



Evaluation of proton decay search sensitivity using the GiBUU model

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1. Proton Decay — A Window to Grand Unification

Grand Unified Theories (GUTs) unify the three gauge interactions and naturally predict proton decay [1].

$p \rightarrow e^+\pi^0$ is the golden channel: high branching ratio and a clear 3-ring Cherenkov signature. For free proton decay, the e^+ and π^0 are back-to-back, each with a monoenergetic momentum of 459 MeV/c.

Limit from the Super-Kamiokande (SK) experiment: $\tau/B > 2.4 \times 10^{34}$ years (90% C.L.) [2].

The sensitivity in Hyper-Kamiokande (HK) is expected to reach $\sim 10^{35}$ years [3].

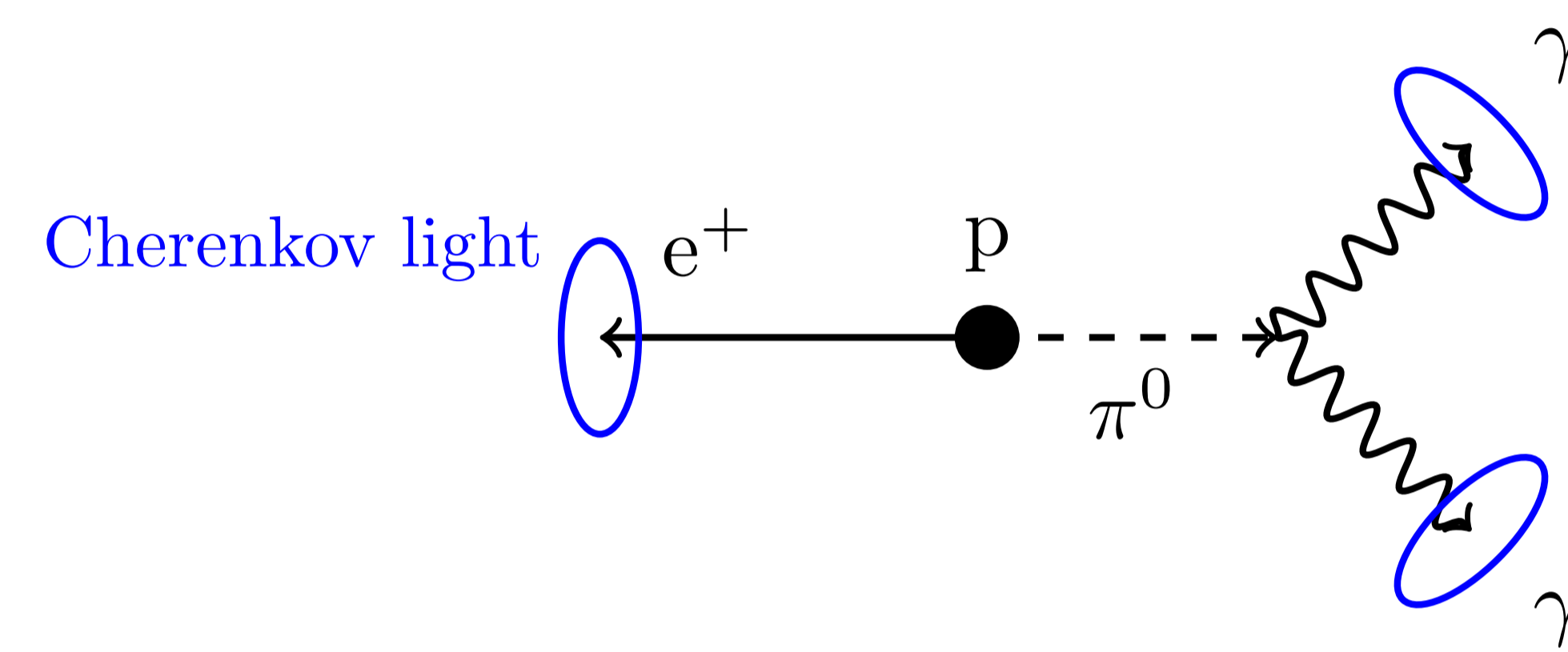


Figure 1: Schematic of $p \rightarrow e^+\pi^0$ in a water Cherenkov detector.

2. Nuclear Effects Complicate the Search

A big problem in proton decay searches is the background from atmospheric neutrinos. $\sim 80\%$ of the target nucleons are bound in ^{16}O in water. Thus, nuclear effects play a significant role in the separation of the proton decay signal and atmo. ν background [2, 4]:

- **Initial state:** Fermi motion (FM), binding energy, short-range correlations (SRC).
- **Final state:** π^0 absorption, charge exchange, elastic/inelastic scattering.

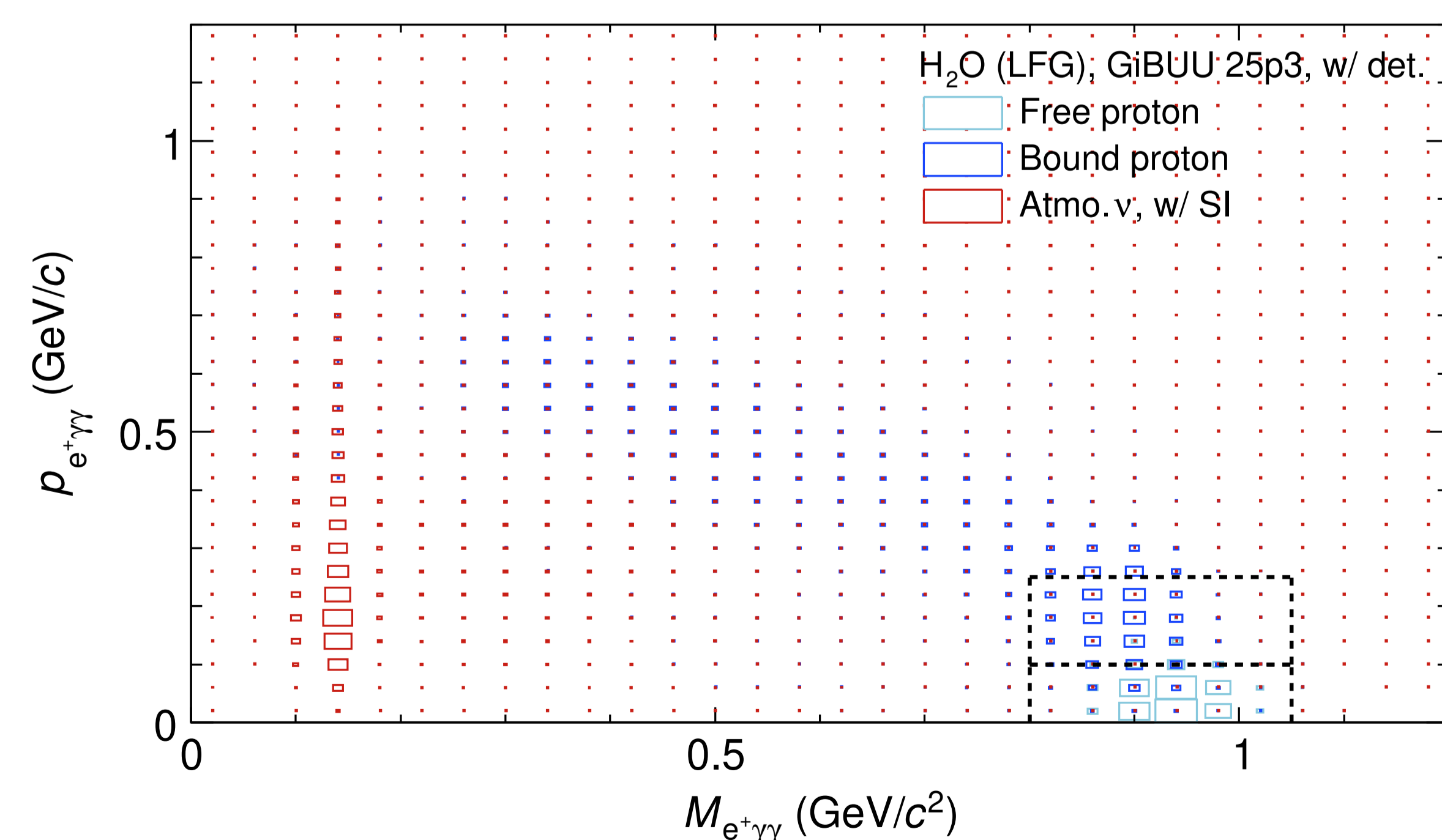


Figure 2: Reconstructed $e^+\pi^0$ invariant mass vs. total momentum of the system. Free proton decay is cleanly separated; bound proton decay overlaps atmo. ν background in the signal region (dashed box).

3. GiBUU — A Unified Transport Model

Quantum-kinetic transport framework [5] providing unified treatment of nuclear effects for signal and background. The default initial proton state is described by the local Fermi gas (LFG) model.

GiBUU simulates the dynamic evolution of the nuclear configuration over time by using quantum-kinetic transport theory:

- **Mean-field + transport:** momentum-dependent potential (Fermi motion, binding); π^0 FSI via BUU collision integral.
- **In-medium Δ broadening:** local nucleon density-dependent [6], reduces πN rescattering.
- **Benchmarked against accelerator neutrino scattering data**, in particular pion production and its nuclear-effect systematics [7].

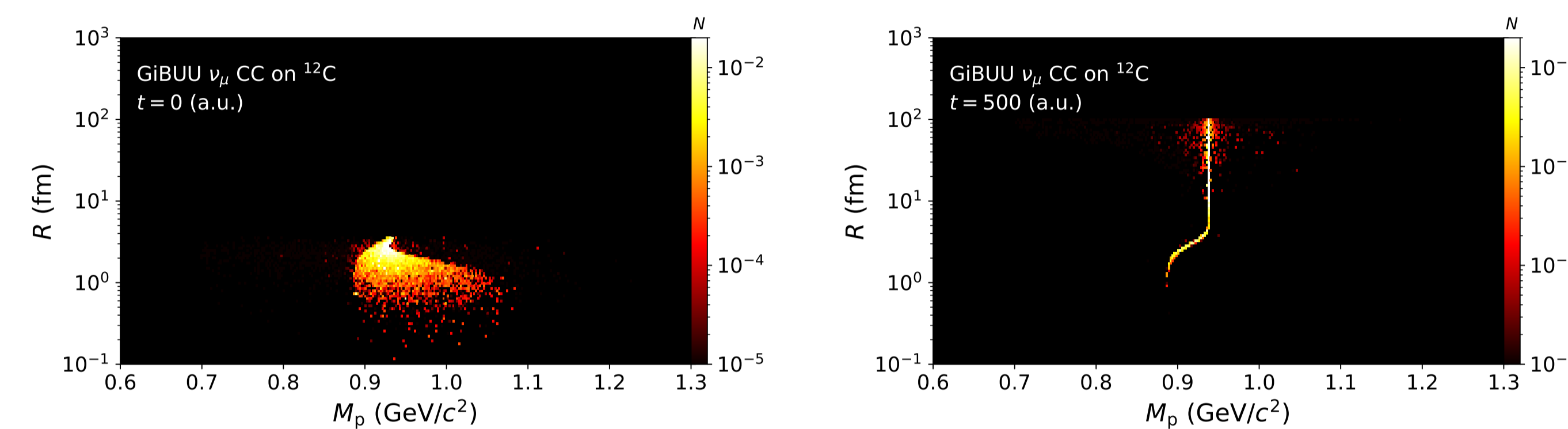


Figure 3: Effective proton mass M_p vs. radial position R at $t = 0$ and $t = 500$ a.u. — off-shell inside nucleus, on-shell outside. From [7].

4. Mock Detector Response & Signal Selection

Based on SK reconstruction performance [8], the particle kinematics were smeared to reproduce the detector response:

- **Momentum dependent resolution:** $\sim 2.81^\circ$ angular, $\sim 4.2\%$ momentum at 500 MeV/c; tuned to reproduce SK π^0 and free proton mass distributions [4].
- **Particle counting:** separate particles with an opening angle greater than 15° . Low-energy particles (< 30 MeV/c) are discarded. PID is assumed to be perfect; 88% Michel- e^- tagging efficiency.
- **Secondary interactions:** simulated with GEANT4-WCSIM [9].

Signal selection (SK-style): 2–3 e-like rings, no Michel e^- , π^0 mass 85 MeV/ c^2 to 185 MeV/ c^2 , $e^+\pi^0$ mass 800 MeV/ c^2 to 1050 MeV/ c^2 , $P_{e^+\pi^0} < 250$ MeV/c, neutron veto. Lower (< 100 MeV/c) and upper (100 MeV/c to 250 MeV/c) signal regions.

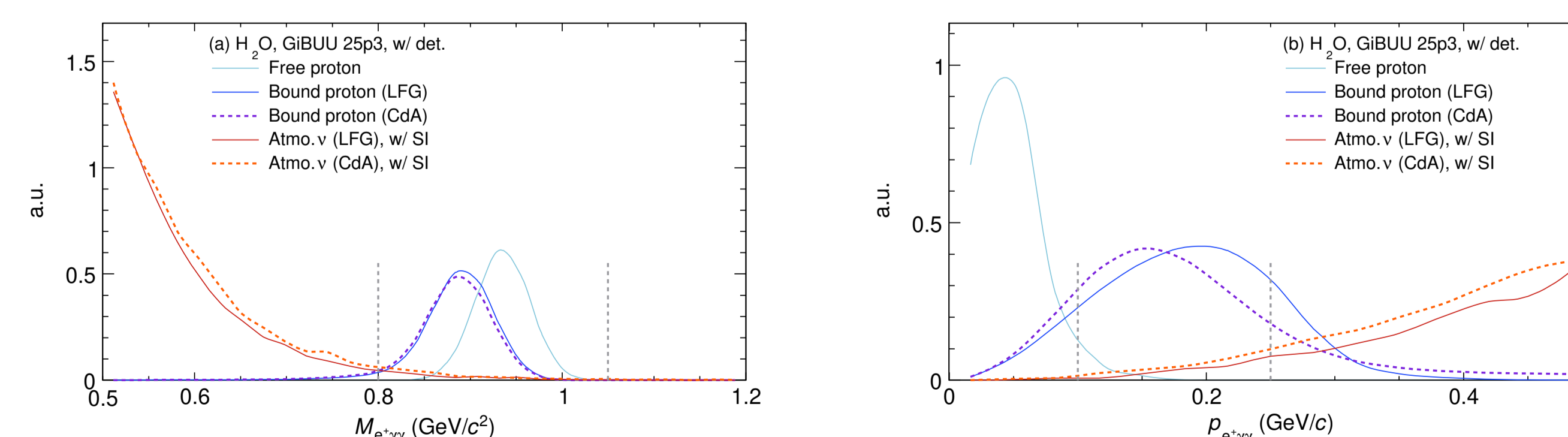


Figure 4: Reconstructed $e^+\pi^0$ mass (left) and momentum (right) with GiBUU+detector smearing. Solid/dashed: LFG/CdA. Lines: signal region cuts.

5. Systematic Uncertainties & Sensitivity Projections

Signal efficiency (GiBUU, LFG): 21.6% (lower $P_{e^+\pi^0}$ region), 17.4% (upper $P_{e^+\pi^0}$ region); comparable to SK ($\sim 38\%$). Background w/o neutron tagging: 1.60 events/(Mton \cdot yr) (SK: 1.83 ± 0.59 [sys]) [2].

Systematic uncertainties evaluated by comparing the LFG and CdA initial proton momentum distributions, and by varying π FSI configurations:

- FM+SRC (LFG vs. CdA): $\sim 50 - 70\%$ on background, 2.3% (lower $P_{e^+\pi^0}$ region) and 7.5% (upper $P_{e^+\pi^0}$ region) on signal.
- π FSI+ ν interactions: 16.1% on background, 0.3% (lower $P_{e^+\pi^0}$ region) and 2.7% (upper $P_{e^+\pi^0}$ region) on signal.

Total systematic uncertainty: 4.3% (lower $P_{e^+\pi^0}$ region), 8.6% (upper $P_{e^+\pi^0}$ region), 71.1% (background). Uncertainties on reconstruction and flux are from SK.

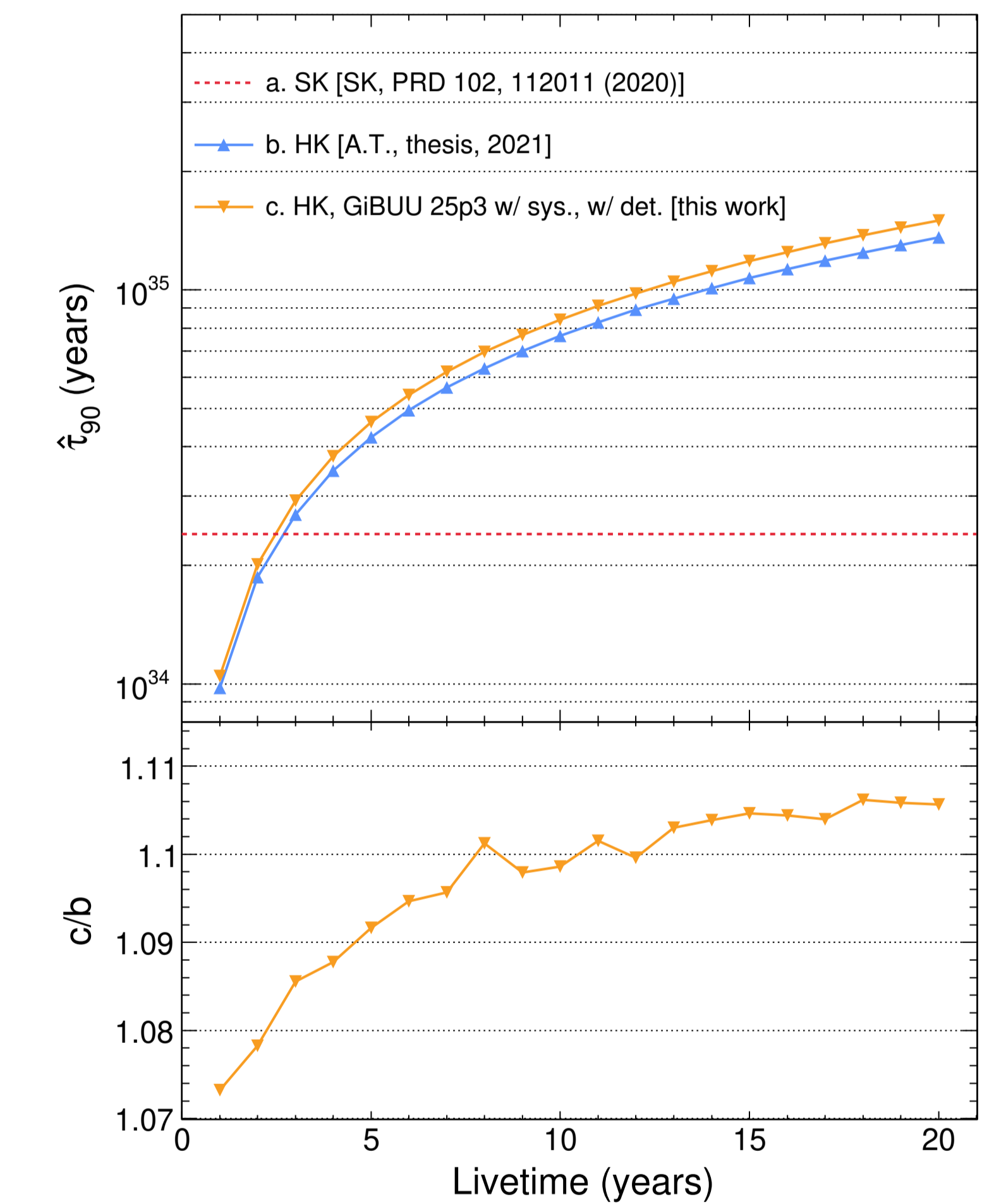


Figure 5: Projected 90% C.L. lower limit on $\tau/B(p \rightarrow e^+\pi^0)$ vs. exposure for HK. GiBUU-based sensitivity (c) is consistent with previous estimates (b) at the $\sim 10\%$ level.

6. Summary

GiBUU reproduces the proton decay search sensitivity previously obtained with other generators, providing an independent, self-consistent characterisation of nuclear effects. The Fermi momentum distribution is the dominant systematic — future searches should account for its impact on the background.

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