New approach to antineutrino from muon decay at rest

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Neutrinos at Spallation Source

- Interaction of a few GeV protons with the target produces charged pions in addition to the spallation neutrons

$$p + X \rightarrow \pi^{\pm} + X'$$

- π^- & daughter μ^- are absorbed in thick, high-Z target
- π^+ are brought to rest in a high-Z beam stop
- π^+ decay produces mono-energetic 29.8 MeV ν_μ & μ^+

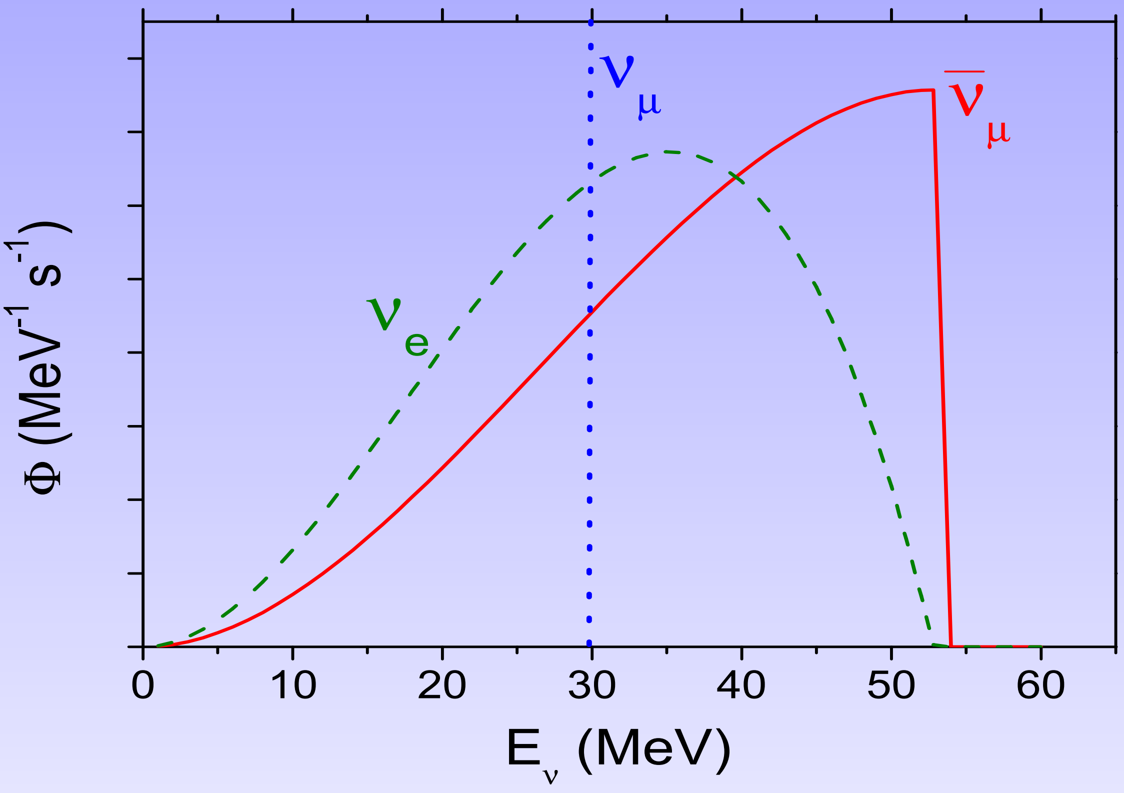
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

- μ^+ decays at rest, providing Michel spectrum

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Decay At Rest (DAR) Source

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



Provides an equal, high-intensity, isotropic, DAR ν_μ, ν_e and $\bar{\nu}_\mu$ beam with tiny $\bar{\nu}_e$ contamination ($\sim 10^{-4}$ to 10^{-5})

DAR Source Facilities

Facility	Power	Proton energy	Time structure	Repetition rate
LAMPF (USA)	56 kW	0.8 GeV	Continuous	N/A
ISIS (UK)	160 kW	0.8 GeV	200 ns	50 Hz
DAEδALUS (USA)	1 - 5 MW	0.8 GeV	Continuous	N/A
SNS (USA)	$>$ 1 MW	1 GeV	380 ns	60 Hz
JSNS (Japan)	1 MW	3 GeV	1 μs	25 Hz
SPL (CERN)	4 MW	3.5 GeV	0.76 ms	50 Hz
ESS (Sweden)	5 MW	1.3 GeV	2 ms (1.4 μs)	17 Hz (50 Hz)

Past, present, and future DAR Source Facilities in different regions of the world

R. Lazauskas, C. Volpe, arXiv:1004.0310v1 [hep-ph]

- LSND (167 tons) at 30 m from LAMPF in Los Alamos
- KARMEN (65 tons) at 17.6 m from ISIS at RAL

Proton Source

- Main technological challenge is the production of a sufficiently intense proton beam with few GeV energy
- Superconducting Linacs : clean & proven technology, can provide multi-MW beams, very expensive & size is large
- Conrad and Shaevitz suggested that new low-cost, high-power proton cyclotrons can deliver multi-MW beams at a cost of 5% of a conventional proton accelerator

Conrad & Shaevitz, PRL 104:141802 (2010)

- DAEδALUS collaboration performing an extensive R&D for a new DAR neutrino source for large Gd-doped water Cherenkov detector at Homestake mine aka DUSEL

Expression of Interest: arXiv:1006.0260 [physics.ins-det]

Physics Goals

Assume that a multi-MW proton beam is affordable

Key for high-intensity DAR neutrino source

- **Test anomalies: LSND, MiniBooNE, Gallium...**
  – ***High*** Δm^2 ***oscillation*** $(L \sim 20 - 50\ m)$
- **Study CP violation in active neutrinos**
  – ***Oscillation at atm.*** Δm^2 $(L \sim 20\ km)$
- **EW precision physics** ($\sin^2\theta_W$ **measurement)**
- **Searches for non-standard neutrino interactions**
- **Coherent** ν**-nucleus scattering** (^{12}**C,** ^{16}**O,** ^{40}**Ar)**
  – ***Supernova*** ν ***spectrum overlaps with DAR*** ν
  – ***Calibration of*** ν ***detectors for supernova***

Where do we stand today?

LSND : L = 30 m, $< E_{\nu_{\bar{\mu}}} > = 40$ MeV

- $3.8\,\sigma$ excess of $\bar{\nu}_e$ events in a beam of $\bar{\nu}_\mu$

MiniBooNE : L = 541 m, $< E_{\nu_\mu, \nu_{\bar{\mu}}} > = 700$ MeV

- No oscillation in the ν-mode for energies above $475\,\mathrm{MeV}$
- An unexplained $3\,\sigma$ excess of ν_e events in the ν-mode below $475\,\mathrm{MeV}$
- A $2.8\,\sigma$ excess of $\bar{\nu}_e$ events in the anti-neutrino mode above $475\,\mathrm{MeV}$, consistent with LSND
- L/E ratio very similar between LSND and MiniBooNE
- Both points to a Δm^2 of the order $0.1 - 10\,\mathrm{eV}^2$

Testing LSND, MiniBooNE..

MiniBooNE is not conclusive w.r.t. LSND

Simple increase in statistics would not resolve the issue

How to address this problem?

We suggest to perform a modern version of LSND

LSND reloaded

SKA, Patrick Huber, arXiv:1007.3228

DAR + Super-Kamiokande (Gd)

- Place DAR source 20m away from the surface of SK, should provide sufficient shielding against neutrons
- $\bar{\nu}_\mu$ from DAR source will oscillate into $\bar{\nu}_e$ & will be detected via inverse beta decay in Gd doped SK

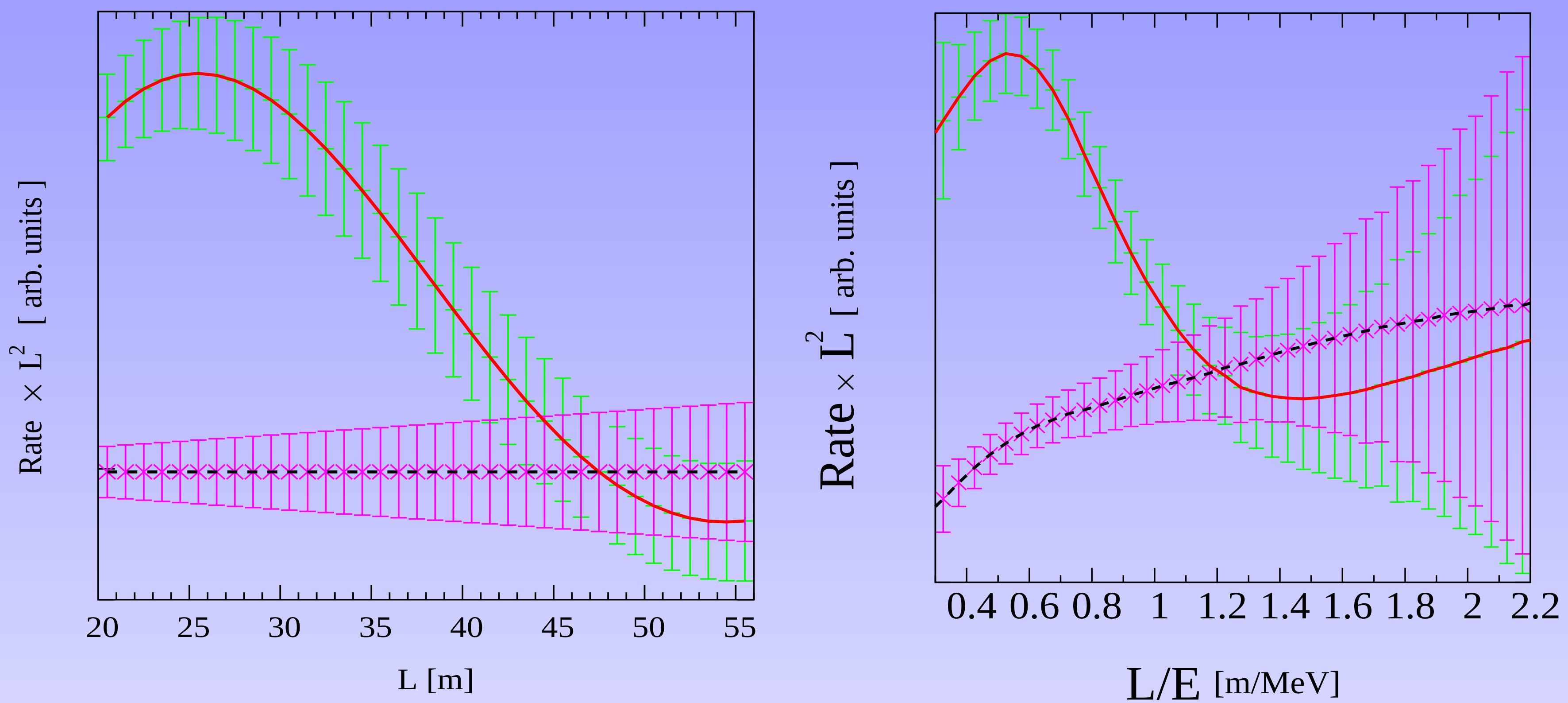
$$\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$$

- Useful coincidence tag between the prompt positron and the delayed neutron capture in a Gd dopped WC detector
- Event rates will be very high in SK due to large fiducial mass of 22.5 kt .vs. 167 t in LSND
- 300 kW proton beam power is sufficient to have 4×10^{21} $\bar{\nu}_\mu$ per year from each cyclotron
- Intrinsic $\bar{\nu}_e$ contamination small, 4×10^{-4} (LSND value)

Gd doped Super-Kamiokande

- Gd doping allows efficient detection of neutron capture (ΔT $\sim$ 30 μs, 8 MeV γ). 67% IBD detection efficiency
- SK is deep ($2,700\,\mathrm{mwe}$) and thus has only very small cosmic background rate compared to LSND ($120\,\mathrm{mwe}$)
- In SK, the large dimensions of the fiducial volume a cylinder of $14\,\mathrm{m}$ radius with a height of $36\,\mathrm{m}$ allow to observe the characteristic L dependence of oscillation
- Beam stop size 0.5 m & vertex resolution in SK 0.75 m added in quadrature yields Δx = 0.9 m. We use 1 m bins
- Energy range: 20 - 52 MeV with $\sigma(E) = 50\%\sqrt{E/MeV}$
- Baseline range: 20 - 56 m
- 38 equally size L/E bins ranging $0.4 - 2.8\,\mathrm{m\,MeV^{-1}}$

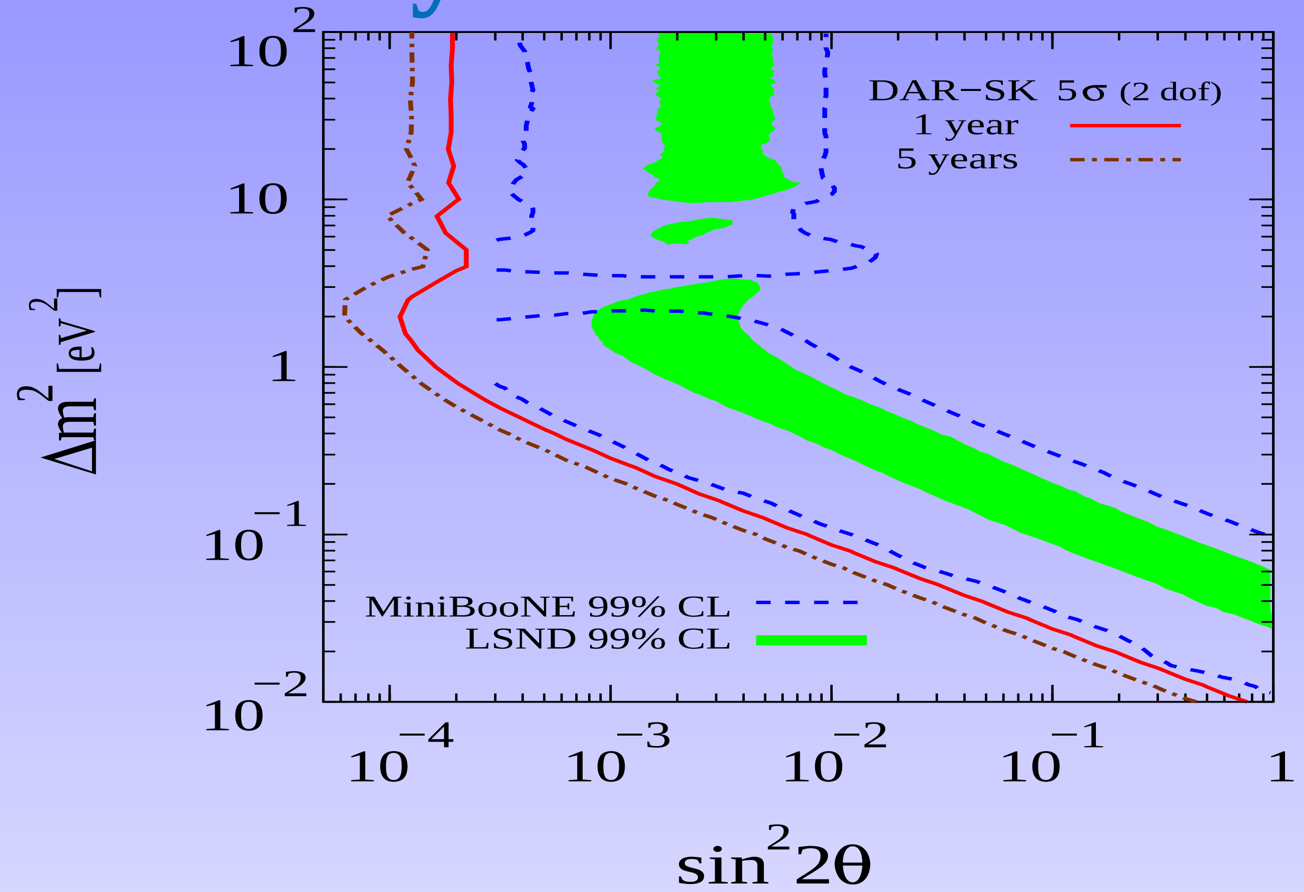
L & L/E pattern in SK



2 flav: $\sin^2 2\theta = 10^{-3}$, $\Delta m^2 = 2\,\mathrm{eV}^2$, L^{osc} = 49.6 m (40 MeV)

- Black: Background (765), Red: Signal (1856 events)
- L/E dependence: powerful handle to reject background and to cancel systematic errors among various bins

Sensitivity to Sterile neutrinos



- We cover the whole 99% CL region from both MiniBooNE and LSND at more than 5σ CL in one year
- If a signal will be seen, we will know whether it is oscillation or something else from L-dependence

It will return the final verdict on LSND

Leptonic CP violation

The discovery of CP violation in the lepton sector would constitute a smoking gun for leptogenesis to explain the baryon asymmetry of the Universe

Can we study CPV using DAR neutrino sources?

The effort of DAEδALUS collaboration

arXiv:0912.4079, 1006.0260, 1008.4967, 1012.4853

LBNE and DAR neutrino source

SKA, Huber, Link, Mohapatra, arXiv:1005.4055

$\bar{\nu}_\mu \to \bar{\nu}_e$ in vacuum

$$
\begin{aligned}
P = \; & \sin^2 2\theta_{13} \; \sin^2\theta_{23} \; \sin^2\Delta_{13} \\
& + \sin\delta_{CP} \; \sin 2\theta_{13} \; \sin 2\theta_{23} \sin 2\theta_{12} \; \sin^2\Delta_{13} \sin\Delta_{12} \\
& + \cos\delta_{CP} \; \sin 2\theta_{13} \; \sin 2\theta_{23} \sin 2\theta_{12} \; \sin\Delta_{13} \cos\Delta_{13} \sin\Delta_{12} \\
& + \cos^2\theta_{23} \sin^2 2\theta_{12} \; \sin^2\Delta_{12}
\end{aligned}
$$

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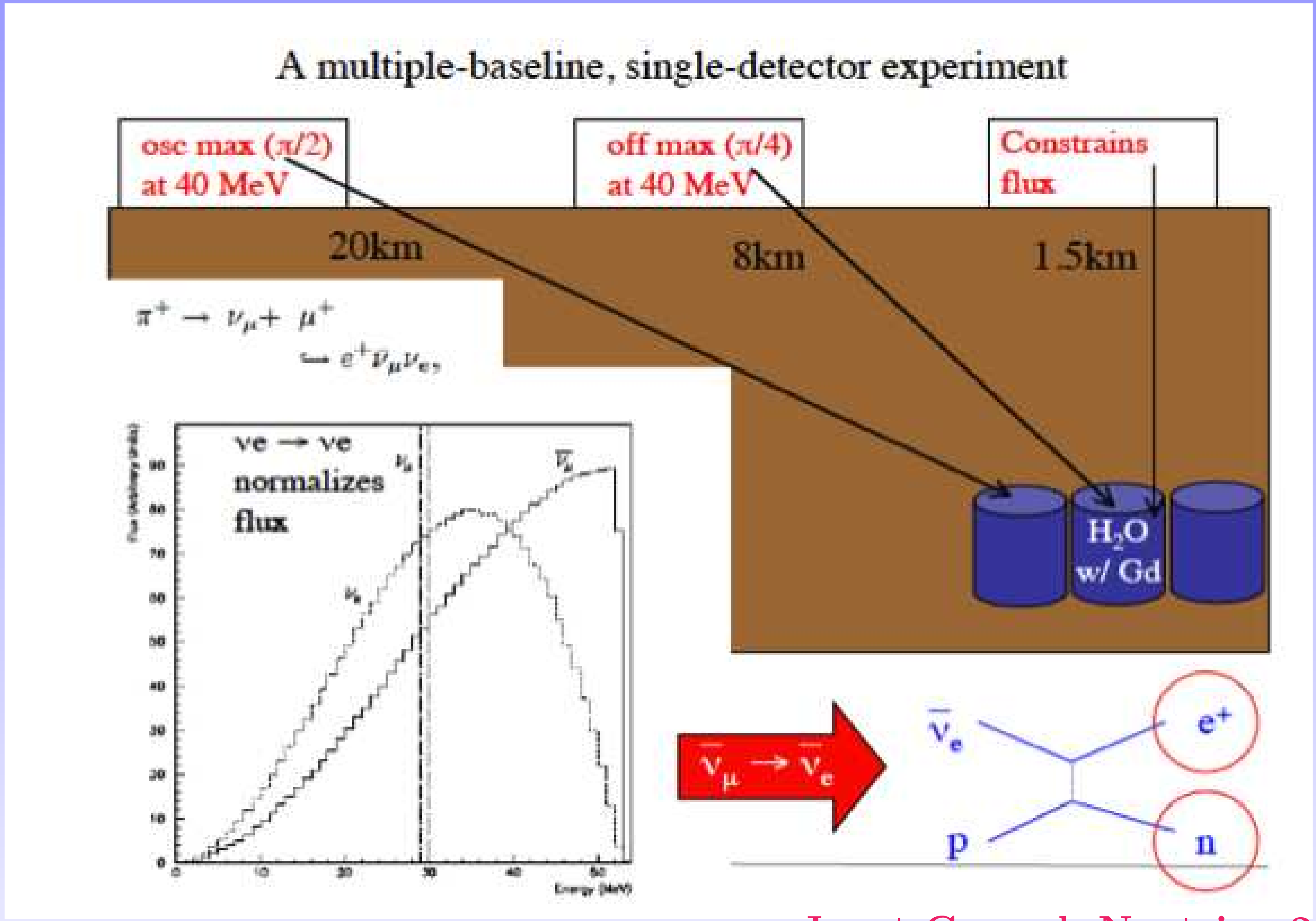
where $\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$

- Want to measure δ_{CP} but θ_{13} and $sgn(\Delta m^2_{31})$ not known
- $1.27\ \Delta m^2_{31} \frac{L}{E} \sim \frac{\pi}{2}$ at E = 40 MeV, L = 20 km (Osc. max)
- $1.27\ \Delta m^2_{31} \frac{L}{E} \sim \frac{\pi}{4}$ at E = 40 MeV, L = 10 km (Off max)
- $1.27\ \Delta m^2_{31} \frac{L}{E} \sim 0$ at E = 40 MeV, L = 1.5 km (flux)

Use the L/E dependence of the interference terms

DAEδALUS setup

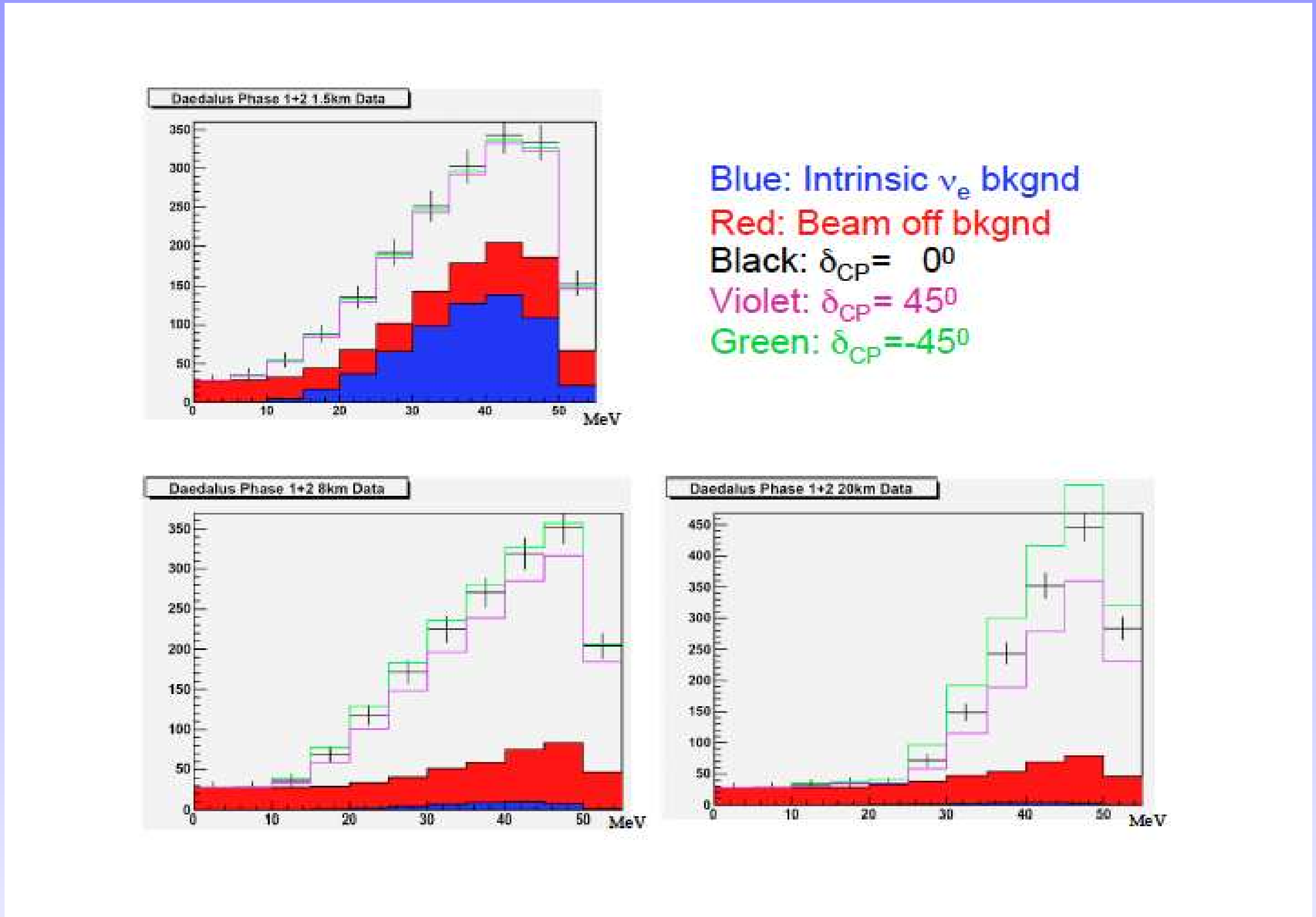


Janet Conrad, Neutrino 2010

DAR $\bar{\nu}_\mu$ beam + 300 kt Gd-doped water detector @ DUSEL

No. of Cyclotrons: 10 (20 km), 4 (8 km), 2 (1.5 km)

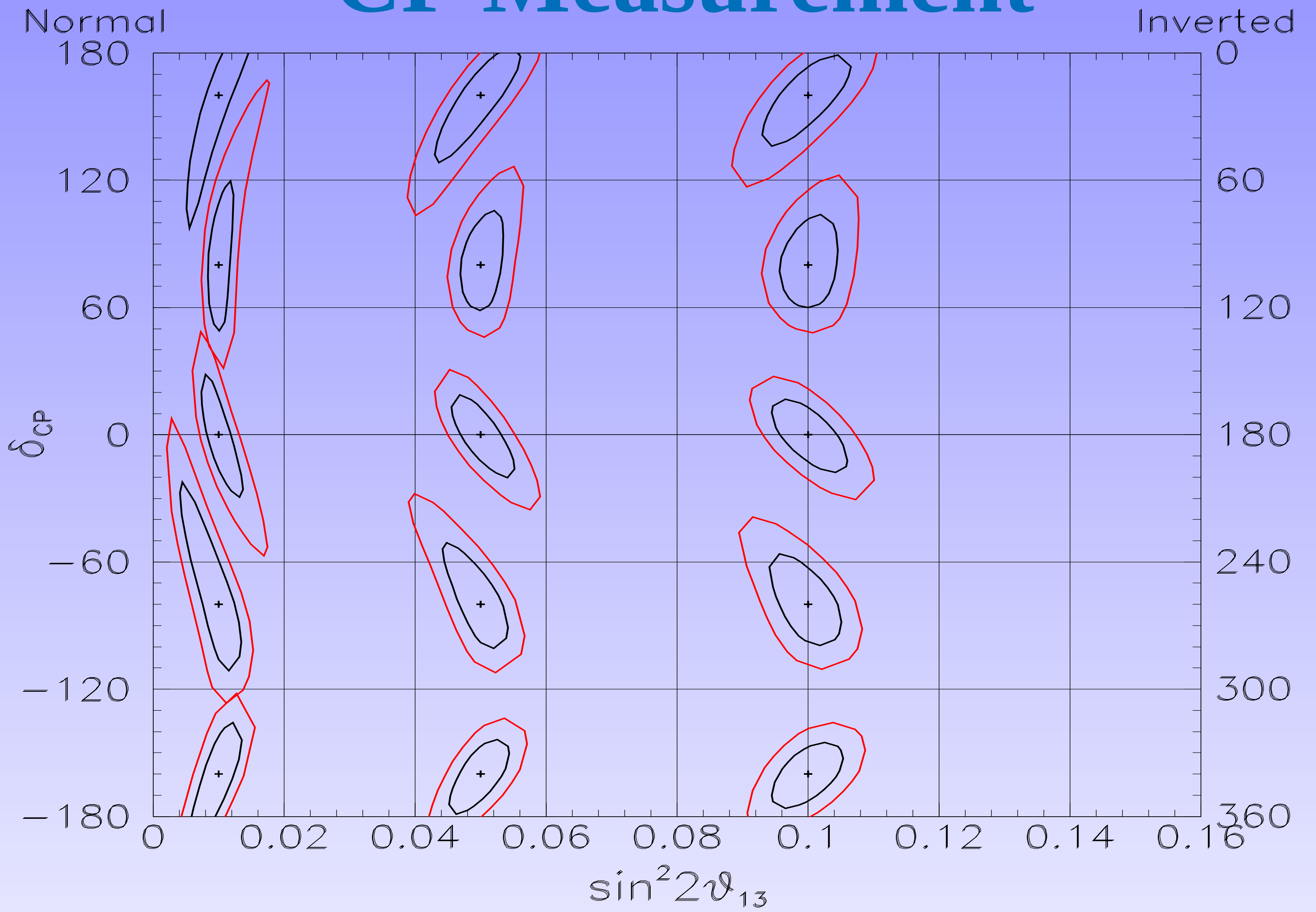
Event .vs. Background



10 years run, NH, $\sin^2 2\theta_{13} = 0.04$, no matter effects

Signal to Background ratio is good at L = 8 and 20 km

CP Measurement



Inner (outer) region is 1σ (2σ) assuming hierarchy is known

[$\delta_{cp} = x^\circ$, NH] is equivalent to [$\delta_{cp} = (180 - x)^\circ$, IH]

DAEδALUS + LBNE

What would happen if we combine DAEδALUS + LBNE experiment?

Why should we combine them?

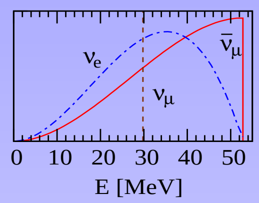
LBNE

Long Baseline Neutrino Experiment

- New, upgraded, intense wide band beam from FNAL towards 300 kt water Cerenkov detector at Homestake mine aka DUSEL at a distance of 1300 km
- LBNE has to run conventional neutrino (HFN) and anti-neutrino (HFA) beams based on the decay of horn focused pions to disentangle CP and matter effects
- Anti-neutrino run in a superbeam is difficult due to lower anti-neutrino production, lower detection cross-sections and large neutrino contamination in the anti-neutrino beam

New Approach

New Approach : DAR + HFN
LBNE : HFA + HFN



4 Proton Accelerators
1 MW, 1 GeV
Low−cost, High−power

DAR — **$4 \cdot 10^{22}$ neutrinos/flavor/year/accelerator**

DAR : $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
20 – 55 MeV

20 km IBD

DUSEL
w / Gd
100 – 300 kton

1300 km CC QE

FNAL

HFN : $\nu_\mu \rightarrow \nu_e$
HFA : $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
0.5 – 6 GeV

Wide Band Beam
700 kW, 120 GeV
$6.2 \cdot 10^{20}$ protons/year

SKA, Huber, Link, Mohapatra, arXiv:1005.4055

Signal .vs. Background

	$\bar{\nu}_\mu \to \bar{\nu}_e$	Bkg	$\nu_\mu \to \nu_e$	Bkg
DAR+HFN	1194	217	1532	428
HFA+HFN	231	158	766	214

$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0°$, **NH and total 6 years run**

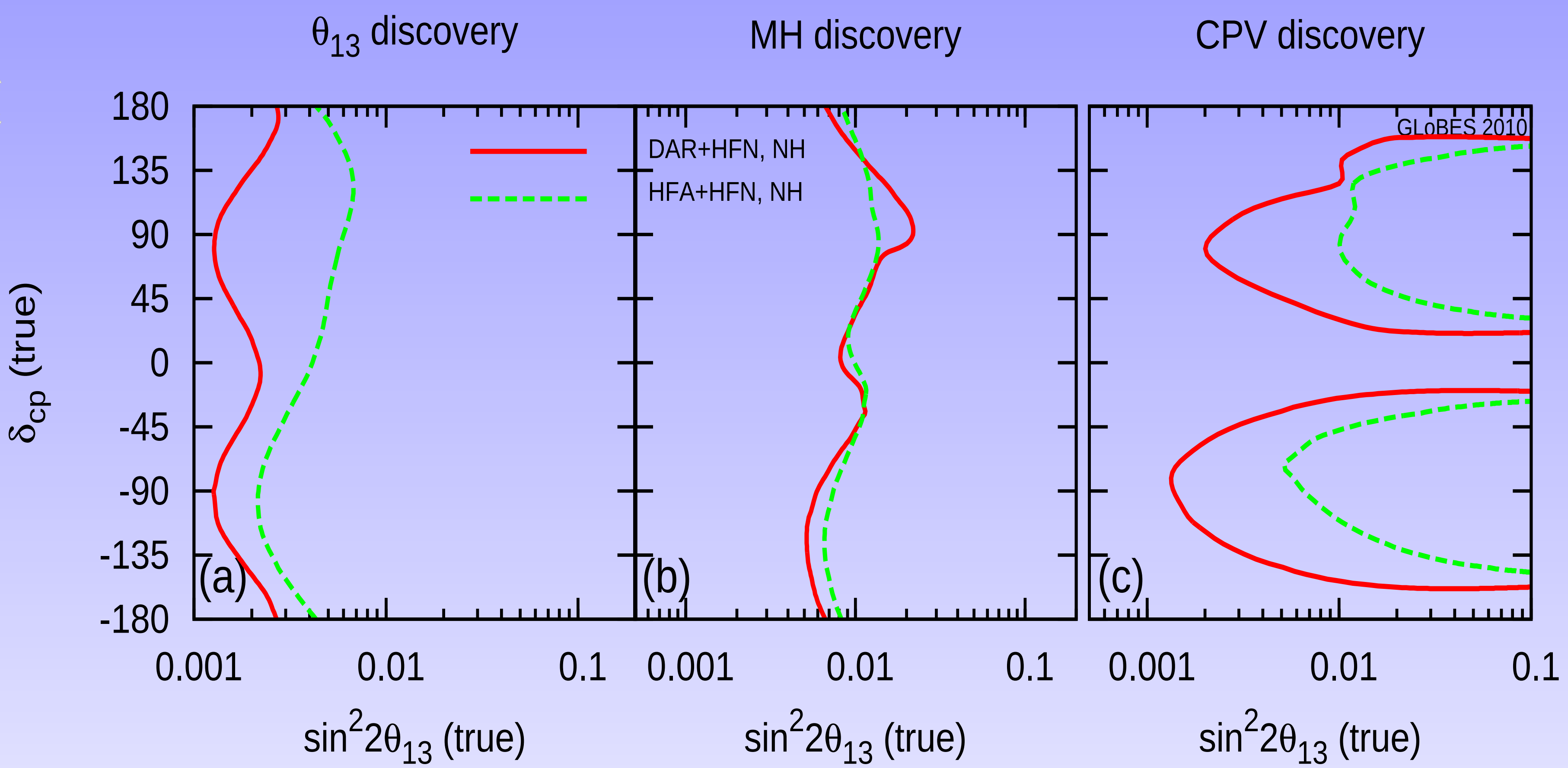
DAR+HFN: **6 years of** *simultaneous* **running of neutrinos and anti-neutrinos**

HFA+HFN: **3 years of** *consecutive* **running of neutrinos and anti-neutrinos**

DAR+HFN: *twice* **the statistics in the neutrino mode and** *five times* **as much statistics with a five times better sig/bkg ratio in the anti-neutrino mode**

SKA, Huber, Link, Mohapatra, arXiv:1005.4055

300 kton & NH



SKA, Huber, Link, Mohapatra, arXiv:1005.4055

Discovery reaches at $3\,\sigma$ confidence level

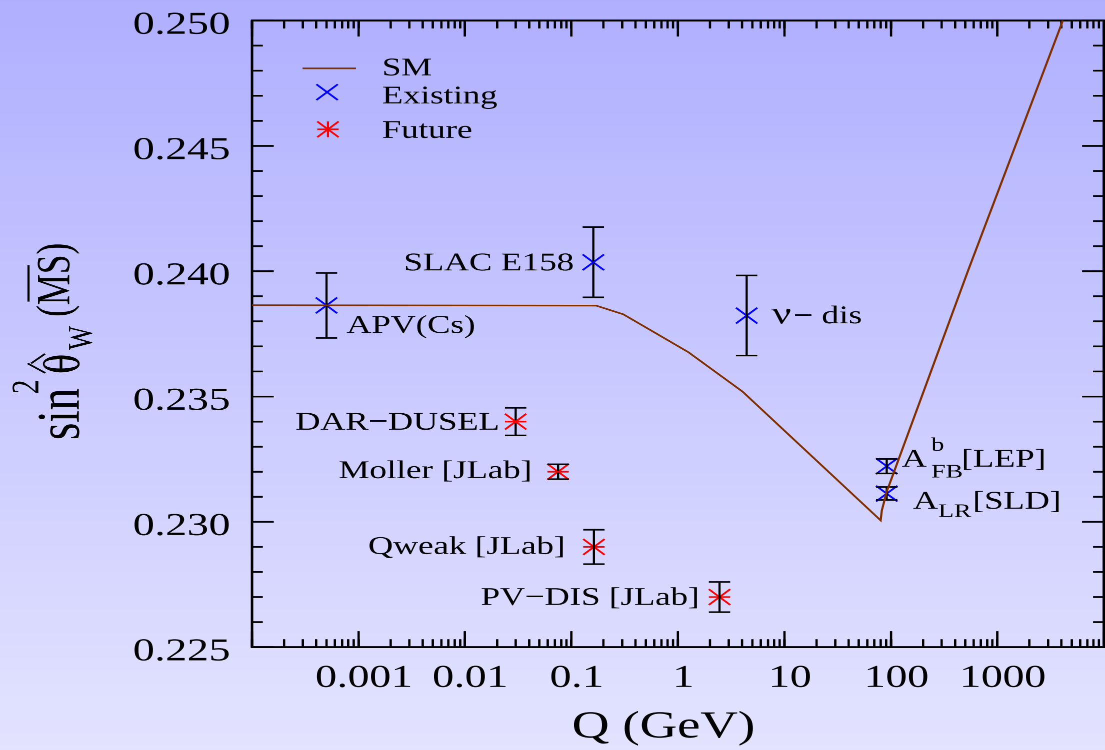
Concluding Remarks

- A stopped pion source provides neutrino beams with energy of a few tens of MeV from pion and muon decay-at-rest
- A rich physics program can be accomplished with such a neutrino source
- Low-cost, multi-MW proton cyclotrons needed
- 300kW proton beam + Gd-doped SK can test LSND, MiniBooNE anomalies in one year at more than 5σ CL
- DAR neutrino sources together with LBNE can accelerate the discovery reach of CP violation

For applications in EW precision physics, see
SKA, Patrick Huber, arXiv:1005.1254

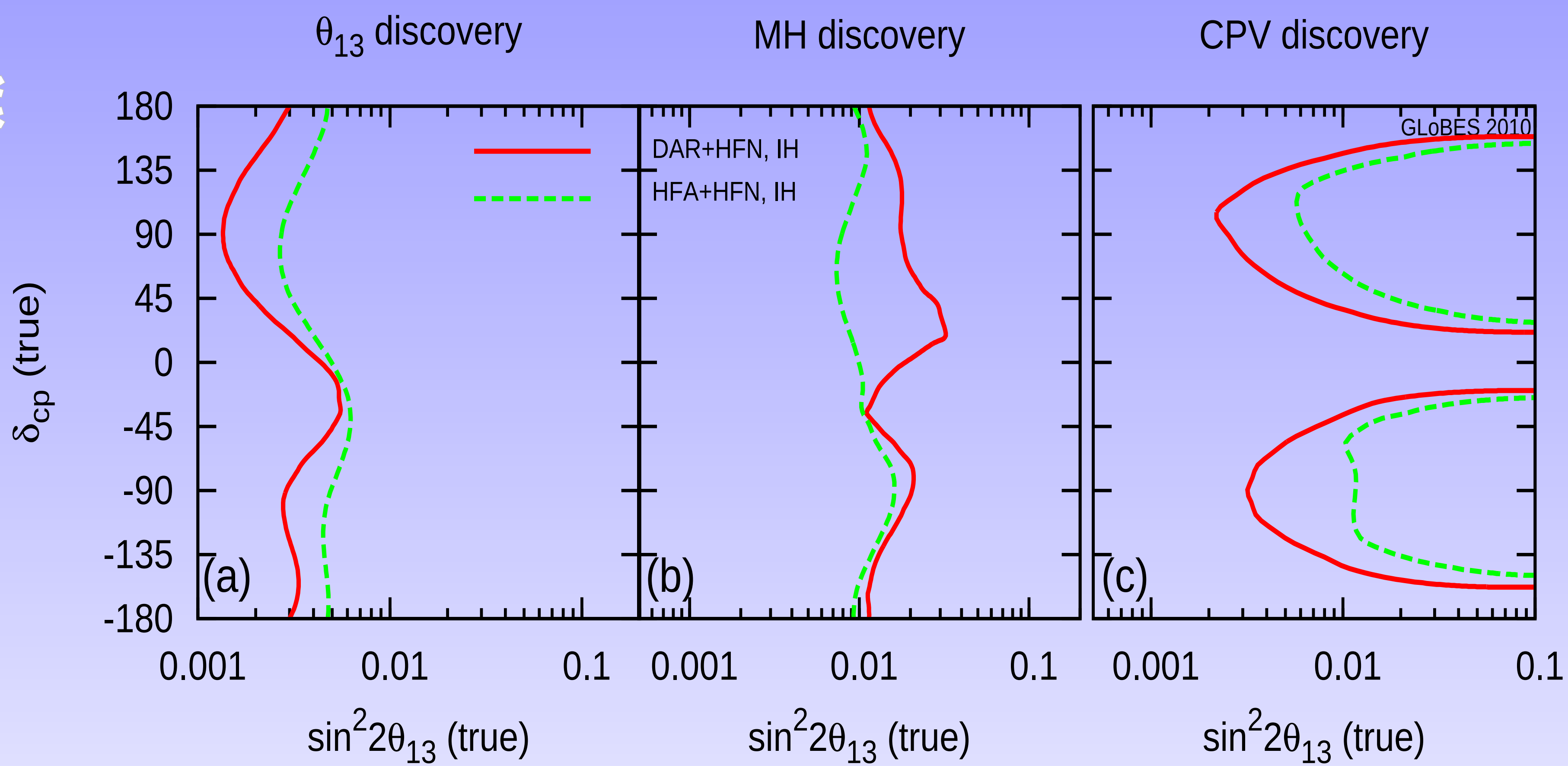
DAR-DUSEL

Our proposed experiment will provide a $\simeq 0.24\%$ measurement of $\sin^2\theta_W$



This configuration can be a natural part of the proposed physics program for DUSEL

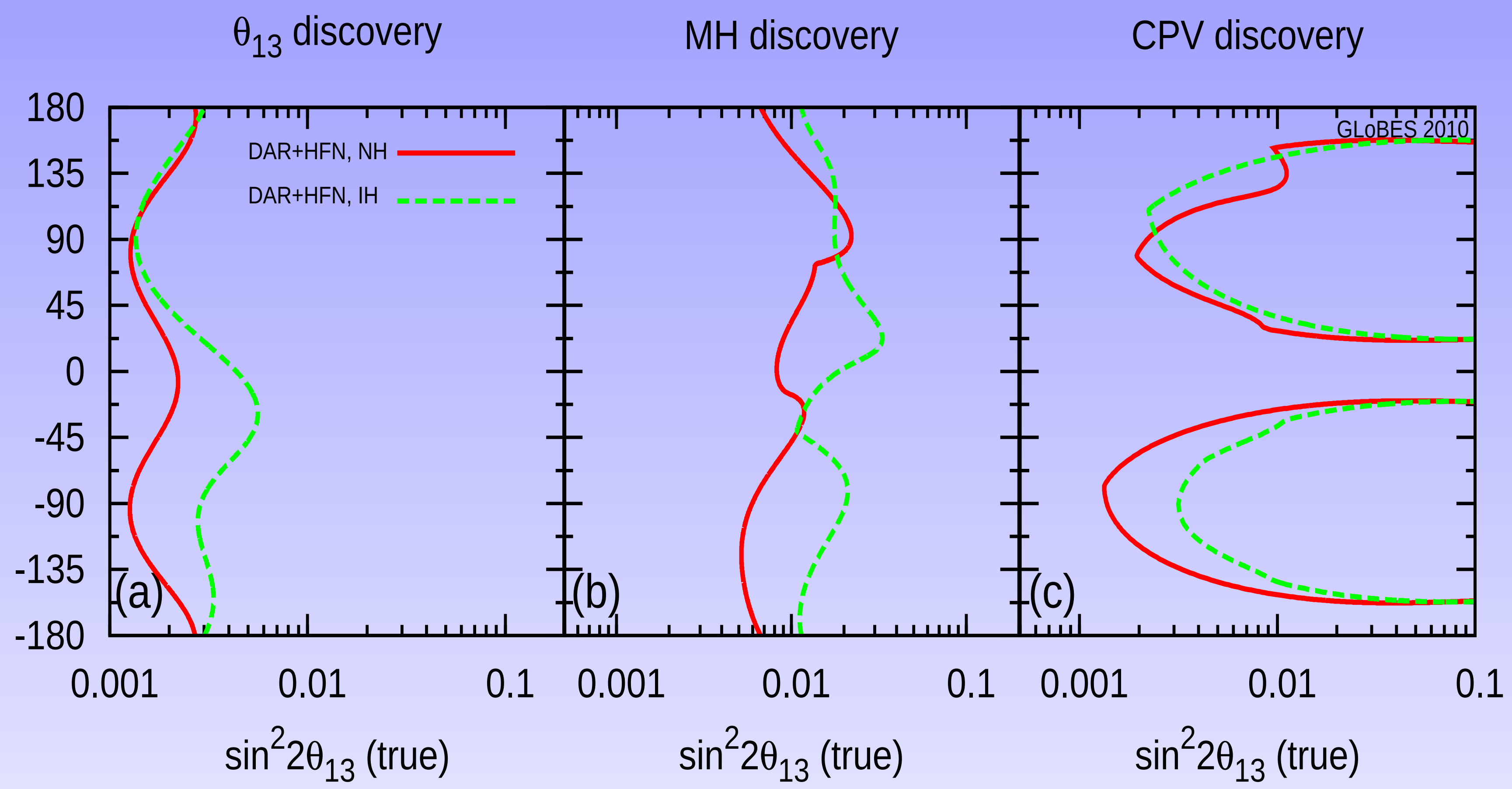
300 kton & IH



Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]

Discovery reaches at $3\,\sigma$ confidence level

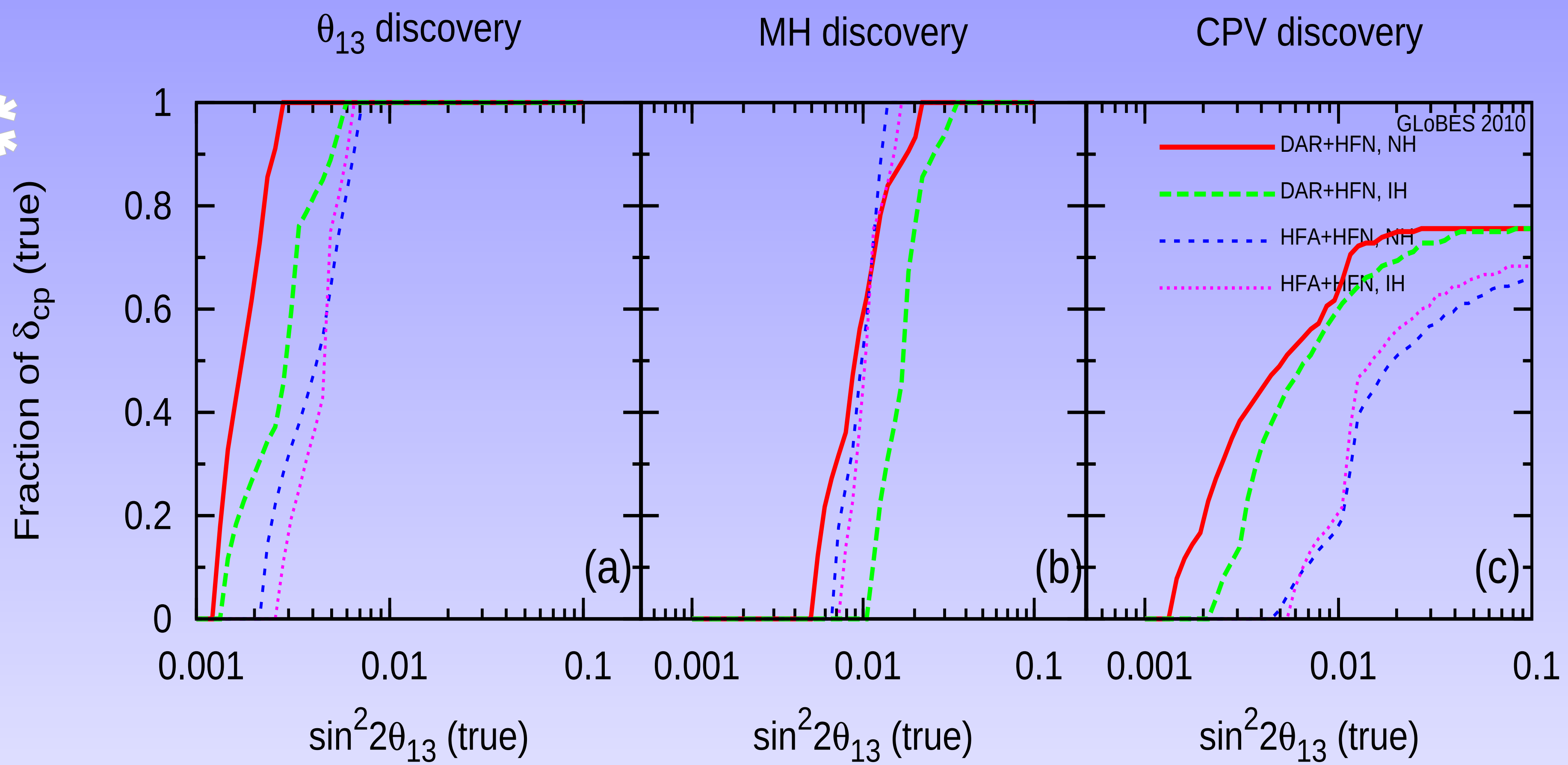
300 kton, NH & IH



Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]

Discovery reaches at $3\,\sigma$ confidence level

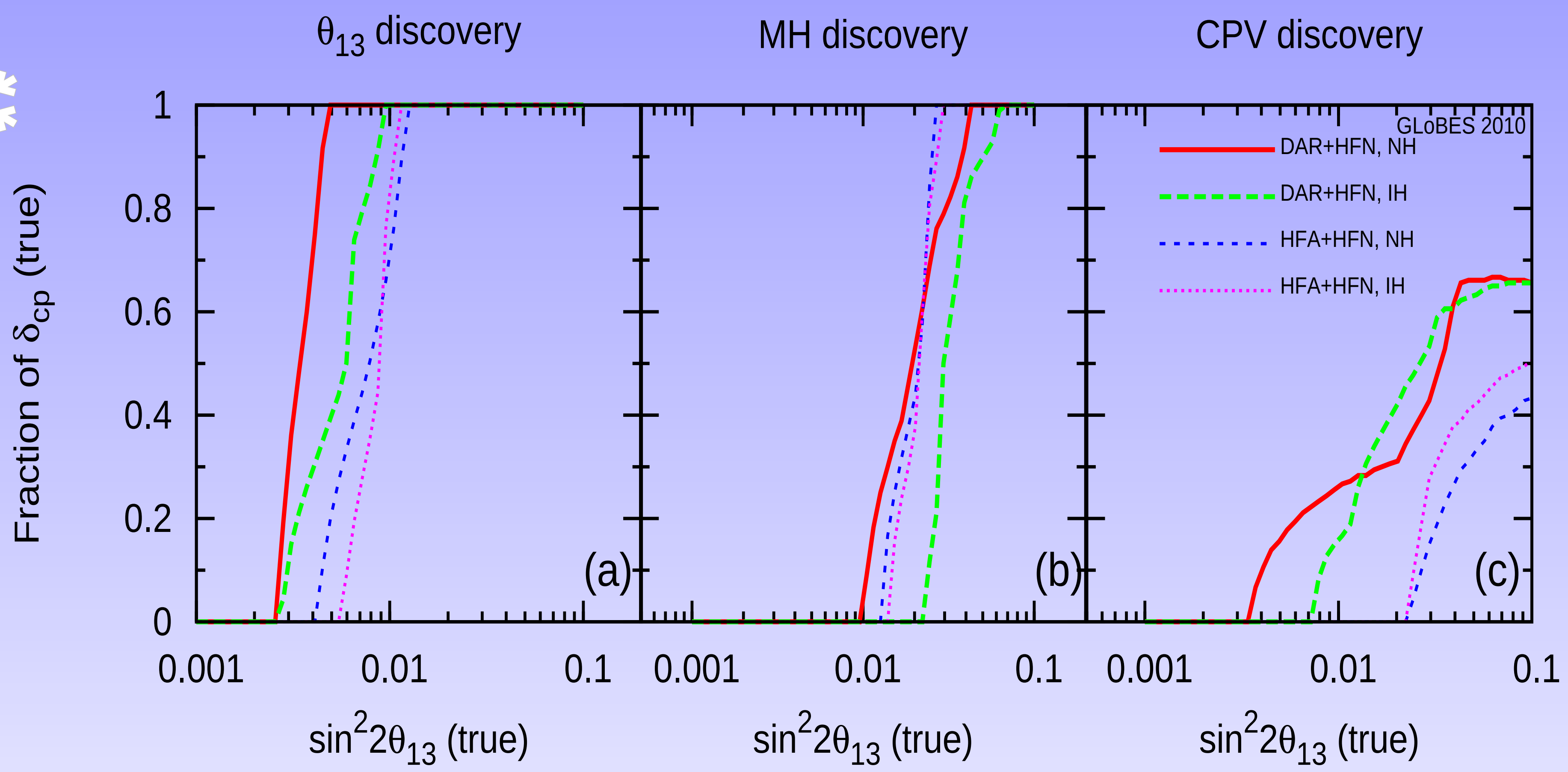
300 kton, NH & IH



Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]

CP fraction for which a discovery at $3\,\sigma$ confidence level is possible as a function of $\sin^2 2\theta_{13}$(true)

100 kton, NH & IH



Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]

CP fraction for which a discovery at $3\,\sigma$ confidence level is possible as a function of $\sin^2 2\theta_{13}$(true)

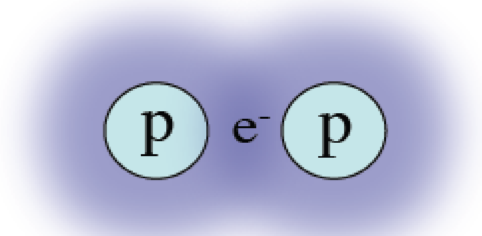
Technologies explored

Linacs

– Cleanest of technologies,
but there are issues of size and cost

Cyclotrons

– Compact Superconducting (proton) Cyclotron
– Stacked (proton) Cyclotron
– H_2^+ Cyclotron -- reduces many problems related to beam loss and extraction compared to other designs



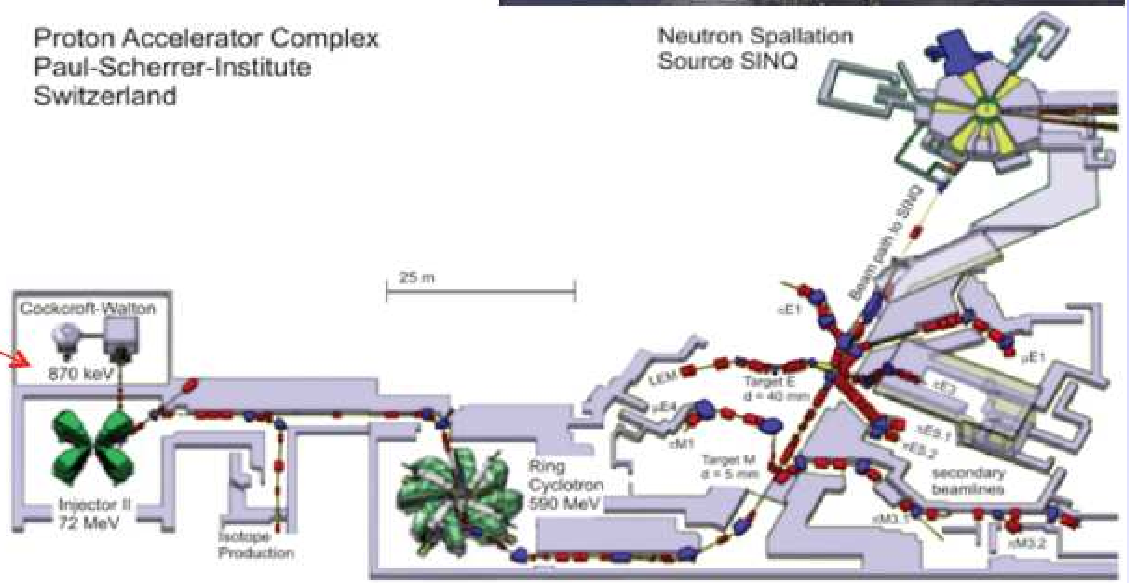
DAEδALUS

Backup Slides

Cyclotron Options

- PSI is best in the world
  - 590 MeV protons
  - 2.2 mA
  - 1.3 MW

Very high
Injection energy



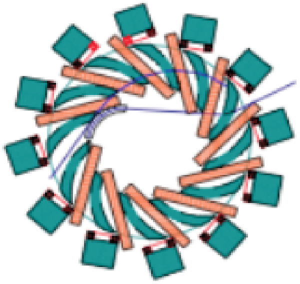
DAEδALUS

Backup Slides

H_2^+ Ring Cyclotron

Promising Design from 1990's

- Concept proposed by Carlo Rubbia ~1994
- Initial designs done by Luciano Calabretta, Catania
  - Reports in European Particle Accelerator Conference
    - Calabretta et al: PAC 99 & EPAC 2000
- 1 GeV, ~6 mA
- High rigidity for H_2^+
  - Superconducting magnets reduce consequences
- Clean extraction (via stripping)



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