Develop particle tracking simulation to study NuMI horn focusing mechanism

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TSD Topical Meeting

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Goal

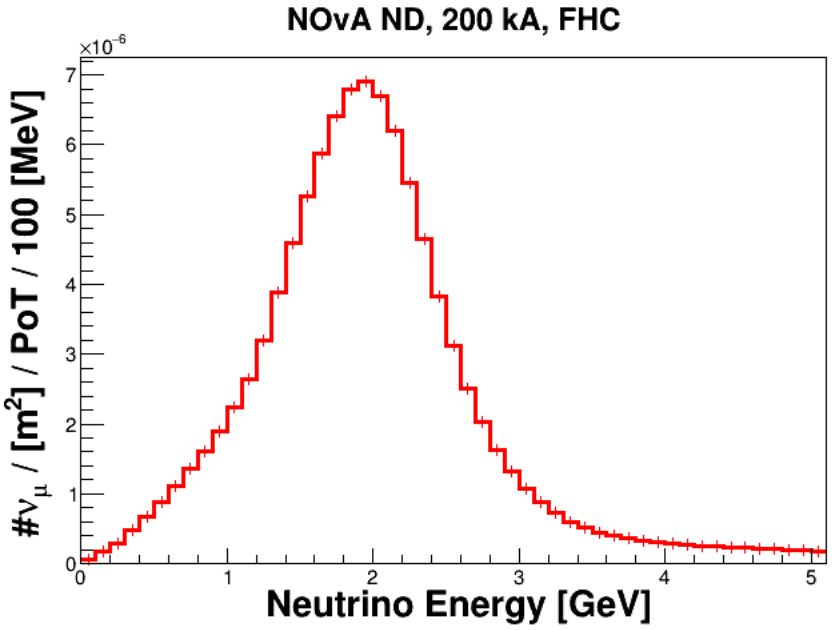
- Develop NuMI beam simulation tool to investigate the horn focusing mechanism
  - Find acceptance (constraint) of the NuMI horn system
    - Study pion phase space evolution from target to the DS end of decay pipe
  - Reconstruct missing link between proton phase space at target to neutrino phase space in the neutrino detector
    - Find a correlation of beam simulations with measurements which are taken at the beam monitors and the neutrino detectors
  - Optimize a dimension of target and horn for future target system design
    - Optimize shape and variation of target material, horn field distribution, dimension of a decay pipe, etc

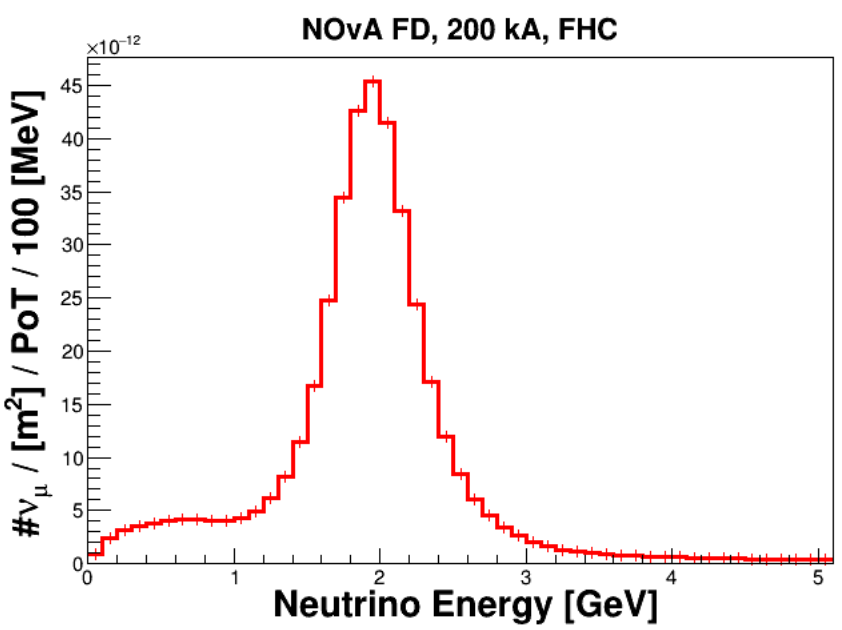
Conventional simulation tool for neutrinos

- g4numi and g4lbnf
  - Geant4 base end-to-end Monte Carlo simulation for the NuMI and LBNF neutrino studies
  - Many post-processors are available to calibrate neutrino signal and to reconstruct neutrino events in neutrino detectors
- Flugg
  - FLUKA base Monte Carlo simulation
  - Use as an event generator
  - Or cross check the neutrino simulation result
- MARS
  - Use for engineering studies for HEP neutrino applications
  - Use for studying low energy neutrino physics
- Geant3
  - T2K uses it for an event generator

Example output from g4numi

N. Bostan





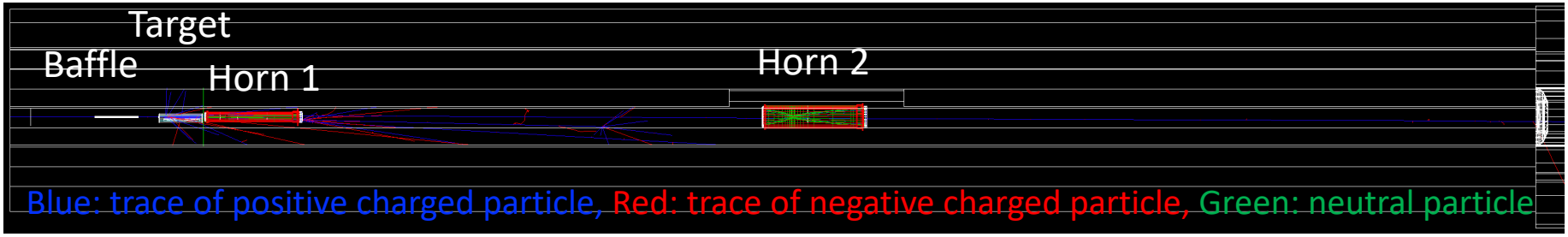
- Simulated neutrino spectrum at the NOvA Near Detector and the Far Detector
- Run 10M test particles in several hours with MPI machine

Look for a new simulation tool

- Conventional neutrino simulation code is customized for neutrino flux estimation
  - Handle very high statistics for a rare neutrino event
  - Omit most intermediate processes in event log
    - Ex: p+C → pi+ → mu+ + nu_mu
  - Omit a particle which does not reach to the neutrino detectors in event log
- In order to design neutrino target, we need to know the particle dynamics in the target, horn, and decay pipe
  - Look for existing simulation code
  - And/Or make a new simulation code

g4beamline

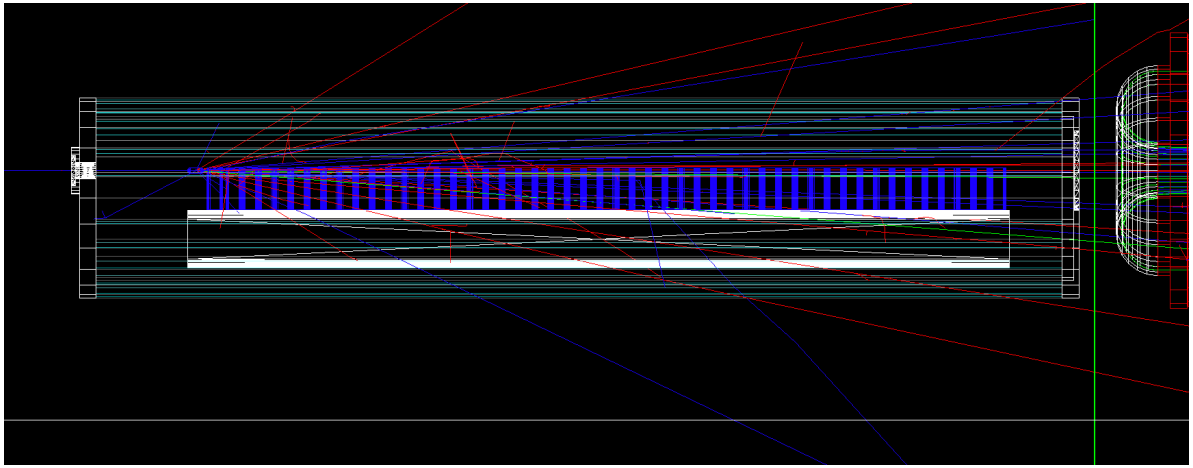
- Geant4 base MC simulation
- Use script to model beam element
  - No compile needed after installation of g4beamline
  - Shortest script only two lines to define a beam and a detector
  - Or ~800 lines to describe the NuMI target system (from baffle to the last muon monitor)
  - Control stochastic process (decay, multiple scattering, etc)
- Run 100k test particles in one hour on my PC
- MPI is available



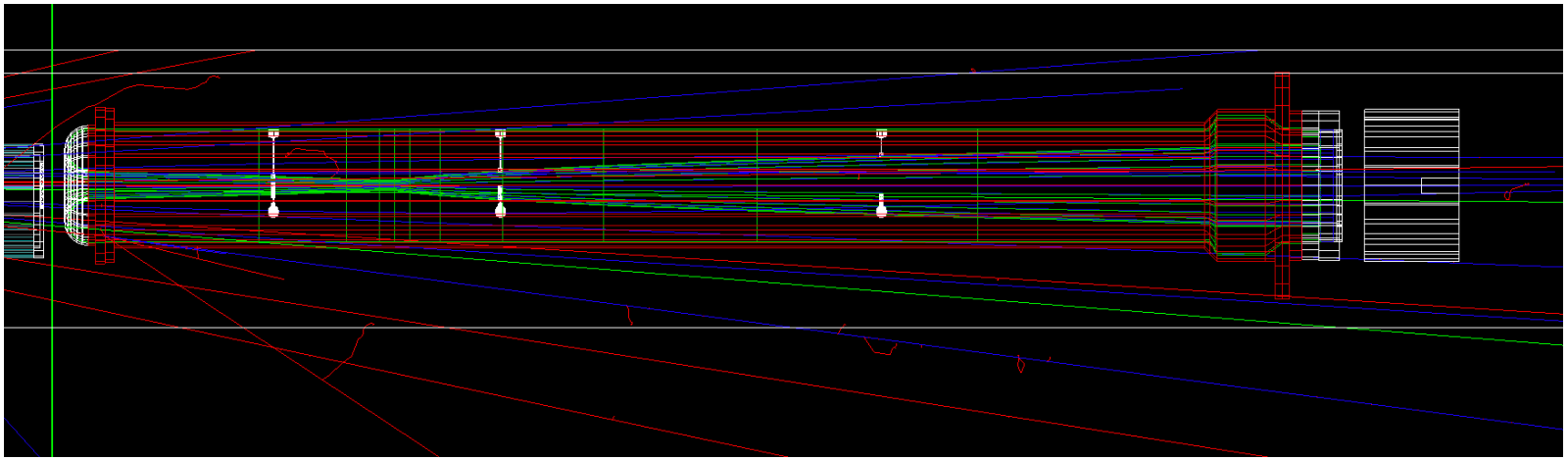
Beam element

P. Snopok

MET-05 + target can + rail



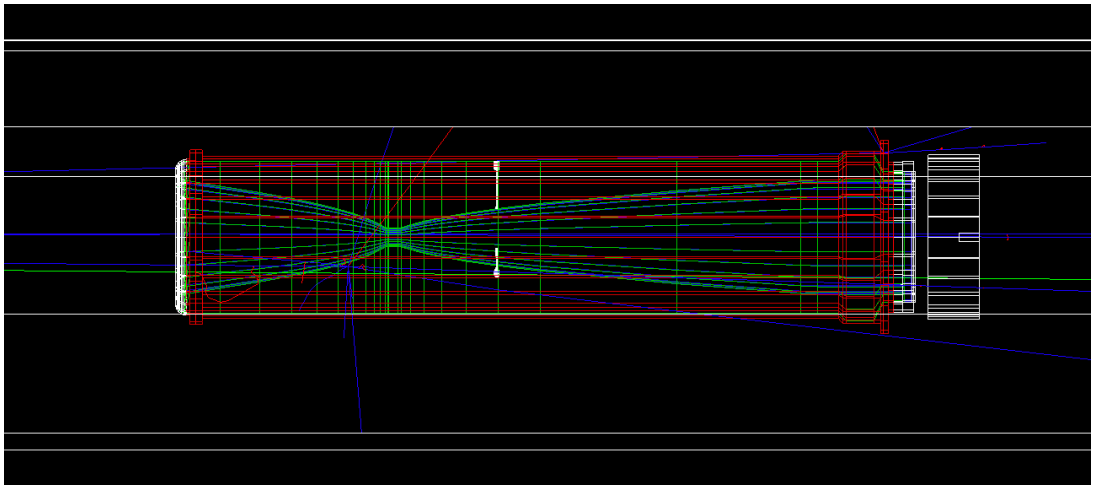
Horn 1 + stripline (Added for studying low energy pions)



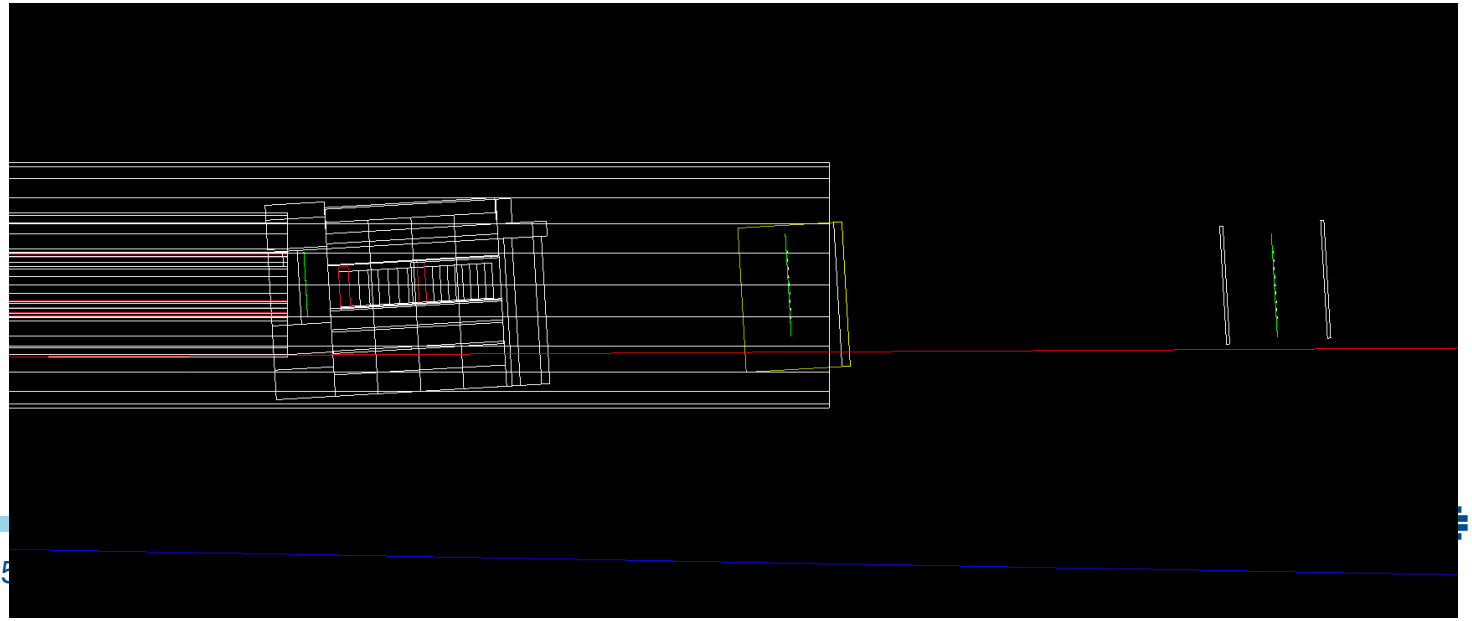
Beam element

P. Snopok

Horn 2 + stripline (Added for studying low energy pions)



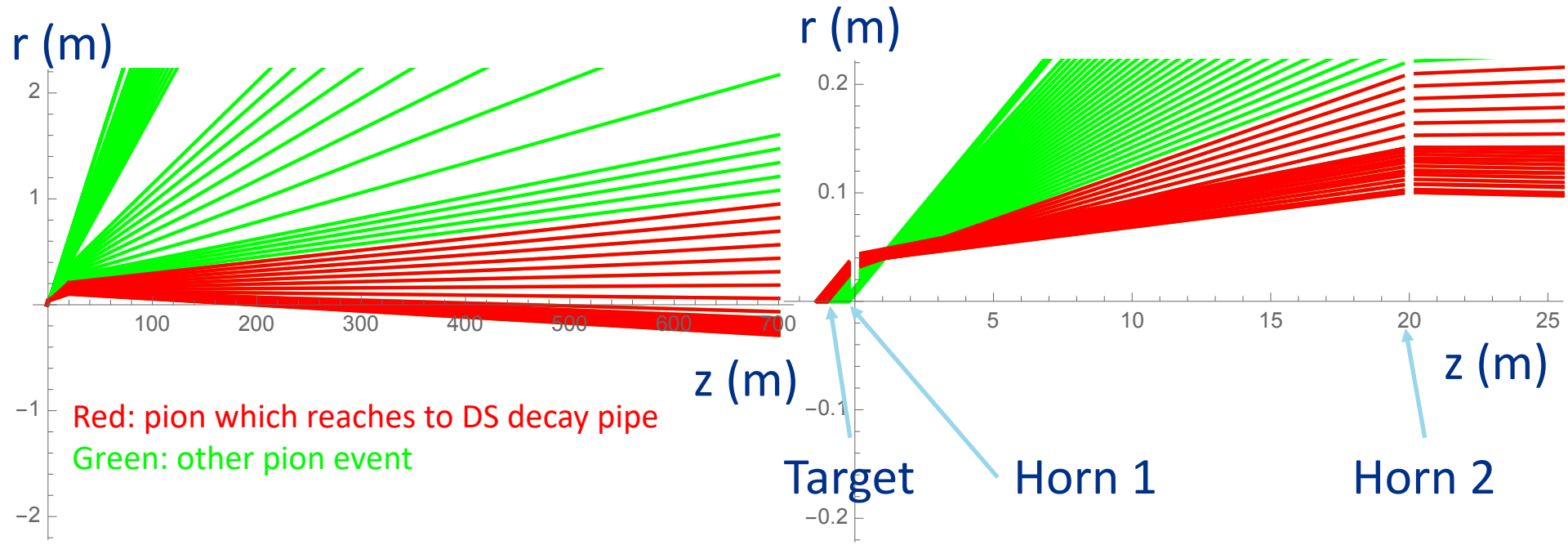
DS Decay pipe window + Hadron monitor + Absorber + Muon monitor



Analytical simulation

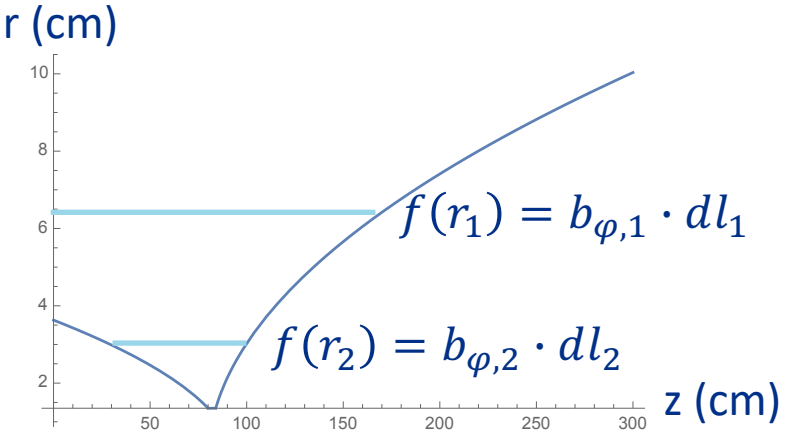
- Mathematica base 1D ray trace simulation
- No stochastic process is involved
- Create transverse kick with the formula
- Extremely fast

$$\theta_{kick} = \frac{0.3 b_{\varphi} \cdot dl}{p_z}$$

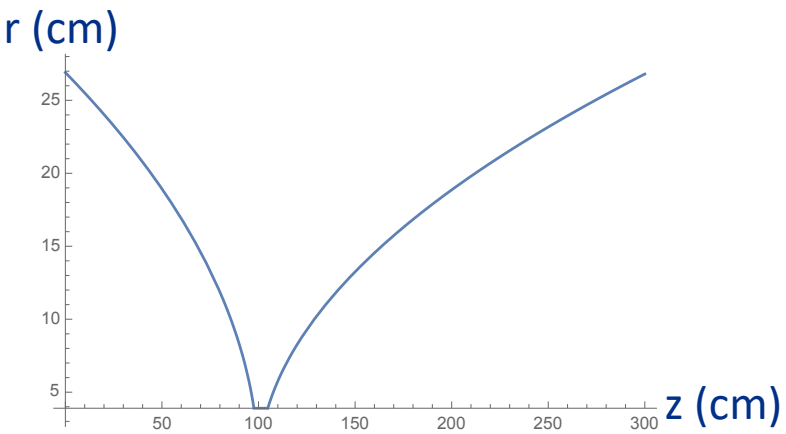


Modeling integrated bdl

- Simplify magnetic field and path length in the horn magnet



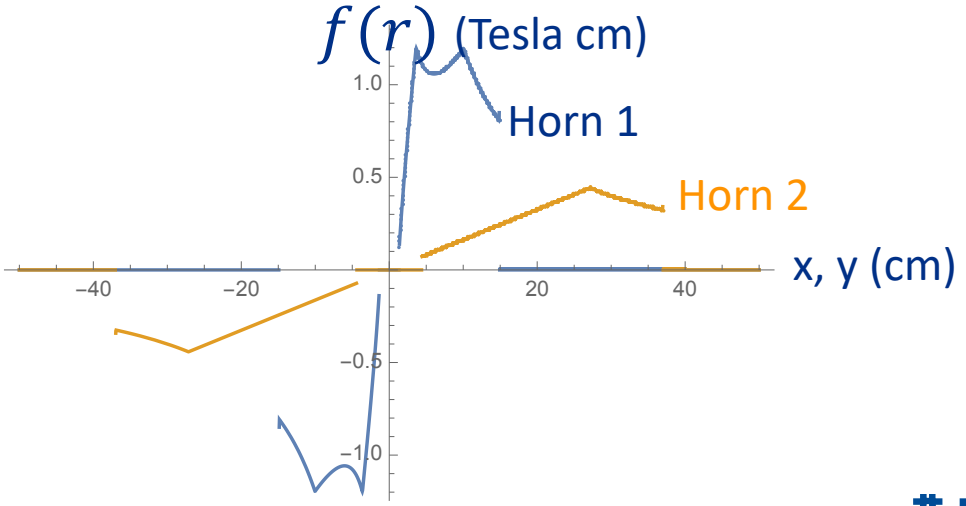
Inner conductor shape of Horn 1



Inner conductor shape of Horn 2

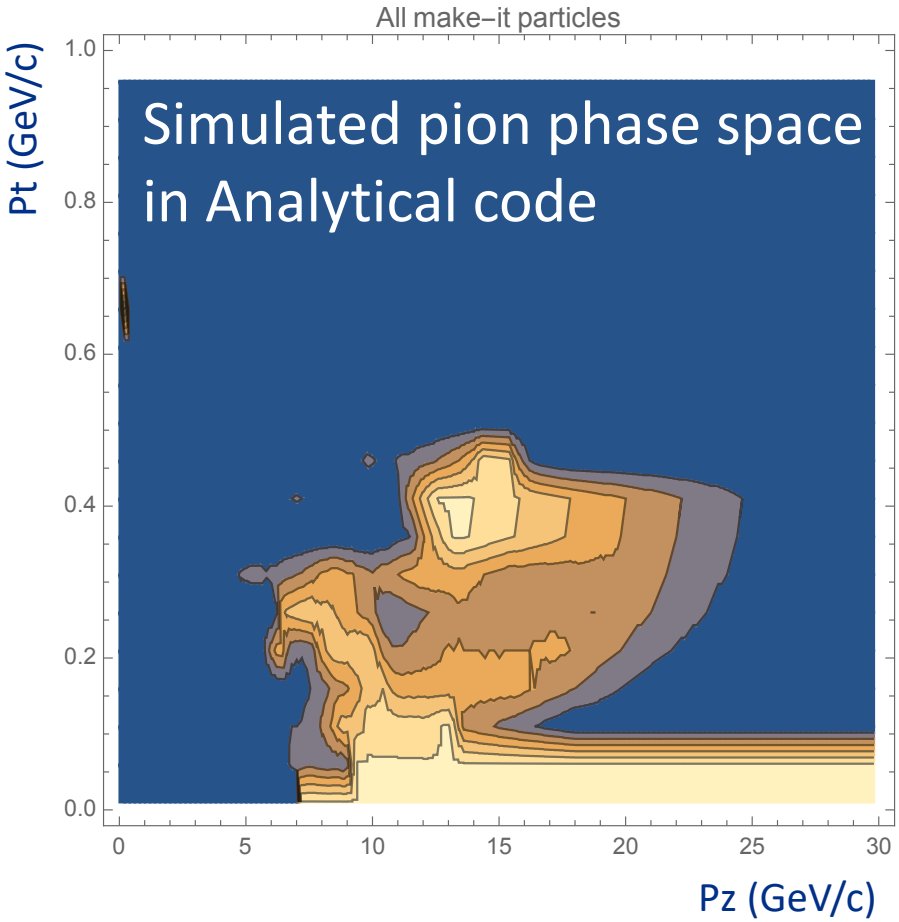
$$\theta_{kick}(r) = \frac{0.3\, f(r)}{p_z}$$

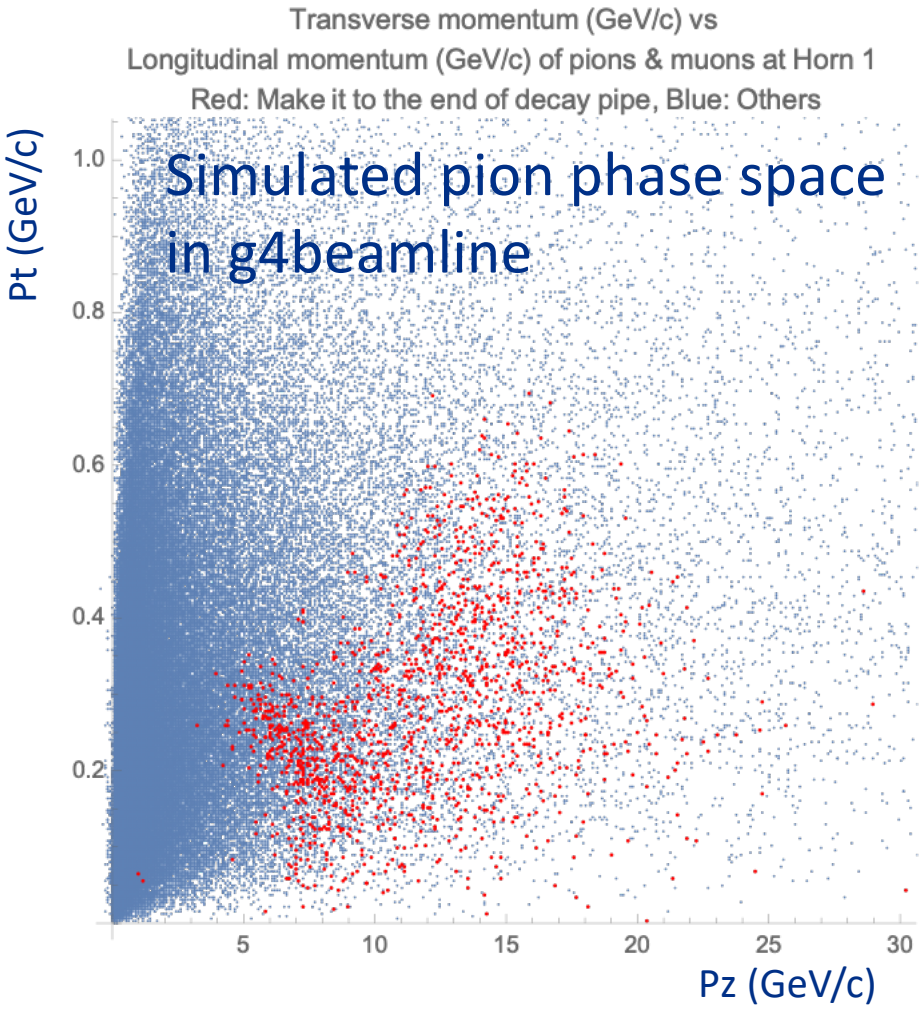
r = x or y



Fermilab

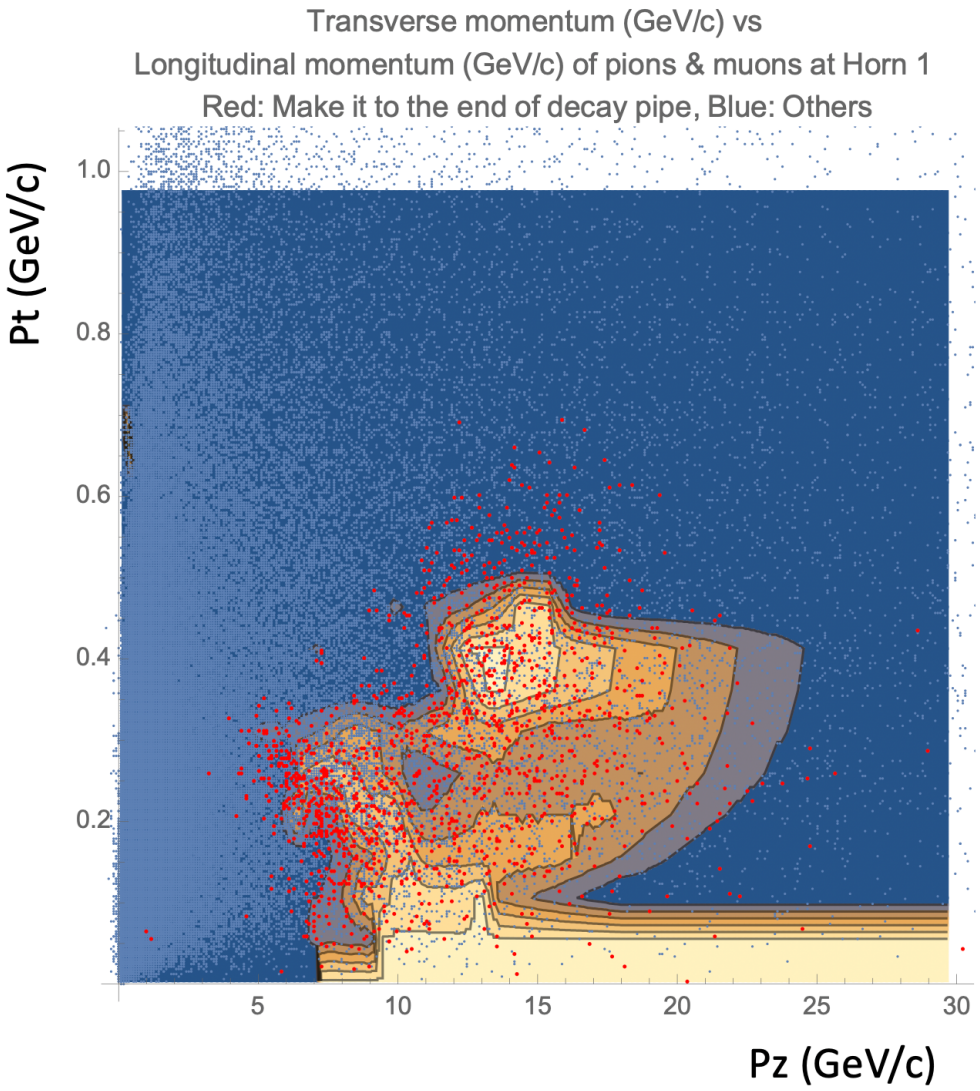
Validation of simulation (I)



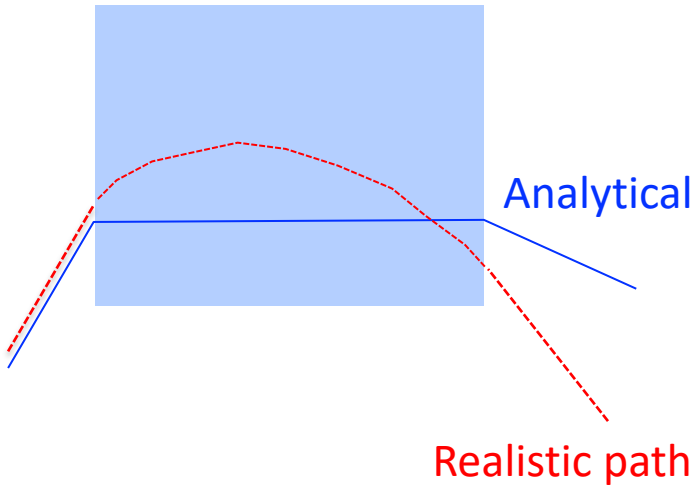


- A big amount of low energy pions is just lost in the target system

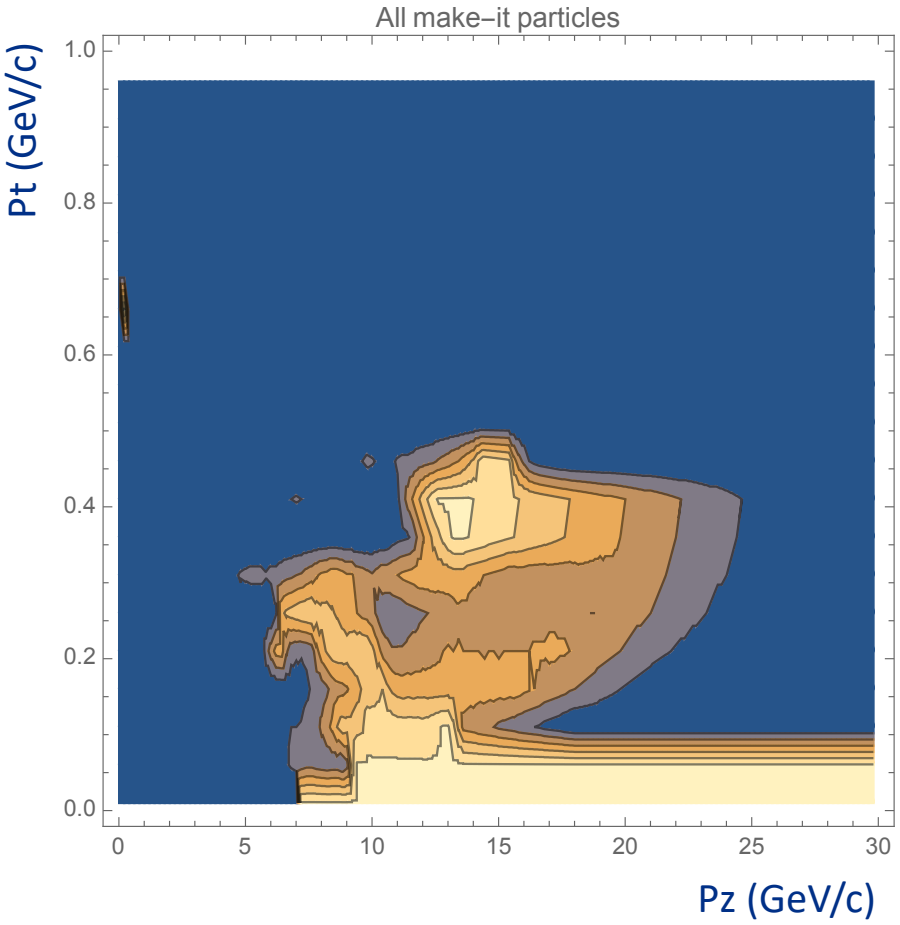
Validation of simulation (II)

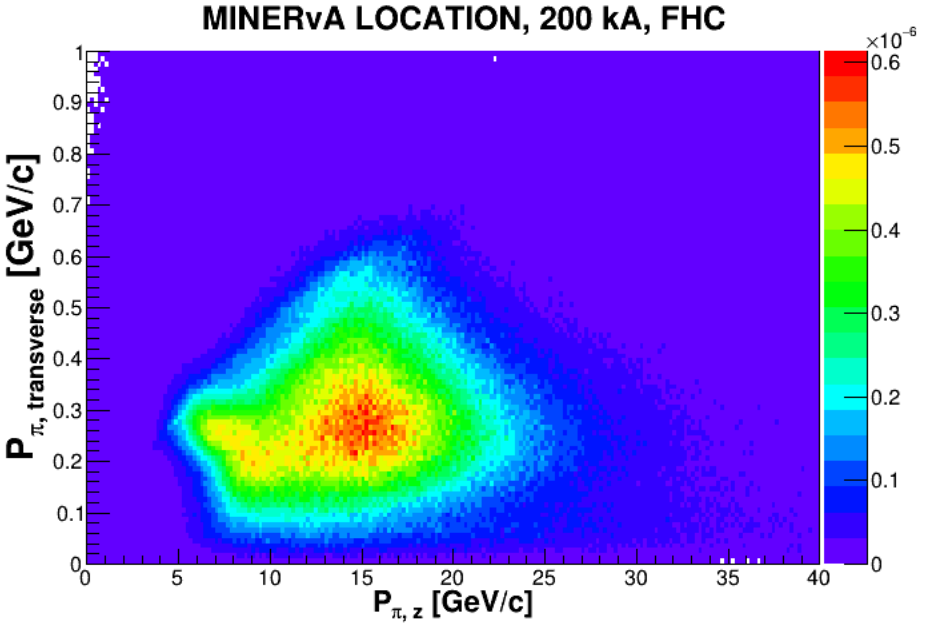


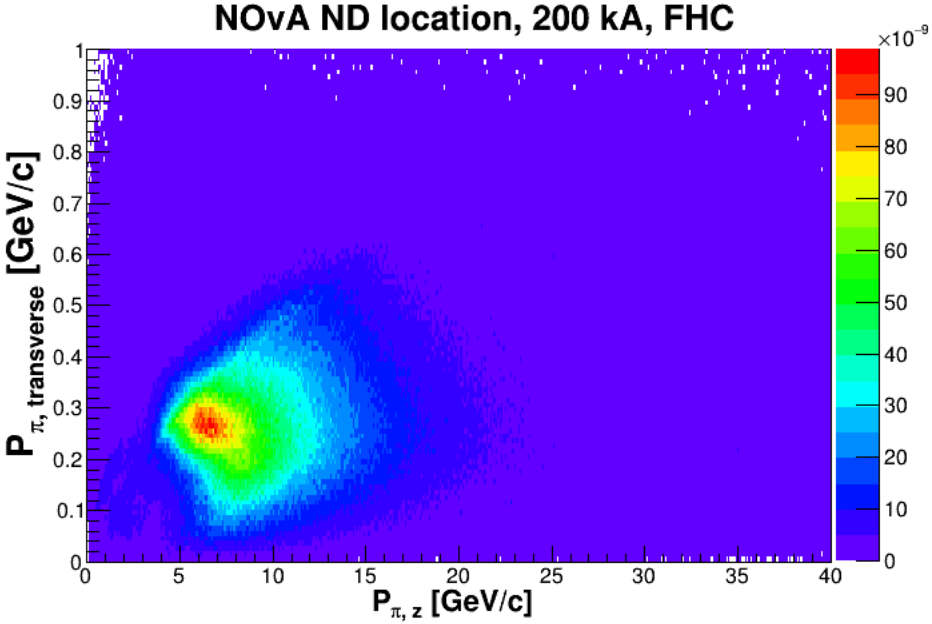
- Both simulations agree quite well
- A difference appears at high pt > 0.5 GeV/c
- Estimated bdl at high pt in Analytical method is too small



Possible connection to neutrino event

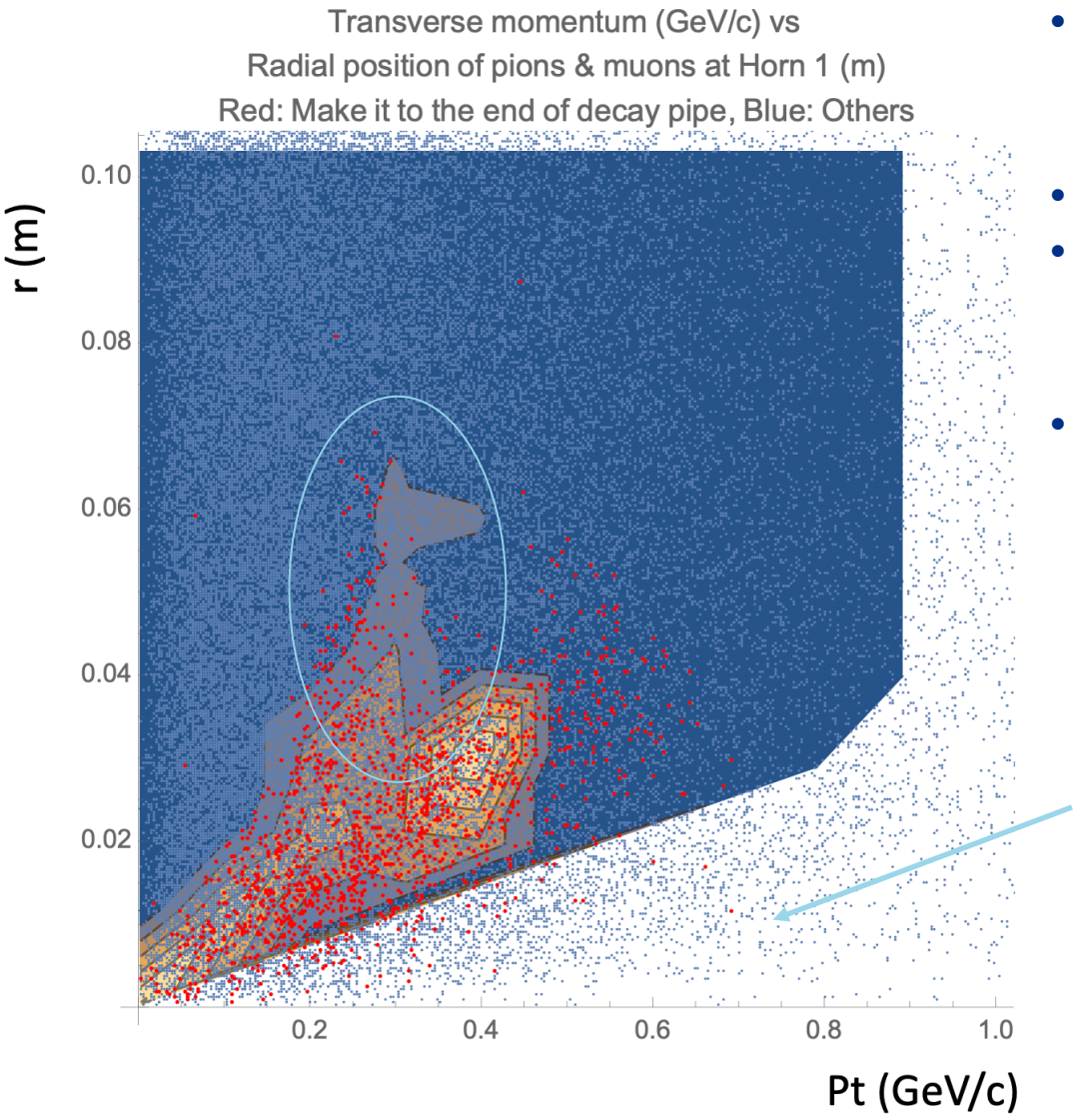






- Analytical and MINERvA are identical
- NOvA is quite different from Analytical

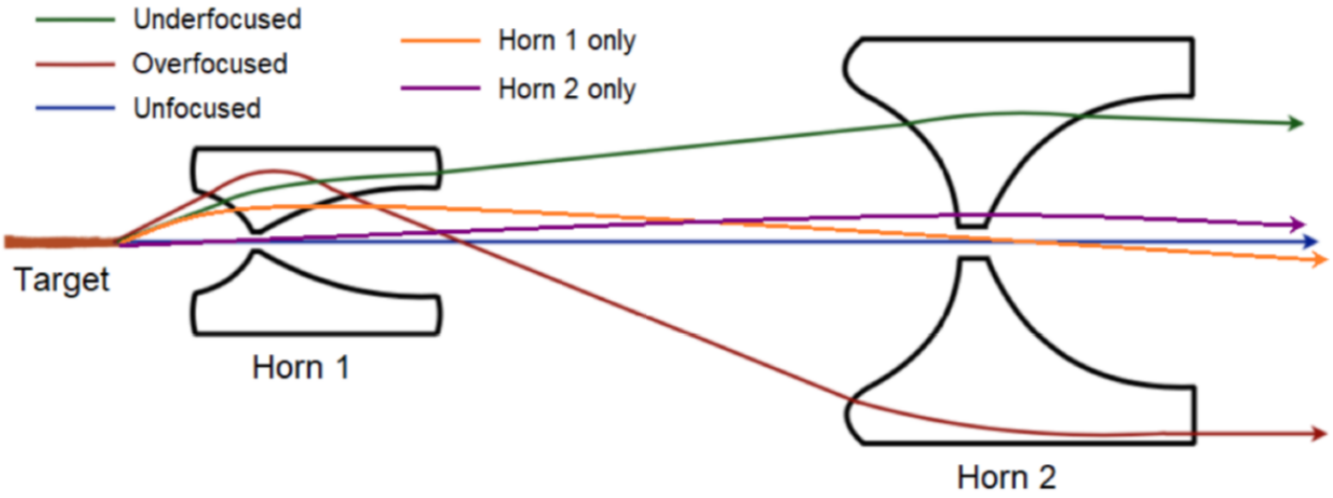
Constraint of pion phase space

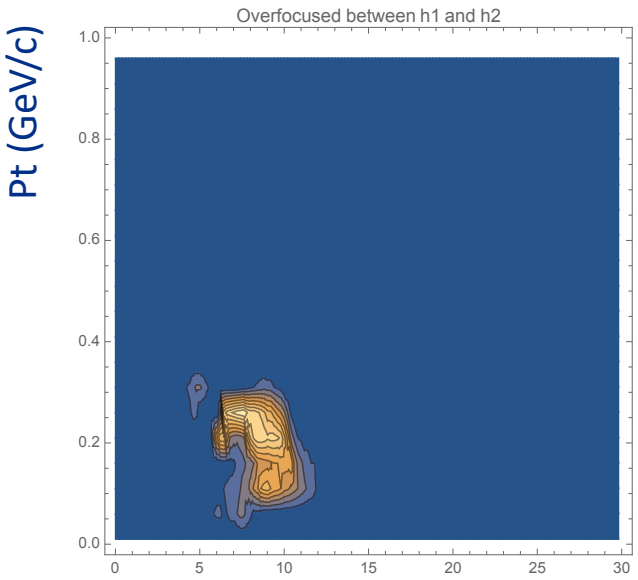


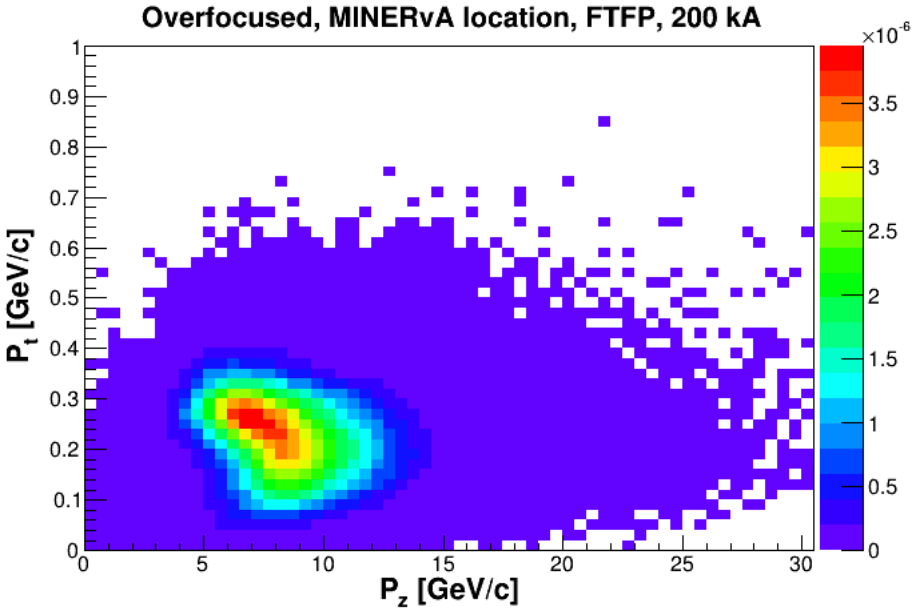
- Higher pt pions which make it to the DS decay pipe has larger radial position at entrance of Horn 1
- It is reproduced in Analytical code
- g4beamline result shows two arms which is reproduced in Analytical code
- Analytical code shows that large radial particles (shown in ellipse) came from low pt (0.2 to 0.4 GeV) and low pz (0 to 5 GeV)

This dead area is a shade of the target

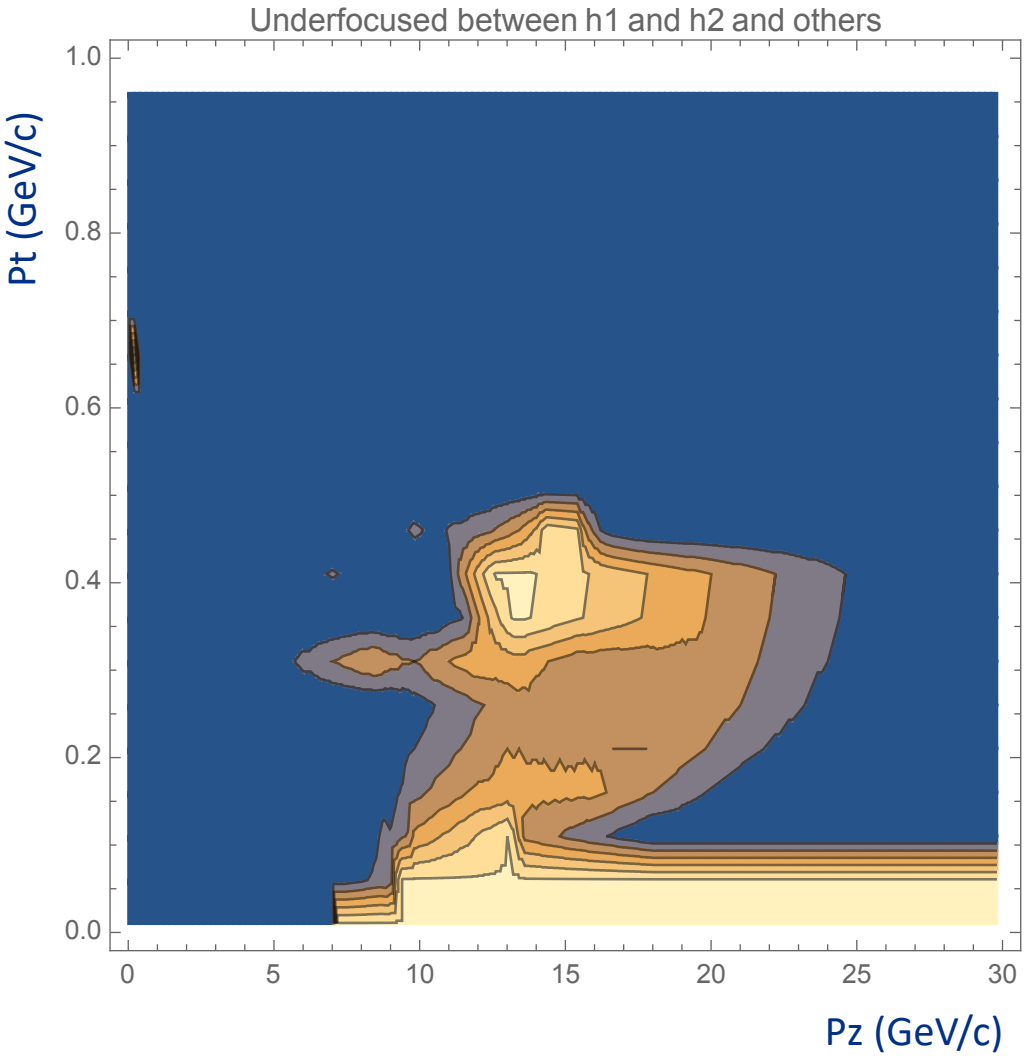
Select focusing component (I)

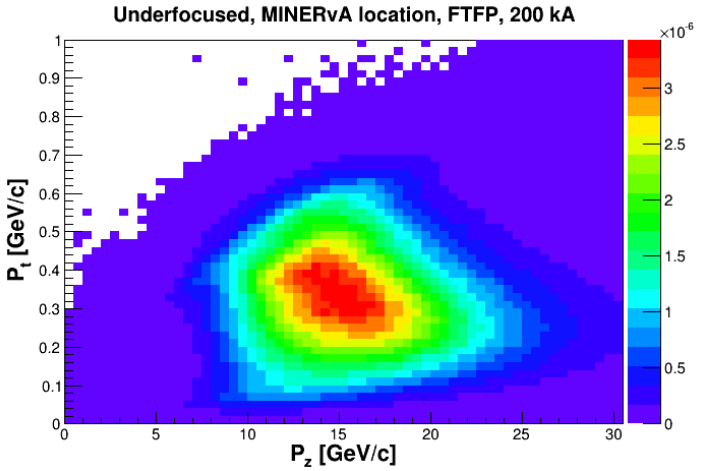


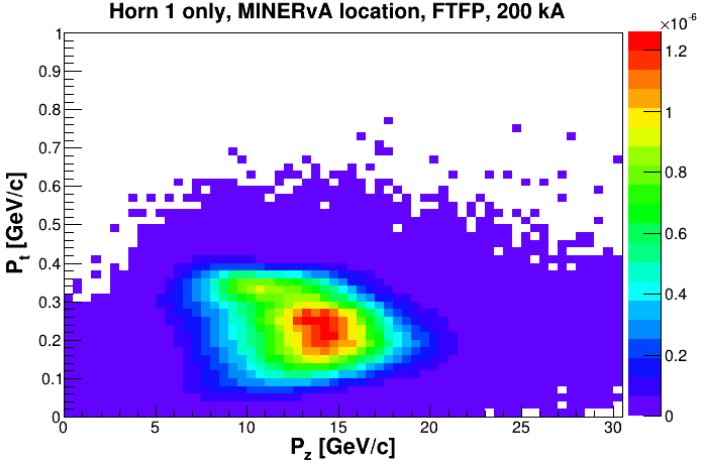




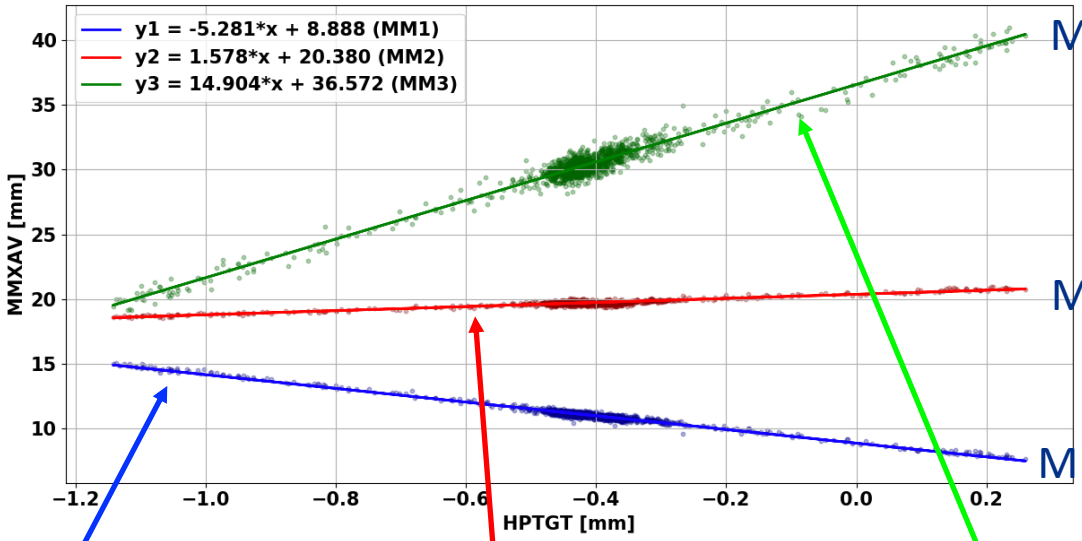
Select focusing component (II)







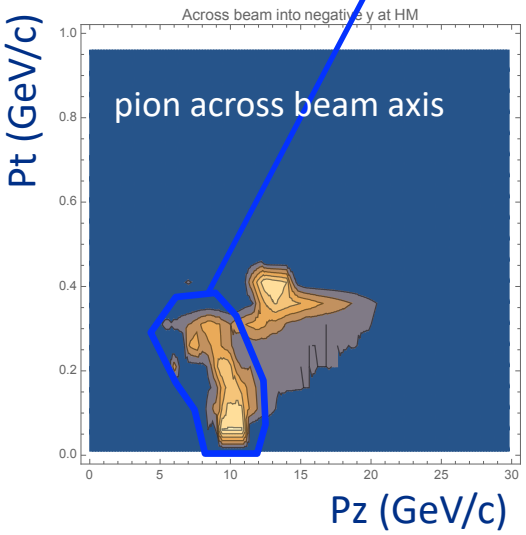
Study correlation between beam detector and pion tracking

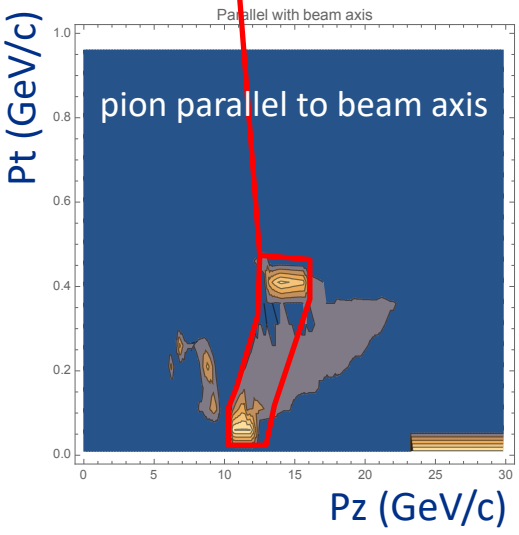


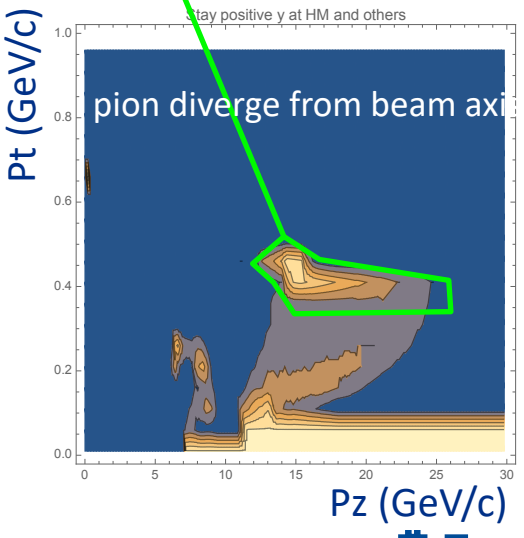
MM3: $p_\pi > 12$ GeV/c

MM2: $p_\pi > 9$ GeV/c

MM1: $p_\pi > 4$ GeV/c

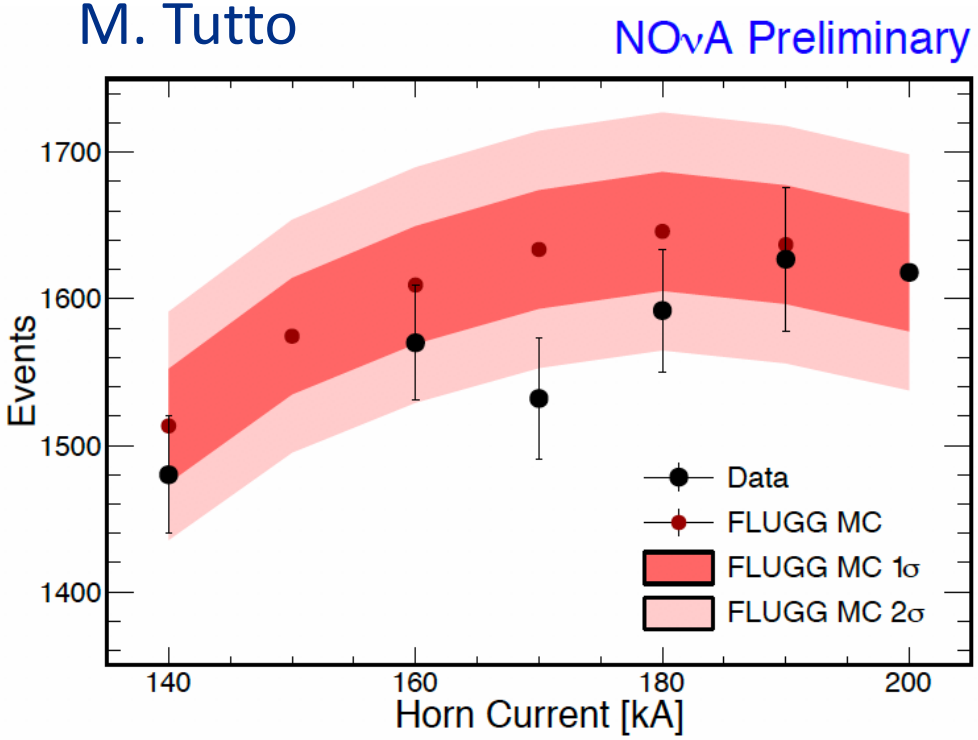






Study Low Horn Current Operation

M. Tutto



(a) Data and FLUGG prediction.

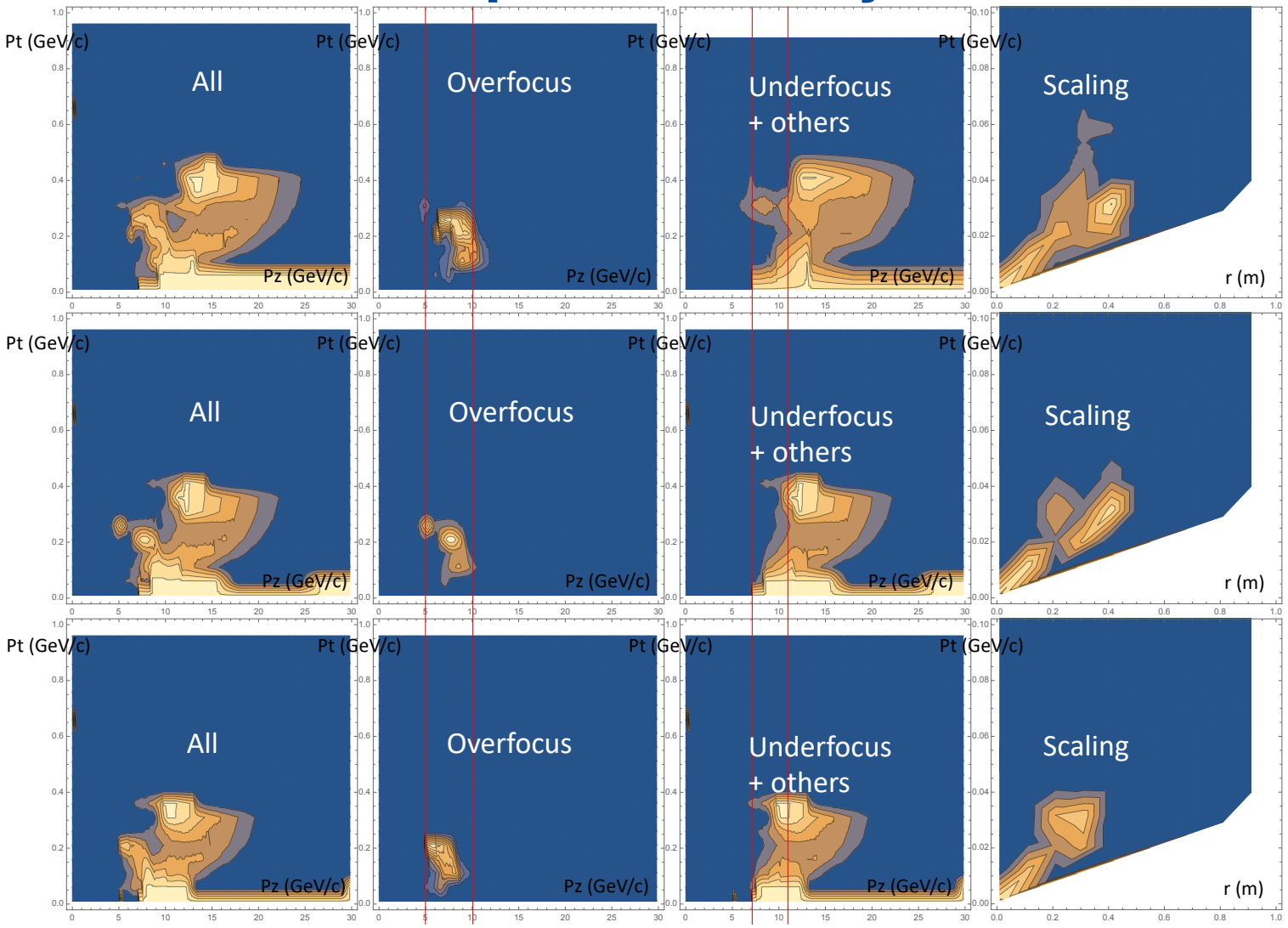
- NOvA beam simulation group has investigated low horn current operation
- Simulation (red point) shows a peak neutrino event at 180 kA (present nominal horn current is 200 kA)
- However, measurement shows some deviation from the simulation

Predicted Pion Phase Space in Analytical Code

200 kA

180 kA

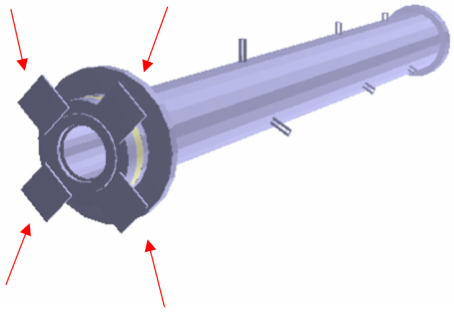
160 kA

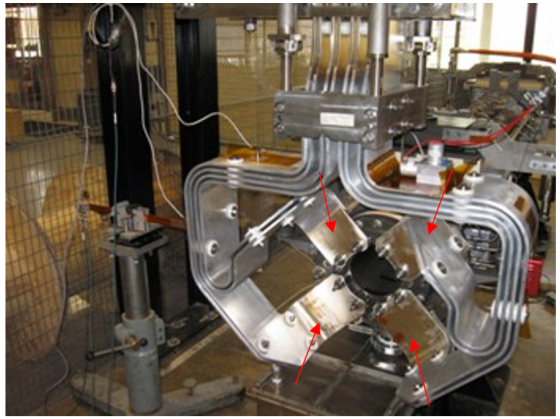


Acceptance of horn system moves lower pz

Possible beam-related systematic in MC simulation

- Low horn current configuration accepts more pions which are a low momentum
- Lower momentum pion has wider angular distribution
- Maybe stripline become an obstacle to eliminate low momentum pions which was omit in neutrino simulation
- g4beamline indicates some change in low energy muons
- Add a stripline model in g4numi and see how the neutrino spectrum is changed by the stripline





R. Chirco

Next step

- Find more phase space constraints
  - target z position vs E
- Add hadronic event weight in Analytical code
  - Simple formula exp(-z/λ) where λ is the interaction length
  - Involve more physics model
- Study low horn current operation
- Study other neutrino beam line
  - LBNF
  - T2K