Low-energy atmospheric neutrinos and DSNB in Super-Kamiokande

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Based on arXiv: 2311.05675 by Bei Zhou, John Beacom

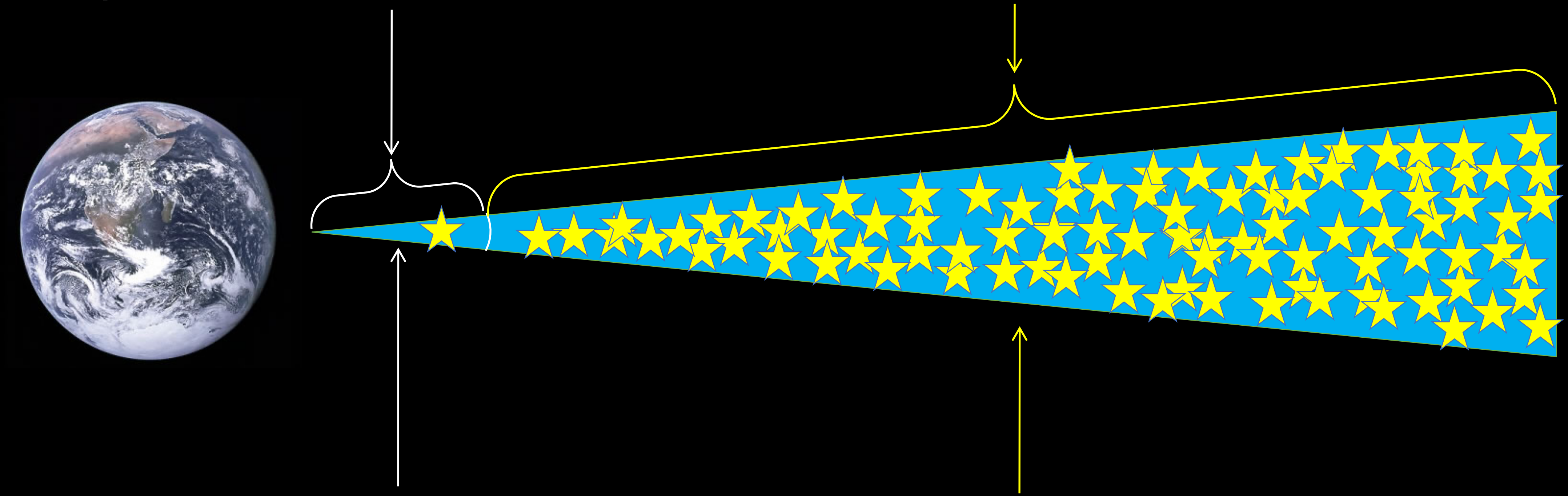
Diffuse Supernova Neutrino Background (DSNB)

Galactic Supernova

DSNB

Detected v per burst: N >> 1

N << 1



Burst rate: ~ 0.01/yr

~ 10^8/yr

Guaranteed steady neutrino flux

What Determines the DSNB Flux

$$\frac{d\phi}{dE_\nu}(E_\nu) = \int_0^\infty [(1+z)\varphi[E_\nu(1+z)]]\,[R_{SN}(z)]\,\left[\left|\frac{c\,dt}{dz}\right| d\,z\right]$$

(Beacom, Ann.Rev.Nucl.Part.Sci. 2010)

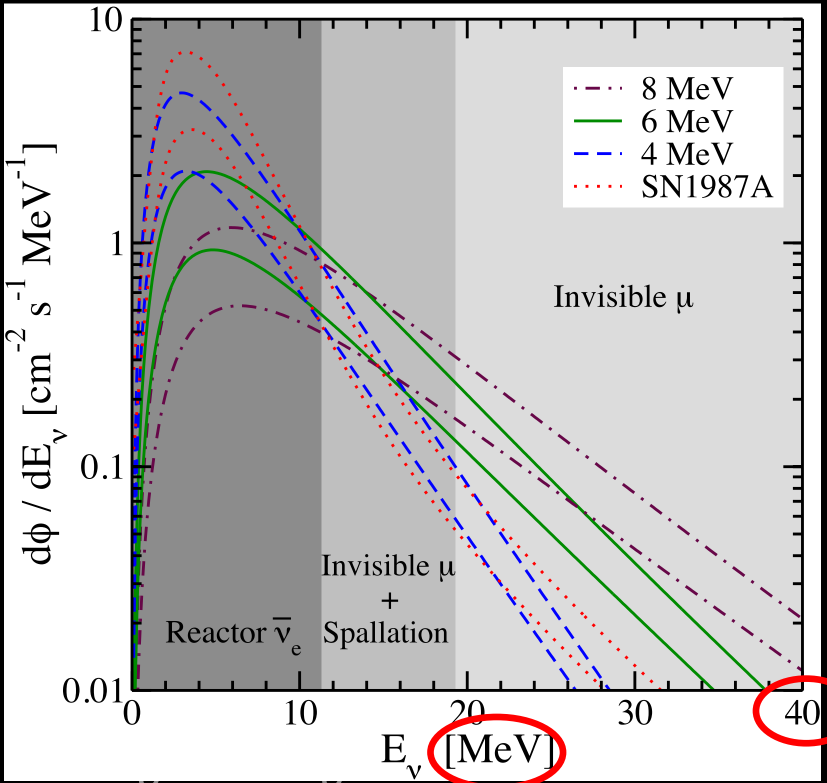
DSNB flux
(~ 10 cm^{-2}s^{-1})

ν spectrum per supernova
(Not very well known)

Cosmic core-collapse rate
(Relatively well known)

Properties:

- All ν flavor
- Steady
- Isotropic
- Averaged ν fluxes of supernovae



Different DSNB flux

Horiuchi, Beacom, Dwek, PRD 2009

Diffuse Supernova Neutrino ~~Background~~ (DSNB)

Signal

Why do we study DSNB?

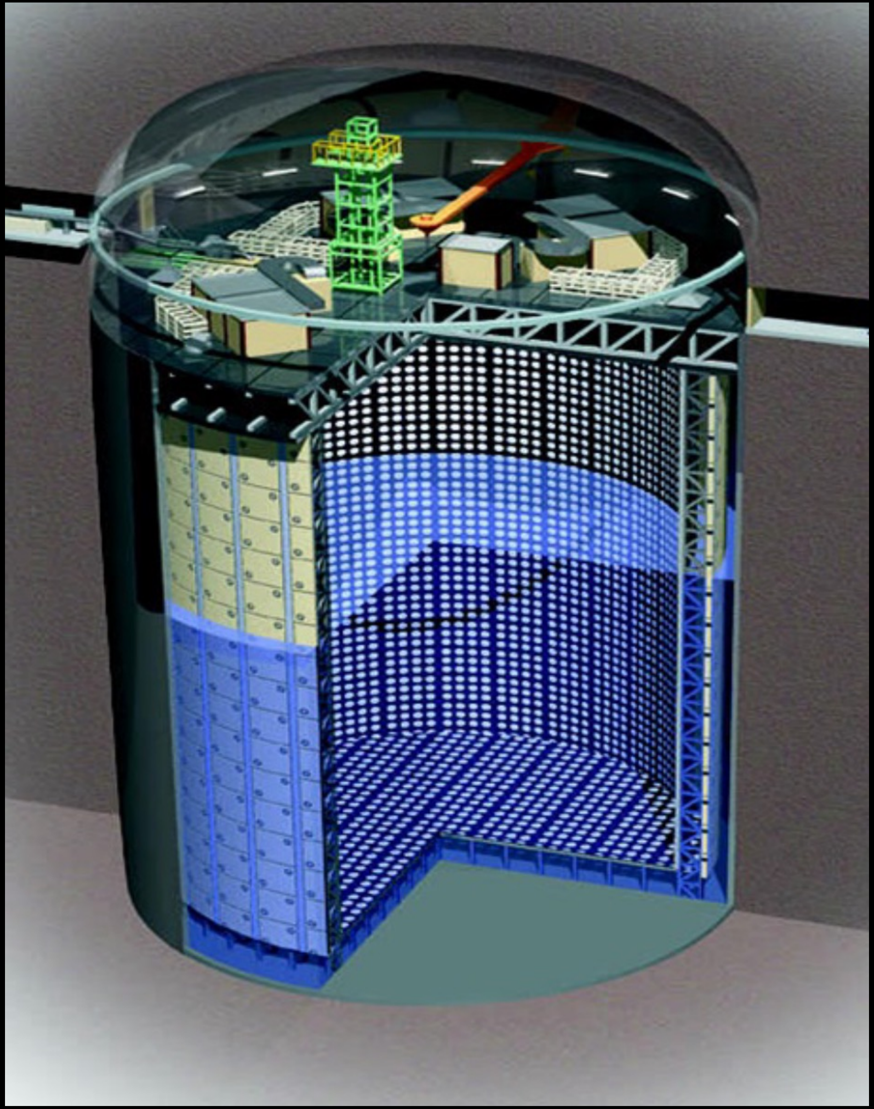
- (Almost) Same physics as galactic supernova neutrinos
    1. SN physics (unreachable by photons)
       (explosion mechanism, ν mixing)
    2. Particle physics
       (electric dipole/magnetic moment, BSM)
- More than galactic supernova neutrinos
  (Cosmic rate of dark collapses, core collapses, and star formation)
- Will be the first (< 100 GeV) neutrino source at cosmic distance

DSNB detection

- Super-Kamiokande (SK)
  (Water Cherenkov Detector)

- Detection process
  $\bar{\nu}_e + p \rightarrow n + e^+$ (Inverse Beta Decay)

- ~ 5 events/yr (theory prediction)
  So ~ 50--100 events collected so far, but not identified.
  (Hyper-Kamiokande will be ~50 events/yr)



(Figure from SK website)

Large Backgrounds

- **Atm. $\nu_\mu/\bar{\nu}_\mu$ (Dominant)**

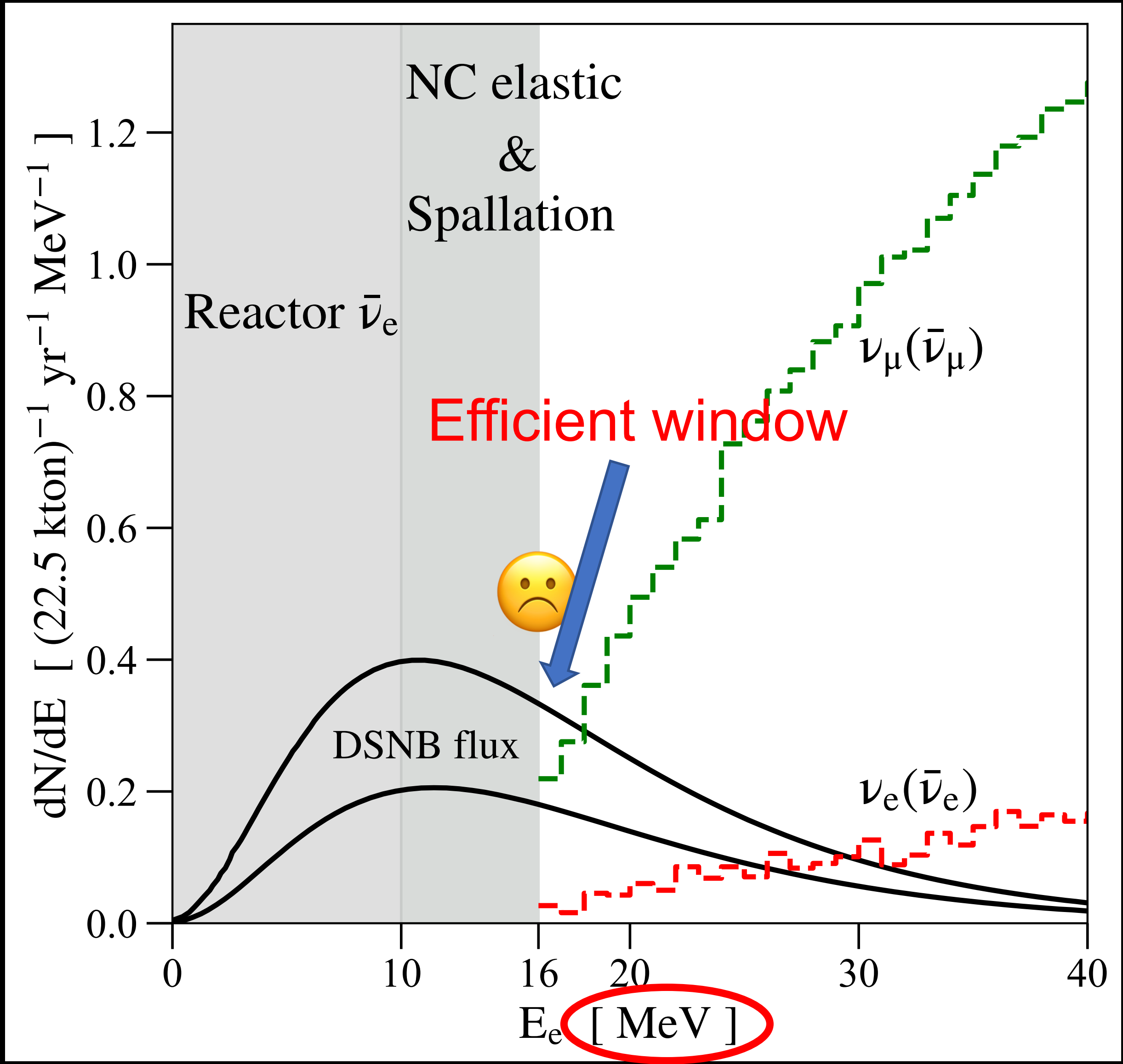
  $\nu_\mu(\bar{\nu}_\mu) + \mathrm{H/O} \rightarrow \mathrm{X} + \mu^-(\mu^+)$, etc.

  $K_\mu < 55$ MeV, invisible

  μ decay to e, mimic DSNB events

- **Atm. $\nu_e/\bar{\nu}_e$ CC**

  $\nu_e(\bar{\nu}_e) + \mathrm{H/O} \rightarrow \mathrm{X} + e^-(e^+)$



SK-Gd, New Era of DSNB Detection

- Add Gd (Gadolinium) to SK water

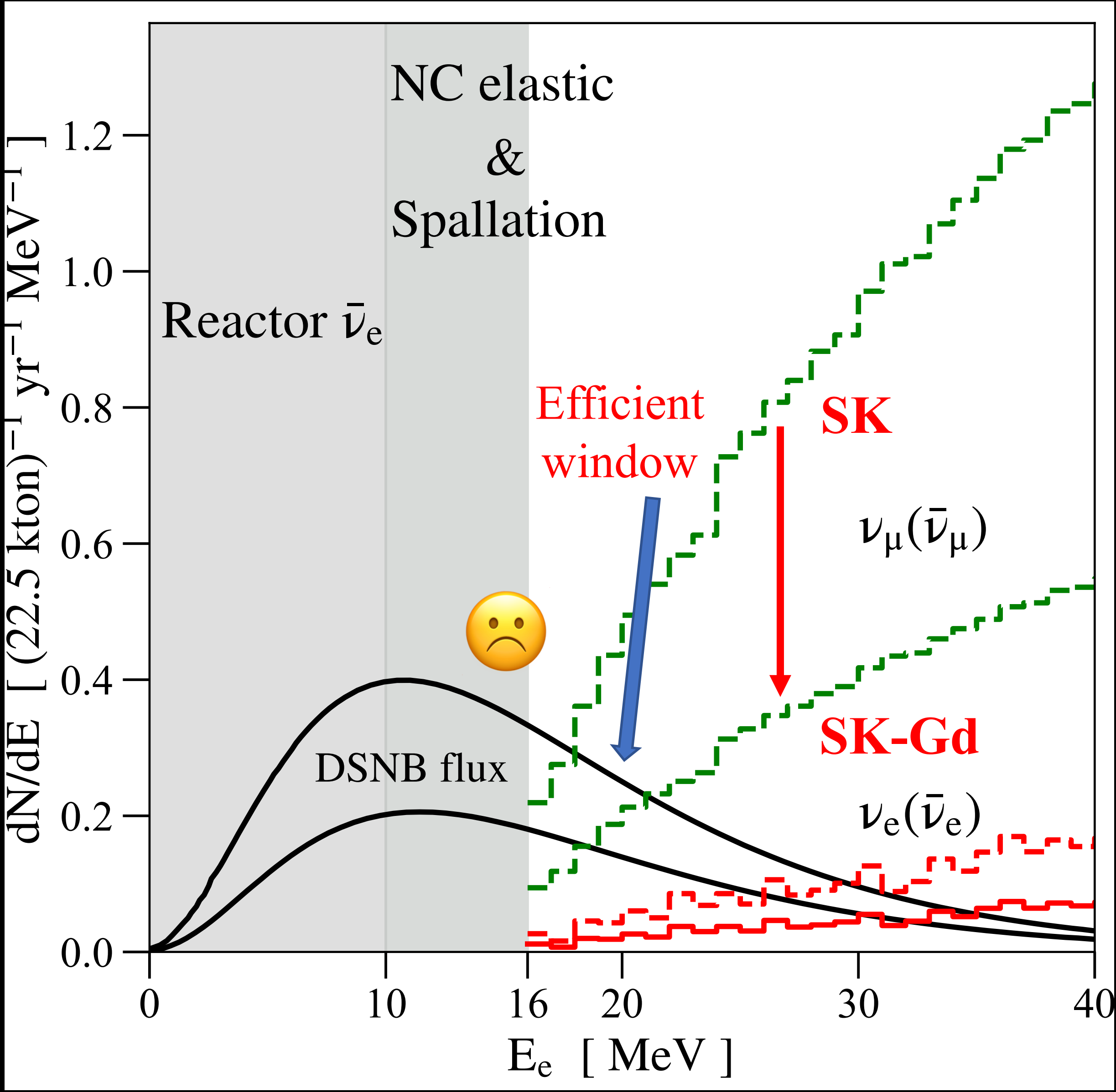
  (Beacom & Vagins, PRL 2004, hep-ph/0309300)

- Enable SK to detect neutrons (multiplicity, etc.)
  (neutron tagging)

- SK → SK-Gd, on going

- Improve DSNB detectability

DSNB	Atm. ν bkgd.
100% one neutron	<~ 50% one neutron

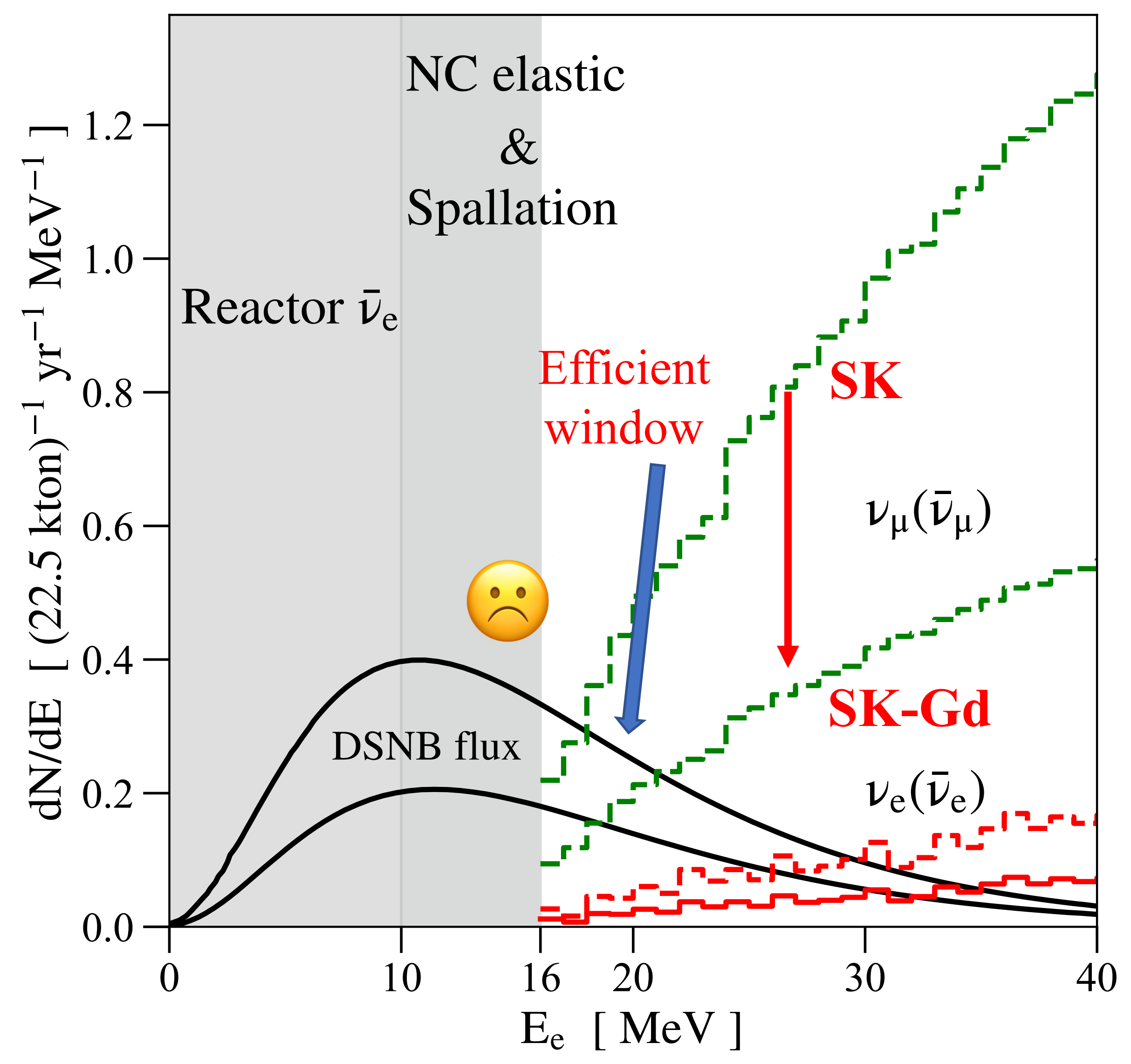


Goal of Our Work

- Study the underlying physics
  - Atm nu flux and oscillation
  - Nu-nucleus (water) interactions
  - Propagations of secondaries in water (*π*/*μ*/neutron/proton)
  - Detection physics of Super-K

  (No systematic study before)

- Find ways to further reduce the background

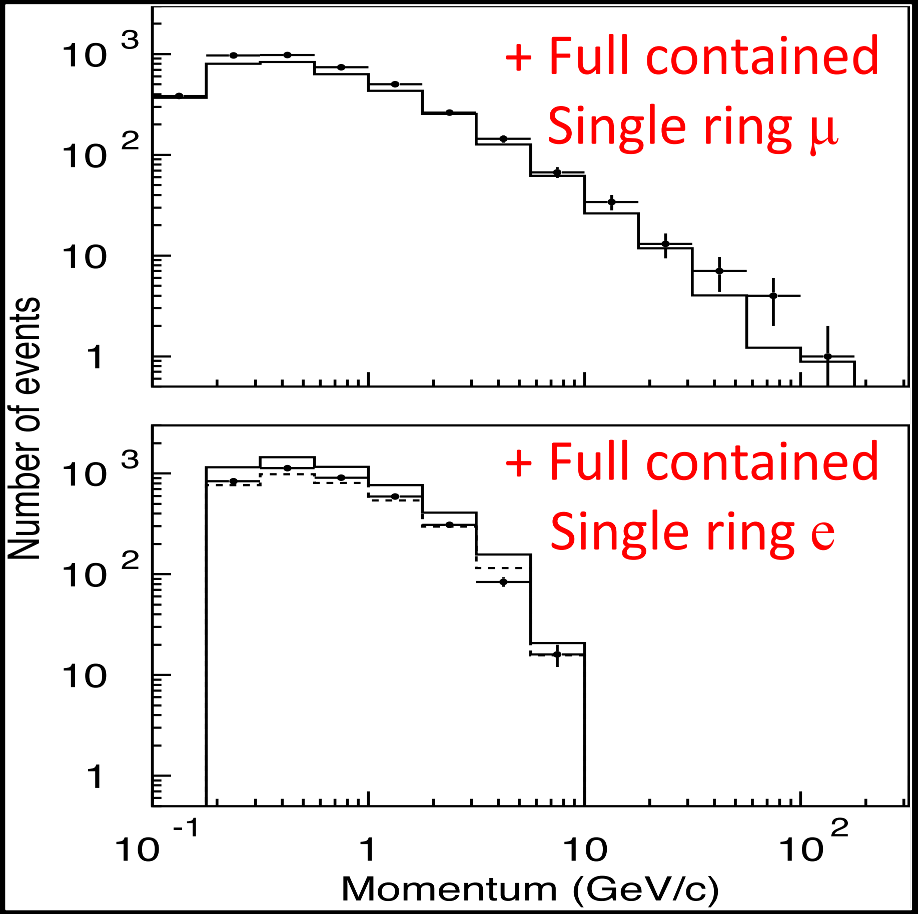


Part 1: study the underlying physics of the atm nu background

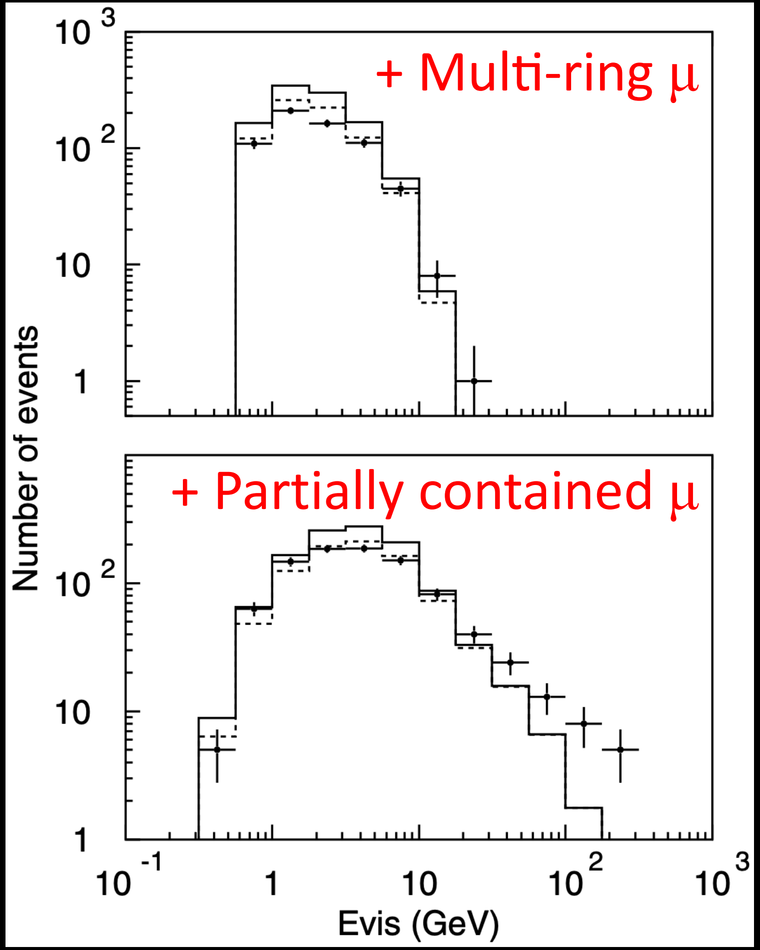
Guidance: reproduce Super-K data

Super-K's high-energy atmospheric neutrino data

Used, lower E, relevant



Not used, higher E, not relevant



Data from SK collaboration (SK-I only), PRD, 2005, hep-ex/0501064, measuring nu oscillations (1510.08127 of SK collaboration has updated measurements but no charged lepton data published)

Basic Calculational Framework

Detector exposure (~1500 days for SK-I)

Detector size (22.5 kton fiducial)

$$\frac{dN_f}{dp_f} = \Delta t \sum_{\nu T \to f} N_T \int dE_\nu \, \frac{d\Phi}{dE_\nu}(E_\nu)\, P_{osc}(E_\nu, \theta_z)\, \frac{d\sigma_{\nu T \to f}}{dp_f}(E_\nu, p_f)$$

SK data

Interaction channels

Atm. ν flux

ν mixings

ν interactions

Atmospheric ν fluxes, oscillations, uncertainties

Atmospheric ν flux (Input) :

< 100 MeV: FLUKA2005

> 100 MeV: HKKM2014

Battistoni et al., Astropart.Phys. 2015
Honda et al., PRD 2015

Neutrino mixing:

3ν framework + matter effect

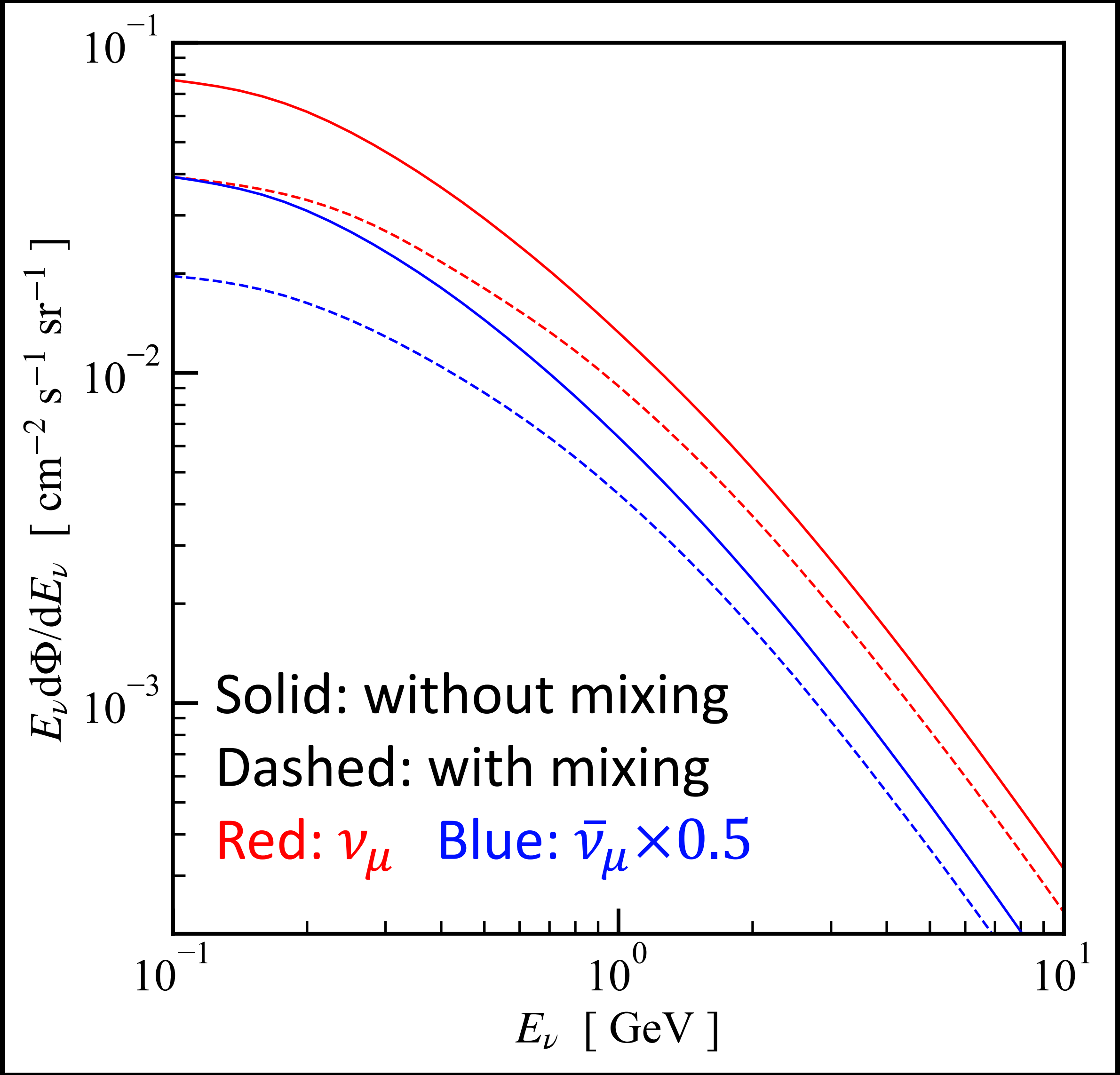
Uncertainties:

10 —100 MeV: ~25%,

0.1— 1.0 GeV: ~20%,

1.0— 10 GeV: ~15%, according to refs:

Battistoni et al., Astropart.Phys. 2015
Honda et al., PRD 2007, PRD 2015
Barr et al., PRD 2006; Evans et al., PRD 2017



BZ, John Beacom, arXiv: 2311.05675

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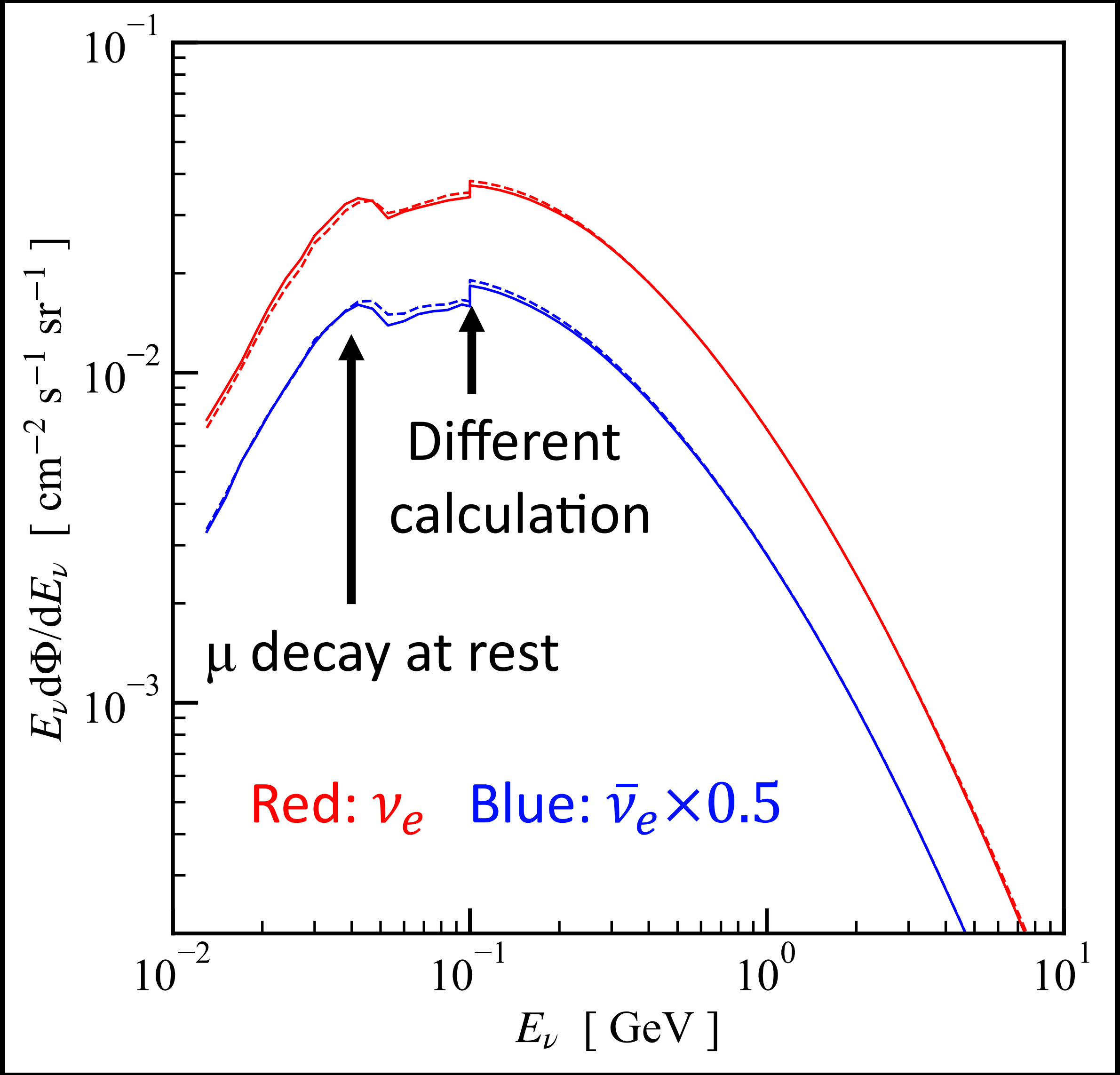

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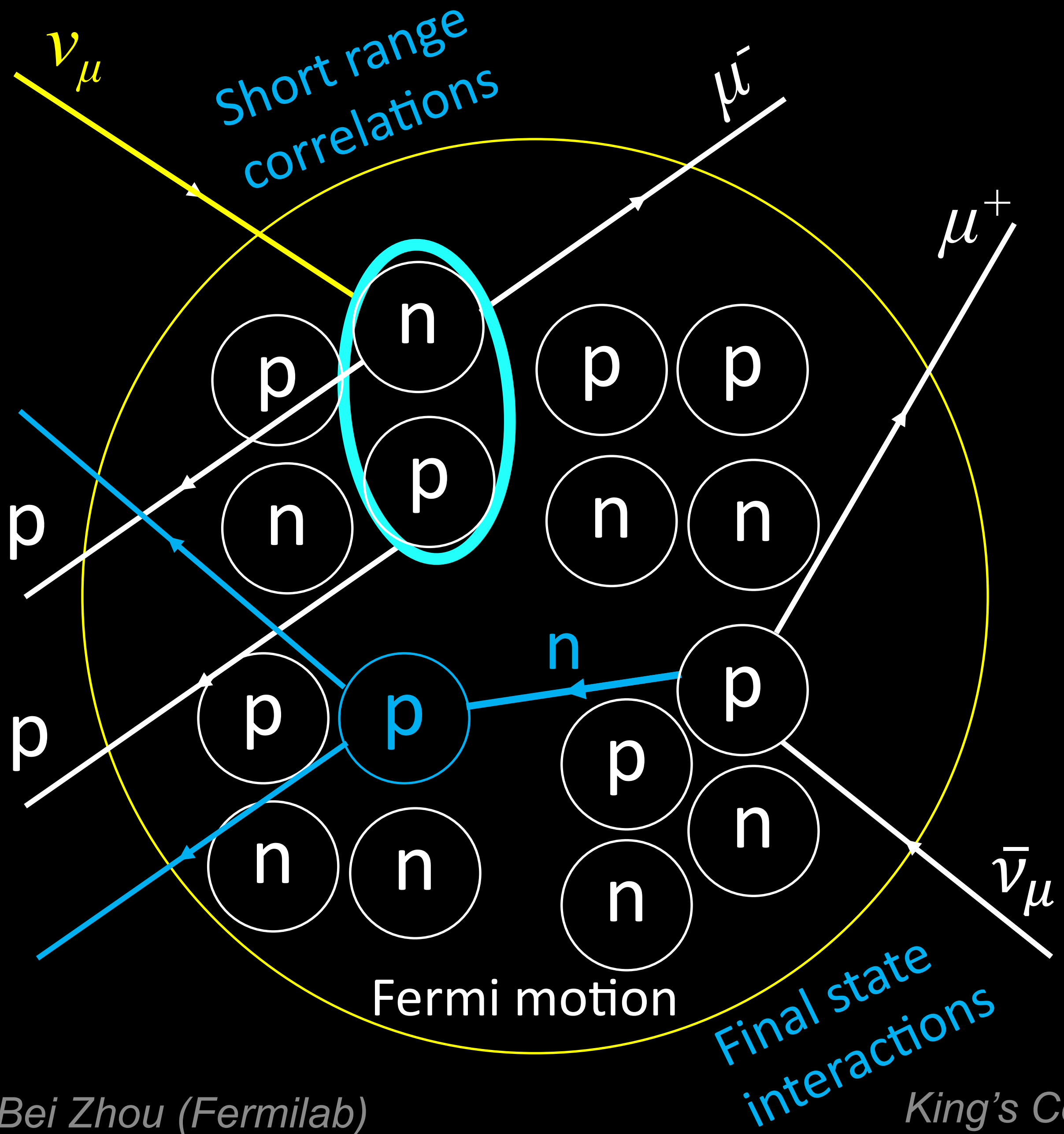
Neutrino-nucleus interactions



We use GENIE v3.02.02:

We use two different model sets of GENIE:

	G18_10a_02_11b (LFG-NAV)	G18_02a_00_000 (RFG-LS)
Nucl. model	Local Fermi gas	Rel. Fermi gas + SRC
Quasielastic scattering	Nieves+2004 (NAV) w/ Coulomb effect	Llewellyn-Smith w/o Coulomb eff.
2p2h	NSV	Dytman
Resonance production	Berger-Sehgal	
Final-state interactions	INTRANUKE/hA 2018 model	

Neutrino-nucleus interactions

Interaction types:

$\lesssim$ 1.0 GeV: Quasi-elastic scattering (QES)

~1–few GeV: Resonance productions (RES)

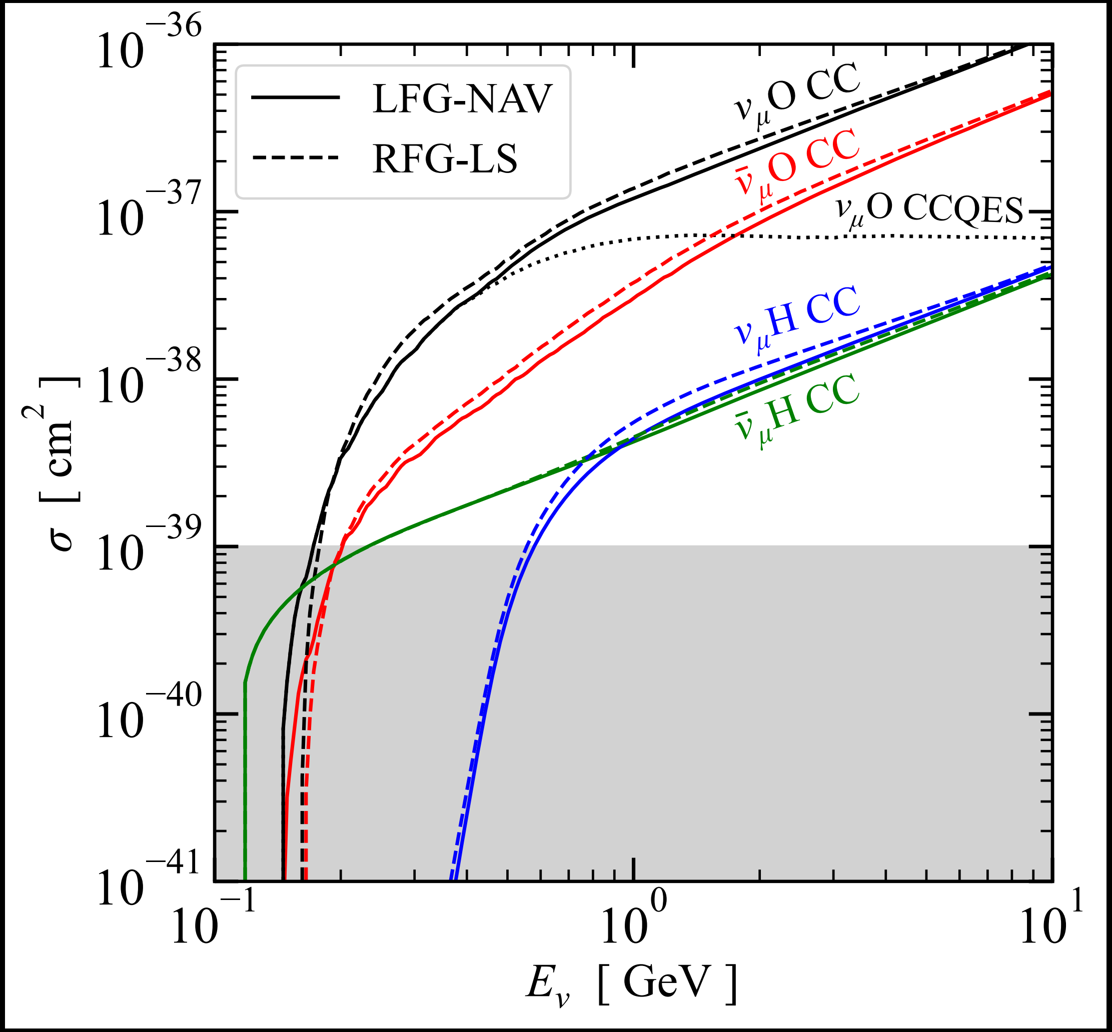
$\gtrsim$ few GeV: Deep-inelastic scattering (DIS)

Uncertainties:

An overall uncertainties of ~20% for hundreds MeV, even larger for sub-100 MeV

e.g.,
SNO Collaboration, ApJ 2006
Super-K Collaboration, PRD 2016

νμ/νμbar



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Neutrino-nucleus interactions

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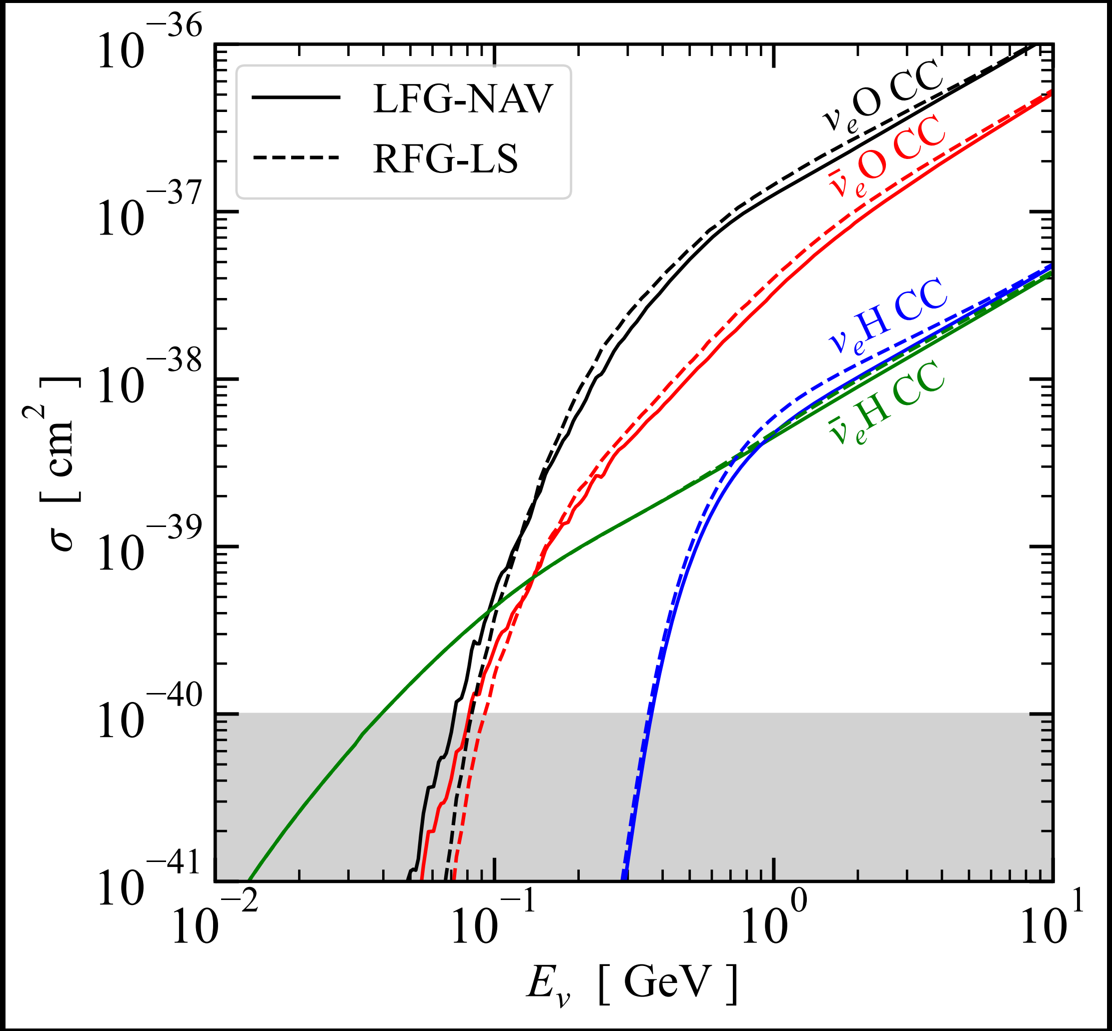
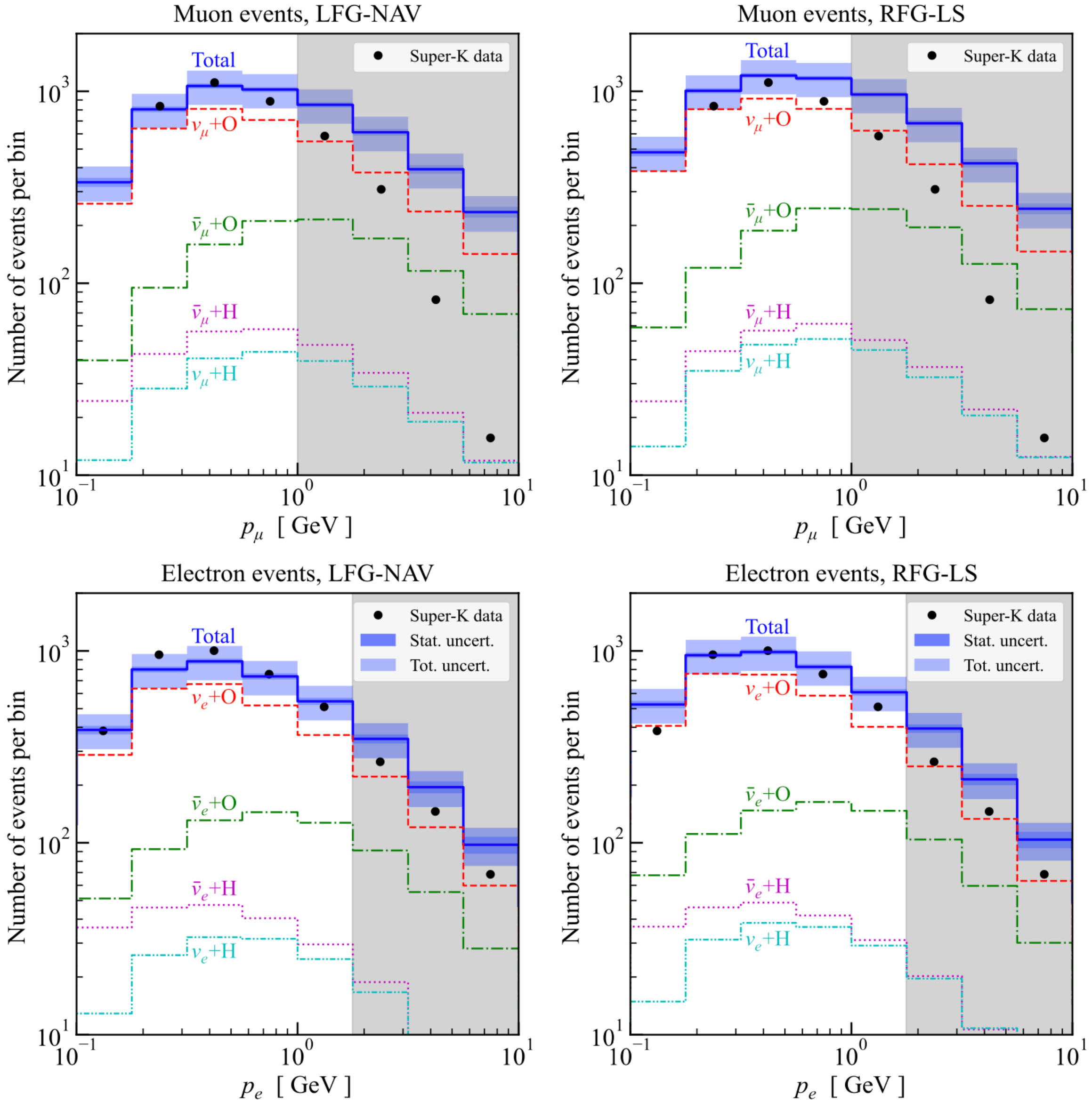
ve/vebar



BZ, John Beacom, arXiv: 2311.05675

We reproduced SK High-Energy Atm. ν Data



BZ, John Beacom, arXiv: 2311.05675

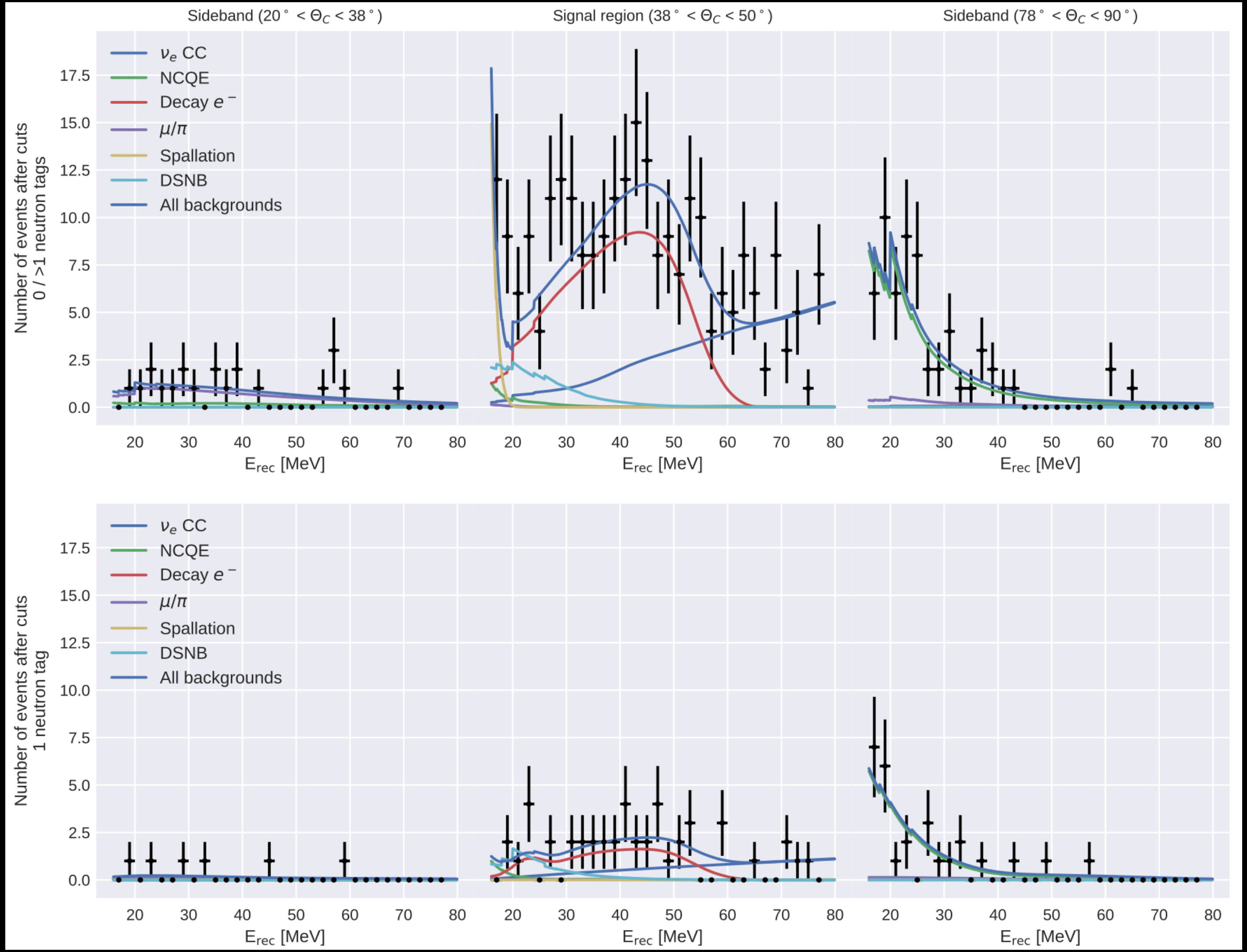
So, our basic framework is correct

Data from SK collaboration (SK-I only), PRD, 2005, hep-ex/0501064

Super-K’s low-energy data for atmospheric nu background

SK-IV

(for DSNB searches)

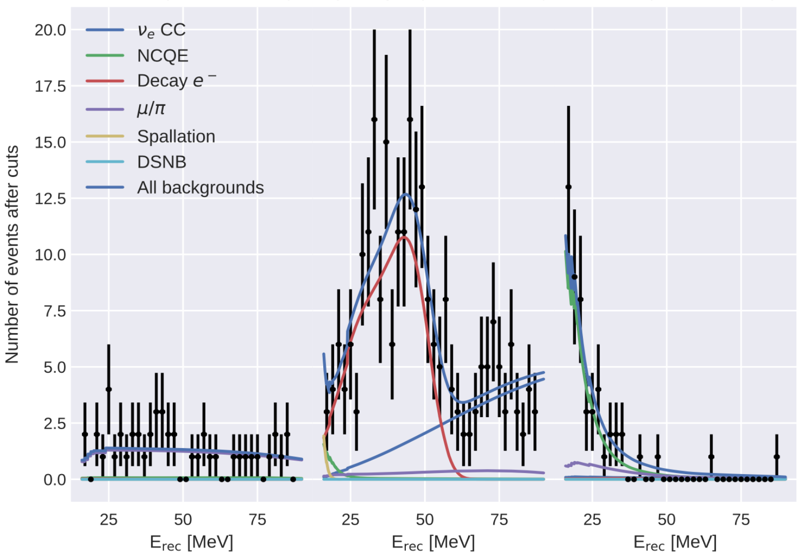


SK collaboration, PRD, 2021, arXiv:2109.11174
DSNB search

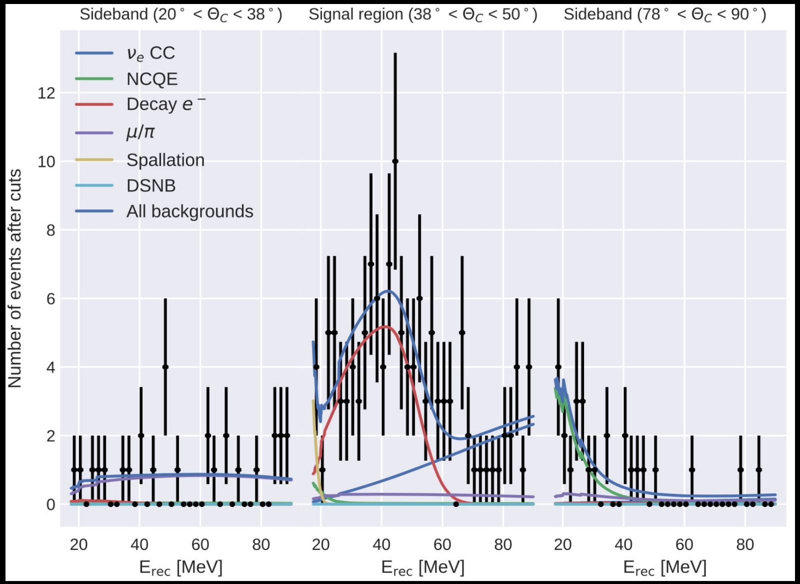
Super-K’s low-energy data for atmospheric nu background

(for DSNB searches)

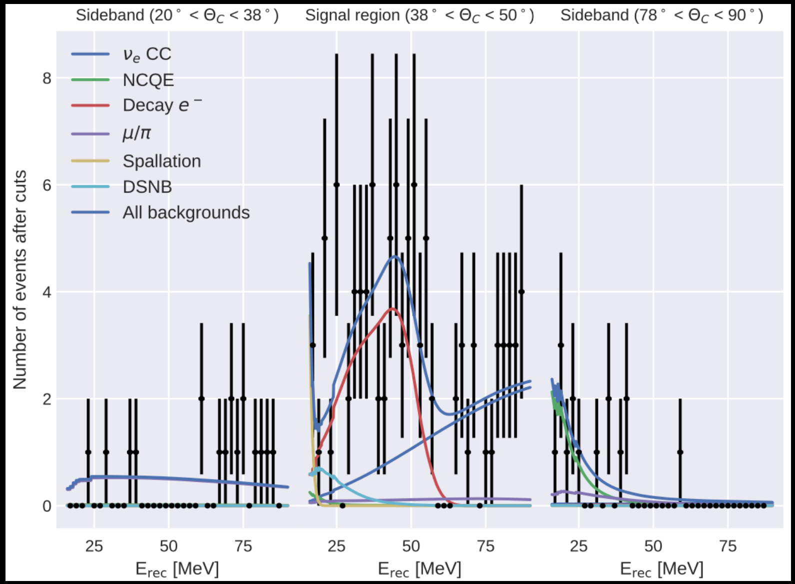
SK-I



SK-II



SK-III



SK collaboration, PRD, 2021, arXiv:2109.11174
DSNB search

SK collaboration, PRD, 2012, arXiv:1111.5031
DSNB search

Basic Calculational framework, naïve calculation for LE data

Detector exposure (~1500 days for SK-I)

Detector size (22.5 kton fiducial)

$$\frac{dN_f}{dp_f} = \Delta t \sum_{\nu T \to f} N_T \int dE_\nu \, \frac{d\Phi}{dE_\nu}(E_\nu) \, P_{osc}(E_\nu, \theta_z) \, \frac{d\sigma_{\nu T \to f}}{dp_f}(E_\nu, p_f)$$

SK data

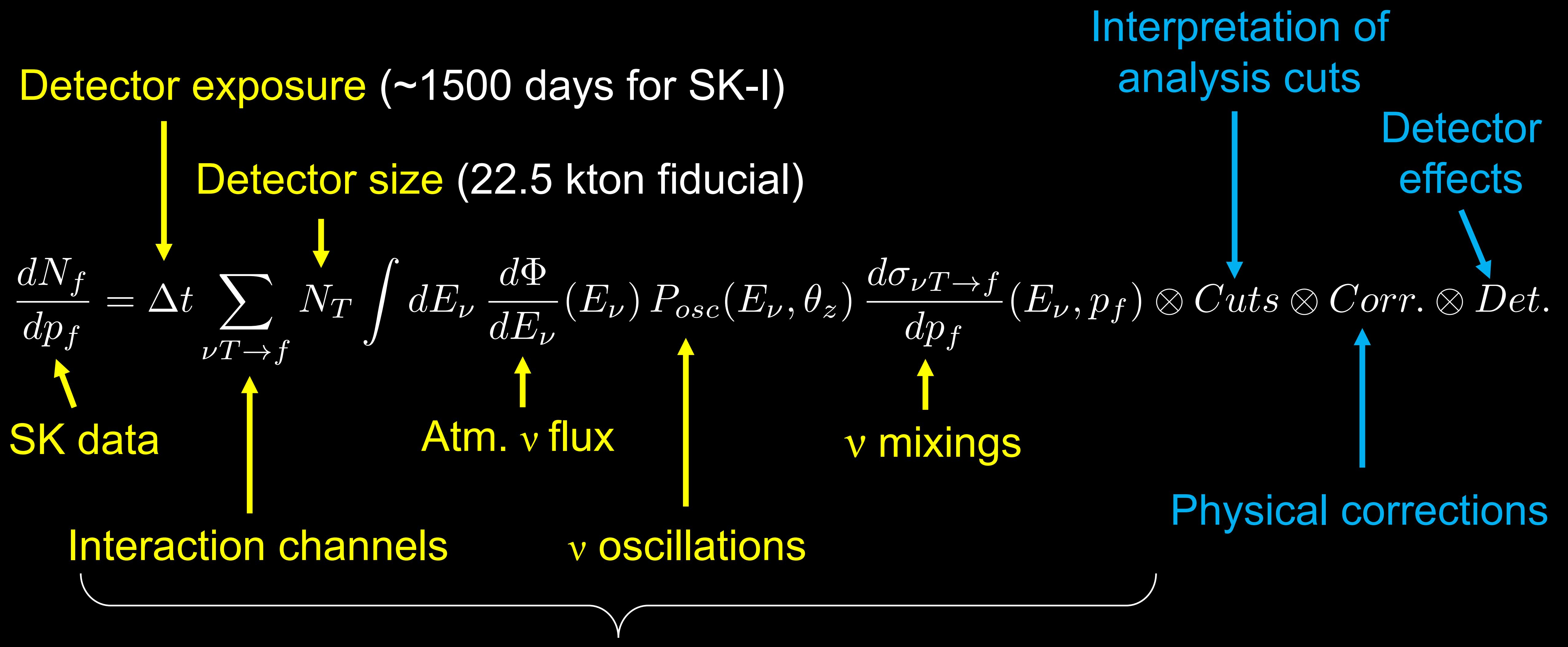
Atm. ν flux

ν interactions

Interaction channels

ν mixings

Full calculational framework, for LE data



Detector exposure (~1500 days for SK-I)

Interpretation of analysis cuts

Detector size (22.5 kton fiducial)

Detector effects

$$\underbrace{\frac{dN_f}{dp_f} = \Delta t \sum_{\nu T\to f} N_T \int dE_\nu \, \frac{d\Phi}{dE_\nu}(E_\nu)\, P_{osc}(E_\nu,\theta_z)\, \frac{d\sigma_{\nu T\to f}}{dp_f}(E_\nu,p_f)}_{\text{Tested by reproducing high-energy data}} \otimes Cuts \otimes Corr. \otimes Det.$$

SK data

Atm. ν flux

ν mixings

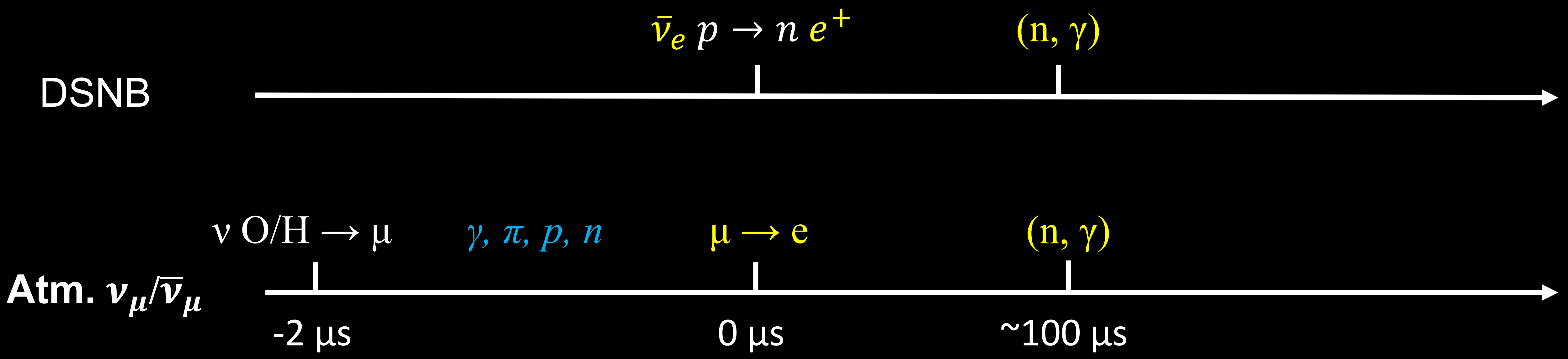
Physical corrections

Interaction channels

ν oscillations

Tested by reproducing high-energy data

Interpretation of analysis cuts: Atm. $\nu_\mu/\bar{\nu}_\mu$



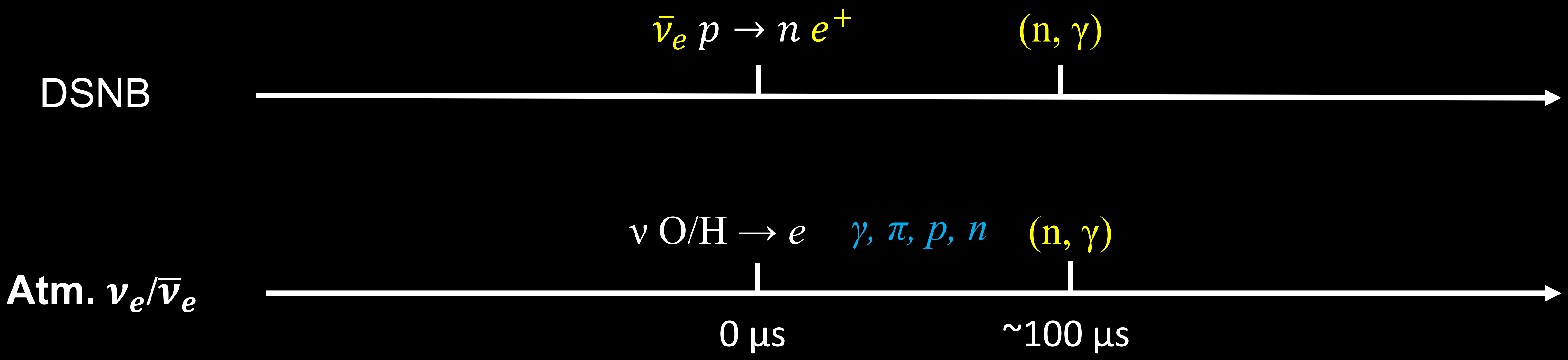
SK analysis cuts

- FV cut; Spallation cut; Solar cut;…
- Double peak cut, Sub-event cut…
- Pion cut; Multi-ring cut; Cherenkov angle cut; …

Our interpretation: we throw away events w/

- Muons and other charged particles above Cherenkov threshold
- Events with π
- Nuclear γ

Interpretation of analysis cuts: Atm. $\boldsymbol{\nu_e/\bar{\nu}_e}$



$\bar{\nu}_e\, p \rightarrow n\, e^+$ (n, γ)

DSNB

ν O/H → e γ, π, p, n (n, γ)

Atm. $\boldsymbol{\nu_e/\bar{\nu}_e}$

0 μs ~100 μs

SK analysis cuts

- FV cut; Spallation cut; Solar cut;…
- Double peak cut, Sub-event cut…
- Pion cut; Multi-ring cut; Cherenkov angle cut; …

Our interpretation: we throw away events w/

- Muons and other charged particles above Cherenkov threshold
- Events with π

We don’t throw away events with nuclear gamma rays

Physical correction 1: μ^- capture

$$\nu_\mu + O \rightarrow \mu^- + X$$
$$\nu_\mu + H \rightarrow \mu^- + X$$
$$\bar{\nu}_\mu + O \rightarrow \mu^+ + X$$
$$\bar{\nu}_\mu + H \rightarrow \mu^+ + X$$

Atomic capture (1s state)

~79%

Decay in bound state

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

Bkgd for DSNB~

~21%

Nuclear capture

$$\mu^- + p \rightarrow \nu_\mu + n \; (n + \gamma)$$

Won’t be bkgd for DSNB~

The numbers are from our FLUKA simulation

Physical correction 2: NCπ^+

π^+ *kinetic energy < 72 MeV, invisible in SK*

invisible $\pi^+ \rightarrow \mu^+ \rightarrow e^+$, background for DSNB

Increase invisible muon # by 30% (LFG-NAV) or 20% (RFG-LS)

1. $\nu_x + p\ (\mathrm{O\ or\ H}) \rightarrow \nu_x + n + \Delta^+$ (NC RES, dominant)

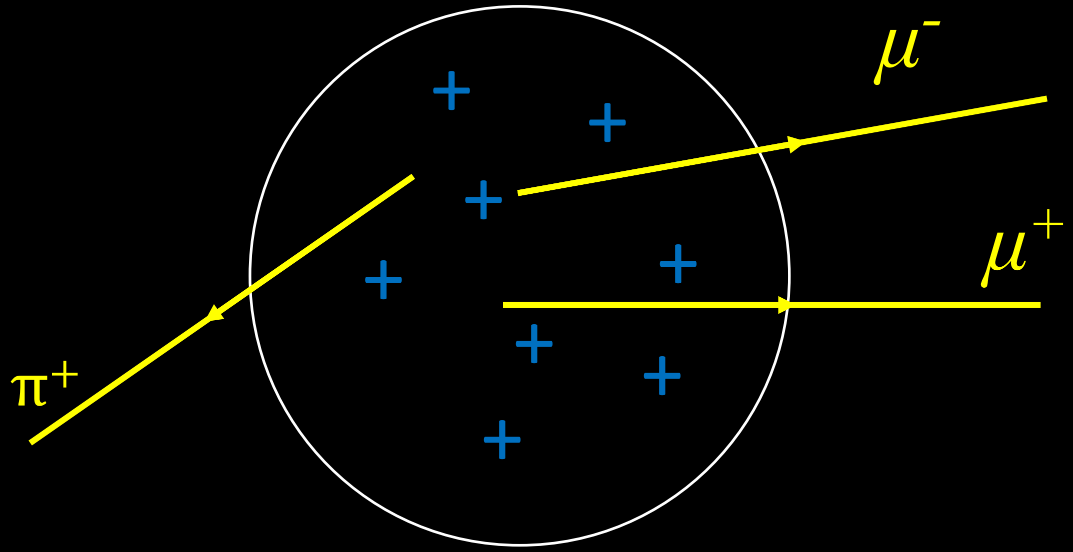
   $\Delta^+ \rightarrow n + \pi^+$
2. $\nu_x + p/n\ (\mathrm{O\ or\ H}) \rightarrow \nu_x + \pi^+ (+\,\mathrm{p})$ (NCQES + FSI)

NC π^0 and π^- are irrelevant

π^0 *decay to two γ's*

π^- *mostly 1) atomic capture 2)~100% nucl. capture, $\pi^- + O \rightarrow p$'s, n's, γ's*

Physical correction 3: Coulomb distortion



We use:

Modified eff. moment. approx. (MEMA).

(*Engel, PRC 1998*)

$$V_{electrostatic} = \frac{3Z\alpha}{2R_A}$$

1) Induce a shift of the total energy
2) Rescale scattering amplitude

Physical effects:

Increase (decrease) momentum for + (-) charged particle:

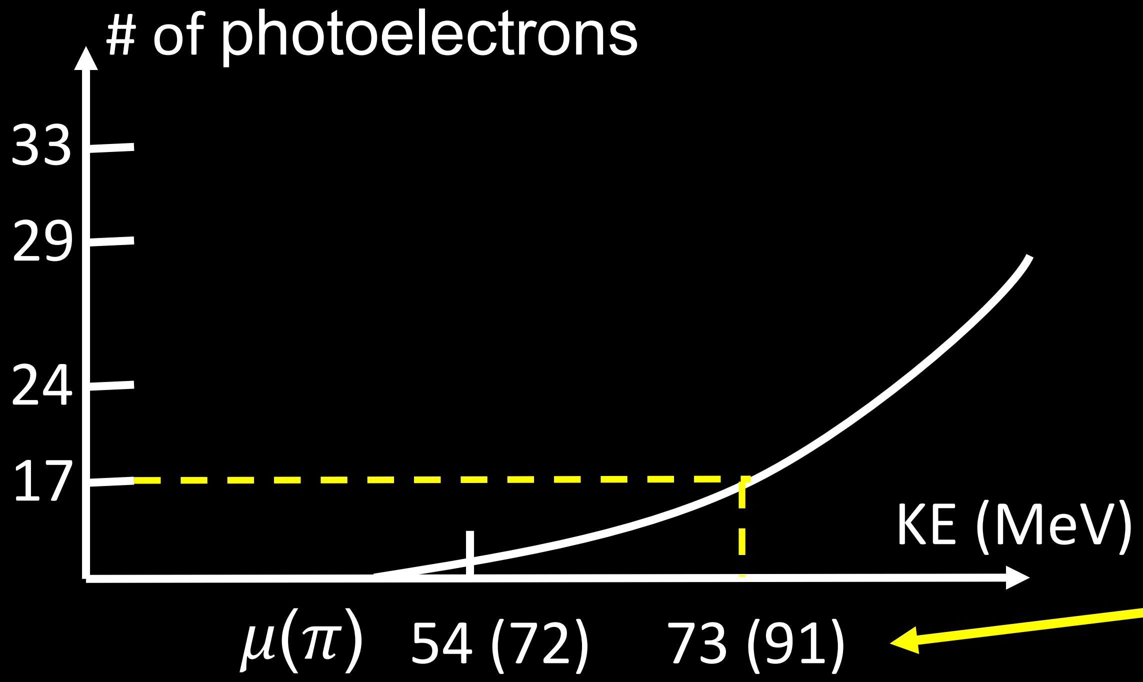
1) Distort the charged particle energy

2) Decrease (increase) overlap with nuclear wavefunction, hence σ

Impact on, e.g., the invisible muon component:

- νμ+O: increases by ≃35%
- νμbar+O: decreases by ≃25%
- νμbar+H: decreases by ≃10%
- NCπ^+: decreases by ≃10%

Detector-effect correction: Cherenkov threshold



Theoretical Cherenkov threshold:

β (particle speed) > 1/n (photon speed)

n, refractive index

However, detector has trigger threshold → Real Cherenkov threshold higher.

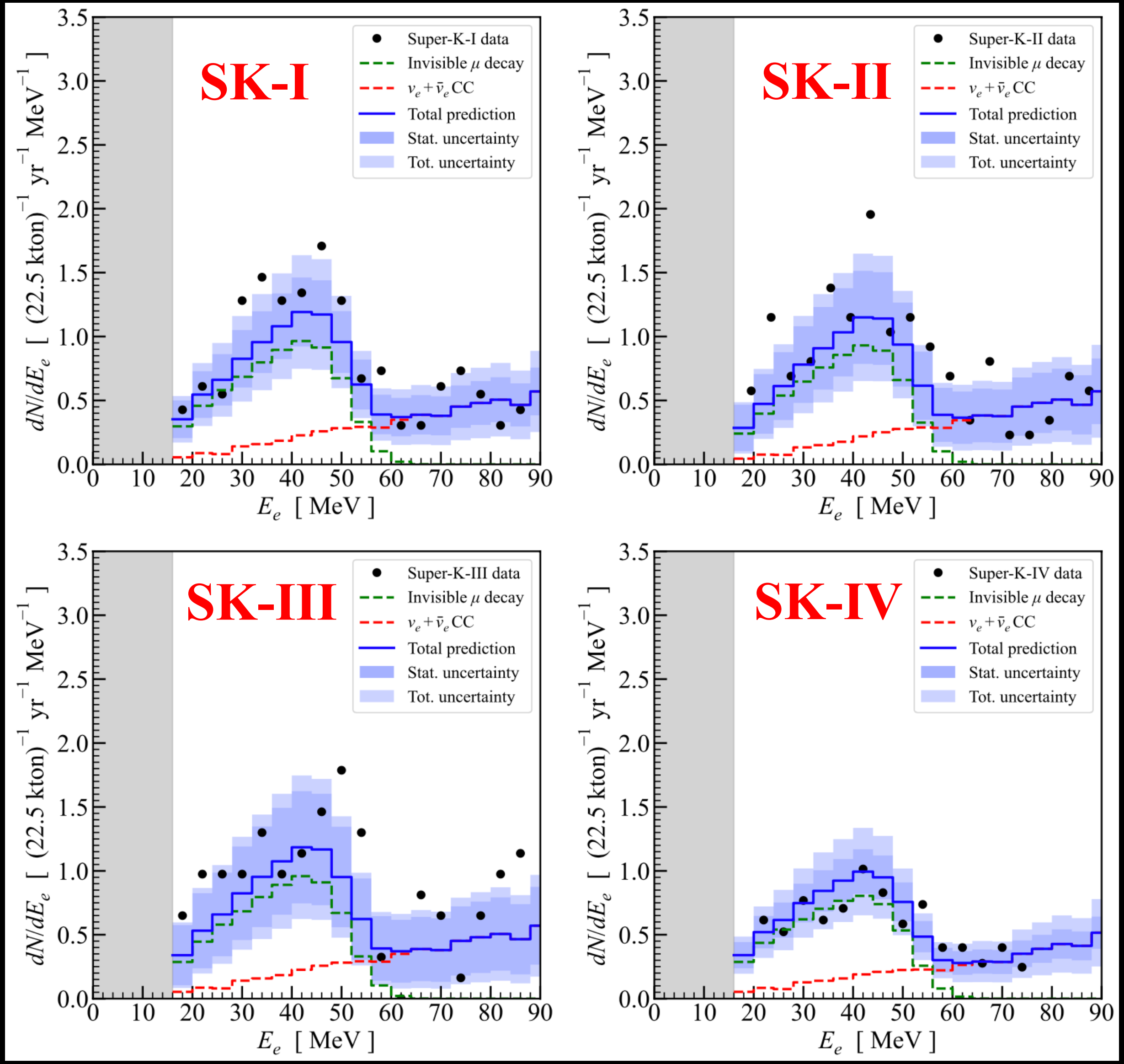
We

- Chose 17 p.e. as the threshold.
- ⟹ ≃340 Cherenkov photons
- ⟹ ≃73 MeV for μ and ≃91 MeV for π

(Consistent with SK’s detector simulations by Chenyuan Xu from SK collaboration)

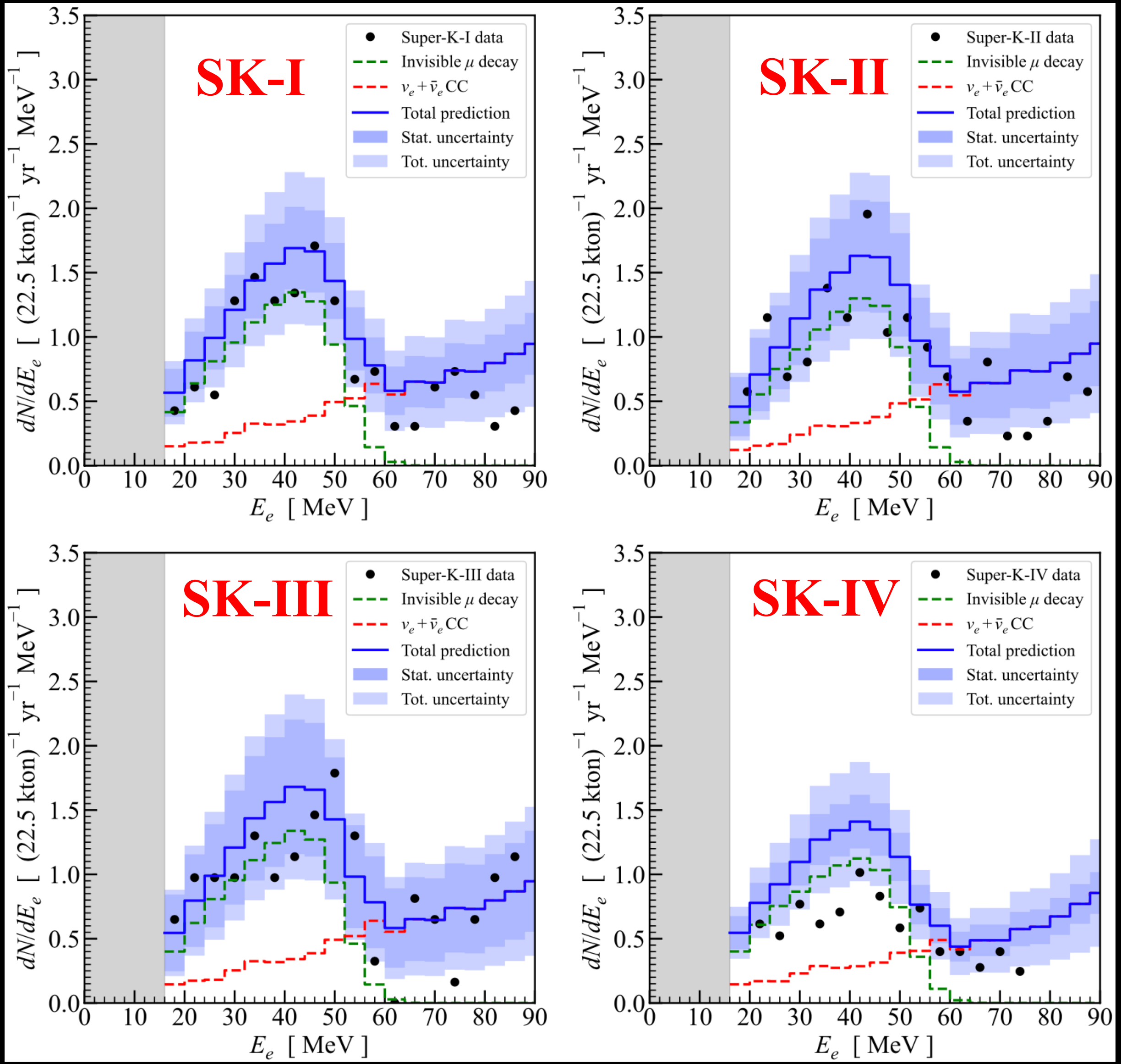
Increase the invisible μ component by ≃30%.

We reproduced SK Low-Energy Atm. ν bkgd: LFG-NAV



BZ, John Beacom, arXiv: 2311.05675

We reproduced SK Low-Energy Atm. ν bkgd: RFG-LS



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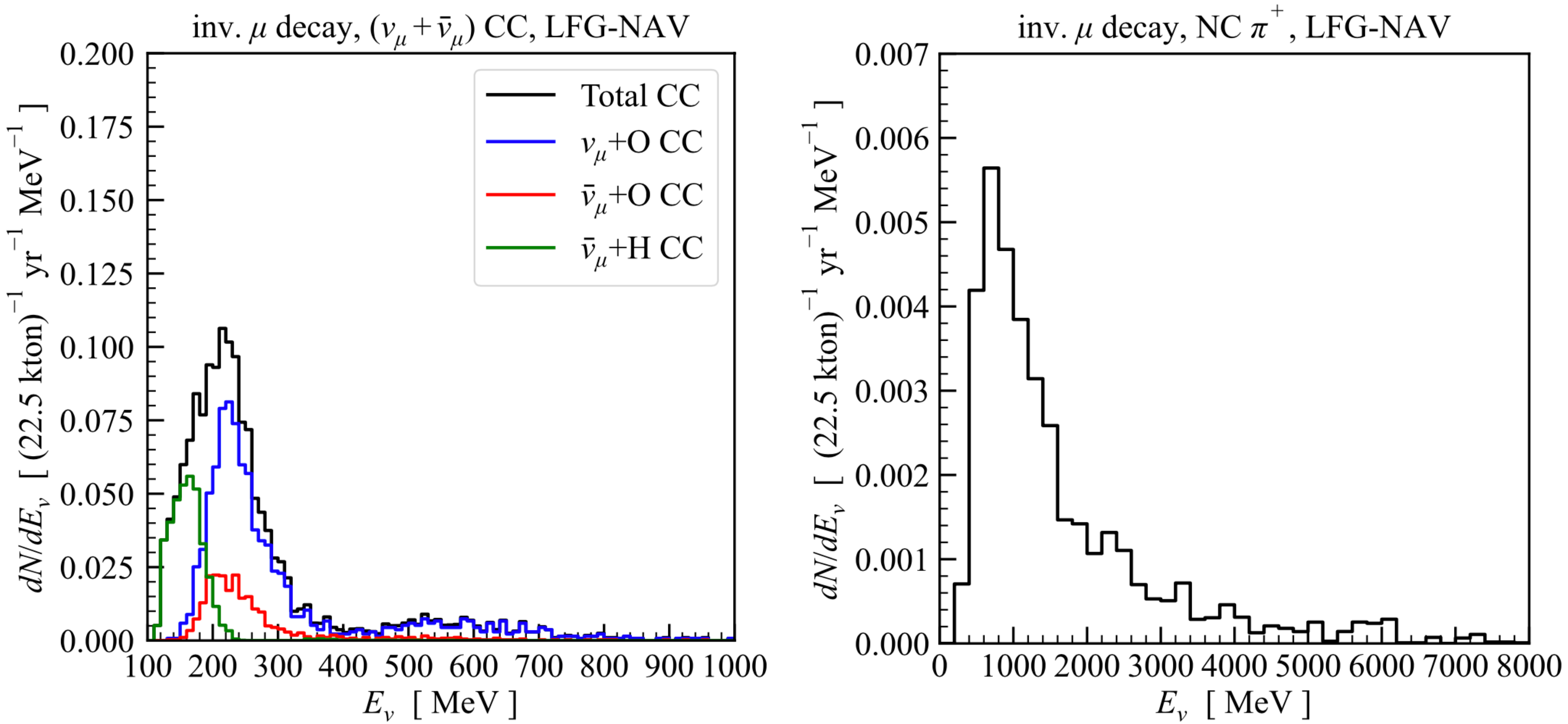
SK Low-Energy Atm. ν bkgd: predicted parent nu distribution



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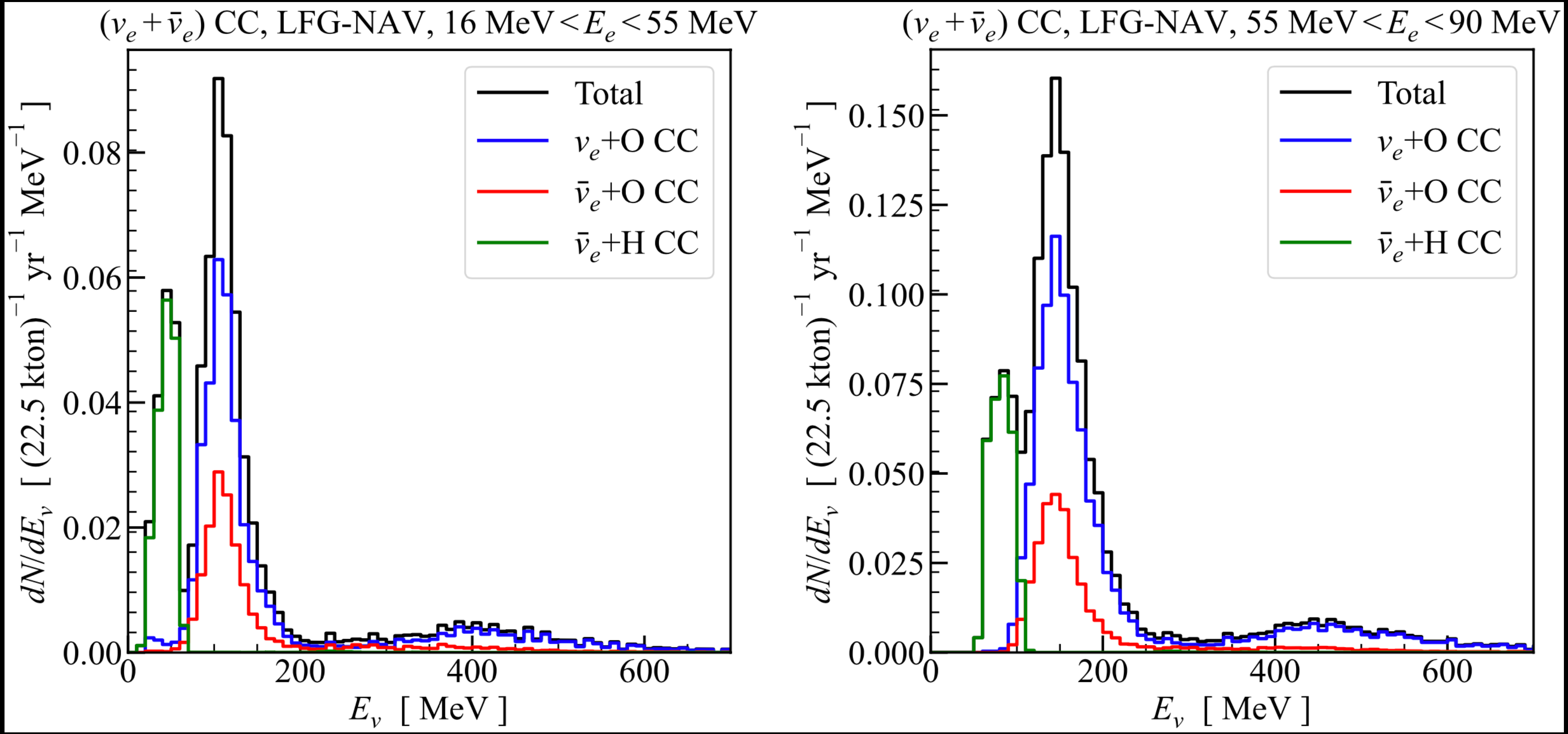
Results from the LFG-NAV model set (similar for RFG-LS)

SK Low-Energy Atm. ν bkgd: predicted parent nu spectrum



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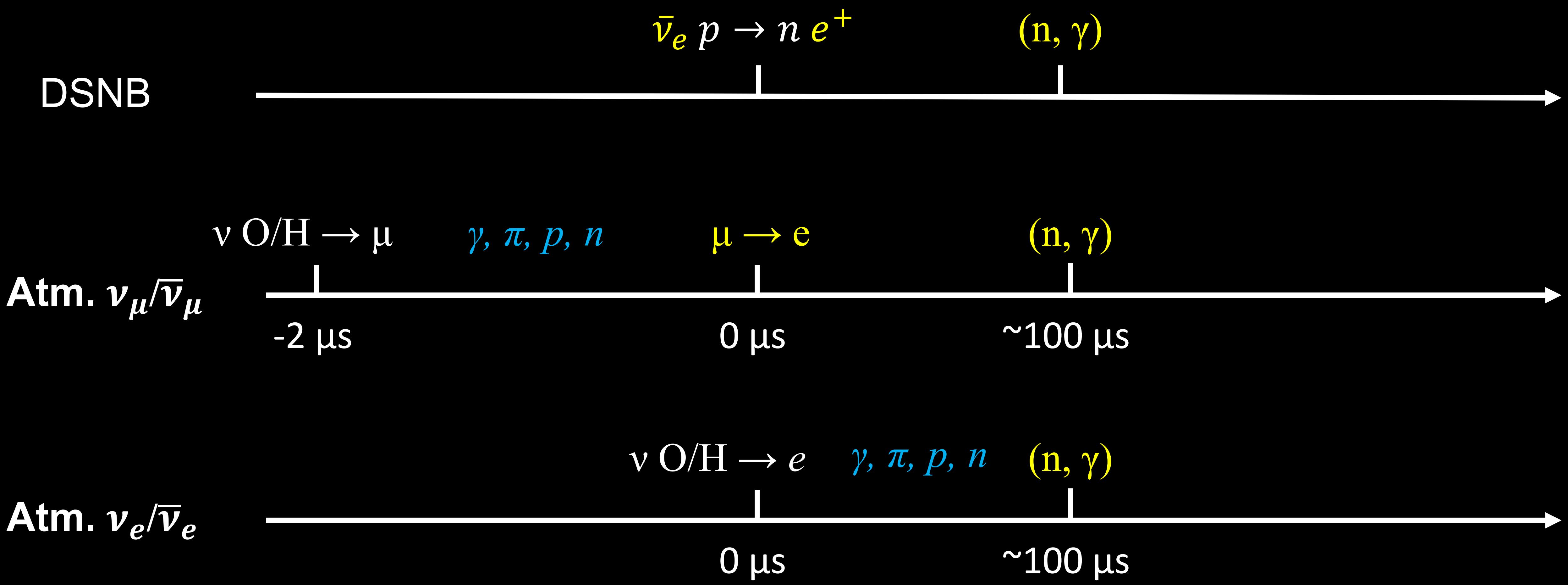
Results from the LFG-NAV model set (similar for RFG-LS)

What's next? Hints from the parent nu spectra



DSNB

$\bar{\nu}_e\, p \rightarrow n\, e^+$ (n, γ)

Atm. $\nu_\mu/\bar{\nu}_\mu$

ν O/H → μ γ, π, p, n μ → e (n, γ)

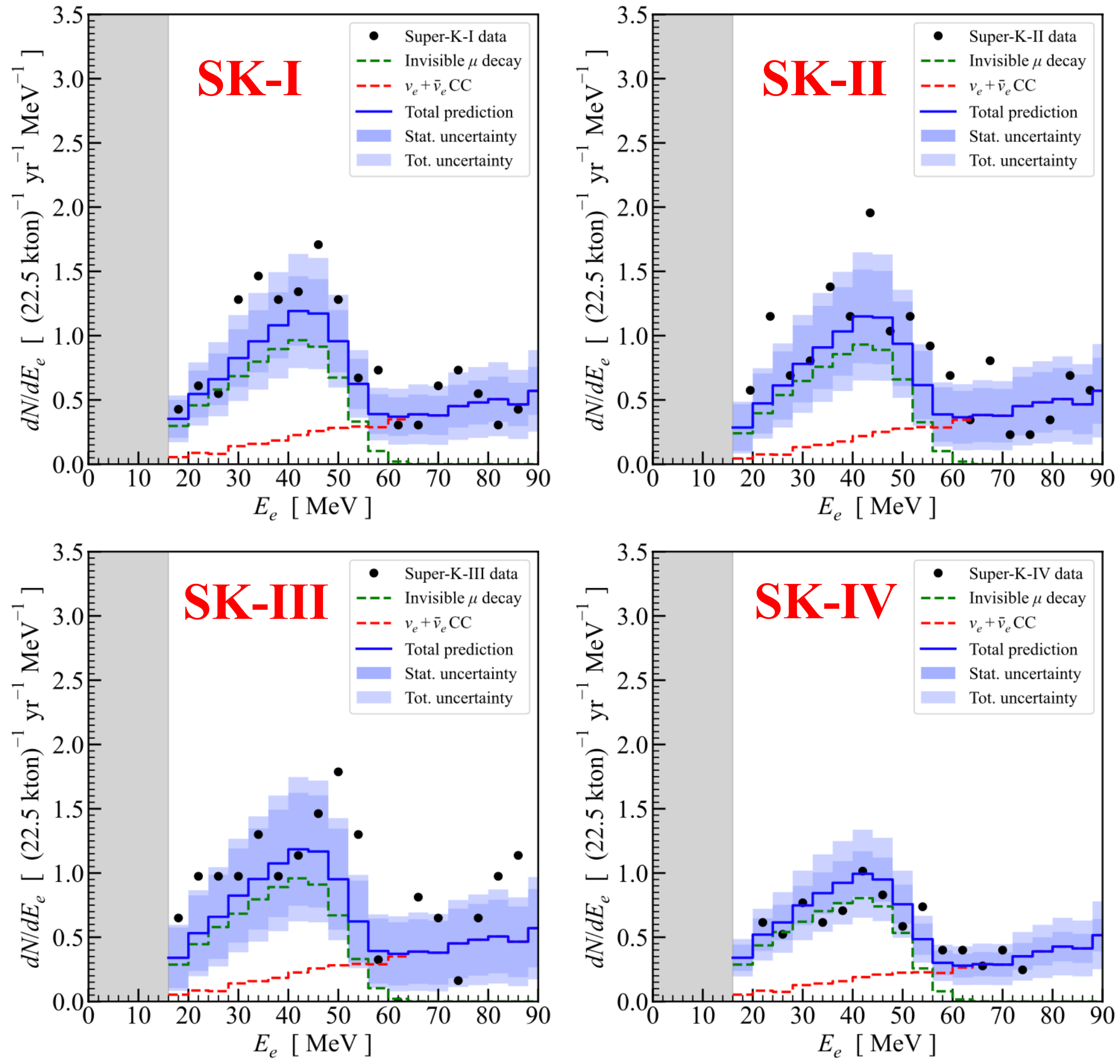
-2 μs 0 μs ~100 μs

Atm. $\nu_e/\bar{\nu}_e$

ν O/H → e γ, π, p, n (n, γ)

0 μs ~100 μs

Conclusion



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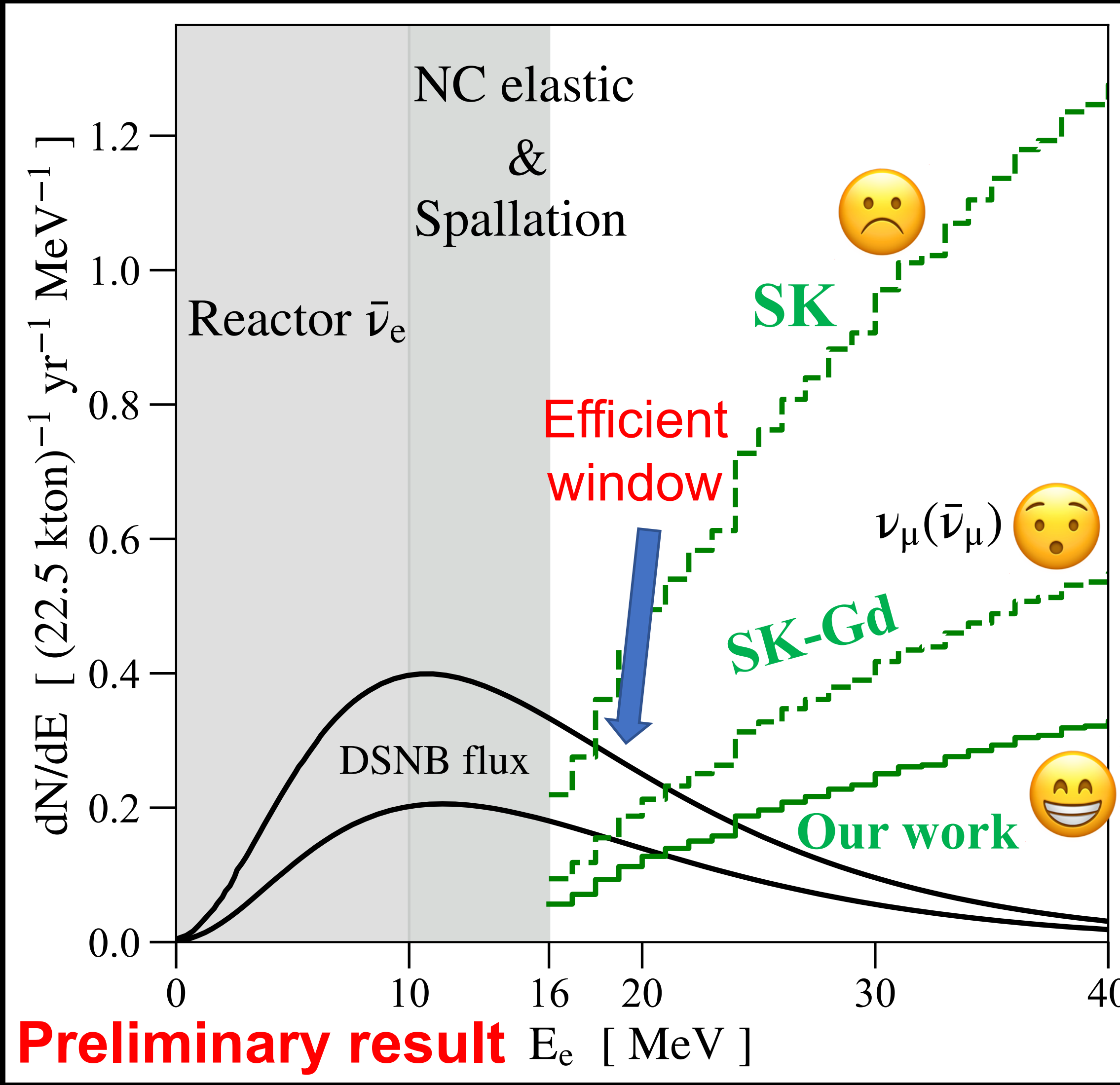

Preliminary result

Thanks for your attention!

Goal of Our Work:

further reduce the one-neutron atm. ν bkgd

Both model sets use:
SIS&DIS: Bodek-Yang
coherent production of pions: Berger-Sehgal
hadronization: AGKY

Other important effects are also included, including Pauli blocking, shadowing, anti-shadowing, EMC, de-excitation, etc.

Interpretation of analysis cuts: nuclear gamma rays

- Theoretical
  - GENIE uses *Ejiri 1993* (theory) and *Kobayashi+ 2005* (experiment)
  - BRγ ~ 50% overall, mostly ~6-8 MeV
  - Consistent with Ankowski+ 2012 (theory), T2K PRD 2014 (experiment).
  - However, above are for one-nucleon kick out. But for our case, multi-nucleon kick-out is very common…

- Experimental
  - We inquired several SK people, but they didn't know how much they cut.

- What we do