Synergies between Neutrinos and Muon Colliders

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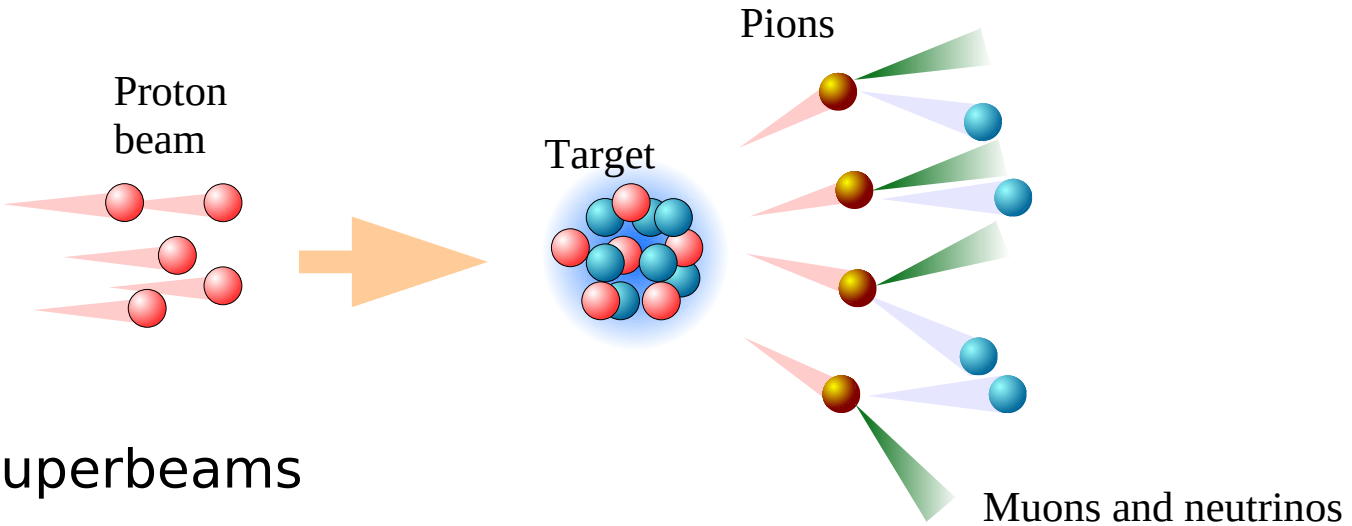
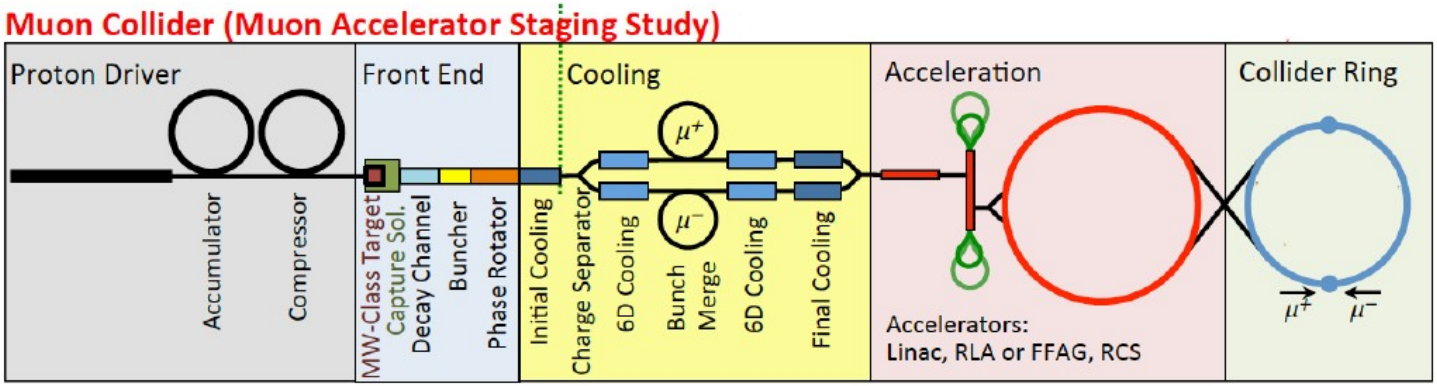
With thanks to
MAP, iMCC, Muon collider forum, nuSTORM coll., NF coll.

Muons and Neutrinos



- Neutrino superbeams
  - P → π → ν + μ
- Muon colliders
  - P → π → ν + μ
- How can we work together?
  - Sharing the fruits of our common R&D
  - Developing the Fermilab proton source as a potential muon source
  - Dedicated neutrino sources using MC technology
- How do you make a muon collider? How does it relate to neutrino sources?

Muon Collider



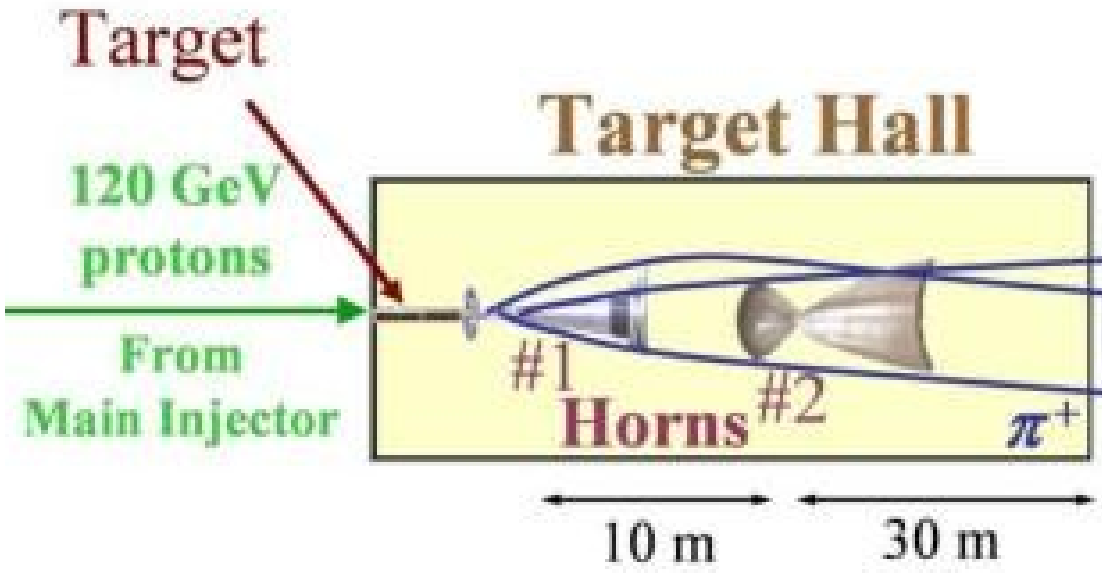
- MW-class proton driver → target
- Pions produced; decay to muons
- Muon capture and cooling
- Acceleration to TeV & Collisions

3

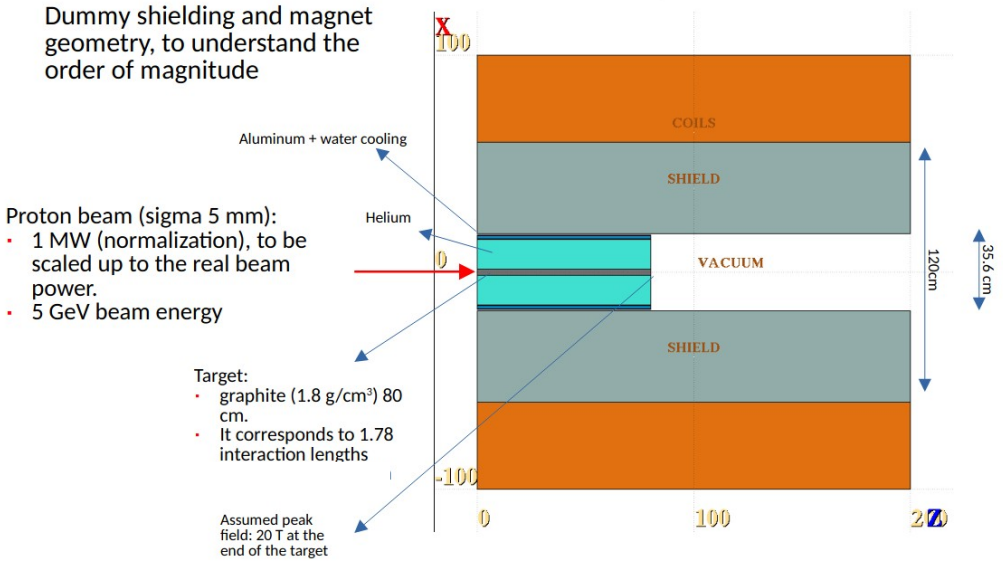
MC Technologies

- What are the Muon collider R&Ds that can support neutrino source?
  - High-power targetry
    - Multi-MW targets required for both applications
  - Rapid acceleration
    - Rapid acceleration technologies developed for MuC can be applied to PIP III
  - RF
    - High voltage RF
    - High efficiency RF source R&D
  - R&D for pulsed proton drivers
    - H- sources
    - H- stripping
    - Accumulation
    - Bunch compression

High Power targetry

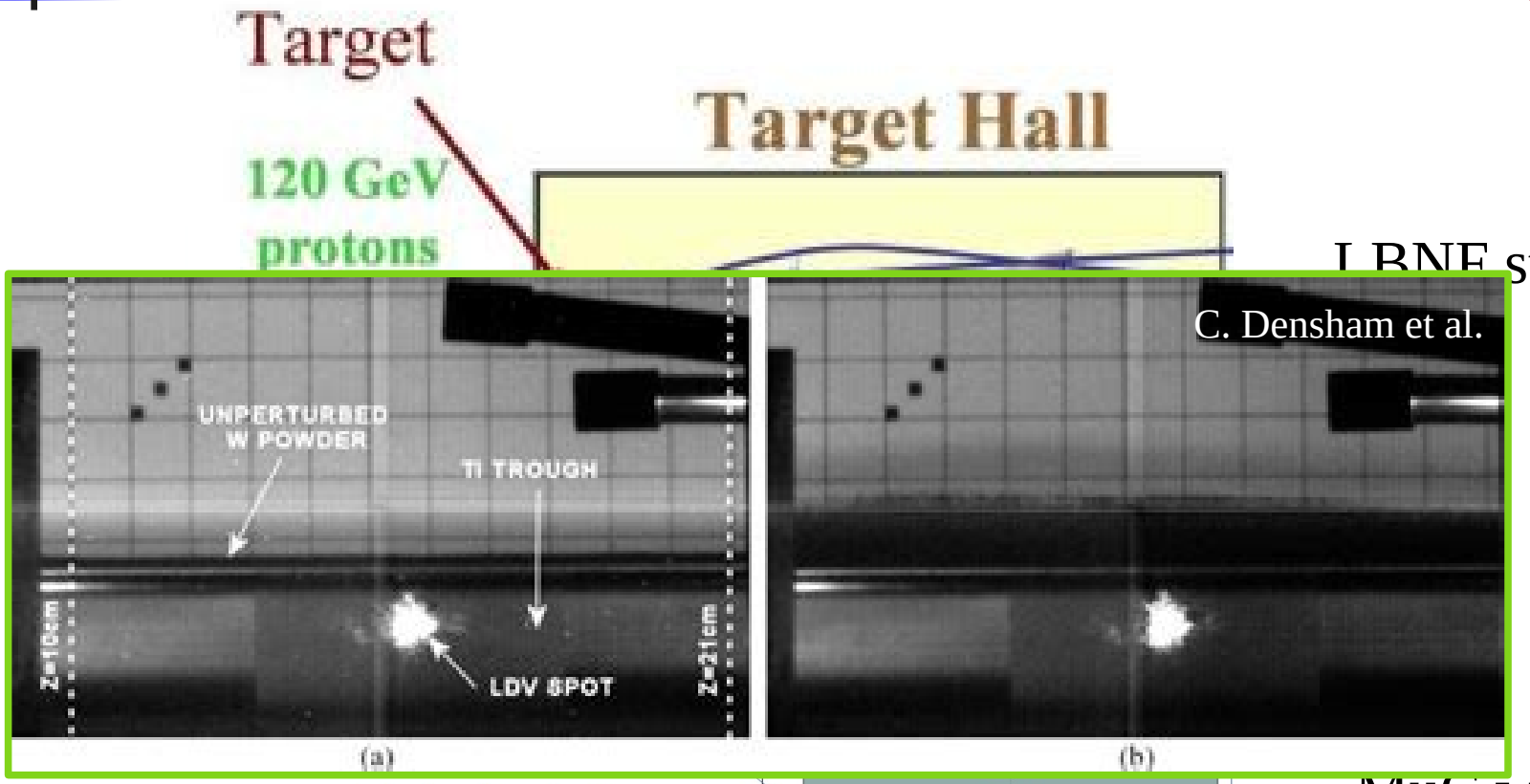


LBNF style target



MuC working Baseline (WIP)

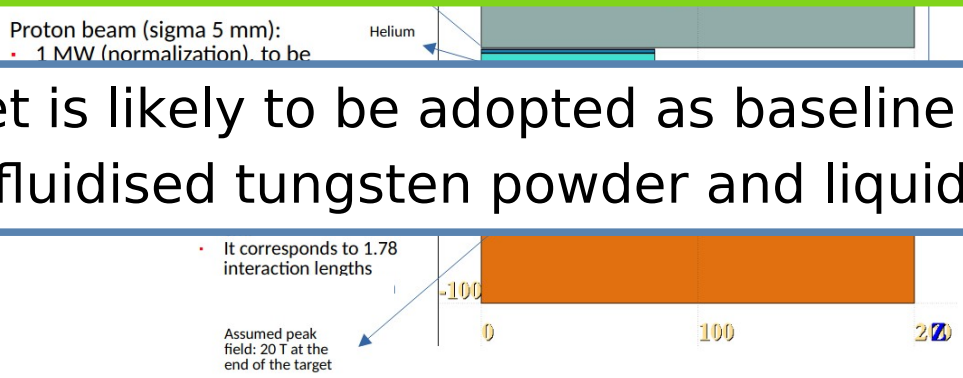
High Power targetry



LBNF style

C. Densham et al.

MuC working



- Carbon target is likely to be adopted as baseline
- Considering fluidised tungsten powder and liquid metal targets

Question

- Can we take the synergy a step further:
  - Can Fermilab proton source be the first step in a muon collider?

Muon collider protons requirements

- Nominal parameters
  - 2 MW proton beam
  - 5 GeV energy
  - 5 Hz rep rate
  - 1-3 ns bunch length

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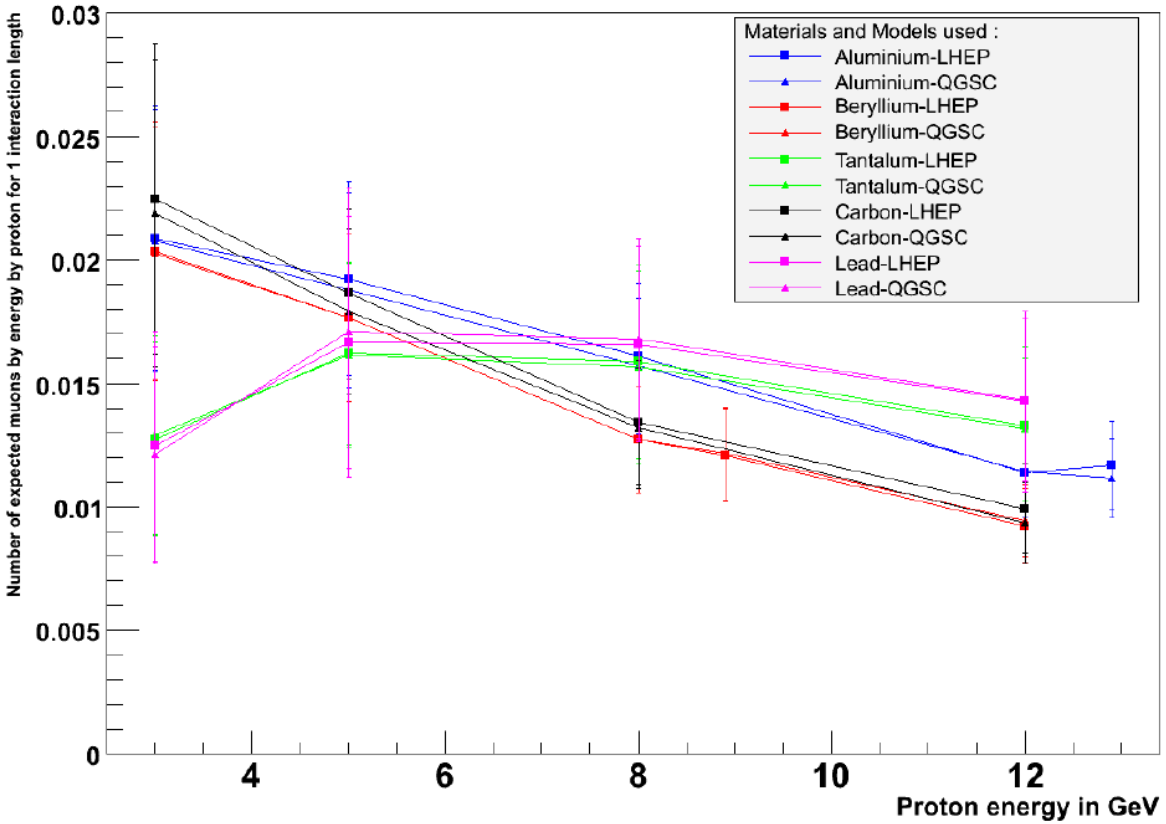

Florian Breton, Clément Le Couedic, F.J.P. Soler, Pion Production for Neutrino Factory – Challenges, NuFact10

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$$L = \frac{N_+ N_- f_0}{2\pi \Sigma_x \Sigma_y}$$

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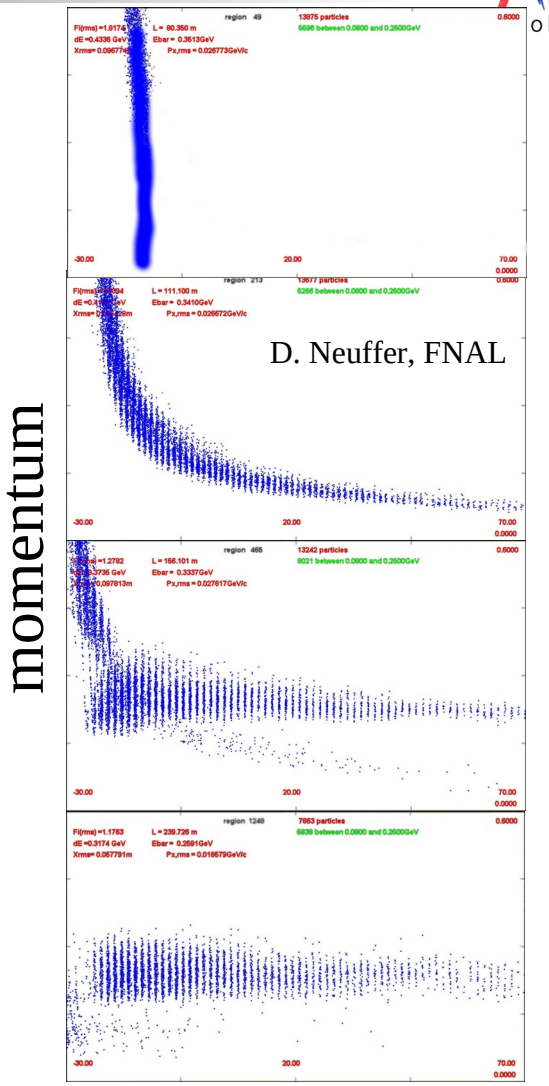
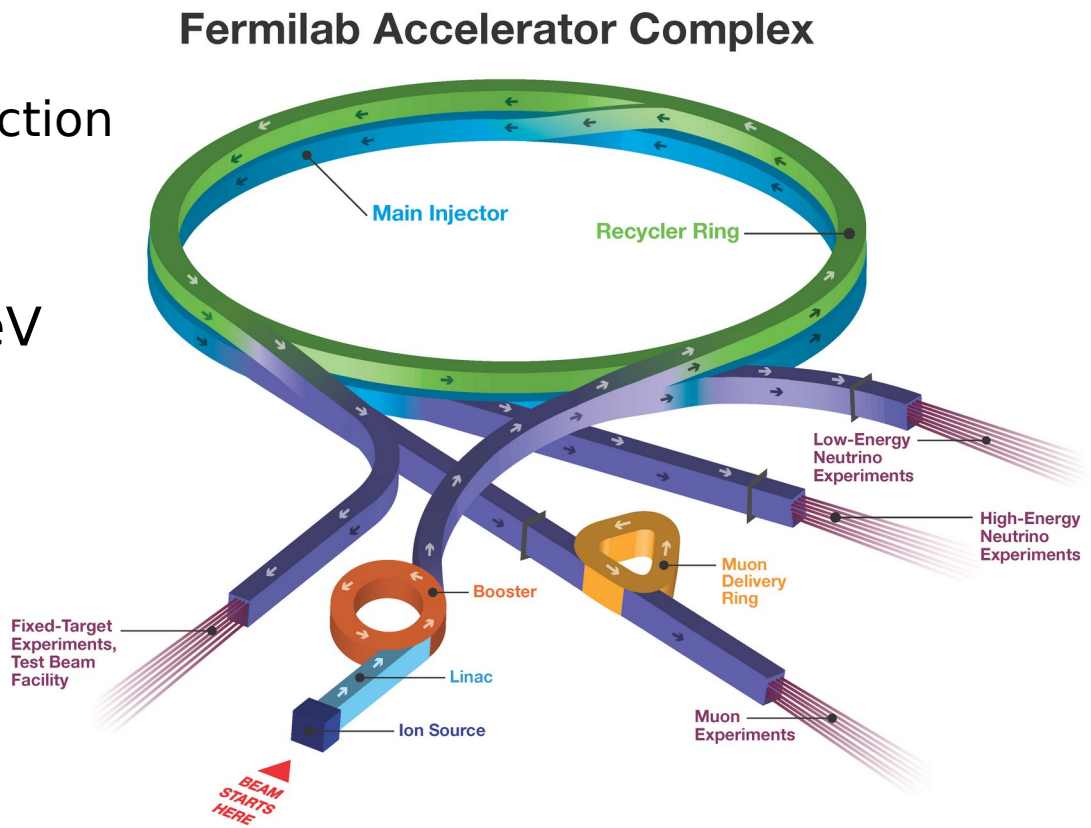


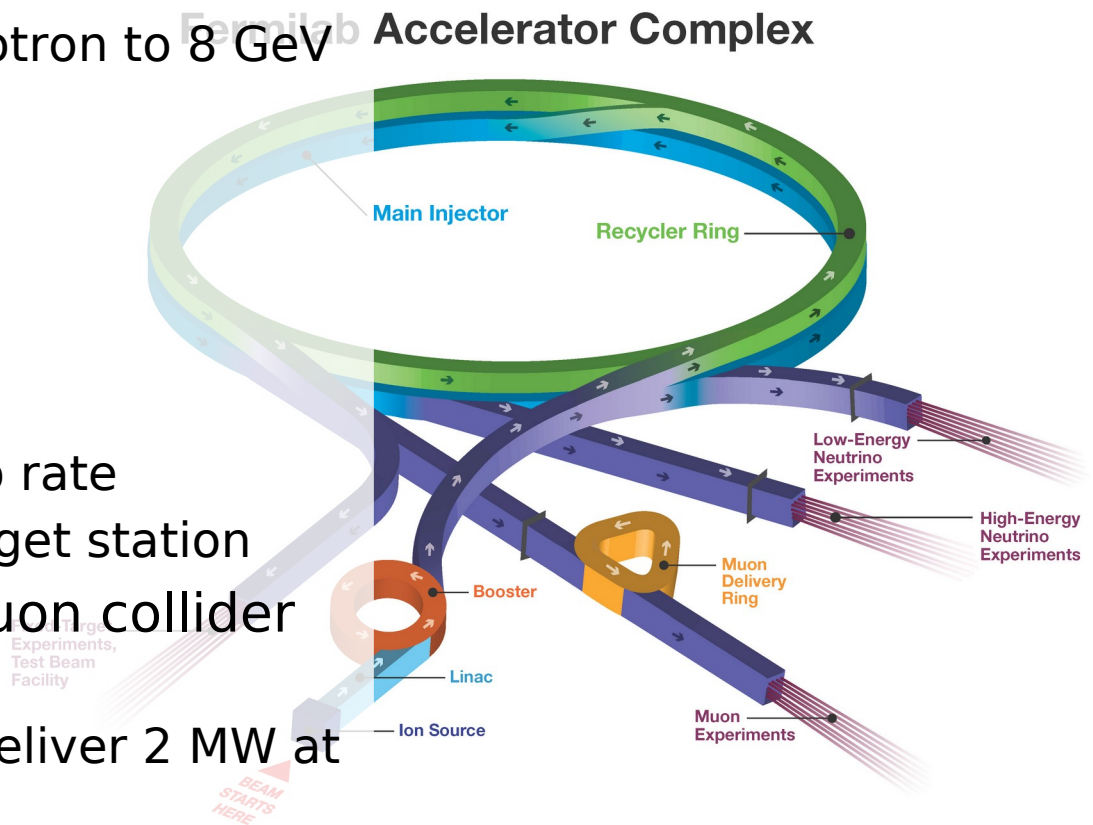
Fermilab Complex

- Linac
  - H- accelerated to 400 MeV
- Booster
  - Charge exchange injection
  - Acceleration to 8 GeV
  - 15 Hz rep rate
- Main Injector → 120 GeV
- (Tevatron → 980 GeV)

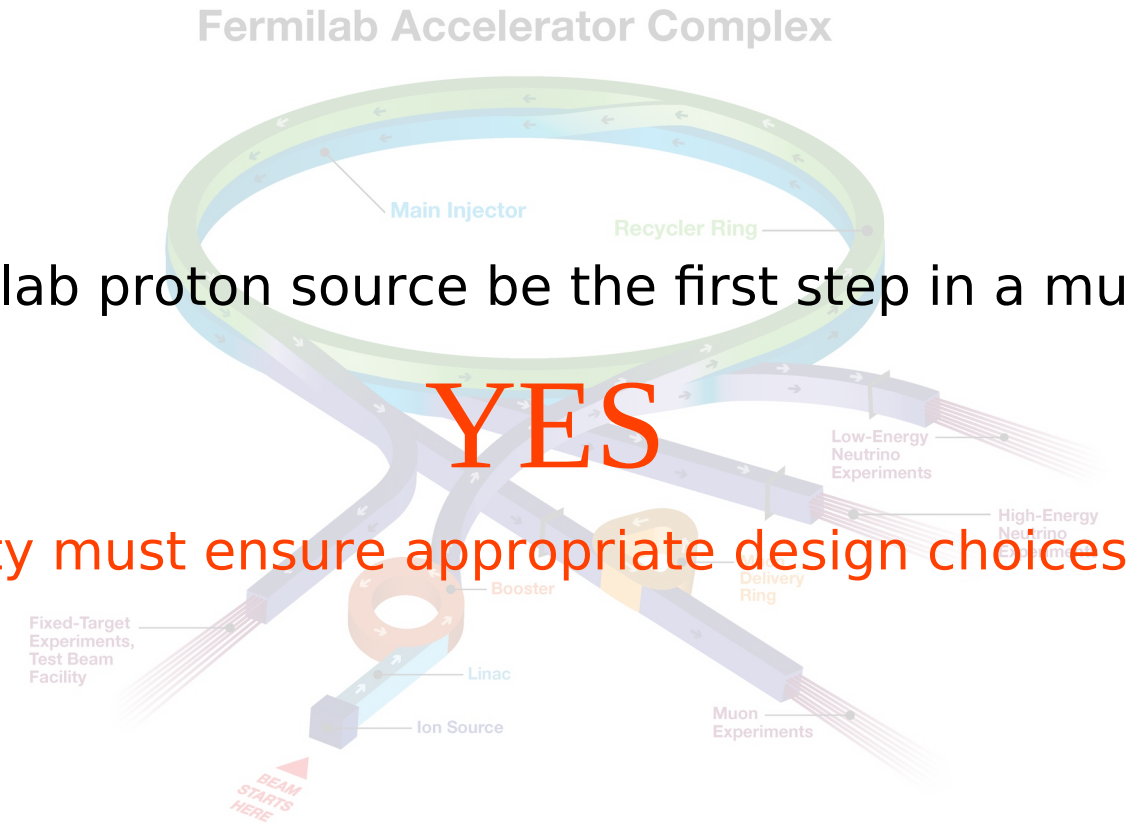


PIP-III

- Either
  - Linac to 2 GeV
  - Rapid Cycling Synchrotron to 8 GeV
- Or
  - Linac to 8 GeV
  - Accumulator ring
- Beam → low energy
- Beam → main injector
  - 120 GeV @ higher rep rate
  - 2.4 MW horn-style target station
- Excellent basis as a muon collider source
  - Post acceleration to deliver 2 MW at ~ O(10) GeV
  - Compressor ring to deliver short bunch



Answer



- Can Fermilab proton source be the first step in a muon collider?

YES

Community must ensure appropriate design choices

Needs for precision in neutrinos

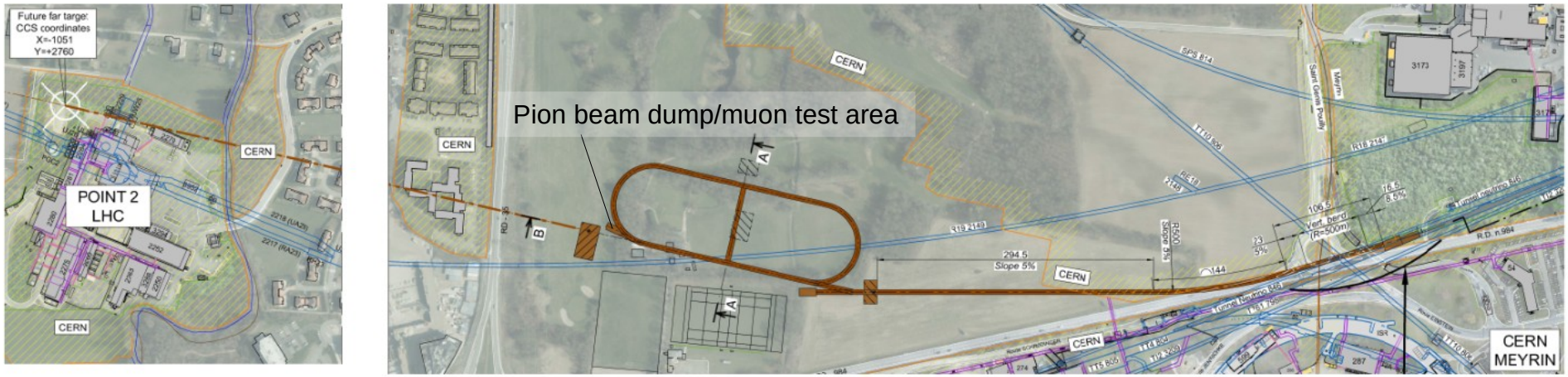
- Neutrino oscillation measurements are limited by two main systematic uncertainties
  - Uncertainty in the number and flavour composition of the beam
  - Uncertainty in the neutrino interactions with matter → neutrino energy

NF Exec summary:
Our current **modeling of neutrino-nucleus interactions is insufficient for the precision required** for the future oscillation program. Improving it will require cooperation among experimentalists making new measurements, nuclear and particle theorists developing new models, and computing professionals enabling the preservation and interoperability of the data, theory, and software tools.

Delivering Precision for the Neutrino Sector

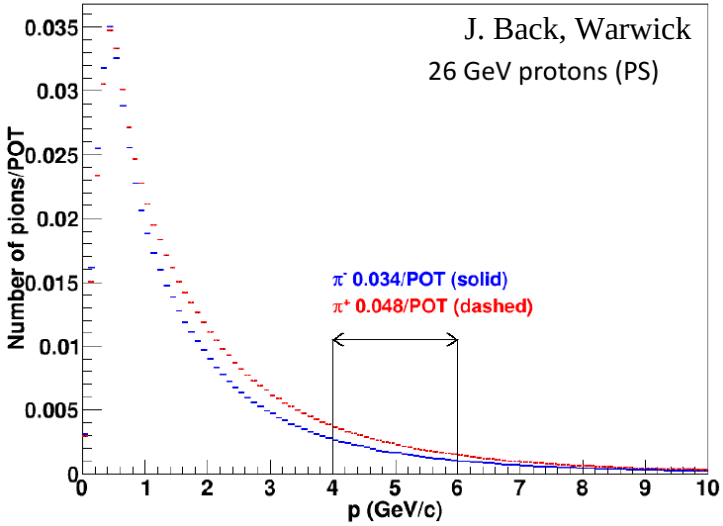
- Muon beams can deliver
  - Precise measurement of neutrino interaction cross sections
    - nuSTORM
  - A beautifully well-characterised neutrino beam for oscillations
    - Neutrino factory
- Muon beams can deal with the two major uncertainties in neutrino physics

nuSTORM facility

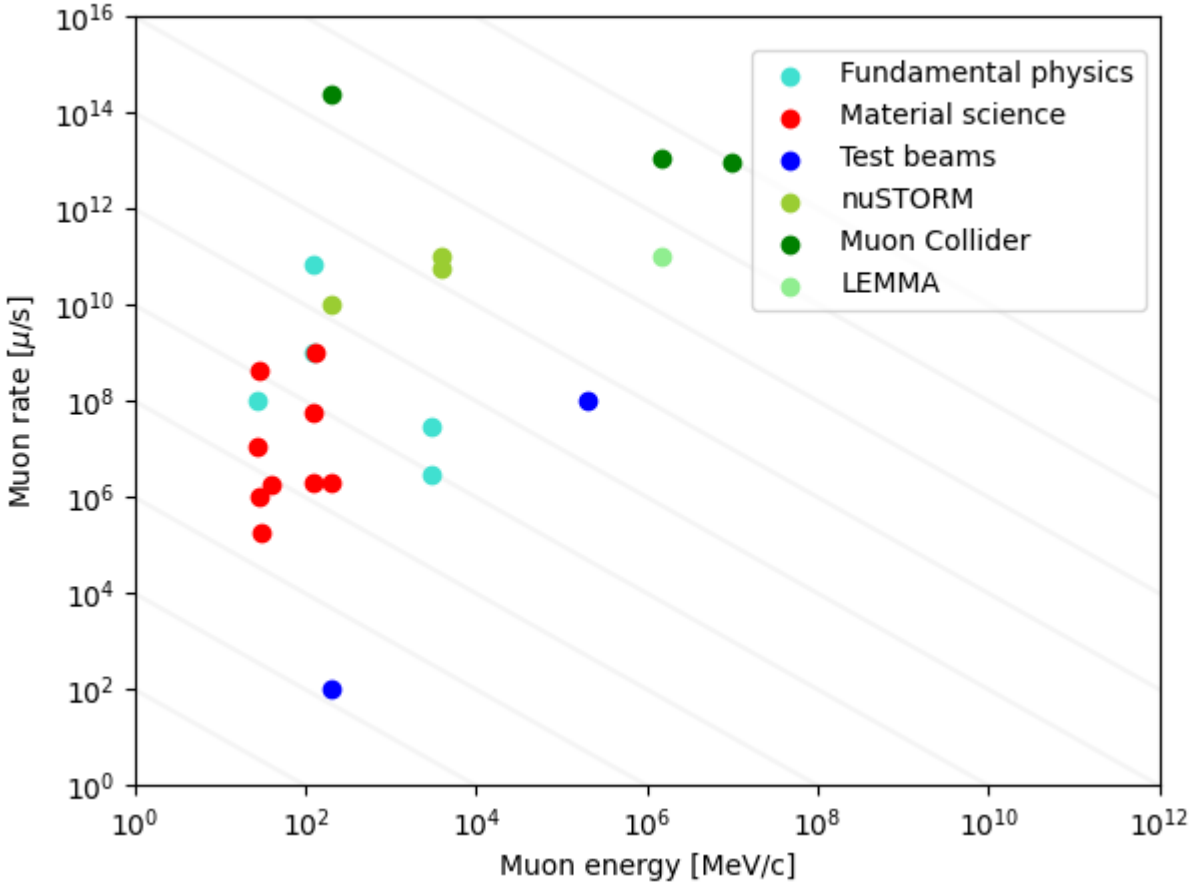


nuSTORM at CERN – Feasibility Study, Ahdida et al, CERN-PBC-REPORT-2019-003, 2020

- Main features
  - ~250 kW target station
  - Pion transport line
  - Stochastic muon capture into storage ring
  - 1-6 GeV stored muons
- Would be highest rate/energy muon beam line
- Could be built at CERN



Survey of Muon Beamlines



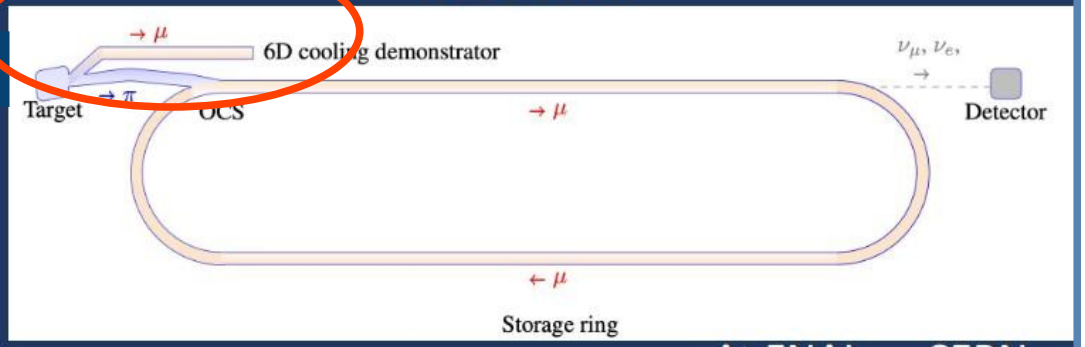
6D Cooling Demo

International MUON Collider Collaboration

Stored Muon Beams

- High flux
- Very well known flavor+energy
- Important demonstration on the road to a muon collider
- While also making precise (1%) ν+A measurements and other physics

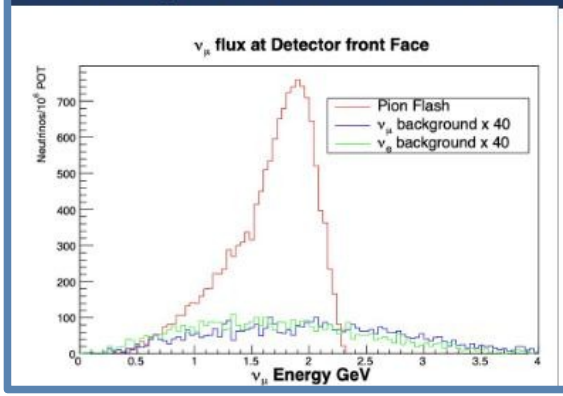
nuSTORM

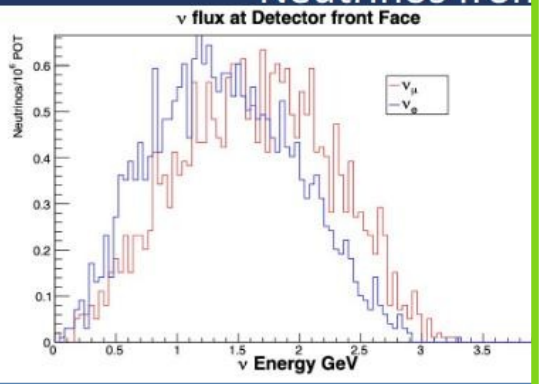


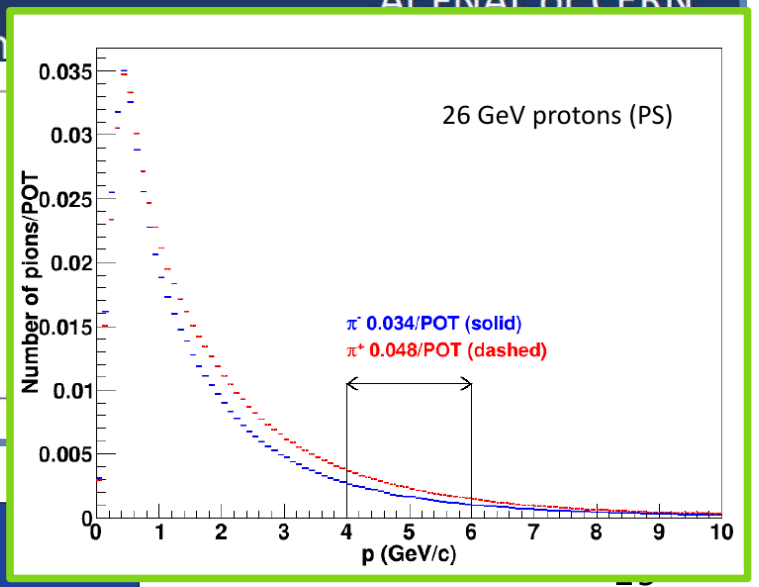
At FNAL or CERN

5 GeV "pion flash" neutrinos

Neutrinos fron







Joshua Klein, Wednesday pm

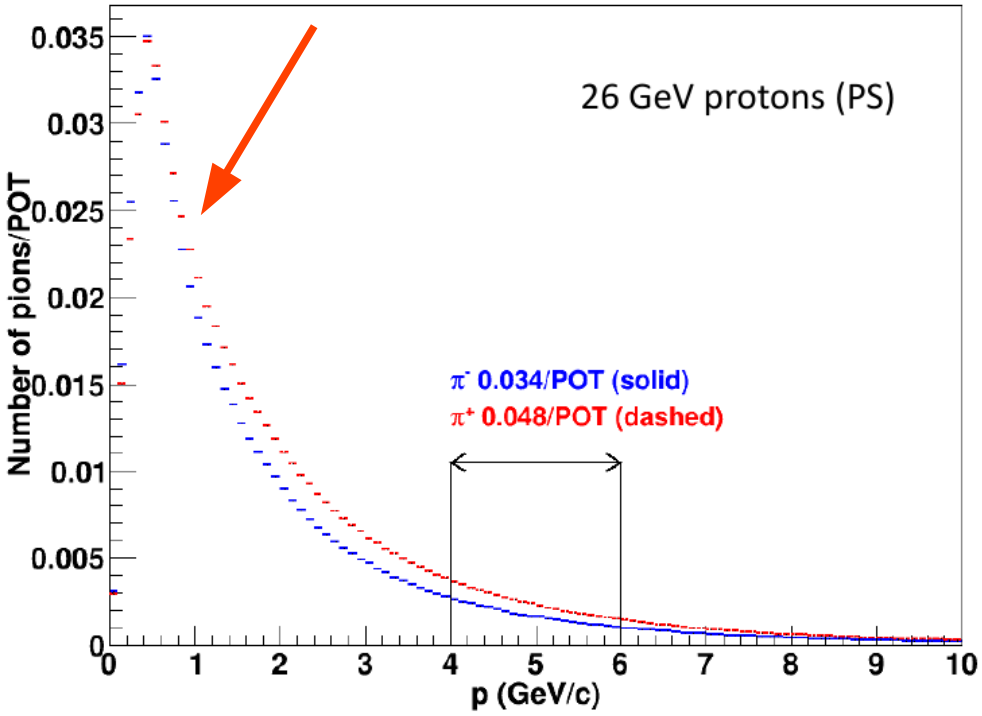
Science & Technology Facilities Council
ISIS Neutron and Muon

NuSTORM in context of MuC

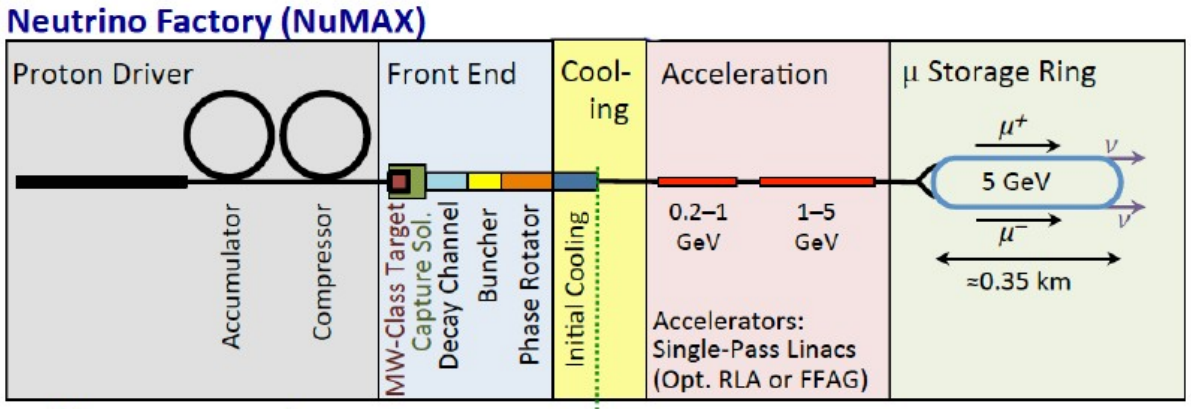
- Accelerator key systems/technology issues:
  - Possibility to test muon collider target concepts
  - 6D ionization cooling Demonstrator
    - High-field solenoids, compact lattice
    - High-gradient RF in magnetic field
  - FFA storage ring can test concepts for rapid acceleration in MuC
  - Beam protection and pion beam handling
- In a facility that delivers neutrino physics
- Could be a European contribution to intnl neutrino programme
  - **Need must be clearly highlighted by the community**

Neutrino Factory

- Almost perfect knowledge of neutrino beam from stored muons
- Can we use this for direct oscillation measurements?
  - **YES**
- Neutrino Factory
  - Longer baseline than nuSTORM → need more statistics
  - Use lower energy muons and accelerate them

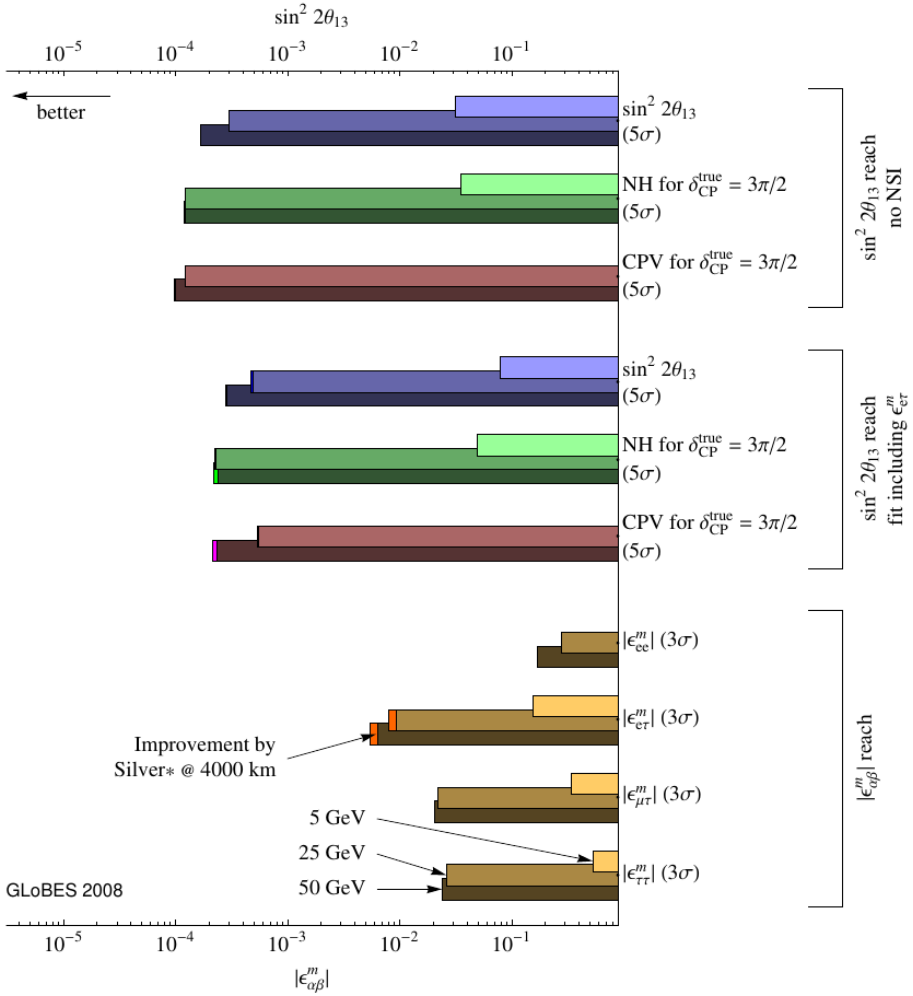


Neutrino Factory



Neutrino Factory

- Improved sensitivities over DUNE phase 2
- Excellent resolution for NSI
  - Source includes muon and electron (anti)neutrinos
- 5 GeV muon option (light bars) requires
  - Proton complex mods, e.g. bunch compressor
  - Magnetic focusing target
  - Muon acceleration to 5 GeV and storage ring
  - Magnetisation of DUNE detectors



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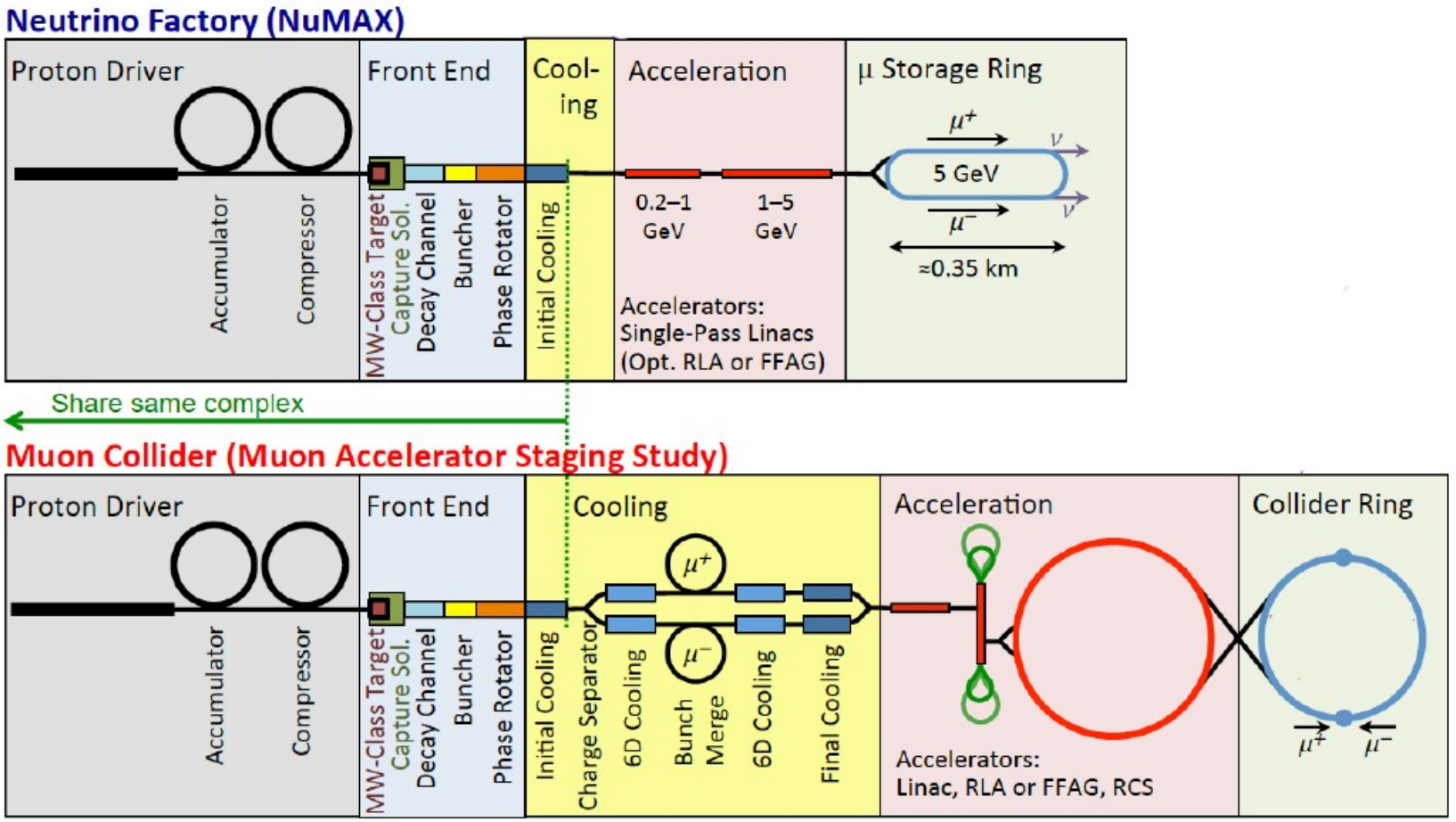

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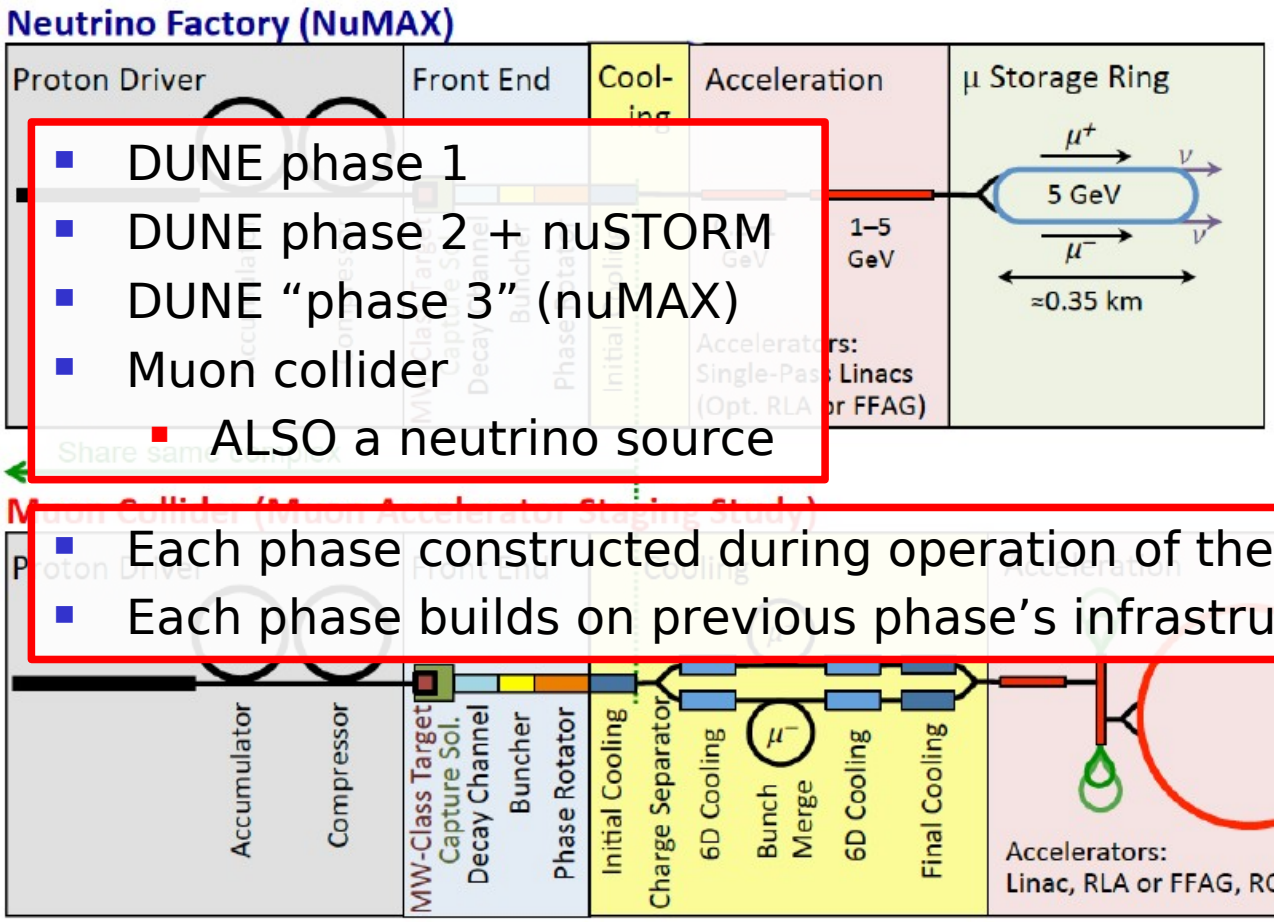

- DUNE phase 1
- DUNE phase 2 + nuSTORM
- DUNE "phase 3" (nuMAX)
- Muon collider
  - ALSO a neutrino source

- Each phase constructed during operation of the previous phase
- Each phase builds on previous phase's infrastructure

White Papers

- The physics case for a neutino factory
  - https://arxiv.org/abs/2203.08094
- Neutrinos from stored muons (nuSTORM)
  - https://arxiv.org/abs/2203.07545
- Many muon collider white papers, summarised by the Muon collider forum
  - https://www.snowmass21.org/energy/muon_forum

Key messages

- The LBNF proton source is compatible with a muon collider
- Many synergies between PIP and MuC R&D
- Muon-based neutrinos (e.g. nuSTORM) enhance DUNE
- There exists at least one strategy that can see
  - continuous improvement of the Fermilab neutrino programme
  - leading to a muon collider
  - minimal interruption of the physics programme

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