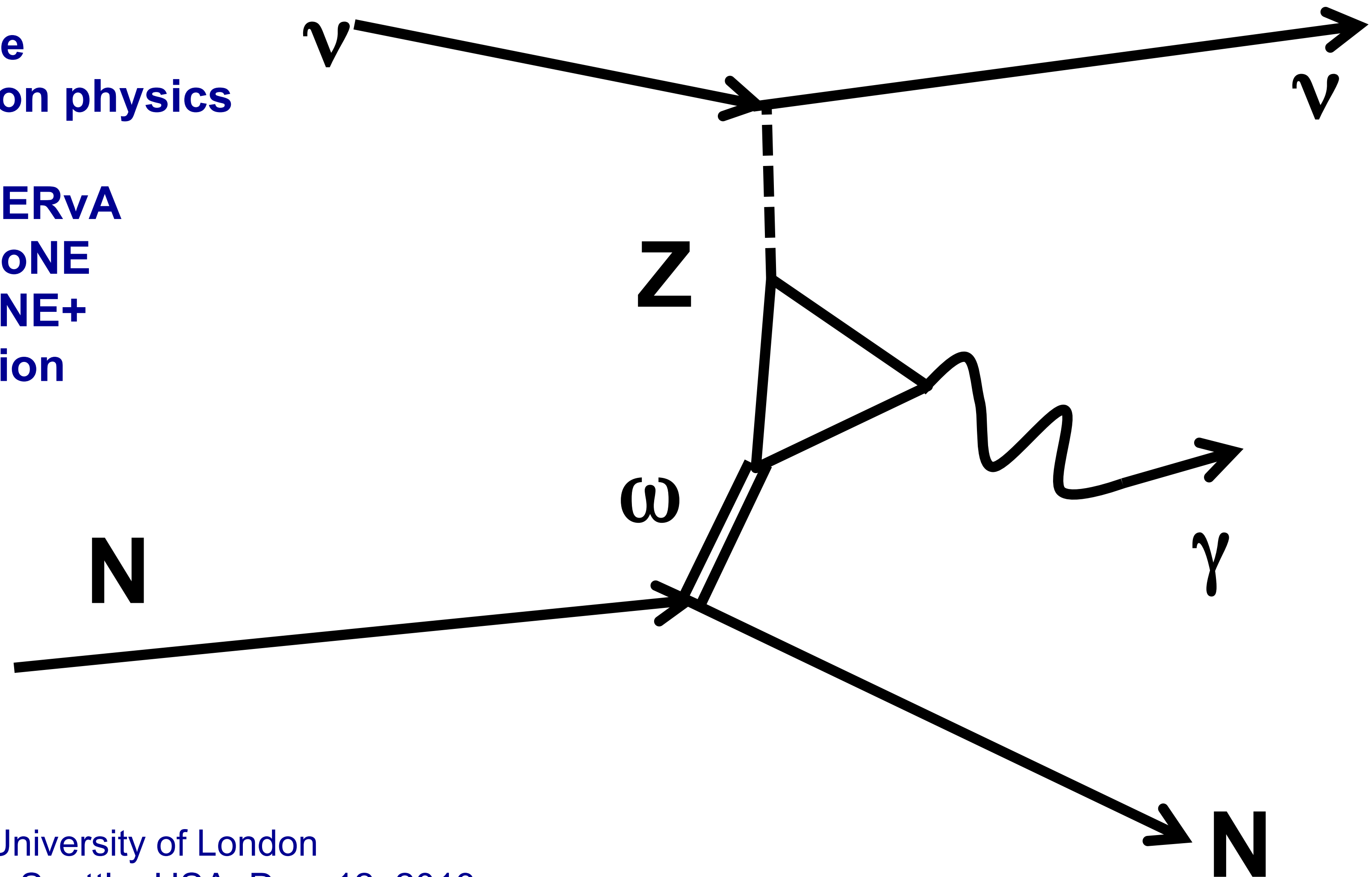
Neutral Current Single Photon Production (NCγ)

Outline

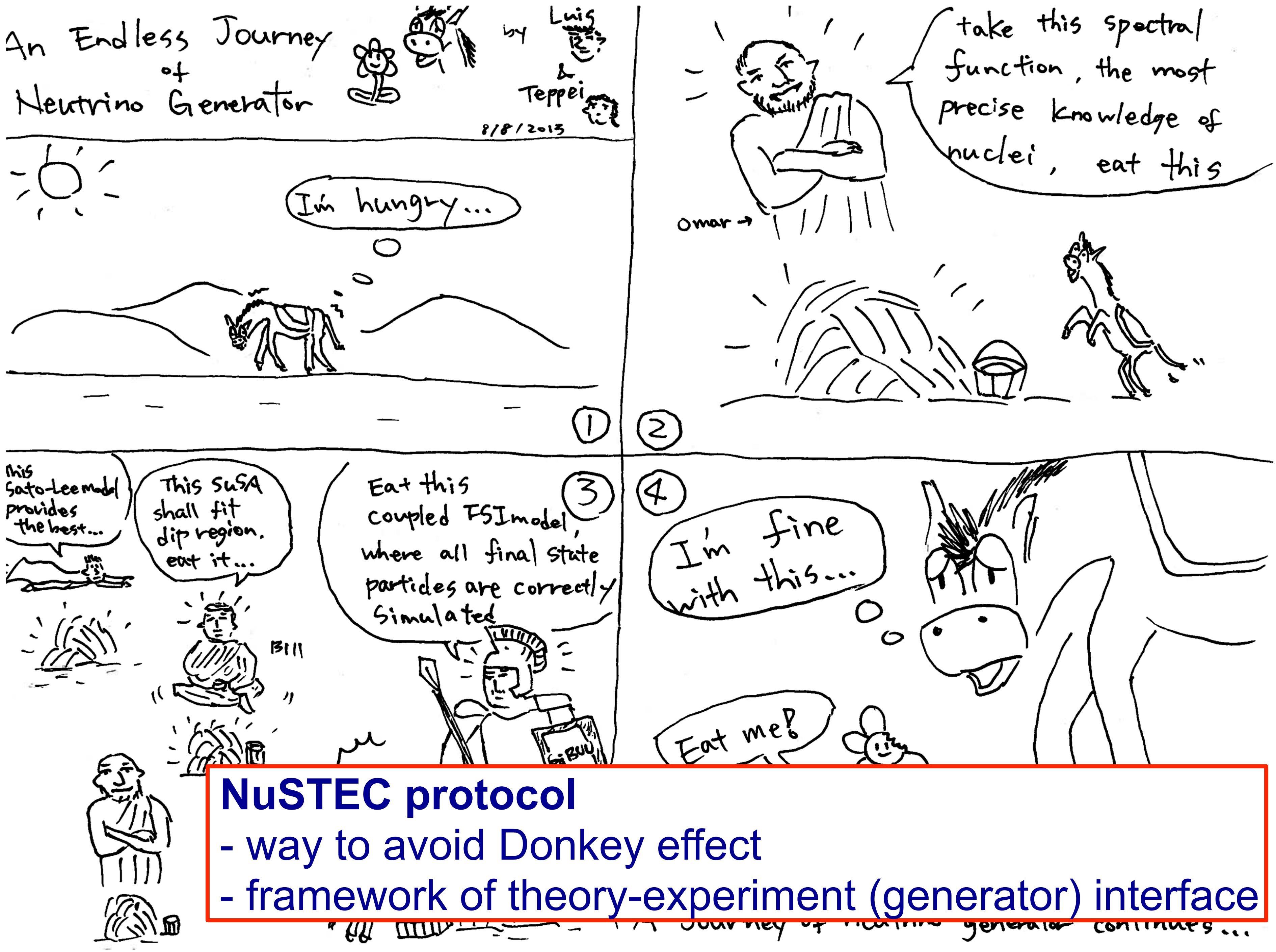
1. **Oscillation physics**
2. **NOMAD**
3. **T2K/MINERvA**
4. **MicroBooNE**
5. **MiniBooNE+**
6. **Conclusion**



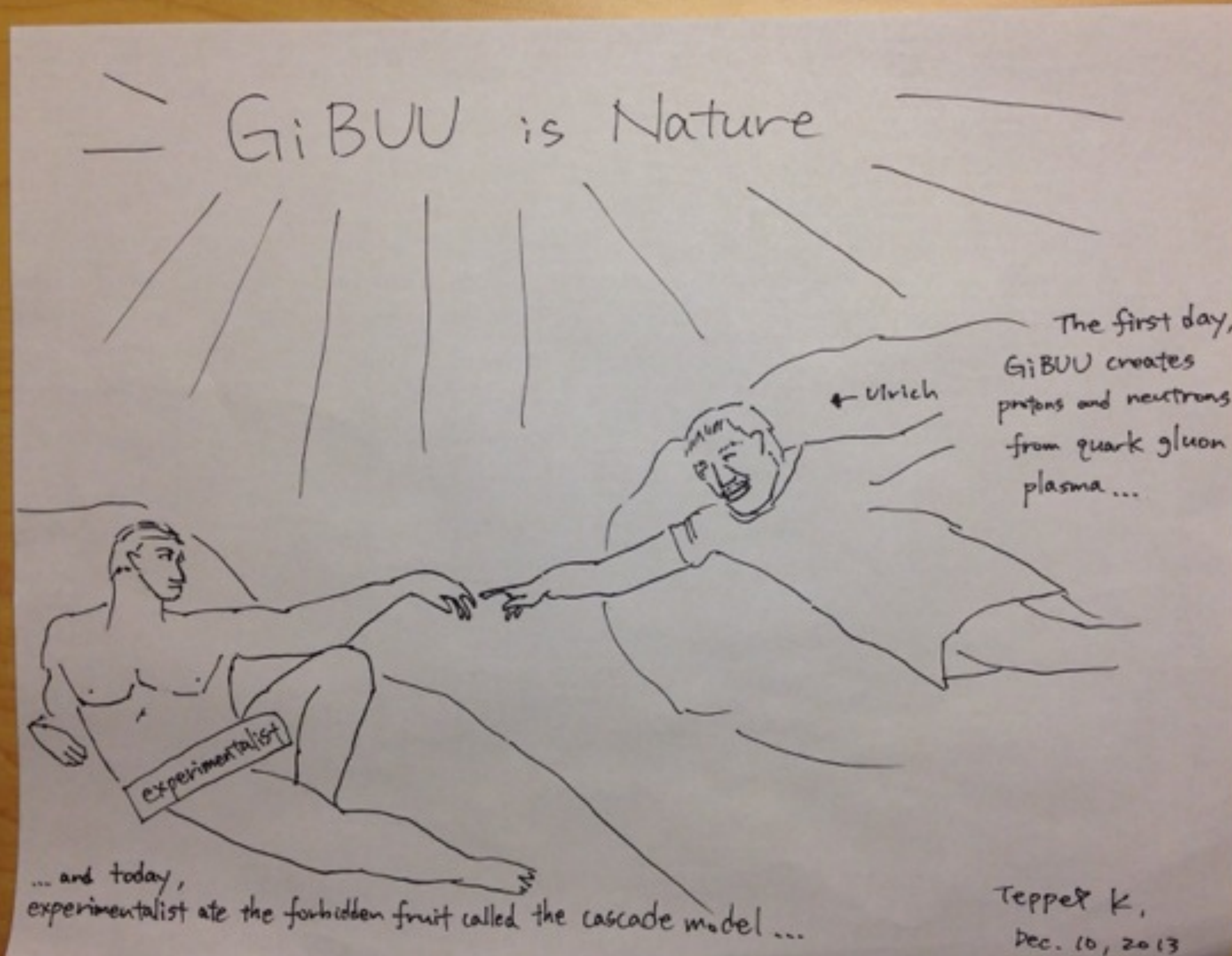
Teppei Katori
Queen Mary University of London

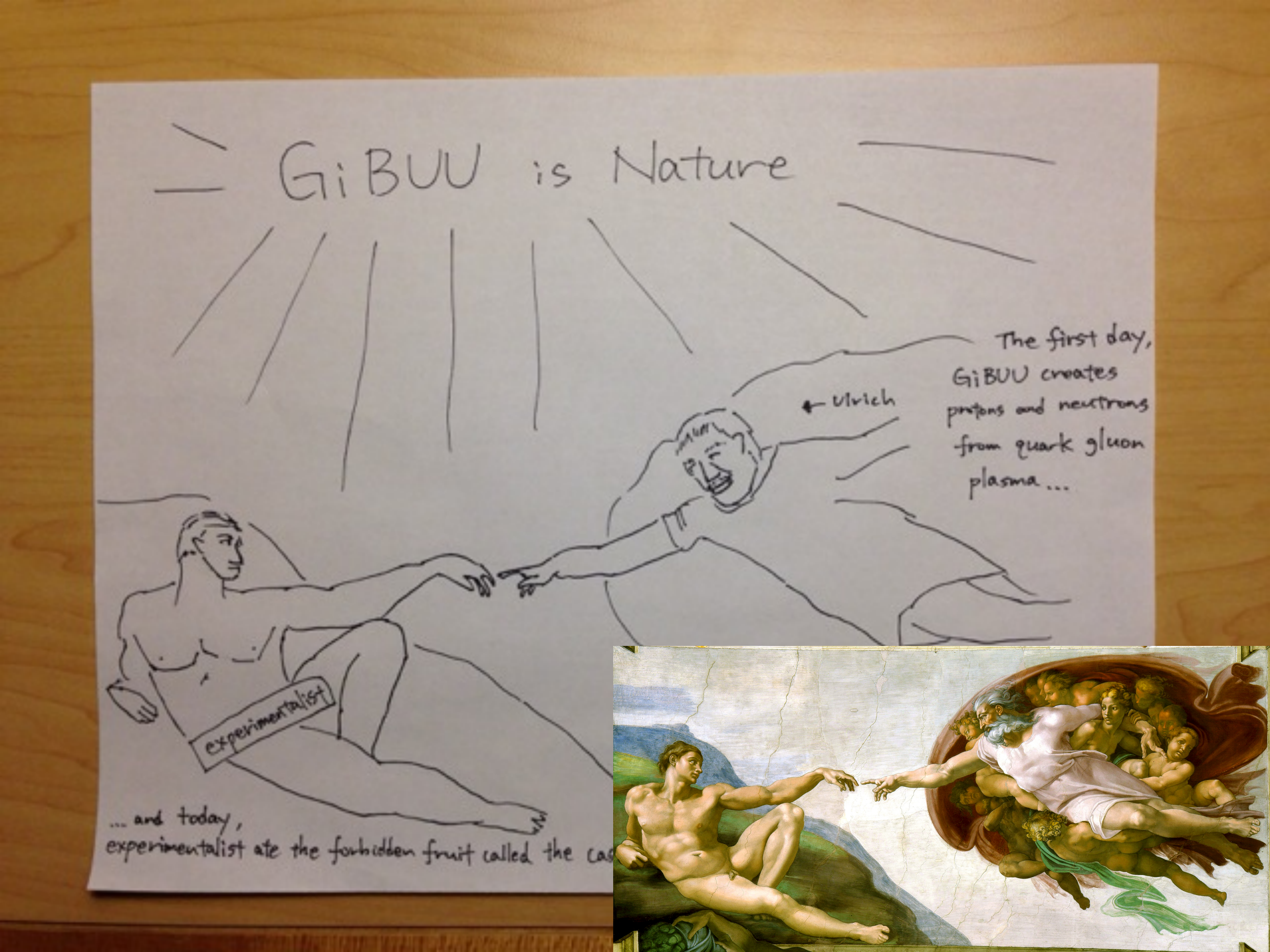
INT workshop, Seattle, USA, Dec. 12, 2013


An Endless Journey of Neutrino Generator
by Luis & Teppei
8/8/2013
I'm hungry...
1
take this spectral function, the most precise knowledge of nuclei, eat this
omar →
2
this Sato-Lee model provides the best...
This SuSA shall fit dip region, eat it...
Eat this coupled FSI model, where all final state particles are correctly simulated
3
Bill
GiBUU
Ulrich
4
I'm fine with this...
Eat me!
Fermi Gas
A Journey of neutrino generator continues...



NuSTEC protocol
- way to avoid Donkey effect
- framework of theory-experiment (generator) interface


GiBUU is Nature
The first day, GiBUU creates protons and neutrons from quark gluon plasma...
← Ulrich
experimentalist
... and today, experimentalist ate the forbidden fruit called the cascade model ...
Teppei K.
Dec. 10, 2013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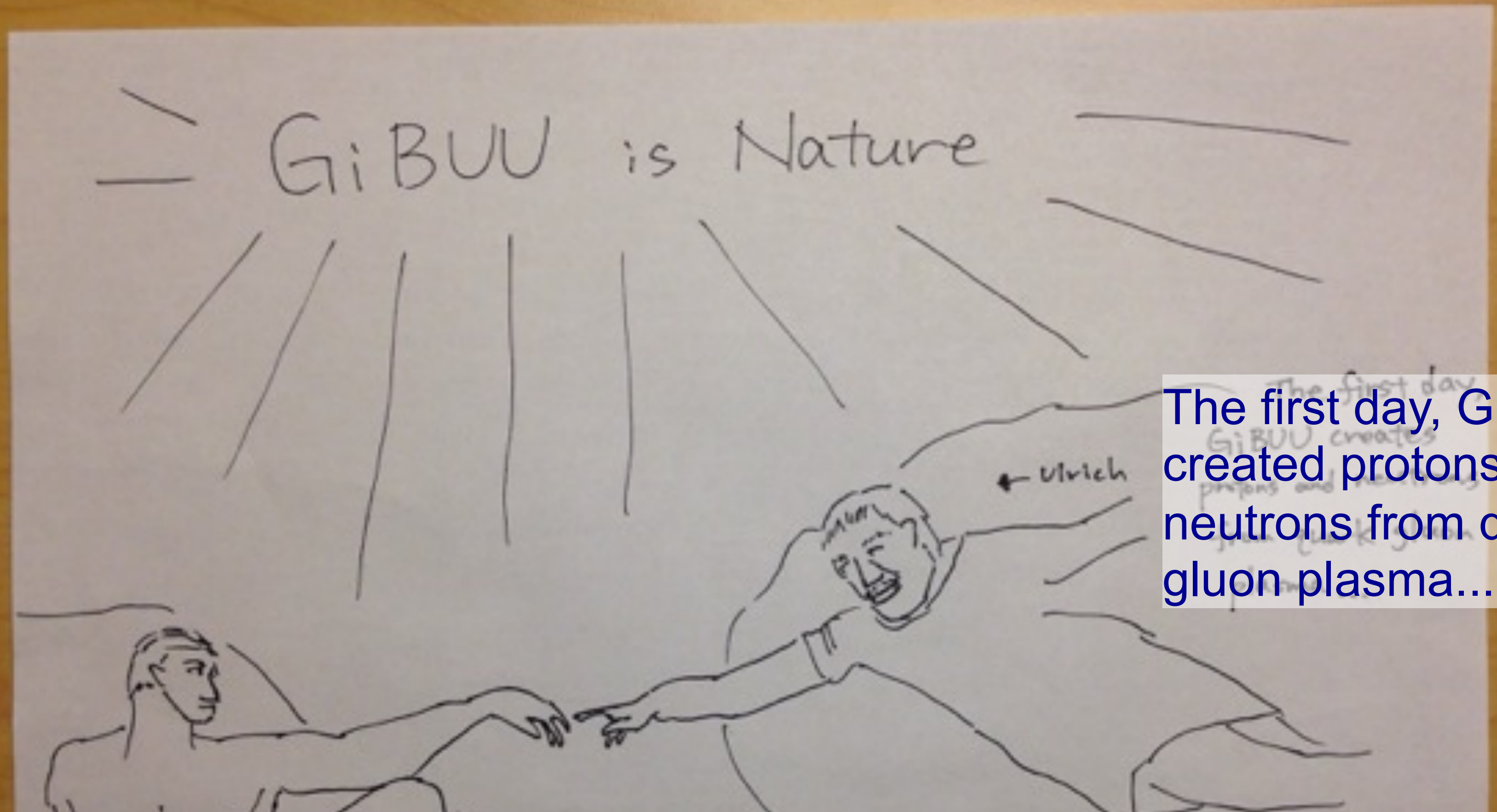

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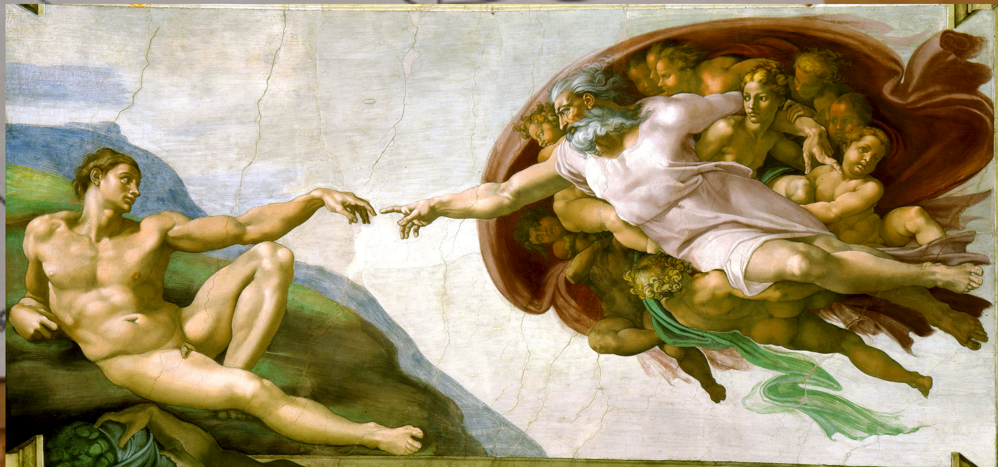


...and today, experimentalists ate the forbidden fruit called the cascade model...

1. Oscillation physics

2. NOMAD

3. T2K/MINERvA

4. MicroBooNE

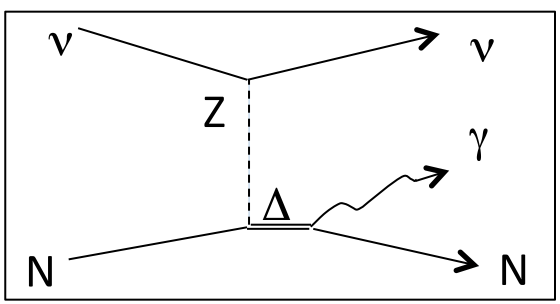
5. MiniBooNE+

6. Conclusion

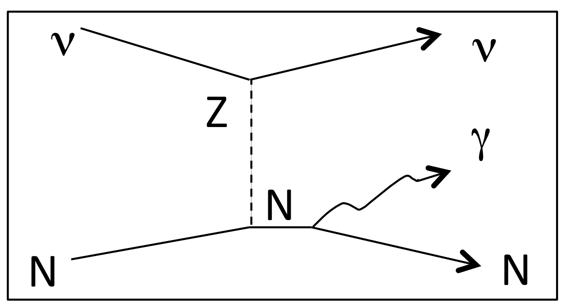
1. Introduction

NCγ, as ν_e appearance background
- all generators estimate NCγ from radiative Δ-decay $\Delta \rightarrow N\gamma$
- cross section is roughly ~0.5% of NC$1\pi^o$ channel

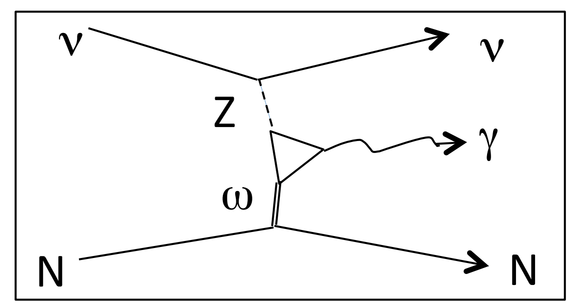
radiative Δ-decay



generalized Compton scattering



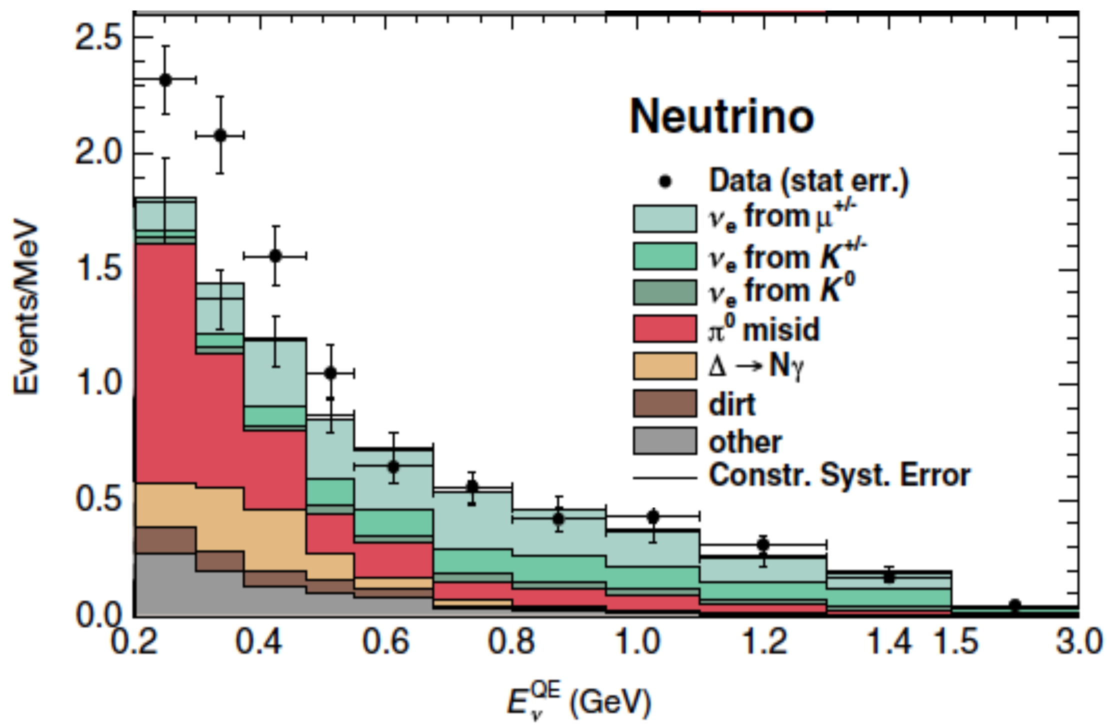
anomaly mediated triangle diagram



1. MiniBooNE

NCγ, as ν_e appearance background
- all generators estimate NCγ from radiative Δ-decay $\Delta \rightarrow N\gamma$
- cross section is roughly ~0.5% of NC1π^o channel

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



1. MiniBooNE

NCγ, as ν_e appearanc
- all generators estim
- cross section is rou

MiniBooNE
- Final oscillation pap ... d in ν_e candidate sample.
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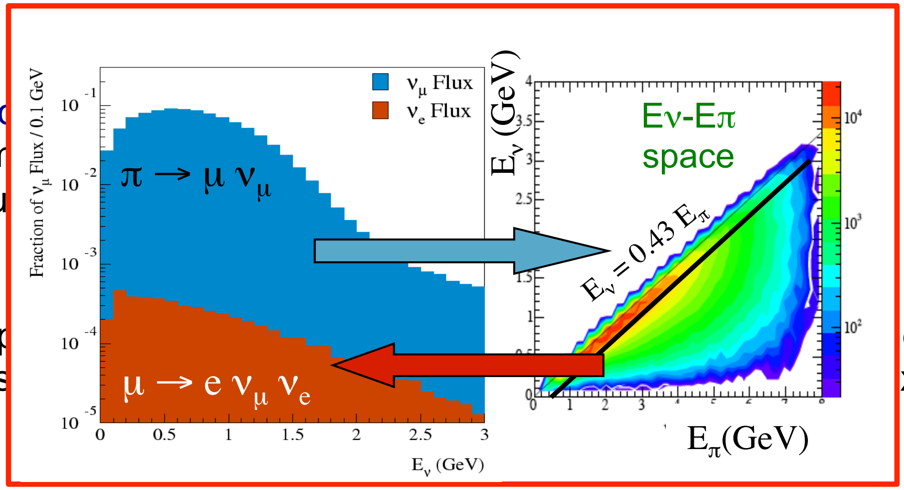
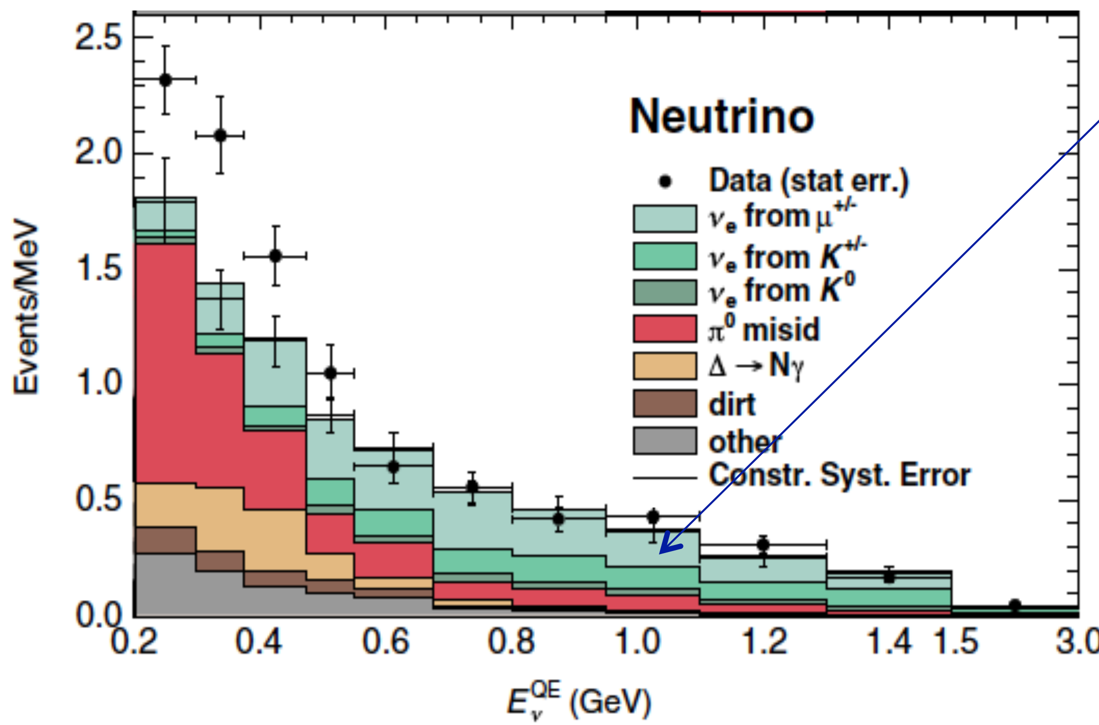


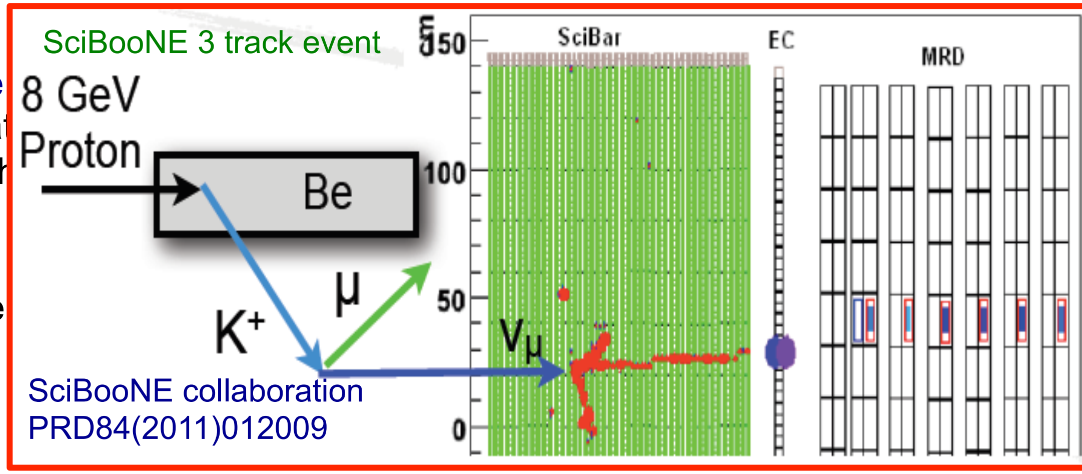
ν_e from μ decay is constrained from ν_μCCQE measurement



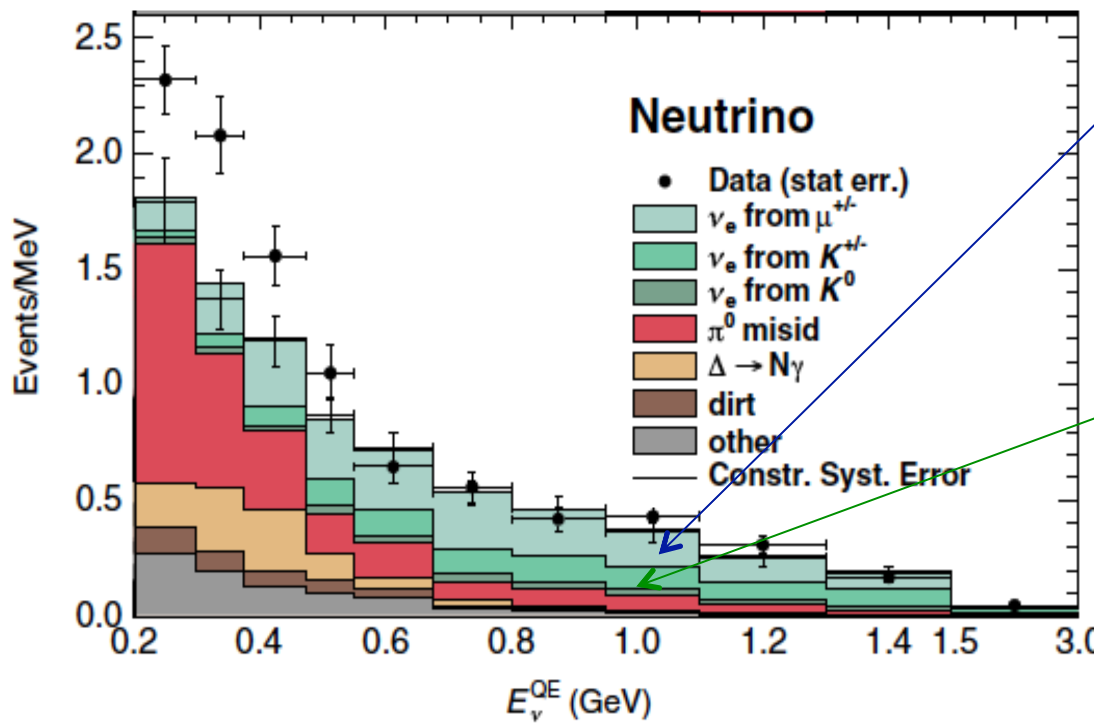
1. MiniBooNE

NCγ, as ν_e appearance
- all generators estimat
- cross section is rough

MiniBooNE
- Final oscillation pape ... ate sample.
- To explain all excess

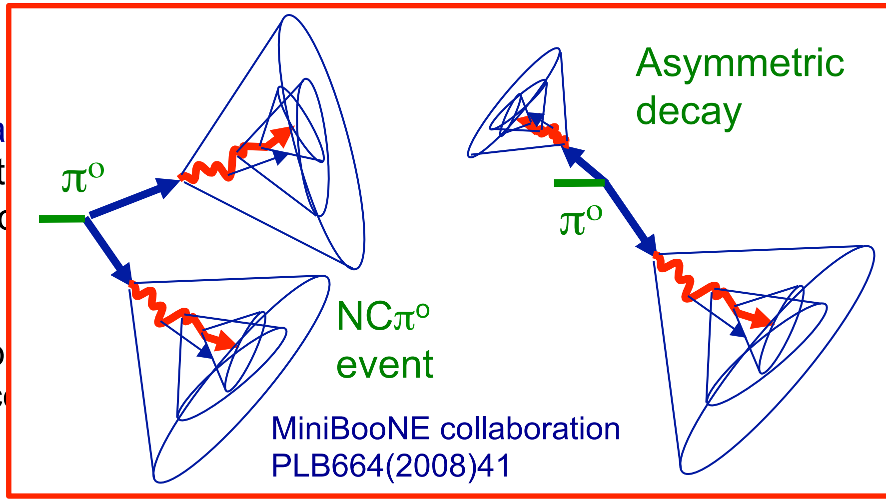


... om μ decay is ... strained from ν_μCCQE measurement



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

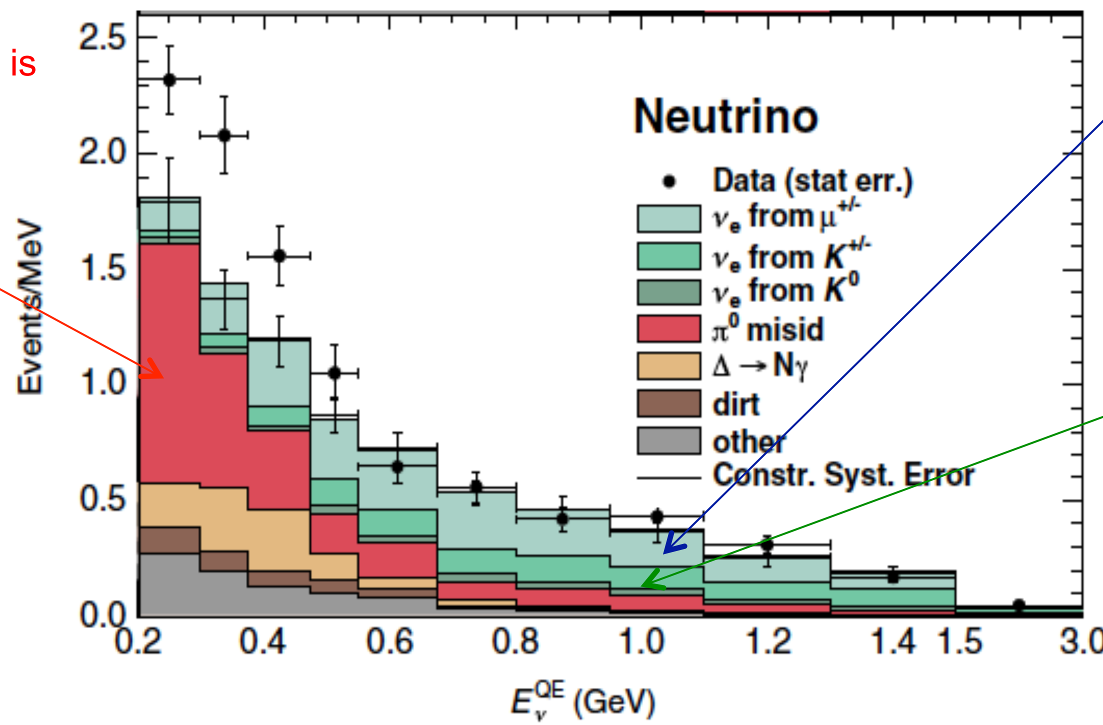
1. MiniBooNE



NCγ, as ν_e appeara
- all generators est
- cross section is r

MiniBooNE
- Final oscillation p ... und in ν_e candidate sample.
- To explain all exc ... o x3.

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



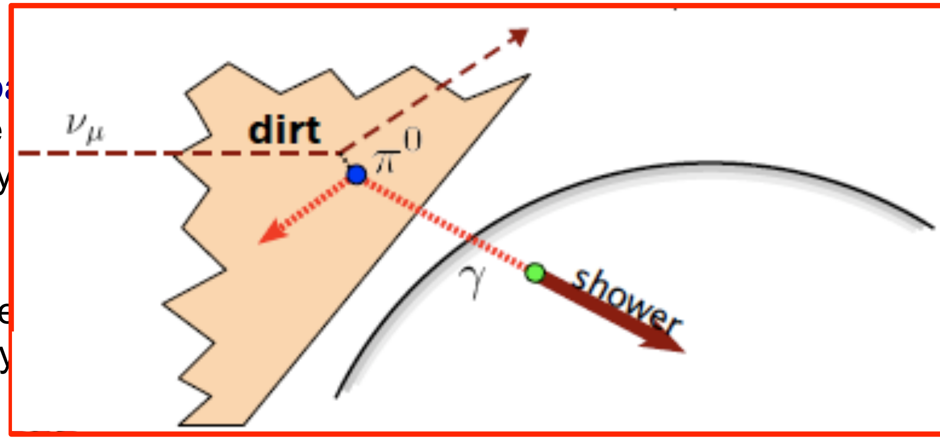
ν_e from μ decay is constrained from ν_μCCQE measurement

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

1. MiniBooNE

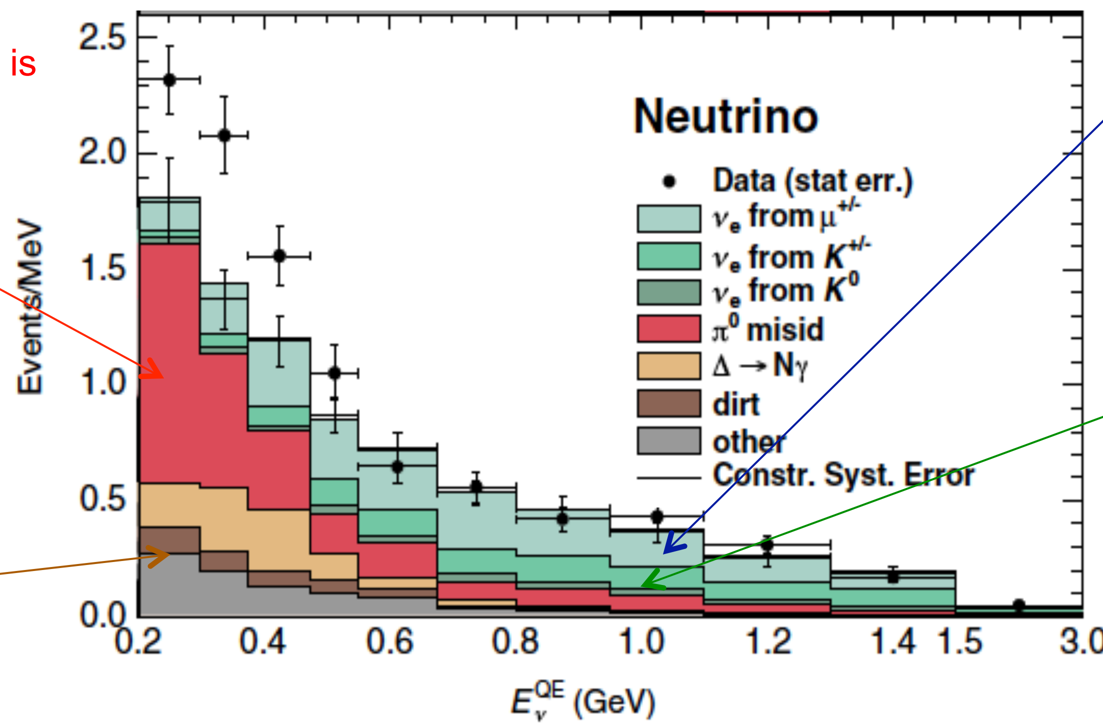
NCγ, as ν_e appearance ba
- all generators estimate
- cross section is roughly

MiniBooNE
- Final oscillation paper e ... candidate sample.
- To explain all excess by



ν_e from μ decay is constrained from ν_μCCQE measurement

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



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

dirt rate is measured from dirt enhanced data sample

1. MiniBooNE

NCγ, as ν_e appearance background
- all generators estimate NCγ from
- cross section is roughly ~0.5% of

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

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

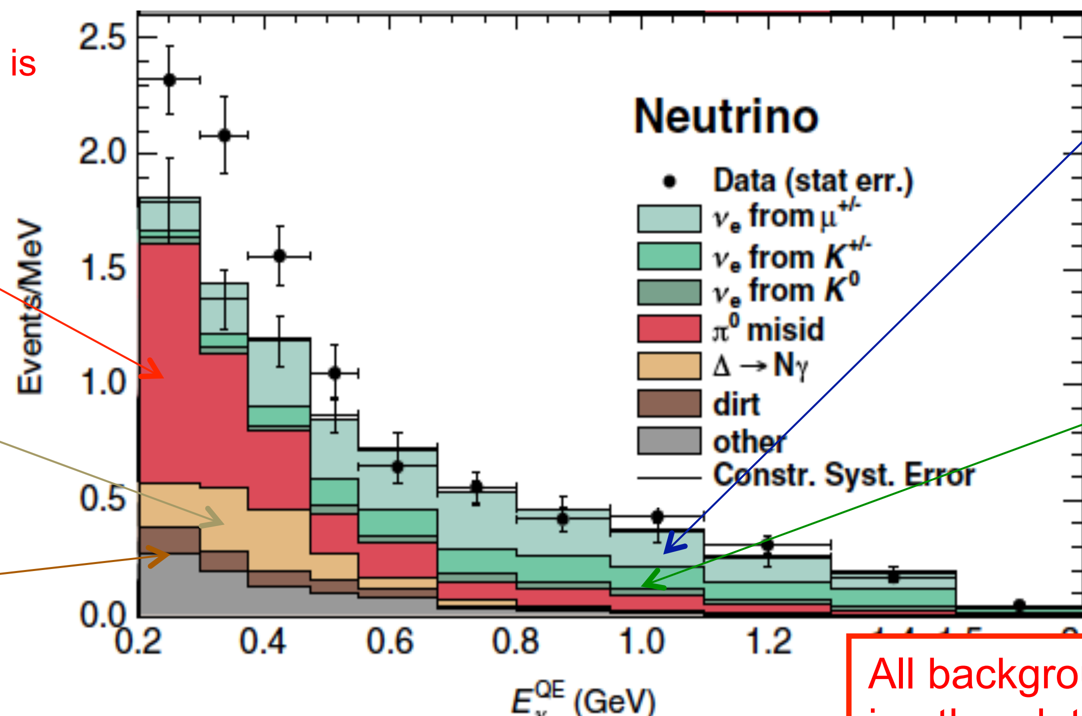
MiniBooNE
- Final oscillation paper estimates N… …und in ν_e candidate sample.
- To explain all excess by NCγ, NC… …o x3.

ν_e from μ decay is constrained from ν_μCCQE measurement

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

dirt rate is measured from dirt enhanced data sample



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

All backgrounds are measured in other data sample and their errors are constrained.

1. T2K

NCγ, as ν_e appearance background
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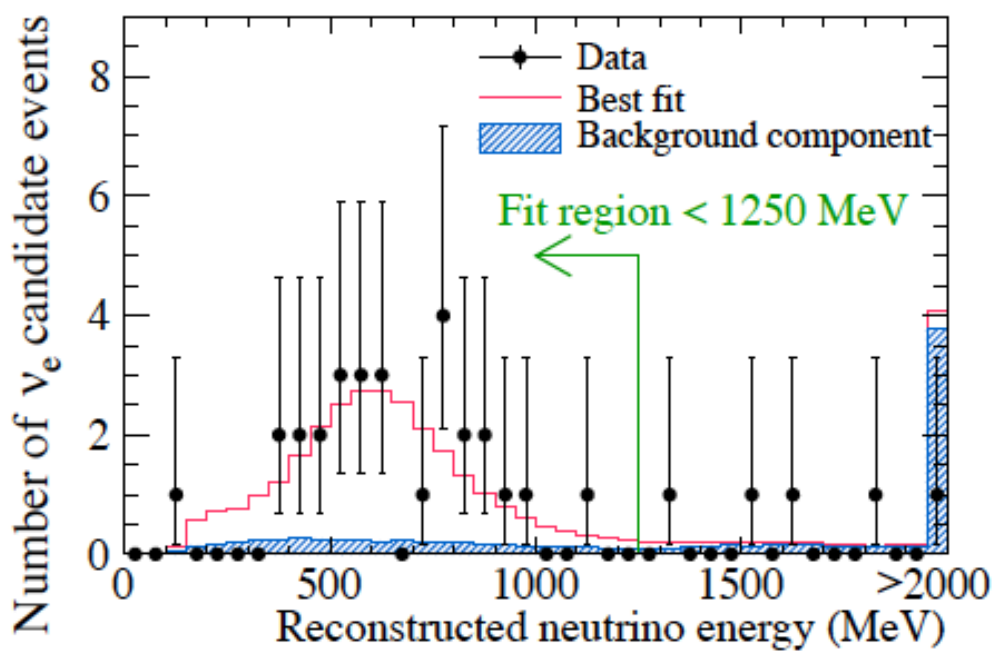
- cross section is roughly ~0.5% of NC1π^o channel

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

T2K
- With $\sin^2 2\theta_{13}$=0.1, oscillation candidate is 17.3 events whereas NC gamma background is ~0.2.
- If NEUT NCγ model is modified to explain MiniBooNE excess, background is ~0.6 to ~0.8.
- Therefore, NCγ model which can explain MiniBooNE excess at most reduce $\sin^2 2\theta_{13}$ 2.3 to 3.5%.



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1. Model comparison

Generator comparison

Total NCγ cross section on carbon target at 600 MeV muon neutrino (unit 1E-42cm^2)

NEUT: ~20
NUANCE: ~25
GENIE:~30

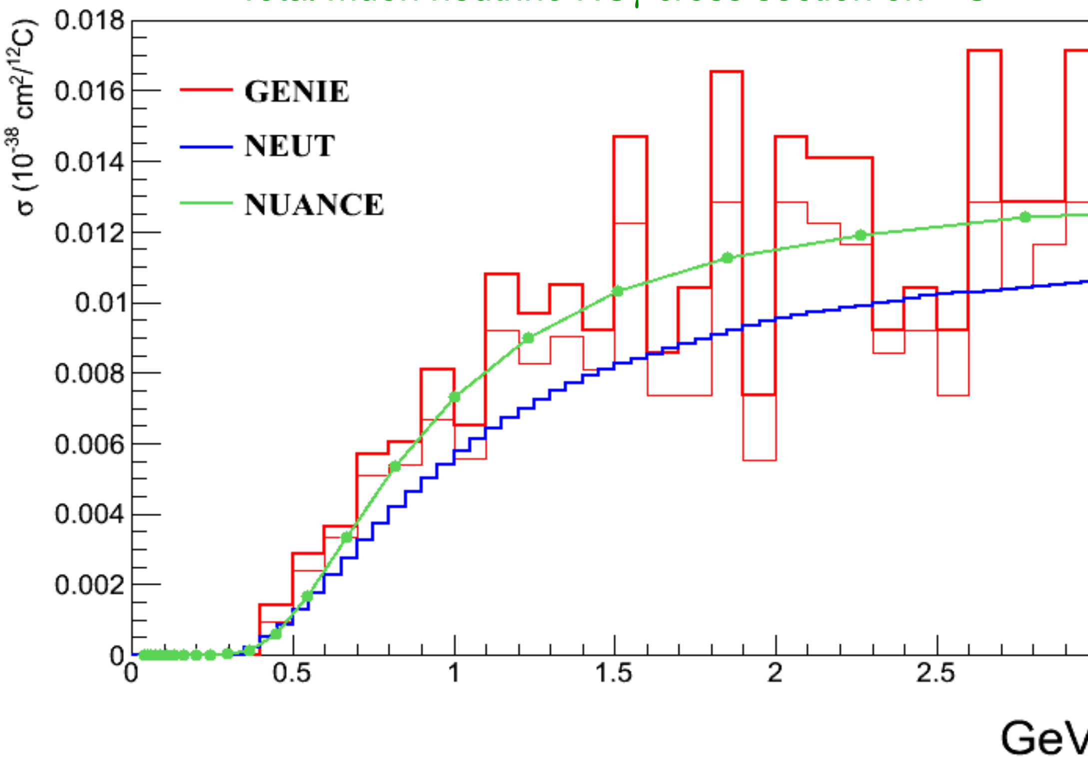
GENIE (no energy cut)
GENIE (E_γ>200 MeV after FSI)

Photon energy cut reduce ~10-20% cross section.

NUANCE is bit higher cross section than NEUT due to invariance mass dependent branching ratio.

GENIE seems to me higher than others because NCγ happen from all resonance contributions (including multi pion production processes)

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



1. Model comparison

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Total NCγ cross section on carbon target at 600 MeV muon neutrino (unit 1E-42cm^2)

NEUT: ~20
NUANCE: ~25
GENIE:~30

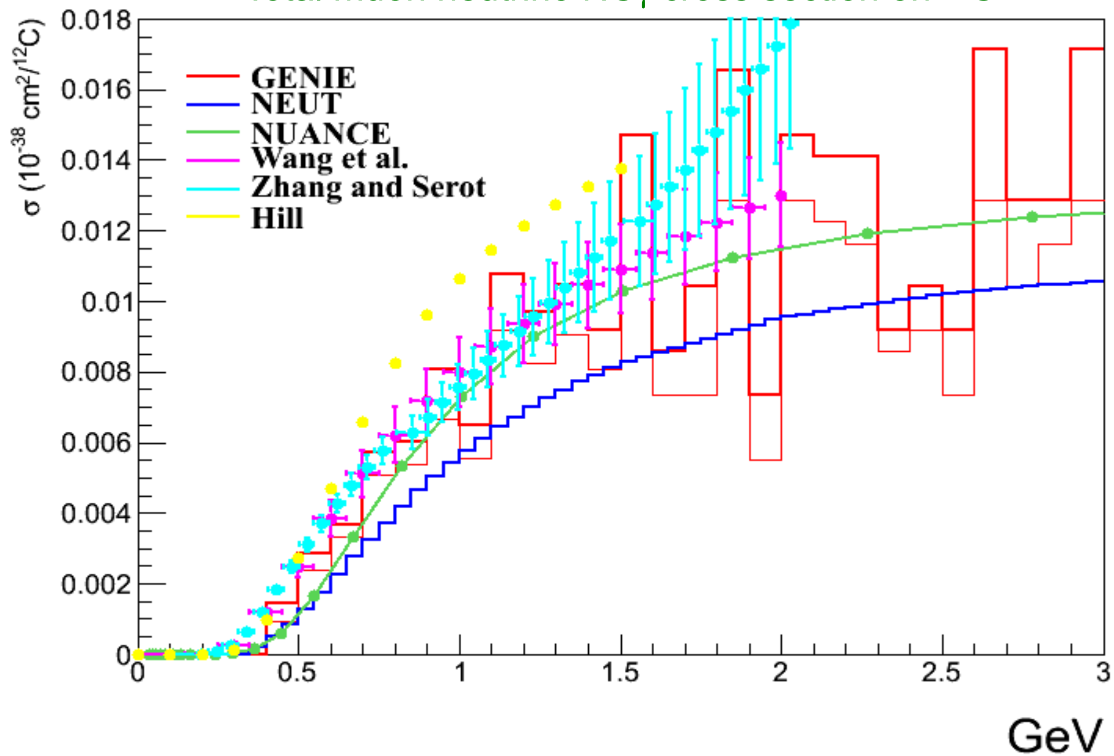
Theory comparison

Wang, Alvarez-Ruso, Nieves: 33-44
(error from ANL-BNL pion data)
Zhang, Serot: 37-41
(error from theoretical parameters)
Hill: 44-58
(error from radiative Δ-decay BR)

The cross section needed to explain MiniBooNE excess is 60-108.

The cross section needed to change $\sin^2 2\theta_{13}$(T2K)~10% is ~200
(NEUT needs to be wrong ~1000%)

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



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1. Oscillation physics

2. NOMAD

3. T2K/MINERvA

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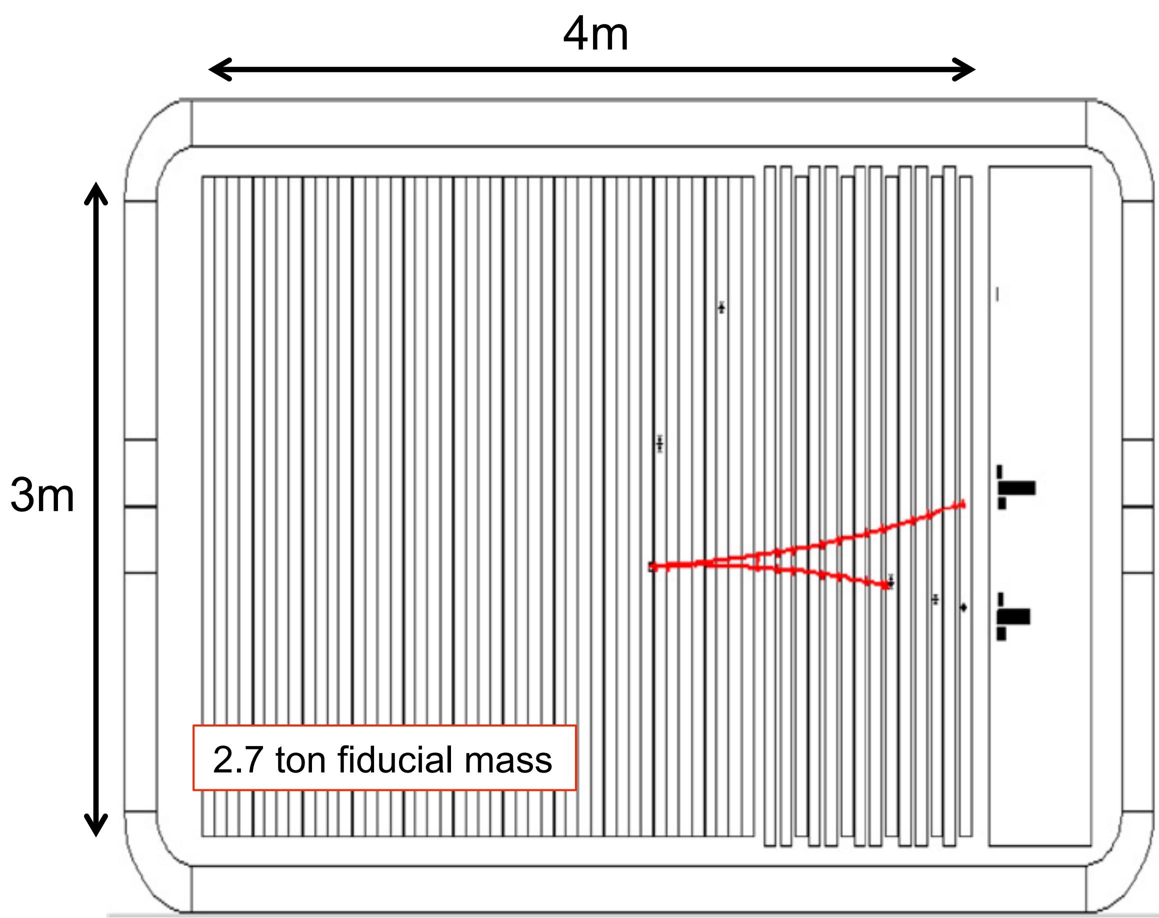
6. Conclusion

2. NOMAD

Single gamma search

Very simple, but robust analysis. They identified all issues on this measurement.

- single e^+-e^- pair
- fiducial cut
- W<50 MeV



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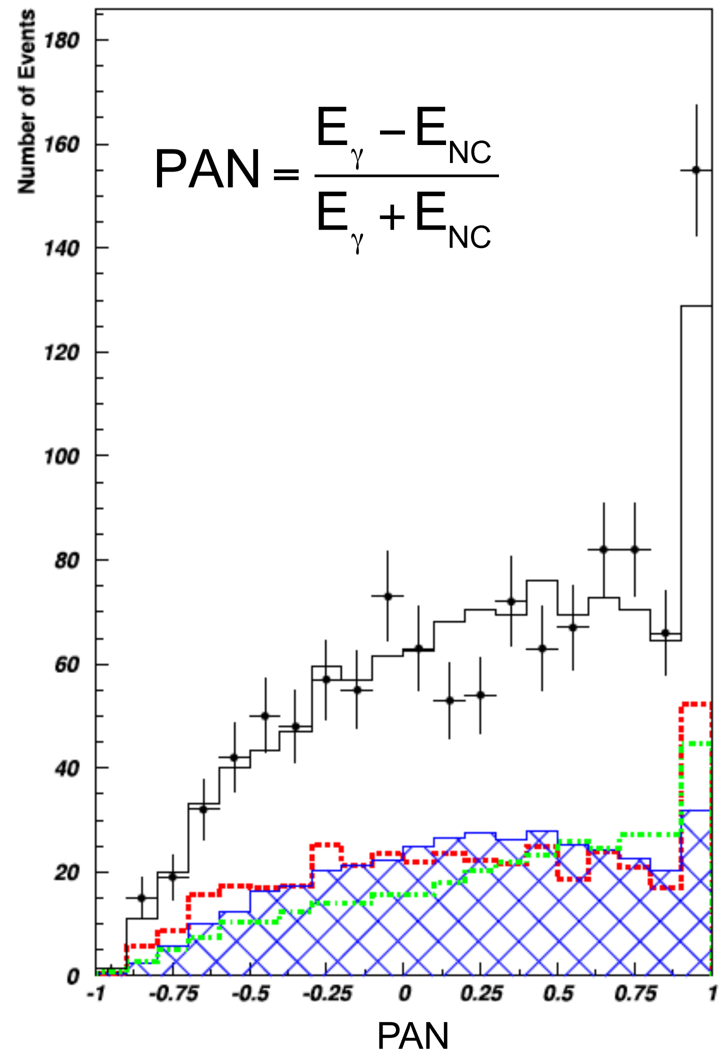
PAN=measure of energy asymmetry between E_γ and E_{NC}

- E_γ = measured gamma energy
- E_{NC} = ECAL energy deposit by neutral particles

PAN is big → less likely to be DIS and more interesting data



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NOMAD Collaboration, PLB706(2012)268

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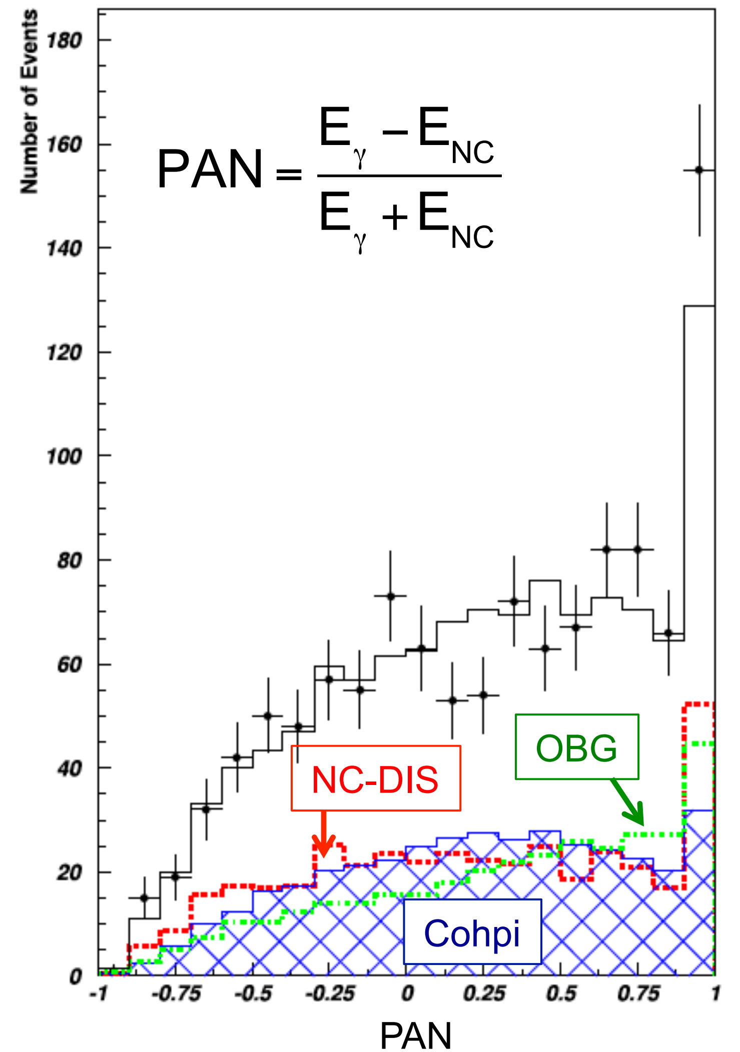
- E_γ = measured gamma energy
- E_{NC} = ECAL energy deposit by neutral particles

Signal box is defined to be PAN>0.9

3 major backgrounds

- NC coherent π^o production (Cohpi)
- outside of fiducial volume background (OBG)
- NC-DIS π^o production (NC-DIS)



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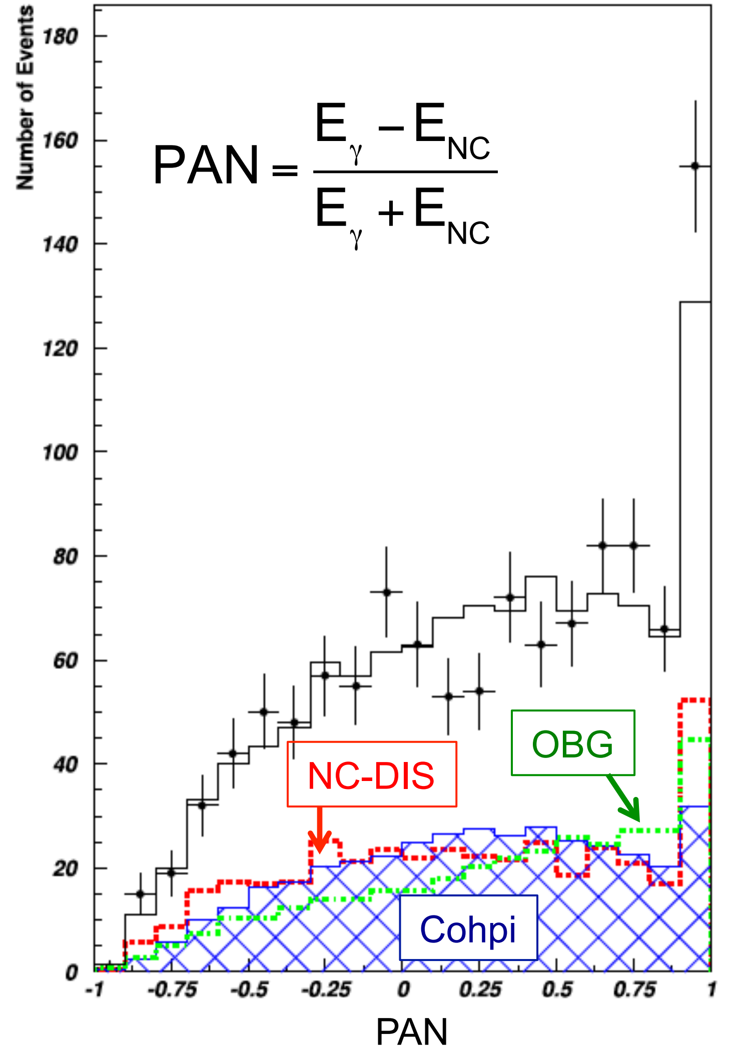
- E_γ = measured gamma energy
- E_{NC} = ECAL energy deposit by neutral particles

Signal box is defined to be PAN>0.9

3 major backgrounds

- NC coherent π^o production (Cohpi)
  → Cohpi model in MC is tuned to the distribution of measured 2γ sample
- outside of fiducial volume background (OBG)
  → Data sample outside of fiducial volume is used for normalization
- NC-DIS π^o production (NC-DIS)
  → Tune using the region $\zeta_\gamma=E_\gamma(1-\cos\theta_\gamma)>0.5$



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2. NOMAD

Result
- no excess, set limit, xs(NCγ/CC) < 4×10^{-4}

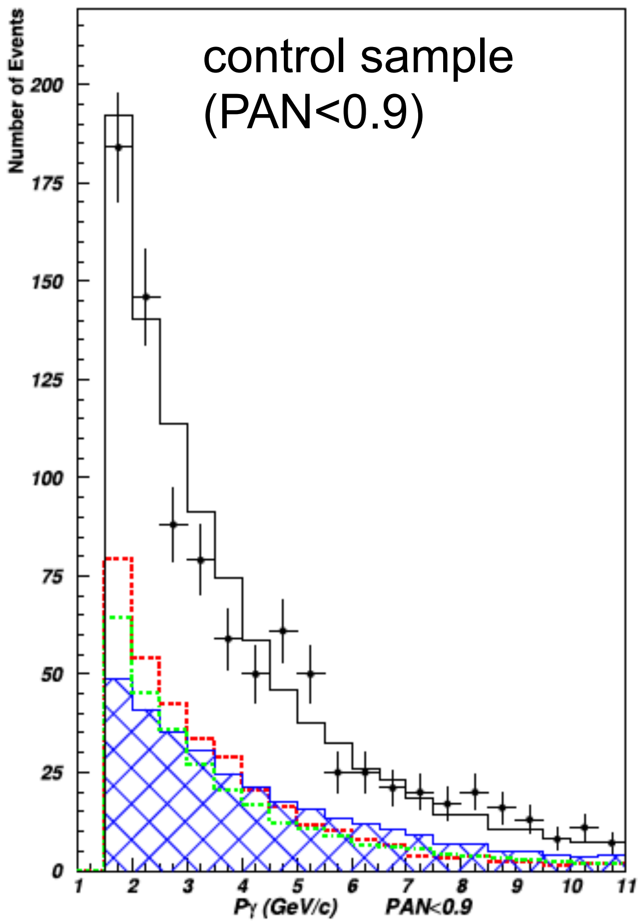


Fig. 3. Comparison of P_γ between data and MC in PAN < 0.9 region.

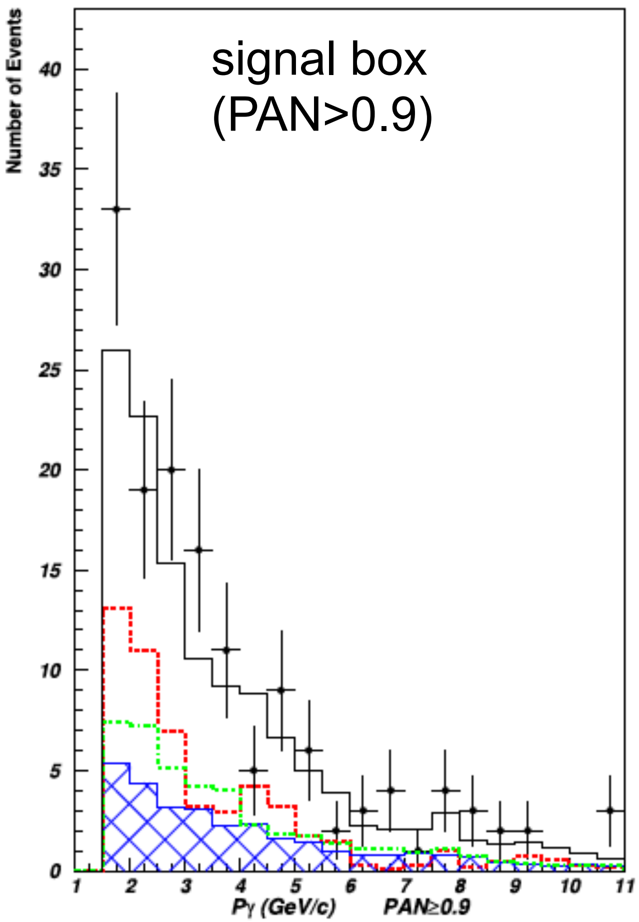


Fig. 5. Comparison of P_γ between data and MC in Box1, PAN ⩾ 0.9 region.

2. NOMAD

Result
- no excess, set limit, xs(NCγ/CC) < 4×10^{-4}

Lesson
- There will be 2 types of backgrounds, internal and external background

- internal background is dominated by NCπ^o production with single γ final state
  → NCπ^o production rate needs to be constraint from the own data

(In general, NCγ cross section is ~0.5% of NCπ^o, so you need to reject 99% of π^o with 10% error, then NCγ would be ~2σ significance (assuming no other background)

- external background is γ coming from outside of the fiducial volume (also mostly π^o origin)
  → External background needs to be tuned from the own data
  → 3mx3mx4m is not big enough to suppressed external background

1. Oscillation physics

2. NOMAD

3. T2K/MINERvA

4. MicroBooNE

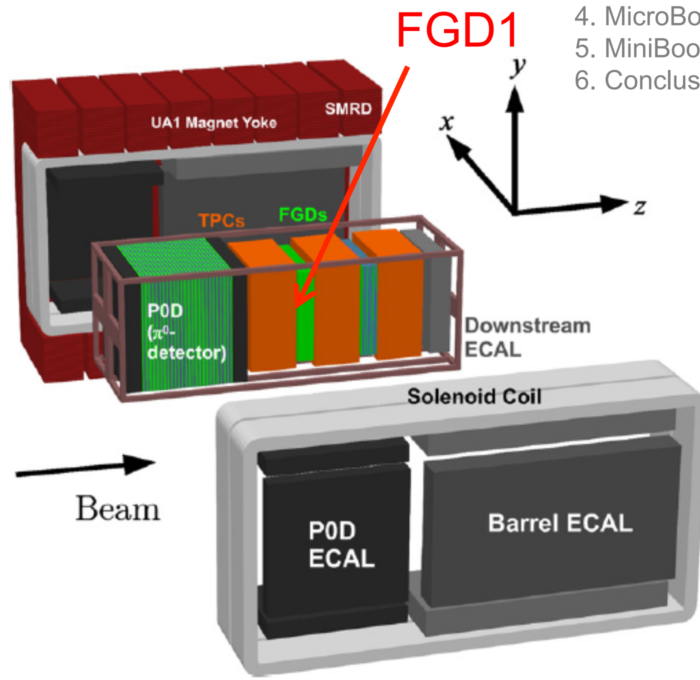
5. MiniBooNE+

6. Conclusion

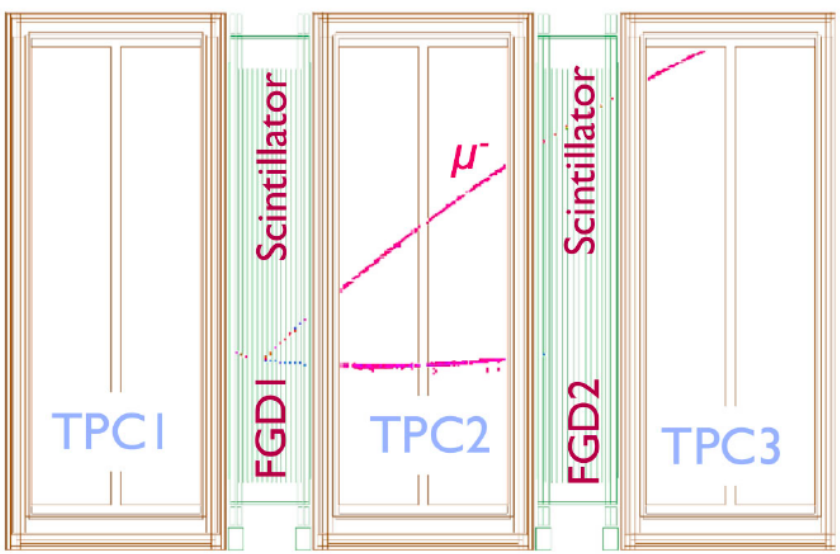
3. T2K

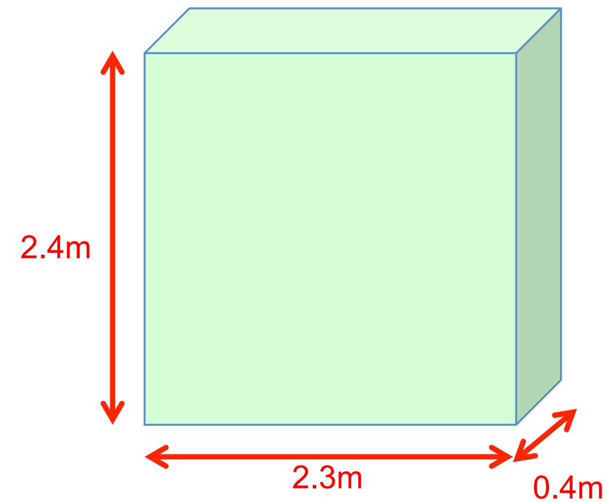
Fine Grained Detector (FGD1)

- The main vertex detector of ND280
- extruded scintillator+WLS fiber X-Y tracker
- ν_μCC inclusive cross section analysis
- 2.3x2.4x0.4m^3
- 1.75x1.75x0.33m^3 fiducial volume (1.1 ton)



μ+X candidate in FGD1





3. T2K

Fine Grained Detector (FGD1)
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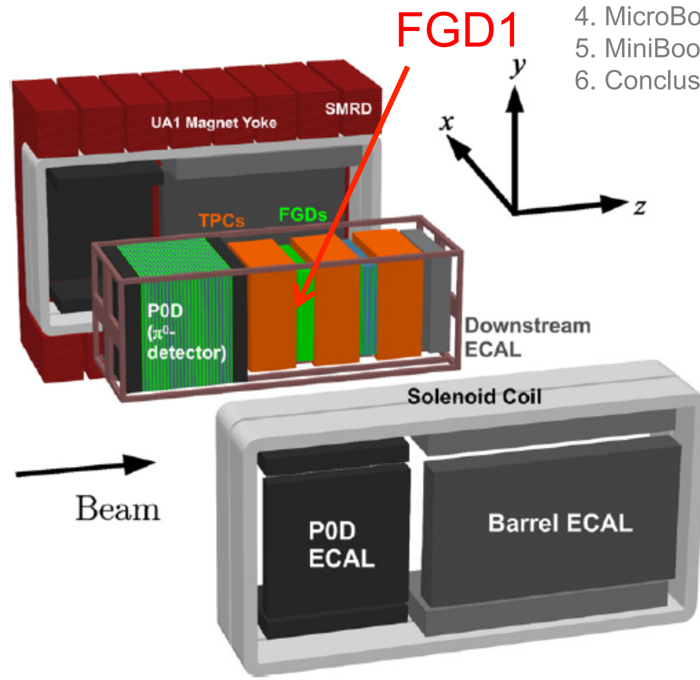
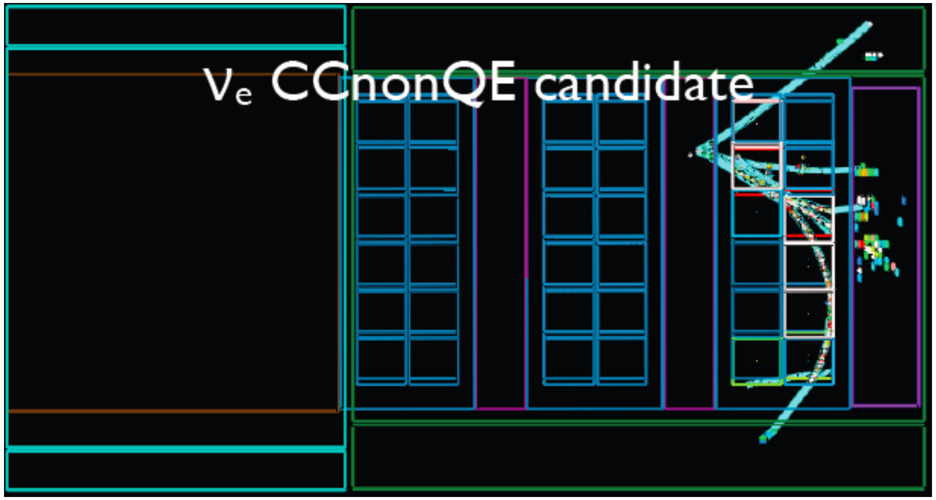
Argon gas TPC
- Capable to track charged particles
- 0.2T magnetic field

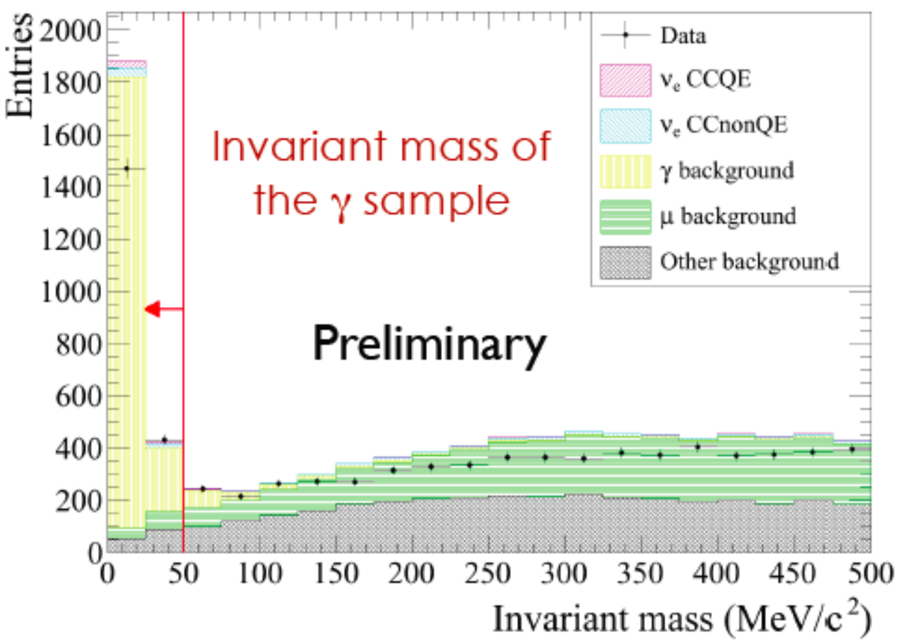




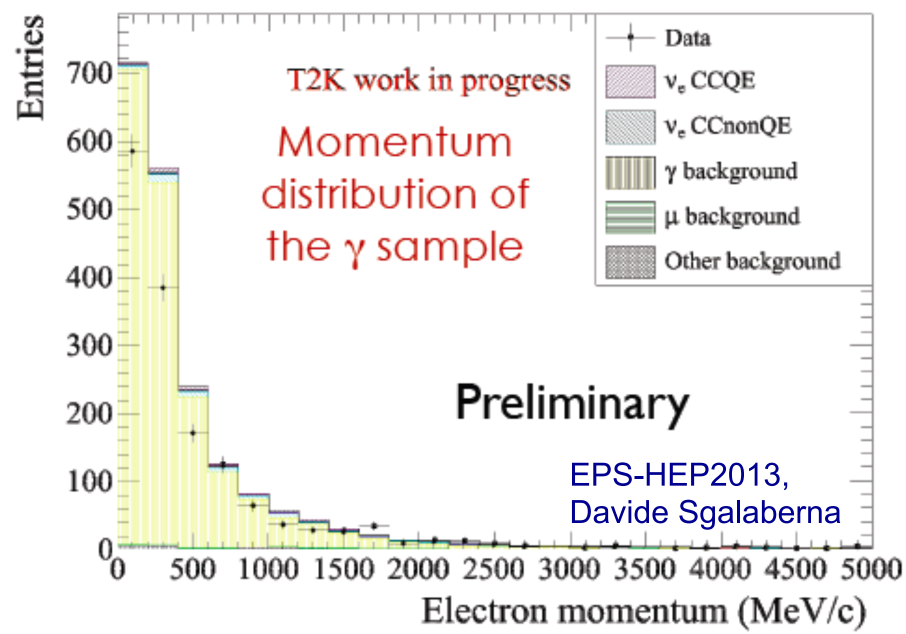
3. T2K

Gamma selection

- Background control sample for ν_eCCQE measurement
- e^+ and e^- tracks are reconstructed, invariant mass is reconstructed
- >95% purity gamma sample!



$e^-(e^+)$ momentum distribution in gamma sample



EPS-HEP2013, Davide Sgalaberna

3. T2K

Gamma selection
- Background control sample for ν_eCCQE measurement
- e^+ and e^- tracks are reconstructed, invariant mass is reconstructed
- >95% purity gamma sample!

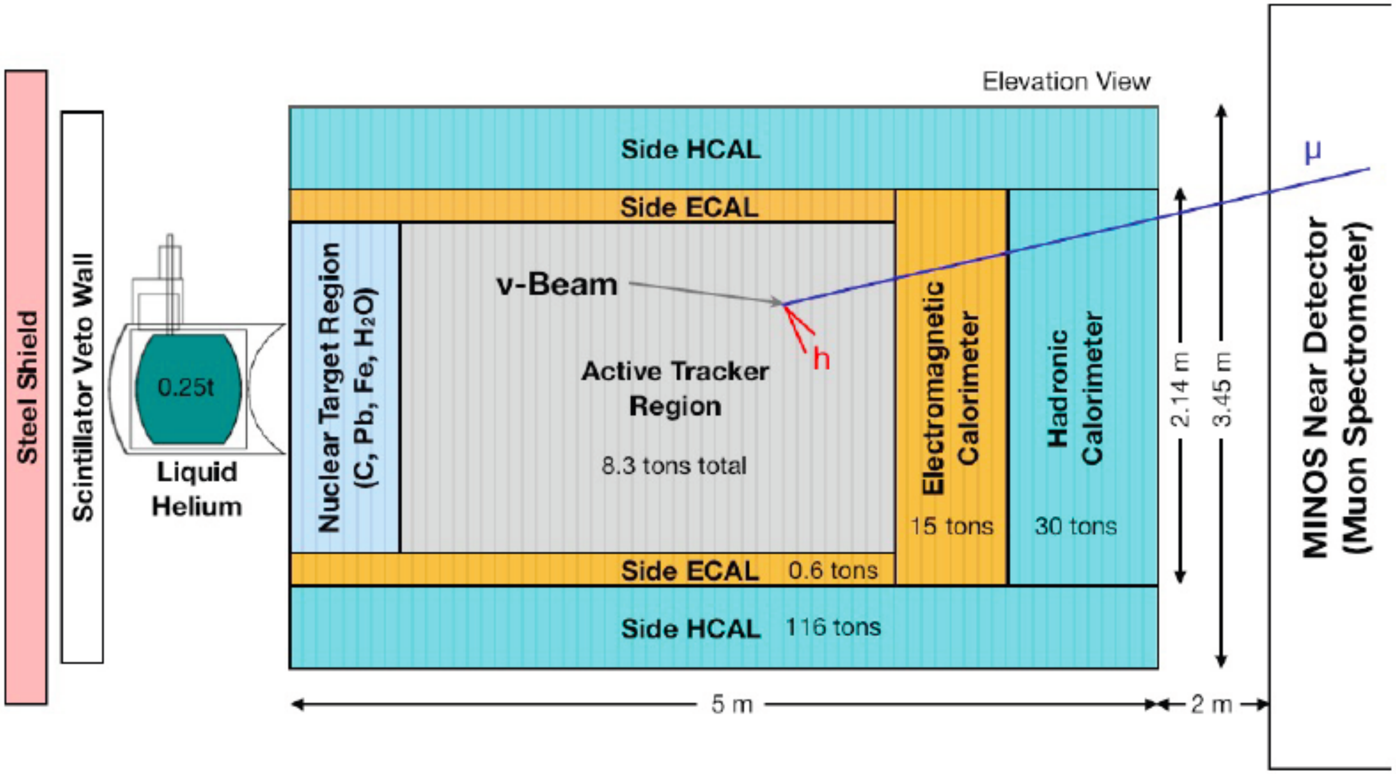
...however, majority may be
- NC1π^o with one gamma missing (asymmetry decay, detector efficiency)
- from outside of FGD1 (π^o production outside of FGD1)

Internal background
- performance of π^o measurement by FGD-TPC is unknown
- angular distribution of gamma may help to reduce internal background, but small acceptance

External background
- smaller fiducial volume is a disadvantage

3. MINERvA

MINERvA
- The main vertex detector is extruded scintillator+WLS fiber U-V tracker
- no magnetic field
- Fiducial volume is (5.57 ton)



3. MINERvA

MINERvA
- The main vertex detector is extruded scintillator+WLS fiber U-V tracker
- no magnetic field
- Fiducial volume is (5.57 ton)

Internal background
- reconstruction efficiency of gamma is not high (no magnetic field)
- π^o measurement performance is unknown

External background
- although fiducial volume is bigger than T2K, beam energy is also higher, so external background is still a lot

1. Oscillation physics

2. NOMAD

3. T2K/MINERvA

4. MicroBooNE

5. MiniBooNE+

6. Conclusion

Neutrino working group snowmass report, arXiv:1310.4340

4. MicroBooNE

Future neutrino cross section measurement experiments
argon target vs carbon target vs TBD

Table 6: Current and proposed experiments for ν cross section measurements or related studies. The upper (lower) part of table summarizes the intermediate- (low-) energy regime.

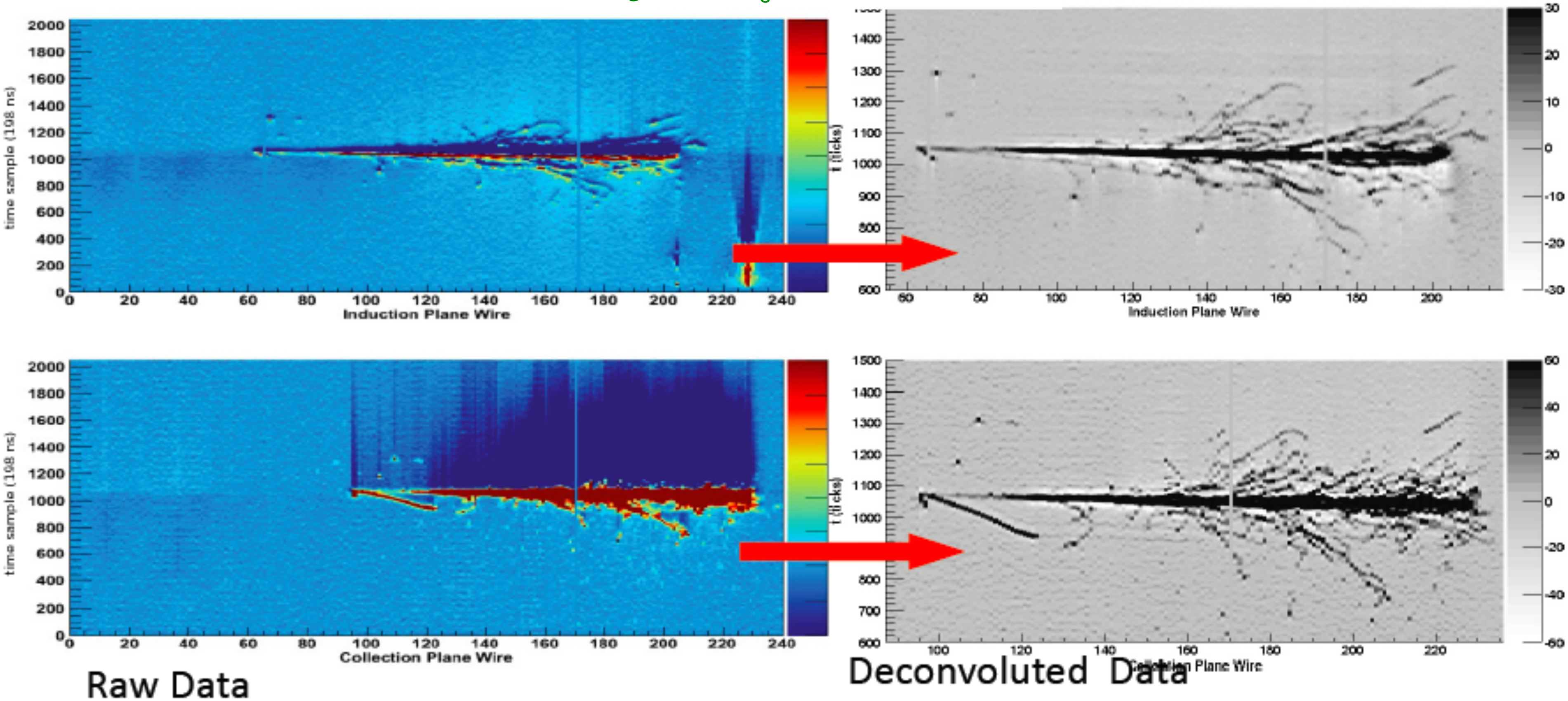
Experiment	Physics[1]	ν Source	Energy (GeV)	Target	Detector[2]	Host	Status
MiniBooNE [193]	MedE	π DIF	0.4-2	CH_2	Ch/calo	Fermilab	Current
T2K [194]	MedE	π DIF	0.3-2	CH	Scitrk/ TPC/calo	J-PARC	Current
MINERvA [195]	MedE	π DIF	1-20	many[3]	Scitrk/calo	Fermilab	Current
MINOS [196]	MedE	π DIF	1-20	CH	Scitrk	Fermilab	Current
ArgoNeuT [197]	MedE	π DIF	1-10	Ar	TPC	Fermilab	Current
NOvA NDOS [198]	MedE	π DIF	1	CH_2	Scitrk	Fermilab	Current
NOvA near [108]	MedE	π DIF	1.5-2.5	CH_2	Scitrk	Fermilab	In constr.
MicroBooNE [199]	MedE	π DIF	0.2-2	Ar	TPC	Fermilab	In constr.
LArIAT [200]	MedE	N/A[4]	0.2-2	Ar	TPC	Fermilab	In constr.
MINERvA [201]	MedE, PDFs	π DIF	1-10	H,D	Scitrk/calo	Fermilab	Proposed
nuSTORM [192]	MedE, ν_e xs	π DIF	0.5-3.5	TBD	TBD	Fermilab	Proposed
SciNOvA [202]	MedE	π DIF	1.5-2.5	CH	Scitrk	Fermilab	Proposed
MiniBooNE+ [203]	MedE	π DIF	0.3-0.5	CH_2	Ch/calo	Fermilab	Proposed
CAPTAIN [204]	MedE	π DIF	1-10	Ar	TPC	Fermilab	Proposed
LBNE near [87]	MedE	π DIF	0.5-5	TBD	TBD	Fermilab	Proposed
CAPTAIN [204]	LowE	π DAR	0.01-0.05	Ar	TPC	ORNL	Proposed
OscSNS [205]	LowE	π DAR	0.01-0.05	CH_2	Ch/calo	ORNL	Proposed
IsoDAR [111]	LowE	^{8}Li DAR	0.002-0.05	TBD	TBD	TBD	Proposed
CENNS [206]	νA coh.	π DAR	0.01-0.05	Ar	Calo	Fermilab	Proposed
CSI [207]	νA coh.	π DAR	0.01-0.05	TBD	TBD	ORNL	Proposed

Neutrino working group snowmass report, arXiv:1310.4340

4. MicroBooNE

Liquid Argon Time Projection Chamber (LArTPC)
- MicroBooNE exists! (under installation)
- Modern bubble chamber, amazing resolution
- 2.3x2.6x10.4m^3 (86 ton TPC volume), fiducial volume may be smaller than that

ArgoNeuT ν_eCC candidate event



4. MicroBooNE

Liquid Argon Time Projection Chamber (LArTPC)
- MicroBooNE exists! (under installation)
- Modern bubble chamber, amazing resolution
- $2.3 \times 2.6 \times 10.4 m^3$ (86 ton TPC volume), fiducial volume may be smaller than that

Internal background
- π^o measurement performance is unknown but probably really good. This constrains most of internal backgrounds. There might be some uncertainty photo-nuclear absorption on Ar?
- It is not clear how "high resolution" helps to reduce internal background. Both $NC\pi^o$ and $NC\gamma$ reactions have coherent and incoherent, so vertex activity may not help to reject backgrounds (Is there any parameters we overlook?)
- angular distribution measurement is tough due to small acceptance.

External background
- fiducial volume is small, external background will be a lot

1. Oscillation physics

2. NOMAD

3. T2K/MINERvA

4. MicroBooNE

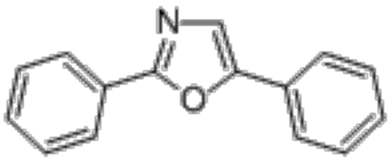
5. MiniBooNE+

6. Conclusion

5. MiniBooNE+

MiniBooNE with neutron tagging

- MiniBooNE+PPO (scintillator), total cost ~$75k
- delayed (τ~186μs) neutron capture is observed



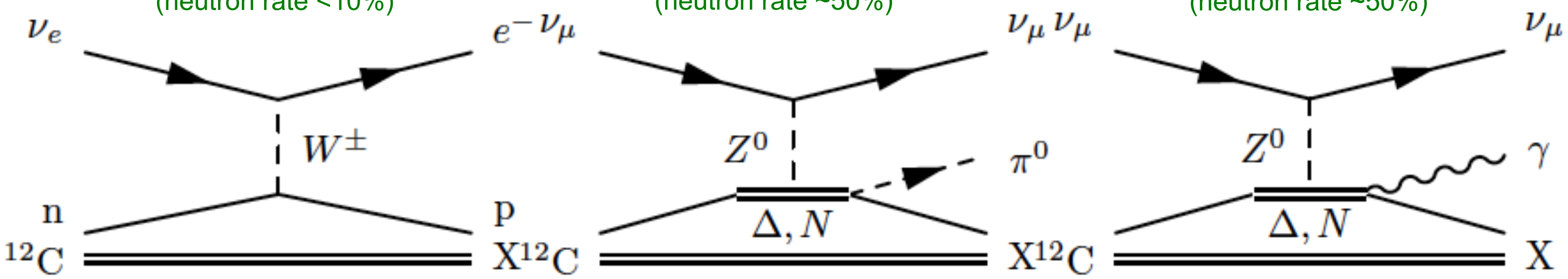
$$n + p \rightarrow d + \gamma \text{ (2.2MeV)}$$

- Now, MiniBooNE can effectively separate NCγ from ν_eCCQE

ν_eCCQE interaction (neutron rate <10%)

NCπ^o production (neutron rate ~50%)

NCγ production (neutron rate ~50%)

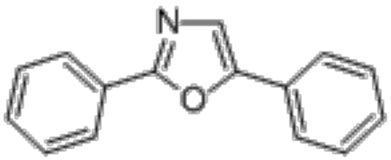


(a) $\nu_e CCQE$ (b) $\nu_\mu NC\pi^0$ (c) $\nu_\mu NC\gamma$

5. MiniBooNE+

MiniBooNE with neutron tagging

- MiniBooNE+PPO (scintillator), total cost ~$75k
- delayed (τ~186μs) neutron capture is observed



$$n + p \rightarrow d + \gamma \text{ (2.2MeV)}$$

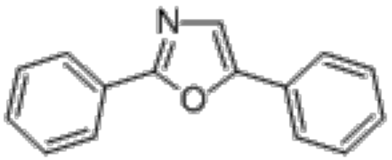
- Now, MiniBooNE can effectively separate NCγ from ν_eCCQE
- $^{12}N_{g.s.}$ de-excitation measurement provide flux normalization

$$12N_{g.s.} \rightarrow {}^{12}C + \nu_e + e^+ \text{ (16.3 MeV end point)}$$

5. MiniBooNE+

MiniBooNE with neutron tagging

- MiniBooNE+PPO (scintillator), total cost ~$75k
- delayed (τ~186μs) neutron capture is observed



$$n + p \rightarrow d + \gamma \text{ (2.2MeV)}$$

- Now, MiniBooNE can effectively separate NCγ from ν_eCCQE
- $^{12}N_{g.s.}$ de-excitation measurement provide flux normalization

Internal background

- MiniBooNE already shows ~5% relative measurement of NC1π^o, say NCγ:NCπ^o:~1:5 in data sample, then >3σ NCγ signal is possible
- I don't know how much scintillation helps to separate NCγ from NCπ^o
- flux normalization

External background

- large volume (12m diameter sphere)is really good to suppress external background

6. Conclusions

Experimental performance summary

	γ reconstruction	internal background	external background	status
NOMAD	magnet		HE, big	done
T2K	magnet	???	LE, small	running
MINERvA	no magnet	???	HE, small	running
MicroBooNE	LArTPC	???	LE, small	start 2014
MiniBooNE+	neutron tagging	high stat π^o	LE, big	???

NCγ measurement is challenging for every experiments

Thank you for your attention!

Backup