Current Status of the PBC-SBN Beamline

PBC Annual Workshop

by **Marc Andre Jebramcik (BE-EA-LE)**

and N. Charitonidis, M. Perrin-Terrin, F. Terranova

26.03.2024

NuTag Studies @ PBC

- A first study of a **long-baseline experiment** was previously supported by PBC. The study was fully site independent.
- The study has concluded; a paper that presents the beamline design has been submitted to **EPJ C** https://arxiv.org/abs/2401.17068
- The physics case of a tagged neutrino experiment is wide: neutrino cross-section measurement, neutrino oscillation etc.
- The design features a double polarity setup; with the beamline having a length of $\sim$63 m
- Two spectrometers required for the tagging process
- The study is not further being pursued within PBC

NuTag: proof-of-concept study for a long-baseline neutrino beam

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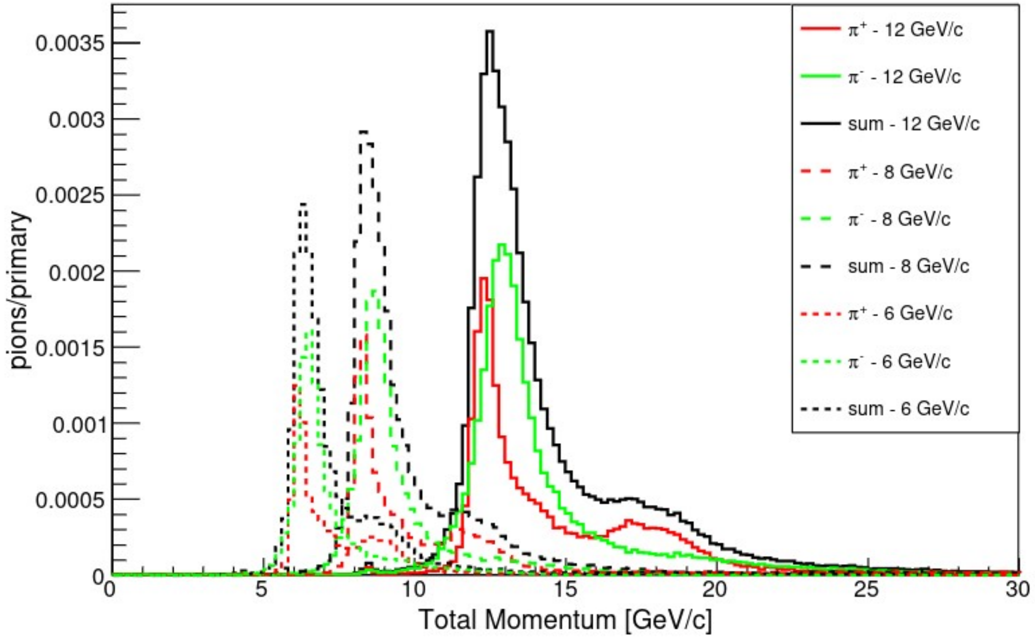
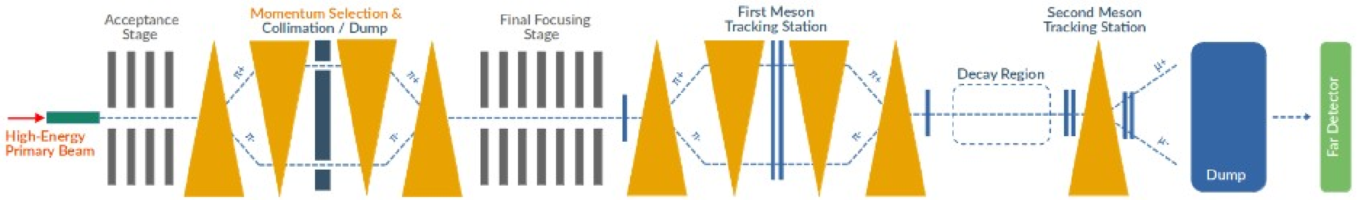
[2] Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France





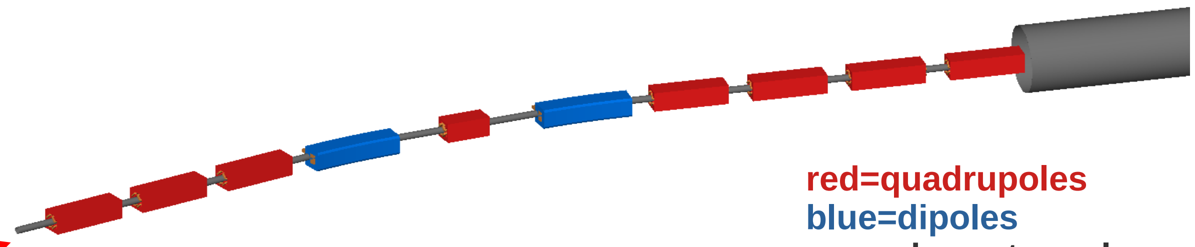
Source: https://arxiv.org/abs/2401.17068

ENUBET Studies @ PBC

- A **short-baseline design** focusing mostly on kaons has been developed by the ENUBET Collaboration (see F. Terranova's talk)
- Mainly aimed at measuring the neutrino cross section
- The physics case mostly targets the ν_e cross section → Transmission of $K^+ \rightarrow \pi^0 + e^+ + \nu_e$ should be maximized
- The initial ENUBET beamline (*baseline* design) is not tunable to intermediate beam/neutrino energies
- An improved design (REF design) that was developed by E. Parozzi solves this issue (operates at p=4, 6 & 8.5 GeV/c) and increases the acceptance & transmission of the ENUBET beamline significantly

Decay tunnel
40 m long,
2 m diameter

The ENUBET REF design



red=quadrupoles
blue=dipoles
gray=decay tunnel

Name	*baseline*	REF
K^+/PoT	3.6×10^{-4}	7.0×10^{-4}
π^+/PoT	4.0×10^{-3}	1.1×10^{-2}

K^+ and Pion yield at p=8.5 GeV/c within $p/p_0 \in [-10\%;10\%]$
with a 400 GeV/c proton beam on target

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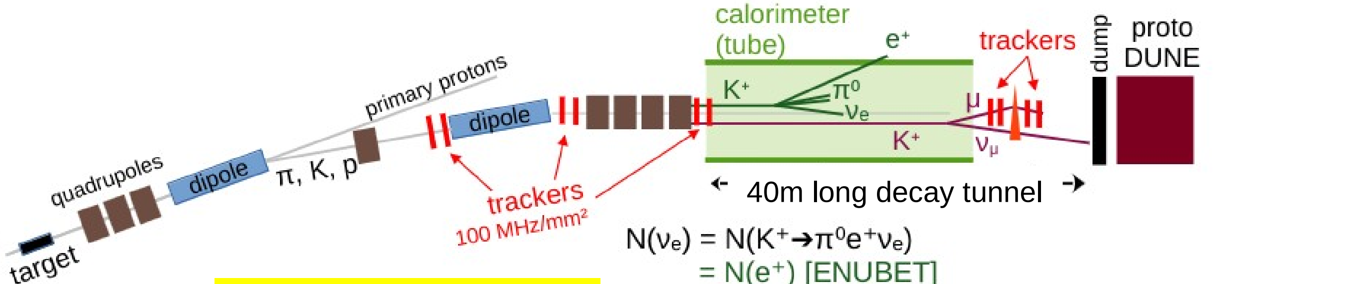
The PBC-SBN, i.e., NuTag embedded into the ENUBET REF design



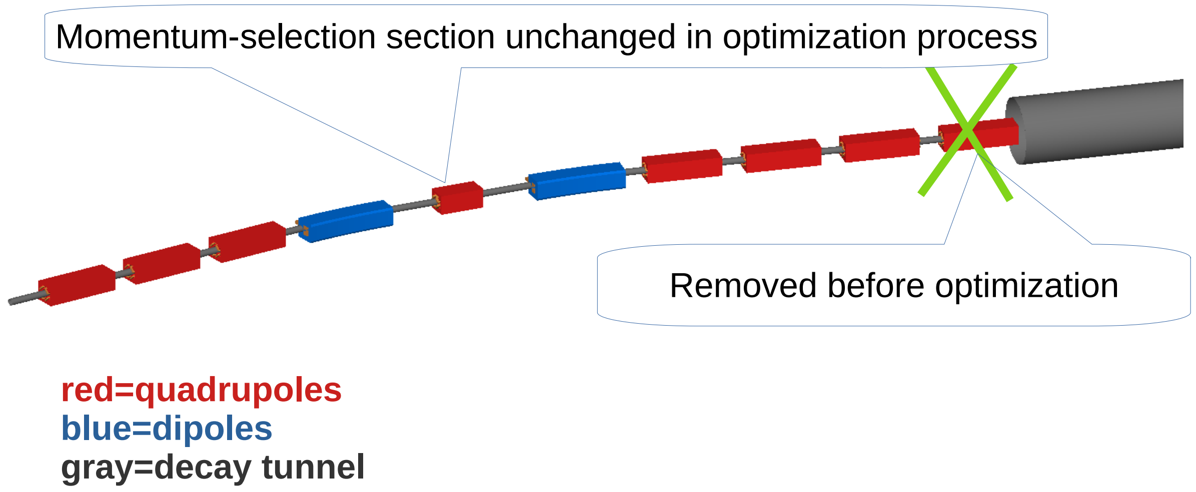
Courtesy M. Perrin-Terrin

PBC-SBN

- Since last year, NuTag and ENUBET are joining forces → **PBC-SBN** is supported within PBC (Conventional Beams Working Group)
- ENUBET's REF design is the ideal starting point to attempt the merger of both experiments' requirements
- **Main modification:** 4D pixel trackers have to be introduced to achieve the tagging

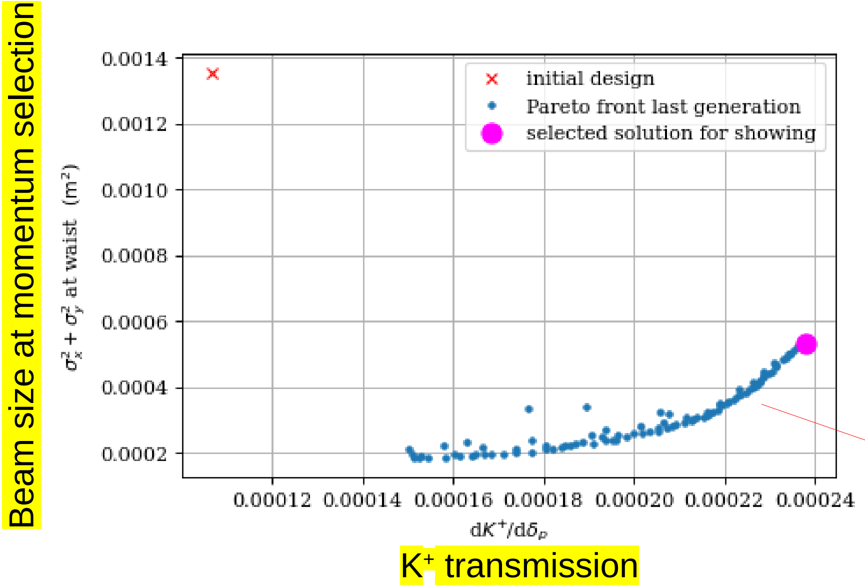
Two-Stage Optimization of the REF design

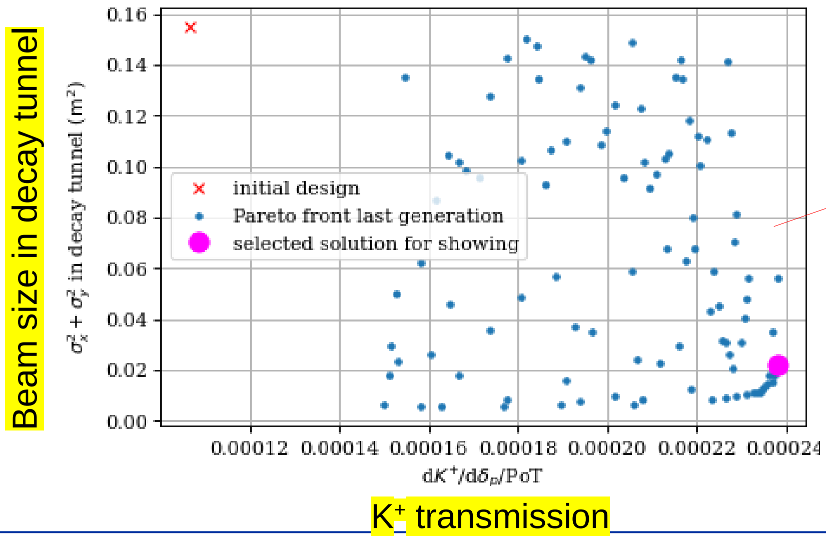
- The beamline needs optimization in any case **independently of any location** → Determines the number of required PoTs to reach the physics goal
- Not using preexisting North Area magnets any more → Quadrupole design has to be checked in terms of feasibility



- The optimization process of the beamline is rather extensive
  - Target (16 targets analyzed), 7 drift spaces, 18 quadrupole parameters (6 magnets with different length, aperture, gradient)
    → **26 free parameters**
  - Multiple objectives: K^+ & π^+ transmission as possible and the beam size has to be as small as possible in the momentum selection and the decay tunnel
    → **3 objectives**
- **1st stage:** Linear optimization of the acceptance with a multi-objective genetic algorithm (MOGA)
  - MOGA is a *state-of-the-art* tool that is used, e.g., in the development of lattices for light sources
- **2nd Stage:** Verification of the optimization process of a start-to-end BDSIM simulation

Multi-Objective Genetic Algorithm Results



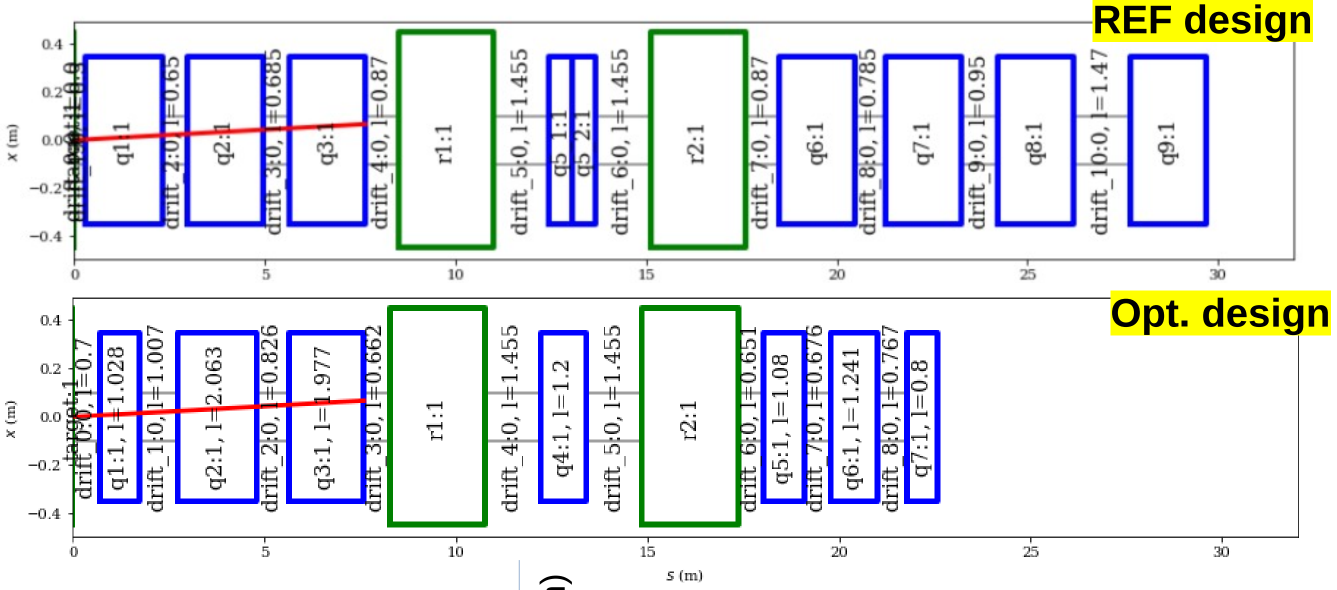


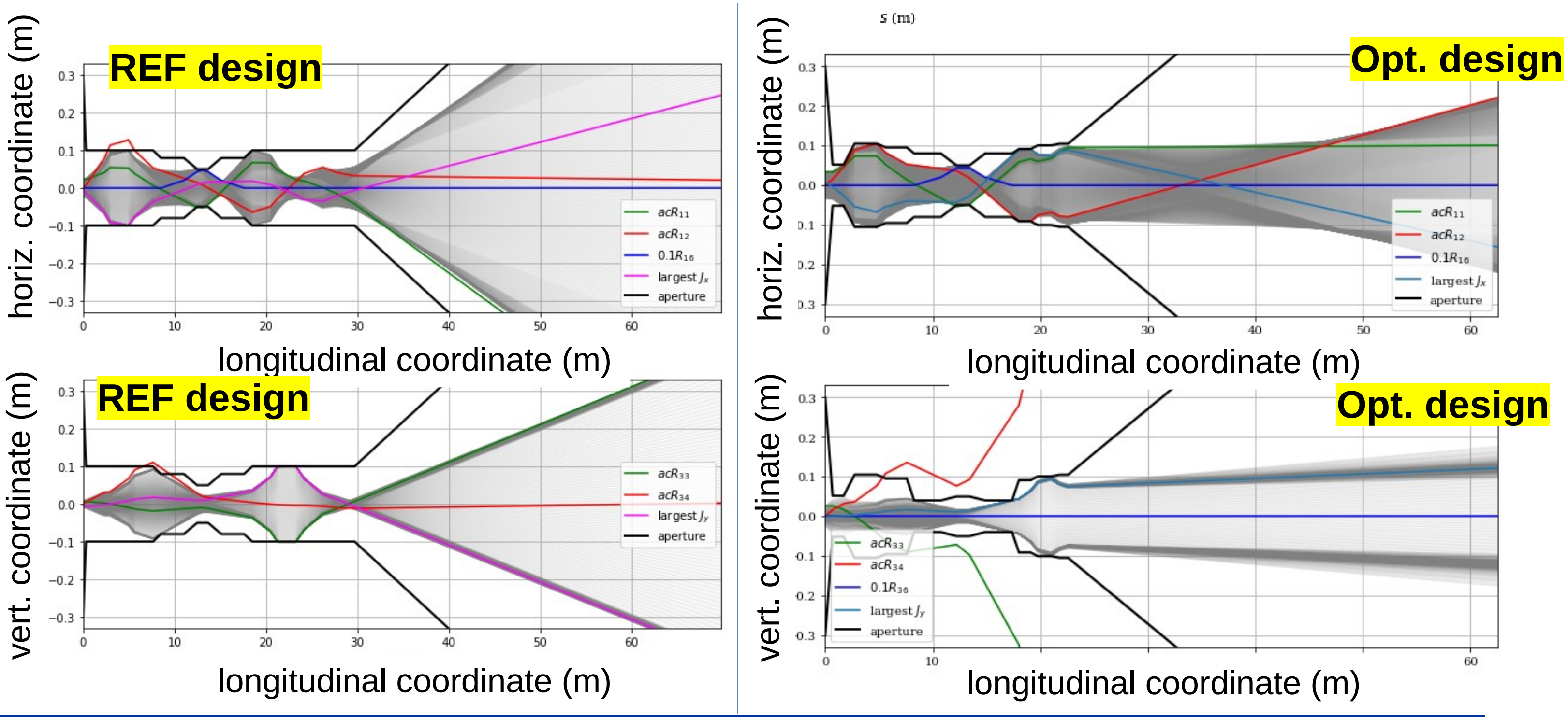
- The optimization was performed with the MOGA algorithms within PYMOO in combination with MADX
- With a few simplifying assumptions, the optimizer has sufficient performance to run on a single CPU (returns acceptable results within few hours)
- MOGA returns a set of optimal (dominant) solutions with the dimension depending on the number of objectives
- The waist size within the momentum selection competes with the transmission efficiency of the beamline
- The beam size at the end of the decay tunnel is not strongly competing with the transmission efficiency of the beamline

An Example Solution

Noteworthy changes as a consequence of the optimization process:

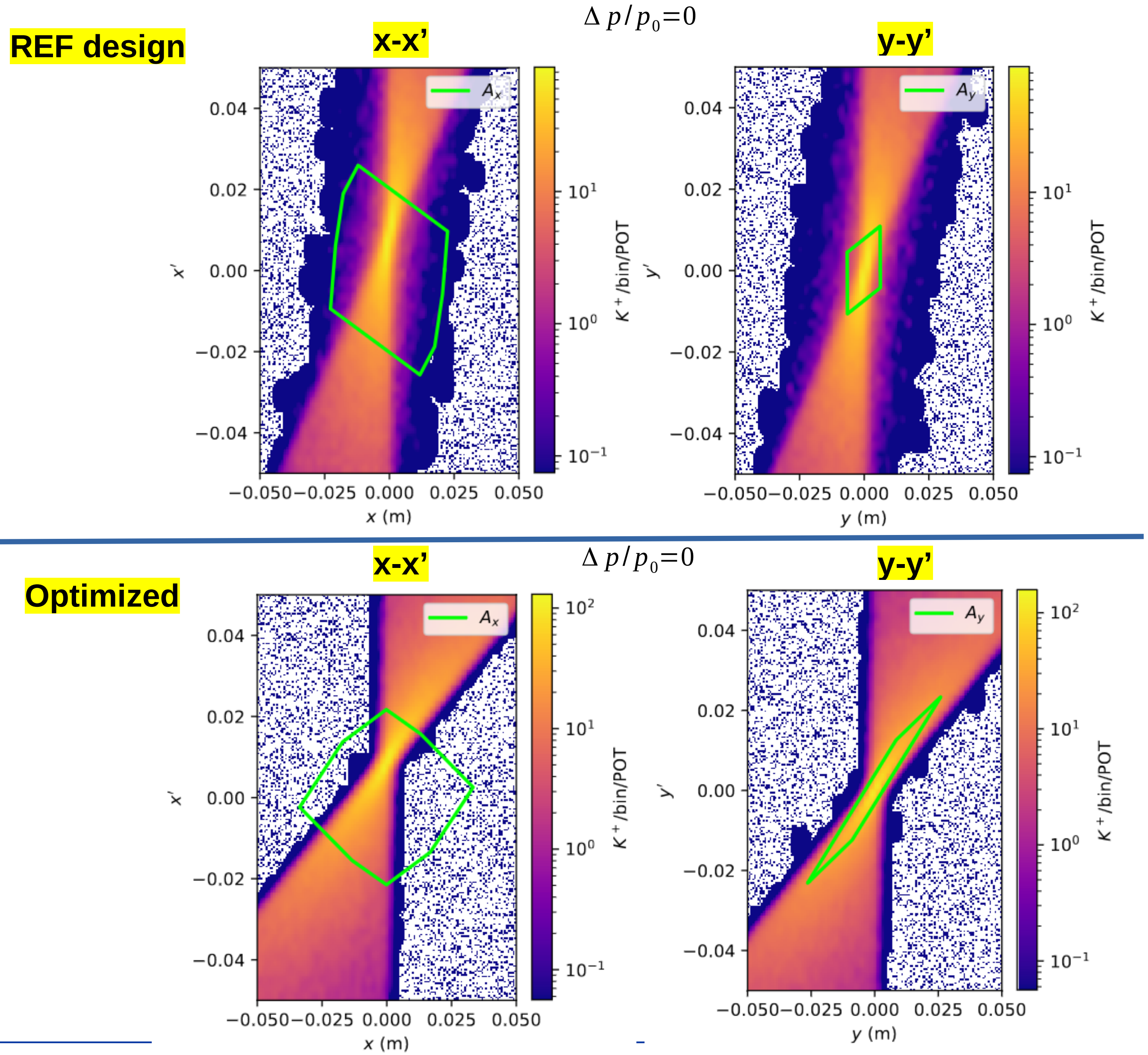
- The optimized beamline is ~7 m shorter
- Quadrupoles got shorter and aperture-gradient relation is optimized
- Beam remains much smaller throughout the decay tunnel (cannot exceed muon tracker station's acceptance)
- Beam is smaller within the momentum selection
- Graphite target changes from L=0.7 m, r=3 cm to a CNGS-like target (L=1.3 m, r=3 mm)
- Acceptance significantly improved **(→ next slide)**





Acceptance Overlap

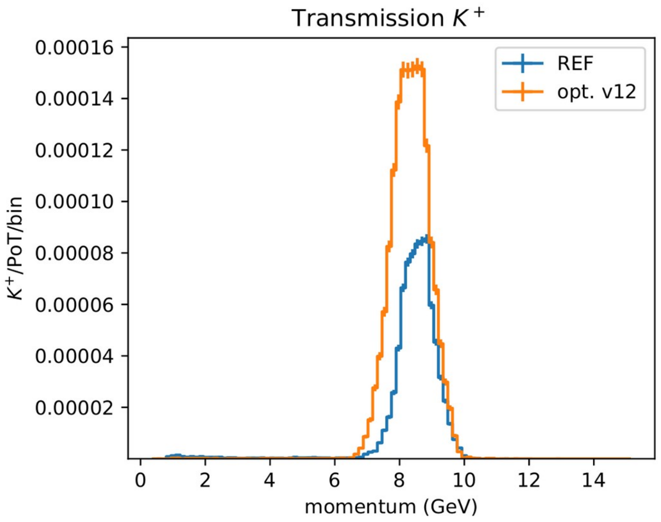
- The overlap of the acceptance with the target histogram is much improved after the optimization process
- CNGS target provides a narrower distribution in phase space that can easier be enclosed by the vertical acceptance
- The optimizer accomplishes a stark y-y' correlation of the vertical acceptance that mimics the correlation of the particles coming out of the CNGS-like target
- The vertical acceptance is smaller than the horizontal acceptance due to the vertical gap width in the dipoles of the momentum selection

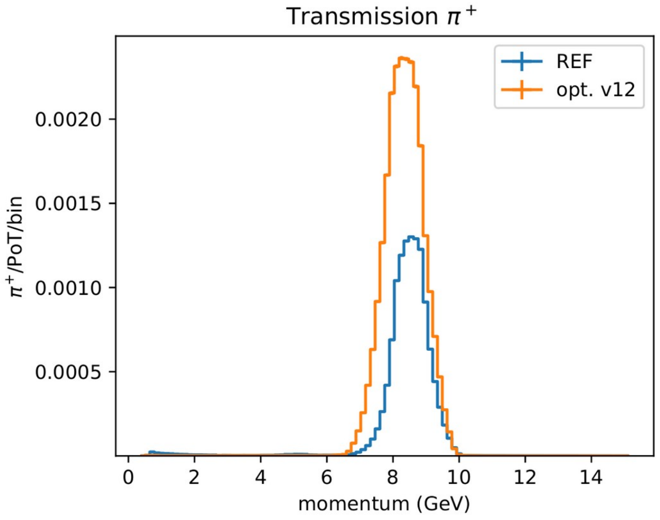


Performance after MOGA Optimization

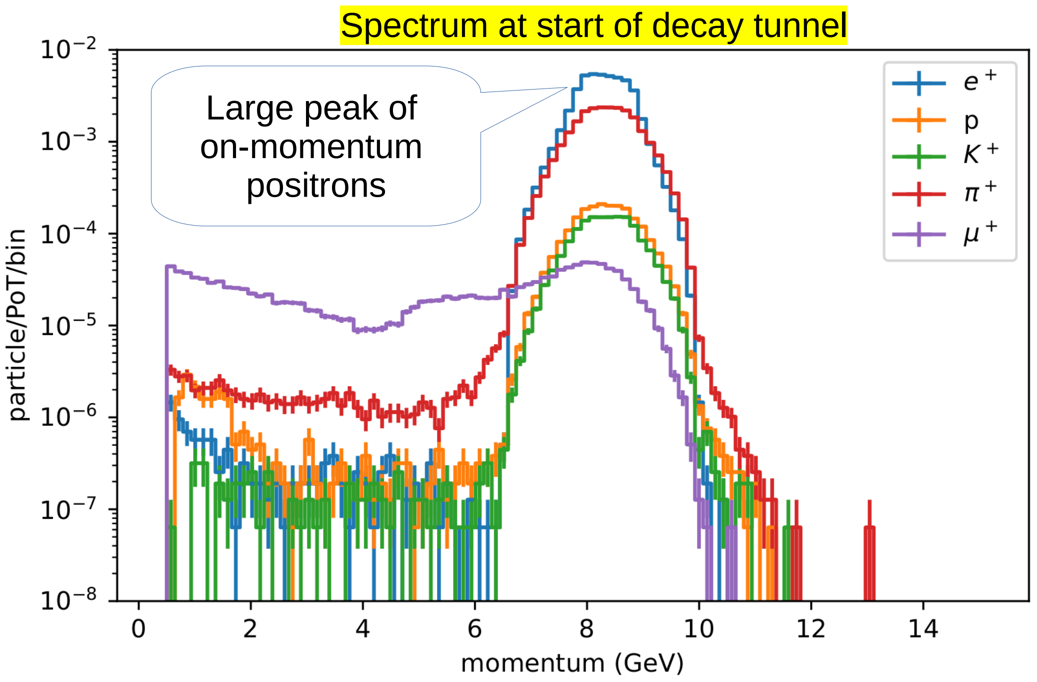
- Have created a BDSIM model of the beamline that in the 2nd stage of the optimization process confirms the transmission
- The transmission improves in the $p/p_0 \in [-10\%;10\%]$ range significantly

Name	*baseline*	REF	optimized REF V12
K^+/PoT	3.6×10^{-4}	7.0×10^{-4}	14.1×10^{-4} (+102%)
π^+/PoT	4.0×10^{-3}	1.1×10^{-2}	2.15×10^{-2} (+101%)

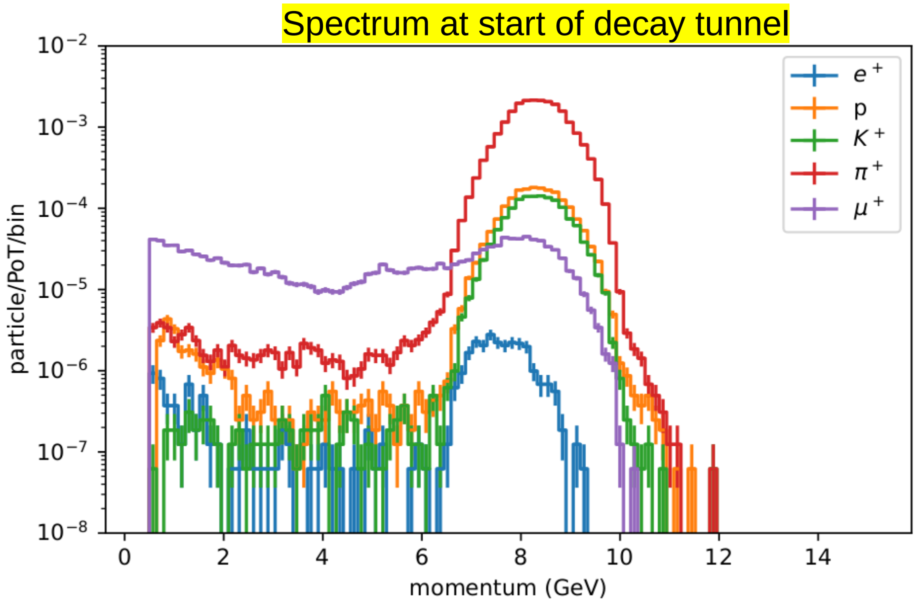




- Since NuTag's technique requires the measurement of the particle momentum on a particle-by-particle basis, there is a pile-up limit that is easily breached by positrons coming out of the target
- With pixel monitors located at the 2nd bend in the beamline, the flux exceeds >400 MHz/mm²

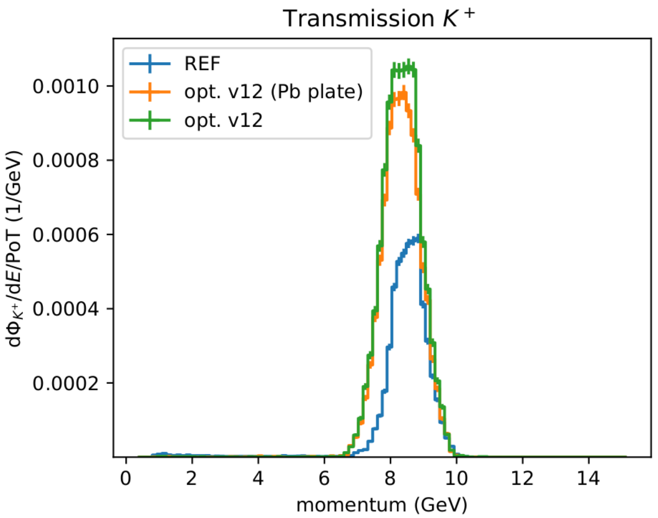


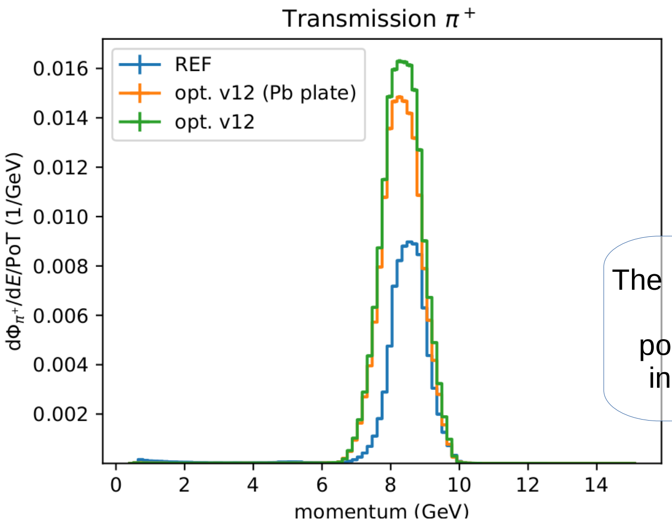
Reducing the Positron Flux



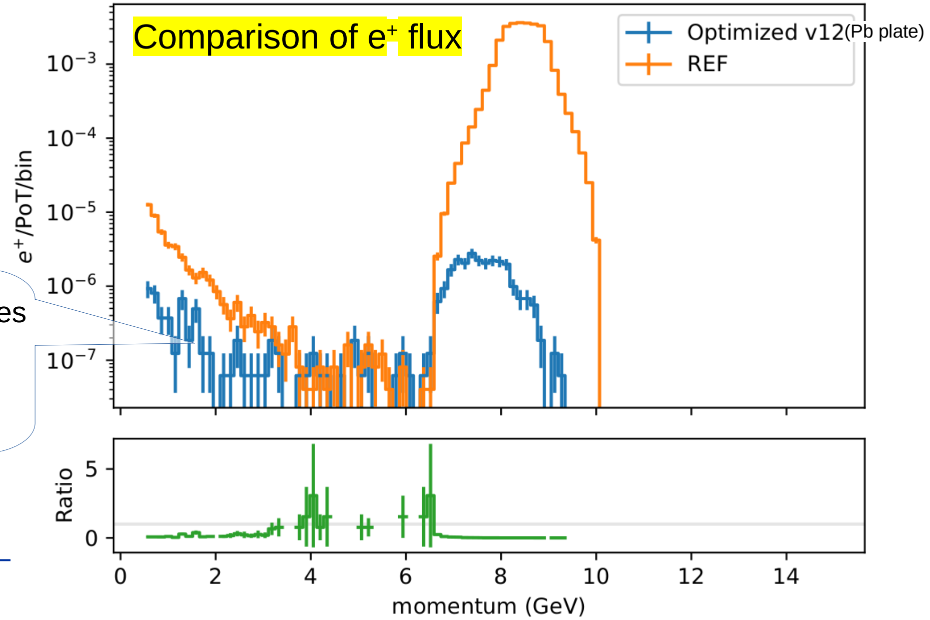
- In order to absorb/filter on-momentum positrons, a 1.2 cm thick Pb plate (~2 radiation lengths) was inserted into the beamline in the middle of the momentum selection (no primary impact, small beam waist)
- The plate causes the loss of some mesons; however, it strongly relaxes the flux on the pixel monitors

Name	*baseline*	REF	optimized REF V12	optimized REF V12 (plate)
K^+/PoT	3.6×10^{-4}	7.0×10^{-4}	14.1×10^{-4} (+102%)	12.7×10^{-4} (+81%)
π^+/PoT	4.0×10^{-3}	1.1×10^{-2}	2.15×10^{-2} (+101%)	1.92×10^{-2} (+80%)





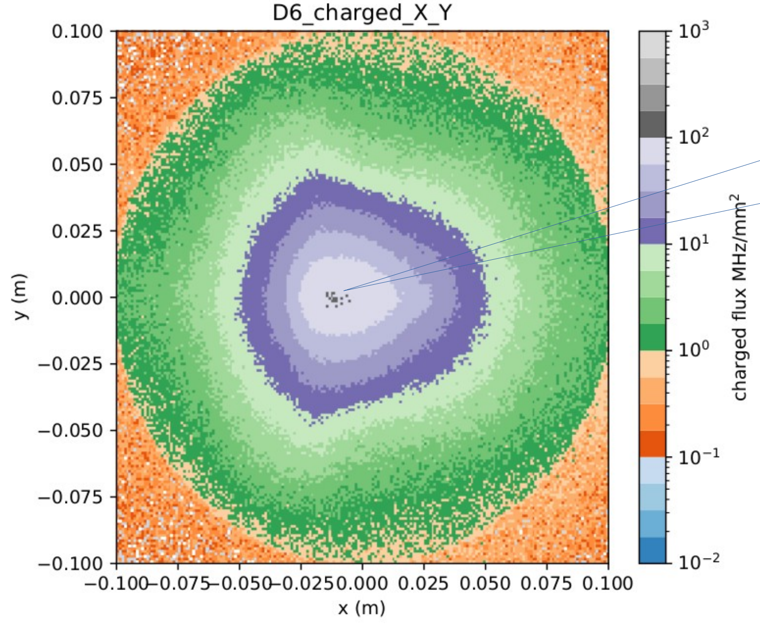
The Pb plate also solves the issue of positron background in the decay tunnel



Pixel Position Monitors (NuTag)

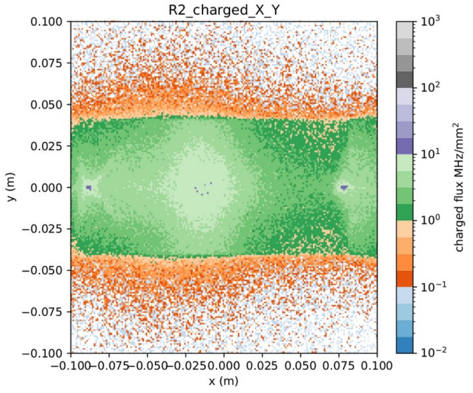
- It requires at least 3 position monitors to achieve a momentum reconstruction
- The maximum flux on the pixel position monitors is 100 MHz/mm² assuming a future technology (developed by TimeSPOT/IGNITE/PicoPix)
- Assuming 5E12 PoT/4.8s within a spill, the momentum reconstruction on a particle-by-particle basis becomes possible
- 4th monitor could be added upstream of the first monitor to introduce redundancy

First monitor

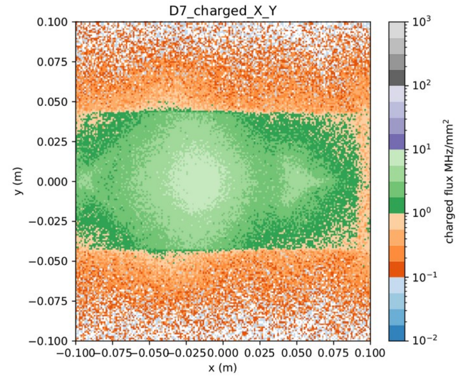


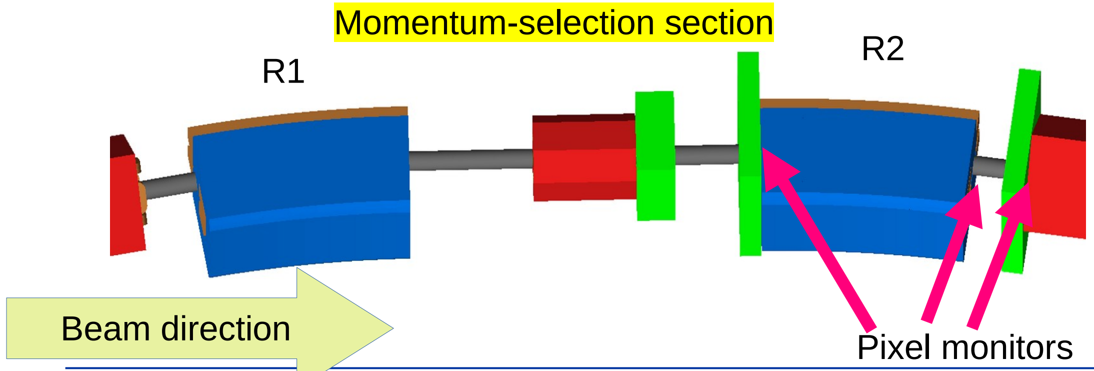
Upstream monitor is the most critical one. Only a few pixels at 100 MHz/mm²

Second Monitor



Third Monitor



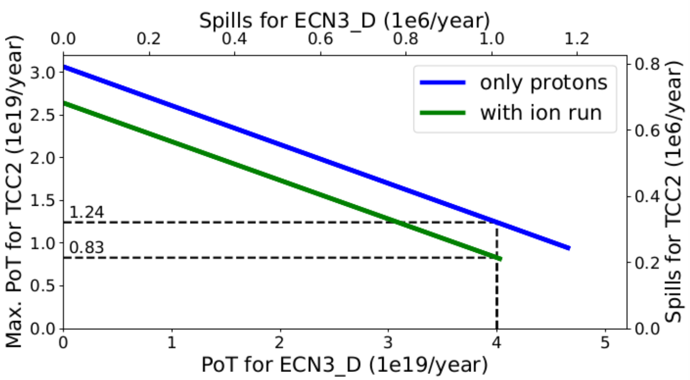


Proton Demand of the PBC-SBN: The SPS as an Example

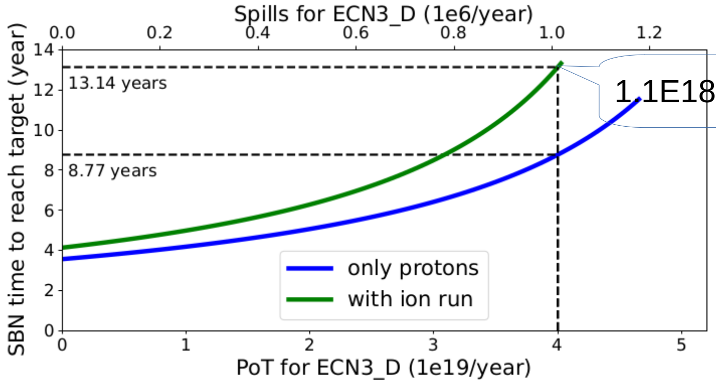
- We want to address the question of how demanding the PBC-SBN is in terms of PoT: We take the SPS as an example
- The overall PoT target with both ProtoDUNEs reduces from 5.0E19 PoT (*baseline*) to 1.4E19 PoT (-62% reduction)
- The PBC **ECN3 Beam Delivery Task Force** has performed the analysis of PoT for year for TCC2 while featuring **dedicated** cycles for SHiP (ECN3)

4.8s FT in SPS*

*4.2E13 p/spill before extraction

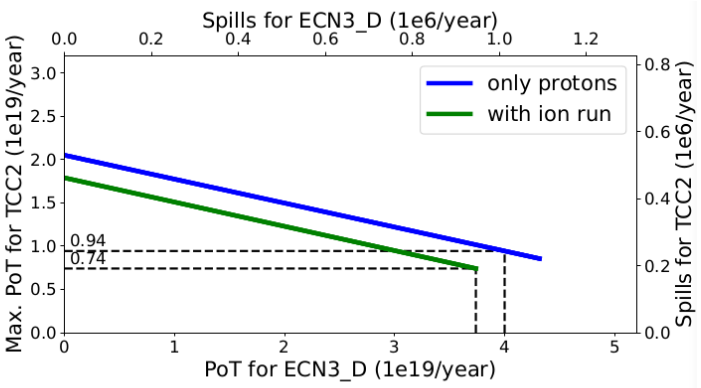


Spill: 5E12 PoT/4.8 s
consuming **13%** of the yearly TCC2 PoT

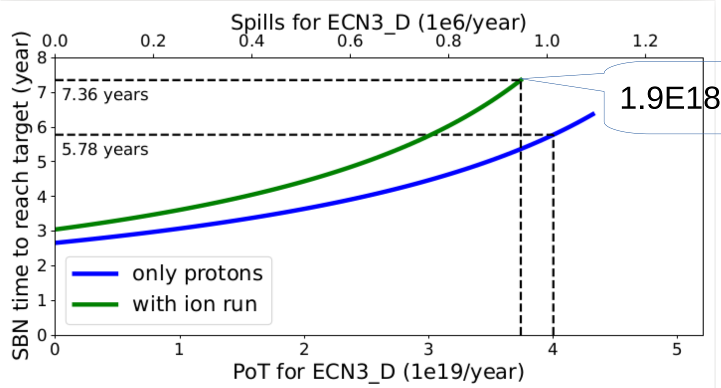


1.1E18 PoT/year

9.6s FT in SPS*



Spill: 1E13 PoT/9.6 s
consuming **26%** of the yearly TCC2 PoT



1.9E18 PoT/year

Courtesy and big thanks to Tirsi Prebibaj!

There is still room for improvement! A longer SPS FT would be beneficial for the SBN!

What is next?

- **Optimized beamline has to be analyzed with the ENUBET simulation code**
- **The BDSIM model has to be completed**
  - Energy-deposition study with successive adjustment of the shielding
  - Design and placement of a beam dump for the primary beam
- **Optimization on the momentum-selection section**
  - Adjustment of Pb plate's location, material, thickness & optics within momentum selection
  - Possible elongation of drifts to improve cleaning efficiency of plate
- **Study whether current monitor setup is suitable for the tagging**

Study of potential sites for such an experiment inside and outside CERN *(within this year)*

  - Examples are: SPS, PS, Fermilab's Main Injector, ...

- **Study of a potential timeline/milestones of such an experiment**
- **Study of the infrastructure related aspects; e.g., radiation protection etc.**
- **Budgeting (initial costing)**

Conclusion

- The MOGA optimization of the ENUBET REF design as the starting point of the SBN was *highly* successful (yield gains in the 80% up to 100% range)

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- The optimized beamline decreases the PoT that are required to achieve the ENUBET physics case from 5E19 PoT down to 1.4E19 PoT (assuming an inserted Pb plate as a positron countermeasure)

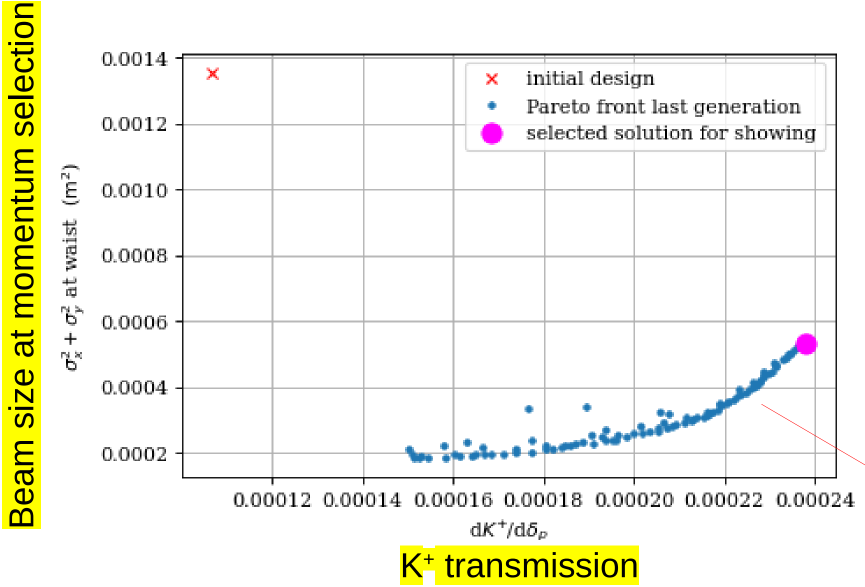
- Further optimization of the meson yield gets increasingly difficult to achieve; improvements not targeting the transmission still possible

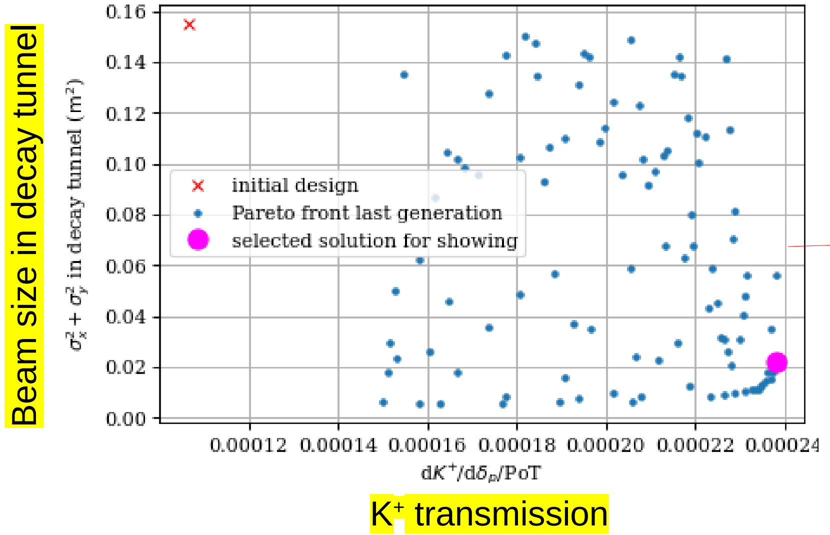
- Taking the SPS as an example: With a yearly consumption that is less than ≤¼ of the TCC2 PoT/year, the ENUBET physics case can be achieved within reasonable time (improvements possible)

- As mentioned on the previous slide: The list of pending items is long and there is still some way to go

Thanks for your attention!
Questions?

Multi-Objective Genetic Algorithm Results





- The optimization was performed with the SMS-EMOA and AGE-MOEA MOGA algorithms (similar to the classic NSGA-II algorithm) within PYMOO in combination with CPYMAD
- With a few simplifying assumptions, the optimizer has sufficient performance to run on a single CPU (returns acceptable results within few hours)
- MOGA returns a set of optimal (dominant) solutions with the dimension depending on the number of objectives
- The waist size within the momentum selection competes with the transmission efficiency of the beamline
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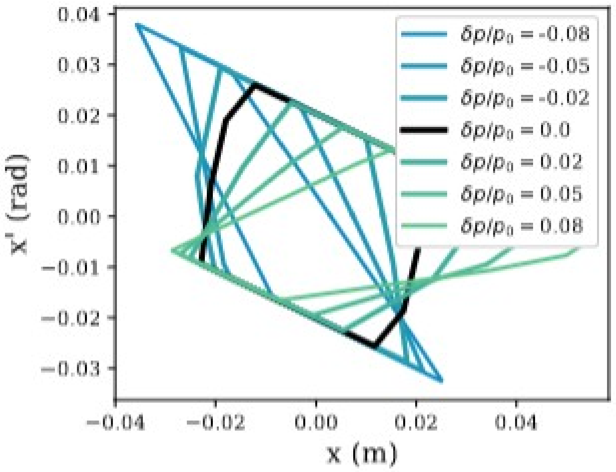
Targets

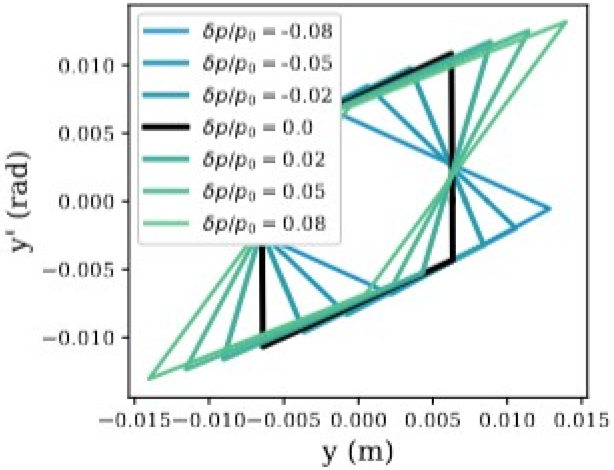
Name	Geometry	Length L (m)	Radius r (mm)	Density ρ (g/cm^2)	K^+ yield f_K (10^{-2}POT/GeV)	π^+ yield f_π (10^{-1}POT/GeV)
ENUBET A	cylinder	0.70	30	2.3	2.0	1.3
ENUBET B (thin)	cylinder	0.70	10	2.3	2.4	1.7
CNGS A (correct)	mulitple cylinders []	1.30*	2/3	1.8	2.1	1.8
CNGS B (collapsed)	cylinder	0.70	2.5	1.7	2.6	2.0
CNGS C (thin)	cylinder	1.30	2	1.7	2.4	2.0
CNGS D (thick)*	cylinder	1.30	3	1.7	2.7	2.1
CNGS E (long)	cylinder	1.40	2.5	1.7	2.7	2.1
CNGS F (short)	cylinder	1.20	2.5	1.7	2.5	2.0
CNGS G (very thick)	cylinder	1.30	13	1.7	2.9	1.9
NuMI	cylinder	0.94	3.7	1.7	2.3	1.7
T2K	cylinder	0.91	13	1.7	2.3	1.5
CNGS H	cylinder	1.30	3.5 (+0.5)	1.7	2.8	2.1
CNGS I*	cylinder	1.30	3	1.8 (+0.1)	2.8	2.1
CNGS J*	cylinder	1.30	3	2.0 (+0.2)	3.0	2.3
CNGS K*	cylinder	1.30	3	2.2 (+0.2)		
CNGS L*	cylinder	1.30	3	2.4 (+0.2)		
CNGS M*	cylinder	1.35 (-0.05)	3	2.4		

Not considered up to V12.

Slicing of the Phase Space

Acceptance for different momentum offsets





CNGS target: Histogram mostly block diagonal

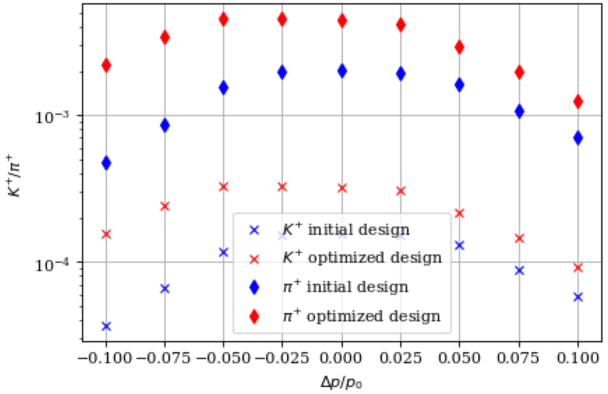
$$\frac{\mathrm{cov}(A,B)}{\sigma_A \sigma_B} = \left|\begin{array}{ccccc} x & p_x & y & p_y & p_z \\ \hline \mathbf{1.0} & \mathbf{0.9} & 1.0\times10^{-3} & 1.3\times10^{-3} & -6.8\times10^{-4} \\ & \mathbf{1.0} & 1.4\times10^{-3} & 1.6\times10^{-3} & -1.6\times10^{-3} \\ & & \mathbf{1.0} & \mathbf{0.9} & 3.2\times10^{-3} \\ & & & \mathbf{1.0} & 4.1\times10^{-3} \\ & & & & \mathbf{1.0} \end{array}\right|$$

Target's momentum dependence

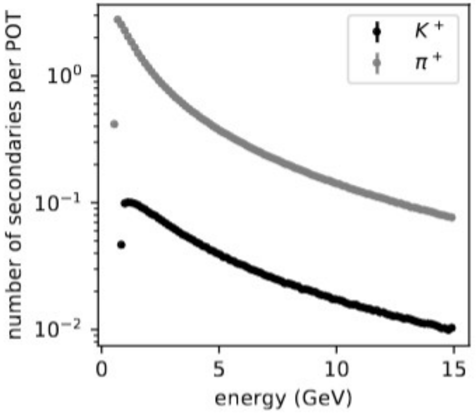
$$\frac{d\Phi_K}{dp}(p) = \frac{2.12\times10^{-2}}{\mathrm{GeV/c}} - (p - 8.5\,\mathrm{GeV/c})\frac{0.39\times10^{-2}}{\mathrm{GeV^2/c^2}} \quad (1)$$

$$\frac{d\Phi_\pi}{dp}(p) = \frac{17.96\times10^{-2}}{\mathrm{GeV/c}} - (p - 8.5\,\mathrm{GeV/c})\frac{3.13\times10^{-2}}{\mathrm{GeV^2/c^2}} \quad (2)$$

Transmission at different momentum offsets

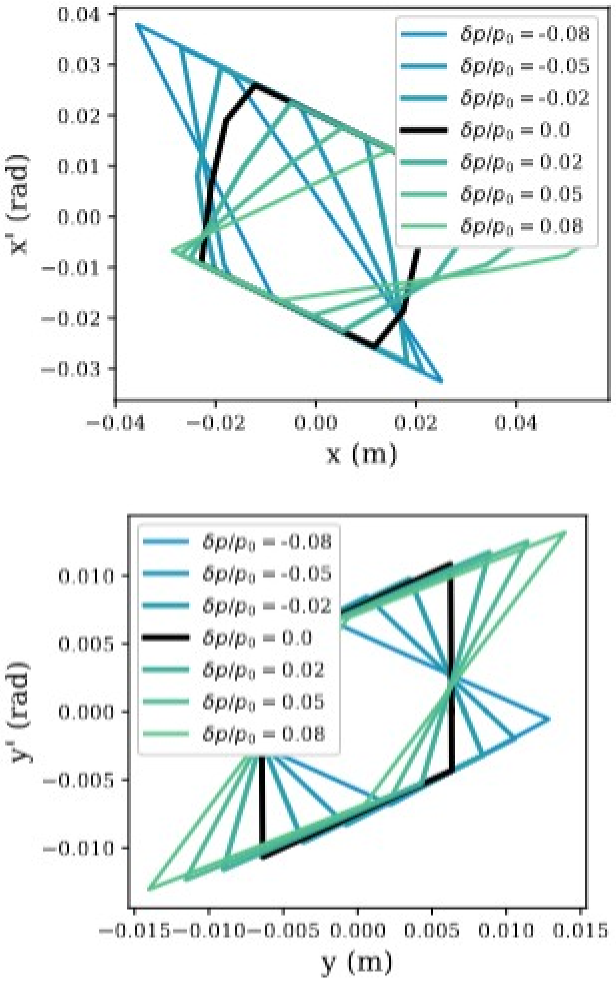


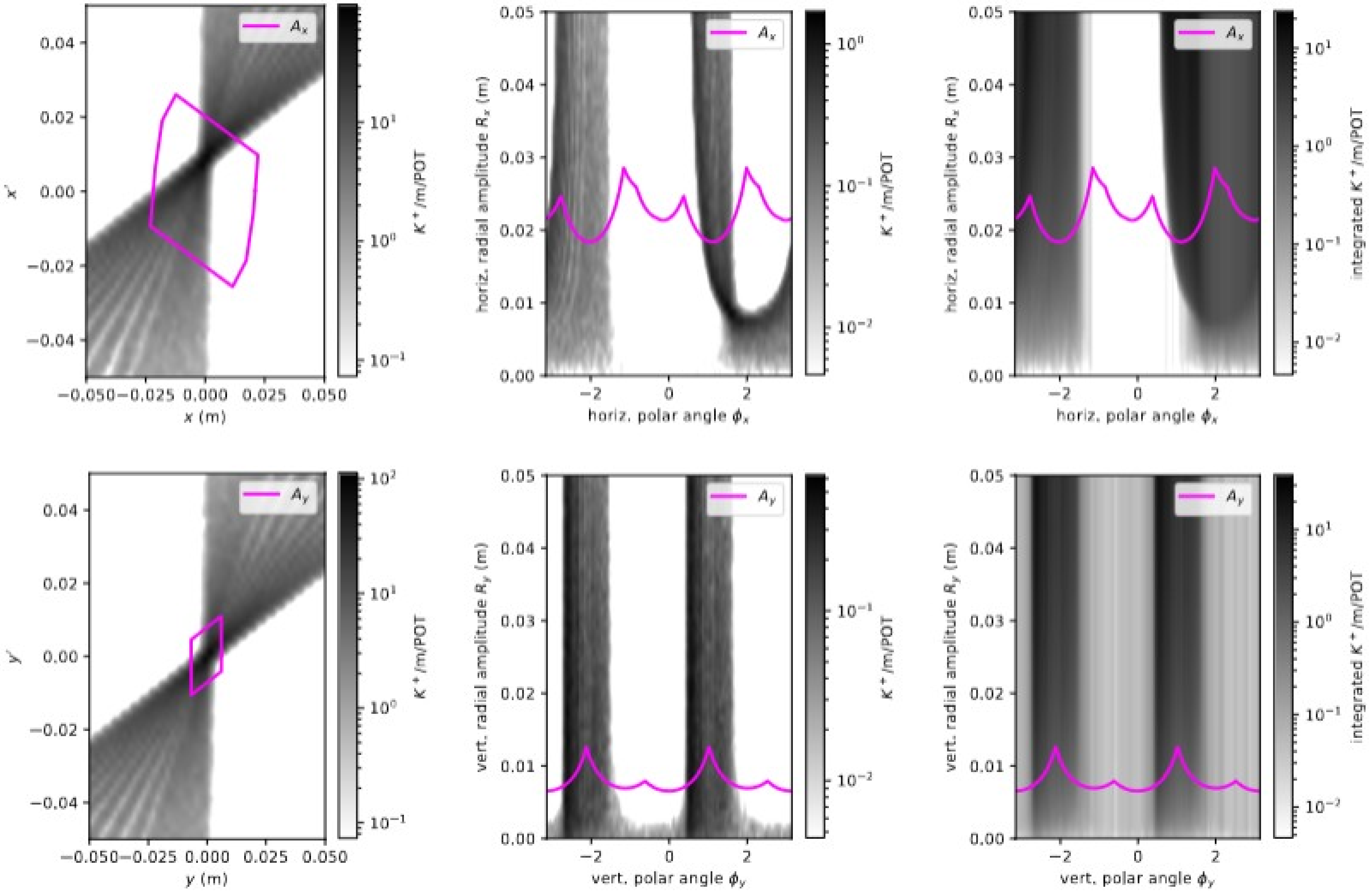
Target's momentum dependence



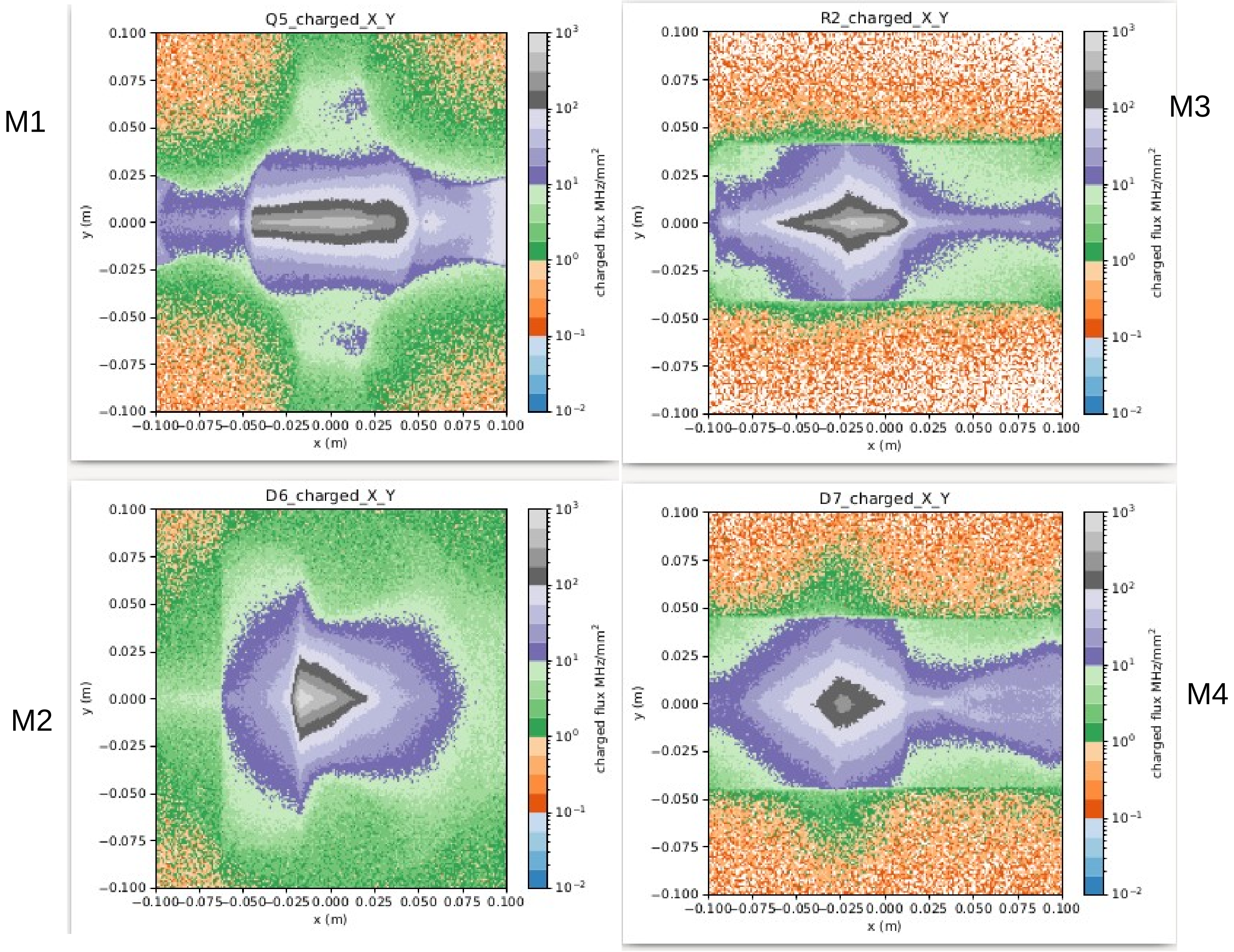
The overlap of the acceptance with the target histogram

Acceptance for different momentum offset





Monitor Flux with 2E13 PoTs/4.8s no Pb plate



- The flux on the first monitor exceeds 700 MHz/cm² with 2E13 PoTs/spill
- The issue is the high positron flux.
- In order to make the monitors work, there has to be some foil or the whole design has to be changed (adding a 2nd achromat/more dipoles)
- The foils requires the following:
  - Located in at double waist
  - Behind R1 to avoid acting as a 2nd target for the primary

Physics List Comparison

- The results are based on the FTFP_BERT physics list (Fritiof Precompound Model with Bertini Cascade Model. The FTF model is based on the FRITIOF description of string excitation and fragmentation. This is provided by G4HadronPhysicsFTFP_BERT.)
- The QGSP_BERT physics list results in in overall decrease of the yield in the 25% range (Quark-Gluon String Precompound Model with Bertini Cascade model. This is based on the G4HadronPhysicsQGSP_BERT class and includes hadronic elastic and inelastic processes. Suitable for high energy (>10 GeV).)

FTFP_BERT result

(V11)

```
Kaons - std: 0.0006975886623416862
Kaons - opt: 0.001291584395221631
opt/std: 1.851498547705753   ratio

Pions - std: 0.010685822951820098
Pions - opt: 0.020612665175162526
opt/std: 1.9289731140128619  ratio
```

unit: particles/PoT

25% decrease

QGSP_BERT result

(V11)

```
Kaons - std: 0.0005225538585793934
Kaons - opt: 0.0009320635260713826
opt/std: 1.7836697801931378 ratio

Pions - std: 0.008820224025817903
Pions - opt: 0.016919161160852354
opt/std: 1.9182235180566667 ratio
```

unit: particles/PoT

Optimization to have largest possible beam size at 1st monitor