BROOKHAVEN NATIONAL LABORATORY

Muon Collaboration

FFAGs: US (and Canadian) Activity

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FFAG03, KEK

People and Activities

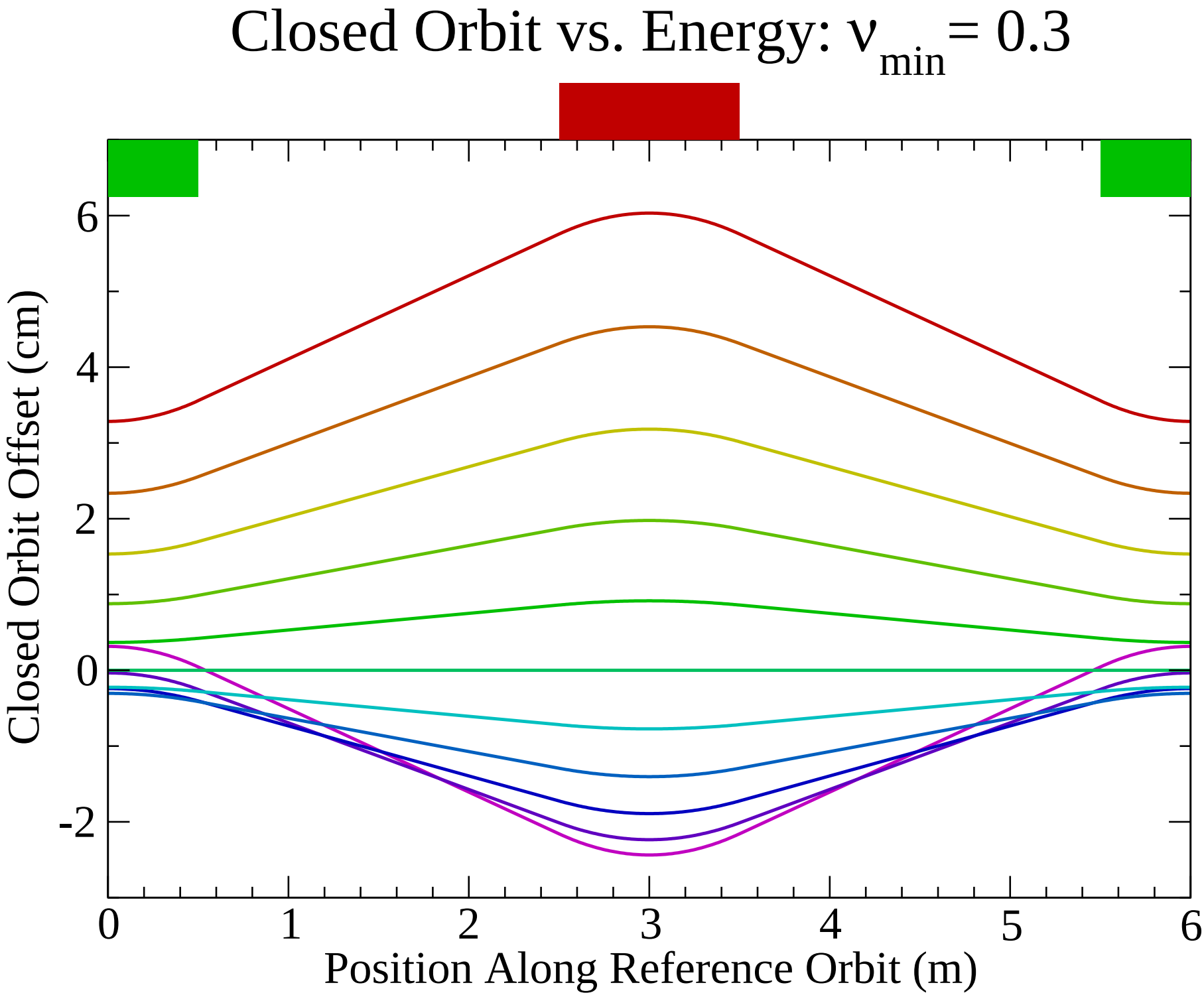
- Primary interest is in muon acceleration
  - Other uses being contemplated: talk by W.T. Weng
- Lattice design: J. Scott Berg, Carol Johnstone, Eberhard Keil, Andy Sessler, Dejan Trbojevic
- Longitudinal dynamics: J. Scott Berg, Shane Koscielniak
- Cost modelling and optimization: J. Scott Berg, Bob Palmer
- Superconducting RF cavity design and testing: P. Barnes, S. Calatroni, E. Chiaveri, R. Geng, Don Hartill, Hasan Padamsee, H. Preis, J. Sears
- Magnetic fields on superconducting cavities: Steve Kahn

Muon Acceleration Goals

- Accelerate to 20 GeV
- Bunch train in 201.25 MHz buckets: RF frequency forced
- 3.4×10^{13} particles in the bunch train at 4 MW (twice that for both signs)
- Longitudinal acceptance of 150 mm
- Transverse acceptance of 30 mm

Non-Scaling FFAGs

- Properties of scaling FFAGs
  - Tunes, momentum compaction constant
  - Energy-dependent closed orbits are geometrically similar
- Non-scaling FFAGs (invented by Carol Johnstone) depart from these properties
  - Tune depends on energy
    - Must avoid single-cell linear resonances
    - Other resonances not a problem with rapid acceleration
  - Non-constant momentum compaction
    - Approximately parabolic path length variation with energy
  - Energy-dependent closed orbits not geometrically similar
    - Become tightly packed and cross at low energies


Closed Orbit vs. Energy: ν min = 0.3
Closed Orbit Offset (cm)
6
4
2
0
-2
0
1
2
3
4
5
6
Position Along Reference Orbit (m)

Longitudinal Dynamics

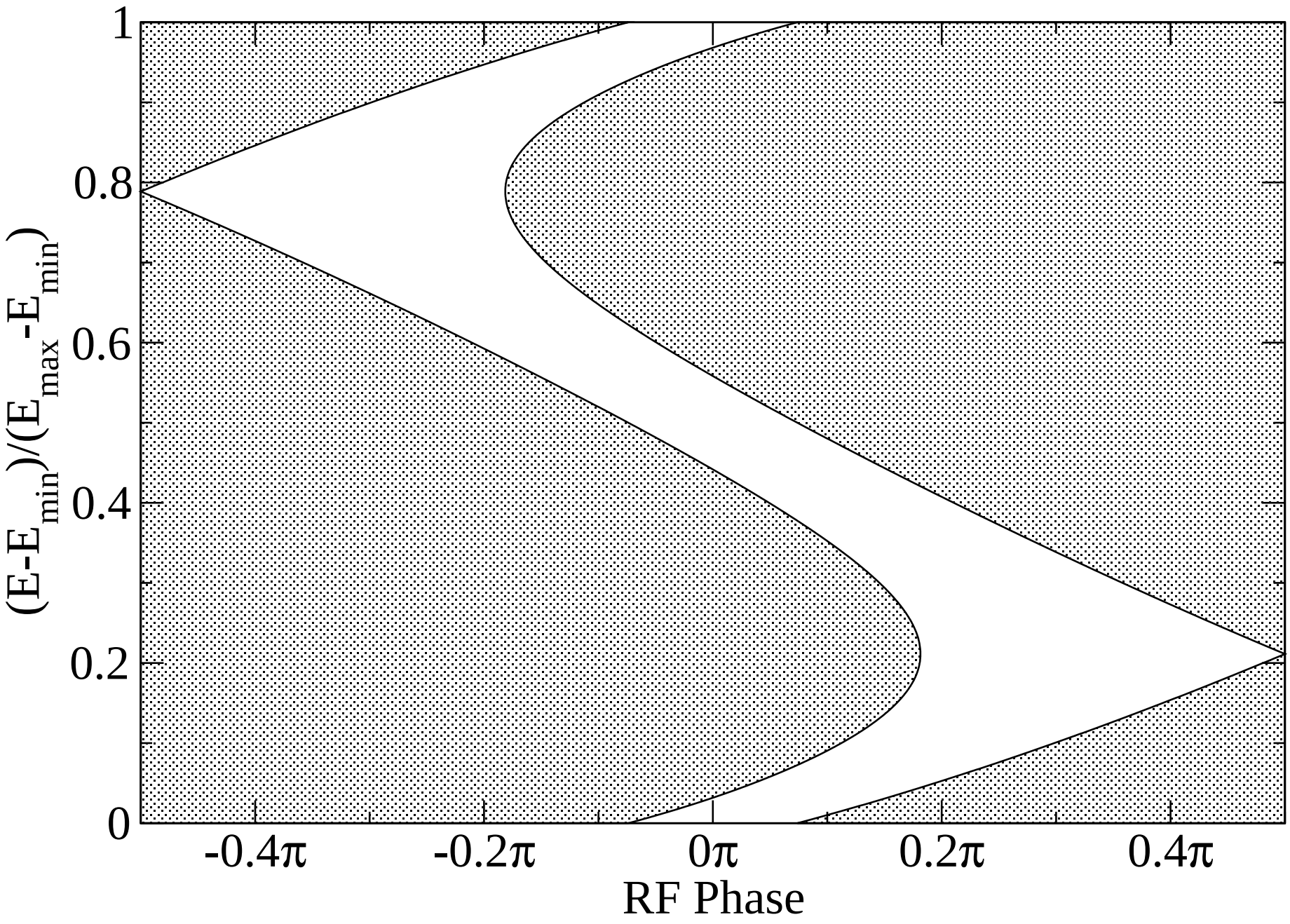
- Parabolic path length dependence leads to motion crossing crest three times
- There is a minimum voltage which accelerates particles from minimum to maximum energy

$$V_{\text{min}} = \frac{\omega \Delta T \Delta E}{24}$$

  - Proportional to frequency
  - Proportional to maximum time-of-flight of parabola ΔT
- This minimum voltage transmits zero longitudinal phase space volume
  - Increase voltage to get larger volume transmitted
  - Adding higher harmonic RF improves transmission/linearity significantly
- Studying parameter space to determine optimum initial distribution and parameters
- More complicated schemes with individual cavity phases seem to give improvement also (Shane Koscielniak)

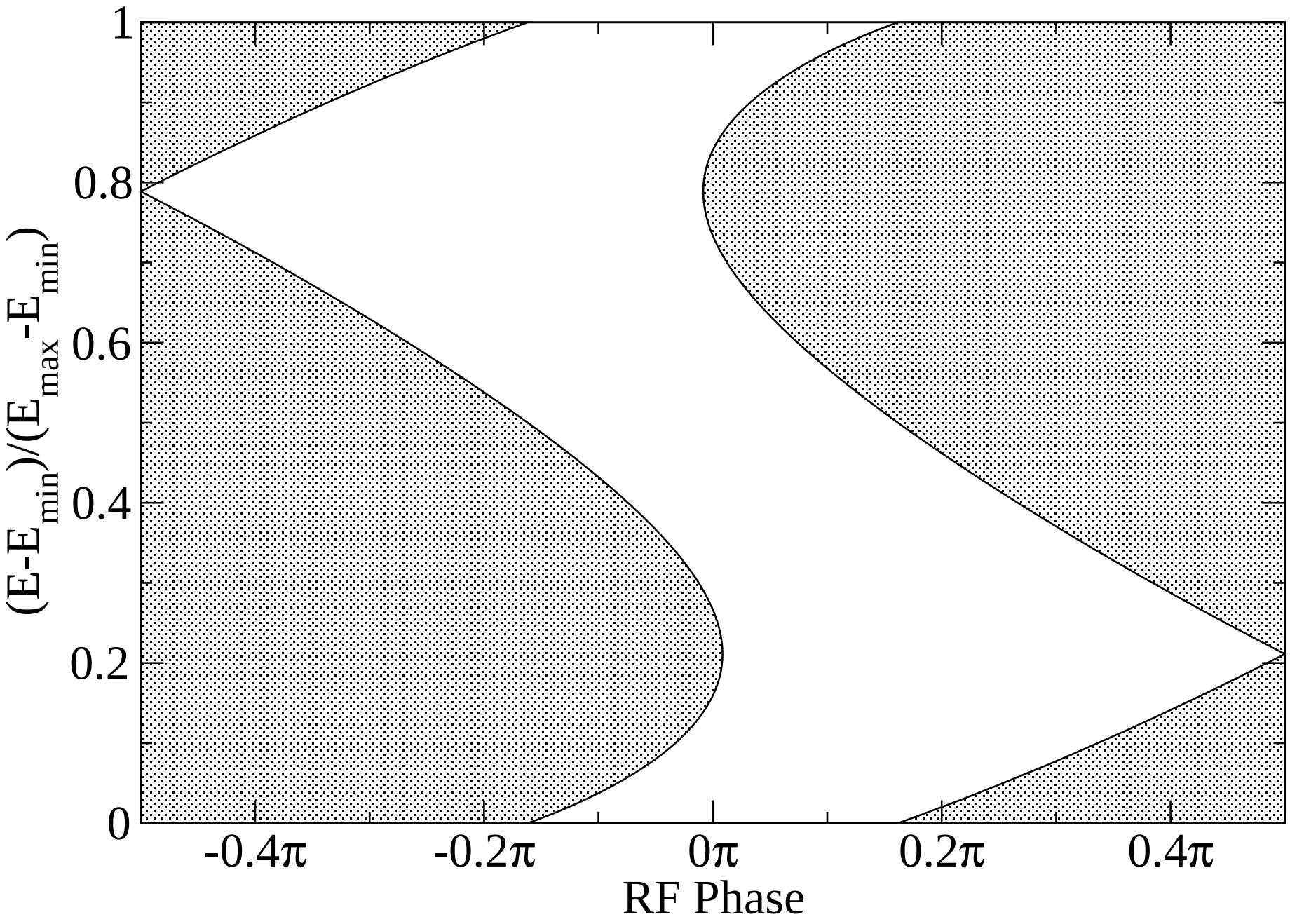
Longitudinal Phase Space, Non-Scaling FFAG

l_0=1/3, v=1/12

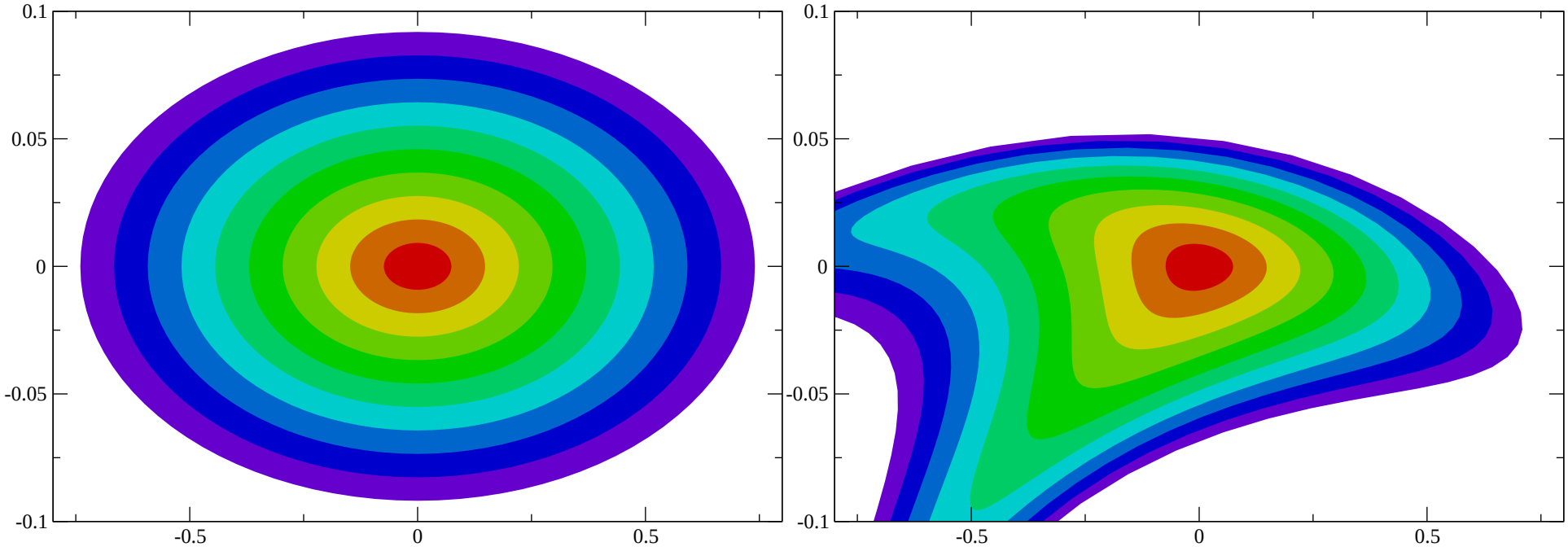


Longitudinal Phase Space, Non-Scaling FFAG

l_0=1/3, v=1/8



Longitudinal Phase Space

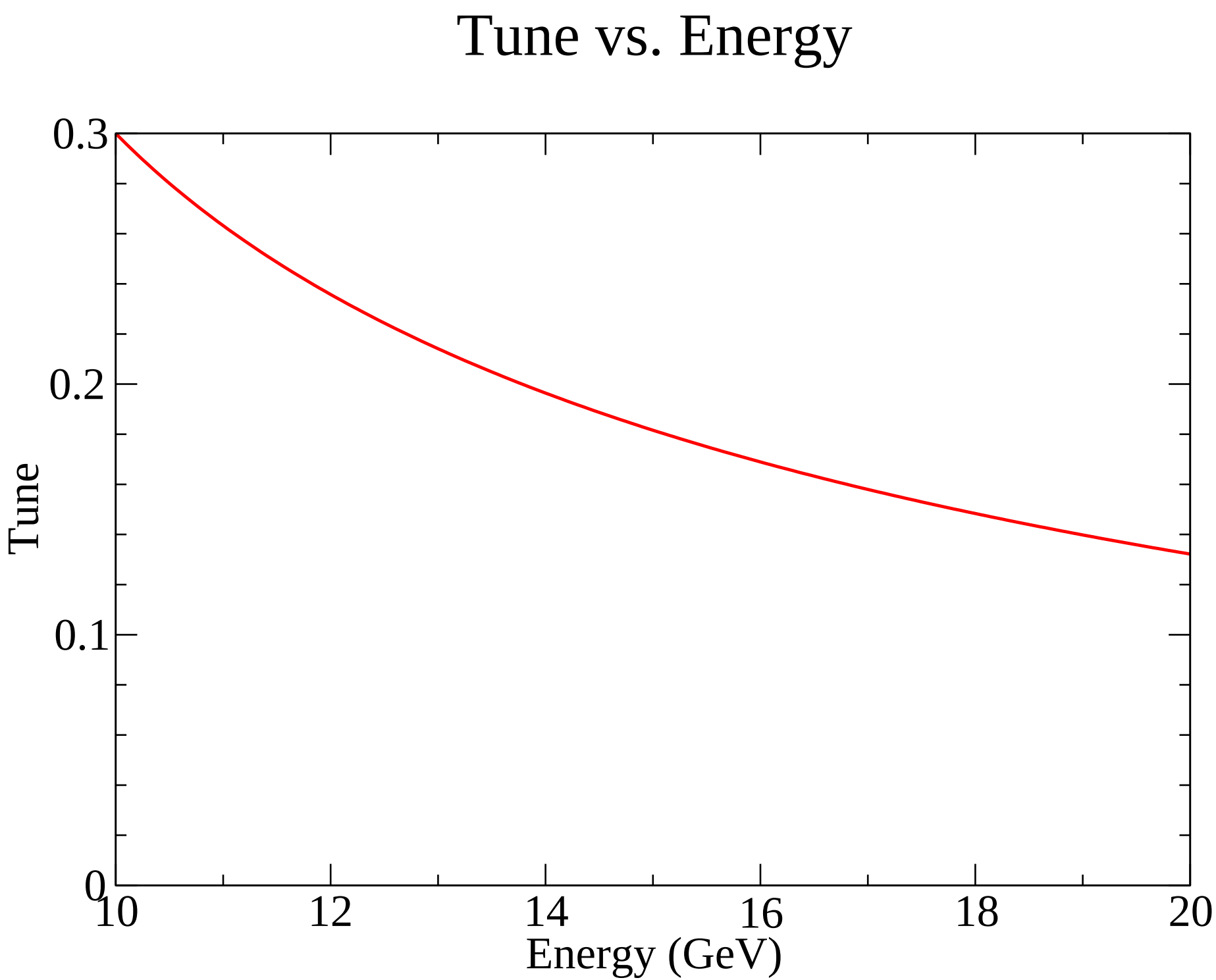


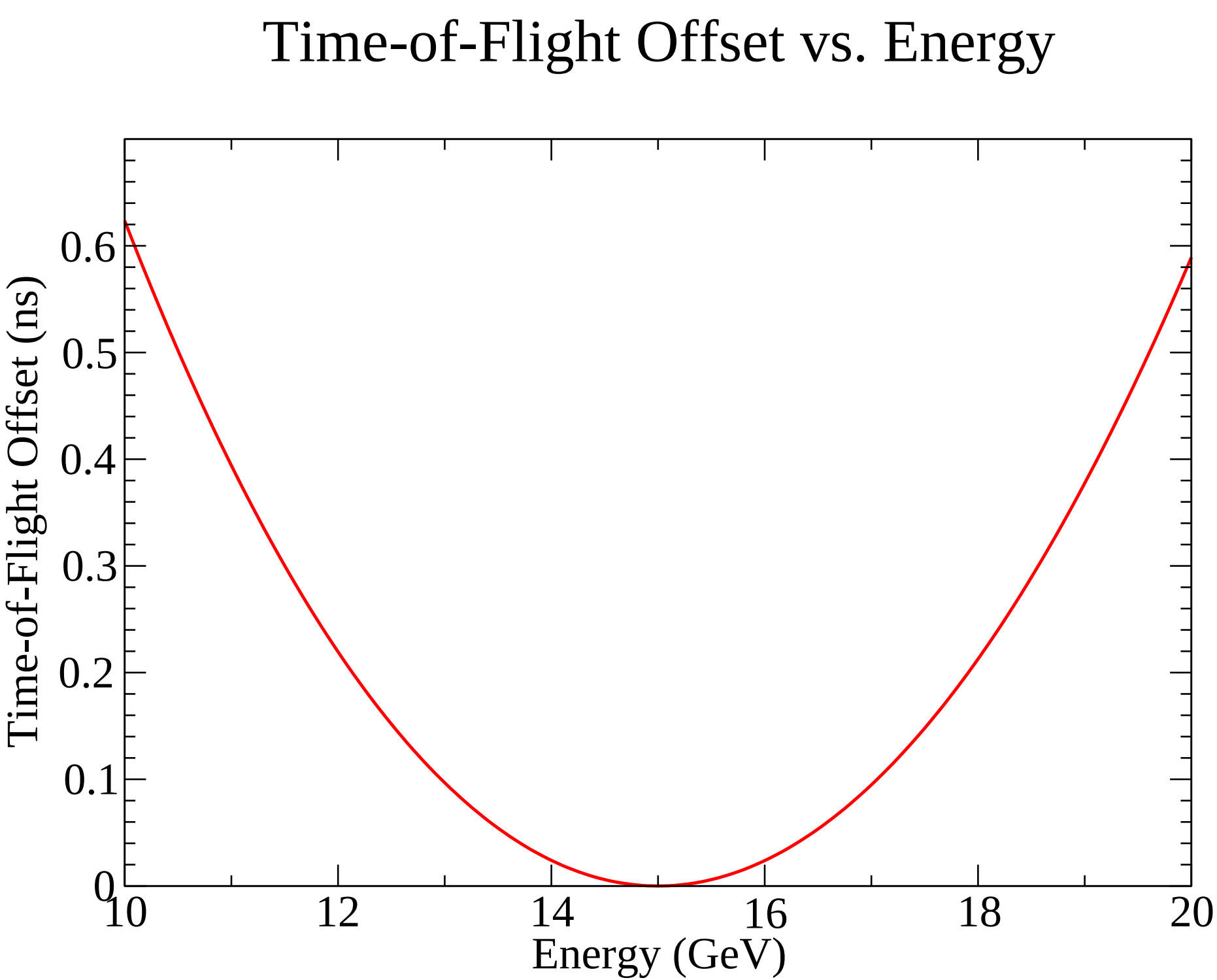
Initial

Final

Lattice Design

- Use linear magnets and simple cell structures
- Cell tune should remain below 0.5 to avoid linear resonances
  - Could instead be between 0.5 and 1.0, but requires sextupoles, reducing dynamic aperture
  - Rapid acceleration: push through linear multi-cell and nonlinear resonances
- Cell tune decreases monotonically with increasing energy
  - Set low energy tune between 0.3 and 0.4
- Put minimum of time-of-flight parabola at central energy
  - Minimizes maximum time-of-flight error
- Lattice choice moving toward triplet, with central quad horizontally defocusing
  - FODO requires two long drifts, triplet only one
  - Minimum emittance lattice evolved to this also
- Biggest issue: getting sufficient longitudinal phase space transmission


Tune vs. Energy
0.3
0.2
0.1
0
Tune
10
12
14
16
18
20
Energy (GeV)


Time-of-Flight Offset vs. Energy
Time-of-Flight Offset (ns)
0
0.1
0.2
0.3
0.4
0.5
0.6
10
12
14
16
18
20
Energy (GeV)

Cost Analysis

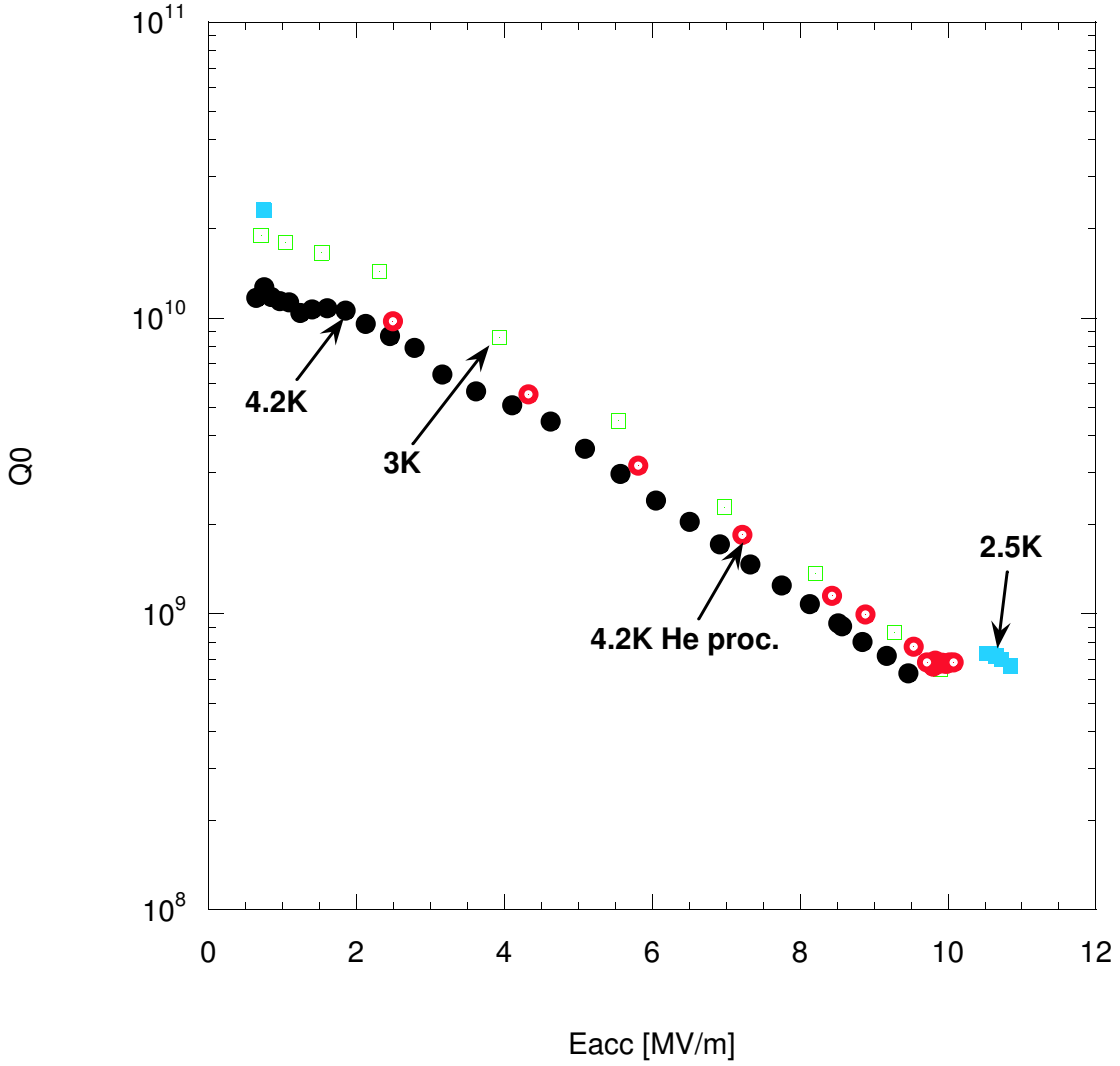
- Bob Palmer has a costing model for magnets/cavities/etc.
- We can produce designs as described above using an optimizer
- Results of analysis
  - Cost per GeV of low energy stages much higher than high energy stages
  - Non-scaling FFAGs appear to be more cost-effective for muon acceleration than scaling
    - ⋆ Haven't really done head-to-head comparison as yet: one goal of WG1
  - Making ring longer may decrease both lattice and RF costs
    - ⋆ Lattice: smaller aperture. Less relevant at lower energy where beam size dominates
    - ⋆ RF: longer lattice, smaller time-of-flight

Cavity-Magnet Distance

- Lowering cell length lowers cost
  - Smaller orbit excursion (dispersion) and therefore aperture
  - Smaller beta functions
  - Smaller time-of-flight range, shorter ring and/or less voltage
- Room temperature cavities probably not OK for FFAGs
  - Need large stored energy due to beam loading
  - Requires very high peak power for room temperature: cost prohibitive
- Studies of gap needed between cavity and magnets to prevent quench
  - Only need fields at 0.1 T at cavity once it is cooled
    - ⋆ 0.1 Gauss before cooled: watch residual magnetization
    - ⋆ Not concerned about small quench: Nb on Cu, Cu keeps cold
  - Looks like we can do this with 50 cm gap (Steve Kahn)

SCRF Testing at Cornell

- 201.25 MHz
- Achieved 11 MV/m
- Large Q-slope
  - Larger than predicted
  - Depends on temperature: surface characteristics
  - Nb film and Cu substrate
- Input power coupoler limits gradient



Concluding Summary

- Many individuals have developed an understanding of how to design Carol's non-scaling FFAG lattices
  - These lattices seem to perform very well for US design parameters
  - We are proceeding to try to design "cost-optimum" lattices
- There has been convergence toward a triplet lattice
- The basics of longitudinal dynamics is well understood
  - More work needs to be done to understand how to find the minimum voltage for a given acceptance
- There has been progress in achieving the designed gradient for a 201.25 MHz superconducting RF cavities
- Work is proceeding on determining the needed space betweean superconducing RF cavities and magnets