Impressions of the M2 beam line

Future of the M2 beam at CERN in the Physics Beyond Colliders Context

Johannes BERNHARD, Dipanwita BANNERJEE, Eva MONTBARBON, Lau GATIGNON
CERN EN-EA
19.03.2018

CERN | EN ENGINEERING DEPARTMENT

IWHSS 2018
Bonn (Germany), 19 – 21 March 2018

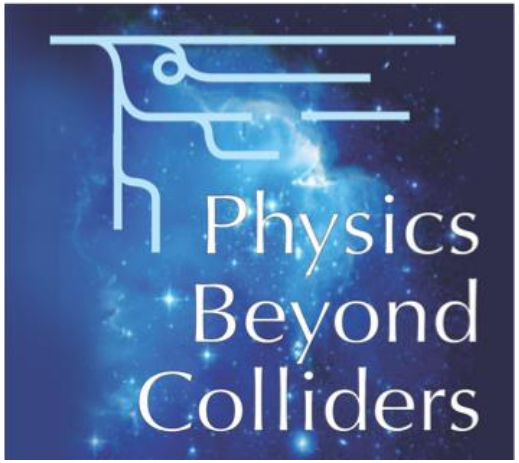
EA

Physics Beyond Colliders

Contact: Johannes.Bernhard@cern.ch

Agenda

- The "Physics Beyond Colliders" Initiative
- North Area Consolidation
- The M2 Beam and Future Options
- 2018 Test Beams in EHN2
- Summary and Outlook



http://pbc.web.cern.ch/

Physics Beyond Colliders – Introduction

- Extrapolatory study aiming at exploiting the full scientific potential of CERN's accelerator complex and its scientific infrastructure through projects complementary to the LHC, HL-LHC and other possible future colliders
- Projects targeting fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments
- Initiated by CERN director-general and coordinated by J. Jaeckel, M. Lamont and C. Vallee (chair)
- Kick-off workshop (September 2016) identified a number of areas of interest, revisited at Annual Workshop (November 2017)
- Working groups in full-swing to pursue studies in these areas
- PBC study remains open to further ideas for new projects

Physics Beyond Colliders – Physics

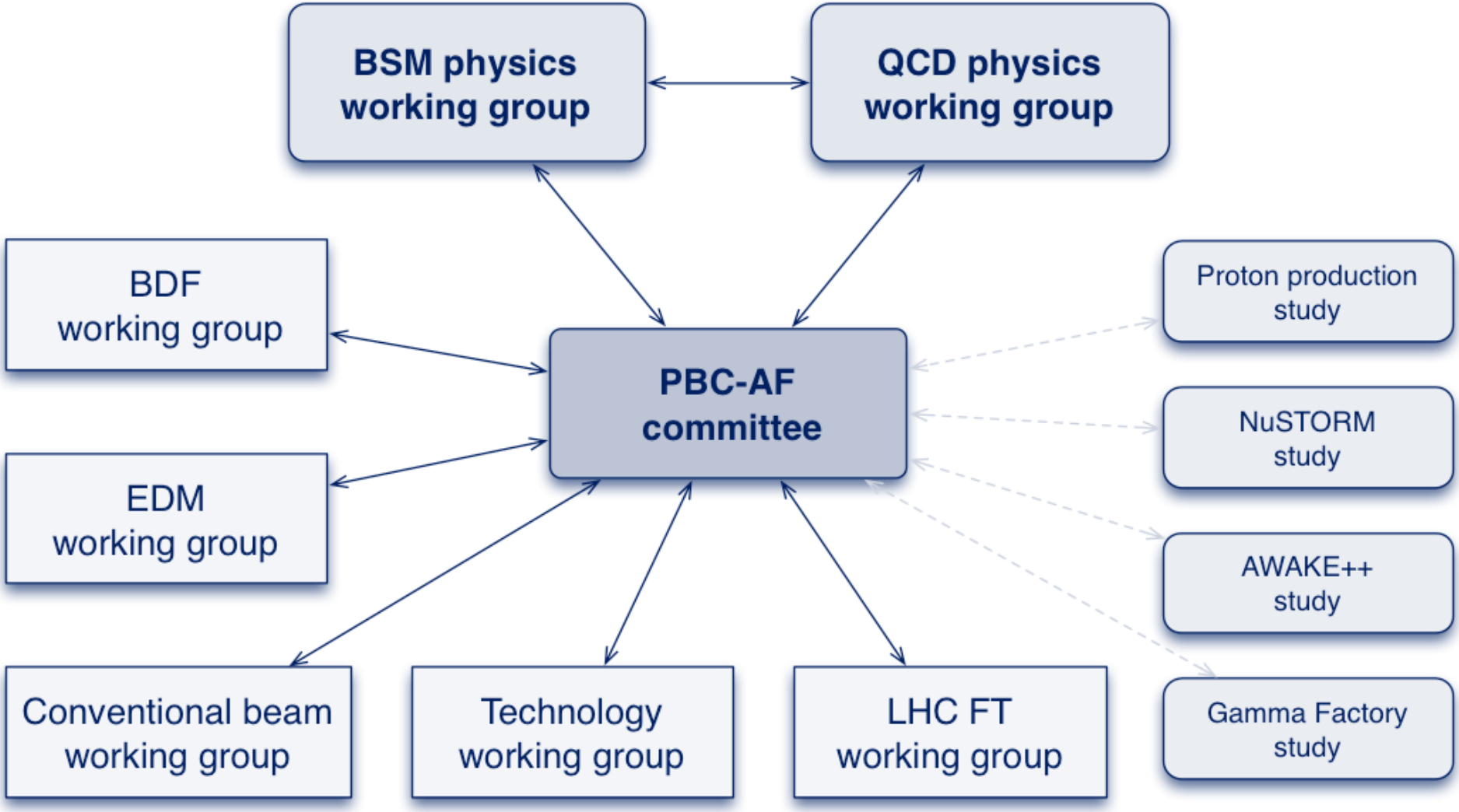
Physics Groups

- **BSM subgroup:** SHIP; NA64++; NA62++; KLEVER; IAXO; LSW; EDM; REDTOP
- **QCD subgroup:** ***COMPASS++***; μ-on-e; LHC FT (gas target + crystal extraction); DIRAC++; NA60++; NA61++

Deliverables:

- Evaluation of the physics case in the worldwide context
- Possible further detector optimization
- For new projects: investigation of the uniqueness of the CERN accelerator complex for their realization

Accelerator Working Group



Conventional Beams – Projects

Under consideration at present:

- NA62: Proposal to operate in beam-dump mode (HNL, axions)
- NA64++: High intensity electron, muon and hadron beams for dark sector searches (A')
- K_LEVER: High intensity K_L beam (high flux, pencil beam, new target) for rare decays, in particular $K_L \rightarrow \pi\nu\nu$
- ***COMPASS++: RF separated beams for hadron structure and spectroscopy; proton radius measurement with muon beam***
- μ-on-e: 150 GeV muon beams for high precision measurement of hadron vacuum polarisation for g-2 of the muon
- DIRAC++: DIRAC@SPS for high statistics of mesonic atoms
- NA60++: Heavy ion beams for di-muon physics and open-charm
- NA61++: Higher intensity ion beam for open-charm studies

Conventional Beams – Structure

CONVENTIONAL BEAMS WORKING GROUP

Conveners: L.Gatignon, M.Brugger
Members: Experiments, H.Wilkens, G.Lanfranchi, T.Spadaro,
EA physicists, HSE, RP, EL, CV, RF, STI

CBWG-ECN3

Convener: L. Gatignon

- K_LEVER
- NA62 Dump
- NA60
- DIRAC

CBWG-EHN2

Convener: J. Bernhard

- COMPASS (μ, RF-separated and low energy pbar beams)
- μ-on-e
- NA64-μ
- CEDAR project

CBWG-EHN1

Convener: N. Charitonidis

- NA61
- NA64 hadrons

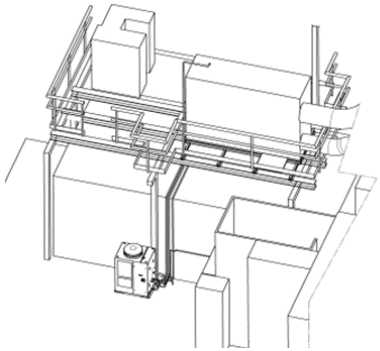
Main deliverable: Conceptual Design Report by end of 2018

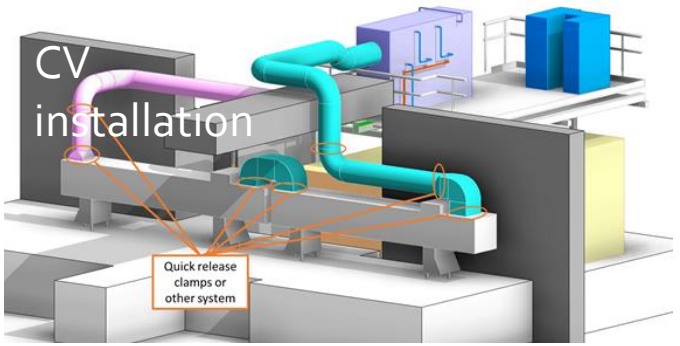
EHN2 Working Group

- Work Breakdown Structure (top level)
  - WP1: Muon beams post 2020
  - WP2: Hadron and Electron beams post 2020
  - WP3: RF-separated beams
  - WP4: Beam Particle Identification (dedicated meetings, WP leader S.Mathot/EN-MME)
- One project associate (full-time) and since March 2018 one fellow (part-time) for studies plus additional resources for WP4
- User presentations for technical details and plans completed, user requirements document prepared
- Several studies launched
- Track progress by continuous reporting, about one WG meeting per month

EHN2 Working Group – WP4

- CEDAR thermal housing completed (main deliverable WP4)
- Duct works being finalised and system being commissioned
- System ready for 2018 physics run

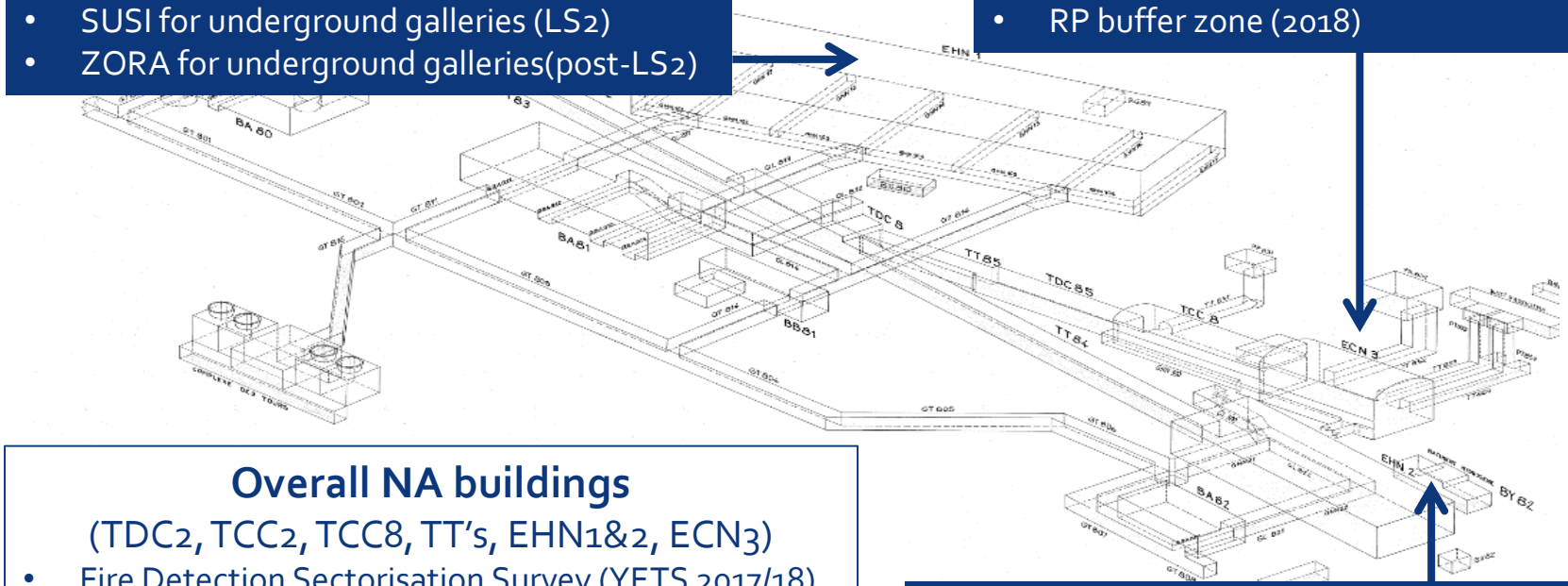




North Area Consolidation – Safety

EHN1
- Flammable gas detection (2018 & LS2)
- Fixed ODH & CO_2 detection (2018 & LS2)
- SUSI for underground galleries (LS2)
- ZORA for underground galleries(post-LS2)

ECN3
- Flammable gas detection (update tbc)
- Fixed ODH detection (update tbc)
- RP buffer zone (2018)



Overall NA buildings
(TDC2, TCC2, TCC8, TT's, EHN1&2, ECN3)
- Fire Detection Sectorisation Survey (YETS 2017/18)
- RP monitoring upgrade (LS2)
- Renovation of the Fire Detection & Evacuation Alarm (post –LS2)
- Renovation of the Beam Imminent Warning & Evacuation Alarm (post LS2)

EHN2
- SUSI to access building (YETS)
- Flammable gas and ODH detection (LS2)
- ZORA for underground galleries (post-LS2)
- RP buffer zone (2018)

Courtesy: Y. Kadi, F. Gautheron

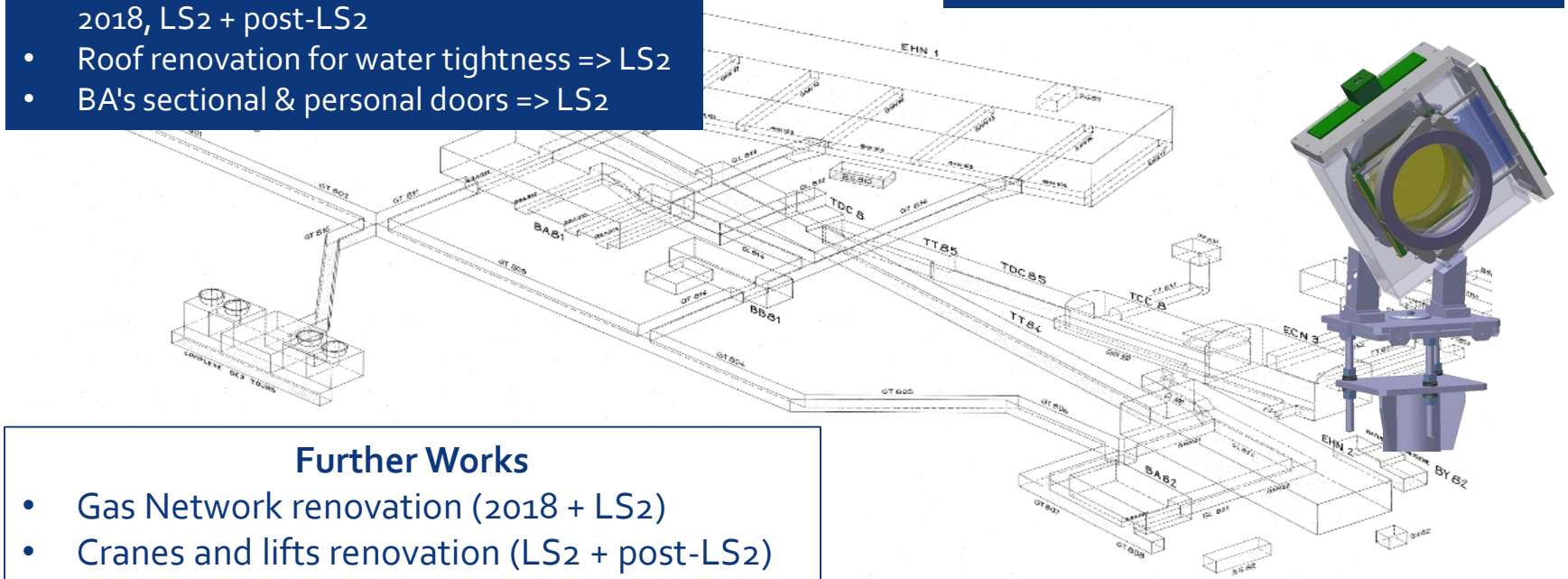
North Area Consolidation

EHN2

- SM2 power converter upgrade (completed)
- Chilled water consolidation (pipework) => 2018, LS2 + post-LS2
- Roof renovation for water tightness => LS2
- BA's sectional & personal doors => LS2

Beam Instrumentation

- XBPF beam profile monitors (SciFis)



Further Works

- Gas Network renovation (2018 + LS2)
- Cranes and lifts renovation (LS2 + post-LS2)
- Consolidation of TCC2/TCC8 target => YETS
- Thermal/FEM studies of primary target and TAX => 2018 & LS2
- Cooling Tower 2 works (2018+YETS)

Courtesy: Y. Kadi, F. Gautheron

The M2 Beam

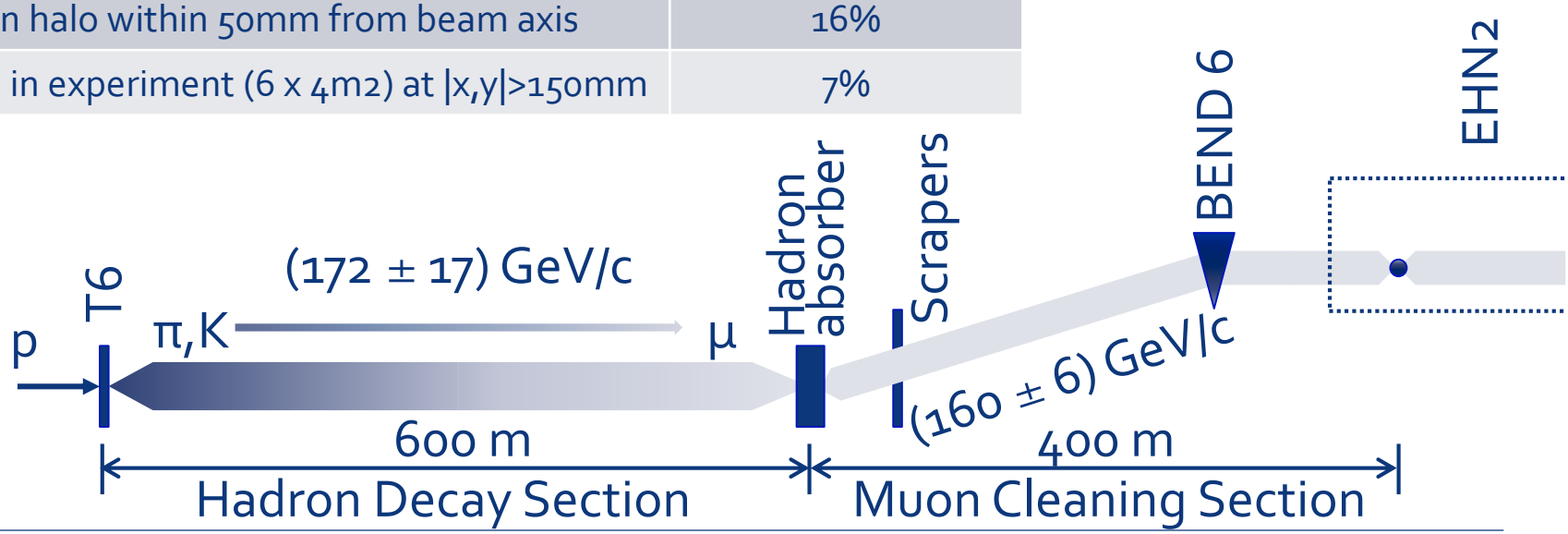
Three main operation modes:

- High-energy, high-intensity muon beam. Normally for muon momenta up to 200 GeV/c. Higher momenta up to 280 GeV/c are possible, but the flux drops very rapidly with beam momentum.
- High-intensity secondary hadron beam for momenta up to 280 GeV/c with radiation protection constraints.
- Low-energy, low-intensity (and low-quality) in-situ electron calibration beam.

Beam Mode	Momentum (GeV/c)	Max. Flux (ppp / 4.8s)	Typical $\Delta p/p$ (%)	Typical RMS spot at target	Polarisation	Absorber (9.9 m Be)
Muons	+208/190 +172/160	~10^8 2.5 10^8	3%	8 x 8 mm	80%	IN
Hadrons	+190 -190 Max. 280	10^8 (RP) 4 10^8 (with dedicated dump)	-	5 x 5 mm	-	OUT
Electrons	-10 to -40	< 2 10^4	-	> 10 x 10 mm	-	OUT

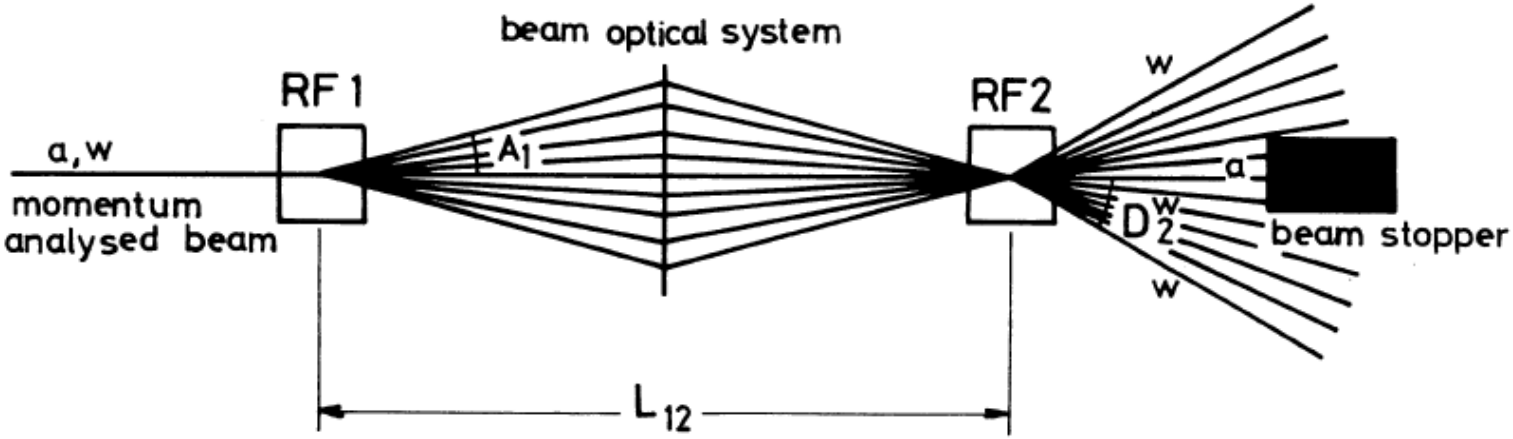
The M2 Beam – Parameters and Principle

Beam Parameters for COMPASS	Measured
Beam momentum p_μ/p_π	160 / 172 GeV/c
Proton flux on T6 per SPS cycle	$1.5\ 10^{13}$
Muon flux at COMPASS per SPS cycle	$2.5\ 10^{8}$
Beam polarisation	-80% ± 4%
Spot size at COMPASS target (σ_x x σ_y)	8mm x 8mm
Divergence at COMPASS target (σ_{dx} x σ_{dy})	0.4mrad x 0.8mrad
Muon halo within 50mm from beam axis	16%
Halo in experiment (6 x 4m2) at |x,y|>150mm	7%



RF-separated Beams

Reminder: Panofsky-Schnell-System with two cavities (CERN 68-29)



- Particle species have same momenta but different velocities
- Time-dependent transverse kick by RF cavities in dipole mode
- RF1 kick compensated or amplified by RF2
- Selection of particle species by selection of phase difference
  $\Delta\Phi = 2\pi (L f / c) (\beta_1^{-1} - \beta_2^{-1})$
- For large momenta: $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2\mathbf{p}^2$

RF-separated Beams - Phases

<u>For $K^{\pm}$ beams:</u> $\Delta\Phi_{\pi p} = 360^{o}$ and Φ_{RF2} such that both π and p go straight i.e. dumped

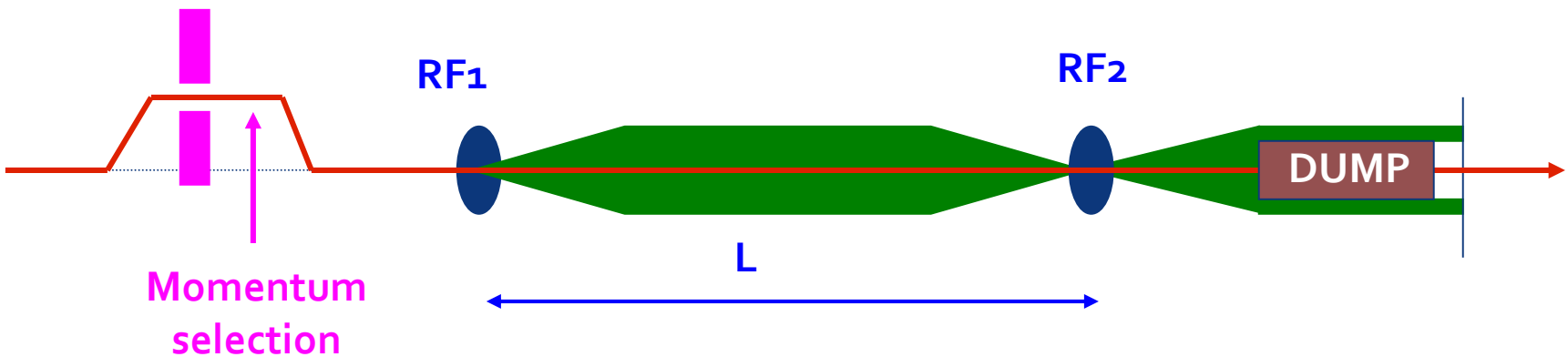
$\Delta\Phi_{pK} = 94^{o}$, i.e. a good fraction of K outside the dump, depending on phase at 1st cavity

<u>For pbar beams:</u> $\Delta\Phi_{\pi p} = 180^{o}$ and then $\Delta\Phi_{pe} = 184^{o}$, $\Delta\Phi_{pK} = 133^{o}$ with phase of RF2 such that pions go straight, antiprotons get reasonable deflection, electrons are dumped effectively and K reduced

RF-separated Beams

$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1})$

For large momenta: $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2\mathbf{p}^2$



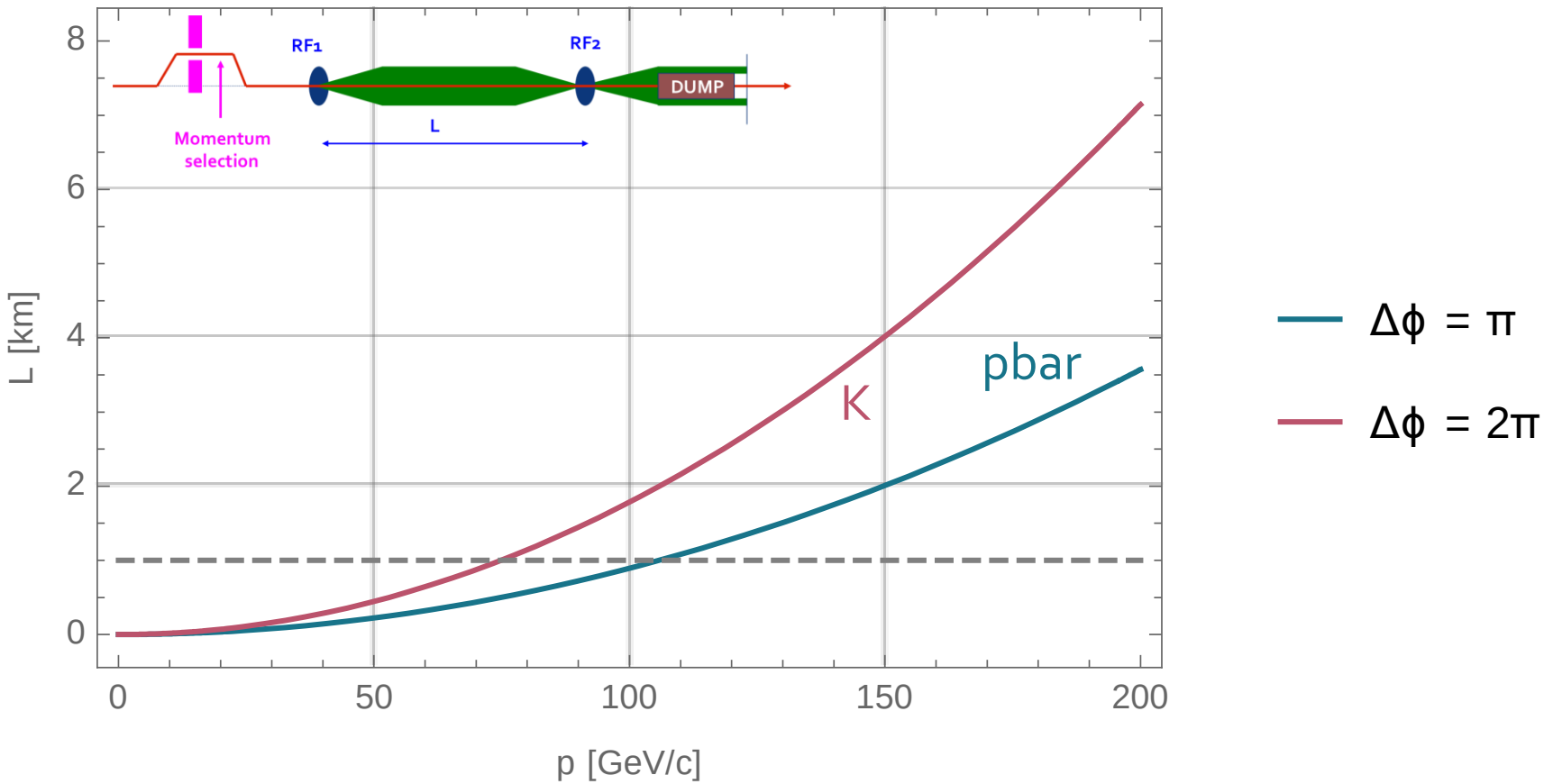
Example: input from CKM studies

- Kick: 15 MeV/c
- f = 3.9 GHz
- dp/p = 2%
- $\Delta\phi_{\pi p} = \pi$ (pbar selection) / $\Delta\phi_{\pi p} = 2\pi$ (K selection)

CKM-based Example

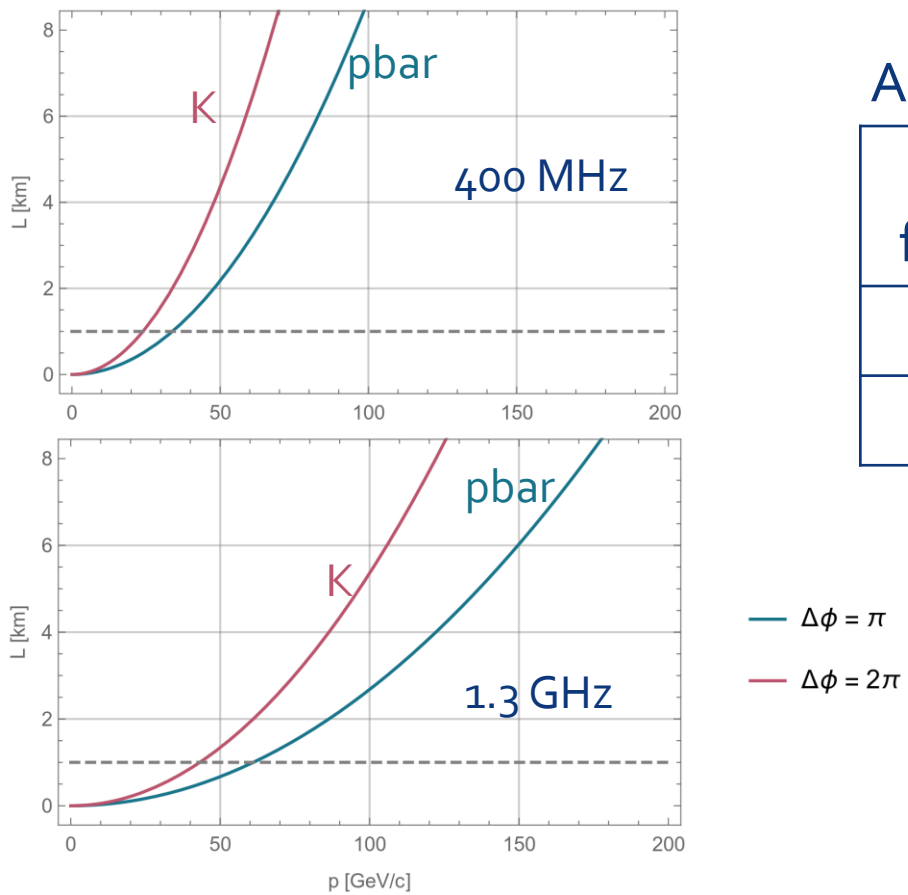
$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1})$

For large momenta: $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2\mathbf{p}^2$



Crab Cavities Example

Currently available technology at CERN: Crab Cavities for LIU SPS upgrade (400 MHz superconducting dipole cavities)



Assume availability of L=800m:

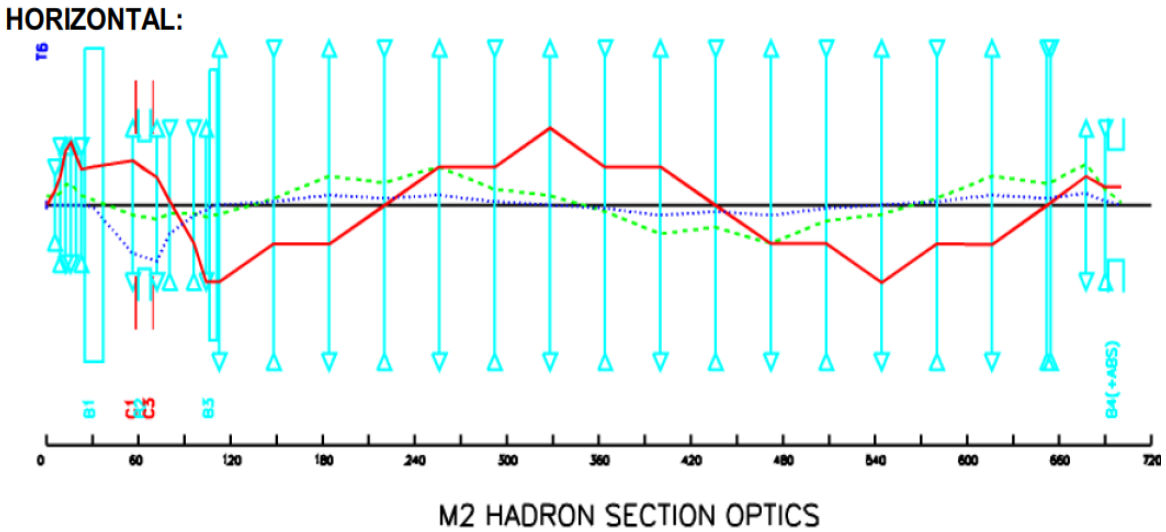
RF frequency	Limit p(K)	Limit p(pbar)
400 MHz	20 GeV/c	30 GeV/c
1.3 GHz	37 GeV/c	55 GeV/c

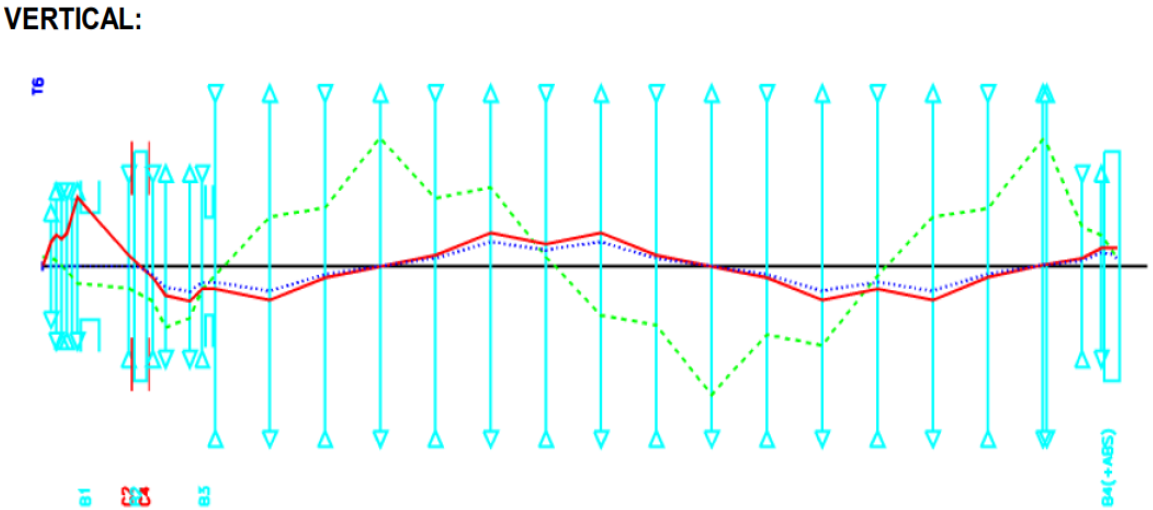
Conclusion: crab cavity design so far not compatible with user requirements, new developments necessary

RF-separated Beams – Hadron Section M2

Front-end

- Hadron section optimised for large acceptance
- About 100m necessary for front-end and momentum selection with goal to keep it for compatibility

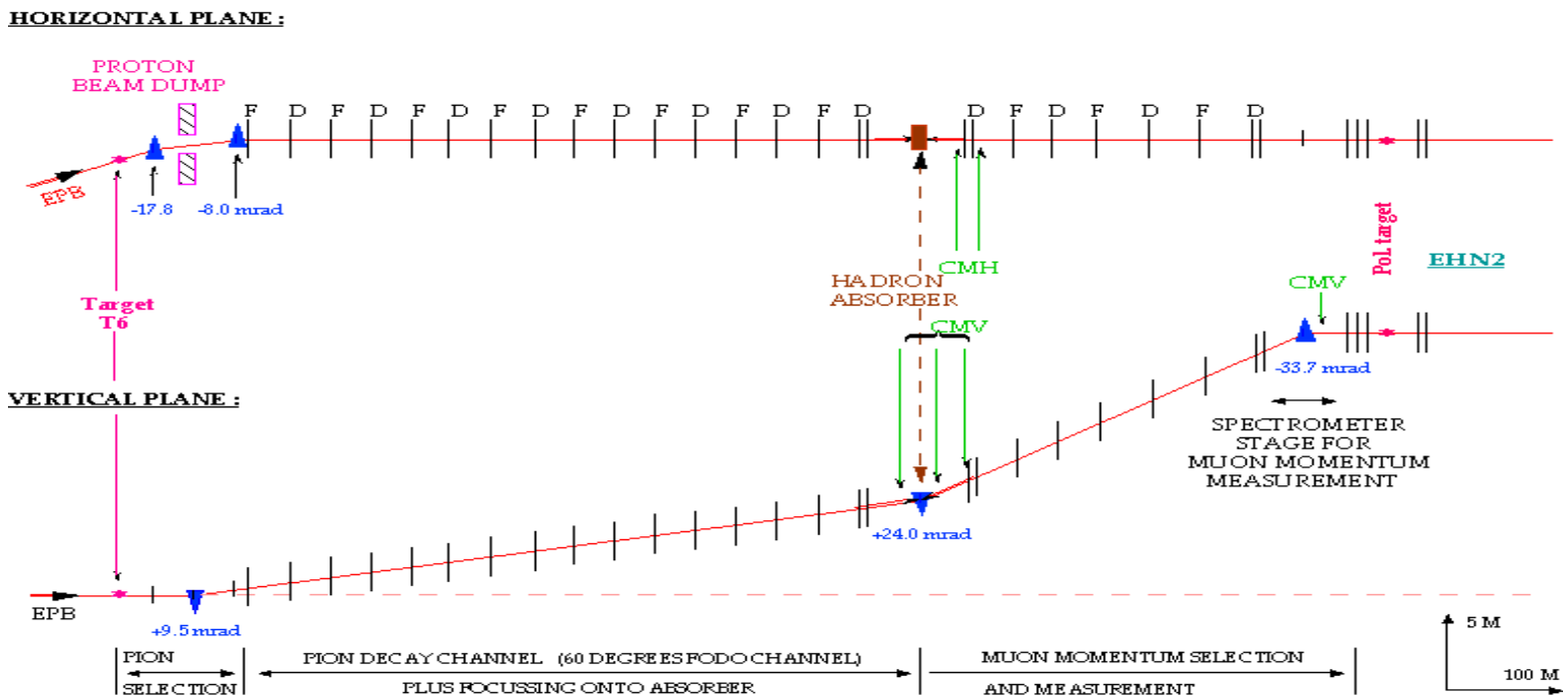




RF-separated Beams – Absorber Region

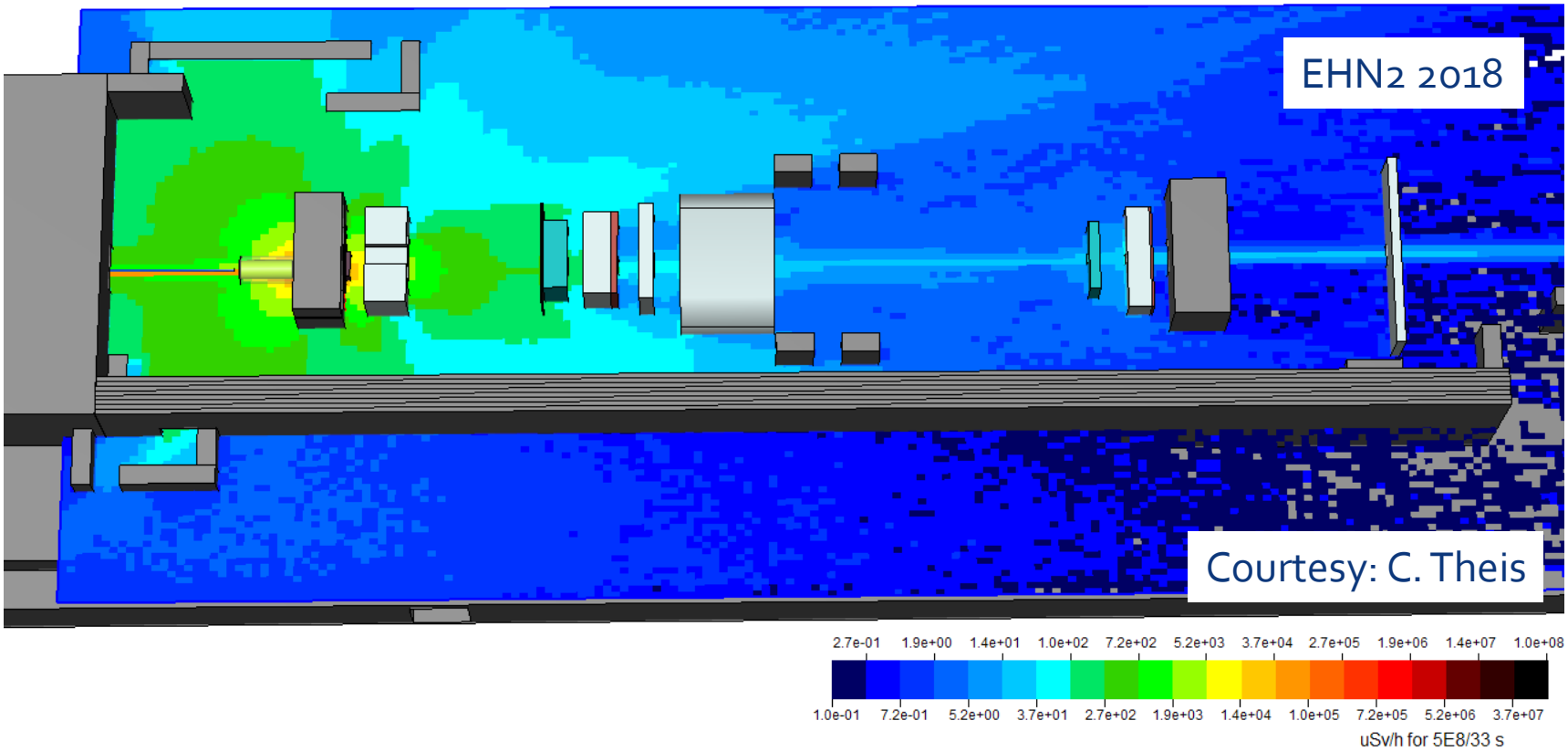
Dispersion challenge

- To make use of the full length of the M2 tunnel, the beam needs to be adjusted vertically to the second slope with BENDs 4+5
- This introduces a new source of dispersion and thus needs to be compensated before the second cavity



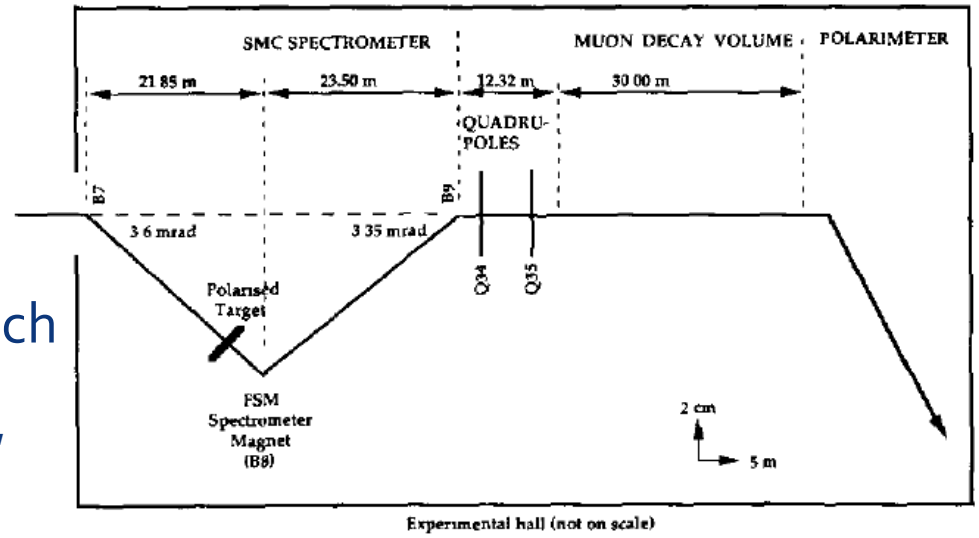
Radiation Protection Considerations

- Intensity limitations: What can be gained with additional (roof) shielding for the beam line and/or a part of experimental set-up?
- To be studied (Summer Student project, new fellow)



Future Options for Experiments in EHN2

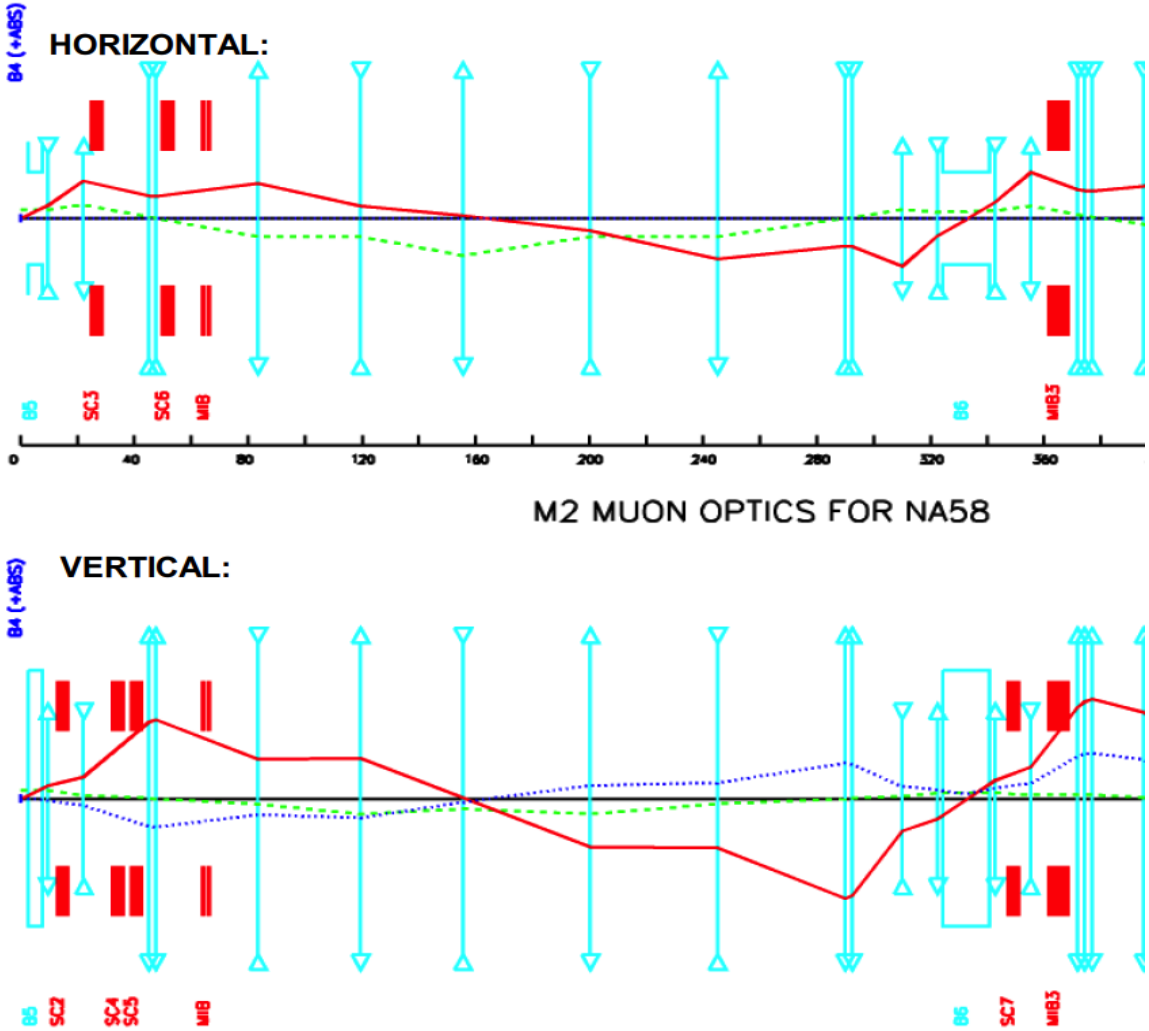
- Historically, EHN2 has already housed more than on muon beam experiment / set-up (e.g. NA2 + NA4, SMC + polarimeter)
- Most important WP1 challenge: Will we be able to run μ-on-e or NA64 together with COMPASS?
- Main questions
  - Are the physics requirements compatible enough (e.g. beam momentum)?
  - Are the required intensities comparable?
  - Is there enough space?
- Need to study this from scratch



L. Gatignon, N. Doble et.al., NIM A 343 (1994) 351-362

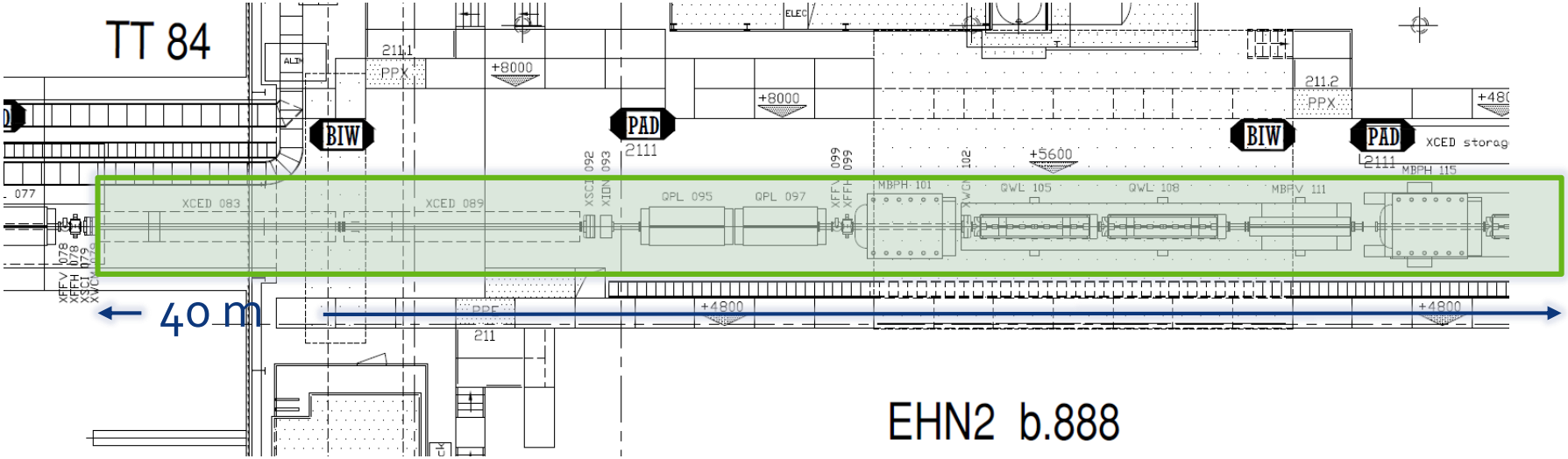
Optics – Muon Section M2

- Focussing on targets non-trivial as the beam is not produced from a point-like source and has a relatively large Δp/p
- Important to know user requirements such as needed divergence and beam spot size to re-design the final focus



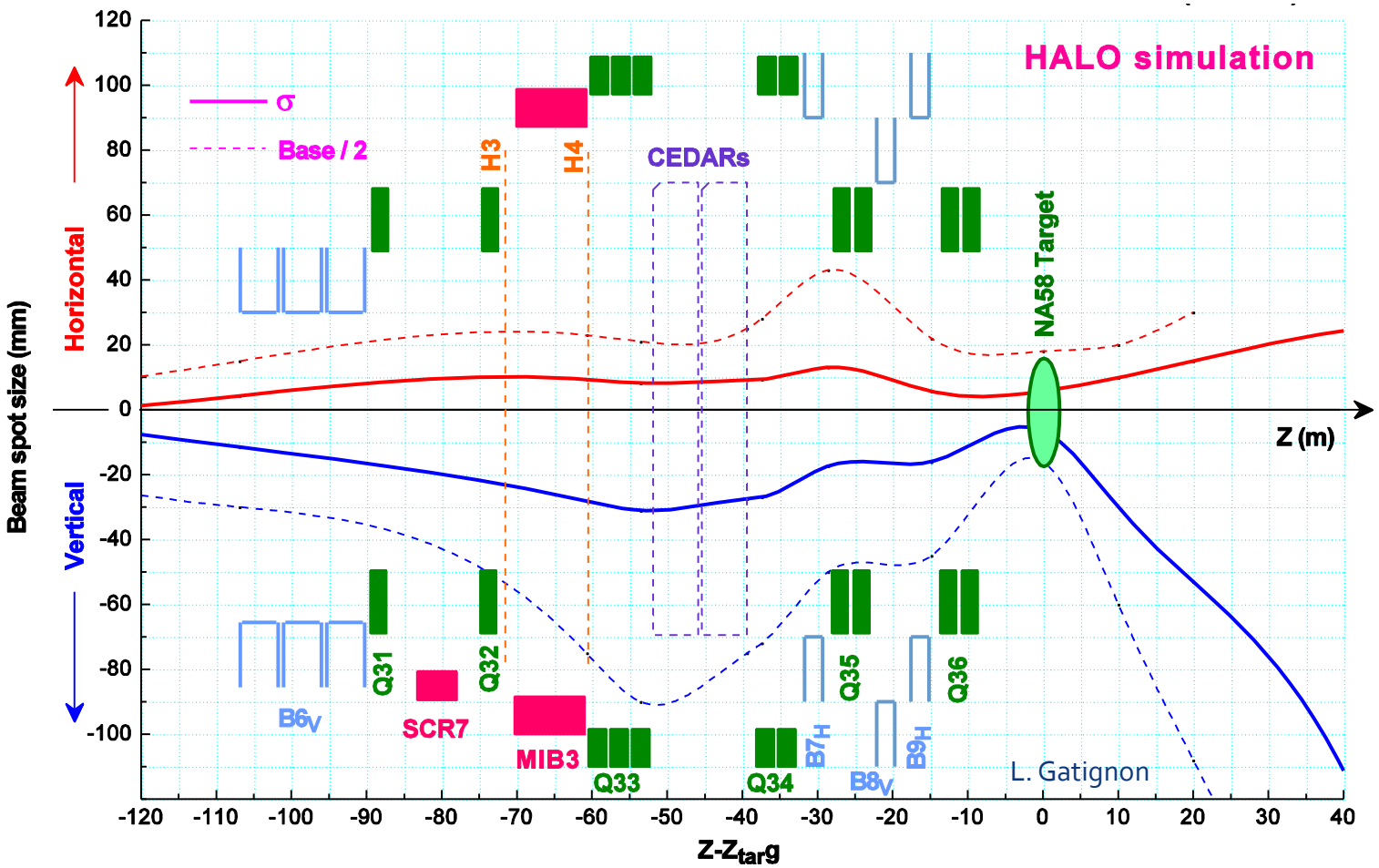
Future Options for μ-on-e in EHN2

- Entrance Area of EHN2
  - Pro: no interference with COMPASS spectrometer, enough space for full set-up
  - Con: needs many weeks change-over time, no installation of CEDARs possible, μ-on-e targets introduce multiple scattering
  - Compatibility with proton radius measurement depends on required beam quality and characteristics (energy, intensity, divergence)



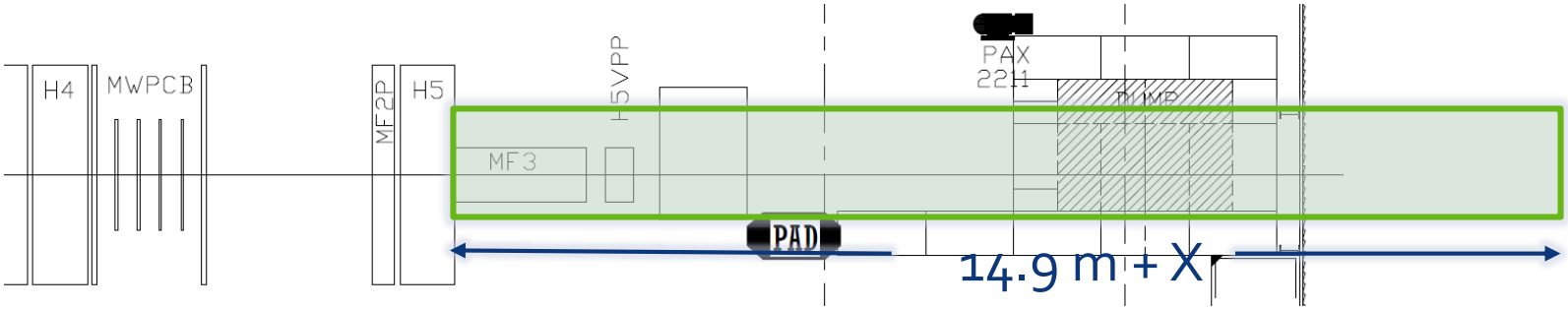
Future Options for μ-on-e in EHN2

- Entrance Area of EHN2



Future Options for μ-on-e/NA64 in EHN2

- Downstream Area of EHN2
  - Pro: compatible with COMPASS running at the same time (able to use full COMPASS set-up)
  - Con: safety aspects (lock ABS in, no hadron beams), limited space, energy loss of muons in COMPASS could imply to re-measure momentum (i.e. another spectrometer magnet), re-/de-focusing of muons would imply 2-3 quadrupoles plus compensation of SM1+SM2 kick, thus an extension of the building

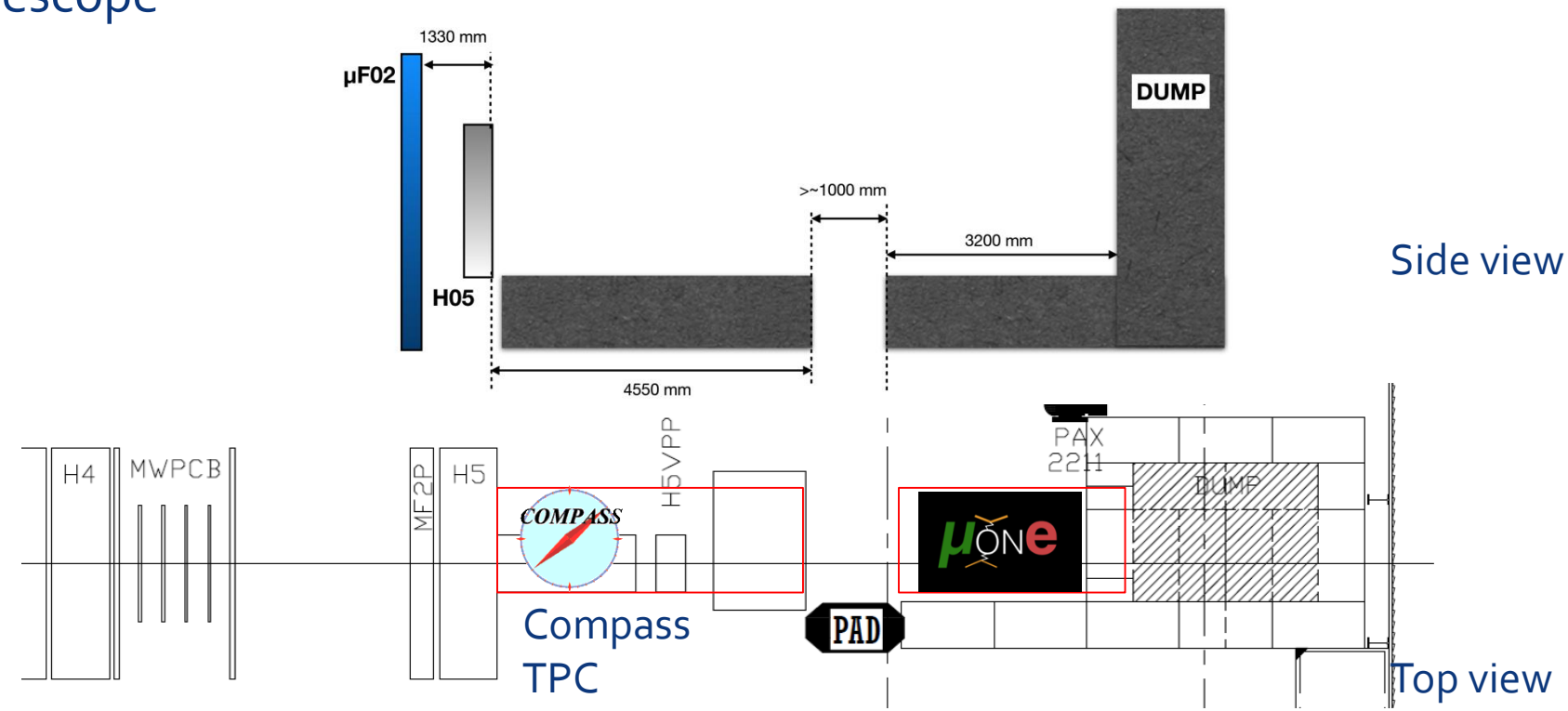


Future Options for NA64 in EHN2

- Installation inside SM2
  - Pro: compatible with COMPASS (able to use full COMPASS set-up)
  - Con: limited space, energy loss of muons within COMPASS, NA64 would need to invest in new non-magnetic calorimeter modules, change-over time

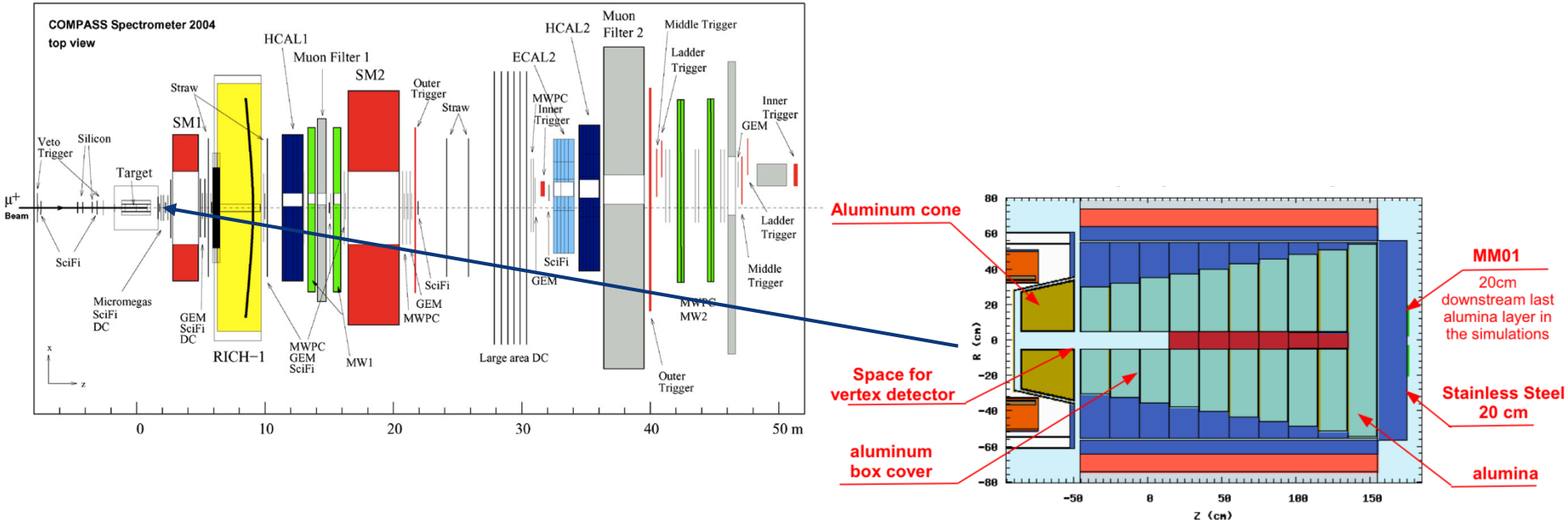
2018 Test Beams

- μ-on-e: Measure μ-e scattering on 2 target modules with Silicon instrumentation + 1 EM calorimeter. Total length 3m.
- Compass TPC: Measure μ-p scattering in high pressure TPC + Silicon telescope



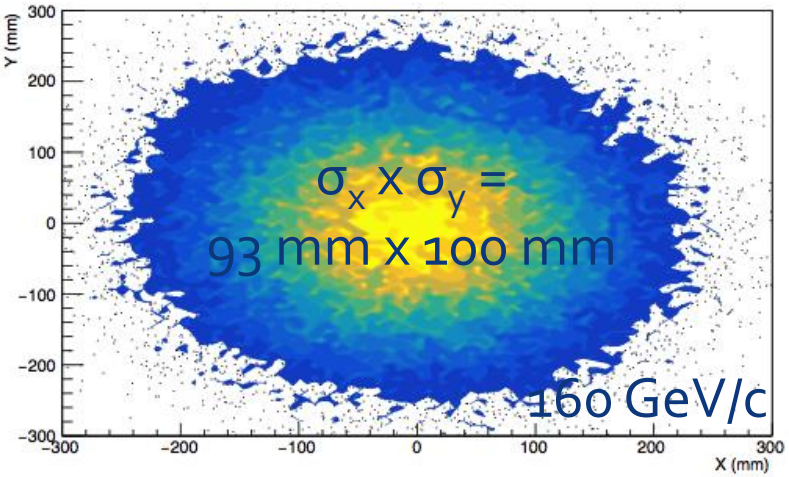
2018 Test Beams

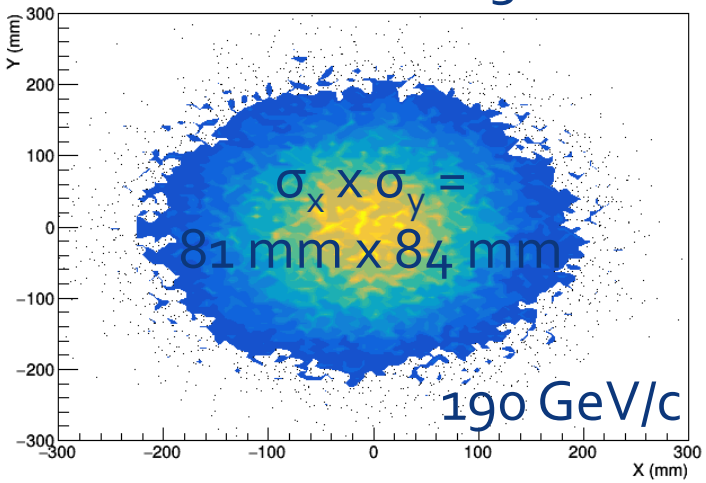
- Studies initialised due to parasitic nature of 2018 tests
- COMPASS has a physics program that uses the 190 GeV/c hadron beam mode with a dedicated hadron absorber
- Goal: Extrapolate muon beam through COMPASS set-up and assert widening of beam due to multiple scattering with HALO



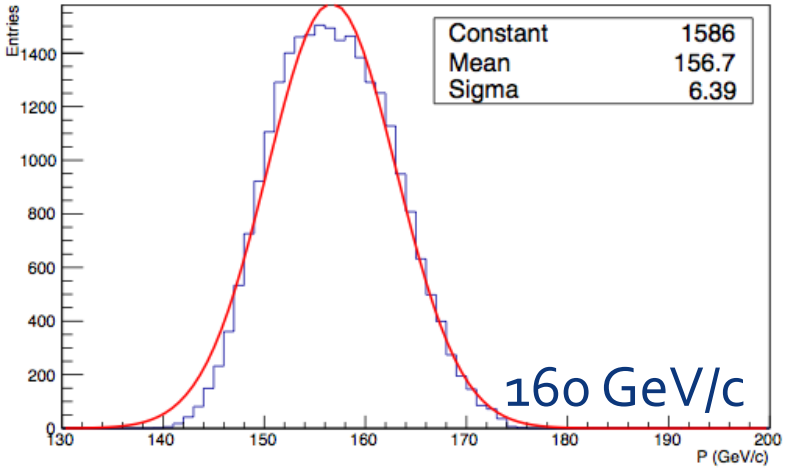
2018 Test Beams

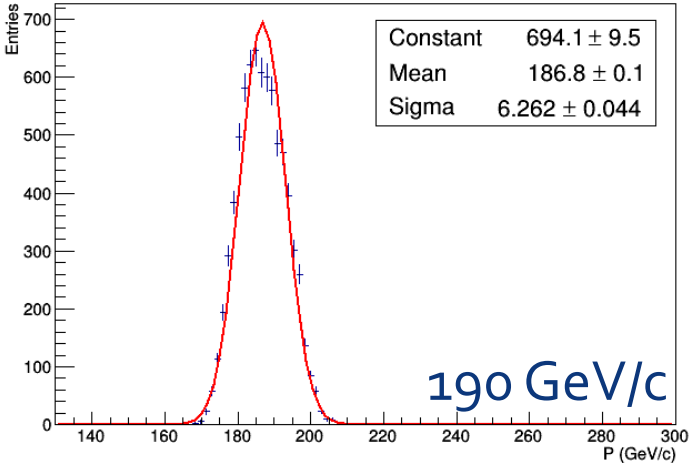
- Beam distribution at test location for muon beam configuration





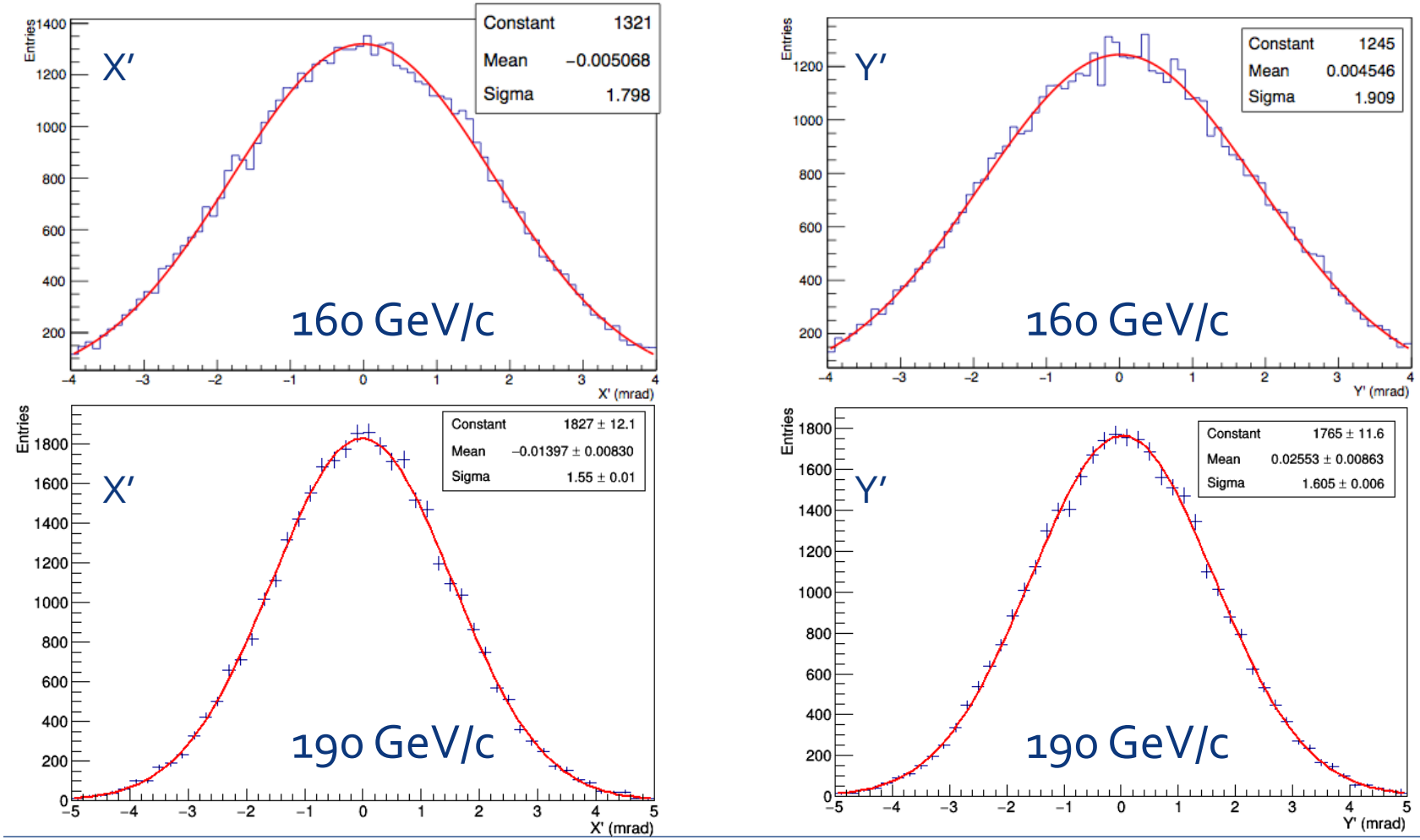
- Beam momentum after passing hadron absorber





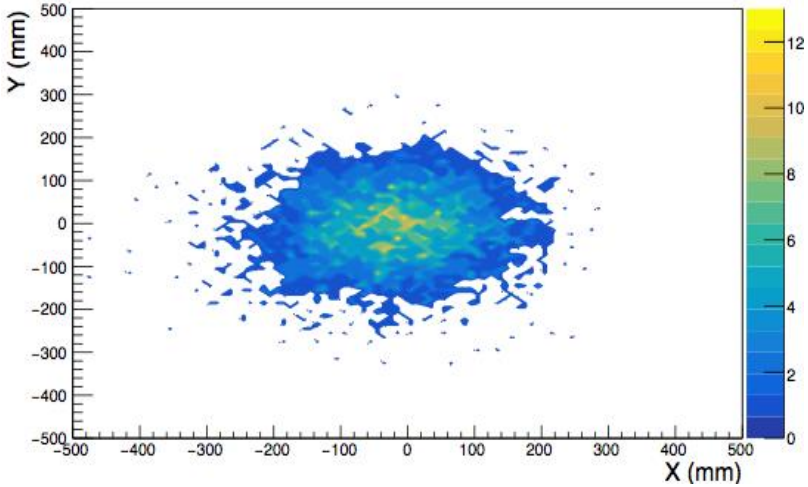
2018 Test Beams

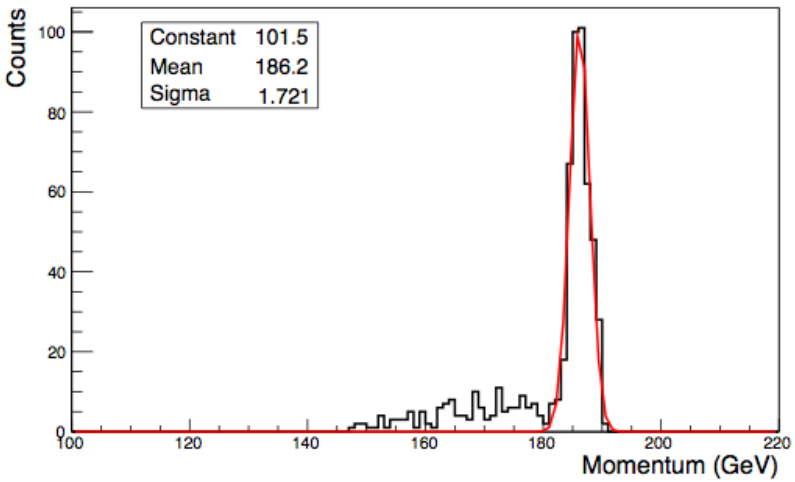
- Beam divergence muon beam (after passing absorber)



2018 Test Beams

- Muon distribution at test location for 2018 190 GeV/c DY hadron beam





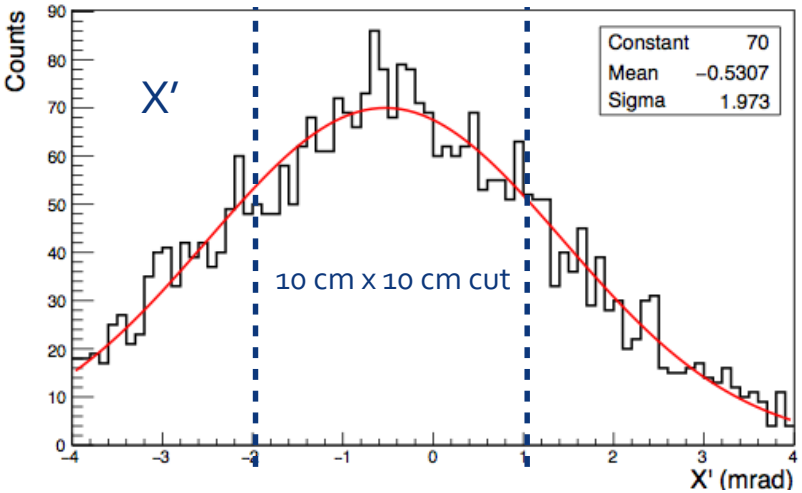
$\sigma_x \times \sigma_y$ = 100 mm x 84 mm

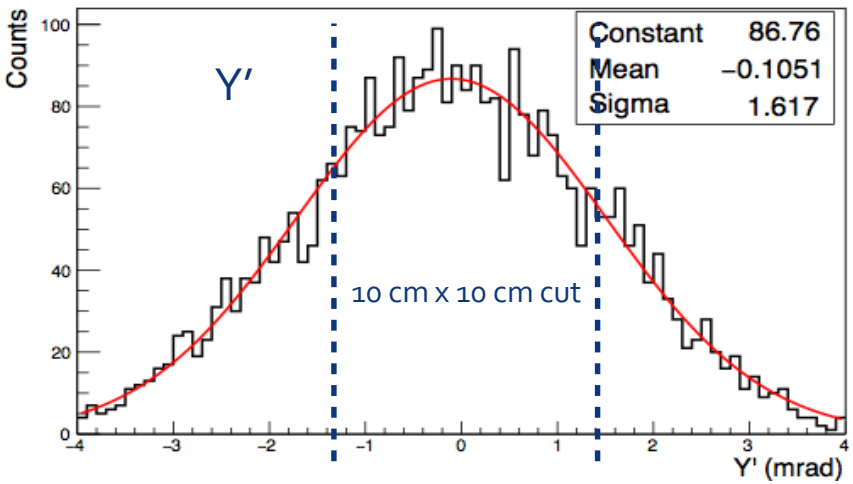
Momentum ~ 186 GeV/c

- Good news, still very useful for tests
- Flux for 10^{13} pot ~ 10^5/spill (within 10cm x 10cm of beam axis)

2018 Test Beams

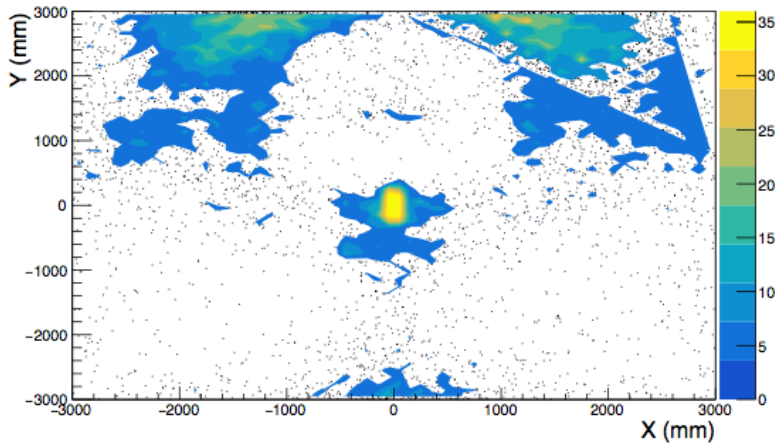
- Beam divergence of muons from DY hadron beam (after passing absorber)

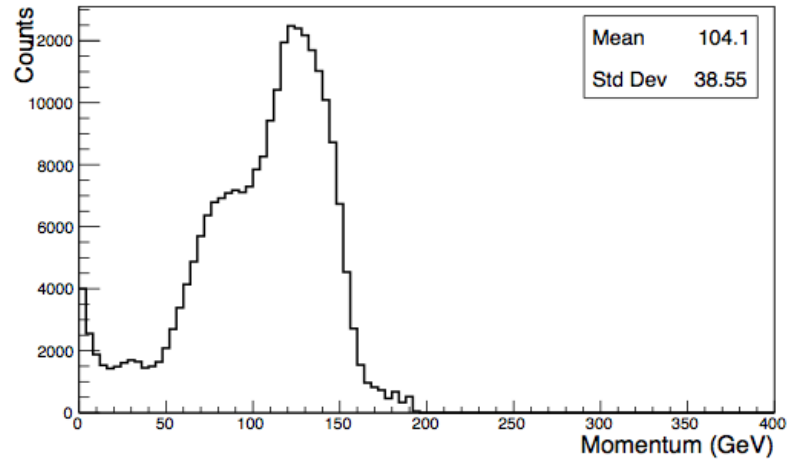


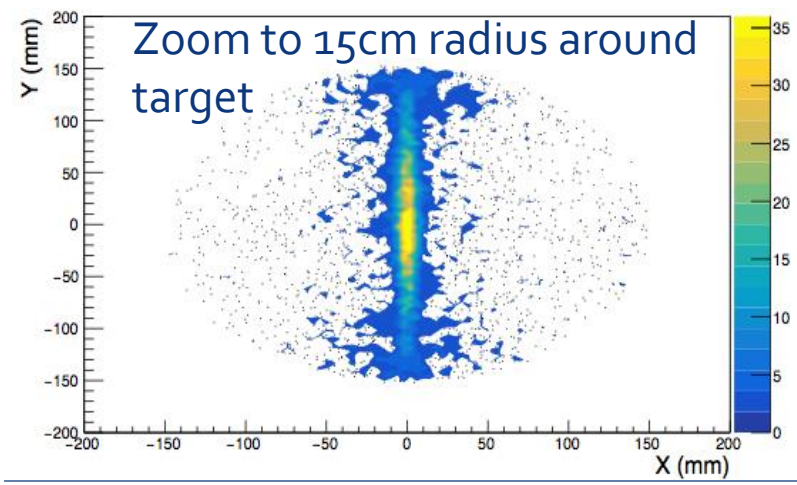


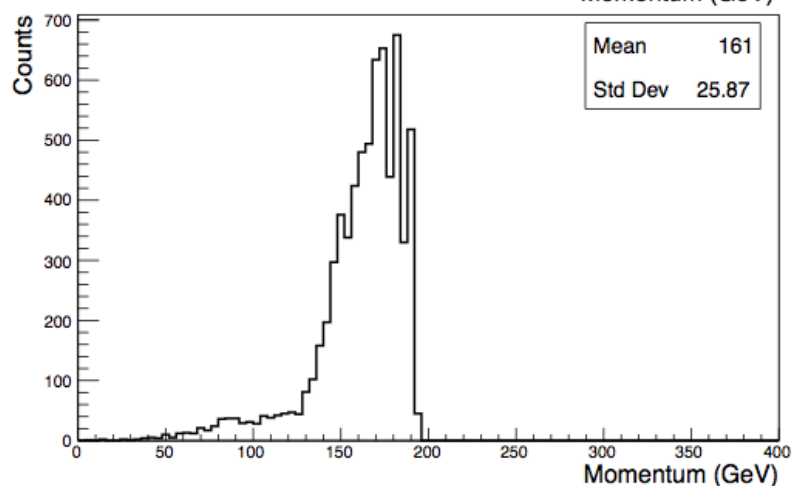
2018 Test Beams

- A little extra output: Muon halo from for 2018 190 GeV/c DY hadron beam at the COMPASS target









Summary and Outlook

- The M2 beam at CERN continues to serve in its 40th year of operation
- Future options of RF-separated beams, other beam configurations (μ, h, e) plus compatibility of proposed experiments and integration of the full set-ups is currently being studied within the conventional beams working group / EHN2 WG of Physics Beyond Colliders
- More personnel available (project associate) for studies since 12/17, more from 03/18 (new fellow)
- North Area Consolidation Study established and first urgent consolidation works already completed
- Optics studies for 2018 tests finalised, proposal: Check RP limit for μ flux with tests this year
- Other news: Expect 10% increase of duty cycle in 2018 due to faster repetition of spills

Physics Beyond Colliders

http://pbc.web.cern.ch/

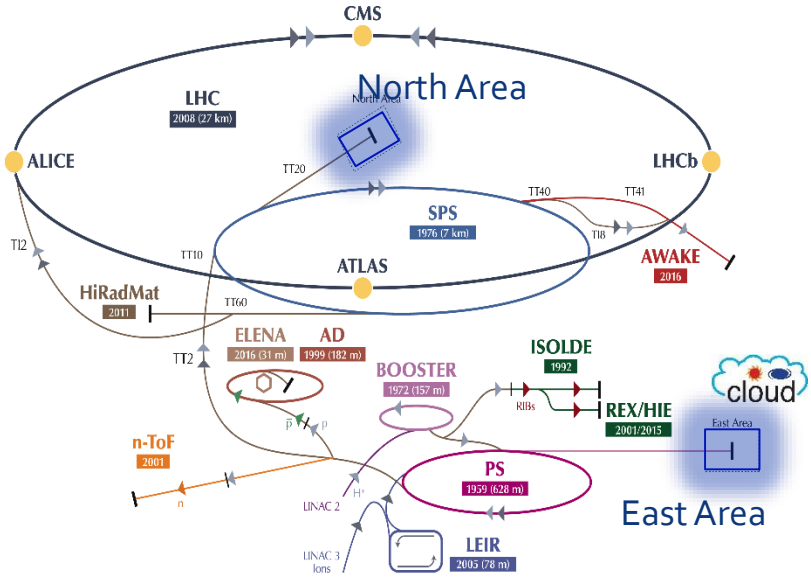
CERN | EN ENGINEERING DEPARTMENT

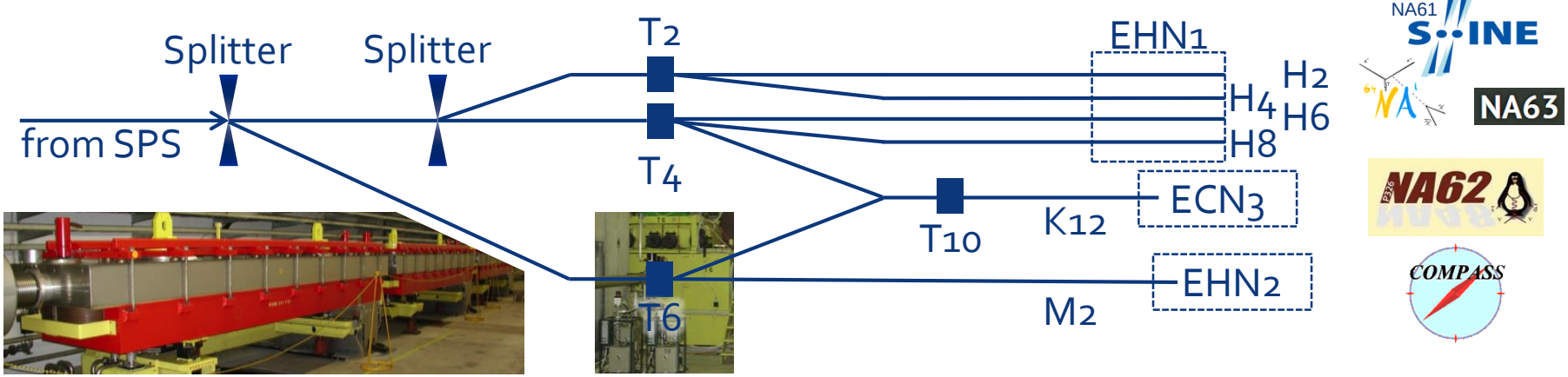
Thank you!

Secondary Beams at CERN

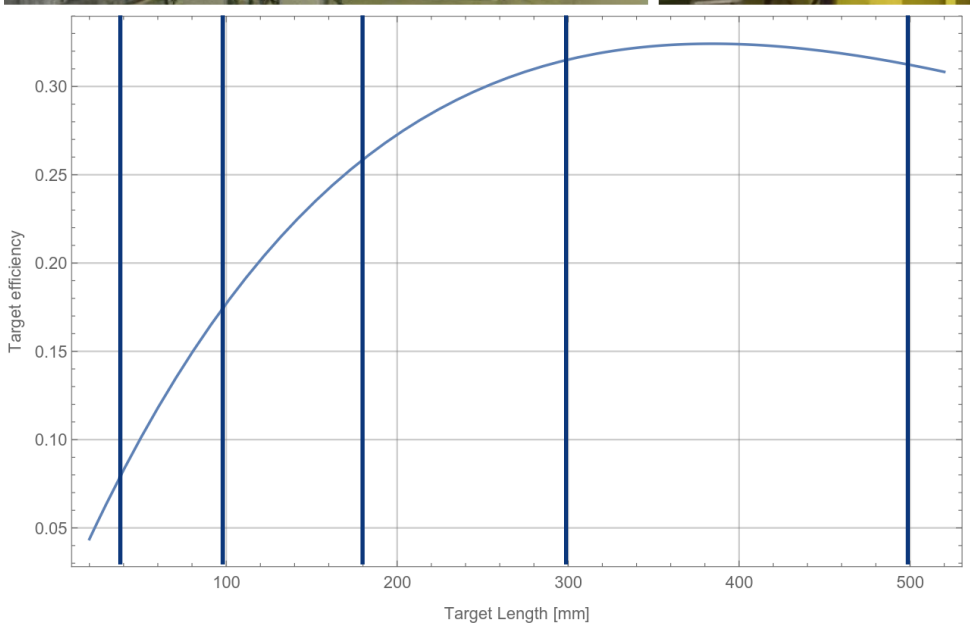
High intensity secondary beams in a wide range of momenta with largely selectable particle species

- East Area / PS (24 GeV/c primary protons and ions for irradiation and 0.5 – 15 GeV/c secondary beams)
- North Area / SPS (400 GeV/c primary protons and up to 380 GeV/c secondary and ion beams)





Production Targets



Position	Material	Length (mm)	Height (mm)	Width (mm)
0	*Air/OUT*	-	-	-
1	Be	500	2	160
2	Be	300	2	160
3	Be	180	2	160
4	Be	100	2	160
5	Be	40	2	160
5x plates, 40 mm inter-plate distance				

Secondary Particle Production

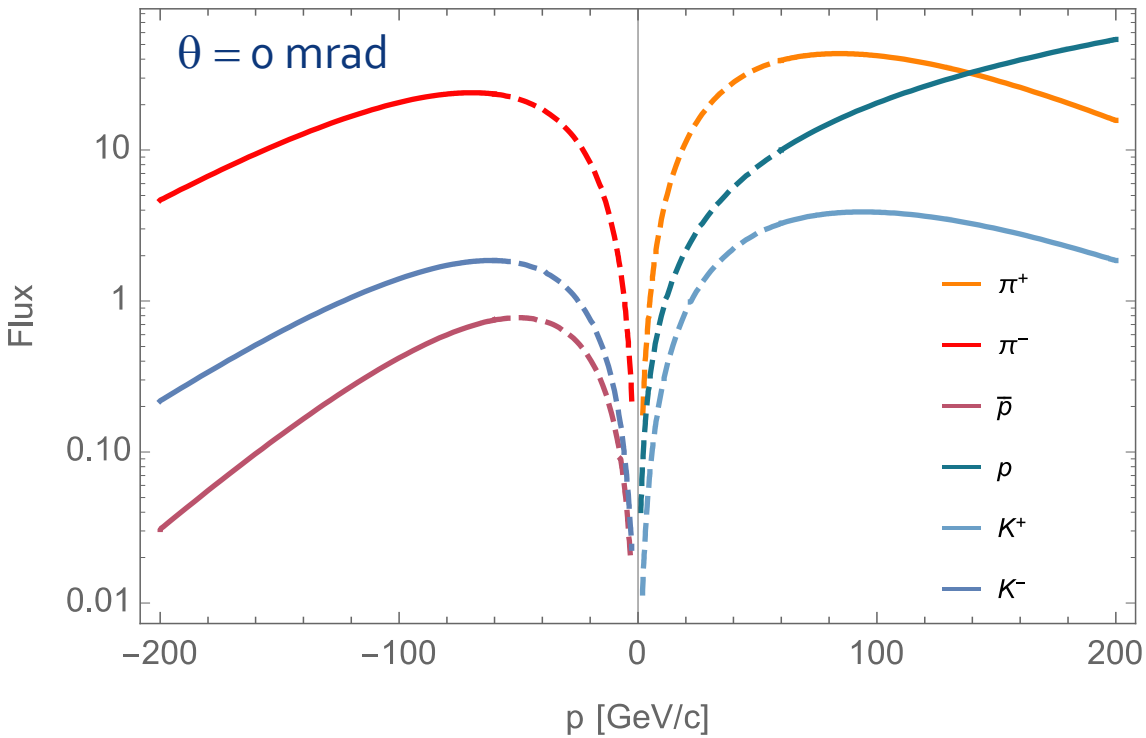
Atherton parameterisation (CERN 80-07):

$$\frac{d^2N}{dp\,d\Omega} = A\left[\frac{B}{p_0}\, e^{-Bp/p_0}\right]\left[\frac{2Cp^2}{2\pi}\, e^{-C(p\theta)^2}\right]$$

$$\frac{d^2N}{dp\,d\Omega} = A\left[\frac{(B+1)}{p_0}\left(\frac{p}{p_0}\right)^B\right]\left[\frac{2Cp^2}{2\pi}\, e^{-C(p\theta)^2}\right]$$

with primary momentum p_0 and production angle θ

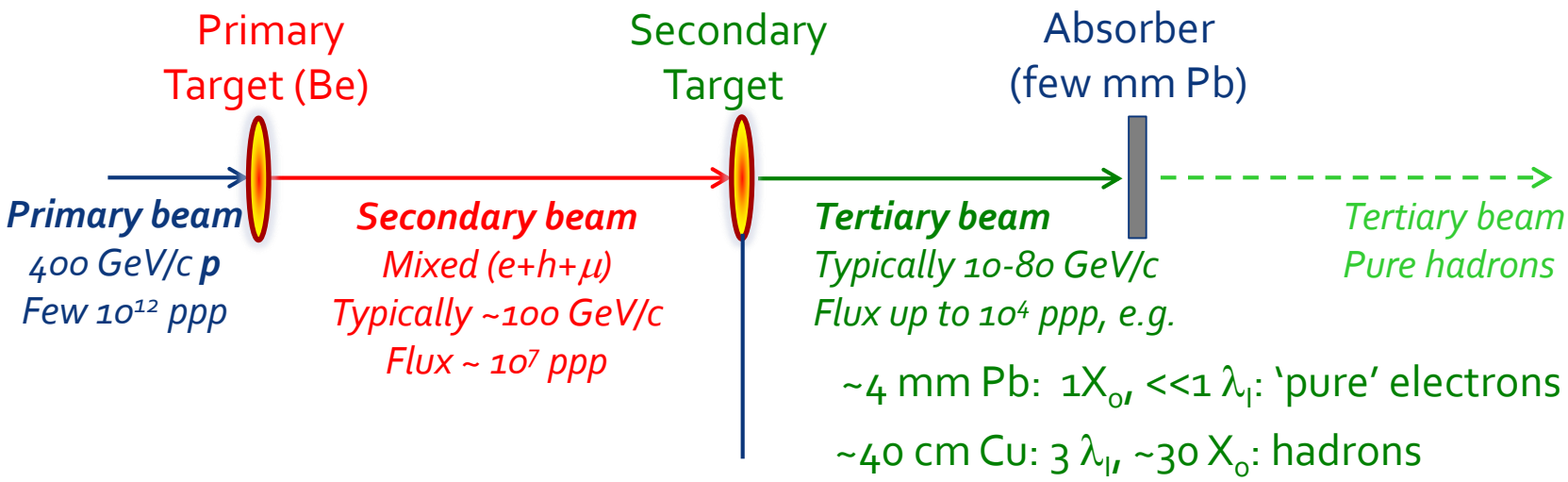
Flux per solid angle [steradian], per interacting proton, and per dp [GeV/c]



	A	B	C
p	0.8	−0.6	3.5

	A	B	C
π^+	1.2	9.5	5.0
π^-	0.8	11.5	5.0
K^+	0.16	8.5	3.0
K^-	0.10	13.0	3.5
$\bar{p}$	0.06	16.0	3.0

Secondary Particle Production



<u>Nota bene:</u> Flux given for a typical EHN1 beam line, e.g. H8