Low Energy Neutrino Factory Option

David Neuffer

April 2009

Outline

- International Scoping Study ν-Factory parameters
  - 25 to 50 GeV μ storage rings
  - 2 long baseline mu decay lines (4000/7500km), 2 50kT detectors
- 4 GeV NuFactory option
  - Overview
- Accelerator components
  - Proton Driver
  - target, capture
  - bunch. φ-E rotate,cool
  - Accelerate, storage Ring
- Detector concept
  - TASD, beam to DUSEL
  - **25 kT**, 0.5T magnet

  - Comments

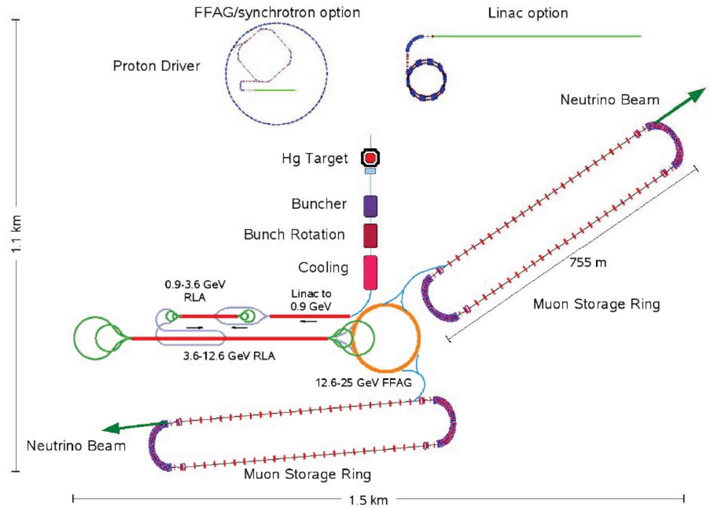
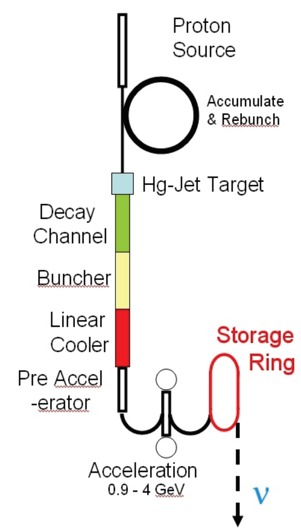


Figure 1: Schematic drawing of the ISS baseline for the Neutrino Factory accelerator complex. The various systems have been drawn to scale.



Neutrino Factory – ISS baseline

- Proton Driver
  - **4MW**, 50 Hz, ~10GeV p
- Target, Capture,
  - $\pi \rightarrow \mu$
- Beam formation
  - bunch, cool
- Acceleration
  - 100 MeV $\rightarrow$ **25 & 50 GeV**
  - linac, RLAs, FFAG
- Storage/Decay ring
  - 2 baselines (~4000, ~7500km)
- Detectors
  - 2 50 kT detectors
- >10^{21} μ-decays /SS /year

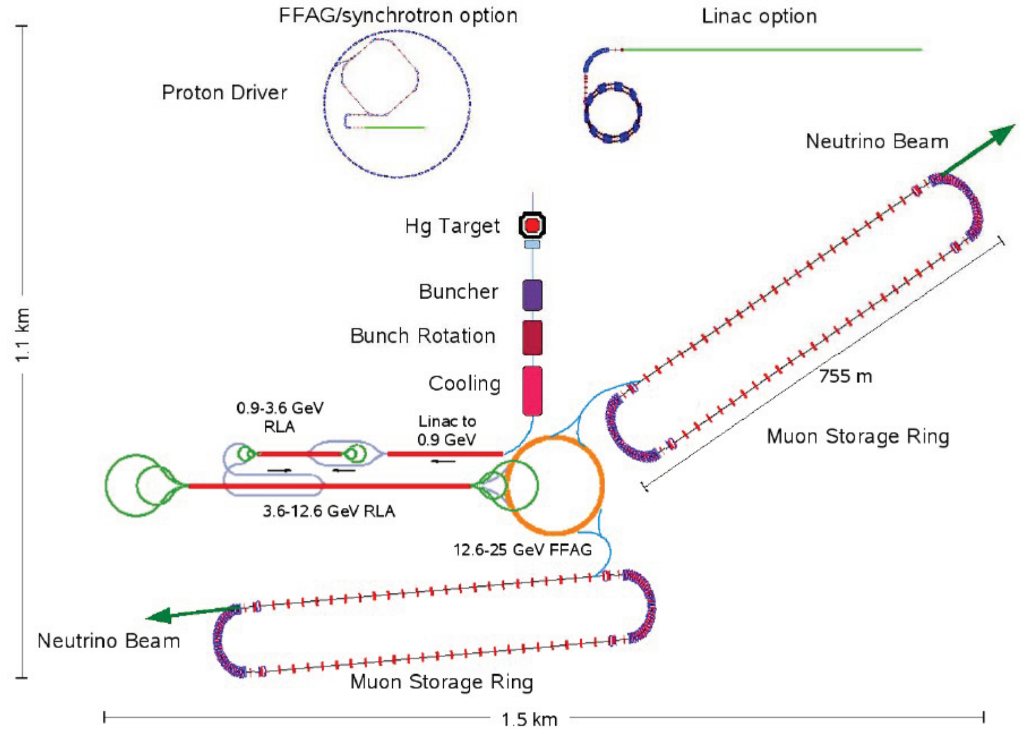


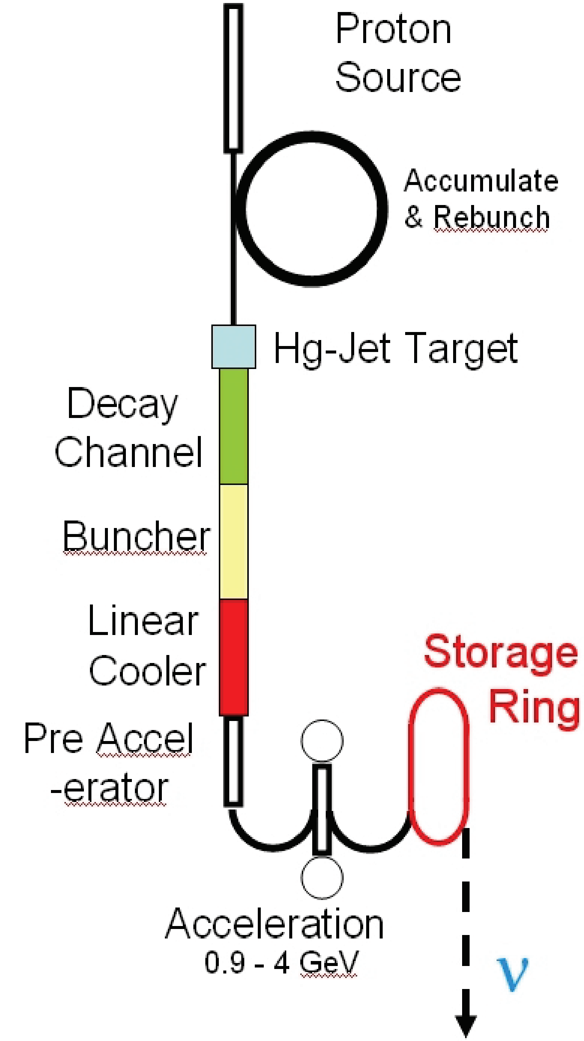
Figure 1: Schematic drawing of the ISS baseline for the Neutrino Factory accelerator complex. The various systems have been drawn to scale.

International Scoping Study Neutrino Factory

Variation: 4 GeV ν-Factory

- **Use magnetized totally active scintillator detector**
- **4 GeV muons provide adequate neutrino beam for detector**
- **Fermilab to DUSEL (South Dakota) baseline -1290km**

S. Geer et al, Phys. Rev. **D75**, 093001 (2007)
A. Bross et al., Phys. Rev. **D77**,093012 (2008)



C. Ankenbrandt et al.
Fermilab-Pub-09-001-APC

Key Publications

- S. Geer, O. Mena, S. Pascoli
  - Phys. Rev. D 75, 093001 (2007)

- A. Bross, M. Ellis, S. Geer, O. Mena, S. Pascoli,
  - Phys. Rev. D 77, 093012 (2008)

➢ C. Ankenbrandt S. A. Bogacz, A. Bross, S.Geer, C. Johnstone, D. Neuffer, R. Palmer, M. Popovic
  - Fermilab-Pub-09-001-APC
  - submitted to PRSTAB

PHYSICAL REVIEW D 75, 093001 (2007)

Low energy neutrino factory for large θ_{13}

Steve Geer*
Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500, USA

Olga Mena†
Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500, USA
INFN—Sezione di Roma, Dipartimento di Fisica, Universitá di Roma "La Sapienza," Piazzale Aldo Moro, 5, I-00185 Roma,

Silvia Pascoli‡
IPPP, Department of Physics, Durham University, Durham DH1 3LE, United Kingdom
(Received 5 February 2007; published 1 May 2007)

If the value of θ_{13} is within the reach of the upcoming generation of long-baseline experiments, T2K and NOνA, we show that a low-energy neutrino factory, with peak energy in the few GeV range, would provide a sensitive tool to explore *CP* violation and the neutrino mass hierarchy. We consider baselines

PHYSICAL REVIEW D 77, 093012 (2008)

Neutrino factory for both large and small θ_{13}

Alan Bross, Malcolm Ellis, and Steve Geer*
Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500, USA

Olga Mena+
zione di Roma, Dipartimento di Fisica, Universitá di Roma "La Sapienza," Piazzale Aldo Moro, 5, I-00185

Silvia Pascoli‡
IPPP, Department of Physics, Durham University, Durham DH1 3LE, United Kingdom
(Received 4 October 2007; published 28 May 2008)

An analysis of the neutrino oscillation physics capability of a low-energy neutrino factory is presented, including a first simulation of the detector efficiency and event energy threshold. The sensitivity of the physics reach to the presence of backgrounds is also studied. We consider a representative baseline of 1480 km, we use muons with 4.12 GeV energy and we exploit a very conservative estimate of the energy resolution of the detector. Our analysis suggests an impressive physics reach for this setup, which can eliminate degenerate solutions, for both large and small values of the mixing angle θ_{13}, and can determine leptonic *CP* violation and the neutrino mass hierarchy with extraordinary sensitivity.

Low Energy Neutrino Factory Design

C. Ankenbrandt[1,4], S. A. Bogacz[2], A. Bross[1], S.Geer[1], C. Johnstone[1], D. Neuffer[1], R. Palmer[3], M. Popovic[1]

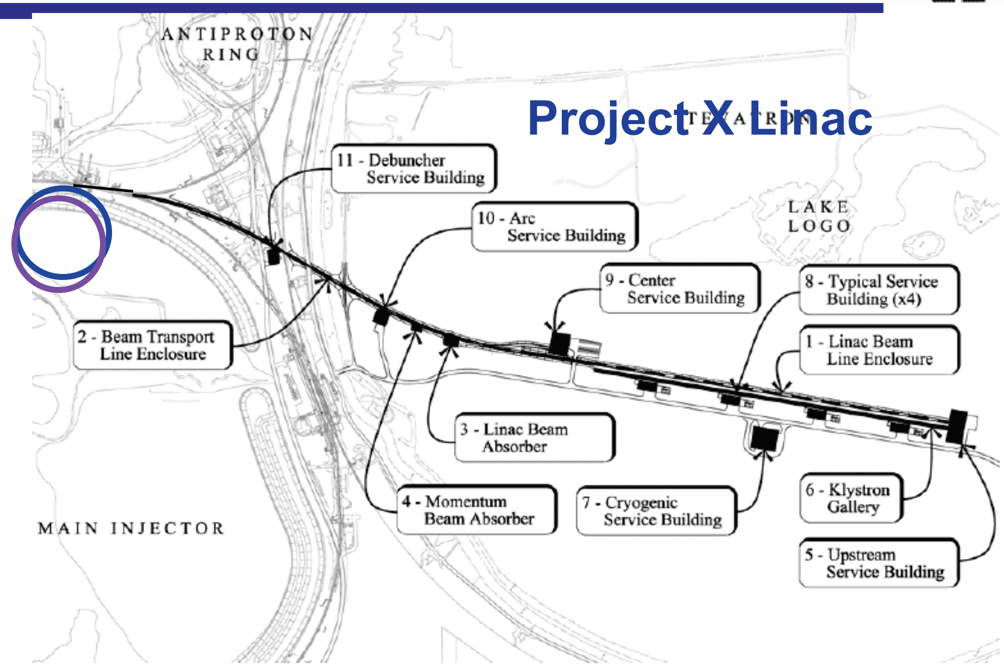
1) Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510
2) Center for Advanced Studies of Accelerators, Jefferson Lab, Newport News, Virginia 23606
3) Brookhaven National Laboratory
4) Muons, Inc.

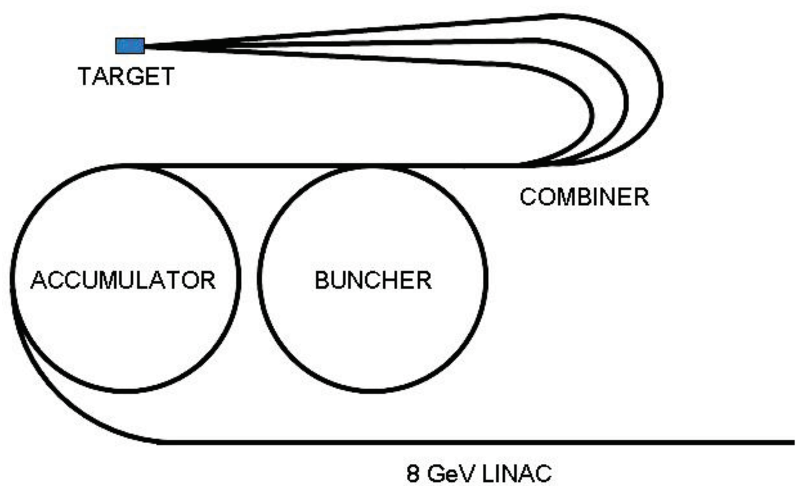
Abstract

The design of a low energy (4 GeV) Neutrino Factory is described, along with its expected performance. The Neutrino Factory uses a high energy proton beam to produce charged pions. The $\pi^{\pm}$ decay to produce muons ($\mu^{\pm}$), which are collected, accelerated, and stored in a ring with long straight sections. Muons decaying in the

Proton Driver

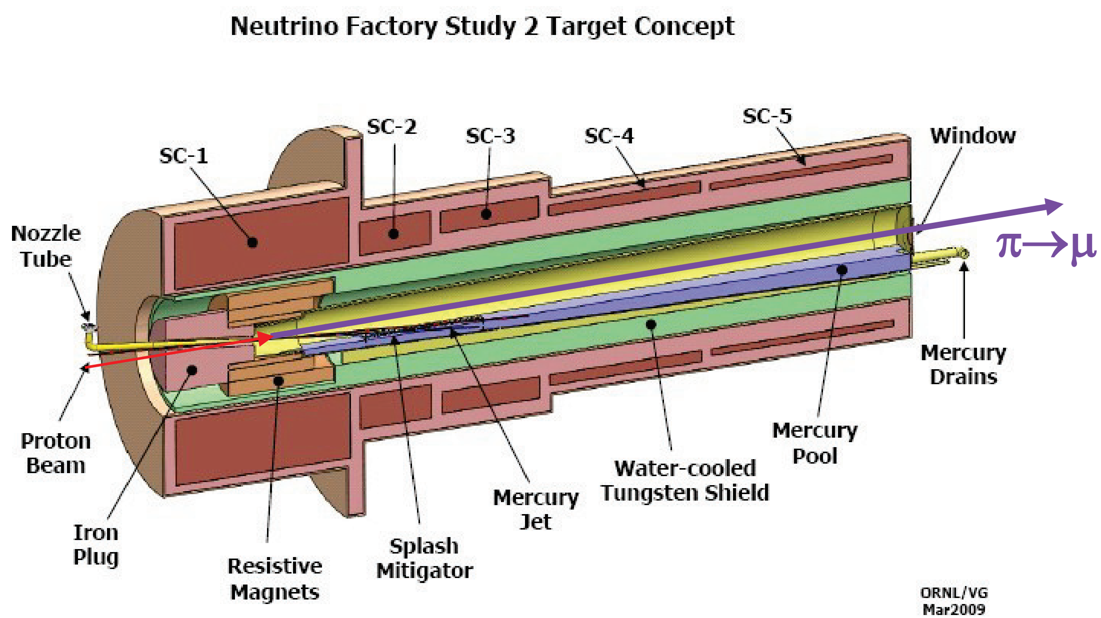
- Baseline is "Project X" 8 GeV Proton Linac
  - 10 Hz, 3×10^{14} p/cycle
    - **4MW** p-beam
- H⁻ inject into "Accumulator"
  - Accumulate linac cycle
- Transfer to "Buncher"
  - form 18 (~3ns long) bunches
    - 8GeV space charge limit
  - extract 3 at a time
    - Combiner places 3 on target at same time
    - alternative is bunch train of 3 bunches

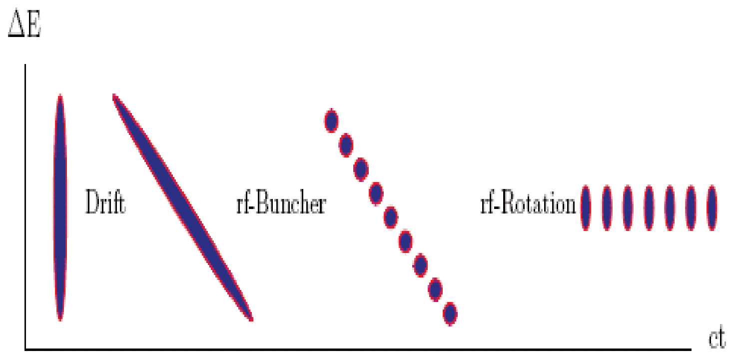




Solenoid lens capture

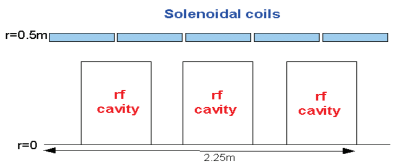
- Target is immersed in high field solenoid
- Particles are trapped in Larmor orbits
  - B= 20T -> ~2T
  - Particles with $p_\perp < 0.3\ B_{sol}R_{sol}/2 = 0.225$GeV/c are trapped
  - $\pi \rightarrow \mu$
  - Focuses both + and – particles
  - **Drift, Bunch and phase-energy rotation**

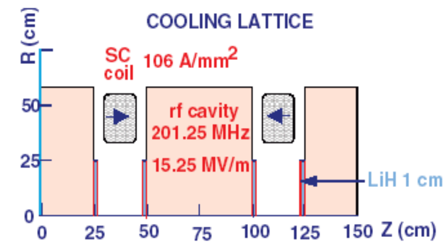


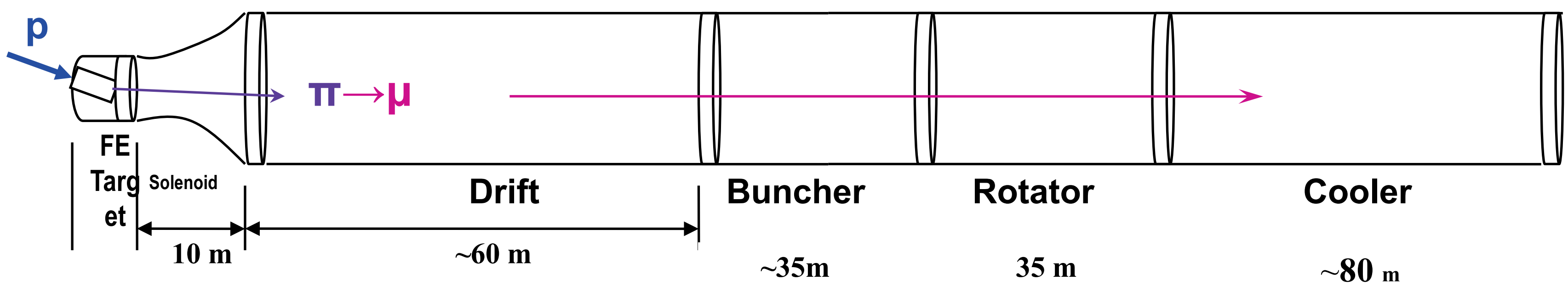


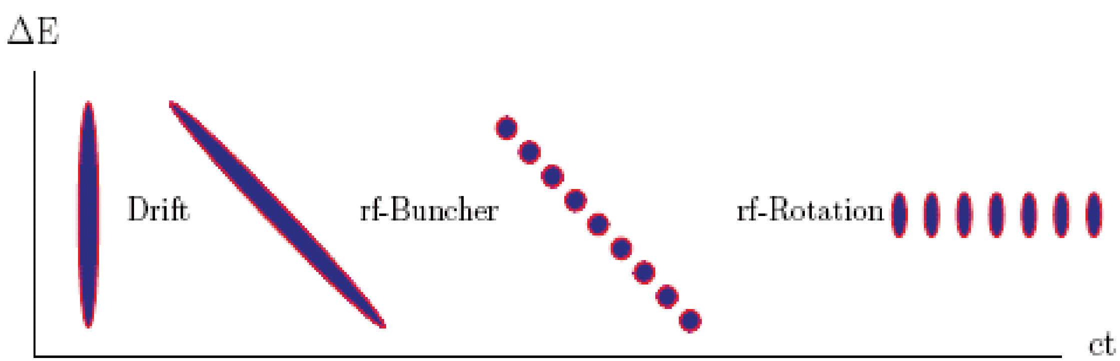
High-frequency Buncher and φ-E Rotator

- Drift (π→μ)
- "Adiabatically" bunch beam first (weak 320 to 240 MHz rf)
- Φ-E rotate bunches – align bunches to ~equal energies
  - 240to 202 MHz, 12MV/m
- Cool beam 201.25MHz

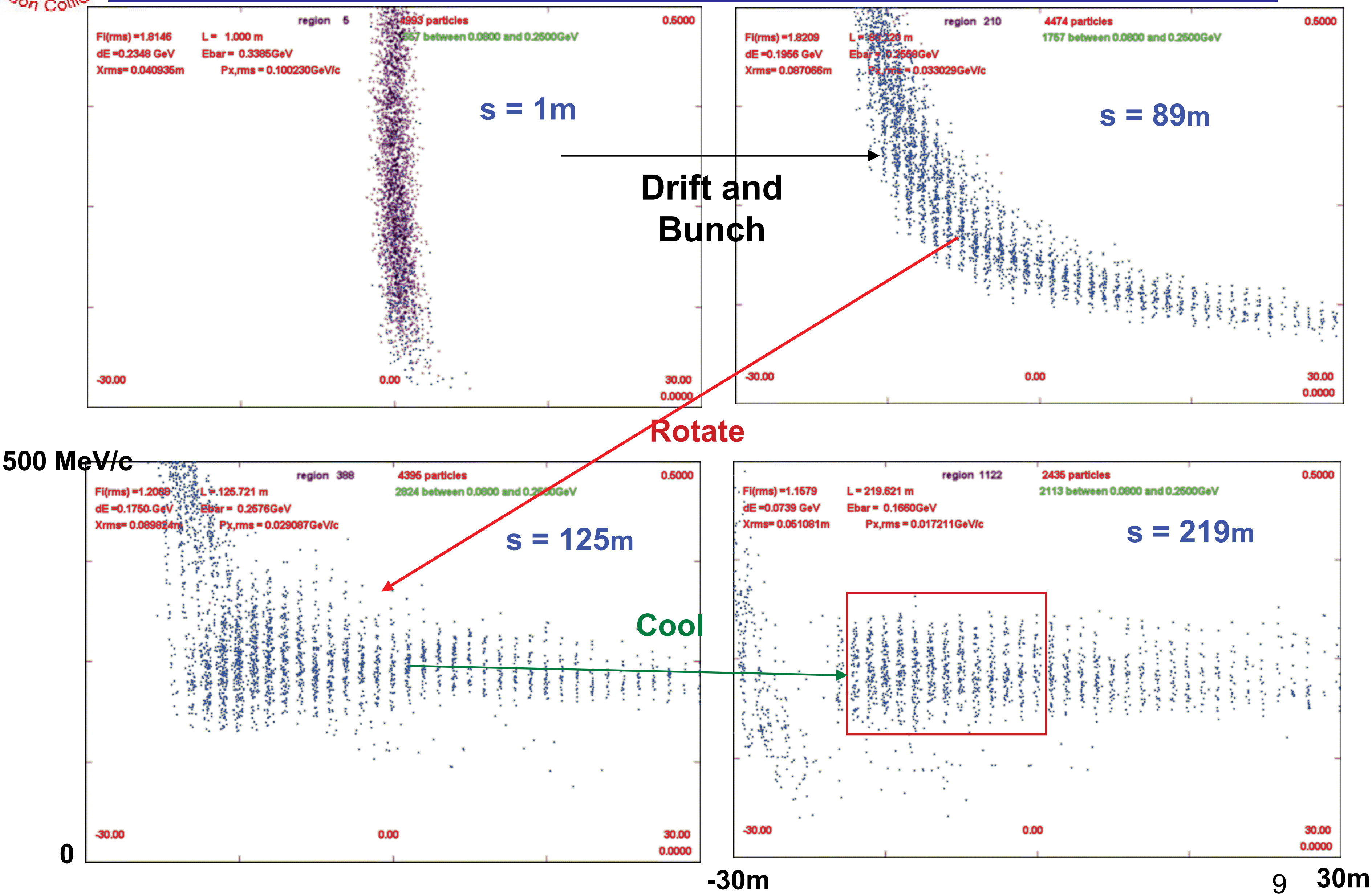




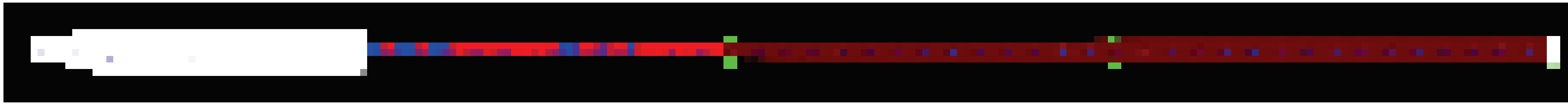




Simulations (N_B=10)



Front End in G4beamline: w. C. Yoshikawa



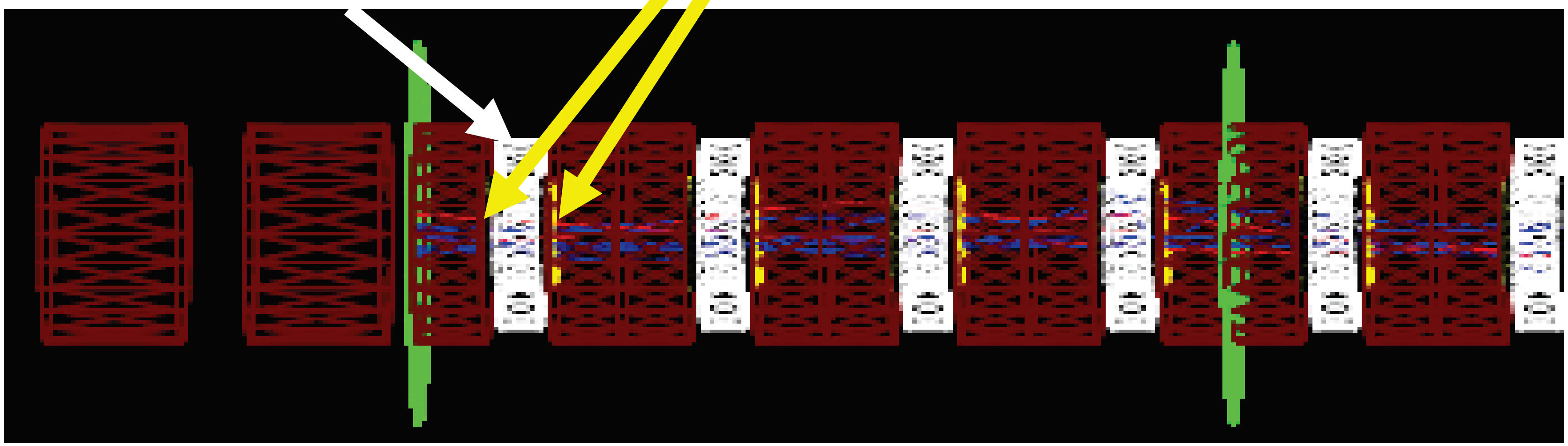
12.9 m capture | 43.5 m drift | 31.5 m buncher | 36 m rotator

50 cm
201.25 MHz
RF cavity

75 cm cell

1 cm LiH

23 cm vacuum



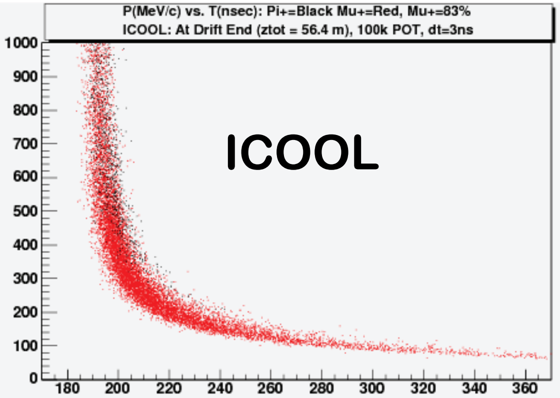
Rotator 36 m long

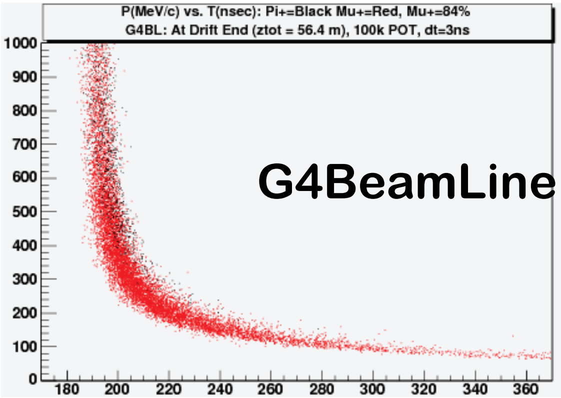
“Cool and Match” 3 m (4x75 cm cells)

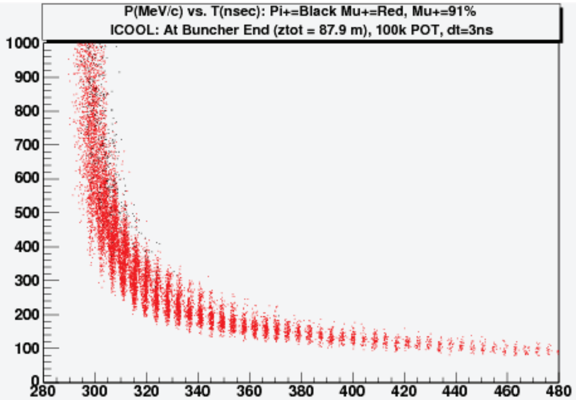
“Cool” 90 m of
75 cm cells

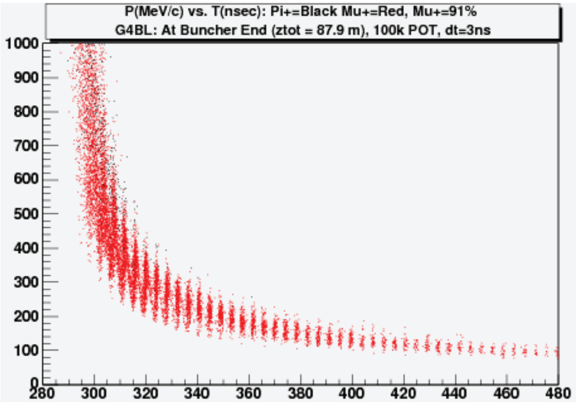
Have tracked N=10 with ICOOL and G4BL

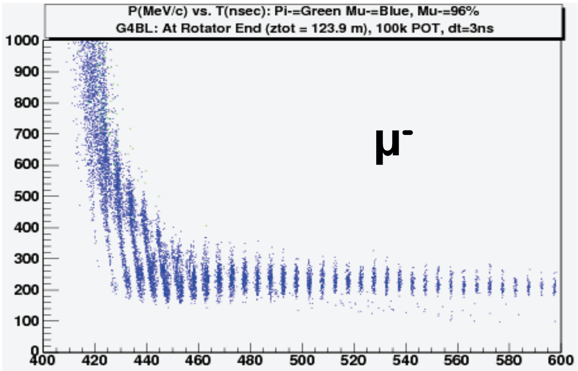
- **Results are similar**
  - Consistency check
- **Additional simulations will allow more variation and optimization**
- **Captures both signs**

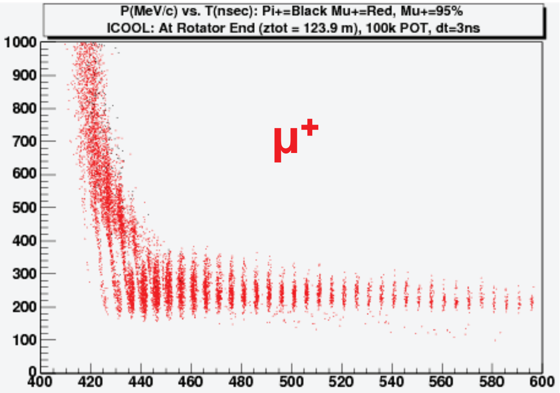


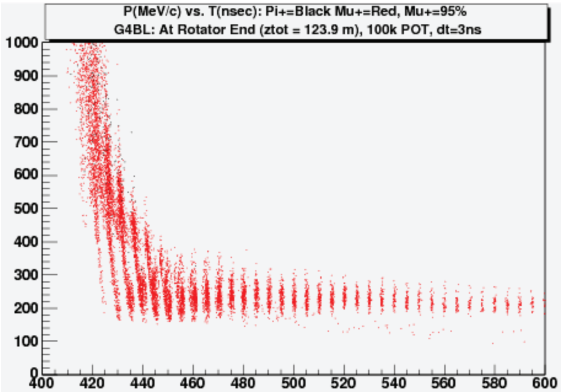






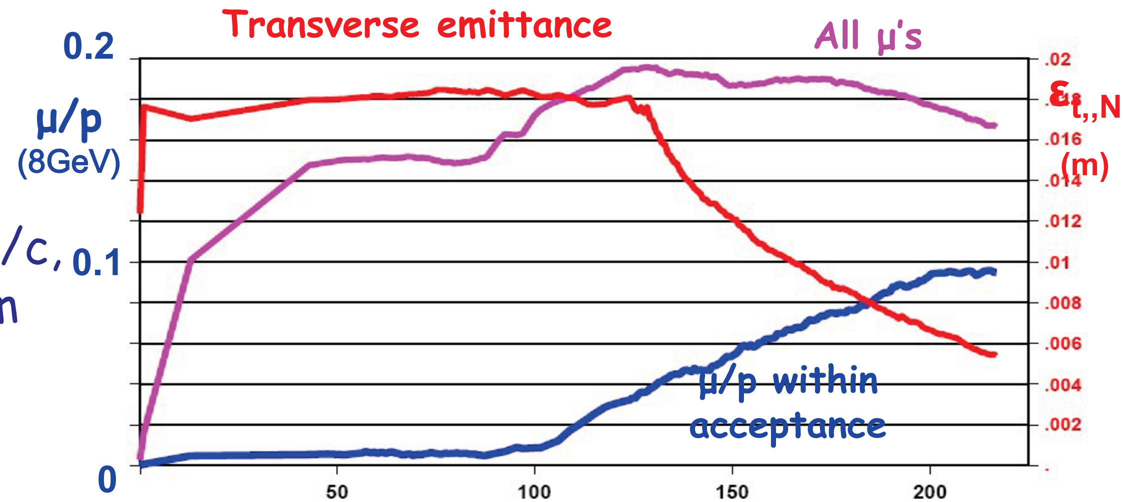


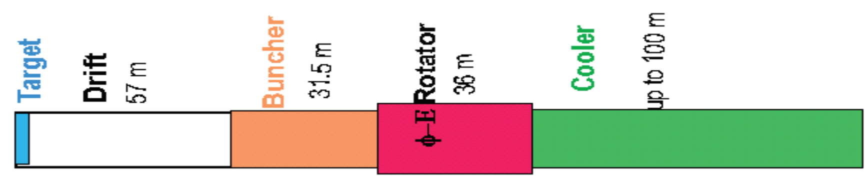




4 GeV ν-factory Front End baseline

- Drift- 56.4m
  - B=2T
- Bunch- 31.5m
  - P_1=280MeV/c, P_2 =154 MeV/c, δn_{rf} = 10; V_{rf}= 0 to 15 MV/m
- φ-E Rotate – 36m –
  - V_{rf} = 15MV/m, B =2T
  - (240 -> 201.5 MHz)
- Match and cool (80m)
  - Alternating solenoid (2.8T)
  - LiH or H_2 absorbers
  - V_{rf}=16, 201.25 MHz



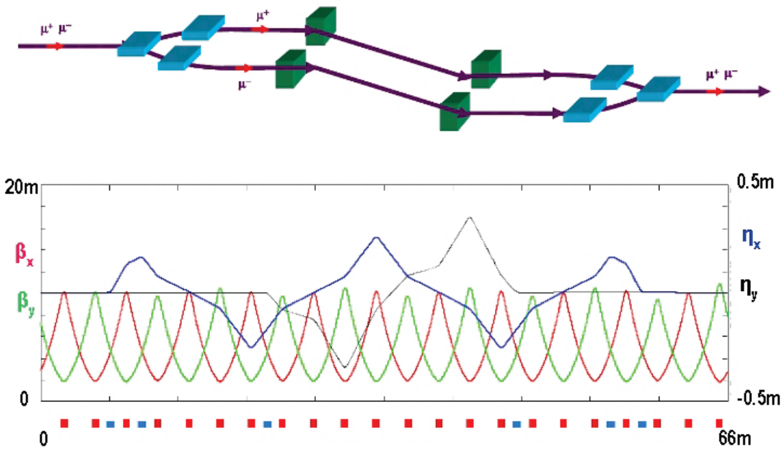


1.5 Zμ/year

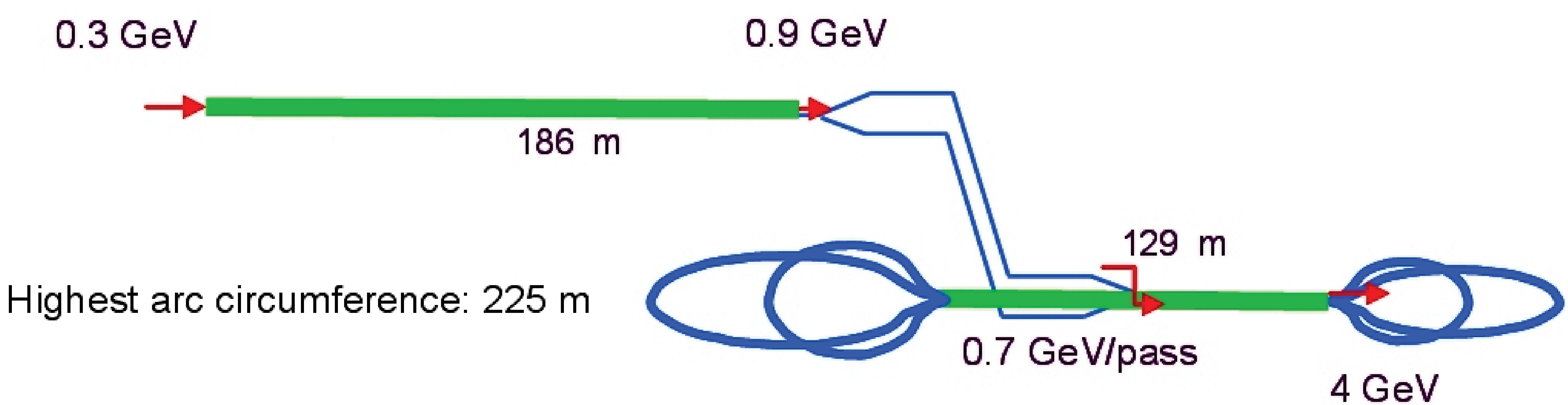
- Obtains ~0.085 μ/ 8 GeV p

4 GeV Neutrino Factory-Acceleration

- **Acceleration** (A. Bogacz)
  - Linac + RLA ~0.3 GeV to 4 GeV
  - accelerates both μ^+ and μ^-
  - Double Chicane drops both signs into middle of RLA Linac
  - 4 ½ turns Dogbone RLA

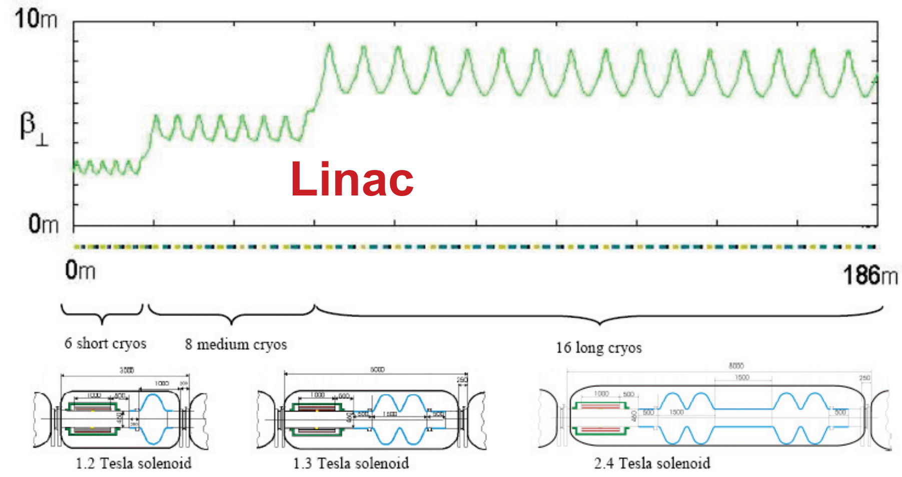


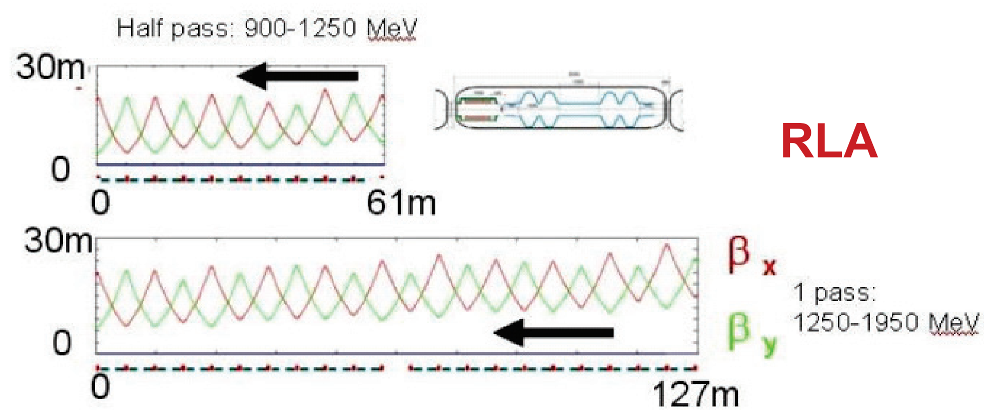
Chicane Optics

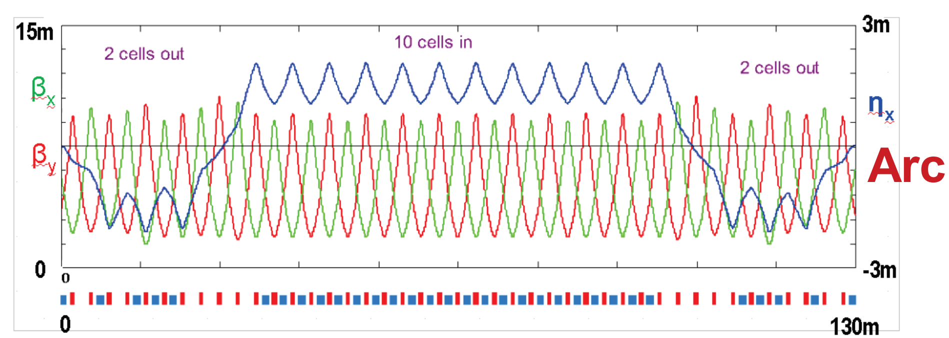


Acceleration Properties

- **Linac**
  - Solenoid focusing
    - stronger to weaker
  - 200 MHZ, 1 to 4 cavities /cell
    - SRF 12MV/m
- **RLA**
  - FODO –quad focusing
    - 127m linac
  - 4 + ½ Passes in Linac
    - 130m to 225m arcs
  - 4 return arcs
    - FODO lattices quad/dipole
- **Performance**
  - 85% survival
  - ~full transverse/longitudinal transmission

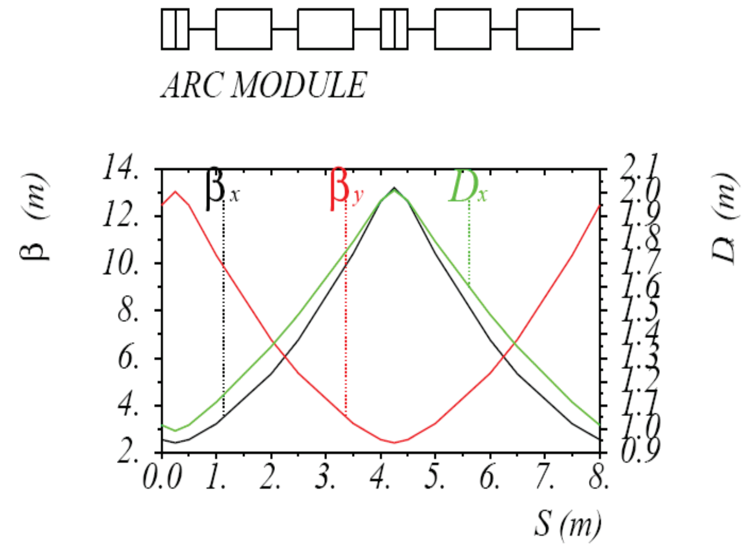


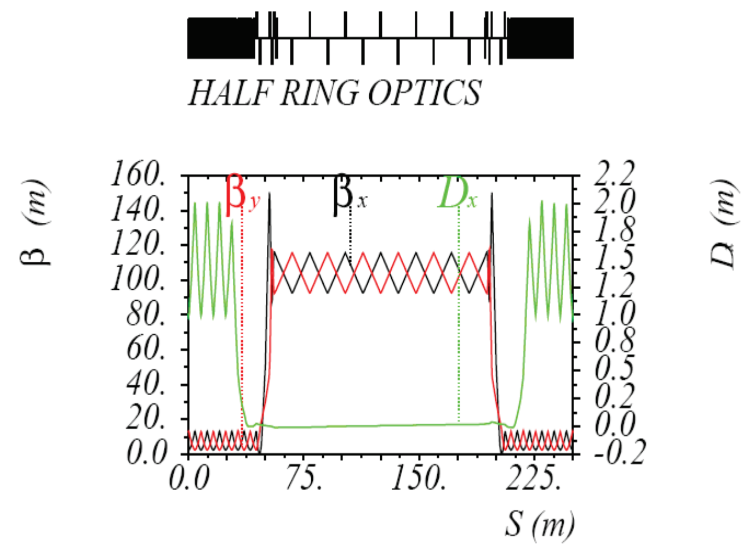


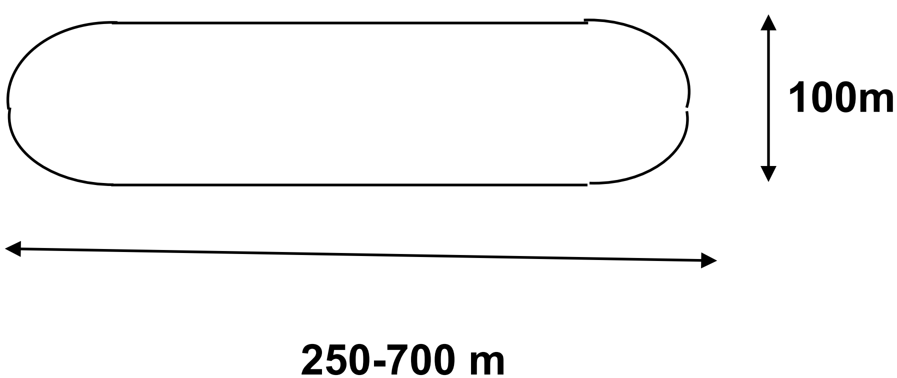


4 GeV – Storage Ring

- **Storage Ring** (C. Johnstone)
  - C = 500 to 1400m, r = 15cm
    - half the circumference of 25 GeV case
  - B < ~1T
    - conventional or permanent magnet
  - Straight section is 150 to 600m
    - $\beta_{x,y}$ >100m
    - 0.3 to 0.4 straight section fraction
  - Tilt toward DUSEL is ~6°





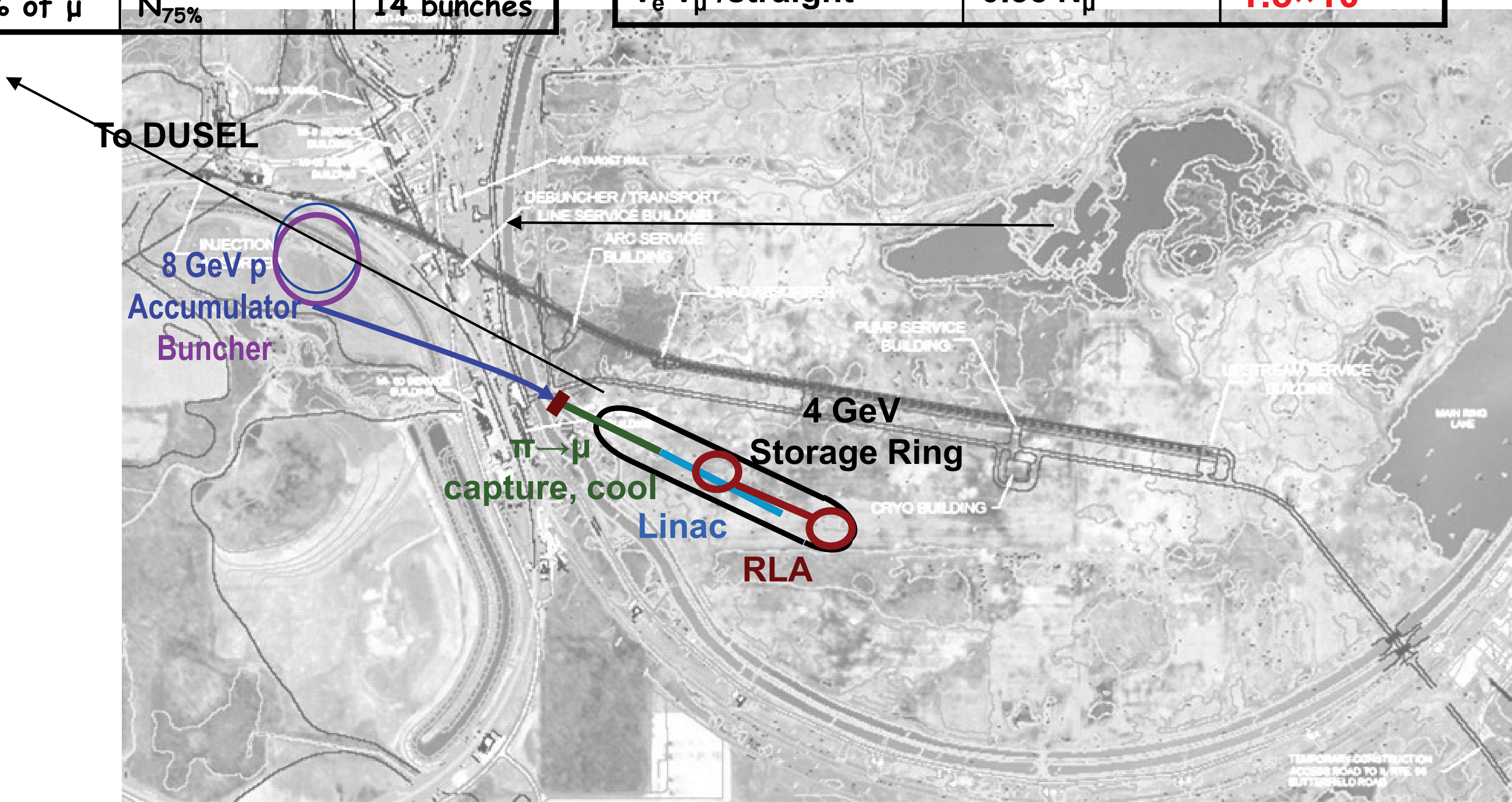


4 GeV ν-Factory Summary

Final Beam Properties

beam rms emittance	$\varepsilon_x, \varepsilon_y$ (Norm.)	0.0054m
beam size (arcs,strt)	σ_{arc} σ_{decay}	4, 13cm
momentum spread	$\sigma_{dp/d}$	1.2%
bunch length	σ_z	0.9cm
bunches/train	N_t	30 (~45m)
train with 75% of μ	$N_{75\%}$	14 bunches

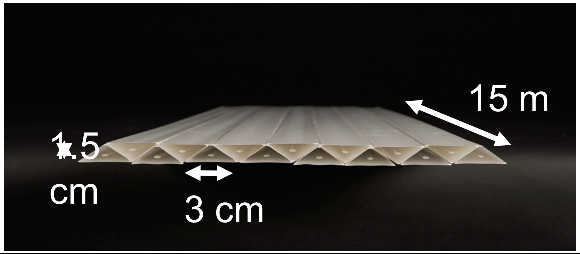
Repetition Rate	f(Hz)	60
Proton Energy	E_p	8GeV (4MW)
Protons/cycle	N_p	$5 \cdot 10^{13}$
Muons/proton	$\mu^+, \mu^-/p$	0.07
Muons/year	$2 \cdot 10^7 N_p f \cdot \mu^-/p$	4.4×10^{21}
ν_e ν_μ /straight	$0.35\ N_\mu$	1.5×10^{21}

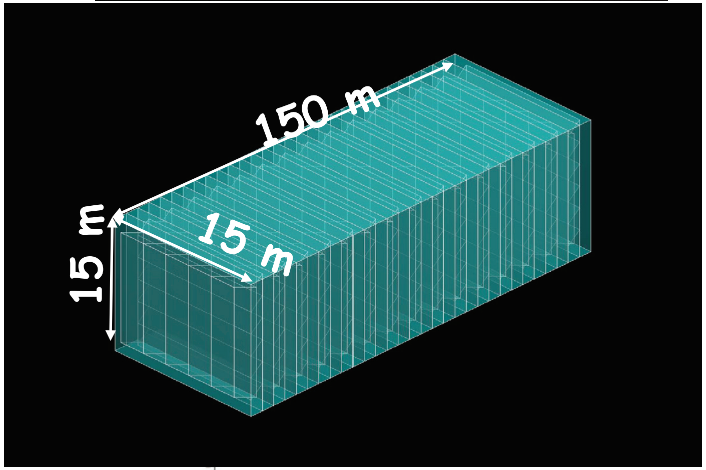


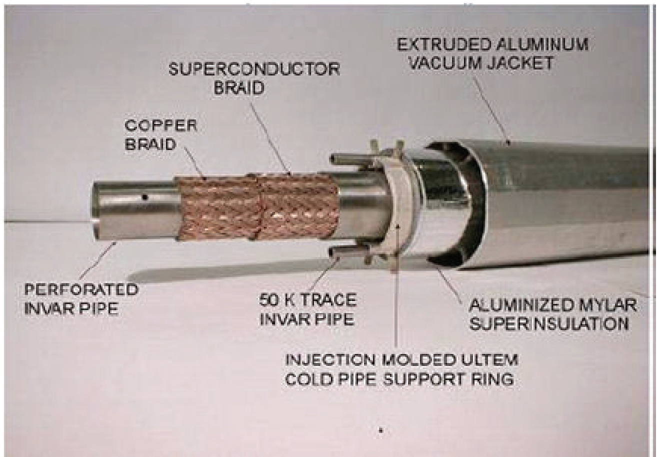
Detector for 4 GeV

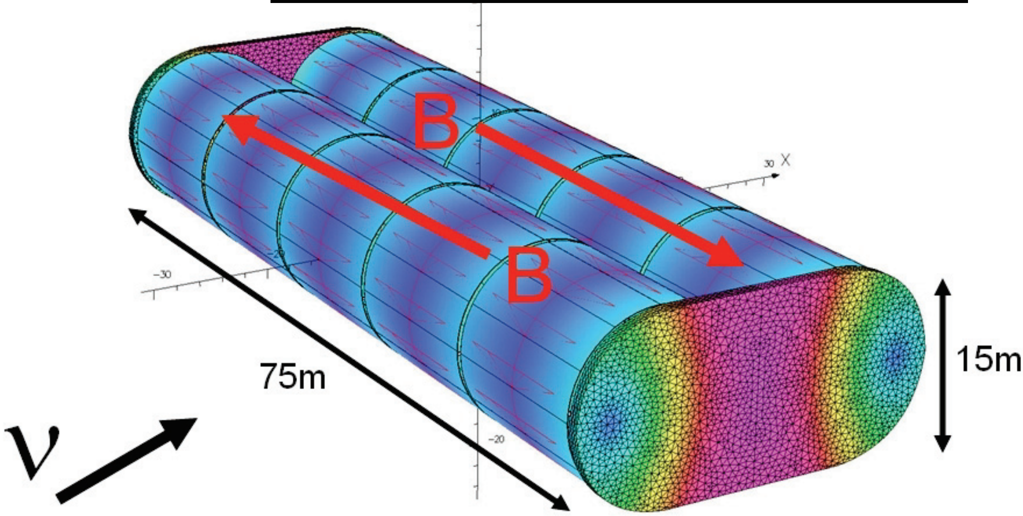
- Factory at Fermilab, Detector at SD
  - ~1290km baseline
- Totally Active Scintillator Detector
  - ~20000 m^3, 25 kT

    3333 Modules (X and Y plane) 4.5mm res.
    Each plane contains 1000 slabs
    Total: 6.7M channels
  - B=0.5T magnetic field
    - High T_c SC
      - No Vacuum Insulation
      - VLHC SC transmission line
    - 50 M$sg



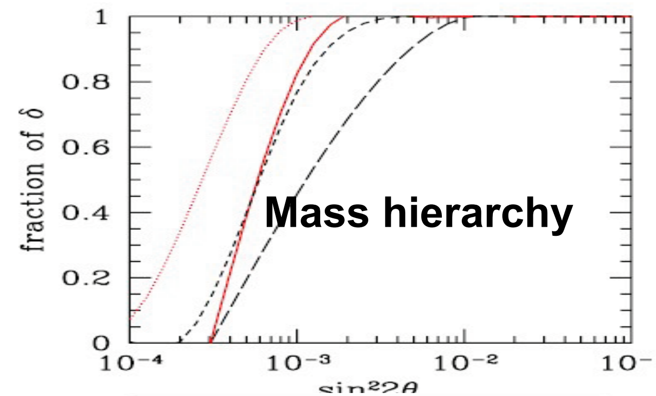


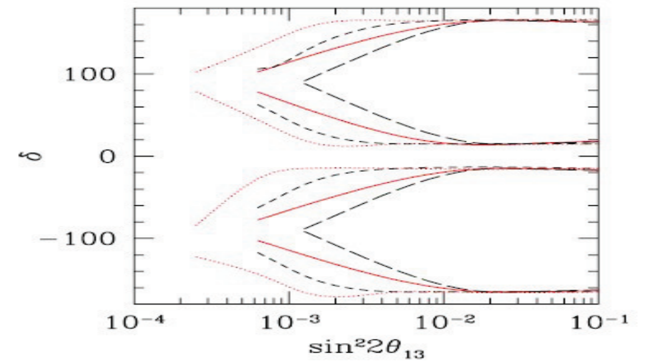


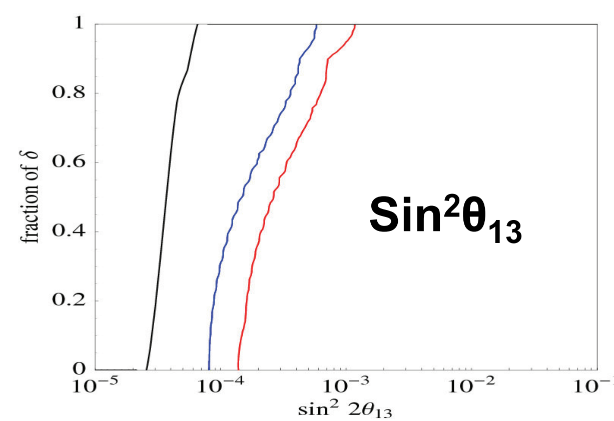


Sensitivity to physics

- **ν's from 4 GeV μ's**
  - $>10^{21}$ μ-decays /SS /year
  - ~0.5 to 1 GeV ν's
  - Use energy dependence
  - no charged τ
- **Can measure**
  - mass hierarchy
  - $\sin^2 2\theta_{13}$ (to <~0.001)
  - CP violating phase δ
- **High-Energy ν-Factory**
  - magnetic field from iron
    - iron/scintillator
  - longer particle tracks, more events
  - $\sin^2 2\theta_{13}$ (to ~0.0001) ?

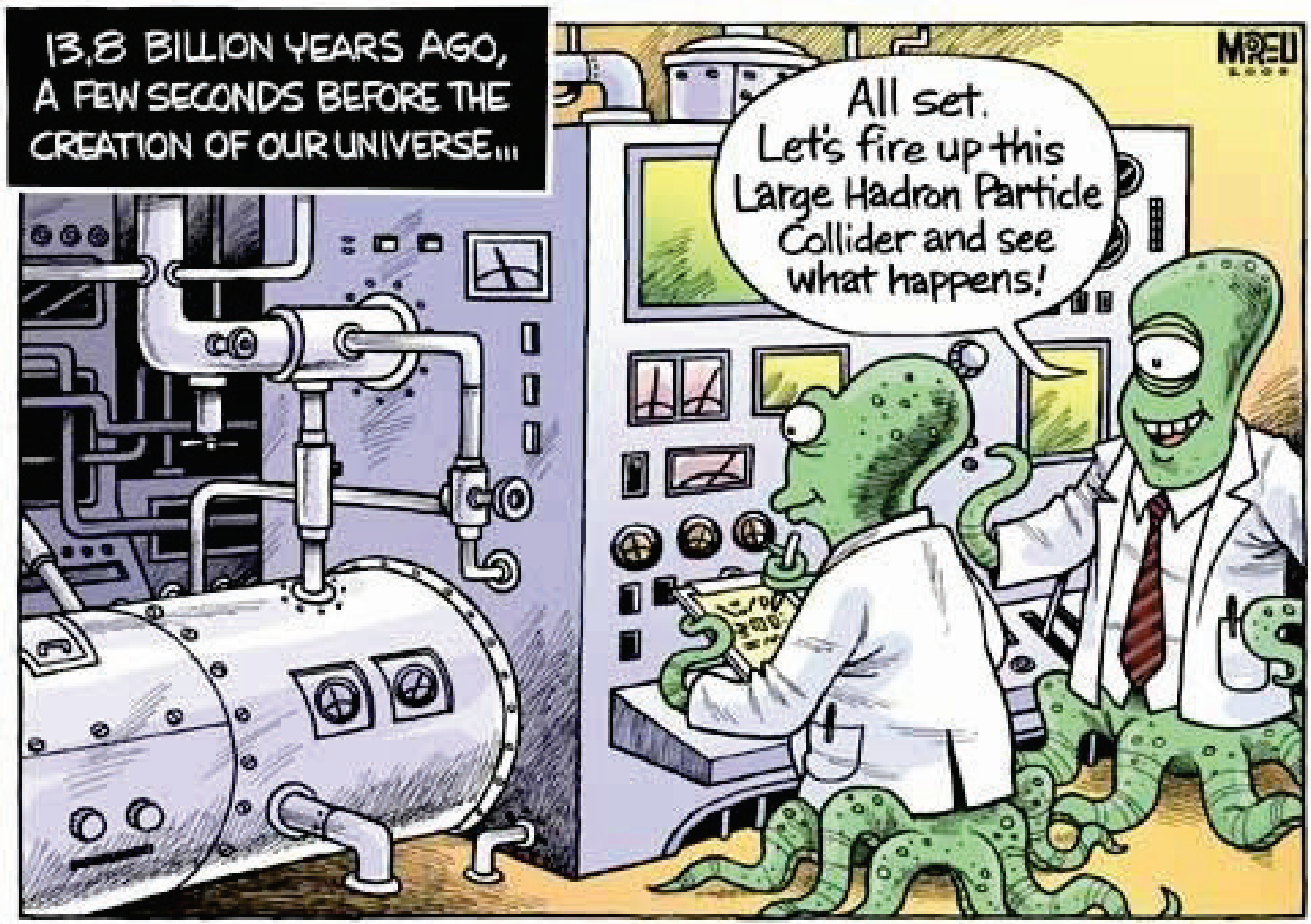






Summary/Progress

- **Have developed and documented Low-Energy neutrino factory design concept**
  - 4 MW front end, compact bunching and cooling
  - compact Linac + RLA acceleration
  - small "permanent magnet" storage ring-4 GeV
  - TASD detector with SCTL magnet
- **Cost reduced from baseline 25 GeV case**
  - Accelerator system ~30% less
  - Detector also reduced
- **Could be upgraded to 25-50 GeV if needed**
  - could also be upgraded to μμ Collider



Origin of dark energy …