I



HNLs [1805.08567]:

- Production: aka massive neutrinos – via leptonic/semileptonic decays of π, K, D, B, W, with form-factors calculated using lattice QCD or light-cone sum rules calibrated on data
- Decays: CC/NC leptonic decays $\boldsymbol{N \to ll'\nu}$ + semileptonic decays $\boldsymbol{N \to m^0\nu/m^\pm l^\mp}$

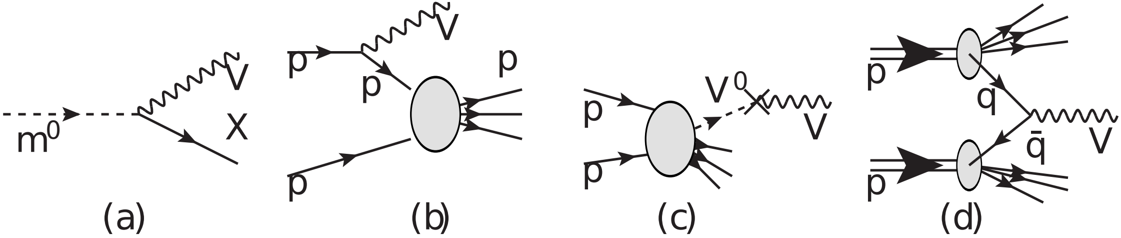
LLP phenomenology: examples II



Dark photons [1801.04847], [2409.09123], [2409.11096]:

– Decays may be extracted from $e^+e^- \to$ **hadrons** the using the VMD+HLS framework

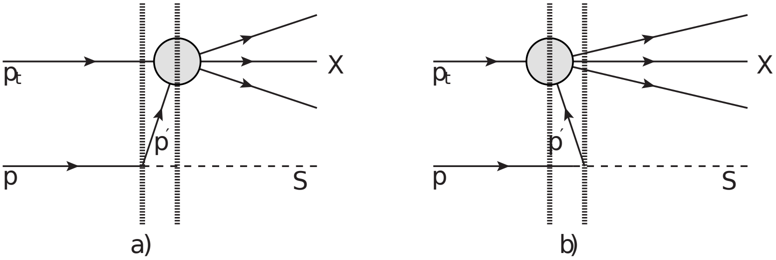
LLP phenomenology: examples III



Dark photons [1801.04847], [2409.09123], [2409.11096]:

- Production: decays of $\pi^0, \eta, \eta' \to V + \gamma$, Drell-Yan process (heavy Vs), proton bremsstrahlung (light Vs, ISR), fragmentation (light Vs, FSR)
- Fragmentation:
  - Implemented in `Pythia8` ([2409.11096] + to appear)
  - Automatically tuned to data
  - Main problem – no heavy resonances in `Pythia`'s fragmentation chain, so the flux is conservative

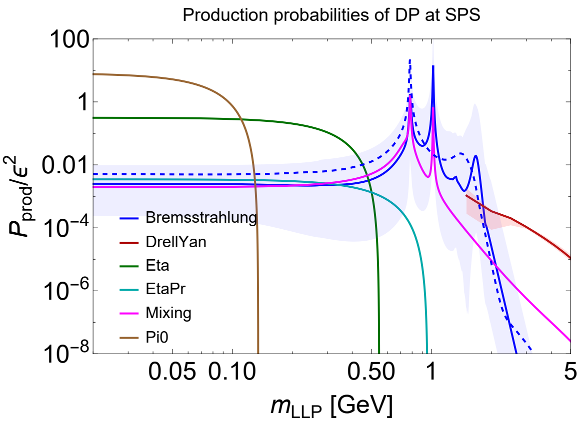
LLP phenomenology: examples IV



Bremsstrahlung [2409.09123]:

- Quasi-real approximation a-la Altarelli-Parisi [1904.10447]
- Free parameter – virtuality of the intermediate proton. Complicated to constrain it it by fitting data (e.g., inclusive ρ^0 production) because fragmentation also contributes
- Elastic proton form-factor in the ppV vertex: need to extrapolate the available data $q^2 < 0, q^2 > 4m_p^2$ to the "unphysical region" $0 < q^2 = m_V^2 < 4m_p^2$
  Heavy uncertainty from varying masses and widths of resonances contributing to the form factor within their measurement errors

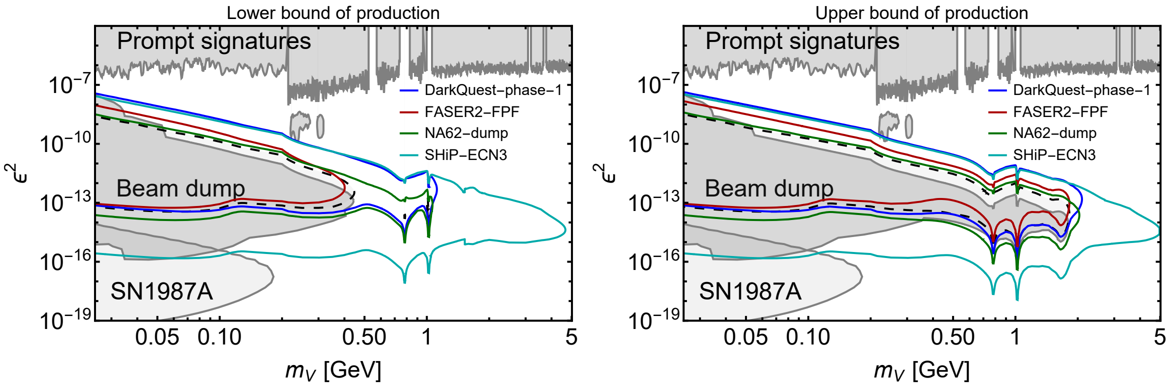
LLP phenomenology: examples V



– Impact of theoretical uncertainties on the production is large

[2409.11096]

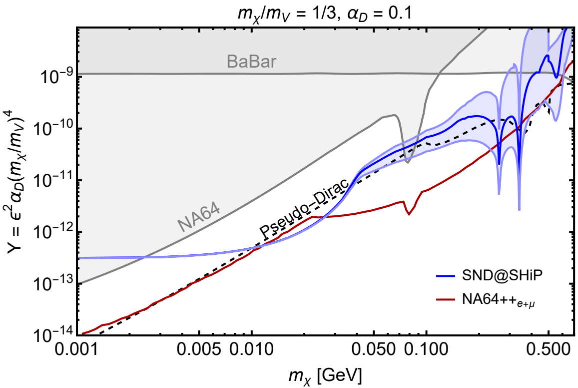
LLP phenomenology: examples VI



– This translates on the dark photon parameter space – both constraints and sensitivities

[2409.11096]

LLP phenomenology: examples VII



– The uncertainties translate to the parameter space of dark sectors whose interactions are mediated by dark photons

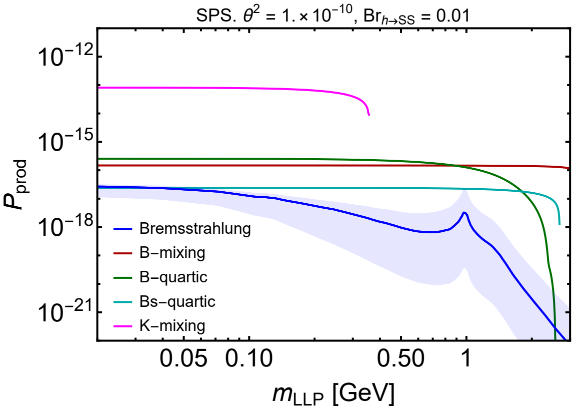
LLP phenomenology: examples VIII

Mediators coupled to the baryon current [1801.04847]:

- Similar status to the dark photon, but + 1 problem: no data for the elastic proton form factor to be used for extrapolation

  In progress

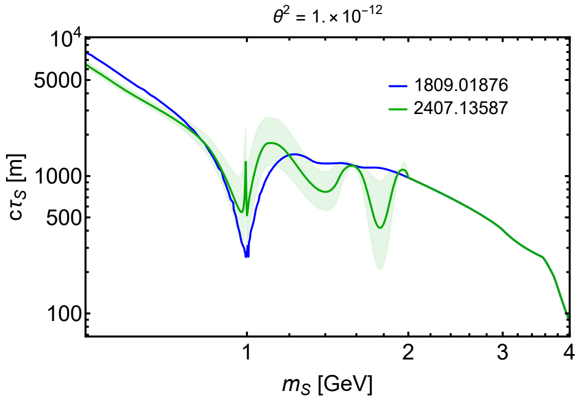
LLP phenomenology: examples IX



Higgs-like scalars $\boldsymbol{S}$ [1904.10447]:

– Production is dominated by exclusive processes: $\boldsymbol{h \to SS}$ and FCNC decays $\boldsymbol{B \to X_{s/d} + S/SS}$, $\boldsymbol{B_s \to SS}$, which are well understood

LLP phenomenology: examples X



- Decays: no data to extract directly, but the scattering data $\pi\pi \to \pi\pi$, $\pi\pi \to KK$ may be used to calculate the width using dispersion relation methods
- Issues: systematic uncertainties in the scattering phase shift significantly affect the calculations + only simplest decays modes ($S \to \pi\pi, KK$) can be studied this way

LLP phenomenology: examples XI

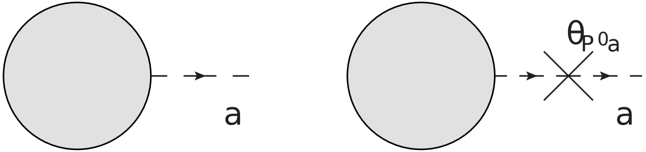
ALPs a [2012.12272], [1811.03474], [2310.03524], [2501.04525]:

- Start with the Lagrangian

$$\mathcal{L} = \frac{a}{f_a}\frac{\alpha_s}{4\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{\partial_\mu a}{f_a}\sum_f c_f \bar{f}\gamma^\mu\gamma_5 f \tag{6}$$

- Perform the chiral rotation $q \to e^{-i\gamma_5\kappa_q a/f_a}q$ with $\mathbf{tr}[\kappa_q] = 1$ eliminating the gluon coupling
- Make a correspondence between the resulting theory and ChPT Lagrangian $\mathcal{L}_{\mathbf{ChPT+a}}[\kappa_q]$ [2012.12272]
- Supplement the interactions with phenomenological Lagrangians describing interactions with other mesons
- Add FCNC couplings generated by the RG flow

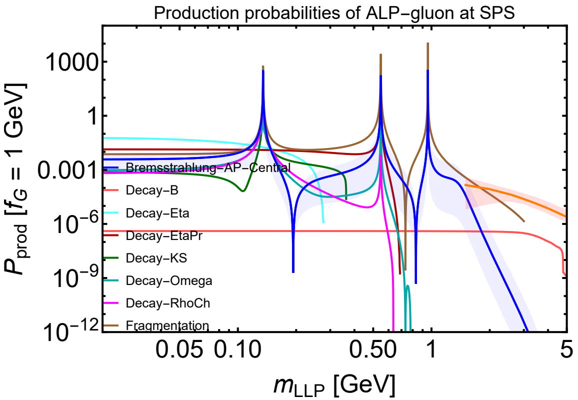
LLP phenomenology: examples XII

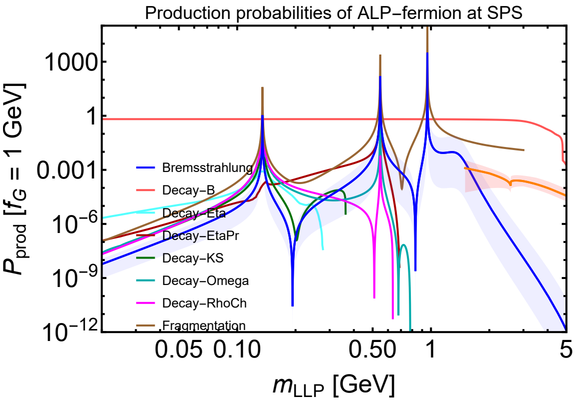


- Resulting Lagrangian must predict κ_q-independent observables [2102.13112] and include all pseudoscalar excitations
- Recipe when including arbitrary interactions [2501.04525]:

$$\mathcal{L}[\Sigma, P] \to \mathcal{L}\left[\exp\left(-ic_G \frac{a}{f_a}\kappa_q\right)\Sigma \exp\left(-ic_G \frac{a}{f_a}\kappa_q\right), P + c_G \frac{a}{f_a}\kappa_q\right] \tag{7}$$

LLP phenomenology: examples XIII





– For solely gluonic coupling, $\mathcal{L} = c_G\alpha_S/4\pi a/f_a G_{\mu\nu}\tilde{G}^{\mu\nu}$, the same issues in the production as for the dark photon [2501.04525]

– For the ALPs having coupling to fermions, FCNC decays of Bs dominate [2310.03524]

LLP phenomenology: examples XIV

- Decays: use phenomenological Lagrangian of interactions of various mesons from [1811.03474] and [2407.18348]
- Problem: mixing of ALPs with heavy pseudoscalar mesons ($\boldsymbol{\pi^0(1300), \eta(1295), \eta(1440)}$) is very sensitive to the operators for simplicity dropped in [2407.18348] when fitting to the data
- Theoretical uncertainties cannot be properly quantified without including these operators in the fits

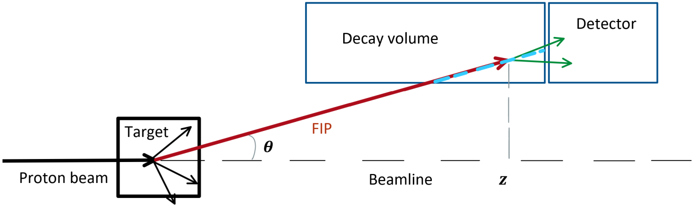
[2501.04525]

Conclusions

- Intensity frontier experiments allow directly seeing new physics particles with tiny couplings
- It is possible to observe thousands of events with GeV-scale new physics particles at these experiments and identify their properties
- However, it may be non-trivial to match the observed particle with some particular model because of theoretical uncertainties in the phenomenology
- Efforts from the theory community are needed to improve the situation

Backup slides

Lower and upper bound of the sensitivity of intensity frontier experiments I



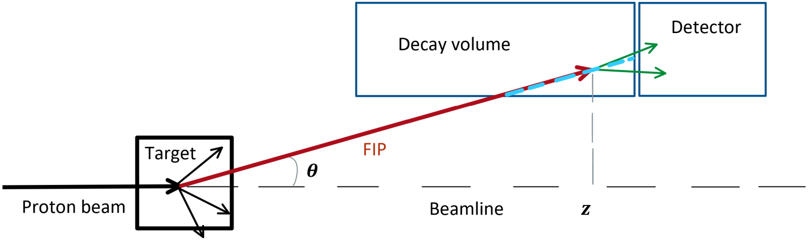
The event rate at the lower bound:

$$N_{\text{events}} \propto N_{\text{prod}} \times \epsilon_{\text{geom}} \times P_{\text{decay}} \times \epsilon_{\text{decay}} \times \epsilon_{\text{reco}} \propto$$

$$\propto N_{\text{pp}} \cdot \overbrace{\mathrm{P}_{\text{pp}\to\text{LLP}}}^{\propto g^2} \times \epsilon_{\text{geom}} \times \overbrace{\Delta z_{\text{fid}} \langle \gamma_{\text{LLP}}^{-1} \rangle}^{\propto g^2} \times \epsilon_{\text{decay}} \times \epsilon_{\text{reco}} \propto g^4 \quad (8)$$

N_{pp}: number of protons. χ_{mother}: rate of mother process per pp. ϵ_{geom}: fraction of LLPs pointing to the detector. Δz_{fid}: length of the decay volume. ϵ_{decay}: decay products acceptance

Lower and upper bound of the sensitivity of intensity frontier experiments II



– The decay probability at the upper bound:

$$P_{\text{decay}}(\gamma) \approx \exp[-L_{\text{min}}/c\tau\gamma] \tag{9}$$

L_{min}: distance from the LLP production point to the beginning of the decay volume

– $c\tau \propto g^{-2} \Rightarrow$ the position of the upper bound grows as $g^2_{\text{upper bound}} \propto \gamma_{\max}/L_{\min}$

What if not excluded but discovered? I

- Let us assume that we are not going to simply exclude the parameter space but actually discover a LLP. What can we learn about it?

A closer look on HNLs

- Two observable ν mass differences $\Rightarrow$ at least two different HNLs $N_{1,2}$ are required.
- HNL mass difference $\Delta m \equiv m_{N_1} - m_{N_2}$ may be arbitrary
- Small $\Delta m \ll m_{N_{1,2}} \approx m_N$ and similar U^2: $N_{1,2}$ form quasi-particle
- However, there are $N_1 \leftrightarrow N_2$ oscillations with frequency $\omega_{\text{osc}} = \Delta m^{-1}$
- Small Δm leads to a resonant enhancement of the lepton-violating processes in the Early Universe $\Rightarrow$ HNL-driven BAU becomes possible
- Depending on the mixing pattern $U_e^2 : U_\mu^2 : U_\tau^2$, may also provide masses to active neutrinos [0605047]

What if not excluded but discovered? II

A closer look on HNLs

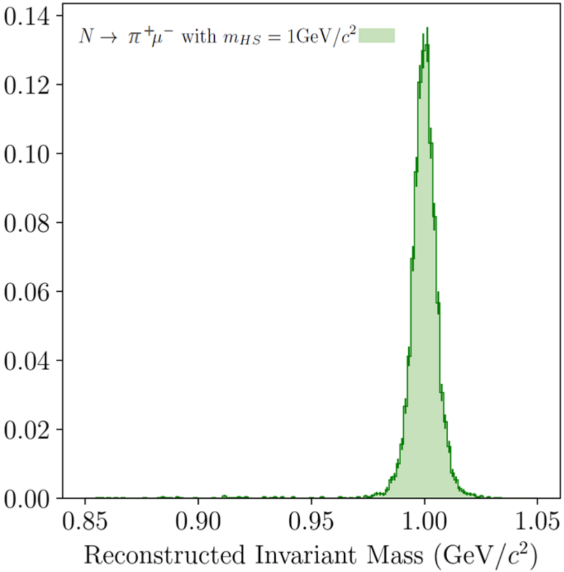
- N_1 effectively behaves as a particle and N_2 as an anti-particle, so oscillations lead to the lepton number violating (LNV) processes
- Three different types of behavior of $N_1 - N_2$ system depending on the scale L of the experiment ($l_{\text{osc}} = 2\pi/\omega_{\text{osc}}c$):
  - $l_{\text{osc}} \ll L$: $N_1 - N_2$ behaves as a single Majorana particle
  - $l_{\text{osc}} \gg L$: $N_1 - N_2$ behaves as a single Dirac particle
  - $l_{\text{osc}} \simeq L$: oscillations may be resolved within the experiment

Resolving HNL oscillations – insights on their relation to BAU

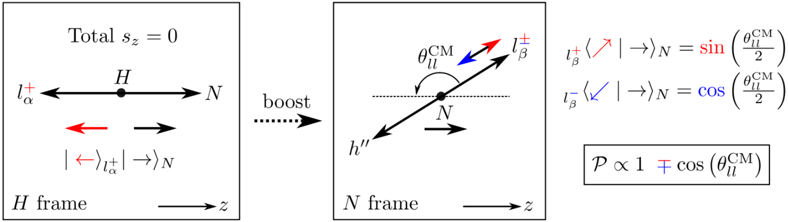
What if not excluded but discovered? III

– **HSDS**:
  - Reconstruct invariant mass
  - Identify decay modes ⇒ distinguishing various LLPs

10-100 events are required (this is why we need large intensity!)



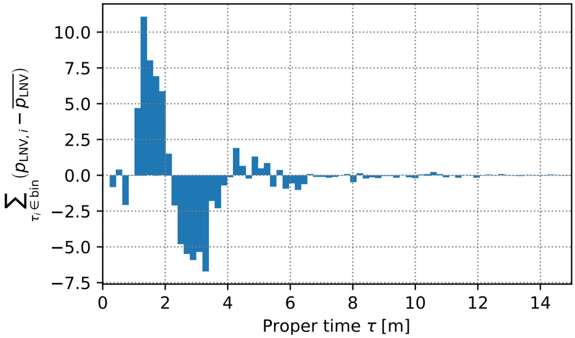
What if not excluded but discovered? IV



- Resolving oscillations requires distinguishing LNV and LNC (lepton number conserving) decays
- It would be easily done if one could get access to the production vertex *via, e.g., the leptons sign correlation in the chain* $B^\pm \to l^\pm + N$, $N \to l^\pm + \pi^\mp$
- This is impossible at SHiP. However, the information about the primary vertex is conserved by HNL helicity, which is related to the lepton number
- Helicity, in turn, affects the angular distribution of HNL decay products

What if not excluded but discovered? V

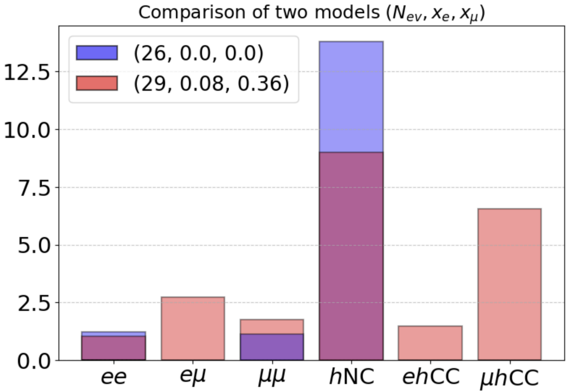
- So the analysis requires reconstructing the ratio of LNC/LNV events as a function of the decay length
- Given the complexity of HNL production modes, simple analytic arguments are not enough to distinguish the LNC and LNV events
- Multivariate analysis based on boosted decision trees has been performed in 1912.05520



For $l_{\text{osc}} \simeq L$, $\mathcal{O}(1000)$ events are required to extract Δm

What if not excluded but discovered? VI

- Are (would-be) discovered HNLs consistent with the normal or inverted hierarchy of neutrino masses?
- The quasi-HNL pair is characterized by its mixing pattern U_e, U_μ, U_τ

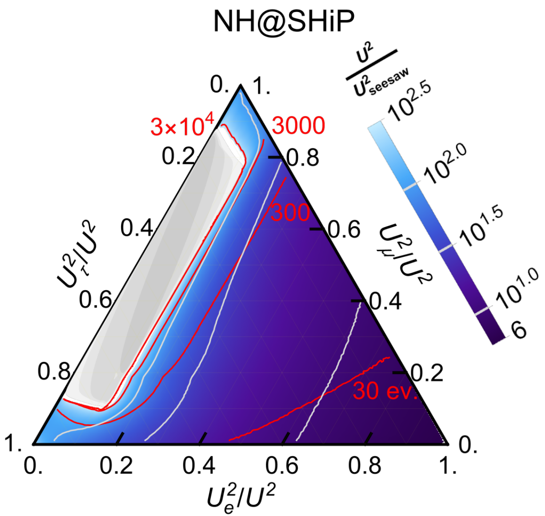


- In the limit $m_N U^2 \gg m_\nu$, the relative ratios $x_\alpha = U_\alpha^2/U^2$ depend only on the active neutrino parameters: measured θ_{ij}, δ_{CP}, Δm_{ij}^2, and a single unknown Majorana phase

What if not excluded but discovered? VII

A proof-of-principle analysis 2312.05163:

- Varying θ_{ij}, δ_{CP}, Δm^2_{ij} within uncertainty range, obtained the region of possible U^2_α/U^2 for the given ν mass hierarchy
- $100-1000$ events are required to test the neutrino hierarchy and extract the Majorana phase



How LLPs affect BBN I

- Ratio $X_n \approx n_n/(n_n + n_p)$ defines the helium abundance:

$$Y_{^4\text{He}} \approx 4\frac{n_{\text{He}}}{n_B} = 2X_n(T_{\text{BBN}}) \tag{10}$$

- Evolution of X_n: conversion $n \leftrightarrow p$ driven by weak interactions+neutron decays

$$\frac{dX_n}{dt} = \Gamma^{\text{weak}}_{p\to n}(T(t))(1 - X_n) - \Gamma^{\text{weak}}_{n\to p}(T(t))X_n \tag{11}$$

How LLPs affect BBN II

$$\frac{dX_n}{dt} = \Gamma^{\text{weak}}_{p\to n}(T(t))(1 - X_n) - \Gamma^{\text{weak}}_{n\to p}(T(t))X_n \tag{12}$$

1. Modifying time-temperature relation

- Dark radiation
- Decaying massive relic

How LLPs affect BBN III

$$\frac{dX_n}{dt} = \Gamma^{\text{weak}}_{p\to n}(T(t))(1 - X_n) - \Gamma^{\text{weak}}_{n\to p}(T(t))X_n \tag{13}$$

2. Disturbing properties of neutrinos

– Changing the neutrino-to-EM ratio:

$$\left.\frac{\rho_{\nu_e}}{\rho_{\text{EM}}}\right|_{T\gg m_e} \neq \frac{g_{*,\nu_e}}{g_{*,\gamma} + g_{*,\text{EM}}} = \frac{7}{22} \tag{14}$$

– Neutrino spectral distortions:

$$f_{\nu_e}(p,T) \neq \frac{1}{\exp[p/T_{\nu_e}] + 1} \tag{15}$$

– Neutrino-antineutrino asymmetry:

$$f_{\nu_e}(p,T) \approx \frac{1}{\exp[(p+\mu_{\nu_e})/T_\nu] + 1} \tag{16}$$

How LLPs affect BBN IV

$$\frac{dX_n}{dt} = \Gamma^{\text{weak}}_{p\to n}(T(t))(1 - X_n) - \Gamma^{\text{weak}}_{n\to p}(T(t))X_n \tag{17}$$

3. Modifying "constants" at MeV temperatures

- Varying the weak scale [2402.08626]
- Changing the neutron-proton mass difference [1401.6460]
- Variations of the gravitational constant [1910.10730]

How LLPs affect BBN V

$$\frac{dX_n}{dt} = (\Gamma^{\text{weak}}_{p\to n} + \Gamma^{\text{new}}_{p\to n})(T(t))(1 - X_n) - (\Gamma^{\text{weak}}_{n\to p} + \Gamma^{\text{new}}_{n\to p})(T(t))X_n \qquad (18)$$

4. Add new $p \leftrightarrow n$ processes

– Decays into metastable particles such as muons and mesons [1812.07585] [2008.00749]

Meson-driven conversion and BBN I

- $\sigma^{\text{meson}}_{p\leftrightarrow n}$ exceeds $\sigma^{\text{weak}}_{p\leftrightarrow n}$ by many orders of magnitude
- As far as even tiny amounts of LLPs are present in the plasma, we may drop the weak conversion rates
- Evolution for $X_n \equiv n_n/n_B$:

$$dX_n/dt = (1 - X_n)\Gamma^{\text{meson}}_{p\to n} - X_n\Gamma^{\text{meson}}_{n\to p} \tag{19}$$

- Dynamical equilibrium solution (valid until the amount of LLPs is hugely exponentially suppressed):

$$X_n(t) = \frac{\Gamma^{\text{meson}}_{p\to n}}{\Gamma^{\text{meson}}_{p\to n} + \Gamma^{\text{meson}}_{n\to p}} \tag{20}$$

Meson-driven conversion and BBN II

– Meson-driven rates:

$$\Gamma^{\text{meson}}_{N\to N'} = n_{\text{meson}} \cdot \langle \sigma^{\text{meson}}_{N\to N'} v\rangle \tag{21}$$

– Number density of mesons given by dynamic equilibrium:

$$n_{\text{meson}} \approx \frac{n_{\text{LLP}}}{\tau_{\text{LLP}}} \cdot \text{Br}_{\text{LLP}\to\text{meson}} \cdot P_{\text{conv}}, \quad P_{\text{conv}} \simeq \frac{n_B\langle \sigma^{\text{meson}}_{N\to N'} v\rangle}{n_B\langle \sigma^{\text{meson}}_{N\to N'} v\rangle + \tau^{-1}_{\text{meson}}} \tag{22}$$

– Depending on the meson, $P_{\text{conv}} = \mathcal{O}(0.1-1)$ at MeV temperatures

– Cross-sections $\langle \sigma^{\text{meson}}_{N\to N'} v\rangle$:

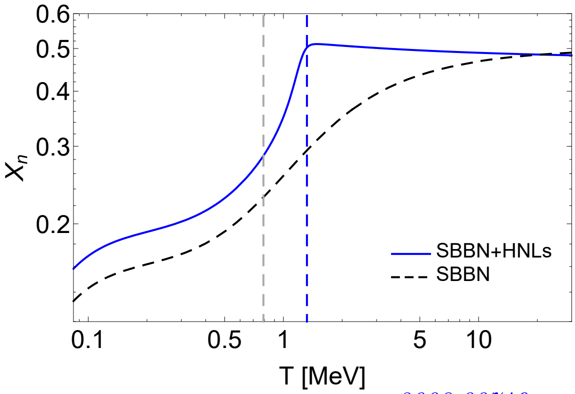
$$\langle \sigma^{\text{meson}}_{n\to p} v\rangle \simeq \sigma^{\text{meson}}_{p\to n} v\rangle \tag{23}$$

due to isospin symmetry

– As result, $X_n \simeq 1$ – much higher than in ΛCDM

Meson-driven conversion and BBN III

– Once mesons disappear, weak processes try to tend $\boldsymbol{X_n}$ to its ΛCDM value
– If weak reactions start decoupling, it is unsuccessful



2008.00749

Qualitative understanding of neutrino thermalization I

– The amount of energy that ends up in the EM plasma right after the injection of high-energy neutrinos is

$$\xi_{\mathrm{EM,eff}}(E_{\nu}^{\mathrm{inj}}, T) = \xi_{\mathrm{EM}} + \xi_{\nu} \times \epsilon(E_{\nu}^{\mathrm{inj}}, T), \tag{24}$$

where $\xi_{\nu} = 1 - \xi_{\mathrm{EM}}$ is the energy fraction that LLPs directly inject into the neutrino sector and ϵ is the effective fraction of ξ_{ν} that went to the EM plasma during the thermalization

*The latter quantity can be split in a contribution from non-equilibrium neutrinos ($\epsilon_{non\text{-}eq} = E_{\nu}^{non\text{-}eq \to EM}/E_{\nu}^{inj}$) and an **EM**pheffective contribution from thermal neutrinos ($\epsilon_{thermal} = E_{\nu}^{thermal \to EM}/E_{\nu}^{inj}$)*

– If $\epsilon > 0.5$, then $\xi_{\mathrm{EM,eff}} > 0.5$, and N_{eff} may become negative

Qualitative understanding of neutrino thermalization II

– A simple estimate of ϵ as a function of the injected neutrino energy $E_{\nu}^{\mathbf{inj}}$ and temperature T. We start with describing the thermalization process of a **EM**phsingle injected neutrino, which causes a cascade of non-equilibrium neutrinos. Such a cascade can result after the injected neutrino participates in the processes

$$\nu_{\text{non-eq}} + \nu_{\text{therm}} \to \nu_{\text{non-eq}} + \nu_{\text{non-eq}} \tag{25}$$
$$\nu_{\text{non-eq}} + \overline{\nu}_{\text{therm}} \to e^{+} + e^{-} \tag{26}$$
$$\nu_{\text{non-eq}} + e^{\pm} \to \nu_{\text{non-eq}} + e^{\pm}, \tag{27}$$

– Assume that in the processes (25) and (27) each non-equilibrium neutrino in the final state carries half of the energy of the non-equilibrium neutrino in the initial state.

– Thus, roughly speaking, the thermalization occurs during $N_{\text{therm}} \simeq \log_2(E_{\nu}^{\text{inj}}/3.15T)$ interactions

– In addition, the process (25) doubles the number of non-equilibrium neutrinos, while (26) makes neutrinos disappear and (27) leaves the number unchanged

Qualitative understanding of neutrino thermalization III

- Therefore, after the k-th step in the cascade, the average number of non-equilibrium neutrinos is given by:

$$\boldsymbol{N_\nu^{(k)} = N_\nu^{(k-1)}\left(2P_{\nu\nu\to\nu\nu} + P_{\nu e\to\nu e}\right) = N_\nu^{(0)}\left(2P_{\nu\nu\to\nu\nu} + P_{\nu e\to\nu e}\right)^k}, \tag{28}$$

with $\boldsymbol{N_\nu^{(0)} = 1}$, and the total non-equilibrium energy is:

$$\boldsymbol{E_\nu^{(k)} = E_\nu^{(k-1)}\left(P_{\nu\nu\to\nu\nu} + \frac{1}{2}P_{\nu e\to\nu e}\right) = E_\nu^{\text{inj}}\left(P_{\nu\nu\to\nu\nu} + \frac{1}{2}P_{\nu e\to\nu e}\right)^k}, \tag{29}$$

where $\boldsymbol{P_{\nu\nu\to\nu\nu}}$, $\boldsymbol{P_{\nu\nu\to ee}}$, **and** $\boldsymbol{P_{\nu e\to\nu e}}$ are the average probabilities of the processes (25)–(27), respectively, and their sum equals unity
- We define these probabilities as $\boldsymbol{P_i = \Gamma_i/\Gamma_\nu^{\text{tot}}}$, where Γ_i is the interaction rate of each process and $\boldsymbol{\Gamma_\nu^{\text{tot}}}$ is the total neutrino interaction rate.

Qualitative understanding of neutrino thermalization IV

– Assuming a Fermi-Dirac distribution for neutrinos and averaging over neutrino flavours, we find:

$$\boldsymbol{P_{\nu\nu\to\nu\nu} \approx 0.76, \quad P_{\nu\nu\to ee} \approx 0.05, \quad P_{\nu e\to\nu e} \approx 0.19} \tag{30}$$

– Finally, the value of $\epsilon_{\textbf{non-eq}}$ that accounts for the energy transfer from non-equilibrium neutrinos to the EM plasma is given by:

$$\boldsymbol{\epsilon_{\text{non-eq}} = \frac{1}{E_{\nu}^{\text{inj}}} \sum_{k=0}^{N_{\text{therm}}} \left(\frac{P_{\nu e\to\nu e}}{2} + P_{\nu\nu\to ee} \right) E_{\nu}^{(k)}} \tag{31}$$

– In addition to the transferred non-equilibrium energy, the non-equilibrium neutrinos catalyze the energy transfer from thermal neutrinos to the EM plasma via the processes (25) and (26).

Qualitative understanding of neutrino thermalization V

- We assume that each reaction (25) transfers an energy amount of $3.15T$ from the thermal neutrino sector to non-equilibrium neutrinos, which then via (26) ends up in the EM plasma
- Moreover, each reaction (26) contributes to another energy transfer of $3.15T$ from thermal neutrinos to the EM plasma
- The effective contribution coming from this transfer is therefore:

$$\boldsymbol{\epsilon_{\text{thermal}} = \frac{3.15T}{E_{\nu}^{\text{inj}}} N_{\nu}^{\text{therm}\to\text{EM}} =}$$
$$\boldsymbol{= \frac{3.15T}{E_{\nu}^{\text{inj}}} P_{\nu\nu\to ee}\left(\sum_{k=0}^{N_{\text{therm}}} N_{\nu}^{(k)} + \left[P_{\nu\nu\to\nu\nu} + \sum_{k=1}^{N_{\text{therm}}}(2P_{\nu\nu\to\nu\nu})^{(k)}\right]\right),} \tag{32}$$

where the first term in the round brackets is the contribution from the process (26) and the terms in the square brackets are the contribution from the process (25)
Note that the factor of 2 in the second sum accounts for the doubling of non-equilibrium neutrinos in the process (25).

State-of-the-art approach to solve the Boltzmann equation I

Special properties of neutrinos and EM particles

- Neutrino interaction cross-sections grow with energy:

$$\sigma_{\nu X}(s_{\nu X})v \sim G_F^2 s_{\nu X} \cdot v^2, \quad X = \nu, \bar{\nu}, e^{\pm} \tag{33}$$

- Neutrino thermalization rates are much smaller than the EM:

$$\frac{\Gamma_{\nu,\text{th}}}{\Gamma_{\text{EM,th}}} \sim \frac{n_\nu G_{\text{F}}^2 \langle s\rangle}{n_e \alpha_{\text{EM}}/T^2} \sim \frac{G_{\text{F}}^2}{\alpha_{\text{EM}}} T^4 \sim 10^{-20}\left(\frac{T}{1\text{ MeV}}\right)^4 \tag{34}$$

EM plasma is always in equilibrium while neutrinos thermalize slowly

What happens if heavy LLPs decay into neutrinos (so $E_\nu \gg 3.15T$)?

State-of-the-art approach to solve the Boltzmann equation II

Answer is in solving the unintegrated neutrino Boltzmann equation:

$$\partial_t f_{\nu_\alpha} - Hp\partial_p f_{\nu_\alpha} = \mathcal{I}_{\text{coll}} \tag{35}$$

State-of-the-art approach discretizes the comoving momentum space $y(t) = p \cdot a(t) \to \{y_i\}$, where $i = \overline{1, n}$ [9506015]:

$$\mathcal{I}_{\text{coll}} = \int G(\vec{x}) d^l \vec{x} = \prod_{k=1}^{l} \sum_{i_k=1}^{n} \tilde{G}, \quad l \geq 2 \tag{36}$$

Past studies are contradictory

- Some predict an increase of N_{eff} [0008138], [2104.11752]
- The others show a (mass- and lifetime-dependent) decrease [2103.09831] [2109.11176]

Direct simulation Monte Carlo I

- Idea: instead of solving Eqs. (35) explicitly, start with $N \gg 1$ particles – neutrinos, EM particles, new physics – and simulate their interactions
- In the physics of rarefied gases, the approach is known as **Direct Simulation Monte Carlo**, or **DSMC** [Physics of Fluids 31, 067104 (2019)]
- Immediate advantages of using Monte Carlo approach:
  - Free from $E_{\nu,\mathrm{max}}$ dependence
  - Phase space of decays/scatterings using accelerator particle physics (independently of the matrix element): `MadGraph`, `PYTHIA`, `SensCalc`
  - Rarefied gases field: high performance in the case of huge N

Direct simulation Monte Carlo II

Vanilla DSMC (utilizing so-called **No-Time-Counter method** [Prog.Astron.Aeron. 117, 211–226 (1989)]): at each time iteration,

0. Update the coordinates and velocities of particles due to external forces[1]
1. Split the system of volume V into cells containing N_{cell} particles
2. For each cell, per timestep Δt, sample

$$N_{\text{sample}} = \frac{1}{2} N_{\text{cell}}(N_{\text{cell}} - 1) \overbrace{\frac{(\sigma v)_{\max}}{V_{\text{cell}}}\Delta t}^{\omega_{\text{cell}}^{\max} \cdot \Delta t} \quad (37)$$

   pairs of particles to interact

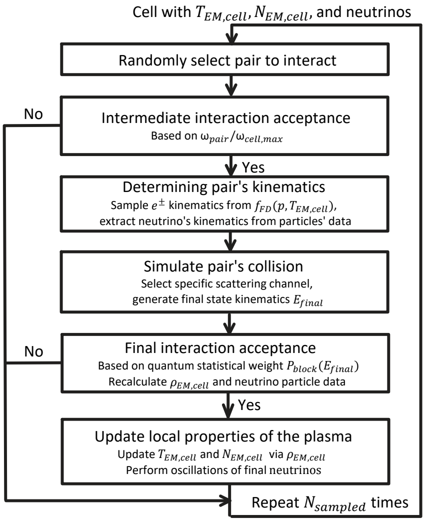
3. Iteratively: for each sampled pair, accept the interaction with the probability $P_{\text{acc}} = (\sigma v)_{\text{pair}}/(\sigma v)_{\max}$, generate the kinematics and final state if accepted

[1] Good news: no need to include the spatial degree of freedom for neutrinos

Neutrino DSMC I

To apply it to neutrinos, DSMC requires fundamental modifications:

1. **Expansion of the Universe**: redshift particles' momenta and system volume
2. **EM plasma properties**: represent the EM particles globally and at cell level by T_{EM}; update it after any interaction involving EM particles
3. **Quantum statistics**: final interaction approval decision based on the blocking factors $1 - f_{\mathrm{final}}(E_{\mathrm{final}})$ for the final states
4. **Decaying particles**: introduce N_{LLP} LLPs, decay $\Delta N_{\mathrm{LLP}} = N_{\mathrm{LLP}}(t)\Delta t/\tau$ particles per each timestep Δt, simulate decays e.g., in `SensCalc/PYTHIA8`



Neutrino DSMC II

- We have developed a **neutrino DSMC prototype** written in `Mathematica`+`C++`
- **Cross-checks:** comparing with the state-of-the-art approaches in the case of a few well-defined setups

Processes with mesons and muons I

- Consider first the case of muons μ. They do not efficiently interact with nucleons, but may annihilate instead:

$$\mu^+ + \mu^- \to e^+ + e^- \tag{38}$$

- Annihilation cross-section:

$$\sigma_{\text{ann}}^{\mu} = \frac{4\pi\alpha_{\text{EM}}^2}{m_\mu^2} \tag{39}$$

- Assume first that annihilation is irrelevant and decays dominate. Then, the muon number density available for annihilations may accumulate during the muon lifetimes τ_μ:

$$n_\mu^{\text{acc}} v \approx n_{\text{LLP}}(t)\frac{\tau_\mu}{\tau_X} \tag{40}$$

Processes with mesons and muons II

– Compare the annihilation and decay rates:

$$\frac{\Gamma_{\mu}^{\text{decay}}}{\Gamma_{\mu}^{\text{ann}}} = \frac{\tau_X}{n_X \tau_{\mu}^{-2} \sigma_{\text{ann}}^{\mu} v} \tag{41}$$

– Plugging in the numbers, we get

$$\frac{\Gamma_{\mu}^{\text{decay}}}{\Gamma_{\mu}^{\text{ann}}} = 3.4 \cdot 10^{-4} \cdot \frac{\tau_X}{0.05\text{ s}} \cdot \frac{0.1 n_{\text{UR}}}{n_X} \left(\frac{3\text{ MeV}}{T}\right)^3 \tag{42}$$

– This means that annihilation is actually highly competitive to decay and dominate until n_X gets enormously suppressed

Processes with mesons and muons III

- Now, consider pions. Their lifetime is two orders of magnitude smaller, but the annihilation cross-section is larger in a comparable way (proceeds via strong interactions)
- In addition, there is the (thresholdless) interaction with nucleons:

$$\pi^+ + n \to p + \pi^0\gamma, \quad \pi^- + p \to n + \pi^0/\gamma \tag{43}$$

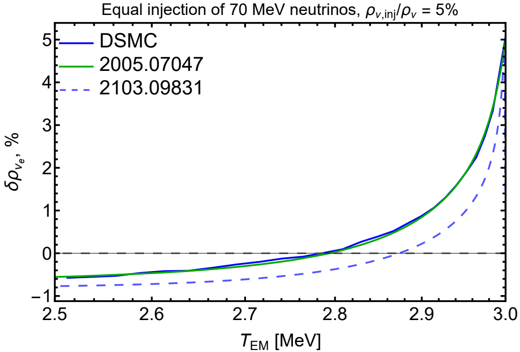
- Cross-section is [Phys. Rev. D 37, 3441]

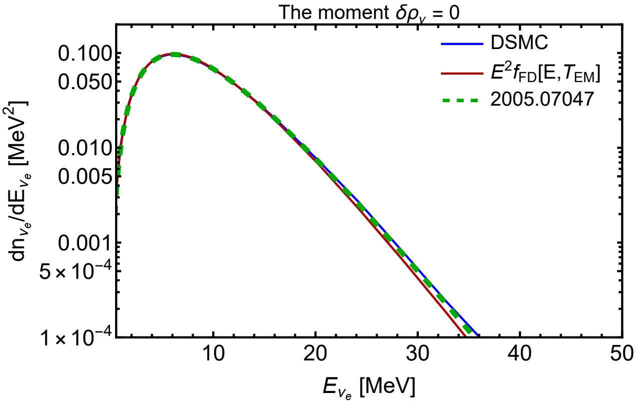
$$\langle \sigma_{\mathrm{nucl}}\beta \rangle \simeq 1.5 \text{ mb} \simeq 4 \text{ GeV}^{-2} \tag{44}$$

- Compare the decay rate with the rate of the interaction with nucleons:

$$\frac{\Gamma_\pi^{\mathrm{decay}}}{\Gamma_\pi^{\mathrm{nucl}}} = \frac{1}{\tau_\pi n_B X_n \sigma_{\mathrm{nucl}} v} \simeq \left(\frac{3 \text{ MeV}}{T}\right)^3 \cdot \frac{10^{-9}}{\eta_B} \tag{45}$$

Impact of neutrino non-thermality and mesons disappearance I

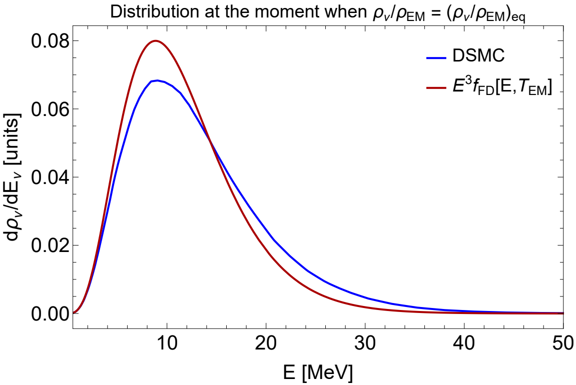




- Consider a toy scenario: instant injection of high-energy neutrinos $\boldsymbol{E_\nu \gg 3T}$ at a temperature when neutrinos start decoupling
- Introduce the quantity $\boldsymbol{\delta\rho_\nu = (\rho_\nu/\rho_{\mathrm{EM}})/\rho_\nu = (\rho_\nu/\rho_{\mathrm{EM}})_{\mathrm{SM}} - 1}$
- $\boldsymbol{\delta\rho_\nu}$ is positive right after injection but quickly drives to negative values. Why?

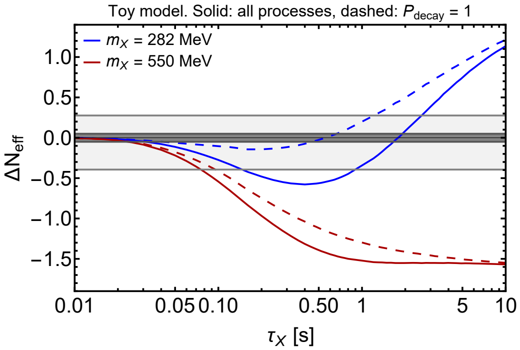
Impact of neutrino non-thermality and mesons disappearance II

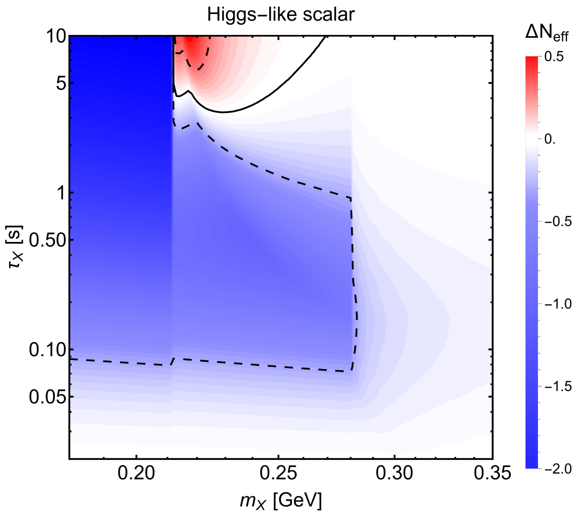
- Interactions of high-energy νs when $\delta\rho > 0$: much faster than thermal interactions ($\sigma_{\text{int}} \sim s$)
- They will either pump the energy to the EM plasma or interact with thermal neutrinos
- The EM plasma thermalizes instantly $\Rightarrow$ no fast inverse reactions
- Characteristic change in actual $p^3 f_\nu(p)$ compared to $p^3 f_{\text{FD}}$:
  - **Overrepresented** at high p
  - **Underrepresented** at low p



At $\delta\rho_\nu = 0$, distortions cause the shift $\nu \to$ EM $\Rightarrow \delta\rho_\nu^{\text{fin}} < 0$

Impact of neutrino non-thermality and mesons disappearance III





- Combined impact of metastable dynamics and non-thermal neutrinos: ΔN_{eff} changes sign
- Effects of mesons disappearance: severe quantitative impact

[2411.00931],[2411.00892]