Precision Neutrino Physics with Neutrino Factories

Topical Seminar: Neutrino Physics

(in memoria di Guido)

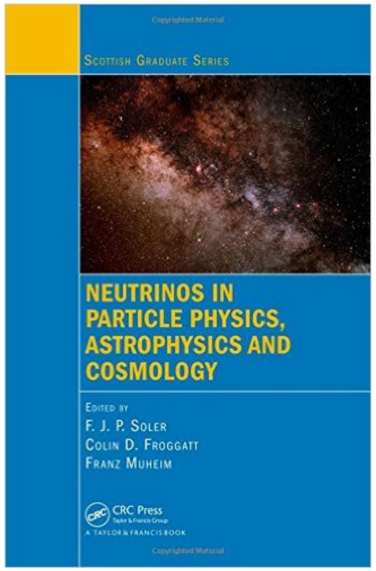
Universita di Roma Tre

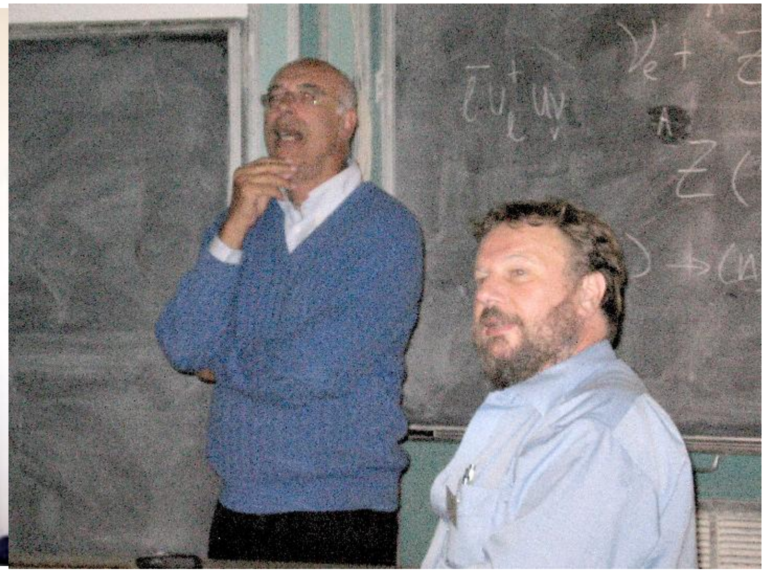
Paul Soler, 18 November 2015

University of Glasgow

Guido Altarelli

- My first encounter with Guido was at the St Andrews Summer School on "Neutrinos in Particle Physics, Astrophysics and Cosmology" in 2006
  - He gave three lectures on Neutrino Masses and Mixing and enjoyed time in Scotland: http://www-archive.ph.ed.ac.uk/sussp61/
  - Lectures documented in text book edited by CRC Press



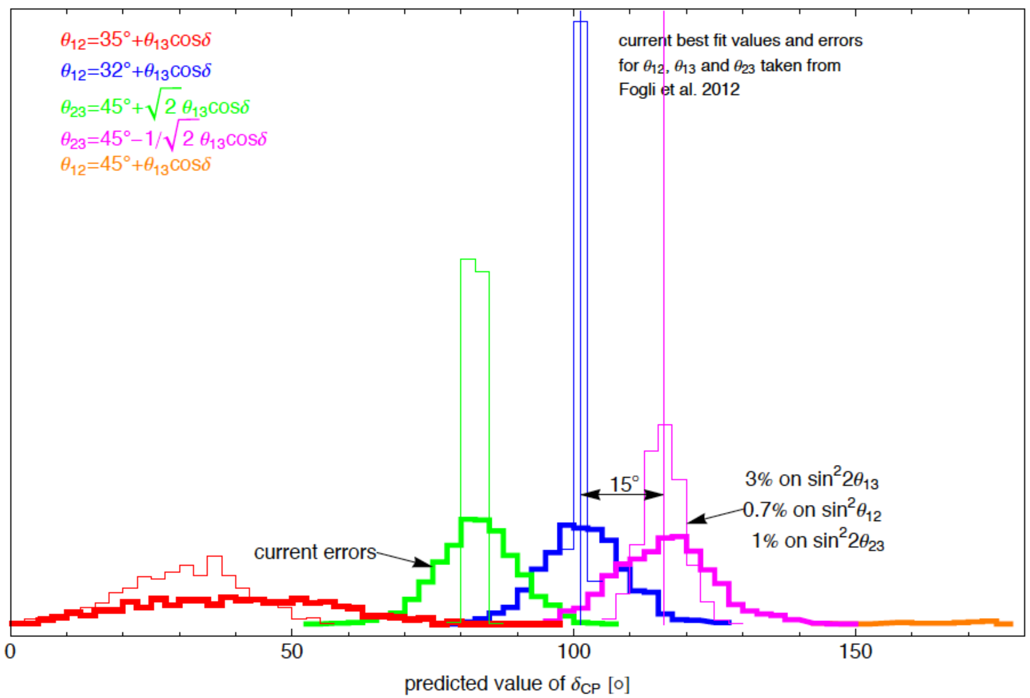


Model predictions

- Guido's approach of using discrete flavour groups to understand neutrino mixing matrices and masses leads to a number of models and predictions of patterns
  - There are distinct pre(post?)dictions for the mixing angles and sum rules with the neutrino CP phase δ_{CP}
  - To test predictions requires very accurate measurements of mixing angles, knowledge of neutrino masses and accuracy in CP phase $\Delta\delta_{CP} \sim 3^o$-$4^o$
  - Models can be tested only if neutrino physics enters into precision era: long baseline neutrino oscillation experiments, neutrino factories, double beta decay and neutrino mass measurements

Model predictions

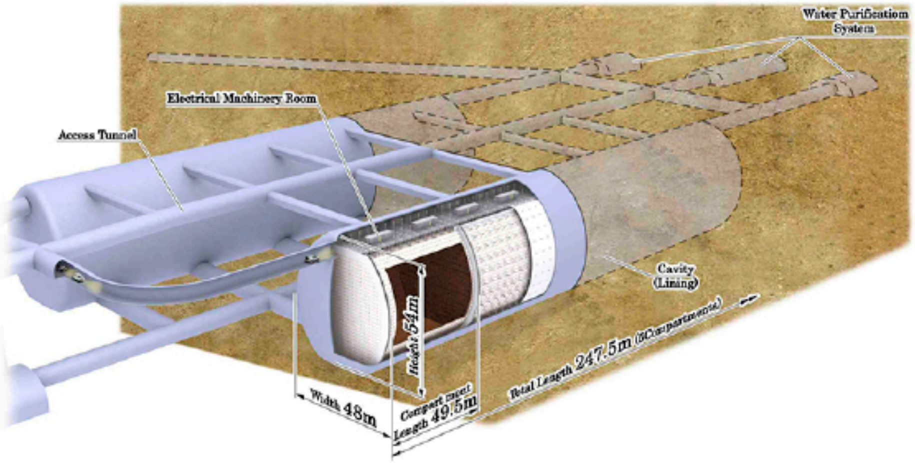
- Sum rule predictions for δ_{CP} need to be tested to advance understanding of neutrino mixing and underlying theory
- CP violation searches from DUNE or Hyper-Kamiokande will give error in the measurement of CP phase $\Delta\delta_{CP} \sim 20^o$
- Distinguish between models requires $\Delta\delta_{CP} < 5^o$ **Neutrino Factories**

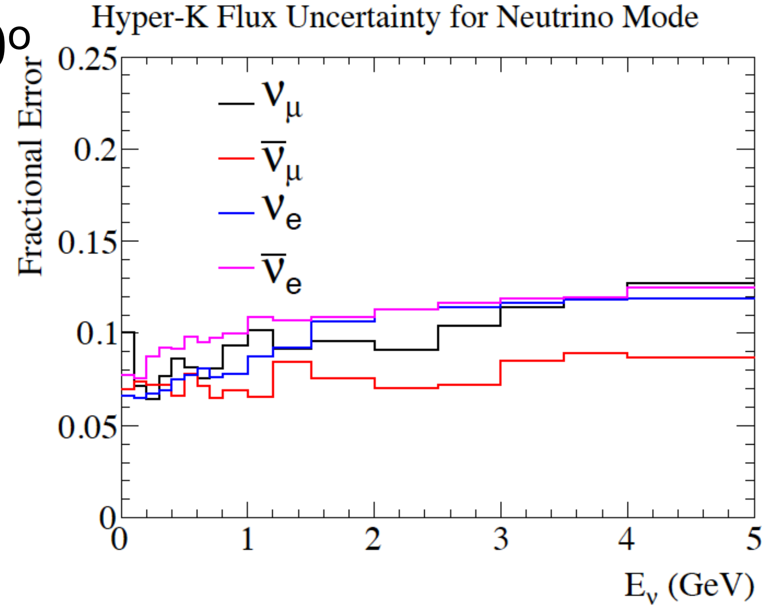


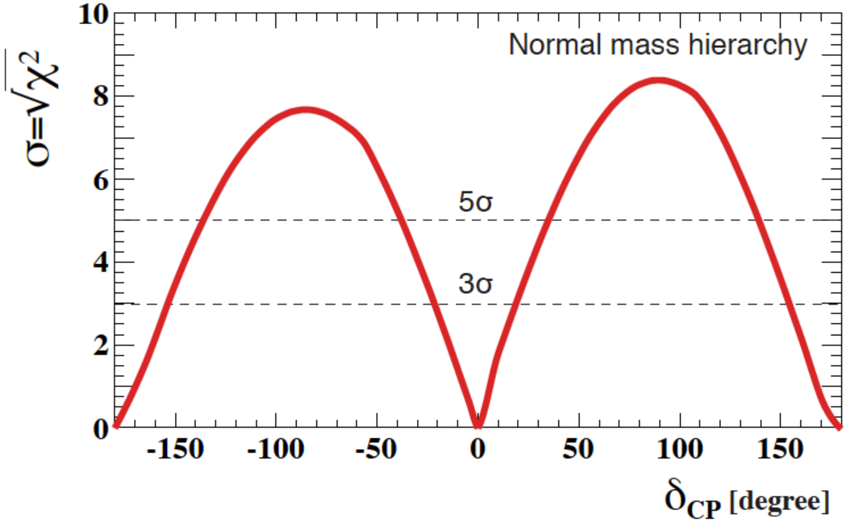
Hyper-Kamiokande

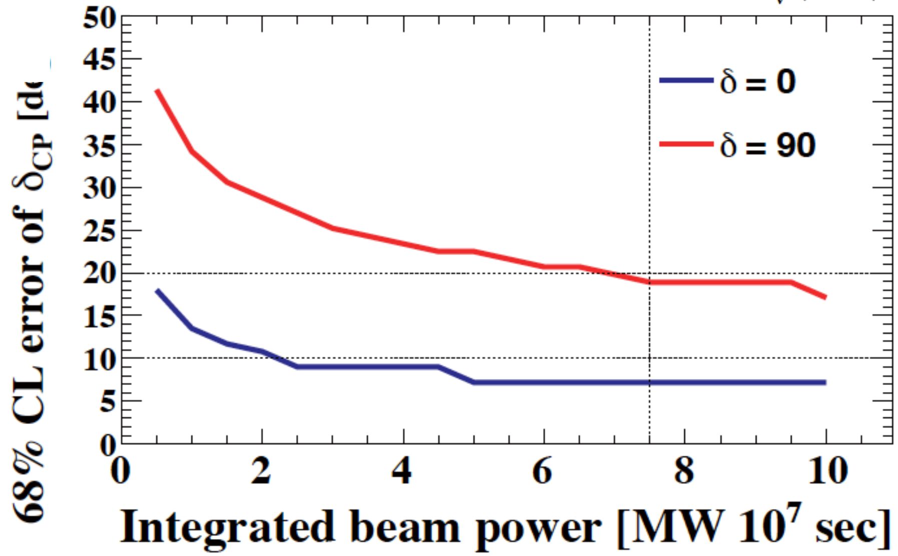
- Expected flux errors ~10%, $\Delta\delta_{CP}$~20°

arXiv:1502.05199





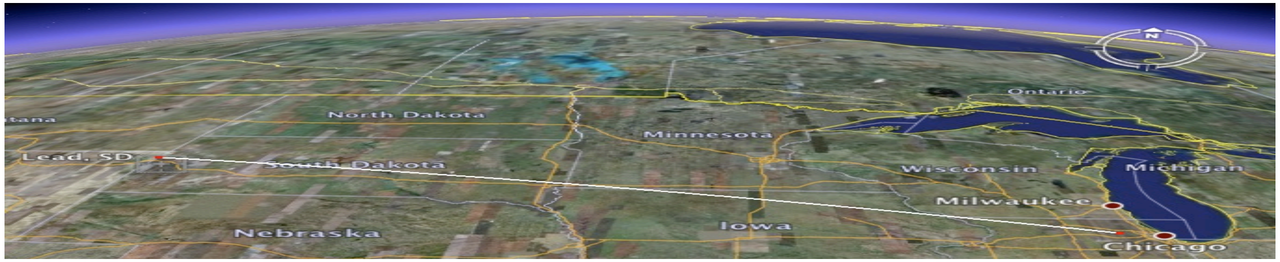


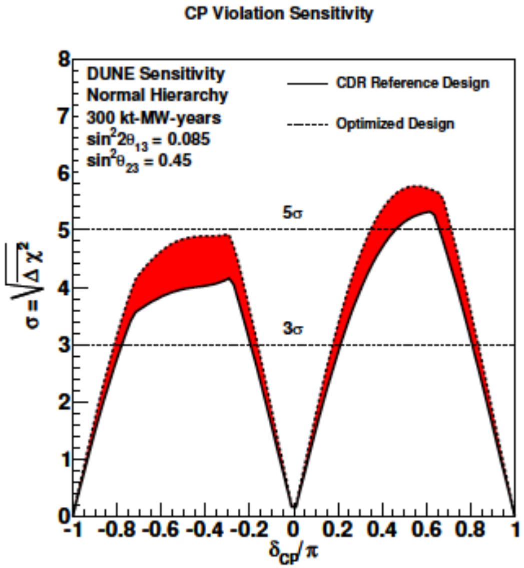


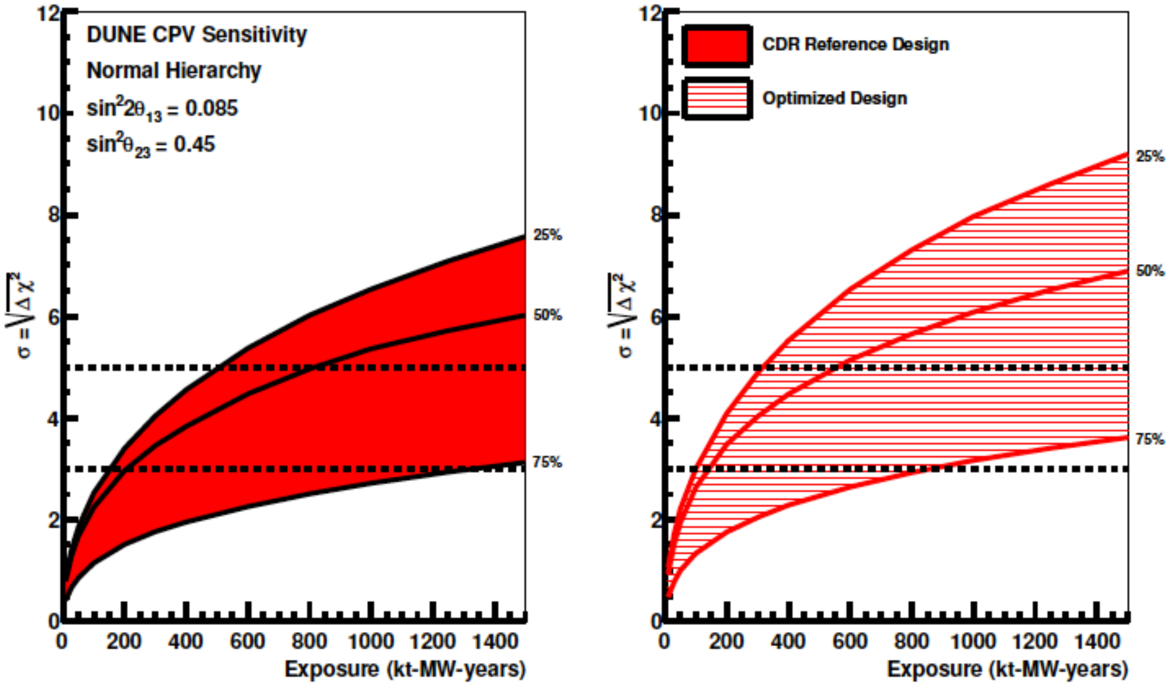
DUNE

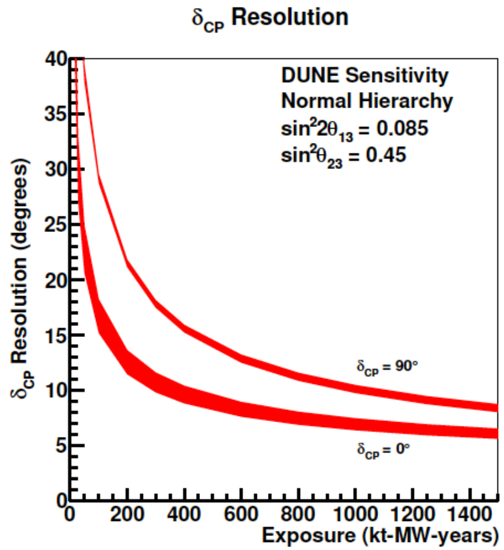
- Expected flux errors ~5%, $\Delta\delta_{CP}$~10°-15°

DUNE Physics Volume CDR, 2015









Neutrino beams

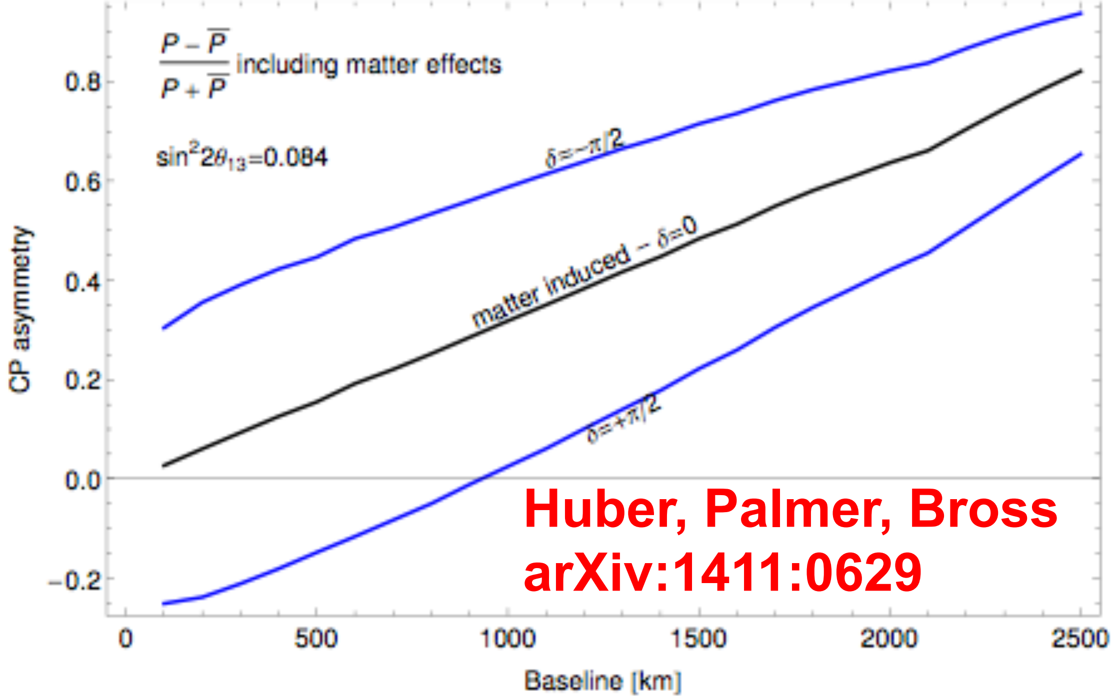
- Neutrino beams have not evolved conceptually since 1963, with the invention of the van der Meer horn
  - Proton beam hits target to create secondary pions, kaons
  - Secondaries are focused by horns
  - Secondaries decay in decay pipe
  - Absorber material and "beam dump" removes charged particles
  - Detectors along beam line are used to monitor flux and direction

- Neutrino flux accuracy depends on secondary pion and kaon production from protons on target: ~ 10-20%

How can we improve CP precision?

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

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



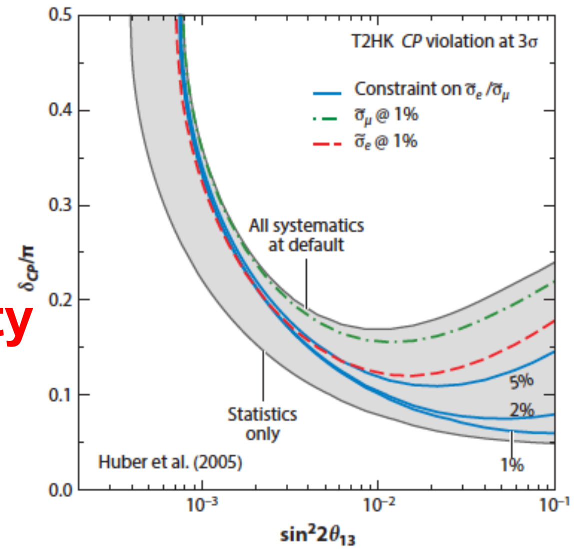
Huber, Palmer, Bross
arXiv:1411:0629

Long baseline physics

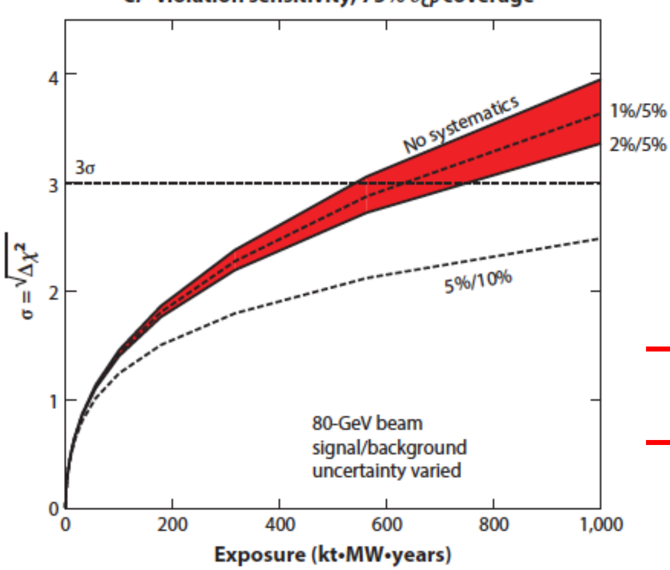
- Precision requirement for CP violation:
  - In disappearance experiment we can satisfy:

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

Huber, Mezzetto, Schwetz arXiv:0711.2950



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



CP violation sensitivity for 75% δ_{CP} coverage at LBNF/DUNE

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

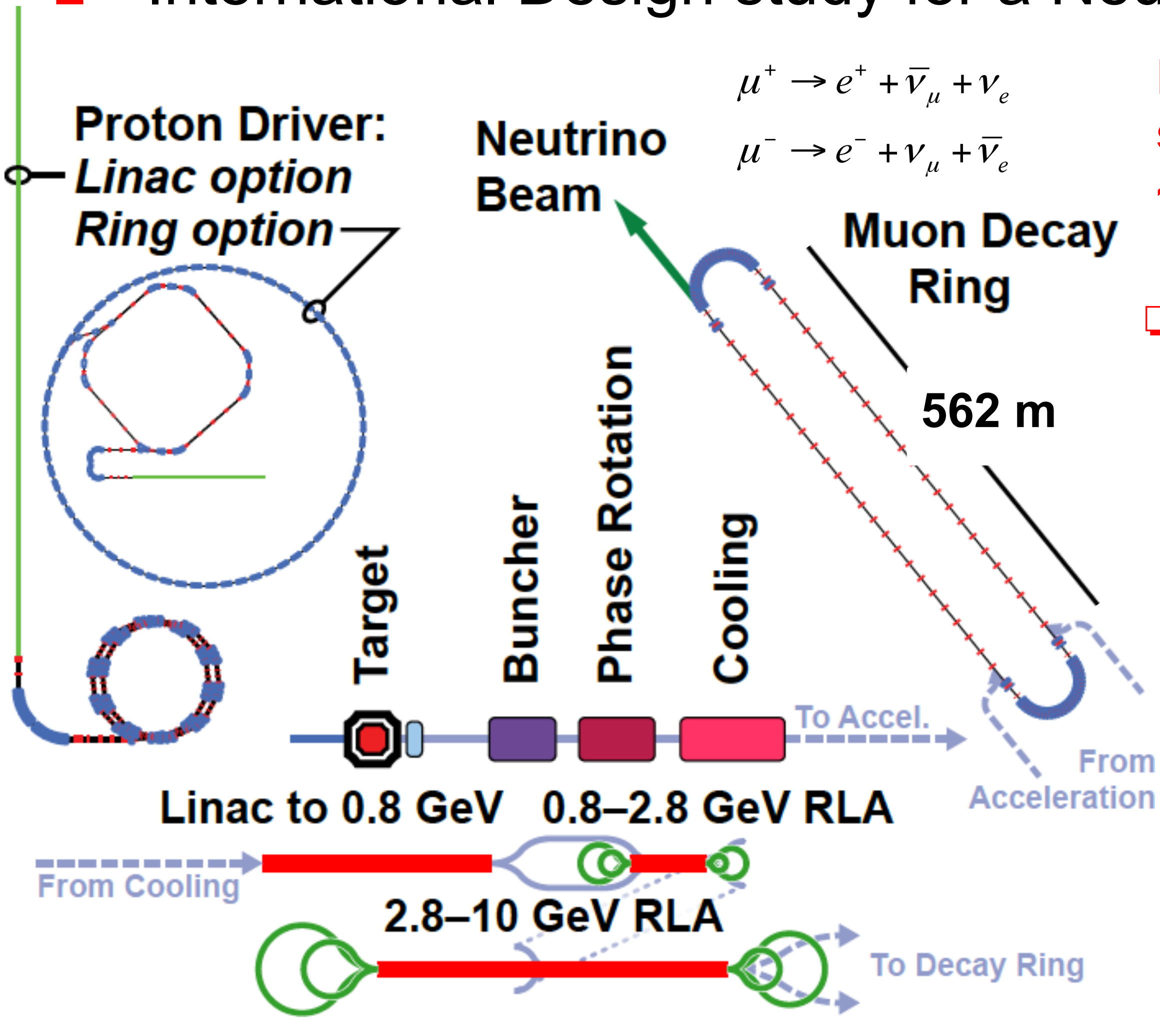
Huber, Palmer, Bross arXiv:1411:0629

Neutrino Factory

- International Design study for a Neutrino Factory (IDS-NF)

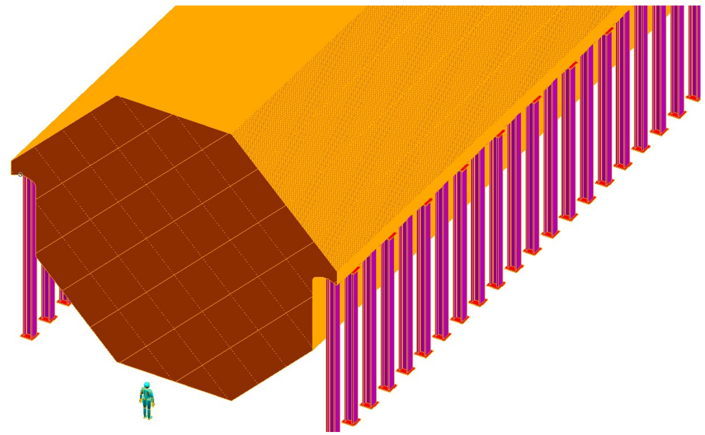
$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$



Baseline: 10 GeV muons, one storage ring with detector at ~2000 km, due to large θ_{13}

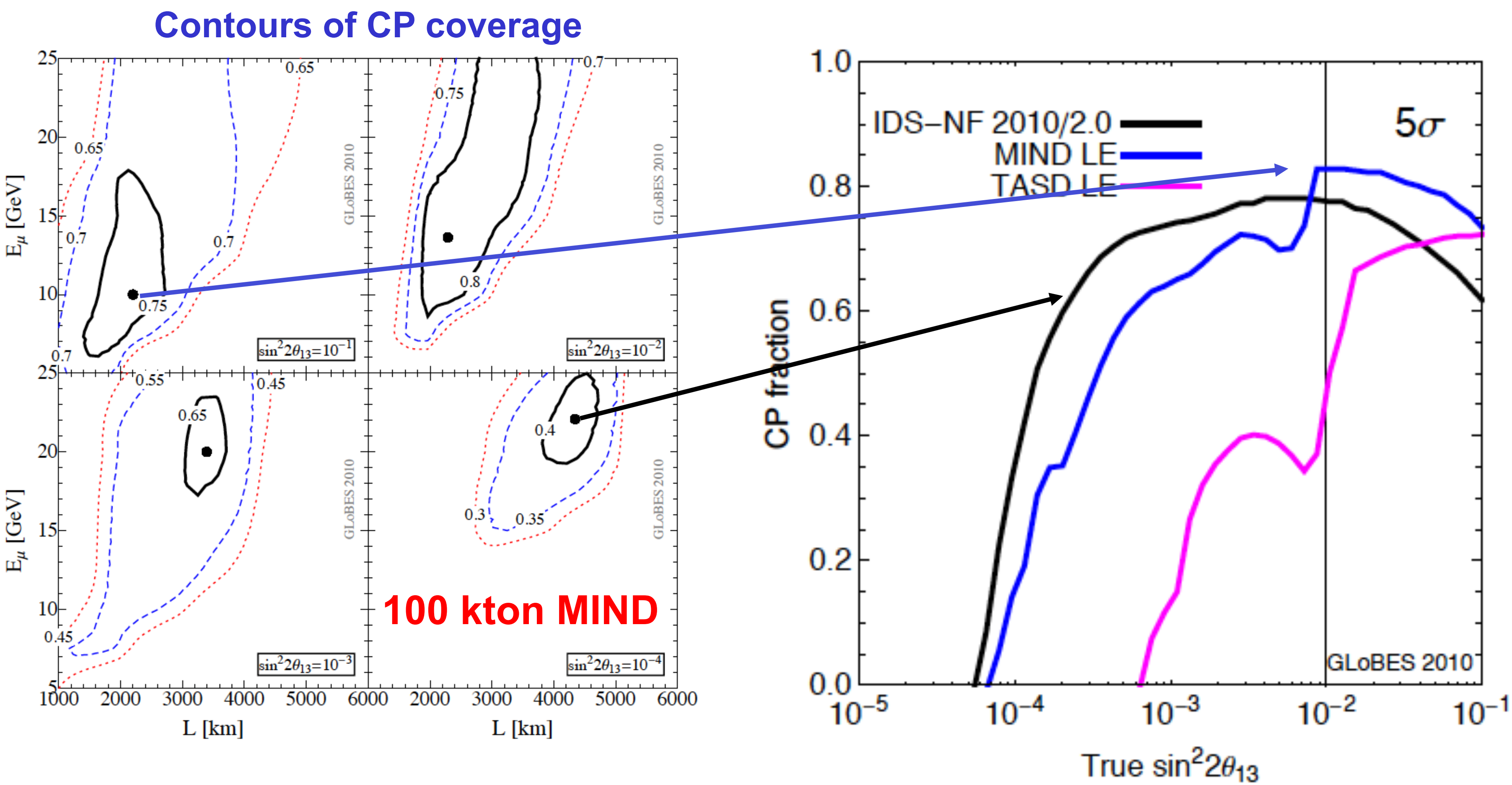
- Magnetised Iron Neutrino Detector (MIND):
  - 100 kton at ~2000 km



IDS-NF Interim Design Report
arXiv:1112.2853

Optimisation of Neutrino Factory

- Optimisation for high θ_{13}: 10 GeV muons and 2000 km

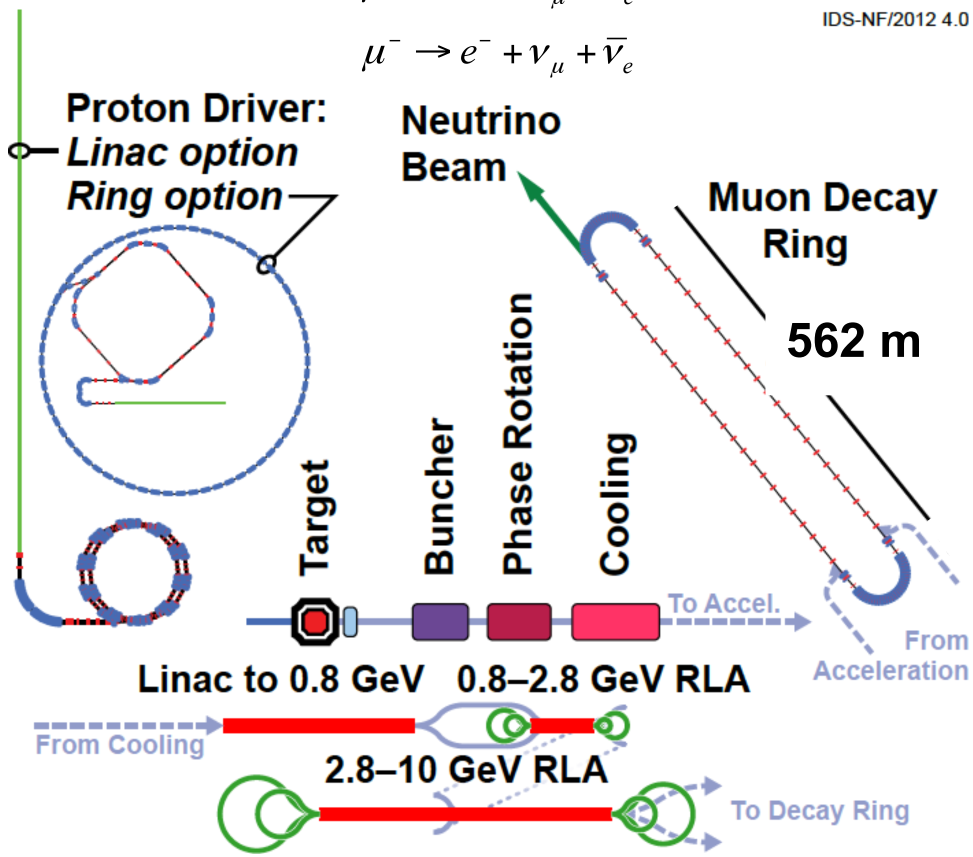


Neutrino Factory Baseline

- Proton driver: 4 MW
  - Proton beam ~8 GeV on target
- Target, capture and decay
  - Create π, decay into μ
    (R&D: MERIT)
- Bunching and phase rotation
  - Reduce ΔE of bunch
- Ionization Cooling
  - Reduce transverse emittance
    (R&D: MICE)
- Acceleration
  - 120 MeV→ 10 GeV with RLAs
- Decay ring
  - Store for ~100 turns
  - Long straight sections
  - 10^{21} muons/year

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

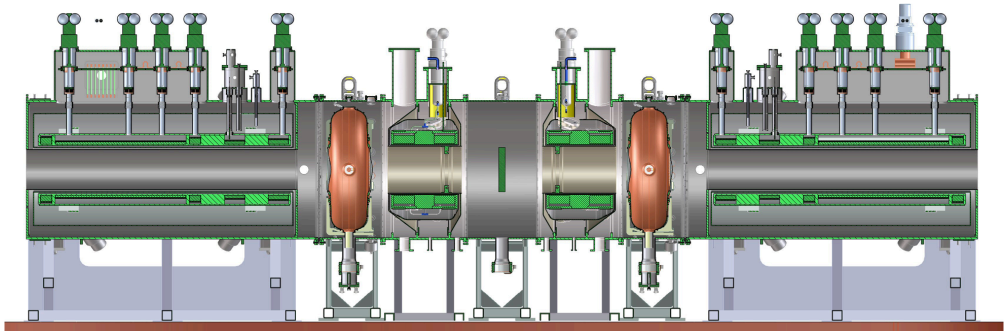
$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$



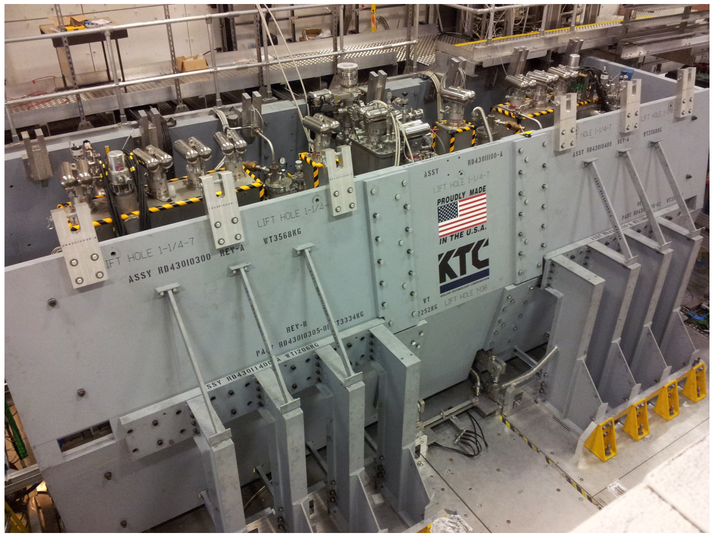
IDS-NF Reference Design Report to be published in JINST special issue on Muon Accelerators

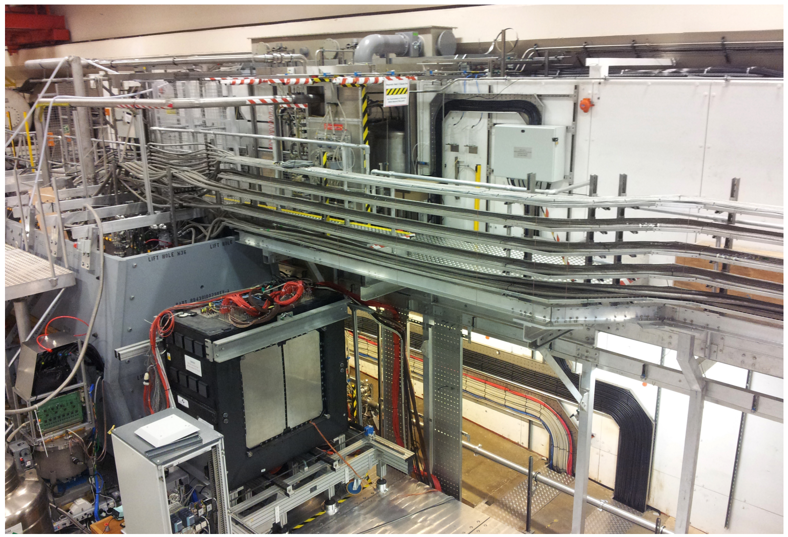
Muon Ionization Cooling Experiment (MICE)

- MICE: demonstration of ionization cooling at Rutherford Appleton Laboratory by 2018:
  - Two RF cavities and LiH absorbers



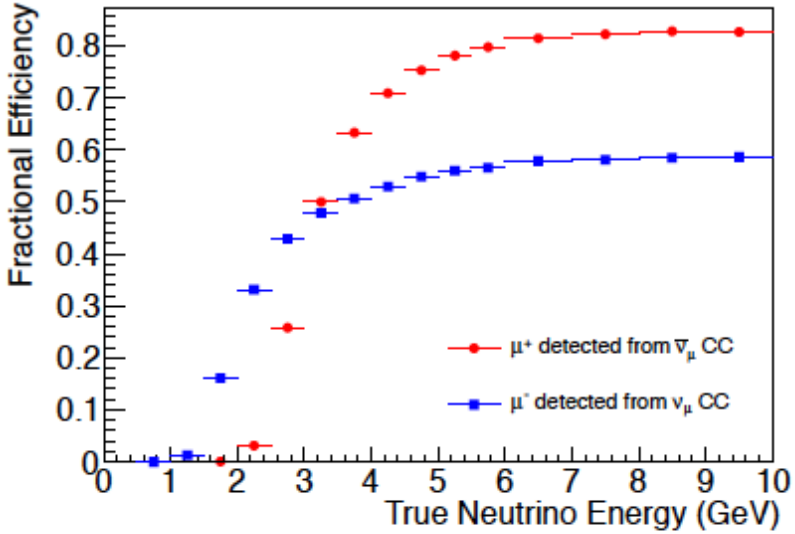
INFN contribution (Milano, Napoli, Pavia, Roma Tre): crucial contribution to PID detectors



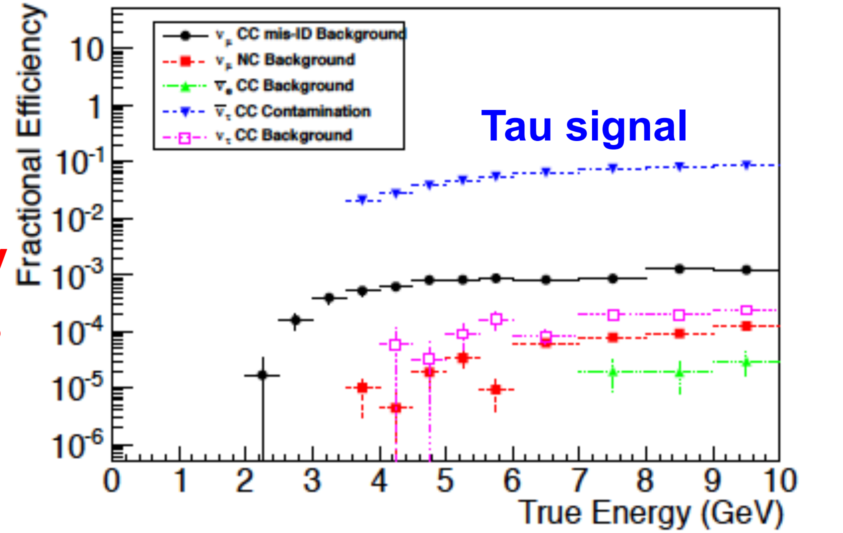


CP violation analysis at IDS-NF

BDT efficiency, focussing μ^+

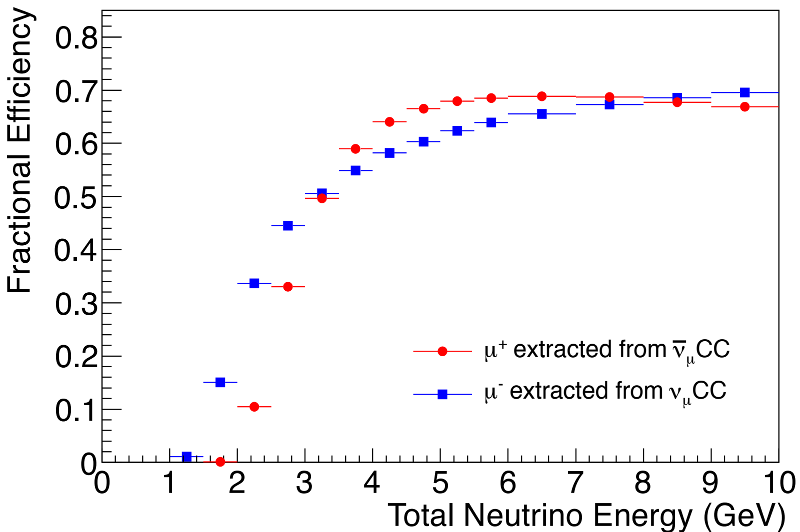


BDT background (stored μ^-, focussing μ^+)

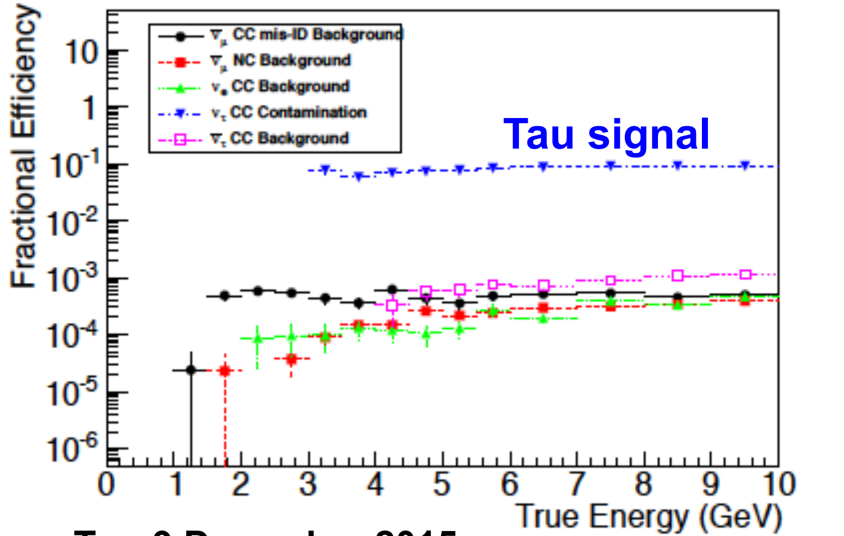


Courtesy R. Bayes

BDT efficiency, focussing μ^-

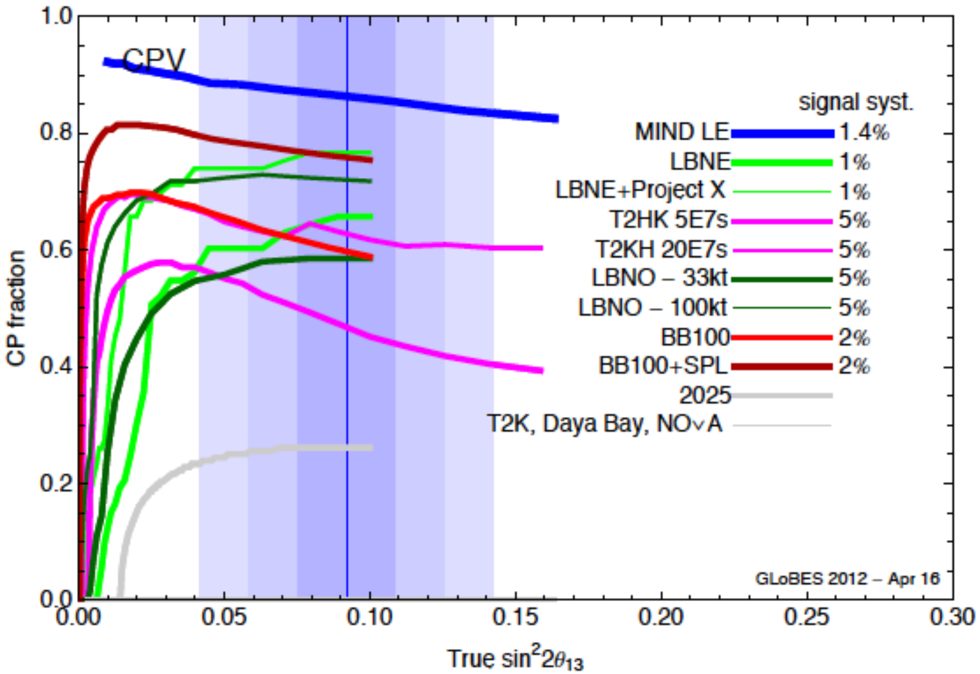


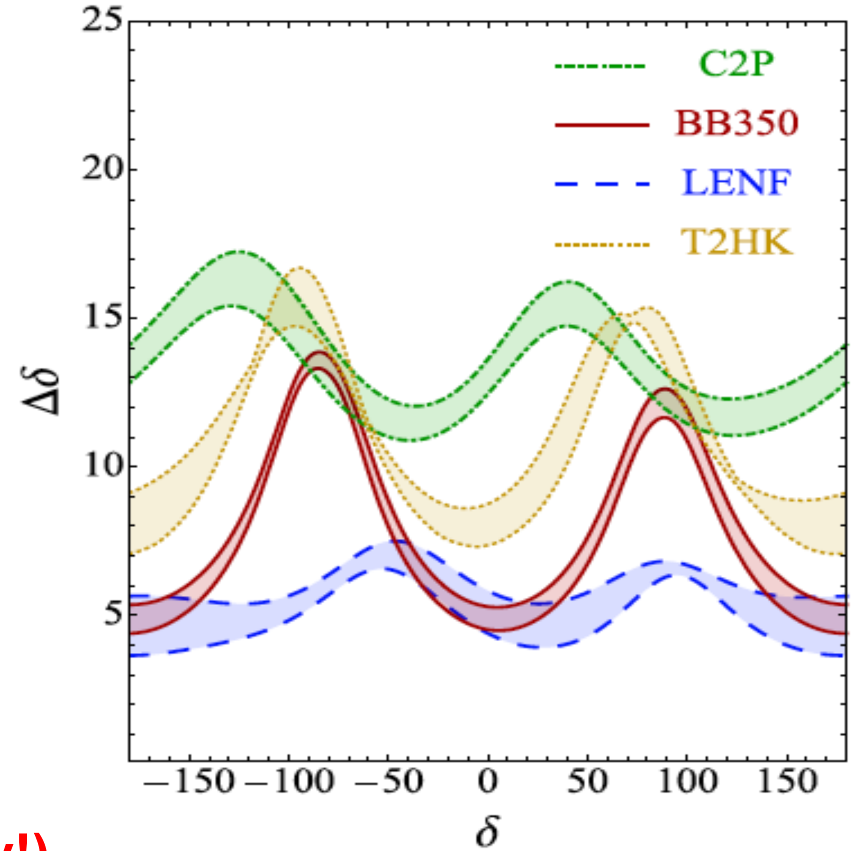
BDT background (stored μ^+, focussing μ^+)



Performance 10 GeV Neutrino Factory

- Analysis shows that 10 GeV Neutrino Factory, with 10^{21} μ/year, 100 kton MIND at 2000 km gives best sensitivity to CP violation





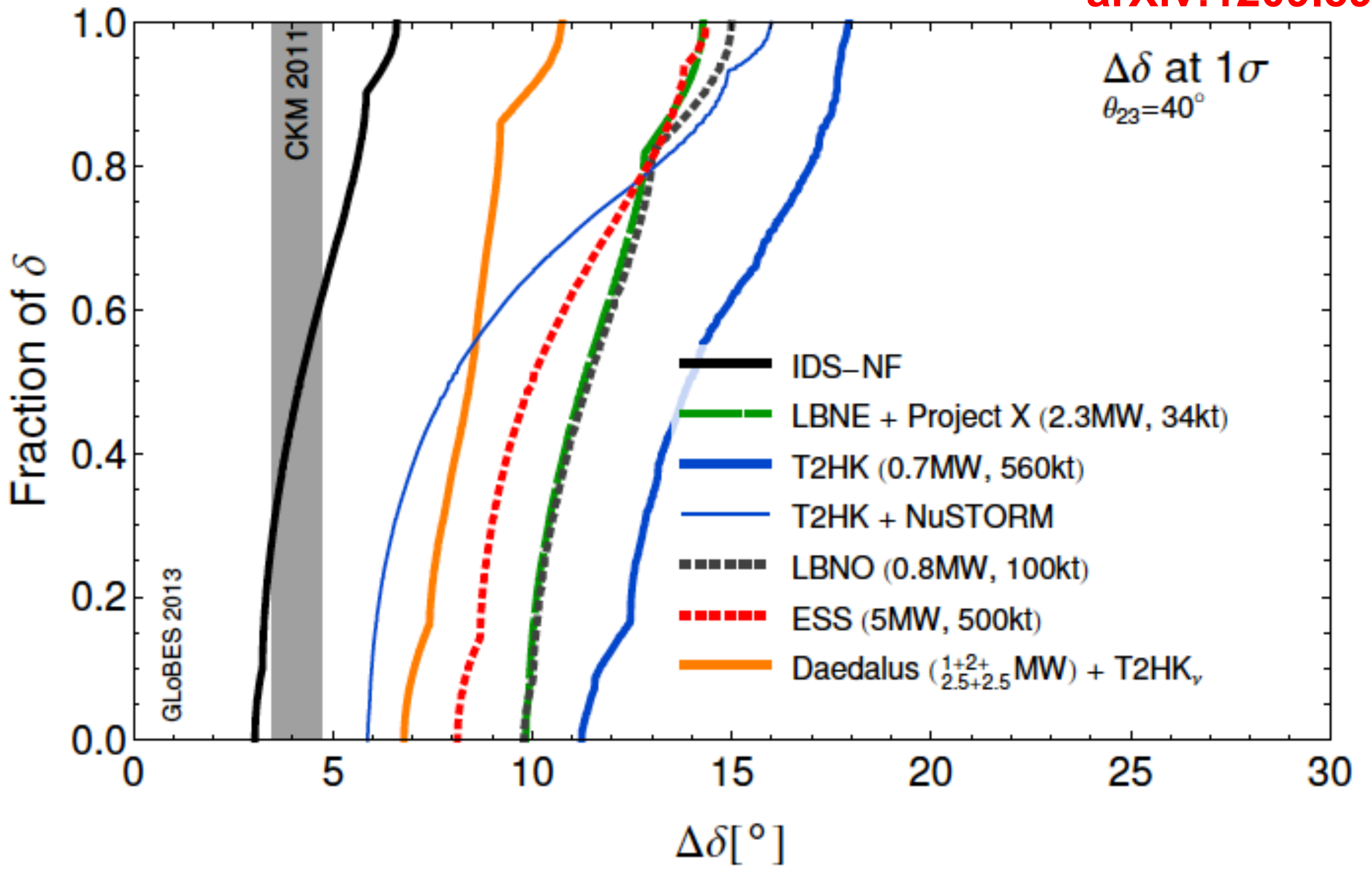
More than 85% 5σ coverage
(ie. 85% probability of CPV discovery!)

arXiv:1203.5651

Neutrino Factory CP sensitivity

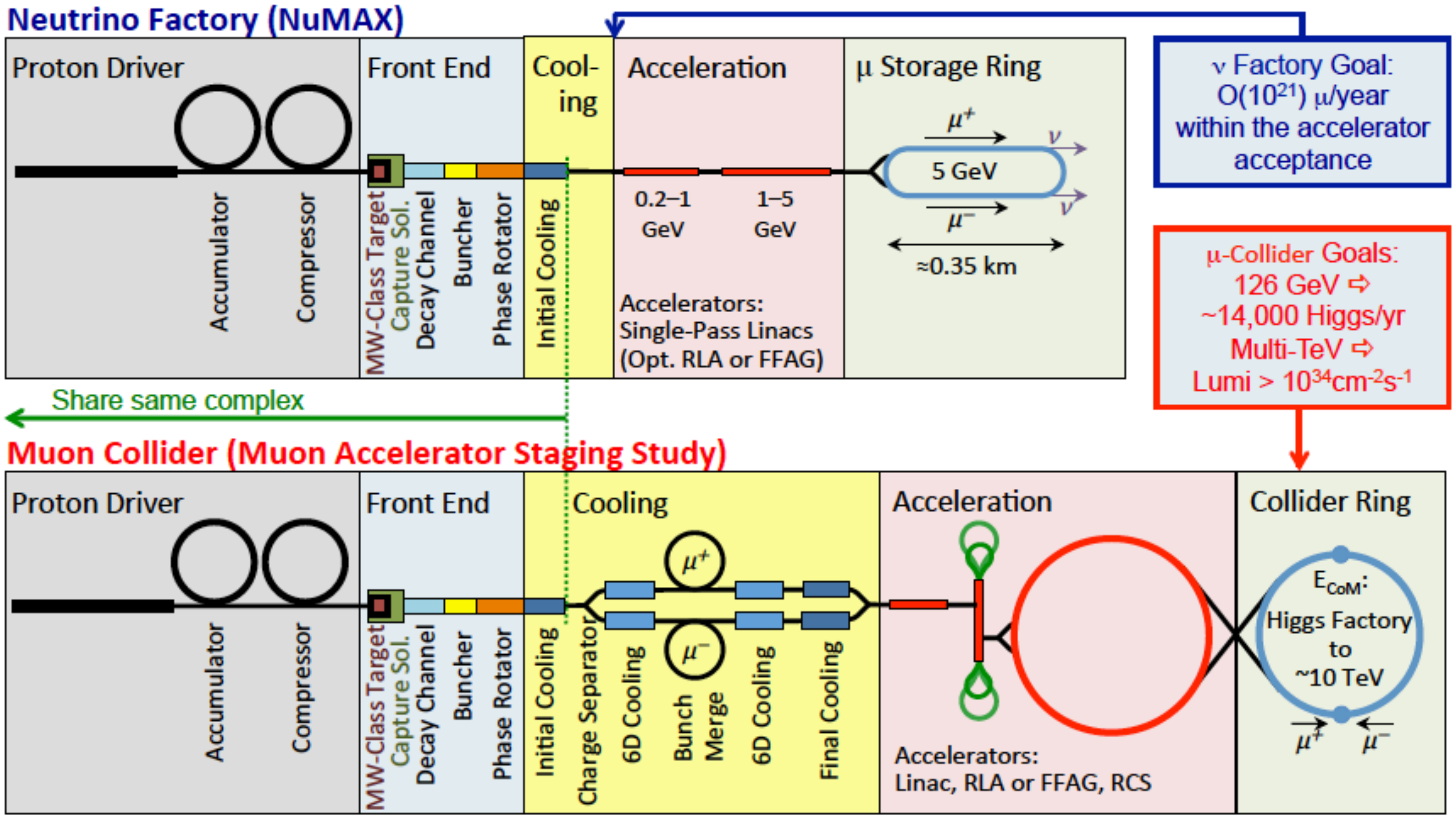
- Analysis shows that 10 GeV Neutrino Factory, with 10^{21} μ/year, 100 kton MIND at 2000 km gives best sensitivity to CP violation

arXiv:1209.5973



Muon Accelerator Staging Programme

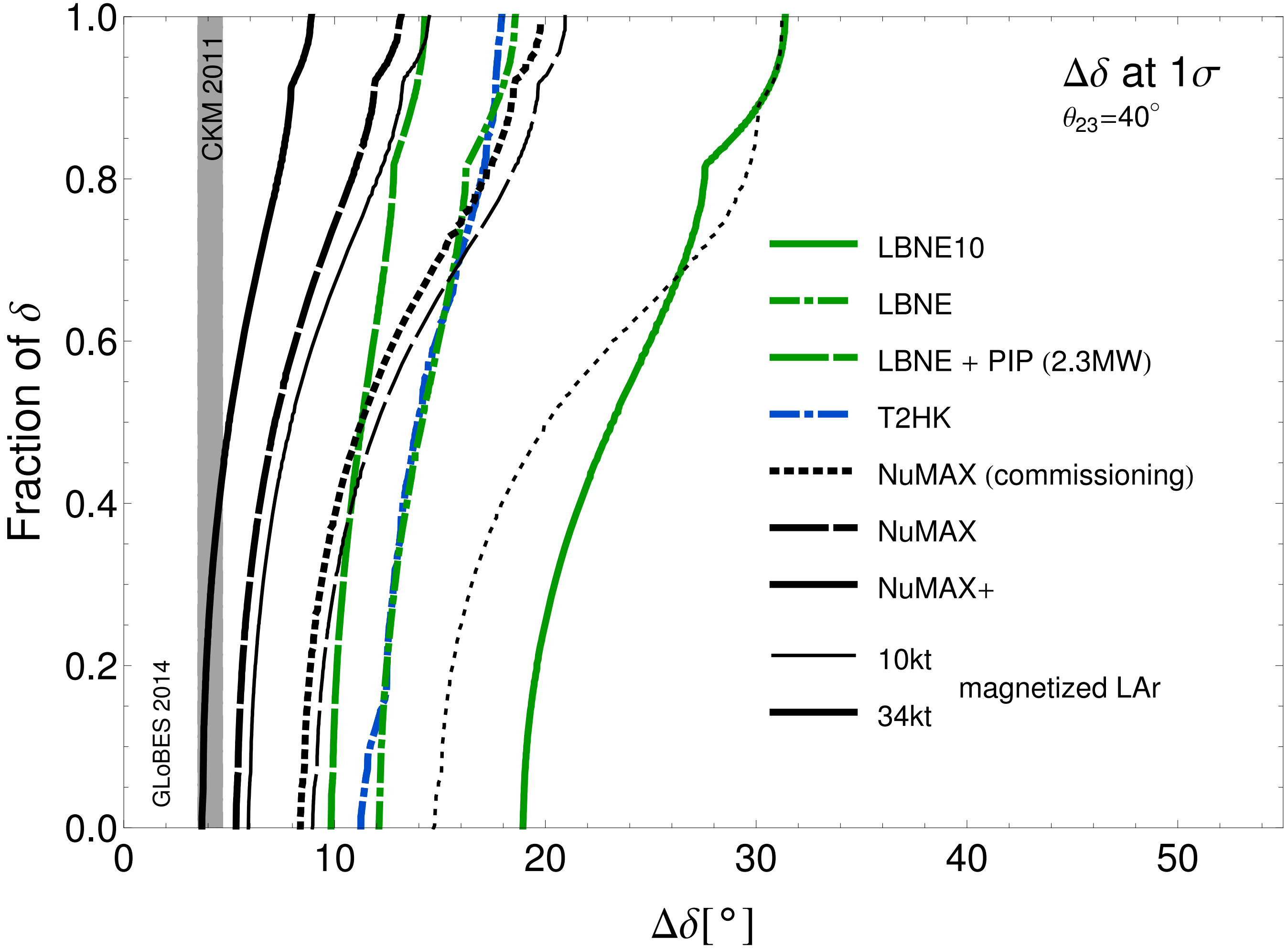
- NuMAX is Neutrino Factory in Fermilab context (5 GeV to Sanford Lab, at 1300 km) – similar sensitivity to IDS-NF
- Synergy with Muon Collider components



Physics performance of NuMAX

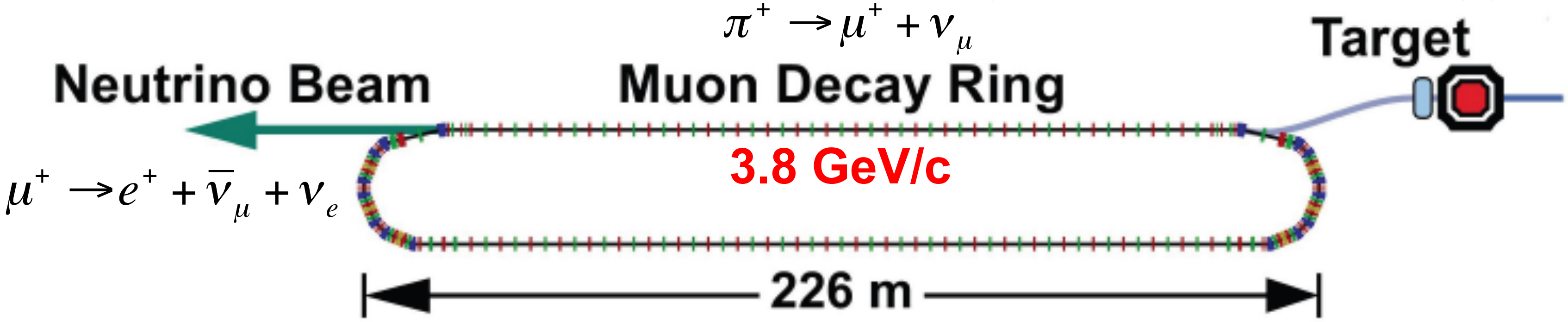
- Physics performance in terms of fraction of CP phase δ with measurement accuracy at or below Δδ

P. Huber



nuSTORM: Neutrinos from STORed Muons

- nuSTORM: first stage neutrino factory with 3.8 GeV/c muons that does not rely on any new technology



  - Pions of 5 Gev/c captured and injected into ring.
  - 52% of pions decay to muons before first turn: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - This creates a first flash of neutrinos from pion decays
  - Ring designed to store muons with p = 3.8 GeV ± 10%
  - Muons decay producing neutrinos: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
  - Creates hybrid beam of neutrinos from pion & muon decay

Physics motivation

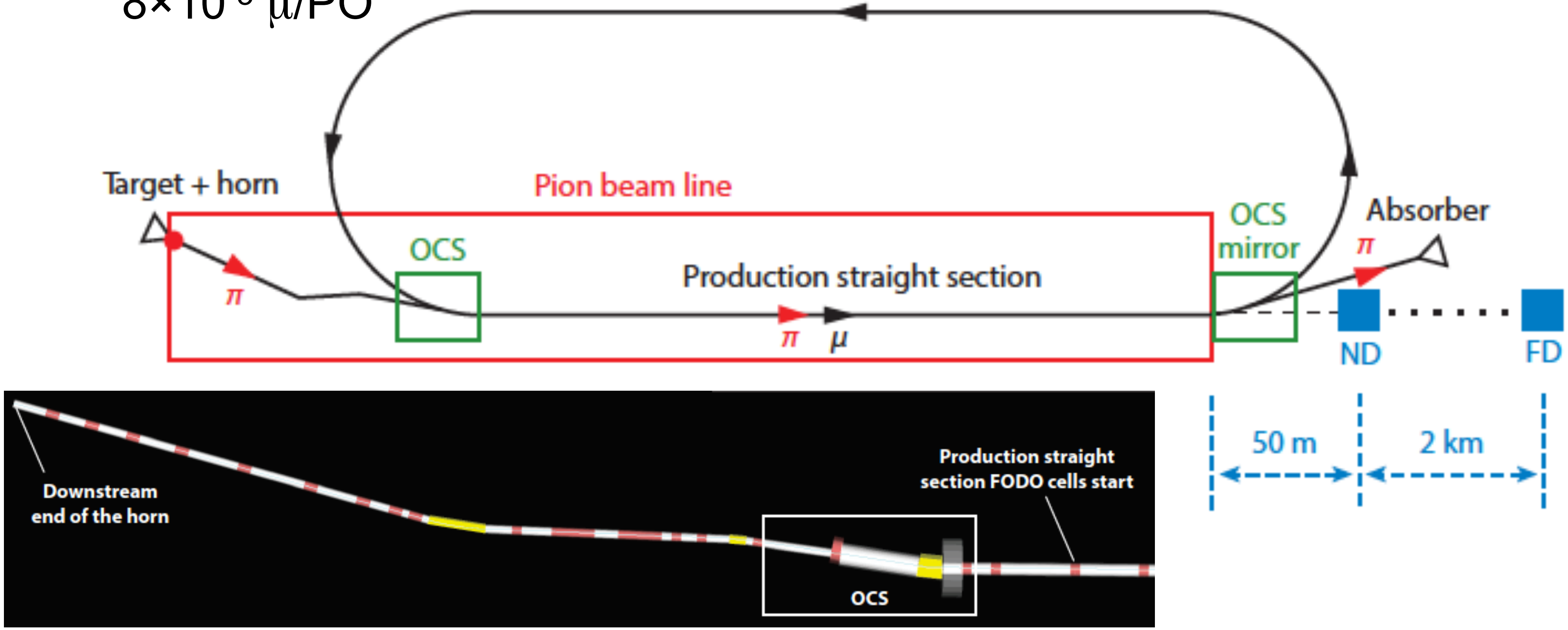
- Physics motivation of nuSTORM:
  - Creation of a neutrino beam with a flux accuracy of 10^{-3} for neutrino scattering physics: "the neutrino light source"
  - Measurement of ν_e cross sections and nuclear effects in neutrino-nucleus collisions, essential for long baseline neutrino oscillation programme
  - Definitive resolution of sterile neutrino problem and search for short-baseline neutrino oscillations
  - Creation of a test bed for muon accelerator R&D for future high intensity neutrino factories and muon collider

A new way of doing neutrino physics

Adey, Bayes, Bross, Snopok, Ann. Rev. Nucl. Part. Sci. 2015 65:145-75.

nuSTORM Facility

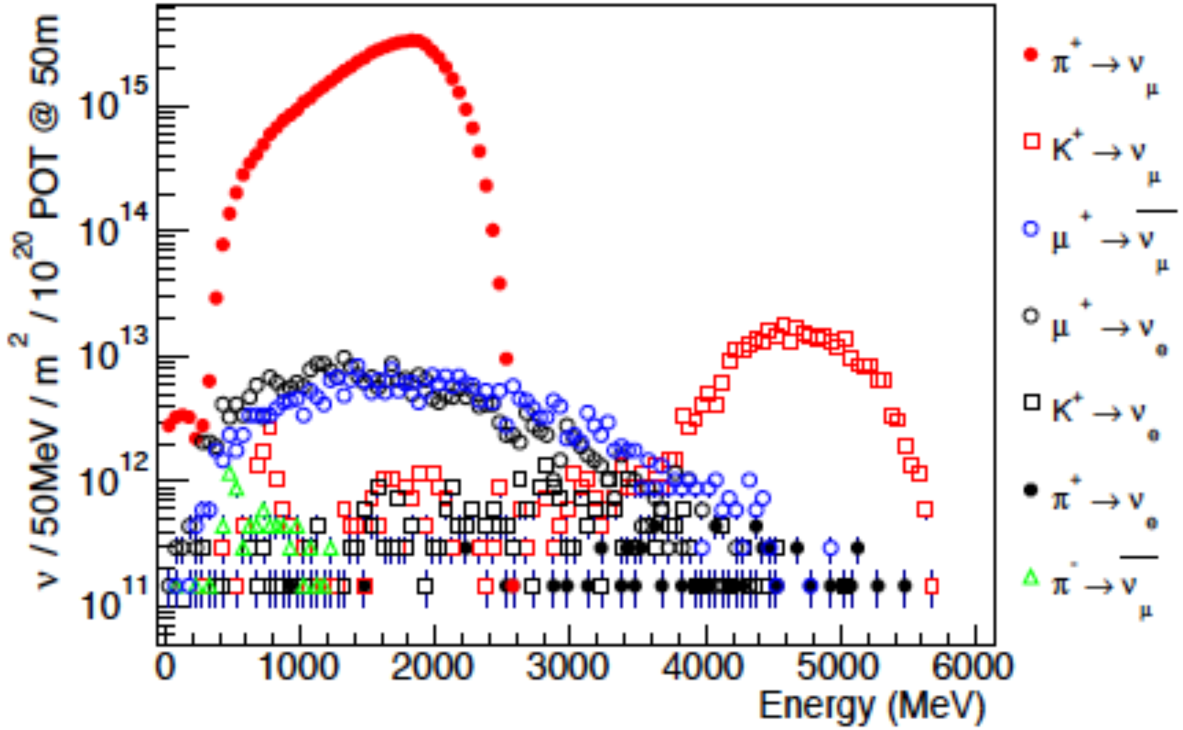
- nuSTORM facility:
  - 120 GeV protons on carbon or inconel target (100 kW)
  - NuMI-style horn for pion collection
  - Injection pions (5 GeV/c ± 10%) into storage ring: 0.09 π/POT
  - Storage ring: large aperture FODO lattice (3.8 GeV/c ± 10%) muons: 8×10^{-3} μ/PO



nuSTORM Flux and Spectrum

- nuSTORM flux and energy spectrum

Use muon decay neutrinos to calibrate hadron decay neutrinos



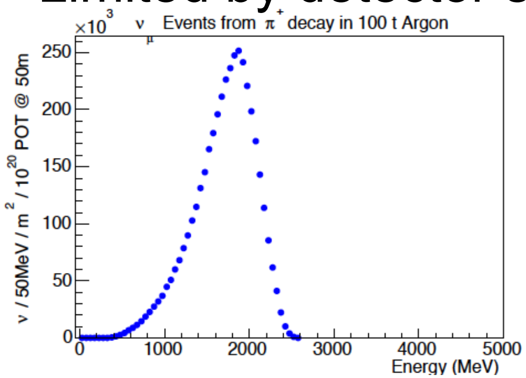
- ν_μ from pion decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$ flux: 6.3×10^{16} ν/m² at 50 m
- ν_e from muon decay $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$ flux: 3.0×10^{14} ν/m² at 50 m
- ν_μ from kaon decay $K^+ \rightarrow \mu^+ + \nu_\mu$ flux: 3.8×10^{14} ν/m² at 50 m
- Used for cross-section measurements and short baseline oscillations

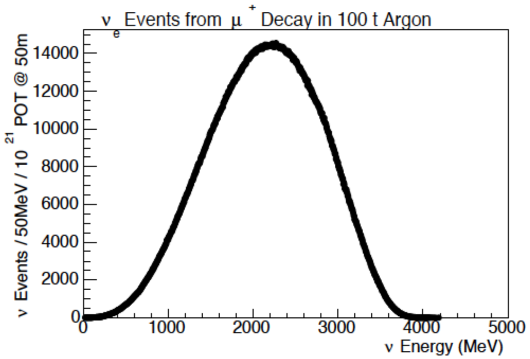
nuSTORM Event Rates

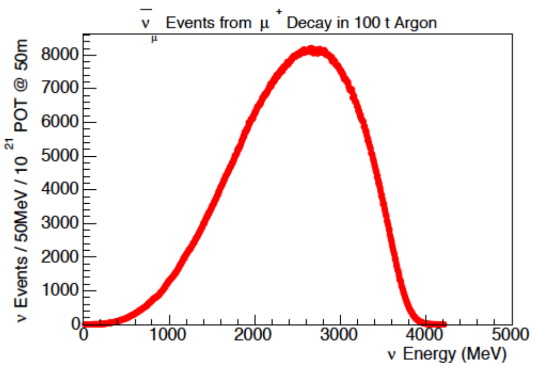
- Flux uncertainties for nuSTORM from beam diagnostics: < 1%
- Event rates per 10^{21} POT in 100 ton Liquid Argon at 50 m

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:







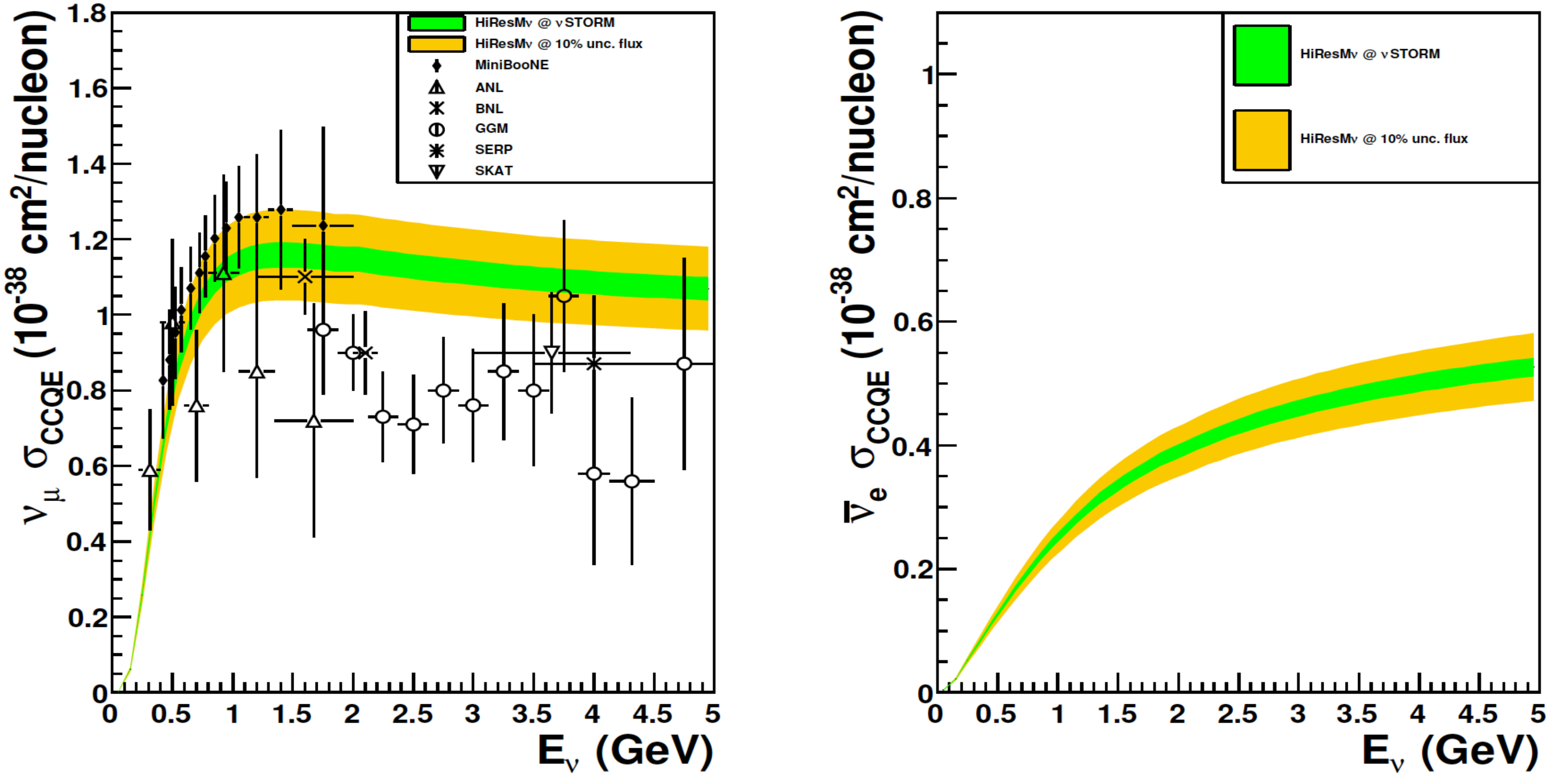
Neutrino interactions at nuSTORM

- Very rich physics programme (just some examples):
  - Electron neutrino ν_e and $\bar{\nu}_e$ cross-section measurements
  - π^0 production in neutrino interactions
  - Charged π and K production
  - Neutrino-electron scattering
  - Neutrino-nucleon scattering: charged current and neutral current (NC/CC ratio and $\sin^2\theta_W$)
  - Nuclear effects in neutrino interactions
  - Semi-exclusive and exclusive processes: measurement of $K_s, \Lambda, \bar{\Lambda}$ production
  - New physics and exclusive processes: test of $\nu_\mu - \nu_e$ universality, heavy neutrinos, eV-scale pseudo-scalar penetrating particles ….

Over 60 physics topics already identified: PhD theses

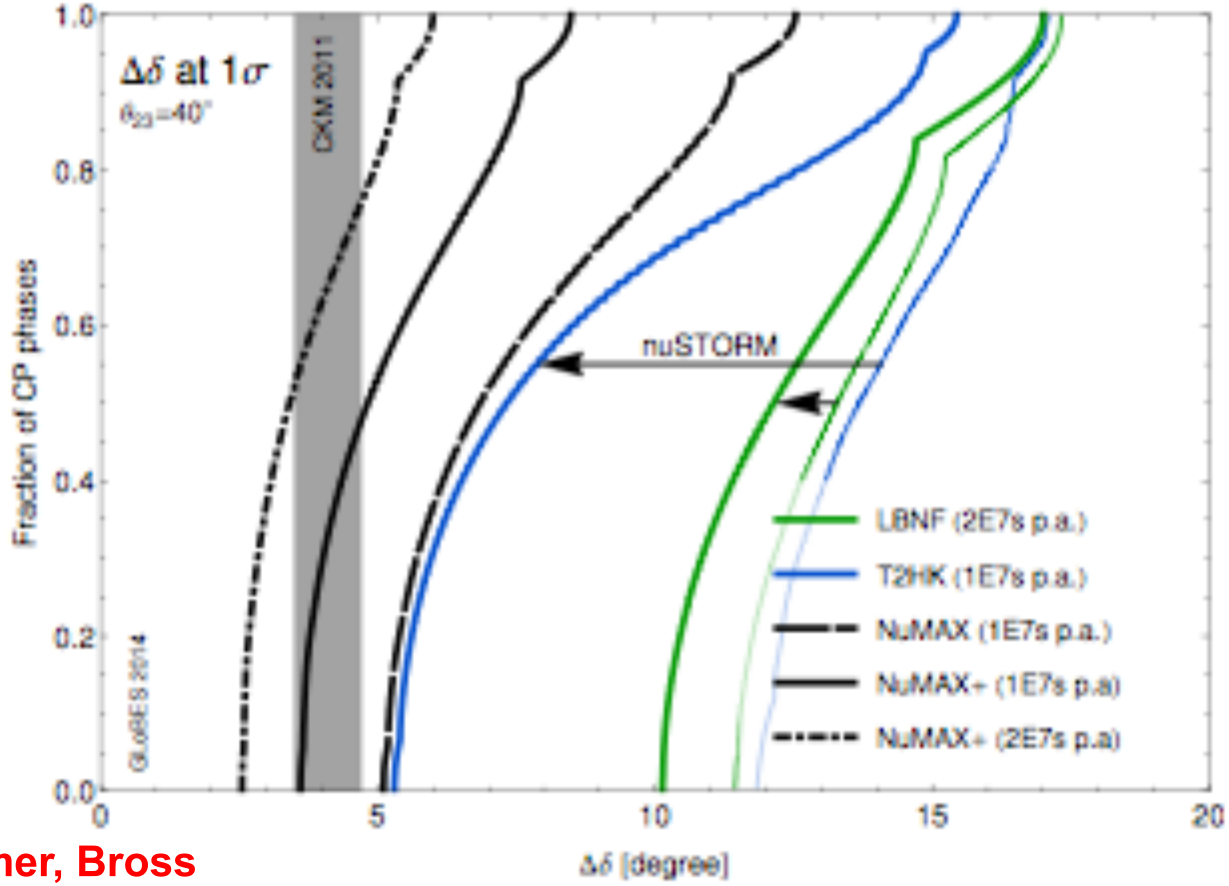
Neutrino interactions at nuSTORM

- Example of CCQE measurement:
  - Expected accuracy for ν_μ and ν_e cross-sections



nuSTORM influence on LBL sensitivities

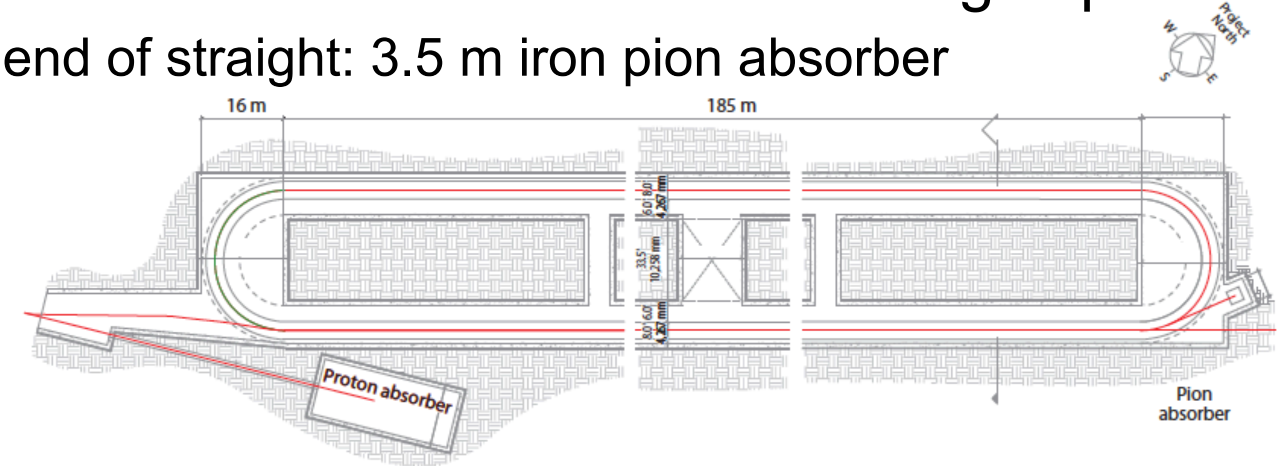
- Influence of measurement of cross-sections with less than 1% precision as potentially provided by nuSTORM
- Significantly improves δ_{CP} accuracy in DUNE and HyperK



Huber, Palmer, Bross
arXiv:1411:0629

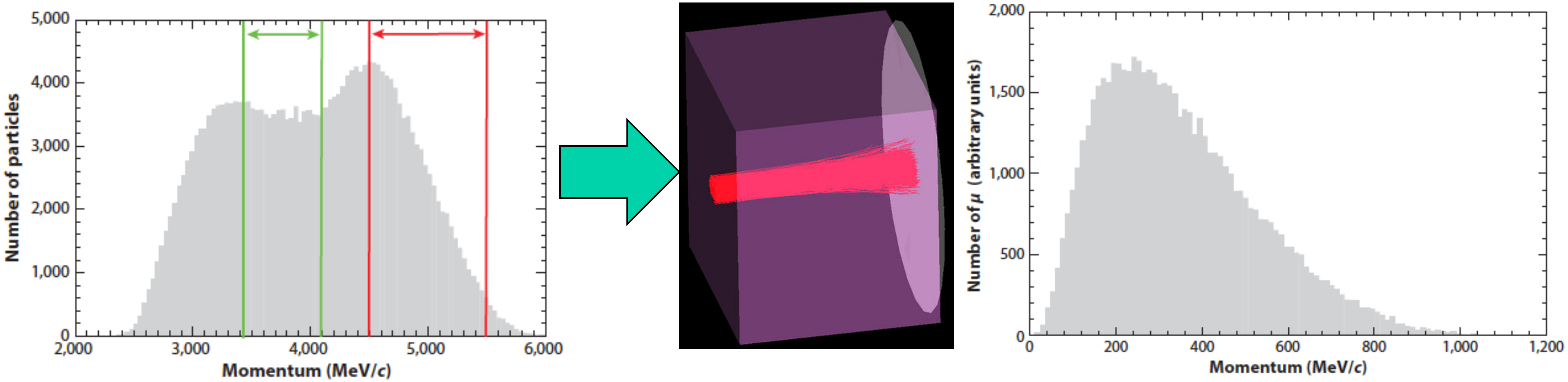
nuSTORM for accelerator R&D

- nuSTORM: testbed for 6D muon cooling experiment
  - At end of straight: 3.5 m iron pion absorber



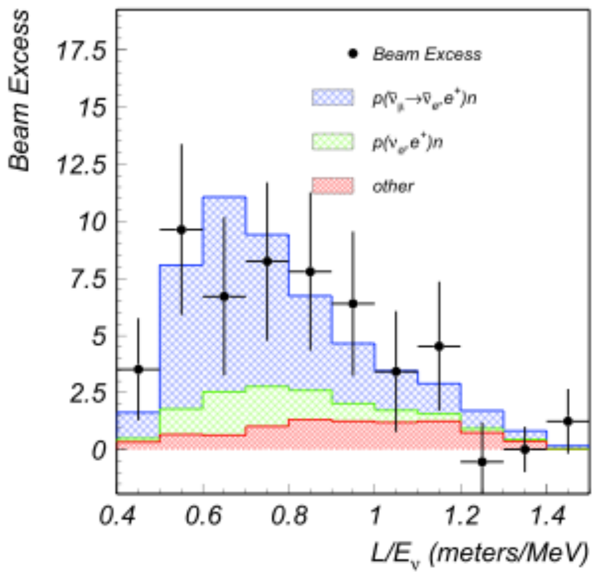
  - After absorber: 10^{10} μ/pulse between 100-300 MeV/c

3.8 GeV±10% **Muons for 6D**

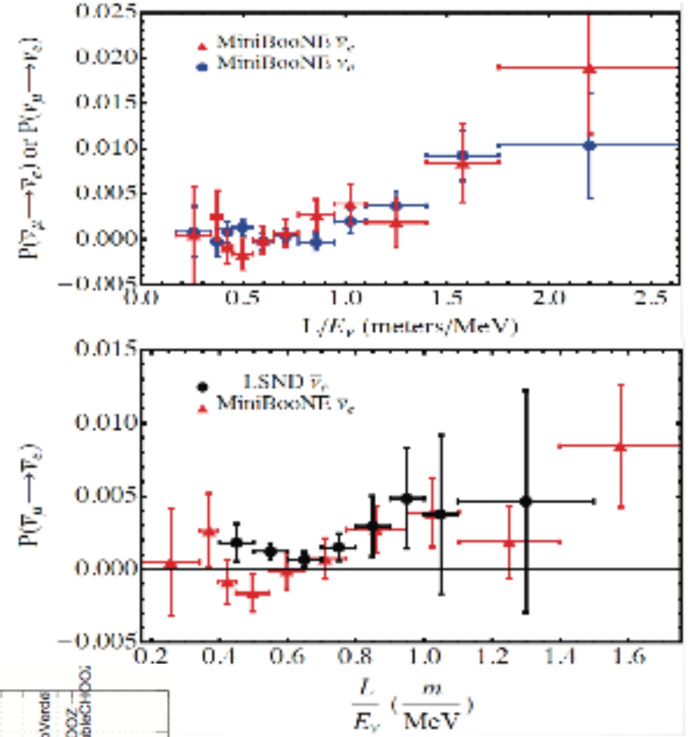


Short baseline physics

- LSND and MiniBooNE hints of $\bar{\nu}_e$ and ν_e appearance
  $P(\bar{\nu}_\mu \to \bar{\nu}_e) \sim 0.003$ and reactor anomaly (6% $\bar{\nu}_e$ deficit)

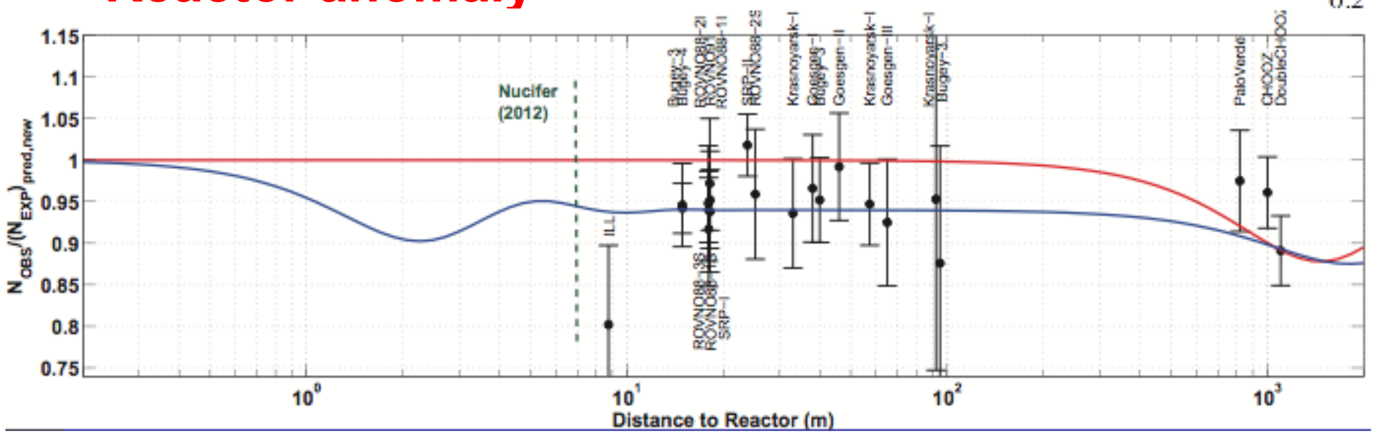


LSND



MiniBooNE

Reactor anomaly



Short baseline physics

- To resolve sterile neutrino hyposthesis need to verify consistency between appearance and disappearance:

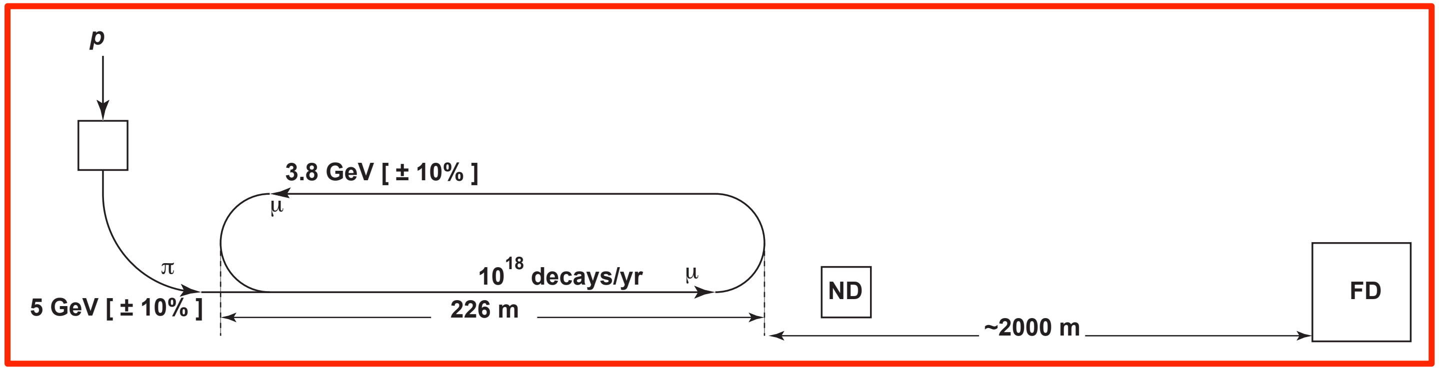
$$P(\nu_\mu \to \nu_e) \le 4\left(1 - P(\nu_\mu \to \nu_\mu)\right)\left(1 - P(\nu_e \to \nu_e)\right)$$

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

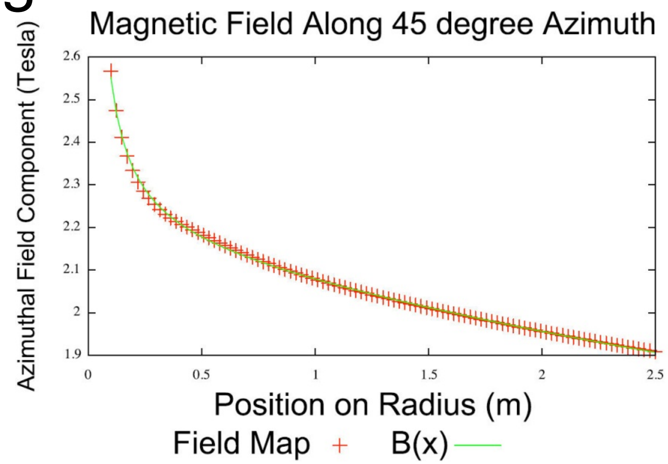
$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$	$\mu^- \to e^- \bar{\nu}_e \nu_\mu$	
$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\bar{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)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

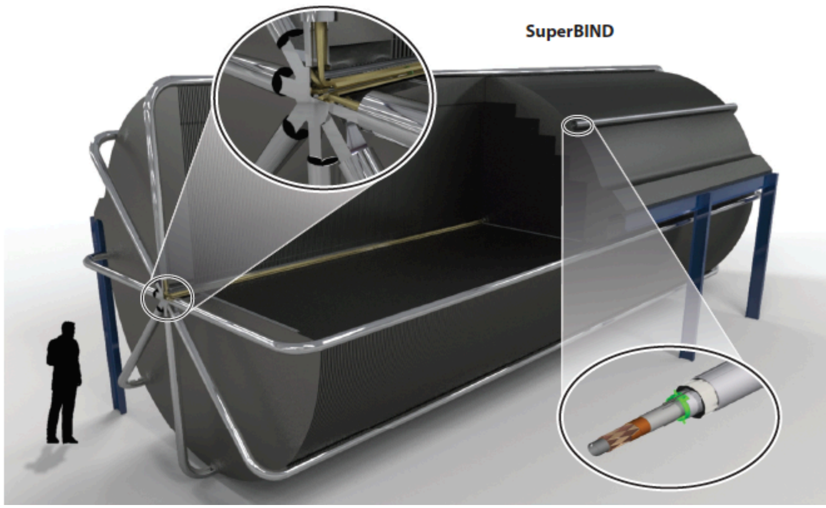
Sterile neutrino search

- Assume two detectors:



- Super-saturated Magnetised Iron: SuperBIND
- Magnetic field: 1.5-2.6 T



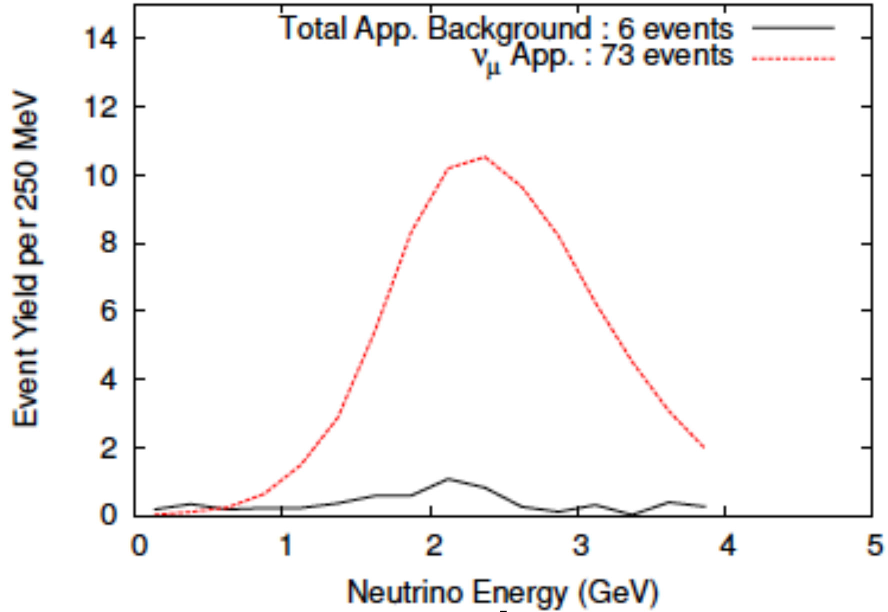


240 kA from 8 Superconducting Trasmission Lines

Sterile neutrino search

- Appearance search: **Adey et al., PRD 89 (2014) 071301**

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



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

- Disappearance search:

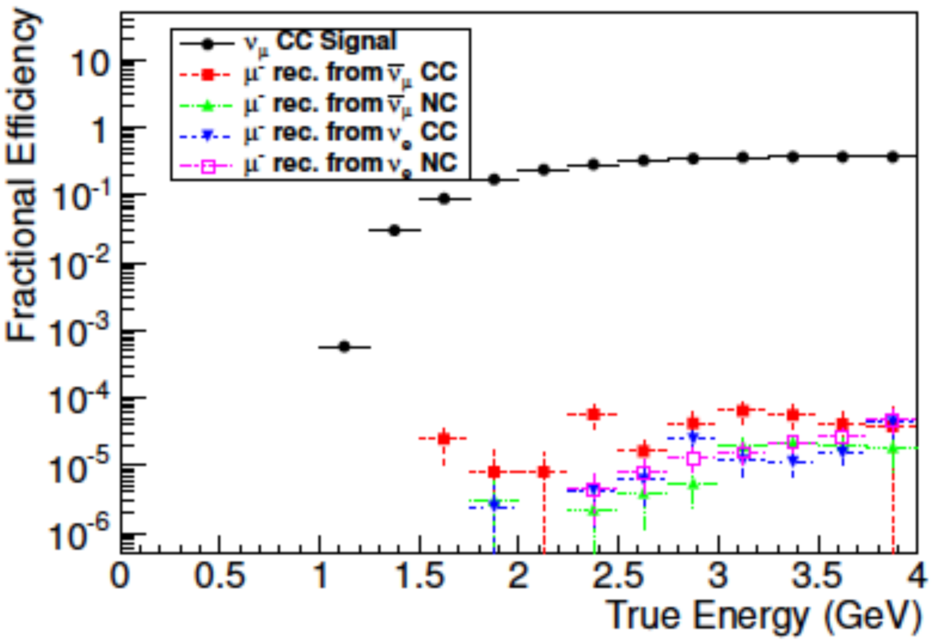
$$P_{\mu\mu}(x) = 4|U_{\mu 4}|^2\left(1-|U_{\mu 4}|^2\right)\sin^2\left(\frac{m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{\mu\mu})\sin^2\left(\frac{m_{14}^2 x}{4E}\right)$$

Sterile neutrino search

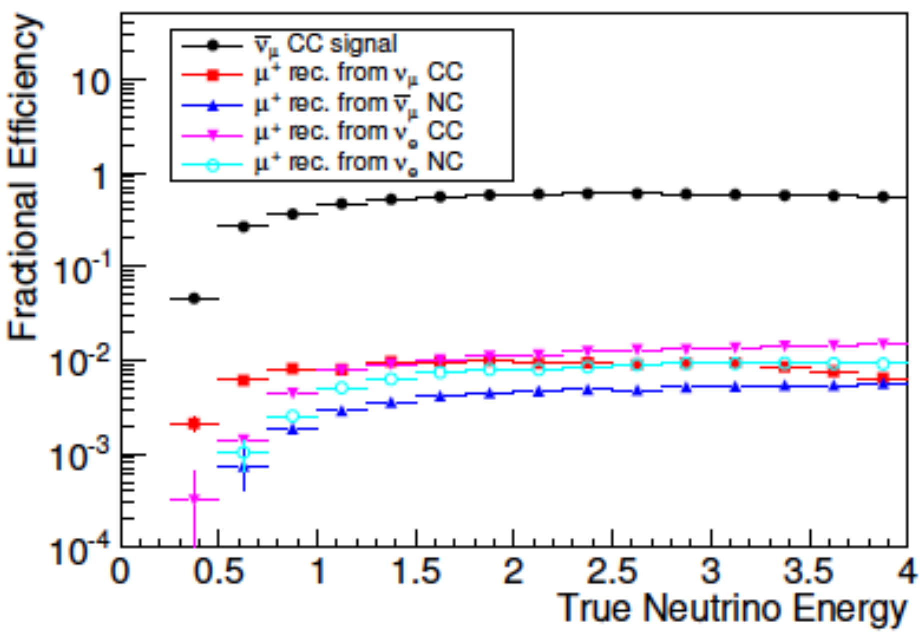
- Short-baseline oscillation search with near detector at 50 m and far detector at 2 km, 10^{21} POT exposure
- Appearance and disappearance multi-variate analyses

Adey et al., PRD 89 (2014) 071301

Appearance efficiencies



Disappearance efficiencies

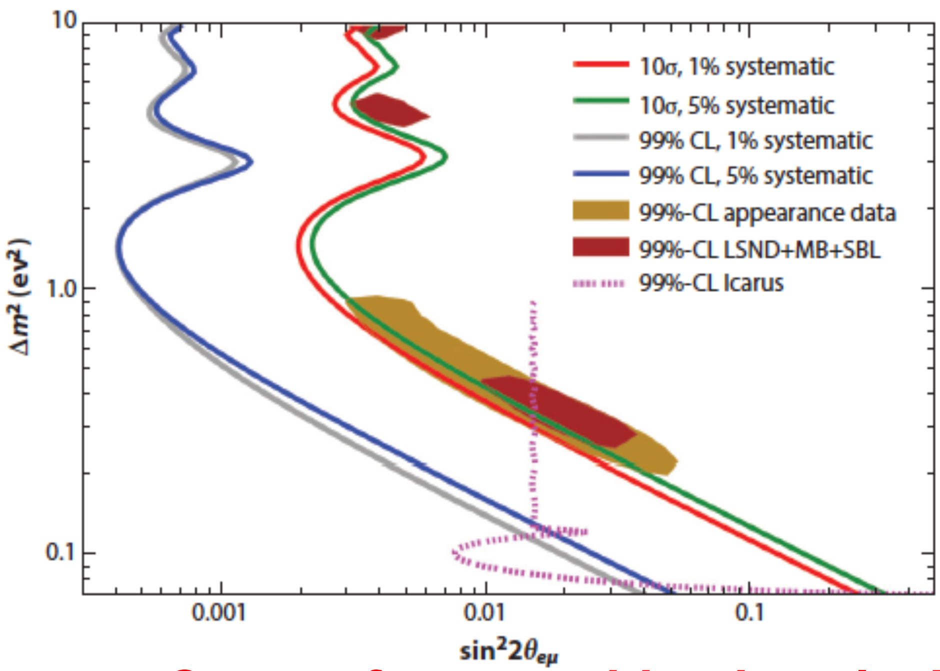


Sterile neutrino search

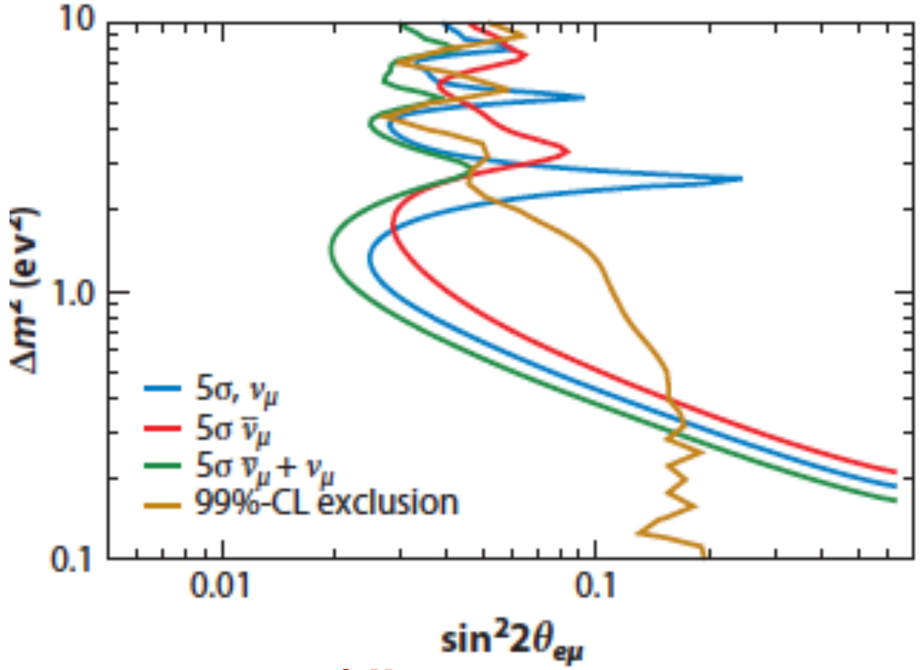
- Short-baseline oscillation search with near detector at 50 m and far detector at 2 km, 10^{21} POT exposure
- Appearance and disappearance multi-variate analyses

Adey et al., PRD 89 (2014) 071301

Appearance sensitivity



Disappearance sensitivity



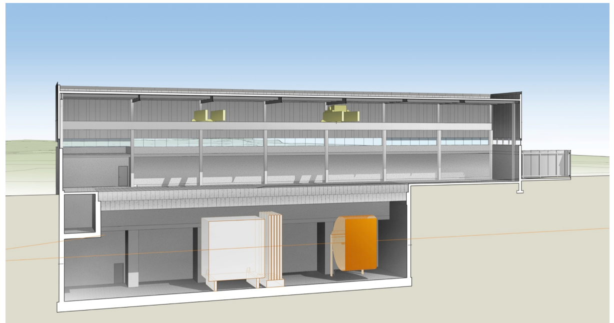
Can perform combined analysis appearance/disappearance

nuSTORM at Fermilab

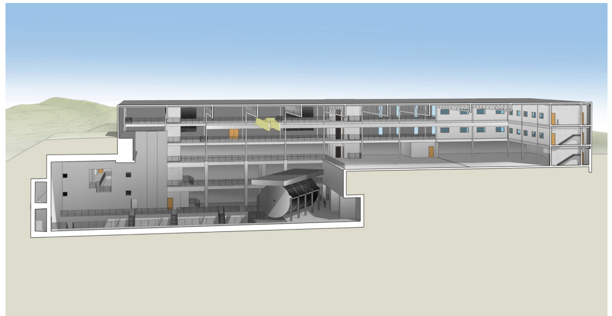
- nuSTORM could be sited at Fermilab

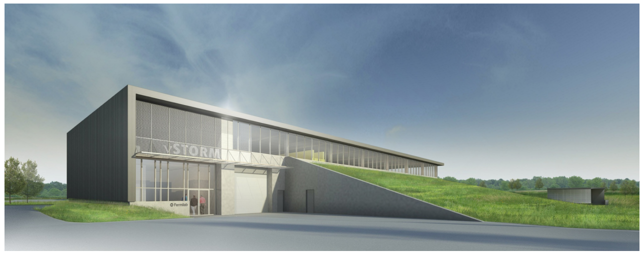
Proposal to FNAL PAC: arXiv: 1308.6822

Near Detector Hall

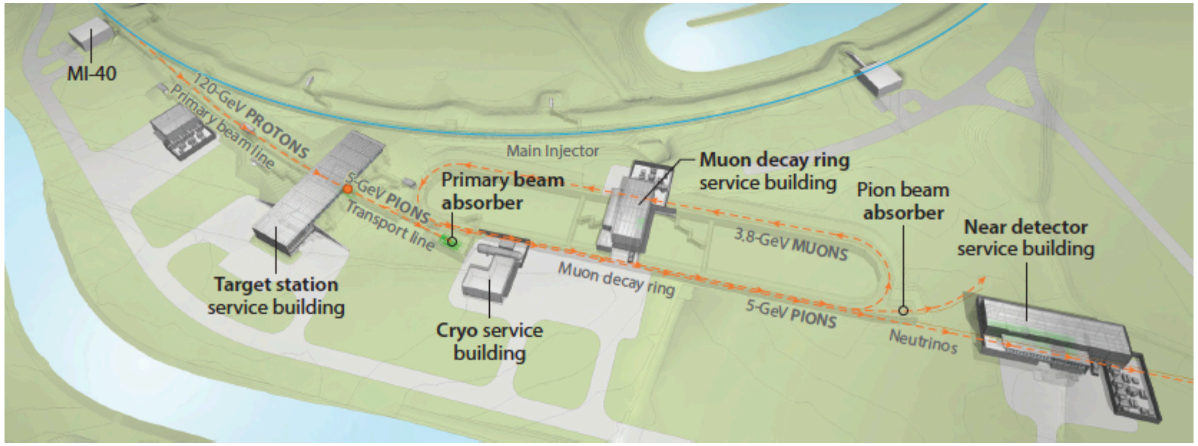


Far Detector Hall (D0)





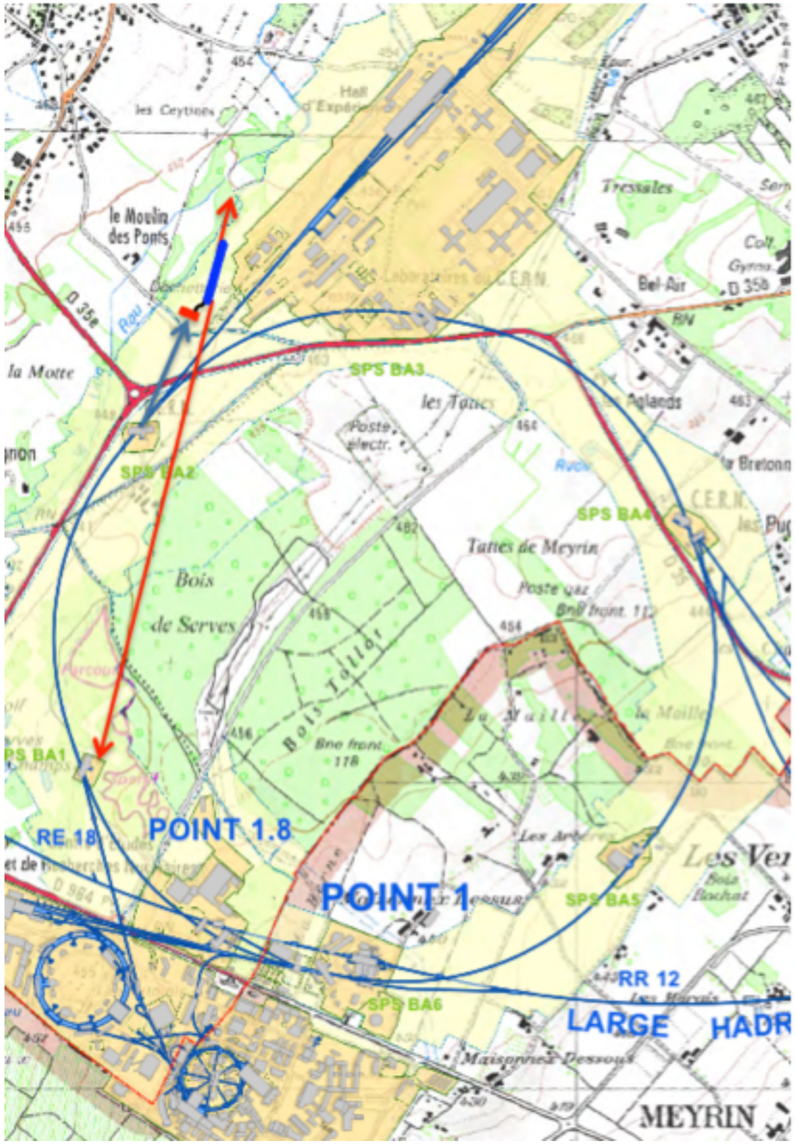
Target building



nuSTORM at CERN

- nuSTORM could be sited at CERN
- Target station in North Area

  Eol to CERN: arXiv:1305.1419



- For two detector oscillation search: near detector in North Area and far detector in Point 1.8

Conclusions

- Expect discovery of CP violation in neutrinos within 15 years
- Neutrino Factories from muon decay can bring neutrino physics into precision era
- First stage: nuSTORM to measure neutrino cross-sections with ~1% precision, can resolve sterile neutrino issue with 10σ sensitivity and can be used to create 6D cooling R&D facility
- nuSTORM would be a fantastic contribution to world-wide neutrino programme complementing long baseline experiments
- Second stage: develop neutrino factory for ultimate precision of CP phase delta $\Delta\delta_{CP} \sim 4^{o}$.
- Neutrino factories are a stepping stone towards a muon collider – R&D is always delivering physics along the way

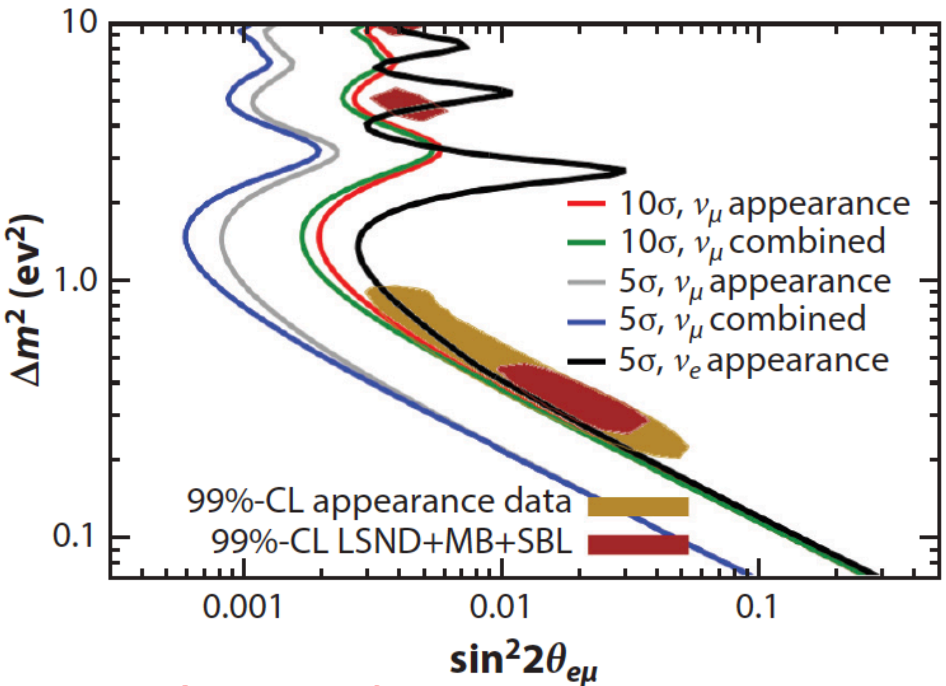
Backup Slides

Sterile neutrino search

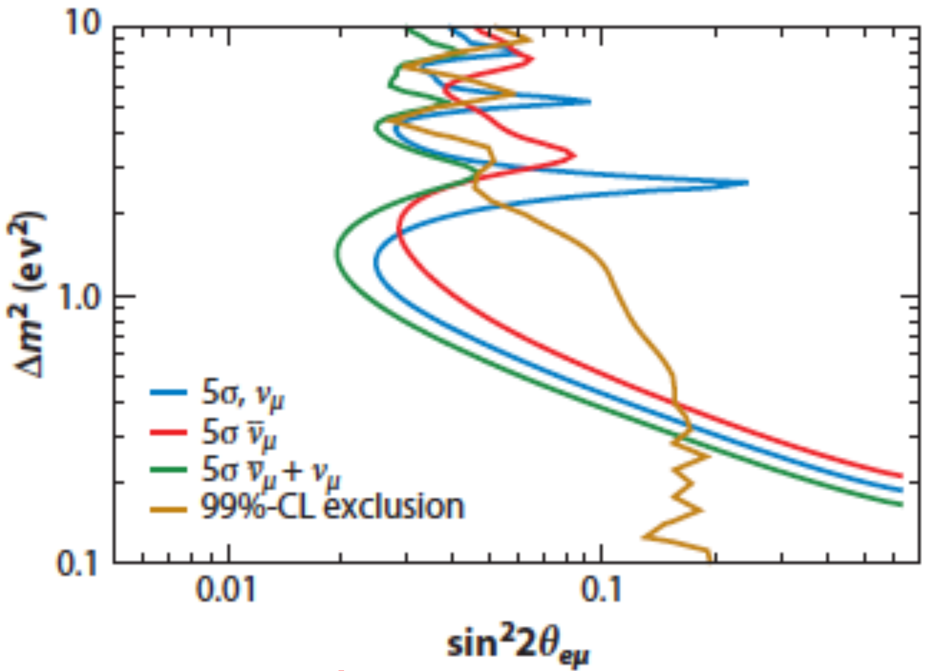
- Short-baseline oscillation search with near detector at 50 m and far detector at 2 km, 10^{21} POT exposure
- Appearance and disappearance multi-variate analyses

Adey et al., PRD 89 (2014) 071301

Appearance sensitivity



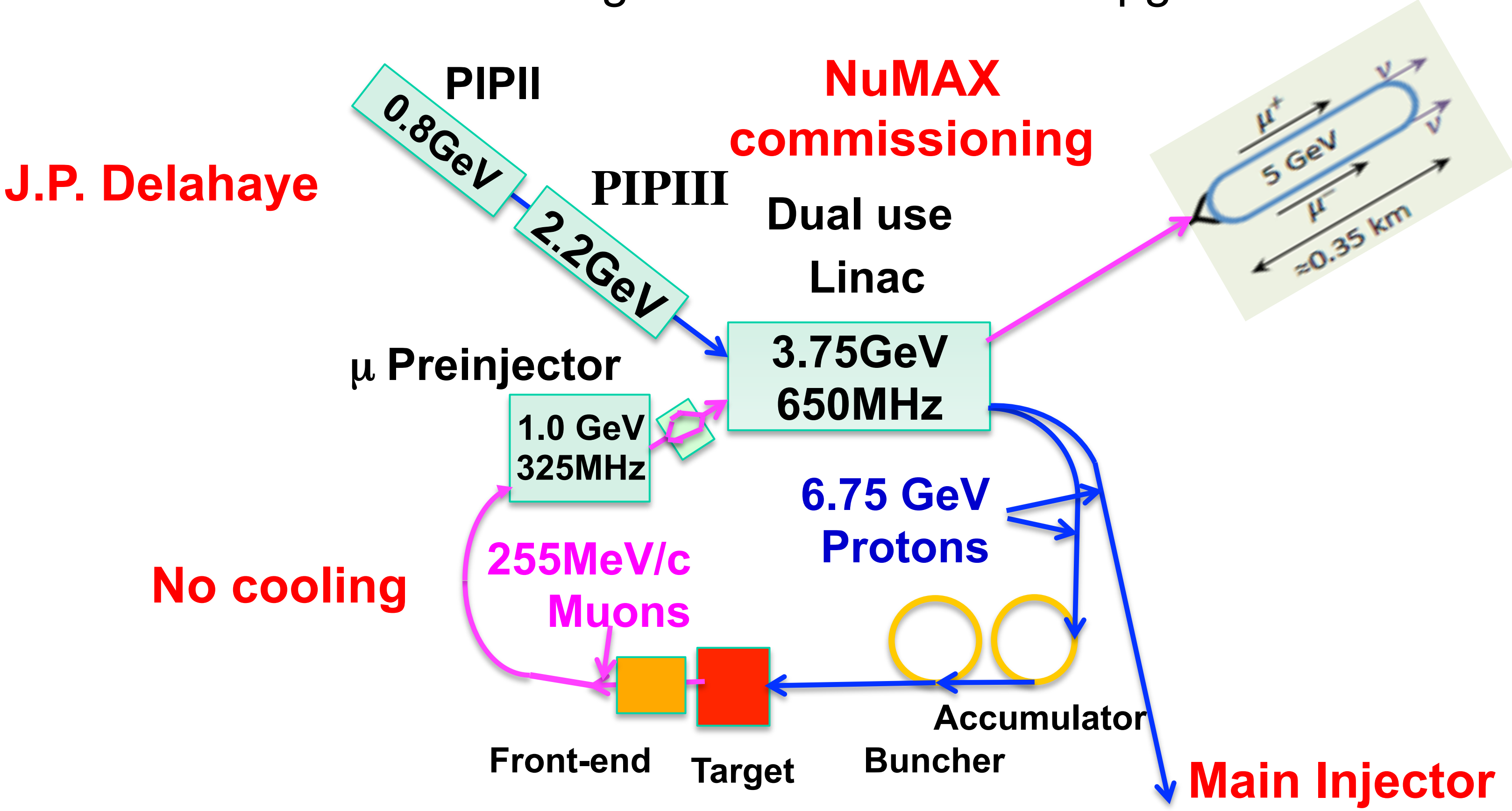
Disappearance sensitivity



Can perform combined analysis appearance/disappearance

NuMAX: Neutrino Factory FNAL/Sanford

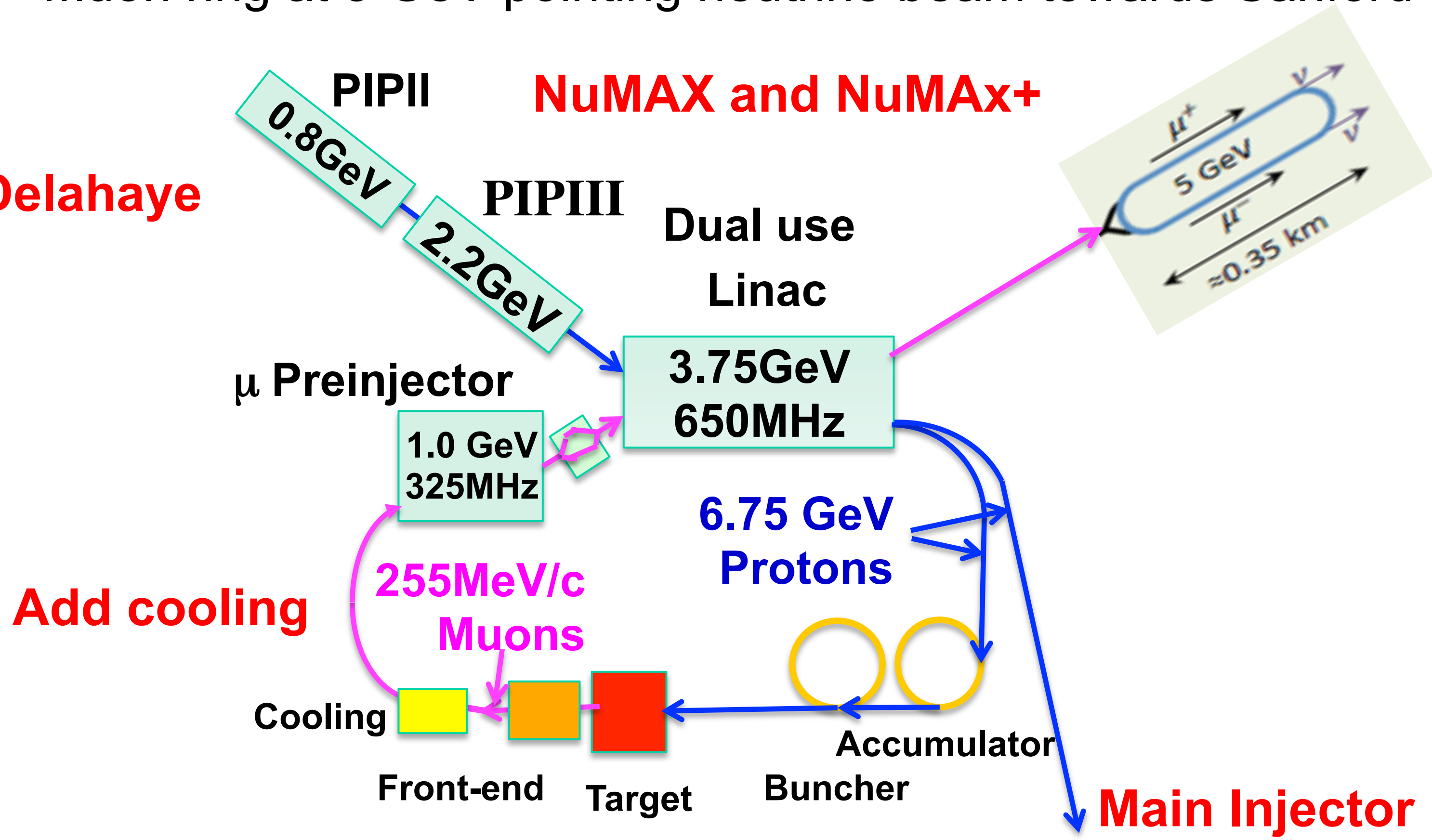
- Neutrinos from a Muon Accelerator CompleX (NuMAX)
  - Neutrino Factory with 10^{20} straight muons decays/year @ 5 GeV
  - Muon ring at 5 GeV pointing neutrino beam towards Sanford
  - A 10kT MIND or magnetized LAr detector upgraded from LBNE



NuMAX: Neutrino Factory FNAL/Sanford

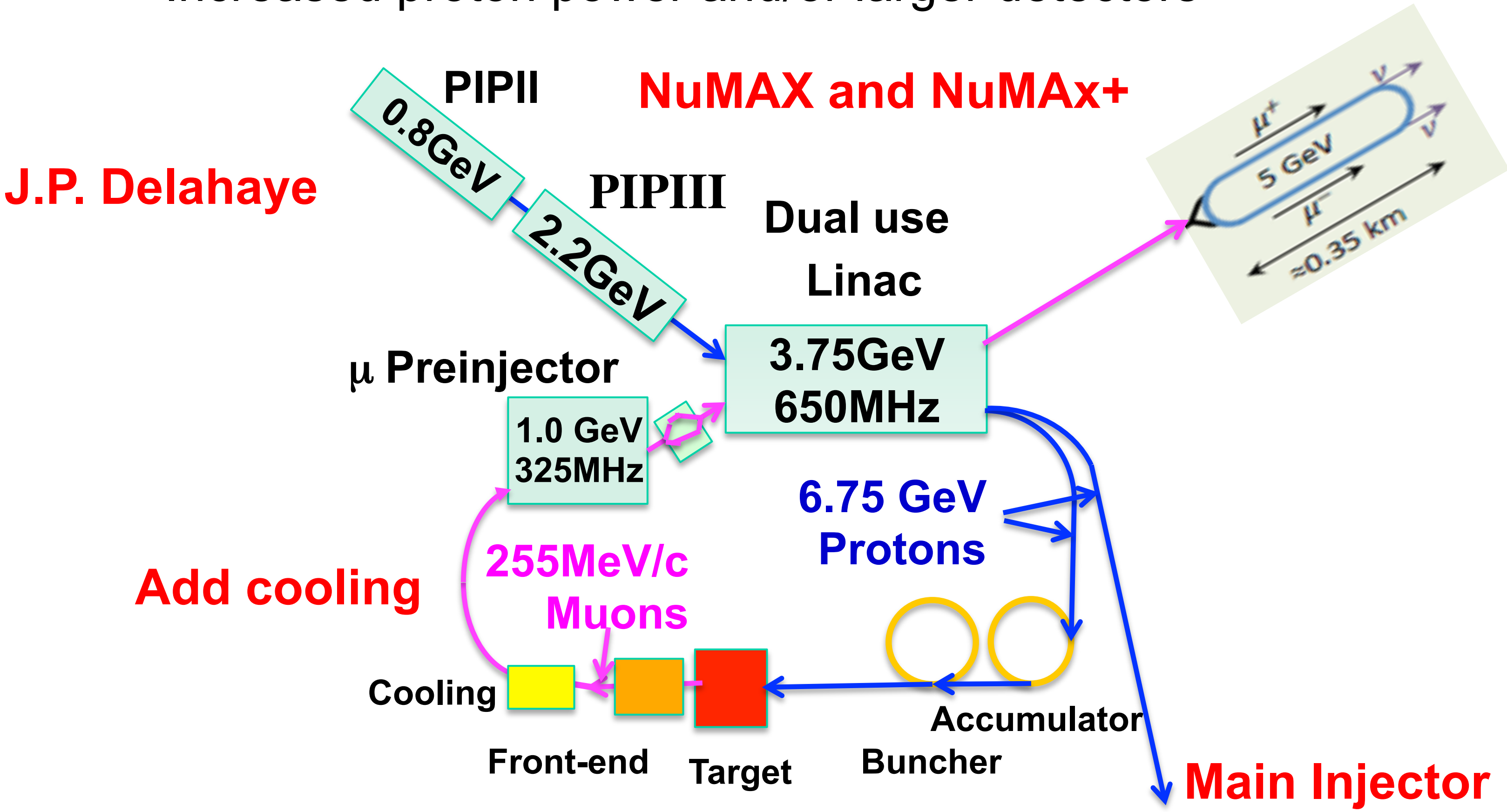
- Neutrinos from a Muon Accelerator CompleX (NuMAX)
  - Add small amount of 6D cooling
  - Neutrino Factory with 5×10^{20} straight muon decays/year @ 5 GeV
  - Muon ring at 5 GeV pointing neutrino beam towards Sanford

J.P. Delahaye



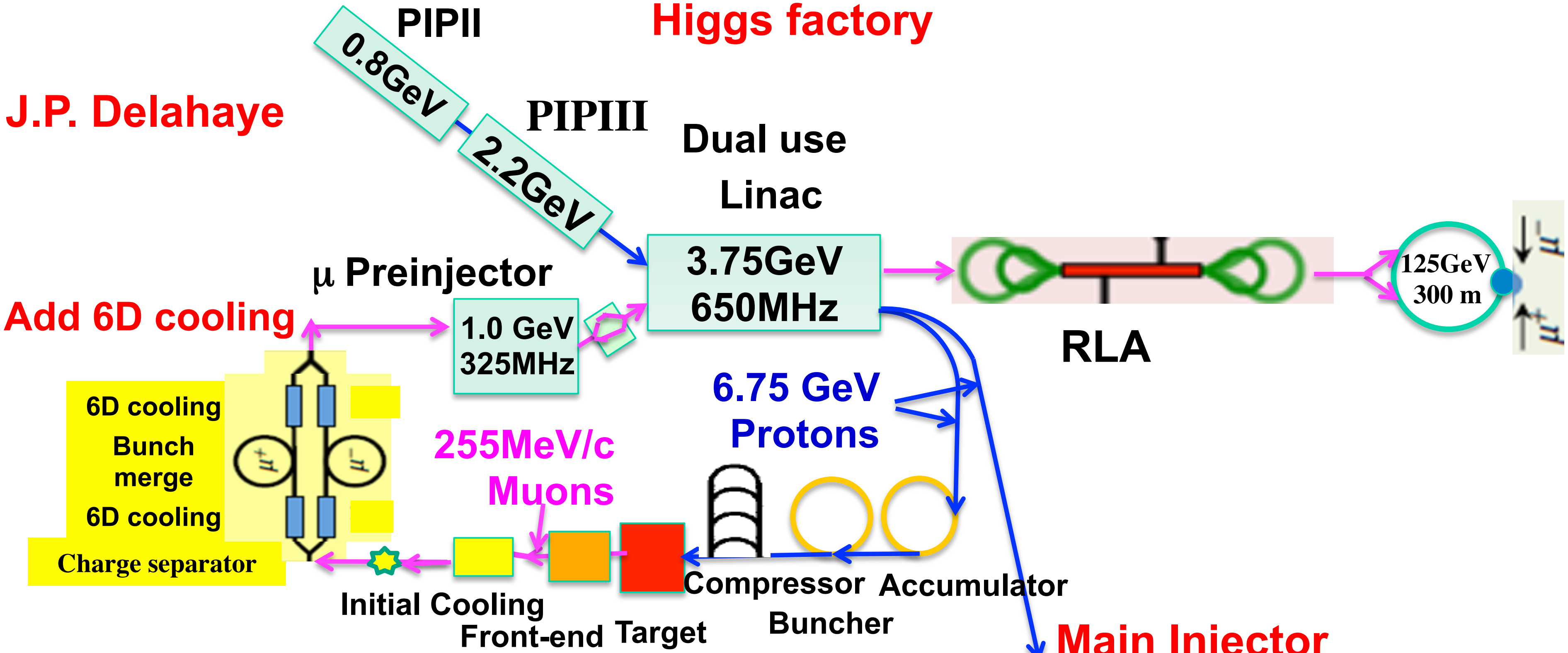
NuMAX+: upgrade NuMax

- Neutrinos from a Muon Accelerator CompleX (NuMAX+)
  - Neutrino Factory with 10^{21} straight muons decays/year @ 5 GeV
  - Muon ring at 5 GeV pointing neutrino beam towards Sanford
  - Increased proton power and/or larger detectors



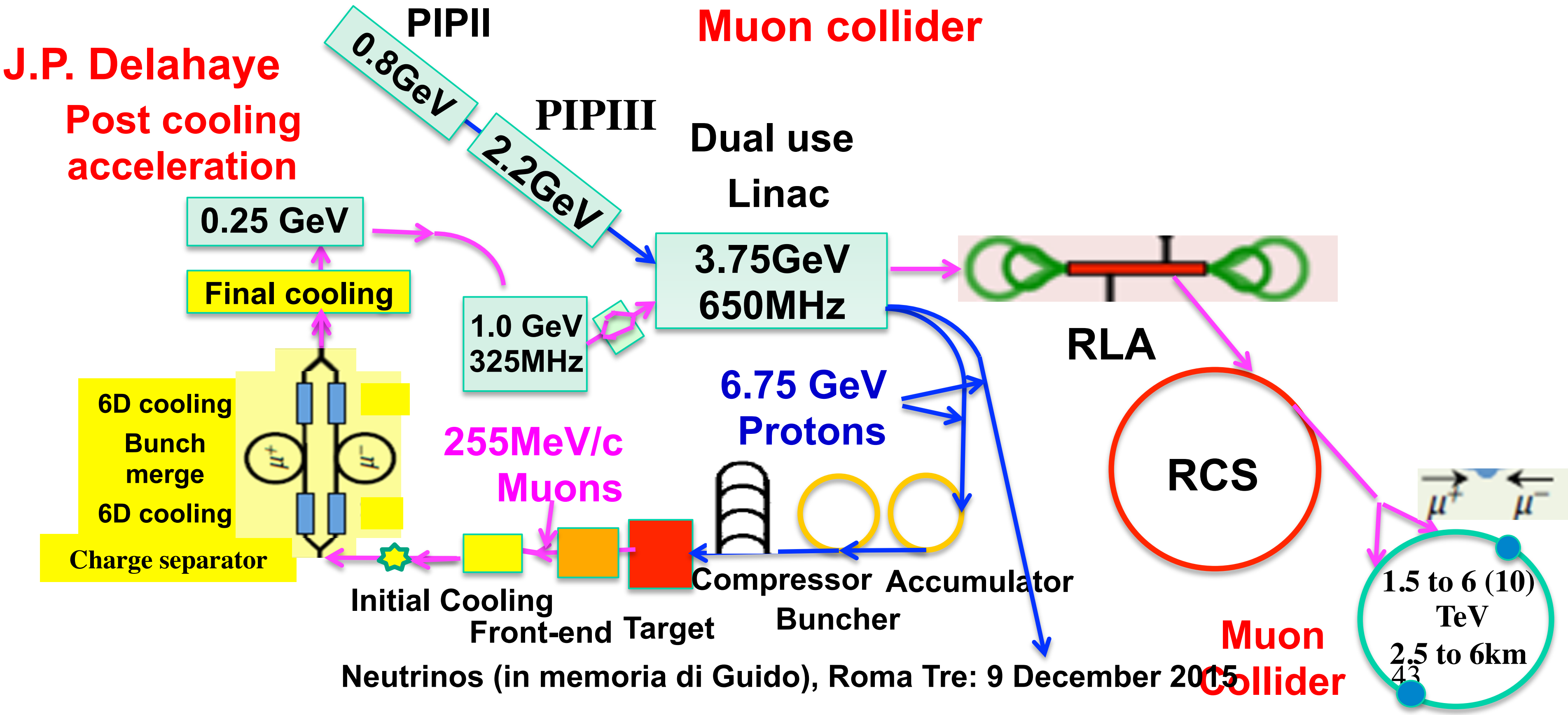
Higgs Factory

- Higgs Factory: production of Higgs at 126 GeV CM
  - Collider capable of providing ~13,500 Higgs events per year with exquisite energy resolution: direct Higgs mass and width
  - Possible upgrade to a Top Factory with production of up to 60000 top particles per year



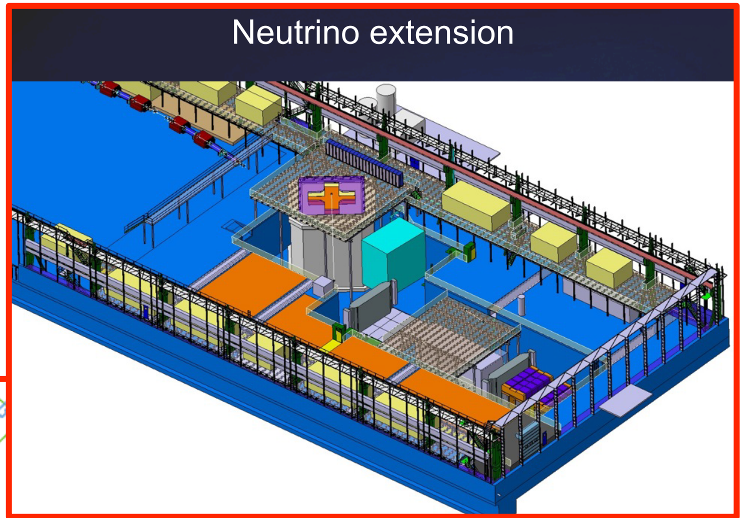
High Energy Muon Collider

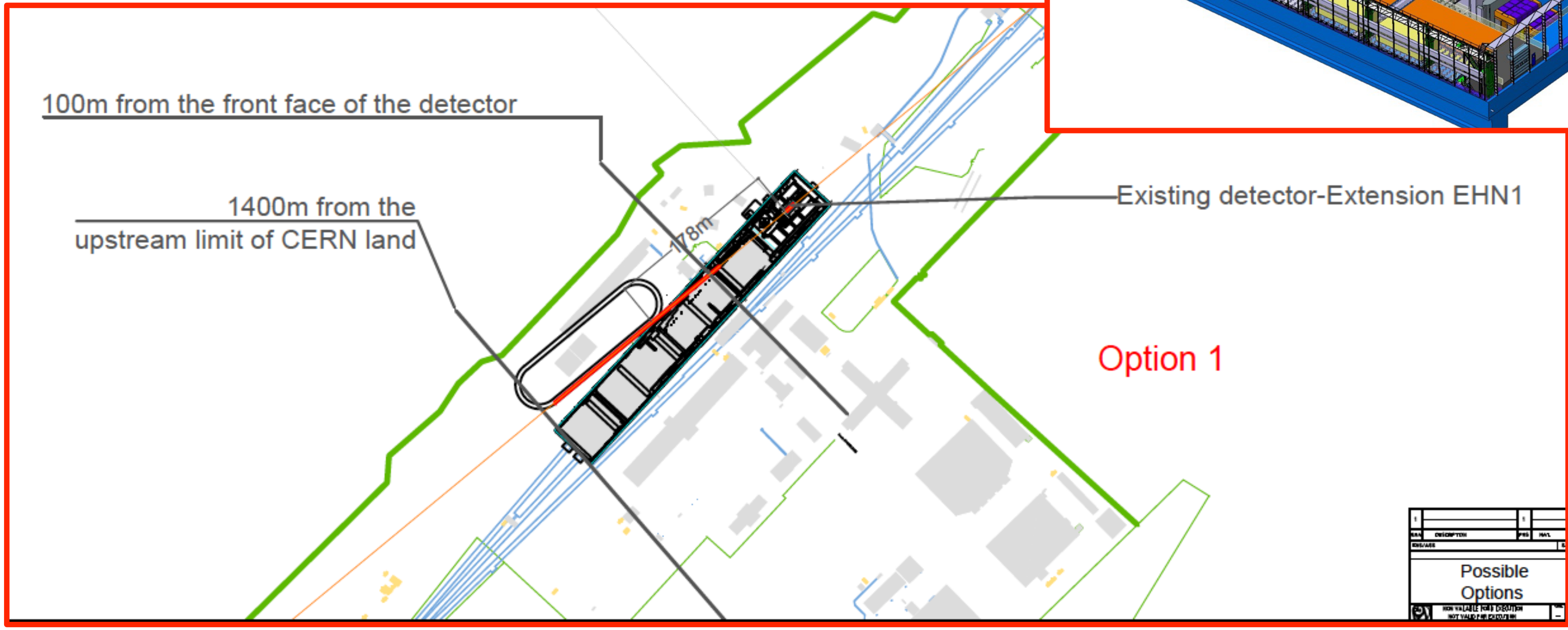
- Multi-TeV muon collider:
  - If warranted by LHC results a muon collider can reach up to 10 TeV
  - Likely offers the best performance, least cost and power consumption of any lepton collider operating in the multi-TeV regime.
  -



nuSTORM at CERN

- nuSTORM serving the Neutrino Platform at CERN





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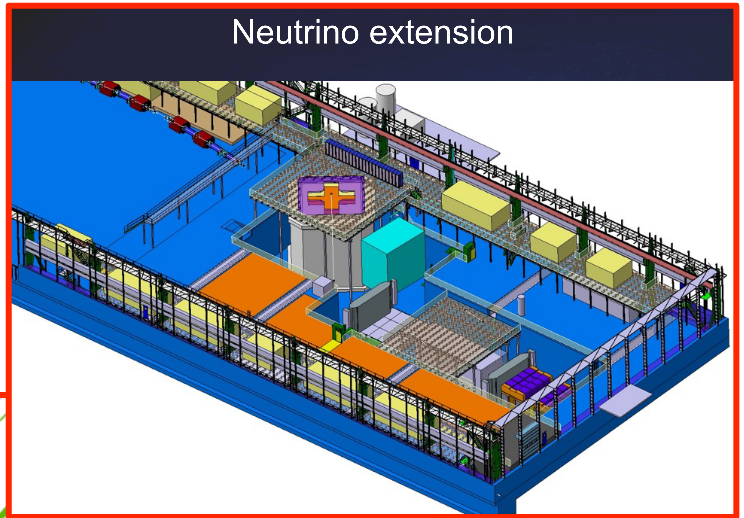

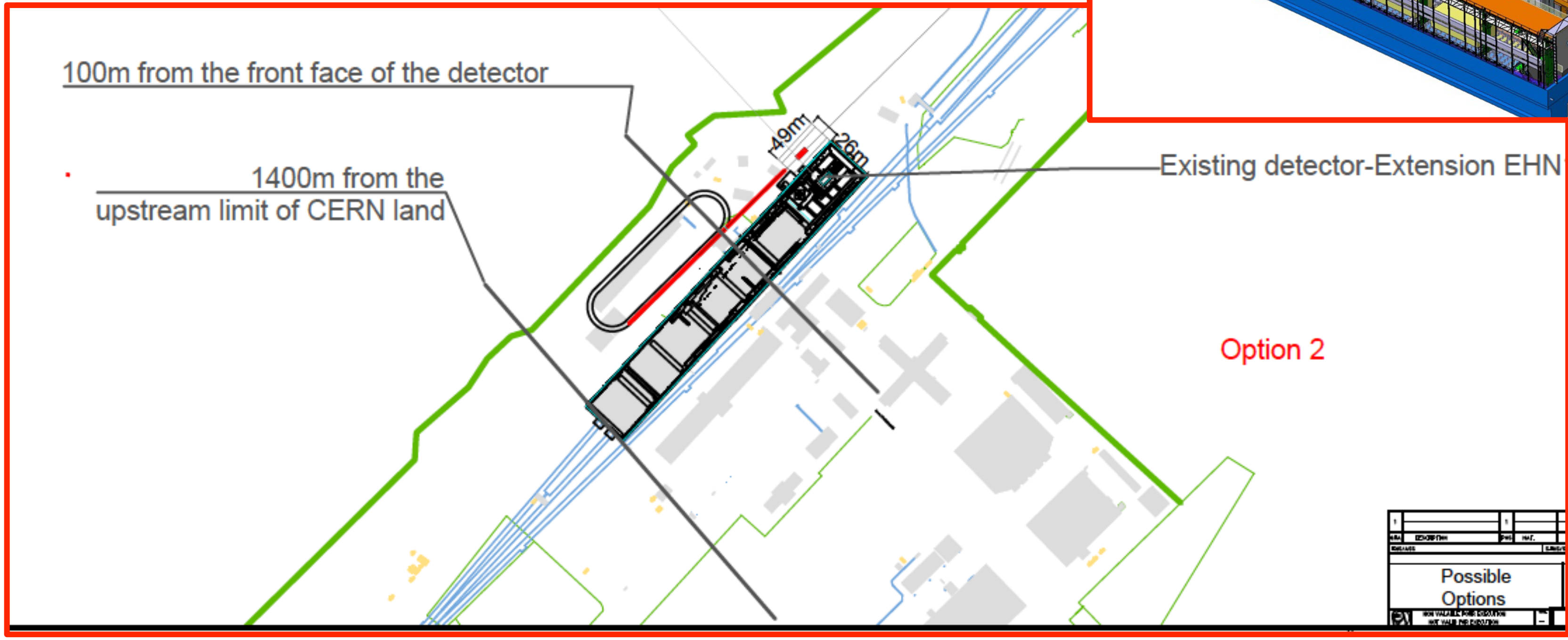

nuSTORM at CERN

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