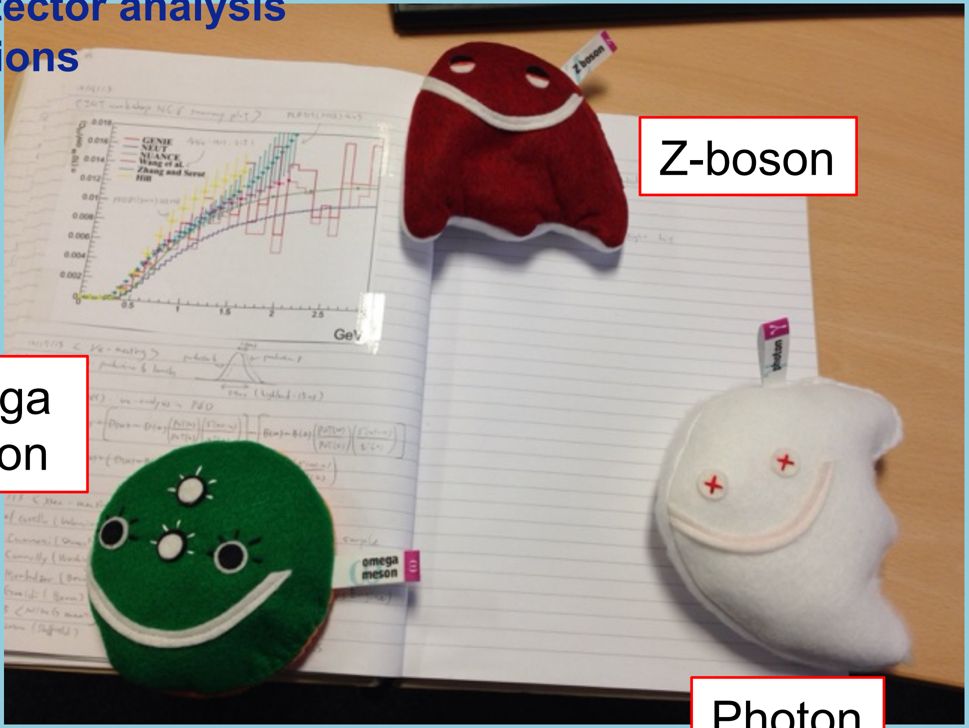
Search of Neutral Current Single gamma production process in T2K near detector

1. Introduction – MiniBooNE oscillation result
2. Neutral current single gamma production (NCγ)
3. T2K off-axis near detector analysis
4. Results and discussions
5. Conclusion



Teppei Katori for the T2K collaboration
Queen Mary University of London
NPC seminar, Fermilab, June 1, 2017

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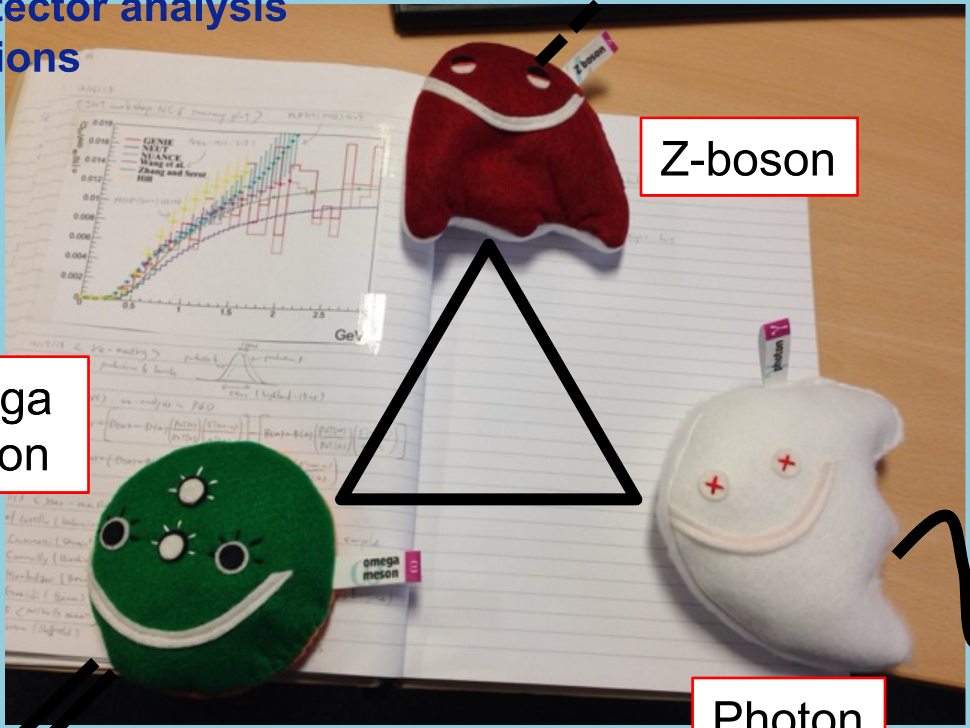

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Main analyzer: Pierre Lasorak (Queen Mary)
and significant contributions from T2K ν_e group

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1. Introduction – MiniBooNE oscillation result

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1. MiniBooNE experiment

MiniBooNE is a short-baseline neutrino oscillation experiment at Fermilab.

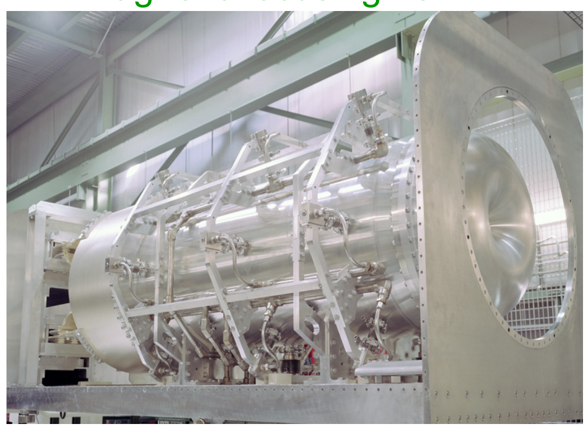
$$\nu_\mu \xrightarrow{oscillation} \nu_e + n \rightarrow e^- + p$$

$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \rightarrow e^+ + n$$

Booster Neutrino Beamline (BNB) creates ~800(600)MeV neutrino(anti-neutrino) by pion decay-in-flight. Cherenkov radiation from the charged leptons are observed by MiniBooNE Cherenkov detector to reconstruct neutrino energy.

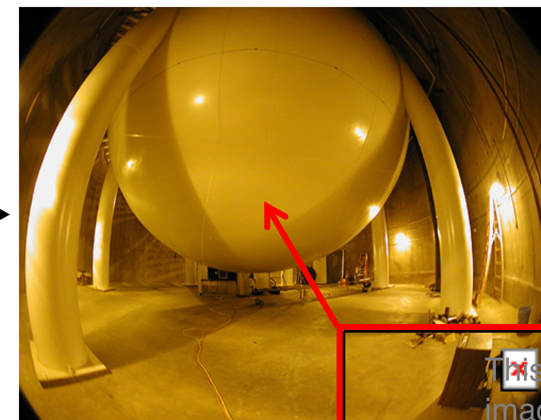
FNAL Booster

Magnetic focusing horn



~520m

MiniBooNE detector



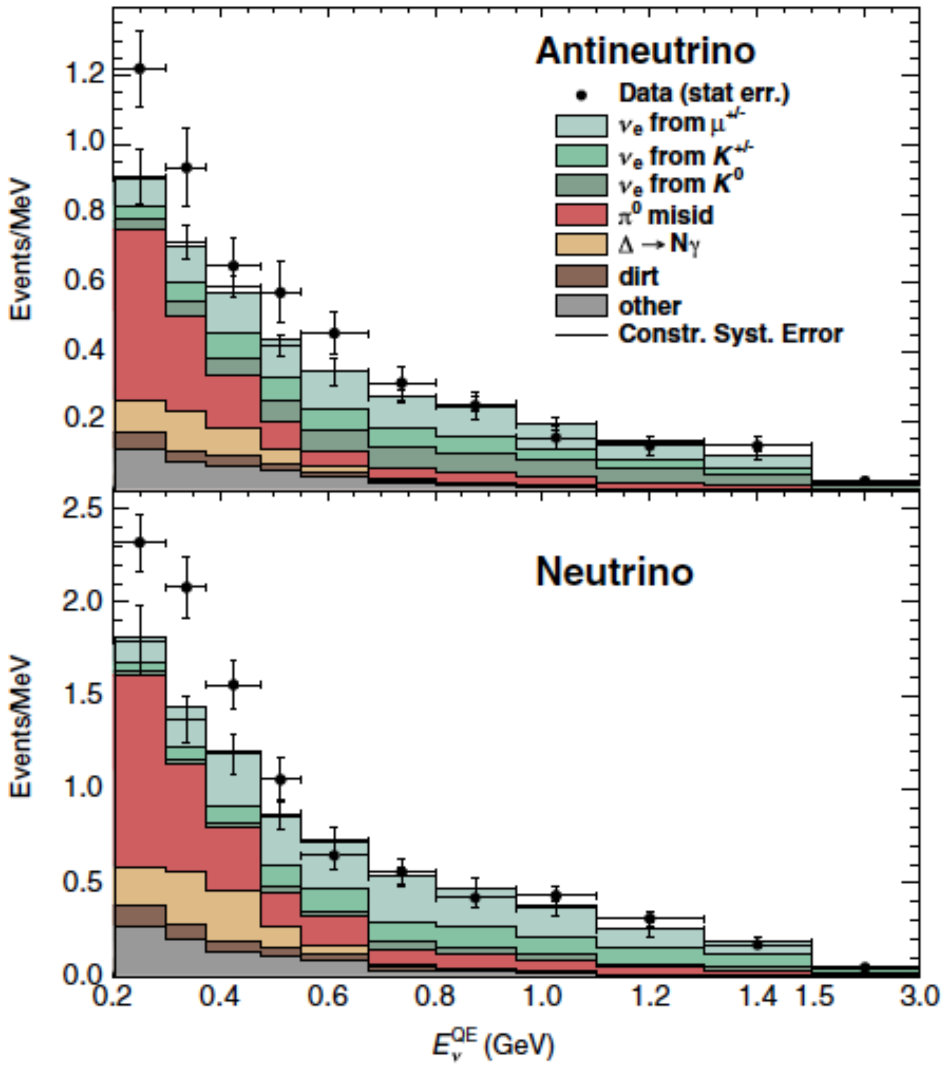
primary beam (8 GeV protons) → secondary beam (1-2 GeV pions) → tertiary beam (800 MeV ν_μ , 600 MeV anti-ν_μ)

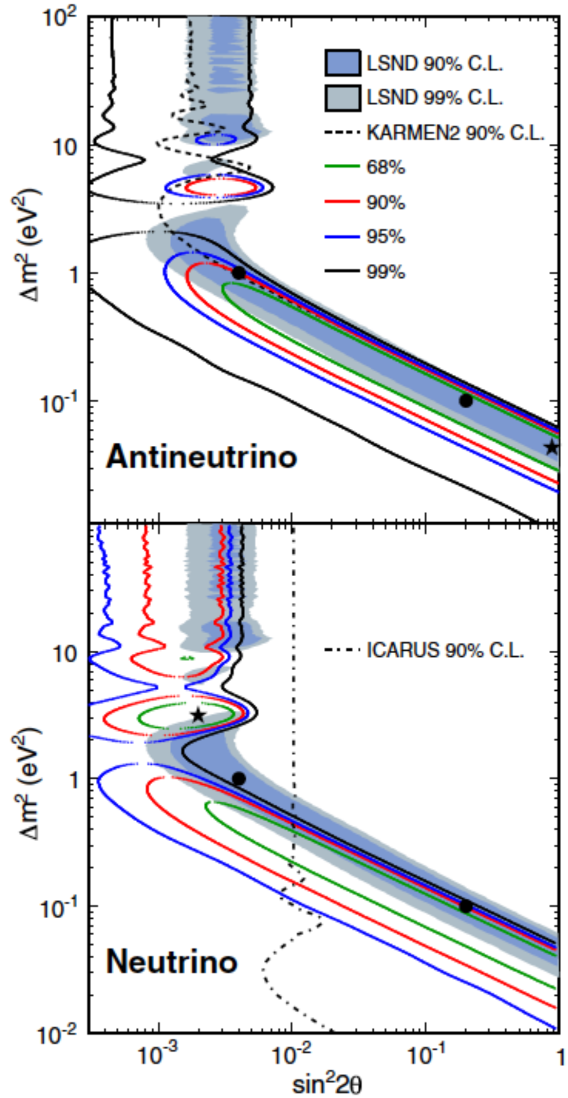
1280 of 8” PMT

1. MiniBooNE oscillation result

MiniBooNE observed excesses at low energy in both ν and $\bar{\nu}$ mode analysis.

- Compatibility with LSND signal under 2ν ($2\bar{\nu}$) osc. hypothesis is ~6% (~5%)





IceCube,PRL117(2016)071801,MINOS&DayaBay,PRL117(2016)151801
Collin et al,PRL117(2016)221801

1. MiniBooNE oscillation result

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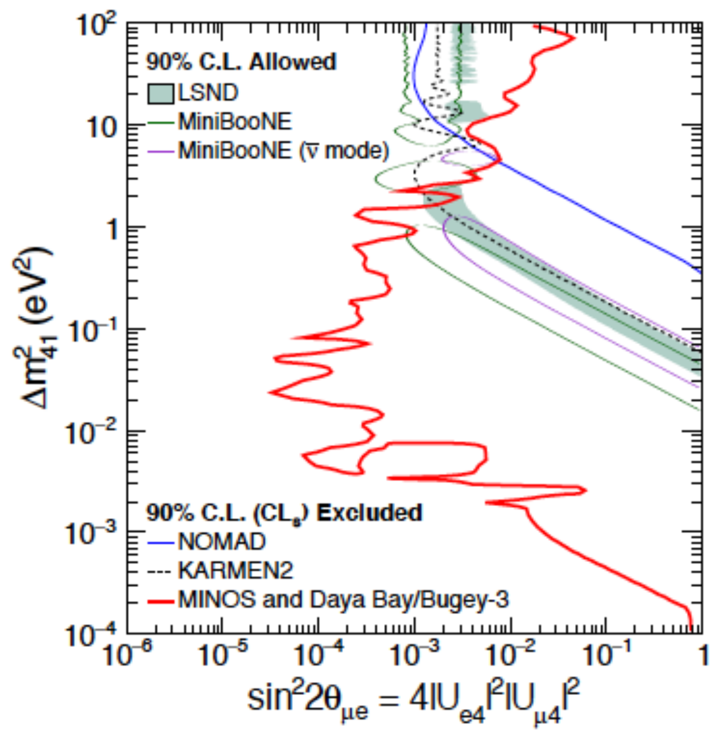
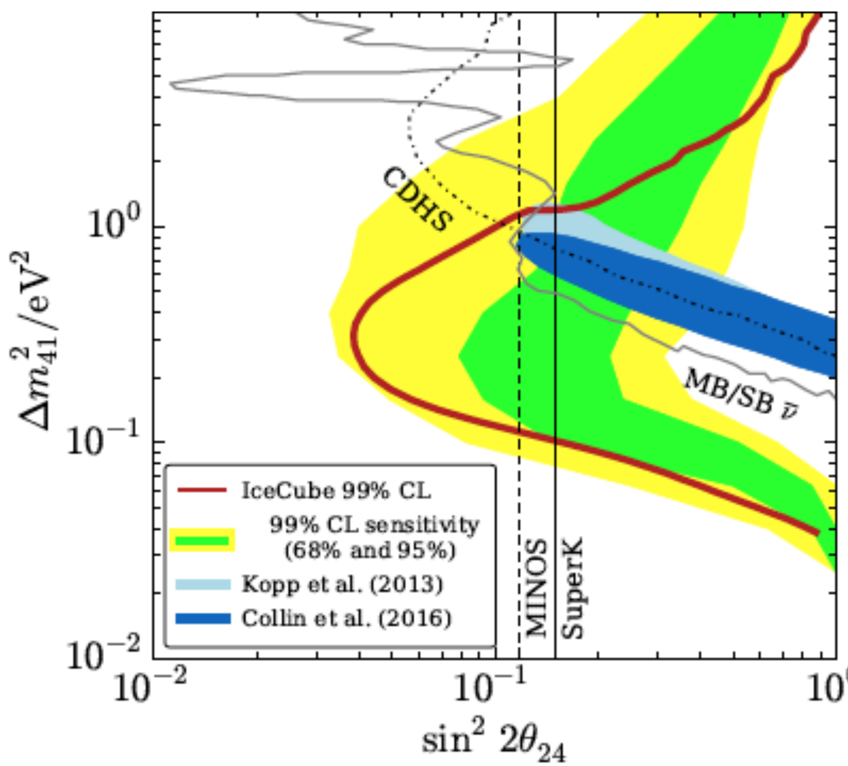
 - Compatibility with LSND signal under 2ν ($2\bar{\nu}$) osc. hypothesis is ~6% (~5%)

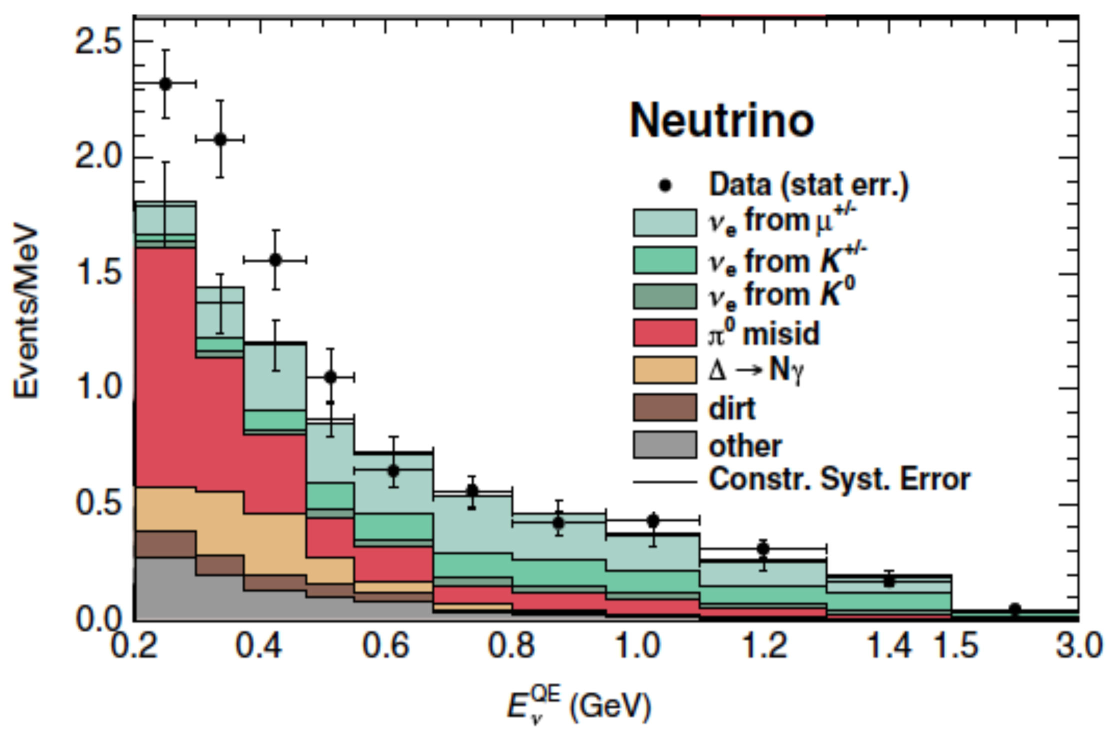
Results from IceCube, Daya Bay, and MINOS excluded majority of phase space.
 - Can excess to be an unknown background?





1. MiniBooNE oscillation result

The detector cannot distinguish e (signal) and γ (background).
- e: intrinsic background (beam ν_e contamination), flat with energy
- γ: misID background (mainly from π^o), accumulate at low E
- All backgrounds are measured in other sample and their errors are constrained.



1. MiniBooNE oscillation result

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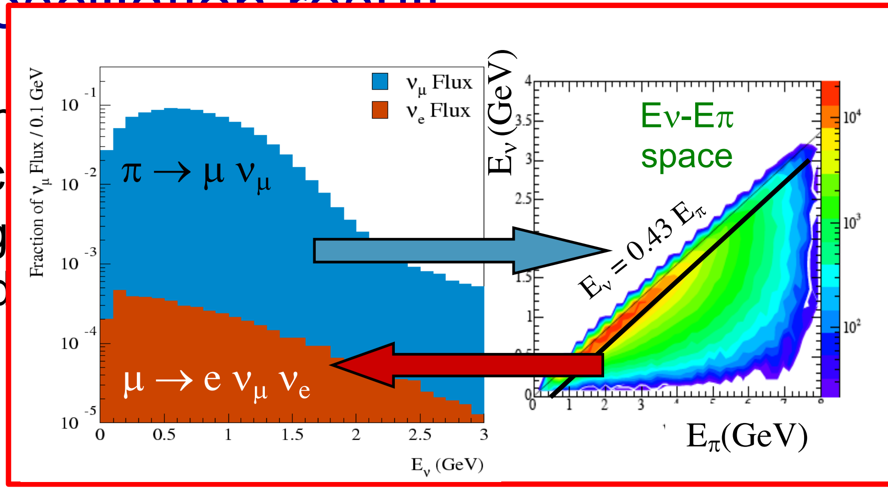
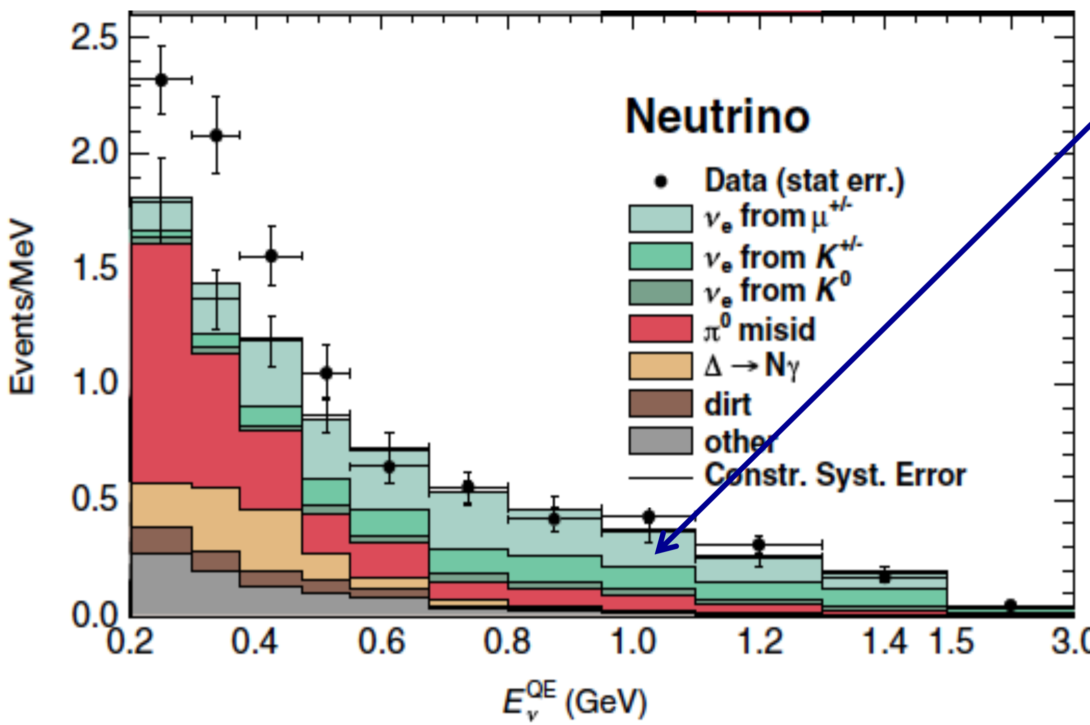


ν_e from μ decay is constrained from ν_μCCQE measurement



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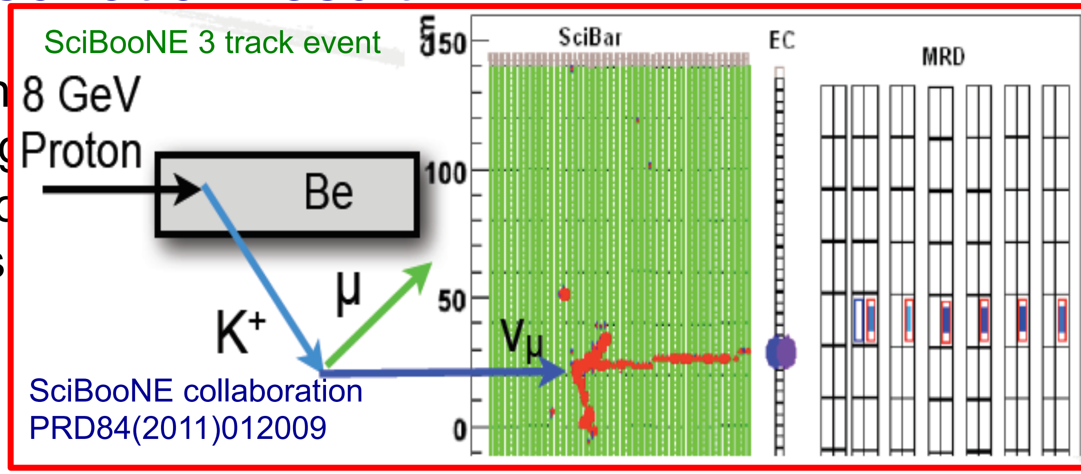

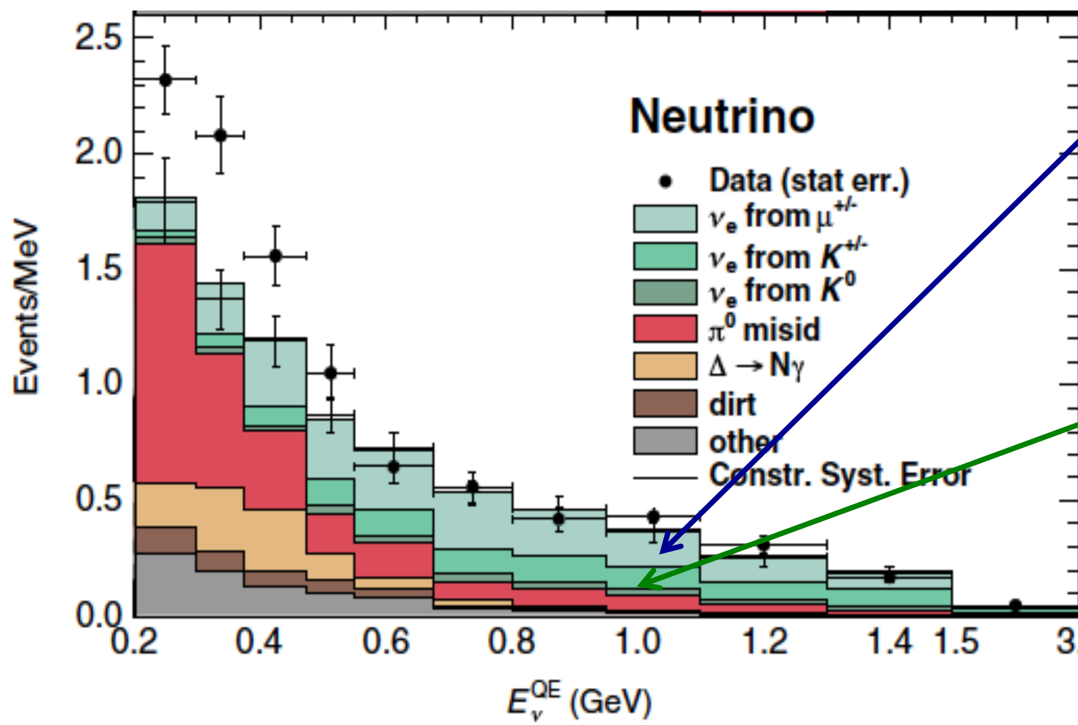

om μ decay is
strained from
ν_μCCQE measurement

ν_e from K decay is constrained from high energy ν_μ event measurement in SciBooNE

1. MiniBooNE

The detector ca ... und).
- e: intrinsic ba ... ith energy
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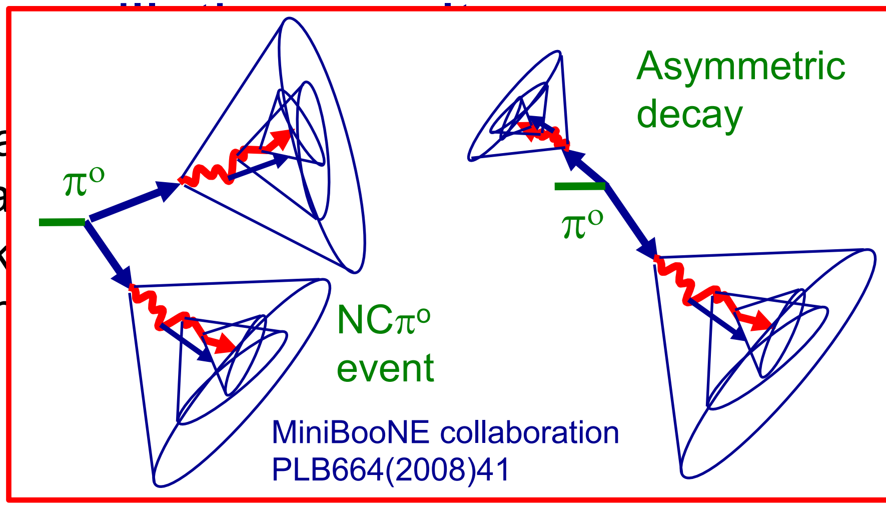
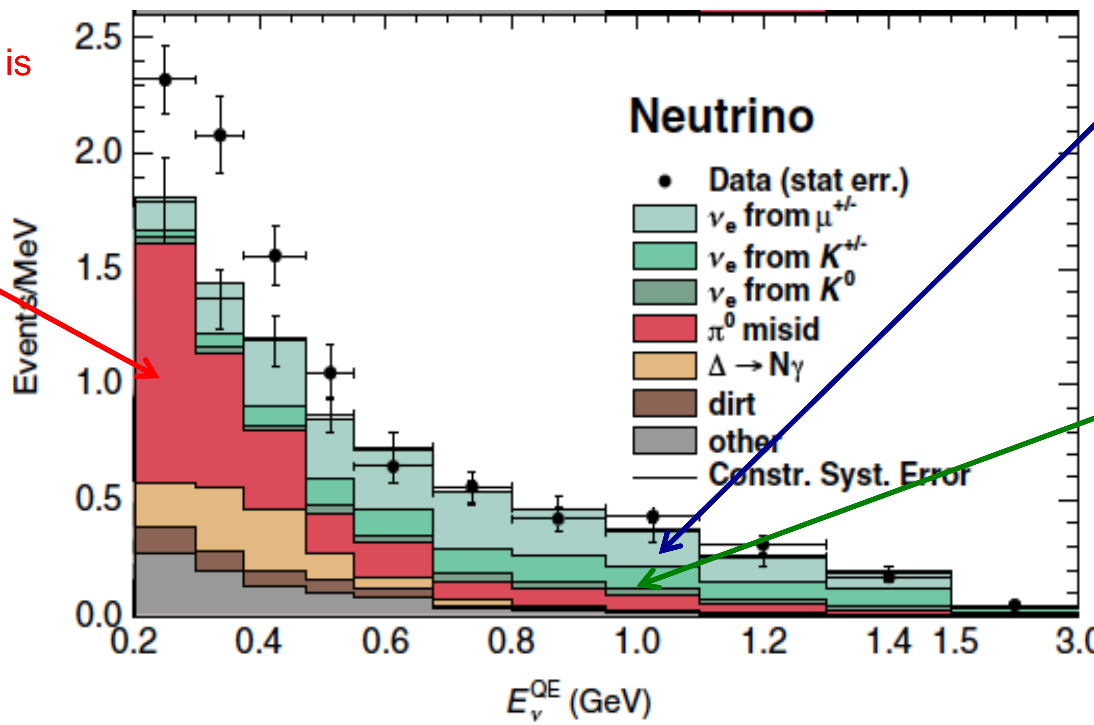


Asymmetric π° decay is constrained from measured CCπ° rate (π°→γ)



ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from high energy ν_μ event measurement in SciBooNE

1. MiniBooNE oscillation result

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- e: intrinsic background (b... ...th energy
- γ: misID background (mai... ...w E
- All backgrounds are meas... ...r errors are constrained.

$$\frac{N_C(\Delta \rightarrow N\gamma)}{N_C(\Delta \rightarrow N\pi^0)} = \frac{3\Gamma_\gamma}{2\Gamma_{\pi^0}\varepsilon}$$

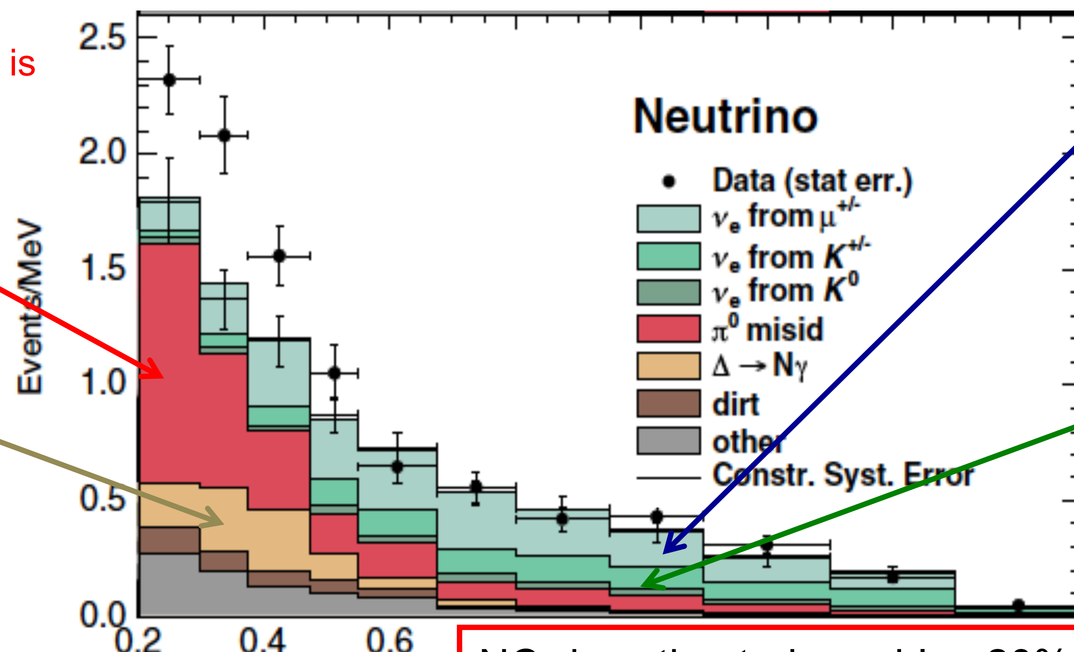
$\Gamma\gamma/\Gamma\pi$: NCγ to NCπ branching ratio
2/3: π^o fraction
ε: π escaping factor

Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \rightarrow \gamma$)

Radiative Δ-decay ($\Delta \rightarrow N\gamma$) rate is constrained from measured NCπ^o

ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from high energy ν_μ event measurement in SciBooNE



NCγ is estimated roughly ~20% of NCπ^o background in ν_e candidate sample. To explain all excess by NCγ, NCγ cross section needs to be x2 to x3 higher.

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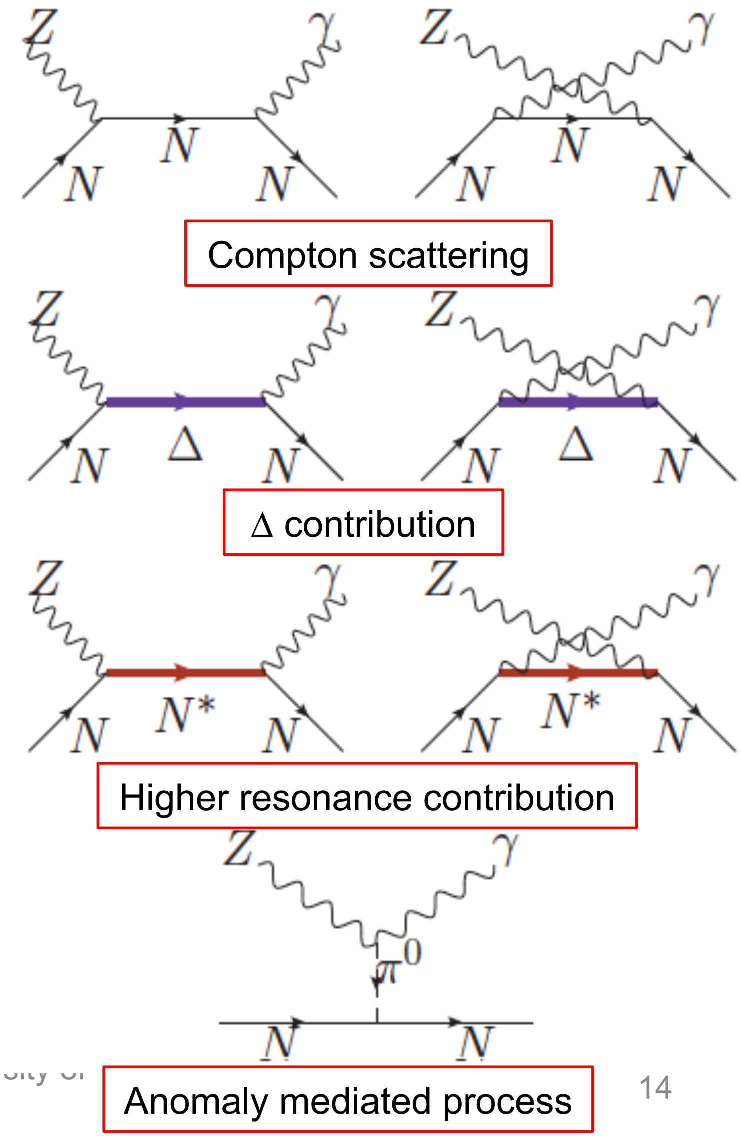
Zhang and Serot,PRC86(2012)015501, Hill,PRD81(2010)013008
Wang et al,PRC89(2014)015503

2. NCγ process with nuclear physics

e.g.) Valencia NCγ model

- Δ and 3 higher resonances
- Nuclear media effects included
- both incoherent and coherent contribution



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Zhang and Serot,PRC86(2012)015501, Hill,PRD81(2010)013008
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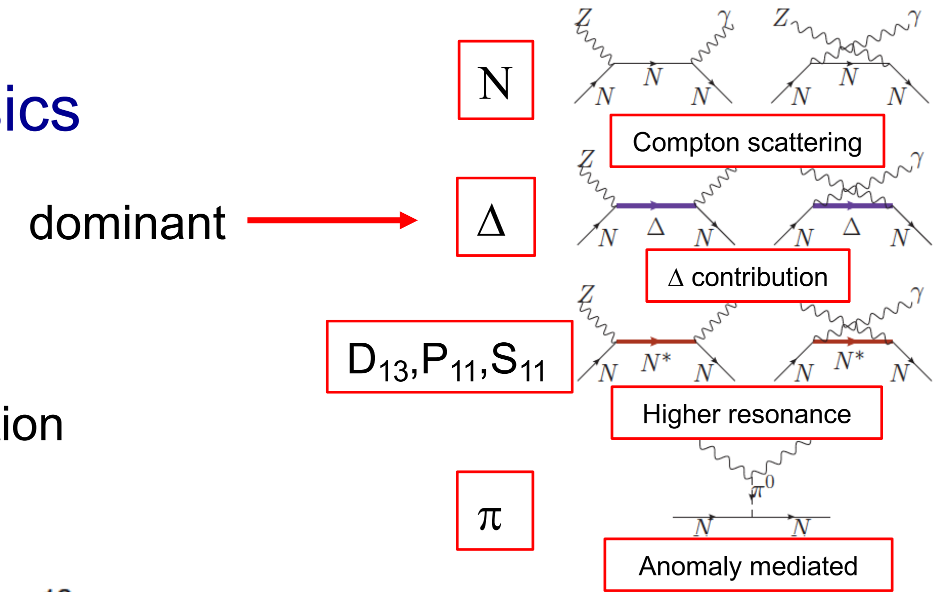

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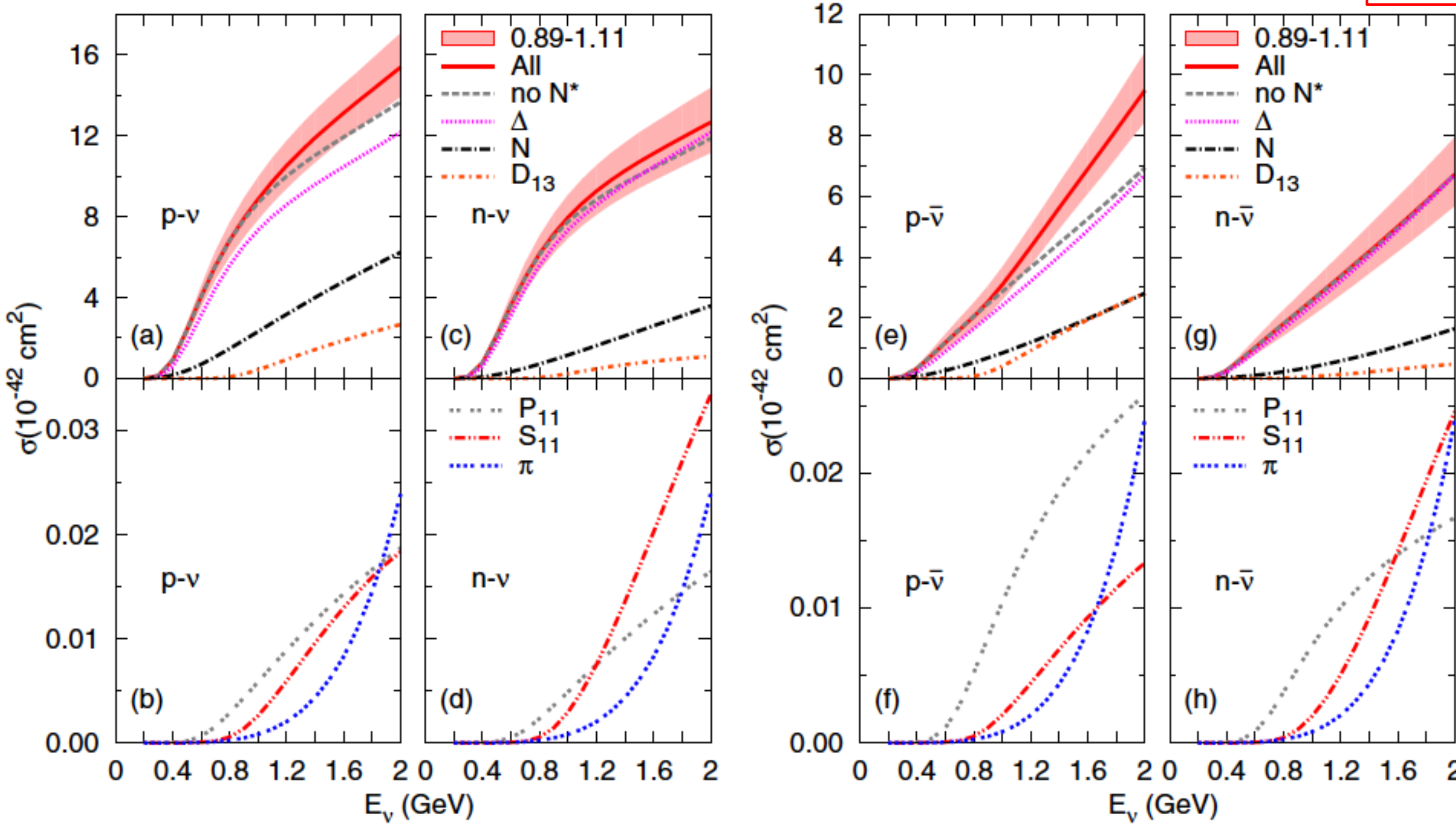

Zhang and Serot,PRC86(2012)01550
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2. NCγ process wi

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- Δ and 3 higher res
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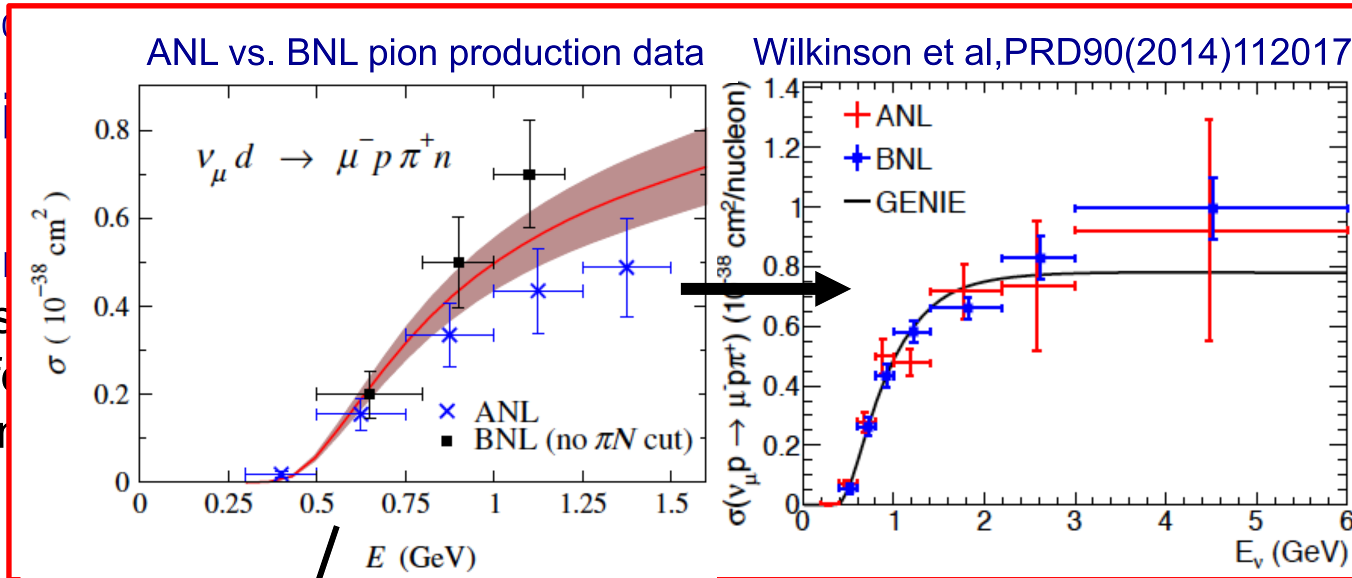
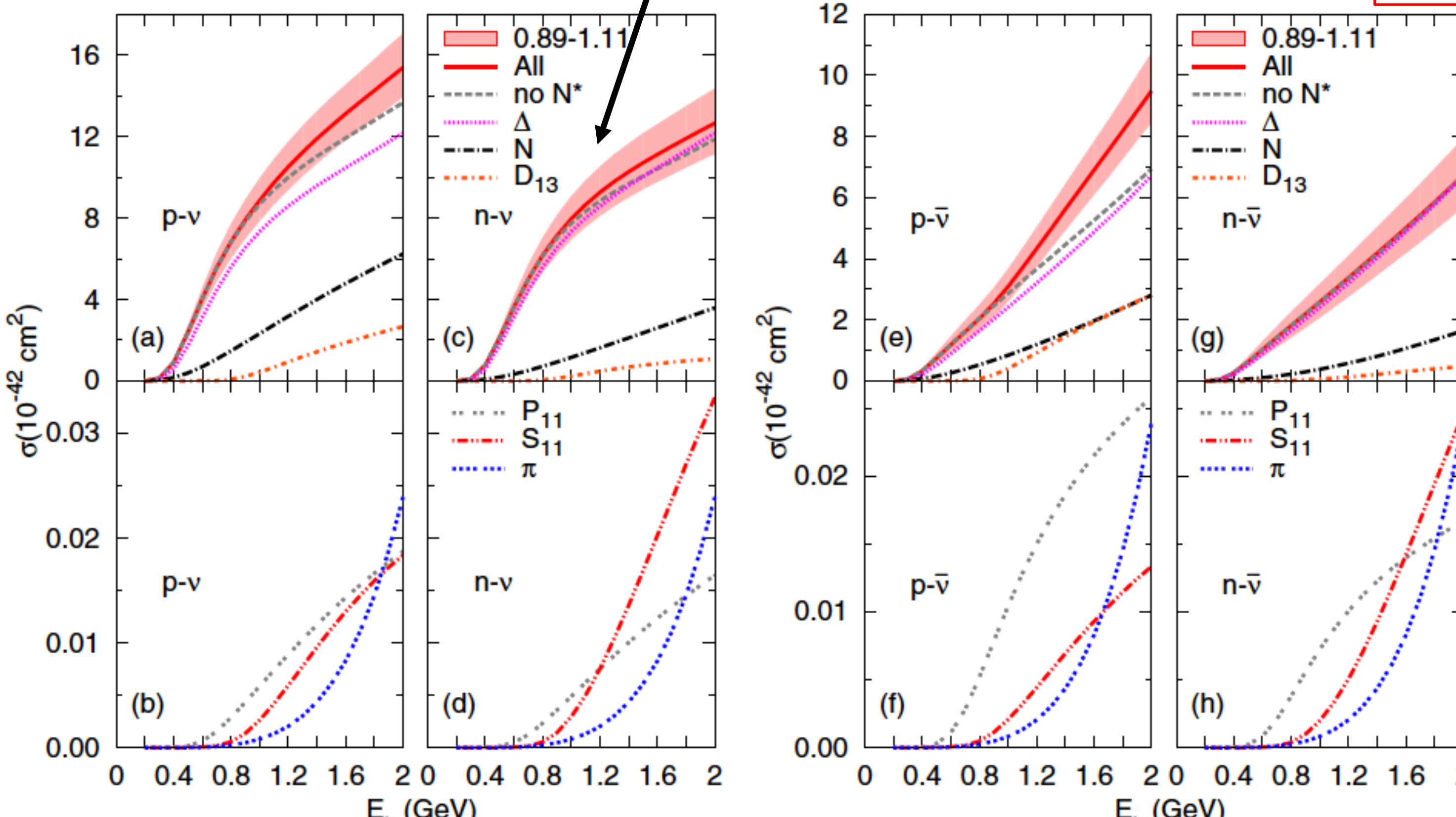


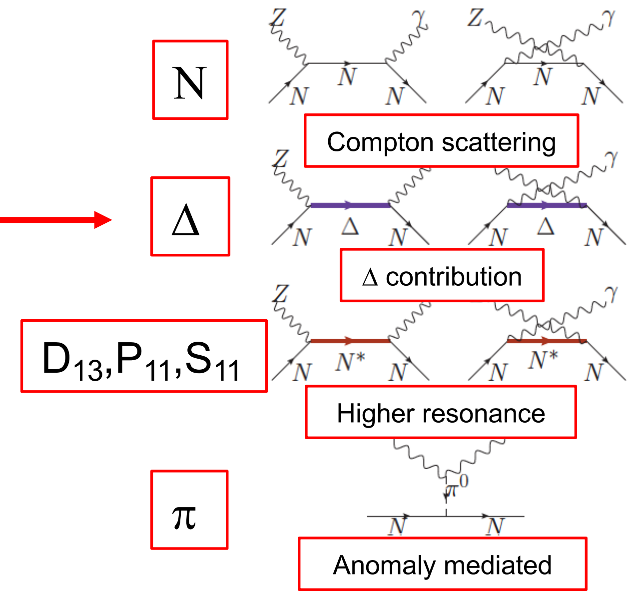


Zhang and Serot,PRC86(2012)015501, Hill,PRD81(2010)013008
Wang et al,PRC89(2014)015503,PLB740(2015)16

2. NCγ process with nuclear physics

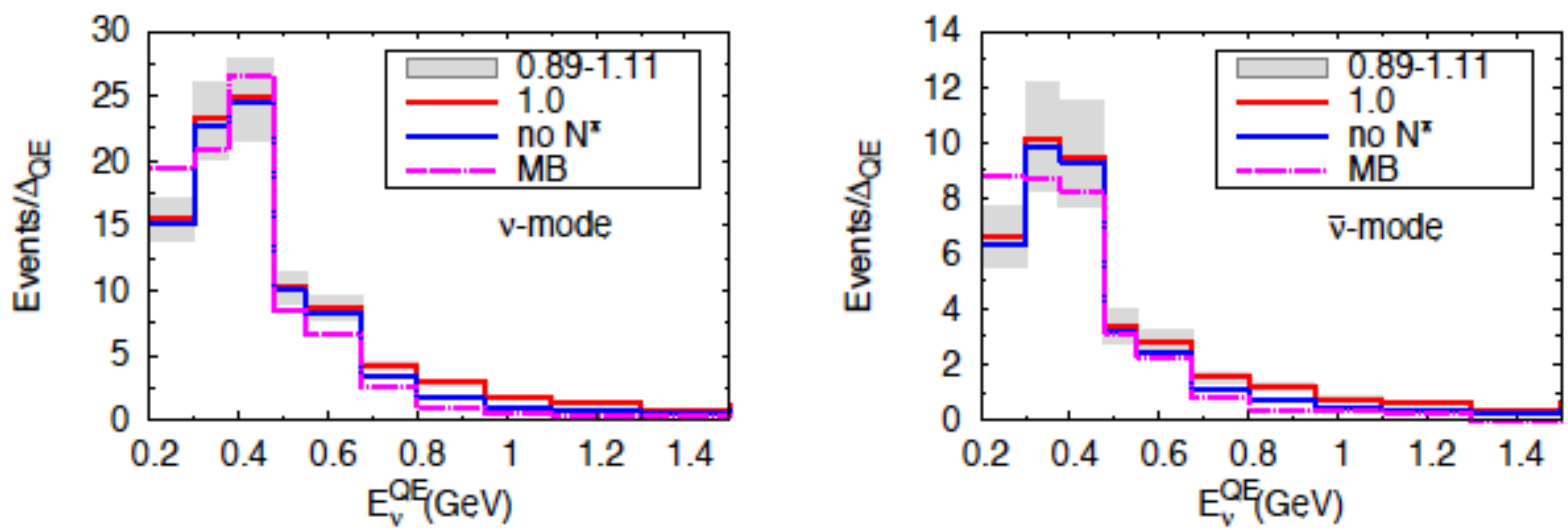
e.g.) Valencia NCγ model
- Δ and 3 higher resonances
- Nuclear media effects included
- both incoherent and coherent contribution

dominant →



It looks modern calculations agree with NCγ model used by MiniBooNE

NCγ event comparison with function of E_ν^{QE}



Lasorak, arXiv:1602.00084
Wang et al.,PRD92(2015)053005

2. NCγ models in generators and theories

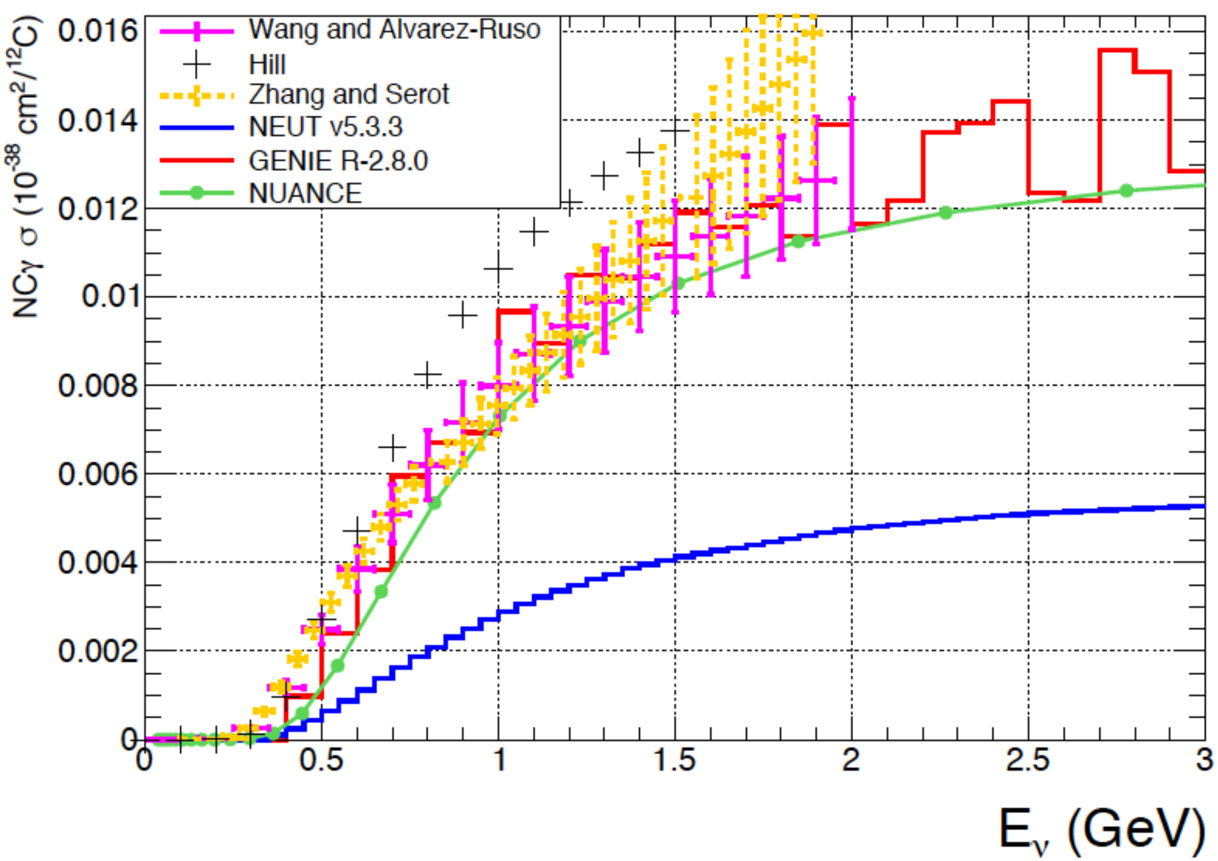
With 600 MeV neutrino beam, total NCγ cross section on carbon is $\sim 10^{-41}\text{cm}^2$

- All models and theories more or less agree
- In T2K oscillation analysis, NEUT NCγ process is doubled with 100% error

Impact on T2K oscillation analysis looks small.

10% changes of $\sin^2 2\theta_{13}$ (T2K) corresponds to σ(NCγ) needs to increase factor 10.

Total muon neutrino NCγ cross section on ^{12}C



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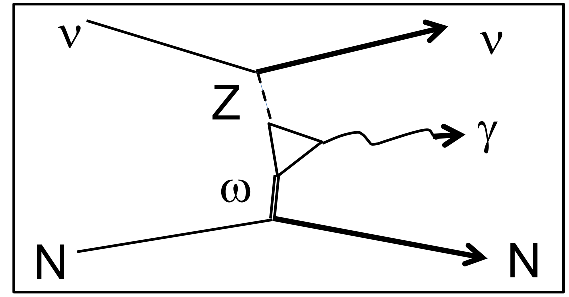
2. Exotic NCγ processes

anomaly mediated triangle diagram



NCγ with new type of interaction within the Standard Model
- anomaly mediated neutrino-photon interaction

PRL 99, 261601 (2007) PHYSICAL RE

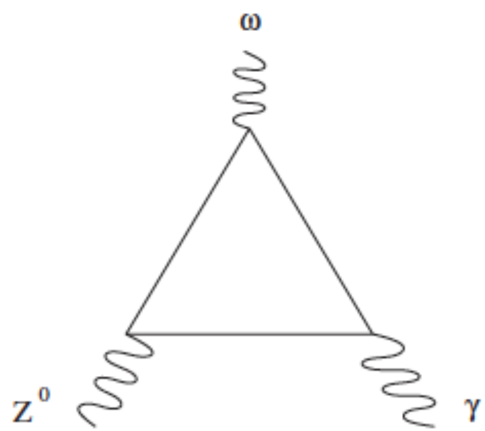


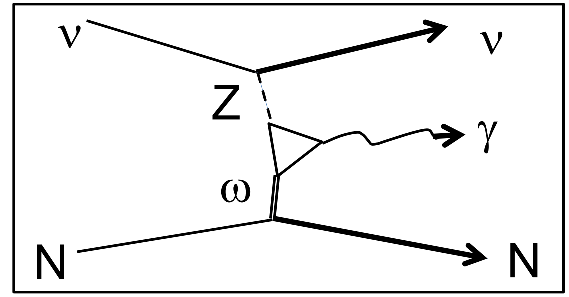
FIG. 1. Triangle diagram at chiral constituent quark level treating γ, Z, and ω as background gauge fields. This is contained in the Wess-Zumino-Witten term, which is an effective action expressing the full anomaly physics of pseudoscalars, axial- and vector mesons and fundamental gauge fields. Integrating out Z and ω leads to a neutrino-photon interaction at finite baryon density.

2. Exotic NCγ processes

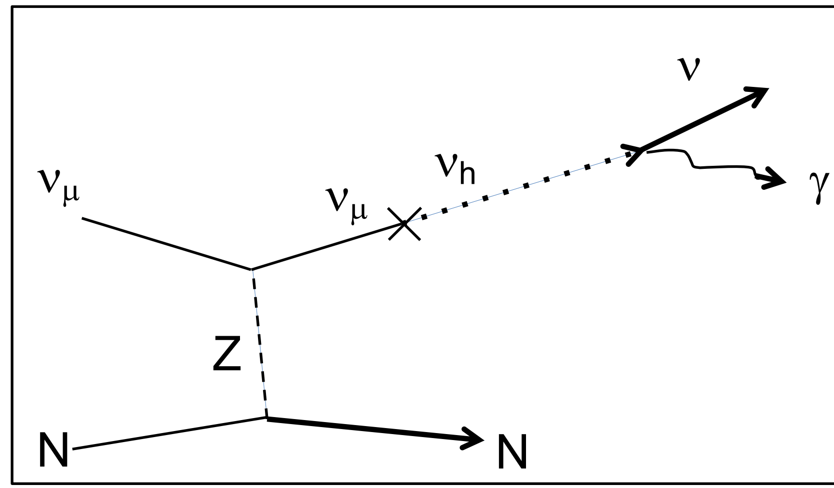
NCγ with new type of interaction within the Standard Model
- anomaly mediated neutrino-photon interaction

NCγ with beyond the Standard Model interaction
- Heavy neutrino decay

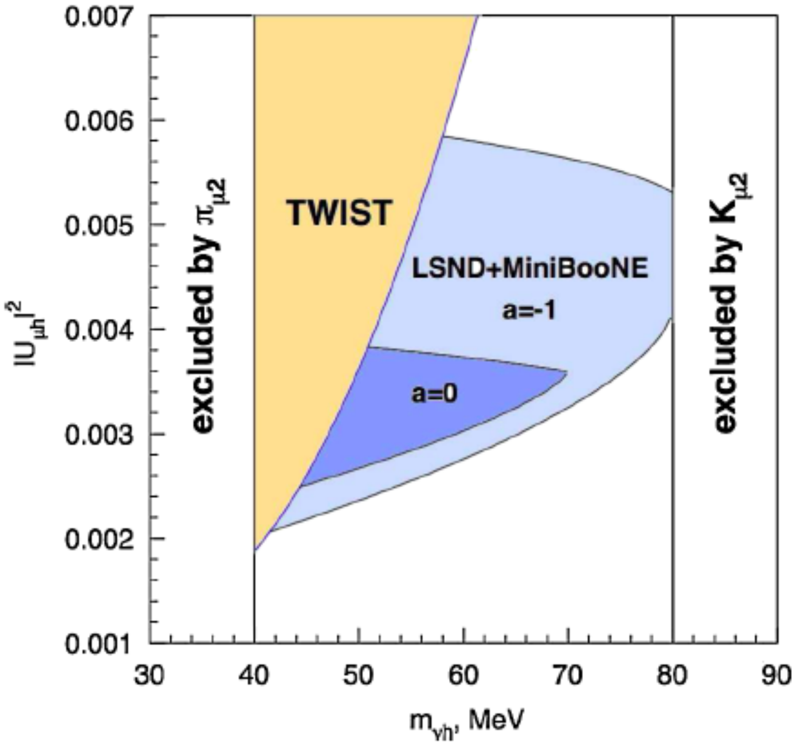
anomaly mediated triangle diagram



heavy neutrino decay



PHYSICAL REVIEW D 83, 015015 (2011)

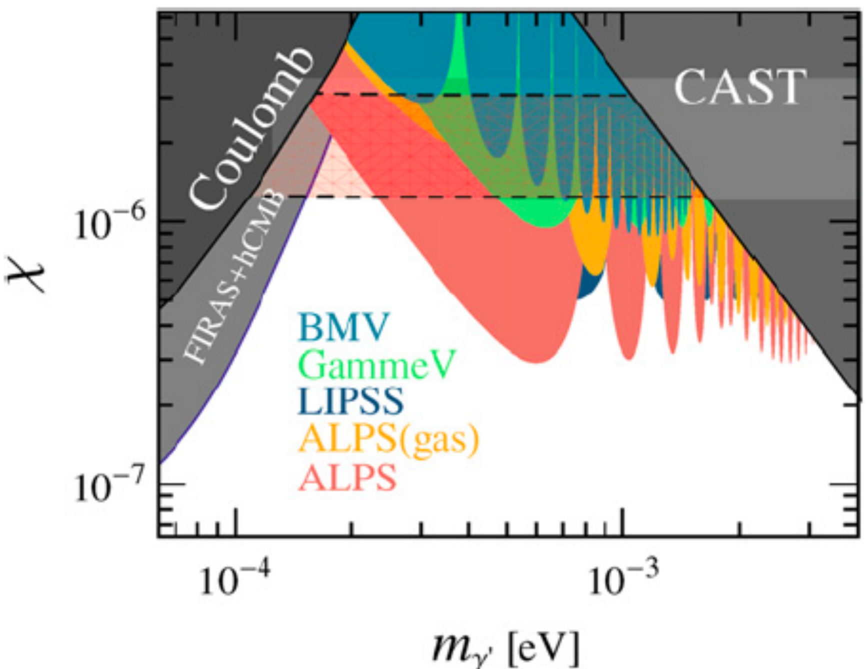


Harvey,Hill,Hill, PRL99(2007)261601,Gninenko, PRL103(2009)241802
ALPS collaboration, PLB689(2010)149

2. Exotic NCγ processes

NCγ with new type of interaction within the Standard Model
- anomaly mediated neutrino-photon interaction

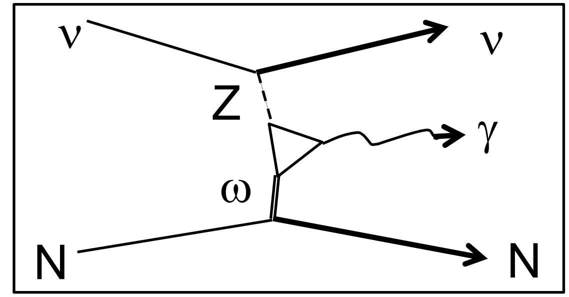
NCγ with beyond the Standard Model interaction
- Heavy neutrino decay
- Dark photon oscillation



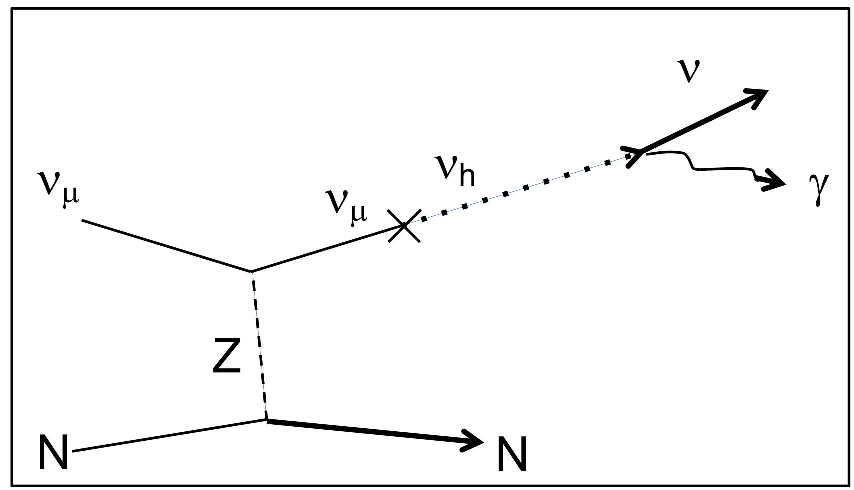
→ T2K

Neutral Current is a home of many new physics!

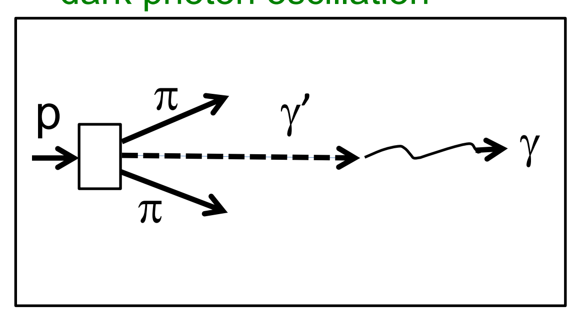
anomaly mediated triangle diagram



heavy neutrino decay



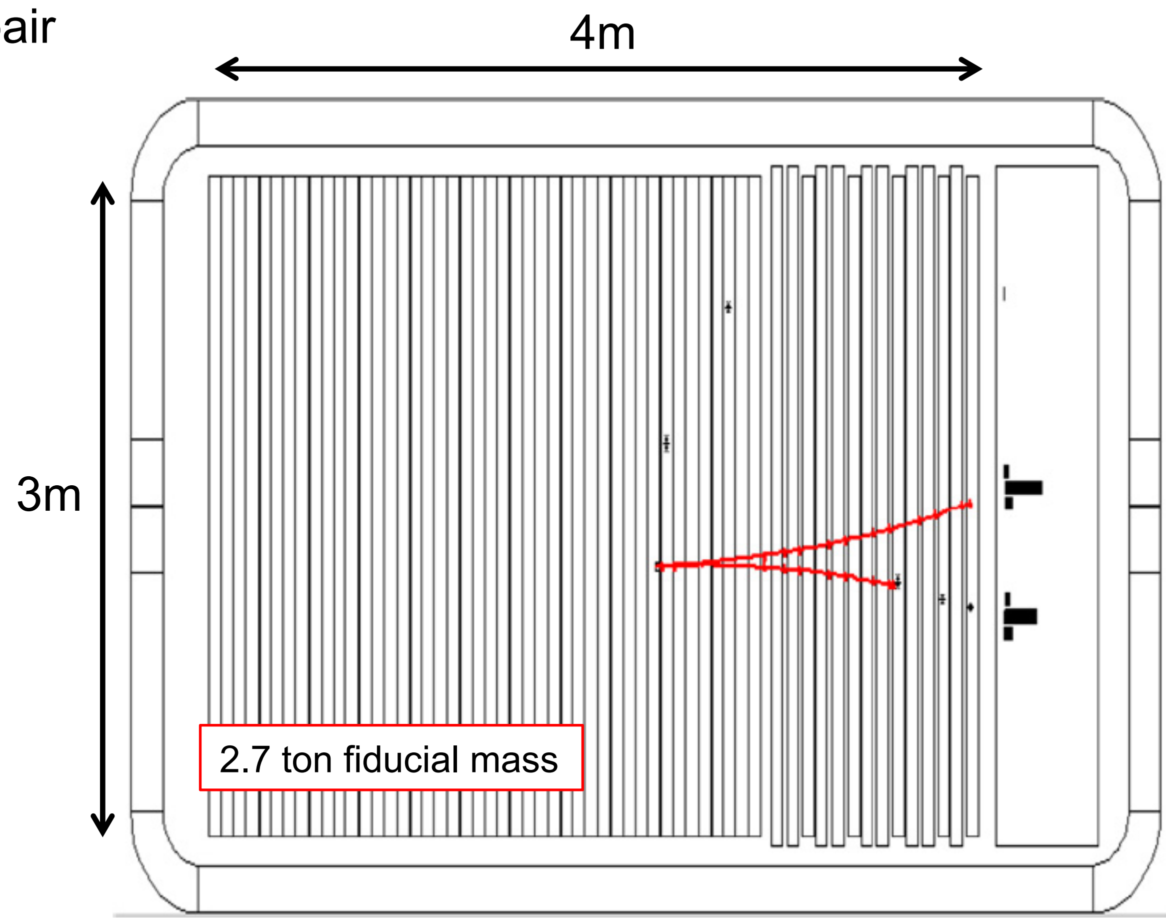
dark photon oscillation



2. NOMAD NCγ analysis

Only one modern NCγ search (motivated by heavy nu model)

Simple, but robust analysis.
- single e^+-e^- pair
- fiducial cut
- W<100 MeV



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Only one modern NCγ search (motivated by heavy nu model)

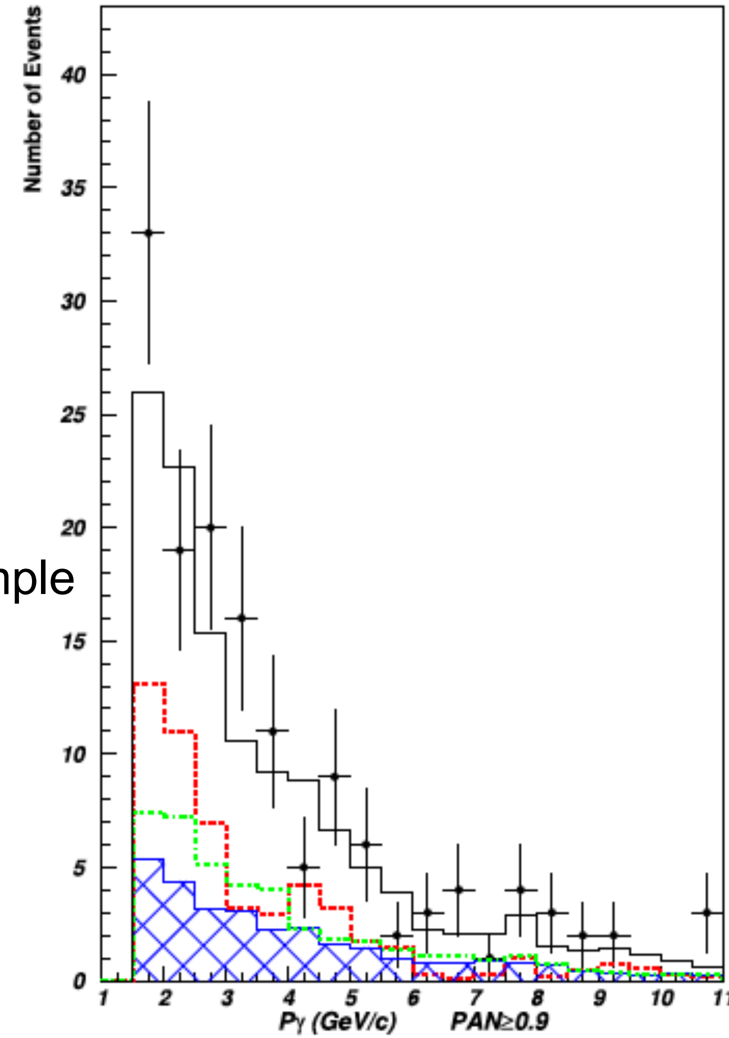
Simple, but robust analysis
- single e^+-e^- pair
- fiducial cut
- W<100 MeV

3 major backgrounds
- NC coherent π^o production
- outside of fiducial volume background
- NC-DIS π^o production

all of them are tuned from background data sample

No excess, NOMAD set a limit on cross section ratio of NCγ to CC inclusive

→ $\sigma(NC\gamma/CC) < 4 \times 10^{-4}$ with <E>~23 GeV



2. NOMAD NCγ analysis

Result

- no excess, set limit, $\sigma(NC\gamma/CC) < 4\times10^{-4}$ with <E>~23 GeV

There are 2 types of backgrounds, internal and external backgrounds

internal background

- dominated by $NC\pi^o$ production (coherent DIS, etc) with single γ final state
  → $NC\pi^o$ production rate is constraint from the own data

external background

- γ coming from outside of the fiducial volume (mostly from π^o)
  → External background is tuned from the own data

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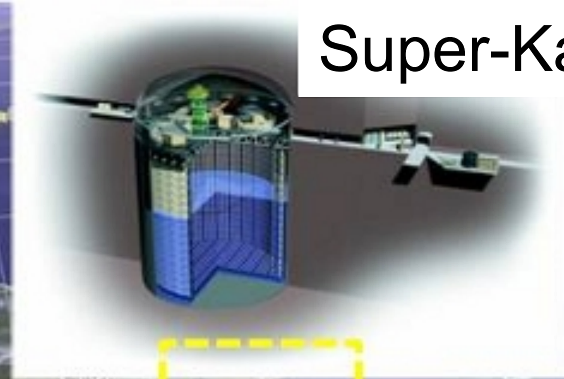
T2K, PRD91(2015)072010

Super-Kamiokande detector



T2K

T2K (Tokai to Kamioka) experiment

295km

Neutrino beam

- J-PARC neutrino beam to Super-Kamiokande
- Observed both ν_μ-disappearance and ν_e-appearance
- Nonzero leptonic CP violation is favored
- 2016 Breakthrough prize winner

(with SNO, SK, DayaBay, KamLAND)

J-PARC

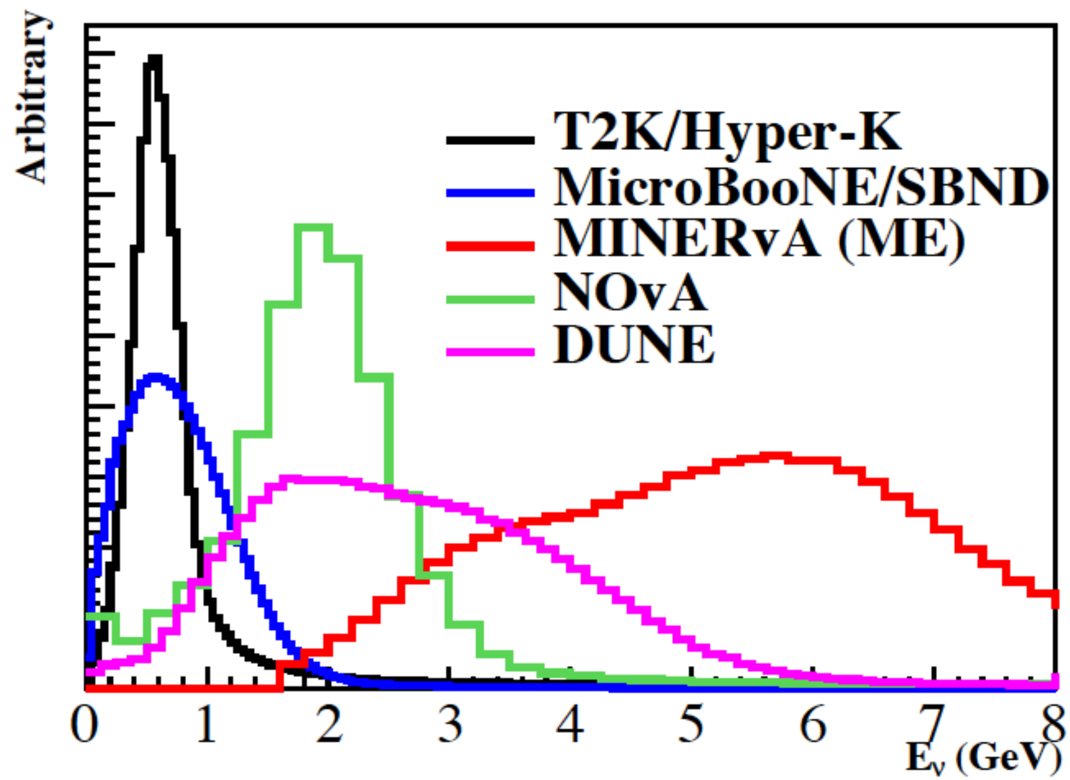
BREAKTHROUGH PRIZE

3. J-PARC neutrino beam

First off-axis neutrino beam oscillation experiment

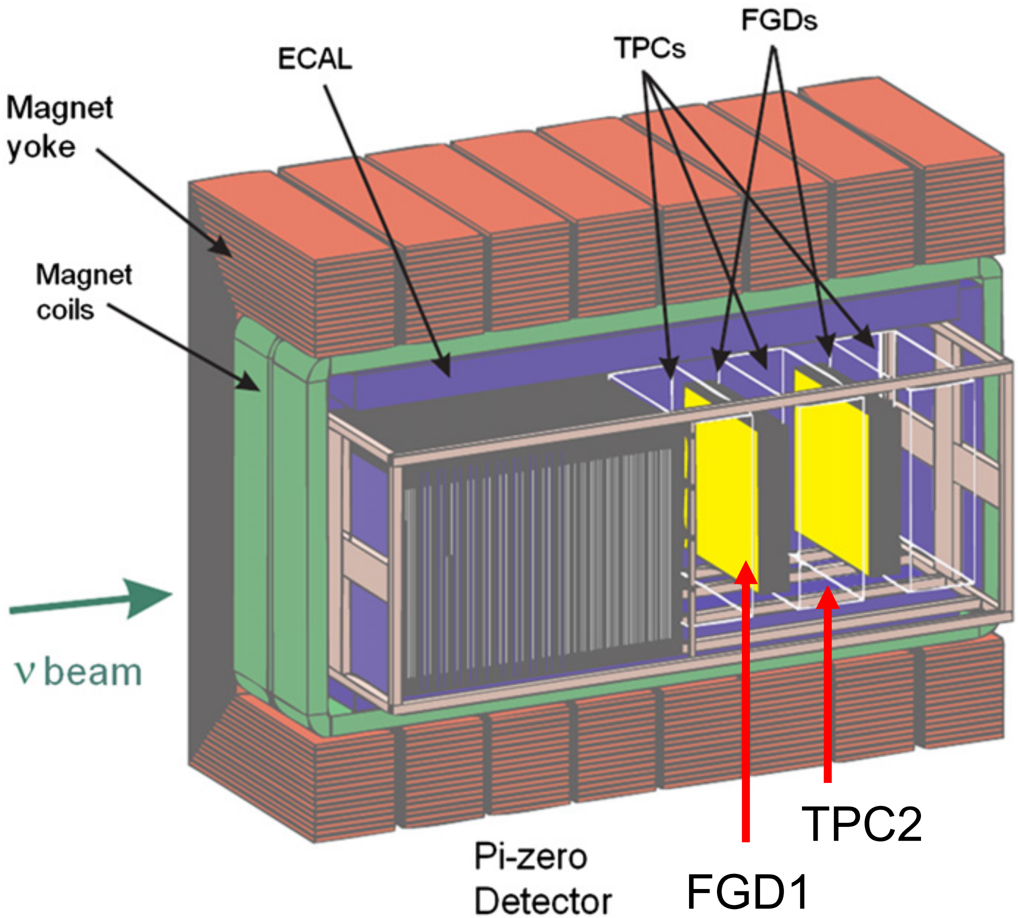
- Extracted from 30 GeV main ring synchrotron
- Hadron production data from NA61/SHINE
- GEANT4 based beamline simulation
- error 5-8% (most precise neutrino beam to date)

→ continuously improving with thick target data



3. T2K off-axis near detector (ND280)

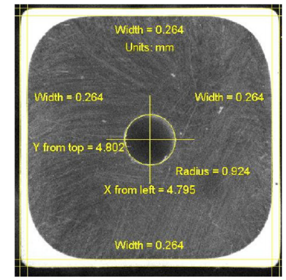
This analysis use FGD1 as a vertex detector, and TPC2 for main tracking&PID
- target material is carbon in FGD1
- e^+-e^- pair is reconstructed in TPC2
- UA1 magnet (0.2 T)

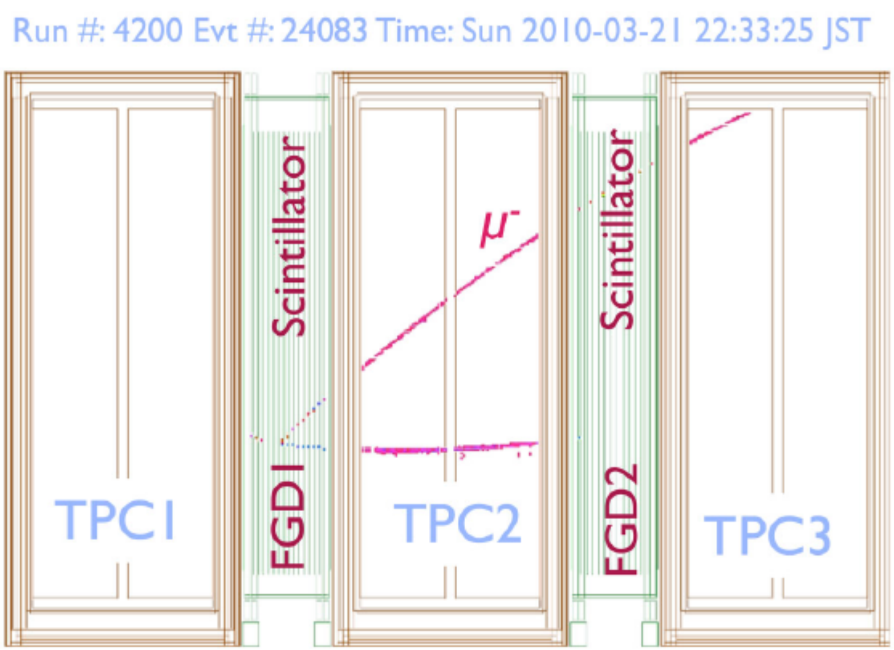


3. FGD (fine-grained detector)

Plastic scintillator x-y tracker (cf, SciBooNE, MINERvA, etc)

- 185cm x 185cm x 33cm
- $1cm^2$ cross section
- extruded polystyrene, 1%PPO, 0.3%POPOP
- co-extruded with T_iO_2 reflector
- Blue-Green WLS fiber + SiPM read out
- ~15p.e. for MIP



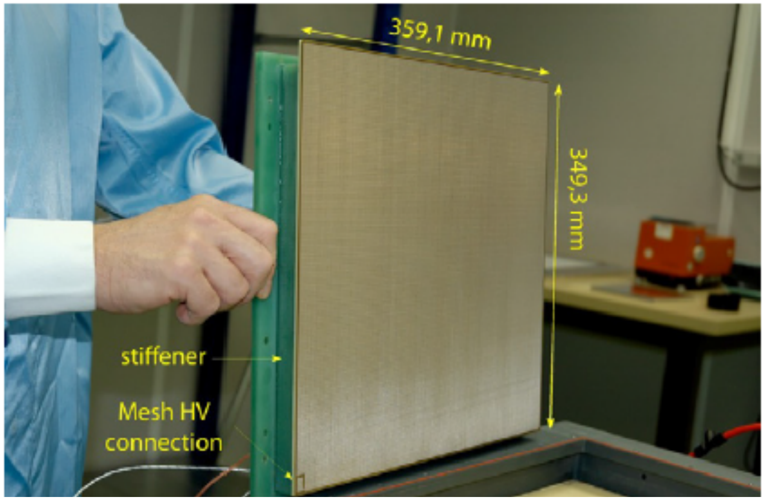


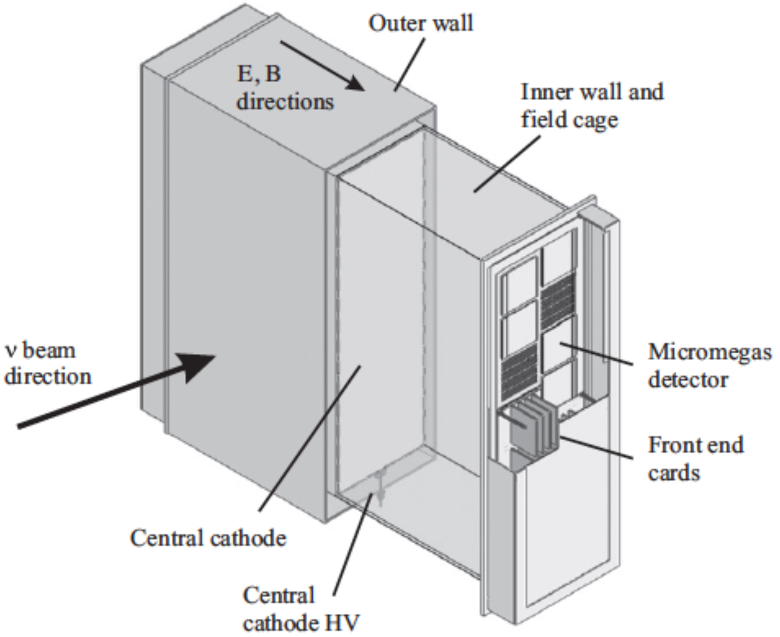
ν_μCC candidate event

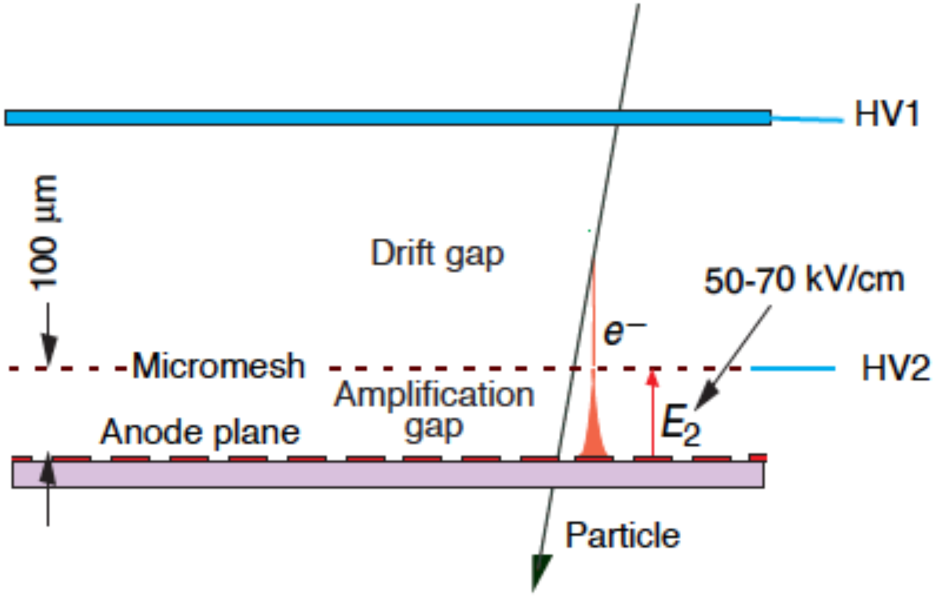
3. TPC

Argon gas time projection chamber

- 180cm x 223cm x 85cm
- $Ar:CF_4:iC_4H_{10}$=95:3:2
- drift voltage ~275V/cm
- Bulk MicroMEGAS reading (1cm pad pitch)
- mesh voltage ~350V→27kV/cm (g~1500)



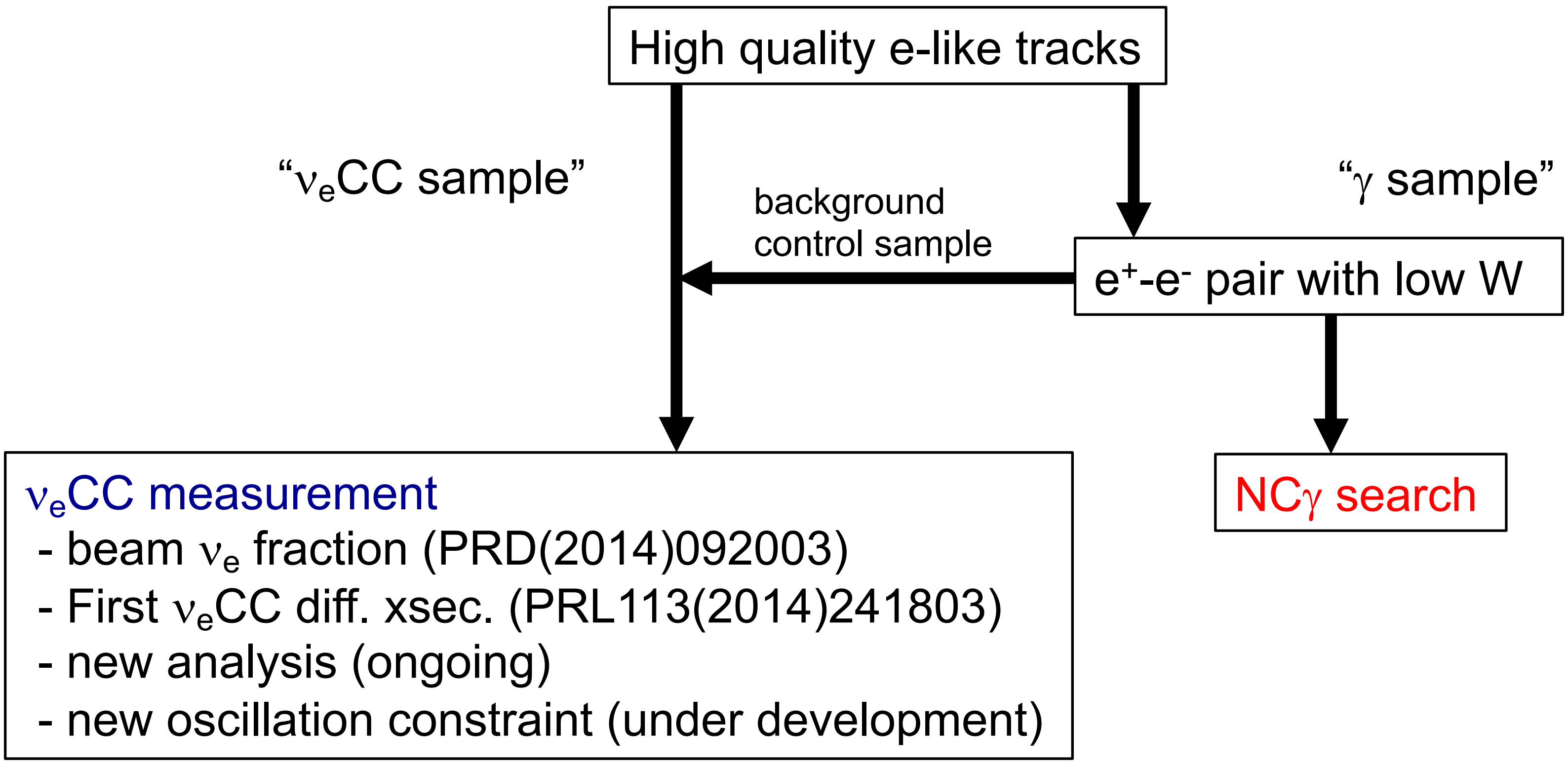




3. Analysis strategy

Highest purity gamma ray sample

- Follow NOMAD strategy
- e^+-e^- selection with low W

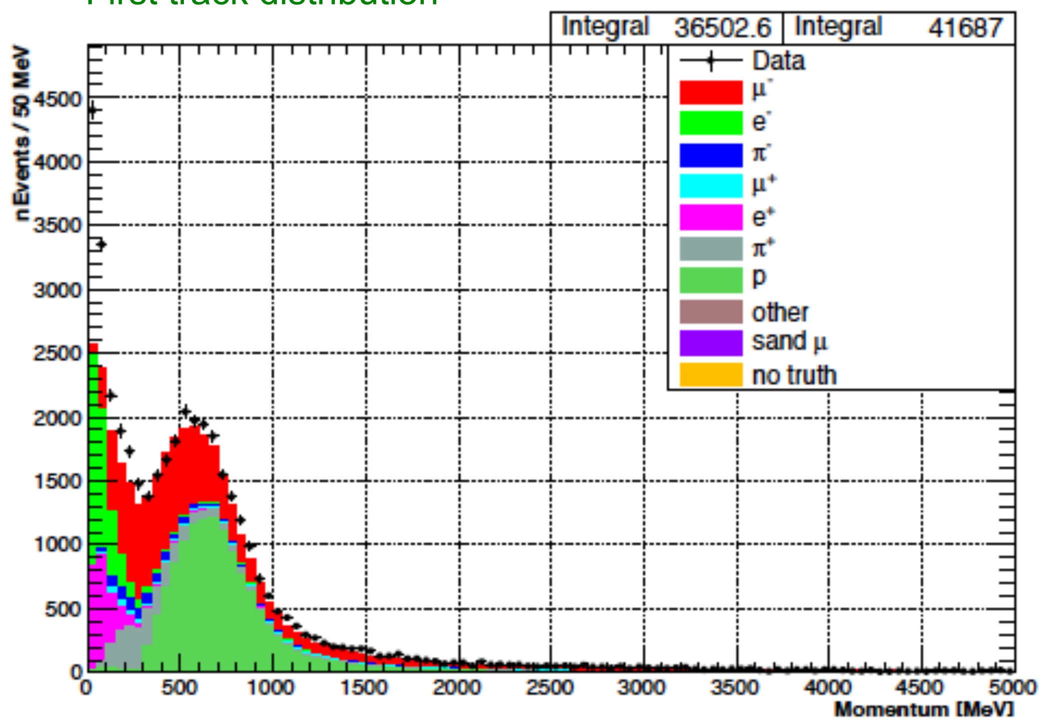


3. Analysis strategy

Track selection
- Starting track from FGD1

First track - Highest momentum track
Second track - Next highest momentum track with opposite charge from the first track

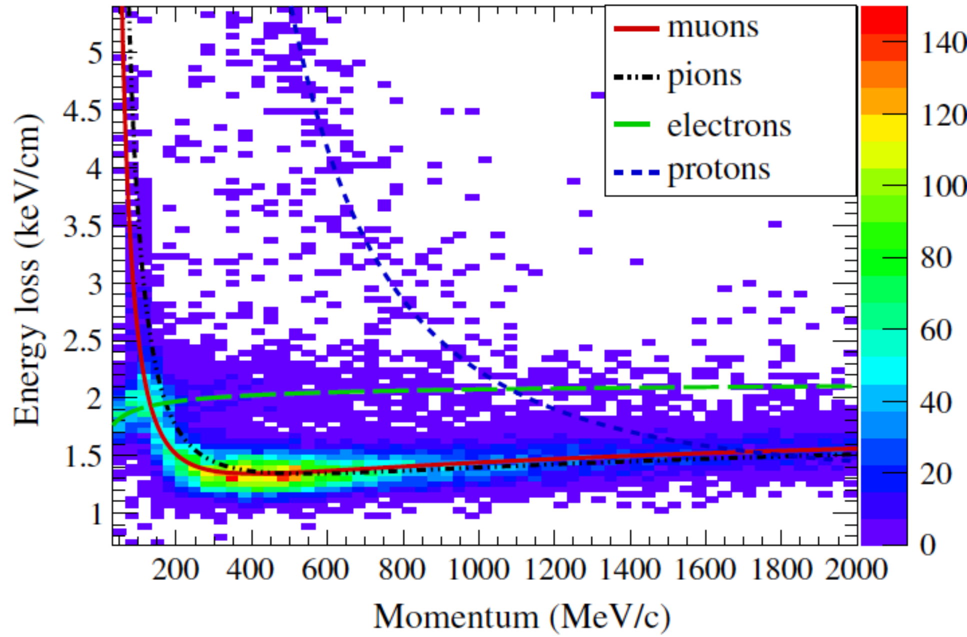
First track distribution



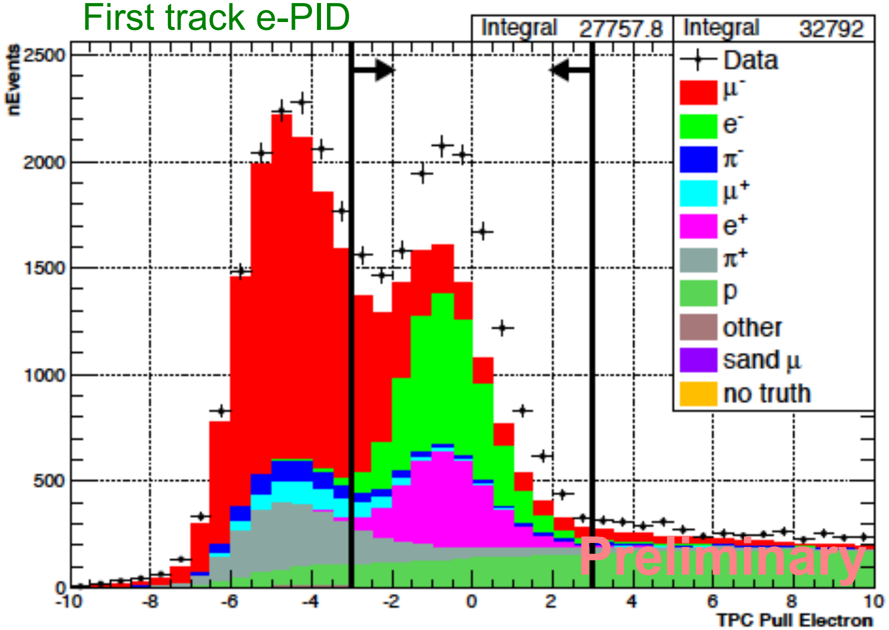
3. Analysis strategy

Track selection
- Starting track from FGD1

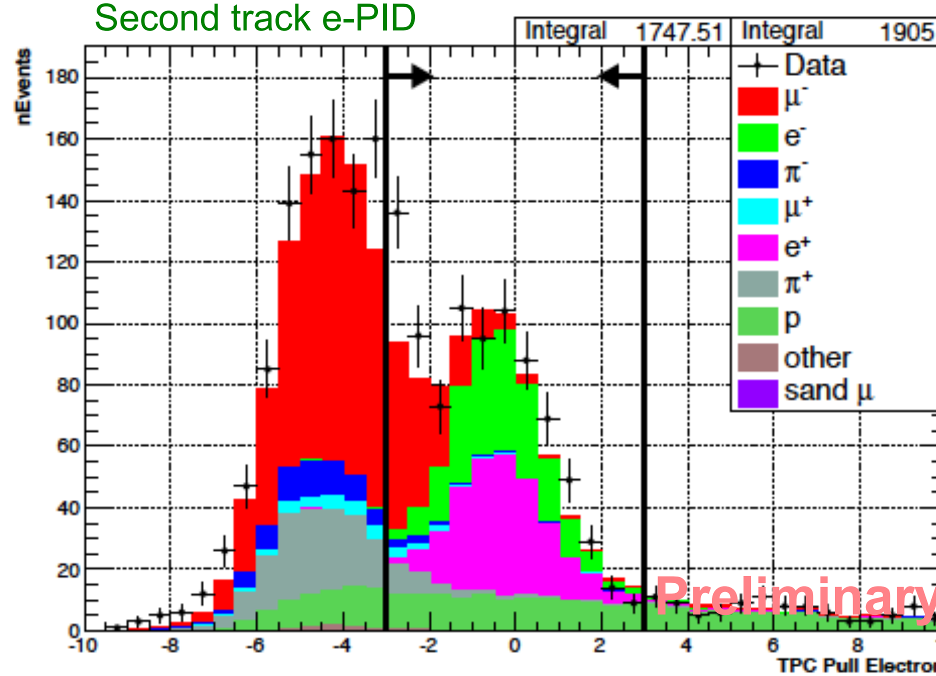
TPC PID
- More than 18 clusters in TPC2
- dE/dx to reject muons
  → large contamination due to short tracks



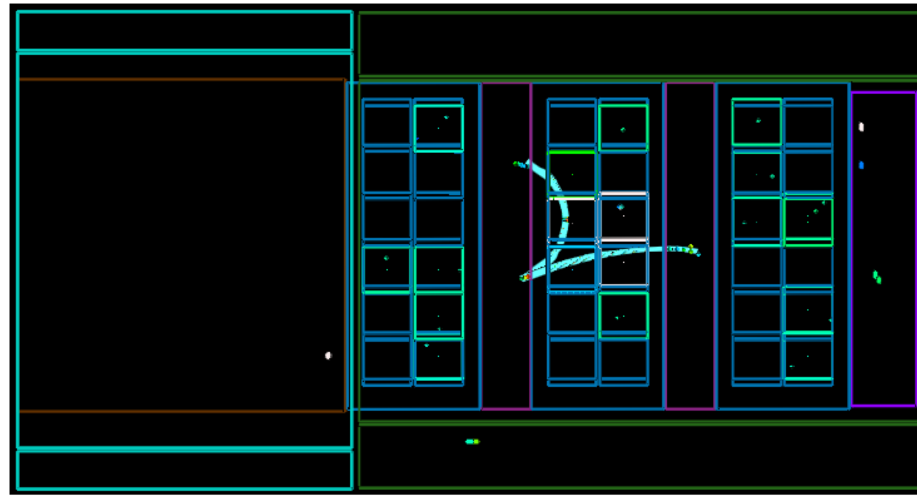
First track e-PID



Second track e-PID

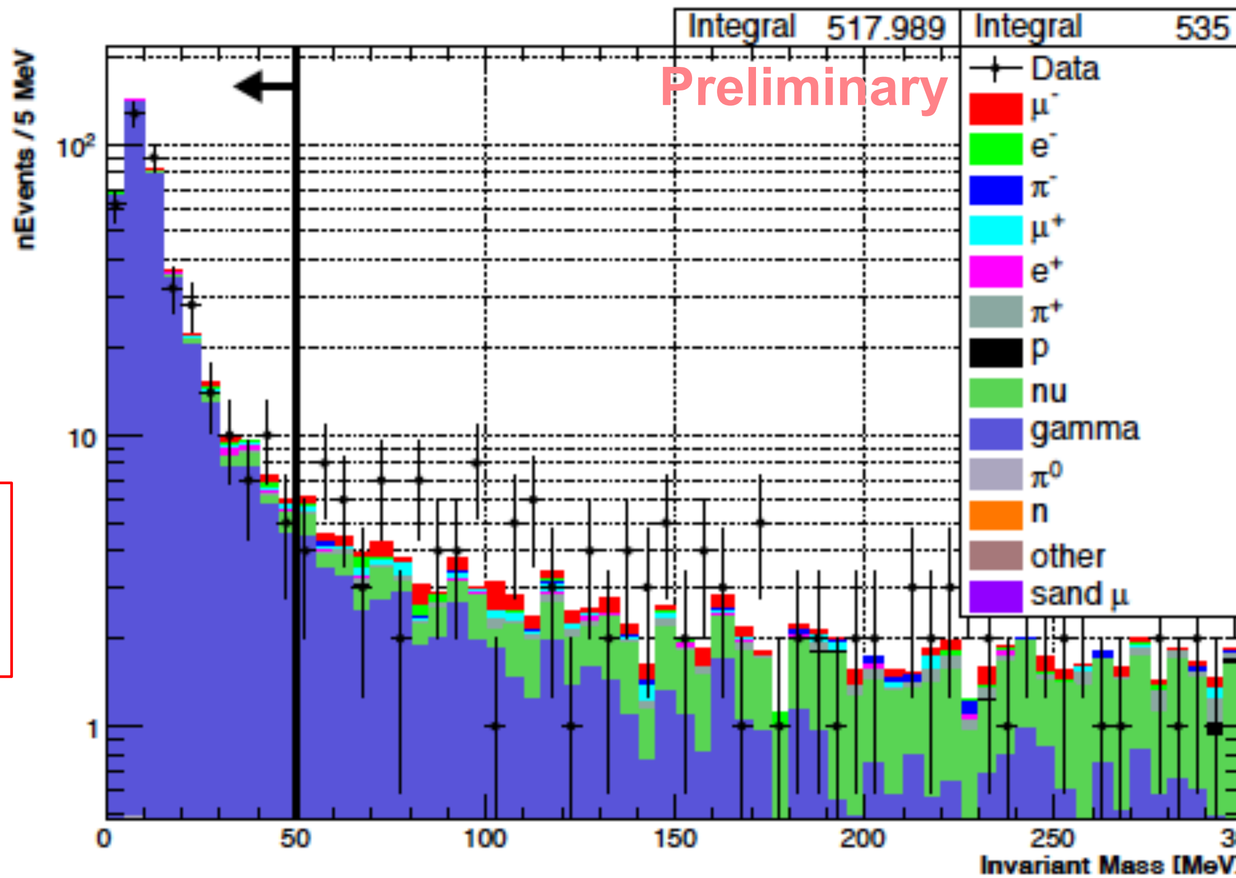


3. Analysis strategy



Gamma selection

- e+-e- tracks < 10cm
- Winv < 50 MeV
- ~94.3% pure single gamma sample



Extremely simple cuts can select extremely high pure gamma sample

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University of London

3. Analysis strategy

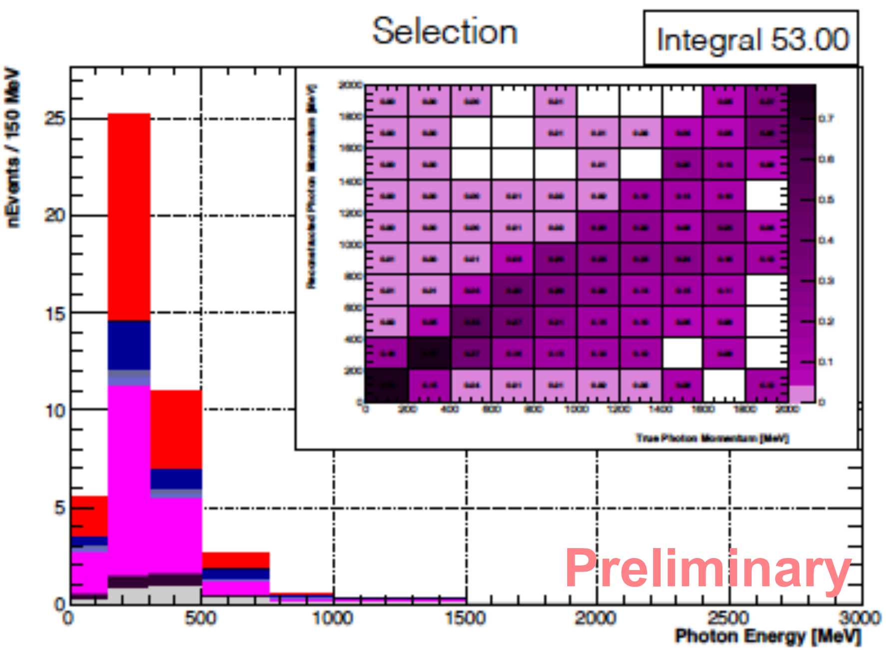
Gamma selection

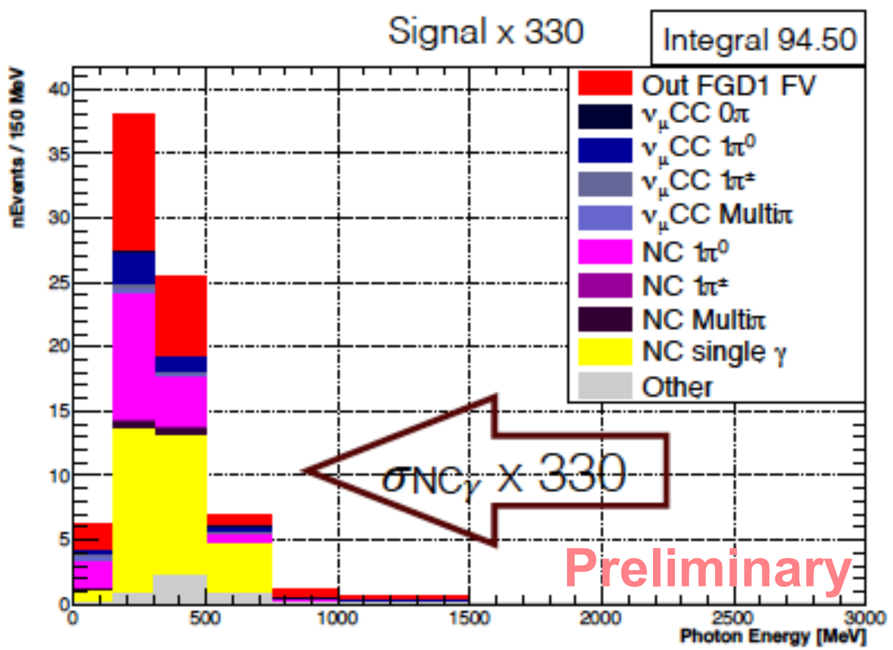
- e+-e- tracks < 10cm
- Winv < 50 MeV
- ~94.3% pure single gamma sample
- expected NCγ signal fraction ~0.2%

Large signal-to-noise tells we are unlikely to find NCγ by this approach
→ Constraining background systematics to set the best limit on NCγ signal

2 main backgrounds

- events coming from outside of FGD1 fiducial volume, external background
- events from π^o production in the FGD1 FV, internal background

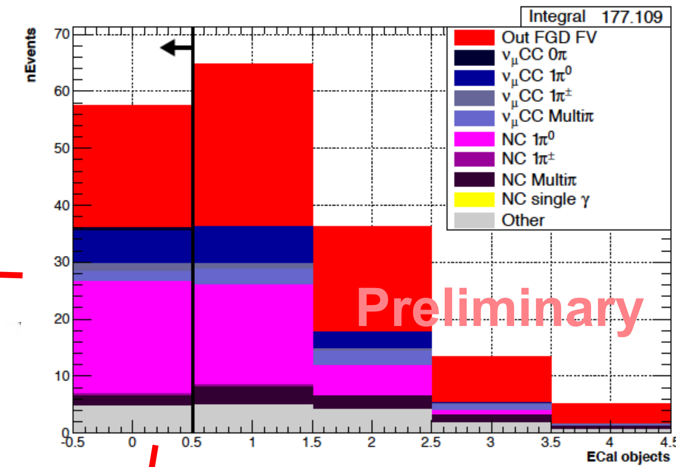


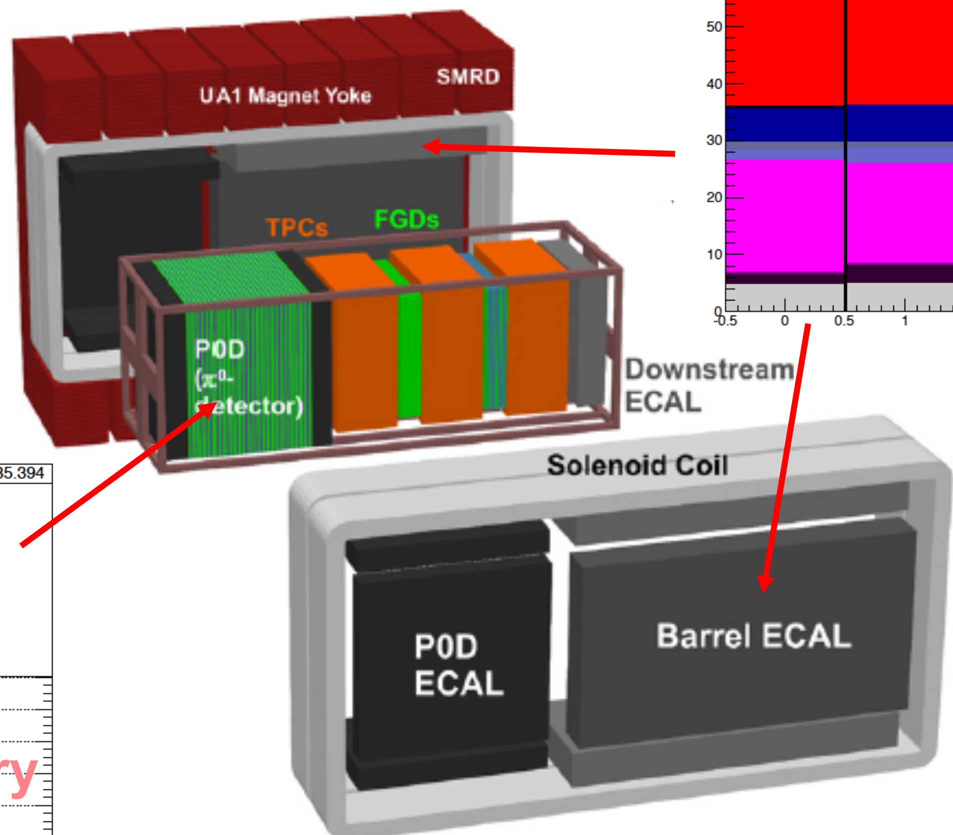


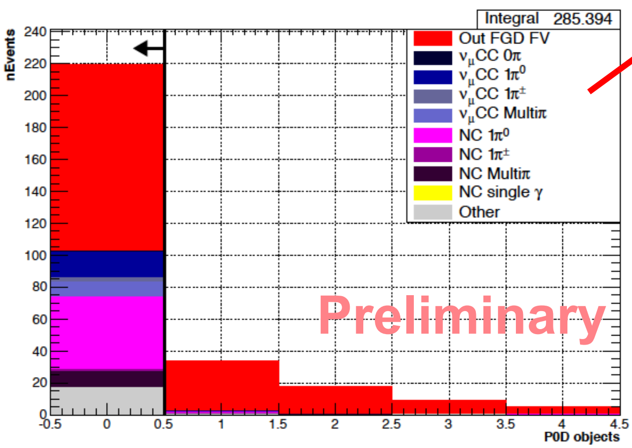
3. External background

Active vetoes from all surrounding detectors

- P0D
- TPC1
- Barrel ECal



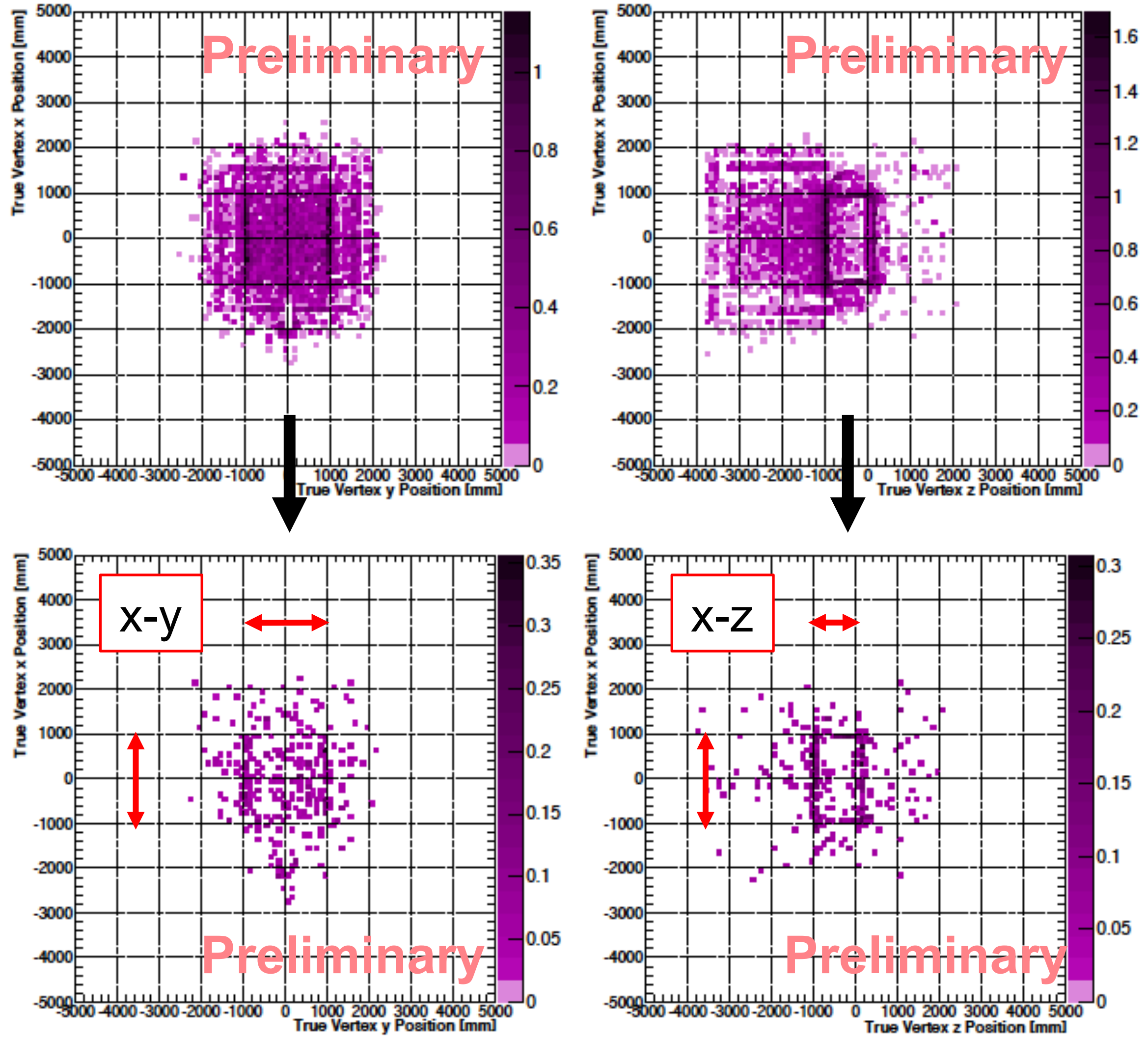




3. External background

Active vetoes from all surrounding detectors
- P0D
- TPC1
- Barrel ECal

Vetos work well, however, there are still many external photons, both from near (inside of veto detectors) and from far
→ need precise characterization of these photons from simulation

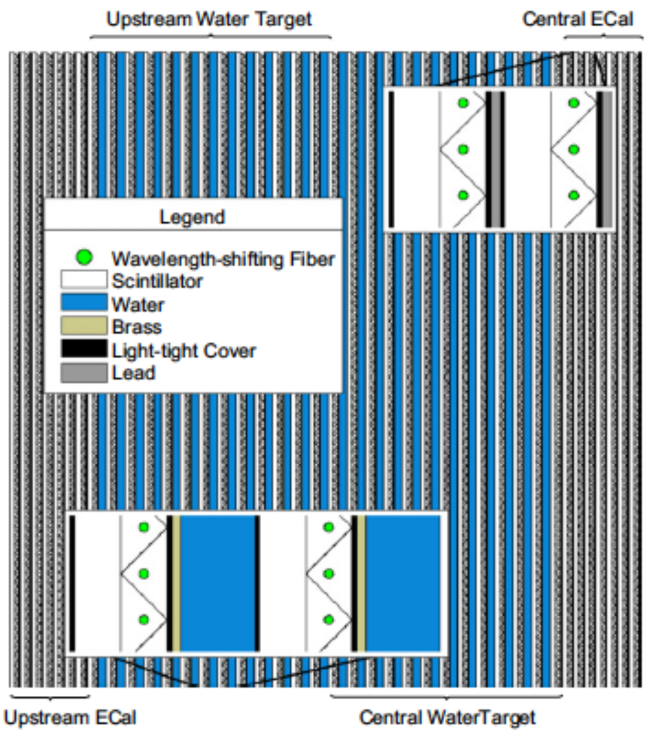


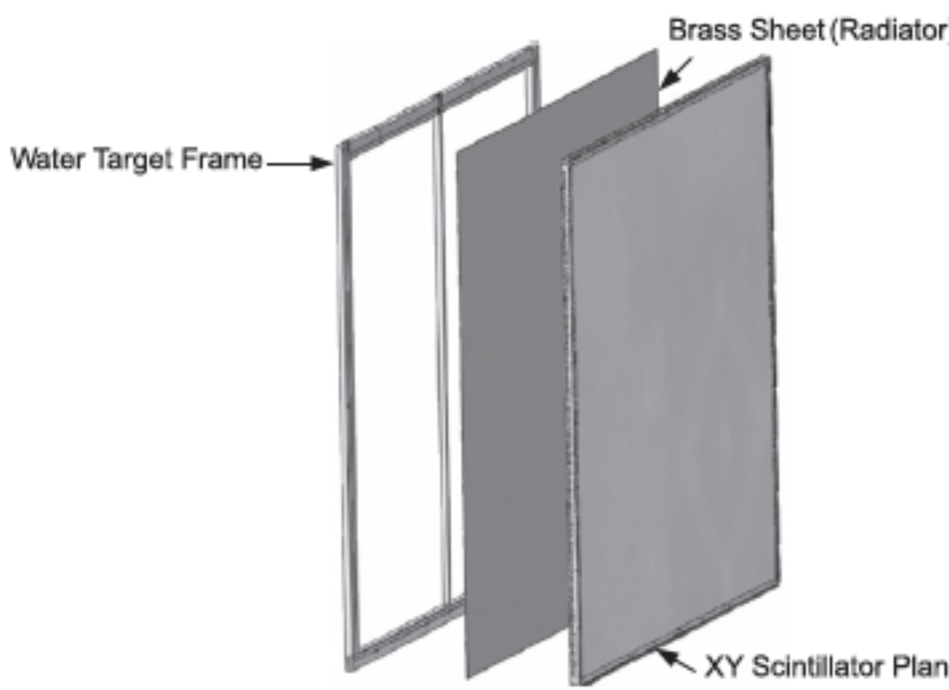
T2K, NIMA686(2012)48,JINST8(2013)P10019

3. External background

Known mass variation
- From production of sub-detectors
- Tend to have larger errors for heavier elements (radiators)

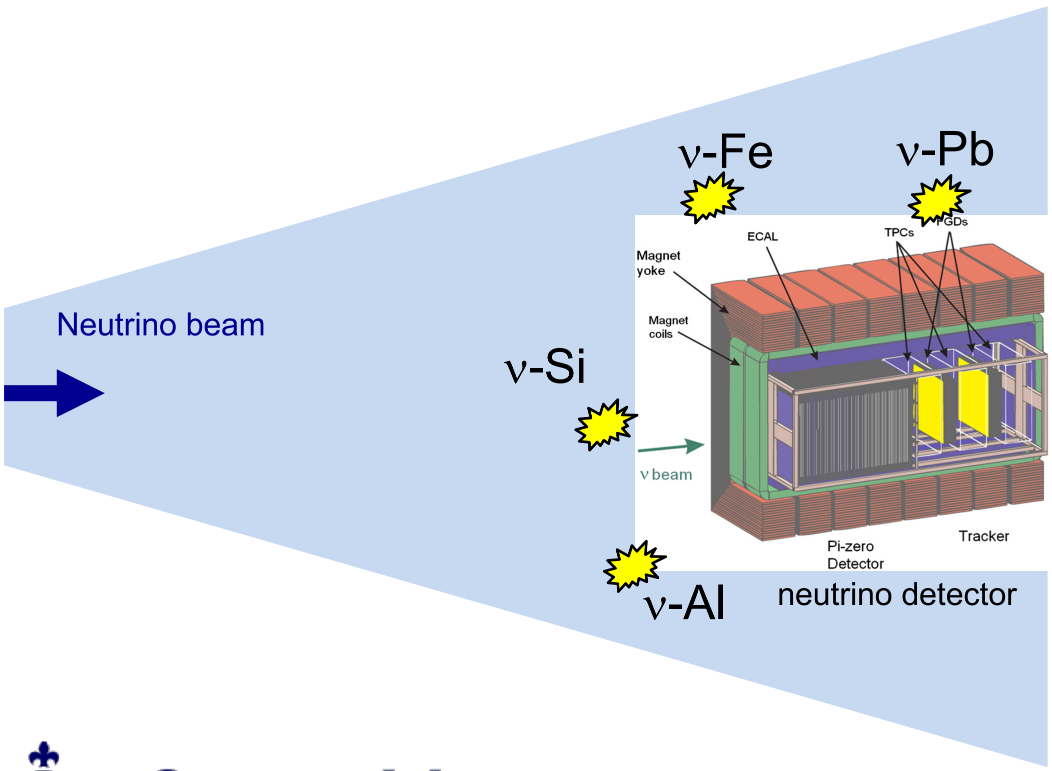
e.g.) P0D module structure
- large errors on brass sheet thickness
- large errors on interaction cross section





3. External background

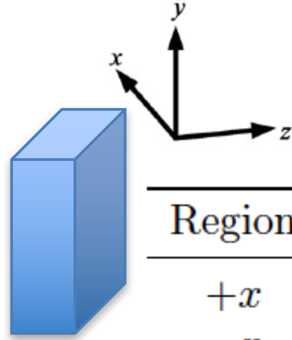
Cross section errors
- heavy elements have large cross section errors
  - carbon = non fiducial part of of scintillators
  - aluminum = support structures of subdetectors
  - lead = radiator of ECal
  - iron = SMRD, etc



Target	Percentage
carbon	53.17
oxygen	2.22
hydrogen	4.28
other	1.23
Total Inside FGD1 FV	60.90
carbon	16.27
oxygen	1.93
hydrogen	1.16
aluminium	8.64
iron	4.63
copper	0.09
lead	5.08
other	1.28
Total Outside FGD1 FV	39.09

Modern neutrino experiments need characterizations of all elements with all energy

3. External background

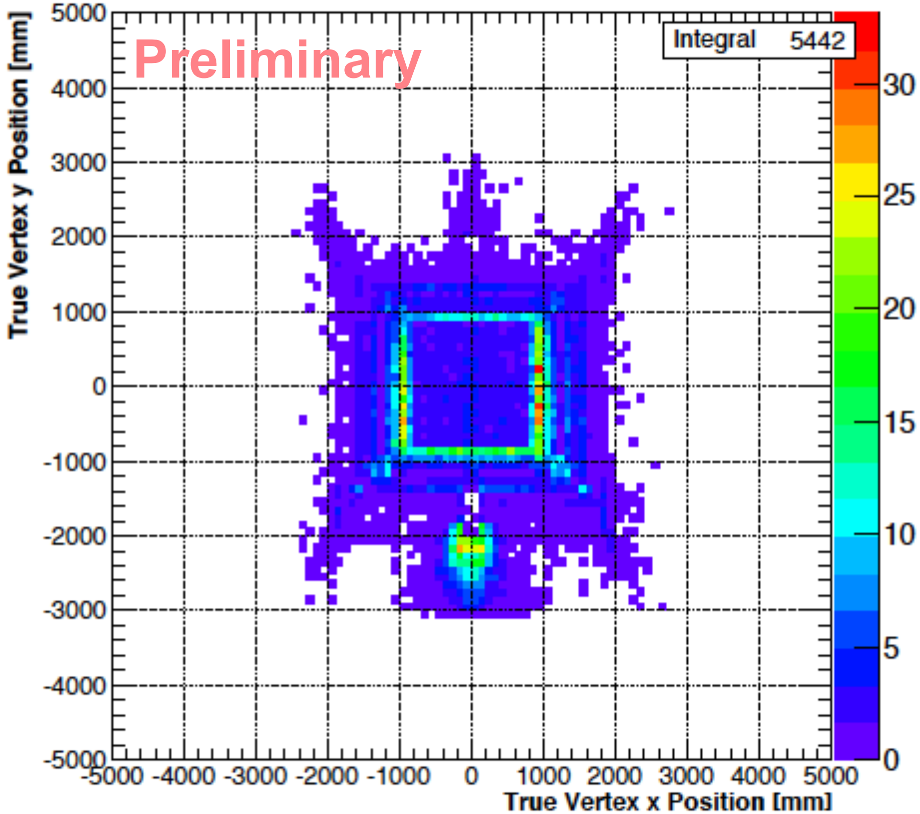


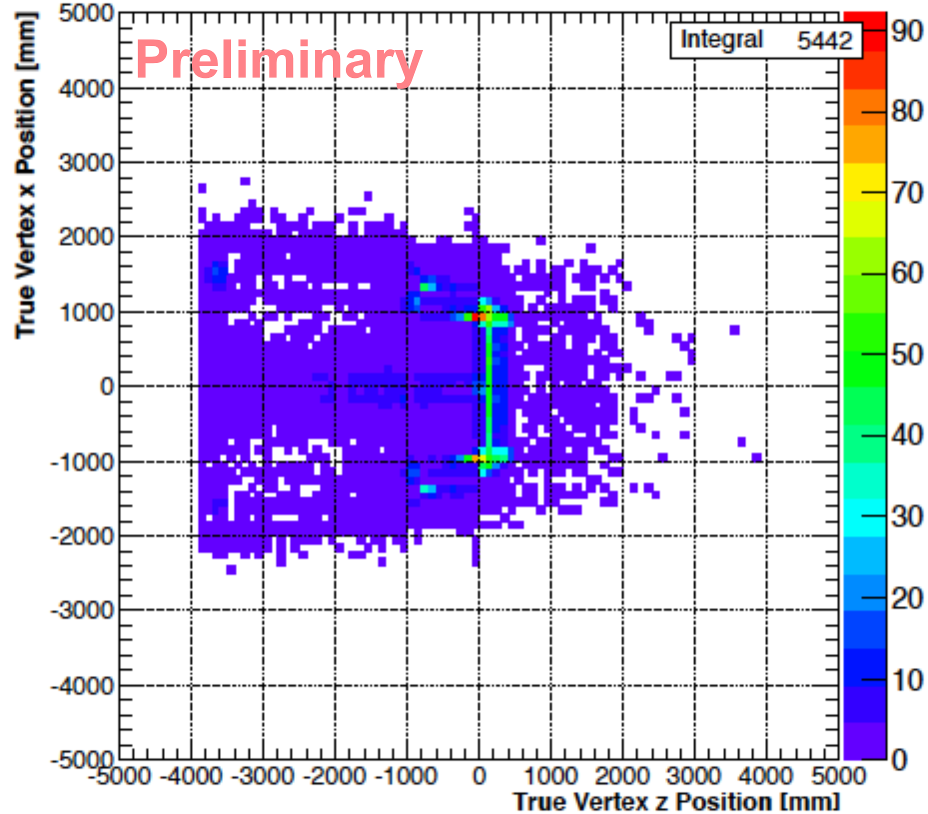
Unknown mass variation

- CC inclusive events are selected from edge of FGD1
- data/MC rate comparisons with different regions to assign mass errors

→ large discrepancy coming from muons from bottom (veto is inefficient?), the main result exclude photons from this region

Region	Mass uncertainty
$+x$	6.6506 %
$-x$	6.0402 %
$+y$	5.5572 %
$-y$	38.2304 %
$-z$	6.5380 %





3. External background

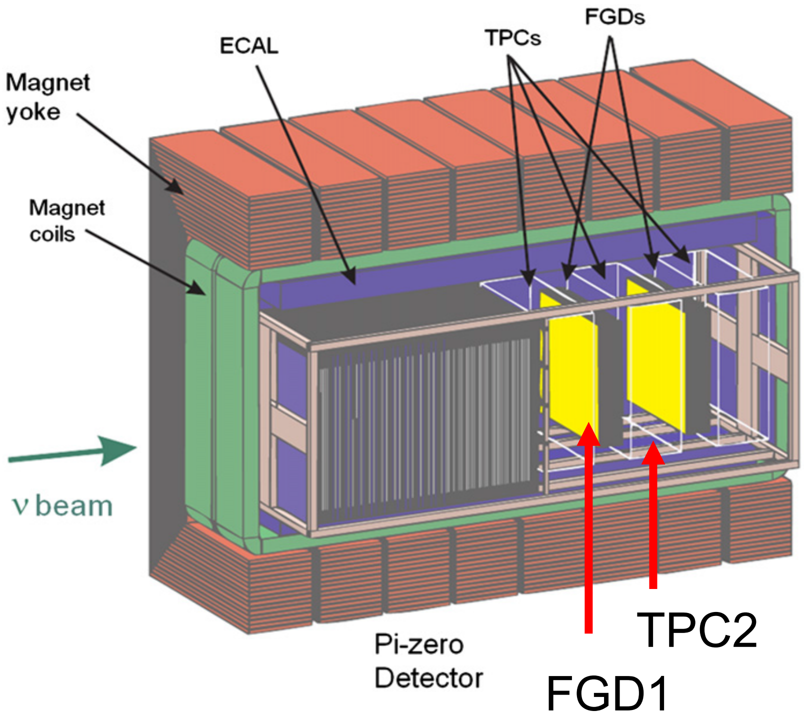
$$1/\lambda = \frac{7}{9}4Z(Z+1)Nr_e^2\alpha\left(\ln(183Z^{-\frac{1}{3}}) - f(Z)\right)$$

Z: atomic number

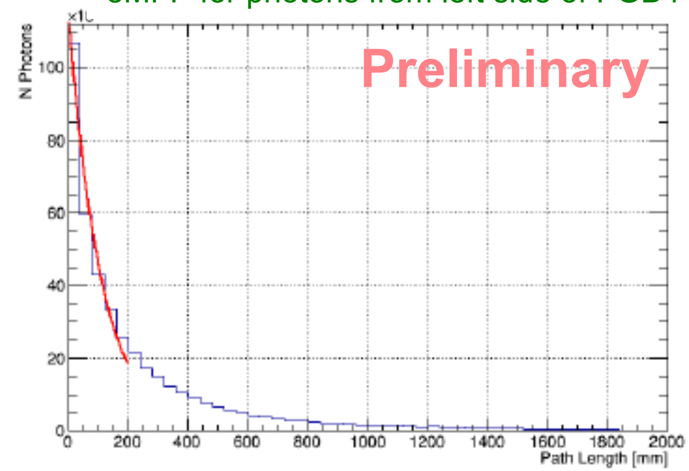
density

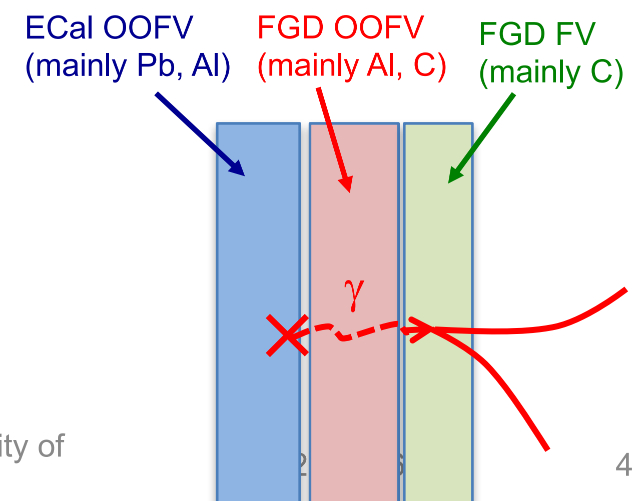
Photon propagation error

- Need to translate mass variations → photon propagations
- From MC, we measure effective Mean Free Path (eMFP) for 12 external regions
- Apply density and Z variation on eMFP



eMFP for photons from left side of FGD1





3. External background

$$1/\lambda = \frac{7}{9} 4Z(Z+1) N r_e^2 \alpha \left(\ln(183 Z^{-\frac{1}{3}}) - f(Z) \right)$$

Z: atomic number

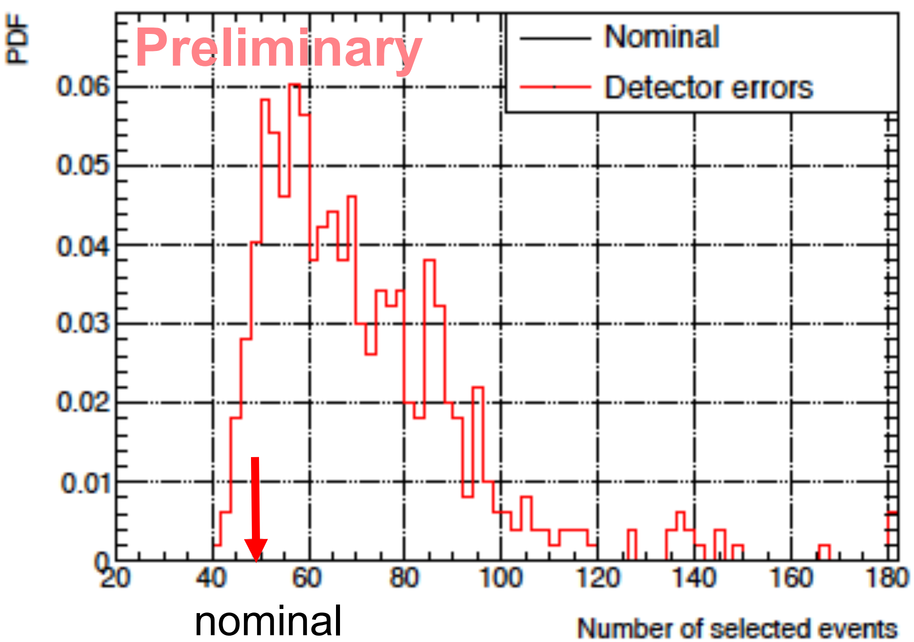
density

Photon propagation error

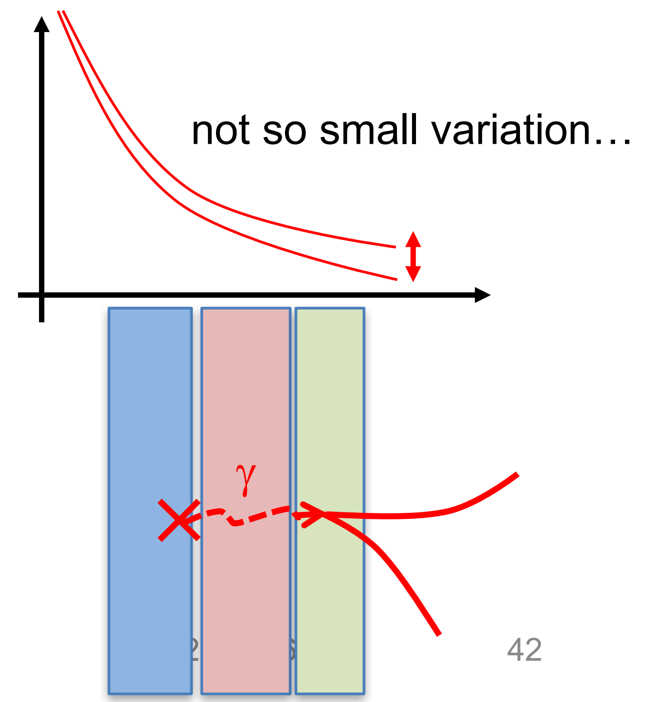
- Need to translate mass variations → photon propagations
- From MC, we measure effective Mean Free Path (eMFP) for 12 external regions
- Apply density and Z variation on eMFP

This method, unfortunately, makes large asymmetric errors
→ small density and atomic number errors in the propagation media results in large error in photon distribution at FGD1 (=tails of exponential)

It makes +23%/-16% error on prediction of external photon contributions
(this error limits NCγ sensitivity)



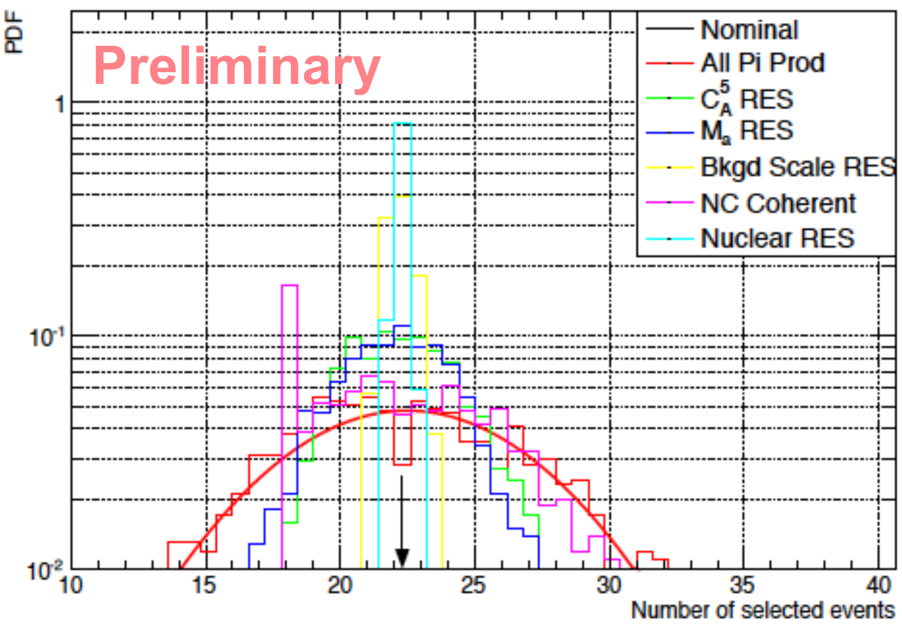
nominal

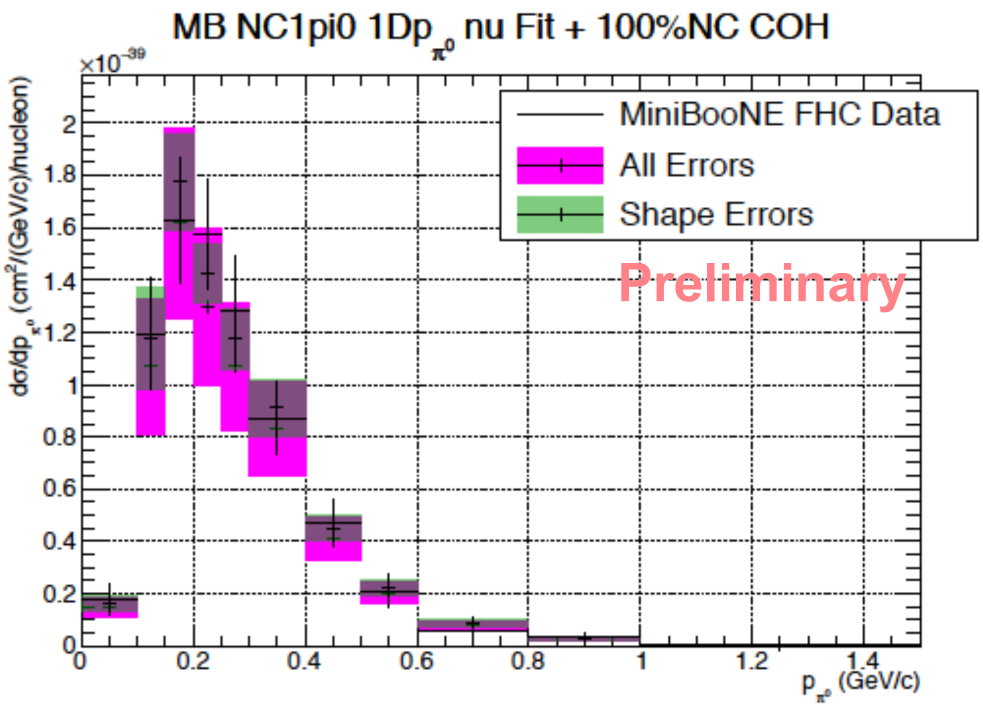


3. Internal background

NC1π^o production error

- Use NUISANCE framework
- From bubble chamber and MiniBooNE NC1π^o data
- Errors inflated to make good coverage



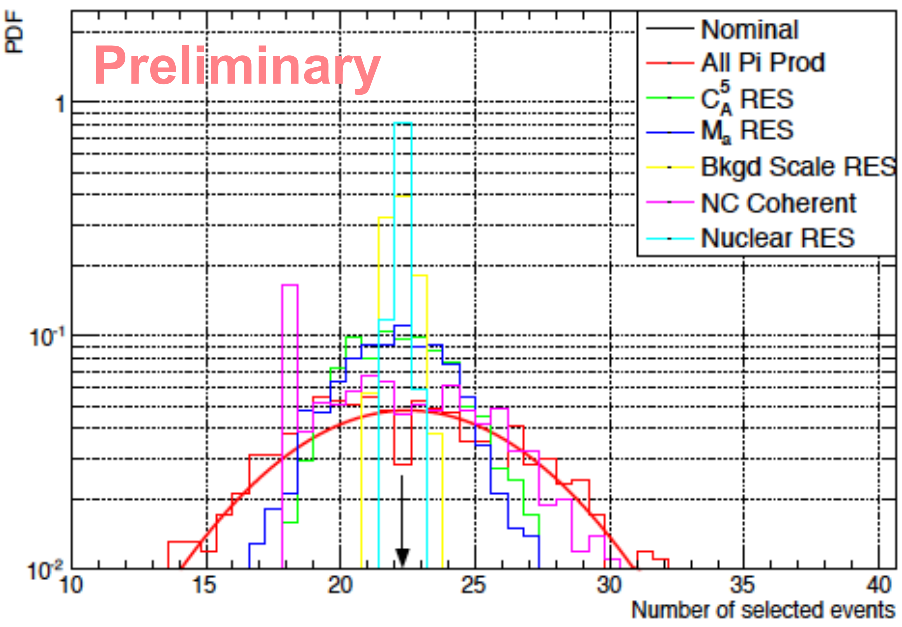


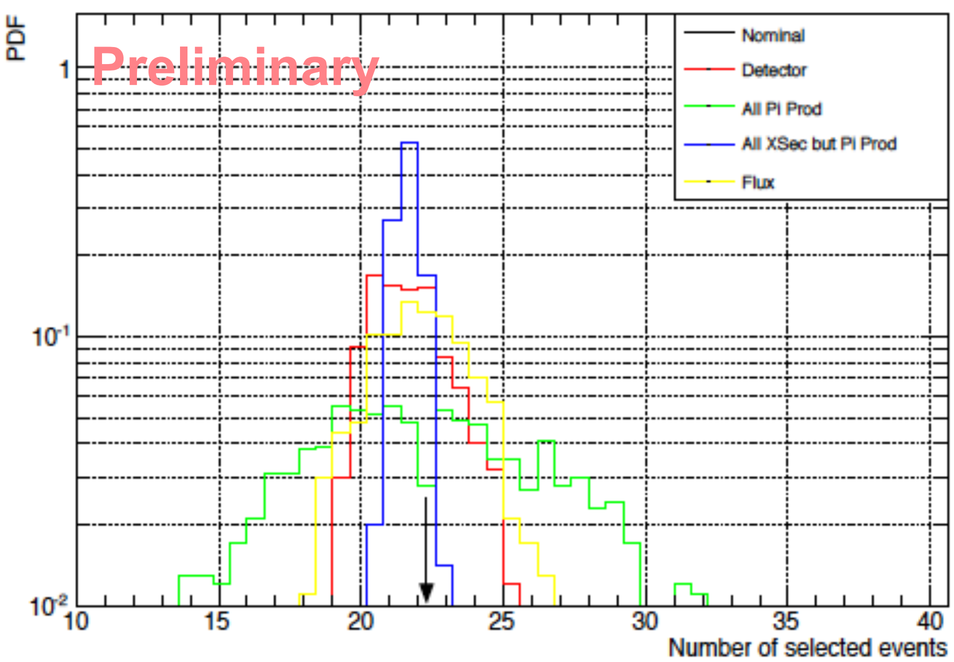
3. Internal background

NC1π^o production error
- Use NUISANCE framework
- From bubble chamber and MiniBooNE NC1π^o data
- Errors inflated to make good coverage

Total errors
- Cross section (mostly NC1π^o production error)
- Detector (π^o propagation error in the detector media)
- Flux

Total ±21% error





1. Introduction – MiniBooNE oscillation result

2. Neutral-Current single gamma production (NCγ)

3. T2K off-axis near detector analysis

4. Results and discussions

5. Conclusions

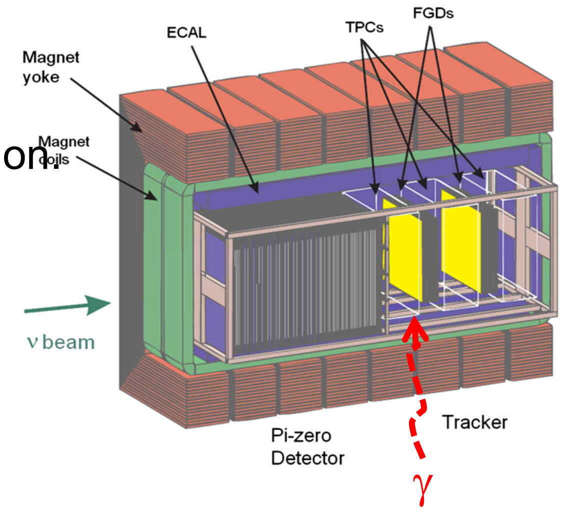
4. Preliminary sensitivity

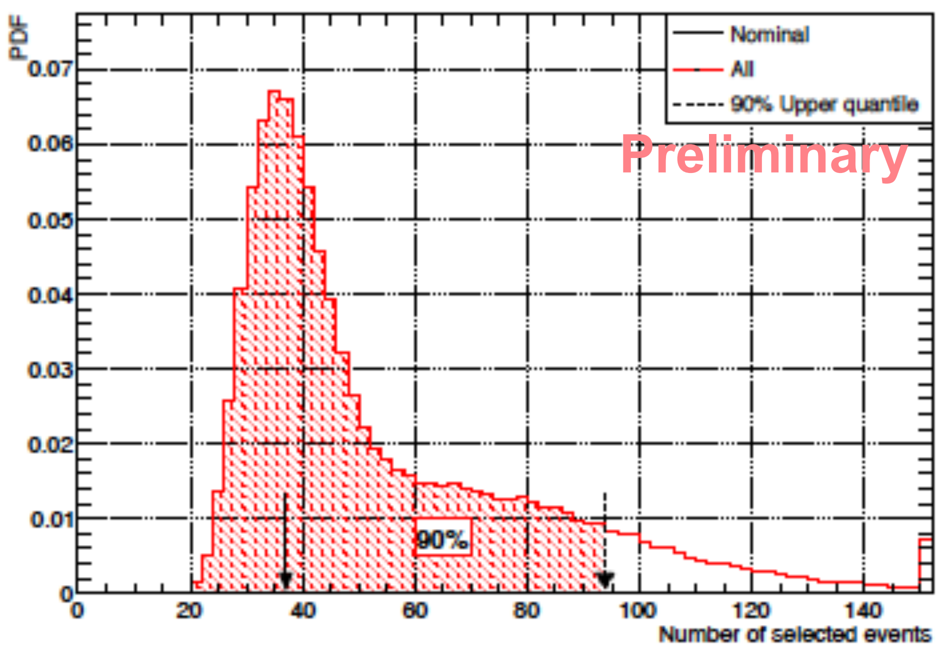
$$\sigma = \frac{N_{\text{Signal}}}{\epsilon \times \int_{E_{\nu\text{Min}}}^{E_{\nu\text{Max}}} \Phi_{E_\nu} dE_\nu \times N_{\text{Nucleon FV}}}$$

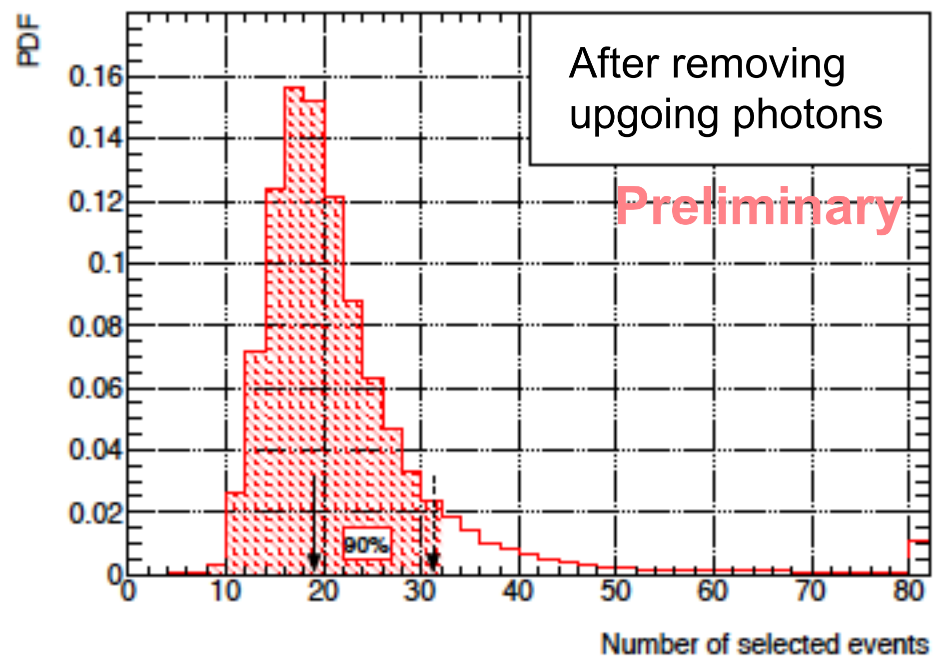
We haven't opened the signal box, yet…

All errors are combined, toy models are thrown on that distribution.

90% upper error is calculated from this distribution.
 - After removing up-going photons, tail of distribution becomes shorter, indicating external photon is the limit of sensitivity

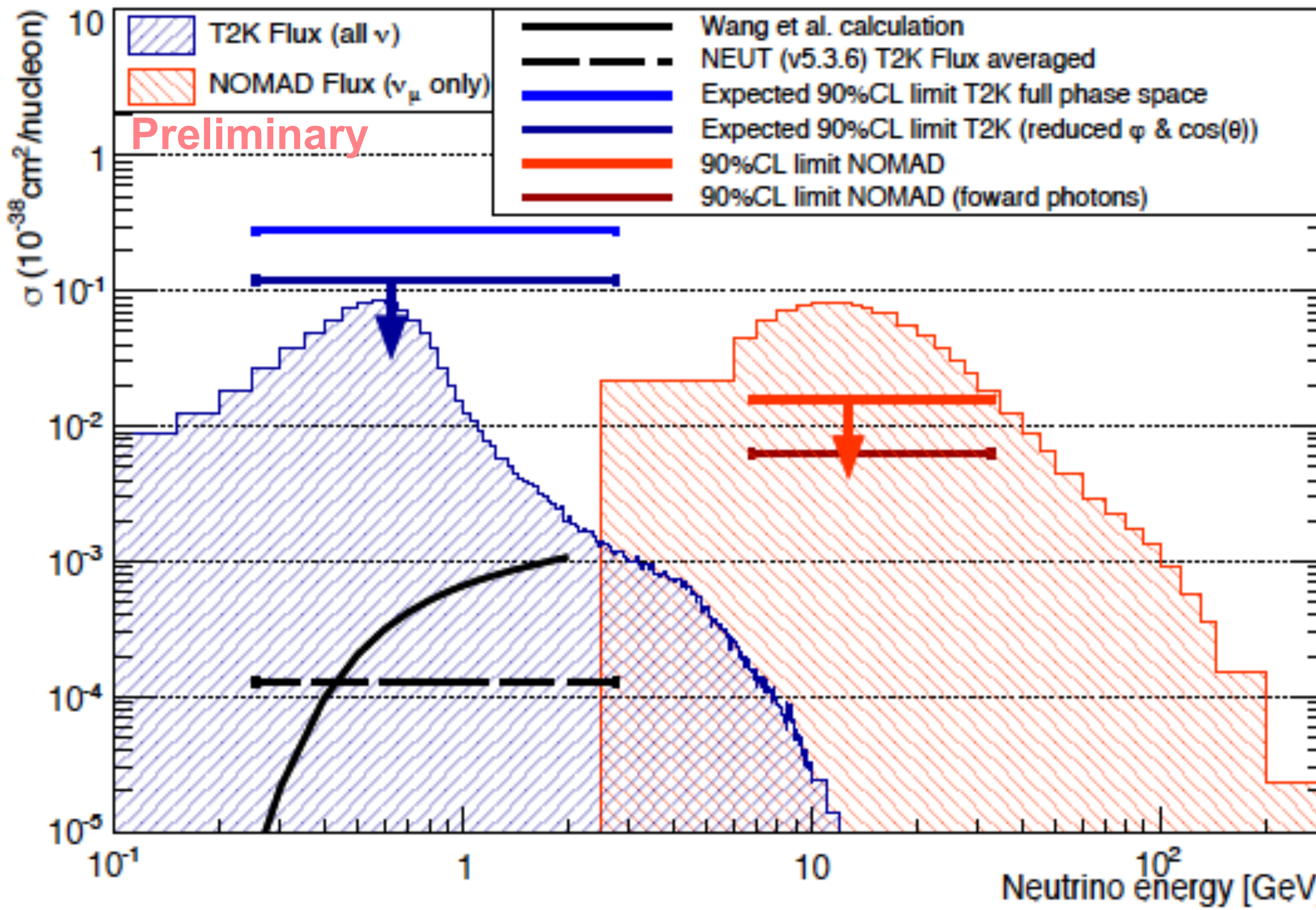






4. Preliminary sensitivity

T2K ND280 FGD NCγ limit is not competitive…



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4. Preliminary sensitivity

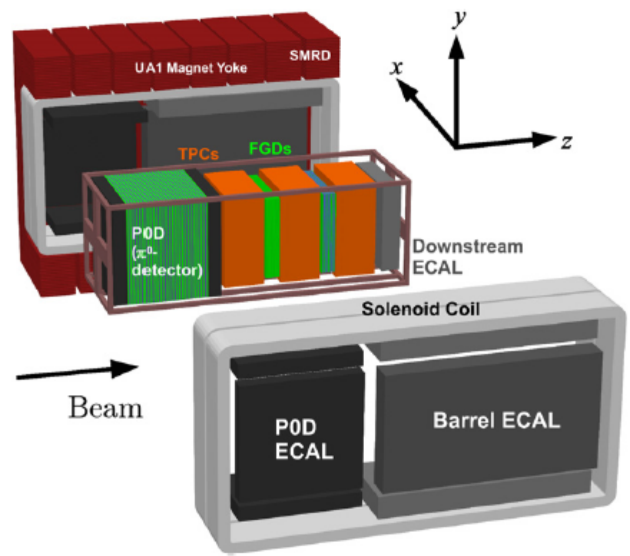
T2K ND280 FGD NCγ limit is not competitive…

Signal box is not open, yet, however, estimated sensitivity is roughly x500 larger than expected cross section.

No constraint of external background
- Small FGD FV volume makes it difficult to perform external background measurement (target volume = Good TPC PID)
→ large active veto with minimum dead material is essential to reduce external background

No constraint of internal background
- π^o reconstruction is not easy for a detector with limited acceptance
→ 4π coverage is important for π^o measurement

Neutral current measurement requires large active veto, small dead materials, and 4π acceptance

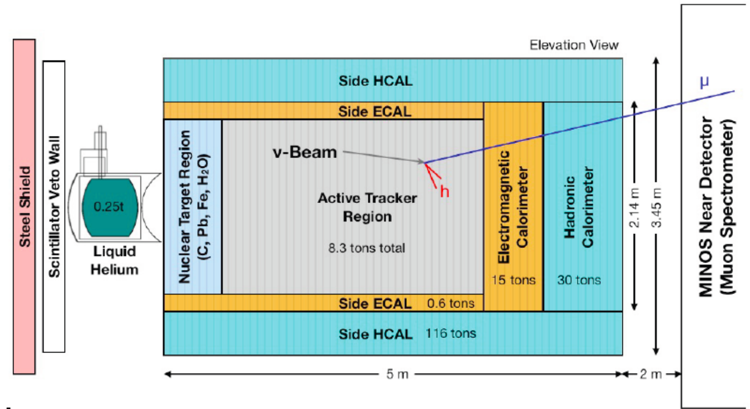


4. Future measurements

MINERvA

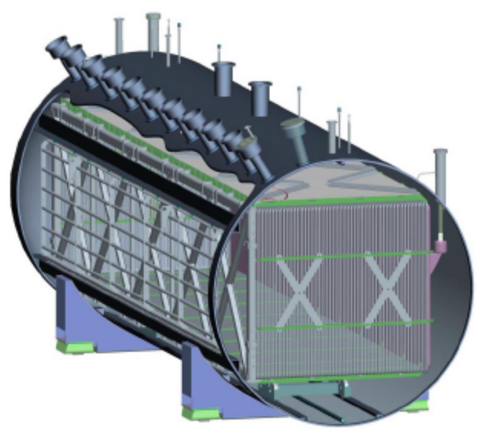
- no good single γ PID
- larger FV, but surrounded by heavy elements
- larger beam energy → more external background
- good π^o measurement performance

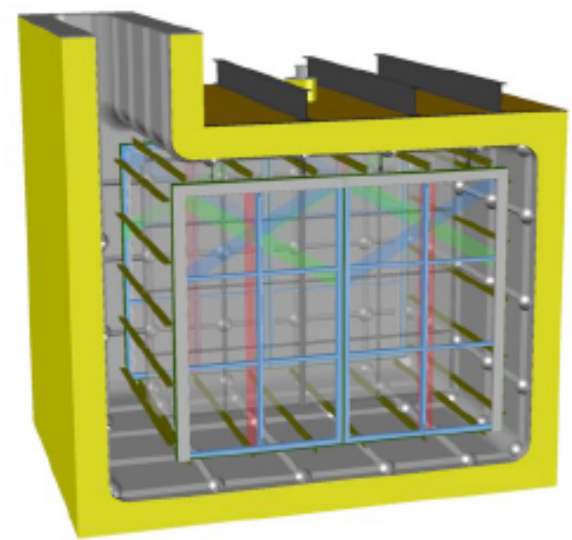
MINERvA, PLB749(2015)130



MicroBooNE/SBND

- good single γ PID(?) from dE/dx + conversion length
- Short radiation length (14cm), good active veto
- Both uB (2.3mx2.6mx10.4m) and SBND (4mx4mx5m) have enough TPC volumes to utilize edge of the TPC as an active veto
- good π^o measurement performance (based on study by ArgoNeuT) ArgoNeuT, arXiv:1511.00941





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5. Conclusion

T2K is a long baseline neutrino oscillation experiment in Japan.

T2K off-axis near detector “ND280” includes plastic scintillator vertex detector “FGD” and argon gas TPC in 0.2T magnet.

By reconstructing electron and positron tracks, ~95% pure gamma sample is made. However, majority of gamma rays come from unknown dead materials or π^o inside of the detector.

We estimate external and internal photon errors to set limit on NCγ process.

For NCγ production per nucleon, we expect ~10^{-39} cm^2 flux-averaged total cross section limit with <E>~600 MeV. This will be the first limit of this channel below 1 GeV.

Detectors with large active veto, less dead material, and 4π coverage will make better results for NCγ and other NC measurements.

Fun Timely Intellectual Adorable!

Lattice QCD

nuclear many-body problem

Spin physics

Leptonic CP violation

Neutrino oscillation

Weak interaction

NuSTEC-News

Nucleon correlation

EMC effect

electron scattering

Dark matter

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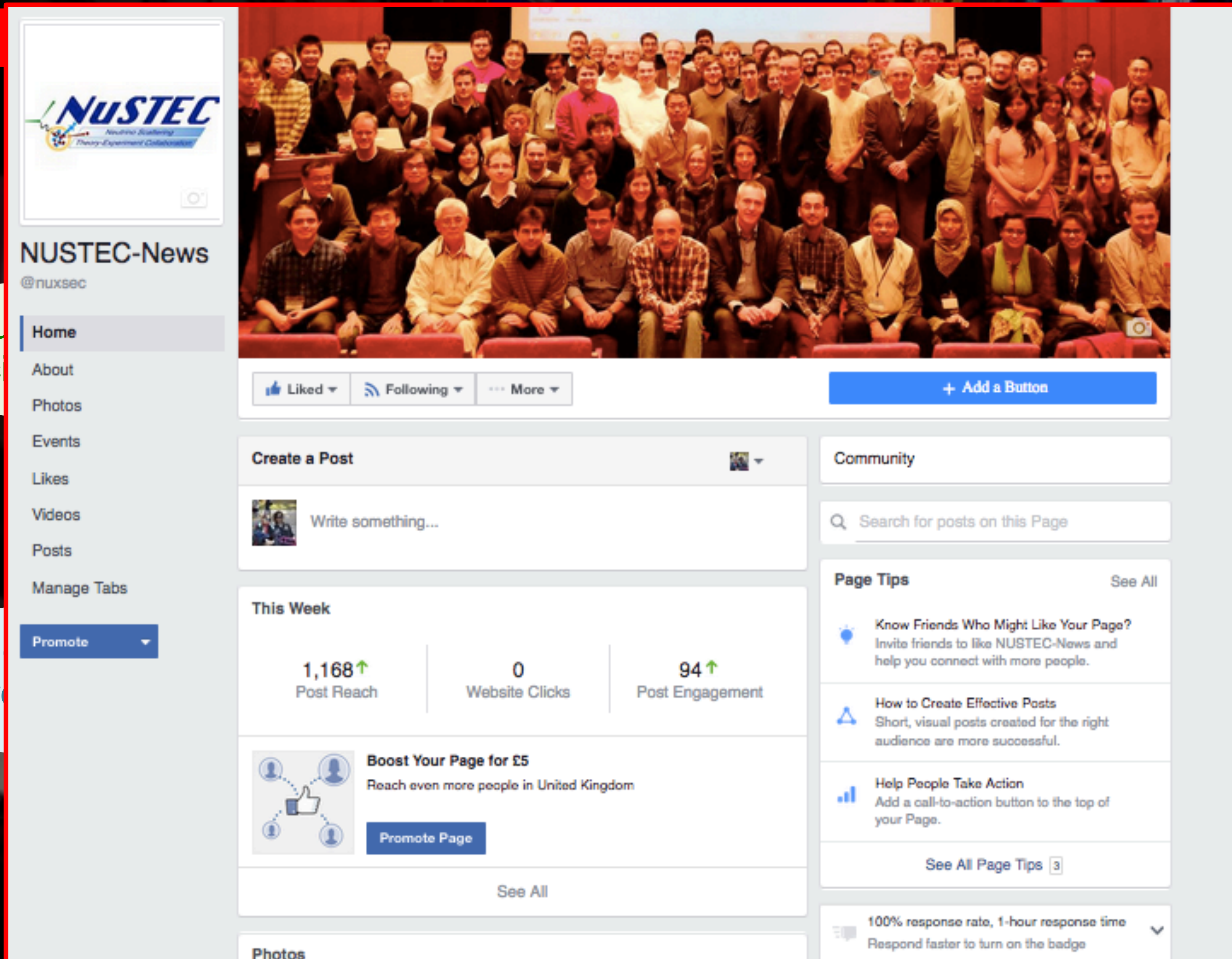

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NuSTEC School 2017

7-15 November, 2017
Fermilab, USA

nustec.fnal.gov/school2017

NuSTEC
Neutrino Scattering
Theory-Experiment Collaboration

The NuSTEC school is a training program in the **physics of neutrino-nucleus scattering**, to be held at **Fermilab, Batavia IL, USA in 7-15 November 2017**.
Registration will be open soon. http://nustec.fnal.gov/school2017/
The program will include **33 hours of lectures** and **12 hours of recitation** encouraging questions and discussion on all of the day's lectures.

A very unique opportunity to learn neutrino interaction physics!

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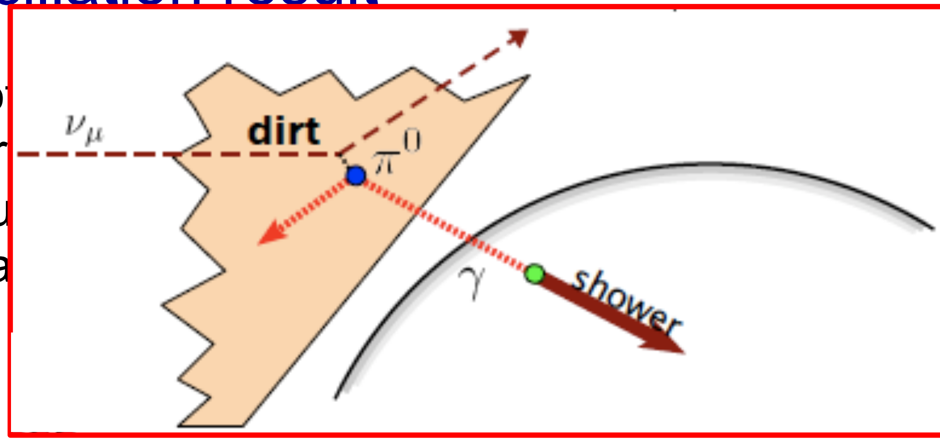
T2K collaboration

Thank you for your attention!

Backup

1. MiniBooNE oscillation result

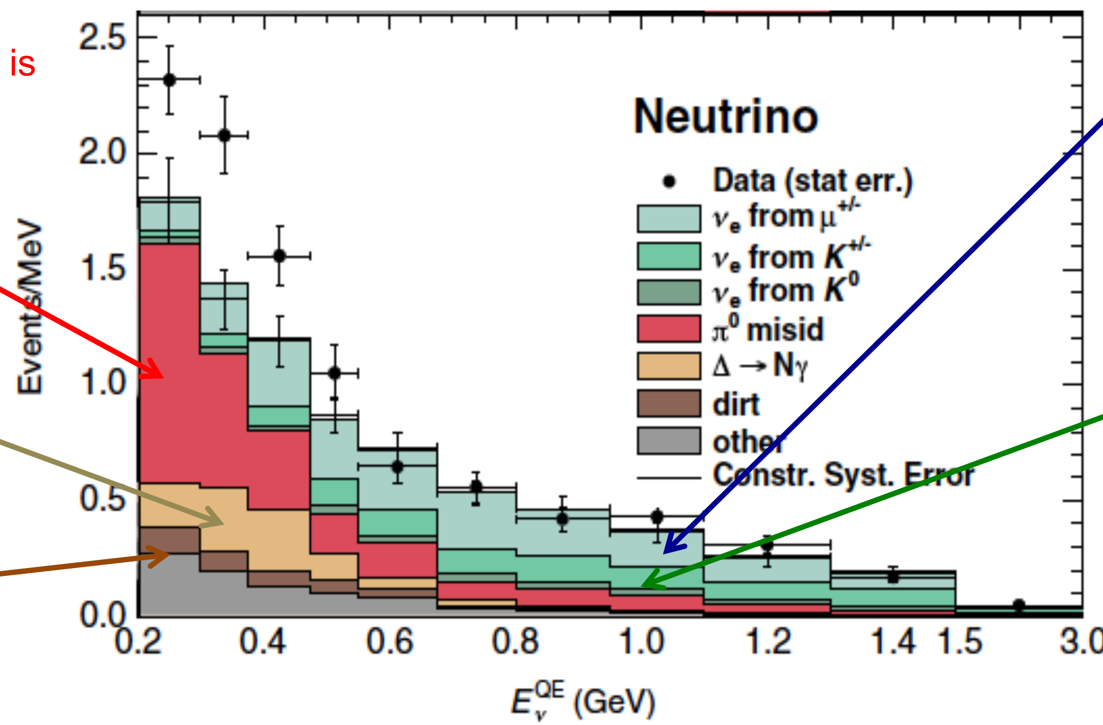
The detector canno
- e: intrinsic backgr ... gy
- γ: misID backgrou
- All backgrounds a ... s are constrained.



Asymmetric π° decay is constrained from measured CCπ° rate (π°→γ)

Radiative Δ-decay (Δ→Nγ) rate is constrained from measured NCπ°

dirt rate is measured from dirt enhanced data sample



ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from high energy ν_μ event measurement in SciBooNE

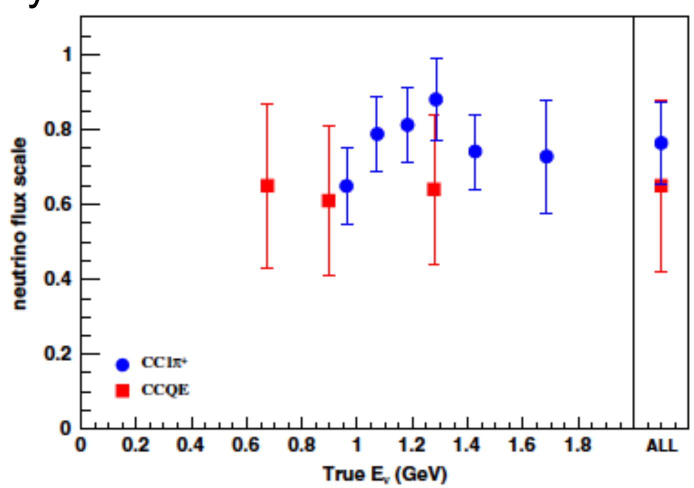
1. MiniBooNE anti-neutrino constraint

Anti-neutrino mode beam accept way more "wrong sign" (WS) neutrinos.

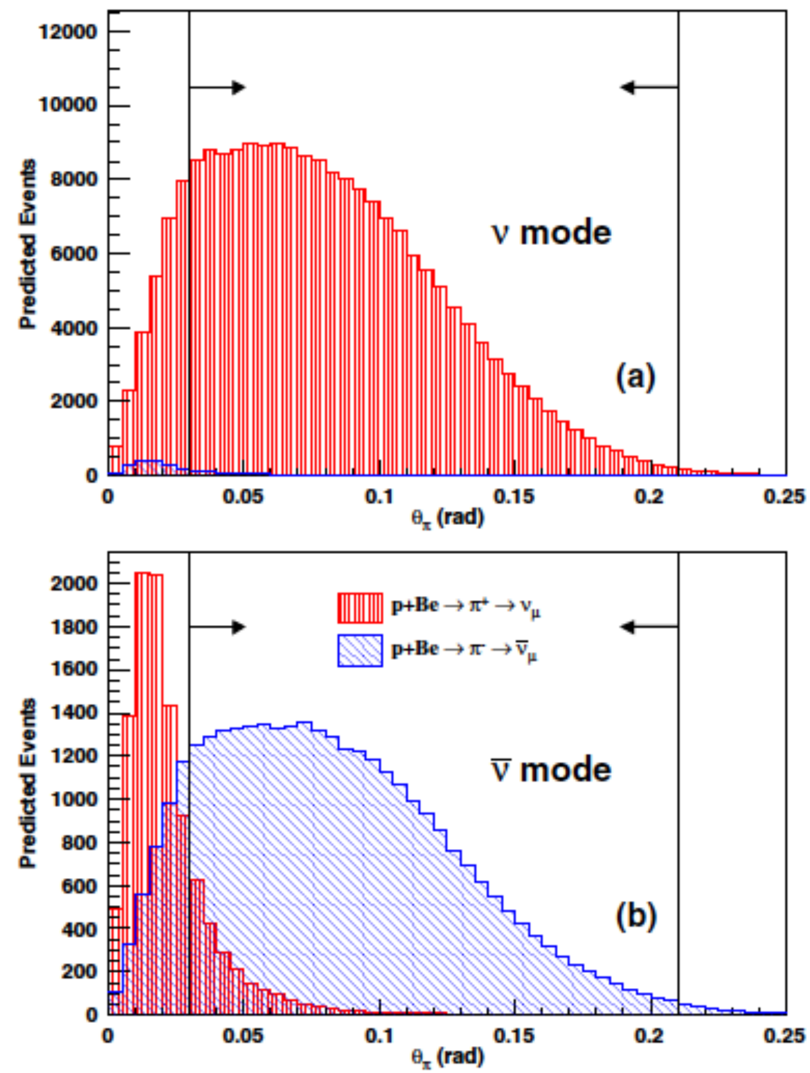
WS neutrinos are from decays of forward going mesons not defocused by magnetic horn.

Very forward going mesons cannot be measured by hadron production experiments, such as HARP

MiniBooNE used 3 independent techniques to constrain WS neutrinos internally, and we consistently found we overestimate WS neutrinos.



PHYSICAL REVIEW D 84, 072005 (2011)



4. Experiment comparison for NCγ measurement

	γ reconstruction	internal background	external background	status
NOMAD	magnet	π^o data	HE beam, large active veto	done
T2K FGD	magnet	no π^o data	LE beam, no active veto	running
MiniBooNE	no magnet	good π^o data	LE beam, large active veto	running
MINERvA	no magnet	π^o data	HE beam, small activeveto	running
uB/SBND	LArTPC	good π^o data	LE beam, good active veto	running