

# Study Horn-based Target System for Muon Collider

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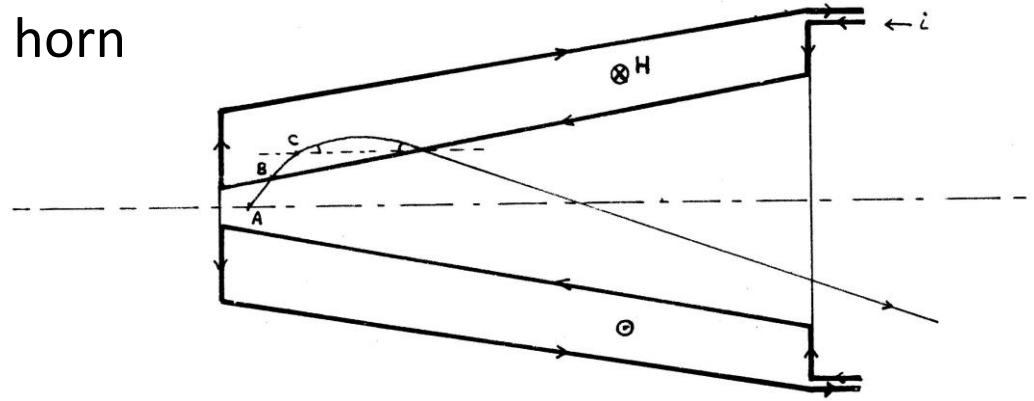
# Motivation

- Challenge to make Multi-Mega-Watt Target System
  - Heat and radiation treatment
    - For NuMI, 1/3 of total beam power is deposited in Target hall, 1/3 in Decay Pipe, and 1/3 in Hadron Absorber
    - For NuMI, C-graphite target was activated 75 Rad/hr on contact after servicing 2yrs with  $1e21$  POT
  - Phase space manipulation for cooling channels
    - Achromatic pion capture optics
- Investigate horn based systems
  - Sub-MW target system exist
  - Make a conceptual model
  - Run numerical simulation to validate a new horn concept

I introduced a solenoid-based target system which is shown in my previous presentation  
<https://indico.cern.ch/event/1049225/>

# Horn-based target system

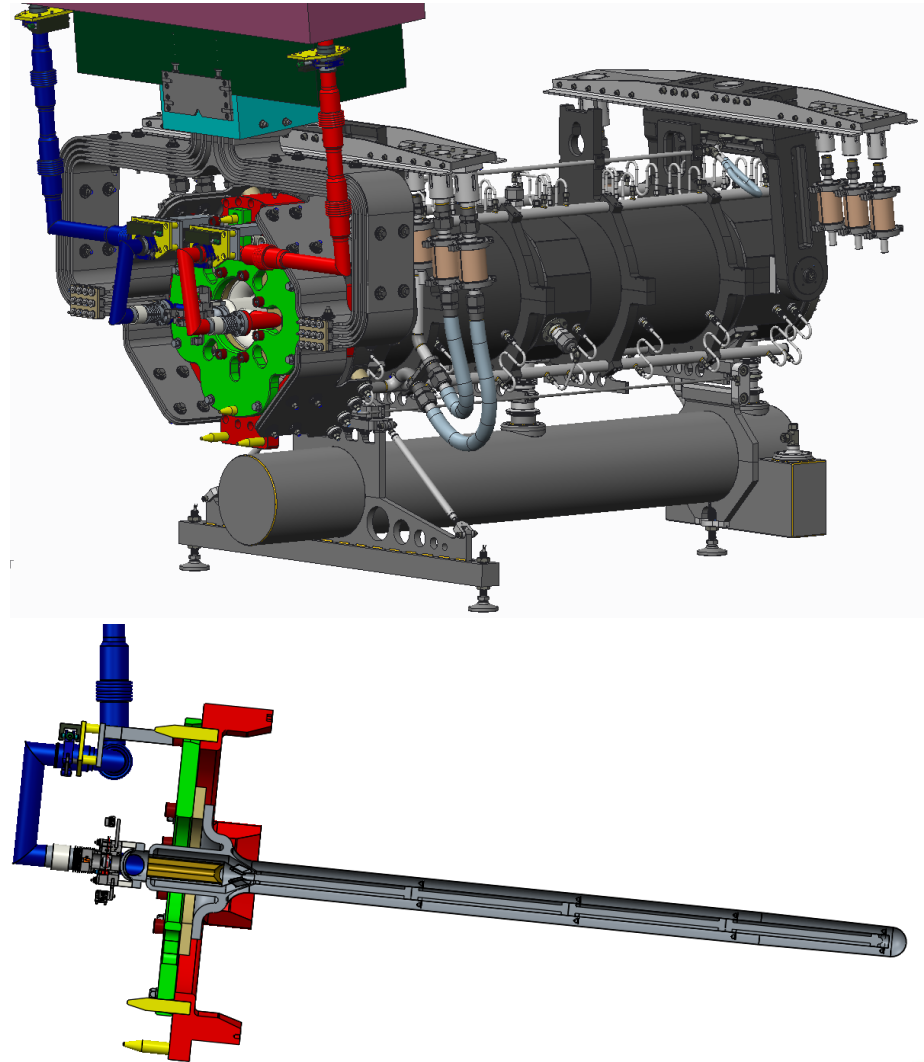
- Lorentz force ( $b_\varphi [r] \cdot p_z$ ) makes focusing
  - Assume path length inside horn field is parabolic
  - $\theta = \frac{eb_\varphi l}{p_z} \propto \frac{l \cdot r}{p_z}$
- Widely used for neutrino experiments
  - T2K: 515 kW (2020)
  - NuMI: 843 kW (2021)
  - Both use C graphite
  - Horn survives more than  $10^7$  beam pulses



Van der Meer's original sketch of magnetic horn in 1961

# Neutrino target system

- LBNF: State of the art target system
  - 1.5-m-long C graphite cantilever target
  - He gas cooling
  - Accept 1.2-MW beam
    - Proton beam momentum 120 GeV/c
    - Proton bunch length 5 ns
    - Beam repetition rate 1.2 second

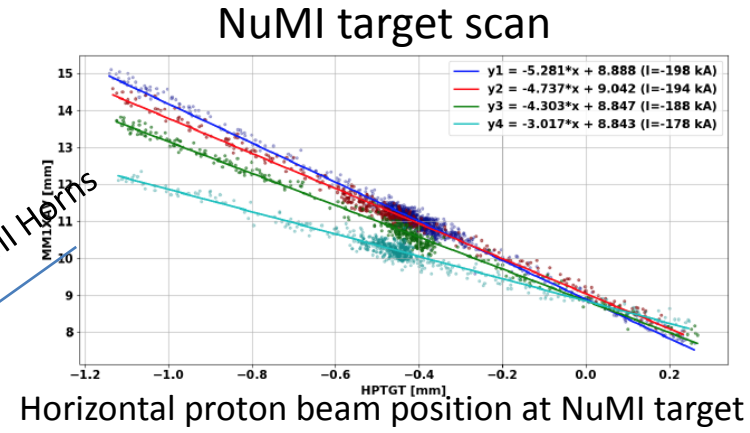


# Apply Horn-based target system for Muon collider

Pros Cons

- Technology exists
  - A big confidence to operate > 1-MW beam
- Focus single charge (?)
- Complex beam optics (?)
- Low energy pion will be lost at inner conductor and cooling water
  - 30 % pion lost reported in the past study (?)

Linear focusing by NuMI Horns



No quantitative study made in the past (or at least I cannot find any citation)

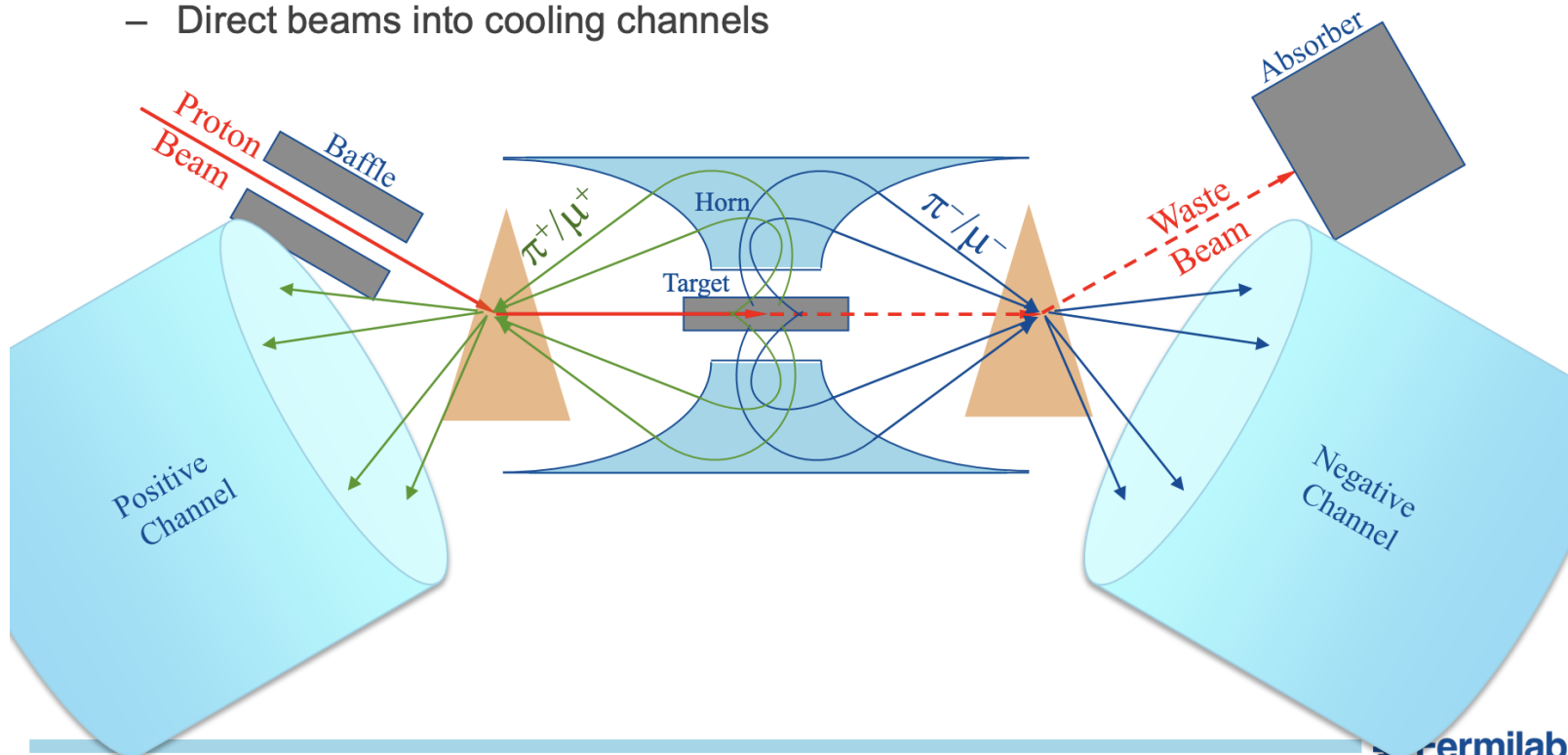


# Conceptual design of Horn (I)

## Horn Capture of Positives and Negatives

- Direct proton beam into target surrounded by a symmetric horn
  - Focus negative (positive) secondaries forward (backward)
  - Dipoles separate incident proton beam from backward positive beam, and waste proton beam from forward negative beam
    - Note: bends are not to scale. Protons will have  $\sim 30x$  rigidity of secondaries.
  - Direct beams into cooling channels

B. Zwaska (2021)



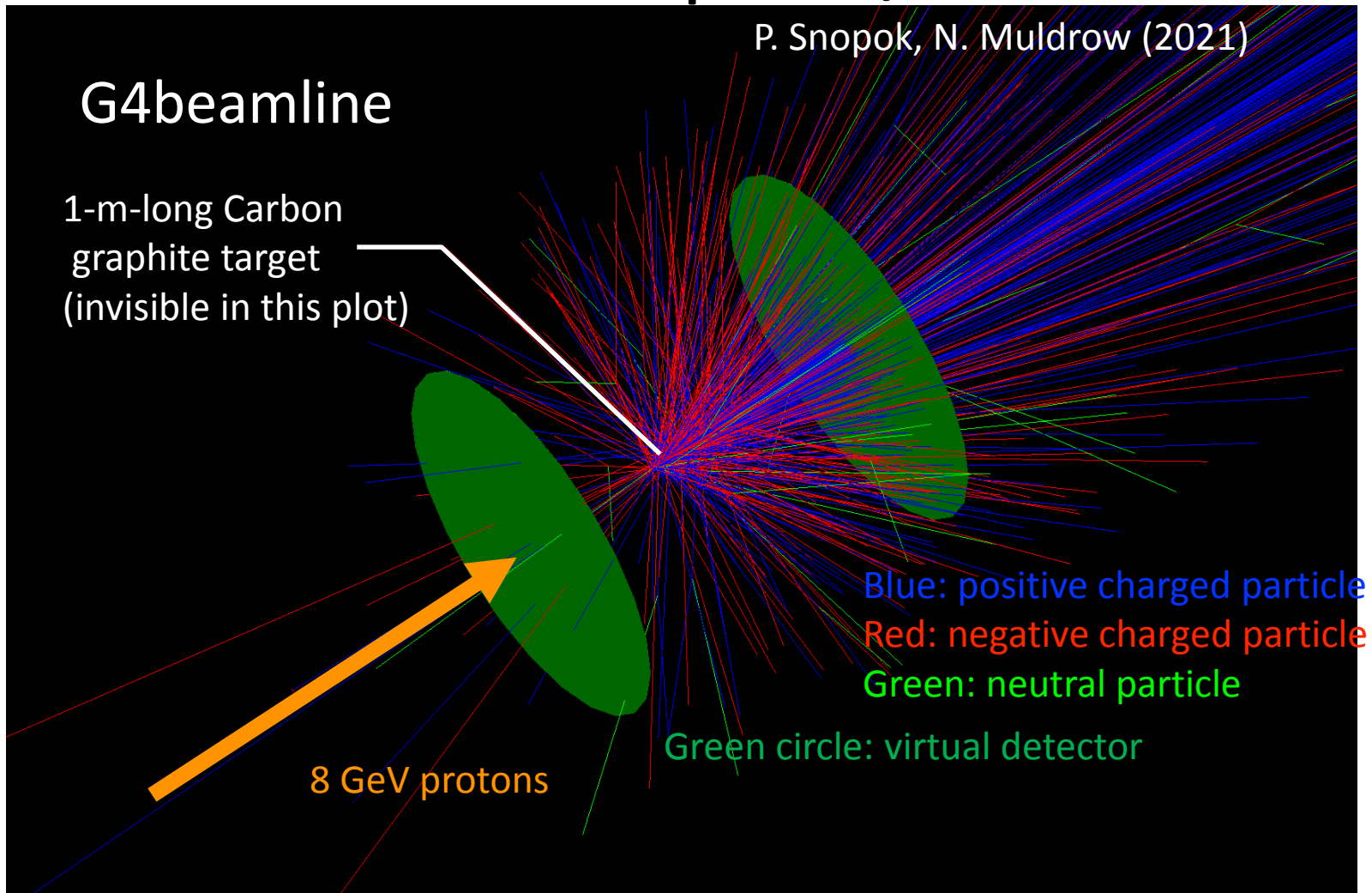


# Numerical study of forward and backward pions/muons

P. Snopok, N. Muldrow (2021)

## G4beamline

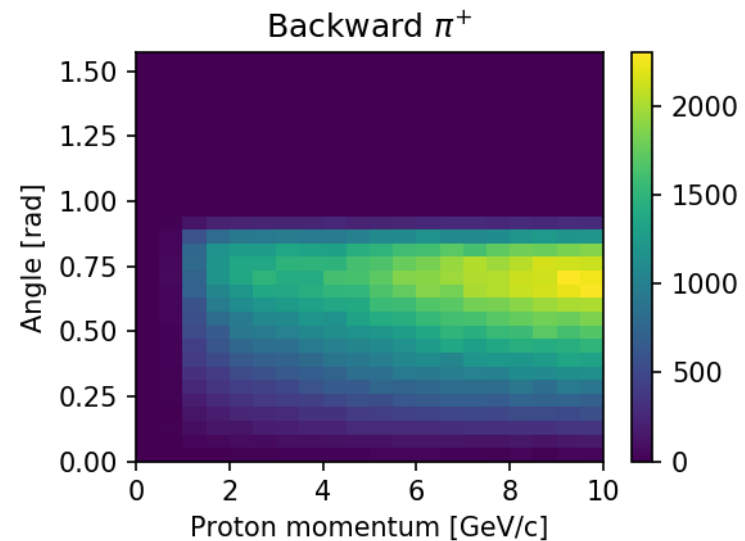
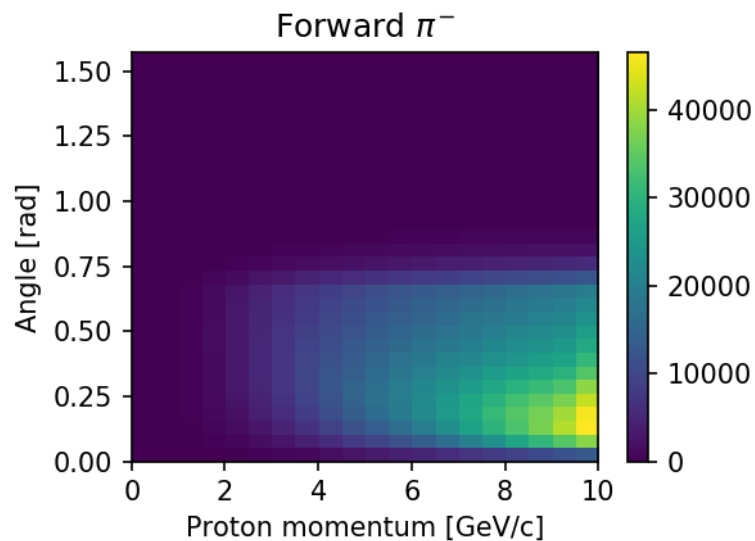
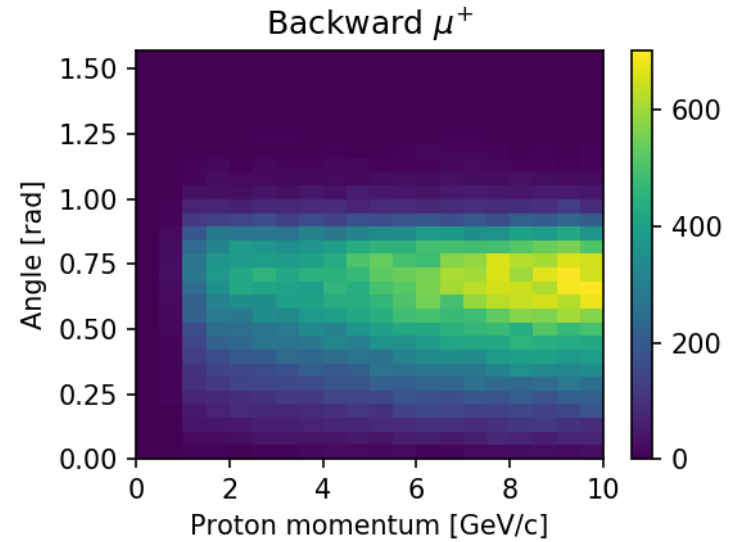
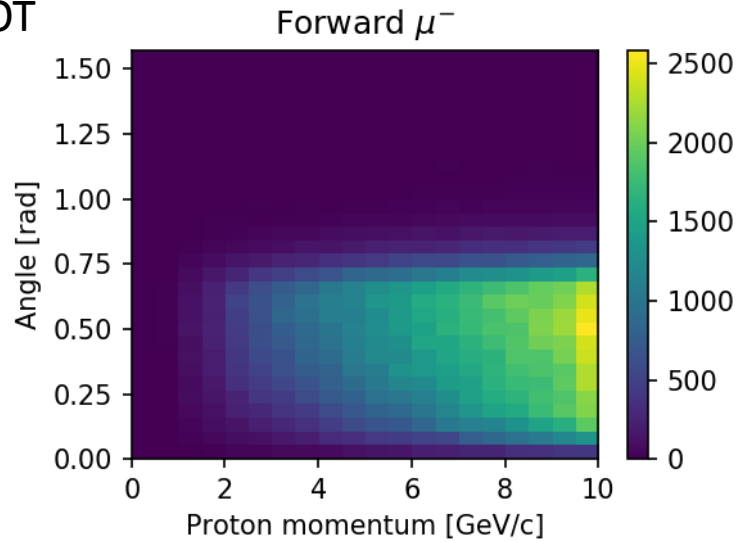
1-m-long Carbon  
graphite target  
(invisible in this plot)



# Preliminary simulation result (I)

Note: Proton momentum 1 to 10 GeV/c

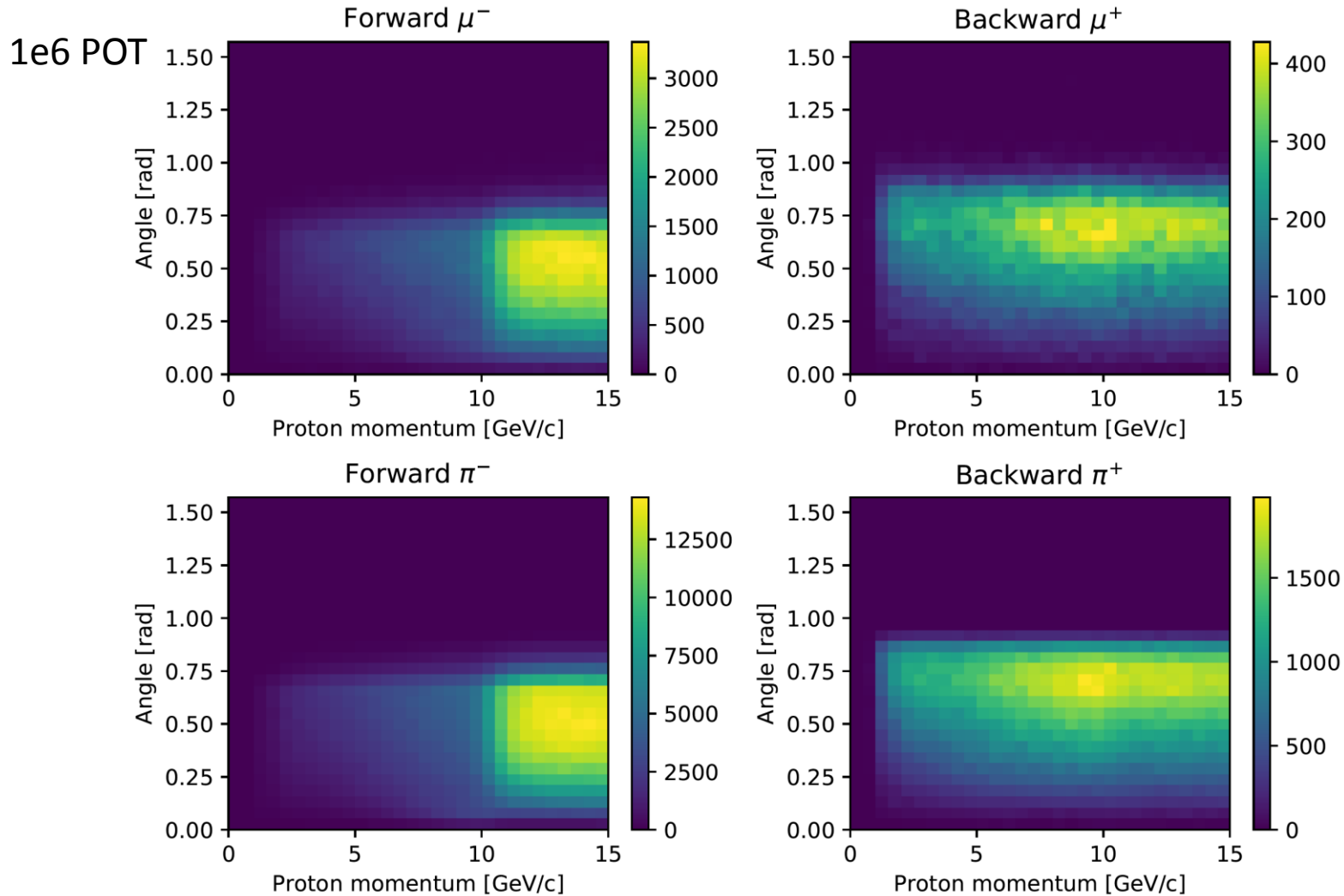
1e6 POT



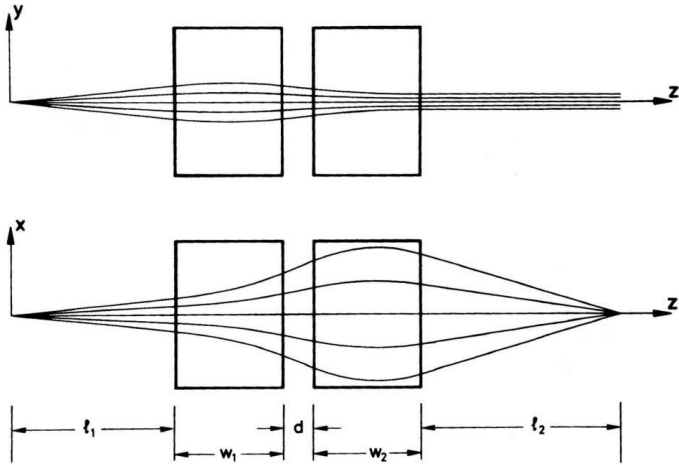


# Preliminary simulation result (II)

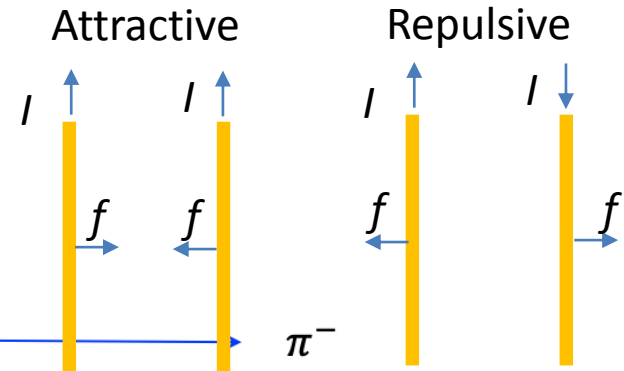
Momentum cut  $100 \leq p \leq 400$  MeV/c



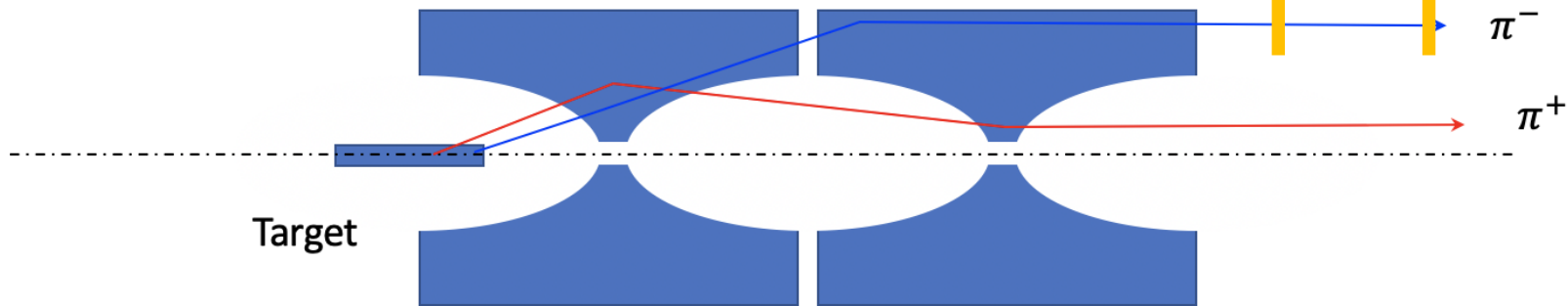
# Conceptual design of Horn (II)



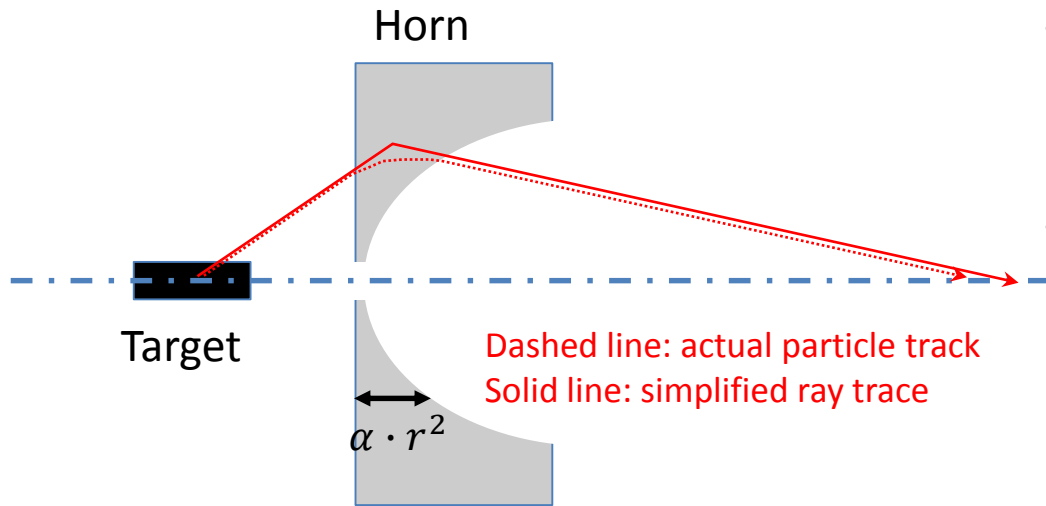
- Horn is axisymmetric, no x-y asymmetry like quad
- Focusing mode in horn depends on a direction of horn current vs beam current



FODO for Positive particles  
DOFO for Negative particles



# Toy model (I)

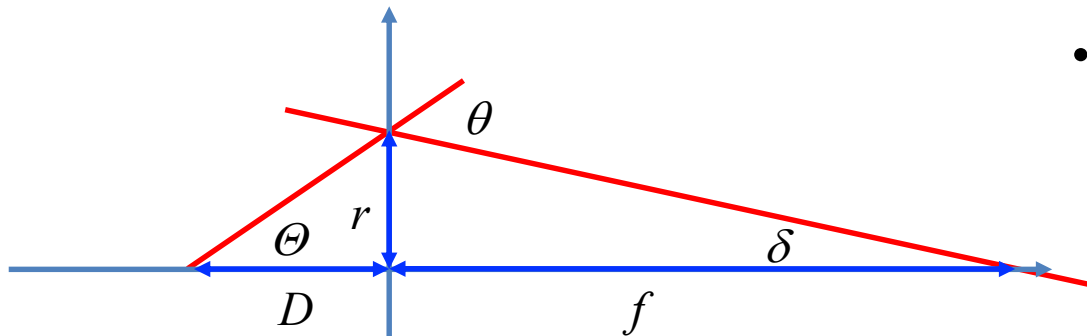


- Horn focusing force

$$\theta = \frac{eb_{\phi}l}{p_z} \propto \frac{I \cdot r}{p_z}$$

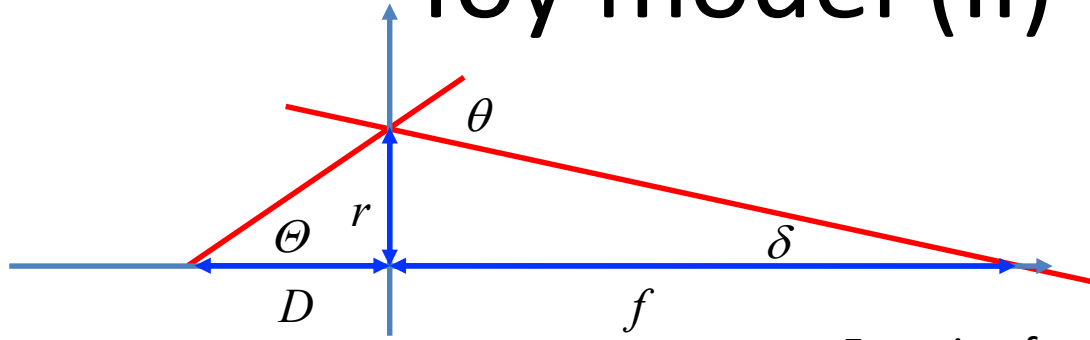
- Cross-sectional shape of horn

$$z = \alpha \cdot r^2$$



- Focusing geometry can be fixed from known dimensions with a simplified model

# Toy model (II)



Geometry constraint

$$\theta = \delta + \Theta \rightarrow \delta = \theta - \Theta$$

$$\tan \delta = \frac{r}{f} = \tan(\theta - \Theta)$$

$$f = \frac{r}{\tan(\theta - \Theta)} = \frac{D \tan \Theta}{\tan(\theta - \Theta)}$$

- If we know  $\Theta$ , all focusing geometries are fixed
- $\Theta = c_0 + \frac{c_1}{p} + O(p)$  is a good approximation for neutrino target
- Will find a correlation from slide 9

Focusing force

$$\theta = \frac{e \cdot b_\phi \cdot dl}{p_z} = \frac{0.3 \cdot b_\phi \cdot dl}{p_z}$$

$$b_\phi(r) = \frac{5I}{r}$$

$$dl(r) = \alpha \cdot r^2$$

$$\theta = \frac{0.3 \cdot \frac{5I}{r} \cdot \alpha \cdot r^2}{p_z} = \frac{1.5\alpha \cdot I}{p_z} r$$

$I$  is horn current (kA)

$r$  is (mm)

$p_z$  is longitudinal momentum (GeV/c)

# Summary

- Study a conceptually new horn-based target system
  - Capture both charges