Optimization of a Short-Baseline Neutrino Beamline at CERN

- A Non-Tracking Based Approach -

NBI Workshop 2024

by **Marc Andre Jebramcik** & Nikolaos Charitonidis (CERN)

also on behalf of F. Terranova, F. Pupilli, M. Perrin-Terrin, A. Longhin *et al.*

08.10.2024

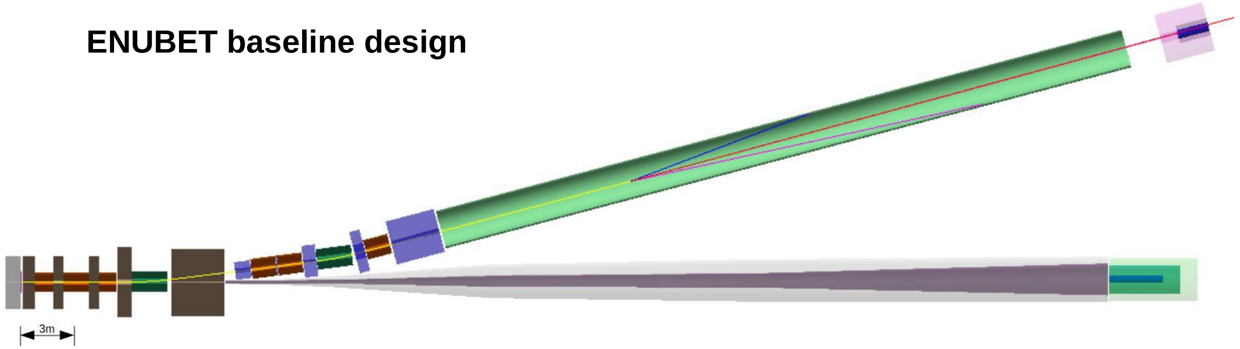
A Short-Baseline Neutrino Experiment: PBC-SBN

- **ENUBET** is a proposed experiment that features a short-baseline secondary beamline. It focuses on the the ν_e and ν_μ cross-section measurement (**see A. Longhin's presentation from yesterday!**)

- **ENUBET** is a **horn-less design** that may use a 4.8s or 9.6s long slow extraction from the SPS (p=400 GeV/c)

- **ENUBET** is a "monitored" neutrino beam experiment: It proposes to measure the beam flux with high precision to achieve the cross-section measurement

ENUBET baseline design



A Short-Baseline Neutrino Experiment: PBC-SBN

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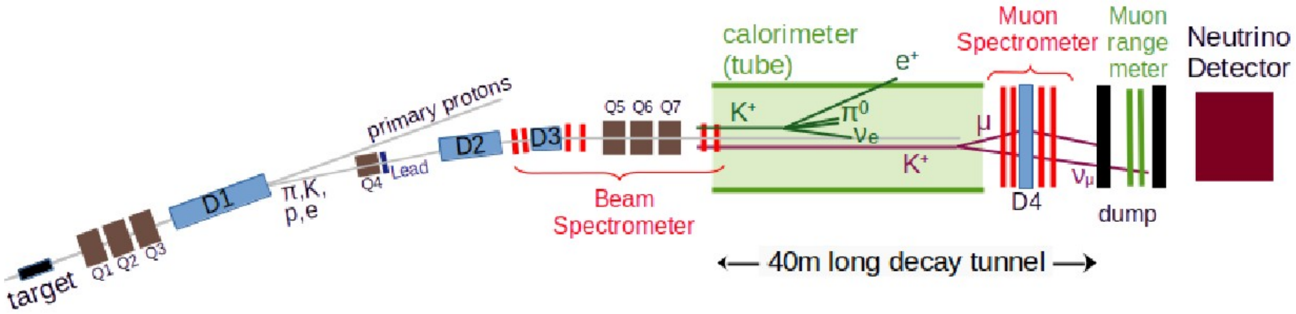
- **ENUBET** is a "monitored" neutrino beam experiment: It proposes to measure the beam flux with high precision to achieve the cross-section measurement.
- **NuTAG** takes it a step further: silicon pixel detectors measure the momentum on a particle-by-particle basis; **and** also measures the momentum of the μ coming out of the two-body decay of K^+ and π^+ with a 2nd tracker station

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



Courtesy M. Perrin-Terrin

PBC-SBN

- NuTag and ENUBET are merging → **PBC-SBN supported within the PBC initiative (Physics Beyond Colliders)**
- Within the PBC, the a new beamline design for ENUBET – the so-called reference (REF) design – was developed that now became the PBC-SBN. It now also includes the silicion-pixel detectors required for the NuTAG physics case.

NuTAG EPJ C paper (accepted): https://doi.org/10.48550/arXiv.2401.17068
ENUBET EPJ C paper (2023): https://doi.org/10.1140/epjc/s10052-023-12116-

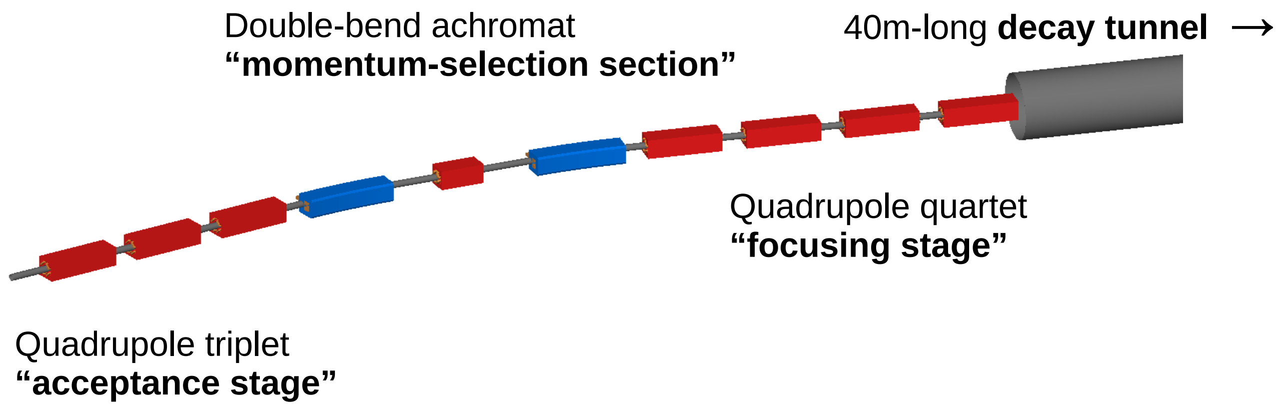
The starting point of the PBC-SBN: the ENUBET line

- The original ENUBET beamline achieved an extremely low background signal in the decay tunnel; however, the kaon/pion yield was not fully optimized. Effectiveness improved by the **REF design developed within the PBC at CERN** (E. Parozzi, N. Charitonidis)

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

400 GeV proton beam; [-10%,10%] momentum interval at p=8.5 GeV/c

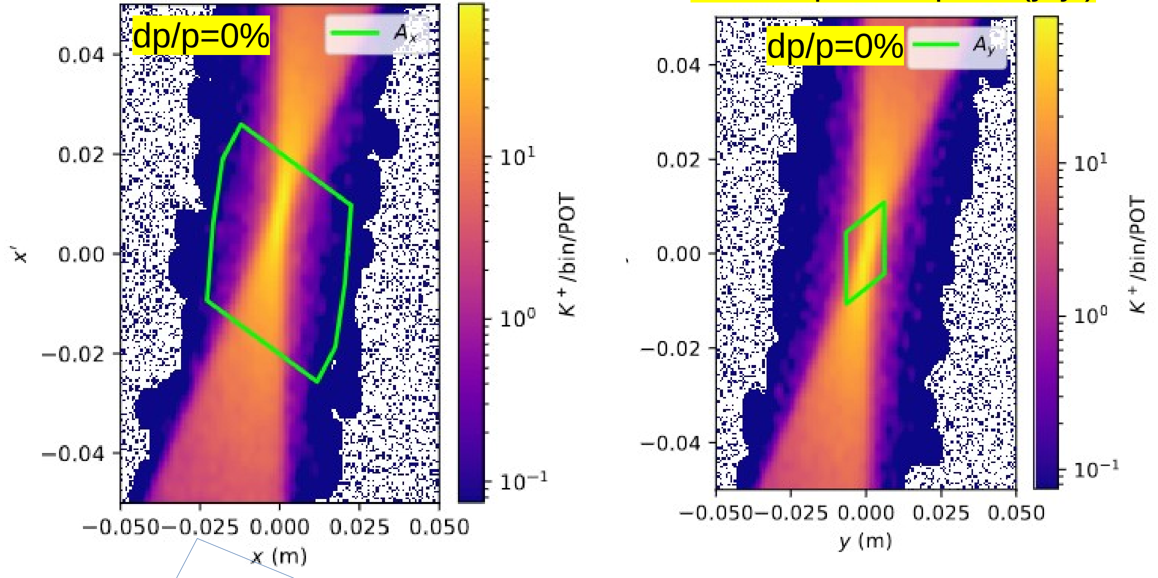
REF design by E. Parozzi & N. Charitonidis @ CERN



- Upcoming proton economics @ CERN (see CERN-PBC-REPORT-2023-001):
  - ECN3/SHiP aims to be operated at 4E19 PoT/year [PoT="protons on target"]
  - North area FT experiments and secondary beamlines is going to be at ~1E19 PoT/year
  - The ENUBET physics case will require 5E19 PoT (assuming the ENUBET *baseline* design)
- The PBC-SBN will be operated in the range of ~5E12 PoT/spill (~67 kW) with (much) less than 1E19 PoT/year
- **We are in desperate need to develop a framework that leads to a full beamline optimization.** Since we have to reduce the number of required PoTs as much as possible.
- **We face a multi-objective problem with a very extended parameter space that exceeds the capabilities of common accelerator-physics codes (MADX, PTC, etc.)**

Optimization Objectives

- Good transmission is mostly obtained by having
  - a beamline that is short (less premature decays)
  - good overlap between the acceptance and the phase-space histogram of secondary mesons



Histogram of K^+ at p=8.5 GeV/c produced by 400 GeV/c protons on C target (obtained from a BDSIM simulation)

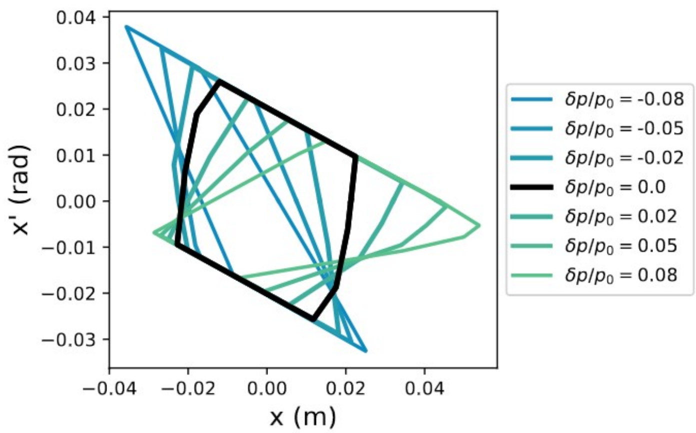
- In the ideal case a self-consistent optimization of the full beamline is carried out with a large number of free parameters for flexibility, to shape the acceptance
- A numerical optimizer is required since
  - one has to optimize the line **for different momenta (and magnet imperfections)** simultaneously
  - there is not only the transmission one has to keep an eye on **(multi objective); e.g., momentum spread, beam properties at key locations**
- We aim for an optimization framework that is light-weight and can run locally on any computer. Hence, tracking is avoided since it is time consuming.
- We want to optimize:
  - quadrupole parameters (aperture, length, gradient)
  - length of drift spaces
  - graphite target (density, length, radius)

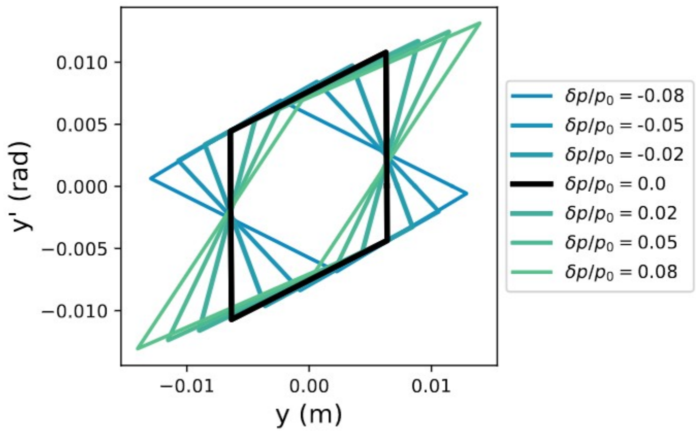
A “Novel” Optimization Approach Using MOGA

Beamline Evaluation

Acceptance curves of the PBC-SBN

- **Preparation:** Calculate the histograms of K^+ and π^+ that come out of the graphite target (**BEFORE** the optimization process)
- **Step 1:** To avoid tracking, calculate the linear acceptance in x-x' and y-y' for different momentum slices (and magnet imperfections!)

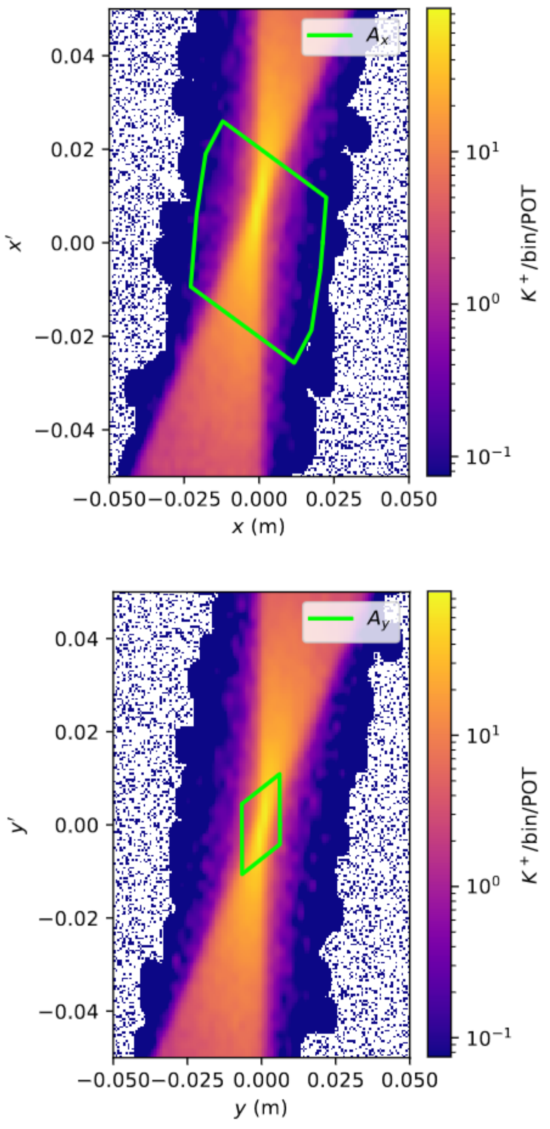




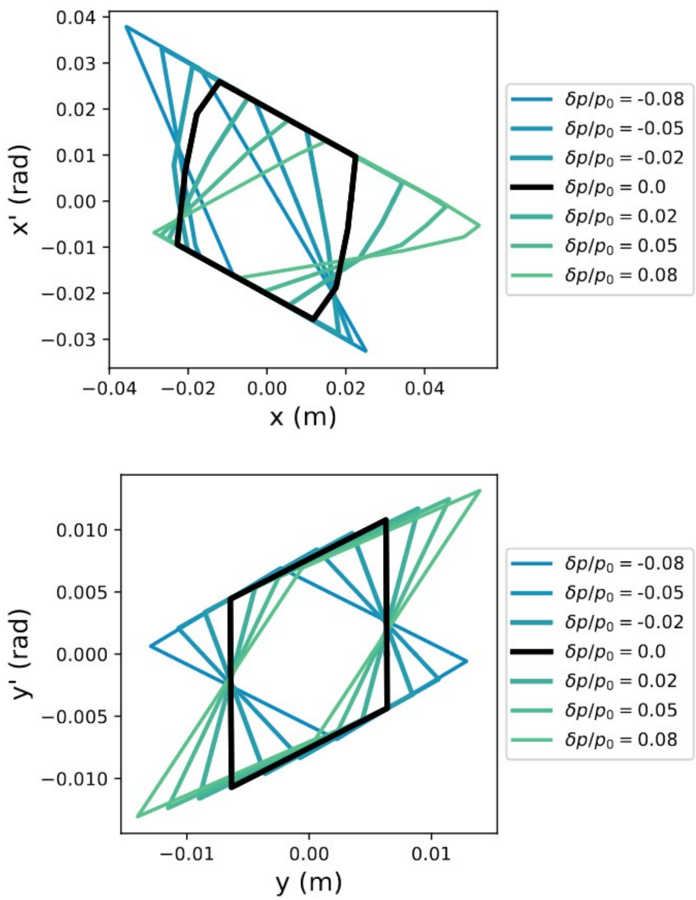
Beamline Evaluation

- **Preparation:** Calculate the histograms of K^+ and π^+ that come out of the graphite target (**BEFORE** the optimization process)
- **Step 1:** To avoid tracking, calculate the linear acceptance in x-x' and y-y' for different momentum slices <u>(and magnet imperfections!)</u>
- **Step 2:** "Count" the number of K^+ and π^+ within the boundary of the acceptance → **beamline transmission (main optimization objective)**

Example: CNGS graphite target



Acceptance curves of the PBC-SBN



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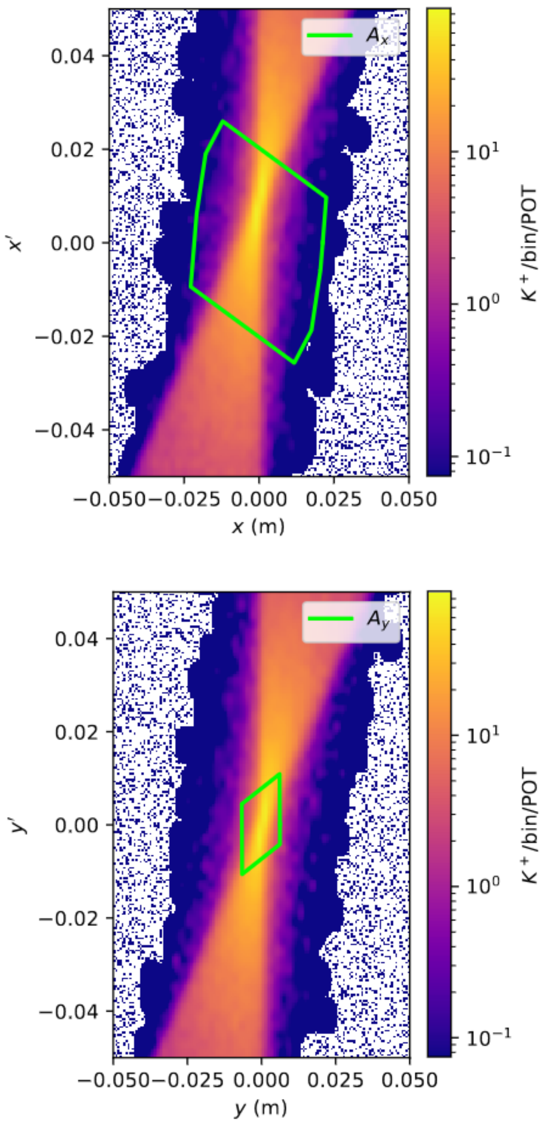
- **Step 2:** "Count" the number of K^+ and π^+ within the boundary of the acceptance → **beamline transmission (main optimization objective)**
- **Step 3…N:** The beam size, momentum spread and other parameters can be calculated analytically and used as **additional optimization objectives**
- A single beamline evaluation with sufficient accuracy takes 1.1s CPU time using some straight forward NumPy implementation + CPYMAD

Example: CNGS graphite target



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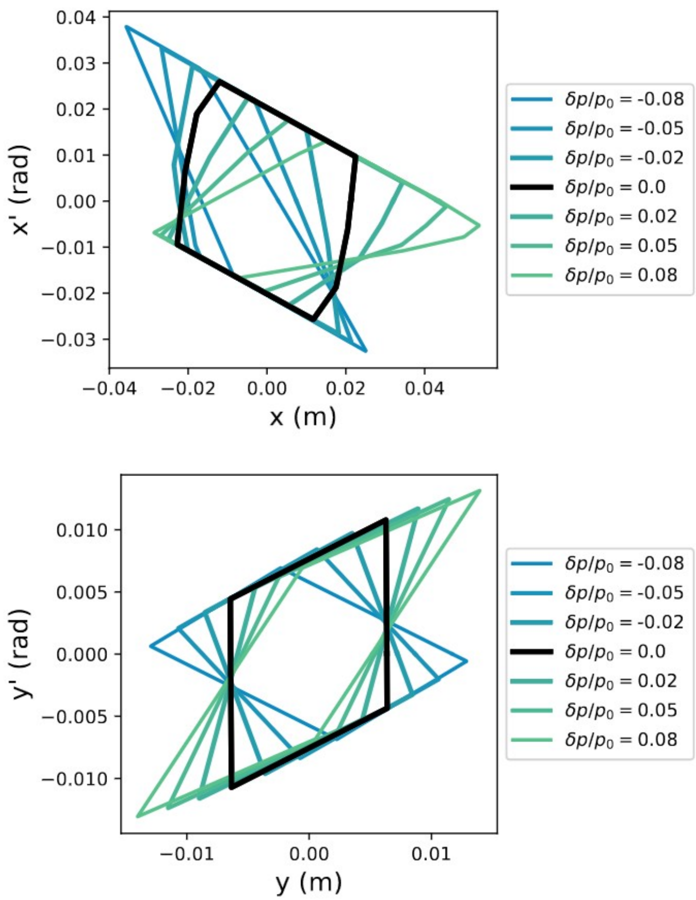
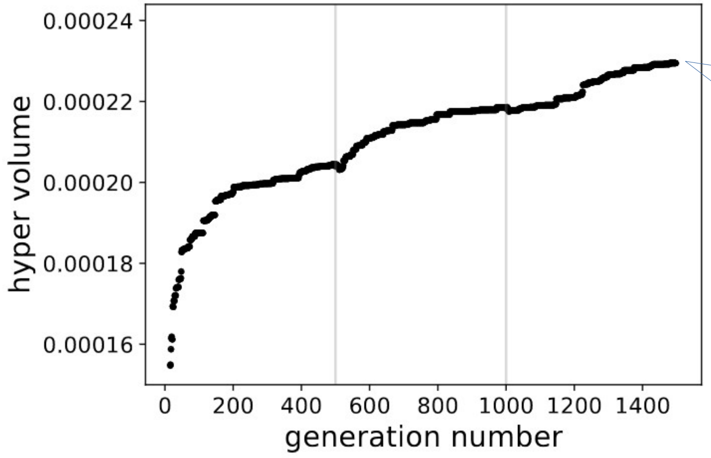


The Results of an Example MOGA Run

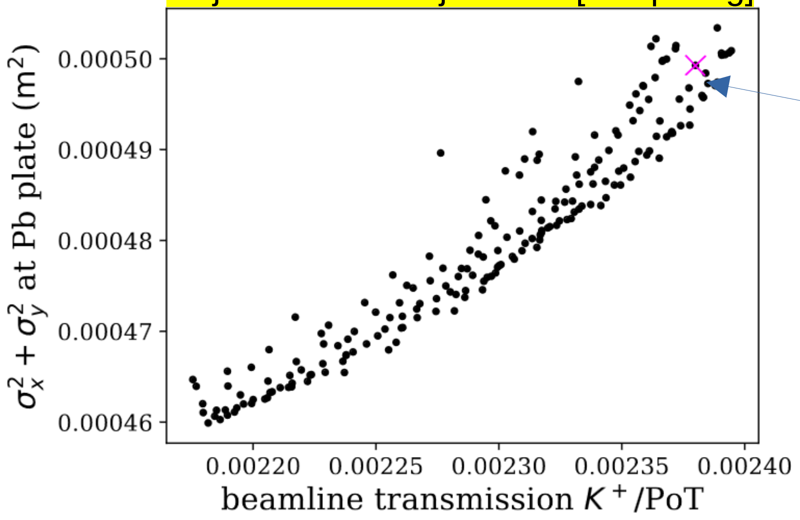
- Example run with 1500 generations
- Hyper volume flattens out over time as expected
- Transmission objective more important than the other two → Select solution with rather large transmission from Pareto that does not lead to a blown up beam in the decay tunnel

Hyper volume evolution

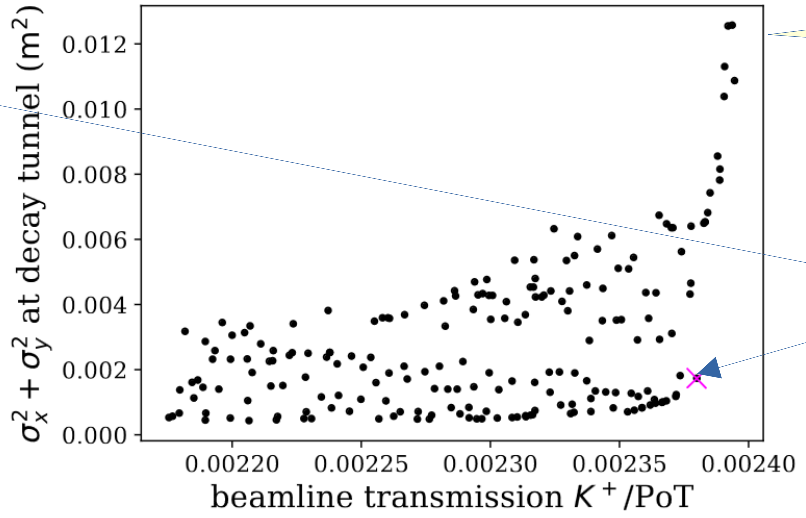


Effectiveness per function call declines.
There is never full certainty
that one cannot squeeze out a bit more

Objective 2 vs Objective 1 [competing]



Objective 3 vs Objective 1 [weakly competing]



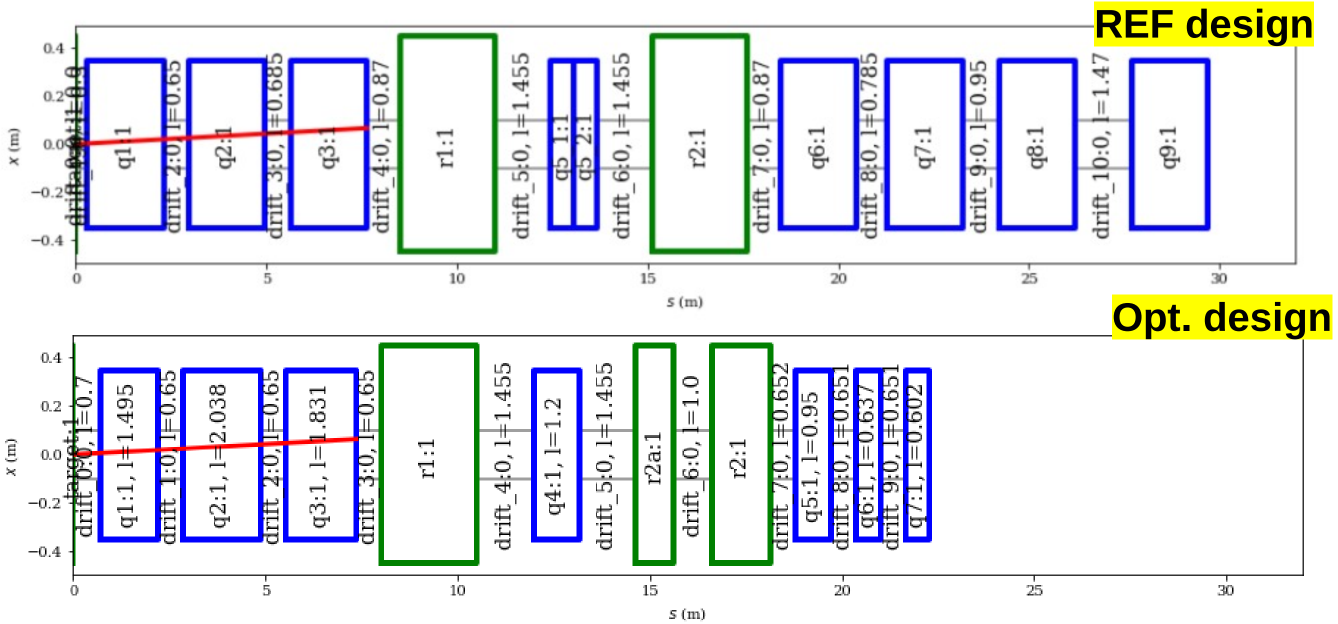
Two 2D projections of 3D Pareto front

Selected solution

Optimized Solution (Layout)

- Optimized beamline is ~7 m shorter
- Quadrupoles in last triplet much shorter
- Beam remains **-42% smaller** throughout the decay tunnel
- Beam is **-82%** smaller at the Pb plate at Q4
- Graphite target has changed from the ENUBET target (L=0.7 m, r=3 cm) to a CNGS-like target (L=1.25 m, r=2.75 mm)
- Transmission improved by **+107%** mostly due to shape of y-y' acceptance

Layout comparison



Optimized Solution (Optics)

- Optimized beamline is ~7 m shorter
- Quadrupoles in last triplet much shorter
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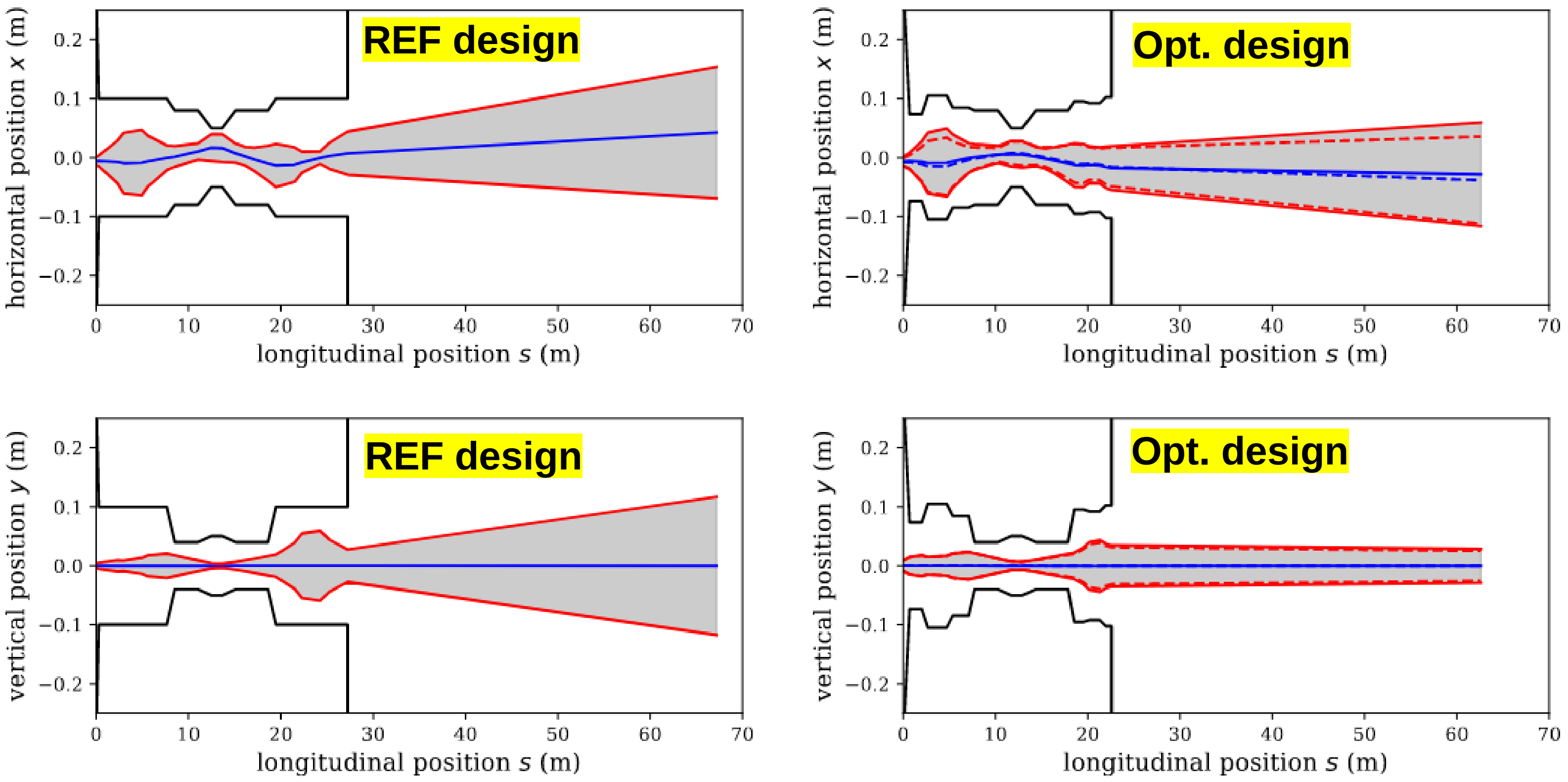
Optics comparison (1σ beam size)



Optimized Solution (Acceptance)

- Optimized beamline is ~7 m shorter
- Quadrupoles in last triplet much shorter
- Beam remains **-42% smaller** throughout the decay tunnel
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- Graphite target has changed from the ENUBET target (L=0.7 m, r=3 cm) to a CNGS-like target (L=1.25 m, r=2.75 mm)
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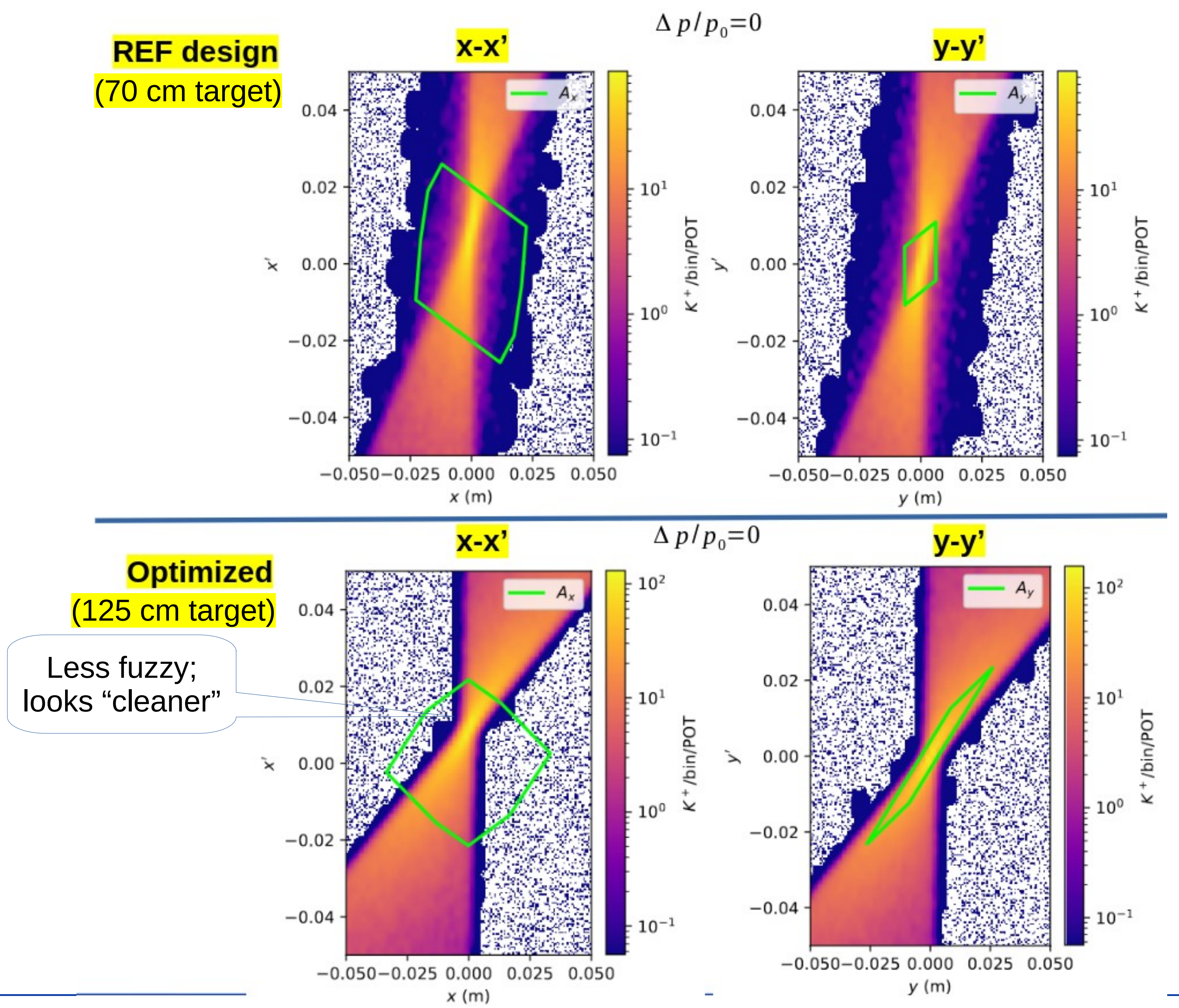
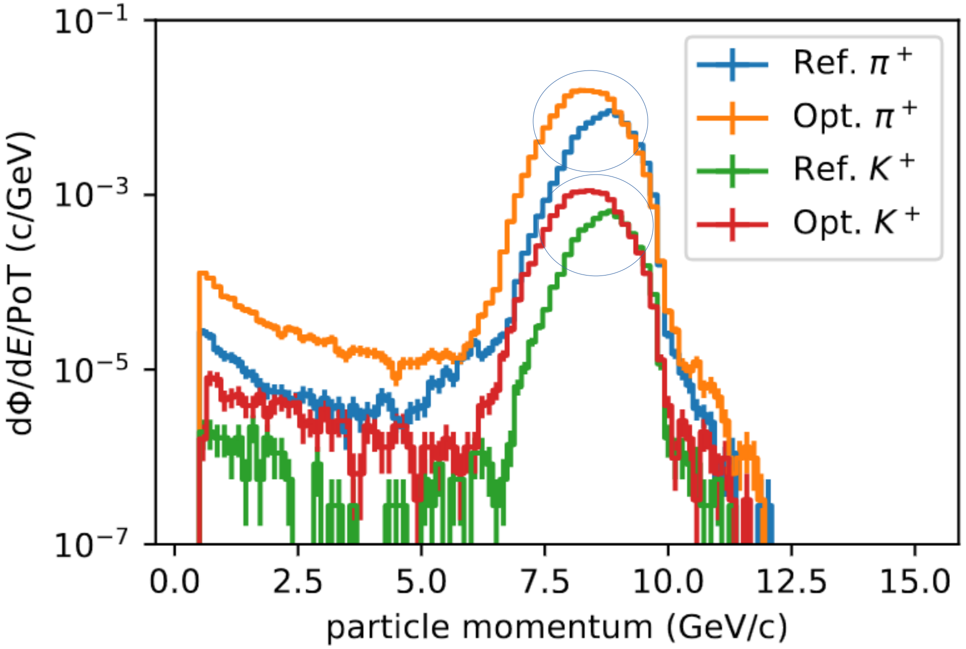
Acceptance comparison



Verification via BDSIM after MOGA Optimization

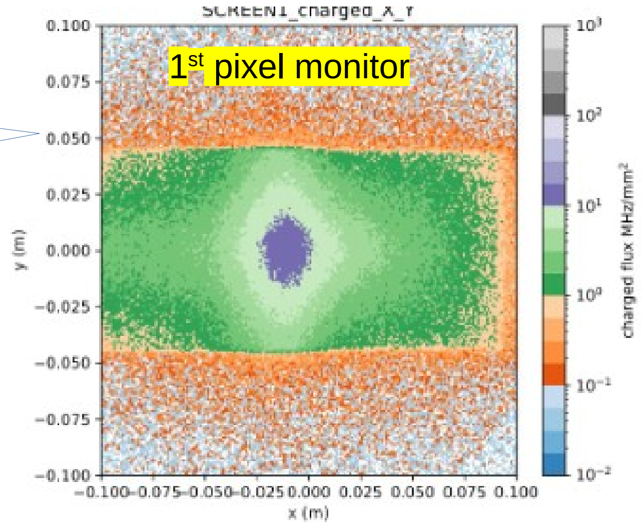
- Have created a BDSIM model (GEANT4 with FTFP_BERT physics list) of the beamline to confirm the transmission gains.

beamline design		K^+/PoT (10^{-4})	π^+/PoT (10^{-3})
Ref.	linear	11.6	15.8
Opt.	linear	23.8 (+107 %)	30.7 (+95 %)
Ref.	BDSIM	6.9	9.9
Opt.	BDSIM	14.5 (+110 %)	20.4 (+105 %)



- Compared to the ENUBET baseline design, the REF design featured 2x transmission. The optimized line improved it by another factor 2x (4x in total); however, a Pb plate had to be inserted to remove positrons from the beam (small loss of intensity)

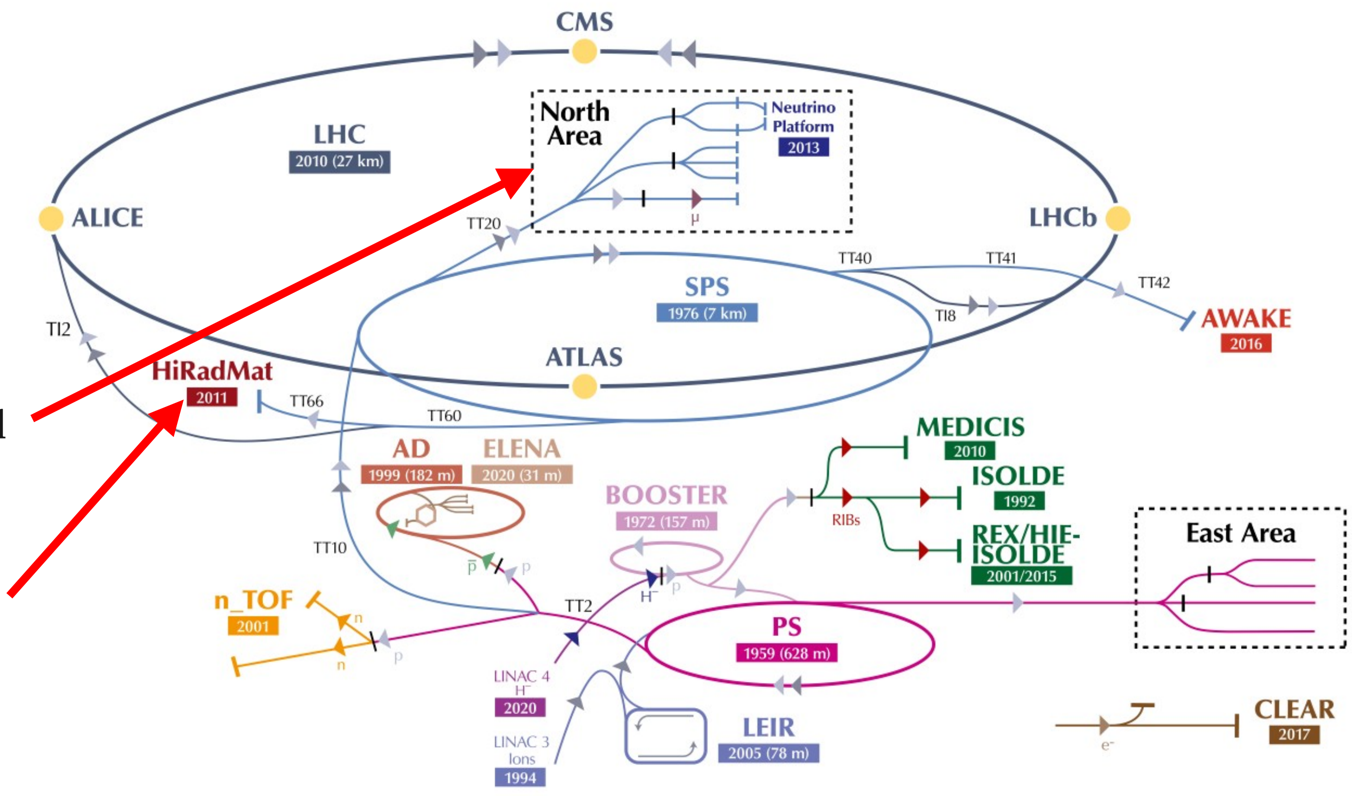
Spill intensity 5E12 PoT/4.8s



A PRAB paper is going to be submitted by Dec. 2024
The code will then become available.

Conceptual Feasibility Analysis for the PBC-SBN

- Current design assumes 5E12 PoT/spill for a 4.8s slow extraction (or 1E13 PoT/spill for a 9.6 s extraction)
- The PoT requirement for the ENUBET physics cases has reduced to 1.4E19 PoT (28% of the initial requirement).
- A conceptual feasibility analysis is ongoing:
  - **The North Area:** features a slow extraction and already houses the ProtoDUNEs; however, the beamline placement is not easily achievable
  - **West Area:** no slow extraction; however, more space and some existing infrastructure
- Our findings will be summarized by the end of the year and will support the application of the PBC-SBN to the ESPPU in March 2025.



Conclusion

- The MOGA optimization based on a concept that uses a non-tracking approach that uniquely couples accelerator-physics concepts with a particle-matter interaction simulation appears to be highly efficient
  - Effectiveness was confirmed within BDSIM simulations
  - Good performance and results even in the range of 26+ free parameters of different types (drift spaces, quadrupole parameters, target properties)
  - Approach highly flexible and may also be used for existing secondary beamlines and new beamline designs
- The PBC-SBN beamline transmission was improved by an additional factor 2x (4x improvement over the ENUBET baseline design). The ENUBET physics case (1e4 ν_e events) could be reached in a time span between **5 and 10 years with a PoT investment between 13% and 26% of the North Area PoT**.
- We are currently investigating a potential placement at CERN's North Area and (former) West Area

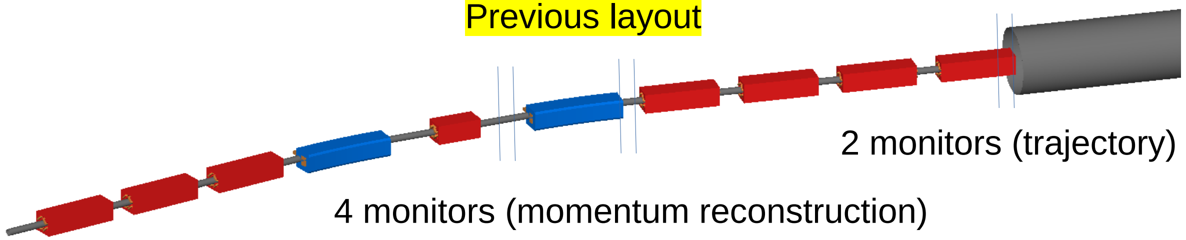
PRAB paper on optimization to be submitted before the end of this year;

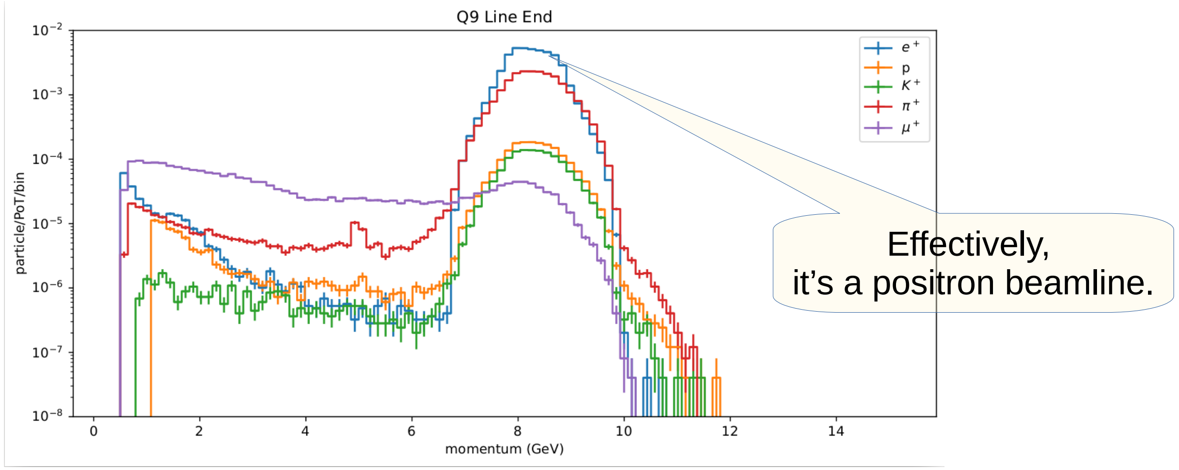
PBC reports (including the PBC-SBN) are being prepared for March 2025 (ESPPU)

Thanks for your attention!
Questions?

Introducing the NuTAG Trackers

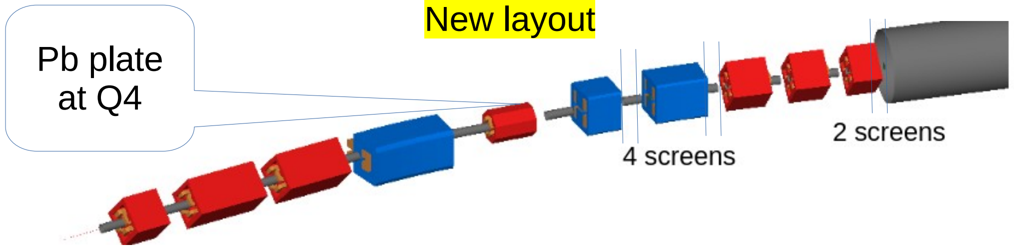
- The beamline as decided cannot be used for the purpose of NuTag:
  - Six pixel monitors are required for a particle-by-particle momentum reconstruction as well as knowing the trajectory in the decay tunnel
  - Too many positrons; first pixel detector easily exceeds 100 MHz/mm² (NA62 GigaTrackers 2 MHz/mm²)

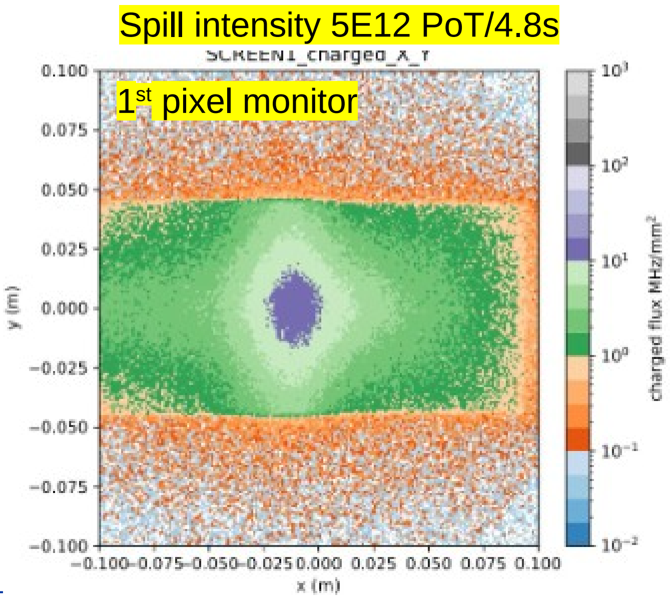




New layout: that removes positrons:

- 1.2 cm Pb plate followed by a short dipole that removes positrons
- Last quad removed





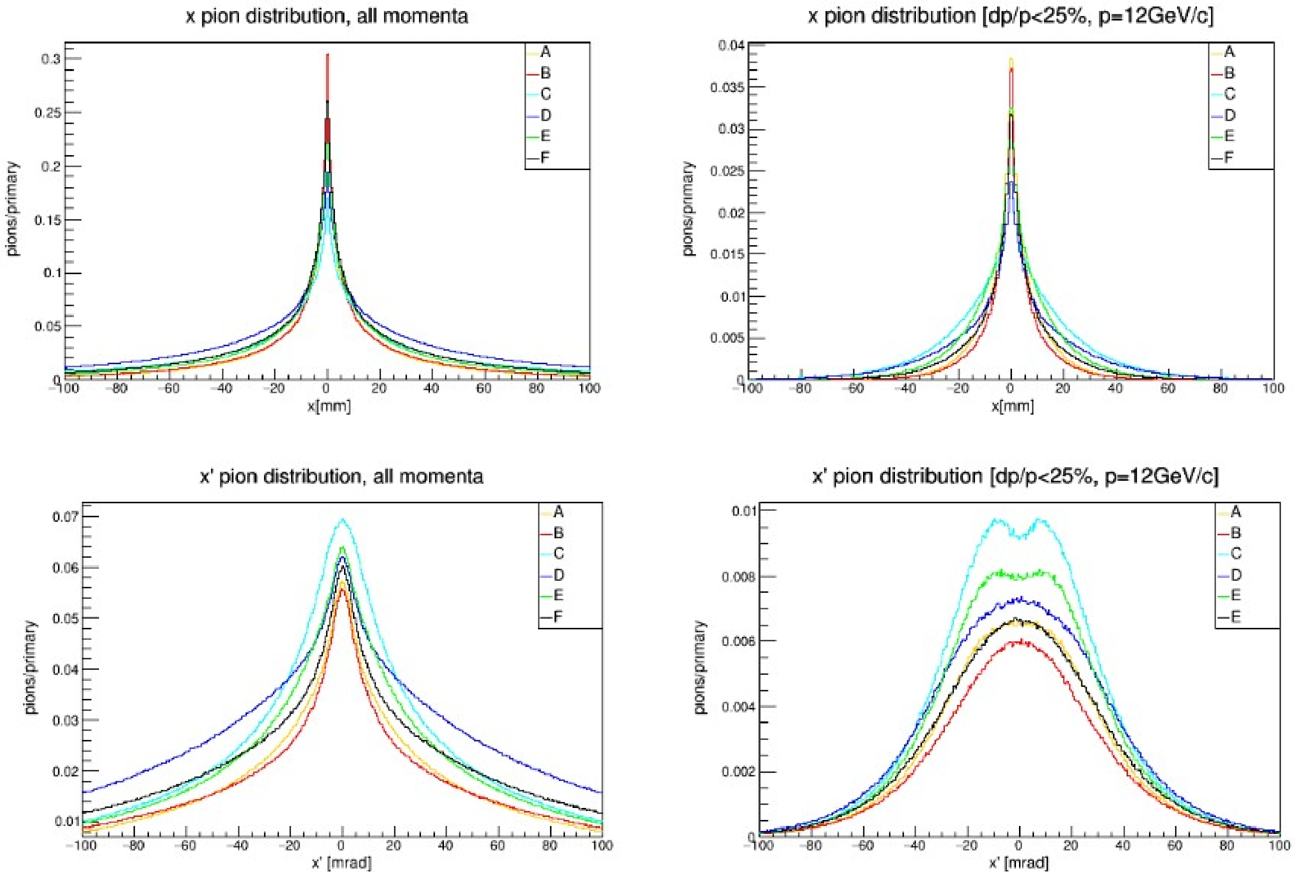
List of Targets

Name	Geometry	Length L (m)	Radius r (mm)	Density ρ (g/cm^2)
ENUBET A	cylinder	0.70	30	2.3
ENUBET B (thin)	cylinder	0.70	10	2.3
CNGS A (correct)	mulitple cylinders	1.30*	2/3	1.8
CNGS B (collapsed)	cylinder	0.70	2.5	1.7
CNGS C (thin)	cylinder	1.30	2	1.7
CNGS D (thick)*	cylinder	1.30	3	1.7
CNGS E (long)	cylinder	1.40	2.5	1.7
CNGS F (short)	cylinder	1.20	2.5	1.7
CNGS G (very thick)	cylinder	1.30	13	1.7
NuMI	cylinder	0.94	3.7	1.7
T2K	cylinder	0.91	13	1.7
CNGS H	cylinder	1.30	3.5 (+0.5)	1.7
CNGS I*	cylinder	1.30	3	1.8
CNGS J*	cylinder	1.30	3	2.0
CNGS K*	cylinder	1.30	3	2.2
CNGS L*	cylinder	1.30	3	2.4
CNGS M*	cylinder	1.35 (-0.05)	3	2.4

Target comparison

A. Baratto-Roldán et al.: NuTag: proof-of-concept study for a long-baseline neutrino beam

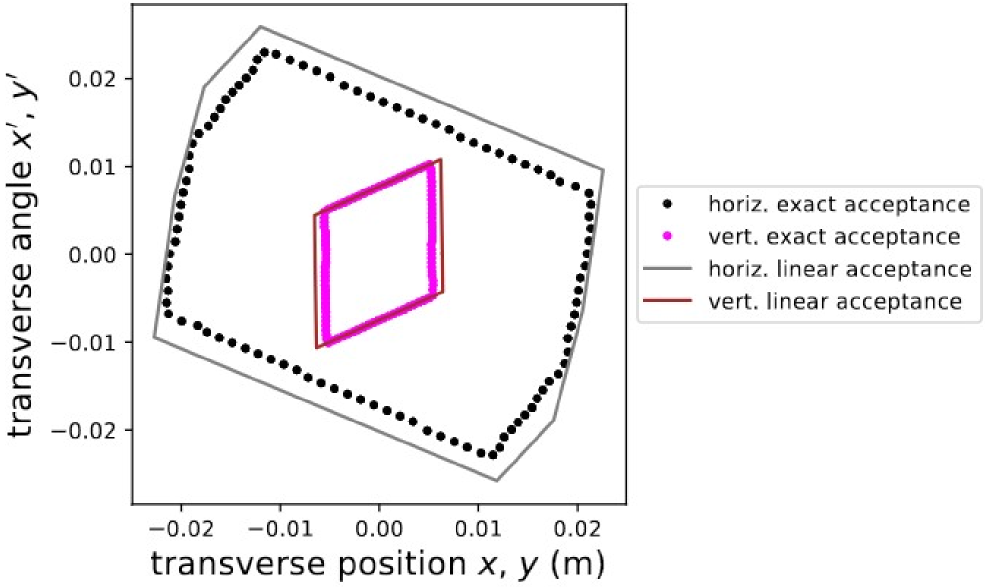
Identifier	Length [cm]	Radius [mm]	Comment
A	70	5	Length of ENUBET proposed target [62]
B	70	13	Length of ENUBET proposed target [62] with T2K's target radius [61]
C	126.1	2.5	Length and radius of CNGS target [58]
D	126.1	13	Length of CNGS target [58] with T2K's target radius [61]
E	94	3.7	Length and radius of NuMi first design target [60]
F	91.4	13	T2K-like target [61]



Does the Linear Acceptance Suffice?

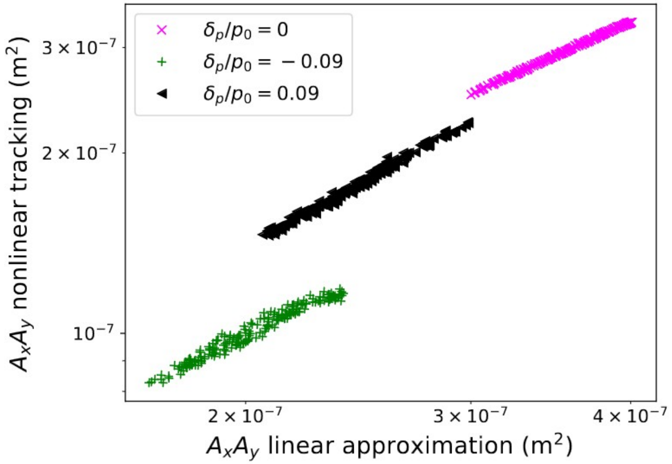
- One can analytically calculate the acceptance of the beamline in the linear limit **(fast)**
- The nonlinear acceptance; however, can only be obtained via tracking **(slow)**

On-momentum acceptance of SBN beamline



Requirement fulfilled **even though**
A) the acceptance is at large action $J_{x/y}$, and
B) the energy offset δ_p is large
in the PBC-SBN line

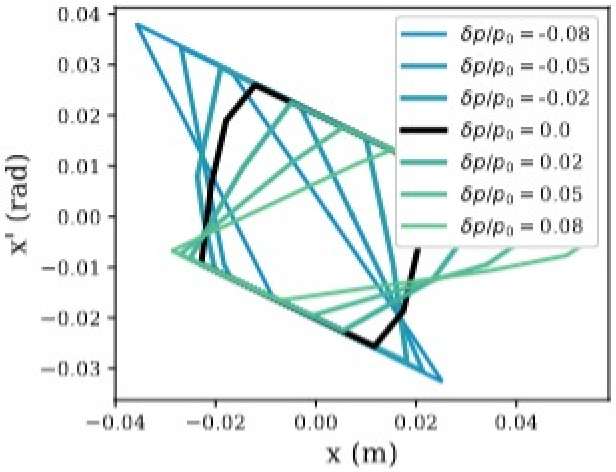
- Clearly the linear approximation overestimates the "real" acceptance; **however, is it terrible?**
- Multi-objective Genetic Algorithms (MOGA) like NSGA-II are mostly based on the sorting of solutions:
  - *"Keep solution A if the transmission is better than that of solution B."*
- The absolute value of the transmission does not matter. The relative comparison between solution matters!
- If the map "nonlinear acceptance" → "linear acceptance" is invertible, we can stick to the optimization within a linear frame work

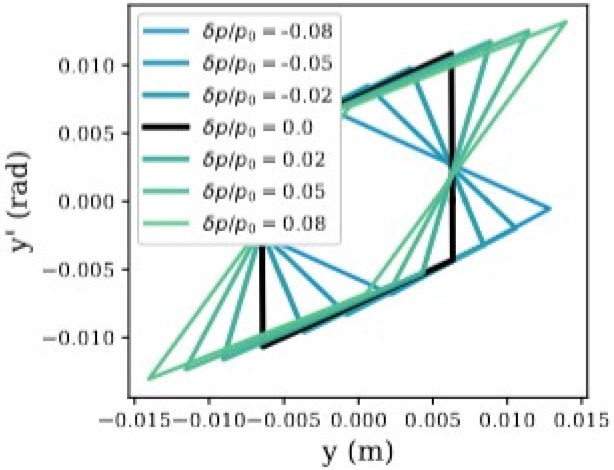


Example with 200 machines: For three different momenta, the product A_xA_y has on average a linear correlation coefficient r=0.999

Slicing of the Phase Space

Acceptance for different momentum offsets





CNGS target: Histogram mostly block diagonal

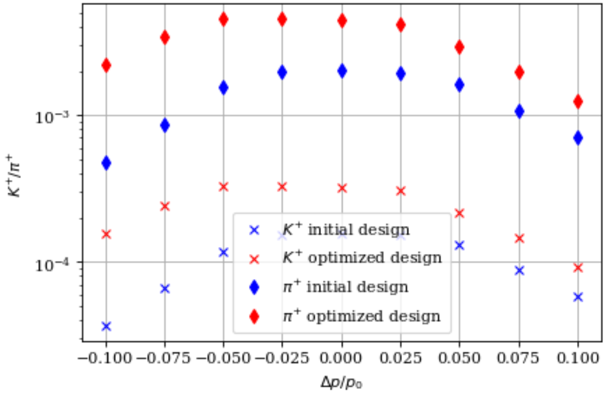
$$\frac{\mathrm{cov}(A,B)}{\sigma_A\sigma_B} = \begin{array}{|ccccc|} x & p_x & y & p_y & p_z \\ \hline \mathbf{1.0} & \mathbf{0.9} & 1.0\times10^{-3} & 1.3\times10^{-3} & -6.8\times10^{-4} \\ & \mathbf{1.0} & 1.4\times10^{-3} & 1.6\times10^{-3} & -1.6\times10^{-3} \\ & & \mathbf{1.0} & \mathbf{0.9}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

Target's momentum dependence

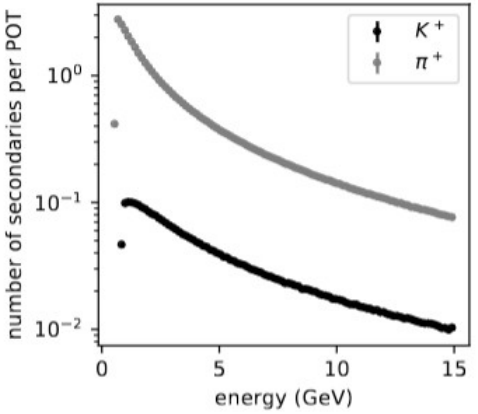
$$\frac{\mathrm{d}\Phi_K}{\mathrm{d}p}(p) = \frac{2.12\times10^{-2}}{\mathrm{GeV/c}} - (p - 8.5\,\mathrm{GeV/c})\frac{0.39\times10^{-2}}{\mathrm{GeV^2/c^2}} \quad (1)$$

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

Transmission at different momentum offsets

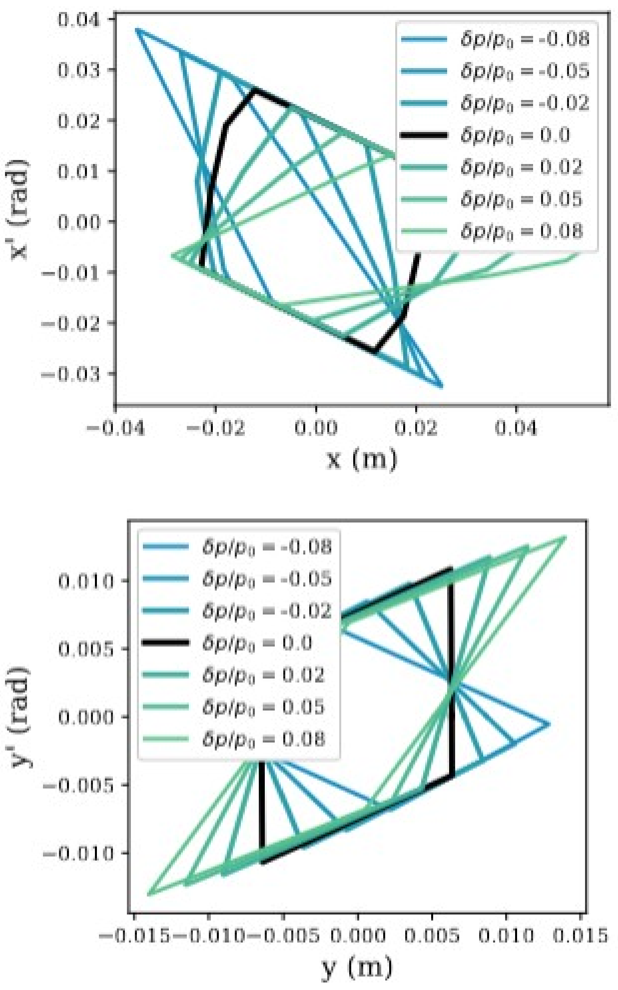


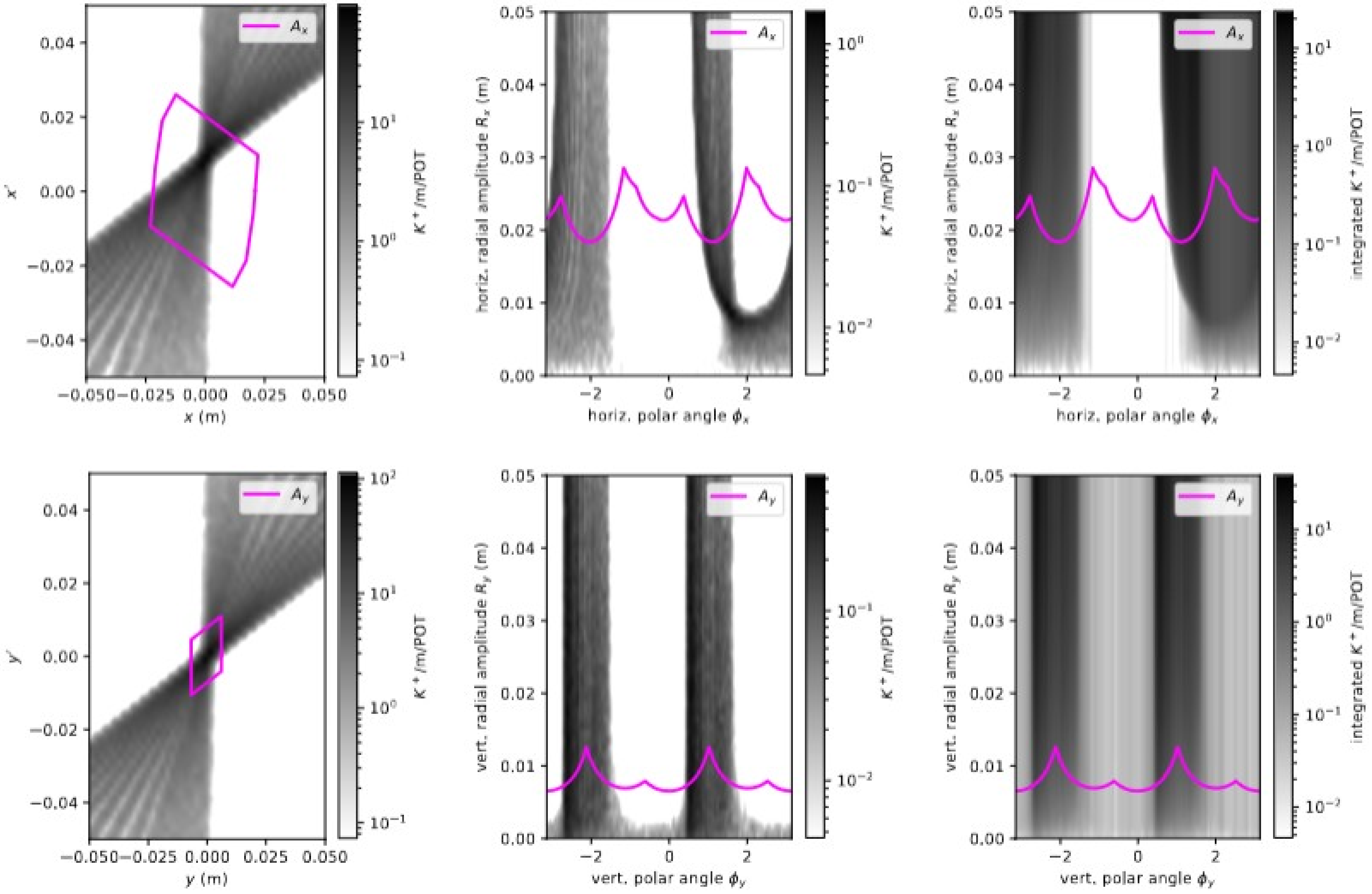
Target's momentum dependence



The overlap of the acceptance with the target histogram

Acceptance for different momentum offset





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