Sweeper Magnet Study

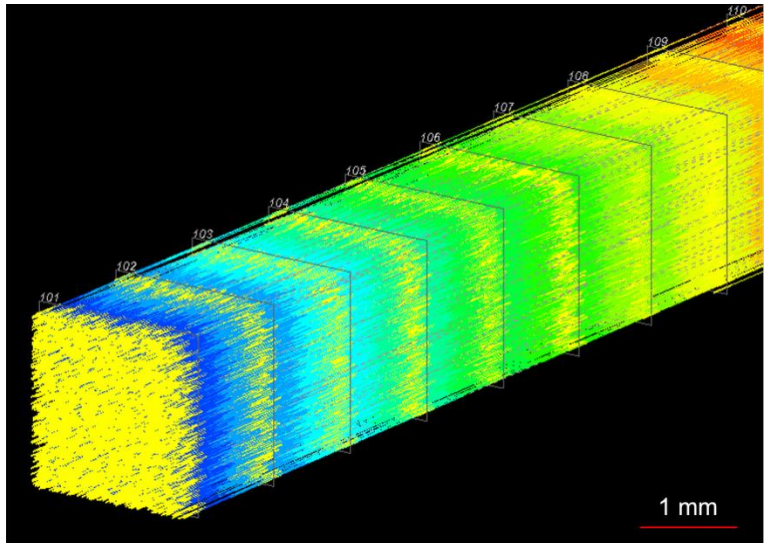
Kohei CHINONE

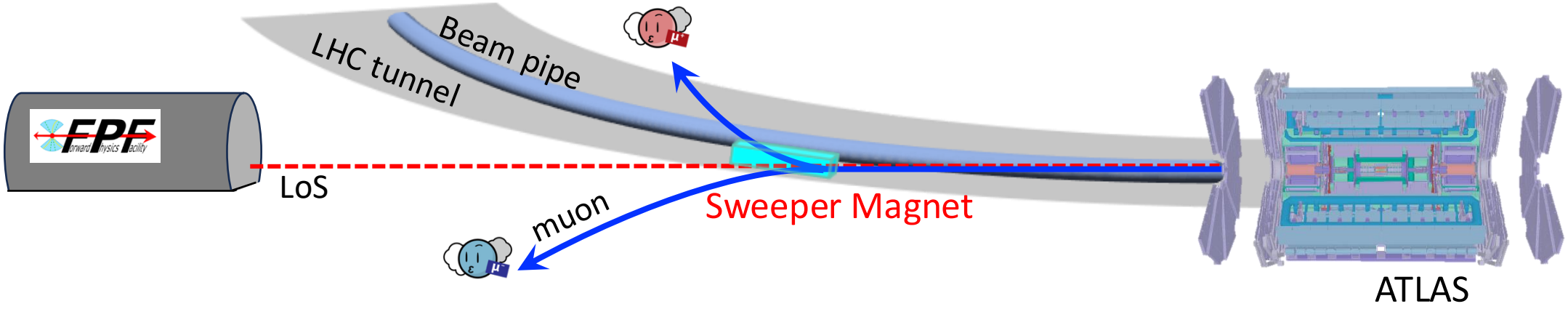
Chiba University

Introduction

- Muon background limits the physics performance of the FPF program
- Strong limit to FASERν2 emulsion detector
  - Muon tracks are accumulated in the emulsion detector
  - Max muon density: $\mathbf{5 \times 10^5 / cm^2}$ (read out & track reconstruction)
  - FASERν detector is replaced 3 times per year in Run3
- With the increased detector size, we aim to reduce detector replacements to once per year in FASERν2

Event display of muon tracks accumulated in the FASERν detector



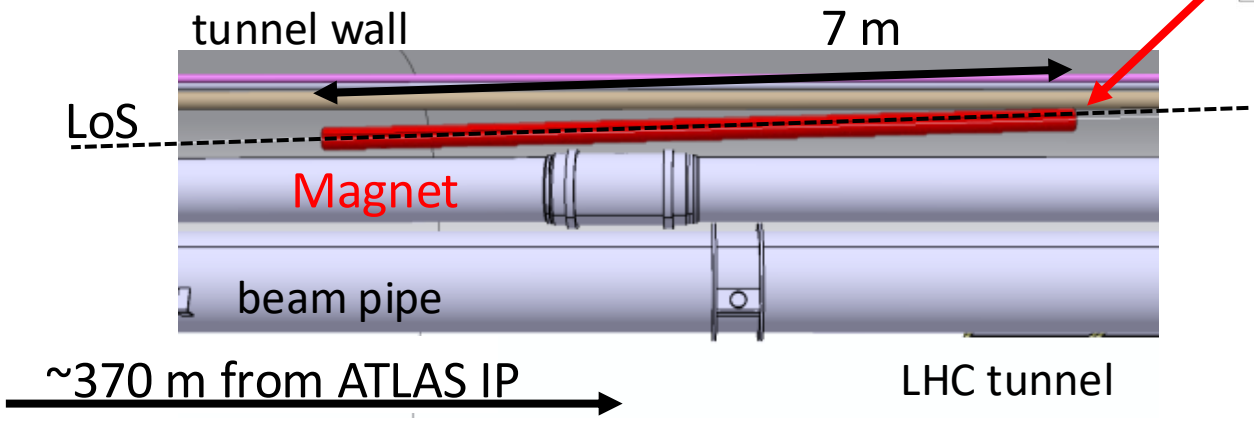


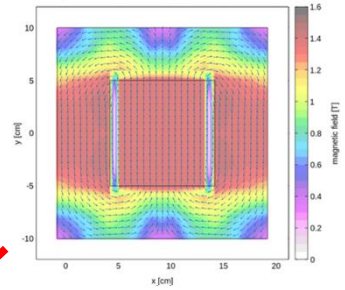
Placing a Sweeper Magnet upstream of the detector to reduce background muons

- For an annual luminosity of $250\ \mathrm{fb}^{-1}$, target muon flux: $\mathbf{2.0 \times 10^3\ /cm^2/fb^{-1}}$

Previous Studies

- CERN STI FLUKA team

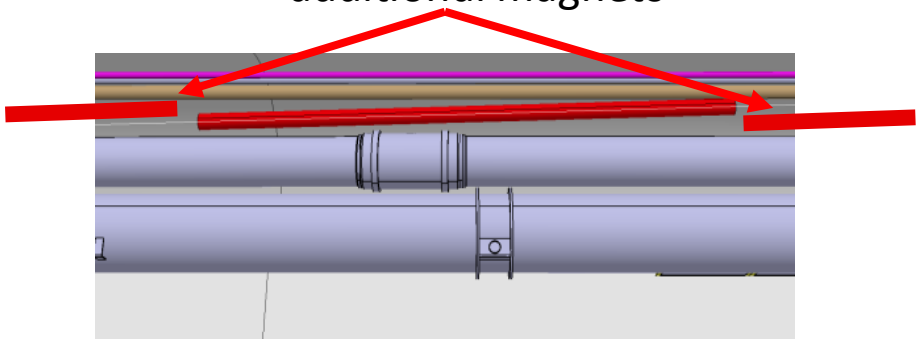


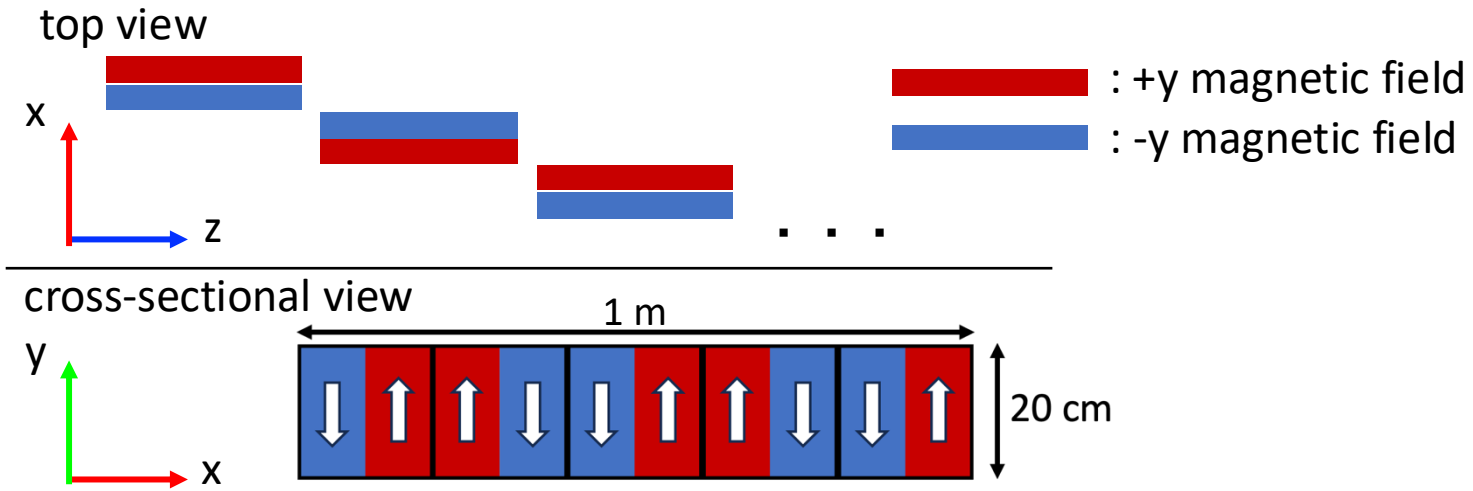


Result

	Muon flux [$cm^{-1}\ s^{-1}$]	
	μ^-	μ^+
No magnet	0.45	0.15
7 Tm magnet	0.45	0.17

- FPF8





Simplified magnetic field was used, and event weights were not included

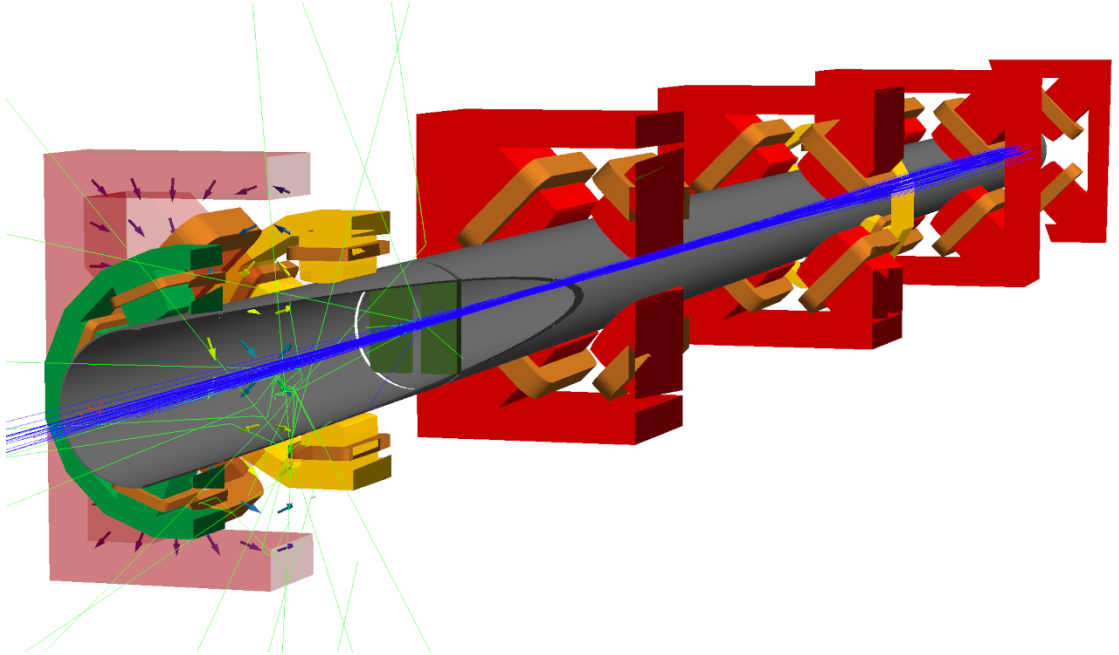
Update from FPF8

- Event weights from BDSIM are properly included in the Geant4 analysis
- Magnetic field models from dedicated field simulations are used
  - 2D simulation using Elmer
- The magnet layout is changed from multiple LoS-parallel magnets to a long tunnel-parallel configuration
- The simulation setup is improved to include the LHC tunnel geometry and TI18
  - Corrected LHC tunnel angle and updated FPF location
- A new input sample based on BDSIM distributions produced in 2025 is used
- The feasibility of the long tunnel-parallel magnet layout is discussed with the CERN integration team

BDSIM

https://bdsim-collaboration.github.io/web/

- Beam Delivery SIMulation software is a Geant4 toolkit for MC-based particle transport and matter interaction simulations.
- BDSIM accepts custom geometry, optics, field maps, beam distributions…
- Broad range of supporting tools such as pybdsim, pymadx, pytransport…



➢ IP1-to-TI12 model validated against FASER muon flux measurements. The IP1-to-TI18 model used for the FPF studies is an x-reflection of this model.

ROYAL HOLLOWAY UNIVERSITY OF LONDON

John Adams Institute for Accelerator Science

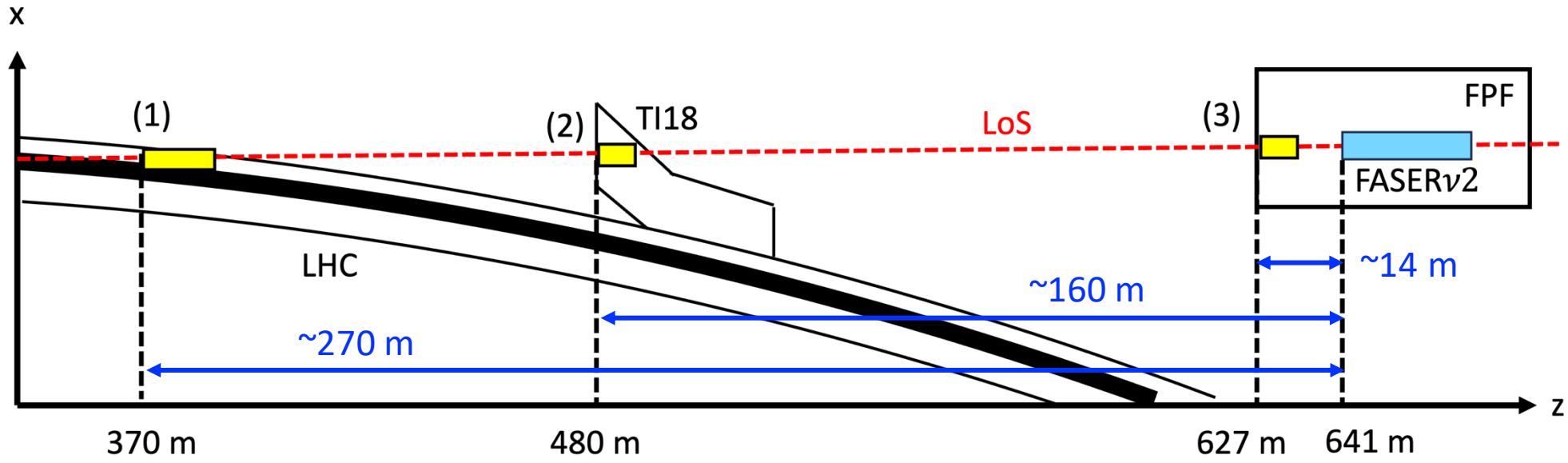
Biasing Methods

- Two biasing methods are applied to increase the muon yield (originally approx. one per 1M pp-collisions):
  - Cross-section biasing for $\pi^{\pm}$ decay, $K^{\pm}$ decay and e^+e^- annihilation, increases the likelihood for muon generation within 500 m of IP1.
  - Muon splitting resamples interactions that produce muons (up to 10 times), propagating each new muon produced.
- The biases are reversed using statistical weights.
- The biases have been tested on 150M pp-collision samples, producing muon flux estimations for FASER that agree within statistical uncertainty.

Process	Vacuum Biasing Factor	Material Biasing Factor
$\pi^{\pm}$ Decay $K^{\pm}$ Decay $e^+e^- \rightarrow \mu^+\mu^-$	10^5	

➢ Cross-section biasing factors.

Magnet Location



(1) LHC tunnel

- 370 m from IP1
- After the LoS exits the beam pipe and just before leaving the tunnel

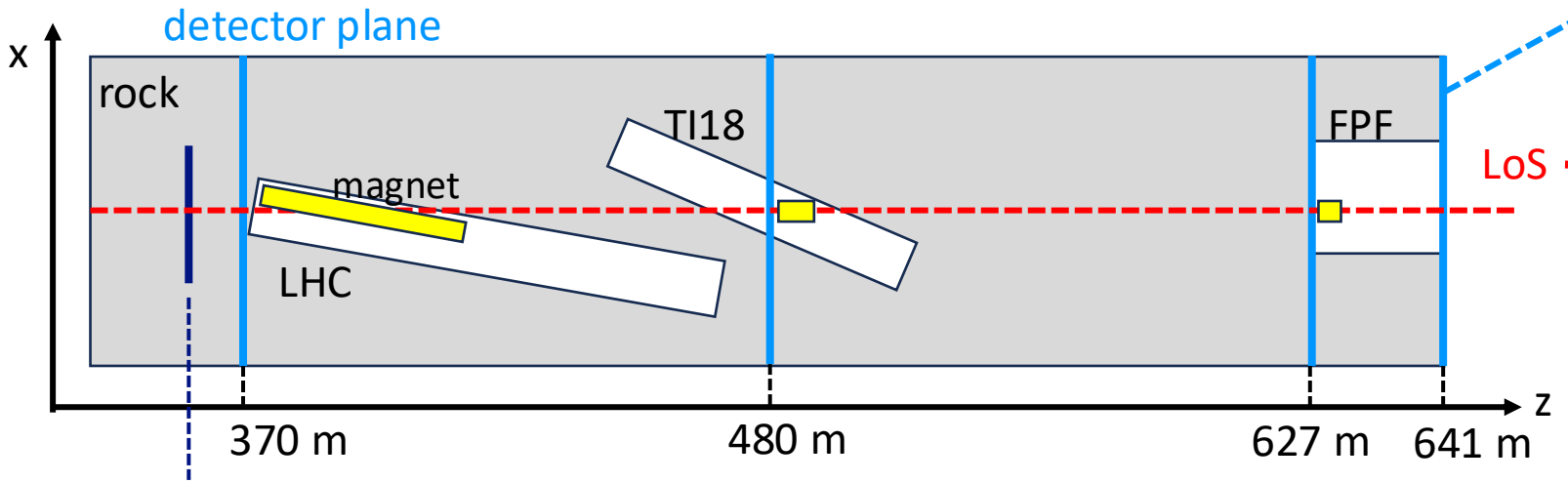
(2) TI18 tunnel

- 480 m from IP1
- Existing tunnel
- SND@HL-LHC will be installed

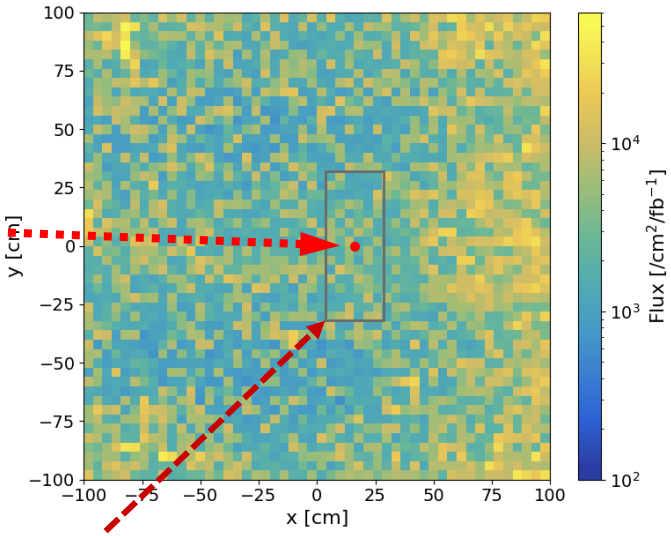
(3) FPF

- 627 m from IP1

Geant4 Simulation Setup



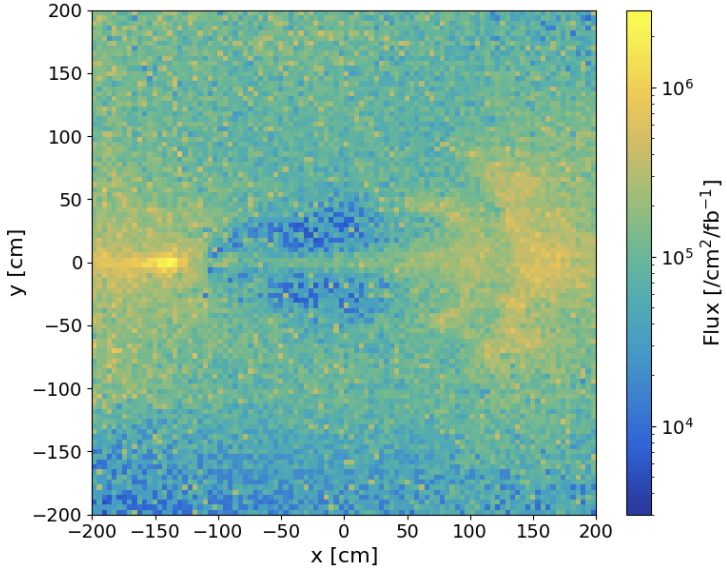
Position distribution at 641 m



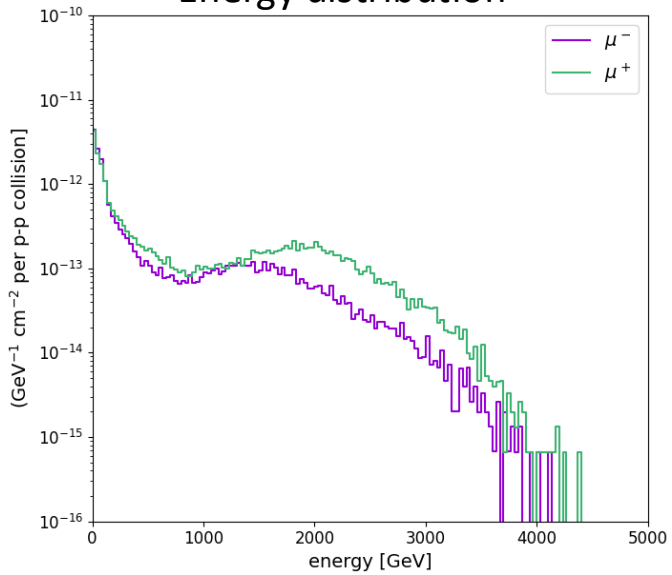
detector region

Input muons (370 m - 10 cm)

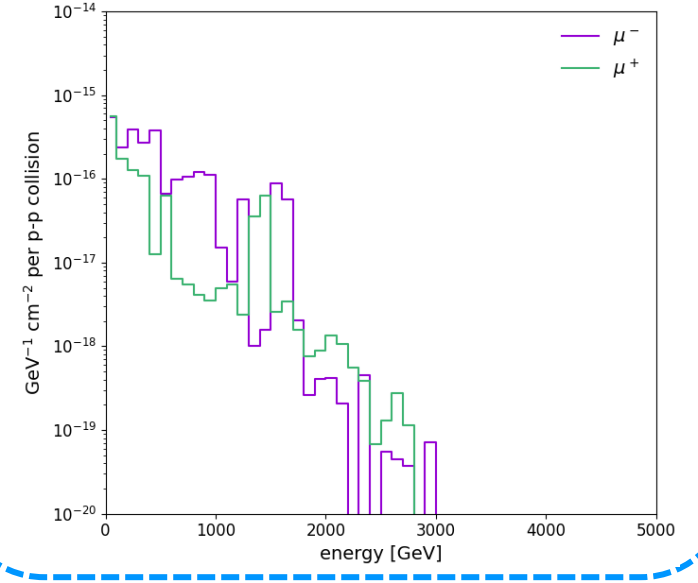
Position distribution



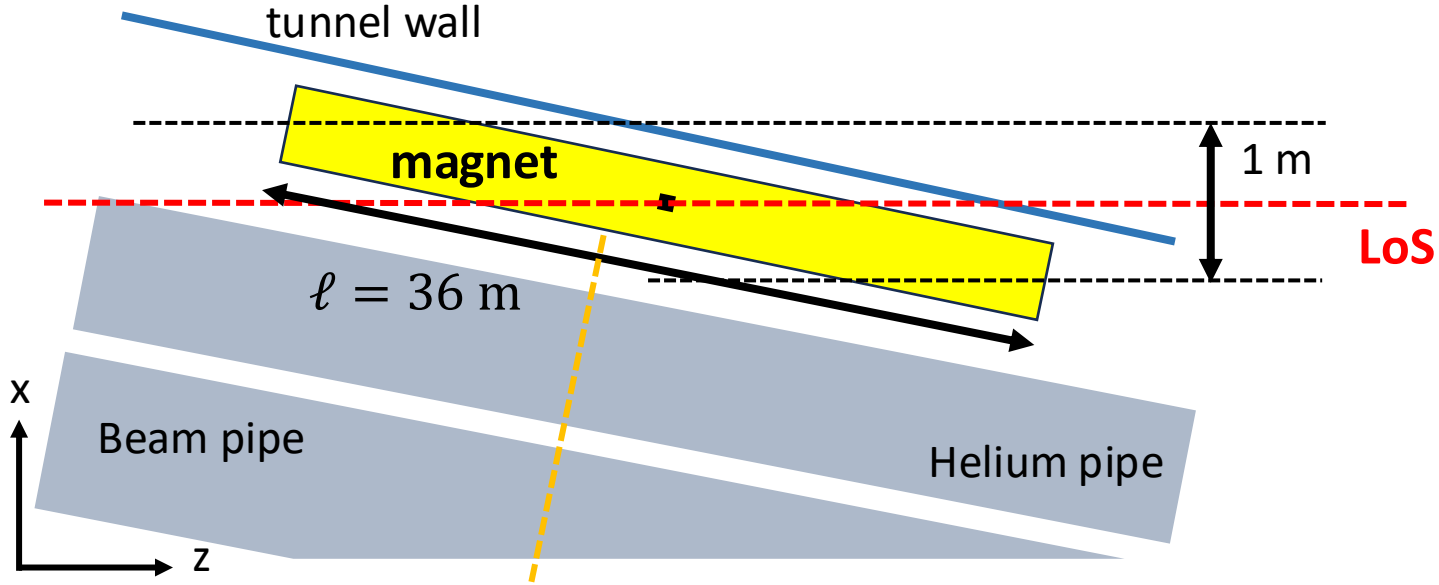
Energy distribution



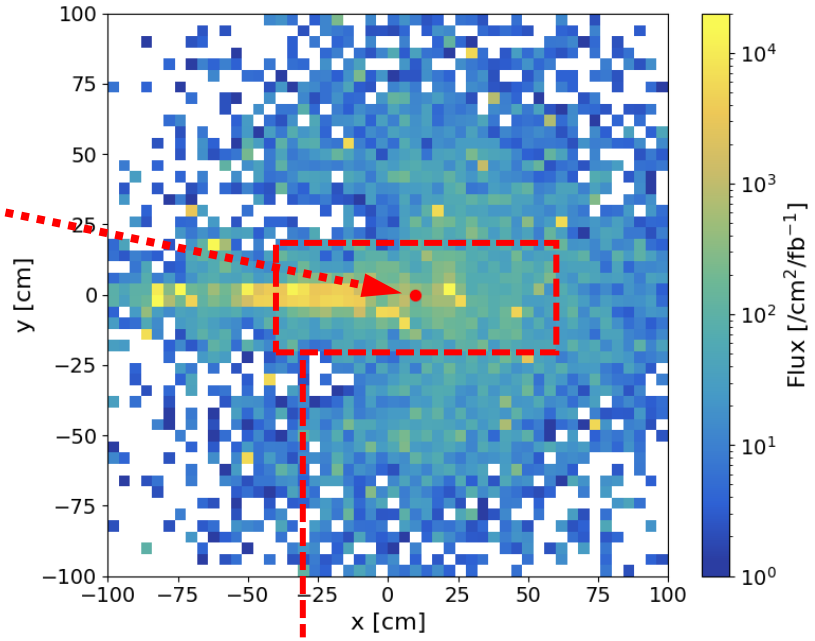
Energy distribution in the detector region



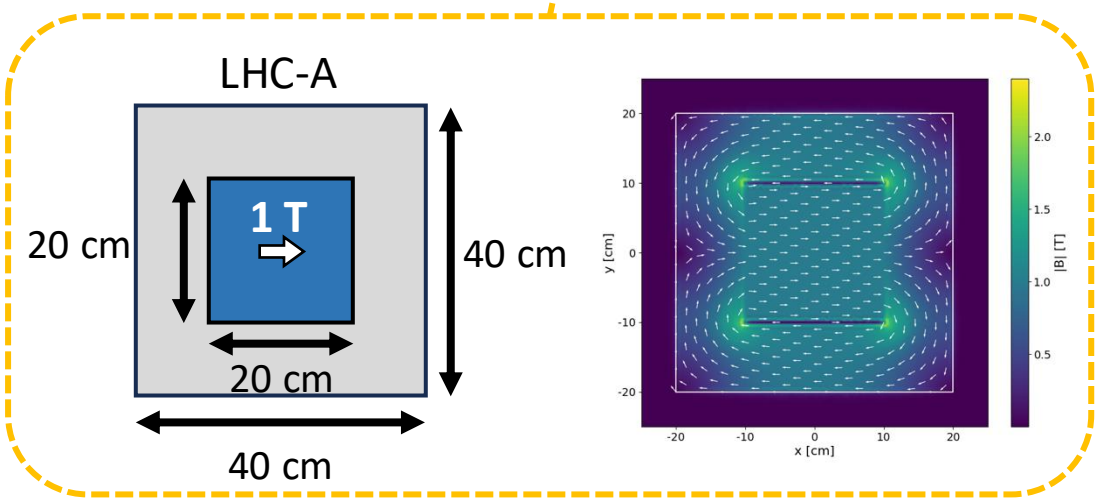
Evaluation of the suppression by magnet in the LHC tunnel



Position distribution of muons reaching the detector at 370 m from IP1

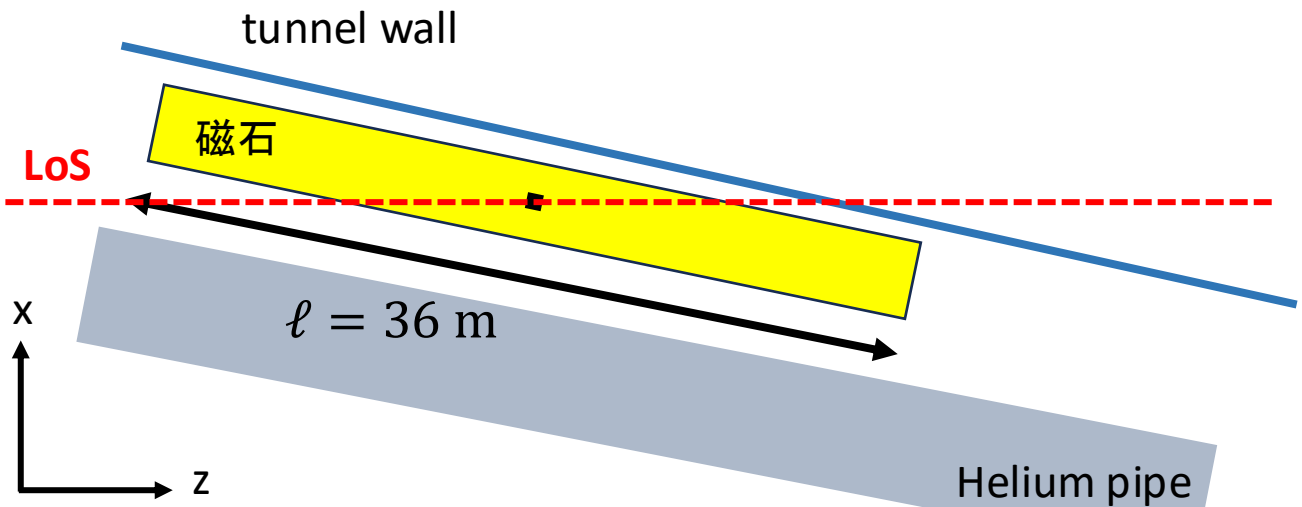


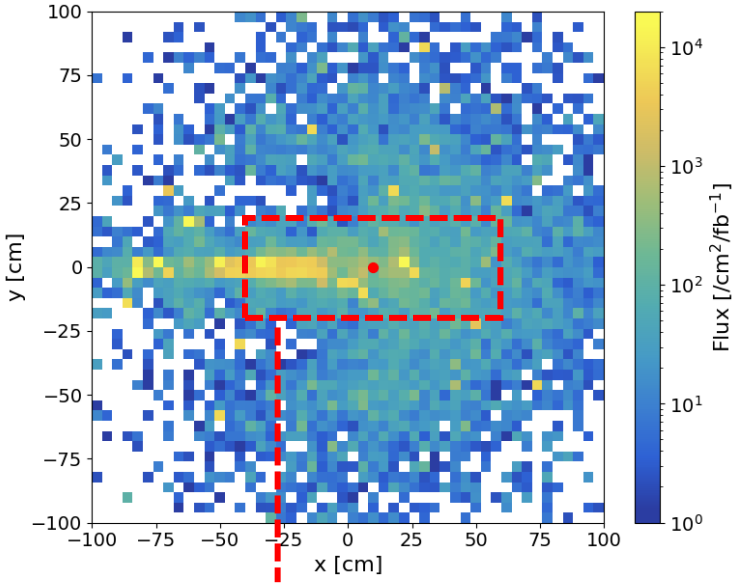
coverage area with 40 cm height magnet



Magnet	Muon flux Φ $[10^3/\mathrm{cm}^2/\mathrm{fb}^{-1}]$	Remaining rate R [%]
No magnet	3.76 ± 0.32	100
LHC-A	$\mathbf{2.61 \pm 0.31}$	$\mathbf{69.4 \pm 10.1}$

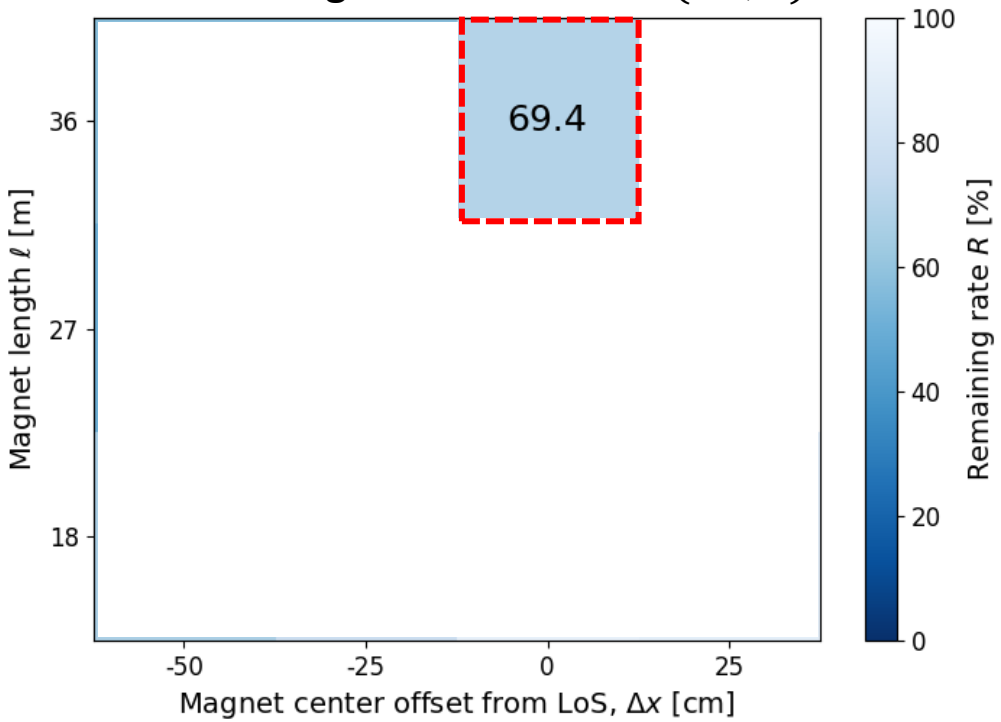
Suppression Effect for Different Magnet Layouts



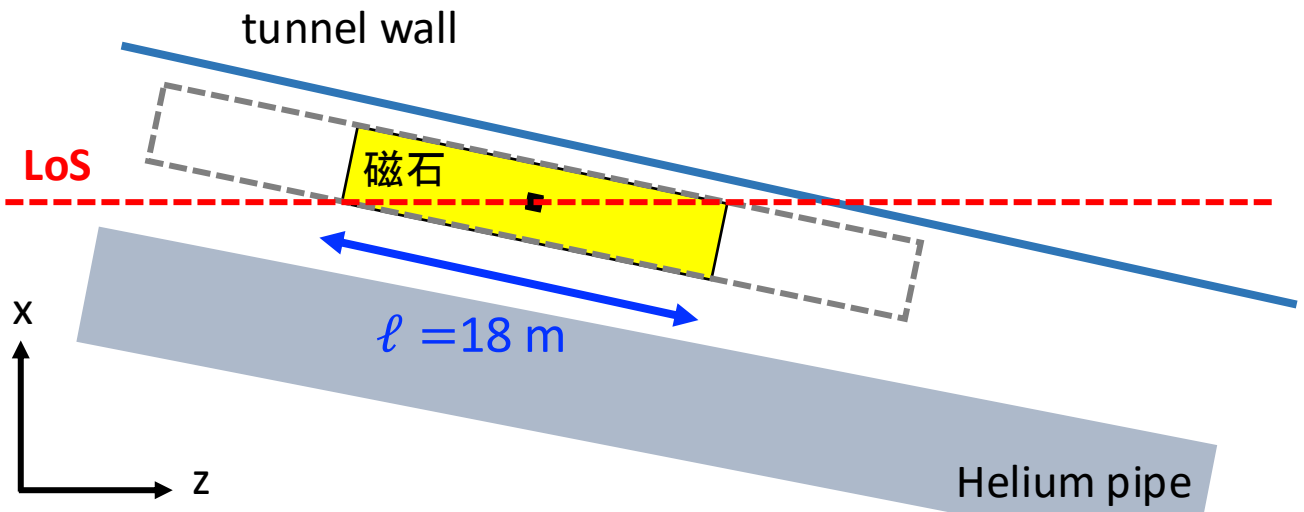


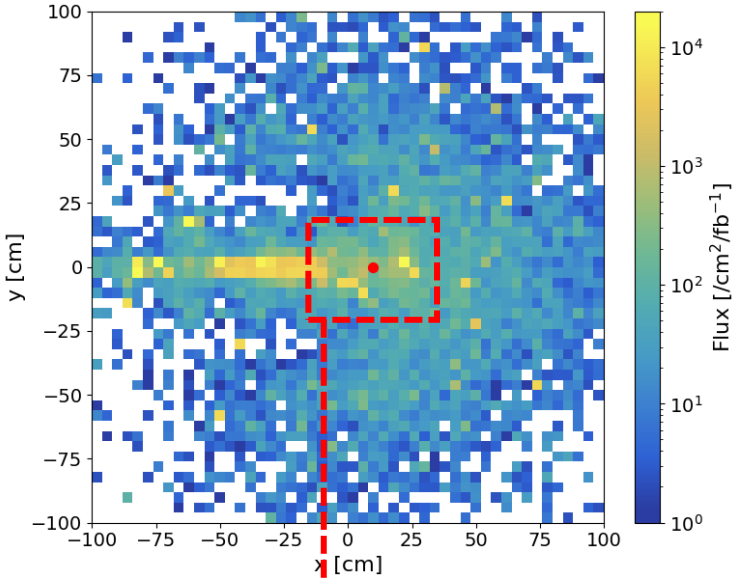
Magnet coverage area ($\ell = 36$ m)

Remaining rate R for each $(\Delta x, \ell)$



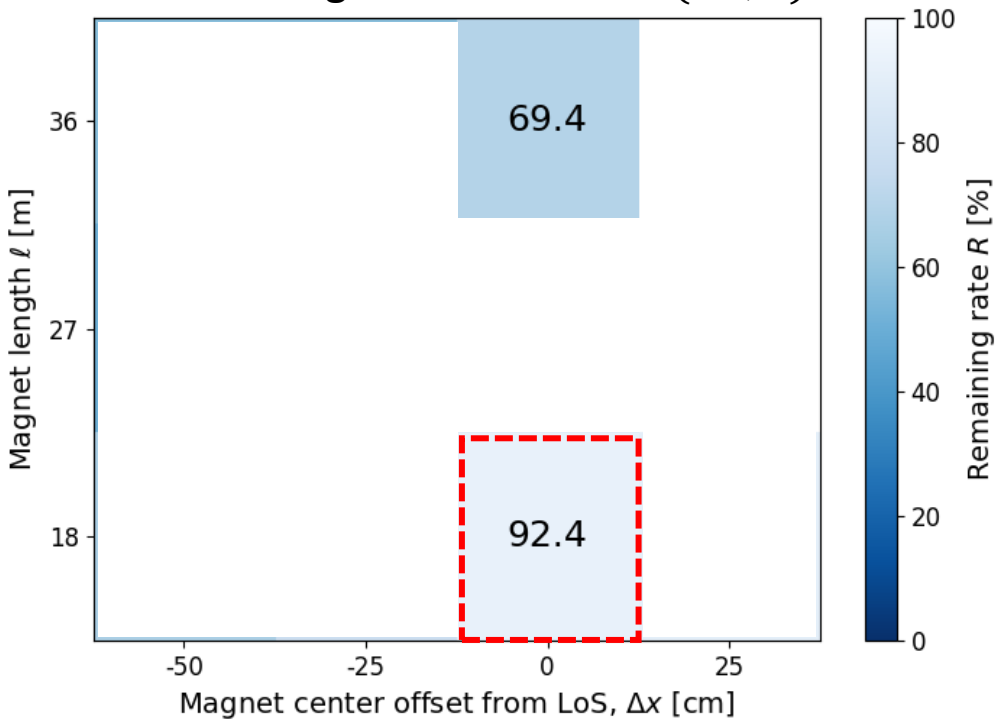
Suppression Effect for Different Magnet Layouts



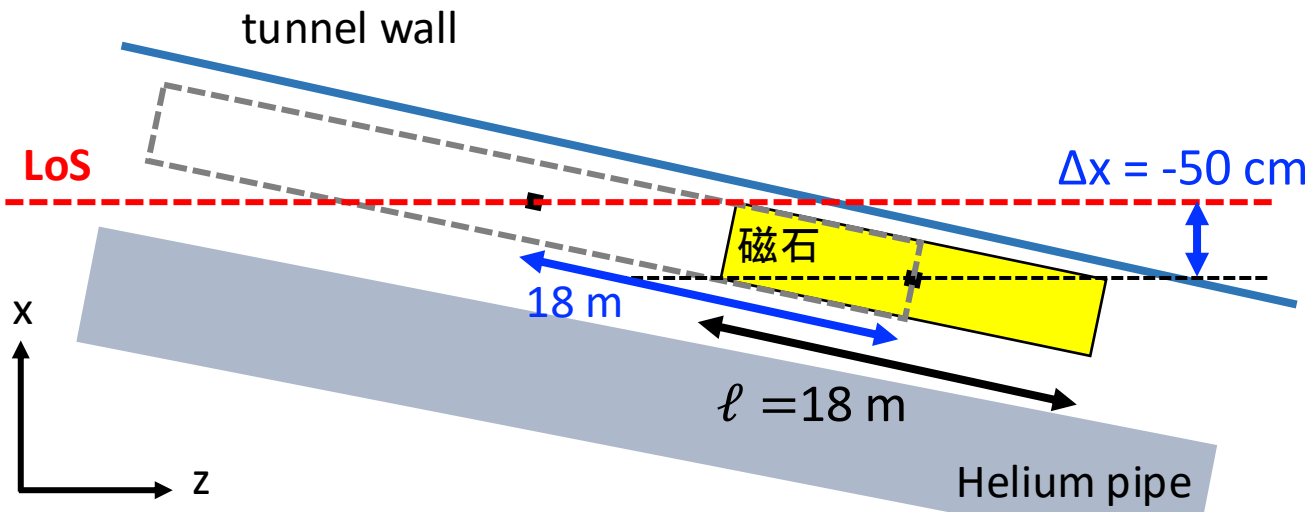


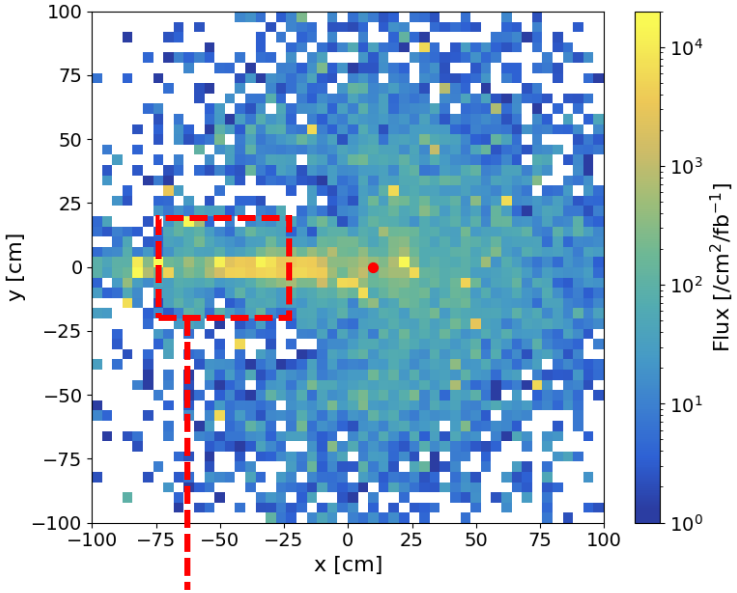
Magnet coverage area ($\ell = 18$ m)

Remaining rate R for each $(\Delta x, \ell)$

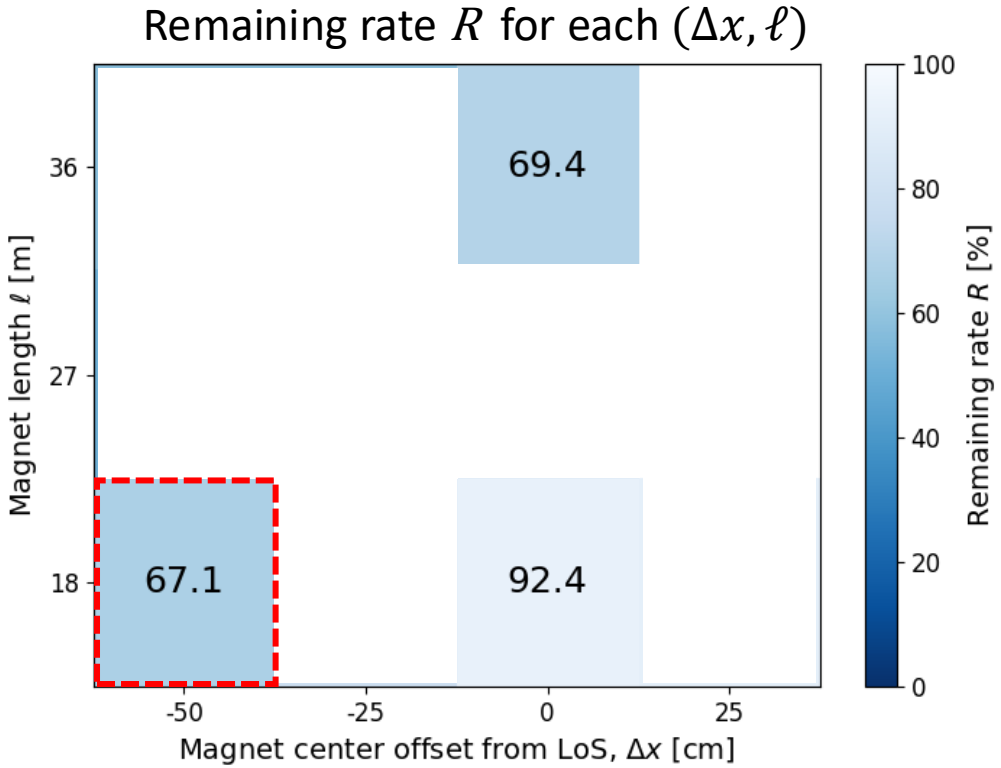


Suppression Effect for Different Magnet Layouts

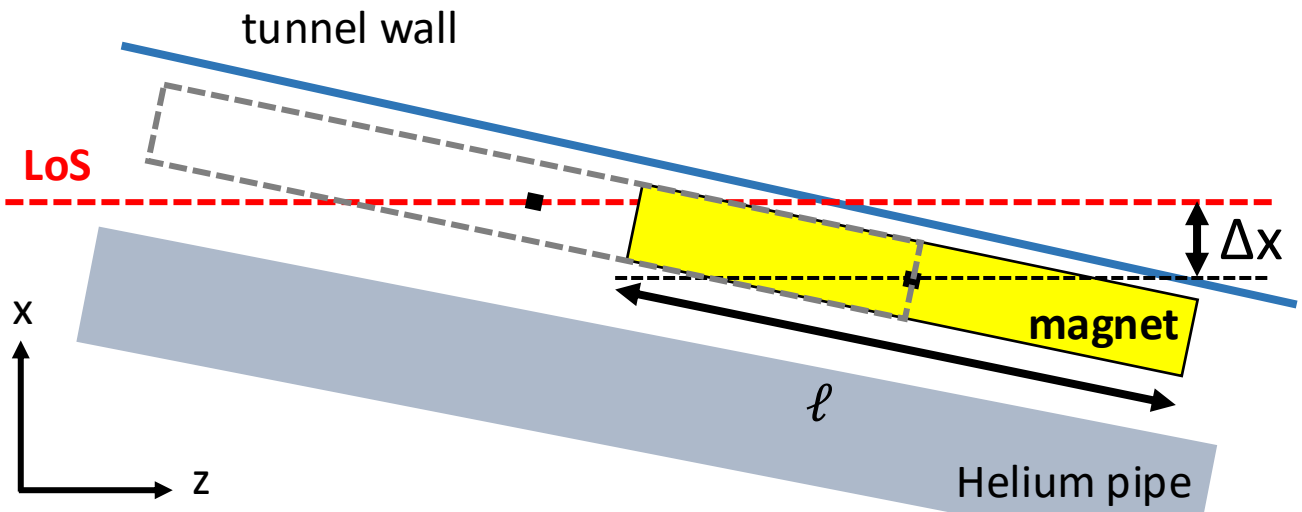


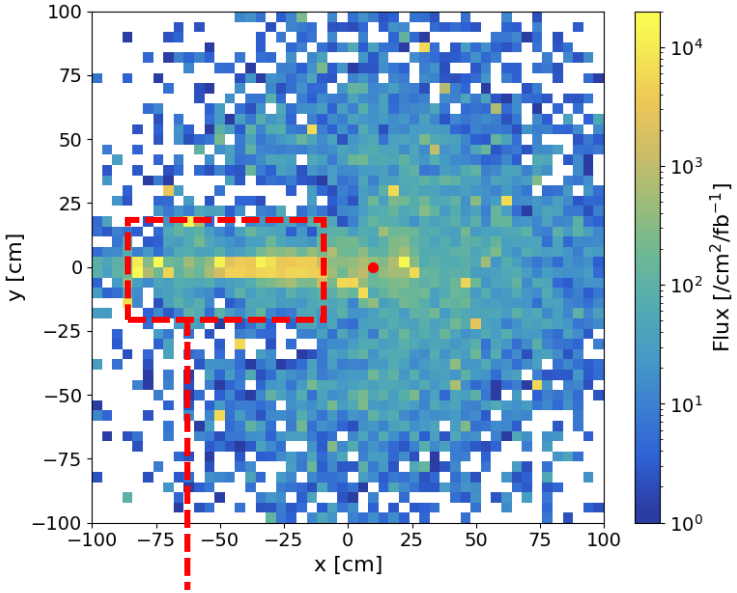


Magnet coverage area ($\ell = 18$ m, $\Delta x = -50$ cm)



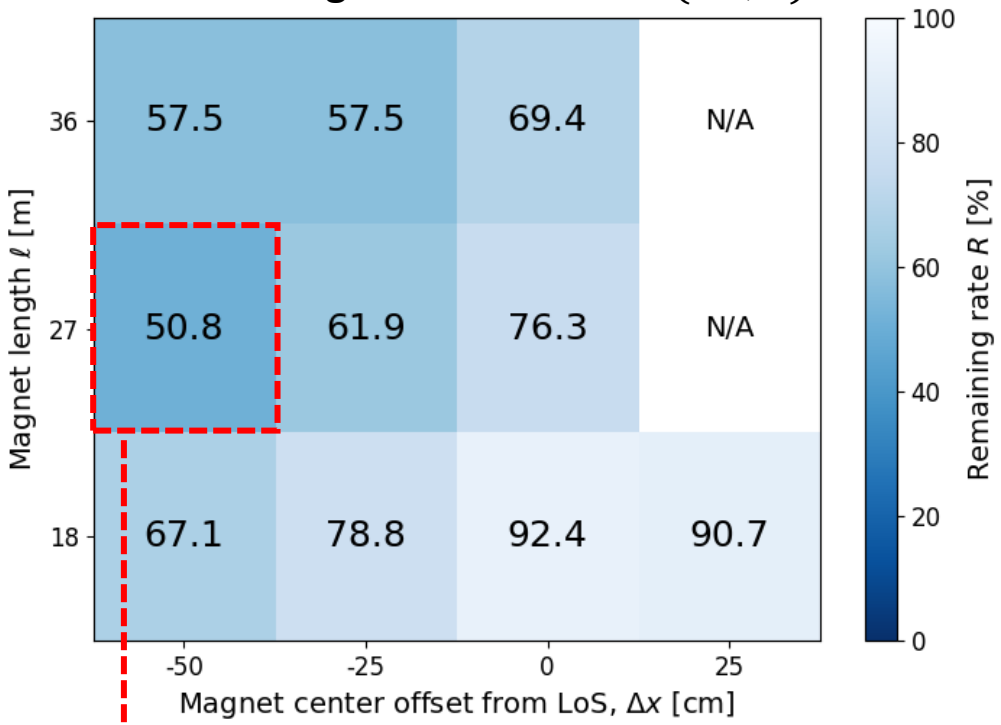
Suppression Effect for Different Magnet Layouts





Magnet coverage area ($\ell = 27$ m, $\Delta x = -50$ cm)

Remaining rate R for each $(\Delta x, \ell)$

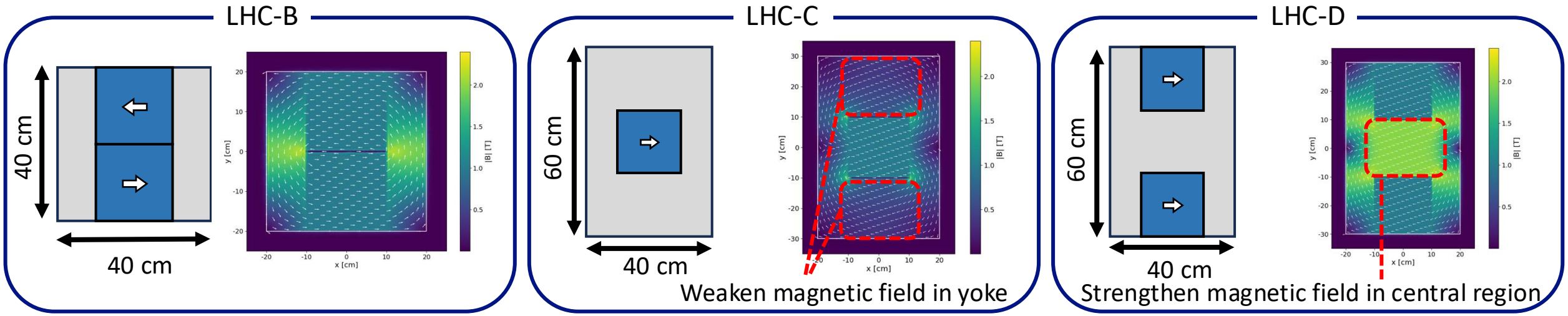


Muon flux under the most effective configuration

Magnet	Δx [cm]	ℓ [m]	Muon flux Φ [10^3/cm^2/fb^{-1}]
No magnet			3.76 ± 0.32
LHC-A	-50	27	$\mathbf{1.91 \pm 0.23}$

Reduced to approximately $\mathbf{2.0 \times 10^3/cm^2/fb^{-1}}$

Suppression Effect for Different Magnet Structures



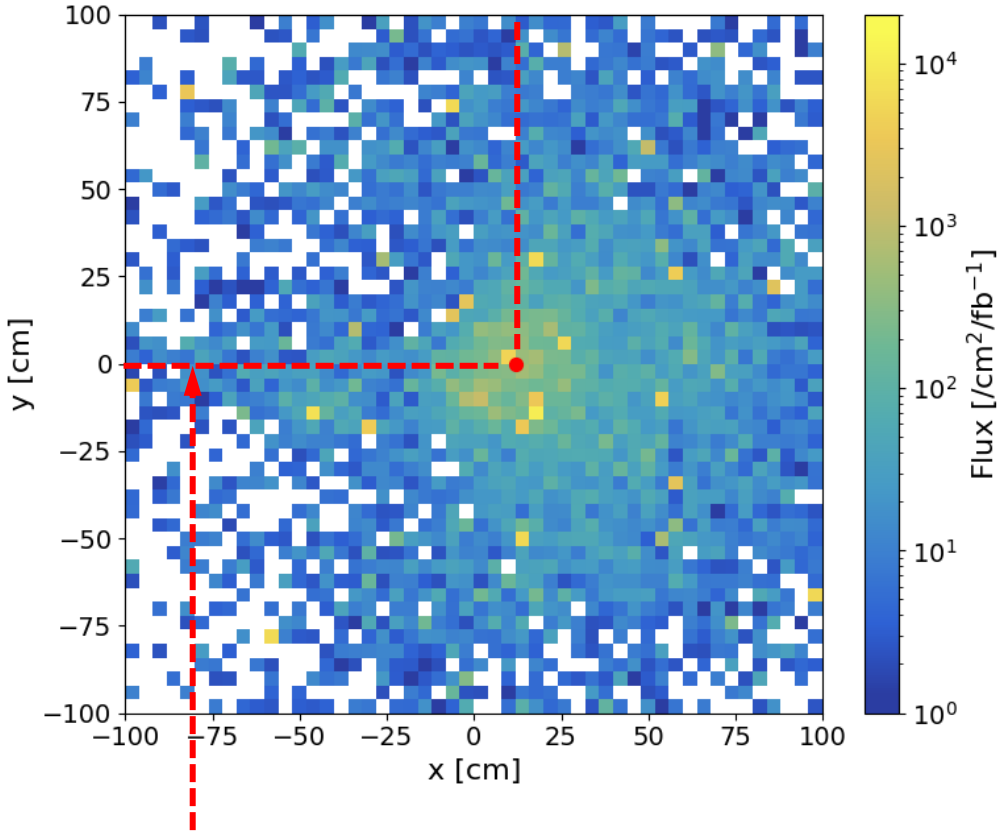
Muon flux under the most effective configuration for each magnet

Magnet	ℓ [m]	Δx [cm]	Muon flux Φ $[10^3/\mathrm{cm}^2/\mathrm{fb}^{-1}]$
No magnet			3.76 ± 0.32
LHC-A	27	-50	1.91 ± 0.23
LHC-B	27	-50	1.89 ± 0.24
LHC-C	36	-50	1.84 ± 0.23
LHC-D	18	-50	1.84 ± 0.23

- All magnets suppress the muon flux to approximately the target flux ($2.0 \times 10^3/\mathrm{cm}^2/\mathrm{fb}^{-1}$)

Evaluation of the suppression by magnet in the TI18

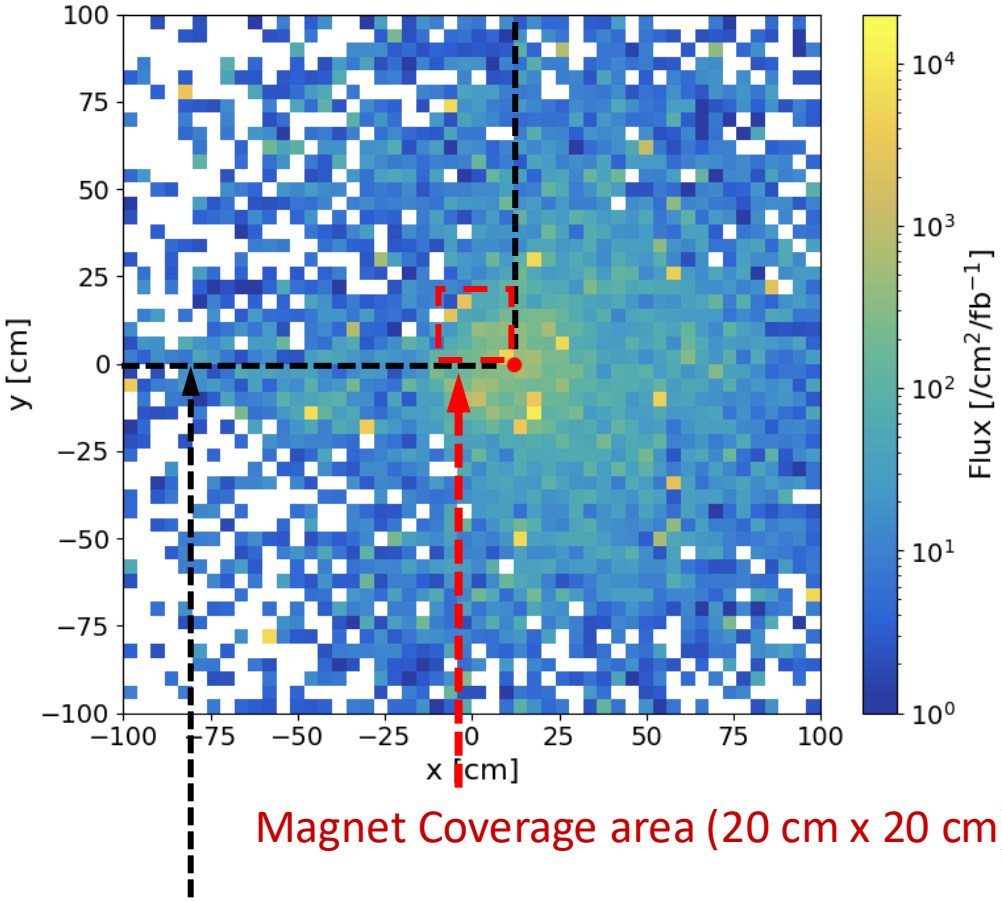
Position distribution of muons reaching the detector at TI18 (480 m from IP1) under LHC-A magnet is placed

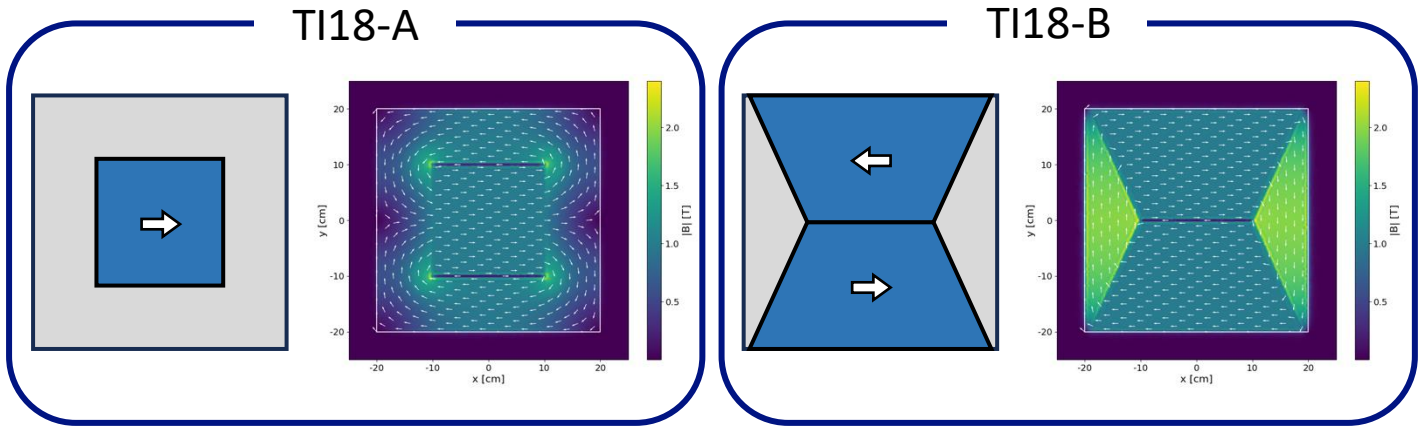


Available area for magnet if SND is installed
(based on the SND@HL-LHC Technical Proposal)

Evaluation of the suppression by magnet in the TI18

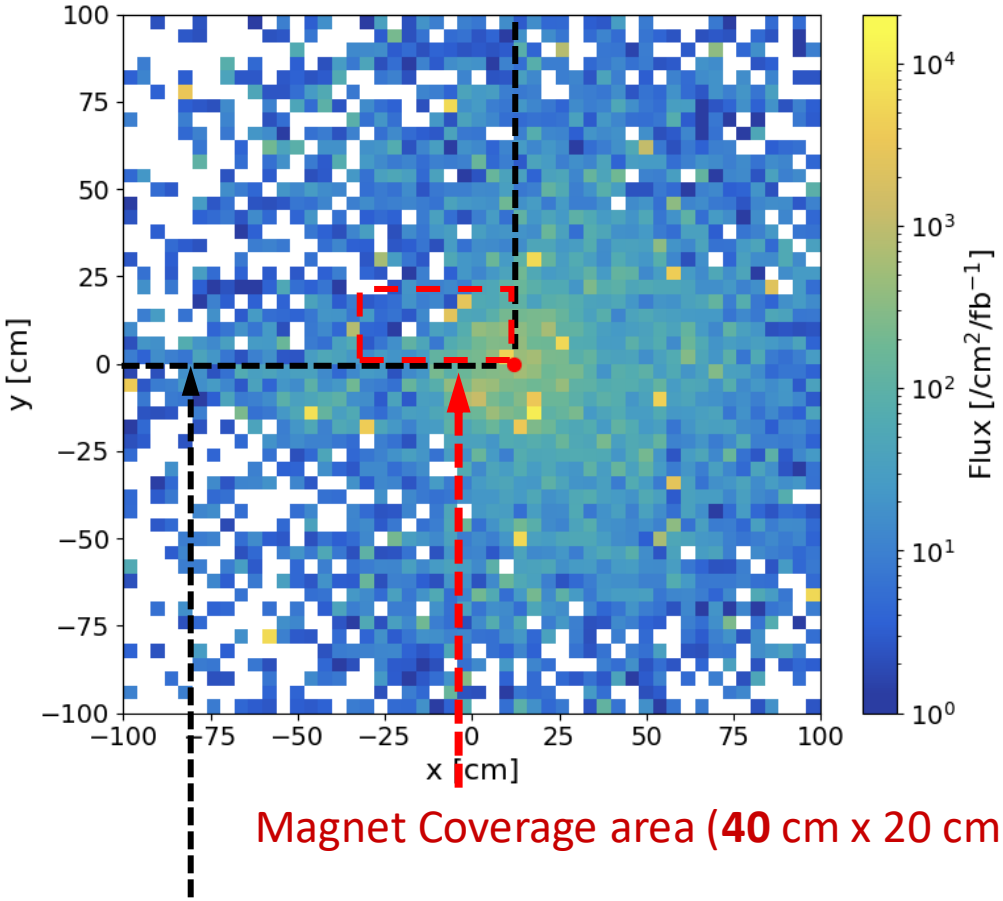
Position distribution of muons reaching the detector at TI18 (480 m from IP1) under LHC-A magnet is placed





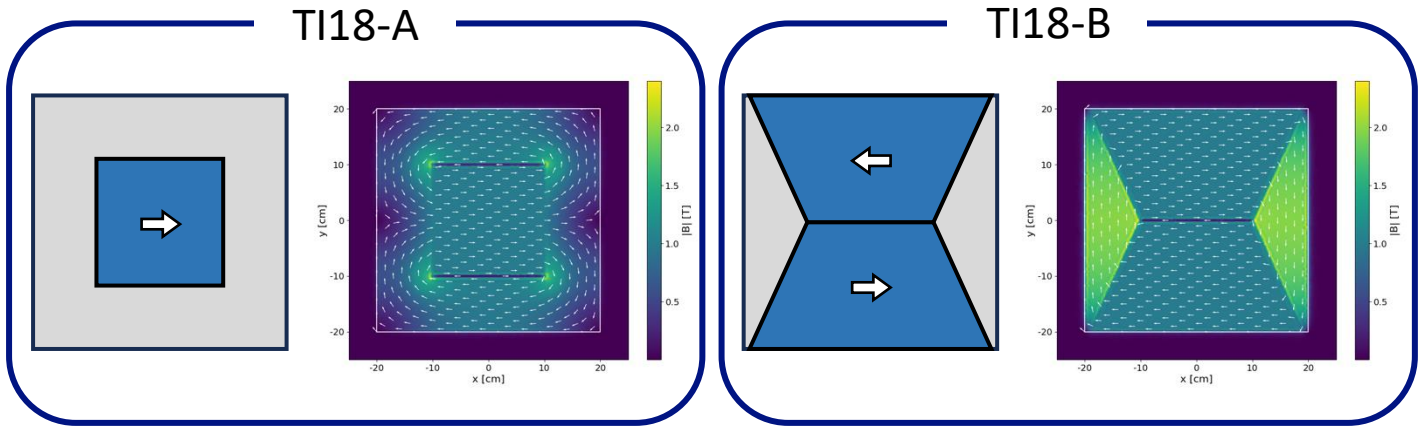
Evaluation of the suppression by magnet in the TI18

Position distribution of muons reaching the detector at TI18 (480 m from IP1) under LHC-A magnet is placed



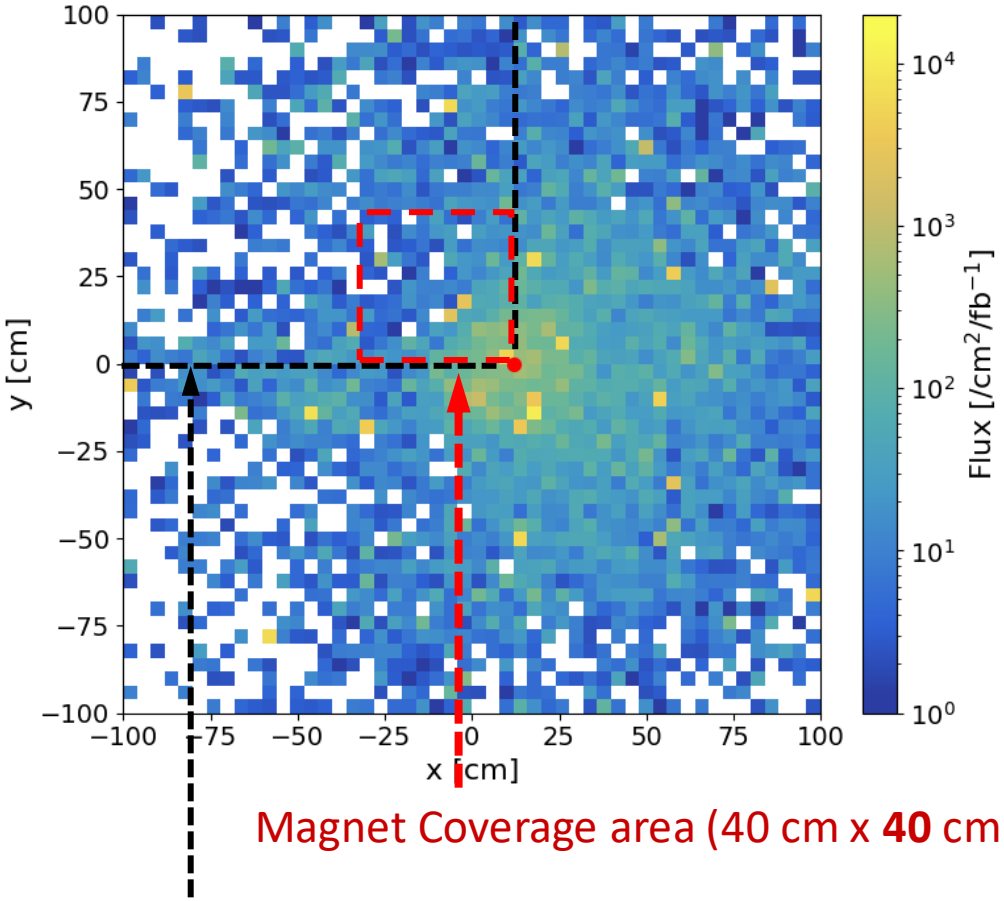
Magnet Coverage area (**40** cm x 20 cm)

Available area for magnet if SND is installed

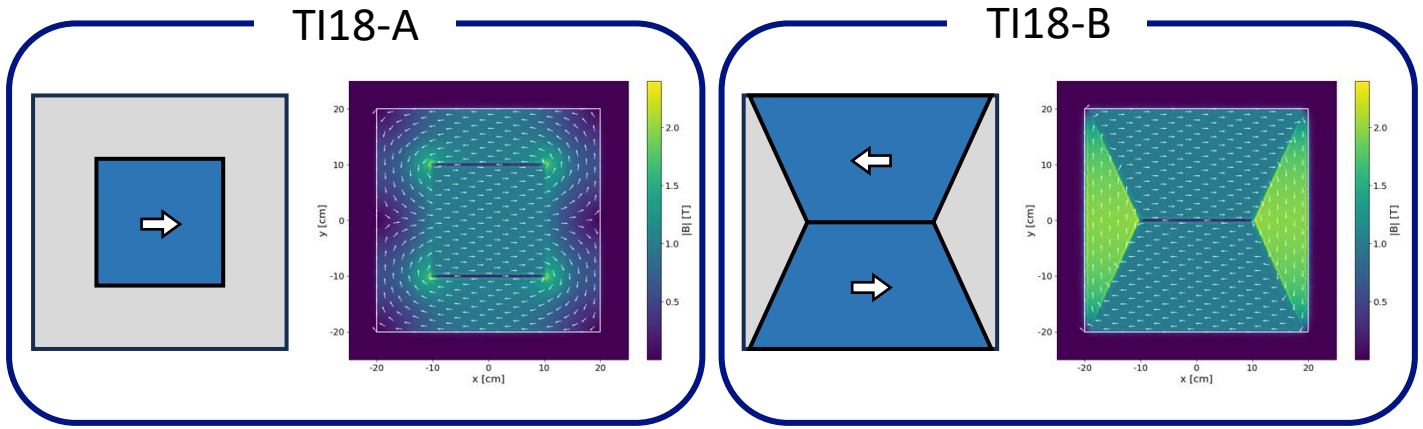


Evaluation of the suppression by magnet in the TI18

Position distribution of muons reaching the detector at TI18 (480 m from IP1) under LHC-A magnet is placed

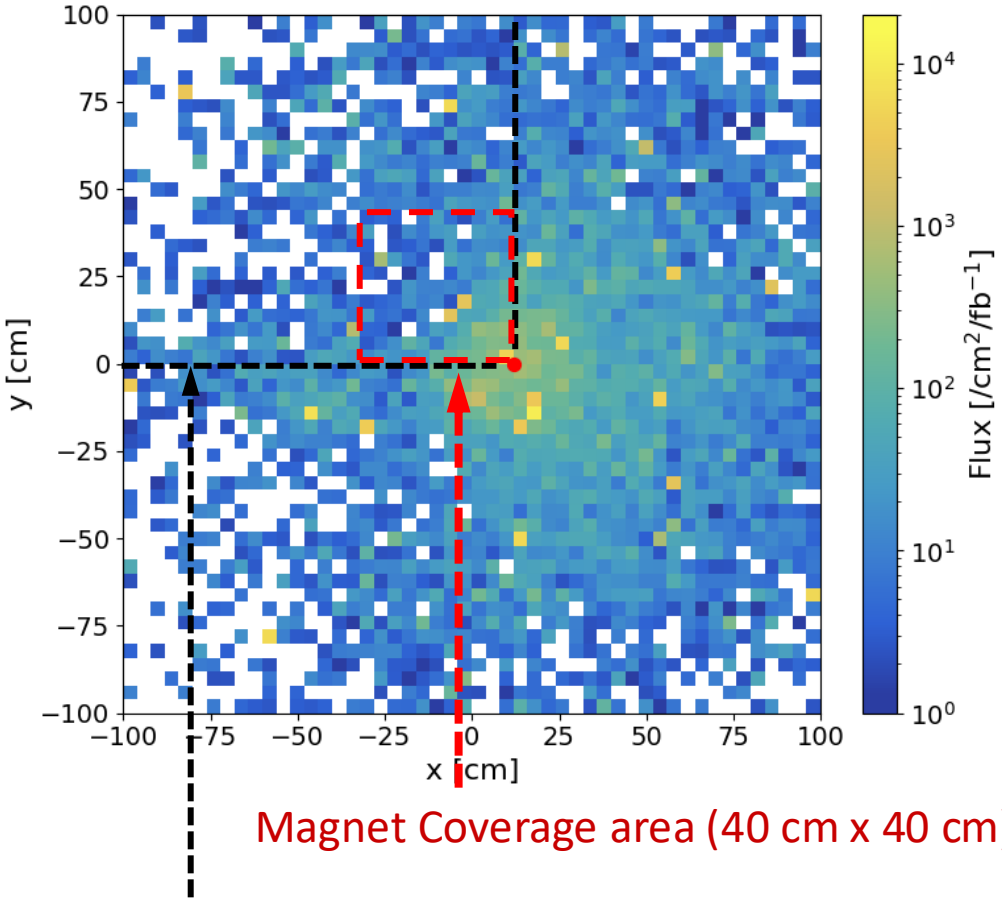


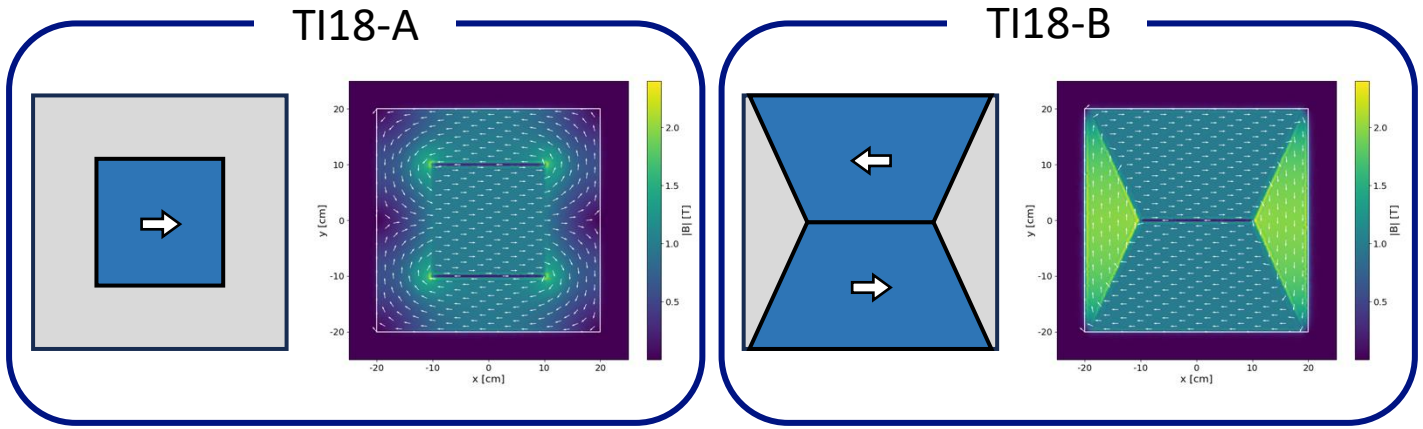
Available area for magnet if SND is installed



Evaluation of the suppression by magnet in the TI18

Position distribution of muons reaching the detector at TI18 (480 m from IP1) under LHC-A magnet is placed





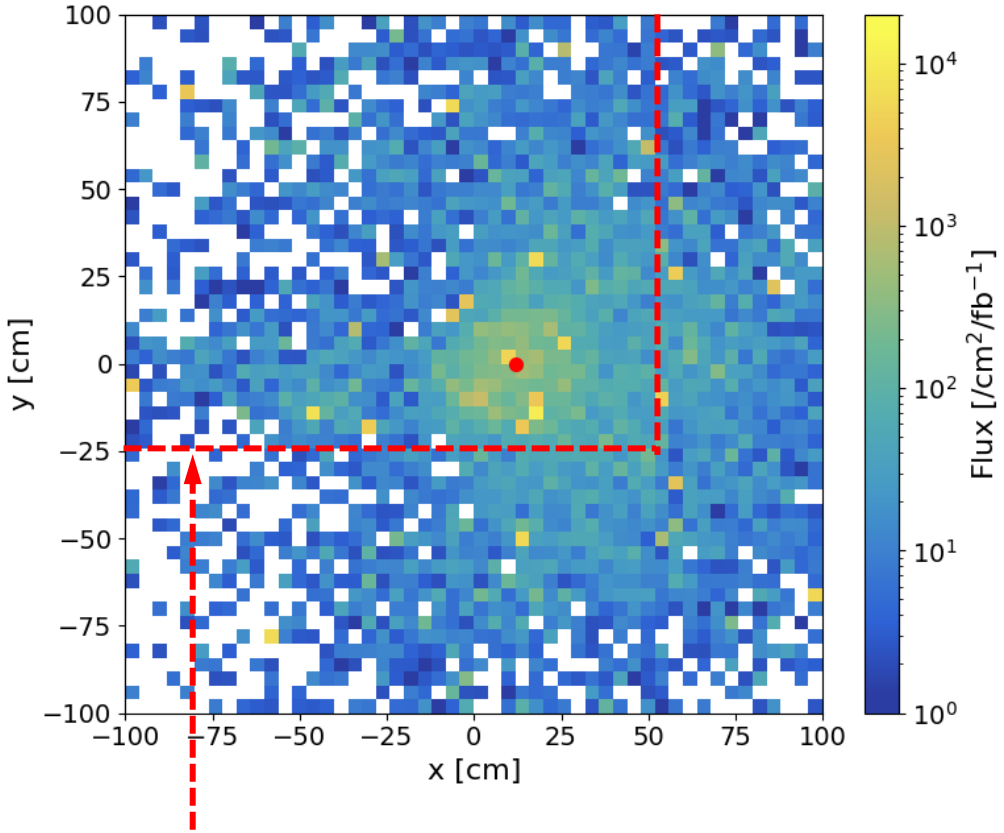
Muon flux under the most effective configuration for each magnet

Magnet	Muon flux Φ $[10^3/\mathrm{cm}^2/\mathrm{fb}^{-1}]$	Remaining rate [%]	Relative rate
LHC-A	1.91 ± 0.23	50.8 ± 7.5	
LHC-A + TI18-A	1.82 ± 0.22	48.5 ± 7.2	0.95 ± 0.16
LHC-A + TI18-B	1.93 ± 0.23	51.3 ± 7.5	1.01 ± 0.17

Placing a magnet in this area is not effective

Evaluation of Magnet Placed on the LoS in TI18

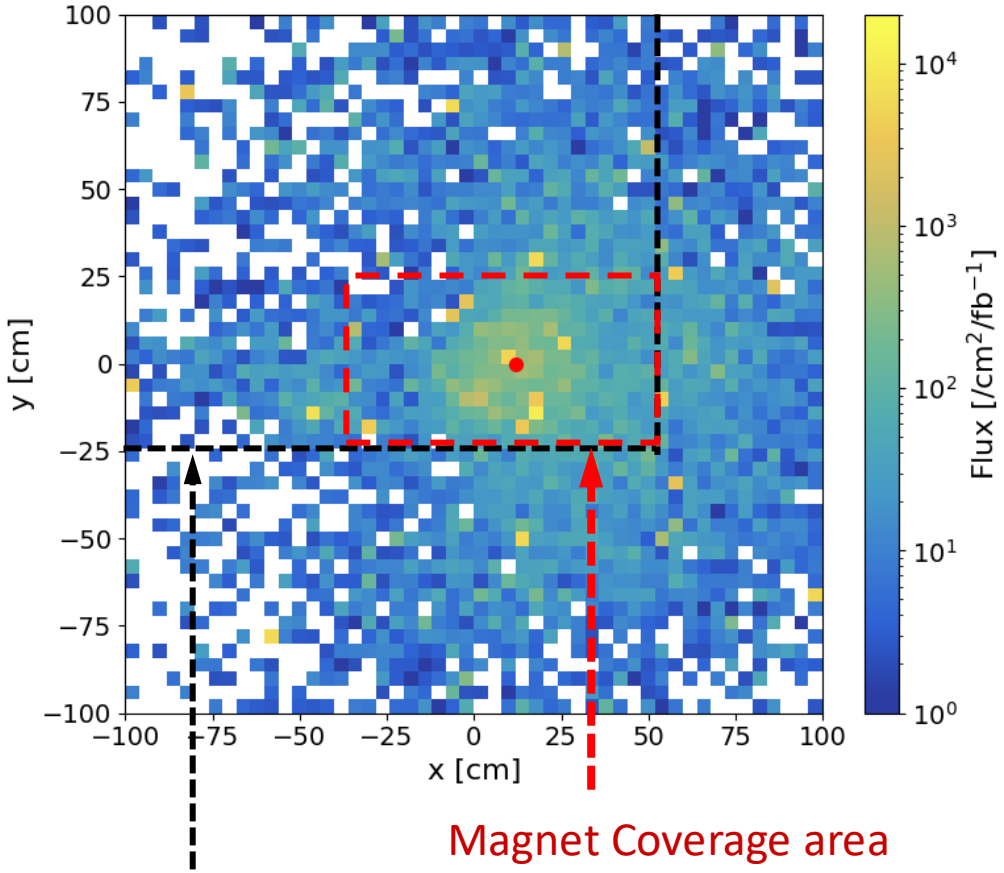
Position distribution of muons reaching the detector at TI18 (480 m from IP1) under LHC-A magnet is placed

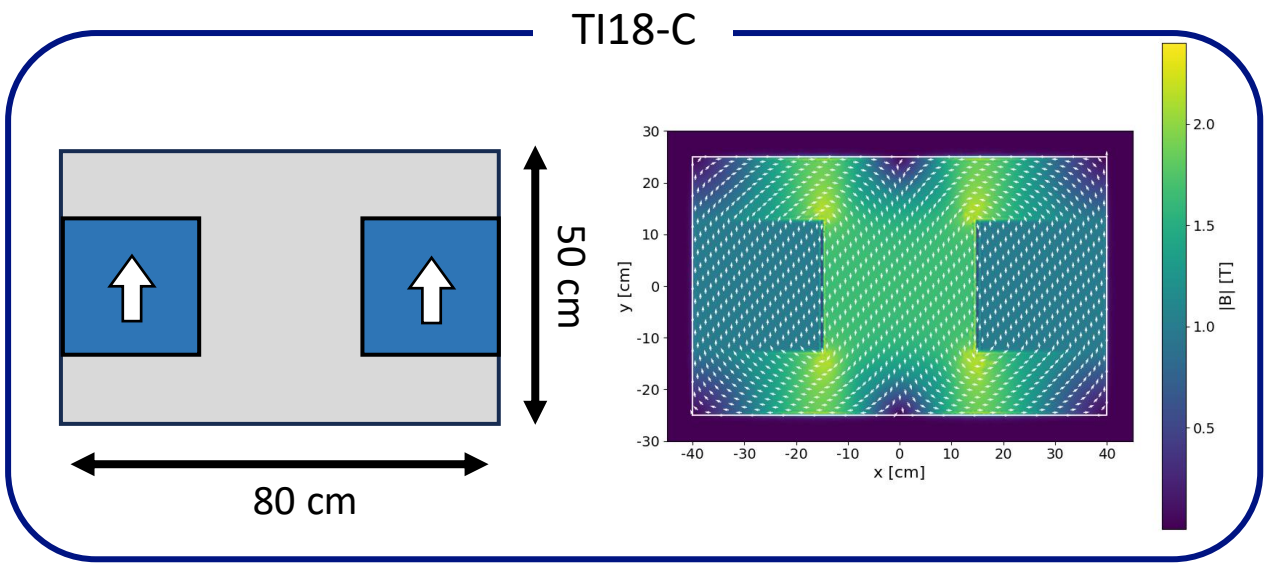


Available area for magnet if SND is NOT installed and tunnel floor is dig out

Evaluation of Magnet Placed on the LoS in TI18

Position distribution of muons reaching the detector at TI18 (480 m from IP1) under LHC-A magnet is placed





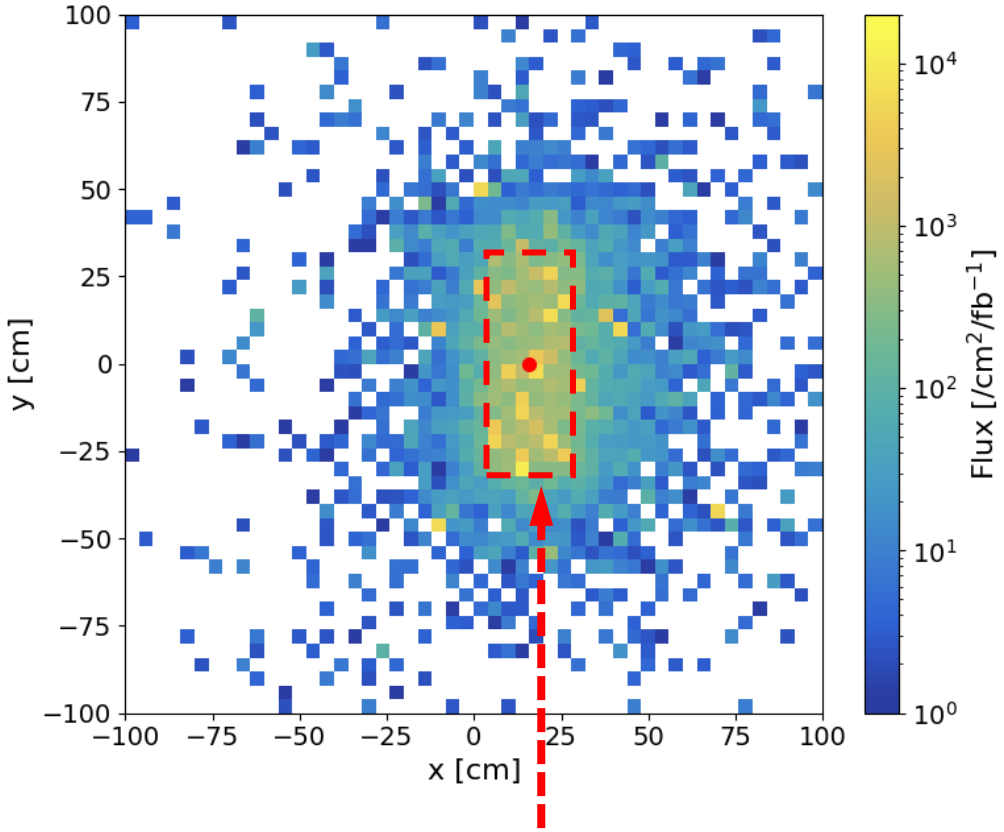
Muon flux and remaining rate

Magnet	Muon flux $\Phi\ [10^3/\mathrm{cm}^2/\mathrm{fb}^{-1}]$	Remaining rate [%]	Relative rate
LHC-A	1.91 ± 0.23	50.8 ± 7.5	
LHC-A + TI18-C	$\mathbf{1.63 \pm 0.20}$	43.2 ± 6.5	0.85 ± 0.15

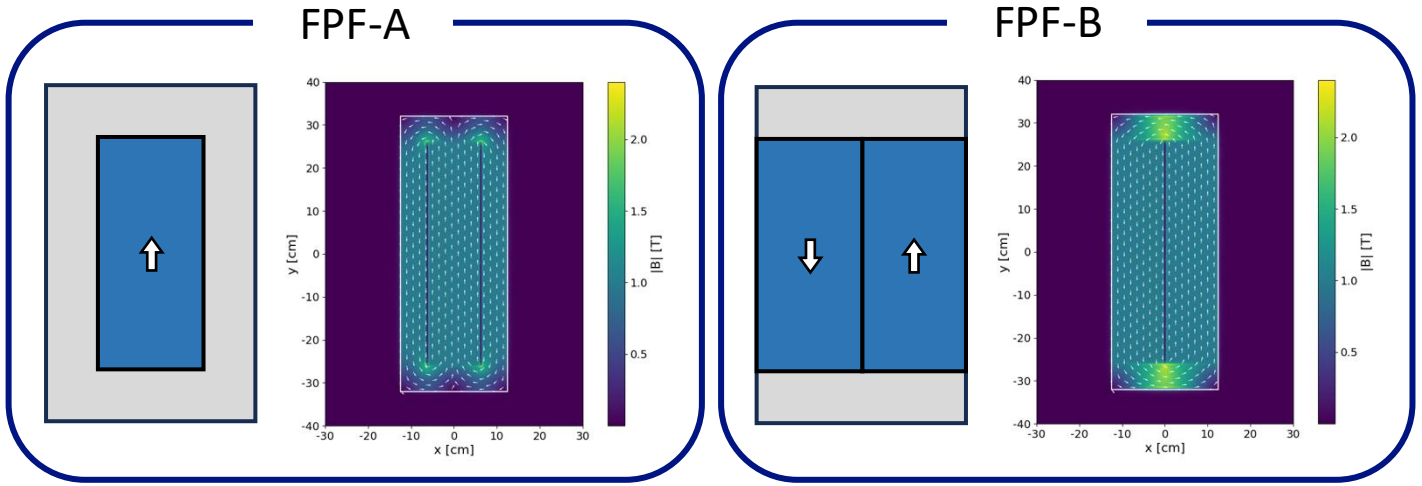
Reduced below the target value ($\mathbf{2.0 \times 10^3/\mathrm{cm}^2/\mathrm{fb}^{-1}}$)

Evaluation of the suppression by magnet in the FPF

Position distribution of muons reaching the detector at FPF entrance (627 m from IP1) under LHC-A magnet is placed

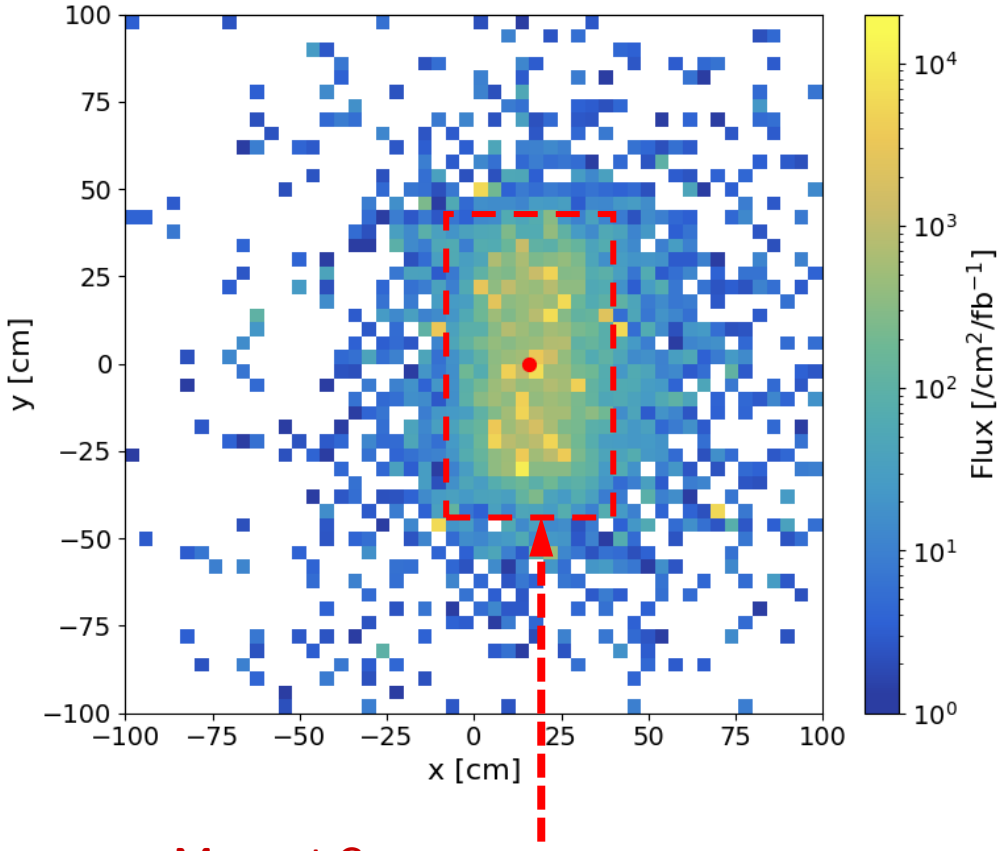


Magnet Coverage area
25 cm x 64 cm (same as detector)

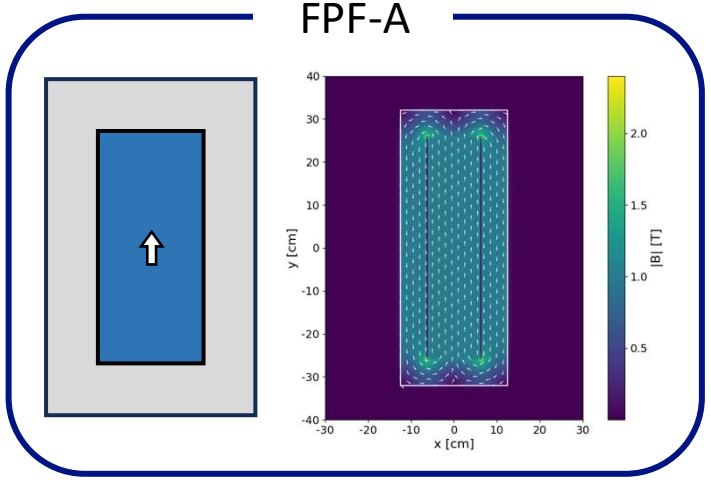


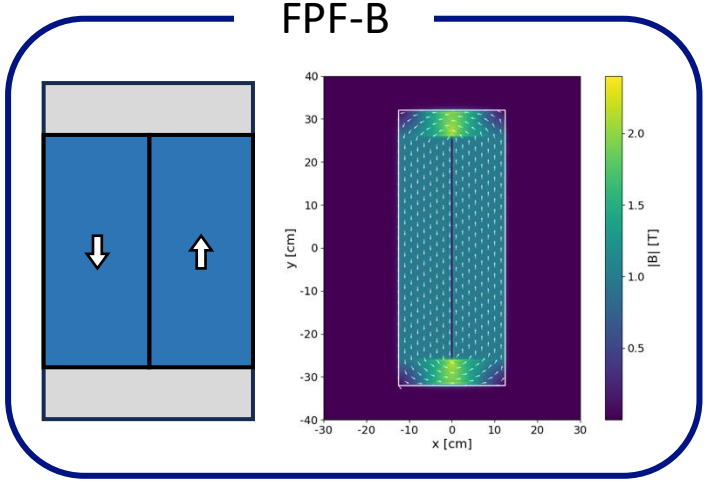
Evaluation of the suppression by magnet in the FPF

Position distribution of muons reaching the detector at FPF entrance (627 m from IP1) under LHC-A magnet is placed



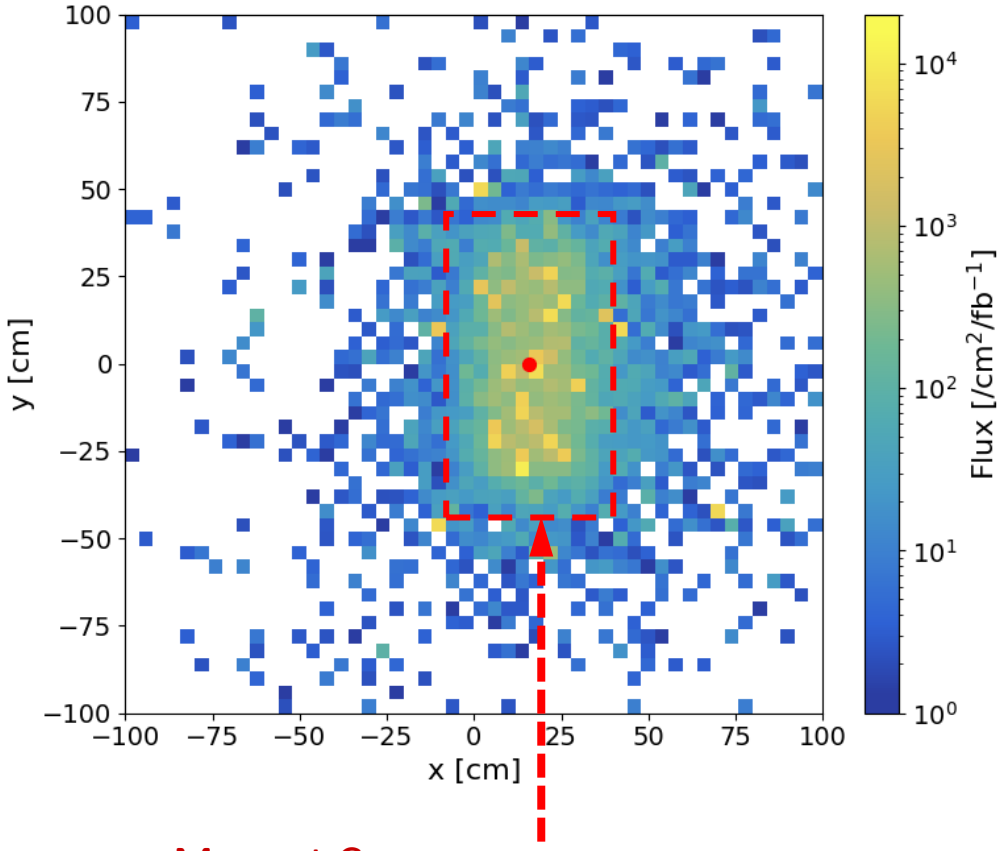
Magnet Coverage area
50 cm x (64+25) cm
(Magnet core height matches the detector height)



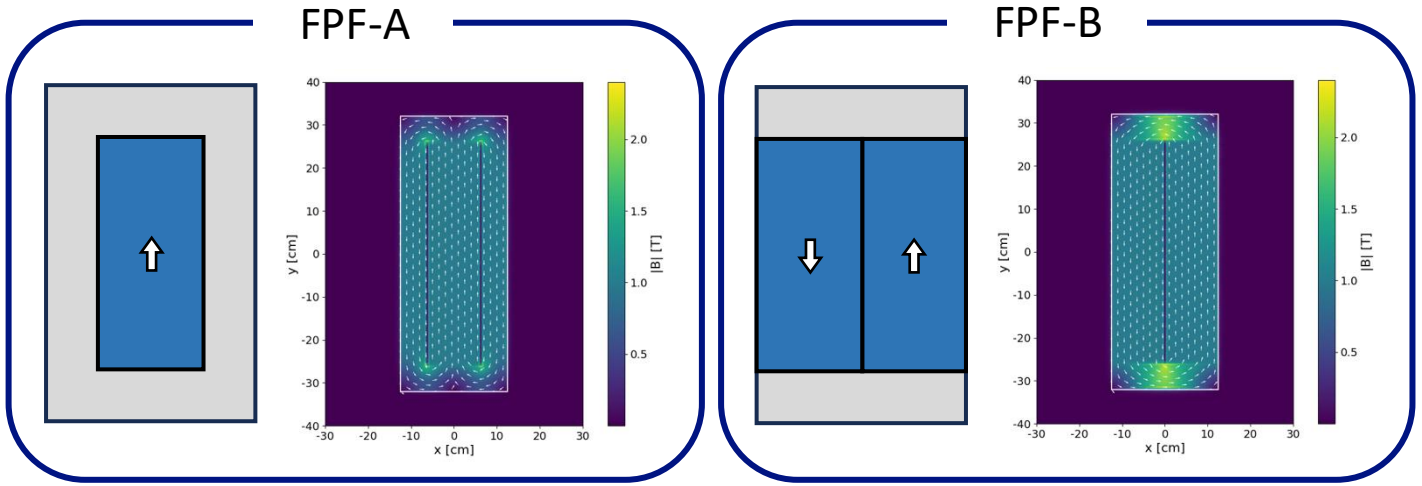


Evaluation of the suppression by magnet in the FPF

Position distribution of muons reaching the detector at FPF entrance (627 m from IP1) under LHC-A magnet is placed



Magnet Coverage area
50 cm x (64+25) cm
(Magnet core height matches the detector height)

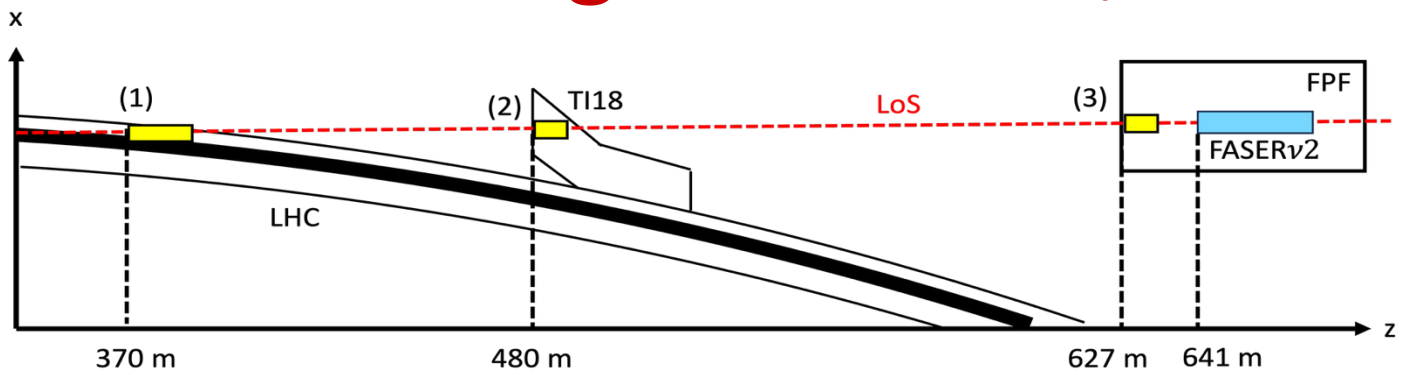


Muon flux under the most effective configuration for each magnet

Magnet	Muon flux Φ $[10^3/\mathrm{cm}^2/\mathrm{fb}^{-1}]$	Remaining rate [%]	Relative rate
LHC-A	1.91 ± 0.23	50.8 ± 7.5	
LHC-A + FPF-A	1.69 ± 0.22	45.1 ± 6.9	0.89 ± 0.16
LHC-A + FPF-B	1.82 ± 0.23	48.4 ± 7.3	0.95 ± 0.17

Magnet at FPF could provide additional suppression

Summary of Additional Magnets in TI18/FPF



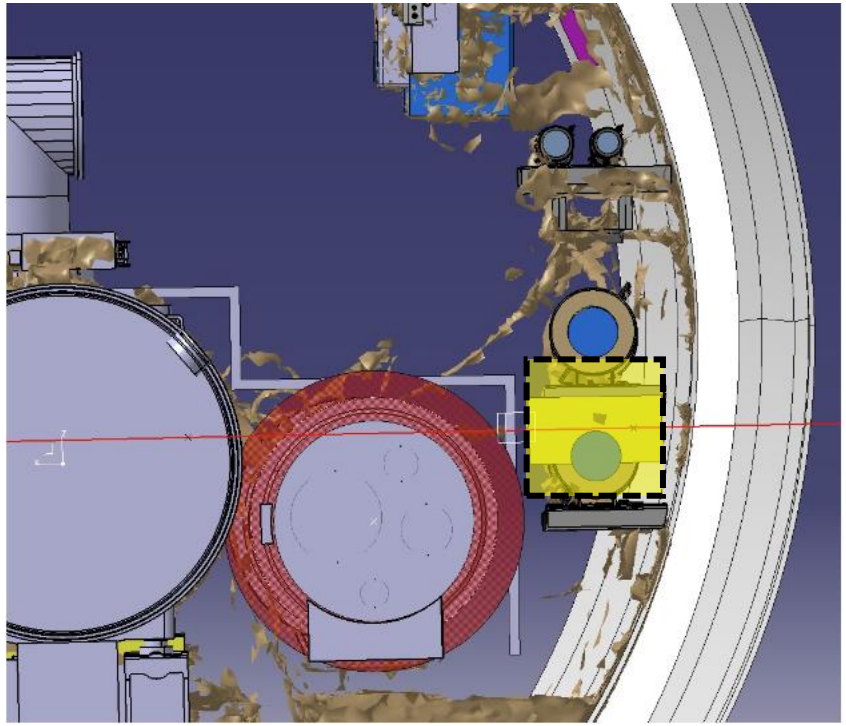
Muon flux and remaining rate for the most effective configuration at each location when magnets were installed at multiple sites

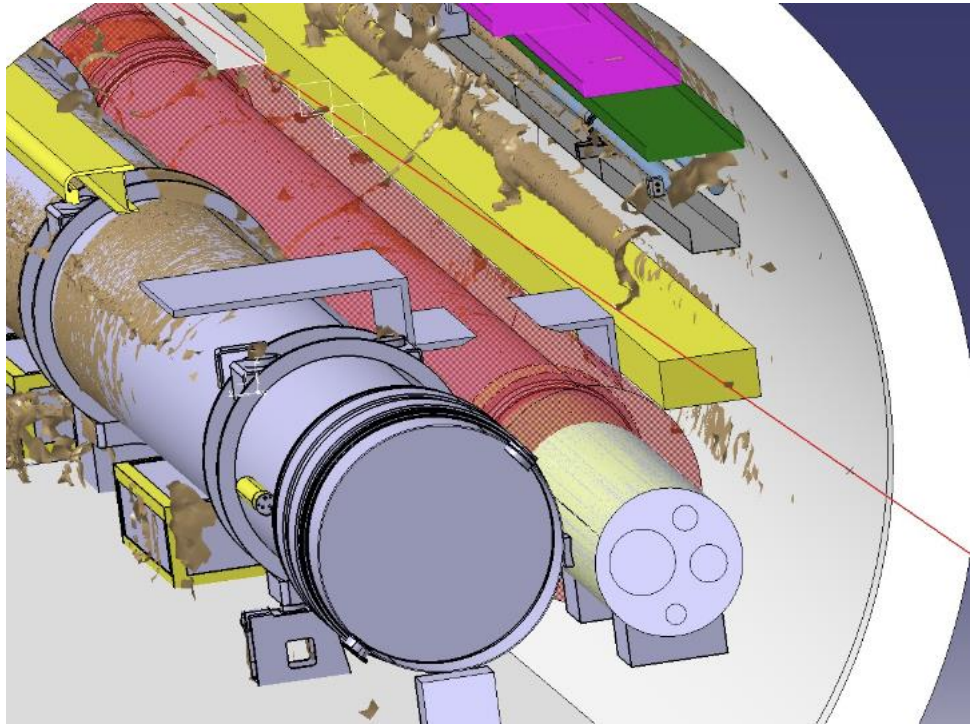
Magnet	Muon flux $\Phi\ [10^3/\mathrm{cm}^2/\mathrm{fb}^{-1}]$	Remaining rate $R\ [\%]$	Relative rate R_{rel} (LHC-A only as baseline)
No magnet	3.76 ± 0.32	100	-
(1) LHC-A	1.91 ± 0.23	50.8 ± 7.5	1
(1) LHC-A + (2) on LoS	$\mathbf{1.63 \pm 0.20}$	43.2 ± 6.5	$\mathbf{0.85 \pm 0.15}$
(1) LHC-A + (3)	$\mathbf{1.69 \pm 0.22}$	45.1 ± 6.9	$\mathbf{0.89 \pm 0.16}$
(1) LHC-A + (2) on LoS + (3)	$\mathbf{1.54 \pm 0.20}$	41.0 ± 6.2	$\mathbf{0.81 \pm 0.14}$

- Additional magnets can improve the suppression effect, and all cases fall below the target flux $(2.0 \times 10^3/\mathrm{cm}^2/\mathrm{fb}^{-1})$

Information from integration team

- 40 cm wide magnet (yellow) placed at the LoS height





- What are blue pipes, can they be moved for ~40 m length?
- How to install and support magnet?
- Are there any radiation and activation issues for permanent magnets?

Summary

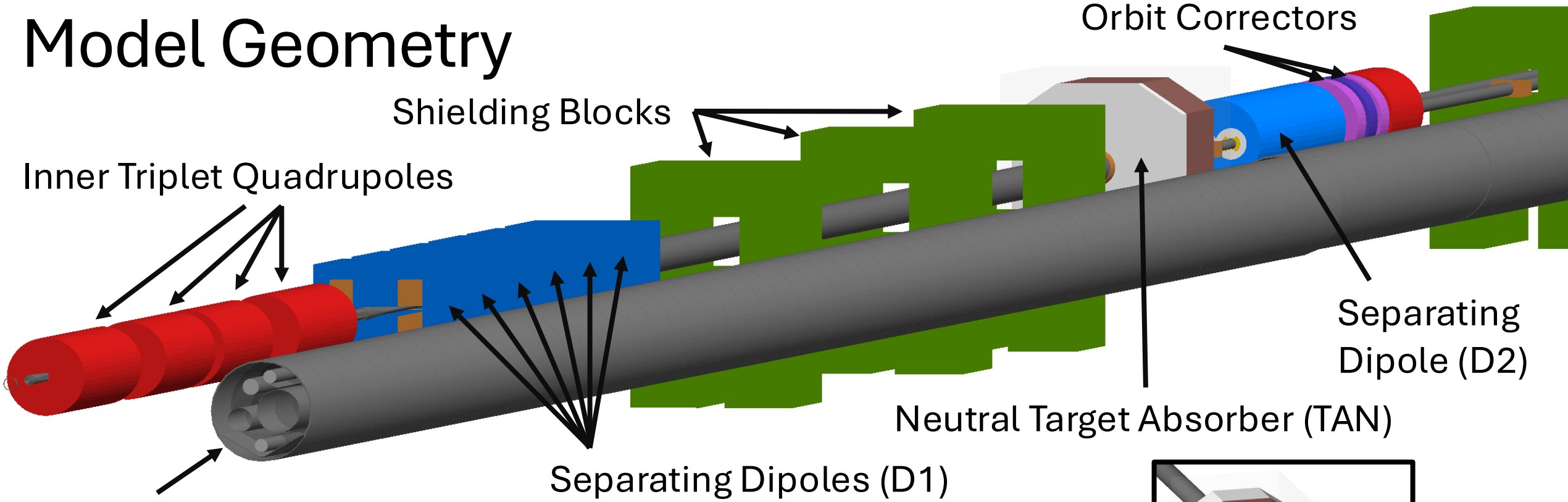
- To enable annual detector replacement in FASERν2, the introduction of a Sweeper Magnet is investigated
  - Target flux: $\mathbf{2.0 \times 10^3/cm^2/fb^{-1}}$
- Candidate locations (LHC tunnel, TI18 tunnel, and FPF entrance) are evaluated using Geant4 simulation
- Installing a tunnel-parallel magnet in the LHC tunnel achieves $\mathbf{(1.84 \pm 0.23) \times 10^3/cm^2/fb^{-1}}$, which is comparable to the target flux
  - With an additional magnet in TI18 (on the LoS): $\mathbf{(1.63 \pm 0.20) \times 10^3/cm^2/fb^{-1}}$
  - With an additional magnet at the FPF entrance: $\mathbf{(1.69 \pm 0.22) \times 10^3/cm^2/fb^{-1}}$
  - With additional magnets in both TI18 and FPF : $\mathbf{(1.54 \pm 0.20) \times 10^3/cm^2/fb^{-1}}$
- Background muon suppression using Sweeper Magnet can enable FASERν2 with 1 detector per year

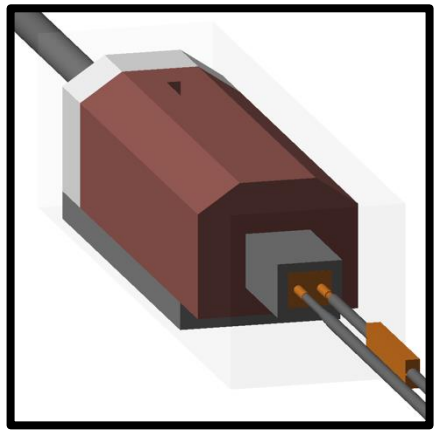
Next step

- Increase statistics and evaluate with more realistic simulations
- Evaluate cost and feasibility of the Sweeper Magnet system
- Study radiation effects and integration feasibility in collaboration with CERN teams

BACKUP

Model Geometry





- Standard + custom magnet geometry and cryogenics pipe.
- Custom tunnel geometry by the CERN STI group.
- Tunnel surrounded by 30 m of soil.

➢ Model created and tested by A. Keyken, H. Lefebvre, L. Nevay and S. Walker in collaboration with the BDSIM Backgrounds Group at RHUL.

ROYAL HOLLOWAY UNIVERSITY OF LONDON

John Adams Institute for Accelerator Science

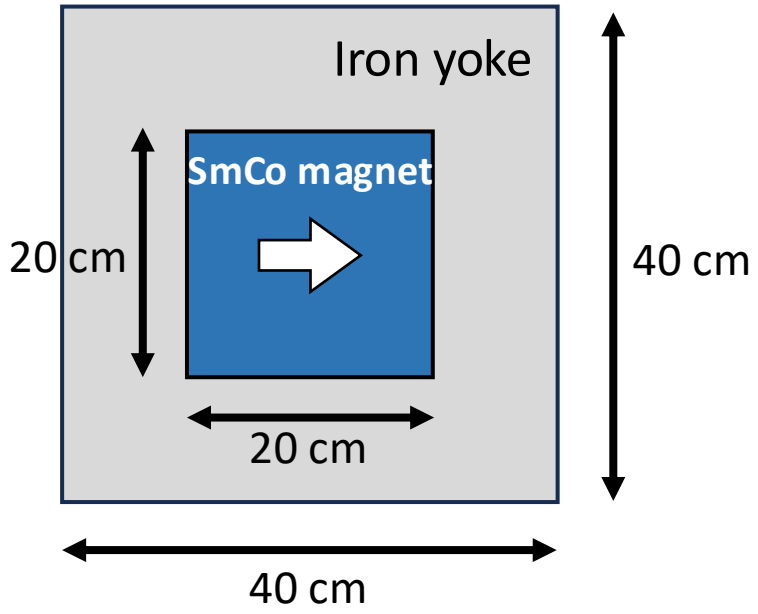
Muon Sample Production

- Used CRMC with SIBYLL 2.3d hadronic generator model to simulate 13.6 TeV pp-collisions. Filtered collision products conservatively for particles with $p_z/p_T > 0.9$ and $E > 10$ GeV.
- Imported LHC magnet settings for 250 μrad horizontal crossing at IP1. TCL4,5 and 6 half-gaps set to 9 mm, 3.1 mm and 1.2 mm, respectively.
- Particles are propagated through the BDSIM model using Geant4 v10.7 with custom physics list: FTFP_BERT (hadronic + scattering), GammaToMuons, PositronToMuons, PositronToHadrons, NeutrinoActivation, MuonNuclear and GammaNuclear included.
- To reduce CPU time, particles under 10 GeV are not created.
- Muon position, momenta and history information are recorded for particles crossing a 1m x 1m sampler cantered on the geometric line-of-sight, 475 m from IP1.

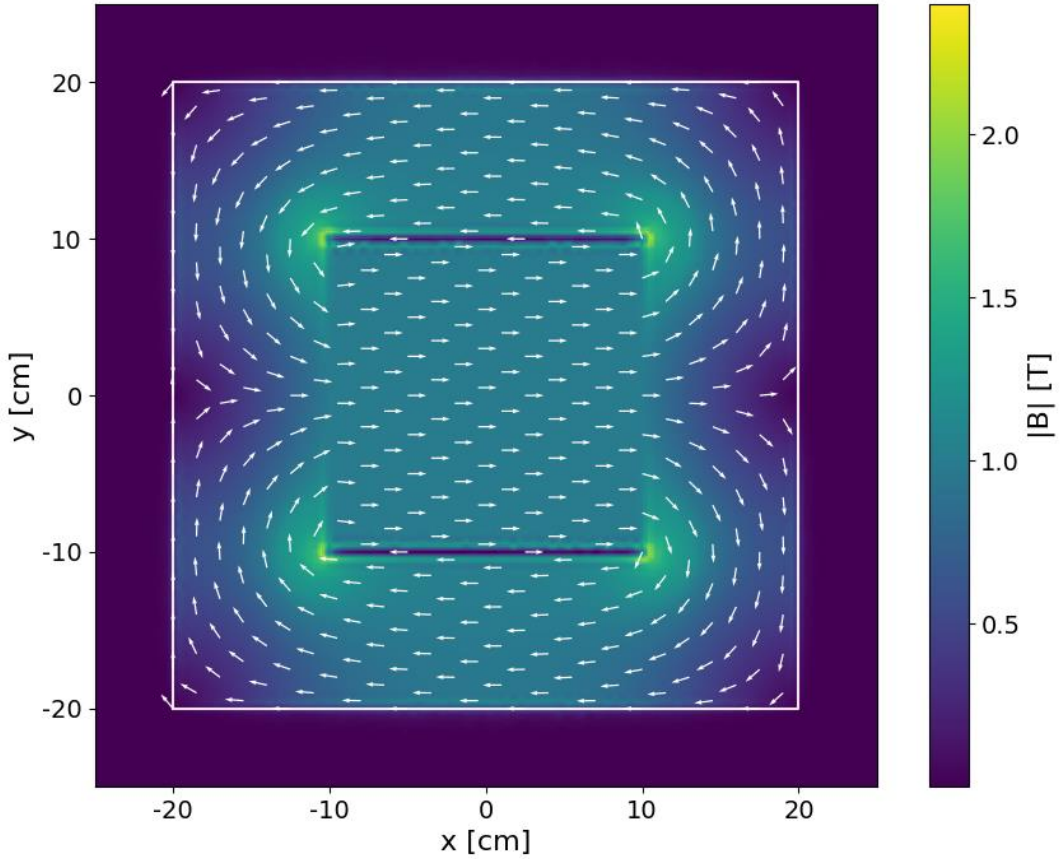
Magntic field simulation

- 2D calculation using Elmer for the magnet cross-section

One of the structures considered for use as magnet within the LHC tunnel

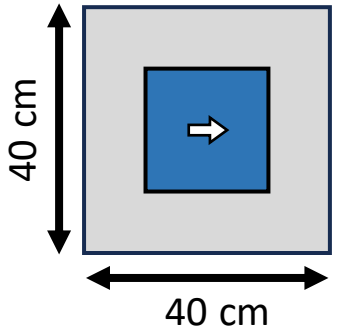


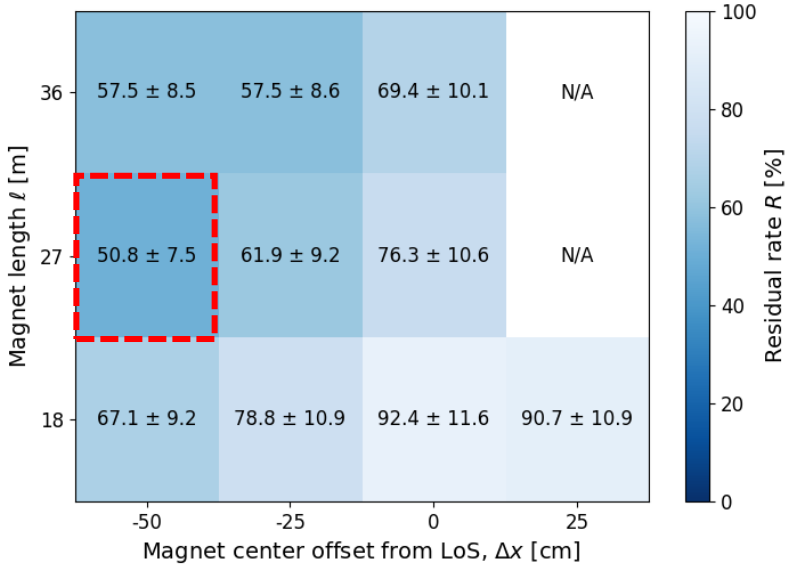
Magnetic field distribution calculated by Elmer



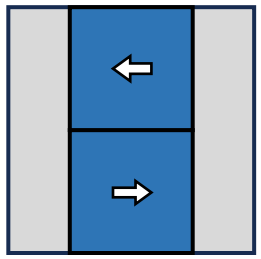
Evaluation of the suppression by magnet in the LHC tunnel

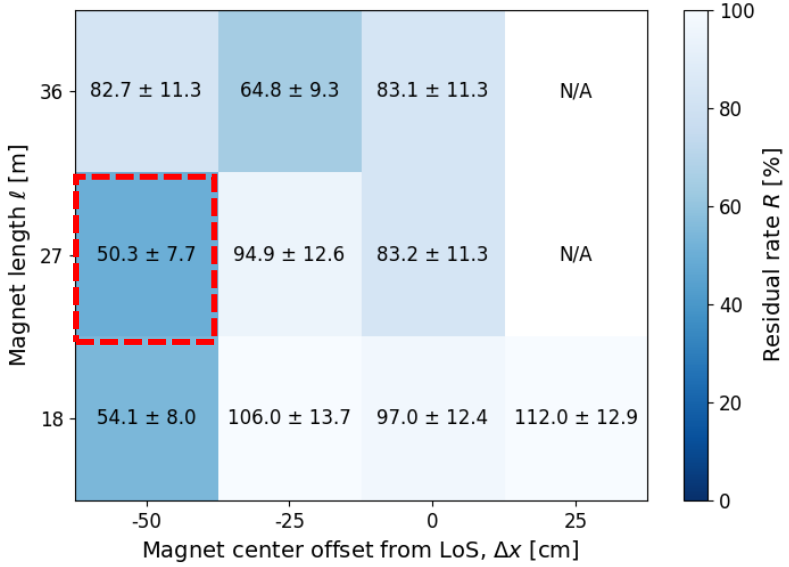
LHC-A



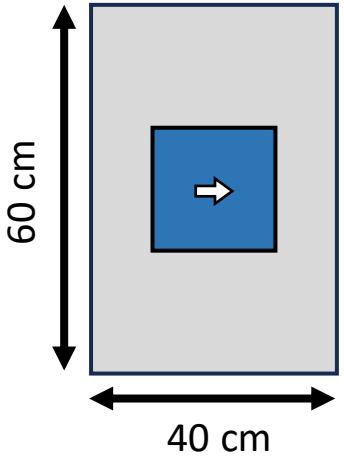


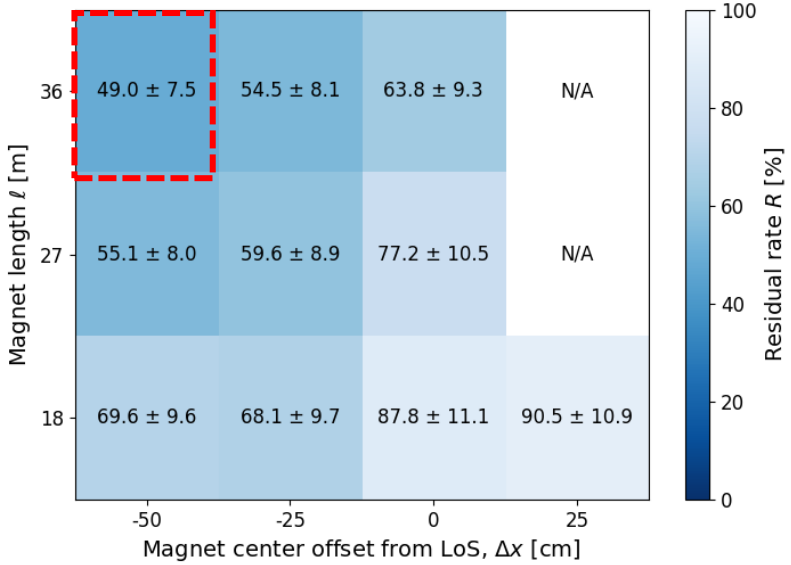
LHC-B



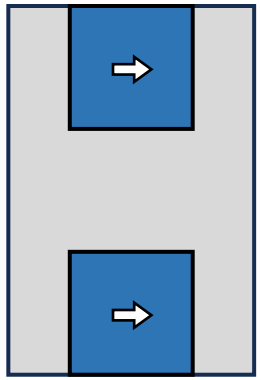


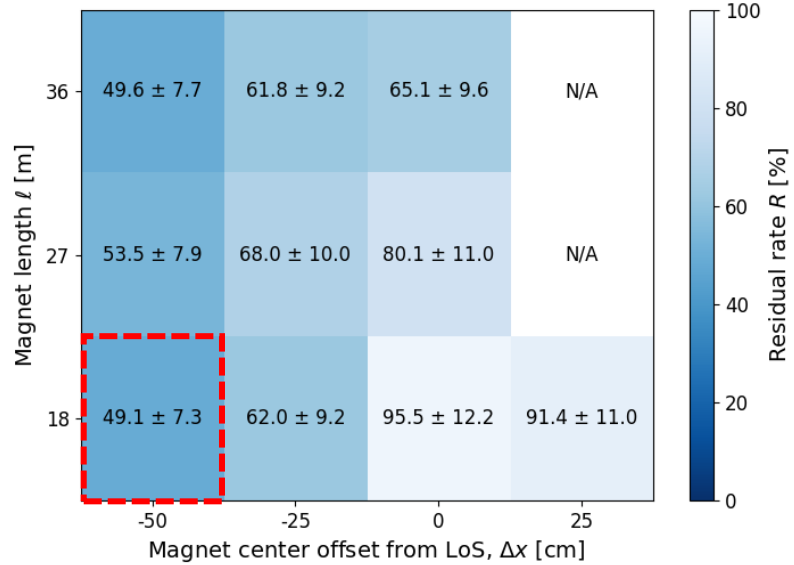
LHC-C





LHC-D

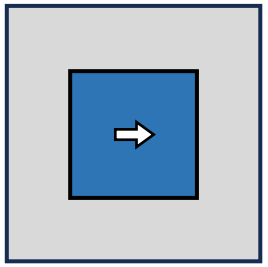




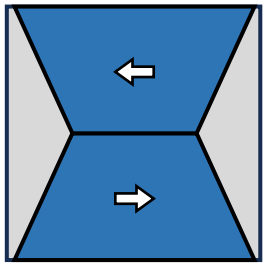
Evaluation of the suppression by magnet in the TI18

- 磁石LHC-Aを設置した条件でTI18トンネル内に追加で磁石を置いた場合

Ti18-A

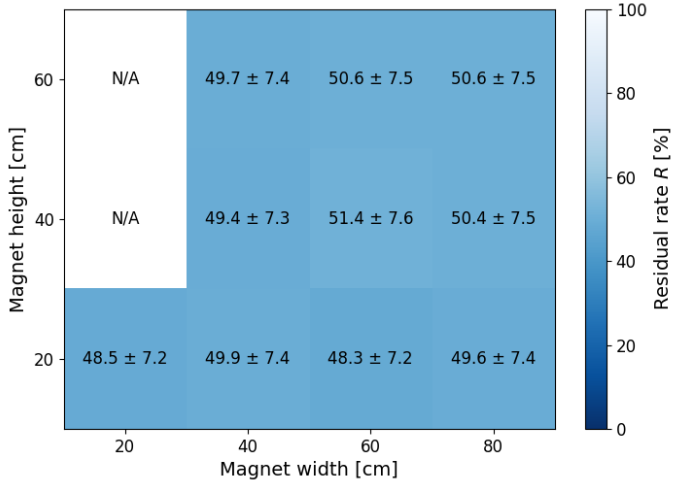


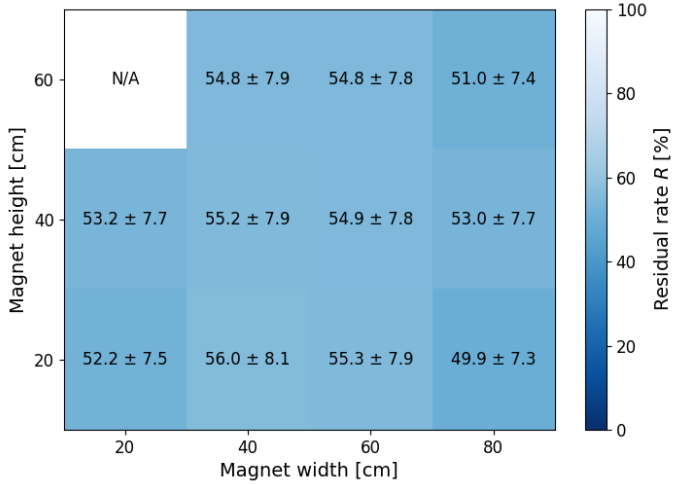
TI18-B



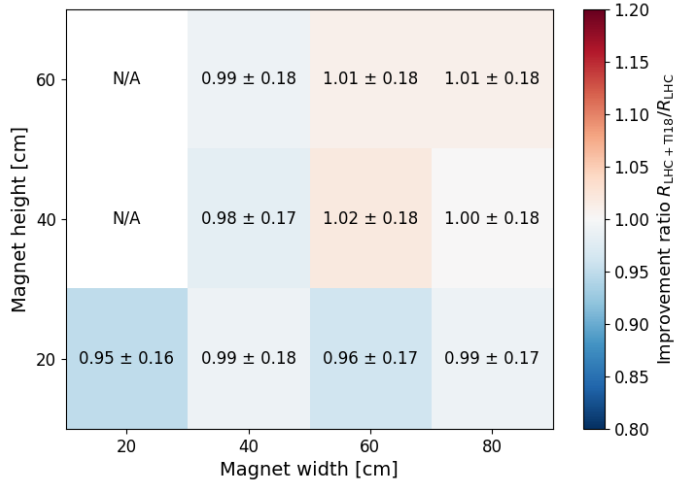
幅・高さを変えて評価

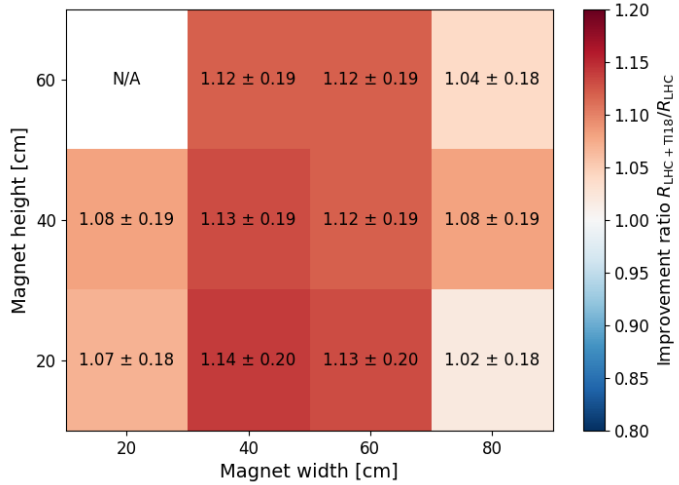
残存率





LHC-Aのみの場合に対する相対残存率



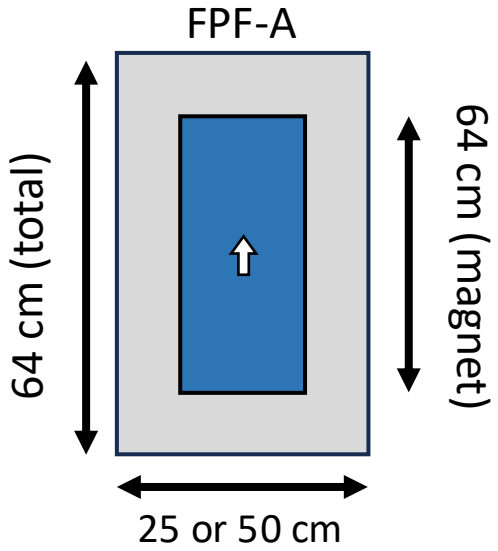


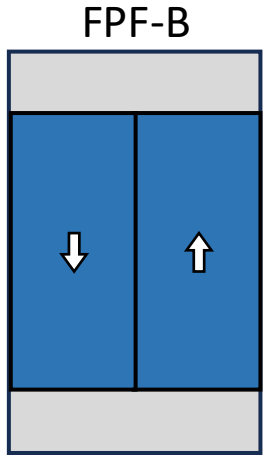
増加傾向

TI18トンネルに追加で設置する磁石の抑制効果は限定的

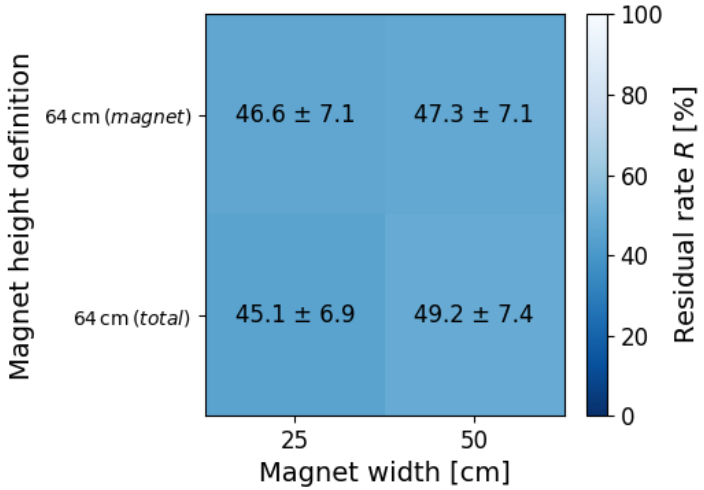
Evaluation of the suppression by magnet in the FPF

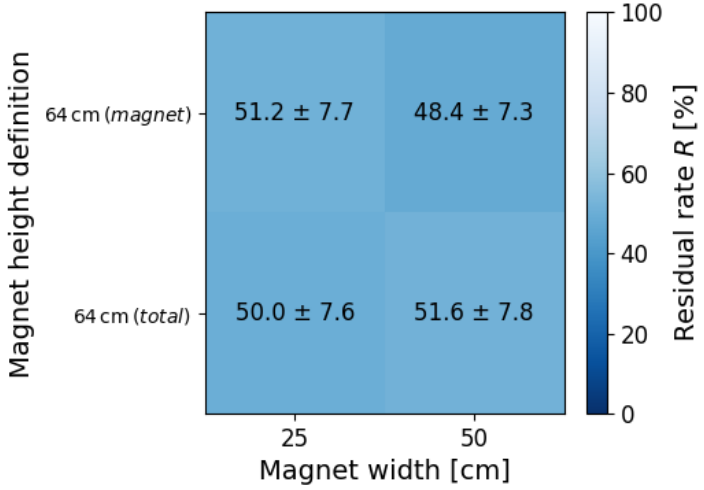
- 磁石LHC-Aを設置した条件でFPF先頭に追加で磁石を置いた場合



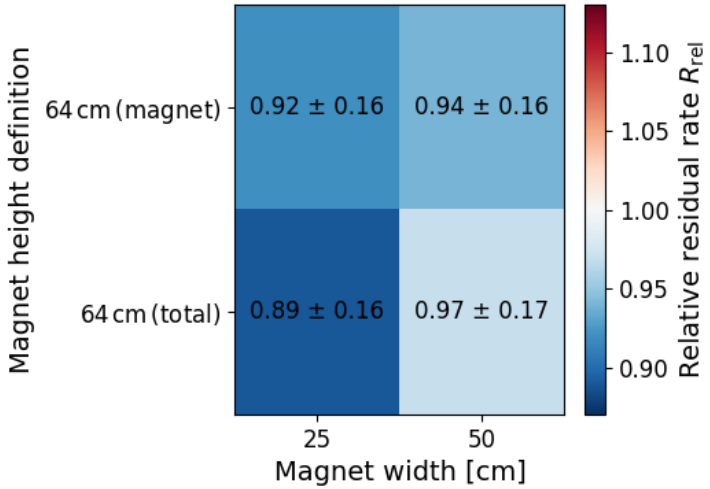


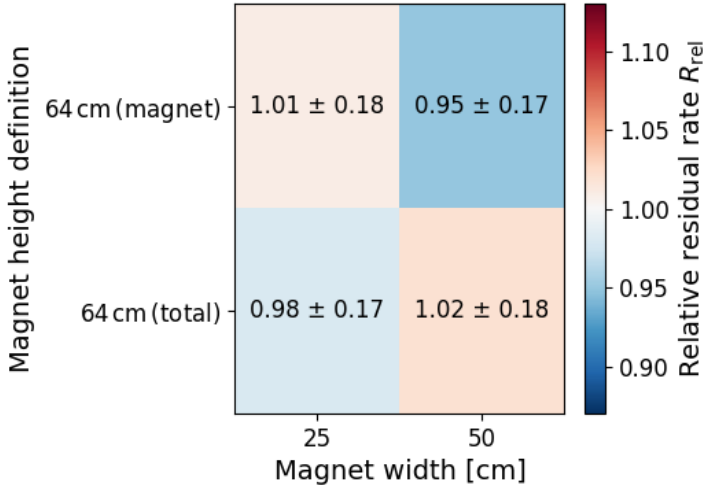
残存率





LHC-Aのみの場合に対する相対残存率





Effect of SND@HL-LHC

- Reproduced SND HCAL magnetic field based on the Technical Proposal

Magnet	Muon fluxΦ $[10^3/\mathrm{cm}^2/\mathrm{fb}^{-1}]$	Remaining rate [%]	Relative rate
LHC-A only	1.91 ± 0.23	50.8 ± 7.5	
LHC-A + SND	1.97 ± 0.24	52.6 ± 7.6	1.03 ± 0.18
LHC-B + SND	2.05 ± 0.26	54.6 ± 8.1	1.07 ± 0.19
LHC-C + SND	1.89 ± 0.24	50.4 ± 7.5	0.99 ± 0.17
LHC-D + SND	2.08 ± 0.26	55.4 ± 8.3	1.09 ± 0.19