RF separated and conventional hadron beam in CERN's secondary M2 beam line

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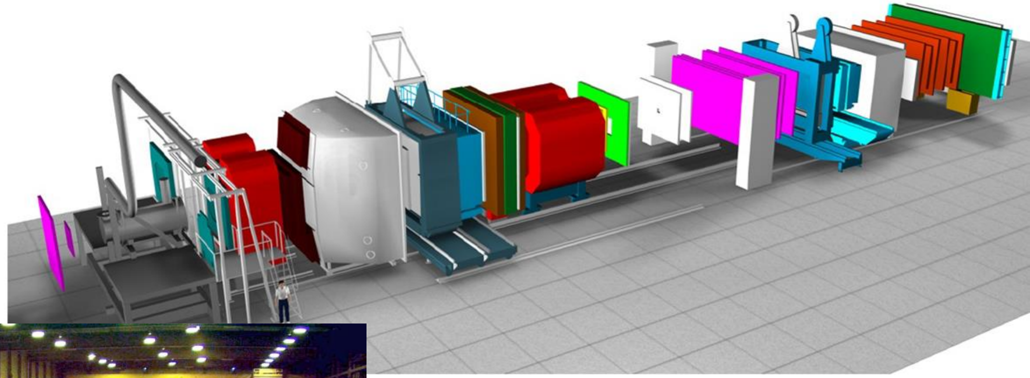
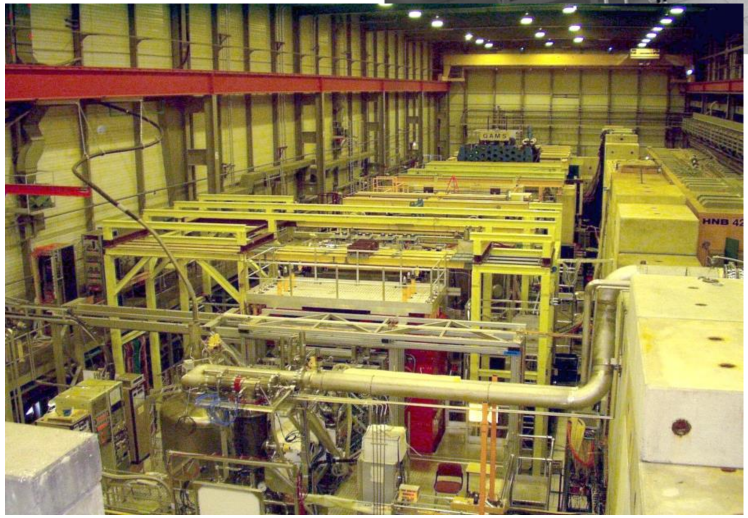
AMBER beam requirements



- 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

RF separated beam

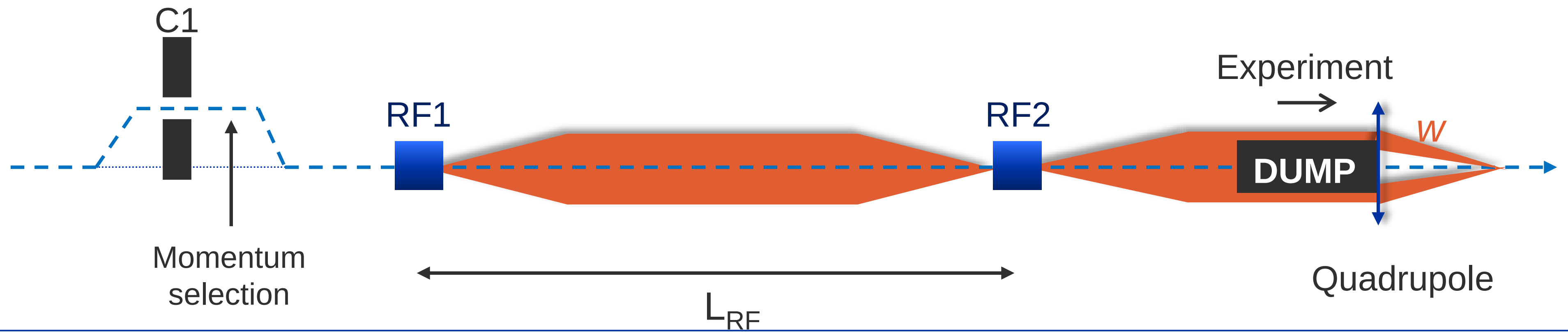
Principle and first results

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**

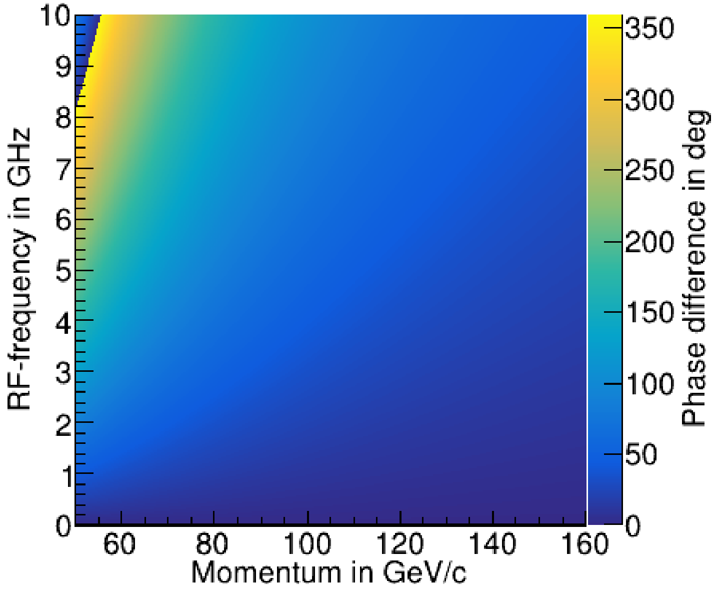
- **Kick by RF1 compensated or amplified by RF2 depending on the velocity**
  - $\theta_{\mathrm{tot}} = \theta\big(\sin(\varphi(t)) + \sin(\varphi(t) + \alpha + \Delta\varphi_{12})\big) = 2\theta \sin\left(\varphi(t) + \frac{\alpha+\Delta\varphi_{12}}{2}\right)\cos\left(\frac{\alpha+\Delta\varphi_{12}}{2}\right)$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



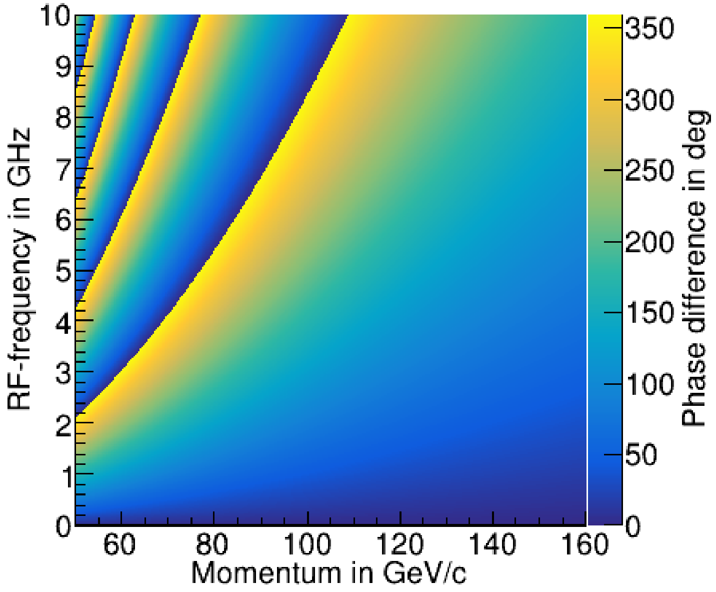
Cavity parameters

- **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 once and for all

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



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

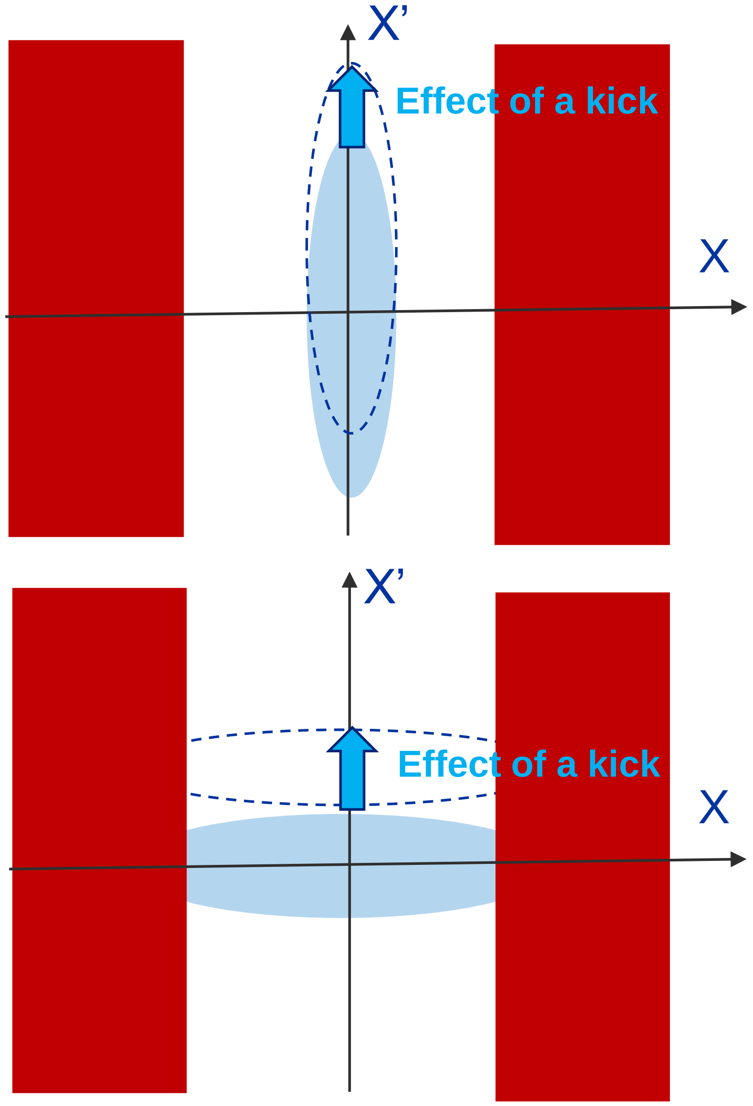


Focused vs. parallel beam in the cavities

- **Started with a focus in the cavities**

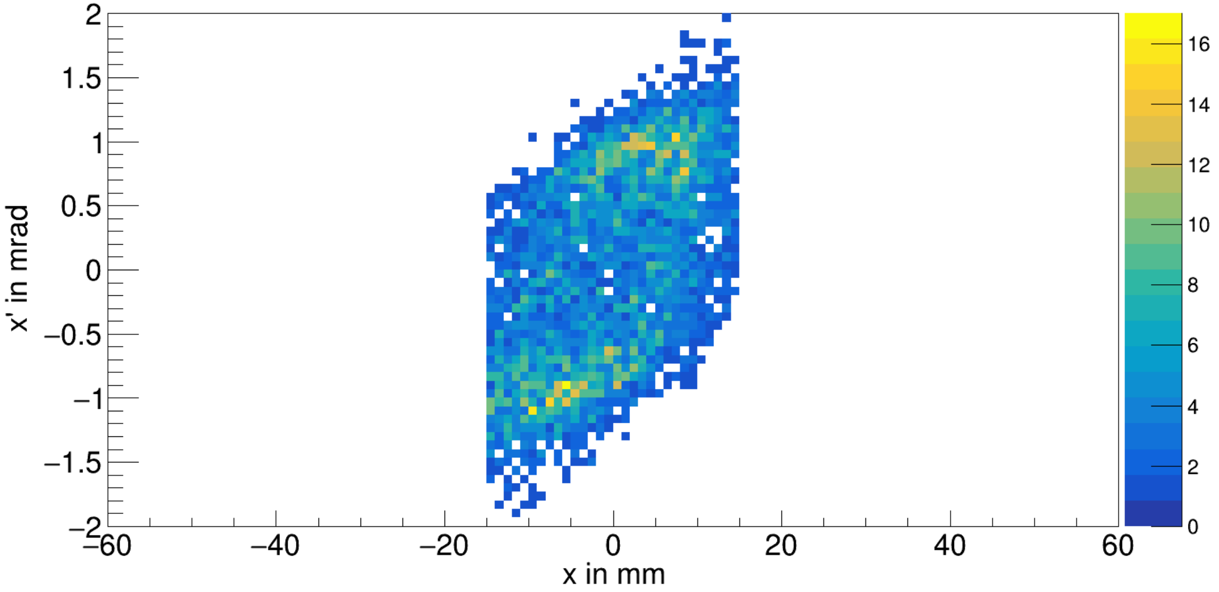
- **Focused beam**
  - Beam is large in x', but small in x
  - Relative effect of the kick is small
  - Beam fits well through the cavity apertures

- **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 

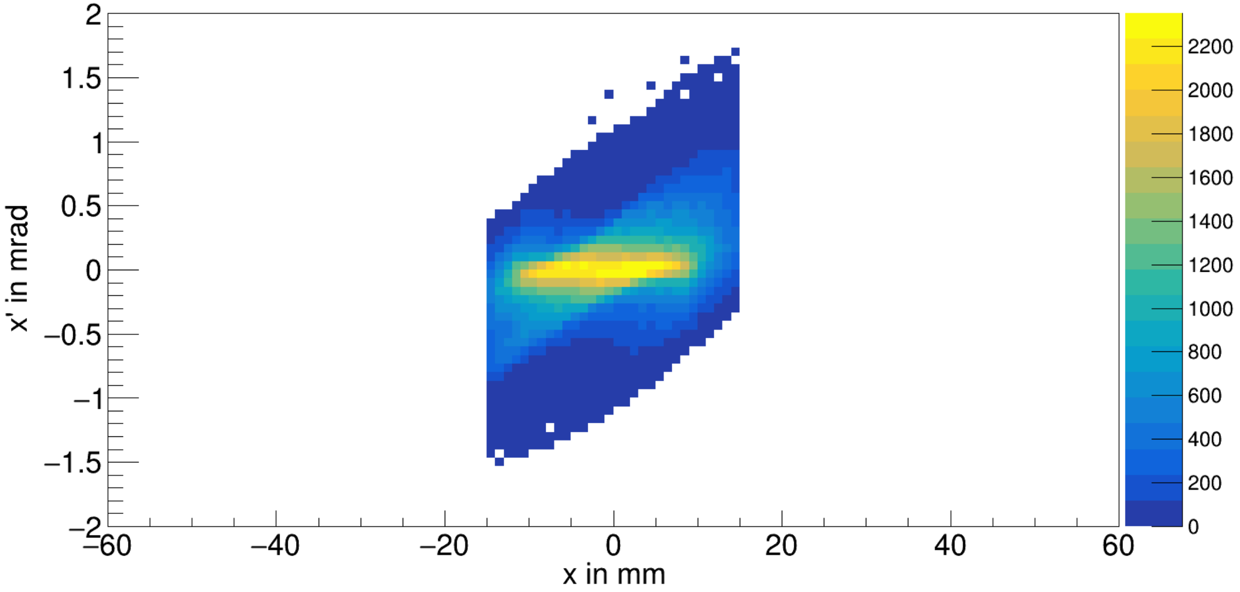


Phase space distribution after RF2

K^- phase space



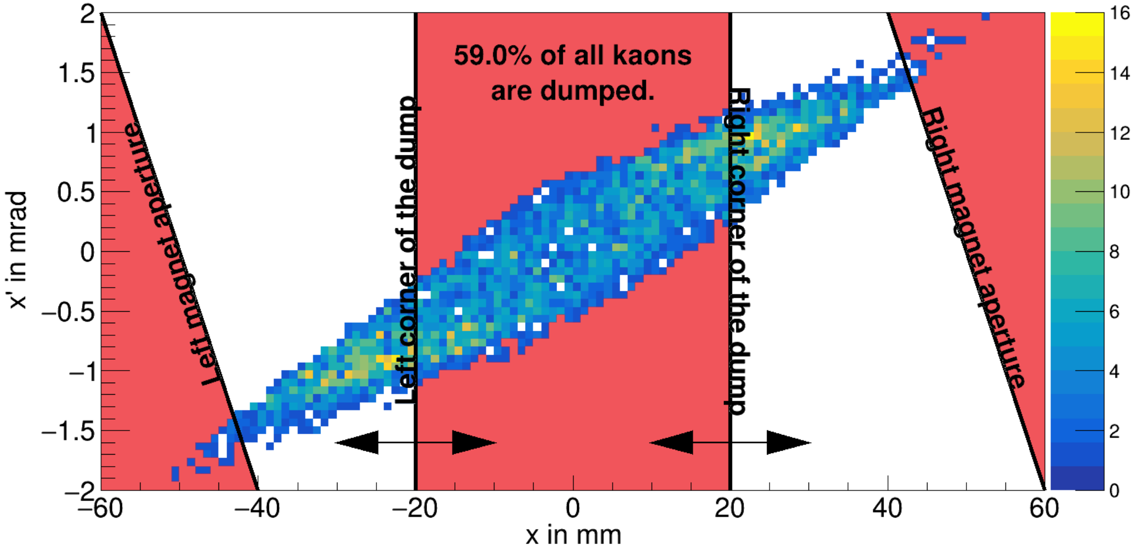
π^- phase space



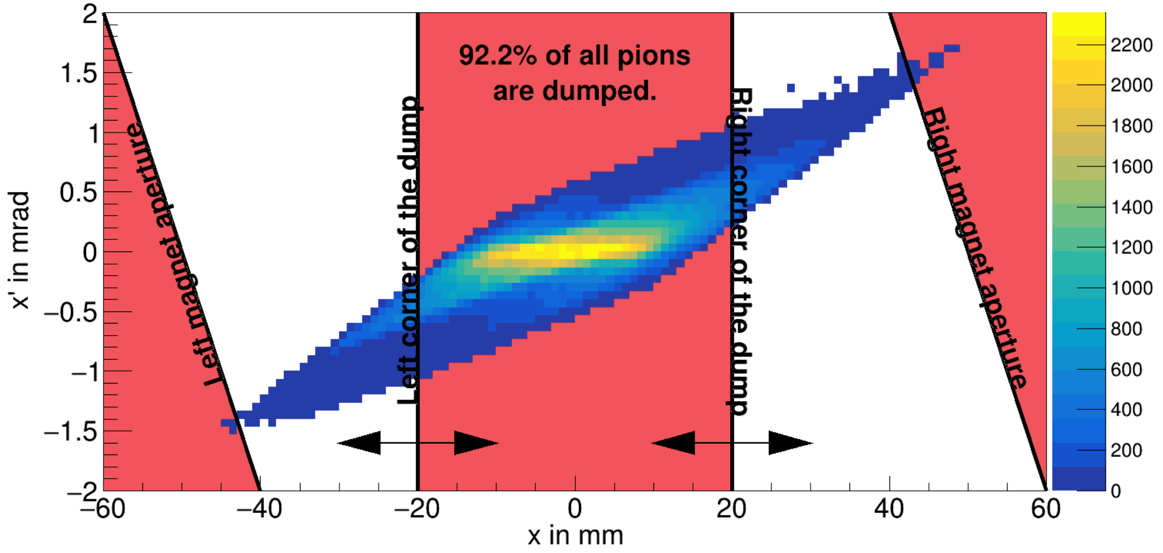
- **Cavity phase tuned such that $\pi^-$and $\bar{p}$ are not deflected**
  - Angular distribution of K^- shows peaks at $\pm 1\mathrm{mrad}$
  - For $\pi^-$and $\bar{p}$ angles are distributed around 0
- **Beam dump filters particles depending on their position**
  - Drift is needed to translate angular differences into spatial separation; currently, approximately $20\mathrm{m}$ of drift

Phase space distribution 20m after RF2 (dump)

K^- phase space

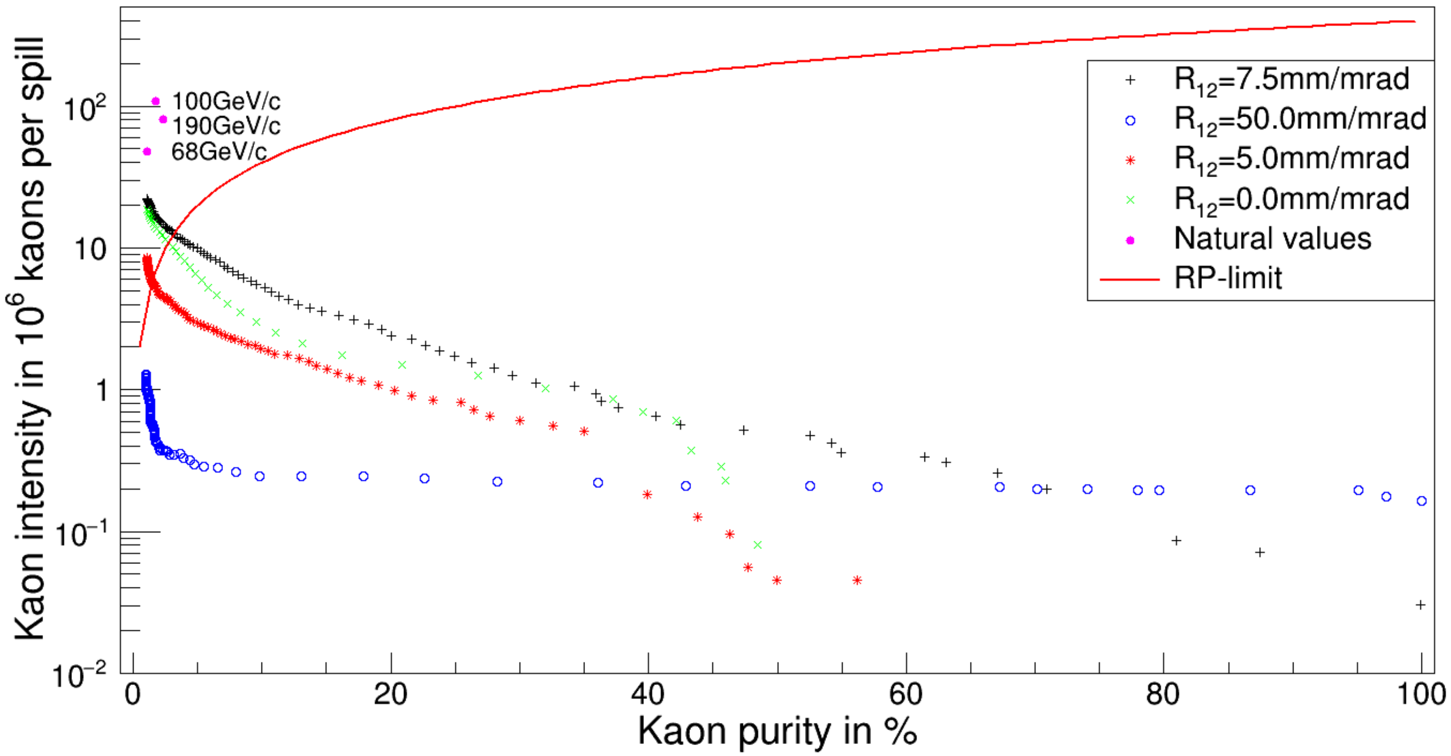


π^- phase space



- Angular separation converted into spatial separation
- With a beam dump, one can optimize the intensity and 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



- **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)**

- **Everything above the solid red curve is currently limited due to radiation protection**
- **Present status: We can deliver 3×10^6 kaons at 20% purity**
- **AMBER requires various beam intensities and purities for its different programs**
  - Open spectrometer: Total intensity needs to be limited → RF separation is an option to increase the kaon-intensity
  - Drell-Yan: Highest intensities necessary → Not possible with RF separation → Investigating other options besides RF separation → Conventional beam

Summary

- **With the current parameters and beam optics, we have $p \approx 68\ {}^{\mathrm{GeV}}/_{c}$ (already close to maximum due to $p \propto \sqrt{fL}$)**

- **Discussions showed:**
  - 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 far too low; purity is of minor interest, so we can increase the total intensity to have a higher kaon rate with a conventional beam and fast PID
  - We discuss the options for Drell-Yan in the following half

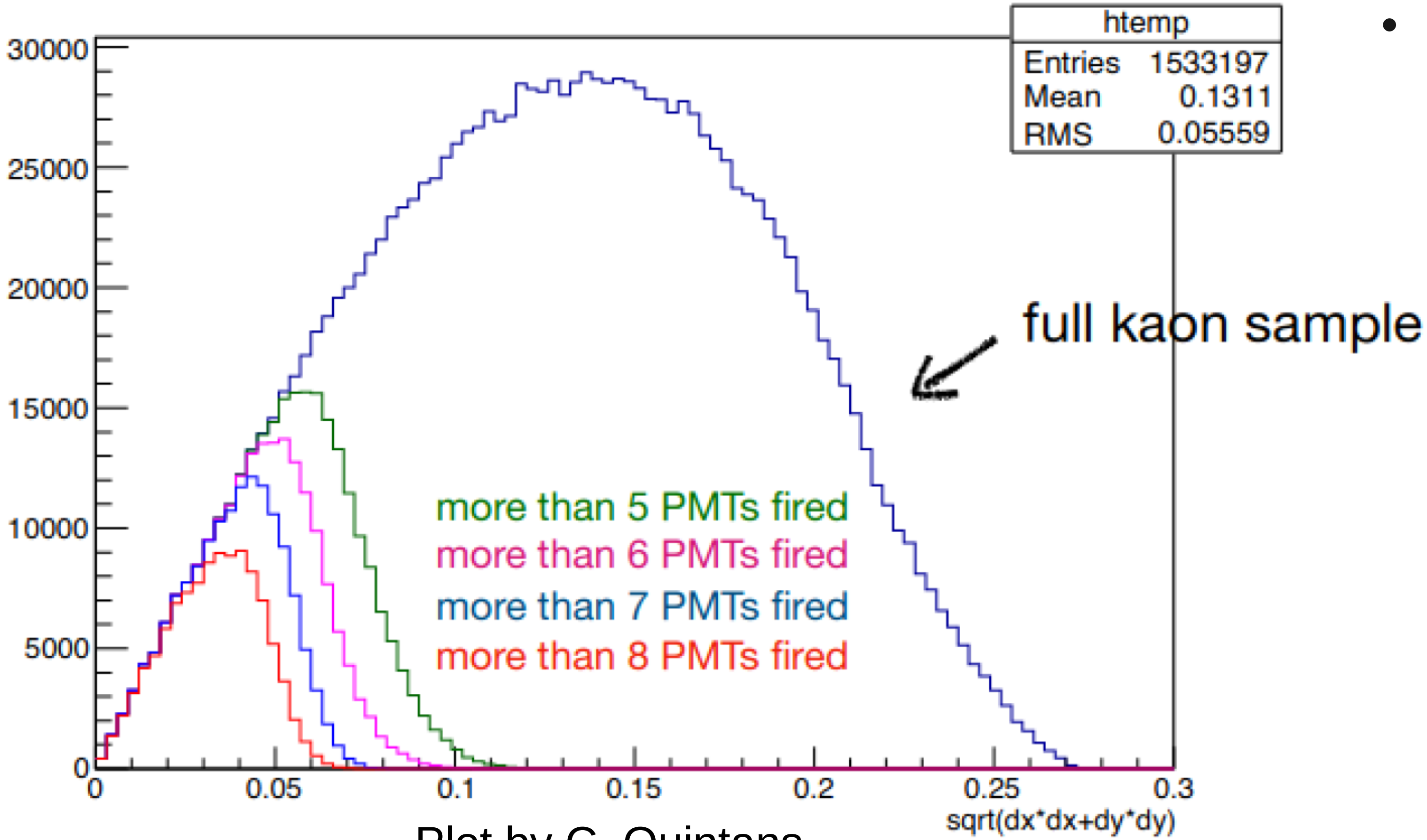
- **We received field maps for the assumed ILC crab cavities**
  - The studies will migrate from MAD-X to BDSIM; in this tool we can make use of realistic field configurations
    - In MAD-X, we only have time-dependent transverse cavities; so, we needed to omit the spatial configuration
  - Then, we can do simulations with spatial- and time-dependent electric and magnetic fields in the cavities

- **Beam PID will be necessary in any case due to impurities and beam purity constraints**

Conventional hadron beam

Optimization for Drell-Yan

Current hadron beam



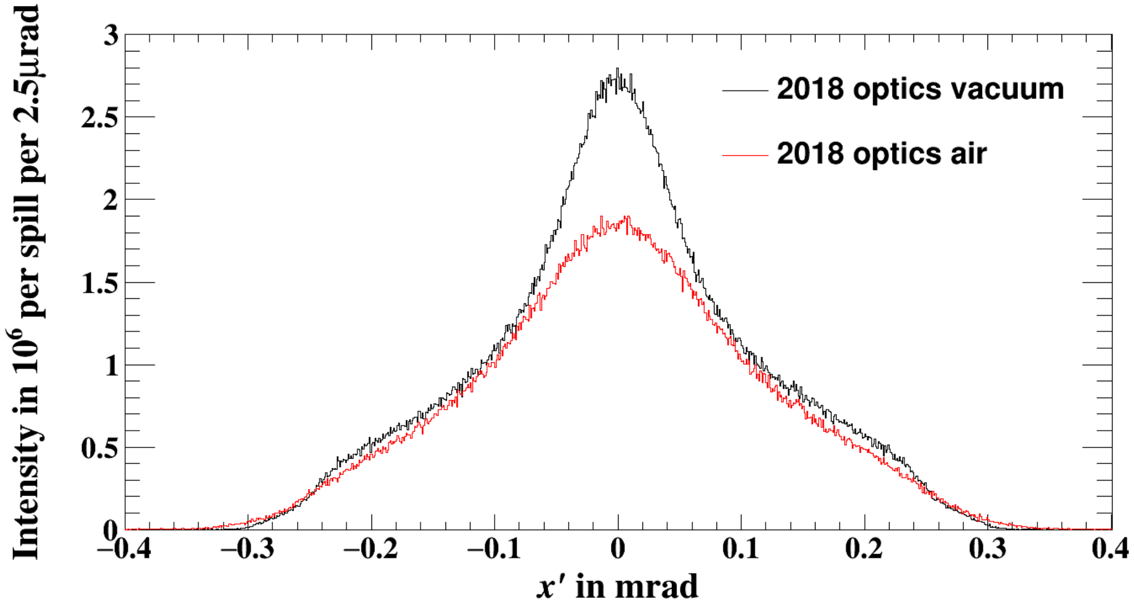
Plot by C. Quintans
AMBER DY-Meeting 30.11.2021

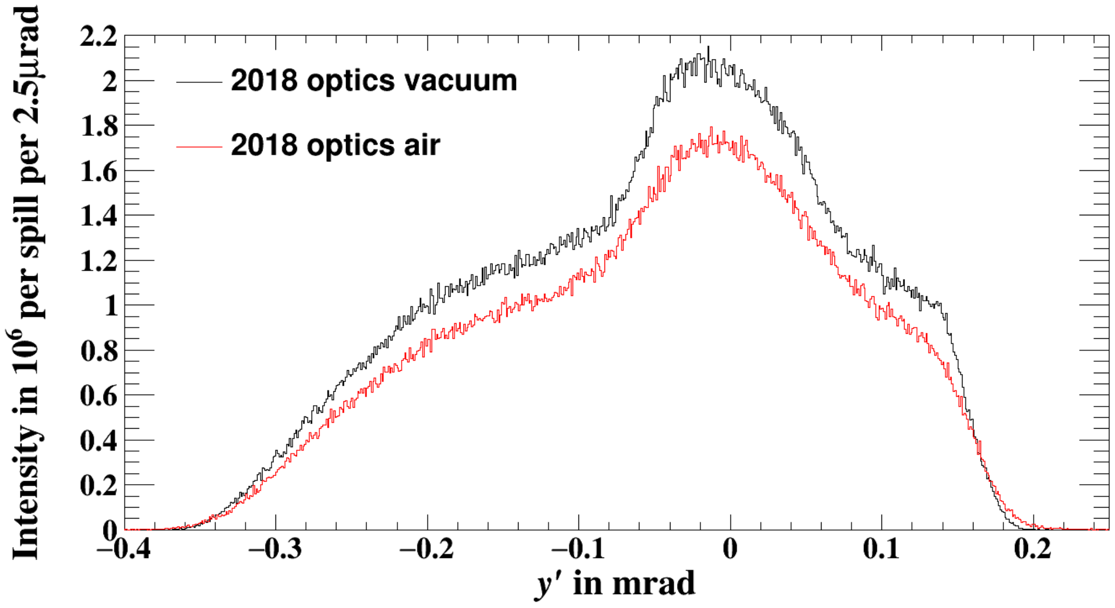
- **Intensity corresponds to kaons detected by the CEDAR Cherenkov counters**
  - Tagging efficiency depends critically on beam divergence at the CEDARs
  - In M2, we have long air sections contributing to multiple scattering and leading to a divergence increase
  - Beam is rather small and therefore too divergent
  - High tagging efficiency required to profit optimally from the beam kaon content → Divergence $\sqrt{x'^2 + y'^2}$ needs to be limited to $60\mu\text{rad}$

M2 hadron beam

- **Currently, here are in total combined $\sim 80\mathrm{m}$ of air at $1\mathrm{bar}$ along the beam line**
  - For $190\ \mathrm{GeV}/c$, this corresponds to $34.9\mu\mathrm{rad}$ multiple scattering (Moliere approximation), affecting beam parallelism and collimation scheme
  - Nine Scraper magnets of $5\mathrm{m}$ length each → Vacuum integration costly and challenging
- **To improve the divergence, we have the options to reduce the amount of air, to modify the optics and to change the collimation scheme**
- **Presented results based on BDSIM simulations**
  - Secondary beam is made much larger than transverse and longitudinal beam line acceptance → Cutting is made completely by the beam line; hence, the relative transmission is independent of initial beam assumptions
  - In the end, we scale it to the known intensity of 4.8×10^8 particles per spill for the 2018 optics
- **There are studies on-going by RP to increase the number of particles allowed per year to 3×10^{14} (assuming $200\mathrm{d}$ with $3000\,\mathrm{spills/d}$)**
  - The prompt intensity in EHN2 is limited to 4.8×10^8 particles per spill; there might be the possibility to increase it with the improved shielding to 10^9 particles per spill (to be seen with RP)
  - We have only a small fraction of kaons in the beam $(2-3\%)$; naturally dominated by pions

Beam divergence at the CEDARs in 2018

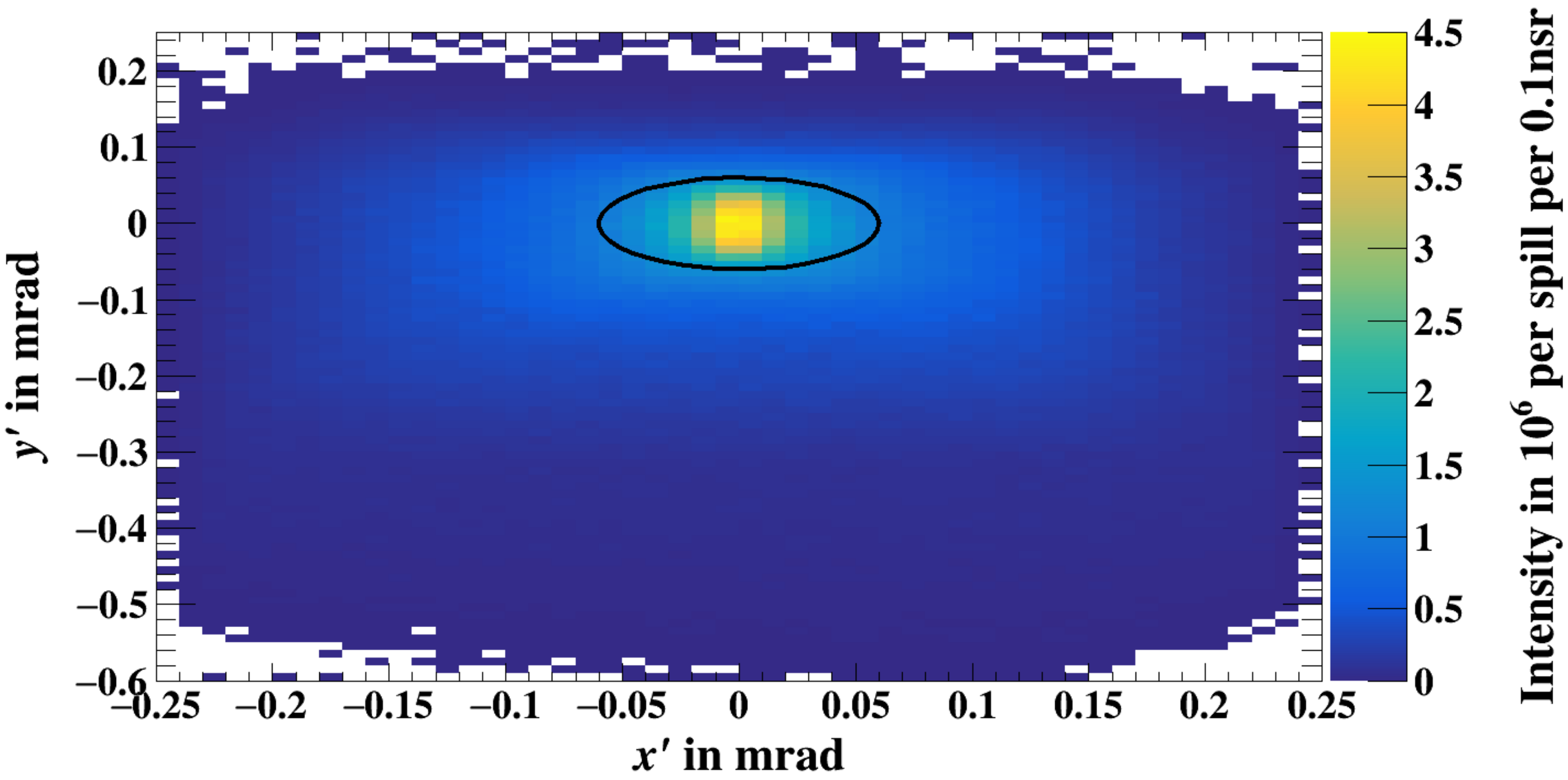




$\sigma_{x'} = \mathbf{117.3\mu rad}, 110.6\mu rad$ $\sigma_{y'} = 117.4\mu rad, 117.0\mu rad$

- **No clear reduction of standard deviation**
  - But peak in x' is 50% higher compared to the current implementation
- **Higher transmission the more vacuum section we have in M2**
  - Full vacuum: 20% more flux
  - Allows better collimation (tighter and cleaner between front-end and last four collimators)
- **Increase from 2.09×10^6 to 3.13×10^6 K^- in $60\mu rad$; we would have $\sim 23\%$ of the beam in this range**

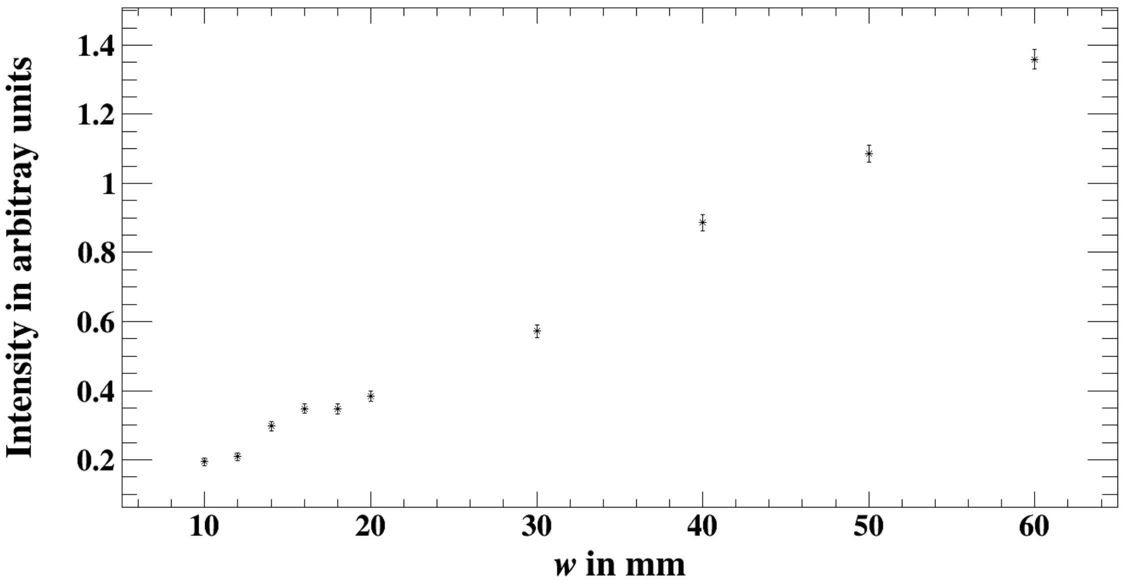
Beam divergence at the CEDARs with new optics

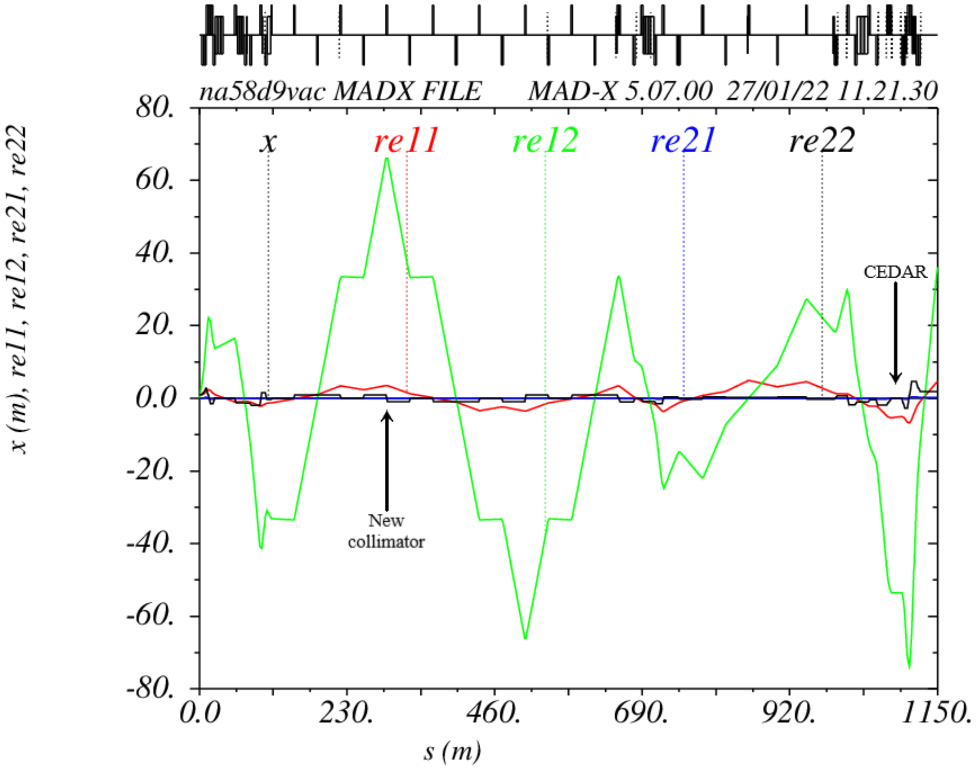


- **We assume full vacuum implementation**
- **In these optics the beam is made larger at the CEDAR location**

- **Same collimation scheme as used in 2018**
- **We have 5.6×10^6 K^- per spill within 60μrad corresponding to $\sim$25% of the total kaon intensity at the CEDARs**
- **The full beam intensity would be 9.14×10^8 particles per spill**
- **Intensity is calculated for 120 units on T6**
  - With going to 150 units, we would gain another 25%

Horizontal collimation





- **Collimator is placed at a location with large beam in horizontal plane**
- **By closing the collimator from 30mm to 15mm, divergence and overall intensity decreases by 50%**
- **At some point, further collimation does not make sense as $\sqrt{x'^2 + y'^2}$ is the determining factor**
- **Vertical collimation shows small improvement**
  - Beam is smaller in vertical plane at the CEDARs → Less parallel
  - M2 is a vertical beam line → Due to the bending magnets we have dispersion in the y-plane

Going to higher intensities

- **With the improved shielding, we might be allowed to send up to 10^9 particles per spill**
  - Still needs to be checked with and confirmed by RP
- **Simulation of beam optics from 2018**
  - Large TAX holes used: $100\text{mm} \times 36\text{mm}$
  - COLL$1-4$ at $\pm 25\text{mm}$
  - COLL5 at $\pm 7\text{mm}$
  - COLL$6-9$ at $\pm 20\text{mm}$
  - With those settings 4.8×10^8 particles per spill in EHN2 with 120 units on T6 were reached
  - The transmission in BDSIM is used as a calibration factor
- **We opened all collimators to $\pm 40\text{mm}$**
  - We flood the CEDARs with a lot of particles outside of $60\mu\text{rad}$
  - But, if the backtracking outside of $60\mu\text{rad}$ is efficient increasing “simply” the intensity might still be beneficial so that we can loosen the collimation thus increasing the number of kaons

High intensity runs

- **We can profit from two effects:**
  - Less collimation → Higher intensity
  - We will discuss the collimation scheme and optics with RP to validate the instantaneous rate
  - 150 units on T6 instead of 120 like in 2018
    - **M2 with the current layout**
      - 9.26×10^8 particles per spill
    - **Adding vacuum**
      - 1.04×10^9 particles per spill
    - **New proposed optics with air**
      - 1.11×10^9 particles per spill
    - **New proposed optics with vacuum**
      - 1.23×10^9 particles per spill
- **We are increasing the momentum spread due to opening COLL5**
  - The influence of the higher spread in momentum would need to be analysed
  - But, according to the numbers we would have some margin to still do some collimation
  - So, we might be able to reduce it

Summary

- **There are three options to reduce the beam divergence at the CEDARs**
  - Reducing the amount of air: Does not reduce the overall spread, but increases the number significantly in the region where they can be tagged
  - Modifying the beam optics: Reduces the overall divergence and increases the overall intensity
  - In case of limited intensity runs we still have the option of tighter collimation to reduce the particle rate outside of the CEDAR's taggable region as they are anyway not counted to the intensity
- **With adding vacuum and changing the beam optics we can gain a factor 1.9 compared to 2018; in addition to that there is the profit from increasing the number of units**
  - The kaon intensity in $60\mu\text{rad}$ can be increased by a factor 2.7
- **For high intensity runs we can profit from more units on T6 and less collimation**
  - This is beneficial if the backtracking tool by COMPASS to tag particles outside of $60\mu\text{rad}$ works efficiently
  - The influence of the larger momentum spread needs to be investigated

Conclusion

- **RF separated beam is a promising option for AMBER studies in which the total intensity needs to be limited still having a reasonable $K^{\pm}$ rate**
  - Up to now, the studies were performed in MAD-X; we could only use infinitely short cavities
  - We move to BDSIM now; received realistic 3D field maps of the ILC crab cavities
    - The field uniformity influences the performance of the separator in a sense that particles that receive a net deflection are deflected differently depending on their transverse coordinates
  - We translate the beam optics to BDSIM and cross-check the outcome with the preliminary results from MAD-X

- **For AMBER Drell-Yan improving the conventional hadron beam is the only possibility**
  - With adding vacuum we increase the overall intensity by $\sim 20\%$
  - We gain in the number of particles in the CEDAR's taggable region
  - Further improvement can be gained by modifying the beam optics
  - With the improved shielding system around the AMBER target it might be even possible (to be checked with RP) to send higher intensities to EHN2 which is possible by increasing the proton intensity and optimising the collimation

Thank you for your attention!

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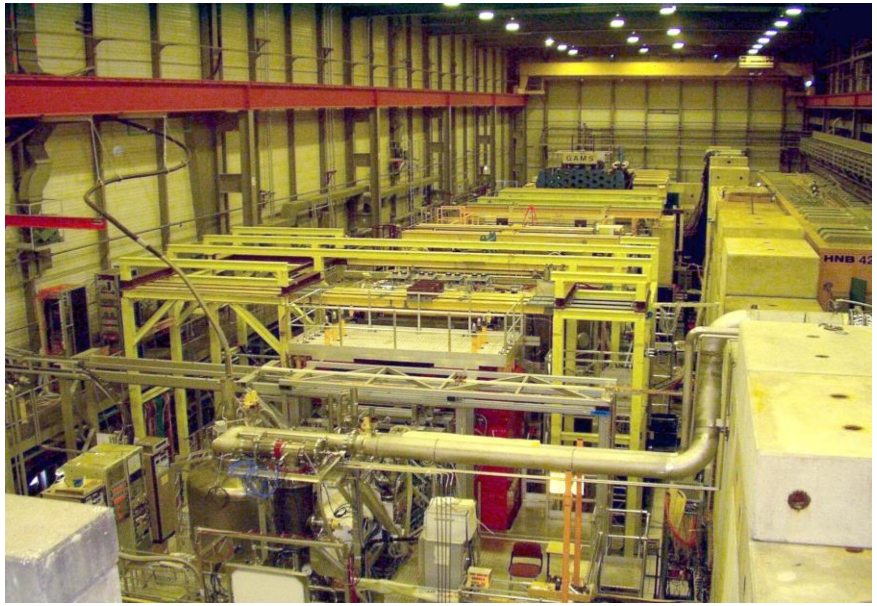
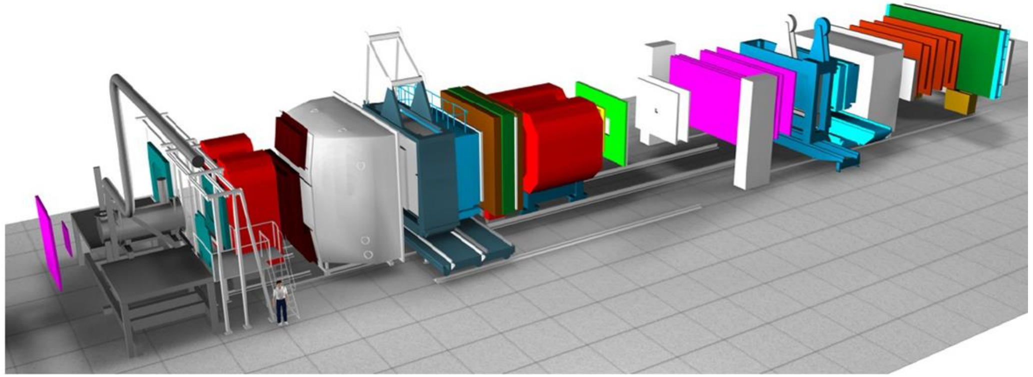
AMBER at CERN's M2 beam line



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	~100	10^8	25-50	$K^\pm$, $\bar{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisability & pion life time	~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



How to tune the phases

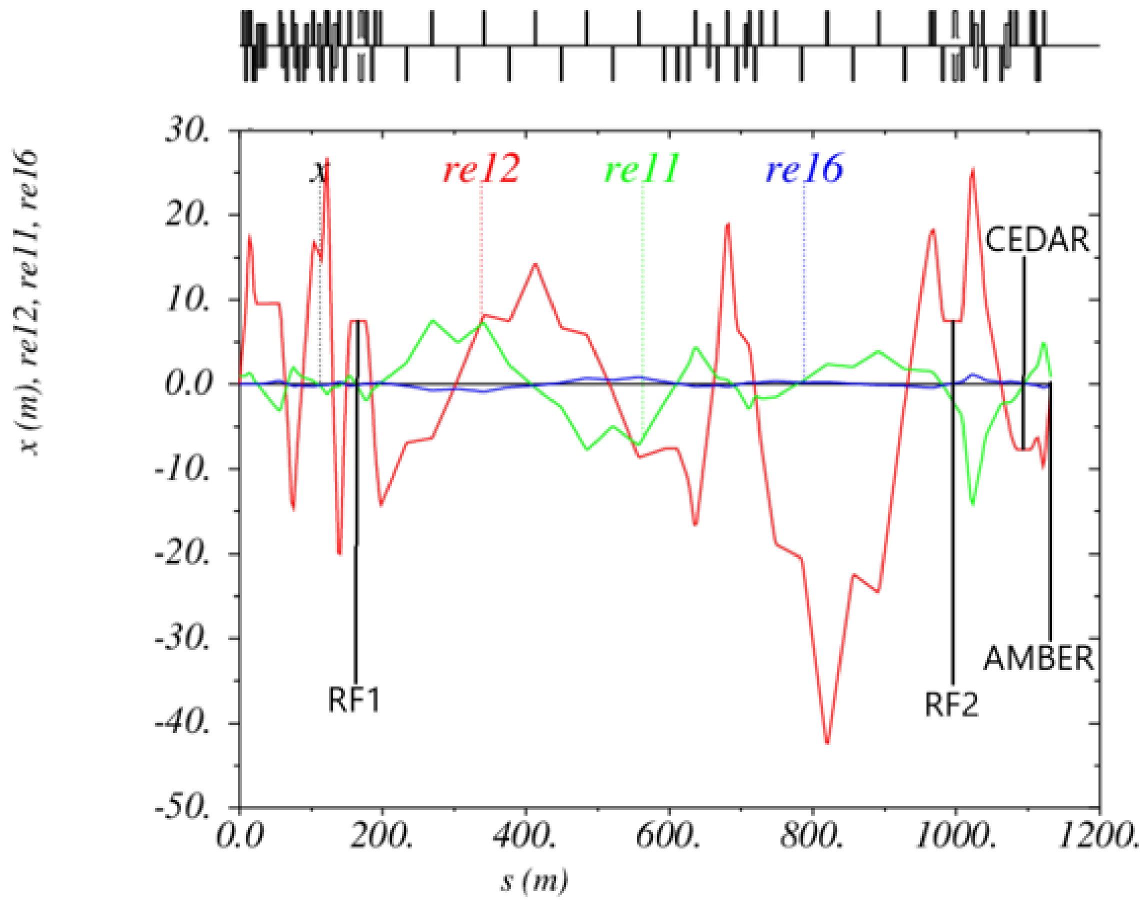
- $\boldsymbol{\theta_{\mathrm{tot}} = \theta\left(\sin\left(\varphi(t)\right) + \sin\left(\varphi(t) + \alpha + \Delta\varphi_{12}\right)\right) = 2\theta \sin\left(\varphi(t) + \frac{\alpha+\Delta\varphi_{12}}{2}\right) \cos\left(\frac{\alpha+\Delta\varphi_{12}}{2}\right)}$
- **Tune $\boldsymbol{\Delta\varphi_{12}}$, 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^-: $\theta_{\mathrm{tot}} \propto \cos\left(\frac{\Delta\varphi_{12}+\varphi_{\pi^-}}{2}\right) = \cos\left(\frac{\pi}{2}\right) = 0$; similar for $\bar{p}$ as $\varphi_{\bar{p}} = \varphi_{\pi^-} + 2\pi$
  - Kick for K^-: $\theta_{\mathrm{tot}} \propto \cos\left(\frac{\Delta\varphi_{12}+\varphi_{K^-}}{2}\right) = \sin\left(\frac{\pi f L}{c}\left(\sqrt{1 + \left(\frac{m_K c}{p}\right)^2} - \sqrt{1 + \left(\frac{m_\pi c}{p}\right)^2}\right)\right) \neq 0$

Optics development

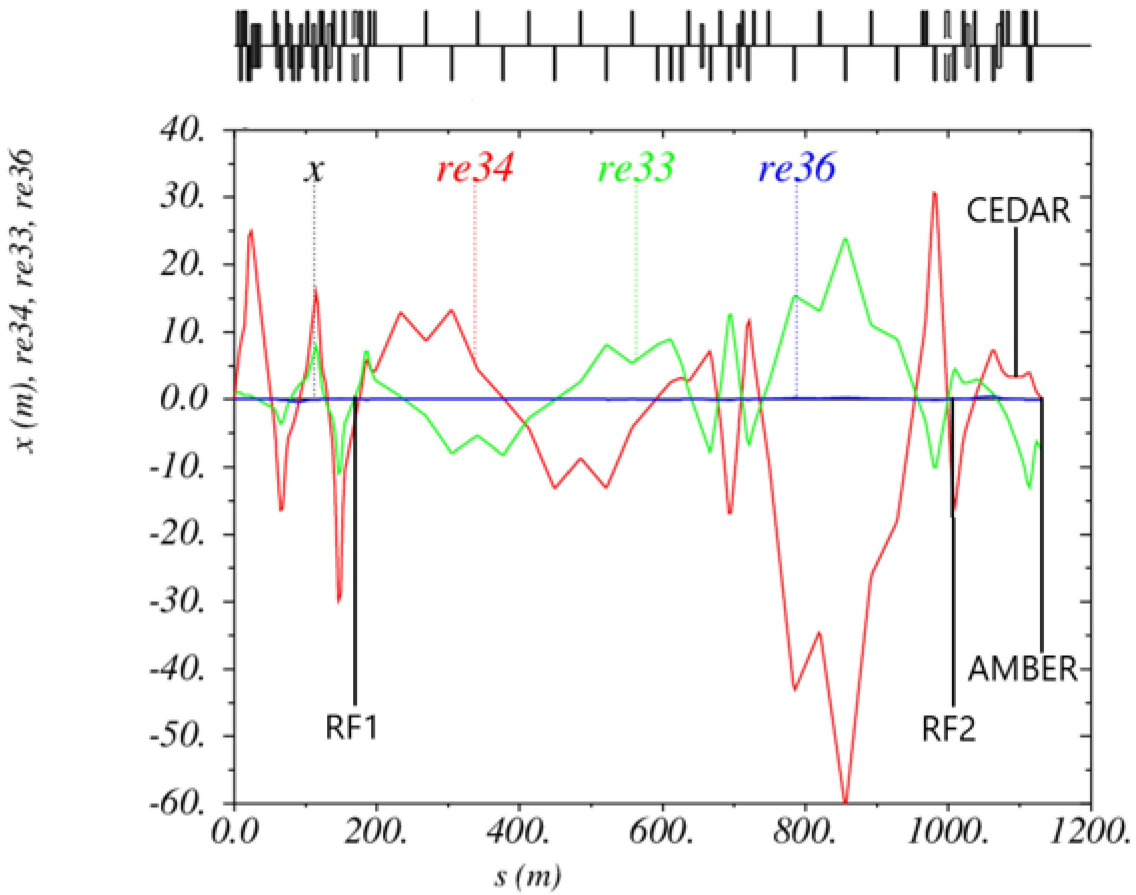
Optics challenges:

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

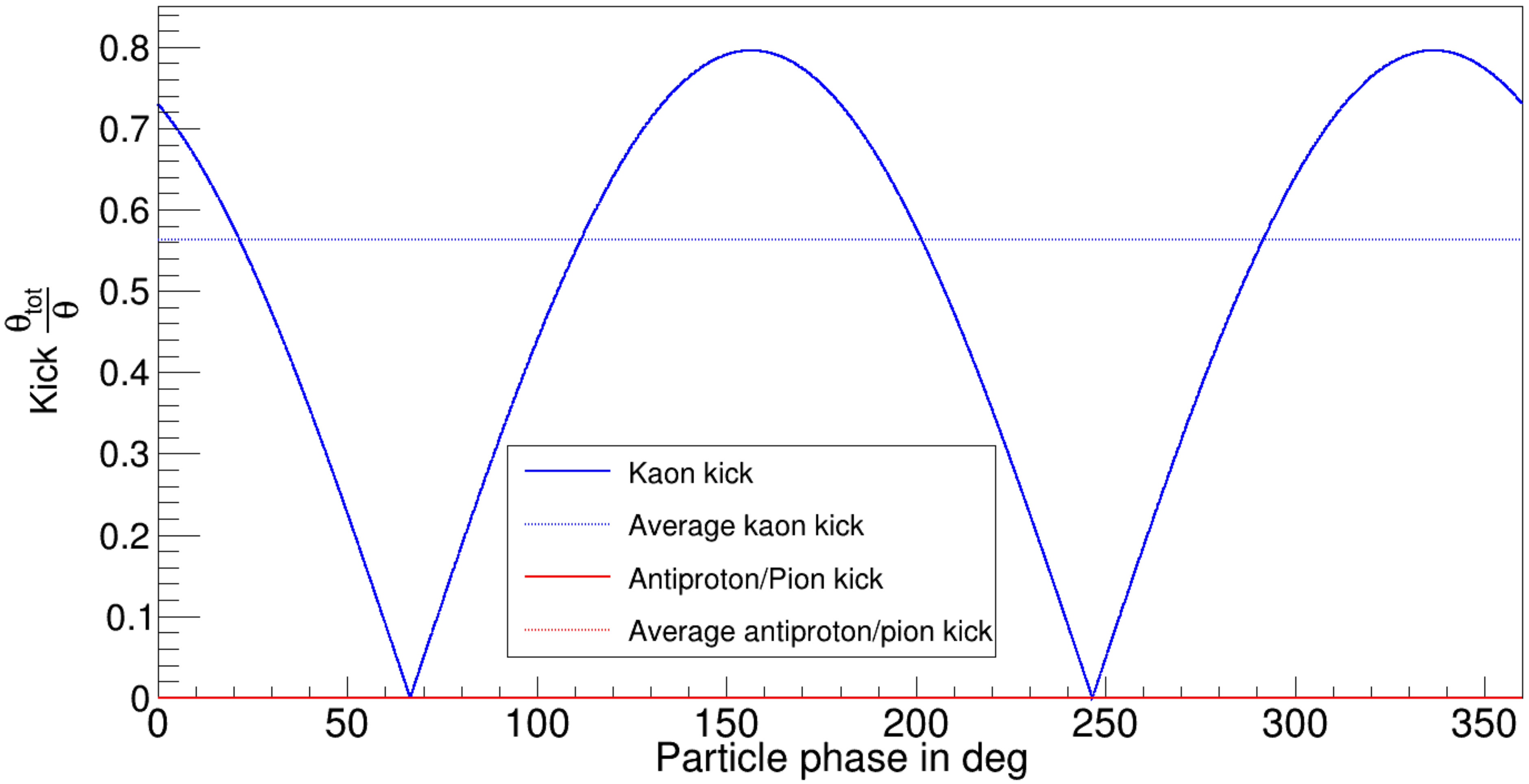
x-plane



y-plane

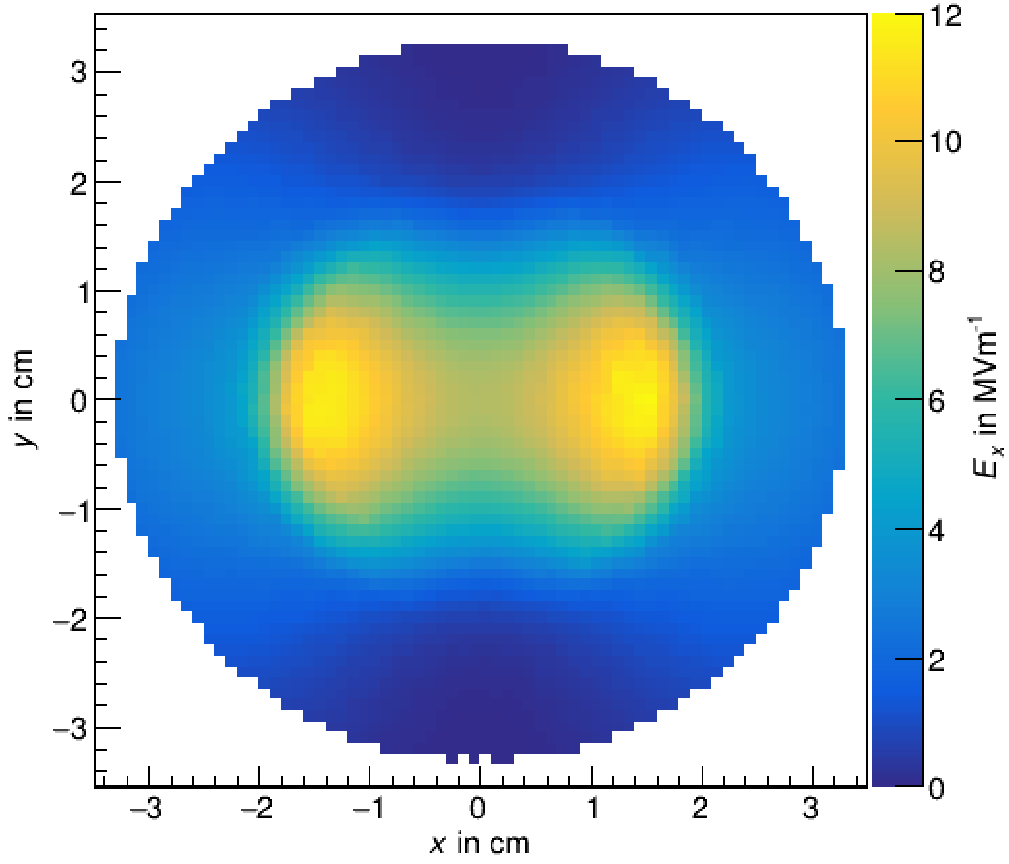


Kick of the cavities

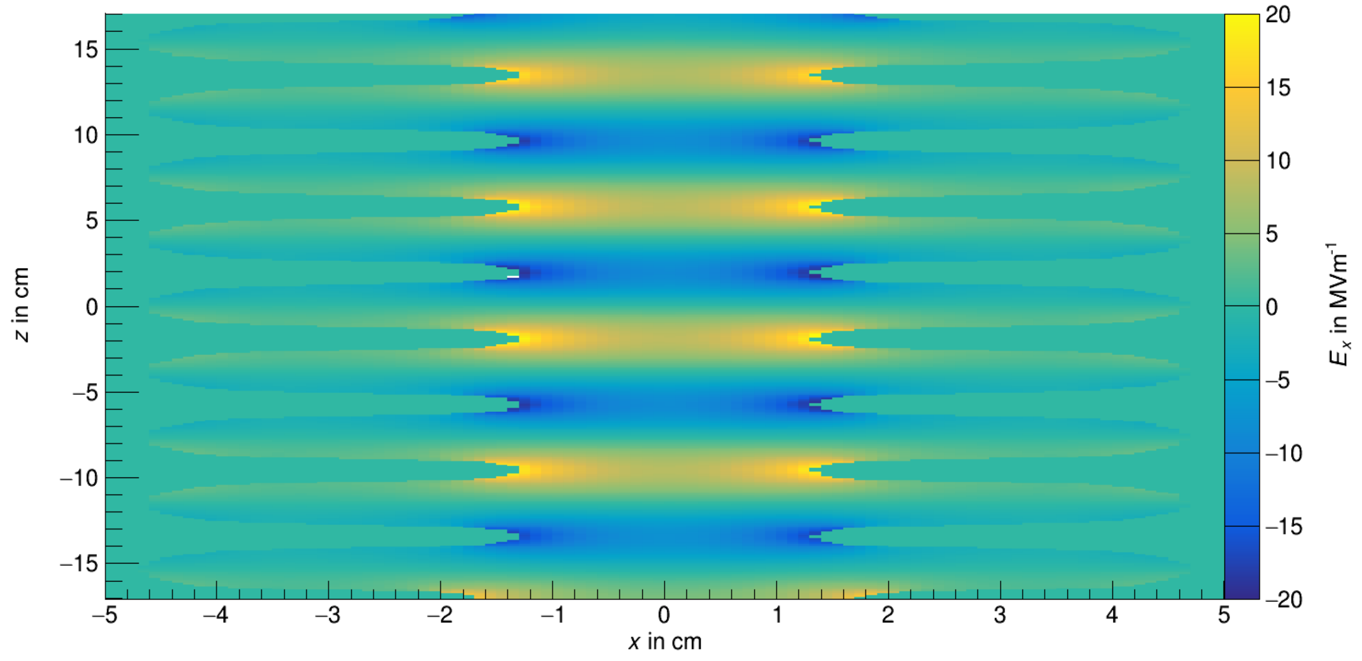


Field of the ILC crab cavities

At $z = 4.6\text{cm}$



At $y = -0.05\text{cm}$

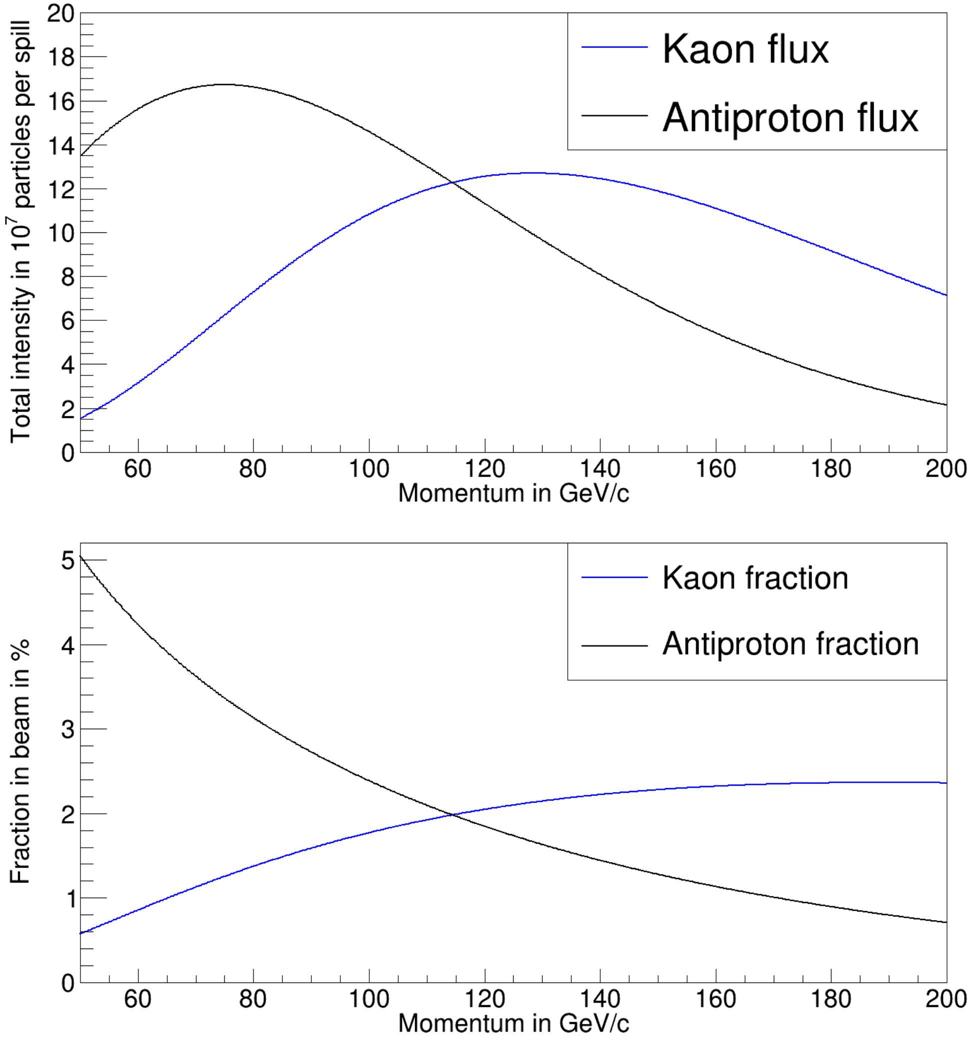


Received field maps from Graeme Burt

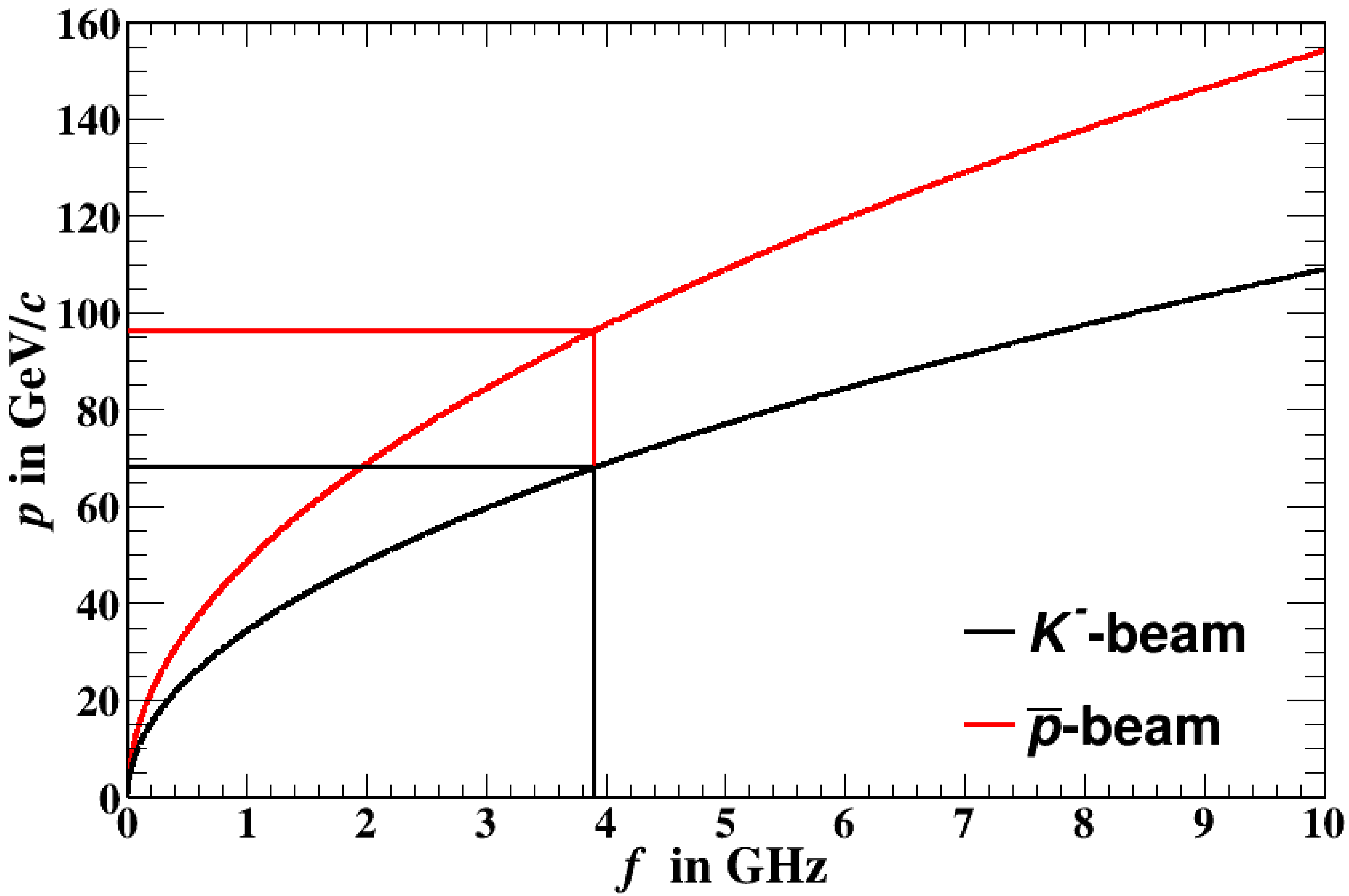
K^- and $\bar{p}$: intensities and fractions

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

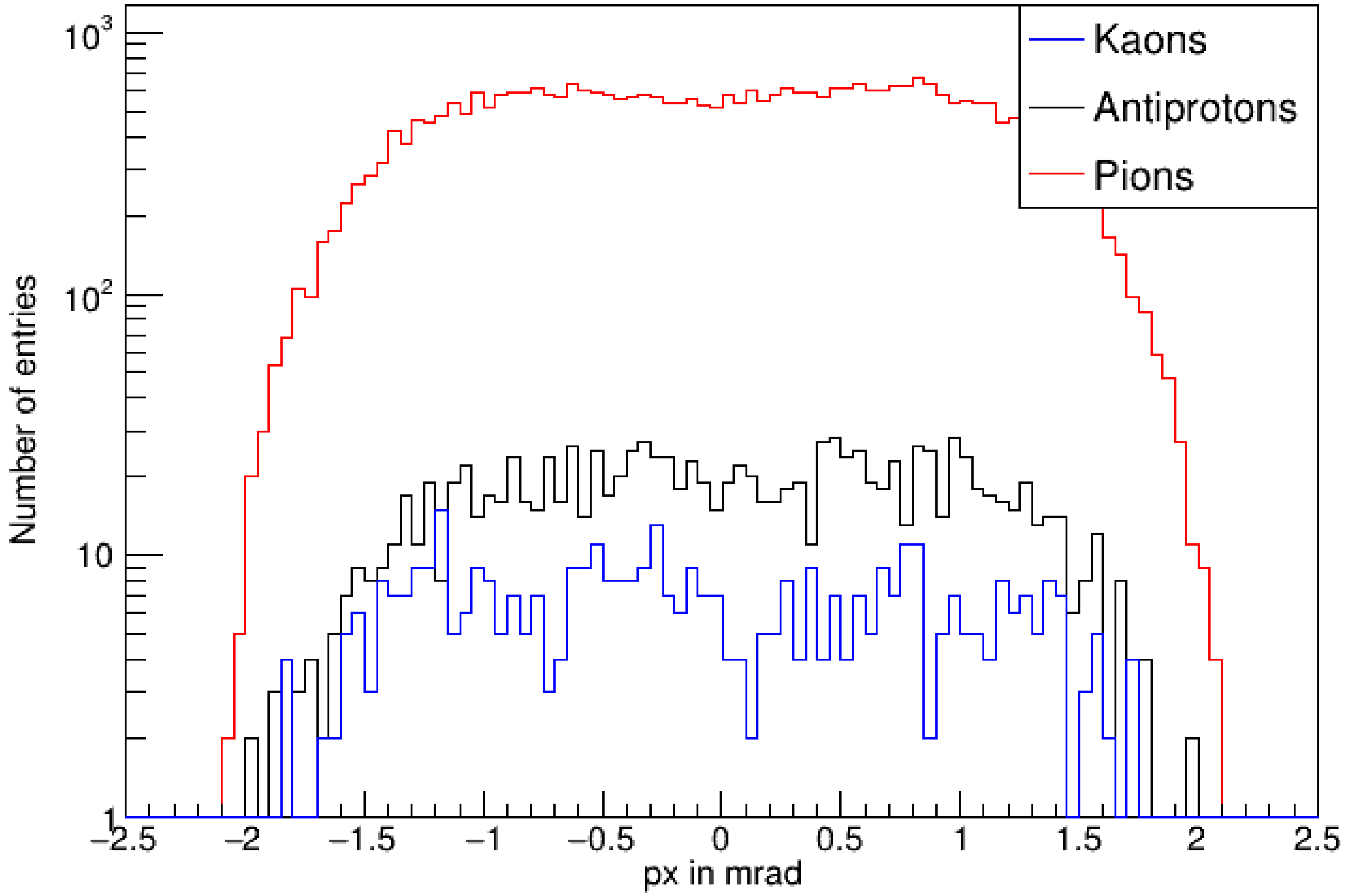
- **Atherton parametrization[1] to calculate number of particles**
  - Parametrization of particle production measured by NA20
  - With $\frac{\Delta p}{p} = 1\%$
  - Angular acceptance of $17.6 \mu \text{sterad}$
  - 1.5×10^{13} ppp on T6
  - 500mm Be-target
  - Distance between T6 and AMBER target of 1138m
  - Electrons are not considered
- $\mathbf{4 \times 10^{8}}$ **particles per spill allowed by RP**



Beam momentum

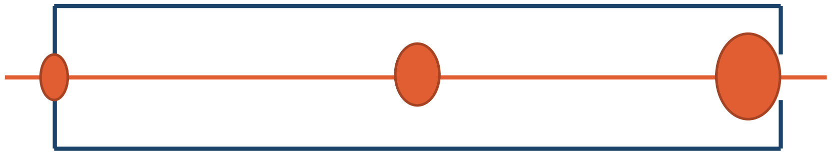


Kick in the first cavity



- 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



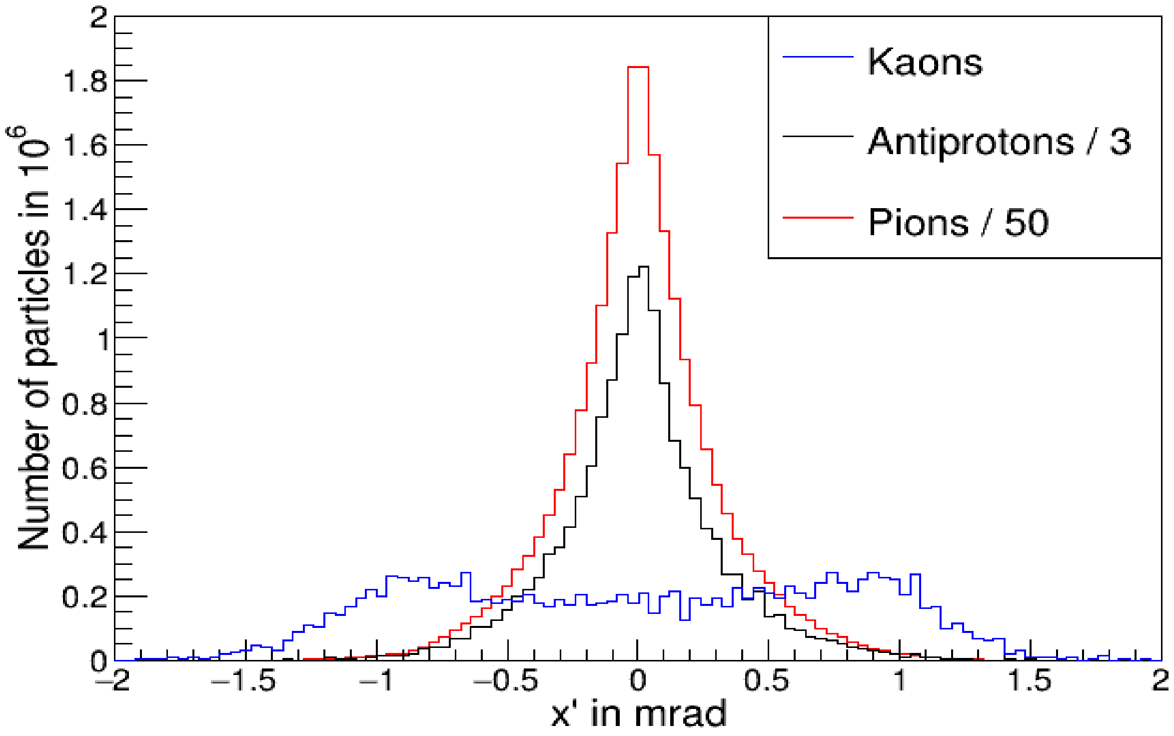
- **In the cavity the angle increases linearly with z:** $x'(z) = \frac{\frac{\mathrm{d}p}{\mathrm{d}z}}{p} \cdot z$
- **Therefore, the offset increases quadratically with z:** $x(z) = \frac{1}{2}\frac{\frac{\mathrm{d}p}{\mathrm{d}z}}{p} \cdot z^2 + x_0$
- **At the end of the cavity, i.e. L_{tot}, the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

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

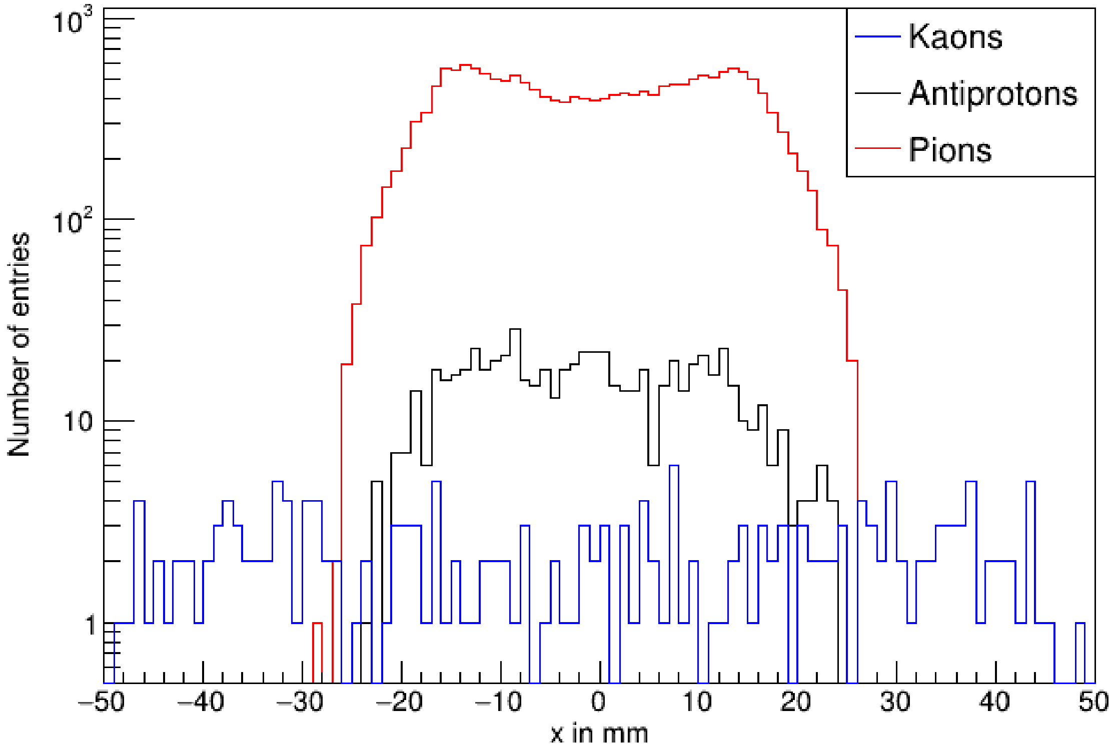
RF separated beam



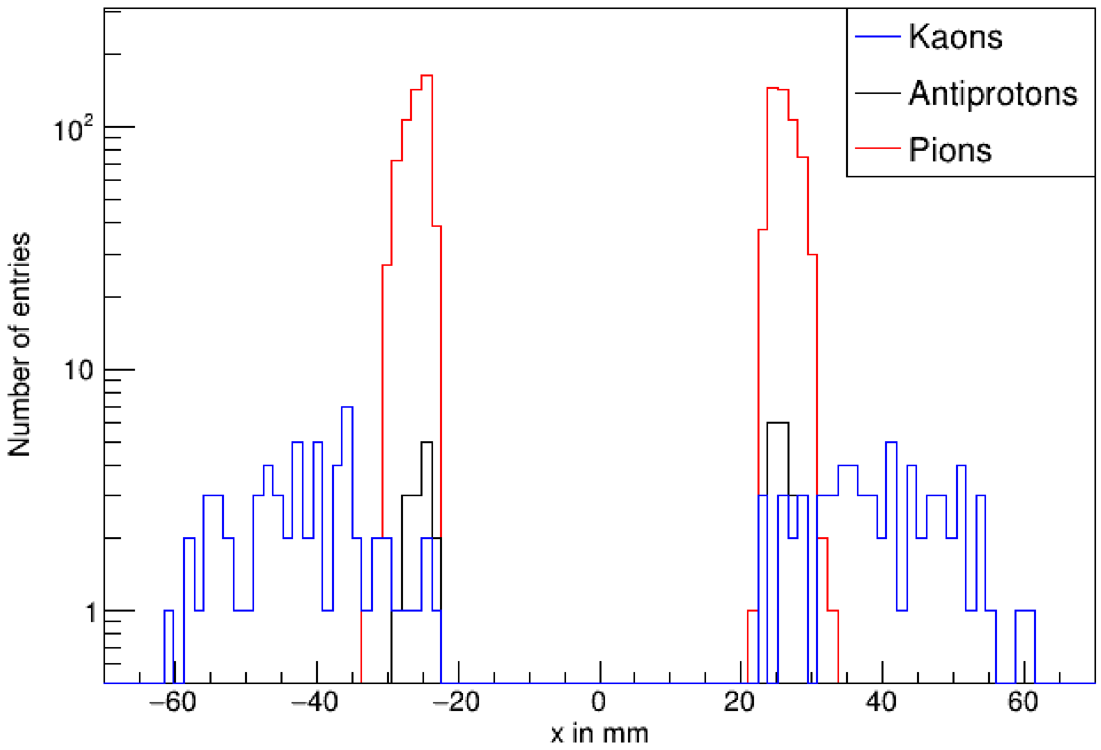
- **Angular distribution after RF2**
- **Cavity phase tuned such that π^- and $\bar{p}$ are not deflected**
  - Angular distribution of K^- peaks at $\pm 1\mathrm{mrad}$
  - For $\pi^-$and $\bar{p}$ angles are distributed around 0
- **Beam dump filters particles depending on their position**
- **Drift is needed to translate angular differences into positional offsets**
  - Currently, we have ca. $20\mathrm{m}$

Absorption

Before the dump



After the dump



CEDAR

10.5170/CERN-1982-013

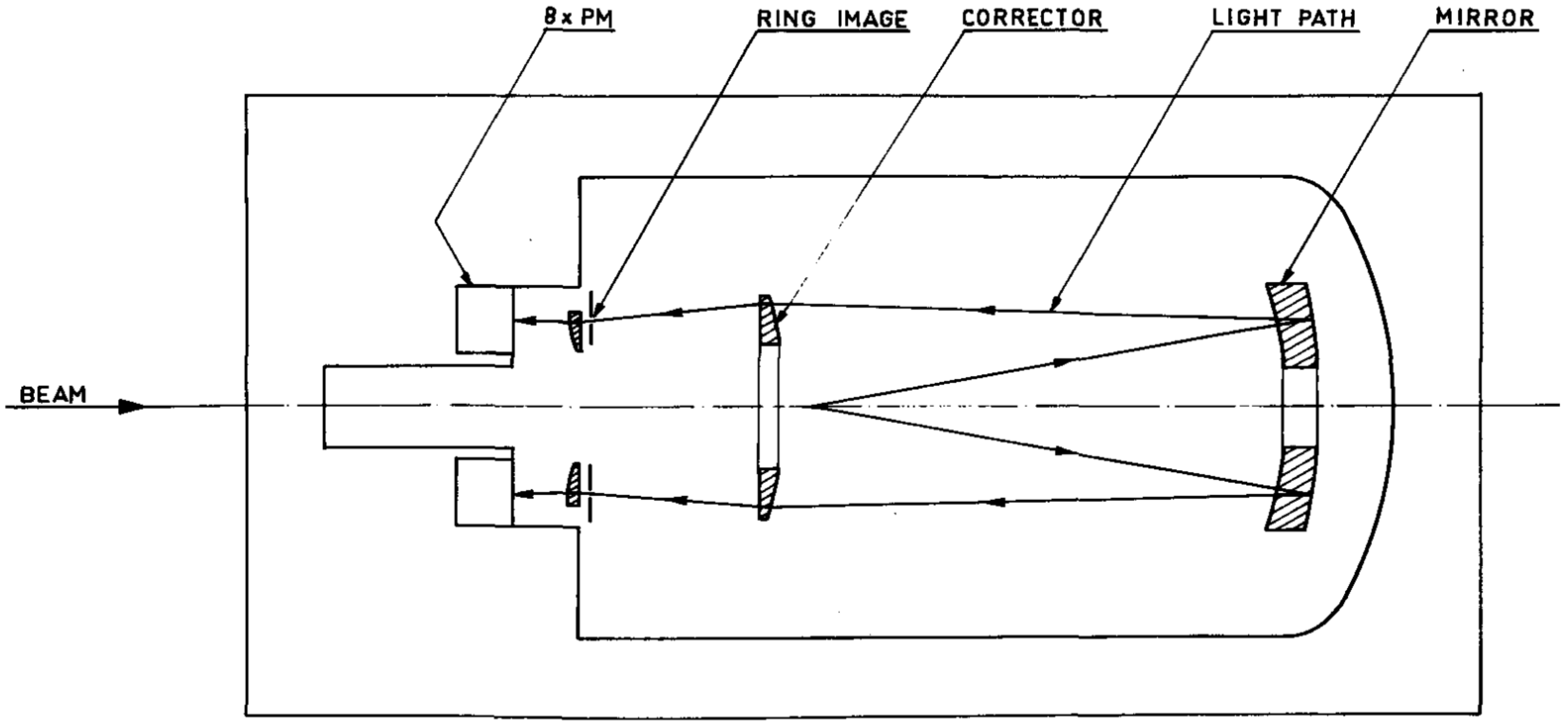


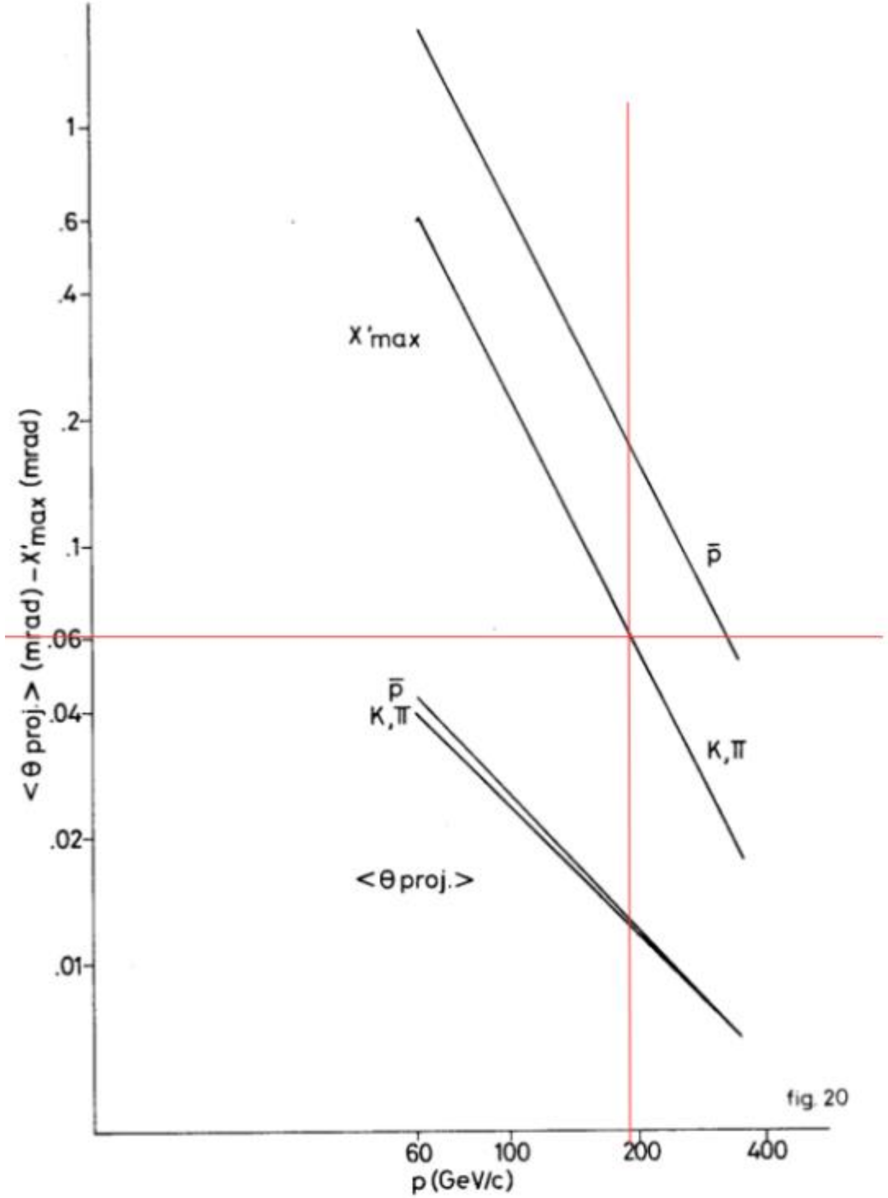
Fig. 2 Schematics of the optics of a differential Čerenkov counter (distorted scale)

$$\cos\theta = \frac{1}{n\beta}$$

$$\Delta\theta \approx \frac{1}{\theta}\frac{\Delta\beta}{\beta}$$

$$\frac{\Delta\beta}{\beta} \approx \frac{m_2^2 - m_1^2}{2p^2}$$

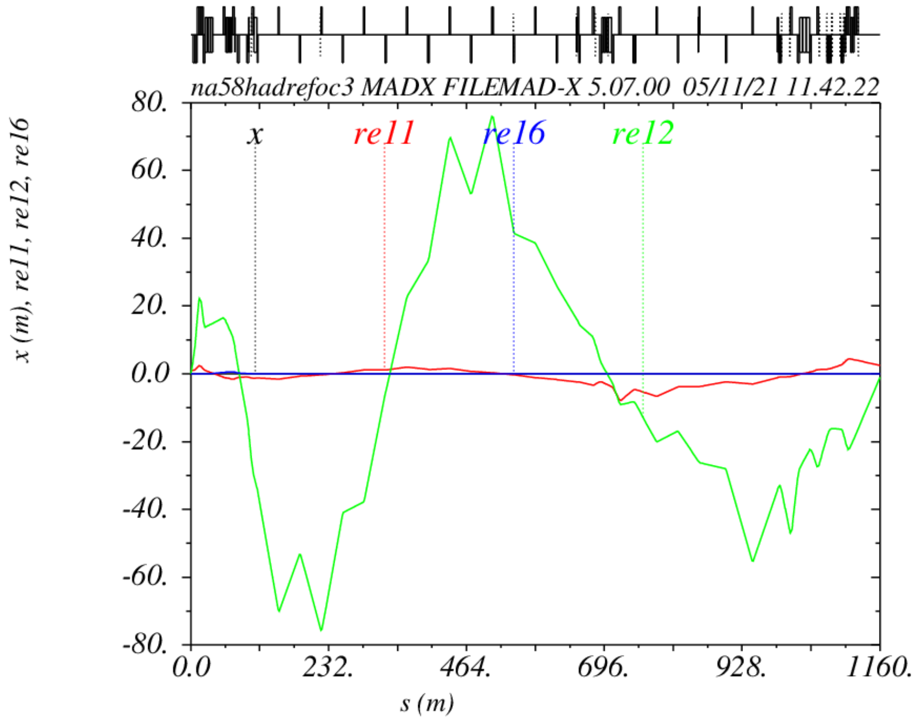
$$\Delta R = f\Delta\theta$$



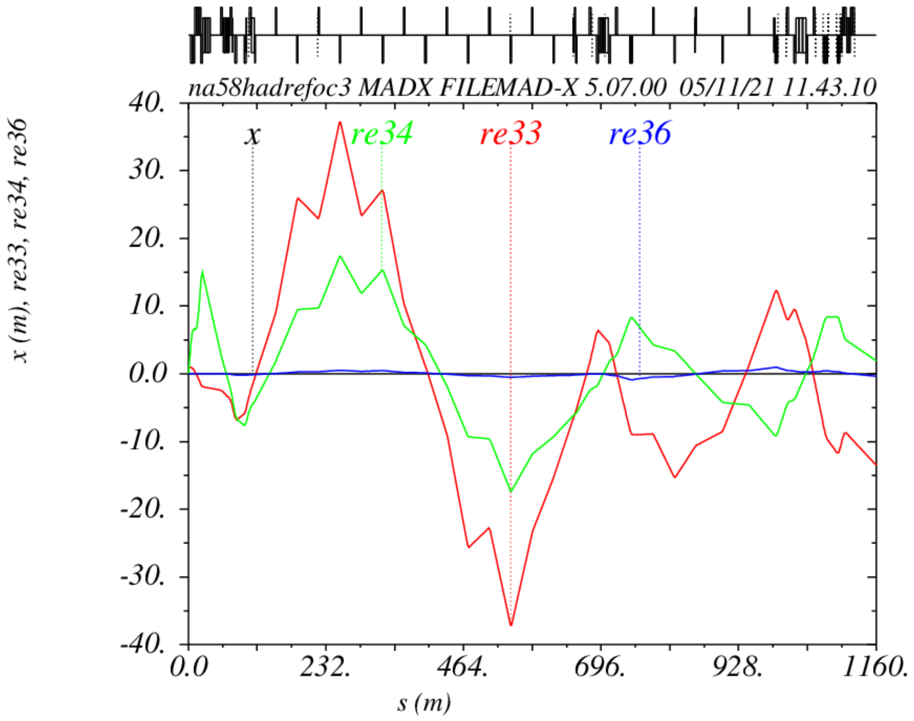
DIVERGENCE AND MULTIPLE SCATTERING IN CEDAR-N

2018 hadron optics

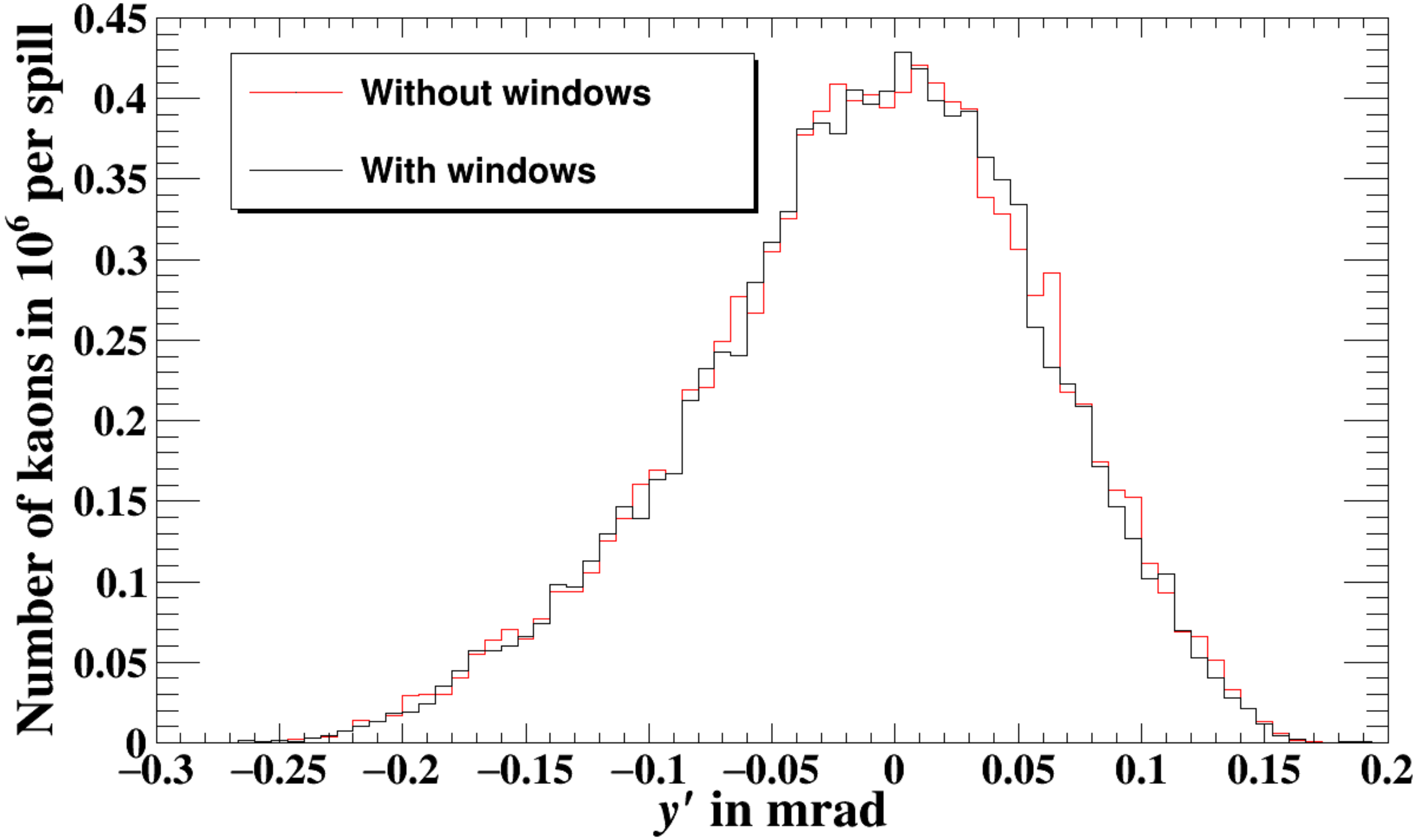
x-plane



y-plane

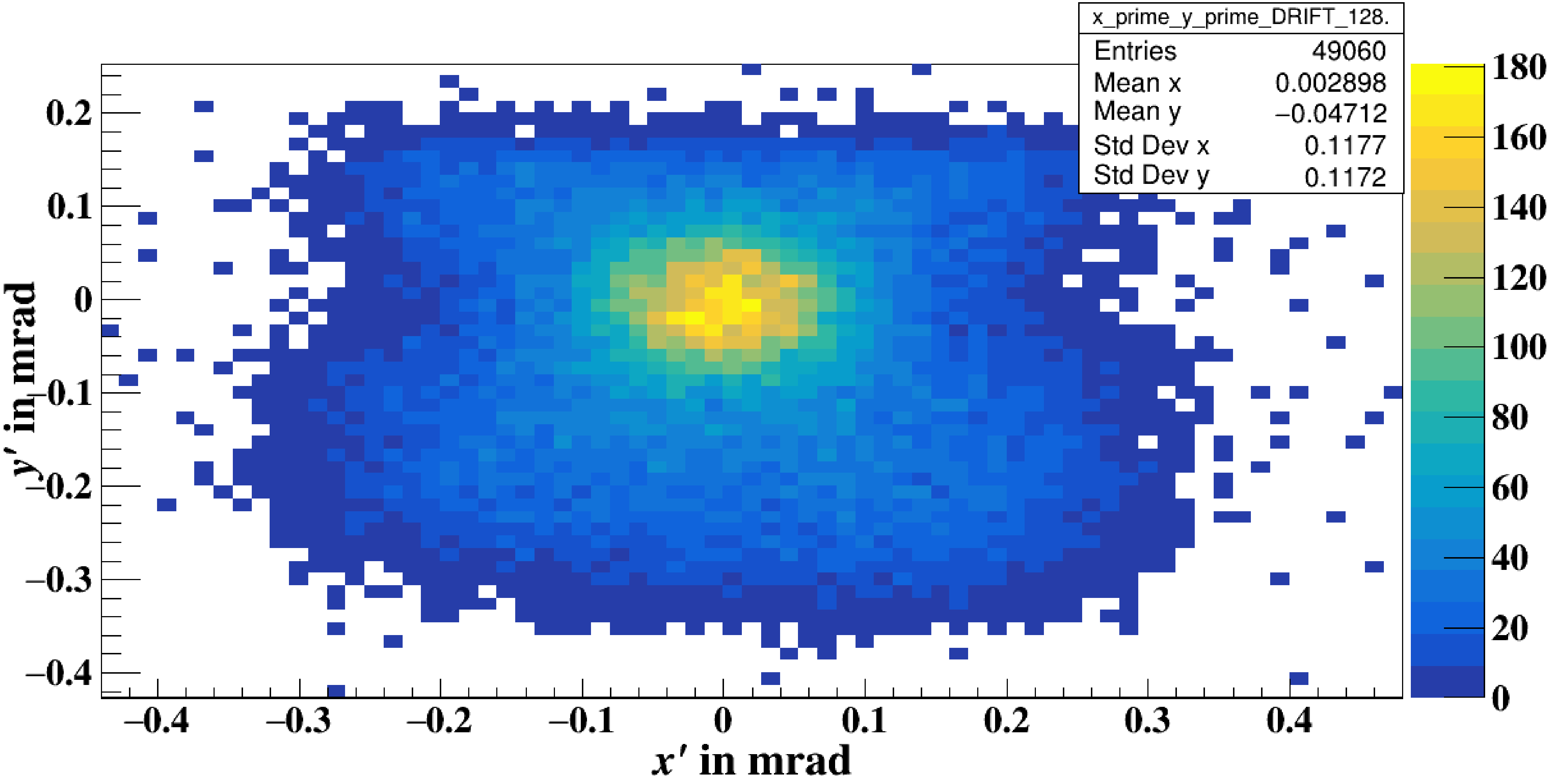


Influence of the vacuum windows



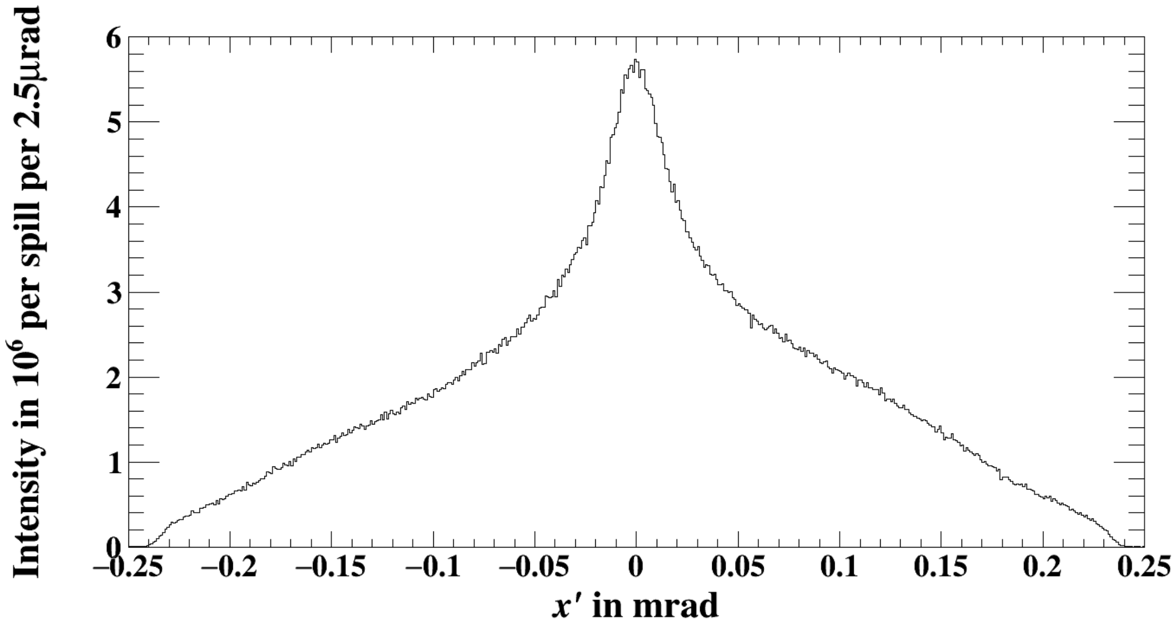
- **In the simulations the vacuum windows have been omitted**
- **Typically, we have $200 \mu m$ of mylar as windows**
  - Some exceptions with even thinner windows
  - Accounts to some mm over the whole $1.1 km$ of beam line
- **Taking these results, it is justified to not use the windows in the simulations as their effect on the beam distributions is negligible**

Beam divergence in 2018

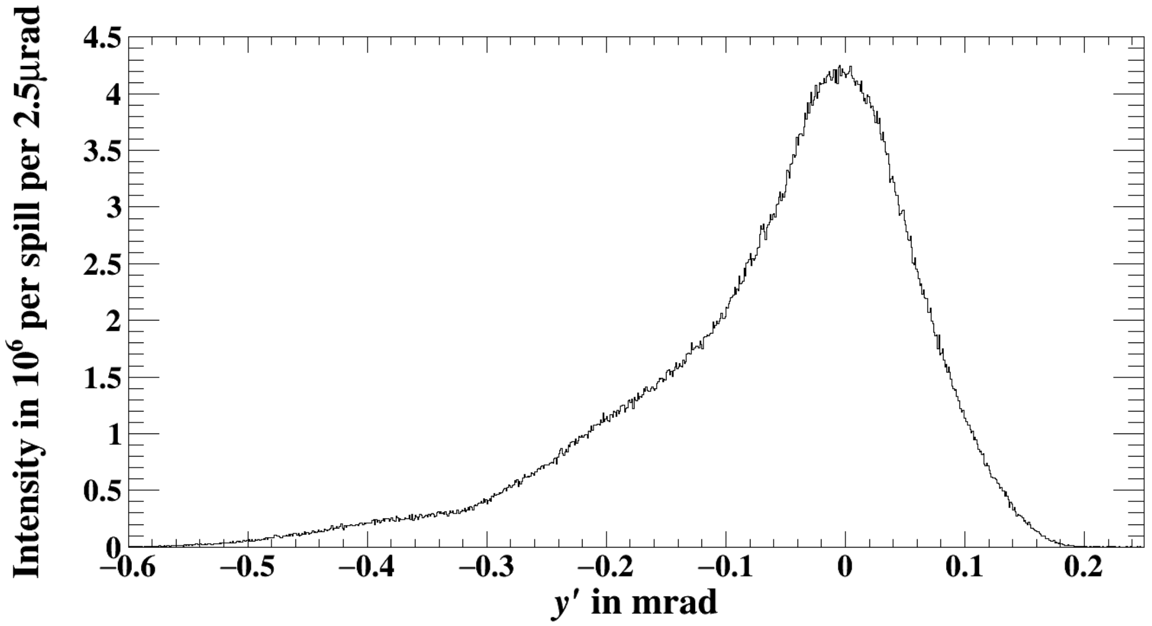


Divergence in the new optics set

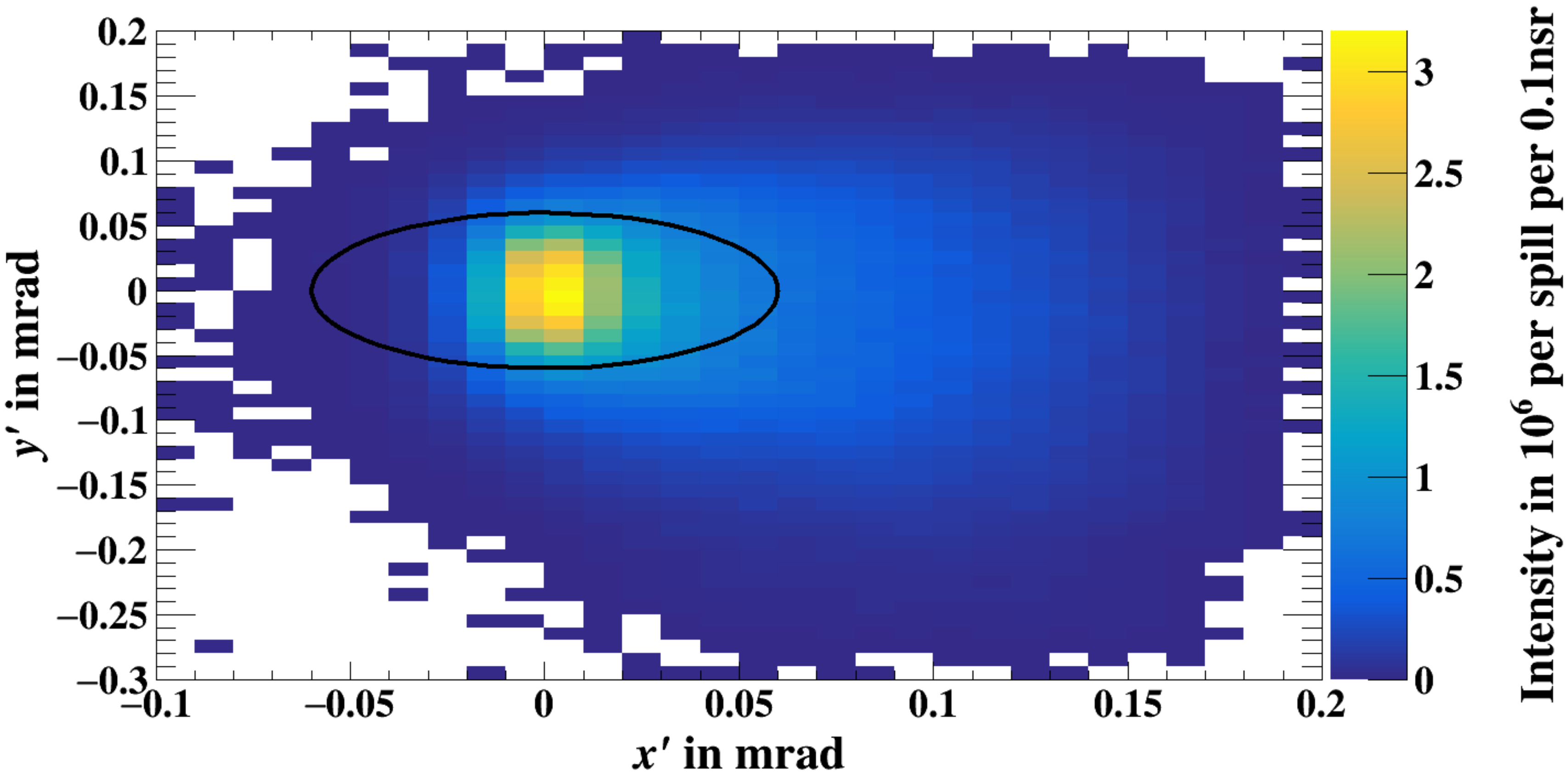
$\sigma_{x'} = 95.8\mu\text{rad}$



$\sigma_{y'} = 125.8\mu\text{rad}$



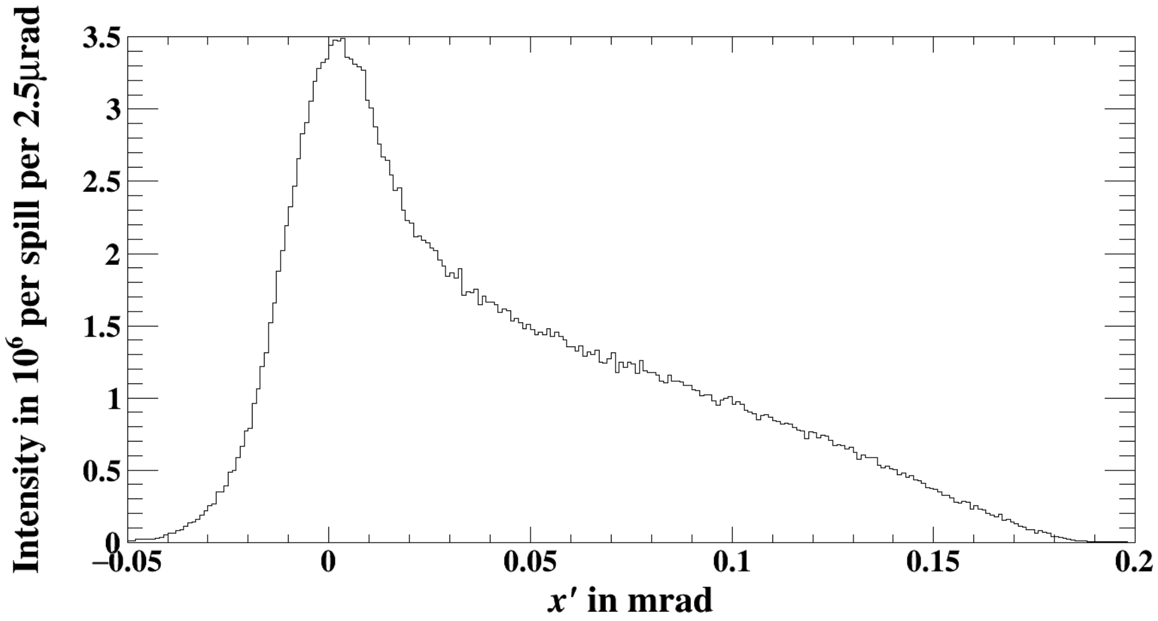
New optics tighter collimated



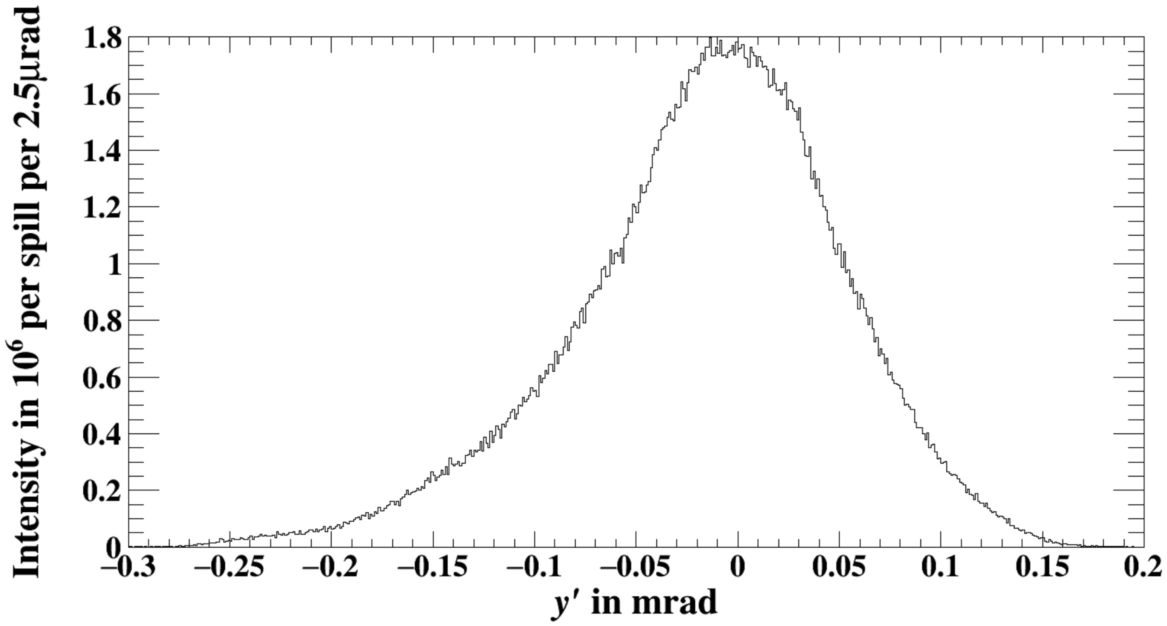
- 2.65×10^8 **particles per spill total intensity**
- 1.21×10^8 **particles per spill in 60μrad**
- **Kaon intensity in 60μrad of** 2.9×10^6 **per spill**

New optics tighter collimated

$\sigma_{x'} = 47.3\mu\text{rad}$



$\sigma_{y'} = 66.4\mu\text{rad}$



Results

Area	Annual dose limit (year)	Ambient dose equivalent rate		Sign
		permanent occupancy	low occupancy	
Non-designated	1 mSv	0.5 µSv/h	2.5 µSv/h	
Supervised	6 mSv	3 µSv/h	15 µSv/h	
Simple Controlled	20 mSv	10 µSv/h	50 µSv/h	
Limited Stay	20 mSv	-	2 mSv/h	
High Radiation	20 mSv	-	100 mSv/h	
Prohibited	20 mSv	-	> 100 mSv/h	NO ENTRY DÉFENSE D'ENTRER

Radiation Area / Controlled Area

- Prompt radiation at **beam level** Y[-30;30]
  - Source: source.for (190 GeV/c π^- beam from before collimator 5 [1])
  - Intensity: $4.8 * 10^8$ π^-/spill and 240 spills/h on Target
  - Magnetic field: magfld.for from [1] (with *qwl_qea.map* and *updated QWLs strengths*)
  - Less than 10% losses from COLL5 source to target (8.5% up to CEDARs and <1% from CEDAR up to target)

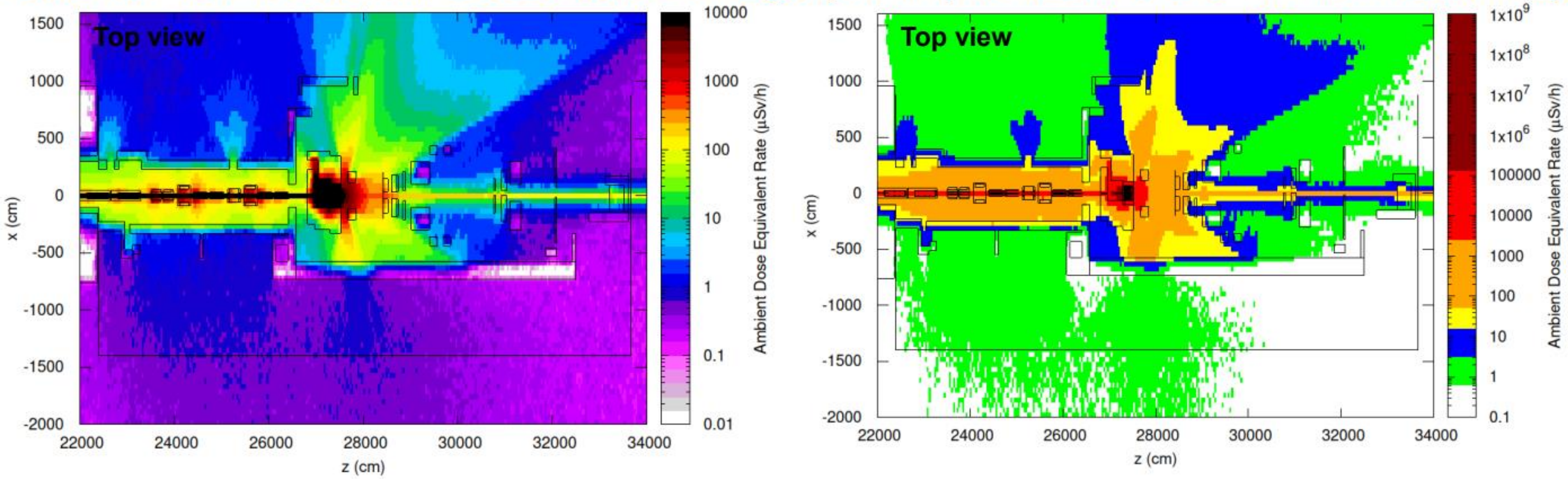


Figure 2: Prompt ambient dose equivalent rate (µSv/h) for $4.8 * 10^8$ π^-/spill and 240 spills/h on Target

Courtesy by A. Devienne

Results

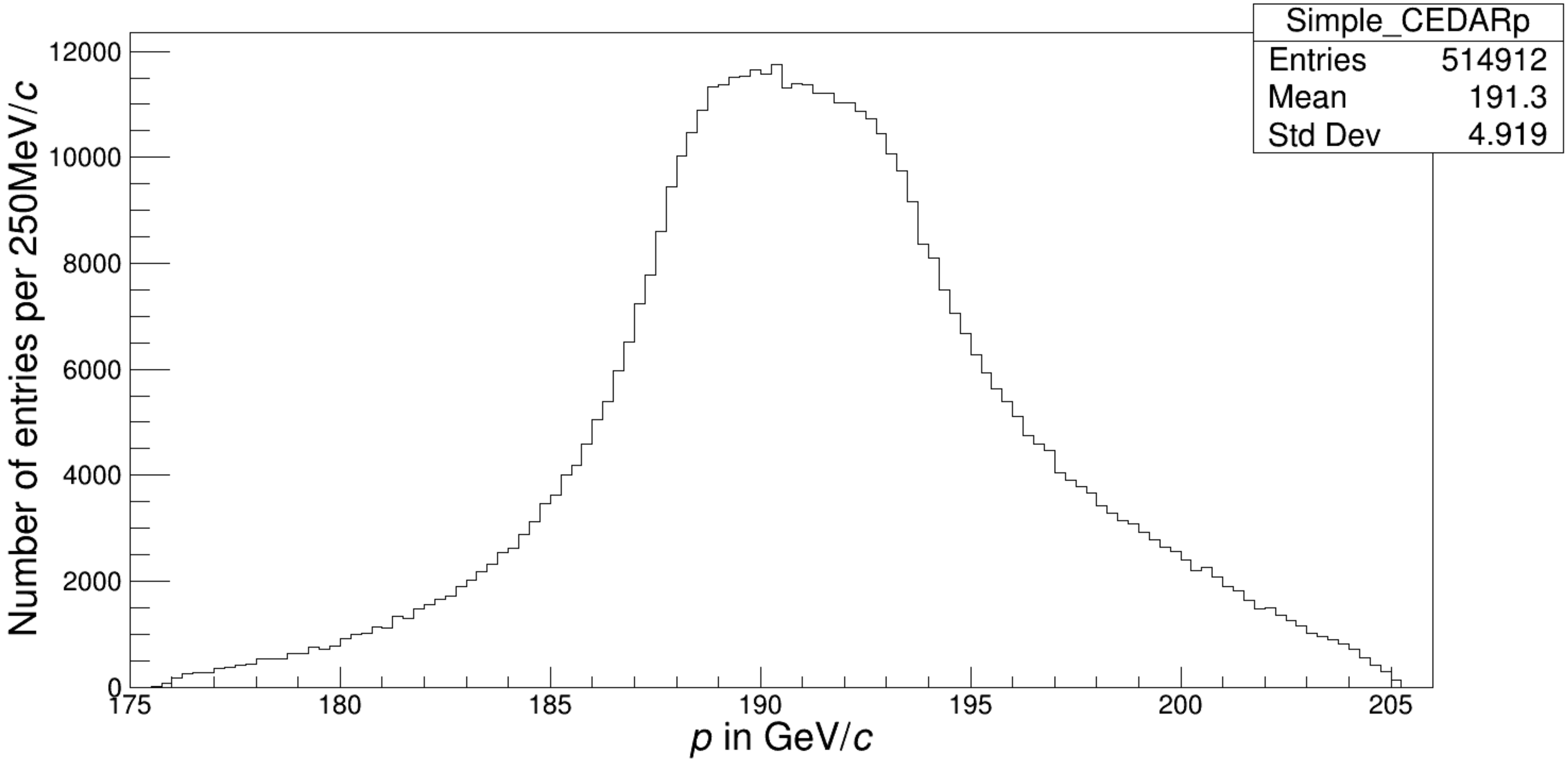
- Skyshine optimization
  - Intensity: $3.07 * 10^{14}\ \pi^{-}$/year on target
  - Limit < 1 mSv/year at CERN fence (#3, #4, #5, #6)
  - Objective < 10 µSv/year exposure from CERN contribution to members of the public (#1,#2)
  - RP3 AMBER area bunker design

#	Name	Effective dose (µSv/year)	Error (%)
1	Reference Point S	**16.9**	4.6%
2	Reference Point P	**1.9**	10.8%
3	PMS823 (Down)	**6.6**	5.1%
4	PMS822 (Mid)	**17.6**	3.8%
5	PMS821 (Jura)	**103.3**	2.1%
6	PMS824 (Salève)	**261.5**	2.4%
7	SMS816 (Up)	**151.3**	2.8%
8	Jura Side Top Hill	**584.1**	1.4%
9	Road Salève	**1078.8**	1.6%

Table 1 : Effective Dose (µSv/year) due to external exposure at 9 reference points for 3.07e14 p/year on target

Courtesy by A. Devienne

Momentum resolution



Beams from SPS