Study Horn-based Target System for Muon Collider

Katsuya Yonehara
Fermilab

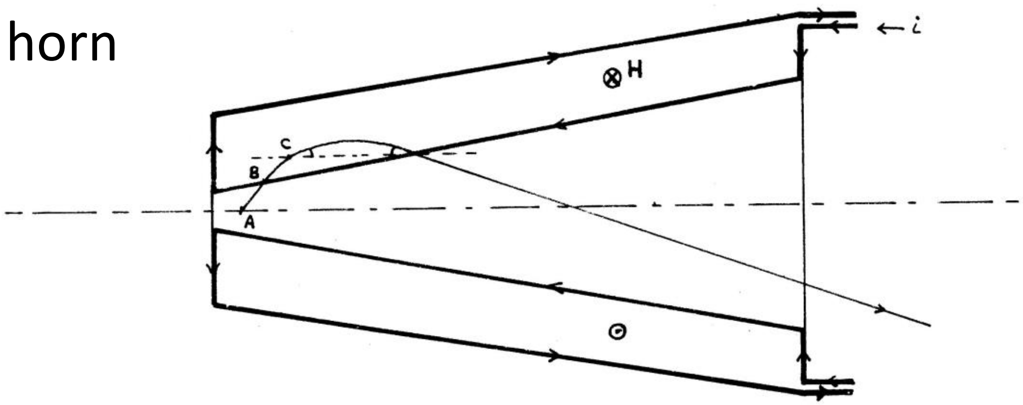
Motivation

- 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

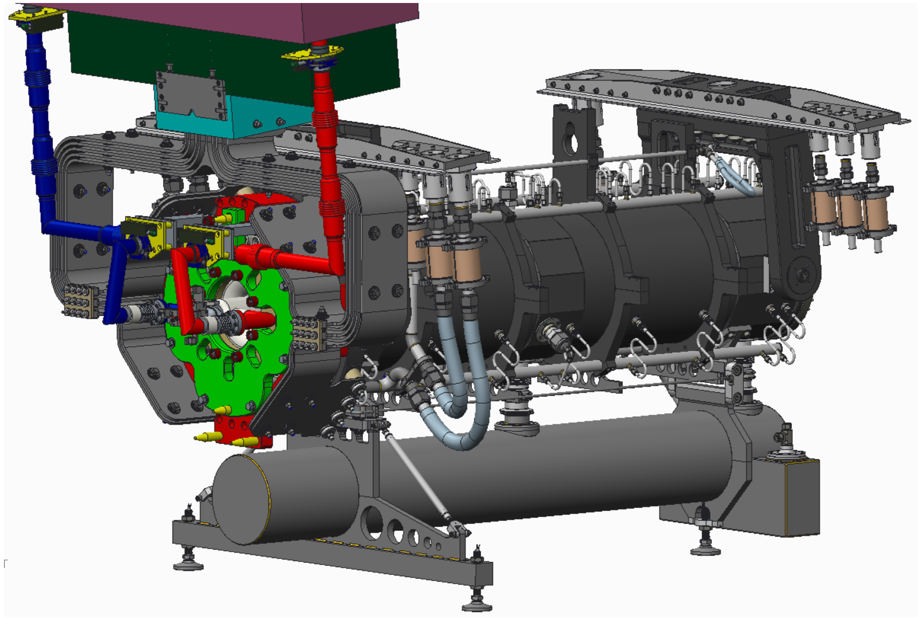
- Lorentz force ($b_\varphi[r] \cdot p_z$) makes focusing
  - Assume path length inside horn field is parabolic
  - $\theta = \frac{e b_\varphi l}{p_z} \propto \frac{I \cdot r}{p_z}$
- Widely used for neutrino experiments
  - T2K: 515 kW (2020)
  - NuMI: 843 kW (2021)
  - Both use C graphite
  - Horn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

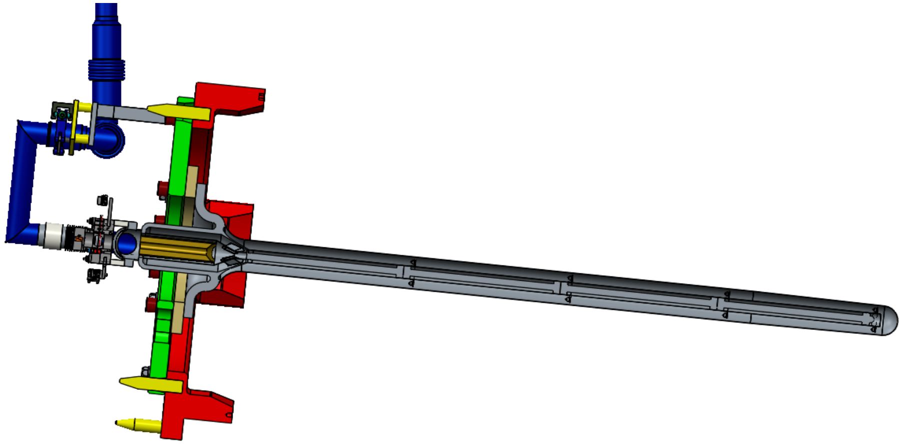


Van der Meer's original sketch of magnetic horn in 1961

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





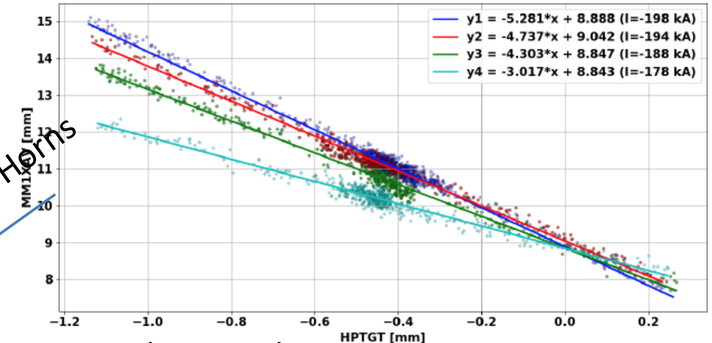
Apply Horn-based target system for Muon collider

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

NuMI target scan



Horizontal proton beam position at NuMI target

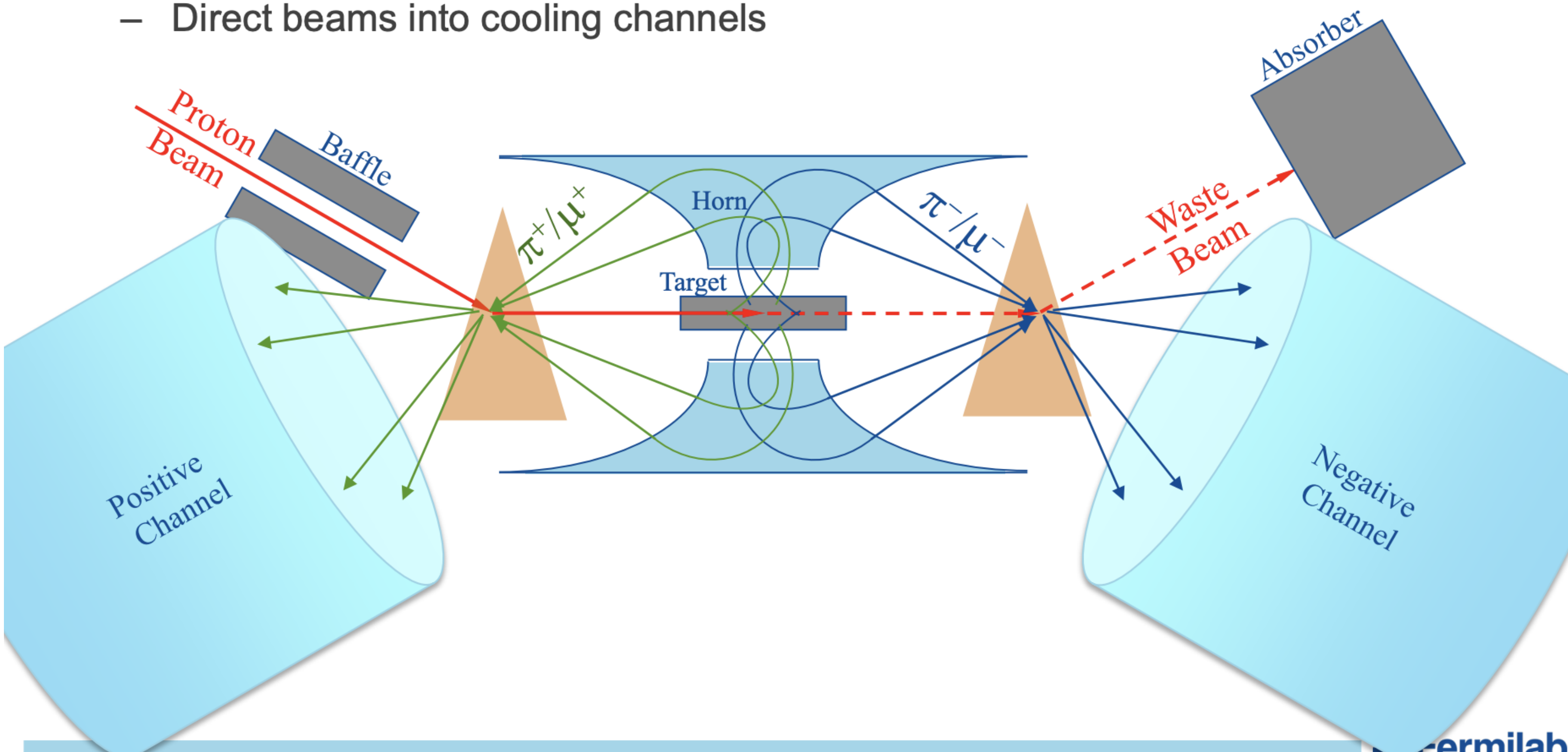
No quantitative study made in the past (or at least I cannot find any citation)

Conceptual design of Horn (I)

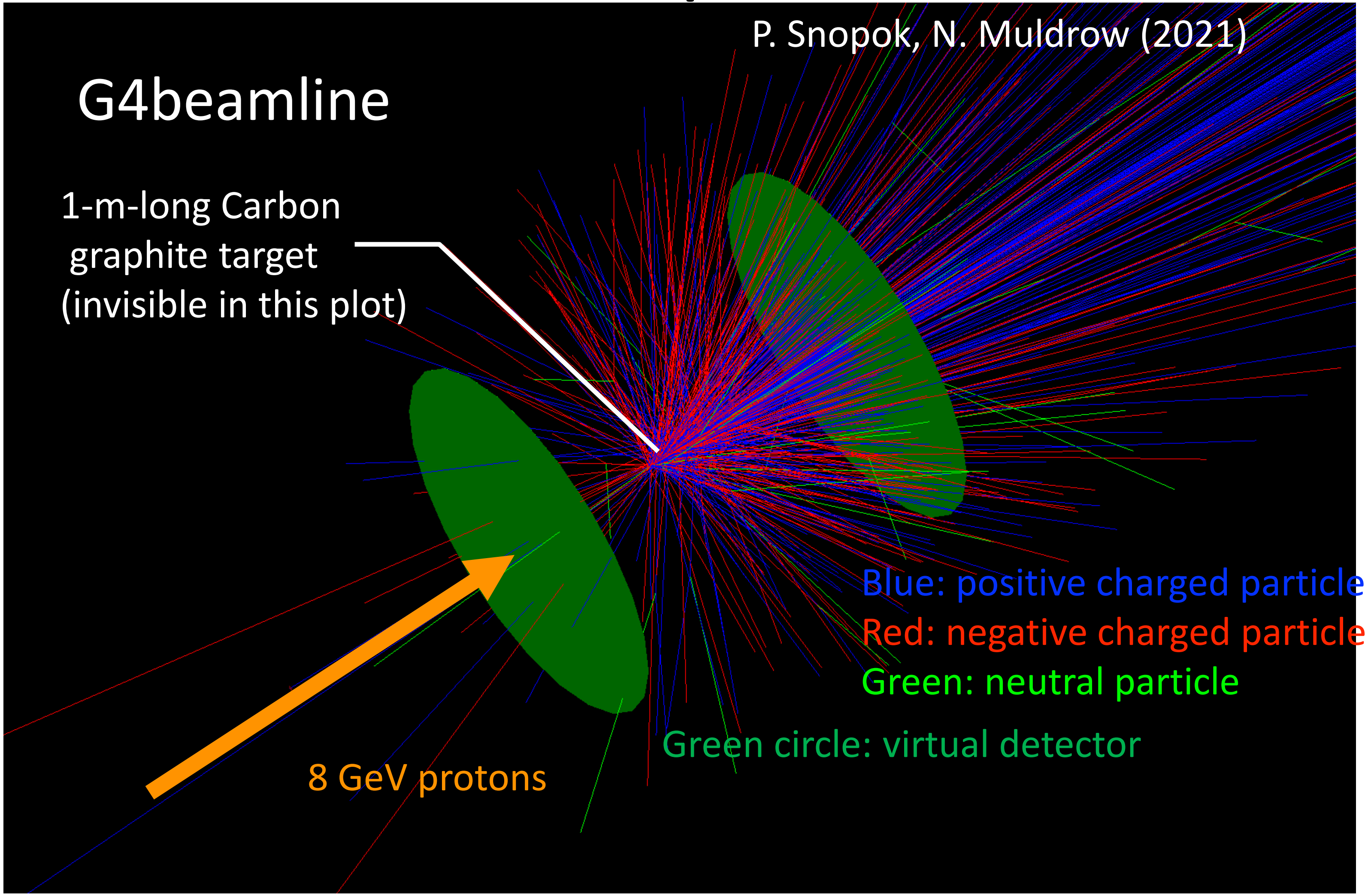
Horn Capture of Positives and Negatives

B. Zwaska (2021)

- 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 ~ 30x rigidity of secondaries.
  - Direct beams into cooling channels



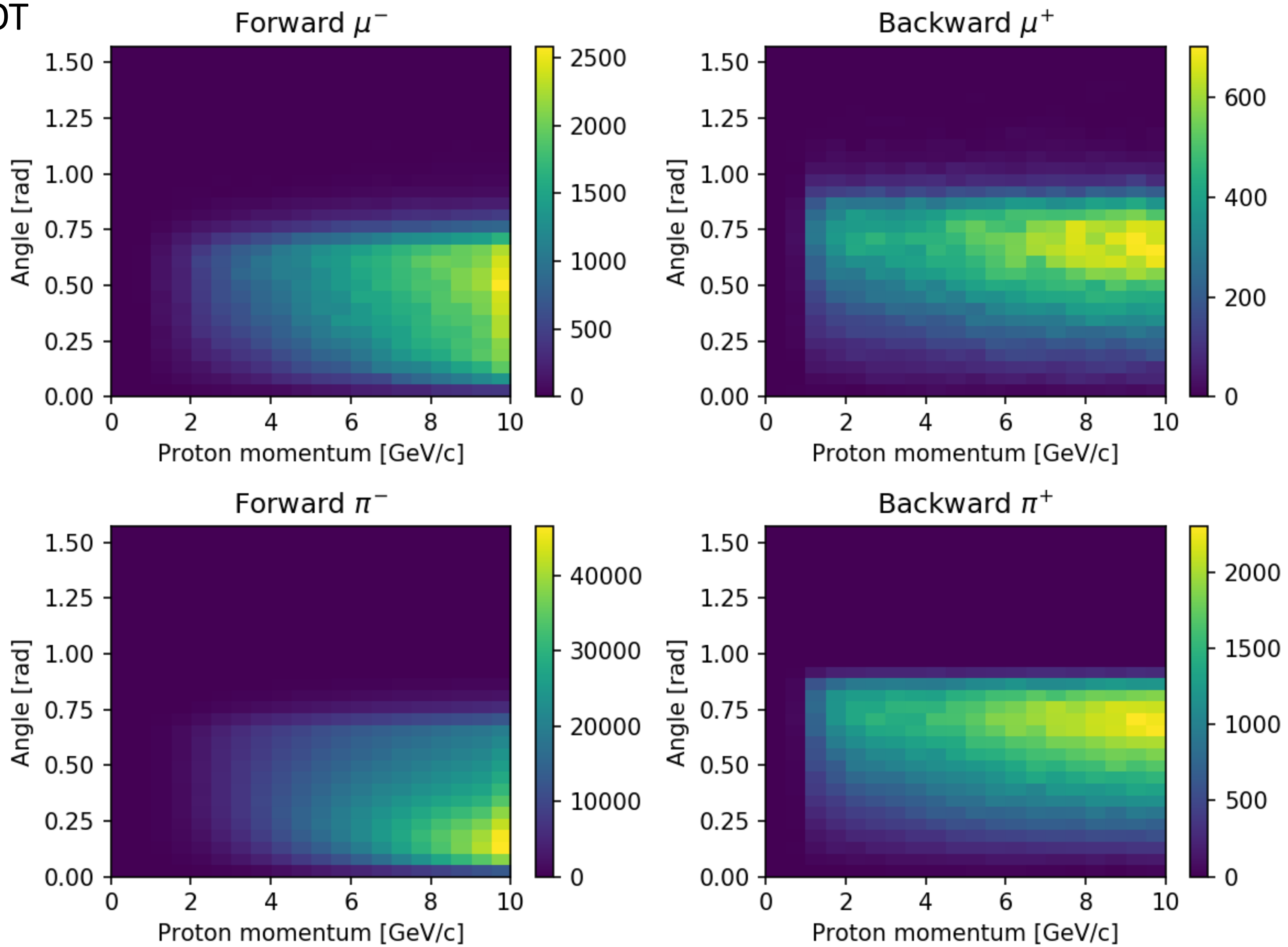
Numerical study of forward and backward pions/muons



Preliminary simulation result (I)

Note: Proton momentum 1 to 10 GeV/c

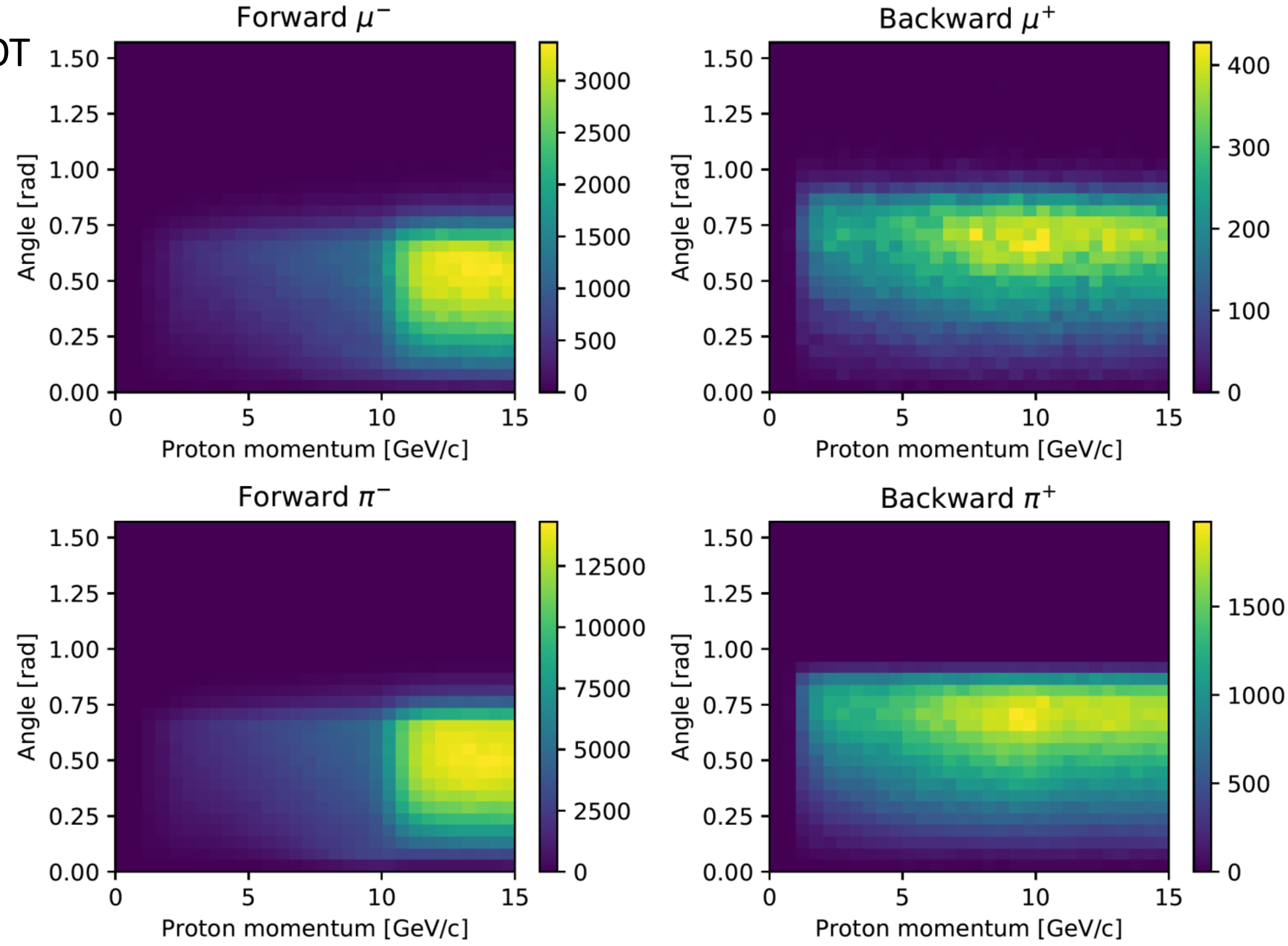
1e6 POT



Preliminary simulation result (II)

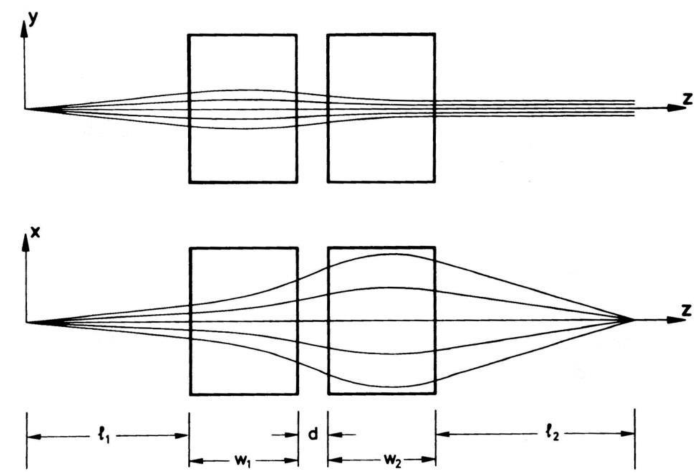
Momentum cut $100 \leq p \leq 400$ MeV/c

1e6 POT

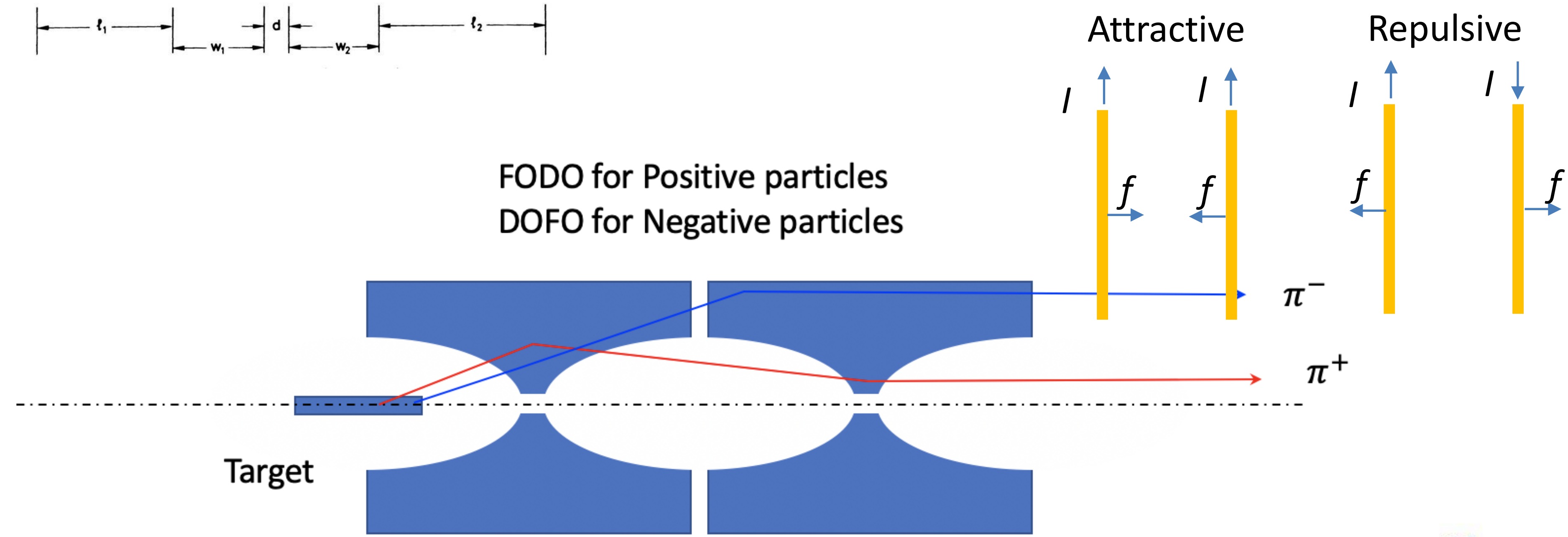


Ratio of forward and backward π/μ = 9:1

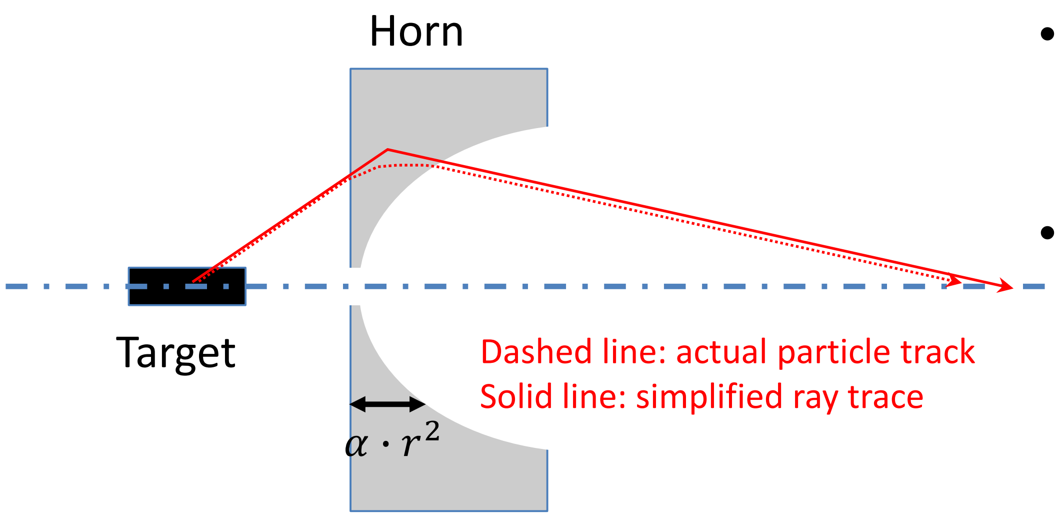
Conceptual design of Horn (II)



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



Toy model (I)

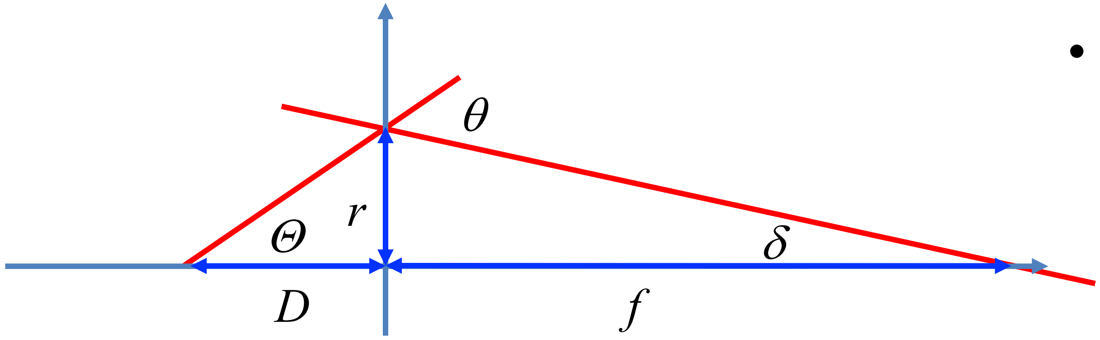


- Horn focusing force

$$\theta = \frac{e b_\varphi l}{p_z} \propto \frac{I \cdot r}{p_z}$$

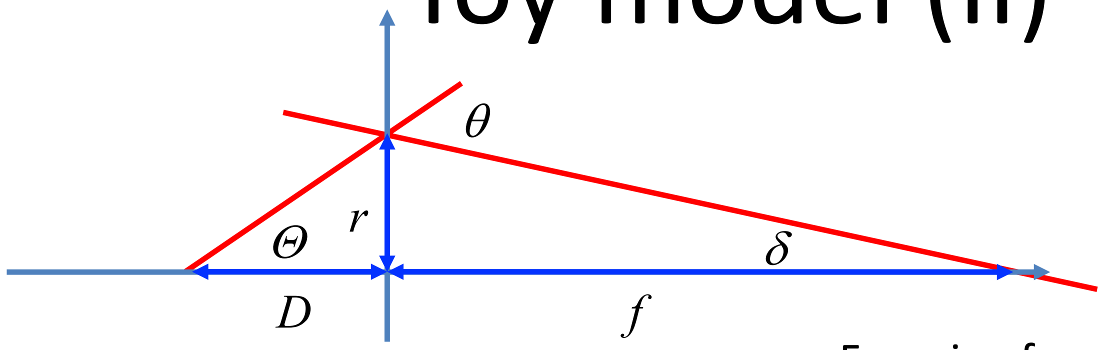
- Cross-sectional shape of horn

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



- 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 Θ, 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

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

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

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

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

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