nuSTORM: Physics and Detectors

Muon beams for particle physics

RAL, 11th October 2018

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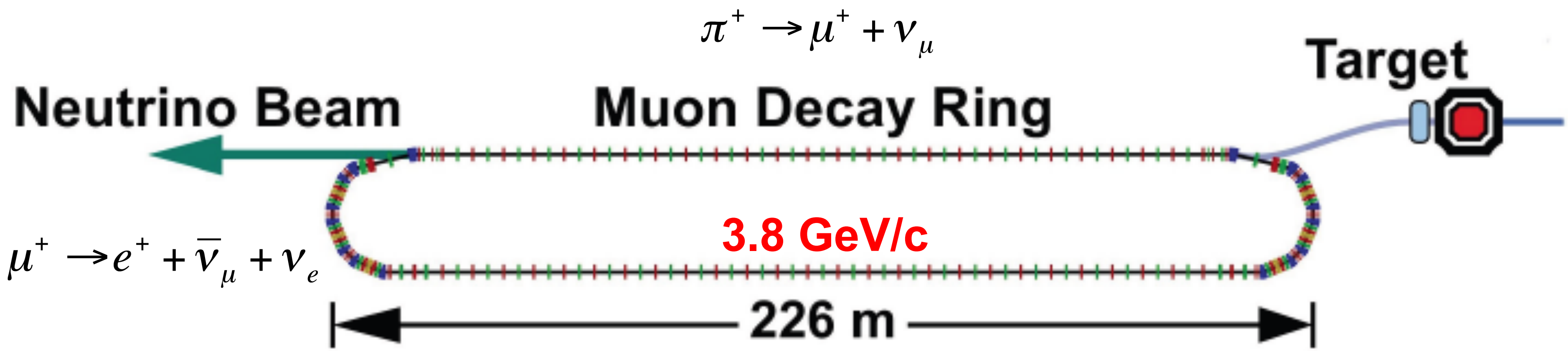
University of Glasgow

nuSTORM: Neutrinos from STORed Muons

- nuSTORM: storage ring for 3.8 GeV/c muons



- Pions of 5 Gev/c captured and injected into ring.
- 52% of pions decay to muons before first turn: $\pi^+ \to \mu^+ + \nu_\mu$
- For 10^{20} POT, flash of neutrinos from 8.6×10^{18} pion decays
- Muon momentum acceptance: p = 3.8 GeV ± 10%
- Muon decays (1 lifetime=27 orbits): $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$
- For 10^{20} POT, expect 2.6×10^{17} μ^+ decays
- Creates hybrid beam of neutrinos from pions & muons

Physics motivation

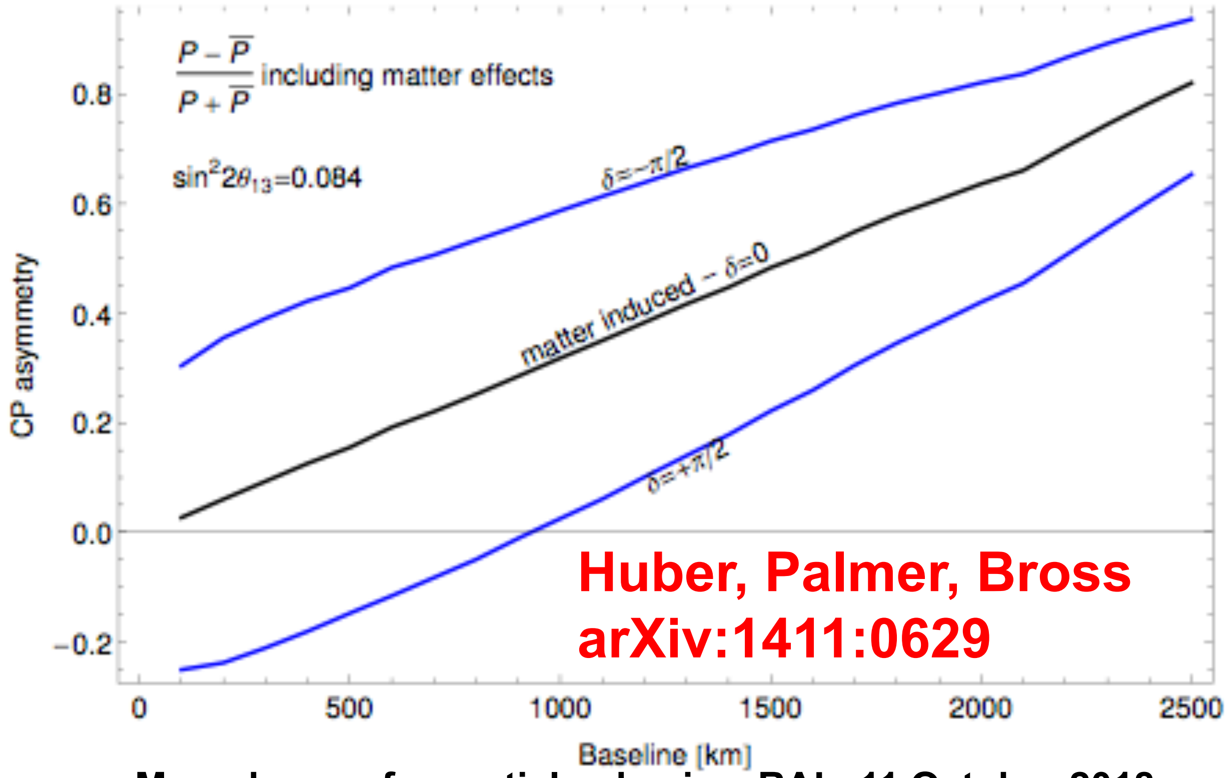
- Physics motivation of nuSTORM:
  - Light sterile neutrino problem: short baseline oscillations
  - Neutrino beam with flux accuracy of 10^{-3} for neutrino scattering physics
  - Measurement of ν_e and ν_μ cross sections and nuclear effects in neutrino-nucleus collisions
  - Test bed for muon accelerator R&D
- Detector concepts for nuSTORM need to address physics topics
  - Magnetised detector for neutrino oscillations
  - Generic high resolution detector for neutrino scattering
  - Low density detector to resolve nuclear effects

nuSTORM and long-baseline physics

νSTORM

- Precision requirement for CP violation:
  - For 75% of CP asymmetry coverage at 3σ: A_{CP} as low as 5%
  - Requires 1.5% measurement of $P - \overline{P}$ (~1% syst. error), but we measure rate:

$$R_{\alpha\beta}(E_{vis}) = N\int dE\Phi_{\alpha}(E)\sigma_{\beta}(E,E_{vis})\varepsilon_{\beta}(E)P(\nu_{\alpha}\rightarrow\nu_{\beta},E)$$



Huber, Palmer, Bross arXiv:1411:0629

nuSTORM and long baseline physics

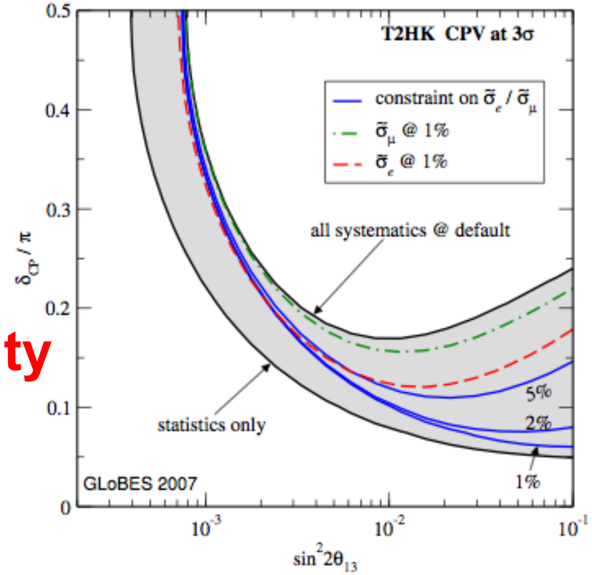
νSTORM

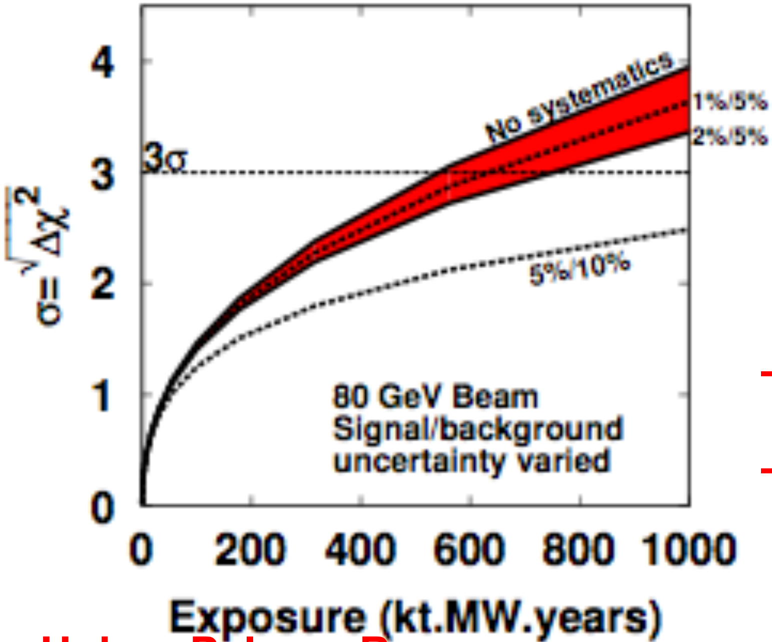
- Precision requirement for CP violation:
  - In disappearance experiment we can satisfy:

$$\frac{R_{\alpha\beta}(far)L^2}{R_{\alpha\beta}(near)} = \frac{N_{far}\Phi_\alpha\sigma_\beta\varepsilon_\beta P(\nu_\alpha \to \nu_\beta)}{N_{near}\Phi_\alpha\sigma_\alpha\varepsilon_\alpha 1} \quad \alpha = \beta$$

  - In an appearance experiment $\alpha \neq \beta$, so ν_α beam cannot measure $\sigma_\beta\varepsilon_\beta$

Huber, Mezzetto, Schwetz
arXiv:0711.2950





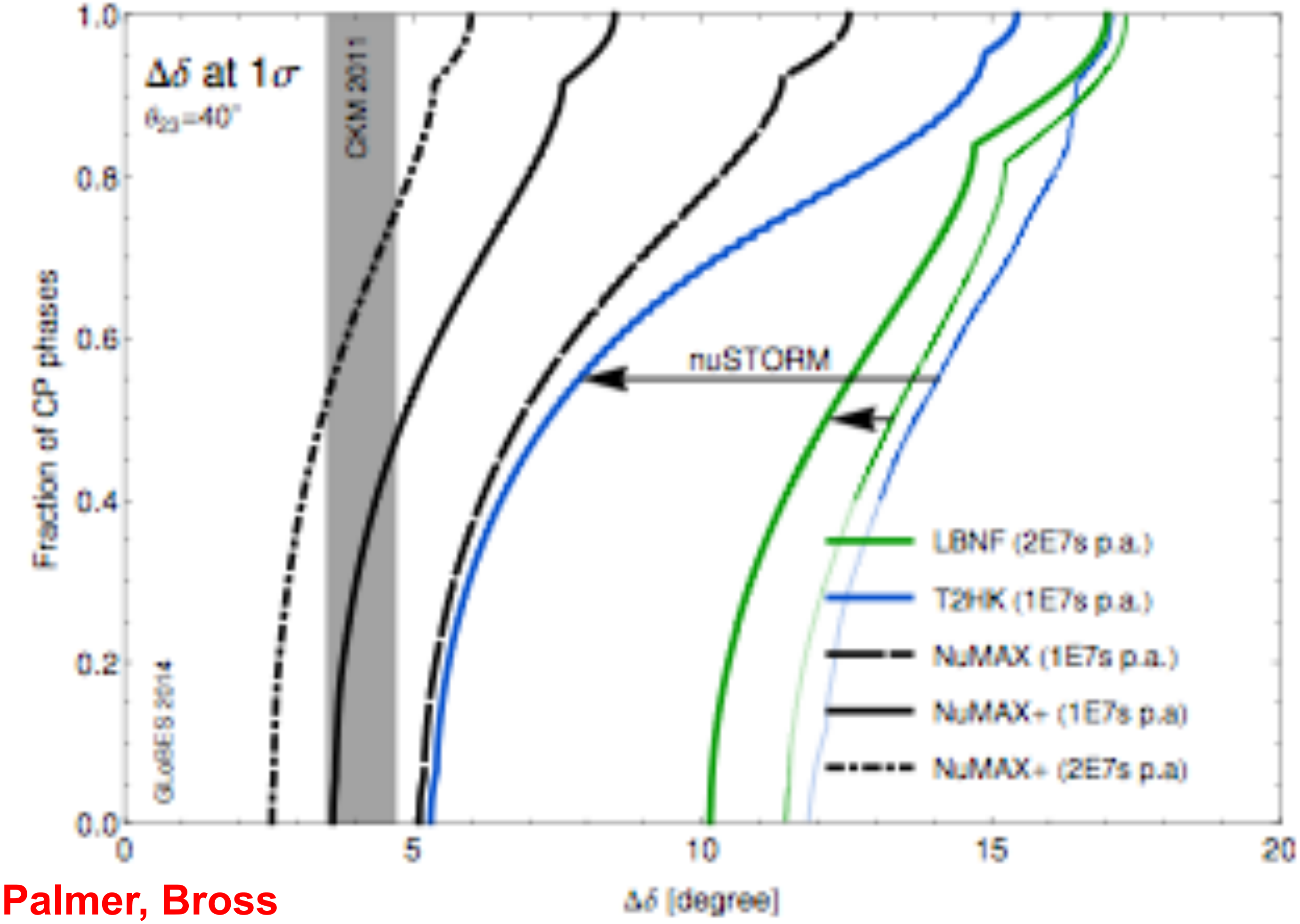
CP violation sensitivity for 75% δ_{CP} coverage at LBNE

Huber, Palmer, Bross
arXiv:1411:0629

- Syst. error on ratio $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ in T2HK
- Difference in σ_{ν_μ} and σ_{ν_e} can be large

nuSTORM and long baseline physics

- Influence of measurement of cross-sections with less than 1% precision as potentially provided by nuSTORM:



Huber, Palmer, Bross
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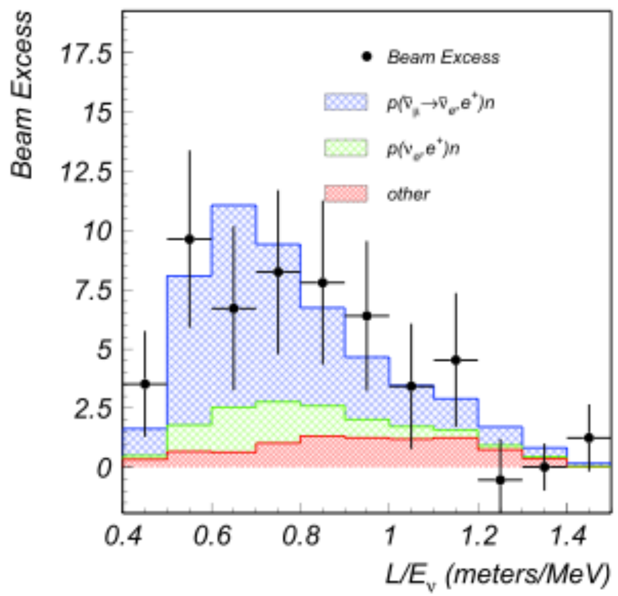
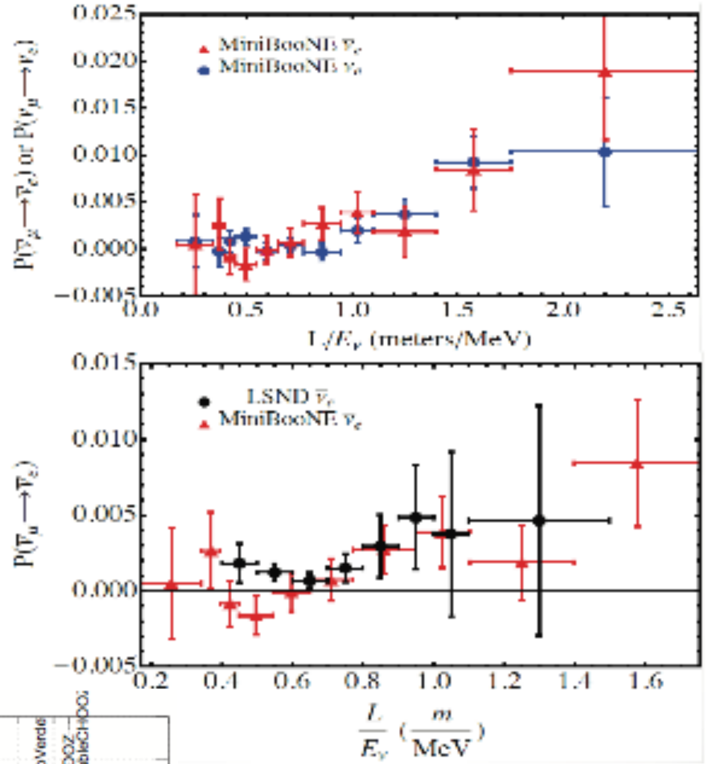
Short baseline physics

❑ LSND and MiniBooNE hints of $\bar{\nu}_e$ and ν_e appearance

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.003$ and reactor anomaly (6% $\bar{\nu}_e$ deficit)

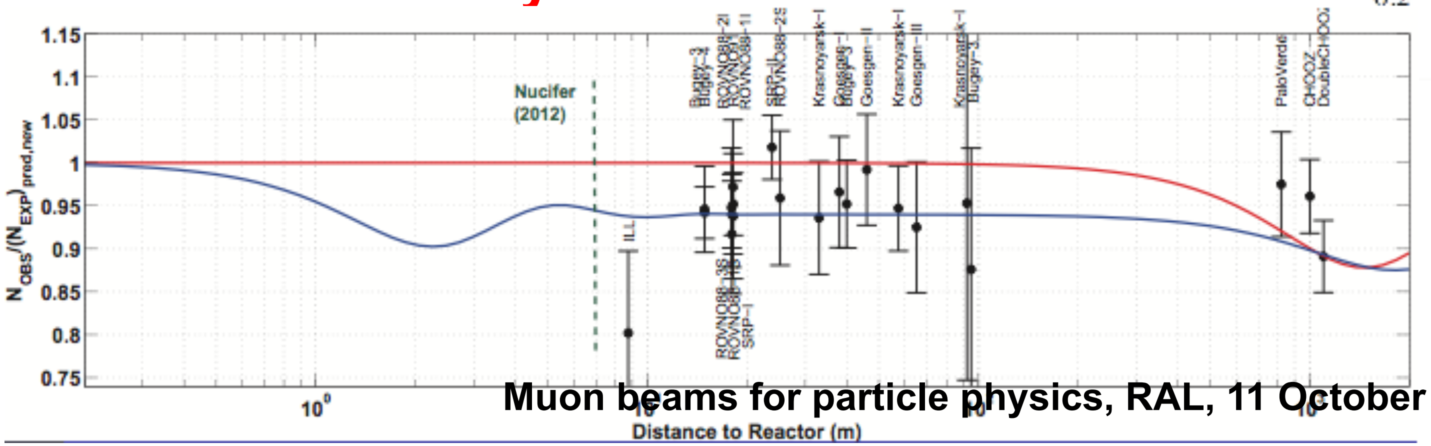


LSND



MiniBooNE

Reactor anomaly



Short baseline physics

νSTORM

- Precision requirement for CP violation:

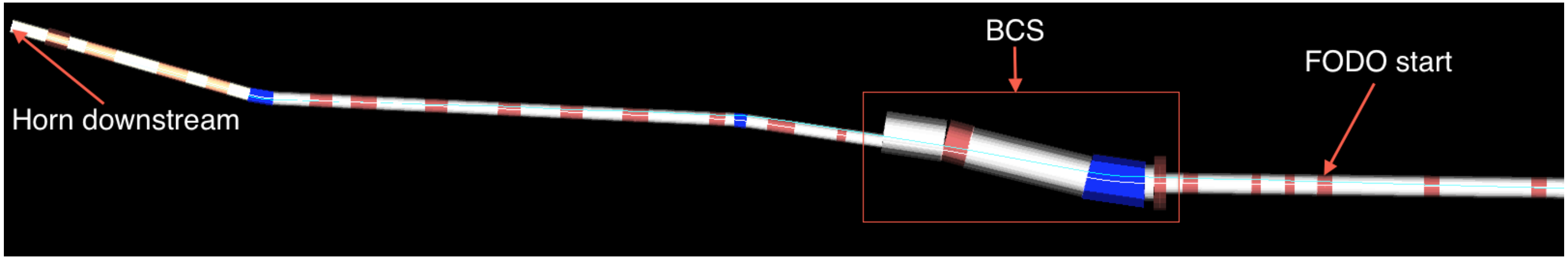
$$P(\nu_\mu \to \nu_e) \leq 4\left(1 - P(\nu_\mu \to \nu_\mu)\right)\left(1 - P(\nu_e \to \nu_e)\right)$$

  – nuSTORM probes all possible sterile neutrino appearance and disappearance channels (if $E_\nu > \tau$ threshold) to test paradigm

$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

nuSTORM Facility

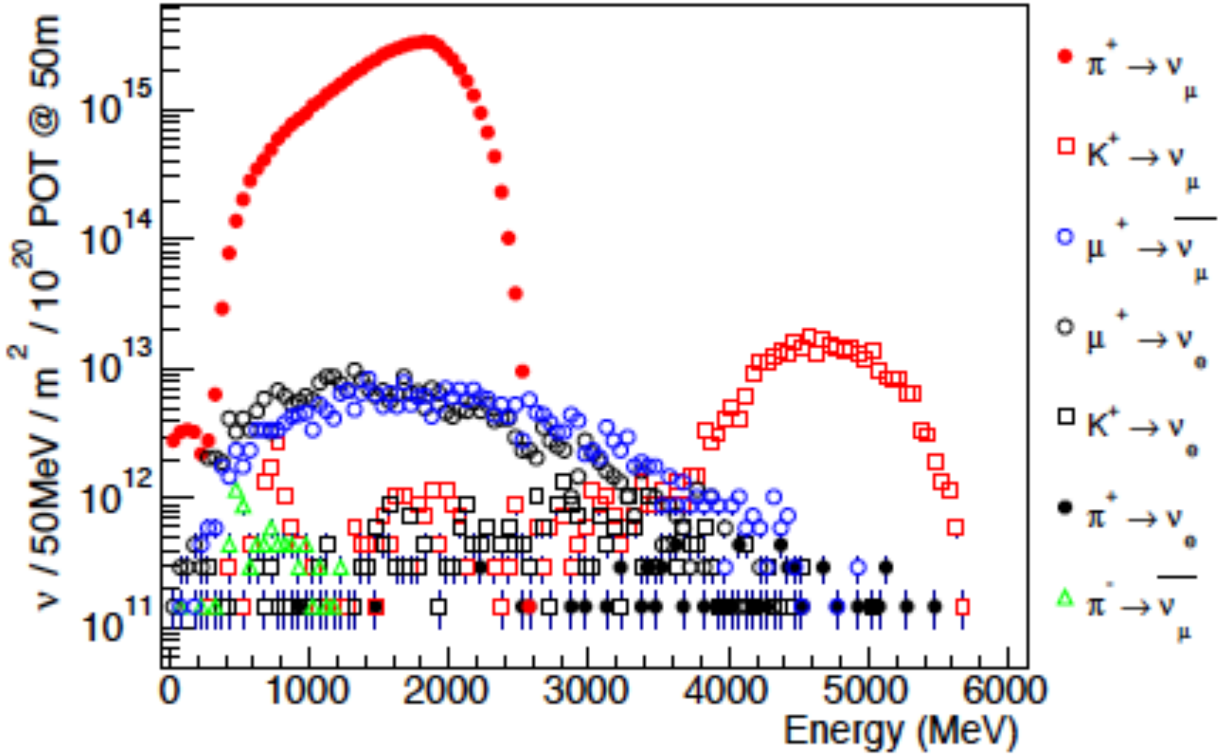
- nuSTORM facility:
  - 120 GeV protons on carbon or inconel target (100 kW)
  - NuMI-style horn for pion collection: recently optimised
  - Injection pions (5 GeV/c ± 10%) into storage ring: 0.09 π/POT
  - Storage ring: large aperture FODO lattice (3.8 GeV/c ± 10%) muons: 8×10^{-3} μ/POT



nuSTORM Flux and Spectrum

- nuSTORM flux and energy spectrum

Use muon decay neutrinos to calibrate hadron decay neutrinos?



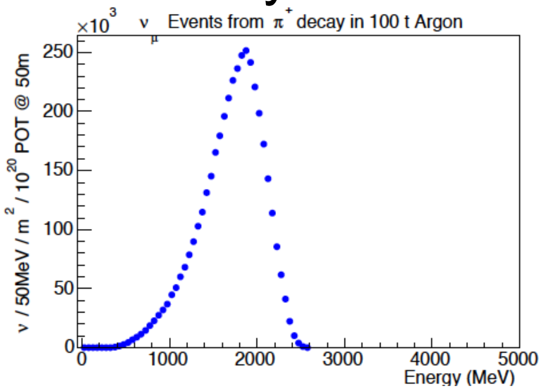
- ν_μ from pion decay $\pi^+ \to \mu^+ + \nu_\mu$ flux: 6.3×10^{16} ν/m^2 at 50 m
- ν_e from muon decay $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$ flux: 3.0×10^{14} ν/m^2 at 50 m
- ν_μ from kaon decay $K^+ \to \mu^+ + \nu_\mu$ flux: 3.8×10^{14} ν/m^2 at 50 m
- Can be used for cross-section measurements and short baseline experiments

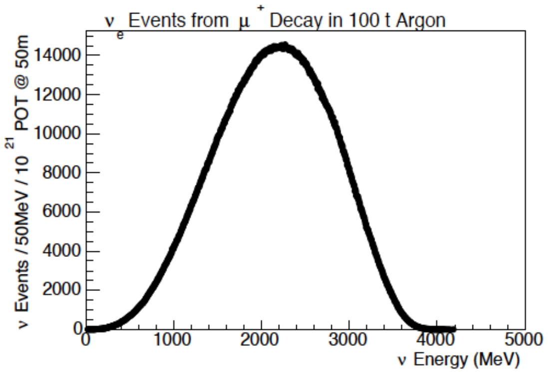
nuSTORM Event Rates

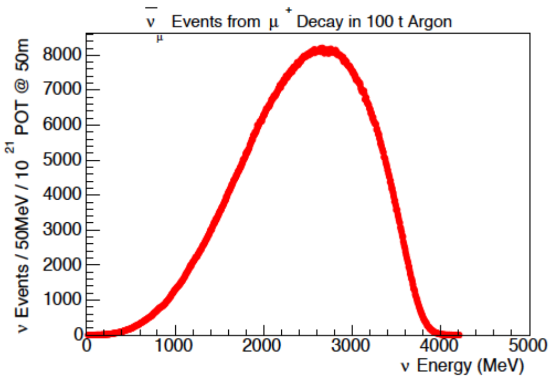
- Flux uncertainties for nuSTORM from beam diagnostics: < 1%
- Event rates per 10^{21} POT in 100 ton Liquid Argon at 50 m

μ^+ Channel	N_{evts}	μ^- Channel	N_{evts}
$\bar{\nu}_\mu$ NC	1,174,710	$\bar{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\bar{\nu}_\mu$ CC	3,030,510	$\bar{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	ν_μ CC	6,060,580
π^+		π^-	
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\bar{\nu}_\mu$ CC	19,939,704

– Limited by detector systematics:

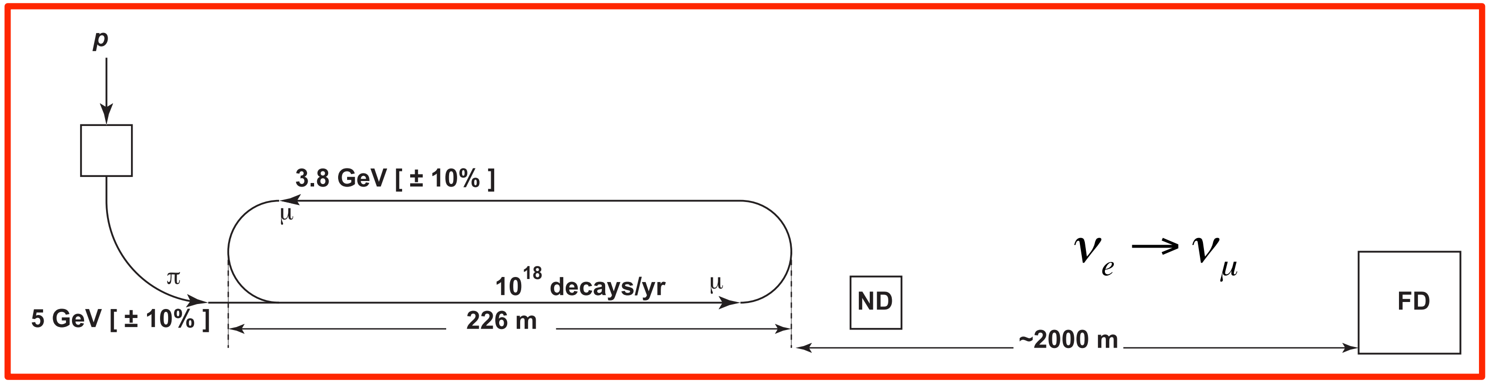




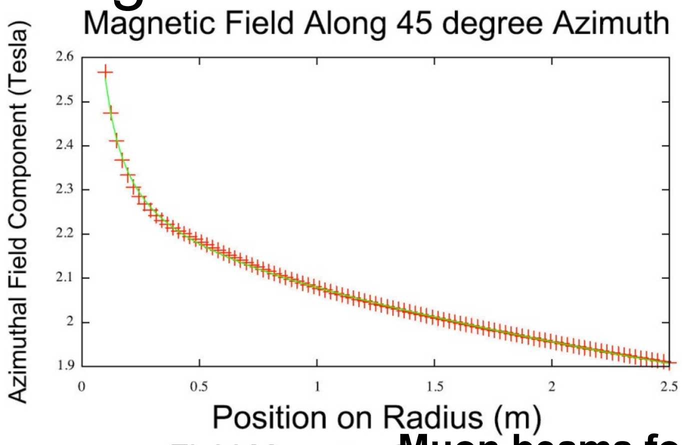


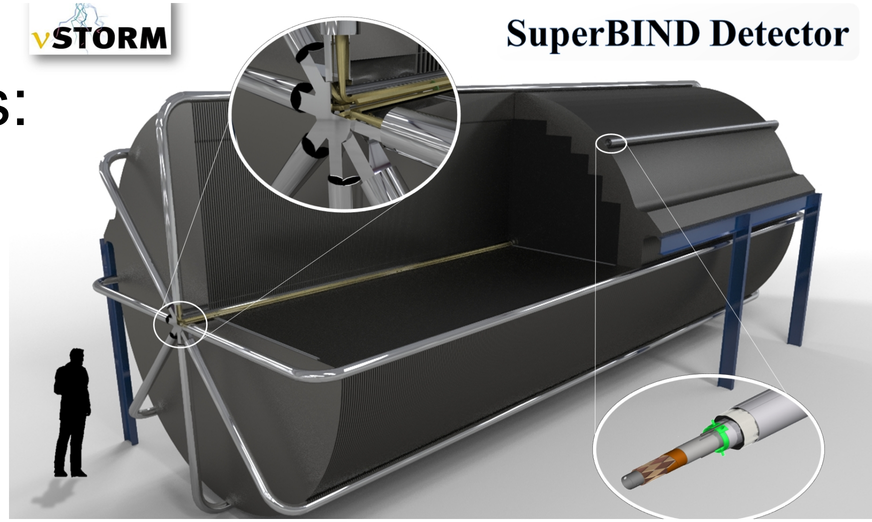
Sterile neutrino search

- Requires two magnetised detectors for neutrino oscillations:



- Super-saturated Magnetised Iron to remove wrong-sign muons: SuperBIND
- Magnetic field: 1.5-2.6 T





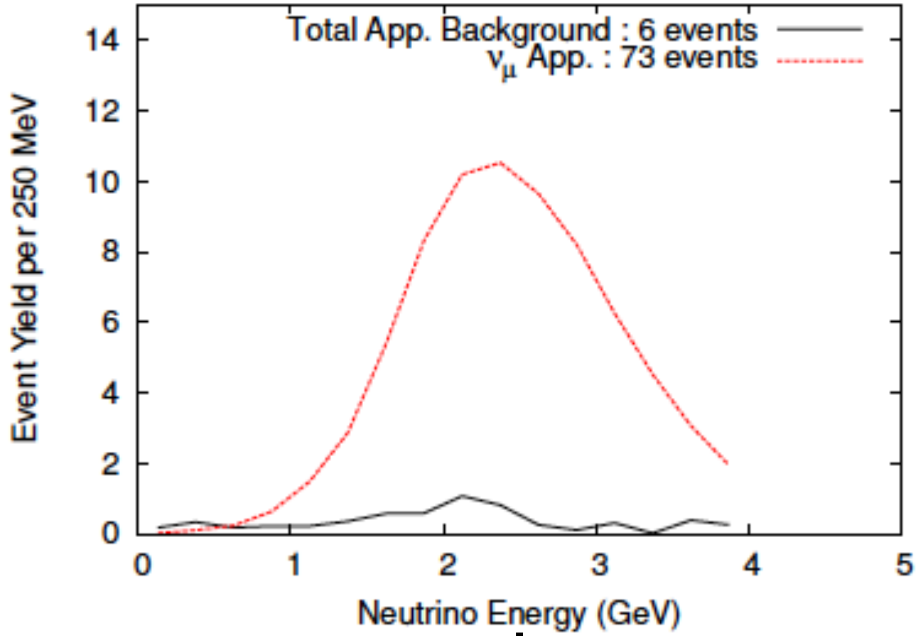
240 kA from 8 Superconducting Trasmission Lines

Sterile neutrino search

- Appearance search:

Adey et al., PRD 89 (2014) 071301

$$P_{e\mu}(x) = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{e\mu})\sin^2\left(\frac{\Delta m_{14}^2 x}{4E}\right)$$



With full reconstruction and efficiencies, 10^{21} POT

- Disappearance search:

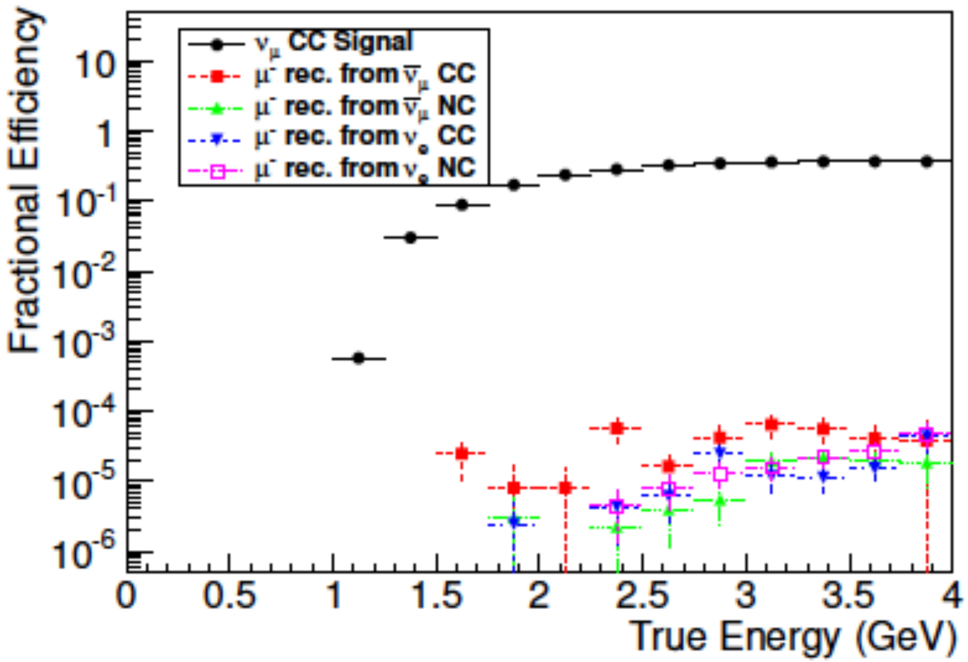
$$P_{\mu\mu}(x) = 4|U_{\mu 4}|^2 \left(1-|U_{\mu 4}|^2\right)\sin^2\left(\frac{\Delta m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{\mu\mu})\sin^2\left(\frac{\Delta m_{14}^2 x}{4E}\right)$$

Sterile neutrino search

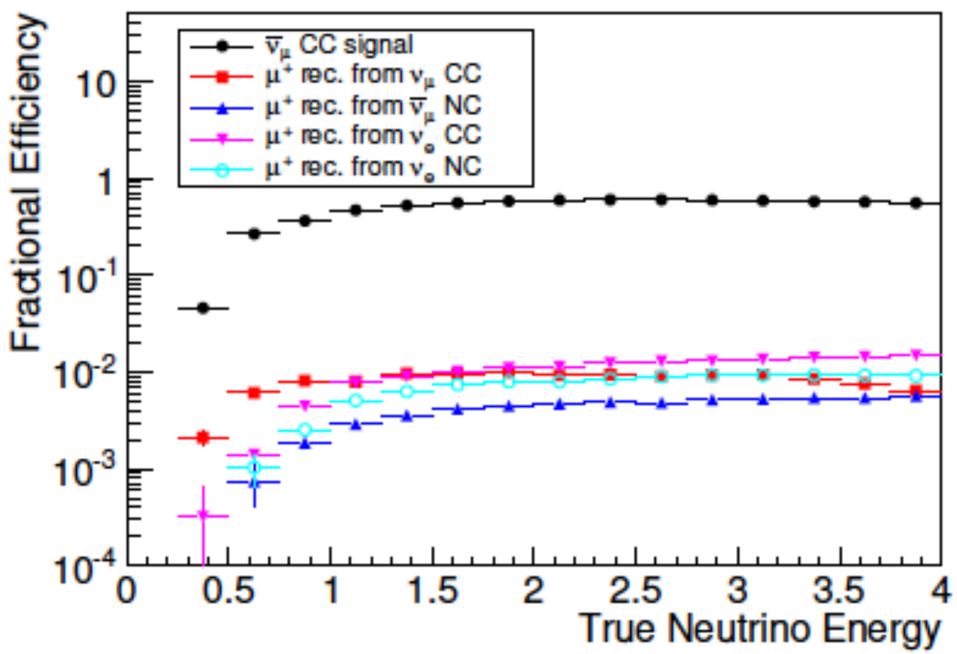
- Short-baseline oscillation search with near detector at 50 m and far detector at 2 km, 10^{21} POT exposure
- Appearance and disappearance multi-variate analyses

Adey et al., PRD 89 (2014) 071301 (Ryan Bayes' analysis)

Appearance efficiencies



Disappearance efficiencies



Sterile neutrino search

νSTORM

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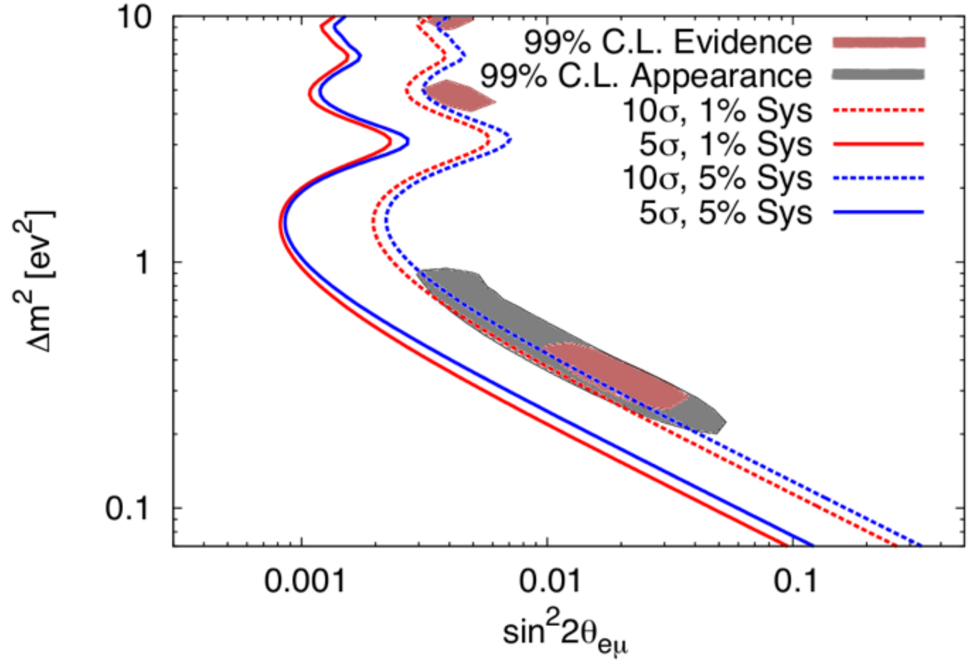
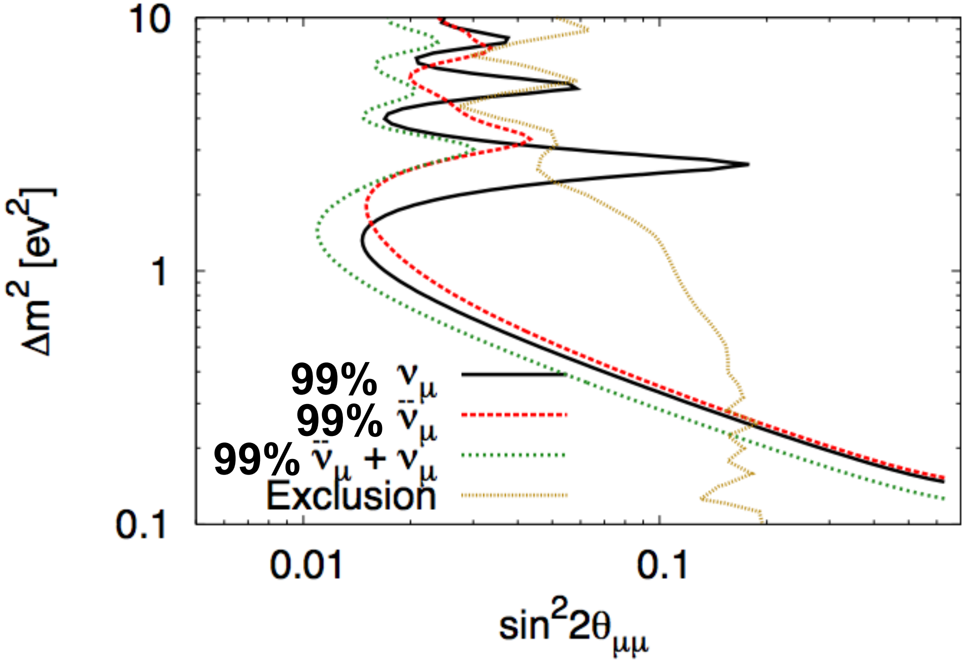
Appearance sensitivity



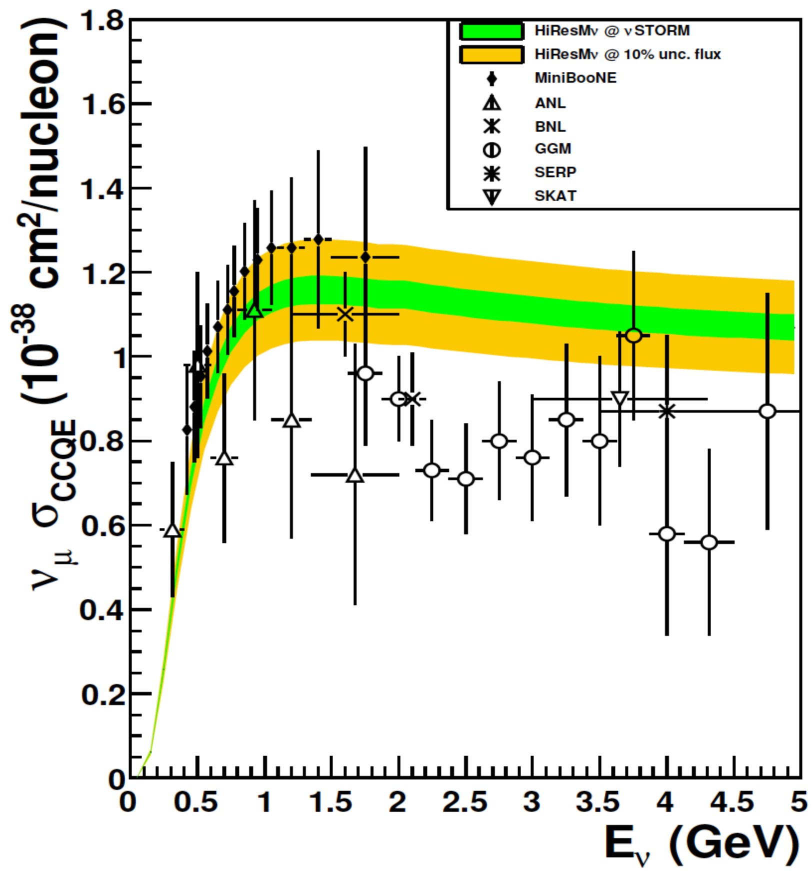
Disappearance sensitivity

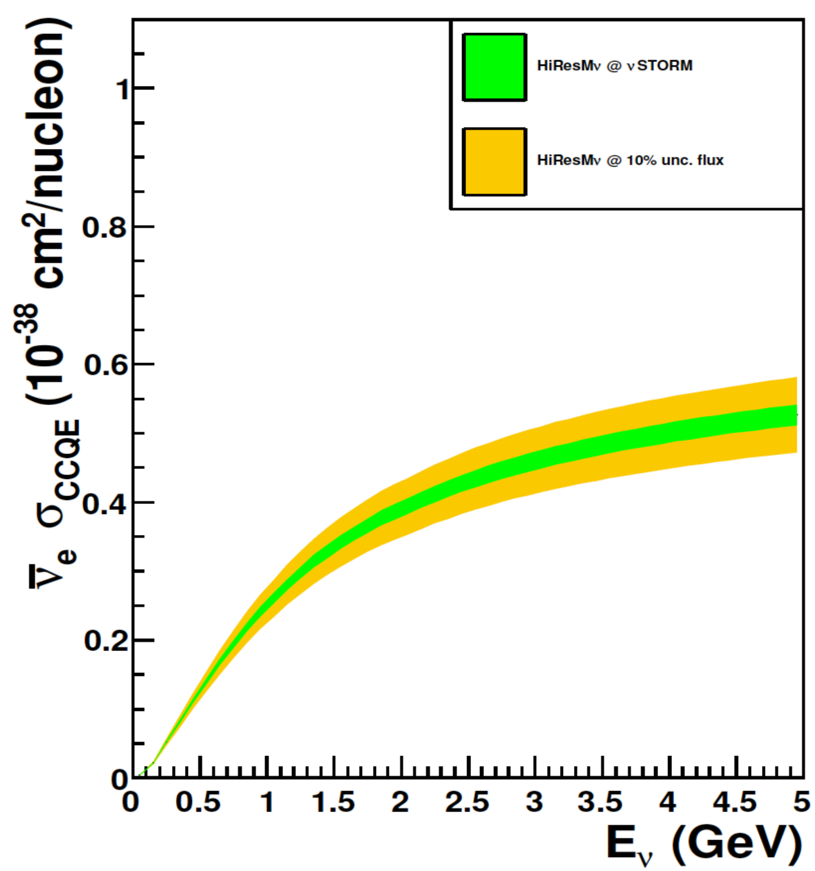


After FNAL SBL programme, sterile neutrinos might not be relevant

Neutrino interactions at nuSTORM

- Example of CCQE measurement errors:
  - Data for ν_μ and $\bar{\nu}_e$ cross-sections
  - Systematic errors completely dominated by detector

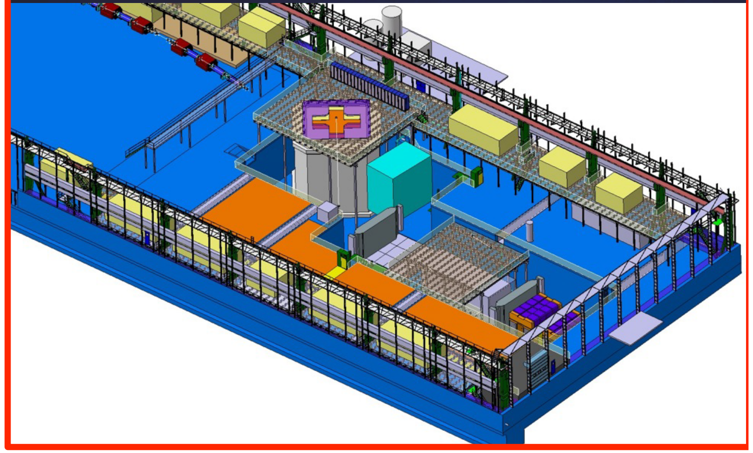


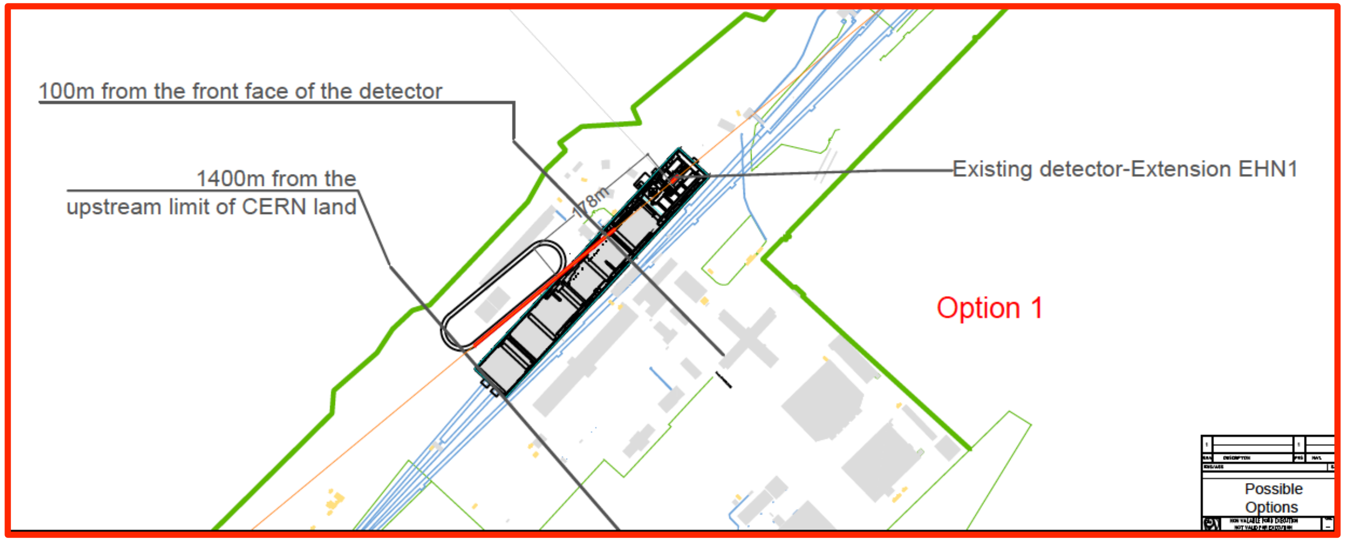


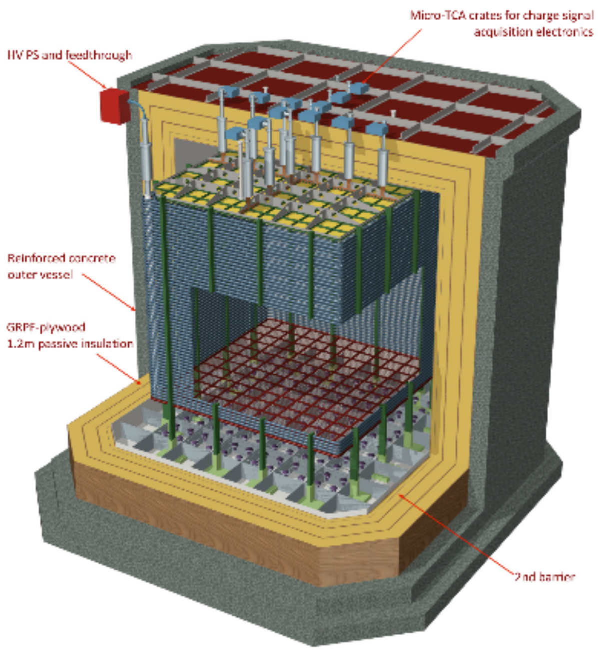
Detectors for neutrino interactions

- ProtoDUNE detectors at CERN:
  - Two 770 ton liquid argon detectors: single phase and dual phase
  - Ideally located in North Area at CERN for nuSTORM

Neutrino extension



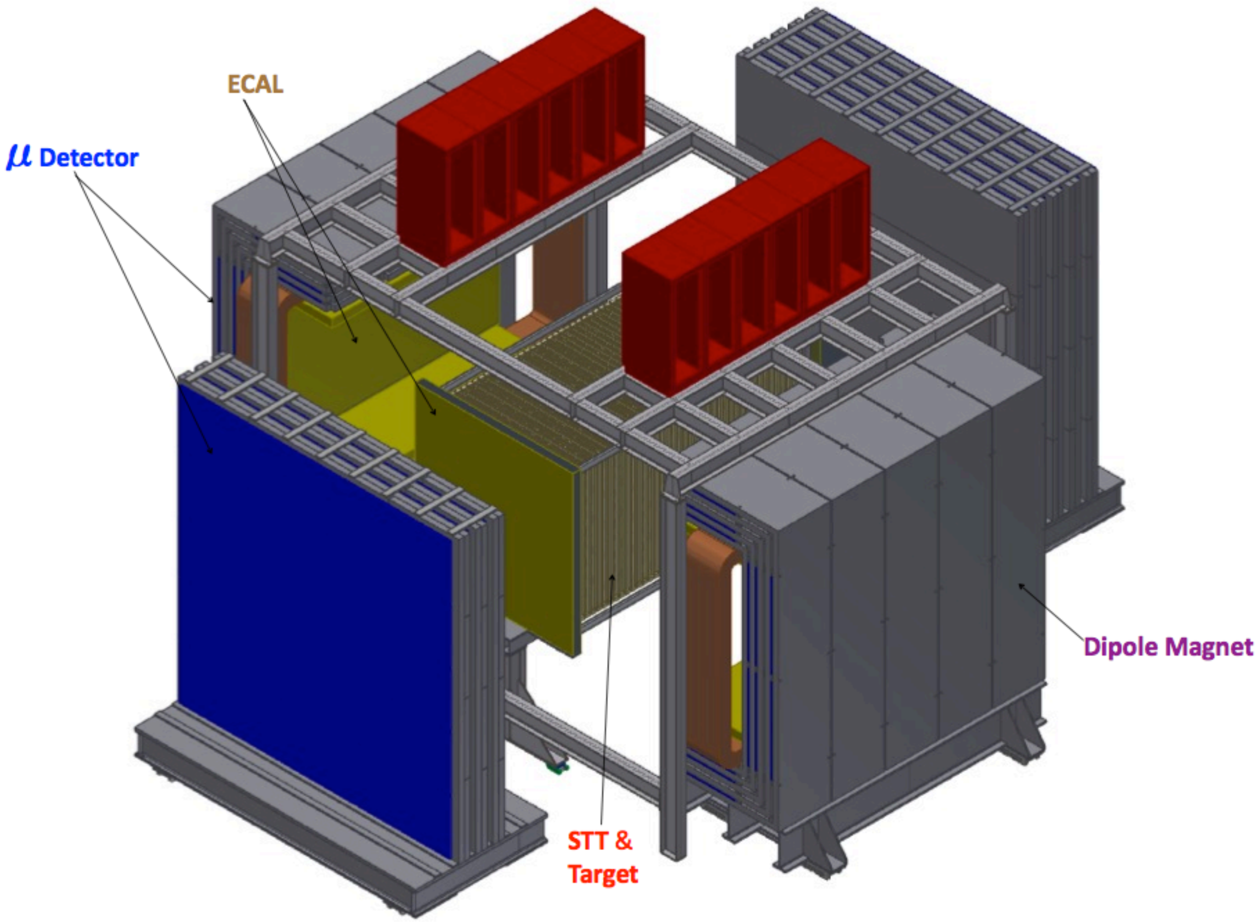




Detectors for neutrino interactions

νSTORM

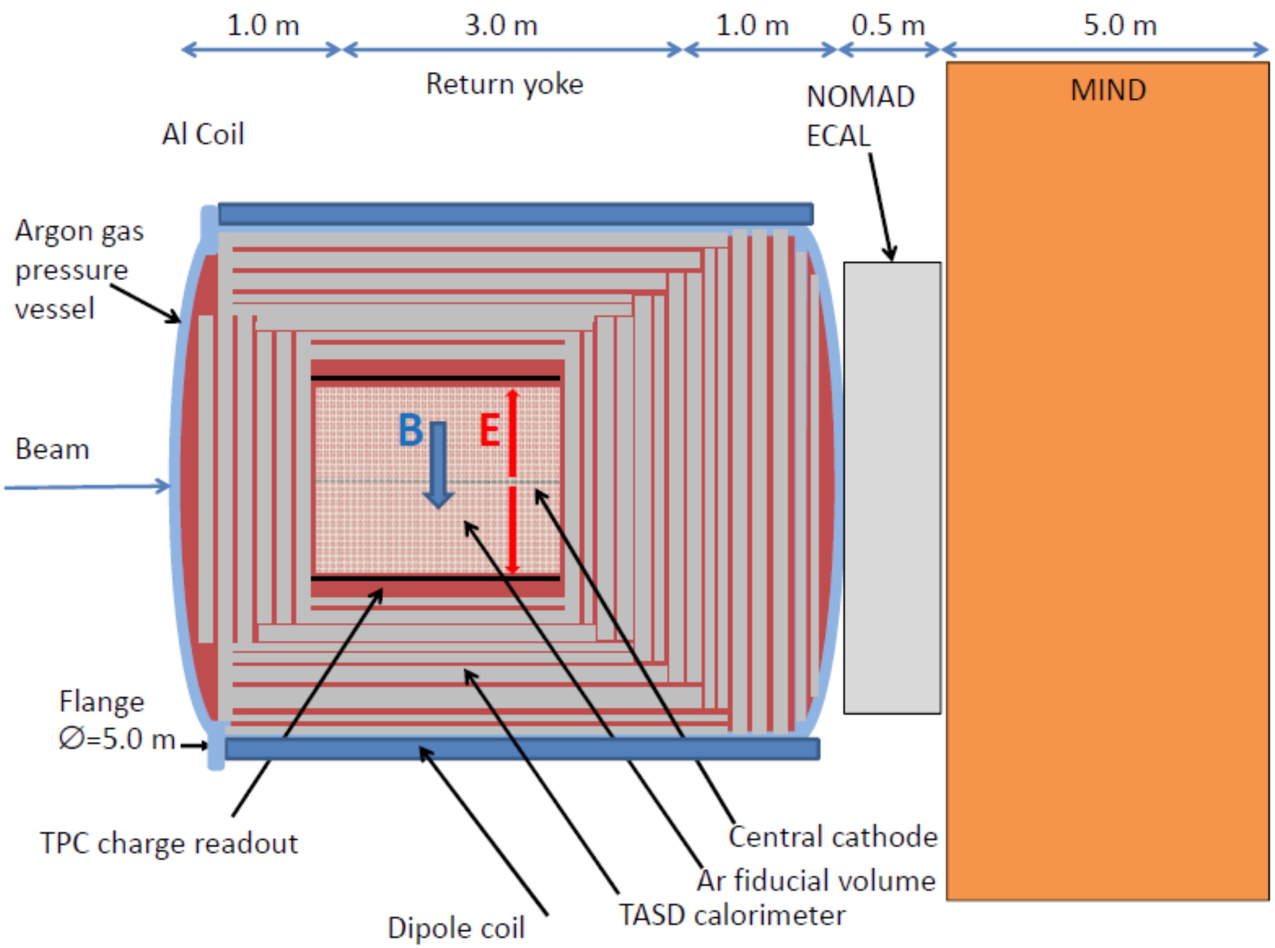
- High resolution straw-tube tracker detector:
  - HiResMuNu as was first proposed for LBNE



Detectors for neutrino interactions

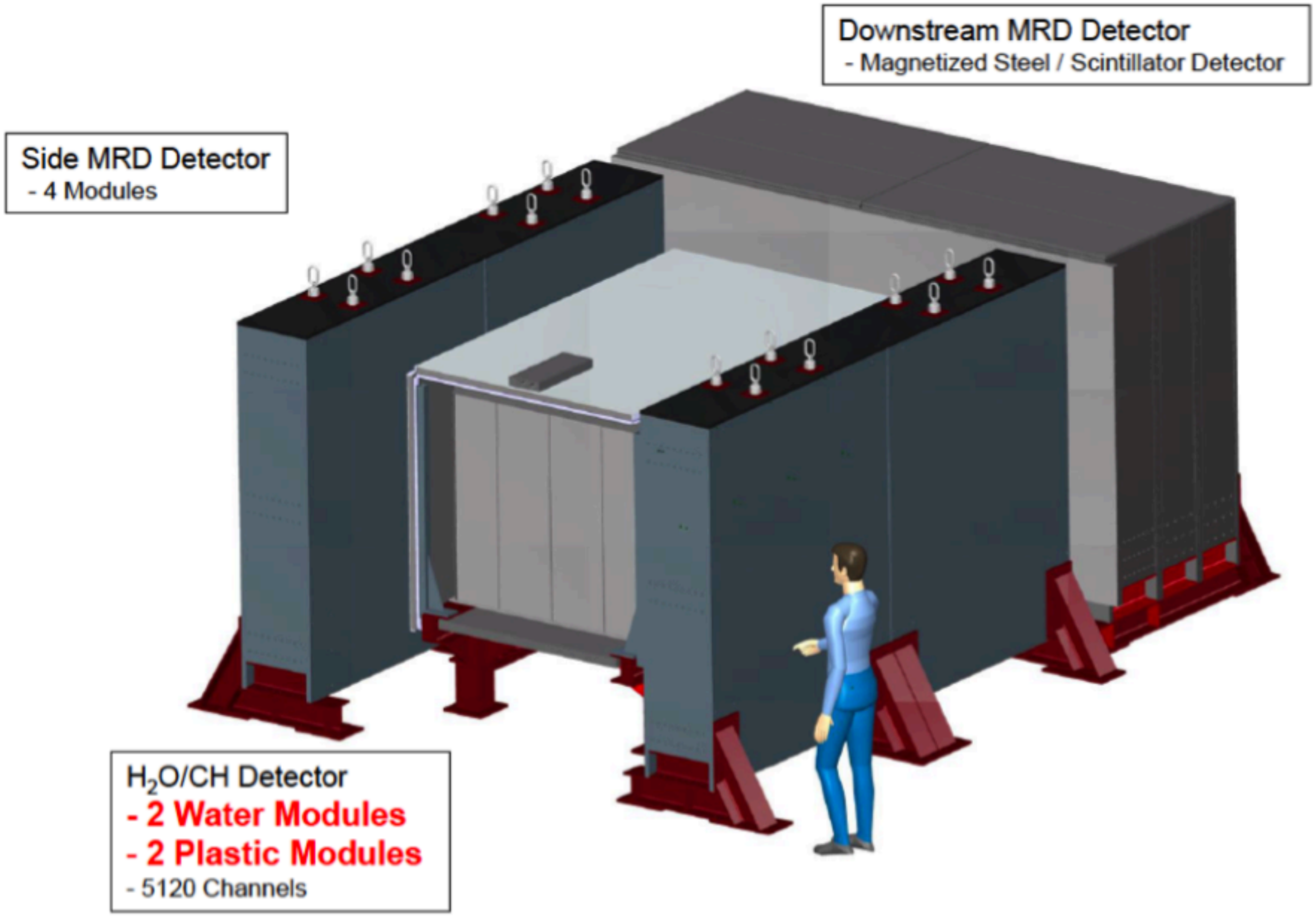
νSTORM

- High pressure argon gas detector:
  - Best resolution to measure nuclear effects in argon



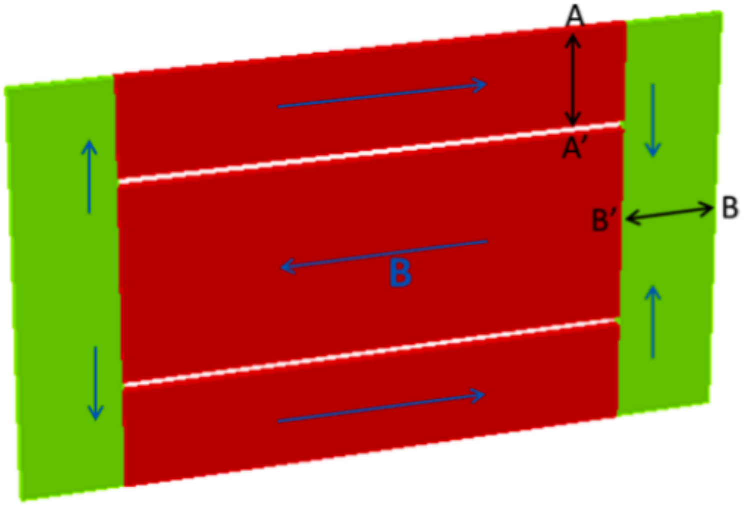
WAGASCI/Baby MIND concept

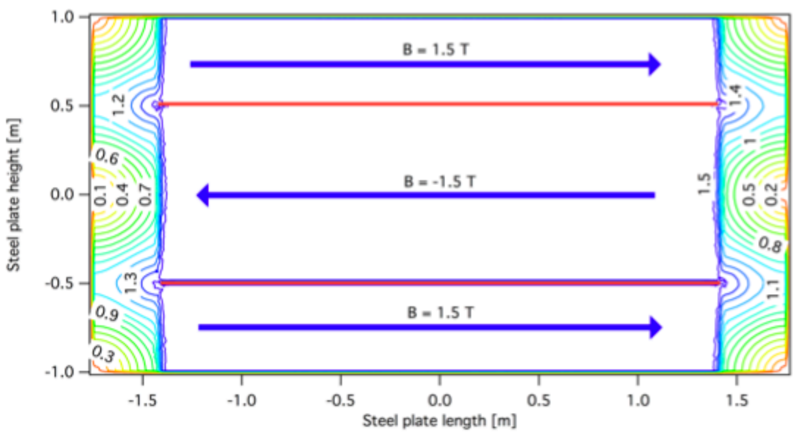
- Totally active scintillator, surrounded by magnetised iron spectrometers (similar to WAGASCI/Baby MIND)

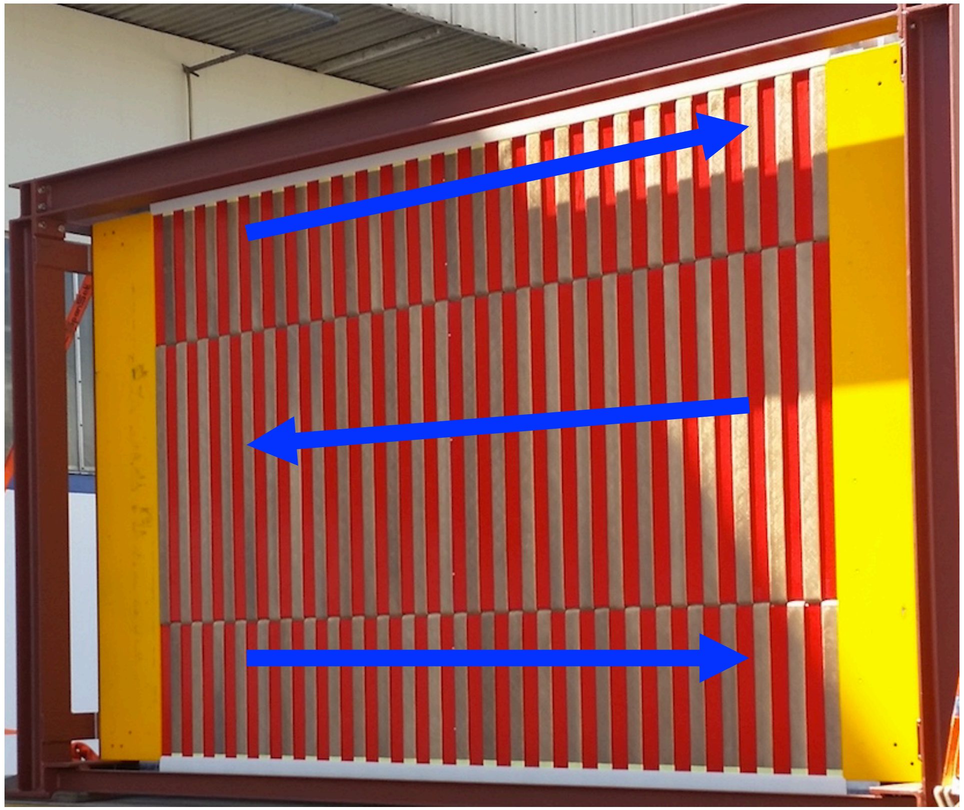


WAGASCI/Baby MIND concept

- Baby MIND concept:
  - Individually magnetised plates with two slots to be able to thread 25 turns of conductor: inexpensive to manufacture



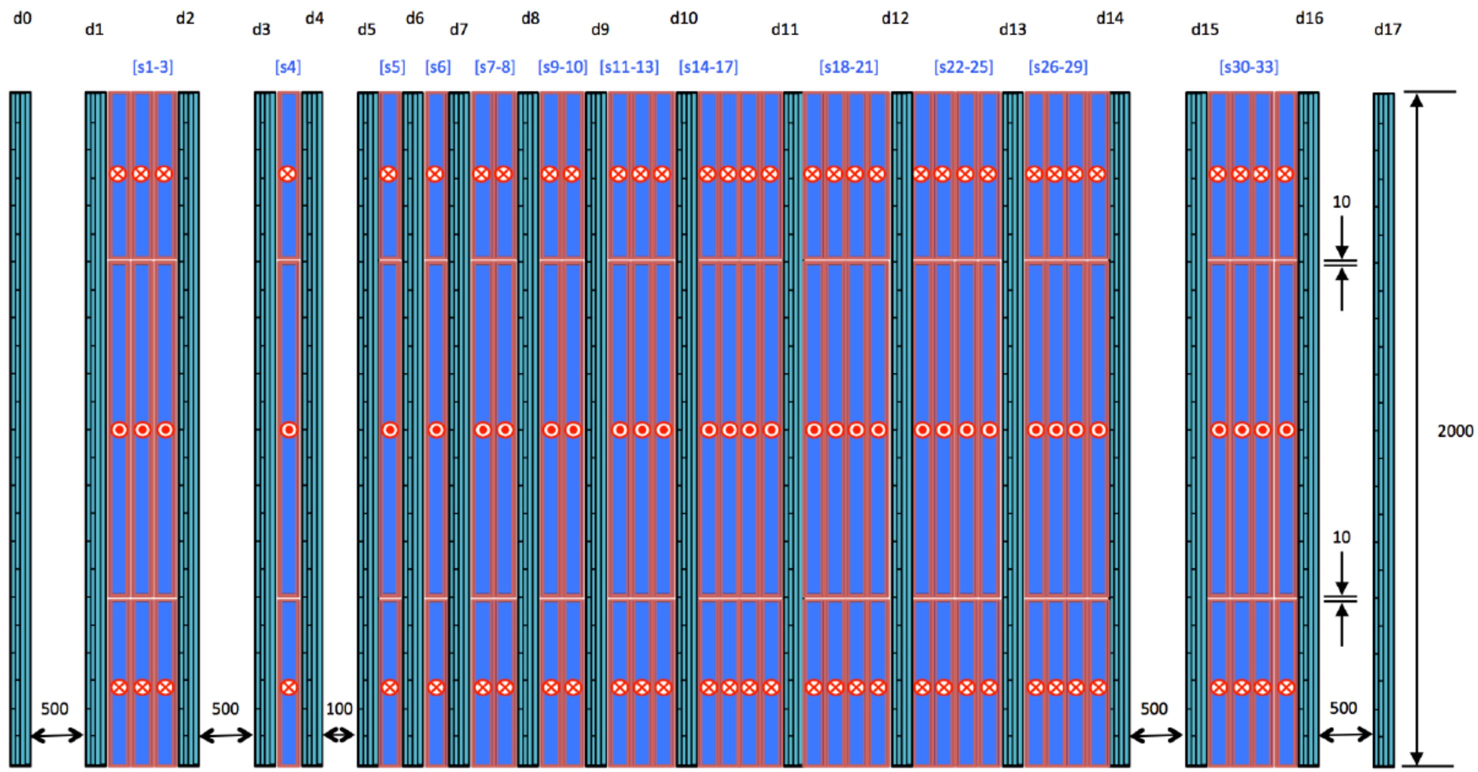




B = 1.5 T, with 140 A (11.5 kW)

WAGASCI/Baby MIND concept

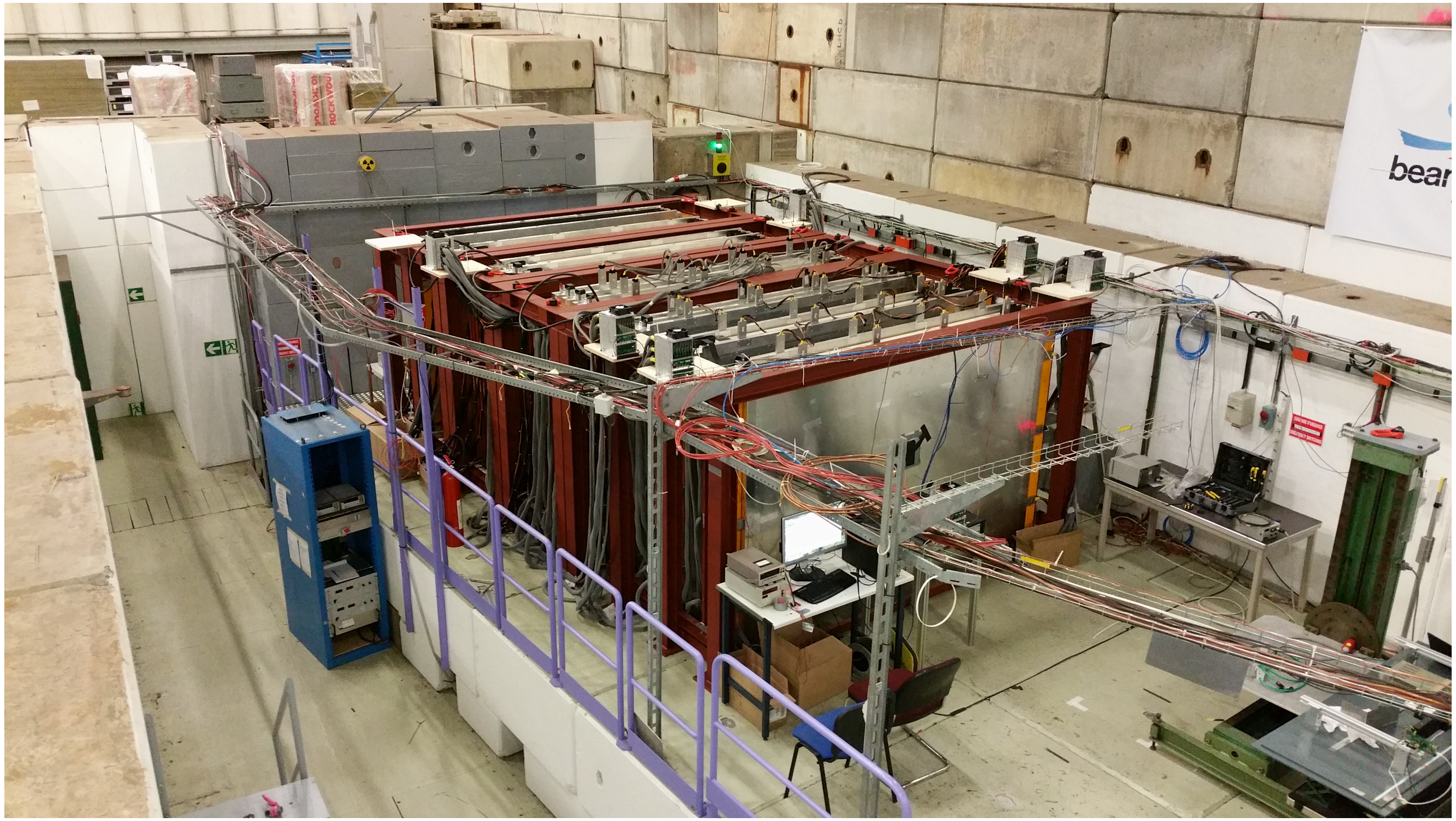
- Baby MIND concept:
  - Modular spectrometer with array of magnetised plates and scintillator planes, which can be interspersed in bespoke ways to optimise acceptance and momentum reconstruction



WAGASCI/Baby MIND concept

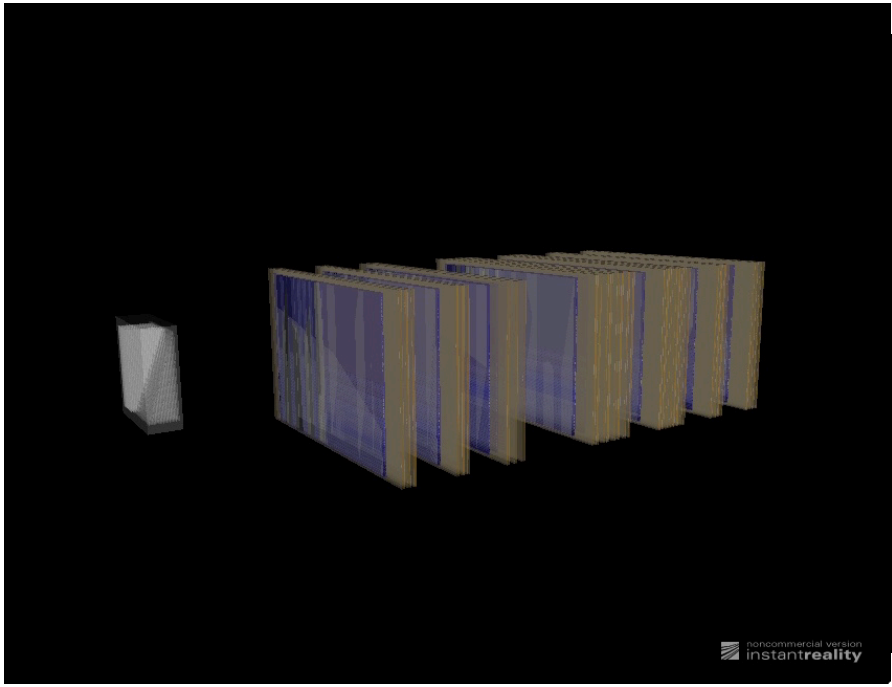
νSTORM

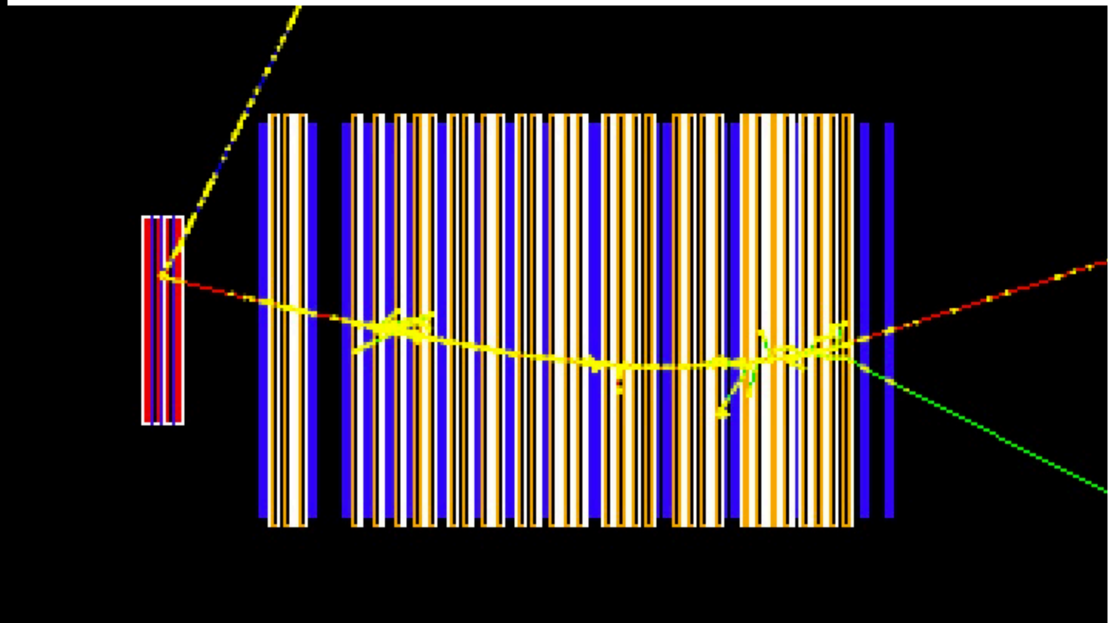
- Baby MIND at T9 Test Beam at CERN
  - Constructed 33 magnetic plates and 18 scintillator planes
  - Tested at CERN test beam and now installed at J-PARC



Preliminary CCQE analysis

- CCQE analysis with Totally Active Scintillator Detector (TASD) + Baby MIND **S.-P. Hallsjö, PhD thesis**
  - Simulation with nuSTORM spectrum + GENIE + GEANT4



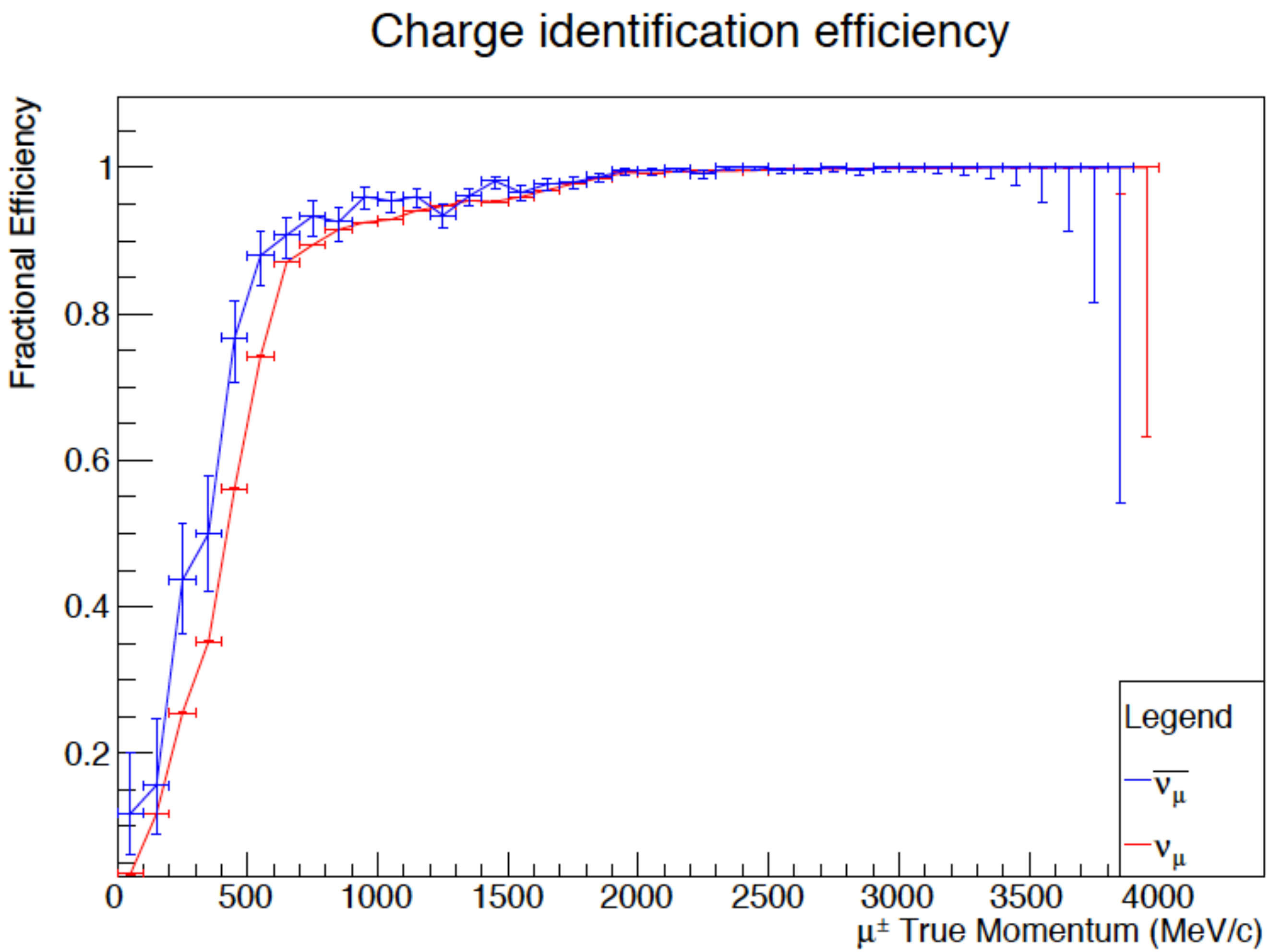


Preliminary CCQE analysis

νSTORM

- CCQE analysis with TASD + Baby MIND
  - Charge identification efficiency

S.-P. Hallsjö, PhD thesis



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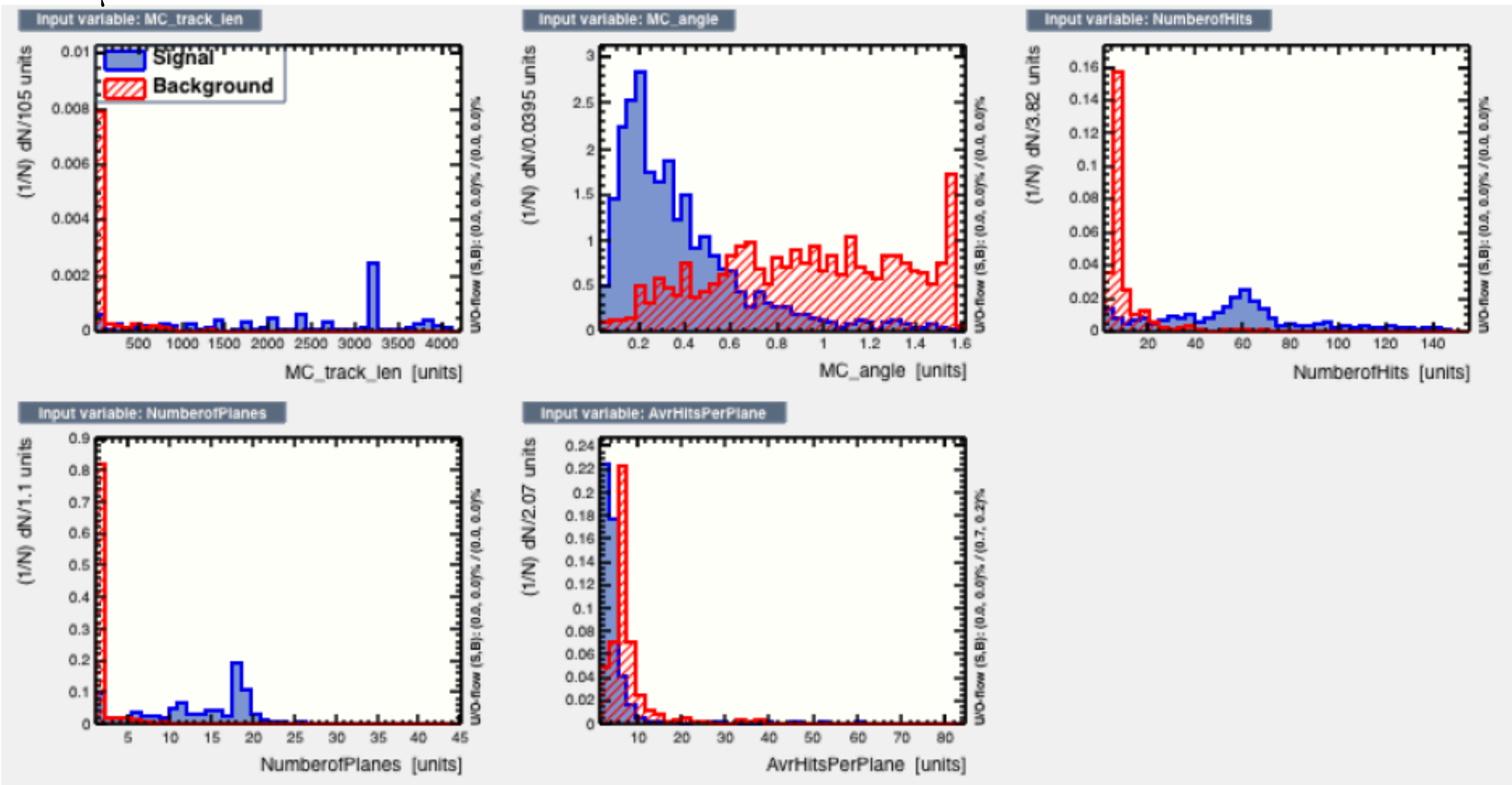
  - Neutrino event selection with TASD **S.-P. Hallsjö, PhD thesis**
  - ν_μ CCQE = signal; $\overline{\nu}_e$ CCQE + NC = background



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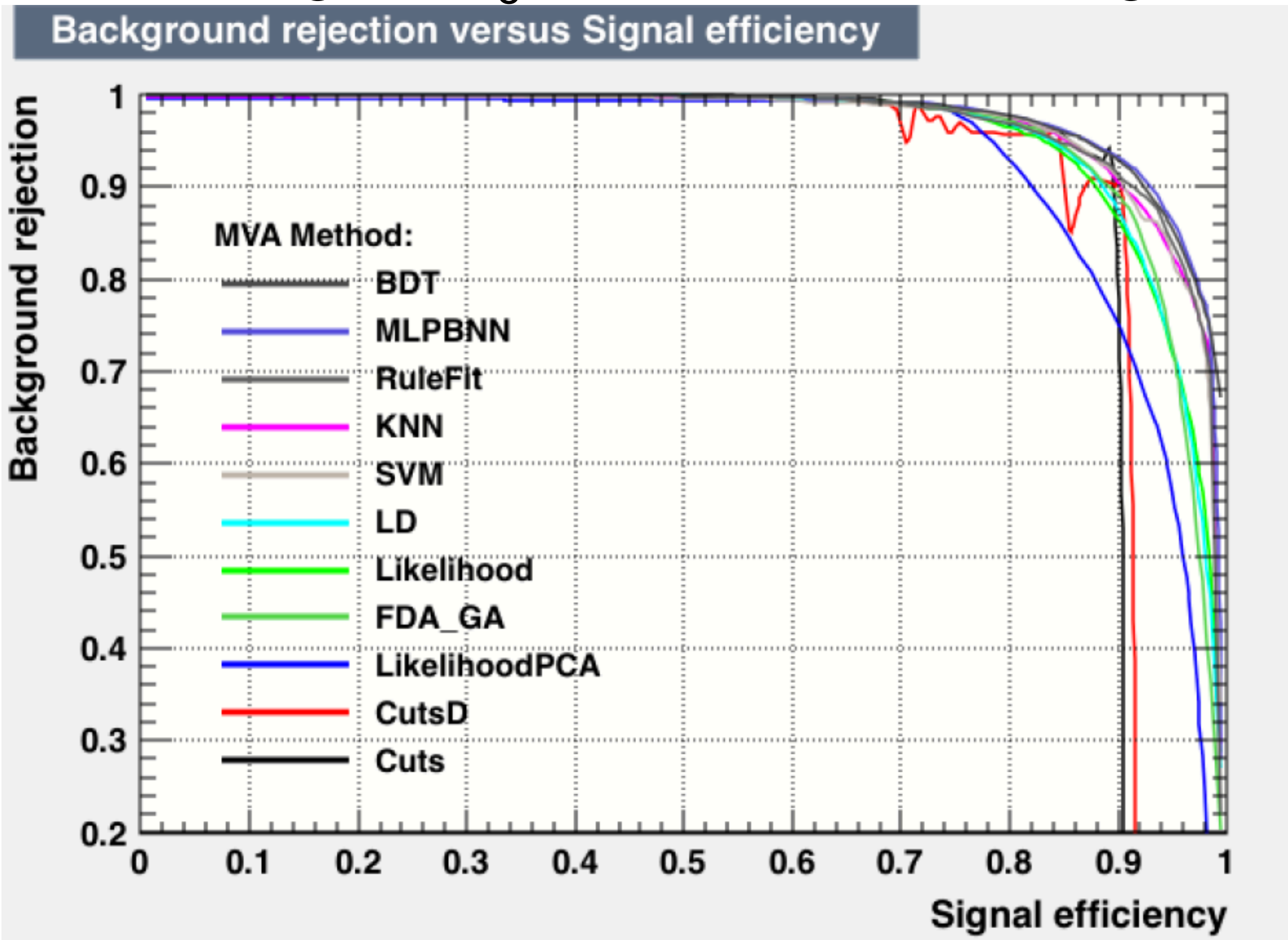

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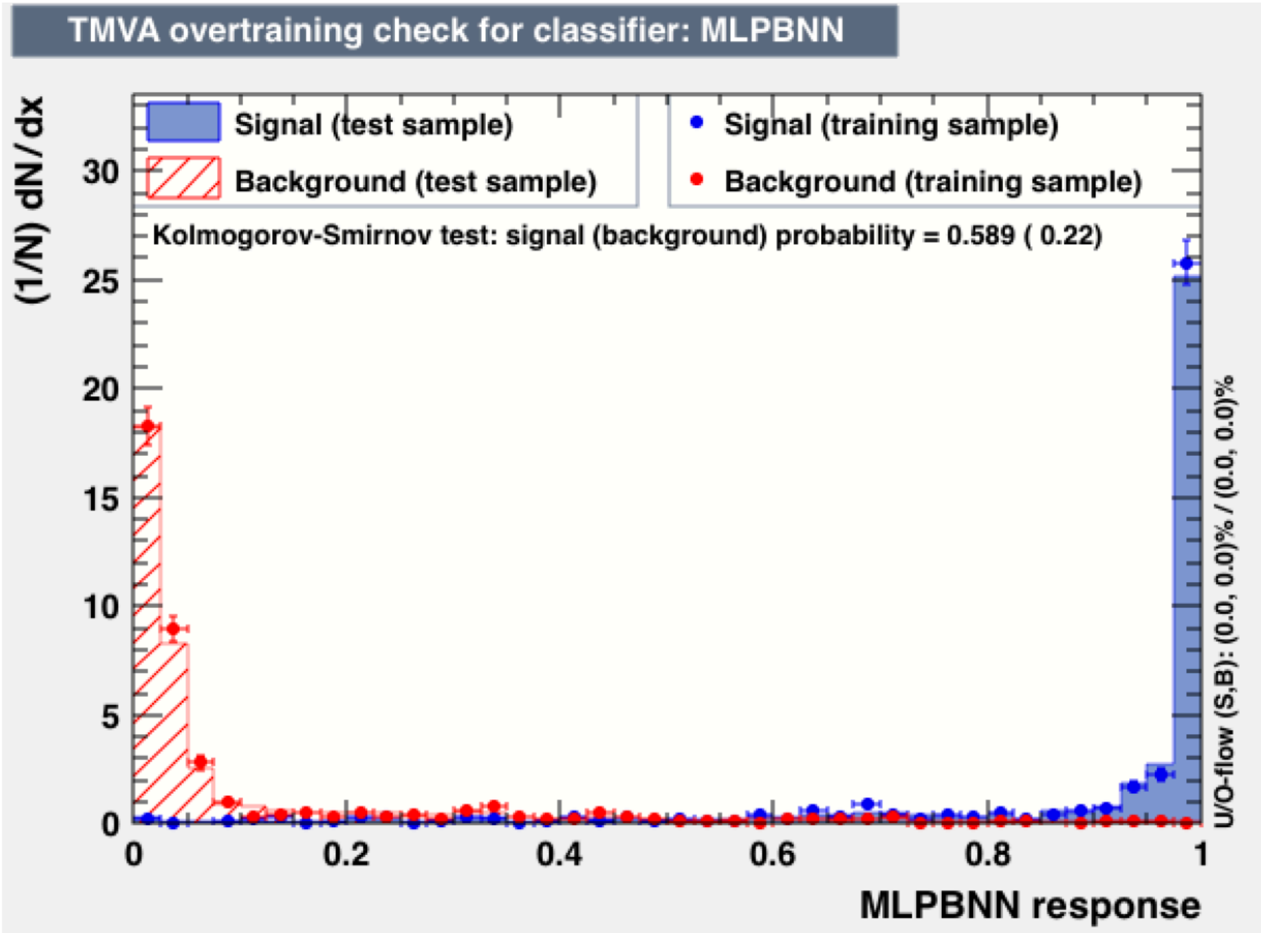

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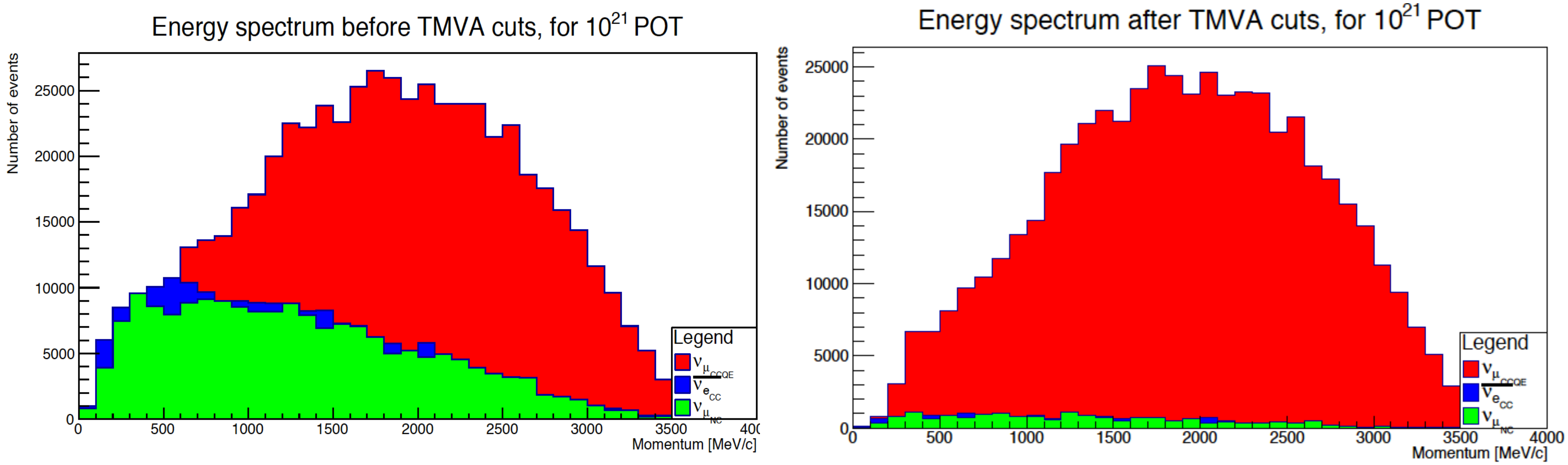
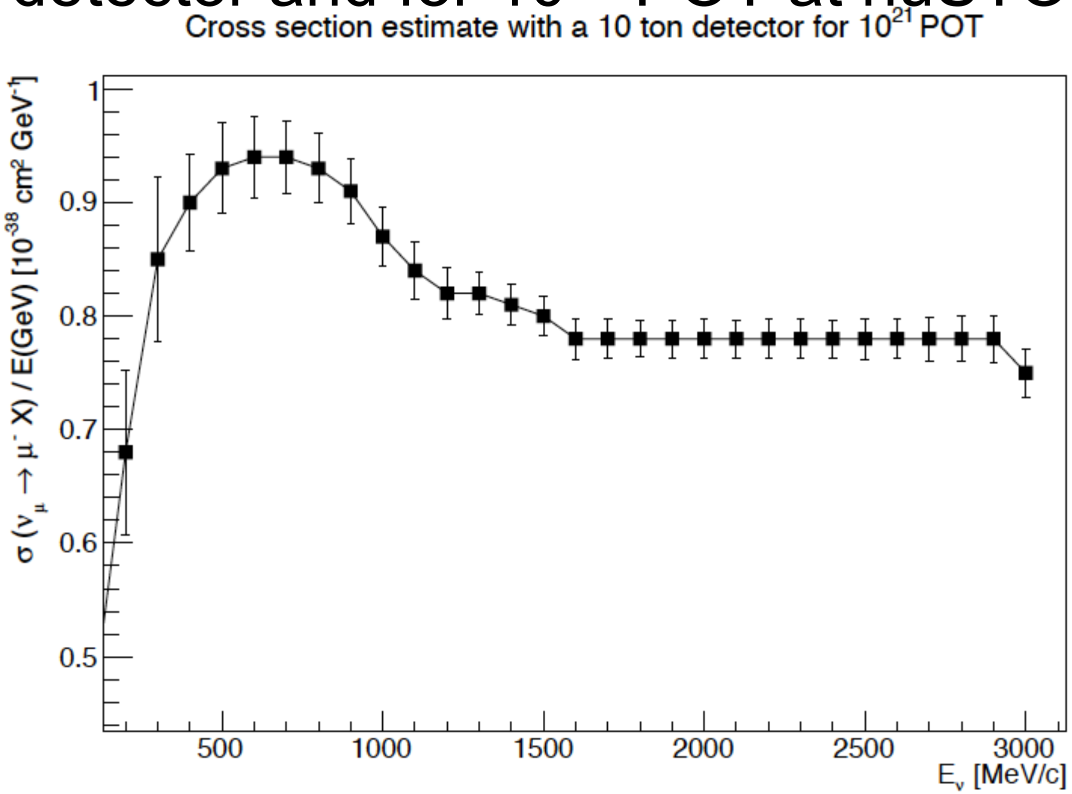
  - Signal efficiency = 84%; background contamination = 7.4%
  - Assume10 ton detector and 10^{21} POT at nuSTORM



Preliminary CCQE analysis

- CCQE analysis with TASD + Baby MIND
  - Neutrino event selection with TASD **S.-P. Hallsjö, PhD thesis**
  - Extract cross section σ(E): $N_{\nu_\mu CCQE} = N_{\text{target}} \int \sigma(E) \times \phi_\nu(E)\, dE$
  - Epected ν_μ CCQE cross section with ~3% errors for 10 ton detector and for 10^{21} POT at nuSTORM



Conclusions

- nuSTORM fluxes very well determined (<1% accuracy)
- For short-baseline neutrino oscillations, requires magnetised detectors to perform "wrong-sign" muon analysis
- For scattering physics, need to measure both ν_μ and $\bar{\nu}_e$
- High-resolution detectors (ie. liquid argon, totally active scintillator or high resolution straw tubes), ideally magnetised
- At CERN, ProtoDUNE LAr detectors would be already in place
- To perform measurements of nuclear re-interactions, gaseous argon would probably be ideal, but mass much lower
- Hybrid detector with active target and modular magnetic spectrometer (à la Baby MIND), could also be possible:
- Performed ~3% differential cross section measurement with a 10 ton totally active detector and 10^{21} POT in nuSTORM