Dark Matter Search in a Proton Beam Dump with MiniBooNE

PRL118(2017)221803

outline

1. MiniBooNE neutrino oscillation experiment
2. MiniBooNE-DM experiment
3. Results
4. Future plans

Teppei Katori for MiniBooNE-DM collaboration
Queen Mary University of London
DMUK meeting, Univ. Bristol, UK, Jan. 17, 2018

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PRL 118, 221803 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

Dark Matter Search in a Proton Beam Dump with MiniBooNE

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MiniBooNE-DM Collaboration

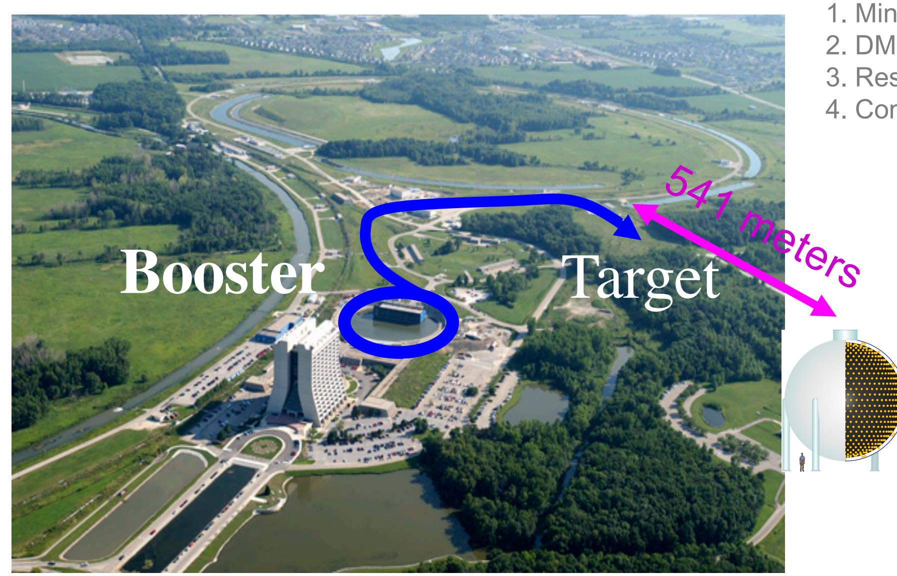
1. MiniBooNE neutrino oscillation experiment

2. MiniBooNE-DM experiment

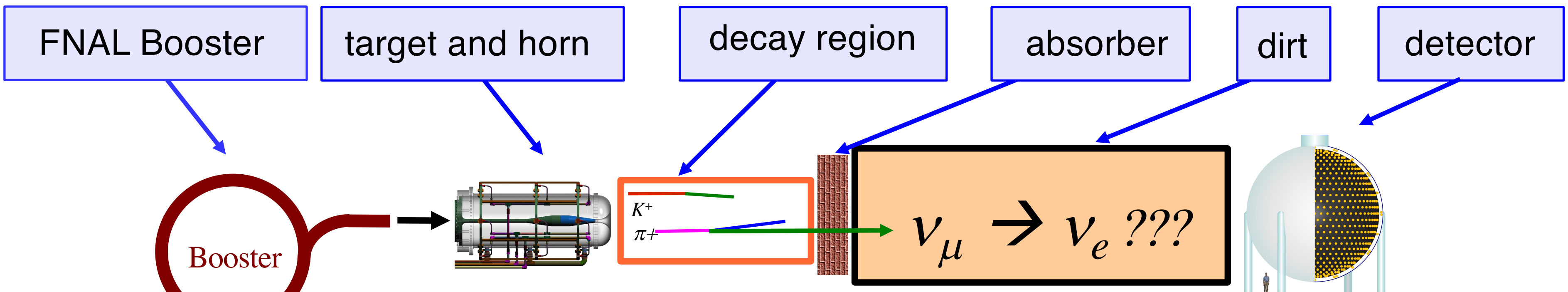
3. Results

4. Future plans

1. MiniBooNE experiment



Booster Neutrino Beamline (BNB)
- 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

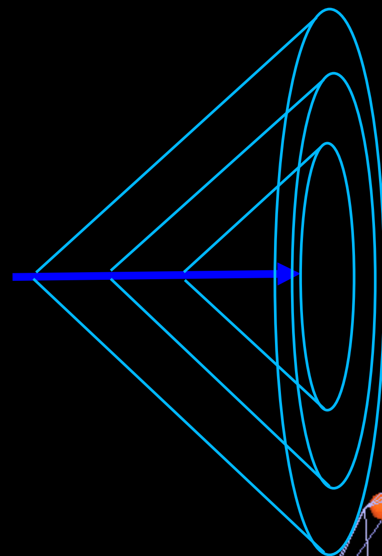
1. Events in the Detector

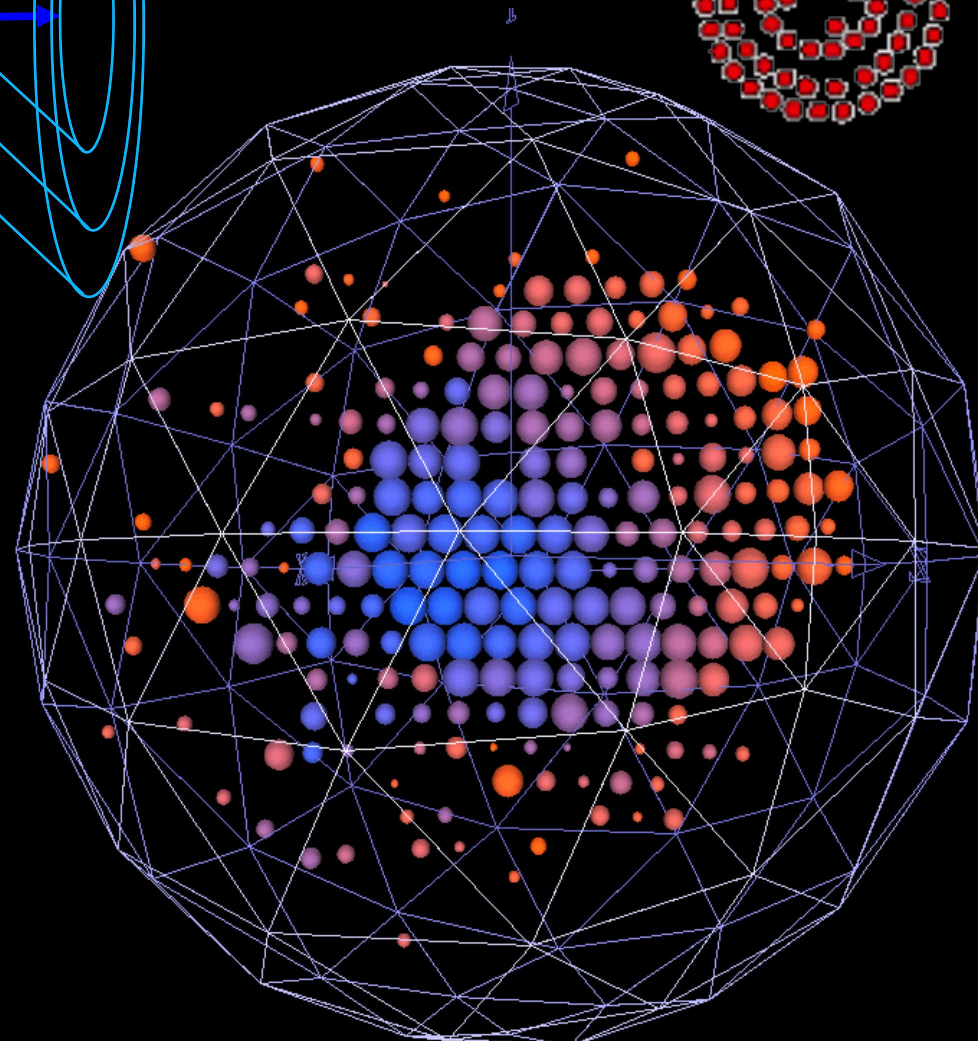
MiniBooNE collaboration, NIM.A599(2009)28

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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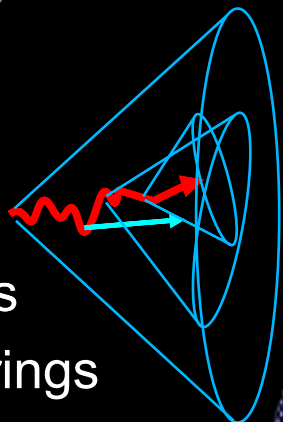

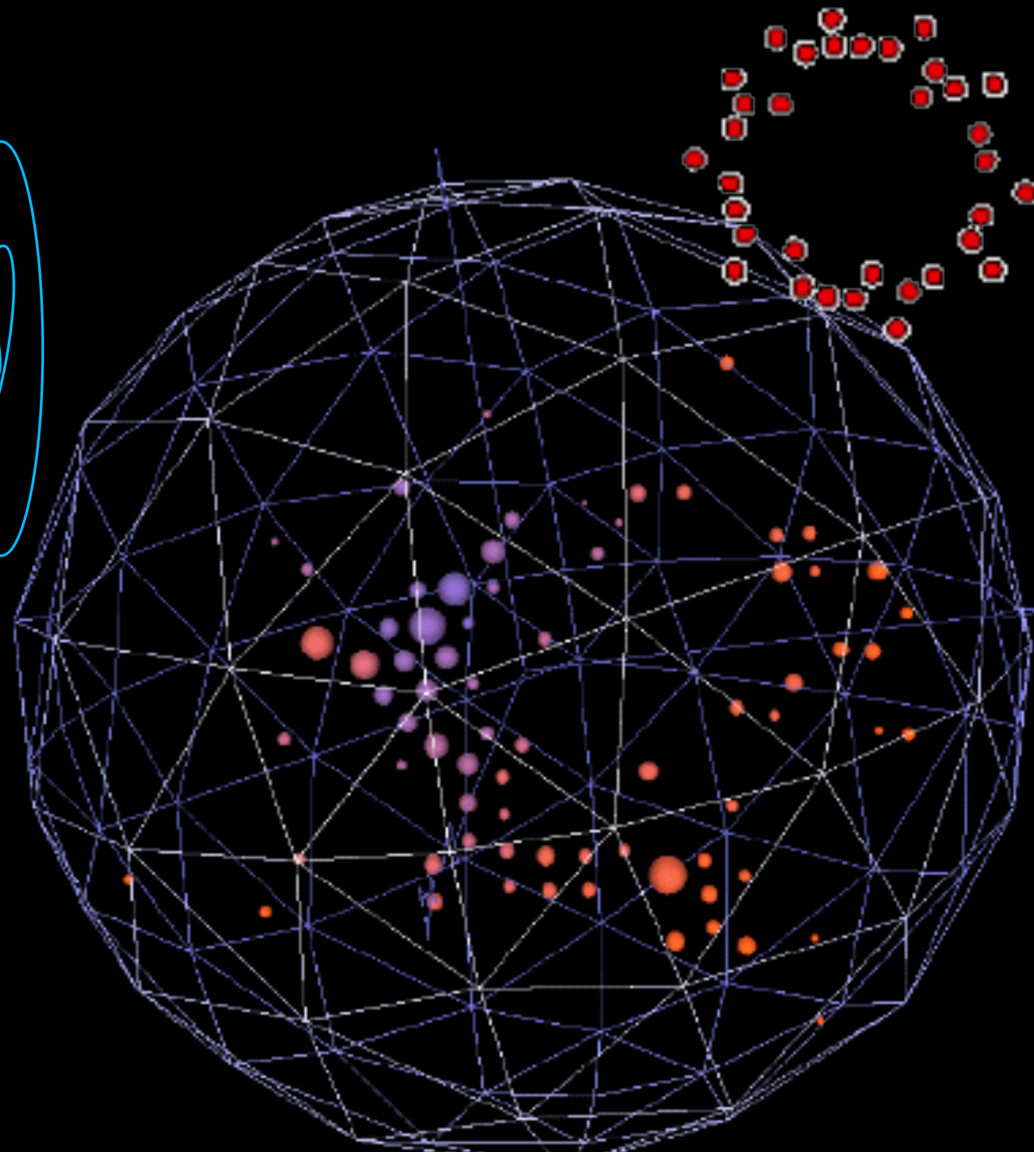

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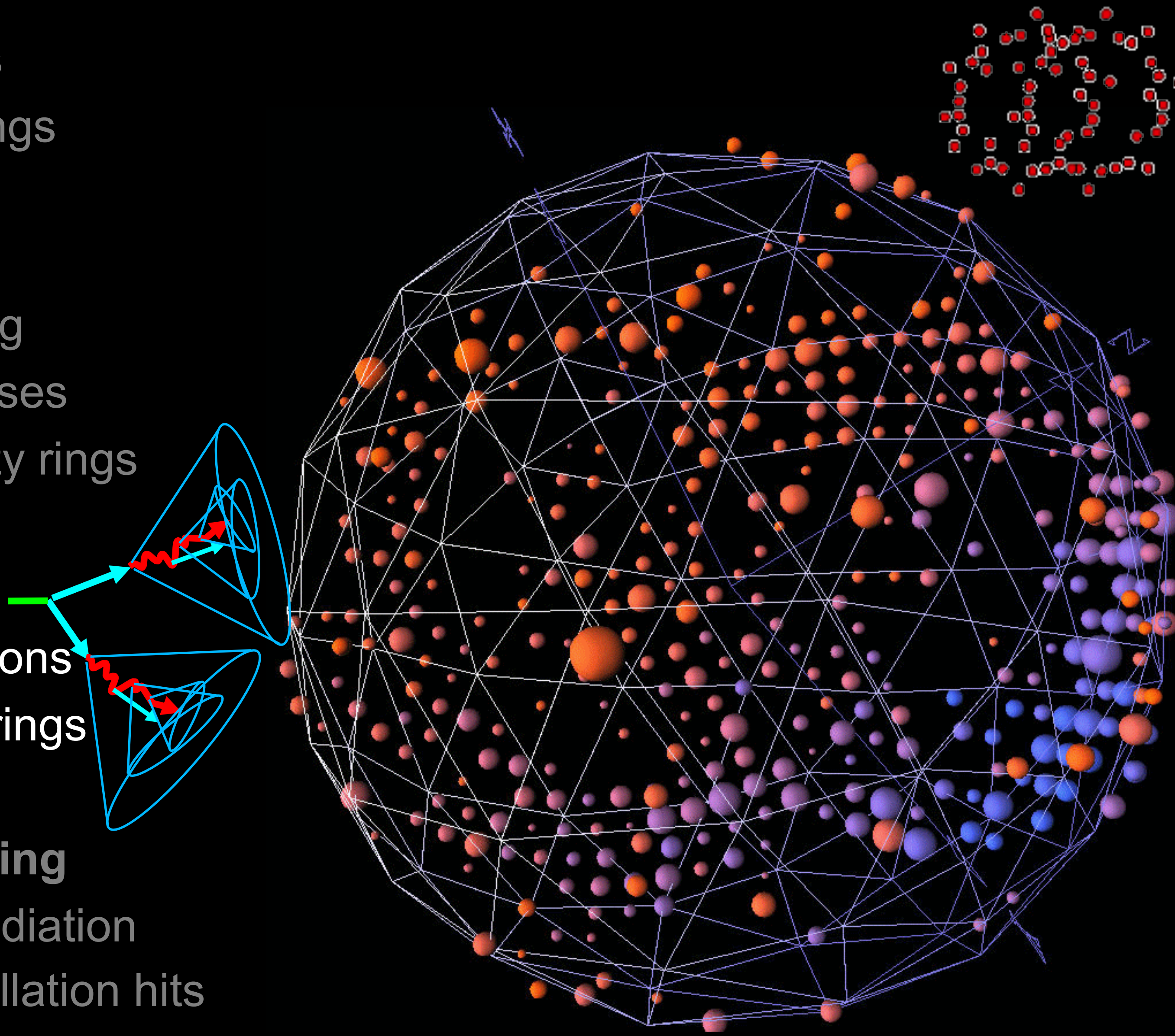

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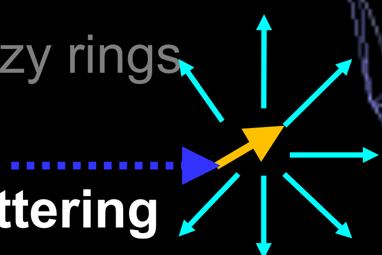

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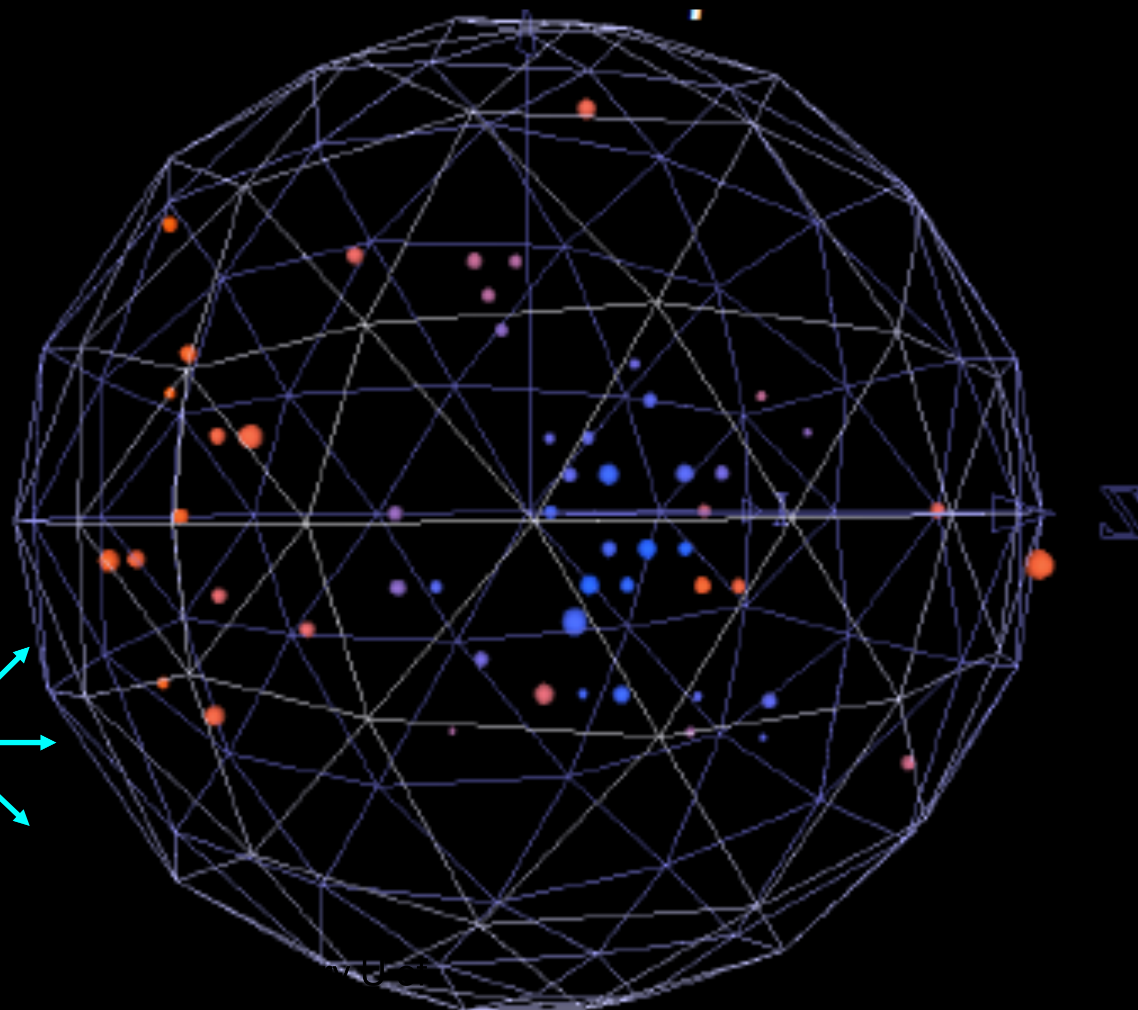


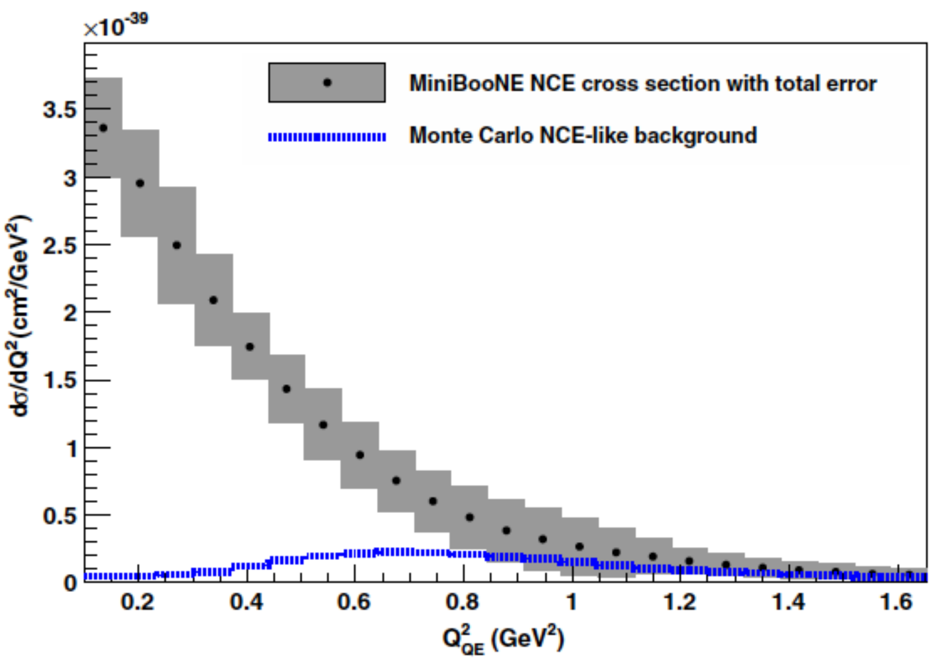
1. Neutral Current Elastic (NCE) cross section measurements

MiniBooNE flux-integrated NCE differential cross section

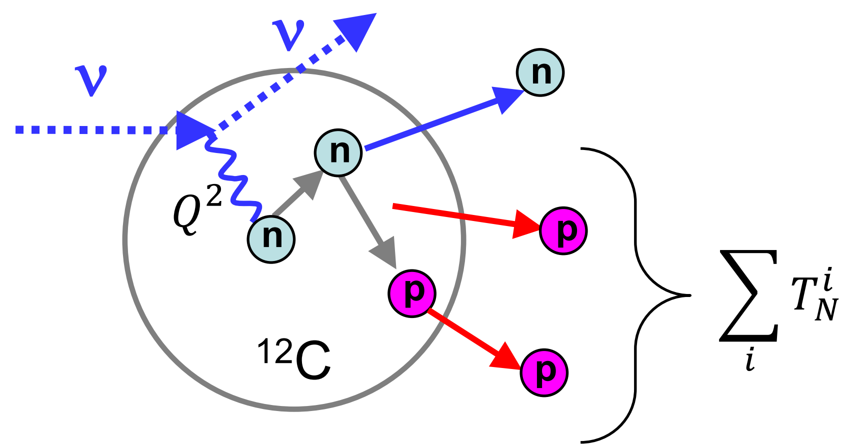
- Total scintillation light is used to estimate total nucleon kinetic energy
- Q^2_{QE} is reconstructed from total nucleon energy deposit

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

neutrino NCE differential cross section



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



1. MiniBooNE neutrino oscillation experiment

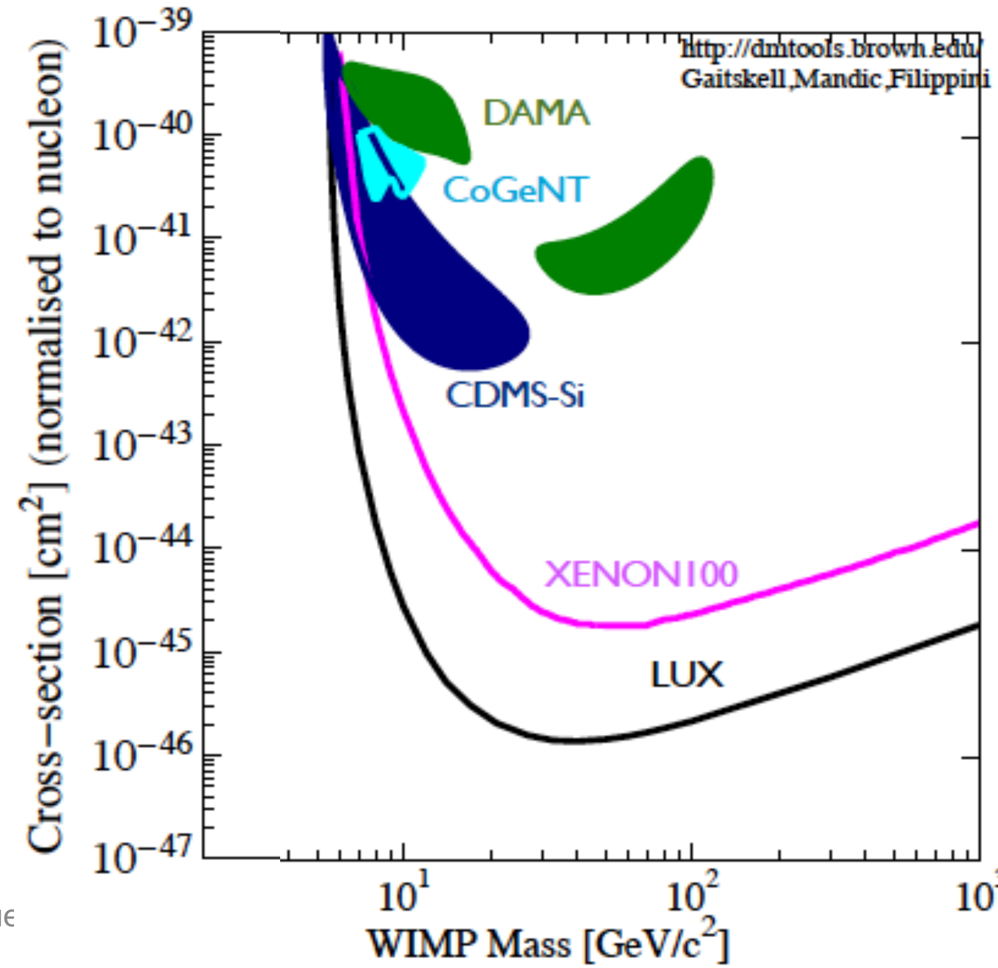
2. MiniBooNE-DM experiment

3. Results

4. Future plans

2. MiniBooNE sub-GeV dark matter search

WIMP dark matter
- Direct detection experiments to target halo DM
- Slow galactic rotation can induce observable recoil
- Very active field



Boehm et al.,Nucl.Phys.B683(2004)219,PRL92(2004)101301

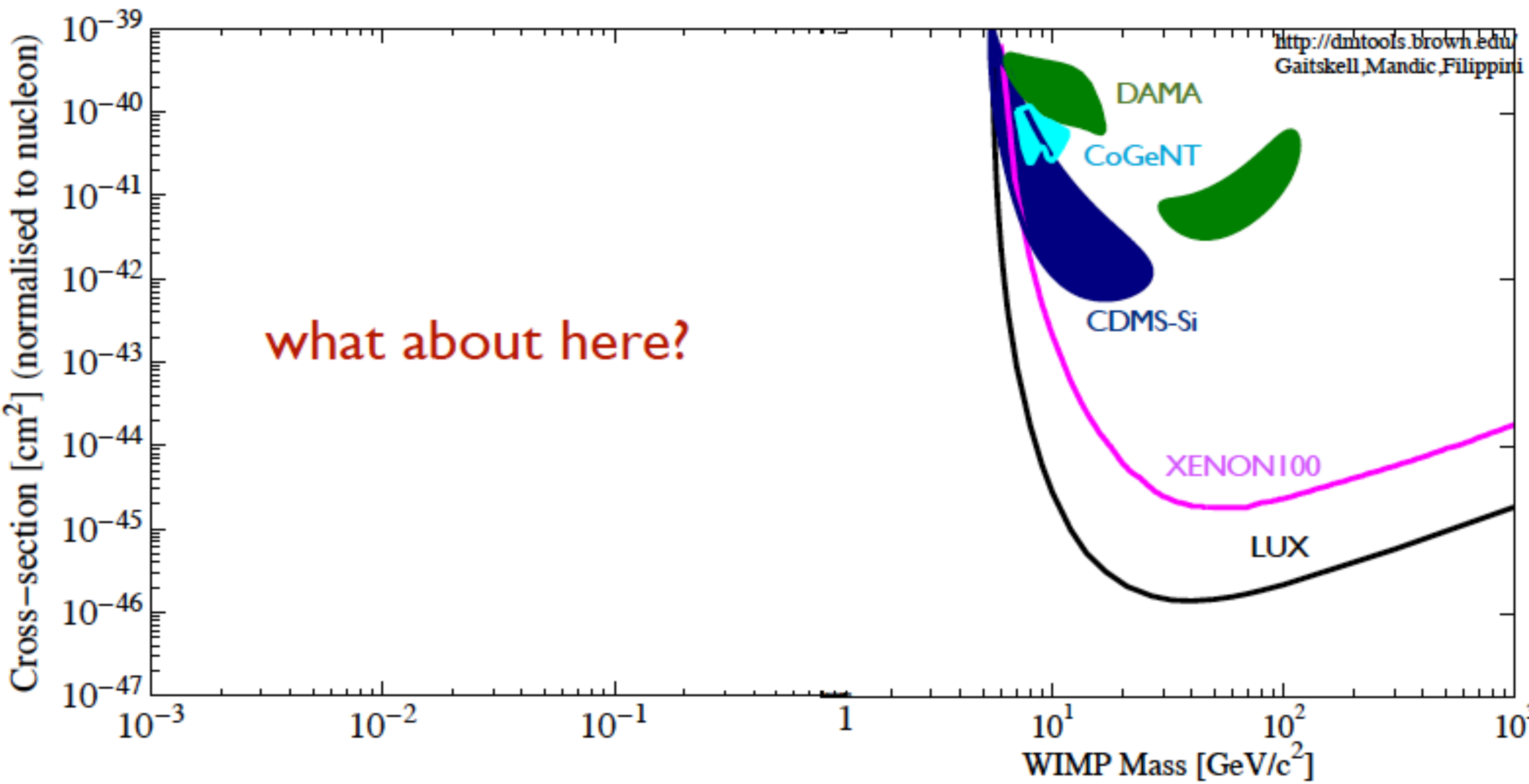
2. MiniBooNE sub-GeV dark matter search

$$L_{V,\chi} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \frac{\varepsilon}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\chi|^2 - m_\chi^2|\chi|^2 \cdots$$

Sub-GeV dark matter

- Not accessible by direct detection experiments

→ Beam dump experiment



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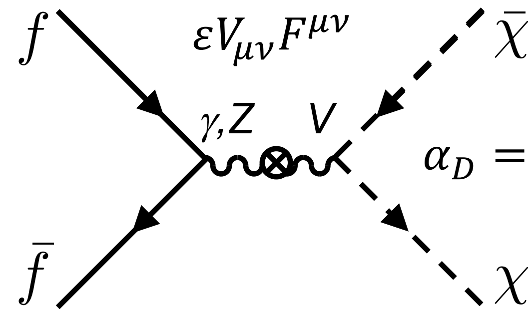
Sub-GeV dark matter

- Not accessible by direct detection experiments
  → Beam dump experiment

Minimal Vector Portal Model

- Light DM with U(1) gauge boson (dark photon)
- dark photon kinematically mixed with photon
- 4 model parameters : m_χ , m_V , ε , g_D



$$\alpha_D = \frac{g_D}{4\pi}$$

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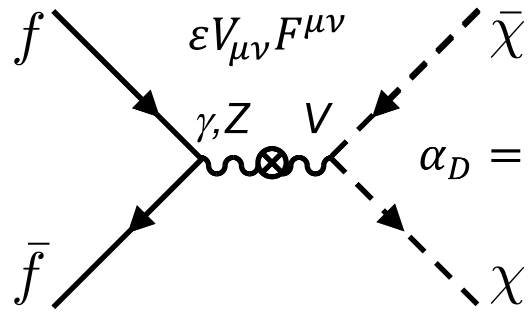

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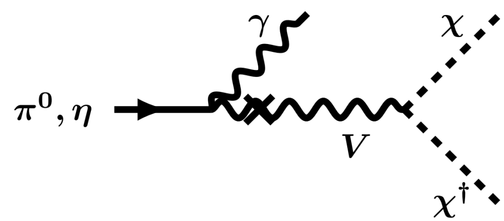
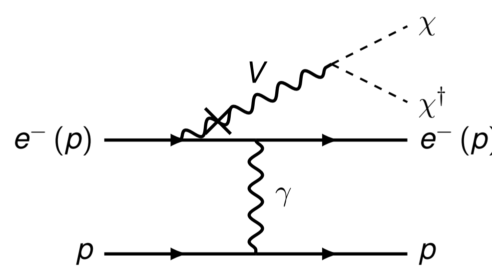
Production

- beam dump from photon-dark photon mixing





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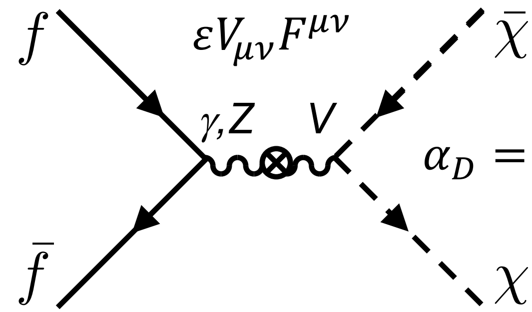

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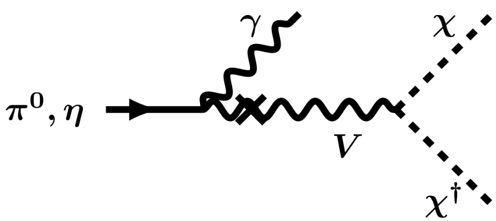
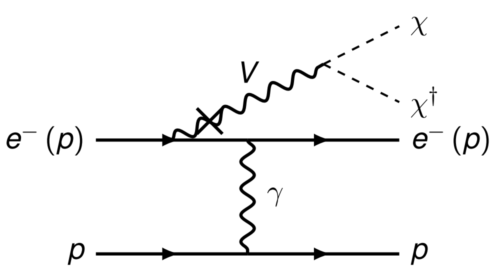
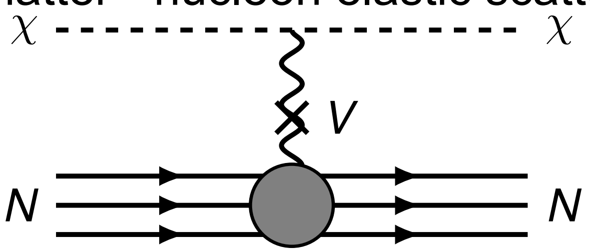




Detection

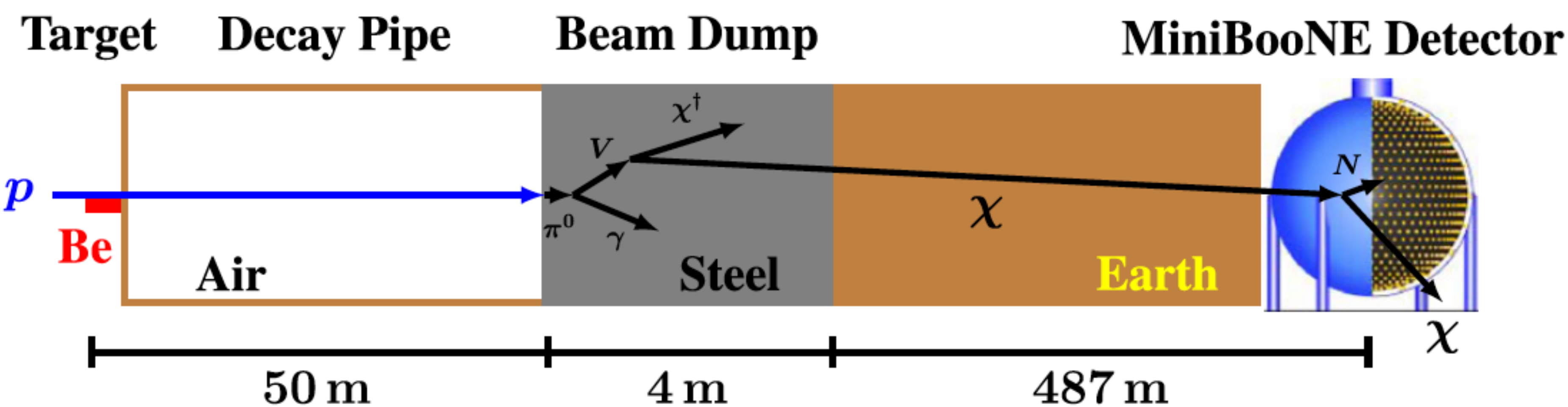
- dark matter - nucleon elastic scattering



2. MiniBooNE beam dump mode

Booster Neutrino Beamline
- 8 GeV proton primary beam

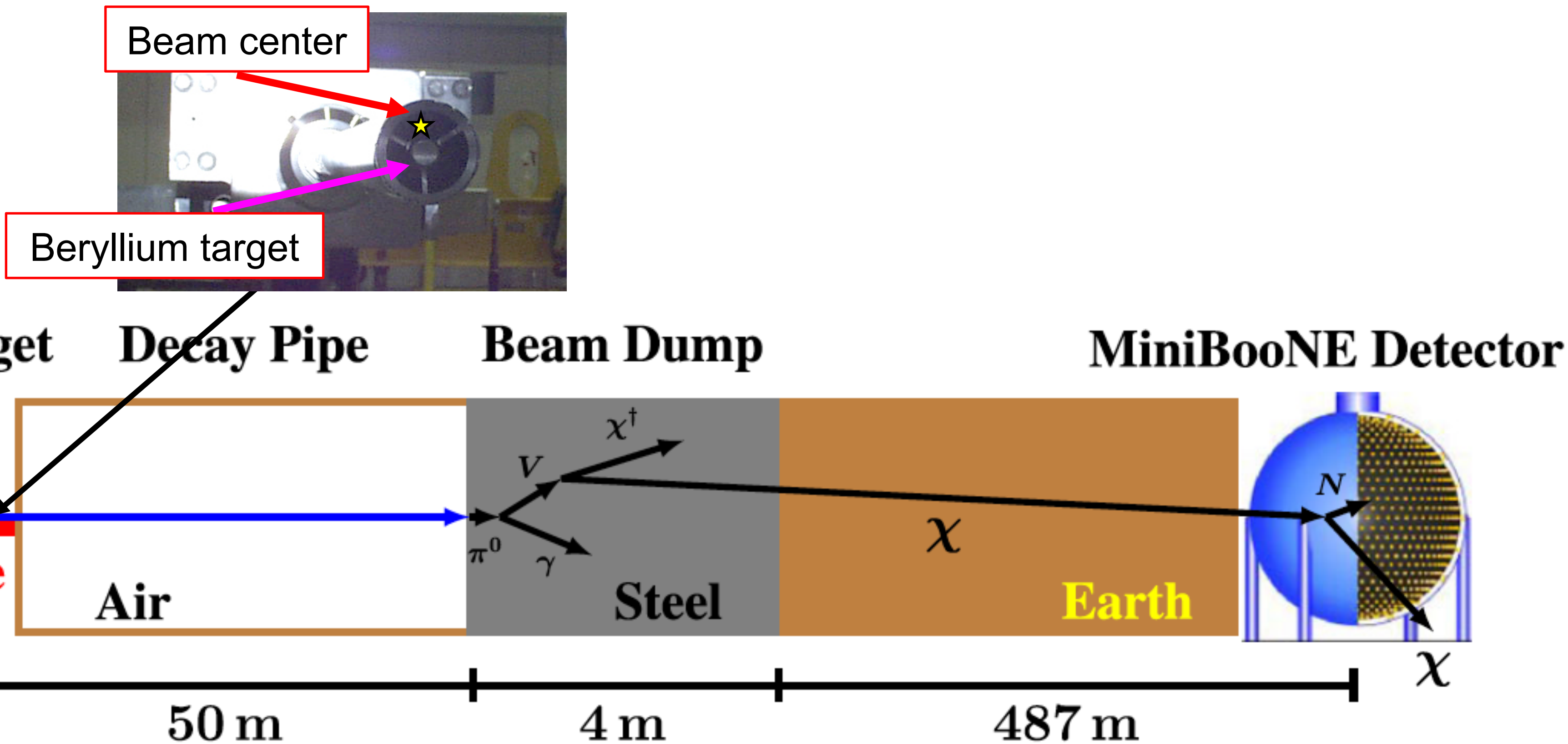
FNAL Booster



2. MiniBooNE beam dump mode

Booster Neutrino Beamline

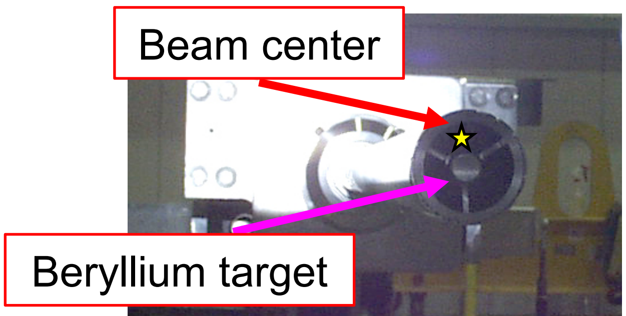
- 8 GeV proton primary beam
- beam is steered to “miss” the beryllium target



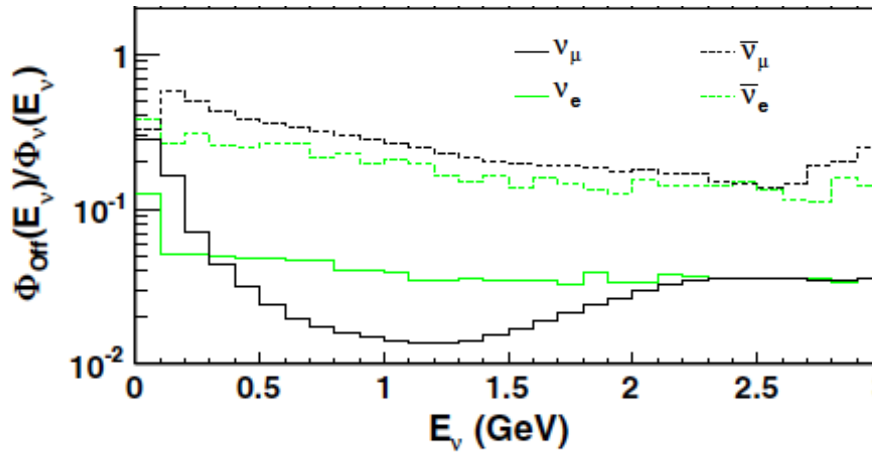
2. MiniBooNE beam dump mode

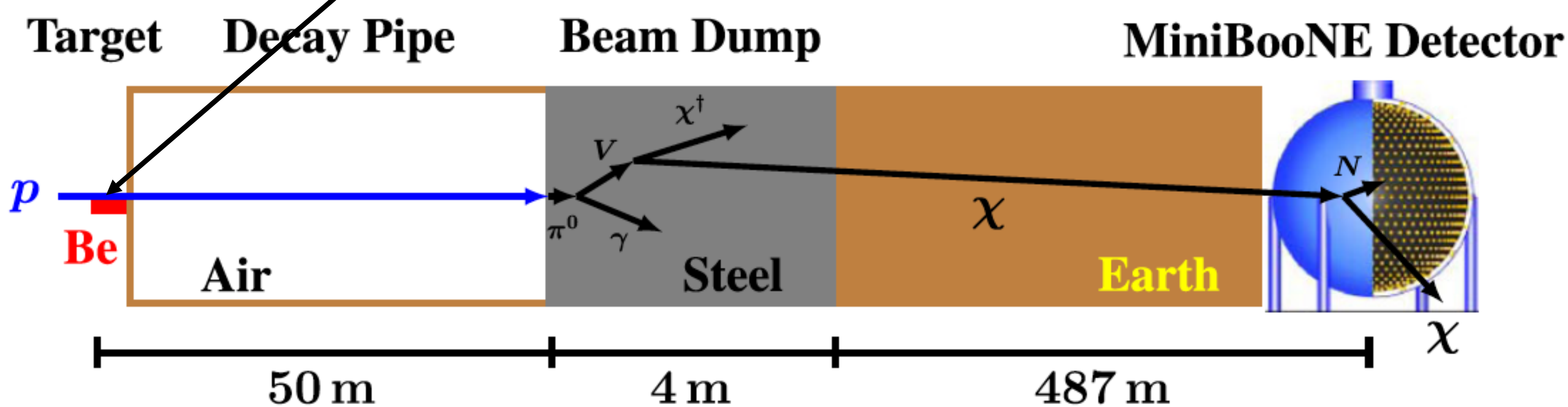
Booster Neutrino Beamline

- 8 GeV proton primary beam
- beam is steered to "miss" the beryllium target
- neutrino flux reduced ~x40



beam-dump mode flux / neutrino mode flux





2. MiniBooNE beam dump mode

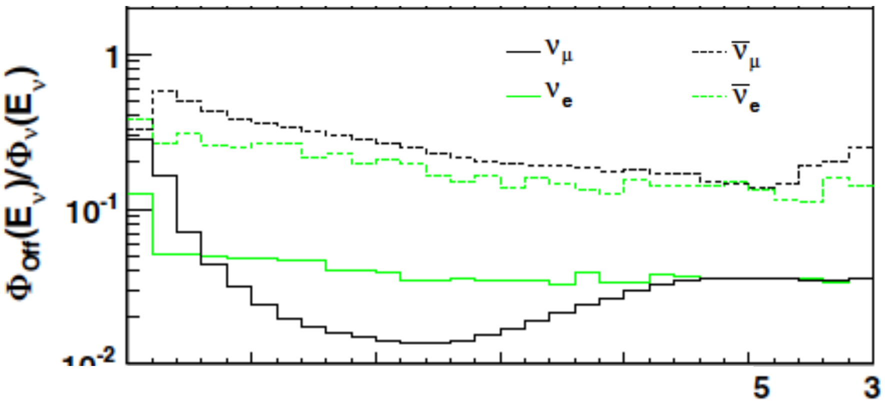
Booster Neutrino Beamline

- 8 GeV proton primary beam
- beam is steered to “miss” the beryllium target
- neutrino flux reduced ~x40
- neutrino interaction rate reduced ~x50

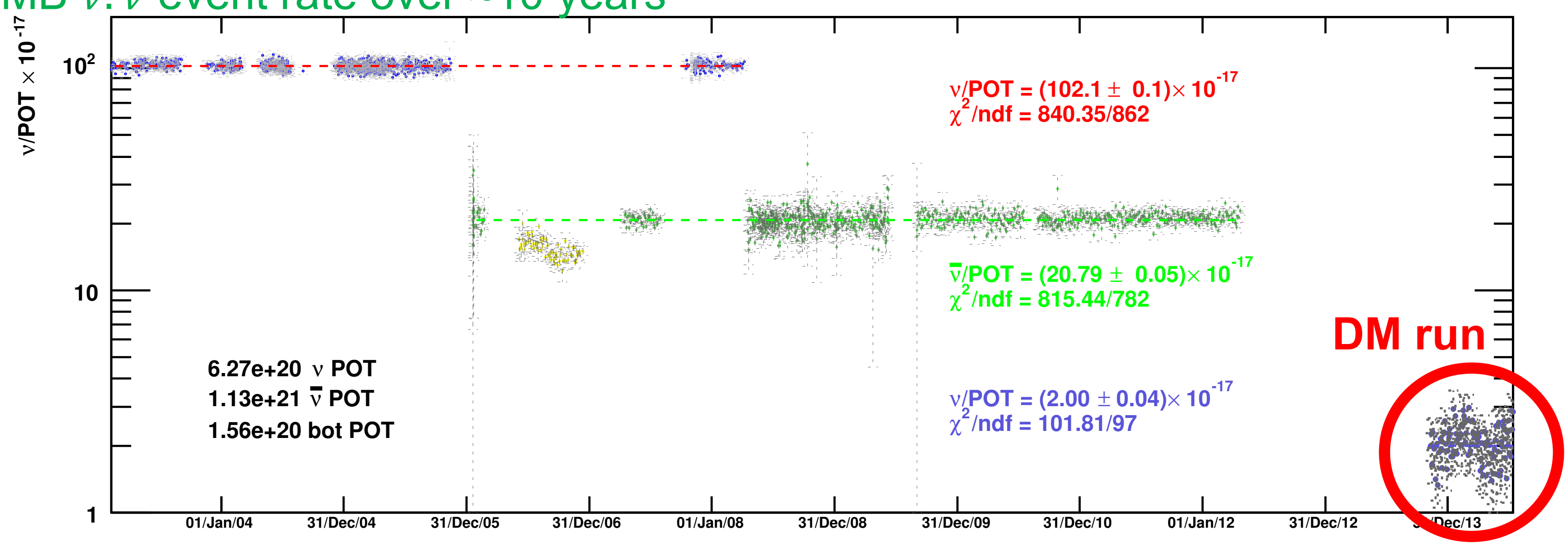
Data

- 8 month run during 2014
- 1.86E20POT collected

beam-dump mode flux / neutrino mode flux



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



1. MiniBooNE neutrino oscillation experiment

2. MiniBooNE-DM experiment

3. Results

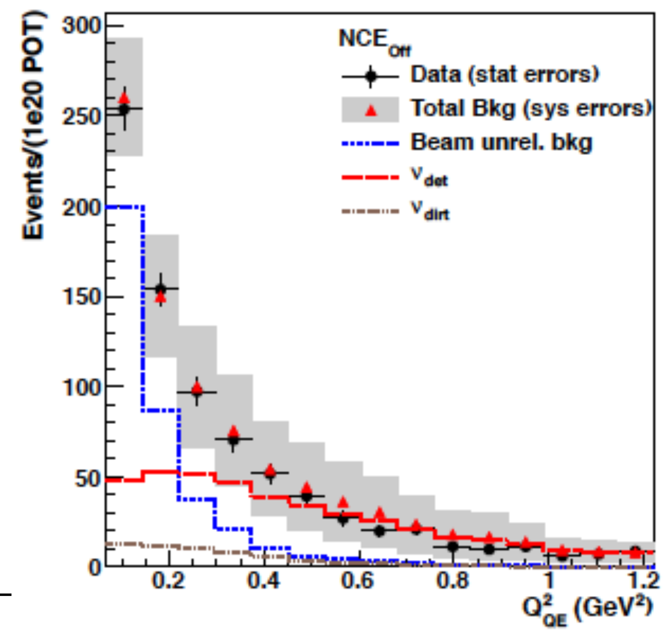
4. Future plans

3. Results

Data

- 8 month run during 2014
- 1.86E20POT collected
- We find **1465±38 interactions** after selection

beam dump mode NCE (signal)



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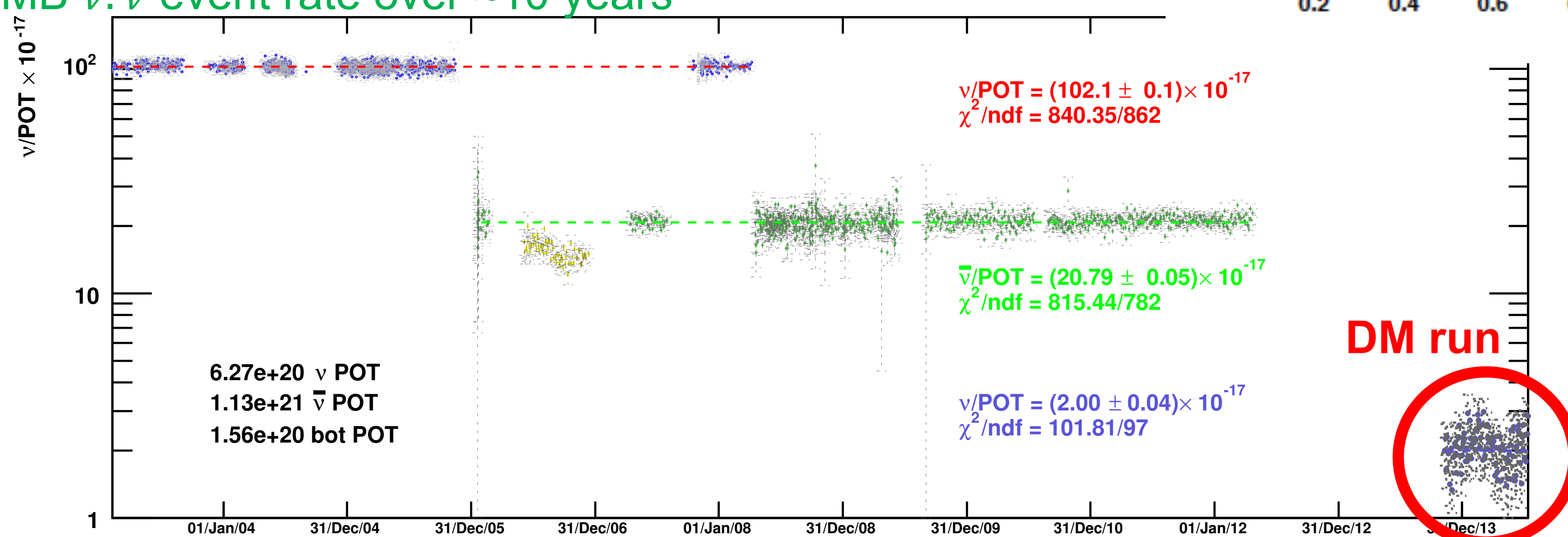
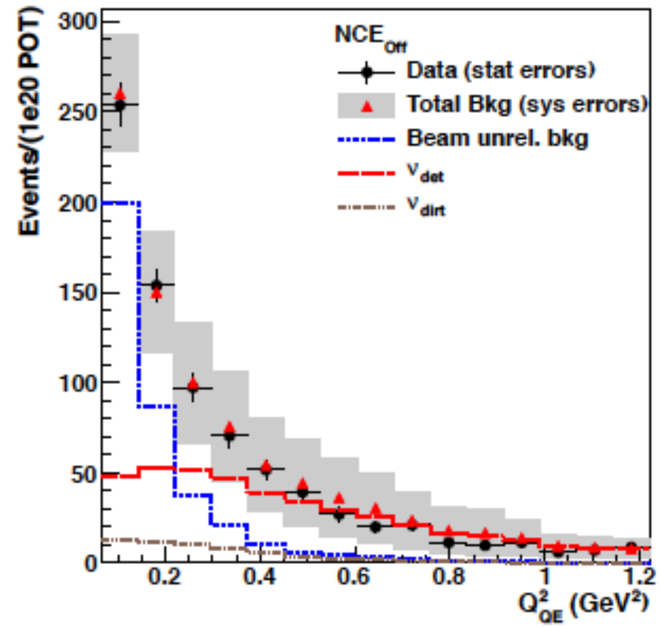


3. Results

beam dump mode NCE (signal)



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

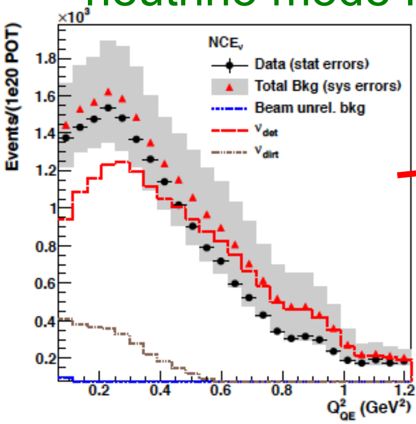
3. Results

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

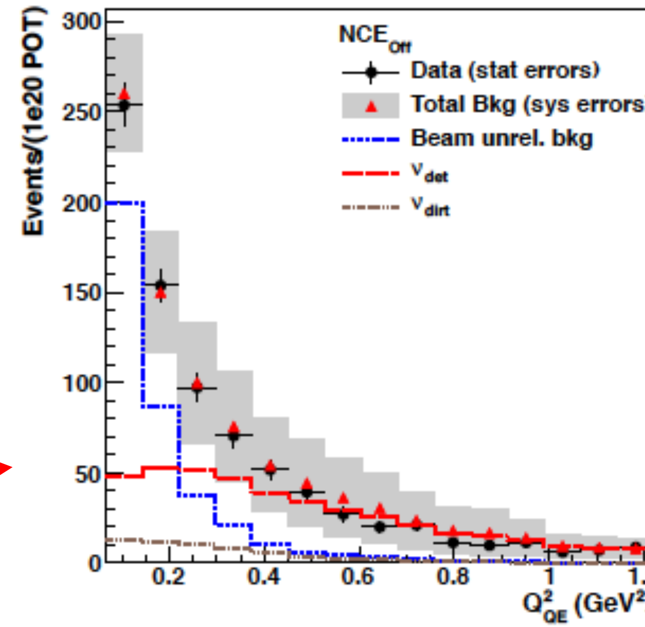
(2–4:) beam related background control

neutrino mode NCE



NCE cross section

beam dump mode NCE (signal)



3. Results

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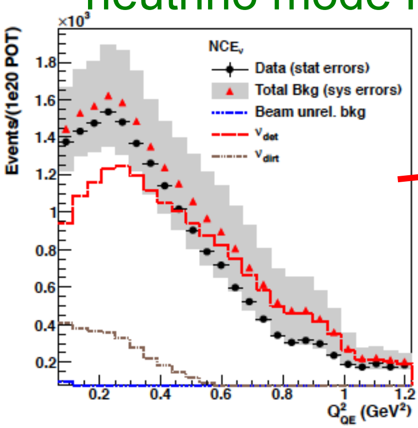
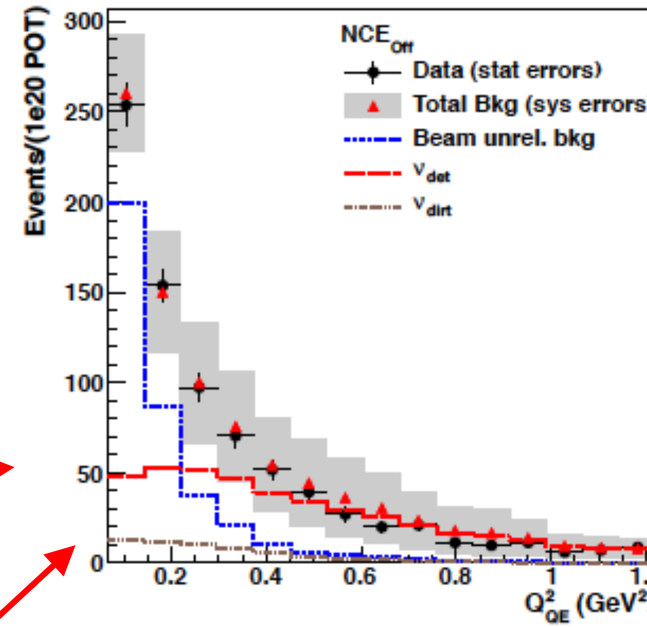
beam related background control

neutrino mode NCE

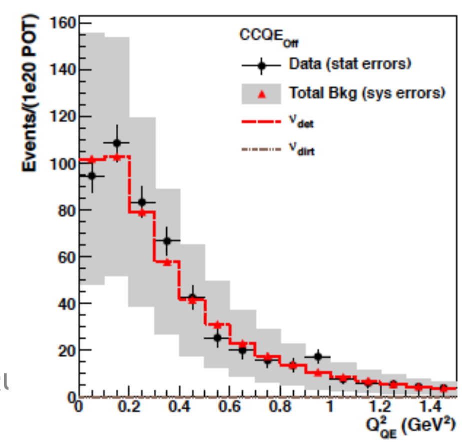


NCE cross section

beam dump mode NCE (signal)



beam dump mode CCQE



beam dump mode neutrino flux

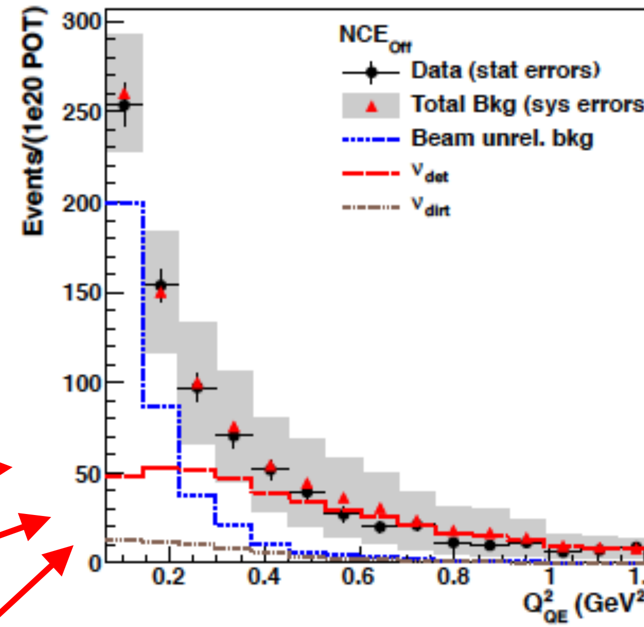
3. Results

Combined fit, simultaneous fit of 4 samples

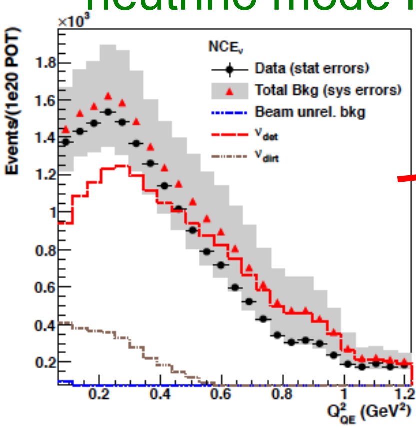
1. beam dump mode NCE (signal)
2. Neutrino mode NCE
3. beam dump mode CCQE
4. Neutrino mode CCQE

beam related background control

beam dump mode NCE (signal)

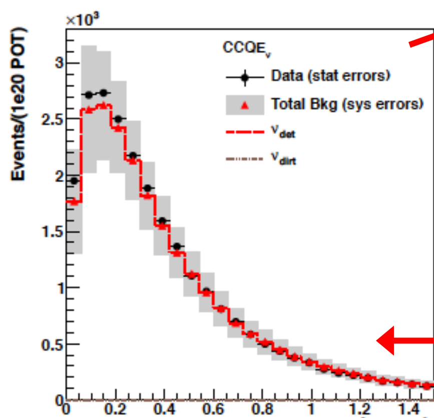


neutrino mode NCE

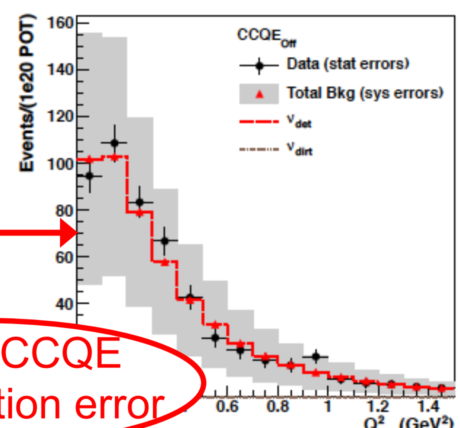


NCE cross section

neutrino mode CCQE



beam dump mode CCQE



beam dump mode neutrino flux

Cancel CCQE cross section error

Queen Mary University of London

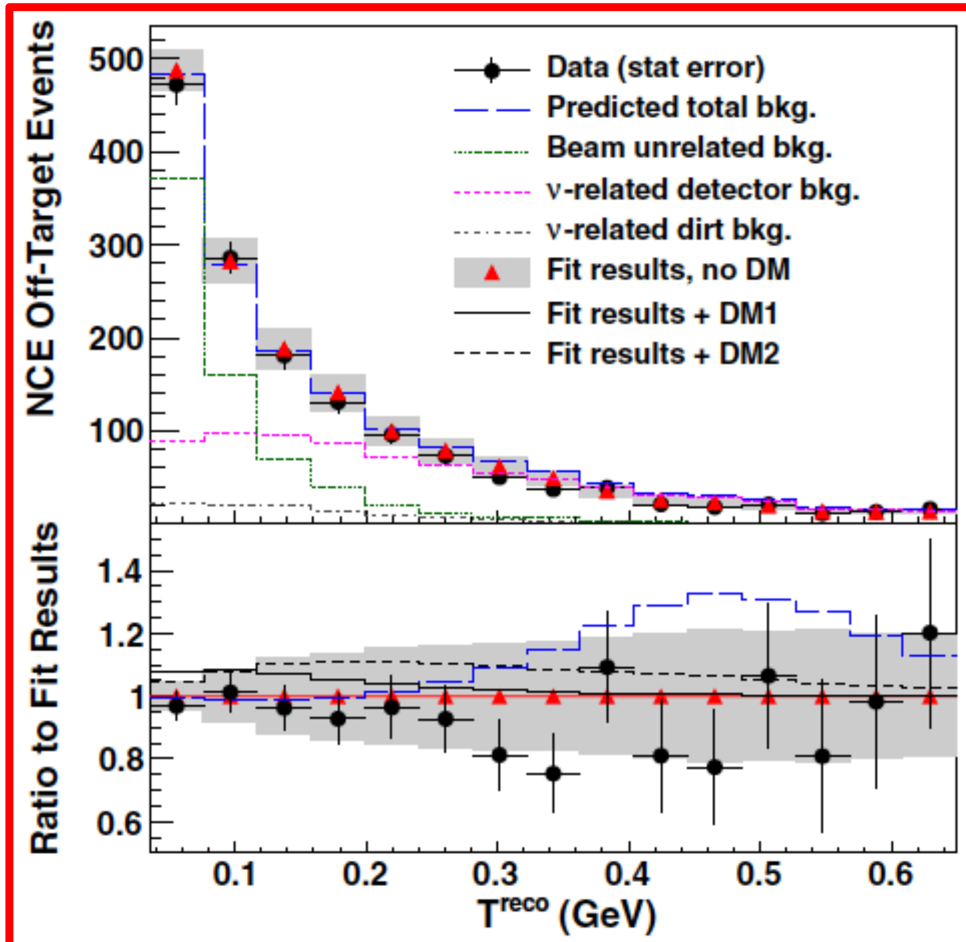
3. Results

beam dump mode NCE (signal)

Simultaneous fit result
- 8 month run during 2014
- 1.86E20POT collected
- We find **1465±38 events** after selection

1548±198 events by cosmic rays and constrained neutrino backgrounds

→ no evidence of Dark Matter



3. MiniBooNE $N\chi \rightarrow N\chi$ limit

We achieved the best limit for dark matter masses of

$0.01 < m_\chi < 0.3$ GeV

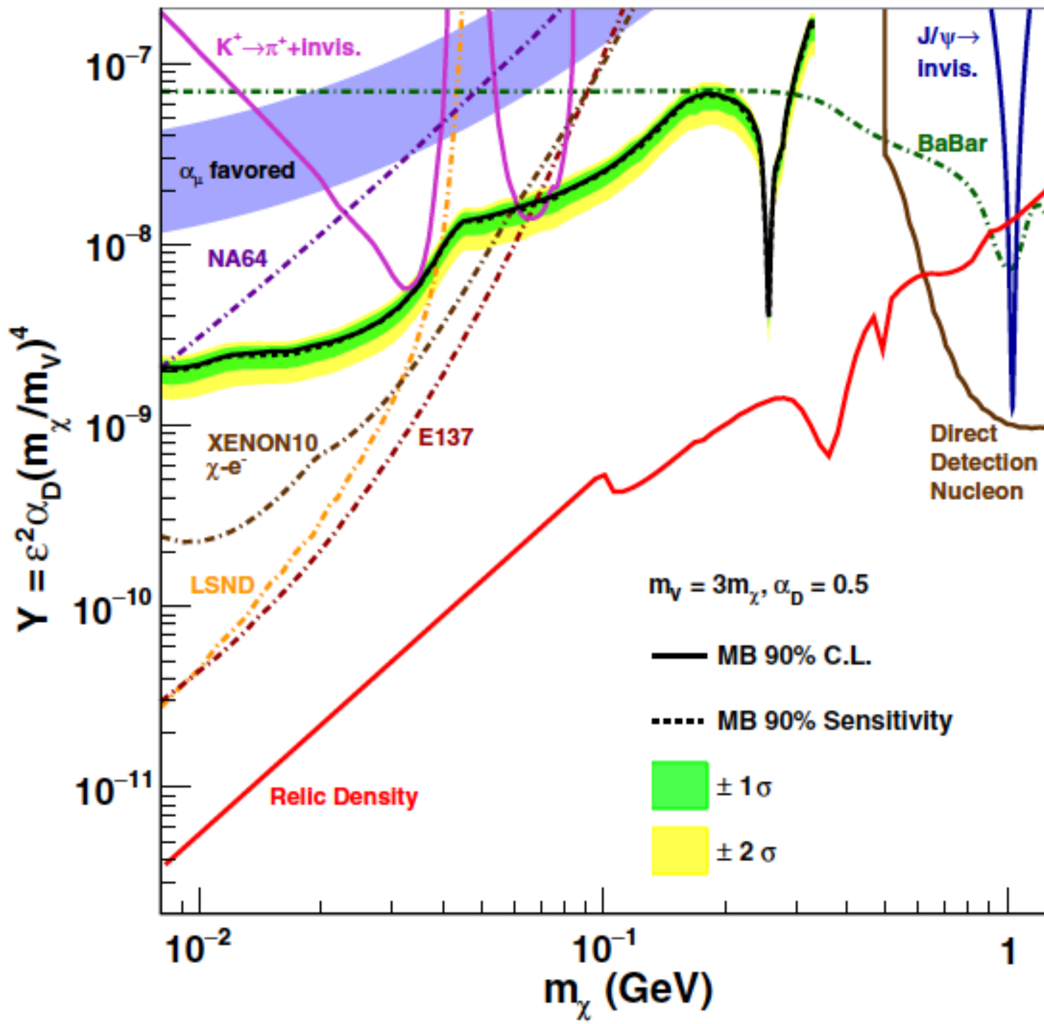
in nucleon scattering mode

ε: kinetic mixing

m_V: dark photon mass

$\alpha_D = g_D/4\pi$: dark photon coupling

($m_V = 3m_\chi$, $\alpha_D = 0.5$)



1. MiniBooNE neutrino oscillation experiment

2. MiniBooNE-DM experiment

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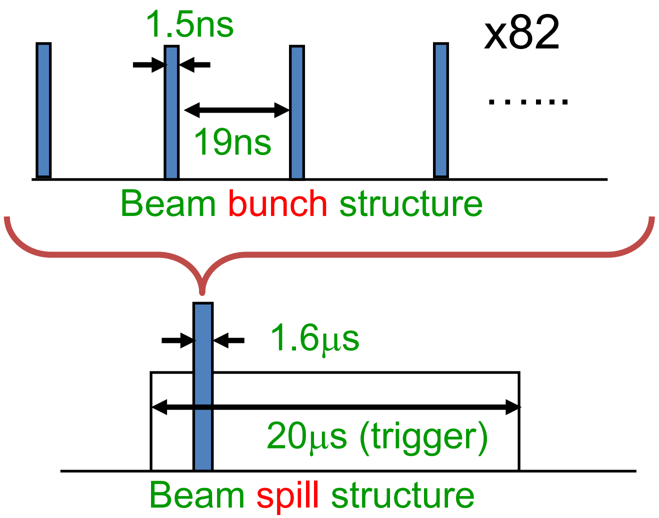
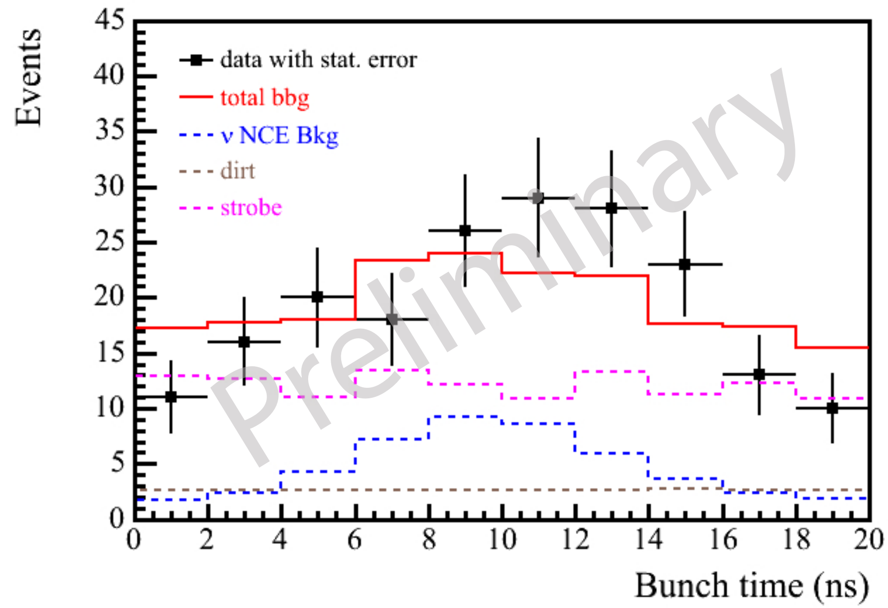
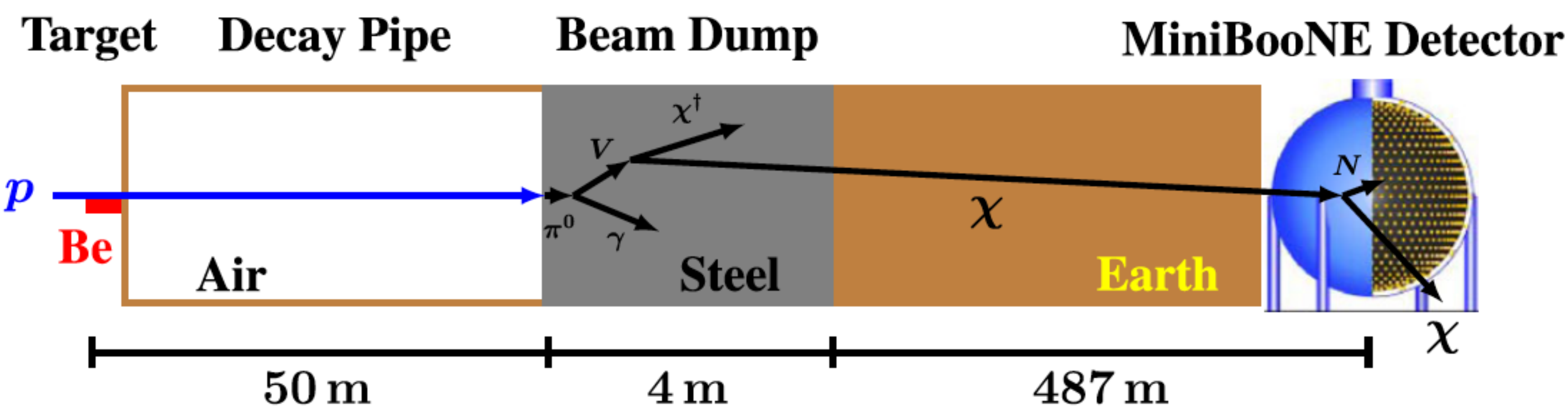
4. Future plans: Dark Matter Time-of-Flight

Dark matter mχ > 50 MeV can be selected by ToF



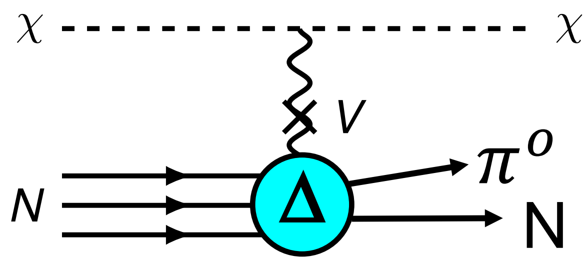


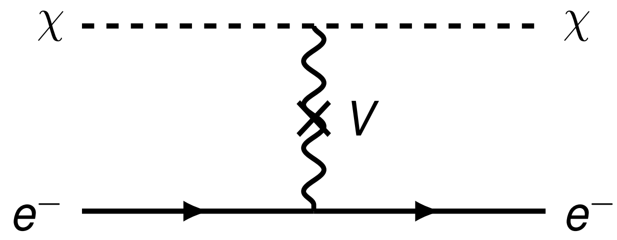


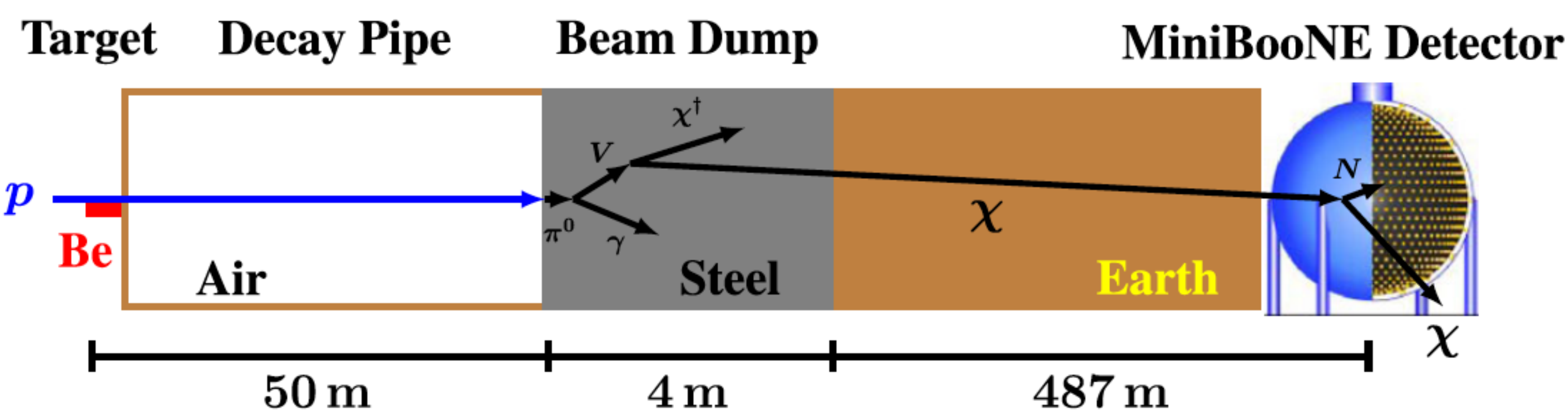
4. Future plans: Inelastic and electron channels

Dark matter m_χ > 50 MeV can be selected by ToF

New channels to study
- inelastic DM scattering
- e-DM scattering



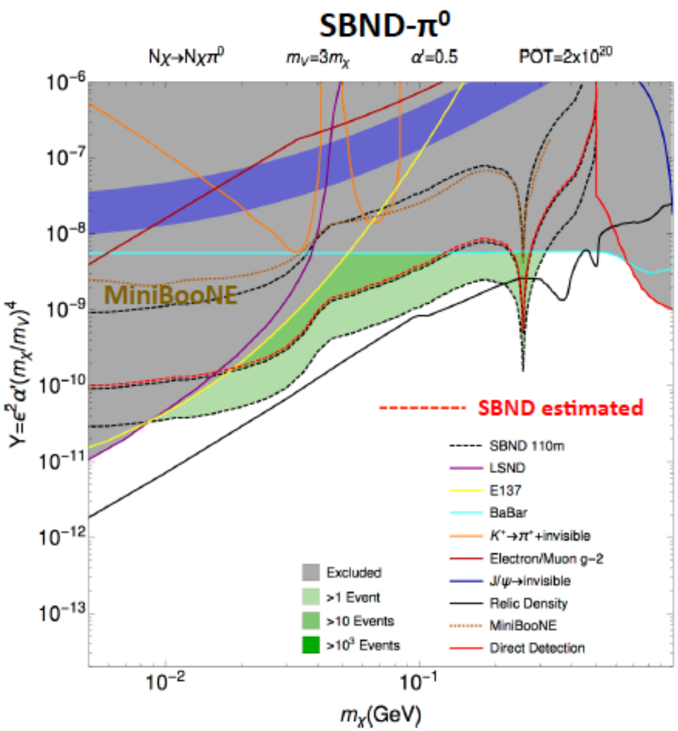


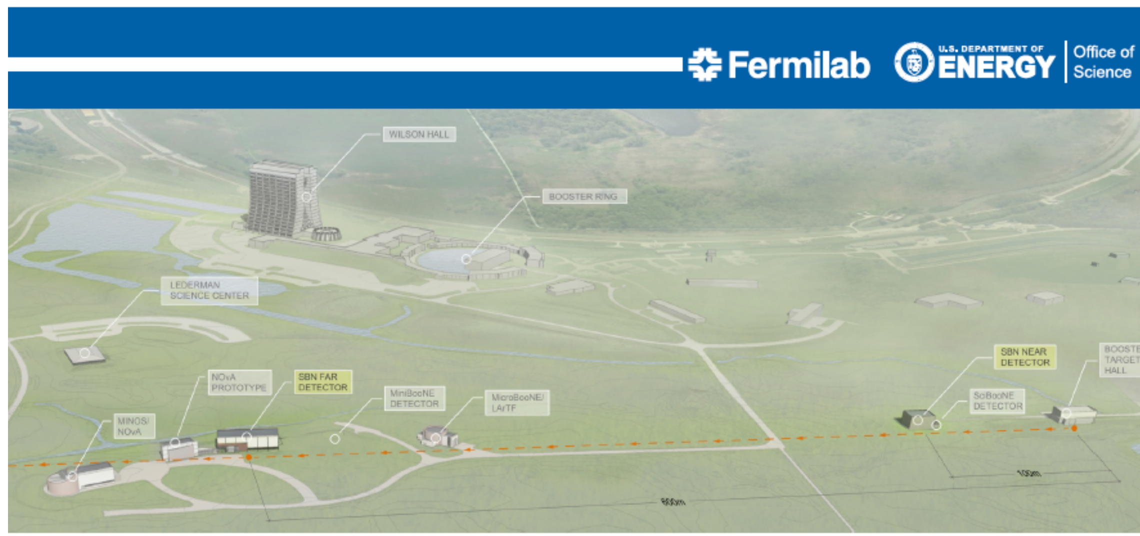


4. Future plans: Beam-dump mode with Fermilab SBN

LoI of new beam dump mode run was submitted to Fermilab PAC, Nov. 2017 (Manchester, Liverpool, Queen Mary)

Many new ideas were presented
- Simultaneous run with neutrino mode (x50 neutrino bkgd reduction)
- New target block (~x1000 neutrino bkgd reduction)





Next Step in Accelerator Sub-GeV Dark Matter Searches at FNAL: An Expression of Interest to Improve the BNB Beam Dump for SBN

R.G. Van de Water (LANL, P-25 Subatomic Physics)

FNAL PAC Nov 16-17, 2017

Queen Mary
University of London

Conclusion

MiniBooNE neutrino beam line enhances production of sub-GeV DM with by the beam dump mode

Scintillation light is used to reconstruct the total nucleon energy

We achieved the best limit for dark matter masses of

$$0.01 < m_\chi < 0.3 \text{ GeV}$$

in nucleon scattering mode

Future plans

- electron and π^o channels will be used for sub-GeV DM searches
- Event timing with RF bunch should allow dark matter TOF
- LoI of beam dump mode run was submitted to Fermilab PAC (Nov. 2017)

Tyler Thornton
(main analyzer)
Indiana university

Thank you for your attention!

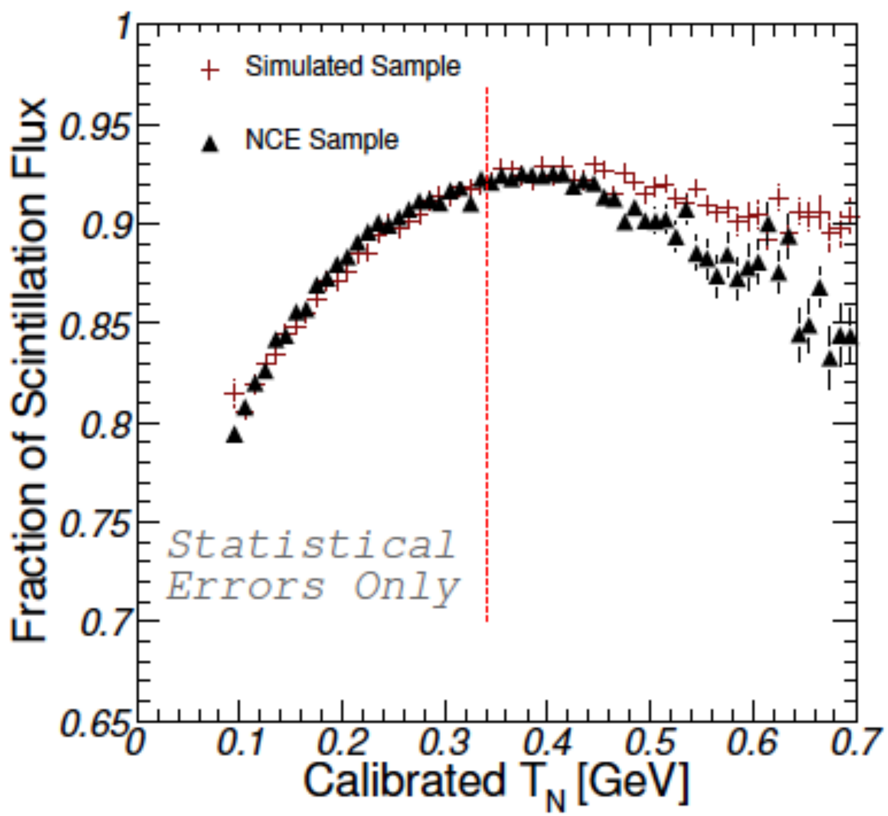
backup

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

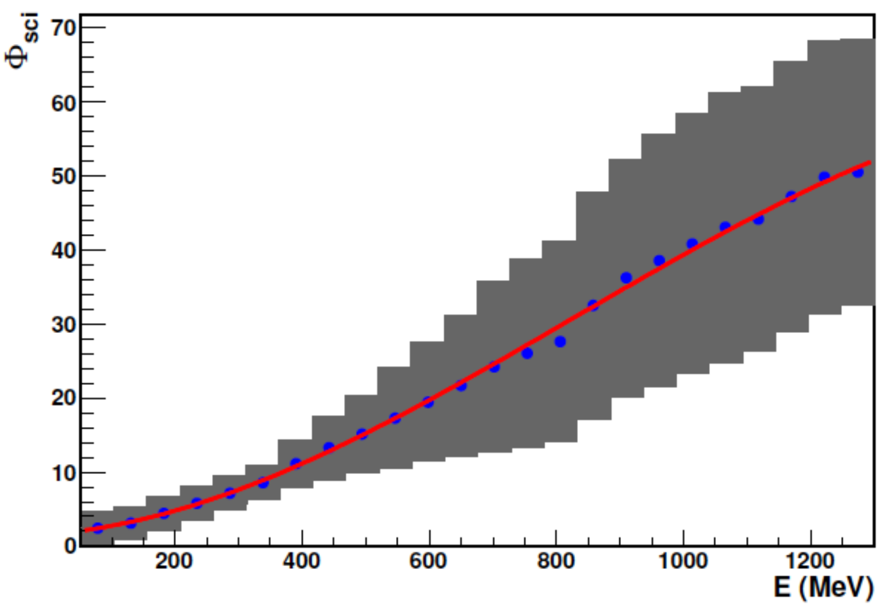
NCE charge prediction

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

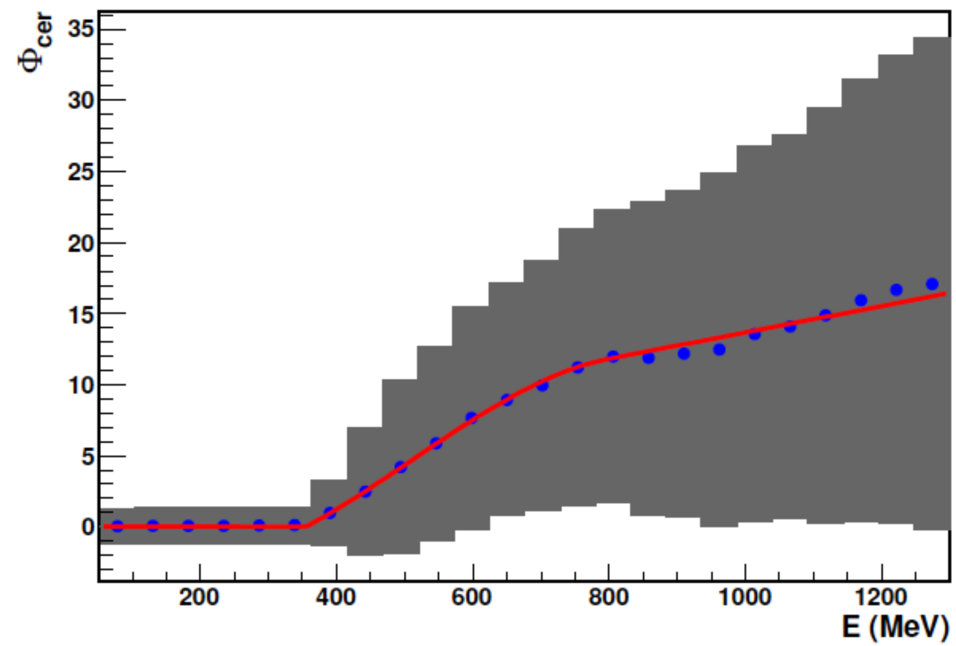
$$\mu_{sci}(\vec{\mathbf{X}}) = \epsilon\Phi_{sci}(E)\frac{\exp(-r/\lambda_{sci}(R))}{r^2}f(\cos\eta)F_{sci}(E,\cos\theta,R)Corr(E,\cos\alpha),$$

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

Scintillation flux



Cherenkov flux



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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

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

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

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

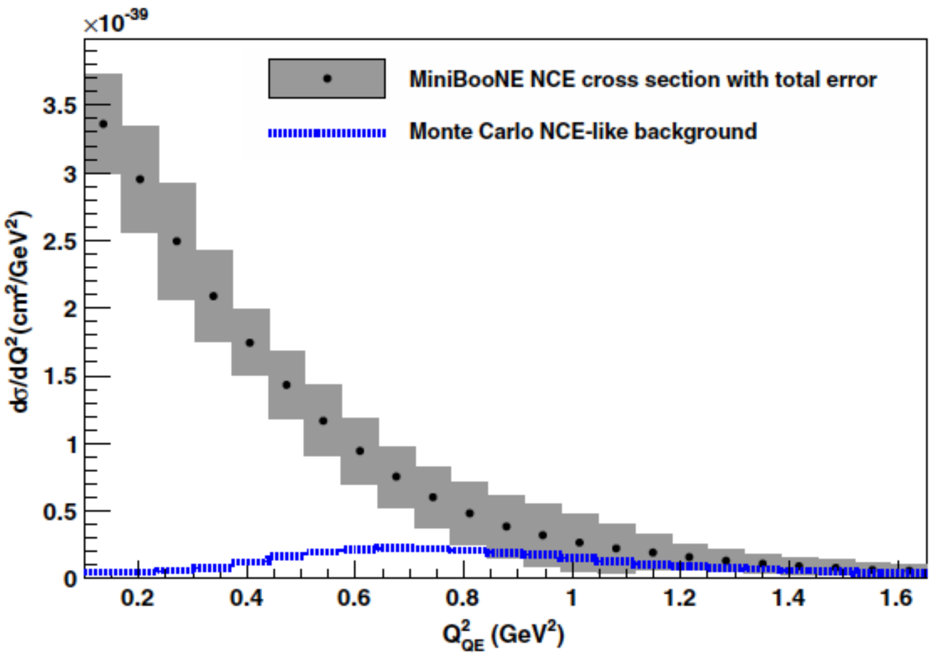
$$f_t^{sci}(t_{corr}) = \frac{1}{2\tau}\exp\left(\frac{\sigma^2}{2\tau^2}-\frac{t_{corr}-t_0}{\tau}\right)\mathrm{Erfc}\left[\frac{\sigma}{\sqrt{2}\tau}-\frac{t_{corr}-t_0}{\sigma}\right]$$

2. Neutral Current Elastic (NCE) cross section measurements

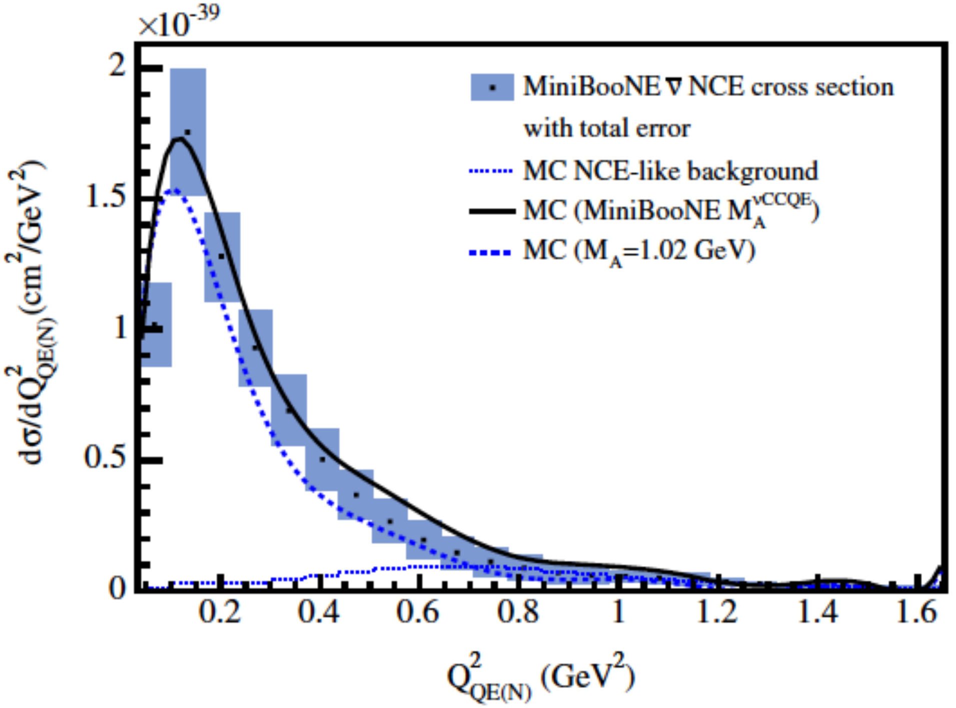
MiniBooNE flux-integrated NCE differential cross section

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

neutrino NCE differential cross section

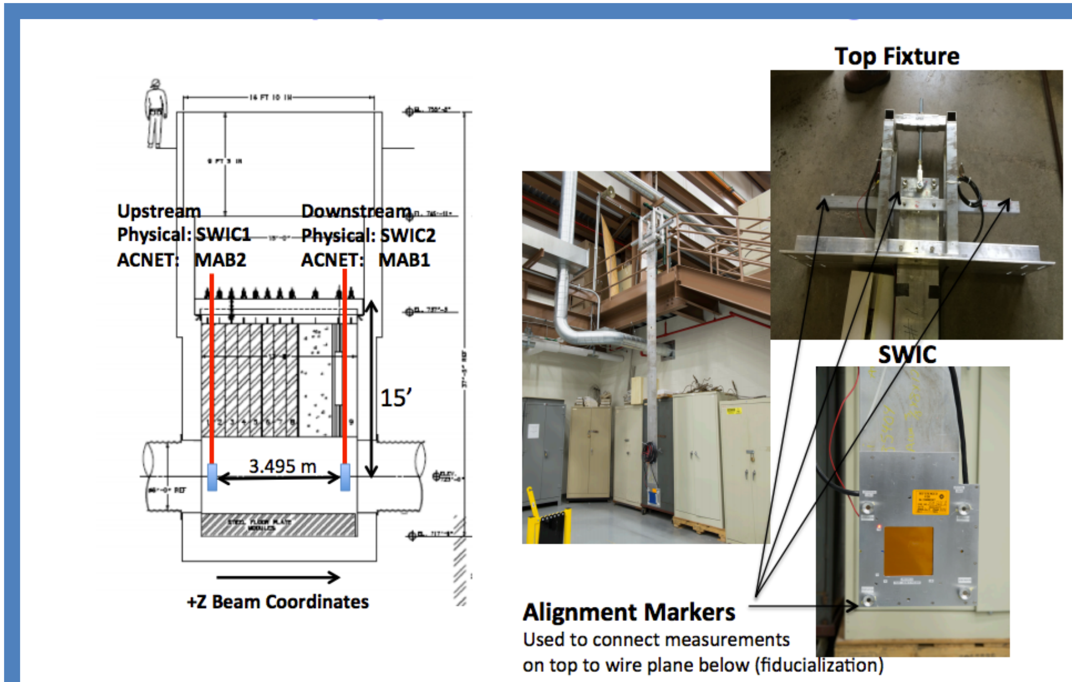


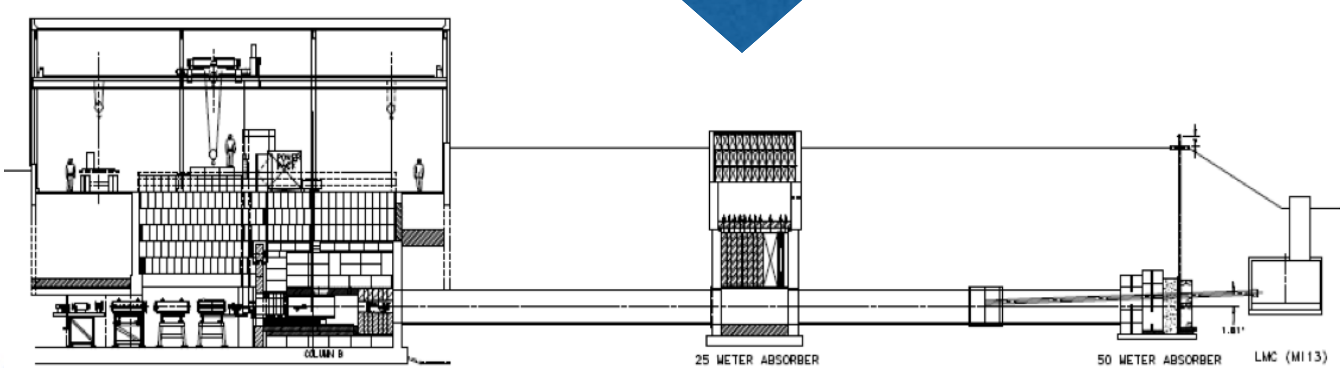
anti-neutrino NCE differential cross section



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

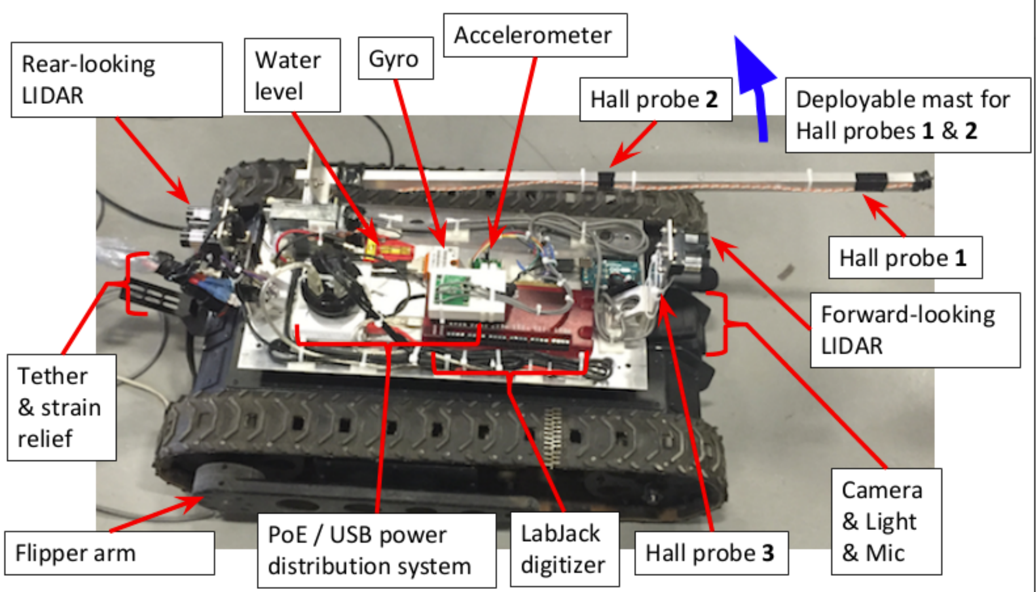


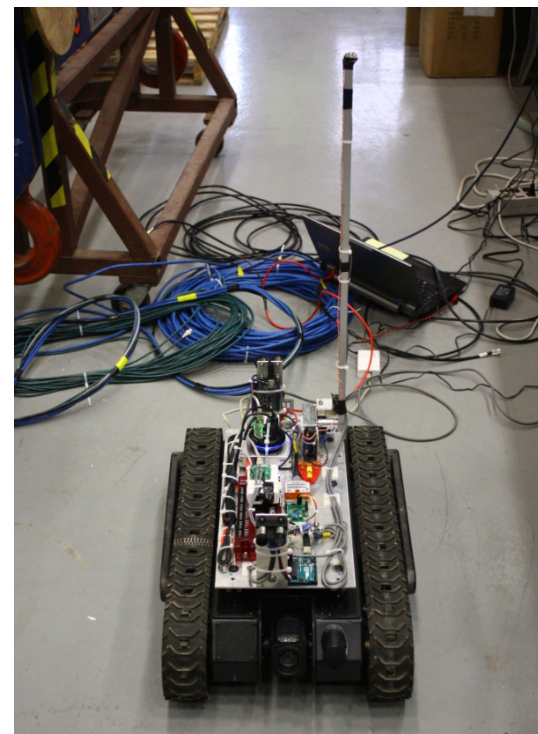


Target hall in MI 12 25m deployable absorber 50m Fe dump

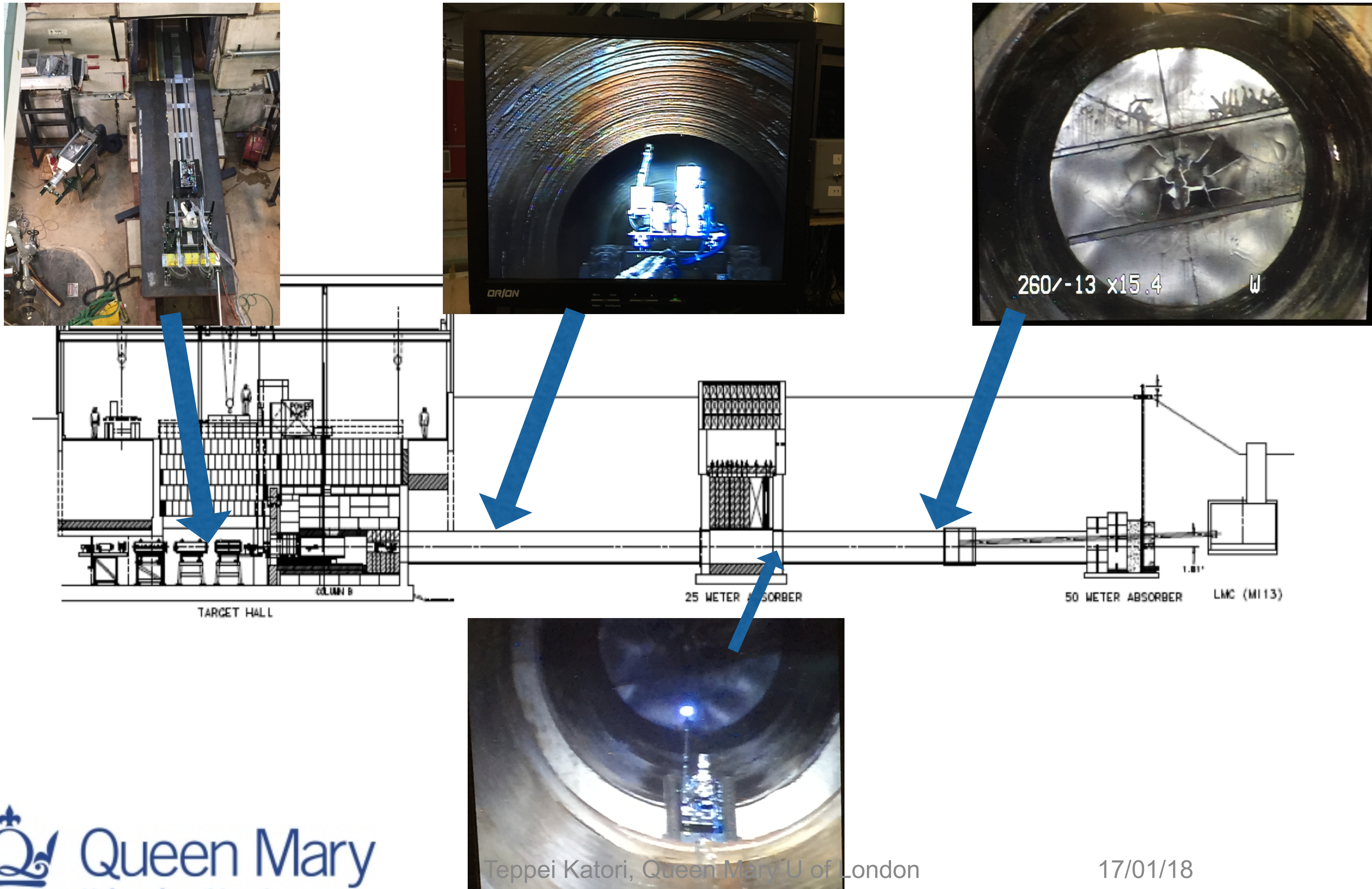
MiniBooNE: DM source

- 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"



LSND, PRD64(2001)112007

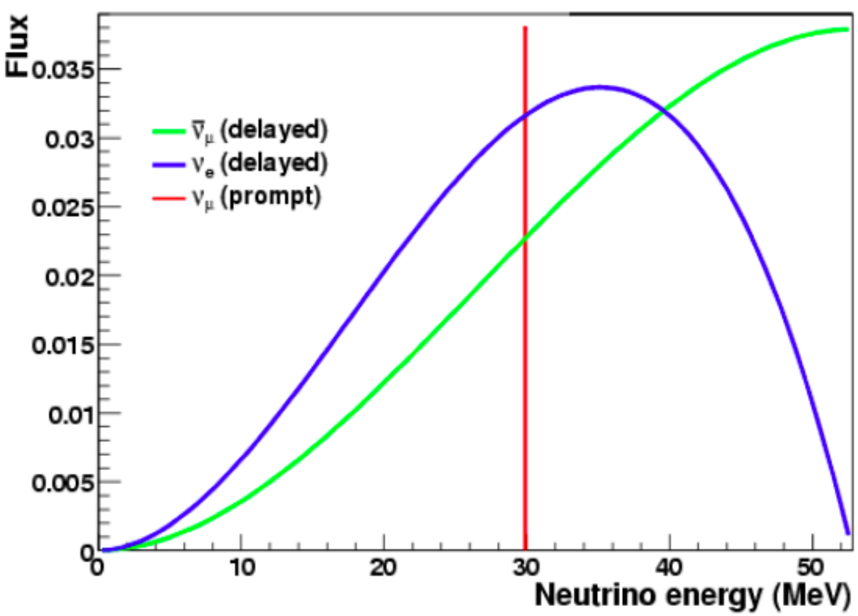
1. LSND

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

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

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

L/E~30m/40MeV~0.7

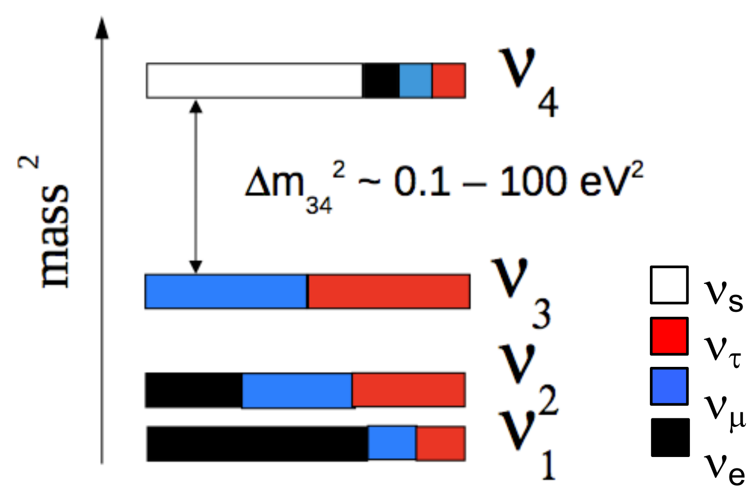


Data is consistent with two massive neutrino oscillation model with $\Delta m^2 \sim 1eV^2$,
$87.9 \pm 22.4 \pm 6.0$ $(3.8.\sigma)$

3 types of neutrino oscillations are found:
LSND neutrino oscillation: $\Delta m^2 \sim 1eV^2$
Atmospheric neutrino oscillation: $\Delta m^2 \sim 10\text{-}3eV^2$
Solar neutrino oscillation : $\Delta m^2 \sim 10\text{-}5eV^2$

But we cannot have so many Δm^2!

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



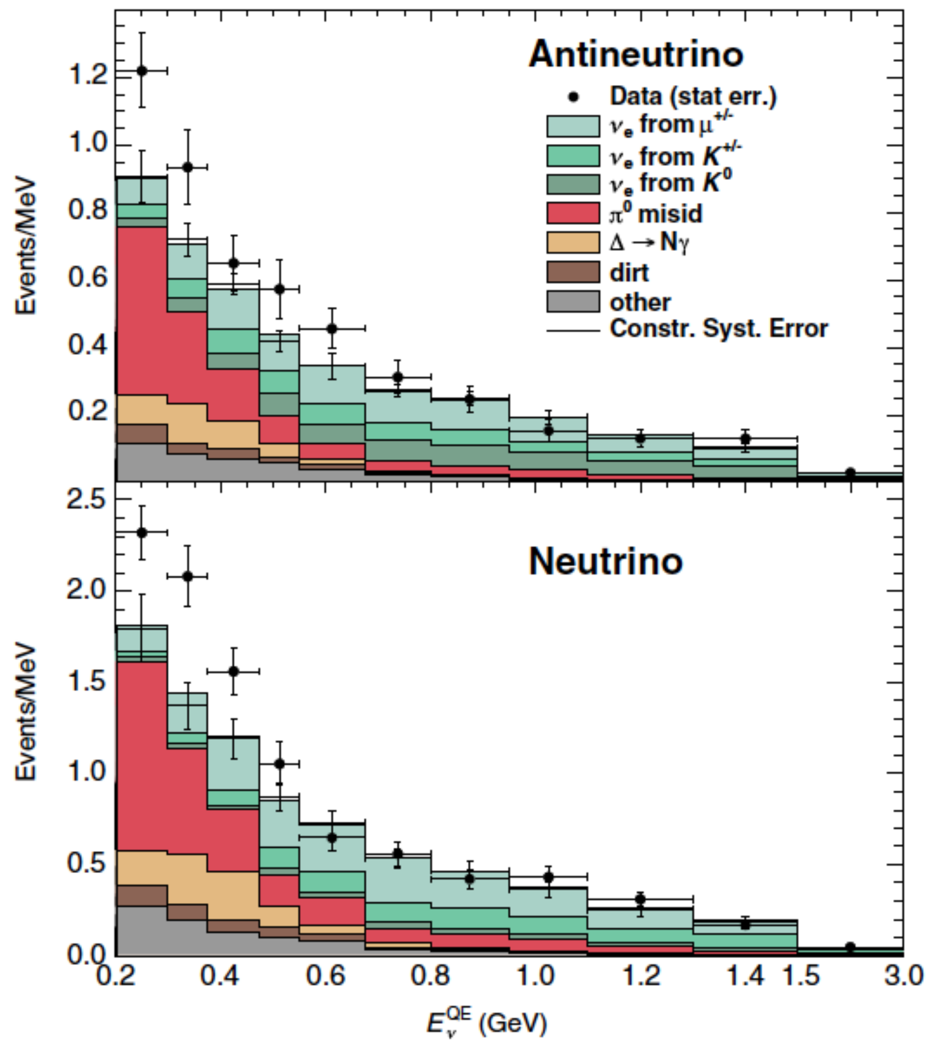
1. MiniBooNE

MiniBooNE observed event excesses in both mode

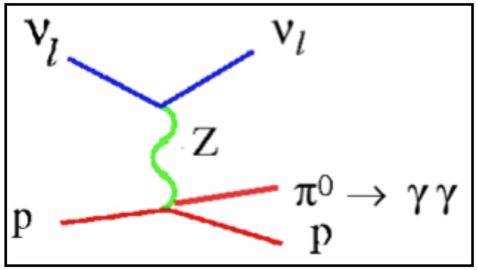
Neutrino mode
162.0 ± 28.1 ± 38.7 (3.4σ)

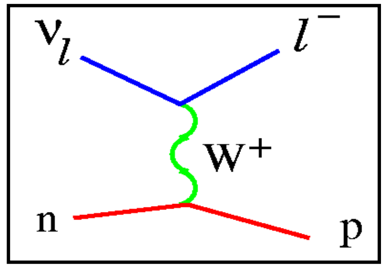
Antineutrino mode
78.9 ± 20.0 ± 20.3 (2.8σ)

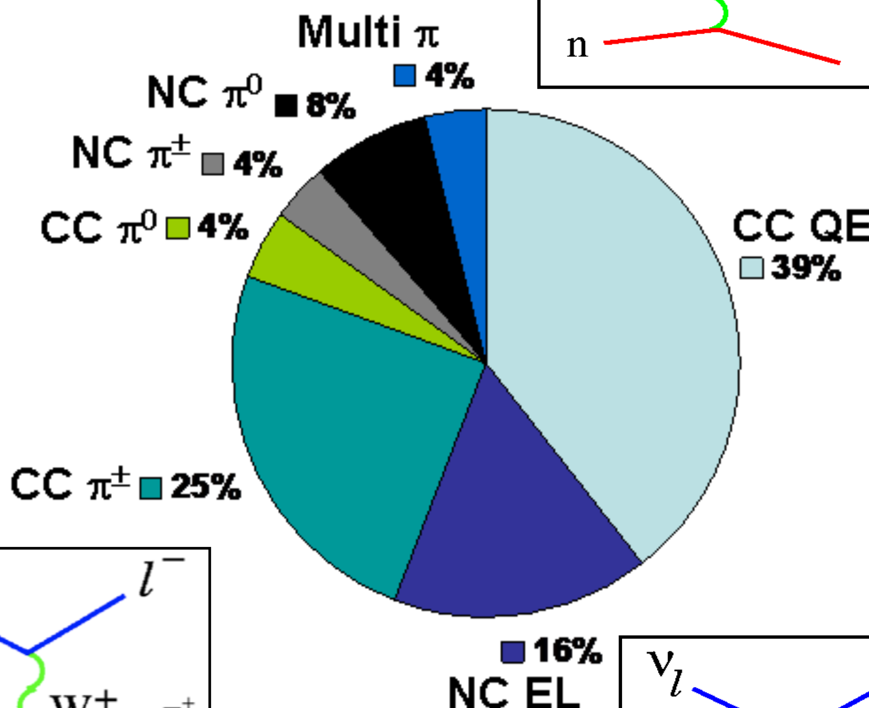
oscillation candidate events

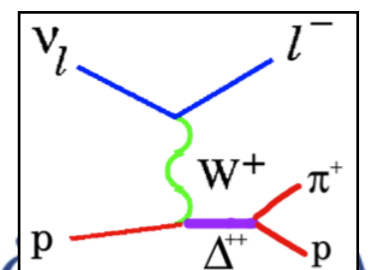


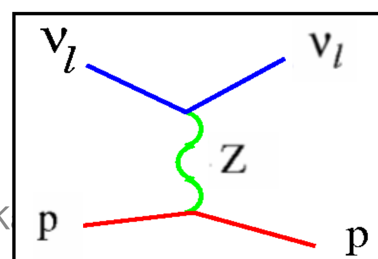
1. Cross section model





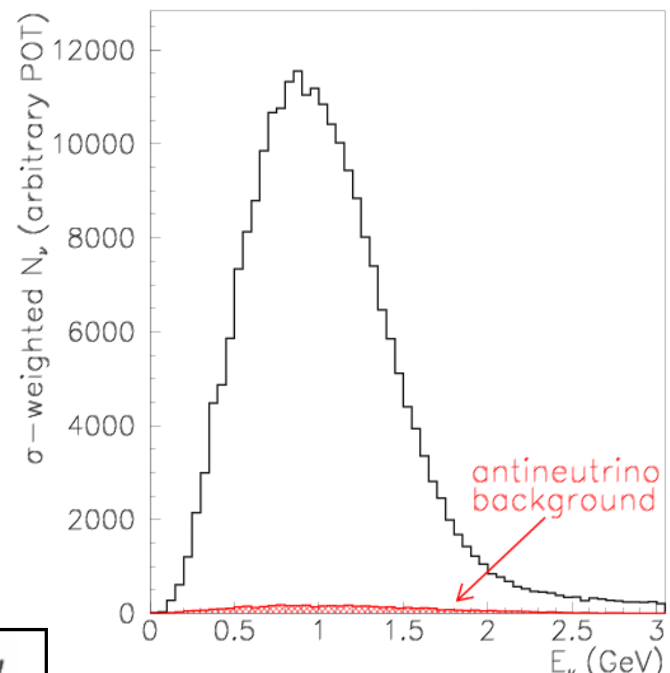






Predicted event rates before cuts (NUANCE Monte Carlo)

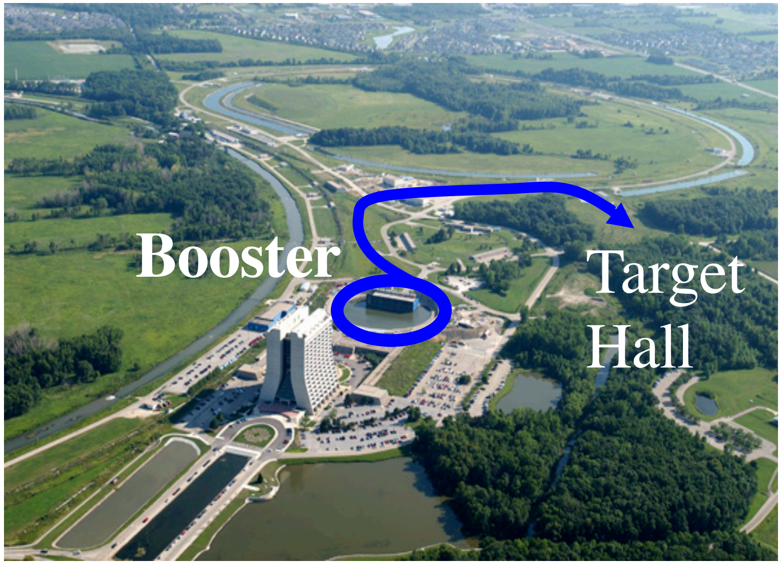
Casper, Nucl.Phys.Proc.Suppl.112(2002)161



Event neutrino energy (GeV)

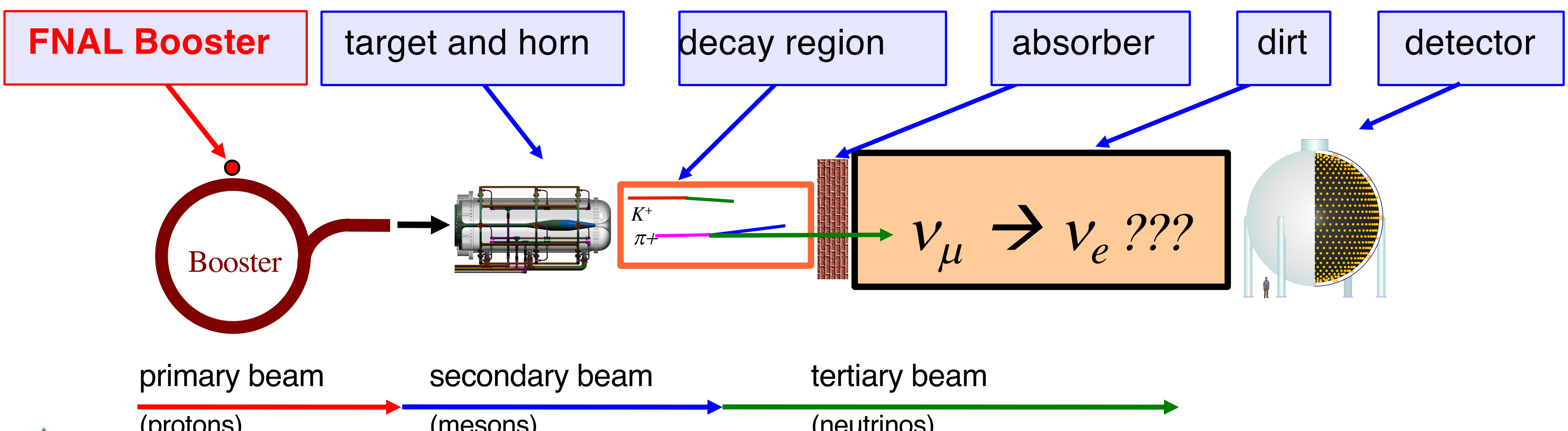
MiniBooNE,PRD79(2009)072002

1. Neutrino beam



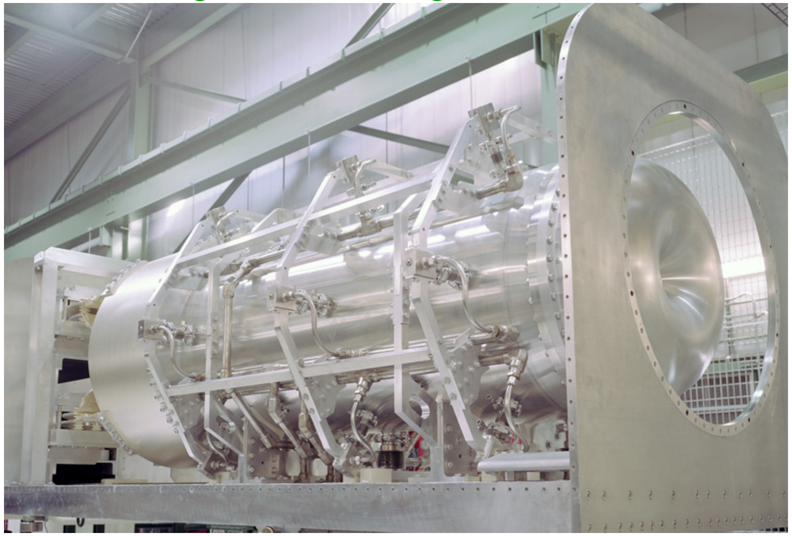
MiniBooNE extracts beam from the 8 GeV Booster

FNAL Booster



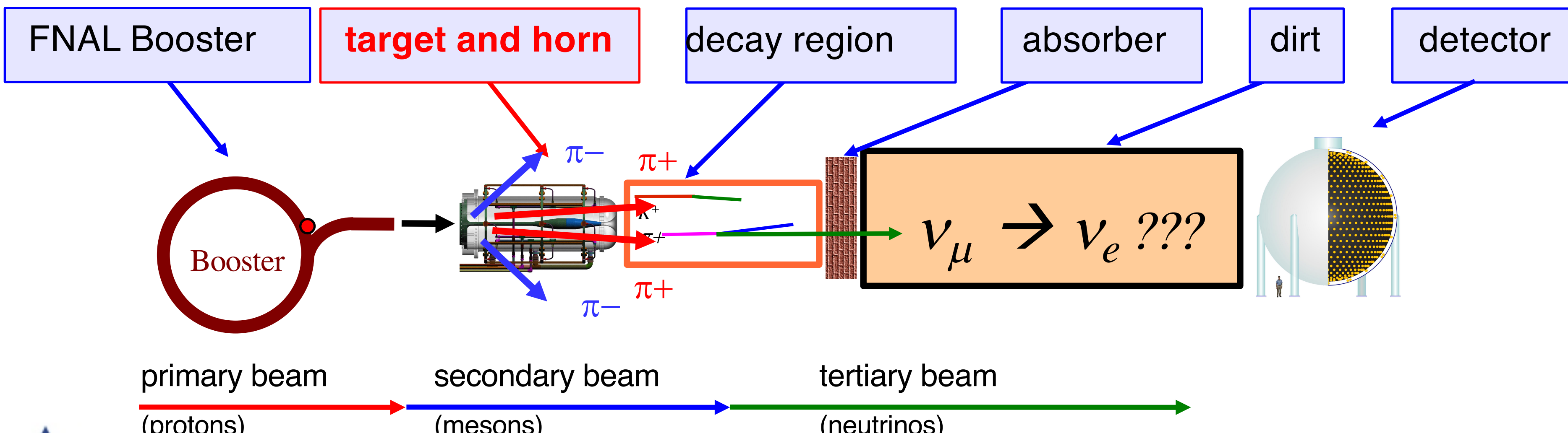
1. Neutrino beam

Magnetic focusing horn



8GeV protons are delivered to a 1.7 λ Be target

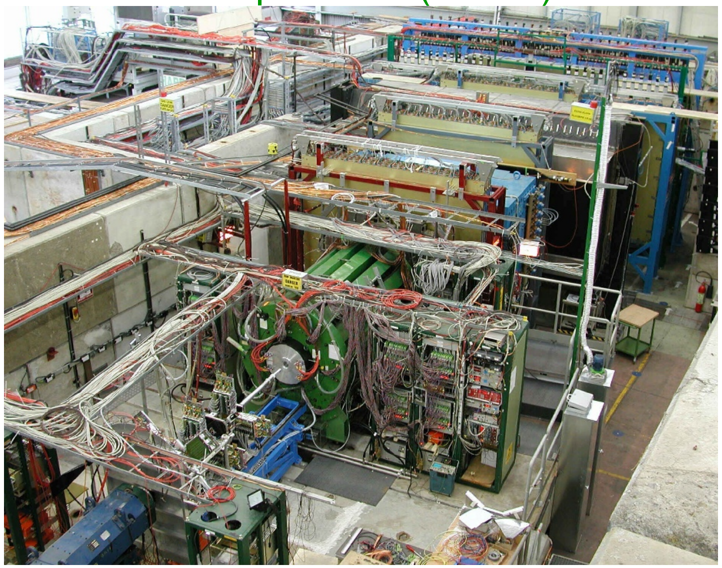
within a magnetic horn (2.5 kV, 174 kA) that increases the flux by x6



MiniBooNE,PRD79(2009)072002

1. Neutrino beam

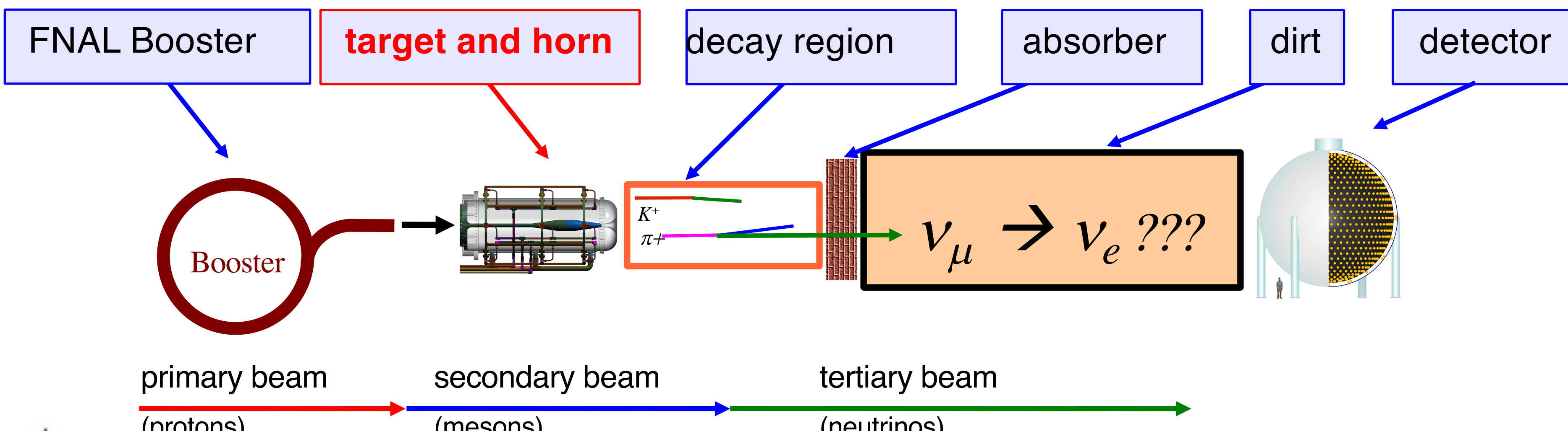
HARP experiment (CERN)



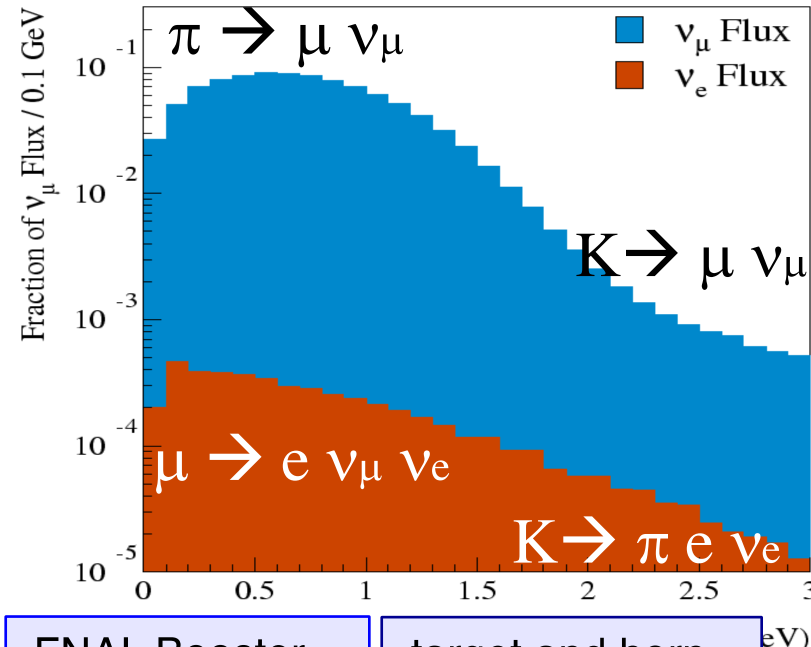
Modeling of meson production is based on the measurement done by HARP collaboration.

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

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



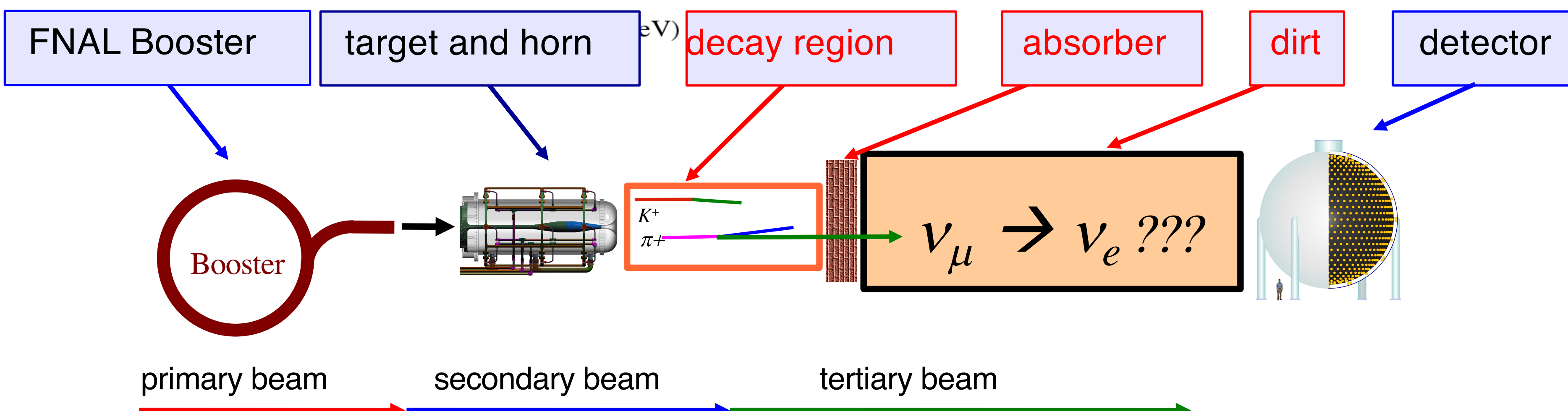
1. Neutrino beam



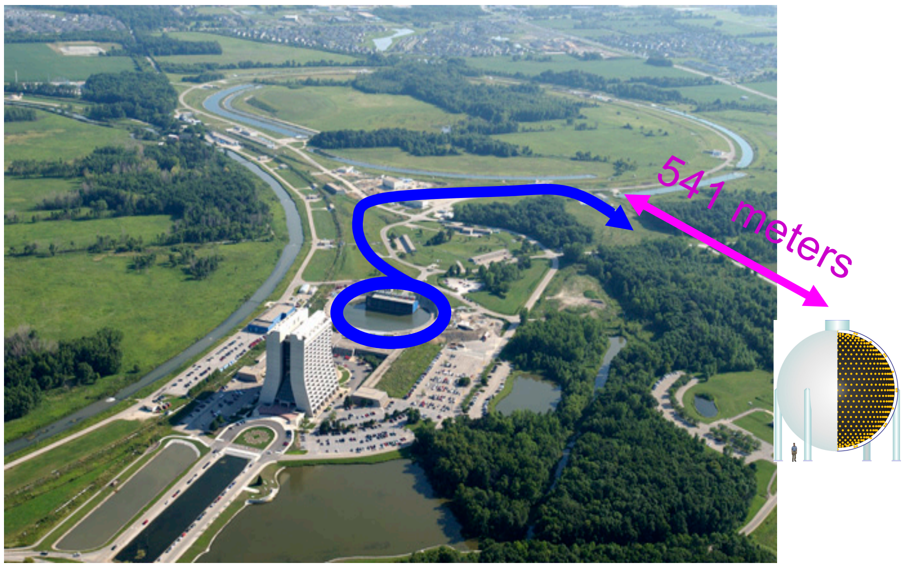
Neutrino flux from simulation by GEANT4

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

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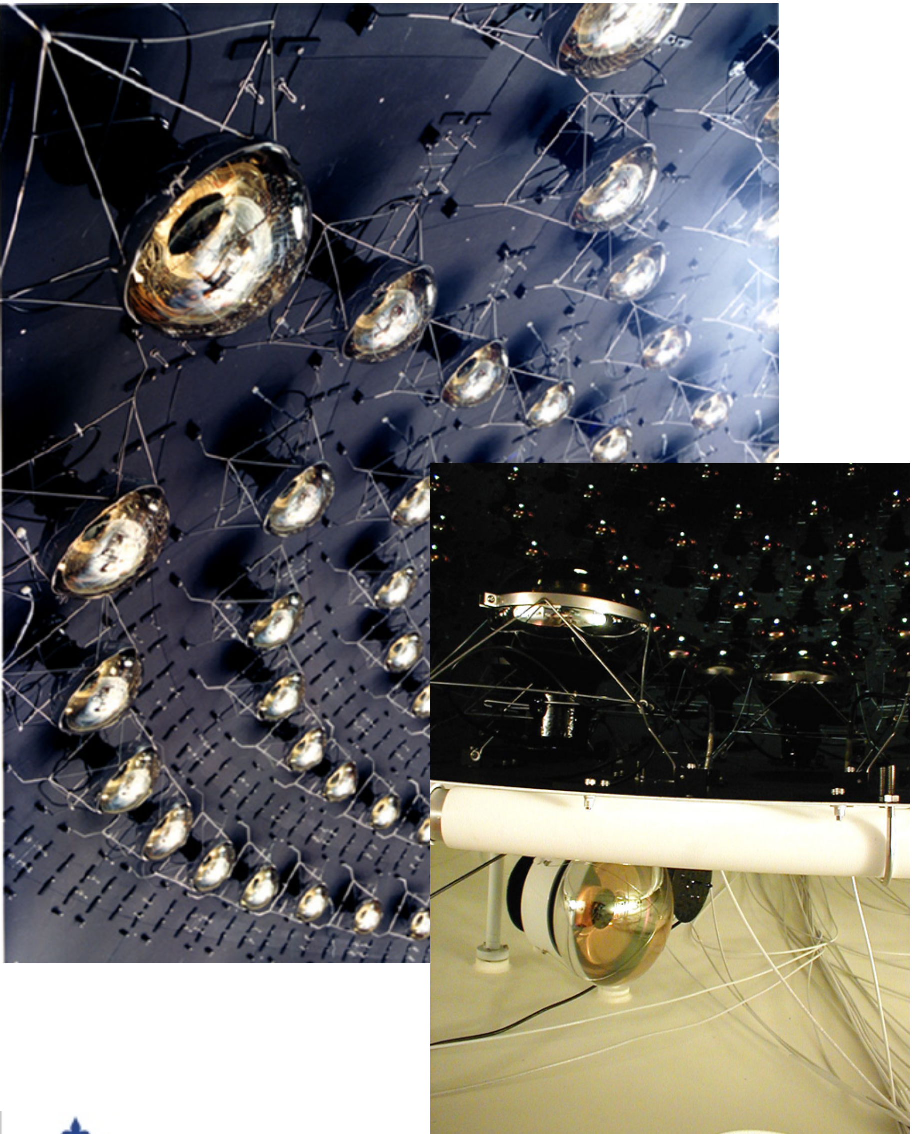

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MiniBooNE,NIM.A599(2009)28

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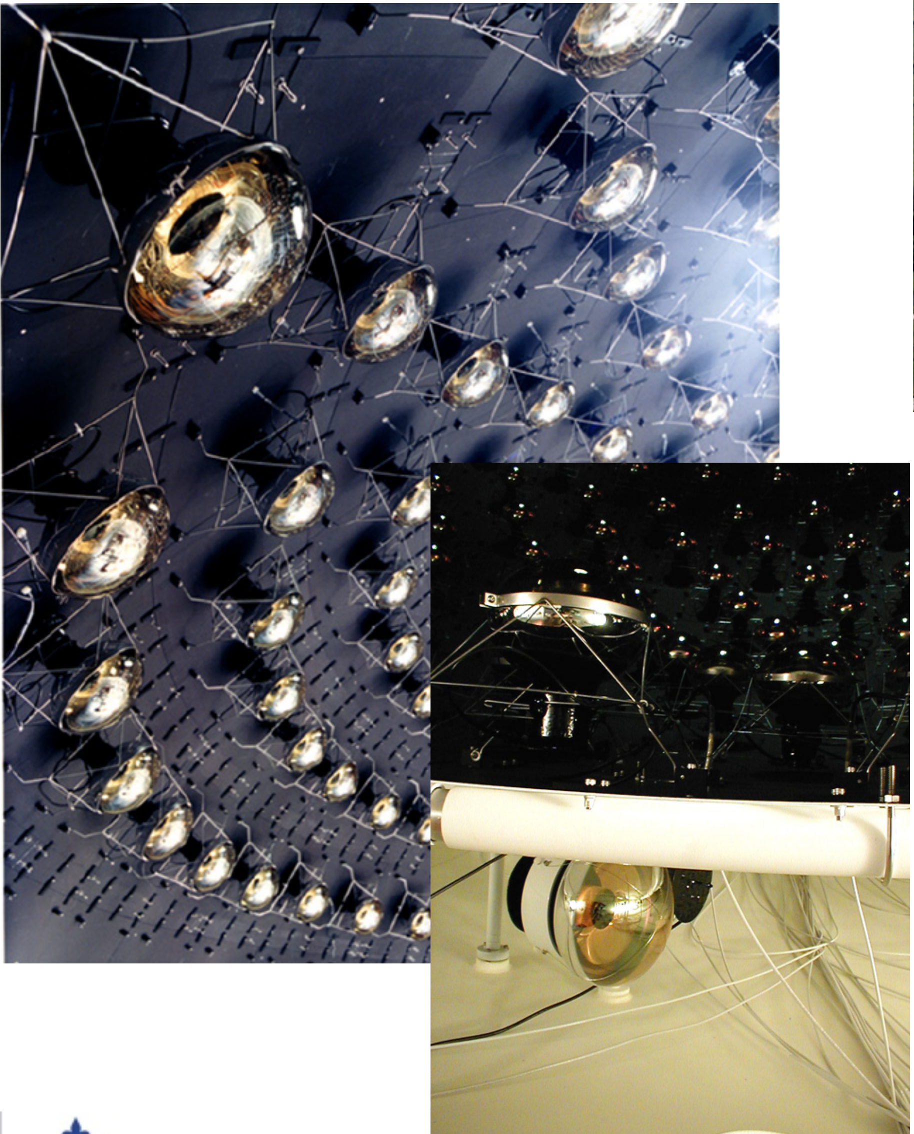

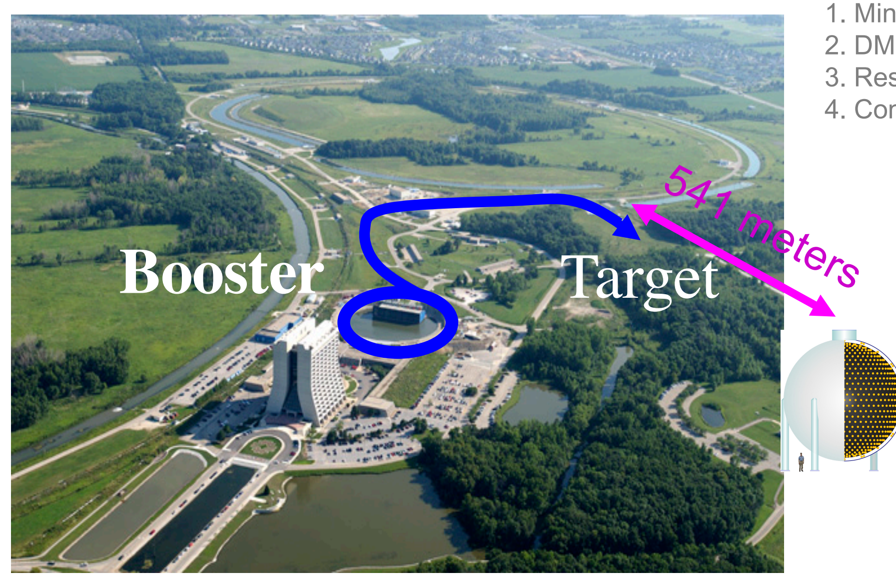

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1. Events in the Detector

Times of hit-clusters (subevents)

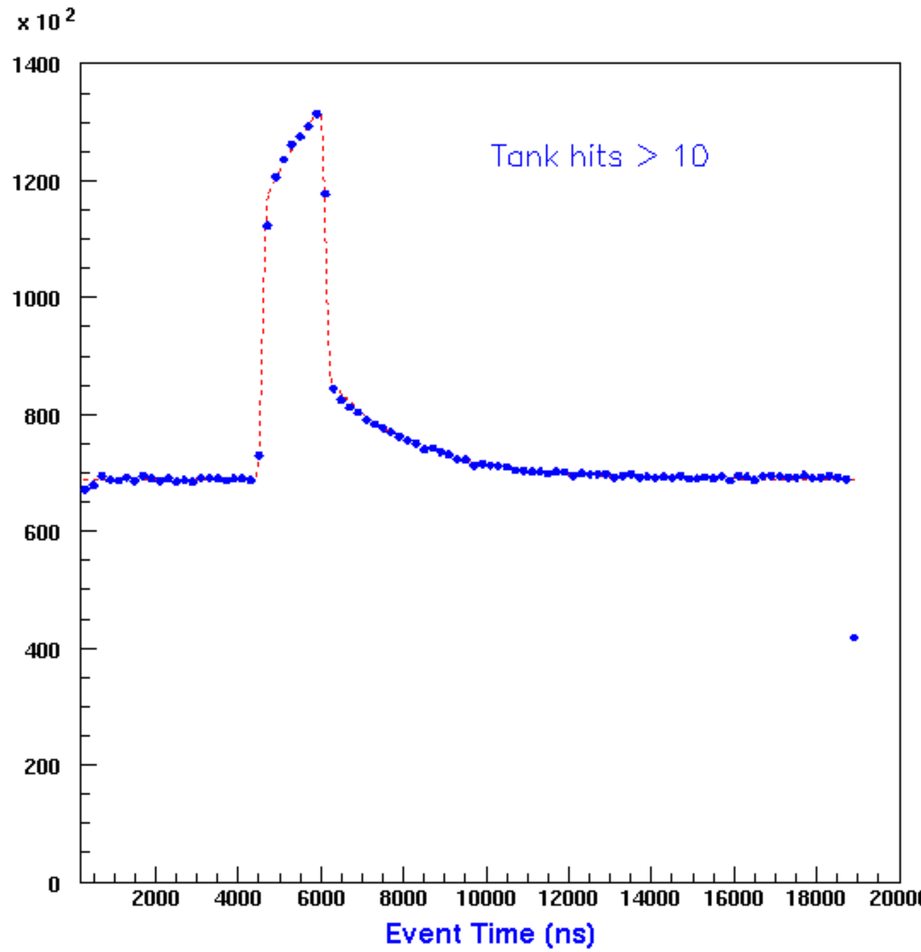
Beam spill (1.6μs) is clearly evident

- 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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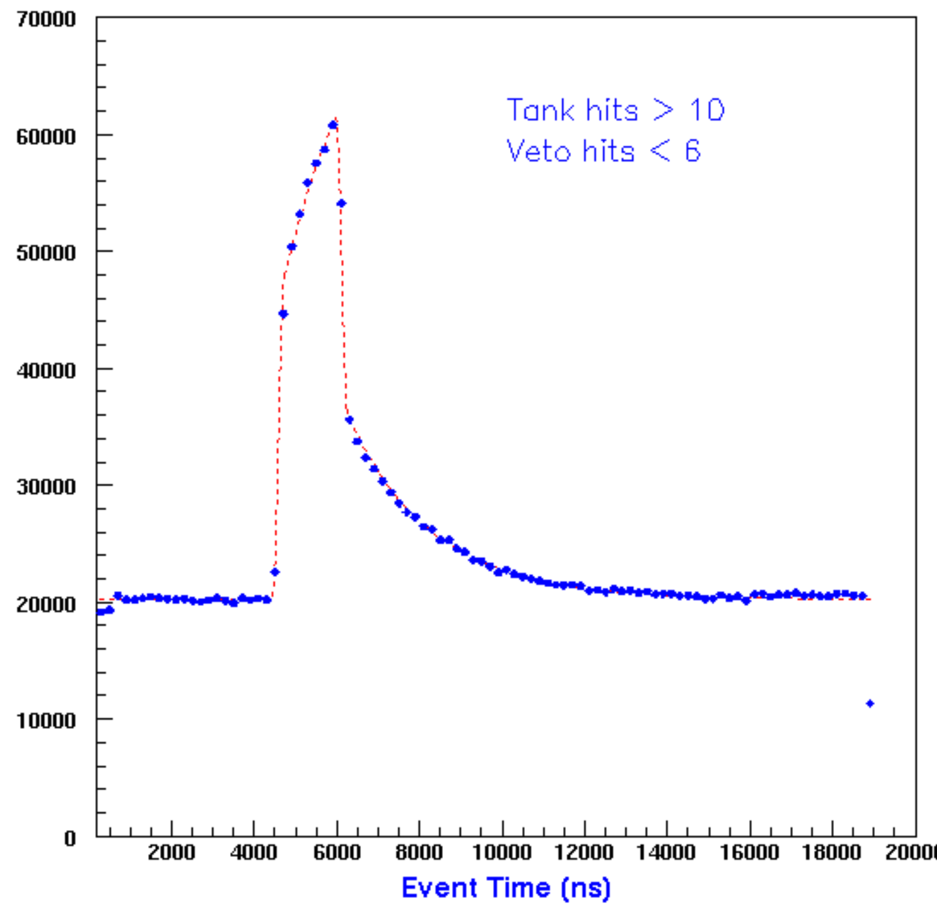
Beam and Michels



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Beam Only

Neutrino Candidate Cuts

<6 veto PMT hits

Gets rid of muons

>200 tank PMT hits

Gets rid of Michels

Only neutrinos are left!