# Dirac vs. Majorana HNLs (and their oscillations) at SHiP

arXiv: 1912.05520

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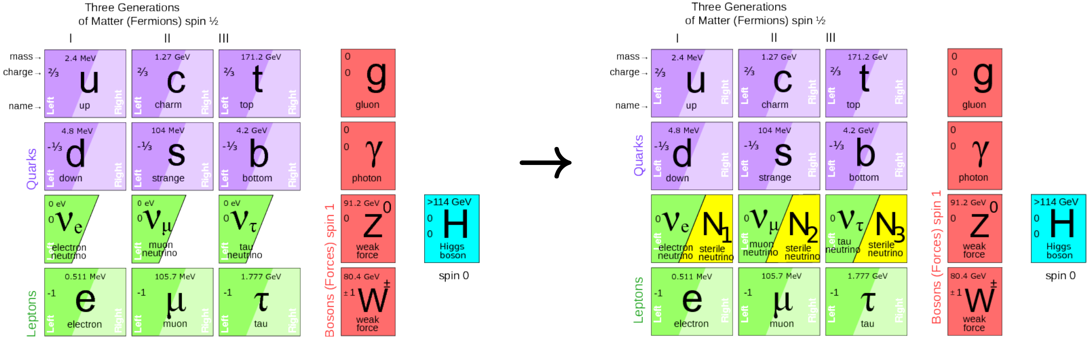
# Feebly interacting particles

- While we wait for the next hadron collider (FCC-hh: 2040–2060) to probe the *energy frontier*, let's explore the *intensity frontier* using low-energy, high-intensity experiments.
  $\rightarrow$ C.f. Oleg's talk this morning.
- **Feebly interacting particles (FIPs):** particles interacting with the SM with a suppressed coupling. The new degrees of freedom are typically *SM singlets*.

### FIP candidates

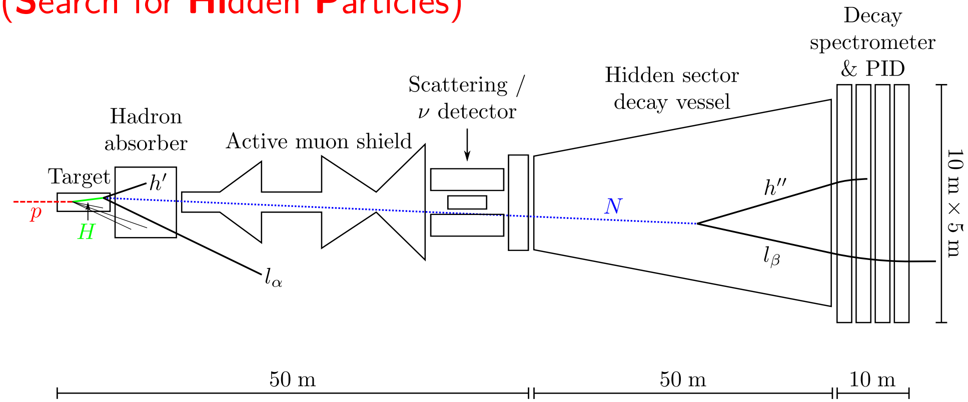
- Renormalizable portals (mix with interacting SM states, or interact with small coupling):
  1. Spin $0$: scalar portal (dark Higgs).
  2. Spin $\frac{1}{2}$: neutrino portal (heavy neutral lepton).
  3. Spin $1$: vector portal (dark photon).
- Non-renormalizable portals (interact through higher dimensional operators):
  - Axion-like particles.
  - ...

# Heavy Neutral Leptons (HNLs)




- HNLs can explain neutrino masses and oscillations (maybe: baryogenesis, dark matter).
- They interact via mixing with flavor eigenstates: $\nu_\alpha = U^{\text{PMNS}}_{\alpha i}\nu_i + \Theta_{\alpha I} N_I$, $\Theta \ll 1$.
- Largely constrained below the kaon mass, the neutrino portal will be probed at the GeV scale by the proposed SHiP experiment.

# SHiP (Search for Hidden Particles)

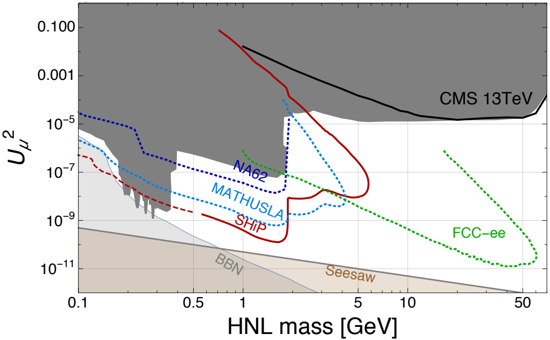



- Low-background (0.1 evts.) beam-dump experiment @ 400 GeV SPS; $2 \cdot 10^{20}$ POT in 5 yr.
- Comprehensive Design Study for SHiP and Beam Dump Facility submitted last December.
- SHiP aims to *observe* HNLs, and *measure* their mass and mixing angles.

*What else can we learn about the properties of HNLs at SHiP?*

# Detour: realistic HNL benchmarks

Sensitivity study [1811.00930] / PBC [1901.09966] assume one Majorana HNL, mixing with one generation only.



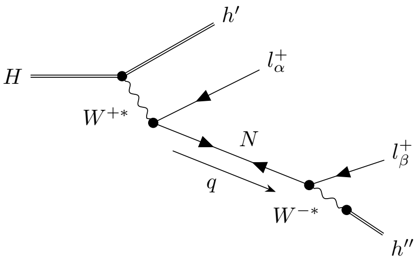

**But:**

- $\nu$ masses generated by see-saw mechanism:

$$m_{\alpha\beta} \cong -\sum_I M_I \Theta_{\alpha I} \Theta_{\beta I}$$

- For one HNL, the seesaw limit is a prediction: E.g. for a 1 GeV HNL, we expect $|\Theta|^2 \sim 10^{-10}$!
- To generate two distinct $\Delta m^2$, at least two HNLs are needed, mixing with at least two generations.
- If multiple HNLs are degenerate as in the $\nu$MSM, their mixing angles can be large.

# Majorana HNLs




- New states: SM singlets w/ Majorana mass term.
- Massive states: Majorana *particles*.
  $\Rightarrow$ Can violate lepton number.
- If we want large mixing angles and correct neutrino masses, lepton number violating (LNV) effects may be suppressed (Shaposhnikov [hep-ph/0605047], Kersten and Smirnov [0705.3221]).

- *Is there any hope of observing LNV at all? At SHiP?*
- Yes & yes!
- We might even measure the mass splitting!

# Main idea

- If there are two quasi-degenerate HNLs, they can oscillate among themselves.
- Oscillations in the sterile sector can be lepton number violating. For $|\Theta|^2 \gg m_\nu / M_M$,

$$\text{LNC rate } \propto 1 + \cos(\delta M \tau)$$
$$\text{LNV rate } \propto 1 - \cos(\delta M \tau)$$

- To observe them, we need to remember that HNLs are *long-lived*.
- Whether LNV is observable depends on the **mass splitting** $\delta M$ and **proper lifetime** $\tau$:

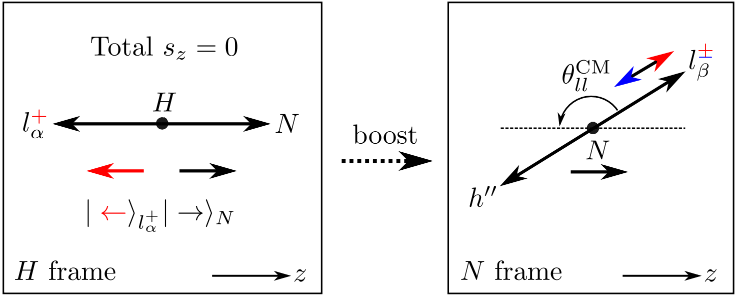
$$\delta M \tau \ll 2\pi \;\Rightarrow\; \text{LNC only}$$
$$\delta M \tau \gg 2\pi \;\Rightarrow\; \text{LNC + LNV with equal integrated rates}$$
$$\delta M \tau \sim 2\pi \;\Rightarrow\; \text{Potentially resolvable oscillations}$$

**Consequences of HNL oscillations**

- LNV may be suppressed (especially at large mass, cf. Drewes, Klarić, Klose [1907.13034]).
  $\Rightarrow$ existing bounds relying on LNV might not be valid.
- Observation of LNV (or LNC only) constrains the number and mass splitting of HNLs.

# Distinguishing LNC / LNV events at SHiP

- Most production processes are $H \to [h'] l_\alpha N$.
- We select the fully reconstructible decay channels $N \to l_\beta \pi$.
- Can we compare the lepton charges?
  $\to$ No! Because the primary decay takes place inside the target.
- HNLs carry not only lepton number, but also spin $\frac{1}{2}$ $\longrightarrow$ look at angular distributions.
- It turns out LNC / LNV processes have very different kinematics! E.g. for 2-body decays:




$$l_\beta^+ \langle \nearrow | \rightarrow \rangle_N = \sin\left(\frac{\theta_{ll}^{\mathrm{CM}}}{2}\right)$$

$$l_\beta^- \langle \swarrow | \rightarrow \rangle_N = \cos\left(\frac{\theta_{ll}^{\mathrm{CM}}}{2}\right)$$

$$\mathcal{P} \propto 1 \mp \cos\left(\theta_{ll}^{\mathrm{CM}}\right)$$

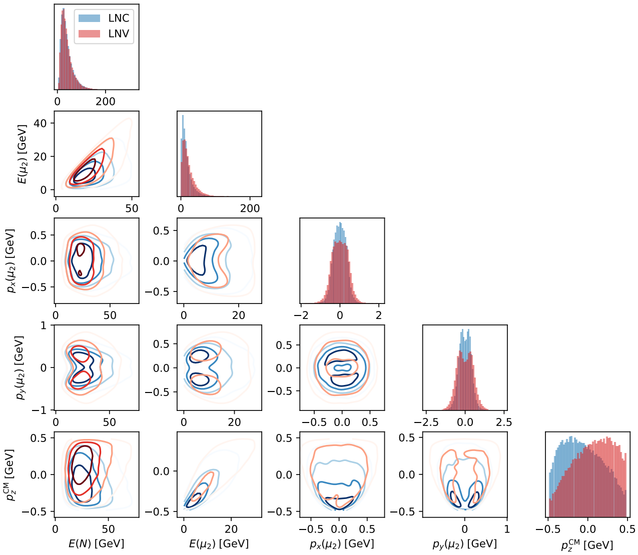
# Complications

- Not all production processes are 2-body decays.
- Decay products ($l_\alpha$, $l_\beta$, $\pi$) are not massless $\Rightarrow$ helicity flips are possible.
- Heavy mesons are not monochromatic $\Rightarrow$ smears out the distribution of decay products.
- We need to take geometrical acceptance into account.

- **To handle these complications, we need a Monte-Carlo simulation!**
- We use our own Monte-Carlo because we need finer control (tracking spin correlations) over matrix elements compared to what Pythia provides.

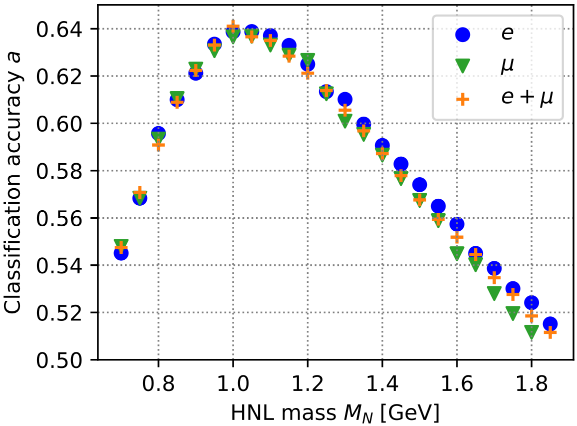
# LNC / LNV distributions

- Most 2/3-body decays implemented.
- $D$-meson spectra from the LEBC-EHS experiment at the SPS @ 400 GeV.
- Basic propagation and geometrical acceptance cuts.
- Different distributions $\Longrightarrow$ can be distinguished given enough events.



# We can discriminate these processes using boosted decision trees

- Generate $3 \cdot 10^6$ events for each mass, split $0.5 : 0.2 : 0.3$ into training / validation / test.
- We use the LightGBM gradient boosting algorithm.
- Accuracy is highest when the HNL kinetic energy in CM $\gtrsim$ heavy meson $p_T$ spread.



# How to quantitatively distinguish Majorana / Dirac?

## Hypotheses we want to distinguish

1. $\mathcal{H}_1$ (Dirac-like): HNLs are Dirac or quasi-Dirac with $\delta M \tau \ll 2\pi$ (LNC only).
2. $\mathcal{H}_2$ (Majorana-like): HNLs are Majorana or quasi-Dirac with $\delta M \tau \gg 2\pi$ (LNC + LNV).

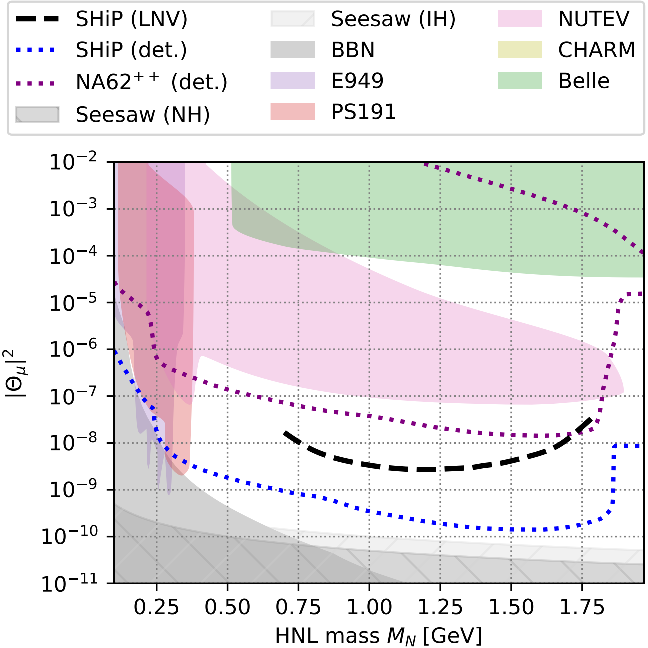
## Model-selection sensitivity

- **Assumptions:** The mass $M_N$ and $U_e^2 : U_\mu^2$ ratio have roughly been measured.
- Compute the likelihood of each hypothesis based on the classifier decisions and accuracy.
- Considering in turn each hypothesis as the null hypothesis, draw the "model-selection" sensitivity curve where SHiP has a $1/2$ probability of excluding this hypothesis at $90\%$ CL if the other is true, after $5$ years of nominal operation i.e. $2 \cdot 10^{20}$ POT.

# Model-selection sensitivity

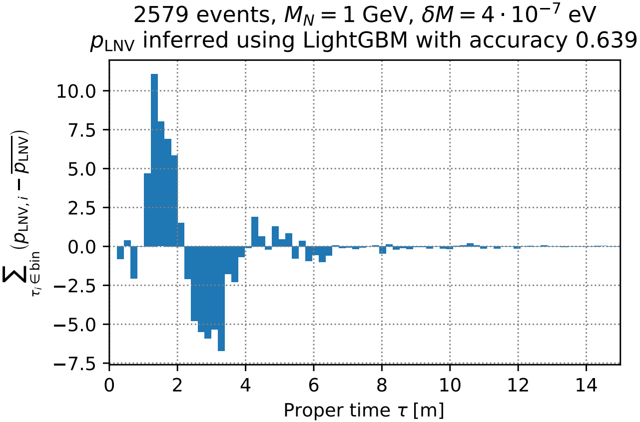
- Dashed line:
  model-selection sensitivity.
- Colored areas:
  existing exclusion bounds
- Dotted lines: future experiments that can reconstruct the HNL mass.
- Hatched areas:
  seesaw lower bound.

Source: Physics Beyond Colliders report (arXiv: 1901.09966)



# Resolving HNL oscillations

- Simultaneous requirement of BAU and DM production in the $\nu$MSM suggests $\delta M$ that could be resolved at SHiP (Canetti and Shaposhnikov [1208.4607]).
- Bin events in proper time, weight them by $P(\mathrm{LNV})$ and subtract the sample average:
- Period of oscillations is $2\pi/\delta M$. Allows measuring the mass splitting.



# Conclusion

For mixing angles $|\Theta|^2 \gtrsim 10^{-9}$–$10^{-8}$, we can expect many fully reconstructed HNL events.

In this region, SHiP can:

- Test the Majorana nature of HNLs,
- If we are lucky, resolve the mass splitting $\delta M$,

... even if current / next-generation experiments like NA62$^{++}$ do not observe any HNLs.

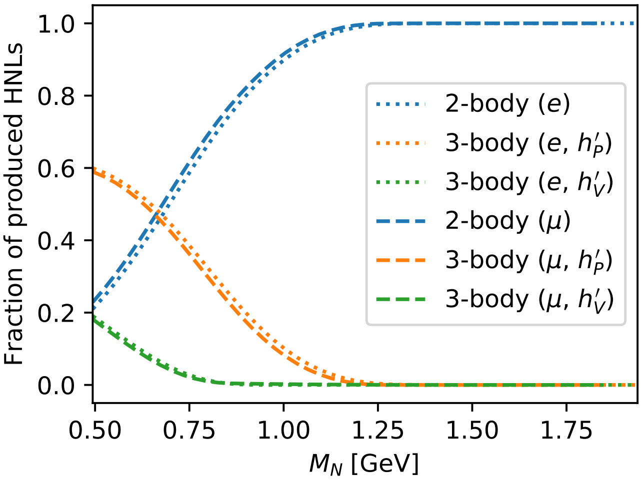
This could help determine the number of nearly-degenerate HNLs (needed to measure $|\Theta_\alpha|^2$).

Along with the HNL mass / mixing angles, this would make the $\nu$MSM cosmology predictive.

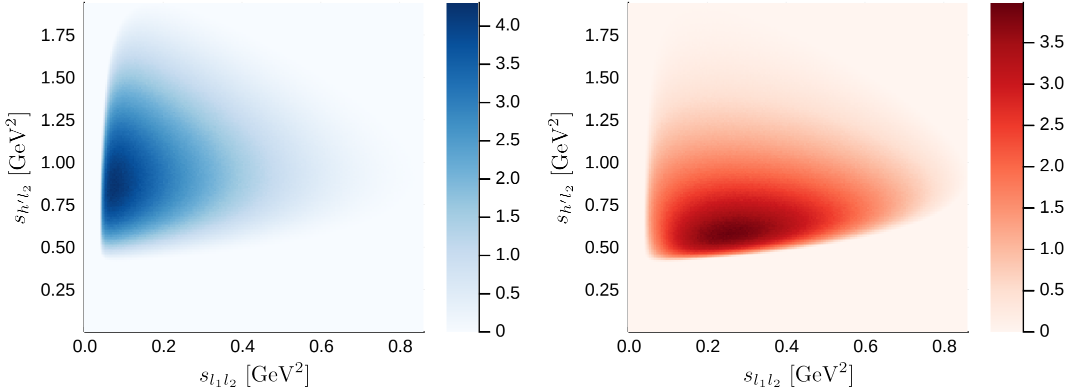
# Related works


- Gorazd Cvetic, Claudio Dib, and C. S. Kim. "Probing Majorana neutrinos in rare pi+ to e+ e+ mu- nu decays". In: *Journal of High Energy Physics* 2012.6 (June 2012), p. 149. arXiv: 1203.0573
- Gorazd Cvetic and C. S. Kim. "Rare decays of B mesons via on-shell sterile neutrinos". In: *Physical Review D* 94.5 (Sept. 2, 2016), p. 053001. arXiv: 1606.04140
- Carolina Arbelaéz et al. "Probing the Dirac or Majorana nature of the Heavy Neutrinos in pure leptonic decays at the LHC". In: *Physical Review D* 97.5 (Mar. 7, 2018), p. 055011. arXiv: 1712.08704
- Claudio O. Dib, C. S. Kim, and Kechen Wang. "Signatures of Dirac and Majorana Sterile Neutrinos in Trilepton Events at the LHC". In: *Physical Review D* 95.11 (June 16, 2017), p. 115020. arXiv: 1703.01934
- A. Baha Balantekin, André de Gouvêa, and Boris Kayser. "Addressing the Majorana vs. Dirac Question with Neutrino Decays". In: *Physics Letters B* 789 (Feb. 2019), pp. 488–495. arXiv: 1808.10518
- P. Hernández, J. Jones-Pérez, and O. Suarez-Navarro. "Majorana vs Pseudo-Dirac Neutrinos at the ILC". In: *The European Physical Journal C* 79.3 (Mar. 2019), p. 220. arXiv: 1810.07210
- Peter Ballett, Tommaso Boschi, and Silvia Pascoli. "Heavy Neutral Leptons from low-scale seesaws at the DUNE Near Detector". In: *arXiv:1905.00284 [hep-ph]* (May 1, 2019). arXiv: 1905.00284

# Fraction of produced HNLs by multiplicity and spin

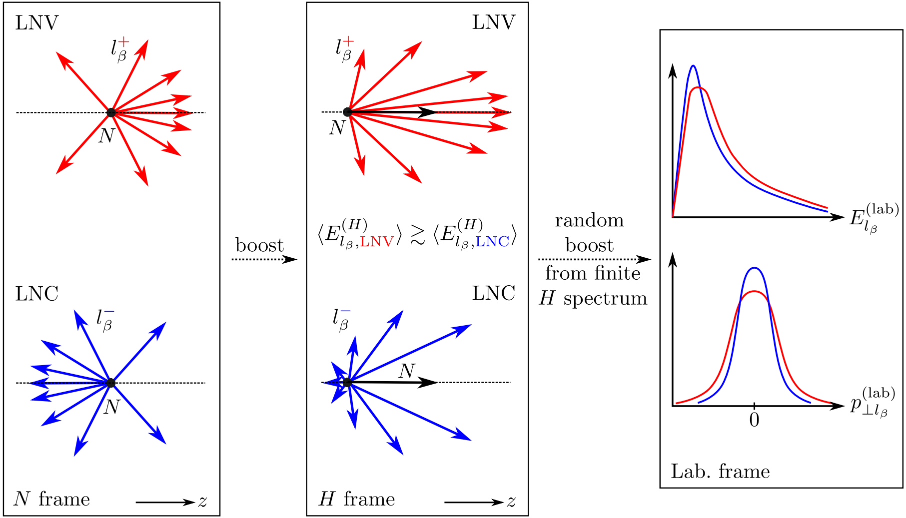


# LNC vs. LNV


1.75
1.50
1.25
1.00
0.75
0.50
0.25
$s_{h'l_2}$ [GeV$^2$]
0.0
0.2
0.4
0.6
0.8
$s_{l_1l_2}$ [GeV$^2$]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
1.75
1.50
1.25
1.00
0.75
0.50
0.25
$s_{h'l_2}$ [GeV$^2$]
0.0
0.2
0.4
0.6
0.8
$s_{l_1l_2}$ [GeV$^2$]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0

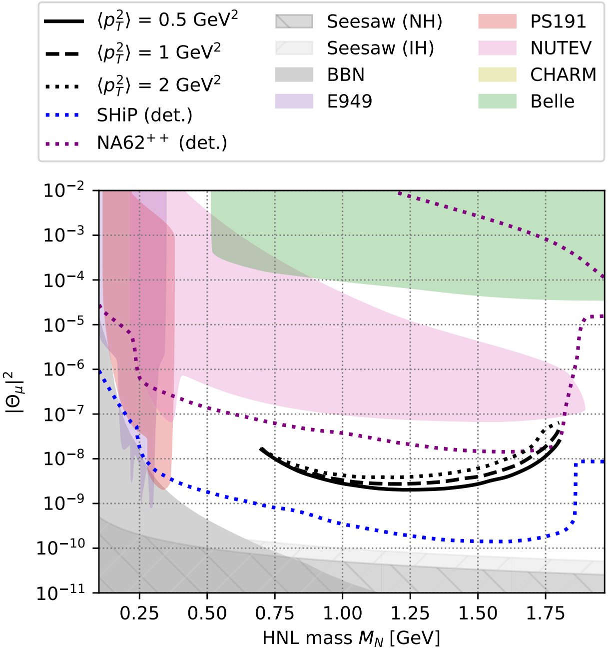
# Angular distribution in the lab frame

- In the lab frame, the meson spectrum smears out the effect along $z$, but not necessarily $p_T$.
- If the HNL $p_T$ (CM) is larger than the heavy hadron $p_T$ spread (lab), a difference is visible.

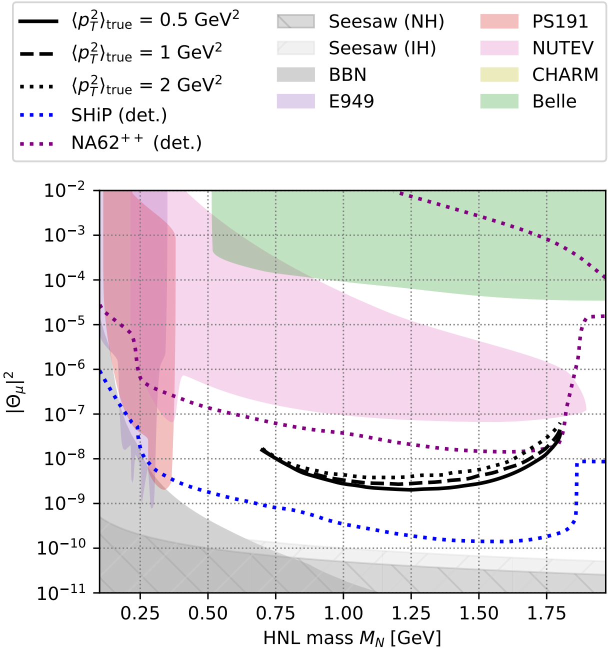


# Impact of meson $p_T$ spread

- Higher $\langle p_T^2 \rangle$
  $\Longrightarrow$ lower accuracy
  $\Longrightarrow$ curve moves upward
- Solid line:
  best fit from LEBC-EHS



# Systematic uncertainty on $\langle p_T^2 \rangle$




- What if the real spectrum is different from the simulated one used for training?
- The accuracy mostly depends on the real spectrum, not the one used for training.
- Solid line:
  best fit from LEBC-EHS