Search for Accelerator-Produced sub-GeV Dark Matter Particles in MiniBooNE

outline

1. MiniBooNE neutrino oscillation experiment
2. Light dark matter particle search
3. Preliminary results
4. Conclusion

Teppei Katori for MiniBooNE-DM collaboration
Queen Mary University of London
IDM16, Univ. Sheffield, UK, July 18, 2016

1. MiniBooNE neutrino oscillation experiment

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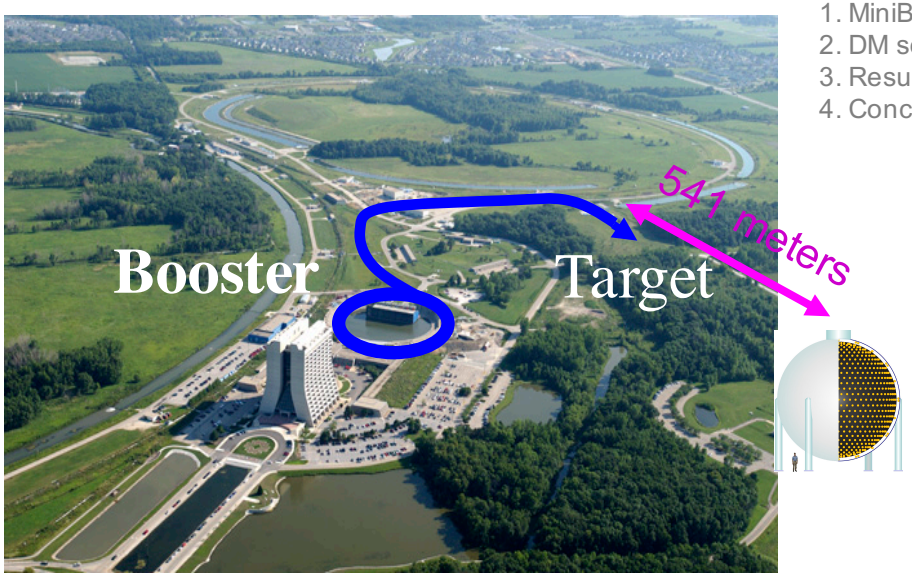
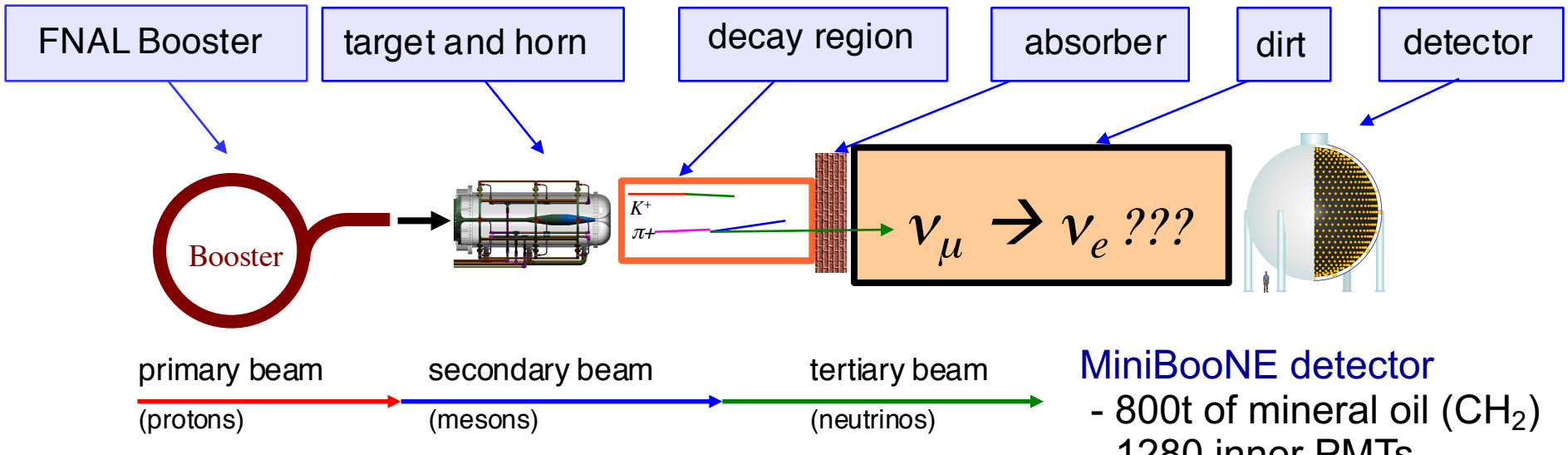
1. MiniBooNE experiment

Booster Neutrino Beamline (BNB) creates ~800(700)MeV neutrino(anti-neutrino) by pion decay-in-flight.





MiniBooNE detector
- 800t of mineral oil (CH_2)
- 1280 inner PMTs
- 240 outer PMTs

1. Events in the Detector

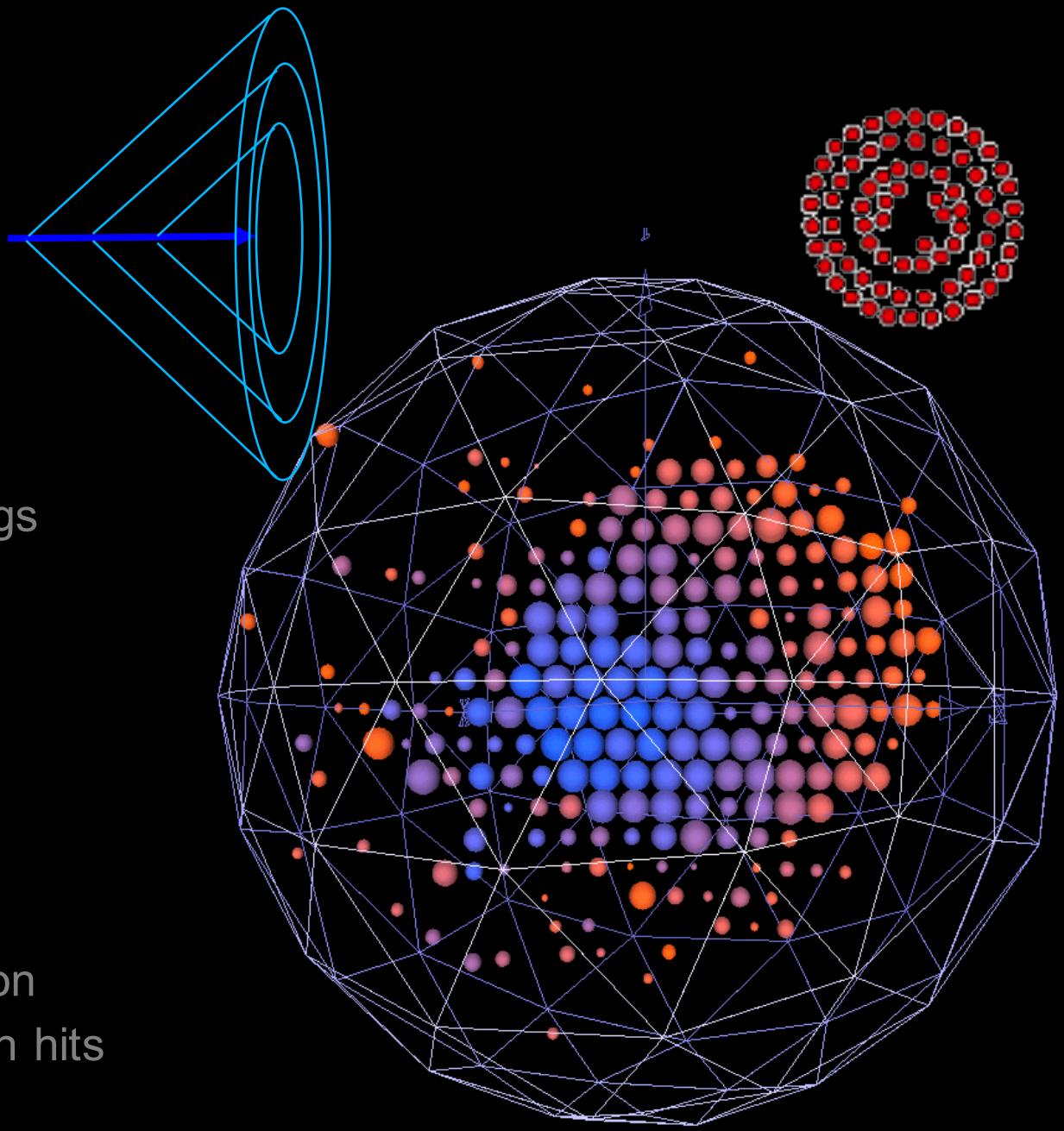
MiniBooNE collaboration,
NIM.A599(2009)28

Muons
- Long strait tracks
  → Sharp clear rings

Electrons
- Multiple scattering
- Radiative processes
  → Scattered fuzzy rings

Neutral pions
- Decays to 2 photons
  → Double fuzzy rings

NC elastic scattering
- No Cherenkov radiation
  → Isotropic scintillation hits



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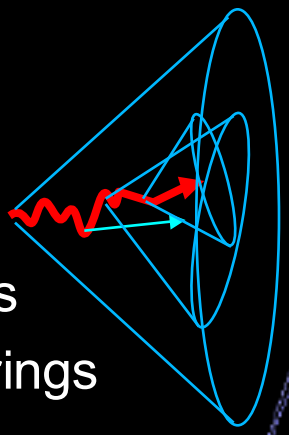

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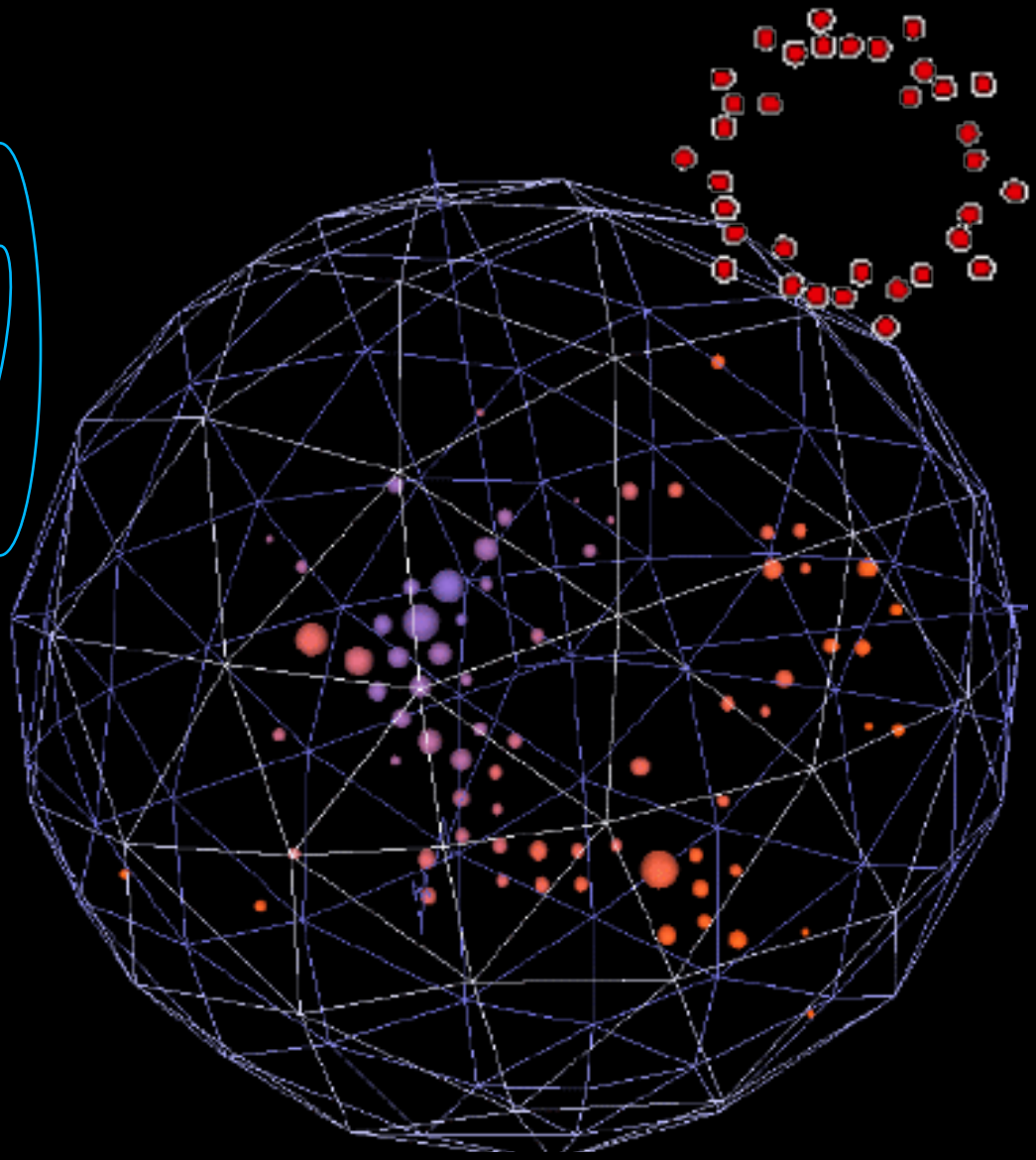

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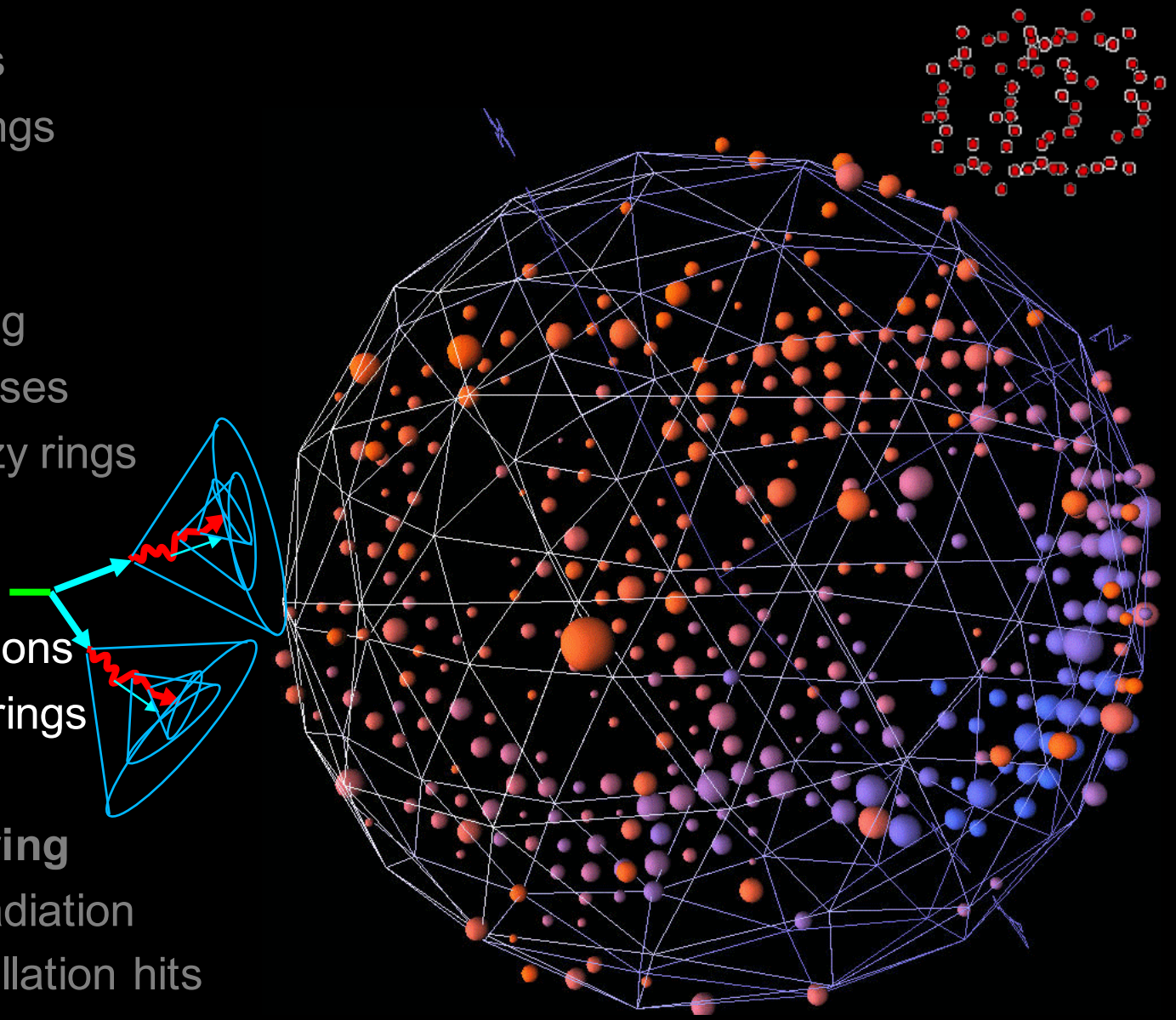

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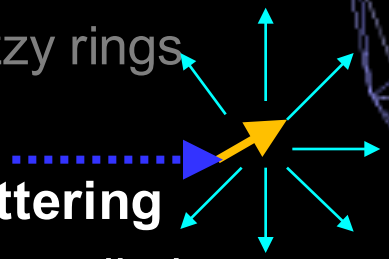

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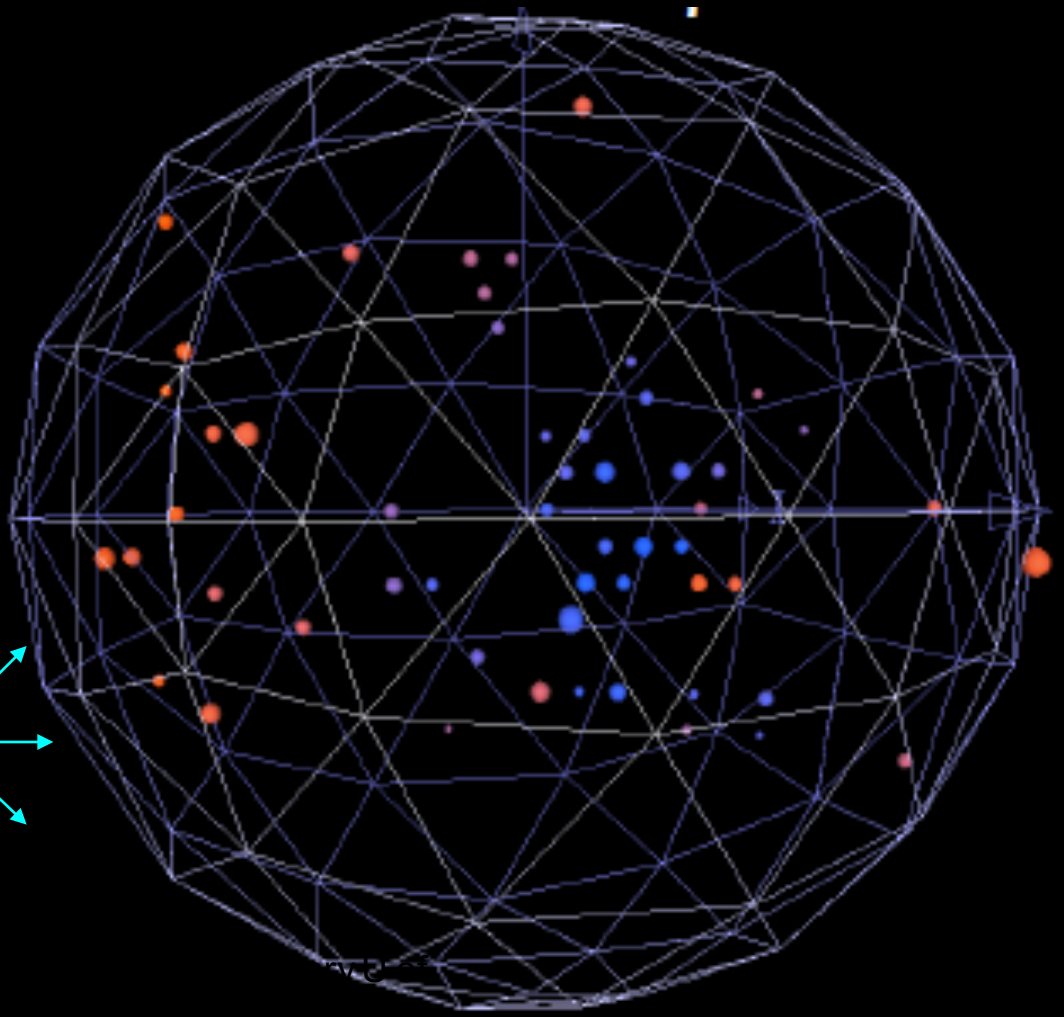


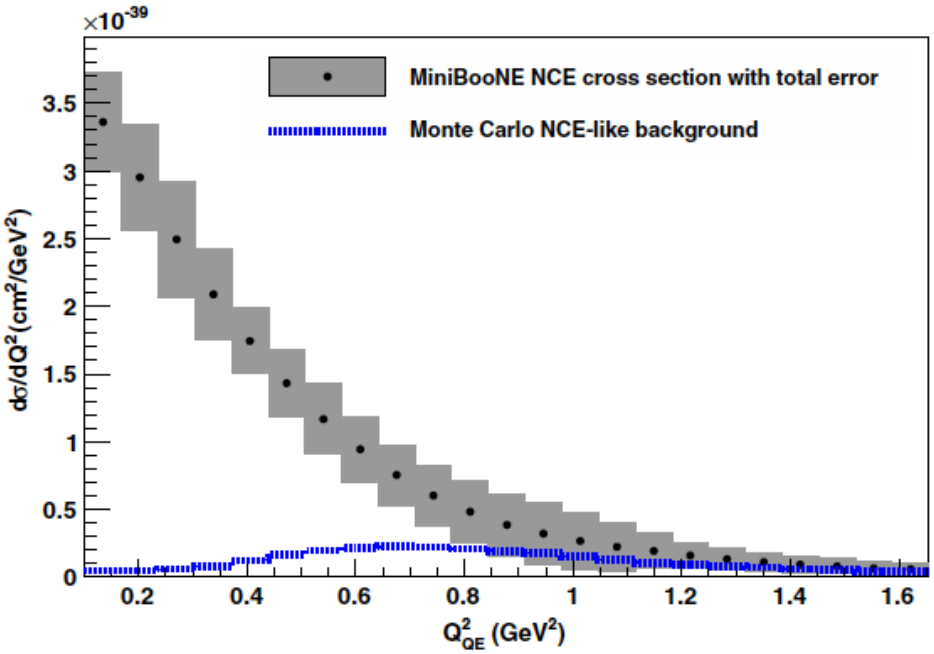
1. Neutral Current Elastic (NCE) cross section measurements

MiniBooNE flux-integrated NCE differential cross section

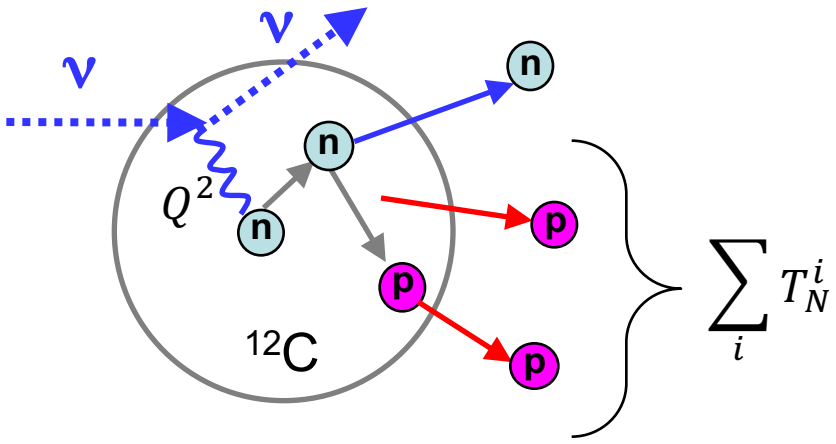
- Total scintillation light is used to estimate total nucleon kinetic energy
- Q^2_{QE} is reconstructed by assuming target nucleon at rest

Total scintillation light ~ $\sum_i T_N^i$, T_N^i=kinitic energy of ith proton final state

neutrino NCE differential cross section



$$Q^2_{QE} = 2m_N \sum_i T_N^i$$



1. MiniBooNE neutrino oscillation experiment

2. Light dark matter particle search

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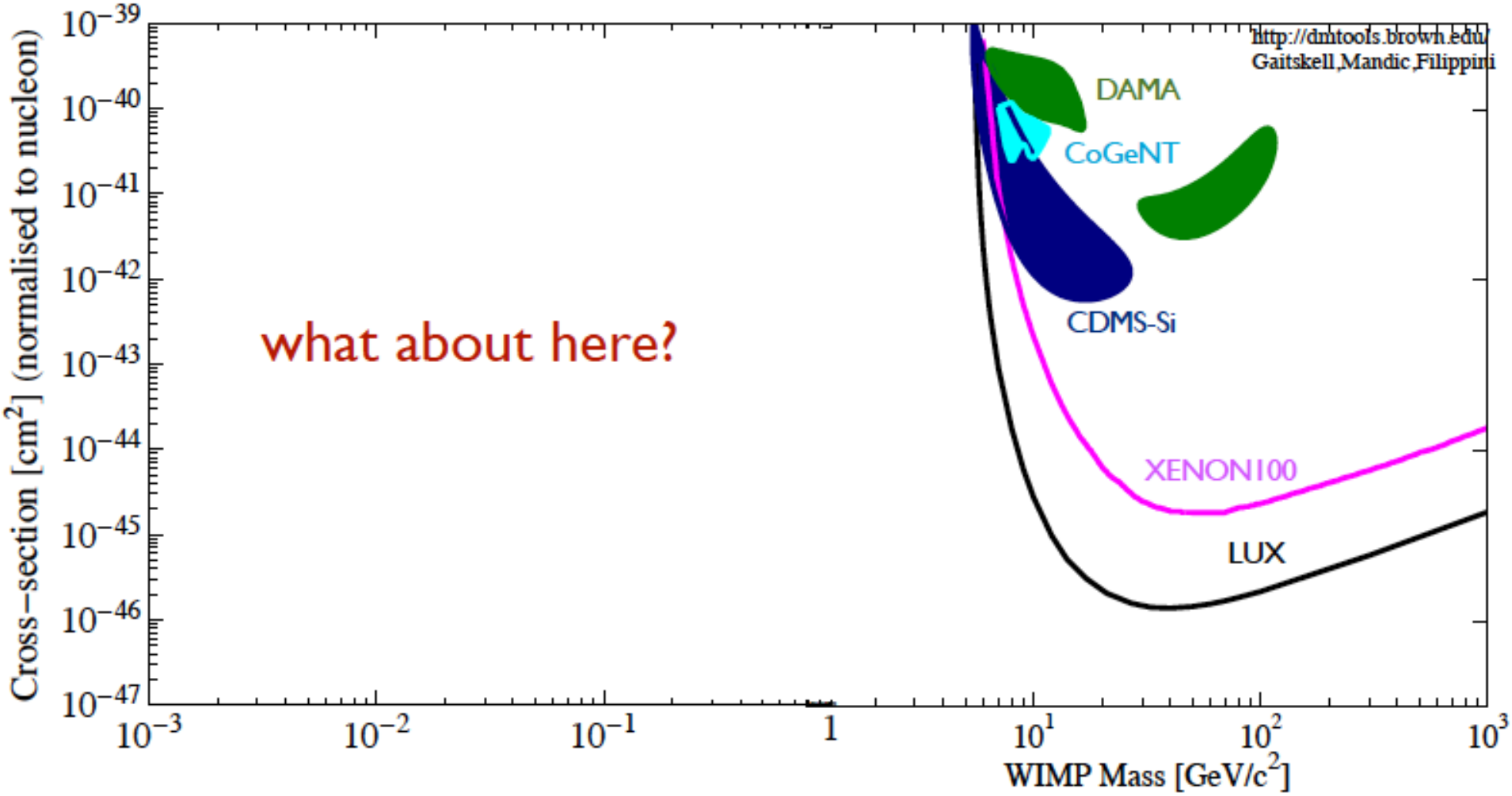
2. MiniBooNE Light dark matter particles search

Light dark matter particles
- Candidate of cold dark matter
- Not accessible with popular direct dark matter techniques

→ beam dump experiments

$$\mathcal{L}_{V,\chi} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \kappa V_\nu \partial_\mu F^{\mu\nu} + |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 + \mathcal{L}_{h'},$$



2. MiniBooNE Light dark matter particles search

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Minimal Vector Portal Model
- Light DM particles with U(1) gauge boson (dark photon)
- dark photon kinematically mixed with photon
- 4 model parameters $m_\chi,\ m_V,\ \kappa,\ g'$

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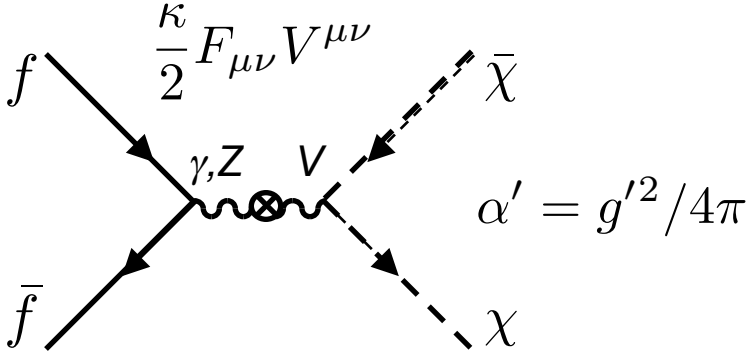

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Production
- beam dump from photon-dark photon mixing

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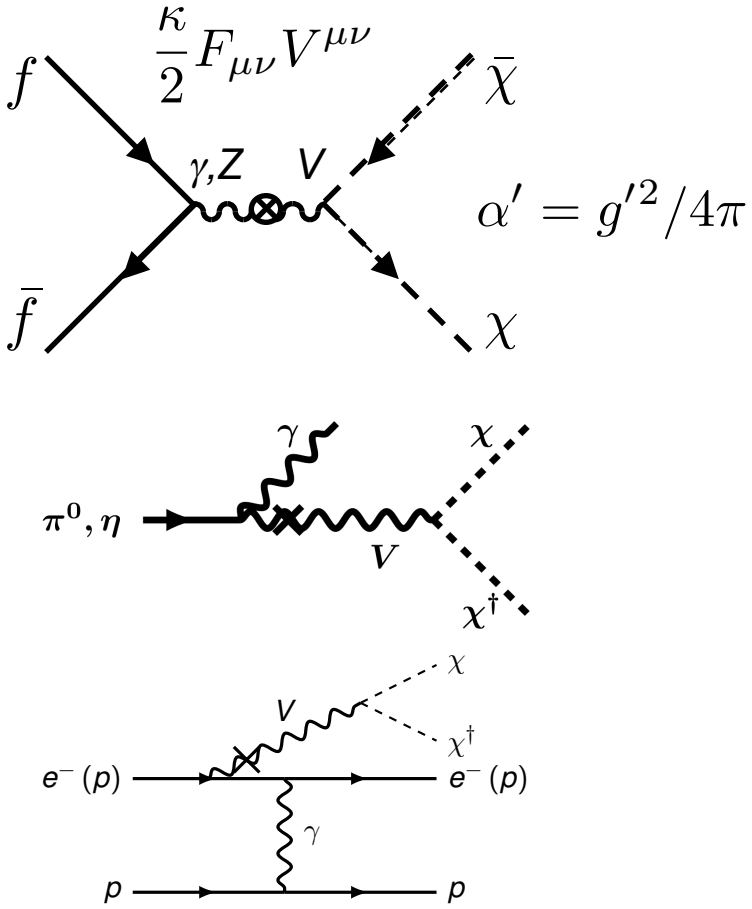

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- beam dump from photon-dark photon mixing

Detection
- dark matter - nucleon elastic scattering

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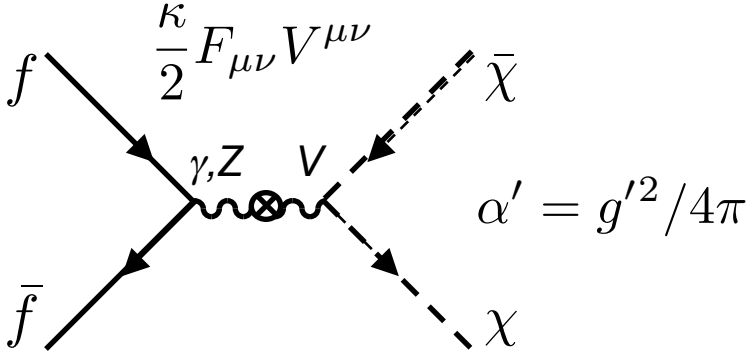

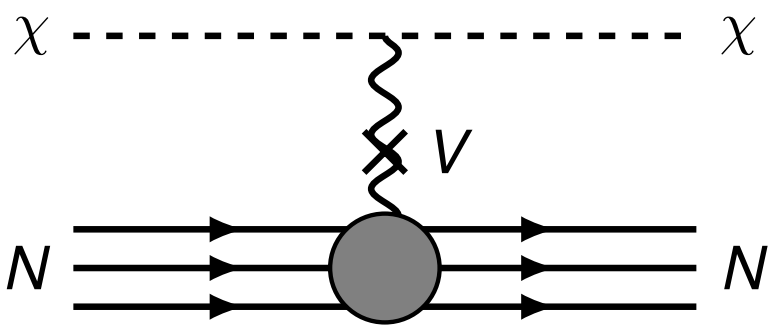

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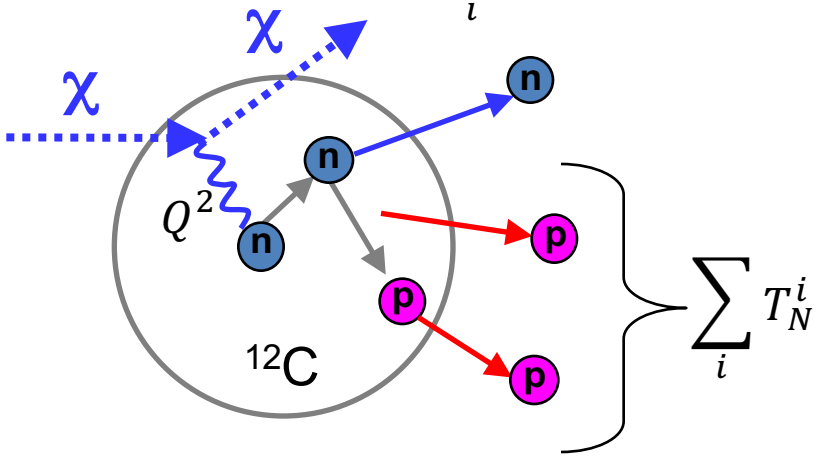
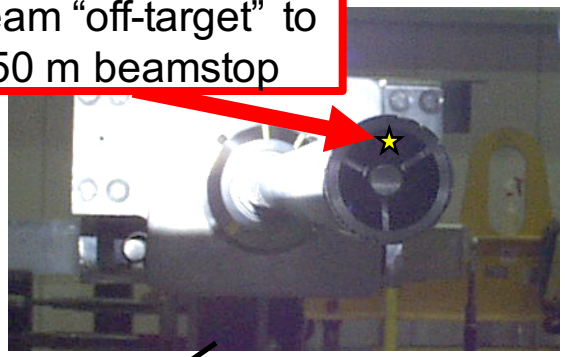


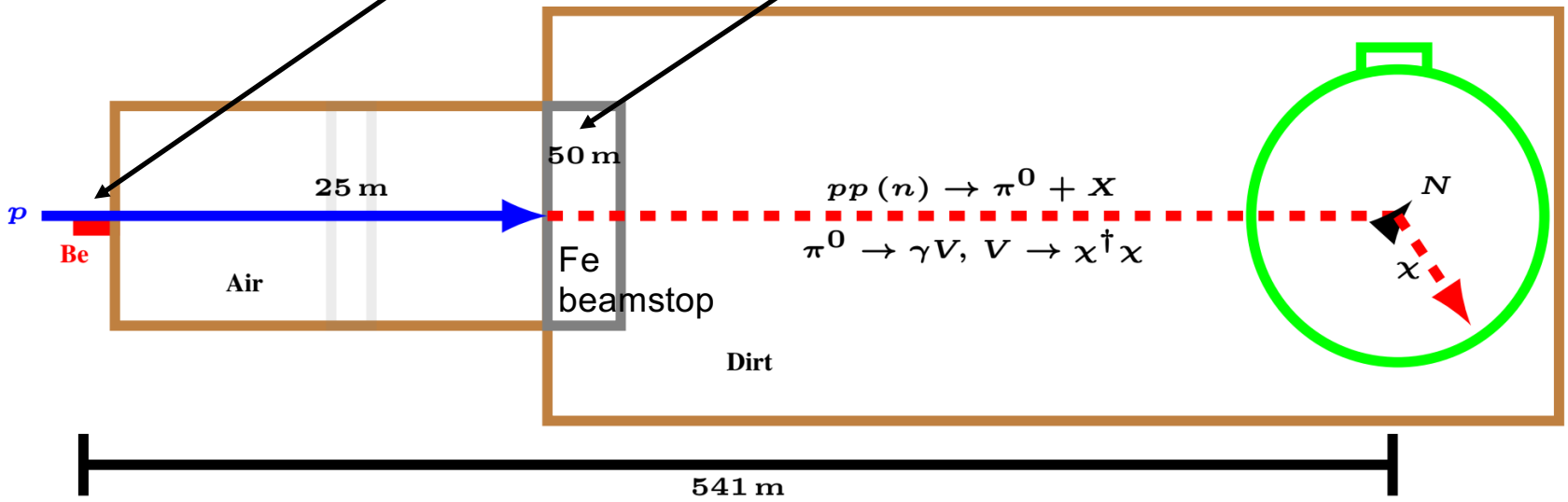
2. MiniBooNE beam dump mode

Booster Neutrino Beamline
- 8 GeV proton primary beam
- beam is steered to "miss" the beryllium target
- neutrino flux reduced ~x40
- neutrino interaction rate reduced ~x50

Beam "off-target" to 50 m beamstop



Fe beamstop



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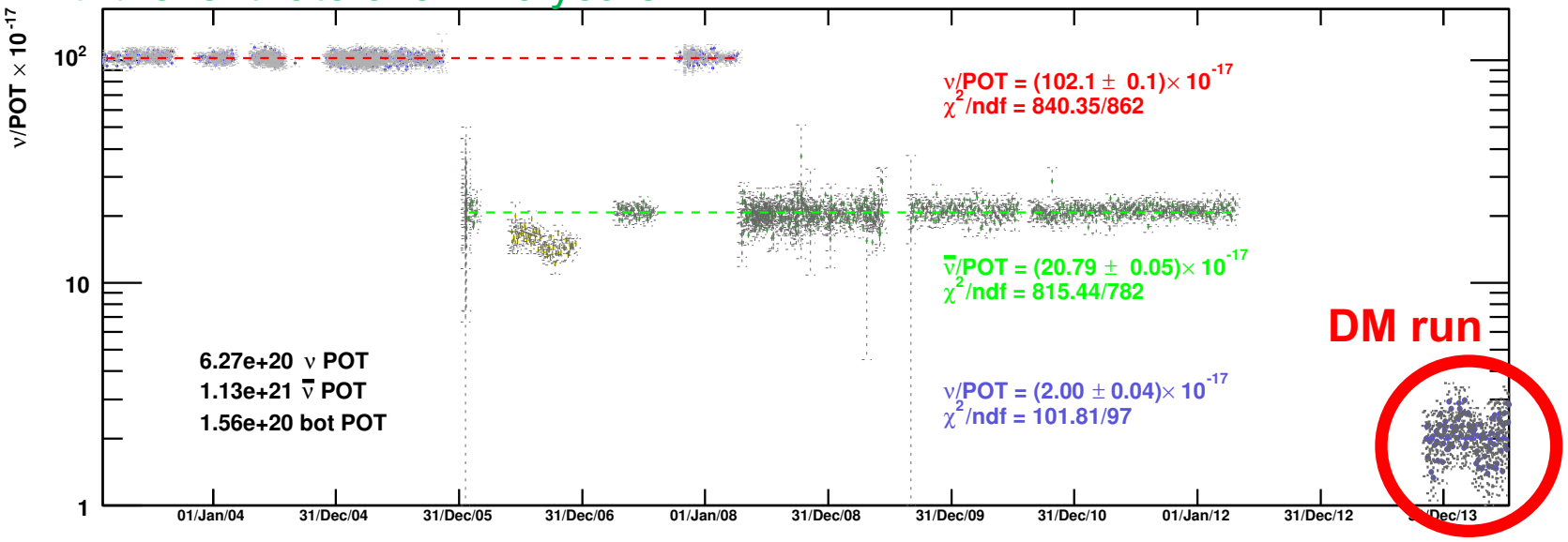
Data

- 8 month run during 2014
- 1.86E20POT collected

MB $\nu, \bar{\nu}$ event rate over ≈10 years



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3. Light DM-nucleon scattering search (preliminary)

Dark matter-nucleon elastic scattering candidates

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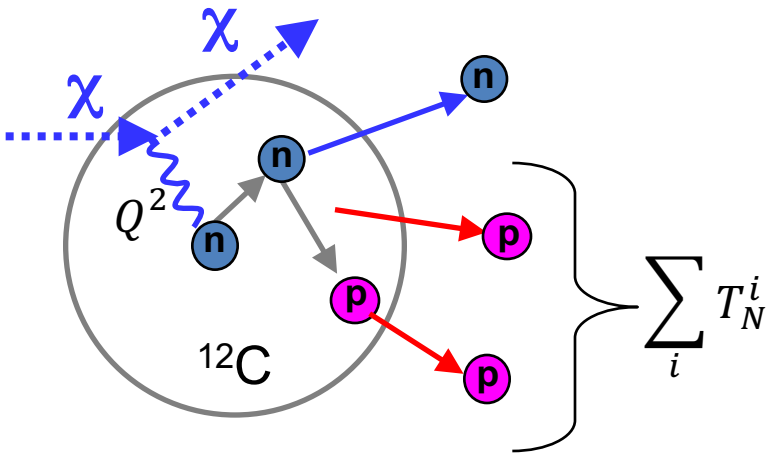
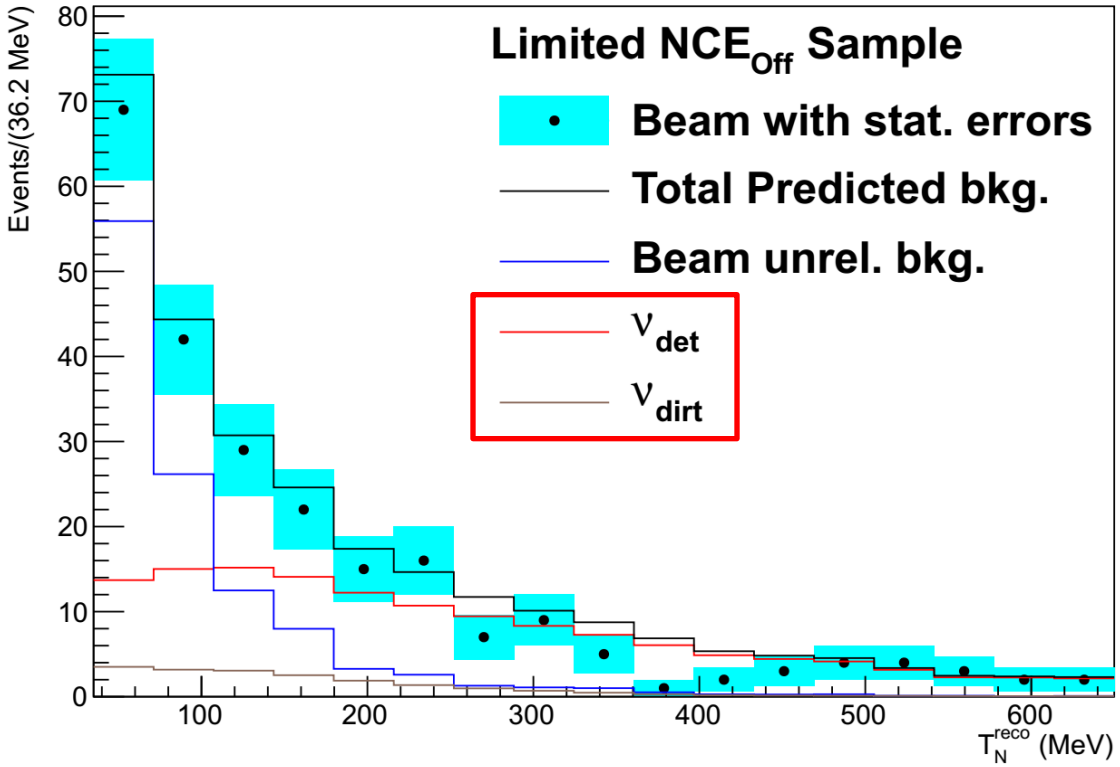


Limited statistics

- 1/6 of total data (3.2E19POT)
- semi-blind analysis
- full sample errors
  - ~ 3% statistical error
  - ~ 10% systematic error



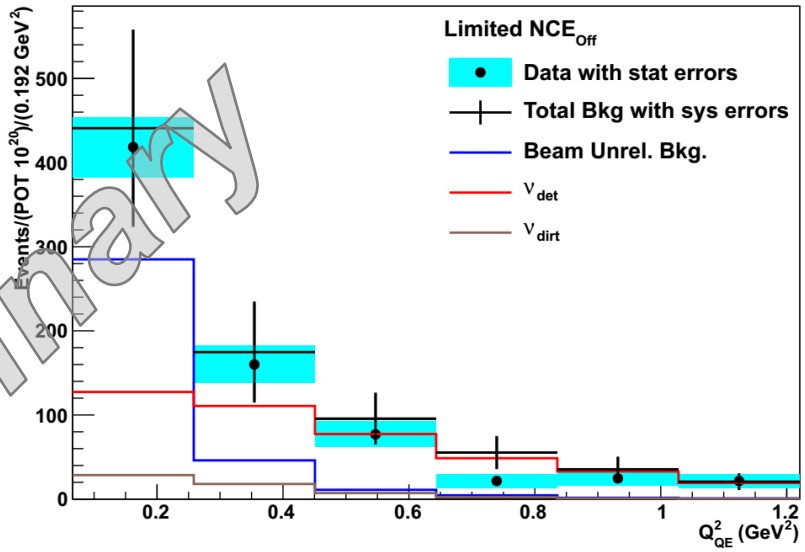
Queen Mary University of London

3. Light DM-nucleon scattering search (preliminary)

Combined fit, simultaneous fit of 4 samples

1. beam dump mode NCE (signal)
2. Neutrino mode NCE
3. beam dump mode CCQE
4. Neutrino mode CCQE

beam dump mode NCE (signal)



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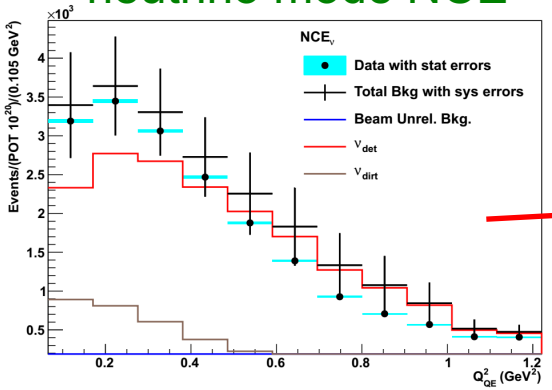
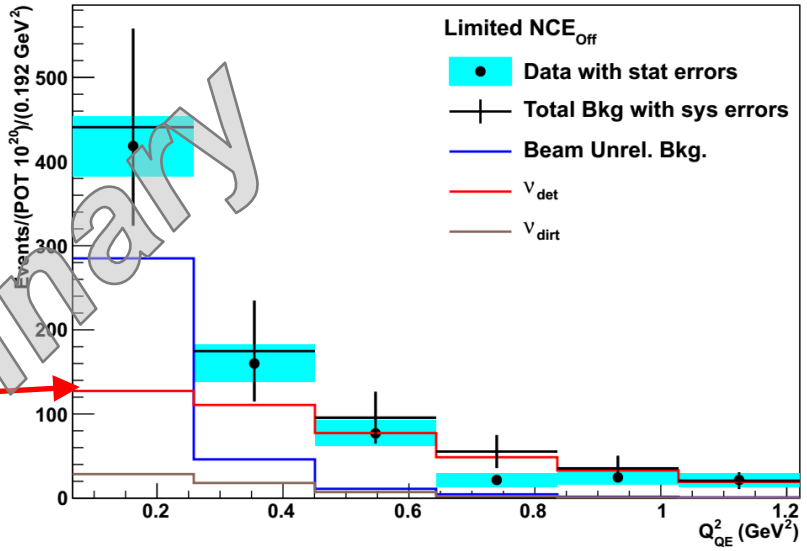
beam related background control

neutrino mode NCE



NCE cross section

beam dump mode NCE (signal)



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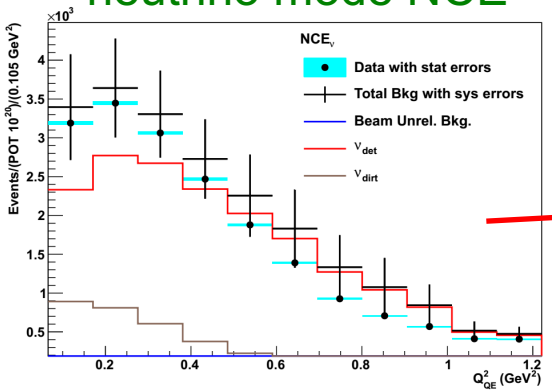

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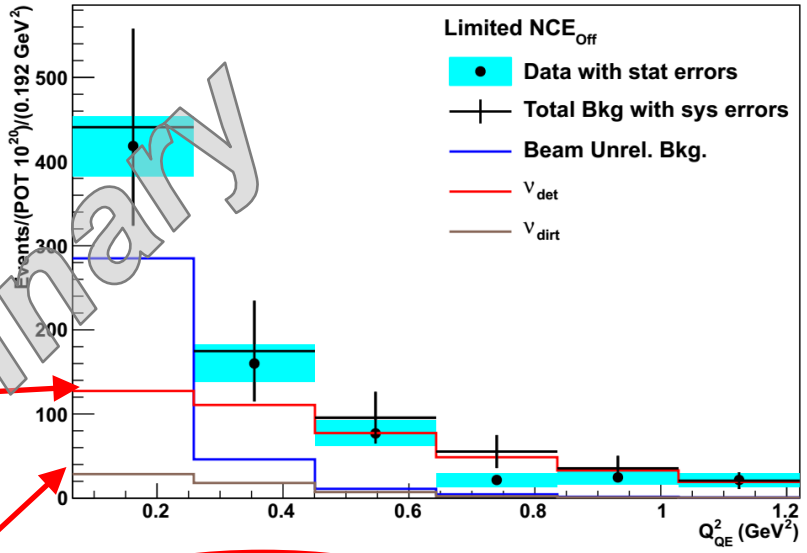
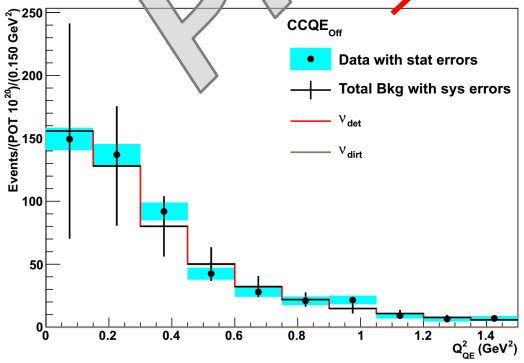


beam dump mode neutrino flux

beam dump mode CCQE



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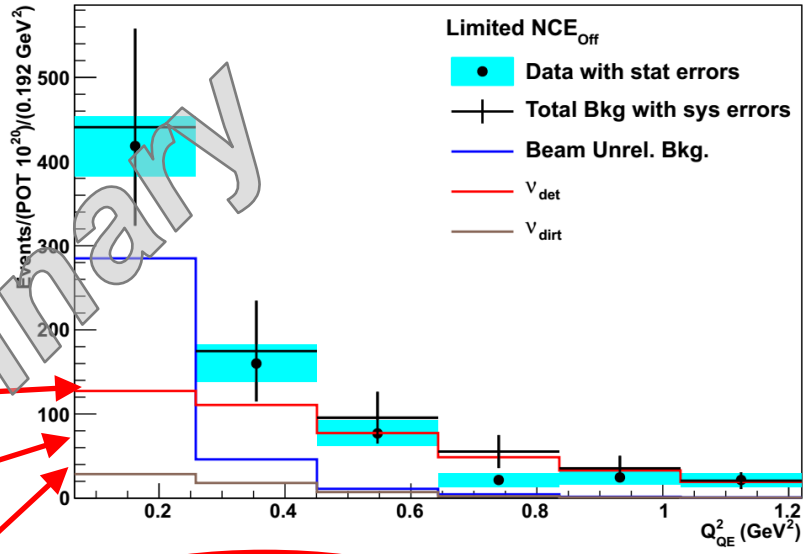
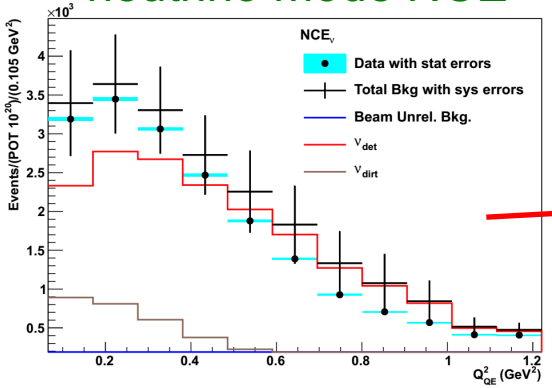


neutrino mode NCE



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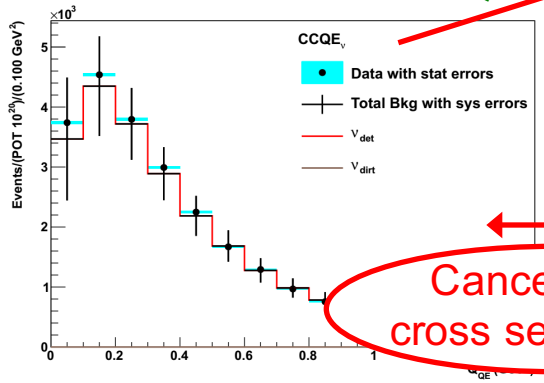
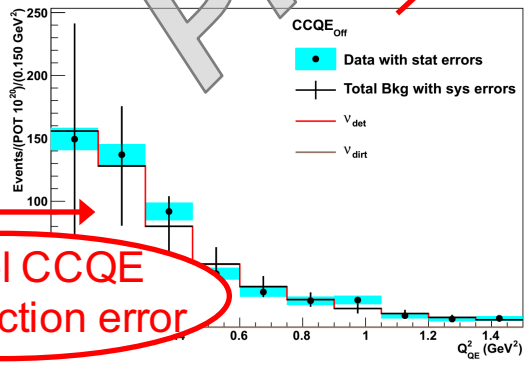


beam dump mode CCQE



Cancel CCQE cross section error

Preliminary

3. Light DM-nucleon scattering search (preliminary)

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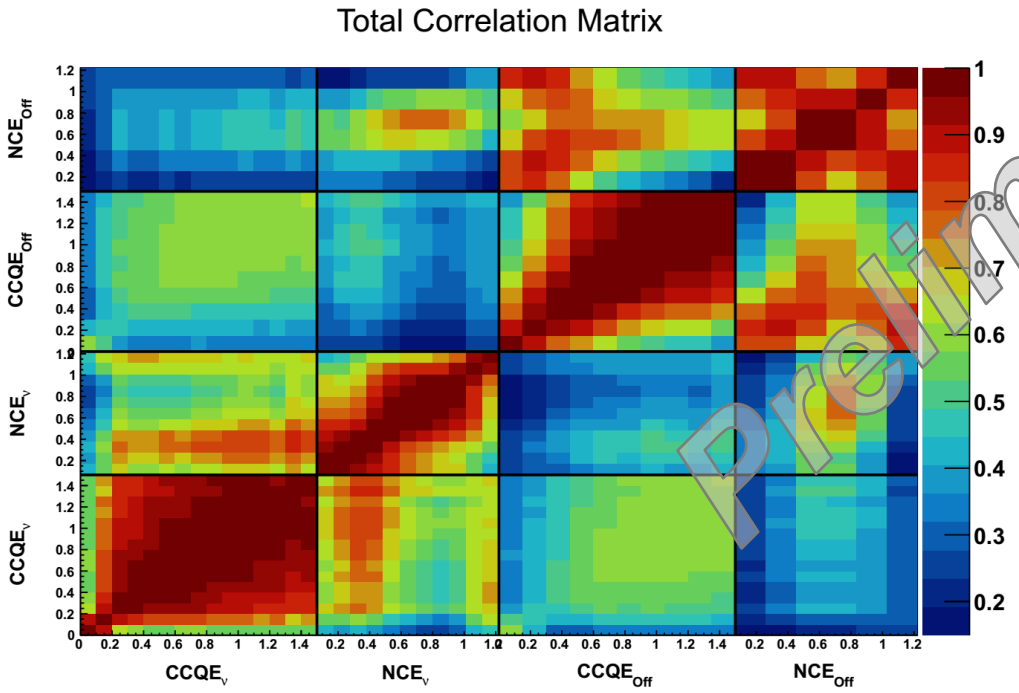

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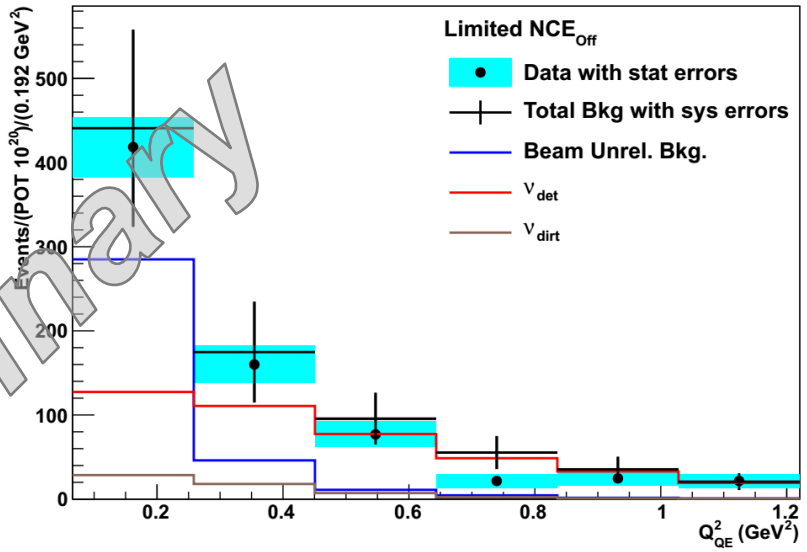


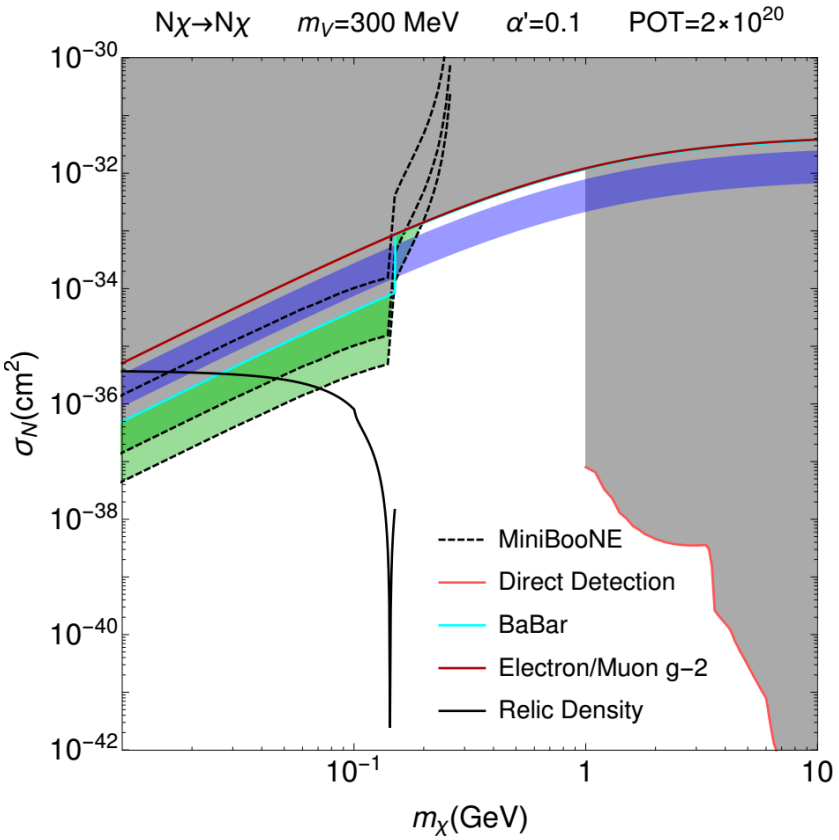
Full covariance matrix is developed for the simultaneous fit to extract 4 parameters

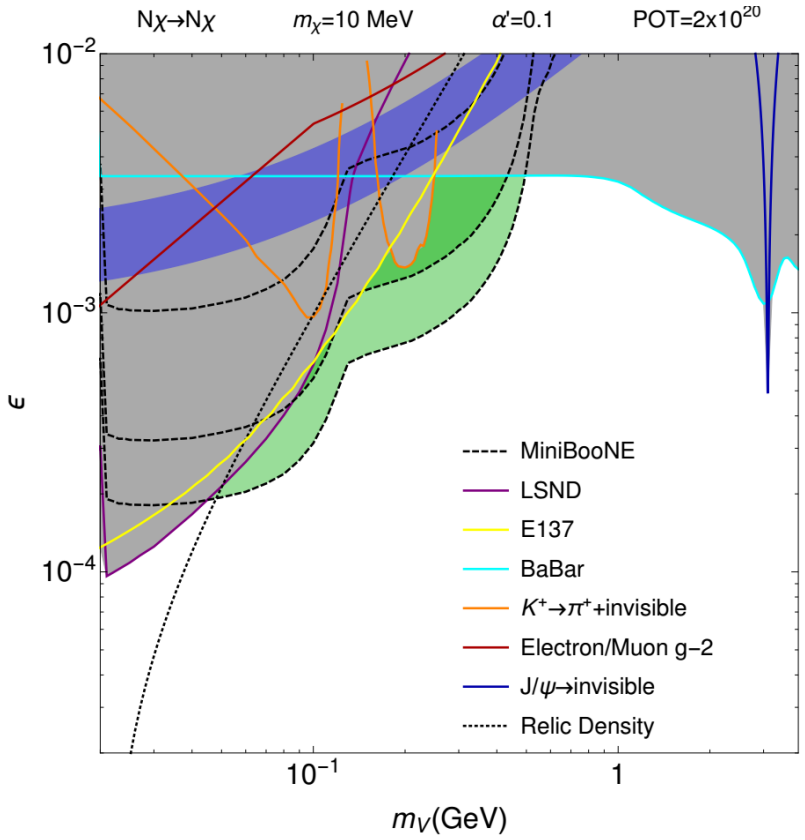
$$m_\chi\ ,m_V\ ,\kappa\ ,g'$$

MiniBooNE,arXiv:1211.2258,
Batell et al.,PRD90(2014)115014

3. MiniBooNE Nχ→Nχ sensitivity

green shaded regions: 1-10, 10-1000 observed events in MiniBooNE





4. Conclusion

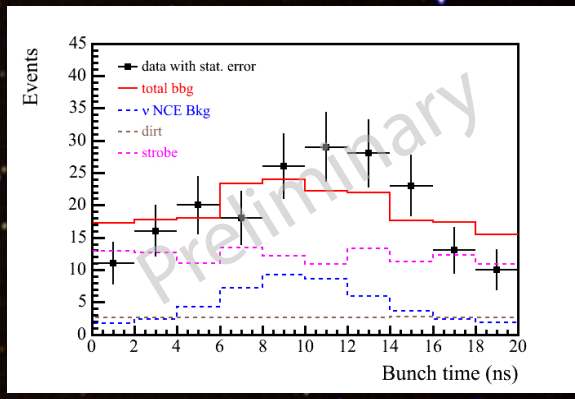
Tyler Thornton (main analyzer)
Indiana university PhD student

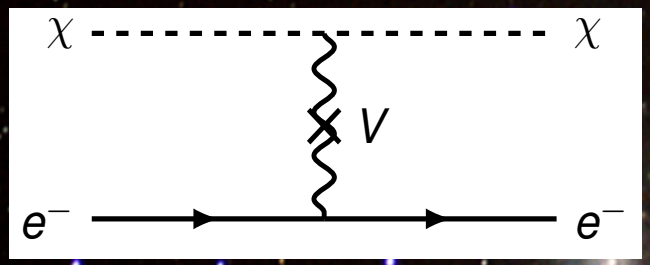
MiniBooNE neutrino beam line enhances production of Light DM with $M\chi<O(1)GeV$ by the beam dump mode

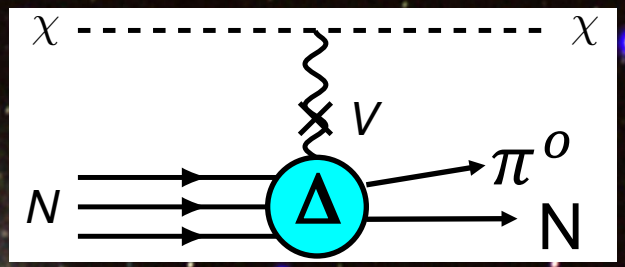
Scintillation light is used to reconstruct the total nucleon energy

More results with full data set are coming soon!

Future
- Event timing with RF bunch should allow dark matter TOF
- electron and π^o channels will be used for light DM searches
- model-independent excess search







Thank you for your attention!

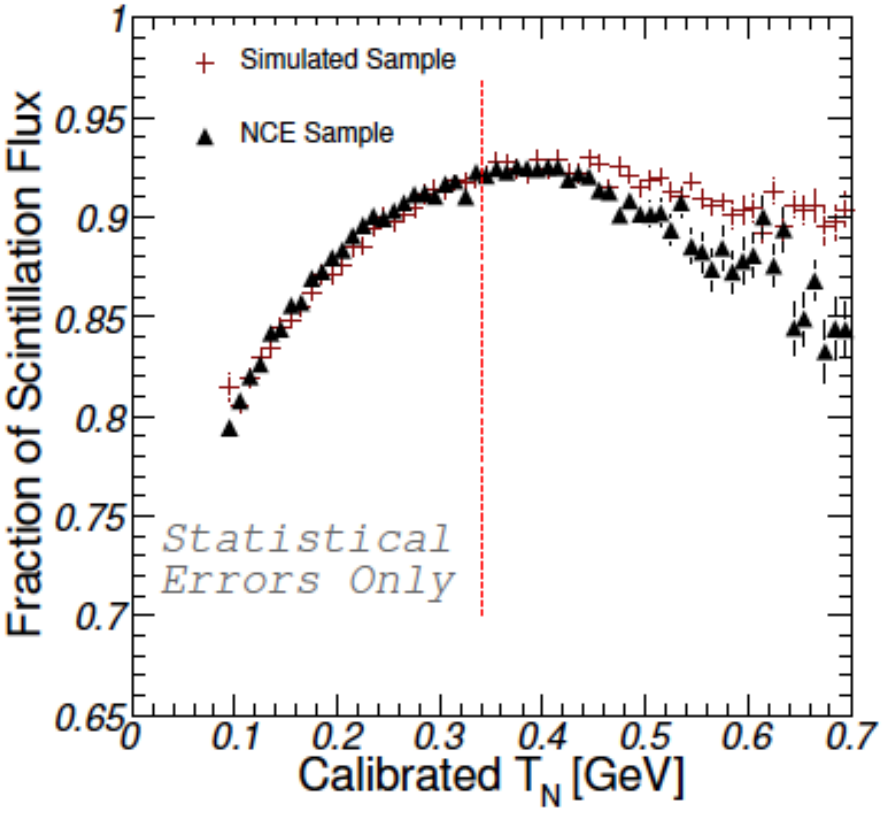
backup

2. Neutral Current Elastic (NCE) event reconstruction

Scintillation vs. Cherenkov

- In general, total scintillation light is used to estimate total nucleon kinetic energy
- Simple model works below Cherenkov threshold

neutrino NCE Cherenkov threshold



2. Neutral Current Elastic (NCE) event reconstruction

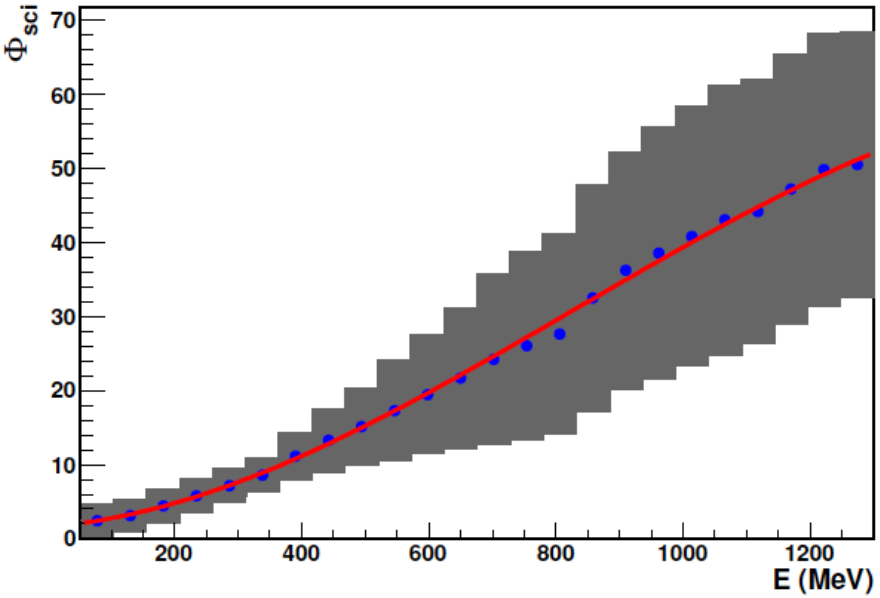
NCE charge prediction

QE of PMT | flux | attenuation | PMT angular response | light angular emission profile | outgoing event correction

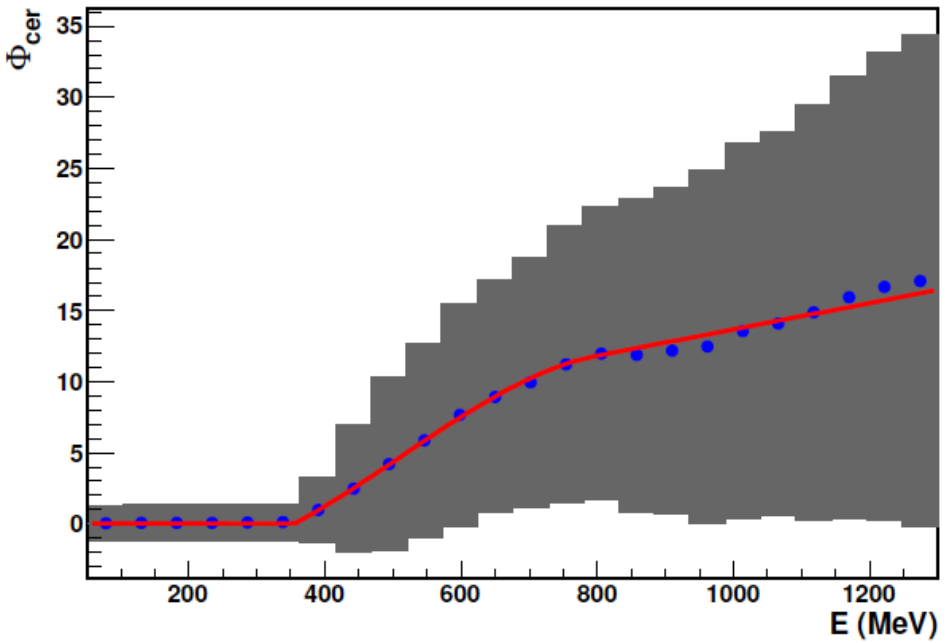
$$\mu_{sci}(\vec{\mathbf{X}}) = \epsilon\Phi_{sci}(E)\frac{\exp(-r/\lambda_{sci}(R))}{r^2}f(\cos\eta)F_{sci}(E,\cos\theta,R)Corr(E,\cos\alpha),$$

$$\mu_{cer}(\vec{\mathbf{X}}) = \epsilon\Phi_{cer}(E)\frac{\exp(-r/\lambda_{cer})}{r^2}f(\cos\eta)F_{cer}(E,\cos\theta,R)Corr(E,\cos\alpha),$$

Scintillation flux



Cherenkov flux



2. Neutral Current Elastic (NCE) event reconstruction

NCE charge prediction

QE of PMT, flux, attenuation, PMT angular response, light angular emission profile, outgoing event correction

$$\mu_{sci}(\vec{\mathbf{X}}) = \epsilon\Phi_{sci}(E)\frac{\exp(-r/\lambda_{sci}(R))}{r^2}f(\cos\eta)F_{sci}(E,\cos\theta,R)Corr(E,\cos\alpha),$$

$$\mu_{cer}(\vec{\mathbf{X}}) = \epsilon\Phi_{cer}(E)\frac{\exp(-r/\lambda_{cer})}{r^2}f(\cos\eta)F_{cer}(E,\cos\theta,R)Corr(E,\cos\alpha),$$

Likelihood fit

$$F(\vec{\mathbf{X}}) = -\ln\mathcal{L}(\vec{\mathbf{X}}) = F_q(\vec{\mathbf{X}}) + F_t(\vec{\mathbf{X}}),$$

Charge likelihood

$$F_q(\vec{\mathbf{X}}) = -\sum_i \ln f_q(q_i,\vec{\mathbf{X}}) \qquad f_q(q_i,\vec{\mathbf{X}}) = f_q(q_i,\mu_i(\vec{\mathbf{X}}))$$

Time likelihood

$$F_t(\vec{\mathbf{X}}) = -\sum_{i,\ q_i>0} \ln f_t(t_i,\vec{\mathbf{X}}) \qquad f_t(t_i,\vec{\mathbf{X}}) = f_t(t_i,\mu_i(\vec{\mathbf{X}}),E)$$

$$f_t(t_{corr},\vec{\mathbf{X}}) = \frac{\mu_{sci}}{\mu_{sci}+\mu_{cer}}f_t^{sci}(t_{corr},\mu_{sci},E) + \frac{\mu_{cer}}{\mu_{sci}+\mu_{cer}}f_t^{cer}(t_{corr},\mu_{cer},E)$$

$$f_t^{cer}(t_{corr},\mu_{cer},E) = \frac{1}{\sqrt{2\pi}\sigma(E,\mu_{cer})}\exp\left[-\frac{(t_{corr}-t_0(E,\mu_{cer}))^2}{2\sigma(E,\mu_{cer})^2}\right]$$

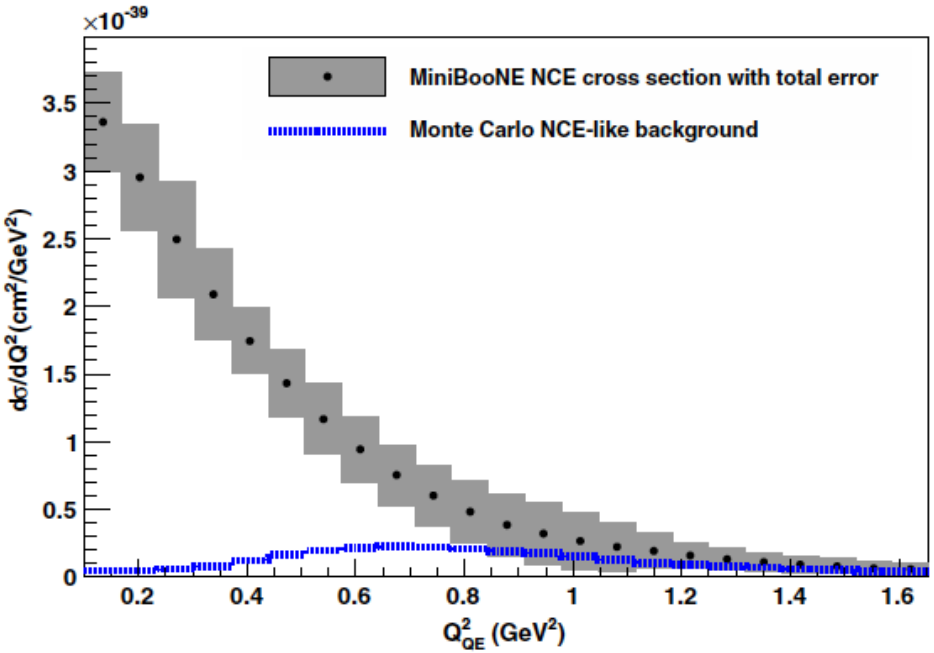
$$f_t^{sci}(t_{corr}) = \frac{1}{2\tau}\exp\left(\frac{\sigma^2}{2\tau^2}-\frac{t_{corr}-t_0}{\tau}\right)\mathrm{Erfc}\left[\frac{\sigma}{\sqrt{2}\tau}-\frac{t_{corr}-t_0}{\sigma}\right]$$

2. Neutral Current Elastic (NCE) cross section measurements

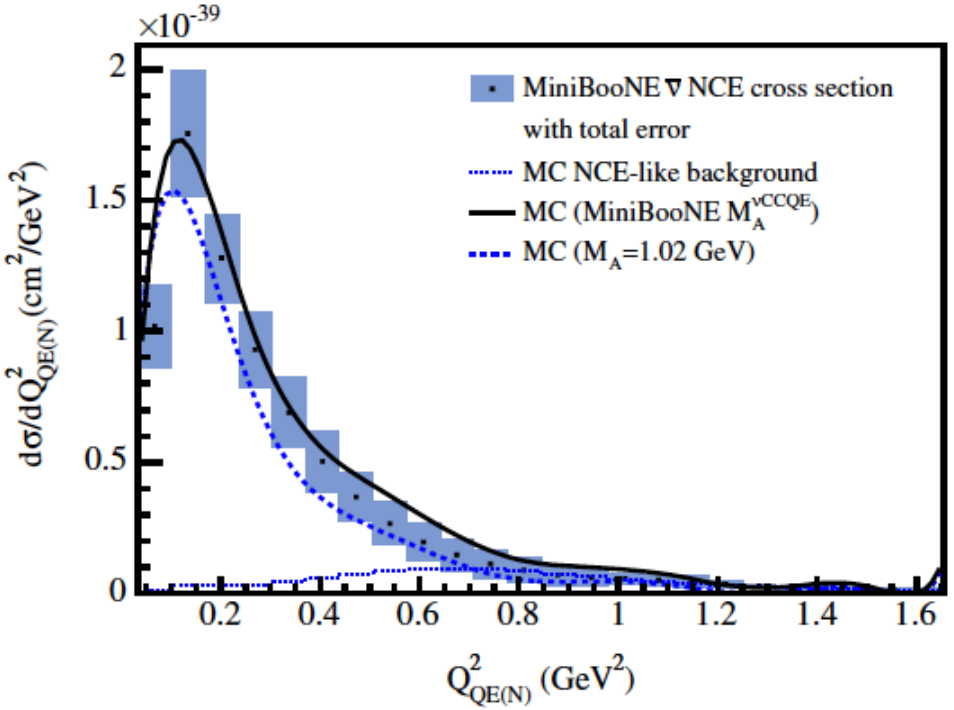
MiniBooNE flux-integrated NCE differential cross section

- In general, total scintillation light is used to estimate total nucleon kinetic energy

neutrino NCE differential cross section



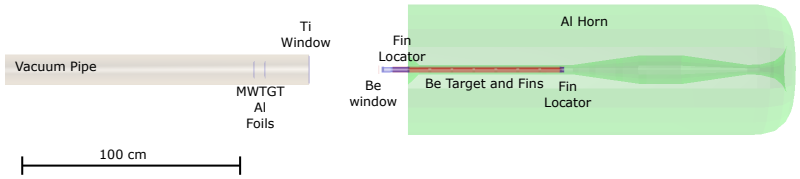
anti-neutrino NCE differential cross section



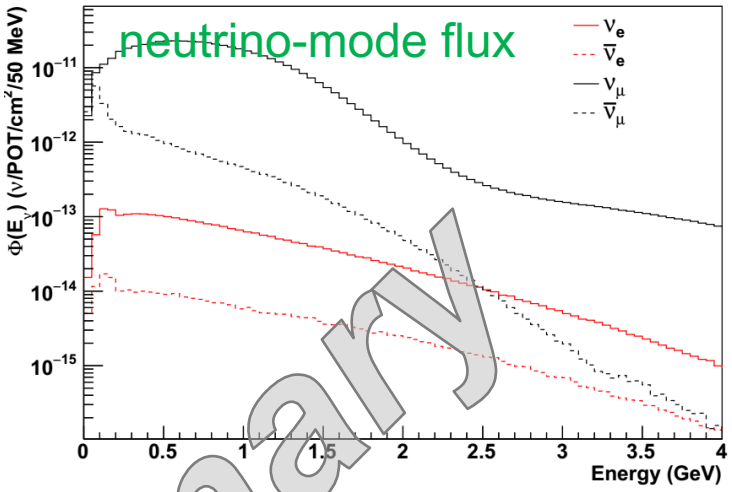
MiniBooNE: DM source

- studied with event rates (off/on) and simulated with GEANT4
- with beam in "off-target", DM mode:
  - ν, $\bar{\nu}$ fluxes reduced by ≈ x40
  - ν, $\bar{\nu}$ rates " " ≈ x50

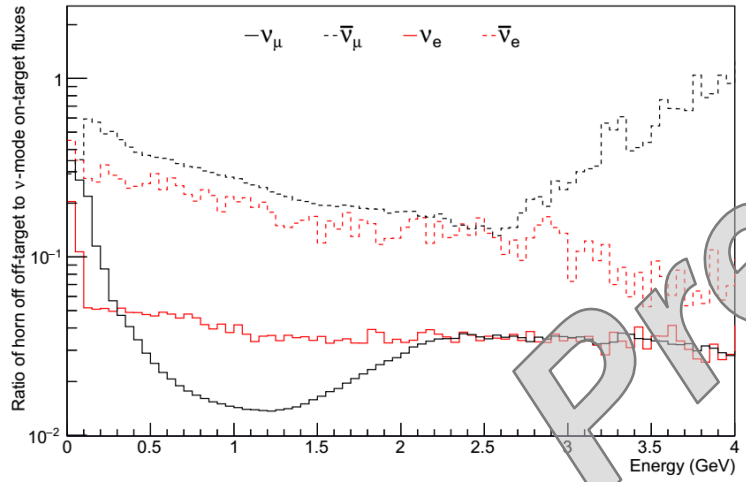
GEANT4 simulation geometry



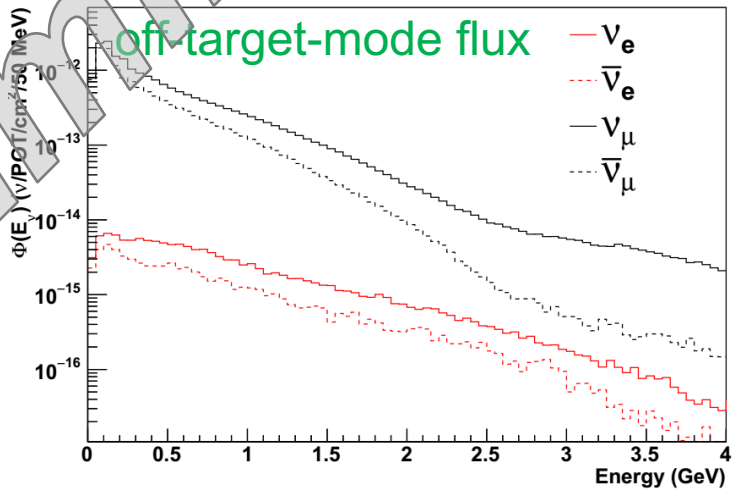
neutrino-mode flux



on/ off flux ratio

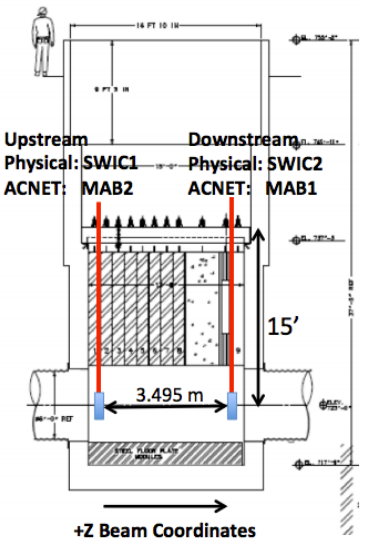


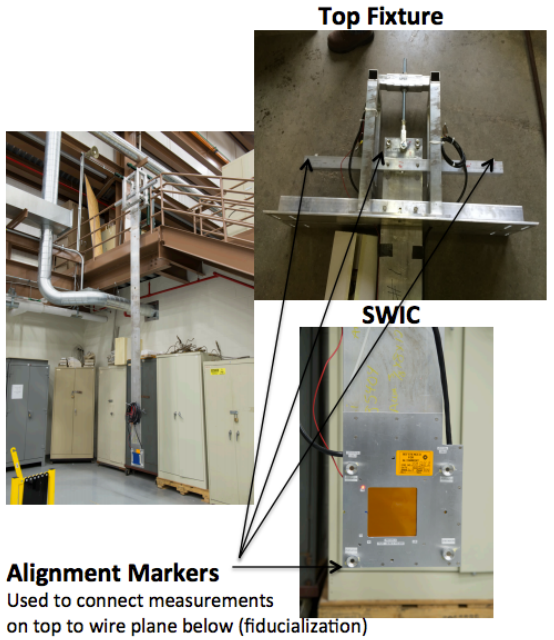
off-target-mode flux

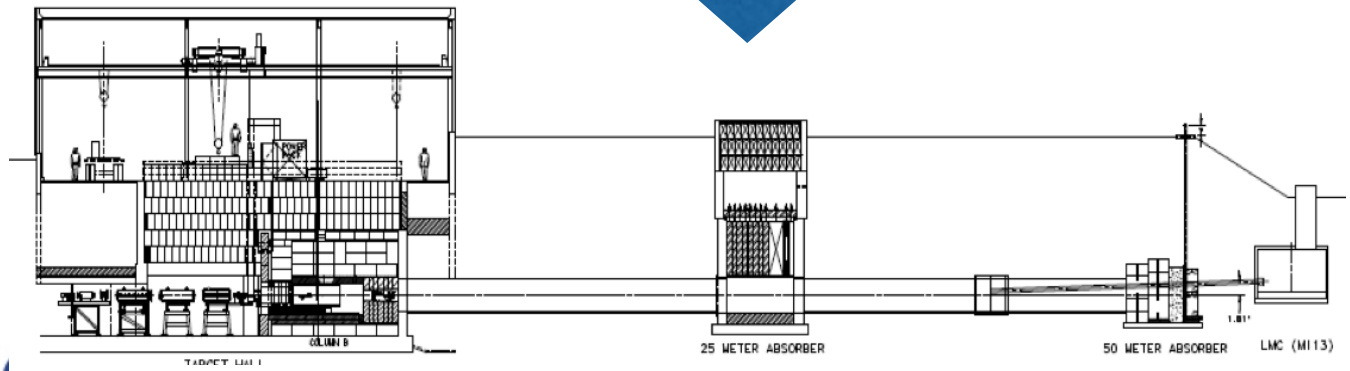


Understanding the beam-off-target configuration

- Beam position/alignment: Low intensity test beam to SWICs at 25 m
- B field measurements and decay pipe inspection: Robot FRED
- Copper cables upgraded optic fibers to relay beam timing information





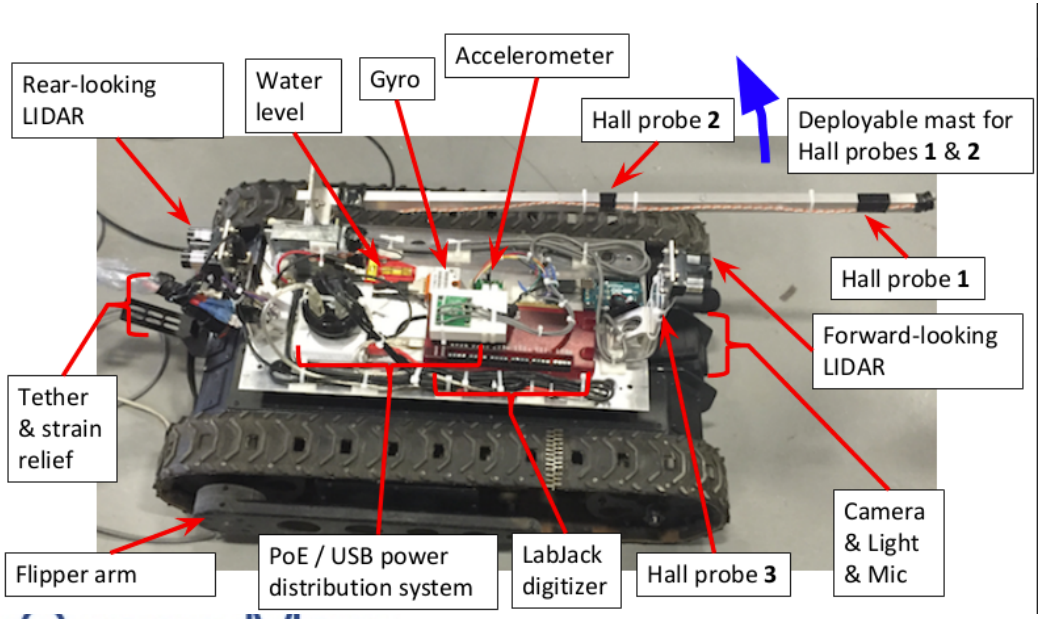


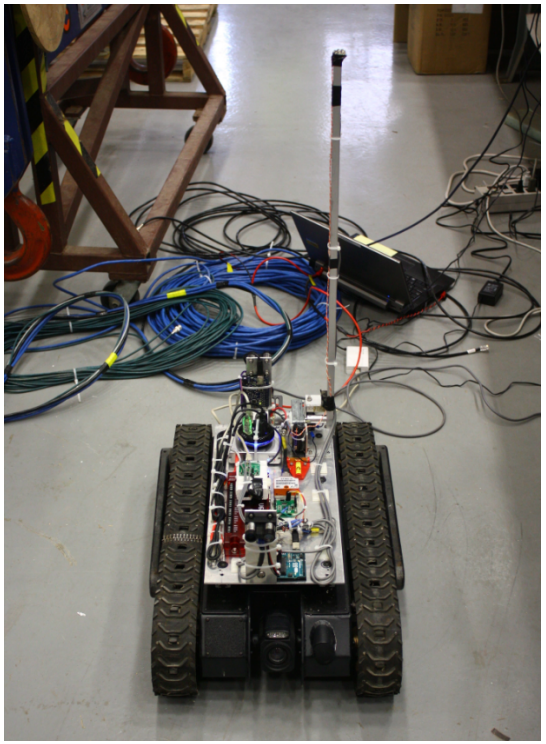
Target hall in MI 12 25m deployable absorber 50m Fe dump

University of London

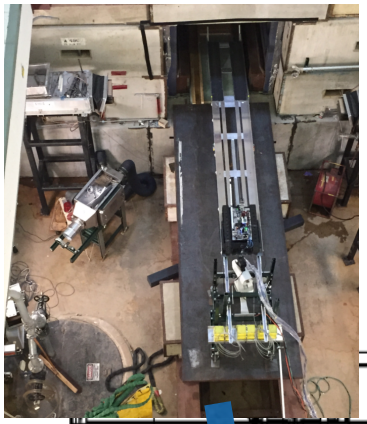
MiniBooNE: DM source

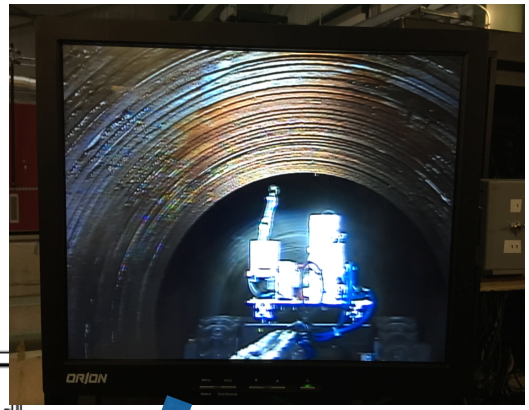
- Understanding the beam-off-target configuration
  - Beam position/alignment: Low intensity test beam to SWICs at 25 m
  - B field measurements and decay pipe inspection: Robot FRED
  - Copper cables upgraded optic fibers to relay beam timing information

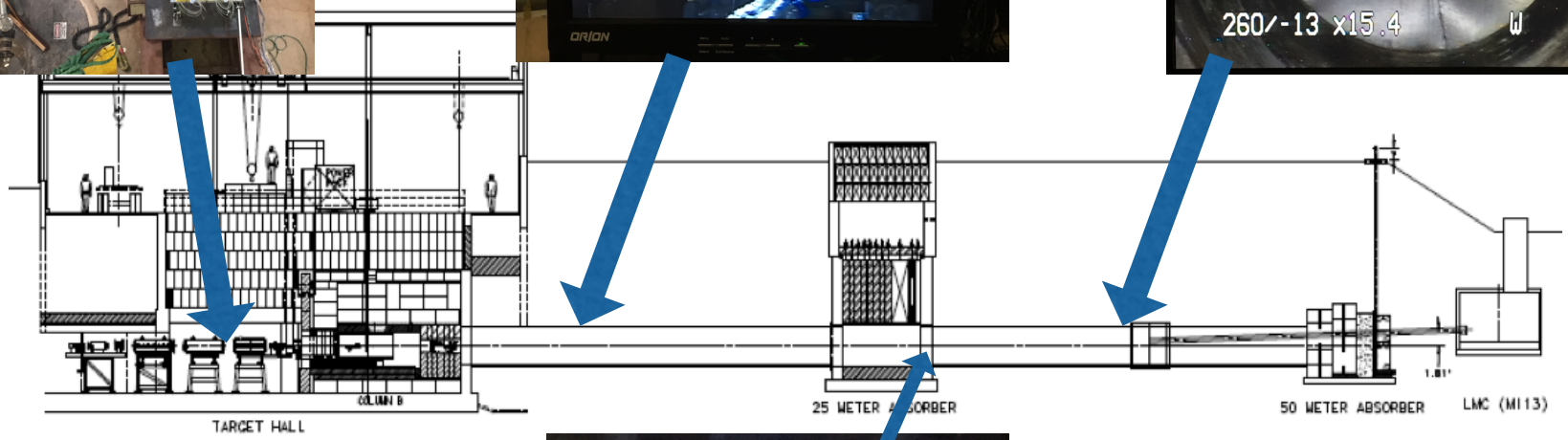


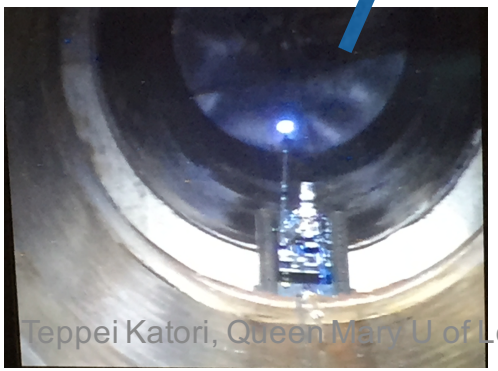


FRED: "Fermilab Robot for Exploration of Decay pipes"



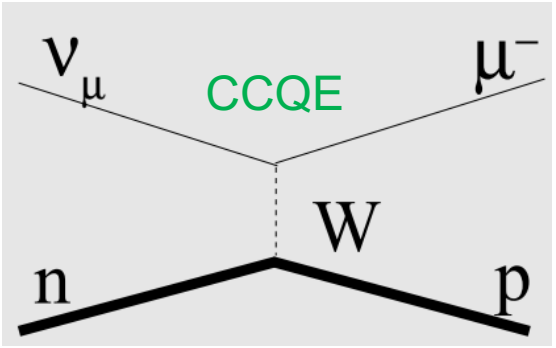


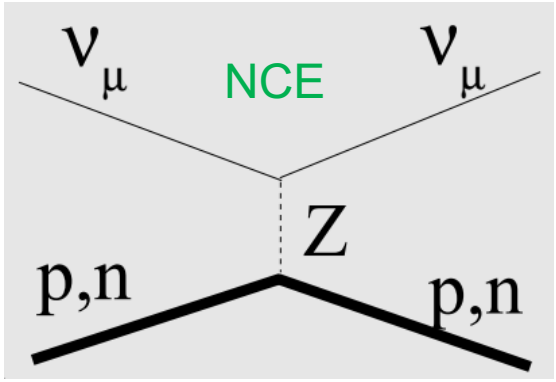




3. Light DM-nucleon scattering search (preliminary)

- Reduce systematics on neutrino-related backgrounds
- via "double-ratio" method: $\frac{\mathrm{N}(NC\chi)}{\mathrm{N}(NC\nu)} / \frac{\mathrm{N}(CC\chi)}{\mathrm{N}(CC\nu)}$
- $\frac{\mathrm{N}(CC\chi)}{\mathrm{N}(CC\nu)}$ (charged-current ratio) reduces flux systematic
- $\frac{\mathrm{N}(NC\chi)}{\mathrm{N}(NC\nu)}$ (neutral-current ratio) reduces NCE background (cross section) systematic
- as function of 4-momentum transfer, Q^2 , calc'd with quasielastic kinematics assumptions (Q^2_{QE}).
  $Q^2_{QE} = 2m_pT$ for NCE nucleon recoil





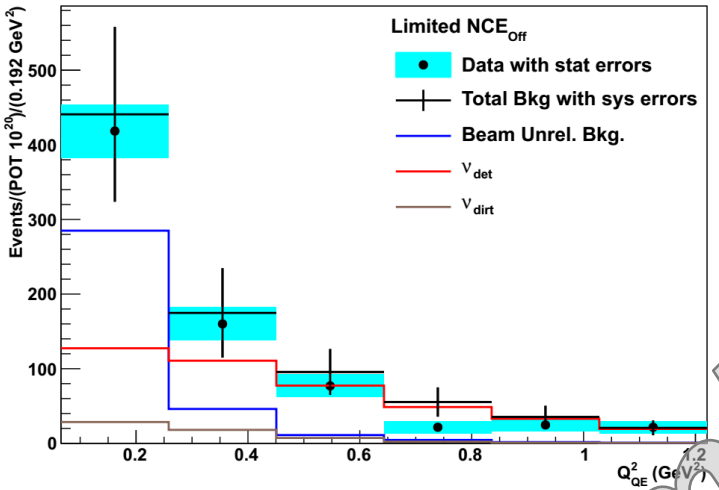
3. Light DM-nucleon scattering search (preliminary)

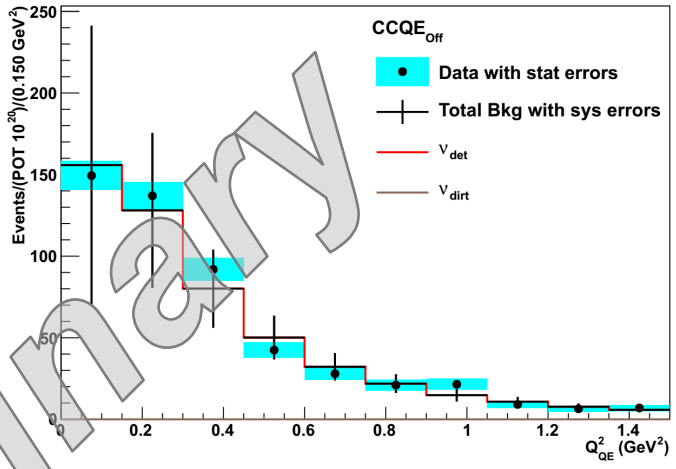
NCE

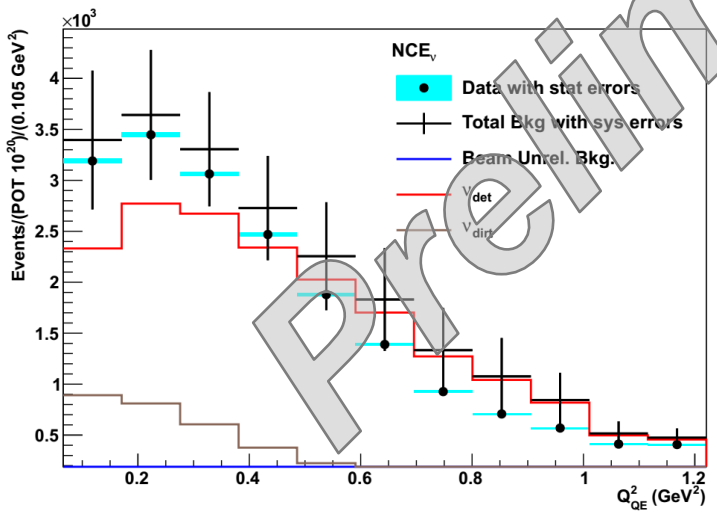
CCQE

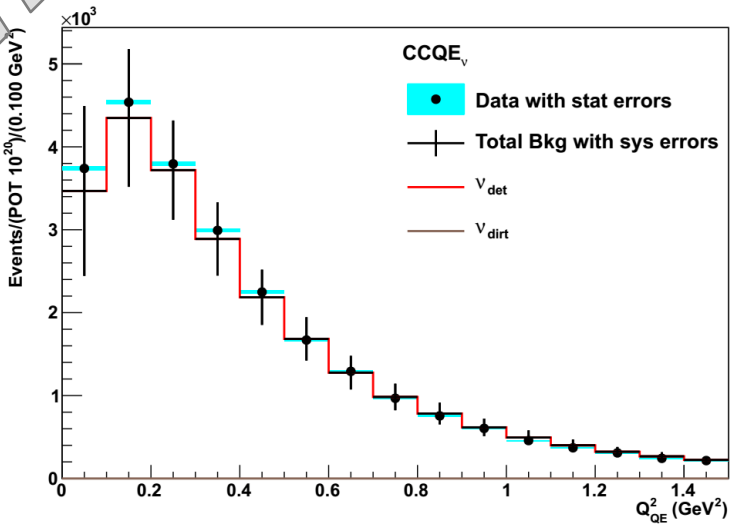
beam dump mode

neutrino mode









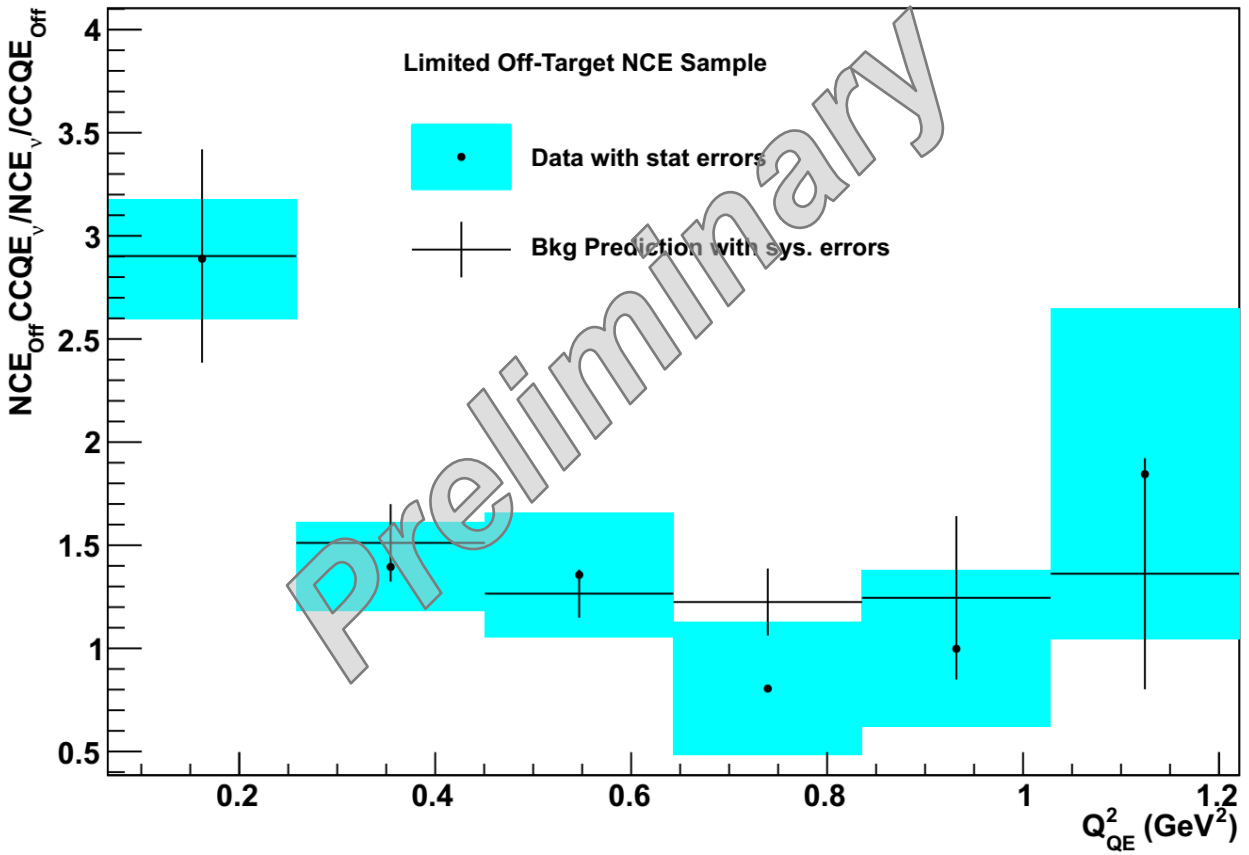
3. Light DM-nucleon scattering search (preliminary)

- "double-ratio" method: $\frac{\mathrm{N}(NC\chi)}{\mathrm{N}(NC\nu)} / \frac{\mathrm{N}(CC\chi)}{\mathrm{N}(CC\nu)}$

- Full covariance matrix is developed with flux and cross section systematics
- χ^2 fit to extract 4 parameters.

$$m_\chi,\ m_V,\ \kappa,\ g'$$

limited sample double-ratio

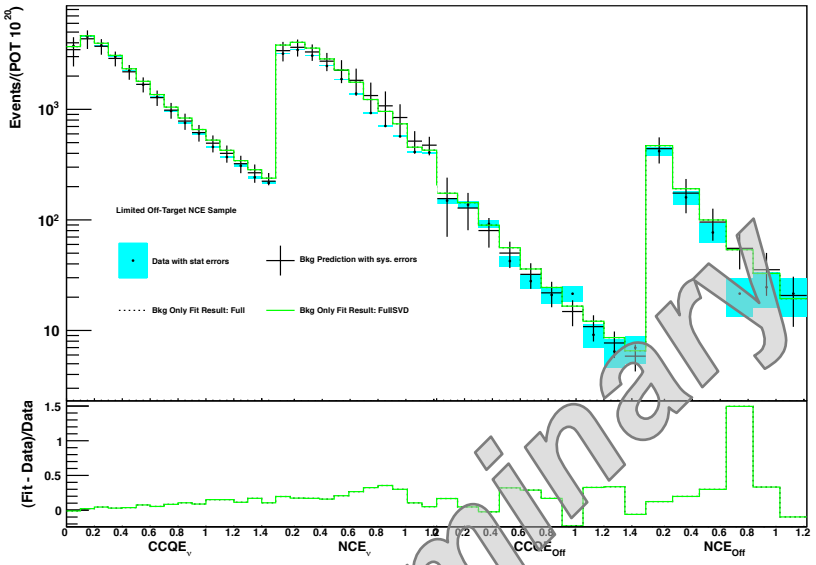


3. Light DM-nucleon scattering search (preliminary)

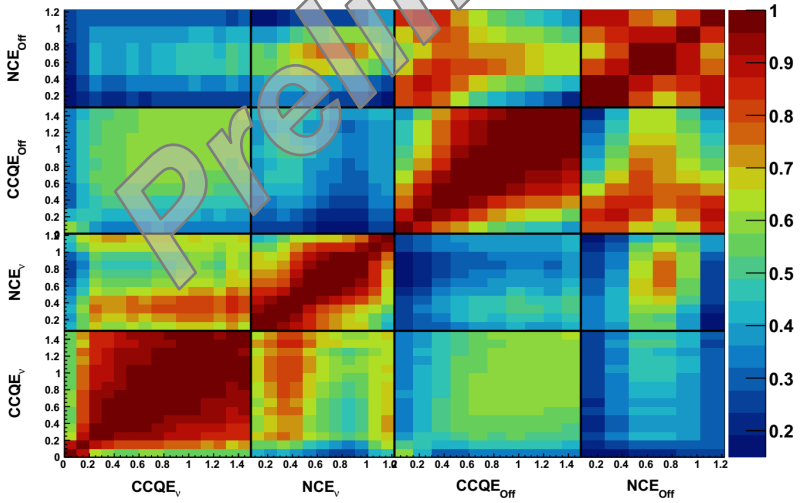
- "double-ratio" method: $\frac{\mathrm{N}(NC\chi)}{\mathrm{N}(NC\nu)}/\frac{\mathrm{N}(CC\chi)}{\mathrm{N}(CC\nu)}$
- in practice use a combined fit to (neutrino/off-target) X (CCQE, NCE) sample
- correlated errors considered
- Fit with:
  - nuisance parameters: flux scale factor, CCQE/NCE cross section corrections
  - Physics parameters:

$$m_\chi,\ m_V,\ \kappa,\ g'$$

double-ratio combined fit



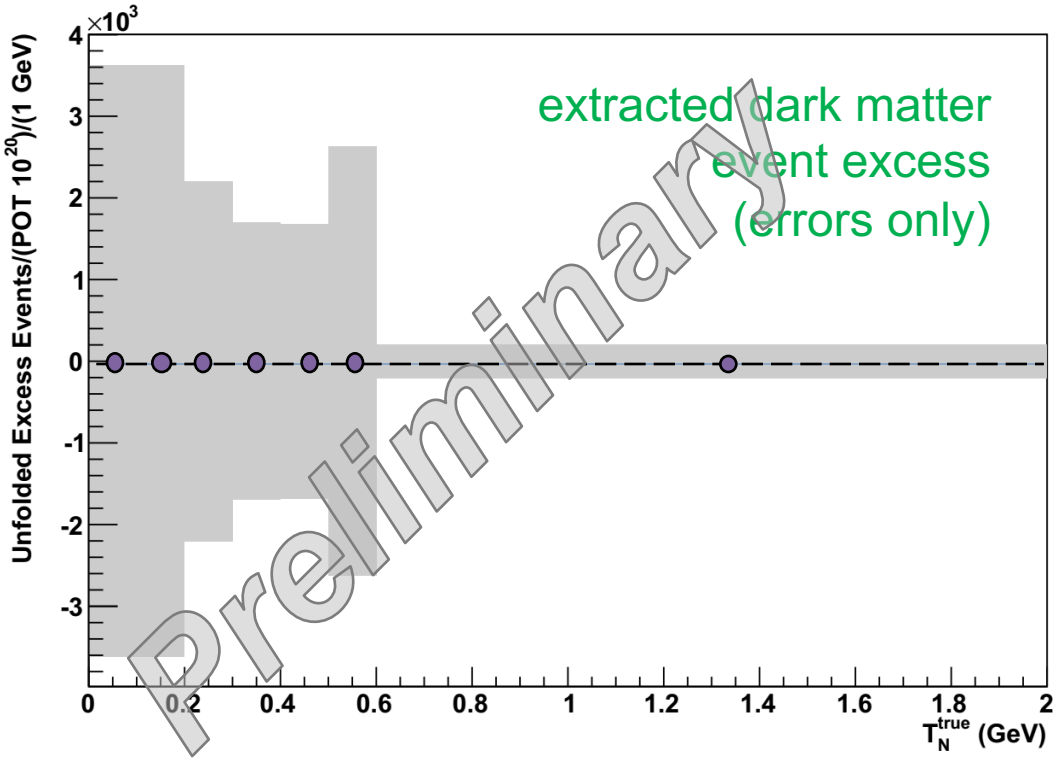
Total Correlation Matrix



3. Light DM-nucleon scattering search (preliminary)

Model-independent event excess search

- Light DM excess in bins of unfolded (true) nucleon kinetic energy
- Together with beamline configuration, flux should allow tests for other models



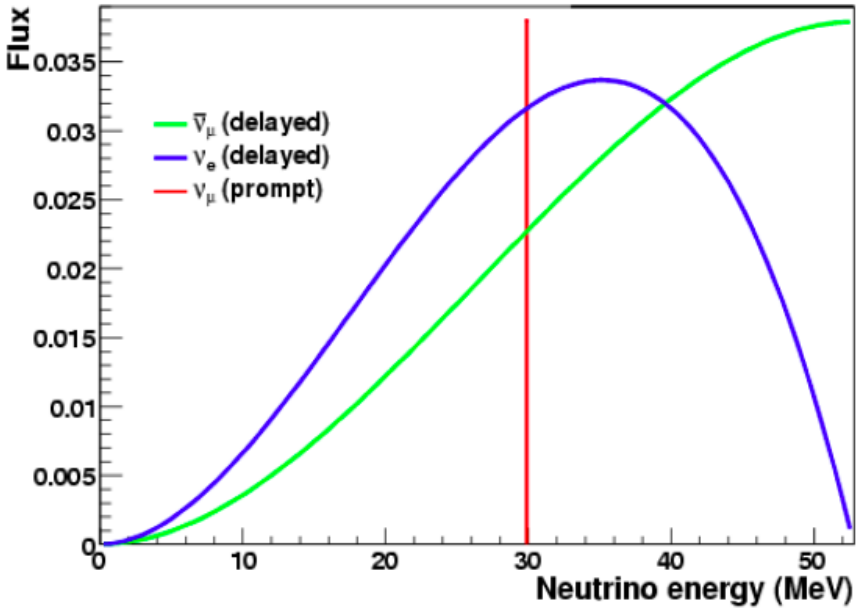
1. LSND

LSND makes muon anti-neutrino beam from decay-at-rest pion beam, to search electron anti-neutrino appearance.

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

L/E~30m/40MeV~0.7

$$n + p \rightarrow d + \gamma$$

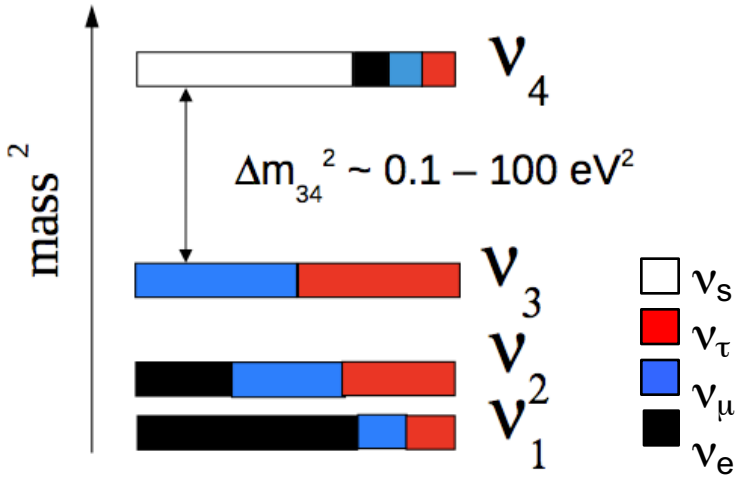


Data is consistent with two massive neutrino oscillation model with Δm^2~1eV^2,
87.9 ± 22.4 ± 6.0 (3.8.σ)

3 types of neutrino oscillations are found:
LSND neutrino oscillation: Δm^2~1eV^2
Atmospheric neutrino oscillation: Δm^2~10-3eV^2
Solar neutrino oscillation : Δm^2~10-5eV^2

But we cannot have so many Δm^2!

$$\Delta m_{13}^2 \neq \Delta m_{12}^2 + \Delta m_{23}^2$$



1. MiniBooNE

MiniBooNE observed event excesses in both mode

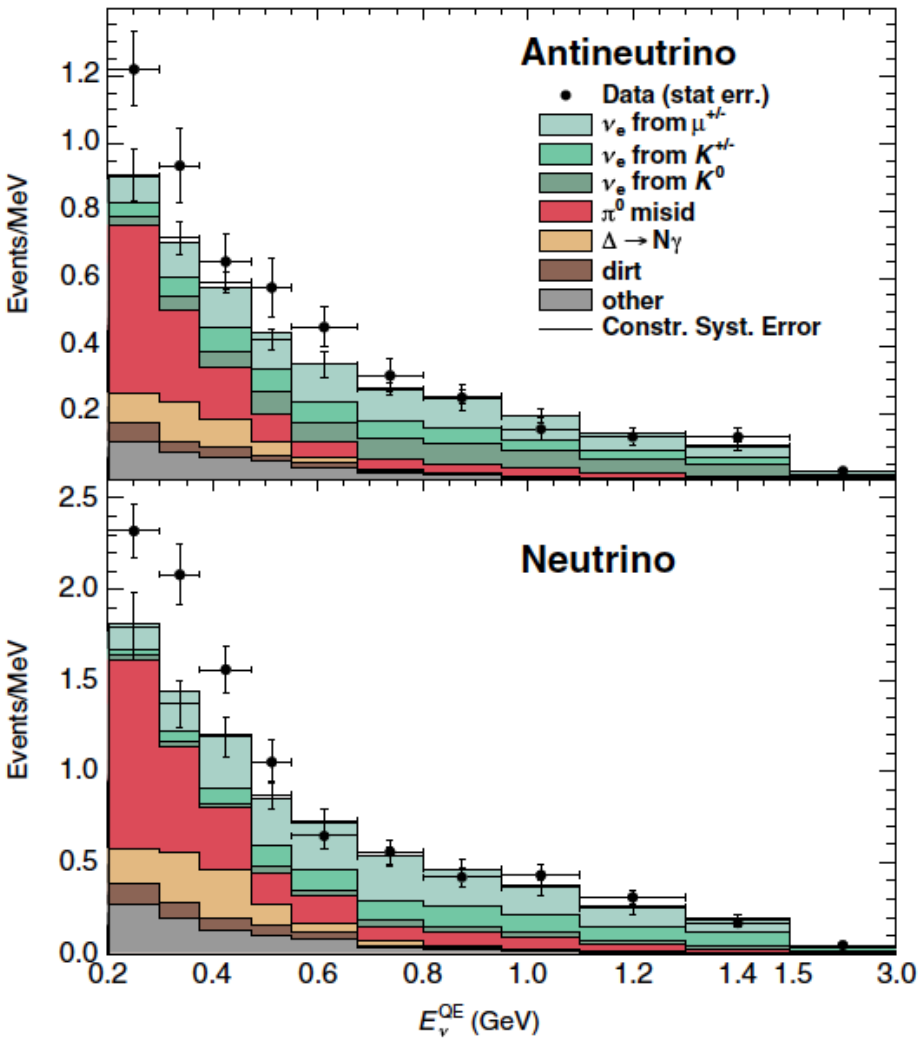
Neutrino mode

162.0 ± 28.1 ± 38.7 (3.4σ)

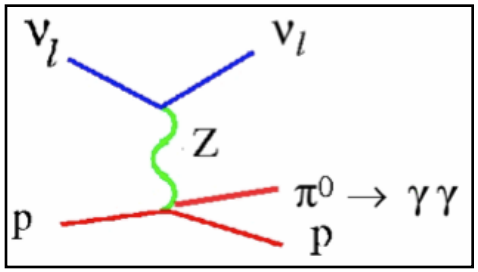
Antineutrino mode

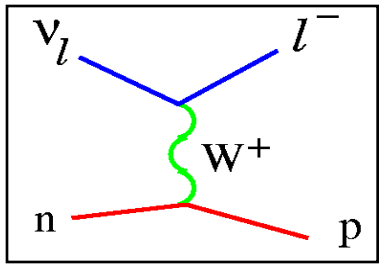
78.9 ± 20.0 ± 20.3 (2.8σ)

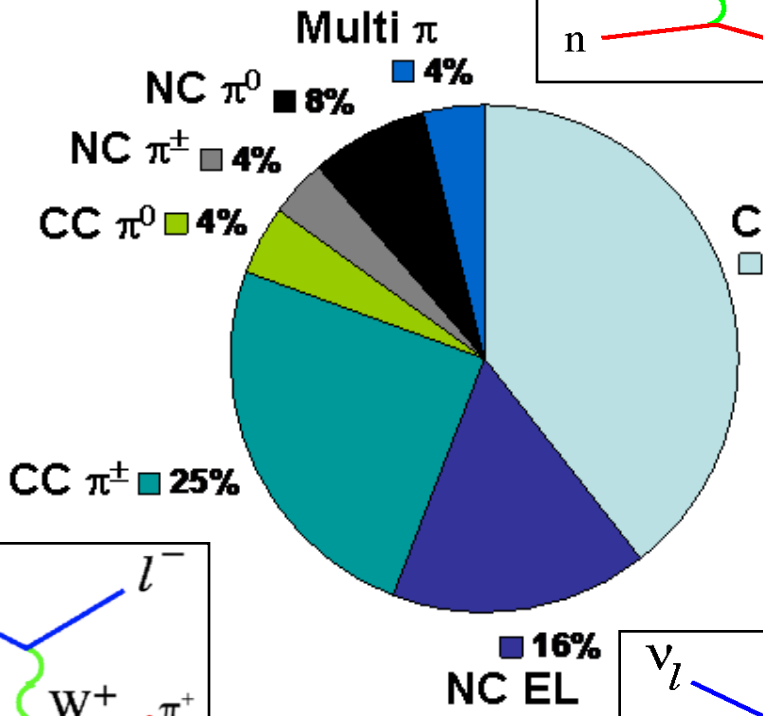
oscillation candidate events

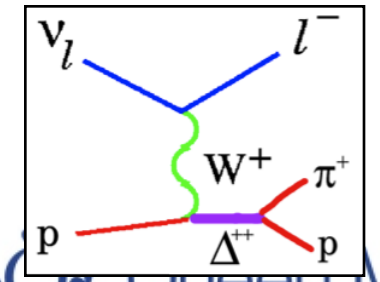


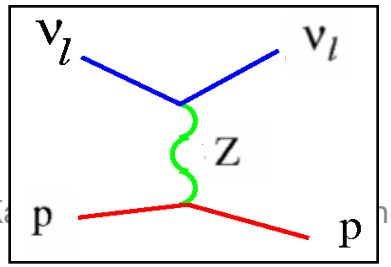
1. Cross section model





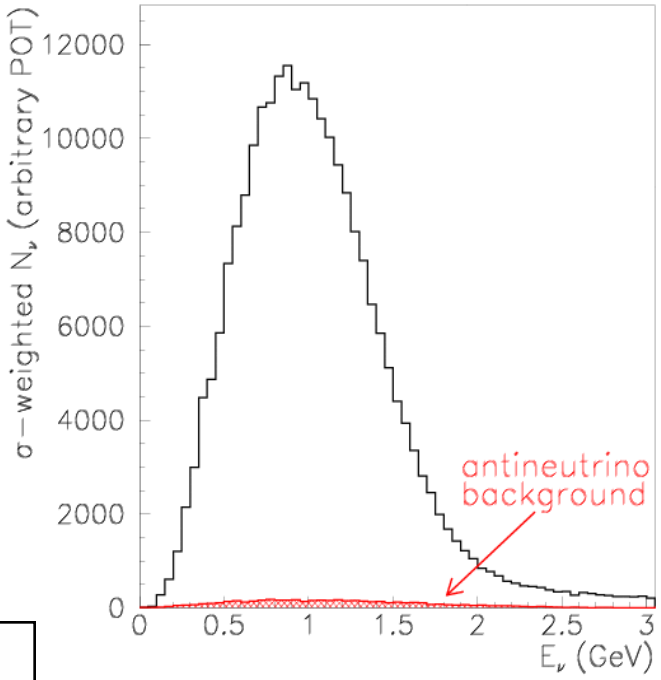






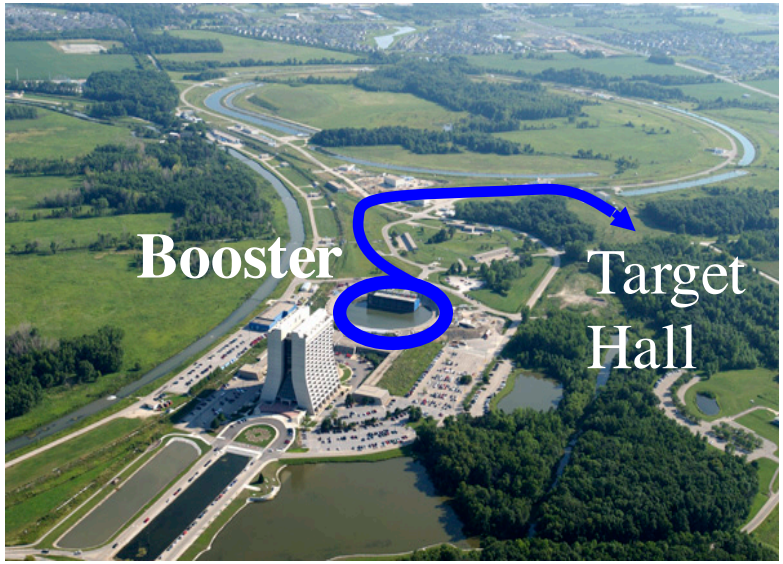
Predicted event rates before cuts (NUANCE Monte Carlo)

Casper, Nucl.Phys.Proc.Suppl.112(2002)161



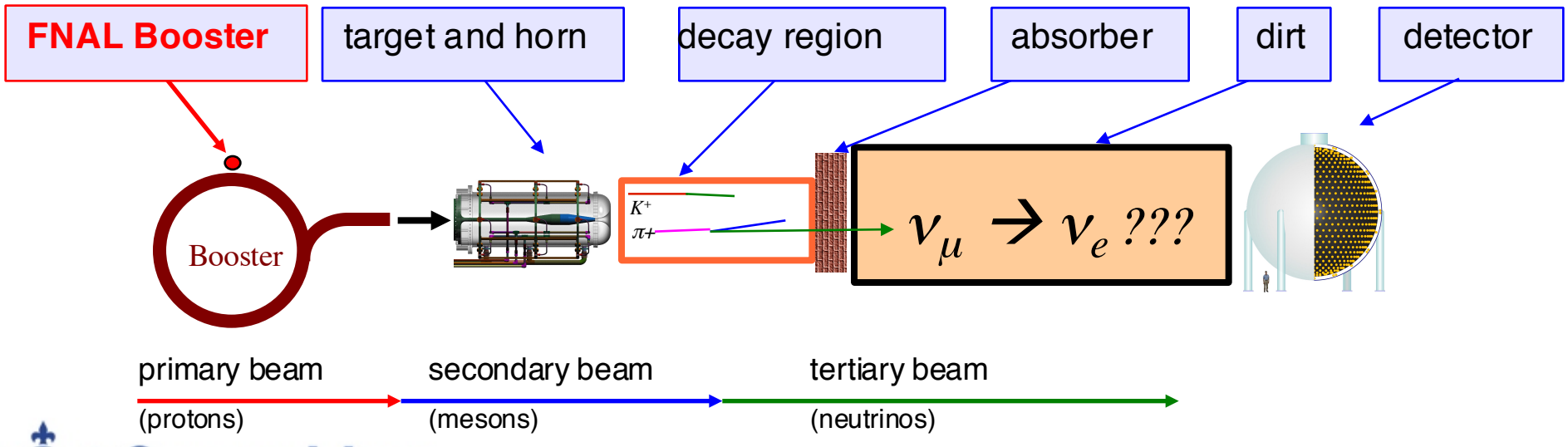
Event neutrino energy (GeV)

1. Neutrino beam



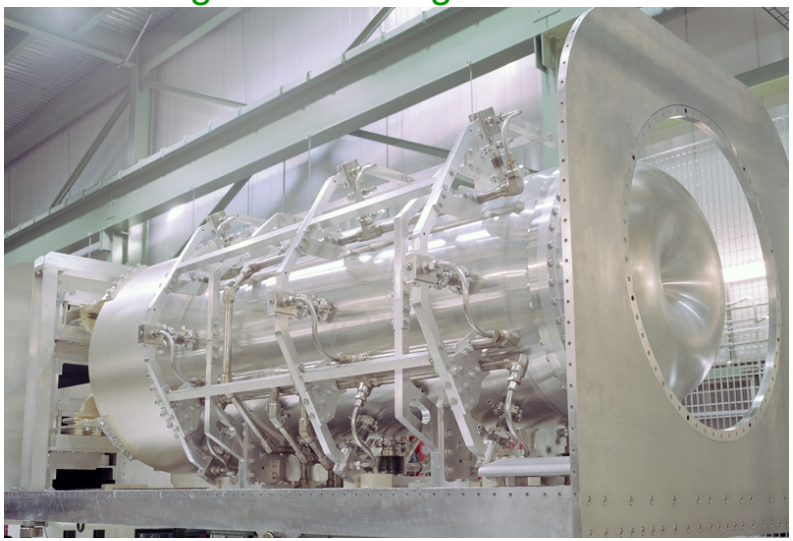
MiniBooNE extracts beam from the 8 GeV Booster

FNAL Booster



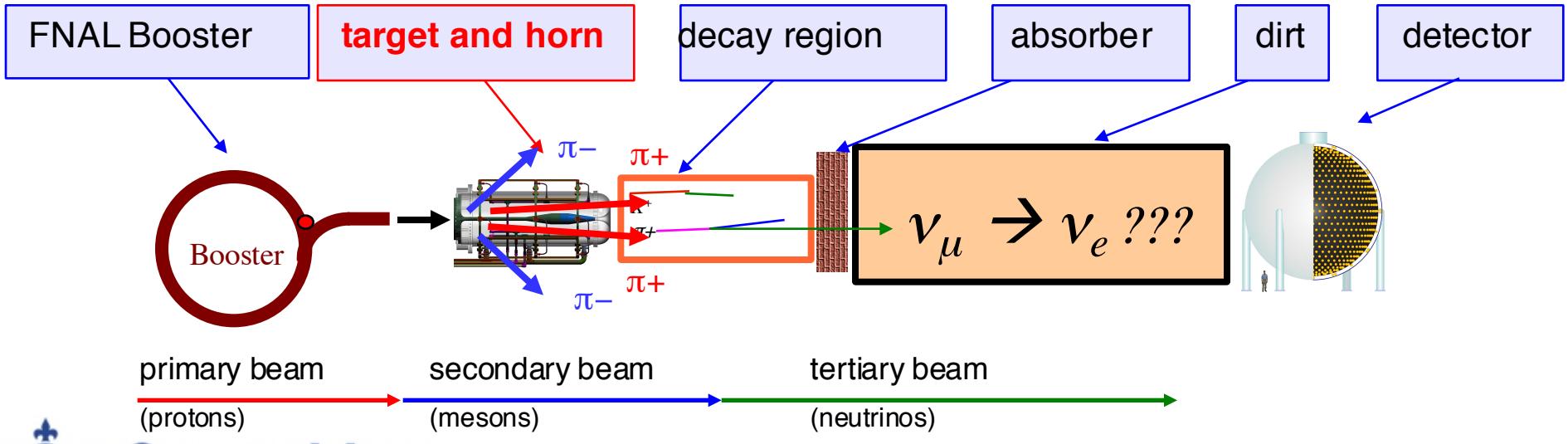
1. Neutrino beam

Magnetic focusing horn



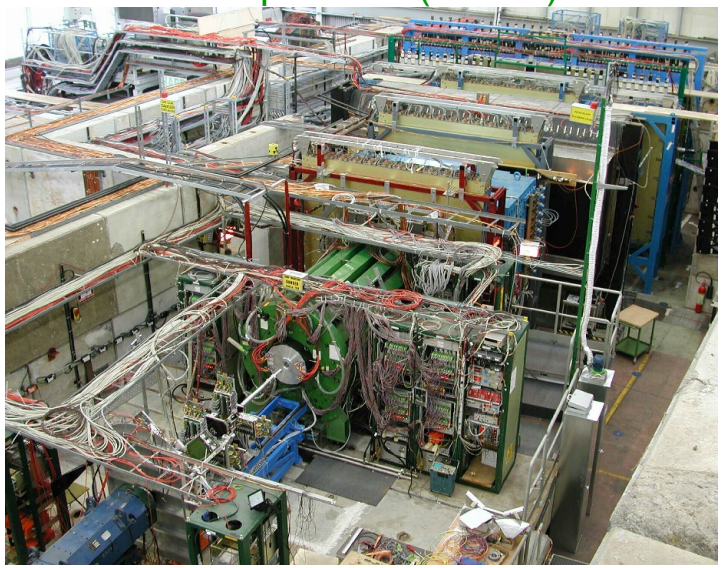
8GeV protons are delivered to a 1.7 λ Be target

within a magnetic horn (2.5 kV, 174 kA) that increases the flux by x6



1. Neutrino beam

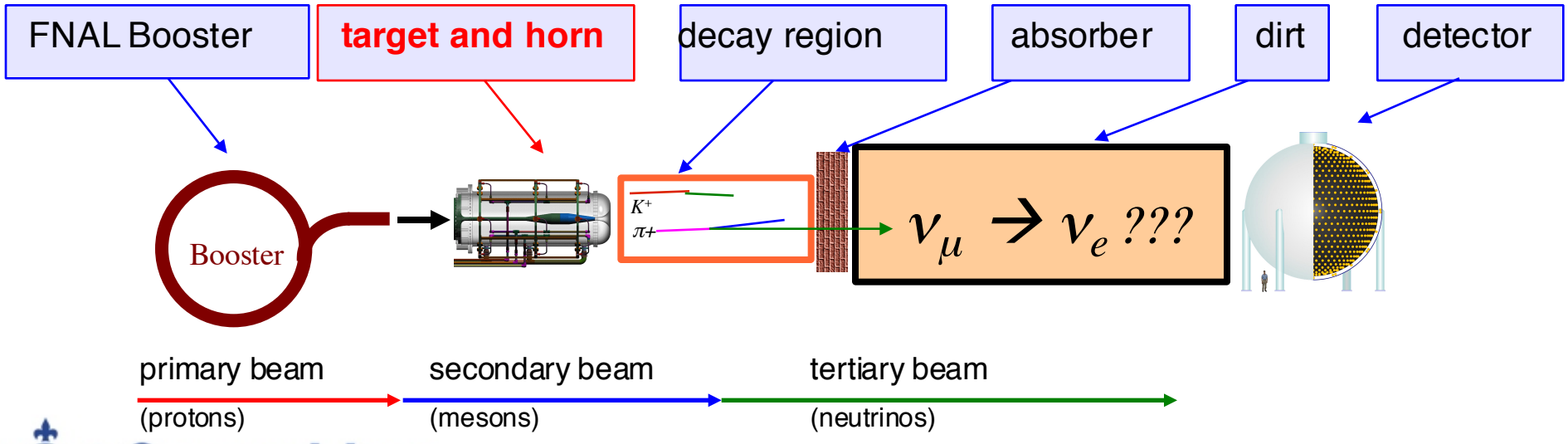
HARP experiment (CERN)



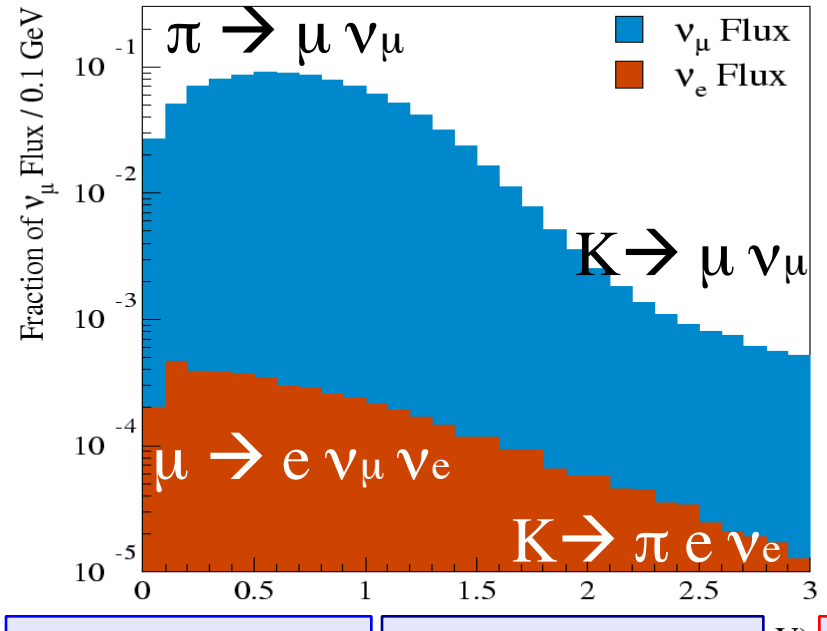
Modeling of meson production is based on the measurement done by HARP collaboration.

HARP collaboration, Eur.Phys.J.C52(2007)29

- Identical, but 5% λ Beryllium target
- 8.9 GeV/c proton beam momentum



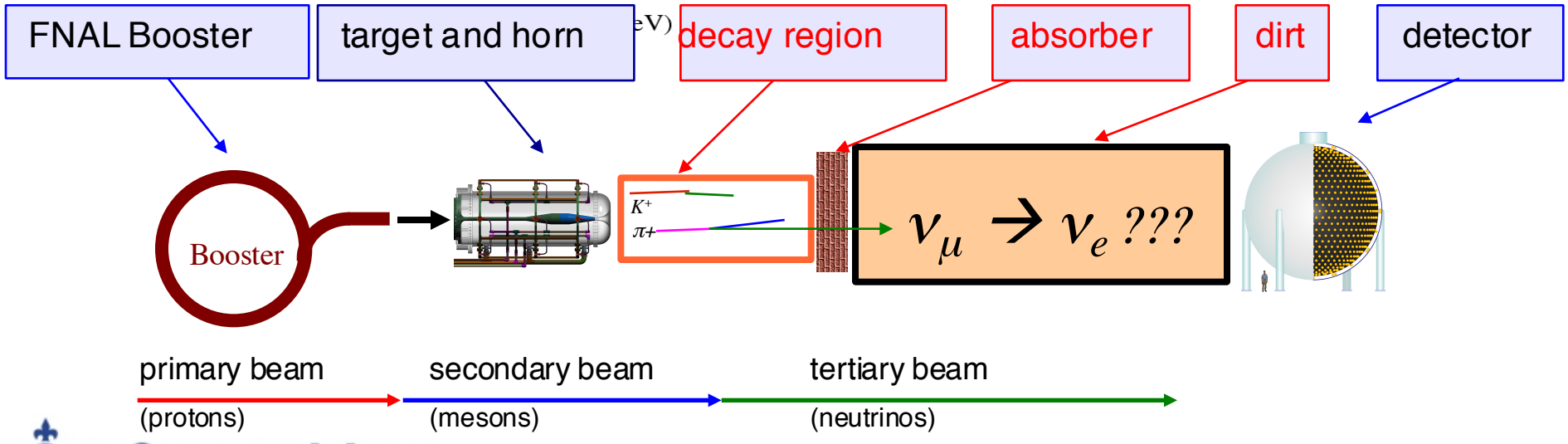
1. Neutrino beam



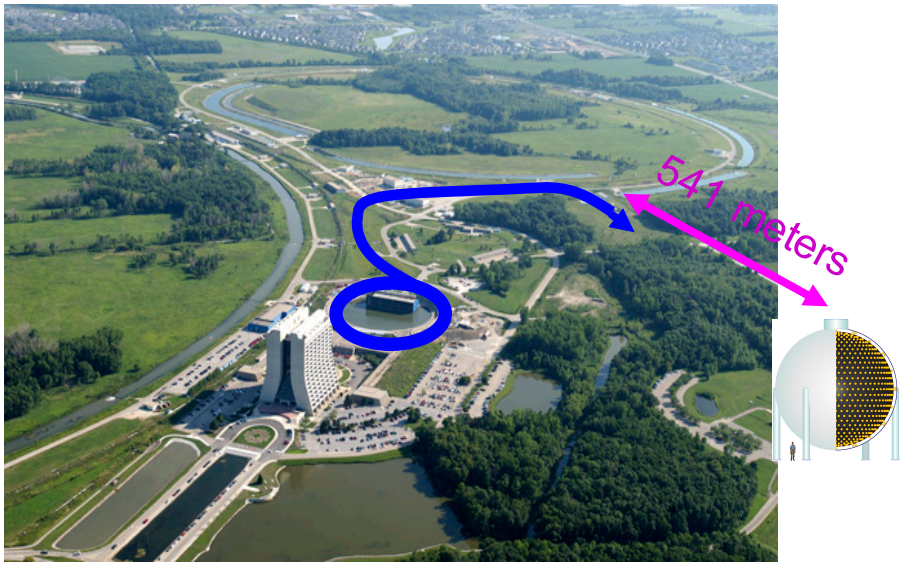
Neutrino flux from simulation by GEANT4

MiniBooNE is the ν_e (anti ν_e) appearance oscillation experiment, so we need to know the distribution of beam origin ν_e and anti ν_e (intrinsic ν_e)

	neutrino mode	antineutrino mode
intrinsic ν_e contamination	0.6%	0.6%
intrinsic ν_e from μ decay	49%	55%
intrinsic ν_e from K decay	47%	41%
others	4%	4%
wrong sign fraction	6%	16%



1. Events in the Detector



The MiniBooNE Detector

- 541 meters downstream of target
- 12 meter diameter sphere

  (10 meter "fiducial" volume)
- Filled with 800 t of pure mineral oil (CH_2)

  (Fiducial volume: 450 t)
- 1280 inner phototubes,
- 240 veto phototubes

1. Events in the Detector

The MiniBooNE Detector

- 541 meters downstream of target
- 12 meter diameter sphere

  (10 meter “fiducial” volume)
- Filled with 800 t of pure mineral oil (CH_2)

  (Fiducial volume: 450 t)
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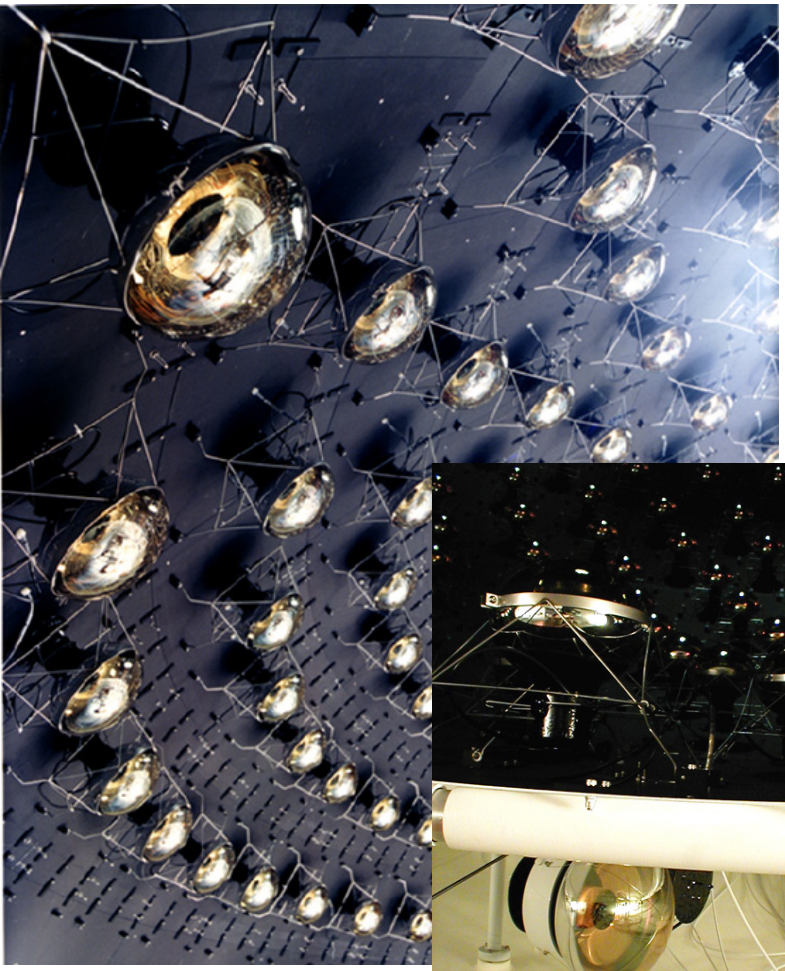
- 240 veto phototubes

1. Events in the Detector



The MiniBooNE Detector

- 541 meters downstream of target
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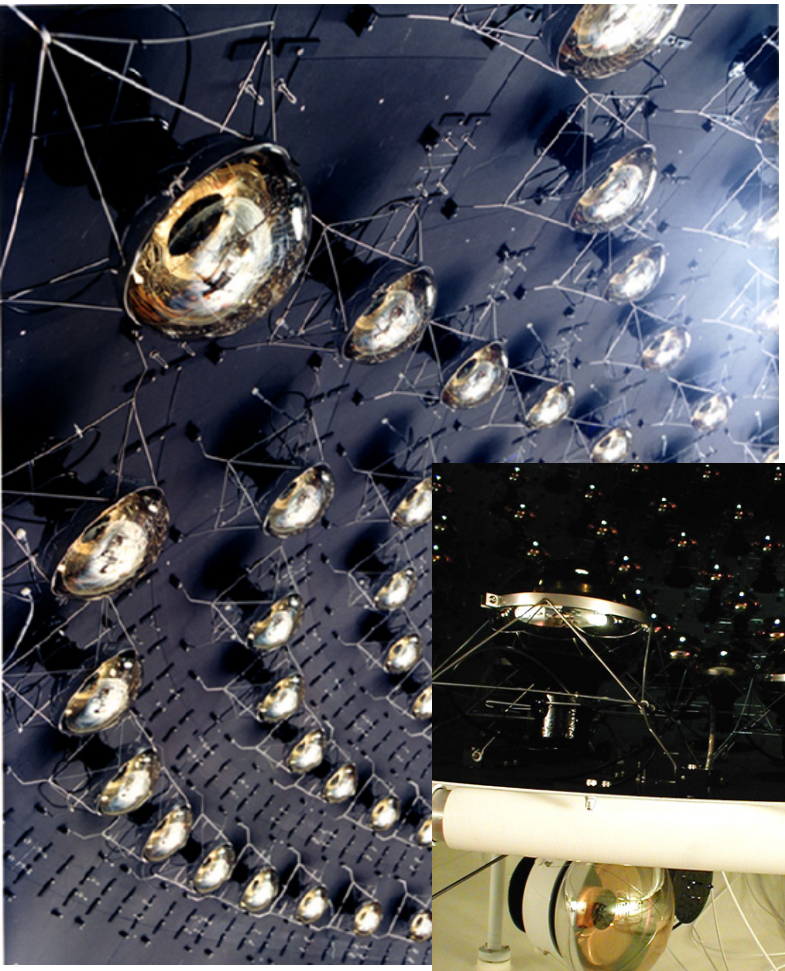

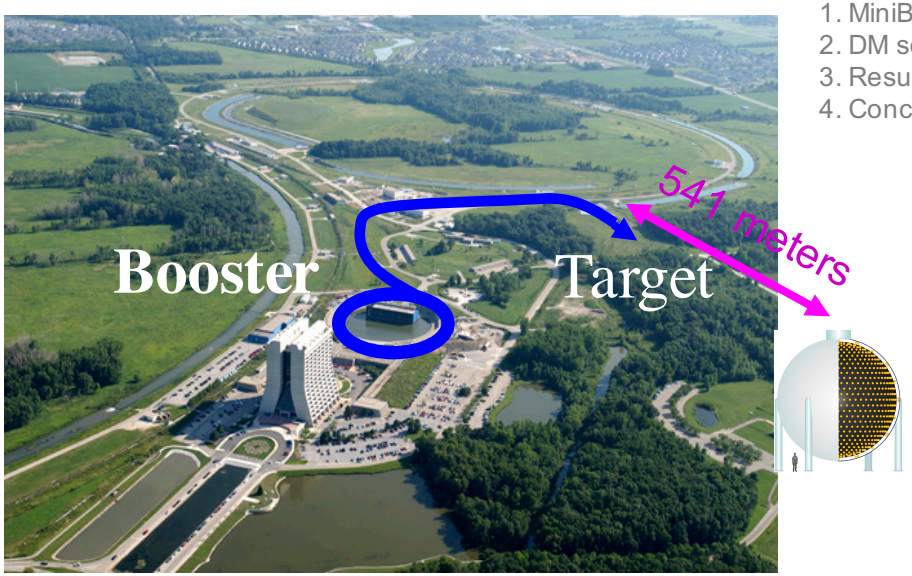

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Beam spill (1.6μs) is clearly evident

simple cuts eliminate cosmic backgrounds

Neutrino Candidate Cuts

<6 veto PMT hits

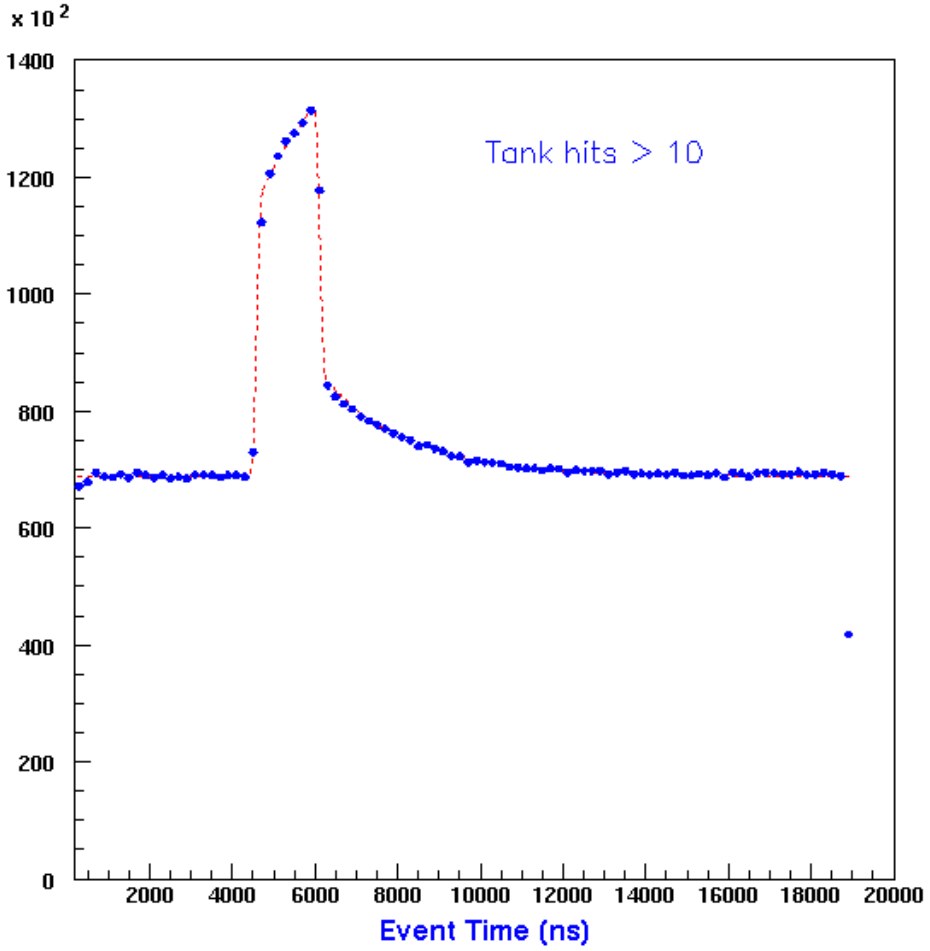
Gets rid of muons

>200 tank PMT hits

Gets rid of Michels

Only neutrinos are left!

Beam and Cosmic BG



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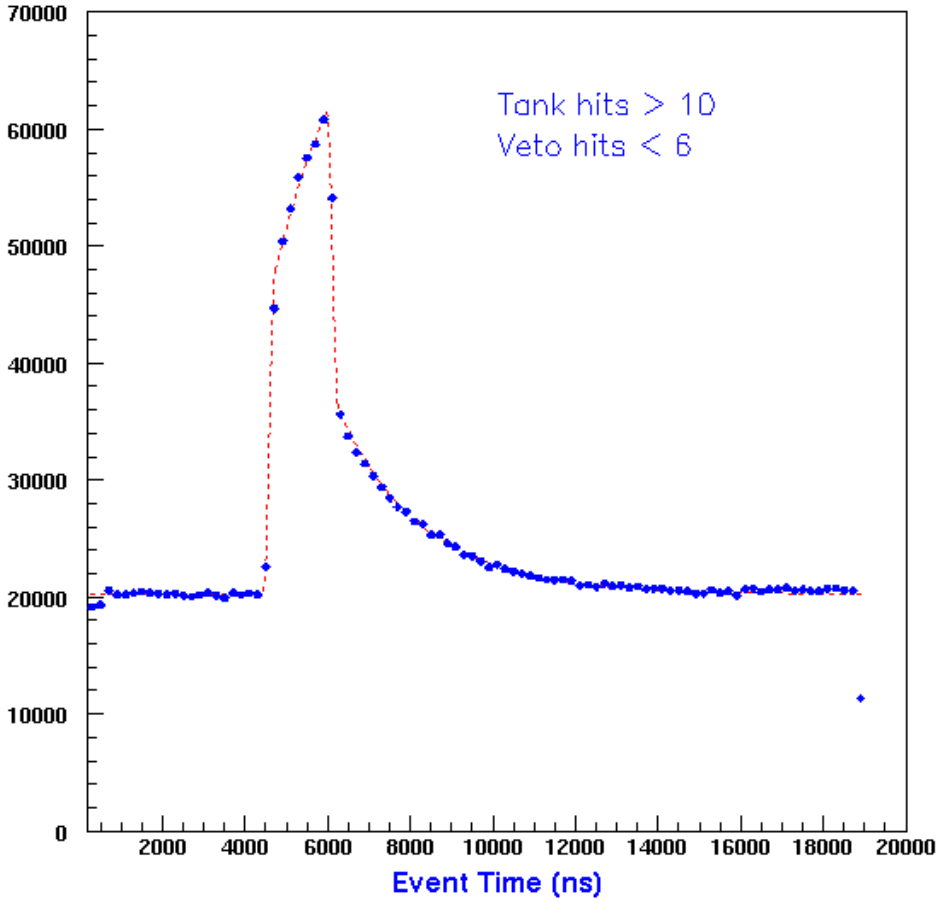

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Beam Only