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LOW ENERGY MONITORED NEUTRINO BEAM TRANSFER LINE DESIGN AND PERFORMANCE



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ESSvSB+ 4th Annual
Meeting

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Optimization

The genetic algorithm

FOM definition

Beamline selection

Completing the simulation

First quadrupole shielding

Soil definition

Near Detector

Air effect

Effect of residual air in the tunnel

Shielding Design

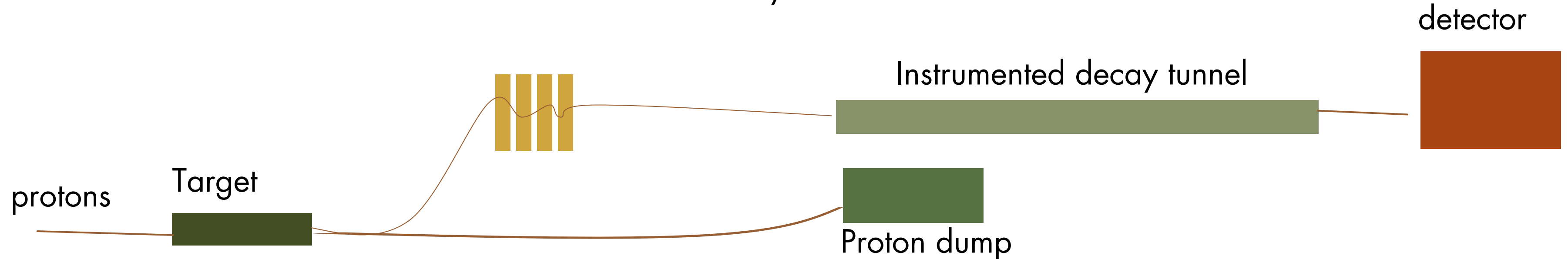
Background study

Performance

LOW ENERGY MONITORED ν BEAM TRANSFER LINE

Goal: focus and transport as many pions with momentum of $1\text{ GeV} \pm 10\%$ as possible at the decay tunnel

- Several constraints: total length as short as possible (avoid early decay)
- Non decaying particles should exit the tunnel without hitting the tagger
- Normal conducting magnets and static design (no focusing horn)
- Particle rate at the tunnel should be sustainable by instrumentation



Base design presented at 2nd Annual Meeting (2024) [link to docDB](#)

Optimized design presented at 3rd Annual Meeting (2025) [link to docDB](#)

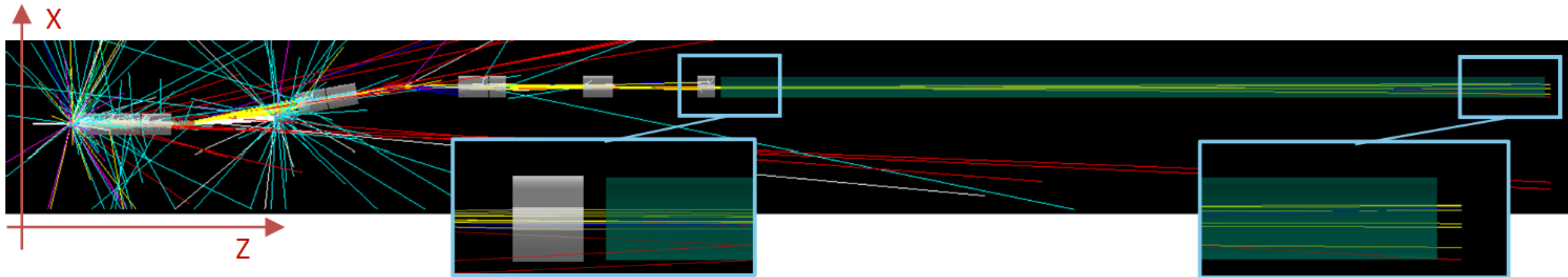
OPTICS OPTIMIZATION WITH A GENETIC ALGORITHM

The preliminary version of the transfer line that was presented as Milestone 7 of WP6 leaves some room for improvement.

Optics Optimization with a **Genetic Algorithm** based approach:

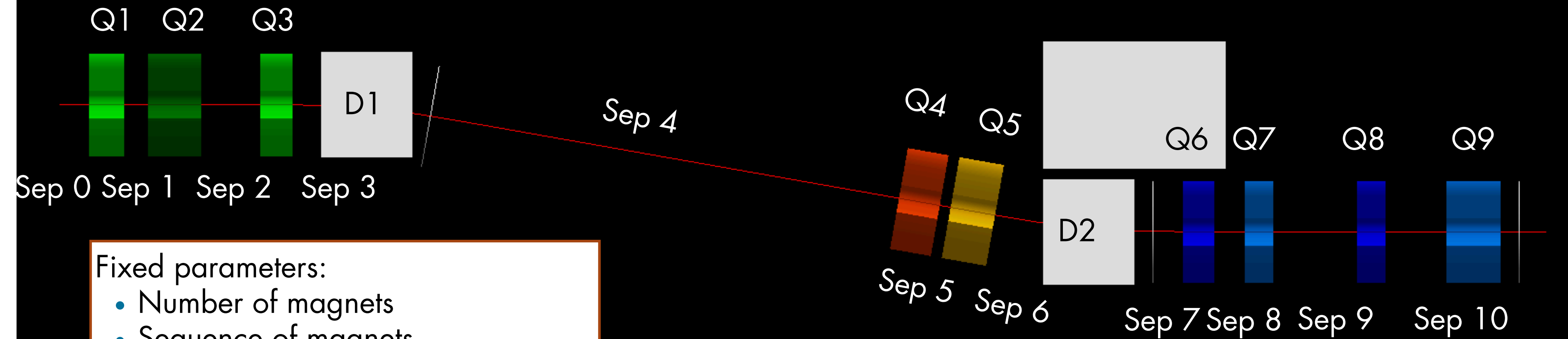
- Allows for optimization on simulated pions from target
- Allows for considering backgrounds in the optimization process > i.e. maximizing pion yield while reducing other particle transport

The base design is unchanged, i.e. number and sequence of dipoles and quadrupoles.



GENETIC ALGORITHM – GENES

- The genes that are optimized are 28:
- 10 distances between objects
 - 9 quadrupole lengths
 - 9 quadrupole gradients



Fixed parameters:

- Number of magnets
- Sequence of magnets
- Dipole bending angle* = 10°
- Dipole lengths = 1 m
- Dipole apertures = $0.5 \times 0.5 \text{ m}^2$
- Quadrupole apertures $\varnothing = 30 \text{ cm}$
- Sep 4** = 5.4 m

*corresponding to $\sim 0.6 \text{ T}$

**Sep 4 should be large enough to allow an efficient separation of pions from the 2 GeV protons coming from the target

OPTIMIZATION

Optimization process needs a “selection criterium” to rank solutions
Two were tested with background (complete target files) and killing elements
The whole optimization takes ~1 week

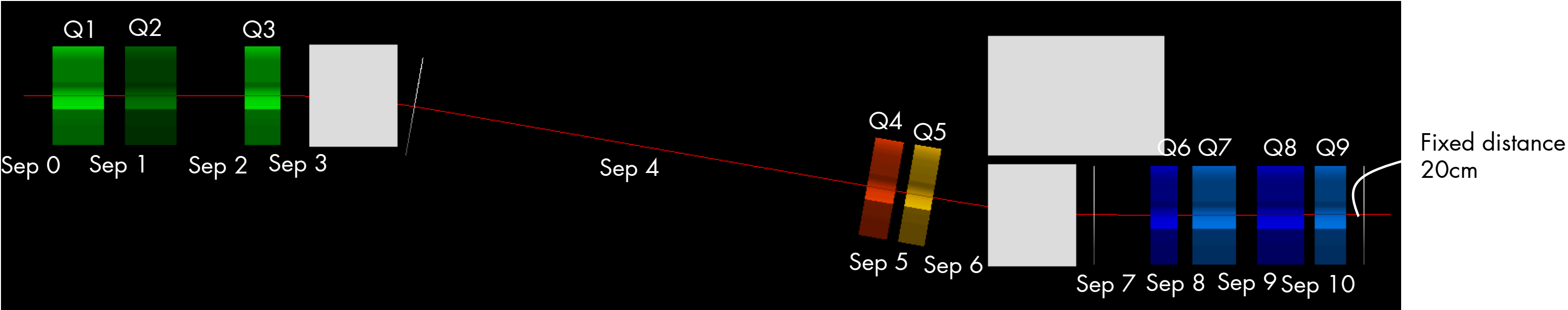
$$FOM = \frac{\pi (endcap)}{\pi + p (walls)}$$

Simply maximizing the FOM	Maximizing the yield up to $10^{-4}/POT$, then maximizing the FOM
Optimal solution: $\pi (endcap) = 0.289 \times \frac{10^{-4}}{POT}$ $\pi + p (walls) = 0.001 \times \frac{10^{-4}}{POT}$	Optimal solution: $\pi (endcap) = 1.117 \times \frac{10^{-4}}{POT}$ $\pi + p (walls) = 0.11 \times \frac{10^{-4}}{POT}$
Low background but low yield → “clean line”	Higher background but higher yield → “high yield line”

For computational efficiency, all the elements in the optimization kill the particles that hit on them

OPTIMIZED BEAMLINES – SUMMARY

The picture is not to scale, just a schematic to identify the elements



CLEAN LINE

sep 0	302.4	mm
sep 1	447.18	mm
sep 2	633.15	mm
sep 3	868.44	mm
sep 4	5400	mm
sep 5	97.7	mm
sep 6	1214.15	mm
sep 7	638.04	mm
sep 8	2071.27	mm
sep 9	2638.34	mm
sep 10	1543.07	mm

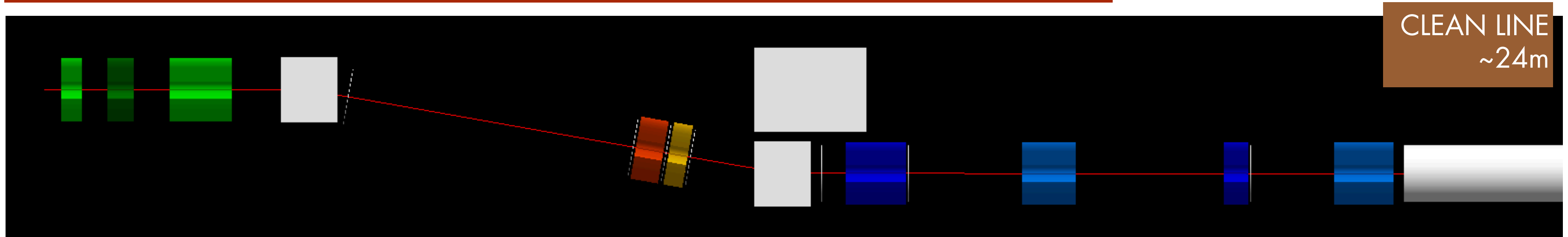
	L (mm)	K (T/m)
Q1	369.03	19.31
Q2	478.97	-9.61
Q3	1117.46	1.59
Q4	496.29	1.71
Q5	341.02	-4.54
Q6	1063.43	1.11
Q7	958.87	-6.89
Q8	424.63	3.69
Q9	1048.09	-0.89

HIGH YIELD LINE

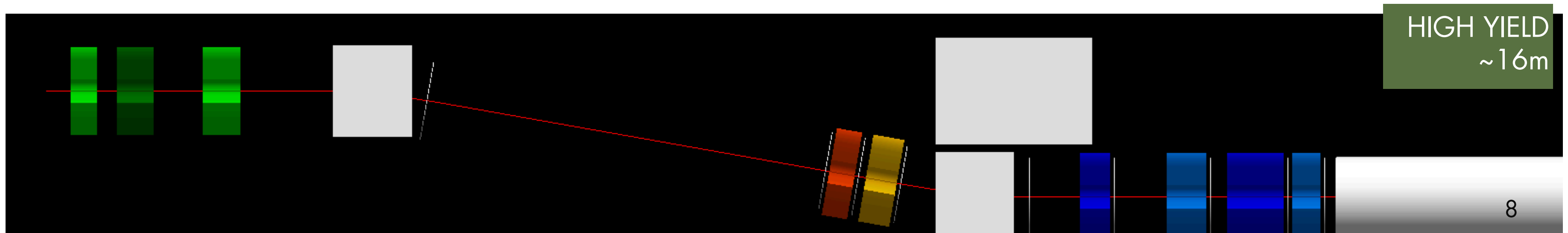
sep 0	316.23	mm
sep 1	255.86	mm
sep 2	620.29	mm
sep 3	1179.36	mm
sep 4	5400	mm
sep 5	145.25	mm
sep 6	505.24	mm
sep 7	844.61	mm
sep 8	716.44	mm
sep 9	262.41	mm
sep 10	100.89	mm

	L (mm)	K (T/m)
Q1	328.22	15.87
Q2	474.4	-12.64
Q3	481.12	4.45
Q4	327.25	2.01
Q5	399.96	-2.53
Q6	395.18	0.51
Q7	504.82	-1.2
Q8	724.43	1.18
Q9	365.28	-1.04

OPTIMIZED BEAMLINE STUDIES



- The optimal solutions provided by the genetic algorithm were tested with 1 GPOT statistics
- The killing conditions is removed.
- Detectors are placed at the exit of each quadrupole to study the beam evolution.
- The tunnel is a cylindrical virtual detector of thickness 1 cm.
- naïve observation: longer bl has lower yield but higher purity



BEAMLINE COMPARISON

$$FOM = \frac{\pi (endcap)}{\pi + p (walls)}$$

CLEAN LINE

$$0.299 \times 10^{-4} \frac{\pi}{POT}$$

entering the tunnel

$$0.289 \times 10^{-4} \frac{\pi}{POT}$$

entering within p range

$$0.0095 \times 10^{-4} \frac{\pi}{POT}$$

hitting walls

$$0.0441 \times 10^{-4} \frac{p}{POT}$$

hitting walls

HIGH YIELD LINE

$$1.411 \times 10^{-4} \frac{\pi}{POT}$$

$$1.113 \times 10^{-4} \frac{\pi}{POT}$$

$$0.0541 \times 10^{-4} \frac{\pi}{POT}$$

$$0.613 \times 10^{-4} \frac{p}{POT}$$

BEAMLINE COMPARISON

$$FOM = \frac{\pi (endcap)}{\pi + p (walls)}$$

CLEAN LINE

0.29 After preliminary study with background, the high yield beamline is selected

- 0.28
- Improving simulation by adding realistic elements
 - Realistic shielding

0.009

$$0.0441 \times 10^{-4} \frac{p}{POT}$$

hitting walls

HIGH YIELD LINE

$$1.411 \times 10^{-4} \frac{\pi}{POT}$$

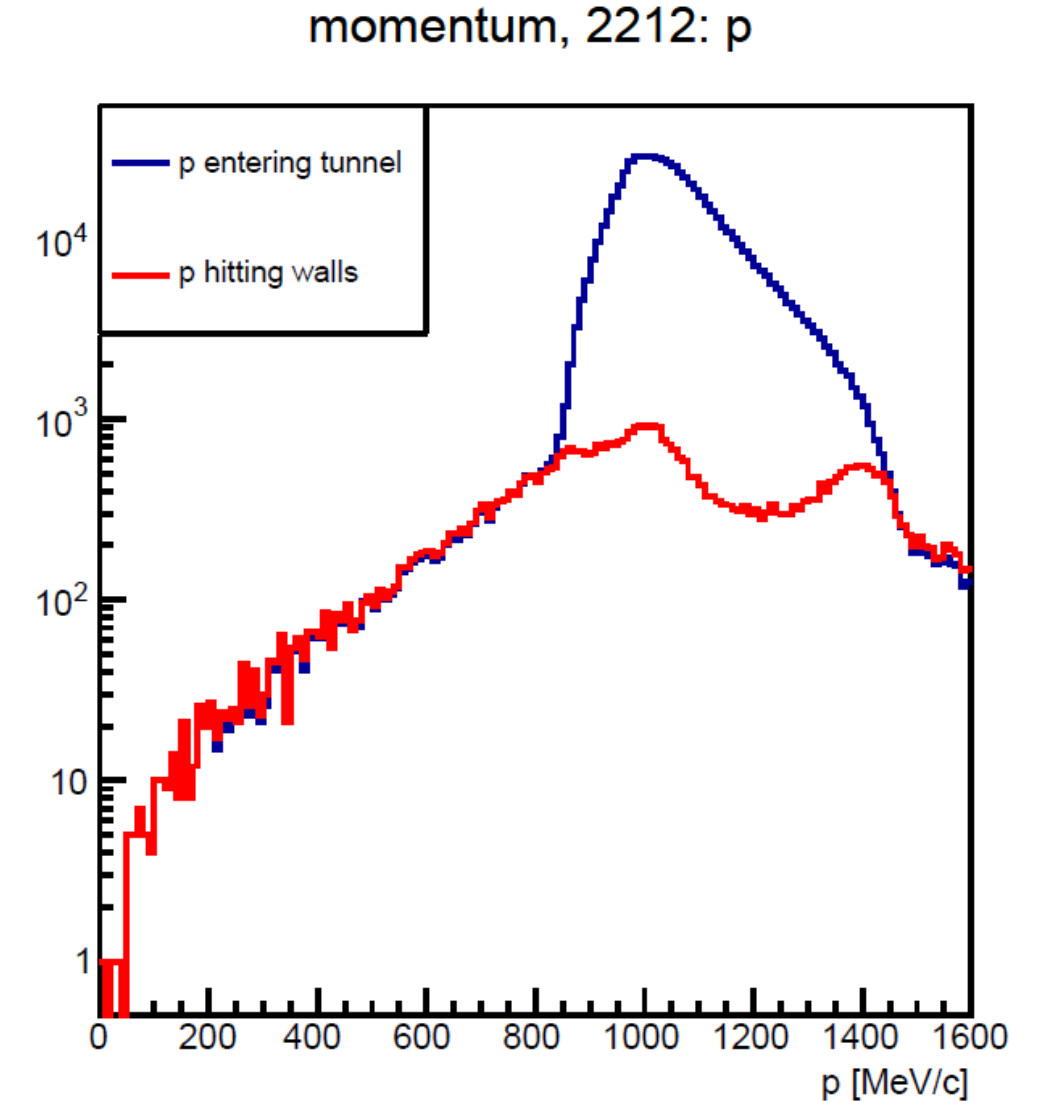
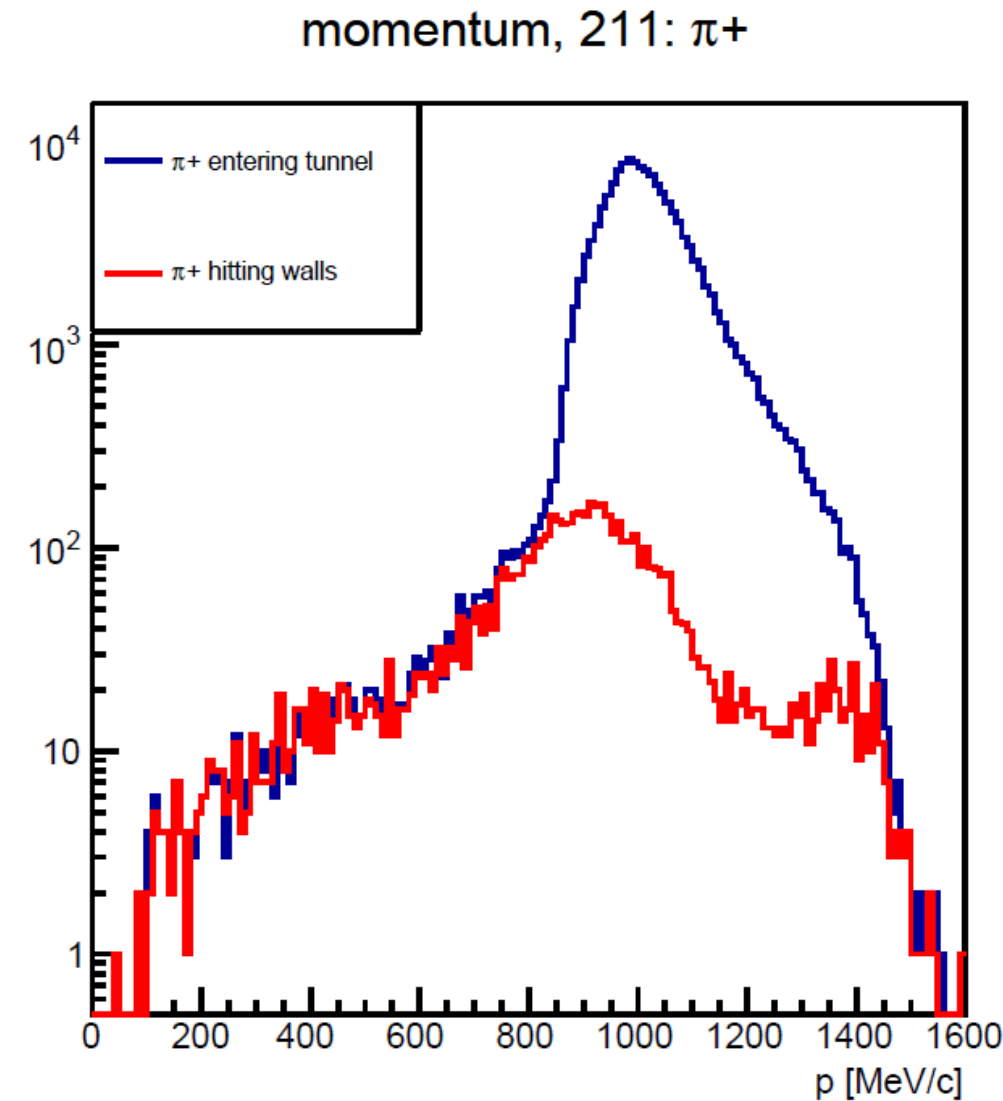
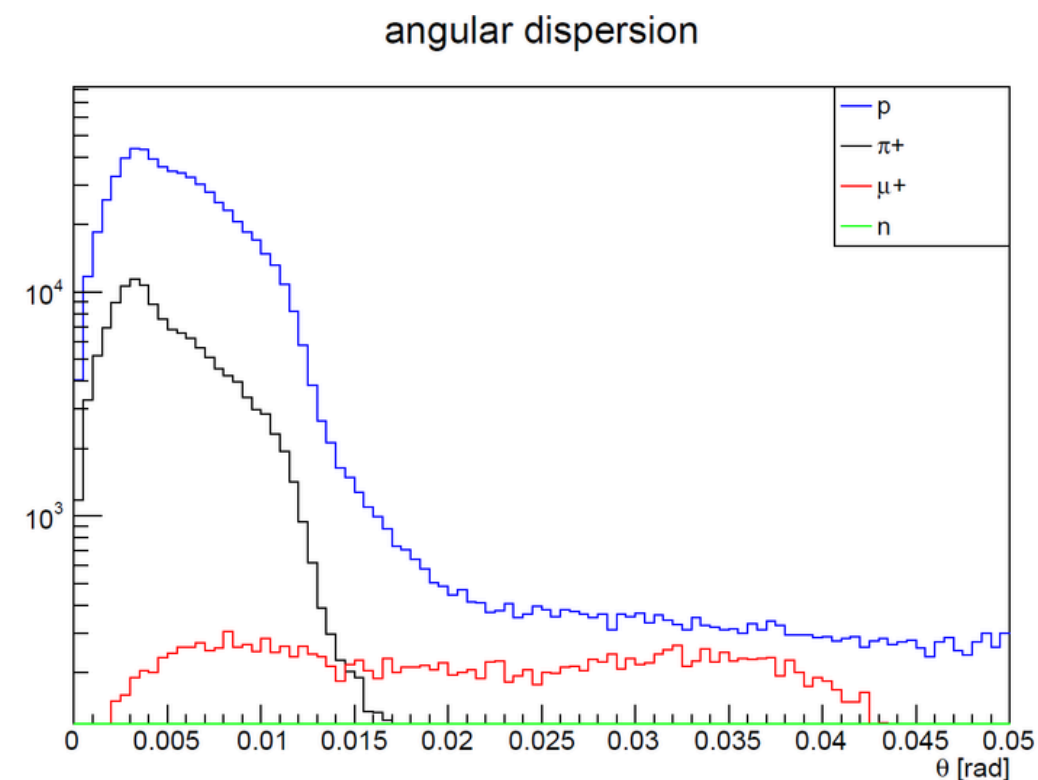
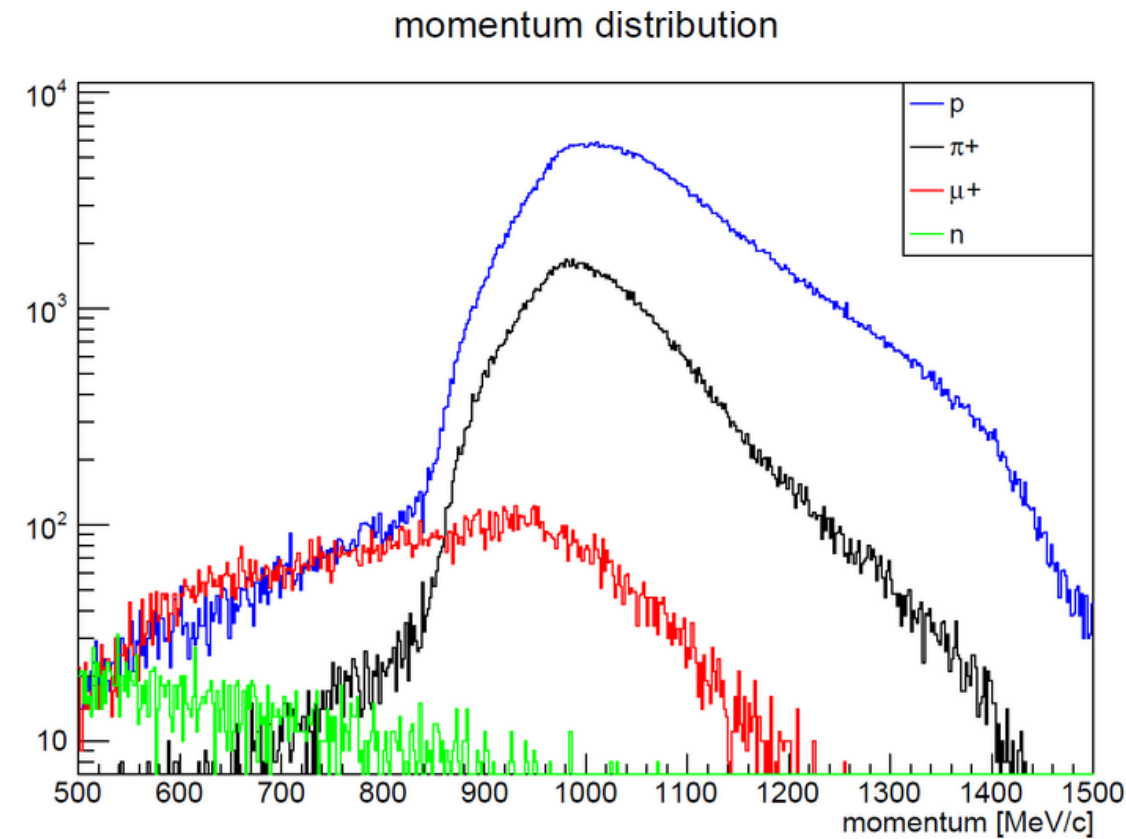
$$1.113 \times 10^{-4} \frac{\pi}{POT}$$

$$0.0541 \times 10^{-4} \frac{\pi}{POT}$$

$$0.613 \times 10^{-4} \frac{p}{POT}$$

NAKED BEAMLINE PERFORMANCE

Momentum and angular dispersion
at the entrance of the tunnel for
different particle species



Tail of protons at high p and high theta > source of background

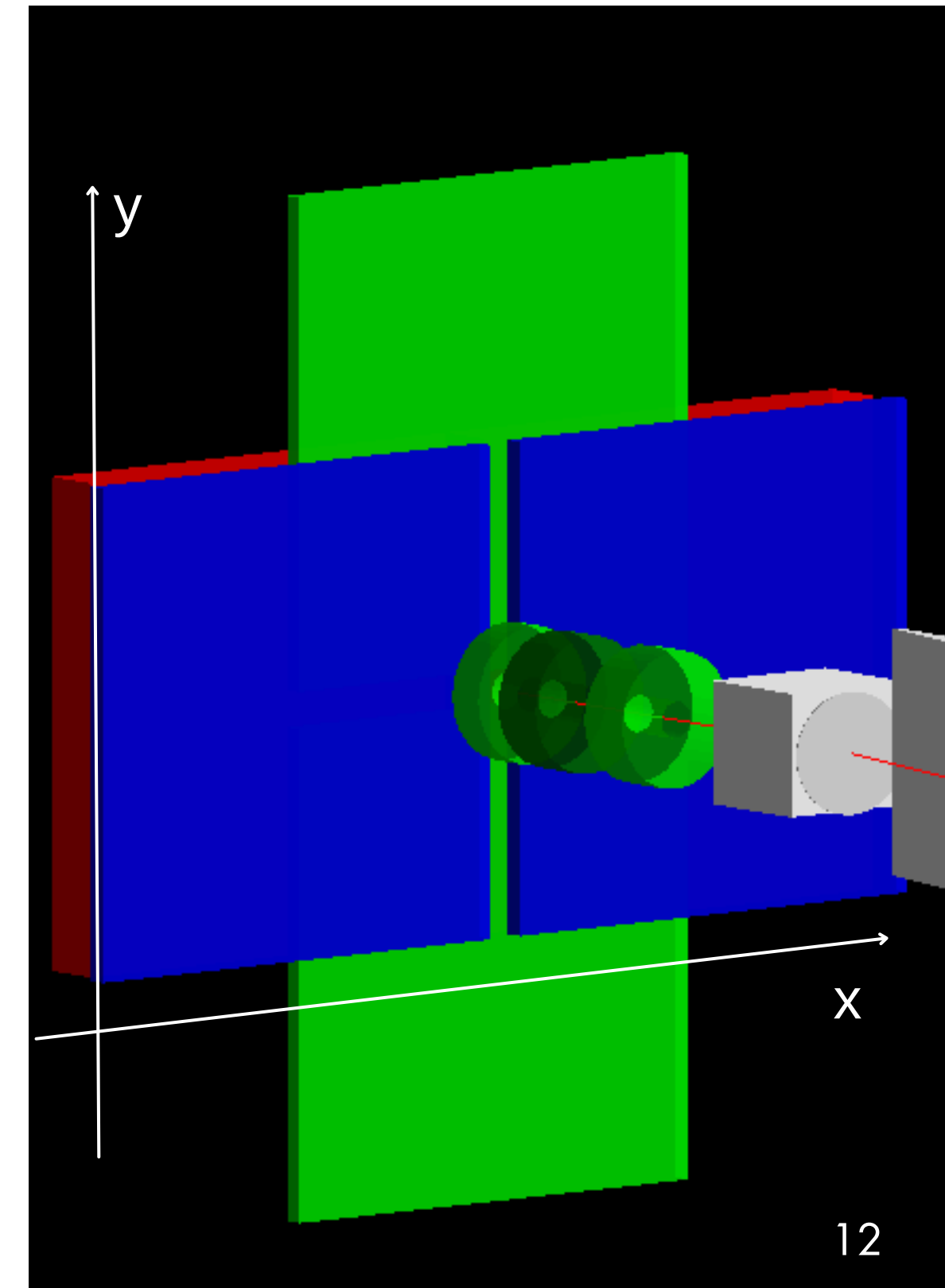
Neutrons have low momenta and flat distribution in theta. Most of them impact on the first section of the tunnel

FIRST QUADRUPOLE SHIELDING

made of Cu blocks (4m x 4m in x, y)

- 2 slabs surround the target (red)
 - Aperture (along x): target diameter
 - Length: target length
- 2 slabs after the target (green):
 - Aperture (along y): first dipole diameter
 - Length: 150 mm
- 2 slabs after the target (blue):
 - Aperture (along x): first dipole diameter
 - Length: 150 mm

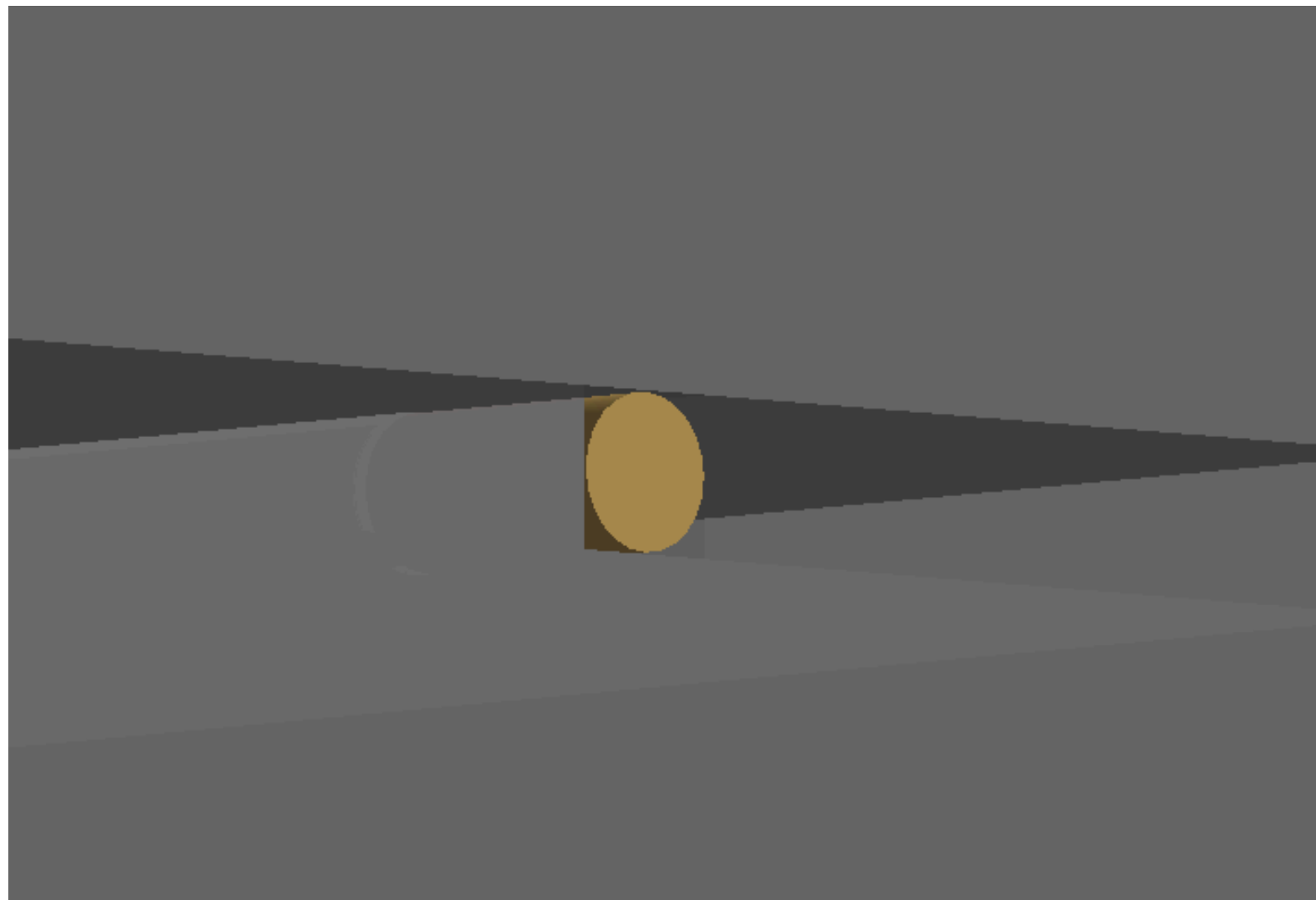
The space between the target and the first quadrupole is 316 mm



TUNNEL DUMP AND SOIL

At the end of the tunnel a 2m Fe dump is placed to stop residual hadrons in the tunnel

The space surrounding the tunnel + the space between the tunnel and the near detector is filled with soil



Soil composition is average earth crust

Soil composition:		Mg	2.33 %
O	46.1 %	K	2.09 %
Si	28.2 %	Ti	0.565%
Al	8.23 %	H	0.14 %
Fe	5.63 %	P	0.105 %
Ca	4.15 %	Mn	0.1 %
Na	2.36 %		

density=2 g/cm³

NEAR DETECTOR

LEMMOND specs:

$d = 50 \text{ m}$

$\varnothing = 5 \text{ m}$

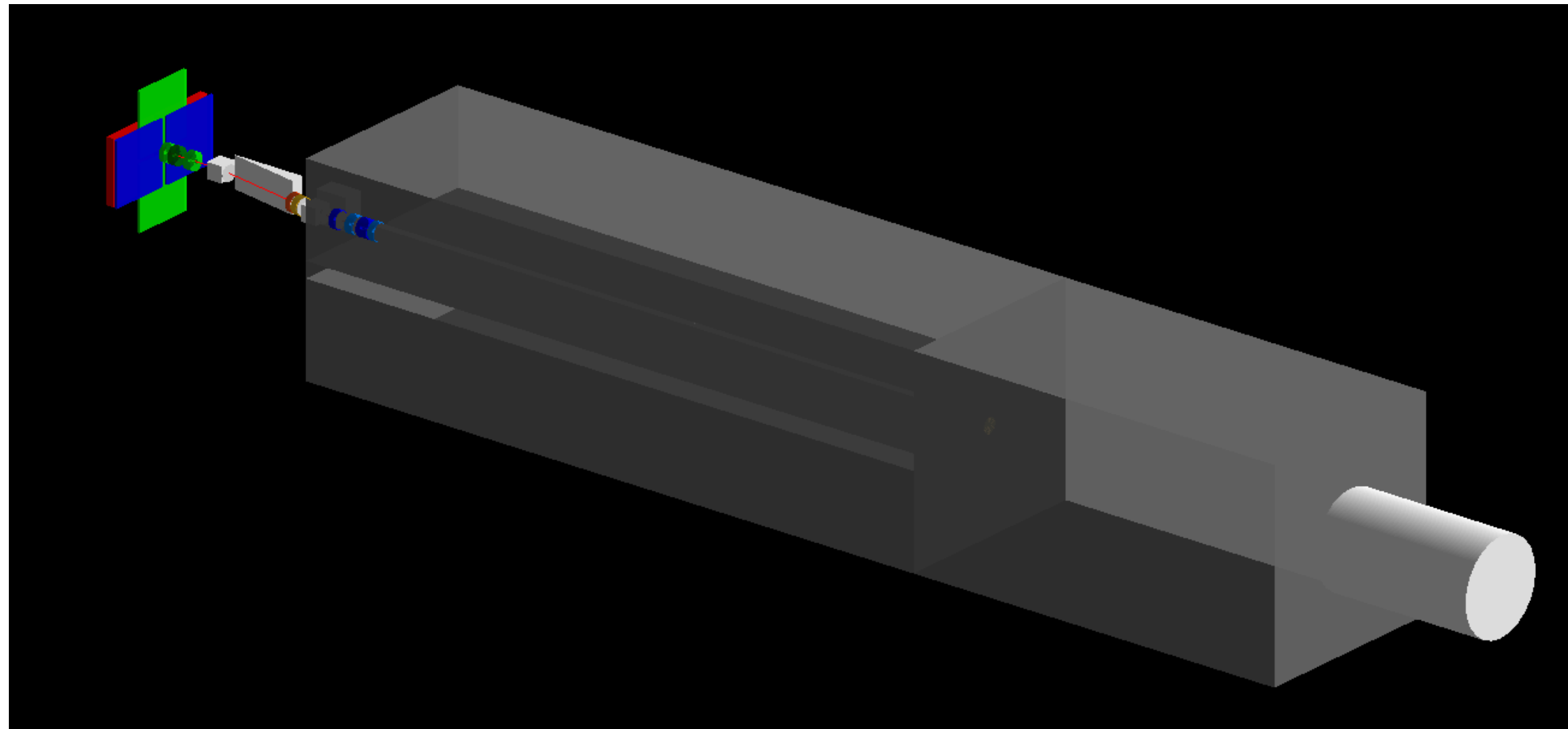
$L = 10.4 \text{ m}$

Near Detector is a cylindrical Virtual Detector placed 25 m downstream of the tunnel

$\varnothing = 6 \text{ m}$

$L = 10.4 \text{ m}$

NB: Diameter and distance do not match LEMMOND specification; this is done for adding flexibility to our study



AIR EFFECT

Test to evaluate the effect of residual air in the decay tunnel

$p = 0.1 \text{ bar}$

$\rho = 0.12 \text{ kg/m}^3$ ($\sim 1/10$ of air density at STP)

No shielding is placed except for the p and had dumps

Tunnel is modeled as 3 virtual detectors

Variables of a hit

$(x, y, z, P_x, P_y, P_z, PDGid, \dots)$

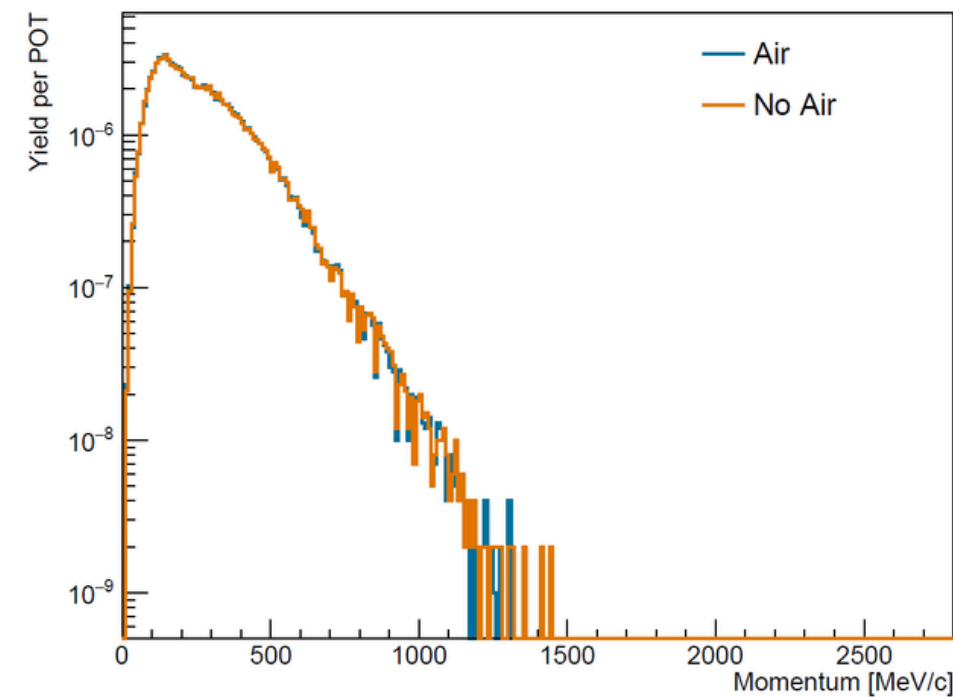
Particle direction is not registered but can be computed for later analysis



AIR EFFECT ON TUNNEL WALLS

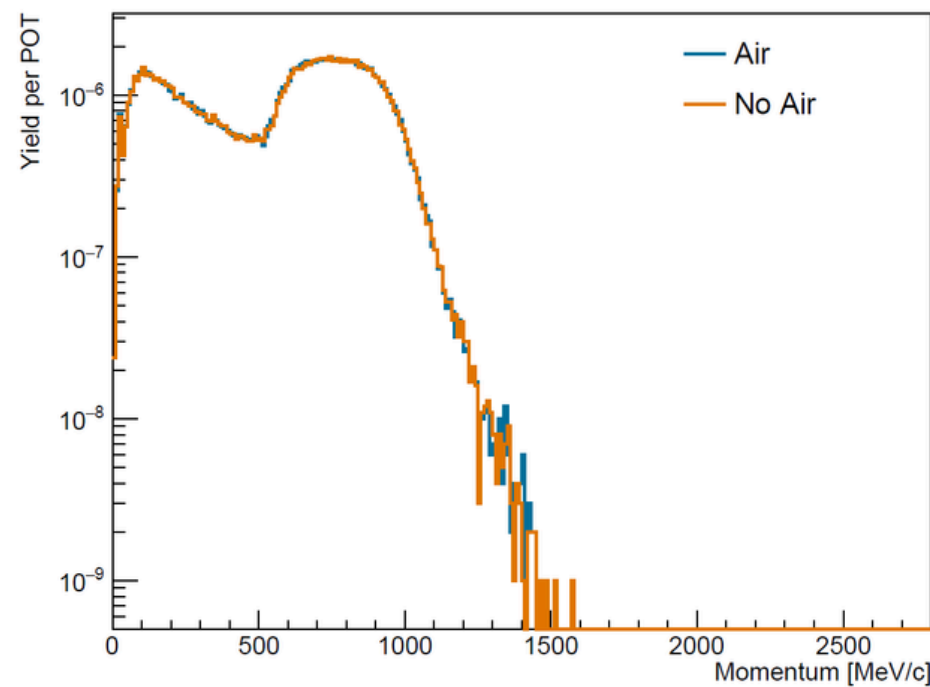
Effect on tunnel walls is negligible for most of particle species, increase of <1%
Quoted numbers refer to a tot of 1GPOT statistics

π^-



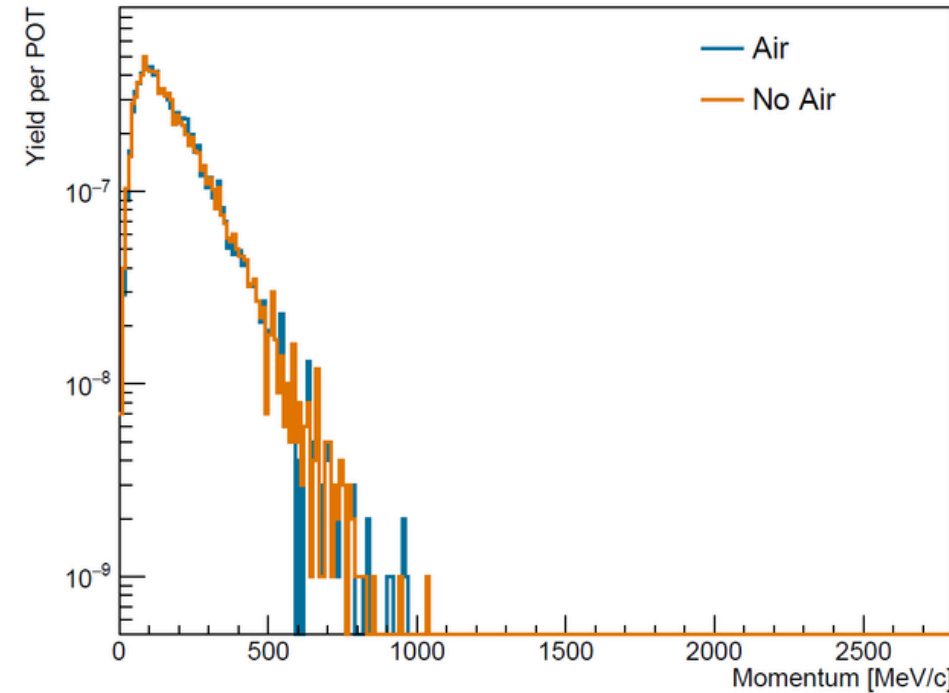
air: 94685
no air: 94309

μ^+



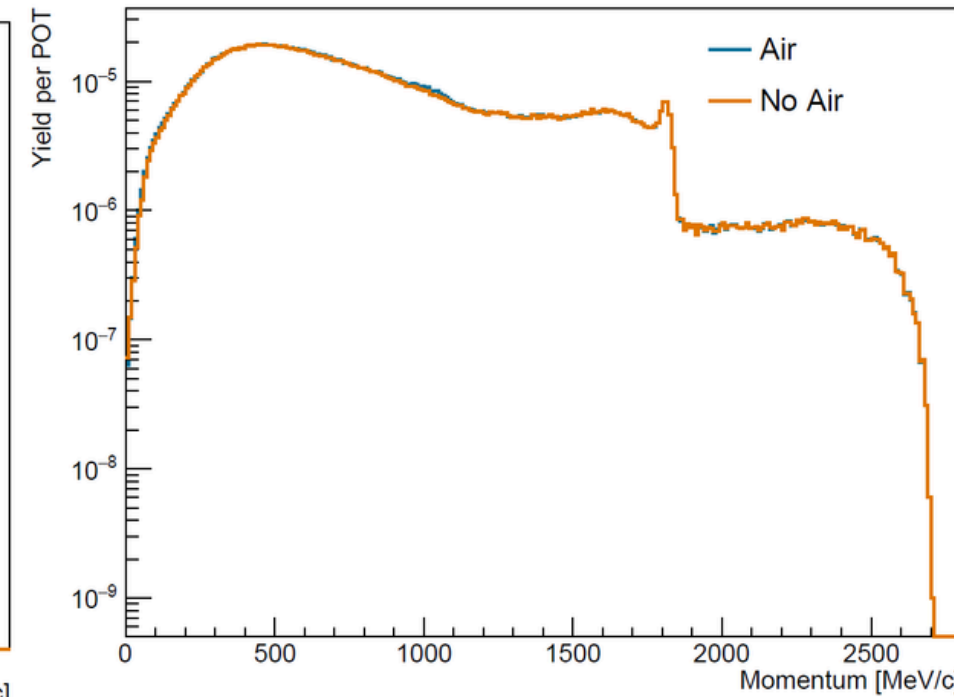
air: 110322
no air: 109904

μ^-



air: 8953
no air: 8894

p

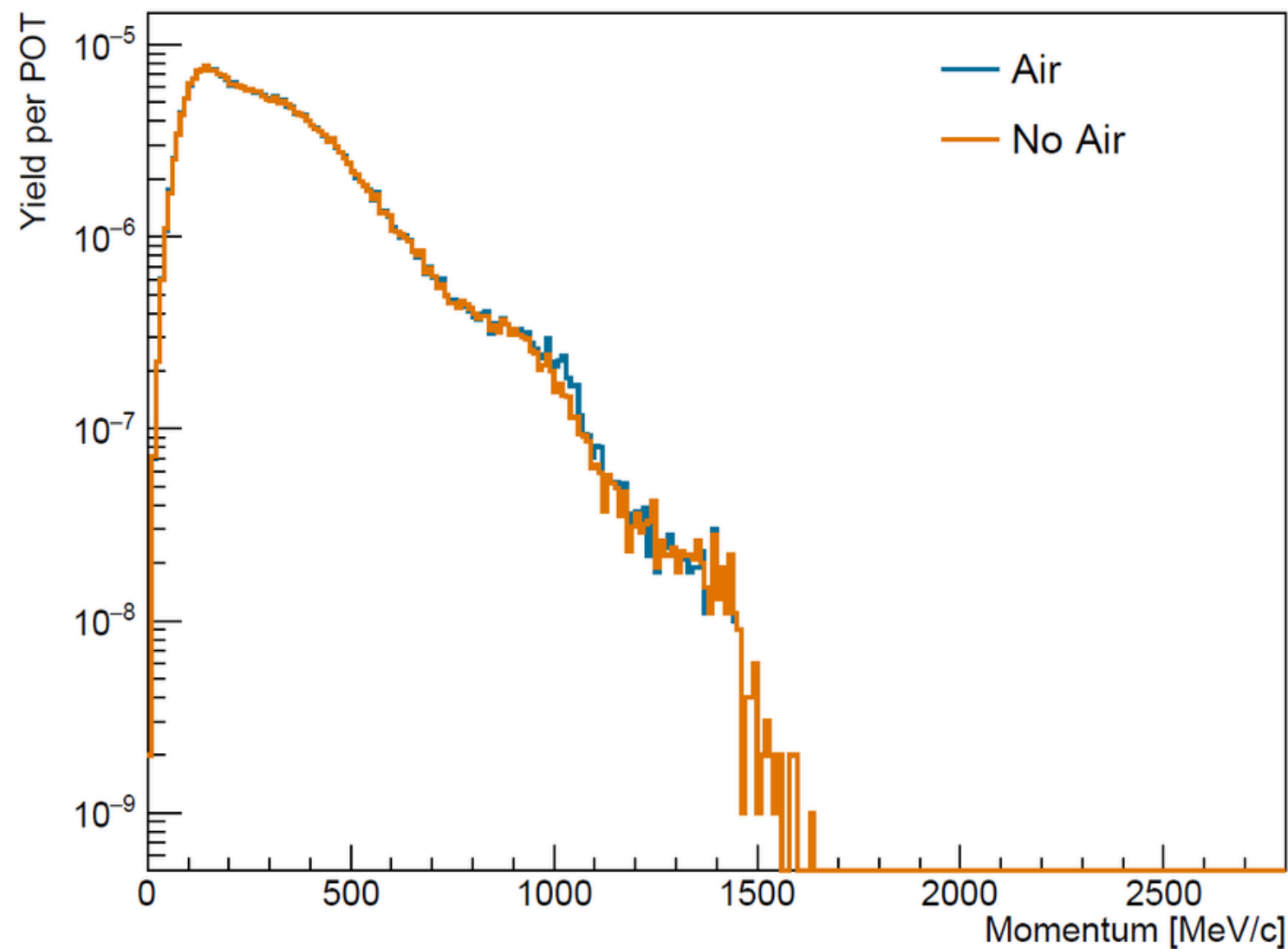


air: 1.79259e+06
no air: 1.7758e+06

AIR EFFECT ON PIONS

Effect on pions is $\sim 1\%$

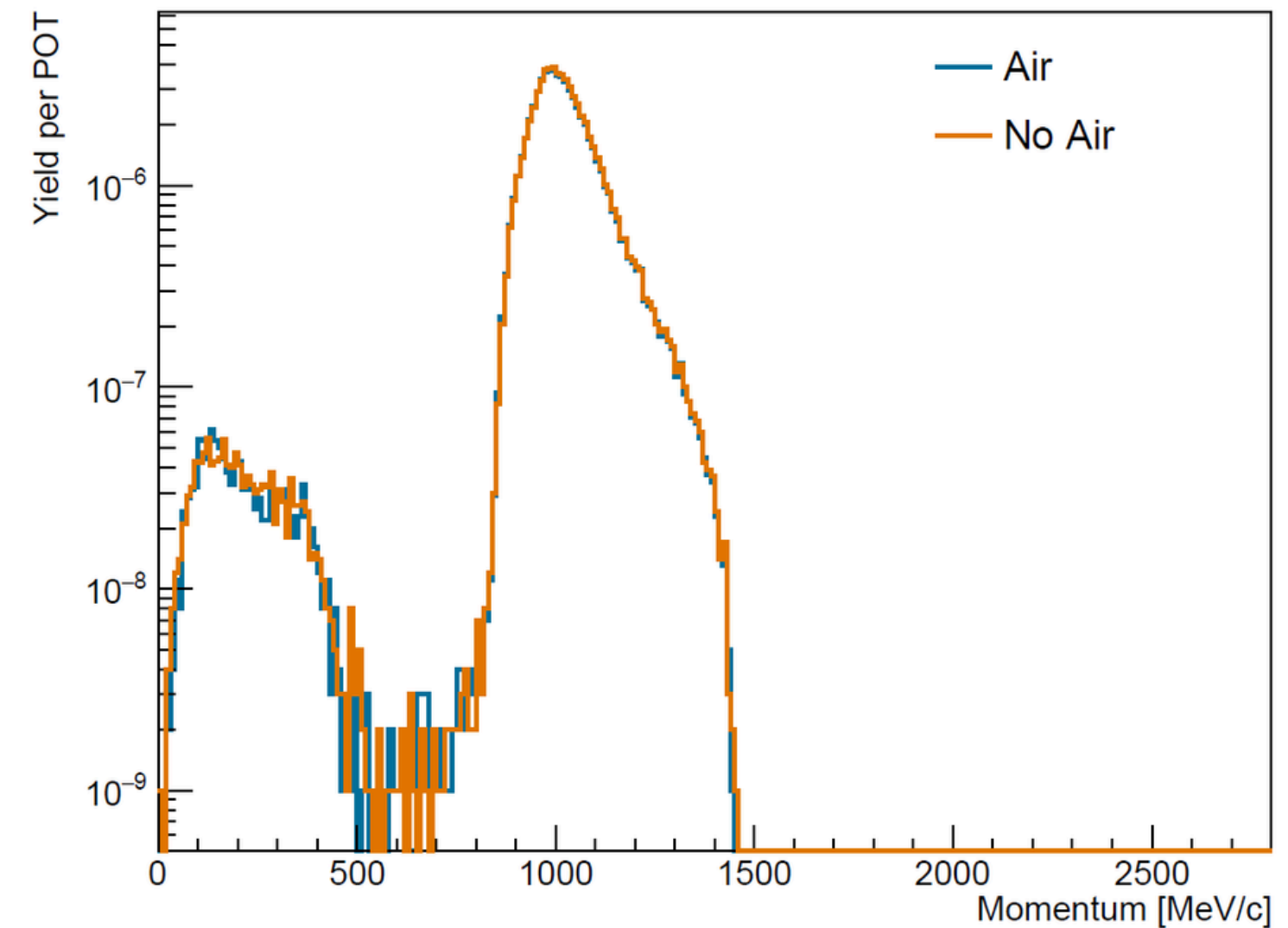
tunnel walls (no cut on direction)



π^+

air: 267102
no air: 265971

downstream endcap (no cut on direction)



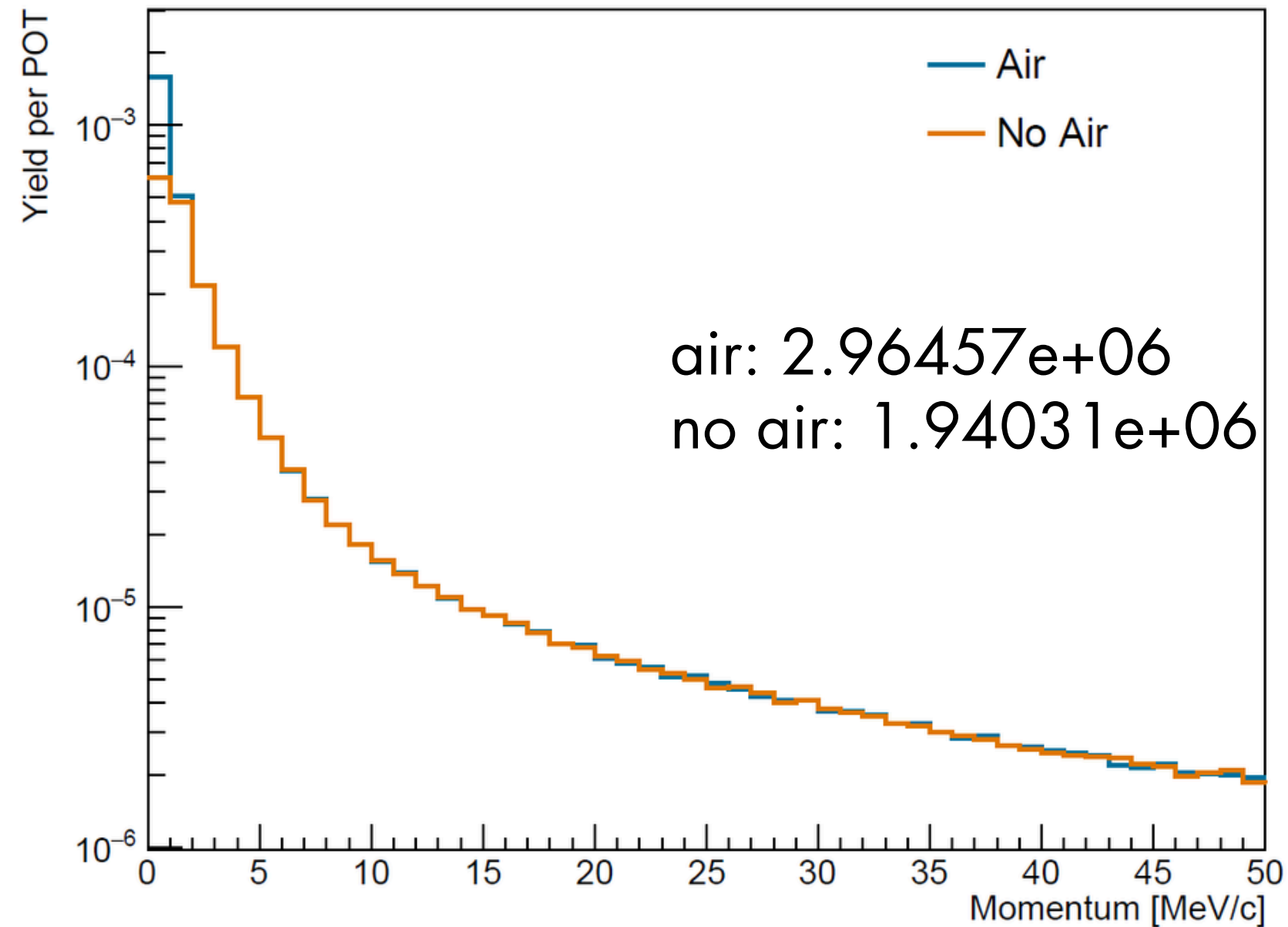
π^+

air: 66561
no air: 67588

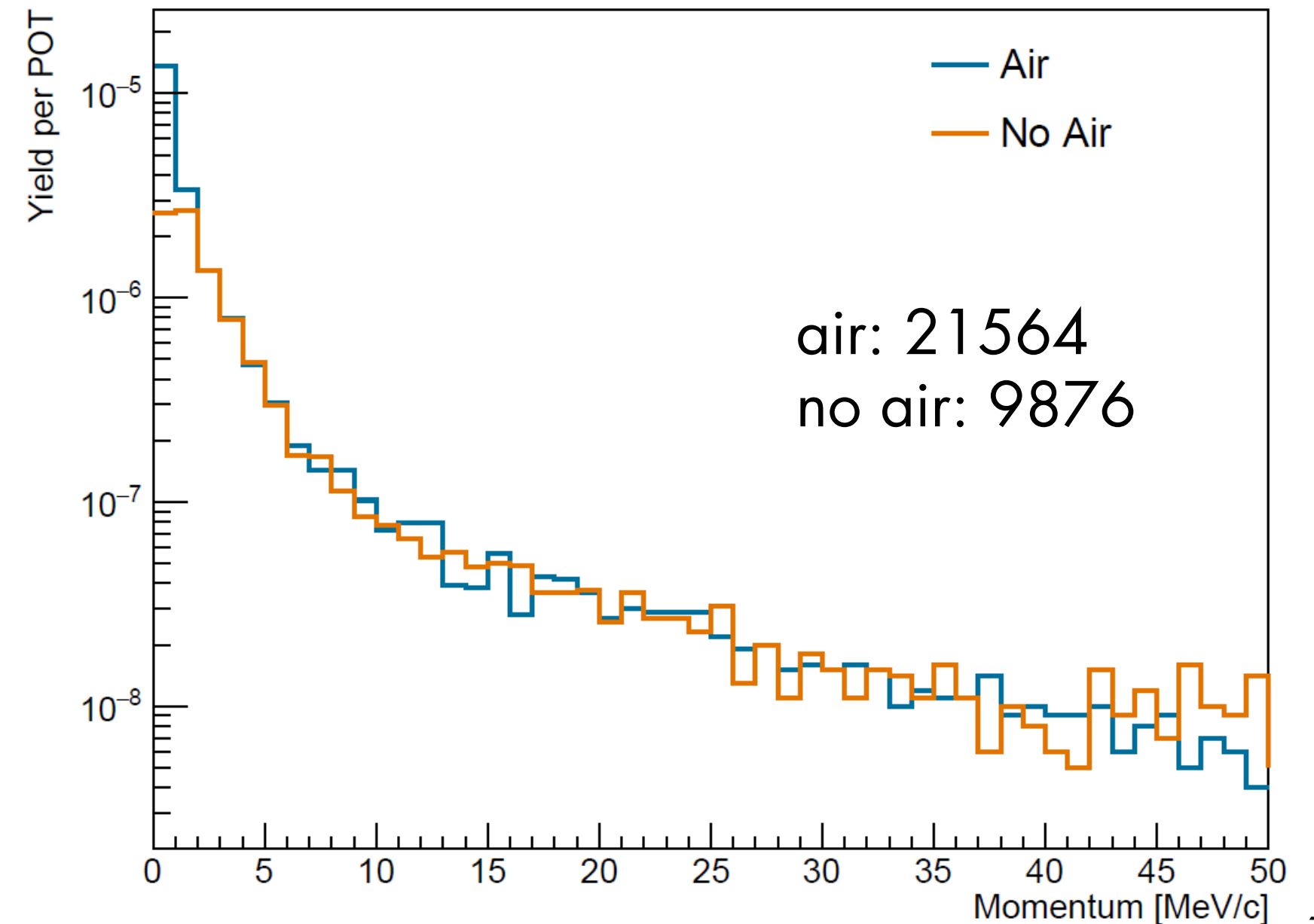
AIR EFFECT ON ELECTRONS

Air effect is more relevant for e in low p range (ionization)

e hitting the tunnel (no cut on e direction)



e hitting the downstream endcap of the tunnel
(no cut on e direction)

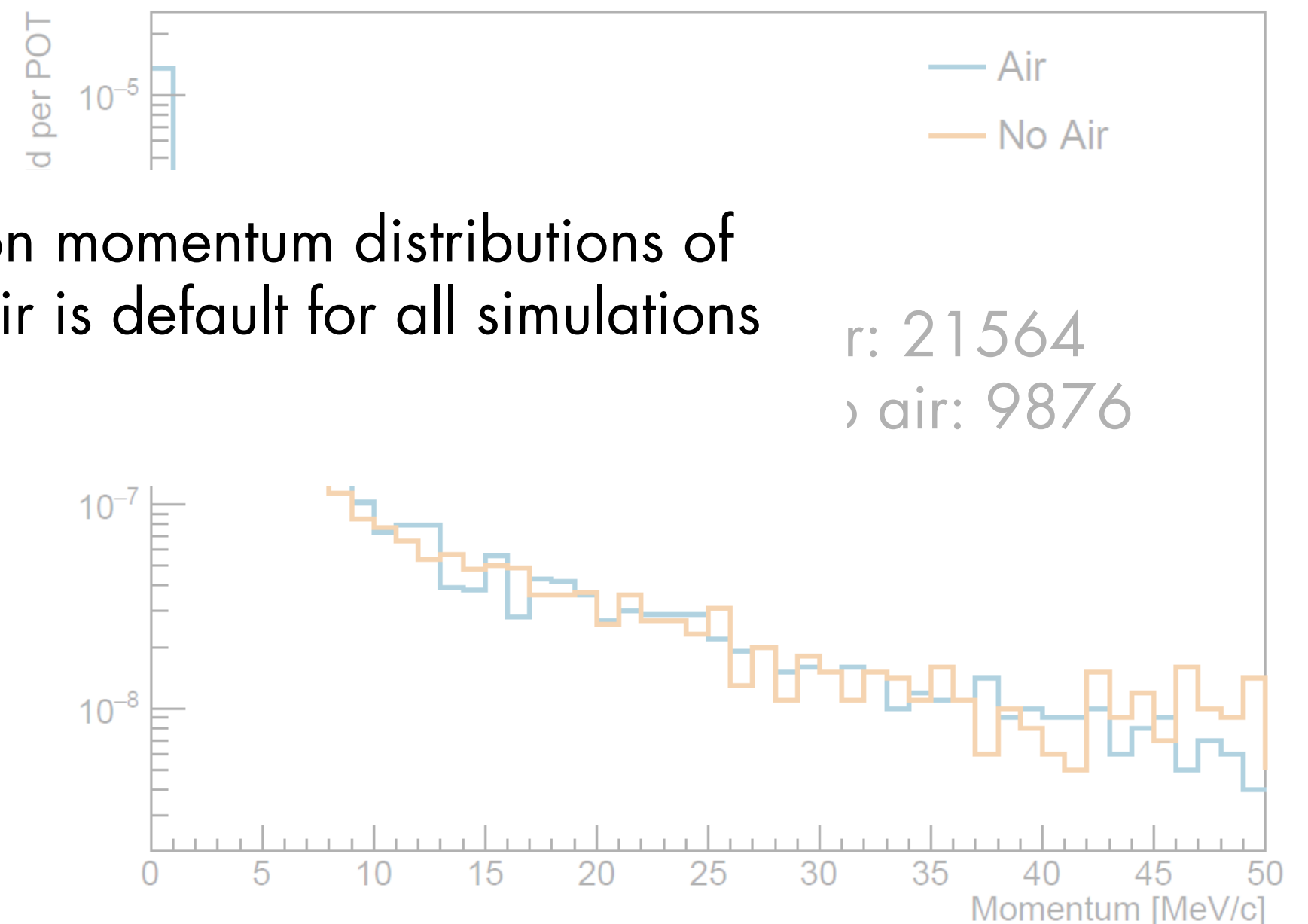
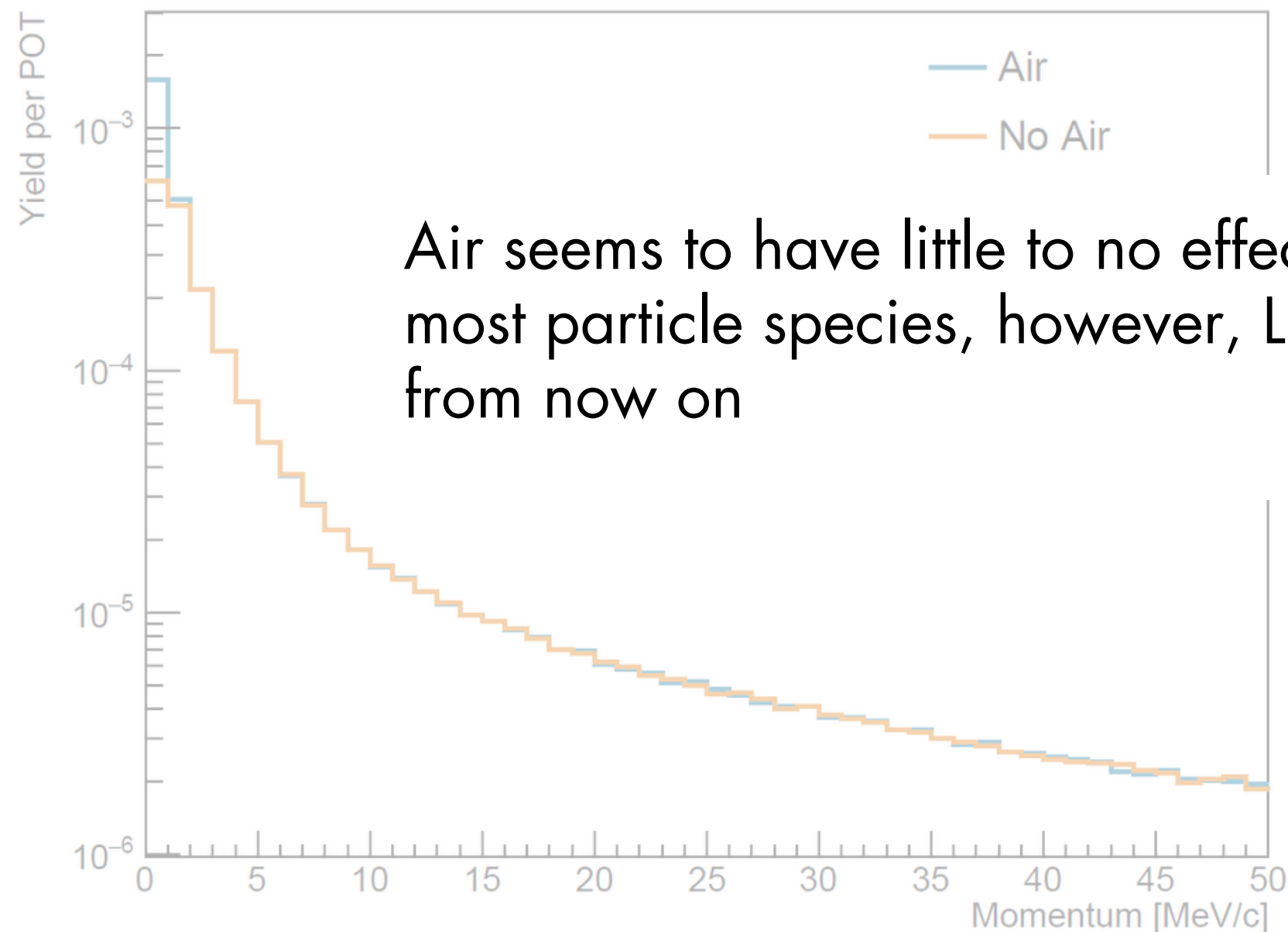


AIR EFFECT ON ELECTRONS

Air effect is more relevant for e in low p range (ionization)

e hitting the tunnel (no cut on e direction)

e hitting the downstream endcap of the tunnel
(no cut on e direction)



BACKGROUND STUDY

Effect of background on tunnel walls

- blind detectors
- damage instrumentation

Background from beamline taken into account in optimization (FOM)
+ additional contribution by radiation coming from outside, e.g. p that interact in the soil surrounding the tunnel

“hot spot” for background is the beam halo
especially downstream the dogtail
especially on the bending plane

an effective way to shield it is necessary

SHIELDING DESIGN

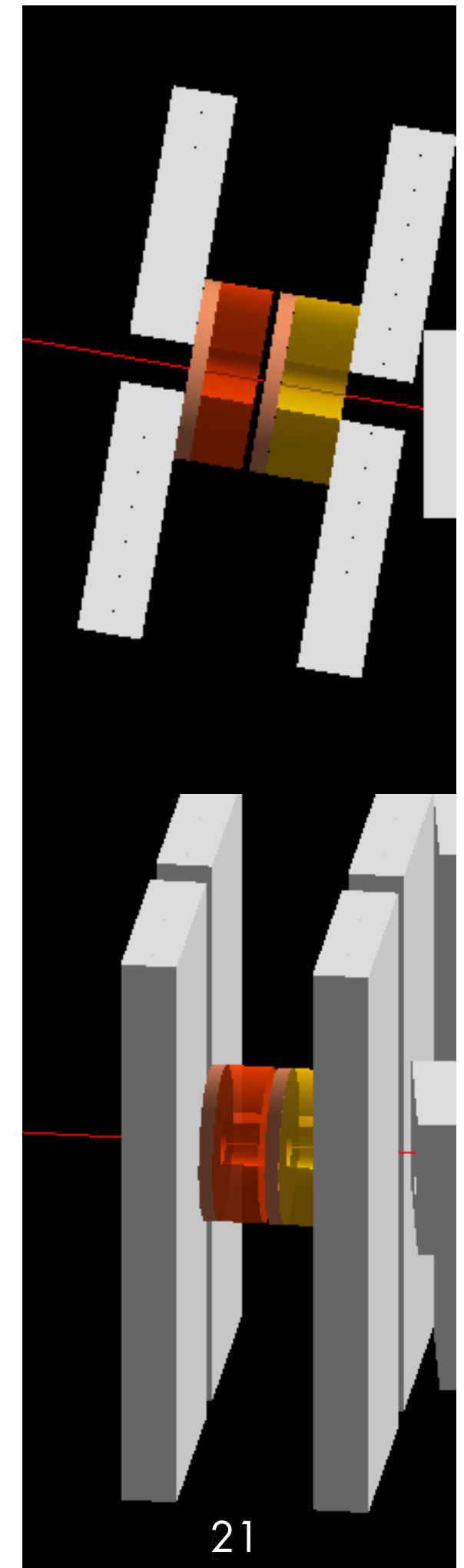
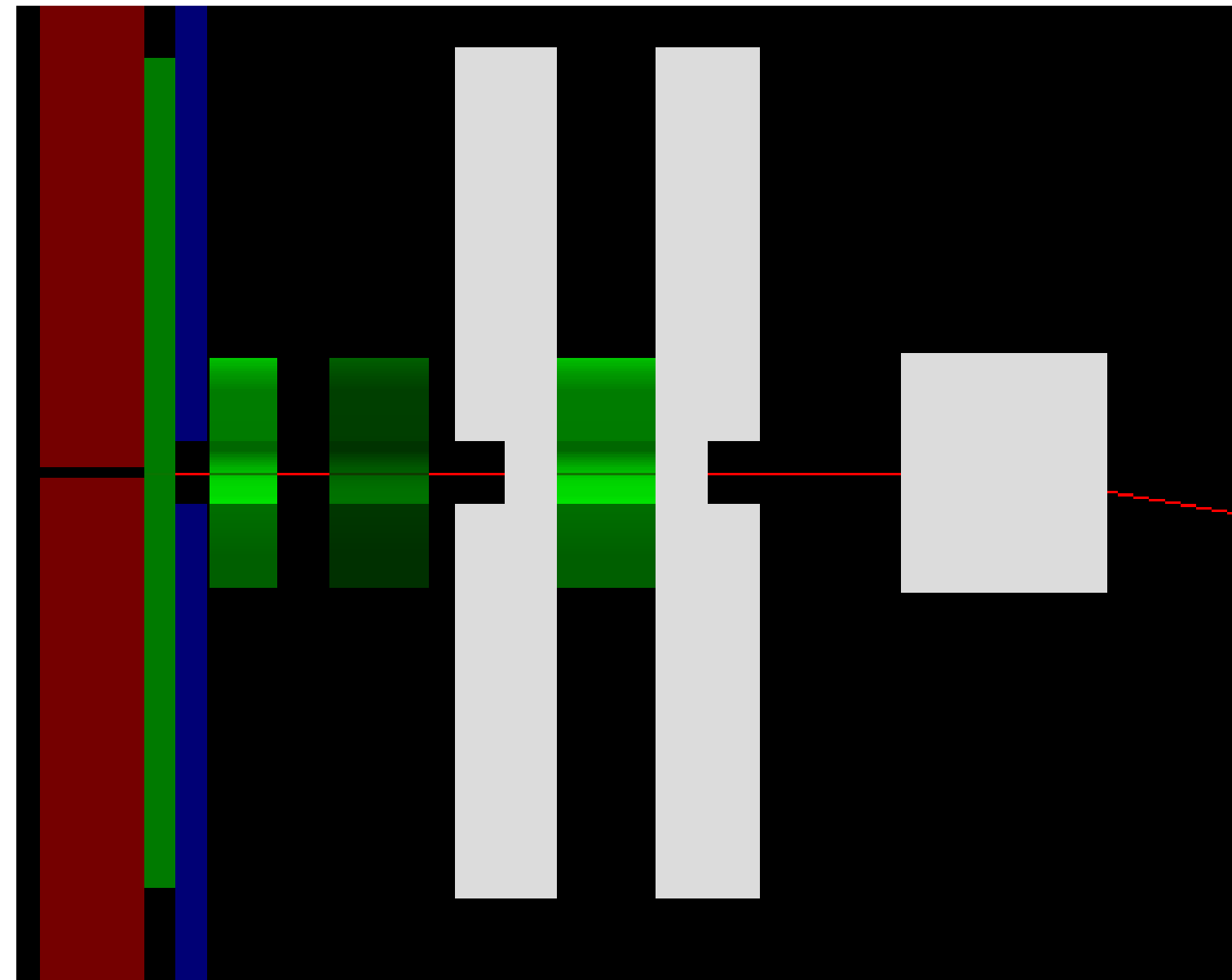
Combination of disks (100 mm thick) and slits, all in concrete

Upstream of the bending:

- combined vertical and horizontal slits (250 mm thick each) surrounding quad3 (not enough room between quad1 and quad2)

Bending section:

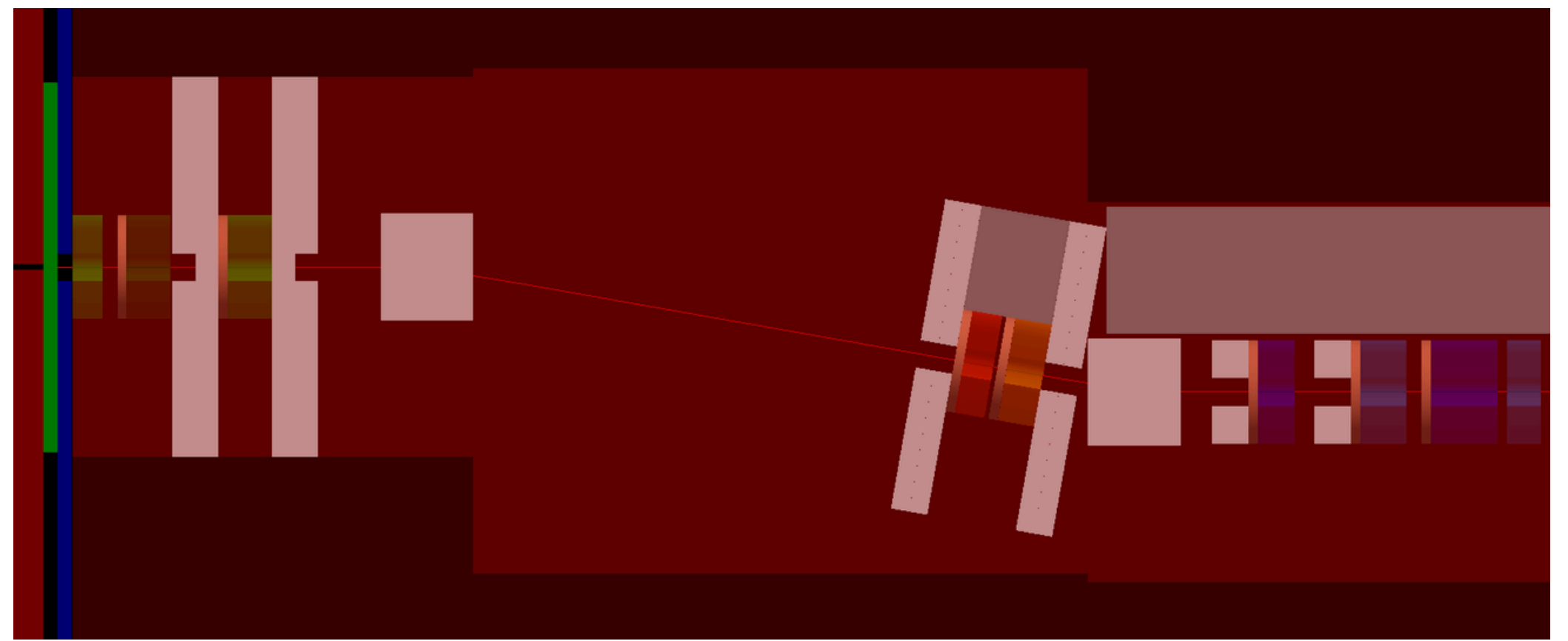
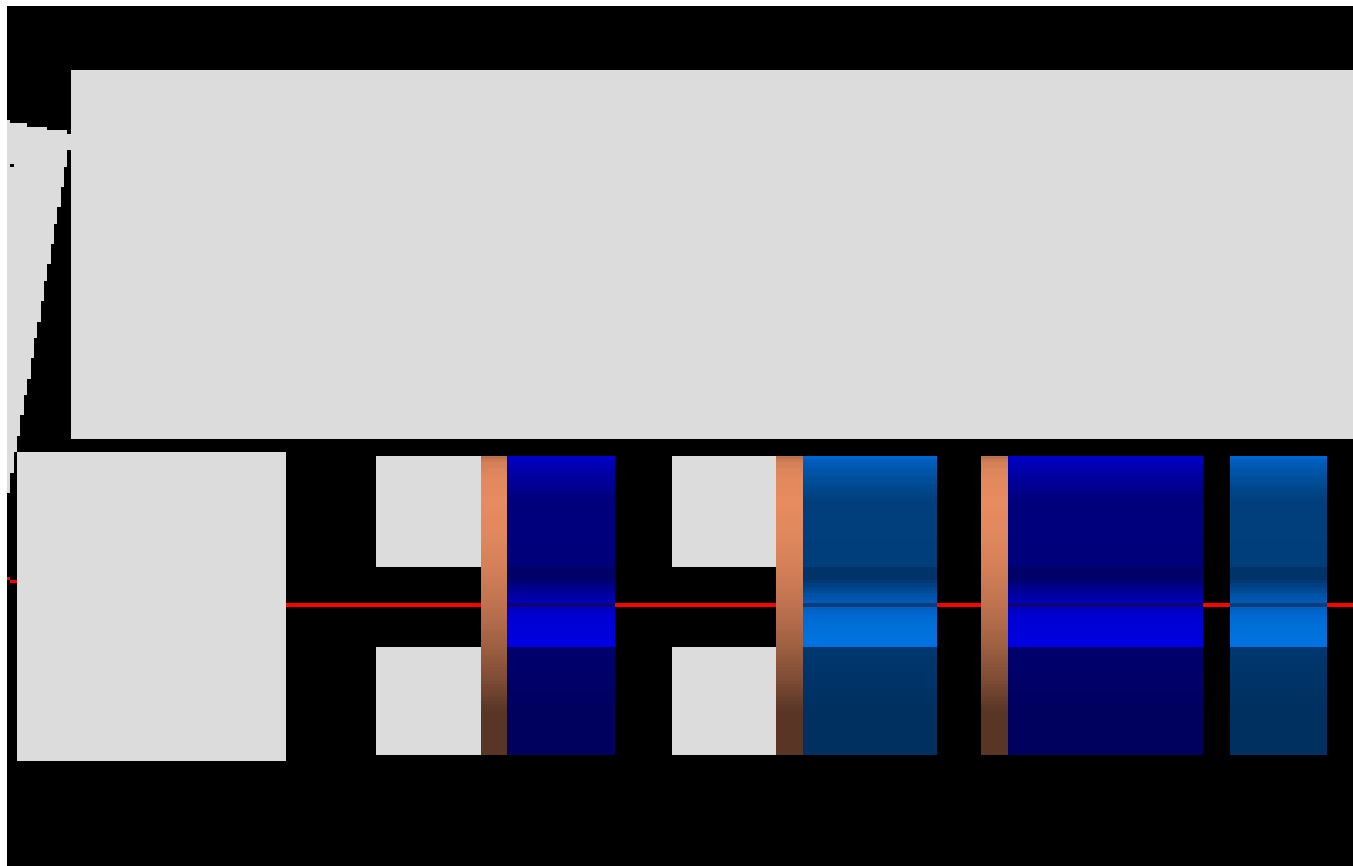
- Concrete shield added before each quad
- Vertical slits (400 mm thick) before and after quad



SHIELDING DESIGN

Downstream of the bending:

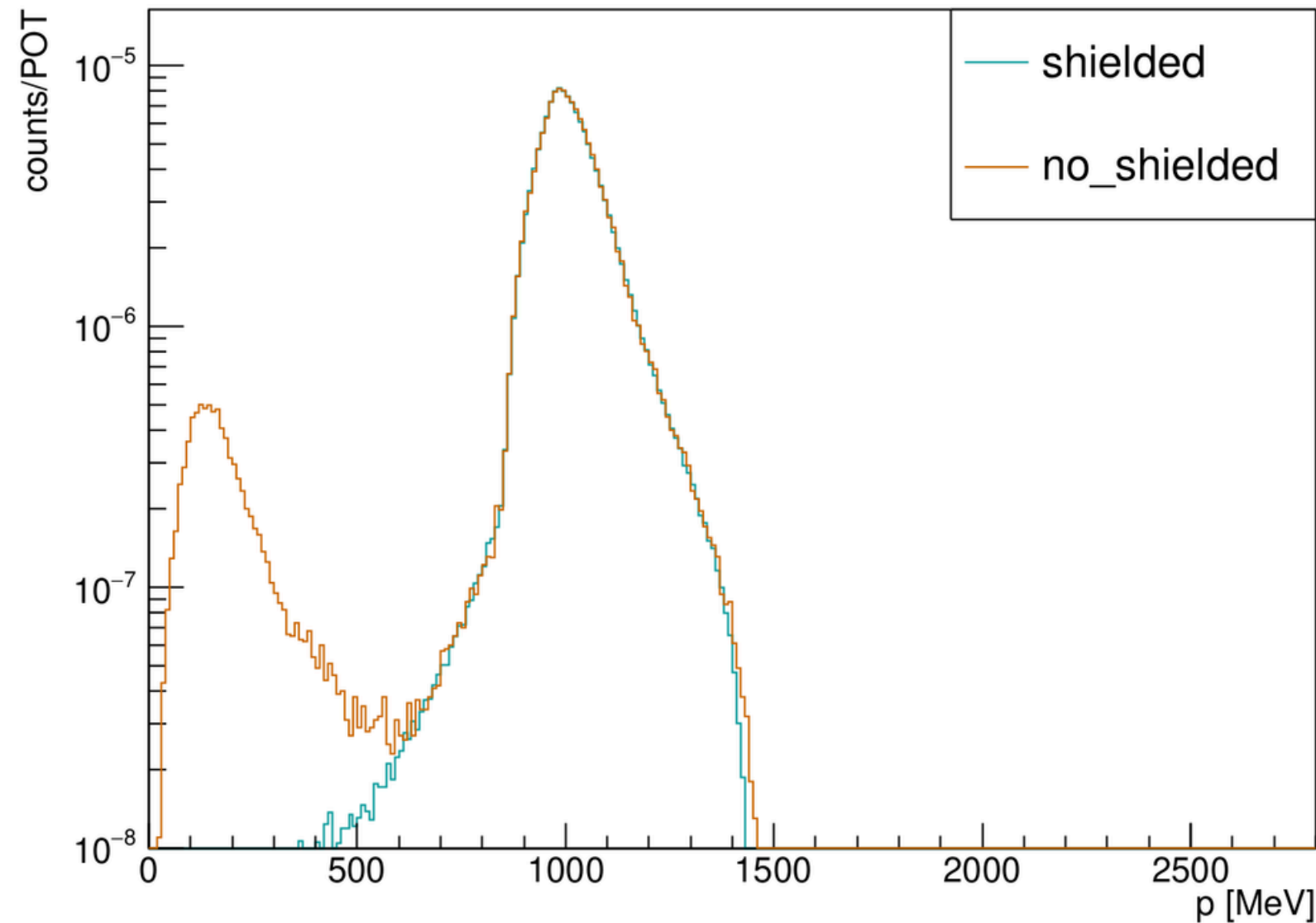
- Concrete shield added before each quad (except quad9)
- Vertical slits (400 mm thick) before quad6 and quad7
- Slit side reduced to allocate proton dump
- p dump at ~ 10 cm from the quad side



PERFORMANCE – TUNNEL ENTRANCE

~10 GPOT for shielded bl
1 GPOT for non shielded bl

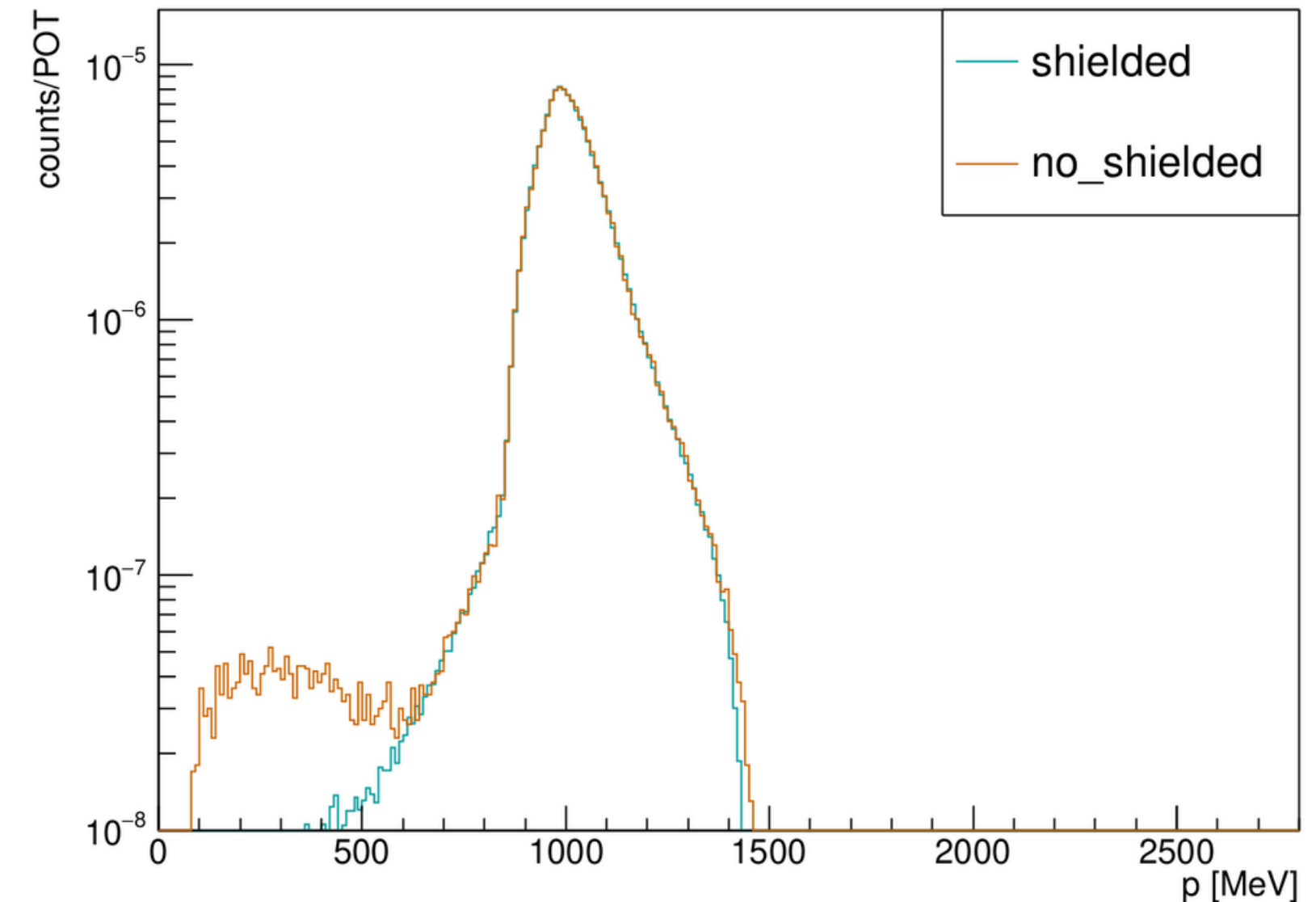
π^+ (all P_z)



$$shielded : (1.408 \pm 0.001) \times \frac{10^{-4}}{POT}$$

$$nonshielded : (1.499 \pm 0.004) \times \frac{10^{-4}}{POT}$$

π^+ ($P_z \geq 0$)

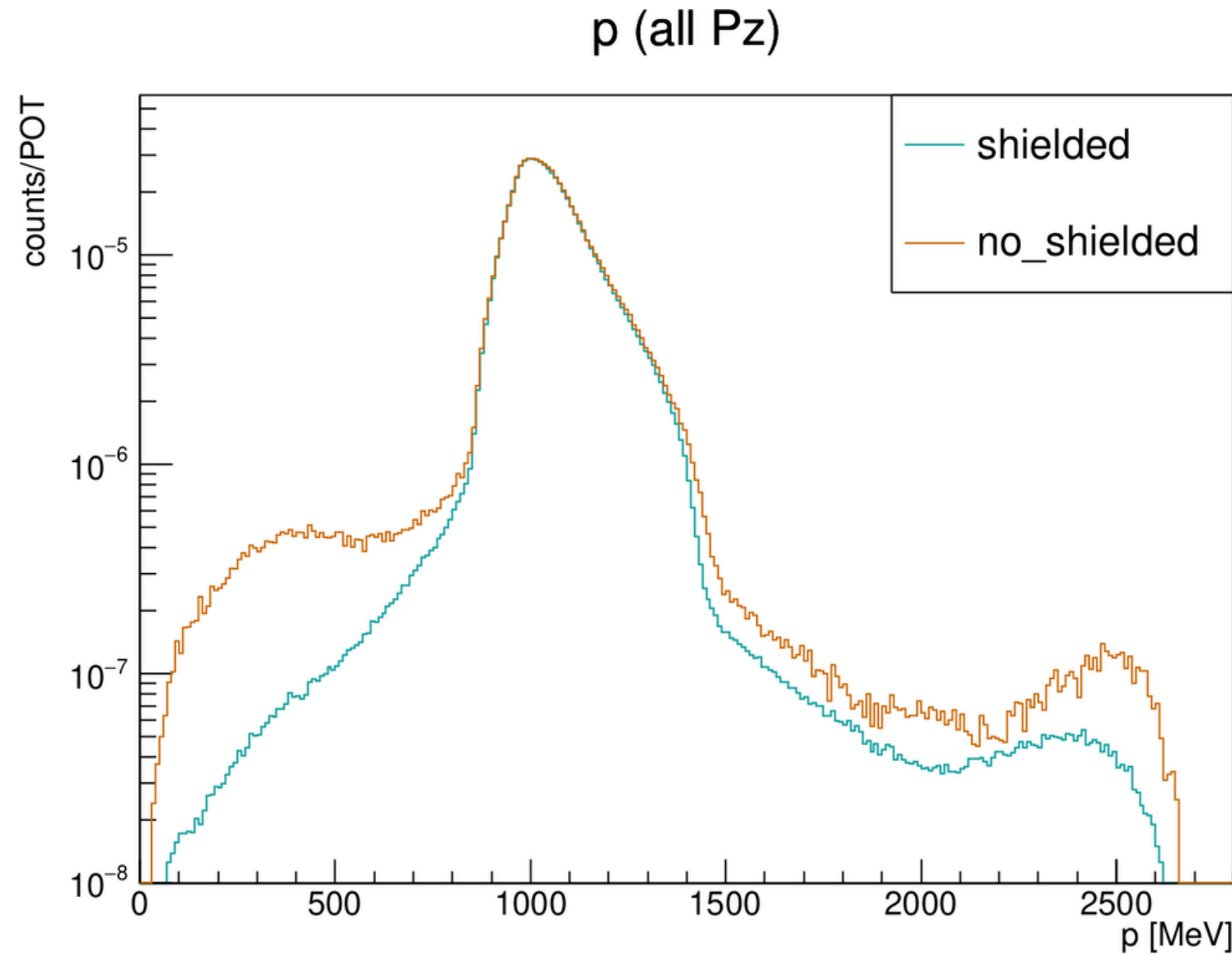


$$shielded : (1.408 \pm 0.001) \times \frac{10^{-4}}{POT}$$

$$nonshielded : (1.499 \pm 0.004) \times \frac{10^{-4}}{POT}$$

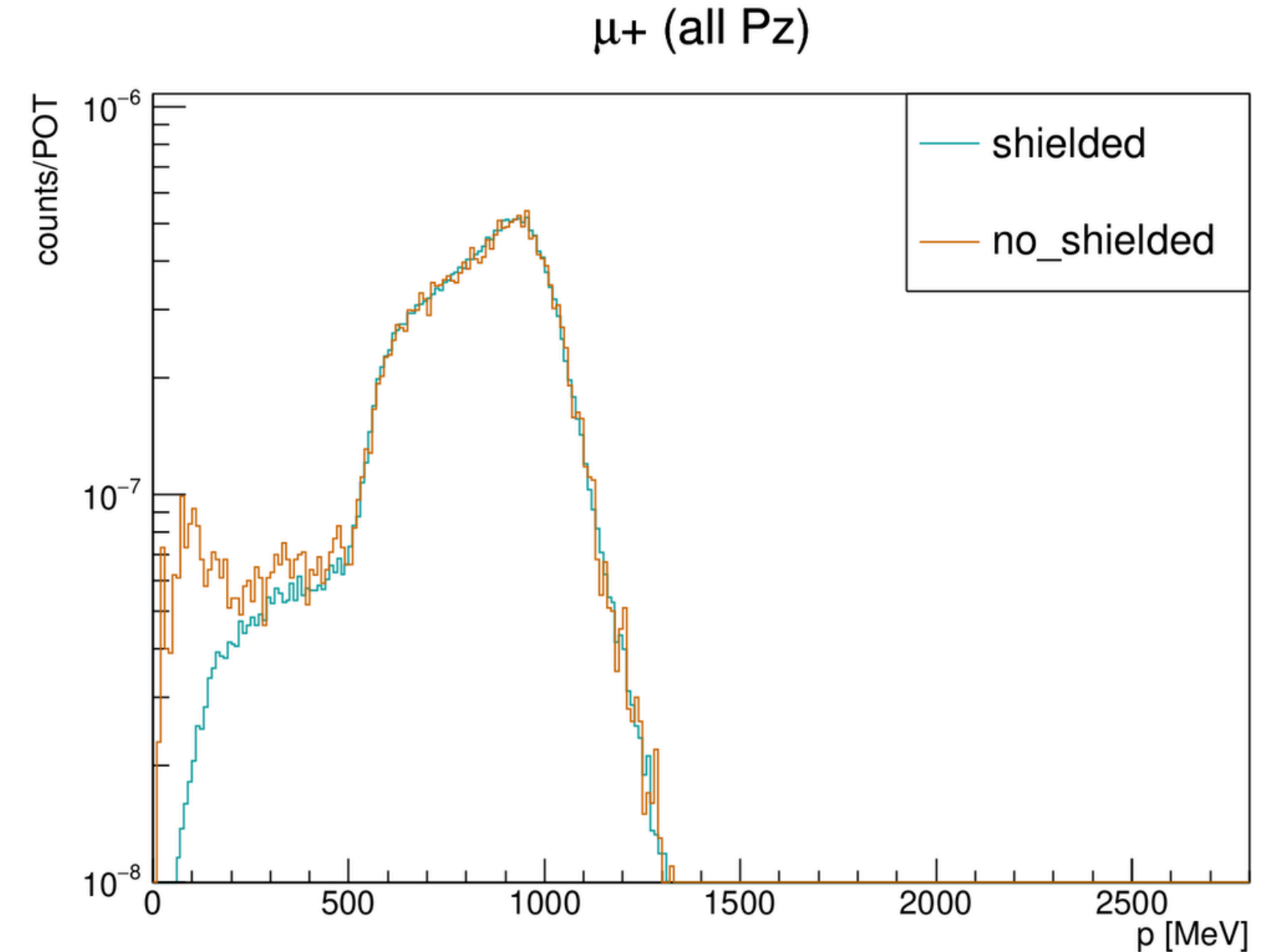
PERFORMANCE – TUNNEL ENTRANCE

~10 GPOT for shielded bl
1 GPOT for non shielded bl



$$\text{shielded} : (6.652 \pm 0.003) \times \frac{10^{-4}}{POT}$$

$$\text{nonshielded} : (7.047 \pm 0.003) \times \frac{10^{-4}}{POT}$$

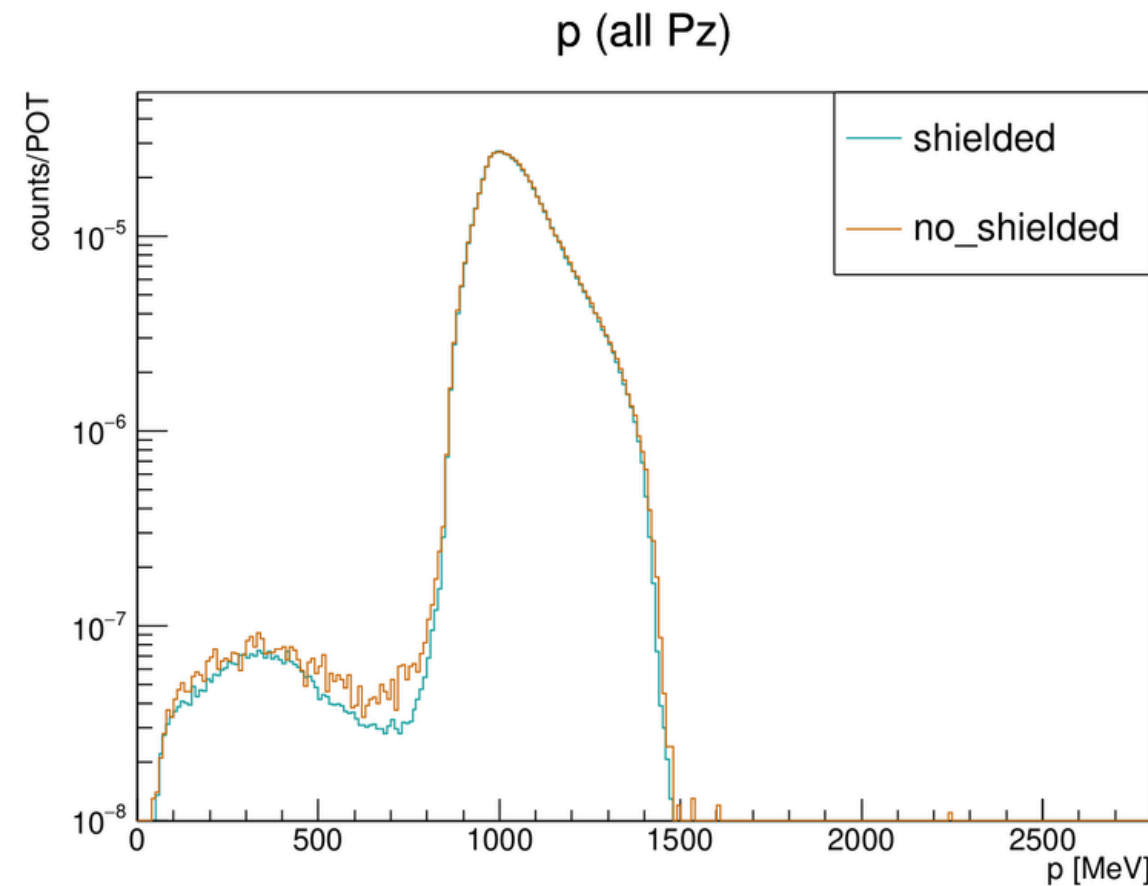


$$\text{shielded} : (2.266 \pm 0.005) \times \frac{10^{-5}}{POT}$$

$$\text{nonshielded} : (2.365 \pm 0.001) \times \frac{10^{-5}}{POT}$$

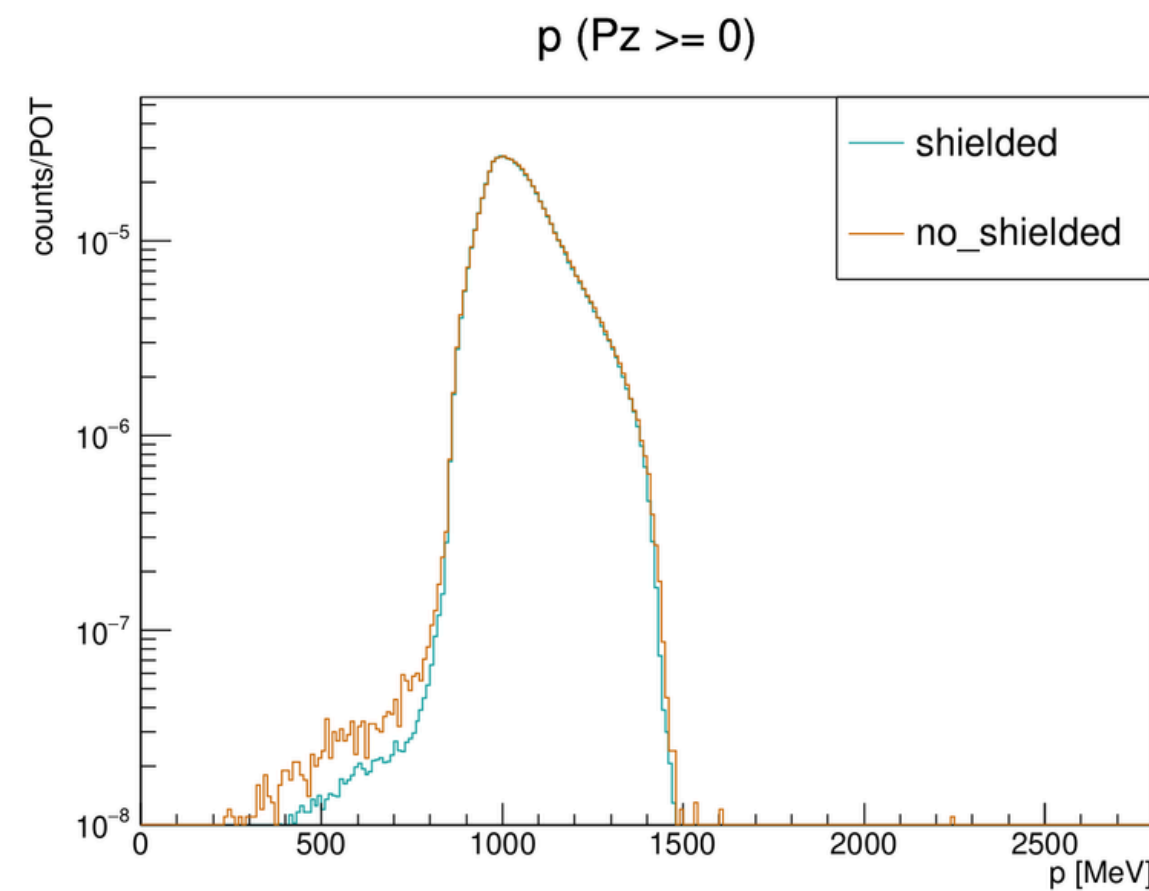
PERFORMANCE – TUNNEL DOWNSTREAM ENDCAP

~10 GPOT for shielded bl
1 GPOT for non shielded bl



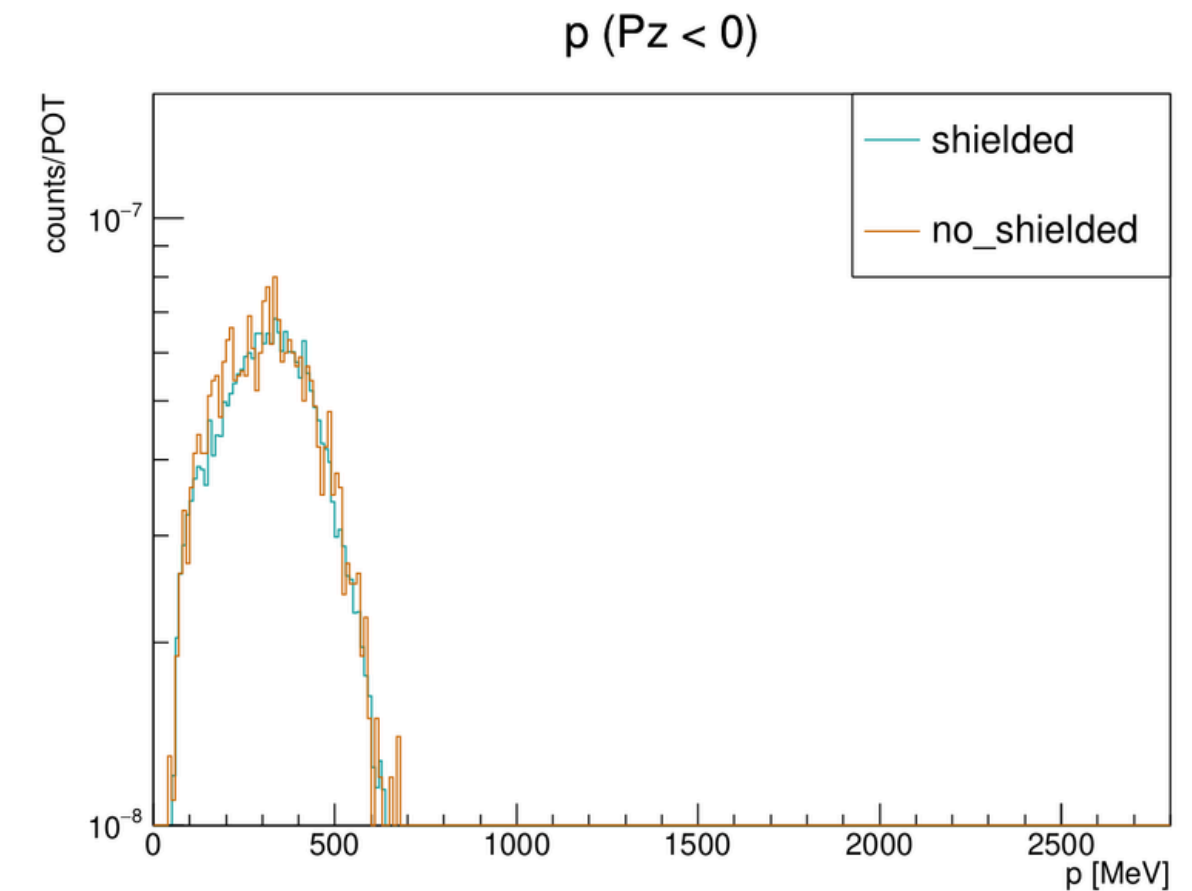
$$shielded : (6.046 \pm 0.003) \times \frac{10^{-4}}{POT}$$

$$nonshielded : (6.109 \pm 0.008) \times \frac{10^{-4}}{POT}$$



$$shielded : (6.019 \pm 0.003) \times \frac{10^{-4}}{POT}$$

$$nonshielded : (6.082 \pm 0.008) \times \frac{10^{-4}}{POT}$$

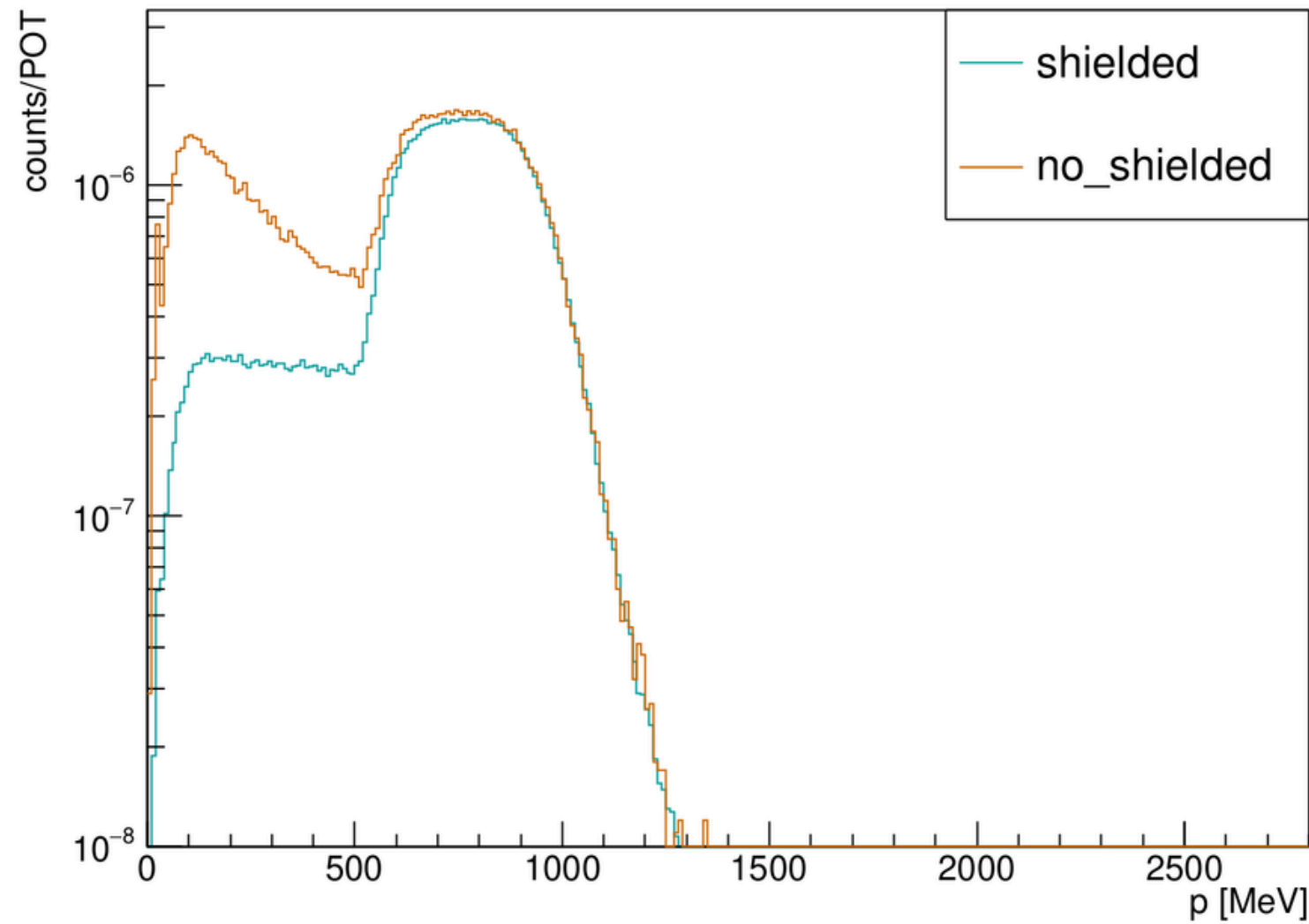


$$shielded : (2.62 \pm 0.02) \times \frac{10^{-6}}{POT}$$

$$nonshielded : (2.74 \pm 0.05) \times \frac{10^{-6}}{POT}$$

PERFORMANCE – TUNNEL WALLS

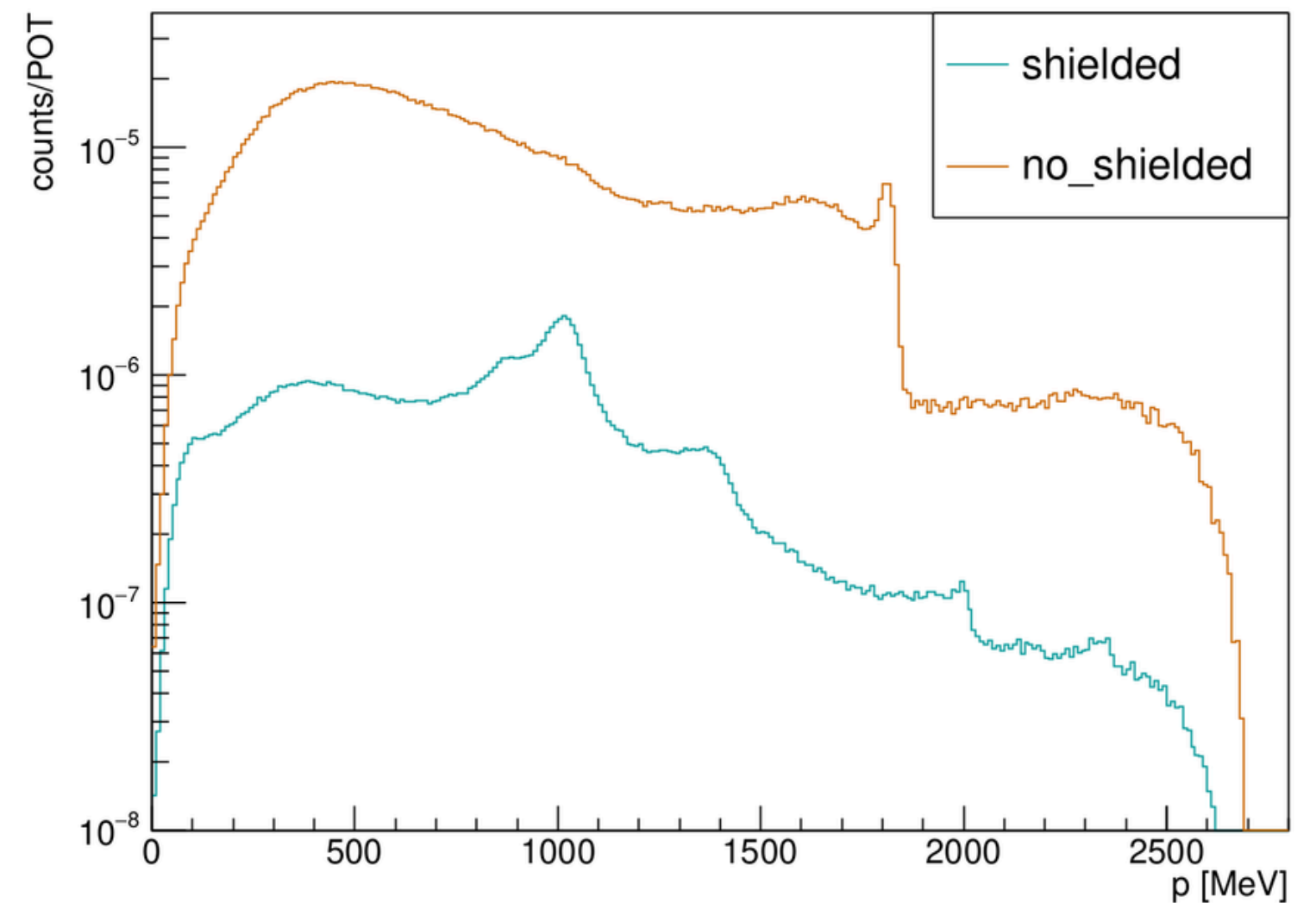
μ^+ (All)



$$shielded : (7.581 \pm 0.009) \times \frac{10^{-5}}{POT}$$

$$nonshielded : (11.03 \pm 0.03) \times \frac{10^{-5}}{POT}$$

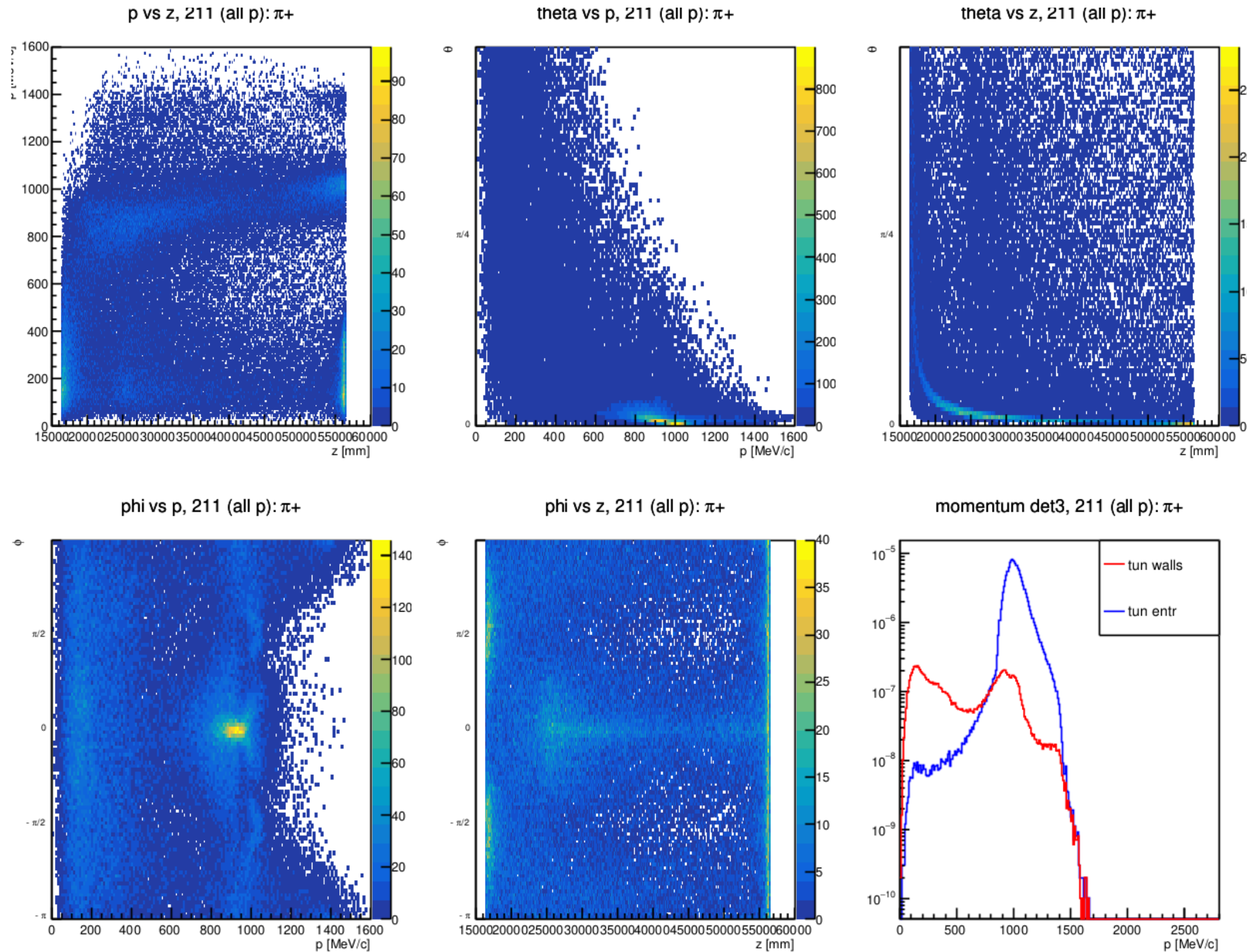
p (All)



$$shielded : (1.235 \pm 0.001) \times \frac{10^{-4}}{POT}$$

$$nonshielded : (17.93 \pm 0.01) \times \frac{10^{-4}}{POT}$$

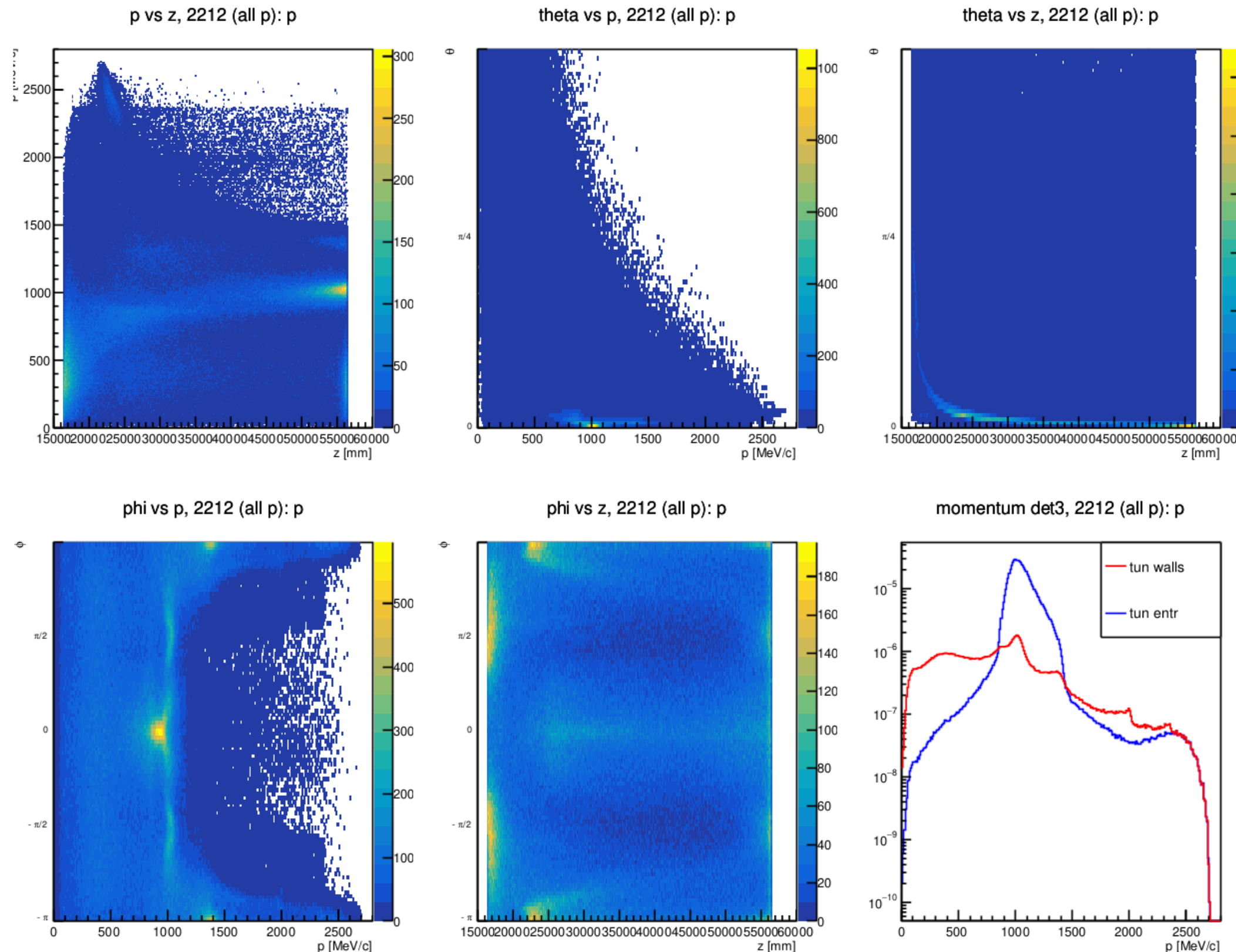
PERFORMANCE – TUNNEL WALLS



Pion distribution at the tunnel walls

Low momentum pions at the tunnel entrance (not focused) and exit (produced in the hadron dump)

PERFORMANCE – TUNNEL WALLS

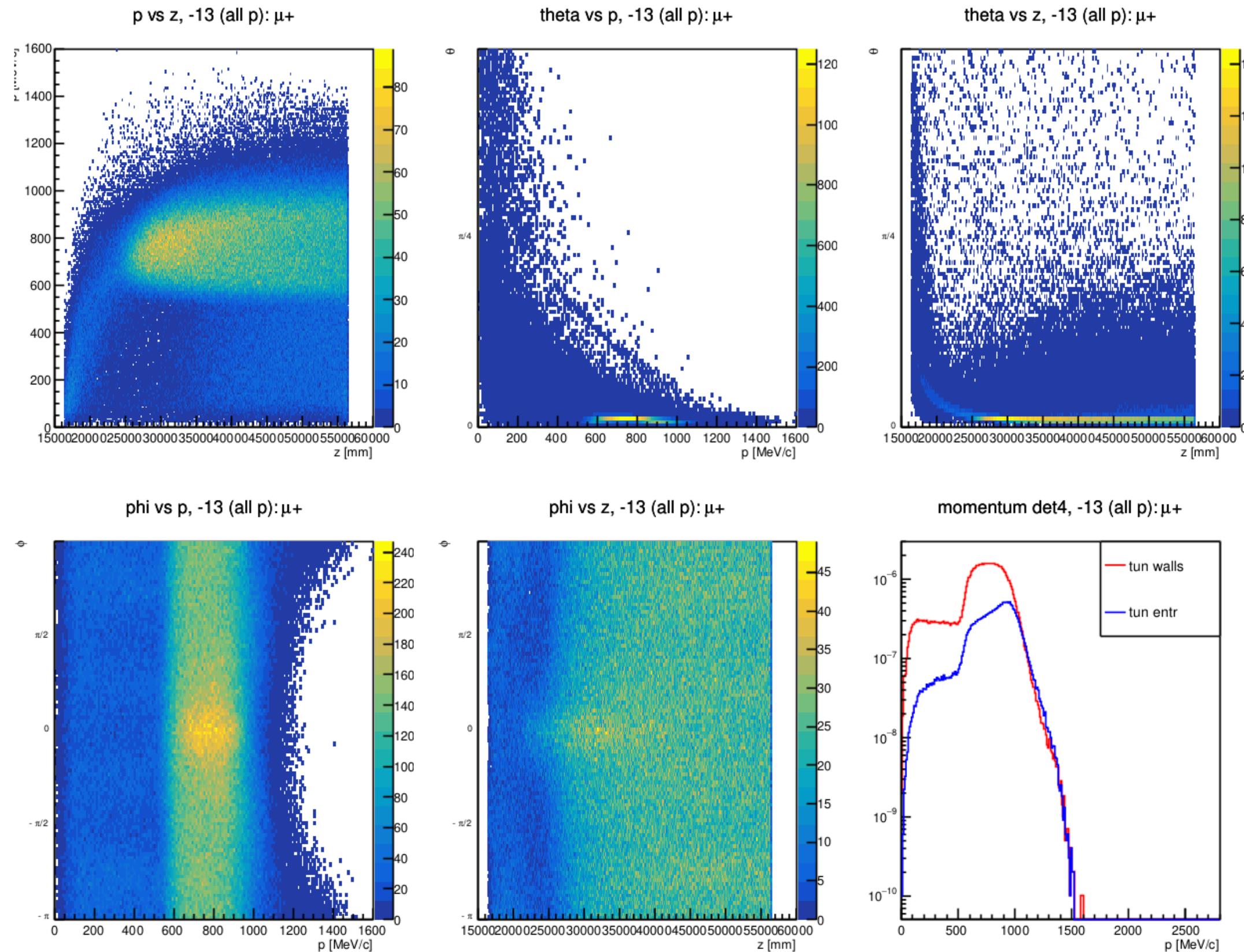


Proton distribution at the tunnel walls

Proton in the momentum bite hit the tunnel walls at the end of the tunnel

Low momentum protons hit the tunnel close to the entrance, maybe improve shielding/proton dump

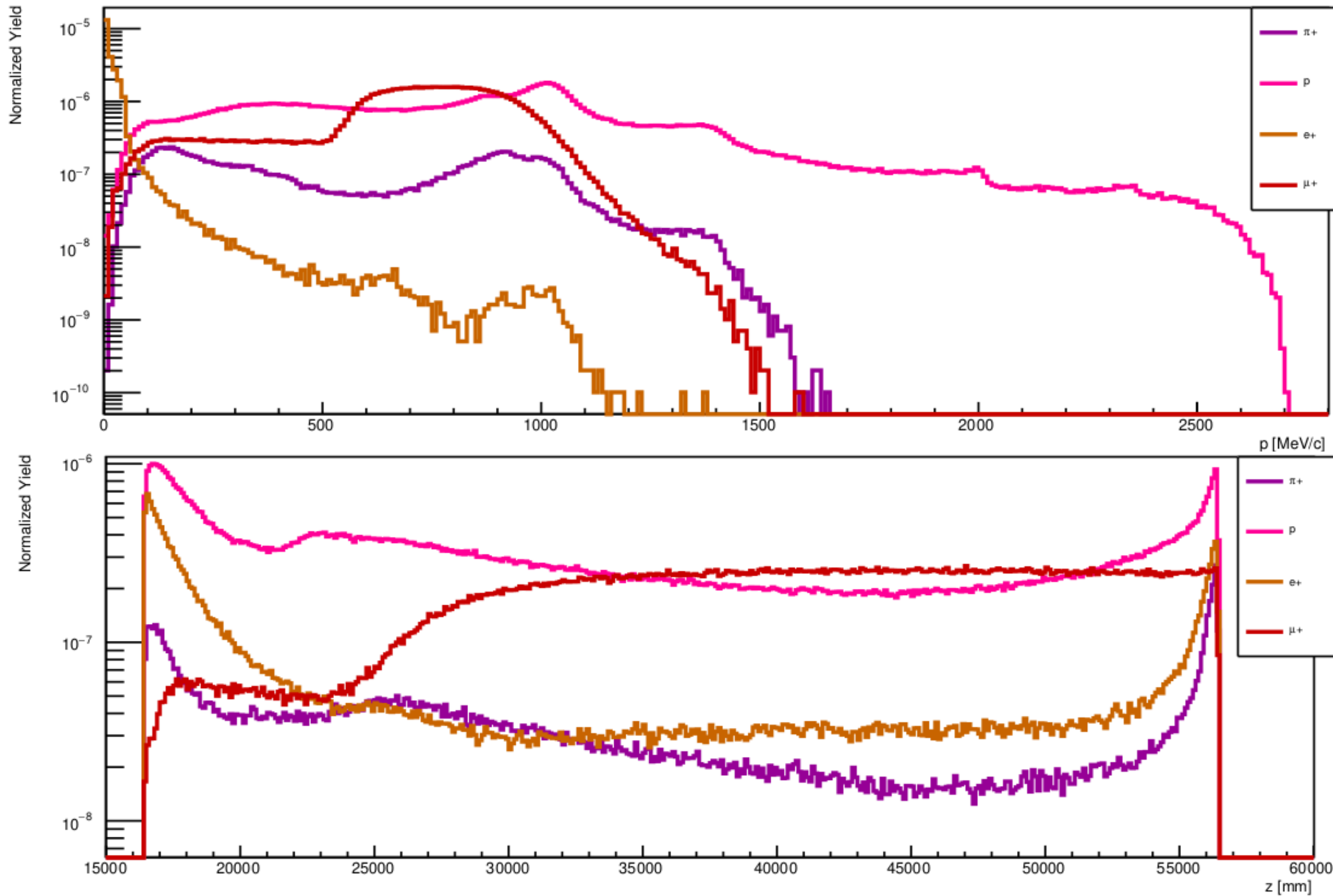
PERFORMANCE – TUNNEL WALLS



Positive muon distribution at the tunnel walls

Most of them are produced in pion decay
> isotropic distribution in ϕ :z

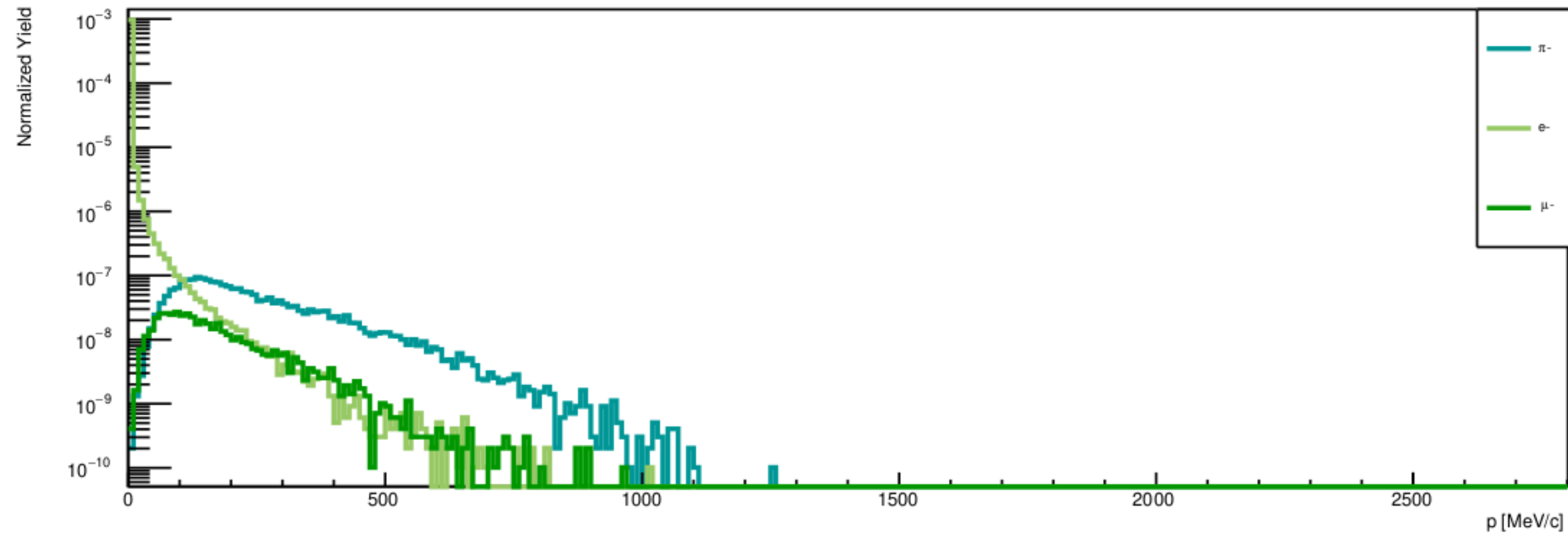
PERFORMANCE – TUNNEL WALLS



Positively charged particle distributions on the tunnel walls (momentum and z)

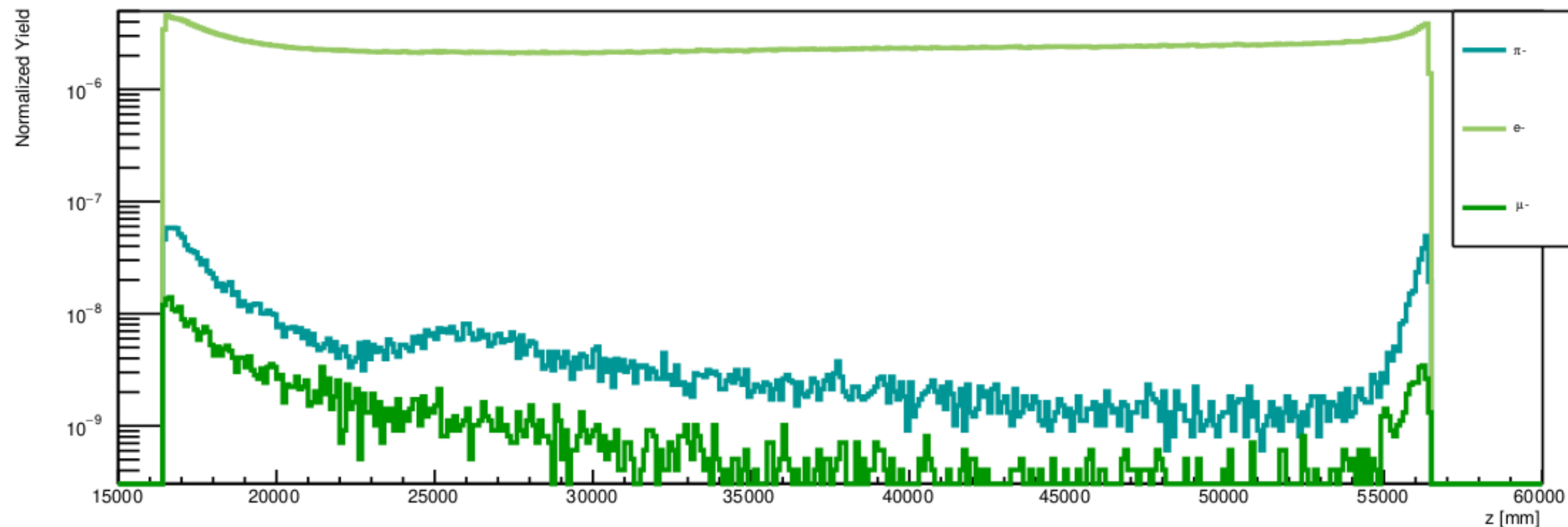
- > increase in flux at high z due to hadron dump (can be optimized)
- > positrons are mainly at low momentum

PERFORMANCE – TUNNEL WALLS



Negatively charged particle distributions on the tunnel walls (momentum and z)

- > increase in flux at high z due to hadron dump (can be optimized)
- > electrons are mainly at low momentum



CONCLUSIONS

- > Optimization with a genetic algorithm provided a Low Energy Monitored Neutrino beamline design that matches specifications (i.e. pion yield larger than $10^{-4}/\text{POT}$)
- > Full beamline simulation is implemented in g4bl, including neutrino detector
- > Residual air effect in the decay tunnel is considered, although quite small
- > Shielding is implemented by combining quadrupole protection elements, slits and a proton dump
- > Performance are evaluated after shielding implementation (-> see Fabio's talk)

THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES

THE GENETIC ALGORITHM

The idea of a genetic Algorithm relies of Natural Selection as explained by C. Darwin

- For the given problem, a set of random solutions is generated
- Each solution set is a collection of variables (genes)
- All the solutions are evaluated and ranked according to the best ones
- A new set of solutions is then generated by combining the genes of the best solutions of previous iterations.

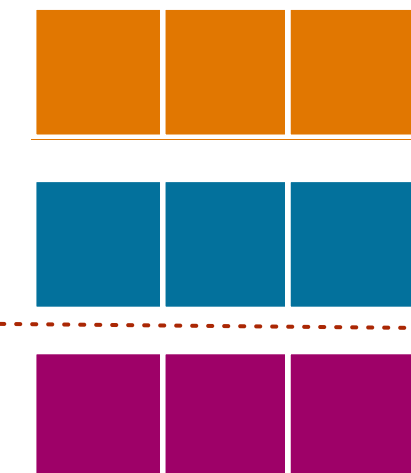
The Genetic Algorithm for optics Optimization is custom.

Its features:

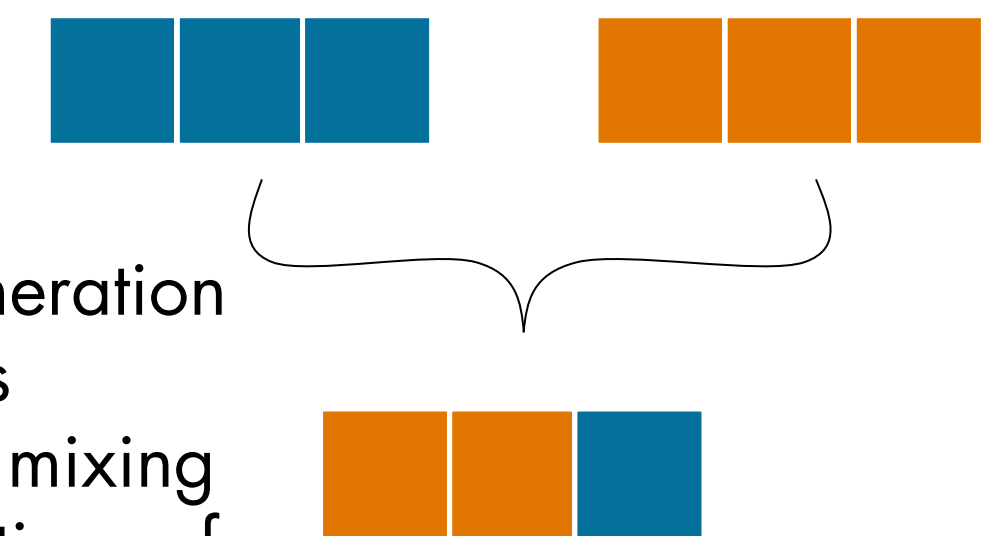
- Genes are length of quadrupoles, separation between quadrupoles and field
- Evaluation is a [g4beamline](#) simulation
- Fitness is pion multiplicity at the tunnel entrance



Random set of variables are evaluated



Sets of variables are ranked



The new generation population is obtained by mixing the best solutions of the previous iteration

THE GENETIC ALGORITHM

LOOP MANAGER

INPUT GENERATOR

G4BL

Input file

No previous
generation

Previous
generation file

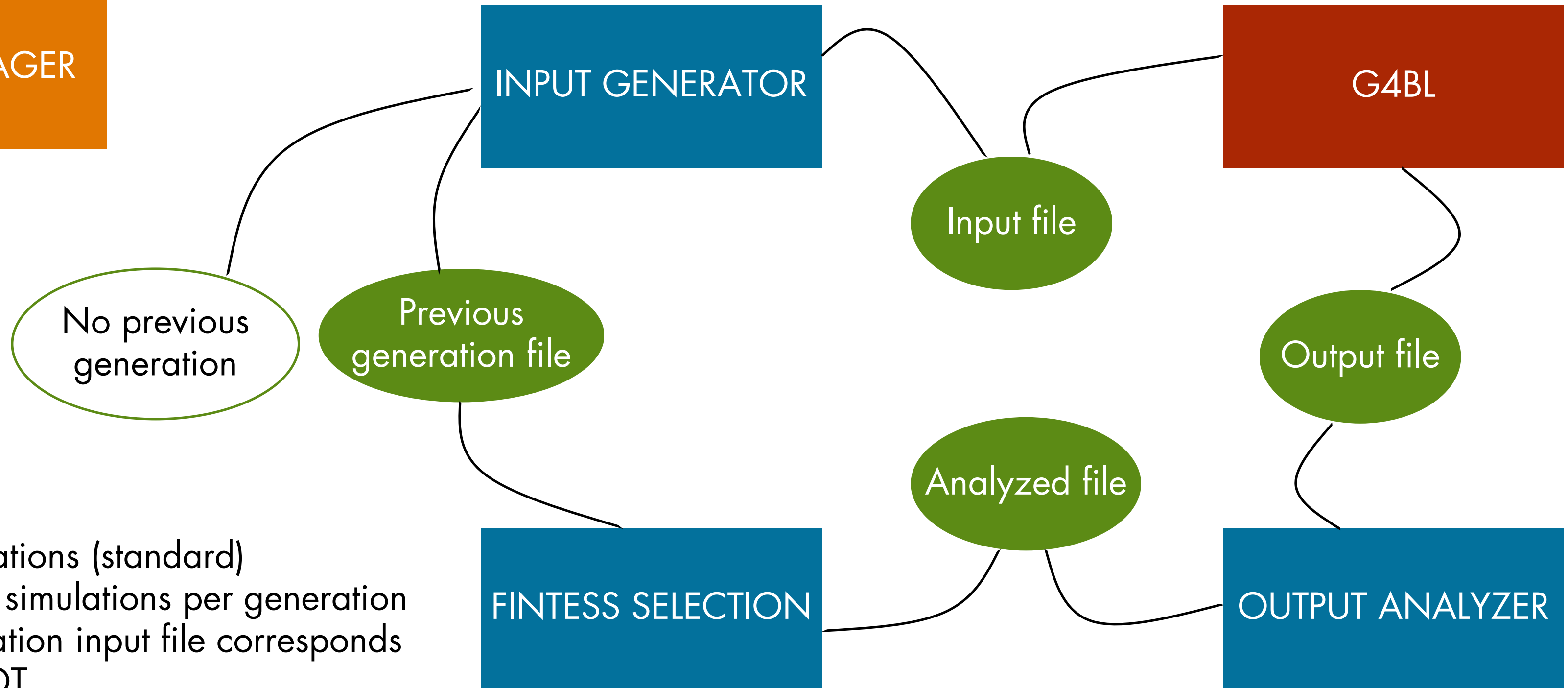
Output file

Analyzed file

FINTESS SELECTION

OUTPUT ANALYZER

- 100 generations (standard)
- 1000 g4bl simulations per generation
- Each simulation input file corresponds to 10^7 POT

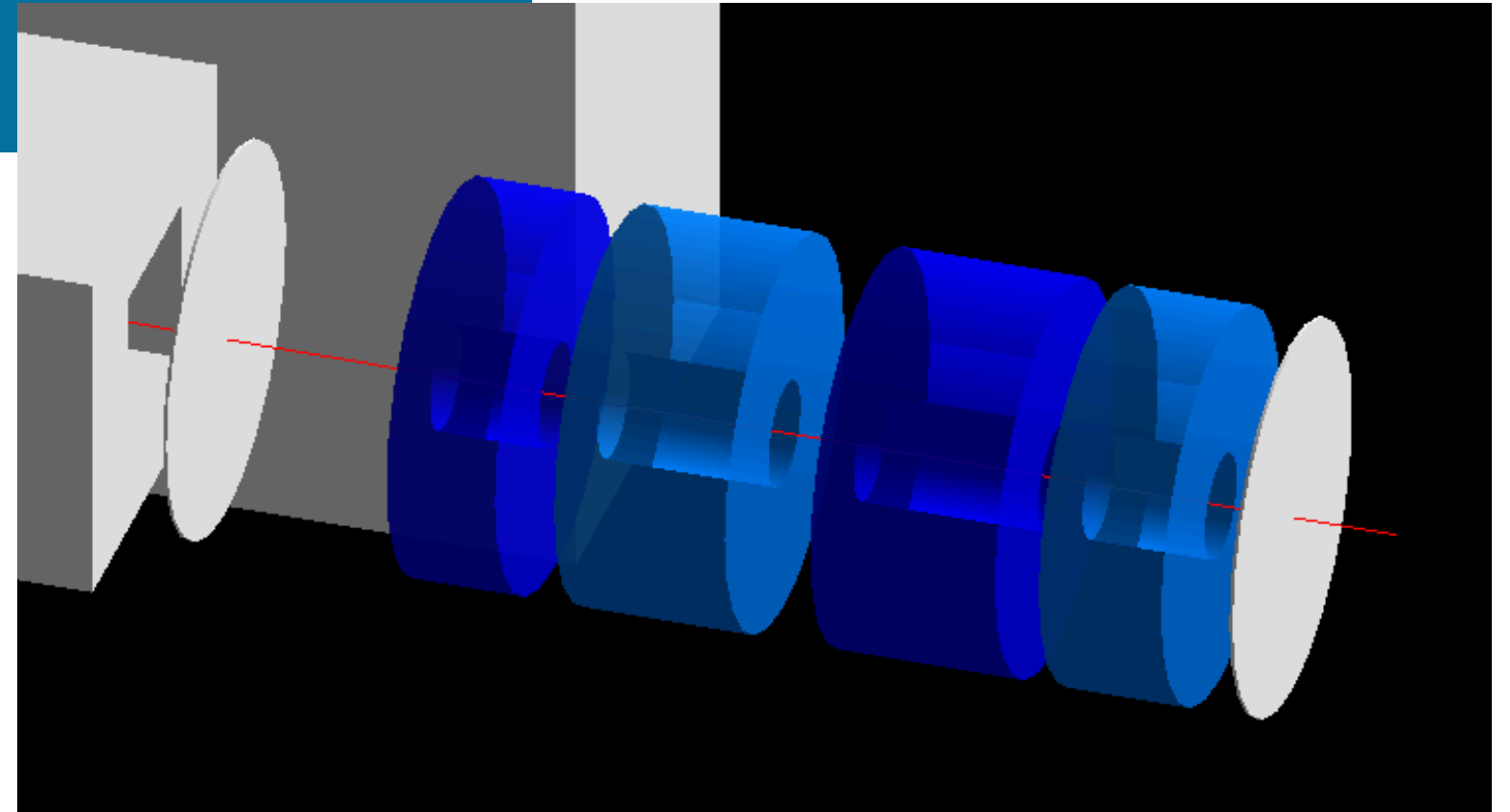


WHAT THE GENETIC ALGORITHM DOES:

The simulation output analysis is mainly focused on the pion yield in various spots of the transfer line.

- The relevant quantity that is maximized is the number N of pions that enter the tunnel and, under the assumption that they don't decay, exit the tunnel whose momentum lies in the design range
- If N is equal for two or more solutions, then the number of pions after the second dipole, M , is maximized.
- If M is equal for two or more solutions, then the number of pions after the first dipole, L , is maximized.

The quantity that drives the optimization is the number of pions at the entrance of the tunnel, except for the first iterations.

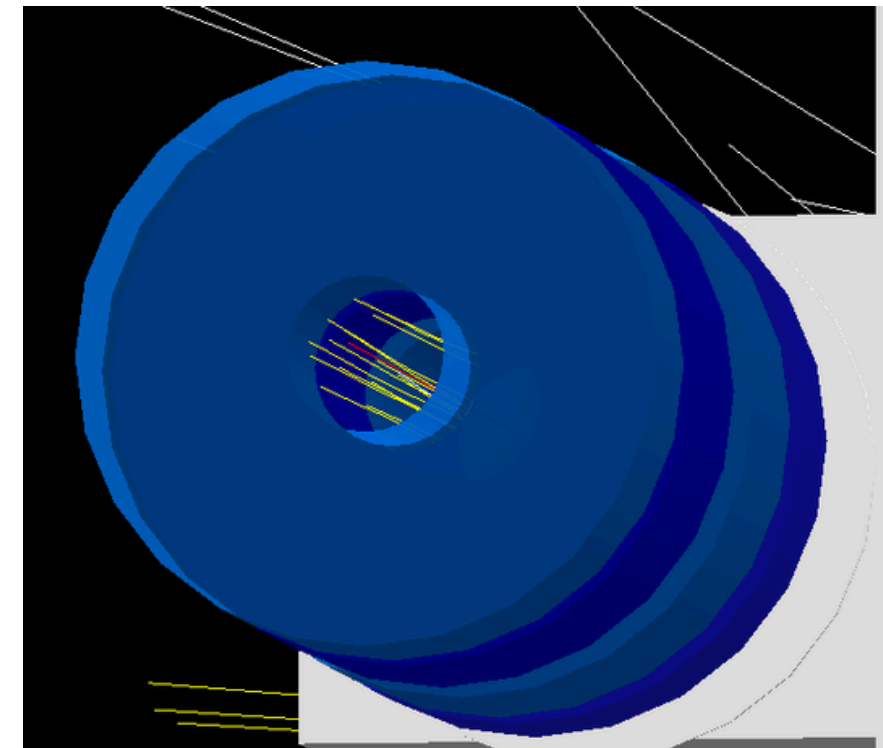
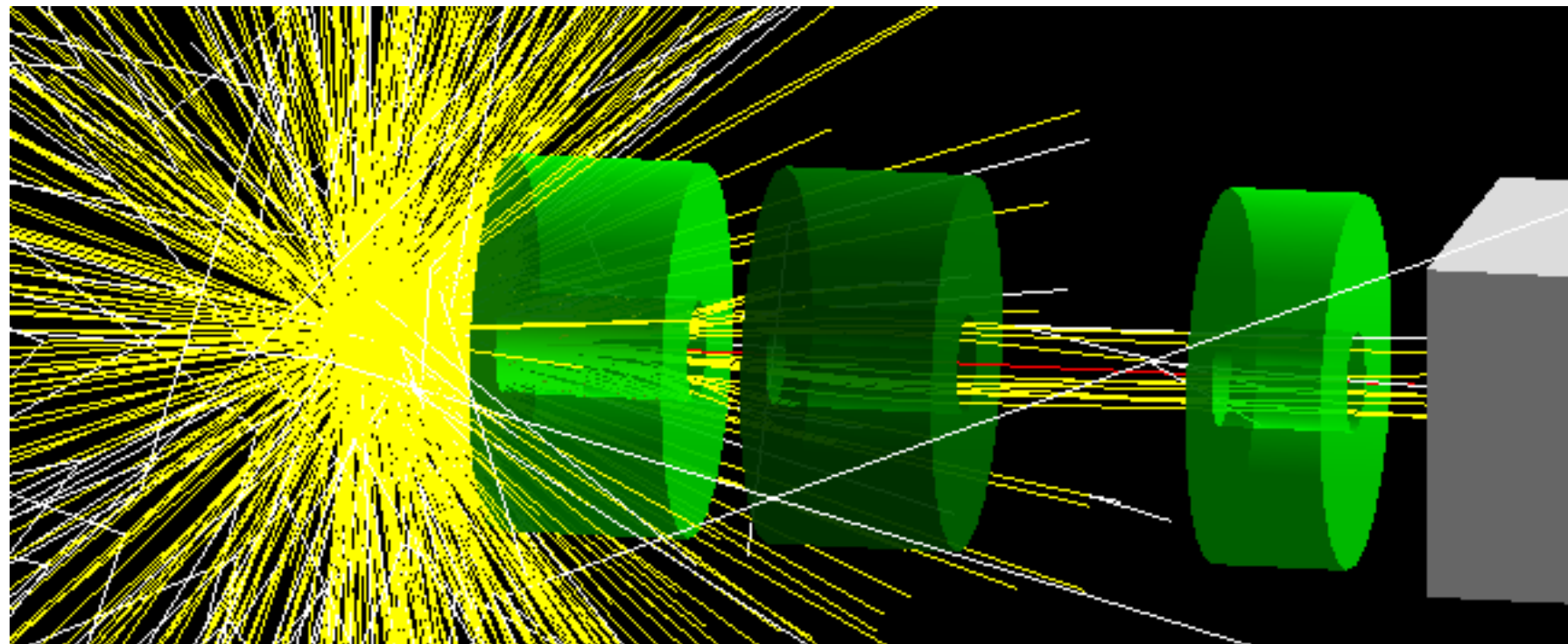
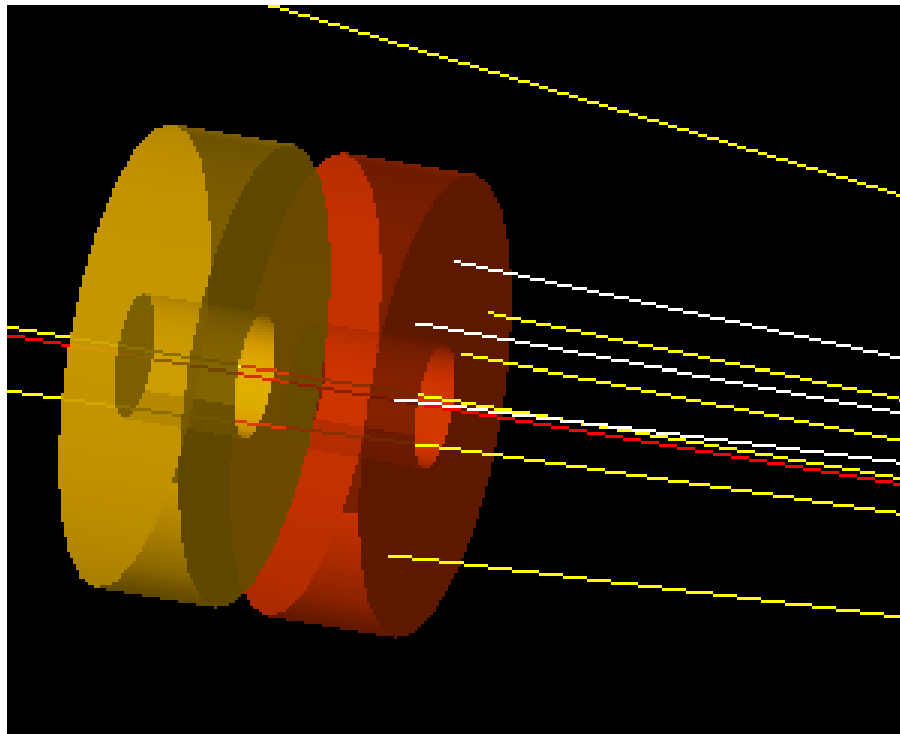


After the solutions are ranked according to N , M and L , the new generation is created:

- 10% are the best 10% of the previous generation (elitism)
- 80% are a combination of the 50% best solutions of the previous generation. The new individual has, for each gene, equal probability to inherit from any of the parents
- 10% are randomly generated at each generation

WHAT THE GENETIC ALGORITHM DOESN'T DO (YET):

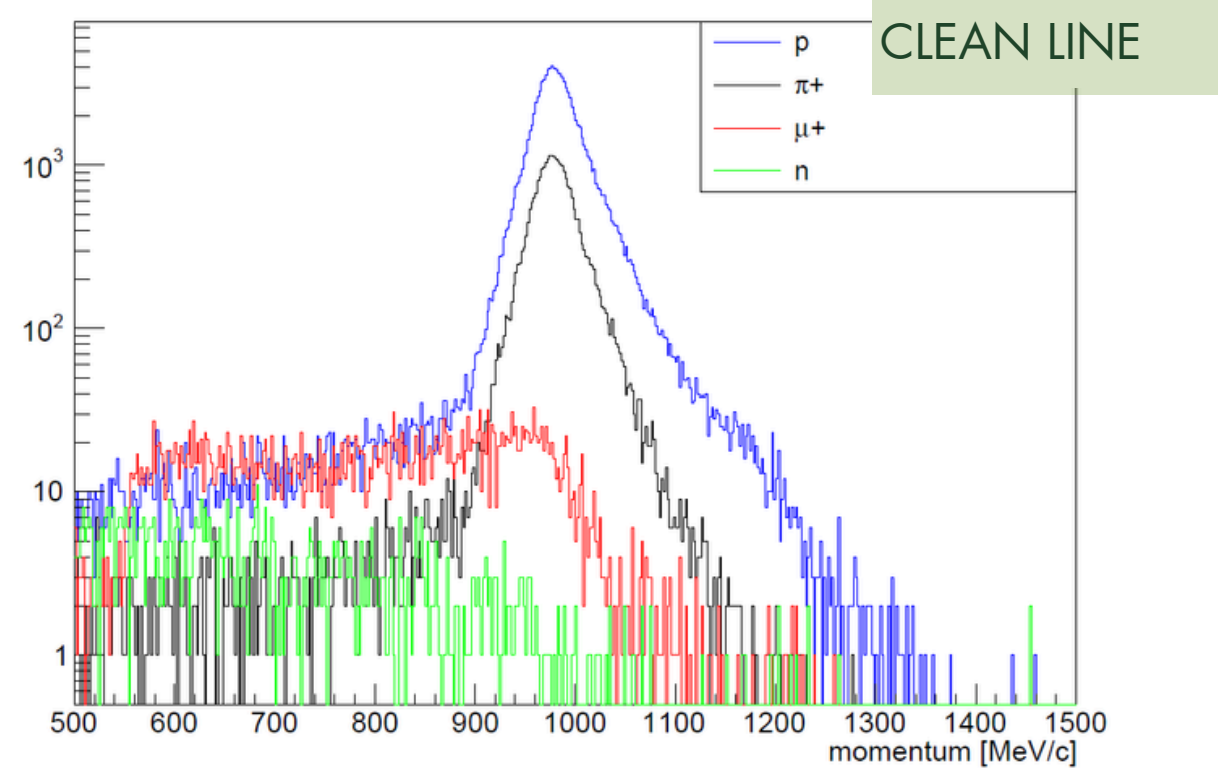
- The input file contains only pions from the FLUKA simulation of protons on the target (see F. Pupilli's [talk](#) at ESSvSB+ 1st Annual Meeting) – backgrounds are not considered for the optimization.
- For now, the beamline is "naked" and does not include shielding and collimators
- The beamline elements are "killing", i.e. any particle that is produced in the interaction with them is not considered
- In the decay tunnel, the number of pions directly hitting the wall is not minimized
- The aperture radius of the quadrupoles is fixed at 30 cm, probably too large
- Fringe fields are not included in the simulation



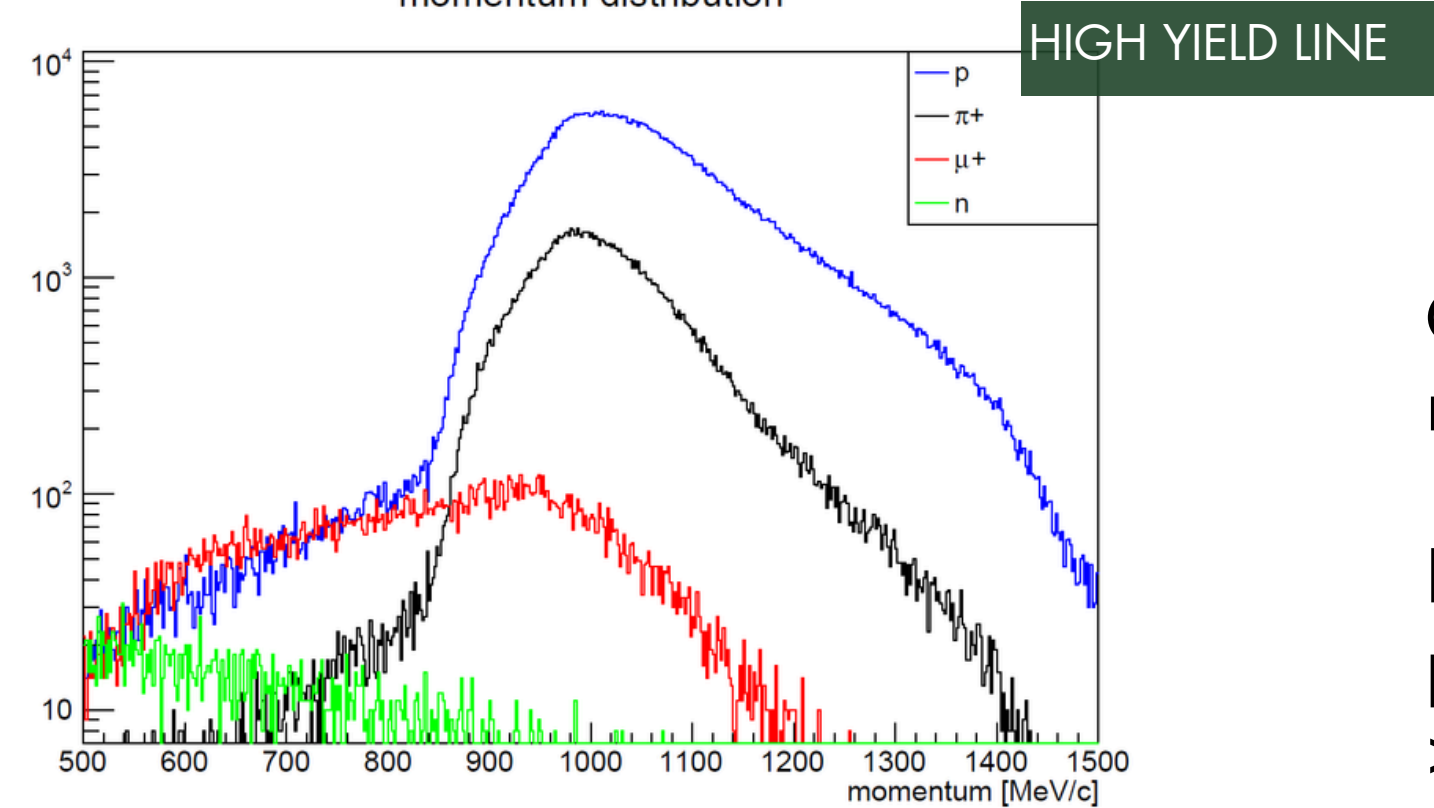
BEAMLINE COMPARISON

Momentum and angular dispersion at the entrance of the tunnel for different particle species

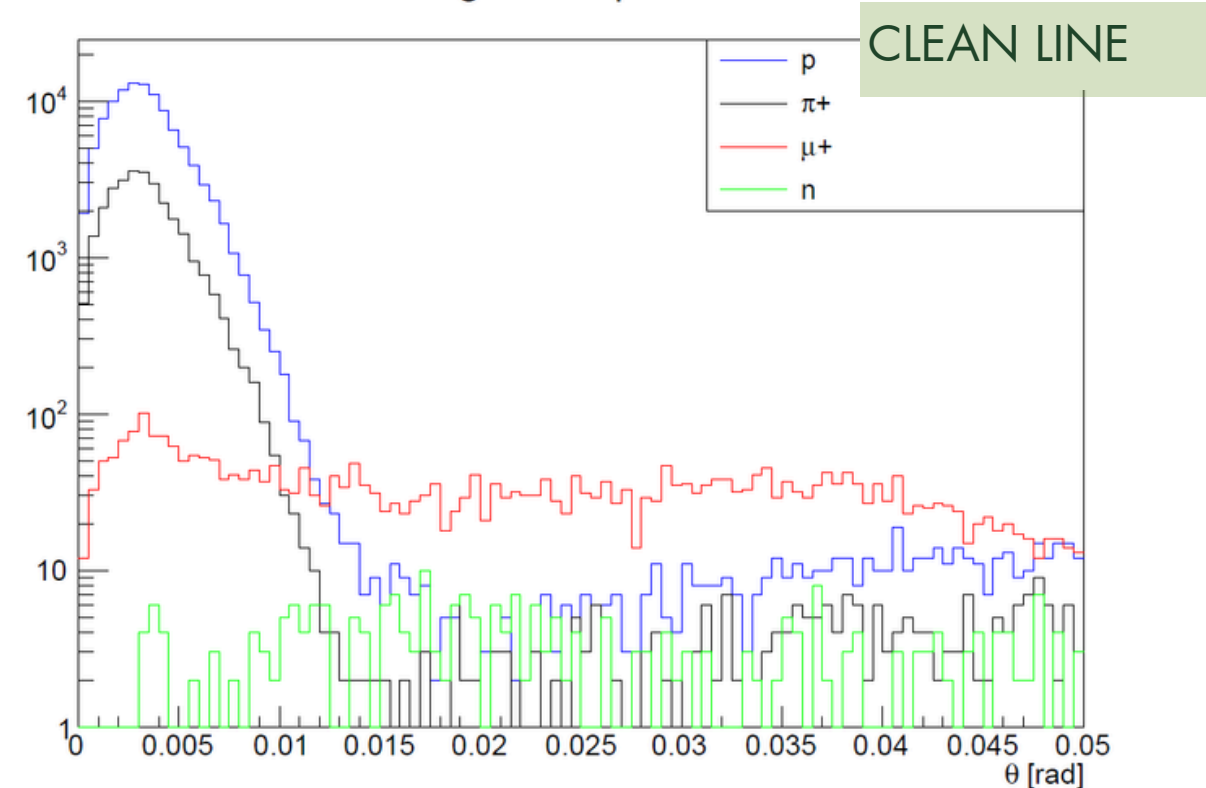
momentum distribution



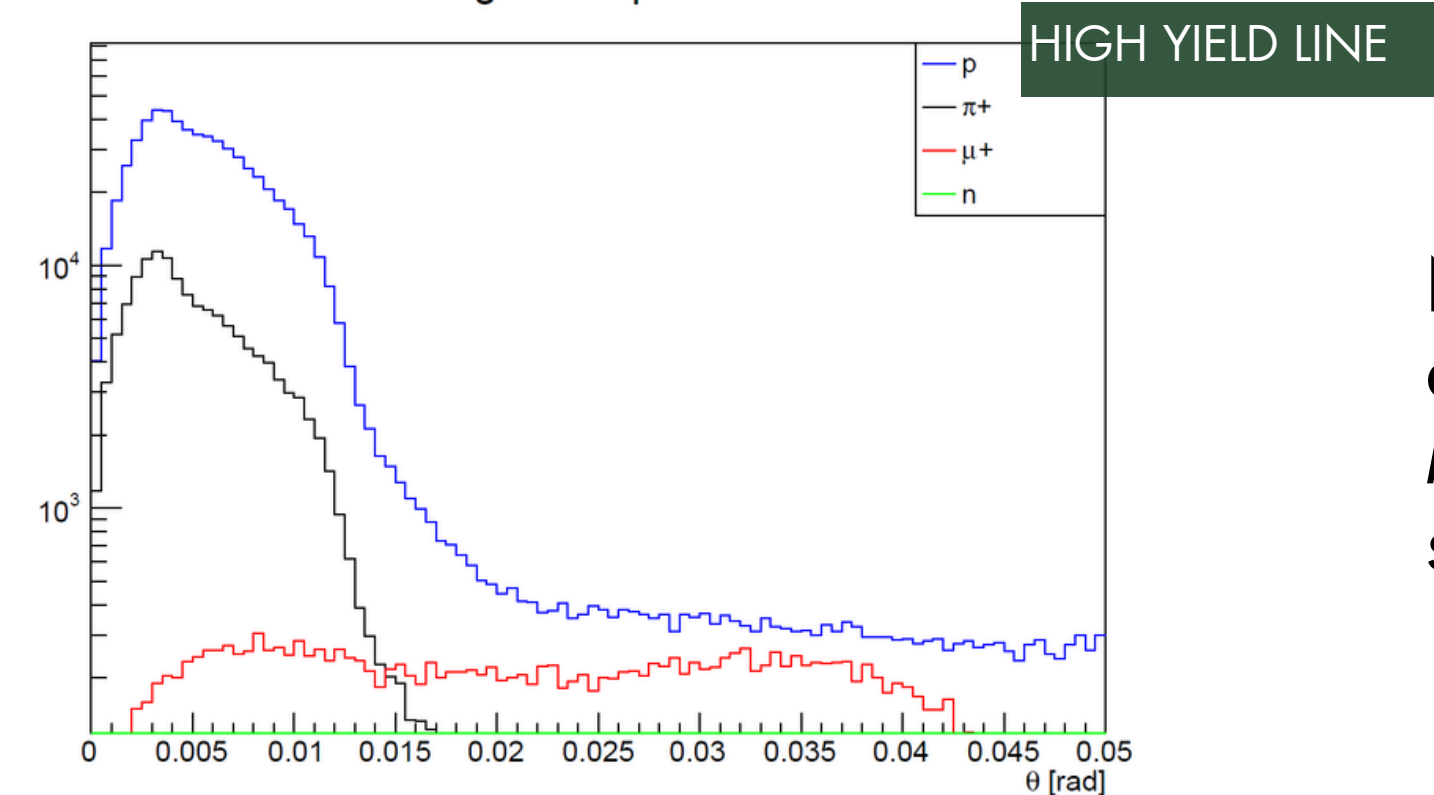
momentum distribution



angular dispersion



angular dispersion



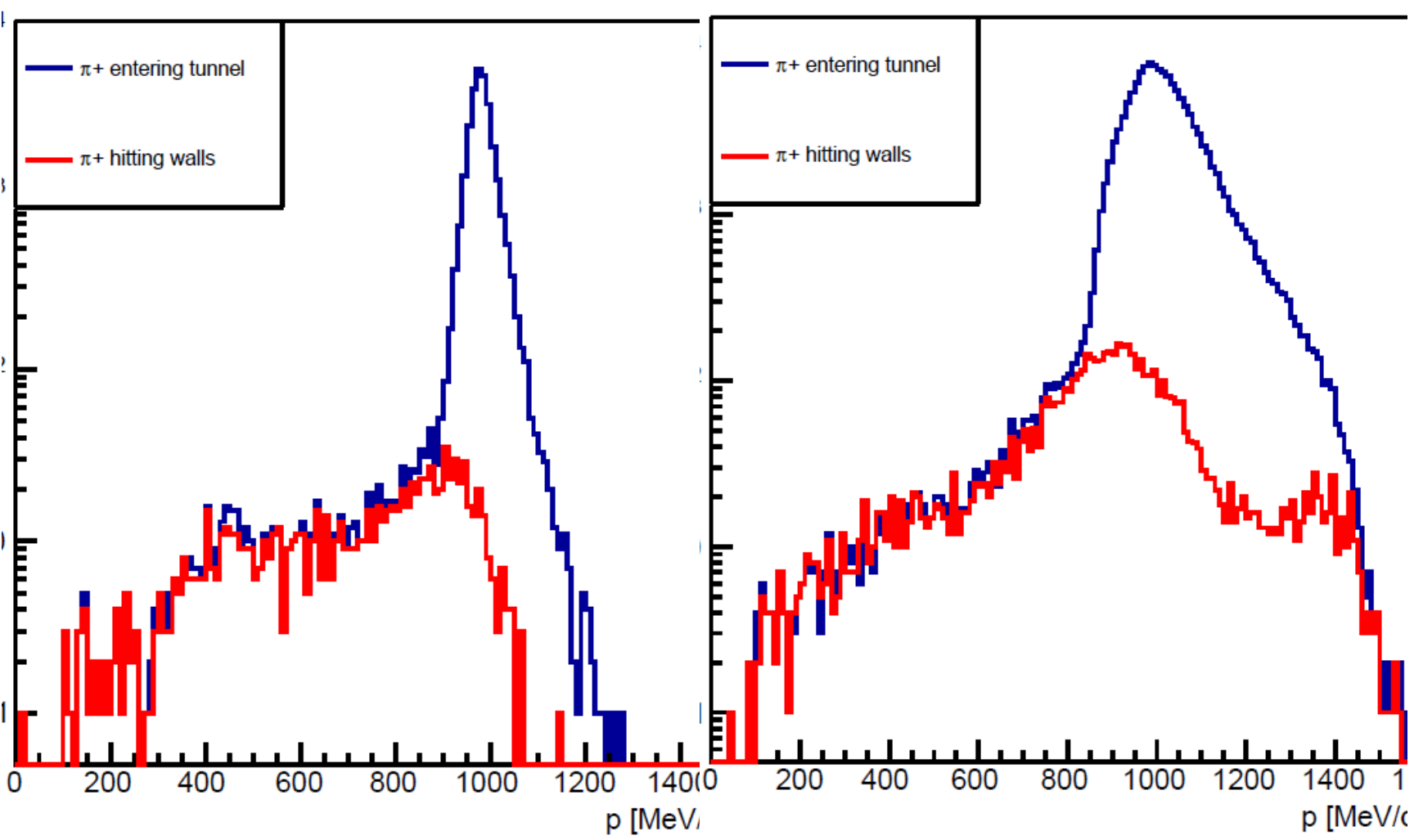
Clean line has narrow peak in momentum for p and pi

High yield line has a "tail" of protons at high p and high theta > source of background

Neutrons have low momenta and flat distribution in theta. Most of them impact on the first section of the tunnel

BEAMLINE COMPARISON

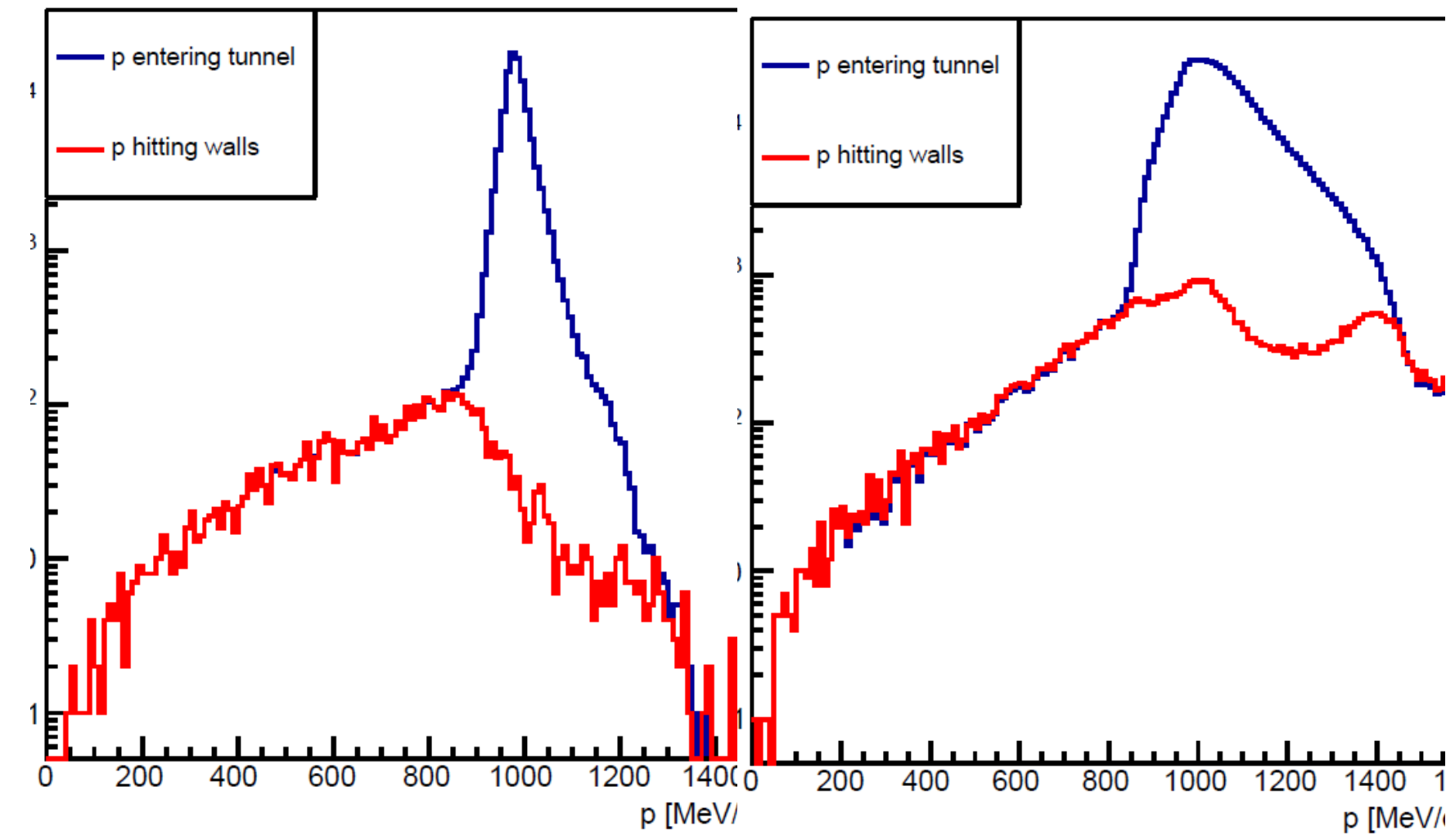
momentum distribution



CLEAN LINE

HIGH YIELD LINE

momentum distribution



CLEAN LINE

HIGH YIELD LINE