

Discovering the Origin of Neutrino Masses at SHiP

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2023 Phenomenology Symposium
University of Pittsburgh
05/08/2023

Based on:
[arXiv:2305.00017](https://arxiv.org/abs/2305.00017) w/ Seyda Ipek

Discovery

Long-lived Pseudo-Dirac Bino in a $U(1)_{R-L}$ Extension of the MSSM at the SHiP Experiment

SHiP

masses at

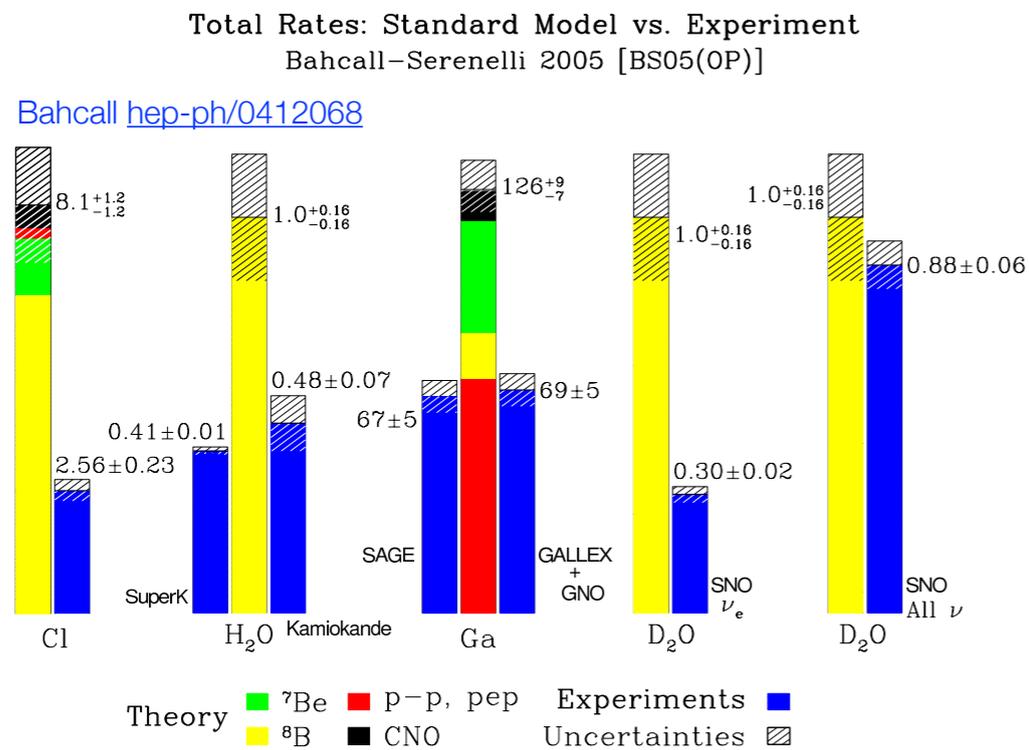
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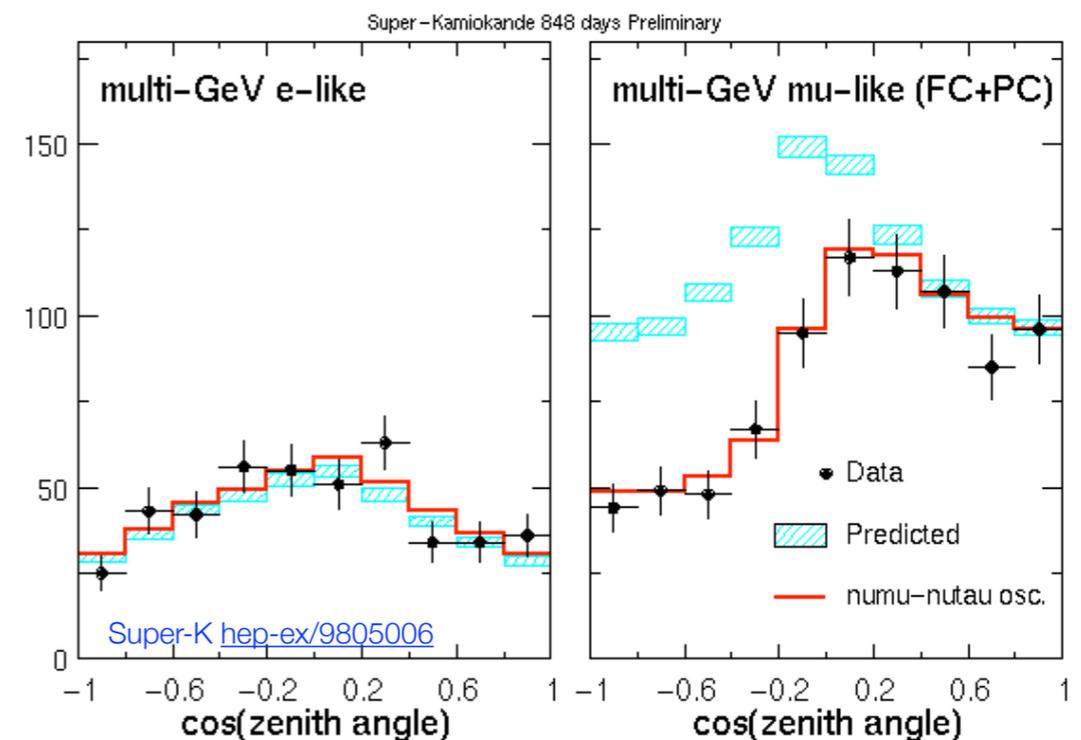
Evidence for Neutrino Masses

Solar Neutrinos



$$\Delta m_{\text{sol}}^2 \simeq 7.4 \times 10^{-5} \text{ eV}^2$$

Atmospheric Neutrinos



$$\Delta m_{\text{atm}}^2 \simeq 2.5 \times 10^{-3} \text{ eV}^2$$

Two separate neutrino mass differences implies that at least two SM neutrinos have non-zero mass

Neutrino Mass Generation

1) Seesaw Mechanism - introduce RH neutrinos N_R

$$\mathcal{L} \supset Y \bar{L} \tilde{H} N_R + \frac{1}{2} M_N \bar{N}_R N_R \xrightarrow{\text{EWSB}} m_D \bar{\nu}_L N_R + M_N \bar{N}_R N_R$$

Dirac Mass $m_D = vY/\sqrt{2}$

Majorana Mass: M_N

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \rightarrow m_\nu \simeq \frac{Y^2 v^2}{M_N}$$

Neutrino masses *inversely proportional to Majorana mass*



Credit: [Symmetry Magazine](#)

If $Y \sim 1$, correct SM neutrino masses for $M_N \sim 10^{14}$ GeV
 If $M_N \sim 1$ GeV, correct SM neutrino masses for $Y^2 \sim 10^{-14}$
 Hard to test experimentally in both cases :(

Neutrino Mass Generation

- 2) Inverse Seesaw Mechanism - neutrinos are Pseudo-Dirac particles.
Introduce two SM singlets: N, N' with lepton number $L = +1, -1$

$$\mathcal{L} \supset Y \bar{L} \tilde{D} N + M_D \bar{N} N'^c$$

Lepton Number Conserving

$$Y' \bar{L} \tilde{H} N' + \mu \bar{N} N^c + \mu' \bar{N}' N'^c$$

Lepton Number Violating

Neutrino masses become
proportional to the Majorana mass

$$m_\nu \sim \frac{Y Y' v^2}{M_D} + \mathcal{O}\left(\frac{Y^2 \mu v^2}{M_D^2}\right)$$

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Wishlist

1. Detectable, TeV scale RH neutrinos $\rightarrow Y \sim 1, M_D \sim \text{GeV} - \text{TeV}$
2. Approximate lepton number conservation e.g $Y' \sim 10^{-12} \rightarrow \mu \sim \text{keV}$

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I love numerology. But where do these hierarchies actually come from??

$U(1)_{R-L}$ Symmetric SUSY*

- Extend the MSSM by $U(1)_{R-L}$ *global symmetry*
- SM particles are not charged under the R -symmetry.

MSSM Field Content

Superfields	$U(1)_R$	$U(1)_{R-L}$
L_i	1	0
E_i^c	1	2
H_u	0	0
$W_{\tilde{B}}^\alpha$	1	1

Q1: Bino has +1 $U(1)_R$ charge \rightarrow can not write down a mass term??

Q2: How is all this connected to neutrino masses??

Ingredients for Neutrino Masses

- 1 Fermionic partner with $-1 U(1)_R$ charge — the **singlino S**
- 2 SUSY breaking sources:

(1) SUSY breaking in a hidden sector at the **scale Λ_M**

$$\int d^2\theta \frac{W'_\alpha}{\Lambda_M} W_{\tilde{B}}^\alpha \Phi_S \rightarrow M_{\tilde{B}} \tilde{B} S \quad \text{Dirac mass for bino-singlino!}$$

(2) $U(1)_{R-L}$ global symmetry breaking from gravity

- 1 gravitino with mass $m_{3/2}$
- 2 LNV **Majorana mass terms**

$$m_{\tilde{B}} \tilde{B} \tilde{B} + m_S S S \quad \text{with} \quad m_{\tilde{B}} \sim m_S \sim m_{3/2} \ll M_{\tilde{B}}$$

If $U(1)_{R-L}$
approximately
conserved



Also, dark matter
motivates $m_{3/2} \sim \text{keV}$

Ingredients for Neutrino Masses

- 2 higher dimensional operators

$$\frac{f_i}{\Lambda_M^2} \int d^2\theta W'_\alpha W_{\tilde{B}}^\alpha H_u L_i \rightarrow f_i \frac{M_{\tilde{B}}}{\Lambda_M} \ell_i h_u \tilde{B}$$

$$\frac{d_i}{\Lambda_M} \int d^4\theta \phi^\dagger \Phi_S H_u L_i \rightarrow d_i \frac{m_{3/2}}{\Lambda_M} \ell_i h_u S$$

\tilde{B} and S act like RH neutrinos!

Dirac Mass: $m_D = \frac{vY}{\sqrt{2}}$

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- Combine ingredients into a full Lagrangian. Cook until ISS completely realized.

$$\mathcal{L} \supset f_i \frac{M_{\tilde{B}}}{\Lambda_M} \bar{\ell}_i h_u \tilde{B} + M_{\tilde{B}} \tilde{B} S$$

This is exactly the ISS Mechanism!

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Small lepton
number violation
keV/TeV $\sim 10^{-9}$

Small Majorana
masses
 $m_{\tilde{B}} \sim m_S \sim m_{3/2}$

All hierarchies
are explained!

Neutrino Masses via ISS

- Neutrino masses generated from the ISS

$$\mathbb{M} = \begin{pmatrix} 0_{3 \times 3} & \mathbf{Y}v & \mathbf{G}v \\ \mathbf{Y}^T v & m_{\tilde{B}} & M_{\tilde{B}} \\ \mathbf{G}^T v & M_{\tilde{B}} & m_S \end{pmatrix} \implies \begin{aligned} m_1 &= 0 \\ m_2 &= \frac{m_{3/2} v^2}{\Lambda_M^2} (1 - \rho) \\ m_3 &= \frac{m_{3/2} v^2}{\Lambda_M^2} (1 + \rho) \end{aligned}$$

- The mixing parameters f_i , d_i are fixed by the measured SM neutrino mixing parameters

$$f_i \simeq \begin{pmatrix} 0.35 \\ 0.85 \\ 0.35 \end{pmatrix}, \quad d_i \simeq \begin{pmatrix} -0.06 \\ 0.44 \\ 0.89 \end{pmatrix}$$

- *More general mixing* than models with “extreme hierarchies” e.g. $f_\alpha \gg f_{\beta,\gamma}$

Model I:	$f_e^2 : f_\mu^2 : f_\tau^2 \simeq 52 : 1 : 1$	“Electron-Mixed”
Model II:	$f_e^2 : f_\mu^2 : f_\tau^2 \simeq 1 : 16 : 3.8$	“Muon-Mixed”
Model III:	$f_e^2 : f_\mu^2 : f_\tau^2 \simeq 0.061 : 1 : 4.3$	“Tau-Mixed”

Phenomenology

- Neutrino mixing interactions

$$\mathcal{L} \supset f_i \frac{M_{\tilde{B}}}{\Lambda_M} \ell_i h_u \tilde{B} + d_i \frac{m_{3/2}}{\Lambda_M} \ell_i h_u S$$

$m_{3/2} \sim \mathcal{O}(\text{keV})$
 S has no pheno role

- After EWSB, $\text{bi}\nu_0$ will acquire interactions of SM neutrinos

$$\mathcal{L} \supset \frac{g_2}{\sqrt{2}} f_i \frac{M_{\tilde{B}}}{\Lambda_M} W_{\mu}^{+} \ell_i \bar{\sigma}^{\mu} \tilde{B} + \frac{g_2}{2 \cos \theta_W} f_i \frac{M_{\tilde{B}}}{\Lambda_M} Z_{\mu} \nu_i \bar{\sigma}^{\mu} \tilde{B}$$

Charged Current

Neutral Current

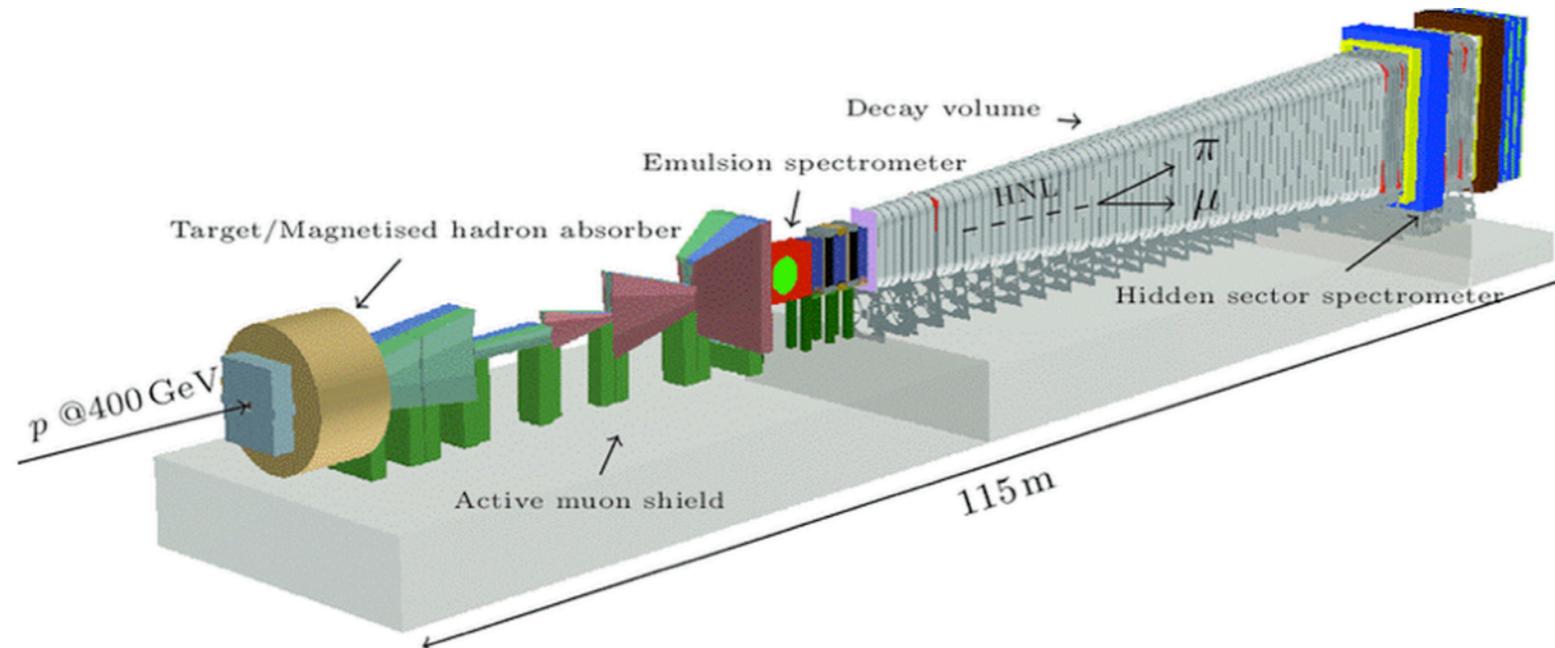
This is just your standard RH/HNL but with more general mixing with SM neutrinos.

$\text{Bi}\nu_0$ will be produced in any process where a SM neutrino is produced.

Can be detected through its decays via weak interactions.

Focus of this talk: MeV - GeV scale $\text{bi}\nu_0$ s \rightarrow beam dump experiments reign supreme!

SHiP Experiment

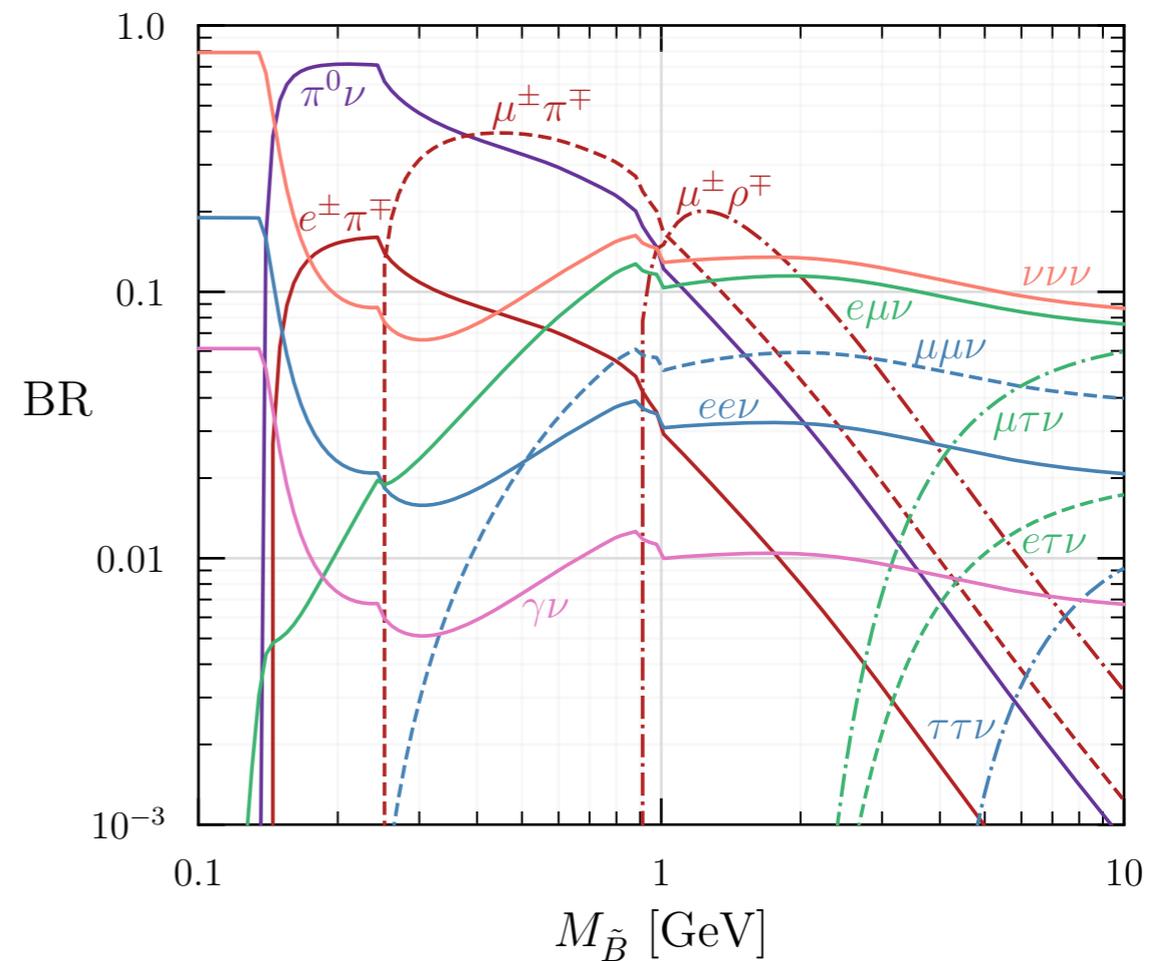
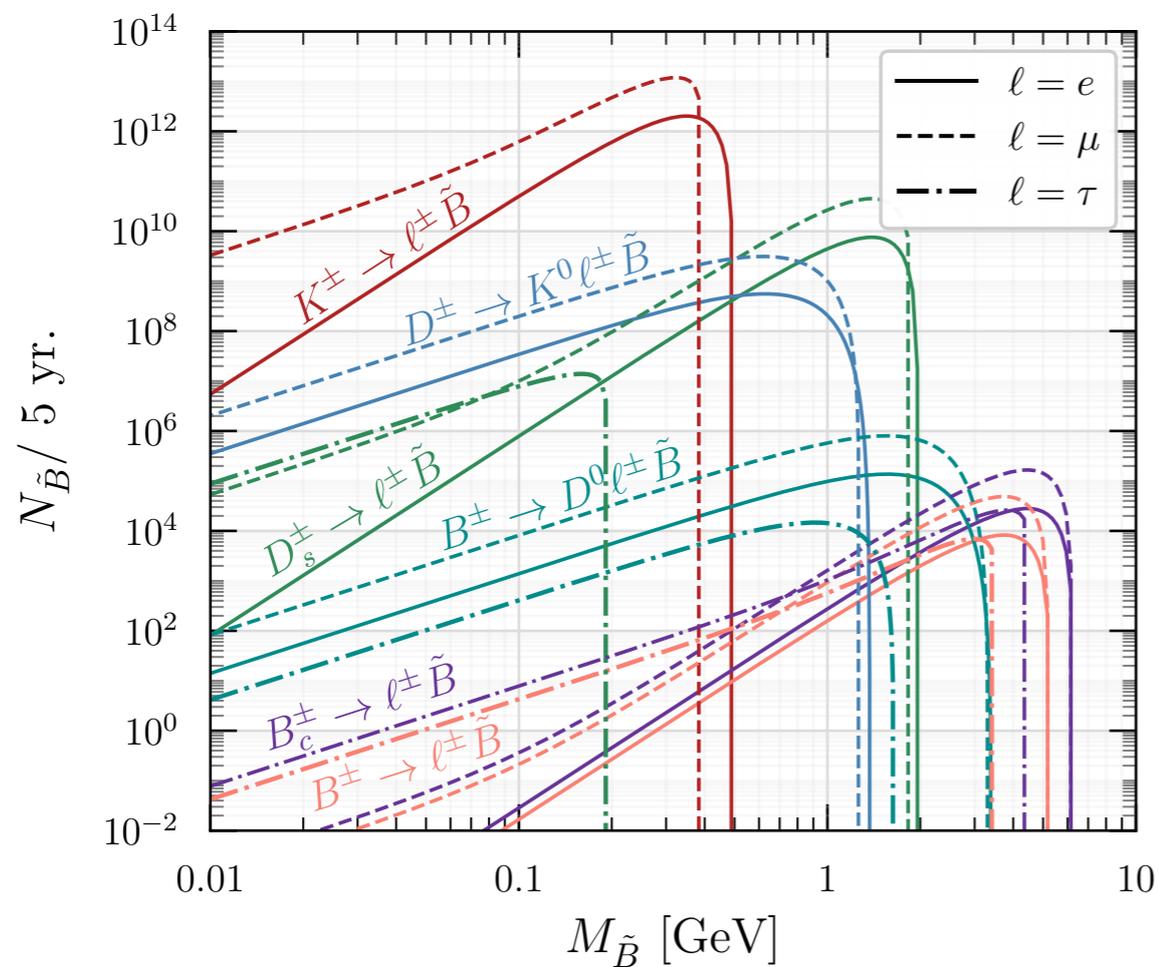
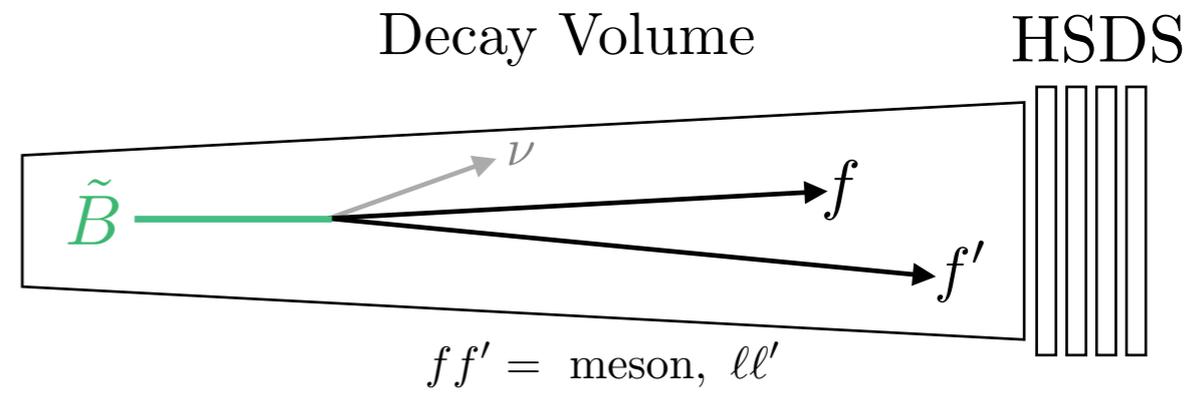
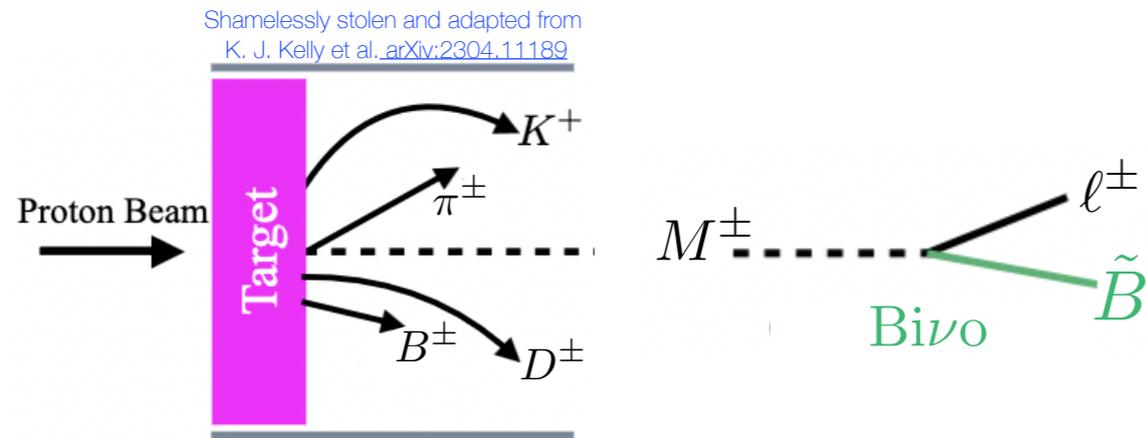


- 400 GeV proton beam - high energy!
- 2×10^{20} protons-on-target in 5 years of operation - large flux of BSM particles!
- Neutrino/DM detector
- Hidden Sector Decay Spectrometer

Large meson production rate!

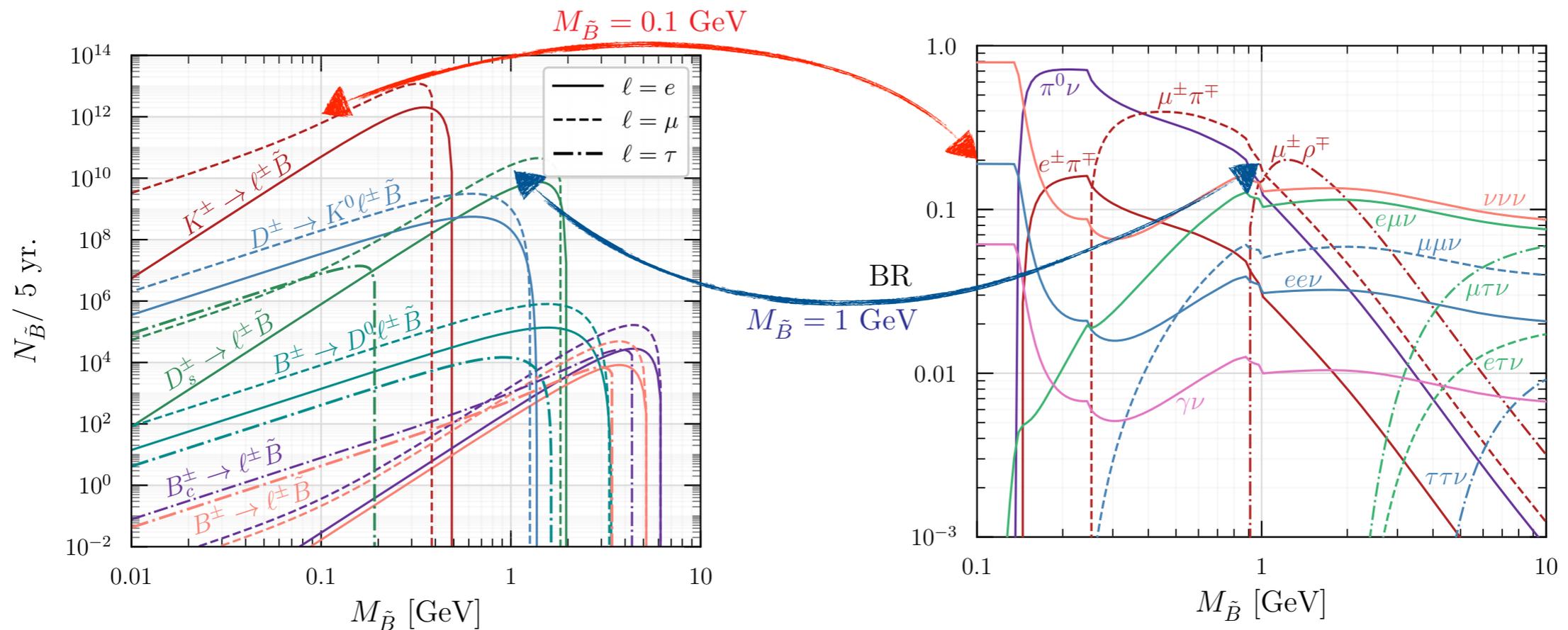
$$\begin{aligned} N_{K^+} &= 5.8 \times 10^{19}, & N_{K^-} &= 1.4 \times 10^{19}, \\ N_{D^\pm} &= 3.2 \times 10^{17}, & N_{D_s^\pm} &= 1.4 \times 10^{17}, \\ N_{B^\pm} &= 4.5 \times 10^{13}, & N_{B_c^\pm} &= 2.8 \times 10^{11}, \end{aligned}$$

Bino Phenomenology



SHiP Sensitivity

- 1) Conservative Analysis - consider only production and decay mode with the highest sensitivity for a given $\tilde{\nu}$ mass



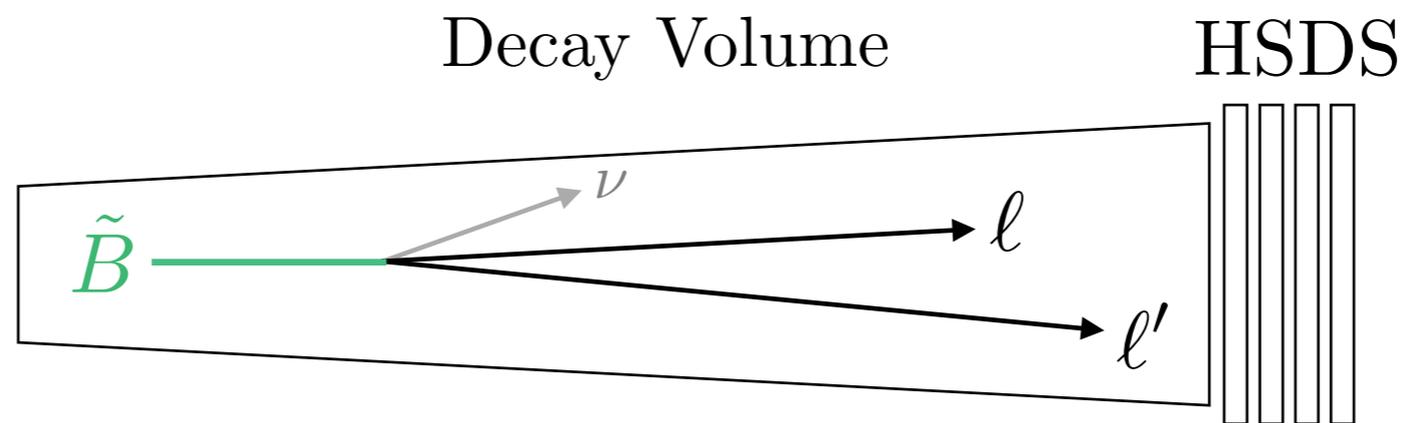
- Simulation -
 - Pythia8 for meson production - kaons, D , and B mesons.
 - Bino 2-body decays analytically. 3-body decays using muBHNL code.

SHiP Sensitivity

2) HNL@SHiP Mathematica Package - combines all production and decay modes.

- D and B meson production with Pythia. No kaons.
- More aggressive limits

- Then need to determine: 1. Geometric acceptance = do final states enter the detector? 2. Efficiency = does the $\tilde{\nu}$ decay in the decay volume?



Transverse displacement

$$x_f = \left| \frac{p_x^{\tilde{B}}}{p_z^{\tilde{B}}} z + \frac{p_x^f}{p_z^f} (\ell_{\text{sh}} + \ell_{\text{decay}} - z) \right| < 2.5\text{m}$$

$$y_f = \left| \frac{p_y^{\tilde{B}}}{p_z^{\tilde{B}}} z + \frac{p_y^f}{p_z^f} (\ell_{\text{sh}} + \ell_{\text{decay}} - z) \right| < 5\text{m}$$

Efficiency

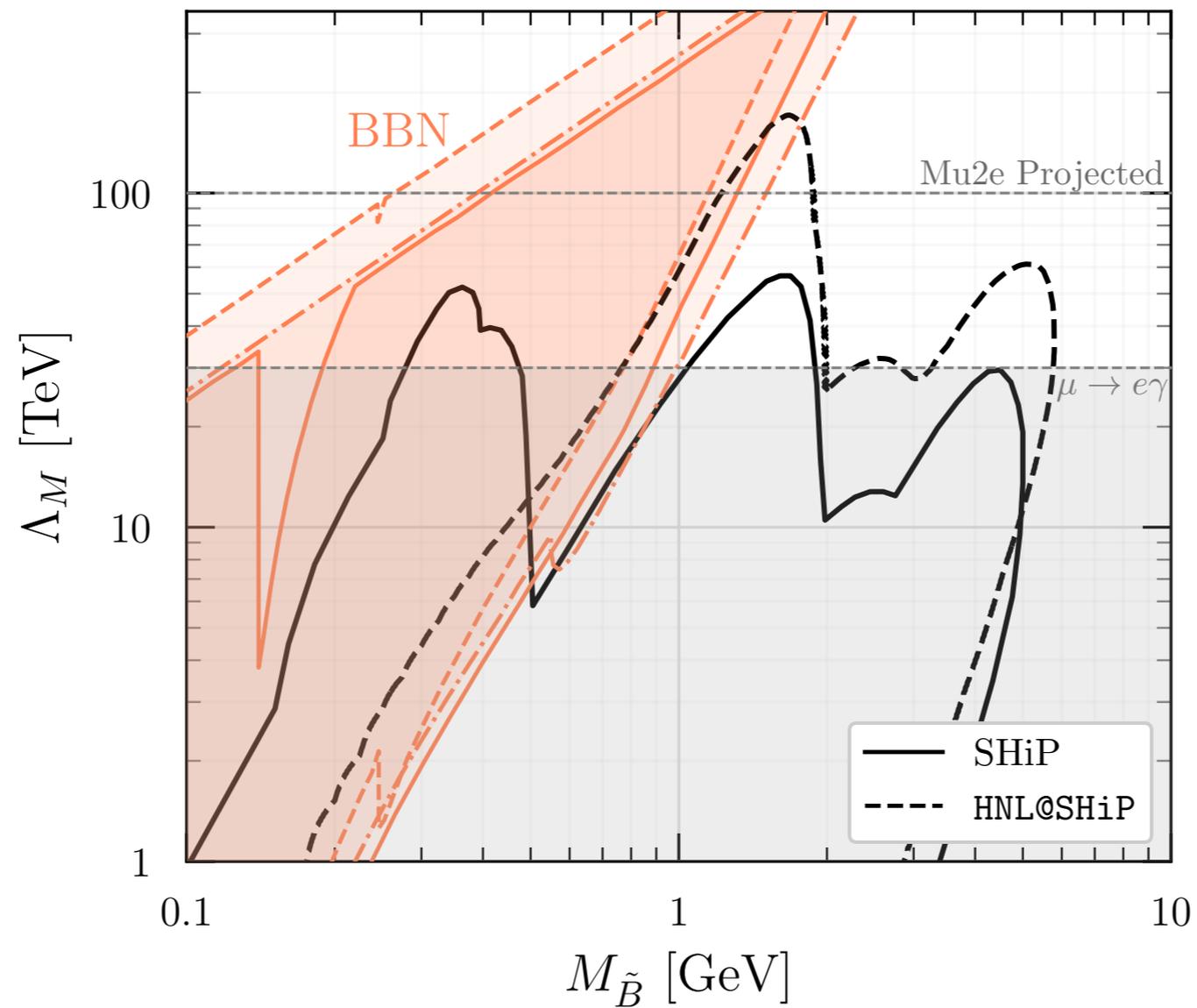
$$\text{eff} = M_{\tilde{B}} \Gamma \int_{z_{\text{min}}}^{z_{\text{max}}} dz \sum_{\text{events} \in \text{geom.}} \frac{e^{-z M_{\tilde{B}} \Gamma / p_z}}{N_{\text{MCP}} p_z}$$

Probability of decaying in decay volume

$$\frac{e^{-z M_{\tilde{B}} \Gamma / p_z}}{N_{\text{MCP}} p_z}$$

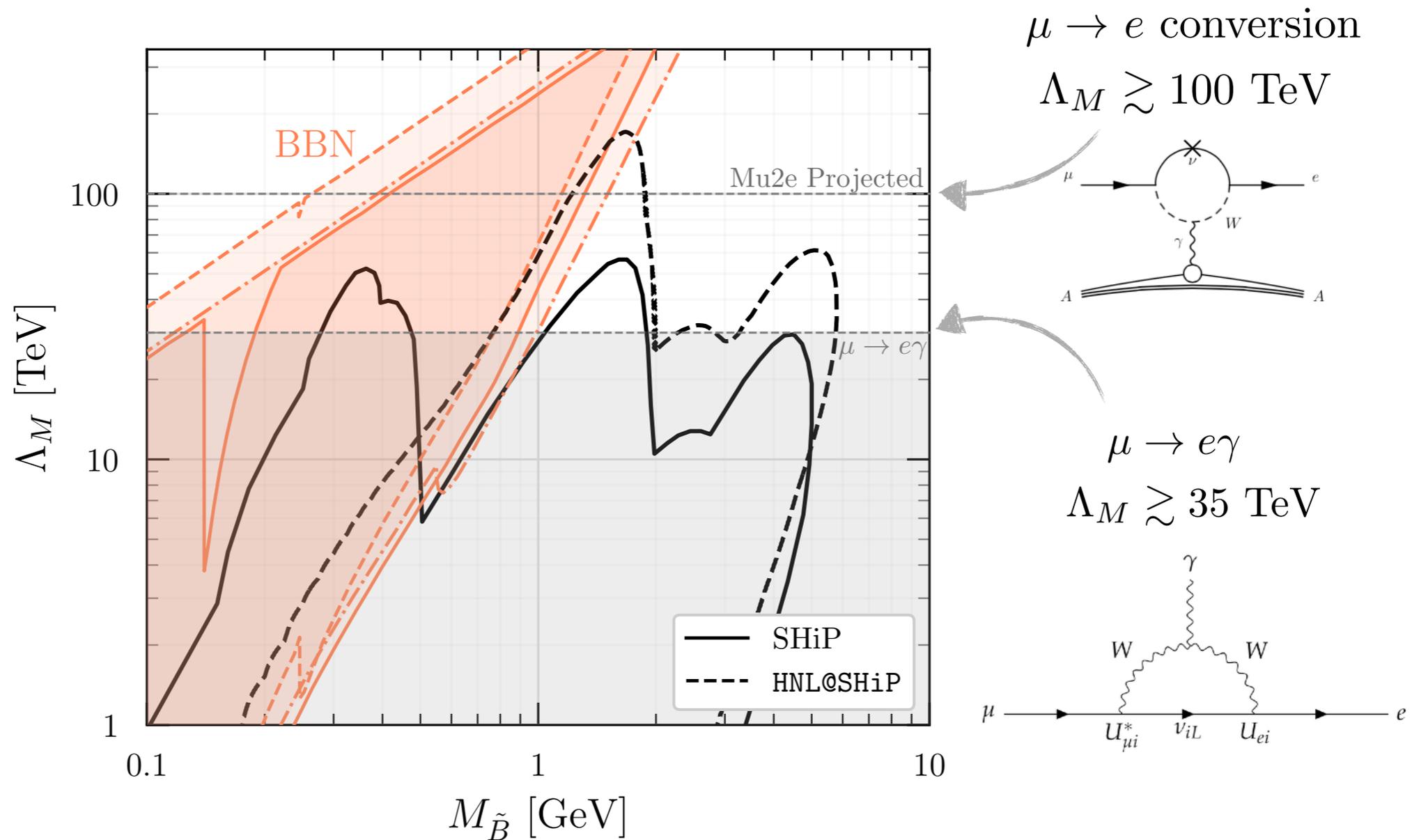
SHiP Sensitivity

95% CL exclusion limits \rightarrow ~ 2 signal events



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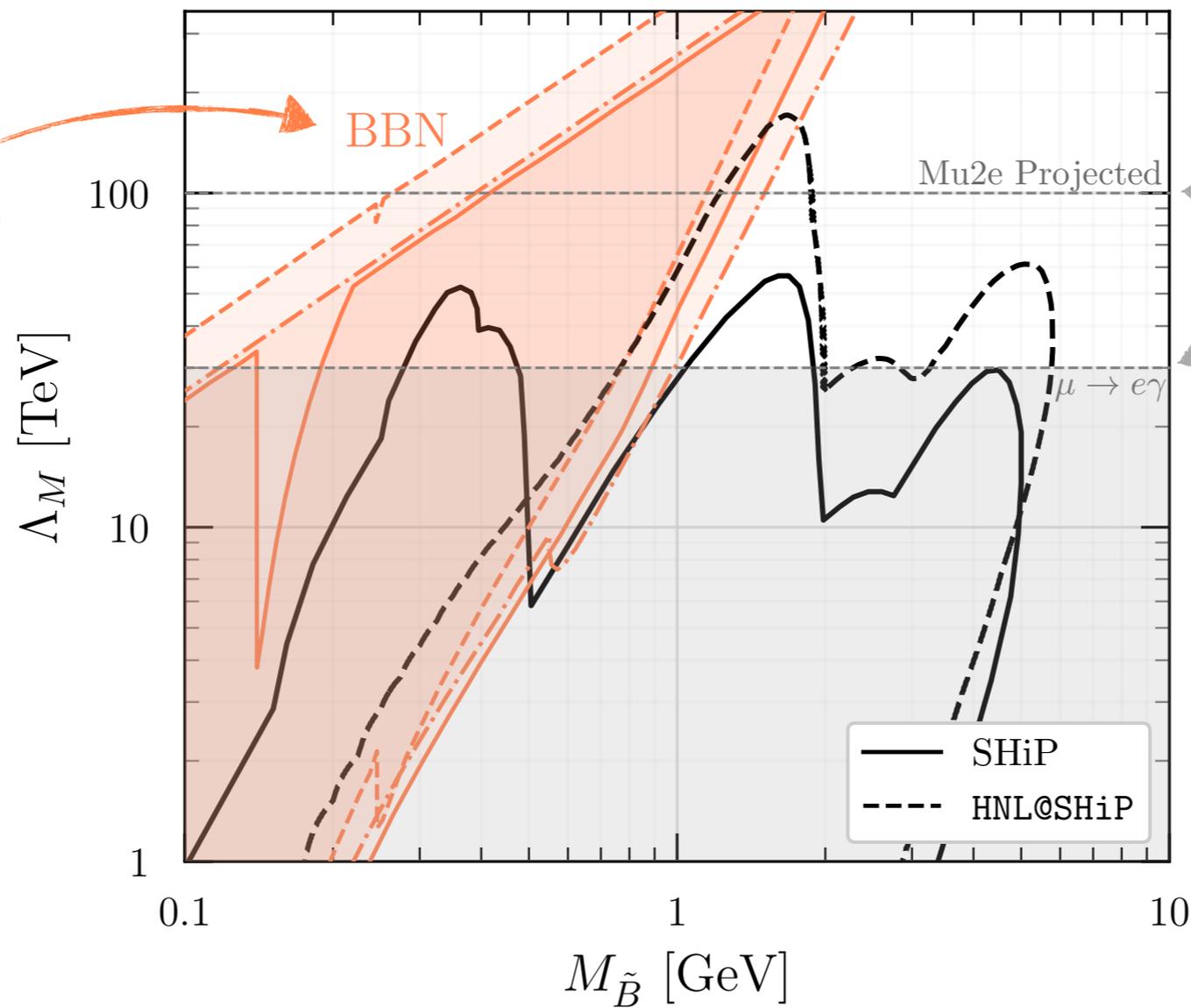
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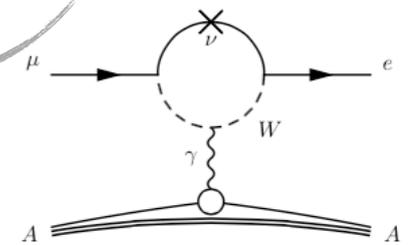
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Big Bang
Nucleosynthesis



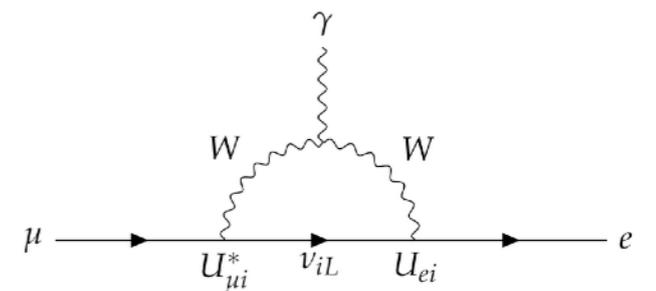
$\mu \rightarrow e$ conversion

$$\Lambda_M \gtrsim 100 \text{ TeV}$$



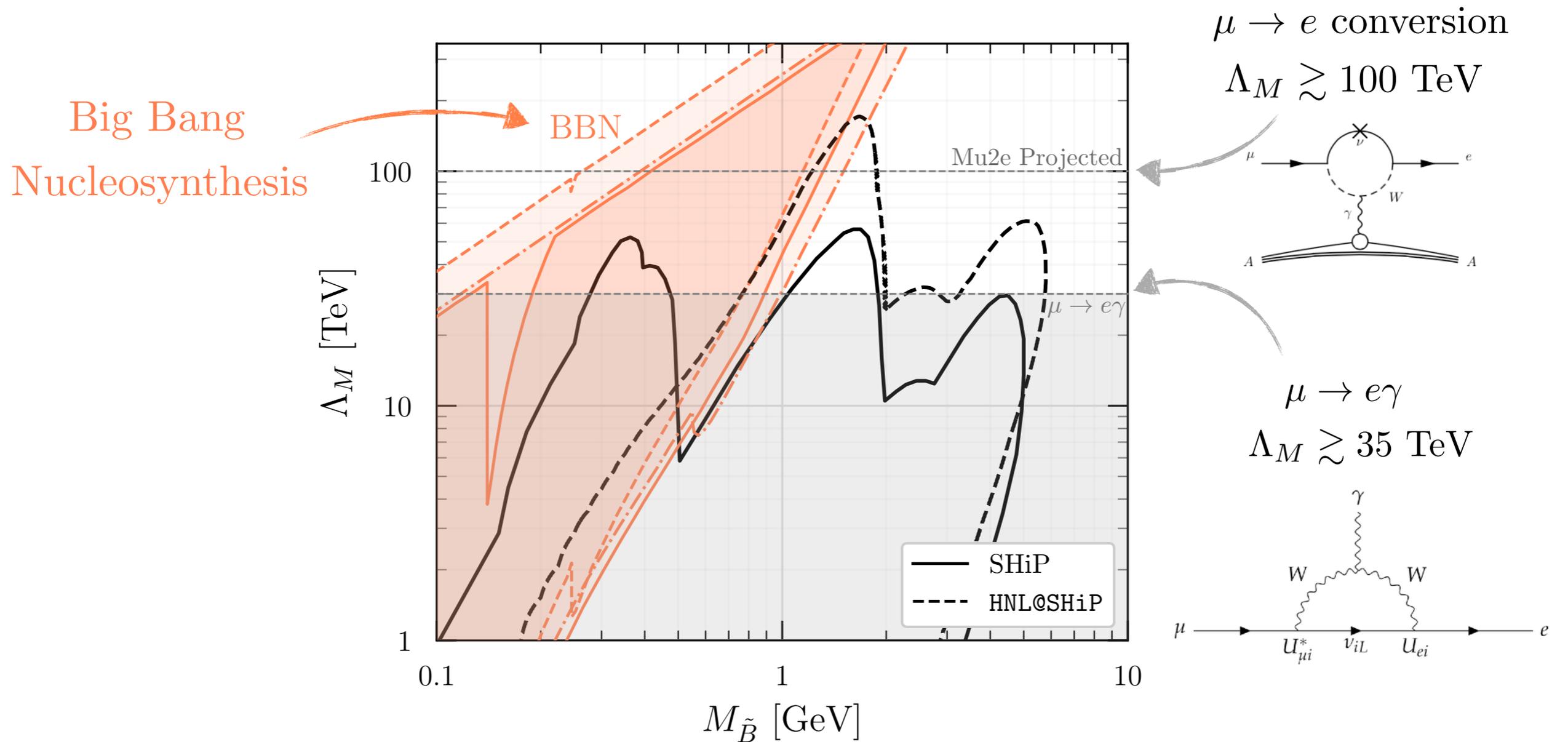
$\mu \rightarrow e \gamma$

$$\Lambda_M \gtrsim 35 \text{ TeV}$$



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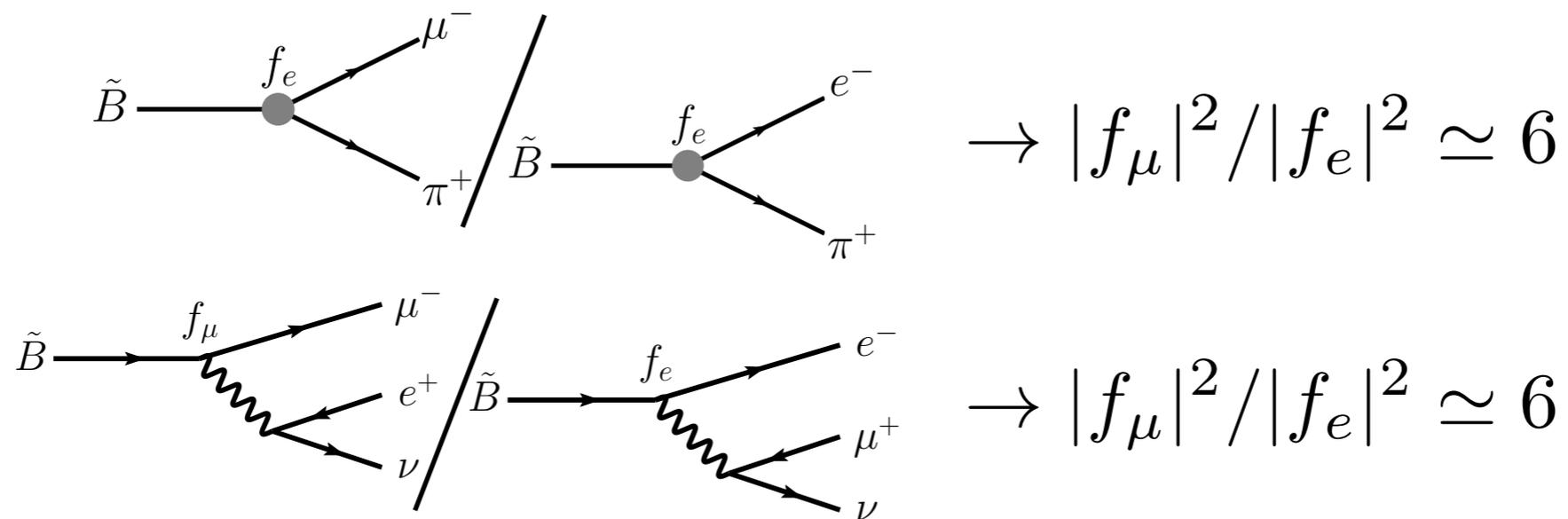
SHiP is competitive and complementary to BBN and cLFV searches.

Smoking Gun Signal

- Recall: the bino mixing parameters are completely determined by the SM neutrino mixing parameters

$$f_i \simeq \begin{pmatrix} 0.35 \\ 0.85 \\ 0.35 \end{pmatrix}, \quad d_i \simeq \begin{pmatrix} -0.06 \\ 0.44 \\ 0.89 \end{pmatrix}$$

- Relative rates of (some) decays electron vs muon vs tau final states are fully determined, given the same production mode.



Relative rate of electron vs muon can tell you if the bino is playing a role in neutrino mass generation!

Conclusions

- Neutrino oscillations $\rightarrow m_\nu \neq 0$
- Inverse Seesaw Mechanism can be naturally realized in a $U(1)_{R-L}$ symmetric MSSM
- Bino and singlino are a pseudo-Dirac pair that act like RH neutrinos, and have general mixing with SM neutrinos completely produced by SM neutrino mixing parameters
- If the bino has MeV-GeV mass, it can be produced in high energy proton beam dump experiments from meson decays. SHiP is the best place to look!
- SHiP is sensitive to new regions of parameter space that are not covered by BBN or cLFV process like $\mu \rightarrow e\gamma$
- Smoking gun signal - ratios of BRs for different leptons can tell us about the mechanism behind neutrino mass generation

Thanks!
Questions?