ハン　29歳　韓国

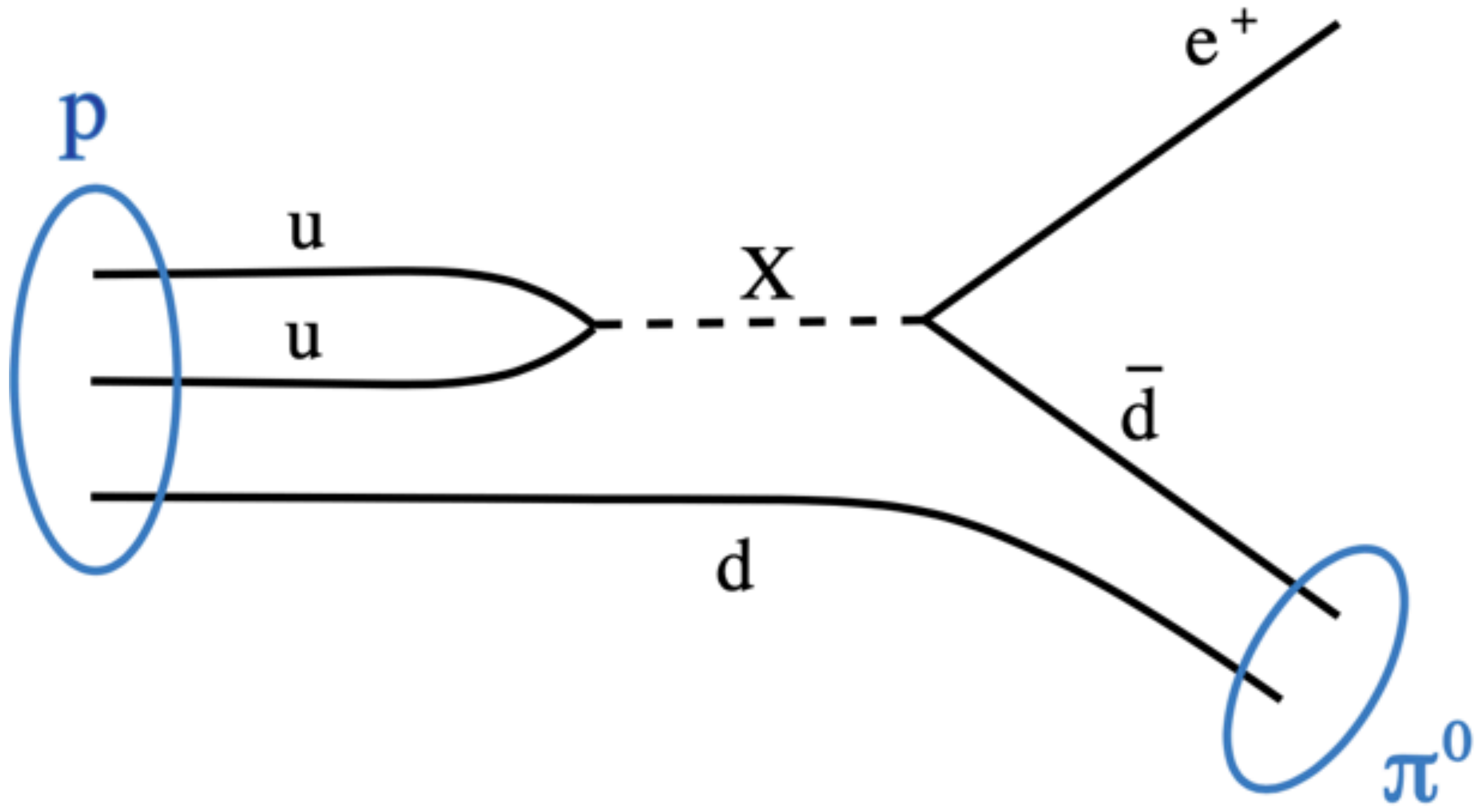
D1 @ 東大宇宙線研　Super-Kamiokande　ニュートリノ

Super-Kamiokande: target physics and issues

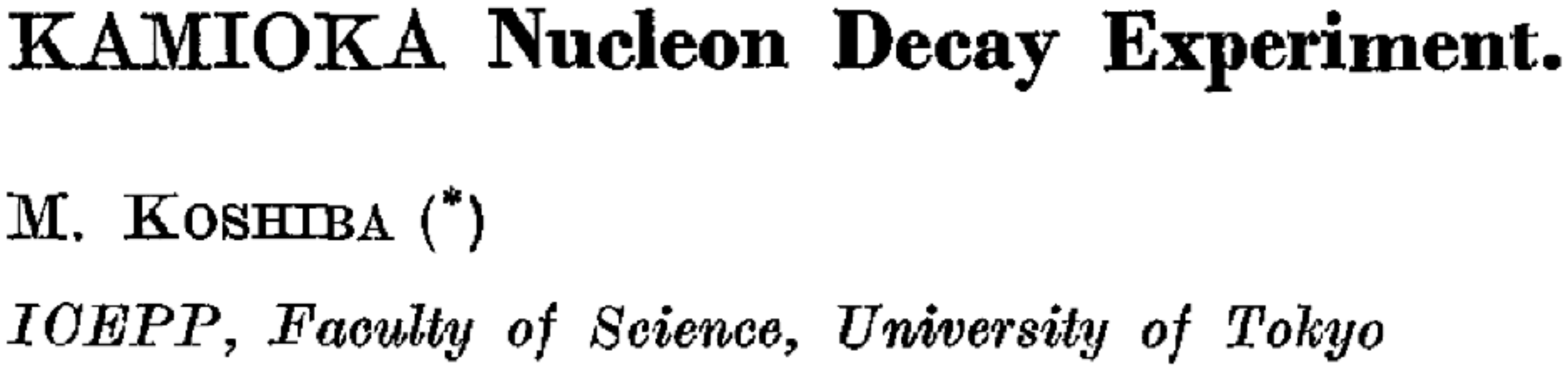
My contribution: delayed particle tagging

A long time ago in a galaxy far, far away….

1974 : SU(5) GUT predicts proton decay



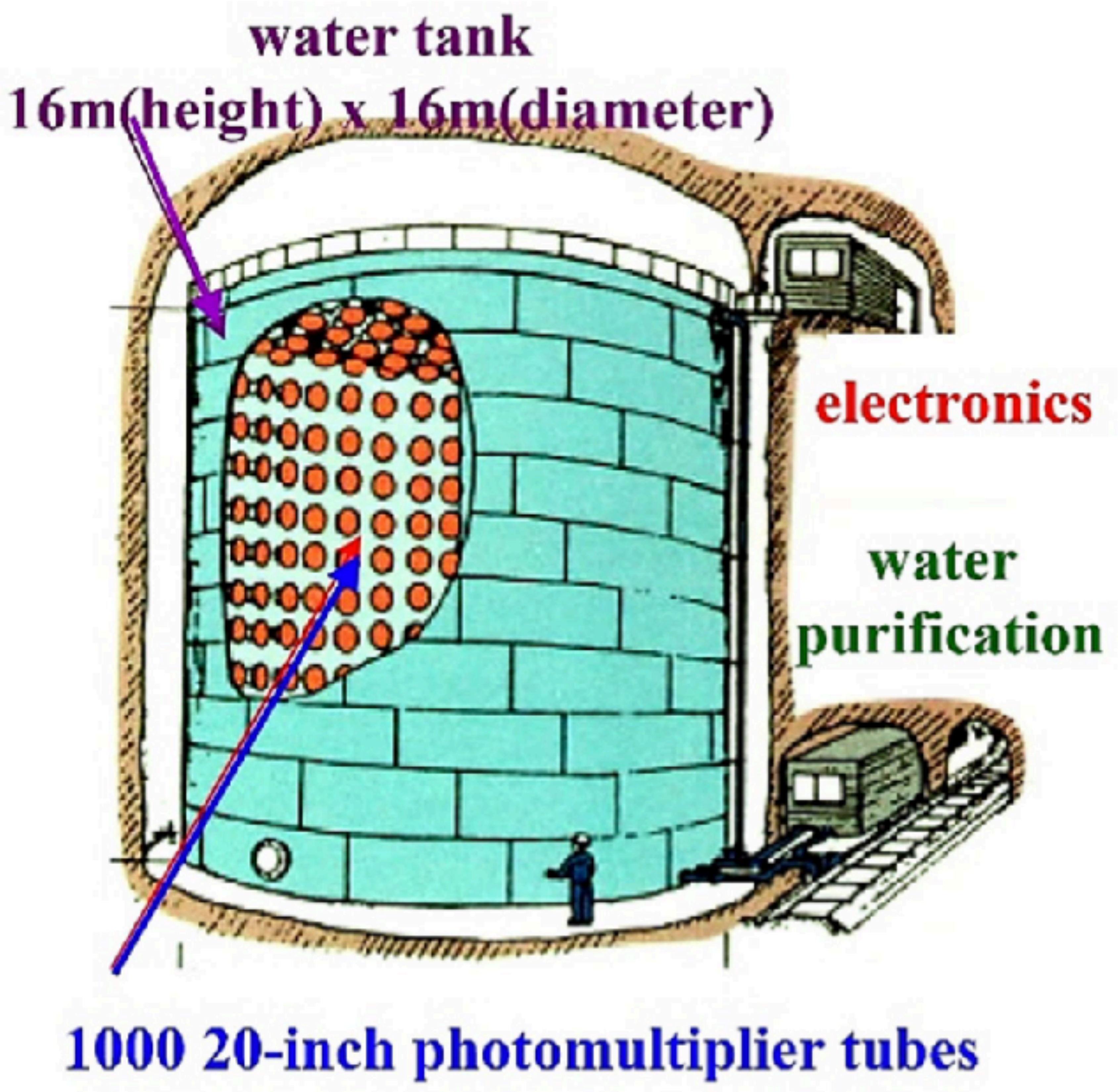
1983 :


KAMIOKA Nucleon Decay Experiment.

M. KOSHIBA (*)

ICEPP, Faculty of Science, University of Tokyo

Underground Water Cherenkov Detector

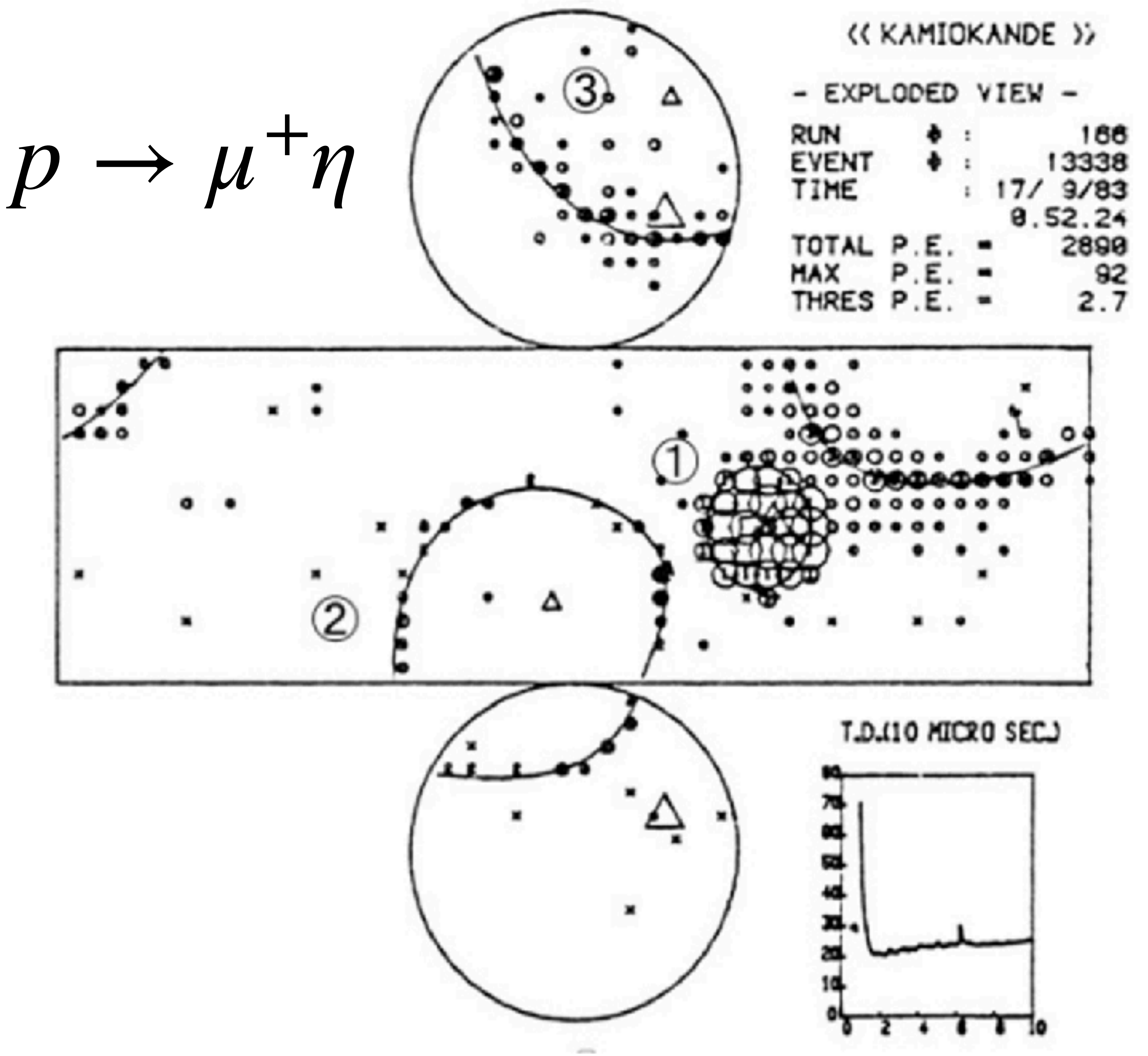


Water 3,000 t +  × 1,000

PMT

Cherenkov “ring”s

$p \to \mu^+ \eta$



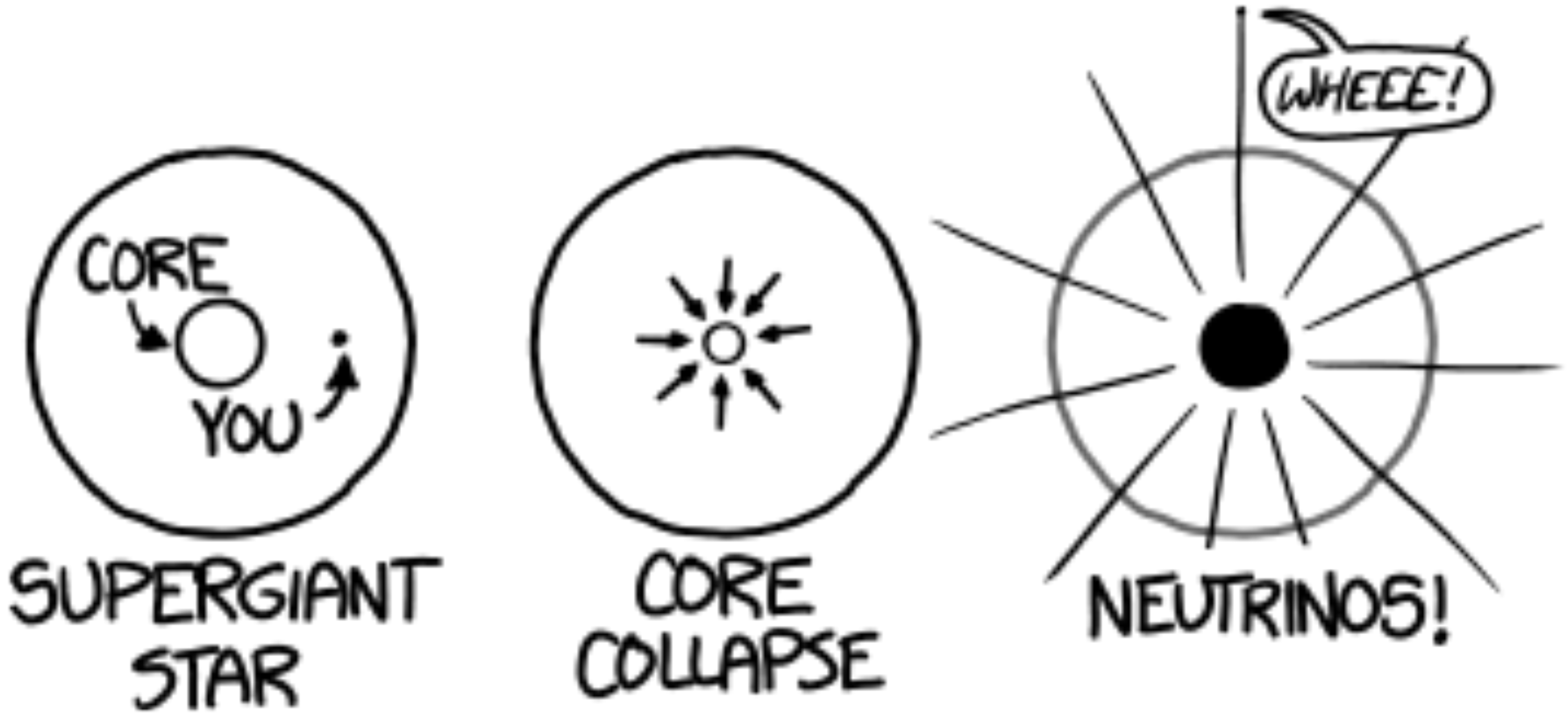
$\nu n \to \mu^- p \pi^0$?

$\bar{\nu} p \to \mu^+ n \pi^0$?

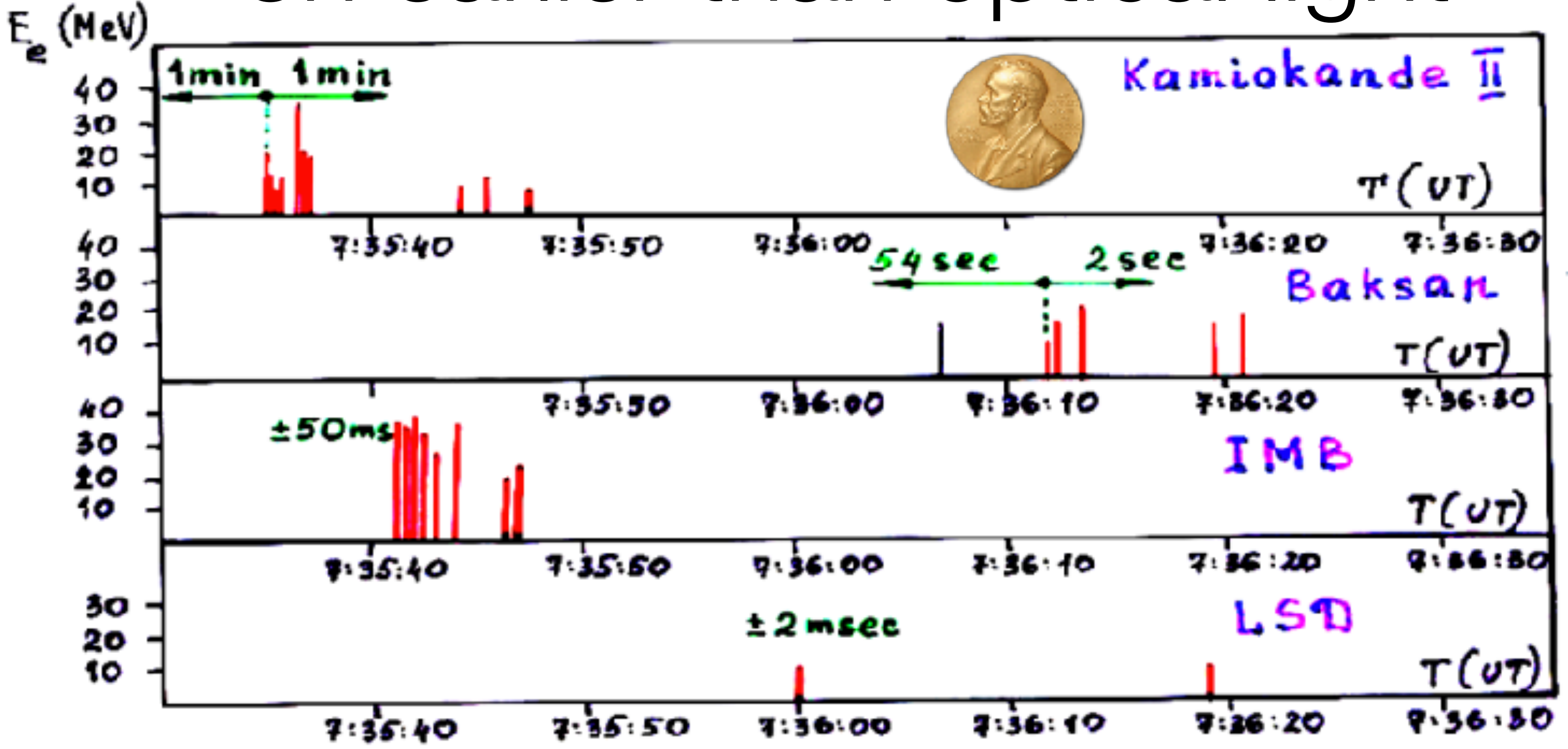
1987 :

UTC 07:35 Feb 23, 1987

24 neutrinos detected on Earth
3h earlier than optical light

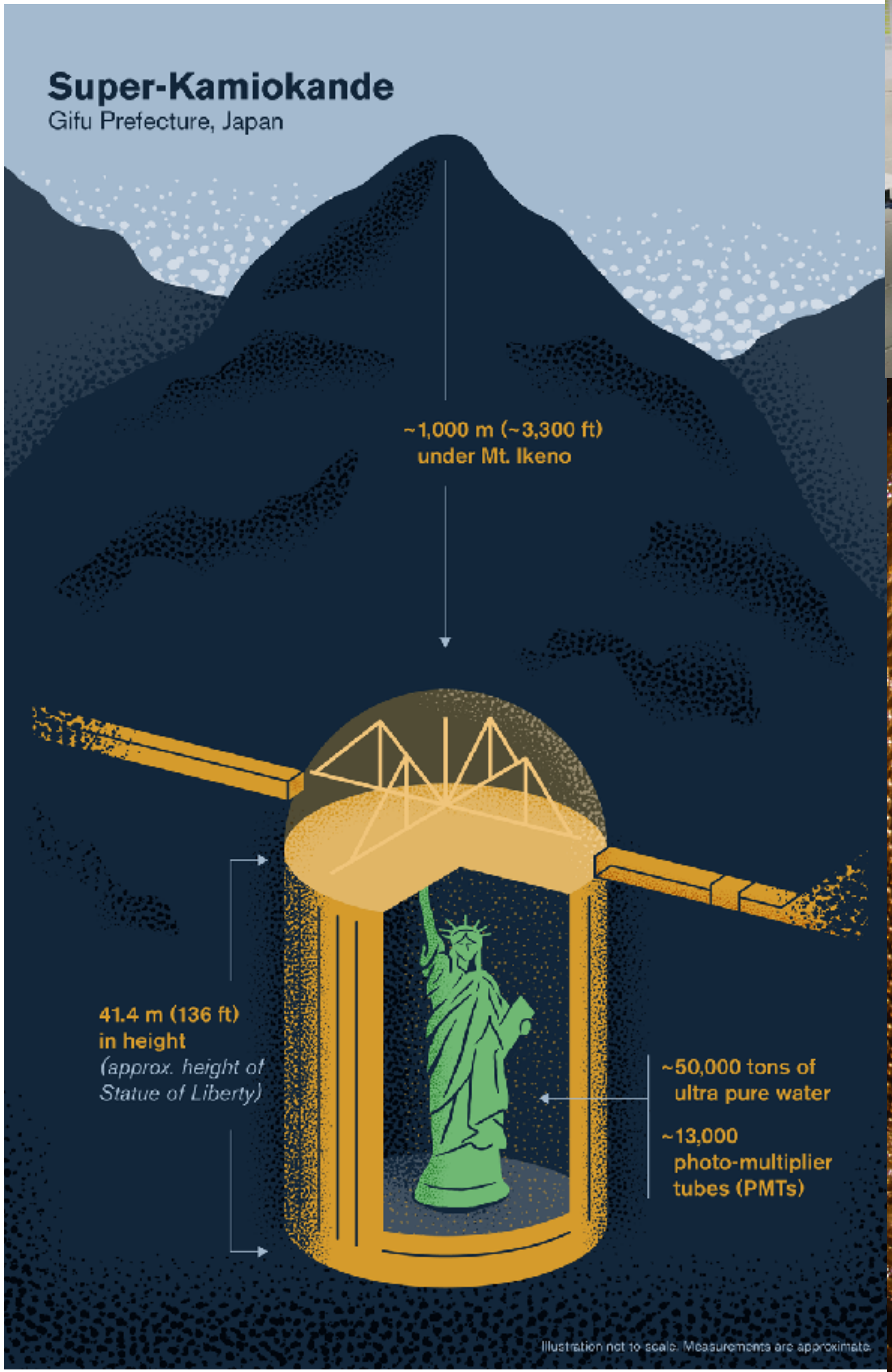


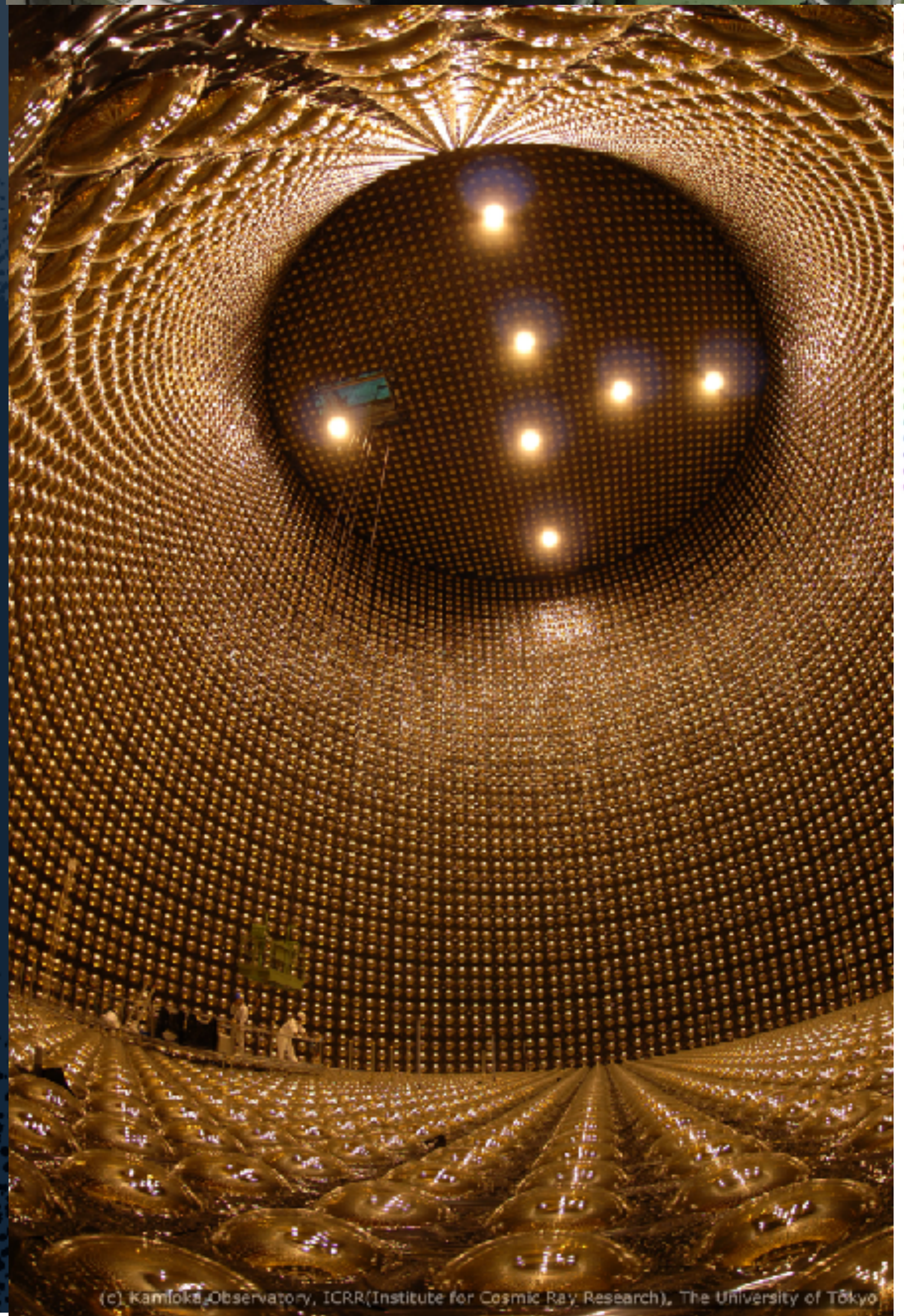
SN1987A

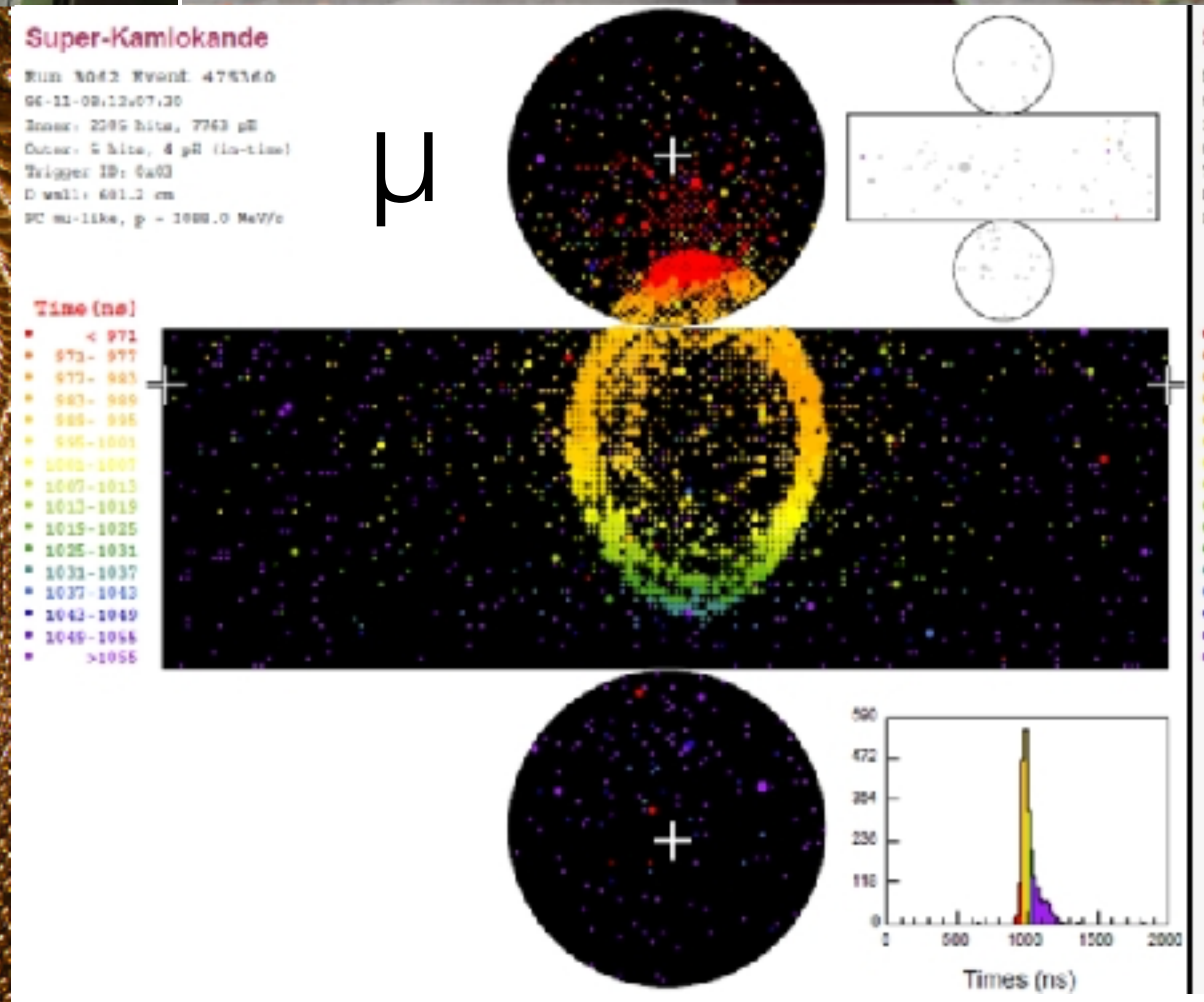


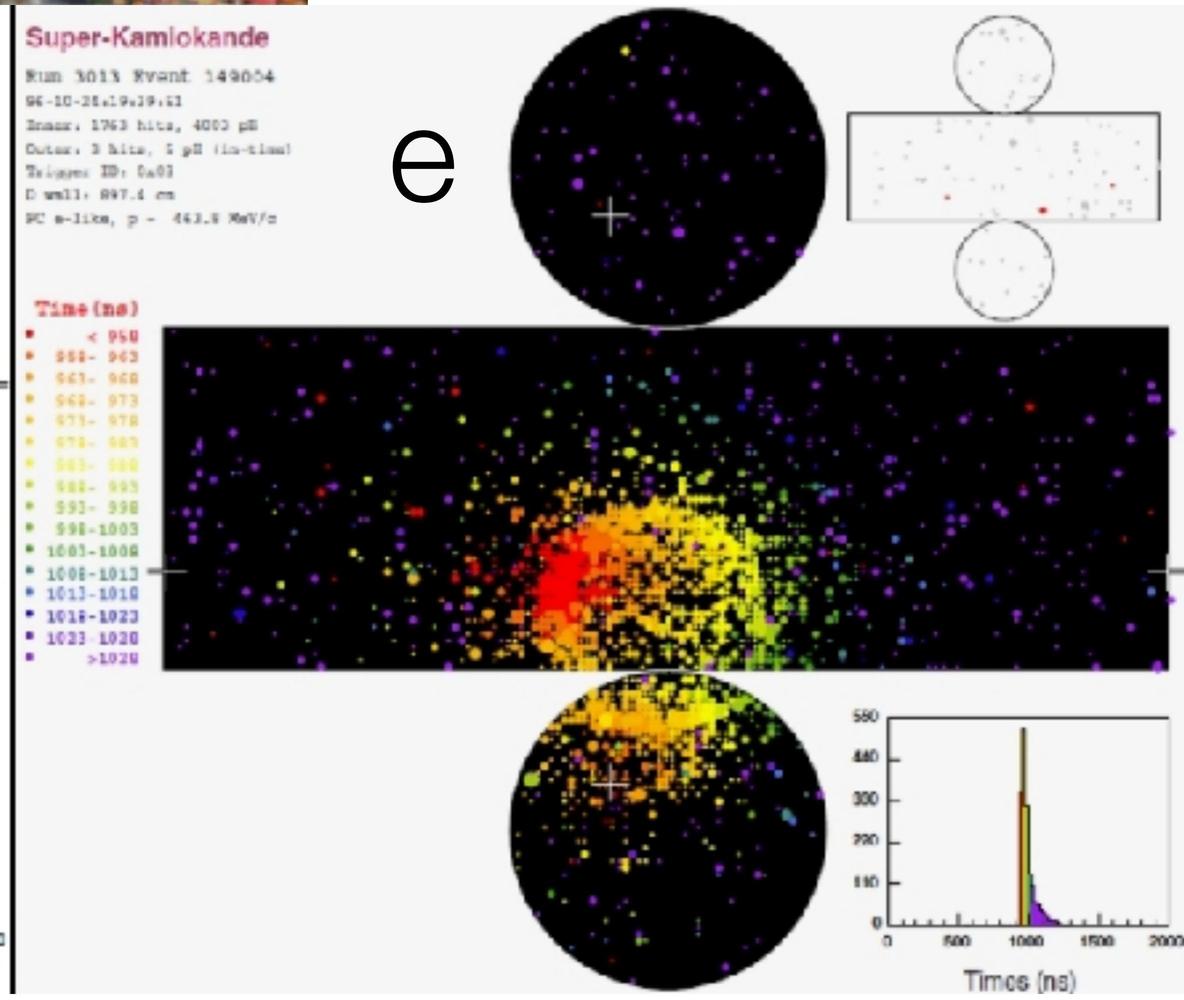
Can we measure the amount of supernova “relic” neutrinos?

1996 :









Water 50,000 t

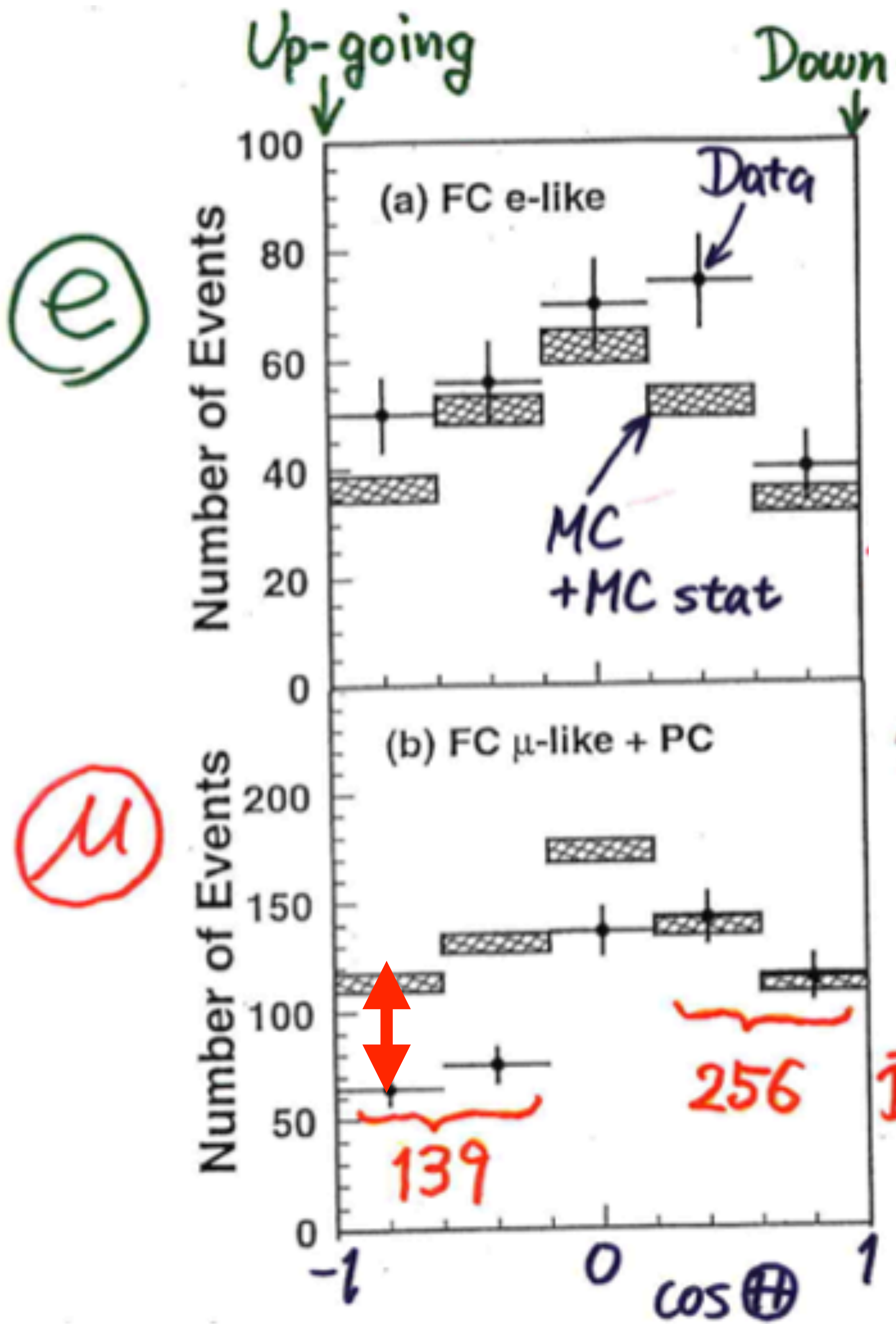

× 12,000

1998 :

VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

Neutrino'98 @ 高山

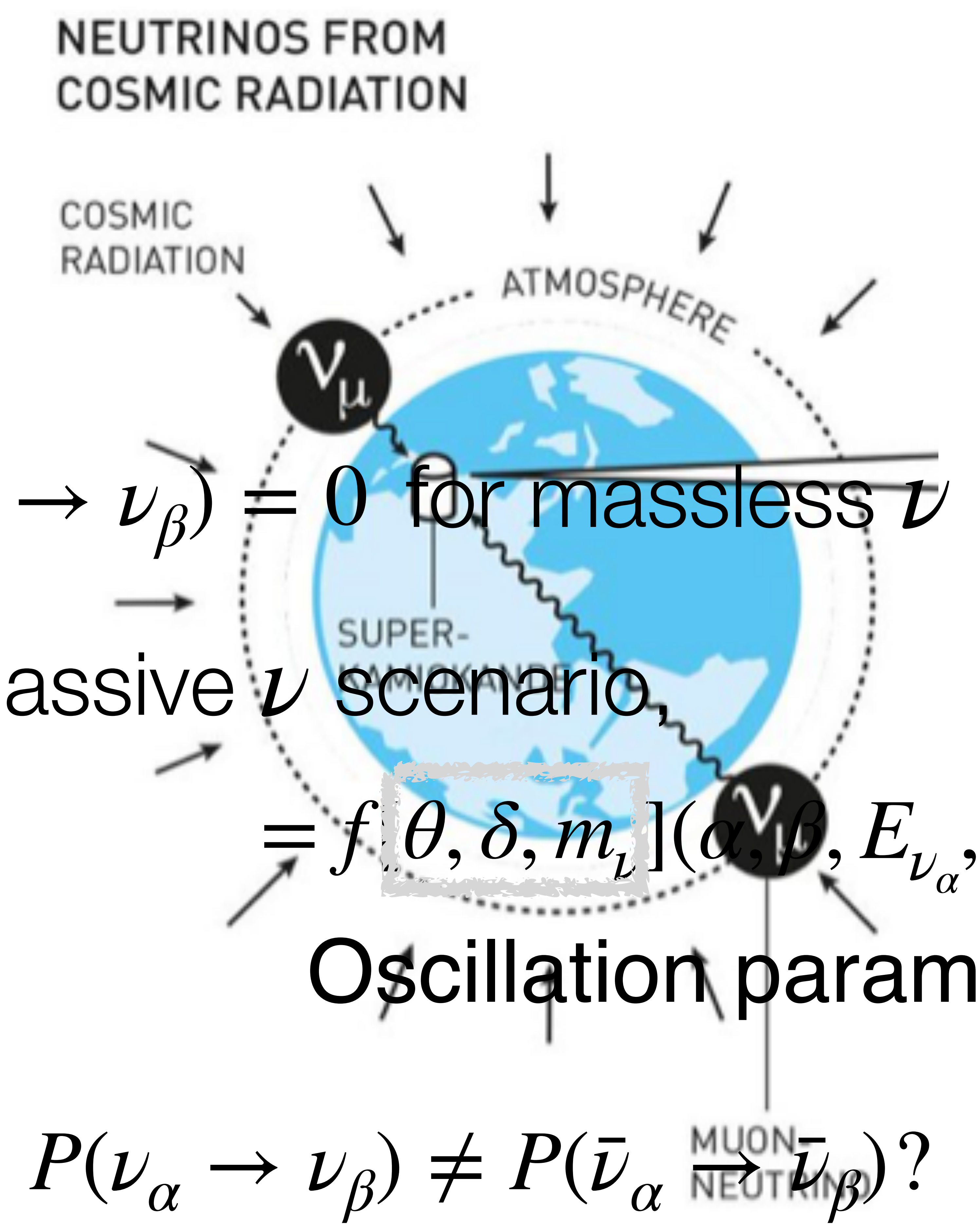


χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(6.2σ!!)

$P(\nu_\mu \to \nu_x) > 0$!



$P(\nu_\alpha \to \nu_\beta) = 0$ ~~for massless ν~~ in SM

In massive ν scenario,

$= f[\boxed{\theta, \delta, m_\nu}](\alpha, \beta, E_{\nu_\alpha}, L_{\nu_\alpha}) > 0$

Oscillation parameters

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

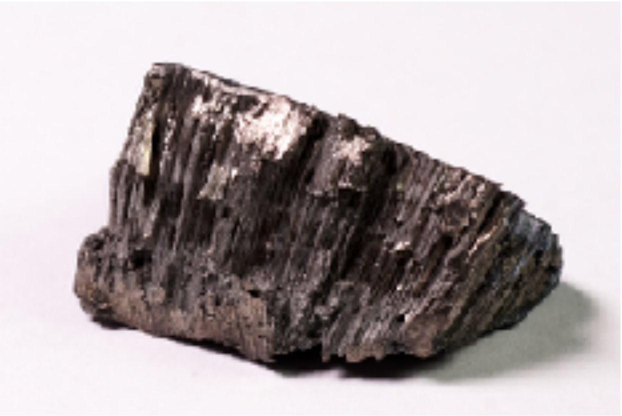
Super-Kamiokande Target Physics

	Motivation	Challenges			Problem
		Lv. 1	Lv. 2	Lv. 3	
Proton decay	Test GUT	Prove p-decay	-	-	Atm. ν BG
Supernova neutrinos	Core collapse Astrophysics Cosmology	Detect SN ν	Prove SN relic ν	-	Atm. ν BG
Atmospheric neutrinos	Test SM Lepton mixing	Prove oscillation	Measure oscillation parameters	Prove CPV	Anti-ν ID

And more…

Solution: n coincidence?

Gd



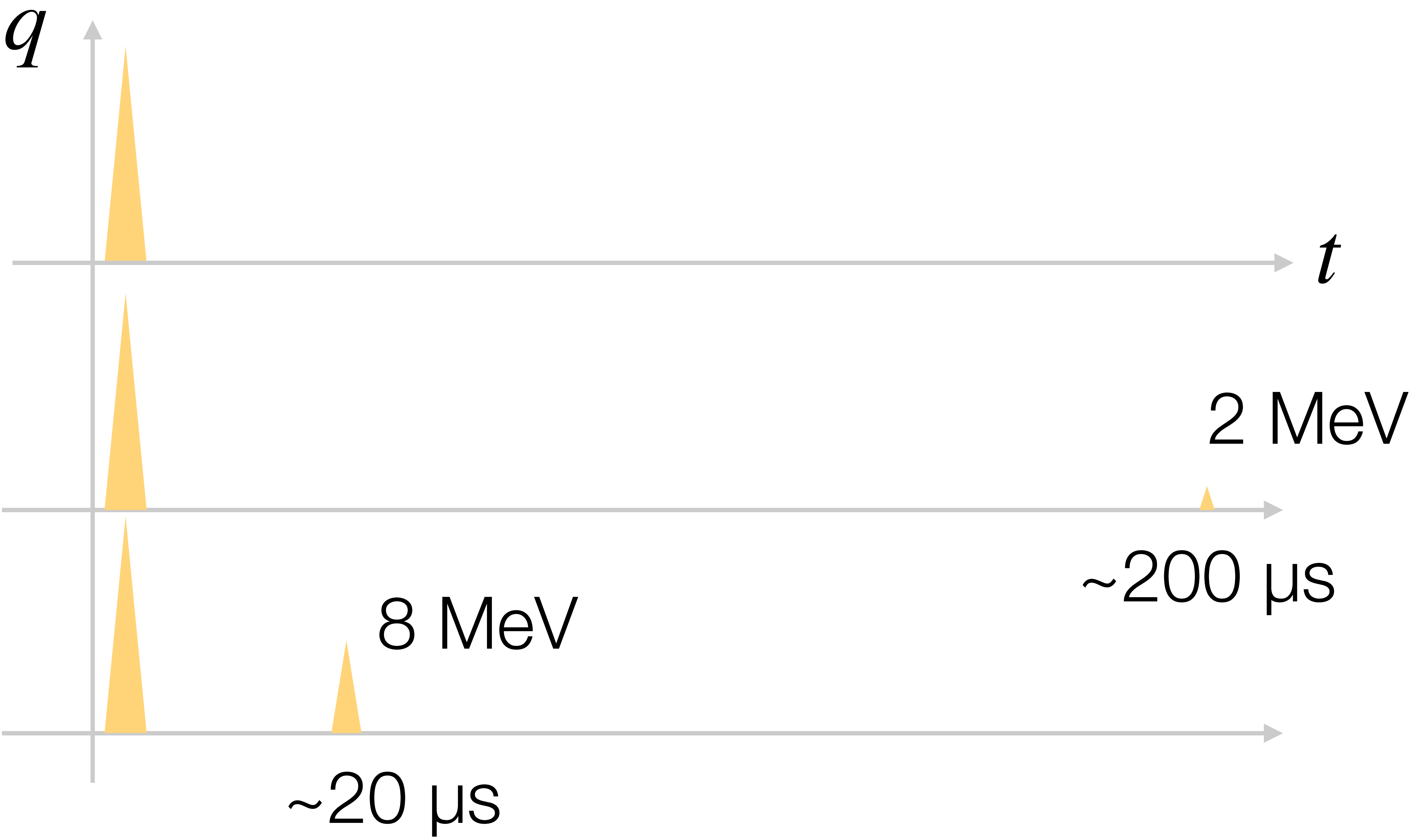
$\sigma^{Gd} > 10^5\sigma^H > 10^3\sigma^O$

H_2O

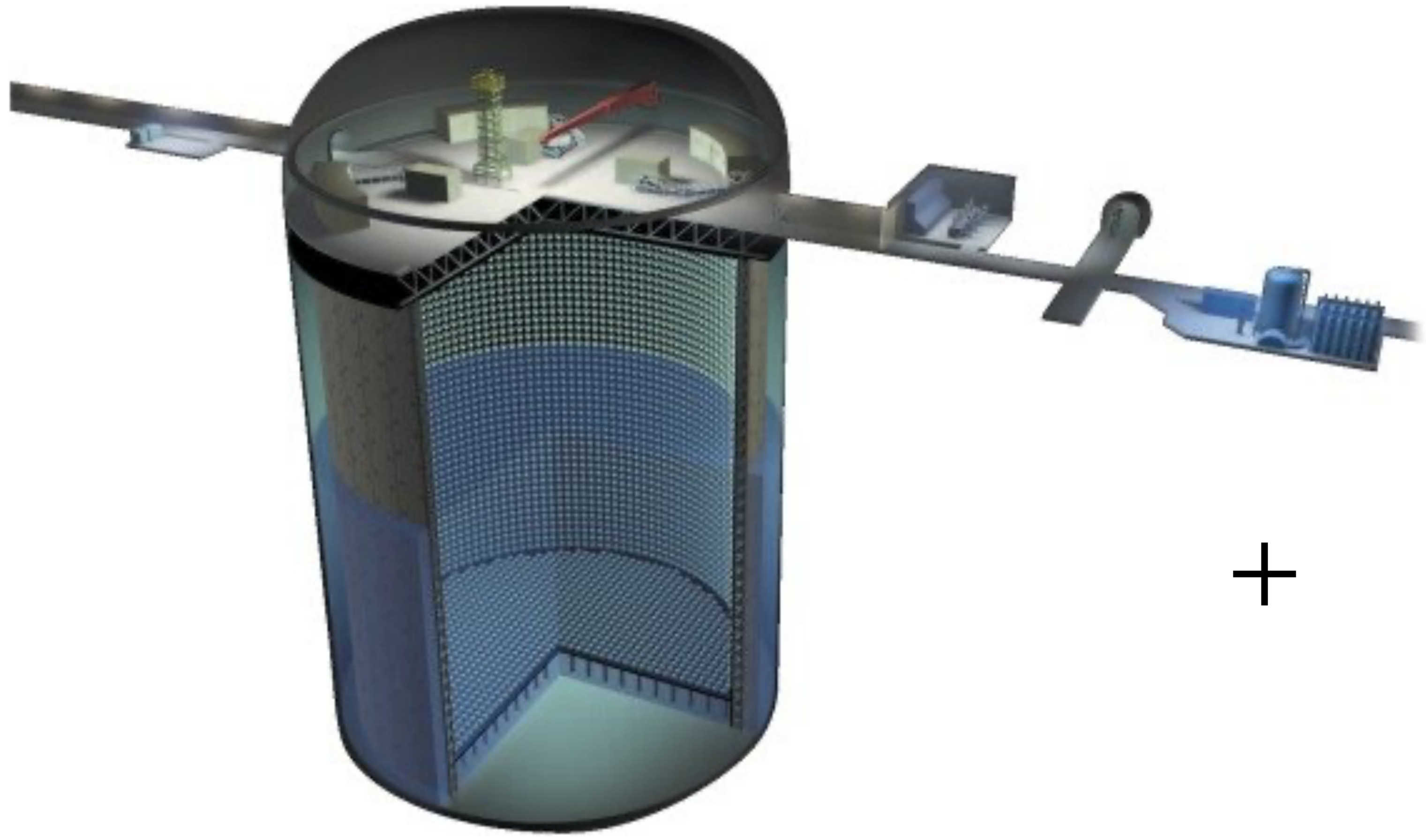
$\nu_\mu + n \rightarrow \mu^- + p$

$\bar{\nu}_\mu + p \rightarrow \mu^+ + n \rightarrow H(n,\gamma)$

$\searrow Gd(n,\gamma)$



SK-Gd

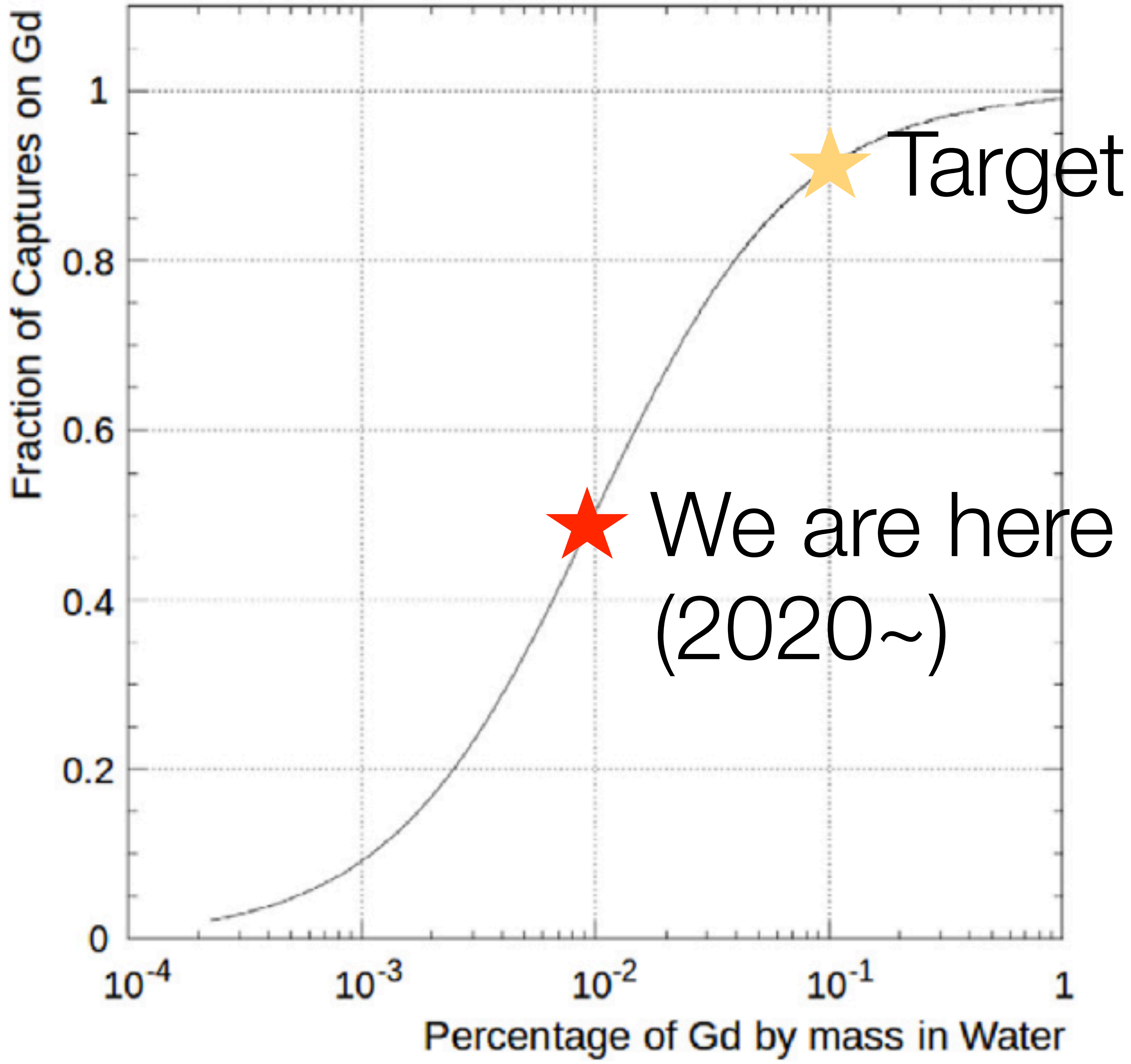


\+

Pure water 50,000,000 kg

August 2020

Gd-sulfide powder 13,000 kg



Issues

- Noise
- Calibration / stability
- ✓ Delayed particle tagging
- Event reconstruction

Takeaway

- SK, is a giant underground water tank with ~10,000 wall PMTs, that can detect rare/weak signals.
- Main targets include p-decay, ν astrophysics and oscillation.
- Recently, Gd was added to improve n detection and thus SNR.

My contribution: delayed particle tagging

Abstract

- Delayed coincidence signals from a ν-event:
  e: Michel electrons from μ-decay
  n: γ-rays from nuclear capture of neutrons

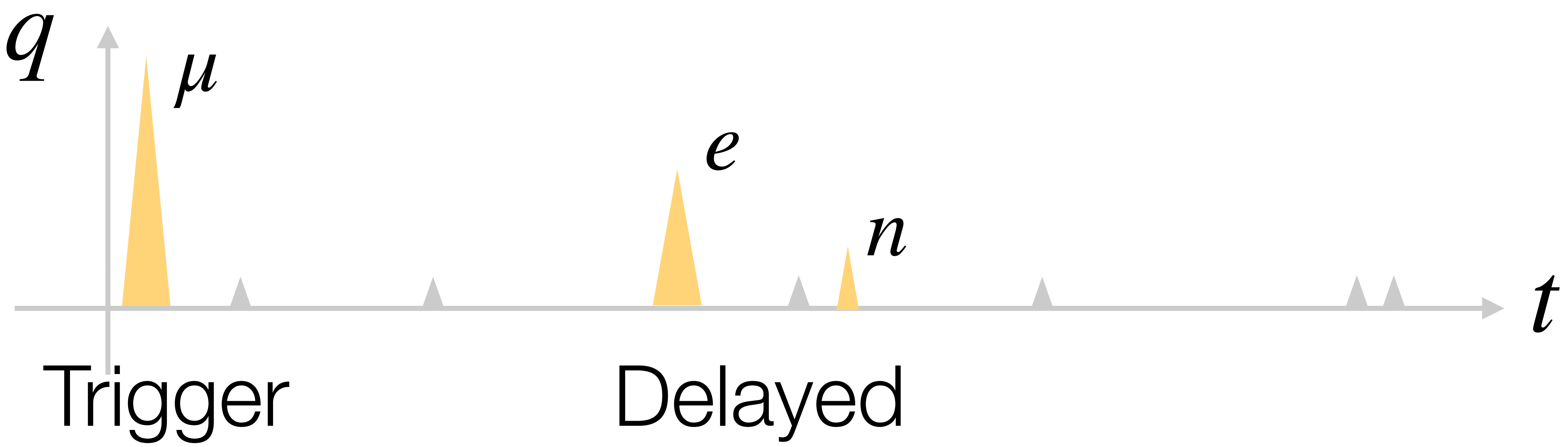
$>$ ν event classification

- In SK so far, we've tagged e and n separately and independently; this results in significant mutual contamination in SK-Gd.

- I unified the e and n detection processes, and evaluated the performance.
  - How?
  - Performance?

Delayed e, n from ν events

$$\bar{\nu}_\mu + p \to \mu + e + n$$



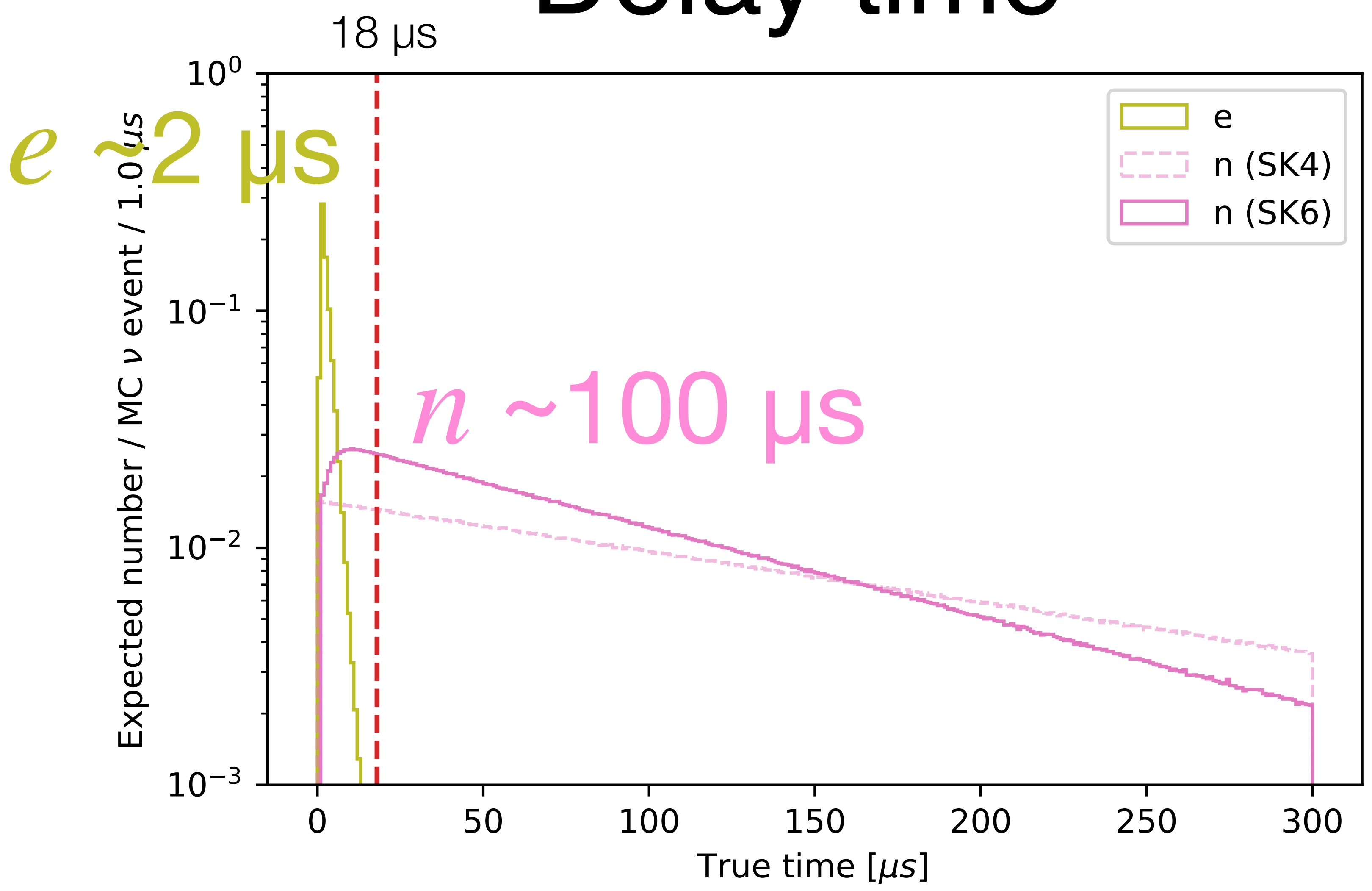
Problem with delayed particle tagging in SK-Gd

Before SK-Gd

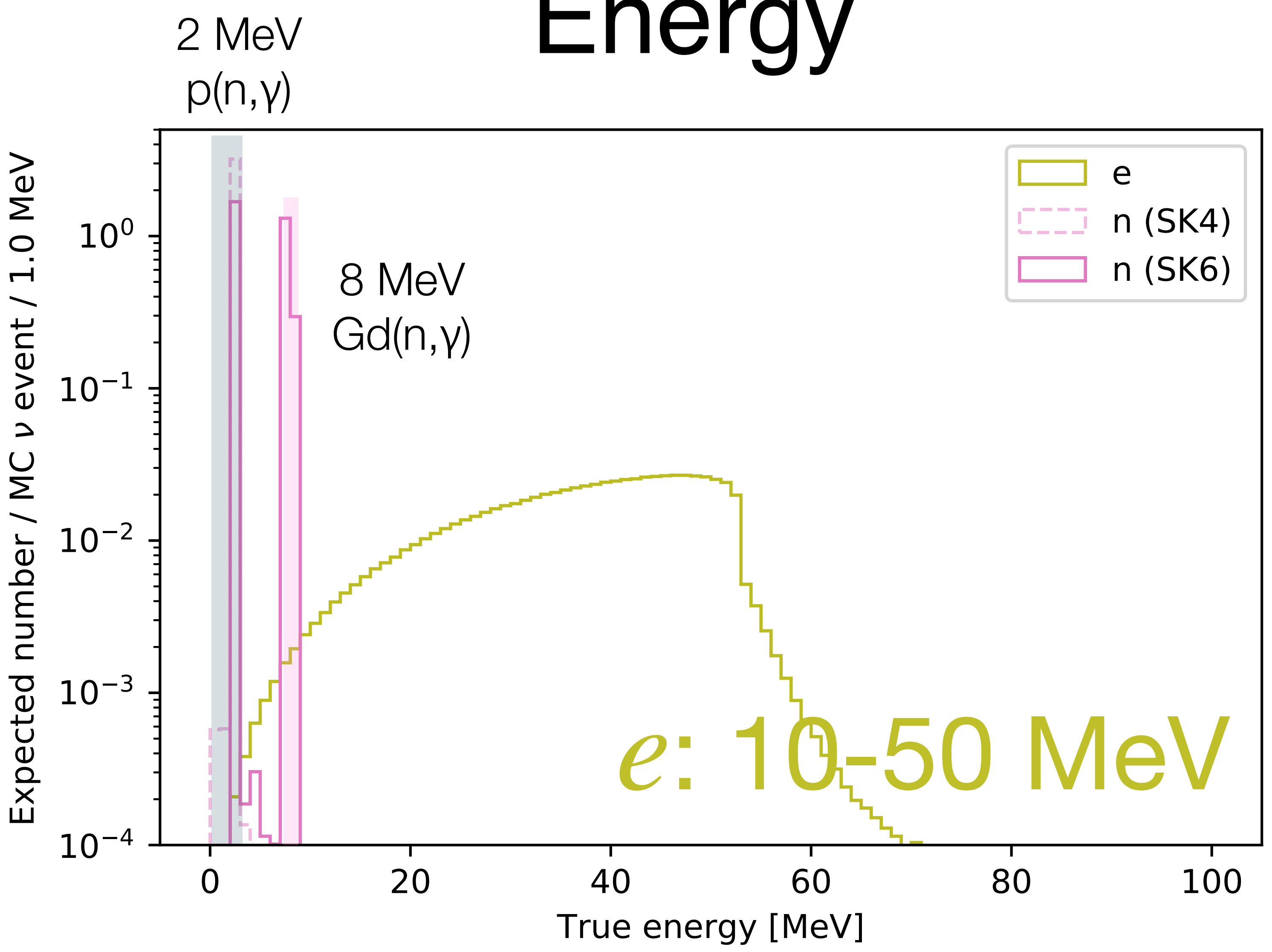
e: Delay time < 30 μs

n: Delay time > 18 μs

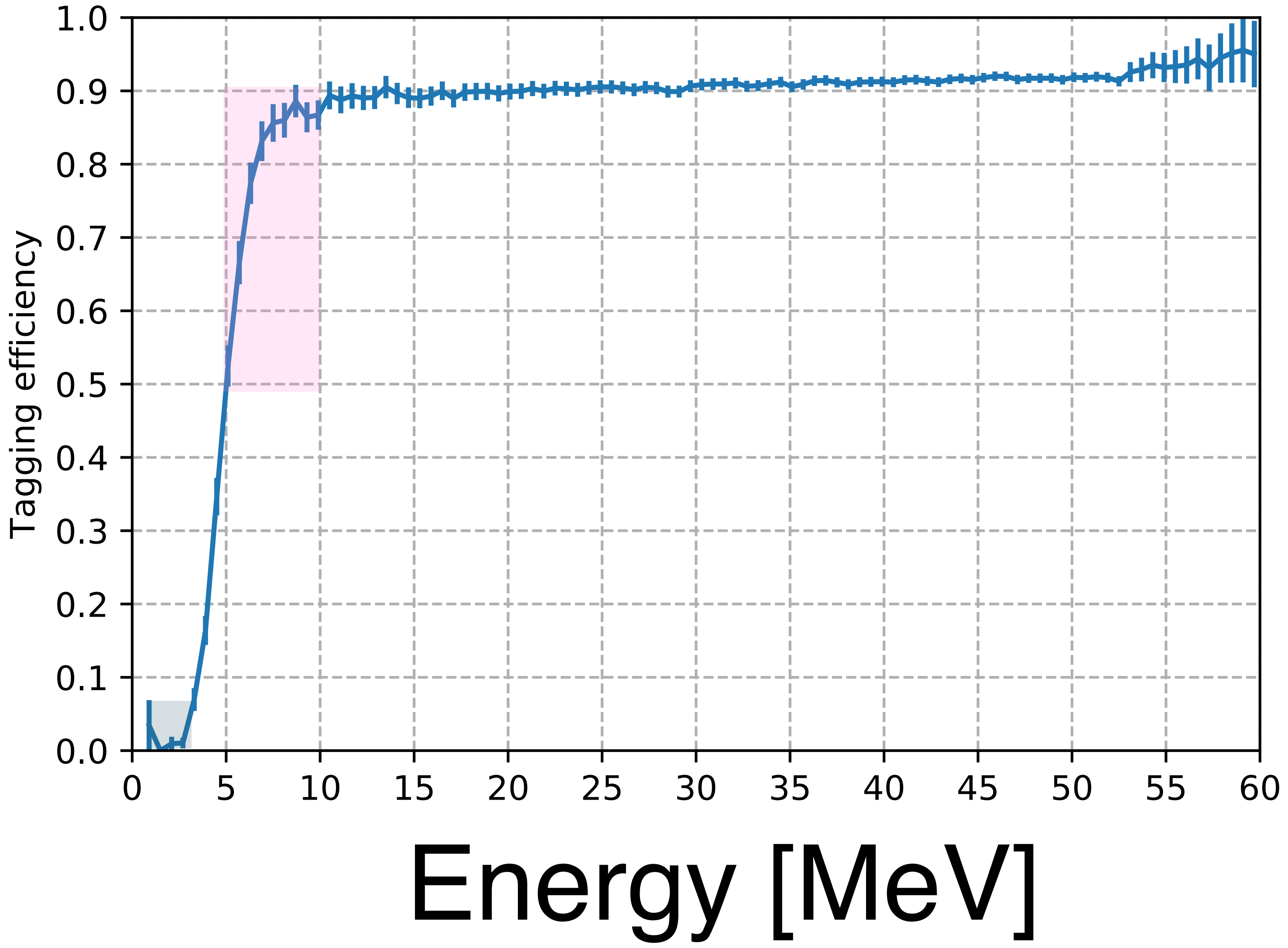
Delay time



Energy



SK e-tag program eff.

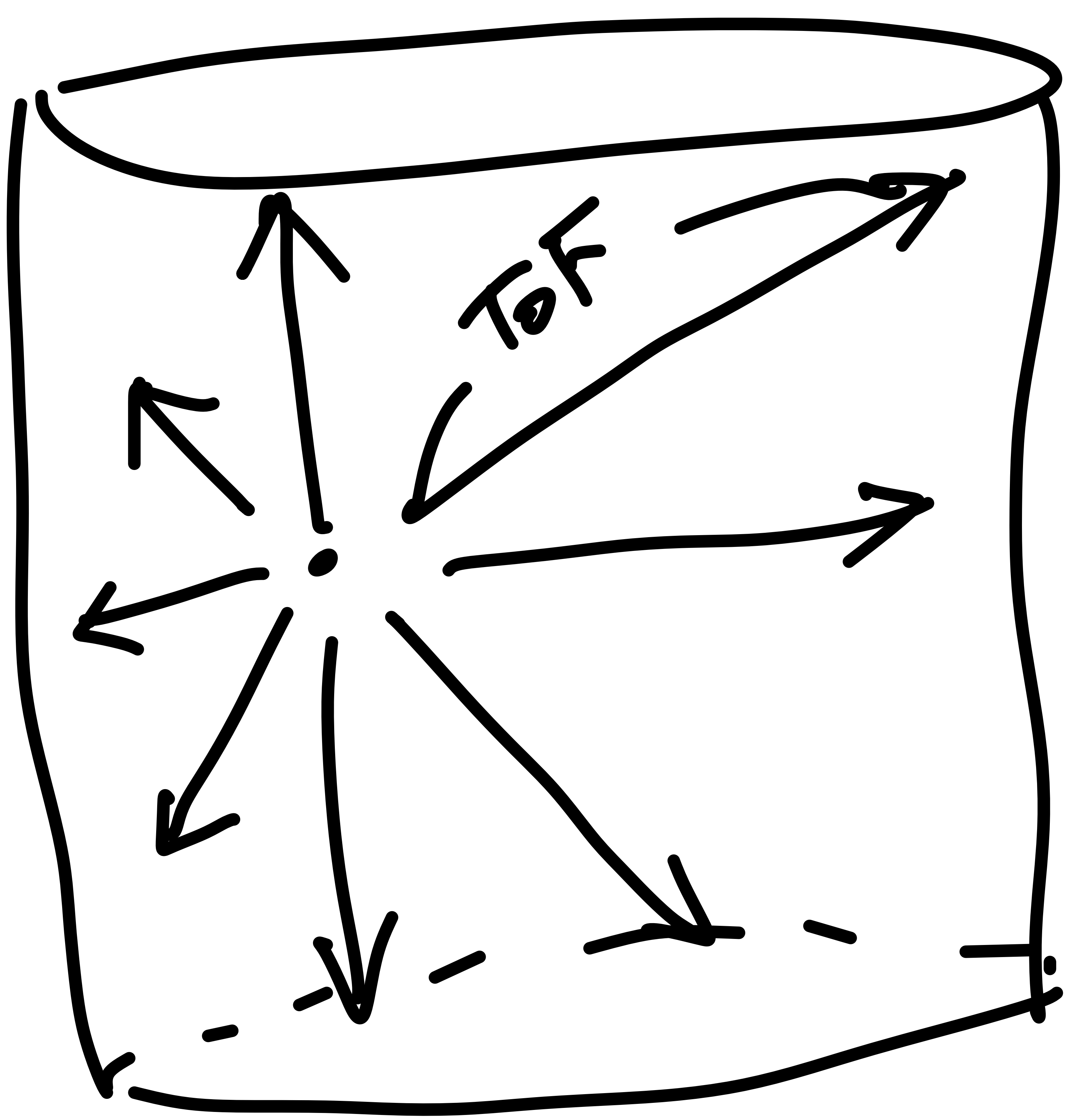


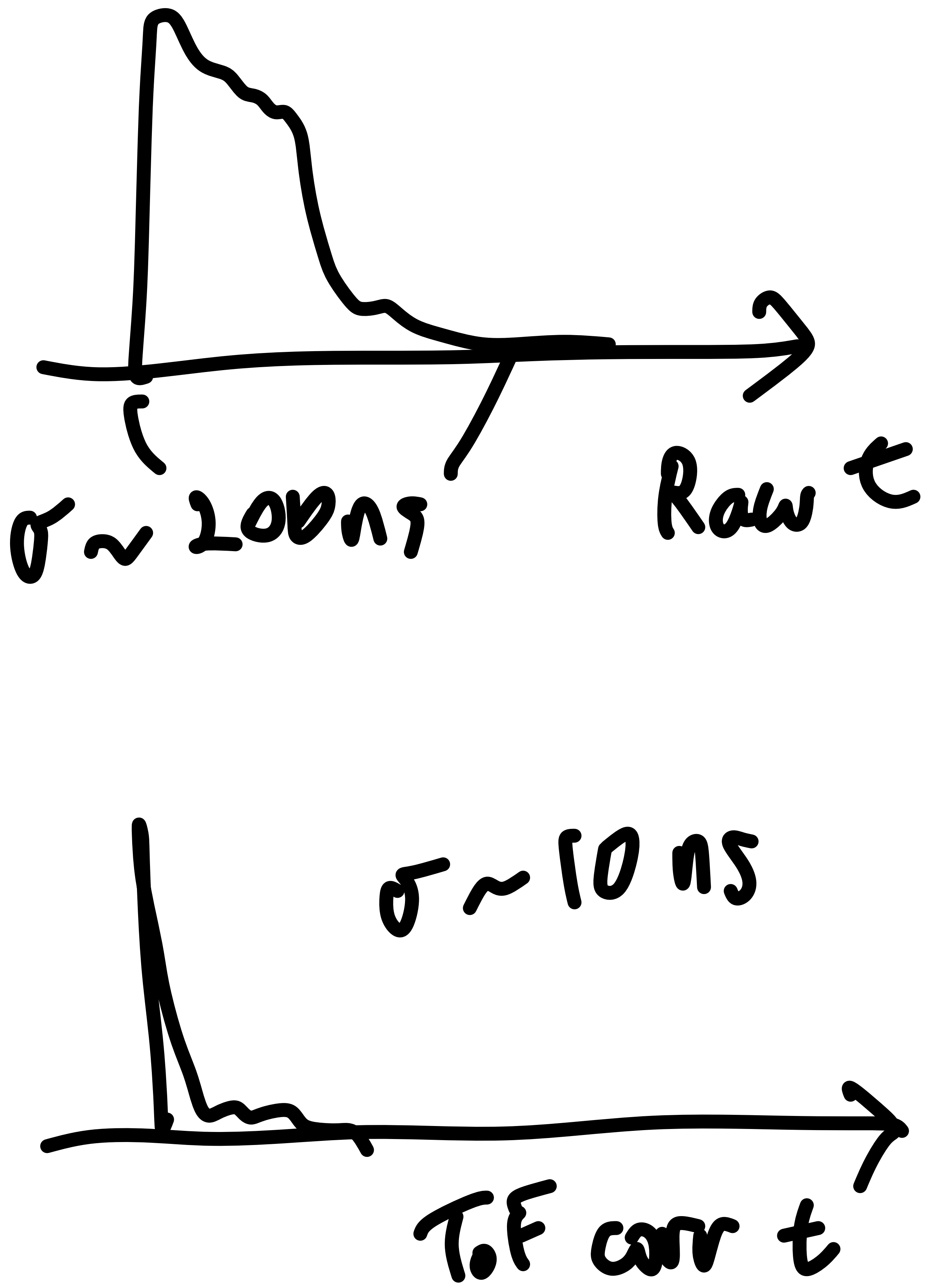
A considerable amount of n would be misclassified as e!

Plus, we lose n efficiency by the delay time > 18 μs cut.

How to detect e, n from ν events?

- Reconstruct ν interaction vertex and apply ToF correction





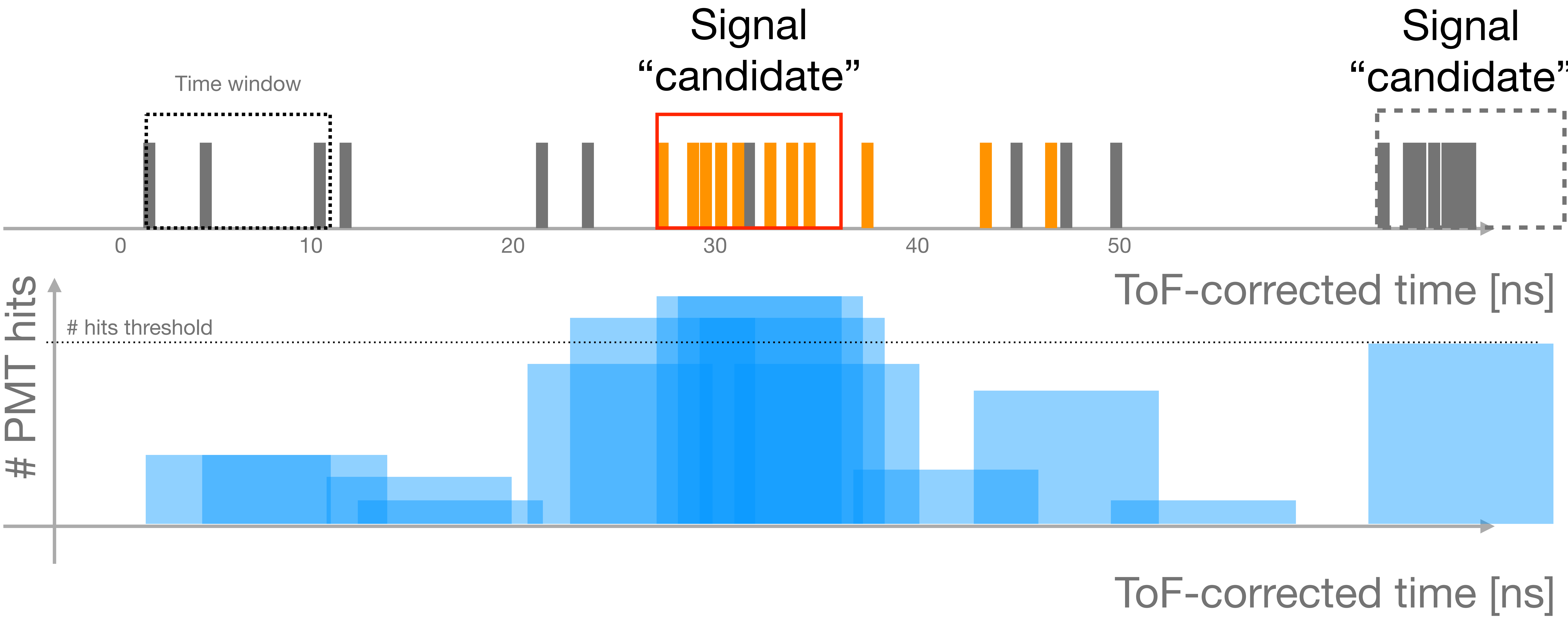
How to detect e, n from ν events?

- Reconstruct ν interaction vertex and apply ToF correction
- Search for signal “candidates” by # PMT hits within a small time window

Candidate search algorithm

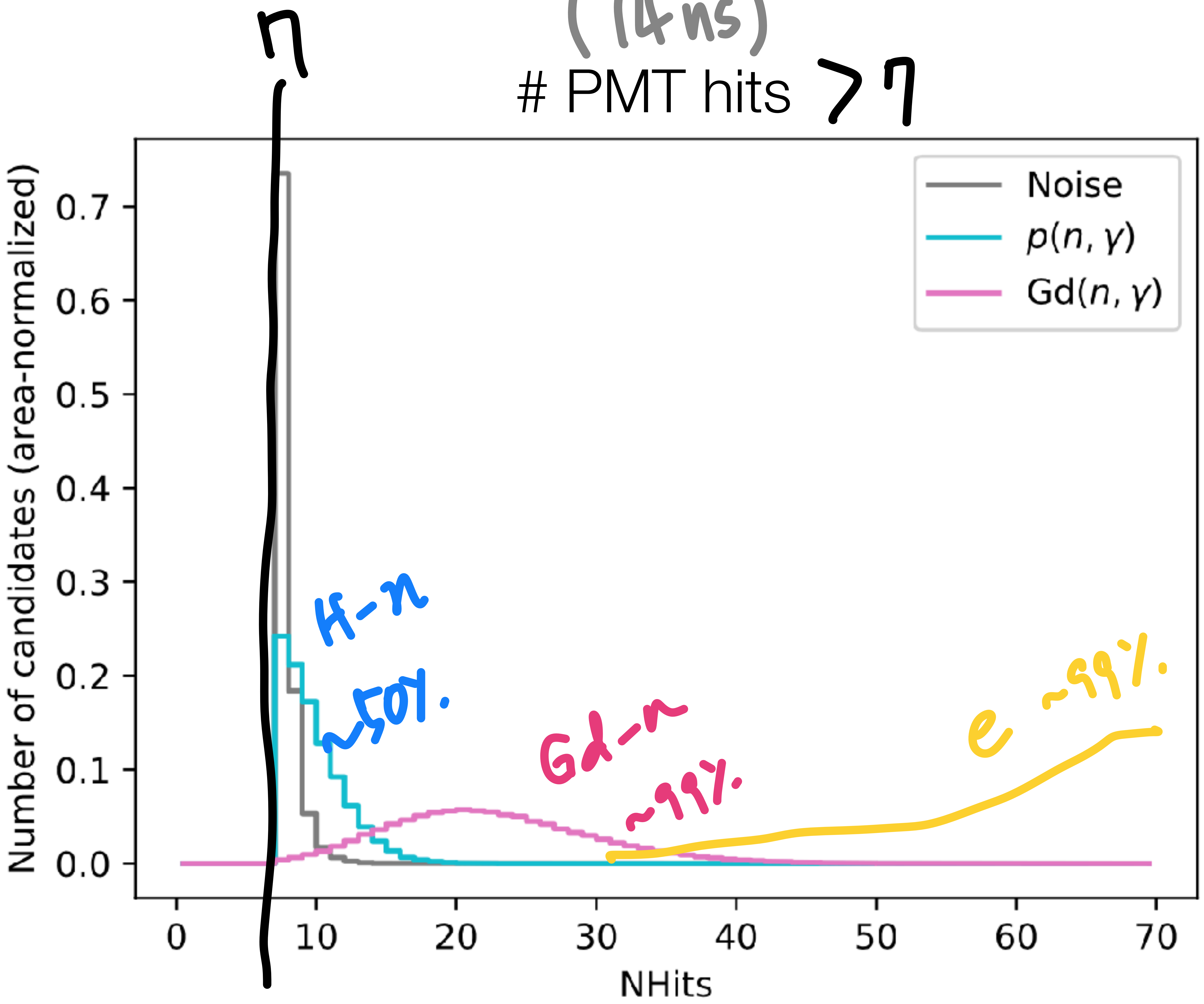
▬ PMT hit: noise

🟧 PMT hit: e, n signal



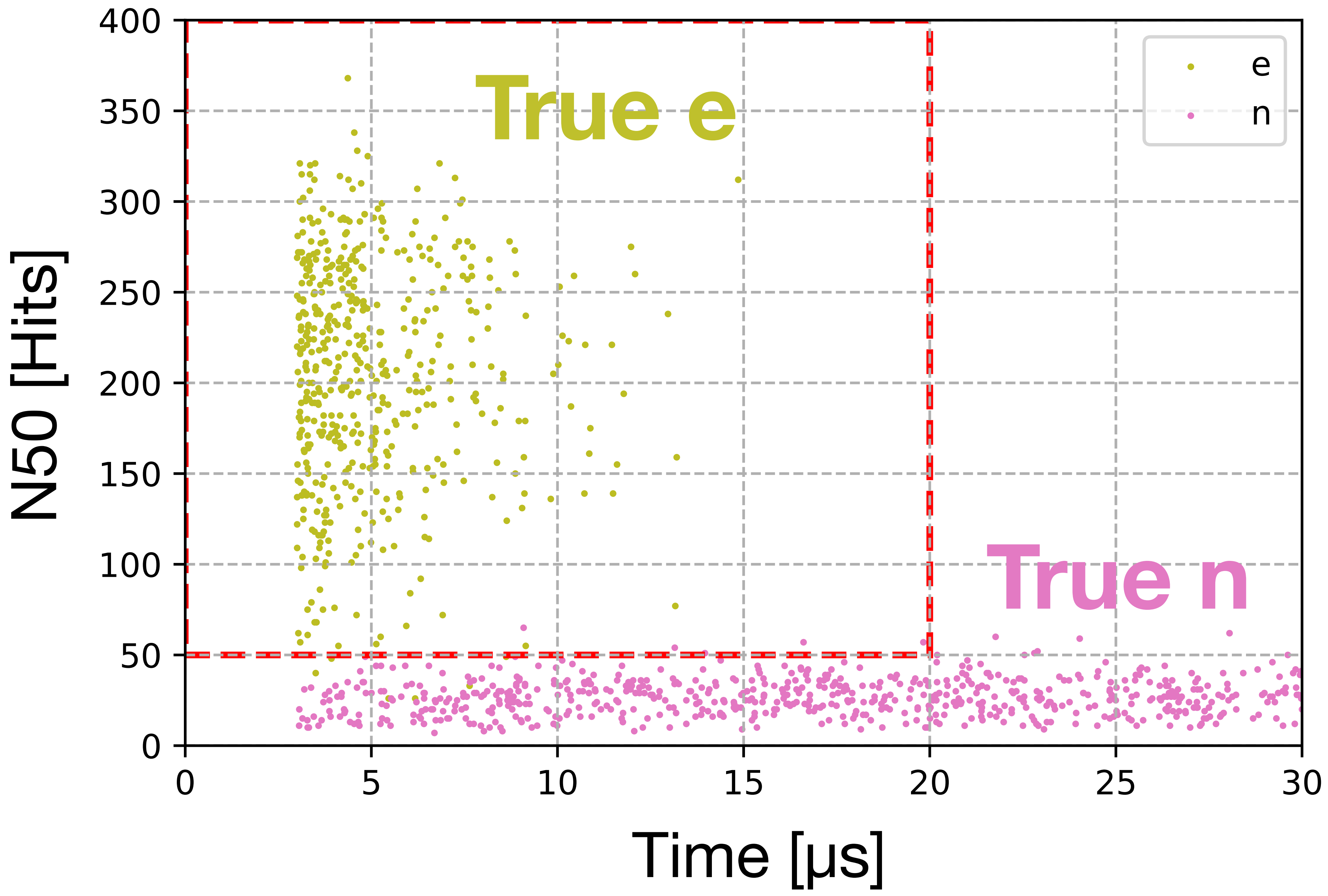
(14ns)

PMT hits >7



How to detect e, n from ν events?

- ToF correction from initial vertex
- Candidate search by # PMT Hits



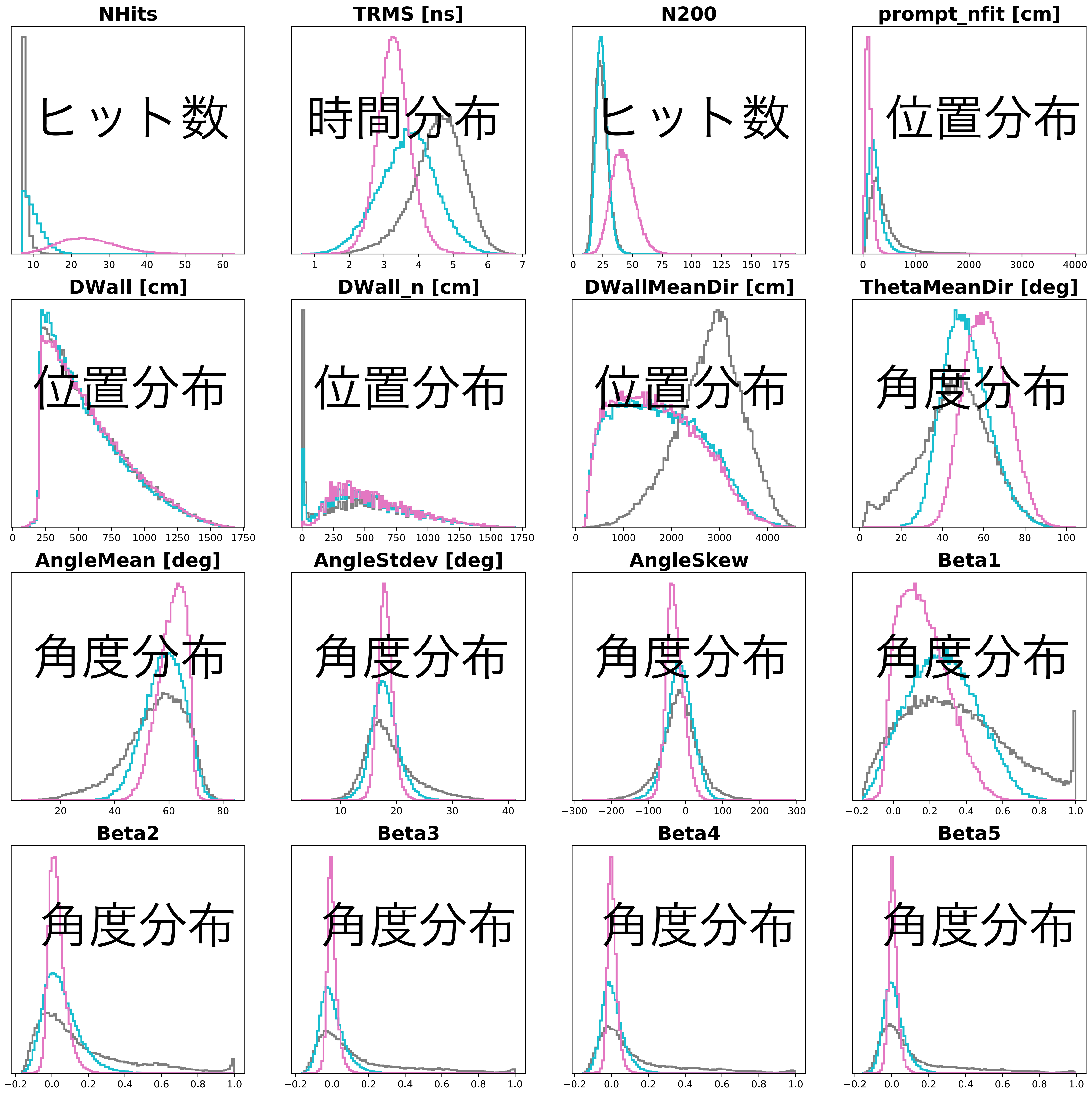
How to detect e, n from ν events?

- ToF correction from initial vertex
- Candidate search by # PMT Hits
- For each candidate:

Delay time < 20 µs && # PMT hits > 50

True? → e

False? → Neural Network



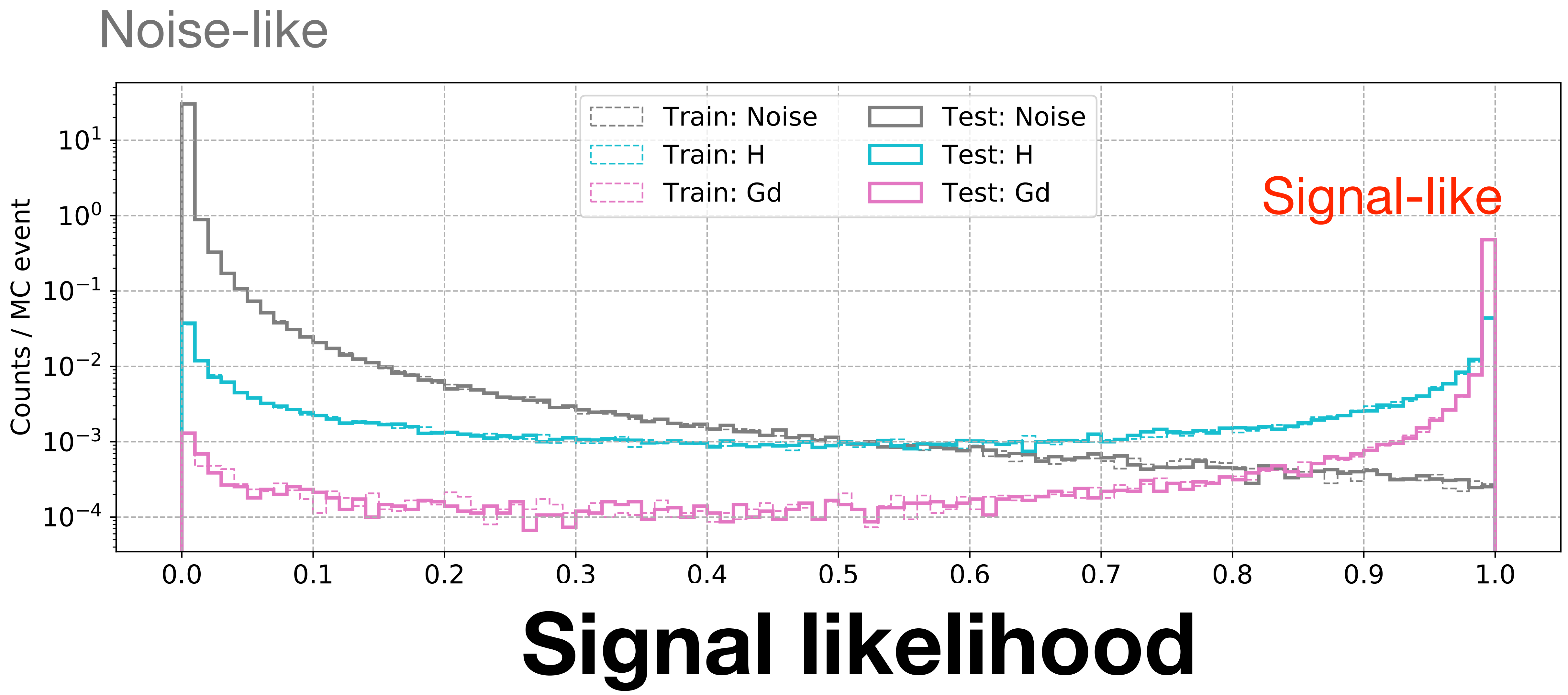
Candidate Features（MC）

▬ ノイズ

▬ p(n,γ) 信号

▬ Gd(n,γ) 信号

NN



More hits

Cherenkov ring

Generated near ν vertex

How to detect e, n from ν events?

- ToF correction from initial vertex
- Candidate search by # PMT Hits
- For each candidate:

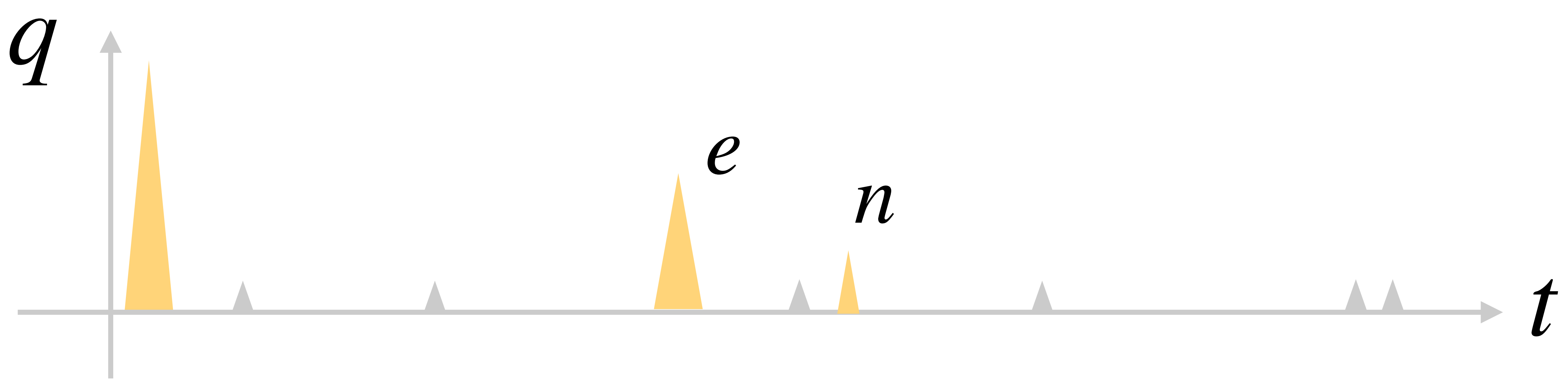
Delay time < 20 μs && # PMT hits > 50

True? → e

False? → Neural Network → n → noise

Single routine for e, n detection!

Check what?



e, n detection efficiency

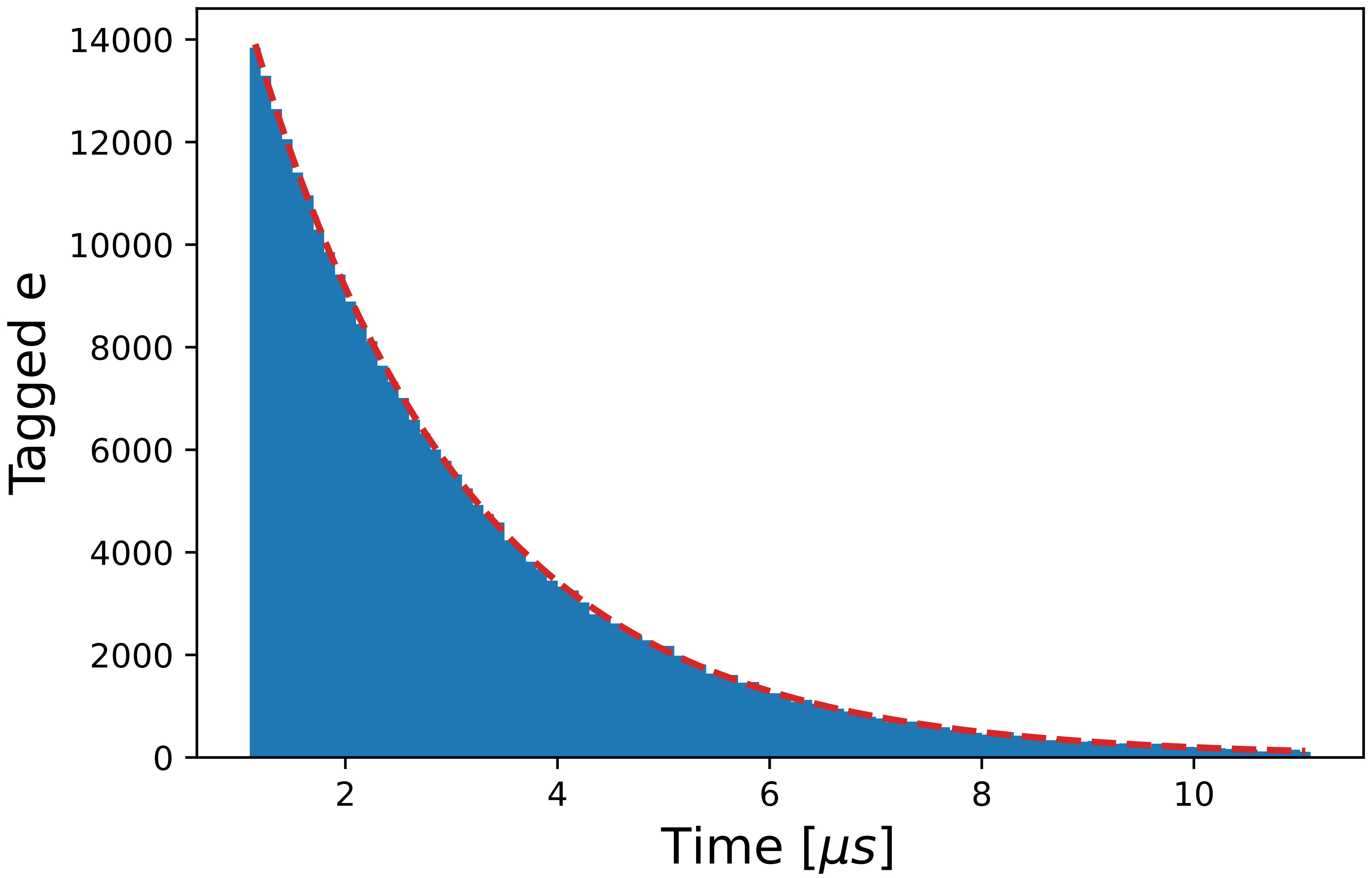
purity (mutual contamination)

e-tagging performance check

- e source: cosmic μ stopping within the detector
- Vertex reconstruction: μ entry point and momentum
  + μ range table in water

Tagged e purity #1

- Try a simple exponential curve fit on t: $Ae^{-t/\tau} + B$
- $$\text{Purity} = \frac{(\#\text{ tagged}) - (\#\text{ flat B})}{(\#\text{ tagged})} = 99.3 \pm 0.3\ \%$$ (MC: 99.2%)

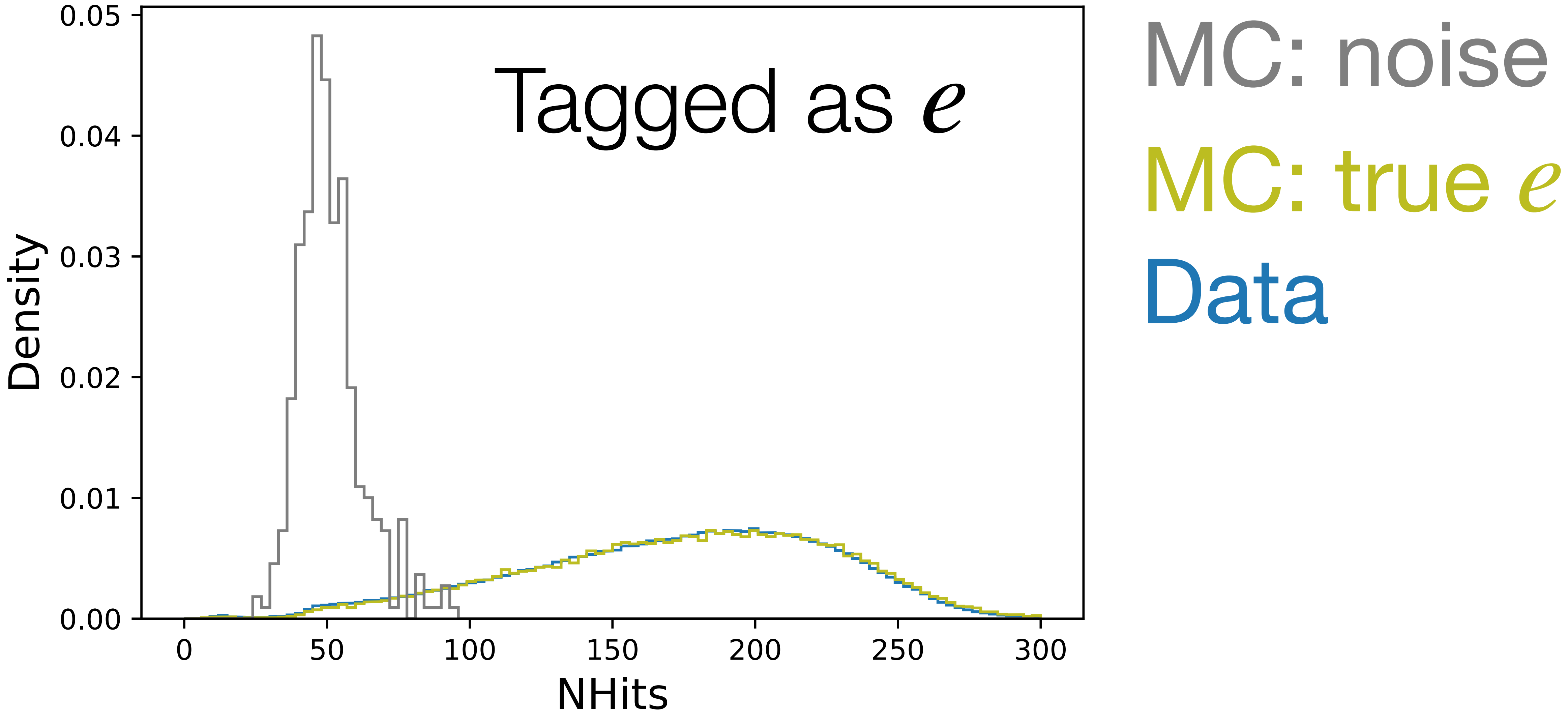


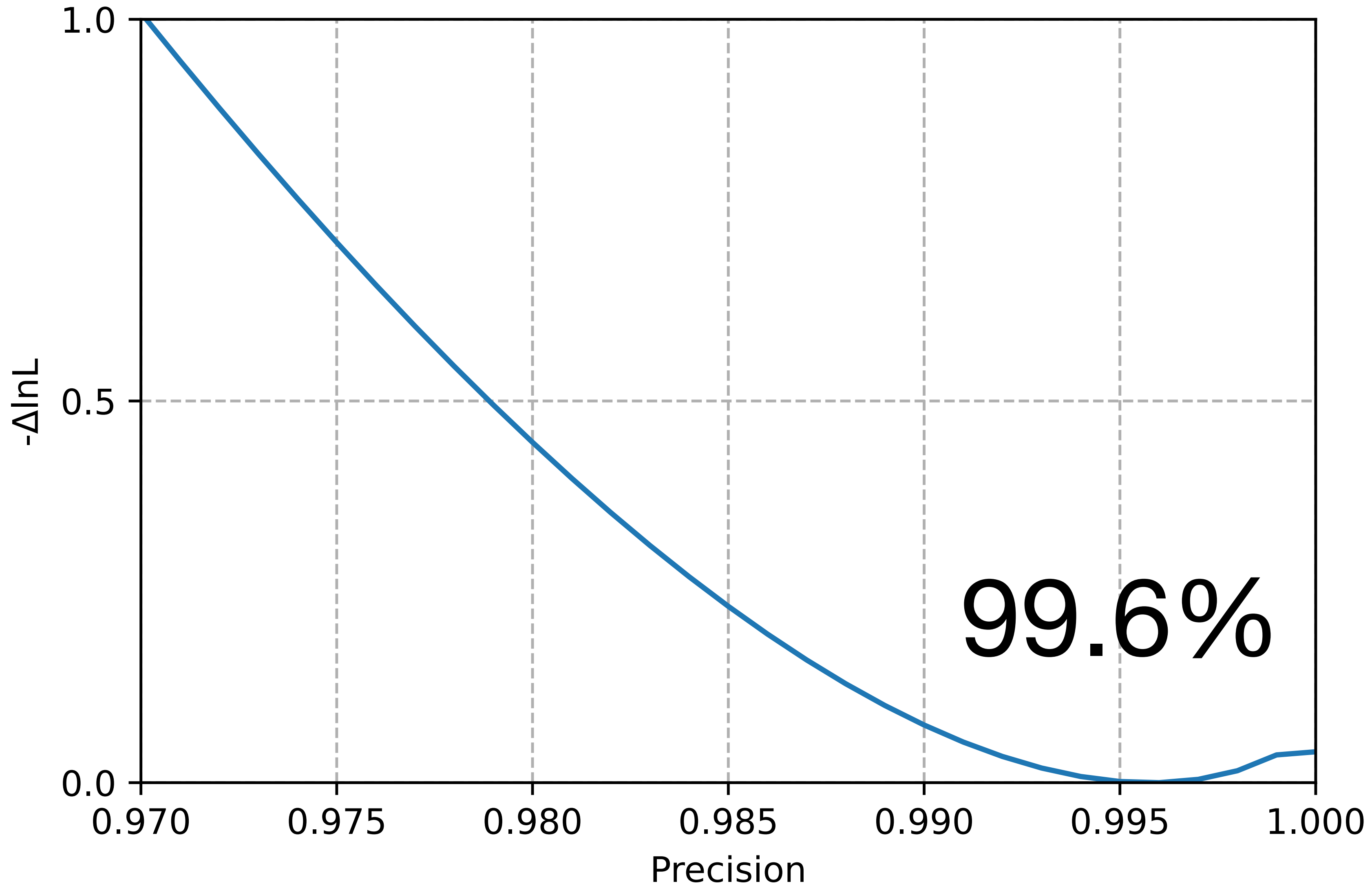
τ = 2.028 ± 0.005 μs

(τ_{exp} = 2.027 μs)

Tagged e purity #2

- Features: # of hits, angular and timing distributions, etc.
- Fit each normalized feature histogram of “data e” with:
  purity × (MC true e) + (1-*purity*) × (MC noise)
- Find the best fit purity that maximizes data’s likelihood





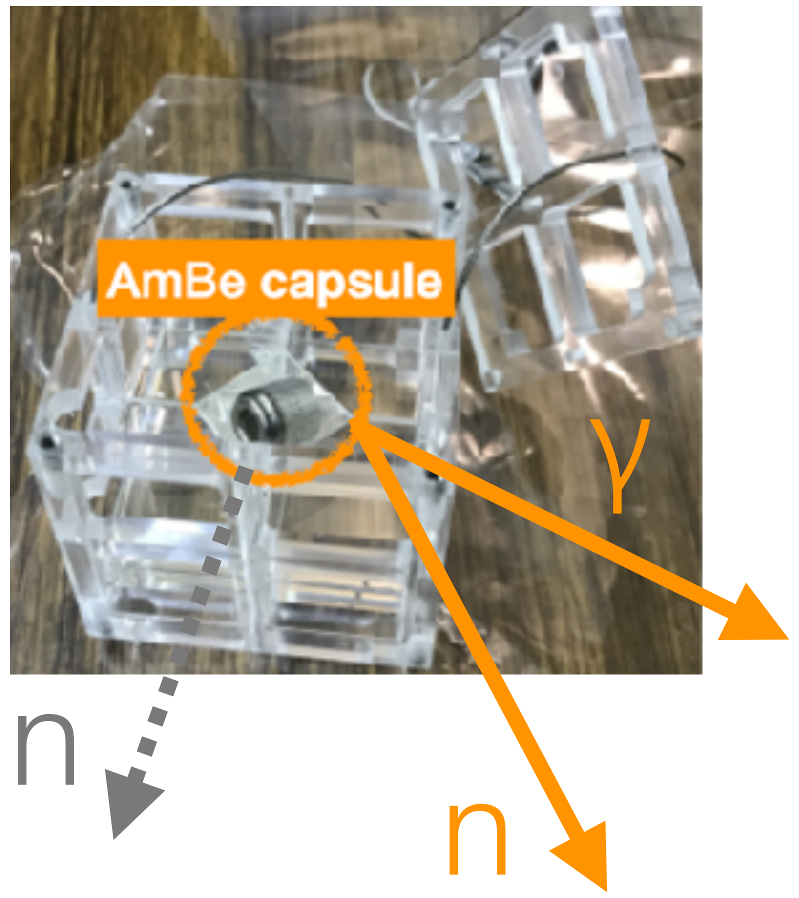
e-tagging performance on cosmic μ (stat errors only)

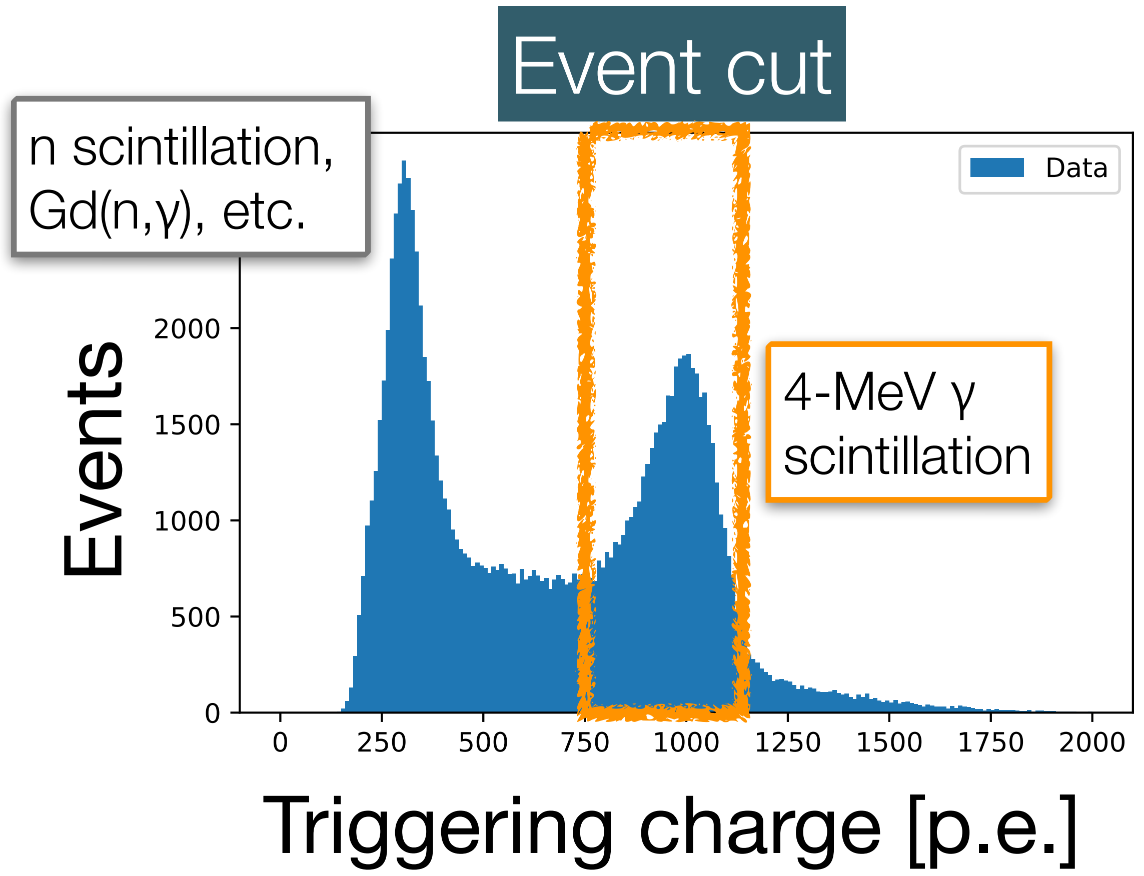
- Purity = [exp. fit] (99.3±0.3)%, [likelihood fit] 99.6% (MC: 99.2%)
- Efficiency* = [exp. fit] (98.6±0.6)%, [likelihood fit] (98.9±0.5)% (MC: 98.8%)

* For e's produced within [1, 20] μs from trigger

n-tagging performance check

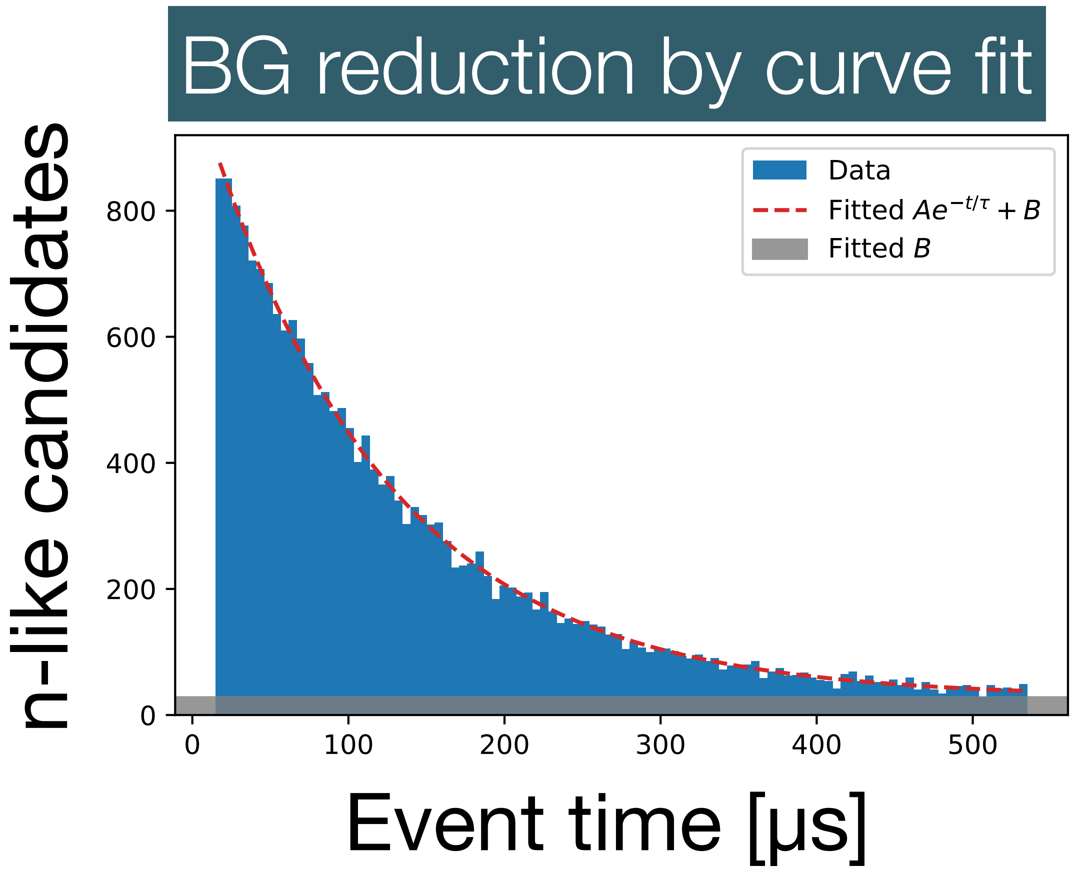
- n source: AmBe + surrounding BGO scintillator
- Vertex: source position (i.e., tank center)





Search candidates

Classify with NN*

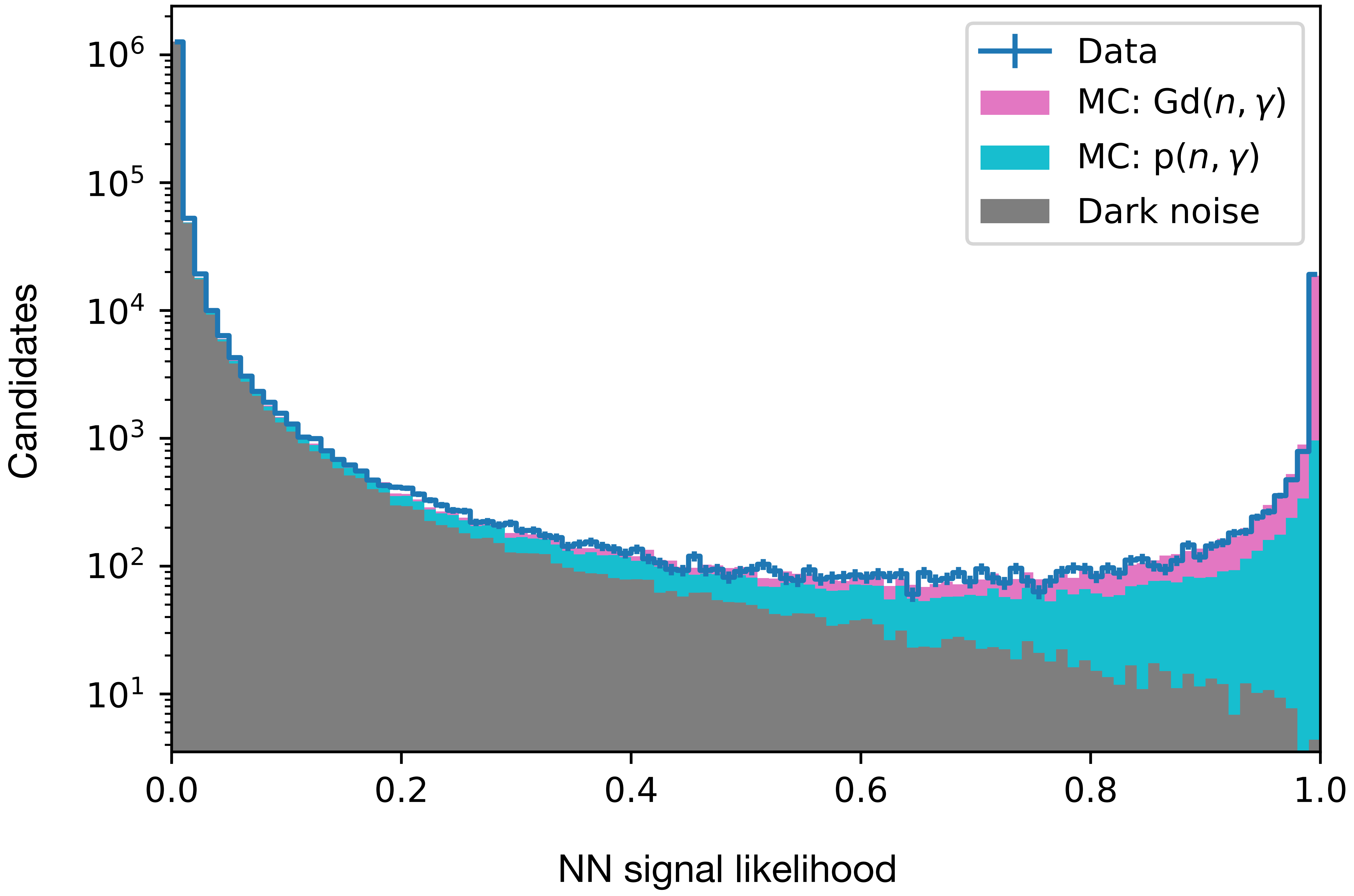


Measured efficiency

$$= \frac{(\text{\# of tagged signals})}{(\text{\# of signal neutrons})}$$

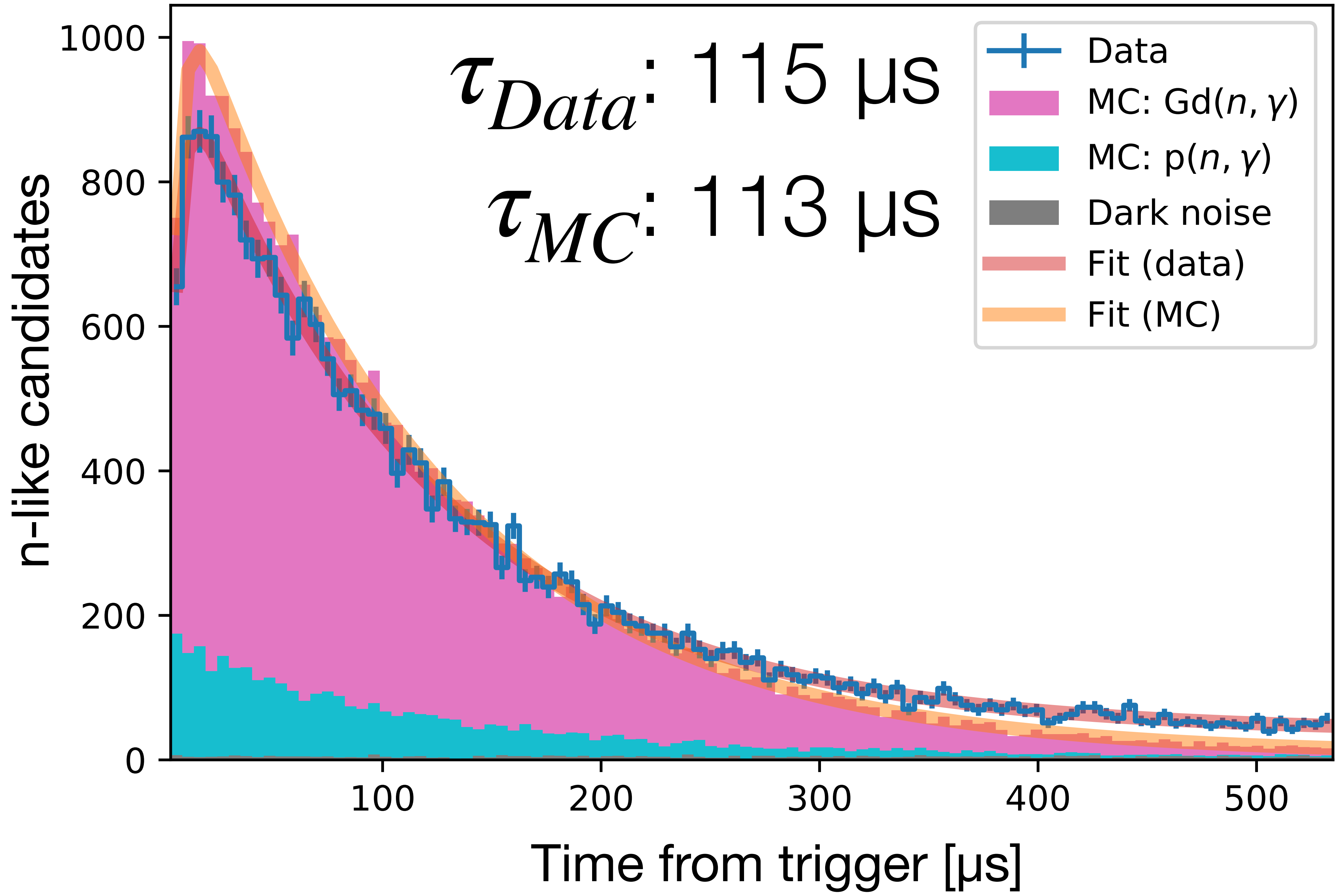
$$\approx \frac{(\text{all n-like}) - (\text{fitted B})}{(\text{\# of events})}$$

Neural-network's n-likelihood output



n-tagging performance on AmBe

$$Ae^{-t/\tau} + B$$



⚠ Work in progress!

Estimated efficiency:

Data 45.6%, MC 49.2%

Estimated purity:

MC ~98%

Results on SK-Gd atmospheric ν MC (<1 GeV)

- Comparing with the conventional method (independent tagging):
- e-tag efficiency: 88%→88%, purity:↑ 83%→96%
- n-tag efficiency:↑ 44%→51%, purity: 99%→99%

Mutual contamination is suppressed,
while maximizing efficiencies!

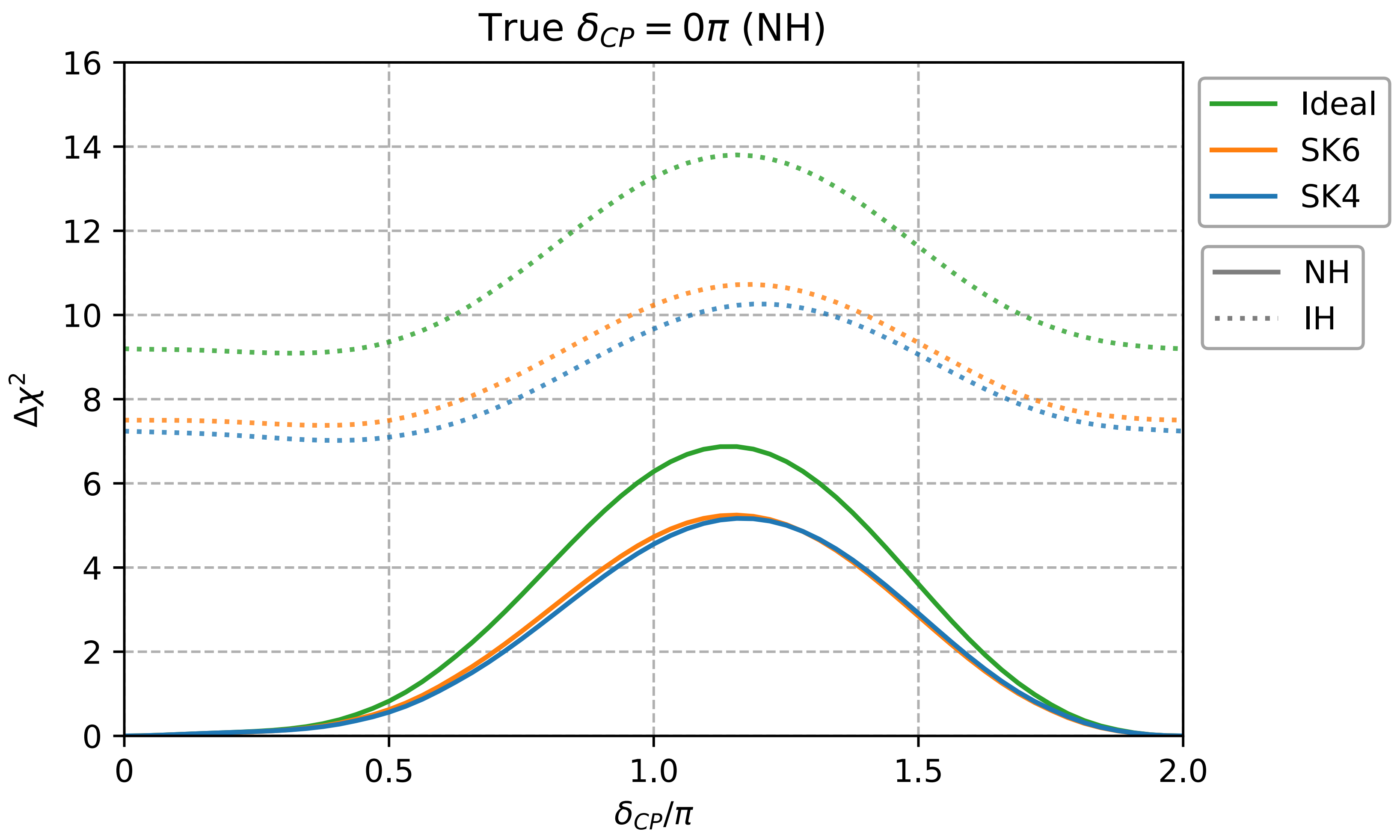
My contribution summary and prospects

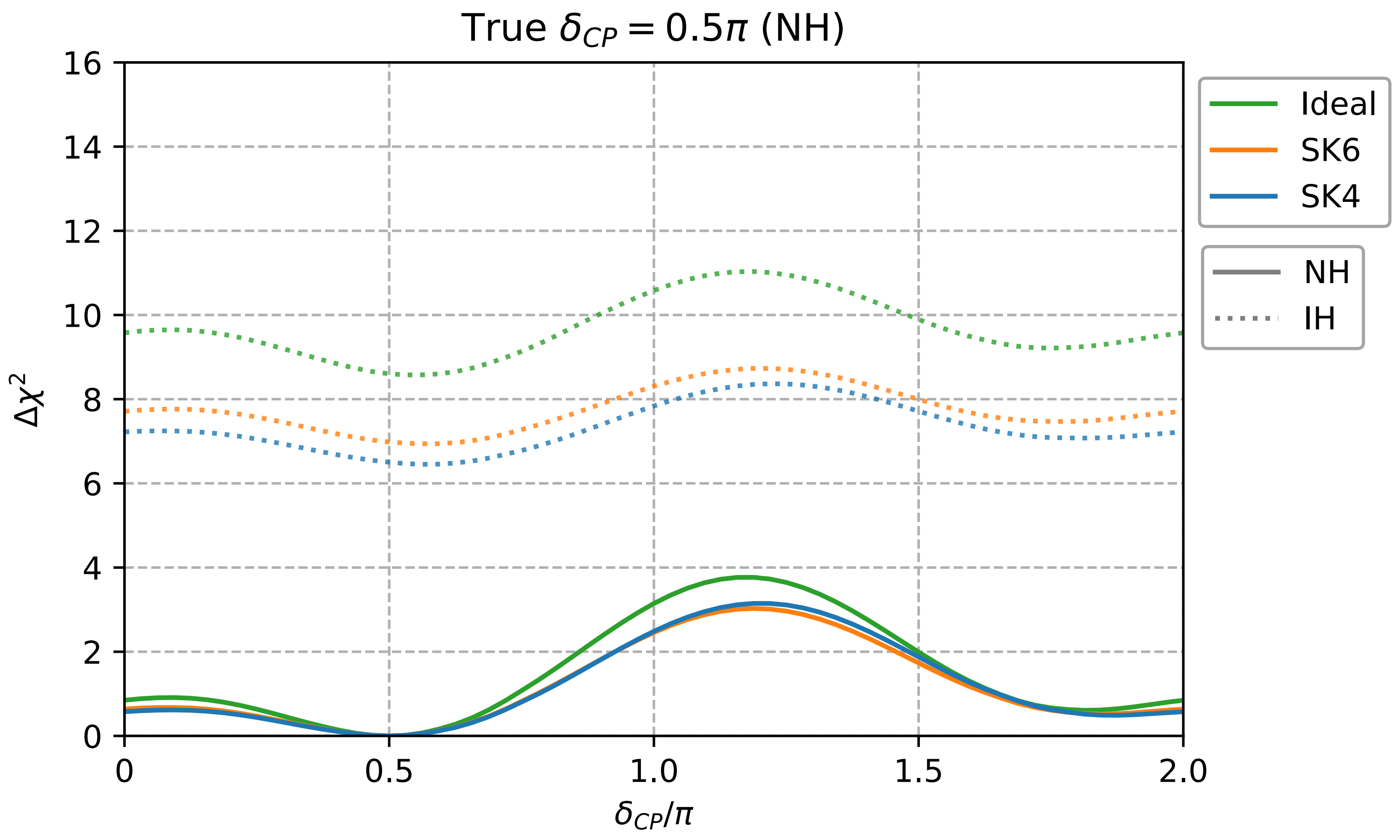
- Tagging e and n separately as in SK results in mutual contamination in SK-Gd.
- I unified the e and n detection processes, and evaluated the performance.
    - e-tagging almost as good as before SK-Gd
    - n-tagging efficiency increases by 15%
    - Mutual contamination is suppressed to minimal level
- We expect to improve oscillation parameter sensitivity with better particle tagging and event classification.

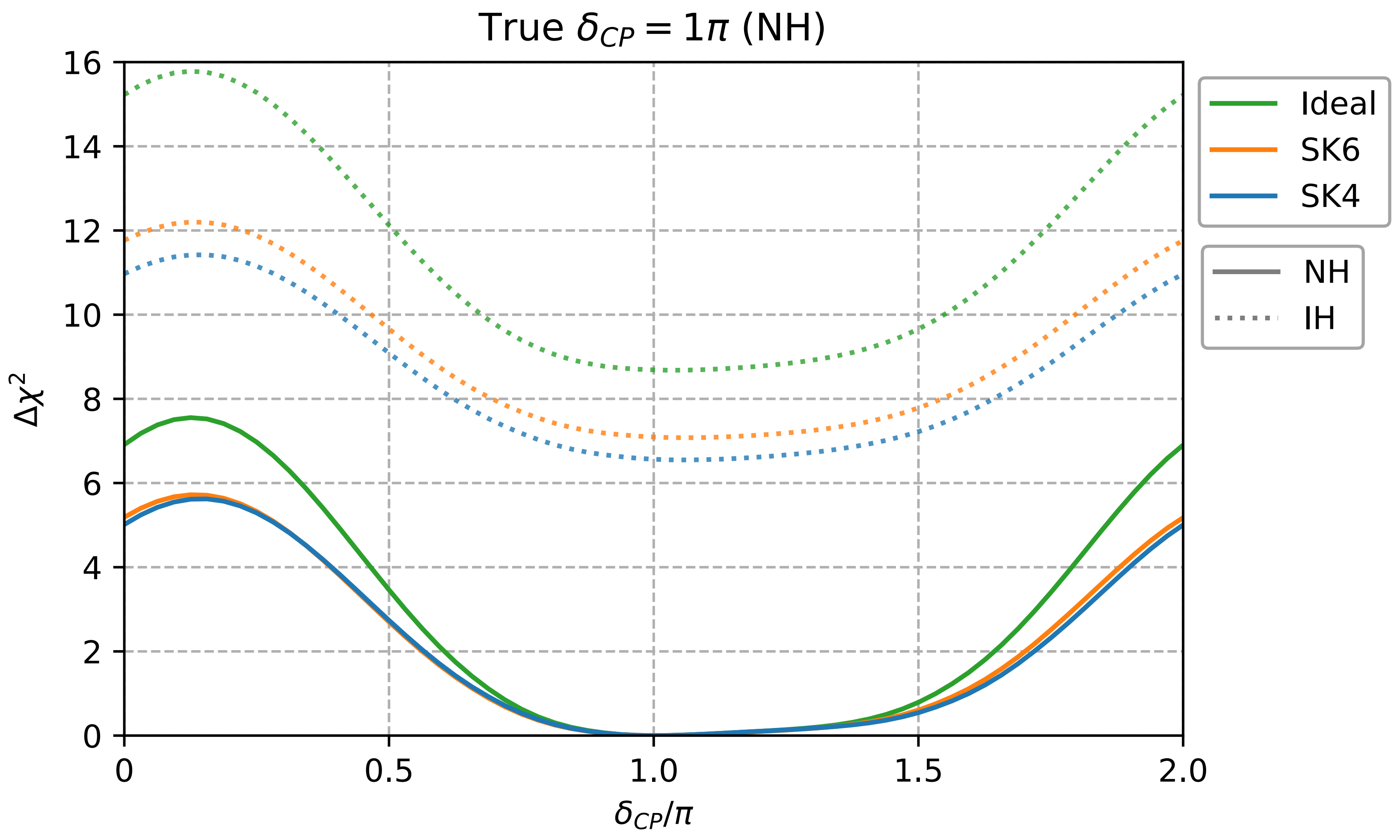
Backup

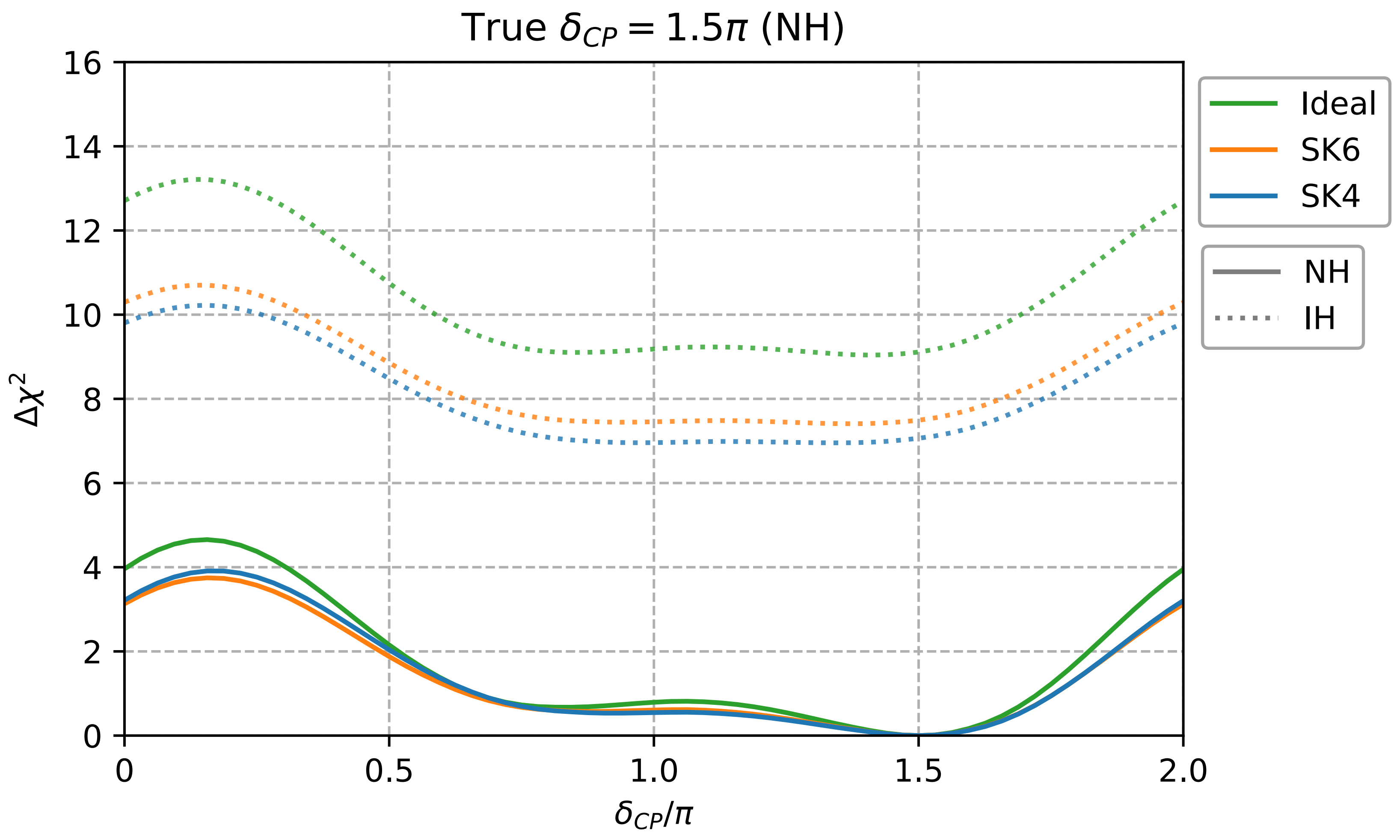
CP and MH sensitivity

X2minCP from BuildContour’s ChiSquared.root



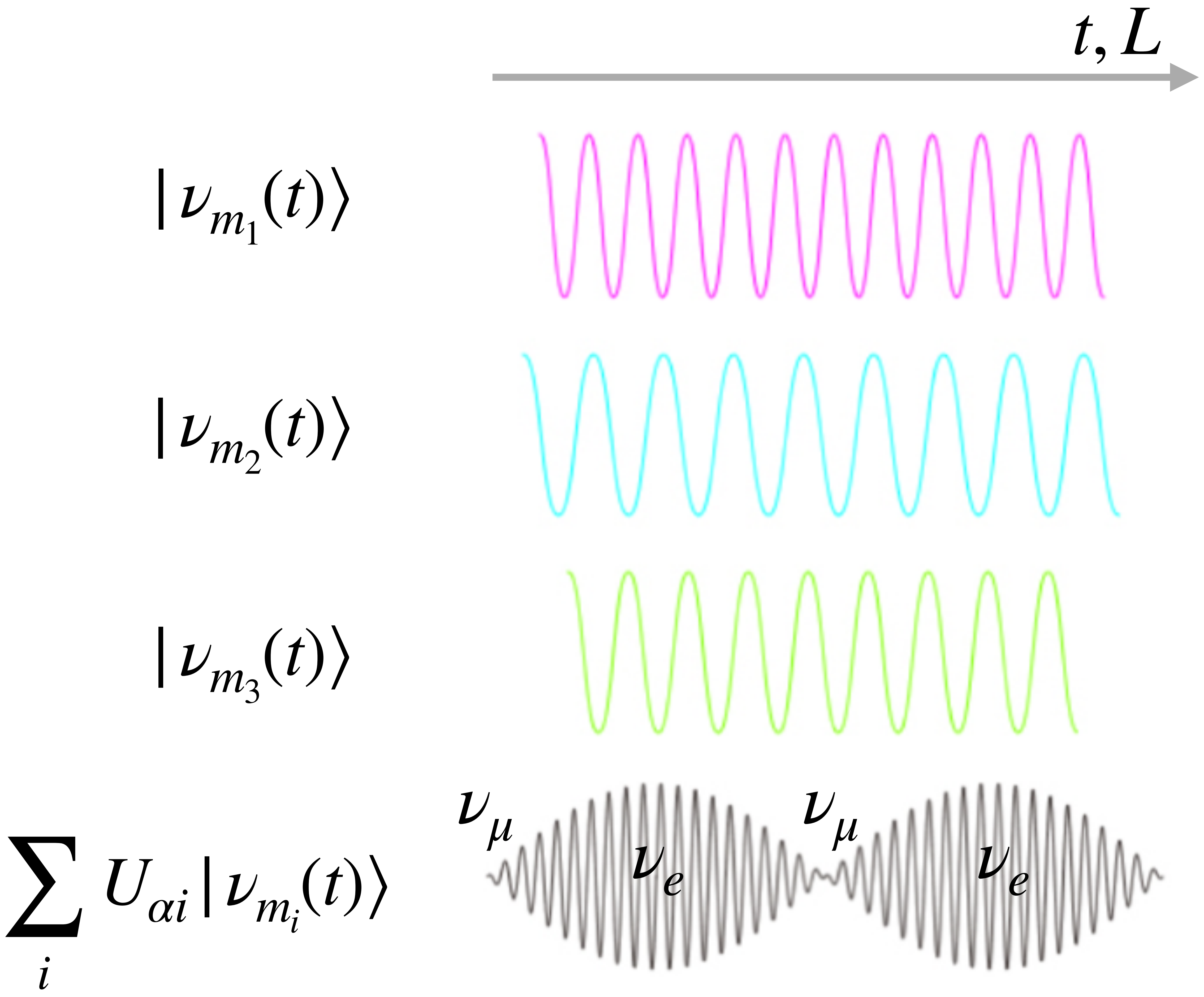






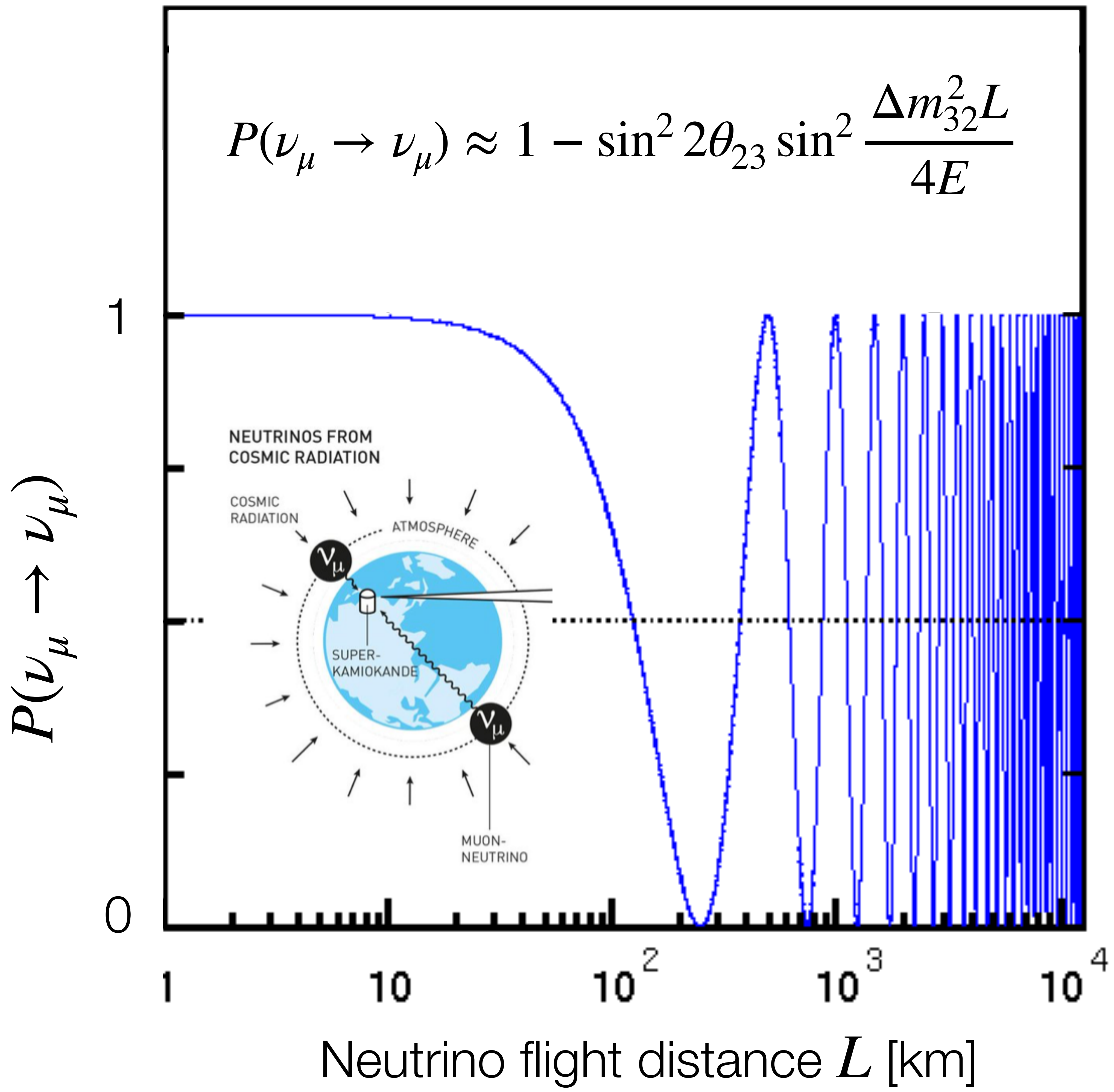
Neutrino sources

- Super-high-E: AGN: astrophysics
- High-E: Atmospheric: osc params, MH, CP
- Mid-E: Artificial beam: osc params, CP, nuN interaction
- Low-E: Solar, reactor, relic: osc params, astrophysics, nucleosynthesis

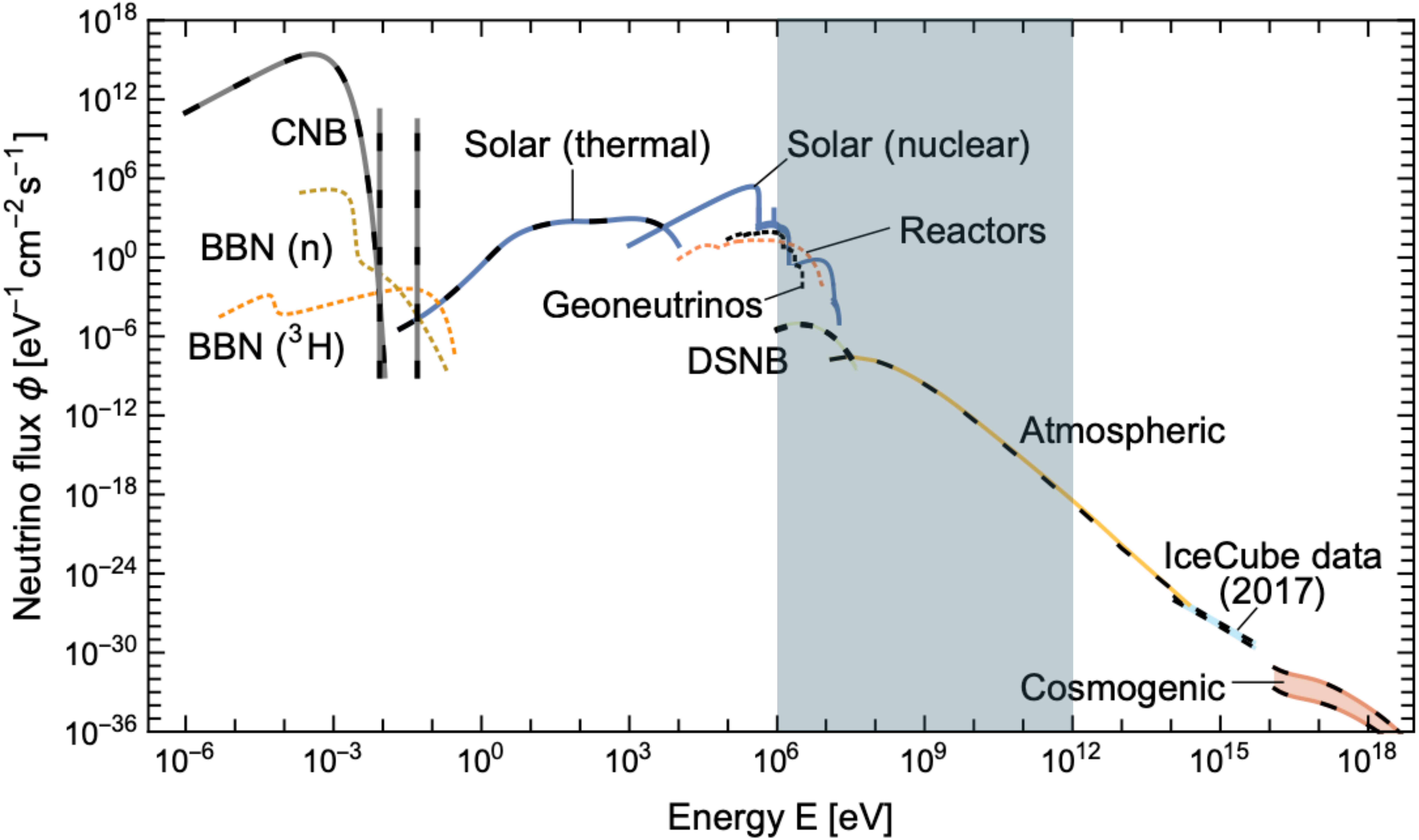


$$P(\nu_\alpha \to \nu_\beta) \propto f(\boxed{\theta, \delta, m}, L, E)$$

1 GeV ν_μ survival probability



$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{32}^2 L}{4E}$$



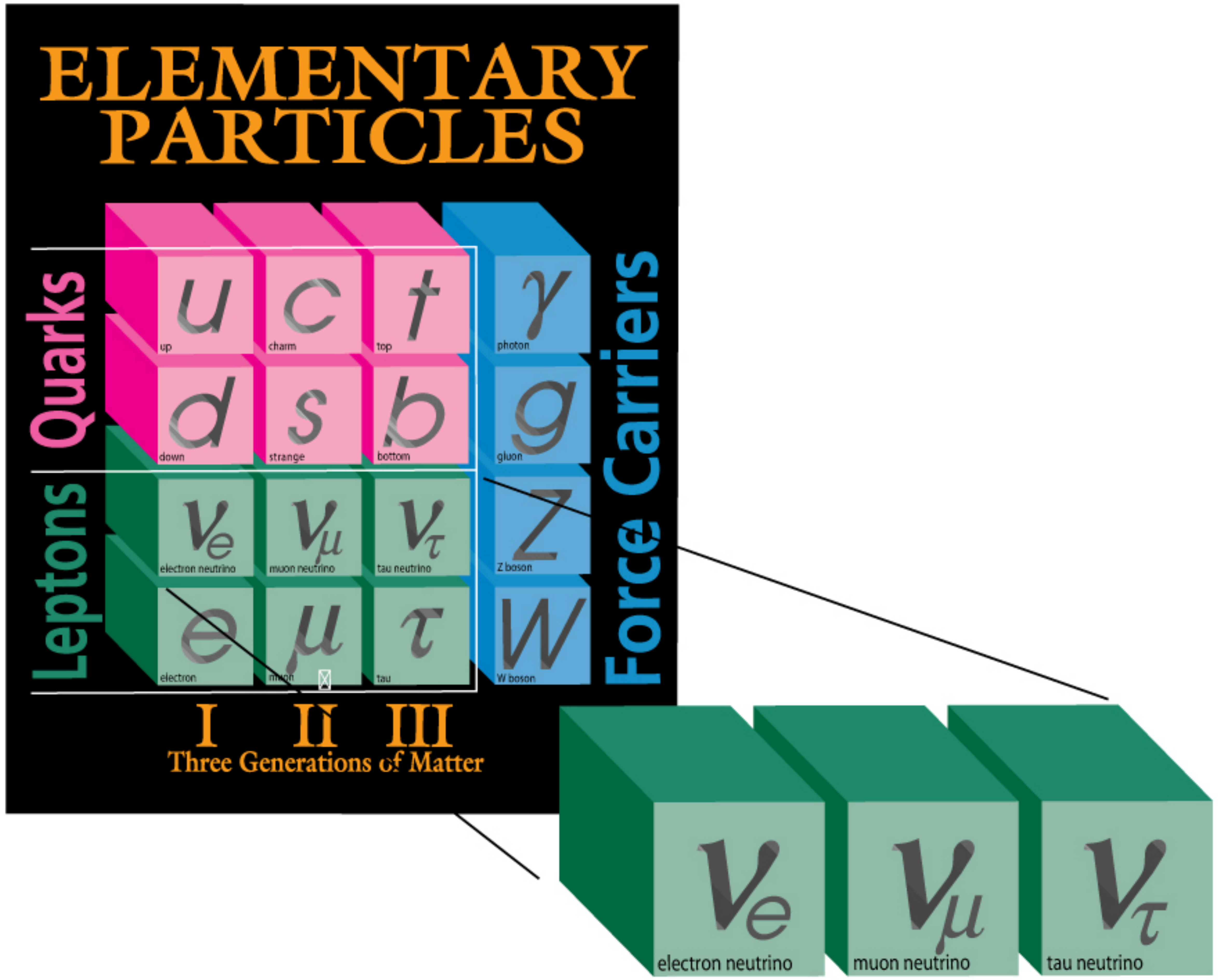
Neutrino flux ϕ [eV^{-1}cm^{-2}s^{-1}]
Energy E [eV]
10^{18}
10^{12}
10^{6}
10^{0}
10^{-6}
10^{-12}
10^{-18}
10^{-24}
10^{-30}
10^{-36}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
CNB
Solar (thermal)
Solar (nuclear)
Reactors
BBN (n)
Geoneutrinos
BBN (^{3}H)
DSNB
Atmospheric
IceCube data (2017)
Cosmogenic

Super-K target physics

Check out the Super-Kamiokande list of publications for more!

Neutrino
- Oscillation
- Astrophysics
- Interaction with nucleus, BSM interactions, etc.

Others   Proton decay, exotic interactions, GUT monopole, DM search, etc.



ν in SM: “massless” neutral leptons

What if ν were massive?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{m_1} \\ \nu_{m_2} \\ \nu_{m_3} \end{pmatrix}$$

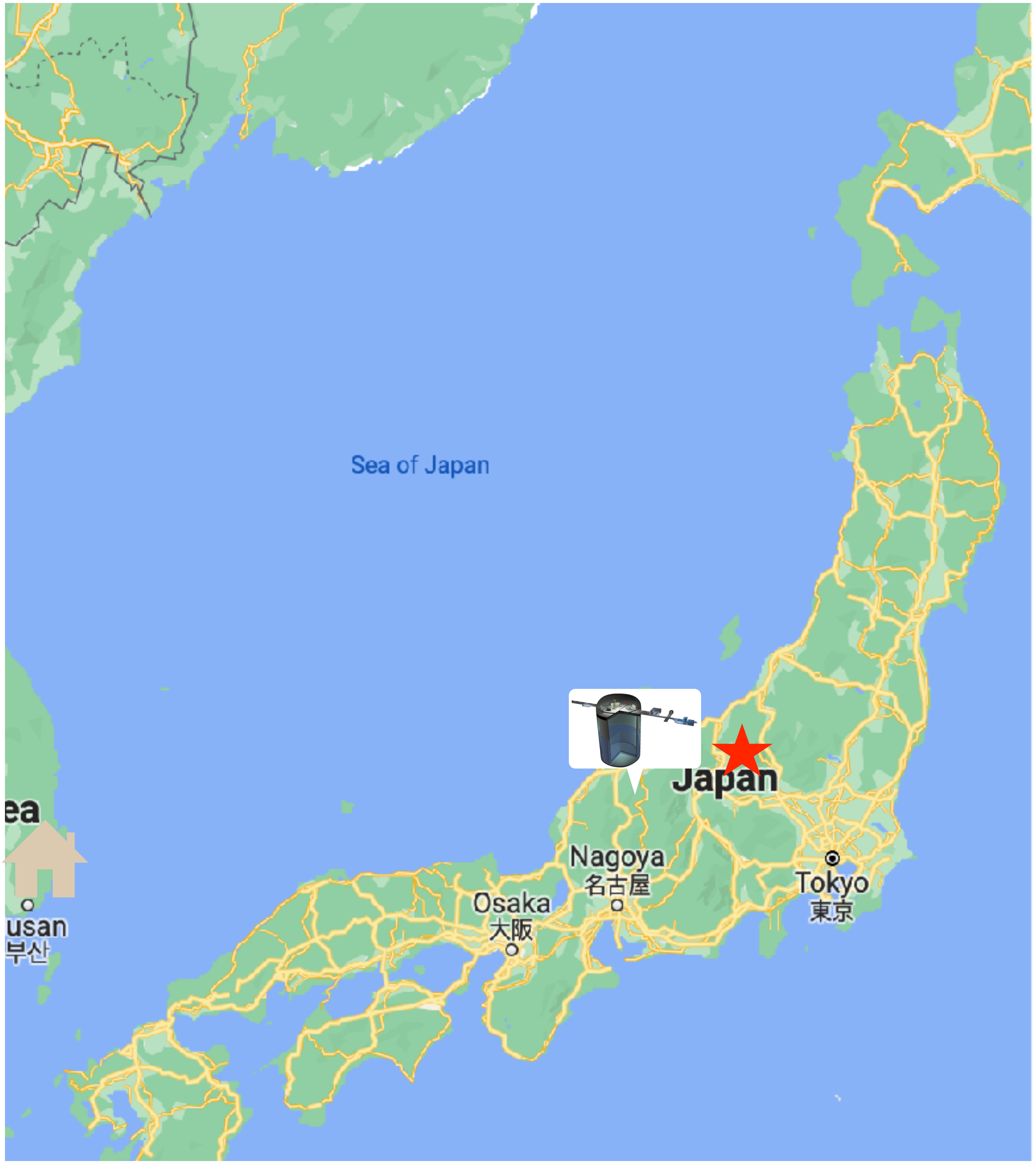
$$\equiv U(\boxed{\theta_{12}, \theta_{13}, \theta_{23}}, \boxed{\delta_{CP}}) \begin{pmatrix} \nu_{m_1} \\ \nu_{m_2} \\ \nu_{m_3} \end{pmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) \propto f(\boxed{\theta, \delta, m,} L, E) > 0$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}) \begin{pmatrix} \nu_{m_1} \\ \nu_{m_2} \\ \nu_{m_3} \end{pmatrix} \qquad U(\theta, \delta) \approx \begin{pmatrix} 0.8 & 0.6 & 0.1 \\ -0.5 & 0.5 & 0.7 \\ 0.3 & -0.7 & 0.6 \end{pmatrix} \quad \text{if } \delta = 0$$

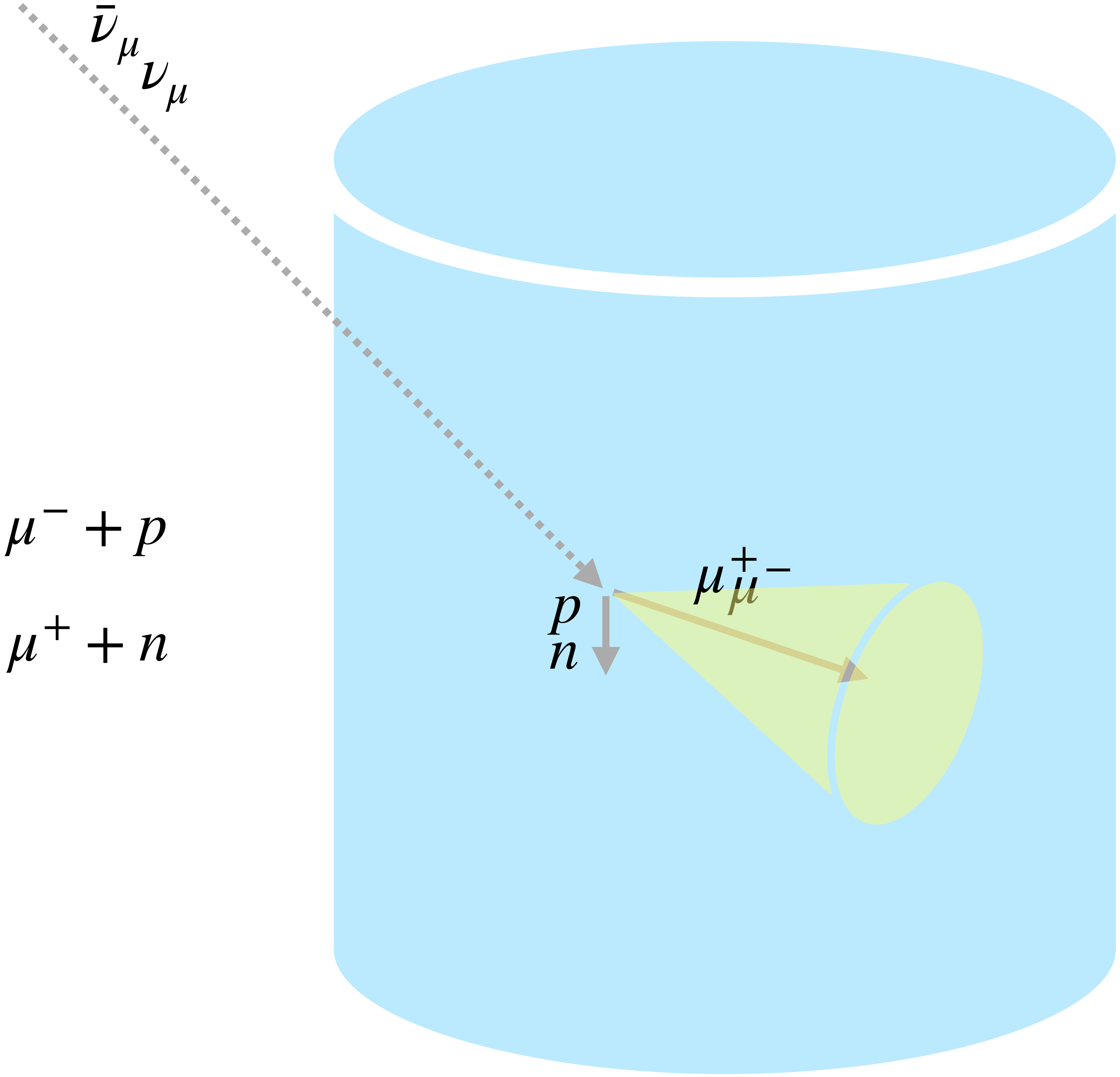
$$P(\nu_\alpha \to \nu_\beta) \propto f(\theta, \boxed{\delta,} m, L, E)$$

$$\boxed{P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \text{ iff } \delta \neq 0}$$



★ We are here

Water Cherenkov detector



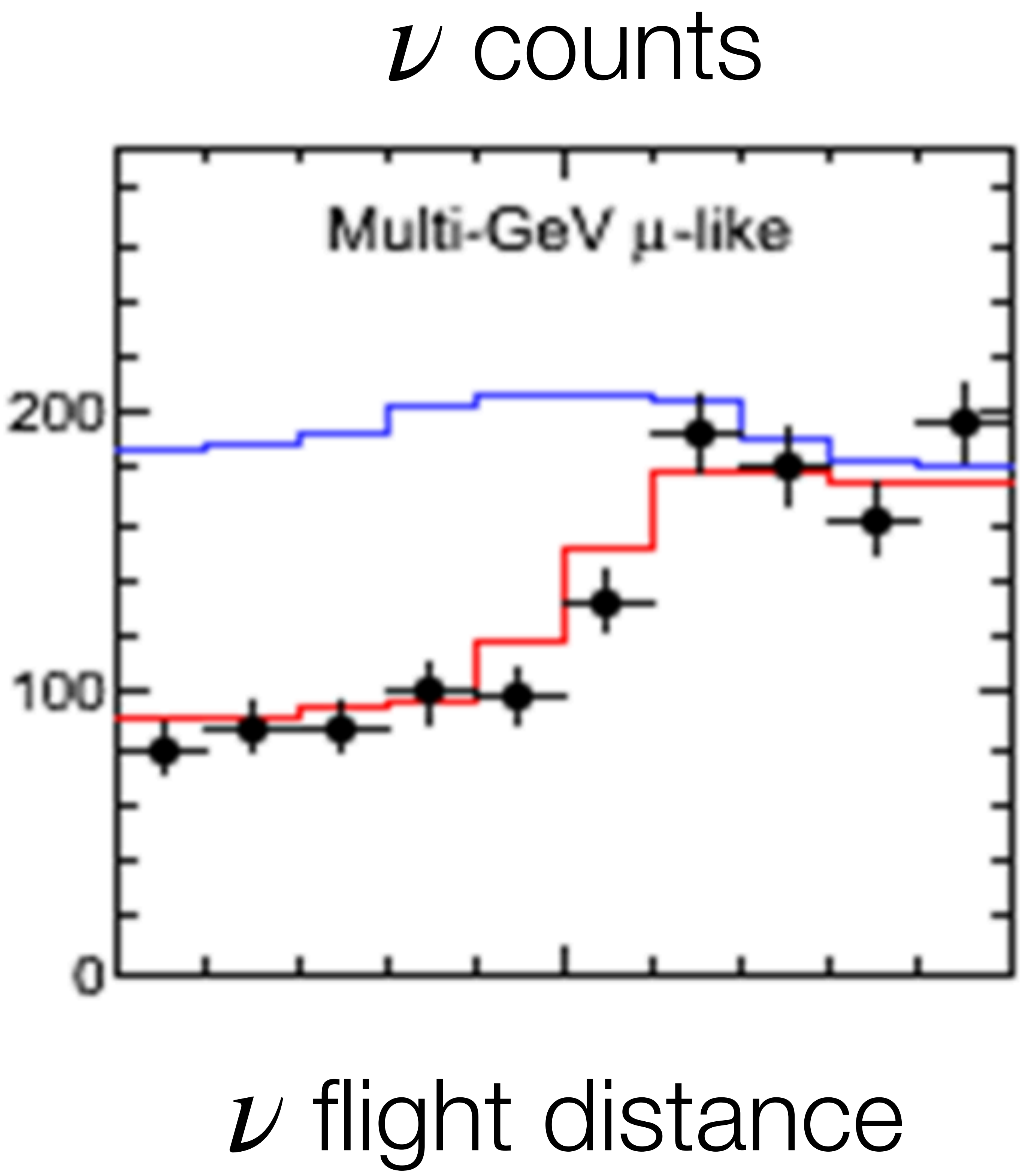
$$\nu_\mu + n \rightarrow \mu^- + p$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

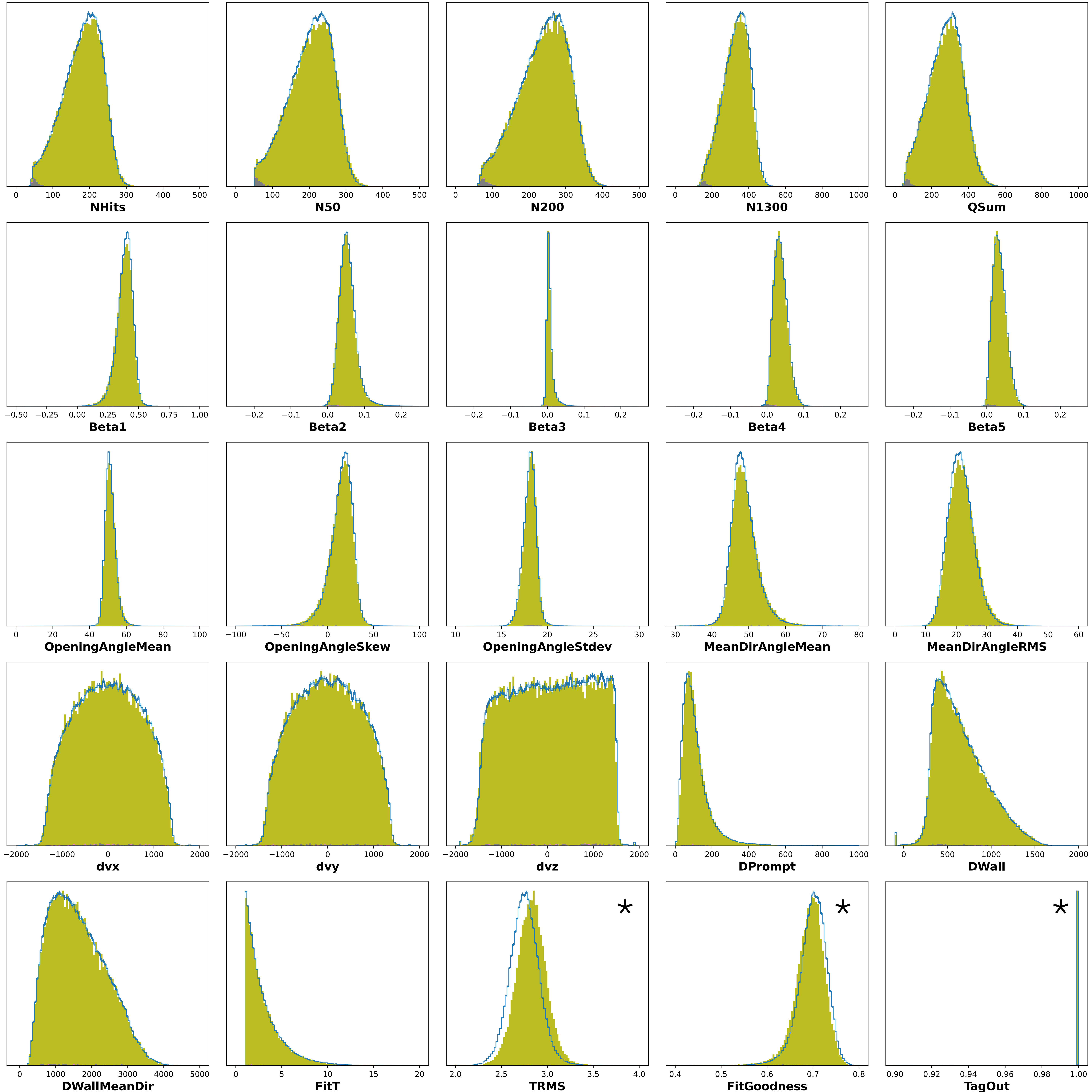
SK mostly sees:
e, μ, γ, π

Why detect e, n from ν events?

Muon decay 2 μs, E~10~50 MeV



- Expected (osc. params) vs.
  = Flux × Oscillation (osc. Params) × XSec (ν int. mode)
- Disentangle ν int modes
  by classifying ν events with detected particles
  - "Trigger" signals:
    - e, μ — flavor
    - 2γ — π^0
  - "Delayed" signals:
    - e — $\pi^{\pm}$, μ
    - n — $\bar{\nu}$



MC: noise

MC: true e

Data

* Not used in fit

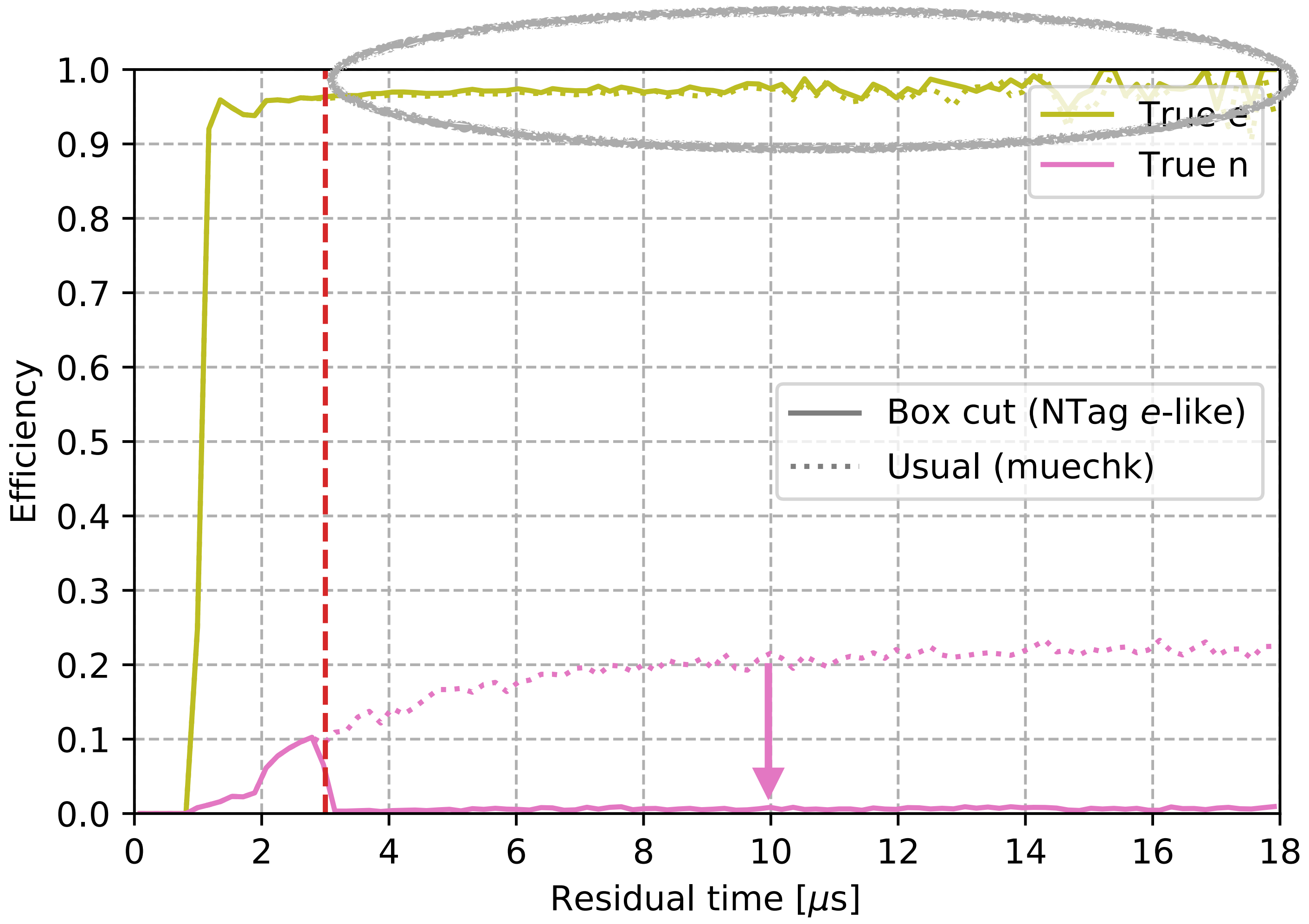
SK6 e-tagging performance by event time

Sub-GeV

Multi-GeV

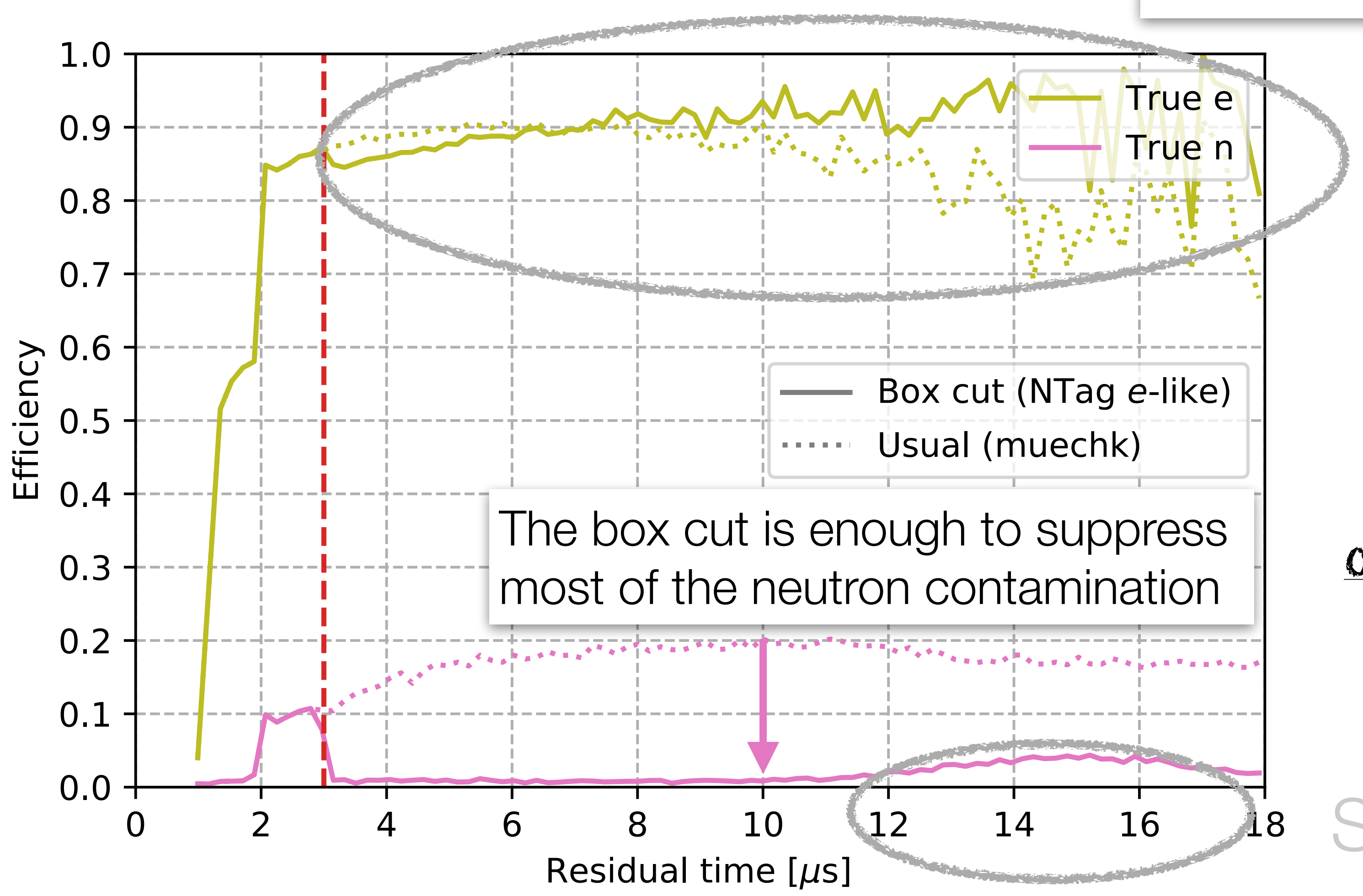
e-tag efficiency is similar
between muechk and NTag e-like box cut

Efficiency



Overall signal (e) efficiency

Box cut: 87.69%
Usual: 87.55%
SK4 Usual: 89.05%

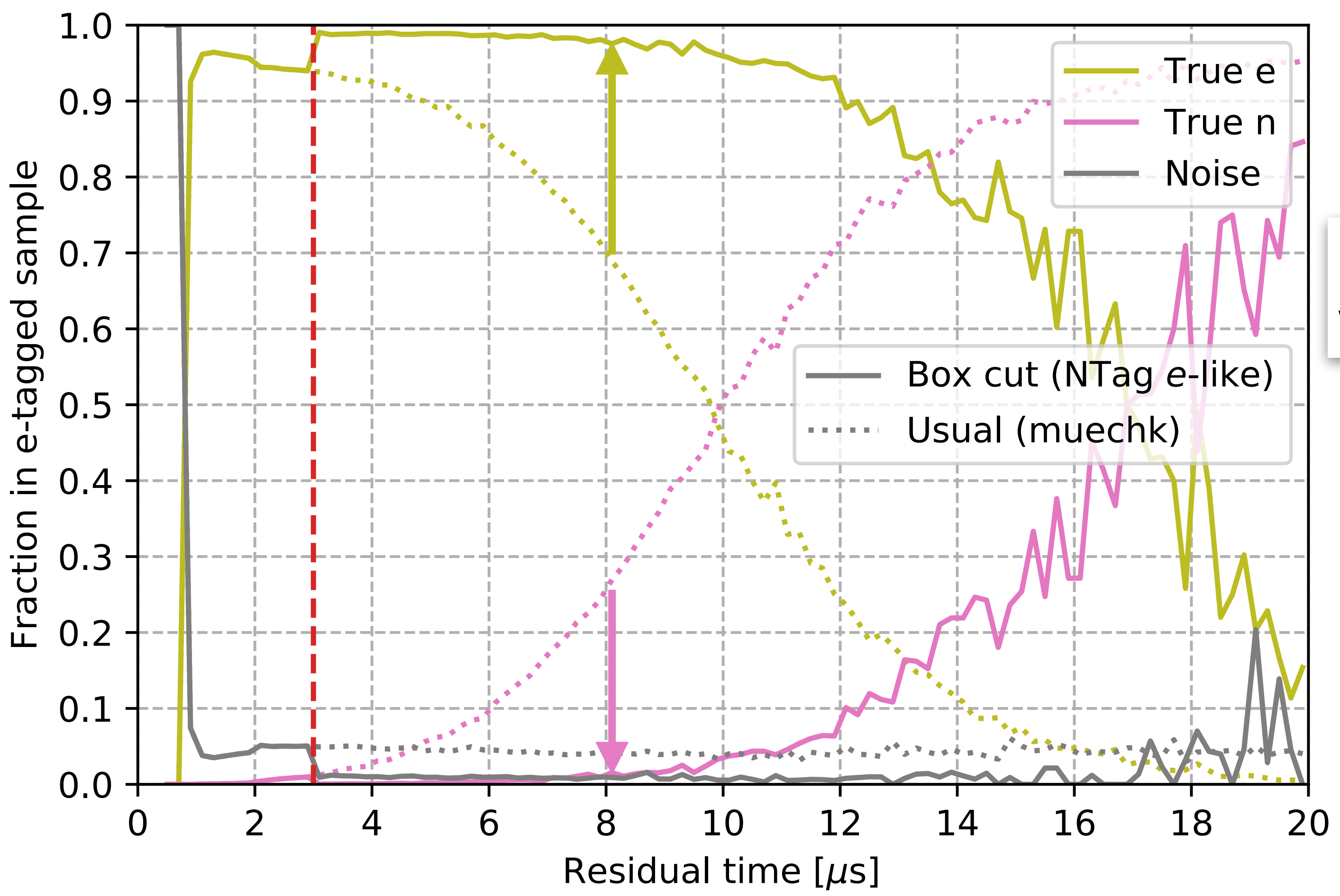


The box cut is enough to suppress
most of the neutron contamination

Overall signal (e) efficiency

Box cut: 68.66%
Usual: 69.13%
SK4 Usual: 72.67%

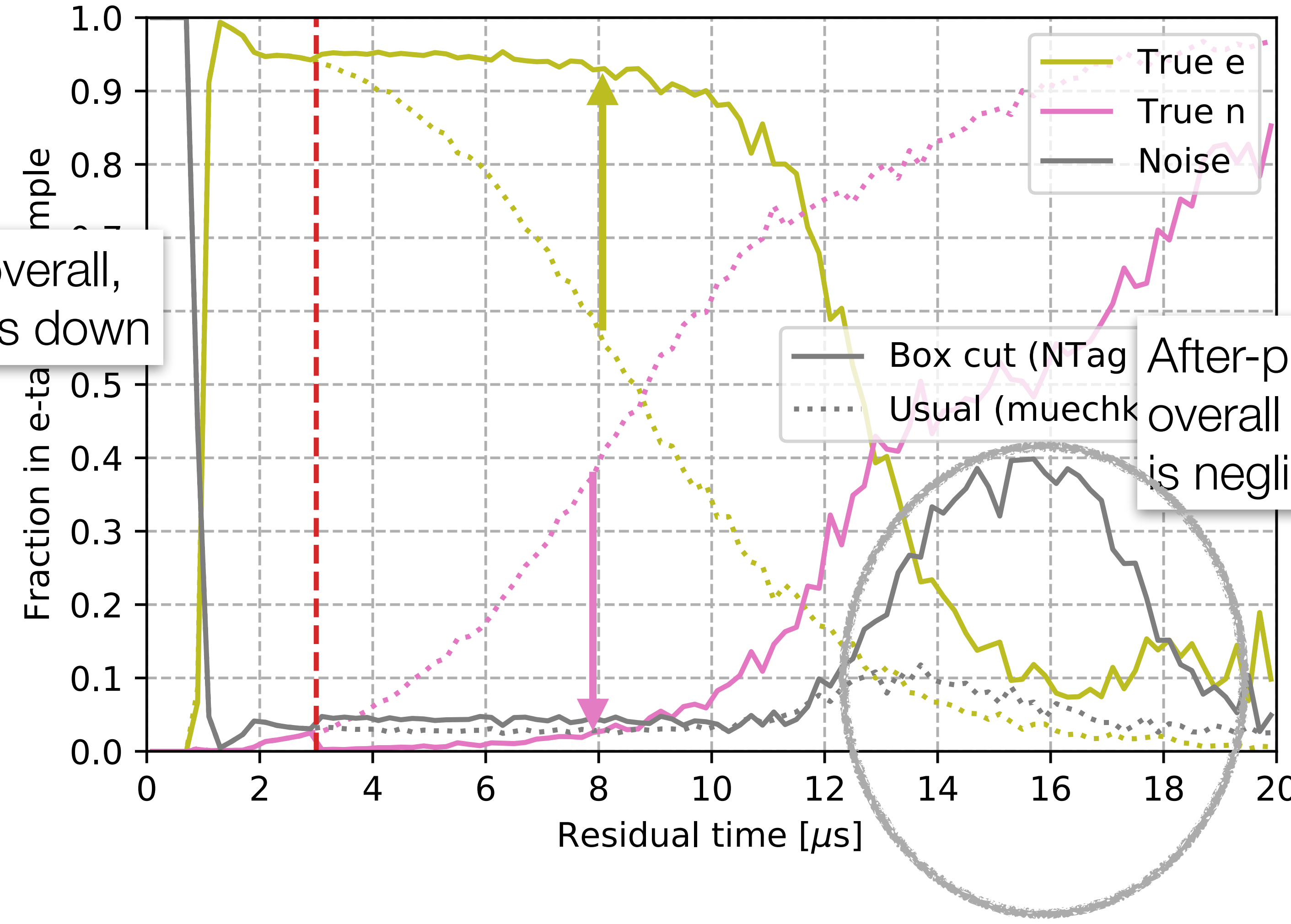
Purity



Decay-e purity goes up by 15-30% overall,
while fraction of n contamination goes down

Overall signal (e) purity

Box cut: 96.39%
Usual: 82.57%
SK4 Usual: 96.42%



After-pulse effect:
overall contribution
is negligible (<1%)

Overall signal (e) purity

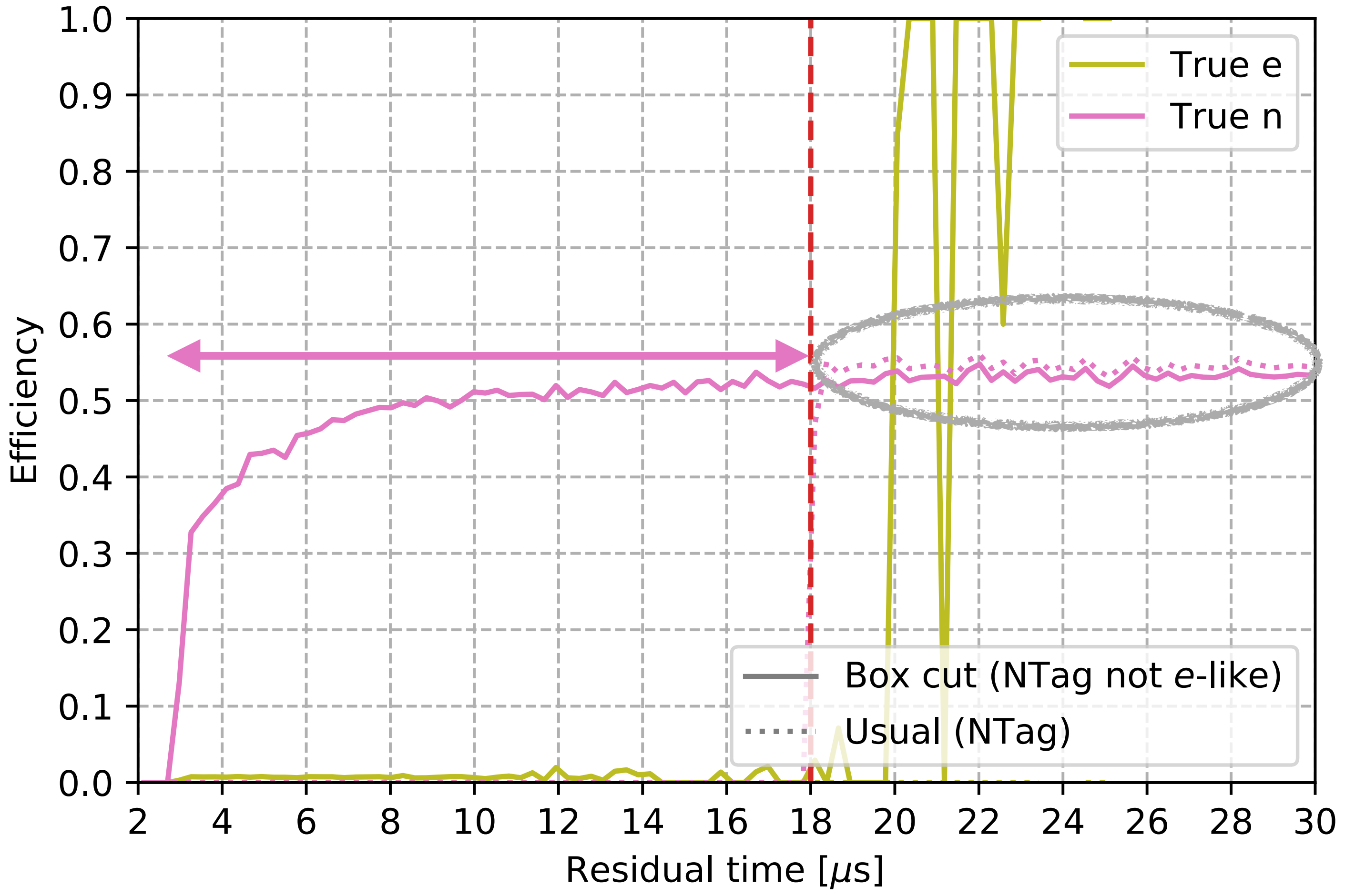
Box cut: 91.10%
Usual: 70.90%
SK4 Usual: 97.05%

SK6 n-tagging performance by event time

Sub-GeV

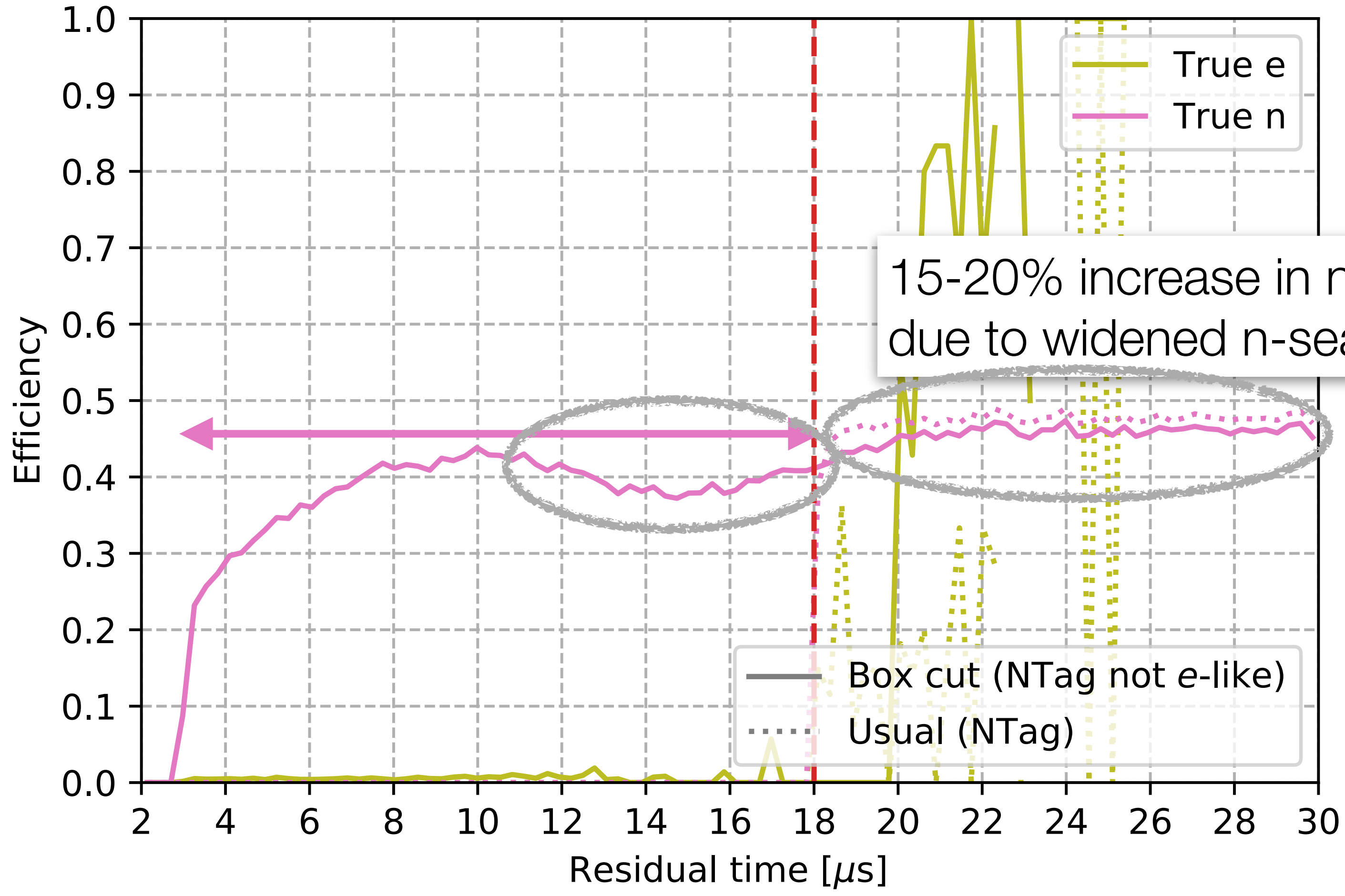
Multi-GeV

Efficiency



Overall signal (n) efficiency

Box cut: 51.39%
Usual: 43.90%
SK4 Usual: 28.80%

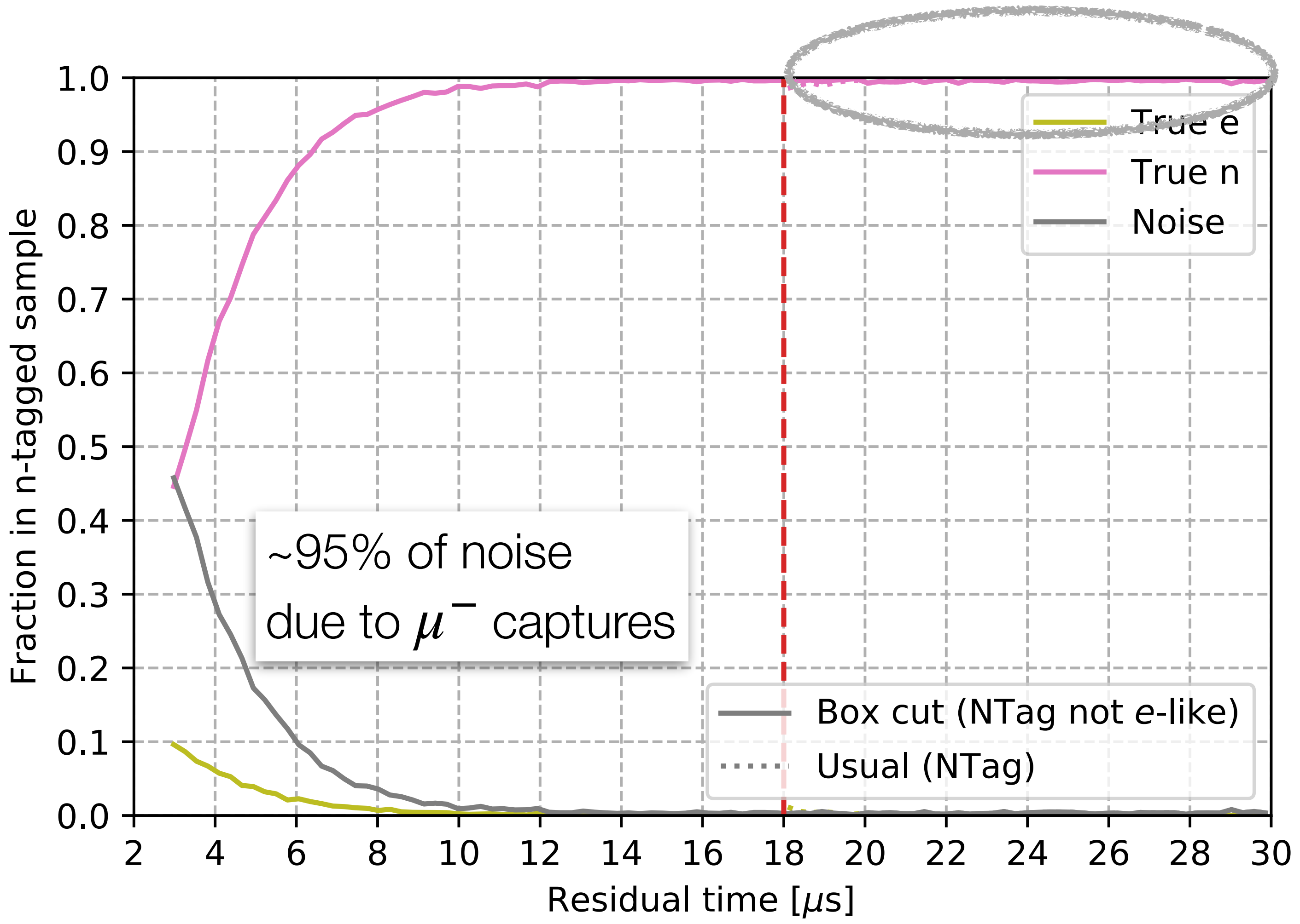


15-20% increase in n-tag efficiency with the box cut, due to widened n-search time range

Overall signal (n) efficiency

Box cut: 44.65%
Usual: 38.90%
SK4 Usual: 26.08%

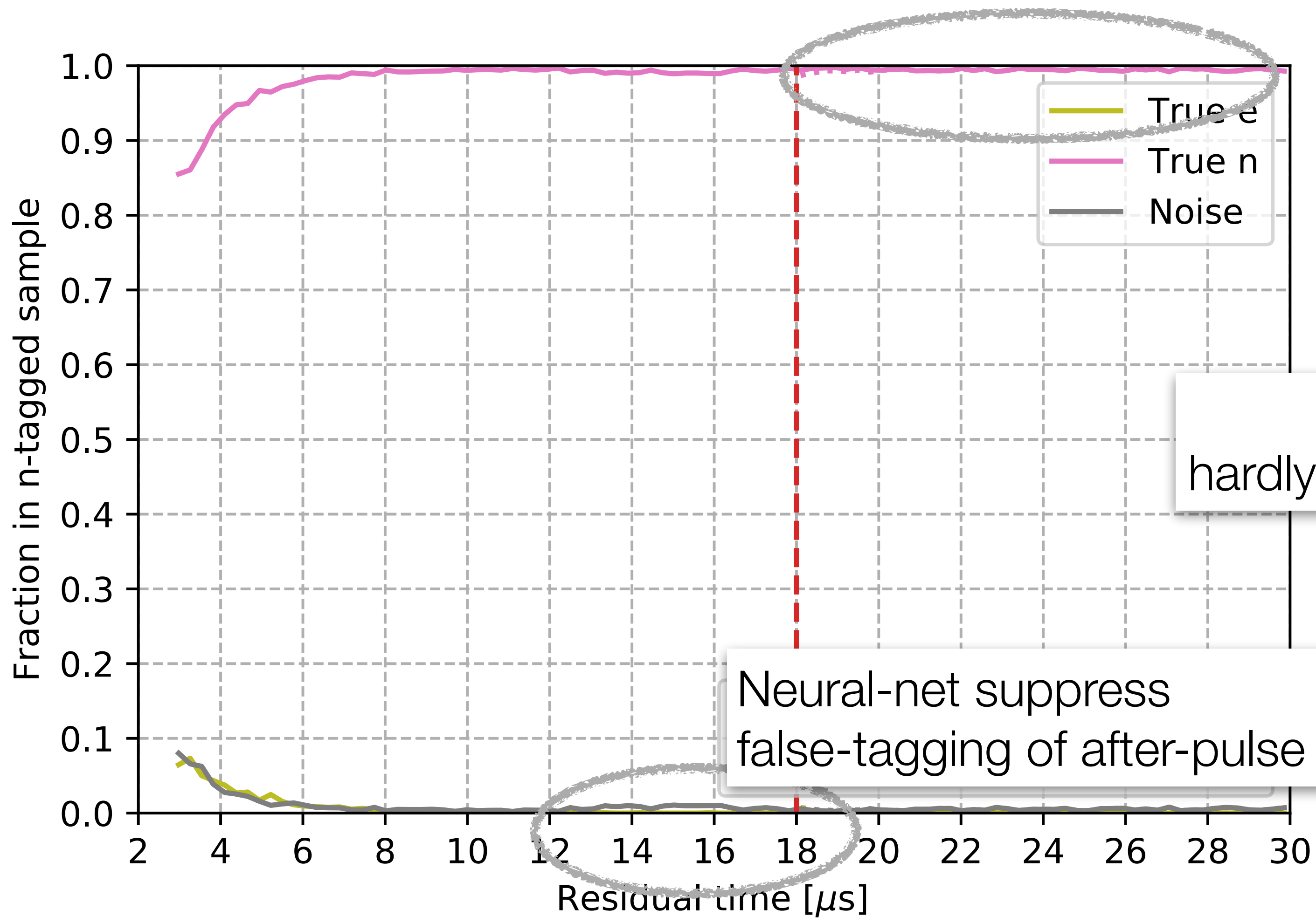
Purity



~95% of noise due to μ^- captures

Overall signal (n) purity

Box cut: 97.83%
Usual: 98.52%
SK4 Usual: 96.78%



n-tag efficiency and purity hardly affected by the e-like removal

Neural-net suppress false-tagging of after-pulse

Overall signal (n) purity

Box cut: 98.88%
Usual: 98.92%
SK4 Usual: 96.03%

How do the new e/n-tag effs. affect ν event classification?

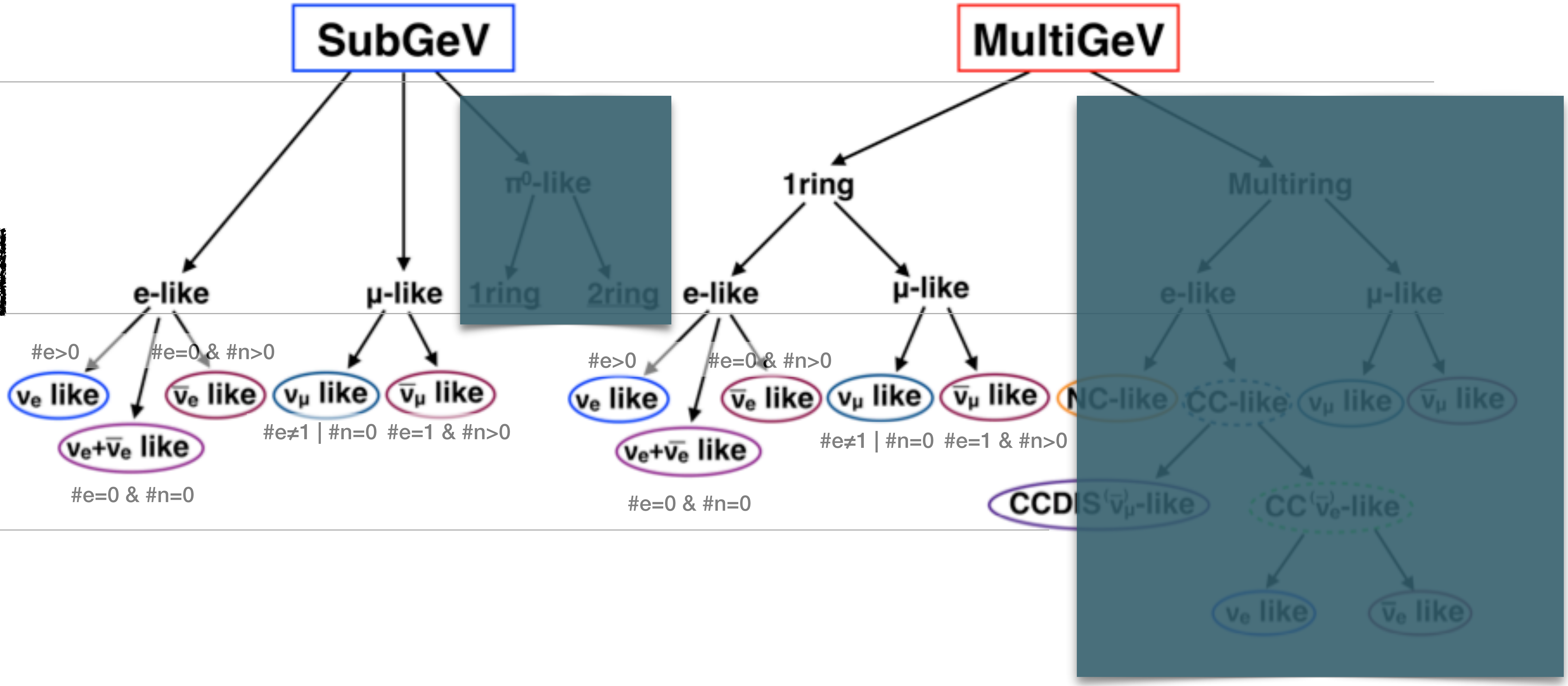
* Pablo’s PhD thesis (2017)

- SK4 neutron-inclusive analysis*:

E_{vis}

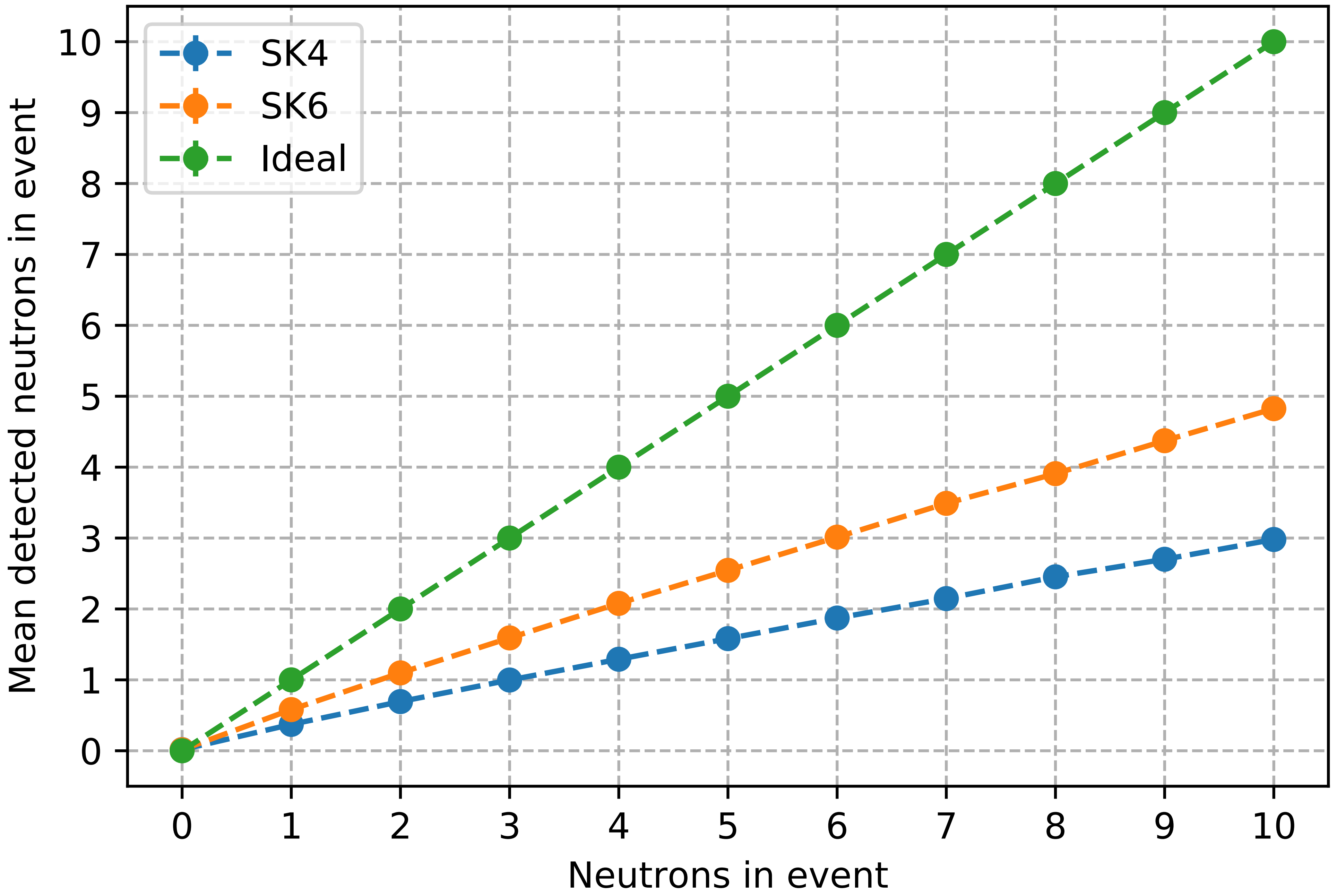
#ring, PID

#e, #n



Three MCs with different n-tag effs. for comparison

- SK4 as usual
- SK6 with the box cut appplied
- SK6 with ideal e/n-tag efficiencies (i.e., # tagged = # true)

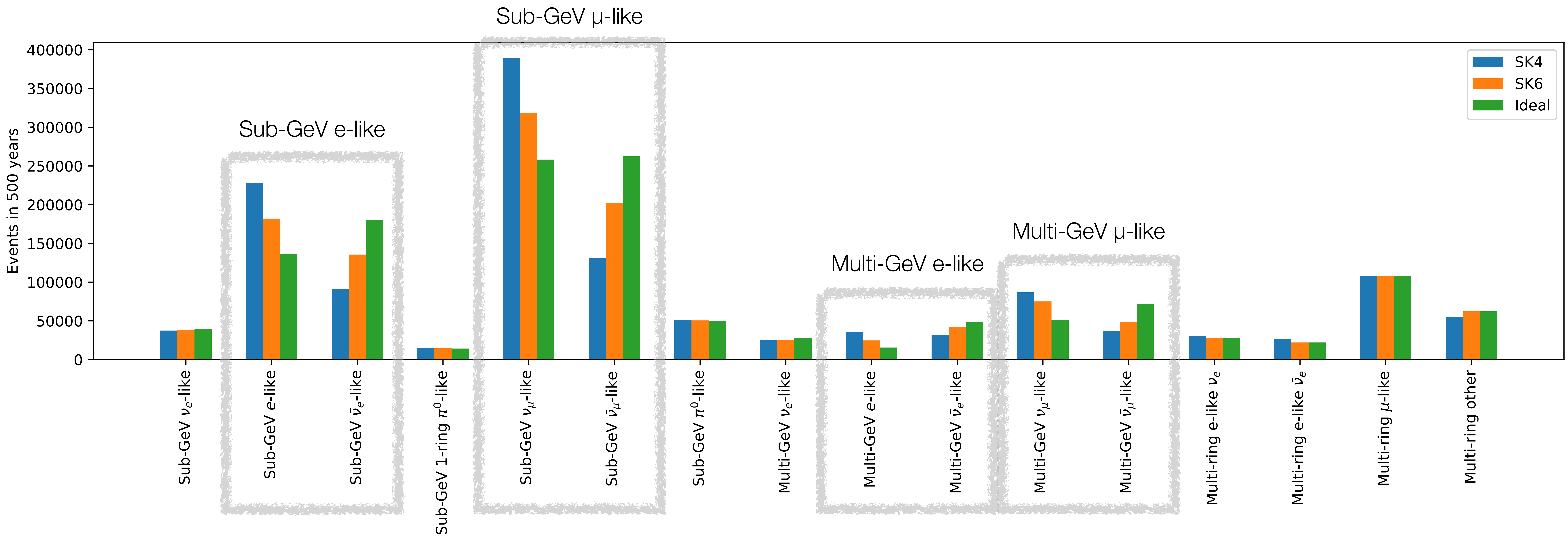


Ideal: 100%

SK6: ~50% (Gd-eff: 79%, H-eff: 16%)

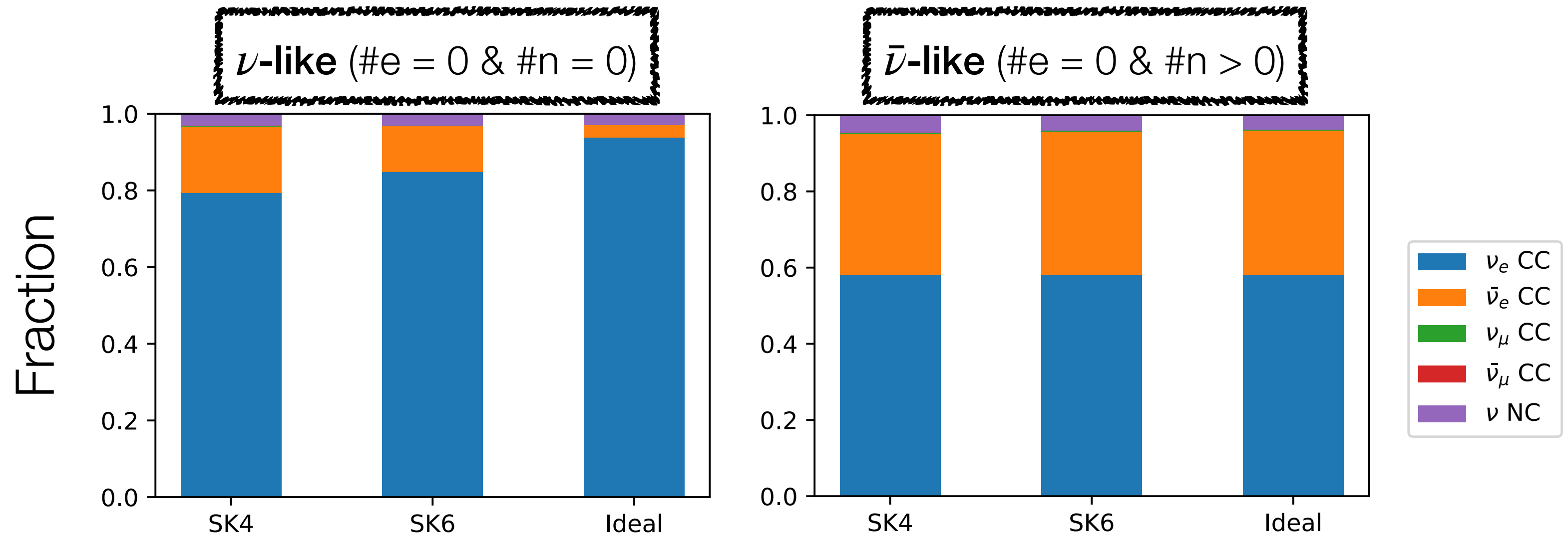
SK4: ~30%

Number of events in each subclass



Improved n-tag efficiency takes away $\bar{\nu}$-like events from ν-like events, as expected.

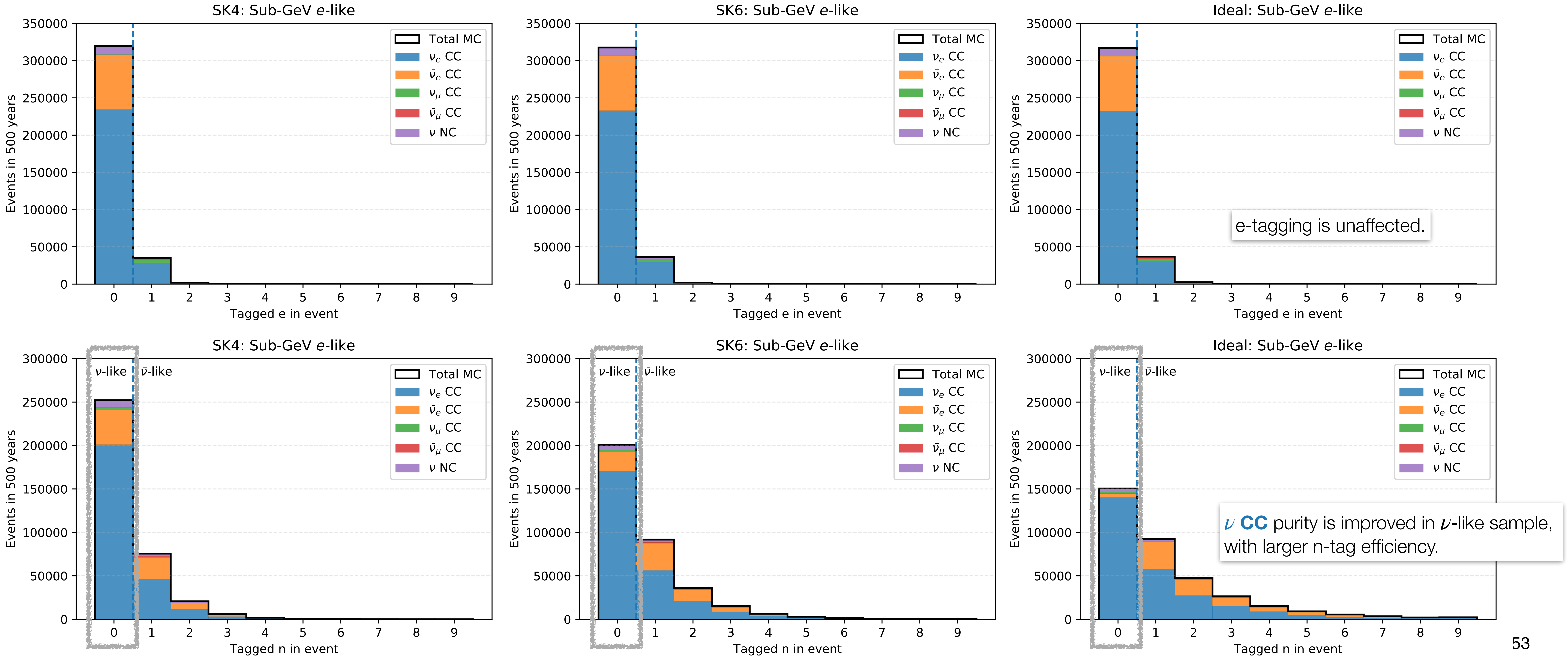
Sub-GeV e-like: tagged multiplicities



SK4 **SK6** **Ideal**

#e

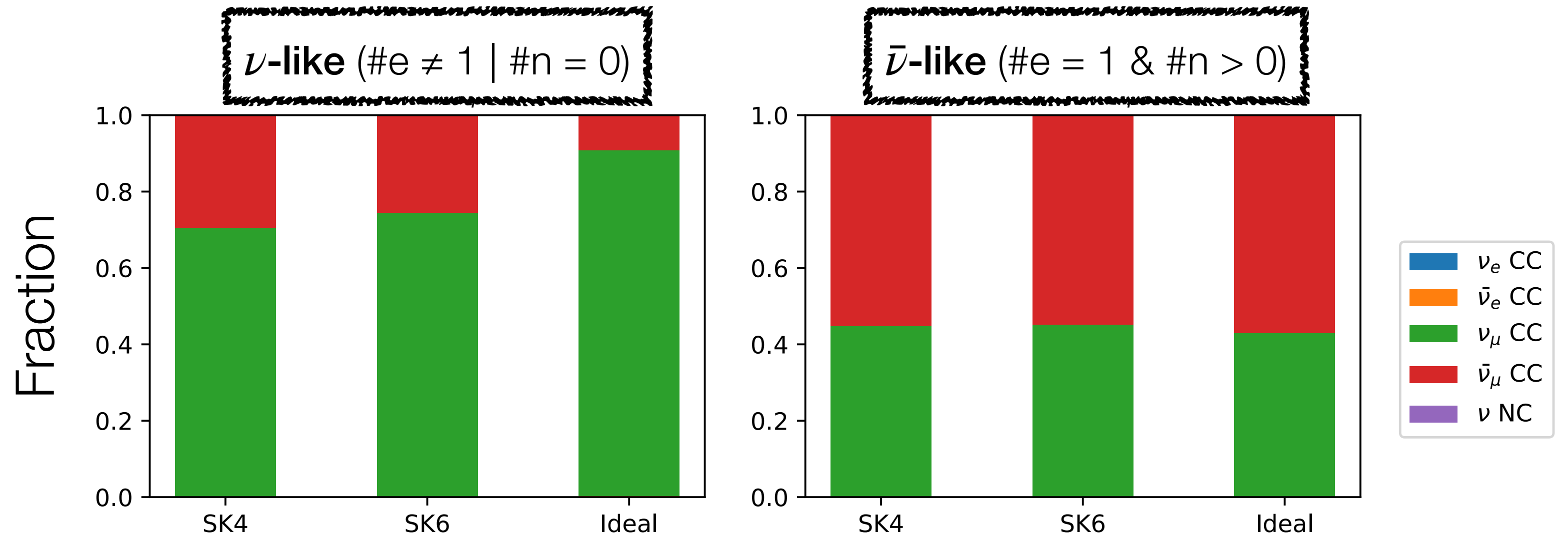
#n



e-tagging is unaffected.

ν **CC** purity is improved in ν-like sample, with larger n-tag efficiency.

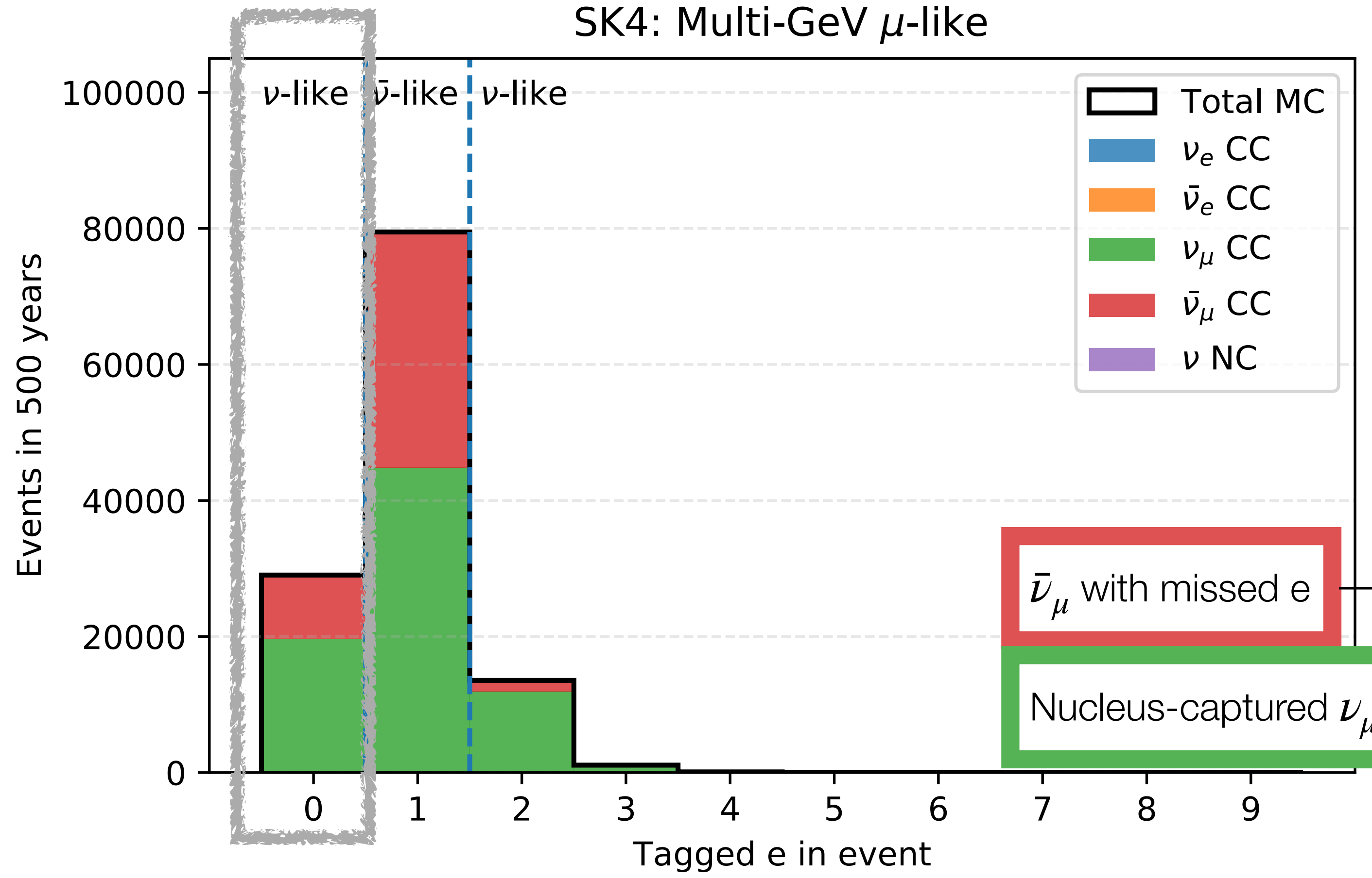
Multi-GeV μ-like: tagged multiplicities



SK4 **SK6** **Ideal**

#e

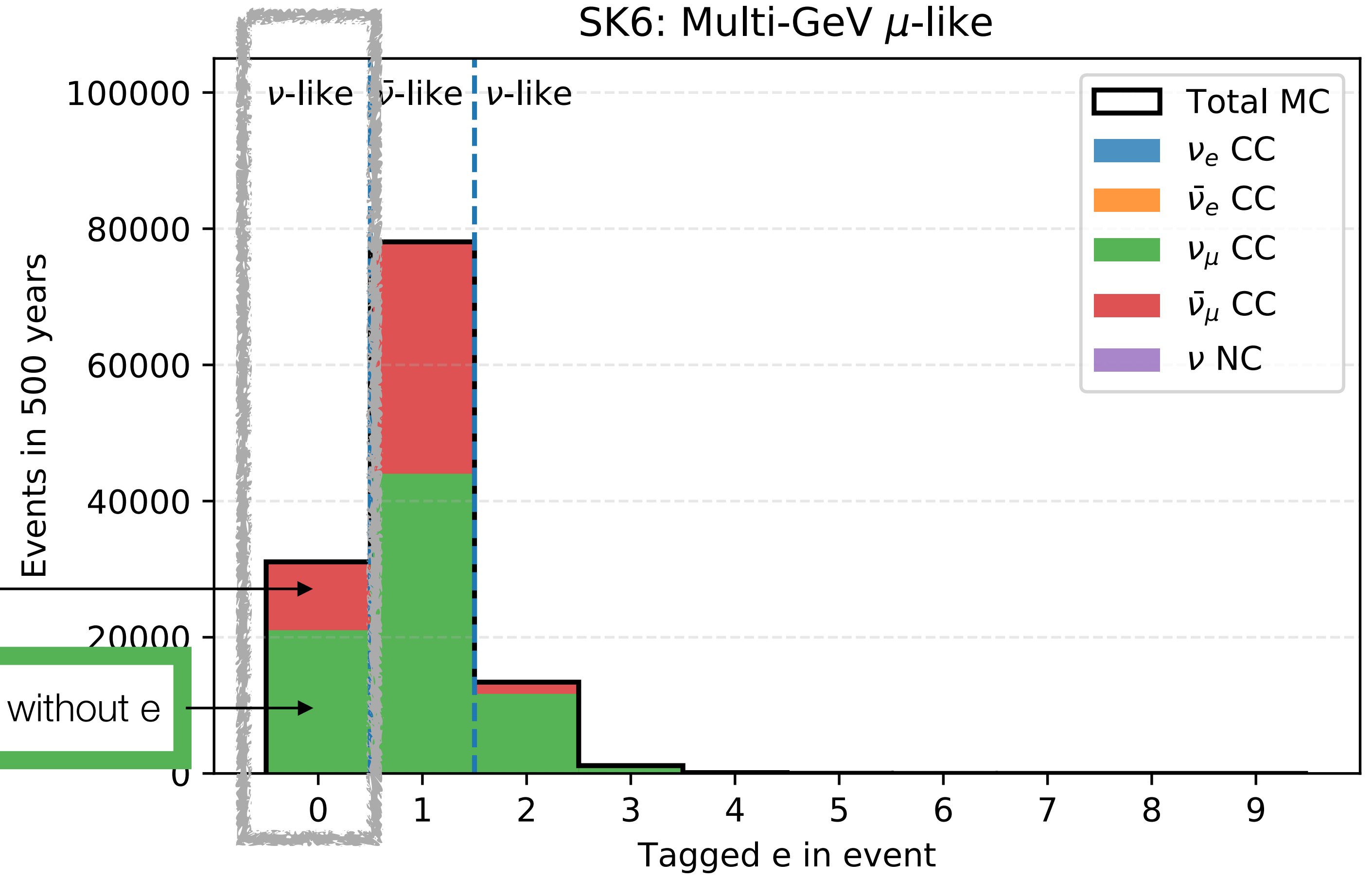
SK4: Multi-GeV μ-like



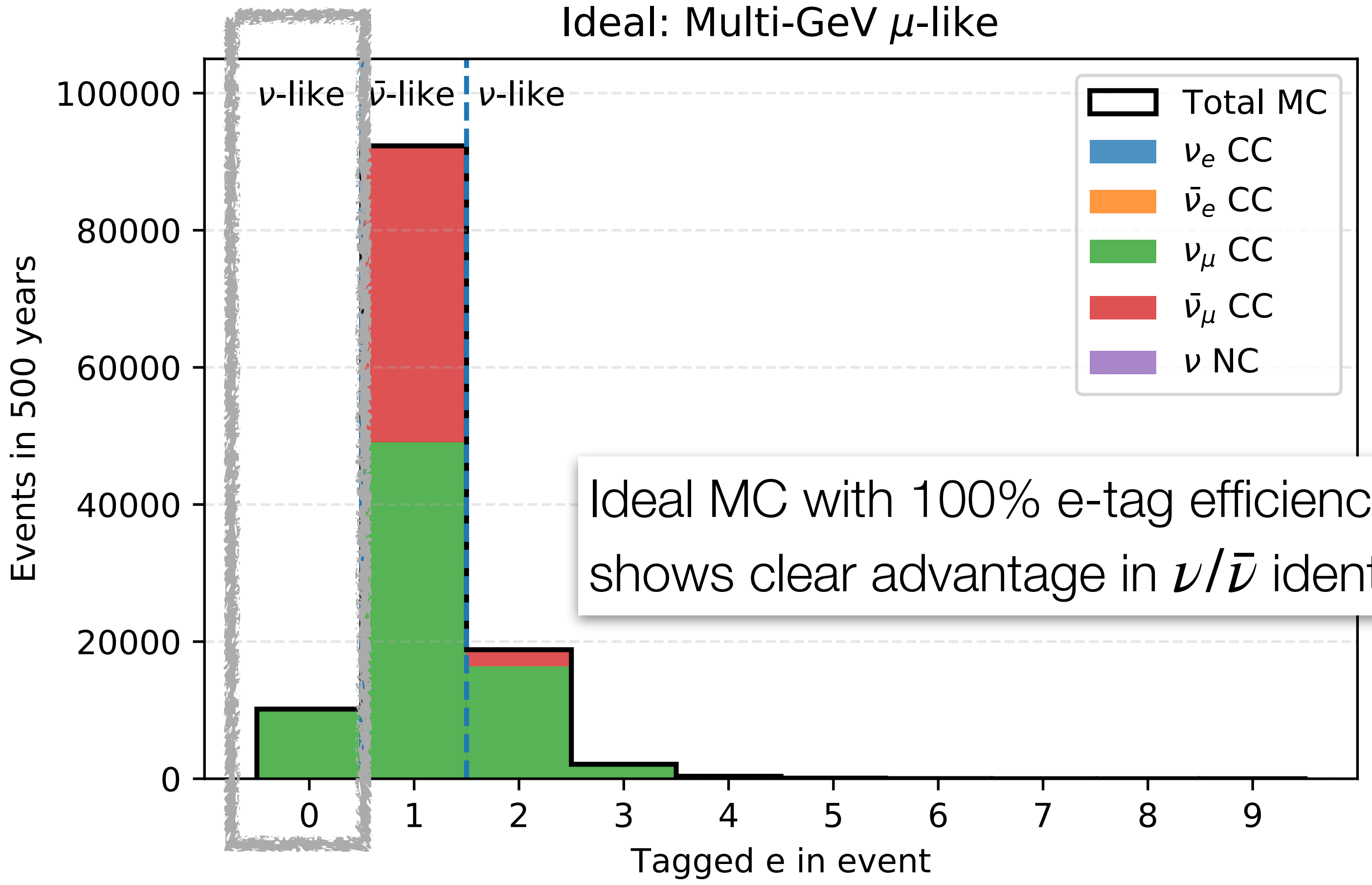
$\bar{\nu}_\mu$ with missed e

Nucleus-captured ν_μ without e

SK6: Multi-GeV μ-like



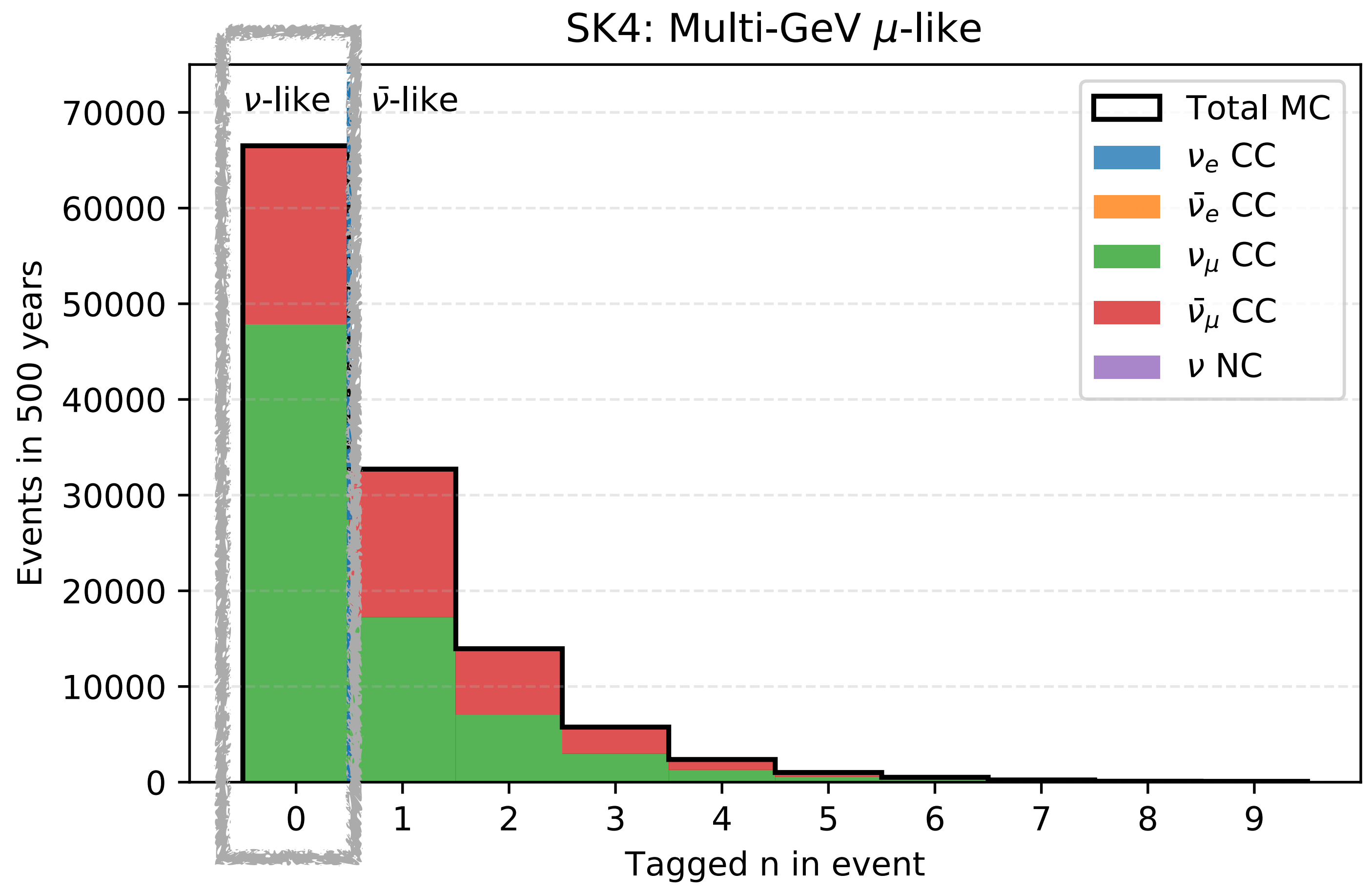
Ideal: Multi-GeV μ-like



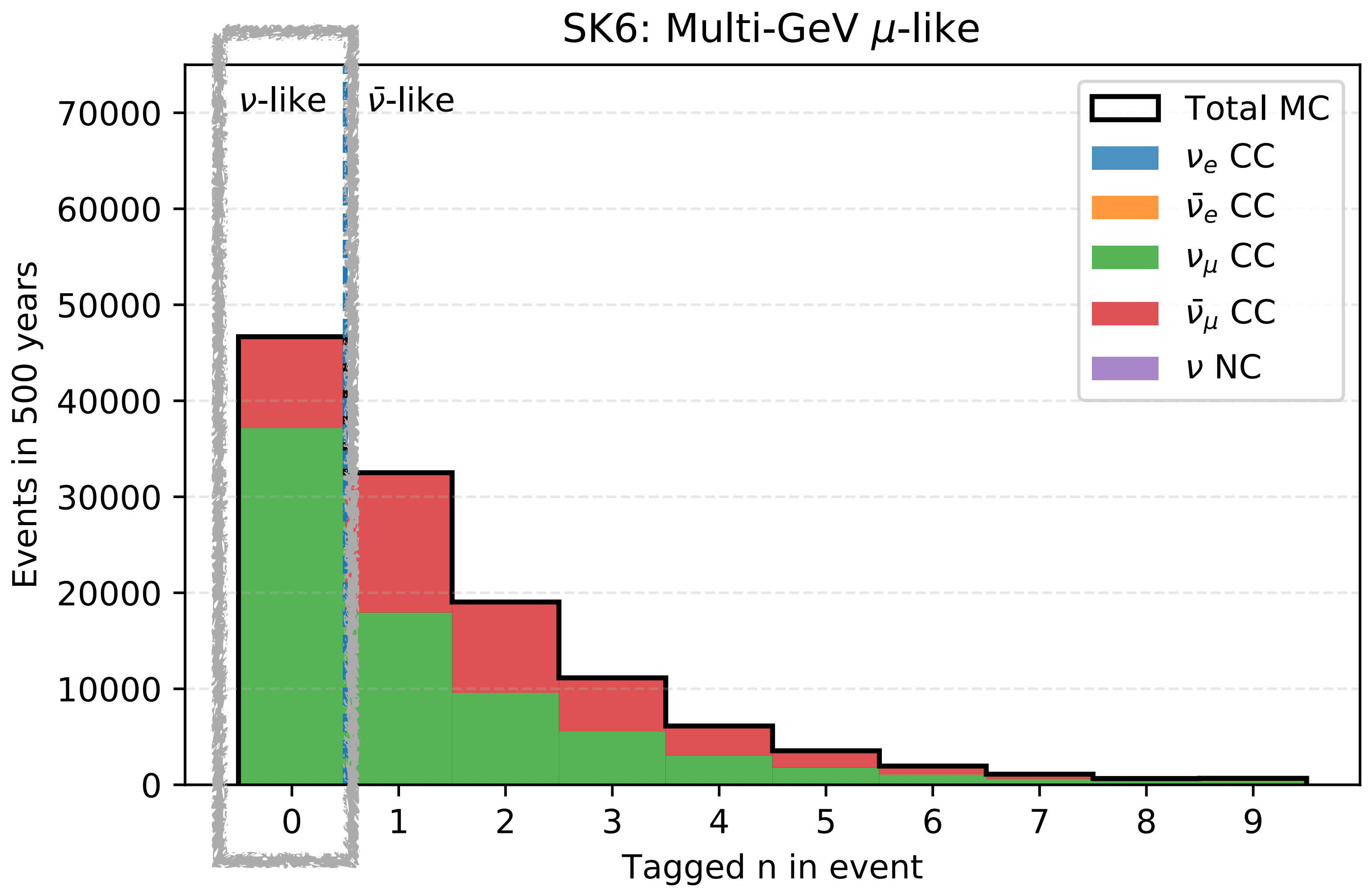
Ideal MC with 100% e-tag efficiency shows clear advantage in $\nu/\bar{\nu}$ identification.

#n

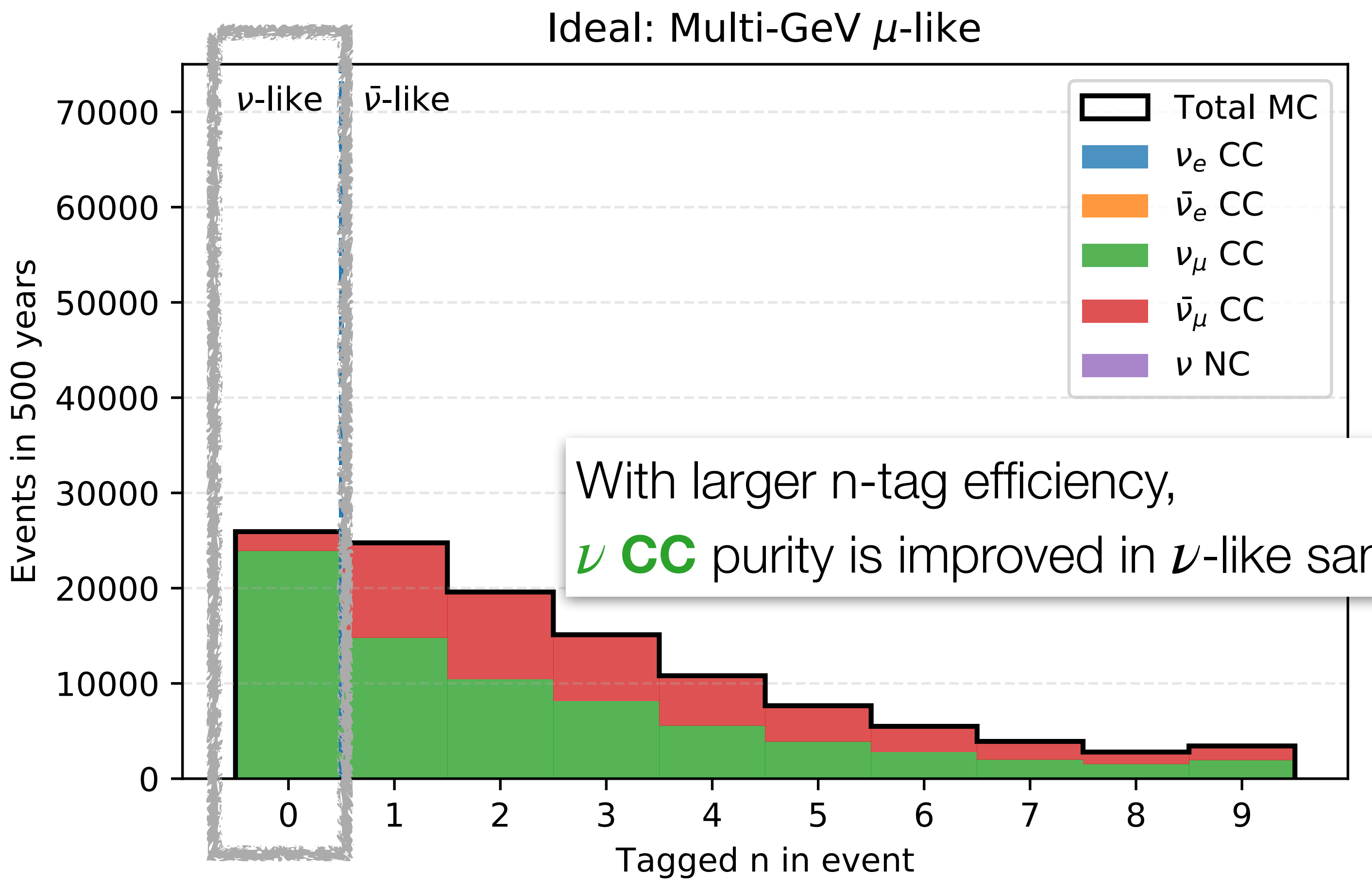
SK4: Multi-GeV μ-like



SK6: Multi-GeV μ-like



Ideal: Multi-GeV μ-like



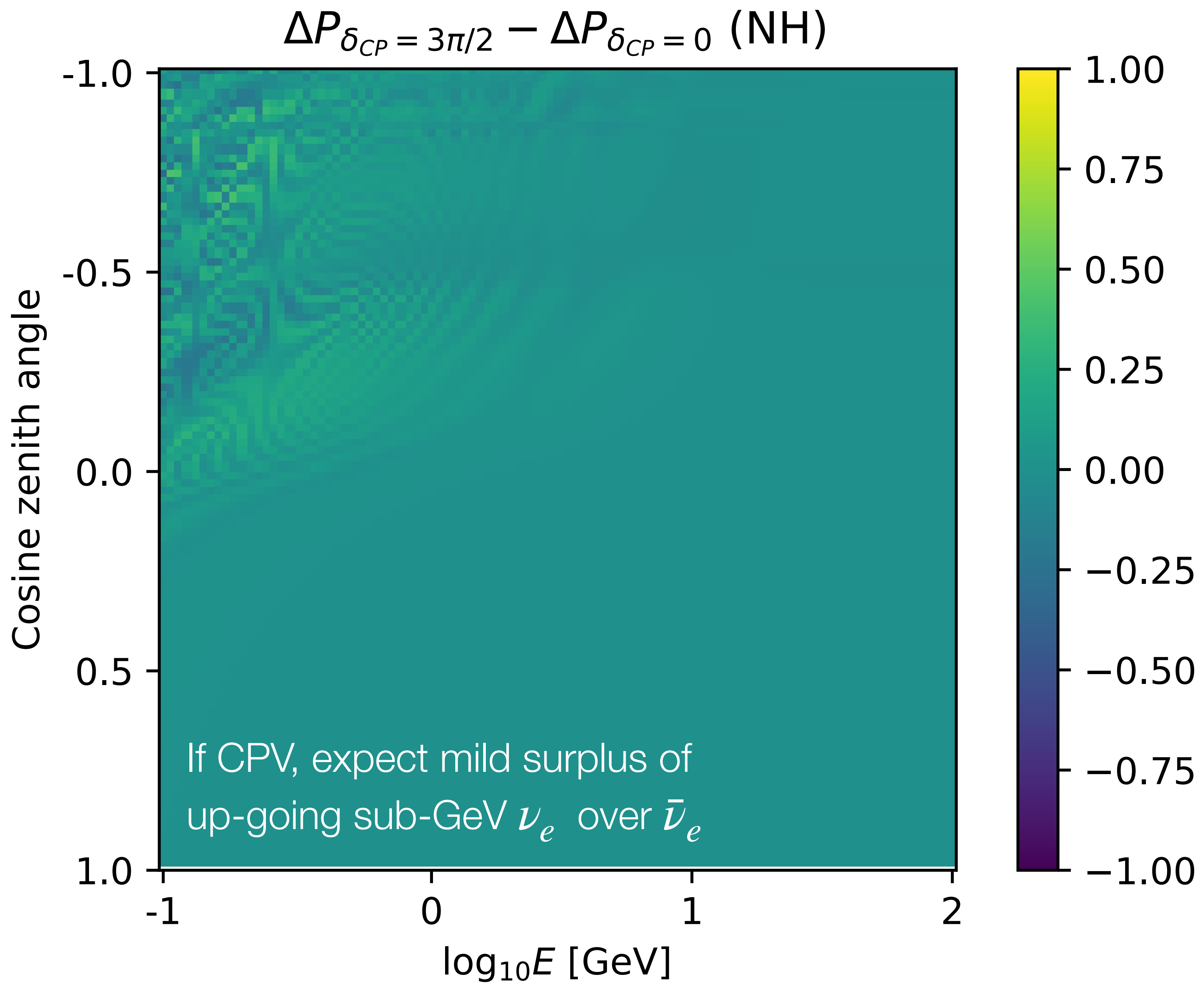
With larger n-tag efficiency, ν **CC** purity is improved in ν-like sample.

Benefits of $\nu/\bar{\nu}$ separation to CP and MH sensitivities

*Prob3++

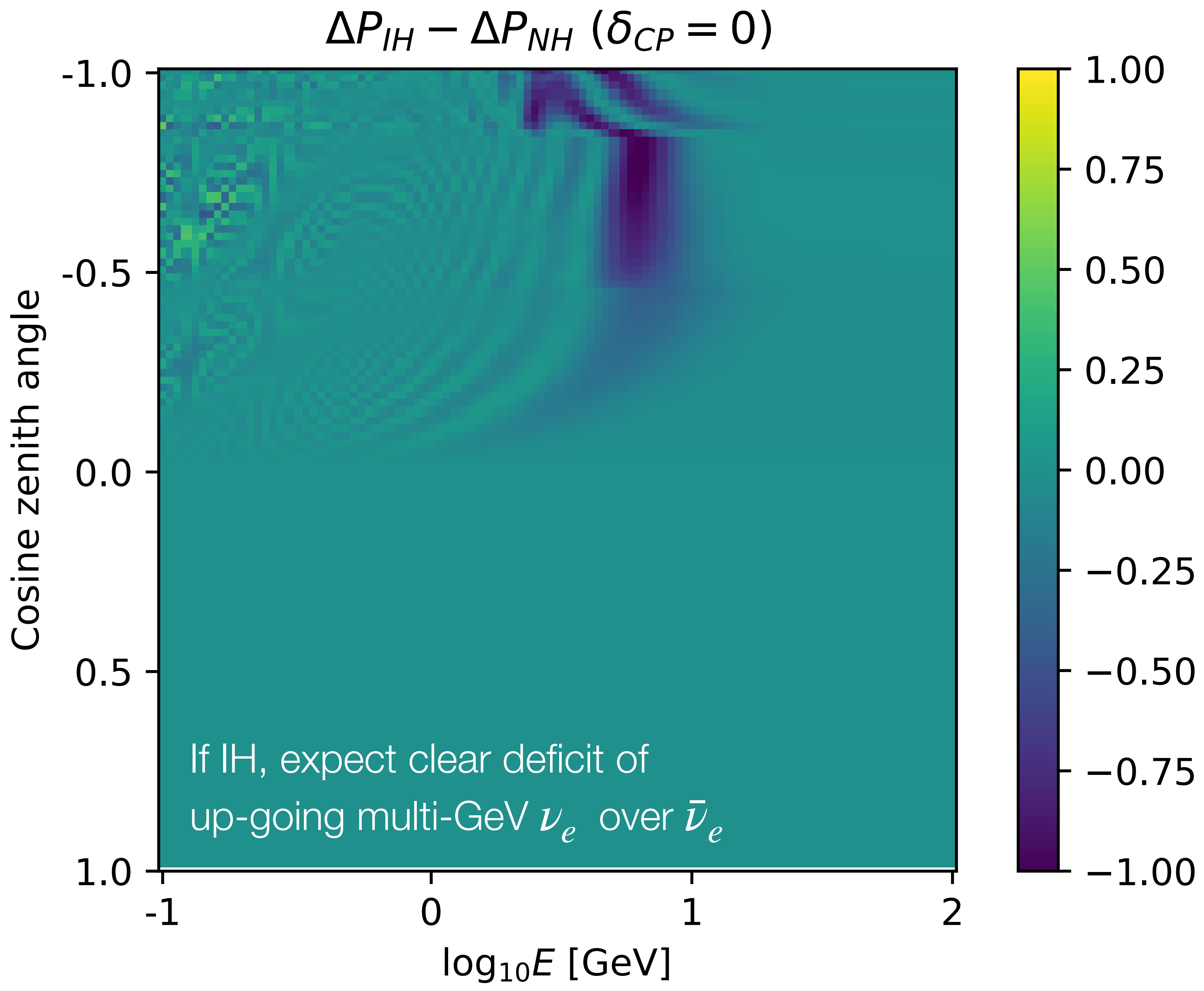
CP and MH effects show up in atmospherics via matter effect.

$\nu/\bar{\nu}$ asymmetry characterizable by $\Delta P \equiv P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$


$\Delta P_{\delta_{CP}=3\pi/2} - \Delta P_{\delta_{CP}=0}$ (NH)

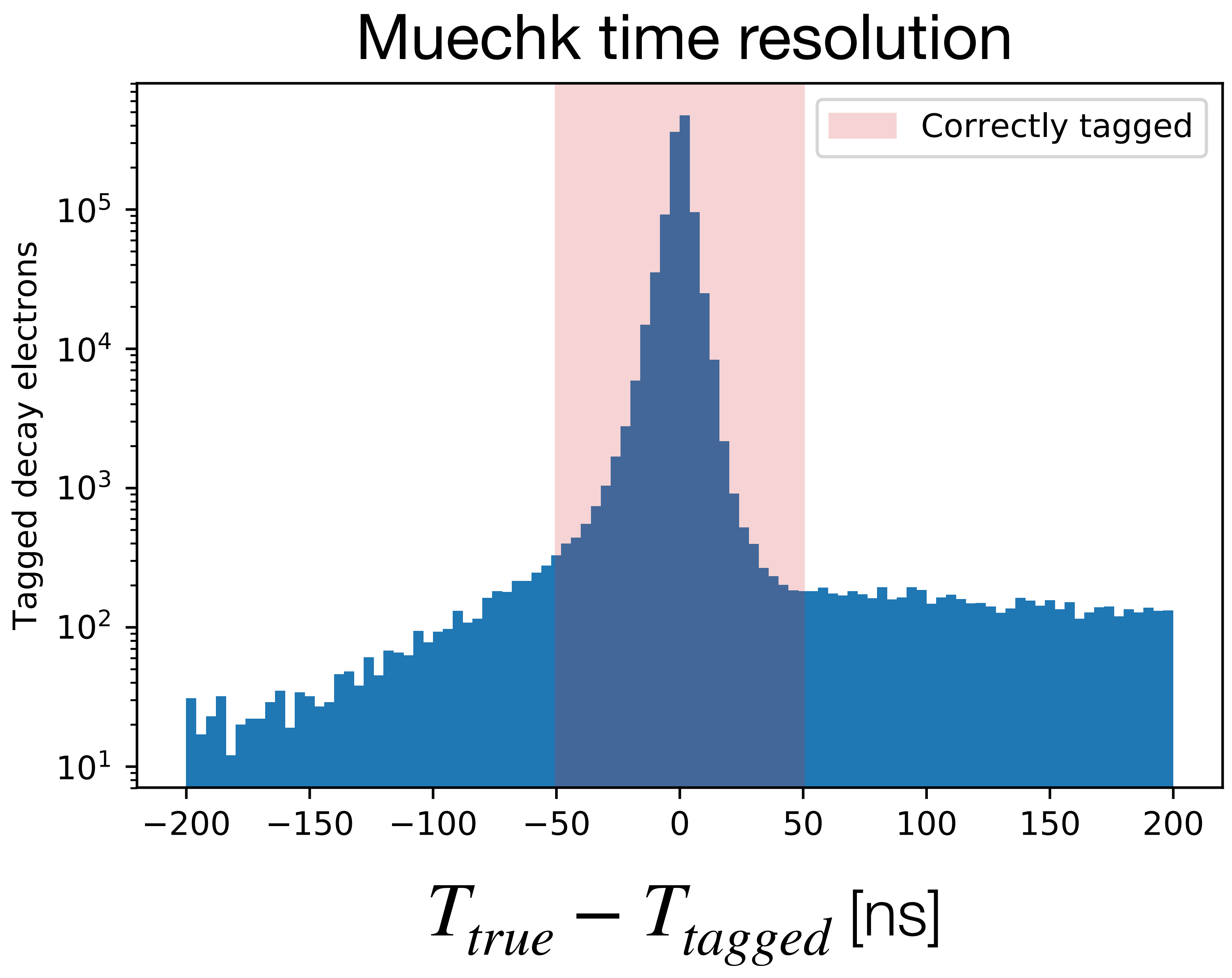
If CPV, expect mild surplus of up-going sub-GeV ν_e over $\bar{\nu}_e$

ΔP difference by CP


$\Delta P_{IH} - \Delta P_{NH}$ ($\delta_{CP} = 0$)

If IH, expect clear deficit of up-going multi-GeV ν_e over $\bar{\nu}_e$

ΔP difference by MH



Assume correctly tagged if:

$|T_{true} - T_{tagged}| < 50$ ns

Material: semi-realistic SK6 atmospheric ν MC

*SK6-specific

For validation with SK4,
see these slides.

1) **Primary vectors**: 500-year-worth SK4 May 19 (2019)

2) **MC simulator**: skdetsim v14 (Rev. 29756) with SK5 COREPMT

  - Gd 0.0110 wt.%
  - No noise generation at this point, added simulated PMT after-pulse only

3) **Dark noise**: SK6 T2K dummy events

  - Randomly picked events taken from Run 85605 - 85902 (Jan 20 - May 22, 2021)
  - Extracted noise appended to [0, 535] μs range of each generated MC event

4) **Reconstruction**: APFit (21a)

5) **Reduction**: fccomb (21a)

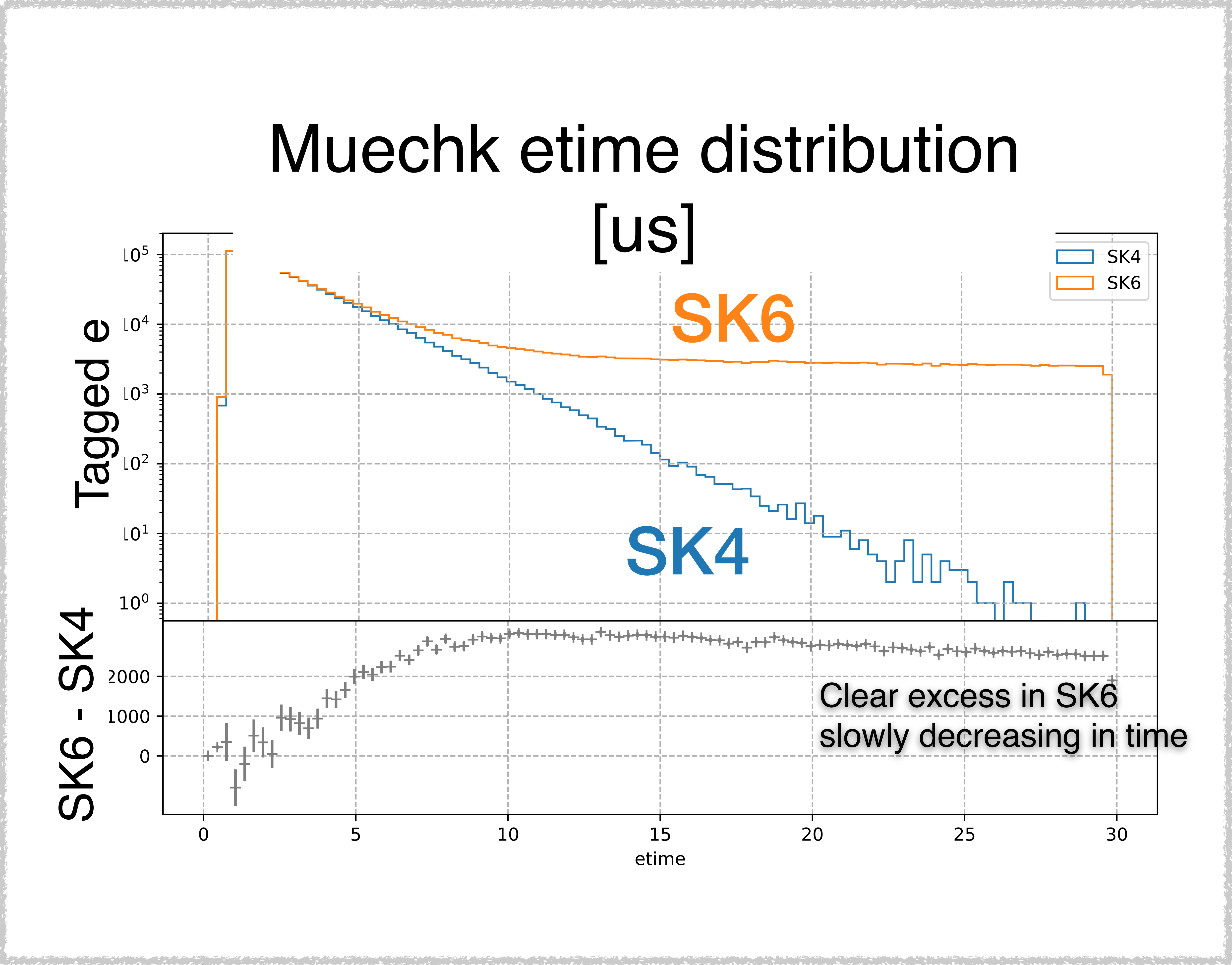
  - SK5/6 “flasher database” assumed to be the same as SK4

6) **Neutron-tagging**: NTag (my own)

  - Neutron search range: **[18, 535]→[3, 535] μs** range in the ToF-subtracted residual time
  - NTag performance on single-neutron-only MC: ~60% tagging efficiency with 98% precision

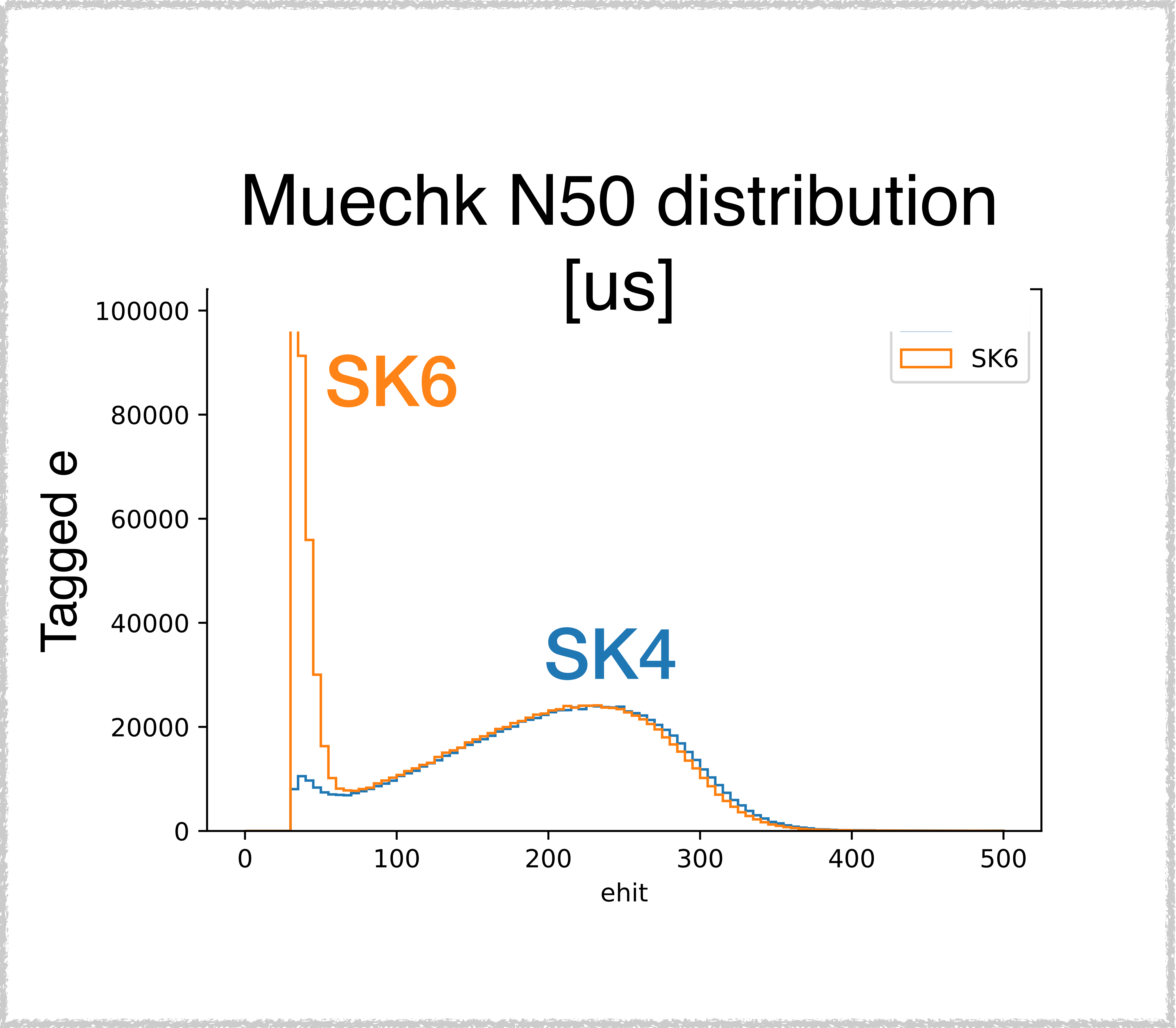
7) **Event classification**: fillnt + OscNtupleBuilder (for neutron-inclusive hybrid analysis) (21a)

Problem: Gd(n,γ)’s are tagged as decay-e in muechk 😩



Muechk etime distribution [us]

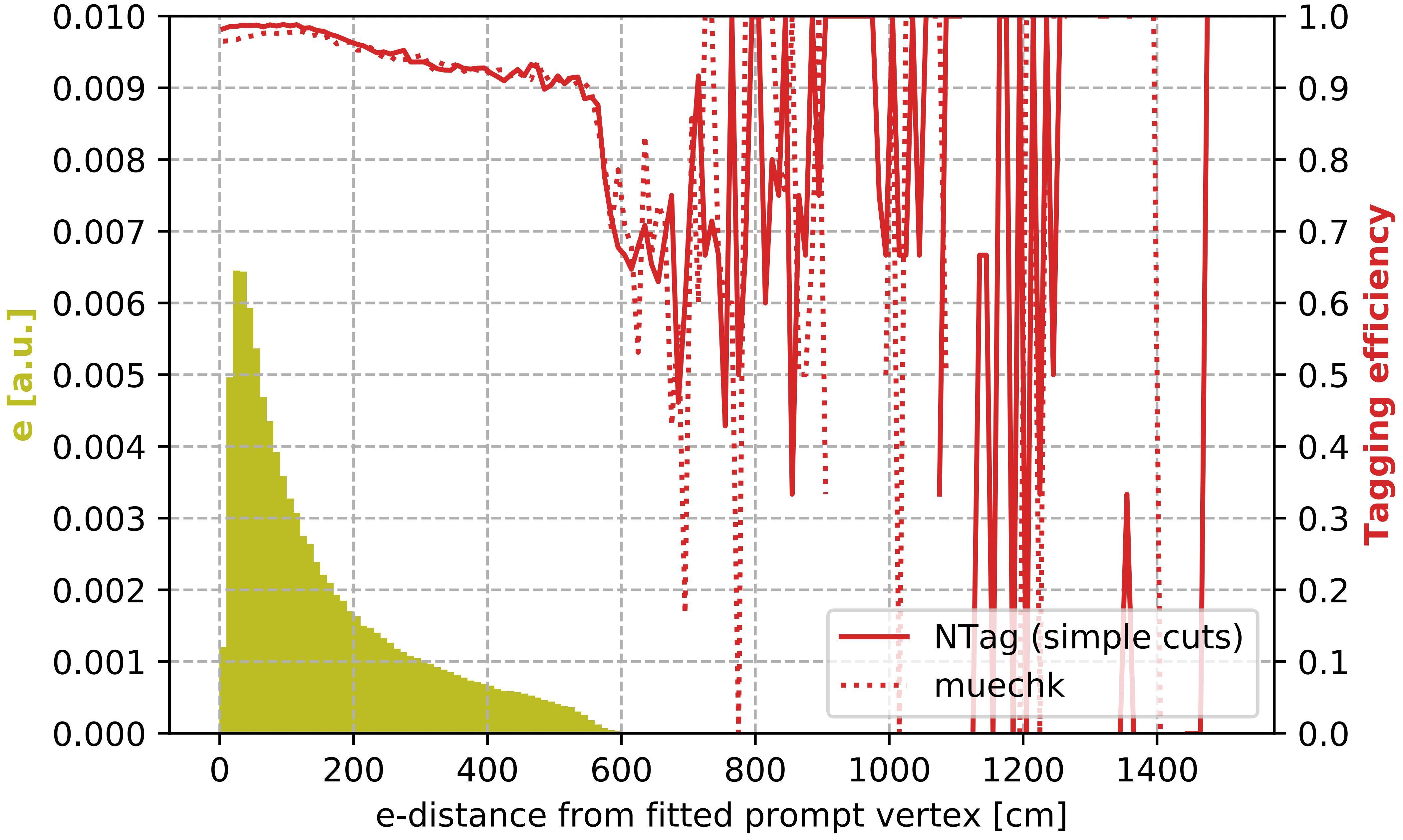
Clear excess in SK6 slowly decreasing in time



Muechk N50 distribution [us]

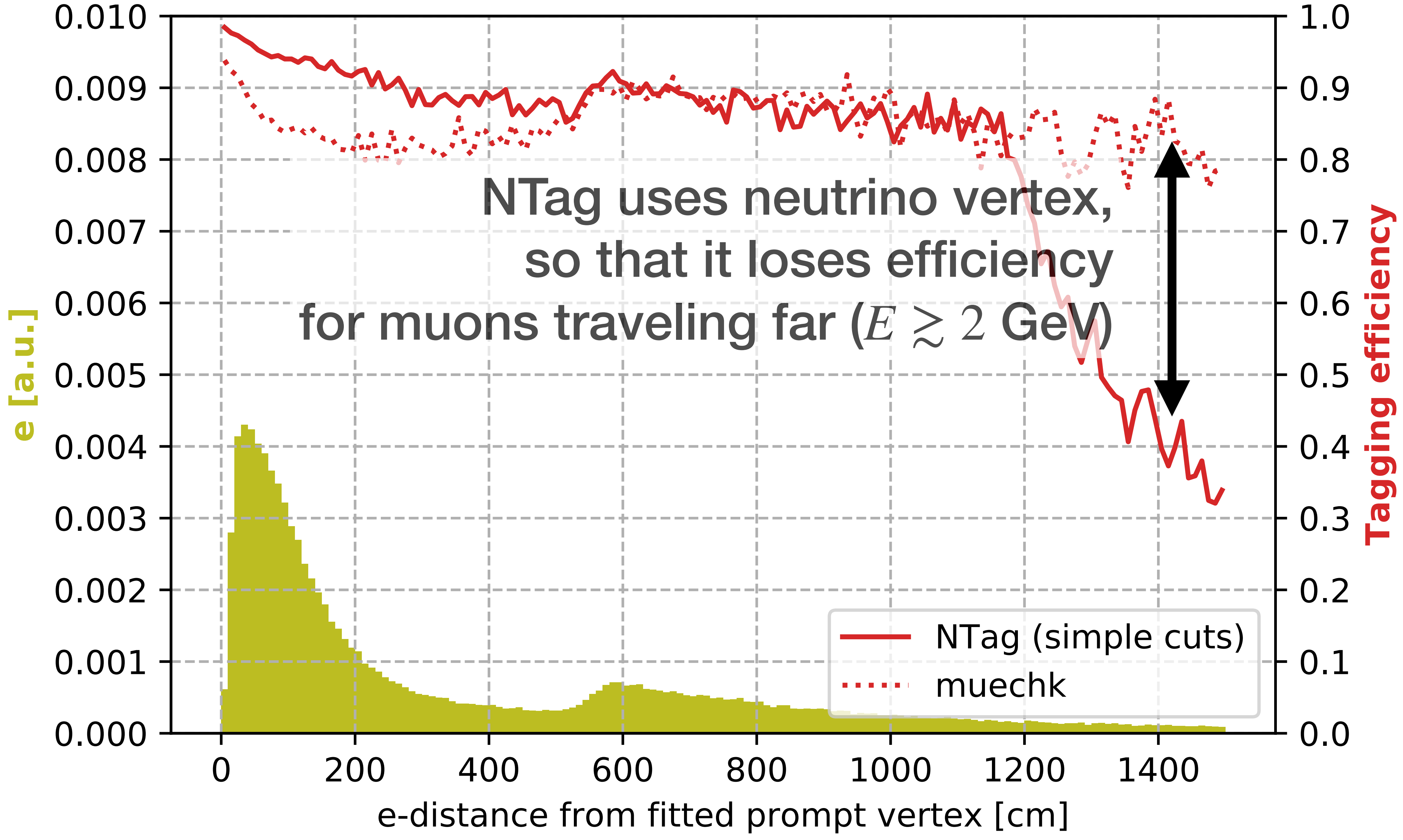
e-tagging efficiency by $|\overrightarrow{x}_e^{True} - \overrightarrow{x}_\nu^{APFit}|$

Sub-GeV



1σ: 184 cm

Multi-GeV



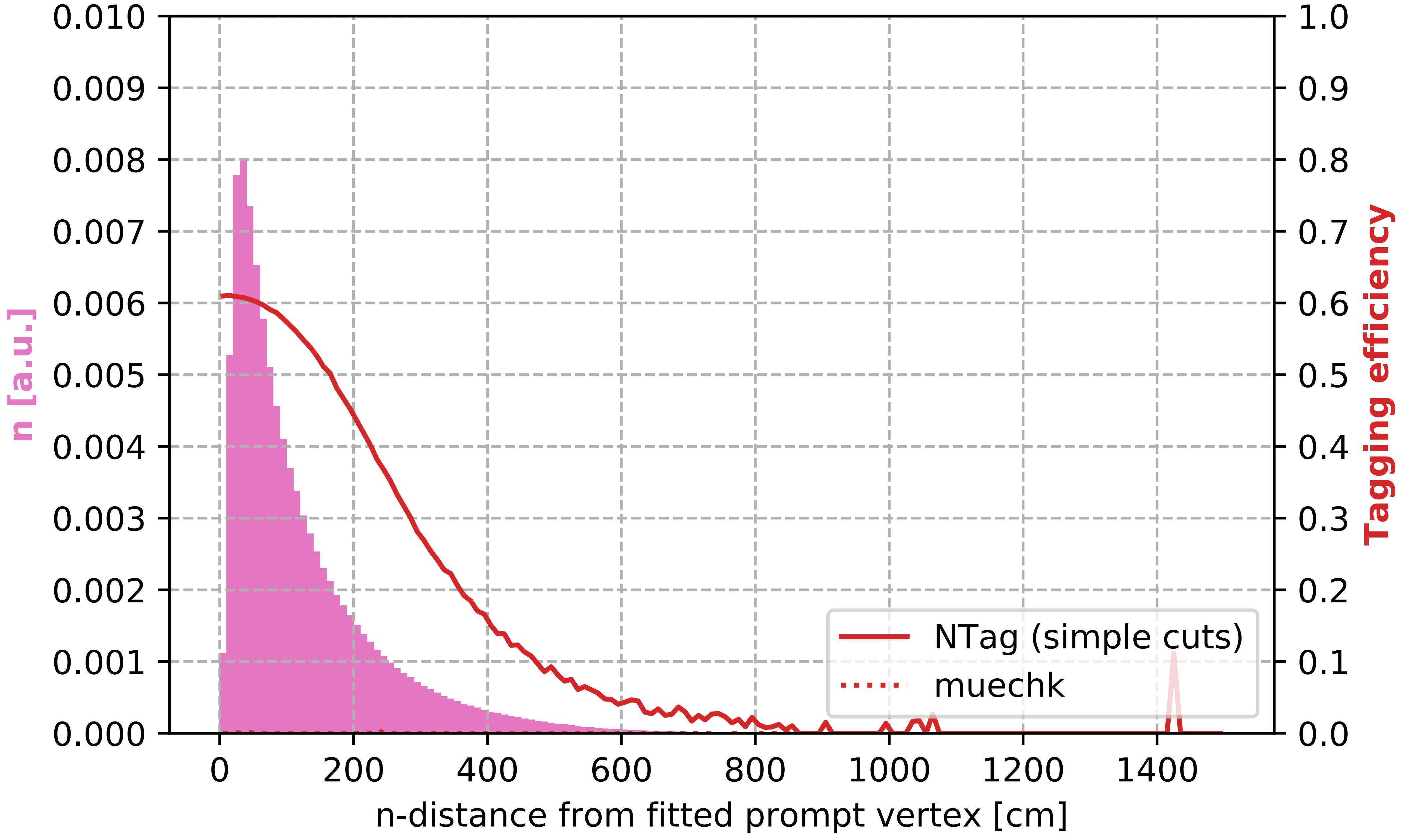
NTag uses neutrino vertex, so that it loses efficiency for muons traveling far ($E \gtrsim 2$ GeV)

1σ: 543 cm

n-tagging efficiency by $|\vec{x}^{True}_{(n,\gamma)} - \vec{x}^{APFit}_{\nu}|$

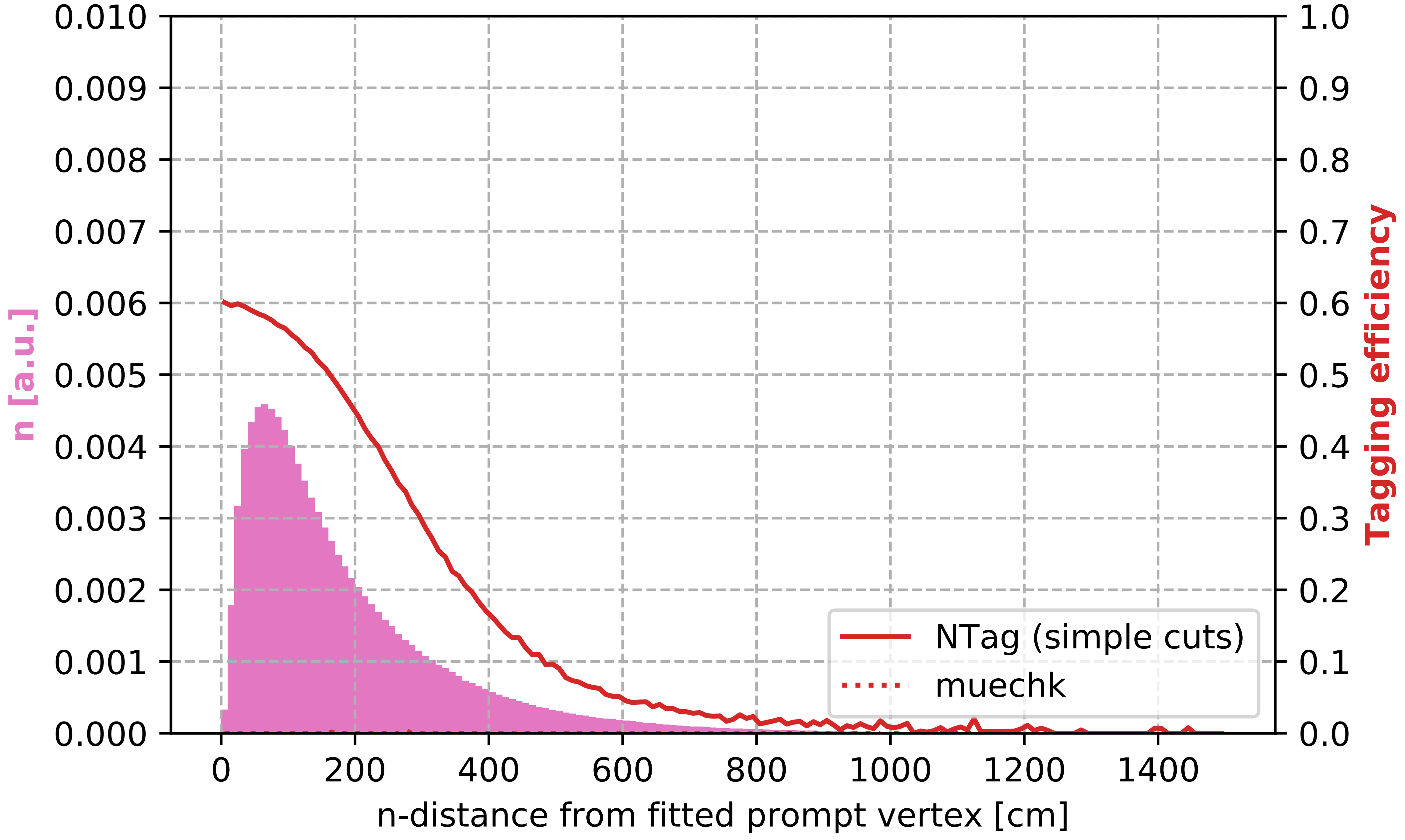
Note: typical AmBe neutrons are expected to travel ~20 cm (1σ), with ~60% tagging efficiency

Sub-GeV



1σ: 138 cm (~50% eff.)

Multi-GeV

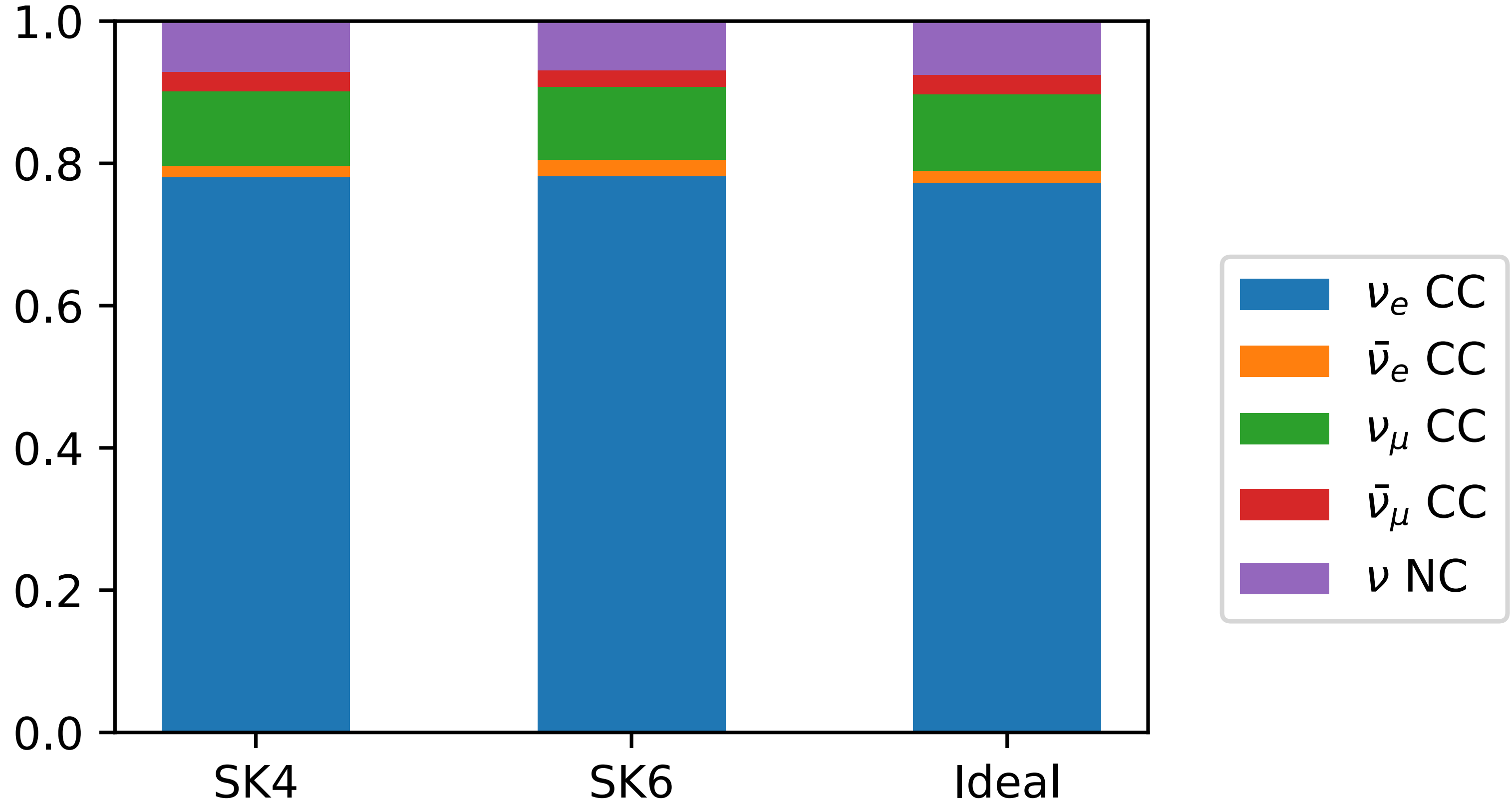


1σ: 209 cm (~45% eff.)

Sub-GeV e-like: true fraction in event subclasses

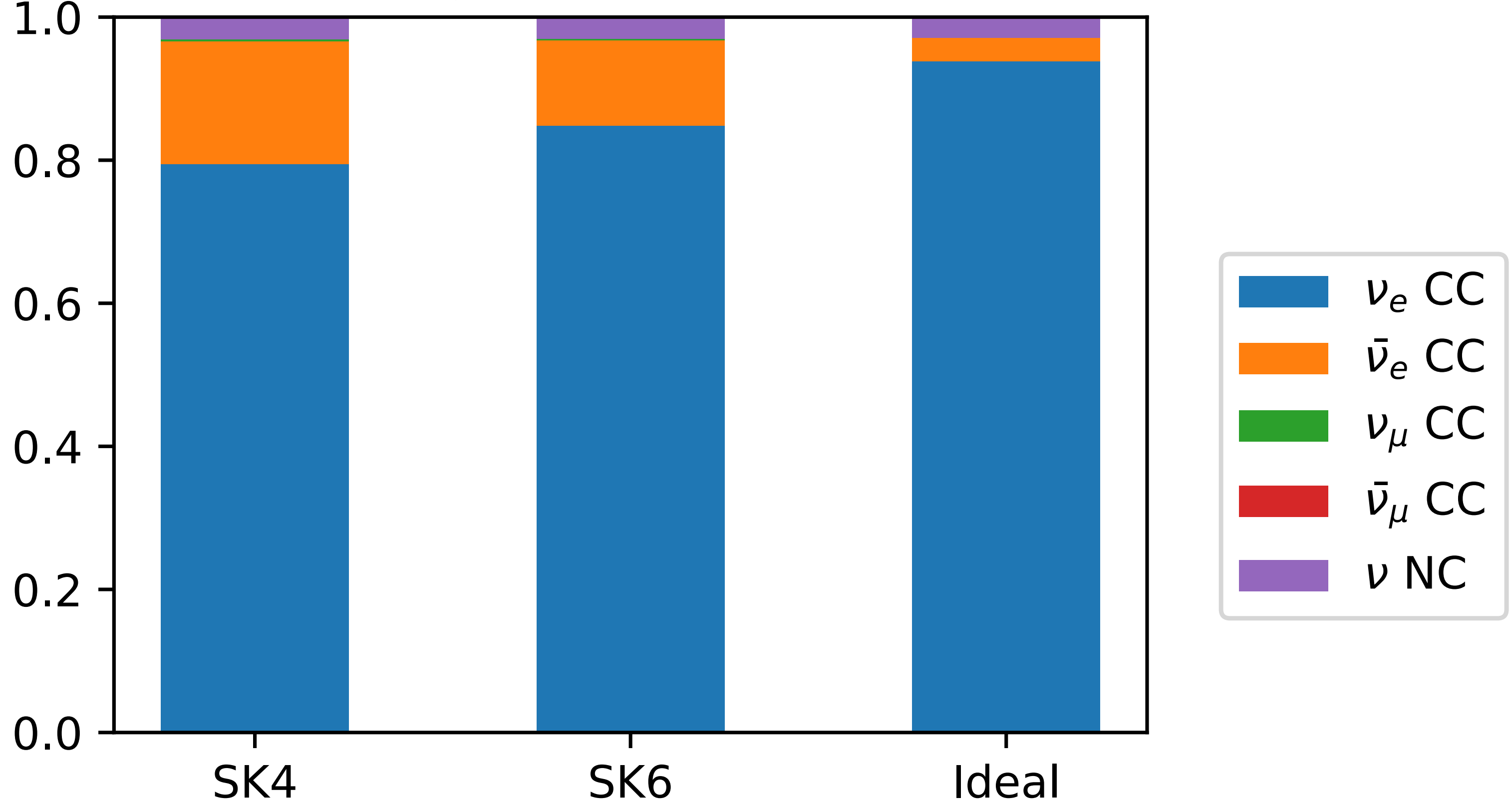
ν_e-like

#e > 0



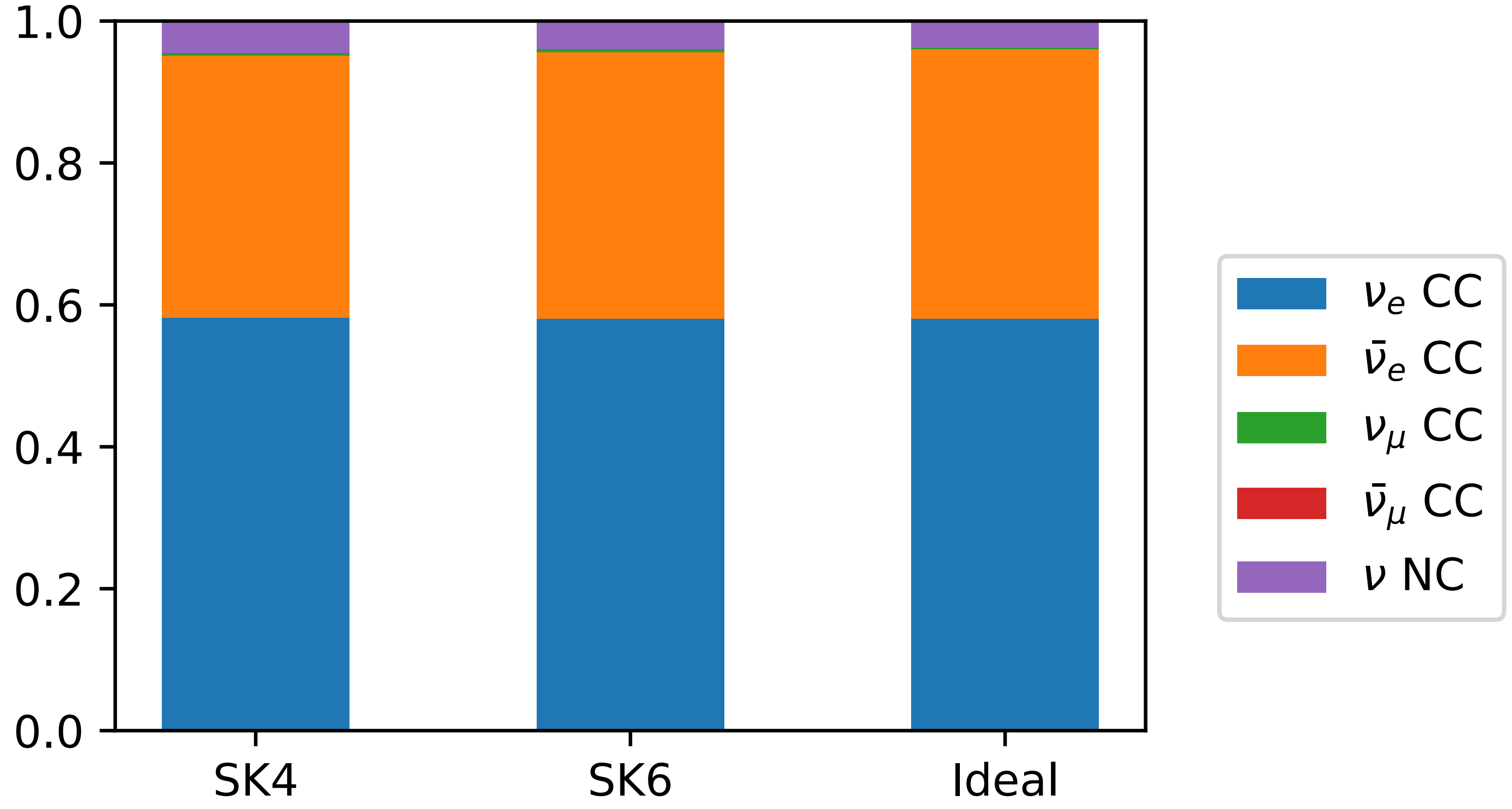
ν_e-like

#e = 0 & #n = 0



$\bar{\nu}_e$-like

#e = 0 & #n > 0



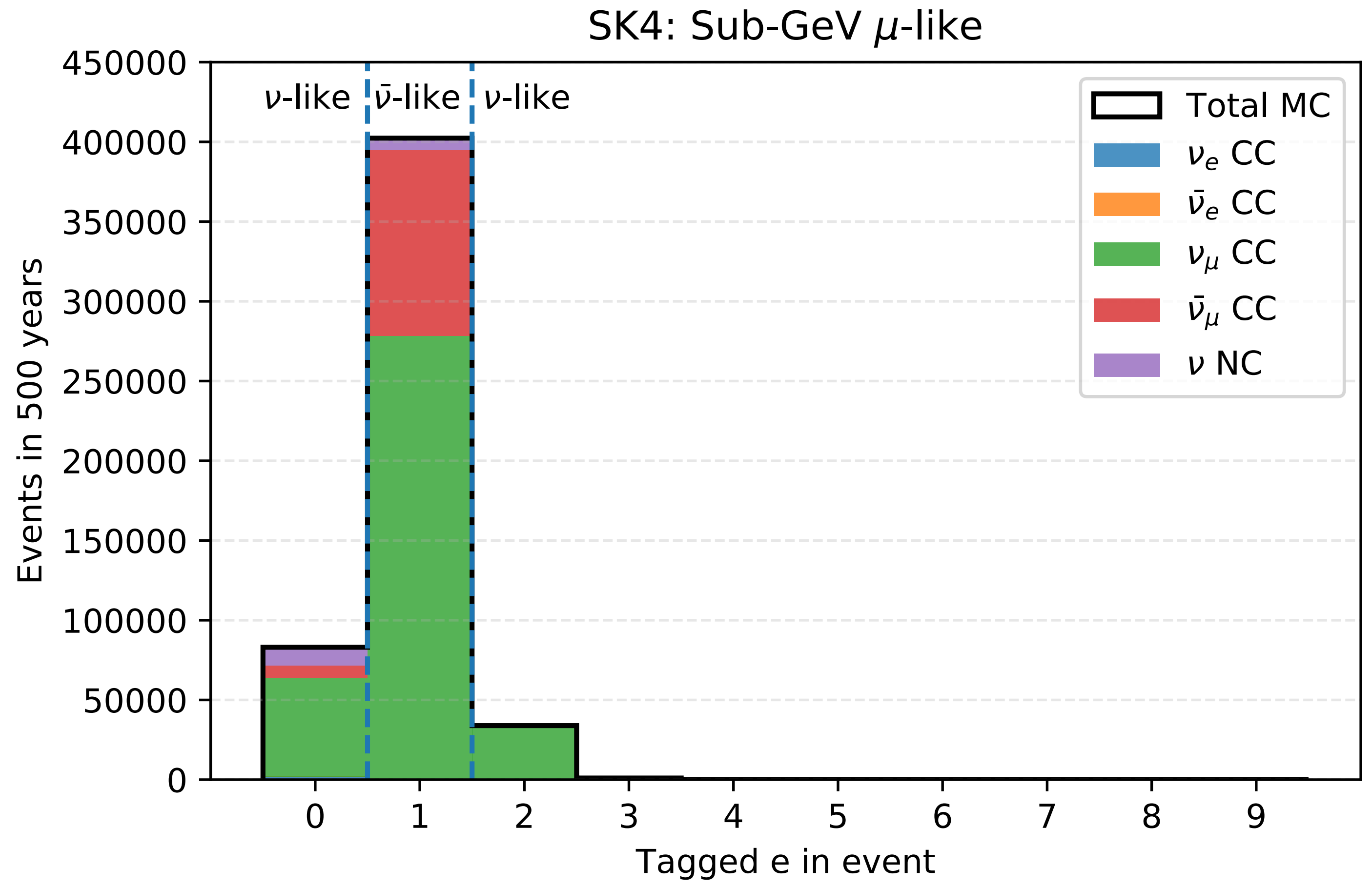
Sub-GeV μ-like: tagged multiplicities

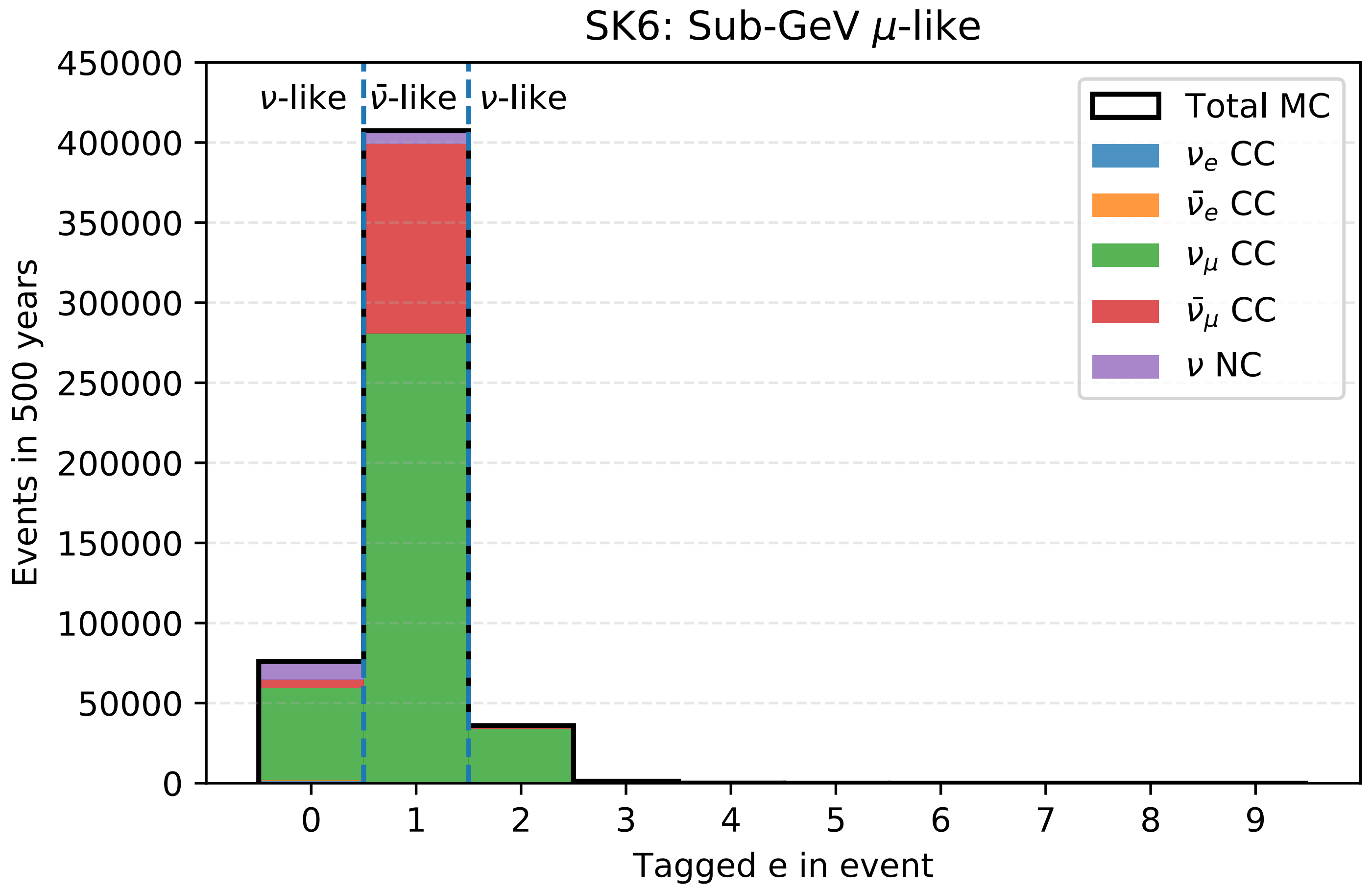
SK4

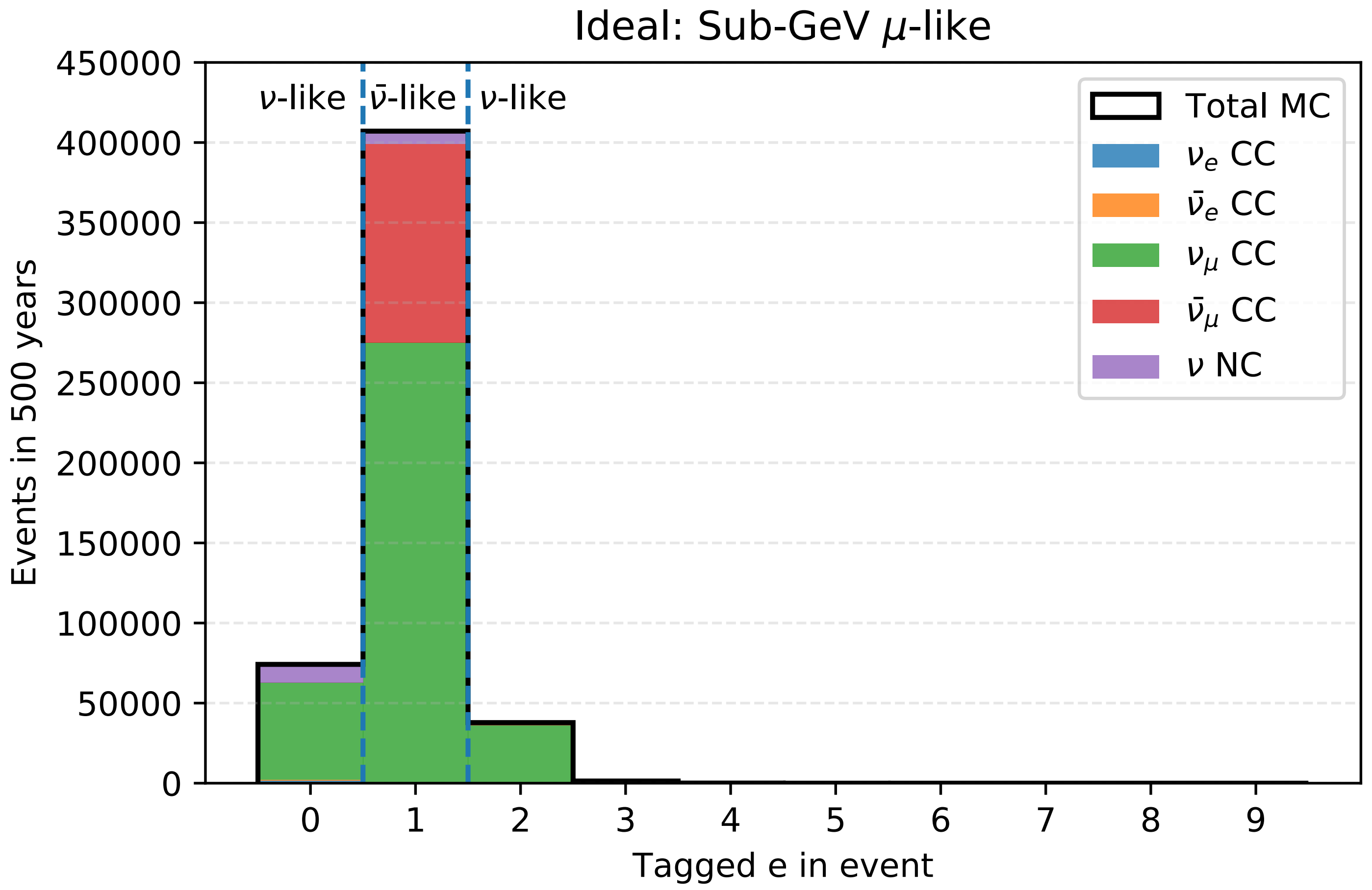
SK6

Ideal

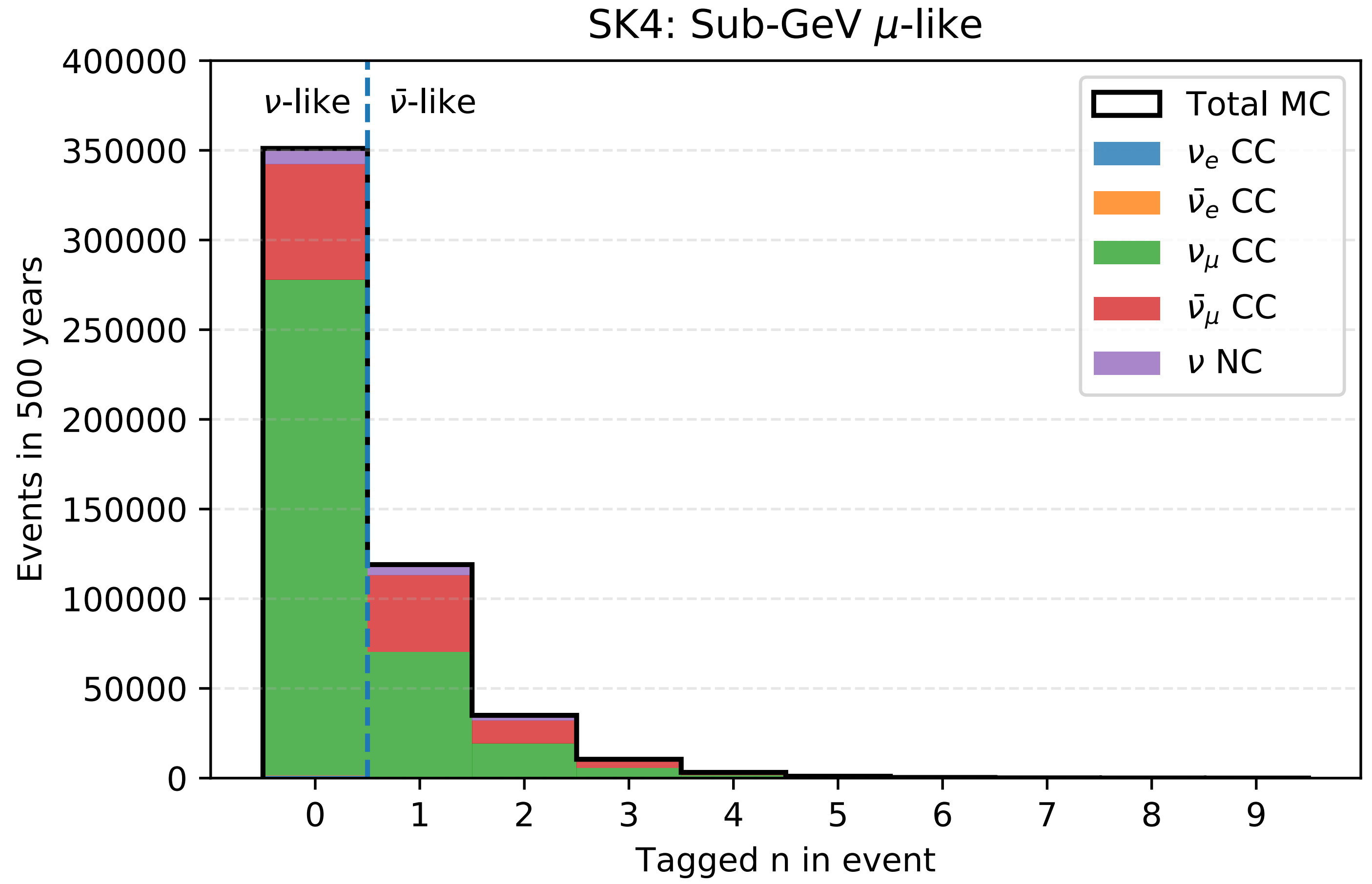
#e

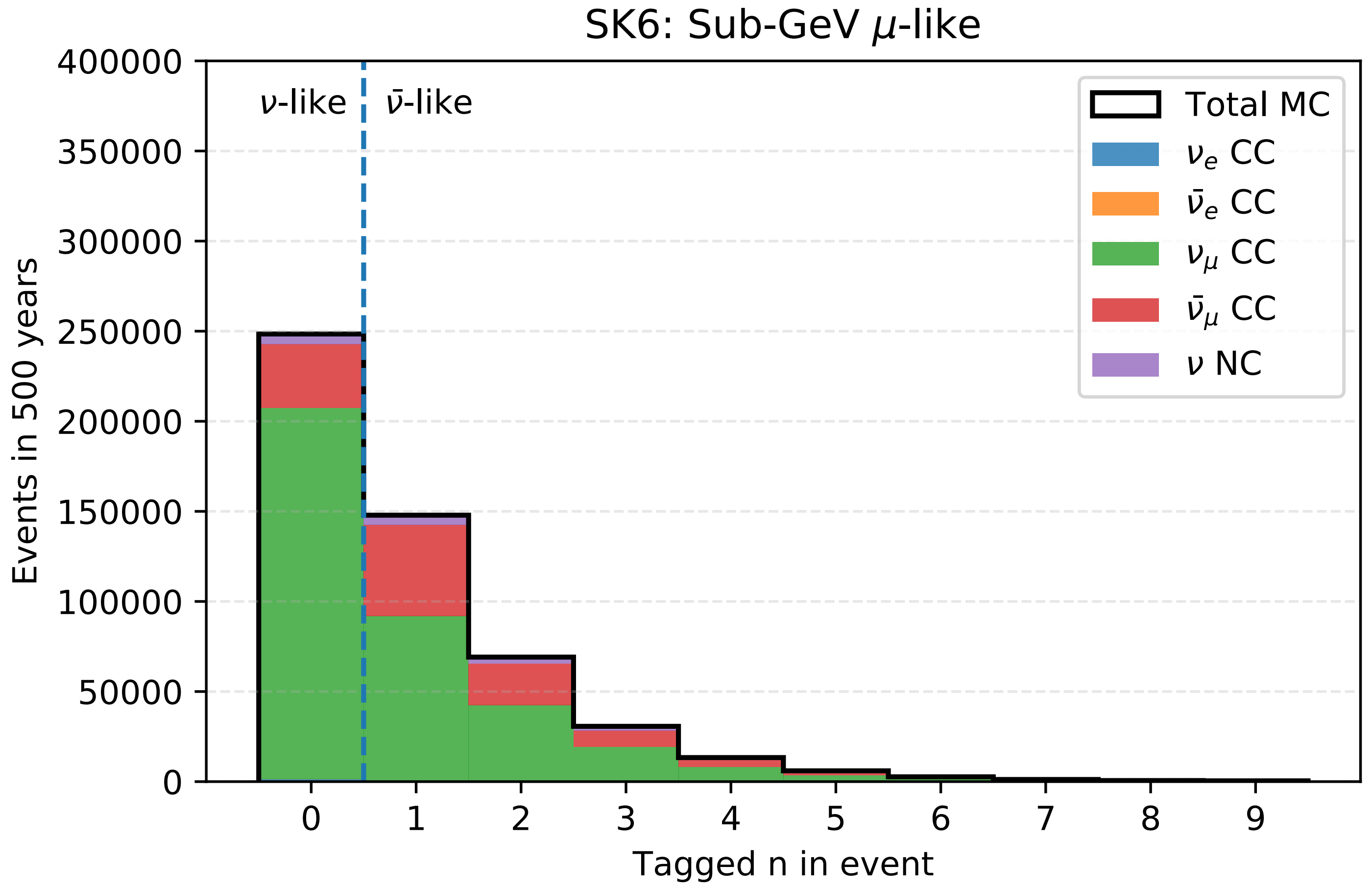


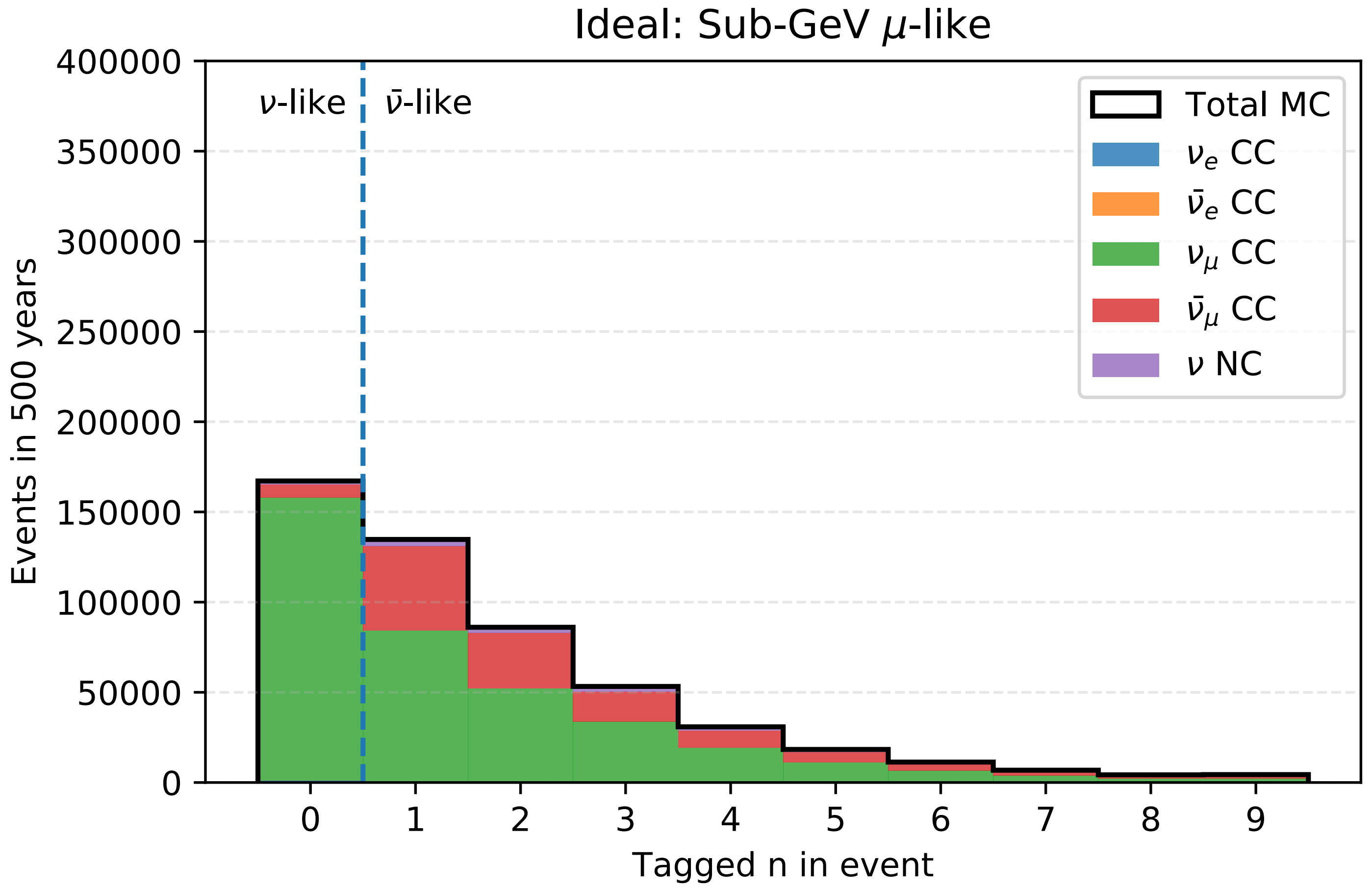




#n



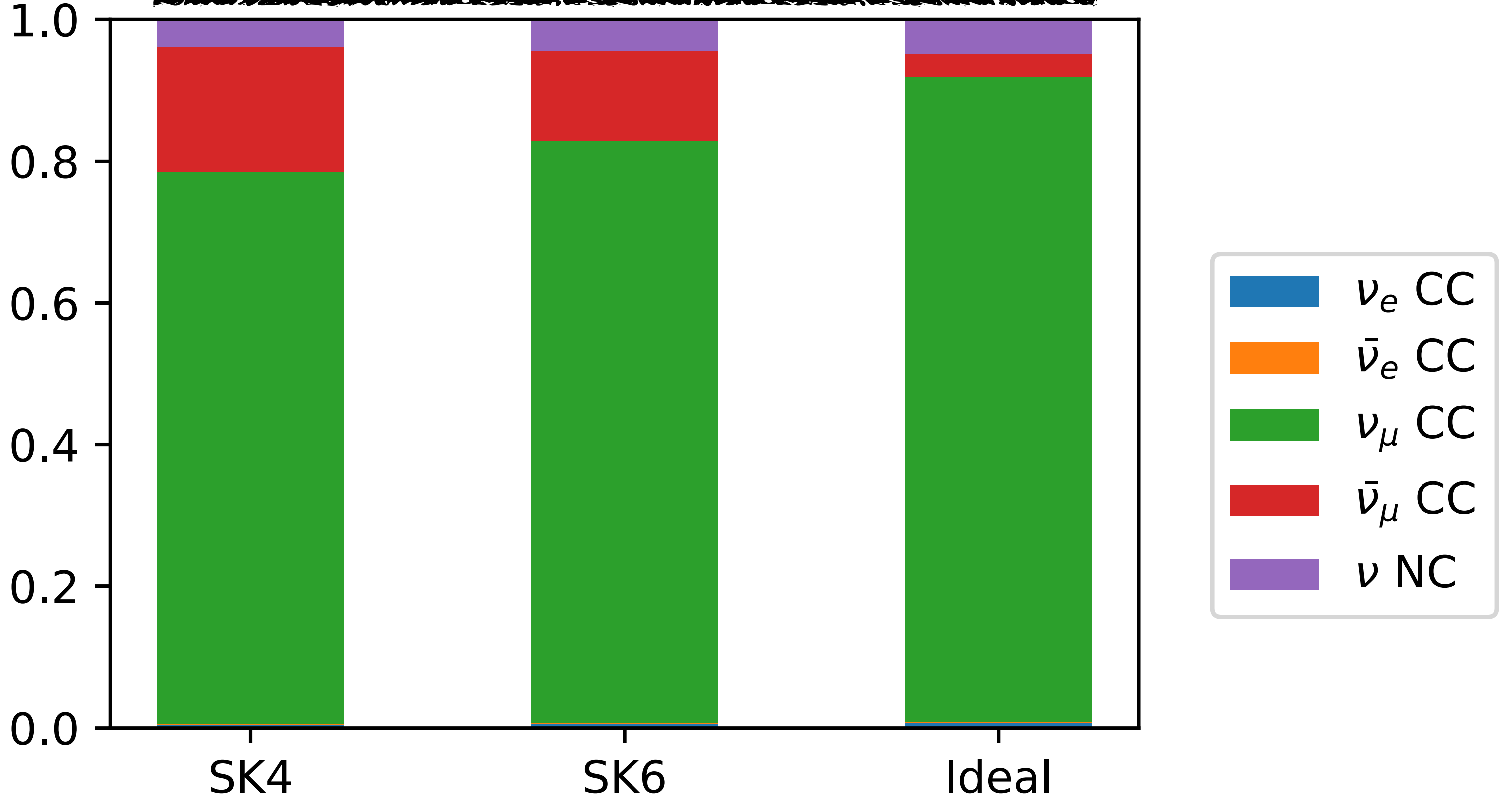




Sub-GeV μ-like: true fraction in event subclasses

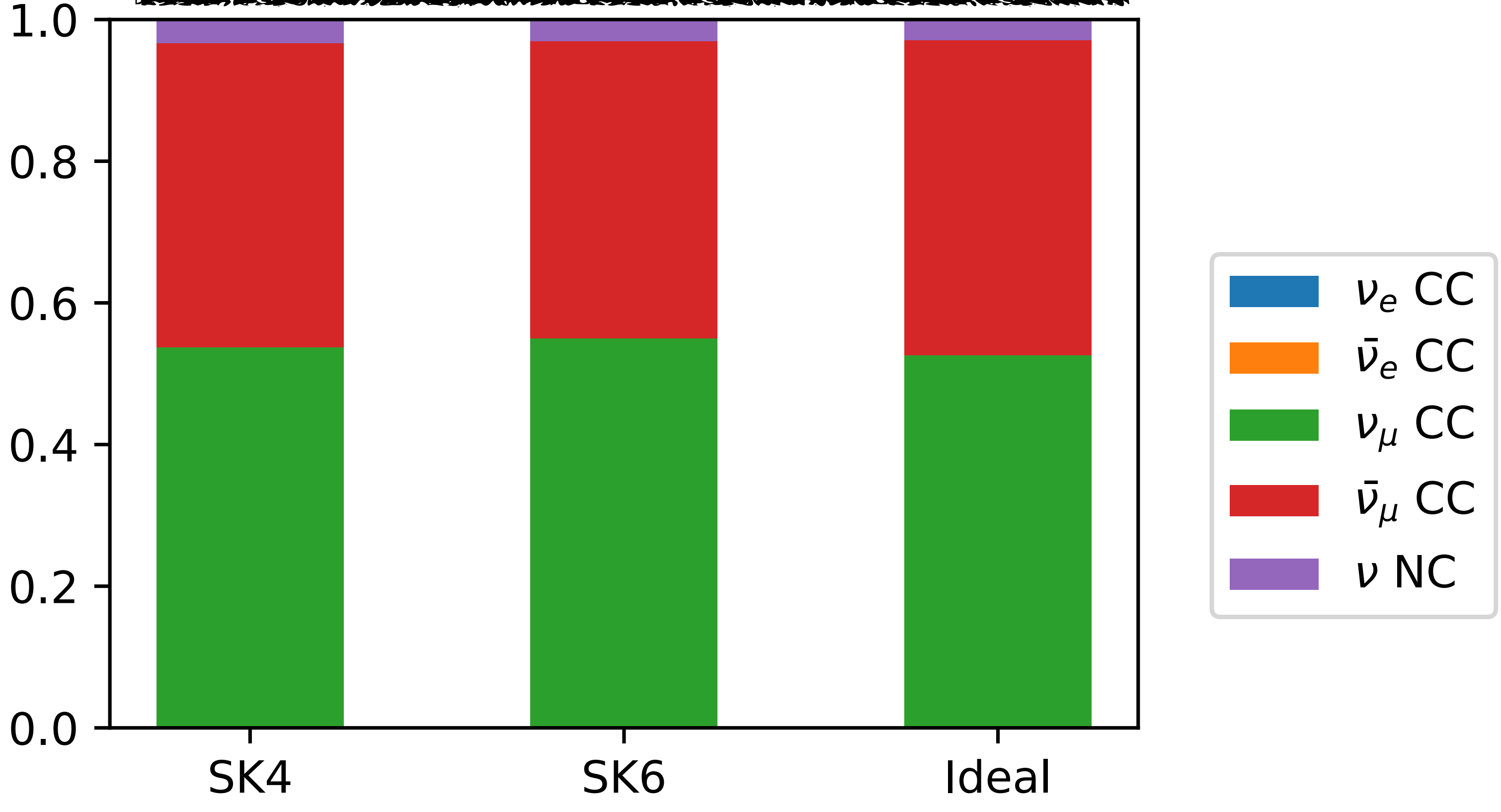
ν_μ-like

#e ≠ 1 | #n = 0



$\bar{\nu}_\mu$-like

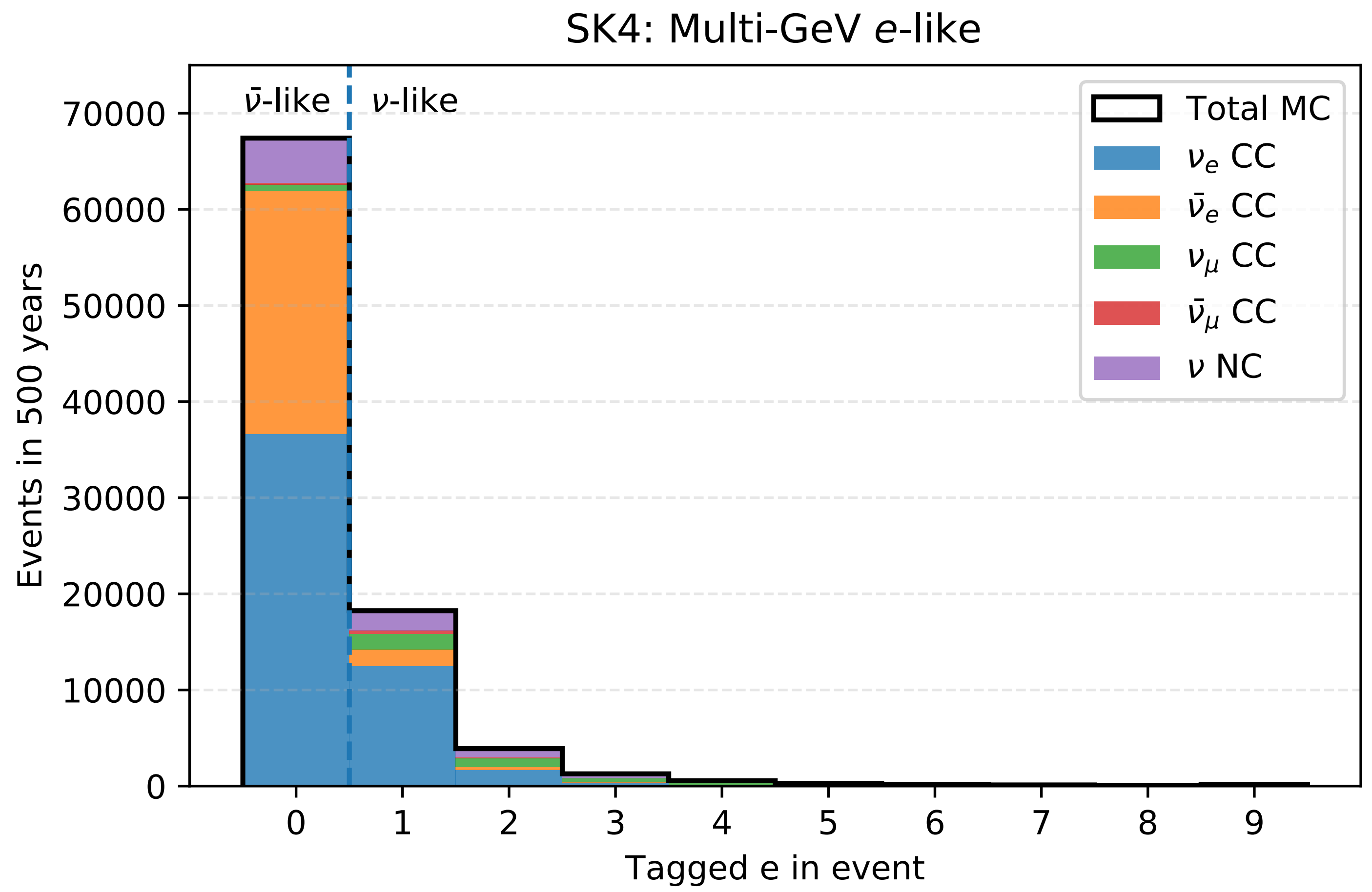
#e = 1 & #n > 0

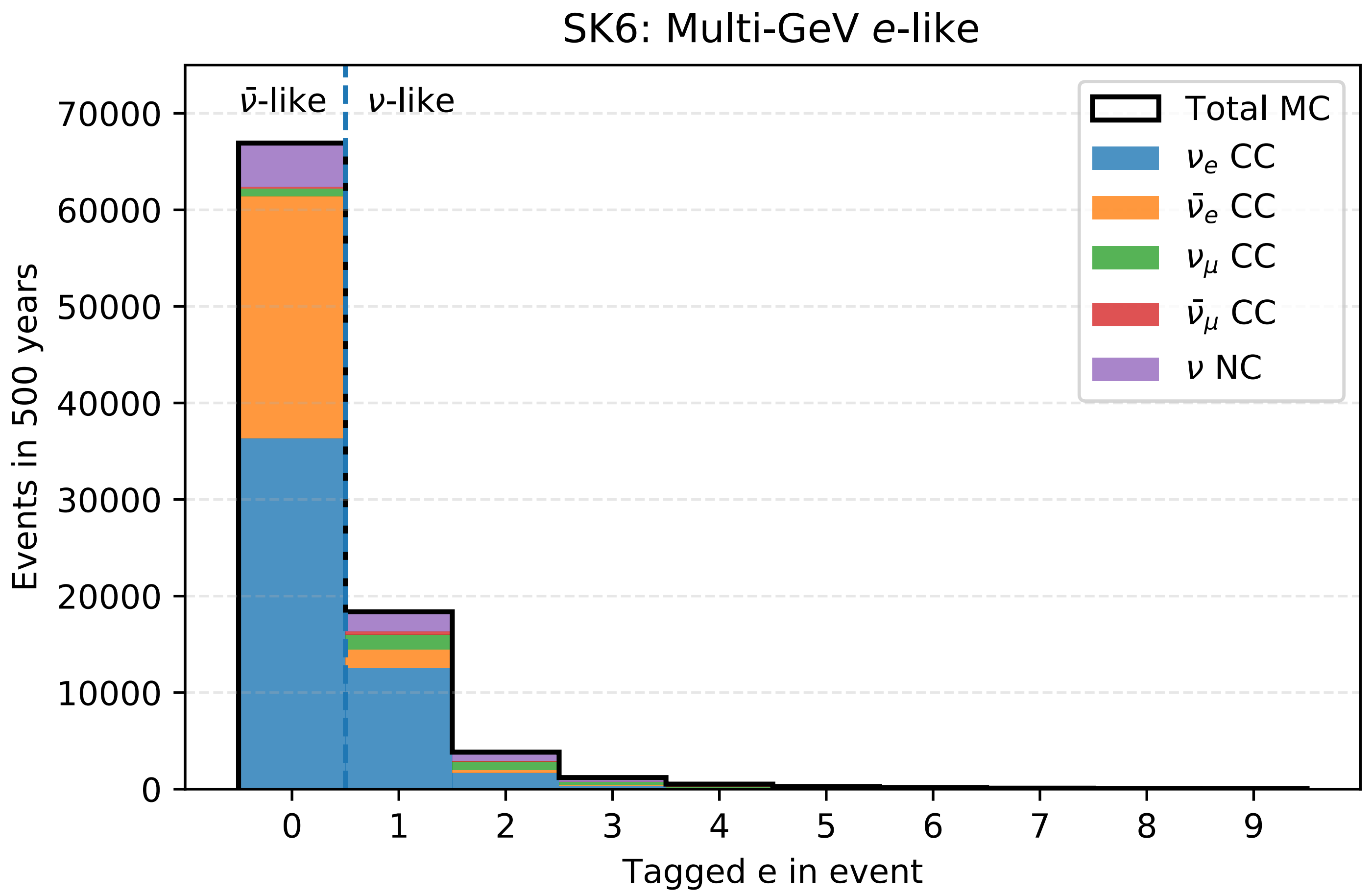


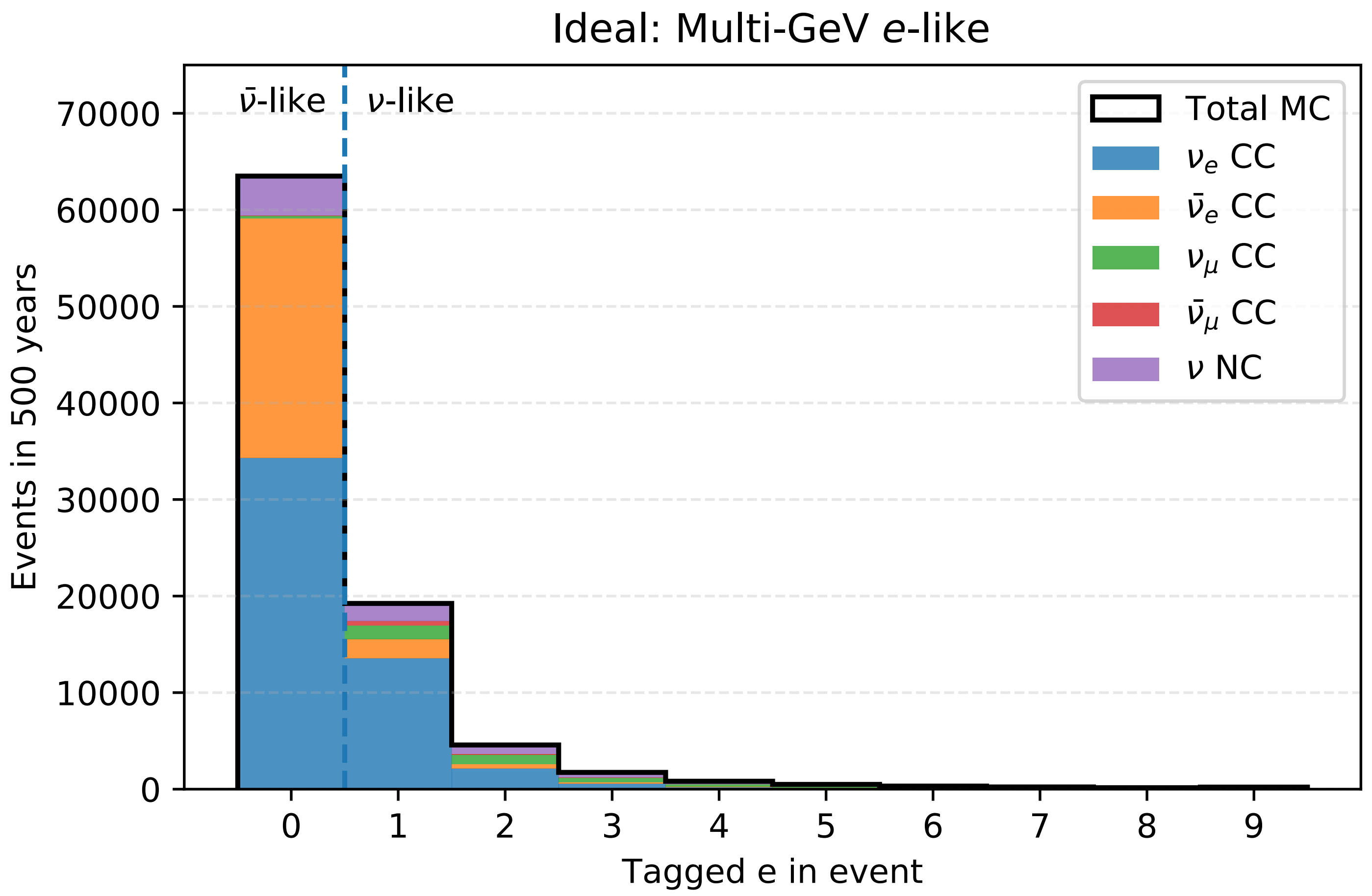
Multi-GeV e-like: tagged multiplicities

SK4 **SK6** **Ideal**

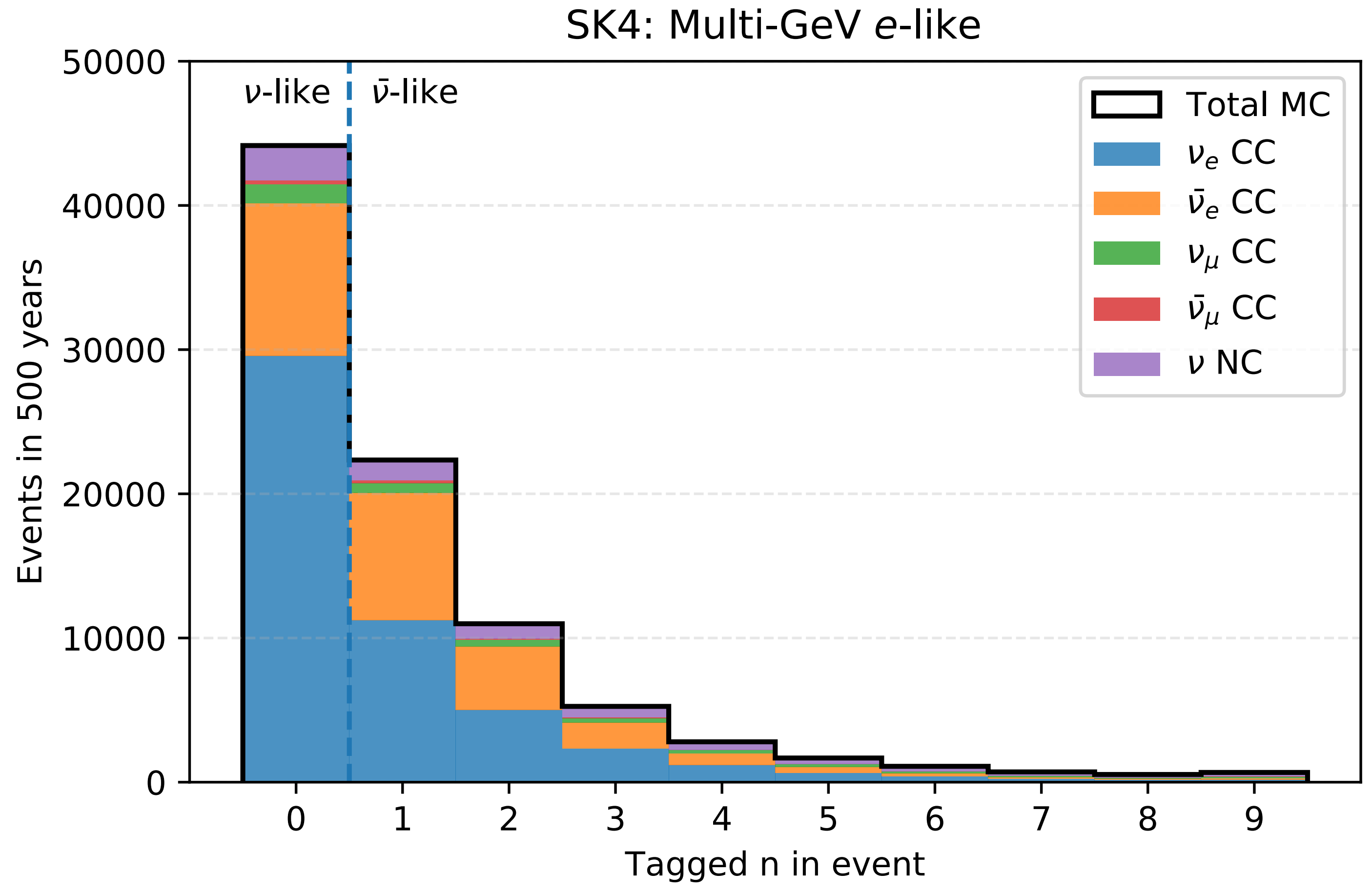
#e

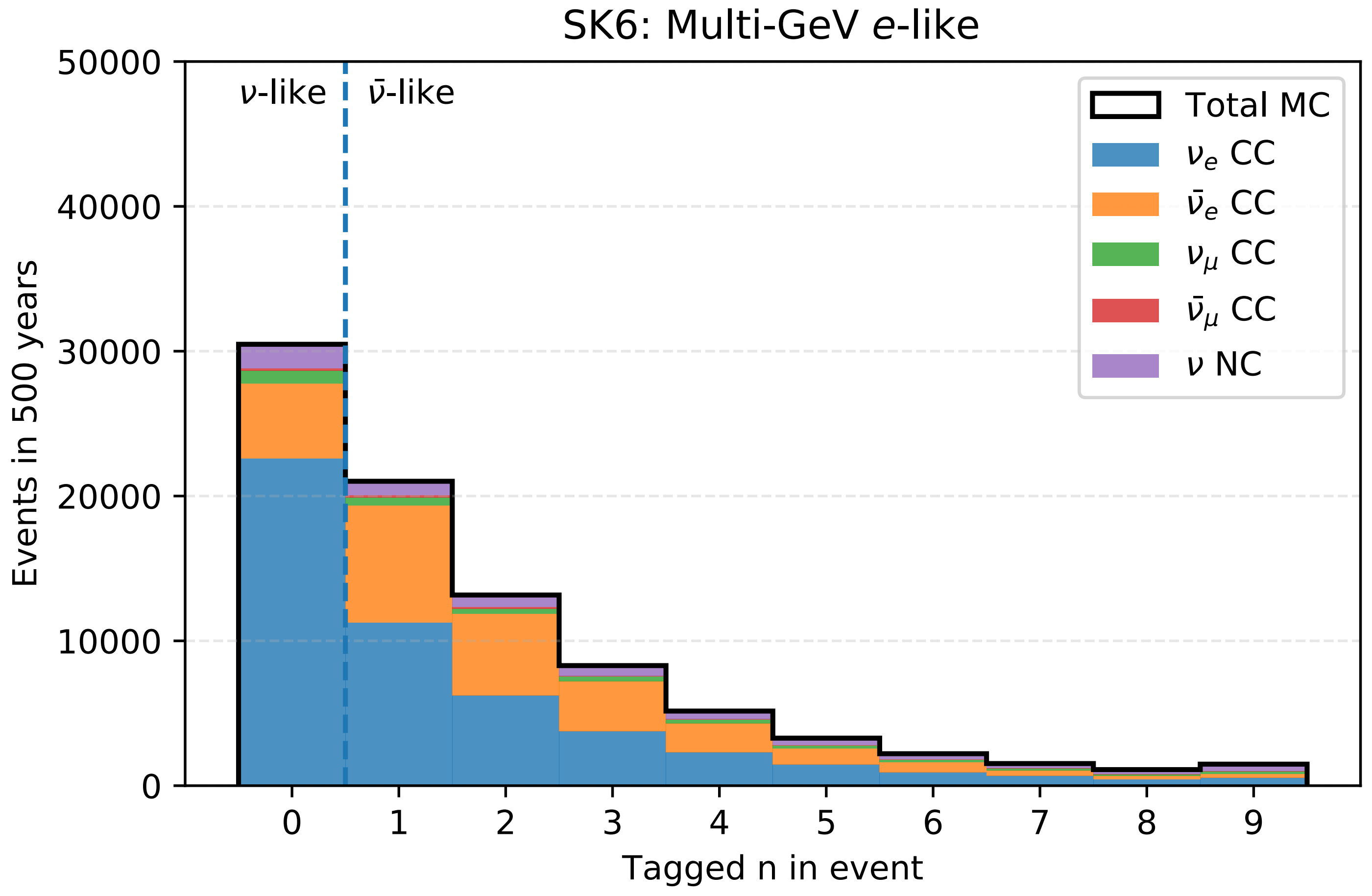


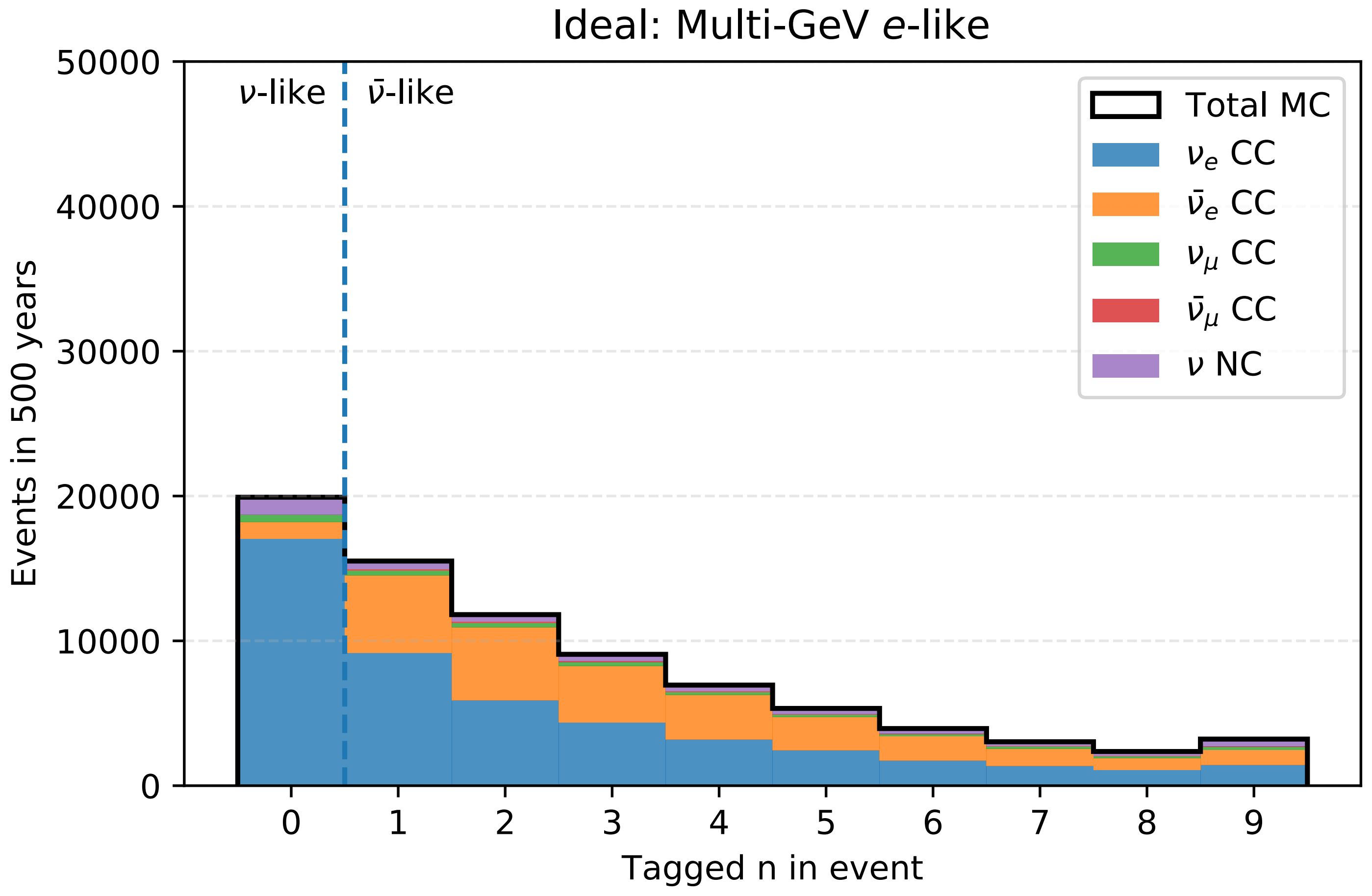




#n



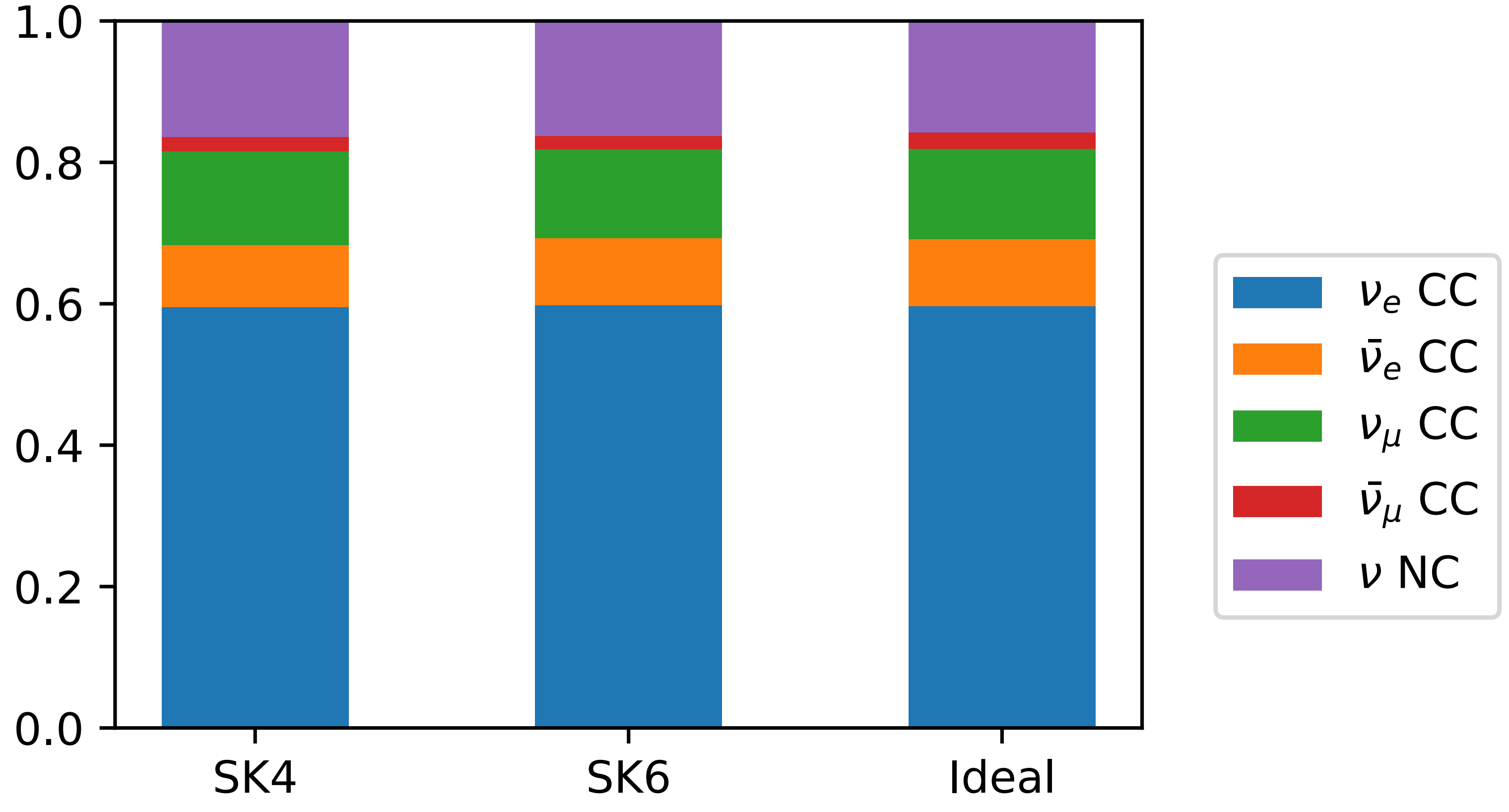




Multi-GeV e-like: true fraction in event subclasses

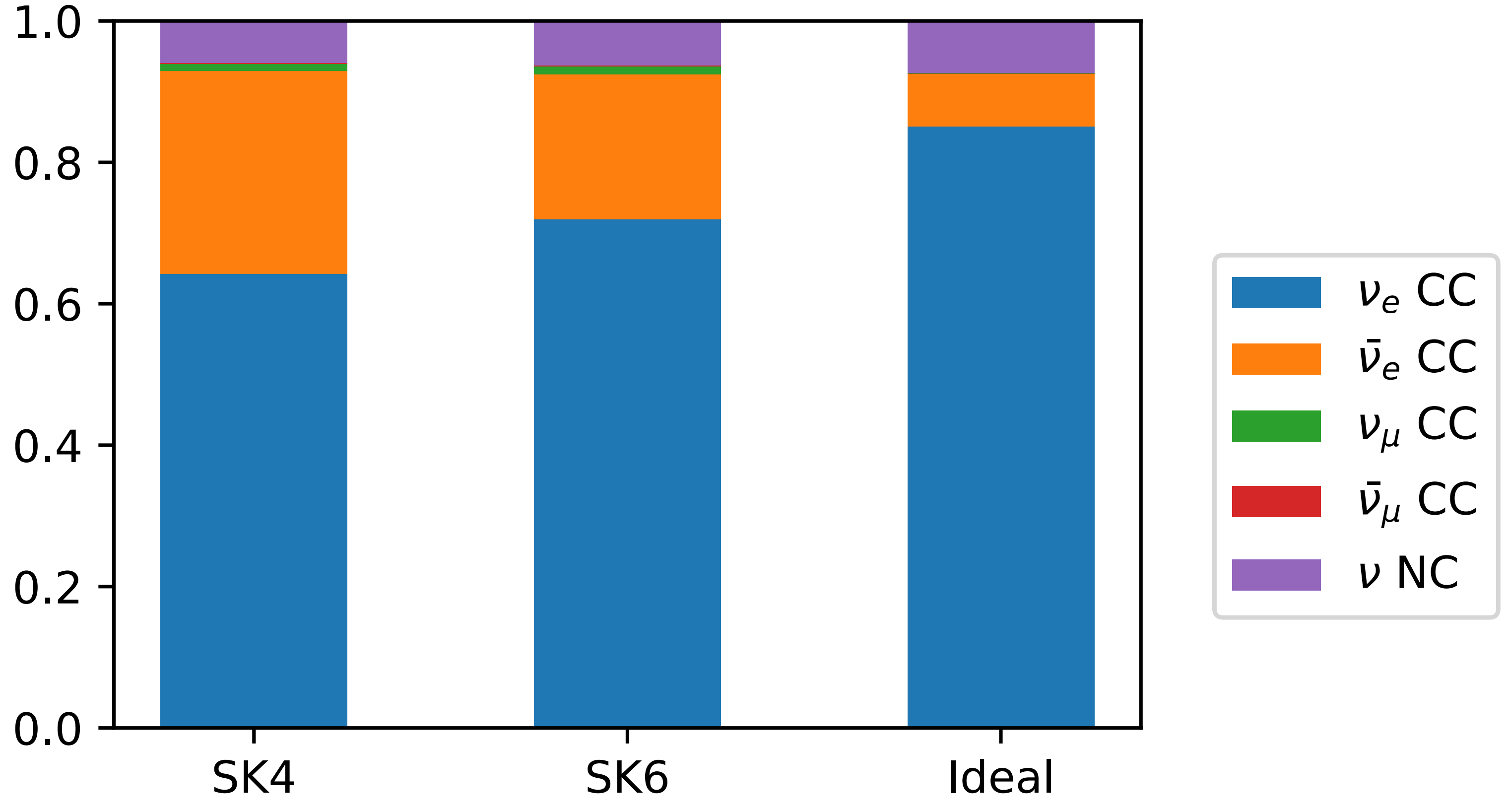
ν_e-like

$\#e > 0$



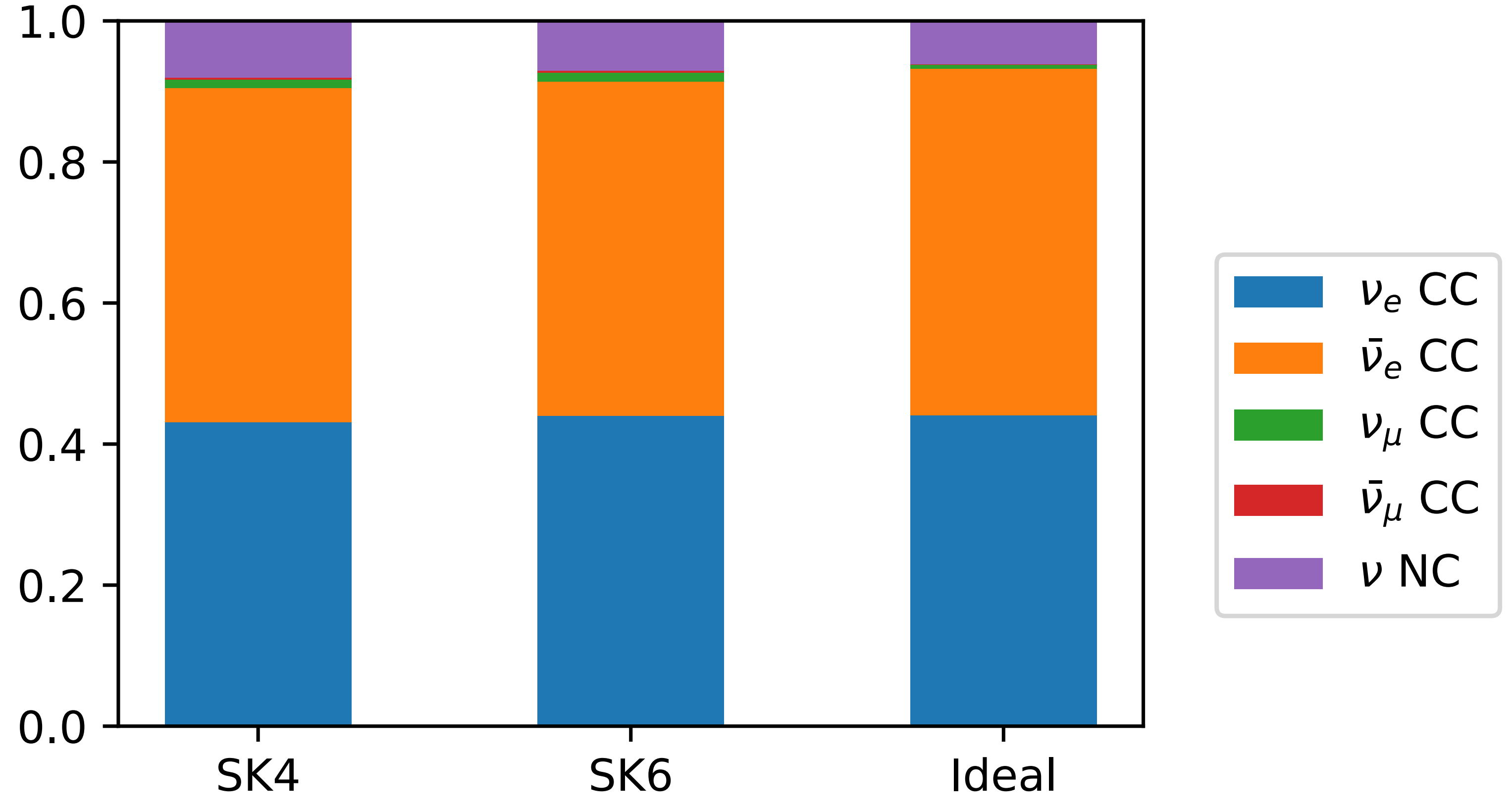
$\nu_e/\bar{\nu}_e$-like

$\#e = 0$ & $\#n = 0$



$\bar{\nu}_e$-like

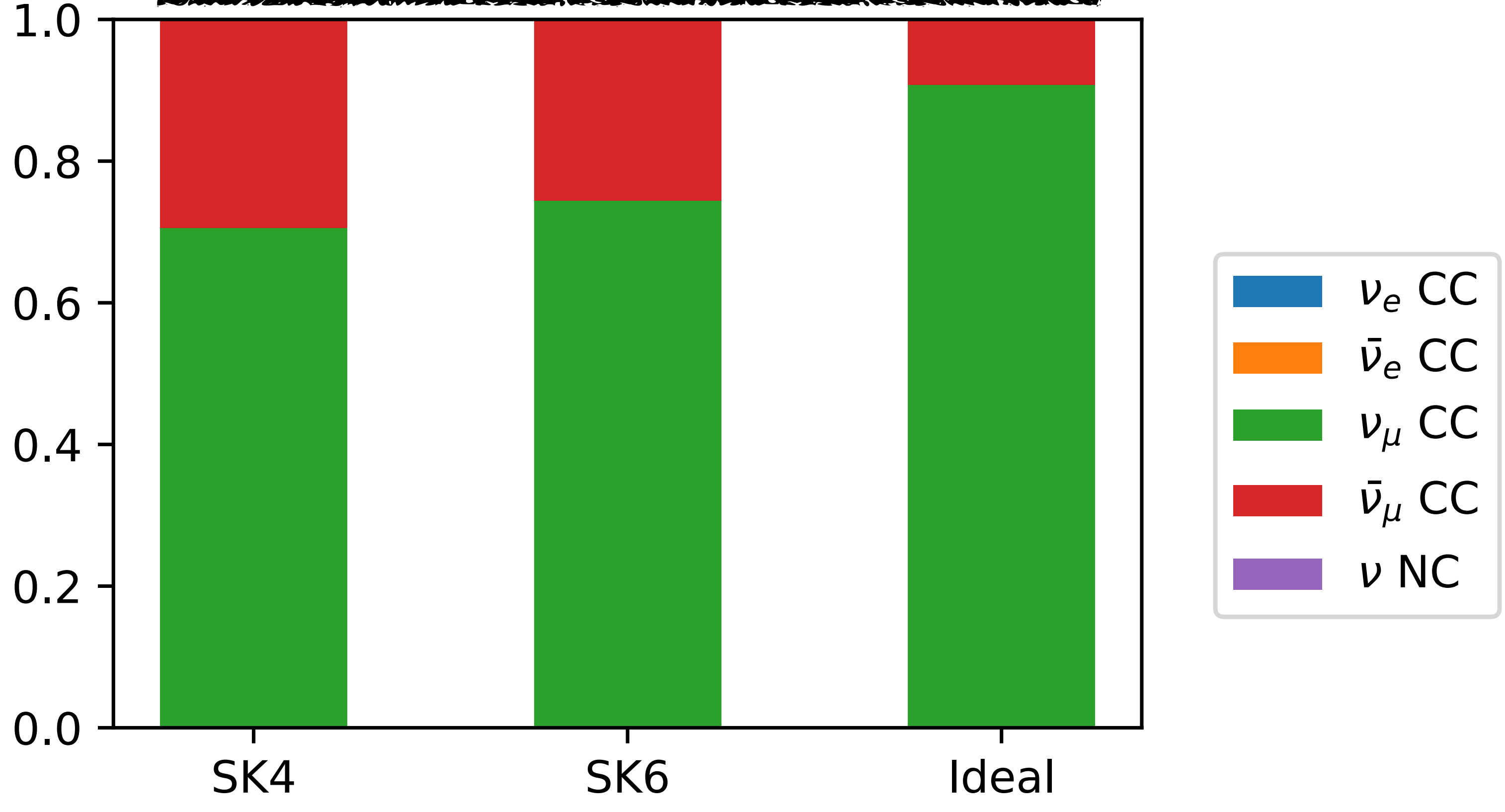
$\#e = 0$ & $\#n > 0$



Multi-GeV μ-like: true fraction in event subclasses

ν_μ-like

#e ≠ 1 | #n = 0



$\bar{\nu}_\mu$-like

#e = 1 & #n > 0