Fermilab “Site Filler”: Muon Collider?

David Neuffer

P. Bhat, A. Bross, J. Eldred, S. Jindariani, N. Mokhov, S. Posen, V. Shiltsev, D. Stratakis, K. Yonehara

Outline

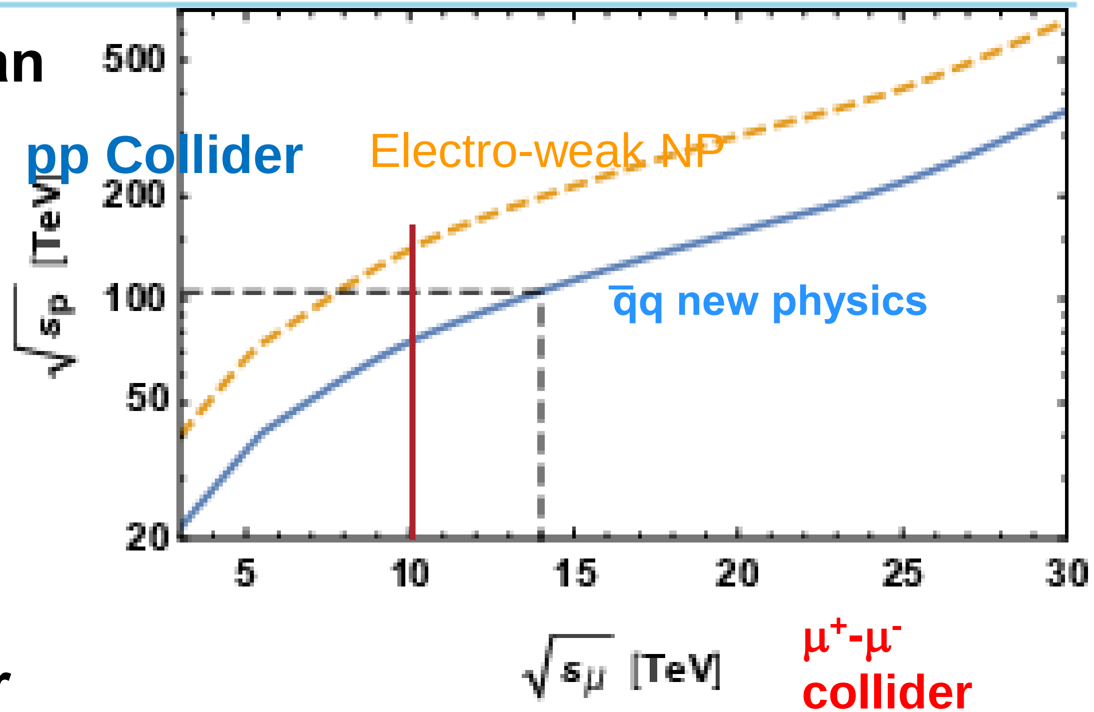
- **Fermilab –**
  - Site filler - Muon Collider ?
    - possible future high-energy facility on Fermilab site
- **Motivation**
  - "Energy Frontier"
- **Muon Collider Components**
  - Muon source
  - Accelerator
    - Fast-cycling
  - Collider Ring
- **Parameters**
  - Up to ~10 TeV Muon collider "site-filler"

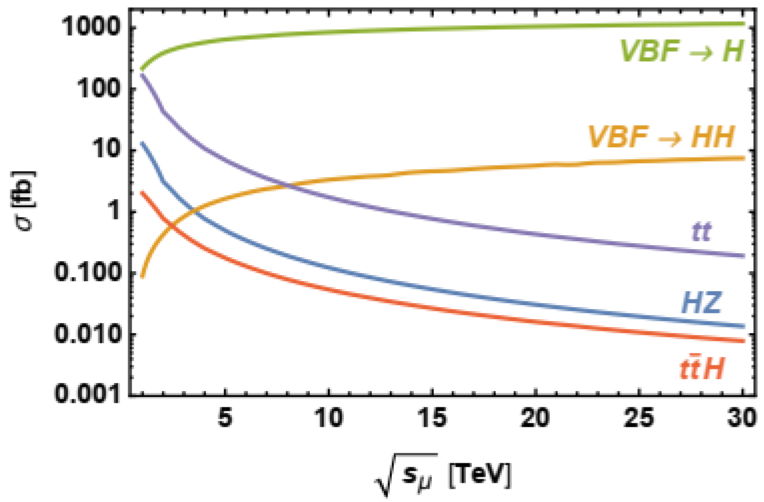
Energy Frontier

- 10TeV μ^+-μ^- collider has an energy reach of 100 TeV pp collider

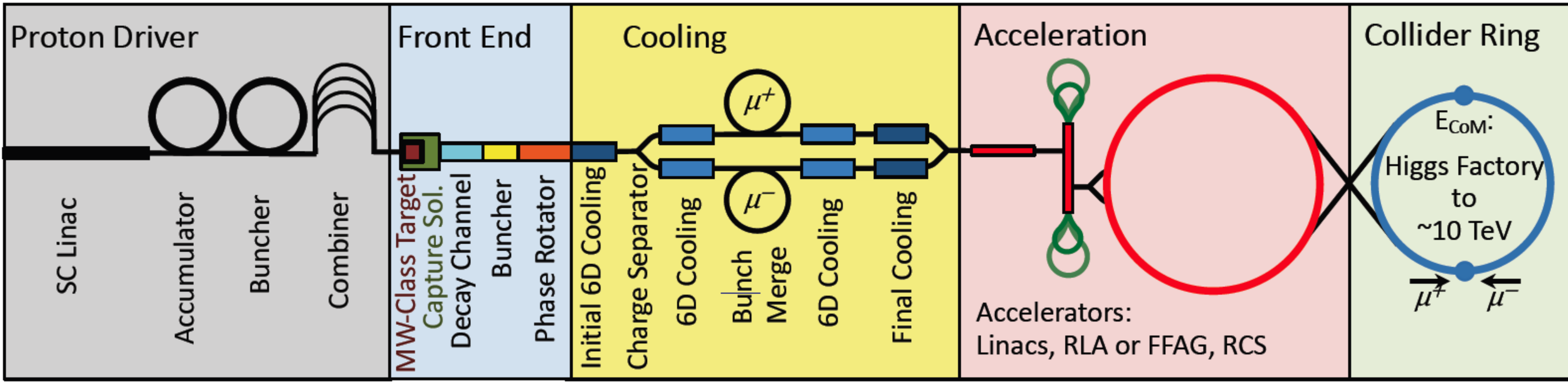
- Need High- Luminosity
  - ($\bar{q}q$ events $\sigma \sim 1/s$)
  - Vector boson fusion
    - $\sigma \sim \ln(s)$

- Goal is ~ 2 attobarn^{-1}/year
  - $L = 2\ 10^{35}\ cm^{-2}s^{-1}\ 10^{7}$ s/year





Muon Collider - MAP Concept



Parameter	Symbol	unit			
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	10^{34}cm^{-2}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.

Site filler Accelerator

➢**Largest**

Radius is ~2.65 km

- **~16.5 km Circumference**
  - **~2/3 LHC**

~RCS accelerator

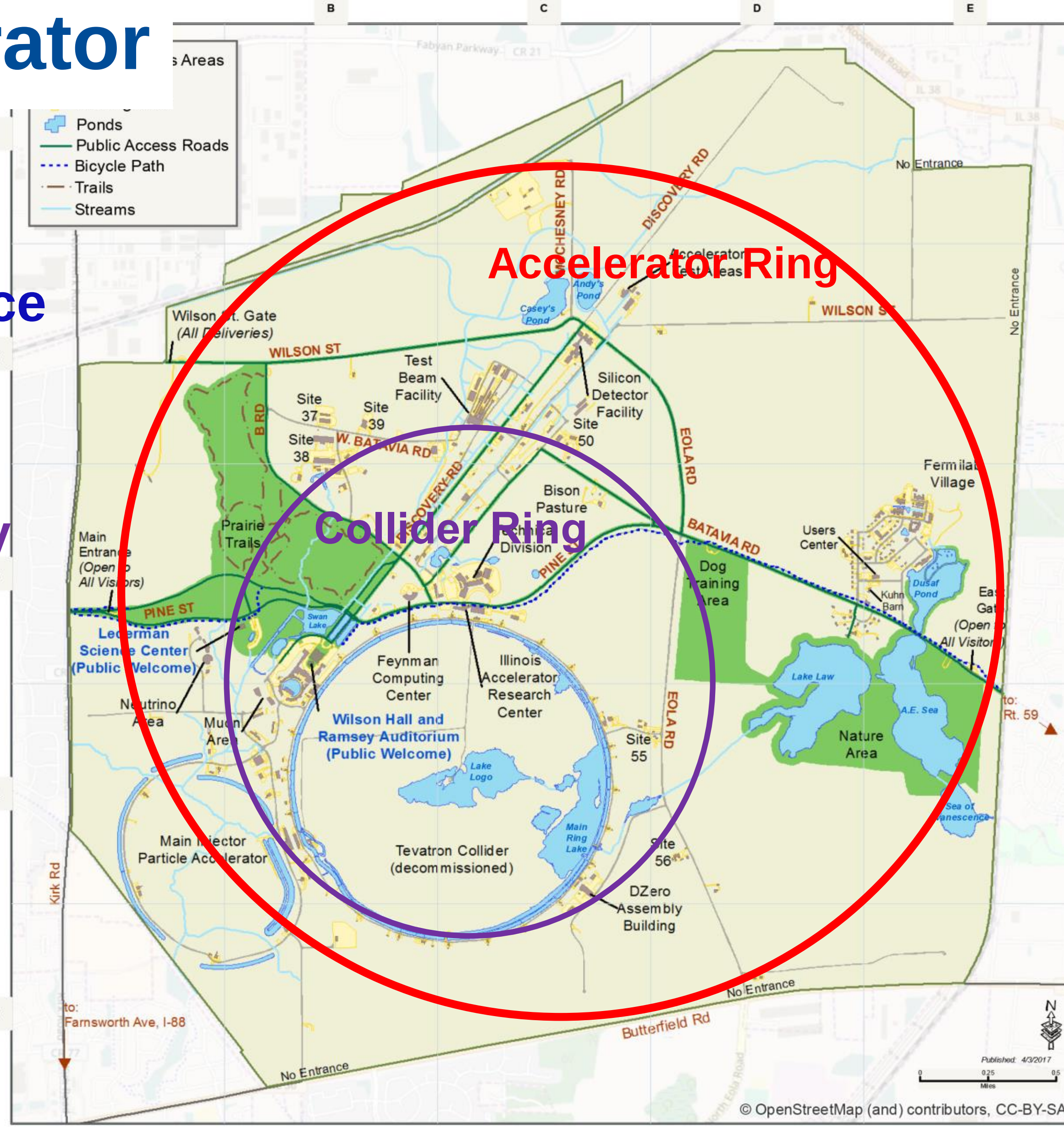
If B_{ave}= 3 T → E_{μ}= 2.4 TeV

(B_{max} = 8T, B_{pulse} =±2T)

Doubled ?

B_{ave}= 6.3 T → E_{μ}= 5 TeV

(B_{max} = 16T, B_{pulse} =±4T)



10 TeV collider

Collider Ring ~10 km

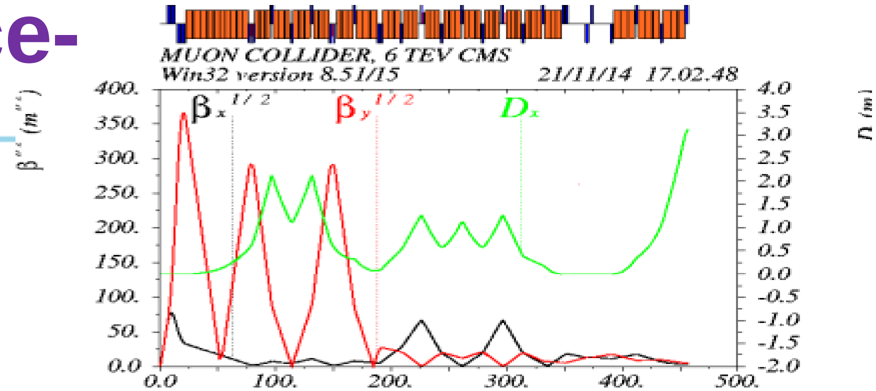
B_{ave} = 10 T

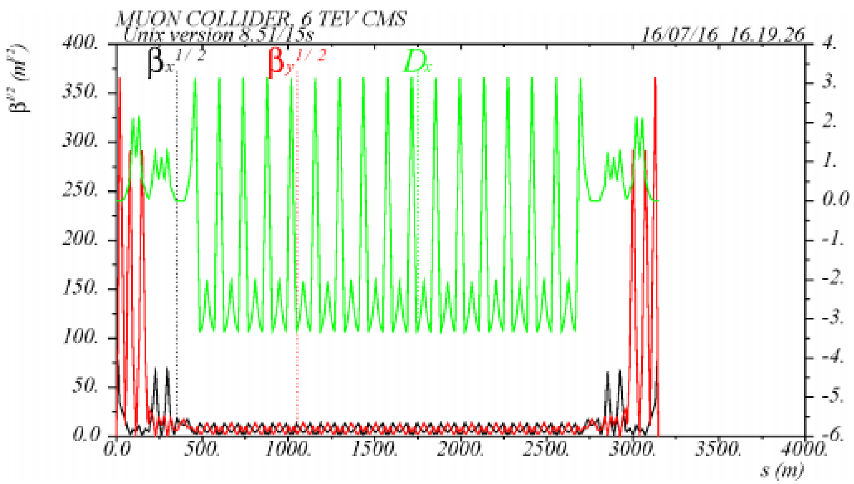
τ_{μ} = 0.104 s

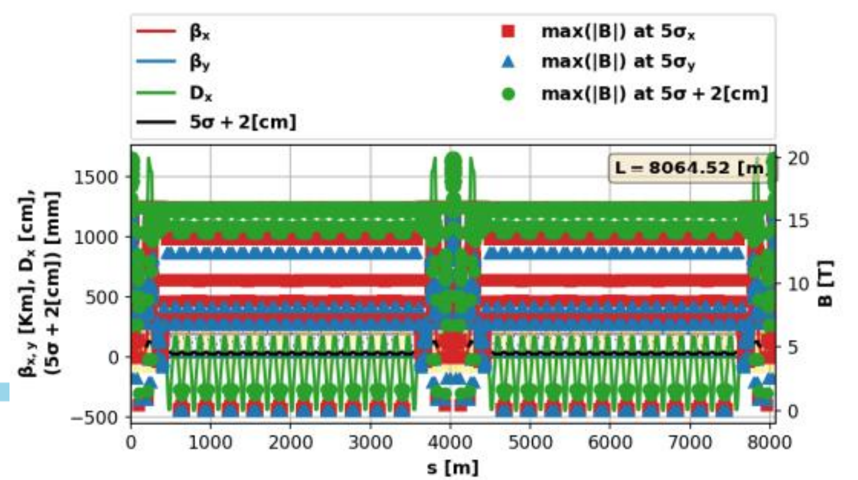
$$R = \frac{B\rho}{B} = \frac{P(GeV/c)}{0.3B(T)} m = \frac{P(TeV/c)}{0.3B(T)} km$$

Sample collider lattice-

- 6 TeV (3x3) lattice – MAP
  - Wang, Nosochkov, Cai and Palmer JINST 11, P09003
  - C=6.3 km (B_{ave}= 10 T)
    - Max pole-tip fields
      - 15-20 T dipoles, 15 T quads
        ~16 T bending
    - ~isochronous
- Extrapolate to 10 TeV
  - C→10.5 km, R=1.67 km
    - Fits within Fermilab site
- First draft lattice
  - Kyriacos Skoufaris and Christian Carli
    - C=8.06 km +
- Accelerator is larger
  - Includes rf, cycling elements



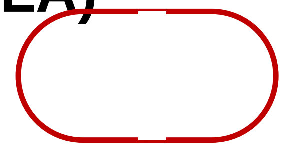




Acceleration methods

- **Linear Accelerator**
  - **5 TeV → > 100 km**

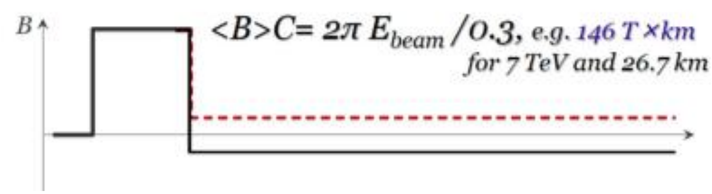
- **Race-track Recirculating Linac (RLA)**
  - **(like CEBAF)**

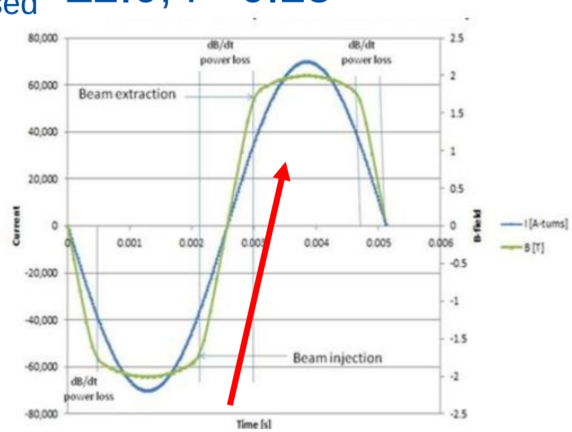


- **Separate return transports**
  - **5-6 turns → ??**
  - **cost/complexity of multiple turns**
- **Rapid Cycling Synchrotron**
  - **B_{typ} = ~1.5 T, 15- 60 Hz**
  - **Hybrid – High field + pulsed**
  - **Example:**

    B_{max}=8T B_{pulsed}=±2.0, f= 0.25

    → 3.5 / 0.5 T





$$B_{ave} = f\,B_{max} + (1 - f\,)B_{pulsed}$$

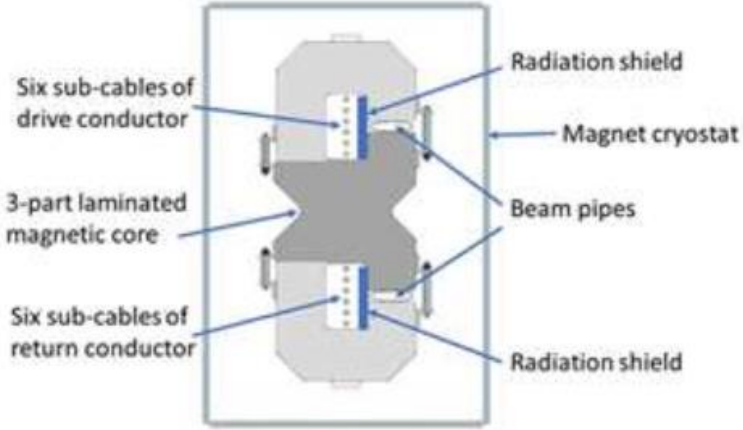
Bending, Accelerating fields:

- Conventional (Ferric)
  - ~ 2T
- Superconducting –NbTi
  - Tevatron ~4 T
  - LHC ~8 T
- Superconducting Nb_3Sn
  - HL-LHC + → 16T
- HTS superconductor …
  - REBCO → 40 T ?
- Pulsed magnets
  - ±2 T → ± 4 T ~200-600 T/s
    - 12 T/s HTS → 270 T/s
    - Piekarz et al. NIM A 943, 162490 (2019)
    - Piekarz et al. Fermilab-conf-21-695 (2021)

SRF accelerating fields

- 17 MV/m (650 MHz PIP-II)
- 30 MV/m (1300 MHz SLS-2)

- Future upgrades
  - 40 → 50 MV/m → 80??
- Pulsed rf – Cu → ??
  - 50 → 100 MV /m



Acceleration to 5 TeV at Fermilab

➢0-65 GeV Linac + 10-turn RLA

3 GeV Linac
- 650 MHz SRF

~6 GeV Recirculating Linac
- 650 MHz
- ~10 turns to 65GeV

➢65 GeV → 5 TeV

- **RCS 1 – 65→330 GeV r=1km**
  - Normal conducting: 0.3→1.55T
- **RCS 2 – 330→1000 GeV r=1km**
  - Hybrid 8±2 T
- **RCS 3 – 1 → 5 TeV "site filler"**
  - **Hybrid 16±4 T**

65 GeV → 5 TeV Scenario

	RCS-LE(nc)	RCS-HE(hybrid)	RCS-HF 16/4 hybrid
Input Energy	65	330	1000 GeV
Output Energy	330	1000	5000 GeV
Circumference	6.28	6.28	16.5 km
Pack Fraction	0.75	0.83	0.88
Total straight section	1.57	1.07	1.96
B-highfield		**8**	**16 T**
B-lowfield		**±2 T**	**±3.95 T**
B_{ave}	0.3→1.55 T	1.4→4.4 T	1.44→7.2 T
Fraction high-field		0.34	0.27
Acceleration Scenario			
Acceleration turns	36	97	270
Acceleration Time	0.76	2.03	15 ms
Beam survival	0.80	0.85	0.75
Rf voltage (ϕ_s = 60°)	8.63 GV	7.94 GV	17.1 GV
Ramp Rate	1650 T/s	1970 T/s	530 T/s

5 TeV with ±2 T RCS components

- **Requires additional site-filler RCS ring**
  - **1->3.25 TeV**
    - **19% 16 T magnets**
  - **3.25→ 5 TeV**
    - **37% 16 T magnets**
- **~ 10 GV more rf**
  - **Decay losses higher**

65 GeV → 5 TeV Scenario

	RCS-LE(nc)	RCS-HE(hybrid)	RCS-HE 1	RCS-HE 2
Input Energy	65	330	1000 GeV	3250 GeV
Output Energy	330	1000	3250 GeV	5000 GeV
Circumference	6.28	6.28	16.5 km	16.5 km
Pack Fraction	0.75	0.83	0.88	0.88
Total straight section	1.57	1.07	1.96	1.96
B-highfield		**8**	**16 T**	**16 T**
B-lowfield		**±2 T**	**±2.0 T**	**±2.0 T**
B_{ave}	0.3→1.55T	1.4→4.4 T	1.44→4.7 T	4.7→7.2T
Fraction high-field		0.34	0.192	0.37
Acceleration Scenario				
Acceleration turns	36	97	161	249
Acceleration Time	0.76	2.03	8.9 ms	13.7 ms
Beam survival	0.80	0.85	0.80	0.85
Rf voltage (ϕ_s = 60°)	8.63 GV	7.94 GV	16.1 GV	8.1 GV
Ramp Rate	1650 T/s	1970 T/s	450 T/s	290 T/s

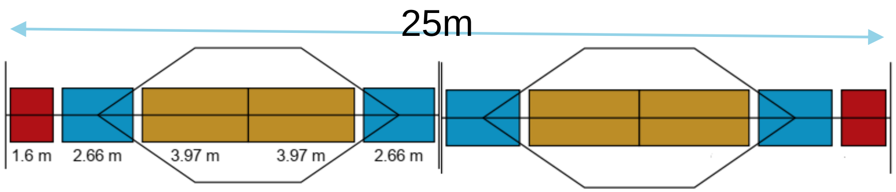
Hybrid RCS Acceleration

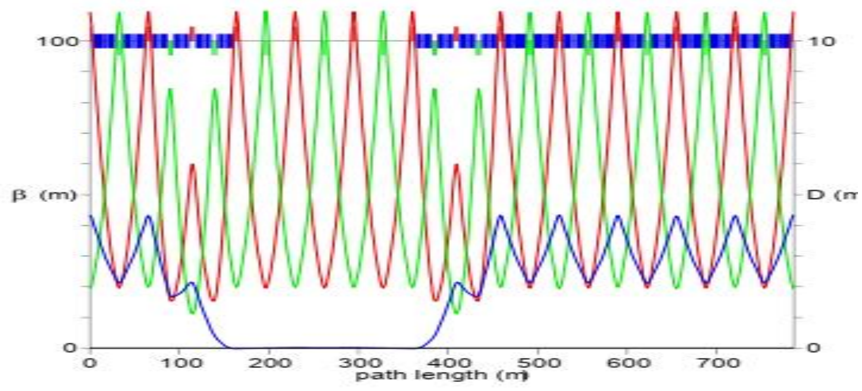
- **High-field fixed and low-field cycling magnets interleaved**

  - **Orbit through cycling magnet varies in acceleration**

  - **Quadrupoles needed**
    - Fixed or ramped ?
      - Fixed fields probably not stable
    - Limited to ramping fields
      - 0→2 T (or 0→4 T at pole tips)
      - Extra length for ramping quads must be included in lattice

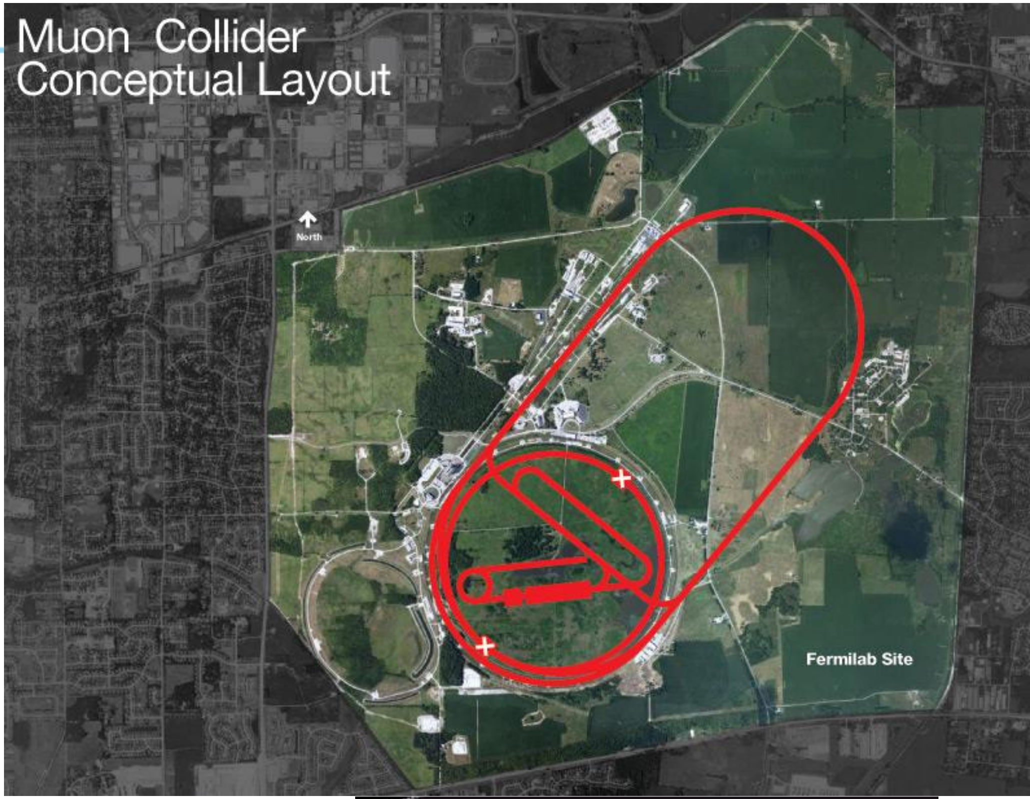
- **Sample Lattice**
  - **A. Garren and S. Berg**
    - MAP-doc-4307 (2011)
  - **750 GeV in Tevatron**





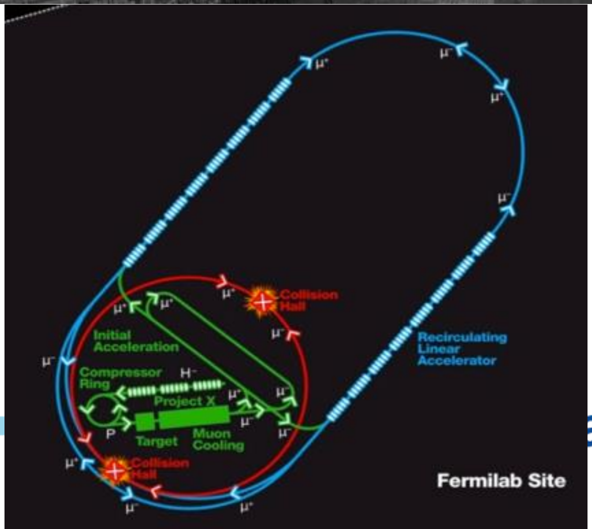
- **Quadrupoles are ramped to keep tune constant**

RLA~4→10 TeV Muon Collider (~2005-RLA



- **4 TeV Muon Collider**
  - **2 TeV ring (~8T magnets)**
  - **RLA accelerator**
    - **~18 turns**
      2km linacs -50 GeV each
      ~30 MV/m rf
      Arcs are ~8T magnets each
- **Not quite site filler**
  - **Easily expand to 2.5x2.5**
  - **(5 TeV)**

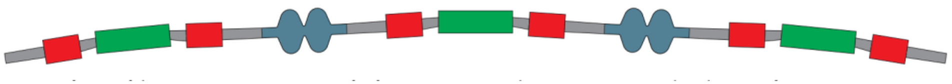
- **Double gradients, B_{max}, larger racetrack**
  - **10 TeV (5 x 5) – (16 T – 60 MV/m)**

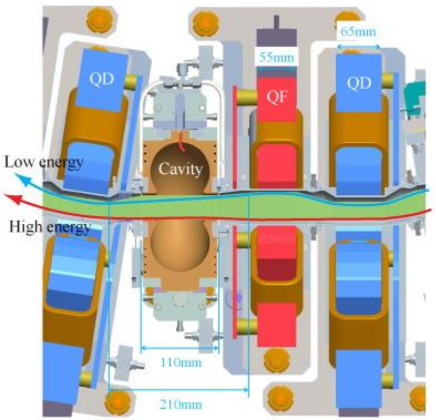


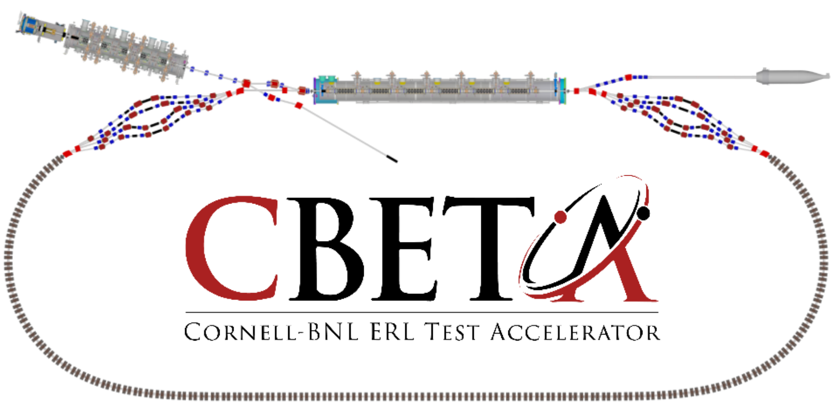
Fixed Field Accelerators

- **Fixed field alternating-gradient (FFA)**
  - **Scaling -> edge focusing**
    - **Constant tunes**
  - **Non-scaling**
    - **Crosses integer tunes**
    - **EMMA demo**
    -
- **CBETA**
  - **~RLA with FFA arcs**
    - **Tests concept of multiple passes in one transport**

- **Muon Acceleration ?**
  - **FFA in arcs**







FFA acceleration

- **Vertical FFAG**
  - S.Brooks, PRSTAB 16, 084001 (2013)
  - ~same circumference for all energies
  - More isochronous
  - **Edge focusing**
- **Scaling → non-scaling**
- **Adaptable to muons ?**

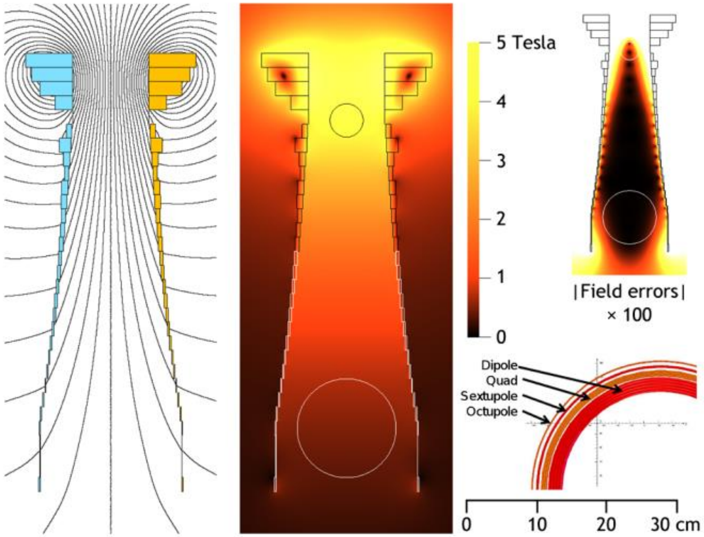


FIG. 5. 2D scaling VFFAG magnet design using block coils:

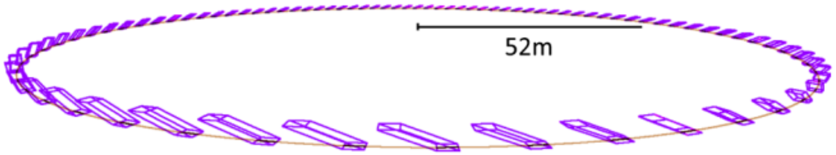


FIG. 8. Perspective view of the 12 GeV ring.

Site filler Accelerator

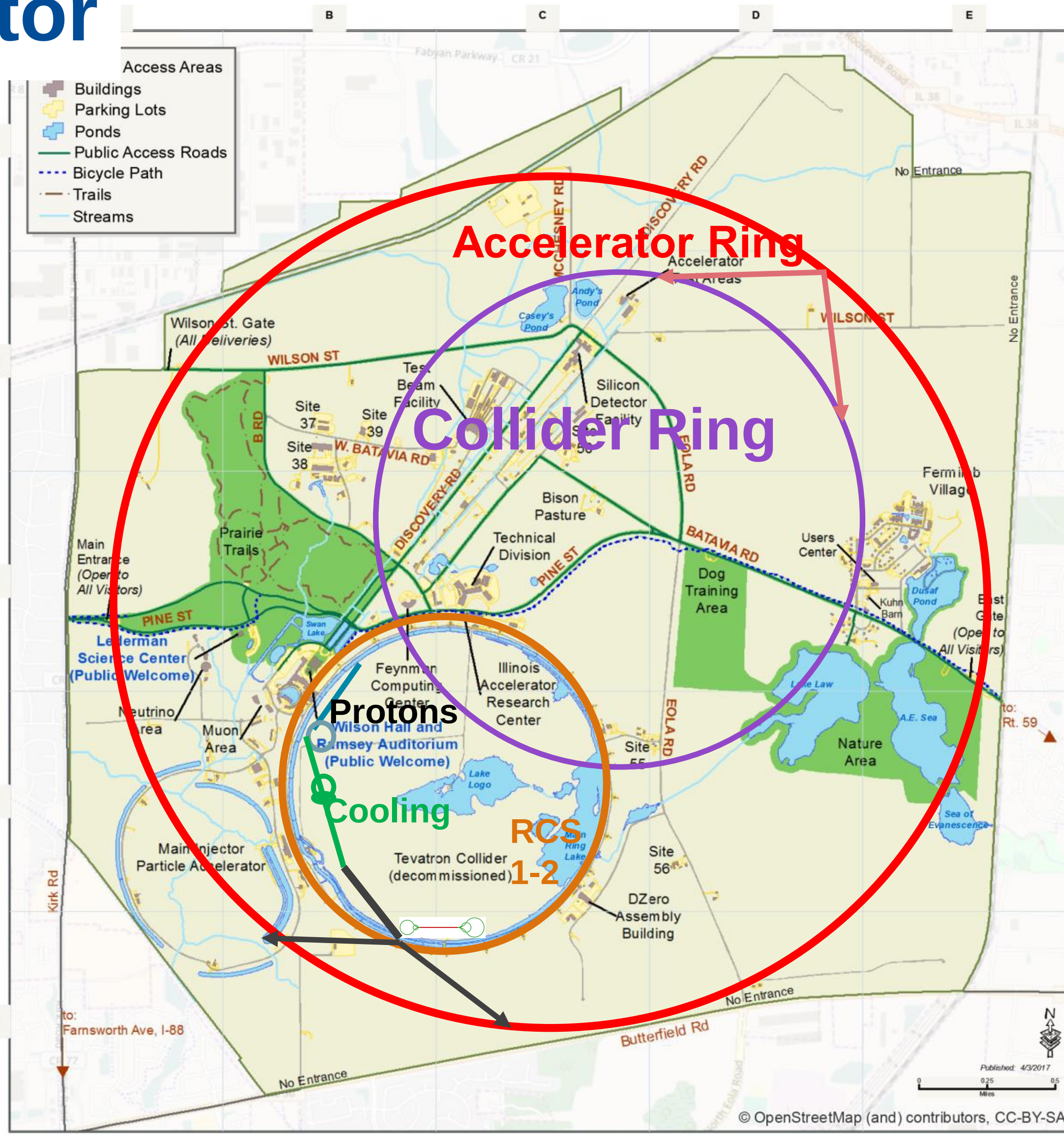
- **Proton Source**
  - PIP-III→target
- **μ Cooling**

- **Linac + RLA → 65 GeV**
  - 125 GeV Higgs
- **RCS 1 and 2 → 1000 GeV**
  - Tevatron-size

- **RCS 3 1 → 5 TeV**
  - Site filler accelerator

10 TeV collider

Collider Ring ~10 km

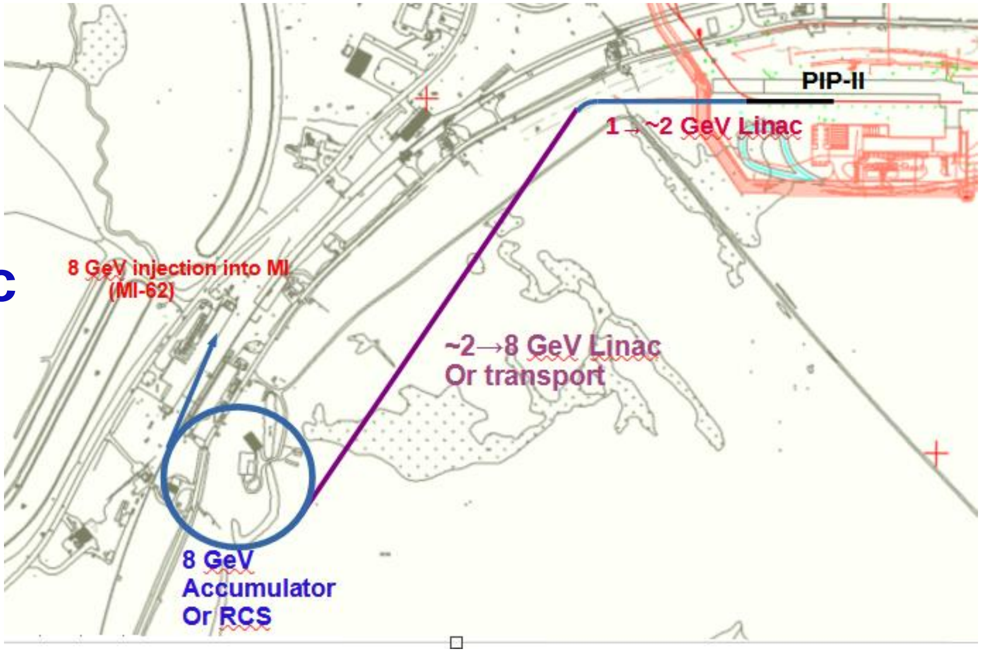


Fermilab

Fermilab Proton Intensity Upgrade

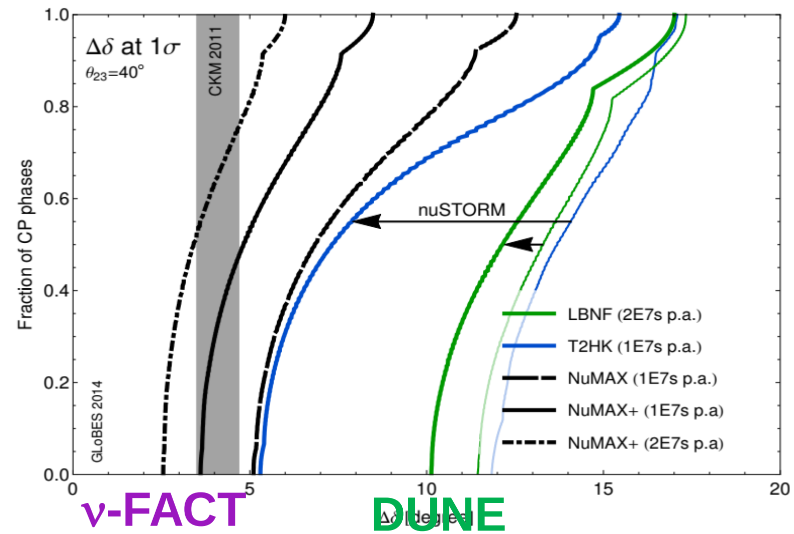
- **PiP-2 upgrade to ~8 GeV**
  - **LBNF-DUNE to 2.4+ MW +p**
  - **RCS –based or 8 GeV Linac**
    - **Inject into MI for DUNE**
    - **8 GeV beam for other experiments**
- **Could provide MW proton beams**
  - **8 GeV Linac upgrade to**
  - **5 ma 2.5ms 20 Hz**
    - **→ 2 MW**

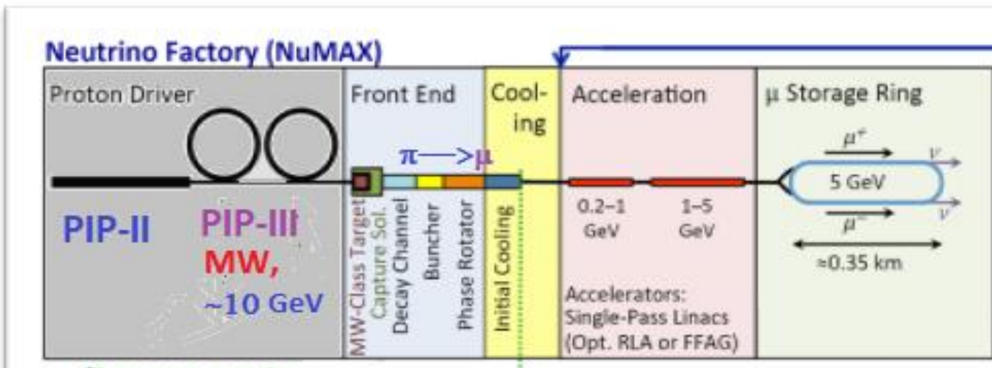
8 GeV RCS 800 kW baseline upgrade by 2.5x to 2 MW

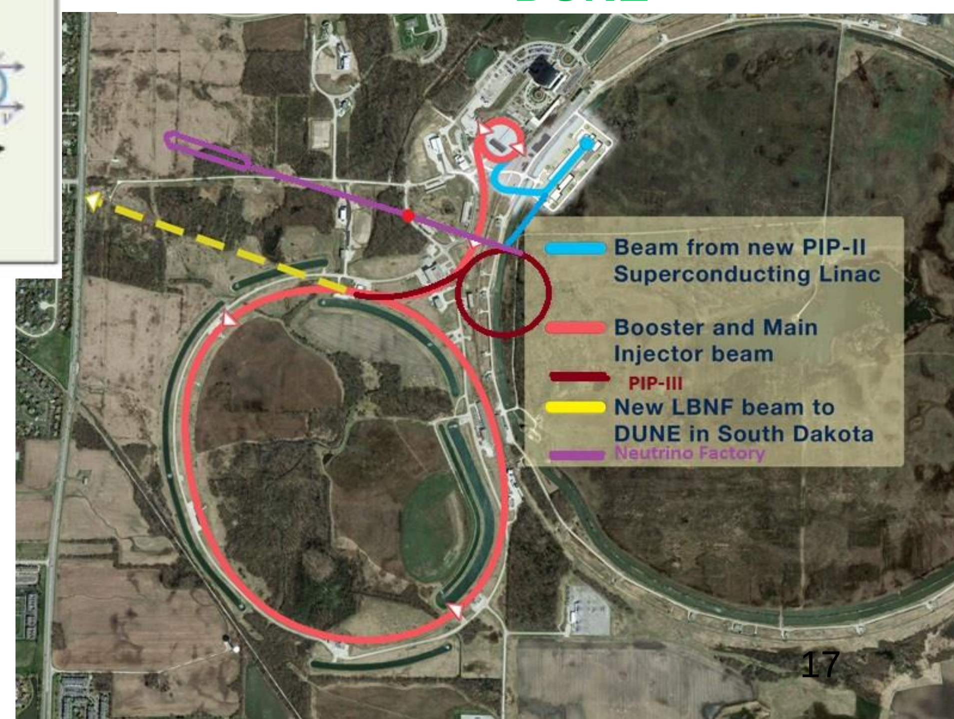


Fermilab "PIP-III" Neutrino options

- DUNE → ???
  - PIP-II→ "PIU"
- Muon-based (μ→eνν*) beams
  - Short BL (nuSTORM)
  - Long baseline → DUNE







  - ~4 GeV μ Storage ring

- Muon source can be extended to feed a high-energy Collider

Costs ??

- **Affordable?**
  - **according to Shiltsev cost model (JINST 9 T07002 (2014)):**

$$TPC \cong \alpha\left(\frac{L}{10\,km}\right)^{\frac{1}{2}} + \beta\left(\frac{E_{cm}}{1TeV}\right)^{\frac{1}{2}} + \gamma\left(\frac{P}{100\,MW}\right)$$

- $\alpha \cong$ 2G$ for civil construction,
- $\beta \cong$ 1, 2 or 10 G$
- for NC, SC magnets or SRF
- $\gamma \approx$ 2B$ wall plug power

- L=16, 60 GV rf, E_{cm}=10, P= ? MW
  - ~10^1 G$?

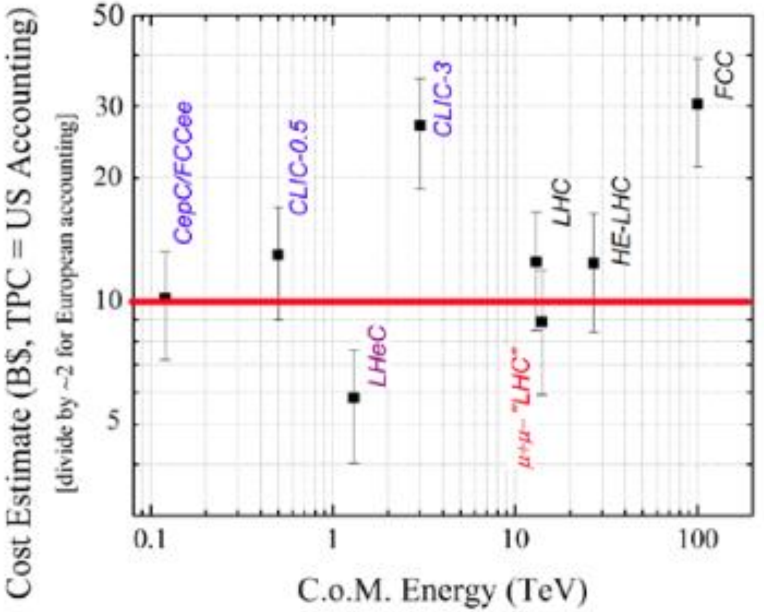


Figure 4: Cost estimates of various future colliders.

Fermilab

Summary

- **Fermilab site filler Collider possible**
  - **Muon Collider up to ~10 TeV Collider is possible**
    - **(5 × 5 TeV)**
    - **Requires ~16 T dipoles , in RCS scenarios**
      - **With rapid-cycling 2—4 T magnets**
    - **RLA/FFA scenarios also possible**

- **Strong interest at Snowmass**
  - **Muon Collider Forum report**
    - **K. M. Black, S. Jindariani et al.**
    - **ArXiv 2209.01318**
  - **Future Collider Options for the US**
    - **P. C. Bhat et al. 2203.08088**

Fermilab

Thank you for your attention