Beam options at the M2 beamline

Fabian Metzger, Dipanwita Banerjee, Johannes Bernhard, Markus Brugger, Nikos Charitonidis, Maarten van Dijk, Lau Gatignon, Laurie Nevay (BE-EA-LE) on behalf of the EHN2 Working Group

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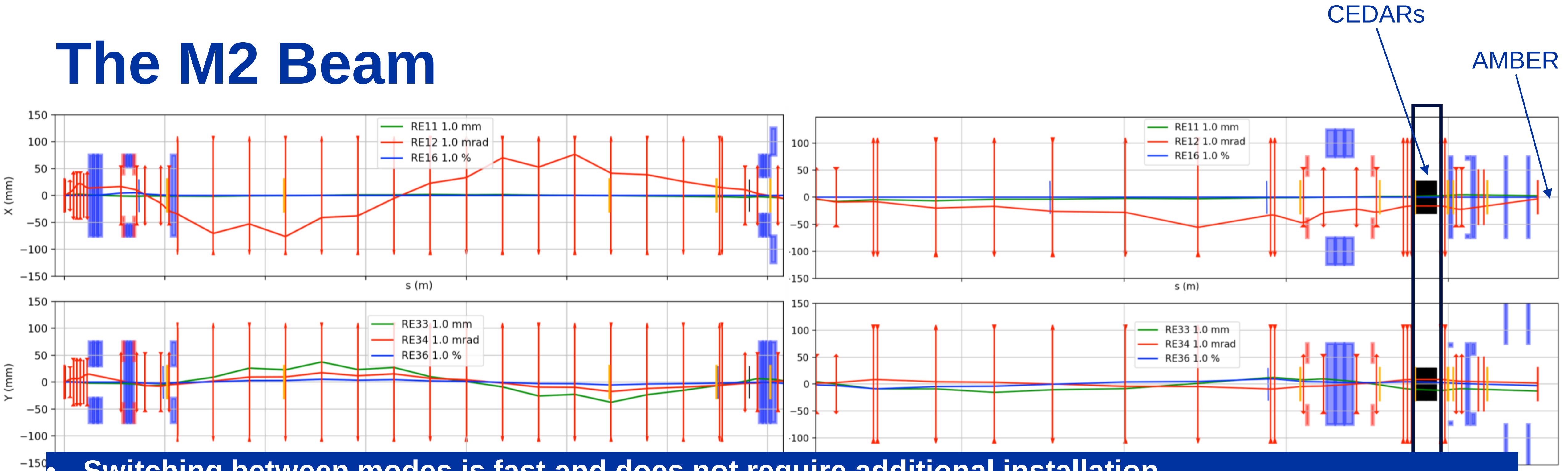
The M2 beam

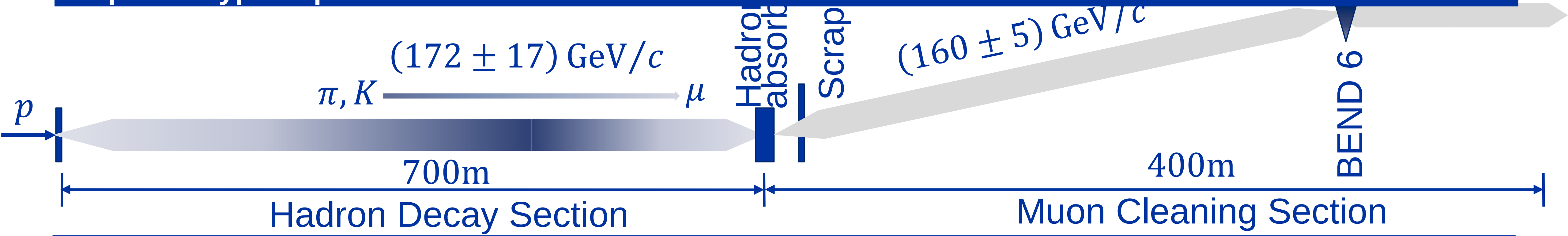
- M2 beamline is $\approx \mathbf{1.1km}$ long transporting secondary particles from T6 to the EHN2
- Consists of a $\mathbf{700m}$ long hadron section to allow hadron decays to muons followed by $\mathbf{9.9m}$ Be inside a bend to absorb the hadrons with the muons passing through
- $\mathbf{400m}$ long muon section selects final muon momentum and cleans beam halo
- M2 has three main operation modes:
  - High-energy, high-intensity muon beam with momenta up to $160\,{}^{\mathrm{GeV}}/_{c}$; higher momenta up to $220\,{}^{\mathrm{GeV}}/_{c}$ possible, but the flux drops very rapidly with beam momentum
  - High-intensity secondary hadron beam for momenta up to $280\,{}^{\mathrm{GeV}}/_{c}$ with radiation protection constraints
  - Low-energy, low-intensity (and low-quality) in-situ electron calibration beam

Beam mode	Momentum in ${}^{\mathrm{GeV}}/_{c}$	Max. flux per $4.8s$	Typical $\Delta p/p$	Typical RMS spot size	Polarisation	Absorber (9.9m Be)	XCIO (5mm Pb)
Muons	$+208/190$ $+172/160$	$\approx 10^8$ 2.5×10^8	3%	$8 \times 8\mathrm{mm}^2$	80%	IN	OUT
Hadrons	± 190 Max. 280	10^8 (RP) 4.8×10^8 (Dump)	$-$	$5 \times 5\mathrm{mm}^2$	$-$	OUT	OUT
Electrons	-10 to -40	$< 2 \times 10^4$	$-$	$> 10 \times 10\mathrm{mm}^2$	$-$	OUT	IN

The M2 Beam



- **Switching between modes is fast and does not require additional installation**
- **In hadron mode an optional pair of differential Cherenkov counters (CEDARs) are available to tag a specific type of particle in the beam**



Muon mode

Experiment locations

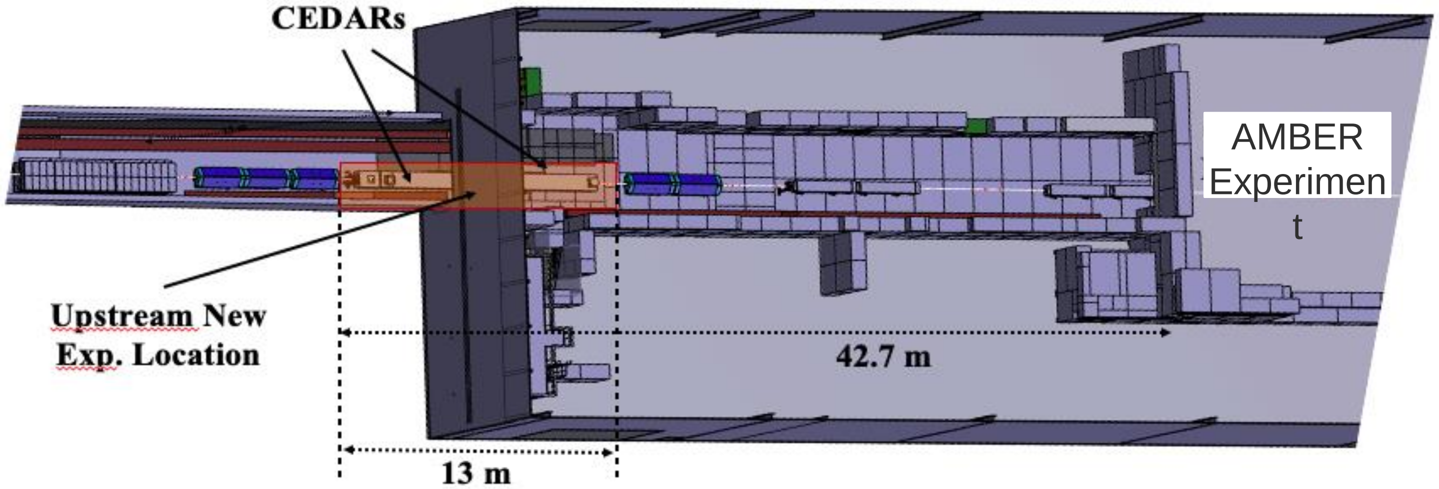
- **Currently, EHN2 houses the AMBER experiment that started physics data-taking in 2023**

- **Upstream of the spectrometer there is space for 2 CEDARs which can be deinstalled if not needed by AMBER**

- **This upstream available space ($\approx 13\mathrm{m}$) is feasible for the test runs as well as the MUonE and NA64μ physics runs without major modifications to the beamline**
  - For final MUonE run with full setup all downstream magnets will be put on rails for easy changeover

- **Two optics options were studied**
  - Size ↔ Divergence
  - Small, divergent beam
  - Large, parallel beam

  → Define optimum with experiments



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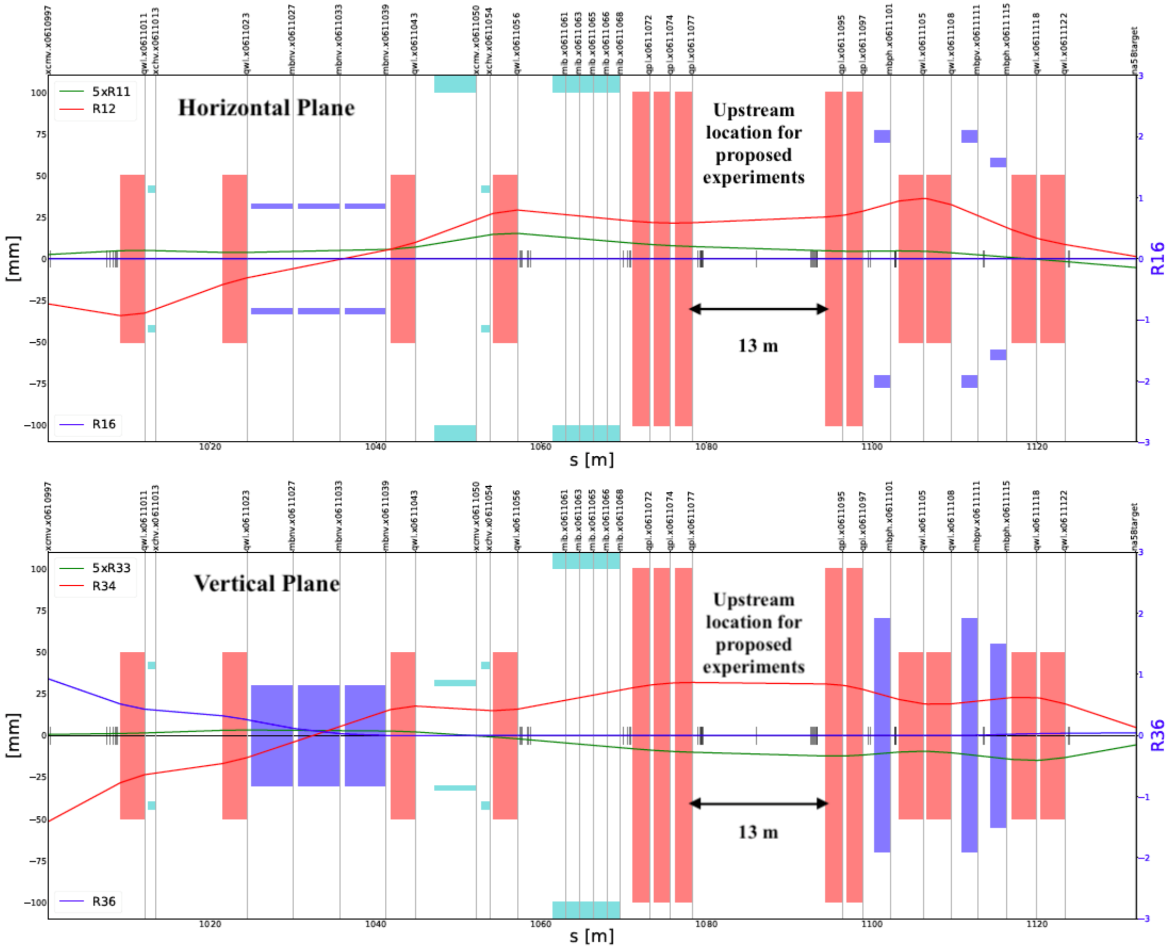
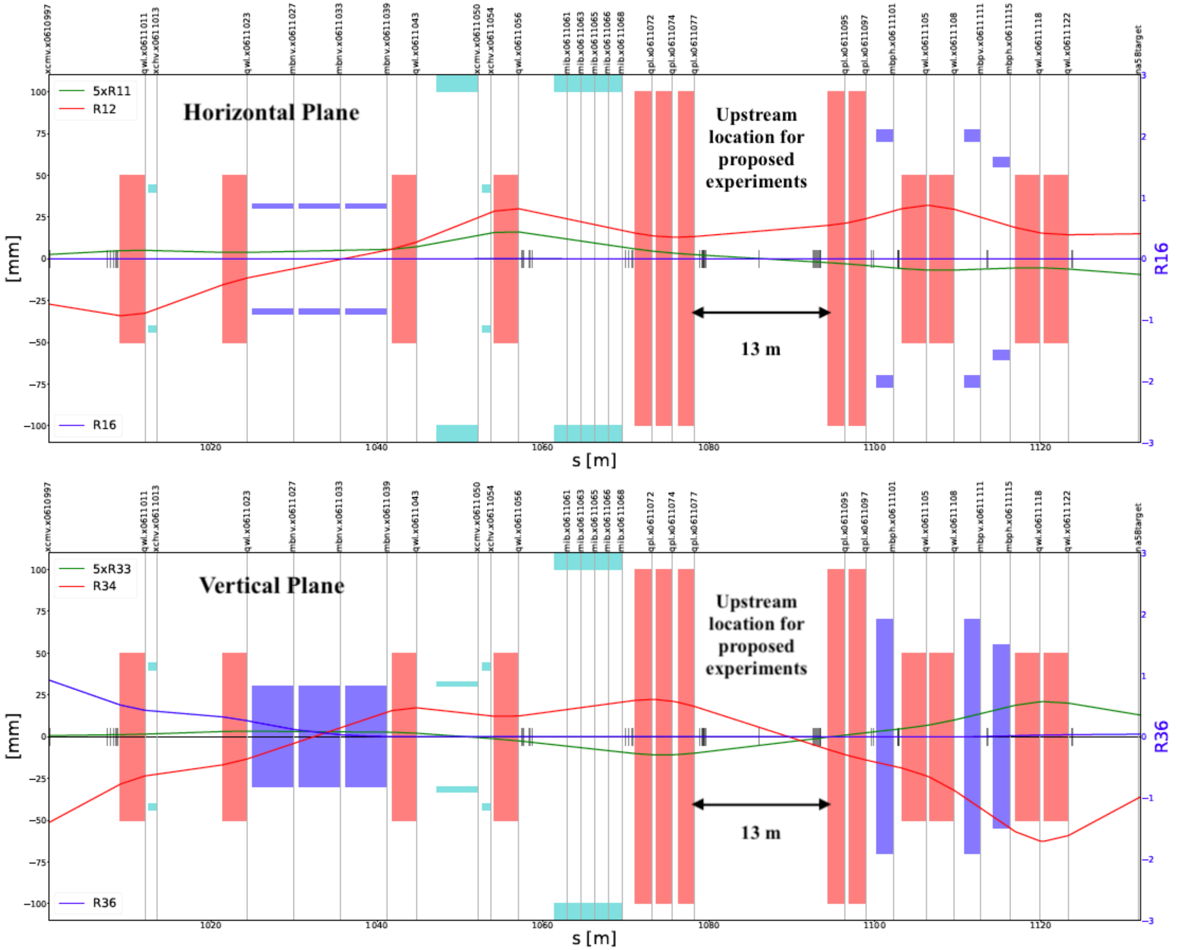
Optics studies

Parallel beam



Focused beam



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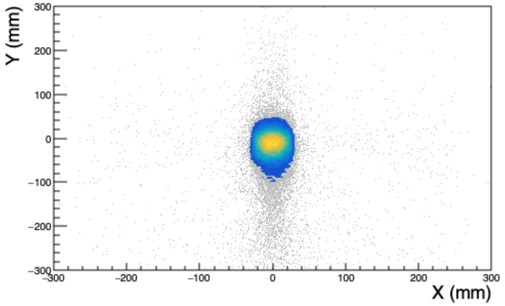
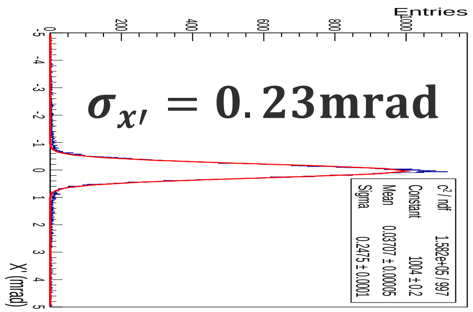
Beam parameters

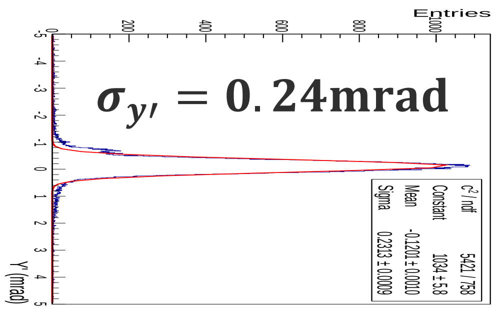
Parallel beam

$\sigma_x = 13\text{mm}$
$\sigma_y = 22\text{mm}$

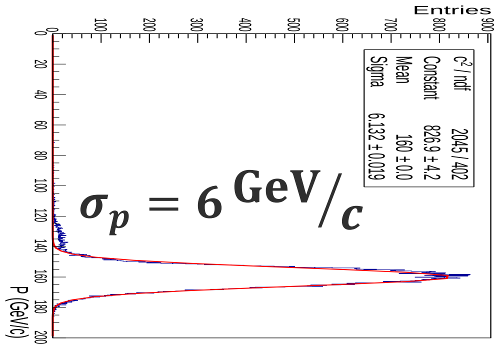




$\sigma_{x'} = 0.23\text{mrad}$



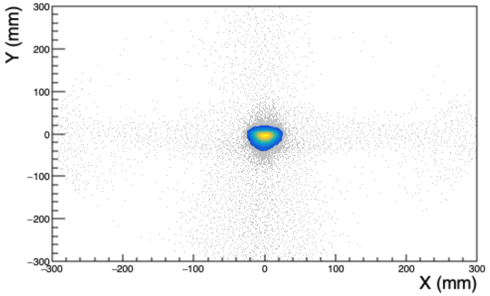
$\sigma_{y'} = 0.24\text{mrad}$

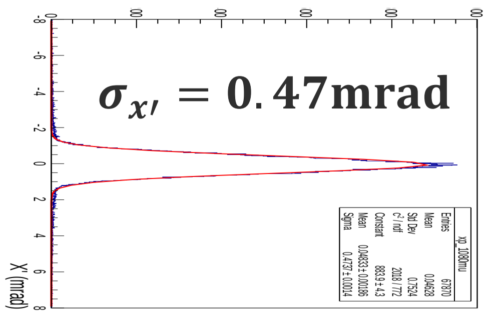


$\sigma_p = 6\ {}^{\text{GeV}}/_{c}$

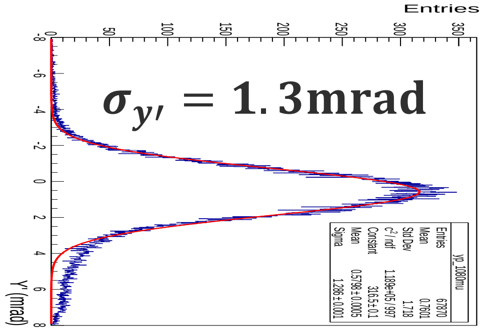
Focused beam

$\sigma_x = 10\text{mm}$
$\sigma_y = 12\text{mm}$

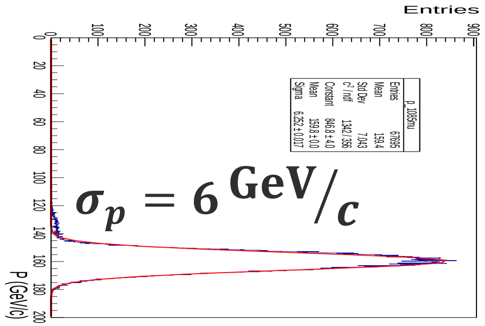




$\sigma_{x'} = 0.47\text{mrad}$



$\sigma_{y'} = 1.3\text{mrad}$



$\sigma_p = 6\ {}^{\text{GeV}}/_{c}$

Halo muons

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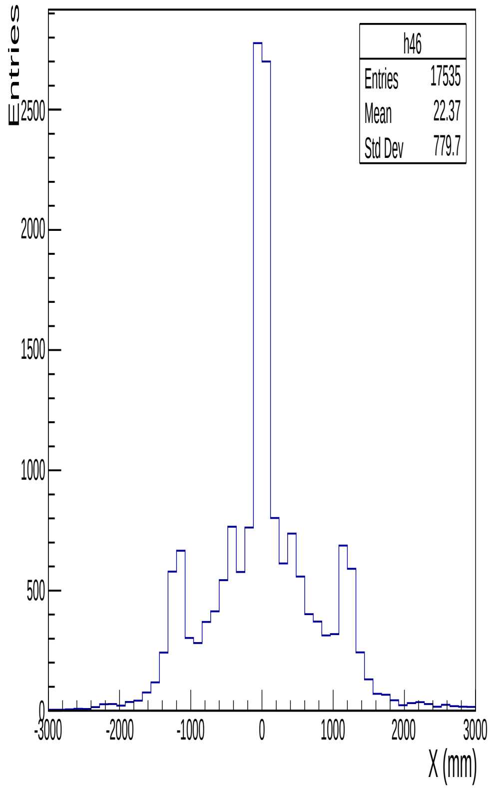
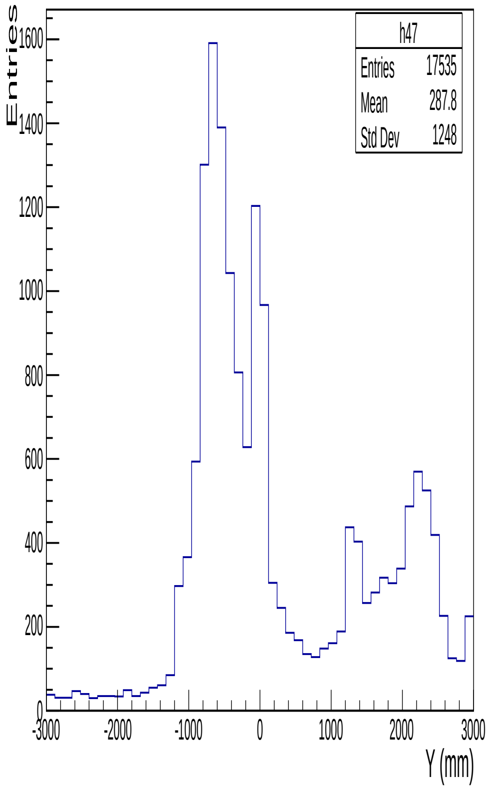
- **Span to almost $3 \times 3\mathrm{m}^2$**
- **Rate is about $10 - 15\%$ of the core of the beam**

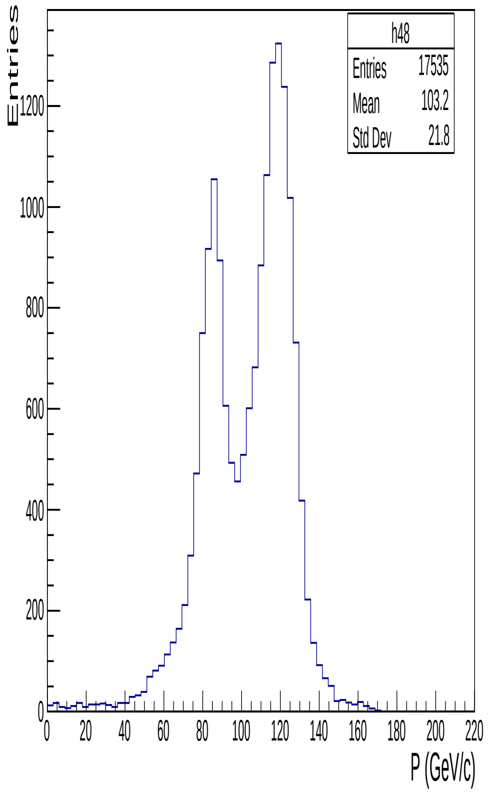
x



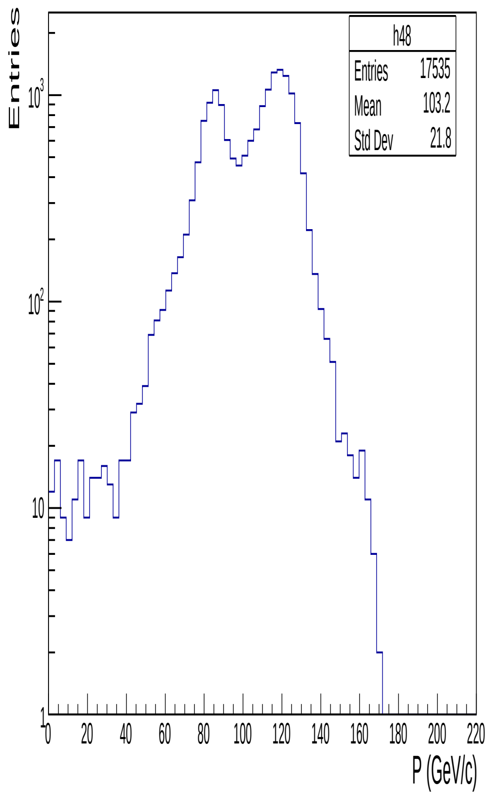
y



p



p (log)



Plots include particles outside of $300\mathrm{mm}$ radius and inside $3 \times 3\mathrm{m}^2$ square

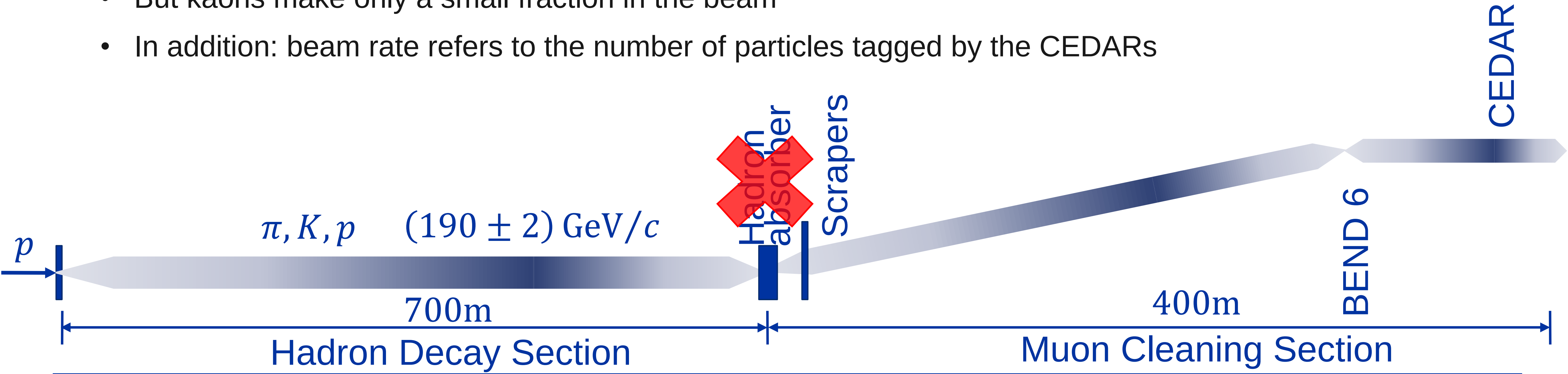
Summary: muon beam

- **Two options were studied for the proposed experiments at the upstream location**
- **Possible to tune the parameters between the two options (smaller beam size → higher divergence)**
- **Halo muons span to about $3 \times 3\mathrm{m}^2$ and account for $10 - 15\%$ of the core of the beam**
- **Study with RP ongoing to increase flux to more than 2×10^8 following MUonE request**
- **Complete beamline simulation available in BDSIM (Geant4 based software)**
  - Includes particle production in T6
  - Beam transmission along the full beamline (no assumptions on acceptance; including hadron absorber, AMBER BMS)
  - Currently validating the simulation together with NA64μ
  - Made use of several biasing techniques to observe reasonable muon and hadron flux at the end
  - Estimated the hadron content in the muon beam for different hadron absorbers which is compared with data taken by NA64μ

Hadron mode

Where are we?

- **AMBER will use the hadron beam extensively in future especially after LS3**
- **No hardware changes in the beamline compared to muon operation besides installation of the CEDARs**
- **AMBER will push the beamline to its limits regarding the intensity**
  - Mainly interested in kaon physics after LS3
  - But kaons make only a small fraction in the beam
  - In addition: beam rate refers to the number of particles tagged by the CEDARs

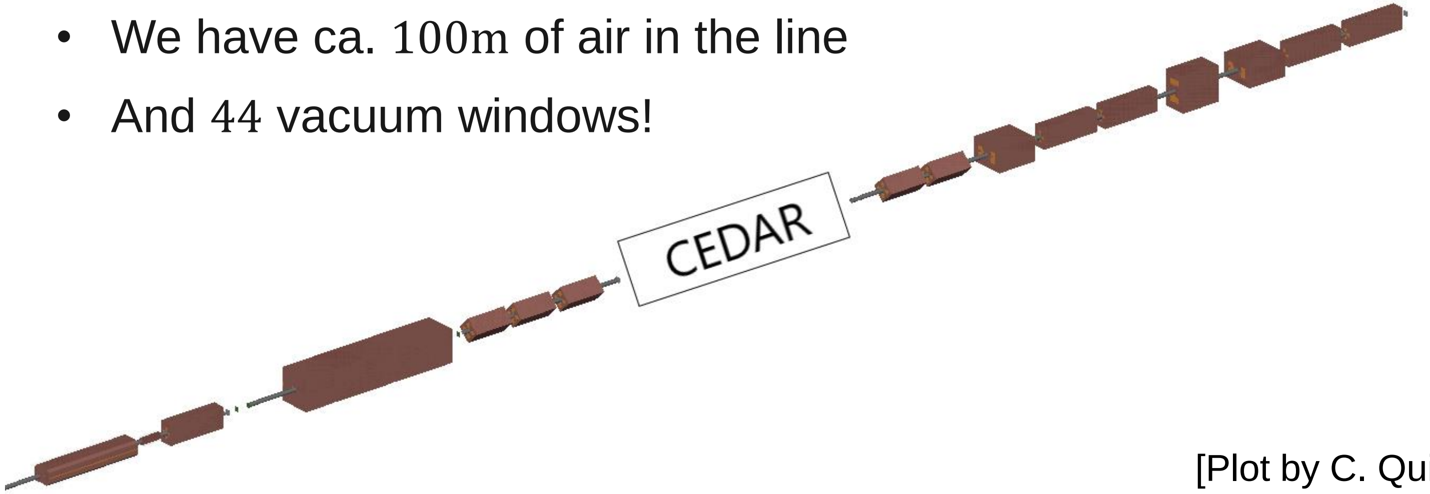


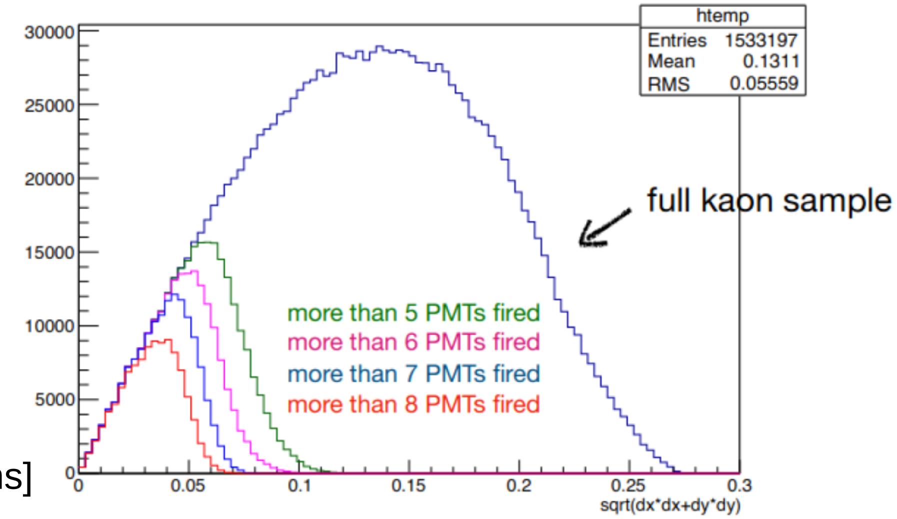
Where are we?

- **Currently, for specific conditions the instantaneous intensity of the hadron beam can be increased to 4.8×10^8 particles/spill (RP) corresponding to $\sim 10^7$ kaons**

- **High tagging efficiency of the CEDARs is therefore required for kaon physics, which depends on the beam divergence**

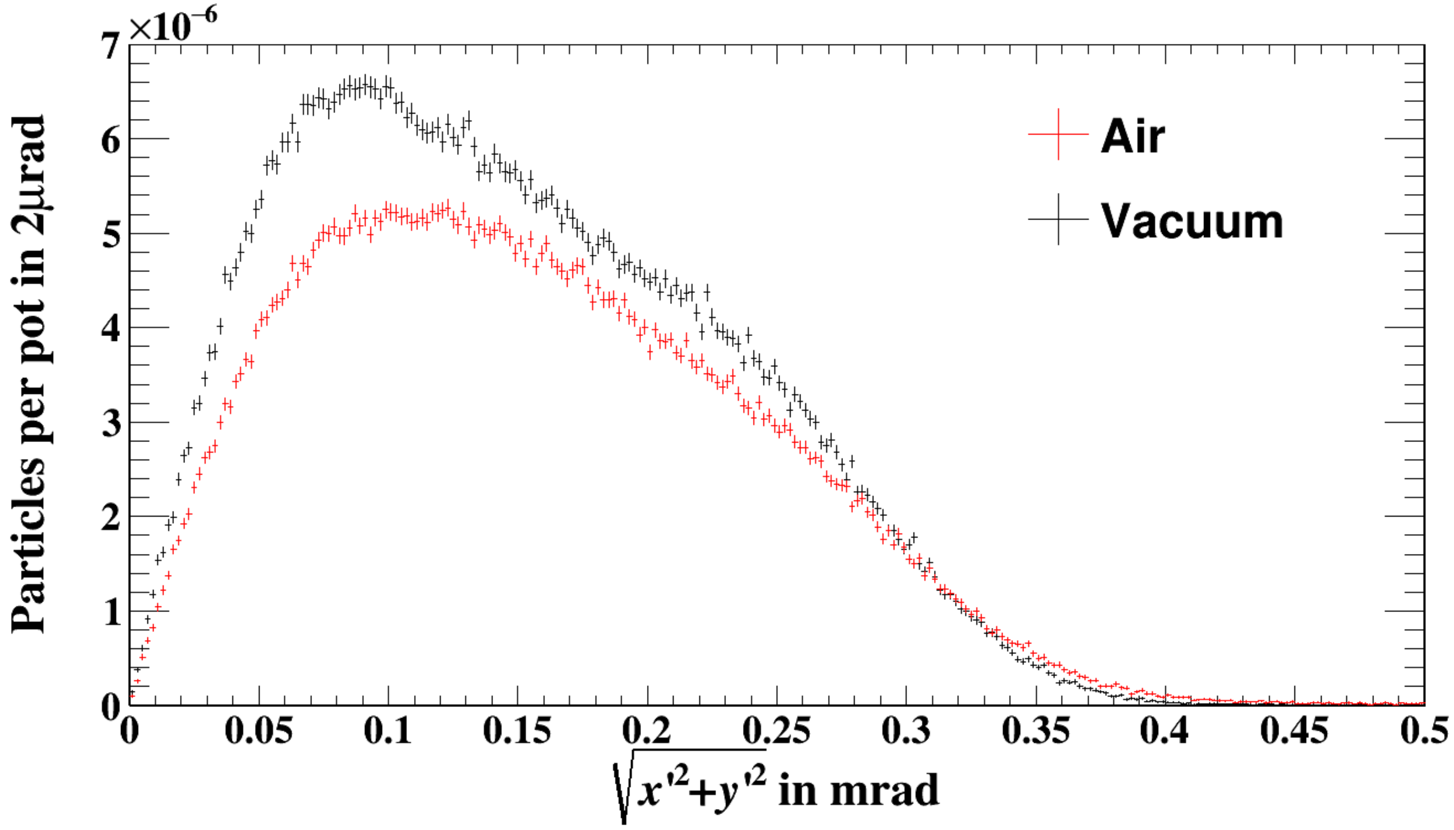
- **To improve the number of identifiable kaons at AMBER the options checked:**
  - Optimising the hadron beam in terms of divergence to increase the tagging efficiency of the CEDARs
  - Increasing the number of accumulated hadrons on the AMBER target to 3×10^{14} per year (RP study)
  - We have ca. $100\mathrm{m}$ of air in the line
  - And 44 vacuum windows!





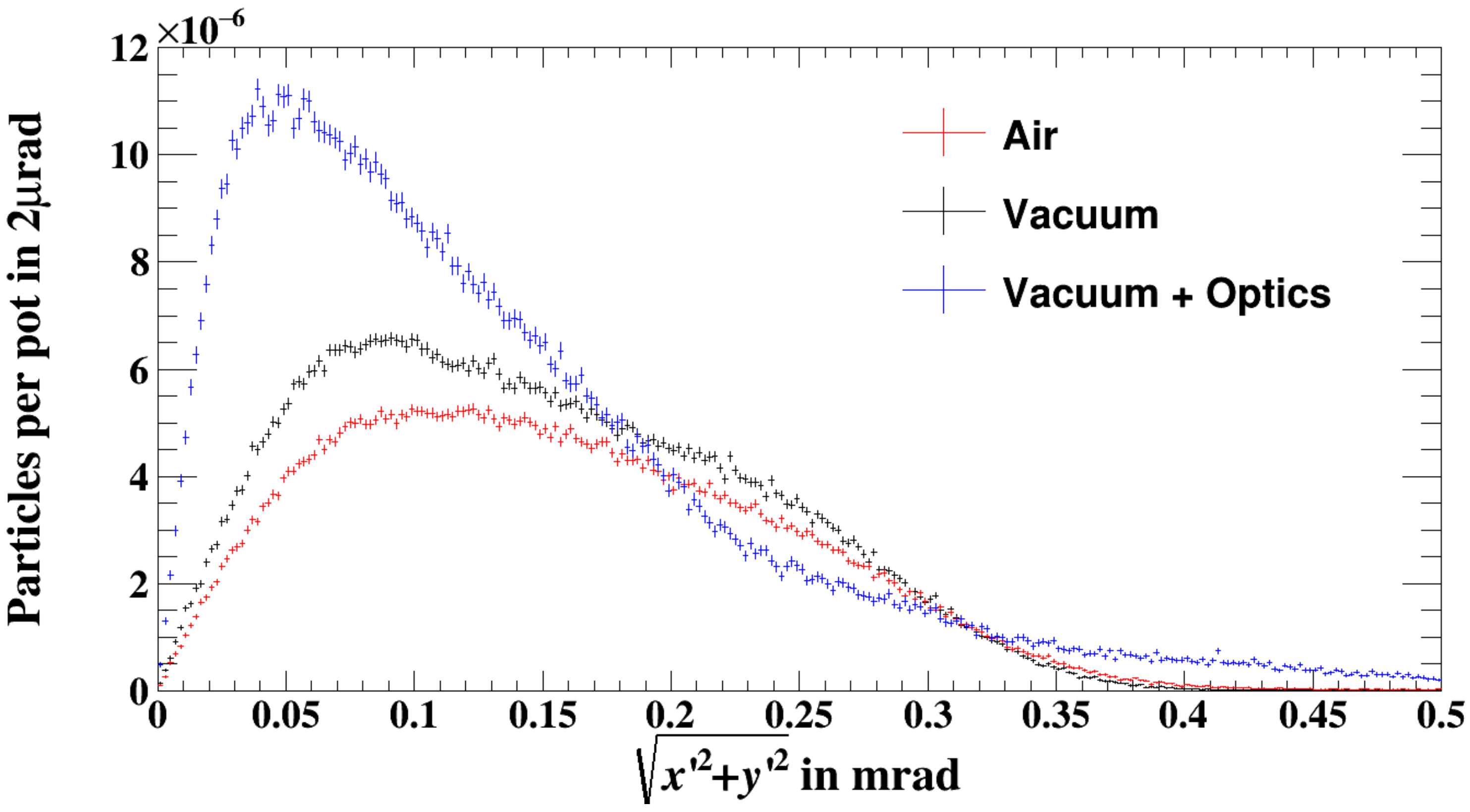
[Plot by C. Quintans]

Vacuum improvements



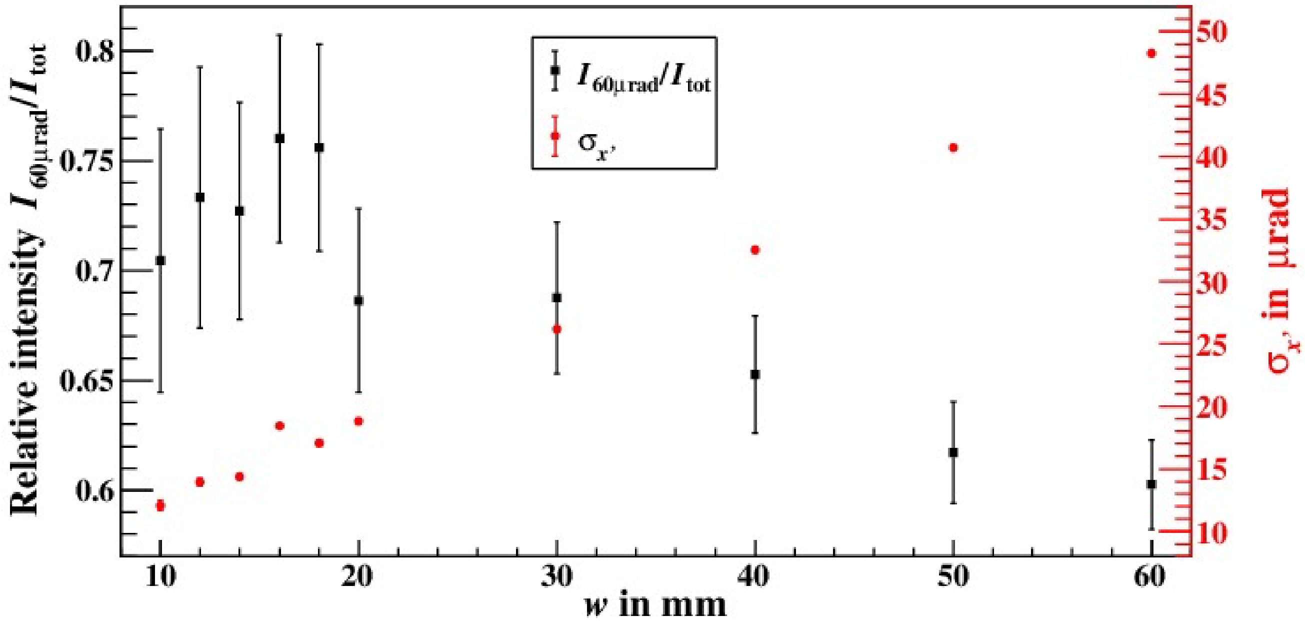
- **Compare divergence for the current layout of M2 with a full-vacuum implementation ($190\ ^{\mathrm{GeV}}/_{c}$ beam momentum)**
- **No clear reduction of standard deviation**
- **Higher transmission the more vacuum sections we have in M2**
  - Full vacuum: 15% more flux
  - Allows better collimation (tighter and cleaner)
- **Increase from 1.2×10^{6} to 1.7×10^{6} kaons in 60μrad**

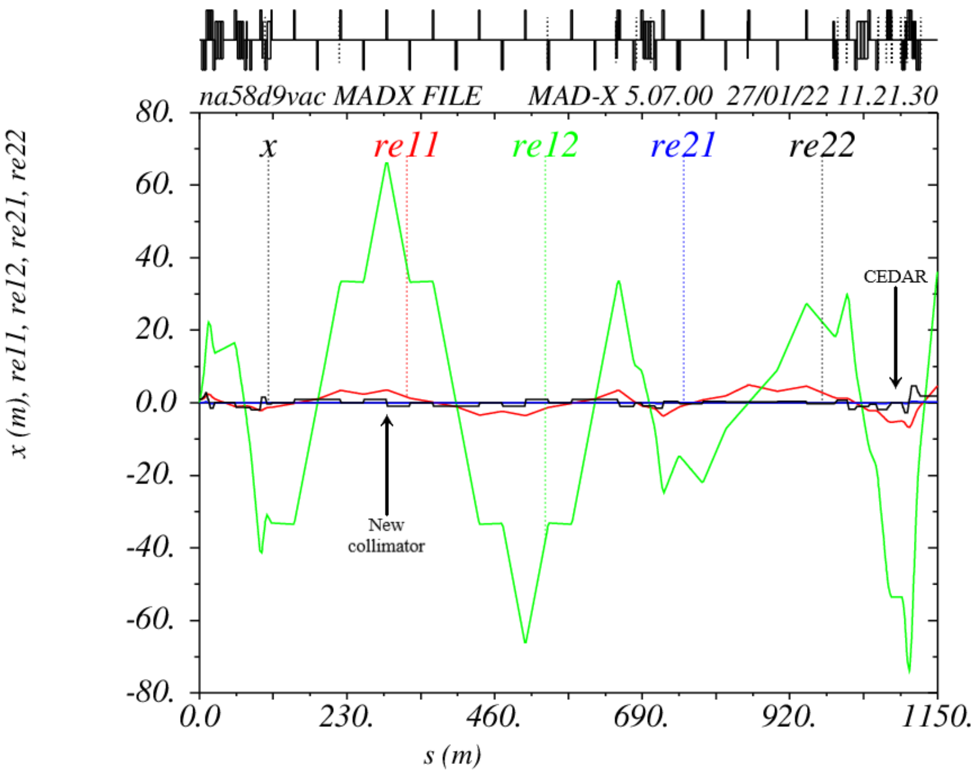
Vacuum improvements + optics



- **Having the full beamline under vacuum → can modify optics for a larger beam at the CEDARs**
- **Increase to 4×10^6 kaons in $60\mu rad$ (enhanced by ≈ 3)**
- **25% of the beam could be identified by the CEDARs**
- **Those numbers are obtained with collimators set to $\pm 20mm$ and $\pm 25mm$**
  - For Drell-Yan: as highest intensity as possible
  - For spectroscopy: only low intensity → collimate the large-angle particles

Horizontal collimation





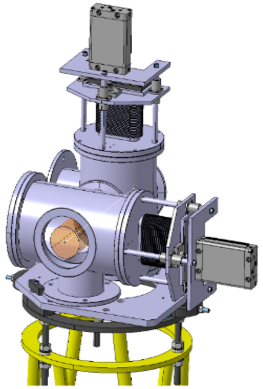
- **Collimator is placed at a location with large beam in horizontal plane**
- **By closing the collimator from 30mm to 15mm, divergence and overall intensity decreases by 50%**
- **At some point, further collimation does not make sense as $\sqrt{x'^2 + y'^2}$ is the determining factor**
- **Vertical 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 y

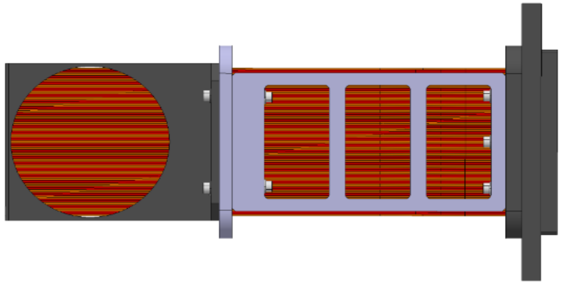
G. Romagnoli
M. Lino Dos Santos

The way to better vacuum

QPL and MBNV - Magnets
3 to be placed under vacuum
To be equipped with new vacuum chambers

XWCM – Analog Wire Chamber - 9 to be placed under vacuum
XCI – Scintillator – 1 to be placed under vacuum
FISC – Profile Monitor – 2 to be placed under vacuum
Initial studies for the program did not included instrumentation in vacuum → Improvement
To be replaced by new XBPF under vacuum in the scope of NACONS





The way to better vacuum

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XCBV – Big 2block vertical Collimator
1 to be placed under vacuum
A full conversion is not possible
Instead, to be replaced by a standard XCSV (2-block collimator) under vacuum

XCM – Magnetic Collimator
9 to be placed in vacuum
A full conversion is under study
Initial proposal will be to equip the XCM with a vacuum chamber (ad hoc/ nonstandard Ø):

- Collimator jaws will be blocked in one aperture/position!
- Apertures are defined in EDMS2798464
- **NOTE:** The vacuum chambers must be removed if different apertures in collimator needed! Only possible during a LS or YETS. If required to be removed in TS the collimator must be equipped with rails in X → **Keeping flexibility for physics**

The way to better vacuum

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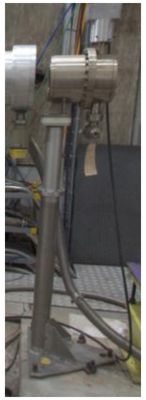

XION- Ionization Chamber - 1 to be placed under vacuum
XTRI/XTRH – Scintillator
Feasibility to be confirmed

XHOD - Hodoscope - 5 to be placed under vacuum
Collaboration between BE and AMBER to determine feasibility

XABS – Absorbers Beryllium
3 to be placed under vacuum
10m section
Feasibility to be confirmed

AL Chamber and collar (nonstandard)

SS Chamber and collar (NA standard)

The way to better vacuum

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2023 to Q3 2024

1. As-built 3D for M2 beamline
2. Detailed 3D of XCM, XABS and XCBV
3. M2 Vacuum after LS3 user requirements approval

Q3 2024 to end 2024

1. Feasibility study
2. ECR / consolidation requests
3. SPSC review

Q1 2025 - Project approval (to meet LS3 window)

Budget / Resources request

2025/2026

1. Detailed design
2. Procurement

LS3

1. Installation

Summary

- **Currently, the number of particles tagged by the CEDARs is limited due to multiple scattering and optics**
- **With completing the vacuum, we see a gain of ca. 50% (about 20% higher transmission overall)**
  - Planning and organisation on the engineering side ongoing
  - Biggest efforts concern the scrapers
- **By additionally modifying the optics, we can enhance the number of taggable particles by ca. factor 3**
- **Shielding improvements may allow us to increase the instantaneous rate to 10^9 particles per spill**
  - With more units on T6, it should be possible to even further collimate the beam to optimally profit from the kaon content
- **With less material in the line: electron rate should be increased drastically!**

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