Particle Beams for FT Experiments

Aim of the seminar:

Go through the basic principles in the design of particle beams

Not full fledge accelerator physics but lots of ideas and challenges behind

Playing with particles is fund and full of surprises !!!

I. Efthymiopoulos — 26 September 2011

EDMS No: 1165938

Particle Beams - what does it mean?

- Particle beams typically refer to **secondary** or **tertiary** beams, i.e. beams produced from other **primary** beams, typically via interaction in a target or by particle decay
  - secondary/tertiary hadron beams :

$$\mathbf{p} + A \rightarrow \quad p,\ \bar{p},\ \pi^{\pm},\ K^{\pm},\ \mu^{\pm}$$
$$\pi^{\pm},\ K^{\pm} \rightarrow \mu^{\pm},\ \nu_{\mu}(\overline{\nu_{\mu}}),\ \nu_{e}(\overline{\nu_{e}})$$

$$\mathbf{p} + A \rightarrow \begin{cases} \Lambda^0(\overline{\Lambda^0}) \rightarrow p, \pi^- \ (\bar{p}, \pi^+) \\ K^0(\overline{K^0}) \rightarrow \pi^{\pm},\ \pi^{\mp} \\ K^0_S\, K^0_L \end{cases}$$

  - secondary/tertiary electron or photon beams : $\mathbf{p} + A \rightarrow \quad e^{\pm}, \gamma$

$$e^{\pm} + A \rightarrow \gamma$$
$$\gamma + A \rightarrow e^{\pm}$$

  - ion fragment beams : $\mathbf{Ion}(\mathrm{Pb}^{82}_{208}) + A \rightarrow \mathrm{Ion\,Fragments}(\mathrm{X}^{Z}_{A})$

Characteristics of Charged Particles

Category	Name		Q	Mass [MeV/c²]	Mean life (τ) [s]	$c\tau$ [m]	Mean decay distance [m/GeV/c]	Decays
Leptons	Electron	e	$\pm e$	0.511	stable			
Leptons	Muon	μ	$\pm e$	105.6	2.2×10^{-6}	659.6	6.3×10^{3}	$\mu^+ \longrightarrow e^+ \overline{\nu}_e \nu_\mu$ (100%)
Hadrons / Mesons	Pion	π	$\pm e$	139.6	2.6×10^{-8}	7.8	56.4	$\pi^+ \longrightarrow \mu^+ \nu_\mu$ (100%)
Hadrons / Mesons	Kaon	K	$\pm e$	493.6	1.23×10^{-8}	3.7	8.38	$K^+ \longrightarrow$ $\mu^+ \nu_\mu$ (63%); $\pi^0 e^+ \nu_e$ (5%); $\pi^0 \mu^+ \nu_\mu$ (3%); $\pi^+ \pi^0$ (...) (28.9%)
Hadrons / Mesons	Kaon	K^0	0	497.6	K^0_S: 8.9×10^{-11}	0.02	0.060	$K^0_S \longrightarrow$ $\pi^0 \pi^0$ (30.7%); $\pi^+\pi^-$ (69.2%)
Hadrons / Mesons	Kaon	K^0	0	497.6	K^0_L: 5.12×10^{-8}	15.34	34.4	$K^0_L \longrightarrow$ $\pi^\pm e^\mp \nu_e$ (40.5%); $\pi^\pm \mu^\mp \nu_\mu$ (27.0%); $3\pi^0$ (19.5%); $\pi^+\pi^-\pi^0$ (12.5%)
Hadrons / Baryons	Proton	p	$\pm e$	938	stable			
Hadrons / Baryons	Lambda	Λ	0	1115.6	2.63×10^{-10}	0.079	0.237*	$\Lambda^0 \longrightarrow p\, \pi^-$ (63.9%)
Hadrons / Baryons	Sigma Hyperons	Σ^+	$+e$	1189.3	8.02×10^{-11}	0.024	0.068*	$\Sigma^+ \longrightarrow p\, \pi^0$ (51.57%)
Hadrons / Baryons	Sigma Hyperons	Σ^-	$-e$	1197.4	1.48×10^{-10}	0.044	0.125*	$\Sigma^- \longrightarrow n\, \pi^-$ (99.84%)

(*) for 10 GeV/c

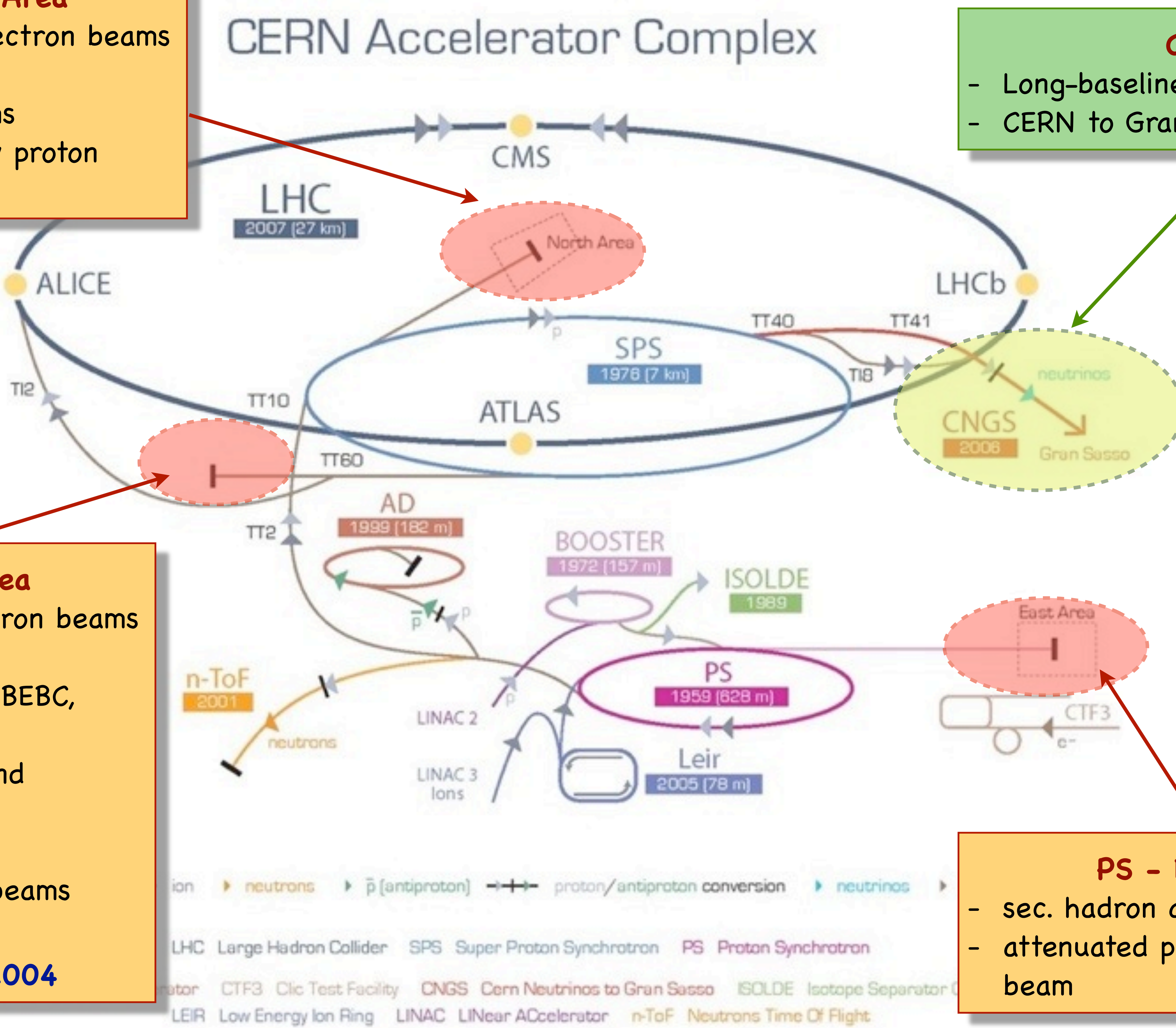
Particle Beams - Design basics

- **Production**
  - primary beam layout and switchyard
  - primary target : material, properties, dimensions
  - capture/front-end : collect the secondary particles, beam acceptance
- **Beam preparation and transport**
  - momentum selection, particle decay
- **Particle selection**
  - selection or particle tagging/identification
  - background (unwanted particles) rejection or optimization - collimation
- **Final focusing to experiments**
  - focal point, spot size, beam divergence, no dispersion

Secondary Particle beams at CERN

SPS - North Area
- sec. hadron and electron beams
- ion beams
- Kaon & Muon beams
- attenuated primary proton beams

CNGS
- Long-baseline neutrino beam
- CERN to Grand Sasso (730km)



SPS - West Area
- sec. hadron and electron beams
- ion beams
- RF separated beams (BEBC, OMEGA exp.)
- Wide and Narrow-band neutrino beams
- Hyperon beams
- Attenuated primary beams

- **Decommissioned in 2004**

PS - East Area
- sec. hadron and electron beams
- attenuated primary proton beam

Secondary Beams & Experimental Halls

Layout Considerations (I)

- Typically there is a strong interest to locate accelerators deep underground
  - lower cost - not need to by the land (at least in EUROPE !)
  - minimize radiation impact to environment and population
  - if site well chosen, avoid problems with underground water

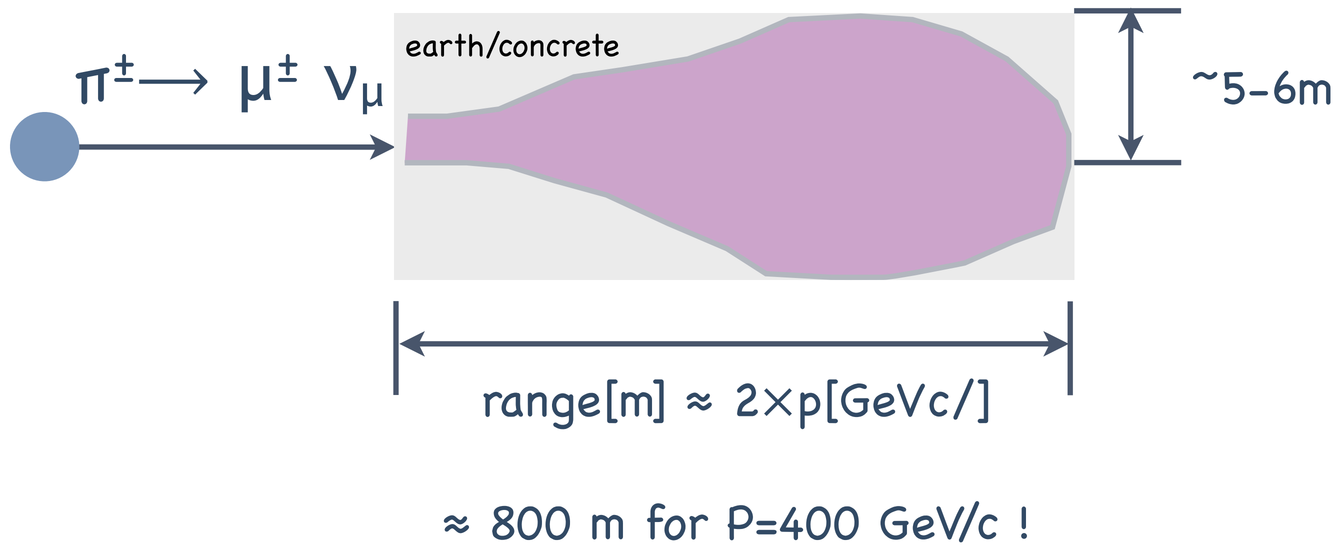
- However there is a strong interest to have the experimental halls at the surface or at shallow depth
  - experiments come with lot of accompanying infrastructure
    - overhead cranes, services: electrical installations, cryogenics, gases, cabling
  - the exp. halls can be made big to accommodate several experiments, running in parallel in different beam lines
    - share the infrastructure --> reduced cost
  - typically the experiments don't run at high intensities (FT physics = forward physics so not easy to cope with lot of rate) so radiation can be under control
    - radiation limits : **< ~10^8 ppb**, shallow depth installations, **< 10^{11} ppb** for underground caverns

- This natural choice has other advantages for the design of the beam lines !!

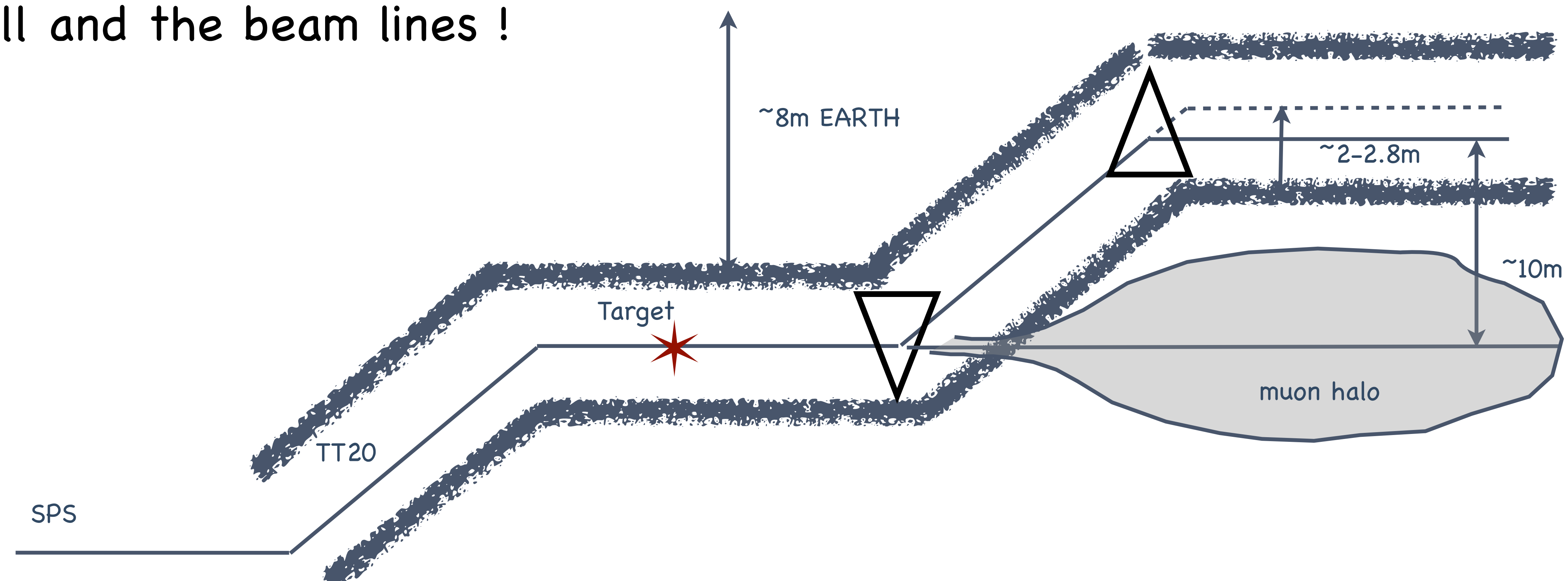
Secondary Beams & Experimental Halls

Layout Considerations (II)

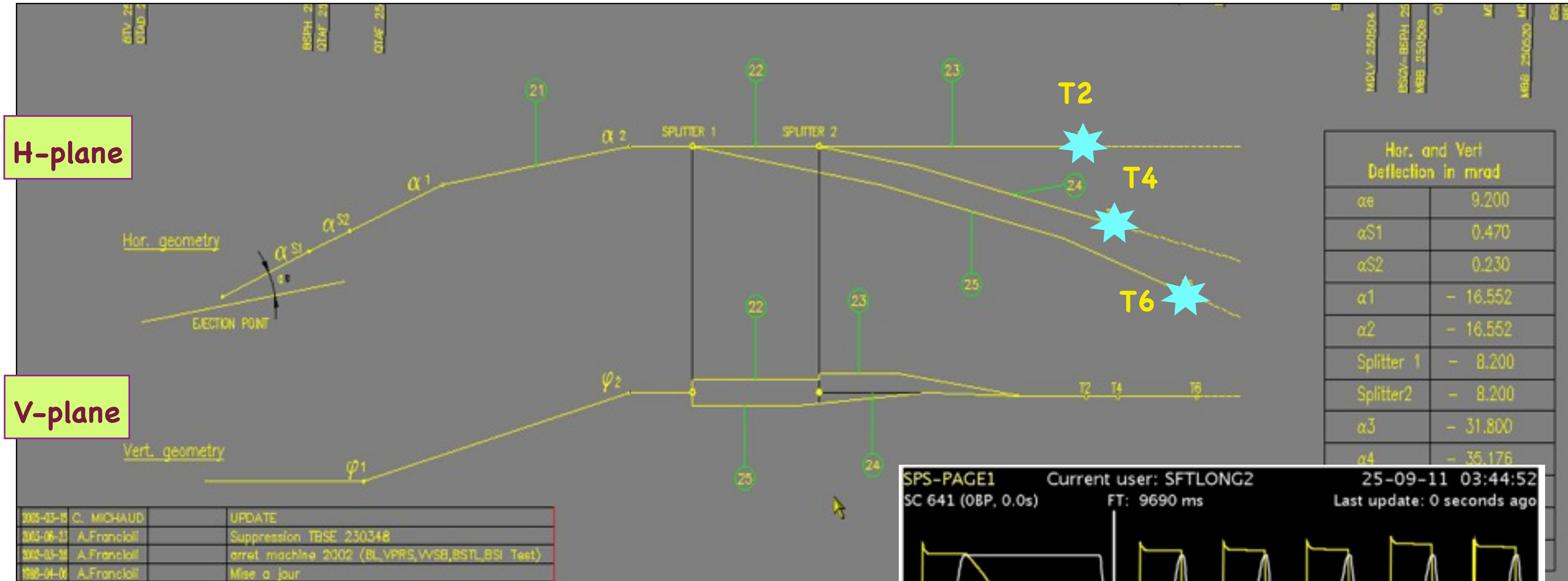
- For high-energy installations (like SPS), the muons will range out after traversing ~**800m** of earth and will be **~5-6m** wide !

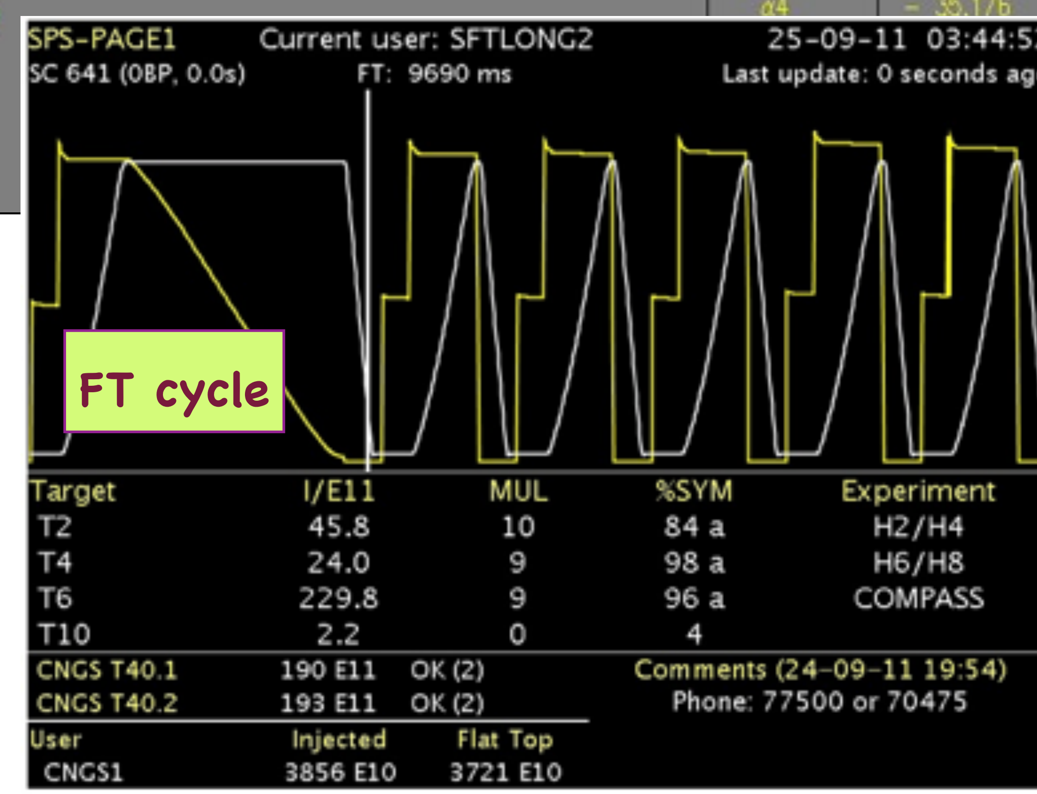


- Therefore to have several beams in a hall, side by side, the target must be separated vertically from the exp. hall and the beam lines !



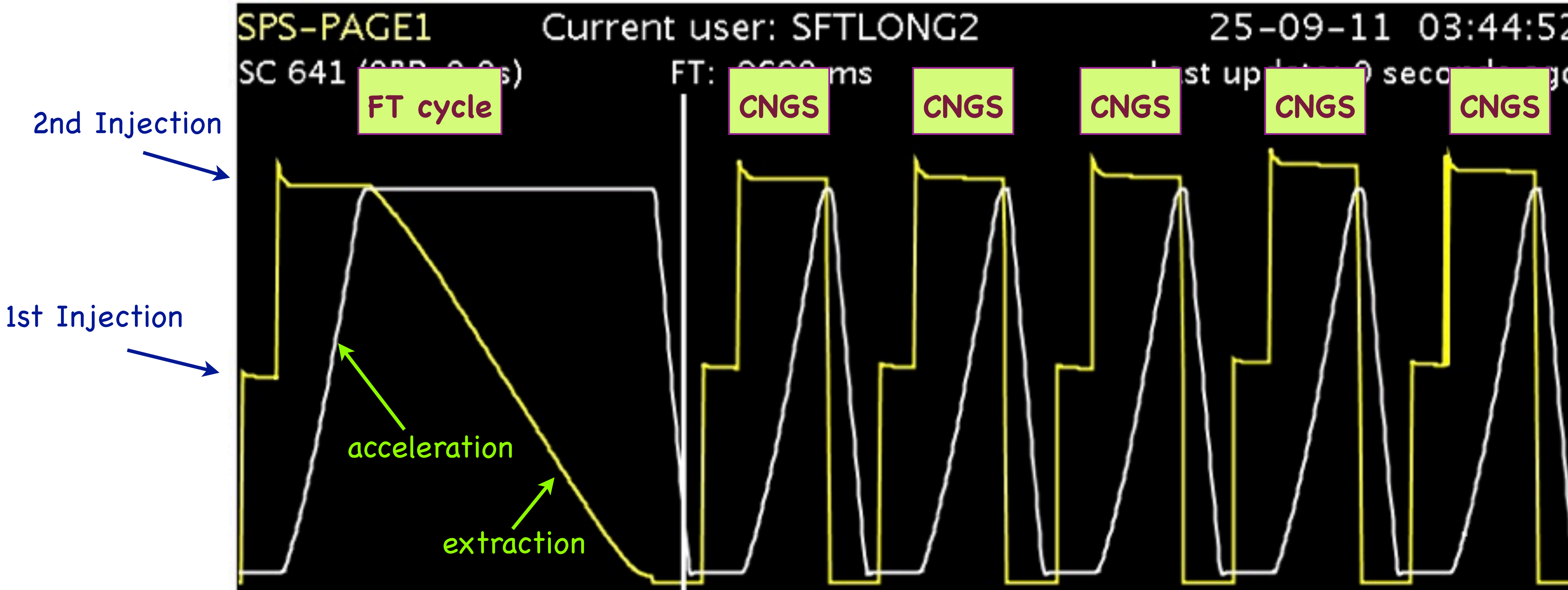
Primary beam extraction and switchyard (I)





- Primary beam:
  - slowly extracted from SPS
  - 400 GeV/c
  - 3×10^{13} protons/extraction

SPS Beam extraction



-yellow line= beam intensity
-white line = magnetic cycle

Target	I/E11	MUL	%SYM	Experiment
T2	45.8	10	84 a	H2/H4
T4	24.0	9	98 a	H6/H8
T6	229.8	9	96 a	COMPASS
T10	2.2	0	4	

CNGS T40.1	190 E11	OK (2)
CNGS T40.2	193 E11	OK (2)

Comments (24-09-11 19:54)
Phone: 77500 or 70475

User	Injected	Flat Top
CNGS1	3856 E10	3721 E10

Primary beam extraction and switchyard (II)

- **Beam splitters** : specially designed magnets that have a field-free region where part of the beam passes without deflection
  - however part of the beam is lost - **very** radioactive objects, also the nearby area!!

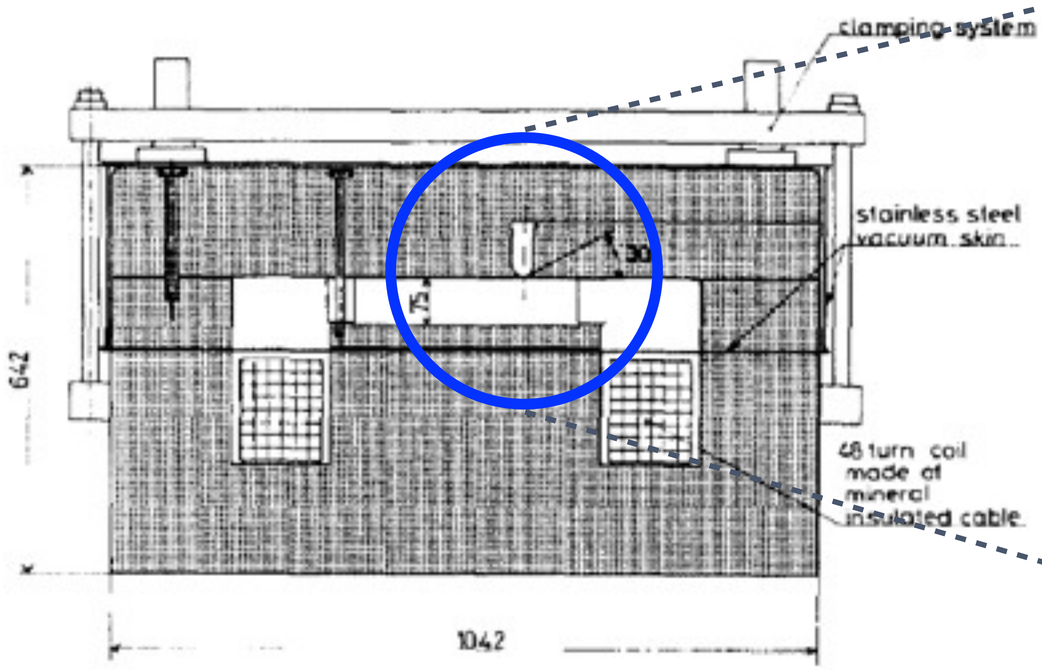
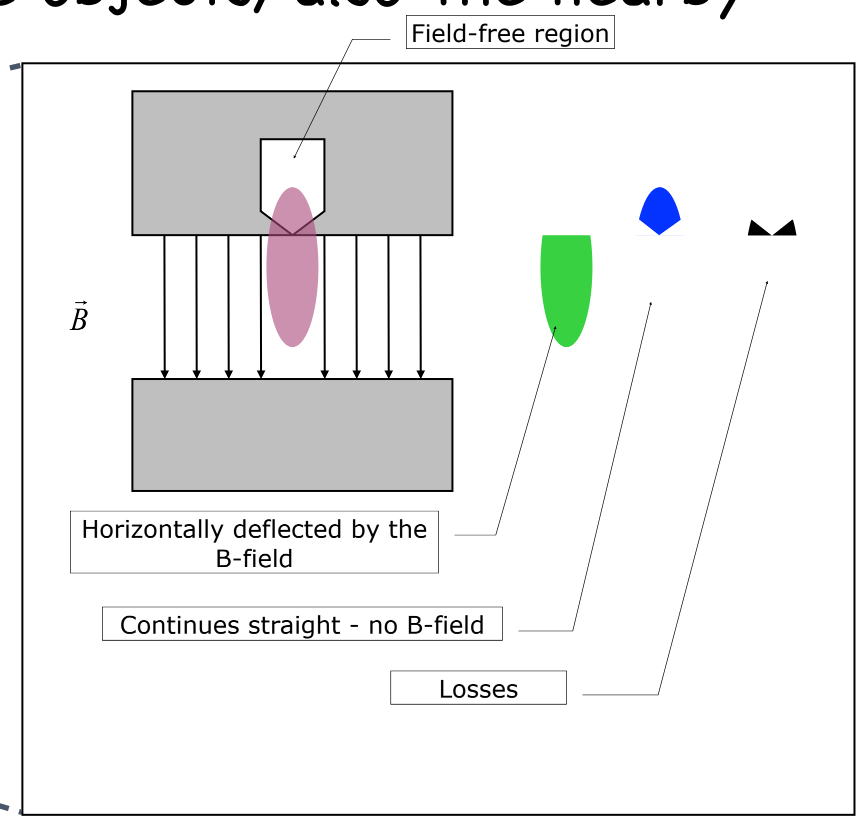
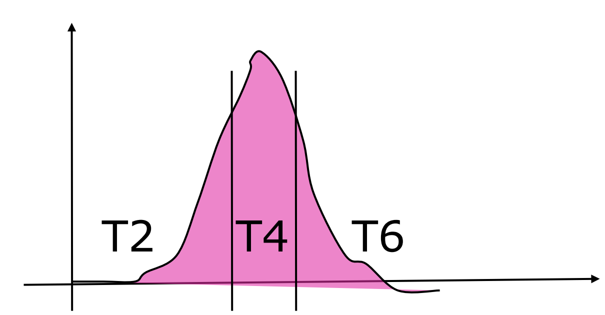


Fig. 5 Cross section of the single septum magnet.

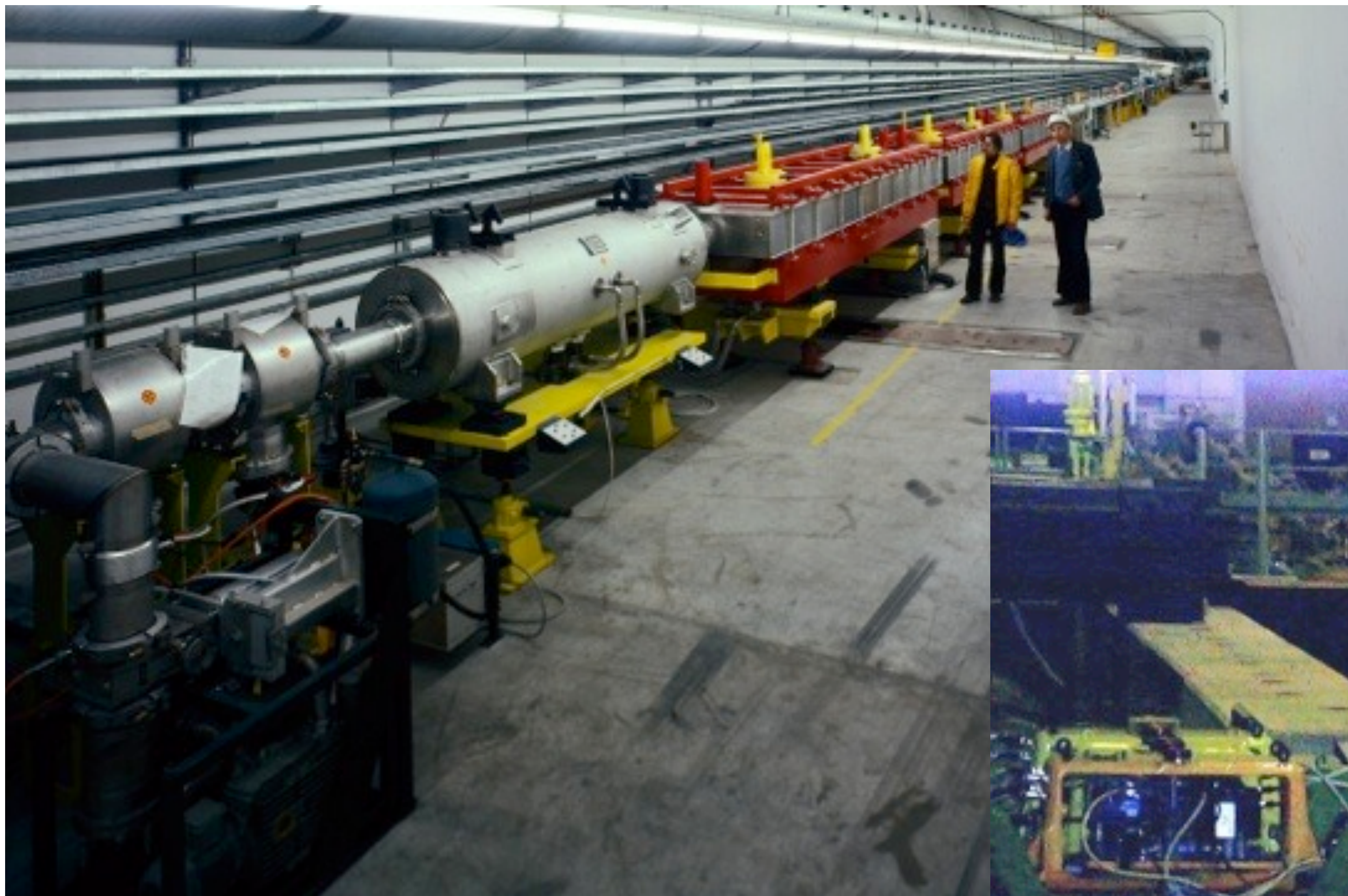


- Optimized beam optics to minimize the losses
  - small β_H(~9m) and large β_V(~23km)



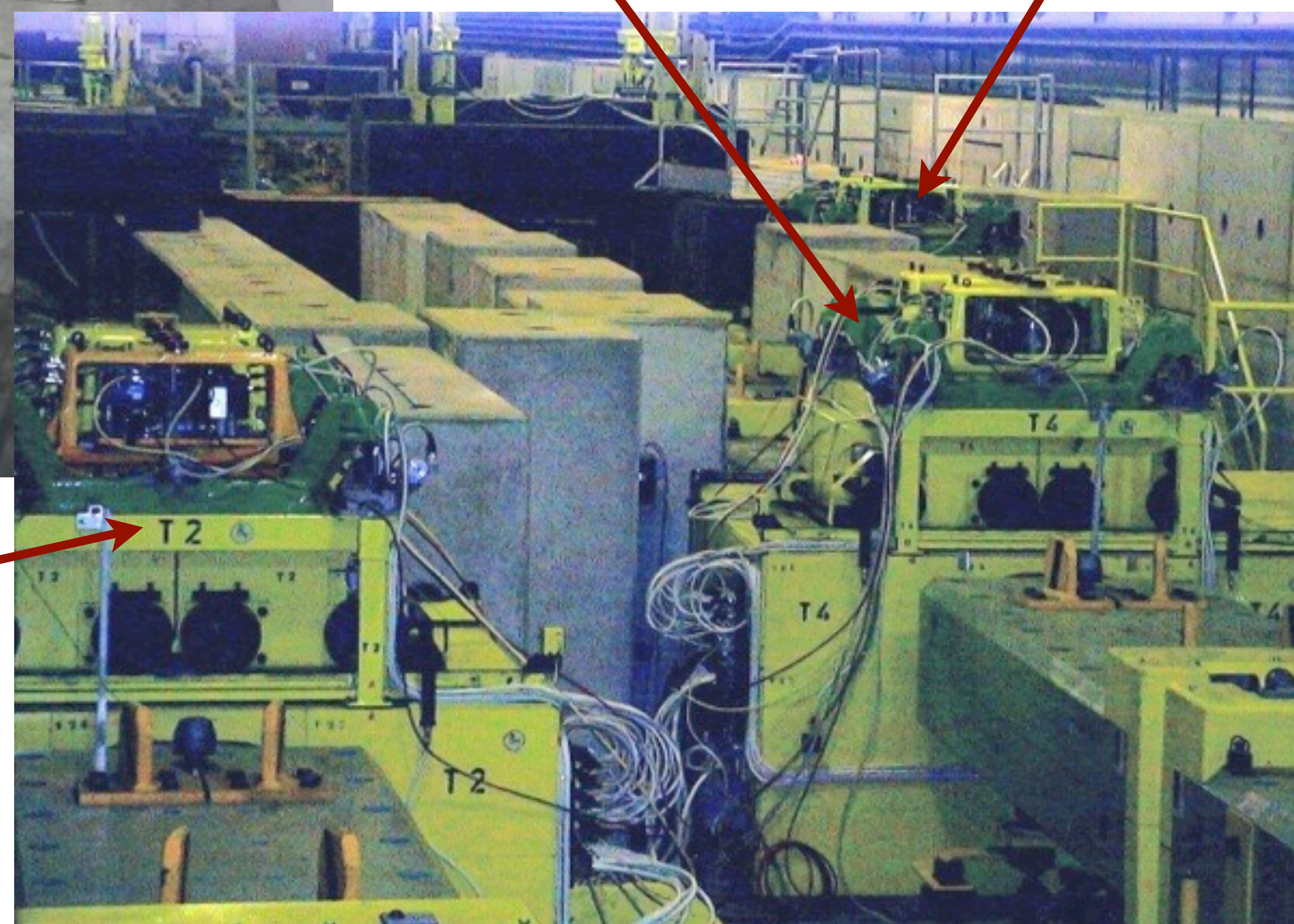
Exercise: can you design such optics,including the focusing to the downstream targets?

Primary beam extraction and switchyard (III)



T6
(M2)

T4
(H6,H8,P0)



T2
(H2,H4)

- What else before the primary beam arrives to the targets?
  - **Wobbling !!**

Secondary Beams @ CERN - SPS North Area

Target station wobbling

- **Goal** : provide additional degrees of freedom and increase the flexibility in using a target station

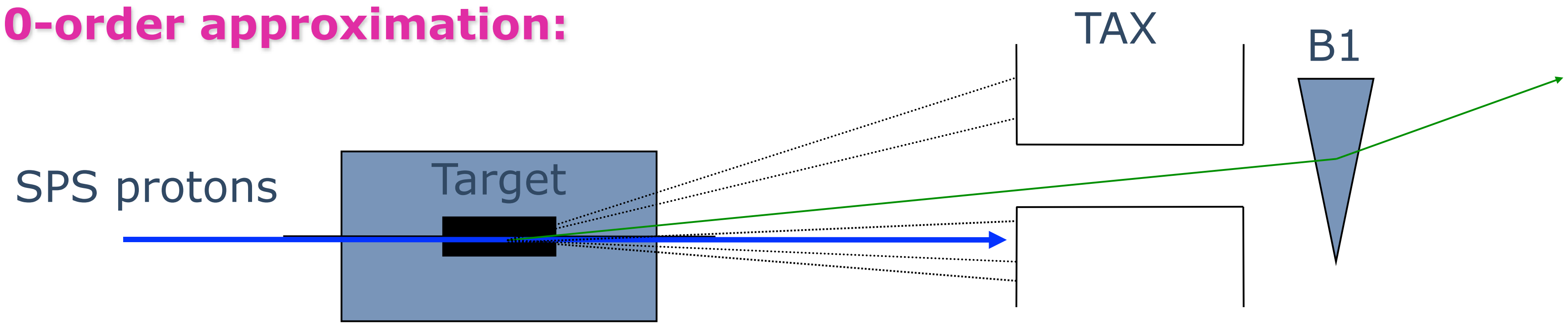
- Produce several (>1) secondary beams from the same target
  - wide spectrum of secondary particles downstream the primary targets
  - all the particles are produced in a large variety of angles and energies
    - note: the most energetic particles are in the forward direction
  - must direct the wanted particles in each beam line to its direction (front-end), as defined by the target station layout

- Besides the secondary beams, the very intense primary proton beam has to be dumped in a controlled way

- Solution: "**target wobbling**"
  - adjust the angle of the primary beam to the target
  - based on physics of particle production, select & optimize the secondary beams

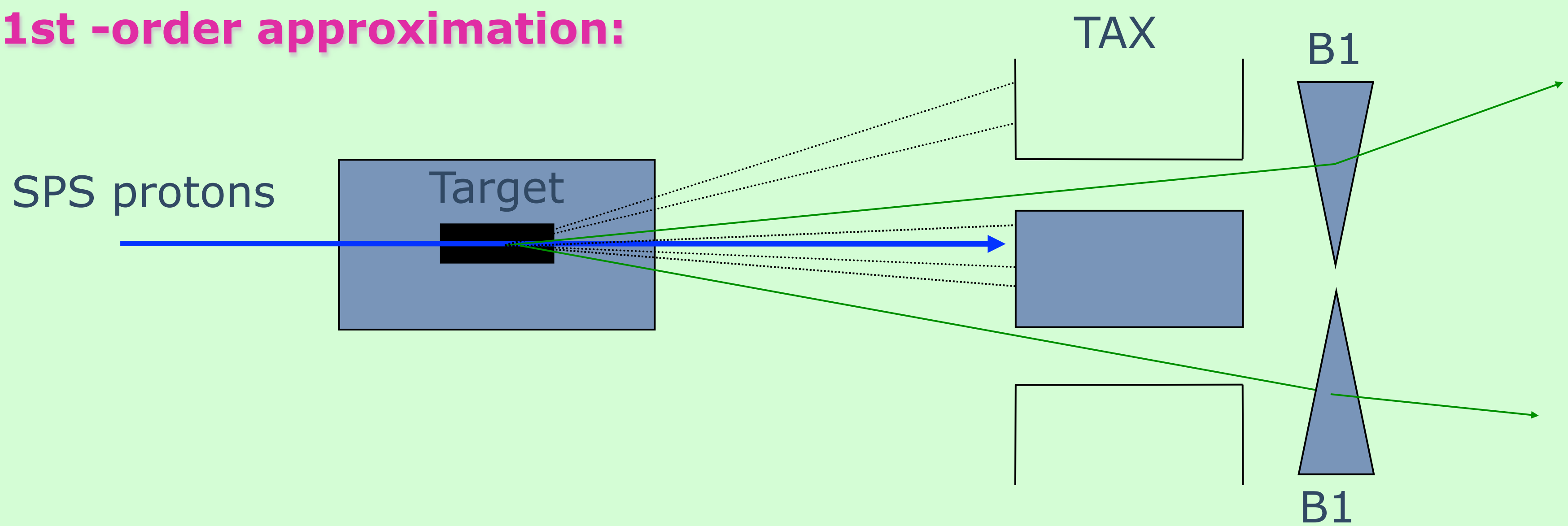
Target station wobbling

0-order approximation:



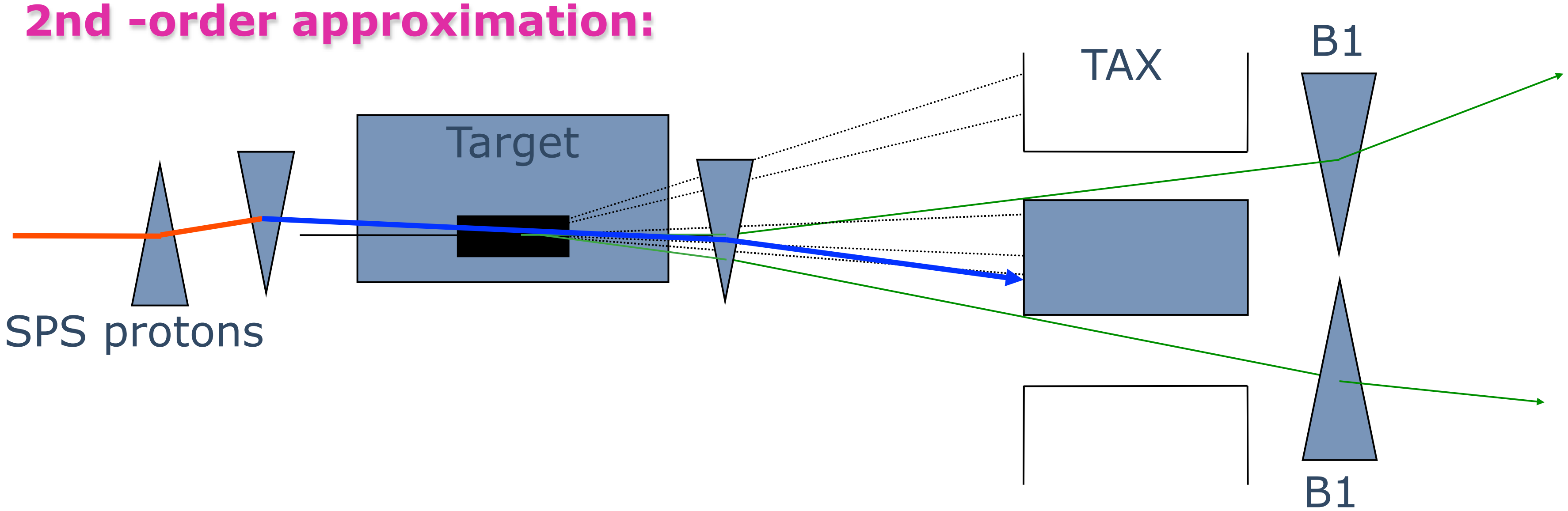
- single secondary or primary beam
- fixed production angle

1st -order approximation:



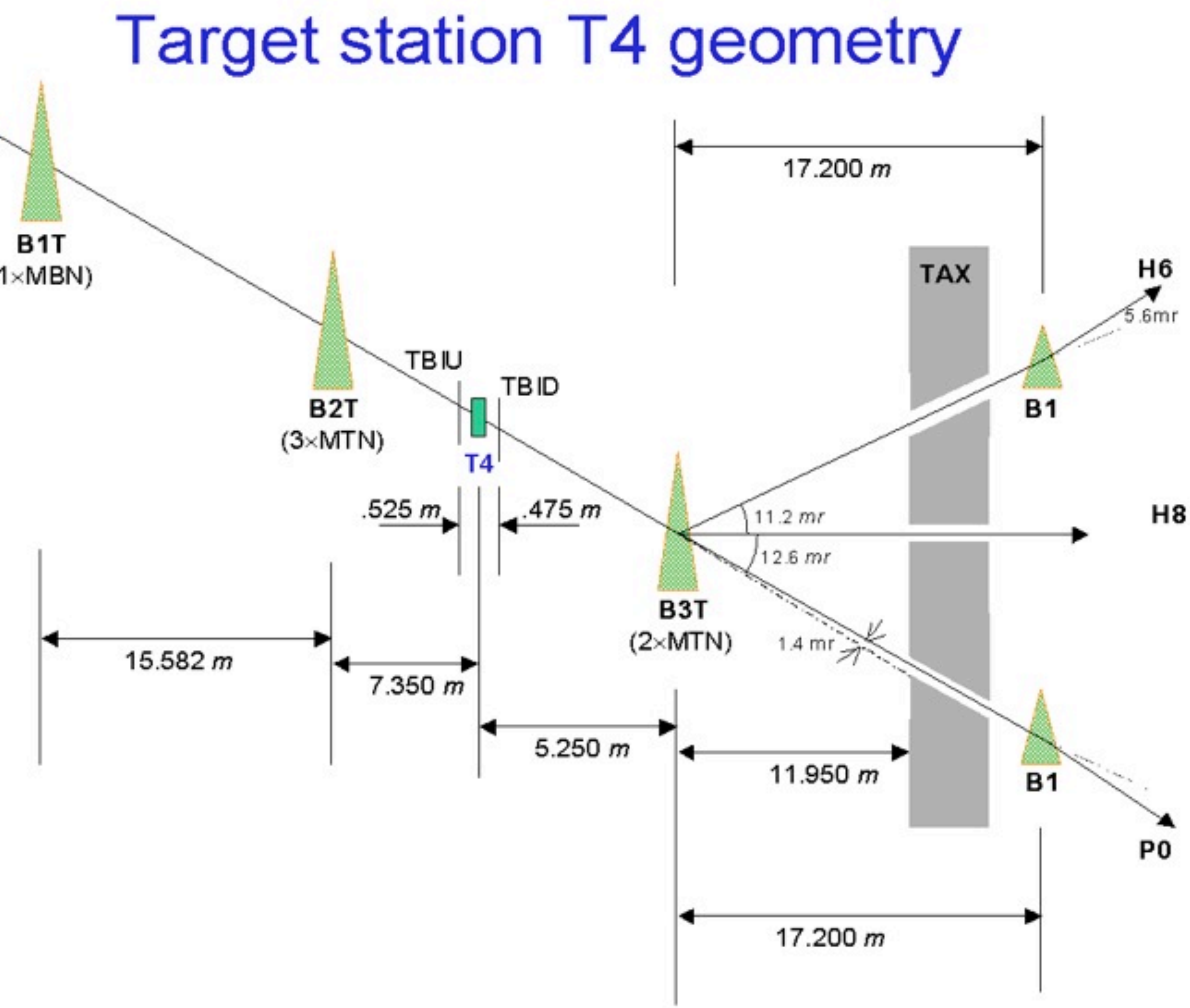
- two secondary beams
  - one could be the primary beam
- fixed production angles

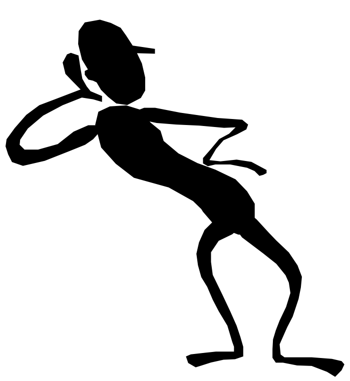
2nd -order approximation:



- two secondary beams
  - one could be the primary beam
- variable production angles

Target station wobbling

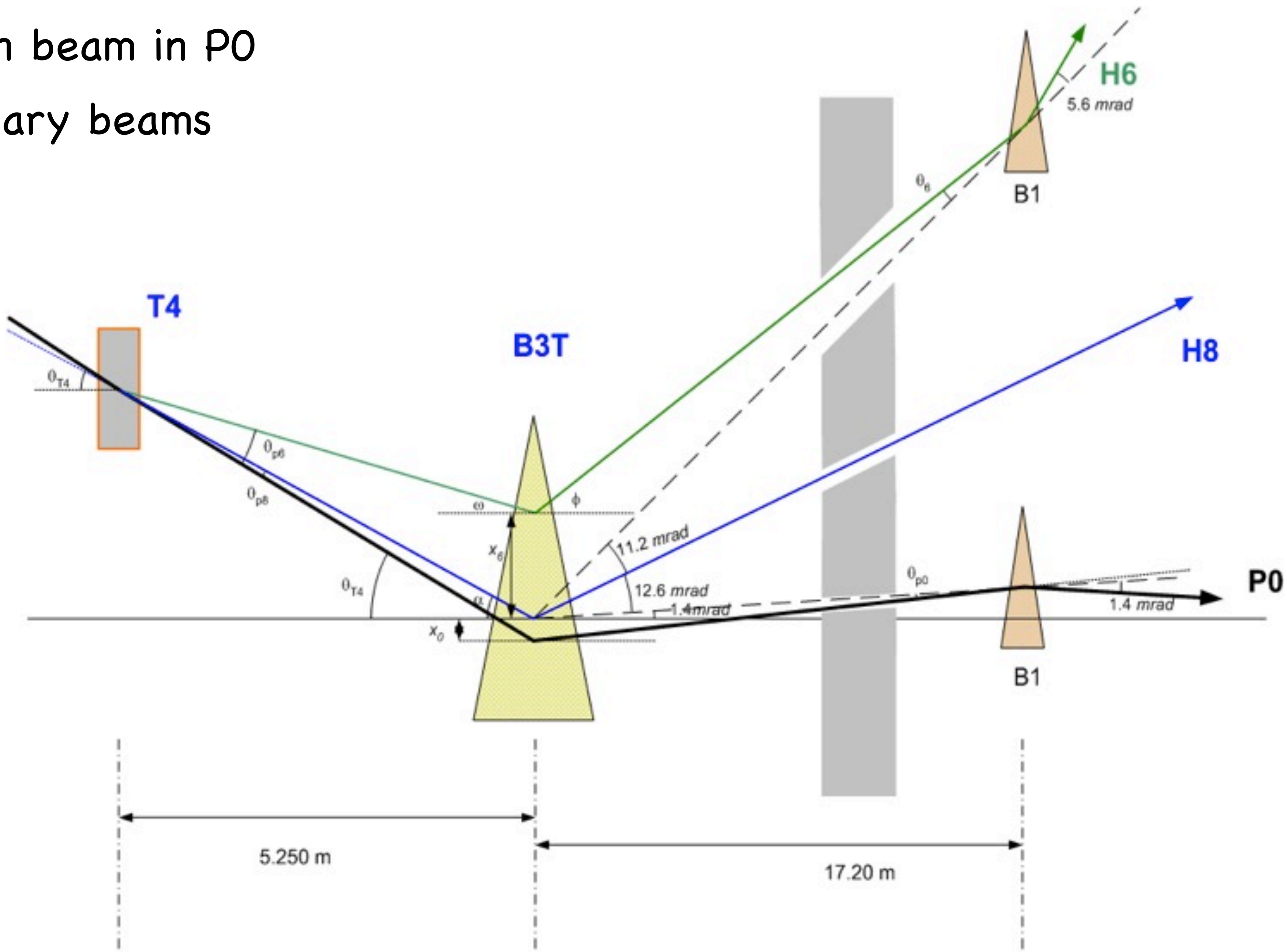




Target station wobbling

Example 1: T4 wobbling

- primary proton beam in P0
- H8, H6 secondary beams



Target station wobbling

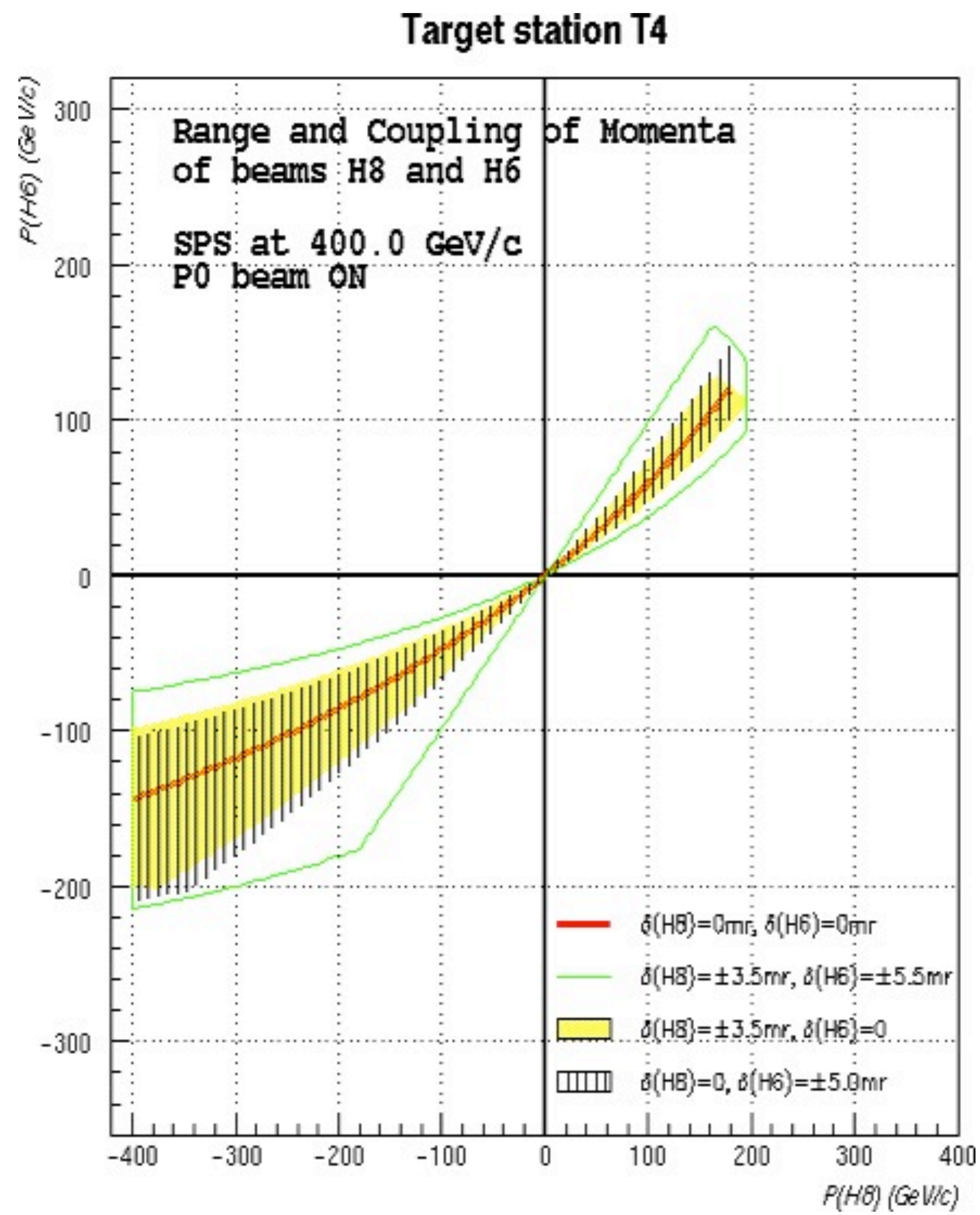
Example 1:

- primary proton beam in P0
- H8, H6 secondary beams

Presently the most frequent case

"standard wobbling" settings:

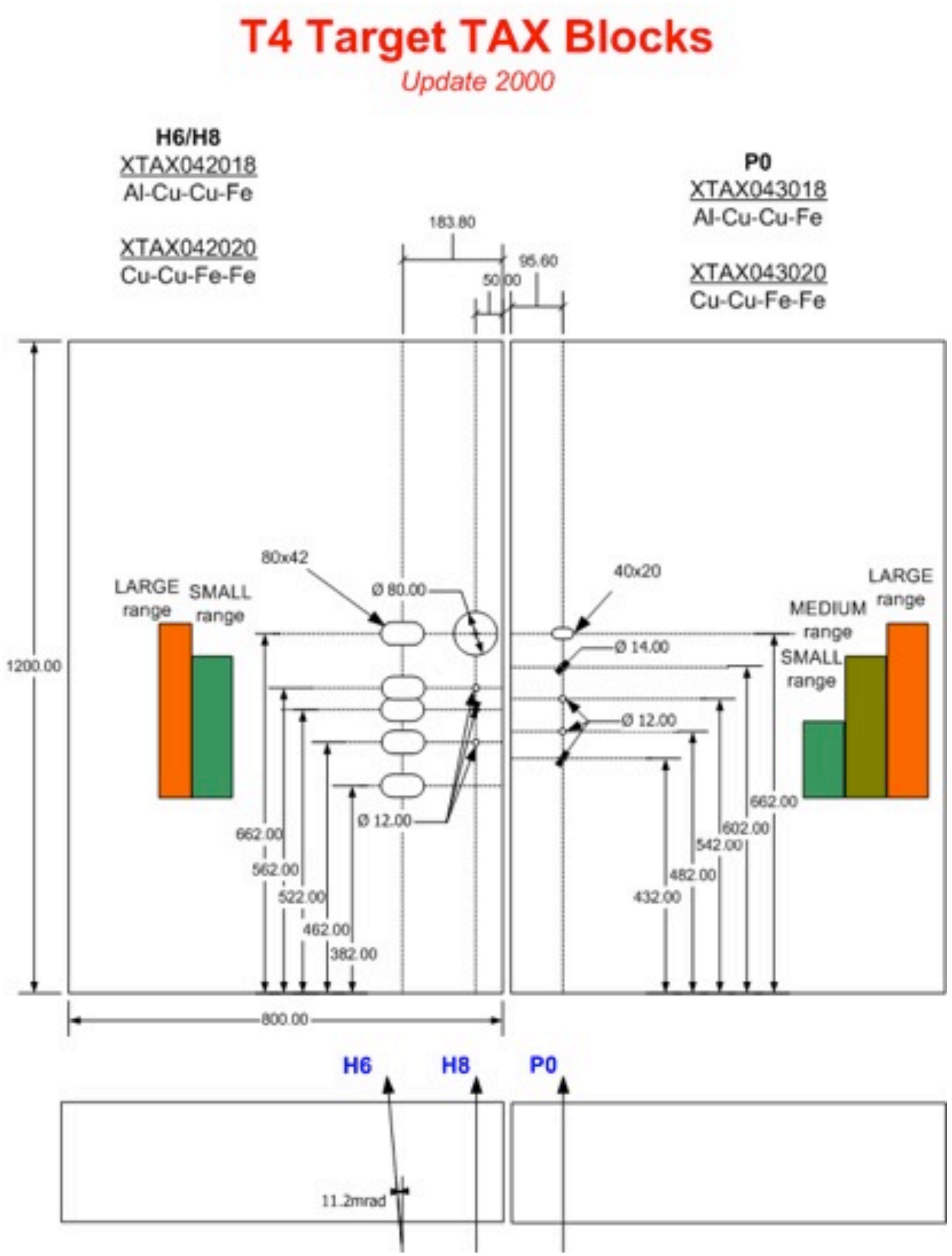
H8	H6	
Energy (GeV/c) @ 0 mrad prod. angle	Energy (GeV/c)	Prod. Angle (mrad)
+180	+120	0
	+100	-5.46
	+80	-13.36
+20	+10	-1.58
	+20	8.58
	+6	-15.13
-250	-100	-0.33
	-200	8.06
	-120	2.15
	-60	-10.23

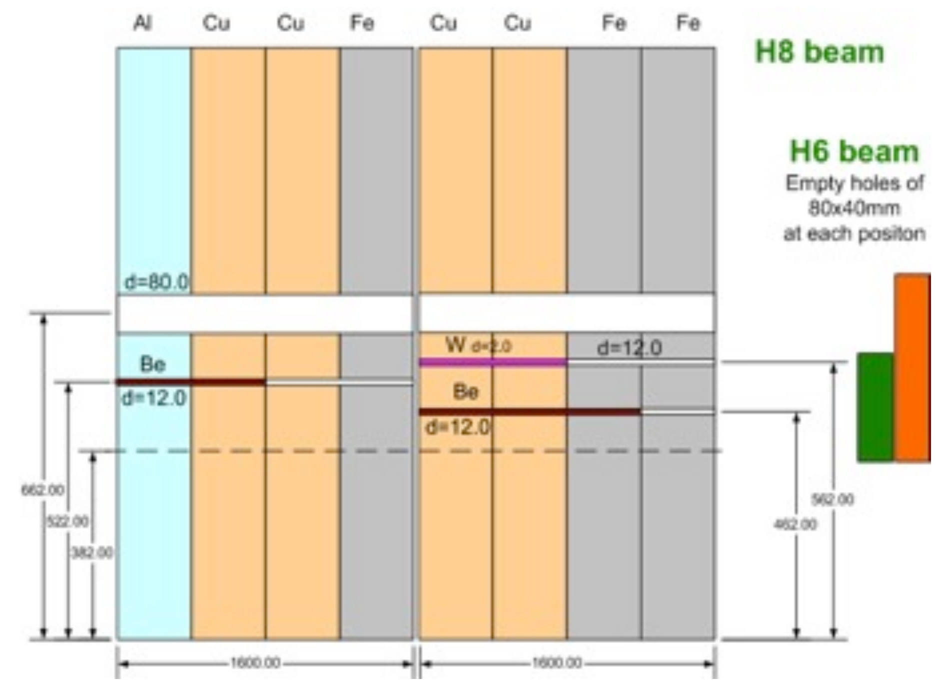


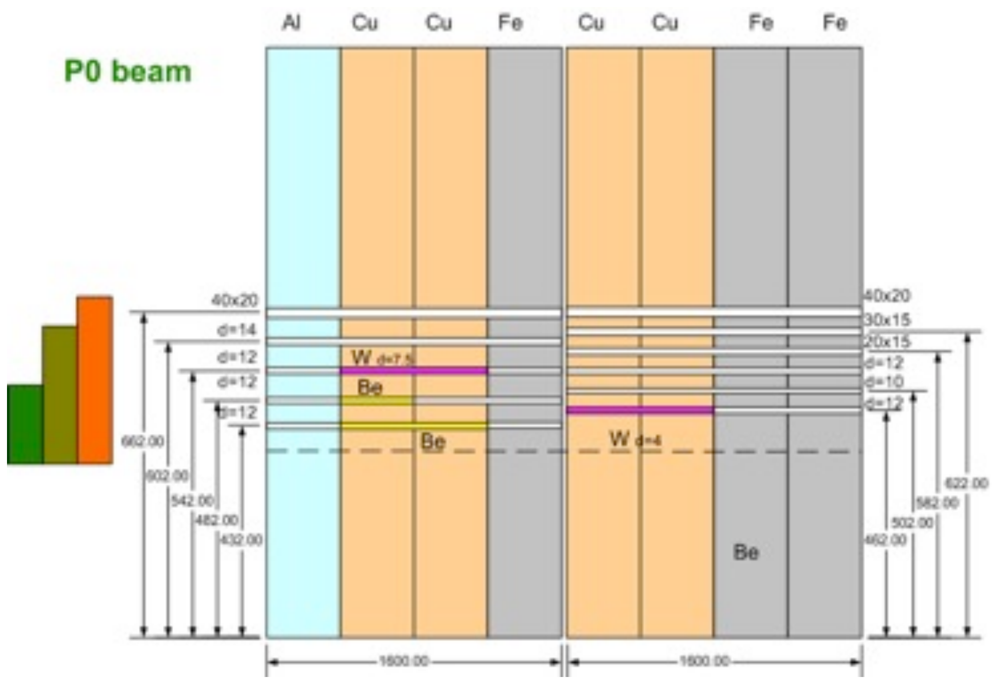
Exercise: can you calculate the settings for at least one case?

Note: H8 doesn't have a B1, therefore must have scew=0 deg!

The TAX absorber attenuator







The TAX absorber attenuator

Preparation and installation of new TAX blocks for T4.

The primary targets

- Target material and length
  - The proton intensity on each target can go up to 1013 protons/pulse
    - limited by target and TAX absorber construction (i.e. cooling, etc.)

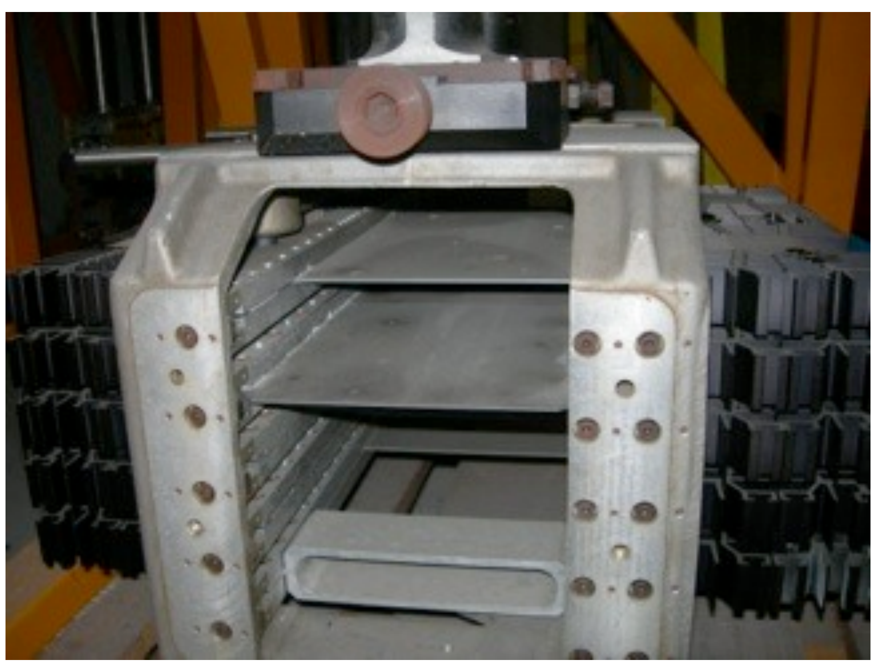
- The material with largest ratio: Xo/λint is preferred **Beryllium**

- Increasing the target length:
  - more production but also more re-absorption
    - lower the energy of the outgoing particles
    - Optimal choice ~ 1 interaction length
    -

Material	X_o (cm)	λ_{int} (cm)	X_o/λ_{int}
Beryllium	35.3	40.7	0.87
Copper	1.50	15.0	0.10
Lead	0.56	17.1	0.03

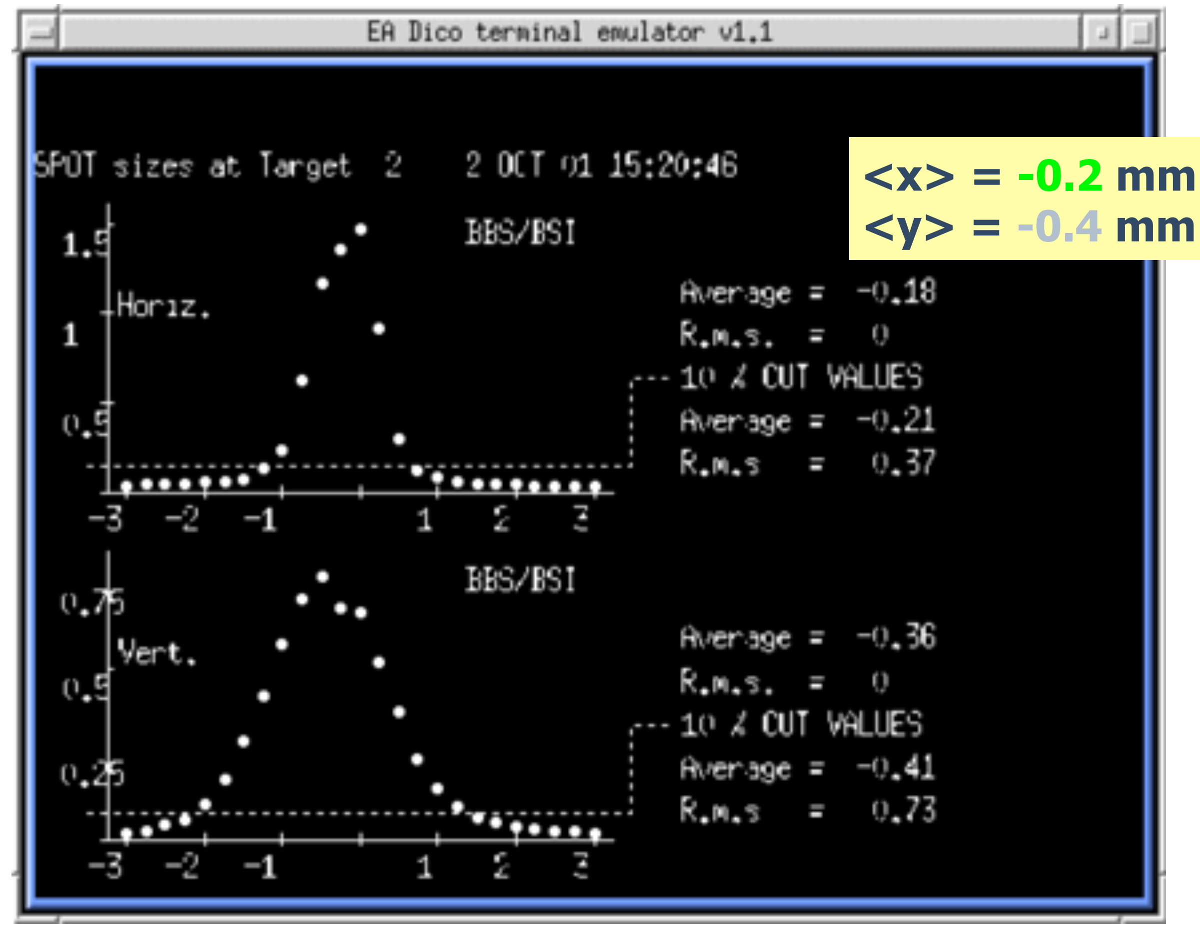
The primary targets

T2 target				
Position	H (mm)	V (mm)	L (mm)	Material
0	EMPTY			
1	160	2	300	Be
2	160	2	500	Be
3	160	2	180	Be
4	160	2	100	Be
5	120	2	40	Be



Exercise: can you design optics to make a MH=MV=1 from the taret to the experiment? Study the impact of a larget target and how affects the final focusing?

- **Beam position monitors**
  - **TBIU** (upstream), **TBID** (downstream)

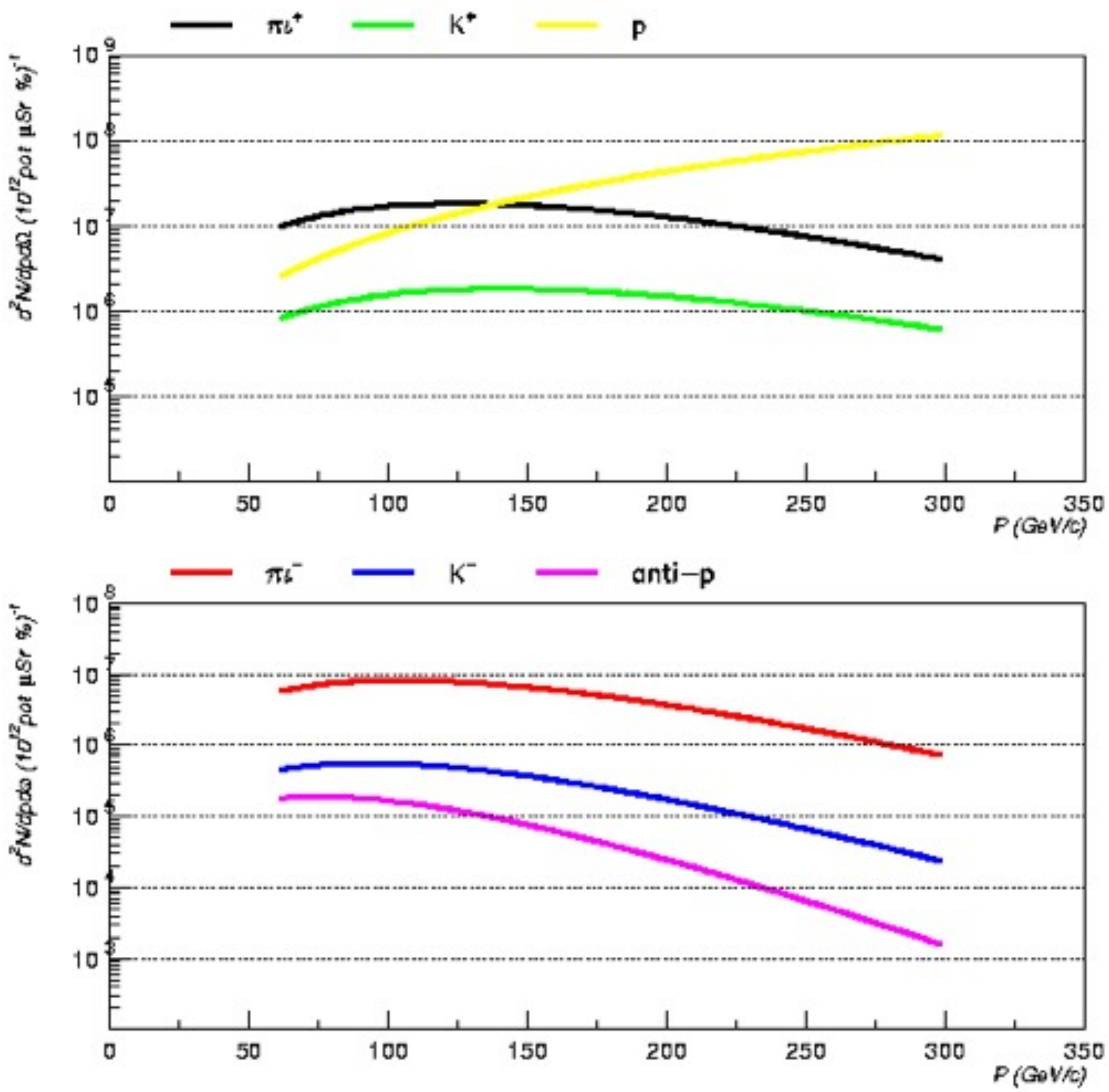


  - mounted on the same girder as the target head for better alignment
  - beam steering onto the target using BSM located ~30m upstream

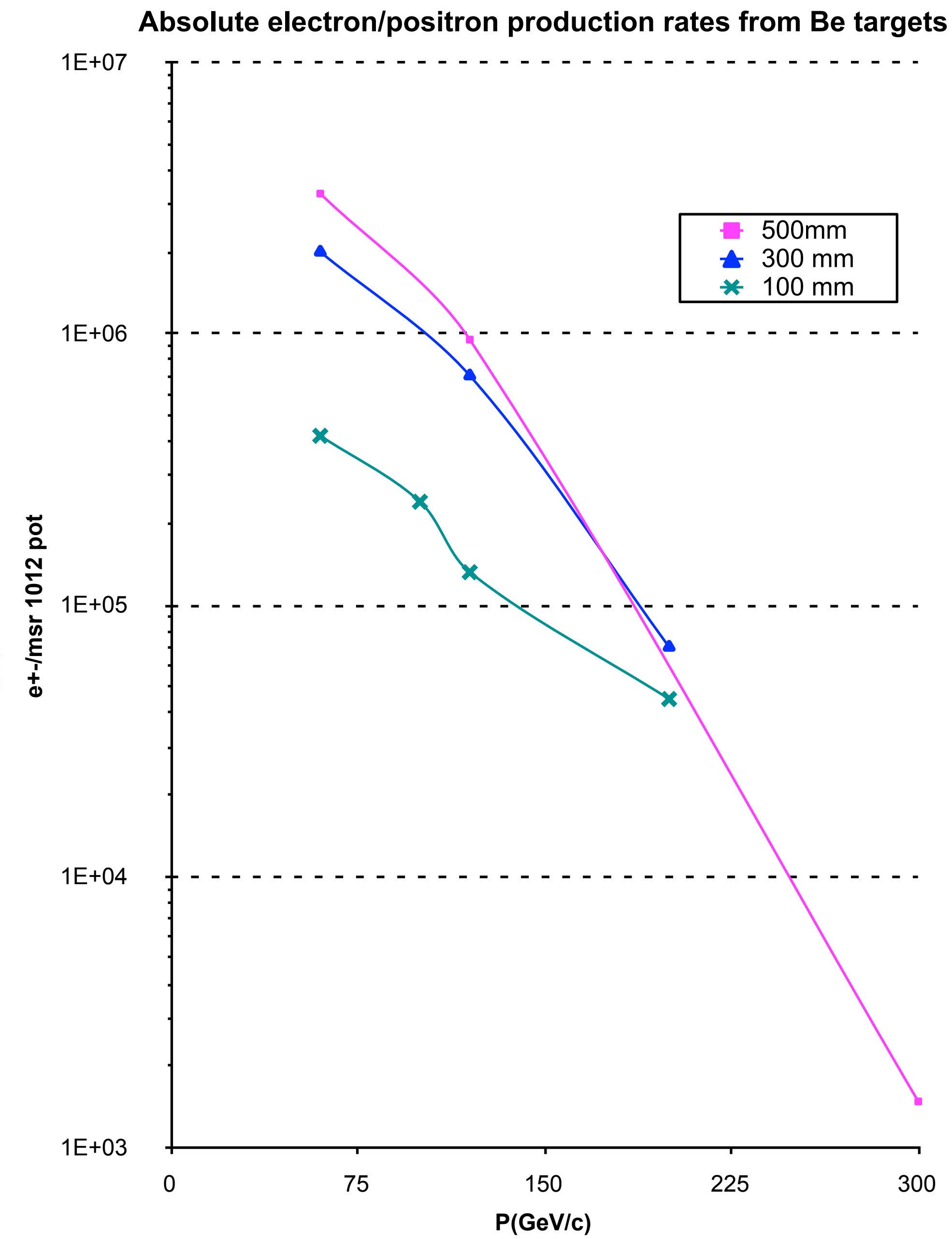
- The primary beam spot and target head size, determine the "source" term for the secondary beam line
  - i.e. affect the final focusing at the experiment

Production rates - primary targets

Hadron beams



Electron beams



Particle production by 400 GeV/c protons on Be targets, H.W.Atherton et. al.

TCC2 Target station - Secondary beams

Particle Beams - Design basics

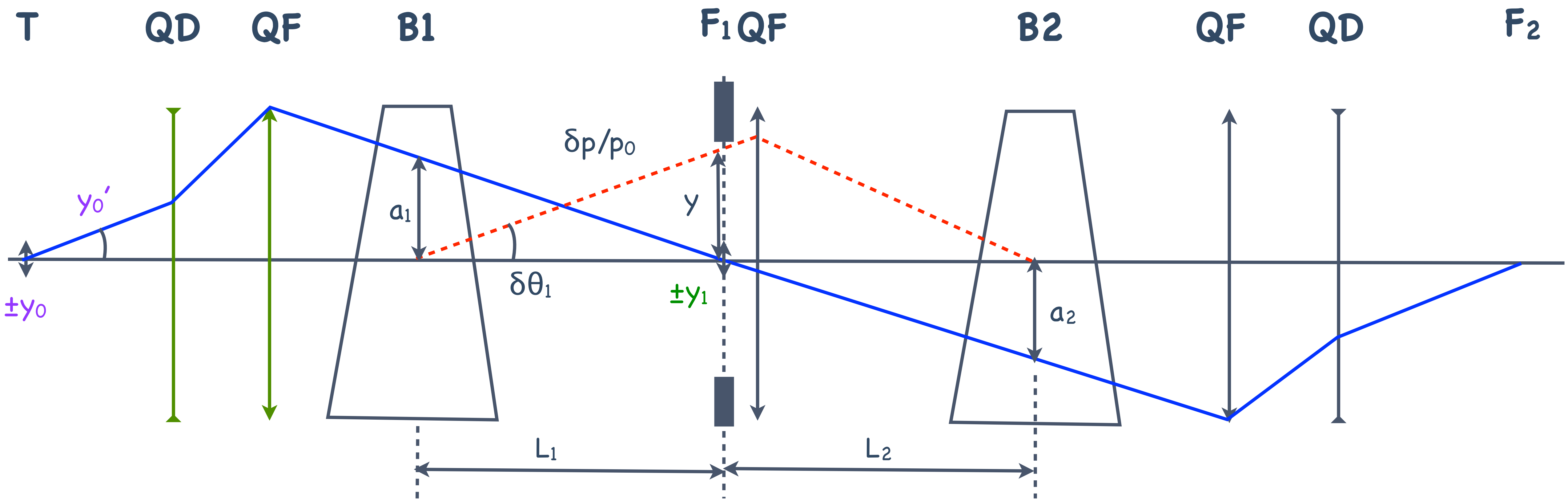
- **Production**
  - primary beam layout and switchyard
  - primary target : material, properties, dimensions
  - capture/front-end : collect the secondary particles, beam acceptance

- **Beam preparation and transport**
  - momentum selection, particle decay

- **Particle selection**
  - selection or particle tagging/identification
  - background (unwanted particles) rejection or optimization - collimation

- **Final focusing to experiments**
  - focal point, spot size, beam divergence, no dispersion

- The momentum acceptance of a beam line ($\delta p/p_0$) is determined by the first principal bend, following the acceptance quadrupoles



Beam emittance: $\varepsilon = y_0 \cdot y_0'$

$\pm y_1$: beam size at focus for the central momentum

$$(\frac{\delta p}{p_0})_{min} = \frac{y_1}{L_1 \cdot \theta_1}$$

Beam dispersion:

$$\delta\theta_1 = -\frac{\delta p}{p_0} \cdot \theta_1$$

$$y = L_1 \cdot \delta\theta_1 = -\frac{\delta p}{p_0} \cdot L_1 \theta_1$$

Intrinsic Resolving Power:

$$\mathbf{R} = \frac{1}{(\frac{\delta p}{p_0})_{min}} = \frac{L_1 \cdot \theta_1}{y_1} = \frac{a_1 \cdot \theta_1}{y_0 \cdot y_0'}$$

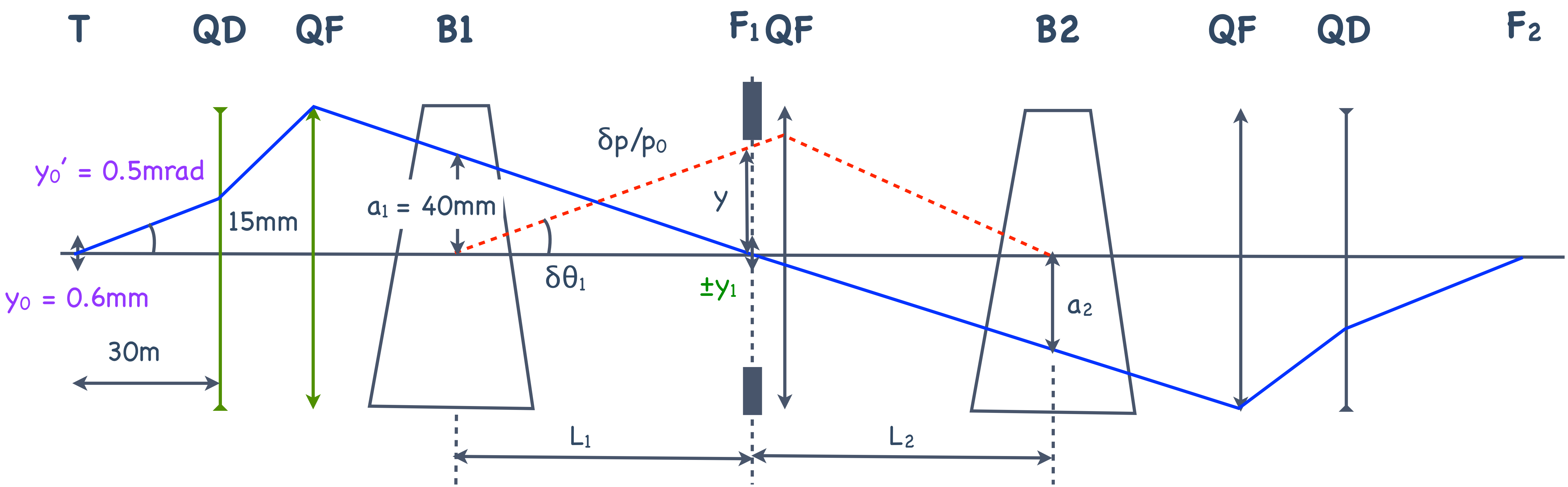
Momentum recombination @ F2 (dispersion correction):

$$\sum_1^n a_n \cdot \theta_n = 0 \rightarrow a_1 \cdot \theta_1 + a_2 \cdot \theta_2 = 0$$

Exercise: can you verify the formula?

Beam line design - momentum selection

- SPS North Area: FT physics in the 70's, key parameter the **pion mass**
  - beam lines with resolution : $\pm\frac{\Delta p_{min}}{p} \simeq \pm\frac{m_\pi/2}{p} \simeq \frac{\pm 70\,MeV/c}{350 GeV/c} = \mathbf{2 \times 10^{-4}}$



$$\theta_1 = R \cdot \frac{y_0 \cdot y_0'}{a_1} = \frac{1}{2 \times 10^{-4}} \cdot \frac{0.6\,\text{mm} \times 0.5\,\text{mrad}}{40} = \mathbf{40}\,\text{mrad}$$

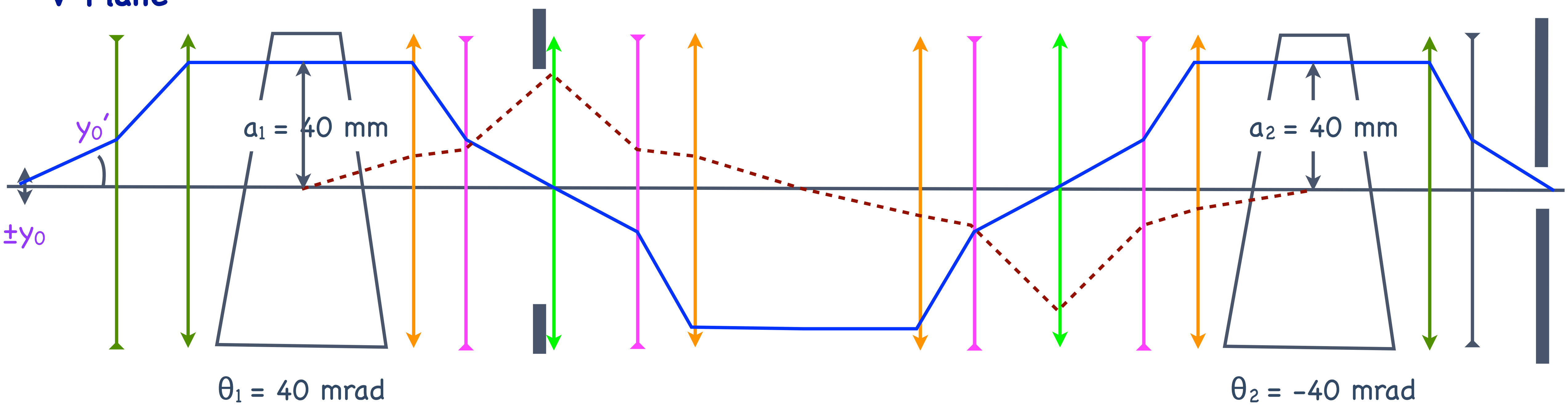
$$L_1 = \frac{R \cdot y_1}{\theta_1} = \frac{5 \times 10^{-3} \cdot 0.6\,\text{mm}}{40\,\text{mrad}} = 75\,\text{m}$$

assuming F1 is a focal point with M=-1 wrt target

Momentum acceptance:

$$y = -\frac{\delta p}{p_0} \cdot L_1 \theta_1 = 30\,\text{mm}/\%\,\delta p/p_0$$

Beam line design - optics



V-plane :

- 4×75m = **300m**, 360 deg phase advance
- momentum recombination (achromatic) at C9 and to the experiment

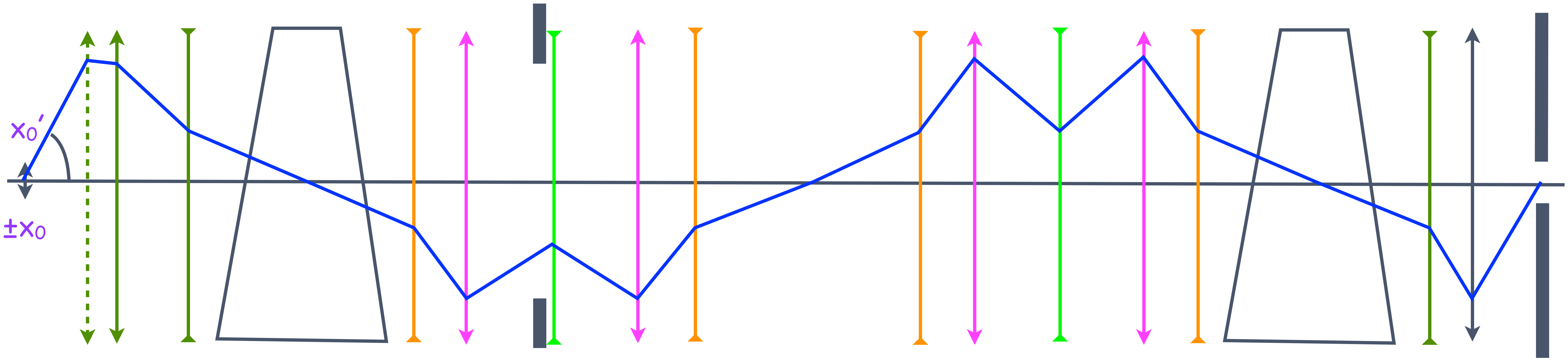
Momentum acceptance :

- 40mm/(30mm/% $\Delta p/p$) ⟶ **1.3%**

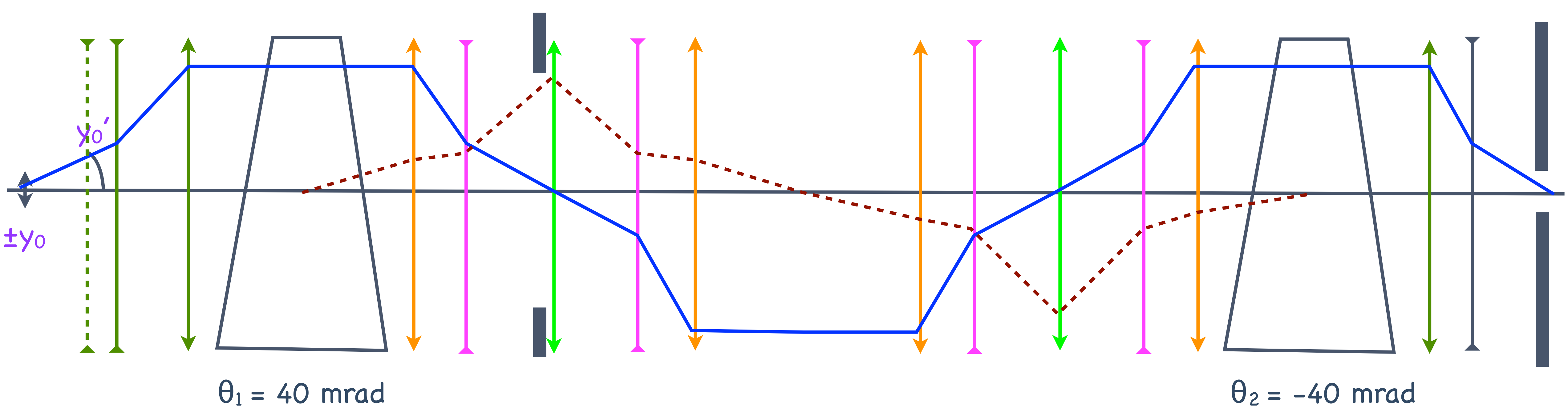
High-transmission optics

Exercise: do you understand why this is called high-transmission optics?

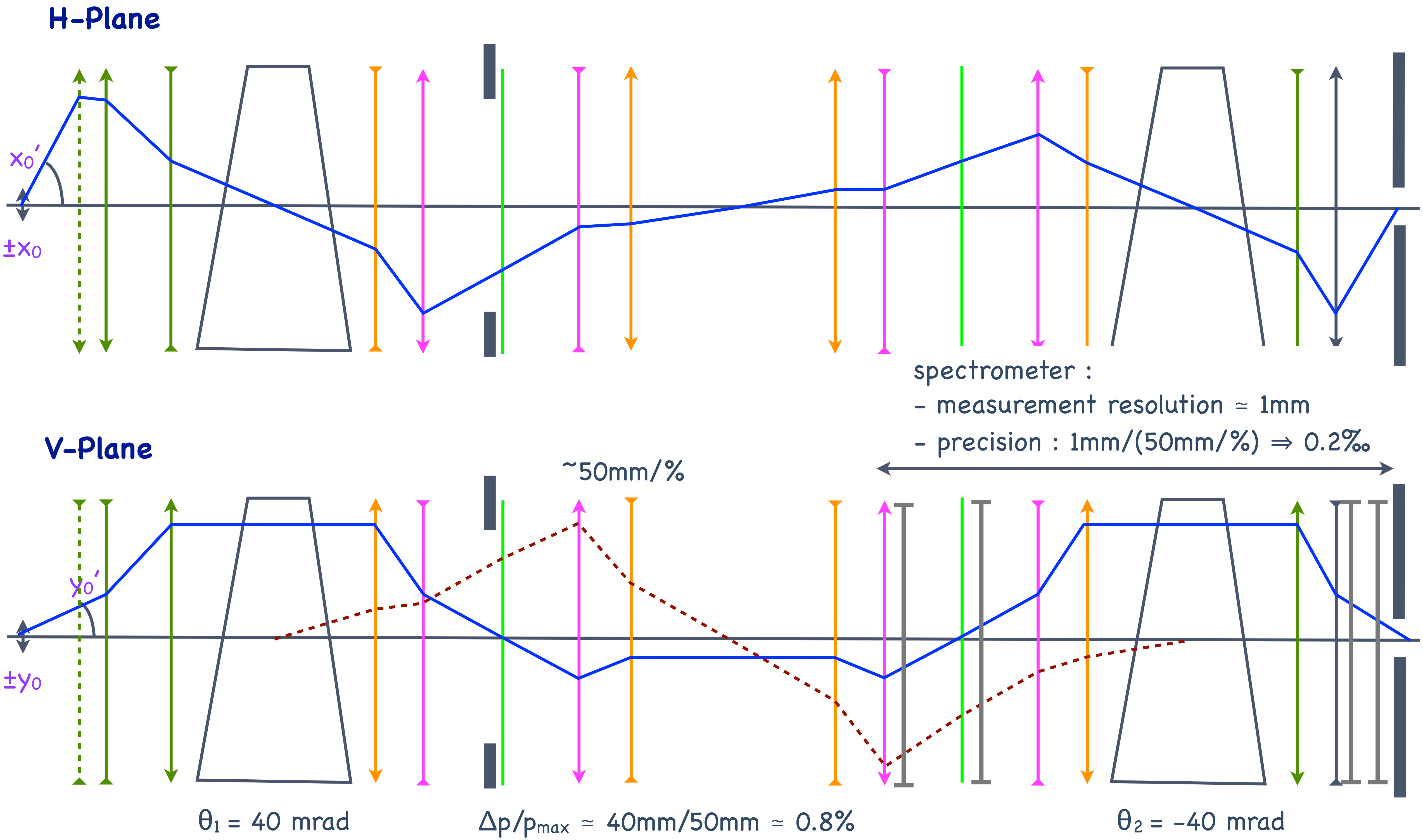
H-Plane



V-Plane

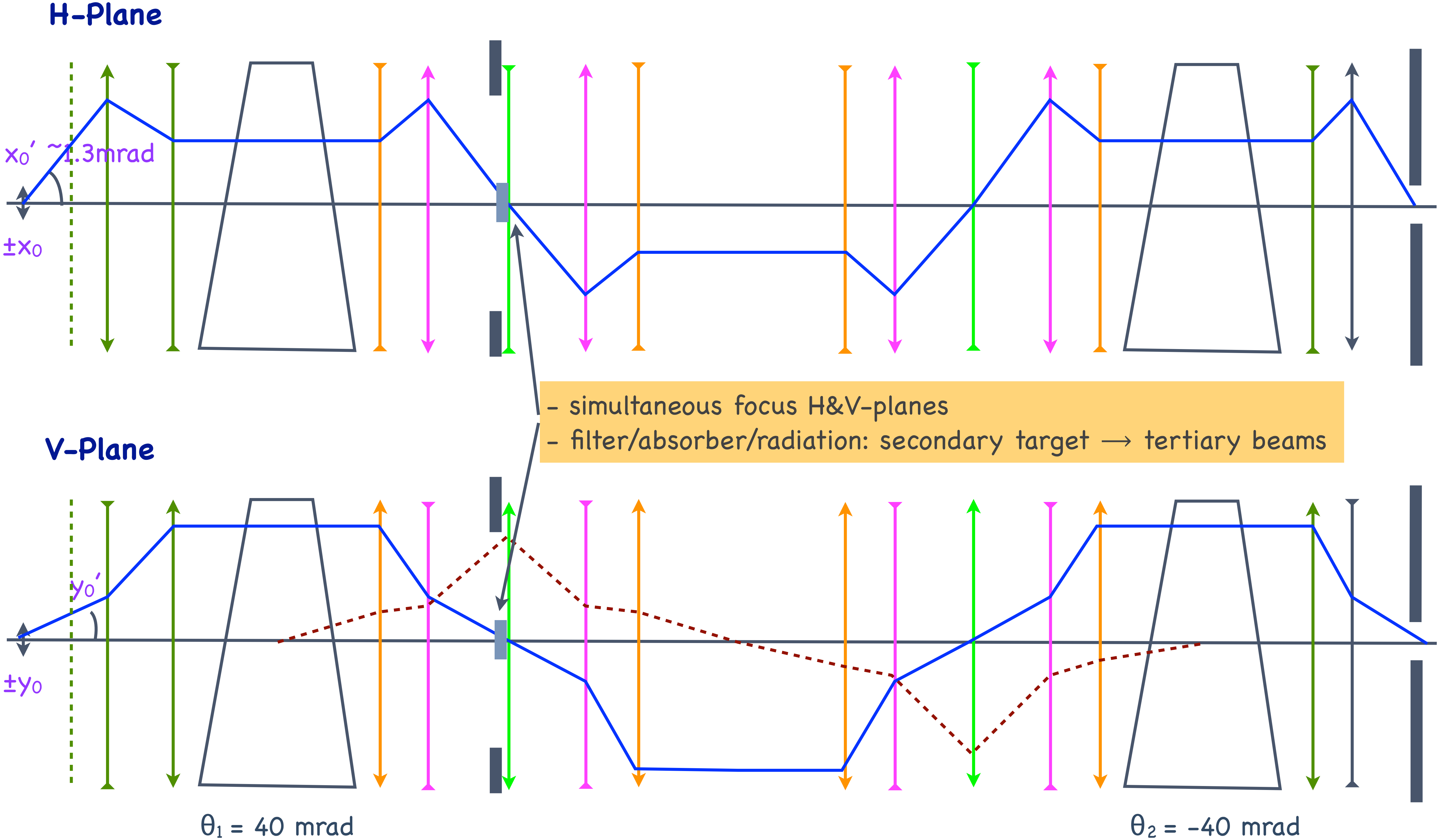


High-resolution optics



SP North Area Secondary Beams - optics

Filter mode optics



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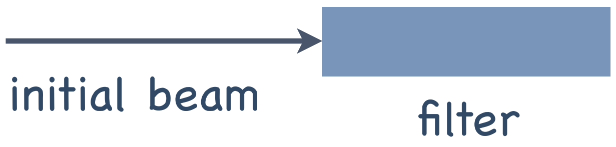
Particle selection - tagging

- **Beam enrichment by differential absorption**



$$a'_i = \frac{a_i\, e^{-L/\lambda_i}}{\sum_i a_i\, e^{-L/\lambda_i}}$$

attenuation of selected particle

total beam attenuation

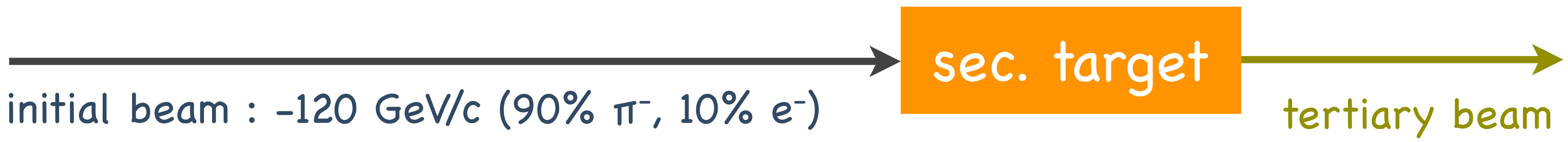
- **Example** :
  - 300 GeV/c positive beam filtered by 3m of $(CH_2)_n$- polyethylene
  - initial flux: ≃ 5 $\times 10^8$ ppb

Particles	% - initial beam	%- filtered beam	flux at experiment
protons	92.5	73.4	7.9×10^6
pions	5.8	19.1	2.1×10^6
kaons	1.7	7.5	8×10^5

- The filter must be placed in a focal point of the beam to minimize the emittance growth due to multiple scattering of the beam

Particle selection - tagging

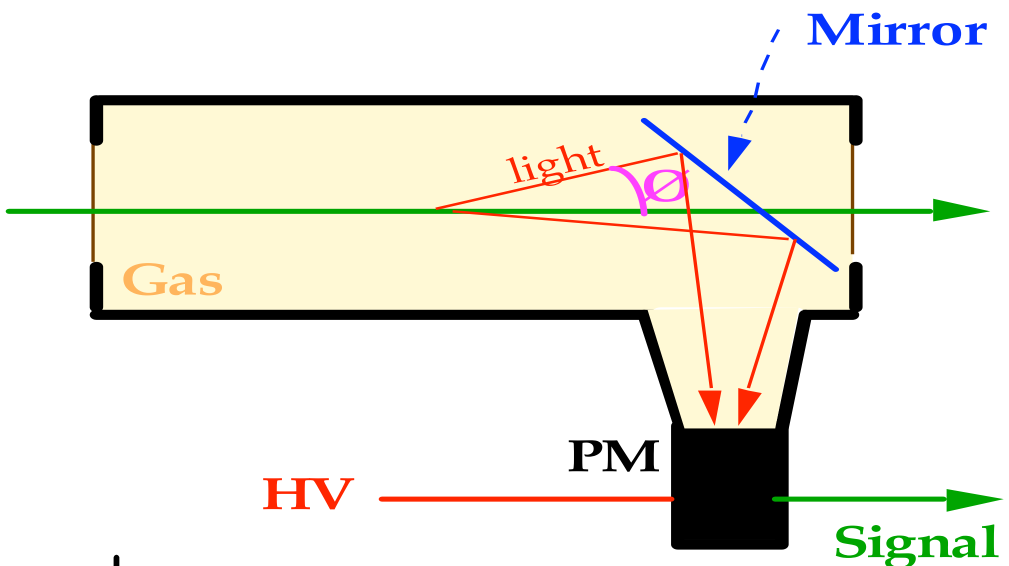
Tertiary beams - via secondary target



- **4mm thick Pb target** — $\simeq 1\ X_0,\ \simeq 0\ \lambda_{int}$ — tertiary beam = pure electron beam
  - almost all pions pass through at -120 GeV/c
  - electrons loose energy due Bremsstrahlung
  - lots of low energy electrons
- **40 cm Cu target** — $\simeq 30\ X_0,\ \simeq 3\ \lambda_{int}$ — tertiary beam = hadron beam
  - electrons are basically absorbed
  - pions interact and loose energy
- **40cm Beryllium target** — $\simeq 1\ X_0,\ \simeq 1\ \lambda_{int}$ — tertiary beam = mixed beam
  - produced both low-energy electrons and pions

Particle tagging with Cherenkov counters

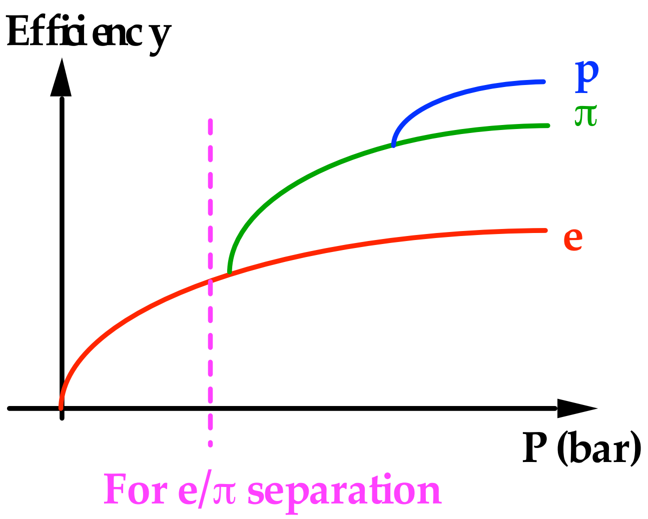
- detect the light emitted in a medium when a particle travels faster than the speed of light in the medium - Cherenkov light



- in a medium: He or N_2 gas
  - particle $v/c = p/\sqrt{p^2 + m^2}$
  - light $v/c = 1/n$
  - the Cherenkov light is emitted in a cone of half angle:

$$\phi^2 = 2\,k\,\mathrm{P} - \frac{m^2}{p^2}$$

  - adjust the pressure (**P**) to allow the light emission for each energy
    - threshold pressure for each particle (**p**)
    - **k** depends on the medium

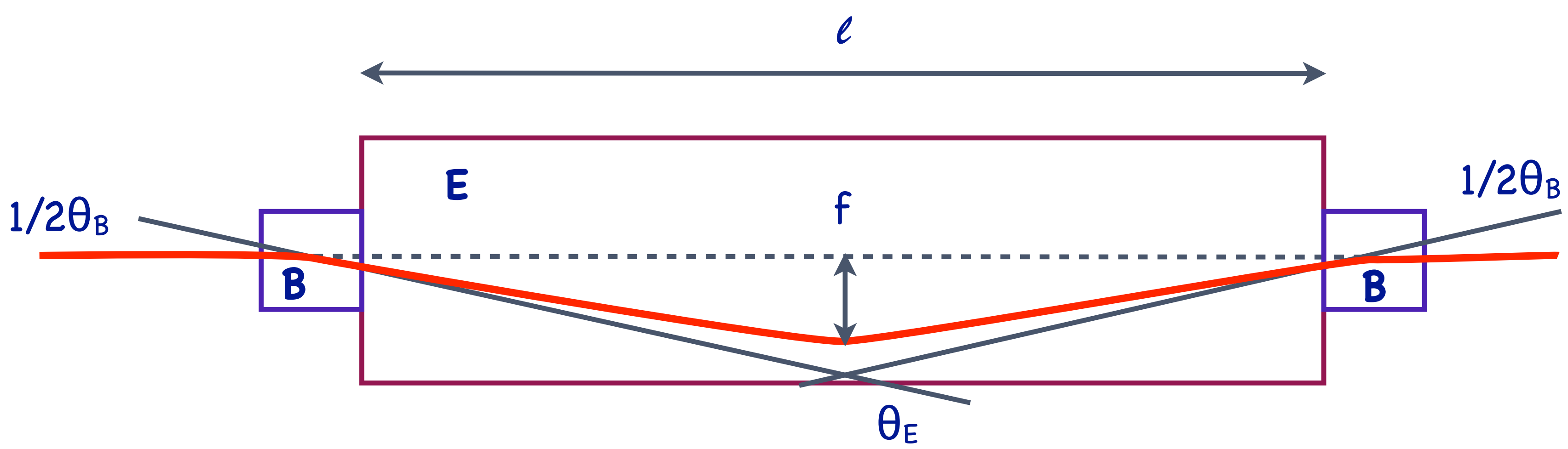


- for high-energies use differential cherenkov counters
  - CEDARs : detect the Cherenkov rings not only the light

Electrostatic separation

- the beam traverses an electric field coupled to a magnetic field at its extremes
- then

$$\frac{d^2x}{ds^2} = 0$$
$$\frac{d^2y}{ds^2} = \frac{e}{p}\left(\frac{E}{v} - B\right)$$



- the separation of two particles with masses m_1 and m_2 becomes:

$$\Delta y = \frac{E\,c^2}{2\,p^3}\left(\frac{l^2}{2} + l\,L\right)\cdot\left(m_1^2 - m_2^2\right)$$

Exercise: can you derive this formula?

  - the wanted particles stay on beam axis, the others are absorbed in collimators

- Issues to consider:
  - acceptance losses due to sagitta - adopt geometry accordignly
  - separation decreases rapidly with momentum - good for K–π separation at low energies
  - chromatic aberration due to spread in the beam momentum

Particle selection - tagging

- **Radio-frequency separation**
  - extension of the electrostatic separator for higher momenta using RF fields

- must ensure 360-deg phase advance between the two RF cavities

$$\Delta\Phi = 2\pi \frac{L\,f}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right), \frac{1}{\beta_1} - \frac{1}{\beta_2} = \frac{(m_1^2 - m_2^2)}{2\,p^2}$$

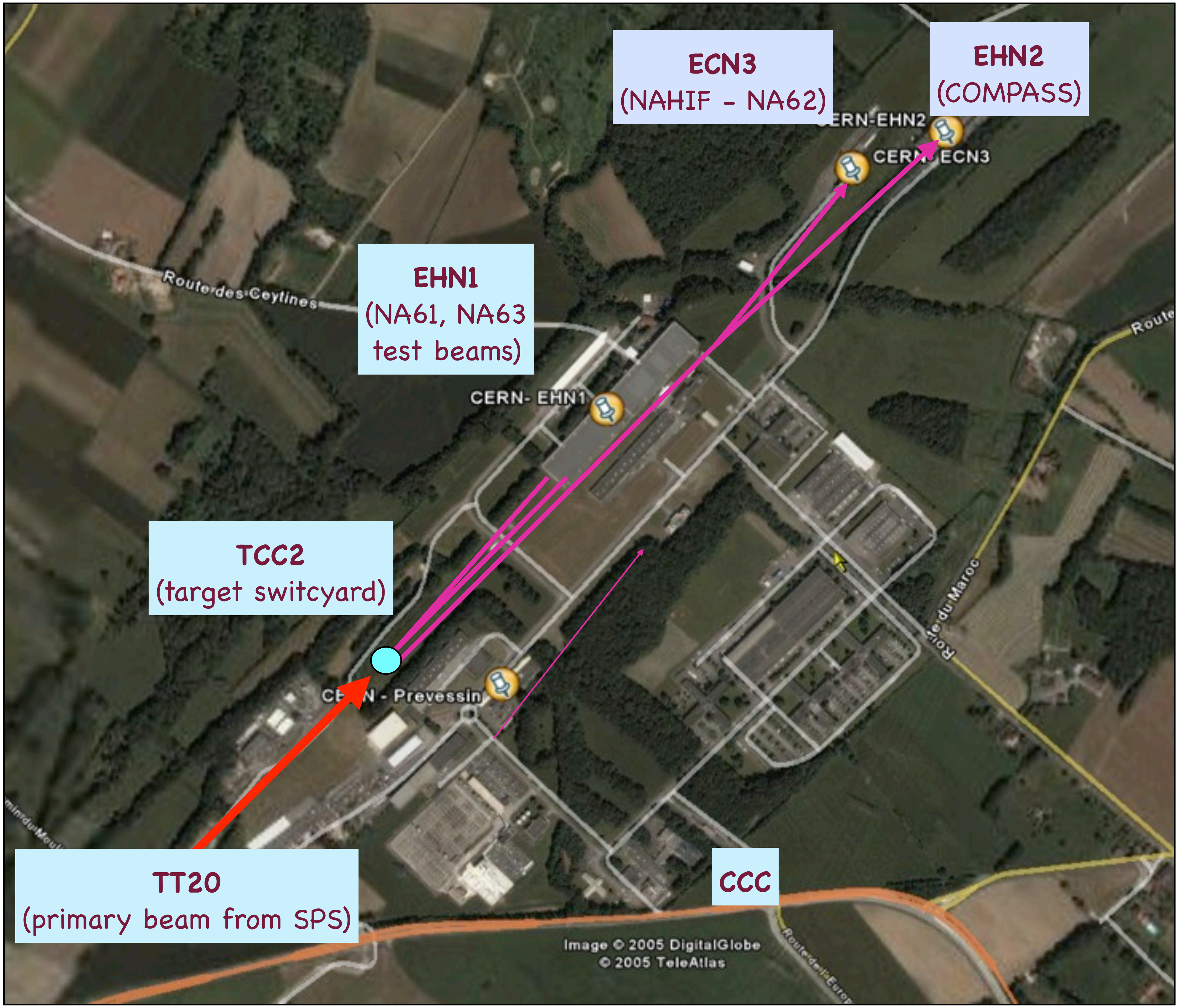
Exercise: can you derive this formula?

- Issues to consider - example K/π separation at 70-100 GeV/c range
  - increase $L \sim p^2$ to keep the phase advance at 360-deg, but decays also ~p
  - separation among particles becomes harder with higher energies
  - effect of momentum spread and bunch length
    - coherence length of the cavity
      - $\lambda = c/f = 5$cm@6GHz; stability $\Delta\Phi = \pi/10 \longrightarrow L_{coh} = \lambda(\pi/10)/2\pi$ = **3mm**
  - beam divergence in the bending and transverse plane - acceptance loss

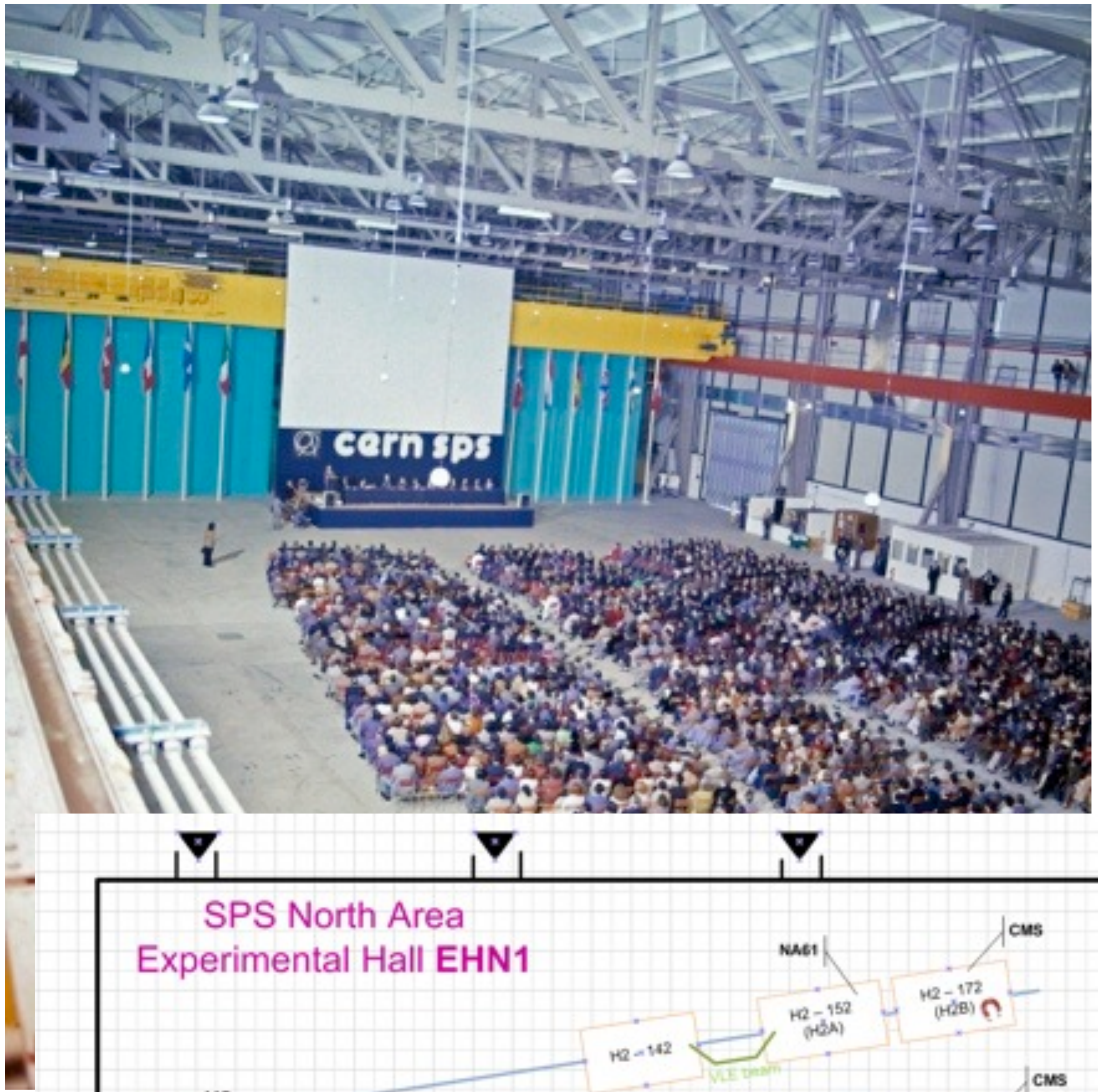
Particle Beams - Design basics

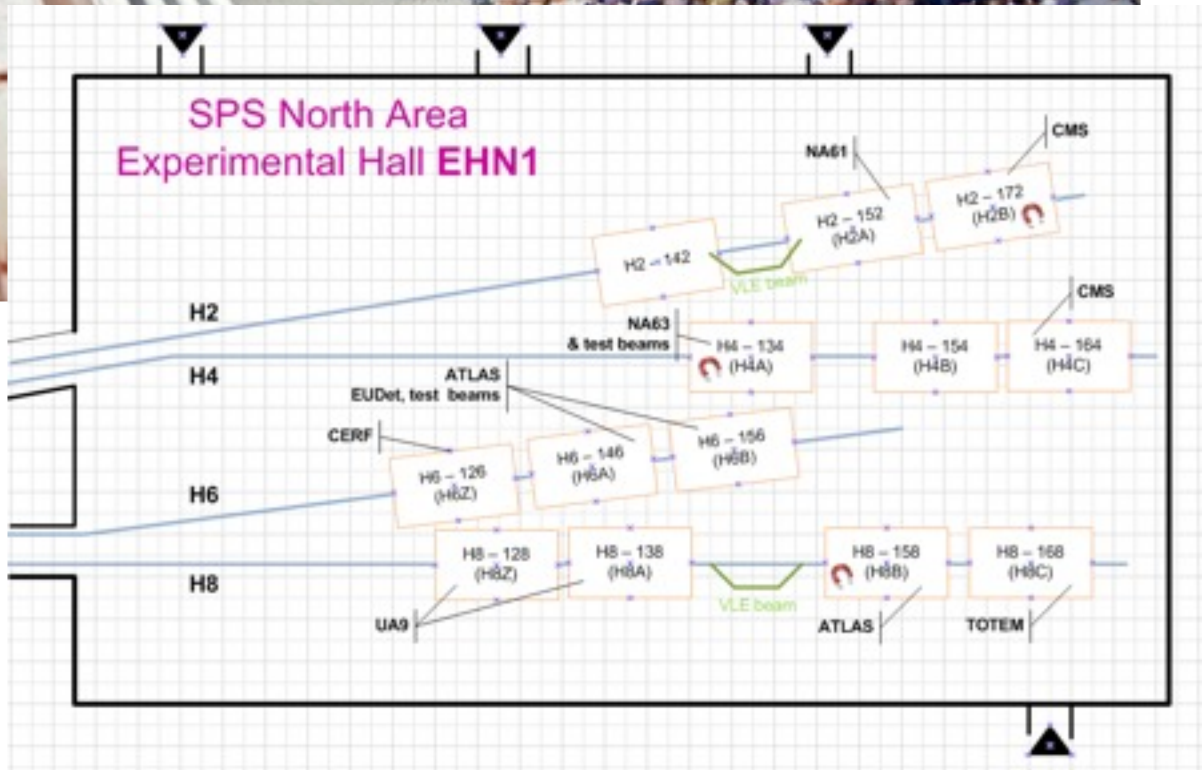
- **Production**
  - primary beam layout and switchyard
  - primary target : material, properties, dimensions
  - capture/front-end : collect the secondary particles, beam acceptance
- **Beam preparation and transport**
  - momentum selection, particle decay
- **Particle selection**
  - selection or particle tagging/identification
  - background (unwanted particles) rejection or optimization - collimation
- **Final focusing to experiments**
  - focal point, spot size, beam divergence, no dispersion

The SPS North Area - General Layout



The SPS North Area - beam lines & Exp. Halls





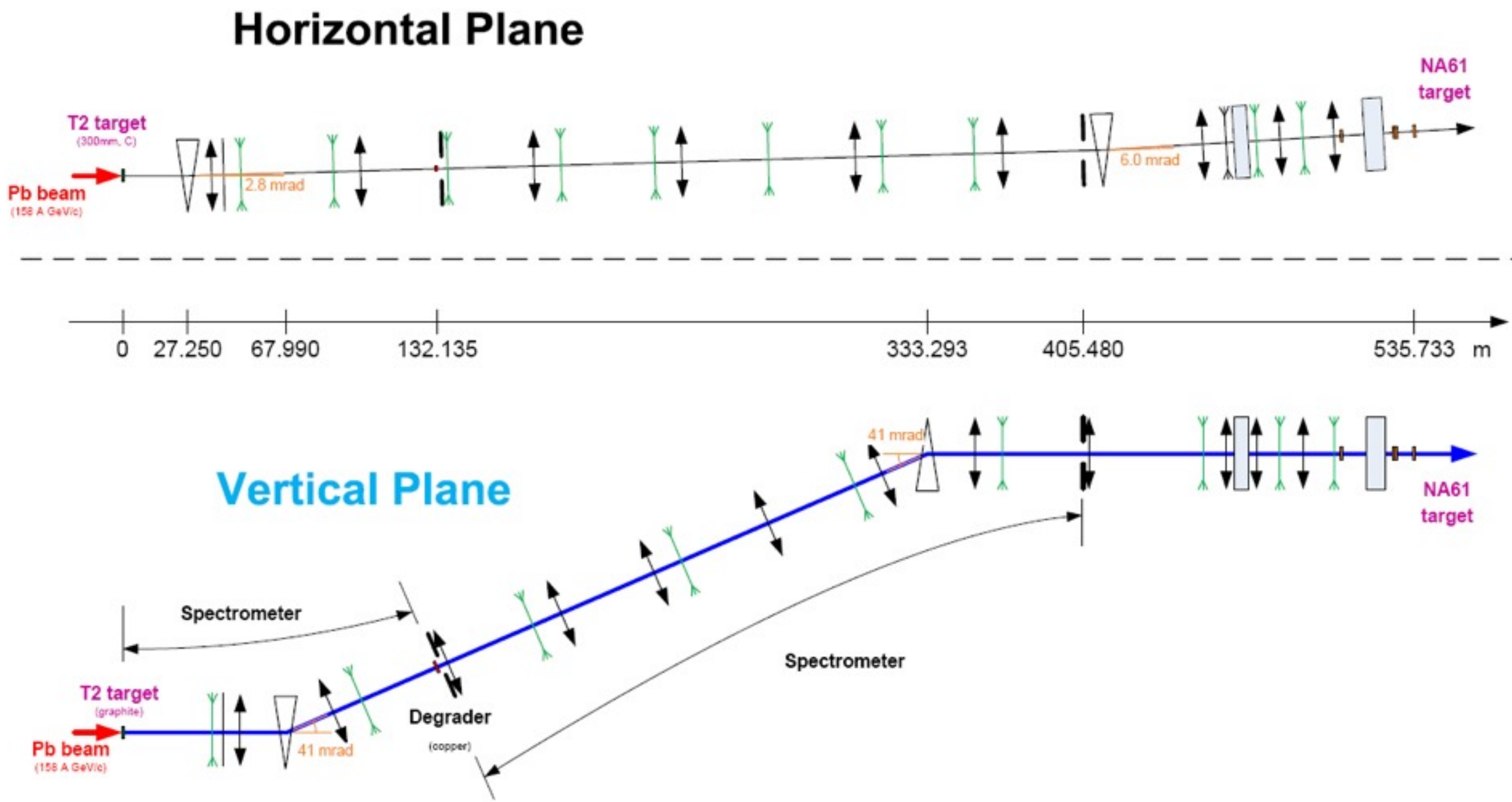
The SPS North Area - Civil engineering & shielding

The SPS North Area Secondary - EHN1 beams

Target	Beam	Characteristics
T2	H2	High-energy, high-resolution secondary beam. Alternatively can be used to transport: attenuated primary beam of protons, electrons from γ-conversion, polarized protons for Λ^0 decay, enriched low-intensity beam of anti-protons, or K^+ <u>Main parameters</u>: P_{max}= 400 (450) GeV/c, Acc.=1.5 μSr, $\Delta p/p_{max}$= ±2.0 %
	H4	High-energy, high-resolution secondary beam. Alternatively can be used to transport: primary protons, electrons from γ-conversion, polarized protons for Λ^0 decay, enriched low-intensity beam of anti-protons, or K^+ <u>Main parameters</u>: P_{max}= 330 (450) GeV/c, Acc.=1.5 μSr, $\Delta p/p_{max}$= ±1.4 %
T4	H6	High-energy secondary beam. <u>Main parameters</u>: P_{max}= 203 GeV/c, Acc.= 2.0 μSr, $\Delta p/p_{max}$= ±1.5 %
	H8	High-energy, high-resolution secondary beam. Alternatively can be used to transport an attenuated primary proton beam <u>Main parameters</u>: P_{max}= 400(450) GeV/c, Acc.= 2.5 μSr, $\Delta p/p_{max}$= ±1.5 %

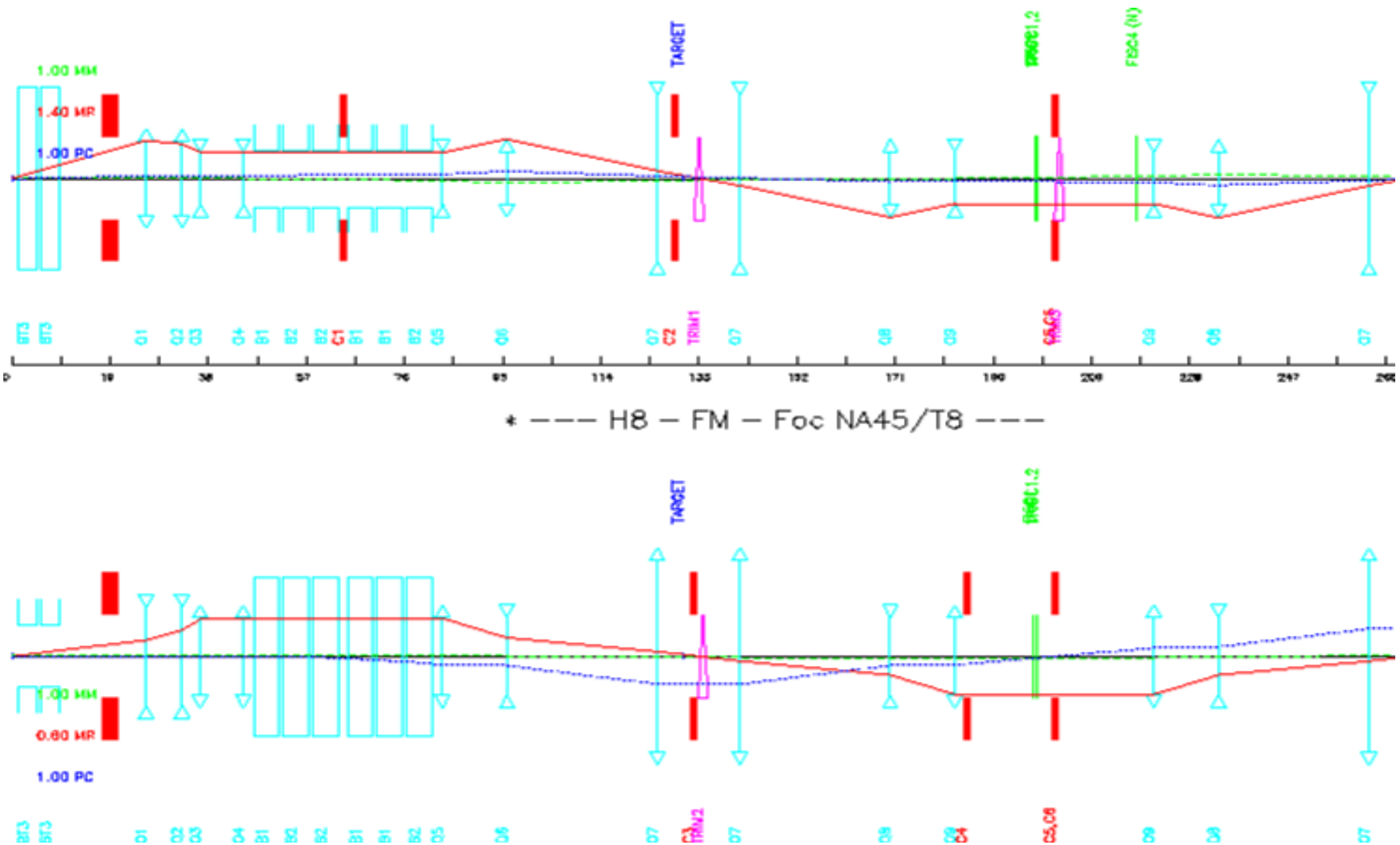
SP North Area Secondary Beams

H2 Beam Line – SPS North Area



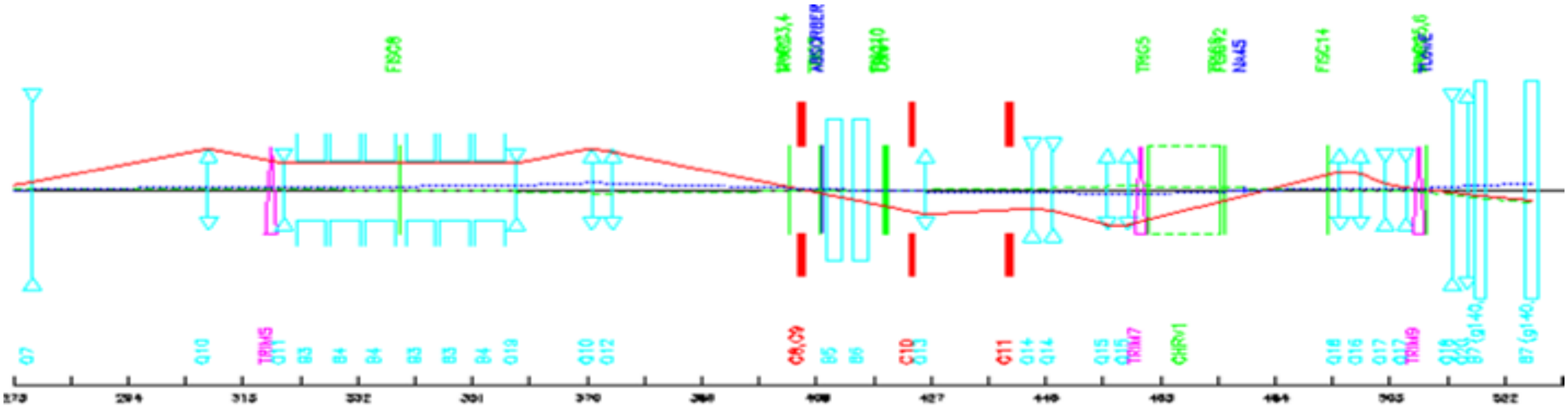
The SPS North Area Secondary - EHN1 beams

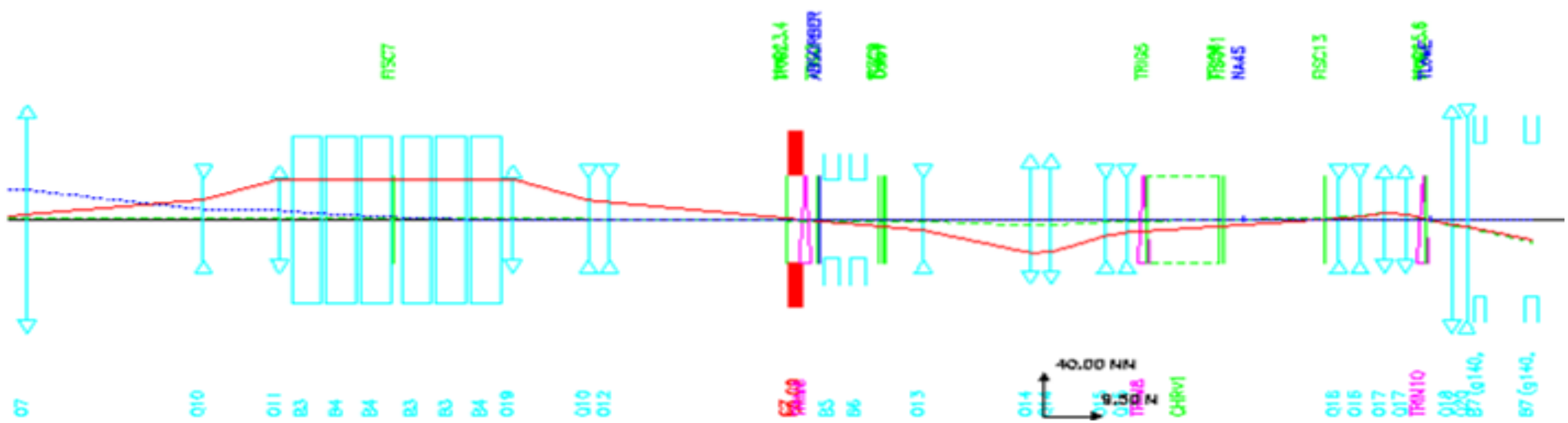
H8 beam line



The SPS North Area Secondary - EHN1 beams

H8 beam line (II)





The SPS North Area Secondary - EHN2 beams

M2 beam requirements for COMPASS Experiment

- The beam serves sometimes as a muon beam, sometimes as a hadron beam.

Beam conditions - muon beam:

- Spot size at the experiment : smaller than **8mm rms** in each plane, with a RMS divergence not exceeding **1mrad**,
- The muon beam intensity at **160 GeV/c** should be up to **2×10^8 muons** per SPS cycle.
- Variable horizontal angle of incidence to the COMPASS target, to compensate for the 1.05T spectrometer field of the experiment

Beam conditions - hadron beam :

- transport secondary hadron beams up to 280 GeV/c,
- particle identification with 2 CEDAR counters, therefore a 15m long parallel section is required,
- spot size: ~3 mm rms and a small divergence
- intensity ~10^8 particles per SPS cycle.

Muons from pion decay

- Pion decay in the π center of mass :

$$p^* = \frac{m_\pi^2 - m_\mu^2}{2\,m_\pi} = 30\,MeV/c$$

$$E^* = \frac{m_\pi^2 + m_\mu^2}{2\,m_\pi} = 110\,MeV/c$$

- boost in the laboratory frame :

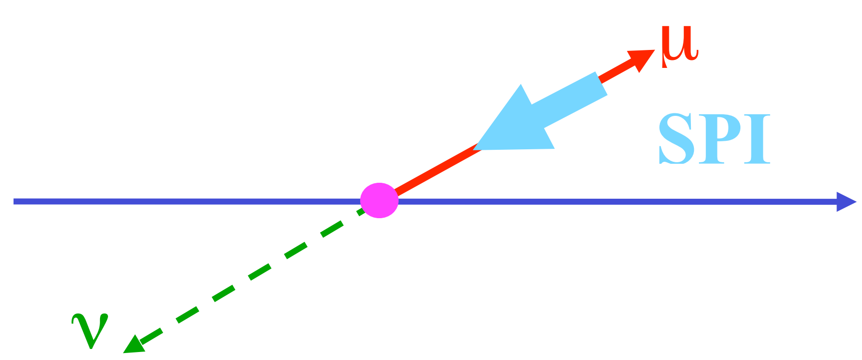
$$E_\mu = \gamma\,\pi\,(E^* + \beta\,\pi\,p^*\,cos\theta^*),\ \beta\,\pi \simeq 1$$

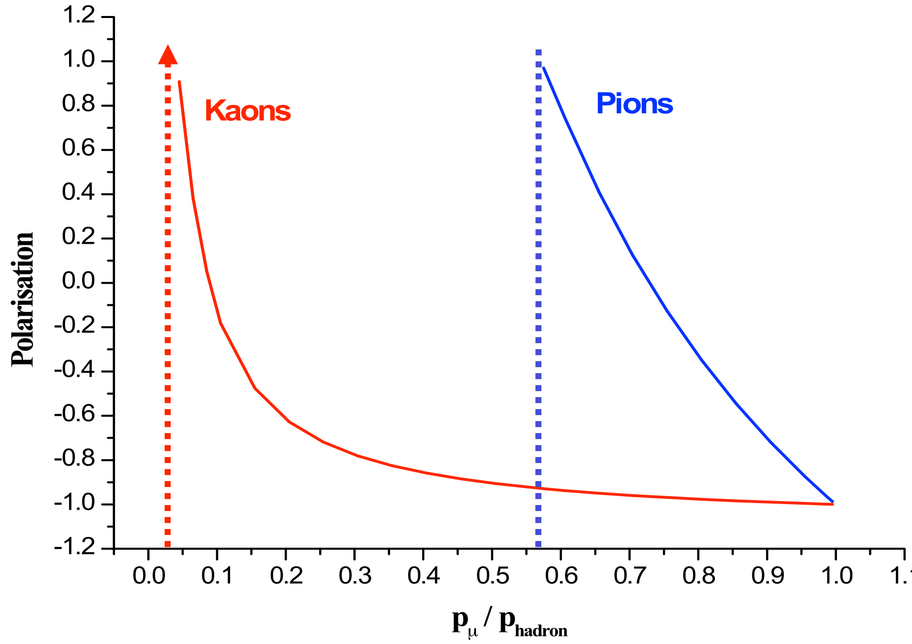
- Limiting cases:

$$cos\theta = +1 \rightarrow E_{max} = 1.0\,E_\pi$$
$$cos\theta = -1 \rightarrow E_{min} = 0.57\,E_\pi$$

$$0.57 < E_\mu / E_\pi < 1$$

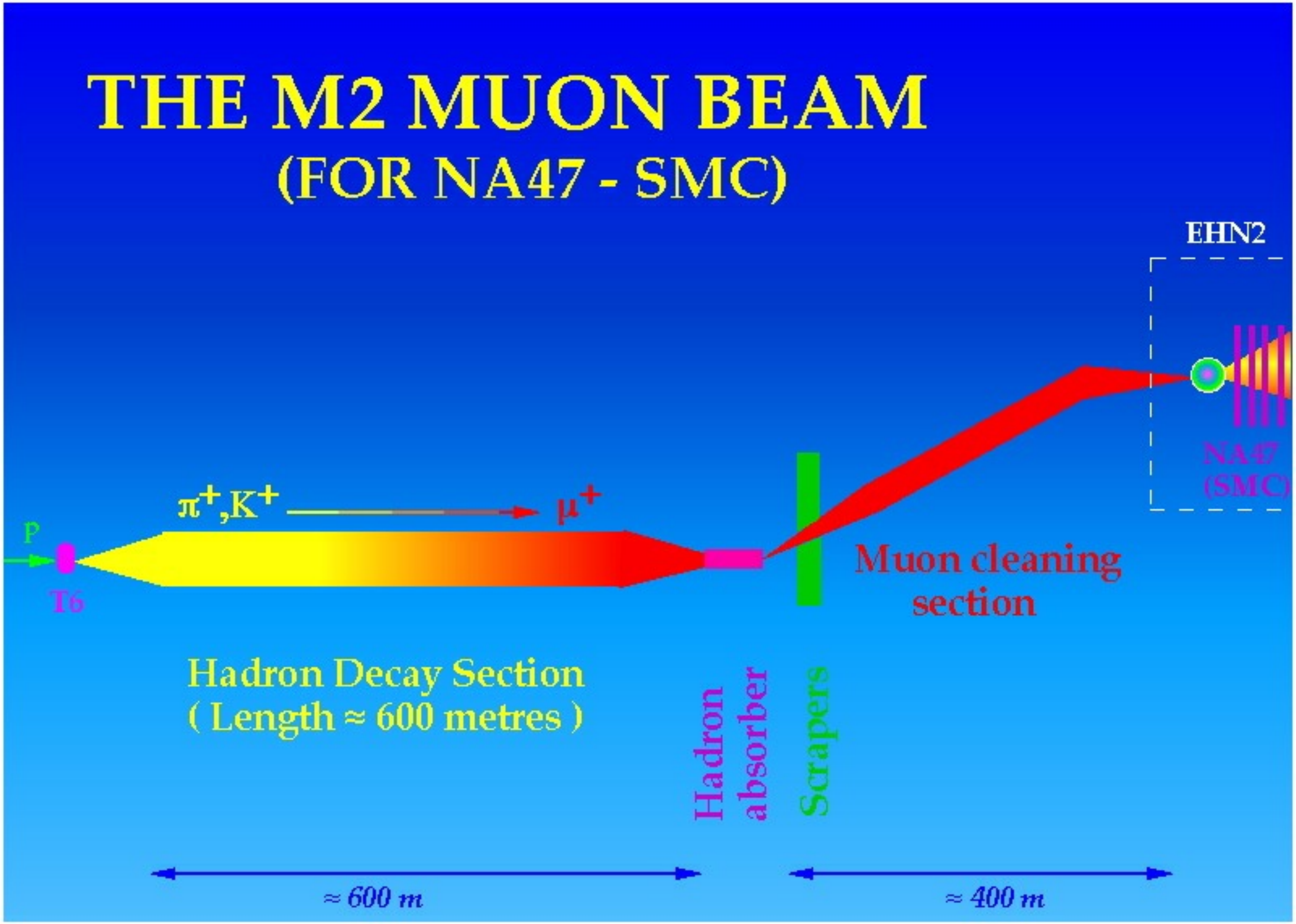
- Muons from pion decay are naturally polarized through parity violation





- **M2 COMPASS beam :**
  - p_μ~0.92 p_π, ~80% polarized

The SPS North Area Secondary - EHN2 beams



The SPS North Area Secondary - EHN2 beams

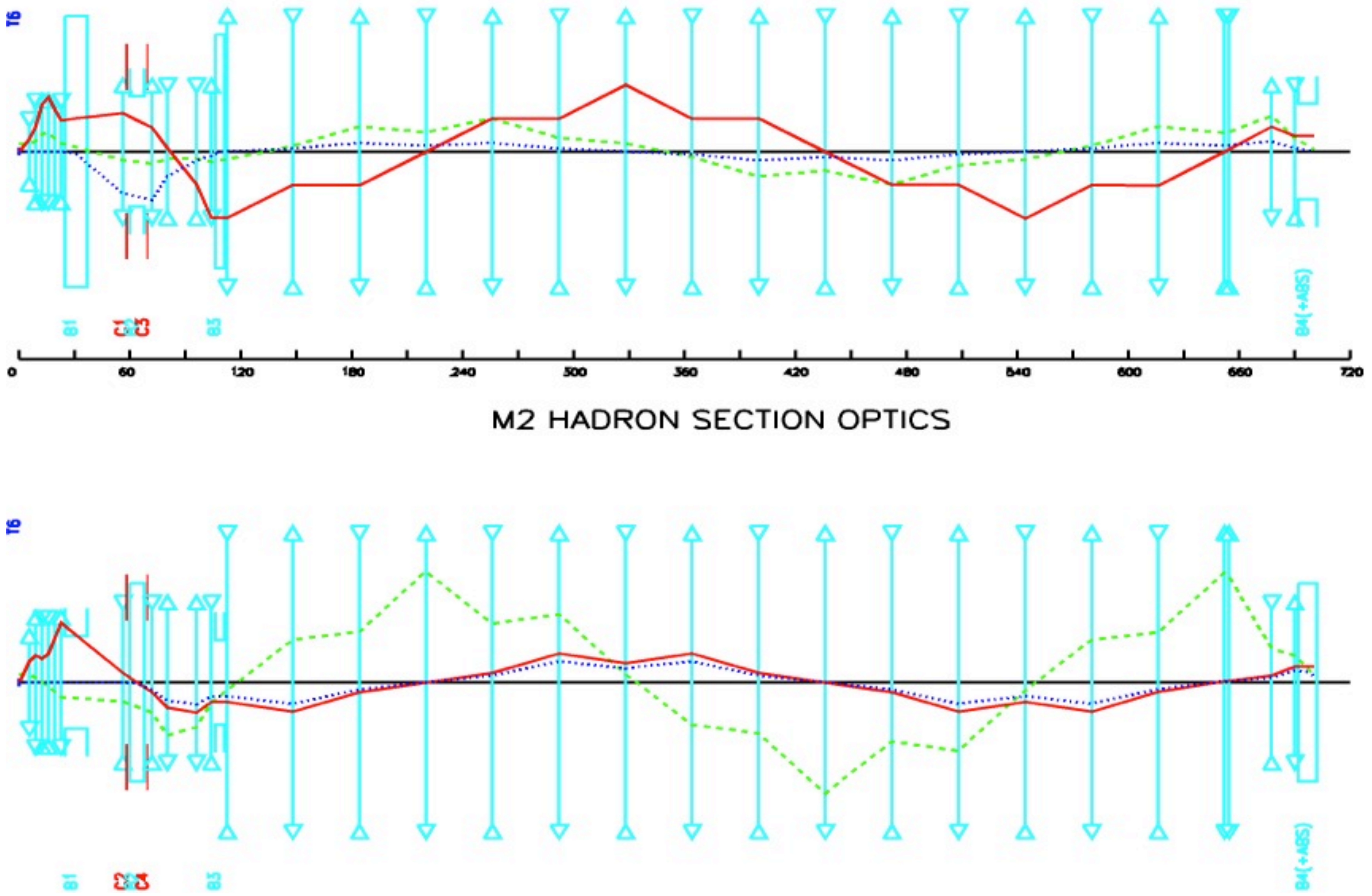
M2 beam optics challenges

- Transport of pions and muons together in the decay volume
  - pions are matched to a long decay channel : 700m long, >5-10% of τ_π
  - the pions have a large momentum spread ±10%
  - pions decay along the length to lower momentum muons that must be transported as well

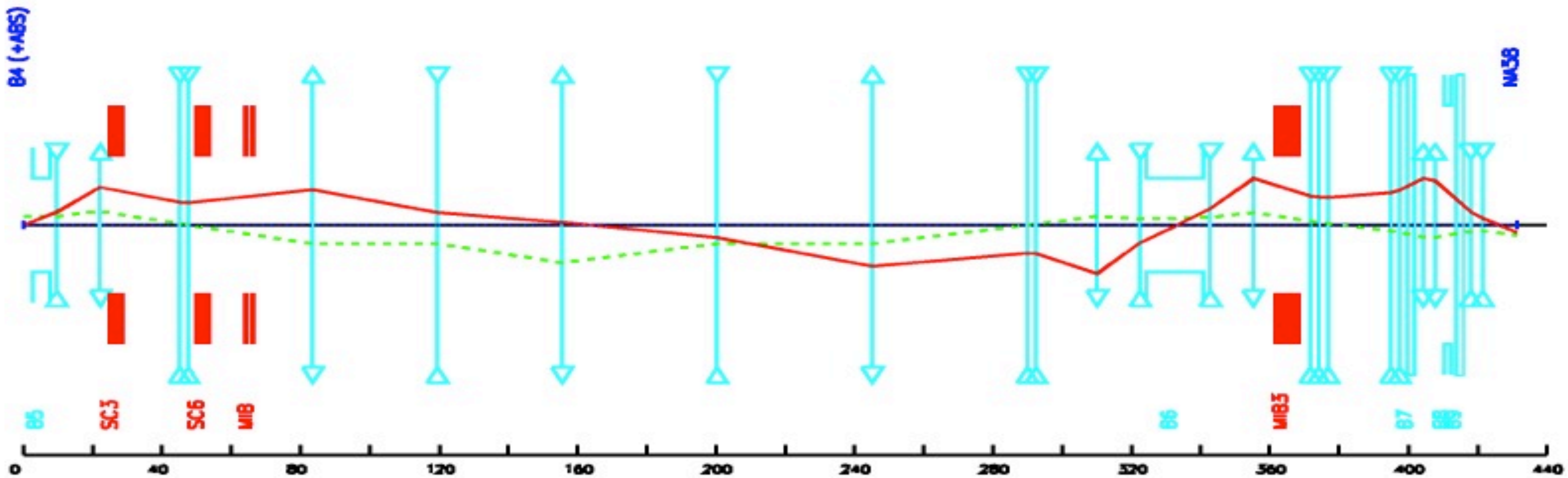
- Transport of the muon beam
  - do the muon selection after the hadron stopper by magnetic collimation
  - unwanted muons must be far from the beam axis, and "ranged-out" in the earth
    - average energy loss ~0.5 GeV/m ; for 200 GeV muons --> 400 meters !
  - the origin of the muons is **not a point source** !

- Solution : use FODO channels
- Use beam simulation tool able to track muons outside the beam aperture - **HALO program**

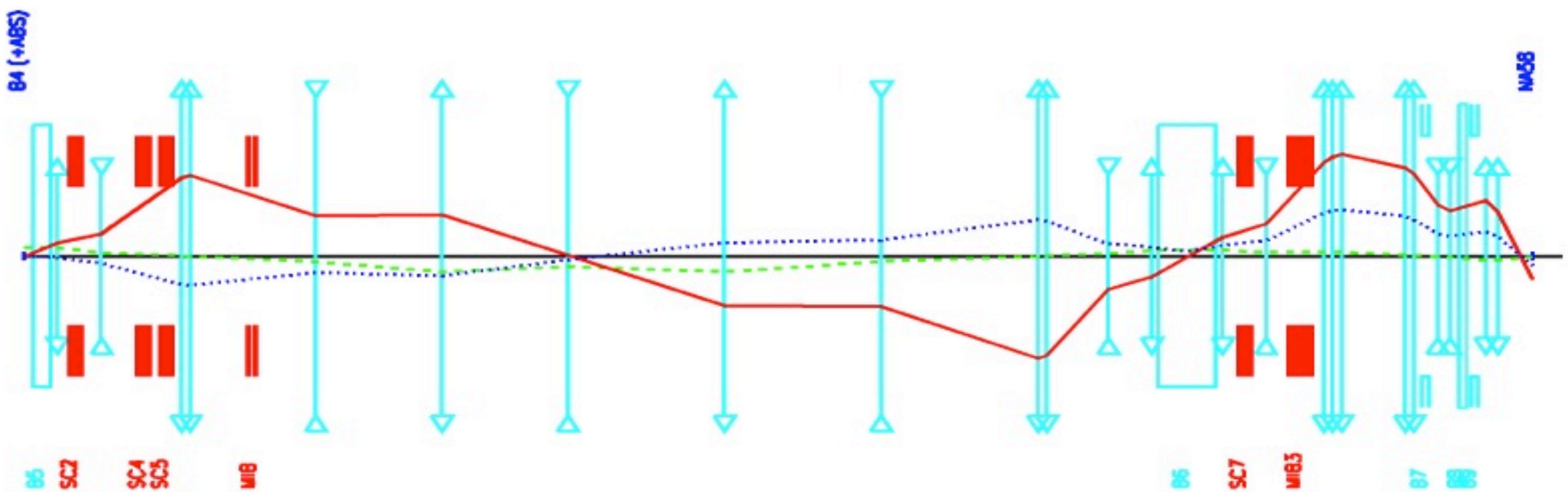
The SPS North Area Secondary - EHN2 beams **M2**



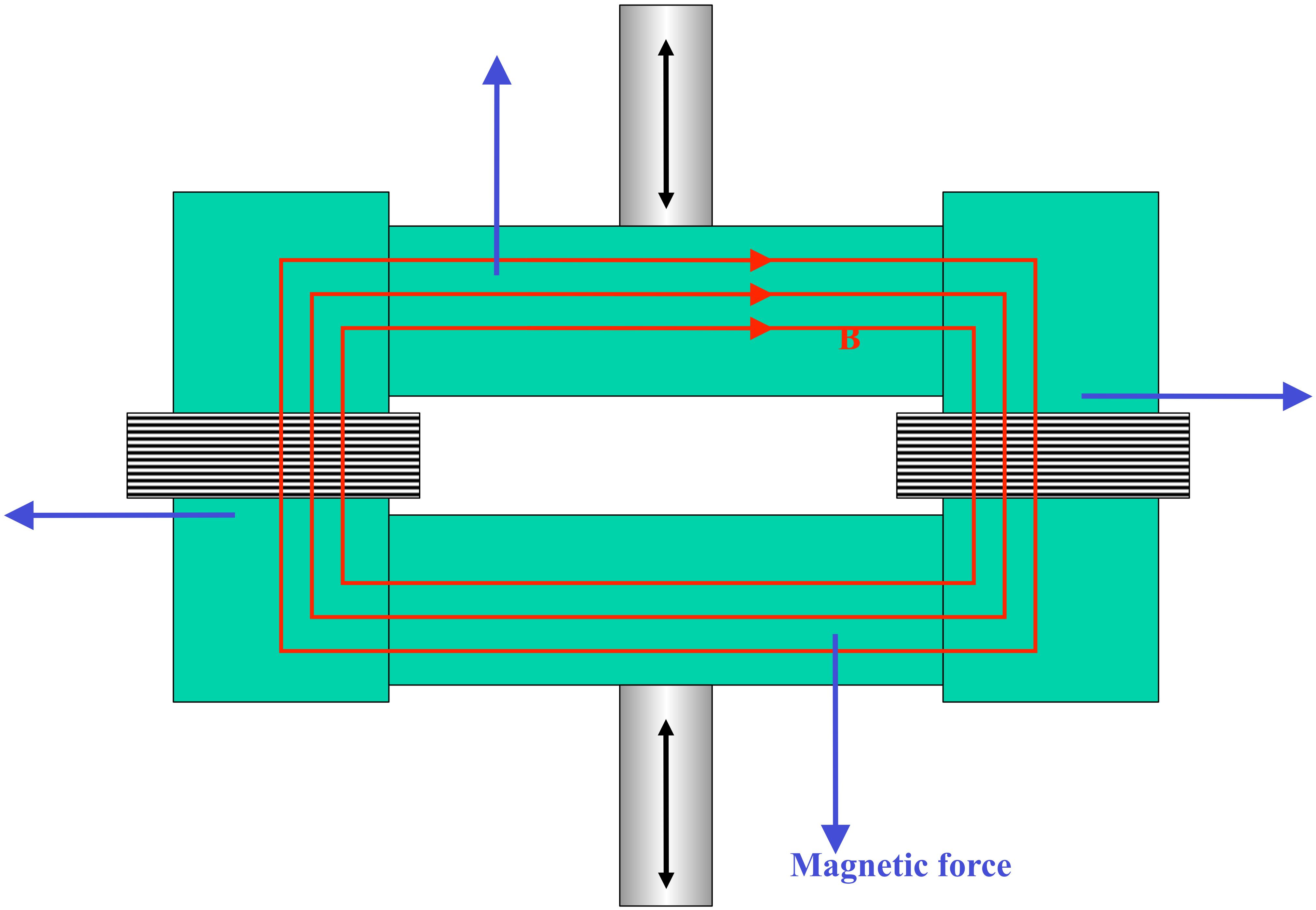
The SPS North Area Secondary - EHN2 beams **M2**



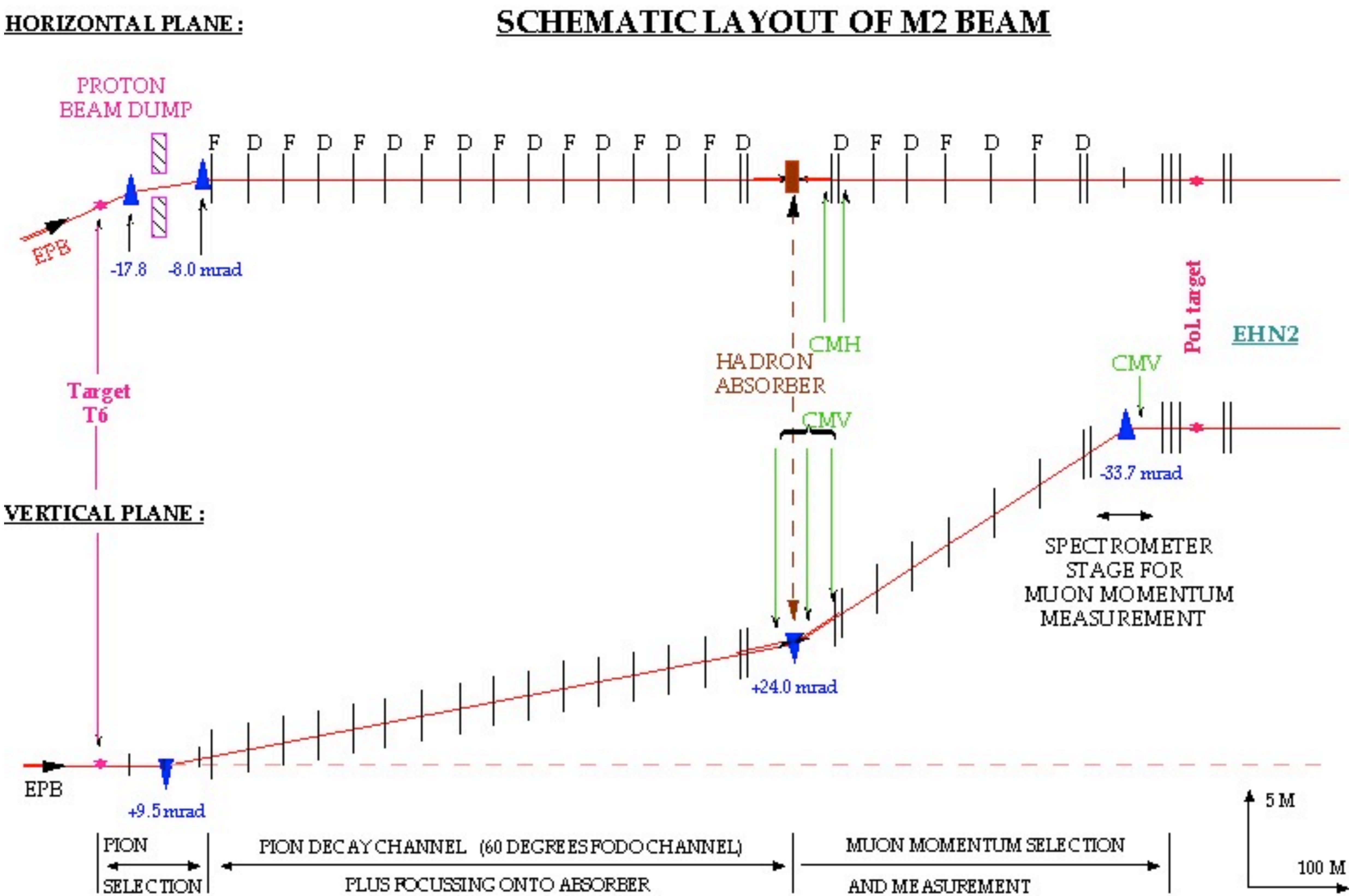
M2 MUON OPTICS FOR NA58



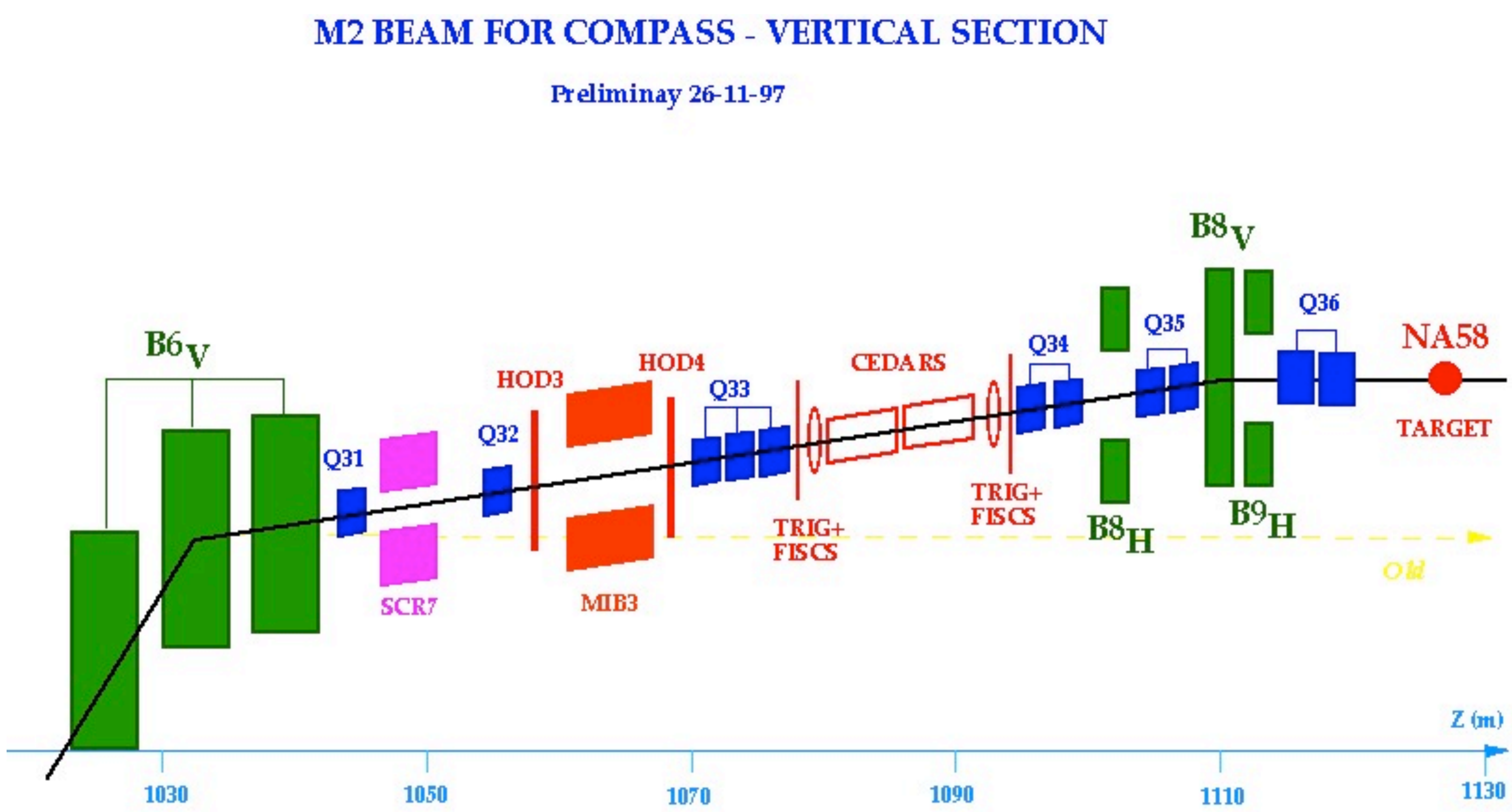
SCRAPERS - Magnetic collimators



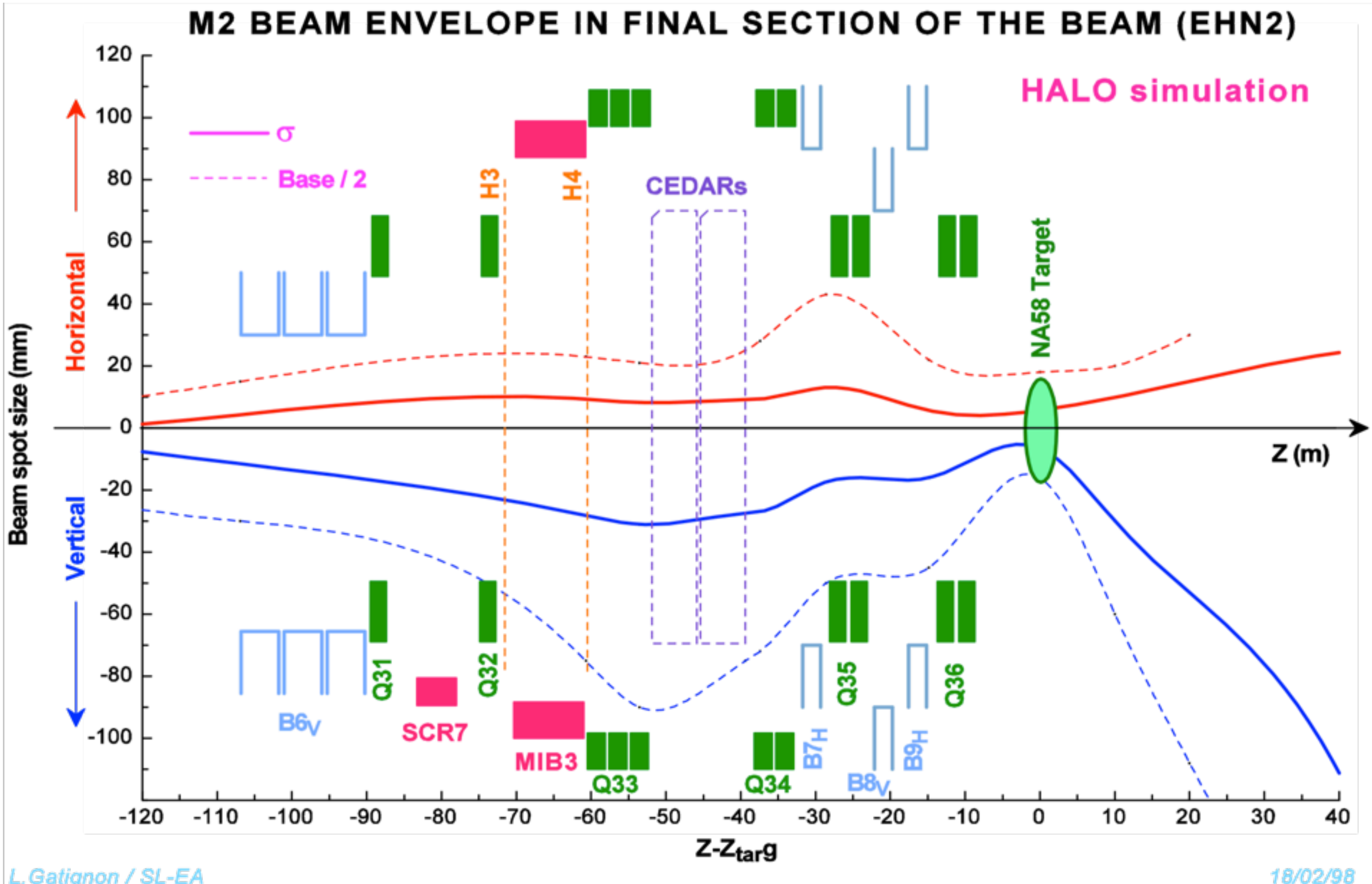
The SPS North Area Secondary - EHN2 beams **M2**



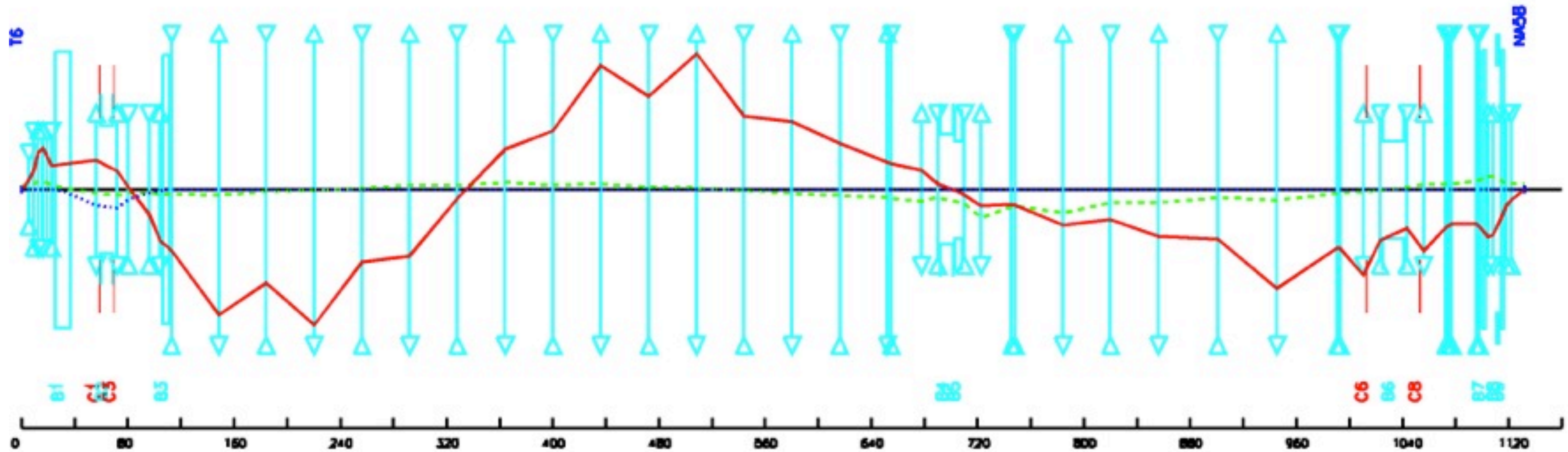
The SPS North Area Secondary - EHN2 beams **M2**



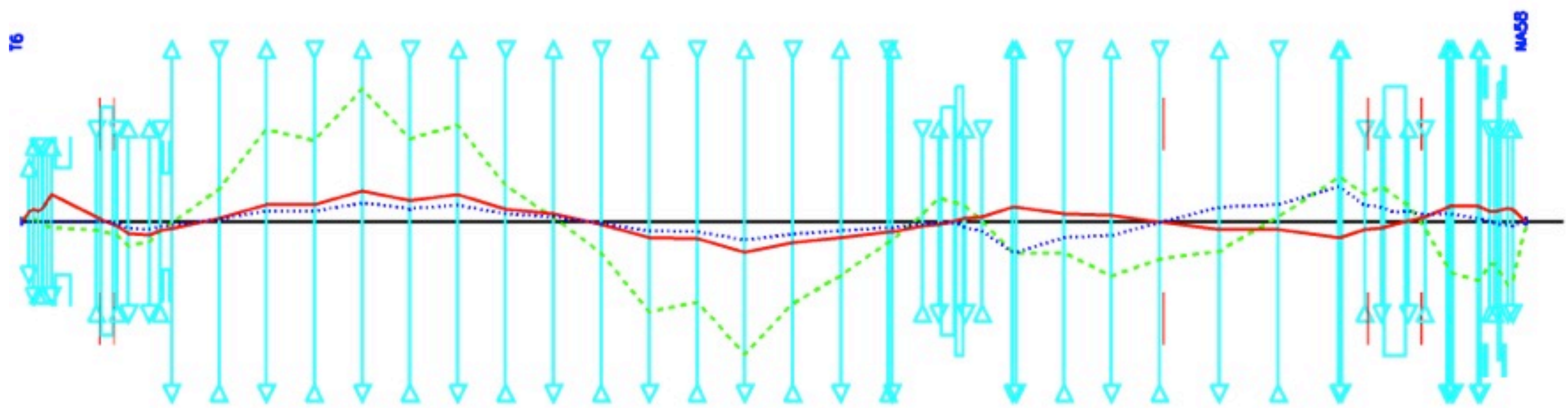
The SPS North Area Secondary - EHN2 beams **M2**



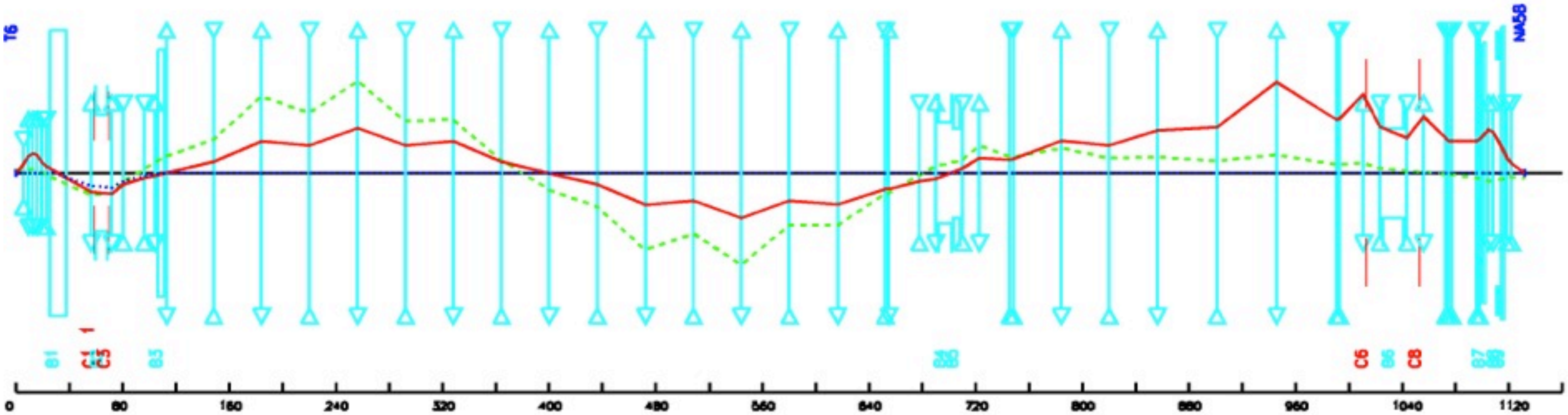
Hadron beam optics (I)



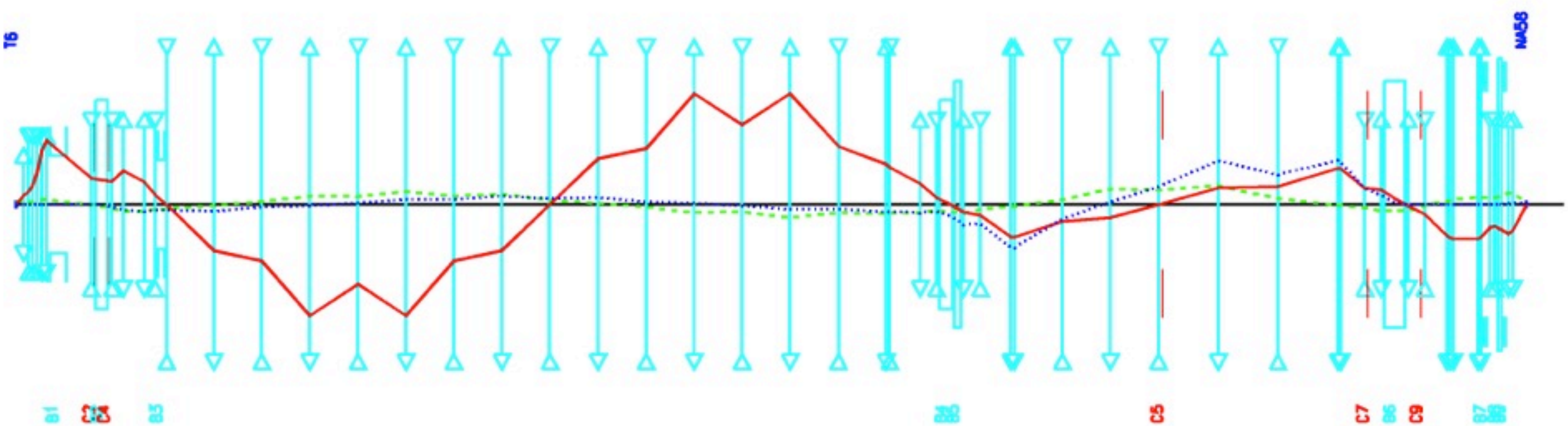
COMPASS HADRON OPTICS COMPATIBLE WITH P6



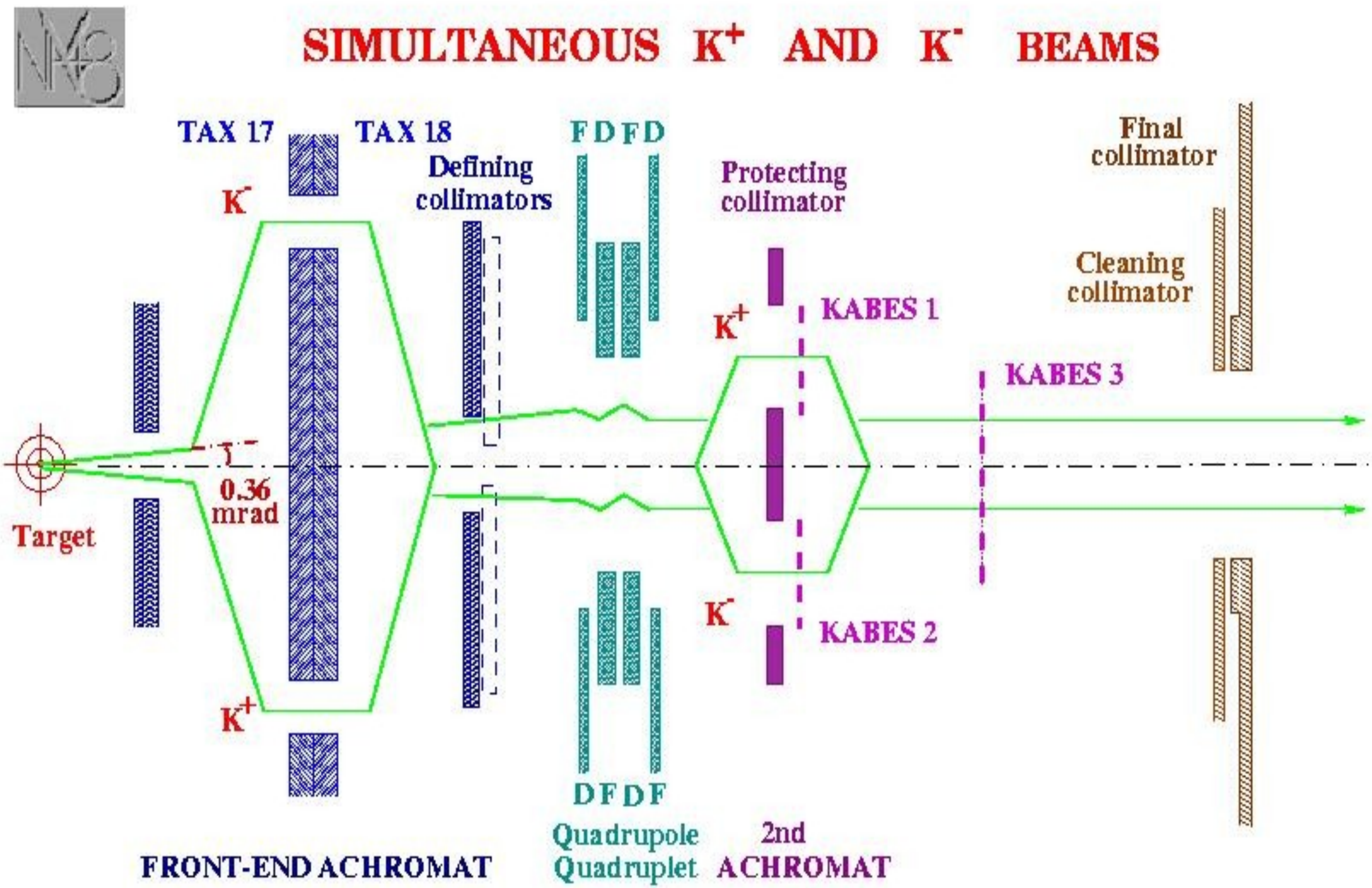
Hadron beam optics (I)



COMPASS HADRON OPTICS

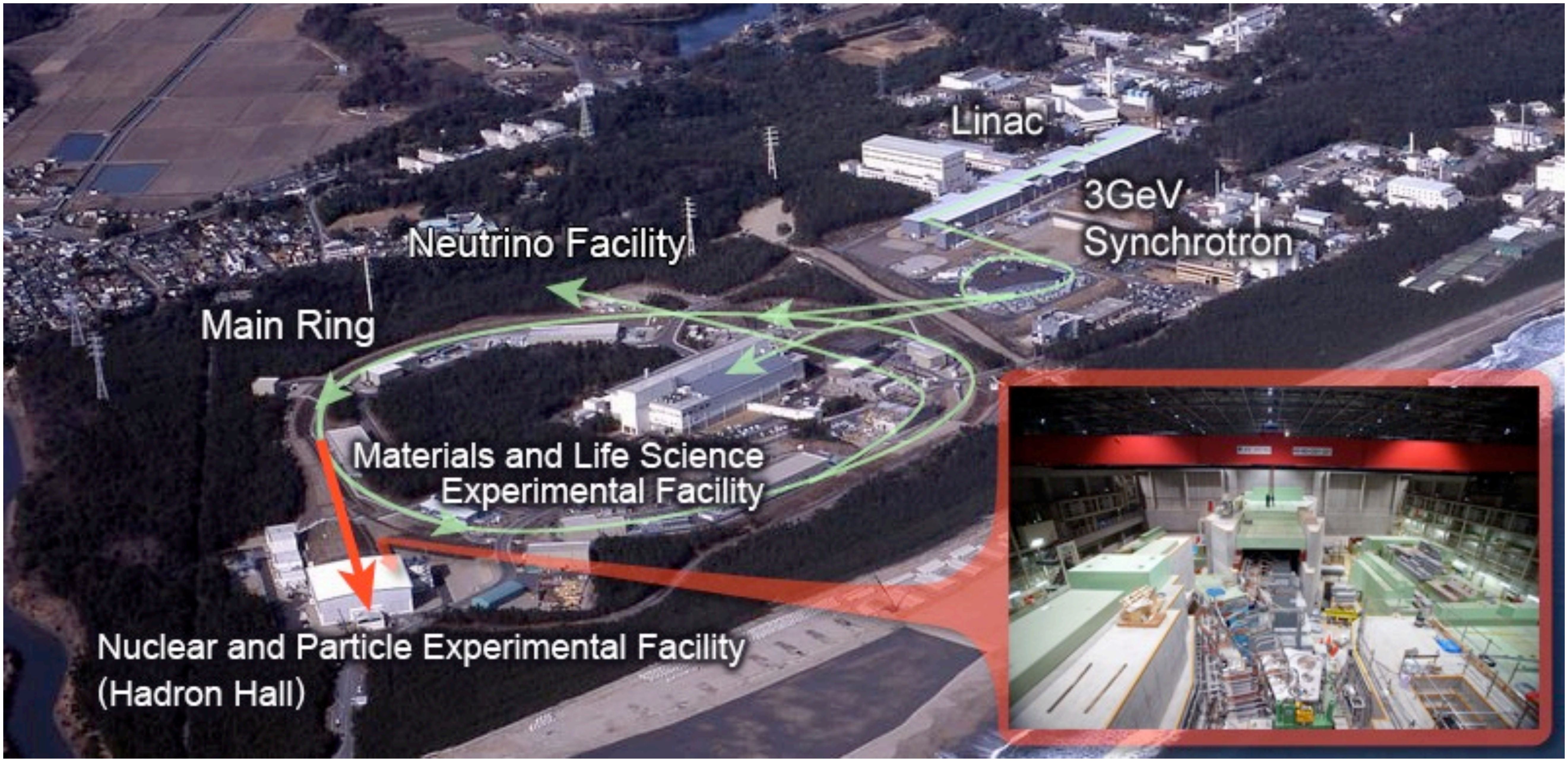


The SPS North Area Secondary - ECN3 beams **K12**

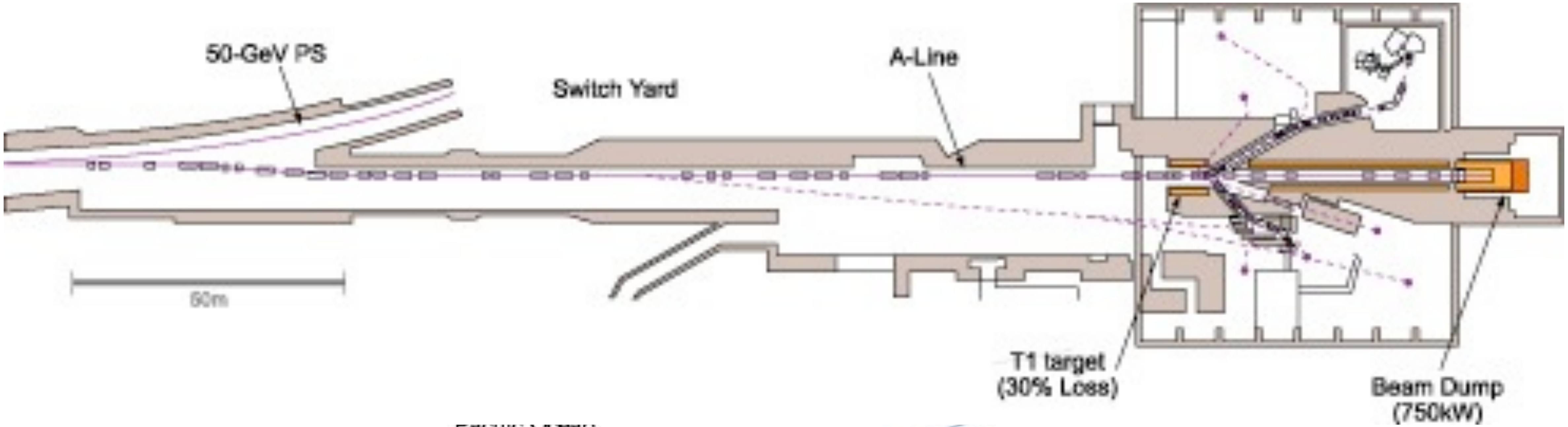


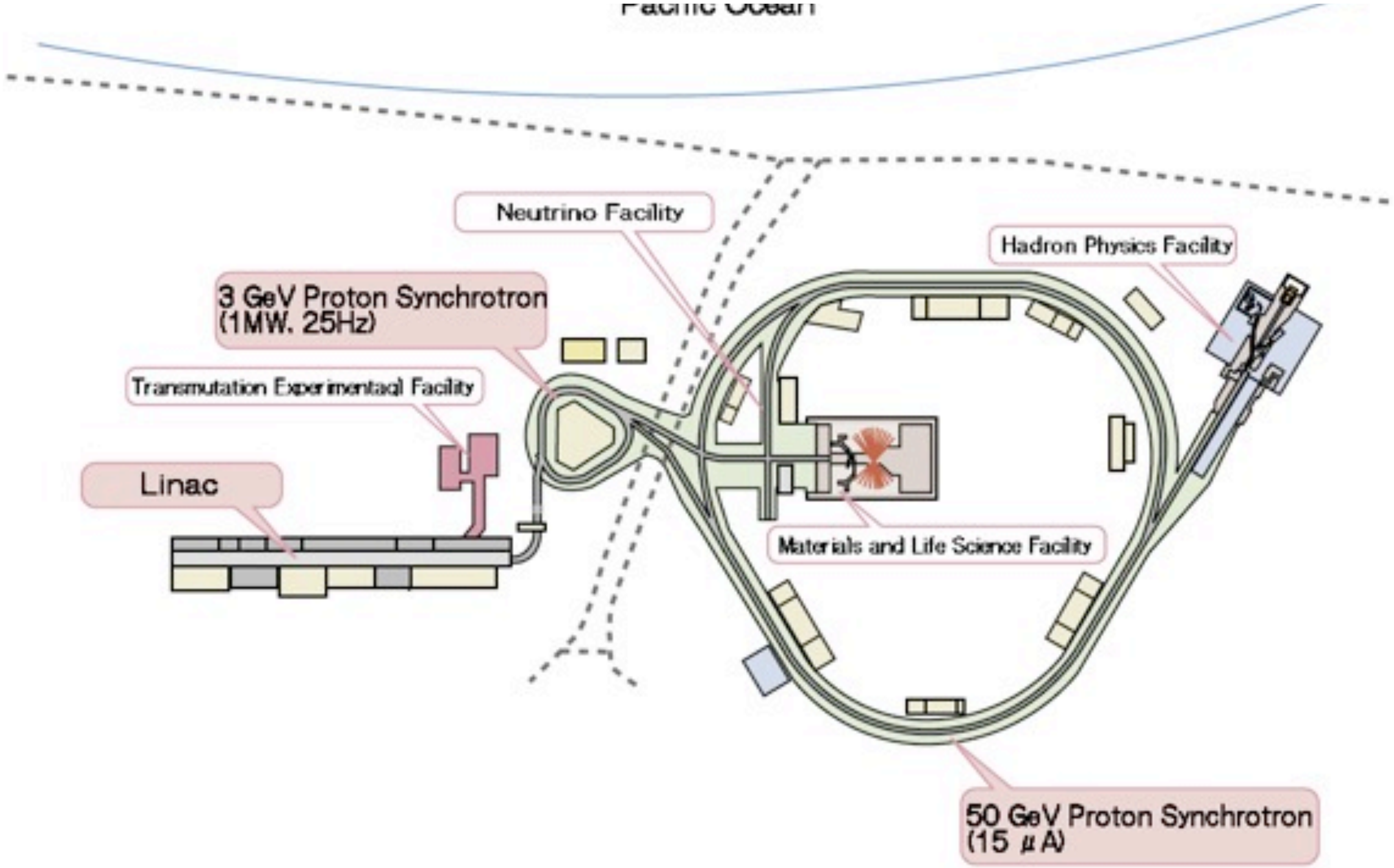
Particle beams outside CERN

- **Hadron beams at J-PARC**

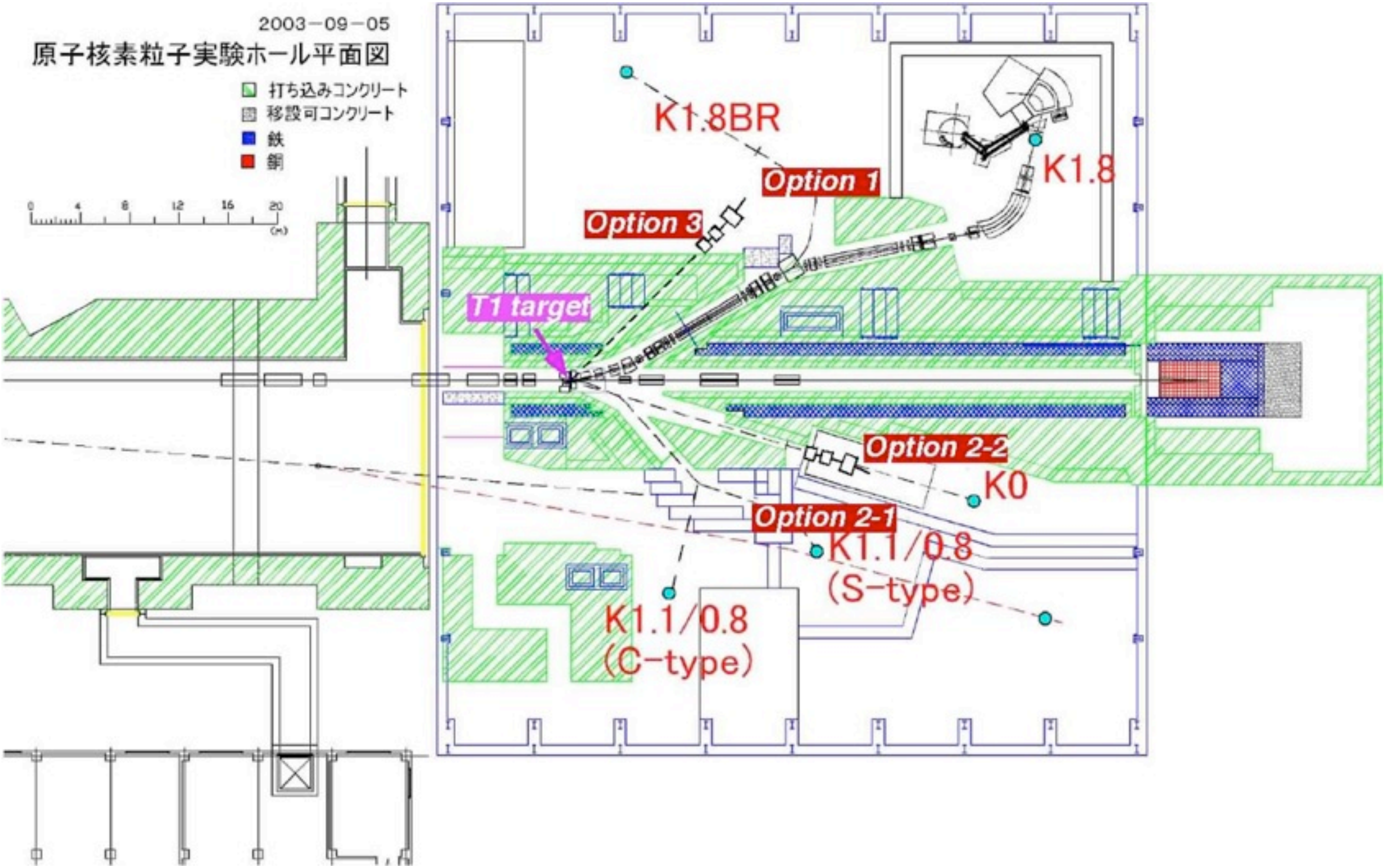


J-PARC Hadron Hall beams



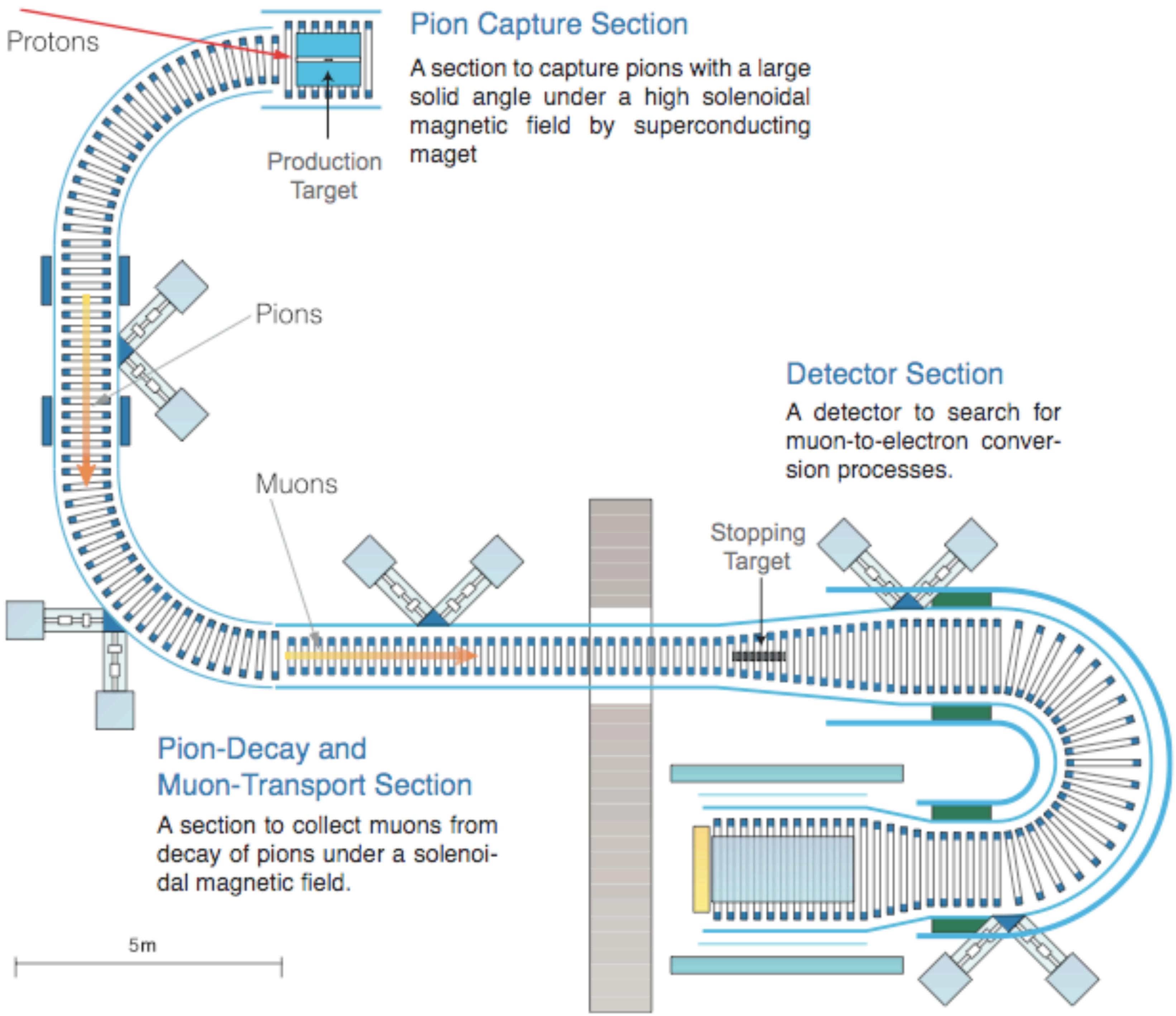


J-PARC Hadron Hall beamlines



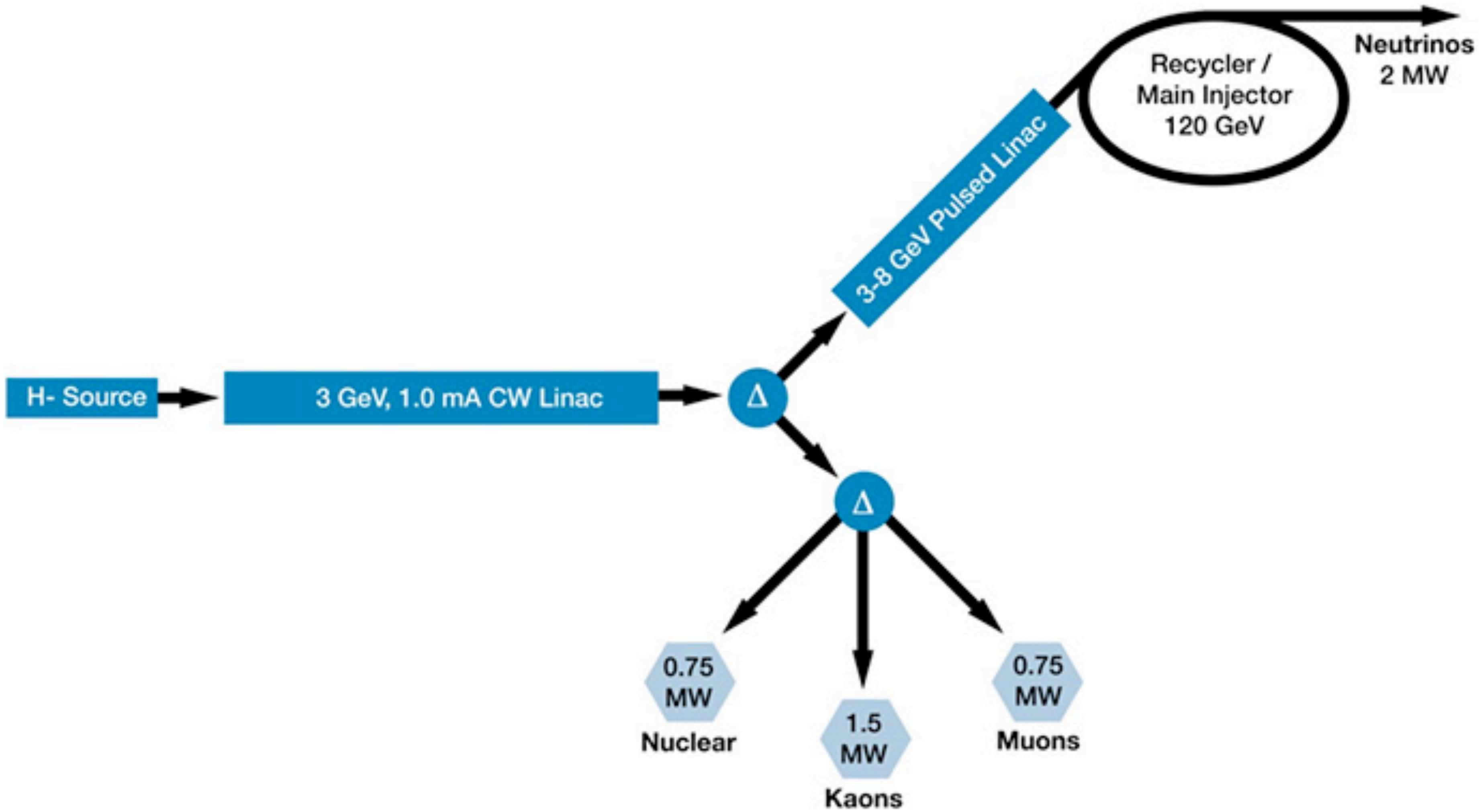
J-PARC muon beam for COMET experiment

- Aim for 10^{-16} **sensitivity** to μ-e conversion
- Require **~10^{18}** muons
- Proton beam: **8 GeV/c**



Particle beams outside CERN

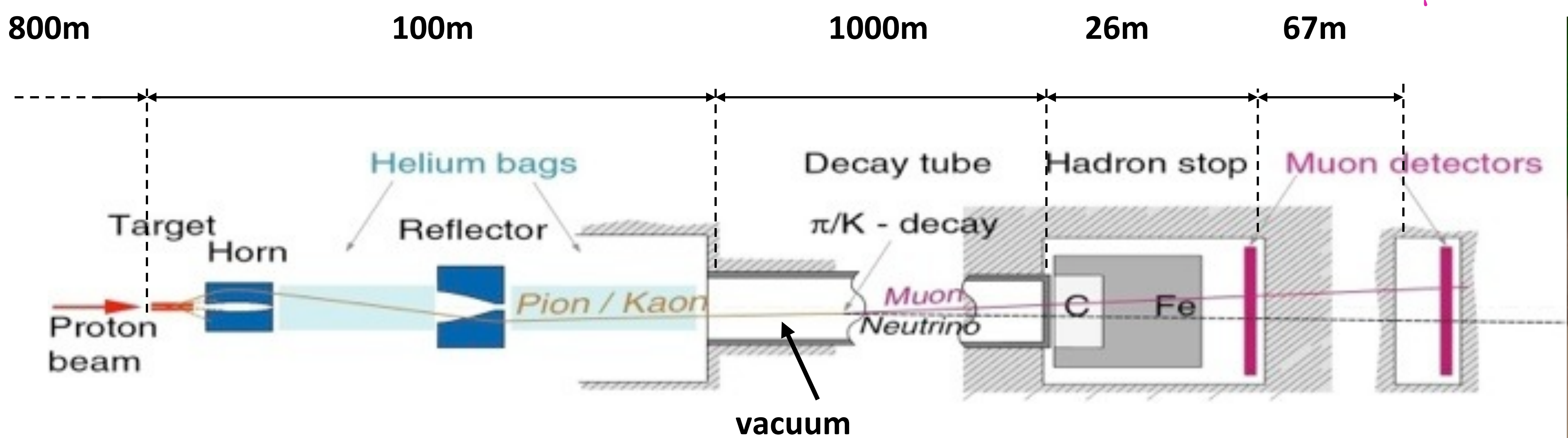
- **FermiLab Project-X**

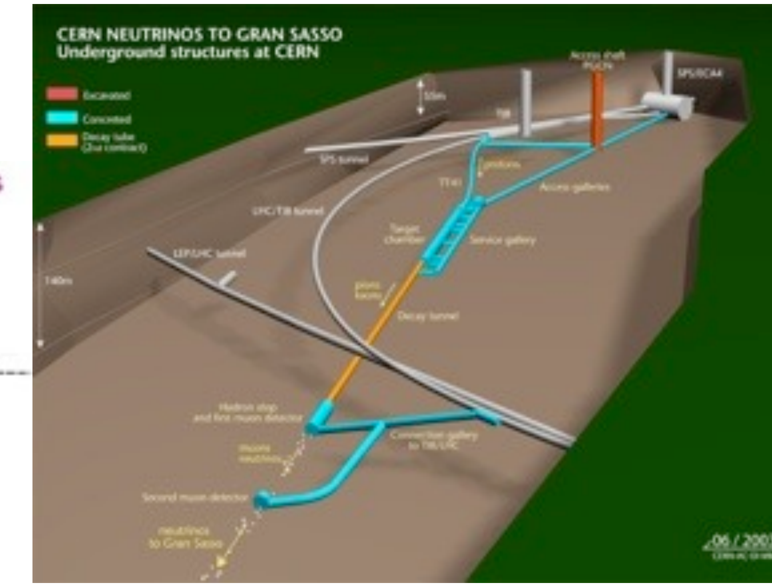


Secondary Neutrino Beams

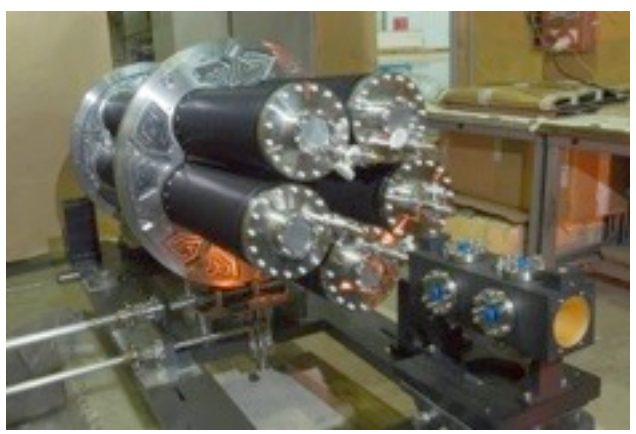
CNGS Neutrino beam at CERN

$p + C \rightarrow \text{(interactions)} \rightarrow \pi^+,\ K^+ \rightarrow \text{(decay)} \rightarrow \mu^+ + \nu_\mu$



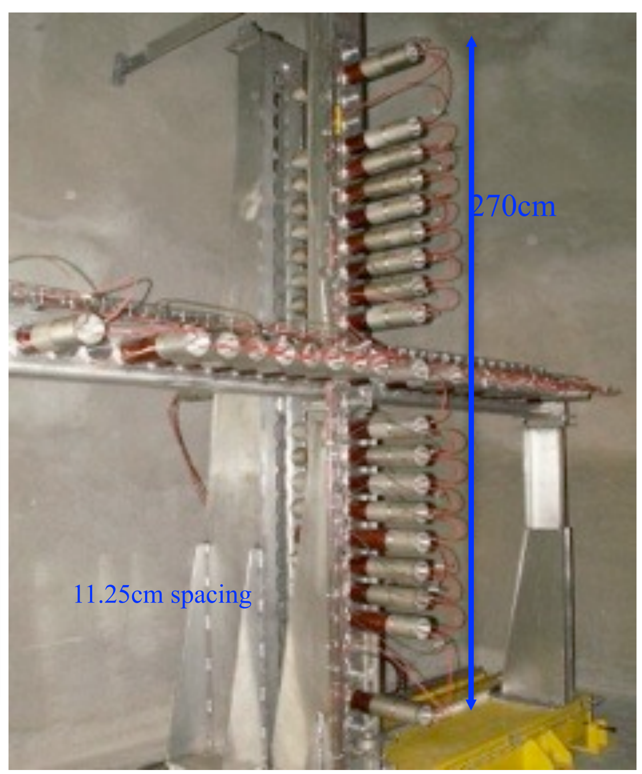


Target Unit



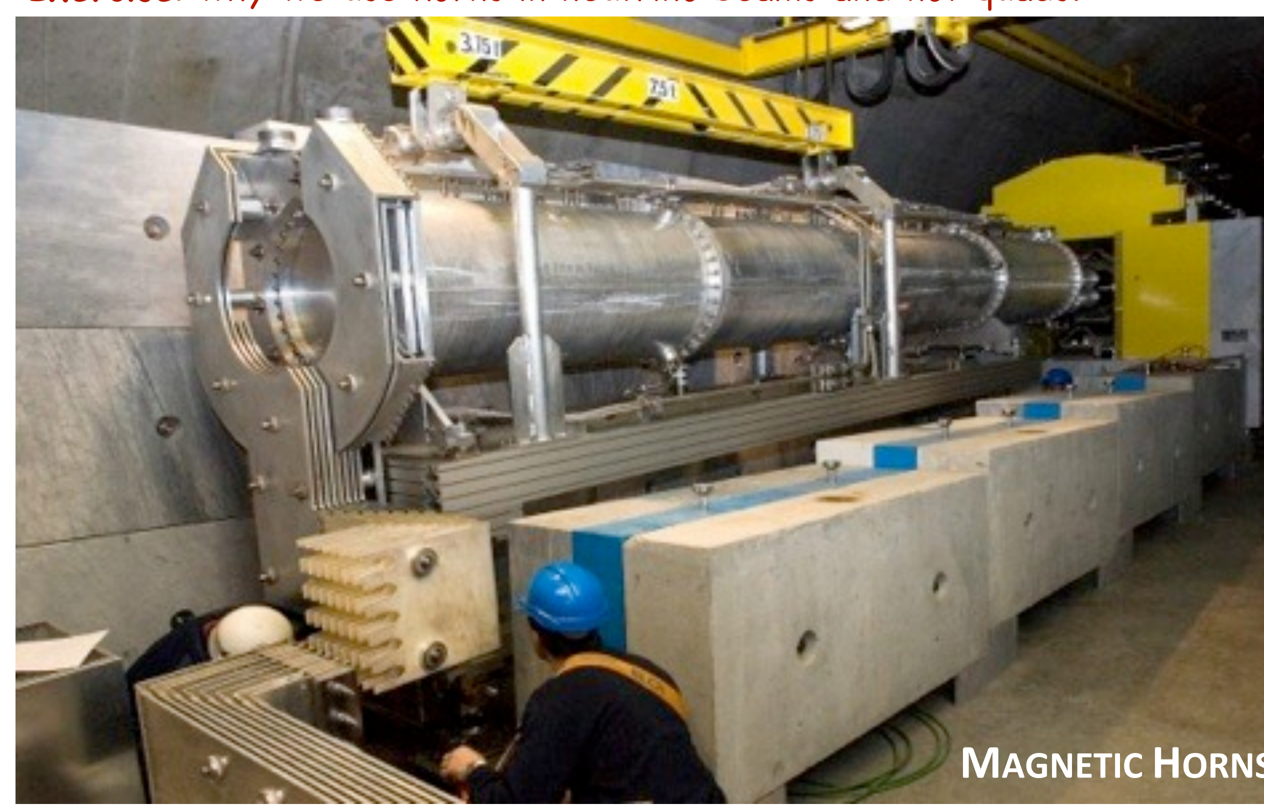
- C rods
- 5(4) mm Ø
- 5 in-situ spares

Muon detectors



- 2 × 41 fixed monitors
- 2 × 1 motorized monitor

Exercise: why we use horns in neutrino beams and not quads?



Thank You for your attention
Questions ?

Many thanks to my colleagues: L. Gatignon, N. Dobble

Bibliography with the school proceedings.