Frictional Cooling
for a Muon Collider

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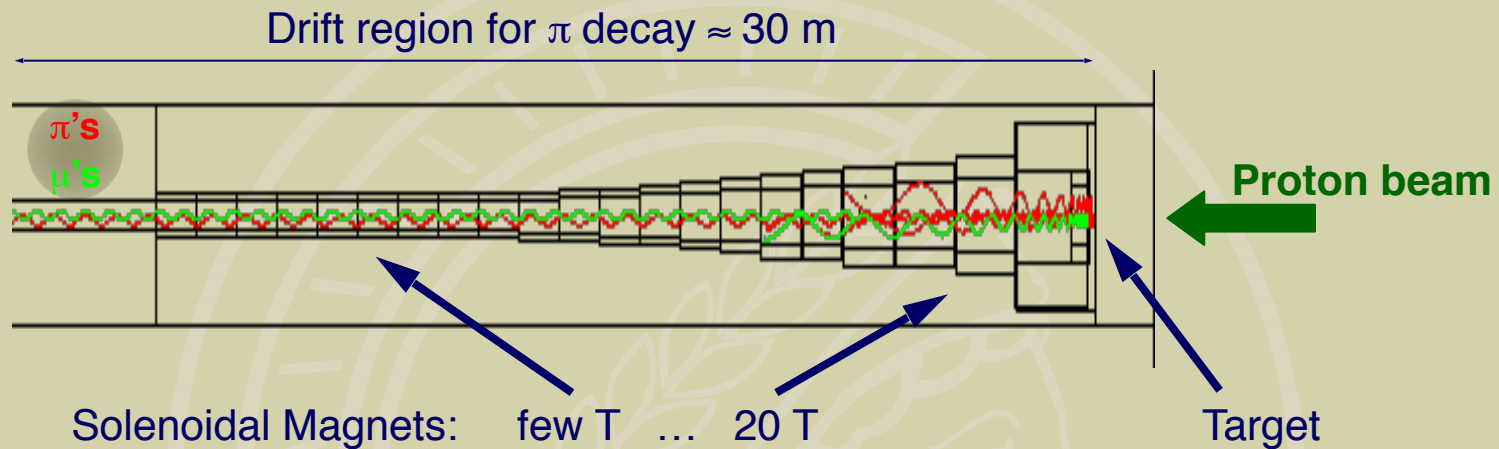
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+ Emily Alden, Christos Georgiou, Daniel Greenwald, Laura Newburgh, Yujin Ning, William Serber, Inna Shpiro (students)

What is the Problem ?

Muons decay with lifetime **2.2 µs**

→ need a multi MW source

- large starting cost

→ large experimental backgrounds

- lots of energetic $e^{\pm}$ from μ decay

→ limited time for cooling, bunching, and accelerating

- need new techniques

→ limitations due to neutrino induced radiation

- cannot be shielded

μ **beam production**

Drift region for π decay ≈ 30 m

π's
μ's

Proton beam

Solenoidal Magnets: few T … 20 T Target

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beam description using 6D emittance
(6D phase space of the beam)

$$\varepsilon_{6D,N} = \frac{\sigma_x \sigma_y \sigma_z \sigma_{p_x} \sigma_{p_y} \sigma_{p_z}}{(\pi\, mc)^3}$$

after drift estimate

rms: x, y, z 0.05, 0.05, 10 m
      p_x, p_y, p_z 50, 50, 100 MeV

$\varepsilon_{6D,N} \approx 1.7 \times 10^{-4}\ (\pi m)^3$
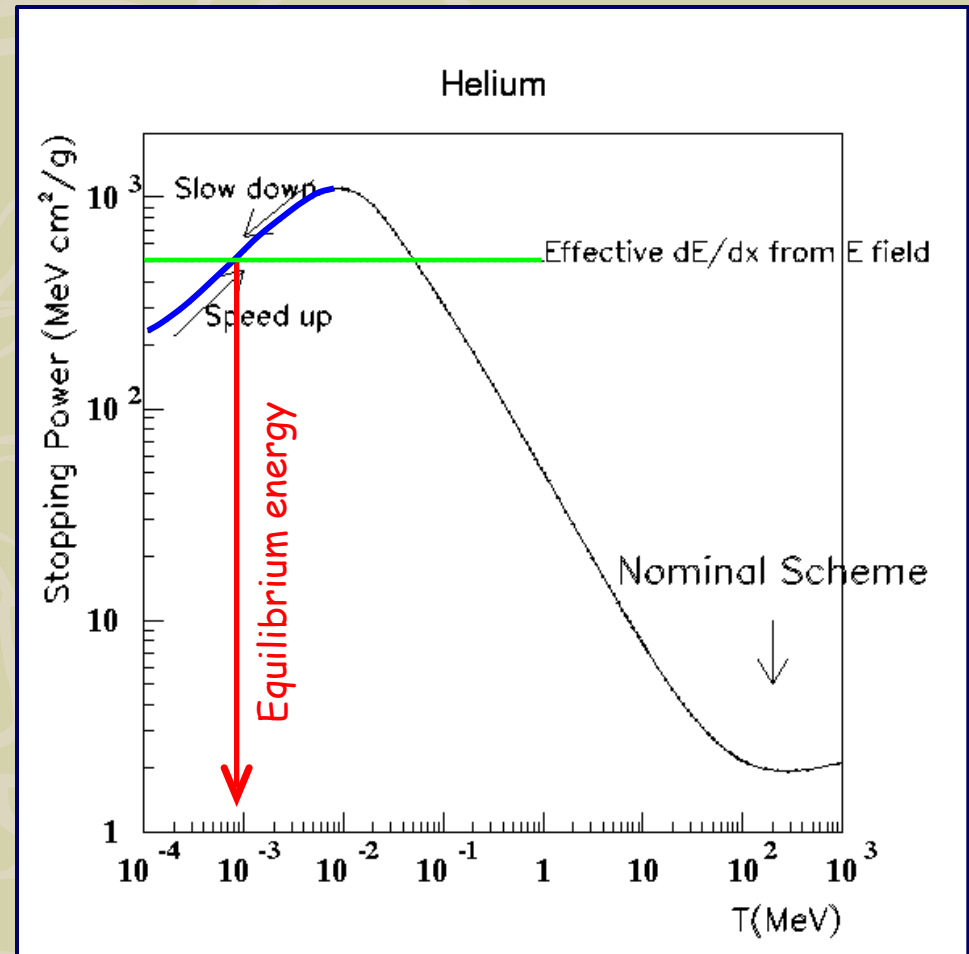
required

$\varepsilon_{6D,N} \approx 1.7 \times 10^{-10}\ (\pi m)^3$

COOLING

Frictional cooling

Idea

- bring muons to kinetic energy *T* where *dE/dx* increases with energy

- apply constant accelerating *E* field to muons resulting in **equilibrium energy**

- big issue – how to maintain efficiency
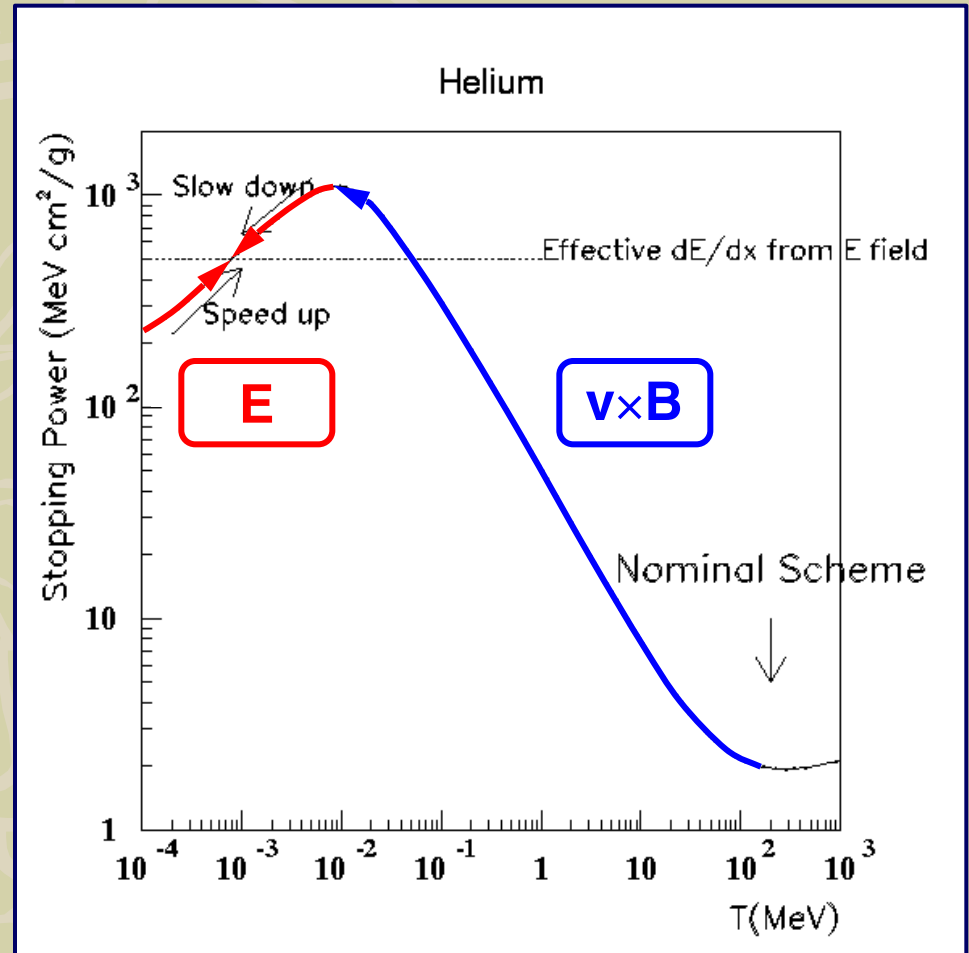
- similar idea first studied by Kottmann et al. at PSI
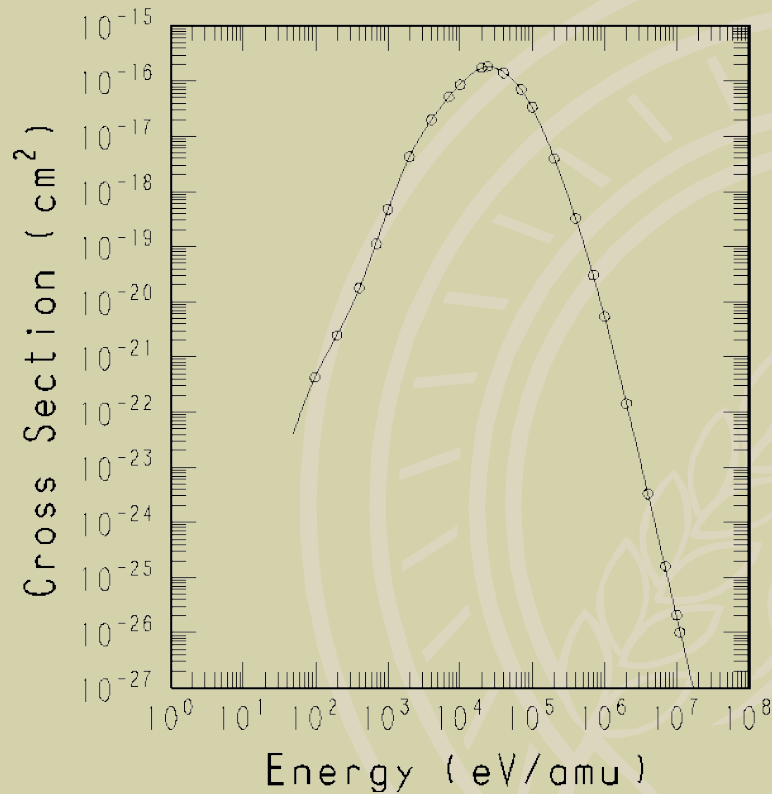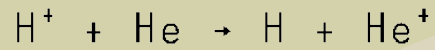
Frictional cooling

Problems/Comments

- large *dT/dx* at low *T*

    → low average density of stopping medium ⟹ **gas**
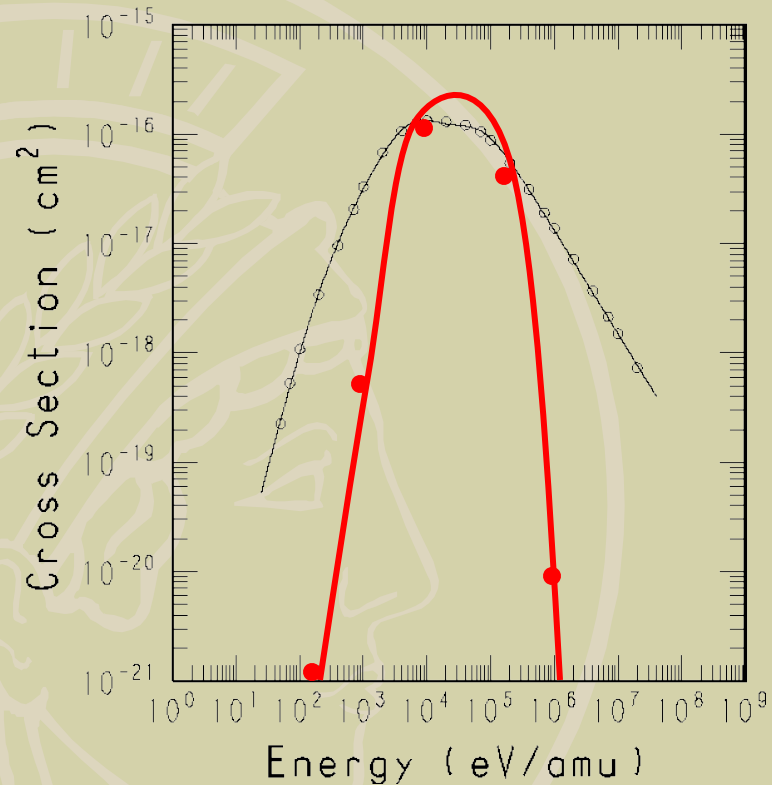
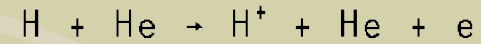- apply **E⊥B** to get below the *dE/dx* peak
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) - \frac{dT}{dx}\vec{v}_0$$

- **slow** μ**'s** don't go far before decaying
$$d = 10\,\text{cm} \times \sqrt{T}$$ with *T* in eV

    → sideward extraction (**E⊥B**)

- μ**+** problem – **muonium formation** dominates over e-stripping except for **He**

- μ**−** problem – **muon capture** at low energies; σ not known

    ⟹ keep *T* as high as possible

Helium

Effective dE/dx from E field

Slow down

Speed up

E

v×B

Nominal Scheme

Stopping Power (MeV cm²/g)

T(MeV)

Neutralization

$$H^+ + He \rightarrow H + He^+$$

Stripping
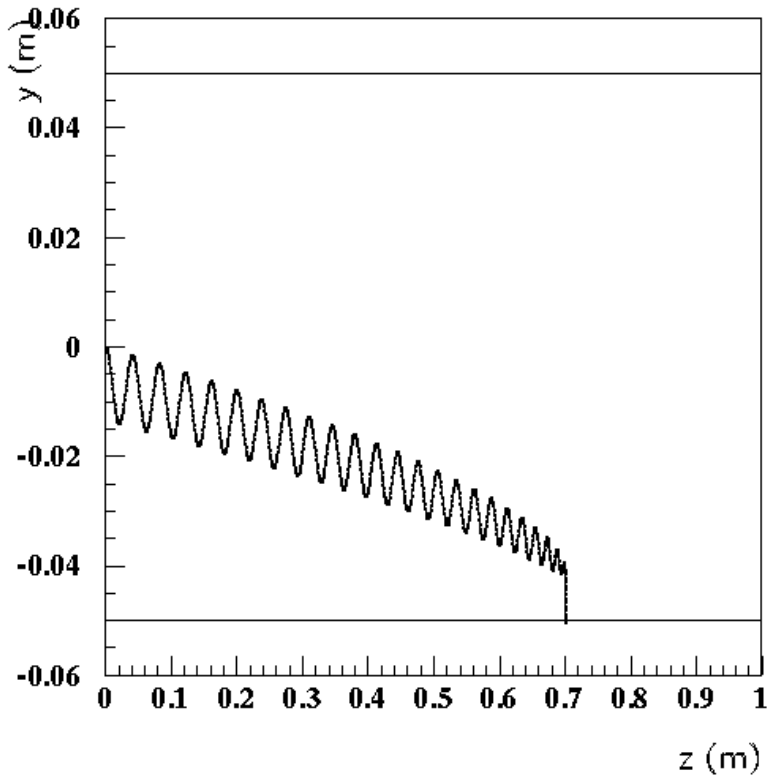
$$H + He \rightarrow H^+ + He + e$$

From Y. Nakai, T. Shirai, T. Tabata and R. Ito, *At. Data Nucl. Data Tables* **37**, 69 (1987)

For μ, energy lower by M_μ/M_P

Frictional Cooling: particle trajectory
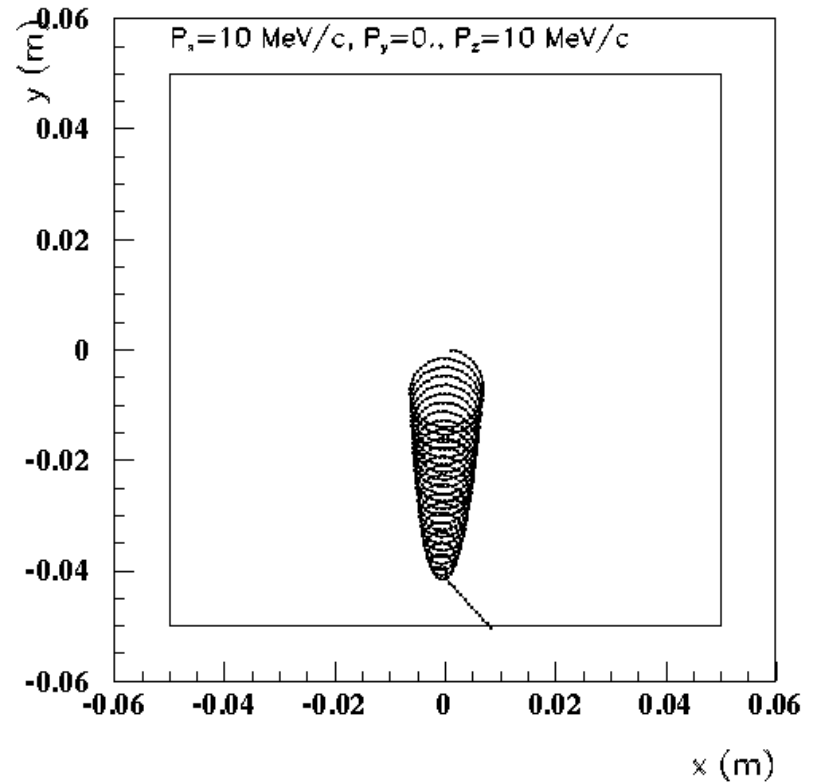
** Using continuous energy loss

Muon collider scheme based on frictional cooling

Not to scale !!

phase rotation — cooling cell — capture & drift — target

p — B=20T..........5T

μ−   π−   π+   μ+

E(t) to reflect beam

reacceleration

collider ring

Simulations performed to this point
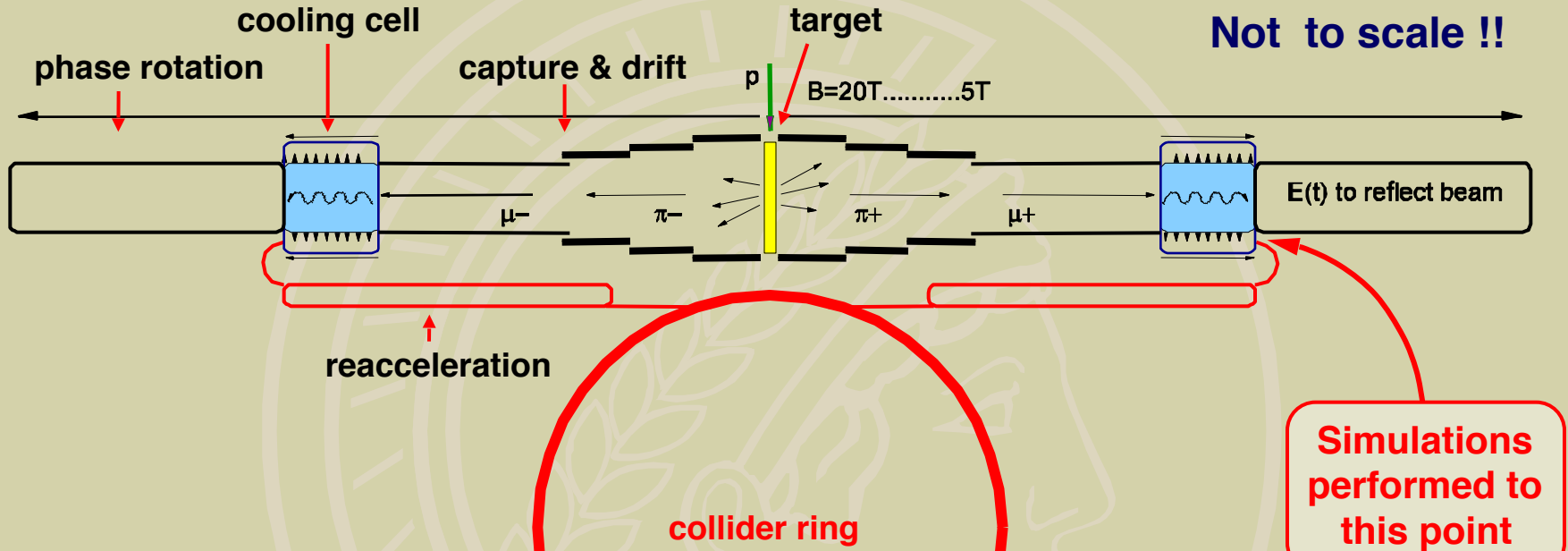
Full MARS simulation of the proton interactions in target (Cu) showed

– larger low energy π yield in transverse directions
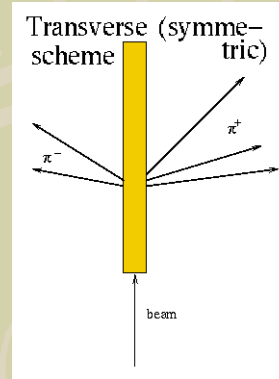– nearly **equal π+ and π− yields** with $T <$ 100 MeV

– **He** gas used for μ+
– **H** gas for μ−
– transverse **E** field **5 MV/m**

– continuous electronic energy loss
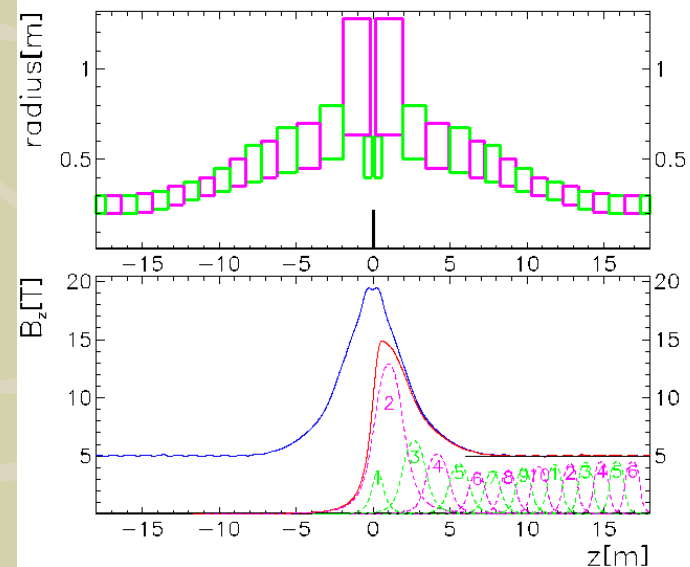– individual nuclear scatters simulated
  → they result in large angles

Target System
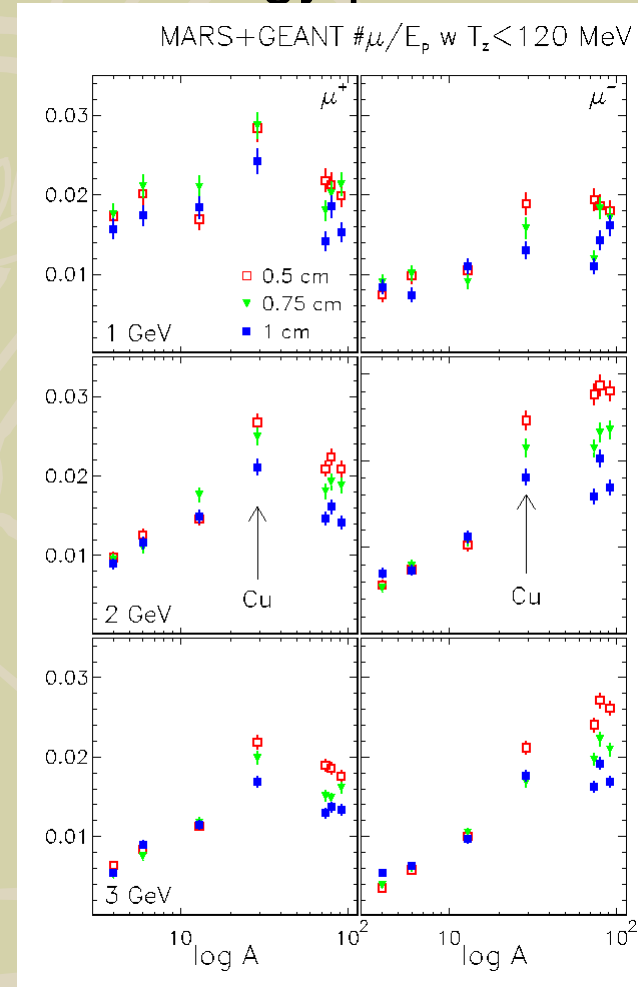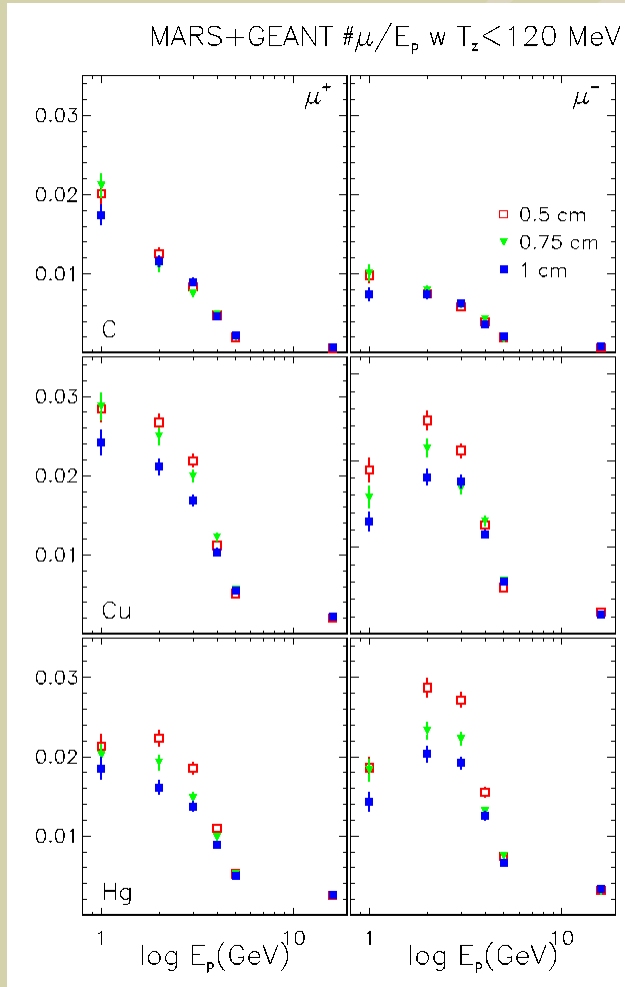

MARS Cu 2 GeV 0.75cm len 30cm
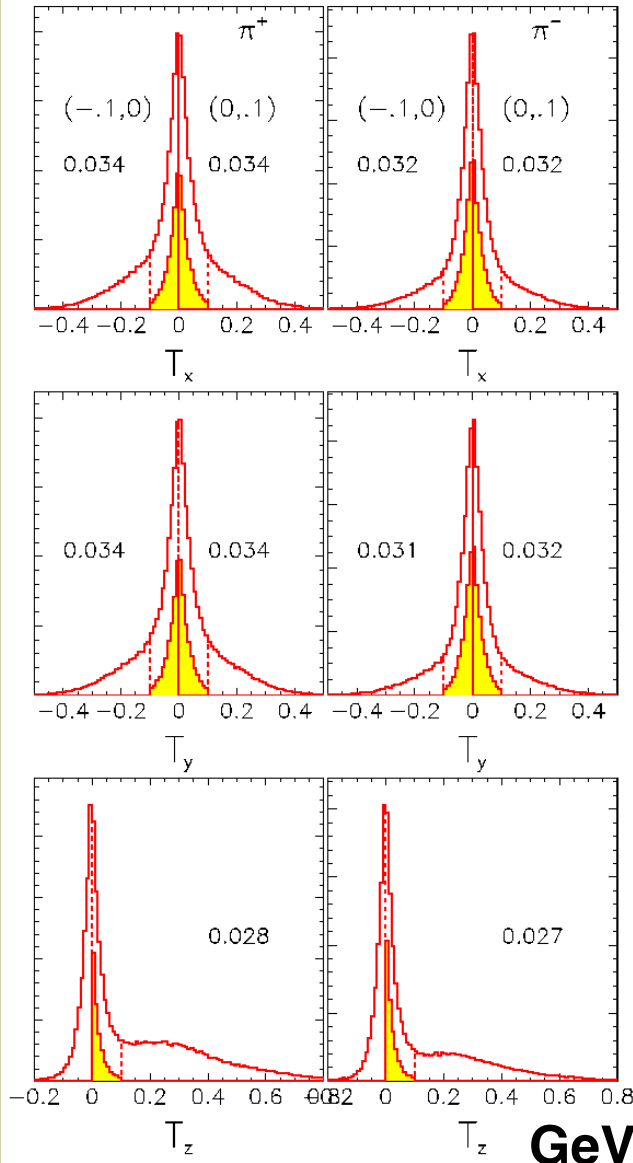
- cool μ+ & μ- at the same time
- calculated new symmetric magnet with gap for target
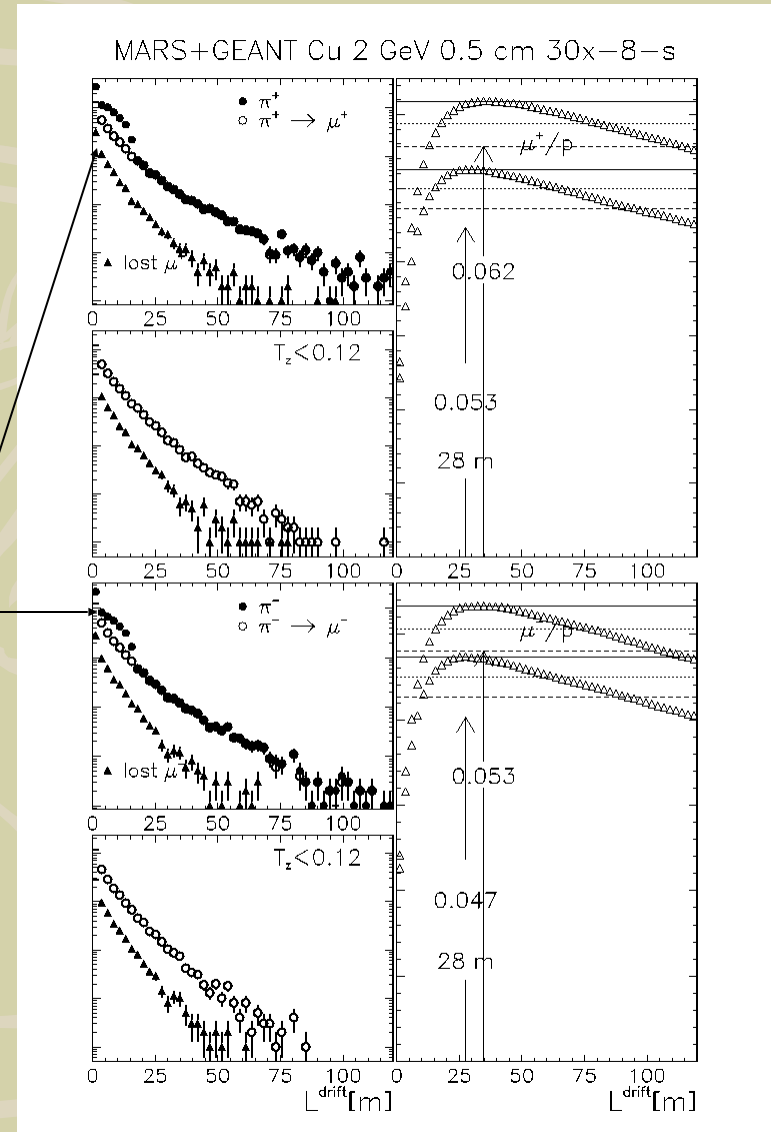

Transverse (symme-tric) scheme

GeV

Full MARS target simulation, optimized for low energy muon yield: 2 GeV protons on Cu with proton beam transverse to solenoids (capture low energy pion cloud).
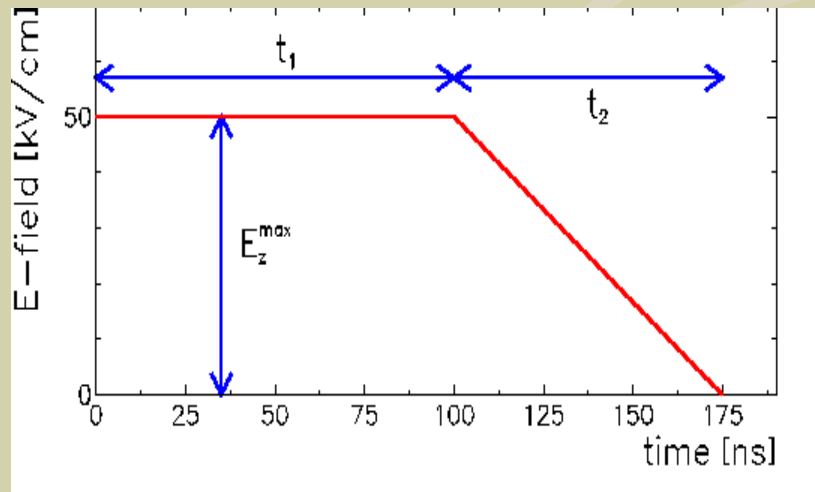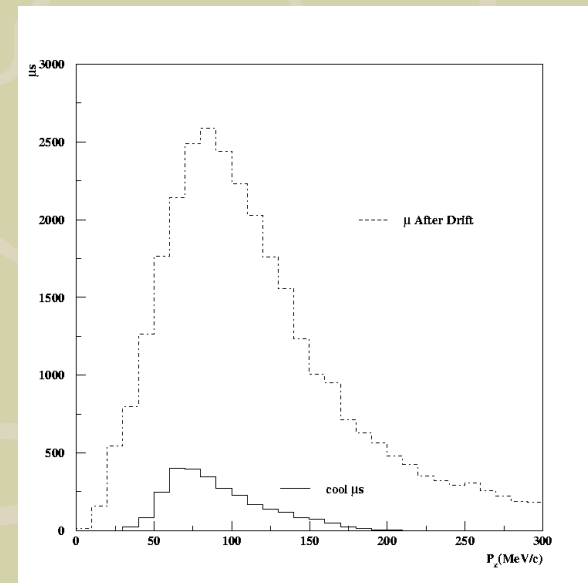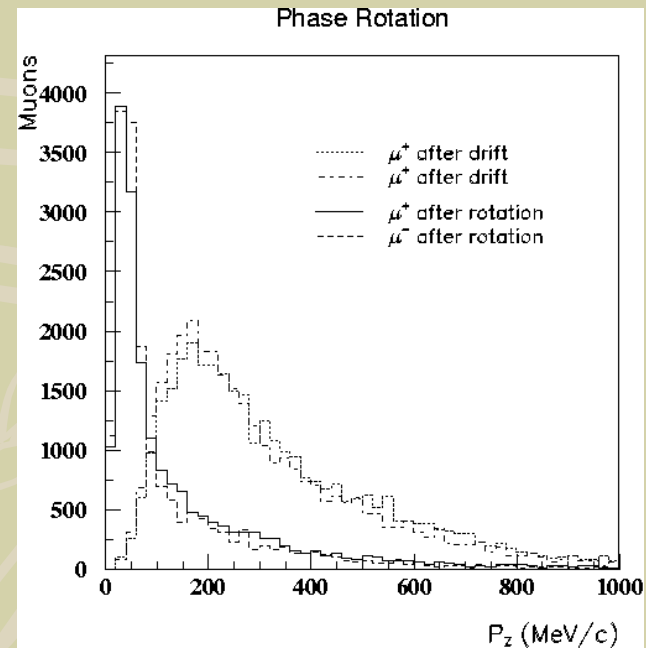
Target & Drift
Optimize yield

• **Optimize drift length for** μ **yield**

• Some π's lost in Magnet aperture

MARS+GEANT Cu 2 GeV 0.5 cm 30x−8−s

Phase Rotation

- First attempt simple form
- Vary t_1, t_2 & E_{max} for maximum low energy yield

Cooling cell simulation

He gas is used for μ^+, H$_2$ for μ^-.

• Individual nuclear scatters are simulated – crucial in determining final phase space, survival probability.

•Incorporate scattering cross sections into the cooling program

•Include μ^- capture cross section using calculations of Cohen (Phys. Rev. A. Vol 62 022512-1)

·Electronic energy loss treated as continuous

Cross Section Comparisons
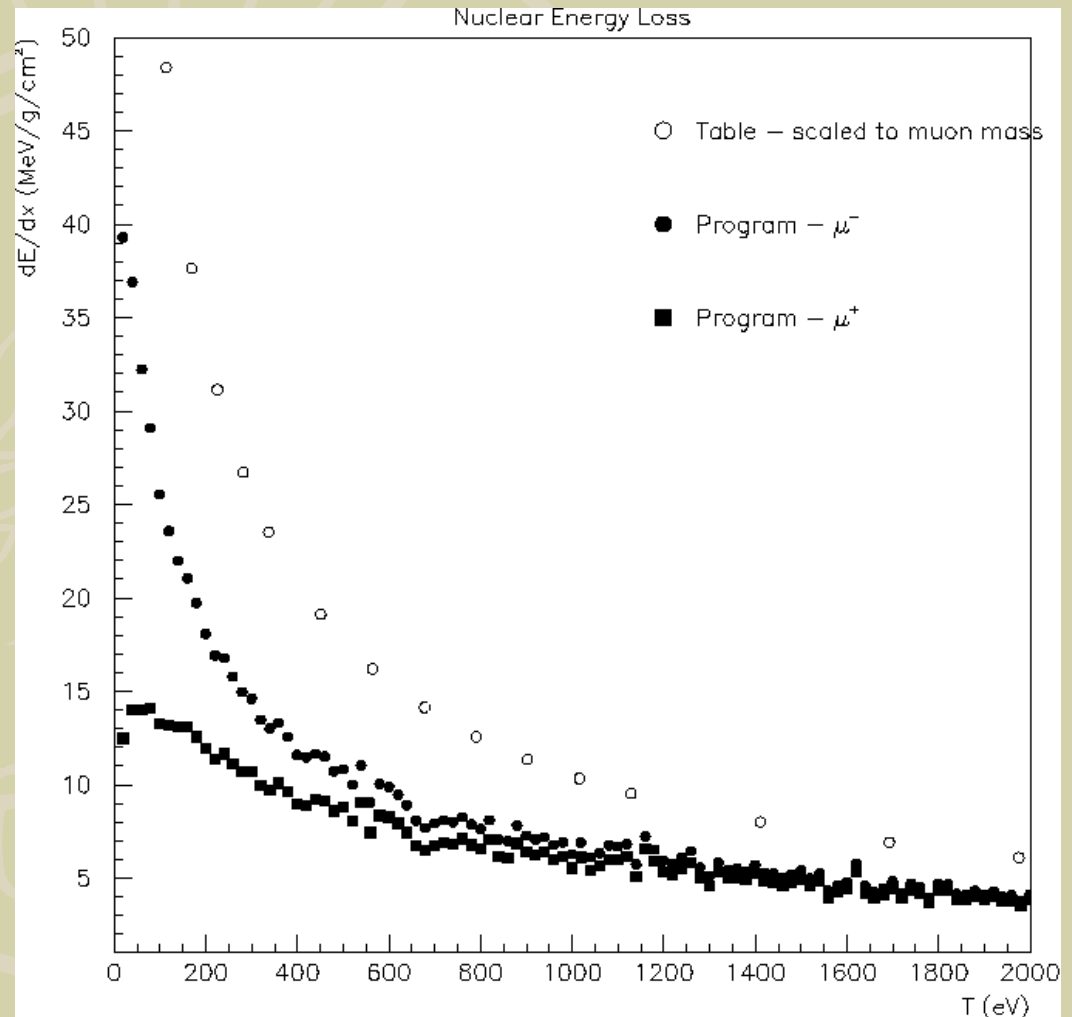
- Capture
- θ>0.1
- θ>1.0
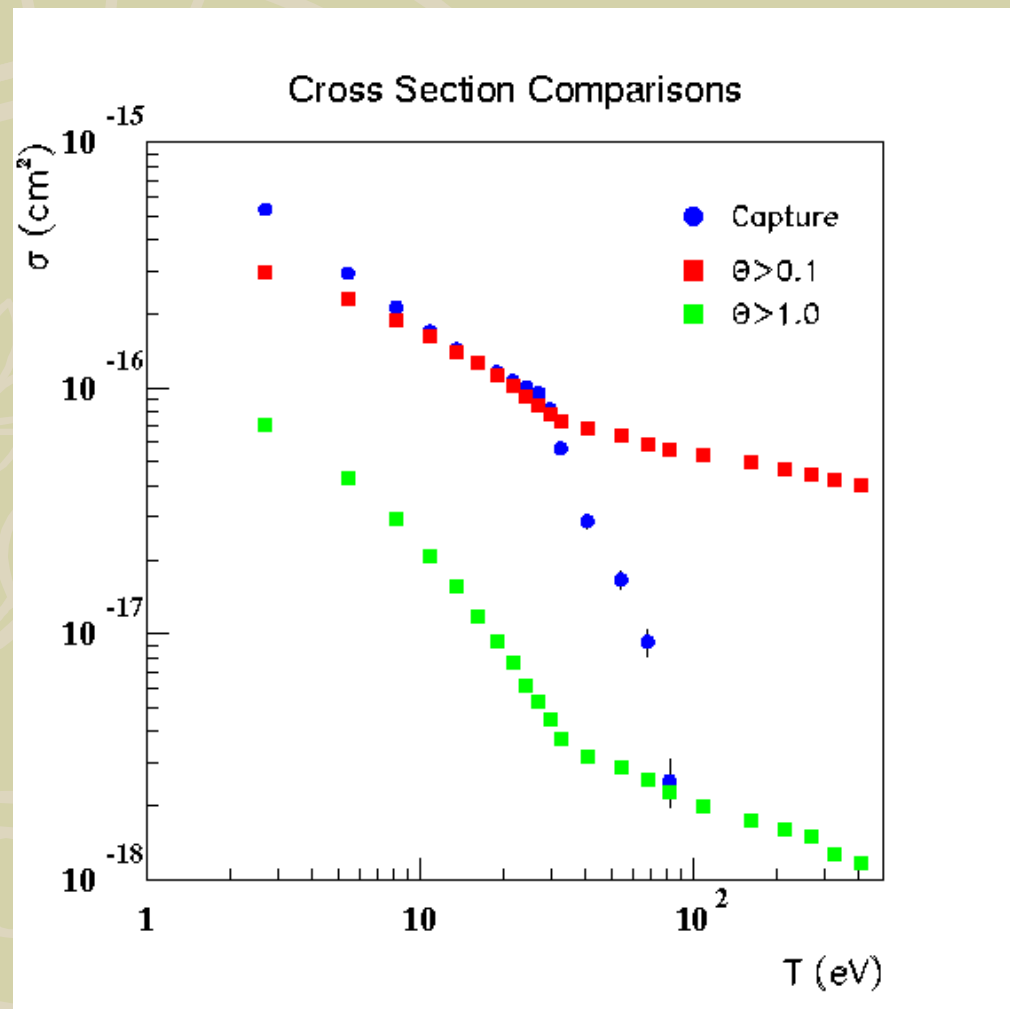
Scattering Cross Sections

• Scan impact parameter and calculate $\theta(b)$, $d\sigma/d\theta$ from which one can get
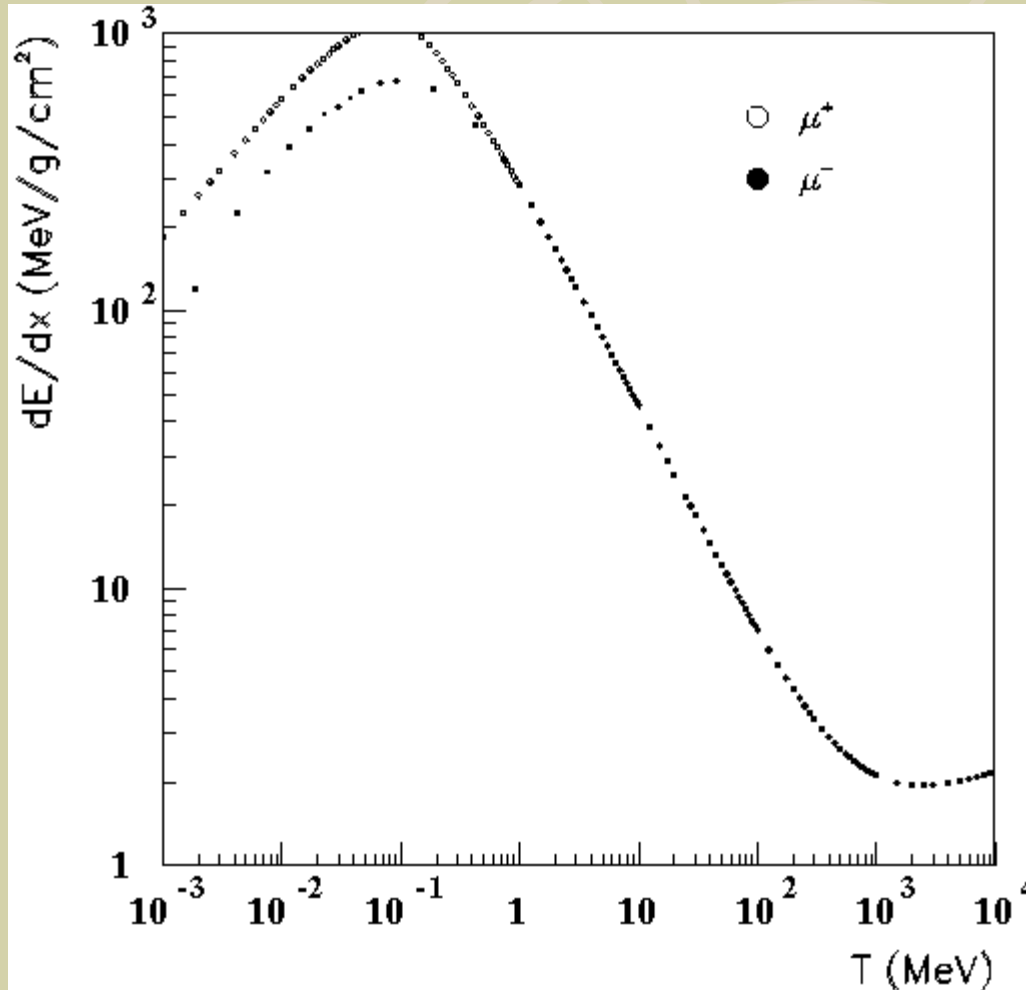
$\lambda_{mean\ free\ path}$

• Use screened Coulomb Potential (Everhart et. al. Phys. Rev. 99 (1955) 1287)

• Simulate all scatters $\theta > 0.05$ rad

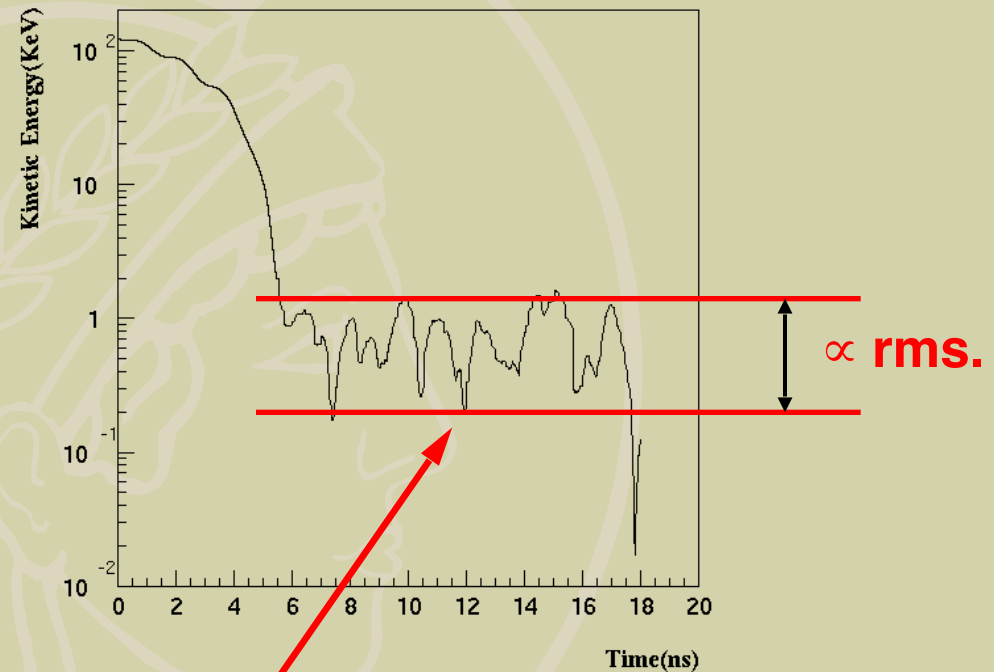• Simulation accurately reproduces ICRU tables for protons
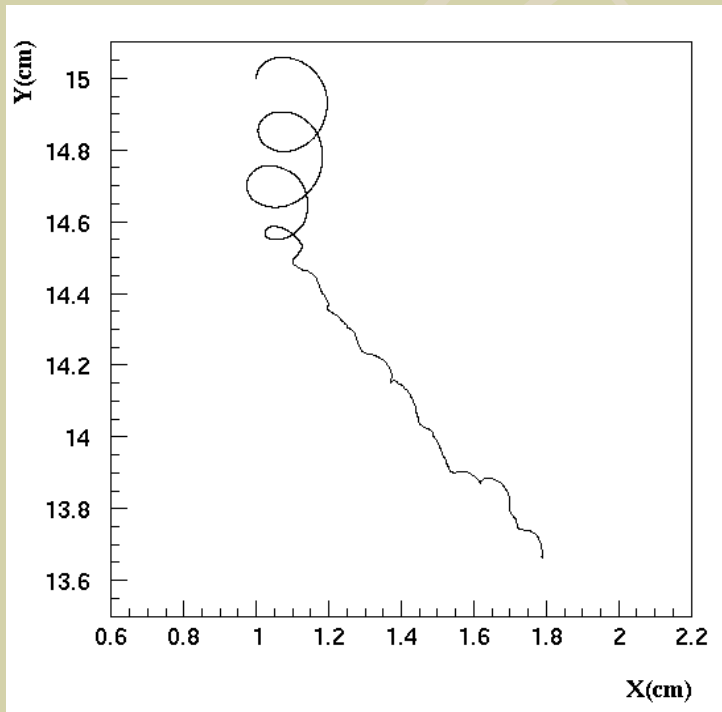
Barkas Effect

- Difference in μ^+ & μ^- energy loss rates at dE/dx peak
- Due to charge exchange for μ^+
- parameterized data from Agnello et. al. (Phys. Rev. Lett. 74 (1995) 371)
- Only used for the electronic part of dE/dx

Simulation of the cooling cell

$\propto$ **rms.**

Oscillations around equilibrium define the emittance

Resulting emittance and yield

Muon beam coming out of 11 m long cooling cell and after initial reacceleration:

> rms: x, y, z 0.015, 0.036, 30 m
> p_x, p_y, p_z 0.18, 0.18, 4.0 MeV
>
> $$\varepsilon_{6D,N} = 5.7 \times 10^{-11} \ (\pi m)^3$$

Results for μ^+, still working on μ^-

$\rightarrow$ better than required $1.7 \times 10^{-10} \ (\pi m)^3$

Yield $\approx$ **0.002** μ **per 2 GeV proton** after cooling cell

$\rightarrow$ need **improvement by factor of 5** or more