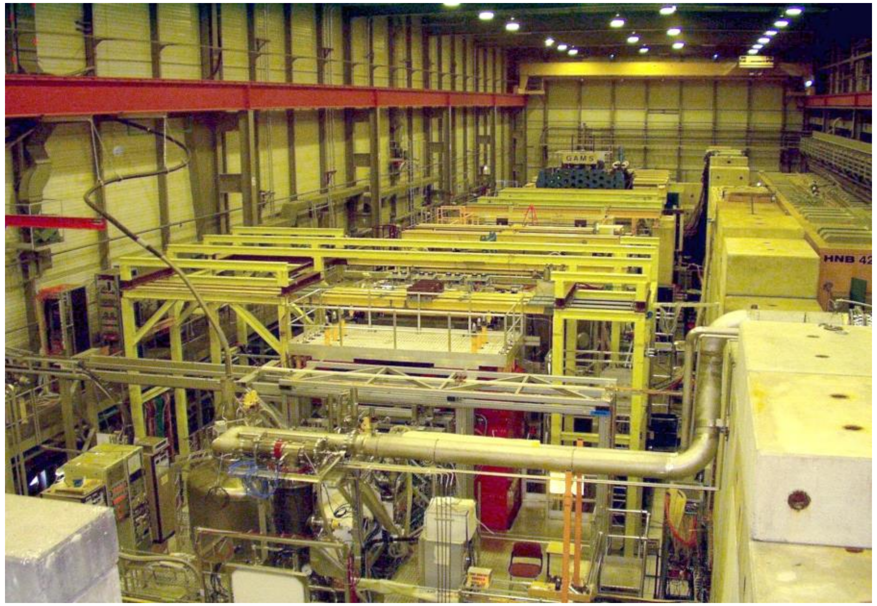
RF separated beams in CERN’s secondary M2 beam line

Fabian Metzger[1,2], Dipanwita Banerjee[1], Johannes Bernhard[1], Markus Brugger[1], Lau Gatignon[3], Alexander Gerbershagen[4], Frank Gerigk[1], Laurie Nevay[1], Silvia Schuh[1] on behalf of the PBC Conventional Beams Working Group
08.11.2022

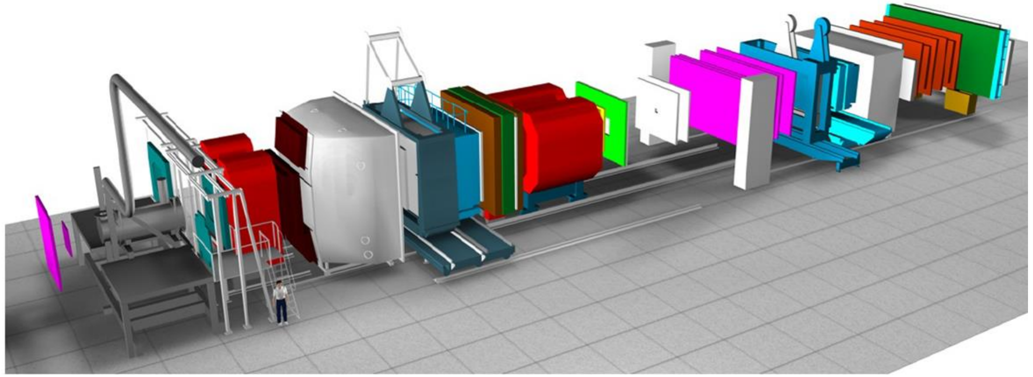
[1]CERN, Geneva, Switzerland
[2]HISKP, University of Bonn, Germany
[3]University of Lancaster, UK
[4]PARTREC, University of Groningen, Netherlands

AMBER at CERN’s M2 beam line



AMBER’s phase 2 measurements

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	$\sim$100	10^8	25-50	$K^{\pm}$, $\overline{p}$	$NH_3^{\uparrow}$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	$\sim$100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^{\pm}$ $\pi^{\pm}$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^{\pm}, \pi^{\pm}$	from H to Pb	2026 1 year	



Very optimistic.
Current estimates: LHC Run 4

AMBER at CERN's M2 beam line - ctd

2 workshops jointly organized by BE Experimental Area Group together with the AMBER collaboration, the EP-SME, SY-RF groups and the CERN TH department:

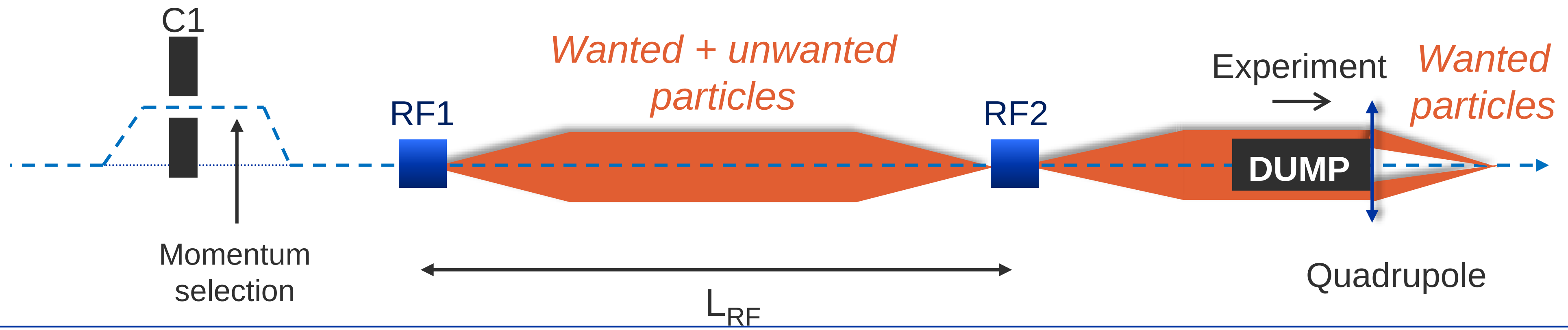
1. **Workshop on RF separated beams, 30 Sep. 2021: https://indico.cern.ch/event/1069879/**
   - Define the physics case(s) for the phase-2 physics measurement goals of the AMBER collaboration
   - Present the status of the currently available RF separated beam line studies
   - Review the present technical limitations, with the goal to define the next steps towards a potential feasibility study
2. **Follow-up Workshop, 23-24 March 2022: https://indico.cern.ch/event/1133376/**
   - Outcome of the RF separated beams workshop of September 2021
   - Review of kaon induced DY with improvements in the conventional beam line setup

Principle of RF separation

- **In a secondary beam, one has different particle species with same momentum**
  - Discriminate those species by their velocities
  - For M2: Large interest in kaon beams

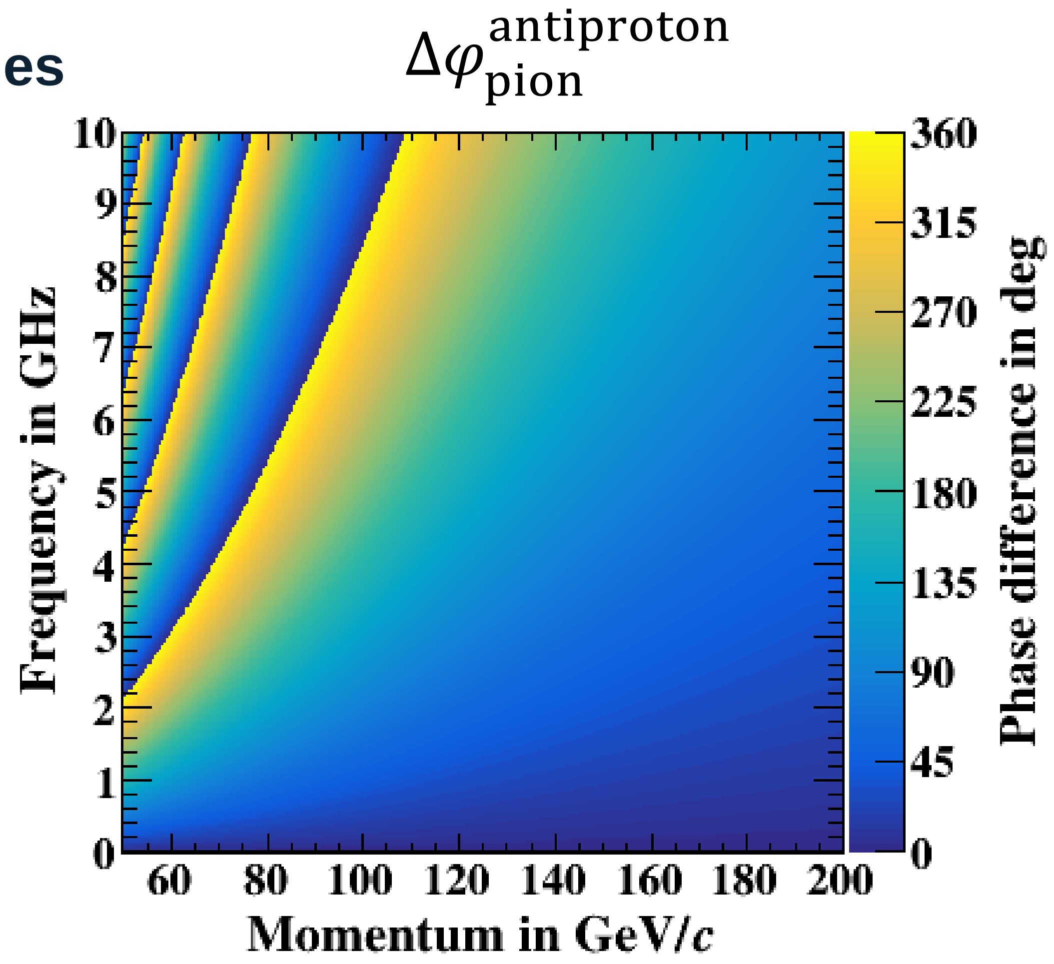
- **Time-dependent transverse kick by RF cavities in transverse dipole mode**

- **Kick by RF1 compensated or amplified by RF2 depending on the velocity**
  - $\theta_{\text{tot}} = \theta\big(\sin(\varphi(t)) + \sin(\varphi(t) + \alpha + \Delta\varphi_{12})\big) = 2\theta \sin\left(\varphi(t) + \frac{\alpha+\Delta\varphi_{12}}{2}\right)\cos\left(\frac{\alpha+\Delta\varphi_{12}}{2}\right)$ Final kick
  - $\bar{\theta} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi}\theta_{\text{tot}}^2(\varphi)\mathrm{d}\varphi} = \sqrt{2}\theta\cos\left(\frac{\alpha}{2}\right)$ Average kick



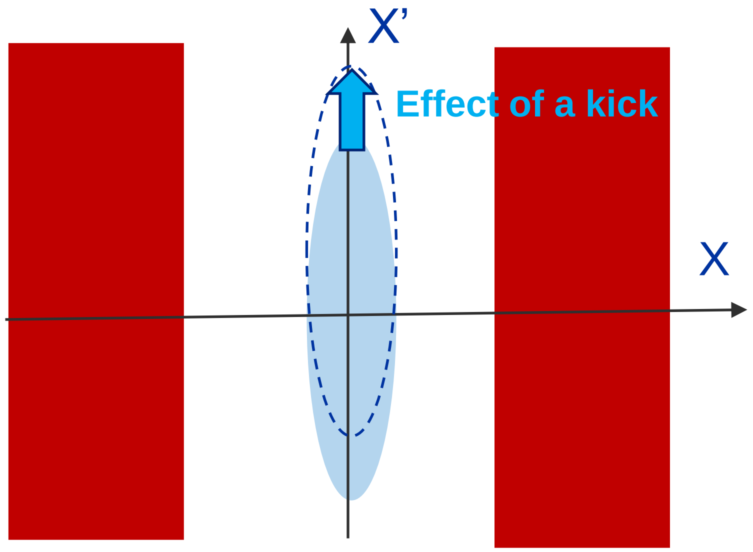
Cavity parameters

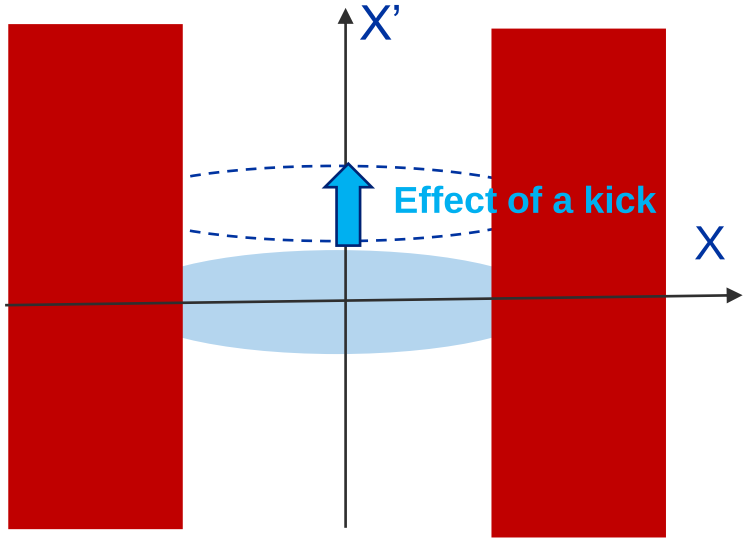
- **We maximized the distance between the cavities**
  - Achieved $L \approx 830\text{m}$
- **Cavity parameters based on ILC crab cavities**
  - Radio frequency: $f = 3.9\text{GHz}$
  - Cavity iris diameter: $2R = 30\text{mm}$
  - Total active cavity length: $L_{\text{tot}} = 10\text{m}$
  - Maximal kick per cavity: $\mathrm{d}p = 50\,{}^{\text{MeV}}/_{c}$
- **Calculate beam momentum**
  - $\Delta\varphi = 2\pi f \Delta t = \frac{2\pi f L}{c} \cdot \frac{E_1 - E_2}{pc} \approx \frac{\pi f L}{c} \cdot \frac{(m_1^2 - m_2^2)c^2}{p^2}$
  - $p \approx \sqrt{\frac{fL}{c}\frac{\pi}{\Delta\varphi}} \times \sqrt{(m_1 c)^2 - (m_2 c)^2}$
  - K^--beam: $\Delta\varphi_{\pi^-}^{\bar{p}} = 2\pi \Rightarrow p \approx 68\,{}^{\text{GeV}}/_{c}$ is **fixed** and close to achievable maximum



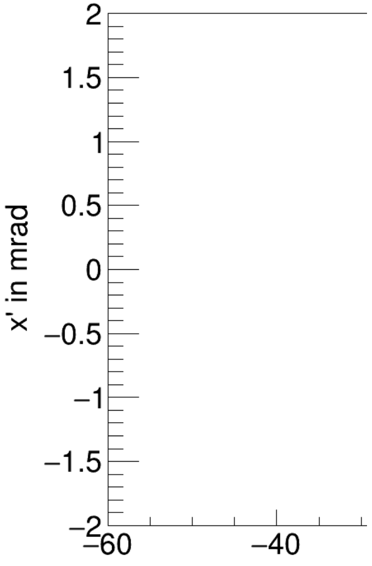
Focused vs. parallel beam in the cavities

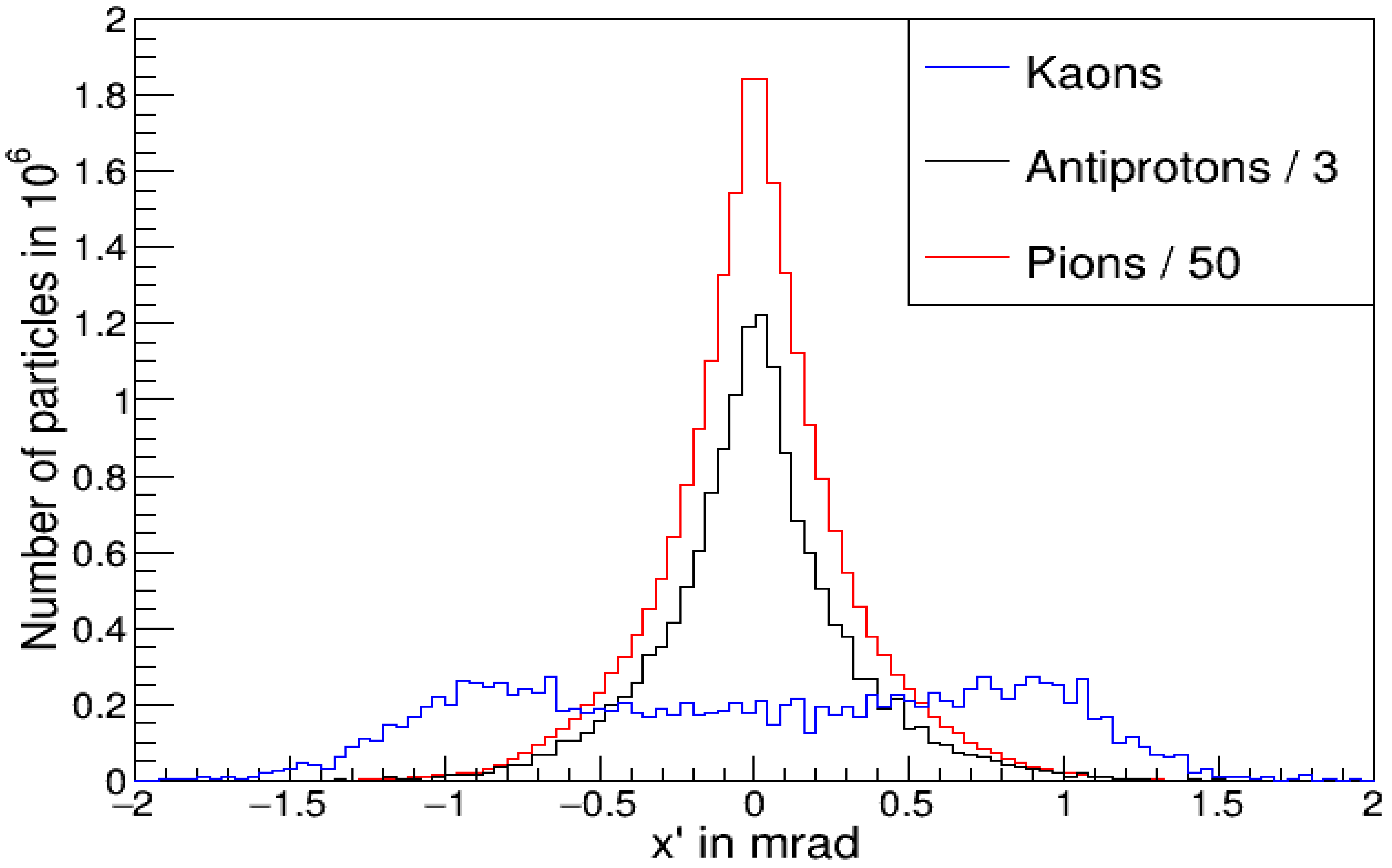
- **Started with a focus in the cavities**
- **Focused beam**
  - Beam is large in x', but small in x
  - Relative effect of the kick is small
  - Beam fits well through the cavity apertures
- **Parallel beam**
  - Beam is small in x', but large in x
  - Relative effect of the kick is larger ⇒ Better separation
  - Emittance is constant ⇒ Smaller divergence means larger beam size
    - Define R_{12} optical function by aperture and beam line acceptance to minimize losses $R_{12} = \frac{\text{Radius of the iris}}{\text{Acceptance}} = 7.5\ ^{\text{mm}}/_{\text{mrad}}$
    - We considered the effective cavity aperture 

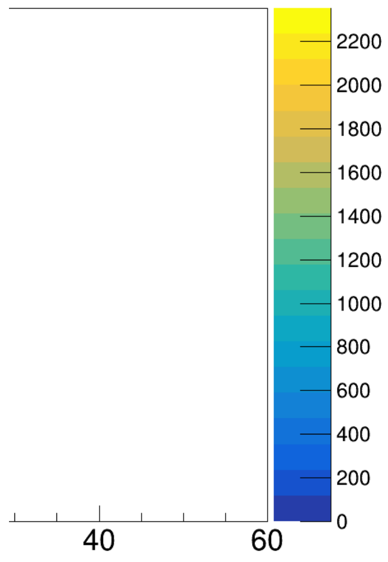




Phase space distribution after RF2



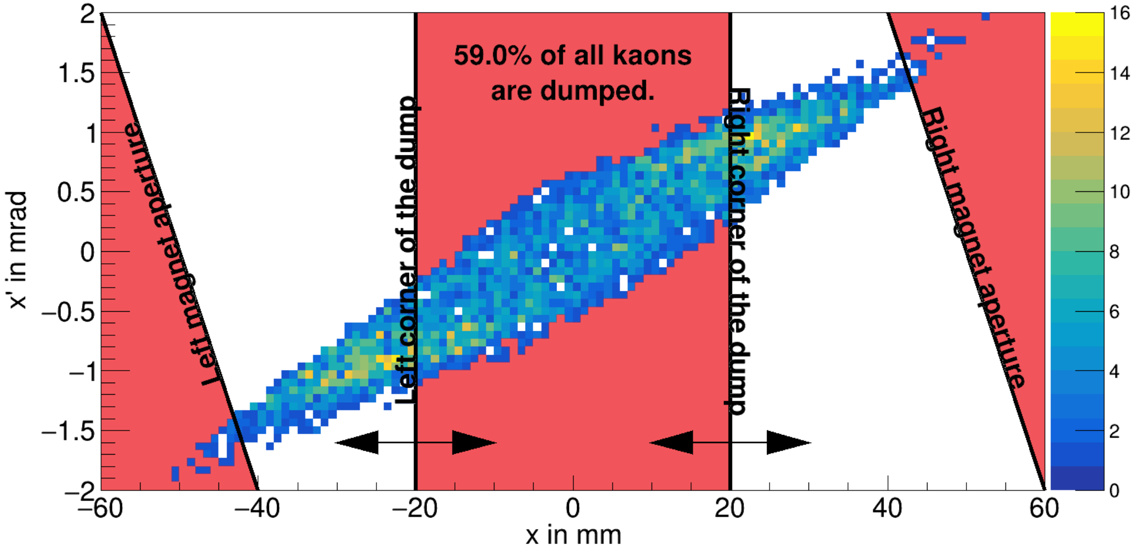




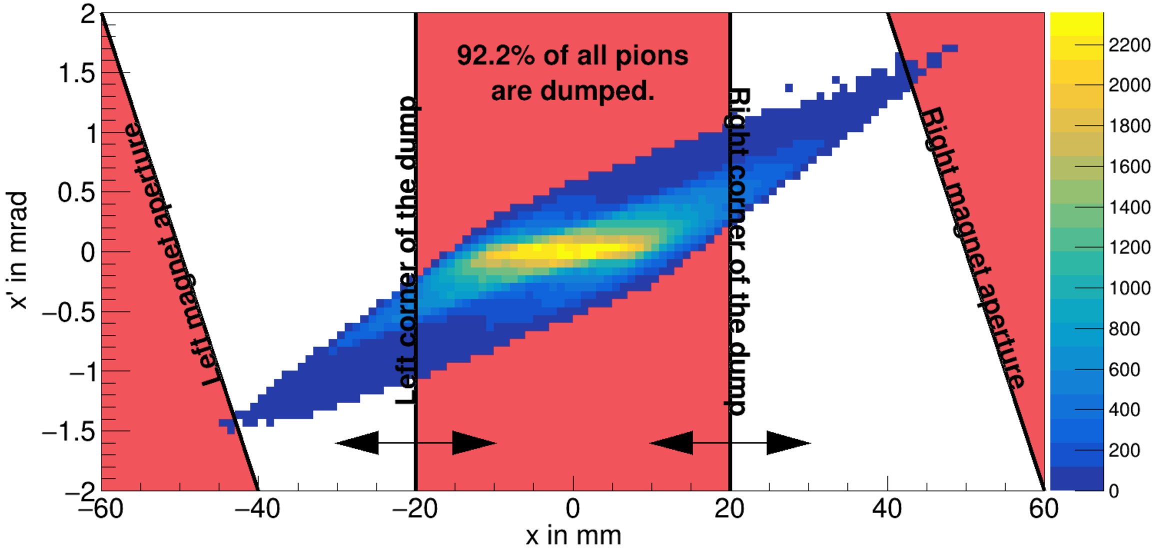
- **Cavity pha**
  - Angular d
  - For π^-an
- **Beam dum**
  - Drift is ne ... ift

Phase space distribution 20m after RF2 (dump)

K^- phase space

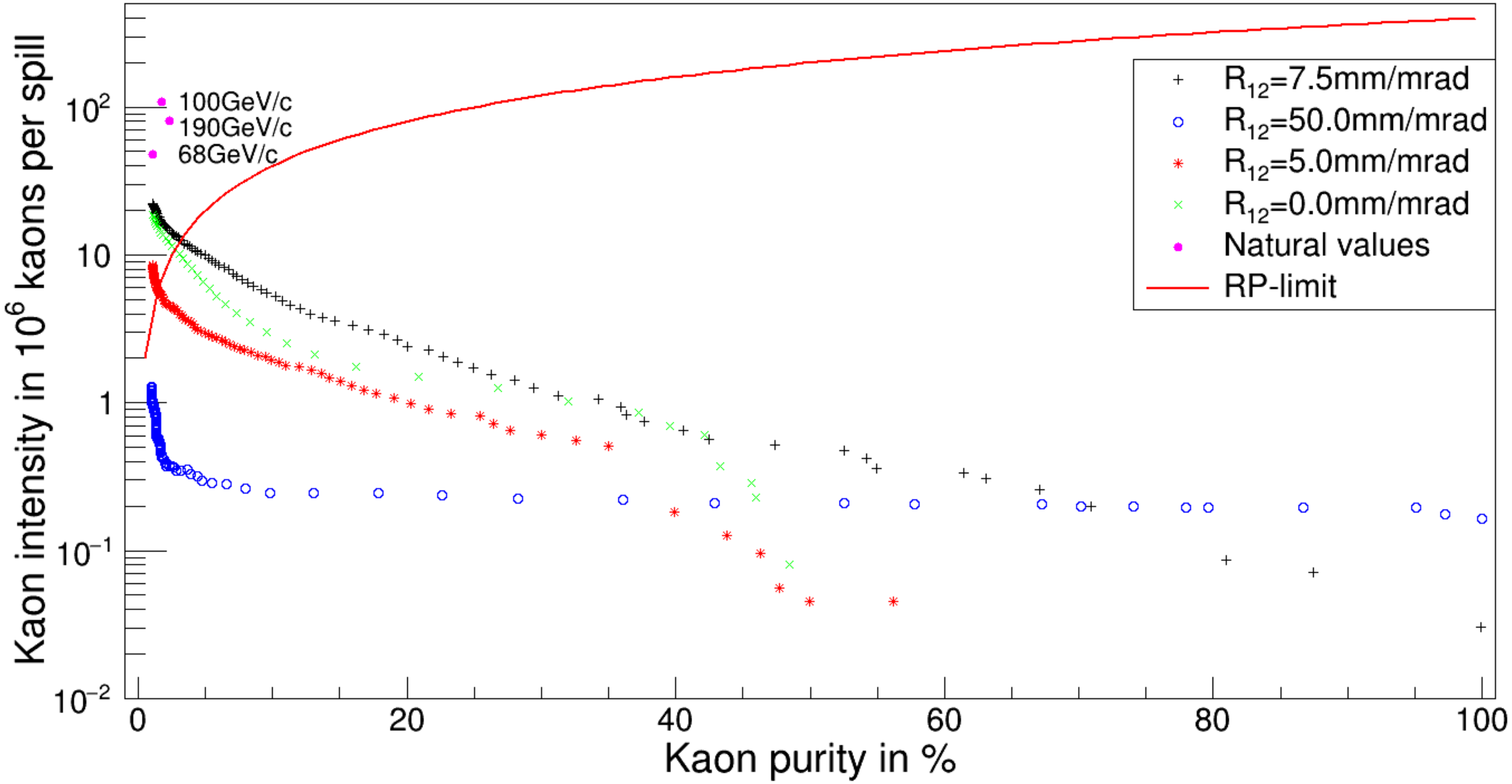


π^- phase space



- **Angular separation converted into spatial separation**
- **With a beam dump, one can optimize either the intensity or the purity; here the share of K^-**
- **For a given cavity kick, the drift needs to be limited; otherwise, particles are lost at the refocussing magnet**

Separation power



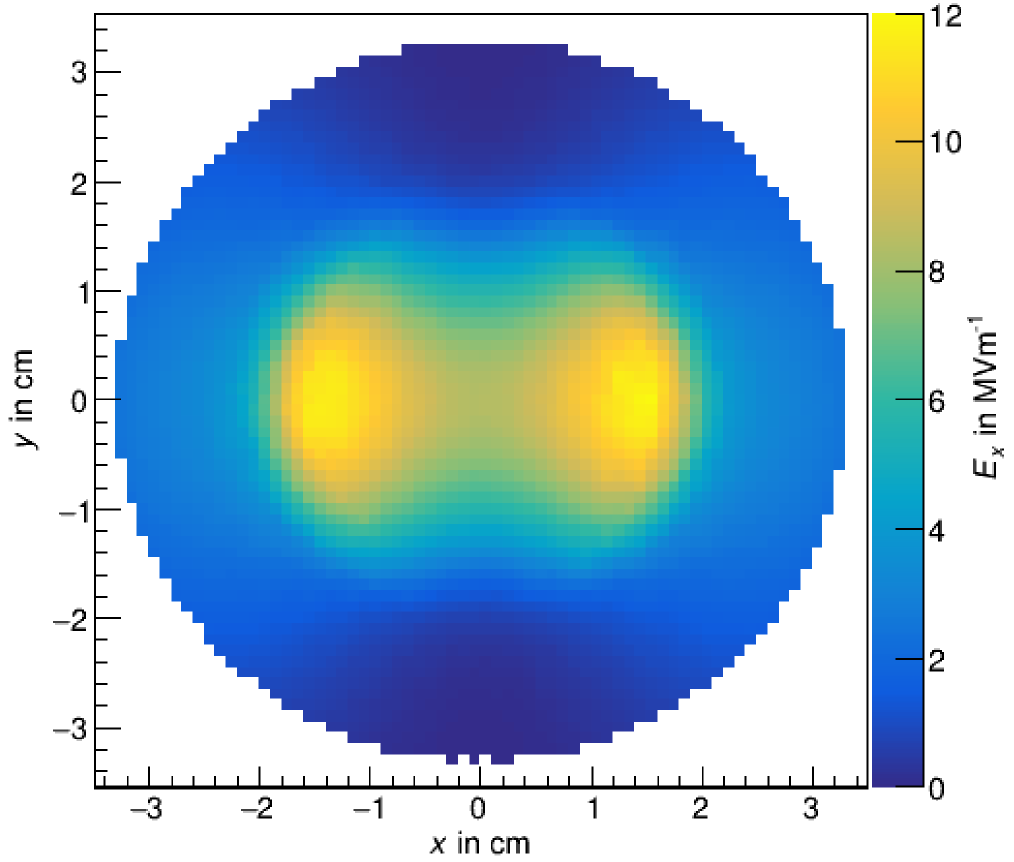
- **Everything above the solid red curve is currently limited due to radiation protection in the EHN2 hall**
- **Simulated with 150 units on T6 (1 unit $\widehat{=}$ 10^{11} protons on target)**
- **SPS spill length is $4.8s$ (beam constantly extracted over this period)**

Summary and conclusions of current status

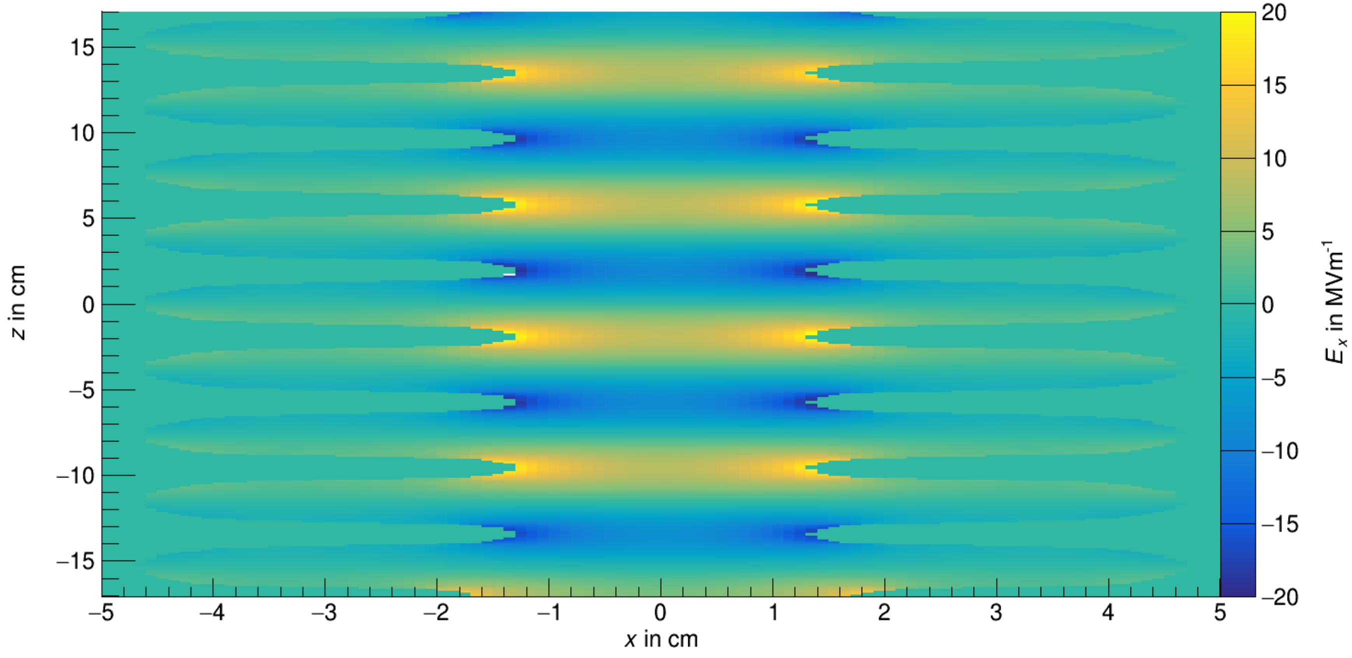
- **We have 5×10^5 kaons per spill with 50% purity; going down to 20% purity means increase to 3×10^6**
- **For the open spectrometer measurements, RF separation shows promising results**
- **For Drell-Yan the intensities are not sufficient**
  - Other options being considered, exploiting upgrades of current beam line with respect to vacuum and optics improvements
- **With the current parameters and beam optics, we have $p \approx 68\ {}^{\mathrm{GeV}}/_{c}$ (already close to achievable maximum due to $p \propto \sqrt{fL}$)**
- **Beam PID will be necessary in any case due to impurities and beam purity constraints**
- **Results are summarized in a PBC-note and submitted to NIM A**
- **Studies to date assumed homogenous electric field over cavity iris**
  - With migration from MAD-X to BDSIM realistic electric field variations are taken into account

Field of the ILC crab cavities

At z = 4.6cm

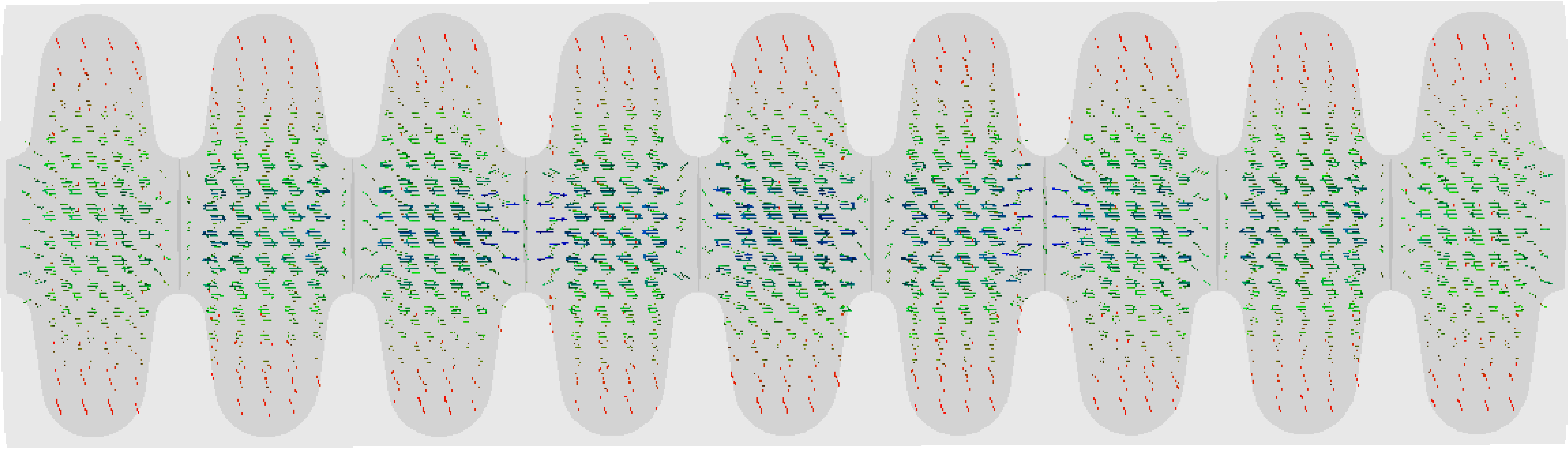


At $y = -0.05$cm



Field maps by G. Burt

Cavity model in BDSIM



- A general description of time-variation has been added to the code (thanks to L. Nevay!)
- Cavity geometry of ILC crab cavities has been modelled and included in BDSIM
- Electric and magnetic field maps (3D) as shown on the previous slide have been overlayed on the cavity geometry
- The model was successfully validated → Tests performed with actual optics and unwanted particles → They receive indeed no kick as intended

Outlook

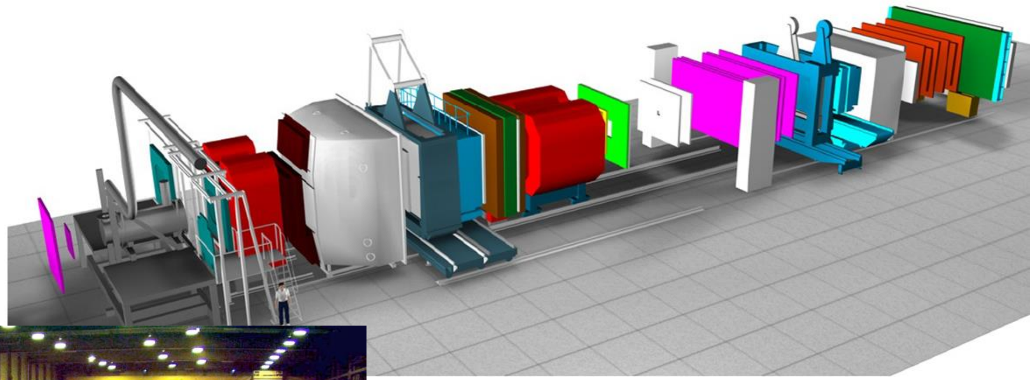
- **Evaluation of impact of inhomogeneities of the realistic electric field on the separation power**
  - For particles of interest, transverse field variations are expected to influence angular separation
  - For unwanted particles, no change expected
  - Reevaluate the separation power plot with both effects considered
- **Background studies**
  - Analysis of particles generated in the beam dump and mitigation thereof
- **Idea of circular polarization (from 2021 workshop)**
  - Exploitation of deflection in both transverse planes
- **Investigate possibility to keep muon beam in M2 parallel to the RF separated beam**

Thank you for your attention!

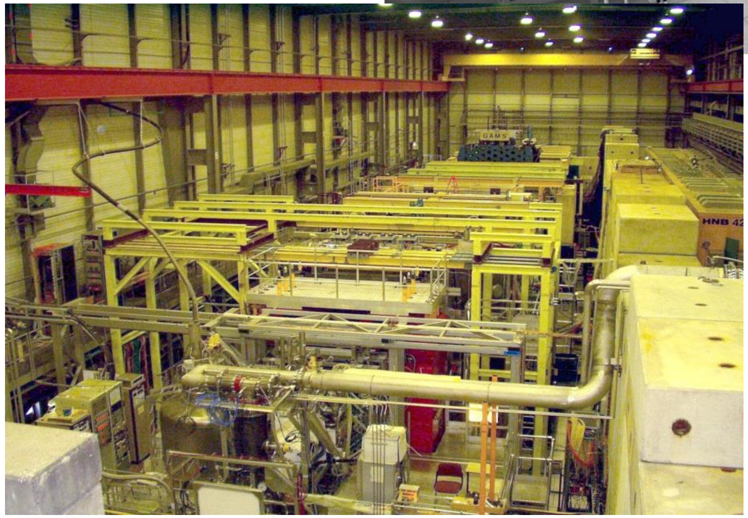
home.cern

Backup

AMBER beam requirements



- RF Workshop
- Follow-Up Workshop
- RF-Separated Beam Project for the M2 Beam Line at CERN

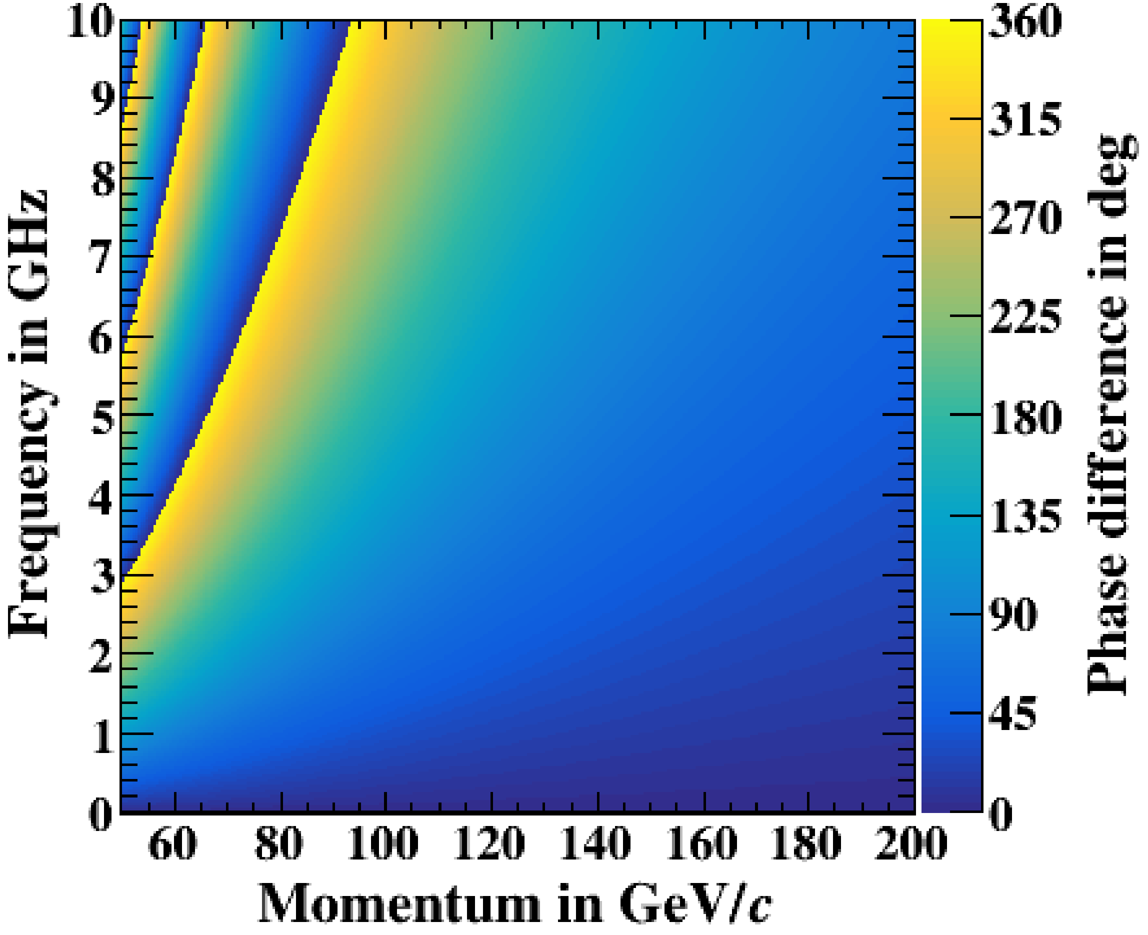


Measurment	Drell-Yan	Kaon polarisability
Energy in GeV	190	100
Kaon intensity in 10^5 per spill	≥ 70	≥ 10

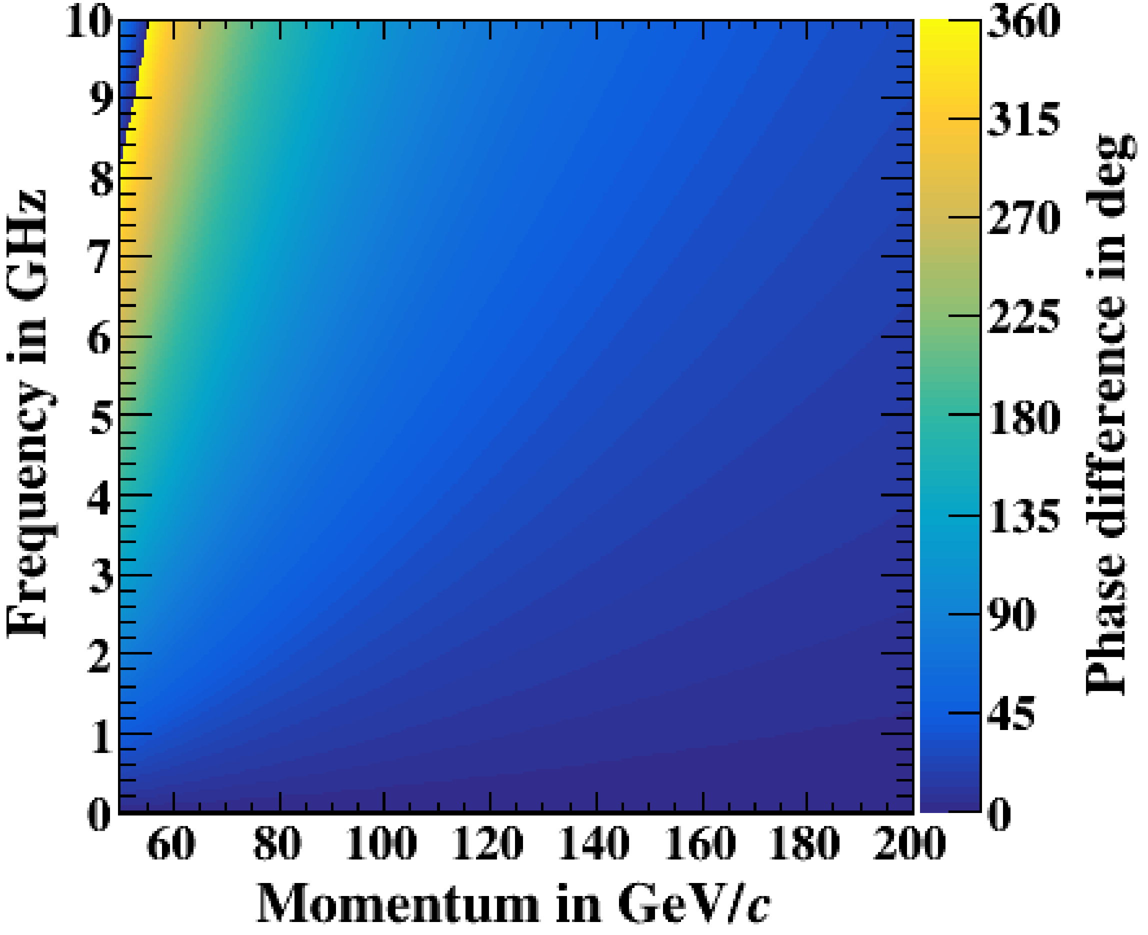
Measurement	Spectroscopy	Primakoff	Prompt photons
Energy in GeV	≥ 80	≥ 80	> 80
Kaon intensity in 10^5 per spill	≥ 4	≥ 2	> 4
Purity after CEDARs $\left({}^{I_K}/{}_{I_\pi}\right)$	> 100	> 1000	> 100

Phase shifts

$\Delta\varphi_{\text{kaon}}^{\text{antiproton}}$



$\Delta\varphi_{\text{pion}}^{\text{kaon}}$

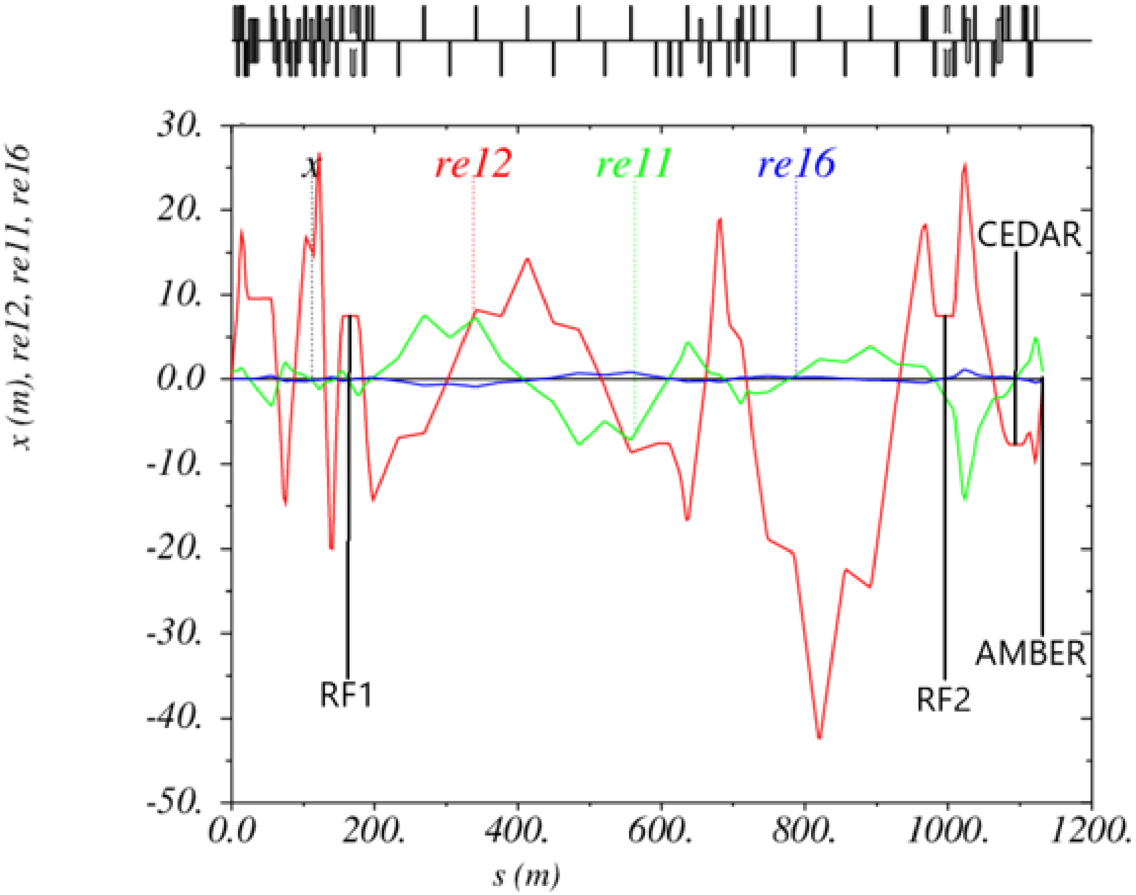


Optics development

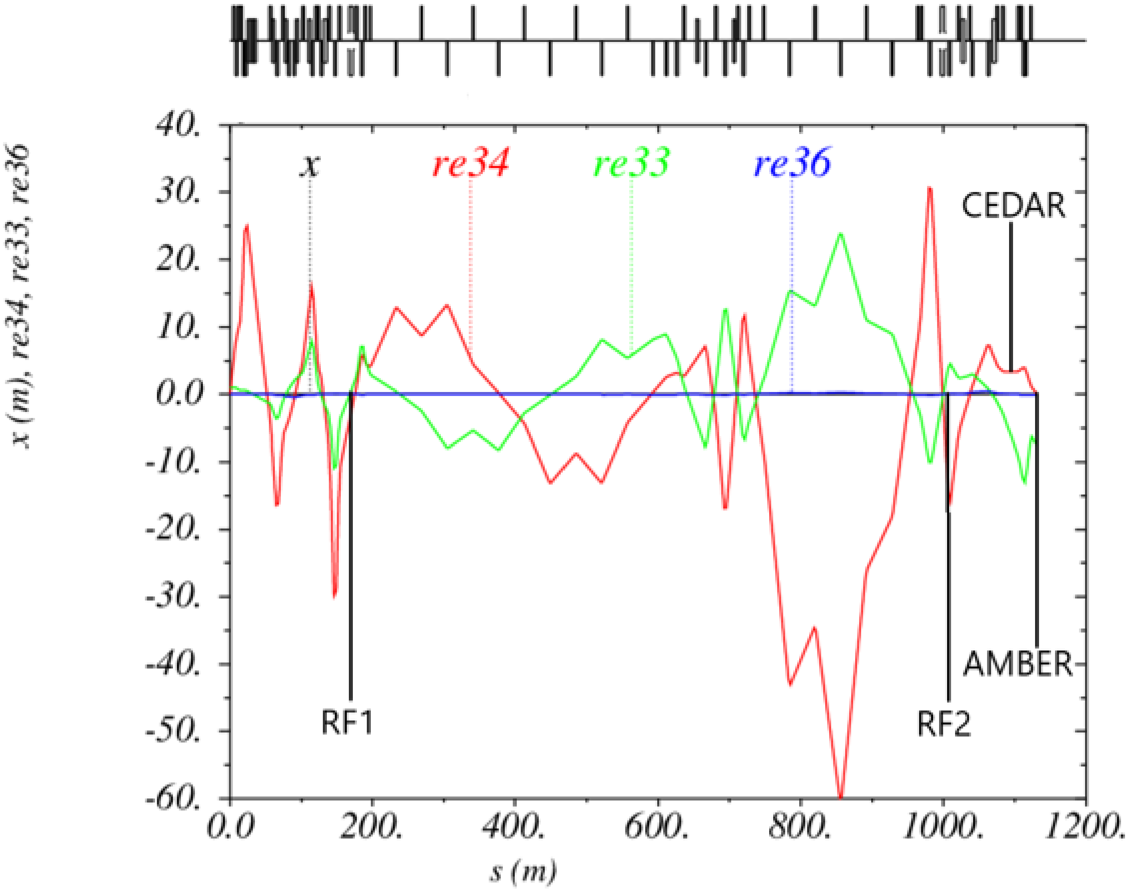
Optics challenges:

- Beam: Compromise between size and parallelism in cavities
  ⇒ Optimization
- Parallel beam in CEDARs
- Focus at AMBER target

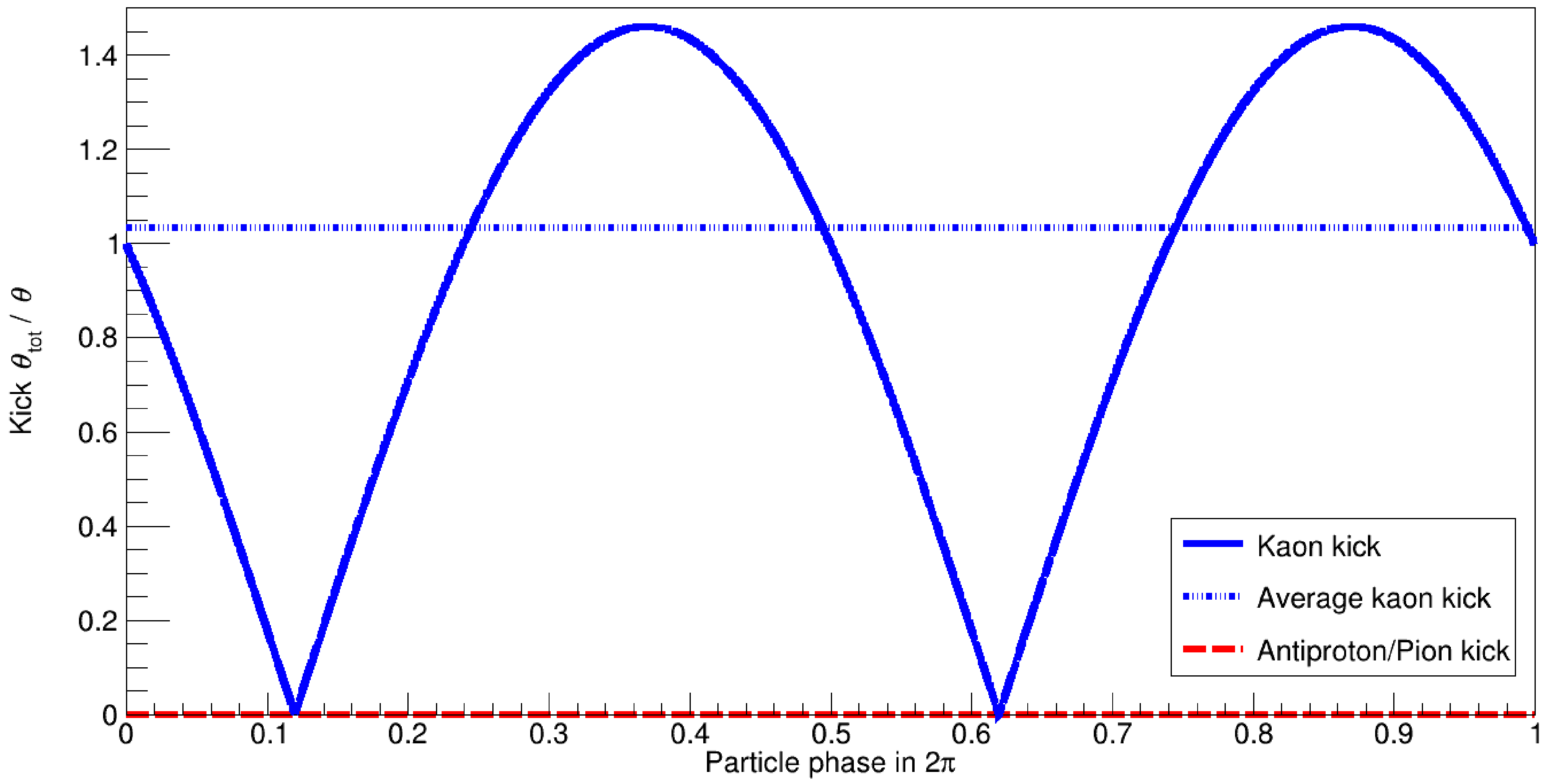
x-plane



y-plane



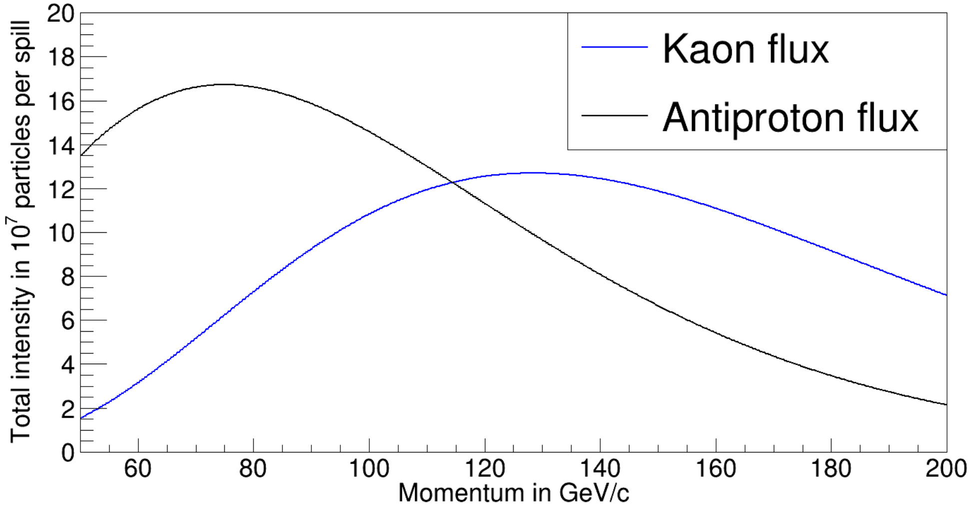
Kick of the cavities

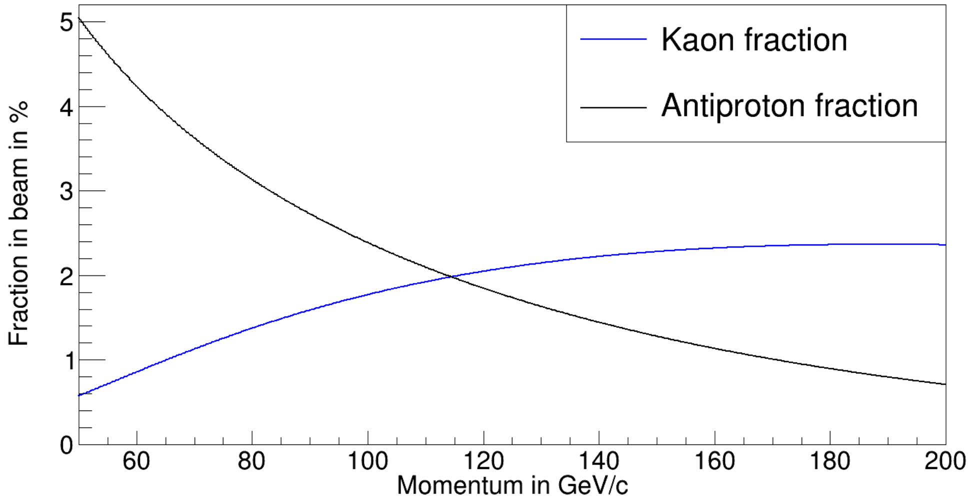


[1]H.W.Atherton et al., Precise measurements of particle production by 400 GeV/c protons on beryllium targets, CERN 80-07, 1980

K^- and $\overline{p}$: intensities and fractions

- **Atherton parametrization[1] to calculate number of particles**
  - Parametrization of particle production measured by NA20
  - With $\frac{\Delta p}{p} = 1\%$
  - Angular acceptance of $17.6\mu\mathrm{sr}$
  - 1.5×10^{13} ppp on T6
  - $500\mathrm{mm}$ Be-target
  - Distance between T6 and AMBER target of $1138\mathrm{m}$
  - Electrons are not considered
- 4.8×10^8 **particles per spill allowed by RP**

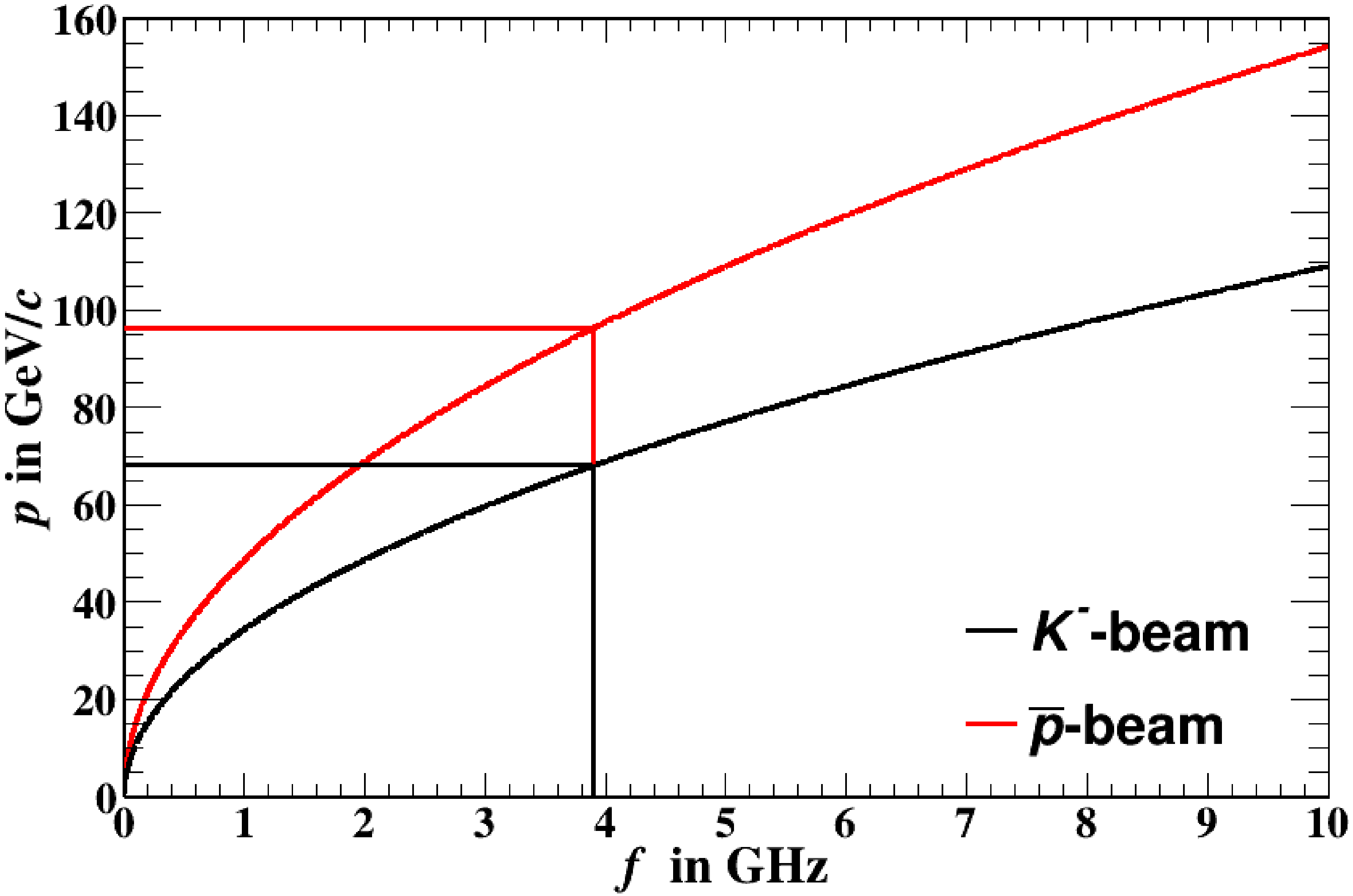




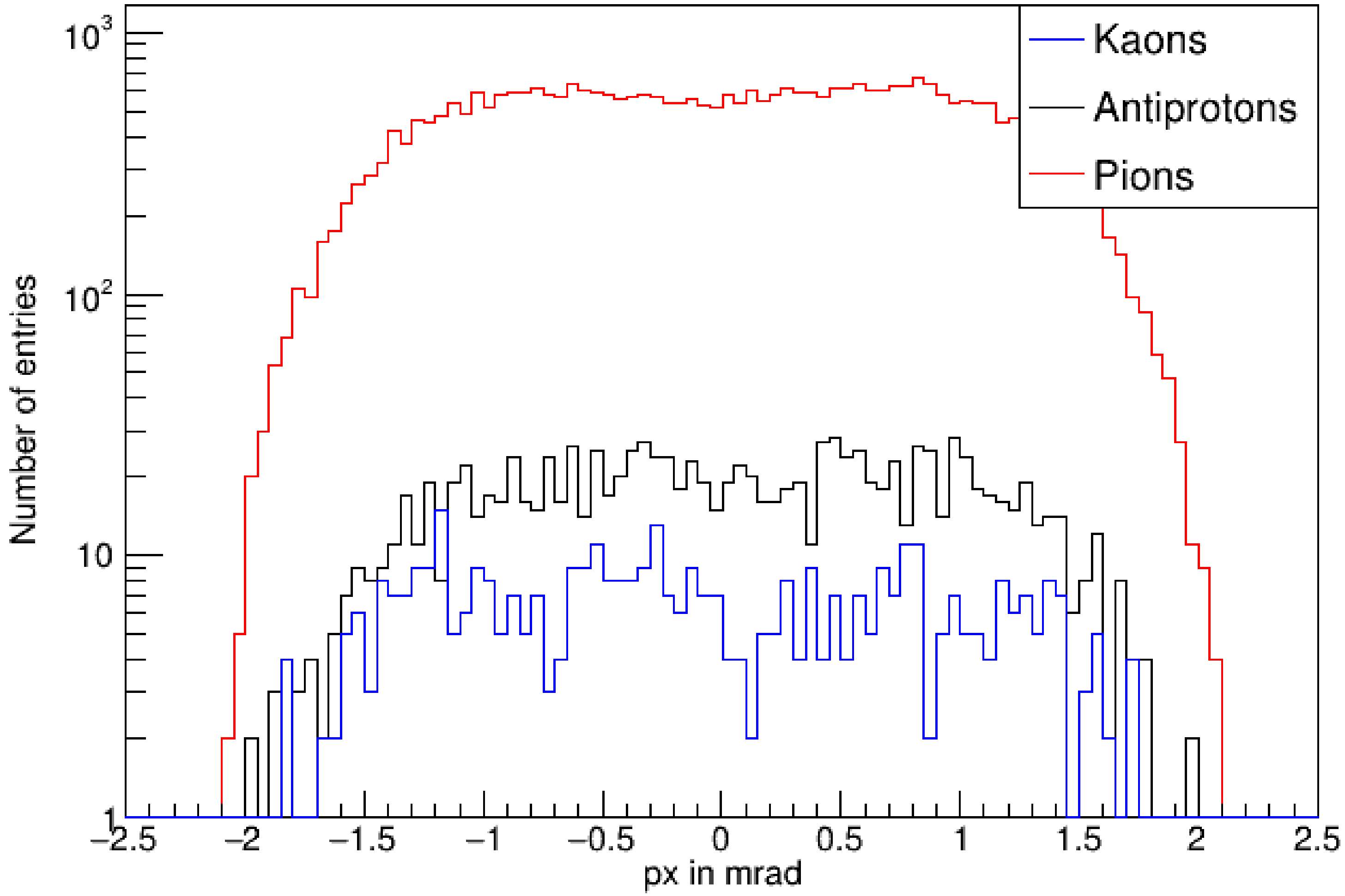
How to tune the phases

- $\boldsymbol{\theta_{\text{tot}} = \theta\left(\sin\left(\varphi(t)\right) + \sin\left(\varphi(t) + \alpha + \Delta\varphi_{12}\right)\right) = 2\theta \sin\left(\varphi(t) + \frac{\alpha+\Delta\varphi_{12}}{2}\right) \cos\left(\frac{\alpha+\Delta\varphi_{12}}{2}\right)}$
- **Tune $\boldsymbol{\Delta\varphi_{12}}$, such that $\boldsymbol{\cos\left(\frac{\alpha+\Delta\varphi_{12}}{2}\right) = 0}$ for unwanted species**
- **For a $\boldsymbol{K^-}$-beam we want the $\boldsymbol{\pi^-}$ and $\boldsymbol{\bar{p}}$ to be dumped**
  - Therefore, we aim at $\Delta\varphi_{\pi^-}^{\bar{p}} = 2\pi$
  - $\Delta\varphi_{12} = \pi - \frac{2\pi f L}{c}\sqrt{1+\left(\frac{m_\pi c}{p}\right)^2}$
  - Time that a π^- needs to fly from RF1 to RF2: $t_{\pi^-} = \frac{L}{\beta c} = \frac{L}{c} \cdot \frac{E}{pc} = \frac{L}{c}\sqrt{1+\left(\frac{m_\pi c}{p}\right)^2}$
  - This can be translated to a phase in RF2: $\varphi_{\pi^-} = \frac{2\pi f L}{c}\sqrt{1+\left(\frac{m_\pi c}{p}\right)^2}$
  - Kick for π^-: $\theta_{\text{tot}} \propto \cos\left(\frac{\Delta\varphi_{12}+\varphi_{\pi^-}}{2}\right) = \cos\left(\frac{\pi}{2}\right) = 0$; similar for $\bar{p}$ as $\varphi_{\bar{p}} = \varphi_{\pi^-} + 2\pi$
  - Kick for K^-: $\theta_{\text{tot}} \propto \cos\left(\frac{\Delta\varphi_{12}+\varphi_{K^-}}{2}\right) = \sin\left(\frac{\pi f L}{c}\left(\sqrt{1+\left(\frac{m_K c}{p}\right)^2} - \sqrt{1+\left(\frac{m_\pi c}{p}\right)^2}\right)\right) \neq 0$

Beam momentum

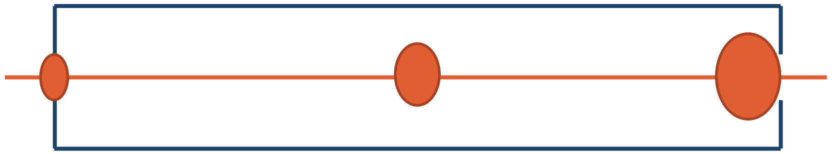


Kick in the first cavity



- **SPS beam is extracted over a given time period**
- **Particles arrive at RF1 with all possible phases**
- **Angular distributions after RF1 look the same for all species**
- **Simulated with a maximal kick of $50\,^{\mathrm{MeV}}/_{c}$ ($\widehat{=}\ 1.5\mathrm{mrad}$) per cavity**

Effect of the cavity kick



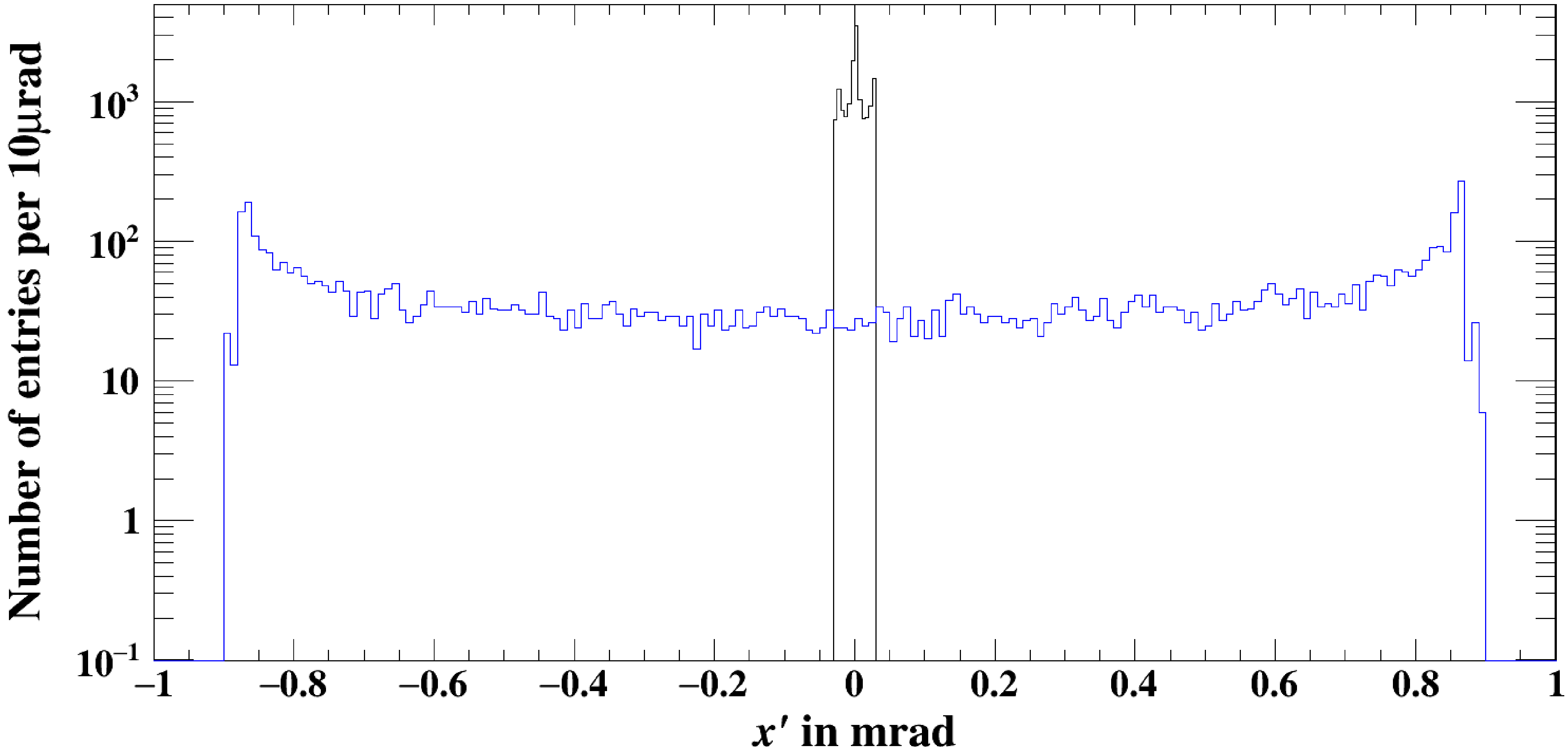
- **In the cavity the angle increases linearly with z:** $x'(z) = \frac{\frac{\mathrm{d}p}{\mathrm{d}z}}{p} \cdot z$
- **Therefore, the offset increases quadratically with z:** $x(z) = \frac{1}{2}\frac{\frac{\mathrm{d}p}{\mathrm{d}z}}{p} \cdot z^2 + x_0$
- **At the end of the cavity, i.e. L_{tot}, the offset should be the cavity radius R at maximum:**

$$x_0 = \frac{1}{2}\left(2R - \frac{\frac{\mathrm{d}p}{\mathrm{d}z}}{p} \cdot L_{\mathrm{tot}}^2\right)$$

- **Effectively usable aperture radius decreases to**

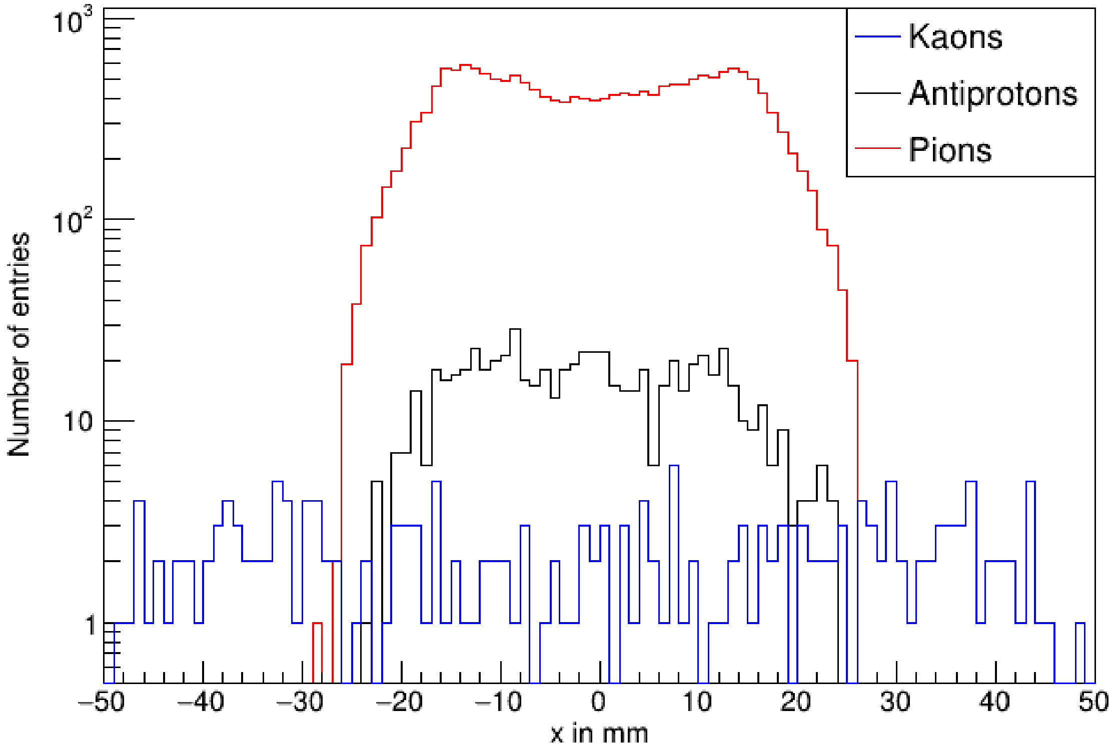
$$\frac{1}{2}\left(30\mathrm{mm} - \frac{5\,{}^{\mathrm{MeV}}\!/_{c}\,/\mathrm{m}}{70\,{}^{\mathrm{GeV}}\!/_{c}} \cdot 100\mathrm{m}^2\right) \approx 11.4\mathrm{mm}$$

Model test in BDSIM

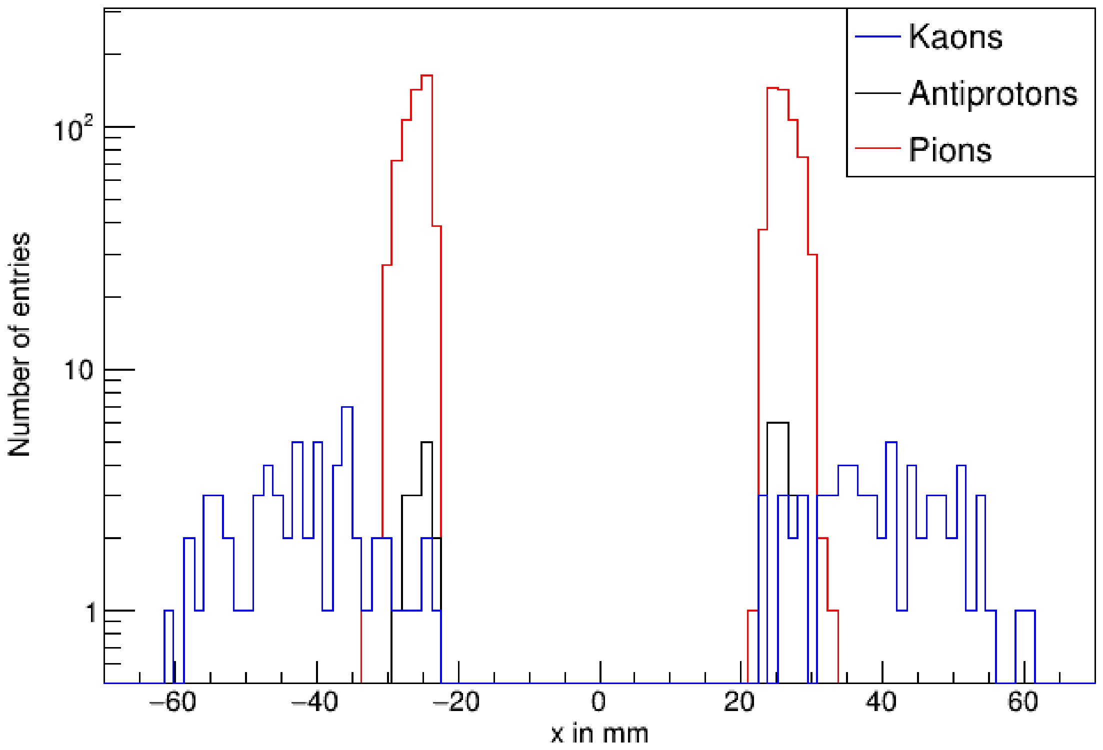


Absorption

Before the dump



After the dump



Beams from SPS