FRONTEND DESIGN & OPTIMIZATION STUDIES

HISHAM KAMAL SAYED BROOKHAVEN NATIONAL LABORATORY

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Collaboration:

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Muon Accelerator Program

BROOKHAVEN NATIONAL LABORATORY

FRONT END DESING & OPTIMIZATION

OUTLINE

Goal : Optmize number of useful muons and limit the proton beam power energy transmitted to the first RF cavity in the buncher

Involved systems:

- Carbon target geometry
- Capture field
- Chicane design
- Be absorber

1- Target geometry parameters:

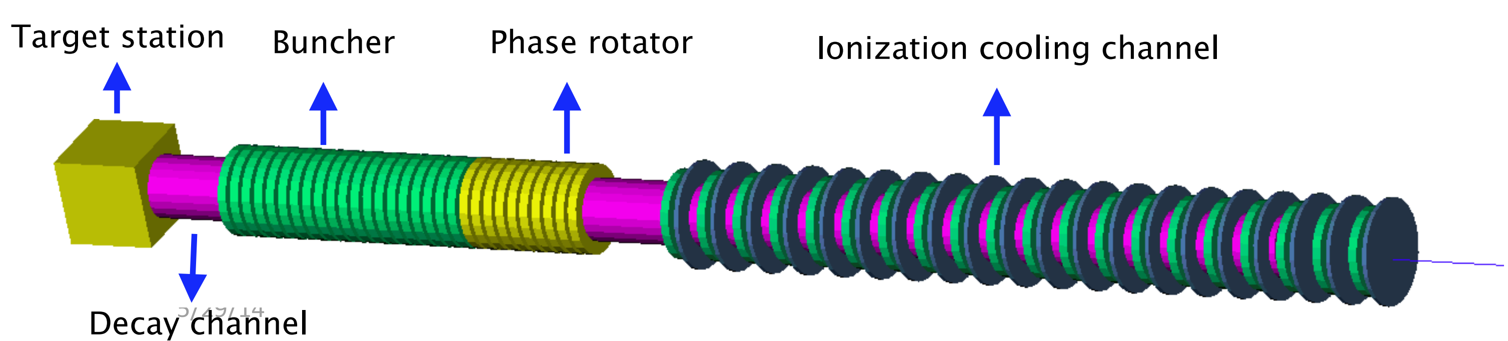
Carbon target length, radius, and tilt angle to solenoid axis

2- Target Capture field: constant field length - taper length - end field

3- Chicane parameters: Length - curvature – focsuing field

4- Be absorber thickness and location

5- Energy deposition in the target area + Chicane will be evaluated and involved in the optimization – future work.

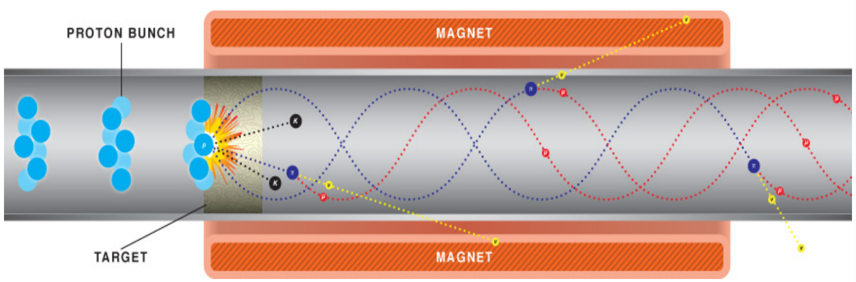


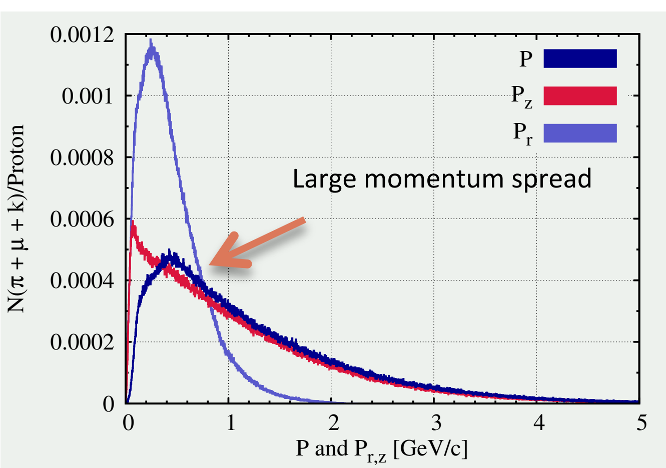
MUON BEAM PRODUCTION

Challenges with muon beams:
- Short lifetime ~ 2 µs
- Require fast and aggressive way of reducing the muon beam transverse and longitudinal emittance to deliver the required luminosity

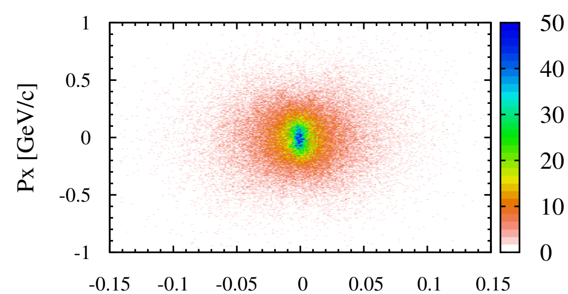
Production and acceleration of muon beam

High energy proton beam on Hg or graphite target

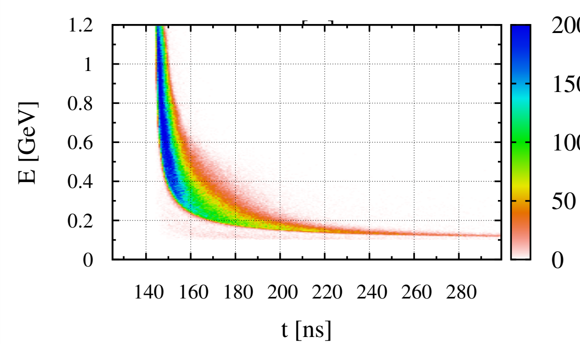




Captured pion beam has a large emittance
Pions decay into muons with even larger emittance



Transverse phase space
$\varepsilon_{T(rms)}$ ~ 25 mm-rad



Longitudinal phase space

TAPERED CAPTURE SOLENOID OPTIMIZATION

Inverse-Cubic Taper

- Initial peak Field B_1
- Taper length z
- End Field B_2

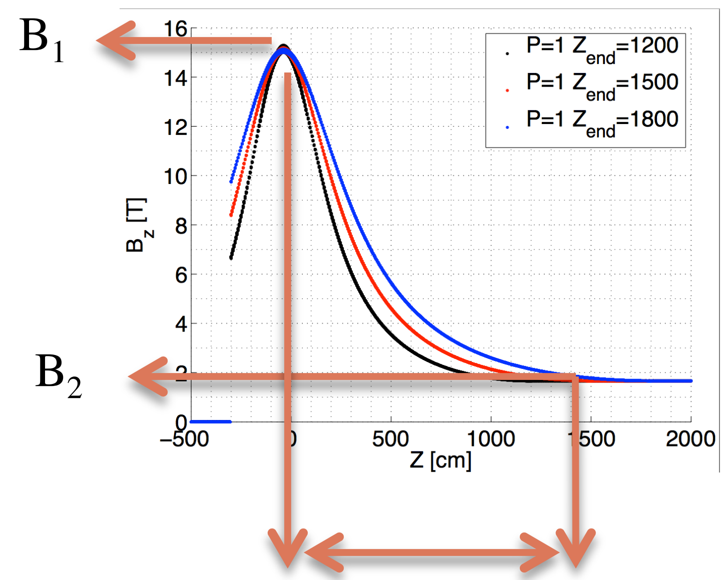
$$B_z(0, z_i < z < z_f) = \frac{B_1}{[1 + a_1(z - z_1) + a_2(z - z_1)^2 + a_3(z - z_1)^3]^p}$$

$$a1 = -\frac{B_1^{'}}{pB_1} \qquad a_2 = 3\frac{(B_1/B_2)^{1/p} - 1}{(z_2 - z_1)^2} - \frac{2a_1}{z_2 - z_1}$$

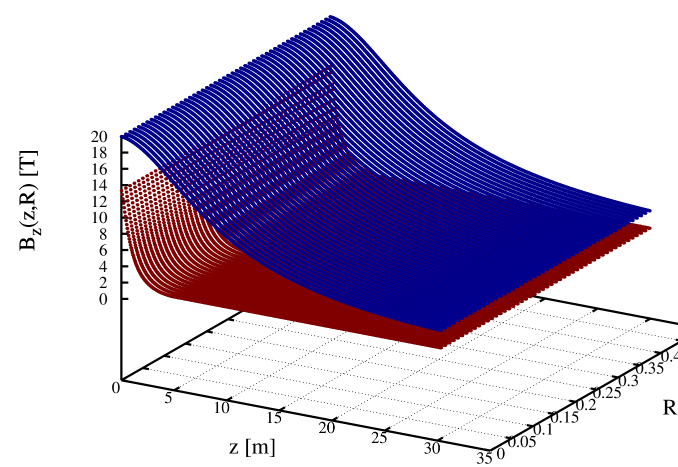
$$a_3 = -2\frac{(B_1/B_2)^{1/p} - 1}{(z_2 - z_1)^3} + \frac{a_1}{(z_2 - z_1)^2}$$

- Impact of the Peak field on the number and phase space of the captured pions
- Impact of taper length on the number and phase space of the captured pions/muons
- Impact of the end field on the number of captured muons

Target Solenoid on axis field



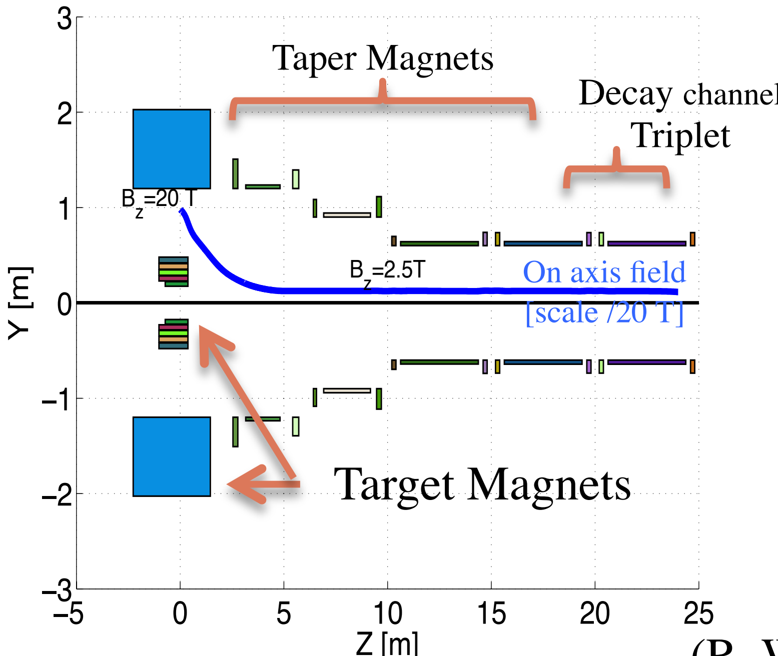
Taper Length z_1-z_2



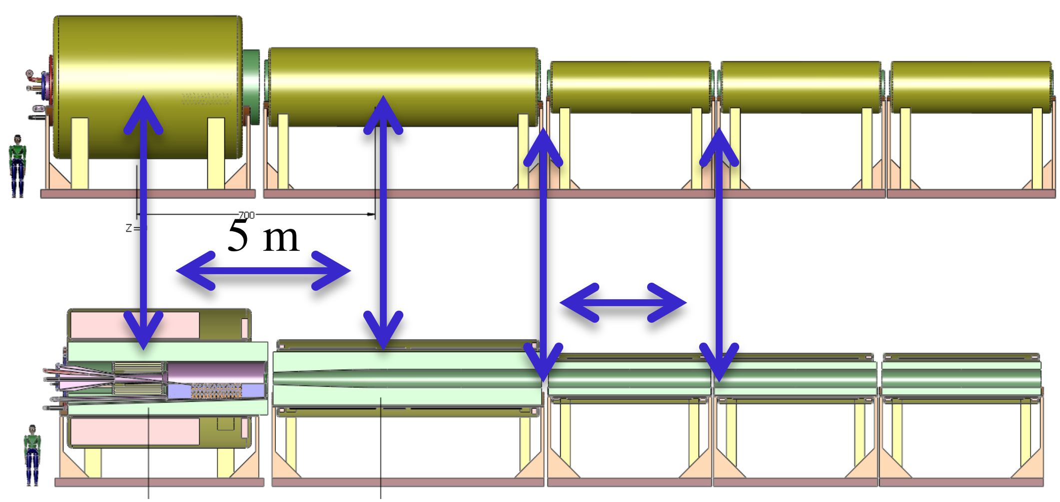
NEW SHORT TARGET CAPTURE WITH REALISTIC SUPERCONDUCTING MAGNETS

New baseline Muon Target Capture Magnet :
Short Taper length = 5 m

B=20-2.0 T, 20 – 2.5 T 20 – 3.5 T

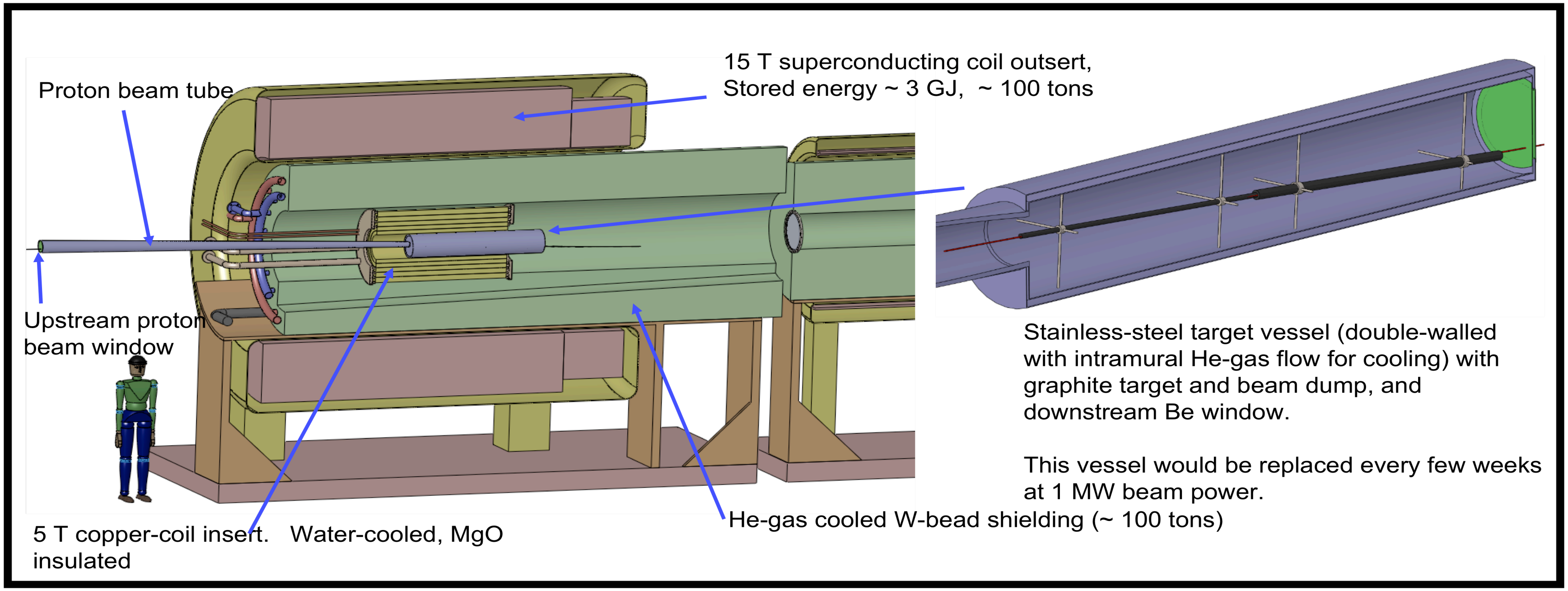


(R. Weggel)



V. Graves

CARBON TARGET GEOMETRY OPTIMIZATION



http://physics.princeton.edu/mumu/target/hptw5_poster.pdf

CARBON TARGET GEOMETRY OPTIMIZATION

- Target geometry parameters (channel includes target + chicane+ decay channel):
  - → Carbon target length -- radius -- tilt angle to solenoid axis
  - → Proton beam size

- Objective: optmize at z=70 m

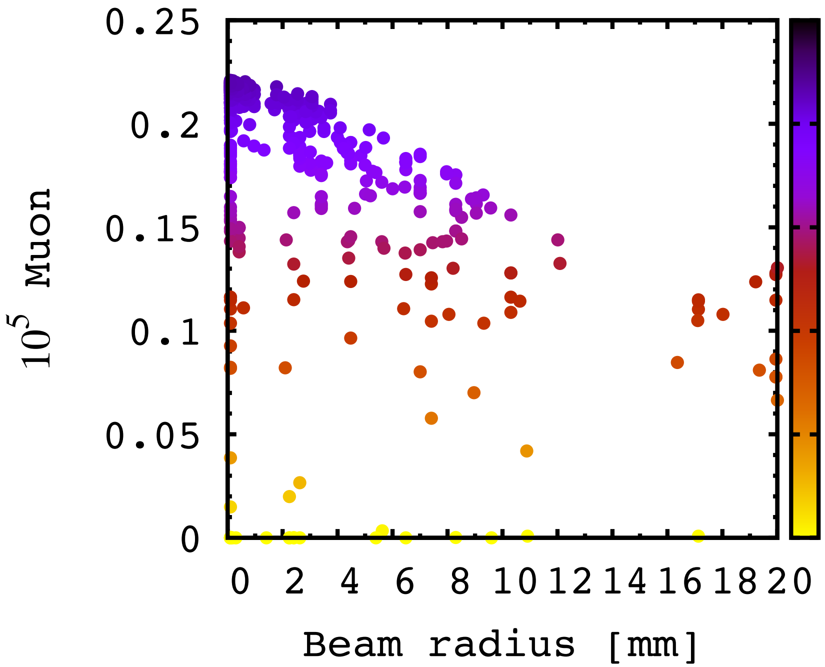
  $\Sigma\ \pi+\mu+\kappa$ within
  $p_z < 450$ MeV/c (to compensate for the Be absorber effect)
  $p_t < 150$ MeV/c

Initial lattice in G4Beamline – using GEANT4 physics list QGSP (Benchmarekd with exp. data – Bungau *et al* PRSTAB 2014)

- $B_z = 20$ - 2.0 T over taper length = 5.0 m
- Initial protons K.E. = 6.75 GeV - $\sigma_t = 2$ ns
- Initial optmization of the beam aperture → 12 cm
- Using optmized short taper of 5 m
- Tracking includes target + chicane + decay channel

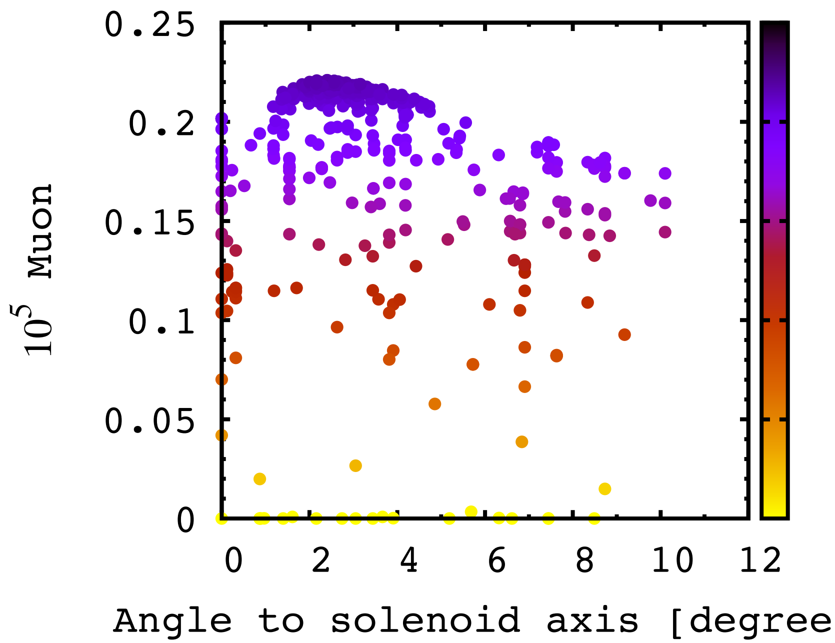
- The optmization run 6 hours on 240 cores at NERSC using Multiobjective – Multivariable parallel genetic algorithm

CARBON TARGET GEOMETRY OPTIMIZATION

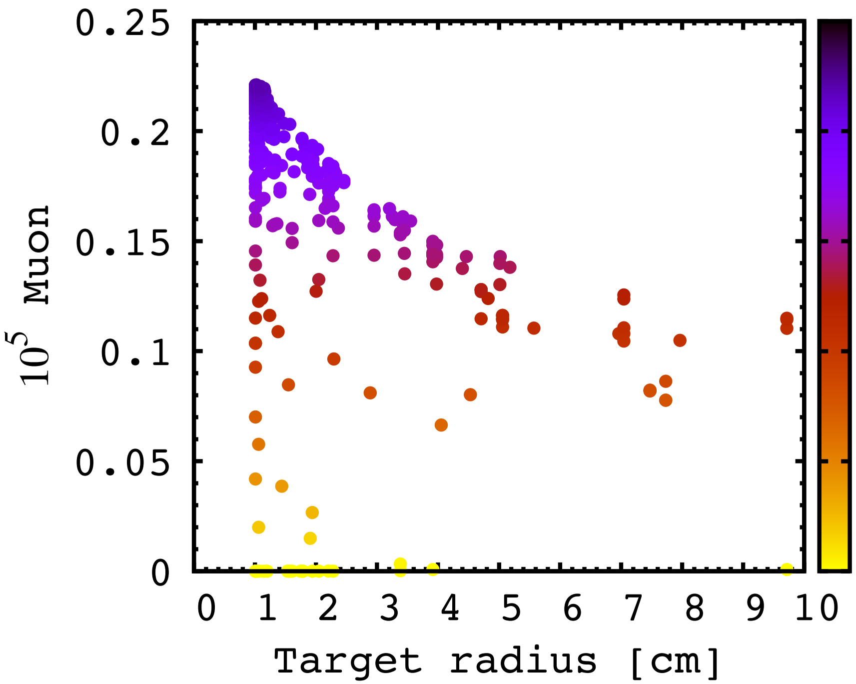


Optimal working point 1-2 mm

Optimal working point 1-3 degrees

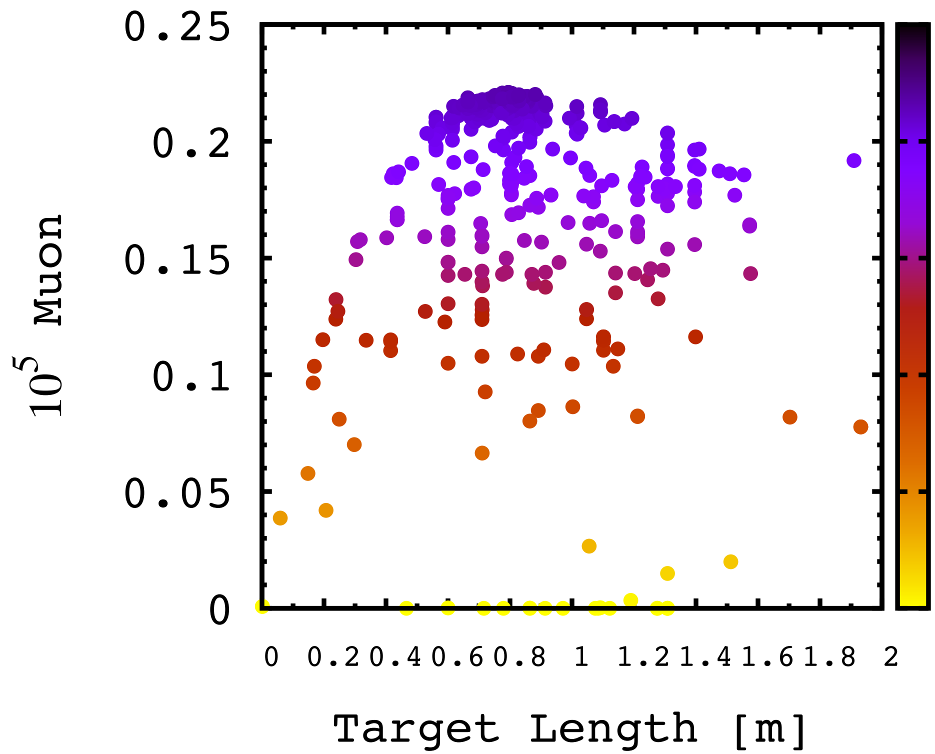


CARBON TARGET GEOMETRY OPTIMIZATION



Optimal working point ~ 1 cm

Optimal working point 70-90 cm



CARBON TARGET GEOMETRY OPTIMIZATION

Optimal working point for C-target

- Proton beam size 1-2 mm
- C–rod Length 80 cm
- C–rod radius 1 cm

Beam + target angle to solenoid axis 2-3 degree

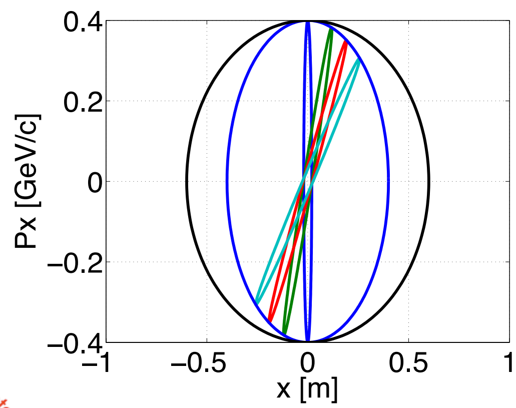
X. Ding: More about MARS simulation of production in today's afternoon talk

Dependence of transverse emittance & Capture efficiency on Peak Field

Emittance growth due to betatron oscillation decohenrce:

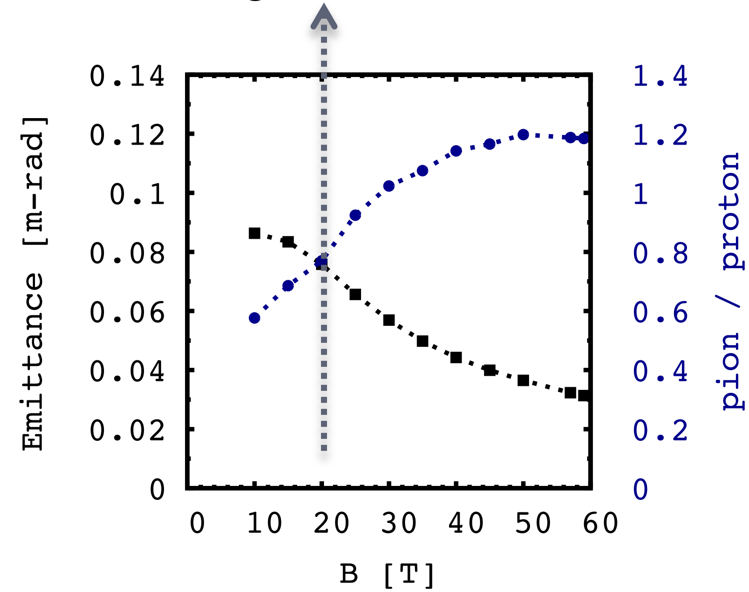
- Pions created at the target
  - Small radial extent (small transverse emittance)
  - Large spread in energy and axial point of origin
- Particles with different energy and different transverse amplitude rotate over the transverse phase space at different oscillation frequencies.

- Strong solenoid field stabilizes the emittance growth by reduction of axial extend
- The final projected transverse emittance is smaller for higher fields



$$\epsilon_{\perp} = \frac{2\sigma_{p_{\perp}}^2}{eB_z m_{\pi} c}$$

Limit of operation of solenoids in high radiation area

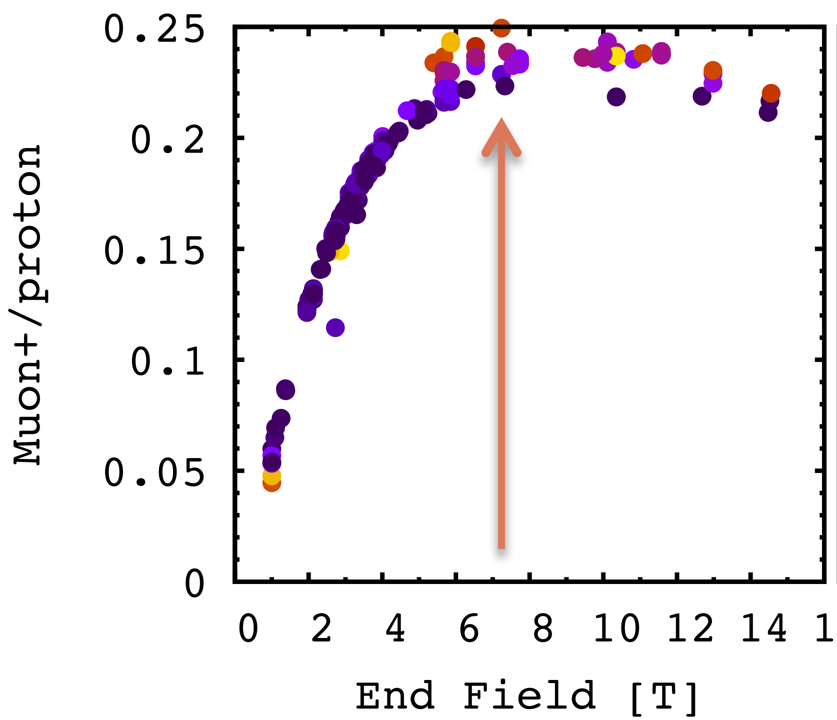


MARS Simulation of π^+ & μ^+ production from 8 GeV proton beam on Hg target.

- Emittance calculation from covariance matrix
- particle count at end of the target

CARBON TARGET GEOMETRY OPTIMIZATION

Optmization of the target end field and decay channel – (no buncher- rotator RF)

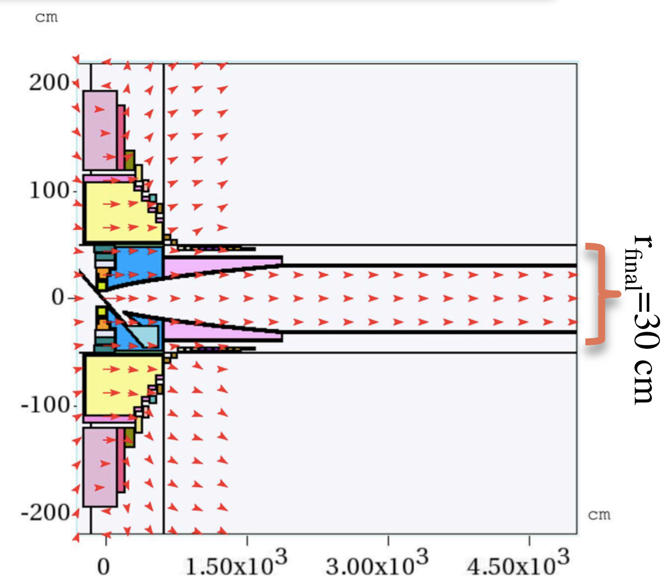


MARS Simulations & Transmission

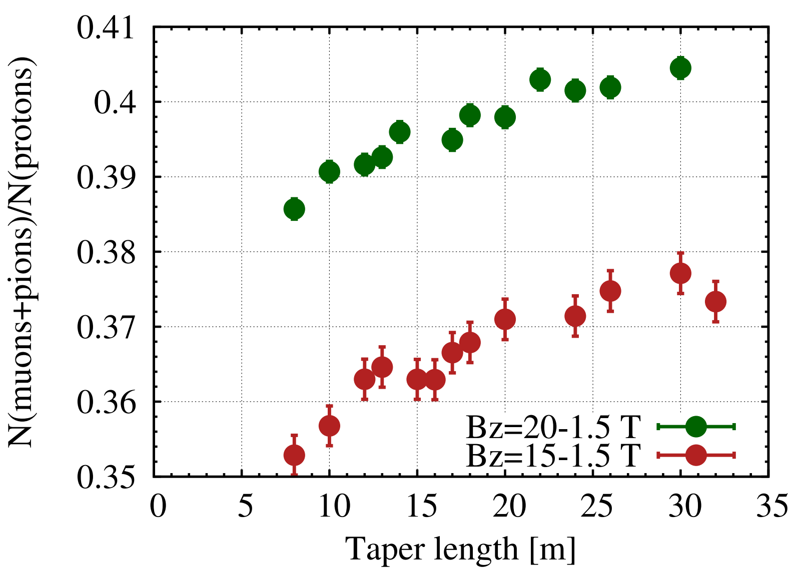
Muon count within energy cut at end of decay channel

Adiabatic condition:
length scale over which the magnetic field changes is large compared to betatron wavelength of the helical trajectory of a particle

$$\frac{2p}{eB^2}\frac{dB}{dz} << 1$$



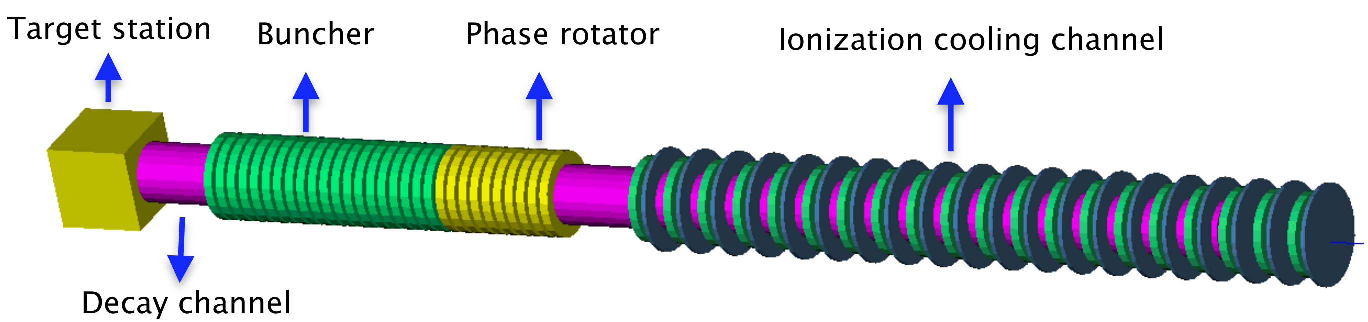
Muon count at z = 50 m increases for longer solenoid taper

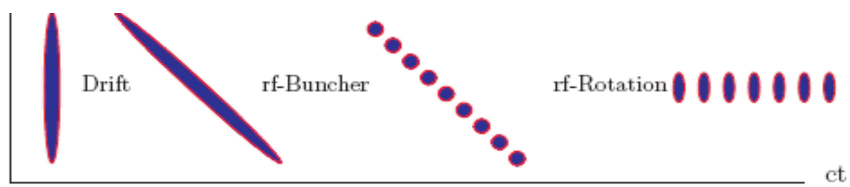


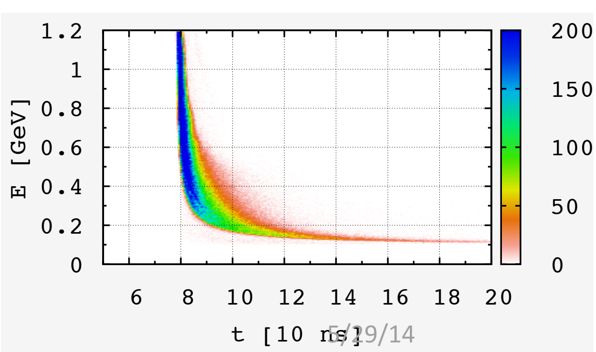
MARS15 Simulation:
Counting muons at 50 m with K.E. 80-140 MeV

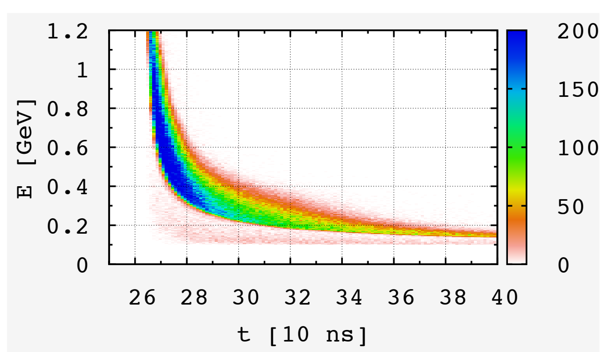
BUNCHER AND ENERGY PHASE ROTATOR

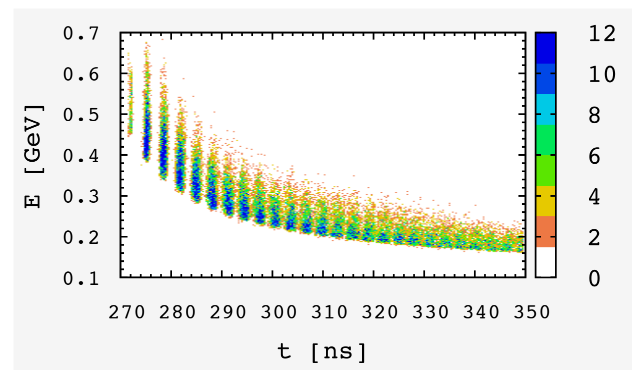
Target: π production
Drift: π's decay to μ's + creation of time-energy correlations
Adiabatic bunch:
Converts the initial single short muon bunch with very large energy spread into a train of 12 microbunches with much reduced energy spread
Energy phase rotatation: Align microbunches to equal energies - RF 232 to 201 MHz - 12 MV/m
Transverse ionization cooling: RF 201.25 MHz









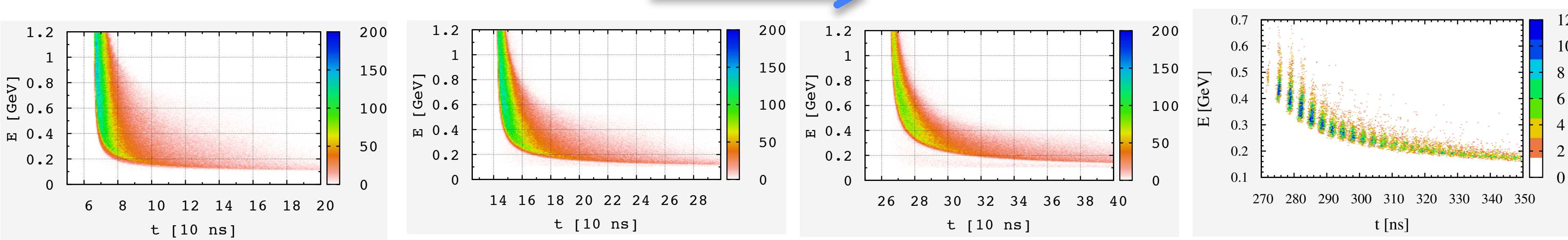


Longitudinal Phase Space Distributions (Short versus long taper)

Temporal difference between the arrival time at a position z of a particle with a nonzero transverse amplitude and that of a particle with zero transverse amplitude

$$\Delta t \approx \frac{p_{\perp}^2 E}{2c^2 p^3} \int_0^z \frac{B_z(z')}{B_z(0)} dz'$$

Long adiabatic taper 40 m



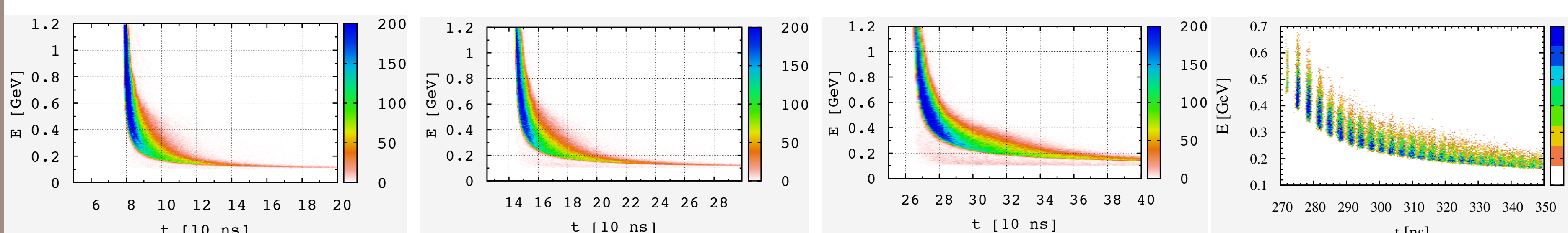
z = 20 m

End of Decay z = 80 m

After buncher

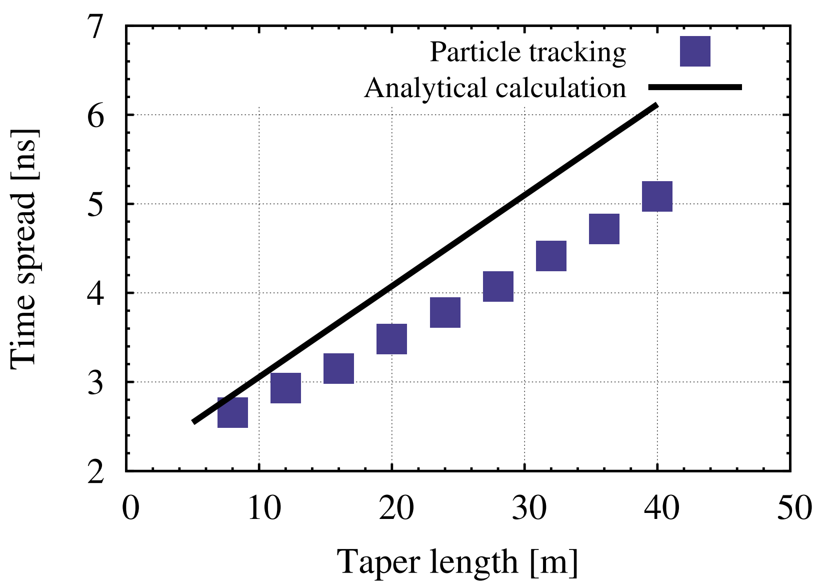
Short taper 4 m

Shorter bunch length
Higher longitudinal phase space density



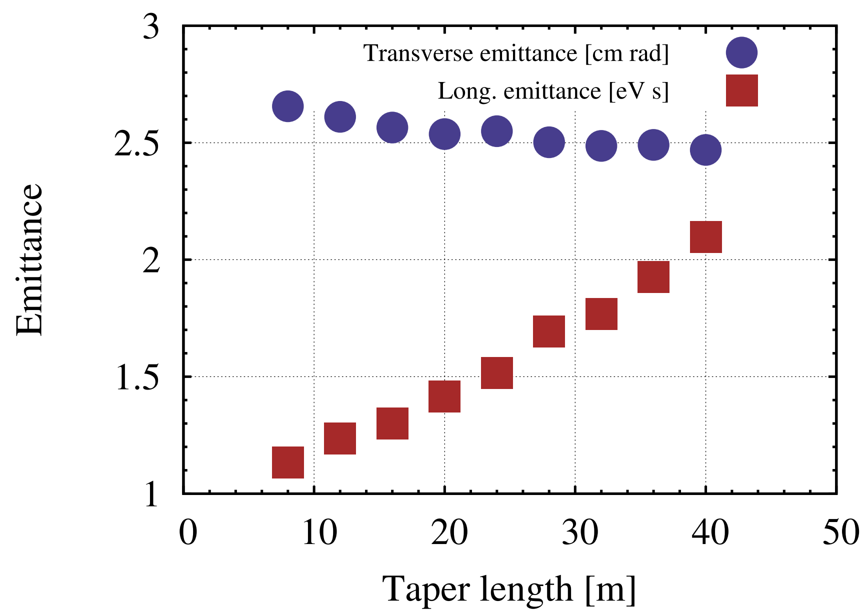
DEPENDENCE OF TIME SPREAD & TRANSVERSE EMITTANCE ON TAPER LENGTH

Time spread dependence on taper length



Time Spread increase by 90%

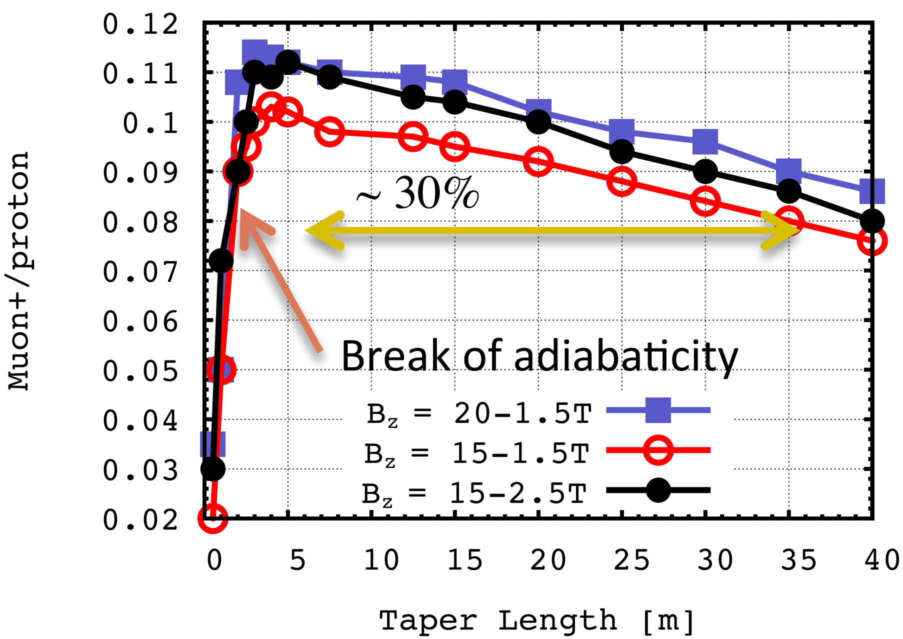
Implication on projected emittance



- Projected transverse emittance did not change dramatically
- Longitudnal emittance decreases more dramatically

FRONT END PERFORMANCE

Muon count within acceleration acceptance cuts at end of ionization cooling channel



Long Solenoid taper:

- More particles
- Large time spread → large longitudinal emittance

Short Solenoid taper:

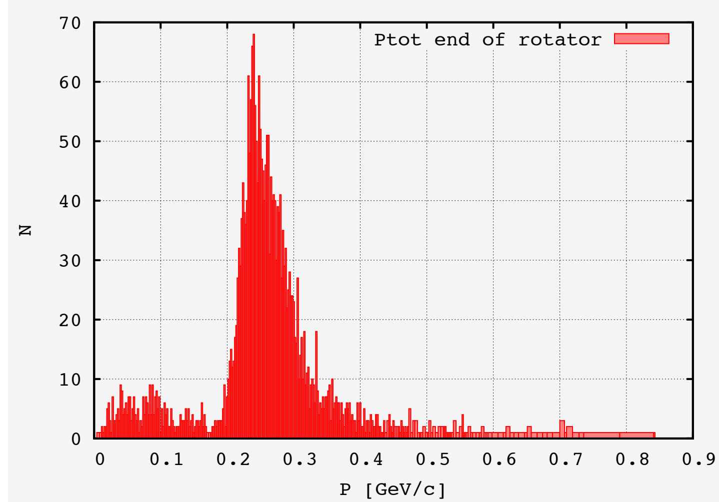
- Smaller time spread → smaller longitudinal emittance
- Fits more particles within the acceptance of buncher/rotator

Shorter taper provide better quality muons → More muons at end of ionization cooling channel

NUMERICAL NONLINEAR GLOBAL OPTIMIZATION ALGORITHMS ON NERSC

- **Expensive objective evaluations on CRAY: (In collaboration with LBNL)**
  - High performance parallel environment: N cores > 1000
    - Run parallel evaluations of the objective functions (Parallel Evolutionary algorithms)
    - Each evaluation of the objective run in parallel to limit the cost of every evaluation (parallel Icool – G4BL , MARS .. etc.).
- **Implemented algorithm:**
  - **Parallel Differential Evolutionary Algorithms**

Momentum distribution of "useful muons" at end of phase rotator

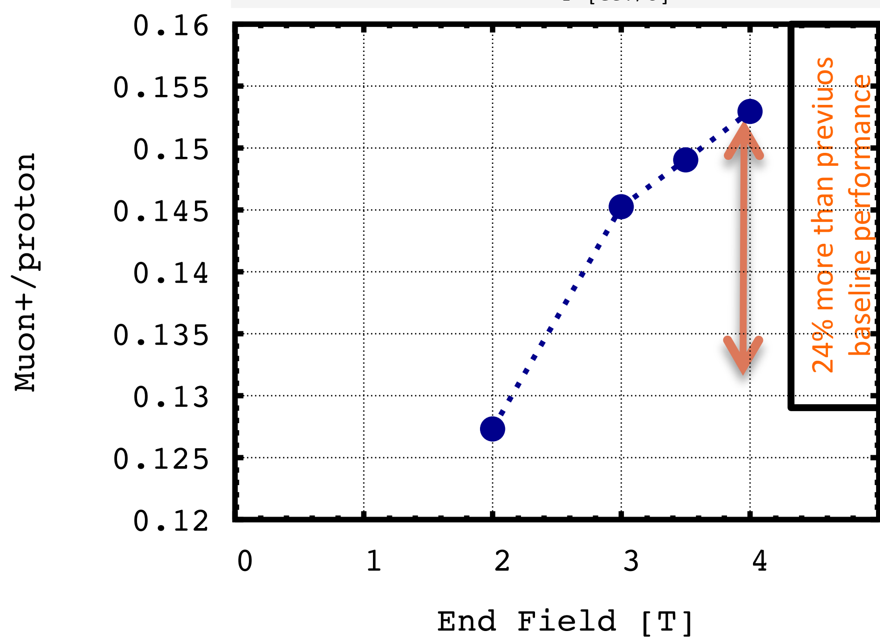


Muon Front End Global Optimization

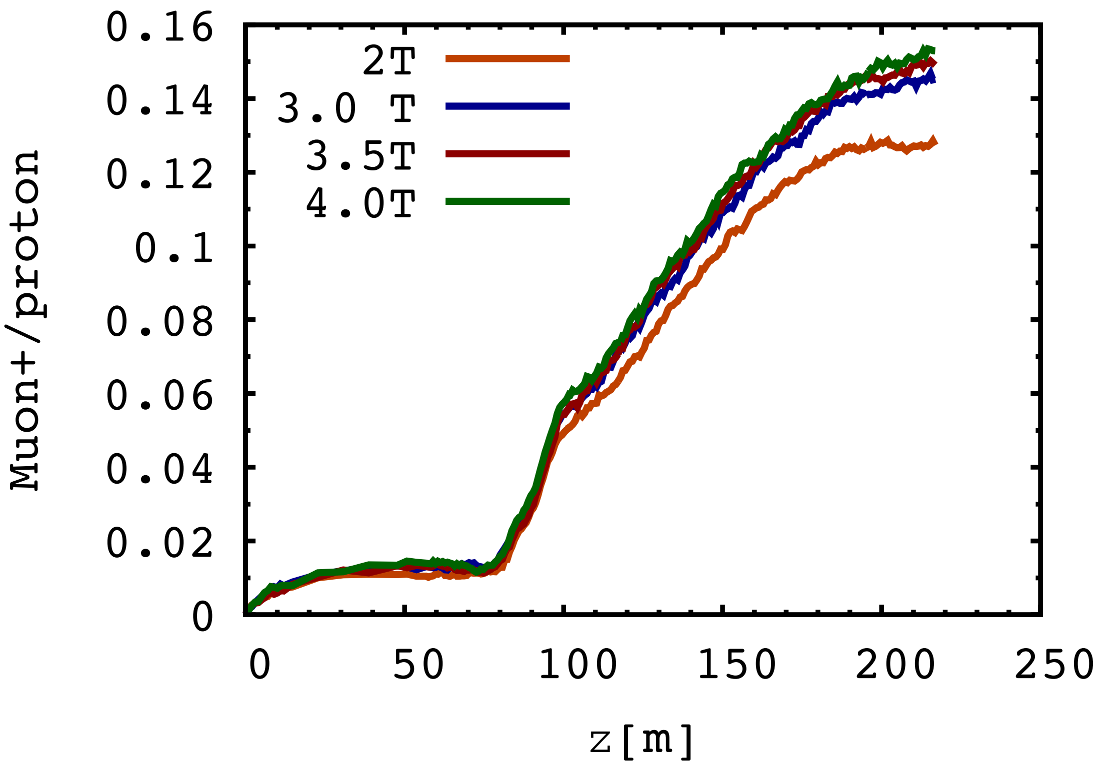
- Multivariable optimization of the Muon Accelerator Front End:
  - Optimal taper length
  - Optimizing the broad band match to the 4D ionization cooling channel

End Field Limitations:

- Operation of RF cavities in magnetic fields

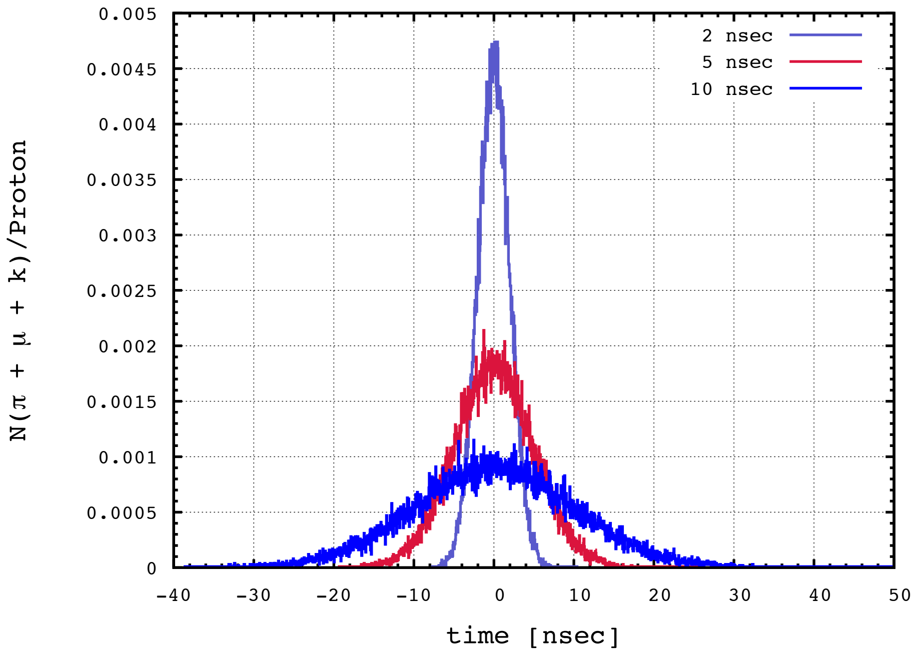


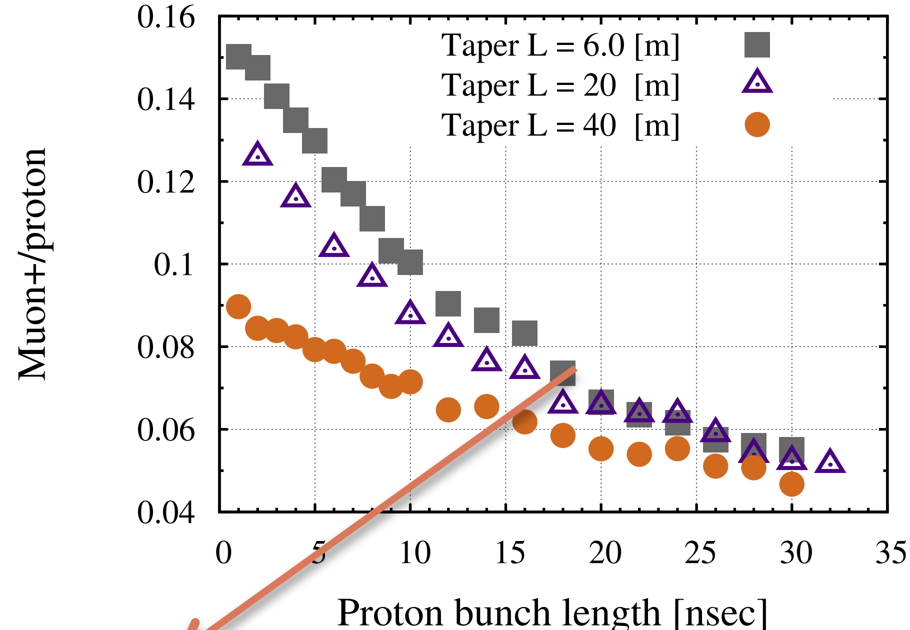
FRONT END PERFORMANCE AT DIFFERENT END FIELDS



Proton Bunch Length

Muon yield versus Proton Bunch Length



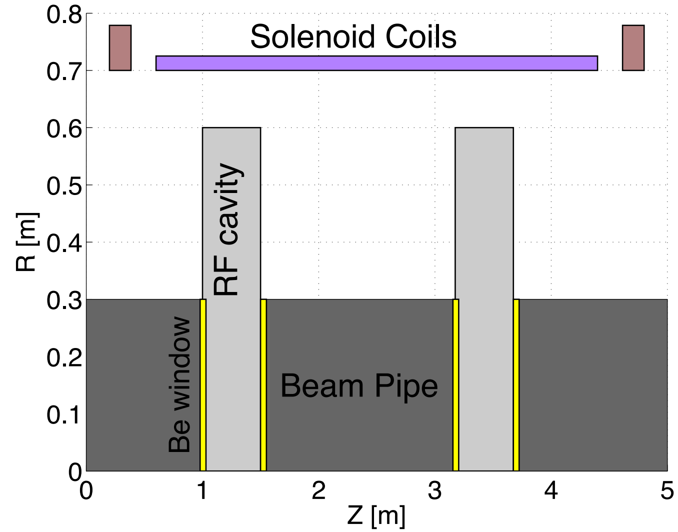


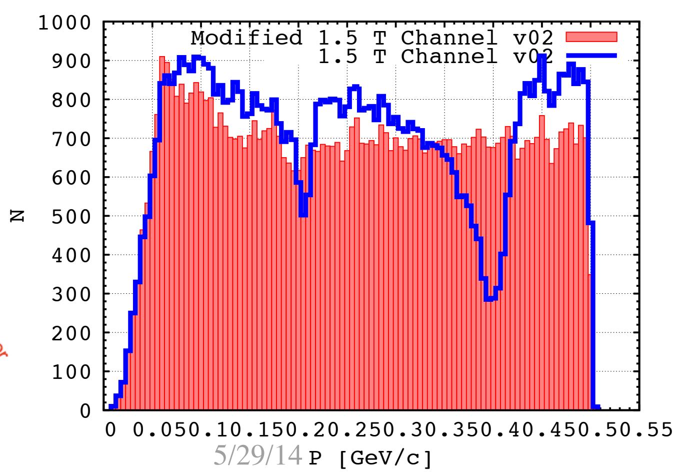
Limit at which short taper losses advantages

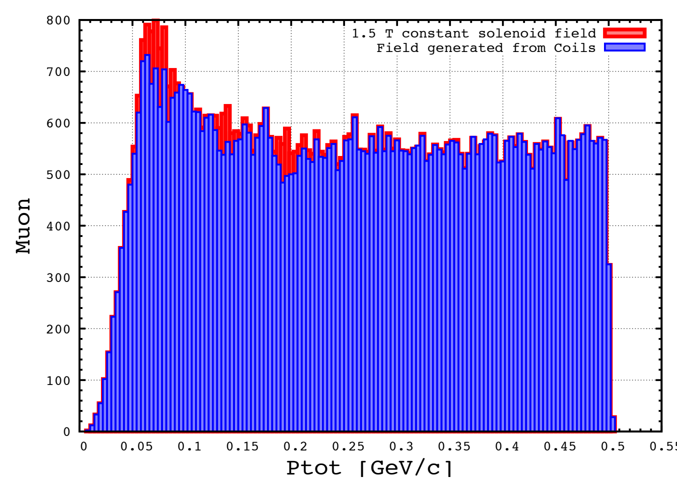
~ 3% loss per 1 nsec increase in bunch length

Realistic Coil based Front End solenoid

Suppression of stop bands in the Decay Channel:
Tracking muons through decay channel 10 cells (50 m) optimize magnet design for best performance







CHICANE

2

Short taper (6 m) integrated with the new chicane from Pavel's G4BL lattice (same parameters as in ICOOL)

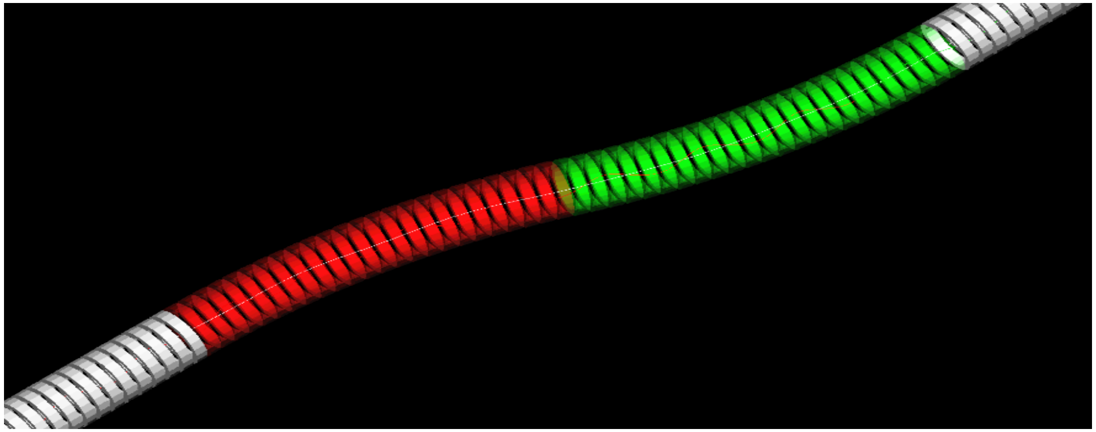
2 Started optimizing the chicane parameters (initial values 2 D. Neuffer's ICOOL lattice)

- Chicane length L (initial value L = 6.0)
- Chicane radius of curvature h (initial value = 0.05818 1/m)
- Be absorber length (initial value = 100.0 mm)
- On-axis field is a free parameter – optimization will be carried for B= 2.0 – 2.5 – 3.0 T -
- Chicane aperture 40 cm (might be a free parameter as well)

- Objectives → minimize total KE of transmitted protons $\Sigma\ KE_{protons}$

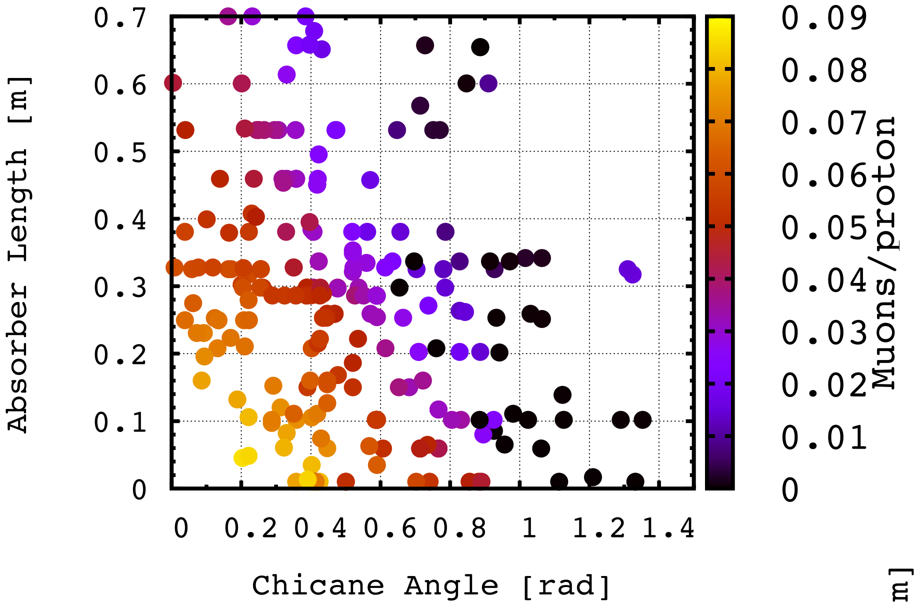
  → Maximaiz number of transmitted muons $\Sigma\ \pi+\mu+\kappa$ within 0 <pz < 450 MeV/c (to compensate for the Be absorber effect) & 0 < pt < 150 MeV/c

Run 100 K particles through the chicane with initial parameters $\Sigma\ KE_{protons}$ = 29 GeV & $\Sigma\ N_{mu}$= 4377

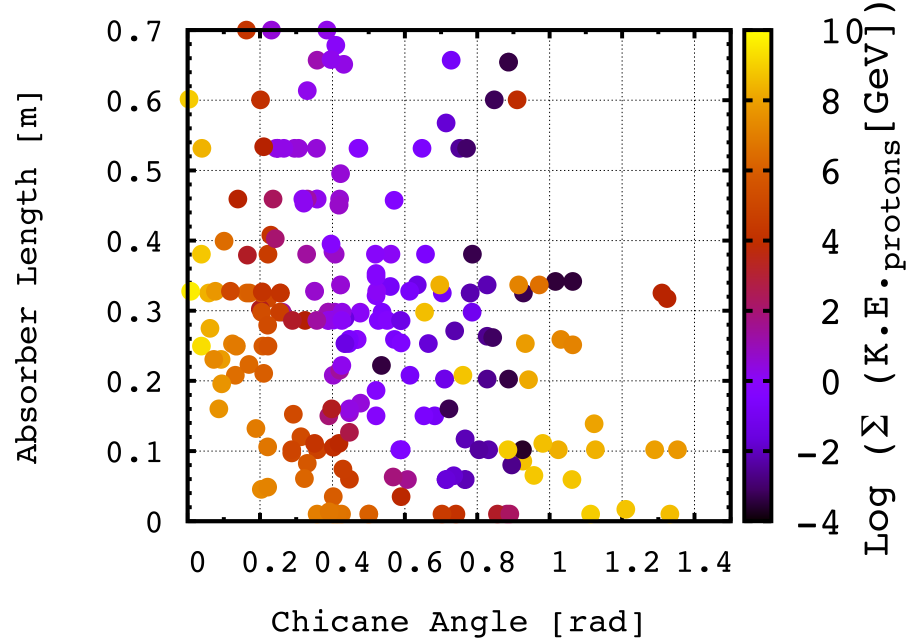


CHICANE

Run 500 K particles through the chicane with automated optmization algorithm



B_0 = 2.0 T



CHICANE

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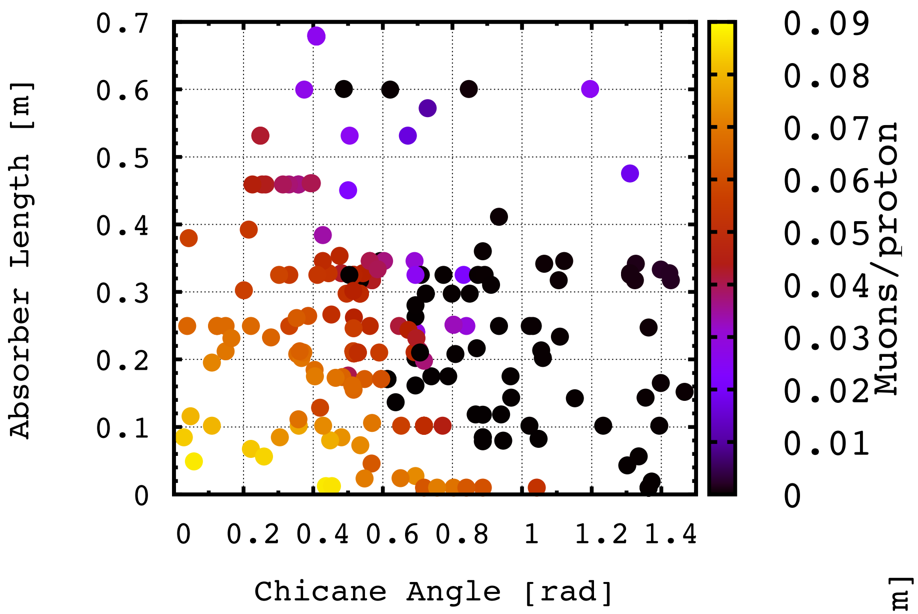
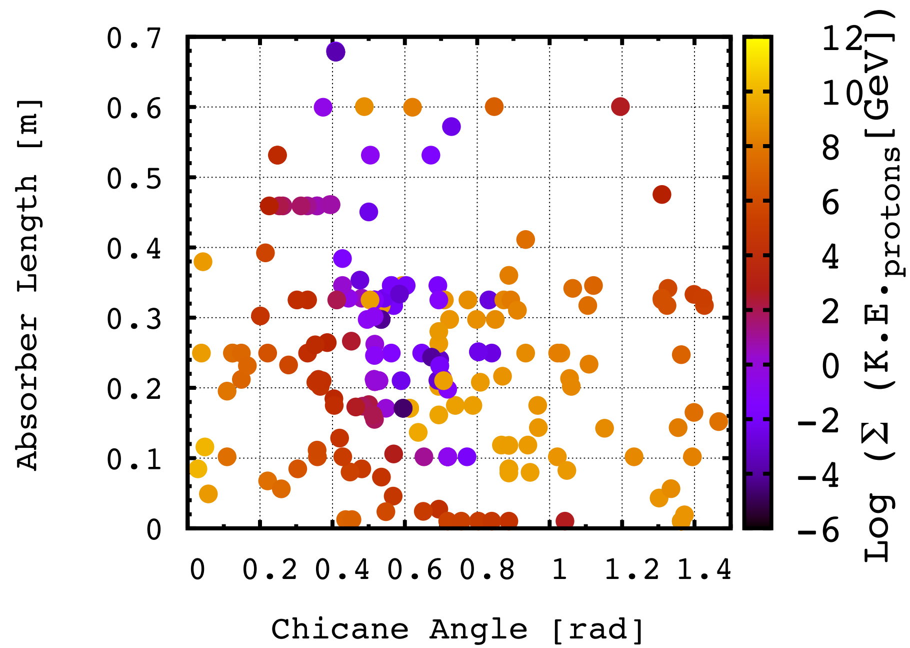
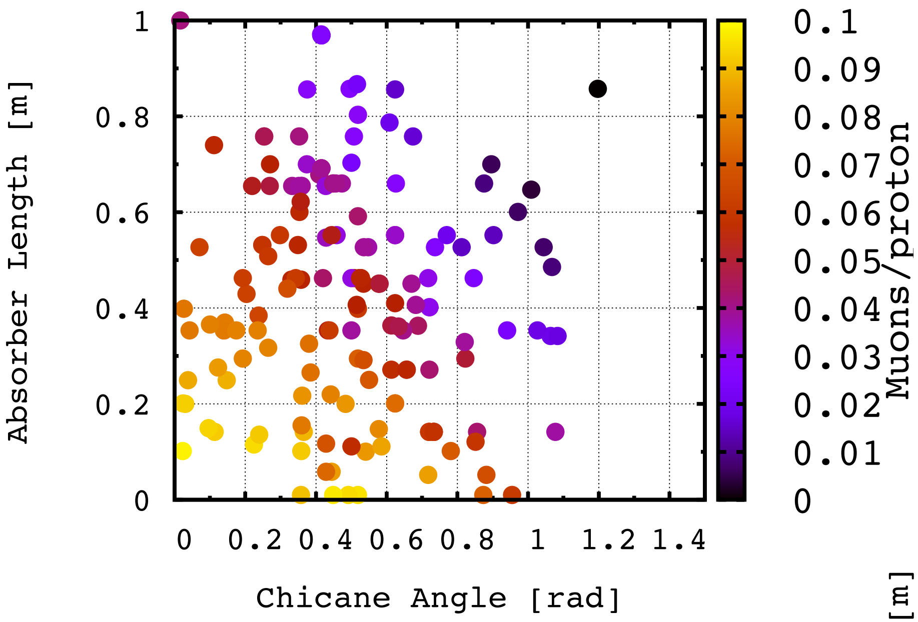


$B_0 = 2.5$ T

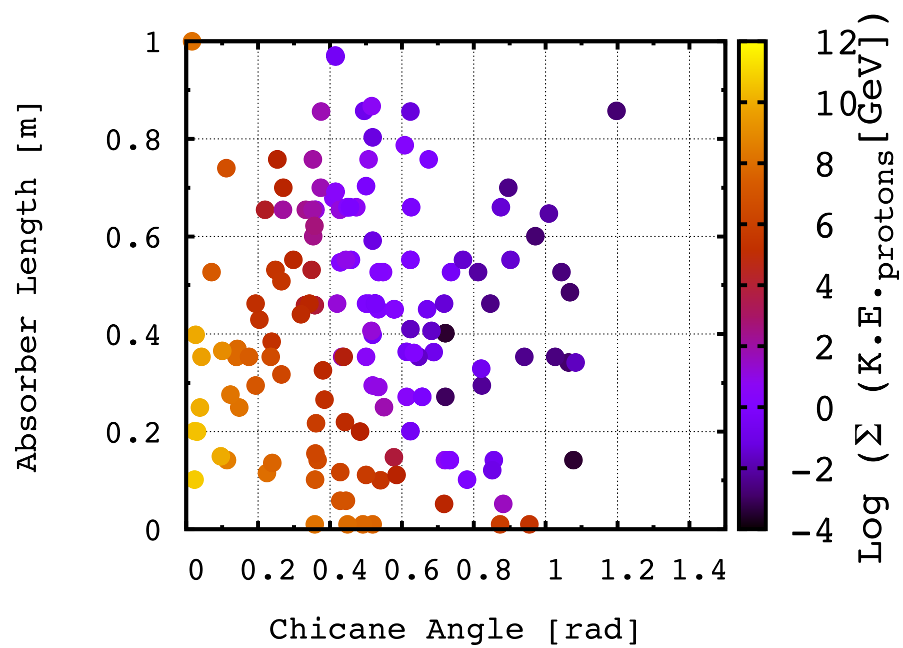


CHICANE

Run 500 K particles through the chicane with automated optmization algorithm



B_0 = 3.0 T



CHICANE

Selected solutions from the chicane optmizations

Bend = 2.0 T

H	L	Be thickness [mm]	Σ $Ke_{protons}$ [GeV]	Σ N_{mu}
0.057587951	10.23983	101.88068	0.547549	13507
0.016493698	26.35389	253.06591	0.219561	13151

Bend = 2.5 T

H	L	Be thickness [mm]	Σ $Ke_{protons}$ [GeV]	Σ N_{mu}
0.020371496	29.21715	171.05875	0.00846724	15259
0.034974192	16.86029	210.25555	0.0737864	13803

Bend = 3.0 T

H	L	Be thickness [mm]	Σ $Ke_{protons}$ [GeV]	Σ N_{mu}
0.025801926	24.19325	200.9732	0.492047	18730
0.040128693	10.19255	678.29223	1.71021	10426

CONCLUSION & SUMMARY

- New objective for front end optimization
    - Handle excesseive proton beam + unwanted secondaries
    - Capture as much muons
- Energy deposition has to be integrated in the optimization study
    - Partitioning of energy deposited in
        - Chicane
        - Be absorber
- Optmization includes
    - Target geomtery
    - Chicane field + chicane geomtery
    - Be absorber
    - Re-tune buncher & phase roation