Super-Kamiokande Results in FY2023: Proton Decays and Atmospheric Neutrinos

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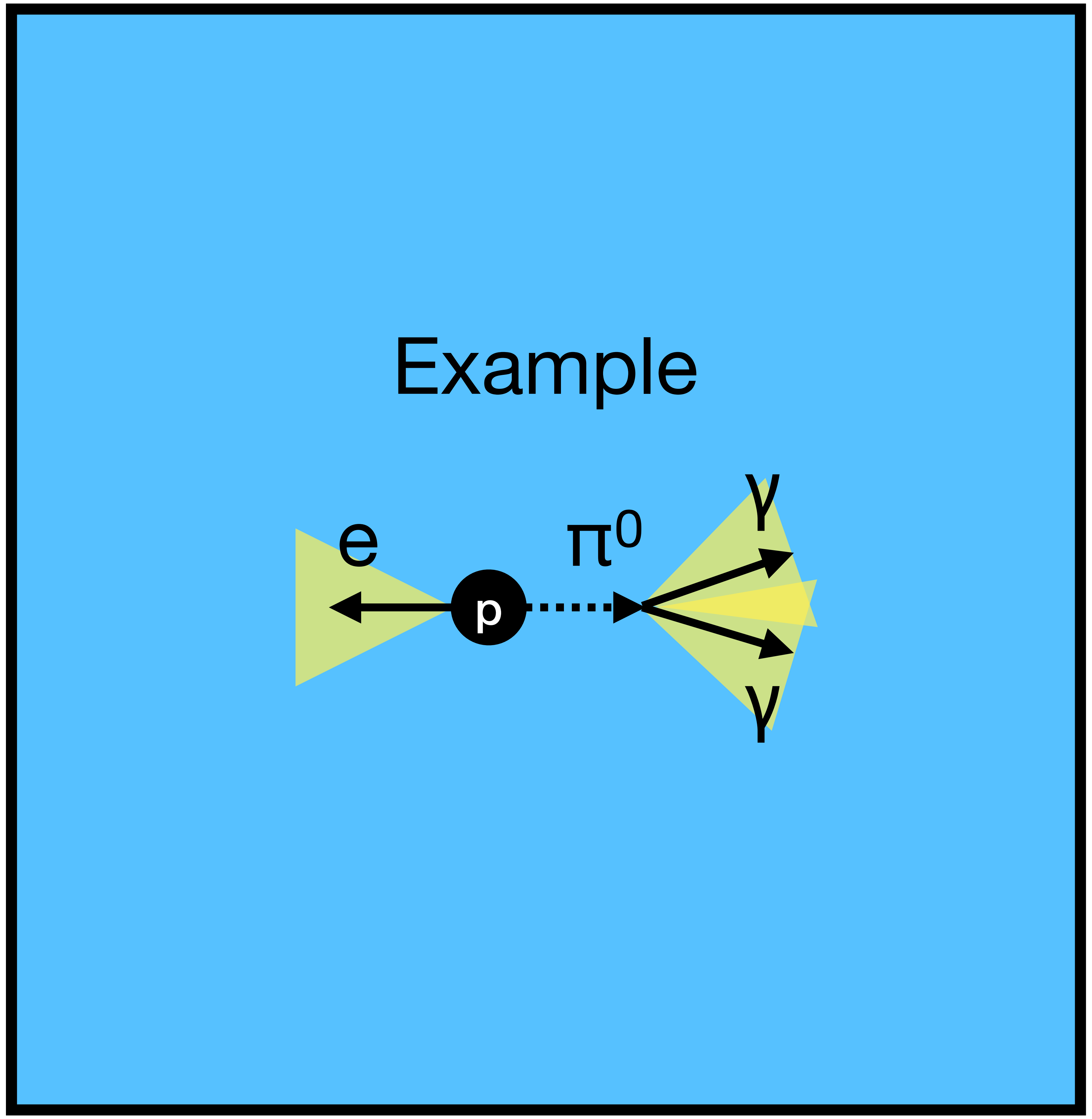
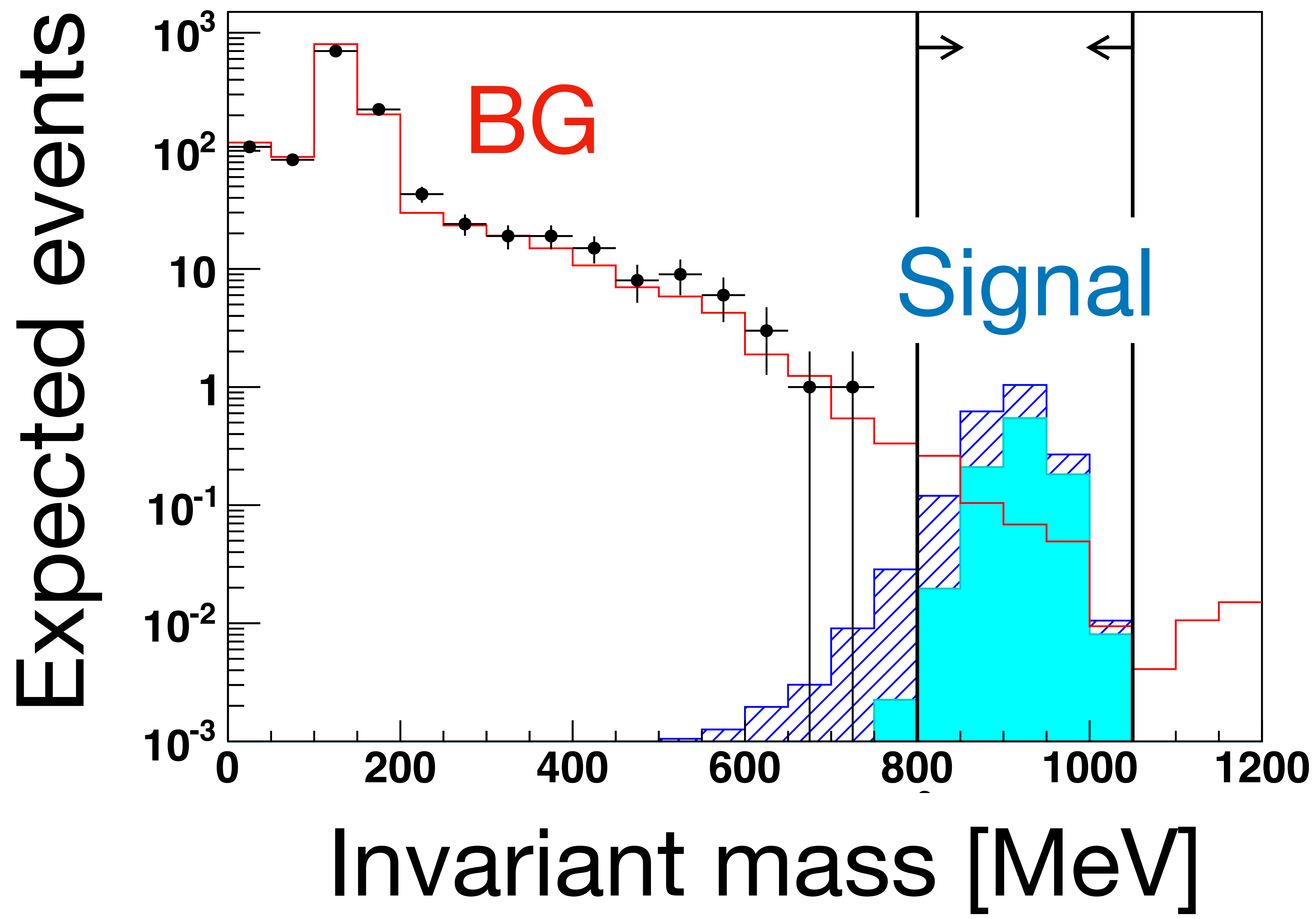
Proton decay

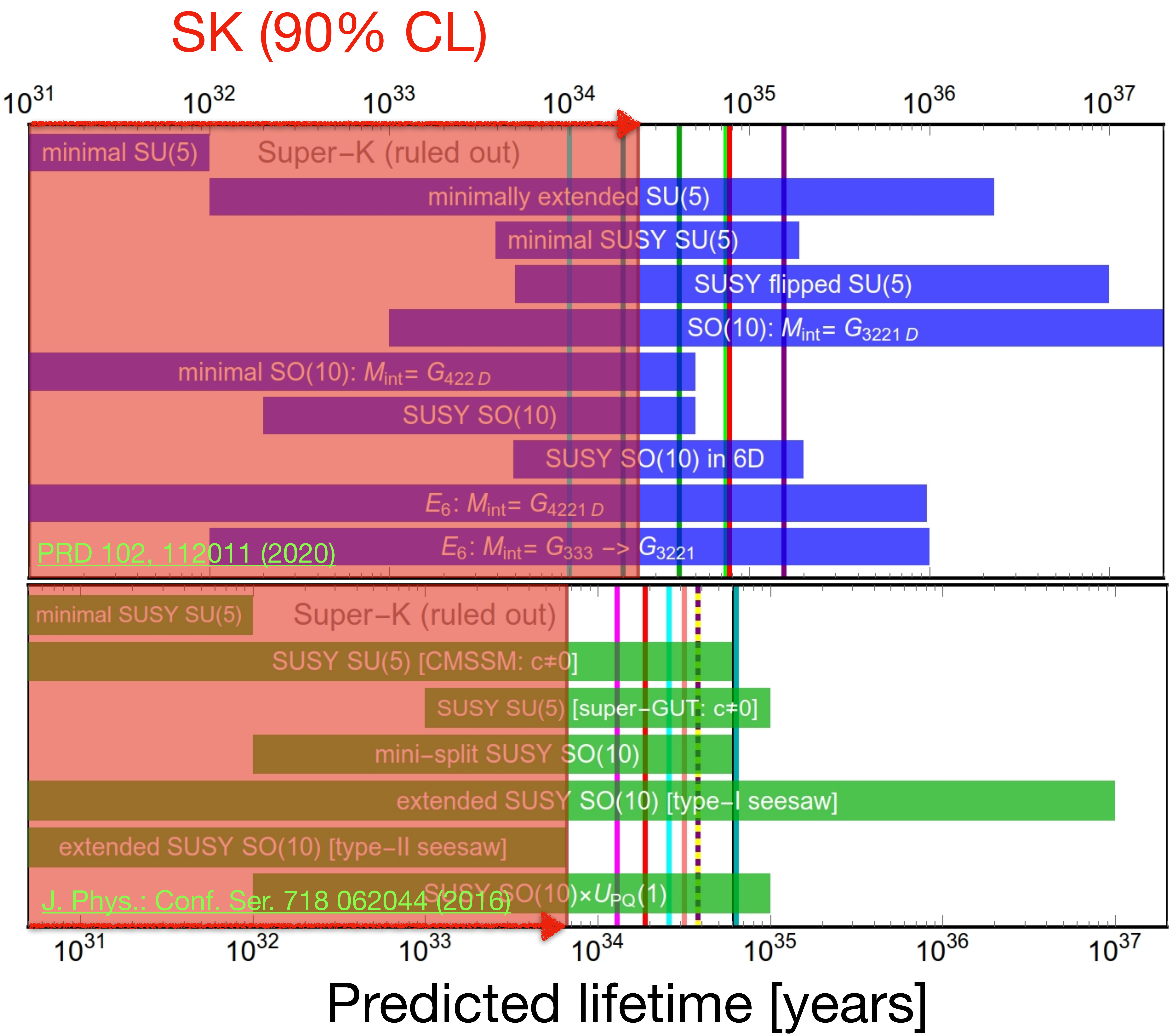


- Quark→lepton (e.g. $p \to e^+\pi^0$, $p \to \bar{\nu}K^+$)
- Lifetime: $\tau_p \sim O(10^{34}\text{-}10^{35})$ years?
- Signal with invariant mass ~ m_p ~ 1 GeV

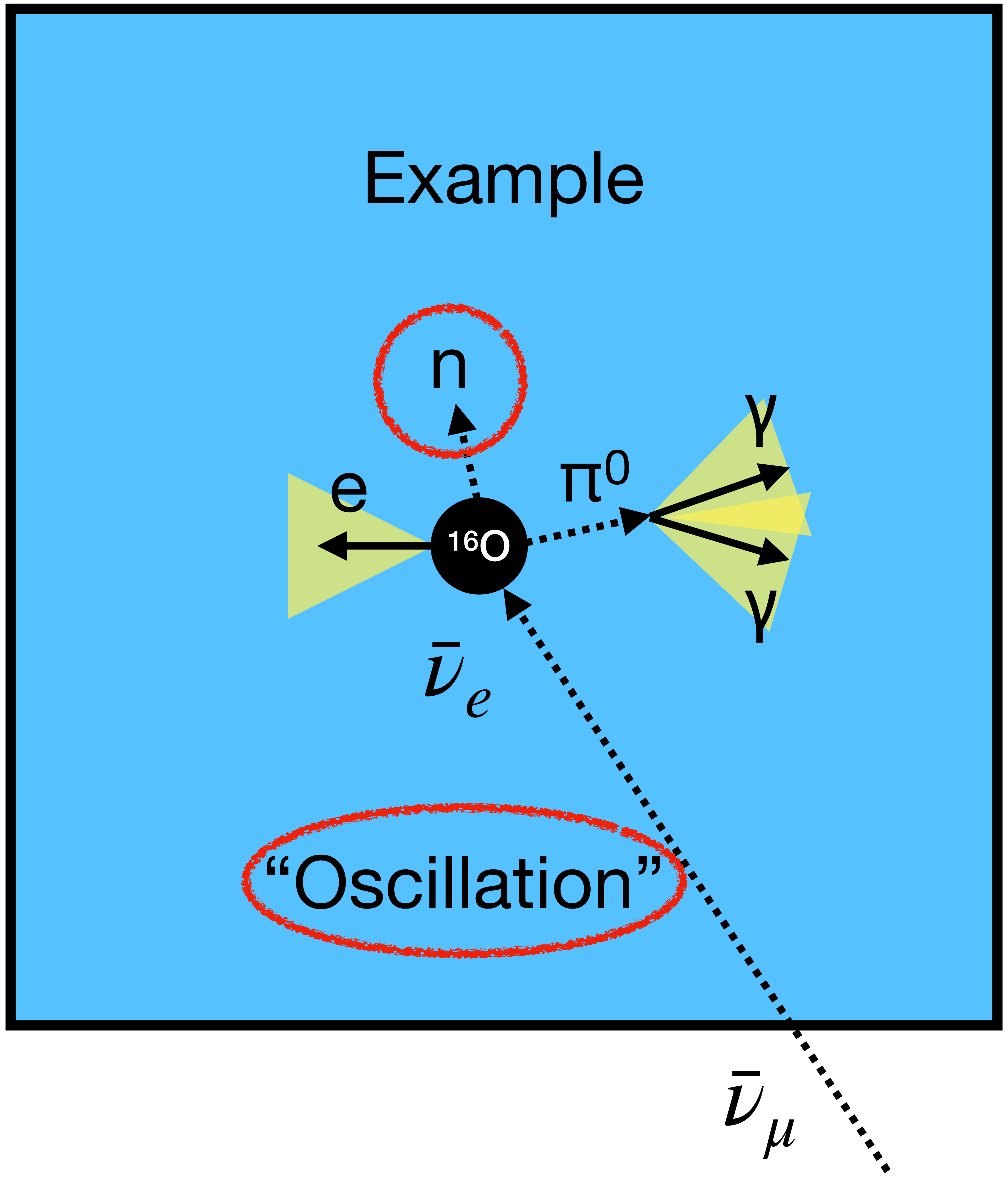


$p \to e^+\pi^0$

$p \to \bar{\nu}K^+$



Source: J. Phys. G: Nucl. Part. Phys. 51 033001 (2024)

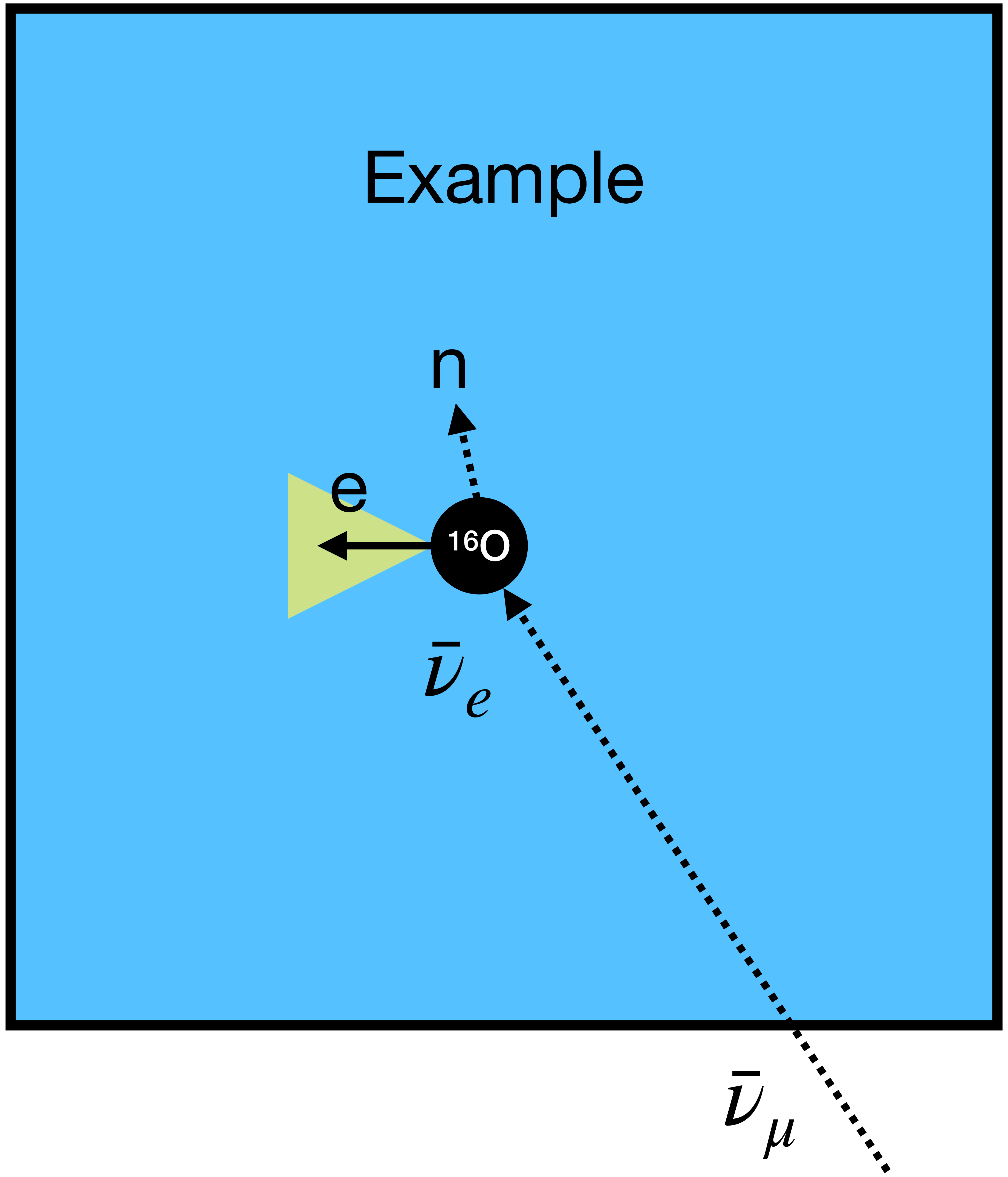


Atmospheric neutrinos

- Byproduct of CR air showers
- All directions, easily pass through the Earth

😢 BG for proton decays → n-tag reduction

😃 Abundant, diverse energy and path lengths



Oscillation studies

$$P(\nu_\alpha \to \nu_\beta) \approx f(\theta_{ij}, \delta_{CP}, \Delta m^2_{ij}; L/E)$$

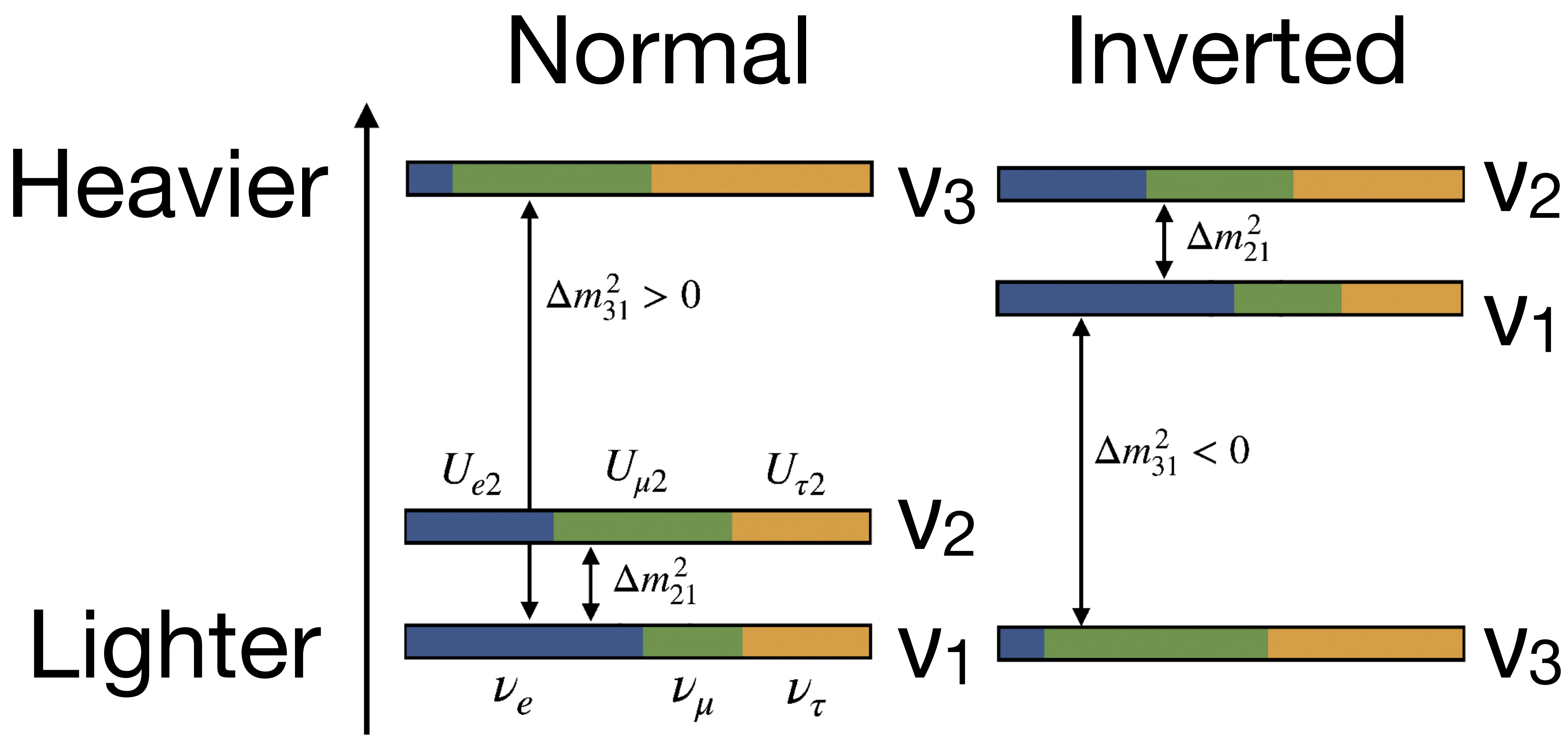
$\nu/\bar{\nu}$, flavor — Parameters — Kinematics

Mixing angles, CP phase, mass splittings

Important questions

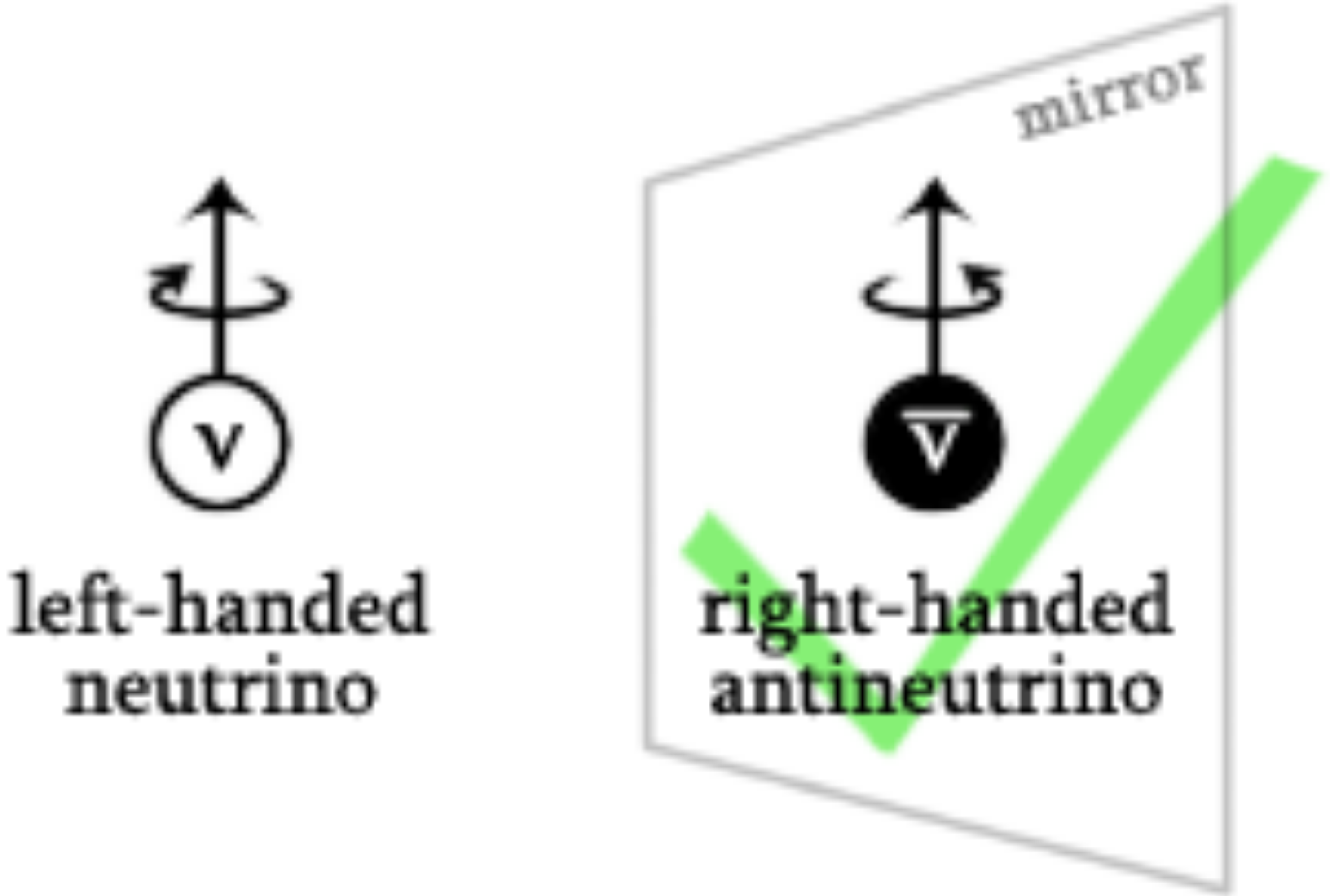
Mass Ordering

e<μ<τ ~ 1<2<3 ?

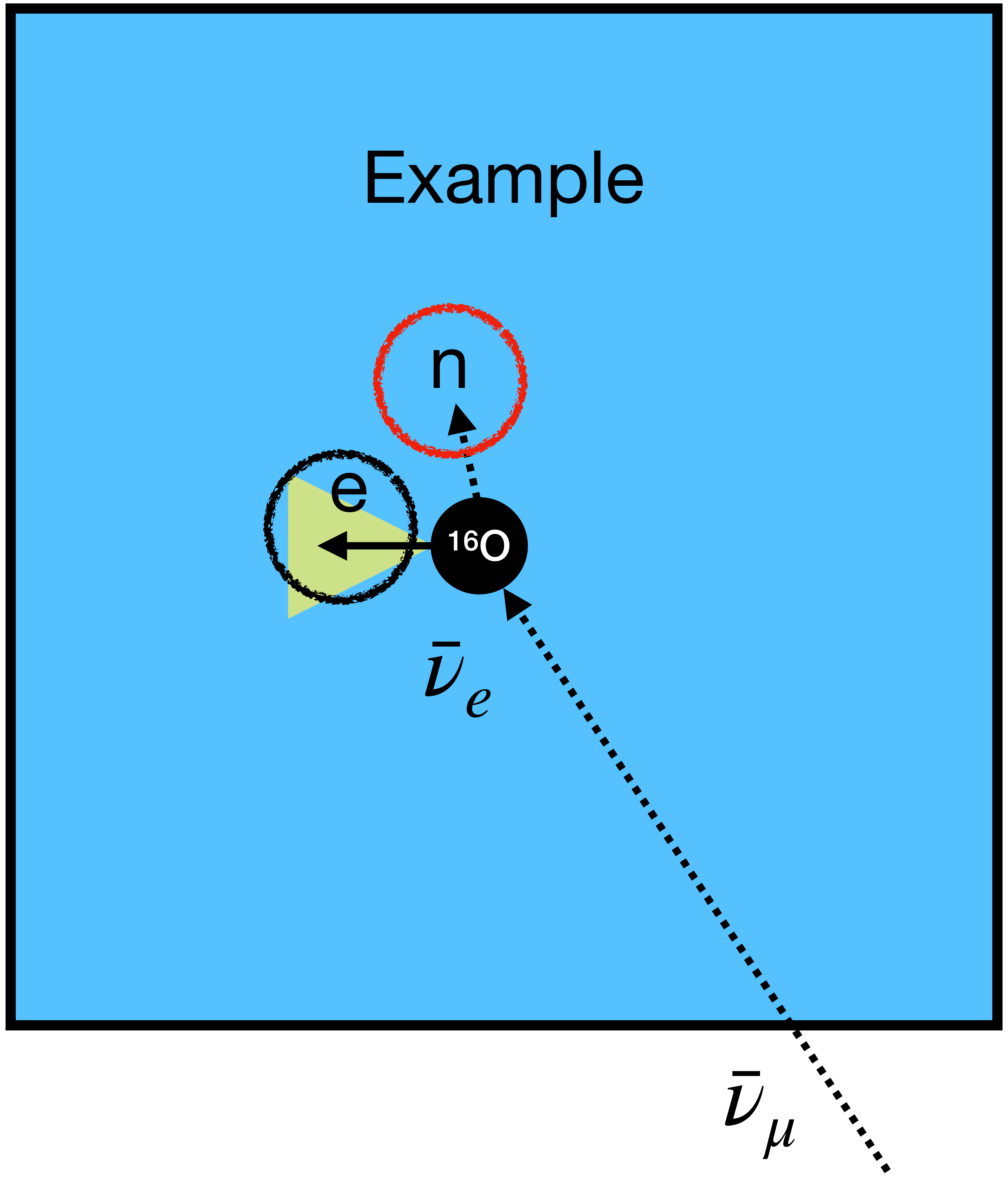


CP symmetry

$P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$?



Second-order effects: require large statistics and accurate neutrino reconstruction



Oscillation studies

$$P(\nu_\alpha \to \nu_\beta) \approx f(\theta_{ij}, \delta_{CP}, \Delta m^2_{ij}; L/E)$$

✗ $\nu/\bar{\nu}$, flavor

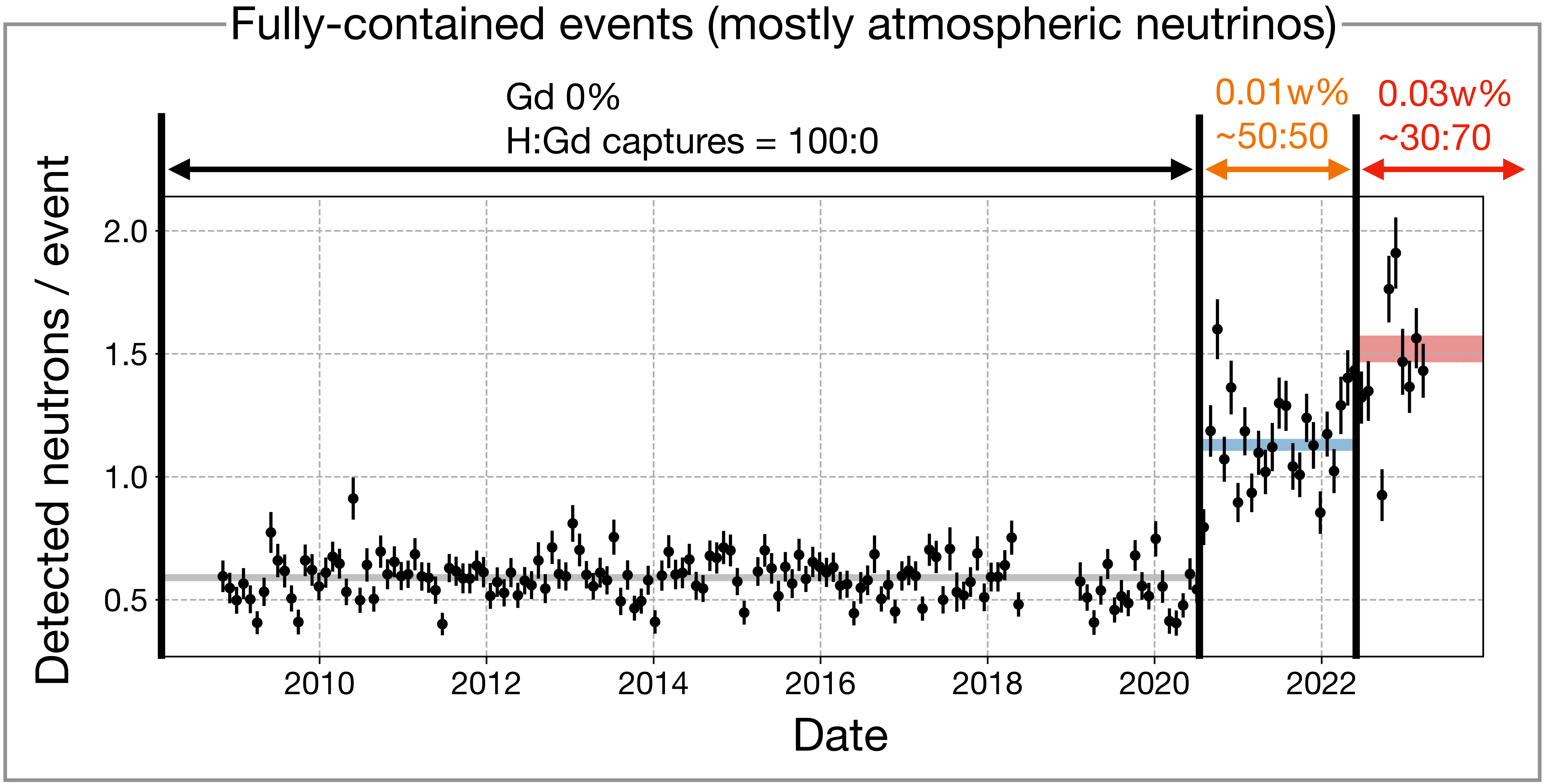
Kinematics

Rely solely on outgoing e/μ, limits in accuracy

Difficult to access the “second-order effects”

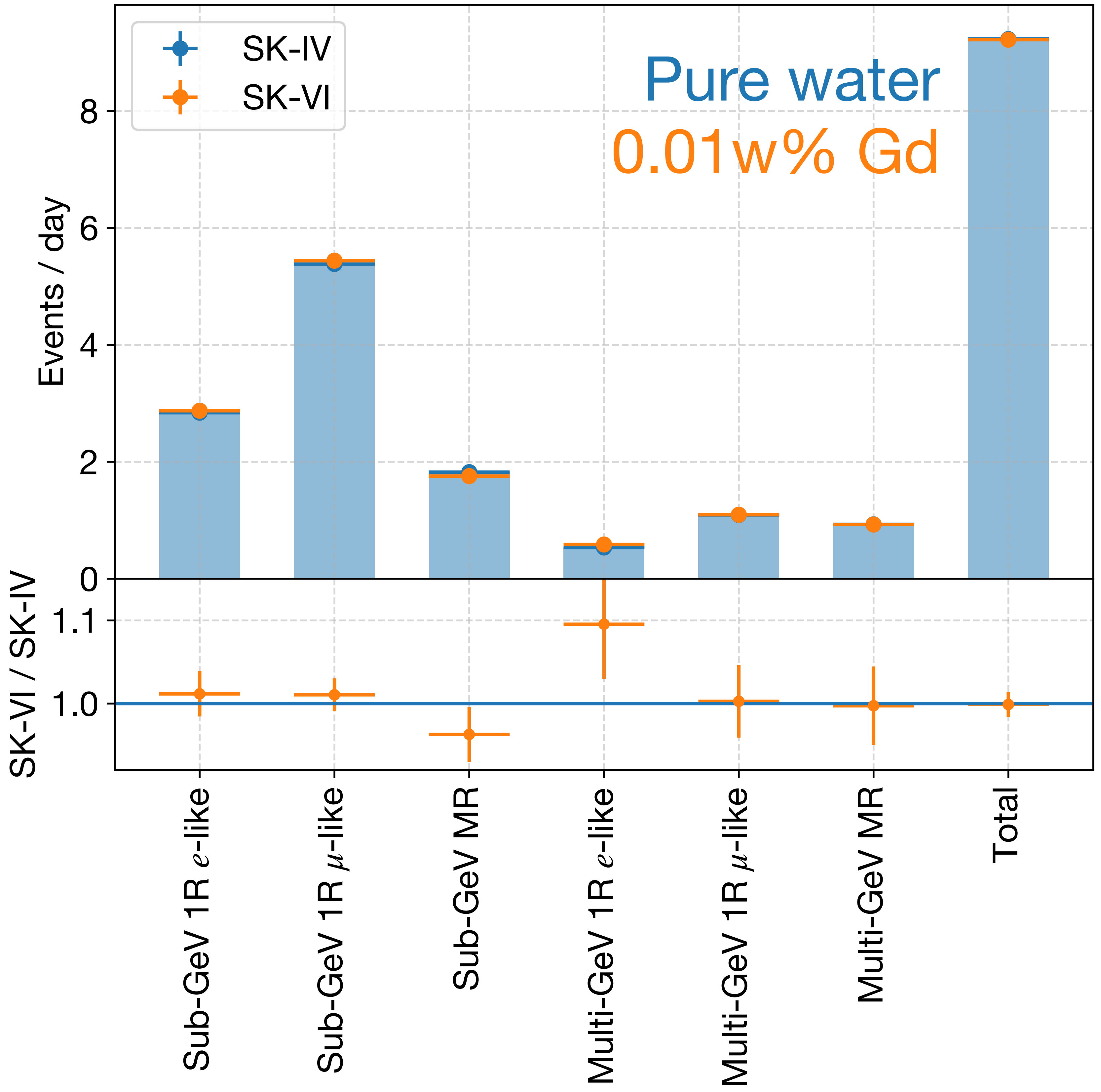
Again, neutron-tagging can help improve $\nu/\bar{\nu}$ ID and ν kinematic reconstruction

Gd-loading effect on neutron detection rate

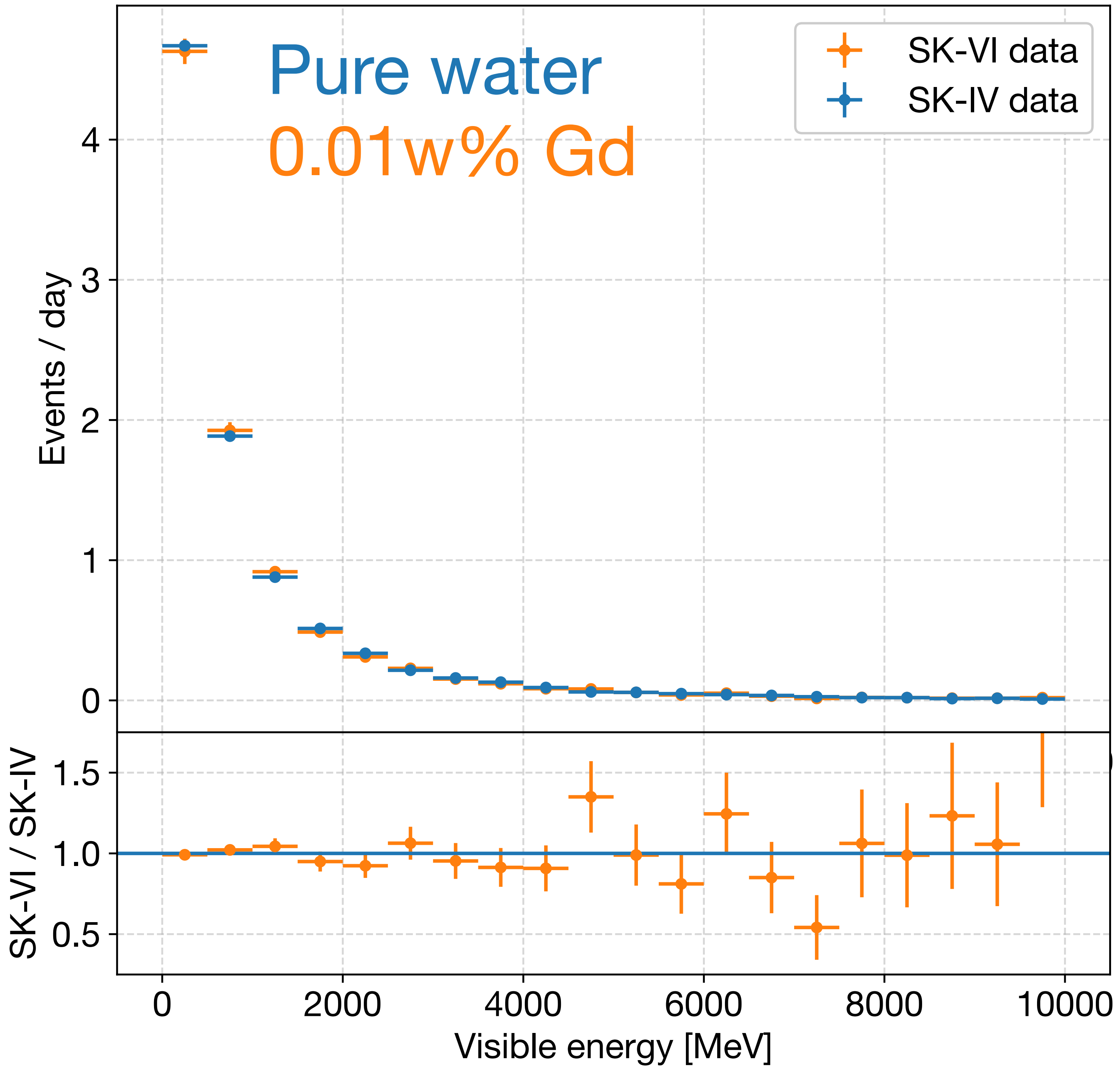


Gd impact on data quality seems small

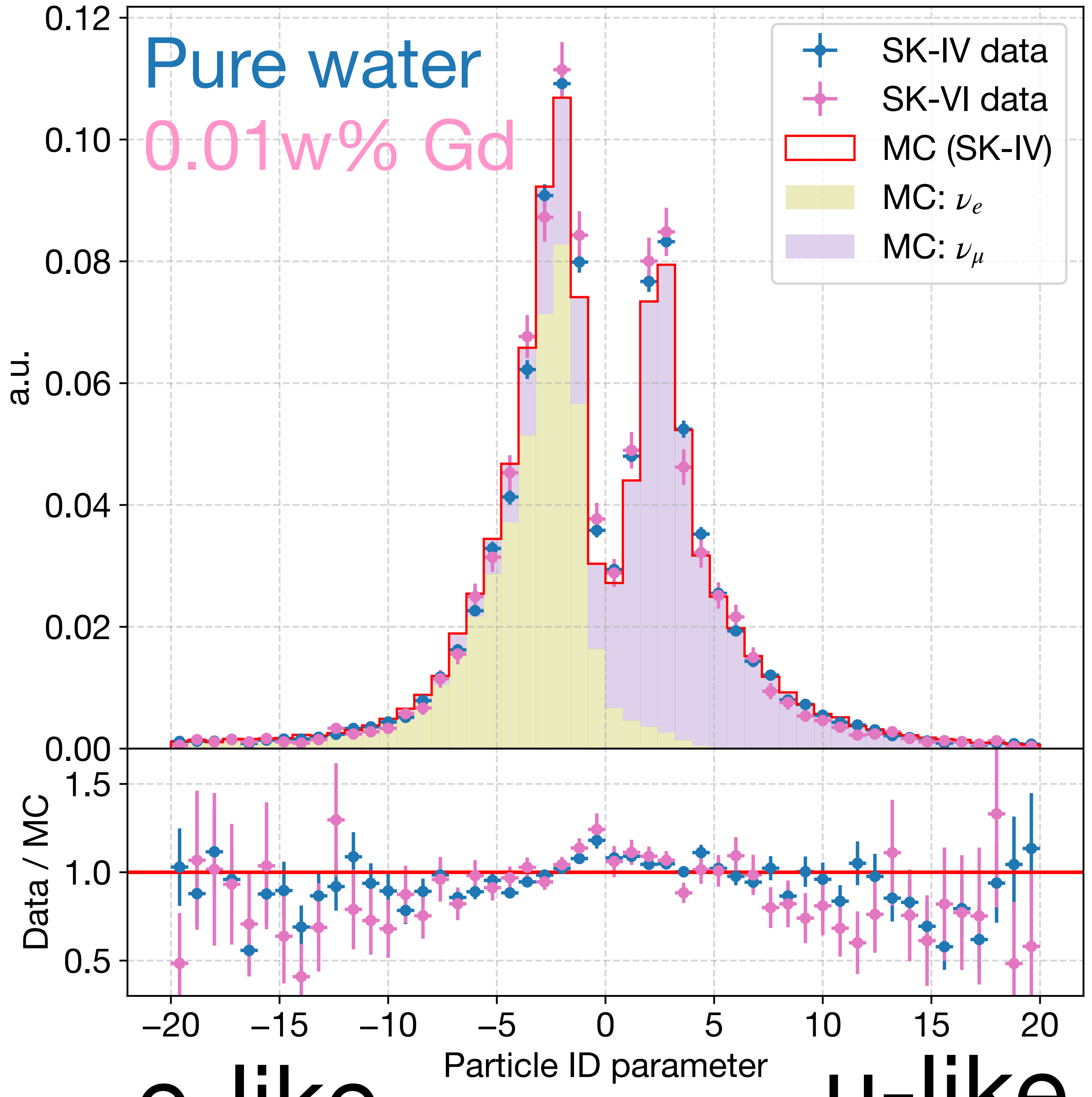
Event rate



Event visible energy



Particle ID likelihood



e-like

μ-like

SK results in FY2023

Pure water

Proton decay

- Search for $p \to e^{+}\pi^{0}\pi^{0}$, $p \to \mu^{+}\pi^{0}\pi^{0}$ (NNN23)

Atmospheric neutrinos

- Neutrino oscillation parameter measurement (arXiv:2311.05105)

0.01w% Gd

- "NCQE" cross section measurement (PRD 109, L011101)
- Neutron production measurement (paper in preparation)

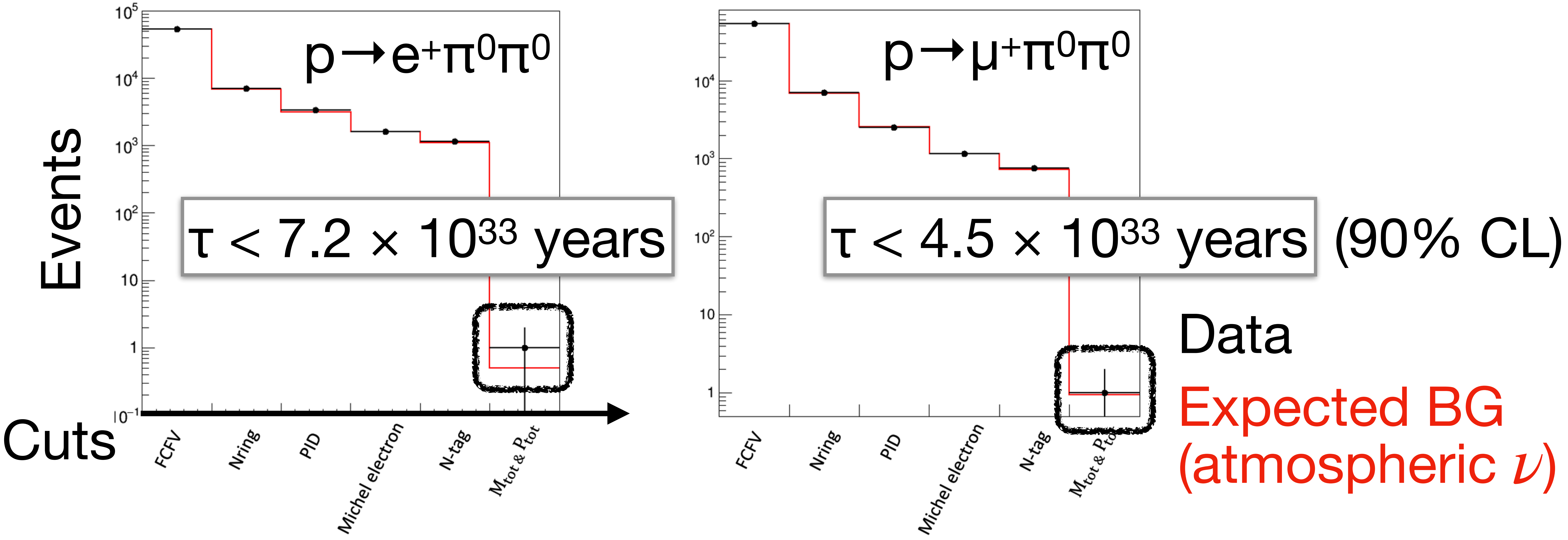
⇧ My PhD work

All results involve neutron-tagging data events

Search for $p \to e^+\pi^0\pi^0$, $p \to \mu^+\pi^0\pi^0$

Decay rates expected to be comparable to $p \to e^+\pi^0$, $p \to \mu^+\pi^0$

Full pure water data: SK I-V (6511.3 days, 0.40 Mt•yrs) + n-tag BG reduction



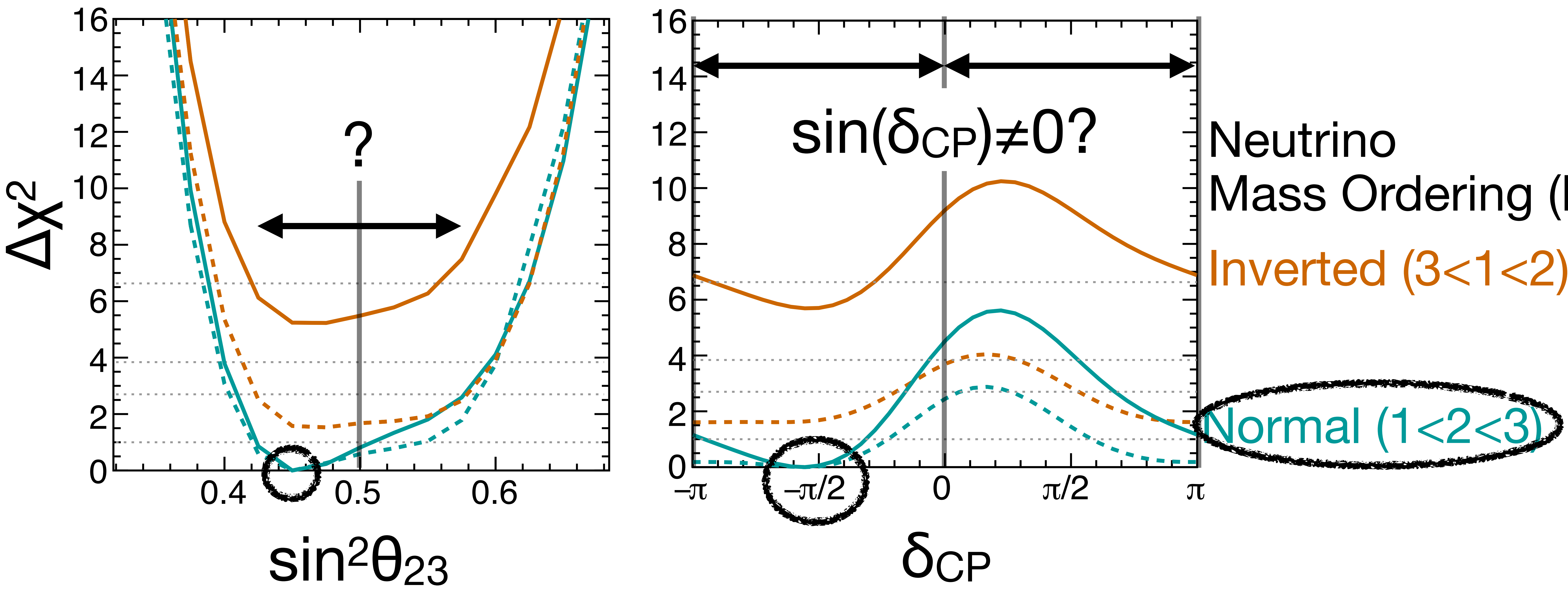
Improves IMB limits (1999) by factor of ~40

Updates in neutrino oscillation studies

Full pure water data: SK I-V (6511.3 days, 0.48 Mt•yrs) + external θ_{13} constraint

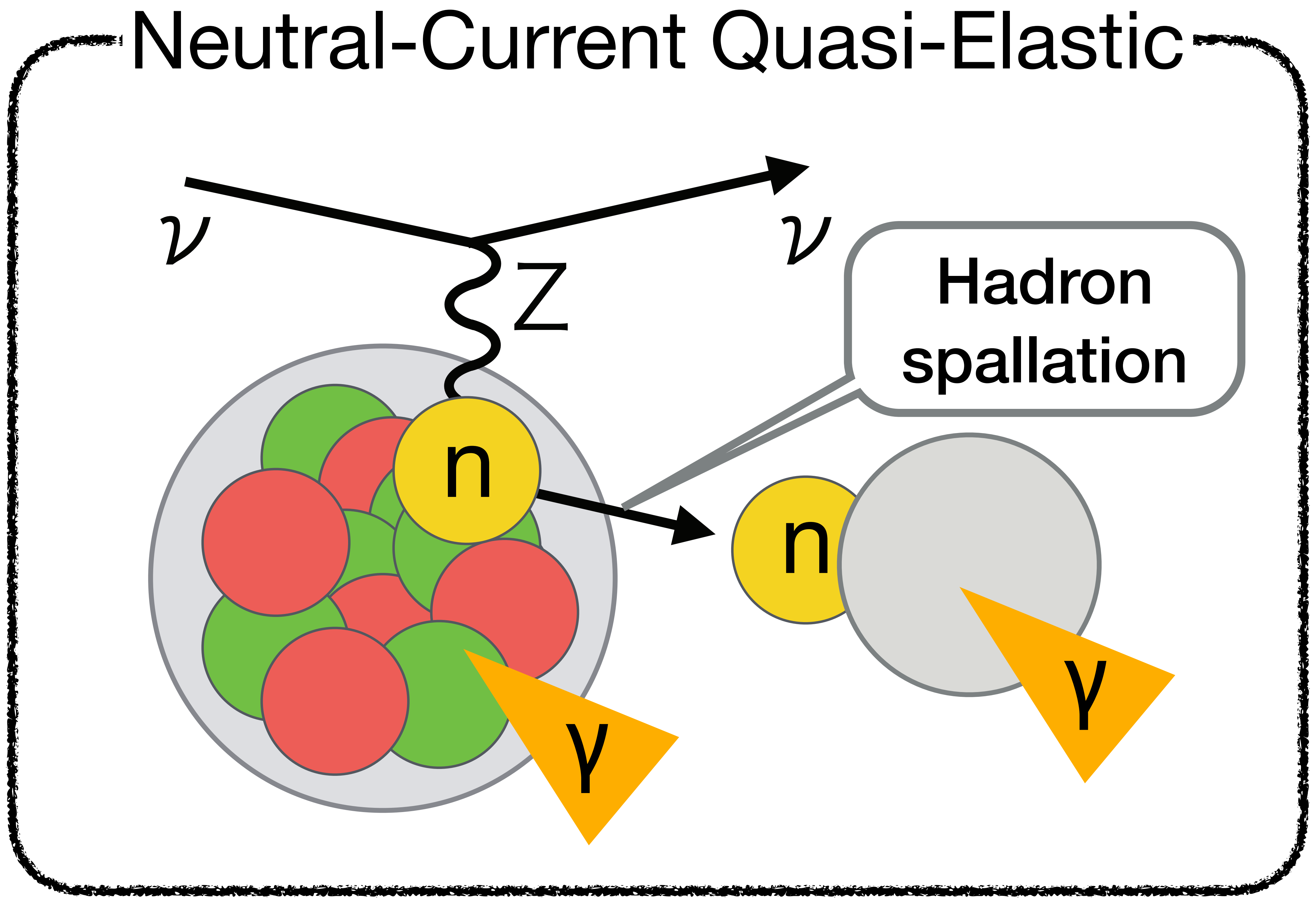
Compared to last publication (2018): 50% stat. ↑ + $\nu/\bar{\nu}$ separation w. n-tag

Expect MO/CP sensitivity ~10%↑



SK (2023) favors: •Lower θ_{23} octant •CP violation •Normal MO (92% CL)

“NCQE” cross section measurement

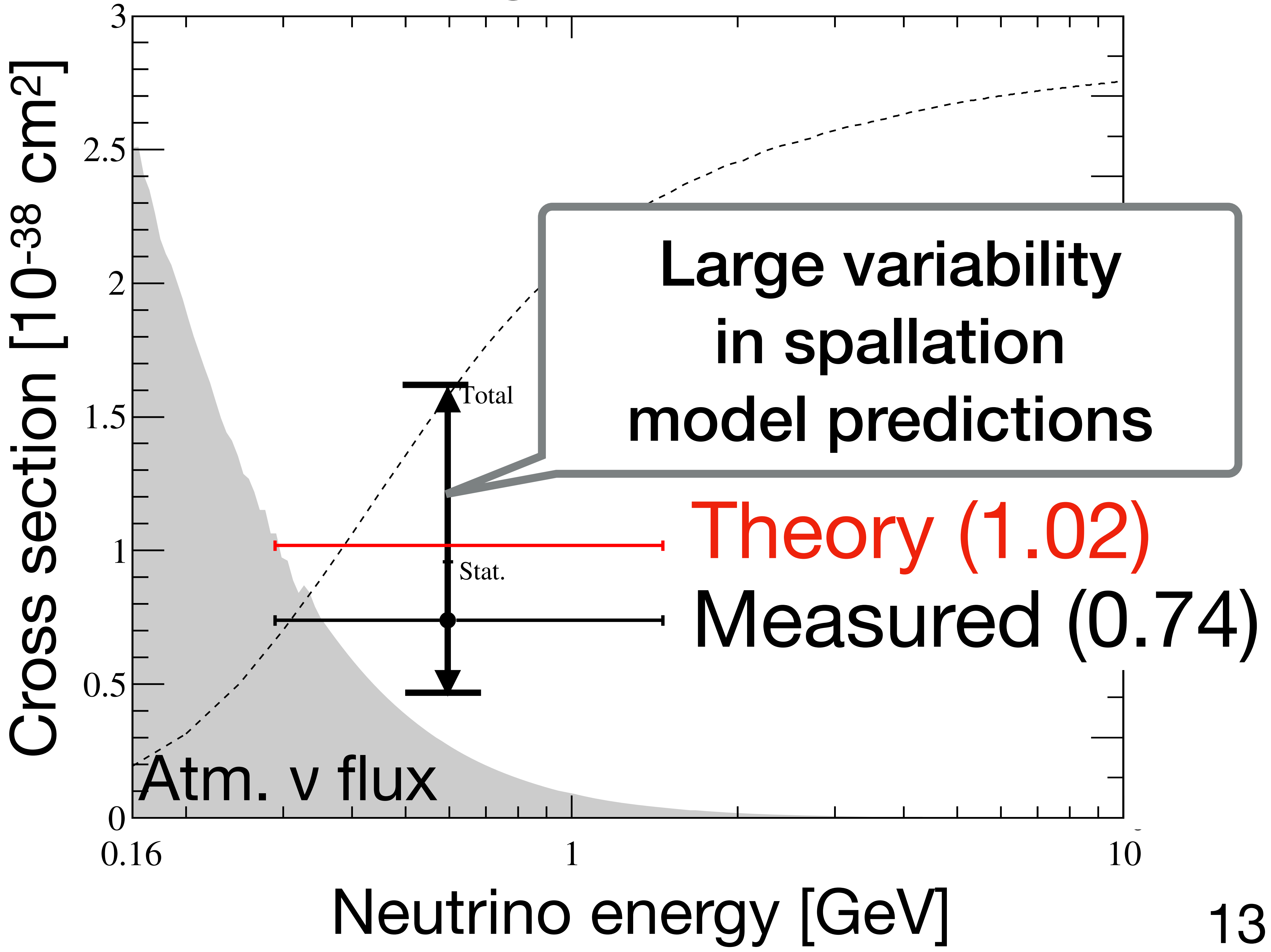


Dominant BG for **Supernova ν signals**

O(1-10) MeV Charged-Current $\bar{\nu}_e p \to e^+ n$

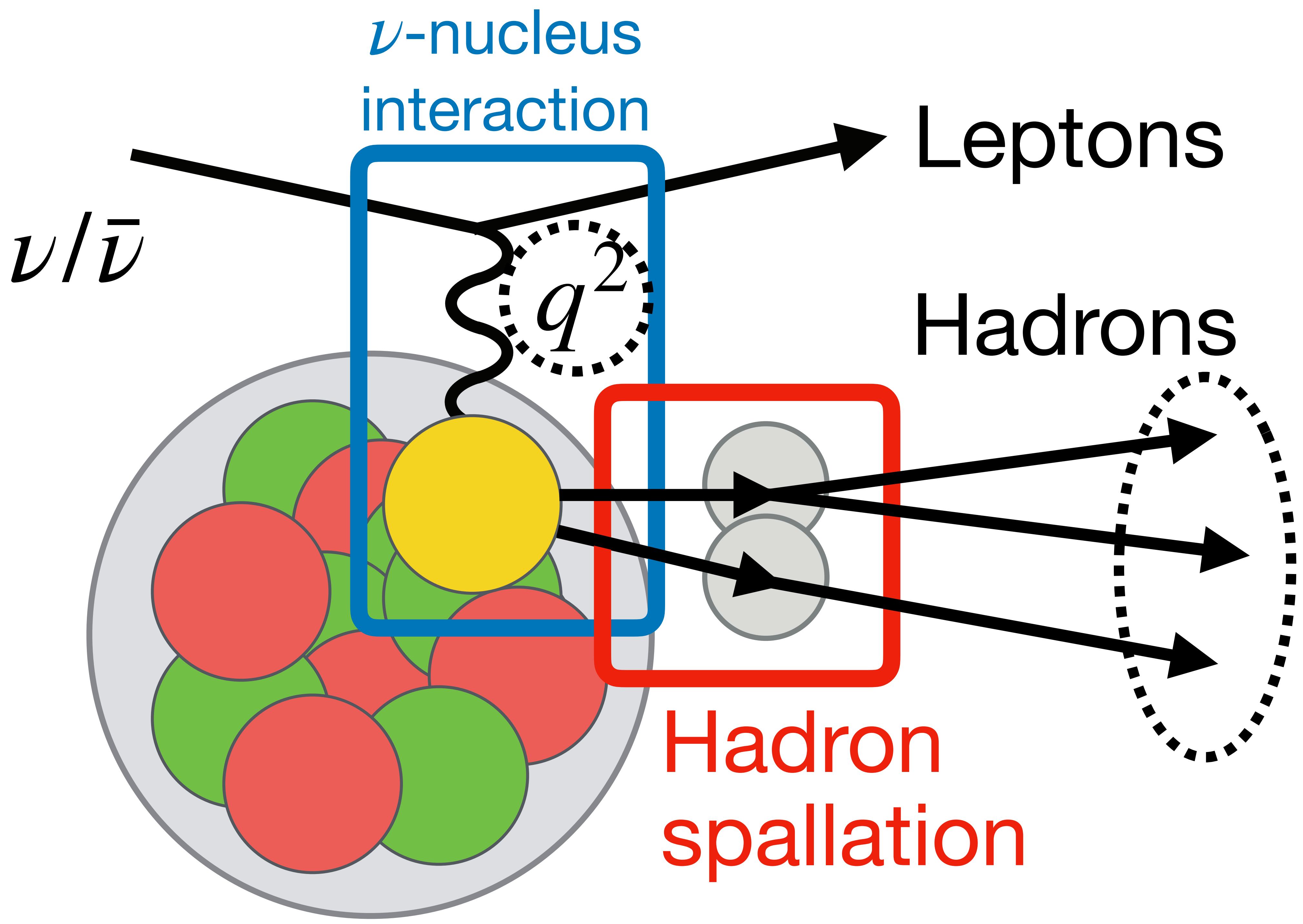
38 NCQE-like events
in 0.01w% Gd data (552.2 days)

Flux-averaged cross section

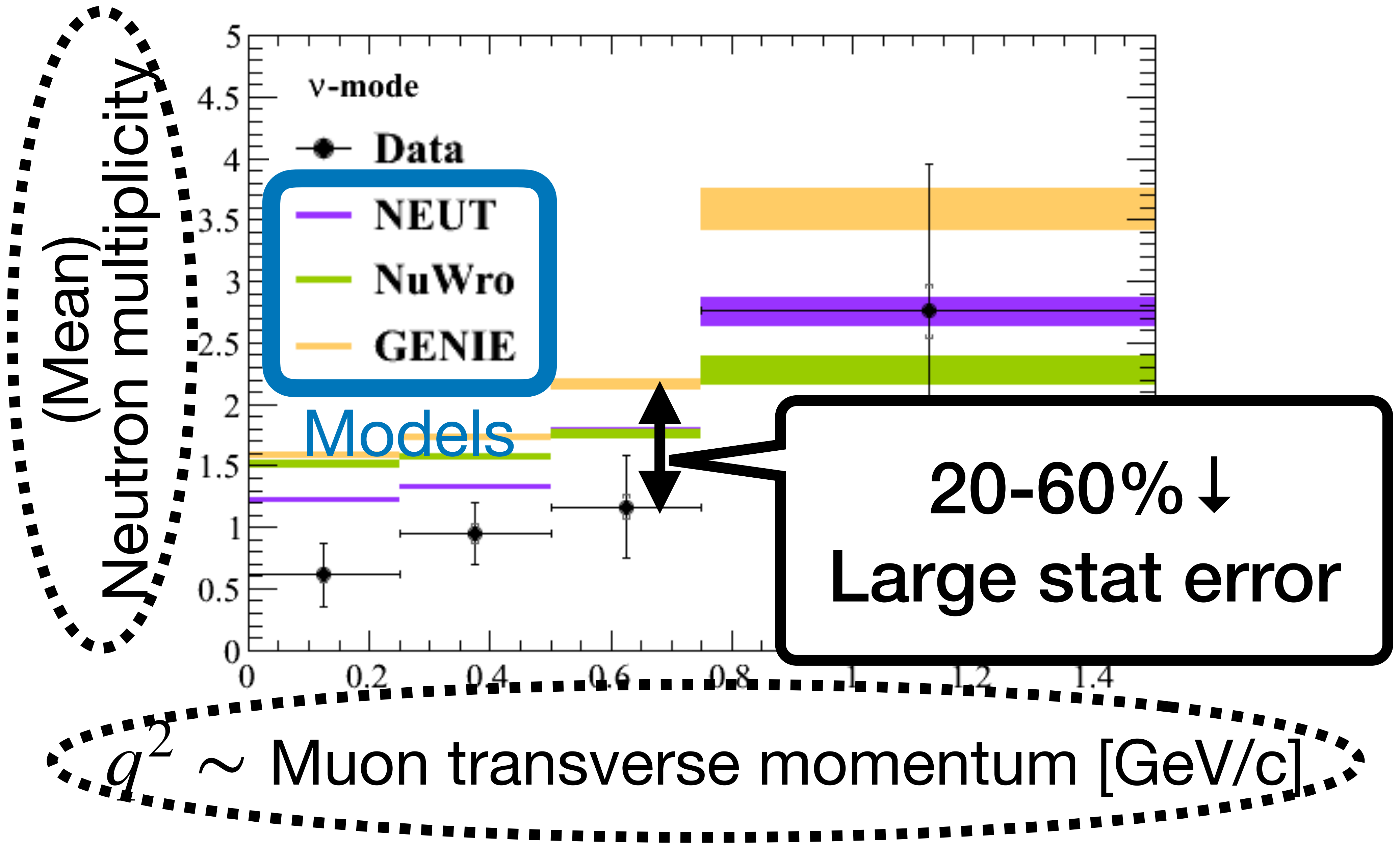


Measurement of neutron production in atmospheric neutrino events

Motivation: Validation of simulation models



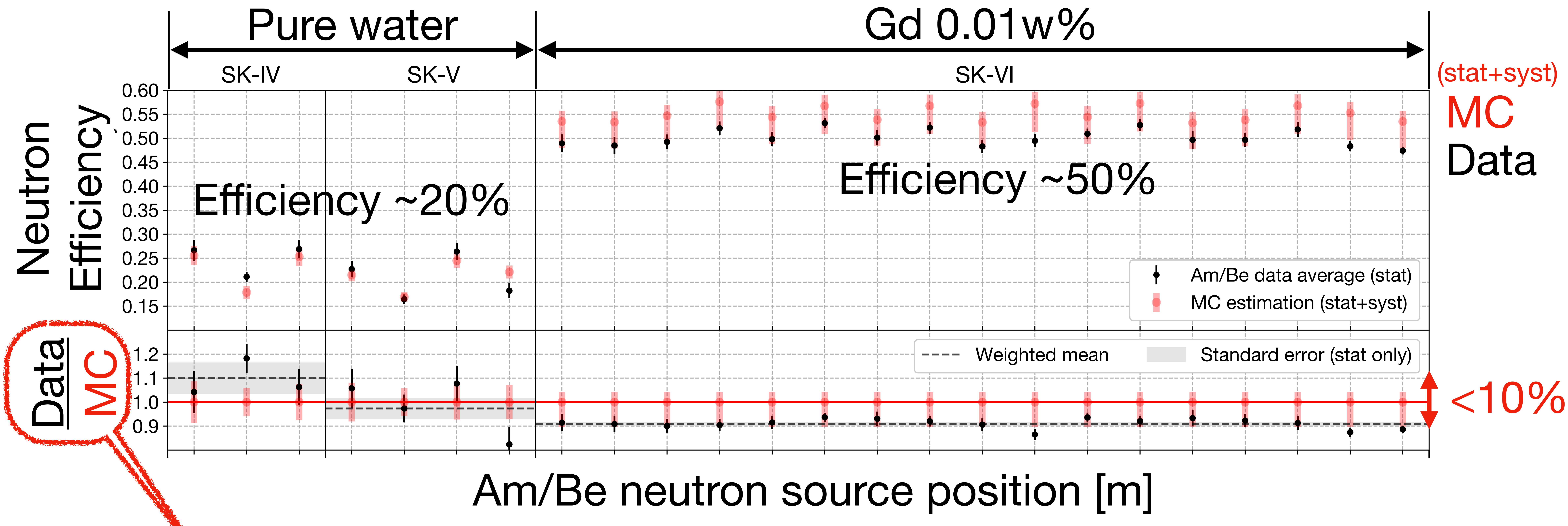
~200 artificial ν_μ events in water (T2K, 2019)



<u>This study</u> - Larger statistics (~40,000 atmospheric ν events in water)

- Investigate variability in **<u>hadron spallation models</u>**

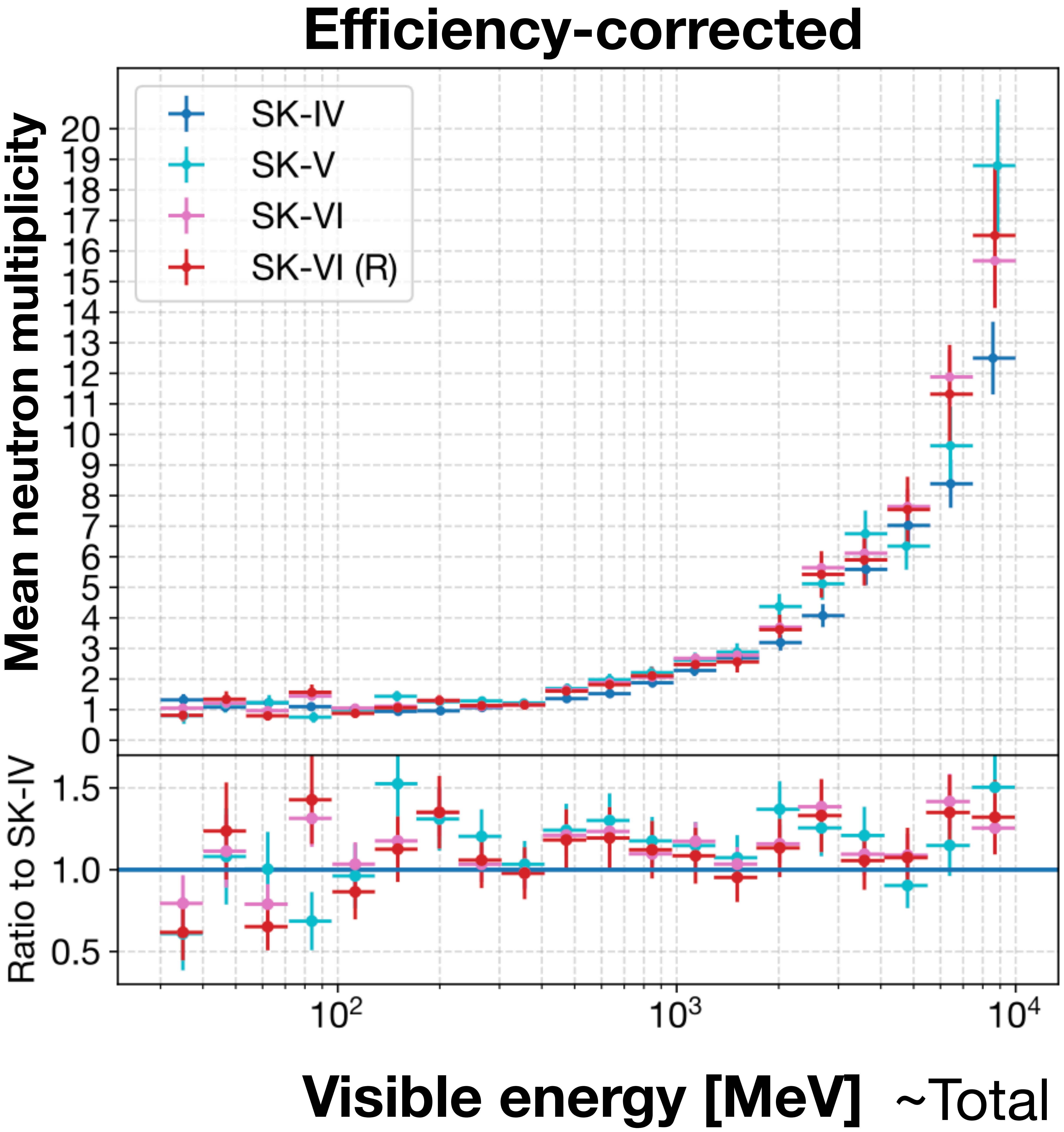
Neutron efficiency: Calibration data vs. MC simulation



Used to adjust MC-expected efficiencies in neutrino events

Assigned overall systematic uncertainty: ~15%

Neutron multiplicity: Phase consistency



~Total PMT charge seen in interaction ~q^2

Atmospheric neutrino data
in different SK operational phases

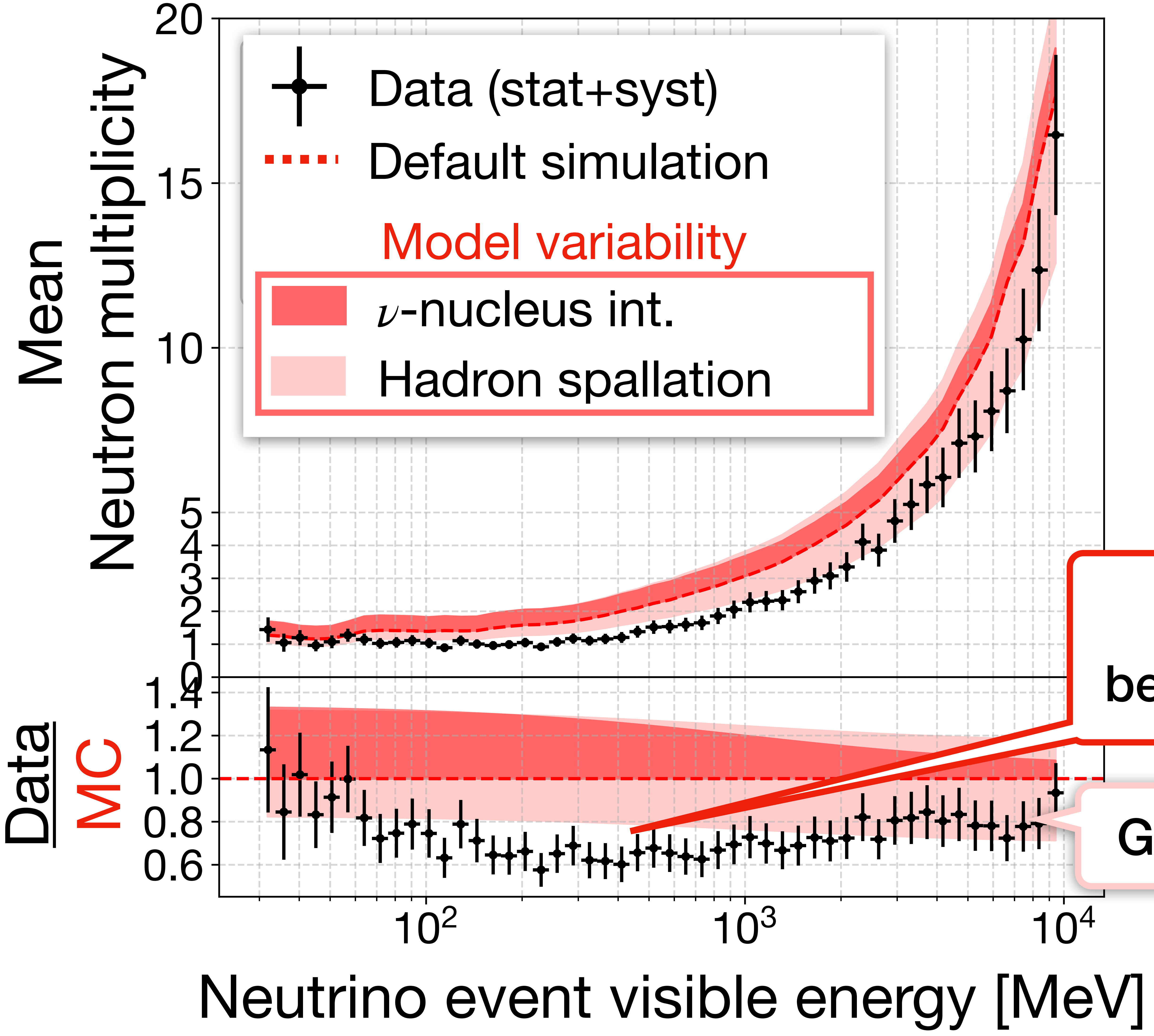
++ Pure water: 2008-2019

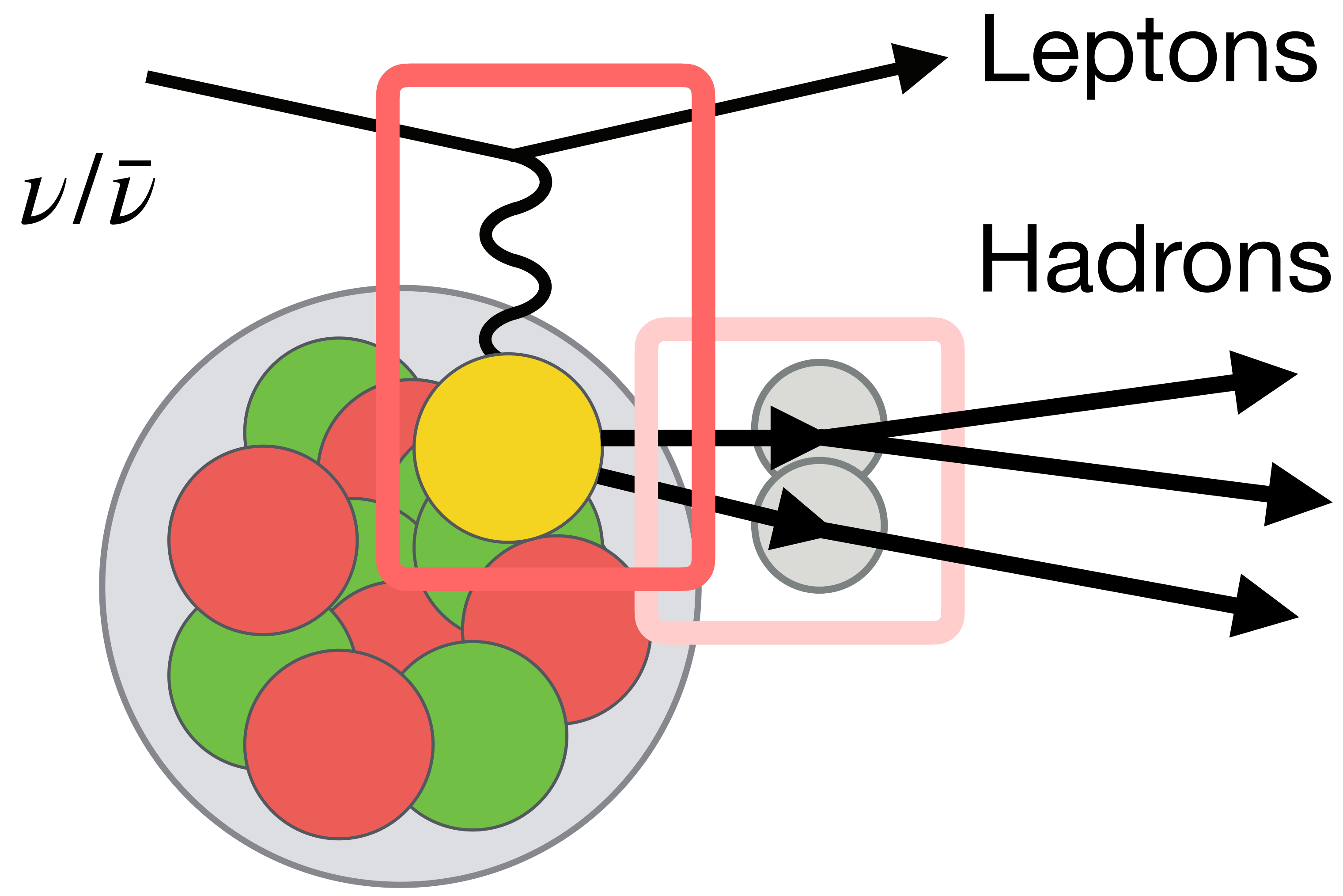
++ 0.01w% Gd-water: 2020-2021

Phases with/without Gd,
having different neutron efficiencies,
show consistent results

Also consistent with past study (SNO, 2019)

Combined Data vs. Models

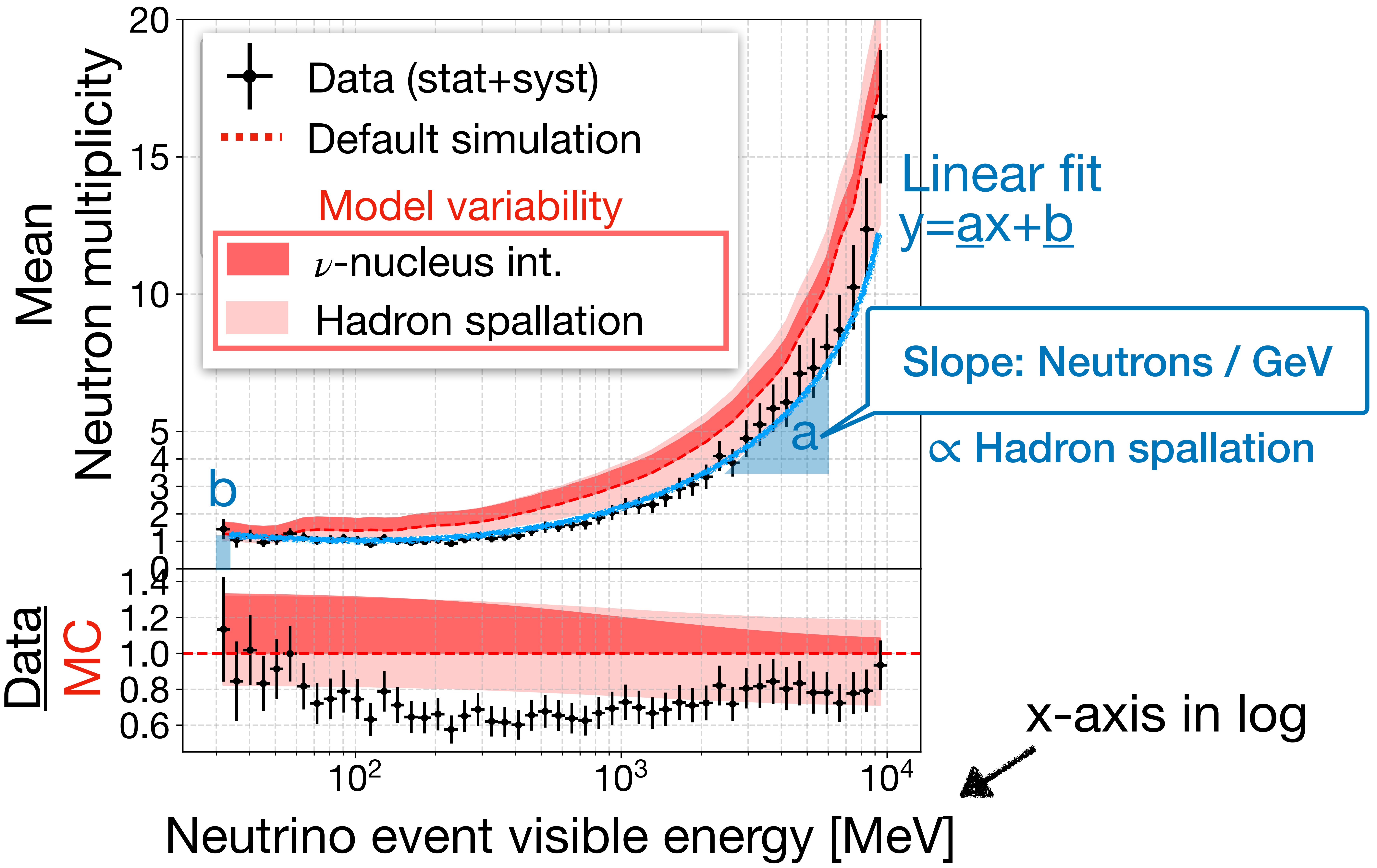




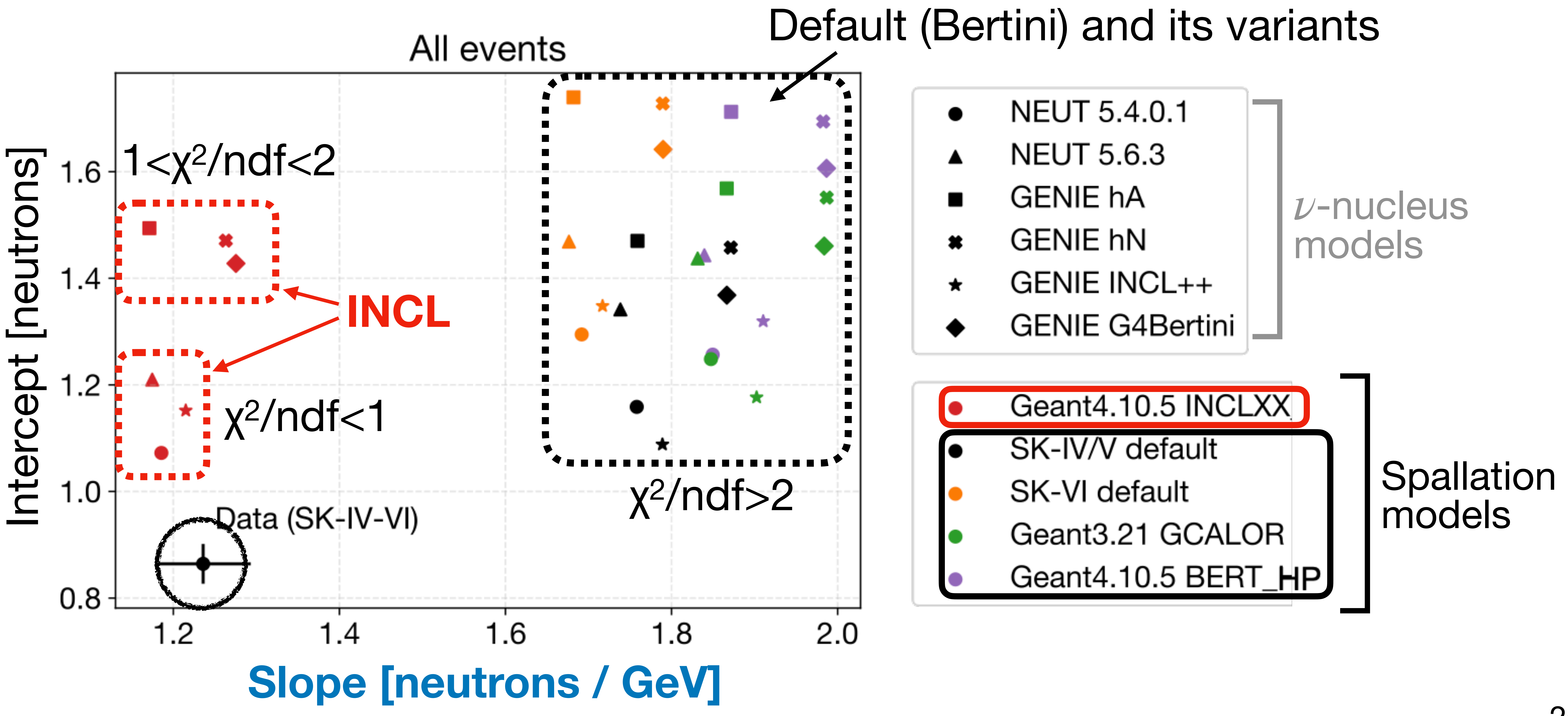
~30% less neutrons observed, beyond ν-nucleus model variability

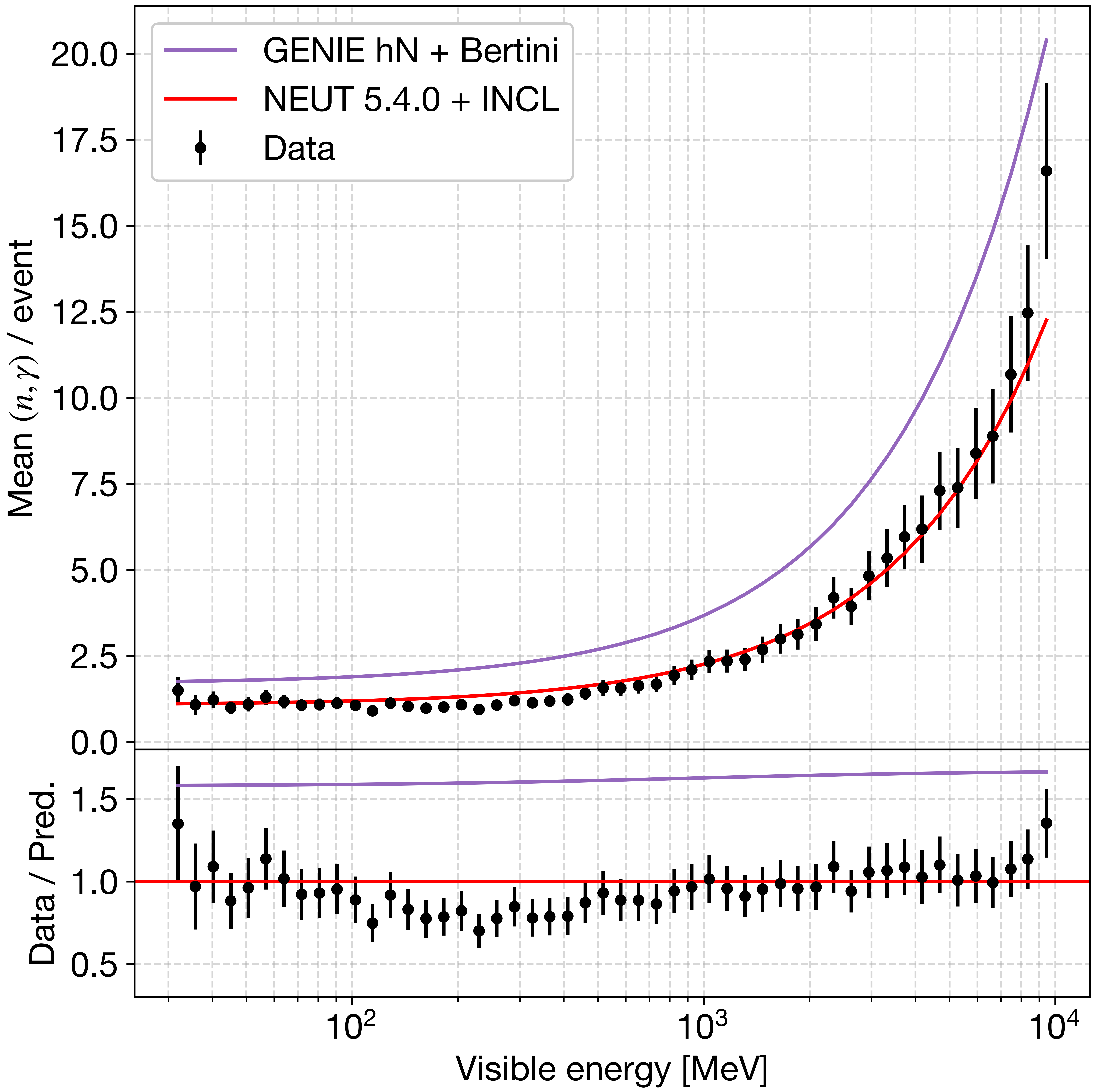
Good agreement with varied spallation model

Combined Data vs. Models



Fitted Slope: Data vs. Models





Default spallation model (Bertini)

~O(1) GeV Intra-Nuclear Cascade model:
Non-interfering 2-body collisions of hadrons

Best spallation model (INCL)

+ "Nuclear effects" which tend to ***reduce*** the estimate of neutron production.

For example:

✓ Nucleon repulsion, interference
✓ "Pauli blocking" of low-energy recoil
✓ Cluster formation

Summary: SK Proton Decay, Atmospheric ν

- **Neutron-tagging** has potential to **reduce BG for proton decays** and **add sensitivity to neutrino mass ordering and CP symmetry**; it is now applied to most analyses and Gd results are just coming up.

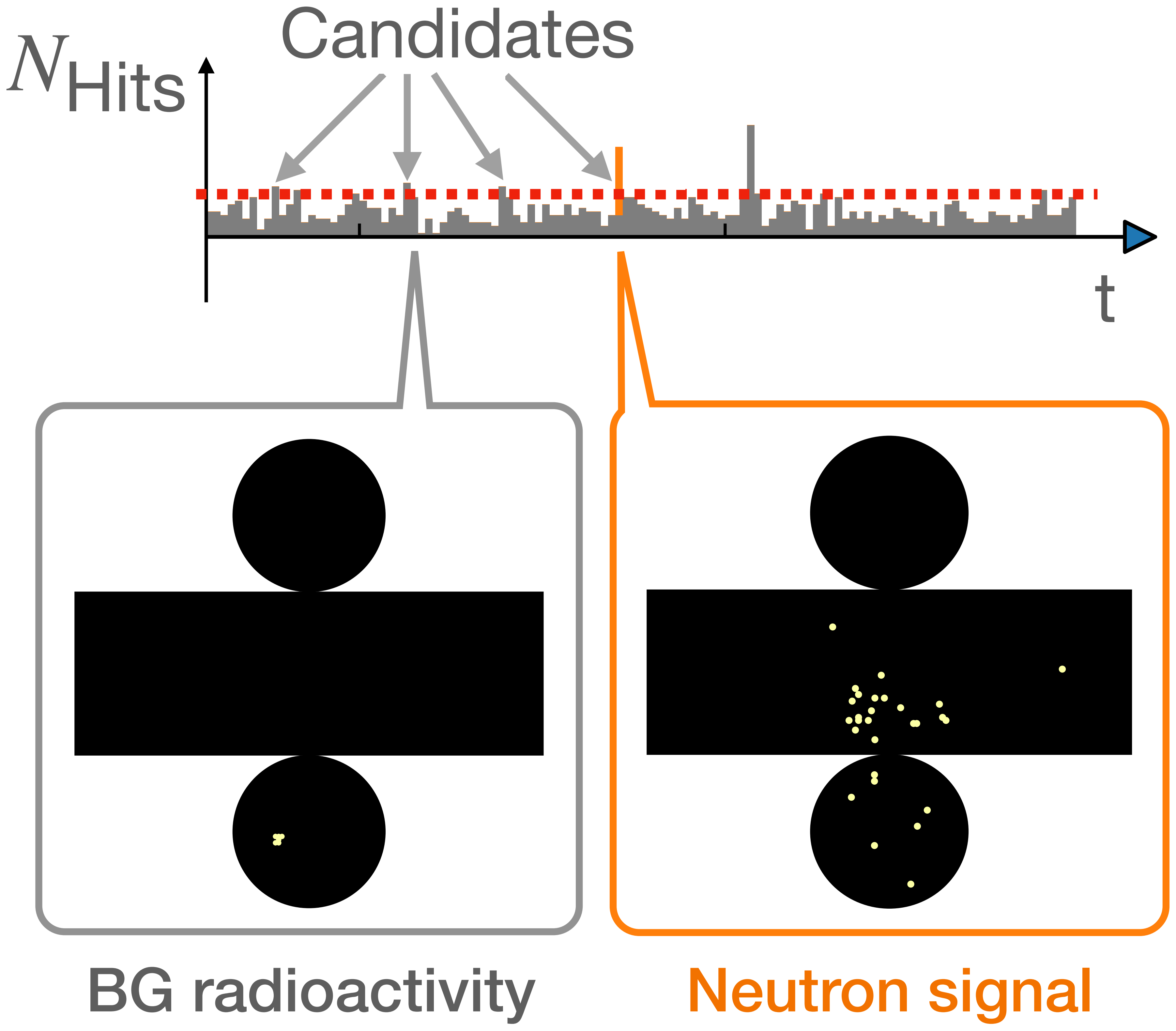
- Gd impact on analyses, including reconstructed variables and neutron efficiency, is constrained through data monitoring and calibration.

- **<u>Measured neutron counts in neutrino data</u>** to reduce large uncertainty; Accuracy in hadron spallation model was critical in explaining the previously reported neutron deficit.

Backup

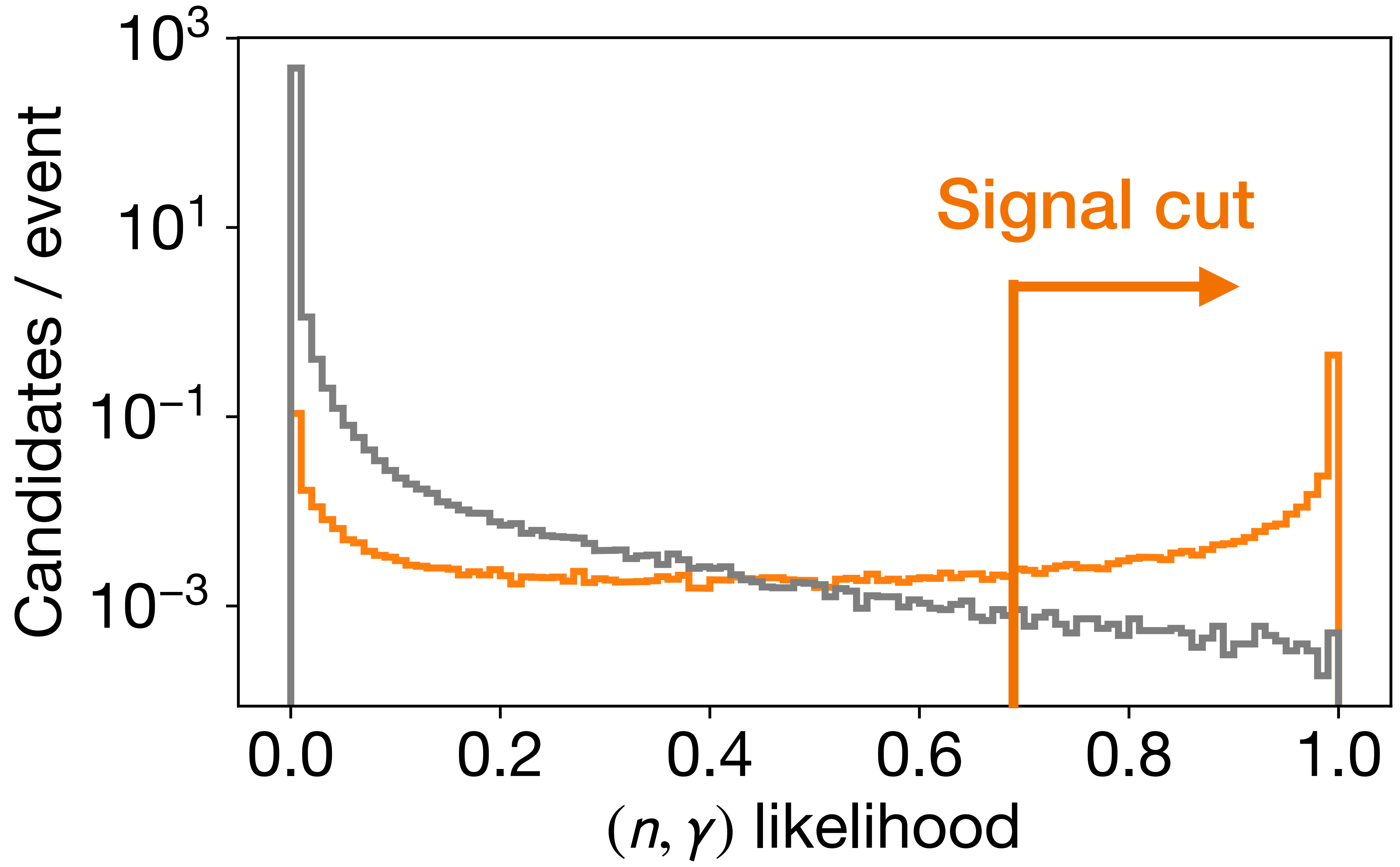
Neutron signal detection algorithm @ SK

(Step 1) PMT hit trigger

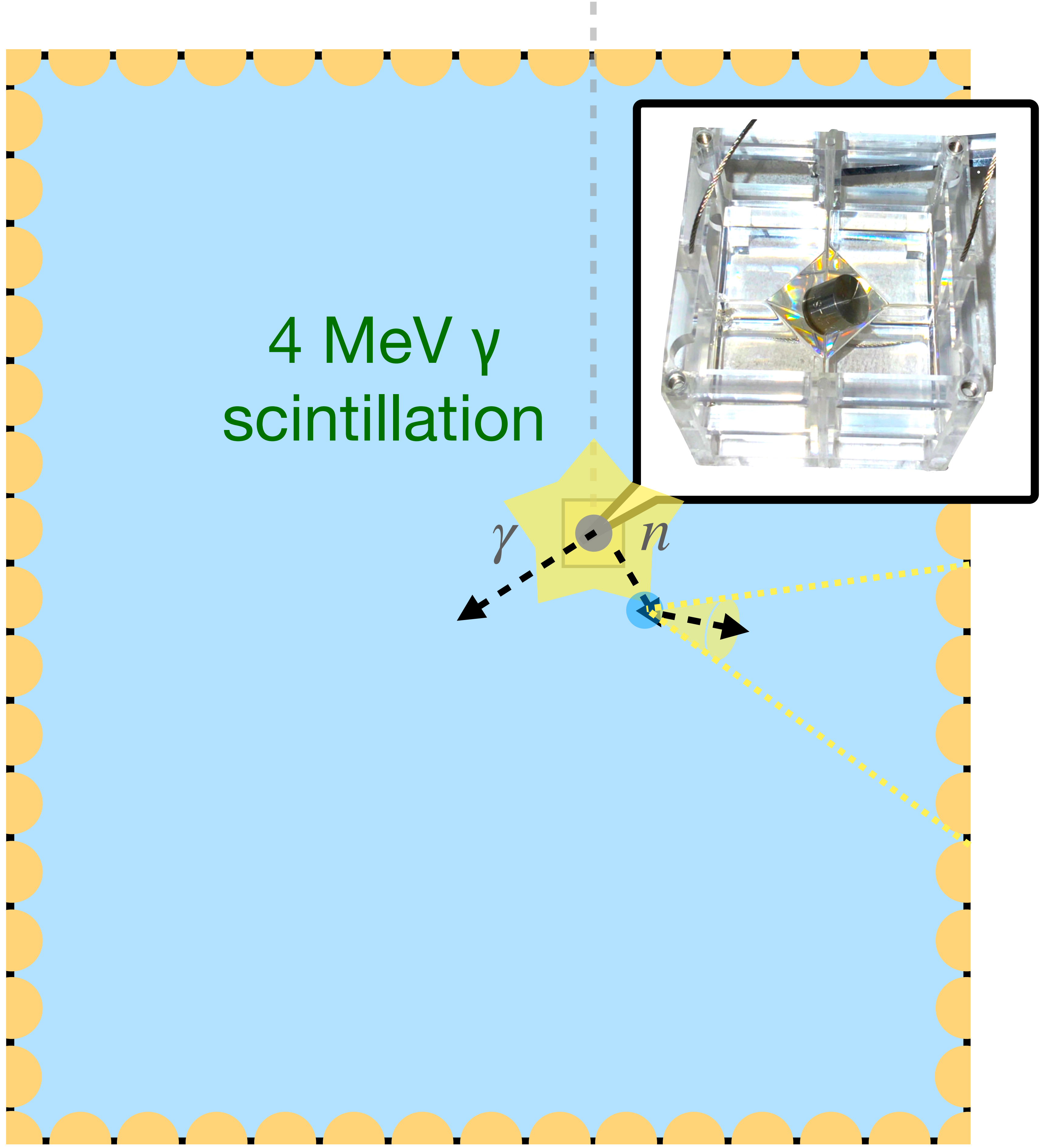


(Step 2) Neural network

Noise vs. Signal classification
using N_{Hits}, positional correlation, etc.



Calibration using neutron point source



- Am/Be neutron source: 1n + 1γ (4 MeV)
- Surround with scintillator for event trigger
- Take data for 0.5-1h at each source position

$$\textbf{Neutron efficiency} \approx \frac{\text{Detected neutron signals}}{\text{4 MeV scintillation triggers}}$$

1n control

Atmospheric neutrinos and neutron signals

$$\bar{\nu}_\mu + {}^{16}\text{O} \rightarrow \mu^+ + n + {}^{15}\text{O}$$