Muon capture and transport line

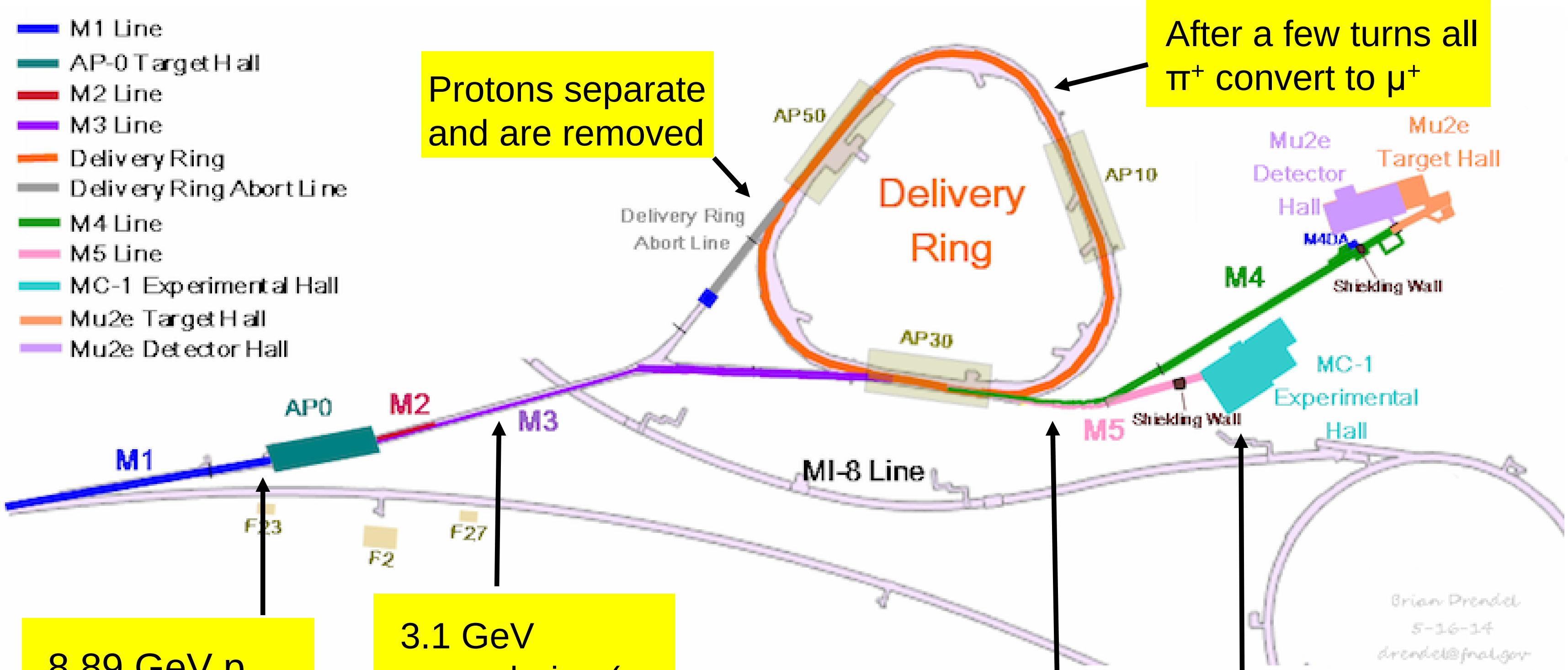
Diktys Stratakis
Fermi National Accelerator Laboratory

USPAS 2019
January 22, 2019

Outline

- Muon and pion capture
- Lattice and optics design
- Expected performance
- Polarization

Muon Campus overview



Protons separate and are removed

After a few turns all π^+ convert to μ^+

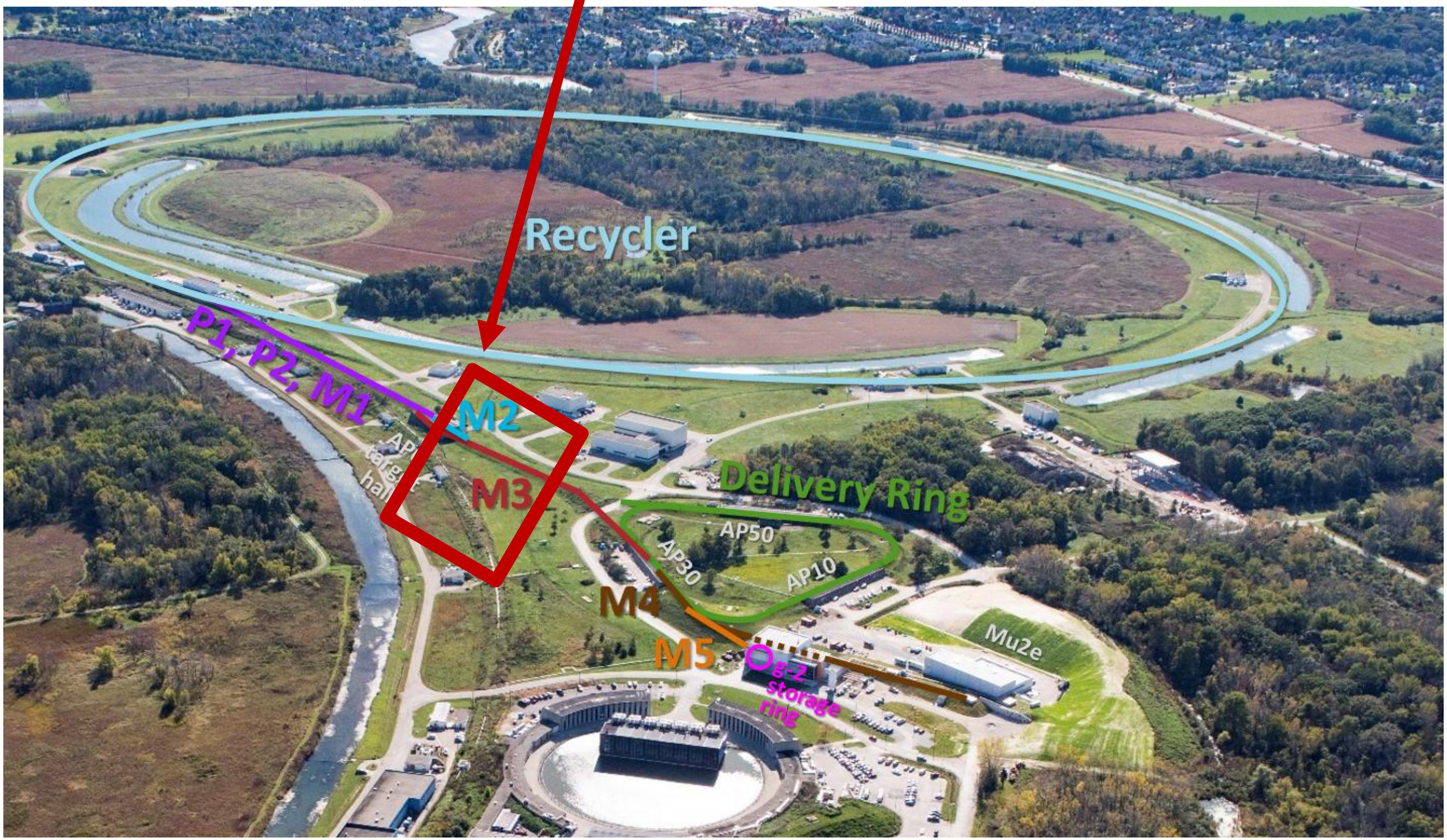
8.89 GeV p beam impacts the target

3.1 GeV secondaries (π, μ, p) travel along M2 & M3

μ^+ are extracted from the ring and transferred into the storage ring via M4, M5

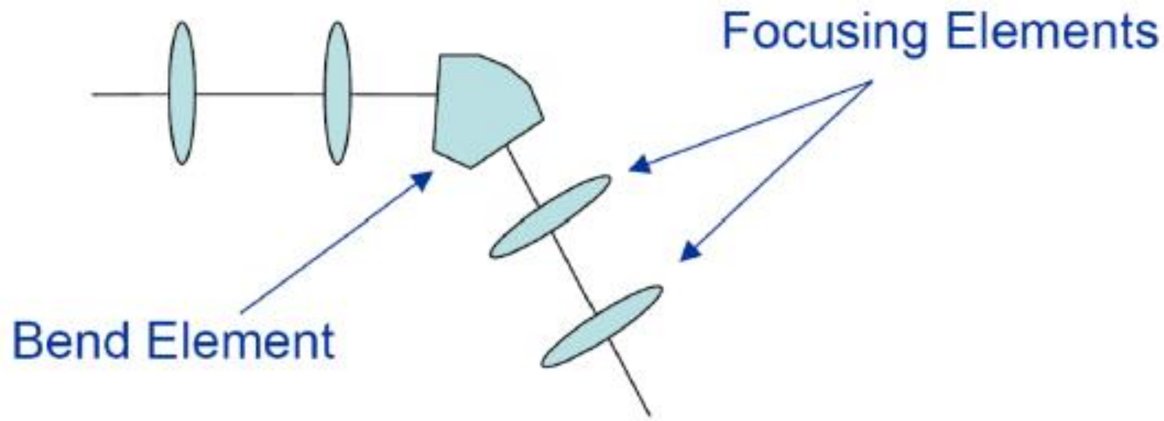
μ^+ enter the g-2 storage ring

Muon capture and transport (M2-M3)



Muon capture & transport line optics

- The capture and transport of secondary beam is done with magnets
- Mainly two types of magnets: bending magnets (dipoles) and focusing magnets (quadrupoles)



Dipole magnets

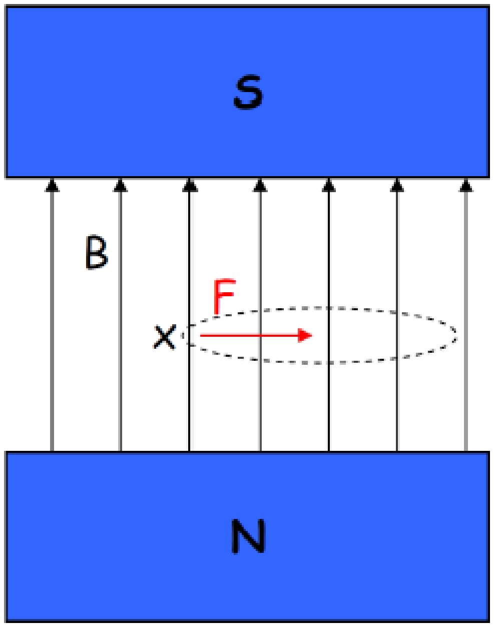
- Recall that the Lorentz force on a particle:

$$F = ma = e(E + v \times B) = \frac{mu^2}{r}$$

- In the absence of an E-field and assuming that B and v are perpendicular:

$$\frac{1}{r} = \frac{eB}{p}$$

- In an accelerator, dipoles are used to bend the beam trajectory. By using the appropriate field, one can tune the system so that particles of certain momentum can transported only



Quadrupole magnets

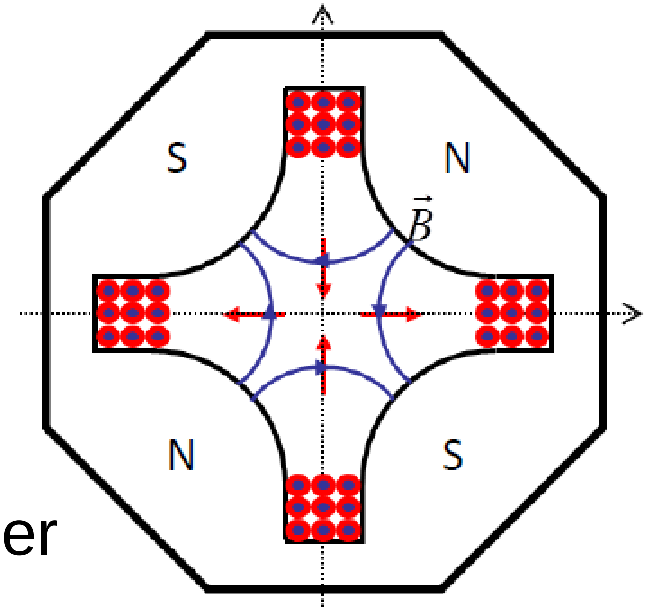
- Quad magnet has four poles and imparts a force proportional to distance from center
- Magnetic Field:

$$B_x = -Gy \text{ and } B_y = Gx$$

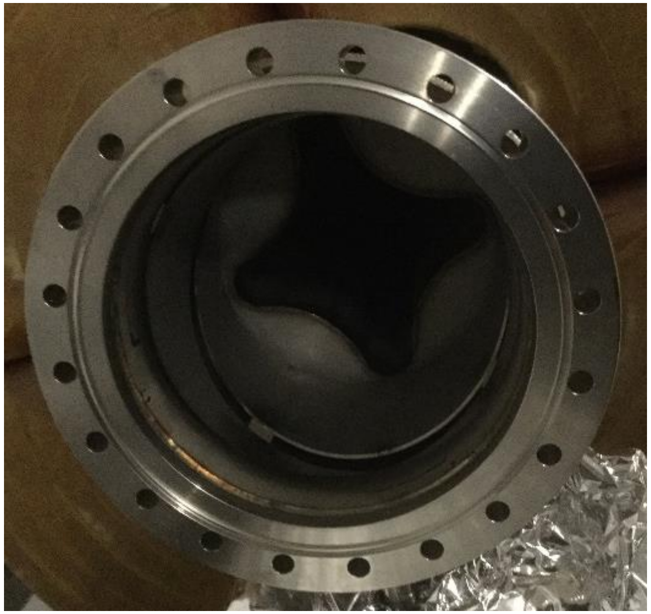
- Magnetic Force:

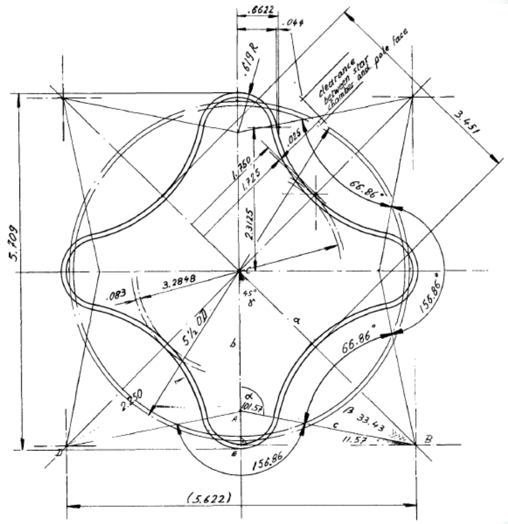
$$F_x = -qvGx \text{ and } F_y = qvGy$$

- Focus in one plane, defocus in the other
- Accelerators consist of a sequence of identical “FODO” cells which combine a focusing & defocusing quad, separated by a drift



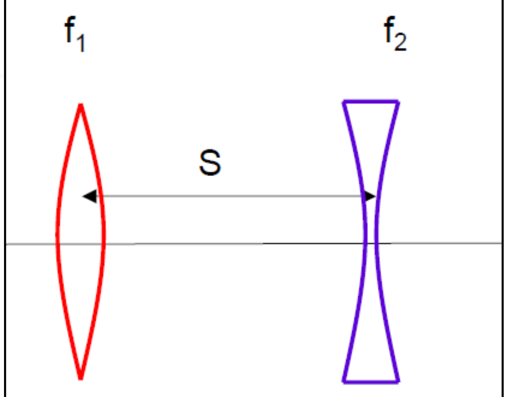
Muon Campus quad magnets





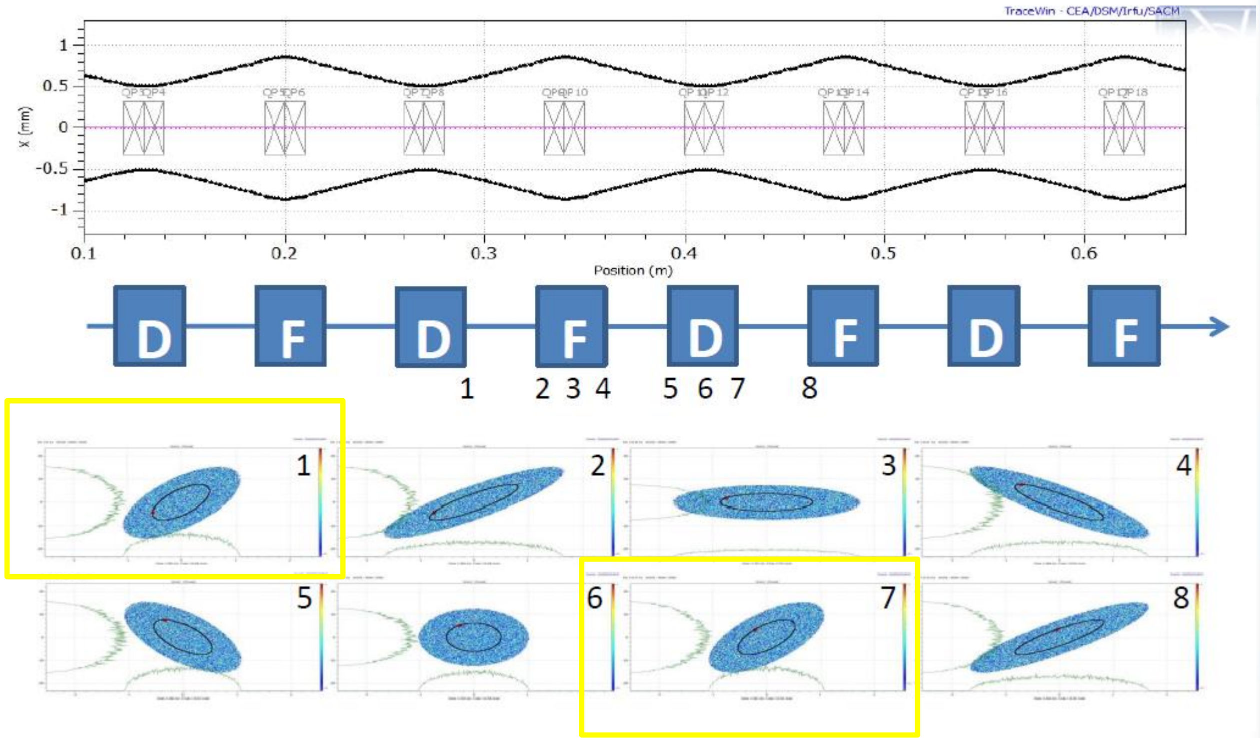
- Most Muon Campus quads have special vacuum chambers that conform to the poles in order to extend the aperture and therefore maximize capture

Focusing Defocusing (FODO) lines



$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{s}{f_1 f_2}$$

$$= \frac{s}{f^2} \quad \text{for } f_2 = -f_1$$



- The beam is matched if after every period the Twiss parameters are identical

Muon Campus beam lines

Muon campus M3 line

Quadrupole magnet

Muon campus Delivery Ring

Dipole magnet

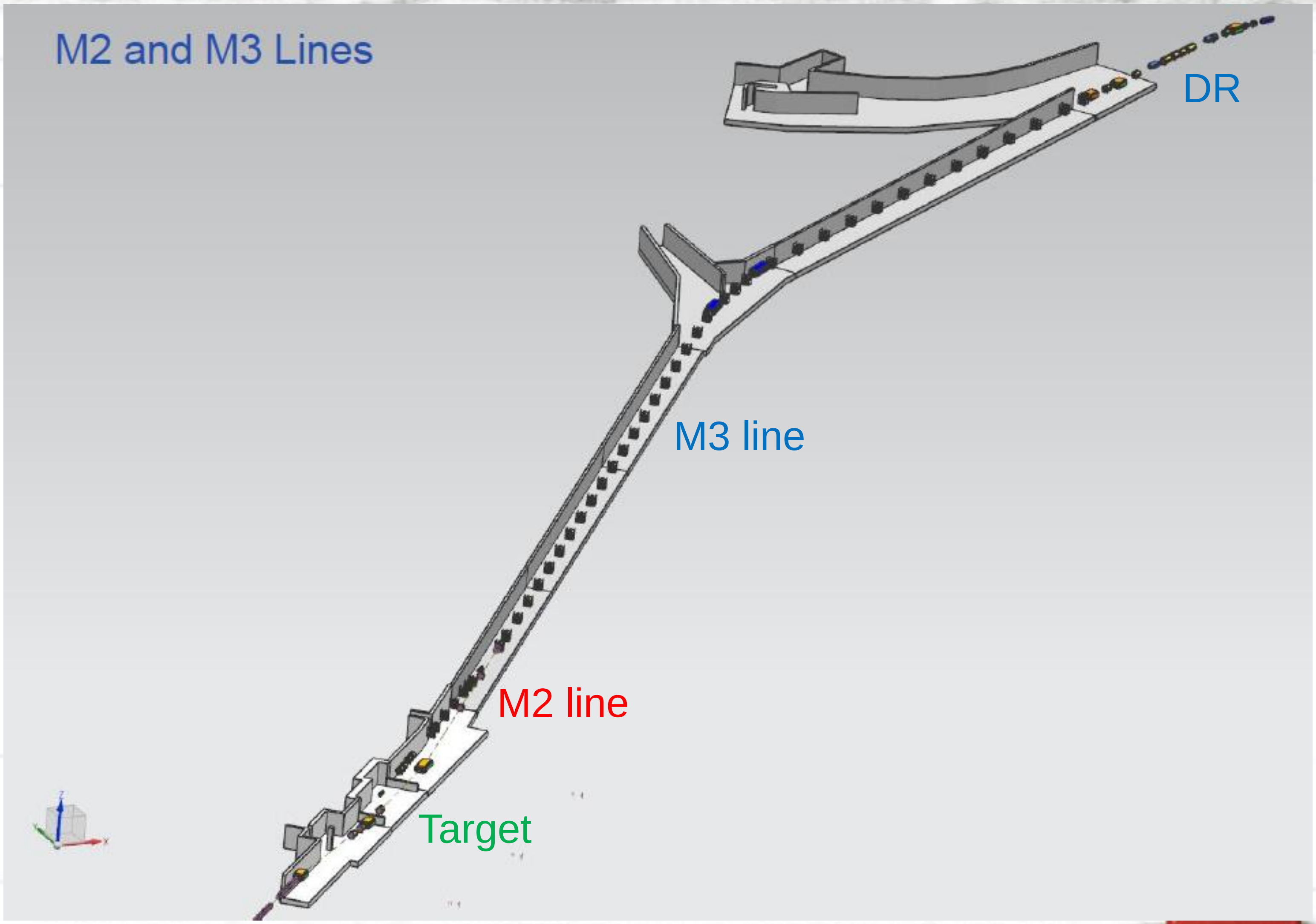
Optics considerations

- M2-M3 lines are 280 m long. Exponential decay law predicts:

$$N = N_0 e^{-(t_{M2M3})/\gamma\tau_\pi} = 0.3N_0 \rightarrow \text{70\% of } \pi^+ \text{ decay}$$

- "Selected pions" from target dipole have a wide momentum spread ~10%
- Daughter muons have equal or lower momentum and even larger momentum spread
- They do not come from a single spot
- The optics of the channel must transport both π^+ and μ^+
- Considerable momentum acceptance is needed

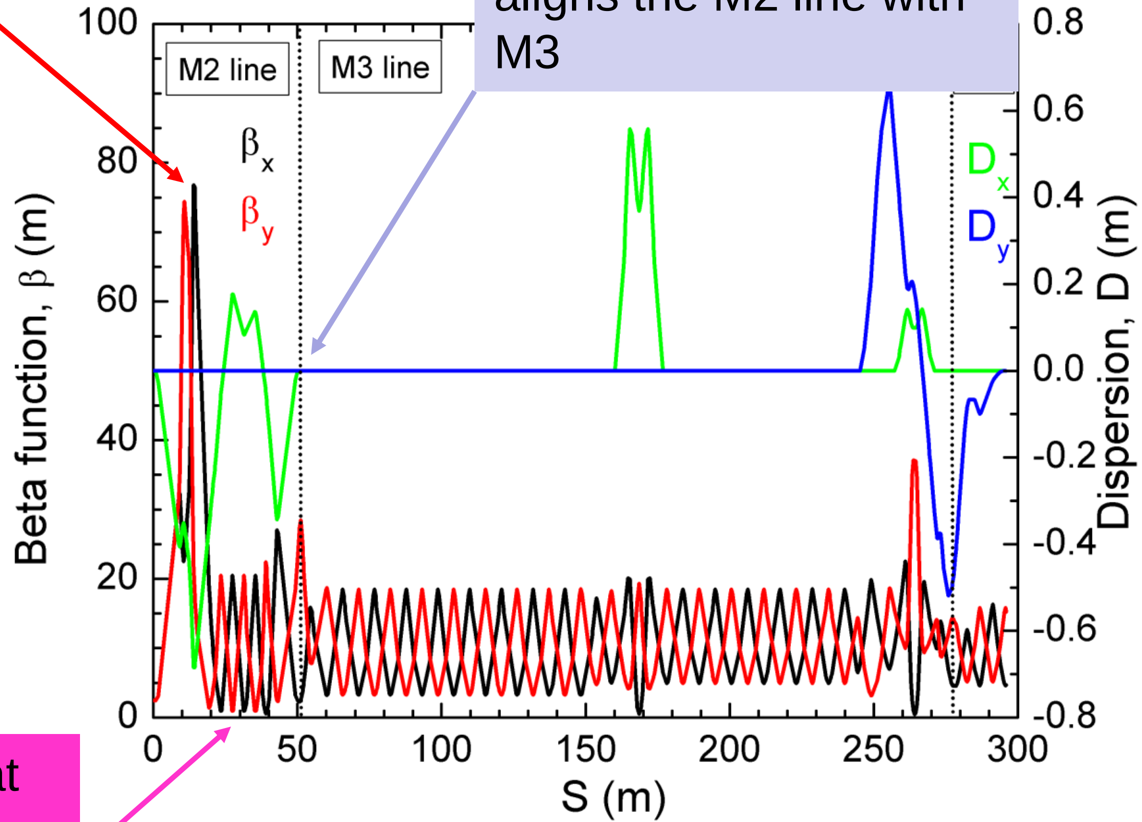
Schematic layout



Muon capture & transport line (M2)

4 quads to match the target generated beam distribution

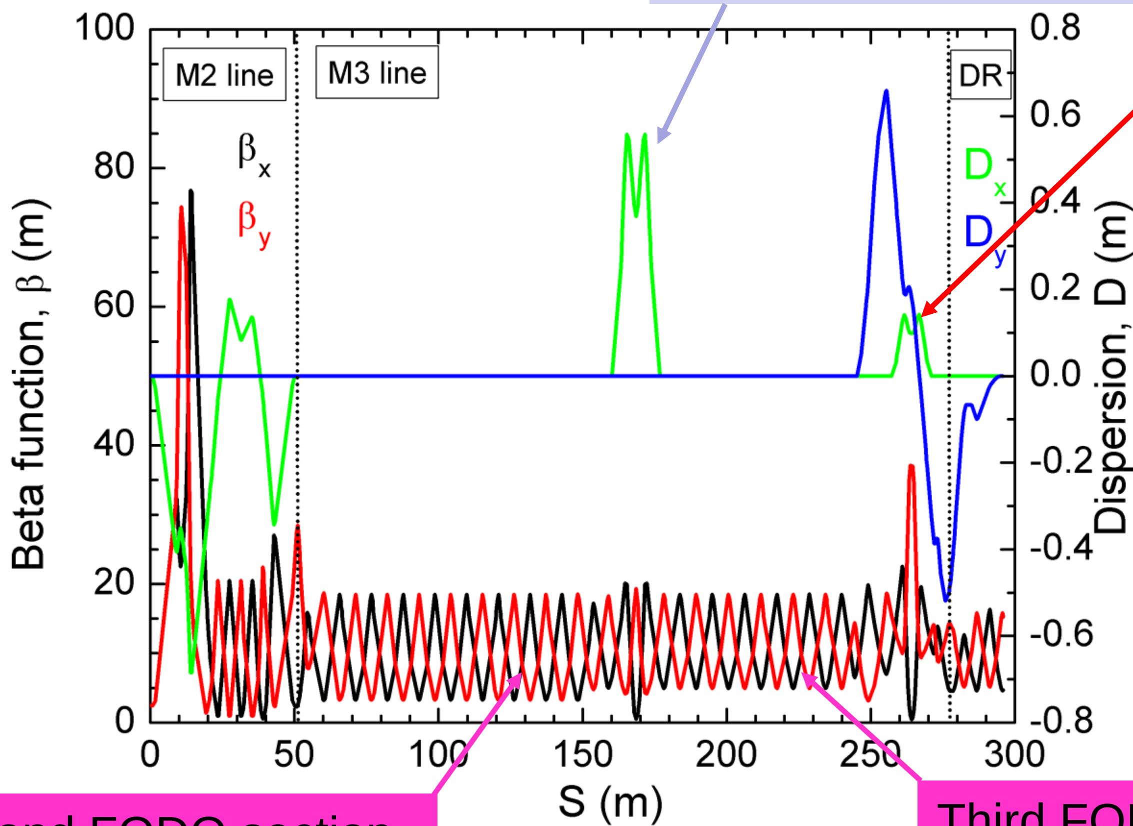
Second 3° bend that cancels dispersion and aligns the M2 line with M3



First FODO section at 120° phase advance

Muon capture & transport line (M3)

Two 9.25 horizontal bending magnets to align with the DR injection leg

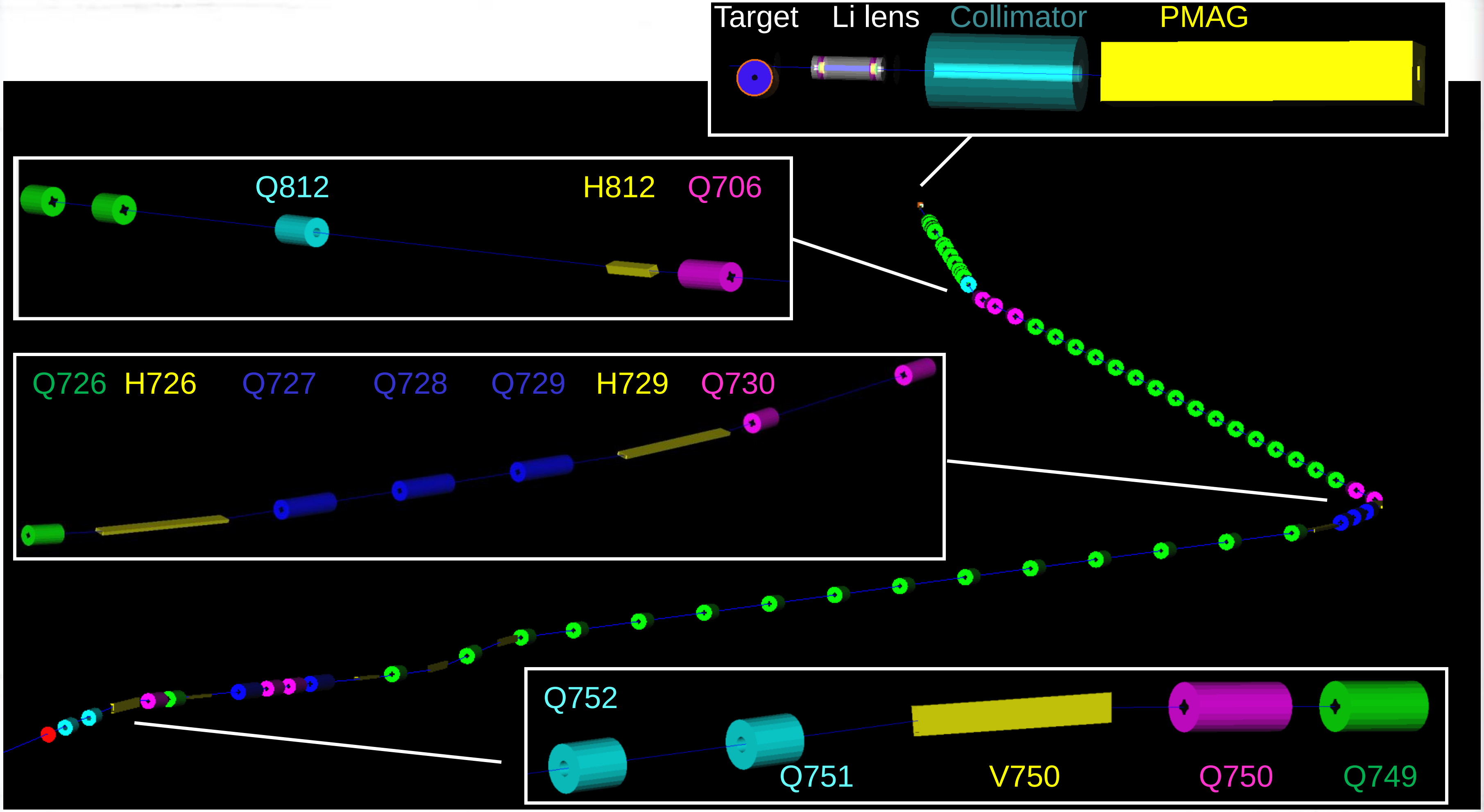


Series of horizontal and vertical bending to align with the injection leg of the DR

Second FODO section at 90º phase advance

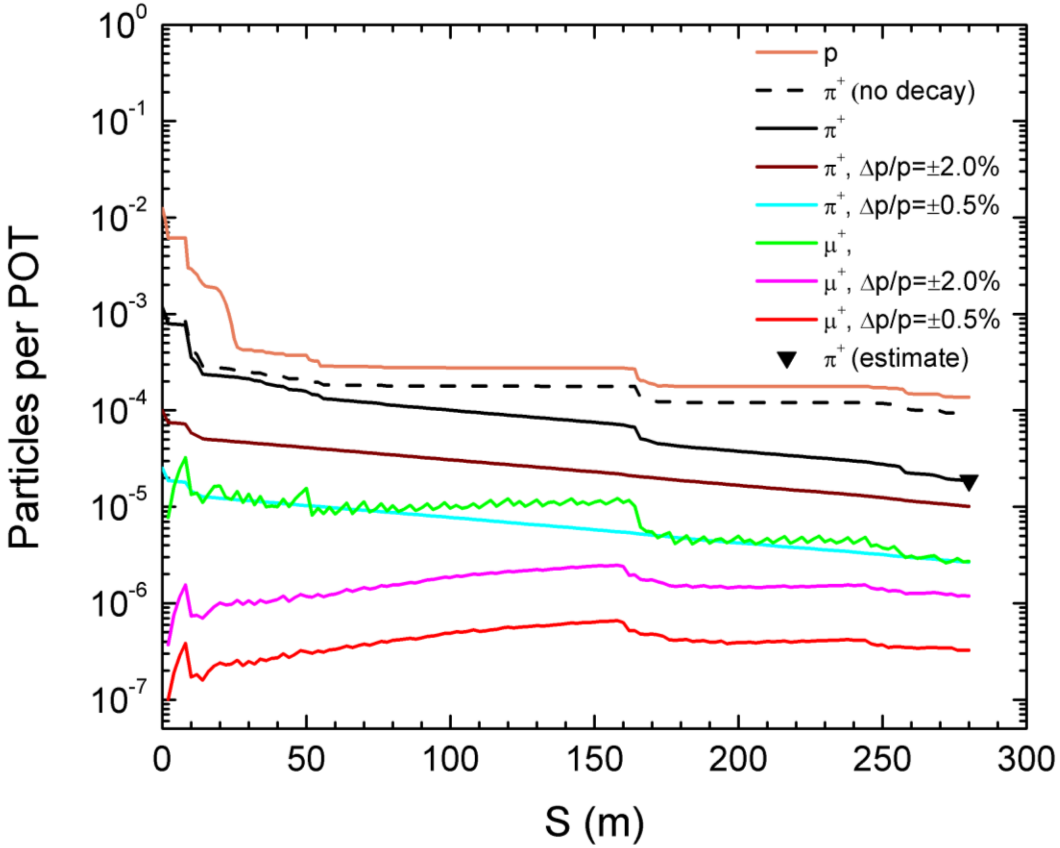
Third FODO section at 72º phase advance

Model for the M2-M3 beamlines



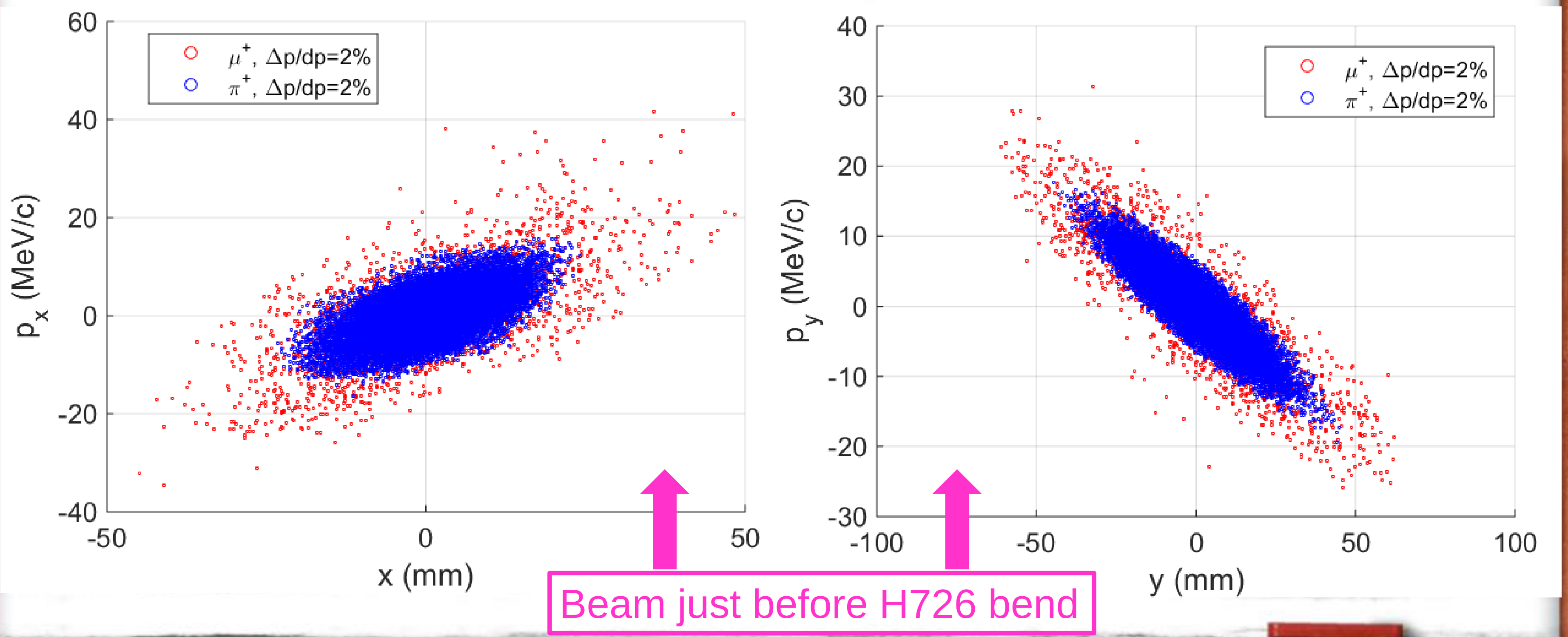
Expected performance

- Secondary beam consist of protons, pions, muons, positrons and deuterons

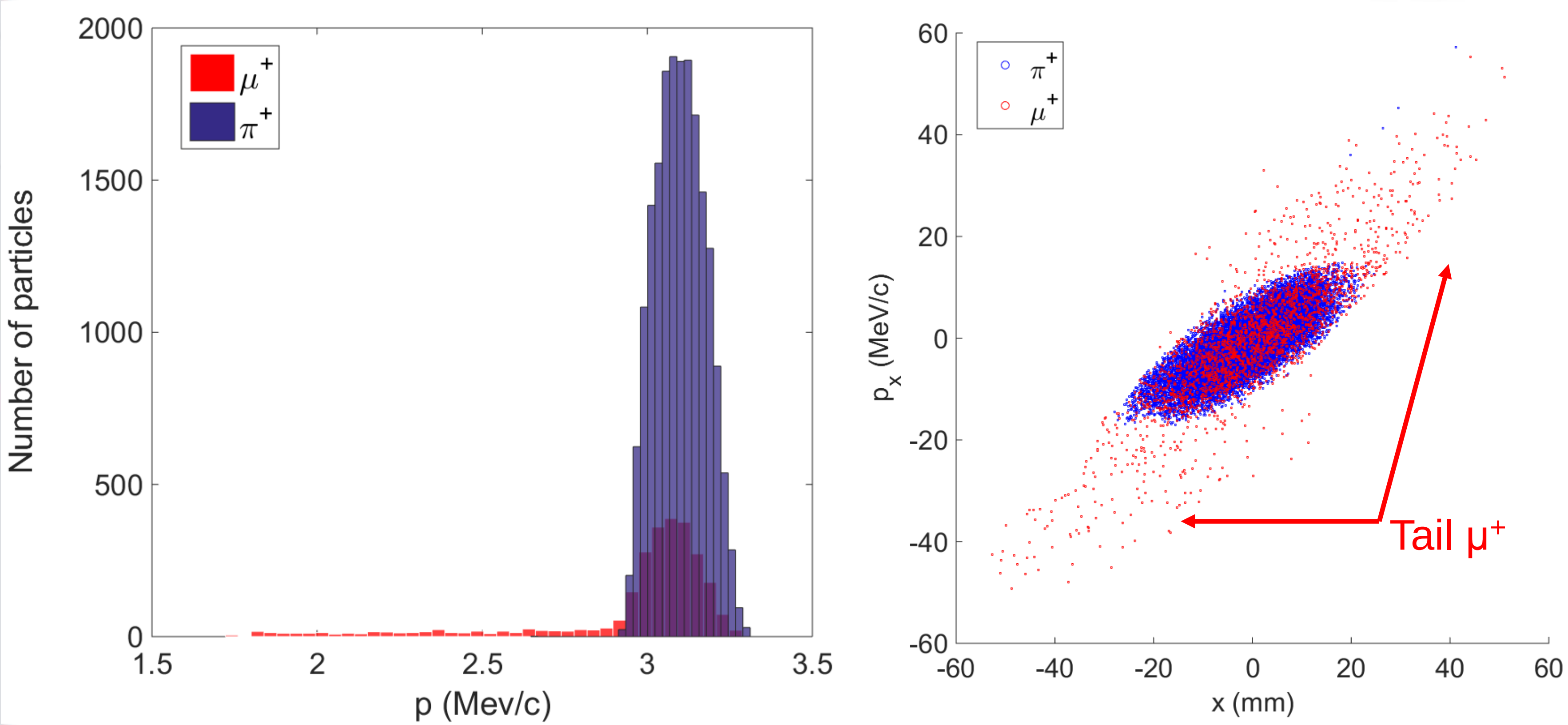


Phase-space analysis: π vs μ

- μ^+ have larger transverse momentum (compared to π^+)
- As a result, muons are lost in apertures between H726 & H729 bends



Muons at the end of M3



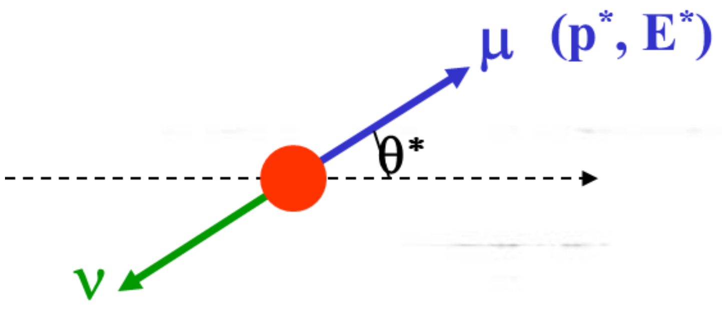
- Distribution contains an order of magnitude more π^+ than μ^+
- Distribution of μ^+ has a long low-momentum tail

Energies of newborn muons

- In the pion rest frame:

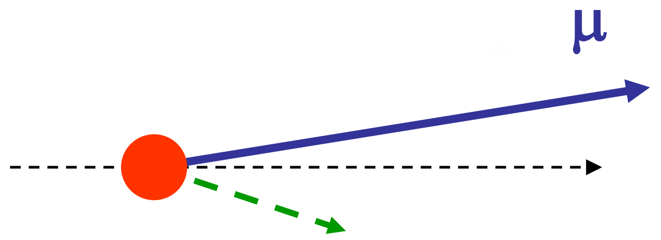
$$p^* = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} = 30\ \mathrm{MeV/c}$$

$$E^* = \frac{m_\pi^2 + m_\mu^2}{2m_\pi} = 110\ \mathrm{MeV}$$



- Boost to laboratory frame:

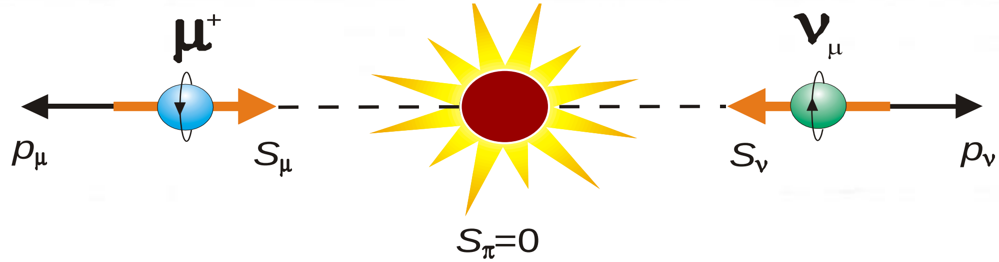
$$E_\mu = \gamma_\pi (E^* + \beta_\pi p^* cos\theta^*)$$



- Limiting cases:
  - $cos\theta = +1 \rightarrow E_{max} = 1.00 \times E_\pi$ (forward decays)
  - $cos\theta = -1 \rightarrow E_{max} = 0.57 \times E_\pi$ (backward decays)

(This will be a homework problem)

Polarization of newborn muons



- Muons from pion decay are naturally polarized. Their polarization is highly depended on the momentum ratio between the new born muon and its parent pion, $x = p_\mu / p_\pi$
- Transverse polarization is given by:

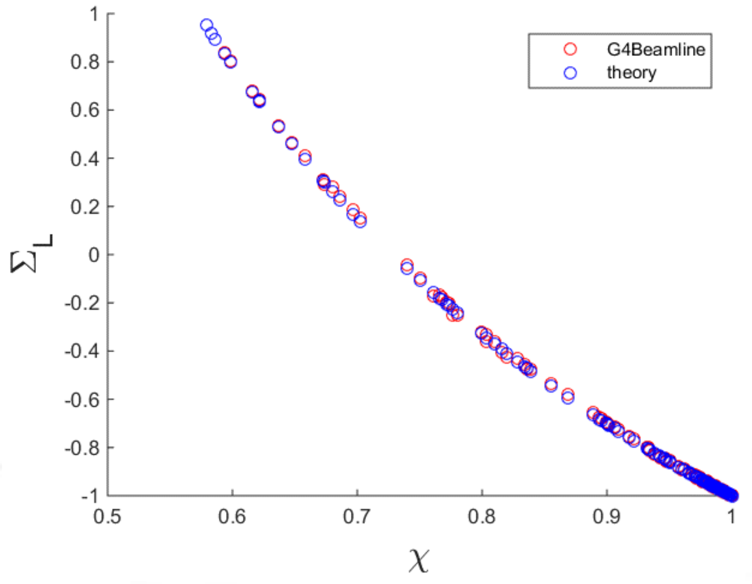
$$P_T = \frac{2b}{x(1-b^2)}[(1-x)(x-b^2)]^{1/2}, \qquad b = m_\mu / m_\pi$$

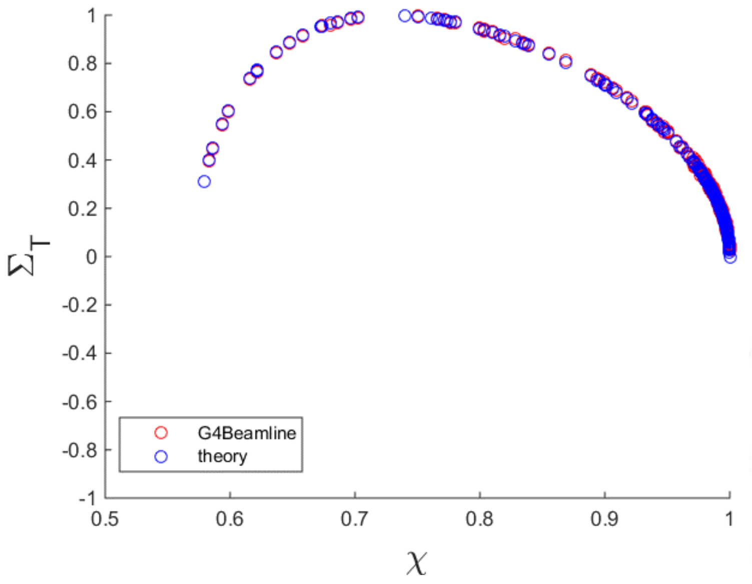
- Longitudinal polarization is given by: $P_L = \frac{x(1+b^2)-2b^2}{x(1-b^2)}$

(This will be a computer lab problem)

Polarization in the Muon Campus (1)

- The rms momentum spread of the Muon Campus is ~2%
- Muons from forward decays are surviving and the muon polarization is expected to be >90%





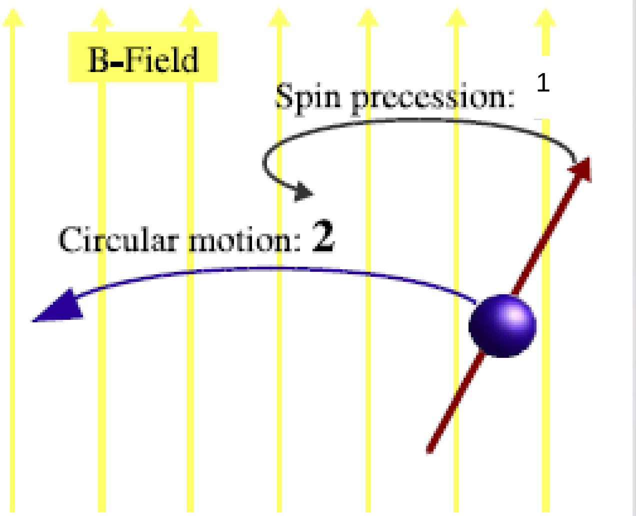
Spin precession in B-fields (1)

- If we put a muon into motion in a plane transverse to a magnetic dipole field, both momentum and spin precess
- Momentum precession (cyclotron motion):

$$\frac{d\vec{p}}{dt} = e\vec{v} \times \vec{B} \rightarrow \omega_c = \frac{eB}{\gamma mc}$$

- Spin precession (Larmor and Thomas motion):

$$\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B} \rightarrow \omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$



Spin precession in B-fields (2)

- Difference between these two outcomes form an anomalous magnetic moment not predicted by pure Dirac theory

$$\omega_a = \omega_c - \omega_s = \left(\frac{g-2}{2}\right)\frac{eB}{mc} = \alpha_\mu \frac{eB}{mc}$$

- In other words, when a muon passes through a bending magnet, its spin vector rotates slightly more than the bending angle due to precession in the B-field.