ν_e - ^{16}O Interactions with Low Energy Atmospheric Neutrinos in Super-Kamiokande

2nd Workshop for Atmospheric Neutrino Production
January 13th, 2021

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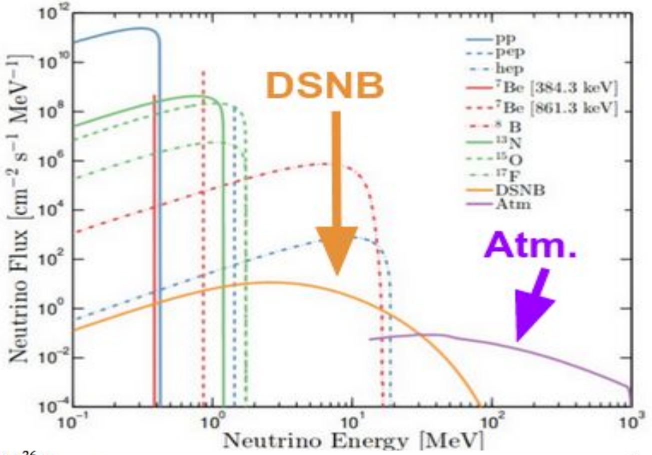
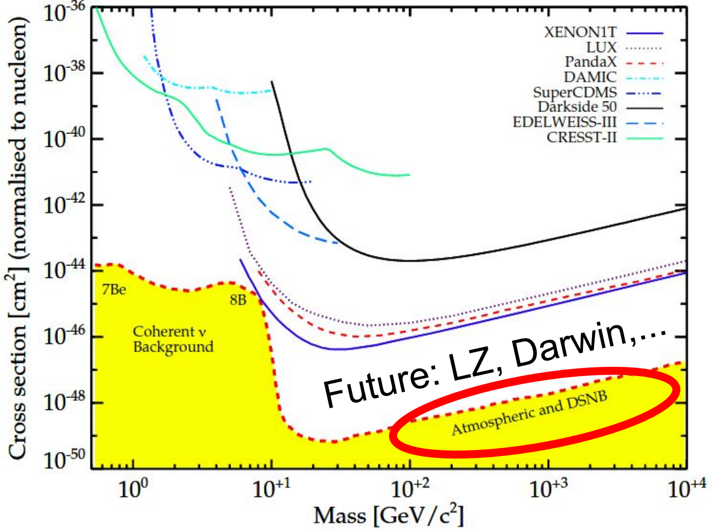
Introduction: Measuring $\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^*$

- **For supernova neutrinos:**
  - Electron neutrino detection channel in supernova bursts for Water Cherenkov detectors, has directional info
  - Background for Diffuse Supernova Neutrino Background (DSNB) searches

- **For atmospheric neutrinos:**
  - Way to probe uncertain low energy atmospheric neutrino flux
  - Atmospheric neutrinos in these energies are background in WIMP dark matter searches via CEνNS



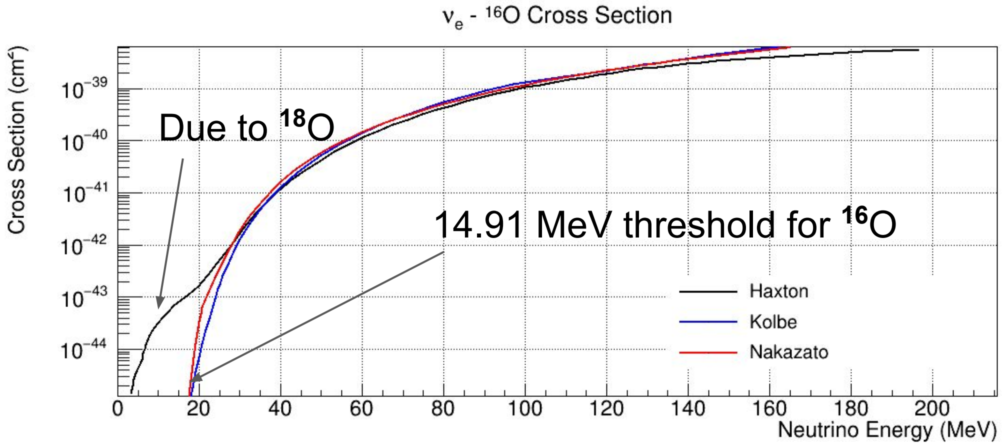
O'Hare
arXiv:1604.03858

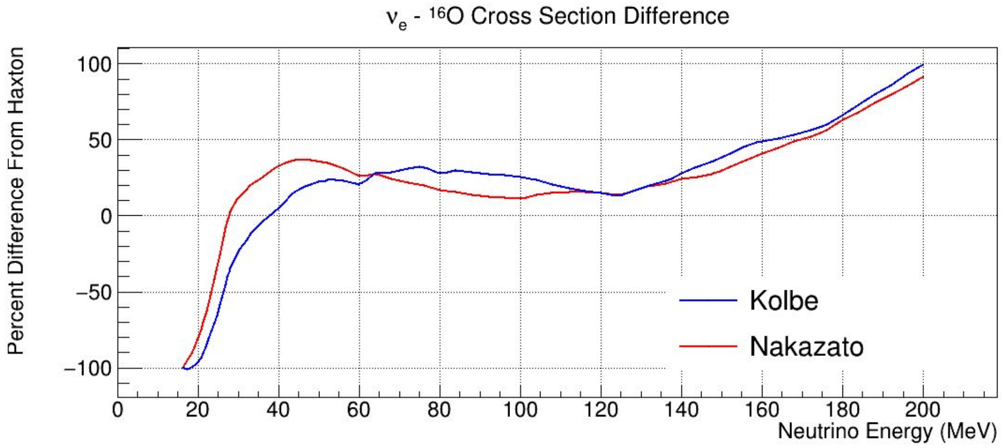


Dutta and Strigari,
arXiv:1901.08876

Introduction: Measuring $\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^*$

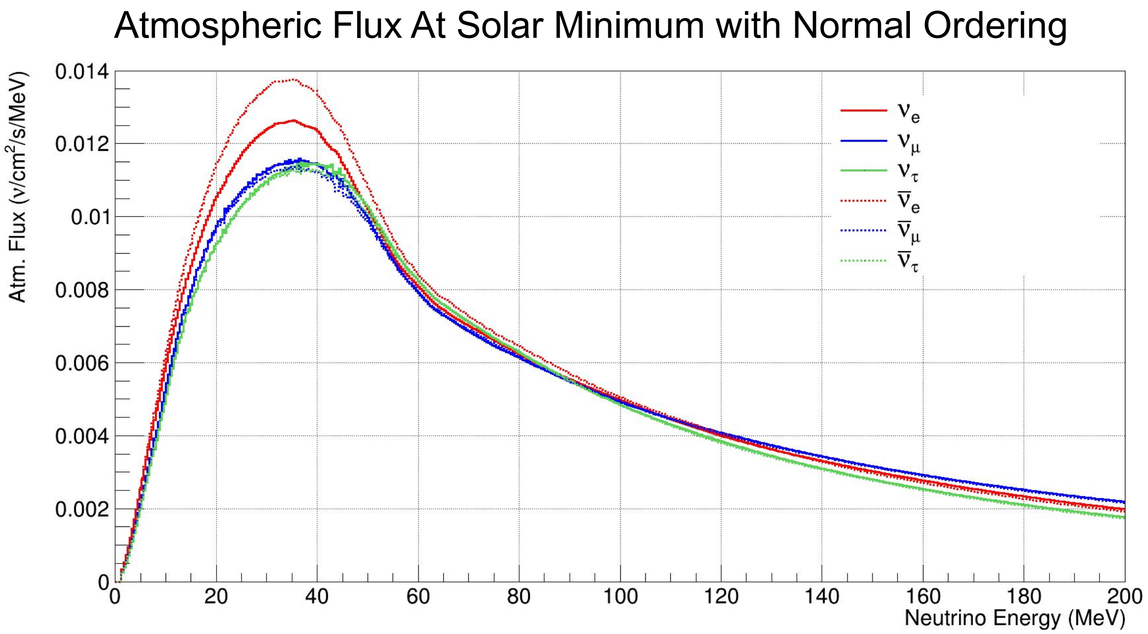
- Not measured between 0-100 MeV
- Various calculations for this energy range differ 30-40 % in total cross section
- We can have measurement of this cross section in SK
  - Will be an atmospheric neutrino flux weighted measurement
  - Need a separate measurement to separate cross-section and flux components
  - Potential for an independent ν_e-^{16}O cross section measurement in the future D_2O detector of COHERENT experiment





Atmospheric Neutrino Flux At 0 - 200 MeV

- **Created by cosmic ray interactions in the atmosphere**
- **~20 % normalization uncertainty at this energy range**
- **Contributes to neutrino floor for high WIMP masses**



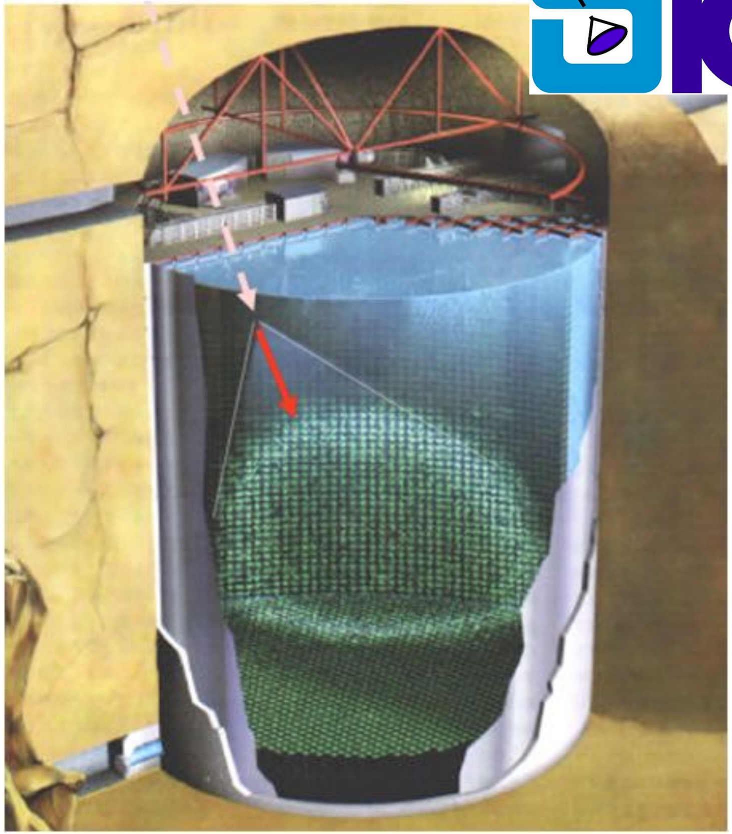
Original Flux at SK Location: (Honda et al.)

- For flux above 100 MeV (Honda et al. arXiv:1102.2688)

Oscillated Via: Prob 3++ Public Library
https://webhome.phy.duke.edu/~raw22/public/Prob3++/

Super-Kamiokande Experiment

- 50 kiloton - 22.5 kTon fiducial - Water Cherenkov Detector
- Well known for neutrino oscillations discovery, proton decay and DSNB limits…
- **It has been recording ν_e - ^{16}O interactions from atmospheric neutrinos for over 20 years: About 120 events expected in 30-100 MeV**



Abe et al. 2013 (SK Collaboration) arXiv:1307.0162
Image from: http://www-sk.icrr.u-tokyo.ac.jp/sk/detector/cherenkov-e.html

Low Energy Electron Neutrino Interactions In Water

Inverse beta decay (IBD):

$$\boxed{\bar{\nu}_e + \mathrm{p} \rightarrow e^+ + \mathrm{n}}$$

Charged current on oxygen:

$$\boxed{\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^*}$$

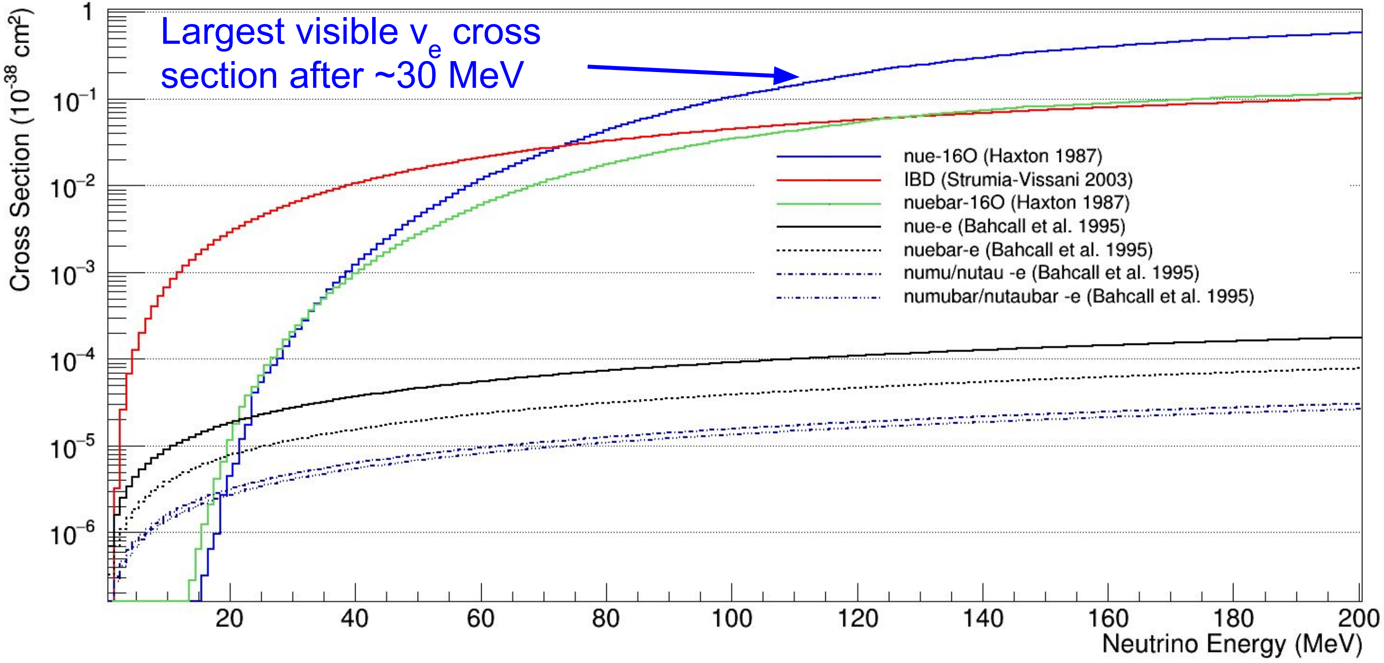
$$\boxed{\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}^*}$$

Neutral current on oxygen:

$$\boxed{\nu + {}^{16}\mathrm{O} \rightarrow \nu + {}^{16}\mathrm{O}^*}$$

ν-e elastic scattering:

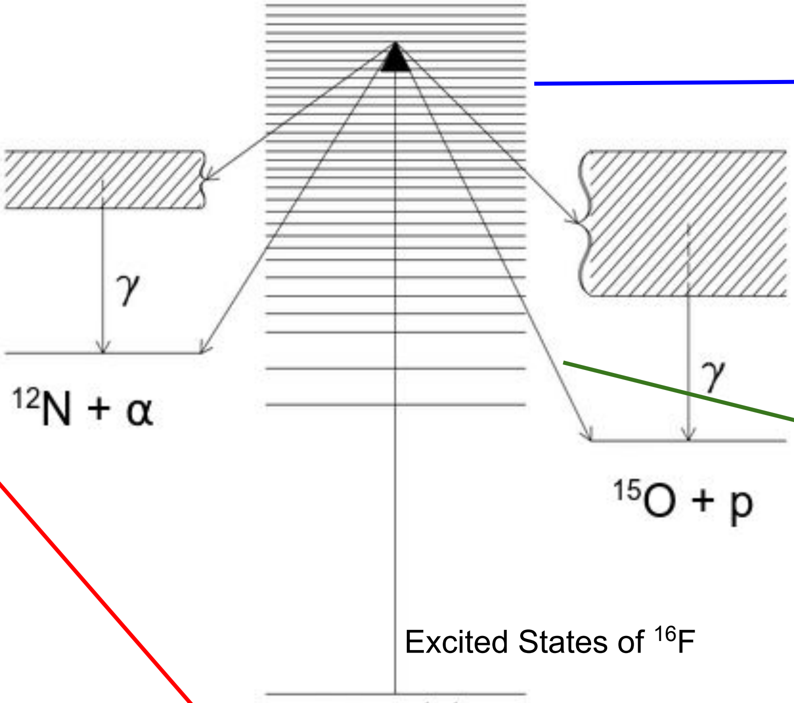
$$\boxed{\nu + e^- \rightarrow \nu + e^-}$$



- Charged current thresholds for ν_μ E = 110 MeV, for ν_τ E ~ 3.5 GeV
- Neutral current is not on the plot
- Charged current on oxygen are not well known….
- *** -> Excited State: Possible observable de-excitation products**

Generating $\nu_e(\bar{\nu}_e)$ - ^{16}O Events:

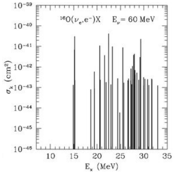
Image Modified from Kolbe et. al.
arXiv:nucl-th/0311022



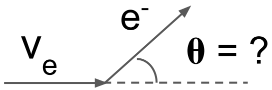
$$\nu_e + {}^{16}O \rightarrow e^- + {}^{16}F^{(*)}$$

Probabilities of excited states, depending on neutrino energy?

From Nakazato et al, arXiv:1809.08398

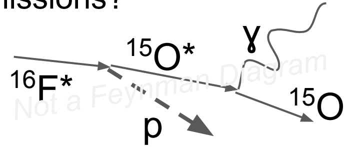


What is the angular distribution of outgoing electron?



From Haxton, 1987

How do excited states decay? Gamma rays, proton/neutron emissions?

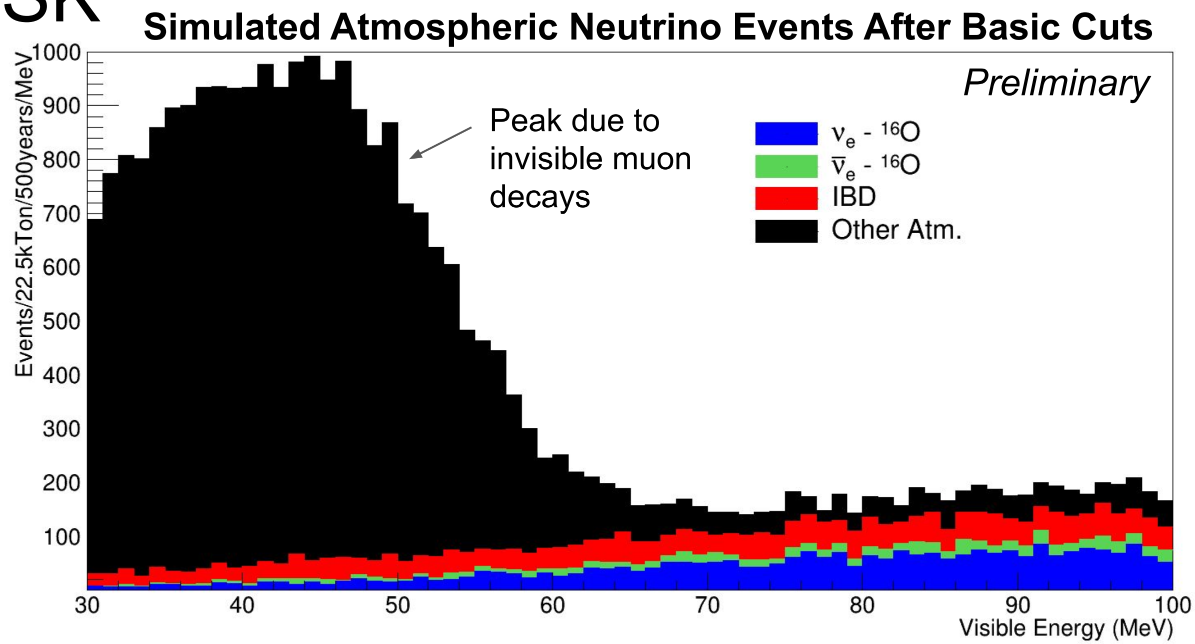


From TALYS Nuclear Reaction Software:
https://tendl.web.psi.ch/tendl_2019/talys.html

- Same questions for: $\bar{\nu}_e + {}^{16}O \rightarrow e^+ + {}^{16}N^{(*)}$
- Combine this info and build a custom event generator:
    - https://github.com/itscubist/newton
- Good up to ~115 MeV neutrino energy

Simulated Events in SK

- Simulate and reconstruct generated events with Super-Kamiokande software
- Apply basic cuts:
  - Within FV
  - 1 ring
  - PID: Electron like
  - No decay electron
- Further cuts are possible:
  - Neutron tagging in SK4 (Tag neutrons from IBD)
  - Currently Studying: Separating Events with Gamma Emissions



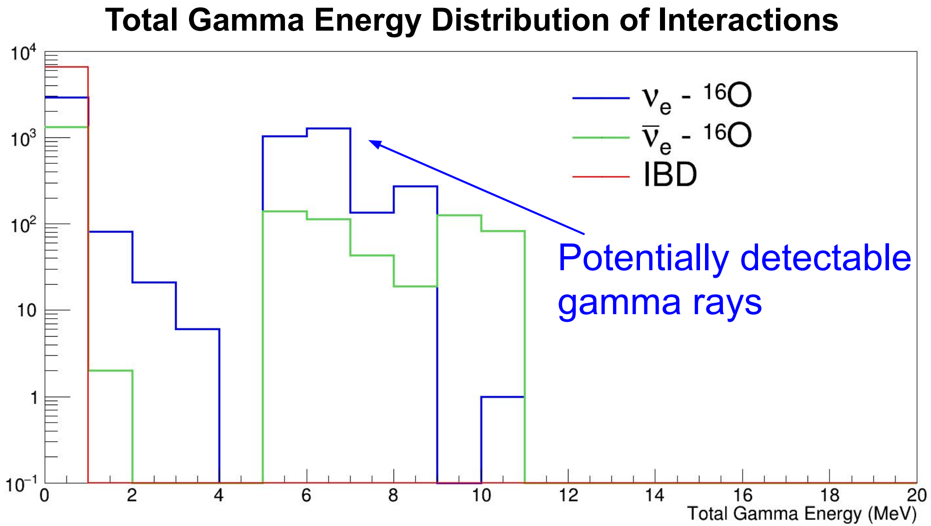
***Other Atm. :**

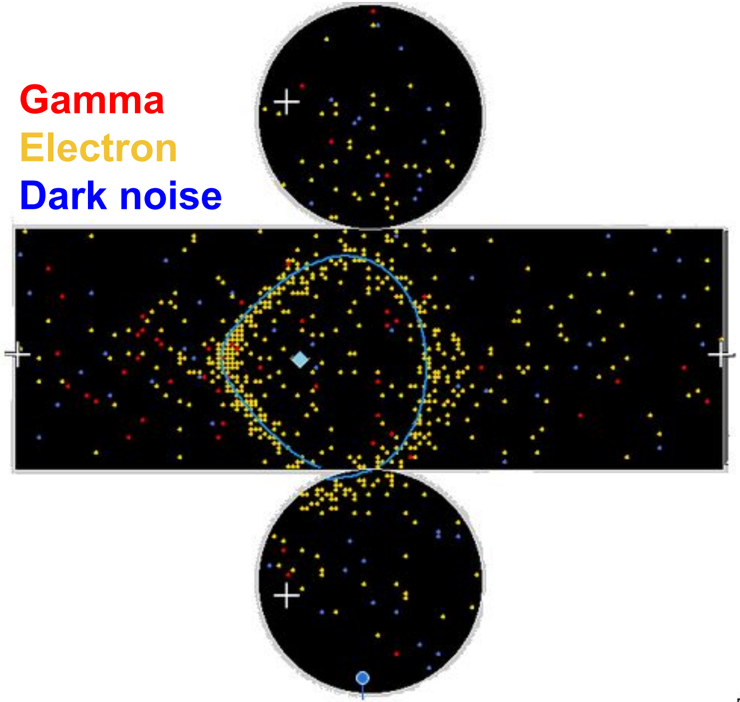
- Peak is due to decay of muons that are below Cherenkov threshold
- Tail is mostly charged current pion creating reactions...

- Currently the plot does not show v_e-^{16}O events that may leak down from >125 MeV neutrinos

Reducing Backgrounds: Gamma Tagging

- About half of the signal events have extra hits due to gamma rays above 3 MeV
- Backgrounds like IBD and decay electrons do not have gamma rays.
- Is it possible to differentiate electron events with and without additional gamma rays?

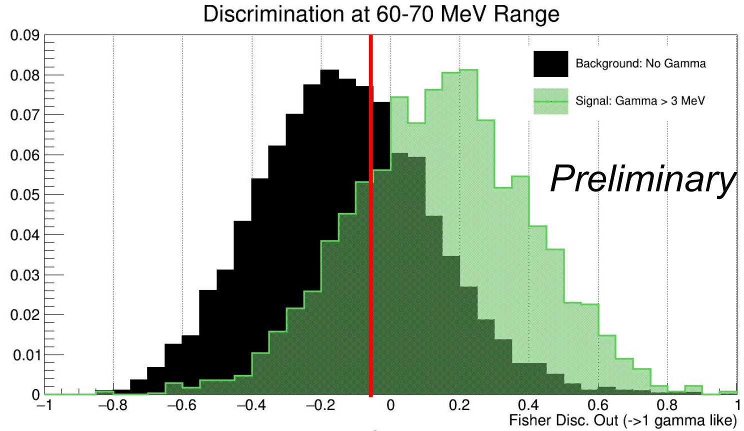


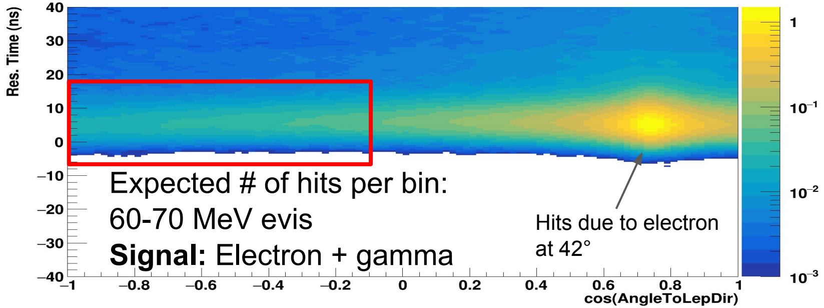


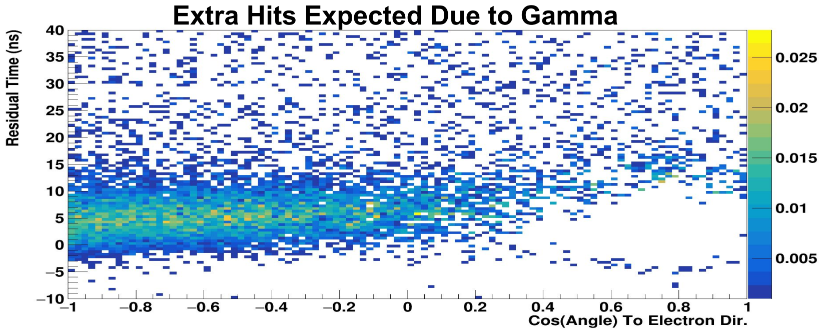
MC ν_e-^{16}O event: A 90 MeV electron accompanied by 3 gamma rays (total of 10 MeV) in SK

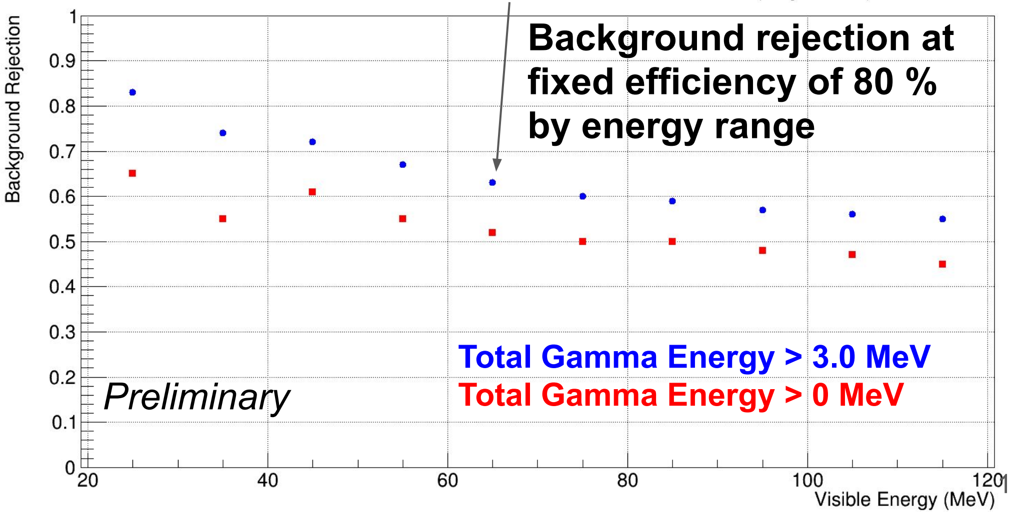
Reducing Backgrounds: Gamma Tagging

- Separate into 10 MeV energy bins
- Calculate variables representing:
  - Number and distribution of hits outside the Cherenkov pattern in time and angle
  - Overall isotropy of the detector
- Combine variables with Fisher Discriminant





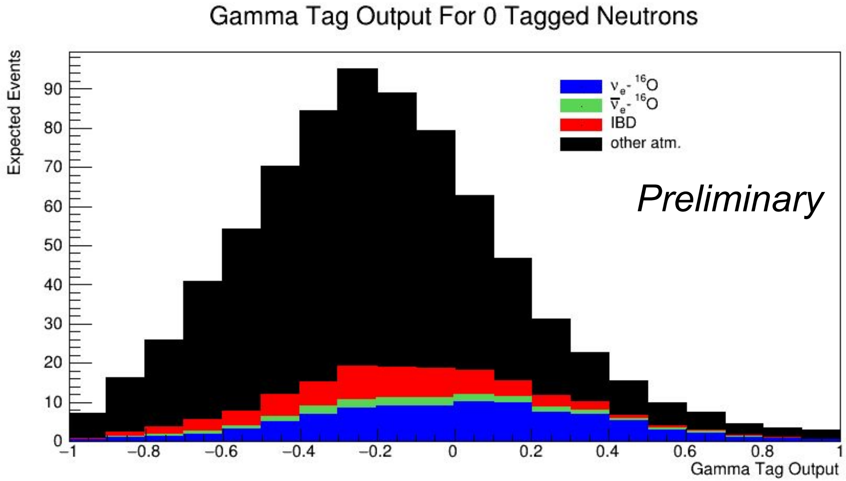


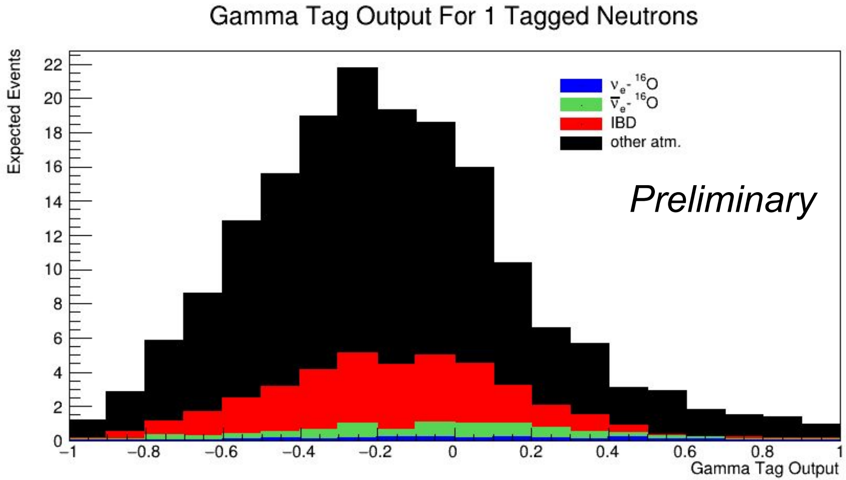


Gamma Tagging

In the plots, gamma tagging outputs of signal and background processes in case of 0 and 1 tagged neutrons:

- $^{16}F^*$ from ν_e-^{16}O interaction is proton rich, so no neutron emissions are expected…
- In 0 neutron histogram, IBD and other atmospheric neutrino backgrounds peak at -0.20
- While ν_e-^{16}O events with gamma emissions shift the peak to 0.1 in gamma tagging output





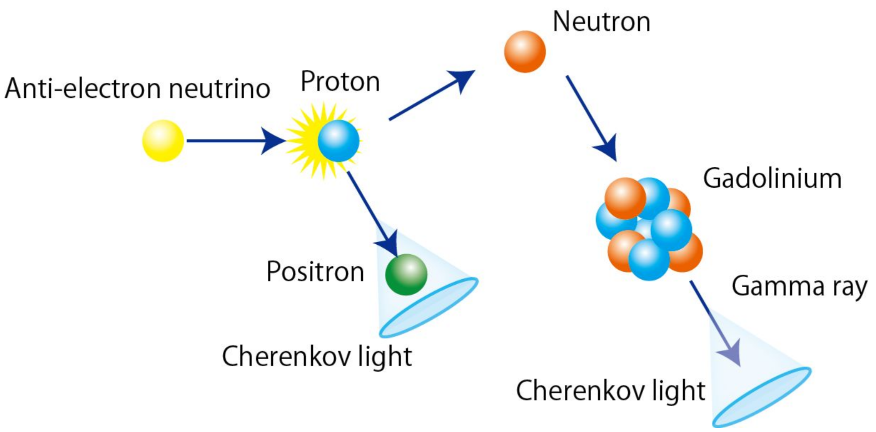
Summary

- Performing an atmospheric flux weighted ν_e-^{16}O cross section measurement in SK within 30 - 100 MeV range.
    - Previously unmeasured!
    - Relevant to supernova and atmospheric neutrino physics, as well as WIMP dark matter searches.
- A custom event generator for MC studies of ν_e-^{16}O events is built based on available information in the literature.
- Working on event selection methods such as identifying events with gamma emissions.
- A future separate cross section measurement will help with decoupling flux and cross-section information.
    - For example, proposed heavy water detector by the COHERENT Collaboration in SNS (ORNL).

BACK UP

SK-IV to SK-V and SK-Gd Upgrade

- **SK-IV to SK-V :**
  - Water leak is reduced to < 0.017 tons/day (< 1/200th of the previous value), this reduction is essential for Gd loading
  - Many PMTs in ID and OD are replaced:
    - More than 200/1885 PMTs in OD
  - PMT high voltages are rearranged
  - Data taking restrated in January, 2019
- **SK - Gd Final Goal:**
  - Dissolve 0.2 % (current 0.02 %) $Gd_2(SO_4)_3$ in SK water by mass
  - Neutron tagging, thanks to high neutron capture rate of Gadolinium, by observing Compton scattering of emitted gamma rays after capture
  - Neutron capture time: ~ 20 us
  - Beneficial to all analyses, mainly to DSNB search by helping select IBD events



- In SK-IV neutron capture on H (in ~180 us) is utilized, with ~ 18% efficiency
- SK-Gd current 0.02 % by mass -> 50 % efficiency
- Sk-Gg final 0.2 % by mass ~90 % efficiency

Gd loading

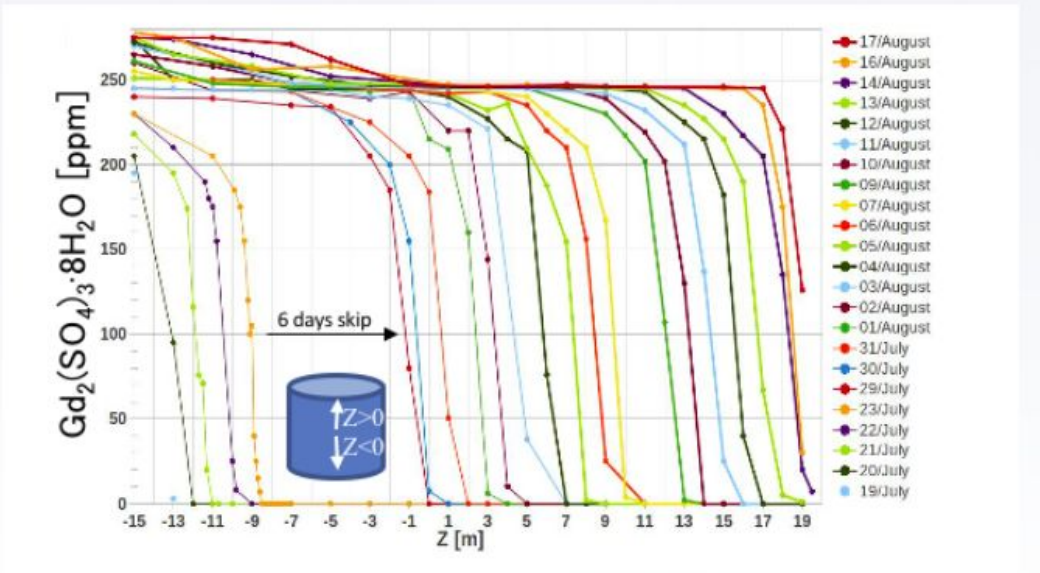
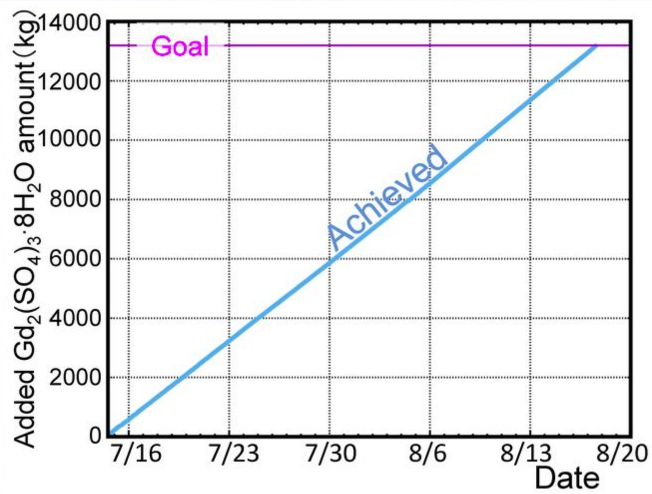


Fig.11 $Gd_2(SO_4)_3 \cdot 8H_2O$ concentration in the tank changed daily

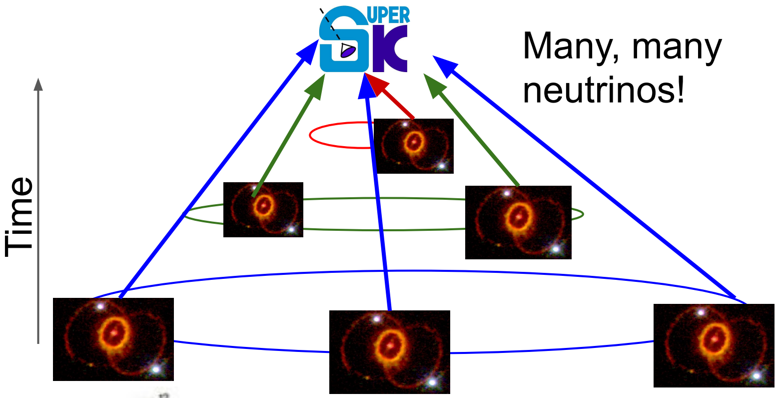
Fig.7 Gadolinium sulfate octahydrate ($Gd_2(SO_4)_3 \cdot 8H_2O$)

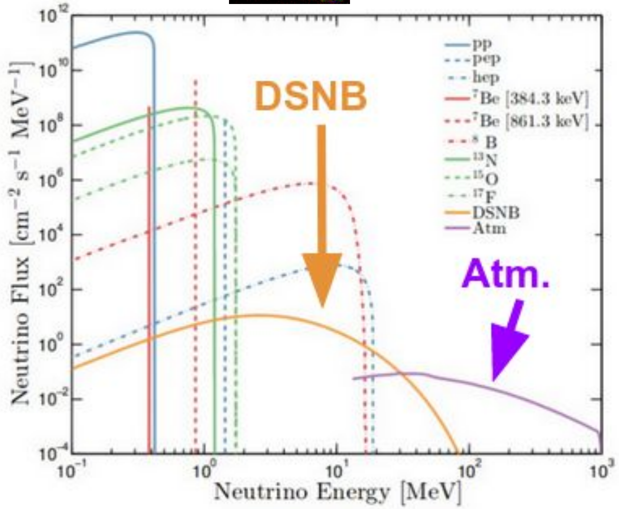


Press release: http://www-sk.icrr.u-tokyo.ac.jp/sk/news/2020/08/sk-gd-detail-e.html

Diffuse Supernova Neutrino Background (DSNB)

- Core collapse SN emit ~10^{46} J of neutrinos
- We can see the bursts within our galaxy
- But they are rare (2-3 per century)
- But there should be a constant stream of neutrinos from all the past SN
  - Isotropic, all flavors…
  - But search for anti-electron neutrinos
    - Remember: $\bar{\nu}_e + \mathrm{p} \rightarrow e^+ + \mathrm{n}$
    - Cross section is high
    - Neutrons can be tagged
  - Predictions ~ 0.05-0.5 $\bar{\nu}_e$ /cm^2/s @ 20 MeV
  - Current limits ~ 1 $\bar{\nu}_e$ /cm^2/s @ 20 MeV
- **Atmospheric neutrinos will be a background even after neutron tagging:**
  - Atmospheric $\bar{\nu}_e$ and ν-^{16}O emitting neutrons

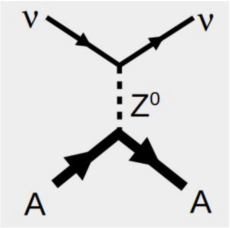




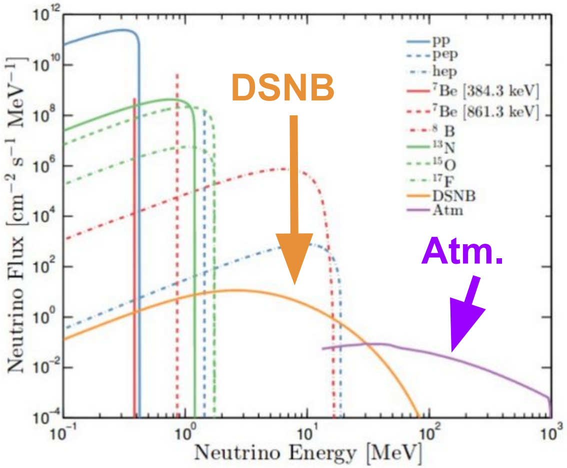
O'Hare arXiv:1604.03858

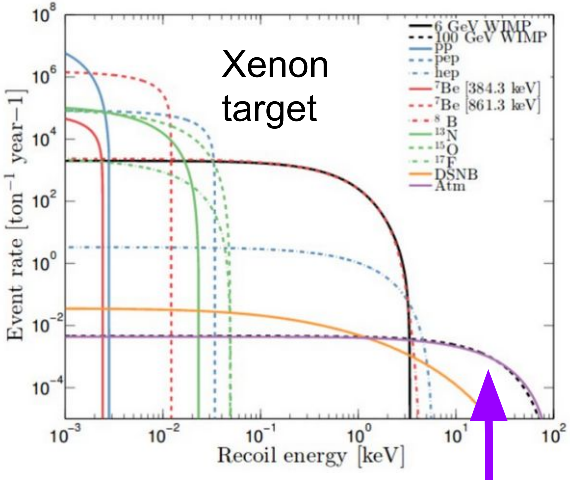
Nuclear Recoils From Atmospheric Neutrinos

- But neutrinos can also cause nuclear recoils via:
- CEvNS: Coherent Elastic Neutrino-Nucleus Scattering
  - All neutrino flavors
  - Mimics WIMP recoils
  - Creates **"neutrino floor"**
  - Atmospheric neutrino recoils mimic ~ 100 GeV and above

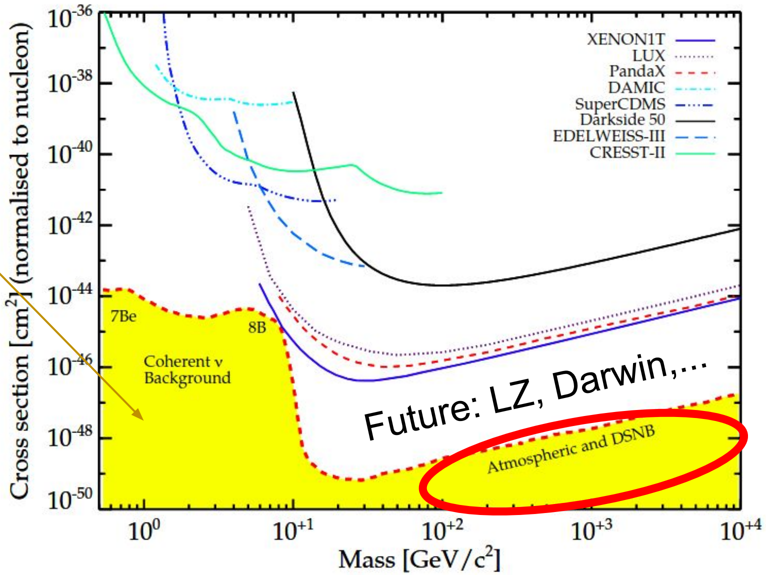


CEvNS Diagram
From:
J. Raybern APS
April 2015





Atm. and ~100 GeV dark matter recoils have similar shape!



Top:
O'Hare
arXiv:1604.03858

Bottom:
Dutta and Strigari,
arXiv:1901.08876

Evis Dist.

For neutrinos below 125 MeV
Use custom generator (NEWTON)

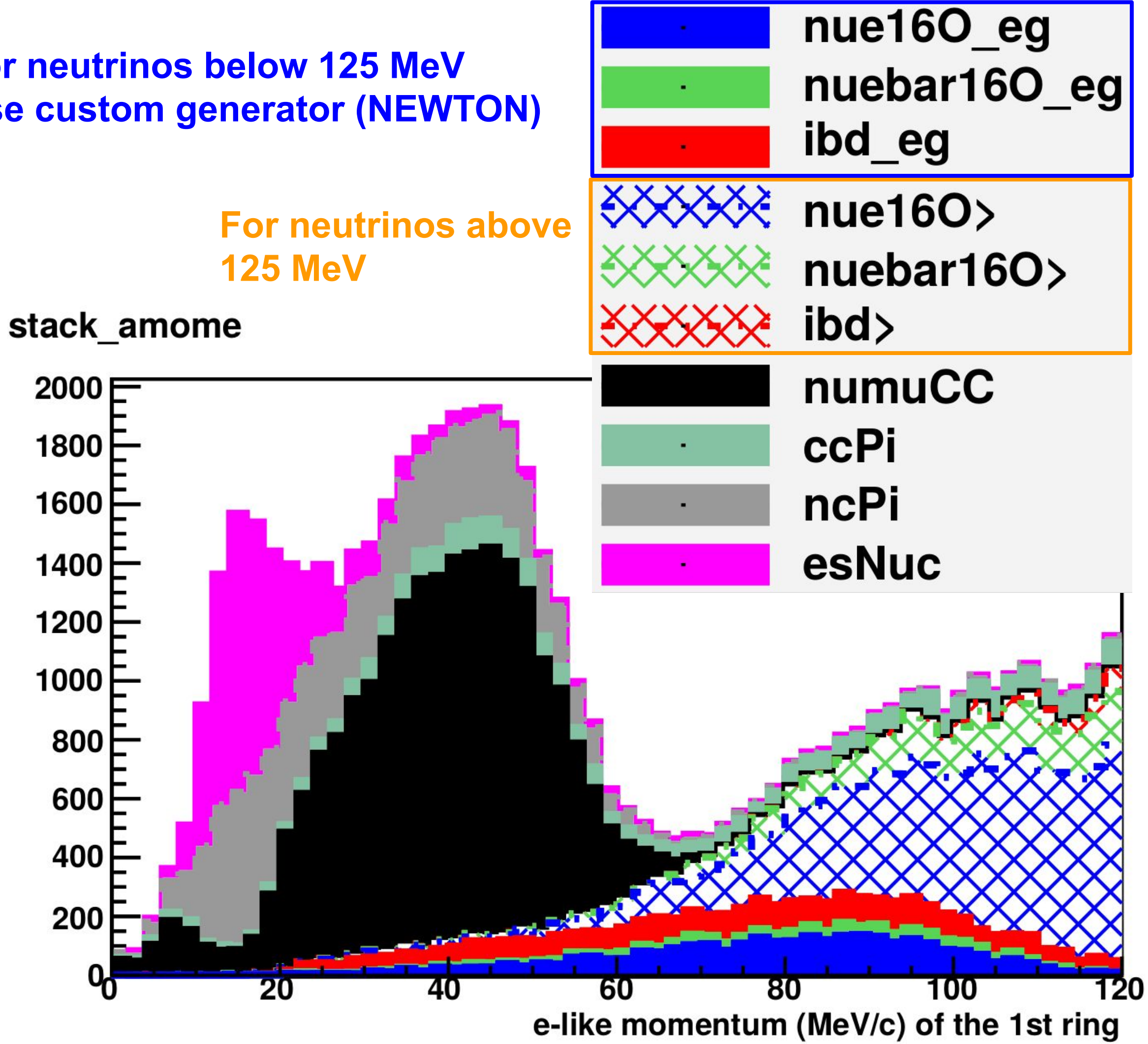
For neutrinos above
125 MeV

Breakdown of events:

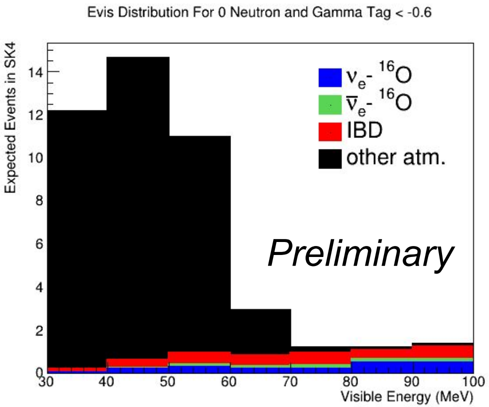
- Replaced below 125 MeV nue-^{16}O, nuebar-^{16}O and IBD events with custom EG, otherwise everything from ATMPD MC

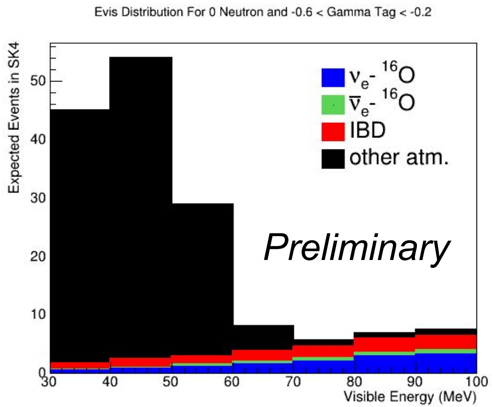
Cuts Applied:

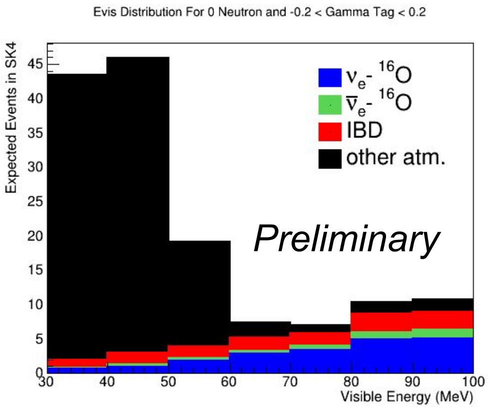
- FC reduction
- wall>200
- nring==1
- nmue==0
- ip[0]==2

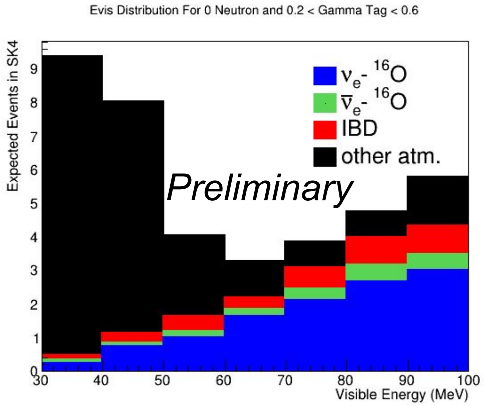


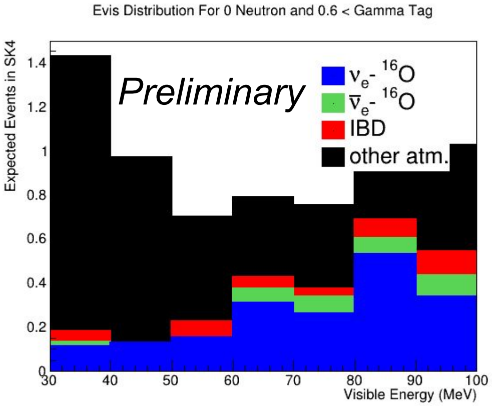
Visible Energy Distributions Across Gamma/Neutron Tagging Groups

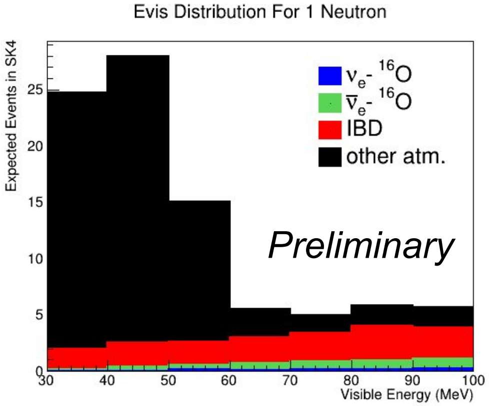








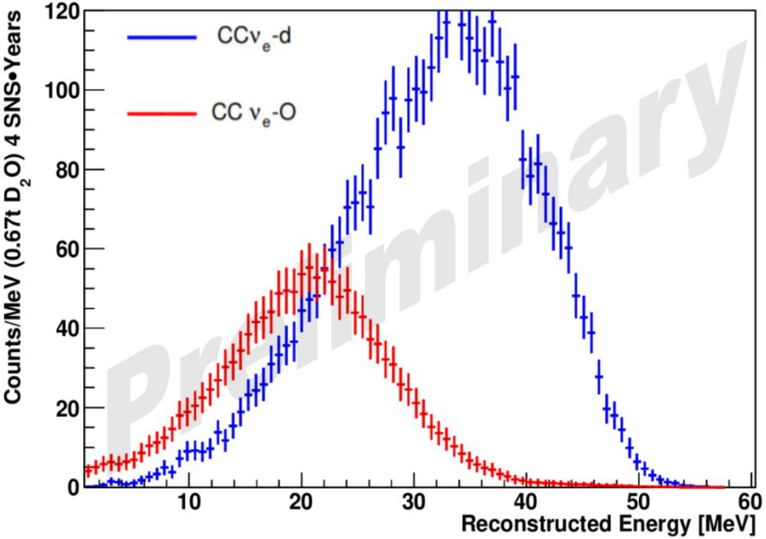




COHERENT D_2O Detector

- COHERENT experiment observed CEvNS for the first time!
  - Neutrino flux from SNS will soon be dominant sys. uncertainty ~ 10 %
- D_2O detector to measure to 3 %, via well known ν_e - deuteron cross section.
  - ν_e - ^{16}O is a background for this meas.
  - The generator can come in handy...
- **More interestingly, possible to measure ν_e-^{16}O cross section up to 50 MeV as well (depends on final design…)**
  - Can help separating flux and cross section components of the SK meas...
- ~300 events for 1.3 ton detector in 2 years

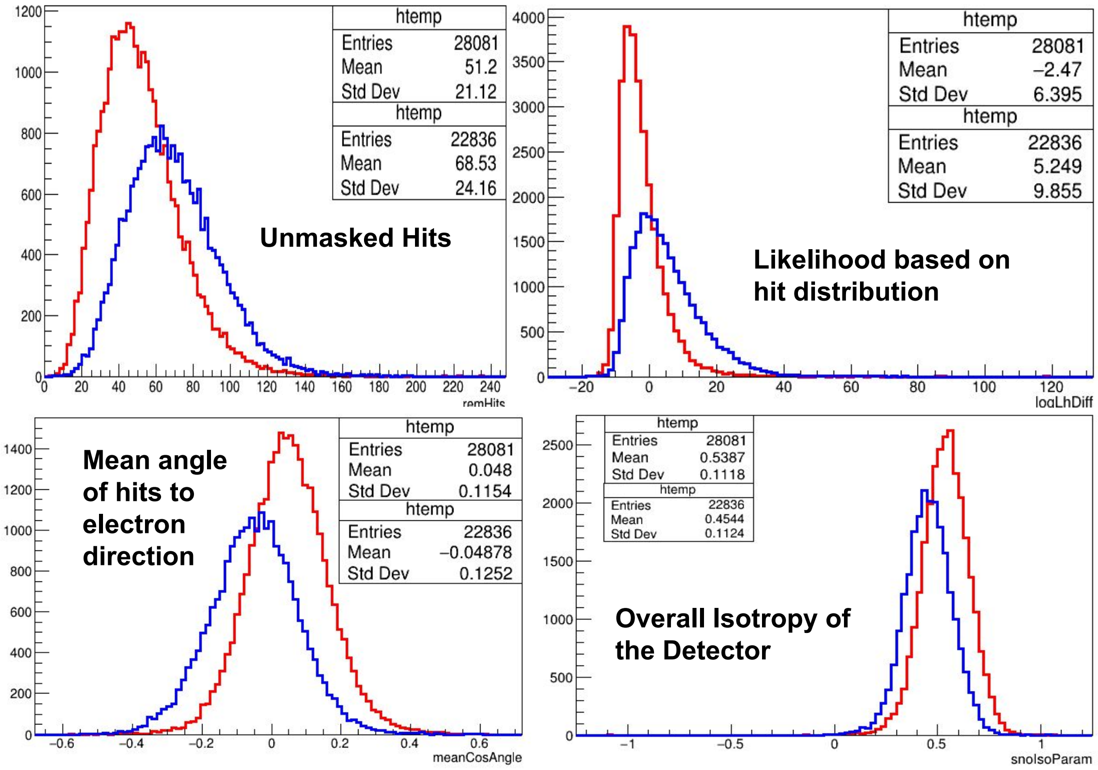
Rapp, arXiv:1910.00630



BACK UP
(Details on Gamma Tagging)

Calculating Variables:

- Number of hits outside the masked region
- Likelihood ratio based on distribution of hits across residual time and angle to electron direction plane
- Mean of angles between each unmasked hit and the electron direction
- Overall isotropy of the detector
- Angle between reconstructed electron direction and reconstructed direction of the unmasked hits
- 4 more variables with lower separation power



Events with no hits from gamma rays
Events with at least 1 hit from gamma rays

Combining Variables with ROOT TMVA

- Combine variables with Fisher discriminant:
  - Best linear combination based on means and covariance matrix of variables to separate signal and background
  - Ignores shape difference of the distributions: so can be improved.
  - Following slides will show the classification with this method

Coefficient of each variable

Used variables

$$t(\mathbf{x}) = a_0 + \sum_{i=1}^{n} a_i x_i$$

$$\mathbf{a} \propto W^{-1} (\boldsymbol{\mu}_0 - \boldsymbol{\mu}_1)$$

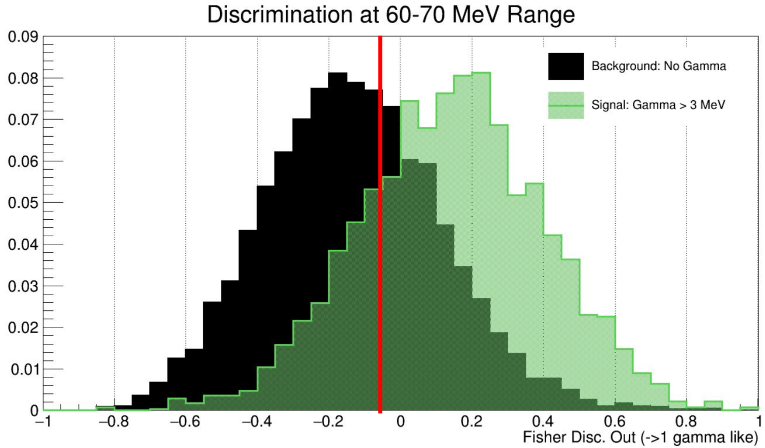
Inverse of covariance matrix (sum of signal and backgrounds cov matrix)

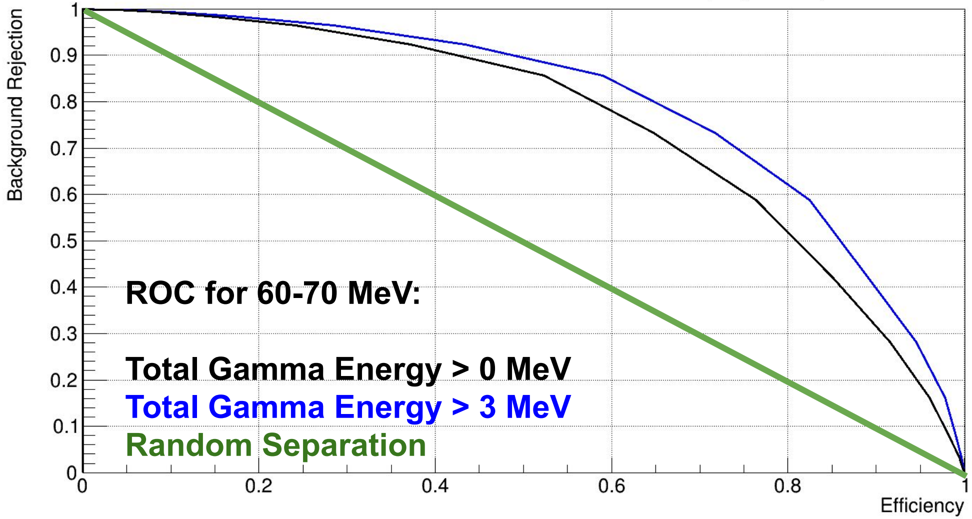
Difference between means of signal and background

- Trying other MVA Classification Methods:
  - So far experimented with Boosted Decision Trees, but no improvement over Fisher discriminant is observed
  - Can try more complex methods like NN in the future...

Results for Evis [60-70) MeV Bin

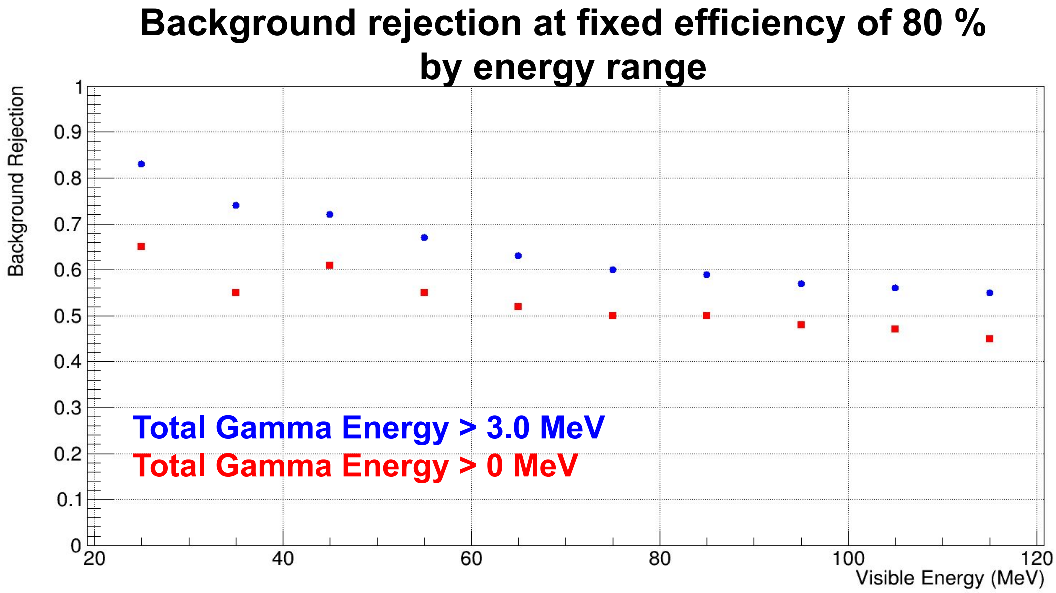
- The output of our MVA (Fisher discriminant) provides visible separation between "electron" and "electron+gamma" events
- When separating events with E > 3 MeV gamma rays, 62 % background rejection at 80 % efficiency is achieved.
- When total gamma energy in the event is less than 3 MeV, there are cases where no hits from gamma rays are observed, reducing the separation

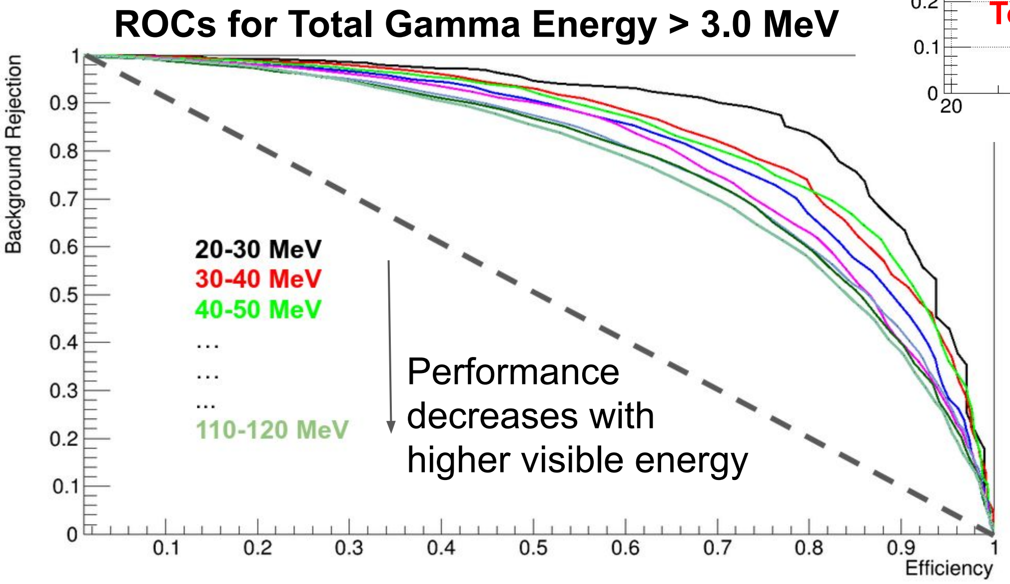




At other energies:

- The performance of gamma tagging is different across energies from 20-120 MeV
- In general better performance at lower energies due to lower scattered hits.

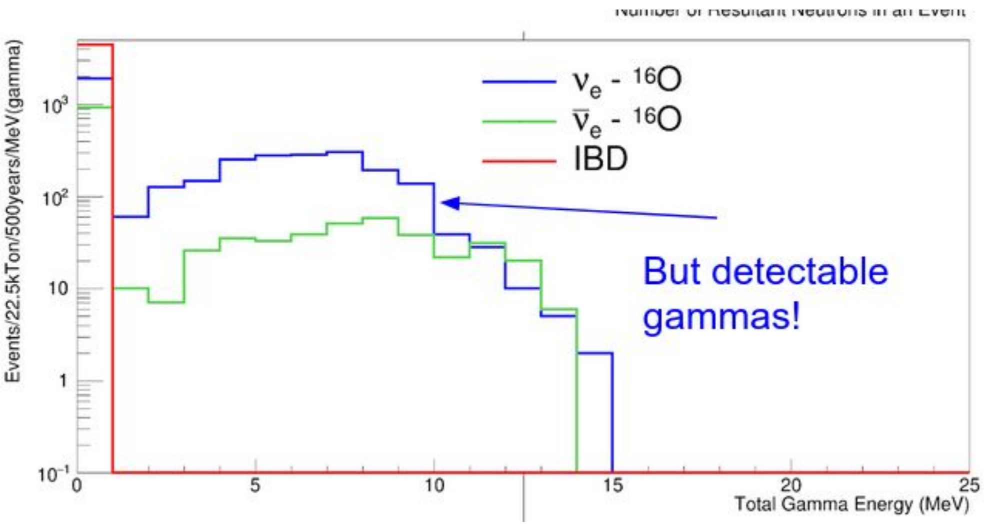




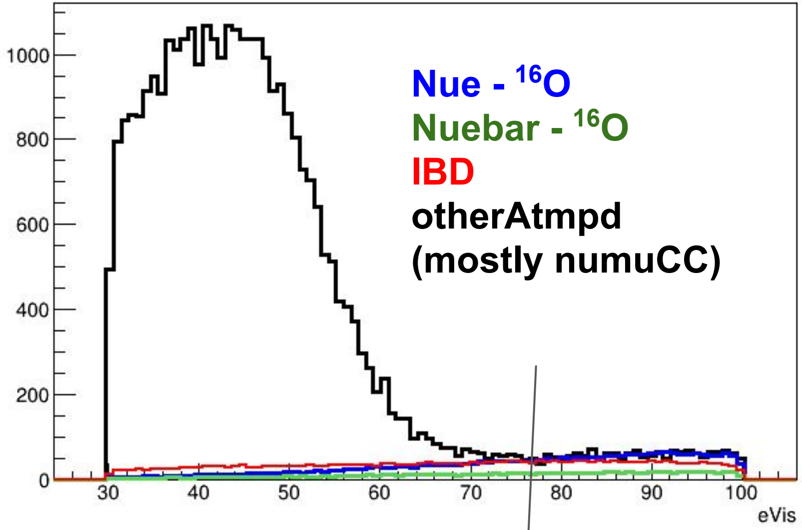
Gamma Tagging Progress and Next Steps

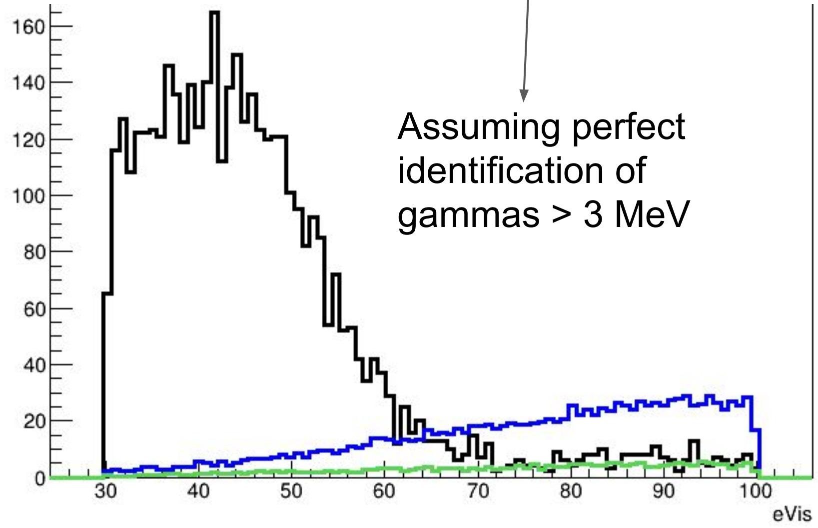
- Identifying events with gamma rays alongside the electrons will help separating ν_e-^{16}O from backgrounds such as IBD.
- Variables that can be used to identify a single electron event from a simultaneous electron+gamma event between 20-120 MeV range are calculated.
- Using Fisher (linear) discriminant method variables are combined into a single variable that can be used to tag gamma events with ~60 % background rejection at 80 % selection efficiency.
- Possible performance increase by using more complex MVA methods and vertex position dependence can be studied in the future.
- Systematics that might be associated with gamma tagging output such as change in water quality also needs to be studied.

Why Gamma Tagging?



- Significant portion of nue-^{16}O events are accompanied by gamma rays
- In contrast IBD interactions has no gamma rays, and neither most of the other atmospheric neutrino events.

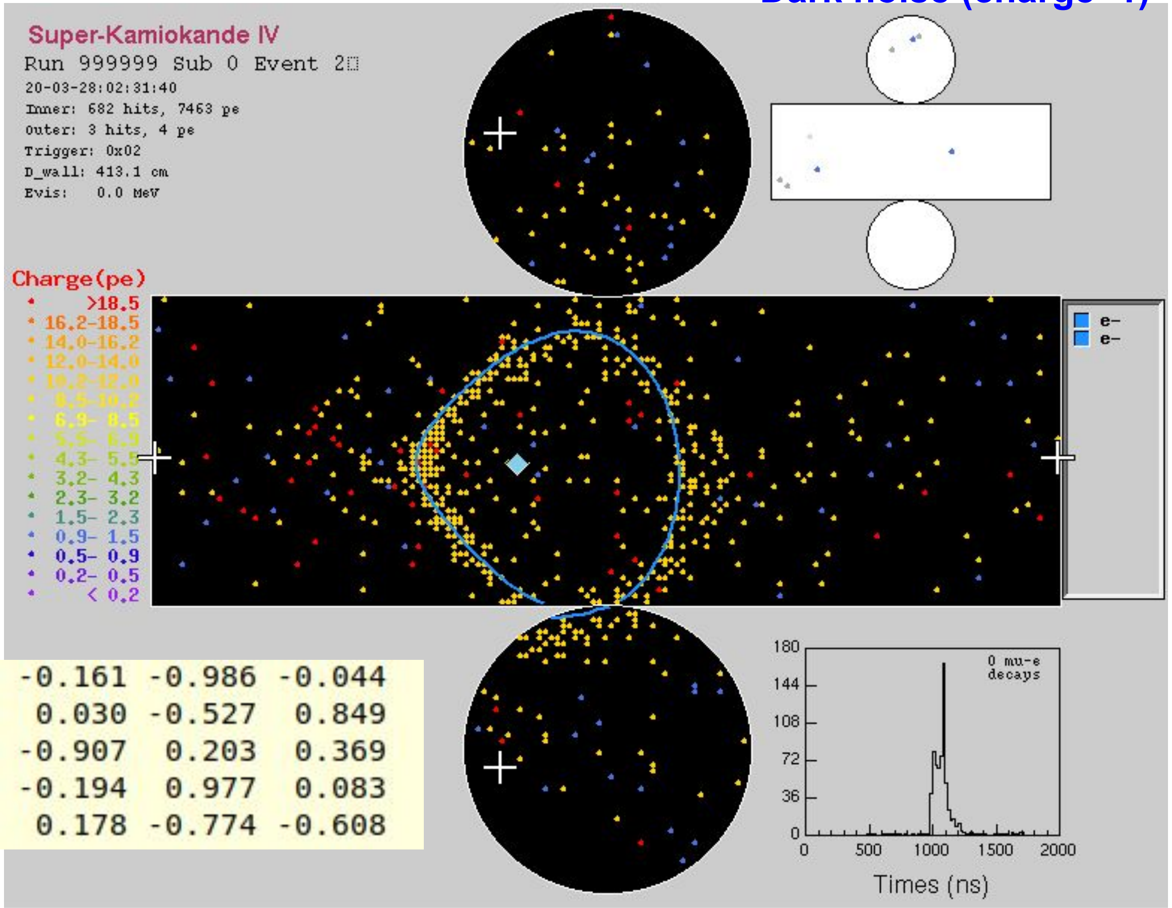




Example nue-16O Event with gamma

- Modified skdetsim to show an example event...
- Gamma rays are emitted right after the interaction
- Total 9 MeV worth of gamma rays, and a 90 MeV electron

Gamma (charge=22)
Electron (charge=11)
Dark noise (charge=1)



e-	M=	0.5	p=	89.2 MeV/c	dir=	-0.161	-0.986	-0.044
p	M=	938.3	p=	69.6 MeV/c	dir=	0.030	-0.527	0.849
gamma	M=	0.0	p=	2.0 MeV/c	dir=	-0.907	0.203	0.369
gamma	M=	0.0	p=	2.0 MeV/c	dir=	-0.194	0.977	0.083
gamma	M=	0.0	p=	7.3 MeV/c	dir=	0.178	-0.774	-0.608

Simulated Samples to Study Gamma Tagging

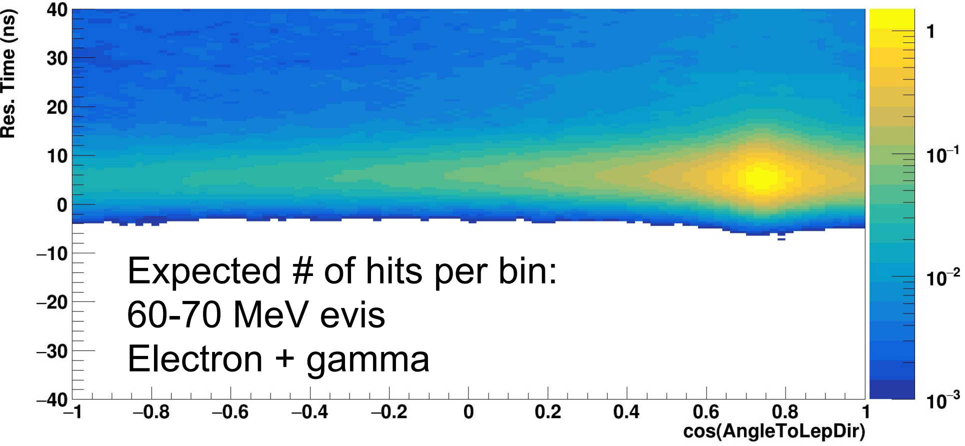
- Simulated 50000 years of nue-16O, nuebar-16O sample
  - About 600000 events
  - About half of the events have gamma energies varying from 0-15 MeV
  - To train/test multivariate approach to gamma tagging
- Simulated 5000 years of nue-16O, nuebar-16O and IBD sample
  - About 115000 events
  - To make the masks for the main sample
- Another 5000 years of nue-16O, nuebar-16O and IBD sample
  - To study the output of the gamma tagging along with the atmpd sample

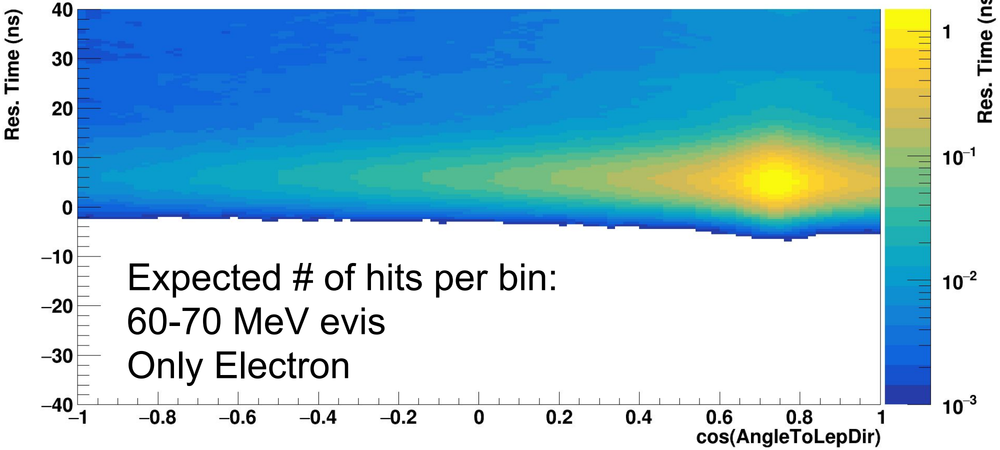
Masking Electron Hits

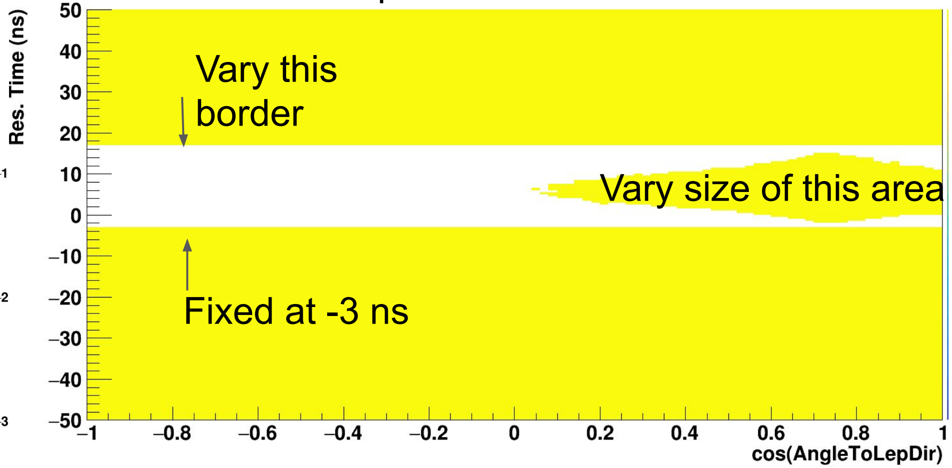
- Since electron creates many more hits than the gamma, we have to mask the hits that are most likely due to electron.
- Originally I was just masking based on angle from the reconstructed electron direction
  - However, after seeing the muon masking method in Takenaka-san's p->nu+K study I adopted that approach.
- In this case only the reconstructed energy of the event is known:
  - Need to make different masks for different reconstructed energies
  - Divide into 10 MeV evis bins from 20-120 MeV
  - In the slides I will show the method on 60-70 MeV energy bin, but all bins are similar, at the end I will show the outcome for all energy bins...

Masking Criterion

- **Deciding where to mask:**
  - Fix lower edge of residual time at -3 ns (almost only dark hits before then)
  - Then vary upper edge of residual cut and upper threshold of expected hits from an electron simultaneously
  - Select the combination that maximizes the difference between electron+gamma and just electron distributions in the unmasked region
    - For 60-70 MeV:
      - Residual Time < 17 ns
      - Expected Electron Hits < 0.06

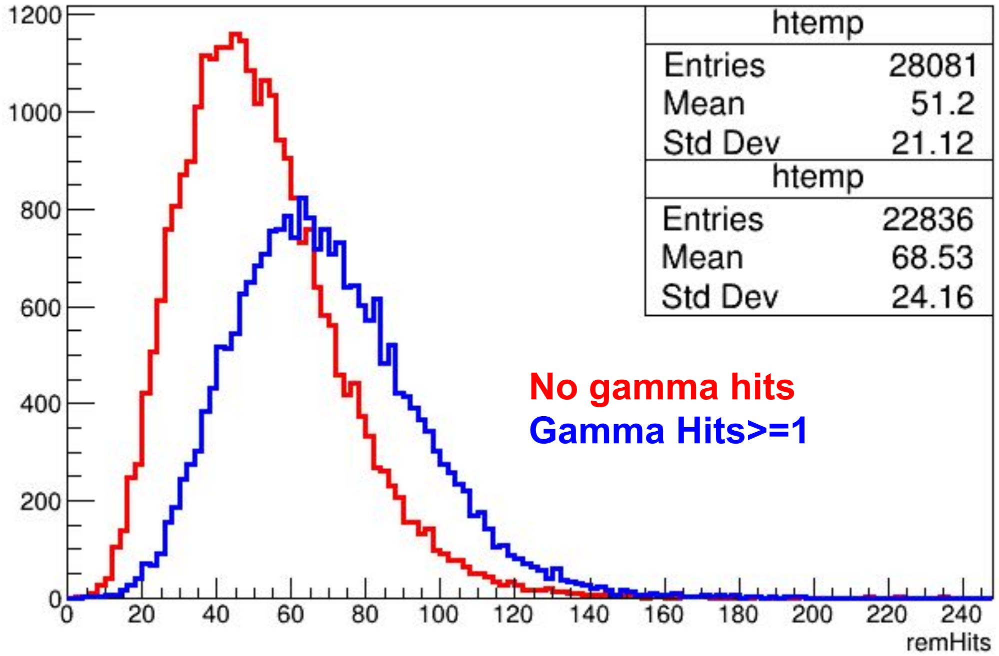


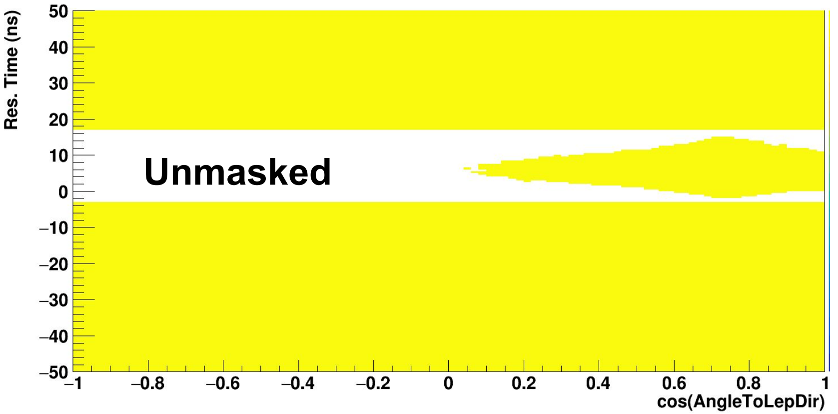




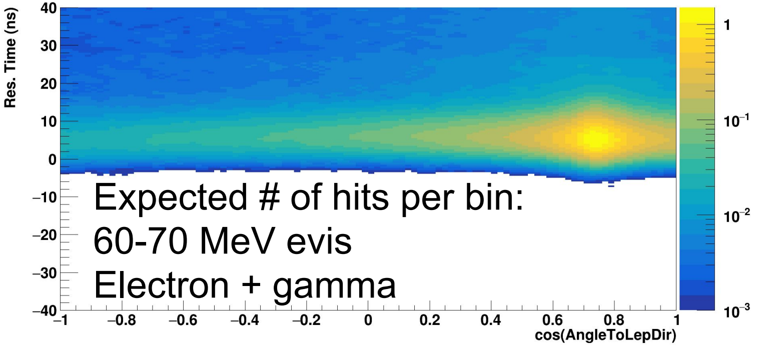
Variables: Unmasked Hits

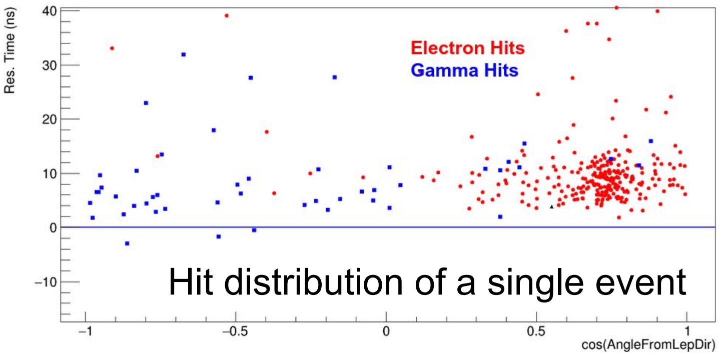
- Simply remaining hits after the masking

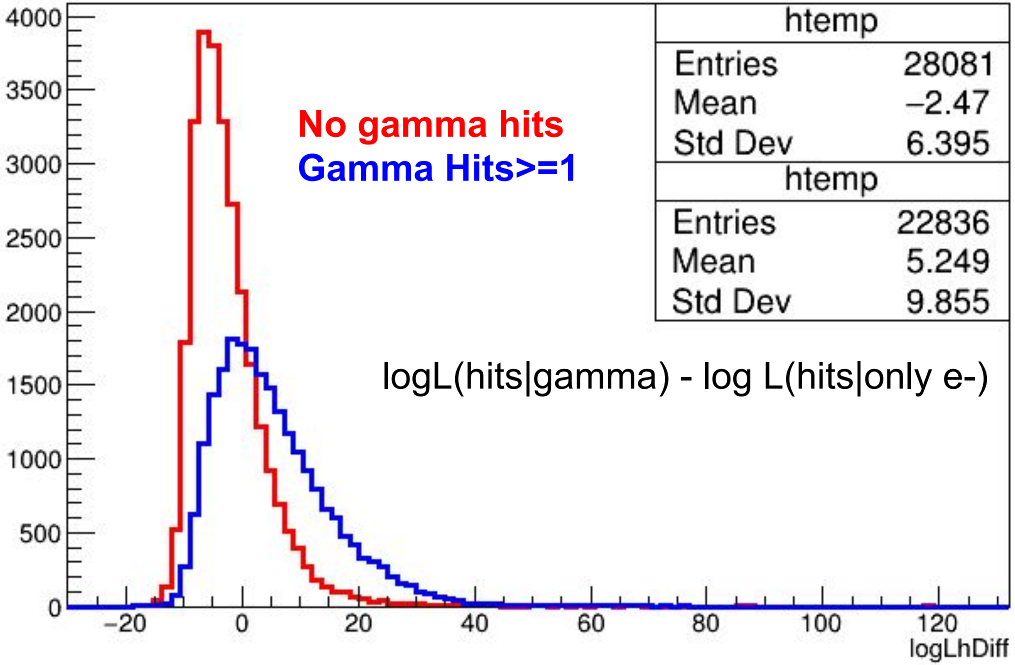




Log Likelihood Difference







- Based on the unmasked area only, calculate the likelihood of this event being a single e- or e- and a gamma:

$$\log L(\boldsymbol{\theta}) = n \log \nu(\boldsymbol{\theta}) - \nu(\boldsymbol{\theta}) + \sum_{i=1}^{n} \log f(x_i; \boldsymbol{\theta})$$

$$= -\nu(\boldsymbol{\theta}) + \sum_{i=1}^{n} \log(\nu(\boldsymbol{\theta})\, f(x_i; \boldsymbol{\theta})),$$

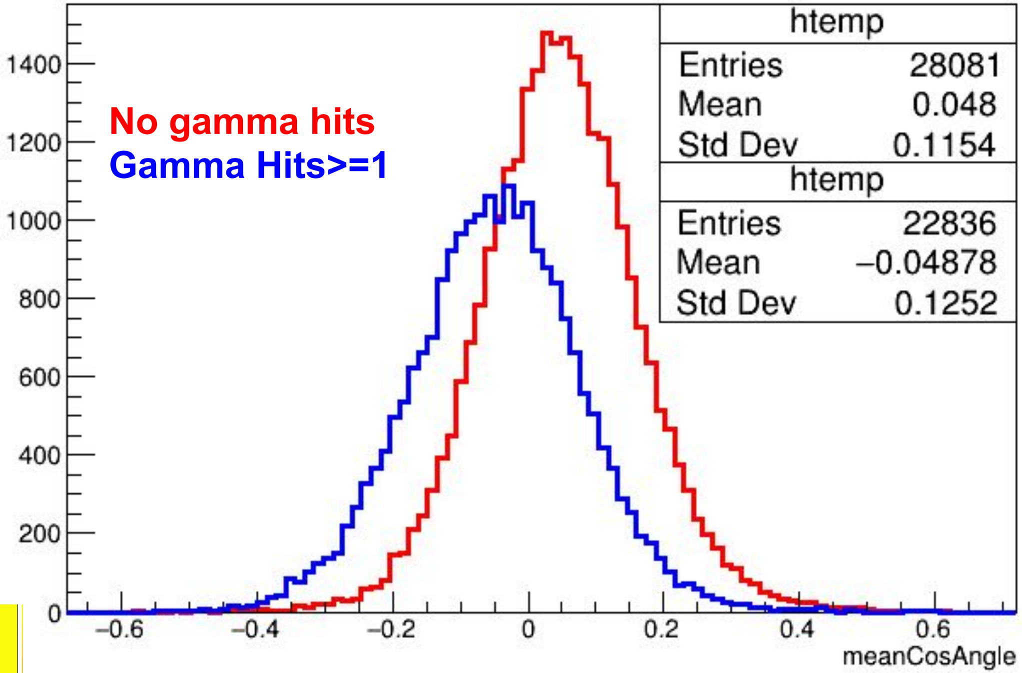
Expected # of hits

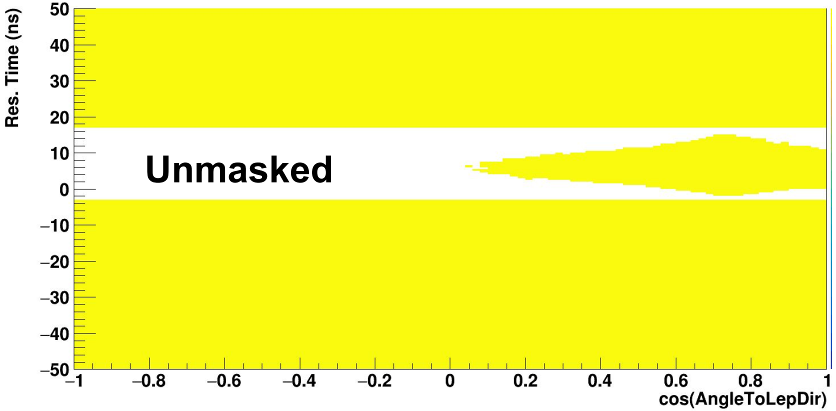
Probability of being the particular hit

Mean Cos Angle to Dir.

Calculate the angle between unmasked hits and the reconstructed electron direction.

Get the mean of those angles and use as a parameter...





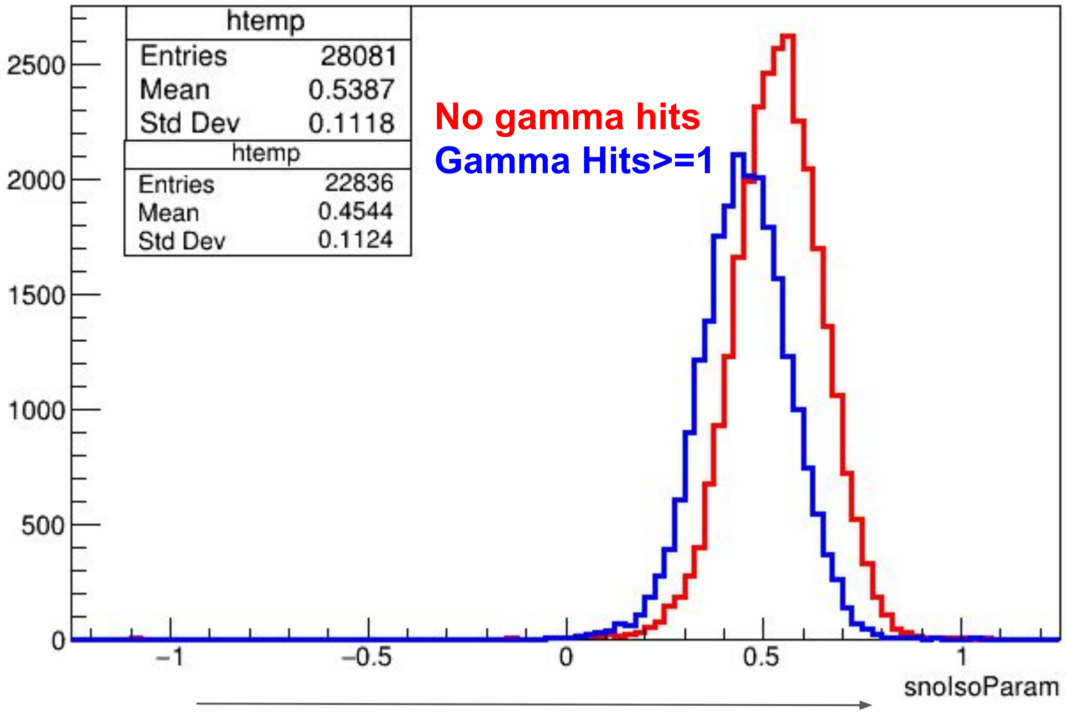
Overall Isotropy Parameter

- Use all hits within 0-10 ns residual time
- Used in SNO experiment to separate neutrons from CC/ES signal
- The events are more isotropic if there are gamma rays:
- snoIsoParam = $\beta_1 + 4\beta_4$ where:

$$\beta_l = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} P_l(\cos\theta_{ij}).$$

Legendre polynomial

Angle between (hit-vertex) vectors



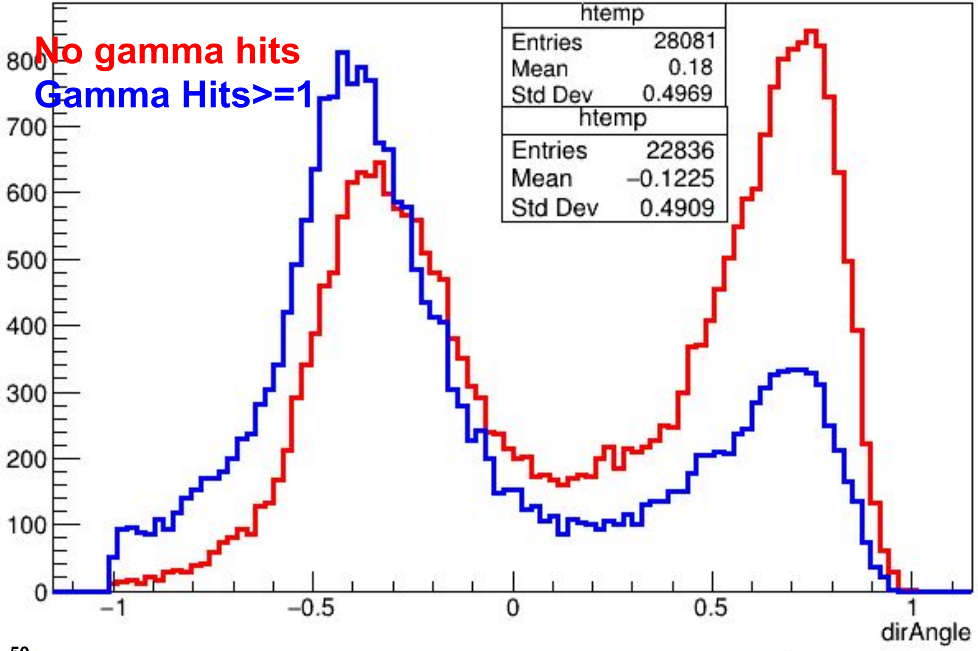
Less Isotropic

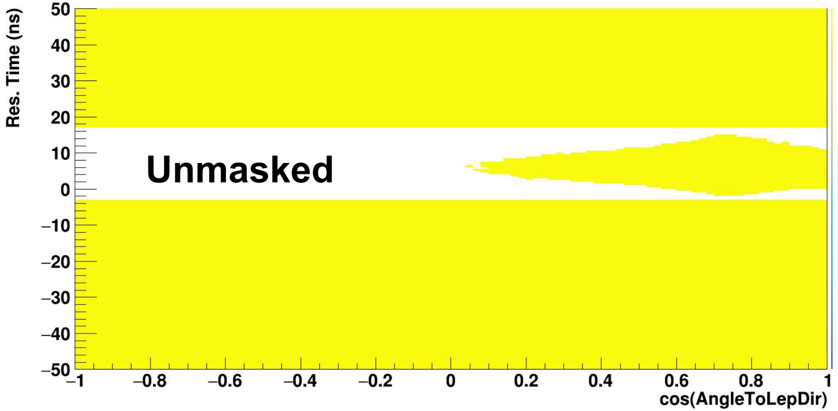
Legendre Pol.

n	$P_n(x)$
0	1
1	x
2	$\frac{1}{2}(3x^2 - 1)$
3	$\frac{1}{2}(5x^3 - 3x)$
4	$\frac{1}{8}(35x^4 - 30x^2 + 3)$

Cos(Angle) Between Dirs

- Mask the hits as explained before
- Give the remaining hits to a low energy fitter to calculate a fit direction (call aplowe/lhrun.F)
- Calculate the angle between that dir electron dir.
- As expected signal events are more negative





Combining Variables with ROOT TMVA

- Combine variables with Fisher discriminant:
  - Best linear combination based on means and covariance matrix of variables to separate signal and background
  - Ignores shape difference of the distributions: so can be improved.
  - Following slides will show the classification with this method

Coefficient of each variable

Used variables

$$t(\mathbf{x}) = a_0 + \sum_{i=1}^{n} a_i x_i$$

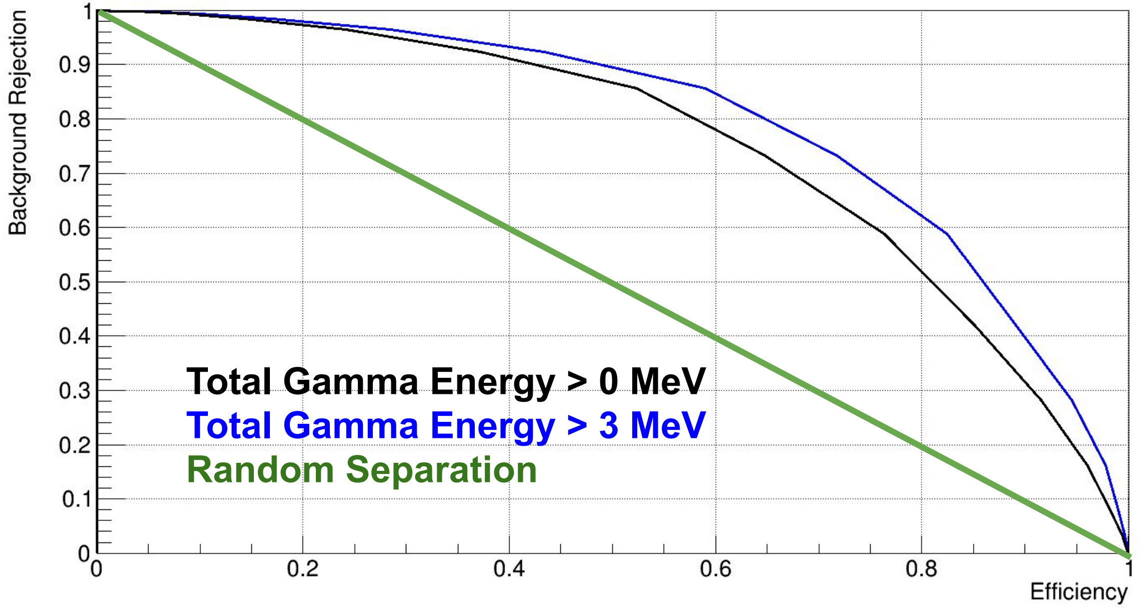
$$\mathbf{a} \propto W^{-1} (\boldsymbol{\mu}_0 - \boldsymbol{\mu}_1)$$

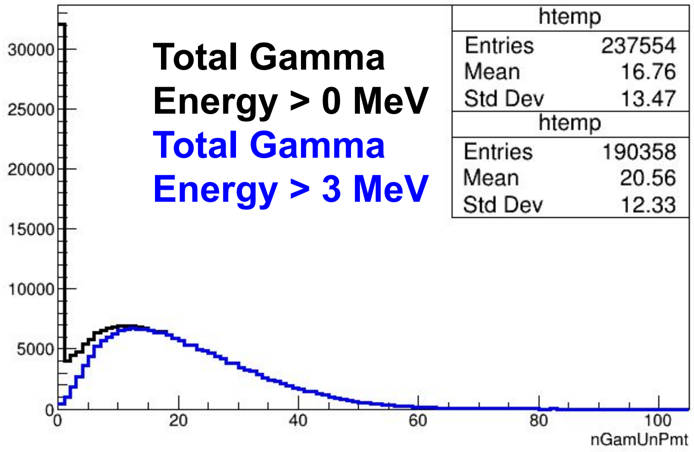
Inverse of covariance matrix (sum of signal and backgrounds cov matrix)

Difference between means of signal and background

- Trying other MVA Classification Methods:
  - So far experimented with Boosted Decision Trees, but no improvement over Fisher discriminant is observed
  - Can try more complex methods like NN in the future...

Results for Evis [60-70) Bin

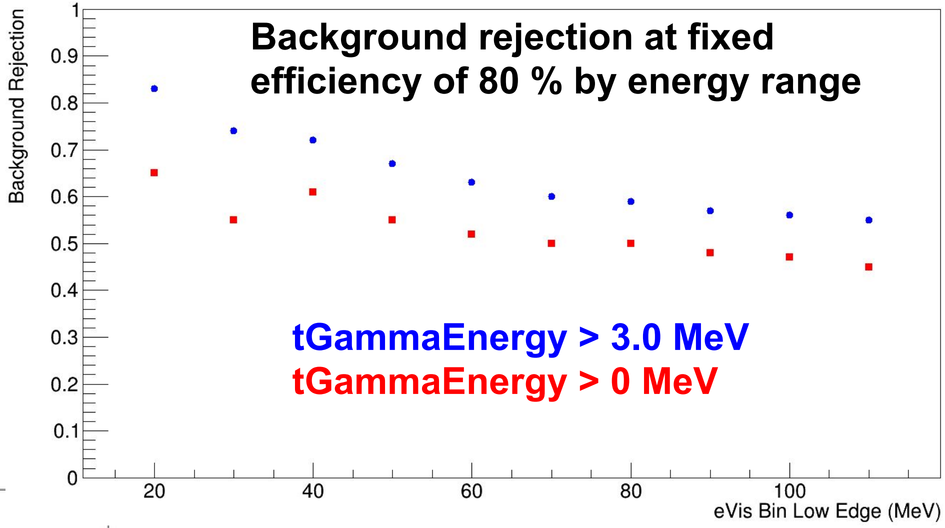




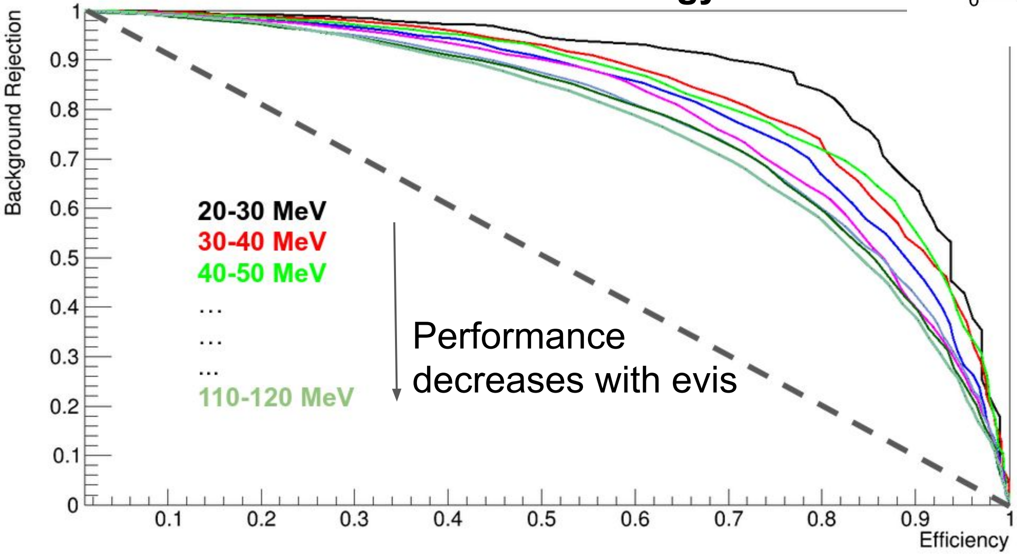
- The difference between two curves is due to low amount of hits (even 0) from lower energy gamma rays in the unmasked region.

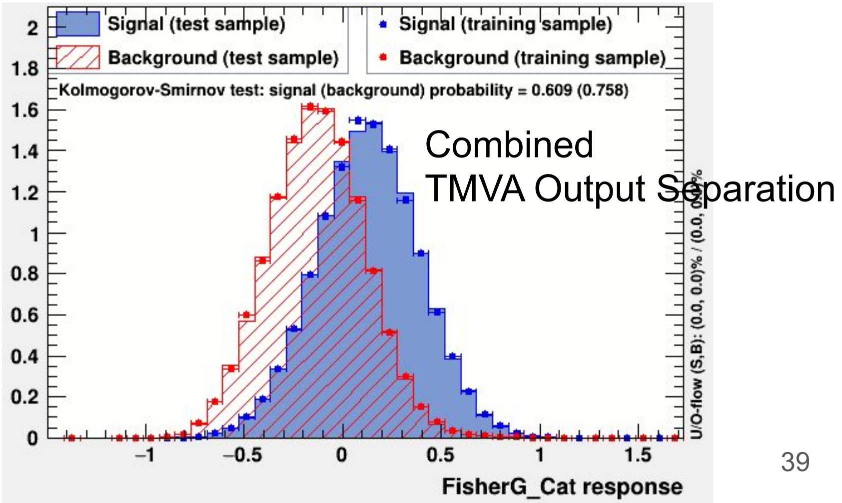
At other energies:

- The performance of gamma tagging is different across energies
- In general better performance at lower energies due to lower scattered hits.



ROCs for tGammaEnergy > 3.0 MeV

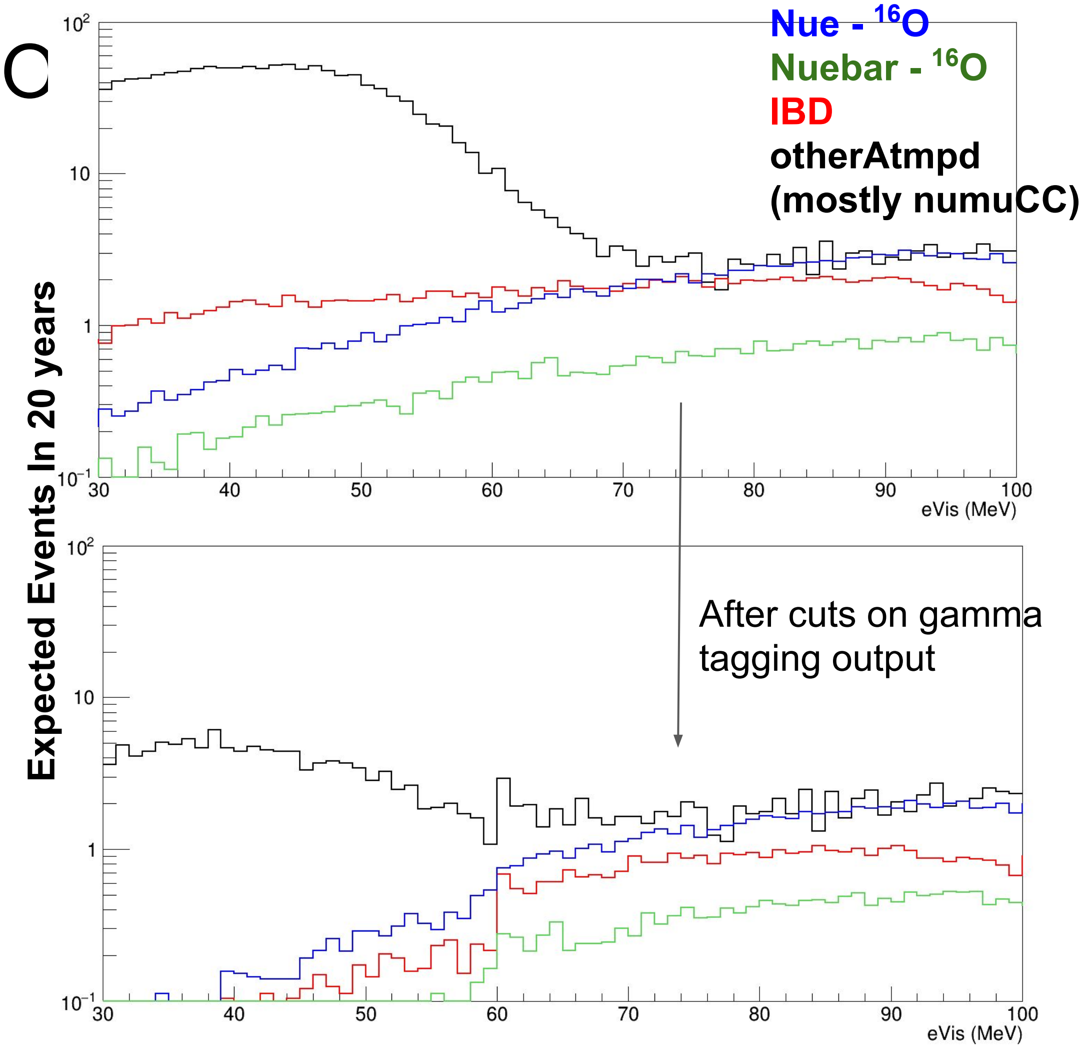




Cut Example For ν_e-^{16}O

- But half of the nue-^{16}O events do not have a gamma associated

- This slide is just an example of effect of gamma tagging:
    - These cuts might not be ideal, need to study carefully
    - Another option would be using gamma tagging output as a fit parameter...



BACK UP
(More on Event Generator)

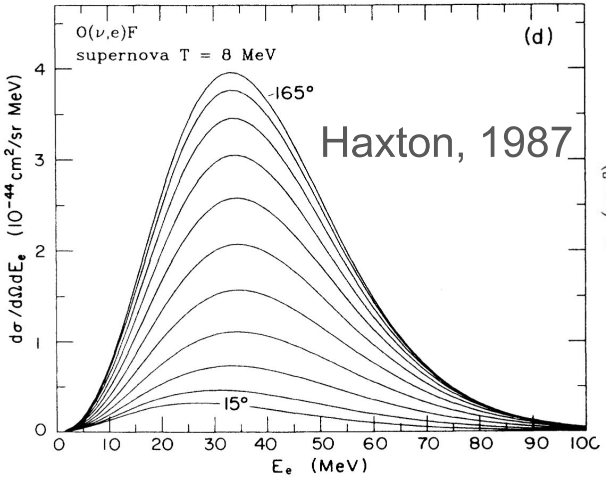
Generating ν - ^{16}O Events:

Accurate representation of the interactions at this energy range is needed:

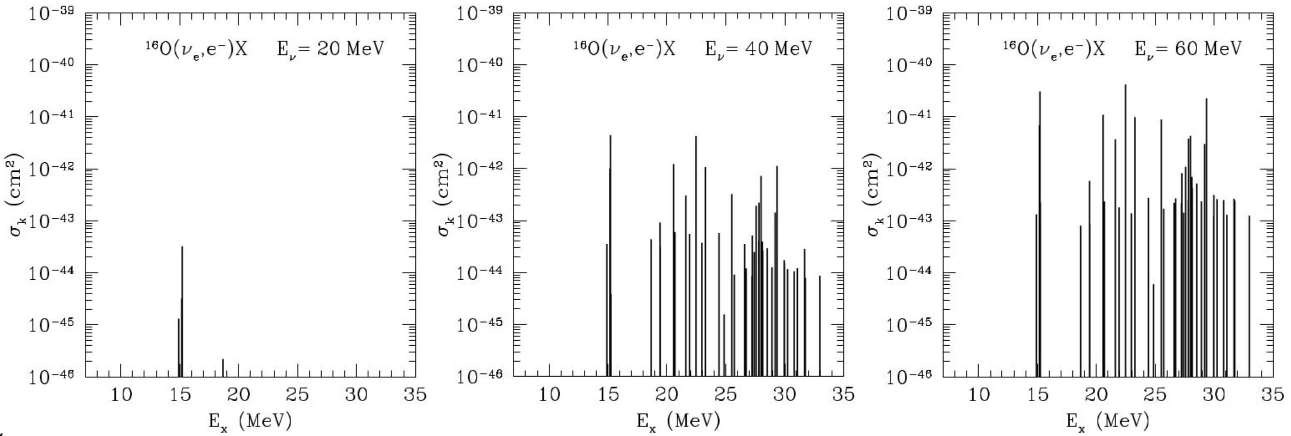
- Lepton angular distributions: (Haxton, 1987)
  - Double differential cross sections averaged over Fermi-Dirac spectrums
- Excitation energy distribution of final nucleus: (Nakazato et al, arXiv:1809.08398)
  - Lepton energy distribution and cross sections of individual excited states
- Decays from excited states of ^{16}N and ^{16}F: (TALYS, https://tendl.web.psi.ch/tendl_2019/talys.html)
  - De-excitation gammas, neutron emissions, higher Q value beta decays are observable in SK
  - TALYS Nuclear Reaction Software is used to model the decay chain
  - $^{16}F^{(*)}$ decays via proton emission but the chain continues from $^{15}O^{(*)}$ gamma and beta decays
  - ^{16}N ground state decays via possibly observable beta decay (Q = 10.4 MeV), $^{16}N^*$ is likely to emit neutrons
    - Also studied in (Kolbe et al. ,2002)

Not fully ready yet, but the code is at: https://github.com/itscubist/newton

Angular Distribution For: $\nu_e + {}^{16}O \rightarrow e^- + {}^{16}F^{(*)}$



Haxton, 1987



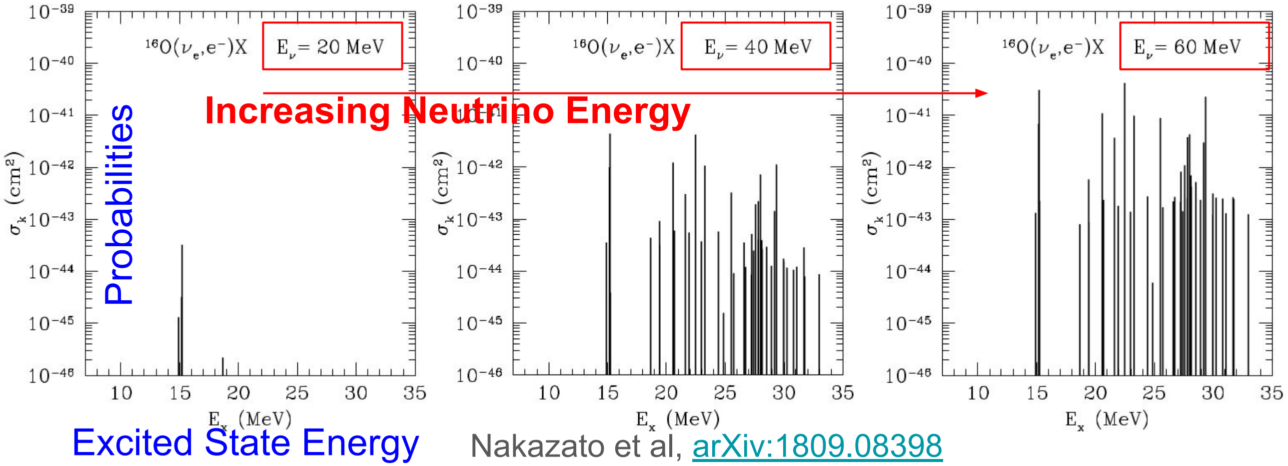
Nakazato et al, [arXiv:1809.08398]

- Select an excited state according to Nakazato's distribution, for a neutrino energy
- For each v-e angle electron energy can be obtained via kinematics
- Read flux weighted cross section for that angle and electron energy from Haxton's graphs
- Unweight by the normalized Fermi-Dirac spectrum
- Repeat same procedure for: $\bar{\nu}_e + {}^{16}O \rightarrow e^+ + {}^{16}N^{(*)}$

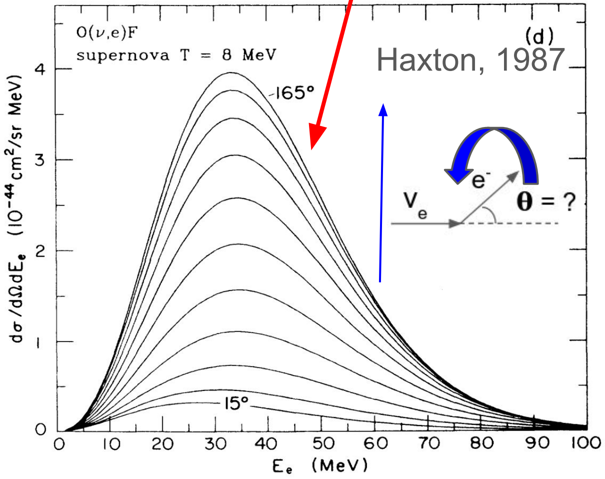
Notice that the angular distribution is backward peaked! Different from the IBD

Angular Distribution And Excited States:

Cross section vs electron energy
Each curve for a different theta



Nakazato et al, [arXiv:1809.08398](https://arxiv.org/abs/1809.08398)



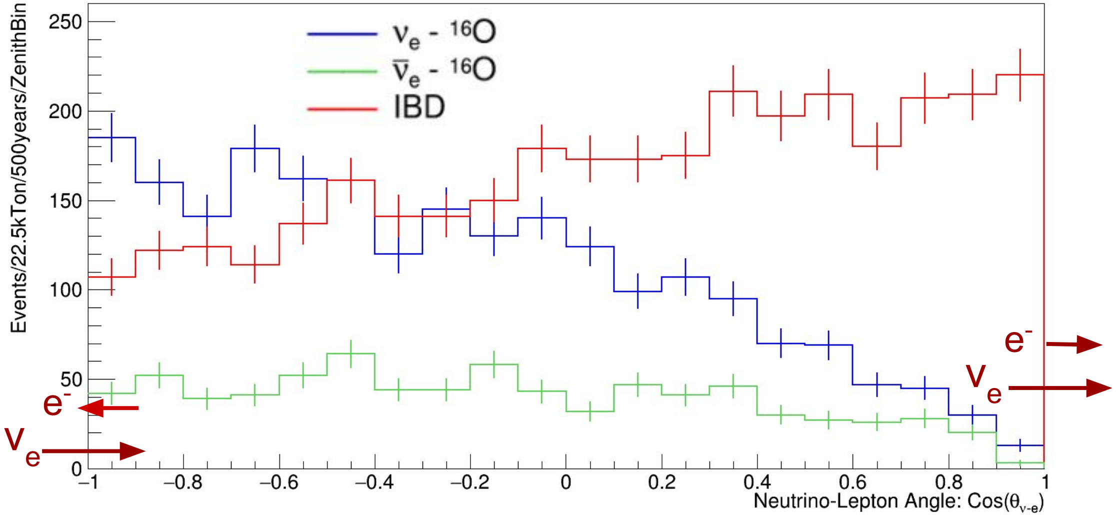
- Combine literature/kinematics to obtain angular/excited state distributions
- Repeat same procedure for: $\bar{\nu}_e + {}^{16}O \rightarrow e^+ + {}^{16}N^{(*)}$

Notice that the angular distribution is backward peaked!

Angular Distribution

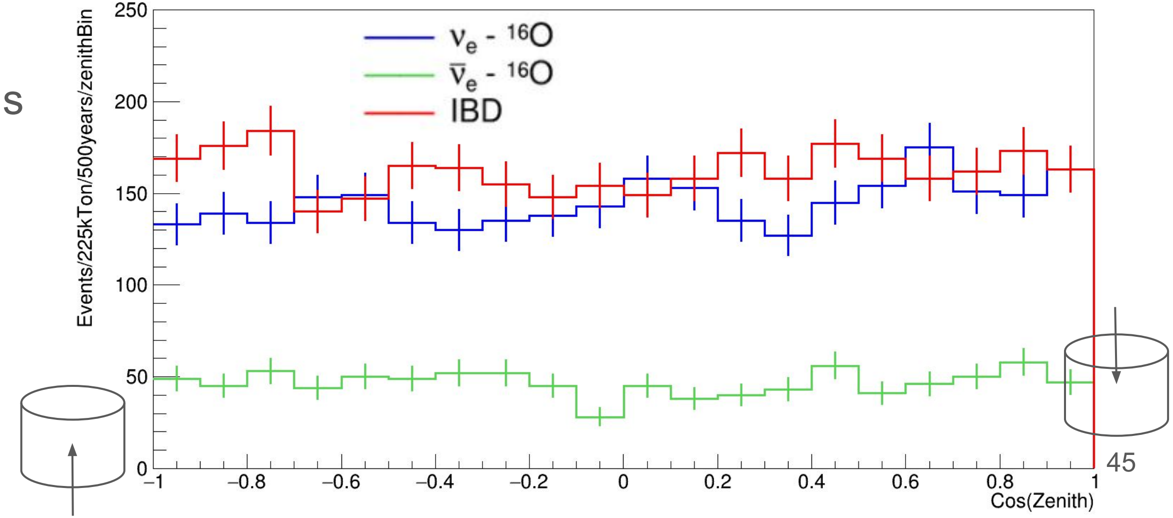
Top: Angle between neutrino and lepton directions of the resultant interactions (over 0 - 100 MeV lepton energy)

- Difference in angular distributions



Bottom: Zenith angle distribution of the outgoing leptons in the detector from atmospheric neutrino interactions

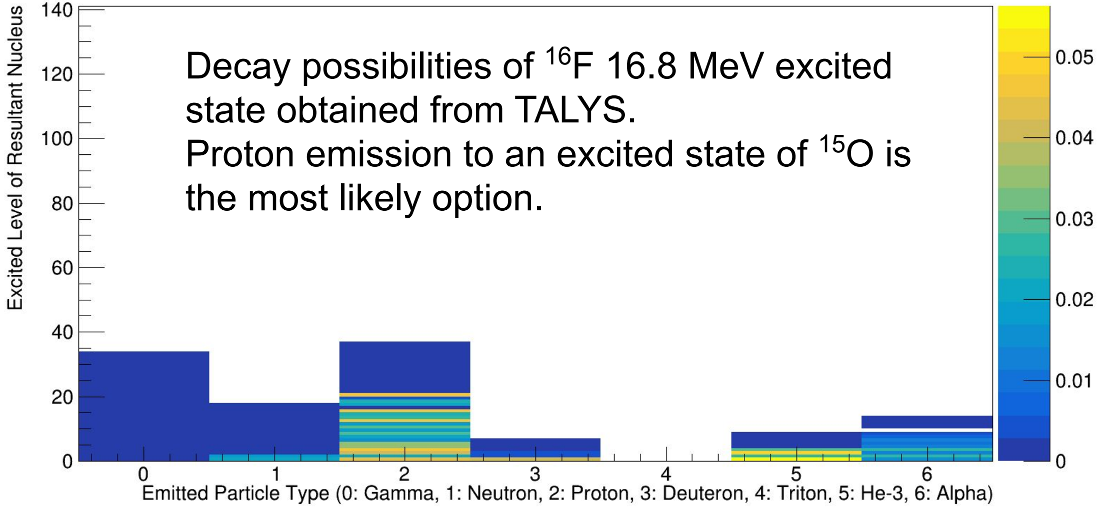
- However atmospheric neutrino angular distribution washes out the lepton angular distribution

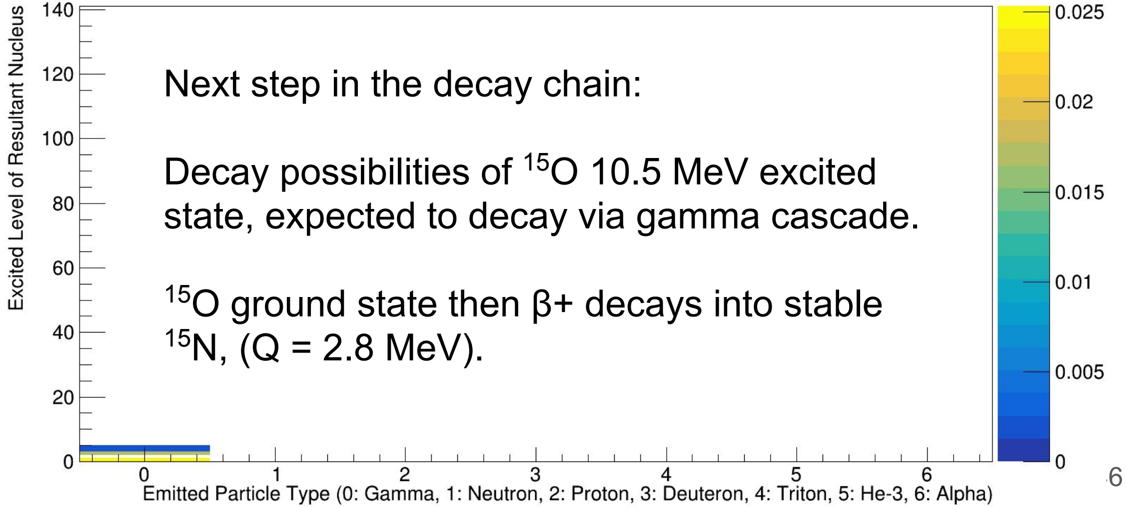


Decays From TALYS

Observation of decay products can help distinguishing signal from the background.

Decay probabilities of each excited state is obtained from TALYS as shown in the plots. If ^{16}F decays via proton emission into ^{15}O the same process will be repeated for ^{15}O.



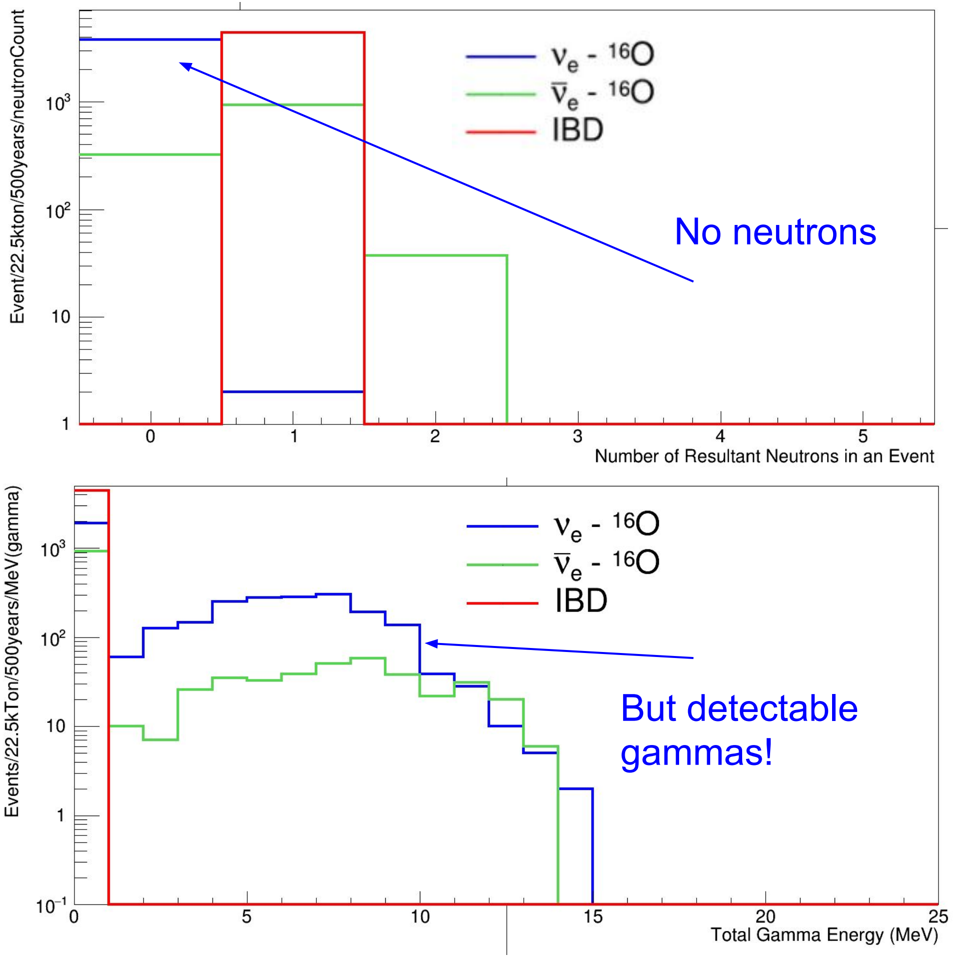


Decays From TALYS

Top: Emitted neutron number distributions

- $\bar{\nu}_e - {}^{16}O$ likely to have neutrons as opposed to $\nu_e - {}^{16}O$

Bottom: Total emitted gamma energy distributions

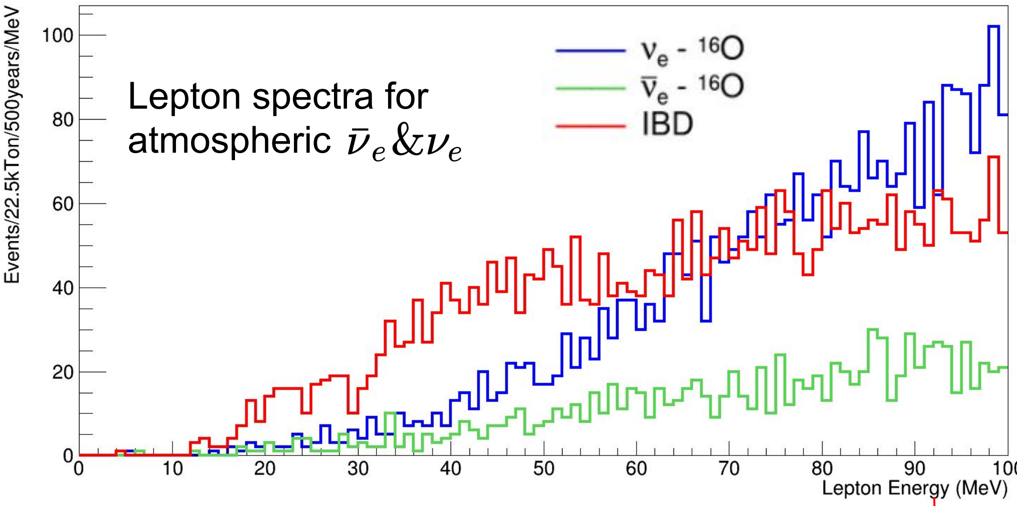


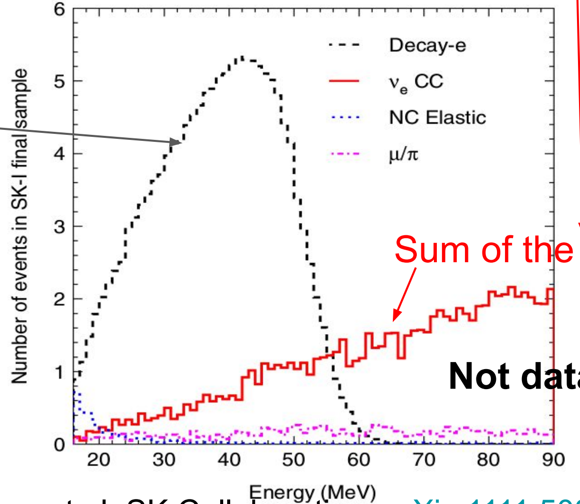
Lepton Energy Spectra

The shape of energy spectra will be useful too. Though it will be smeared out by resolution/threshold effects after detector simulation and reconstruction.

Other backgrounds for: $\nu_e - {}^{16}\mathrm{O}$

- 20 - 50 MeV:
  - Michel electrons
  - DSNB flux?
- < 20 MeV:
  - Spallation from muons
  - Solar…
  - Neutral Current Gammas
- Also:
  - Higher energy atmospherics leaking down...





Sum of the top plot

Not data, MC!

Bays et al, SK Collaboration, [arXiv:1111.5031]

Event Rates & Preliminary Estimates

- Assume only counting experiment: Not true, but can only be better.
- Consider statistical errors only: Not true, but not studied systematics yet
- Assume not well known mean background rate...
- Then uncertainty in measurement:

For E>30 MeV:

$$\frac{\sqrt{(S+B)+B}}{S} \approx 33\%$$

For E>50 MeV:

$$\frac{\sqrt{(S+B)+B}}{S} \approx 21\%$$

Tabulated events rates are in 20 years and 22.5 kTon FV. First 4 rows count products of E<132 MeV only.

	Interaction	30 - 100 MeV Lepton Energy	50 - 100 MeV Lepton Energy
Signal	$\nu_e - {}^{16}\mathrm{O}$	**117.3**	**107.2**
Backgrounds	$\bar{\nu}_e - {}^{16}\mathrm{O}$	37.8	33.8
	IBD	131.6	105.0
	Total ES	1.7	1.1
	Michel e^-	530	80
	Total BG	700	220
	Total	820	330

Numbers are here to show the simplest estimate. The goal is to use the information presented in the previous slides to improve this! But large systematics can make it worse… Only more work will tell!

More details on information at Nakazato et al.

Cross sections for 4 different groups of excitation energies are explicitly given at the paper, and an equation to fit is proposed.

The graphs above showed cross sections for all 42 states at 3 different energies, which can be used to solve for fit parameters.

Using 42 states rather than 4 has advantage of being more accurate in decays chain.

E_ν	$^{16}\mathrm{O}(\nu_e, e^-)\mathrm{X}$			
(MeV)	$\widetilde{\sigma}_1$ (cm^2)	$\widetilde{\sigma}_2$ (cm^2)	$\widetilde{\sigma}_3$ (cm^2)	$\widetilde{\sigma}_4$ (cm^2)
12	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18	9.61E−45	0.00E+00	0.00E+00	0.00E+00
21	6.20E−44	3.24E−46	0.00E+00	0.00E+00
24	2.03E−43	2.78E−44	0.00E+00	0.00E+00
27	4.94E−43	2.22E−43	1.93E−45	0.00E+00
30	1.01E−42	7.31E−43	1.73E−44	3.62E−44
33	1.83E−42	1.73E−42	6.66E−44	3.10E−43
36	3.07E−42	3.41E−42	1.83E−43	9.72E−43
39	4.80E−42	6.00E−42	4.14E−43	2.16E−42
42	7.14E−42	9.74E−42	8.19E−43	4.03E−42
45	1.02E−41	1.49E−41	1.47E−42	6.74E−42
50	1.70E−41	2.70E−41	3.30E−42	1.36E−41
55	2.63E−41	4.45E−41	6.39E−42	2.42E−41
60	3.82E−41	6.78E−41	1.11E−41	3.92E−41
65	5.29E−41	9.71E−41	1.77E−41	5.92E−41
70	7.00E−41	1.32E−40	2.64E−41	8.44E−41
80	1.11E−40	2.16E−40	5.05E−41	1.51E−40
90	1.57E−40	3.09E−40	8.29E−41	2.34E−40
100	2.06E−40	3.98E−40	1.21E−40	3.28E−40

$$\log_{10}\left(\frac{\widetilde{\sigma}_g(E_\nu)}{\mathrm{cm}^2}\right) \approx a_g + b_g\Lambda(E_\nu) + c_g\left\{\Lambda(E_\nu)\right\}^2$$

$$\Lambda(E_\nu) = \log_{10}\left\{\left(\frac{E_\nu}{\mathrm{MeV}}\right)^{1/4} - \left(\frac{\widetilde{E}_{x,g}}{\mathrm{MeV}}\right)^{1/4}\right\},$$

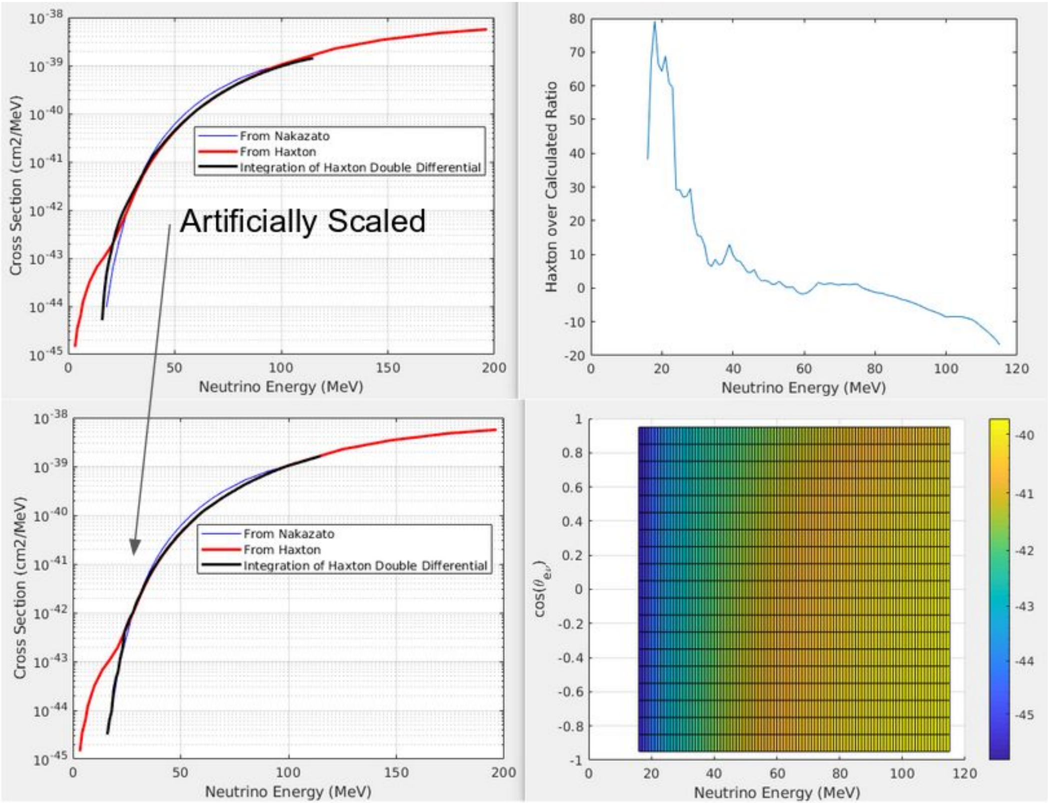
reaction	group g	$\widetilde{E}_{x,g}$ (MeV)	a_g	b_g	c_g
$^{16}\mathrm{O}(\nu_e, e^-)\mathrm{X}$	1	15.21	−40.008	4.918	1.036
	2	22.47	−39.305	4.343	0.961
	3	25.51	−39.655	5.263	1.236
	4	29.35	−39.166	3.947	0.901

Obtained ν_e - ^{16}O Cross Sections

The integral of angular cross section obtained with the above method, matches the total xscn given in Haxton within 10 % for 30 - 110 MeV neutrino energies.

That is a check for our method of obtaining angle and excitation energy distribution.

^{18}O contribution is not considered for now.

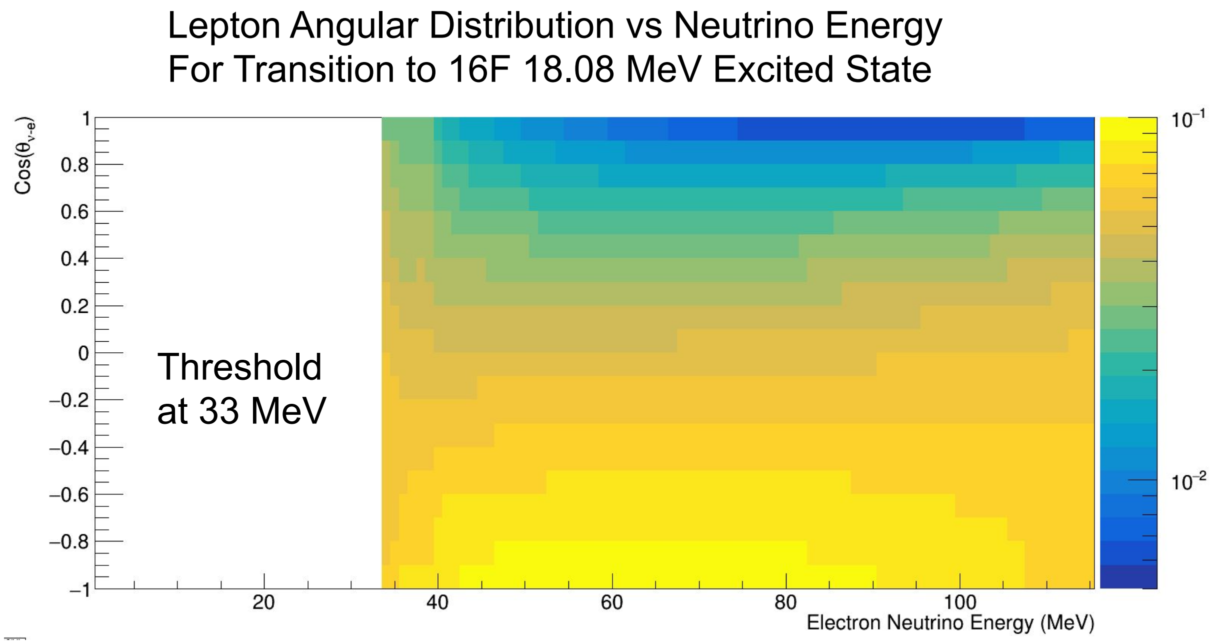


ν_e - ^{16}O Angular Distribution of Example Excited State

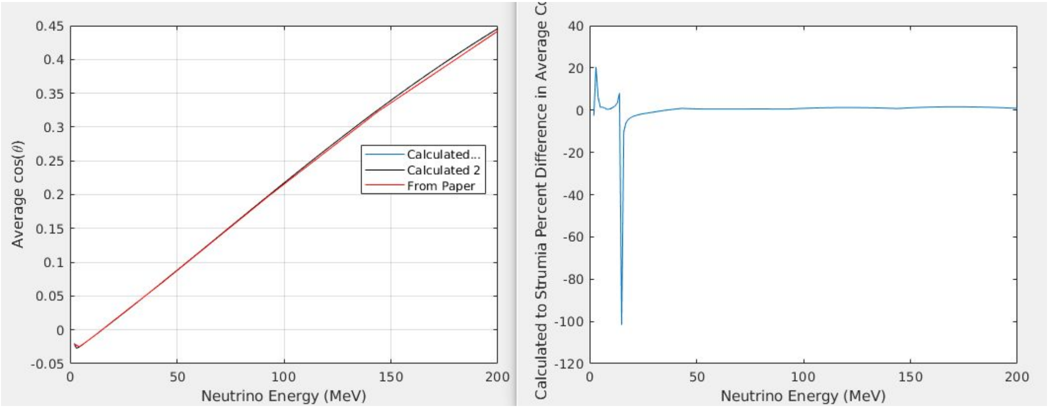
Each columns should add to 1. This is only relative probability of angles.

Such distributions are calculated for each excited state.

Backward peaked...

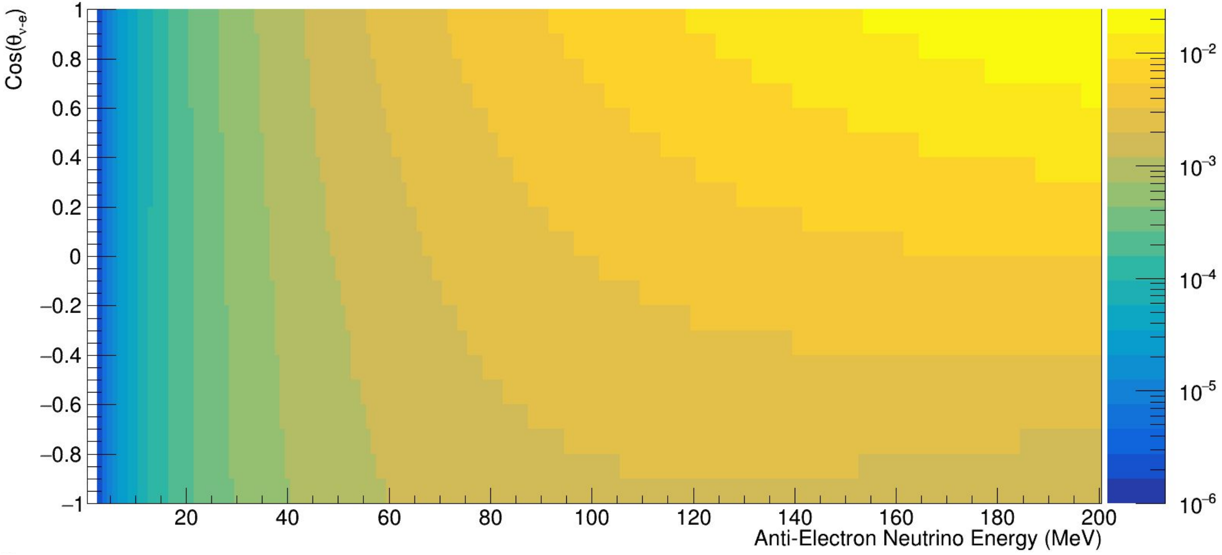


IBD Double Differential:



Calculated up to 200 MeV from Strumia-Vissani, 2003 paper:

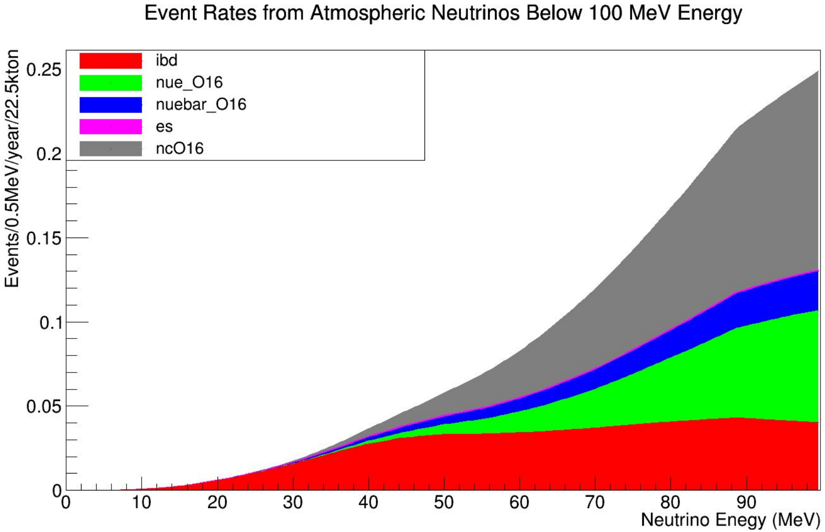
- At very low energies cross section is slightly backward
- At higher energies lepton is scattered forward due to kinematics
- Color scale should be multiplied by 10^{-38} cm^2

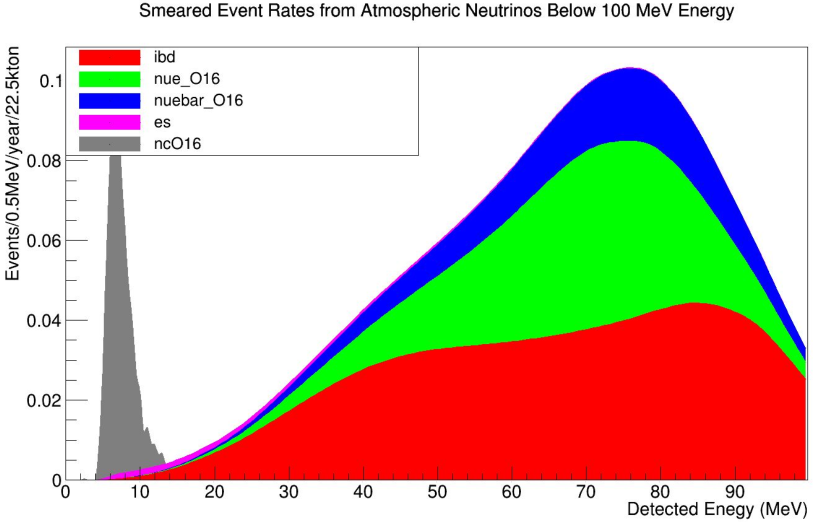


SNOwGLoBES Event Rates

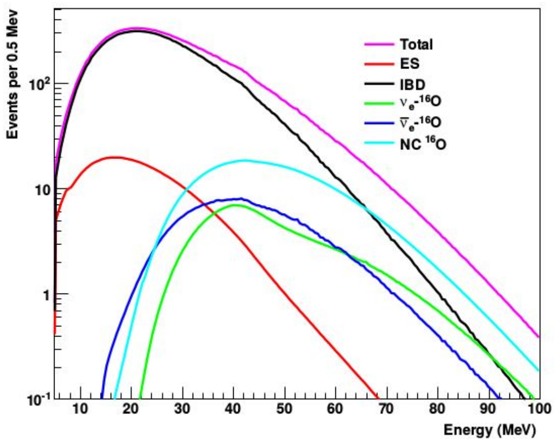
Also showing NC rates:

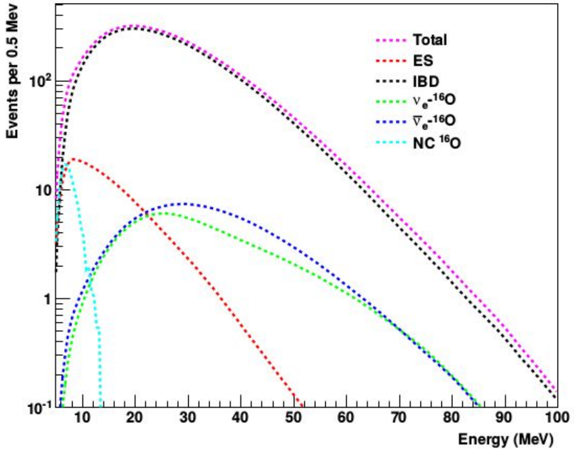
- Higher event rate since all flavors
- NC signal will look different
- No charged lepton
- Only de-excitation gammas, and some particle emission
- Smeared graph not accurate above 75 MeV…
- Available at:
  https://github.com/SNOwGLoBES/snowglobes





Supernova Event Rates in Water Cherenkov Detectors





Scholberg, 2015 arXiv:1205.6003 via SNOwGLoBES: This is in 100 kTons at 10 kPc (GVKM) model

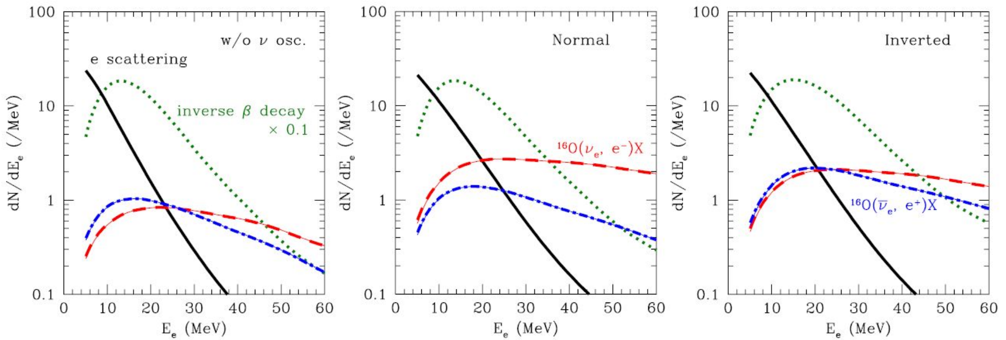


Table 6 Expected event numbers with a threshold energy of $E_e = 5$ MeV for the models in Table 5.

	ordinary supernova			black hole formation		
reaction	no osc.	normal	inverted	no osc.	normal	inverted
$^{16}\mathrm{O}(\nu_e, e^-)\mathrm{X}$	41	178	134	2482	2352	2393
$^{16}\mathrm{O}(\bar{\nu}_e, e^+)\mathrm{X}$	36	58	103	1349	1255	1055
electron scattering	140	157	156	514	320	351
inverse β-decay	3199	3534	4242	17525	14879	9255
total	3416	3927	4635	21870	18806	13054

From Nakazato: 10 kpC, 32 kTon

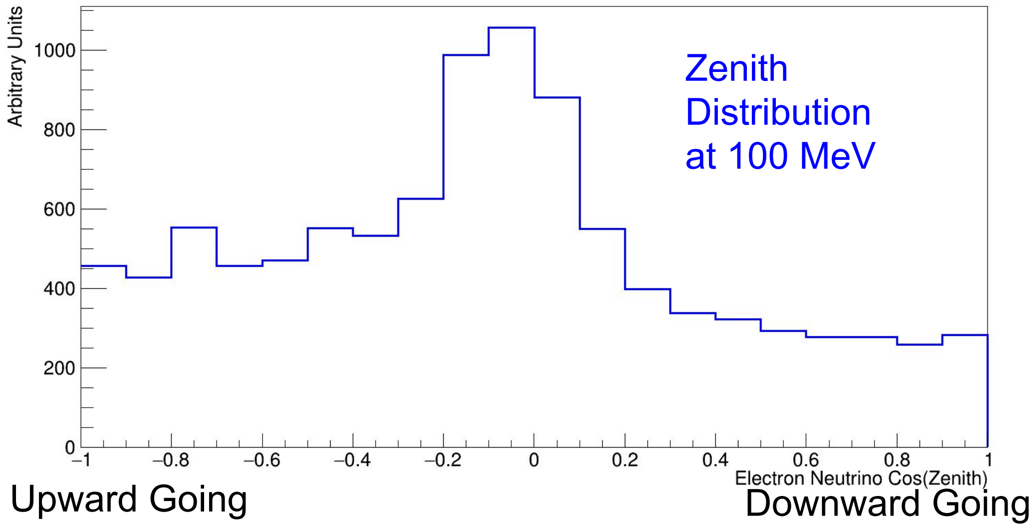
Low Energy Atmospheric Neutrino Directionality

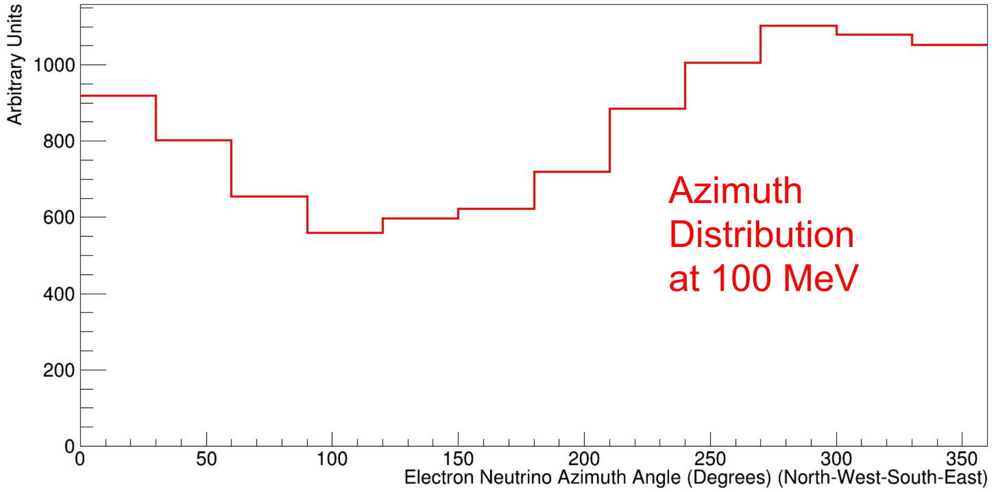
Zenith Distribution :

- Upward - downward asymmetry due to geomagnetic cutoff difference at primary particle entry locations
- Enhancement at center due to geometric effects, travelled atmosphere thickness

Azimuth Distribution :

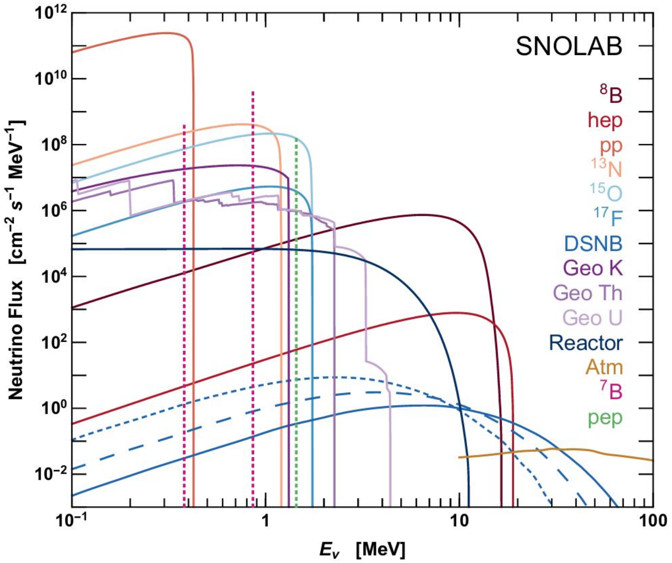
- East-West Effect (Earth’s magnetic field)
- Stronger at lower energies



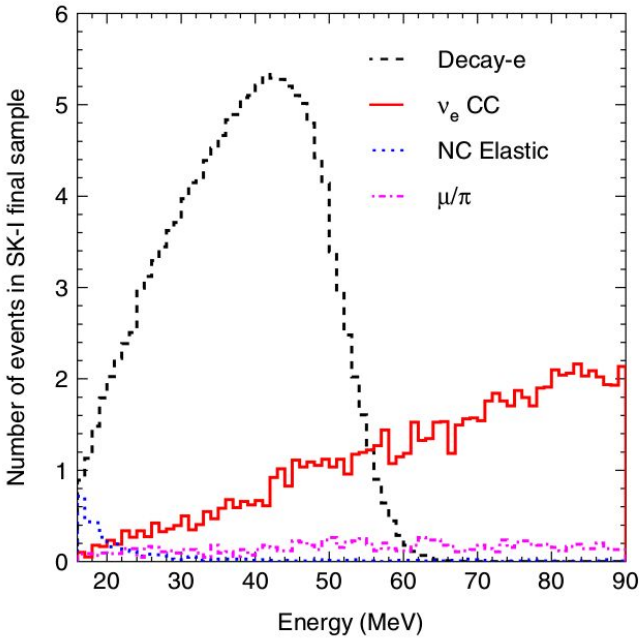


More About Backgrounds...

- Michel spectrum (decay of below Cherenkov threshold muons)
- DSNB Flux
- Solar
- Spallation from muons
- Leptons from higher energy neutrinos

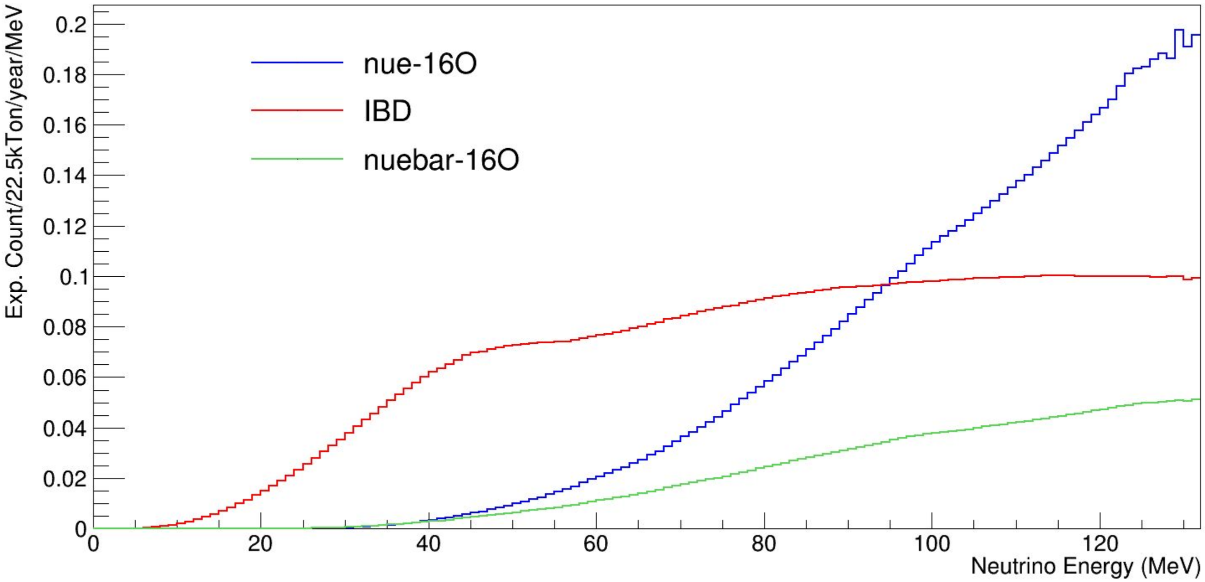


Gelmini et al. , [arXiv:1804.01638v3](https://arxiv.org/abs/1804.01638v3)



SK Collaboration, [arXiv:1111.5031](https://arxiv.org/abs/1111.5031)

Expected Counts vs Neutrino Energy



SK Physics Parameters:

Threshold (SK-IV) ~3.5 MeV electron kinetic energy

For 10 MeV electron: 23 degree direction , 14 % energy, 50 cm vertex resolution

Better at higher energy -> energy resolution for electrons:

    0.6 + 2.6/sqrt(p in GeV): 8 % at 100 MeV

BG contamination ~ 0.1 % in FC sample, so at most 3 muons/year but should not be at low energy...

Cosmic muon rate 2 Hz...