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Muon Synergies:

Muon Colliders, Neutrino Factories, and Rare Processes

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Fermilab

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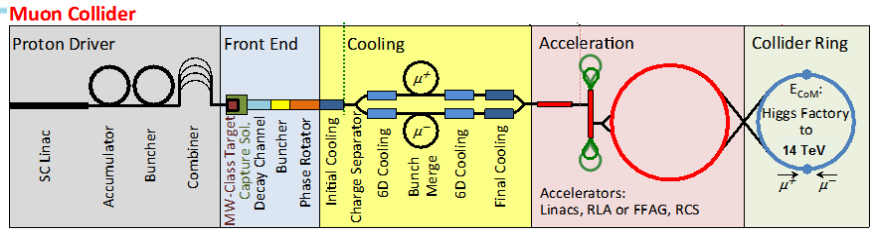
Synergies (HEP → Precision frontier)

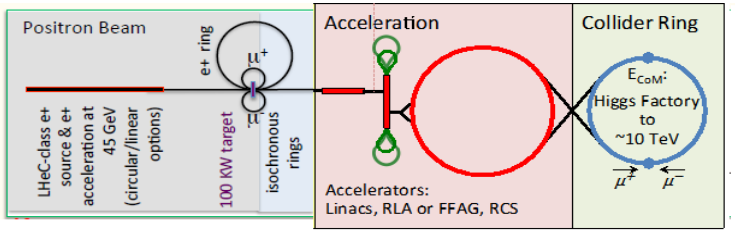
- **High-Energy Frontier is a primary focus in HEP**
  - **Multi TeV μμ Collider ?**
- **Challenging problems → interesting solutions**

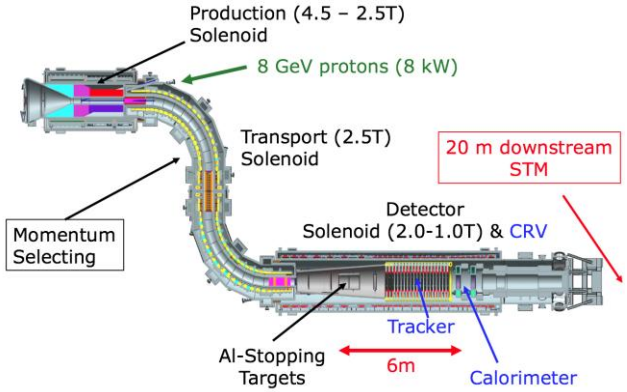
- **graduate students, associates and scientists**

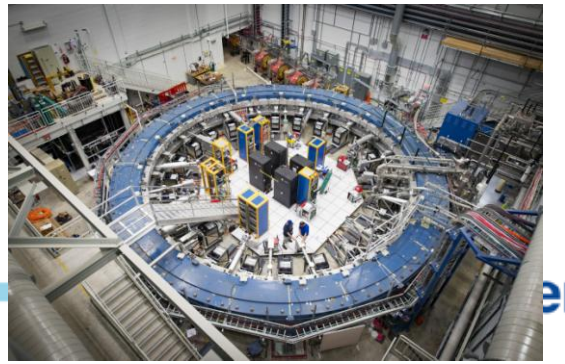
- **→Intensity Frontier**
- **Neutrino beams**

- **Fundamental particle physics**
- **Lepton conversion**
- **Rare decays**
- **Precision measurements**









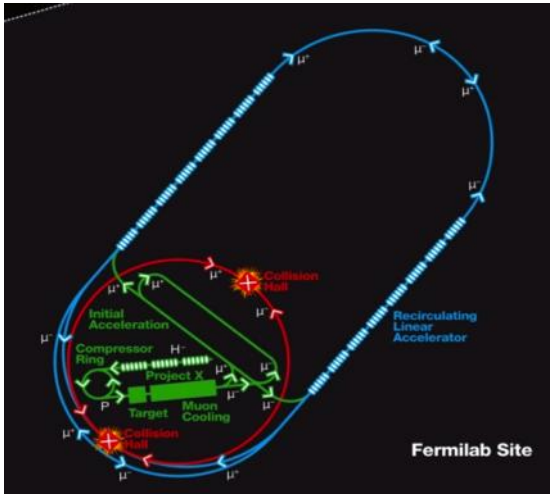
Some past synergies

- **Muon Collider**
  - **Some muon Collider R&D since 1994 (BNL, Fermilab)**
  - **~2000 – Neutrino Factory R&D**
- Fermilab (~2006: Energy Frontier → Intensity frontier)
  - Neutrinos

- **MECO → Mu2e**
  - Built upon concepts developed for Muon collider
  - Fermilab-based LOI generated through MC/NF
- **g-2** at Fermilab
  - Key discussions on transporting experiment to Fermilab at NuFACT 2008 Valencia – L. Roberts & D. Hertzog

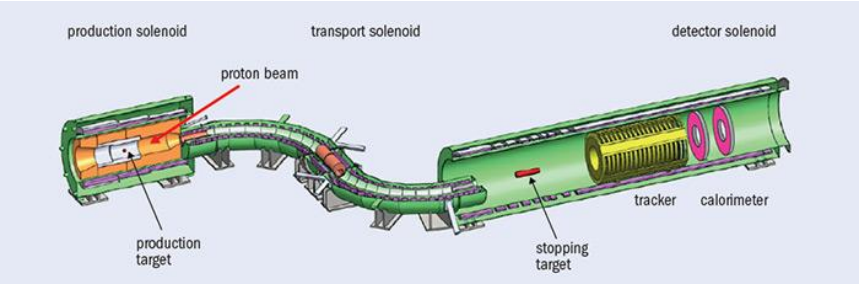
Collider / rare decay requirements:

- **Muon Collider**



- **Needs > ~10^{20}cold μ/year**
- **Proton source + high intensity target**
- **Use same design tools:**

- **Mu2e**



- **Needs > ~10^{18} stopped μ/year**

  For > ~10^{-17} sensitivity

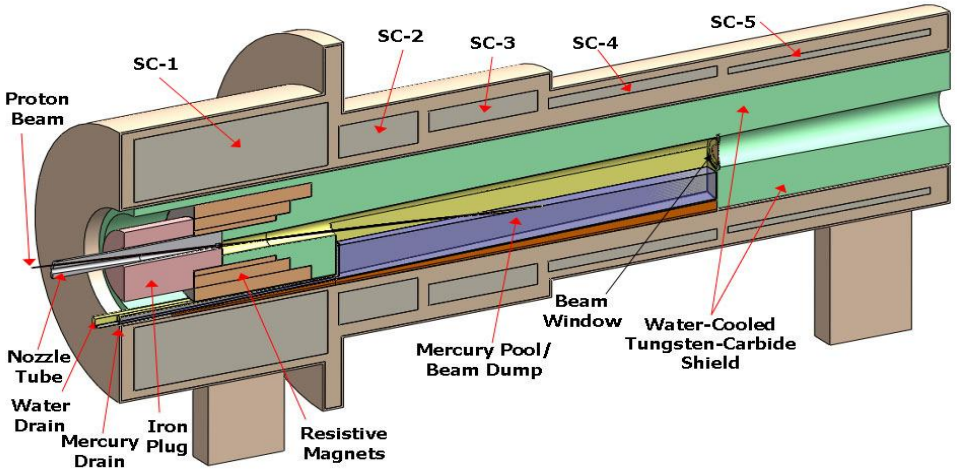
- **Initial proton source is based on muon collider proton source studies**

G4Beamline – developed for muon cooling

MARS –enhanced by MCNF studies

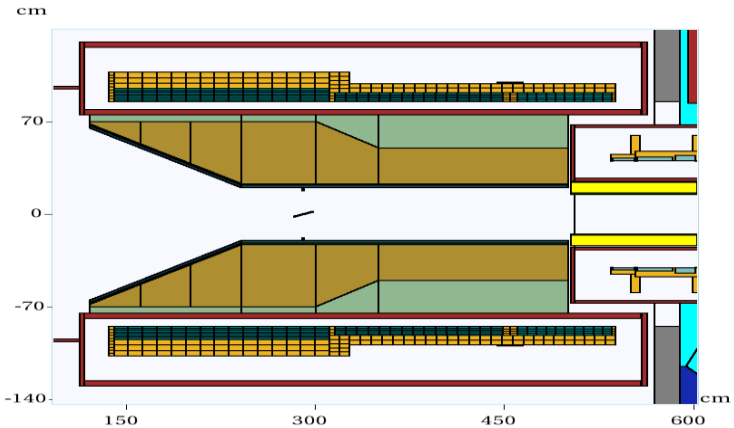
Production target and transport

- **Muon collider / neutrino factory**



- **Proton beam on production target**
- **~20T → 2 T solenoid**
  - **Capture π→ μ ~200 MeV**

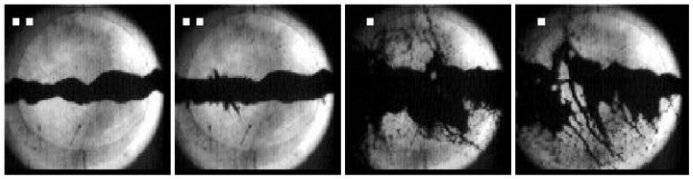
- **Mu2e has production target within high field solenoid**



- **~5T → 2.5 T → 1T**
- Capture π⇨μ ~5 MeV

Target studies

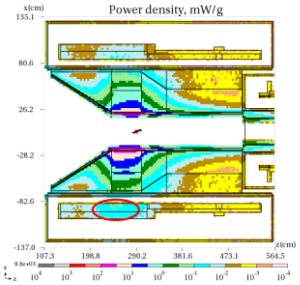
- **Up to 4 MW on target**
  - **Hg Jet target**



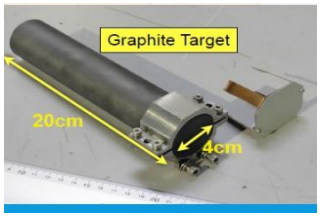
    - **Also C target and other possibilities**

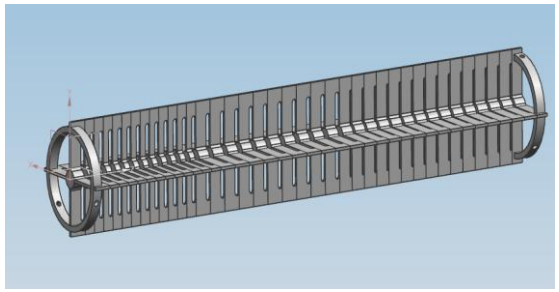
Synergy with ν, ν

  - **Inside superconducting magnet**
    - **Radiation, shielding studies**

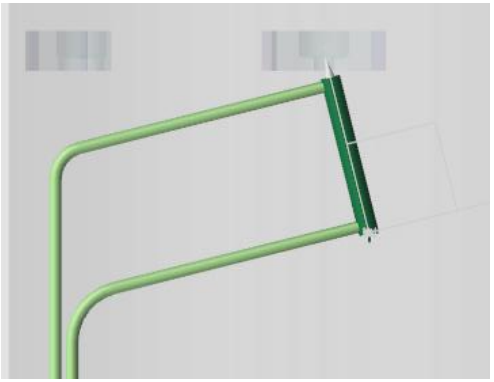


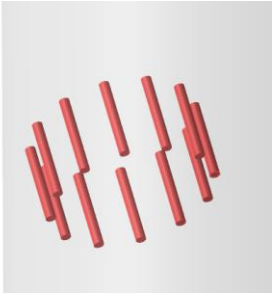
- **0.01→1MW on target**





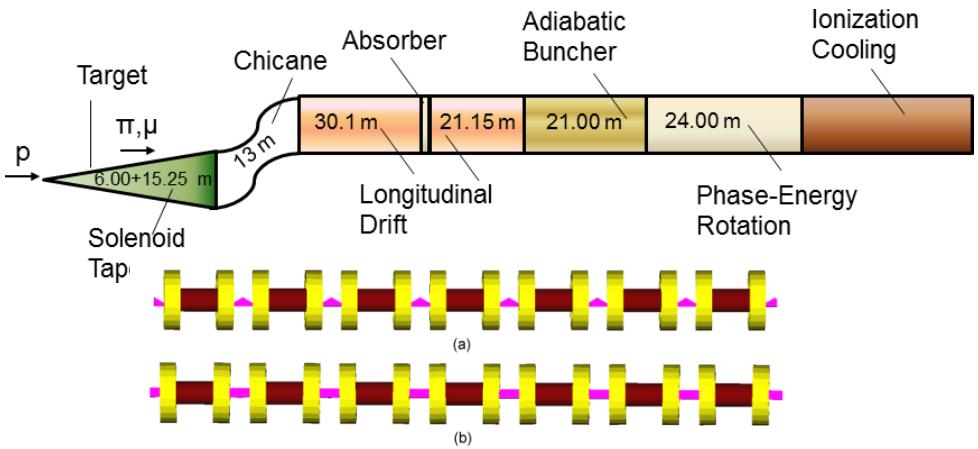
- **MuSIC, mu2e, mu2e-II**

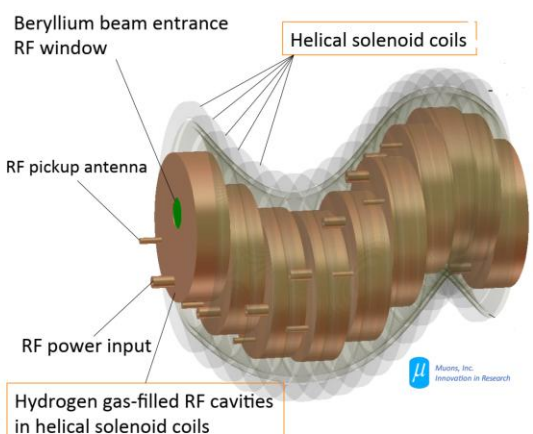




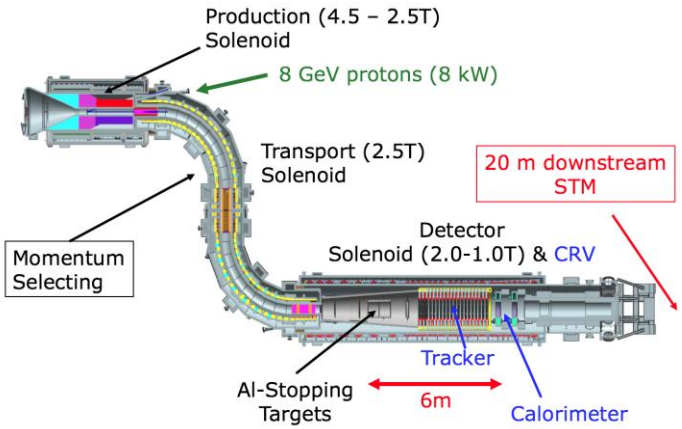
Solenoid transport

- **Initial transport and cooling is mostly solenoids**
  - **~200 MeV/c**
  - **Focuses both μ^+ and μ^-**
  - **Focuses radially**

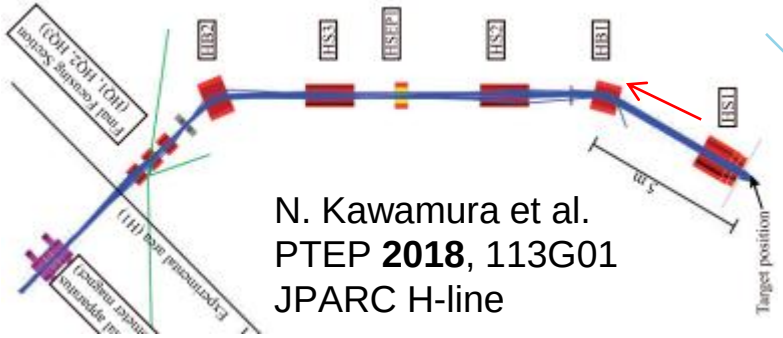




- **Used in mu2e**



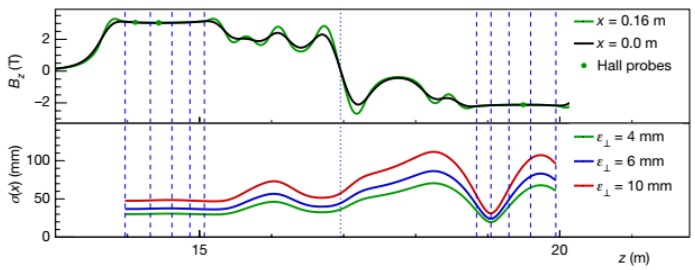
- **In future higher-acceptance low-energy beam lines**

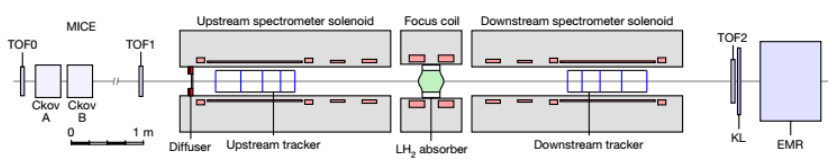


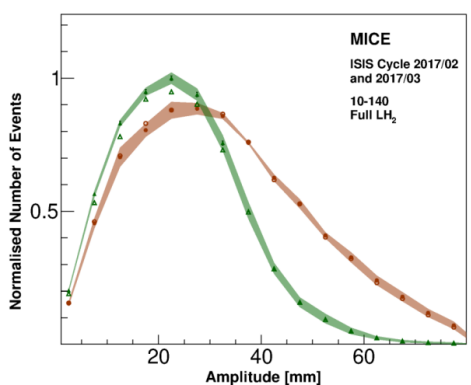
N. Kawamura et al.
PTEP **2018**, 113G01
JPARC H-line

Ionization Cooling

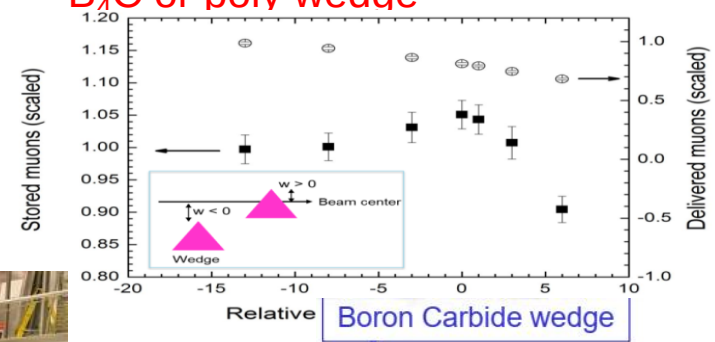
- **Needed for high-luminosity muon collider**
- **First demonstration of muon ionization cooling:** **Nature 57, p. 53 (2020)**







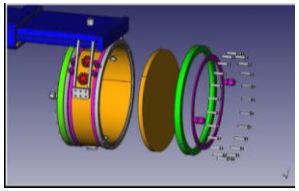
- **Could be used to improve beam for low-energy muon and proton beams**
- **First use of muon cooling to improve intensity**
  - (g-2 exp, D. Stratakis et al., 2019- LDRD)
    - Increases useful μ's by 8%, reduces background by ~30%
    - B_4C or poly wedge



Boron Carbide wedge

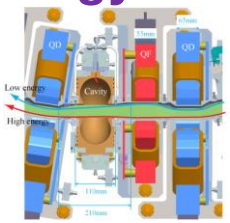
Need fast Acceleration for μ, π

- **RF in magnetic fields**
  - **>40 MV/m operation in up to 5 T B-field**
  - **For cooling**



- **Fast-Ramping magnets**
  - **20T/s HTS record**
    - **Piekarz et al. NIM A 943, 162490 (2019)**
  - **Need 200T/s, ±2→ ±4T**

- **FFAG research**
  - **Non ramping magnet**
    - **Large energy change**
  - **EMMA**

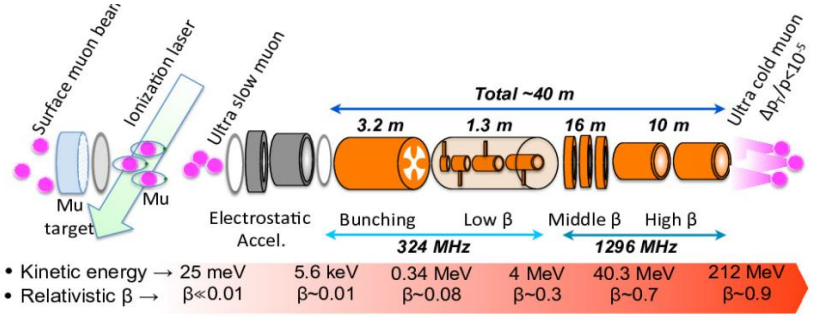


  - **vertical FFAG**

- **First rf acceleration of μ's**

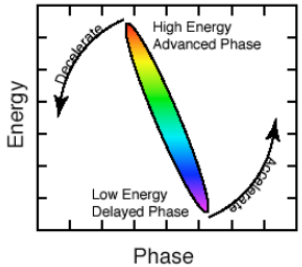
JPARC – MUSE rfq (5→ 89keV)

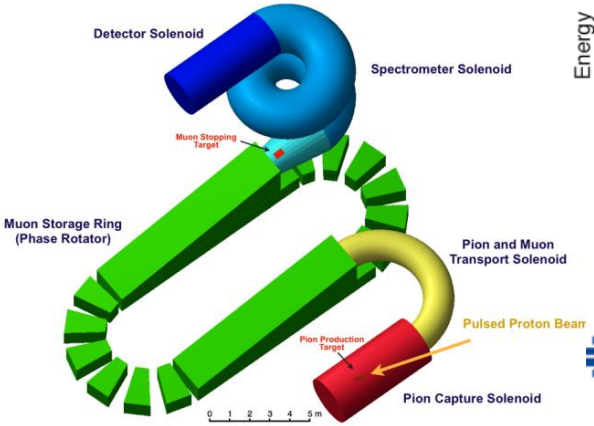
For g-2 and EDM expt. E-34



PRISM-PRIME experiment

Use rf/induction linac in for ϕ-E rotation

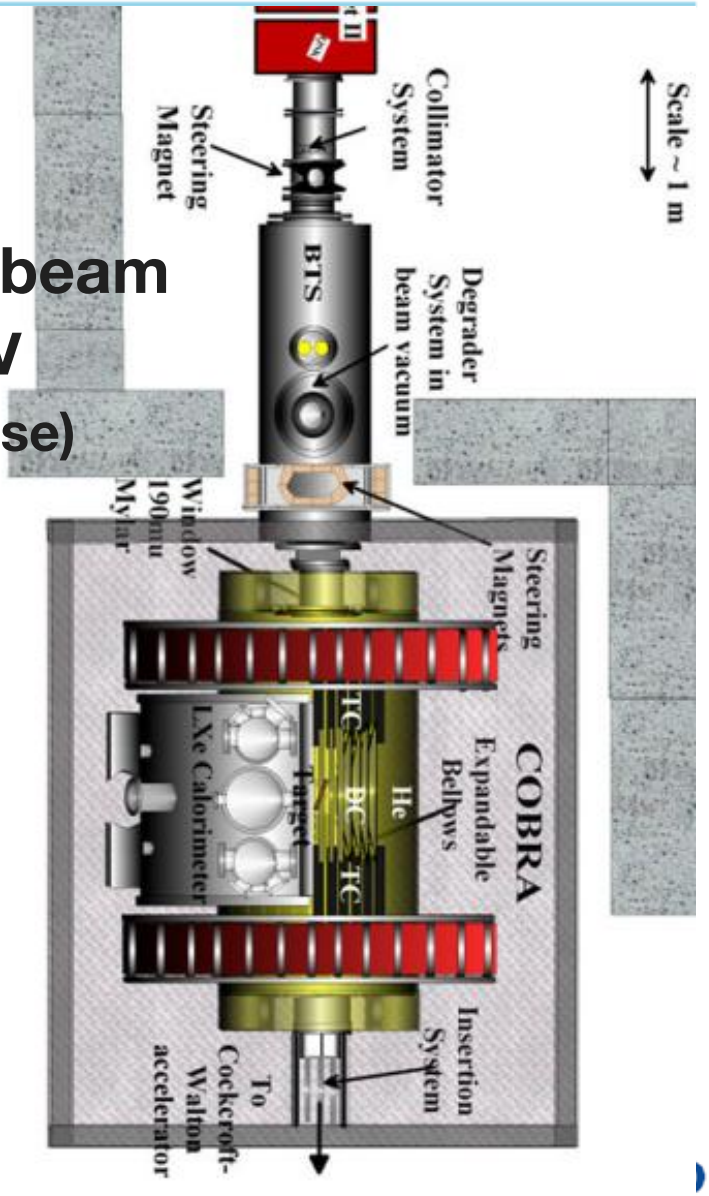




Fermilab

Example of acceleration to improve rare processes

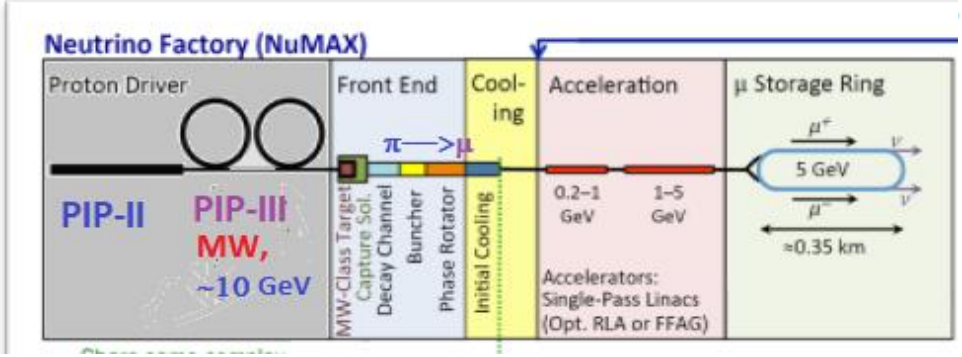
- $\mu \rightarrow e + \gamma$
- Recent best experiment **COBRA**
- **Uses 30 MeV/c (4.1 MeV) μ surface-beam**
  - **Decelerated by energy loss to 2MeV**
    - **(large losses, energy spread increase)**



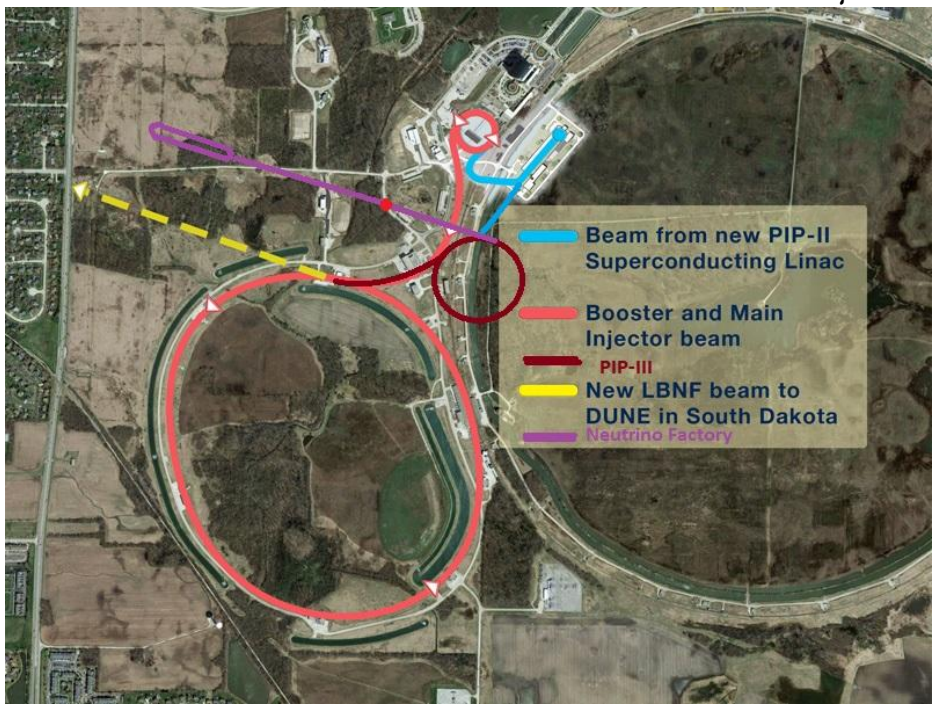
- **Alternative (from mu2e)**
  - **Start with higher-intensity μ-beam**
    - **50 MeV/c ~5 MeV**
  - **Decelerate with rf (or induction ?)**
    - **Use ϕ/E rotation or wedge cooling**

Neutrino Factory

- Proton bunches on target
  - $\pi \rightarrow \mu$ bunches
  - ϕ-E rotation and cooling
- Accelerate to X GeV and store
- ν-beams from μ decay provide better quality beam
  - Adds well-defined ν_e beam
- Long baseline to DUNE detector
- Other neutrino beam ideas?

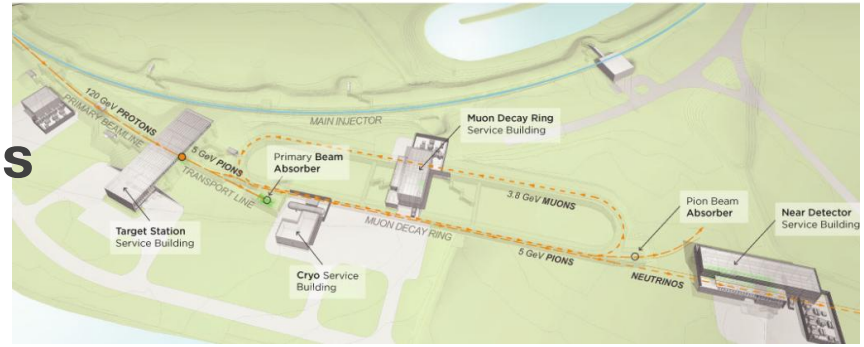


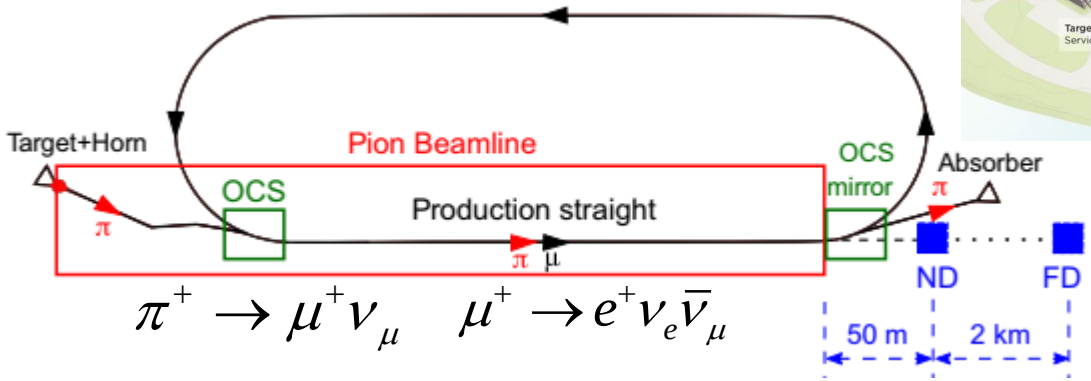
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \qquad \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$



Neutrino beams from Muons

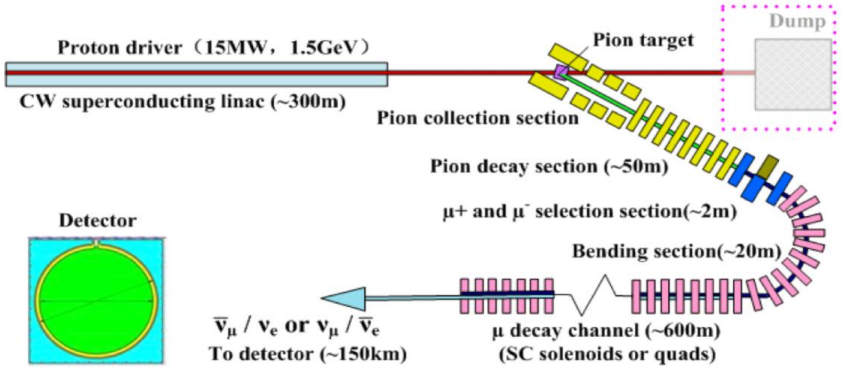
- **"nuSTORM"**
  - **Neutrinos from stored muons**





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

- **Linac →Muon decay line**
  - GeV p →~ 100 MeV/c π → μ
    - Low-E ν →



J. Cao et al. Phys. Rev. ST Accel. Beams 17, 090101 (2014)

European based Collaboration

- An international collaboration on Muon Collider
  - MUST (MUon STudy)
- 3 → 10→ 14 TeV Collider
- μμ Collider R&D included in European Strategy Document

Parameter	Symbol	unit			
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Average field	$\langle B \rangle$	T	7	10.5	10.5
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ϵ_L	MeVm	7.5	7.5	7.5
Transverse emittance	ϵ	μm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP betafunction	β	mm	5	1.5	1.07
IP beam size	σ	μm	3	0.9	0.63

Table 1: Tentative target parameters for a muon collider at different energies.

Rare Processes – Intense low-E muons

- **Current Fermilab Program –muon campus**
  - g-2 experiment, mu2e
- **Future Fermilab Program**
  - 1.6 MW PIP-II 0.8 GeV p – can provide π, μ, n, ν
  - Particle physics – g-2, mu2e-II ($Z+\mu \rightarrow Z+e$), μEDM,
  - **$\mu \rightarrow e + \gamma$, $\mu \rightarrow e + e^+ + e^-$**
  - **Rare** π decays
  - **Synergies: Nuclear physics (muonic atoms, …), μSR, μ radiology**
- Possible next experiment: **$\mu \rightarrow e + \gamma$**

Thank you for your attention