Neutral Current Single Photon Production (NC$\gamma$)

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

I'm hungry...

Omar: take this spectral function, the most precise knowledge of nuclei, eat this

This SuSA shall fit dip region, eat it...

Eat this coupled TSI model, where all final state particles are correctly simulated.

I'm fine with this...

Eat me?

A Journey of neutrino generator continues...
NuSTEC protocol
- way to avoid Donkey effect
- framework of theory-experiment (generator) interface
GiBUU is Nature

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

The first day, GiBUU creates protons and neutrons from quark gluon plasma ...

Ulrich

Tepper K.,
Dec. 10, 2013
 GiBUU is Nature

...and today, experimentalist ate the forbidden fruit called the case...

The first day, GiBUU creates protons and neutrons from quark gluon plasma...
The first day, GiBUU created protons and neutrons from quark gluon plasma...

...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 νe appearance background
- all generators estimate NCγ from radiative Δ-decay Δ→Nγ
- cross section is roughly ~0.5% of NC1π⁰ channel
1. MiniBooNE

NC\(_\gamma\), as \(\nu_e\) appearance background
- all generators estimate NC\(_\gamma\) from radiative \(\Delta\)-decay \(\Delta \rightarrow N\gamma\)
- cross section is roughly \(\sim 0.5\%\) of NC\(1\pi^0\) channel

MiniBooNE
- Final oscillation paper estimates NC\(_\gamma\) is roughly \(\sim 20\%\) of NC\(\pi^0\) background in \(\nu_e\) candidate sample.
- To explain all excess by NC\(_\gamma\), NC\(_\gamma\) cross section needs to be higher x2 to x3.
1. MiniBooNE

NC$_\gamma$, as $\nu_e$ appearance background - all generators estimate
- cross section is roughly $0.5\%$ of NC1

MiniBooNE - Final oscillation paper estimates NC$_\gamma$ is roughly $20\%$ of NC
- To explain all excess by NC$_\gamma$, NC$_\gamma$ cross section needs to be higher x2 to x3.

$\nu_e$ from $\mu$ decay is constrained from $\nu_\mu$ CCQE measurement
1. MiniBooNE

NCγ, as νe appearance - all generators estimate - cross section is roughly ~0.5% of NCπo channel

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

SciBooNE 3 track event

νe from K decay is constrained from high energy νμ event measurement in SciBooNE

νe from µ decay is constrained from νμ CCQE measurement

SciBooNE collaboration PRD84(2011)012009
1. MiniBooNE

NC_{\gamma}, as \nu_e appearance
- all generators estimate
- cross section is roughly ~0.5% of NC_{1\pi^0}

MiniBooNE
- Final oscillation paper estimate
- To explain all excess by NC_{\gamma}, NC_{\gamma} cross section needs to be higher x2 to x3.

\nu_e from \mu decay is constrained from \nu_\mu CCQE measurement

\nu_e from K decay is constrained from high energy \nu_\mu event measurement in SciBooNE

Asymmetric \pi^0 decay is constrained from measured CC\pi^0 rate (\pi^0 \rightarrow \gamma)
1. MiniBooNE

NC$\gamma$, as $\nu_e$ appearance background
- all generators estimate
- cross section is roughly $\approx 0.5\%$ of NC$\pi^o$ channel

MiniBooNE
- Final oscillation paper estimates
  - NC$\gamma$ is roughly $\approx 20\%$ of NC$\pi^o$ background in $\nu_e$ candidate sample.
- To explain all excess by NC$\gamma$, NC$\gamma$ cross section needs to be higher x2 to x3.

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

dirt rate is measured from dirt enhanced data sample

$\nu_e$ from $\mu$ decay is constrained from $\nu_\mu$ CCQE measurement

$\nu_e$ from $K$ decay is constrained from high energy $\nu_\mu$ event measurement in SciBooNE
1. MiniBooNE

NC$_{\gamma}$, as $\nu_e$ appearance background
- all generators estimate NC$_{\gamma}$ from radiative $\Delta$-decay $\Delta \rightarrow N\gamma$
- cross section is roughly $\sim$0.5% of NC$\pi_o$

MiniBooNE
- Final oscillation paper estimates NC$_{\gamma}$ is roughly $\sim$20% of NC$\pi_o$ background in $\nu_e$ candidate sample.
- To explain all excess by NC$_{\gamma}$, NC$_{\gamma}$ cross section needs to be higher x2 to x3.

Asymmetric $\pi^0$ decay is constrained from measured CC$\pi^0$ rate ($\pi^0 \rightarrow \gamma$)

Radiative $\Delta$-decay ($\Delta \rightarrow N\gamma$) rate is constrained from measured NC$\pi^0$
dirt rate is measured from dirt enhanced data sample

All backgrounds are measured in other data sample and their errors are constrained.
1. T2K

NCγ, as νe appearance background
- all generators estimate NCγ from radiative Δ-decay Δ→Nγ
- cross section is roughly ~0.5% of NC1π⁰ channel

MiniBooNE
- Final oscillation paper estimates NCγ is roughly ~20% of NCπ⁰ background in νe candidate sample.
- To explain all excess by NCγ, NCγ cross section needs to be higher x2 to x3.

T2K
- With sin²2θ₁₃=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 sin²2θ₁₃ 2.3 to 3.5%.
1. Model comparison

Generator comparison
Total NC\(\gamma\) cross section on carbon target at 600 MeV muon neutrino (unit 1E-42cm\(^2\))

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

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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 NC\(\gamma\) happen from all resonance contributions (including multi pion production processes)

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![Graph showing comparison of cross sections](image-url)
1. Model comparison

Generator comparison
Total NC$\gamma$ 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 $\Delta$-decay BR)

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

The cross section needed to change $\sin^22\theta_{13}(T2K)\sim10\%$ is ~200
(NEUT needs to be wrong ~1000%)
1. Oscillation physics

2. NOMAD

3. T2K/MINERvA

4. MicroBooNE

5. MiniBooNE+

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

NOMAD Collaboration, PLB706(2012)268
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

PAN=measure of energy asymmetry between $E_\gamma$ and $E_{NC}$
- $E_\gamma$ = measured gamma energy
- $E_{NC}$ = ECAL energy deposit by neutral particles

PAN is big $\rightarrow$ less likely to be DIS and more interesting data
2. NOMAD

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PAN=measure of energy asymmetry between $E_\gamma$ and $E_{NC}$
- $E_\gamma$ = 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 $\pi^0$ production (Cohpi)
- outside of fiducial volume background (OBG)
- NC-DIS $\pi^0$ production (NC-DIS)
2. NOMAD

Single gamma search
Very simple, but robust analysis. They identified all issues on this measurement.
- single e⁺-e⁻ pair
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PAN=measure of energy asymmetry between $E_\gamma$ and $E_{NC}$
- $E_\gamma$ = 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 $\pi^0$ production (Cohpi)
  → Cohpi model in MC is tuned to the distribution of measured $2\gamma$ sample
- outside of fiducial volume background (OBG)
  → Data sample outside of fiducial volume is used for normalization
- NC-DIS $\pi^0$ production (NC-DIS)
  → Tune using the region $\zeta_\gamma=E_\gamma(1-\cos\theta_\gamma)>0.5$
2. NOMAD

Result
- no excess, set limit, $x_s(\text{NC}_\gamma/\text{CC}) < 4 \times 10^{-4}$

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Fig. 3. Comparison of $P_\gamma$ between data and MC in PAN < 0.9 region.

Fig. 5. Comparison of $P_\gamma$ between data and MC in Box 1, PAN $\geq 0.9$ region.
2. NOMAD

Result
- no excess, set limit, \( \text{xs}(\text{NC}_\gamma/\text{CC}) < 4 \times 10^{-4} \)

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

- **internal background** is dominated by \( \text{NC}_\pi^0 \) production with single \( \gamma \) final state
  \[ \rightarrow \text{NC}_\pi^0 \text{ production rate needs to be constraint from the own data} \]
  (In general, \( \text{NC}_\gamma \) cross section is \( \approx 0.5\% \) of \( \text{NC}_\pi^0 \), so you need to reject 99\% of \( \pi^0 \) with 10\% error, then \( \text{NC}_\gamma \) would be \( \approx 2\sigma \) significance (assuming no other background))

- **external background** is \( \gamma \) coming from outside of the fiducial volume (also mostly \( \pi^0 \) origin)
  \[ \rightarrow \text{External background needs to be tuned from the own data} \]
  \[ \rightarrow \text{3mx3mx4m is not big enough to suppressed external background} \]
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
- $\nu_\mu$CC inclusive cross section analysis
- 2.3x2.4x0.4m$^3$
- 1.75x1.75x0.33m$^3$ fiducial volume (1.1 ton)
3. T2K

Fine Grained Detector (FGD1)
- The main vertex detector of ND280
- extruded scintillator+WLS fiber X-Y tracker
- $\nu_\mu$ CC inclusive cross section analysis
- $2.3 \times 2.4 \times 0.4 \text{m}^3$
- $1.75 \times 1.75 \times 0.33 \text{m}^3$ fiducial volume (1.1 ton)

Argon gas TPC
- Capable to track charged particles
- 0.2T magnetic field

3. T2K

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

![Invariant mass of the $\gamma$ sample](image1.png)

![$e^-(e^+)$ momentum distribution in gamma sample](image2.png)

![Momentum distribution of the $\gamma$ sample](image3.png)

T2K work in progress

**EPS-HEP2013, Davide Sgalaberna**
3. T2K

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

...however, majority may be
- NC1$\pi^0$ with one gamma missing (asymmetry decay, detector efficiency)
- from outside of FGD1 ($\pi^0$ production outside of FGD1)

**Internal background**
- performance of $\pi^0$ 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)
- $\pi^0$ 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
## 4. MicroBooNE

Future neutrino cross section measurement experiments

argon target vs carbon target vs TBD

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Physics¹</th>
<th>$\nu$ Source</th>
<th>Energy (GeV)</th>
<th>Target</th>
<th>Detector²</th>
<th>Host</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>MiniBooNE [193]</td>
<td>MedE</td>
<td>$\pi$ DIF</td>
<td>0.4-2</td>
<td>CH₂</td>
<td>Ch/calo</td>
<td>Fermilab</td>
<td>Current</td>
</tr>
<tr>
<td>T2K [194]</td>
<td>MedE</td>
<td>$\pi$ DIF</td>
<td>0.3-2</td>
<td>CH</td>
<td>Scitkr/calo</td>
<td>J-PARC</td>
<td>Current</td>
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<tr>
<td>MINERvA [195]</td>
<td>MedE</td>
<td>$\pi$ DIF</td>
<td>1-20</td>
<td>many³</td>
<td>Scitkr/calo</td>
<td>Fermilab</td>
<td>Current</td>
</tr>
<tr>
<td>MINOS [196]</td>
<td>MedE</td>
<td>$\pi$ DIF</td>
<td>1-20</td>
<td>CH</td>
<td>Scitkr</td>
<td>Fermilab</td>
<td>Current</td>
</tr>
<tr>
<td>ArgoNeuT [197]</td>
<td>MedE</td>
<td>$\pi$ DIF</td>
<td>1-10</td>
<td>Ar</td>
<td>TPC</td>
<td>Fermilab</td>
<td>Current</td>
</tr>
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<td>NOvA NDOS [198]</td>
<td>MedE</td>
<td>$\pi$ DIF</td>
<td>1</td>
<td>CH₂</td>
<td>Scitkr</td>
<td>Fermilab</td>
<td>Current</td>
</tr>
<tr>
<td>NOvA near [108]</td>
<td>MedE</td>
<td>$\pi$ DIF</td>
<td>1.5-2.5</td>
<td>CH₂</td>
<td>Scitkr</td>
<td>Fermilab</td>
<td>In constr.</td>
</tr>
<tr>
<td>MicroBooNE [199]</td>
<td>MedE</td>
<td>$\pi$ DIF</td>
<td>0.2-2</td>
<td>Ar</td>
<td>TPC</td>
<td>Fermilab</td>
<td>In constr.</td>
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<td>LArIAT [200]</td>
<td>MedE</td>
<td>$N/A$⁴</td>
<td>0.2-2</td>
<td>Ar</td>
<td>TPC</td>
<td>Fermilab</td>
<td>In constr.</td>
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<tr>
<td>MINERvA [201]</td>
<td>MedE, PDFs</td>
<td>$\pi$ DIF</td>
<td>1-10</td>
<td>H,D</td>
<td>Scitkr/calo</td>
<td>Fermilab</td>
<td>Proposed</td>
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<tr>
<td>nuSTORM [192]</td>
<td>MedE, $\nu_e$ xs</td>
<td>$\pi$ DIF</td>
<td>0.5-3.5</td>
<td>TBD</td>
<td>TBD</td>
<td>Fermilab</td>
<td>Proposed</td>
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<tr>
<td>SciNOvA [202]</td>
<td>MedE</td>
<td>$\pi$ DIF</td>
<td>1.5-2.5</td>
<td>CH</td>
<td>Scitkr</td>
<td>Fermilab</td>
<td>Proposed</td>
</tr>
<tr>
<td>MiniBooNE+ [203]</td>
<td>MedE</td>
<td>$\pi$ DIF</td>
<td>0.3-0.5</td>
<td>CH₂</td>
<td>Ch/calo</td>
<td>Fermilab</td>
<td>Proposed</td>
</tr>
<tr>
<td>CAPTAIN [204]</td>
<td>MedE</td>
<td>$\pi$ DIF</td>
<td>1-10</td>
<td>Ar</td>
<td>TPC</td>
<td>Fermilab</td>
<td>Proposed</td>
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<td>LBNE near [87]</td>
<td>MedE</td>
<td>$\pi$ DIF</td>
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<td>TBD</td>
<td>TBD</td>
<td>Fermilab</td>
<td>Proposed</td>
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<tr>
<td>CAPTAIN [204]</td>
<td>LowE</td>
<td>$\pi$ DAR</td>
<td>0.01-0.05</td>
<td>Ar</td>
<td>TPC</td>
<td>ORNL</td>
<td>Proposed</td>
</tr>
<tr>
<td>OscSNS [205]</td>
<td>LowE</td>
<td>$\pi$ DAR</td>
<td>0.01-0.05</td>
<td>CH₂</td>
<td>Ch/calo</td>
<td>ORNL</td>
<td>Proposed</td>
</tr>
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<td>IsoDAR [111]</td>
<td>LowE</td>
<td>$^8$Li DAR</td>
<td>0.002-0.05</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>Proposed</td>
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<tr>
<td>CENNS [206]</td>
<td>$\nu A$ coh.</td>
<td>$\pi$ DAR</td>
<td>0.01-0.05</td>
<td>Ar</td>
<td>Calo</td>
<td>Fermilab</td>
<td>Proposed</td>
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<tr>
<td>CSI [207]</td>
<td>$\nu A$ coh.</td>
<td>$\pi$ DAR</td>
<td>0.01-0.05</td>
<td>TBD</td>
<td>TBD</td>
<td>ORNL</td>
<td>Proposed</td>
</tr>
</tbody>
</table>
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 $\nu_e$CC candidate event
4. MicroBooNE

Liquid Argon Time Projection Chamber (LArTPC)
- MicroBooNE exists! (under installation)
- Modern bubble chamber, amazing resolution
- 2.3x2.6x10.4m³ (86 ton TPC volume), fiducial volume may be smaller than that

Internal background
- \( \pi^0 \) 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\( \pi^0 \) 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
  \[ n + p \rightarrow d + \gamma \ (2.2\text{MeV}) \]
- Now, MiniBooNE can effectively separate NCγ from νeCCQE

---

νeCCQE interaction (neutron rate <10%)
NCπ⁰ production (neutron rate ~50%)
NCγ production (neutron rate ~50%)

Neutrino working group snowmass report, arXiv:1310.4340
5. MiniBooNE+

MiniBooNE with neutron tagging
- MiniBooNE+PPO (scintillator), total cost ~$75k
- delayed ($\tau\sim186\mu s$) neutron capture is observed

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

- Now, MiniBooNE can effectively separate $\text{NC}\gamma$ from $\nu_e\text{CCQE}$
- $^{12}\text{N}_{\text{g.s.}}$ de-excitation measurement provide flux normalization

\[ 12\text{N}_{\text{g.s.}} \rightarrow ^{12}\text{C} + \nu_e + e^+ \ (16.3\ \text{MeV end point}) \]
5. MiniBooNE+

MiniBooNE with neutron tagging
- MiniBooNE+PPO (scintillator), total cost ~$75k
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\[ n + p \rightarrow d + \gamma \ (2.2\text{MeV}) \]

- Now, MiniBooNE can effectively separate NC$\gamma$ from $\nu_e$CCQE
- $^{12}$N$_{g.s.}$ de-excitation measurement provide flux normalization

Internal background
- MiniBooNE already shows ~5% relative measurement of NC1$\pi^o$, say NC$\gamma$:NC$\pi^o$:~1:5 in data sample, then $>3\sigma$ NC$\gamma$ signal is possible
- I don’t know how much scintillation helps to separate NC$\gamma$ from NC$\pi^o$
- flux normalization

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

Experimental performance summary

<table>
<thead>
<tr>
<th></th>
<th>$\gamma$ reconstruction</th>
<th>internal background</th>
<th>external background</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOMAD</td>
<td>magnet</td>
<td></td>
<td>HE, big</td>
<td>done</td>
</tr>
<tr>
<td>T2K</td>
<td>magnet</td>
<td>???</td>
<td>LE, small</td>
<td>running</td>
</tr>
<tr>
<td>MINERvA</td>
<td>no magnet</td>
<td>???</td>
<td>HE, small</td>
<td>running</td>
</tr>
<tr>
<td>MicroBooNE</td>
<td>LArTPC</td>
<td>???</td>
<td>LE, small</td>
<td>start 2014</td>
</tr>
<tr>
<td>MiniBooNE+</td>
<td>neutron tagging</td>
<td>high stat $\pi^0$</td>
<td>LE, big</td>
<td>???</td>
</tr>
</tbody>
</table>

NC$\gamma$ measurement is challenging for every experiments

Thank you for your attention!